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PI/PD Name: Abraham Loeb

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race: (Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status: (Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☐ U.S. Citizen ☒ Permanent Resident ☐ Other non-U.S. Citizen

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PI/PD Name: Charles Alcock

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

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PI/PD Name: Lars E Hernquist

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☐ Not Hispanic or Latino

Race: (Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status: (Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

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PI/PD Name: Christopher W Stubbs

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race: (Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status: (Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☐ None

Citizenship: (Choose one) ☒ U.S. Citizen ☐ Permanent Resident ☐ Other non-U.S. Citizen

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PI/PD Name: Matias Zaldarriaga

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☒ Hispanic or Latino ☐ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status:
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☐ U.S. Citizen ☒ Permanent Resident ☐ Other non-U.S. Citizen

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PI/PD Name: Jacqueline N Hewitt

Gender: ☐ Male ☒ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☐ Not Hispanic or Latino

Race:
(Select one or more)

☐ American Indian or Alaska Native
☐ Asian
☐ Black or African American
☐ Native Hawaiian or Other Pacific Islander
☒ White

Disability Status:
(Select one or more)

☐ Hearing Impairment
☐ Visual Impairment
☐ Mobility/Orthopedic Impairment
☐ Other
☒ None

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PI/PD Name: Angelica de Oliveira-Costa

Gender: ☐ Male ☒ Female

Ethnicity: (Choose one response) ☒ Hispanic or Latino ☐ Not Hispanic or Latino

Race:
(Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☐ White

Disability Status:
(Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☐ None

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PI/PD Name: Colin J Lonsdale

Gender: ☒ Male ☐ Female

Ethnicity: (Choose one response) ☐ Hispanic or Latino ☒ Not Hispanic or Latino

Race: (Select one or more)
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Black or African American
- ☐ Native Hawaiian or Other Pacific Islander
- ☒ White

Disability Status: (Select one or more)
- ☐ Hearing Impairment
- ☐ Visual Impairment
- ☐ Mobility/Orthopedic Impairment
- ☐ Other
- ☒ None

Citizenship: (Choose one) ☐ U.S. Citizen ☒ Permanent Resident ☐ Other non-U.S. Citizen

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Reich, P., Max-Planck-Institut fur Radioastronomie
Reich, W., Max-Planck-Institut fur Radioastronomie
Ress, Martin, J., Cambridge U.
Ricciardi, S., Universita di Roma, La Sapienza
Rodrigo, P., Onsala
Romeo, G., INGF
Rovilos, E., Jodrell Bank Observatory
Ruhl, J.R., CWRU
Rusin, D., Penn

Reviewers not to include contd...

Sandvik, H.B., Industry
Santini, P., Universita di Roma, La Sapienza
Santos, M., Davis
Sault, R., U. Melbourne
Schlegal, D., LBNL
Schloerb, F.P., Umass
Schmitt, A., Washington U.
Schnittman, J., Johns Hopkins
Scoccimarro, R., Columbia
Scranton, R., CMU
Seljak, U., Princeton
Shankar, U., RRI, India
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Shelton, J., Rutgers
Shirokov, A., CITA
Silk, J., Oxford
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Stansby, B., Curtin University of Technology
Staveley-Smith, L., UWA
Stevens, J., University of Tasmania
Strauss, M., Princeton
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Tekle, E., LLNL
Thrall, H., Jodrell Bank Observatory
Torbet, E., UCSB
Torr, G. Australia National University
Townes, C.H., UC Berkeley
Traub, W.A., JPL
Trotter, C., Industry
Tsai, J., Industry
Turner, E.L., Princeton University
Tuthill, P.G., USYD
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Vilenkin, A., Tufts
Vittorio, N., Universita di Roma, Tor Vergata
Waga, I., Brazil
Wang, X., Chicago
Wang, Y., OU
Watson, R., Tenerife
Wayth, R., SAO
Webster, R., Melbourne University
Weinberg, D.H., OSU
Wheeler, C., Austin
Wheeler, J.A., Retired
White, S., Munich
Wyithe, J.S.B., Melbourne University
Xu, Y.X., LANL

Reviewers not to include contd...

Zehavi, I., CWRU
Zheng, Z., OSU
Zoller, P. Innsbruck U.

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 08-1		FOR NSF USE ONLY
NSF 07-567	01/30/08	NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)		
PHY - PHYSICS FRONTIER CENTER		

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNS# (Data Universal Numbering System)	FILE LOCATION
				082359691	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN)	SHOW PREVIOUS AWARD NO. IF THIS IS ☐ A RENEWAL ☐ AN ACCOMPLISHMENT-BASED RENEWAL	IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES ☐ NO ☒ IF YES, LIST ACRONYM(S)
042103580		

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
Harvard University	Harvard University 1350 Masschusetts Avenue Cambridge, MA. 021383846
AWARDEE ORGANIZATION CODE (IF KNOWN) 0021550000	
NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE Harvard College Observatory	ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE Harvard College Observator 60 Garden Street Cambridge, MA 02138-1516
PERFORMING ORGANIZATION CODE (IF KNOWN) 5300006452	

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

TITLE OF PROPOSED PROJECT **Collaborative Research: Fundamental Physics from 21cm Cosmology**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 4,995,978	60 months	08/01/08	0753452

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

☐ BEGINNING INVESTIGATOR (GPG I.G.2)
☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
☐ PROPRIETARY & PRIVILEGED INFORMATION (GPG I.D, II.C.1.d)
☐ HISTORIC PLACES (GPG II.C.2.j)
☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.D.1)
☐ VERTEBRATE ANIMALS (GPG II.D.5) IACUC App. Date ________
PHS Animal Welfare Assurance Number ________
☐ HUMAN SUBJECTS (GPG II.D.6) Human Subjects Assurance Number ________
Exemption Subsection ______ or IRB App. Date ________
☒ INTERNATIONAL COOPERATIVE ACTIVITIES: COUNTRY/COUNTRIES INVOLVED (GPG II.C.2.j)
AS
☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
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CO-PI/PD Matias Zaldarriaga	PhD	1998	617-384-9665	mzaldarriaga@cfa.harvard.edu

TPI 6754594

CERTIFICATION PAGE

Certification for Authorized Organizational Representative or Individual Applicant:

By signing and submitting this proposal, the Authorized Organizational Representative or Individual Applicant is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), nondiscrimination, and flood hazard insurance (when applicable) as set forth in the NSF Proposal & Award Policies & Procedures Guide, Part I: the Grant Proposal Guide (GPG) (NSF 08-1). Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

Conflict of Interest Certification

In addition, if the applicant institution employs more than fifty persons, by electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of the NSF Proposal & Award Policies & Procedures Guide, Part II, Award & Administration Guide (AAG) Chapter IV.A; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be dislosed to NSF.

Drug Free Work Place Certification

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Debarment and Suspension Certification

(If answer "yes", please provide explanation.)

Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

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Certification Regarding Lobbying

The following certification is required for an award of a Federal contract, grant, or cooperative agreement exceeding $100,000 and for an award of a Federal loan or a commitment providing for the United States to insure or guarantee a loan exceeding $150,000.

Certification for Contracts, Grants, Loans and Cooperative Agreements

The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

(2) If any funds other than Federal appropriated funds have been paid or will be paid to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with this Federal contract, grant, loan, or cooperative agreement, the undersigned shall complete and submit Standard Form-LLL, ''Disclosure of Lobbying Activities,'' in accordance with its instructions.

(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

This certification is a material representation of fact upon which reliance was placed when this transaction was made or entered into. Submission of this certification is a prerequisite for making or entering into this transaction imposed by section 1352, Title 31, U.S. Code. Any person who fails to file the required certification shall be subject to a civil penalty of not less than $10,000 and not more than $100,000 for each such failure.

Certification Regarding Nondiscrimination

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative is providing the Certification Regarding Nondiscrimination contained in Exhibit II-6 of the Grant Proposal Guide.

Certification Regarding Flood Hazard Insurance

Two sections of the National Flood Insurance Act of 1968 (42 USC §4012a and §4106) bar Federal agencies from giving financial assistance for acquisition or construction purposes in any area identified by the Federal Emergency Management Agency (FEMA) as having special flood hazards unless the:

(1) community in which that area is located participates in the national flood insurance program; and
(2) building (and any related equipment) is covered by adequate flood insurance.

By electronically signing the NSF Proposal Cover Sheet, the Authorized Organizational Representative or Individual Applicant located in FEMA-designated special flood hazard areas is certifying that adequate flood insurance has been or will be obtained in the following situations:

(1) for NSF grants for the construction of a building or facility, regardless of the dollar amount of the grant; and
(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME		

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER

*SUBMISSION OF SOCIAL SECURITY NUMBERS IS VOLUNTARY AND WILL NOT AFFECT THE ORGANIZATION'S ELIGIBILITY FOR AN AWARD. HOWEVER, THEY ARE AN INTEGRAL PART OF THE INFORMATION SYSTEM AND ASSIST IN PROCESSING THE PROPOSAL. SSN SOLICITED UNDER NSF ACT OF 1950, AS AMENDED.

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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NSF 07-567	01/30/08	NSF PROPOSAL NUMBER
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) PHY - PHYSICS FRONTIER CENTER		

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042103594		

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE	ADDRESS OF AWARDEE ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE
Massachusetts Institute of Technology	77 MASSACHUSETTS AVE Cambridge, MA 02139-4307
AWARDEE ORGANIZATION CODE (IF KNOWN) 0021782000	
NAME OF PERFORMING ORGANIZATION, IF DIFFERENT FROM ABOVE	ADDRESS OF PERFORMING ORGANIZATION, IF DIFFERENT, INCLUDING 9 DIGIT ZIP CODE
PERFORMING ORGANIZATION CODE (IF KNOWN)	

IS AWARDEE ORGANIZATION (Check All That Apply) (See GPG II.C For Definitions) ☐ SMALL BUSINESS ☐ FOR-PROFIT ORGANIZATION ☐ MINORITY BUSINESS ☐ WOMAN-OWNED BUSINESS ☐ IF THIS IS A PRELIMINARY PROPOSAL THEN CHECK HERE

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$ 4,999,998	60 months	08/01/08	0753473

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

- ☐ BEGINNING INVESTIGATOR (GPG I.G.2)
- ☐ DISCLOSURE OF LOBBYING ACTIVITIES (GPG II.C)
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- ☐ HISTORIC PLACES (GPG II.C.2.j)
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- ☐ HIGH RESOLUTION GRAPHICS/OTHER GRAPHICS WHERE EXACT COLOR REPRESENTATION IS REQUIRED FOR PROPER INTERPRETATION (GPG I.G.1)

PI/PD DEPARTMENT	PI/PD POSTAL ADDRESS
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CERTIFICATION PAGE

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NAME		

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Summary

Over the past four decades, cutting-edge observations of our Universe resulted in the discovery of startling new fundamental physics: dark matter, dark energy, and a possible early period of cosmic inflation. We propose a center that will explore a new frontier for making precision measurements through most of the observable volume of the Universe.

The atomic hydrogen gas formed soon after the big-bang was affected significantly by processes ranging from quantum fluctuations during a possible early epoch of inflation to irradiation by the first galaxies at late times. Mapping this gas through its resonant 21cm line serves a dual role as a powerful probe of both fundamental physics and astrophysics.

The three-dimensional 21cm maps could set unprecedented statistical constraints on the power spectrum of cosmic density fluctuations and its growth with cosmic time. The reduced uncertainties could allow for precise measurements of fundamental parameters, such as the mass of the neutrino or the equation of state of dark energy (from acoustic oscillations in the 21cm power spectrum), and will test generic predictions of cosmic inflation for deviations of the density fluctuations from scale invariance and gaussianity. The measured growth of the fluctuations with cosmic time would constrain alternative theories of gravity.

The proposed *Center for 21cm Cosmology (CTC)* will provide a forum for bringing together theoretical physicists, instrument builders, and data analysts to work side by side in initiating this frontier field of physics. We will use cosmological simulations and basic theory to forecast the information that might be extracted from future observations of the Universe at redshifts $z \gtrsim 20$ or $z \lesssim 6$ (corresponding to less than 200 million years or more than a billion years after the big bang) in the presence of foregrounds. The *Murchison Wide-Field Array* (MWA), funded for construction by NSF and the Australian government, is focused on astronomical questions and is designed to cover the redshift range of 6–17 which falls outside the cosmic epochs that are most useful for constraining fundamental physics. Our studies will define the requirements to be met by the design of a future extension of MWA, termed the *Array for Imaging the Dark Ages* (AIDA). As soon as data becomes available from MWA, we will use it to improve the modeling of the ionosphere and the Galactic synchrotron foreground. In parallel, we will start to develop critical technology for future observatories that will operate at the relevant low frequencies of $200\mathrm{MHz}[(1+z)/7]^{-1}$. Overall, the proposed *CTC* would foster theoretical and experimental work that will make use of the data coming from the MWA and will establish the basis for its future extension to explore inflation, dark matter, and dark energy, as well as to be alert to possible new physics.

The proposed research has a broad impact for society that goes well beyond studies of fundamental physics and the tracing of our origins to the beginning of the Universe. Developing the technology of low-frequency radio detectors may well lead to improvements in communication and tracking devices as well as in defense-related systems. Better measurements and models of the ionosphere will provide a better understanding of the Earth's environment. The proposed *CTC* will educate students and postdocs in electromagnetism, low-frequency radio technology, ionospheric plasma physics, and advanced computer algorithms, all of which should be extremely useful for practical applications of benefit to high-tech industry and society at large.

TABLE OF CONTENTS

For font size and page formatting specifications, see GPG section II.C.

Appendix Items:

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

TABLE OF CONTENTS

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Appendix Items:

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Executive Summary

Over the past four decades, cutting-edge observations of our Universe resulted in the discovery of startling new fundamental physics: dark matter, dark energy, a possible early period of cosmic inflation, and neutrino masses. These discoveries were made possible by new, more accurate observational tools. We propose a center that will explore a new frontier for making precision measurements through most of the observable volume of the Universe. Such measurements should shed light on the nature of dark matter, dark energy and inflation, and could potentially open the door for unexpected discoveries.

The atomic hydrogen gas formed soon after the big-bang was affected significantly by processes ranging from quantum fluctuations during a possible early epoch of inflation to irradiation by the first galaxies at late times. Mapping this gas through its resonant 21cm line serves a dual role as a powerful probe of both fundamental physics and astrophysics. The facets of fundamental physics include the initial density fluctuations imprinted by inflation as well as the nature of the dark matter which amplifies these fluctuations during the matter-dominated era. It is possible to avoid the contamination from uncertain astrophysical processes by observing the Universe before the first galaxies formed (the so-called *Dark Ages*) or at late times when the remaining dense pockets of hydrogen trace the distribution of matter on large spatial scales. According to the current concordance cosmological model, the 21cm brightness fluctuations of hydrogen were shaped by fundamental physics (inflation, dark matter and atomic physics) at redshifts $z \gtrsim 20$ and $z \lesssim 6$, and by astrophysical processes at intermediate redshifts.

21cm cosmology opens a new window into the Universe and its underlying physics. This window could potentially provide us with new clues about the origin (inflation) and composition (dark matter and dark energy) of the Universe. The 21cm signal covers most of the three-dimensional volume of the observable Universe, orders of magnitude beyond the volume available in existing cosmological data sets. 21cm images would also trace density fluctuations on smaller spatial scales than ever before probed, at an early time when the fluctuations are still in the perturbative regime. They therefore hold the promise for obtaining better statistical constraints on the power-spectrum of cosmic density fluctuations and its growth with cosmic time. The reduced cosmic variance could allow for precise measurements of fundamental parameters, such as the mass of the neutrino (in the range expected from the latest atmospheric neutrino data) or the equation of state of the dark energy (from acoustic oscillations in the 21cm power spectrum), and will test generic predictions of inflation for deviations of the density fluctuations from scale invariance and gaussianity. The measured growth of the fluctuations with cosmic time would constrain alternative theories of gravity.

The Murchison Wide-Field Array (MWA), funded by NSF and the Australian government, is focused on astronomical aspects of 21cm cosmology and is designed to cover the redshift range of 6–17 which falls outside the cosmic epochs where fundamental physics is most easily accessible. The investigators on this proposal serve as the American partners in this pathfinder observatory. We plan to use the information obtained from MWA in examining the prospects for constraining fundamental physics by a future extension of it, termed the *Array for Imaging the Dark Ages (AIDA)*. The goal of the proposed *Center for 21cm Cosmology (CTC)* is to bring together physicists, astrophysicists, and instrumentalists, to examine the role of 21cm cosmology in constraining fundamental physics. The time is ripe to foster such activity, as MWA prepares to measure the anticipated 21cm signal. In analogy, the

Center for Gravitational Wave Physics was established at Penn State University following the investments of NSF funds in LIGO and prior to the detection of gravitational waves.

Challenging experimental frontiers is not new in cosmology. Four decades ago, experimentalists could not have imagined that anisotropies in the Cosmic Microwave Background (CMB) radiation at a fractional amplitude of $\sim 10^{-5}$ would become readily detectable thanks to advances in technology. The theoretical and experimental work on the CMB between 1960-1990 paved the way for the great advances that we have witnessed over the past decade in terms of measuring fundamental parameters of our Universe. The 21cm data set should provide a natural extension of current CMB research in that it can potentially provide a far larger data set on the distribution of cosmic matter (in three dimensions and down to smaller spatial scales). If all experimental challenges are met, redshifted 21cm observations could detect with unprecedented precision new dark matter components (such as massive neutrinos), constrain the behavior of dark energy at high redshifts, as well as unravel deviations from scale-invariance and gaussianity which are naturally predicted by popular models of inflation. These signatures can be extracted from the 21cm power-spectrum at both high or low redshifts, or from the angular dependence of the power-spectrum due to velocity perturbations at intermediate redshifts.

The proposed *CTC* will provide a focus for bringing together theoretical physicists, instrument builders, and data analysts to work side by side in initiating this frontier field of physics. The Center mode of support is critical to this effort because it will ensure that these different groups are able to work together at the same time. We will use cosmological simulations and basic theory to forecast the information that can be extracted from future observations of the Universe at redshifts $z \gtrsim 20$ or $z \lesssim 6$ in the presence of radiation from foreground sources. These simulations will define the requirements and contribute to the design of *AIDA*. As soon as data becomes available from MWA, we will use it to improve the modeling of the ionosphere and the subtraction of the Galactic synchrotron foreground. In parallel, we will start to develop critical technology for future observatories that will operate at the relevant low frequencies of $200\text{MHz}[(1+z)/7]^{-1}$. Overall, the proposed Center will foster theoretical and experimental work that will make use of the data coming from the NSF-supported MWA and will establish the basis for its future extension to explore inflation, dark matter, dark energy, and unexpected new physics.

MIT and Haystack observatory are heavily involved in the experimental component of MWA and will lead the antenna development effort for *AIDA*. The proposed antenna testing will be done at the MIT Lincoln Laboratory. Harvard University is currently supporting the *Institute for Theory and Computation* (ITC [1]) in which major theoretical work on 21cm cosmology has been done over the past four years. The proposed data analysis and cosmological simulations will be performed in the ITC high-performance computational facility, which currently includes a 4096 processor IBM BlueGene, as well as a new Beowulf cluster consisting of 10^3 processors and having a total memory of several Tbytes.

The proposed research has a broad impact for society that goes well beyond studies of fundamental physics and the tracing of our origins to the beginning of the Universe. Developing the technology of low-frequency radio detectors may well lead to improvements in communication and tracking devices as well as in defense-related systems. Better measurements and models of the ionosphere will provide a better understanding of the Earth's environment. The Center will educate students and postdocs in electromagnetism, low-frequency radio technology, ionospheric plasma physics, and advanced computer algorithms, all of which should be extremely useful for practical applications of benefit to high-tech industry and society at large.

The fundamental goals of the *Center for 21cm Cosmology* will be approached through six major activities (MAs):

- **MA1: Fundamental Physical Processes** – involves a detailed theoretical study of the underlying physics. We will explore implications of future 21cm data for models of cosmic inflation and the nature of dark matter and dark energy. We will also study the underlying atomic physics of the cosmic gas with better accuracy than previously done.
- **MA2: Observable Signatures** – involves a detailed theoretical study of the expected 21cm signal and the redshift (or observed wavelength) ranges where it is likely to provide the most useful information on fundamental physics.
- **MA3: Data Analysis and Signal Extraction** – involves a study of the expected signal-to-noise ratio and the foreground contamination at different observed wavelengths and angular scales.
- **MA4: Testbed Data and Antenna Development** – involves the analysis of MWA data (MA4.1) and its implications for the design of *AIDA*, as well as the development of antennas (MA4.2) to achieve the goals defined by MA1–MA3.
- **MA5: Design of *AIDA*** – involves a design of a future array for the study of fundamental physics, based on MA1–MA4.
- **MA6: Leveraging the Activity to Society at Large** – involves training and education initiatives that uniquely relate to the proposed activity. We will organize and host visitors and community workshops, and will establish and maintain links between the center and the broader physics community.

The associated senior investigators include **Hernquist**, **Loeb** (PI), and **Zaldarriaga**, who led many of the recent advances in theoretical studies of *21cm Cosmology*; **Guth** who pioneered inflation; **Wilczek** who pioneered fundamental aspects of the standard model of particle physics (including the axion as a dark matter candidate); **Bertschinger**, **Narayan**, and **Tegmark**, who led studies of cosmological structure formation and derived some of the best statistical constraints from existing data on dark matter and inflation; **Burke**, **Greenhill**, **Hewitt** (leading co-I), **Lonsdale**, and **Rogers**, who are leading the experimental effort to measure the 21cm signal with MWA; **Dalgarno**, **Kirby**, **Rybicki**, and **Sadeghpour**, who pioneered studies of the underlying atomic physics; **Alcock**, **Shapiro**, and **Stubbs**, who derived fundamental constraints on the theory of gravity and the nature of dark matter; **de-Oliviera Costa** and **Finkbeiner** who are experts on the low-frequency foregrounds; and **Gould** and **Porro** who lead our educational and public outreach effort. The senior investigators will focus their contributions on their complementary areas of expertise. The leaders of each **MA** are listed (by order of relevance) in the proposal.

List of Participating Senior Investigators by Name, Institutional Affiliation, and Department Affiliation

Harvard University, Departments of Astronomy and Physics: Charles Alcock, Alexander Dalgarno. Douglas Finkbeiner, Lincoln Greenhill, Lars Hernquist, Kate Kirby, Abraham Loeb (PI), Ramesh Narayan, George Rybicki, Irwin Shapiro, Christopher Stubbs, Matias Zaldarriaga

Smithsonian Astrophysical Observatory (SAO), Atomic & Molecular Physics Division: Hossein Sadeghpour

SAO, Science Education Department: Roy Gould

Massachusetts Institute of Technology (MIT), Kavli Institute for Astrophysics and Space Research: Ed Bertschinger, Bernard Burke, Angelica de Oliveira Costa, Alan Guth, Jacqueline Hewitt (leading co-I), Irene Porro, Max Tegmark, Frank Wilczek.

MIT, Haystack Observatory: Colin Lonsdale, Alan Rogers

Results from Prior NSF Support

1. "The Low Frequency Array (LOFAR) - A Digital Radio Telescope," AST-0121164 -$2,000,000- PI's: C. J. Lonsdale, J. N. Hewitt, J. E. Salah; 1 Sep 2001 - 30 Oct 2004

Our interest in studying the high-redshift Universe through the redshifted 21cm line of neutral hydrogen began in 1999 with MIT's involvement, by invitation, in the newly created Low Frequency Array (LOFAR) project led by the Dutch. MIT's participation in LOFAR was supported by the award of this ITR grant, and continued through the Preliminary Design Review (PDR) in October 2003. The decision by the Dutch to build LOFAR in northern Europe, where radio frequency interference is significant, led to MIT's decision to collaborate instead with the Australia Telescope National Facility and several Australian universities on an array, the Mileura Widefield Array [now Murchison Widefield Array (MWA)], to be built in the radio quiet Western Australian outback. For LOFAR, the MIT group carried out science definition, technical design, performance simulation, site evaluation, and education and outreach. These activities, supplemented by funding from MIT, fed directly into the MWA effort as described below.

For the Epoch of Reionization (EoR) science definition, a series of papers presenting techniques for detecting the 21cm EoR power spectrum and a calculation of the expected performance of a low frequency array were published and greatly influenced the design of the MWA. For the technical design, subsystem designs for a 110-240 MHz antenna tile, a beamformer, and a widefield correlator were developed. In the case of the antenna tile and beamformer, prototypes were constructed and tested in the field in Western Australia. A software package dubbed "MAPS" (MIT Array Performance Simulator) was written that is capable of providing realistic simulations of low-frequency radio array data. This software is publicly available and we are using it to guide our final design of the MWA. MIT supported the LOFAR site evaluation activities which led to our selection of the Western Australian site.

List of Resulting Publications:

• J.D. Bowman, M.F Morales and J. N. Hewitt, "The Sensitivity of First Generation Epoch of Reionization Observatories and Their Potential for Differentiating Theoretical Power Spectra", Astrophys. J. **638**, 20 (2006).

• J.D. Bowman, M.F. Morales and J.N. Hewitt, "Probing the Epoch of Reionization with Power Spectrum Measurements by the First Generation of Low Frequency Radio Arrays", Bulletin of the American Astronomical Society **37**, 1217 (2005).

• E. Kratzenberg, M. N. Afsar and Y. Wang, "Complex permittivity measurement using the annular slot,", IEEE Antennas and Propagation Society International Symposium, 3-8 July 2005, Washington, DC, **pt. 3A**, 400 (2005).

• C. J. Lonsdale, "LOFAR: The Low Frequency Array," Future Directions in High Resolution Astronomy: A Celebration of the 10th Anniversary of the VLBA, ASP Conference Series **340**, J.D. Romney and M.J. Reid, Eds., p. 547 (2005).

• J.E. Salah, C.J. Lonsdale, D. Oberoi, R.J. Cappallo and J.C. Kasper, "Space weather capabilities of low frequency radio arrays," Proceedings of the SPIE **AM133**, 59010G (2005).

• M.F. Morales and J. N. Hewitt, "Toward Epoch of Reionization Measurements with Wide-

Field Radio Observations", Astrophys. J. **615**, 7 (2004).

• B.E. Cohanim, J. N. Hewitt, J. N. and O. de Weck, "The Design of Radio Telescope Array Configurations using Multiobjective Optimization: Image Performance versus Cable Length" Astrophys. J. Suppl. **154**, 705 (2004).

• C.J. Lonsdale, S.S. Doeleman and D. Oberoi, "Efficient imaging strategies for next-generation radio arrays", Experimental Astronomy **17(1-3)**, 345 (2004).

• D. Oberoi and J.C. Kasper, J.C., "LOFAR: The potential for solar and space weather studies", Planetary and Space Science, **52**, 1415 (2004).

• A.E.E. Rogers, P. Pratap, E. Kratzenberg and M.A. Diaz, "Calibration of active antenna arrays using a sky brightness model", Radio Science, **39(2)**, RS2023 (2004).

• J. N. Hewitt, "Prospects for Observing the Collapse, Reheating, and Reionization of Post-Recombination Neutral Hydrogen", Bull. Am. Astr. Soc. **33**, 1426 (2002).

• C.J. Lonsdale, "Frequency-dependent tradeoffs in array configurations," SKA: Defining the Future, Proceedings of a Workshop held in Berkeley, CA, July 9-12 (2001). http://www.skatelescope.org/skaberkeley/html/presentations/pdf.htm

• S. Doeleman, "Simulating a large-N SKA", SKA: Defining the Future, Proceedings of a Workshop held in Berkeley, CA, July 9-12 (2001). http://www.skatelescope.org/skaberkeley/html/presentations/pdf.htm

• R. Cappallo, "Large Array Signal Processing", SKA: Defining the Future, Proceedings of a Workshop held in Berkeley, CA, July 9-12 (2001). http://www.skatelescope.org/skaberkeley/html/presentations/pdf.htm

• C.J. Lonsdale, S.S. Doeleman, R.J. Cappallo, J.N. Hewitt and A.R. Whitney, "Exploring the Performance of Large-N Radio Astronomical Arrays", Proc. SPIE **4015**, 126 (2000).

2. "Theoretical Studies of Fluctuations in the Redshifted 21cm Line"" AST-0506556 -$375,880- PI's: M. Zaldarriaga, L. Hernquist; 15 Jul 2005 - 30 June 2008

We analyzed results from a large volume simulation of Hydrogen reionization to track the growth of ionized regions around high-redshift galaxies. The large volume allowed us to accurately characterize the size distribution of ionized regions throughout most of the reionization process. This work confirmed a picture anticipated by our analytic models: ionized regions grow collectively around highly-clustered sources, and have a well-defined characteristic size. In another paper, we used our simulations to make detailed predictions of the power spectrum of 21cm brightness temperature fluctuations from the epoch of reionization. In particular, we considered the contribution of 3rd and 4th order terms to the power spectrum, which arise because the 21cm brightness temperature involves a product of the hydrogenic neutral fraction and the gas density. In our simulated models, the higher-order terms are significant: neglecting them leads to 100% errors in 21cm power-spectrum predictions on wave-numbers of $k > 1$ Mpc^{-1} when the neutral fraction is $\langle x_H \rangle \sim 0.5$. In a different paper we investigated to what extent future 21cm observations could constrain cosmological parameters. We found that upcoming observatories will be sensitive to the 21cm signal over a wide range of scales, from larger than 100 to as small as 1 comoving Mpc. We further showed that the first generation of 21cm observations should moderately improve existing constraints on cosmological parameters for certain low-redshift reionization scenarios. We also investigated the potential of second generation measurements of redshifted 21cm radiation from before and during the EoR to reconstruct the matter density fluctuations along the line of sight using gravitational lensing.

List of Resulting Publications:

• A. Lidz, O. Zahn, M. McQuinn, M. Zaldarriaga and L. Hernquist, "Detecting the Rise and Fall of 21 cm Fluctuations with the Murchison Widefield Array," arXiv:0711.4373 [astro-ph].

• C. A. Faucher-Giguere, J. X. Prochaska, A. Lidz, L. Hernquist and M. Zaldarriaga, "A Century of Cosmology: A Direct Precision Measurement of the Intergalactic Lyman-alpha Opacity at $2 < z < 4.2$," arXiv:0710.4522 [astro-ph].

• M. McQuinn, A. Lidz, M. Zaldarriaga, L. Hernquist and S. Dutta, "Probing the Neutral Fraction of the IGM with GRBs during the Epoch of Reionization," arXiv:0710.1018 [astro-ph].

• C. A. Faucher-Giguere, J. X. Prochaska, A. Lidz, L. Hernquist and M. Zaldarriaga, "A Direct Precision Measurement of the Intergalactic Lyman-alpha Opacity at $2 < z < 4.2$," arXiv:0709.2382 [astro-ph].

• M. McQuinn, L. Hernquist, M. Zaldarriaga and S. Dutta, "Studying Reionization with Ly-alpha Emitters," arXiv:0704.2239 [astro-ph].

• C. A. Faucher-Giguere, A. Lidz, M. Zaldarriaga and L. Hernquist, "The Line-of-Sight Proximity Effect and the Mass of Quasar Host Halos," arXiv:astro-ph/0701042.

• M. McQuinn, A. Lidz, O. Zahn, S. Dutta, L. Hernquist and M. Zaldarriaga, "The Morphology of HII Regions during Reionization," Mon. Not. Roy. Astron. Soc. **377**, 1043 (2007) [arXiv:astro-ph/0610094].

• O. Zahn, A. Lidz, M. McQuinn, S. Dutta, L. Hernquist, M. Zaldarriaga and S. R. Furlanetto, "Simulations and Analytic Calculations of Bubble Growth During Hydrogen Reionization," Astrophys. J. **654**, 12 (2006) [arXiv:astro-ph/0604177].

• M. McQuinn, O. Zahn, M. Zaldarriaga, L. Hernquist and S. R. Furlanetto, "Cosmological Parameter Estimation Using 21 cm Radiation from the Epoch of Reionization," Astrophys. J. **653**, 815 (2006) [arXiv:astro-ph/0512263].

• K. Lai, A. Lidz, L. Hernquist and M. Zaldarriaga, "The Impact of Temperature Fluctuations on the Lyman-alpha Forest Power Spectrum," Astrophys. J. **644**, 61 (2006) [arXiv:astro-ph/0510841].

• S. R. Furlanetto, M. Zaldarriaga and L. Hernquist, "The Effects of Reionization on Lyman-alpha Galaxy Surveys," Mon. Not. Roy. Astron. Soc. **365**, 1012 (2006) [arXiv:astro-ph/0507266].

• M. McQuinn, S. R. Furlanetto, L. Hernquist, O. Zahn and M. Zaldarriaga, "The Kinetic Sunyaev-Zel'dovich Effect from Reionization," Astrophys. J. **630**, 643 (2005) [arXiv:astro-ph/0504189].

• O. Zahn, M. Zaldarriaga, L. Hernquist and M. McQuinn, "The influence of non-uniform reionization on the CMB," Astrophys. J. **630**, 657 (2005) [arXiv:astro-ph/0503166].

3. "Mileura Wide-Field Array Science and Technology Demonstrator," AST-0457585 -$4,898,882- PI's: C. J. Lonsdale, L. J. Greenhill,J. N. Hewitt, J. E. Salah; 1 June 2006 - 31 May 2010

The MIT collaboration, joined by the Harvard-Smithsonian Center for Astrophysics

(CfA), successfully proposed to build the MWA low-frequency demonstrator for which one of the principal science goals is to demonstrate the performance needed to detect the EoR power spectrum if the Universe is still sufficiently neutral at redshifts of 12 or smaller. In the first year of this program, papers forecasting our ability to recover cosmological parameters and exploring the challenges of removing foregrounds have been published. Papers describing field testing (supported by MIT seed funds) in Western Australia and detection with the test system of a giant pulse from a pulsar were also published. A manufacturing prototype for the 80-300 MHz antenna tiles was built and tested, and the correlator design was finalized. A beta version of the real-time calibration system (supported by CfA seed funds) is nearly complete.

List of Resulting Publications:

• J.D. Bowman, A.E.E. Rogers and J.N. Hewitt, "Toward Empirical Constraints on the Global Redshifted 21cm Brightness Temperature During the Epoch of Reionization", Astrophys. J., in press (2007).

• C.L. Carilli, J.N. Hewitt and A. Loeb, "Low Frequency Radio Astronomy from the Moon: Cosmic Reionization and More", Astrophysics Enabled by the Return to the Moon, M. Livio, Ed., Cambridge University Press, in press (2007). [arXiv:astro-ph/0702070]

• J.D. Bowman, M.F. Morales and J.N. Hewitt, "Constraints on Fundamental Cosmological Parameters with Upcoming Redshifted 21cm Observations", Astrophys. J. **661**, 1 (2007).

• J.D. Bowman, A.E.E. Rogers and J.N. Hewitt, J. N. "First Constraints on the Global Redshifted 21cm Background During the Epoch of Reionization", Bull. Am. Astr. Soc. **211**, #119.06 (2007).

• R. Bhat, R. Wayth, H. Knight, J. Bowman, D. Oberoi, D. Barnes, F. Briggs, R. Cappallo, D. Herne, J. Kocz, C. Lonsdale, M. Lynch, B. Stansby, J. Stevens, G. Torr, R. Webster and S. Wyithe, "Detection of Crab Giant Pulses Using the Mileura Widefield Array Low Frequency Demonstrator Field Prototype System", Astrophys. J. **655**, 618 (2007).

• J. Bowman, D. Barnes, F. Briggs, B. Corey, M. Lynch, R. Bhat, R. Cappalo, S. Doeleman, B. Fanous, D. Herne, J. Hewitt, C. Johnston, J. Kasper, J. Kocz, E. Kratzenberg, C. Lonsdale, M. Morales, D. Oberoi, J. Salah, B. Stansby, J. Stevens, G. Torr, R. Wayth, R. Webster and S. Wyithe, "Field Deployment of Prototype Antennas for the Mileura Widefield Array Low Frequency Demonstrator", Astrophys. J. **133**, 150 (2007).

• M.F. Morales, J.D. Bowman and J.N.Hewitt, "Improving Foreground Subtraction in Statistical Observations of 21cm Emission from the Epoch of Reionization", Astrophys. J. **648**, 767 (2006).

• M.F. Morales, J.D. Bowman, R. Cappallo, J.N. Hewitt, "Statistical EOR Detection and the Mileura Widefield Array", New Astronomy Reviews **50**, 173 (2006).

• M.F. Morales, J.D. Bowman and J.N. Hewitt, "Improving Foreground Subtraction in EOR Power Spectrum Observations", Bull. Am. Astr. Soc. **37**, 1217 (2005).

4. "CMB and 21cm Cosmology in the Presence of Foregrounds," AST-0607597 -$437,789- PI's: A. de Oliveira-Costa and M. Tegmark; 1 June 2006 - 31 May 2009

Two of the most promising cosmological probes are the Cosmic Microwave Background (CMB) polarization maps and three-dimensional tomographic maps of redshifted 21cm emission, with the potential to constrain the nature of dark matter, dark energy, the early Universe, and the end of the cosmic dark ages, with unprecedented accuracy. However, these constraints will only be as good as our understanding of galactic foreground contamination. The proposed project involves a comprehensive study of polarized and unpolarized galactic emission from 50 MHz to 500 GHz combining available data with simulations, useful both for foreground-cleaning of actual measurements and for "optimizing" the design of future experiments. Publicly available products will include improved foreground-cleaned unpolarized and polarized WMAP CMB maps with well-quantified residuals, realistic 21cm foreground data cubes, cleaning algorithms and software as well as information-theory-based "designer's guide" software translating experimental design specifications and foreground modeling into attainable cosmological constraints. In the first year of our study we already developed an unpolarized galactic emission model from 10 MHz to 94 GHz. We are in the final stages of making publicly available the sky maps that this model produces, as well as all the data we used to produce our model.

List of Resulting Publications:

• A. de Oliveira-Costa, M. Tegmark, B. Gaensler, J. Jonas and T. Landecker, "A model of the diffuse Galactic Emission from 10 MHz to 100 GHz", Astrophys. J., to be submitted (2007).

• G. De Troia, P.A.R. Ade, J.J. Bock, J.R. Bond, J. Borrill, A. Boscaleri, P. Cabella, C.R. Contaldi, B.P. Crill, P. de Bernardis, G. De Gasperis, A. de Oliveira-Costa, G. Di Stefano, P. G. Ferreira, E. Hivon, A.H. Jaffe, T.S.Kisner, M. Kunz, W.C. Jones, A.E. Lange,M.Liguori, S. Masi, S. Matarrese, P.D. Mauskopf, C.J. MacTavish, A. Melchiorri, T.E. Montroy, P. Natoli, C.B. Netterfield, E. Pascale, F. Piacentini, D. Pogosyan, G.Polenta, S. Prunet, S. Ricciardi, G. Romeo, J.E. Ruhl, P. Santini, M. Tegmark, M. Veneziani and N. Vittorio, "Searching for non Gaussian signals in the BOOMERanG 2003 CMB maps", Astrophys. J. **670**, 73 (2007).

• W.C. Jones & the BOOMERanG Collaboration, "Observations of the temperature and polarization anisotropies with BOOMERANG", NewAR **50**, 945 (2007).

• S. Masi & the BOOMERanG Collaboration, "The millimeter sky as seen with BOOMERanG", NewAR **51**, 236 (2007).

• F. Piacentini & the BOOMERanG Collaboration, "CMB polarization with BOOMERANG 2003", NewAR **51**, 244 (2007).

• G. de Troia & the BOOMERanG Collaboration, "Searching for non-Gaussian signals in the BOOMERanG 2003 CMB map: Preliminary results", NewAR **51**, 250 (2007).

• A. de Oliveira-Costa, M. Tegmark, "CMB multipole measurements in the presence of foregrounds", Phys. Rev. **D74**, 023005 (2006).

I. MA1: FUNDAMENTAL PHYSICAL PROCESSES

(**Loeb**, *Zaldarriaga, Tegmark, Guth, Wilczek, Bertschinger, Stubbs, Dalgarno, Finkbeiner, Hernquist, Rybicki, Kirby,Sadeghpour, Hewitt,Narayan;10 Postdocs,10 grads,5 undergrads*)

A. Preface

About 400,000 years after the Big Bang the temperature of the Universe dipped for the first time below a few thousand degrees Kelvin, and atoms of the most abundant cosmic element, *hydrogen*, had formed. Since that time, the growth of the primordial density perturbations (probably seeded by quantum fluctuations during an early epoch of *inflation*) was strongly enhanced by the presence of dark matter – an unknown entity that makes up the vast majority ($\sim 83\%$) of the cosmic density of matter. According to the standard cosmological model, dark matter is cold, i.e., it behaved since that time as a collection of collisionless particles with negligible thermal velocities that responded exclusively to gravitational forces.

The ground state of hydrogen exhibits hyperfine splitting involving the spins of the proton and the electron. The state with parallel spins (the triplet state) has a slightly higher energy (0.068K) than the state with anti-parallel spins (the singlet state). The 21cm line associated with the spin-flip transition from the triplet to the singlet state is often used to detect neutral hydrogen in the local universe. The relative occupancy of the spin levels is usually described in terms of the hydrogen spin temperature T_S, defined by $(n_1/n_0) = 3\exp\{-T_*/T_S\}$, where n_0 and n_1 refer respectively to the singlet and triplet hyperfine levels in the atomic ground state ($n = 1$), and $T_* = 0.068$ K is the temperature equivalent to the transition energy of 5.9×10^{-6} eV, corresponding to a frequency of 1420 MHz. The hyperfine levels tend to thermalize with the cosmic microwave background (CMB) temperature, $T_{\rm cmb}$. If other processes shift the hyperfine level populations away from thermal equilibrium, then the gas becomes observable against the CMB in emission (if $T_s > T_{\rm cmb}$) or in absorption (if $T_s < T_{\rm cmb}$). The finite speed of light allows us to trace how the Universe looked at earlier times. A 21cm survey can reconstruct the growth of structure in the Universe through 99% of its 13.7 billion years of history.

The residual fraction of free electrons after cosmic recombination (redshift $z \sim 10^3$) coupled the gas thermally to the CMB for 65 million years ($z \sim 200$), but afterwards the gas decoupled and cooled faster than the CMB through its cosmic expansion. In the redshift interval $20 \lesssim z \lesssim 200$, defining the so-called *Dark Ages* before the first stars formed, $T_s < T_{\rm cmb}$, and the gas appeared in absorption at its resonant transition wavelength of 21cm. The primordial inhomogeneities of the gas produced varying levels of 21cm absorption and hence brightness fluctuations. At lower redshifts, $z \lesssim 20$, the X-rays emitted by the first galaxies heated T_s above $T_{\rm cmb}$, and cosmic hydrogen glowed in emission. The 21cm emission continued until the present time, where it originates from dense pockets of residual hydrogen in a mostly ionized Universe.

The cosmic expansion stretches the 21cm wavelength of photons from early epochs to an observed wavelength of 21cm $\times (1 + z)$ today. Hence, observations at different wavelengths slice the Universe at different redshifts z and can be used to map the hydrogen distribution in three dimensions (two sky coordinates + distance). Altogether, there are more than $\sim 10^{16}$ independent pixels on the 21cm sky (instead of $\sim 10^7$ for the CMB), which span most of the observable volume of the Universe and extend to small spatial scales. 21cm cosmology offers the potential to probe most of the observable Universe. In comparison, existing data sets are rather limited in the cosmic volume that they access. For example, the CMB anisotropies probe a thin two-dimensional surface. The limitation of existing redshift surveys of galaxies [2, 3] is apparent in Fig. 1 which plots the comoving volume of the Universe out to a redshift z as a function of z. State-of-the-art galaxy redshift surveys, such as the spectroscopic sample of luminous red galaxies (LRGs) in the *Sloan Digital Sky Survey (SDSS)* [4, 5], extend only out to $z \sim 0.3$ and probe $\sim 0.1\%$ of the observable Universe. 21cm cosmology promises to open *a new window* into the distribution of matter through most of the volume of the observable Universe.

Given the promise of 21cm cosmology, several radio arrays are currently being constructed (such as MWA [6], LOFAR [7], PAPER [8], 21CMA [9]) and more ambitious designs are being planned (SKA [10]) to detect the theoretically-predicted emission signal.

The 21cm fluctuations are expected to simply trace the primordial power-spectrum of matter density perturbations (which is shaped by the initial conditions from inflation and the dark matter) either before the first galaxies had formed (at redshifts $z \gtrsim 20$)[11, 12] or after reionization ($z \lesssim 6$) – when only dense pockets of self-shielded hydrogen (such as damped Lyα systems[13]) survive [14, 15]. During the epoch of reionization, the fluctuations are mainly shaped by the topology of ionized regions [16–18], and thus depend on uncertain astrophysical details involving star formation. However, even during this epoch, the line-of-sight anisotropy of the 21cm power spectrum due to peculiar velocities (see MA2.B), can in principle be used to separate the implications for fundamental physics from the astrophysics [16, 19].

The main obstacle towards detecting the 21cm signal is the synchrotron foreground contamination from our Galaxy and extragalactic point sources, whose flux rises steeply towards lower frequencies and makes the detection of the 21cm line more challenging at higher redshifts. This fact directed most experimental and theoretical work so far towards the study of the astrophysics-dominated era at intermediate redshifts ($6 \lesssim z \lesssim 20$), during which the 21cm fluctuations were sourced mainly by the growth of ionized bubbles around galaxies. In particular, the MWA is designed to cover the redshift range of z =6–17, which falls outside the cosmic epochs where fundamental physics can be cleanly explored.

In general, cosmological surveys are able to measure the spatial power spectrum of primordial density fluctuations, $P(k)$, to a precision that is ultimately limited by cosmic variance, namely the number of independent Fourier modes that fit within the survey volume. 21cm observations are advantageous relative to existing data sets because they access a 3D volume instead of the 2D surface probed by the CMB, and they extend to a sufficiently high redshift (well beyond the horizon of galaxy redshift surveys [4, 5]) where most of the comoving volume of the observable Universe resides. At these high redshifts, small-scale modes are still in the perturbative (linear growth) regime where their analysis is straightforward. The expected 21cm power extends down to the pressure-dominated (Jeans) scale of the cosmic gas which is orders of magnitude smaller than the comoving scale at which the CMB anisotropies are damped by photon diffusion [11]. Altogether, the above factors make 21cm surveys appear to be an ideal cosmological probe of fundamental physics. In particular, mapping of the 3D distribution of hydrogen through its 21cm transition can be used to constrain models of inflation as well as the nature of dark matter [11, 20] and dark energy [21].

B. 21cm Cosmology: A New Probe of Fundamental Physics

As stated above, a new frontier in observational cosmology may soon be opened using the 21cm line of hydrogen to map the structure of the Universe at epochs and on scales that have not yet been explored. To put in perspective the potential of 21cm observations, the right panel of Fig. 1 shows a scaled sketch of our observable Universe. It shows the regions that can be mapped with various cosmological probes. We are located at the center of the diagram. Nearby galaxies map the distribution of matter in a 3D region at low redshifts. The CMB can be used to infer the distribution of matter in a thin shell at $z \sim 10^3$. The region available for observation with the 21cm line of hydrogen is shown in light blue. Clearly the 21cm line of hydrogen has the potential for allowing us to map the largest fraction of our Hubble patch and as a result contains, at least in principle, the largest amount of information that we could ever obtain to constrain our cosmological model.

At the high redshift end ($z > 20$) the 21cm signal is relatively simple. At intermediate times, during the epoch of reionization (EoR), the signal is strongly affected by the first generation of radiation sources that heated the gas and ionized hydrogen. Modeling this era requires understanding a wide range of astrophysical processes. At low redshifts ($z \lesssim 6$), the 21cm line can be used to trace neutral gas in galaxies and map the large scale distribution of those galaxies.

Observations of the 21cm line from the EoR and higher redshifts would map the distribution of hydrogen at epochs for which we currently have no other observational probe, pushing the redshift frontier. Measurements of the 21 cm signal as a function of redshift will constrain the expansion history of the Universe, the growth rate of perturbations, and the thermal history of the gas during an epoch that has yet to be probed.

These observations can potentially push the "scale frontier," significantly extending the range of spatial scales that are accessible to study cosmology. This extension is illustrated in Fig. 2 where the scales probed by different techniques are compared to what is available from 21cm observations. Neutral hydrogen is a good probe of the small scales because of two separate but related reasons. On the one hand one can potentially make observations at higher redshifts, where more of the scales of interest are in the linear regime and thus can be better modeled and used to constrain cosmology. Furthermore, at the early times in the history of the Universe, hydrogen is still very cold and thus its distribution is expected to trace that of the dark matter down to very small spatial scales, where pressure forces counteract gravity.

This combination of a large available volume with the presence of fluctuations on small spatial scales that can be used to probe cosmology, implies that the amount of information that at least in principle can be obtained from 21cm data is extremely large. This can be illustrated by calculating the number of Fourier modes that can be measured with this technique. This number can be compared with the number of modes measured to date with various other techniques such as galaxy surveys or the CMB. Figure 3 compares the number of modes available from existing cosmological data sets, such as the CMB and low-redshift galaxy surveys, with future 21cm surveys [20]. Preliminary 21cm observatories that are currently under construction (such as MWA) will survey only a few percent of the sky and process only $\sim 15\%$ of the available frequency range. The ultimate number of modes available to be observed through the 21cm line is upward of 10^{16}. Many practical issues will

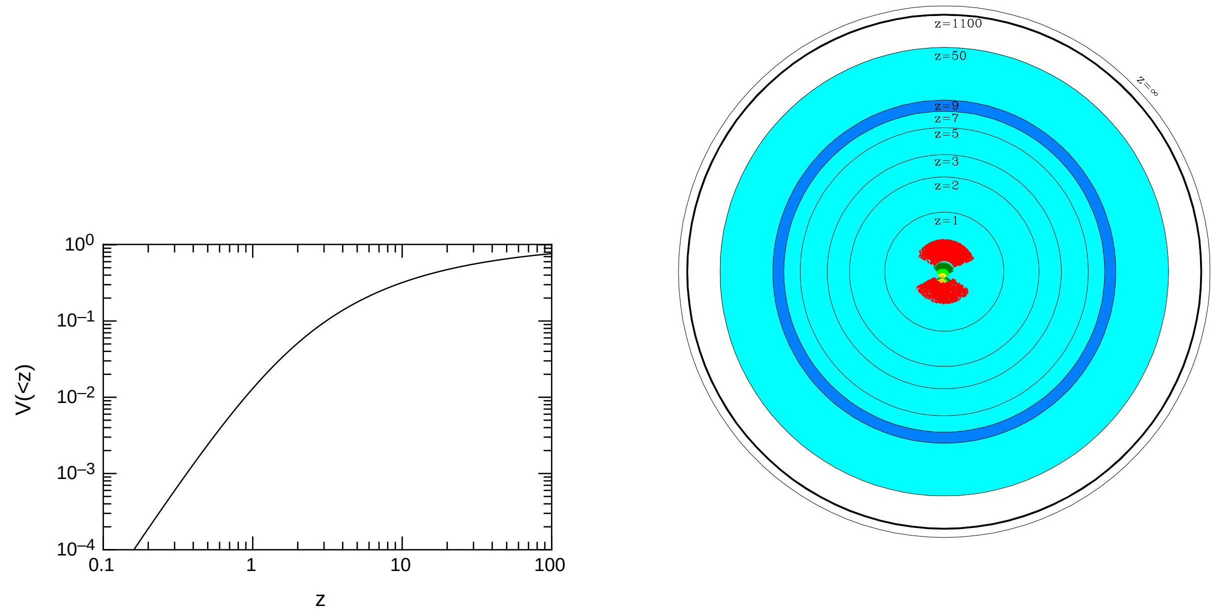


FIG. 1: *Left:* The fraction of the total comoving volume of the observable Universe that is available up to a redshift z. *Right:* 21cm tomography can potentially map most of our observable Universe (light blue/gray), whereas the CMB probes mainly a thin shell at $z > 10^3$ and current large-scale galaxy surveys (here exemplified by the Sloan Digital Sky Survey and its luminous red galaxies) map only small volumes near the center. The final phase of the epoch of reionization is marked by dark blue.

certainly limit the number of modes that will be probed in the immediate future. The aim of the proposed *Center for 21cm Cosmology (CTC)* is to design an array that can begin this journey of exploration in time and scale to capture as much of this additional cosmological information as feasible.

It is not possible to predict reliably what might be discovered when a new observational window is opened. However, it is important to understand what range of phenomena might be expected in order to design an instrument that can best probe them. We term the future 21cm observatory that will seek to constrain fundamental physics, the *Array for Imaging the Dark Ages (AIDA)*, and will discuss its general characteristics in subsequent sections. But first let us discuss some of the questions an array like *AIDA* would be able to investigate. Within the proposed *CTC* we will study these questions in detail and sharpen the predictions for future experiments. The phenomena of interest will manifest themselves on different scales and might require different choices in terms of surveyed volume, angular and frequency resolution, etc. Part of the aim of the *CTC* involves understanding how different design trade-offs will affect the science questions that *AIDA* can address.

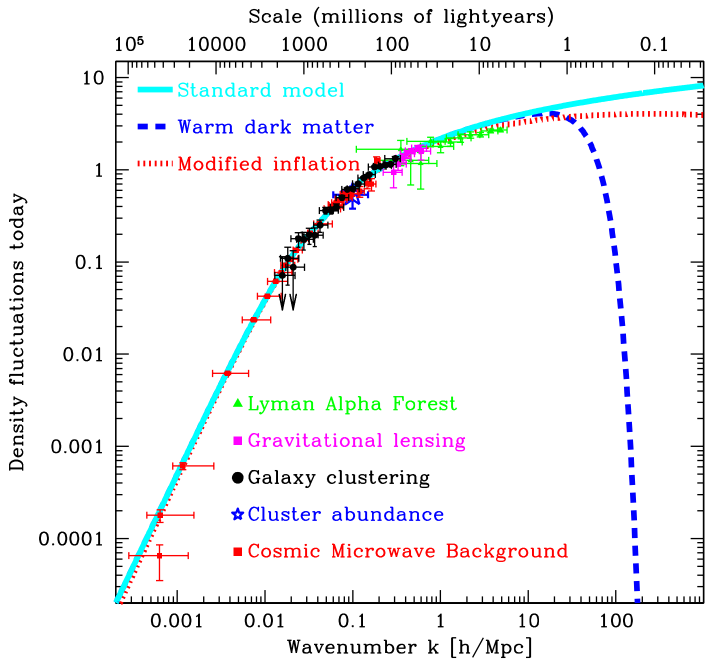


FIG. 2: 21cm tomography can push the scale frontier far beyond that of current measurements of cosmic clustering, potentially all the way down to the Jeans scale at the right edge of the figure. This allows distinguishing between a host of alternative inflation and dark matter models that are consistent with all current data; e.g. a warm dark matter with mass 14 keV (dashed curve) or greater and inflation with a running spectral index more extreme than $dn_s/d\ln k = -0.03$ (dotted).

C. The scale frontier

Inflation. Explaining the large scale properties of our Universe is at the heart of physics and modern cosmology. Why is the Universe isotropic and homogeneous on large scales? Why is its spatial geometry so close to flat? By postulating a period of accelerated expansion during the very early Universe ($\ddot{a}(t) > 0$, with $a(t)$ the scale factor of the metric describing the Universe), a period of inflation, these basic large-scale properties of our Universe can be explained.

Although homogeneous and isotropic on large scales, our Universe is very inhomogeneous on small scales. Perhaps the most profound accomplishment of inflationary cosmology is its ability to simultaneously make the Universe homogeneous and flat on large scales but also generate small inhomogeneities with an almost scale invariant spectrum that gravity can amplify in the course of the 13.7 billion year lifespan of our Universe to give rise to the structures that we observe. This impressive result is obtained without adding any additional ingredient. The dynamics of the inflaton, the field whose energy density dominates during this period, that is required to produce the accelerated expansion in slow-roll inflation models, also leads to a nearly scale invariant spectrum of perturbations. The quantum mechanical fluctuations of the inflation become the seeds for structure formation.

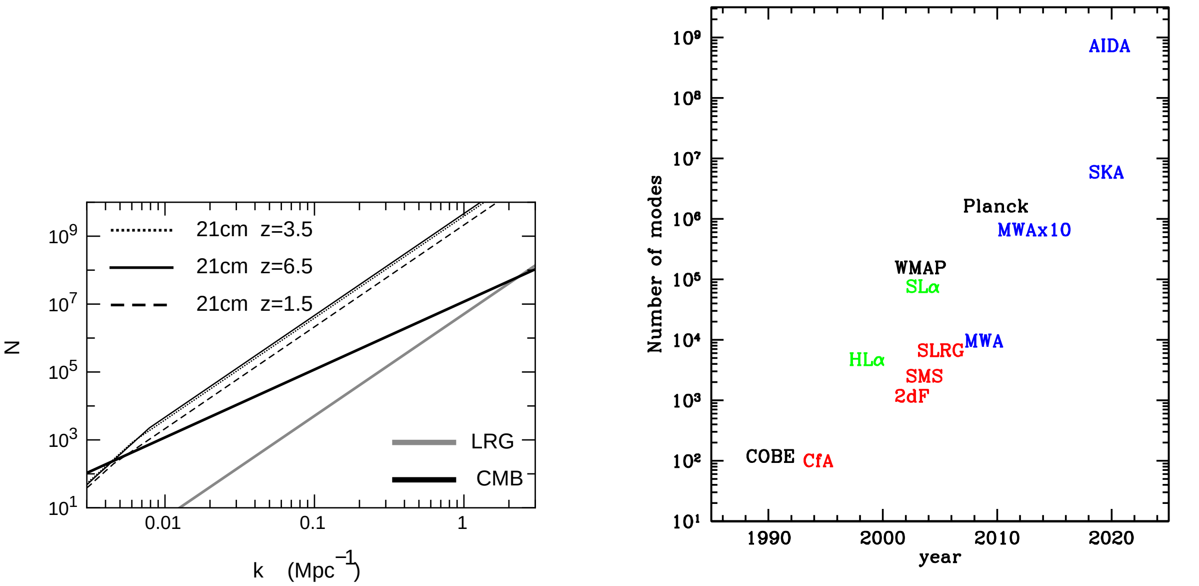


FIG. 3: *Left:* Number of Fourier modes N within a wave-number bin of width $\Delta k = k/10$ centered on k, that are available for different methods of cosmological surveys. The thick grey line corresponds to a state-of-the-art galaxy redshift survey (*SDSS*-LRG [4]), while the thick dark line corresponds to an all-sky CMB data set (such as *WMAP* [22]). The thin lines show the number of modes accessible in a 21cm survey covering a 65% of the sky within a redshift range spanning a factor of 3 in $(1+z)$, and centered on redshifts $z = 1.5, 3.5$ and 6.5. The results incorporate the limited ability of a 21cm survey to probe large scale modes due to the removal of the radio foreground (which also varies slowly across large frequency shifts). *Right:* Total number of modes measured in specific data sets. We show illustrative examples of galaxy redshift surveys [CfA, PsCz, 2dF, SDSS main sample (SMS), SDSS Luminous red galaxies (SLRG)], CMB experiments (COBE, WMAP and Planck), "Lyα forest" measurements (HLα), SDSS spectra (SLα)), and planned 21cm experiments (MWA, SKA), culminating with a particular example of our proposed observatory *AIDA* with 1024×1024 dipoles and 10^3 hours of observation.

The successes of inflation have made it the standard paradigm in cosmology. Our theories of high energy physics, however, do not uniquely predict the physics of inflation. It is currently a task for observations to make as many measurements to characterize the inflationary period as possible. These measurements could give us the first hints of the physics at energies not currently accessible in the laboratory. It is even possible that cosmology could become the first experimental window into quantum mechanical effects in gravity.

The way observational cosmology can provide information about inflation is by measuring the detailed characteristics of the primordial seeds of structure formation. In particular, departures from scale invariance are a natural consequence of inflationary models. For example, recent observations indicate that the spectrum of perturbations is red with a tilt that is in agreement with simple expectations from inflation (e.g., [2, 22–24]), although the statistical significance of this result is as yet far from overwhelming.

Departures from Gaussianity of the primordial perturbations could shed interesting light on the physics of inflation. In inflationary models perturbations tend to be very close to Gaussian with possible observable departures only for the three-point correlation function. Single-field models of inflation, in which the quantum fluctuations of the same field that dominates the energy density during inflation become the seeds for structure formation, satisfy a consistency relation that relates the shape of the three-point correlation function to the dynamics of the inflaton field (e.g., [25–27]) . Testing this relation could allow us to distinguish single-field models from other alternatives, measure the "sound-speed" (c_s) of perturbations during inflation and could potentially invalidate inflation as a mechanism to generate the perturbations.

Future 21cm observations have the potential to greatly enhance our knowledge of the properties of the primordial seeds. By extending the range of spatial scales that are accessible to observation and greatly increasing the number of modes that can be measured, one expects to get significantly improved constraints on the shape of the primordial power spectrum. Furthermore, the logarithmic range of scales over which scale invariance could be tested can be doubled. This might allow us to measure the variation ("running") of the power-law index of the primordial power-spectrum at the level predicted by inflation, and to significantly increase the number of available constraints on the shape of the inflaton potential. The 21cm data could also constrain other effects that might be operating during inflation[28]. Moreover, the large amount of information available would permit testing the inflationary consistency relation for the three-point correlation function even for the models with the smallest non-Gaussianity (those for which the sound speed $c_s = c$) [29, 30]. A high signal-to-noise-ratio detection of the inflationary three-point function with its scale and shape dependence would be a gold mine for inflationary cosmology, allowing one to distinguish single field models of inflation from other scenarios and constraining the dynamics of the inflation during inflation, and measuring c_s, which is not possible in any other way. Just as a detection of gravitational waves would provide valuable information to understand how inflation fits into our theories of physics at high energy and the early Universe, so would a detailed measurement of the non-Gaussianities and the shape of the power spectrum. For example, in D-brane inflation it seems currently impossible to simultaneously have a small sound speed (and thus relatively large non-Gaussianities) and a red tilt [31].

Dark-matter properties. Our current understanding of cosmology and structure formation requires the existence of dark matter which we have not yet detected directly in the laboratory. Although the current paradigm has been very successful in explaining the evolution of structure in the linear regime, observations on the scale of galaxies have been more difficult to accommodate. In particular, the distribution of dark matter inside of halos is predicted to be very clumpy; also the density profile in the inner regions of halos is calculated to be steep (at least in dark-matter-only simulations). Both of these facts appear to be in conflict with observations of galactic-scale halos which has raised the possibility that the standard scenario is wrong or at least incomplete.

The difficulty could be in our understanding of what the standard cosmological model actually predicts for small spatial scales. 21cm observations have the potential of measuring perturbations on small (galactic) scales at an early enough time that they are still in the linear regime, and in doing so settle any remaining uncertainty on the small-scale power spectrum in the standard model. Furthermore, with a sufficiently high resolution, the 21cm maps could be used as backgrounds for gravitational lensing experiments that could detect the presence of dark substructure in lower redshifts halos [32–34]. Gravitational lensing can also tightly constrain the power spectrum of the dark matter on large spatial scales [35, 36].

Neutrinos. Expanding the range of scales that are accessible to observations would also allow one to constrain other physical effects that affect the small-scale transfer-function. In particular, one could obtain a measurement of neutrino masses. Neutrinos introduce a feature in the power spectrum, whose location and strength depend on the neutrino mass. With sufficient statistical power one could measure the detailed shape of this feature and potentially constrain independently more than one neutrino mass. Measurement of the time evolution and strength of the feature would provide further consistency checks that could be used to distinguish this effect from others.

Our proposed Center will design future 21cm surveys that would potentially cover a major portion of the sky and large frequency bandwidths. To illustrate the potential of such surveys, we show in Fig. 4 the expected precision in the determination of the matter power spectrum at redshifts $z \lesssim 6$, which could enable a highly significant detection of the signature of a neutrino mass ~ 0.05 eV, in the range suggested by atmospheric neutrino data [37]. Similarly, the evolution of the linear growth factor with redshift could also constrain exotic theories of gravity or dark energy [20].

D. The time frontier

The 21cm observations of high redshift hydrogen will provide a window into an epoch in the history of our Universe that has not yet been observed. The standard model of particle physics makes very definite predictions for the expansion history, the thermal history of the gas, and the growth of structure during this epoch. Measurements of the 21cm line during the dark ages could test these predictions.

The study of the thermal history of the gas can constrain a late energy injection such as one that could be produced by annihilations of dark matter in the center of halos or the decay of some long-lived relic. In fact the 21cm signal is extremely sensitive to an energy input. In the standard scenario, the kinetic temperature of the gas, which sets the spin temperature at $30 \lesssim z \lesssim 200$, is $20[(1+z)/30]^{-2}$ K, whereas an instantaneous input of 0.01 eV per baryon would raise the gas temperature by 50 K. In comparison, the Lyα forest is sensitive to injections of ~ 1 eV per baryon. Therefore, the presence of an unknown particle or of primordial black holes, even if these objects inject a very small amount of energy, could be detected in the 21cm signal. Studies that have looked at annihilating or decaying light dark-matter models and sterile neutrino models find that these dark-matter candidates significantly change the 21cm signal (e.g., [38–40]).

The most natural candidate for extra energy injection is the decay or annihilation of weakly-interacting massive particles (WIMPs) that make up the dark matter. Any WIMP that is a thermal relic of the Big Bang has a freeze-out density related to its annihilation cross section at freeze-out, and would still be annihilating at a low level even today. In order to obtain the correct relic density ($\Omega_{DM}h^2 = 0.11$), a particle mass in the range $100 < m < 1000$ GeV is required. It is particularly desirable to search for consequences of any WIMP heavy enough to avoid disturbing Big Bang nucleosynthesis ($m > 10$ MeV) and light enough to evade the unitarity bound on the cross section ($m \sim$ many TeV).

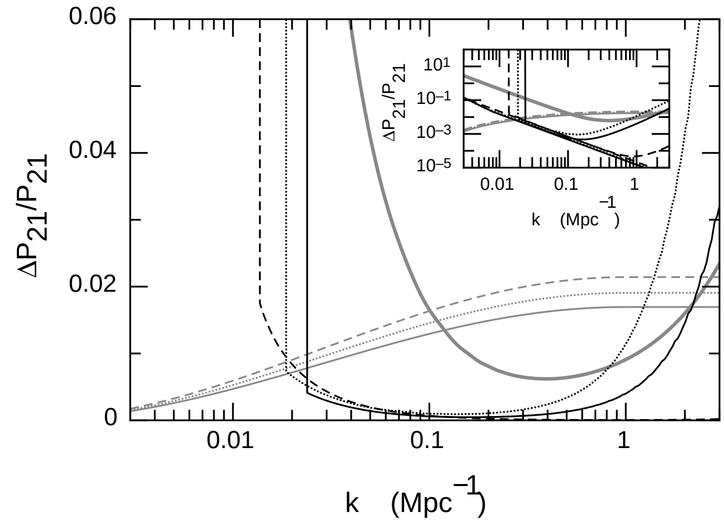


FIG. 4: The fractional change in the amplitude of the power spectrum as a function of wavenumber k, owing to the presence of a massive neutrino (horizontal grey lines, asymptoting towards a constant at high k values). The case shown [20] corresponds to a neutrino mass $m_\nu = 0.05$eV, as suggested by the latest atmospheric neutrino data [37]. For comparison, the limits imposed by cosmic variance on the measurements of the power spectrum from a state-of-the-art spectroscopic galaxy survey, such as *SDSS*-LRG [4], are marked by the thick grey line. In comparison, the *U*-shaped error curves correspond to an all-sky 21cm survey over a redshift range spanning a factor of 3 in $(1+z)$ with a future observatory that has ten times the collecting area of MWA and a 10^3-hour integration per field. The redshifts $z = 1.5, 3.5, 6.5$ are denoted by dashed, dotted, and solid lines, respectively. The inset shows these results on logarithmic axes that span a larger dynamic range of achievable precision. The straight thin lines in the inset show the cosmic-variance uncertainty in the power-spectrum measurement owing only to the number of available modes.

It is instructive to consider the consequences of a specific class of WIMPs. In the supersymmetric extension to the standard model, the lightest supersymmetric particle (LSP) is generically a WIMP candidate. In many parts of parameter space the LSP is the lightest of the 4 neutralinos, each a linear combination of the superpartners of the neutral standard model bosons (the photon, the Z boson, and 2 neutral Higgs bosons). The four superpartners themselves are not mass eigenstates, and depending on what linear combination of them forms the LSP, its properties can vary. However scans of parameter space for the simplest case (minimal supersymmetry) indicate that for a mass of a few hundred GeV, a neutral, stable, particle with the correct freeze-out cross section σ is obtainable. When this particle is dominated by s-wave annihilation (for which σv is independent of velocity v), the cross section at redshift $z = 10 - 50$ is possibly high enough to have observable consequences.

How might we search for a WIMP at high redshifts? The gamma rays and high-energy particles resulting from its annihilation heat and ionize the Universe, perturbing the standard ionization history. The gas heating for two neutralino models (with WIMP masses of 36 and 100 GeV) was calculated in [40]. The particle and photon spectra produced by their annihilations were estimated, with the result that the gas temperature would be brought up to $T_{\rm cmb}$ by $z = 30$ and would be 100 times greater than the no-heating case by $z = 10$. Such dramatic effects would be observable by future 21cm observations. Furthermore, the annihilation rate would be very sensitive to the clumpiness of the dark matter. Theoretically, we expect the dark matter to clump at Jupiter mass scales [41, 42], but present observations only probe structures with $\gtrsim 10^9\ M_\odot$. The heating of the gas from annihilations could be used to probe these Jupiter mass scales.

Finally there is also the possibility of using our understanding of the detailed atomic physics of the 21cm line to constrain the time variation of fundamental constants such as the fine structure constant (e.g., see [43]).

E. The Lower redshifts: Constraining the Dark Energy

Observations of quasar spectra indicate that a few percent of the cosmic hydrogen remains atomic at low redshifts, $z \lesssim 6$ [13]. The residual neutral gas, confined to dense regions with a high recombination rate, is expected to generate a detectable 21cm signal after reionization [14], primarily because the Galactic synchrotron foreground scales down considerably at high frequencies. A dedicated 21cm survey at $z \lesssim 6$ would probe the cumulative emission from a large number of 21cm sources without resolving them individually. The cumulative emission would be modulated on large scales by the power spectrum of density fluctuations. A precise measurement of the power spectrum can be used to constrain fundamental parameters [20], such as the neutrino mass (Fig. 4). The growth of its amplitude with cosmic time would provide new constraints on alternative theories of gravity [44, 45].

The scale of the Baryonic Acoustic Oscillations (BAOs) in the 21cm power spectrum provides a cosmic yardstick that can be used to measure the dependence of both the angular-diameter distance and the Hubble parameter on redshift [21]. The BAO wavelength is defined by the sound horizon at the recombination epoch. Given our knowledge of the physical size of this yardstick, measurements of the angular-diameter distance and the redshift scale that it occupies could be used to constrain the possible evolution of the vacuum energy density (often called 'dark energy' or 'cosmological constant') with cosmic time. This idea was first applied to the CMB and later proposed in relation to galaxy redshift surveys [46–48]. It subsequently received significant theoretical attention [49–52] and its validity was demonstrated within large surveys of galaxies at low redshifts [4, 53].

The origin of dark energy in our accelerating Universe is one of the unsolved puzzles in fundamental physics, and so it is not known a priori which redshift range should be studied in order to provide "optimal" constraints on possible theories for it. 21cm measurements at $z \gtrsim 1$ would be capable of ruling-out existing quantum-gravity models in which the dark energy makes a significant contribution to the cosmic mass budget at all cosmic times [54, 55].

Acoustic oscillations in the 21cm power spectrum should be detectable using future low frequency arrays [15, 21, 56]. Depending on the characteristics of *AIDA*, it might be possible to constrain the contribution of dark energy to the cosmic mass budget through most of cosmic history since the big bang. The 21cm mapping will extend existing BAO surveys to much higher redshifts, where the conventional sources (galaxies or Type Ia supernovae) are too faint to be detectable. No other probes of dark energy are currently being applied to the redshift range of $1.5 \lesssim z \lesssim 30$ [57].

II. MA2: OBSERVABLE SIGNATURES

(**Hernquist**,*Loeb,Zaldarriaga,Tegmark,Dalgarno,Bertschinger,Rybicki,Finkbeiner,Narayan, Kirby,Sadeghpour,de Oliveira Costa, Hewitt; 10 postdocs,10 grads,5 undergrads*)

The radiation produced by the first galaxies ($z \lesssim 20$) heated and ionized the cosmic gas. Clustering of the first sources produced significant spatial variations in the gas temperature and neutral (atomic) fraction, leading to 21cm brightness fluctuations that do not simply trace the matter density fluctuations.

Inference of cosmological information is most straightforward before star formation began ($z \gtrsim 20$), or after the reionization process ended ($z \lesssim 6$) – when the residual hydrogen clumps simply trace the matter density distribution. However, as discussed below, the gravitationally-driven peculiar velocities of the gas break the angular isotropy of the 21cm signal at all redshifts, allowing to isolate the gravitational potential effects even in the presence of astrophysical effects [19]. An important goal of the proposed *CTC* would be to determine the advantages and disadvantages of studying fundamental physics at various redshifts.

A. Numerical simulations

As we have argued, the 21cm signal from cosmic gas at high redshift contains information that can be used to constrain the fundamental physics underlying the formation of large-scale structure, stars, and galaxies. An example of this possibility is provided in Fig. 5, which shows the outcome of simulations of the growth of structure in two plausible models of the Universe. Both show the distribution of baryons at $z = 20$, prior to the epoch when radiation from stars would have significantly affected the thermal and ionization states of the gas. The simulations are identical, except that the one shown on the left assumes that the dark matter is “cold,” while in the one on the right, the dark matter is “warm.” For the latter case, the dark matter particle mass is 1 keV, while it is essentially infinite for the cold dark matter (CDM) case, as far as the growth of structure on these scales is concerned.

By inspection, it is clear that the nature of dark matter can leave an observable imprint on the luminous matter distribution as cosmological structure forms. The baryons are much more smoothly distributed in the case of warm dark matter, owing to the larger residual thermal motions of the particles. This distribution will significantly impact the 21cm power spectrum at early times, before reionization, when the dominant contribution to the 21cm signal comes from baryonic density fluctuations. This effect is especially important at very high redshifts, when the density field is still nearly linear and before the differences on small scales, like those illustrated in Fig. 5, are washed out by large-scale non-linear effects. In principle, then, a measurement of the 21cm power spectrum at these high redshifts would enable direct, new constraints to be placed on the nature of dark matter.

Moreover, differences like those shown in Fig. 5 will dramatically influence the formation and nature of the first luminous objects in the Universe. This influence is indicated in Fig. 6, which gives the mass function of dark matter halos of galaxies in these two cases. It is believed that the first generation of stars and galaxies formed in the first regions to collapse gravitationally into bound structures, because only there would the gas densities be sufficient

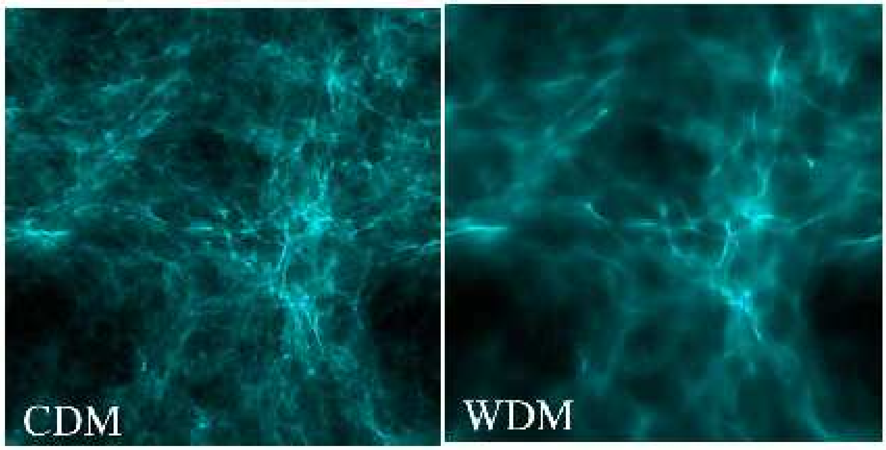


FIG. 5: Projected distribution of gas on the sky at redshift $z = 20$ in Universes containing cold and warm dark matter, left and right panels, respectively [58]. Each panel is 1 Mpc across.

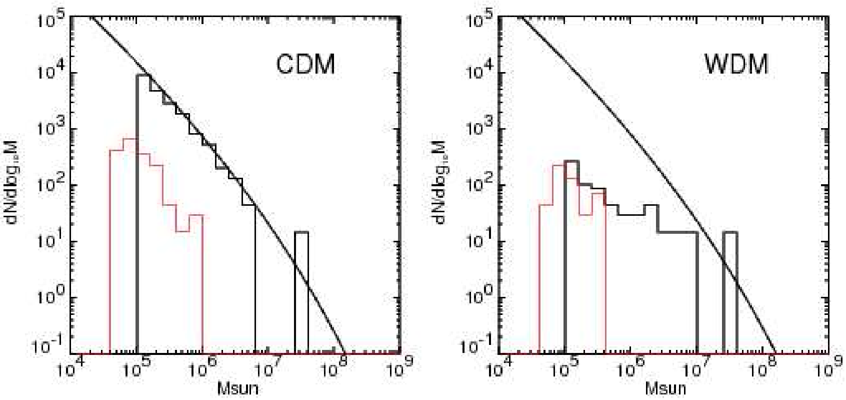


FIG. 6: Number of dark matter halos per logarithmic mass bin in the simulations shown in Fig. 5 (histograms) compared with analytic estimate from Press-Schechter theory (solid curve) [58]. Histograms extending to the left are for halos that are not well-resolved numerically.

to enable the gas to cool and form molecular hydrogen. In the example shown in Fig. 6, the abundance of these collapsed regions is suppressed by several orders of magnitude at these times when the dark matter is warm, rather than cold. Warm matter will significantly delay the onset of early star formation and affect the evolution of the cosmic 21cm signal. If the matter remains unaffected by stellar radiation for a more extended period, the transition from a 21cm signal being dominated by density fluctuations to one dominated by ionization fluctuations will be shifted. In principle, precise measurements of the evolution of the 21cm power spectrum could thus be used to study the nature and characteristic redshift of this transition.

The matter distribution is also determined by the nature of the density fluctuations generated during the period of inflation, which presumably occurred soon after the Big Bang. Variations with scale and departures from Gaussianity of the primordial fluctuations will lead to differences in the matter distribution at high redshifts similar to those illustrated in Fig. 5, which can again be probed by the cosmic 21cm signal.

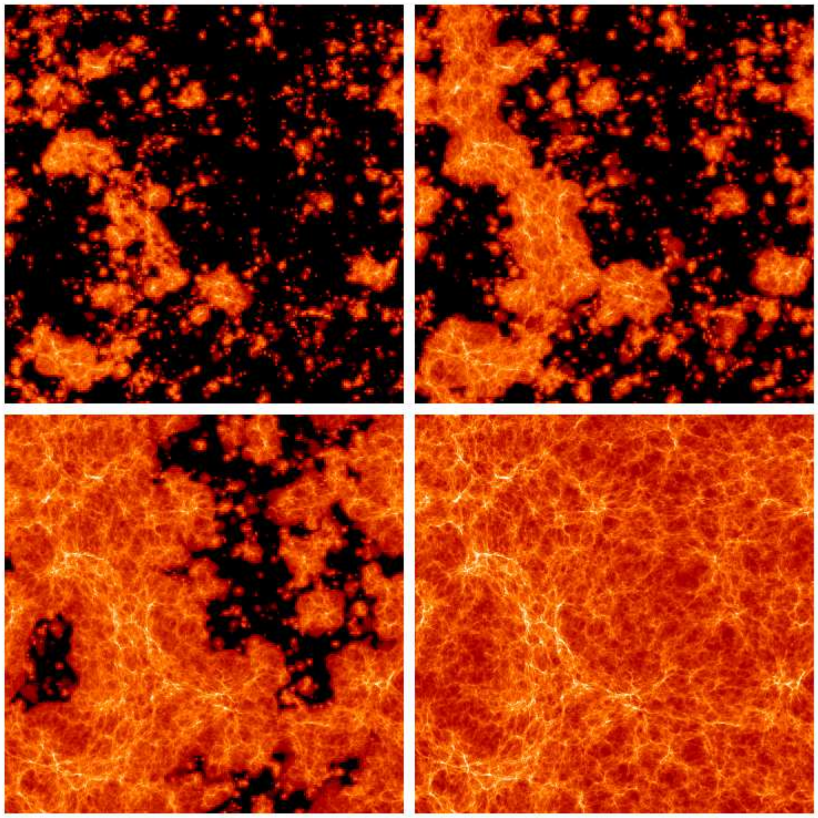


FIG. 7: Density of hydrogen in a $70 \times 70 \times 1.5$ Mpc slice through a simulation in which ionizing radiation is produced only by ordinary stars. The panels show the ionization state ranging from fully neutral (dark) to increasingly ionized (red to white) progressively at redshifts $z = 9, 8, 7$, and 6 [59].

Figure 7 shows the evolution of the ionization field of hydrogen at later times, when large numbers of ionizing sources (in this case, ordinary stars) have formed. In this example, a radiative transfer code was used to calculate the ionization state of the gas given a plausible distribution of sources inferred from a cosmological simulation. At very early times, the ionized regions surround individual star-forming objects, but as more gas is converted into stars, the ionized volumes overlap, coalesce, and eventually fill the entire volume (but not uniformly). In this regime, the 21cm power spectrum will transition from being determined by density fluctuations to being set mainly by ionization fluctuations. Note, however, that even at late times once the volume is essentially entirely ionized, the filamentary pattern produced by density inhomogeneities is still apparent in the ionization field on small scales, as traced by the white regions at $z = 6$ in Fig. 7.

As shown by [16], reionization is sensitive to the nature and abundance of the ionizing sources. Large numbers of relatively faint ionizing sources (as in Fig. 7) lead to a pattern in which the morphology of the ionization field resembles the appearance of the matter distribution. The ionized bubbles are significantly larger (20 comoving Mpc and more) than the Stromgren spheres around an individual galaxy (of order half a comoving Mpc). This difference is a consequence of the clustering of sources: groups of sources appearing in the filaments and their intersections act as a combined brighter source that is able to ionize a significantly larger region. In terms of our numerical models, the larger sizes of the bubbles imply that we need to model reionization using very large simulation boxes. However, if the individual sources were much brighter, but rarer, the ionization field would be dominated by shot noise. Thus, a measurement of the 21cm power spectrum during reionization would enable useful constraints to be placed on early star and galaxy formation.

It is clear, then, that the 21cm signal encodes information about the fundamental physics of the Universe, i.e., the nature of dark matter and inflation, as well as the astrophysical sources responsible for reionization. Attempts to interpret 21cm data must, therefore, be based on detailed calculations that describe variations in the expected signal from the underlying basic physics and the uncertain nature of the ionizing sources. Further, 21cm measurements will likely be dominated by a number of foregrounds that are estimated to be many orders of magnitude brighter than the signal of interest. This interplay must also be examined using accurate models of both the foregrounds and the distribution and ionization state of hydrogen in the Universe, and determining how these evolve in time. Given the complex processes involved, this detailed modeling will require the use of computer simulations that follow the evolution of dark matter and gas, and codes to compute radiative transfer through the gas. These simulations must be combined with simple analytic treatments to isolate the most important physics and to explore parameter space efficiently.

In the last few years, we have constructed both analytical and numerical models of reionization. We presented our analytic techniques in [60]. Our model is based on a generalization of the excursion set formalism [61] to calculate the mass function of halos. Our numerical scheme for doing radiative transfer was presented in [62] and further improved in [63, 64]. In our approach, we use a hierarchical ray-casting algorithm to identify ionized regions around all the sources present in large-scale cosmological simulations. Our method accurately follows the ionizations and recombinations along the full number of rays needed to determine the complete ionization state of the gas. We have also constructed a hybrid scheme where we combine the density field obtained from simulations with a barrier technique borrowed from our excursion set formalism to decide whether or not any given fluid element is ionized. This technique is very fast, involving only fast Fourier transforms to smooth the density field on various scales. In [63] we showed that the maps produced in this way have statistical properties consistent with our analytic calculations and bubble morphologies similar to those produced by the full radiative transfer code.

As part of the proposed research, we plan to perform detailed numerical simulations of reionization. We will study various statistical probes such as the power spectrum of the fluctuations, higher order statistics, and the size distribution of the bubbles. We intend to use our analytic methods to understand how these different diagnostics depend on the parameters of our models. We will use our numerical models to include effects that were neglected in the analytical treatment, and will study how they affect the results.

We intend to modify our radiative transfer code to allow for harder sources of radiation. Currently the code assumes that the thickness of the ionization fronts is narrower than the resolution element of the simulations, which is justified for hydrogen reionization by ordinary (present-day) stars and probably even the much hotter first stars. However, if quasars/miniquasars play a role in cosmological reionization, then their power-law spectra can lead to thicker ionization fronts.

To understand when the 21cm signal can be observed, we need to know how the spin temperature evolves with time. As stated in MA1, both the spin temperature and the kinetic temperature of the gas track the CMB temperature down to $z \sim 200$. After this point, the gas evolves adiabatically, becoming colder than the CMB, $(T_{gas}/T_{\rm cmb}) \propto 1/a$ where $a = (1+z)^{-1}$ is the cosmological scale factor. Collisions between hydrogen atoms are efficient at coupling T_s and T_{gas} down to $z \sim 30$ and so the spin temperature follows the kinetic temperature to about that redshift. At much lower redshifts, the Hubble expansion makes the collision rate subdominant relative to the rate of radiative coupling to the CMB, and so T_s tracks $T_{\rm cmb}$ again. Consequently, there is a redshift window between $30 < z < 200$, during which the cosmic hydrogen absorbs the CMB flux at its resonant 21cm transition.

After the appearance of collapsed objects, the gas is heated and the spin temperature becomes much higher than the CMB temperature, so one expects to see hydrogen in emission. There is thus a second window, the epoch of reionization, between the time that the gas is heated and the time it becomes fully ionized, when hydrogen should appear in emission.

Currently, our numerical models do not track the kinetic temperature of the gas or its spin temperature self-consistently. This aspect of the calculations must be generalized in order to infer the expected signal prior to and during the epoch of reionization.

An important consideration involves the dynamic range of scales in our fully simulation-based approach. Ultimately, we would like to simulate volumes hundreds of Mpc across to characterize the large ionized regions near the end of reionization, and to resolve halos as small as $\sim 10^8 M_\odot$ with virial temperatures $\sim 10^4$K, which is the threshold above which cooling by atomic processes is efficient and can lead to rapid star formation. To date, we have performed most of our simulations in volumes < 100 Mpc per side, resolving halos down to $\approx 10^9 M_\odot$, with $N = 1024^3$ particles. The unresolved halos are added to our radiative transfer calculations using approximate methods to relate the abundance and clustering of halos to the resolved density field. We propose to improve the accuracy of our modeling by increasing the dynamic range in mass of our N-body simulations by a factor > 100, by performing simulations with $N = 5000^3$ particles. These increases will enable us to fully resolve halo masses down to $\sim 10^8 M_\odot$ in volumes > 200 Mpc across, so that we would identify the locations of all plausible sources of radiation directly, eliminating the need to account for unresolved halos in an approximate manner. These new simulations, with $N = 125 \times 10^9$ particles, will be by far the largest calculations run for this purpose.

Ultimately, in order to properly characterize the transition from the regime in which the 21cm signal is dominated by density fluctuations to that in which ionization fluctuations are most important, we need to understand theoretically when the first stars and galaxies appear. As implied by Figures 5 and 6, the abundance of the sites where the first luminous objects will form is sensitive to the fundamental physics governing the evolution of structure in the Universe. Furthermore, [65] have shown that the properties of the first stars depend on the ionization state of the gas. The more free electrons there are during this period, the higher is the rate of formation of HD molecules, providing additional sources of cooling. If the gas can cool to lower temperatures, the Jeans mass is decreased, yielding lower mass stars. The rate of production of ionizing photons depends on stellar mass, so the subsequent evolution of the ionization state of the intergalactic medium is altered, modifying the 21cm signal.

Determining the nature and abundance of these first luminous sources requires simulations of great dynamic range, but on smaller scales than those needed to model the epoch of reionization, as in Fig. 7. Moreover, these calculations must incorporate all the relevant physics that contribute to cooling and heating of the gas: creation and destruction of the relevant molecules and atoms, radiative cooling and heating, transport of energy by radiation and mechanical feedback, and chemical enrichment of the gas as heavy elements are produced by nucleosynthesis. These calculations must have enough resolution to determine the mass spectrum of these objects, yet be performed in volumes of sufficient size that the cosmological impact of these stars and their effect on subsequent star formation can be described. These needs will require the use of adaptive algorithms, as in [65] but over much larger volumes.

As part of the proposed research, we will perform simulations that resolve stellar densities in cosmological volumes, extending the state-of-the-art work of [65] by several orders of magnitude in mass resolution. We will infer the properties of the collapsed objects and characterize their impact on the surrounding intergalactic medium, on later star formation, and the evolution of the cosmic 21cm signal.

B. Peculiar Velocities

Even though astrophysical effects contribute to the 21cm signal at $6 \lesssim z \lesssim 20$, the density fluctuations – which contain pristine information about the cosmology – can be separately measured by using the unique angular dependence that is imprinted on the signal by peculiar velocities [19] (i.e., the excess velocities of matter relative to the Hubble expansion). The redshift range where astrophysical signals are important is the target of the first generation of 21cm interferometers, and this redshift range is also where the signal-to-noise ratio of observations is largest.

Overdense regions appear brighter in 21cm because of the infall of matter, whereas the opposite is true for underdense regions. In Fourier space, this effect injects power into spatial modes oriented along the line of sight, breaking the rotational symmetry of the 21cm power spectrum. The power spectrum with peculiar velocities takes the following form [19]:

$$P_{21\mathrm{cm}}(\mathbf{k}) = P_{\mu^0} + \mu^2\, P_{\mu^2} + \mu^4\, P_{\mu^4}, \tag{1}$$

where μ is the cosine of the angle between the spatial wavevector $\mathbf{k}$ and the line-of-sight and where $k = |\mathbf{k}|$. If the effects of peculiar velocities are not included than $P_{21\mathrm{cm}} = P_{\mu^0}$. Interestingly, $P_{\mu^4} = \bar{T}_b^2\, P_{\delta\delta}(k)$, where $\bar{T}_b$ is the average 21cm brightness temperature and $P_{\delta\delta}(k)$ is the power spectrum of density fluctuations [19]. Even at redshifts where Lyα pumping, X-ray preheating, and reionization, affect the 21cm signal, observations can use this angular decomposition to infer cosmological information via $P_{\delta\delta}$.

Figure 8 illustrates how well the MWA and the planned Square Kilometer Array (SKA [10]) will be able to separate the P_{μ^0} and P_{μ^4} terms for average ionization fractions $\bar{x}_i = 0.7$ (left panel) and $\bar{x}_i = 0.1$ (right panel). The blue dashed curves are the sensitivity of MWA to P_{μ^4} (the black dashed curve) and the red dashed curve is the same but for the SKA. While the MWA will not have the sensitivity to separate the terms with different μ dependences, the SKA will be able to separate these terms at $z = 8$ and measure $P_{\delta\delta}$ over

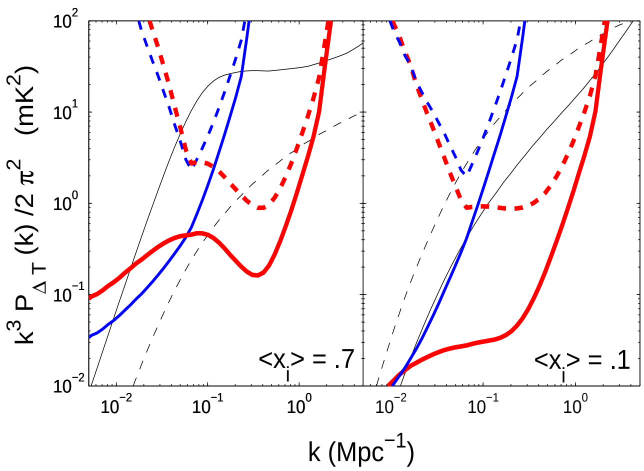


FIG. 8: The 21cm signal (*thin curves*) and detector noise plus cosmic variance errors (*all other curves*) at $z = 8$ for a 2000 hour observation in two different fields, for the P_{μ^0} (*solid curves*) and P_{μ^4} (*dashed curves*) components of the signal [16]. In the left panel the average ionization fraction is $\bar{x}_i = 0.7$, and in the right panel $\bar{x}_i = 0.1$. The sensitivity curves for MWA (*medium-width curves*) and for SKA (*thick curves*) have a bin width of $\Delta k = 0.5\,k$.

a decade in $|k|$ with sensitivity $\delta P_{\mu^4}/P_{\mu^4} \approx 0.1$. A dedicated observatory like *AIDA* can potentially perform significantly better than SKA.

At $z \gtrsim 30$, the P_{μ^x} are each proportional to $P_{\delta\delta}$, and the proportionality constant is known in the standard cosmological model. If some unknown energy injection is present at these redshifts that changes these proportionality constants in the high redshift signal (see MA1), the μ decomposition will offer independent checks on the injection mechanism. For example, if the injected energy is proportional to ρ^2 (as would be the case at scales for an annihilating particle where the annihilation products inject their energy locally) the ratios of the P_{μ^x} would be different than if the injected energy is proportional to ρ (as with a decaying particle) or ρ^0 (non-local energy injection).

C. Analytical models for X-ray heating and Lyα coupling

If 21cm observations of the period after star formation begins are to be used to constrain cosmology and exotic heating mechanisms, an accurate "standard" thermal history must first be calculated. Ultimately, this calculation will require detailed numerical simulations, but for the moment analytic models provide a useful description. Figure 9 (left panel) shows various effects that astrophysics can have on the thermal history.

Current modeling of luminous sources at high redshift ($z \gtrsim 6$) is based upon extrapolation from well-characterized, low-redshift sources [67]. From the perspective of predicting the 21cm signal, we require detailed knowledge of the clustering and spectrum of sources emitting in three bands: ionizing UV photons, Lyα – Lyman limit, and X-ray photons ($100\,\text{eV} \lesssim E_\gamma \lesssim 30\,\text{keV}$). These photons are responsible for ionization, Lyα coupling, and heating, respectively. The planned development of new optical and infrared telescopes, such as the

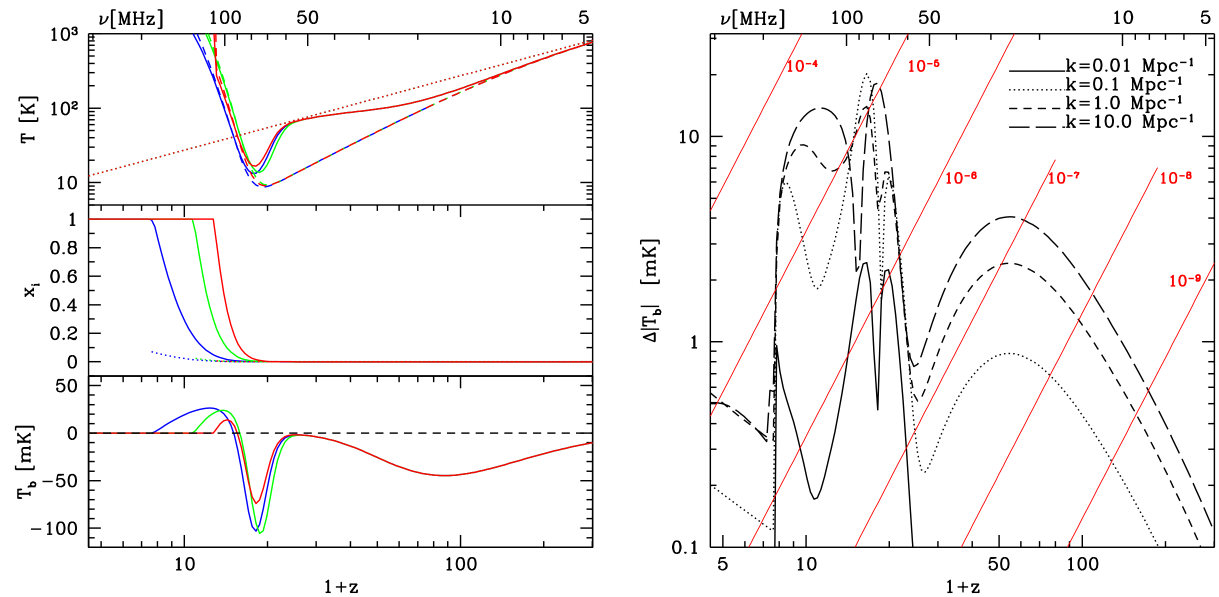


FIG. 9: *Left: Top panel:* Evolution of the mean CMB (dotted curve), intergalactic medium (IGM, dashed curve), and spin (solid curve) temperatures. *Middle panel:* Evolution of the filling fraction of ionized bubbles (solid curve) and electron fraction outside the bubbles (dotted curve). *Bottom panel:* Evolution of mean 21cm brightness temperature. Three different astrophysical models are plotted, corresponding to the -1σ (red curve), "best-fit" (green curve), and $+1\sigma$ (blue curve) optical depth values derived from WMAP [22]. *Right:* Redshift evolution of the angle-averaged 21cm power spectrum $\bar{\Delta}_{T_b}$ in the -1σ model for wave-numbers $k = 0.01$ (solid curve), 0.1 (dotted curve), 1.0 (short dashed curve), and 10.0 Mpc^{-1} (long dashed curve). Diagonal lines indicate the foreground brightness of the sky $T_{\text{sky}}(\nu)$ times a factor r ranging from 10^{-4} to 10^{-9}, indicative of the level of foreground subtraction required [66].

James Webb Space Telescope, will help constrain the properties of the high-redshift sources in the future.

Photons emitted between Lyα and the Lyman limit propagate until they redshift into a Lyman series resonance. Atomic cascades then convert some fraction into Lyα photons, which provide a coupling between T_s and T_{gas}. Photons produced just below the Lyβ resonance may travel $\sim 300\,\text{Mpc}$ before redshifting into the Lyα resonance [68]. As such the resulting Lyα background might be expected to be spatially uniform. However, the clustering of sources and strong distance dependence of the flux increase the fluctuations. Multiple scattering of Lyα photons around sources further amplifies Lyα fluctuations. An objective of the proposed *CTC* will be to model the atomic physics of Lyα fluctuations in greater detail. Determining the clustering of Lyα sources constrains the dark matter distribution, which provides the scaffolding for structure formation.

Compact objects, formed as stellar remnants, are known to be associated with strong X-ray sources in the local Universe. Predominantly power-law emitters, these sources are thought to provide a significant source of heating by X-rays for the cold intergalactic medium (IGM) soon after the first stars form. In the IGM, an X-ray photon can travel a distance of

$\sim 5\,x_{\rm HI}^{-1/3}\,[(1+z)/15]^{-2}\,(E/300\,{\rm eV})^3$ Mpc before photo-ionizing a hydrogen or helium atom. This ionization results in an energetic photoelectron whose subsequent scattering deposits energy into further ionization and heating of the IGM. In addition, some energy will be deposited as excitation of hydrogen atoms whose relaxation can generate Lyα photons. This Lyα flux is comparable with and may exceed that produced by stars. Although hard X-rays ($E \gtrsim 2\,{\rm keV}$) can have mean free paths comparable with the size of the Universe, soft X-rays ($E \lesssim 2\,{\rm keV}$), which contain the bulk of the emitted energy, are absorbed within tens of Mpc from the sources. This extra effect makes heating and the Lyα background from X-ray sources more inhomogeneous than that from stars [69].

The pattern of temperature fluctuations depends not only upon heat input at late times, but also upon the conditions before star formation begins. Improving precision in calculation of recombination and thermal decoupling will be necessary for separating out possible particle-physics sources of heating. Additional astrophysical sources of heating, such as shocks around large-scale structure, are likely to exist and will also need to be explored. Since exotic heating processes are unlikely to track the distribution of galaxies, they will produce a different spectrum of temperature fluctuations than astrophysical sources. Thus, the combination of measurements of the spatial variation and the redshift evolution of the signal should provide a powerful tool for distinguishing different heating processes.

D. Evolution of the 21cm signal and the impact of luminous sources

Although the details of early star formation remain unknown, we can extrapolate from the local Universe to produce plausible astrophysical models. Figure 9 (right panel) quantifies the evolution of the 21cm signal from $z = 300$ to $z = 3.5$ for one such model. At redshifts $z \gtrsim 20$, the power spectrum of 21cm brightness fluctuations tracks primordial density fluctuations. To learn about the physics of inflation it would be preferable to make measurements in this "pristine" regime. During reionization, fluctuations in the spin temperature and the presence of ionized bubbles alter the shape of the power spectrum significantly. The brightness of the Galactic synchrotron foreground increases at low frequencies ν ($T_{\rm sky} \propto \nu^{-2.6}$), favoring observations of low redshifts. Detecting the pristine signal from $z \gtrsim 20$ requires foreground removal at the level of 10^{-7}, two orders of magnitude larger than that required to detect fluctuations during reionization. Fortunately, fundamental physics can also be derived after reionization ($z \lesssim 6$) where the foreground is weak and the residual hydrogen, once again, traces the large scale distribution of the dark matter.

It is important to identify the highest redshift at which astrophysics begins to affect the 21cm signal. This defines the frequency range required to probe the pristine Dark Ages. Since fluctuations in the Lyα flux are likely to be the first source of astrophysical effects, we may quantify the end of the pristine regime by the redshift $z_{\rm trans}$ at which Lyα fluctuations contribute equal power to the 21cm signal as do density fluctuations. This transition is shown in Fig. 10 for the parameters f_α and f_X, which scale the Lyα and X-ray luminosity of a fiducial model. Since the fraction of collapsed matter grows exponentially with time, $z_{\rm trans}$ depends only weakly on these parameters, so that robust modeling of $z_{\rm trans}$ should be feasible despite uncertainty in the properties of luminous sources.

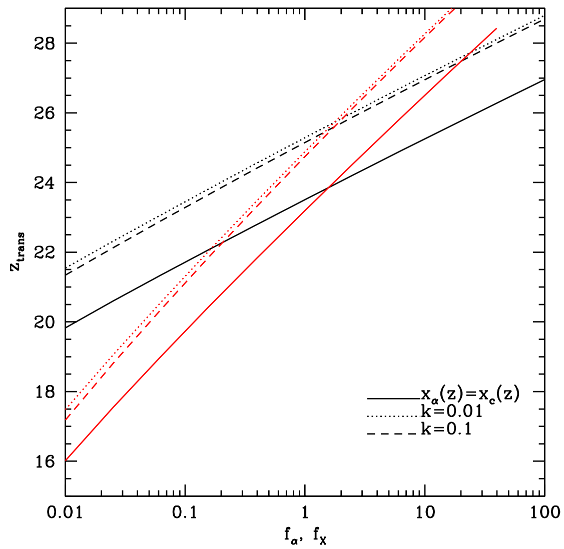


FIG. 10: Evolution of $z_{\rm trans}$ with f_α (black curves) and f_X (red curves) for $k = 0.01$ (dotted curves), 0.1 (short dashed curve), and 1 Mpc^{-1} (long dashed curve). Also plotted is the redshift at which Lyα and collisional coupling are equally effective $x_\alpha = x_c$ (solid curves). Adapted from [66].

E. Precise Atomic Physics and Radiative Transfer

Essential to the science described above (and in MA1) is the ability to compute the detailed state of the hydrogen in the medium, particularly the spin temperature of the hydrogen hyperfine states that are responsible for the 21cm line. After recombination but before the first sources turn on, the most important effects are radiative interactions with the CMB, and various atomic and molecular processes involving hydrogen. Once structure formation has proceeded far enough, the first objects form, providing new sources of radiation, which affect the surrounding medium by heating, ionization and excitation. Atomic and molecular processes continue to be important in determining the 21cm line. But now, radiation in the Lyα line, emitted directly by the sources or as a byproduct of recombination, may have important effects. It heats the gas and also provides a strong mechanism for mixing the hydrogen hyperfine states. It has been known since the work of Wouthhuysen [70] and Field [71] that the hyperfine spin temperature is a specific average of three temperatures: the gas temperature; the brightness temperature of the 21cm line itself; and the color temperature of the radiation in the neighborhood of the Lyα resonance. Because the photon mean free path in the Lyα line is typically small, the spectrum near the Lyα line is not simply the spectrum emitted by the sources, but one that has been changed through the process of resonance line scattering. The problem of computing the observed 21cm signal thus requires not only knowledge of the relevant atomic and molecular physics but also of radiative transfer in the scattered Lyα line [72–74]. We plan to perform the associated calculations to the precision required in order to infer new cosmological information from future 21cm data.

III. MA3: DATA ANALYSIS AND SIGNAL EXTRACTION

(**Zaldarriaga**, *Tegmark, de Oliveira Costa, Stubbs, Hewitt, Greenhill, Lonsdale, Rogers, Finkbeiner, Loeb; 5 postdocs, 5 grads, 2 undergrads*)

By allowing us to observe the faint signal from very high redshift neutral hydrogen, technological advances over the last decades may have opened a dramatic new window for cosmology. We could be at the verge of a new epoch of exploration both in time and in scale. In the next decades we might be able to observe times in the history of our Universe to which we never before had access and a range of spatial scales that still remains unexplored. As described in the previous sections the science returns for cosmology, physics, and astrophysics could be vast. But of course the new journey is not without challenges.

The predicted fluctuations in the 21cm brightness temperature during the Dark Ages are comparable to, or possibly even exceed, those predicted for the epoch of galaxy formation and reionization. The main obstacle for detecting the redshifted 21cm signal is the synchrotron foreground from our Milky-Way galaxy and extragalactic sources. The Galactic synchrotron brightness temperature [75], ~ 350 K $[\nu/140\text{MHz}]^{-2.6}$, is larger than the expected signal by a factor $\sim 10^5[(1+z)/10]^{2.6}$. The detection of the high redshift signal will necessarily involve a major increase in collecting area over what will be available from the first generation of arrays and a substantial improvement in the control of systematic effects. Furthermore the large data volumes involved in MWA and any future array imply that a substantial part of the data reduction process such as the array calibration, the correction for the Earth's ionospheric distortions, and the removal of the flux from bright point sources will have to be done in real time, thus posing significant computational challenges.

One of the main activities of the proposed *CTC* will be to determine how to observe the signal from high redshift and small spatial scales. Our plan consists of three main efforts:

- **Quantitative understanding of the challenge:** We will use MWA data to develop a quantitative understanding of all the challenges that *AIDA* will have to overcome. We will build models of the ionosphere and of foregrounds, and carry out accurate instrument calibration, which will then be extrapolated to lower frequencies in order to set the requirements for *AIDA*.

- **Science driven specifications:** We will establish a set of high level science driven specifications for *AIDA* and the control of systematics.

- **Meeting science specifications in practice:** We will determine how the high level science driven specifications translate into specific practical requirements for both the software and hardware components of the array.

The proposed activity will also inform current discussions at NASA about putting low-frequency arrays on the far side of the Moon [76], where human radio interference and ionospheric distortions are absent. In what follows we detail our plans in these three areas.

A. Quantitative understanding of the challenge

1. Data volumes

The MWA correlator is expected to generate 16 Gbytes of data per second corresponding to 1.5×10^9 complex visibilities (see MA5) in four Stokes parameters every half second. The data rate is so large that one cannot afford to store all the raw data for later reduction. We will collect a sample of nearly raw visibility data that will allow us to develop and test calibration algorithms. To study foreground subtraction, we will collect a long (several hundred hour) series of data that will be combined into map cubes (position on the sky $\times$ frequency), one for each twenty minutes of integration.

As part of the proposed research (see MA4), we plan also to collect some data at the lowest MWA frequencies to allow us to extend the testing and optimization of our algorithm to frequencies where ionospheric effects will be the most severe. The resulting combined database of observations for this proposal will be roughly 200 Tbytes.

Any instrument designed to detect hydrogen at even higher redshift ($z \gtrsim 17$) will require a far larger collecting area than that of MWA. To preserve the large field of view of the antenna, it would be desirable to achieve the larger area by adding more antenna elements of the same size. However, this addition could increase the correlated data rate by several orders of magnitude. The cost of processing may drive us instead to increasing the size of the antenna elements, or to some combination of the two approaches. Another entirely different approach that may circumvent these issues is the FFT Telescope, which we discuss in section MA5.

We propose to use the lessons learned from the MWA to choose the data rates and integration schemes that will be suitable for *AIDA*. We will perform simulations and use MWA data to develop a data-management strategy for *AIDA*. The data-processing requirements will be a significant driver for the cost of the array so having an accurate model for the data-processing needs will be very important for properly designing and assessing the cost of *AIDA*.

2. Calibration

Since one of the main challenges is recovering the neutral hydrogen signal in the presence of strong foregrounds, it is absolutely critical that the antenna response, including the reponse to polarized signals, be understood with high accuracy. In addition, because the raw visibility data must be integrated to produce deep images, the array must be calibrated in real time. Foreground subtraction at the EoR frequencies being studied with the MWA requires that antenna phase errors average down to less than one degree of angle; for the Dark Ages that are the goal of this study we will need to improve the accuracy of this subtraction by about a factor of ten. The current MWA calibration algorithm identifies bright sources in the full field of view and updates models of the co-polarization and cross-polarization for each antenna tile once every eight seconds. We will evaluate the performance of the calibration algorithm at both the higher EoR frequencies and at the lowest frequencies accessible with the MWA. We will refine the algorithm as necessary. Possibilities include a faster calibration cadence, more realistic antenna models, antenna elements with smoother and/or frequency-independent beams (see MA5), and modifications of the antenna response algorithm.

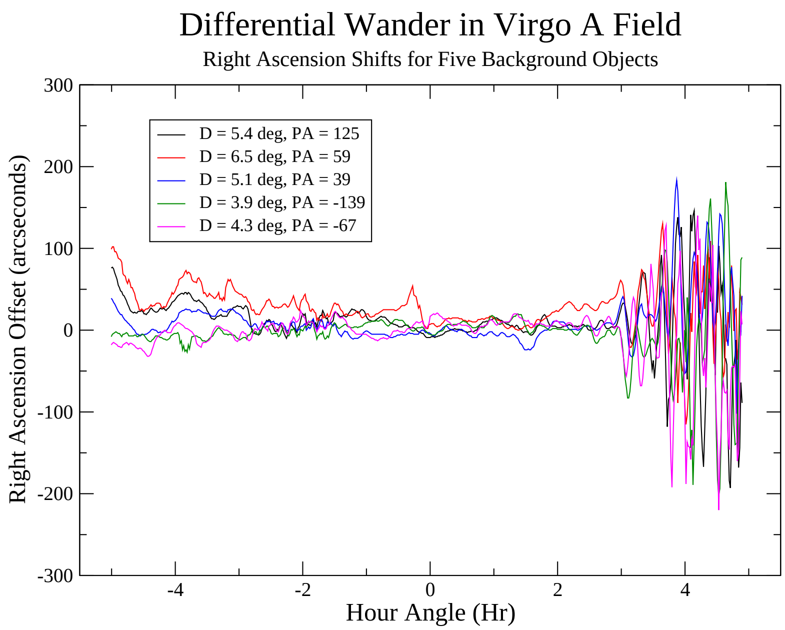


FIG. 11: Time-varying and position dependent "wander" of sources as measured at 74 MHz with the VLA due to fluctuations in the electron density of the ionosphere[77]. The dramatic increase in amplitude starting at an hour angle of 3hr may be due to the onset of dawn.

The visibility data also need to be corrected in real time for the distortions introduced by the ionosphere. Figure 11 shows the time-varying and position-dependent "wander" of sources as measured at 74 MHz with the VLA, due to fluctuations in the electron density of the ionosphere. While the changes in position are significant and must be corrected for, the effect for the short baselines of the MWA is simply refractive and can be tracked by following the positions of bright sources. The raw data need to be integrated for a long enough period so as to be able to detect a sufficient number of these sources. On the other hand, the ionosphere changes on short time scales so that calibration has to be done often. As a result of these competing needs, the array calibration and ionospheric models will have to be updated approximately every 8 seconds for the MWA. *AIDA* will need to be accurately calibrated in real time and the larger ionospheric distortions at lower frequencies will set stringent constraints on the design in order to achieve the required level of accuracy.

We will construct a model of the ionosphere fluctuations using MWA observations that allow us to simulate realistic ionospheric distortions with their proper time and scale characteristics. This model will allow us to undertake a study of the residuals in the ionospheric fits as a function of array design. We will also be able to propagate the effects of these residuals forward to determine their influence on the science products and thus feed into the requirements for the design.

Even after combining the ionospheric models and instrument-calibrated data into deep integrations, a major challenge for observing the 21cm signal is to be able to distinguish it from foreground emission. Foreground "cleaning" will have to be extremely accurate in order to allow detection of the relatively weak cosmological signal. The foreground emission is expected to be a smooth function of frequency, whereas the cosmological signal is expected to fluctuate rapidly because a change in frequency corresponds to a change in location of the signal along the line of sight. MWA plans to use this distinguishing feature to separate foreground emission from the cosmological signal. We expect that *AIDA* will use a similar method for foreground removal, but the requirements would be significantly more stringent.

In the frequency range relevant to 21cm surveys, the dominant physical mechanism known to cause foreground (polarized and unpolarized) contamination is synchrotron emission. When coming from extragalactic objects, this radiation is usually referred to as point source contamination and affects mainly small angular scales. When coming from the Milky Way, this diffuse Galactic emission fluctuates mainly on large angular scales.

In preparation for the proposed project and other work on 21cm observations, we have built a global sky model of diffuse Galactic emission from 10 MHz to 100 GHz using all currently available unpolarized large-area radio surveys (see Figure 12), digitized with optical character recognition when necessary and compiled into a uniform format [78]. We quantified the statistical and systematic uncertainties in these surveys by comparing them with various global multi-frequency model fits. As illustrated by Figure 13, a principal-component-based model with only three components can fit the 11 most accurate data sets (at 10, 22, 45 & 408 MHz and 1.4, 2.3, 23, 33, 41, 61, 94 GHz) rather accurately. The fits suggest that the emission is dominated by synchrotron radiation below a few GHz, vibrating dust above $\sim$ 40GHz, and spinning dust in the intermediate range [79]. Figure 14 shows all-sky maps of the sky temperature, frequency spectral index β, and running of the spectral index γ at 150 MHz. This preliminary sky model, which is publicly available at *http://space.mit.edu/home/angelica/gsm* will help guide our initial simulation and design work.

Unfortunately, we still know basically nothing about the polarized contribution of the Galactic synchrotron component at MHz frequencies, since it has only been measured at a few lower frequencies and extrapolations are complicated by Faraday Rotation. We therefore plan to tackle this problem head on, extending the methodology developed for the unpolarized model mentioned above. We will also refine these polarized and unpolarized models by using the MWA (which will be both more sensitive and better calibrated than instruments used in previous surveys), as soon as it becomes available.

Synchrotron emission from extragalactic sources is also a very serious challenge for *AIDA*, because this foreground component fluctuates on small angular scales much like the 21cm signal itself [80, 81]. Fortunately, there are numerous relevant low-frequency point source catalogs that we can use both as real templates and for modeling of source counts (how many sources to expect above various flux thresholds at different frequencies) and source clustering (departures from Poisson power spectrum). Such modeling will be an integral part of our proposed effort.

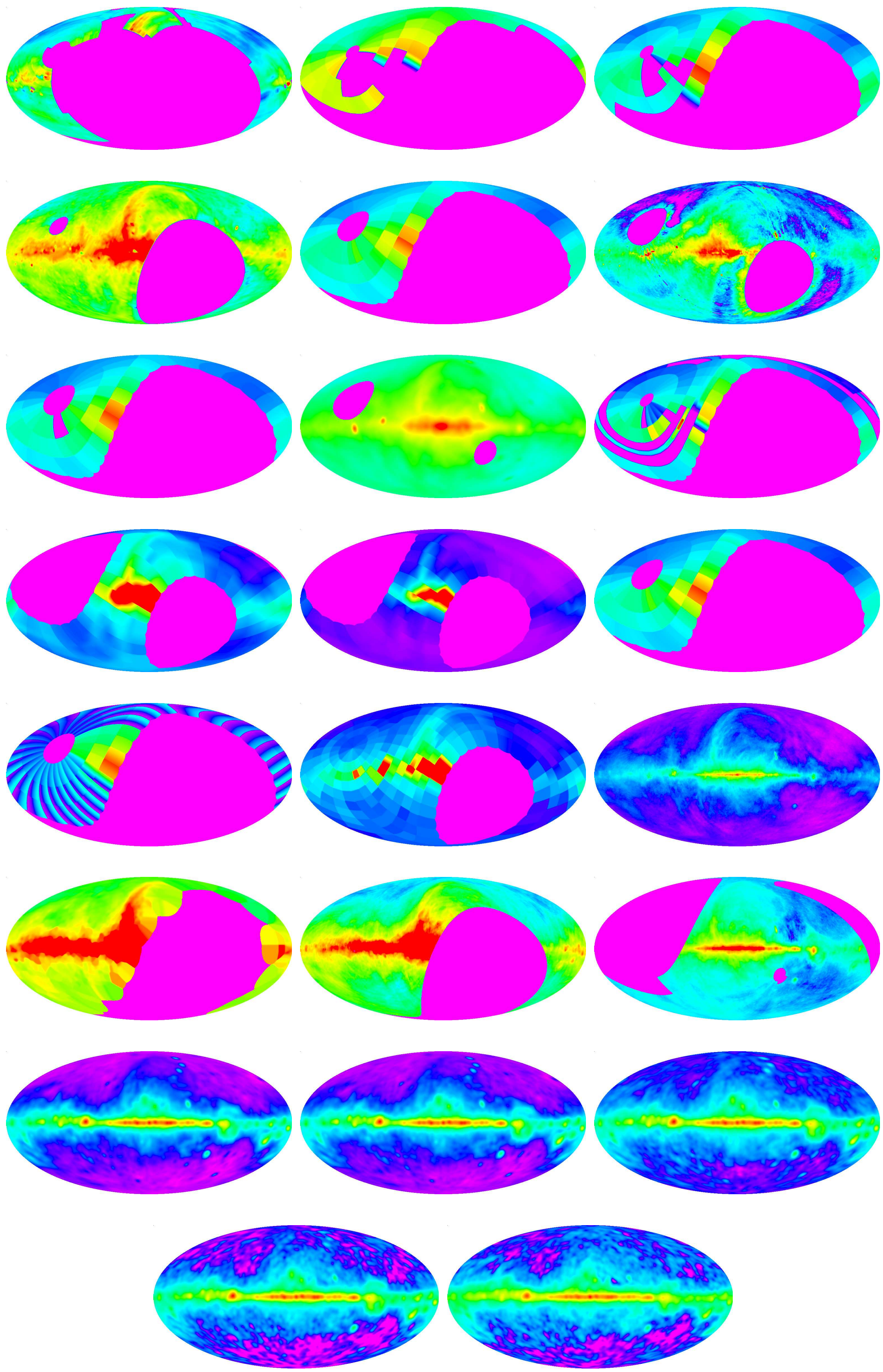


FIG. 12: The maps show (from left to right, top to bottom) the 10 MHz [82], 13.5 MHz [83], 17.5 MHz [83], 22 MHz [84], 26 MHz [85], 35 MHz [86], 38 MHz [85], 45 MHz [87], 81.5 MHz [83], 85 MHz [88], 150 MHz [88], 176 MHz [85], 400 MHz [85], 404 MHz [89], 408 MHz [90], 820 MHz [91], 1420 MHz [92] and 2326 MHz [93] surveys, and the CMB-free WMAP foreground maps at 23, 33, 41, 61 and 94 GHz [94–96].

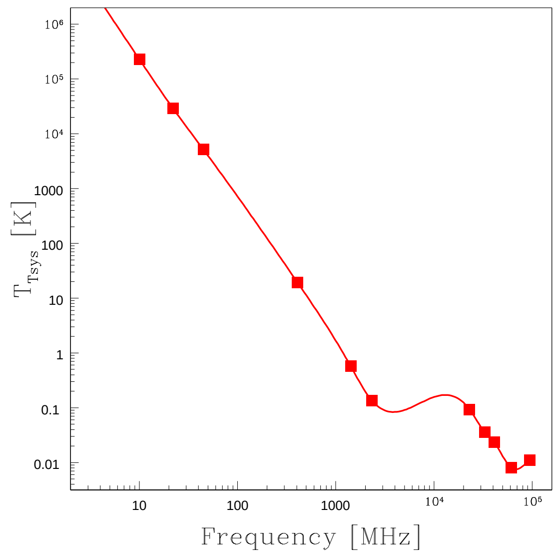


FIG. 13: Squares show the 11 measurements available at a pixel at (l, b)=(11.3,89.6), and the curve shows the model from [78]. The sharp rise of the synchrotron intensity towards lower frequencies makes accurate foreground cleaning crucial for the success of *AIDA*.

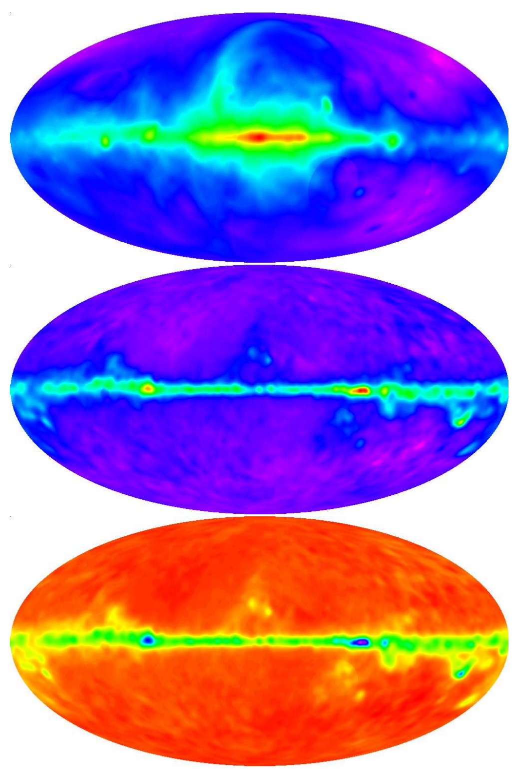


FIG. 14: The sky maps are (from top to bottom): temperature, spectral index β, and the running of spectral index γ at 150 MHz.

4. Instrumental systematics

It is extremely important to control any systematic effect that could lead to a spurious rapid variation of the signal with frequency as this is the distinguishing feature of the cosmological signal. There are various examples of such effects: even though the foreground emission in total-intensity is expected to be smooth as a function of frequency, Faraday rotation will lead to very fast variations in the orientation of the linear polarization with wavelength. As a result, errors in the array calibration that leak polarization into total intensity measurements need to be tightly controlled. Furthermore, if the instrument's sidelobes have a complex structure that varies rapidly with frequency, strong sources in the sidelobes could produce rapid variations in the spectrum that would be misinterpreted as a cosmological signal. Being able to calibrate the array response very accurately and in real time is a crucial requirement for detecting the cosmological 21cm signal. Lessons learned in the analysis of MWA data will be fundamental for the design of a more sensitive array. We will exploit the interaction of instrument builders, software designers, and scientists enabled by the *CTC* to evaluate the entire data stream – from antenna through calibration, foreground subtraction, and mapping – to ensure that the systematic effects are reduced or understood at the level required for extracting cosmological results. We will build models of these systematic effects that will allow us to simulate them and track both their level and our ability to correct for them as a function of array design. Results from these models will feed directly into the design phase of *AIDA*.

B. Science driven specifications

Our theoretical efforts as part of MA1 and MA2 will allow us to sharpen the scientific questions that *AIDA* will be designed to address. As a result of those efforts we will have various goals for measurements of fluctuations for different look-back times and spatial scales. We will also have understood what statistical measures encode the information we seek. Certain questions will require measurements of the power spectrum on some range of spatial scales, others will require measuring higher moments or probability distribution functions. Some questions will require tracking the redshift evolution of various quantities while others will require comparing different scales.

Thus, the specifications for the array in terms of calibration and control of systematics, will heavily depend on the choice of scientific questions. The proposed *CTC* will define the most desirable final science products, as described in MA1 and MA2. We will then use the detailed models and simulations to translate those requirements into design requirements for *AIDA*.

C. Meeting science specifications in practice

The final part of the plan is to develop a strategy to meet the specifications we have developed. This strategy involves propagating the specifications to the level of specific hardware and software components. We discuss each of these separately below.

1. Hardware challenges

The antenna tiles being used for the MWA have advantages and disadvantages. Chief among the disadvantages is the complicated frequency-dependent structure of the beam. An important task of the *CTC* will be to evaluate whether the MWA antenna tiles and calibration algorithms perform at the level required for Dark Ages studies. In order to address this we will: *(1)* determine the level of precision achievable with the MWA over its range of frequencies; *(2)* use simulations informed by the MWA measurements to extrapolate these results to lower frequencies; *(3)* use simulations informed by our studies of different antenna designs to evaluate the performance of the calibration algorithms when applied to antennas with smoother beams; and *(4)* set specifications on the performance of the antennas. Of course, it may turn out that a different type of antenna design will prove superior for meeting the needs of *AIDA* (see MA5).

2. Software challenges

The deep integrations from *AIDA*, once foreground cleaned, will be used to constrain cosmological parameters and to be alert to the unexpected. Placing such constraints requires the ability to make maps of the sky with an algorithm that preserves the cosmological information and is efficient enough to be able to handle the large volumes of data. The ionospheric corrections and the foreground cleaning steps will introduce various filtering effects and distortions in the input data to the map-making algorithm. These will have to be carefully characterized, monitored and corrected for, so as not to bias the cosmological parameter extraction. The maps will then be used to determine spatial power spectra and higher order statistics from which the values of cosmological parameters can be inferred. It is again important to be able to use a method that does not affect the information content of the signal in this step. Throughout this process, the noise properties of the maps and the various statistics derived from them will have to be computed as they are a crucial ingredient for constraining cosmological parameters and for disclosing the unexpected. The above challenges will be investigated by members of the *CTC* and the resulting optimized algorithms will be applied and tested on the data archive that will be produced by the MWA project.

IV. MA4: TESTBED DATA AND ANTENNA DEVELOPMENT

(**Hewitt**, *Lonsdale, Rogers, Burke, Greenhill, Tegmark, Zaldarriaga, de Oliveira Costa, Loeb; 10 postdocs,10 grads,5 undergrads*)

A. MA4.1: The Testbed Data Archive

As described above, we will use MWA data to develop and test calibration, mapping, and analysis algorithms, and to establish the technical requirements for *AIDA*. The first generation MWA-demonstrator will have 512 antenna tiles of 4×4 antennae each. In this section we describe our plan to collect the test data and to set up an archive for use by the *CTC* collaboration. We will also make the archive freely available to the astronomy and physics communities through the internet.

The MWA has been designed to achieve three major science goals: observation of the Epoch of Reionization (EoR); study of the ionosphere, heliosphere and space weather; and surveys for astronomical radio transients. Therefore, the 512 antenna tiles of the MWA will operate in the 80 MHz to 300 MHz frequency range (redshifts from 17 to 4); 31 MHz of bandwidth will be collected at any one time, with the band tuned within the operating range. Data from all baselines, including both polarizations and 3072 frequency channels, will be correlated, producing over 1.5×10^9 complex visibilities every half second for a correlated data output rate of over 12 Gbyte/second. The correlations will be processed by a real-time calibration and modeling system, in which corrections for antenna response and for ionosphere fluctuations, respectively, will be applied before producing maps. The calibration corrections will be derived from complex antenna gain patterns; these corrections and the ionosphere models will be updated every eight seconds. The eight-second sky maps will then be passed to an integrator, which will feed the data archive.

FIG. 15: Three MWA antenna tiles on site at the Radio Astronomy Park in Western Australia. These tiles are part of a 32-tile array that is currently under evaluation in preparation for construction of the full 512-tile array. Each tile consists of a four-by-four array of crossed dipoles operated as a phased array, an example of which can be seen in the foreground of this image.

As of this writing, 32 antenna tiles have been constructed and are being tested at the MWA site in Western Australia (see Fig. 15). After testing, we expect to construct the full 512-tile array during the second, third, and fourth quarters of 2008. After a six-month commissioning period in 2009, science observations will begin.

The NSF/AST MWA cooperative agreement, already funded, is intended to support only the construction of the array and initial EoR science (and ionospheric, heliospheric, and transient science). To address the EoR science, the MWA EoR science collaboration plans to observe two fields chosen to have low levels of Galactic foreground and polarization. A total of 1800 hours of observations are planned during the 2009-2010 observing season (see timeline in Fig. 16). These observations will provide very deep integrations of the two EoR fields with the sensitivity required to detect the ionization fluctuations predicted by EoR models. The observing time will be divided between two frequencies, one that corresponds to neutral hydrogen at redshift $z = 6.2$ (200 MHz) and one that corresponds to neutral hydrogen at redshift $z = 8$ (160 MHz). The sensitivity of the MWA is not sufficient for studying the EoR at higher redshifts. The NSF/AST agreement provides funding for only 50 Tbytes of storage; therefore, maps will be averaged for 20 minutes before being deposited into the archive, and no visibility data will be saved. The archive will also store environmental data, data on the configuration of the instrument, and the calibration and ionospheric solutions that were applied to the data. The NSF/AST agreement supports the development of the software associated with these tasks.

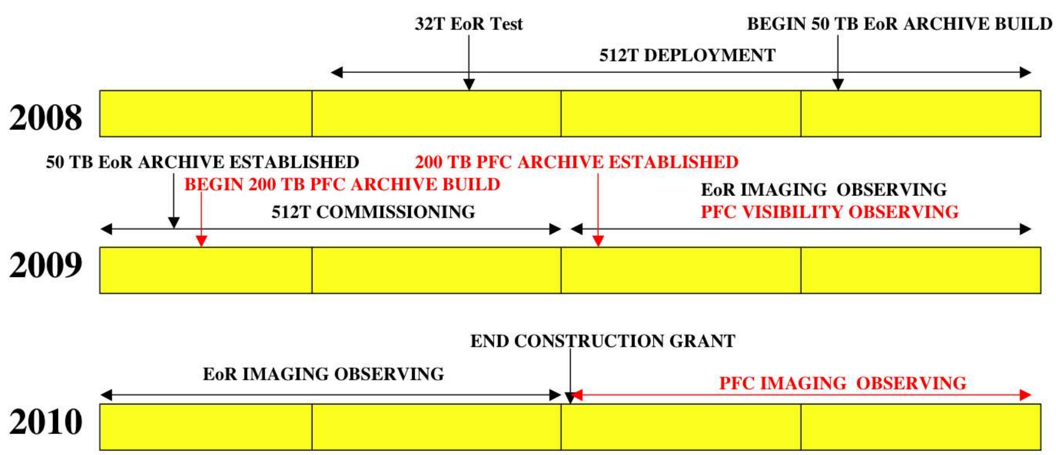


FIG. 16: Baseline timeline of MWA construction and operations. "32T" refers to the existing 32-tile array; "512T" refers to the 512-tile array under construction. Items in black are already funded by the NSF/AST cooperative agreement. Items in red/grey are proposed here. Note that "mapping" and "imaging" are used interchangeably throughout this proposal.

Observations proposed for this study. We propose to collect the data that will make it possible to extend our studies beyond the EoR (galaxy formation and reionization) to the physics of inflation and dark matter. As described in MA1, these studies require either probing high redshifts *before* galaxy formation ($z \gtrsim 20$), low redshifts after reionization ($z \lesssim 6$), or being able to separate the peculiar velocity effects during reionization (see

MA2.B). The data that will be collected for the EoR archive will allow us to test algorithms for mapping and foreground subtraction at relatively high frequencies, pushing them to the high accuracy required for Dark Ages studies. However, we also must test calibration algorithms at all relevant radio frequencies, investigating the challenges of larger ionospheric effects and higher sky noise. Testing calibration algorithms requires storing visibility data in addition to the calibrated maps used for mapping and foreground-subtraction studies. *Therefore, additional data must be collected: uncalibrated visibility data and data at lower radio frequencies.*

The collection of visibility data will proceed quickly because of the enormous data rates. The first computation step in the MWA real-time system is to average the visibilities for 2 to 8 seconds (the choice depends on baseline length and the need to preserve the field of view) and to sum the spectra to a resolution of 40 kHz. After this step the data rate is 1.7 GBytes/second for nearly 3×10^9 visibilities per 8-second time interval. We plan to tap into the real-time system after this averaging step, and collect ten hours of data, for a total of 60 Tbytes. We will monitor the ionosphere during the observations, and collect data in such a way that a range of ionospheric conditions is sampled. These visibility data will be distributed over frequency, from 80 MHz to 150 MHz, enabling a quantitative analysis of calibration and modeling algorithms and their behavior at a range of frequencies. We will carry out these observations during the time allocated for EoR observing in the last half of 2009.

In addition to the visibility data, we will collect data from a long integration on a low-foreground field at 80-110 MHz, enabling tests of mapping and foreground subtraction at the lowest usable frequencies of the MWA. These observations will take place during the third and fourth quarters of 2010. We anticipate several hundred hours of observing time for this task, and the data will be stored in the remaining 140 Tbytes of storage available in the proposed 200Tbyte archive.

Maintaining the Archive. As part of the MWA construction activity we are developing software that will allow users to select maps based on various selection criteria, including date and time, quality of the calibration solution, quality of the ionospheric solution, and environmental parameters. For this effort, we will develop the software that will manage the storage and access of visibility data. We will also devote resources to maintaining the additional storage required for the Dark Ages studies.

Summary of Goals for this Major Activity:

- Establish a 200 Tbyte archive for storing the data required for Dark Ages studies
- Execute a short (ten-hour) observing run in late 2009 to collect uncalibrated visibility data at a range of frequencies
- Execute a long (several hundred hour) observing run in late 2010 to produce maps of a low-foreground field at the lowest MWA frequencies
- Maintain the archive and make it available via the internet to the collaboration and the community.

B. MA4.2: Antenna development and testing

General Considerations. One of the main goals of our proposed program is to consider in detail an array design that will overcome the effects of increased sky noise at low frequencies in a cost-effective way. However, even at this stage we can use scaling relationships to estimate the collecting area needed. For example, increasing the collecting area, A, of the array while holding the size of the antenna elements constant (and hence the field of view) results in a signal-to-noise ratio for the power spectrum that scales with A^2, because of the dependence on the etendue [97]. This scaling drives the design toward a large number of small elements. On the other hand, the cost of much of the signal processing in a correlating array scales with the square of the number of antenna elements, driving the design instead toward a smaller number of larger elements. While the choice of antenna size and array area have yet to be made, it seems clear that overcoming the effects of the increased sky noise will require collecting areas that are a factor of ten to one hundred times larger than that of the MWA and other first-generation experiments, and that this collecting area will be composed of many (many hundreds to a few thousand) elements. It is necessary to develop an antenna design that can be manufactured at very low cost so that the required collecting area will be affordable.

As discussed in MA3, the increased brightness of Galactic and extragalactic foregrounds at low frequencies also exacerbates the foreground subtraction problem, requiring that the cosmological signal be separated from the foreground when the former is as small as one part in 10^6 of the latter. Errors in the modeling of frequency-dependent sidelobes in the antenna response pattern introduce a frequency-dependent source of systematic errors in sky images, complicating foreground subtraction techniques that rely on their spectral smoothness. Furthermore, because of patchy Faraday rotation the polarized Galactic foreground has structure on angular scales of interest, even in regions of smooth total continuum emission[98]. Therefore, frequency-dependent cross-polarization of the antenna response also introduces systematic effects that make foreground subtraction difficult. For foreground subtraction to succeed at the levels required by pre-reionization studies, the sidelobes and cross-polarization properties of the antennas must be well understood. For the stringent requirements of *AIDA*, we also seek to develop antenna elements that have smaller sidelobes and cross-polarization than do the MWA elements, in addition to being inexpensive to manufacture. Careful studies are required to evaluate the achievable precision in the calibration of the antennas.

Finally, a frequency range of interest for *AIDA*, 30–90 MHz, is a region of the spectrum plagued by man-made interference. The MWA is located in the Radio Astronomy Park in Western Australia, a low population density area being designated as a radio quiet zone by the Australian government. This environment, or a similarly radio-quiet one (such as exists in South Africa), will be necessary for *AIDA*.

Thus, even without detailed modeling of the performance of a low-frequency array for cosmology, it is clear that such an array will require a very large collecting area composed of many antenna elements, precise calibration, and placement in an environment that is relatively free of radio frequency interference (RFI). We propose a program of antenna development and testing that will address each of these considerations.

In Search of Low Cost and Calibration Capability. Four EoR pathfinder experiments under development have begun the process of choosing antennas for redshifted 21cm studies.

Each experiment is employing a different antenna design. These designs can be placed into three general categories: *(1)* tiles, or stations, that are phased arrays of smaller elements; *(2)* dipoles-in-a-cavity; and *(3)* log-periodic antennas. We discuss each in turn, and propose to perform a comparative study of their relative merits and weaknesses.

Tile designs: The MWA, LOFAR [7] and 21CMA [9] arrays are all based on tile or station designs. We have already referred to the MWA example, a phased array of dipoles, in Fig. 15. The tile design was chosen by the MWA project primarily because it can be steered electronically. Disadvantages are large sidelobes and cross-polarization, and significant variations of the beam-shape and overall gain with frequency. An example of the beam patterns of an MWA tile, measured in the MIT Lincoln Laboratory anechoic chamber, is shown in Fig. 17. The large sidelobes and cross-polarization are quite clearly evident. The measurements also show, not surprisingly, that the structure of the beams varies considerably with frequency. Developing tile designs is a very active area of research which continues to be a priority of the MWA collaboration, and is also being pursued in the European Square Kilometer Array Design Study (SKADS; http://www.skads-eu.org).

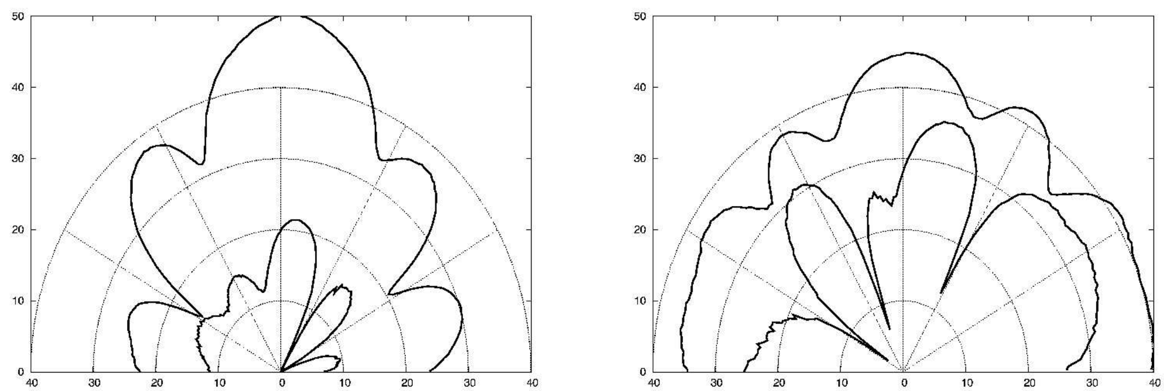


FIG. 17: *Left:* Measured co- (outer plot) and cross-polarization (inner plot) beams of the MWA tile at 150 MHz. This is a cut through the zenith, showing a nicely formed parallel-polarization beam with cross-polarization 30dB down for most directions. *Right:* Same for a cut 45 degrees away from zenith, with a beam still pointing at zenith. In this direction at this frequency the sidelobes and the cross-polarization are large.

Dipole-in-a-Cavity Designs: The EoR pathfinder experiment PAPER [8] and the all-sky monitoring experiment STARE[99] are examples of designs exploiting the dipole-in-a-cavity (see Fig. 18). The presence of the cavity suppresses the dipole's back lobe by about 30 dB and increases the directivity of the forward lobe. The dipole can be designed to be broadband; in the case of PAPER this is done with a "sleeve" design. The advantages of the dipole-in-a-cavity are its simplicity and its relatively low sidelobe level. Disadvantages are the large fixed beam, and variations of beam shape with frequency.

Log-Periodic Designs: The Cosmological Reionization Experiment (CoRE [100]) makes use of an antenna which consists of a two-arm log-spiral winding on a styrofoam pyramidal support structure (see Fig. 19). This design is very similar to the feeds being deployed in the Allen

FIG. 18: Two examples of dipole-in-a-cavity antenna designs. *Left:* Prototype antenna from the PAPER experiment. *Right:* Antenna used in the STARE radio transient monitoring experiment.

Telescope Array (http://ral.berkeley.edu/ata)[101]. For low-frequency aperture arrays such "feeds" would be operated as individual antenna elements instead, pointing upward toward the sky. We note that the 21CMA antenna elements are directional (yagis) with log-periodic directors, so this experiment combines elements both of tile design and of log-periodic design. The advantages of the log periodic designs are the near independence of beam shape with frequency and relatively low sidelobes; a disadvantages is the large fixed beam.

FIG. 19: Two examples of log-periodic antenna designs. *Left:* Prototype antenna from the CoRE experiment. *Right:* Prototype feeds for the Allen Telescope Array.

We propose to evaluate these three classes of antenna design with respect to cost and calibration capability, reviewing the literature, working with the other groups, and carrying out modeling, anechoic chamber measurements, and field measurements as necessary. A critical part of our analysis will be to exploit the synergies of the *CTC* and include information about the antenna properties in our evaluation of calibration, mapping, and foreground algorithms. As an example, the tile antennas, with complicated frequency-dependent beams, are likely to affect the performance of the algorithms quite differently from a dipole-in-a-cavity antenna with much smoother beams. Our goal is to identify an antenna design for low-frequency arrays that allows accurate calibration and foreground subtraction. Success in this area would be broadly beneficial to low-frequency array design for astronomy and many other purposes.

Site Surveys. The range of redshifts that we wish to target for our cosmological studies puts the 1.4 GHz neutral hydrogen radio line in a region of the spectrum allocated to radio, television and other services. Furthermore, nearly all man-made devices (computers, auto ignition systems, lighting, pagers, etc.) radiate at these frequencies. Fig. 20 compares RFI spectra at three sites in Australia: a major city, a town with a population of about 7000, and a remote sheep ranch near the Murchison Radio Observatory (MRO) in Western Australia. These plots clearly demonstrate the impact of a large human population. The problem of radio frequency interference (RFI) is severe and can be addressed on Earth only by going to the remotest sites. Even at the remotest sites, it is also necessary to enforce controls on radio emissions. The RFI problem is such a concern that placing a low-frequency radio array on the far side of the Moon is being seriously considered[102].

The MRO, where the MWA and several other EoR pathfinder experiments are located, is recognized as one of the most radio-quiet sites in the world that is also reasonably accessible. The Australian government is in the process of designating it a protected radio astronomy park, and MRO is currently one of two contenders for the site of the proposed Square Kilometer Array telescope. The MWA project is collaborating with the Australia Telescope National Facility (ATNF) on the preservation of the radio-quiet environment as the MWA is constructed. The controls being put in place at the MRO as of this writing only extend down in frequency as far as 100 MHz. We propose to work with ATNF personnel to evaluate the RFI environment in the 30 to 100 MHz range. We also will work to evaluate the environment of the other proposed SKA site in South Africa.

Summary of goals:

- Identify one or more antenna elements in the 30-200 MHz range that are inexpensive to manufacture, have small sidelobes, and small levels of cross-polarization. We will focus on the three classes of antenna design described above, but will consider other designs as appropriate. This task will involve reviewing the development work already done by other groups and carrying out electromagnetic modeling.

- Build scale models of promising designs, and verify their properties in the Lincoln Lab anechoic chamber.

- Build full-scale models of one or two of the most promising designs and field test a small (four-element) array in a radio-quiet area such as the MRO.

- Publish a comparison of the strengths and weaknesses of the three (or more) classes of designs.

- Incorporate the properties of the antenna designs in simulations for the development of algorithms for signal extraction.

- Carry out a study of the 30-90 MHz radio environment at the Radio Astronomy Park in Western Australia that will inform the array design. Investigate other sites as appropriate.

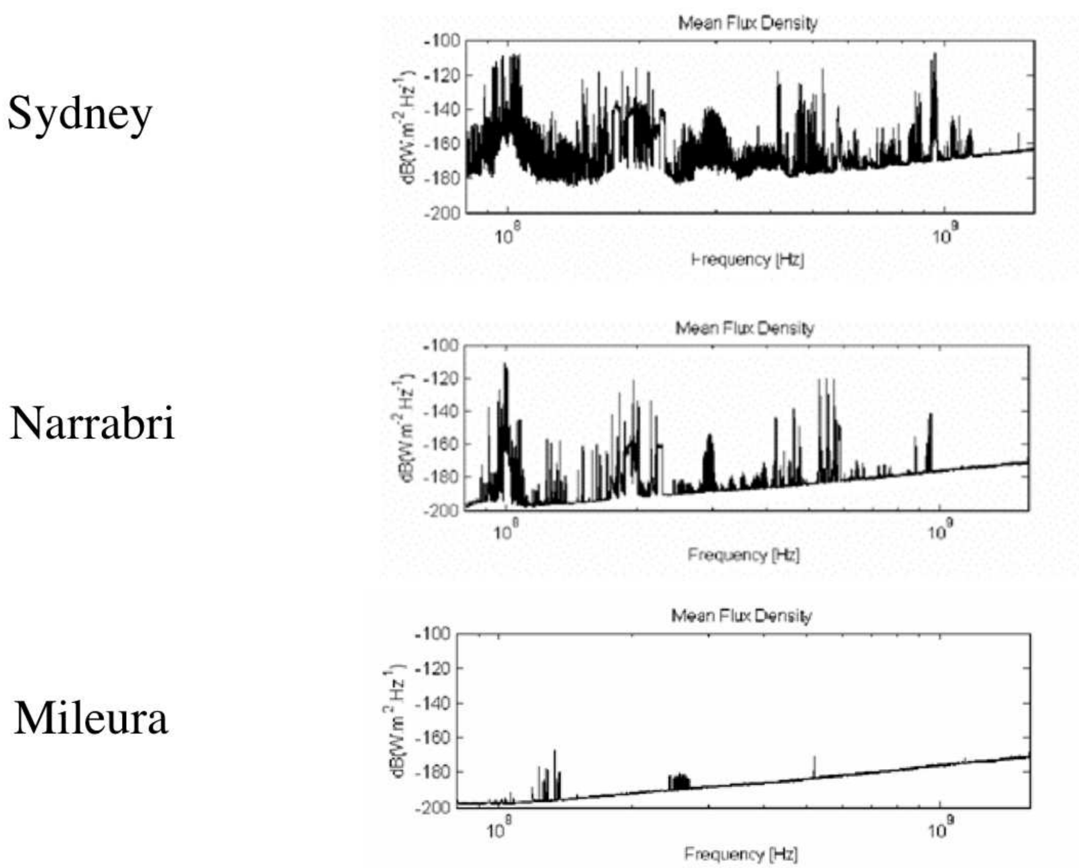


FIG. 20: Plots of the radio frequency interference (RFI) power at three sites in Australia: Sydney, Narrabri, and Mileura Station (in the MRO)[103].

V. MA5: DESIGN OF *AIDA*

(**Tegmark**, *Zaldarriaga, Hewitt, Rogers, Burke, Greenhill, Lonsdale, de Oliveira Costa, Loeb, Shapiro, Alcock; 5 postdocs, 5 grads, 2 undergrads*)

Our science goals require *AIDA* to image the sky with unprecedented accuracy (see MA3). To learn how to meet these challenging technical specifications on a reasonable budget, we will explore some novel design ideas for *AIDA*. Below we describe two such ideas: an all-digital correlating interferometer, and its implementation as a "Fast Fourier Transform Telescope". Both of these ideas are timely, only recently made possible because the exponential increase with time (Moore's law) of computer speed (and corresponding increases in signal processing speed), and offer potentially large improvements in image quality per dollar spent.

A. Digital Radio Telescopes: A New Paradigm for the 21st Century

We are at a critical point in the evolution of the technology that might address Dark Ages studies: a completely new approach to radio telescope design is now enabled by the enormous improvement in the performance-to-cost ratio in digital electronics. Forty years ago, the high cost of receivers and associated signal processing electronics drove designs toward large monolithic collecting areas, with one or a small number of feeds and receivers mounted at the focal point. The development of radio interferometers in the late 1950's, led to the spectacular accomplishments of the National Radio Astronomy Observatory's (NRAO's) Very Large Array and Very Large Baseline Array. The technology of operating several telescopes together to form a large collecting area and allowing high angular resolution via the use of widely-spaced individual telescopes ("interferometer elements") led to these accomplishments. The construction cost of a radio dish of diameter D, scales roughly as $D^{2.7}$ [104]. The cost of the receivers scales with the number of telescopes N; the cost of the signal processing in a correlating array (see below for more detail) scales with N^2. Therefore, in designing an interferometer telescope array with a given collecting area, there is an antenna element diameter $D_{\rm opt}$ that minimizes the cost. As the cost of signal processing continues to decrease, *the "optimum" antenna element size continues to become smaller, and radio telescopes are being built as interferometer arrays with larger numbers of smaller elements.* This trend is illustrated in Fig. 21, which shows the evolving design of radio telescopes over the last several decades.

The only practical way to combine signals from a large number of telescopes is digitally, and the plummeting cost of signal processing also greatly influences telescope design. The signal can now be digitized *at the antenna elements* so that all processing after that point is done digitally, including the receiver functions of filtering and mixing. In fact, in arrays operating at low radio frequencies, such as the one that would be used to study the Dark Ages, mixing is not necessary and the full bandwidth is sampled at baseband - i.e., frequencies from zero to $f_{\rm max}$, where $f_{\rm max}$ is the maximum frequency being studied. For example, the signals from the MWA antenna elements are sampled at 660 million samples per second, giving a working bandwidth of 0-330 MHz for the science. There are many advantages to a digital radio telescope: after the digitization, the signals are not altered by changes in environmental factors such as temperature; the operation of the array (e.g., changes in pointing direction and spectral resolution) can be changed simply by changing the processing programs; and the array is easily upwards scalable, at least technically: one simply adds antennas and processing capability. Another advantage of the digital radio telescope is that *it can be built with no moving parts*, greatly reducing cost and maintenance requirements. Again, consider the MWA as an example: the MWA tiles are placed on the ground such that the dipole "beams" point vertically upwards. Pointing of the tiles is achieved by operating them as a phased array and electronically steering the beams of the tiles around the sky.

We propose to explore array designs for *AIDA* that fully exploit these new capabilities and reduced costs, achievable with a digital radio telescope. Specifically, we will explore two classes of design: the correlating array and a new concept, the digital FFT array.

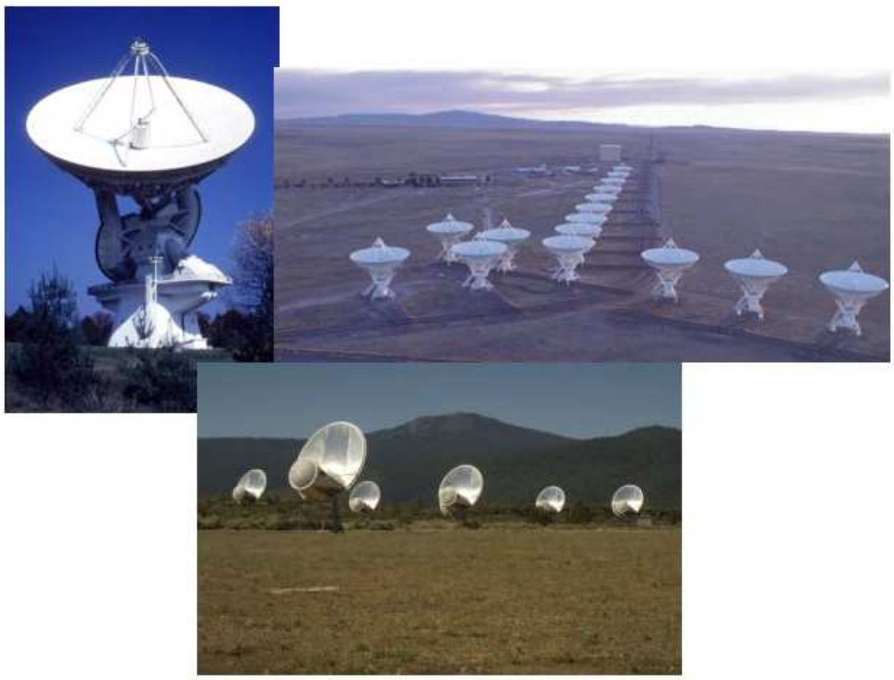


FIG. 21: Examples of radio telescopes that show the evolving design over the last several decades. (Top left) NRAO's 43-meter telescope, completed in 1965. (Top right) NRAO's Very Large Array (VLA), completed in 1980. The VLA is made up of 27 25-meter parabolic dishes (images courtesy of NRAO/AUI). (Bottom) Part of the Allen Telescope Array being built by the SETI Institute and Berkeley (image courtesy of the Seti Institute). The array consists now of 42 6-meter antenna elements; the goal is 350 antenna elements.

B. Correlating Arrays

A very successful design for large-aperture radio arrays is the aperture synthesis telescope. Martin Ryle received the 1974 Nobel Prize in physics for having pioneered the aperture synthesis technique, and his Nobel lecture describes his early work in this area. (Aperture synthesis involves filling in as well as feasible the "holes" in the aperture by moving the geographical placement of the antennas and/or making use of the Earth's rotation.) The motivation for much of the early work was to carry out measurements with high angular resolution. As a consequence, the early arrays were sparse arrays (i.e. mostly "holes"), with the longest baseline determining the achievable angular resolution, and the shortest baselines filling in the aperture to the extent needed for the detection of the source(s) under study. Our motivation here is to synthesize a large collecting area, and the arrays we will be considering will therefore not be highly sparse.

The fundamental idea underlying the correlating array is that the correlation known as the *visibility* between the signals measured by two antennas (in the so-called u-v plane) measures a component of the Fourier transform of the sky brightness distribution, specifically the Fourier component corresponding to the vector difference between the two antenna positions. Collecting many visibility measurements with many pairs of antennas at many Earth orientations, and performing the inverse Fourier transform, can therefore produce an estimate of the sky brightness distribution (see, for example [105]). Some of the mathematical details of this procedure are described below in connection with equation (9).

Early interferometers formed visibilities by summing the signals from each pair of antennas. The technique of phase switching, first introduced in 1952 [106], introduced the measurement of the *product* of each signal pair. A measurement of the product is much less sensitive to fluctuations in amplifier noise and gain, and is used in all large astronomical radio arrays today. The averaged product is proportional to the correlation coefficient of the two signals, and these arrays are therefore referred to as correlating arrays. In modern systems the incoming signals are digitized and the data streams are multiplied together. The number of multiplications that need to be carried out scales with the square of the number of antenna elements, and is an important cost driver for arrays composed of a large number of elements.

For the *AIDA* radio array, our goal is to carry out very accurate statistical measurements of the full sky 21cm signal. The signal-to-noise ratio of our measurements with a correlating array will be larger if we have a larger array collecting area, a larger field of view, a longer integration time, and a larger radio bandwidth. For the low radio frequencies considered here the noise is dominated by sky noise, and does not drive the design (other than through secondary effects such as the field of view and pointing direction). The field of view is set by the area of the individual antenna elements; a smaller element gives a larger field of view. Larger radio bandwidths or more frequency channels require more signal processing capability. It is possible to parameterize the performance of the array in terms of these characteristics, and to compute the signal-to-noise ratio of the 21cm measurements that one would expect with different array designs. Examples of these calculations are given for the MWA by [16, 107, 108], who took as inputs the radial distribution of antennas in the array, the antenna size, receiver parameters, and observing parameters. From these inputs, they computed the sensitivity of power spectrum measurements, assuming perfect foreground subtraction. We propose to generalize these calculations to include antenna beam shapes, different foreground models, and different foreground subtraction techniques, thus providing a more realistic way to propagate design choices through the model to produce a performance metric for evaluating each array design. These calculations will be carried out for observable signatures that include the power spectrum, higher-order statistical moments, and possibly the full probability distribution function of the 21cm fluctuations.

With an understanding of antenna properties and costs (the goal of MA4.2), it should be reasonably straightforward to develop a cost model for the whole array. In selecting between different array designs, cost is obviously a factor. We will compute the cost of each array design under consideration. Using the performance and cost models, we will carry out studies to find the design that can accomplish *AIDA*'s scientific goals within "reasonable" cost constraints.

Once such a design (or a small number of good designs) is identified, we will develop a plan for data handling and signal processing. At the end of this study, we expect to be able to propose a plan for construction and commissioning of a correlating array that would meet the scientific goals of *AIDA*.

C. Fast Fourier Transform Telescope

We also propose to develop and test an all-digital telescope design which combines key advantages of both single dishes and interferometers. The electric field sensed by the antennas is digitized at antennas on a square grid, after which a series of Fast Fourier Transforms recovers simultaneous multi-frequency images of up to half the sky at each "snapshot". The main advantages over a single dish telescope are cost and orders of magnitude larger field-of-view, translating into far better sensitivity for large-area surveys. The key advantages over traditional interferometers are cost (the correlator computational cost for an N-element FFT array scales as $N \log_2 N$ rather than N^2) and a compact synthesized beam. We show that 21cm imaging may be a promising first application of this Fast Fourier Transform telescope, which would provide large sensitivity improvements per dollar spent and mitigate the off-beam point-source foreground problem with its clean beam.

1. The basic idea

From a mathematical point of view, telescopes are Fourier transformers. We want to know individual Fourier modes $\mathbf{k}$ of the electromagnetic field, as their direction $\widehat{\mathbf{k}}$ encodes our image and their magnitude $k = \omega/c = 2\pi/\lambda$ encodes the wavelength, but the field at a given spacetime point $(\mathbf{r}, t)$ is represented by a sum of all these Fourier modes weighted by phase factors $e^{i[\mathbf{k}\cdot\mathbf{r}+\omega t]}$.

Traditional telescopes perform the spatial Fourier transform from $\mathbf{r}$-space to $\mathbf{k}$-space by analog means using lenses or mirrors, which are accurate in a relatively small field of view, and perform the temporal Fourier transform from t to ω using slits, gratings or band-pass filters. Traditional interferometers used analog means to separate frequencies and measure electromagnetic field correlations between different receivers, then Fourier-transformed to $\mathbf{r}$-space digitally, using computers. In the tradeoff between resolution, sensitivity and cost, single-dish telescopes and interferometers are highly complementary, and which is better depends on the science goal at hand.

As mentioned above, we can now build all-digital interferometers up to about 1 GHz, where the analog signal is digitized at each antenna; subsequent correlations and Fourier transforms are done by computers. In addition to reducing various systematic errors, this digital revolution enables the "Fast Fourier Transform Telescope" described below. This idea is explained in full detail in a new paper [109] written by co-investigators on this proposal; we provide only a brief summary below. An FFT telescope acts much like a single-dish telescope with a larger field of view, yet is potentially much cheaper than a standard interferometer with comparable collecting area. If a modern all-digital interferometer such as the MWA is scaled up to a very large number of antennas N, its price becomes completely dominated by the computing hardware cost for performing of order N^2 correlations between all its antenna pairs. The key idea behind the FFT Telescope is that, if the antennas are arranged on a rectangular grid, these can be cut to scale merely as $N\log_2 N$ using Fast Fourier Transforms. As we will see, this design also eliminates the need for individual antennas or antenna groups that are pointable (mechanically or electronically), and has the potential to very substantially improve the sensitivity of future telescopes like *AIDA* and the Square Kilometer Array without increasing their cost.

Although this basic idea seems rather obvious in hindsight, we have found little exploration of it in the literature, perhaps because the idea was not particularly useful before A/D conversion became feasible up to the GHz range. We have discovered that a Japanese group worked on an 8×8 FFT Telescope about 15 years ago [110], but this effort appears to have been abandoned, presumably because of insurmountable challenges in making it work with analog rather than digital signal processing. The prospects of scaling this design up to $N \gg 8$ must have seemed hopeless at the time, which is presumably the reason that this group did not explore general theoretical issues and applications like we propose. We also learned that a North American group is considering a one- rather than two-dimensional array that can be analyzed with FFT's, exploiting Earth rotation to fill in the missing two-dimensional information [111]. A detailed analysis of this design is given in [109], showing that the 2-dimensional FFT provides much greater large-scale sensitivity.

2. How the Telescope works

Since the FFT Telescope images half the sky at once, the flat-sky approximation that is common in radio astronomy is not valid. Here we briefly summarize the formalism for a curved sky. Suppose we have a set of antennas at positions $\mathbf{r}_n$ with sky responses $\mathbf{B}_n(\widehat{\mathbf{k}})$ at a fixed radio frequency $\omega = ck$, $n = 1, ...,$ and a sky signal $\mathbf{s}(\widehat{\mathbf{k}})$ from the direction given by the unit vector $-\widehat{\mathbf{k}}$ (this radiation thus travels in the direction $+\widehat{\mathbf{k}}$). The signal received, $\mathbf{d}_n$, at each antenna in response to a sky signal $\mathbf{s}(\widehat{\mathbf{k}})$ is then

$$\mathbf{d}_n = \int e^{-i[\mathbf{k}\cdot\mathbf{r}_n + \omega t]}\mathbf{B}_n(\widehat{\mathbf{k}})\mathbf{s}(\widehat{\mathbf{k}})d\Omega_k. \tag{2}$$

Details related to polarization are covered in [109], but are irrelevant for the present section. For now, all that matters is that $\mathbf{s}(\widehat{\mathbf{k}})$ specifies in part the sky signal, $\mathbf{d}_n$ specifies the data that is recorded, and $\mathbf{B}_n(\widehat{\mathbf{k}})$ specifies the relation between the two. Specifically, $\mathbf{s}$ is the so-called Jones vector (a 2-dimensional complex vector field giving the electric field components – with phase – in two orthogonal directions), $\mathbf{d}_n$ is a vector containing the two complex numbers recorded by the antenna, and $\mathbf{B}_n(\widehat{\mathbf{r}})$ is a 2×2 complex matrix field that defines both the polarization response and the sky response (beam pattern) of the antenna. The only properties of equation (2) that matter for our derivation below are that it is a linear relation (which comes from the linearity of Maxwell's equations) and that it contains the phase factor $e^{-i\mathbf{k}\cdot\mathbf{r}}$ (which comes from the path length $\widehat{\mathbf{k}}\cdot\mathbf{r}$ that a wave travels to reach the antenna location $\mathbf{r}$).

The sky signal $\mathbf{s}(\widehat{\mathbf{k}})$ has a slow time dependence because of the slow motion of the sky overhead (due to the Earth's rotation), because of variable astronomical sources, and because of distorting ionospheric fluctuations. However, since these changes are many orders of magnitude slower than the electric field fluctuation timescale ω^{-1}, we can to an excellent approximation treat equation (2) as exact for a snapshot of the sky. Below we derive how to recover the snapshot sky image from these raw measurements; for convenience we ignore sky rotation and other variability.

The statements above hold for *any* radio telescope array. For the special case of the FFT telescope, all antennas have approximately identical beam patterns ($\mathbf{B}_n = \mathbf{B}$) and lie in a plane, which we can without loss of generality take to be the $z = 0$ plane so that $\widehat{\mathbf{z}}\cdot\mathbf{r}_n = 0$. Using the fact that

$$d\Omega_k = \sin\theta d\theta d\phi = \frac{dk_x dk_y}{k\sqrt{k^2 - {k_\perp}^2}}, \tag{3}$$

where $k_\perp \equiv \sqrt{k_x^2 + k_y^2}$ is the length of the component of the $\mathbf{k}$-vector perpendicular to the z-axis, we can rewrite equation (2) as a 2-dimensional Fourier transform

$$\mathbf{d}_n = \int e^{-i[\mathbf{q}\cdot\mathbf{x}_n + \omega t]}\frac{\mathbf{B}_n(\mathbf{q})\mathbf{s}(\mathbf{q})}{k\sqrt{k^2 - q^2}} d^2q = \widehat{\mathbf{s}}_{\mathbf{B}_n}(\mathbf{x}_n)e^{-i\omega t}, \tag{4}$$

where we have defined the 2-dimensional vectors

$$\mathbf{q} = \begin{pmatrix} k_x \\ k_y \end{pmatrix}, \quad \mathbf{x} = \begin{pmatrix} x \\ y \end{pmatrix}, \tag{5}$$

and the function

$$\mathbf{s}_{\mathbf{B}_n}(\mathbf{q}) \equiv \frac{\mathbf{B}_n(\mathbf{q})\mathbf{s}(\mathbf{q})}{k\sqrt{k^2 - q^2}}. \tag{6}$$

Here the 2-dimensional function $\mathbf{s}(\mathbf{q})$ is defined to equal $\mathbf{s}(q_x, q_y, -[k^2 - q_x^2 - q_y^2]^{1/2})$ when $q \equiv |\mathbf{q}| < k$, zero otherwise, and $\mathbf{B}_n(\mathbf{q})$ is defined analogously. $\mathbf{s}_{\mathbf{B}}$ can therefore be thought of as the windowed, weighted and zero-padded sky signal. Equation (4) holds under the assumption that $B_n(\widehat{\mathbf{k}})$ vanishes for $k_z > 0$, *i.e.*, that a ground screen eliminates all response to radiation heading up from below the horizon, so that we can limit the integration over solid angle to half the sphere.

One usually models the fields arriving from different directions as uncorrelated, so that

$$\langle \mathbf{s}(\widehat{\mathbf{k}})\mathbf{s}(\widehat{\mathbf{k}}')^\dagger \rangle = \delta(\widehat{\mathbf{k}}, \widehat{\mathbf{k}}')\mathbf{S}(\widehat{\mathbf{k}}), \tag{7}$$

where $\mathbf{S}(\widehat{\mathbf{k}})$ is the 2×2 sky intensity Stokes matrix and the spherical δ-function satisfies

$$\delta(\widehat{\mathbf{k}}, \widehat{\mathbf{k}}') = \delta(\mathbf{q} - \mathbf{q}')k\sqrt{k^2 - {k_\perp}^2} \tag{8}$$

so that $\int \delta(\widehat{\mathbf{k}}, \widehat{\mathbf{k}}')g(\widehat{\mathbf{k}}')d\Omega_k' = g(\widehat{\mathbf{k}})$ for any function g. For the special case where all antennas have the same sky response $\mathbf{B}(\widehat{\mathbf{k}})$, combining equation (4) with equation (7) implies that the correlation between two measurements, traditionally referred to as a *visibility*, has the expectation value

$$\langle \mathbf{d}_m \mathbf{d}_n^\dagger \rangle = \int e^{-i\mathbf{q}\cdot(\mathbf{x}_m - \mathbf{x}_n)} \frac{\mathbf{B}(\mathbf{q})^\dagger \mathbf{S}(\mathbf{q}) \mathbf{B}(\mathbf{q})}{k\sqrt{k^2 - q^2}} d^2q = \widehat{\mathbf{S}}_B(\mathbf{x}_m - \mathbf{x}_n), \tag{9}$$

where

$$\mathbf{S_B}(\mathbf{q}) \equiv \frac{\mathbf{B}(\mathbf{q})^\dagger \mathbf{S}(\mathbf{q}) \mathbf{B}(\mathbf{q})}{k\sqrt{k^2 - q^2}}. \tag{10}$$

is the beam-weighted, projection-weighted and zero-padded sky brightness map.

In summary, the FFT telescope data processing is not significantly more complicated than for standard interferometry in small sky patches (where the flat sky approximation is customarily made). One can therefore follow the usual radio astronomy procedure with minimal modifications: first measure $\widehat{\mathbf{S}}_\mathbf{B}(\Delta\mathbf{x})$ at a large number of baselines corresponding to different antenna separations $\mathbf{x}_m - \mathbf{x}_n$, then use these measurements to estimate the Fourier transformation of this function, $\mathbf{S_B}(\mathbf{q})$. Finally, we recover the desired sky map $\mathbf{S_B}$ by inverting equation (10):

$$\mathbf{S}(\mathbf{q}) = k\sqrt{k^2 - q^2}\mathbf{B}(\mathbf{q})^{-\dagger} \mathbf{S_B}(\mathbf{q}) \mathbf{B}(\mathbf{q})^{-1}. \tag{11}$$

Equation (9) shows that the Fourier transformed beam-convolved sky $\widehat{\mathbf{S}}_B$ is measured at each "baseline",i.e., each separation vector $\mathbf{x}_m - \mathbf{x}_n$ for an antenna pair. A traditional correlating array with N_a antennas measures all $N_a(N_a - 1)/2$ such pairwise correlations, and optionally fills in more missing parts of the Fourier plane exploiting Earth rotation. Since the cost of antennas, A/D-converters, *etc.* scales roughly linearly with N_a, the cost of a truly large array like *AIDA* or SKA will be dominated by the cost of the correlator boards, which scales like N_a^2.

For the FFT telescope, the N_a antenna positions are chosen to form a rectangular grid. Thus, all $N_a(N_a - 1)/2 \sim N_a^2$ baselines are defined by this rectangular grid, typically with any given baseline being reproduced by many different antenna pairs. As detailed in [109], the sums of $\mathbf{d}_m \mathbf{d}_n^\dagger$ for each baseline can be computed with only of order $N_a \log_2 N_a$ (as opposed to N_a^2) operations by using Fast Fourier Transforms. Crudely speaking, what we wish to find in the Fourier plane are the antenna measurements (laid out on a 2D grid) convolved with themselves; this N_a^2 convolution can be reduced to an FFT, a squaring, and an inverse FFT. Indeed, after FFT-ing the 2D antenna grid, one already has the two electric field components in real space, and can multiply them to measure the sky intensity from each direction (Stokes I, Q, U and V) without any need to return to Fourier space, as illustrated in Figure 22. This procedure is then repeated for each time sample and each frequency, and the many intensity maps at each frequency are averaged (after compensating for sky rotation, ionospheric changes, etc.) to improve the signal-to-noise ratio.

The computational cost for the entire FFT telescope signal processing pipeline is (up to some unimportant log factors) merely proportional to the total number of measurements made by all antennas throughout the duration of the observations. In particular, the time required for the spatial FFT operations is of the same order as the time required for the time-domain FFT's that are used to separate out the different frequencies from the time

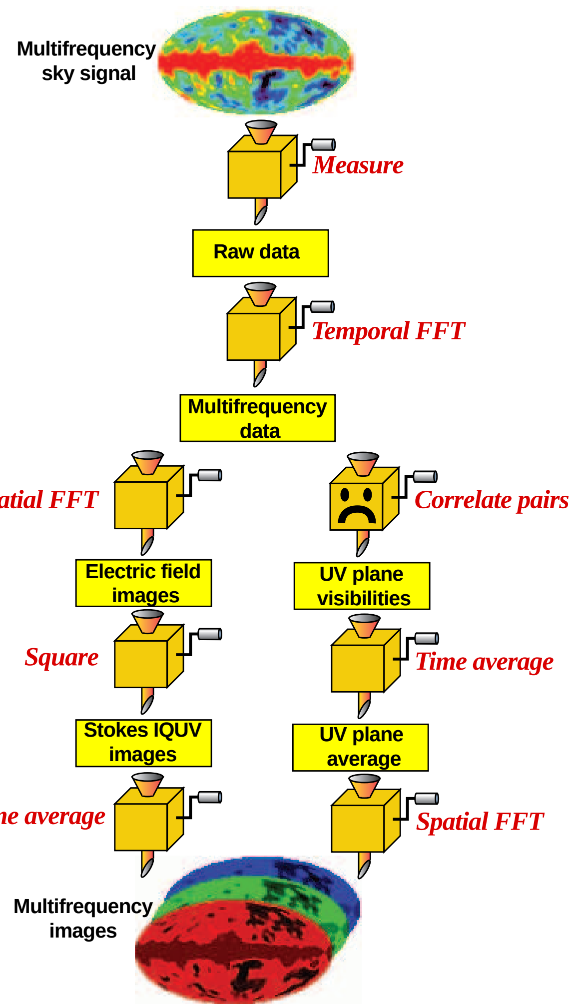


FIG. 22: arranged in a rectangular grid as in the FFT telescope, the signal processing pipeline can be dramatically accelerated by eliminating the correlation step (indicated by a sad face): its computational cost scales as N_a^2, because it must be performed for all *pairs* of antennas, whereas all other steps shown scale linearly with N_a. The left and right branches recover the same images on average, but with slightly different noise. Alternatively, if desired, the FFT telescope can produce images that are mathematically identical to those of the right branch (while retaining the speed advantage) by replacing the correlation step marked by the sad face by a spatial FFT, "squaring," and an inverse spatial FFT.

signal using standard digital filtering. If the antennas form an $n_a \times n_a$ square array, so that $N_a = n_a^2$, and each antenna measures n_t different time samples (for a particular polarization), then it is helpful to imagine this data arranged in a 3-dimensional $n_a \times n_a \times n_t$ block. The temporal and spatial FFT's (left branch in Figure 22) together correspond to a 3D FFT of this block, performed by three 1-dimensional FFT operations:

1. For each time and antenna column, an FFT in the x-direction.

2. For each time and antenna row, an FFT in the y-direction.

3. For each antenna, an FFT in the t-direction.

We need to process one such block for each of the two polarizations. These three steps each involve of order $n_a^2 n_t$ multiplications (up to the order-of-unity factor $\log n_a/n_t$). After step 2, one has the two electric-field components from each direction at each time step. After step 3, one has the two electric-field components from each direction at each frequency. If one is interested in sharp pulses that are not well-localized in frequency, one may opt to skip step 3 or perform a broad band-pass filtering rather than a full spectral separation.

The FFT telescope cuts down not only on CPU time, but also on data-storage costs, since the amount of data obtained at each snapshot scales as the number of time samples taken times N_a rather than N_a^2.

3. An FFT Telescope Prototype

Although [109] lays out the mathematical framework for an FFT telescope, none has so far been built, and there are a number of practical issues that require better understanding. We propose to test the basic concept by building a small (probably 16×16) prototype FFT telescope from a grid of dual-polarization antennas. To minimize costs, we propose to use the exact same dipole antenna elements and analog-to-digital conversion boards that are being mass-produced for the MWA, and to perform all processing and analysis of the digitized antenna signals post hoc on existing Harvard/MIT computers rather than in real time on custom hardware. The prototype array would be located geographically close to our Center, probably on the large flat roof of MIT's building 37, with the option of subsequent migration to a more radio-quiet environment. The performance would be evaluated and quantified by measuring bright sky signals such as satellites, the Sun, and other known astrophysical radio sources. Analysis of data from this prototype would help us answer a number of important questions:

1. How do gain fluctuations in the individual array elements affect the noise properties of the recovered sky map, and to what extent can this effect be mitigated by calibration in software?

2. How many "dummy" antennas are needed to be placed in rows and columns around the active instrumented part of the array to ensure that the beam patterns of all utilized antennas are sufficiently identical?

3. What antenna design of our FFT telescope will maximize gain in the relevant frequency range? The limit of an infinite square grid of antennas on an infinite ground screen is quite different from the limit of a single isolated antenna, and modeling mutual coupling effects becomes crucial when computing the response function $\mathbf{B}(\widehat{\mathbf{k}})$ from equation (2).

4. How severe are the problems that common-mode signals pose, and to what extent can they be mitigated?

5. What unforeseen challenges does the FFT telescope entail, and how can they be overcome?

How telescope specifications scale with size and wavelength.

	Single dish telescope	FFT Telescope
Angular resolution $\theta_{\min}$	$\frac{\lambda}{D}$	$\frac{\lambda}{D}$
Field of view $\theta_{\max}$	$\left(\frac{\lambda}{D}\right)^{1/3}$	1
Resolution elements $(\theta_{\max}/\theta_{\min})^2$	$\left(\frac{D}{\lambda}\right)^{4/3}$	$\left(\frac{\mathbf{D}}{\lambda}\right)^2$
Etendue $A\Omega$	$D^{4/3}\lambda^{2/3}$	D^2

The goal of our proposed work on the FFT telescope prototype is a practical design for the massive scale required to meet the specifications for *AIDA*.

D. *AIDA* Design Goal

The table [109] shows that the specifications for an FFT telescope scale the same as for a single-dish telescope if they both have the same total area, except that the solid angle $\Omega \sim \theta_{\max}^2$ of the field of view is larger by a factor $(D/\lambda)^{2/3}$. For a $D = 1000\lambda$ FFT telescope, each patch of sky in a large-area survey can be mapped 100 times longer, thus greatly improving the signal-to-noise ratio. This field-of-view advantage (which the FFT also has over typical interferometer designs) is quite separate from the above-mentioned cost $N^2 \mapsto N \log_2 N$ cost reduction The one advantage of a traditional correlating array over the FFT telescope is angular resolution.

One of the goals of our *AIDA* design study is a detailed comparison of the FFT telescope with more traditional correlating-array designs as well as with combinations of the two. For example, an interesting possibility is a correlating array with a large FFT telescope core that provides the exquisite sensitivity required on large cosmological scales, combined with a smaller number of antennas at greater separations that provide better angular resolution for point source identification and calibration.

The proposed **CTC** *will provide a forum for bringing together theoretical physicists, instrument builders, and data analysts, to work side by side in initiating the frontier field of physics described in MA1 through MA5. The "glue" provided by the Center mode of support is critical to this effort because it will ensure that these different groups are able to interact and work together on a common goal.*

VI. MA6: LEVERAGING THE ACTIVITY TO SOCIETY AT LARGE

(**Gould**, *Stubbs, Porro, Loeb, Tegmark, Wilczek, Guth, Hewitt, Shapiro, Alcock; 2 postdocs, 2 grads, 8 undergrads*)

Our proposed *CTC* aims to enhance education, diversity, and outreach by nurturing a community of teaching and learning, inspired by the Center's interdisciplinary approach to investigating fundamental physics questions about the early Universe and our cosmic origins. The goal of our education and outreach plan is to engage undergraduate students, pre-college students and teachers, teen out-of-school program participants, and public audiences in experiencing and communicating the grand *CTC* story of how advances in scientific understanding and the societal benefits of research are intimately tied to: *(a)* developments in technology and instrumentation, *(b)* progress in theoretical and computer-based modeling of physical phenomena, and *(c)* application of human creativity and knowledge to the design of new research experiments. This proposal builds on the substantial educational assets at both MIT and Harvard, and a growing partnership between the education and outreach groups at the astrophysics research centers of these two institutions that is specifically attentive to broadening the opportunities for underrepresented groups to participate in science and engineering.

We also intend to have the Center serve as a focal point for contact and fruitful exchange between the observational astrophysics and fundamental physics communities. At the present time robust evidence for new fundamental physics comes from astrophysical observations. We anticipate that the new field of 21cm observations will make discoveries of great interest to the fundamental physics communities. Our Center will host both long-term and short-term visitors, and we will convene annual workshops to strengthen the ties that will be essential to success in the decade ahead.

A. Existing Strengths and Successful Coordination

The Science Education Department (SED) of the Harvard-Smithsonian Center for Astrophysics (CfA) brings to this collaboration over 20 years of experience of contributing to the improvement of science education, with groups involved in research on student learning (at the college and pre-college levels); in educational media including scientific visualization and simulations; in the development of high-quality field-tested curriculum materials and instructional tools and technologies for astronomy and science learning; and in professional development programs for science educators.

The specific objective of the MIT Kavli Institute (MKI) education and outreach group is to provide a progression of opportunities for underserved and underrepresented youth to be meaningfully engaged in science so as to be encouraged to eventually pursue competitive professional roles in scientific disciplines. Because of the great potential that the out-of-school-time setting offers to reach out to the minorities and underrepresented groups, MKI, with the support and collaboration of the CfA, has been focusing its efforts on responding to the need for quality out-of-school science programming and for the professional development of a qualified out-of-school-time workforce, most recently with the NSF-funded Youth Astronomy Apprenticeship (YAA) program. To this end, MKI incorporates and adapts many of the research-based educational resources produced by the CfA as it develops its youth astronomy learning activities and its training programs for astronomy teaching fellows (usually recent college graduates) and after-school professionals.

B. Fostering Diversity and Enhancing Science Learning.

For the proposed education and outreach effort, the CfA and MKI will develop a portfolio of educational resources and programmatic activities to engage our target audiences in the grand story of *CTC* research, while making a measurable contribution in recruiting youth from underrepresented communities to the pursuit of science and engineering learning. We will build especially on the CfA's unique MicroObservatory online telescope network and its associated curriculum and training materials, and on MKI's programs and partnerships with both local and national networks of youth-serving community-based organizations. We will also place particular emphasis on the involvement of undergraduates in our pre-college outreach programs. Studies suggest such involvement can solidify their own understanding of science principles; enhance their communication skills; and build relationships between universities and surrounding communities. We intend to use the Center framework as a means to build the existing ties between MIT and Harvard, and to leverage, coordinate, and complement their existing individual strengths.

Engaging Students and Enhancing Diversity with Online Telescopes. We will create a series of investigations for students using Harvard's online telescopes. These automated imaging telescopes were designed for education, and enable students to explore the night sky from the convenience of their classrooms. The telescopes provide an ideal scaffolding experience for introducing a variety of concepts and skills relevant to the *CTC*'s research on imaging the Dark Ages: student's images of galaxies initiate discussions of look-back time, cosmic evolution, and the electromagnetic spectrum; the students will gain familiarity with instrumentation and observations, and issues of field-of-view, resolution, and signal-to-noise ratios. Students also will gain experience in determining what constitutes good research design, and practice in data-analysis skills. The investigations will be designed, field-tested and disseminated among three groups: undergraduates; high-school classrooms; and after-school youth groups, and will build on the CfA's prior curriculum exploring the expansion of the Universe (From the Ground Up). The activities will be coordinated with the CfA's new NSF-sponsored research project, "Exploring Frontiers of Science Using On-line Telescopes," which will invite the participation of *CTC* scientists as guides and explainers. These activities will be used in conjunction with the CfA's DVD-based professional development program for teachers, "Beyond the Solar System"; several thousand teachers, faculty and informal educators nationwide now use the DVD for teaching and learning about the structure and evolution of the Universe. We will directly link this effort to the MKI's initiative in reaching out to underserved and underrepresented youths.

Engaging Science Undergraduates in Community-based Outreach. Training strategies developed for MKI's YAA program will be used to promote the participation of MIT and Harvard undergraduate students in some of the *CTC* outreach projects. Undergraduates will work with MKI and CfA education professionals to develop their teaching and science-communication skills and to plan a series of community outreach events based on the topic of their research.

C. Engaging the Broader Physics Community

Crosscutting Workshops. Our Center will act as a bridge between the fundamental-physics and observational-astrophysics communities. We will forge and strengthen the ties between the observers and the fundamental-physics sectors by hosting annual workshops that are specifically aimed at elucidating observable consequences of the physics that gave rise to inflation. We envision holding these workshops annually, alternating between the East and West coasts and the middle of the country in order to maximize the participation by interested students.

Research Experiences for Undergraduates. We will solicit applications from undergraduates across the nation to join us at the Center during the summer, to participate in the research and education activities here. These visiting undergraduates will be incorporated into both the Center's activities and into the vibrant undergraduate summer research participation programs at MIT, its Haystack Observatory, and the Harvard-Smithsonian CfA. They will have opportunities to present their own work at the end of the summer in the symposiums held at Harvard or MIT, thereby honing their presentation and communication skills. We of course see this as an opportunity to attract potential graduate students into our programs, as well.

Visitor Program. We will actively solicit both short term and long term visitors whose academic interests are aligned with the research and educational goals of the Center. These visitors will be given desks and computer access, and will be full members of the Center's intellectual community, and we will expect all visitors to engage in both the research and outreach aspects of Center life.

D. Implicit Broader Impacts

In addition to the specific activities described above, each of which will enhance diversity and improve science learning, the work we will undertake through this Center also implicitly addresses a number of the NSF's broader impact goals. The students and postdocs who participate in the Center's work will benefit from a climate in which research, education and outreach are integrated. We note also that many of the technical challenges we face, e.g. optimally configuring sparse RF apertures and devising optimized schemes for extracting information from extensive data sets, have significant overlap with national-security issues.

The proposed research has a broad impact for society that goes well beyond studies of fundamental physics and the tracing of our origins to the beginning of the Universe. Developing the technology of low-frequency radio detectors will likely lead to improvements in communication and tracking devices as well as in defense-related systems. Better measurements and models of the ionosphere will provide a better understanding of the Earth's environment. The proposed *CTC* will educate students and postdocs in electromagnetism, low-frequency radio technology, ionospheric plasma physics, and advanced computer algorithms, all of which should be extremely useful for practical applications of benefit to high-tech industry and society at large.

8. EDUCATION AND PUBLIC OUTREACH PLAN (see also MA6)

The proposed *CTC* embodies one of the most compelling stories in all of science: the quest for fundamental laws of physics, using the early Universe as a unique laboratory. Nestled within the larger story are important opportunities for teaching and learning (1) the nature of scientific inquiry, including the interplay of theory, simulation, and observation; (2) core principles of physics, such as the interaction of light and matter; and (3) the role of basic research as a driver of new technologies with societal benefits. Our outreach plan is designed to engage diverse audiences in the significance of this story, while making measurable gains in their understanding of physics generally. We will engage four audiences: pre-college teachers and their students; minority youth in after-school programs; undergraduates; and the public.

This proposal builds on the substantial educational assets at Harvard and MIT. The Science Education Department (SED) of the CfA brings to this collaboration over 20 years of experience contributing to the improvement of science education, with groups involved in: *i.* research on learning (at the college and pre-college levels); *ii.* the creation of innovative audiovisual media, including scientific visualizations; *iii.* the development of high-quality, field-tested instructional tools for the physical sciences; and *iv.* professional development programs for pre-college science teachers. The education group at the MIT Kavli Institute (MKI) has been developing opportunities for underserved youth to be meaningfully engaged in science and to pursue careers in scientific disciplines. Due to the great potential that the out-of-school time setting offers to reach minorities and underserved groups, MKI has focused on providing high-quality out-of-school science programs for teens, along with professional development for teaching fellows and after-school professionals.

We have planned a program that builds on our strengths and is leveraged by existing projects. Our plan features the judicious use of new educational technologies; partnerships with community-based organizations; and the involvement of undergraduates in our pre-college outreach programs. Following is a brief summary.

Engaging Pre-college Teachers and Students. Knowledge of the early Universe, including the big bang, is mandated in the National Science Education Standards [112], but a lack of good curriculum materials has left this topic largely untouched in schools. In our recent survey (2004) of more than 600 physics and astronomy teachers in 47 states, 77% of teachers said they would address the standards related to the physics of the (early) Universe and many cited dark matter and dark energy as well if only there were better educational materials available. Only 4% cited lack of student or teacher interest as a limiting factor. To meet this need, we will develop a set of activities that enables teachers to address both the content standards and the nature of scientific inquiry, including a glimpse of the key questions that comprise this remarkable research frontier. We will develop activities that build on two successful education initiatives: the MicroObservatory online telescopes, and the QuarkNet high-energy physics education program. And we will use high-profile events: results from the new Large Hadron Collider at CERN, and the International Year of Astronomy in 2009, to provide 'teachable moments' in the classroom.

Investigations with online telescopes. Harvard's MicroObservatory is a network of five automated, imaging telescopes that were designed for education and can be accessed from home or classroom; they have proven highly successful in teaching and learning fundamental concepts of physics, such as the behavior of light and of matter [113]. The telescopes will provide an ideal scaffolding experience for introducing a variety of standards-based physics concepts relevant to the *CTC*'s research: students' images of galaxies, e.g., will initiate discussions of look-back time, cosmic evolution, and the electromagnetic spectrum. Students will gain familiarity with instrumentation and observations; they will address issues of resolution, signal-to-noise ratio, data analysis, and what constitutes good research design. The activities will be designed, piloted, field-tested, and disseminated as a supplement to a concurrent program, *Exploring Frontiers of Science using Online Telescopes* (NSF 0733252); the activities will be ready for release in 2010, and aligned with leading pre-college texts. *CTC* scientists will serve as guides and explainers, through online videotaped interviews, so as to bring the flavor of frontier research into the classroom, to enrich students' own investigations.

These activities will also be incorporated into the CfA's DVD-based professional development program for science teachers, called *Beyond the Solar System*; this NASA-funded program is designed to increase teachers' comfort level with the standards related to the early Universe, and is being used by several thousand teachers nationwide.

QuarkNet and CERN. We have established an informal collaboration with educators at FermiLab and Lawrence-Berkeley National Laboratory to enhance the NSF-sponsored QuarkNet program and other initiatives in high-energy physics education. Our plan is to move this collaboration forward by developing a set of activities tailored to QuarkNet teachers and advanced placement physics courses that help pre-college physics teachers to motivate their discussions of dark matter and the high-energy physics frontier, through connection to astronomical observations. (For example, students will explore evidence for dark matter in galaxy clusters, in part by using their own images along with x-ray images of the clusters, and applying basic physics concepts to estimate the mass of the clusters.) FermiLab's education manager, Marge Bardeen, has called this use of the telescopes a welcome development and likely to be an important new tool for physics teachers by helping students apply physics concepts to an area that we know catches their interest [114].

Engaging Minorities and Underserved Communities. To ensure the meaningful participation of minorities, we will build on MKI's programs for engaging underserved audiences through after-school programs, most recently with the NSF-funded *Community Science Learning through Youth Astronomy Apprenticeships* (YAA) program (ESI-0610350). Using strategies developed for this program, we will recruit and train undergraduates from MIT and Harvard to provide leadership for the youth. The undergraduate trainees will communicate aspects of the *CTC*'s science and technology that have particular appeal for young audiences, and will help to design self-contained activities and kits specifically for use in out-of-school settings. The kits will emphasize aspects of *CTC* technology such as the physics of radio antennas and concepts of signal-to-noise ratios that have applications to the technology we use in daily life. The kits will enable youth teams to map the radio-frequency background of their neighborhood, and explore the spatial- and time-variation of radio background noise and its sources, and how it affects radio communications and scientific investigations. (These activities will build on prior outreach projects from MIT's Haystack Observatory and NASA-Goddard's Radio JOVE project [115].) The undergraduates will hone their teaching and communication skills by helping to plan a series of outreach events to community centers that are part of the network served by the YAA program. The hands-on experiences for youth will be piloted at these centers and then further disseminated by 2011, through one-day training workshops presented at regional and national conferences of the Community Technology Centers Network (CTCNet http://ctcnet.org/).

Engaging Undergraduates. Our strategy for undergraduates comprises four parts: First, undergraduates will be trained to serve as mentors for after-school youth. Studies suggest that mentoring solidifies undergraduates' own understanding of the science; enhances their communication skills; and strengthens ties between their university and the surrounding community [116]. Second, in collaboration with the CfA's Science Media Group, the *CTC* will develop a suite of scientific visualizations and interactive learning tools that will help students to understand how fundamental physics can be inferred from observations of the early Universe. Students will be enabled, e.g., to vary physical laws and constants to see how the choice of model affects observable parameters. At present, students are familiar with the iconic images of the early Universe, but are baffled as to how to interpret them.

To ensure broad impact, we will adapt these visualizations and learning tools for inclusion in the online, distance-learning course, *Research Frontiers in Contemporary Physics*, being produced by the CfA's Science Media Group in collaboration with the Annenberg Foundation. One of the *CTC*'s co-Is (Stubbs) serves as content director for this course, ensuring synergy between it and the *CTC*. The course will be released to students in 2010; prior courses in this series have engaged thousands of undergraduates, including pre-service teachers. To further broaden the impact of our research experiences for undergraduates, we will solicit applications from undergraduates across the nation to join us at the *CTC* for six weeks every other summer, and participate in the research and education activities here. These visiting undergraduates will be incorporated into the Center's vibrant summer programs at MIT, Haystack and Harvard, and will have the opportunity to present their own work at a joint symposium, which will alternate between Harvard and MIT.

Engaging the Public. The International Year of Astronomy (IYA) in 2009 will focus attention on Galileo, the first great physicist to use observations of the heavens to help deduce laws of physics. Via the Internet, we plan to give the public a front-row seat for the latest installment of this story, by featuring the *CTC*'s work and placing it in the broader context of astronomy as the continuing cradle for new physics with highlights from the last 400 years such as Newton's formulation of gravity, the discovery of infrared light, and tests of Einstein's theory of gravity. The *CTC*'s educational website will link to, and draw visitors from, the websites of the CfA, MKI, and Smithsonian Institution, as well as from the U.S. IYA website. A senior member of the *CTC* sits on the U.S. Program Committee for the IYA and will be well-positioned to feature the *CTC*'s important theme. In the last two years of the 5-year project, we will focus on the interplay among theory, modeling, experiment, and technology. The Boston Museum of Science has agreed to collaborate with *CTC* education staff to create public presentations for their 'Current Science and Technology' demo stage. We will also contribute to Harvard's new Initiative in Innovative Computing (IIC), designed to highlight and disseminate new approaches to scientific visualization, especially for data in 3 dimensions and higher. As of this writing, Harvard's expansion plans include a public outreach space for the IIC to engage the larger community. Finally, *CTC* staff will be proactive in bringing the flavor, content, and excitement of their work to the public through popular articles, lecture series, open houses and other events.

9. SHARED FACILITIES

Harvard University is providing seed funds to support the Institute for Theory and Computation (ITC) in which much of the theoretical work on 21cm cosmology was done over the past five years. All Harvard affiliated co-Is are members of the ITC. The proposed data analysis and cosmological simulations will be performed in the ITC high-performance computational facility and will enable us to carry out the proposed work. In particular, we have recently acquired a 4096 processor IBM BlueGene. Moreover, in the coming months, we will acquire a new Beowulf cluster that will be dedicated to research in numerical cosmology. This machine will likely consist of roughly 1000 processors and have a total memory of several Tbytes. The IBM BlueGene and the new cluster will be essential for the numerical simulations and data analyses described in MA2 and MA3.

For MA4.1, the MIT Kavli Institute (MKI) for astrophysics and space research will supply laboratory space, cooling, and electrical capacity for the 200~Tbyte archive. The MKI 100Gbit/second connection to the internet will be used to transfer data, limiting the data rate to 10Gb/second to prevent interference with other activities. We have budgeted for Dr. E. Morgan to run the archive and develop a web interface to the community. We will collect the data using the Murchison Widefield Array (MWA) in Western Australia, a radio array under construction and supported by the NSF. The operation of the MWA is supported by the NSF for the first two years of the PFC operation; after that we expect that it will be supported by the University of Western Australia and continued NSF support.

For MA4.2 and MA5, MKI will provide laboratory space, technical support, and laboratory instruments for testing antennas. MIT's Lincoln Laboratory will make available anechoic chambers for antenna testing. We have budgeted for the technician time needed to run the facility. If field testing of the antennas is necessary, we will carry out these measurements at the MWA site, making use of the existing MWA infrastructure.

10. COLLABORATION WITH OTHER SECTORS

The antennae design and manufacturing will provide business to the company "Burns Industries" in New Hampshire. Antenna testing will be done in collaboration with MIT's Lincoln Laboratory.

11. INTERNATIONAL COLLABORATION

A major component of the proposed PFC program is exploiting the Murchison Widefield Array (MWA) to provide experience with a low-frequency radio array and the analysis of its data for cosmology. The MWA project is a collaboration between MIT Kavli Institute (MKI), Haystack Observatory, the Harvard-Smithsonian Center for Astrophysics, Australia National University, a consortium of Australian universities led by the University of Melbourne, and the Raman Research Institute. We are collaborating with CSIRO (Commonwealth Scientific and Industrial Research Organization) in siting the array at the Murchison Radio Observatory in Western

Australia. We expect that the 512-element array will be operational in late 2009. We will send personnel to the site to acquire the data we need. Most of the local operations support will be provided by the Australians under the leadership of the University of Western Australia.

Our MWA collaboration includes an active scientific collaboration that has as its goal the study of the Epoch of Reionization (EoR). Many members of that collaboration share our desire to extend EoR studies to the more demanding but also extremely exciting studies of fundamental physics possible with 21cm observations. We have semiannual meetings of the collaboration where ideas are exchanged and plans for using the MWA are discussed. These activities will continue, and will enhance and enrich the activities of the PFC.

12. SEED FUNDING AND EMERGING AREAS

We reserve some flexibility in re-allocating funds from our visitor program to unanticipated emerging needs. No such needs exist for the first year of the PFC.

13. MANAGEMENT PLAN

The purpose of the Management Plan is to help ensure that the scientific goals of the proposed *Center for 21cm Cosmology (CTC)* are achieved with the resources that are requested. The goals are extremely ambitious, comprising an "intellectual thread" that originates in fundamental physics, necessarily includes novel cosmological investigations, and extends into the design of innovative observational technologies that offer excellent prospects for testing fundamental theories and discovering new physics. The management plan detailed below ensures the integrity of the thread joining the six major activities of the *CTC* into one program.

The Director of the *CTC* will be A. Loeb, Director of the Institute for Theory and Computation (ITC) at Harvard University. The Associate Director will be J. Hewitt, who is currently the Director of the MIT Kavli Institute (MKI) for Astrophysics and Space Research. Hewitt's term as Director of MKI ends in June 2008, so Hewitt will be a regular member of the faculty of the MIT Department of Physics during the duration of the Center. Hewitt will report to the Head of the Department of Physics, and her responsibilities for leading the *CTC* research at MIT will be monitored by the new Director of MKI. Both the Head of the Department of Physics and the Director of MKI report to the MIT Dean of Science, Marc Kastner. Loeb reports to the Center for Astrophysics Director, Charles Alcock. This structure provides institutional oversight.
In addition, the *CTC* will be reviewed annually by an outside committee of experts selected by Alcock and the MKI Director. This committee will have four members and meet annually for two days, one each at Harvard and MIT, with participation of *CTC* members from both institutions on both days. The Advisory Committee will scrutinize, evaluate, and comment on all aspects of the *CTC*'s work. This committee will report on the progress of the Center and provide guidance. Its report will be delivered to the CfA Director, to the MKI Director, to the MIT Dean of Science, and also to the NSF. Our budget request includes funds to support this committee.

Loeb and Hewitt will supervise the activities and personnel (listed below) at their respective institutions. Budgeting and financial management and tracking will be carried out by the administrative staffs of the CfA and MKI.
The PI (who also leads *Major Activity 1*) and the other five *Major Activity* leaders (MALs) are responsible for the intellectual integrity and the timely completion of the various specific elements of the overall program. These leaders will form the Executive Committee (EC) of the *CTC*, with the PI serving as chairperson. Regular meetings of the EC will be devoted to overseeing the various project activities: in Year 1 these meetings will occur weekly, rotating between Harvard and MIT (some meetings may have telephone participants, as necessary). At the end of Year 1, we will re-evaluate the cadence of these meetings, and may elect to reduce their frequency and, for certain critical periods, perhaps increase their frequency; under no circumstance will there be less than one meeting of the EC per month. The EC will also be responsible for the timely submission of all necessary reports to the NSF.

Communication among the various participants in the *CTC* will take many forms: an on-line calendar and newsletter; reports to and from the *CTC* Advisory Committee; and seminars at the ITC when held at Harvard, and at MKI when held at MIT. Many of these seminars will be given by members of the proposed Center, or by visitors invited as part of its program. These seminars will contribute to the vital exchange of information and new results within the collaboration; sharing with the broader national and international scientific community will be via publications and on-line access to reports and videos of lectures and symposia.

The research of the *CTC* will be carried out in the five Major Activities (MAs) and our extensive education & public outreach program defines the sixth MA. The organization of the efforts in the MAs is the responsibilities of the individual MA leaders (MALs). There are different challenges confronting each of these, as addressed below.

The Major Activities

MA1

The "intellectual thread" begins in MA1. Fundamental theoretical investigations led by Guth and Wilczek will define the physics goals, which will be propagated into theoretical cosmology by Loeb (PI & MAL), Bertschinger, Finkbeiner, Hernquist, Narayan, Tegmark, and Zaldarriaga, working with the *CTC* postdocs and students. There are presently strong collaborations within this group, which we can expect to work well.

New atomic physics will be required. This proposal benefits greatly from proximity to the Institute of Theoretical Atomic, Molecular & Optical Physics (ITAMP, funded by NSF Physics), and will call on the expertise of Dalgarno, Kirby, & Sadeghpour as needed. Rybicki will integrate the new atomic physics into the cosmological investigations.

Stubbs and Hewitt will connect these investigations directly into observational programs with the MWA, and the technology-development efforts. The MA1 work will reside within the very successful and interactive theory groups at the ITC and MKI. These two existing groups have demonstrated their ability to attract first-rate postdocs and students, and to develop a stimulating, productive atmosphere.

MA2

The simulation effort is concentrated in MA2. Led by Hernquist, it builds upon his successful modeling effort in the ITC, and will profit from expected new Harvard investments in the infrastructure for high performance computing; the hosting and operation of this cluster computing will be performed at no cost to this proposal.

The simulation effort will allow de Oliveira-Costa to make detailed predictions of the observable signatures that may be expected in various physical cosmologies that arise from the fundamental physics.
This vital connection between physics and observation is, and must continue to be very tightly coupled to MA1. Many of the senior personnel are common to both MAs, and some of the postdocs will participate in both. This MA will also be integrated into the existing groups at the ITC and the MKI.

MA3

MA3 confronts directly the greatest challenge to the observational program: the separation of the faint 21cm signal emitted by atomic hydrogen at high redshifts from the much brighter continuum emission of foreground galaxies (prominently our own), and corruptions from the ionosphere of the Earth. These challenges involve cosmology, astrophysics, radiophysics, and very sophisticated data analysis and algorithm development. This team, led by Zaldarriaga, is unusually well prepared for this effort, and includes the broad range of expertise necessary for the tasks.

This effort extends beyond the theory and computational groups discussed above and necessarily draws in the technical expertise of the radio astronomers. Hewitt will manage the relationship with the parallel effort of the MWA program.

MA4

MA4 is very different in nature from the first three MAs. Hewitt, who is also a principal investigator in the MWA program, will lead this effort. The MWA does not probe the redshift ranges targeted by this program, but it does provide a perfect testbed for the testing of telescope array designs, for algorithm development, and especially for work on the removal of astrophysical foregrounds.

The timeline for the observations conducted with the MWA is given in Figure 16. These observations will be taken in 2009 and 2010, following design and preparation in 2008, and allowing two years of analysis in 2011 and 2012.
MA4 connects tightly with MA3. Hewitt will be responsible for the integration of the results from MA3 into the design and testing performed in MA4.

MA5

The design of the *Array for Imaging the Dark Ages (AIDA)*, the radio array that will ultimately perform the observational program spawned by the work of the *CTC*, will be led by Tegmark with Lonsdale advising on the associated engineering work. This MA requires the full range of expertise available to the *CTC*. The ultimate goal is to develop an affordable, sustainable and scalable design that can be proposed in the future for implementation. MA5 connects directly to MA4, since AIDA depends on the results from the antenna work.

MA6 and Education and public outreach Program

Gould, who will coordinate closely through Stubbs to the core intellectual program, will manage this effort. Gould and Porro work well together, and will draw upon the substantial resources of the CfA and MIT education and outreach programs.

Managing the postdoctoral Fellowship Program

The ITC has a vibrant, highly successful postdoc program. The *CTC* postdocs who sit at Harvard will be integrated into the ITC. This integration has several considerable benefits in addition to providing an intellectual home. First, many of the ITC postdocs and graduate students already work on research closely related to this proposal. Given the strong interests of the faculty, we expect this relationship will continue, offering considerable leverage to the NSF supported effort. *Note that the contributions of these postdocs, who will not be supported directly by the CTC, are included in the total personnel counts for each MA in the main body of this proposal.*

The MKI is also an exciting environment in which to work, and the *CTC* postdocs at MIT will be integrated into the MKI. This integration will have analogous advantages for the program.

A committee comprising the PI and four additional members of the senior staff of the *CTC* will select its postdocs.

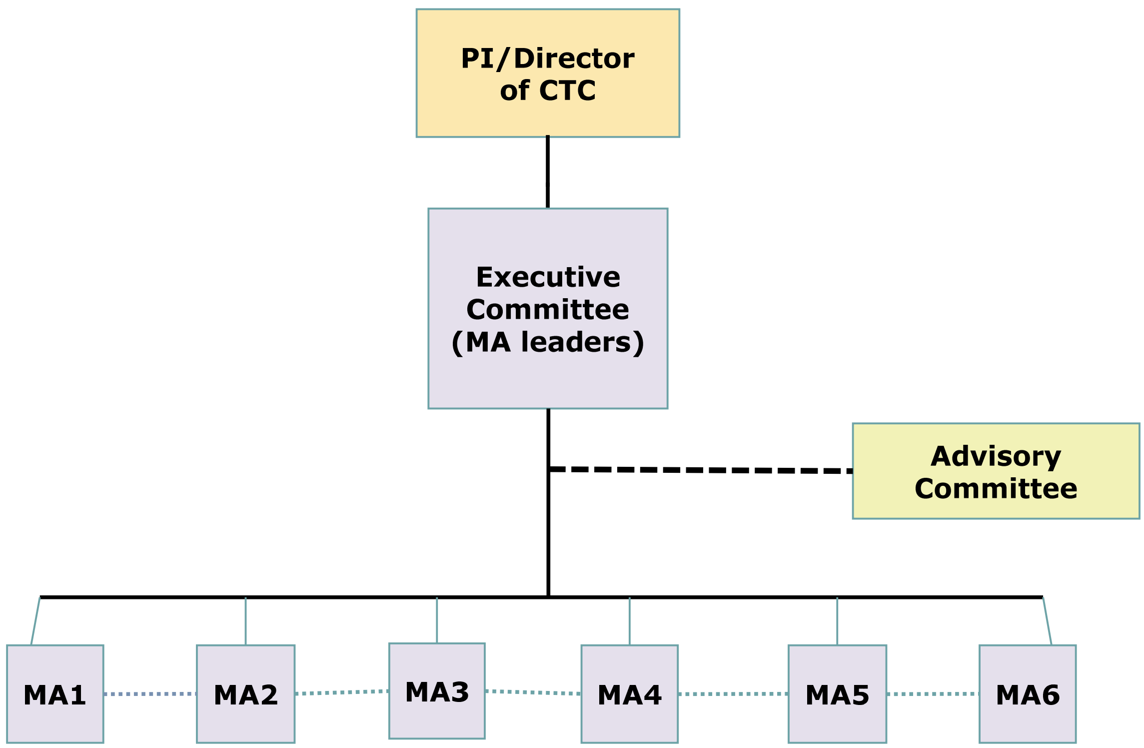
The visitor program

We have budgeted for a very substantial visitor program. This program will be managed in the ITC, and is modeled on the existing ITC visitor program. The visitors will spend time at the ITC or MKI, frequently both, with these decisions driven primarily by the intellectual efforts at the ITC and at MKI. The visitors will bring new ideas into the program, work on *CTC*-related research, and disseminate results to the larger community.

Seed Funding and Activity

MIT and Haystack observatory are heavily involved in the experimental component of MWA and will lead the antenna development effort for *AIDA*. The proposed antenna testing will be done at the MIT Lincoln Laboratory. Harvard University is currently supporting the ITC in which major theoretical work on 21cm cosmology has been done over the past four years. The proposed data analysis and cosmological simulations will be performed in the ITC high-performance computational facility, which currently includes a 4096 processor IBM BlueGene, as well as a new Beowulf cluster consisting of 1000 processors and having a total memory of several Tbytes.

CTC Organizational Chart



14. INSTITUTIONAL AND OTHER SECTOR SUPPORT

Harvard University is providing seed funds to support the Institute for Theory and Computation (ITC) in which much of the theoretical work on 21cm cosmology was done over the past five years. All Harvard affiliated co-Is are members of the ITC. The proposed data analysis and cosmological simulations will be performed in the ITC high-performance computational facility. and will enable us to carry out the proposed work. In particular, we have recently acquired a 4096 processor IBM BlueGene. Moreover, in the coming months, we will acquire a new Beowulf cluster that will be dedicated to research in numerical cosmology. This machine will likely consist of roughly 1000 processors and have a total memory of several Tbytes. The IBM BlueGene and the new cluster will be essential for the numerical simulations and data analyses described in MA2 and MA3. Harvard Office space will be provided for all faculty and their postdocs and students; as well as for the visitor and internship programs budgeted in the proposal. Harvard will also provide infrastructure as needed for workshops and meetings.

The MIT Kavli Institute (MKI) for Astrophysics and Space Research is an enthusiastic participant in the proposed PFC. Five faculty members (Hewitt, Bertschinger, Tegmark, Burke, Wilczek, Guth) are participants (the primary appointments of Wilczek and Guth are in the Center for Theoretical Physics). MKI's research staff (Morgan, Villasenor, de Oliveira Costa) have specialized skills in antenna construction and testing, computer network operation, software, and data analysis. These skills are required for the work proposed and will be made available to the PFC. Office space is provided for all faculty (including Guth and Wilczek) and their postdocs and students. Laboratory facilities, computer facilities, and other infrastructure will be made available to the PFC. MKI's office of education and outreach has invested in developing after school programs, teaching training programs, and has well established relationships with middle and high schools in the Boston area. These facilities and relationships will also be made available to the PFC. MKI has a collaborative arrangement with MIT's Lincoln Laboratory (LL) in which LL makes their extensive laboratory facilities available to MKI personnel; for this proposal the availability of antenna test facilities are particularly relevant. MKI and LL personnel participate in joint seminars that are offered several times a semester, alternating between campus and LL sites. For MA4.1, the MIT Kavli Institute (MKI) for astrophysics and space research will supply laboratory space, cooling, and electrical capacity for the 200~Tbyte archive. The MKI 100Gbit/second connection to the internet will be used to transfer data, limiting the data rate to 10Gb/second to prevent interference to other activities. We have budgeted for Dr. E. Morgan to run the archive and develop a web interface to the community. We will collect the data using the Murchison Widefield Array (MWA) in Western Australia, a radio array under construction and supported by the NSF. The operation of the MWA is supported by the NSF for the first two years of the PFC operation; after that we expect that it will be supported by the University of Western Australia and continued NSF support. For MA4.2 and MA5, MKI will provide laboratory space, technical support, and laboratory instruments for testing antennas. MIT's Lincoln Laboratory will make available anechoic chambers for antenna testing. We have budgeted for the technician time needed to run the facility. If field testing of the antennas is necessary, we will carry out these measurements at the MWA site, making use of the existing MWA infrastructure.

Summary Table of Requested NSF Support (Harvard)

Activity	Year 1	Year 2	Year 3	Year 4	Year 5	Total
MA 1: Fundamental Physical Processes	$ 168,857	$ 176,186	$ 183,233	$ 190,562	$ 198,184	$ 917,022
MA 2: Observable Signatures	$ 168,857	$ 176,186	$ 183,233	$ 190,562	$ 198,185	$ 917,022
MA 3: Data Analysis and Signal Extraction	$ 168,857	$ 176,186	$ 183,233	$ 190,562	$ 198,185	$ 917,023
MA 4: Testbed Data and Antenna Development	$ -	$ -	$ -	$ -	$ -	$ -
MA5: Design of *AIDA*	$ -	$ -	$ -	$ -	$ -	$ -
MA6: Leveraging the Activity to Society at Large (see Outreach)	$ -	$ -	$ -	$ -	$ -	$ -
Shared Facilities	$ 400,000	$ 75,000	$ 75,000	$ 258,000	$ 75,000	$ 883,000
Outreach/MA6	$ 264,936	$ 273,732	$ 259,704	$ 259,519	$ 262,066	$ 1,319,958
Administration (advisory committee travel)	$ 8,354	$ 8,400	$ 8,400	$ 8,400	$ 8,400	$ 41,954
Total	**$ 1,179,861**	**$ 885,689**	**$ 892,803**	**$ 1,097,606**	**$ 940,019**	**$ 4,995,978**

Summary Table of Requested NSF Support (MIT)

Activity	Year 1	Year 2	Year 3	Year 4	Year 5	Total
MA 1: Fundamental Physical Processes	$ 65,392	$ 72,513	$ 122,060	$ 121,982	$ 125,126	$ 507,073
MA 2: Observable Signatures	$ -	$ -	$ -	$ -	$ -	$ -
MA 3: Data Analysis and Signal Extraction	$ 80,181	$ 83,343	$ 128,780	$ 130,595	$ 133,725	$ 556,624
MA 4: Testbed Data and Antenna Development	$ 155,649	$ 152,636	$ 247,785	$ 218,974	$ 225,029	$ 1,000,073
MA5: Design of *AIDA*	$ 203,963	$ 336,590	$ 322,747	$ 308,325	$ 316,791	$ 1,488,416
MA6: Leveraging the Activity to Society at Large	$ 84,184	$ 91,728	$ 150,531	$ 146,268	$ 150,001	$ 622,712
Shared Facilities	$ 256,345	$ 25,000	$ -	$ -	$ -	$ 281,345
Outreach	$ 97,774	$ 99,667	$ 100,087	$ 100,580	$ 101,147	$ 499,255
Administration	$ 8,900	$ 8,900	$ 8,900	$ 8,900	$ 8,900	$ 44,500
Total	**$ 952,388**	**$ 870,377**	**$ 1,080,890**	**$ 1,035,624**	**$ 1,060,719**	**$ 4,999,998**

Summary Table of Requested NSF Support (Harvard and MIT)

Activity	Year 1	Year 2	Year 3	Year 4	Year 5	Total
MA 1: Fundamental Physical Processes	$ 234,249	$ 248,699	$ 305,293	$ 312,544	$ 323,310	$ 1,424,095
MA 2: Observable Signatures	$ 168,857	$ 176,186	$ 183,233	$ 190,562	$ 198,185	$ 917,022
MA 3: Data Analysis and Signal Extraction	$ 249,038	$ 259,529	$ 312,013	$ 321,157	$ 331,910	$ 1,473,647
MA 4: Testbed Data and Antenna Development	$ 155,649	$ 152,636	$ 247,785	$ 218,974	$ 225,029	$ 1,000,073
MA5: Design of *AIDA*	$ 203,963	$ 336,590	$ 322,747	$ 308,325	$ 316,791	$ 1,488,416
MA6: Leveraging the Activity to Society at Large	$ 84,184	$ 91,728	$ 150,531	$ 146,268	$ 150,001	$ 622,712
Shared Facilities	$ 656,345	$ 100,000	$ 75,000	$ 258,000	$ 75,000	$ 1,164,345
Outreach	$ 362,710	$ 373,399	$ 359,791	$ 360,099	$ 363,213	$ 1,819,213
Administration	$ 17,254	$ 17,300	$ 17,300	$ 17,300	$ 17,300	$ 86,454
Total	**$ 2,132,249**	**$ 1,756,066**	**$ 1,973,693**	**$ 2,133,230**	**$ 2,000,738**	**$ 9,995,976**

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Biographical Sketch - ABRAHAM LOEB

Professional Preparation

The Hebrew University of Jerusalem, Jerusalem, Israel:
B.Sc in Physics and Mathematics (1983); M.Sc. in Physics (1985); Ph.D. in Physics (1987)
Institute for Advanced Study, Princeton: Long Term Member (8/88-1/93)

Appointments

2007-	Director, Institute for Theory & Computation (ITC), Harvard University (http://www.cfa.harvard.edu/itc/)
1997-	Professor of Astronomy, Harvard University
1995-1996	Associate Professor, Astronomy Department, Harvard University.
1993-1995	Assistant Professor, Astronomy Department, Harvard University.

Related Publications (out of a total of 273)

- Loeb, A., Wyithe, J.S.B., "Precise Measurement of the Cosmological Power Spectrum With a Dedicated 21cm Survey After Reionization", Phys. Rev. Lett., submitted, preprint arXiv:0801.1677
- Wyithe, S., Loeb, A., & P. M. Geil, "Baryonic Acoustic Oscillations in 21cm Emission: A Probe of Dark Energy'', MNRAS, submitted, 2007. [arXiv:0709.2955]
- Barkana, R., & Loeb, A. "The Physics and Early History of the Intergalactic Medium'', Rep. Prog. Phys., 70, 627-657, 2007. [astro-ph/0611541]
- Wyithe, J. S. B., & Loeb, A., "A Size of 10Mpc for the Ionized Bubbles at the End of Cosmic Reionization'', Nature, 432, 194, 2004. [astro-ph/0409412]
- Barkana, R., & Loeb, A., "A Method for Separating the Physics from the Astrophysics of High-Redshift 21 Centimeter Fluctuations'', ApJ, 624, L65, 2005.
- Loeb, A., & Zaldarriaga, M. "Measuring the Small-Scale Power Spectrum of Cosmic Density Fluctuations Through 21 cm Tomography Prior to the Epoch of Structure Formation'', Phys. Rev. Lett., 92, 211301, 2004.

Synergistic Activities

- ''The Dark Ages of the Universe'', Scientific American, Nov. issue, 2006
- ''Let There Be Light'', Time magazine cover story, 9/4/06 issue
- Ten lectures for students entitled "First Light'' at the SAAS-Fee 2006 advanced course (158 pages), published by Springer Verlag (2007). [astro-ph/0603360]

Recent Collaborators and Other Affiliations: S. Wyithe; V. Bromm; R. Barkana; B. Schmidt; C.L. Carilli; E. Waxman; D. Stark; R.S. Ellis; A. Broderick; E. Quataert; M.J. Reid; D. Maoz; C. Hirata; N. Afshordi; S. Furlanetto; U. Keshet; J. Granot; E. Ramirez-Ruiz; B. Zhang; M. Milosavljevic; L. Gao; P.J.E. Peebles; S.D.M. White; L. Chuzhoy; D.N. Spergel; J.P. Ostriker; K. Nagamine; E. Pfahl; O. Doré; G. Holder; M. Santos; S. Gaudi.
Graduate and postdoc advisors: L. Friedland; S. Eliezer; J. Bahcall. **Graduate advisees:** D. Eisenstein; Z. Haiman; R. Perna; E. Woods; R. Pilla; A. Refregier; D. Heyrovsky; X. Wang; P. Chatterjee; S. Furlanetto; L. Hoffman; D. Babich; R. O'Leary; J. Munoz; B. Kocsis; L. Blecha; B. Maruca; I. Ginsburg; E. Visbal.

Biographical Sketch - CHARLES ALCOCK

Professional Preparation

Auckland University, New Zealand	Physics	B.Sc. (Hons)	1972
California Institute of Technology	Astronomy	Ph.D.	1977

Appointments

Harvard-Smithsonian Center for Astrophysics, Director	8/2004 – present
University of Pennsylvania, Professor of Astronomy	9/2000 – 7/2004
Lawrence Livermore National Laboratory	
Deputy Associate Director for Physics	4/1998 – 8/2000
Head, Inst. of Geo. & Planetary Physics	6/1996 – 8/2000
Astrophysics Center Head	7/1986 – 6/1996
MIT, Associate Professor of Physics	9/1981 – 6/1986
Institute for Advanced Study, Long Term Member	10/1977 – 8/1981

Publications

"Possible gravitational microlensing of a star in the Large Magellanic Cloud", C. Alcock, et al (The MACHO Collaboration) (1993) Nature, 365, 621.
"First Observation of Parallax in a Gravitational Microlensing Event", C. Alcock, et al (The MACHO Collaboration) (1995) Ap. J. Letters, 454, L125.
"MACHO Alert 95-30: First Real-Time Observation of Extended Source Effects in Gravitational Microlensing", C. Alcock, et al (The MACHO & MOA Collaborations) (1997), Ap. J., 491, 436.
"EROS and MACHO Combined Limits on Planetary Mass Dark Matter in the Galactic Halo", C. Alcock, et al (The EROS & MACHO Collaborations) (1998) Ap.J., 499, L9.
"Discovery and Characterization of a Caustic Crossing Microlensing Event in the Small Magellanic Cloud", C. Alcock, et al (The MACHO Collaboration), (1999), Ap. J., 518, 44.
"The MACHO Project: Microlensing Results from 5.7 years of LMC Observations", C. Alcock, et al (The MACHO Collaboration) (2001), Ap. J. 542, 281.
"Direct Detection of a Microlens in the Milky Way", C. Alcock, et al (The MACHO Collaboration), (2001), Nature, 414, 617.
"Statistical Methods for Detecting Stellar Occultations by Kuiper Belt Objects: the Taiwanese American Occultation Survey", C.-L. Liang, J.A. Rice, I. De Pater, C. Alcock, T. Axelrod, & A. Wang (2003), accepted for inclusion in the Astrostatistics volume of Statistical Science (Ed. L. Wasserman) http://xxx.lanl.gov/abs/astro-ph/0209509.
"The Proper Motion of the Large Magellanic Cloud using HST", N. Kallivayalil, van der Marel, R., Alcock, C., et al, (2006), Ap. J., 638, 772.

Active Collaborators (not at CfA): Wen Ping Chen (National Central University, Taiwan), Typhoon Lee (Academia Sinica, Taiwan), Roeland van der Marel (Space Telescope Science Institute)
Graduate Advisor: Peter Goldreich (Inst. of Advanced Study)
Post-doctoral Advisor: John Bahcall (Deceased)
Post-graduate Scholars Sponsored in Past Five Years: Matthew Lehner (Harvard-Smithsonian Center for Astrophysics), Lorenzo Faccioli (Lawrence Berkeley National Laboratory), Nitya Kallivayalil (Massachusetts Institute of Technology), Taryn Nihei (Left the field)

Biographical Sketch - LARS HERNQUIST

Professional Preparation

B.S. in Physics, Cornell University, 1977
Ph.D. in Physics, California Institute of Technology, 1985
Postdoctoral Research Fellow, UC, Berkeley, 1984–87
Postdoctoral Research Fellow, Institute for Advanced Study, 1987–90

Appointments

Chair of Astronomy, Harvard University, 2003–06
Professor of Astronomy, Harvard University, 1998–
Professor of Astronomy, UC Santa Cruz, 1996–98
Associate Professor of Astronomy, UC Santa Cruz, 1993–96
Assistant Professor of Astronomy, UC Santa Cruz, 1990–93

Publications

Furlanetto, S., Zaldarriaga, M., Hernquist, L. 2004, "The growth of HII regions during reionization," ApJ, 613, 16

Zaldarriaga, M., Furlanetto, S., Hernquist, L. 2004, "21 centimeter fluctuations from cosmic gas at high redshifts," ApJ, 608, 622

Furlanetto, S., Hernquist, L., Zaldarriaga, M. 2006, "The effects of reionization on Ly-alpha galaxy surveys," MNRAS, 365, 1012

Furlanetto, S., McQuinn, M., Hernquist, L. 2006, "Characteristic scales during reionization," MNRAS, 365, 115

Yoshida, N., Omukai, K., Hernquist, L. 2007, "Formation of massive primordial stars in a reionized gas," ApJL, in press (astro-ph/0706:3597)

Collaborators in the last 48 months

T. Abel, A. Aguirre, M. Bolte, G. Bryan, R. Cen, S. Chakrabarti, P. Chatterjee, S. Colombi, T. Cox, R. Croft, R. Dav'e, T. de Zeeuw, J. Dubinski, A. Evrard, C.-A. Faucher-Giguere, S. Furlanetto, J. Gardner, B. He, U. Hellsten, J. Heyl, P. Hopkins, S. Hozumi, K. Johnston, H. Kang, N. Katz, Y. Li, D. Lloyd, A. Loeb, L. Lubin, C.-P. Ma, J. Makino, M. McQuinn, R. Melhem, C. Mihos, J. Miralda-Escude, K. Nagamine, D. Narayanan, M. Norman, J. Ostriker, G. Quinlan, P. Quinn, M. Rauch, B. Robertson, W. Sargent, S. Sigurdsson, A. Sokasian, D. Spergel, V. Springel, R. Taam, J. Terman, R. van der Marel, I. Walker, M. Weil, D. Weinberg, M. Weinberg, N. Yoshida, M. Zaldarriaga, O. Zahn. **PhD Students:** M. Weil, K. Johnston, I. Walker, J. Heyl, R. Dave, A. Aguirre, D. Lloyd, A. Sokasian, P. Chatterjee, B. Robertson, M. McQuinn, P. Hopkins, G. Besla, C.-A. Faucher-Giguere, R. Marcus, C. Hayward, L. Hoffman. **Postdocs:** S. Sigurdsson, C. Mihos, G. Quinlan, J. Dubinski, G. Xu, U. Hellsten, T. Abel, V. Springel, K. Nagamine, N. Yoshida, TJ Cox, Y. Li, H. Trac. **Graduate Thesis:** R. Blandford (Caltech, now at Stanford). **Postdocs:** J. Arons (Berkeley), J. Bahcall (IAS).

Biographical Sketch - CHRISTOPHER STUBBS

Professional Preparation

University of Virginia	Physics	B.Sc. 1981
University of Washington	Physics	Ph.D. 1988
UC Berkeley	Physics	Postdoc 1988-1991

Appointments

2003-	Professor of Physics and of Astronomy	Harvard University
1998-2003	Professor of Physics and of Astronomy	Univ. of Washington
1994-1998	Associate Professor of Physics and of Astronomy	Univ. of Washington
1991-1994	Assistant & Associate Professor of Physics	UC Santa Barbara
1989 - 1991	Center for Particle Astrophysics Fellow	UC Berkeley

Publications

A. Riess et al., (The High-z Supernova Team), Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant, AJ 116, 1009 (1998).

W. M. Wood-Vasey et al., (the ESSENCE collaboration), Observational Constraints on the Nature of Dark Energy: First Cosmological Results from the ESSENCE Supernova Survey, ApJ 666, 694 (2007).

Stubbs, C. and Tonry, J., Toward 1% Photometry: End-to-End Calibration of Astronomical Telescopes and Detectors, ApJ 646, 1346 (2006)

Stubbs, C. et al., Toward More Precise Survey Photometry for PanSTARRS and LSST: Measuring Directly the Optical Transmission Spectrum of the Atmosphere, PASP in press, (2007).

Collaborators and Other Affiliations (last 48 months)

SuperMacho microlensing collaboration (PI), ESSENCE supernova cosmology project (PI), APOLLO lunar laser ranging collaboration (co-I), LSST Project, PanSTARRS Project, South Pole Telescope. **Thesis advisors and postdoctoral supervisors:** Adelberger and Heckel (Univ. of Washington). **Postdoctoral Supervisor:** Sadoulet (UC Berkeley) **Past Graduate Students (9) and Postdoctoral Scholars (3) Supervised:** Marshall, PhD, now at Kavli Institute, SLAC; Pratt, PhD, now at Perkin Elmer; Becker, PhD, now at University of Washington; Diercks, PhD and Reiss, PhD, both now at ISB Seattle; Krisciunas, PhD, now at Texas A&M; Miknaitis, PhD, now at Fermilab; Miceli, PhD, now at Argonne National Lab; Strasburg, PhD, now at Pacific Northwest National Laboratory; Magnier (postdoc) now at IfA Hawaii; Tomany (postdoc) now at Perkin Elmer; Murphy (postdoc) now at UC San Diego.

Biographical Sketch - MATIAS ZALDARRIAGA

Professional Preparation

University of Buenos Aires	Physics	Licenciado en Ciencias Fisicas 1994
MIT	Physics	PhD 1998
Institute for Advanced Study	Astrophysics	Postdoctoral Fellow 1998-2001

Appointments

Professor of Astronomy & Physics, Harvard University 7/2004 -
Associate Professor in Astronomy & Physics, Harvard University 1/2003- 7/2004
Assistant Professor, New York University, 1/2001-2002
Keck Visiting Professor, Institute for Advanced Study, 9/2001-12/2002
Long-term member, Institute for Advanced Study, 9/1998-1/2001

Publications

The Morphology of HII Regions during Reionization, A. Lidz, O. Zahn, S. Dutta, L. Hernquist and M. Zaldarriaga. Roy. Astron. Soc. 377, 1043 (2007)

Quasar Proximity Zones and Patchy Reionization, M. McQuinn and M. Zaldarriaga J. 670, 39 (2007)

Simulations and Analytic Calculations of Bubble Growth During Hydrogen Reionization O. Zahn, et al.; Astrophys. J. 654, 12 (2006)

The Growth of HII Regions During Reionization, S. Furlanetto, M. Zaldarriaga and L. Hernquist; Astrophys. J. 613, 1 (2004)

21 Centimeter Fluctuations from Cosmic Gas at High Redshifts, M. Zaldarriaga, S. R. Furlanetto and L. Hernquist; Astrophys. J. 608, 622 (2004)

Signature of gravity waves in polarization of the microwave background, U. Seljak and M. Zaldarriaga; Phys. Rev. Lett. 78, 2054 (1997)

Collaborators in the last 48 months

P. Ade, Cardiff U.; N. Arkani-Hammed, Harvard; C. Baccigalupi, SISSA; J. Bock, JPL; J. Borrill, LBL; A. Cooray, U. Cal. Irvine; P. Creminelli, ICTP (Italy); M. Dobbs, McGill U.; S. Dodelson, Fermilab; S. Dubovsky, Harvard; J. Dunkley, Princeton; G. Dvali, NYU; S. Furlanetto, UCSD; K. Gorski, JPL; A. Gruzinov, NYU; S. Hanany, U. Minnesota; L. Hernquist, Harvard; G. Hinshaw, NASA GSFC; W. Hu, Chicago; L. Hui, Columbia; K. Irwin, NIST; A. Jaffe, Imperial Coll.; C. Lawrence, JPL; A. Lee, Berkeley; L. Levinson, Weizmann Inst.; A. Loeb, Harvard; S. Meyer, Chicago; A. Miller, Columbia; A. Nicolis, Columbia; L. Page, Princeton; J. Ruhl, Case Western Reserve; R. Scoccimarro, NYU; M. Seiffert, JPL; U. Seljak, Princeton; K. Smith, Cambridge; M. Tegmark, MIT; G. Tucker, Brown. Advisors: E. Bertschinger, MIT; J. Bahcall, IAS; D. Harari, Buenos Aires, Argentina. Advised: N. Afshordi, Harvard; D. Babich, Caltech; K. Benabed, France; S. Dutta, Harvard; A. Lidz, Harvard; A. Lewis, Cambridge; O. Zhan, Berkeley. Havard Students: K. Lai, C.-A Faucher-Giguere, K. Mandel, M. McQuinn, S. Tassev.

Biographical Sketch - ALEXANDER DALGARNO

Professional Preparation

1947 B.Sc. 1st class honors in Mathematics - University College, London
1948 B.Sc. Advanced subjects with distinction - University College, London
1951 Ph.D. Theoretical Physics - University College, London

Appointments

1977- present	Phillips Professor of Astronomy, Harvard University
1967 - present	Senior Physicist, Smithsonian Astrophysical Observatory
1988 - 1993	Director, Institute for Theoretical Atomic and Molecular Physics.

Publications

A.Dalgarno, The Growth of Molecular Complexity in the Universe, Faraday Discuss. _133,_ 9, 2006.

A. Dalgarno and M.P.J. van der Loo, Recombination of H2 by Raman Association in the Early Universe ApJL, _646_ L91, 2006.

A. Dalgarno Molecular Processes in the Early Universe, J. Phys. Conf. Series 4, 10, 2005.

H.K. Chung and A. Dalgarno, Diffusion of Hydrogen Atoms in Helium Gas and Helium Atoms in Hydrogen Gas, Phys. Rev. A. _66_, 012712, 2002.

P.C. Stancil, S. H. Lepp and A. Dalgarno, Atomic and Molecular Processes in the Early Universe, J. Phys. B. _35_, R57, 2002.

Collaborators since 2005

R.V. Krems, J. Klos, M.F. Rode, M.M. Szczesniak, G. Chalaminski, Teck-Ghee Lee, C. Rochow, R. Martin, T. K. Clark, P. C. Stancil, D. R. Schultz, J.G. Ferland, G. Barinovs, M.C. van Heimert, M. Bouledroua, H. R. Sadeghpour, G. C. Groenenboom, A. van der Avoird, D. Zgid, C. Zhu, J. Babb, S. Jonell, A. Szenz, P. Froelich, B. Zygelman, P.C. Brandt, R. de Majistre, T.J. Inmel, J.-H. Yee, L. J. Paxton, V. Kharchenko, C. Cecchi-Pestellini, S. Casu, X. Chu, A. Voroni, J. L. Fox, C.M. Dutta, C. Oubre, P. Nordlander, M. Kimura, M. Jamieson, L. Wei, M.P. J. van der Loo, Y.V. Vanne, T.P. Sasseen, M. Hurwitz, C.M. Lisse, D. Christian, S. J. Wolk, M.M. Sirk, D. Koutroumpa, R. Lallement, R. Pepino, Z. Izmodenov, E. Quemarais, B.C. Shepler, B. H. Yang, T. J. Dhilip Kumar, P.C. Stancil, J. M. Bowman, N. Balakrishnan, P. Zhang, E. Bodo, R. C. Forrey, E. Abrahamsson, C. Zhu, R. Coté.

Biographical Sketch - DOUGLAS FINKBEINER

Professional Preparation

University of Michigan	Physics & German	B.S. (with highest honors) 1994
UC, Berkeley	Physics, NSF Fellow	Ph.D. (Uhl Award) 1999
UC, Berkeley	Astronomy	postdoc, 1999-2001
Princeton University	Astronomy	postdoc, 2001-2006

Appointments

7/06 – present, Assistant Professor, Harvard University, Astronomy Department
7/03 - 7/06, Russell-Cotsen Fellow, Astrophysical Sciences, Princeton University
7/01 - 6/03, Hubble Fellow, Astrophysical Sciences, Princeton University
5/99 – 6/01, Postdoc (NASA ADP) & Hubble Fellow, (7/00 - 6/01), University of California, Berkeley

Publications

Prospects for Detecting Dark Matter with GLAST in Light of the WMAP Haze, D. Hooper, G. Zaharijas, D. P. Finkbeiner, & G. Dobler 2007, Phys. Rev. D, in press, and arXiv: 0709.3114

Possible evidence for dark matter annihilations from the excess microwave emission around the center of the Galaxy seen by WMAP, D. Hooper, D. P. Finkbeiner, & G. Dobler 2007, Phys. Rev. D, 76, 083012 and arXiv:0705.3655

Exciting Dark Matter and the INTEGRAL/SPI 511 keV signal, D. P. Finkbeiner & Neal Weiner 2007, Phys. Rev. D, 76, 083519, and astro-ph/0702587

Detecting Dark Matter Annihilation with CMB Polarization: Signatures and Experimental Prospects, N. Padmanabhan & D. P. Finkbeiner 2005, Phys. Rev. D, vol. 72, 023508, and astro-ph/0503486

Synergistic Activities

With Schlegel & Padmanabhan, performed "ubercalibration" of the Sloan Digital Sky Survey (calibration by inverting matrix of 70 million repeat observations).

Member, astrometry.net collaboration (David Hogg, PI), which provides astrometric solutions for astronomical images with no prior information on position or scale.

Collaborators and other Affiliations in the last 48 months:

Member of the SDSS (Sloan Digital Sky Survey) and DEIMOS (DEep Imaging Multi-Object Spectrograph) survey collaborations. Other collaborators are: Avery Broderick (CITA), Greg Dobler (Harvard), Dan Hooper (Fermilab), Ed Turner (Princeton), Neal Weiner (NYU), and Gabrijela Zaharijas (Fermilab). **Thesis Adviser:** Marc Davis, UC Berkeley. **Postdoc advised:** Greg Dobler. **Graduate students advised:** None.

BIOGRAPHICAL SKETCH - ROY GOULD

Professional Preparation

Cornell University	Chemistry	A.B. 1968
Harvard University	Biophysics	Ph.D. 1974
U. of Wisconsin, Madison	Biophysics	1974-1977

Appointments

Harvard-Smithsonian Center for Astrophysics (CfA), 1994 - present. Education Analyst, and Director, NASA-Smithsonian Education Forum on the Structure and Evolution of the Universe.
Museum of Science, Boston, 1983 - 1994. Science Planner and Senior Exhibition Producer.
Harvard University, 1980 - 1983. Research Fellow in Science and Environmental Policy, Interdisciplinary Programs in Health.
NOVA Science Series, Public Television, 1977 - 1979. Associate Producer.

Selected Publications

Gould, R., M. Dussault, & P. Sadler, "What's educational about online telescopes?: Evaluating 10 years of MicroObservatory," Astron. Ed. Rev. 5(2), (2006).

White, V., S.K. Croft, A. Gould, R. R. Gould, T. O'Dea, & P. Roche, "No Ph.D. Required: Remote Telescopes Reaching a Wider Audience," Astronom. Soc. of the Pacific Conference Series, in press, (2007)

Gould, R., "Cosmic Questions," National Traveling Exhibition (PI). Materials and evaluation at http://cfa-www.harvard.edu/seuforum/learningresources.htm, (2003).

Gould, Roy R., "Answer to Question 7: The Spin-Statistics Theorem" Am. J. Phys. 63(2), 109 (1995).

Collaborators

Philip M. Sadler and Mary Dussault (CfA); Denise Smith (Space Telescope Science Institute); no students.

Synergistic Activities

PI: "Exploring Frontiers of Science with Online Telescopes," NSF-sponsored project that researches new approaches to educational technologies and to assessing learning. (2007). Lowell Lecture Series (Invited), "Who Needs Physics?" 2005. At Museum of Science, Boston, and online at WGBH-TV (www.wgbh.org). Chair, Education Programs, Space Science International Partnership Conference, NASA Headquarters, (May 15-17, 2000). Invited Testimony before the U.S. Senate Environment Committee (May 1982).

Biographical Sketch - LINCOLN J. GREENHILL

Professional Preparation

Massachusetts Institute of Technology: S.B. in Physics (1984)
Harvard University : M.A. in Astronomy (1985); Ph.D. in Astronomy (1990)
University of California at Berkeley: Astronomy Fellow (1990-1992)

Appointments

2007 – Senior Research Fellow, Faculty of Arts and Sciences, Harvard University

2003 – 2004	Visiting Physicist, Kavli Inst. for Particle Astrophysics and Cosmology
2000 –	Lecturer, Harvard University, Department of Astronomy
1997	Assistant Director, Maria Mitchell Observatory
1992 –	Radio Astronomer, Harvard-Smithsonian Center for Astrophysics
1990 – 1992	Fellow, Miller Institute for Basic Research in Science, U.C., Berkeley

Publications (out of a total of 80)

Rawlings, S., Abdalla, F.B., Bridle, S.L., Blake, C.A., Baugh, C.M., Greenhill, L.J., & van der Hulst, J.M., "Galaxy evolution, cosmology and dark energy with the Square Kilometer Array," New Astr. Rev. 48, 1013 (2004).

Greenhill, L.J., Kondratko, P.T, Lovell, J.E.J., Kuiper T.B.H., Moran, J.M., Jauncey, D.L., & Baines, G.A. "The Discovery of H2O Maser Emission in 7 AGN and at High Velocities in the Circinus Galaxy," Ap.J., 582, L11-L14 (2003).

Herrnstein, J.R., Moran, J.M., Greenhill, L.J., Diamond, P.J., Inoue, M., Nakai, N., Miyoshi, M., Henkel, C., & Riess, A., "A Geometric Distance to the Galaxy NGC 4258 from Orbital Motions in a Nuclear Gas Disk," Nature, 400, 539-541 (1999).

Greenhill, L.J., Gwinn, C.R., Schwartz, C., Moran, J.M., & Diamond, P.J., "Coexisting Conical Bipolar and Equatorial Outflows from a High-Mass Protostar," Nature, 396, 650-653 (1998).

Miyoshi, M., Moran, J.M., Herrnstein, J.R., Greenhill, L.J., Nakai, N., Diamond, P.J., & Inoue, M., "Evidence for a Massive Black Hole from High Rotation Velocities in a Subparsec Region of NGC4258," Nature, 373, 127-129 (1995).

Synergistic Activities

Science Advisory Group for EVLA
NASA Deep Space Network Executive Management Board
Square Kilometer Array:US Consortium board member, International Science W. Group
AUI Visiting Committee to the NRAO
Public/College/High School Science Lecturers: Harvard-Smithsonian CfA, MIT and U Tas. Departments of Physics, and Summer Science Program, Ojai, CA

Recent Collaborators and Other Affiliations

Graduate and postdoc advisors: J. Moran, S. Rappaport, C. Townes, W. Welch.
Graduate advisees: J.A. Eisner, C. Goddi, P. T. Kondratko, E. M. L. Humphreys, L. D. Matthews, D. A. Mitchell, S. M. Ord, A. Tilak, R. B. Wayth, B. Maruca, R.J. Harris.
Other: MWA collaboration (10) and 102 more.

Biographical Sketch - KATE KIRBY

Professional Preparation
A.B., cum laude, Chemistry and Physics, Harvard/Radcliffe, 1967
M.S., Chemistry, University of Chicago, 1968
Ph.D., Chemical Physics, University of Chicago, 1972

Appointments
Director, Institute for Theoretical Atomic, Molecular and Optical Physics, 2001—
Senior Research Fellow, Harvard College Observatory (HCO), 2002—
Associate Director, Harvard-Smithsonian Center for Astrophysics, heading the Atomic and Molecular Physics Division, 1988—2001
Deputy Director, Institute for Theoretical Atomic and Molecular Physics at Harvard-Smithsonian Center for Astrophysics, 1989—1998
Research Physicist, Smithsonian Astrophysical Observatory, 1973—
Lecturer, Harvard University Department of Astronomy, 1973—1986
Postdoctoral Research Fellow, 1972—73 in astrophysics at HCO

Publications
The Molecular Line Opacity of MgH in Cool Stellar Atmospheres, P. Weck, etal., Ap. J. 582, 1059-1065 (2003)
Fully Relativistic R-matrix Calculation of Electron Impact Excitation of Ne IX G.X. Chen etal., Phys.Rev. A 74, 42709 (2006)
Solution of the 3C/3D Line Ratio Problem in Ni XIX: new ab initio theory and experimental results G.X. Chen etal., Phys.Rev. Lett. 97, 143201 (2006)
Atomic and Molecular Physics for Forefront Astronomy, AIP Conference Proceedings, 901, 26-32 (2007)
Cosmic Code Breakers, D.W. Savin etal., Sky & Telescope, March (2007), 32-37.

Collaborators & Other Affiliations
Thesis Advisor: Prof. Juergen Hinze, retired.
Postdoctoral Advisor: Prof. Alex Dalgarno (Harvard University)
Recent Co-Authors: J. Babb, N. Brickhouse, R. Coté, B. McLaughlin, P. Hauschildt, P. Stancil, S. Kotochigova, R. Santra, S. Yelin

Biographical Sketch - RAMESH NARAYAN

Professional Preparation

Madras University (India)	Physics	B.Sc. 1971
Bangalore University (India)	Physics	M.Sc. 1973, PhD. 1979
Raman Research Institute (India)	Scientist	9/1978 - 8/1983
Caltech	Postdoctoral Fellow	9/1983 - 8/1985

Appointments

Thomas Dudley Cabot Professor of the Natural Sciences, Harvard Univ., 2003-
Professor, Department of Astronomy, Harvard Univ., 1991-
Professor, Department of Astronomy, University of Arizona, 1990-1991
Associate Professor, Department of Astronomy, University of Arizona, 1985-1990

Publications

Fermat's principle, caustics and the classification of gravitational lens images, Blandford, R. and Narayan, R. 1986, ApJ, 310, 568

Advection-dominated accretion and black hole event horizons, Narayan, R., Garcia, M. R. and McClintock, J. E. 1997, ApJ, 478, L79

New evidence for black hole event horizons from Chandra, Garcia, M. R., McClintock, J. E., Narayan, R., et al. 2001, ApJ, 553, L47

Estimating the spin of stellar-mass black holes via spectral fitting of the X-ray continuum, Shafee, R., McClintock, J. E., Narayan, R., Davis, S., Li, L.-X., Remillard, R. A. 2006, ApJ, 636, L113

The spin of the near-extreme Kerr black hole GRS 1915+105, McClintock, J. E., Shafee, R., Narayan, R., et al. 2006, ApJ, 652, 518

Collaborators in the last 48 months:

N. Afshordi, F. K. Baganoff, C. D. Bailyn, A. E. Broderick, C-K. Chan, W. Cui, A. Cumming, S. W. Davis, K.Y. Eksi, A.Farmer, Y-Z. Fan, J. Goodman, J. E. Grindlay, J. D. Hartman, C. O. Heinke, P. F. Hopkins, E. Keto, K. Kohri, W-T. Kim, P. Kumar, C. J. Lada, L-X. Li, D. Lin, J. Liu, L. Macri, T. Mazeh, J. McClintock, J. McKinney, J. M. Miller, B. Mukhopadhyay, J. Orosz, K. Ohsuga, W. Pietsch, T. Piran, E. Quataert, M. J. Rees, R. Remillard, A. Shporer, D. Steeghs, D-M. Wei, Y-D. Xu, Y-F. Yuan, F. Yuan, E. R. Zimmerman. **Graduate Advisor:** Prof. S. Ramaseshan, Raman Res. Inst., Bangalore, India (deceased); **Postgraduate Employers**: Prof. Roger Blandford (Stanford) & Prof. Peter Goldreich (Princeton); **Recent Graduate Advisees:** M. Vivekanand, G. Raghurama, R. Romani, S. Grossman, R. Popham, S. Wallington, R. Mahadevan, A. Esin, E. Quataert, K. Menou, F. A. Özel, R. Hickox, R. Cooper, R. Shafee, A. Tchekhovskoy, R. Shcherbakov.

Biographical Sketch - GEORGE RYBICKI

Professional Preparation

1956 B.S., Physics, Carnegie-Mellon University
1957 A.M., Physics, Harvard University
1965 Ph.D., Physics, Harvard University

Appointments

1979-present	Professor of the Practice of Astronomy, Harvard University
1964-present	Senior Physicist, Smithsonian Astrophysical Observatory
1997-2004	Associate Director, Theoretical Astrophysics Division, Harvard-Smithsonian Center for Astrophysics

Publications

Rybicki, G.B., & Dell'Antonio, I.P. 1993, Spectral distortions in the CMB from recombination. In Observational Cosmology, Astron. Soc. Pacific Conf. Ser., Vol. 51, ed. Chincarini, G., Iovino, A., Maccacaro, T., & Maccagni, D. (San Francisco: Astron. Soc. Pacific), 548-553.

Rybicki, G.B., & Dell'Antonio, I.P. 1994, The time development of a resonance line in the expanding universe. ApJ, 427, 603-617.

Loeb, A., & Rybicki, G.B. 1999, Scattered Lyman alpha radiation around sources before cosmological reionization. ApJ, 524, 527-535.

Rybicki, G.B., & Loeb, A. 1999, Polarization of the Lyman alpha halos around sources before cosmological reionization. ApJL, 520, L79-L81.

Rybicki, G.B. 2003, A new kinetic equation for Compton scattering. ApJ, 584, 528-540.

Rybicki, G.B. 2006, Improved Fokker-Planck Equation for Resonance Line Scattering. ApJ, 647, 709-718.

Synergistic Activities

Dr. Rybicki has worked and published widely in the fields of radiative transfer and radiative processes, and his book "Radiative Processes in Astrophysics" is a standard text in many undergraduate and graduate astronomy programs. He has developed a number of novel computational techniques in the field of radiative transfer and in statistical analysis.

Collaborators in past 48 months

CfA: S. Bogdanov, J. E. Grindlay, E. Keto, J. E. McClintock, & R. Narayan; E. Bergin, Dept. of Astronomy, U. of Michigan; C. O. Heinke, Dept. of Astron., U. of Virginia; R. Plume, Max-Planck. **Thesis advisee**: S. Bogdanov.

Biographical Sketch - HOSSEIN SADEGHPOUR

Professional Preparation

B.S. Mechanical Engineering (1981), Louisiana State University.
M.S. Mechanical Engineering (1983), LSU.
Ph.D. Physics (1990), LSU. Dissertation research at JILA.
Fellow of American Physical Society.

Appointments

1994- present	Staff Physicist, Harvard-Smithsonian Center for Astrophysics.
1990 - 1993	Postdoctoral Fellow, Harvard University.
1993 - 1994	Research Associate, Harvard University.

Publications

M. Yan, H. R. Sadeghpour, and A. Dalgarno, Photoionization Cross Sections of He and H2, Astrophysical Journal 496, 1044 (1998).

A. B. Alekseyev, H.-P. Lieberman, R. J. Buenker, N. Balakrishnan, H. R. Sadeghpour, etal., Spin-Orbit Effects in Photodissociation of Sodium Iodide, Journal of Chemical Physics 113, 1514 (2000).

D. Vrinceanu, S. Kotochigova, and H. R. Sadeghpour, Pressure Broadening and Shift of He(2 3P0,1,2) - He(2 3S) lines, Physical Review A 69, 0022714 (2004).

Z. Pavlovic, R. V. Krems, R. Côté, and H. R. Sadeghpour, Magnetic Feshbach resonances and Zeeman relaxation in bosonic chromium gas with anisotropic interaction, Physical Review A 71, 061402(R) (2005).

T. Pohl, H. R. Sadeghpour, etal., Cooling by Spontaneous Decay of Highly Excited Antihydrogen Atoms in Magnetic Traps, Physical Review Letter, 92, 213001 (2006).

Collaborators & Other Affiliations - last four years

Klaus Bartschat (Drake Univ.), N. Balakrishnan (UNLV), Lenz Cederbaum (U. of Heidelberg), Robin Cote (UCONN), Alex Dalgarno (Harvard Univ.), Gerald Gabrielse (Harvard University), Brian Granger (U. of Santa Clara), Shachar Klaiman (Technion), Roman Krems (Univ. of British Columbia), Nimrod Moiseyev (Technion), Moshe Shapiro (Weizmann \& UBC), Daniel Vrinceanu (Los Alamos), Thomas Pohl (ITAMP), , Yasunori Yamazaki (RIKEN), Zong-Chao Yan (New Brunswick). **Graduate & Postgraduate Advisors:** Chris Greene (JILA) and Alex Dalgarno (Harvard Univ.). **Thesis Advisor & Postgraduate Sponsor - last four years:** Babak Hosseini (U. of Heidelberg), Zoran Pavlovic (UCONN), Brian Granger (U. of Santa Clara), Roman Krems (UBC), Daniel Vrinceanu (Los Alamos), Thomas Pohl (ITAMP).

Biographical Sketch - IRWIN SHAPIRO

Professional Preparation
Ph.D. Harvard University, 1955 (Physics)
A.M. Harvard University, 1951 (Physics)
A.B. Cornell University, 1950 (Mathematics, with highest honors)

Appointments
Timken University Professor, Harvard University, 1997-
Schlumberger Professor Emeritus, M.I.T., 1985-
Senior Scientist, Smithsonian Astrophysical Observatory, 1982-

Publications

Falco, E.E., I.I. Shapiro, L.A. Moustakas, A. Leonidas, and M. Davis, An estimate of H_0 from Keck spectroscopy of the gravitational lens system 0957+561, Astrophys. J., 484, 70-78, 1997.

Shapiro, I. I., A Century of Relativity, Rev. Mod. Phys., 71, S41-S53, 1999.

Shapiro, I. I., E.C. Lorenzini, J. Ashenberg, C. Bombardelli, P.N. Cheimets, V. Iafolla, D.M. Lucchesi, S. Nozzoli, F. Santoli, and S. Glashow, Testing the Principle of Equivalence in an Einstein Elevator, International Journal of Modern Physics D, 16/11, 1-17, 2007

Synergistic Activities
1. Developed course, "The Nature of Science," covering all major science specialties, and taught it at the Harvard Graduate School of Education for six years, primarily for and to preservice science teachers (including about 15% underserved minorities);

2. Developed with colleagues over c. two decades, ten books on various physical sciences, for elementary, middle, and high school classes;

3. Taught various science topics, as guest, in preschool, kindergarten, elementary, middle, and high school classes over the past few decades;

4. Taught at university level, undergraduate and graduate courses, for forty years.

Collaborators in the last 48 months:
See co-authors above for a list of collaborators in the last 48 months.

Biographical Sketch - JACQUELINE N. HEWITT

Professional Preparation

Bryn Mawr College, Bryn Mawr, PA. A.B. in economics (*magna cum laude),* 1980.
Massachusetts Institute of Technology, Cambridge, MA. Ph.D. in physics, 1986
Postdoctoral Associate, Haystack Observatory, 1986-1988

Appointments

2002-present Director, MIT Kavli Institute for Astrophysics and Space Research (formerly the Center for Space Research); *2000-present* Professor of Physics, Massachusetts Institute of Technology; *1994-2000* Associate Professor of Physics, Massachusetts Institute of Technology; *1989-1994* Assistant Professor of Physics, Massachusetts Institute of Technology; *1988-1989* Research Staff, Department of Astrophysical Sciences, Princeton University

Related Publications

Bowman*, J. D., Morales, M. F., and Hewitt, J. N. "Constraints on Fundamental Cosmological Parameters with Upcoming Redshifted 21cm Observations," 2007, ApJ, 661, 1.

Bowman*, J. D., et al. "Field Deployment of Prototype Antennas for the Mileura Widefield Array Low Frequency Demonstrator," 2007, ApJ, 133, 150.

Bowman*, J. D., Morales, M. F., and Hewitt, J. N. "The Sensitivity of First Generation Epoch of Reionization Observatories and their Potential for Differentiating Theoretical Power Spectra," 2006, ApJ, 683, 20.

Bowman*, J. D., Hewitt, J. N., and Kiger, J. R. "Gravitational Lensing Signatures of Supermassive Black Holes in Future Radio Surveys," 2004, ApJ, 617, 81.

Morales, M. F., and Hewitt, J. N. "Toward Epoch of Reionization Measurements with Widefield Radio Observations," 2004, ApJ, 615, 7.

*Student supervised by JNH

Collaborators & Other Affiliations: Barnes, J., Swinburne; Bertschinger, E., MIT; Bhat, N., Swinburne; Bolton, A. S., Harvard-Smithsonian Center for Astrophysics; Bowman, J. D., Caltech; Boyce, E., University of Manchester; Briggs, F., Australia National University; Burles, S., MIT; Cappallo, R. J., Haystack Observatory; Carilli, C. L., National Radio Astronomy Observatory; Corey, B. E., Haystack Observatory; de Oliveira Costa, A., MIT; Doeleman, S. S., Haystack Observatory; Fanous, B., Haystack Observatory; Gaensler, B., Sydney University; Greenhill, L., Smithsonian Astrophysical Observatory; Guth, A., MIT; Herne, D., Curtin Univ. of Technology; Hernquist, L., Harvard; Kasper, J. C., Smithsonian Astrophysical Observatory; Kosc, J., Australia National University; Kratzenberg, E., Haystack Observatory; Livio, M., Space Telescope Science Institute; Loeb, A., Harvard; Lonsdale, C. J., Haystack Observatory; Lynch, M., Curtin Univ. of Technology; Mitchell, D., Smithsonian Astrophysical Observatory; Morales, M, F., MIT; Myers, S. T., National Radio Astronomy Observatory; Oberoi, D., Haystack Observatory; Ray, R., Naval Research Laboratory; Rogers, A., Haystack Observatory; Salah, J. E., Haystack Observatory; Stansby, B., Curtin Univ. of Technology; Stevens, J., University of Tasmania; Tegmark, M., MIT; Torr, G., Australia National University; Wayth, R., Smithsonian Astrophysical Observatory; Webster, R., Melbourne University; Wilczek, F., MIT; Winn, J. N., MIT; Wyithe, J. S. B., Melbourne University; Zaldarriaga, M., Harvard University **Graduate Advisors and Postdoctoral Sponsors:** Burke, B. F., MIT; Salah, J. E., Haystack Observatory; Turner, E. L., Princeton University **Thesis Advisor and Postgraduate-Scholar Sponsor:** Advisor of 13 PhD Thesis Students: Bowman, J., Caltech; Boyce, E., University of Manchester; Chen, G.; Cohen, A., Naval Research Laboratory; Ellithorpe, J., Model N; Haarsma, D., Calvin College; Katz, C., Smithsonian Astrophysical Observatory; Lehar, J. CombinatoRx ;Matejek, M., MIT; Moore, C.; Trotter, C.; Williams, C., MIT; Winn, J., MIT. Advisor of one postgraduate scholar: Morales, M., MIT.

Biographical Sketch of Angelica de Oliveira-Costa

Professional Preparation:

National Space Science Institute, Brazil	Ph.D. in Astrophysics	1993-1996
Princeton Univiversity	Postdoc in Astrophysics	1996-1999
Institute for Advanced Study	Postdoc in Astrophysics	1998-1999
University of Pennsylvania	Research Investigator	Jan 2000-June 2001

Appointments:

Massachusetts Institute of Technology	Principal Research Scientist	Sept 2004-Today
University of Pennsylvania	Research Assistant Professor	July 2001-Dec 2004

Publications Closely Related to this Project:

- "A Model of Diffuse Galactic Emission from 10 MHz to 100 GHz" 2008, **de Oliveira-Costa**, A., Tegmark, M., Gaensler, B., Jonas, J., Landecker, T. & Reich, P. 2007; *in preparation*
- "The Quest for Microwave Foreground X", **de Oliveira-Costa**, A., Tegmark, M., Davies, R.D., Gutierrez, C.M., Lasenby, A.N., Rebolo, R. & Watson, R. 2004, *ApJ*, **606**, L89-92
- "A high resolution foreground cleaned CMB map from WMAP", Tegmark, M., **de Oliveira-Costa**, A. & Hamilton, A. 2003, *Phys. Rev. D.*, **68**, 123523
- "The Large-Scale Polarization of the Microwave Background and Foreground", **de Oliveira-Costa**, A., Tegmark, M., O'Dell, C.W., Keating, B.G., Timbie, P., Efstathiou & G., Smoot, G.F. 2003, *Phys. Rev. D.*, **68**, 083003
- "Foregrounds and Forecasts for the CMB", Tegmark, M., Eisenstein, D., Hu W. & **de Oliveira-Costa**, A. 2000, *ApJ*, **530**, 133-165

Recent Collaborators:

Ade, P.A.R.(Cardiff), Bock, J.J.(JPL), Bond, J.R.(CITA), Borrill, J.(LBNL), Boscaleri, A.(IFAC-CNR), Cabella, P.(Universita di Roma, Tor Vergata), Contaldi, C.R.(Imperial College), Crill, B.P.(IPAC/Calthec), Davies, R.D.(Jodrell Bank), de Bernardis, P.(Universita di Roma, La Sapienza), De Gasperis, G.(Universita di Roma, Tor Vergata), De Troia, G.(Universita di Roma, La Sapienza), Devlin, M.J.(Upenn), Di Stefano, G.(INGF), Ehlers, P.(University of Toronto), Gaensler, B.(University of Sydney), Gutierrez, C.M.(Tenerife), Hamilton, A.(University of Colorado, Boulder), Hivon, E.(IPAC/Calthec), Hristov, V.V. (Calthec), Iacoangeli, A.(Universita di Roma, La Sapienza), Jaffe, A.H.(Imperial College), Jonas, J.(Rhodes University), Jones, W.C.(Calthec), Kisner, T.(CWRU), Landecker, T. (Dominion Radio Astrophysical Observatory), Lange, A.E.(Calthec), Lasenby, A.N.(Cambridge), MacTavish, C.(University of Toronto), Marini-Bettolo, C.(Universita di Roma, La Sapienza), Masi, S.(Universita di Roma, La Sapienza), Mason, P.(Calthec), Mauskopf, P.(Cardiff), Melchiorri, A.(Universita di Roma, La Sapienza), Miller, A.D.(Columbia), Montroy, T.(CWRU), Nati, F.(Universita di Roma, La Sapienza), Nati, L.(Universita di Roma, La Sapienza), Natoli, P.(Universita di Roma, Tor Vergata), Netterfield, C.B.(University of Toronto), Page, L.A.(Princeton University), Pascale, E.(University of Toronto), Piacentini, F.(Universita di Roma, La Sapienza), Pogosyan, D.(university of Alberta), Polenta, G.(Universita di Roma, La Sapienza), Prunet, S.(IAP), Rebolo, R.(Tenerife), Reich, P.(Max-Planck-Institut fur Radioastronomie), Reich, W.(Max-Planck-Institut fur Radioastronomie), Ricciardi, S. (Universita di Roma, La Sapienza), Romeo, G.(INGF), Ruhl, J.E.(CWRU), Santini, P.(Universita di Roma, La Sapienza), Tegmark, M.(MIT), Torbet, E.(UCSB), Veneziani, M.(Universita di Roma, La Sapienza), Vittorio, N.(Universita di Roma, Tor Vergata), Watson, R.(Tenerife) Xu, Y.X.(LANL) & Zaldarriaga, M.(Havard,CfA)

Biographical Sketch - COLIN J. LONSDALE

Professional Preparation:

St. Andrews University, Scotland, Applied Mathematics & Astronomy: BSc. Hons., 1978
Nuffield Radio Astronomy Labs., Jodrell Bank, England, Radio Astronomy: Ph.D., Fall 1981

Appointments:

1981-1983	Postdoctoral Fellow at the Nuffield Radio Astronomy Laboratories,
1983-1986	Research Associate at the Pennsylvania State University.
1986-2001	Research Scientist, MIT Haystack Observatory
2001-present	Principal Research Scientist, MIT Haystack Observatory
2006-present	Assistant Director, MIT Haystack Observatory

Selected Recent Publications:

Bhat, N. D. Ramesh; Wayth, Randall B.; Knight, Haydon S.; Bowman, Judd D.; Oberoi, Divya; Barnes, David G.; Briggs, Frank H.; Cappallo, Roger J.; Herne, David; Kocz, Jonathon; **Lonsdale, Colin** et al., "Detection of Crab Giant Pulses Using the Mileura Widefield Array Low Frequency Demonstrator Field Prototype System", *ApJ* **665**, 618, 2007

Bowman, Judd D.; Barnes, David G.; Briggs, Frank H.; Corey, Brian E.; Lynch, Merv J.; Ramesh Bhat, N. D.; Cappallo, Roger J.; Doeleman, Sheperd S.; Fanous, Brian J.; Herne, David; **Lonsdale, Colin** et al., "Field Deployment of Prototype Antenna Tiles for the Mileura Widefield Array Low Frequency Demonstrator", **133**, 1505, 2007.

CJ Lonsdale, PJ Diamond, H Thrall, HE Smith, Carol J Lonsdale, "VLBI images of 49 Radio SNe in Arp 220", *ApJ,* **647**, 185, 2006.

CJ Lonsdale, SS Doeleman, D Oberoi, "Efficient imaging strategies for Next-generation radio Arrays", *Experimental Astronomy*, **17**, 345, 2005.

Doeleman, S.S**., Lonsdale, C.J.,** Kondratko, P.T., Predmore, C.R., "Using VLBI to probe the Orion KL outflow on AU scales," *ApJ.*, **607**, 361D, 2004.

Lonsdale, C.J., "OH Megamasers," in proceedings of IAU 206, Cosmic Masers, p.413, 2002.

Lonsdale, C.J., Doeleman, S.S., Cappallo, R.J., Hewitt, J.N, Whitney, A.R., "Exploring the performance of large-N radio astronomical arrays," *Proceedings of SPIE*, **4015**, 126, 2000.

Synergistic Activities:

MWA International Project Leader, responsible for overall execution of the Project. PI on NSF grant for the MWA, starting June 2006

Collaborators and Other Affiliations: David Barnes (Swinburne), Ramesh Bhat (Swinburne), Judd Bowman (Caltech), Frank Briggs (ANU), John Bunton (CSIRO) Roger Cappallo (MIT Haystack), John Conway (Onsala), Brian Corey (MIT Haystack), Katherine deKleer (MIT), Anthea Coster (MIT Haystack), Angelica de Oliviera-Costa (MIT), David deBoer (CSIRO), Phil Diamond (Jodrell Bank Observatory), Shep Doeleman (MIT Haystack), Bryan Gaensler (U. Sydney), Lincoln Greenhill (CfA), Jackie Hewitt (MIT), Justin Kasper (Harvard), Paul Kondratko (CfA), Carol Lonsdale (Caltech IPAC), Mervyn Lynch (Curtin), Daniel Mitchell (CfA), Miguel Morales (MIT), Divya Oberoi (MIT Haystack), Rodrigo Parra (Onsala), C. Read Predmore (U. Mass. Amherst), Peter Quinn (UWA), Alan Rogers (MIT Haystack), Emmanuel Rovilos (Jodrell Bank), Joe Salah (MIT Haystack), Bob Sault (U. Melbourne), Uday Shankar (RRI, India), Gene Smith (UCSD), Lister Staveley-Smith (UWA), Max Tegmark (MIT), Hannah Thrall (Jodrell Bank), Randall Wayth (CfA), Rachel Webster (U. Melbourne), Alan Whitney (MIT Haystack), Stuart Wyithe (U. Melbourne)

Biographical Sketch – MAX TEGMARK

Professional Preparation

B.A. in economics from the Stockholm School of Economics, June 1989
B.Sc. in physics from the Royal Institute of Technology, Stockholm, June 1990
Ph.D. in physics (theoretical cosmology) from U.C. Berkeley, May 1994

Appointments

Sep. 1994-Sep. 1996:	Research associate, Max-Planck-Institut fur Physik, Munich
Oct. 1996-1999:	Hubble Fellow, member, IAS, Princeton
July 1999-June 2003:	Assistant Professor, Univ. of Pennsylvania
July 2003-April 2005:	Associate Professor with tenure, Univ. of Pennsylvania
July 2004-June 2005:	Associate Professor without tenure, MIT
July 2005-:	Associate Professor with tenure, MIT

Selected Publications

1. *Cosmological parameters from SDSS and WMAP*, Max Tegmark et al (63 authors), astro-ph/0310571, PRD, 69, 103501
2. *Cosmological Constraints from the SDSS Luminous Red Galaxies,* M Tegmark et al 2006, astro-ph/0608632, PRD, 74, 123507
3. *How small were the first cosmological objects?* M Tegmark, J Silk, M J Rees, A Blanchard, T Abel & F Palla 1997, ApJ, 474, 1-12
4. *How accurately can 21 cm tomography constrain cosmology?* Yi Mao, Max Tegmark, Matt McQuinn, Matias Zaldarriaga & Oliver Zahn, to be submitted to PRD
5. *Twenty-one Centimeter Tomography with Foregrounds*, Xiaomin Wang, Max Tegmark, Mario Santos & Lloyd Knox 2006, astro-ph/0501081, ApJ, 650, 529

Recent collaborators: Abazajian, K (LANL), Aguirre, A (UCSC), Alford M, Barkats D, Blanton, M (NYU), Bostrom N (Oxford), Budavari, T, Bunn E (Richmond), Burles, S (MIT), Cabi S (MIT), Connolly, A, Contaldi, C R (Imperial), Creminelli, P (Harvard), Crill, B P (IPAC), de Bernardis, P (Rome), de Oliveira-Costa, A(MIT), De Troia, G (Rome), Devlin, MJ (Penn), Diego, J M (Santander), Efstathiou G (Cambridge), Eisenstein, D J, Faulkner, T (MIT), Feldman H A, Finkbeiner, D (Princeton), Frieman, JA (Chicago), Gunn, JE (Princeton), Guth A (MIT), Hamilton, A (Boulder), Hedman M M, Hertzberg, M (MIT), Hill, C (MIT), Hogg, DW (NYU), Hut P (IAS), Jain, B (Penn), Johnston, D, Jones, W C (Caltech), Kachru, S (Stanford), Keating B, Knapp, G R (Princeton), Knox, L (Davis), Lange, A E (Caltech), Lasenby, A N (Cambridge), Lupton, R H (Princeton), M Strauss, M (Princeton), MacTavish, C (Toronto), Mackenty, J (STSci), Mao Y (MIT), Masi, S(Rome), McDonald, P(Princeton), Netterfield, CB (Toronto), Nichol, R C, Ozcan, O (MIT), Padmanabhan, N (LBNL), Page, L A (Princeton), Park C-G, Percieval W J, Piacentini, F (Rome), Pogosian, L, Pope, A, Protopapas, P (CfA), Rees M, Ruhl, JE(CWRU), Rusin D, Sandvik, H B, Santos, M (Davis), Schlegel, D (LBNL), Scoccimarro, R(Columbia), Scranton, R, Seljak, U(Princeton), Senatore, L, Shelton, J (Rutgers), Swanson, M (MIT), Szalay, A S, Taylor, W (MIT), Vilenkin A, Waga I (Brazil), Wang, X(Chicago), Wang, Y(OU), Weinberg, DH, Wheeler J A, Wheeler, C (Austin), Wilczek F Xu, Y (LANL) Zaldarriaga, M (CfA) Zehavi, I (CWRU), Zheng, Z
(Because of the 1-page limit, I'm not including about 10^2 SDSS and Boomerang co-authors who are not close collaborators, but merely co-authors by virtue of belonging to the SDSS or Boomerang collaborations and being listed on our data release papers.)

Advisors: Joe Silk (PhD), Georg Raffelt, Simon White, John Bahcall (postdoc)

Advisees: D Rusin, Y Xu, X Wang, D, M Swanson, Y Mao, T Faulkner, M Hertzberg, A Liu, L Rogers, C Peterson, C Hill, A Rahlin, H Sandvik, J Diego

Biographical Sketch – Edmund Bertschinger

Professional Preparation
PhD in Astrophysical Sciences, Princeton University, 1984
BS in Physics, California Institute of Technology, 1979

Appointments

2008 –	Head, Department of Physics, MIT
2002 – 2007	Division Head of Astrophysics, MIT
1996 –	Professor of Physics, MIT
1991 – 1996	Associate Professor of Physics, MIT
1986 – 1991	Assistant Professor of Physics, MIT
1985 – 1986	Miller Research Fellow, UC Berkeley
1983 – 1985	Postdoctoral Research Associate, University of Virginia

Publications

E. Bertschinger 2006, "The Effects of Cold Dark Matter Decoupling and Pair Annihilation on Cosmological Perturbations," Phys. Rev. D74, 063509

E. Bertschinger 2006, "On the Growth of Perturbations as a Test of Dark Energy and Gravity," ApJ 648, 797

C.-P. Ma & E. Bertschinger 2004, "A Cosmological Kinetic Theory for the Evolution of Cold Dark Matter Halos with Substructure: Quasi-Linear Theory," ApJS 612, 28

S. Bashinsky & E. Bertschinger 2002, "Dynamics of Cosmological Perturbations in Position Space," Phys. Rev. D65, 123008

E. Bertschinger 2001, "Multiscale Gaussian Random Fields and Their Application to Cosmological Simulations," ApJS 137, 1

Synergistic Activities

1. Led MIT alumni tours to astronomical observatories in Chile, 2006 and 2007.
2. Organized "An Astronomical Event" one-day symposium for MIT alumni and donors, March 8, 2007.
3. Supervised high school students during summers 1998 – 2007 in the RSI program, including two top-ten prize-winners of the Intel (formerly Westinghouse) Science Talent Search. Natalia Toro (hispanic female) won First Prize in 1999 and Vivek Venkatachalam won Ninth Prize in 2002. Website: http://www.cee.org/rsi/

Collaborators and Other Affiliations

Collaborators: Roya Mohayaee (IAP)

Graduate and Postdoctoral Supervisors: Jeremiah Ostriker (Princeton), Roger Chevalier (U. Virginia), Chris McKee (UC Berkeley).

Thesis advisor for: Rennan Barkana (Tel Aviv), Sergei Bashinsky (LANL), James Frederic (industry), James Gelb (industry), Lam Hui (Columbia), Bhuvnesh Jain (UPenn), Chung-Pei Ma (UC Berkeley), Jamie Portsmouth (industry), Jeremy Schnittman (Johns Hopkins), Uros Seljak (UC Berkeley), Alexander Shirokov (CITA), John Tsai (industry), Matias Zaldarriaga (Harvard).

Postdoc advisor for: Greg Bryan (Columbia), Neal Katz (UMass), Ali Nayeri (Harvard).

Biographical Sketch - BERNARD F. BURKE

Professional Preparation

Massachusetts Institute of Technology, Cambridge, Massachusetts. Physics S.B, 1950
Massachusetts Institute of Technology, Cambridge, Massachusetts. Physics, Ph.D., 1953
Carnegie Institution of Washington, Washington DC, Temporary Staff Member, 1953 – 1956

Appointments

2001 to present William A.M. Burden Professor of Astrophysics Emeritus, Massachusetts Institute of Technology
1981 to 2001 William A.M. Burden Professor of Astrophysics, Massachusetts Institute of Technology
1965 to 1981 Professor of Physics, Massachusetts Institute of Technology
1992 to 1993 Visiting Professor of Physics, University of Manchester (England)
1971 to 1972 Visiting professor of Experimental Astrophysics, University of Leiden
1953 to 1965 Staff Member, Carnegie Institution of Washington

Publications

Bernard F. Burke and Francis Graham-Smith, "Introduction to Radio Astronomy, Second Edition", Cambridge University Press, 2002; 3rd ed. In press, to be published 2007
Muterspaugh, M.W., Lane, B.F., Konacki, M., Burke, B.F., Colavita, M.M., Kulkarni, S.R., & Shao, M., "PHASES High-Precision Differential Astrometry of δ Equulei" Astron J, 130, 2866, 2005
Muterspaugh, M.W., Lane, B.F., Konacki, M., Burke, B.F., Colavita, M.M., Kulkarni, S.R., & Shao, M., "PHASES Differential Astrometry and the Mutual Inclination of the V819 Herculis Triple Star System", Astron & Astroph, 446, 723, 2006
Muterspaugh, M.W., Lane, B.F., Konacki, M., Wiktorowicz, S., Burke, B.F., Colavita, M.M., Kulkarni, S.R., & Shao, M., "PHASES Differential Astrometry and Iodine Cell Radial Velocities of the κ Pegasi Triple Star System", ApJ, 636, 1020, 2006
Burke, B.F., JENAM 2003, Gurvits, L.I., Frey, S., Rawlings, S., eds, "Radio Astronomy from Karl Jansky to Microjansky JENAM'03", EAS Pub Series, Volume 15, 27, 2005

Synergistic Activities

1. Jansky Lecturer, National Radio Astronomy Observatory, 1998
2. Keck Interferometer Science Working Group, NASA, 2003 to present
3. Consultant to Federal Aviation Authority on Radio Navigation for airports, 1998-2000
4. Pecek Lecturer, International Institute of Astronautics, 1999
5. Report Reviews, National Research Council, 2004, 2005

Collaborators and Other Affiliations:

Muterspaugh, M.W., University of California at Berkeley (PhD Thesis Supervisor)
Lane,B.F., Massachusetts Institute of Technology (Sponsor, Pappalardo Fellowship)
Konacki, M., California Institute of Technology
Colavita, M.M., Jet Propulsion Laboratory
.,Kulkarni, S.R., California Institute of Technology
Shao, M., Jet Propulsion Laboratory

Biographical Sketch – ALAN H. GUTH

Professional Preparation

Massachusetts Institute of Technology, Cambridge, MA. Ph.D. in physics, 1972, and S.B. and S.M. in physics, 1969.

Postdoctoral Associate, Stanford Linear Accelerator Center, 1979-80
Postdoctoral Associate, Cornell University, 1977-79
Postdoctoral Associate, Columbia University, 1974-77
Postdoctoral Associate, Princeton University, 1971-74

Appointments

Massachusestts Institute of Technology

1992-present Victor F. Weisskopf Professor of Physics
1989-1991 Jerrold Zacharias Professor of Physics
1980-present Visiting Associate Professor, Associate Professor, Professor, Department of Physics

Related Publications

Borde, A., Guth, A., and Vilenkin, A. 2003, "Inflationary Spacetimes are Incomplete in Past Directions," Phys. Rev. Lett. 90, 151301.

Randall, L., Soljacic, and Guth, A. 1996, "Supernatural Inflation: Inflation from Supersymmetry with no (Very) Small Parameters," Nucl. Phys., B472, 377.

Carroll, S. M., Farhi, E., Guth, A., and Olum, K. D. 1994, "Energy-Momentum Restrictions on the Creation of Gott Time Machines," Phys. Rev. D, 50, 6190.

Farhi, E., Guth, A., and Guven, J. 1990, "Is it Possible to Create a Universe in the Laboratory by Quantum Tunneling?" Nucl. Phys., B339, 417.

Blau, S. K., Guendelman, E. I., and Guth, A. 1987, "The Dynamics of False Vacuum Bubbles," Phys. Rev. D, 35, 1747.

Guth, A., and Pi, S.-Y. 1982, "Fluctuations in the New Inflationary Universe," Phys. Rev. Lett., 49, 1110.

Guth, A., and Weinberg, E. J. 1983, "Could the Universe Have Recovered from a Slow First Order Phase Transition?" Nucl. Phys., B212, 321.

Guth, A. 1981, "The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems," Phys. Rev. D, 23, 347.

Collaborators & Other Affiliations:

Edward Farhi, MIT
Noah Graham, Middlebury College
Philip Mannheim, U. Connectut
R. Ruben Rosales, MIT
Alexander Vilenkin, Tufts
Jaume Garriga, U. Barcelona
David Kaiser, MIT
Ali Nayeri, Harvard
Max Tegmark, MIT

Graduate and Postdoctoral Advisees

Kristin Burgess, Princeton
Justin Khoury, Perimeter Institute
Yi Mao, MIT
Leonardo Senatore, Harvard
Serkan Cabi, MIT
Hugh Manini, LLNL
Jamie Portsmouth, industry
Ephraim Tekle, LLNL

BIOGRAPHICAL SKETCH - IRENE L. PORRO

Professional Preparation

University of Torino, Italy	Physics	Laurea (equivalent to BS) - 1991
University of Padova, Italy, and Harvard-Smithsonian Center for Astrophysics	Space Science and Technology	Ph.D. - 1996
Max-Planck Institut fuer Astronomie (MPIA) - Heidelberg, Germany	Astronomy – optical and infrared interferometry	Post-Doctoral Position 1997 - 1999

Professional Appointments

2007 – Pres. – Public Education and Communications Officer, MIT Kavli Institute: Director of the Youth Astronomy Apprenticeship program and Chandra Astrophysics Institute.
2000 - 2007. – Education and Public Outreach Scientist, MIT Kavli Institute: Designer, developer and coordinator of EPO initiatives associated with NASA missions with MKI lead.
2000 - 2001 – Education and Public Outreach Scientist, Harvard-Smithsonian Center for Astrophysics**:** EPO program coordinator for the IOTA project.
1999 - 2000 – Visiting Scientist, Harvard-Smithsonian Center for Astrophysics: optical design, interferometry observations on Mt. Hopkins, Arizona, analysis of interferometry data, and EPO program for the NASA funded IOTA project.

Publications (selected)

Porro I.L., Dini V., Prol T., "Youth Astronomy Apprenticeship: An Initiative to Promote Science Learning Among Urban Youth and Their Communities" ASP's 119th Annual Meeting, 2007

Hartman M., Porro I.L., Baganoff F., Grove J., "What can science do for me? Engaging urban teens in the Chandra Astrophysics Institute" ASP's 119th Annual Meeting, 2007

Porro I.L., "Astronomy and Space Science in Out-of-School Time: Science Learning Opportunities for Underrepresented Urban Teens", ASP's 117th Annual Meeting, 2005

Porro I.L., Berkefeld Th., Leinert Ch., "Simulation of the effects of atmospheric turbulence on mid-infrared visibility measurements with MIDI-VLTI", Applied Optics, Vol. 39 No. 10, 2000

Porro I.L., Traub W.A., Carleton N.P., "Effect of telescope alignment on a stellar interferometer", Applied Optics, Vol. 38 No. 28, 1999

Collaborators and Co-Editors:

Bartolone, L. (Adler Planetarium); Belcher, J. (MIT); Carleton, N. P.(Harvard); Coudé du Foresto, V. (Observatoire de Paris); Craig, N. (UC Berkely); Danchi, W. C. (GSFC); Dussault, M. (SAO); Gould, R. R. (SAO); Krishnamurthi, A. (GSFC); Hartman, M. (MIT); Lacasse, M. G. (SAO); Lestition, K. (SAO); Lochner, J. (GSFC); Mendez, B. J. (UC Berkely); Millan-Gabet, R. (JPL); Monnier, J. D. (UMich); Morel, S. (ESO); O'Connor, S. (TSN); Perrin, G. (Observatoire de Paris); Plait, P. (SSU); Range, S. (Stanford U.); Reinfeld, E. (SAO); Schloerb, F. P. (UMass) ; Steel, S. J. (SAO); Townes, C. H. (UC Berkley); Traub, W. A. (JPL); Tuthill, P. G. (USYD).

Graduate and Postdoctoral Advisors:

Wesley A. Traub (JPL), Nat Carleton (Harvard), Christoph Leinert (MPIA - Germany)

Biographical Sketch - ALAN E. E. ROGERS

Professional Preparation:
B.Sc. University College of Rhodesia, 1962 (Mathematics and Physics)
S.M. Massachusetts Institute of Technology, 1964 (Electrical Engineering)
Ph.D. Massachusetts Institute of Technology, 1967 (Electrical Engineering)

Appointments:

2006 – Present	Research Affiliate at M.I.T. Haystack Observatory
1968 – 2006	Senior Research Scientist at Haystack Observatory
1993 - 2006	Associate Director of M.I.T. Haystack Observatory
1968	Lecturer at University of Zimbabwe
1962 - 1967	Research Assistant at MIT

Publications:

Bowman J. D., Rogers, A.E.E., Hewitt, J.N., "Toward Empirical Constraints on the Global Redshifted 21 cm Brightness Temperature during the Epoch of Reionization," *Ap. J.*, "*In press*", 2008

Rogers, A.E.E., Carter, J.C, Derome, M., Smythe, D.L., "Extending The Dynamic Range of a Spectrum Monitor Using Comparison Switching and Spectral Averaging," *IEEE Transactions on Instrumentation and Measurement*, "*In press*", 2008.

Rogers, A.E.E., Dudevoir, K.A, Bania, T.M., "Observations of the 327 MHz Deuterium Hyperfine Transition," A.J., **133,** 1625-1632, 2007

Rogers, A.E., Pratap, P., Carter, J.C., Diaz, M.A., "Radio Frequency Interference Shielding and Mitigation Techniques for a Sensitive Search for the 327 MHz Line of Deuterium," *Radio Science*,**40,** 2005.

Rogers, A.E.E., Bania, T., Dudevoir, K.A., Carter, J.C., Fanous, B.J., Kratzenberg, E., "Deuterium Abundance in the Interstellar Gas of the Galactic Anticenter from the 327 MHz Line," Ap.J., **630**;L41-L44, 2005.

Rogers, A.E.E., Pratap, P., Kratzenberg, E., "Calibration of active antenna arrays using a sky brightness model," Radio Science, **39**, 2004.

Rogers, A.E.E., Doeleman, S.S., Moran, J.M., "Fringe Detection Methods for Very Long Baseline Arrays", A.J.,**109**, 1391-1401, 1995.

Synergistic Activities:
Development of Small Radio Telescope for Education
Member of National Academies Committee on Radio Frequencies (CORF)

Collaborators and Other Affiliations: Bania, T.M., Boston University, Bowman, J. D., Caltech, Cappallo, R. J., Haystack Observatory; Carter, J.C., Haystack Observatory, Corey, B. E., Haystack Observatory; Derome, M., Haystack Observatory, Doeleman, S. S., Haystack Observatory; Dudevoir, K. A., Haystack Observatory, Fanous, B., Haystack Observatory; Hewitt, J. N., MIT, Kratzenberg, E., Haystack Observatory; Lonsdale, C. J., Haystack Observatory; Oberoi, D., Haystack Observatory; Pratap, P., Haystack Observatory, Salah, J. E., Haystack Observatory, Smythe, D.L., Haystack Observatory, Wayth, R., Smithsonian Astrophysical Observatory.

Graduate Advisors: Barrett, A.H.

Biographical Sketch – FRANK WILCZEK

Professional Preparation

Princeton University, Ph.D. in physics, 1974, and M.A. in mathematics, 1972
University of Chicago, B. S. in mathemetics, 1970

Appointments

2000-present Massachusetts Institute of Technology, Herman Feshbach Professor of Physics
2002-present Centros Estudios Cientificos, Validiva, Chile, Adjunct Professor
1990-2000 Institute for Advanced Study, School of Natural Science, J. R. Oppenheimer Professor of Physics
1980-1988 University of California, Santa Barbara, Institute for Theoretical Physics, Chancellor Robert Huttenback Professor
1974-1980 Princeton University, Assistant Professor, Associate Professor
1987-1988 Harvard University, Visiting Professor

Selected Honors and Academic Awards

Fellow, Am. Phil. Soc., NAS, American Academy of Arts and Science, AAAS, UCS
King Faisal Foundation, King Faisal International Prize in Science, 2005
Royal Swedish Academy of Sciences, Stockholm Sweden, Nobel Prize in Physics, 2004
Charles University, Prague, Faculty of Mathematics & Physics Commemorative Medal 2003
European Physical Society, High Energy Physics Prize, 2003
American Physical Society, Lilienfeld Prize, 2003; J. J. Sakurai Prize, 1986
Royal Netherlands Academy of Arts and Sciences, Lorentz Medal, 2002

Related Publications

Tegmark, M., Aguirre, A., Rees, M., and Wilczek, F. 2006, "Dimensionless Constants, Cosmology, and Other Dark Matters," Phys. Rev. D, 73N2, 023505.

"Asymptotic Freedom: From Paradox to Paradigm" (Nobel lecture). 2004, *Les Prix Nobel* (Almqvist & Wiesell International, Stockholm, Sweden) 100-124.

Dimopoulos, S., Raby, S., and Wilczek, F. 1981, "Supersymmetry and the Scale of Unification," Phys. Rev. D, 24, 1681.

Wilczek, F. 1977, "Problems of Strong P and T Invariance in the Presence of Instantons," Phys. Rev. Lett., 40, 279.

Wilczek, F. 1977, "Decay of Heavy Vector Mesons into Higgs Particles," Phys. Rev. Lett., 39, 1304.

Wilczek, F., and Gross, D. 1973, "Asymptotically Free Gauge Theories, I," Phys. Rev. D, 8, 3633.

Collaborators & Other Affiliations:

Anthony Aguirre, UC Santa Cruz
Andres Gomberoff, CECS, Chile
Marc Hennaeux, U. Brussels
Robert L. Jaffe, MIT
Konstantin Matchev, U. Florida
Hiroshi Umetsu Okayama, IQP, Japan
Andreas Schmitt, Washington U. and MIT
Claudio Teitelboim, CECS, Chile
Curtis Callan, Princeton
Elena Gubankova, MIT
Satishi Iso, KEK Tsukuba, Japan
W. Vincent Liu, U. Pittsburgh
E. G. Mishchenko, U. Utah
Martin J. Ress, Cambridge U.
Max Tegmark, MIT
Peter Zoller, Innsbruck U.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION: **Harvard University**				FOR NSF USE ONLY — PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Abraham Loeb**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Abraham Loeb - Prof.**	0.00	0.00	0.00	$ 0	$	
2. **Charles Alcock - Prof.**	0.00	0.00	0.00	0		
3. **Lars E Hernquist - Prof.**	0.00	0.00	0.00	0		
4. **Christopher W Stubbs - Prof.**	0.00	0.00	0.00	0		
5. **Matias Zaldarriaga - Prof.**	0.00	0.00	0.00	0		
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0		
7. (5) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (3) POST DOCTORAL SCHOLARS	12.00	0.00	0.00	169,042		
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0		
3. (3) GRADUATE STUDENTS				86,399		
4. (0) UNDERGRADUATE STUDENTS				0		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (0) OTHER				0		
TOTAL SALARIES AND WAGES (A + B)				255,441		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				38,654		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				294,095		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) **Beowulf Cluster** $ 400,000						
TOTAL EQUIPMENT				400,000		
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				4,000		
2. FOREIGN				1,000		
F. PARTICIPANT SUPPORT COSTS						
1. STIPENDS $ 0						
2. TRAVEL 50,000						
3. SUBSISTENCE 7,000						
4. OTHER 43,000						
TOTAL NUMBER OF PARTICIPANTS (90) TOTAL PARTICIPANT COSTS				100,000		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				0		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0		
3. CONSULTANT SERVICES				0		
4. COMPUTER SERVICES				0		
5. SUBAWARDS				0		
6. OTHER				113,903		
TOTAL OTHER DIRECT COSTS				113,903		
H. TOTAL DIRECT COSTS (A THROUGH G)				912,998		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct (Rate: 67.0830, Base: 397810)**						
TOTAL INDIRECT COSTS (F&A)				266,863		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				1,179,861		
K. RESIDUAL FUNDS				0		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 1,179,861	$	
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $					

PI/PD NAME: **Abraham Loeb**	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

SUMMARY PROPOSAL BUDGET

YEAR 2

ORGANIZATION **Harvard University**				FOR NSF USE ONLY	
				PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Abraham Loeb**				AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Abraham Loeb - Prof.**	0.00	0.00	0.00	$ **0**	$
2. **Charles Alcock - Prof.**	0.00	0.00	0.00	**0**	
3. **Lars E Hernquist - Prof.**	0.00	0.00	0.00	**0**	
4. **Christopher W Stubbs - Prof.**	0.00	0.00	0.00	**0**	
5. **Matias Zaldarriaga - Prof.**	0.00	0.00	0.00	**0**	
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**5**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	**0**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**3**) POST DOCTORAL SCHOLARS	12.00	0.00	0.00	**175,804**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**3**) GRADUATE STUDENTS				**89,855**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**265,659**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**39,556**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**305,215**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) **Parts, Analysis machine, Opteron Comp.** $ **75,000**					
TOTAL EQUIPMENT				**75,000**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**4,000**	
2. FOREIGN				**1,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **72,000** 3. SUBSISTENCE **7,000** 4. OTHER **21,000**					
TOTAL NUMBER OF PARTICIPANTS (**100**) TOTAL PARTICIPANT COSTS				**100,000**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**119,208**	
TOTAL OTHER DIRECT COSTS				**119,208**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**604,423**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct (Rate: 68.0000, Base: 413627)**					
TOTAL INDIRECT COSTS (F&A)				**281,266**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**885,689**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **885,689**	$

M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $		
PI/PD NAME **Abraham Loeb**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

2 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI 6754594

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION **Harvard University**				**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Abraham Loeb**				AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Abraham Loeb - Prof.**	0.00	0.00	0.00	$ **0**	$
2. **Charles Alcock - Prof.**	0.00	0.00	0.00	**0**	
3. **Lars E Hernquist - Prof.**	0.00	0.00	0.00	**0**	
4. **Christopher W Stubbs - Prof.**	0.00	0.00	0.00	**0**	
5. **Matias Zaldarriaga - Prof.**	0.00	0.00	0.00	**0**	
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**5**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	**0**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**3**) POST DOCTORAL SCHOLARS	12.00	0.00	0.00	**182,836**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**3**) GRADUATE STUDENTS				**93,449**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**276,285**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**41,138**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**317,423**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) **Parts** **$ 75,000**					
TOTAL EQUIPMENT				**75,000**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**4,000**	
2. FOREIGN				**1,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **50,000** 3. SUBSISTENCE **7,000** 4. OTHER **43,000**					
TOTAL NUMBER OF PARTICIPANTS (**90**) TOTAL PARTICIPANT COSTS				**100,000**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**111,490**	
TOTAL OTHER DIRECT COSTS				**111,490**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**608,913**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **Modified Total Direct (Rate: 68.0000, Base: 417485)**					
TOTAL INDIRECT COSTS (F&A)				**283,890**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**892,803**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **892,803**	$

M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $		
PI/PD NAME **Abraham Loeb**	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

3 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI 6754594

SUMMARY PROPOSAL BUDGET

YEAR 4

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Harvard University

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Abraham Loeb

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Abraham Loeb - Prof.	0.00	0.00	0.00	$ 0	$
2. Charles Alcock - Prof.	0.00	0.00	0.00	0	
3. Lars E Hernquist - Prof.	0.00	0.00	0.00	0	
4. Christopher W Stubbs - Prof.	0.00	0.00	0.00	0	
5. Matias Zaldarriaga - Prof.	0.00	0.00	0.00	0	
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (5) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (3) POST DOCTORAL SCHOLARS	12.00	0.00	0.00	190,149	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (3) GRADUATE STUDENTS				97,187	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				287,336	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				42,784	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				330,120	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) New cluster $ 258,000					
TOTAL EQUIPMENT				258,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				4,000	
2. FOREIGN				1,000	
F. PARTICIPANT SUPPORT COSTS					
1. STIPENDS $ 0					
2. TRAVEL 72,000					
3. SUBSISTENCE 7,000					
4. OTHER 21,000					
TOTAL NUMBER OF PARTICIPANTS (100) TOTAL PARTICIPANT COSTS				100,000	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				112,037	
TOTAL OTHER DIRECT COSTS				112,037	
H. TOTAL DIRECT COSTS (A THROUGH G)				805,157	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Modified Total Direct (Rate: 68.0000, Base: 430072)					
TOTAL INDIRECT COSTS (F&A)				292,449	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				1,097,606	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 1,097,606	$

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Abraham Loeb

ORG. REP. NAME*

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI 6754594

SUMMARY PROPOSAL BUDGET

YEAR 5

FOR NSF USE ONLY	
PROPOSAL NO.	DURATION (months) Proposed / Granted
AWARD NO.	

ORGANIZATION: **Harvard University**

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Abraham Loeb**

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Abraham Loeb - Prof.	0.00	0.00	0.00	$ 0	$
2. Charles Alcock - Prof.	0.00	0.00	0.00	0	
3. Lars E Hernquist - Prof.	0.00	0.00	0.00	0	
4. Christopher W Stubbs - Prof.	0.00	0.00	0.00	0	
5. Matias Zaldarriaga - Prof.	0.00	0.00	0.00	0	
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (5) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	0	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (3) POST DOCTORAL SCHOLARS	12.00	0.00	0.00	197,755	
2. (0) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	0	
3. (3) GRADUATE STUDENTS				101,074	
4. (0) UNDERGRADUATE STUDENTS				0	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (0) OTHER				0	
TOTAL SALARIES AND WAGES (A + B)				298,829	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				44,495	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				343,324	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) Parts, disk space, memory machine $ 75,000					
TOTAL EQUIPMENT				75,000	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				4,000	
2. FOREIGN				1,000	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 0; 2. TRAVEL 50,000; 3. SUBSISTENCE 7,000; 4. OTHER 43,000					
TOTAL NUMBER OF PARTICIPANTS (90) TOTAL PARTICIPANT COSTS				100,000	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				0	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0	
3. CONSULTANT SERVICES				0	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				114,236	
TOTAL OTHER DIRECT COSTS				114,236	
H. TOTAL DIRECT COSTS (A THROUGH G)				637,560	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) Modified Total Direct (Rate: 68.0000, Base: 444792)					
TOTAL INDIRECT COSTS (F&A)				302,459	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				940,019	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 940,019	$

M. COST SHARING PROPOSED LEVEL $ 0 AGREED LEVEL IF DIFFERENT $

PI/PD NAME: **Abraham Loeb**

ORG. REP. NAME*

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI 6754594

SUMMARY PROPOSAL BUDGET

Cumulative

ORGANIZATION **Harvard University**	**FOR NSF USE ONLY** PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Abraham Loeb**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Abraham Loeb - Prof.**	0.00	0.00	0.00	$ **0**	$
2. **Charles Alcock - Prof.**	0.00	0.00	0.00	**0**	
3. **Lars E Hernquist - Prof.**	0.00	0.00	0.00	**0**	
4. **Christopher W Stubbs - Prof.**	0.00	0.00	0.00	**0**	
5. **Matias Zaldarriaga - Prof.**	0.00	0.00	0.00	**0**	
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**5**) TOTAL SENIOR PERSONNEL (1 - 6)	0.00	0.00	0.00	**0**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**15**) POST DOCTORAL SCHOLARS	60.00	0.00	0.00	**915,586**	
2. (**0**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	0.00	0.00	0.00	**0**	
3. (**15**) GRADUATE STUDENTS				**467,964**	
4. (**0**) UNDERGRADUATE STUDENTS				**0**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**0**) OTHER				**0**	
TOTAL SALARIES AND WAGES (A + B)				**1,383,550**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**206,627**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**1,590,177**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) $ **883,000**					
TOTAL EQUIPMENT				**883,000**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**20,000**	
2. FOREIGN				**5,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **0** 2. TRAVEL **294,000** 3. SUBSISTENCE **35,000** 4. OTHER **171,000**					
TOTAL NUMBER OF PARTICIPANTS (**470**) TOTAL PARTICIPANT COSTS				**500,000**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**0**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**0**	
3. CONSULTANT SERVICES				**0**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**570,874**	
TOTAL OTHER DIRECT COSTS				**570,874**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**3,569,051**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				**1,426,927**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**4,995,978**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **4,995,978**	$

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME **Abraham Loeb**	**FOR NSF USE ONLY** INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

C ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI 6754594

Budget Justification: Full Proposal

PI: Loeb
Harvard University
NSF PFC 07-567 - Physics Frontiers Centers

Collaborative Research: Fundamental Physics from 21cm Cosmology

The Harvard budget totals $4,995,978 for a period of five years starting 8/1/08.

Senior Personnel
The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

We are not requesting summer salary support for the PI and Co-PIs.

Other Personnel
We request full support each year for three graduate students and three postdoctoral fellows. They will be directly involved in the research laid out in this proposal. No fringe is applied to graduate student stipends. A fringe of 22.9% is applied to postdoctoral salary in year 1, and 22.5% thereafter.

Equipment
Year 1, $400,000, will require the funding of a Beowulf Cluster with Intel Quad-core 8GB per node, with Infiniband interconnect, for a total of 100 nodes, and 20TB of disk space. Year 2, $75,000, will require the funding of expenses to purchase replacement parts, a 128 GB RAM analysis machine, and a 16 Core Opteron computer. Year 3, $75,000, will consist of expenses to purchase replacement parts. Year 4, $258,000, will require funding for a new cluster equivalent to year 1. The specific technology will depend on new technical developments. Year 5, 75,000, will require funding for replacement parts, 20 TB of disk space upgrade, and a new large memory machine. The above equipment is essential for the numerical simulations and data analyses described in MA2 and MA3.

Budget Justification: Full Proposal
2/4

Domestic Travel
Funds are requested to support travel expenses to Harvard University, Cambridge, MA for 4 domestic members of the Center Advisory Committee for an annual meeting of 3 days. The estimate includes Cambridge perdiem, airfare, and ground transportation.

Foreign Travel
Funds are requested to support travel expenses to Harvard University, Cambridge, MA for one foreign member of the Center Advisory Committee for an annual meeting of 3 days. The estimate includes Cambridge perdiem, airfare, and ground transportation.

Participant Support
In years 1, 3, and 5, we have budgeted $40,000 for a summer undergraduate internship program for up to 20 students. The cost includes student travel, housing, and stipend; publication of papers; posters and mailing costs; other labor; and administrative fees.

In each year, we have budgeted $10,000 for a workshop, which will cover workshop set-up costs and catering services.

In each year, we have budgeted $50,000 for a visitors' program spread out over the year for up to 50 visitors. The cost includes reimbursement of airfare, lodging, ground transportation, and meals perdiem.

In years 2 and 4, we have budgeted $40,000 for a 4-day annual conference with approximately 30 speakers. The cost includes partial reimbursement of travel costs for the speakers, 2 coffee breaks per day, one banquet, and conference set-up costs.

The table below explains the distribution of participant costs across subcategories:

Budget Justification: Full Proposal
3/4

	Travel	Subsistence	Other	# of Participants
Year 1				
● Internship			$40,000	20
● Workshop		$7,000	$3,000	20
● Visitors	$50,000			50
Year 2				
● Workshop		$7,000	$3,000	20
● Visitors	$50,000			50
● Conference	$22,000		$18,000	30
Year 3				
● Internship			$40,000	20
● Workshop		$7,000	$3,000	20
● Visitors	$50,000			50
Year 4				
● Workshop		$7,000	$3,000	20
● Visitors	$50,000			50
● Conference	$22,000		$18,000	30
Year 5				
● Internship			$40,000	20
● Workshop		$7,000	$3,000	20
● Visitors	$50,000			50

Other Direct Costs - Other
The Harvard-Smithsonian Center for Astrophysics (CfA) is a scientific collaboration between the separate legal entities of Harvard College Observatory (Harvard University) and the Smithsonian Astrophysical Observatory – SAO (Smithsonian Institution).

Total SAO costs: year 1, $98,715; year 2, $103,412; year 3, $95,062; year 4, $94,952; year 5, $96,468.

Dr. Roy Gould, Principal Investigator, @1.2 calendar months in Years 1-5 at no cost to the project. Gould will oversee the SAO's education / outreach component, including the selection of activities, development of software learning tools, and external collaborations. Dr. Simon Steel, Education Manager

@3 calendar months in Years 1-5. Steel will oversee daily project management including design of education activities and involvement of participating scientists. Mary Dussault, Education Specialist, @3 calendar months in Years 1-5. Dussault will oversee the involvement of teachers, the development of education activities, and the design and implementation of assessment plans. Travel is for 1 person to conduct workshops and present results at the meeting of the American Association of Physics Teachers and the National Science Teachers Association in Yrs 1 - 5. Materials and supplies include mechanical and optical systems needed to maintain operation of the MicroObservatory telescopes; materials needed for production of scientific visualizations, kits, and other activities; and other (non-computer) hardware items needed at $20K in Years 1-2 and $15K in Years 3-5. Printing and reproduction costs field-testing of curriculum total $3,000 in Yrs 1-3 and $1,000 in Yrs 4-5. Other SAO costs include the services of a graphic designer, web programmer, and evaluator, totaling $12K in Year 1, $15K in Year 2, and $10K in Yrs 3-5.

Graduate student tuition is also included in this line item: year 1, $15,188; year 2, $15,796; year 3, $16,428; year 4, $17,085; year 5, $17,768.

Indirect Cost
Overhead rates are 67% for year 1 and 68% thereafter. Overhead does not apply to graduate student tuition, equipment, and participant support.

SUMMARY PROPOSAL BUDGET

YEAR 1

ORGANIZATION: **Massachusetts Institute of Technology**				FOR NSF USE ONLY — PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Jacqueline N Hewitt**				AWARD NO.		
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)	
1. **Jacqueline N Hewitt - Professor**	0.00	0.00	1.00	$ 17,167	$	
2. **Angelica de Oliveira-Costa - Principal Research Scientist**	4.00	0.00	0.00	22,688		
3. **Colin J Lonsdale - none**	1.00	0.00	0.00	10,679		
4. **Max E Tegmark - Professor**	0.00	0.00	1.00	11,444		
5.						
6. (0) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0		
7. (4) TOTAL SENIOR PERSONNEL (1 - 6)	5.00	0.00	2.00	61,978		
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)						
1. (0) POST DOCTORAL SCHOLARS	0.00	0.00	0.00	0		
2. (7) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	17.50	0.00	0.00	120,209		
3. (2) GRADUATE STUDENTS				55,900		
4. (4) UNDERGRADUATE STUDENTS				21,120		
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0		
6. (1) OTHER				21,057		
TOTAL SALARIES AND WAGES (A + B)				280,264		
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				65,053		
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				345,317		
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)						
Fabricated Equipment (Test FFT array)			$ 113,250			
Hardware (200 Tbyte archive)			143,095			
TOTAL EQUIPMENT				256,345		
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				13,000		
2. FOREIGN				14,000		
F. PARTICIPANT SUPPORT COSTS						
1. STIPENDS $ 5,000						
2. TRAVEL 0						
3. SUBSISTENCE 0						
4. OTHER 24,457						
TOTAL NUMBER OF PARTICIPANTS (110) TOTAL PARTICIPANT COSTS				29,457		
G. OTHER DIRECT COSTS						
1. MATERIALS AND SUPPLIES				16,200		
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				0		
3. CONSULTANT SERVICES				5,000		
4. COMPUTER SERVICES				0		
5. SUBAWARDS				0		
6. OTHER				41,300		
TOTAL OTHER DIRECT COSTS				62,500		
H. TOTAL DIRECT COSTS (A THROUGH G)				720,619		
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Off-Campus) (Rate: 8.0000, Base: 27846) (Cont. on Comments Page)**						
TOTAL INDIRECT COSTS (F&A)				231,769		
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				952,388		
K. RESIDUAL FUNDS				0		
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 952,388	$	
M. COST SHARING PROPOSED LEVEL $ 0	AGREED LEVEL IF DIFFERENT $					

PI/PD NAME: **Jacqueline N Hewitt**	FOR NSF USE ONLY — INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

1 *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI 6762414

SUMMARY PROPOSAL BUDGET COMMENTS - Year 1

**** I- Indirect Costs**
F&A (On-Campus) (Rate: 68.0000, Base 337560)

SUMMARY PROPOSAL BUDGET

YEAR 2

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months) Proposed	Granted
AWARD NO.		

ORGANIZATION
Massachusetts Institute of Technology

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Jacqueline N Hewitt

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Jacqueline N Hewitt - Professor**	0.00	0.00	1.00	$ **17,682**	$
2. **Angelica de Oliveira-Costa - Principal Research Scientist**	4.00	0.00	0.00	**23,369**	
3. **Colin J Lonsdale - none**	1.00	0.00	0.00	**11,000**	
4. **Max E Tegmark - Professor**	0.00	0.00	1.00	**11,788**	
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**4**) TOTAL SENIOR PERSONNEL (1 - 6)	5.00	0.00	2.00	**63,839**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**1**) POST DOCTORAL SCHOLARS	12.00	0.00	0.00	**51,051**	
2. (**7**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	17.50	0.00	0.00	**123,815**	
3. (**2**) GRADUATE STUDENTS				**57,577**	
4. (**4**) UNDERGRADUATE STUDENTS				**21,754**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**1**) OTHER				**25,353**	
TOTAL SALARIES AND WAGES (A + B)				**343,389**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**85,334**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**428,723**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) **Beowulf Cluster** $ **25,000**					
TOTAL EQUIPMENT				**25,000**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**13,000**	
2. FOREIGN				**14,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **5,000** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **24,000**					
TOTAL NUMBER OF PARTICIPANTS (**110**) TOTAL PARTICIPANT COSTS				**29,000**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**18,400**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**6,540**	
3. CONSULTANT SERVICES				**5,150**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**43,838**	
TOTAL OTHER DIRECT COSTS				**73,928**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**583,651**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Off-Campus) (Rate: 8.0000, Base: 28681) (Cont. on Comments Page)**					
TOTAL INDIRECT COSTS (F&A)				**286,726**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**870,377**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **870,377**	$

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Jacqueline N Hewitt

ORG. REP. NAME*

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INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI 6762414

SUMMARY PROPOSAL BUDGET COMMENTS - Year 2

**** I- Indirect Costs**
F&A (On-Campus) (Rate: 68.0000, Base 418283)

SUMMARY PROPOSAL BUDGET

YEAR 3

ORGANIZATION **Massachusetts Institute of Technology**				FOR NSF USE ONLY PROPOSAL NO.	DURATION (months) Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Jacqueline N Hewitt**				AWARD NO.	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Jacqueline N Hewitt - Professor**	0.00	0.00	1.00	$ **18,212**	$
2. **Angelica de Oliveira-Costa - Principal Research Scientist**	4.00	0.00	0.00	**24,070**	
3. **Colin J Lonsdale - none**	4.00	0.00	0.00	**45,333**	
4. **Max E Tegmark - Professor**	0.00	0.00	1.00	**12,141**	
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**4**) TOTAL SENIOR PERSONNEL (1 - 6)	8.00	0.00	2.00	**99,756**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**2**) POST DOCTORAL SCHOLARS	24.00	0.00	0.00	**105,164**	
2. (**6**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	19.50	0.00	0.00	**154,759**	
3. (**2**) GRADUATE STUDENTS				**59,305**	
4. (**4**) UNDERGRADUATE STUDENTS				**22,406**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**1**) OTHER				**33,927**	
TOTAL SALARIES AND WAGES (A + B)				**475,317**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**127,632**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**602,949**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**13,000**	
2. FOREIGN				**14,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **5,000** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **22,000**					
TOTAL NUMBER OF PARTICIPANTS (**110**) TOTAL PARTICIPANT COSTS				**27,000**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**18,400**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**8,200**	
3. CONSULTANT SERVICES				**5,305**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**47,097**	
TOTAL OTHER DIRECT COSTS				**79,002**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**735,951**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Off-Campus) (Rate: 8.0000, Base: 118203) (Cont. on Comments Page)**					
TOTAL INDIRECT COSTS (F&A)				**344,939**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**1,080,890**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **1,080,890**	$
M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $				
PI/PD NAME **Jacqueline N Hewitt**		FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION			
ORG. REP. NAME*		Date Checked	Date Of Rate Sheet	Initials - ORG	

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI 6762414

SUMMARY PROPOSAL BUDGET COMMENTS - Year 3

**** I- Indirect Costs**
F&A (On-Campus) (Rate: 68.0000, Base 493358)

SUMMARY PROPOSAL BUDGET

YEAR 4

ORGANIZATION: **Massachusetts Institute of Technology**				FOR NSF USE ONLY	
				PROPOSAL NO.	DURATION (months): Proposed / Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR: **Jacqueline N Hewitt**				AWARD NO.	

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Jacqueline N Hewitt - Professor**	0.00	0.00	1.00	$ **18,758**	$
2. **Angelica de Oliveira-Costa - Principal Research Scientist**	4.00	0.00	0.00	**24,792**	
3. **Colin J Lonsdale - none**	4.00	0.00	0.00	**46,693**	
4. **Max E Tegmark - Professor**	0.00	0.00	1.00	**12,506**	
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**4**) TOTAL SENIOR PERSONNEL (1 - 6)	8.00	0.00	2.00	**102,749**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**2**) POST DOCTORAL SCHOLARS	24.00	0.00	0.00	**108,319**	
2. (**5**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	16.50	0.00	0.00	**138,458**	
3. (**2**) GRADUATE STUDENTS				**61,084**	
4. (**4**) UNDERGRADUATE STUDENTS				**23,078**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**1**) OTHER				**32,685**	
TOTAL SALARIES AND WAGES (A + B)				**466,373**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**123,687**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**590,060**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**13,000**	
2. FOREIGN				**14,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **5,000** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **20,000**					
TOTAL NUMBER OF PARTICIPANTS (**110**) TOTAL PARTICIPANT COSTS				**25,000**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**7,700**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**3,300**	
3. CONSULTANT SERVICES				**5,464**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**49,023**	
TOTAL OTHER DIRECT COSTS				**65,487**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**707,547**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Off-Campus) (Rate: 8.0000, Base: 121749) (Cont. on Comments Page)**					
TOTAL INDIRECT COSTS (F&A)				**328,077**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**1,035,624**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **1,035,624**	$

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME: **Jacqueline N Hewitt**	FOR NSF USE ONLY		
	INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

TPI 6762414

SUMMARY PROPOSAL BUDGET COMMENTS - Year 4

** I- Indirect Costs
F&A (On-Campus) (Rate: 68.0000, Base 468142)

SUMMARY YEAR 5
PROPOSAL BUDGET

	FOR NSF USE ONLY		
ORGANIZATION **Massachusetts Institute of Technology**	PROPOSAL NO.	DURATION (months) Proposed	Granted
PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR **Jacqueline N Hewitt**	AWARD NO.		

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. **Jacqueline N Hewitt - Professor**	0.00	0.00	1.00	$ **19,321**	$
2. **Angelica de Oliveira-Costa - Principal Research Scientist**	4.00	0.00	0.00	**25,536**	
3. **Colin J Lonsdale - none**	4.00	0.00	0.00	**48,094**	
4. **Max E Tegmark - Professor**	0.00	0.00	1.00	**12,881**	
5.					
6. (**0**) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	**0**	
7. (**4**) TOTAL SENIOR PERSONNEL (1 - 6)	8.00	0.00	2.00	**105,832**	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (**2**) POST DOCTORAL SCHOLARS	24.00	0.00	0.00	**111,290**	
2. (**5**) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	16.50	0.00	0.00	**142,613**	
3. (**2**) GRADUATE STUDENTS				**62,916**	
4. (**4**) UNDERGRADUATE STUDENTS				**23,771**	
5. (**0**) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				**0**	
6. (**1**) OTHER				**33,514**	
TOTAL SALARIES AND WAGES (A + B)				**479,936**	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				**127,254**	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				**607,190**	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.)					
TOTAL EQUIPMENT				**0**	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				**13,000**	
2. FOREIGN				**14,000**	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ **5,000** 2. TRAVEL **0** 3. SUBSISTENCE **0** 4. OTHER **18,000**					
TOTAL NUMBER OF PARTICIPANTS (**110**) TOTAL PARTICIPANT COSTS				**23,000**	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				**7,400**	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				**2,800**	
3. CONSULTANT SERVICES				**5,628**	
4. COMPUTER SERVICES				**0**	
5. SUBAWARDS				**0**	
6. OTHER				**51,355**	
TOTAL OTHER DIRECT COSTS				**67,183**	
H. TOTAL DIRECT COSTS (A THROUGH G)				**724,373**	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE) **F&A (Off-Campus) (Rate: 8.0000, Base: 125402) (Cont. on Comments Page)**					
TOTAL INDIRECT COSTS (F&A)				**336,346**	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				**1,060,719**	
K. RESIDUAL FUNDS				**0**	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ **1,060,719**	$

M. COST SHARING PROPOSED LEVEL $ **0**	AGREED LEVEL IF DIFFERENT $		
PI/PD NAME **Jacqueline N Hewitt**	FOR NSF USE ONLY INDIRECT COST RATE VERIFICATION		
ORG. REP. NAME*	Date Checked	Date Of Rate Sheet	Initials - ORG

 ***ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET**

SUMMARY PROPOSAL BUDGET COMMENTS - Year 5

**** I- Indirect Costs**
F&A (On-Campus) (Rate: 68.0000, Base 479874)

SUMMARY PROPOSAL BUDGET

Cumulative

FOR NSF USE ONLY		
PROPOSAL NO.	DURATION (months)	
	Proposed	Granted
AWARD NO.		

ORGANIZATION
Massachusetts Institute of Technology

PRINCIPAL INVESTIGATOR / PROJECT DIRECTOR
Jacqueline N Hewitt

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title, A.7. show number in brackets)	NSF Funded Person-months CAL	ACAD	SUMR	Funds Requested By proposer	Funds granted by NSF (if different)
1. Jacqueline N Hewitt - Professor	0.00	0.00	5.00	$ 91,140	$
2. Angelica de Oliveira-Costa - Principal Research Scientist	20.00	0.00	0.00	120,455	
3. Colin J Lonsdale - none	14.00	0.00	0.00	161,799	
4. Max E Tegmark - Professor	0.00	0.00	5.00	60,760	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET JUSTIFICATION PAGE)	0.00	0.00	0.00	0	
7. (4) TOTAL SENIOR PERSONNEL (1 - 6)	34.00	0.00	10.00	434,154	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (7) POST DOCTORAL SCHOLARS	84.00	0.00	0.00	375,824	
2. (30) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	87.50	0.00	0.00	679,854	
3. (10) GRADUATE STUDENTS				296,782	
4. (20) UNDERGRADUATE STUDENTS				112,129	
5. (0) SECRETARIAL - CLERICAL (IF CHARGED DIRECTLY)				0	
6. (5) OTHER				146,536	
TOTAL SALARIES AND WAGES (A + B)				2,045,279	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				528,960	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				2,574,239	
D. EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $5,000.) $ 281,345					
TOTAL EQUIPMENT				281,345	
E. TRAVEL 1. DOMESTIC (INCL. CANADA, MEXICO AND U.S. POSSESSIONS)				65,000	
2. FOREIGN				70,000	
F. PARTICIPANT SUPPORT COSTS 1. STIPENDS $ 25,000 2. TRAVEL 0 3. SUBSISTENCE 0 4. OTHER 108,457					
TOTAL NUMBER OF PARTICIPANTS (550) TOTAL PARTICIPANT COSTS				133,457	
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES				68,100	
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				20,840	
3. CONSULTANT SERVICES				26,547	
4. COMPUTER SERVICES				0	
5. SUBAWARDS				0	
6. OTHER				232,613	
TOTAL OTHER DIRECT COSTS				348,100	
H. TOTAL DIRECT COSTS (A THROUGH G)				3,472,141	
I. INDIRECT COSTS (F&A)(SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS (F&A)				1,527,857	
J. TOTAL DIRECT AND INDIRECT COSTS (H + I)				4,999,998	
K. RESIDUAL FUNDS				0	
L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)				$ 4,999,998	$

M. COST SHARING PROPOSED LEVEL $ **0** AGREED LEVEL IF DIFFERENT $

PI/PD NAME
Jacqueline N Hewitt

ORG. REP. NAME*

FOR NSF USE ONLY		
INDIRECT COST RATE VERIFICATION		
Date Checked	Date Of Rate Sheet	Initials - ORG

C *ELECTRONIC SIGNATURES REQUIRED FOR REVISED BUDGET

TPI 6762414

MIT BUDGET JUSTIFICATION

A. Senior Personnel

We request five months of summer salary support for the PI, Professor Jacqueline Hewitt. Professor Hewitt will lead the MIT component of the PFC program and will be responsible for overseeing the MIT activities and for coordinating closely with Professor Abraham Loeb at Harvard University. Hewitt will lead the activities under MA4.1 (Testbed Data Archive) and MA4.2 (Antenna Development and Testing). She will also participate in MA1 (Basic Theory), MA2 (Observable Signatures), MA3 (Data Analysis and Signal Extraction), MA5 (Design of AIDA), and MA6 (Leveraging the Activity to the Society at Large). Hewitt has been an active participant in the design and development of the MWA, and she is the spokesperson of the MWA EoR science collaboration.

We request five months of summer salary support for Professor Max Tegmark. Professor Tegmark will lead the activities under MA5 and will participate in MA1, MA2, MA3, MA4, and MA6. His experience in Cosmic Microwave Background (CMB) data analysis will be brought directly to bear on the problems of foreground subtraction, optimum mapping, and parameter estimation.

We request 20 months of salary support for Dr. Angelica Costa Tegmark. She will participate in MA3, leading the foreground subtraction effort. Her experience in foreground subtraction in CMB analyses is directly relevant. She will also participate in MA5, as the development and testing of foreground subtraction algorithms will have a strong influence on the design of the 21cm array. Finally, she will participate in MA2, MA4, and MA6.

We request one month each of salary support for Dr. Colin Lonsdale and Dr. Roger Cappallo during the first two years. During this time they will participate in MA4.1. As Project Leader and System Engineer for the MWA project their experience and knowledge of the system is important for successful execution of first observations and for possibly modifying operating parameters of the MWA to provide the dataset relevant for the PFC studies. In years 3, 4, and 5 we increase their support to four months per year, as they will play a major role in MA5 bringing their experience in array design and construction to the effort, providing important input for the models of performance and cost. They will also participate in MA3 and MA6 where intimate knowledge of the MWA system will be an important contribution.

We request 2.5 months per year of support for Dr. Irene Porro. Dr. Porro will lead the MIT Education and Outreach activities.

Unfunded collaborators Professors Alan Guth, Frank Wilczek, and Edmund Bertschinger, will participate in MA1 and MA6, emphasizing theoretical studies of inflation models and dark matter candidates. Bertschinger will also participate in MA2. Unfunded collaborators Professor Bernard Burke and Dr. Alan Rogers, who have extensive experience in radio astronomy and antenna and array design, will participate in MA4.2, MA5, and MA6. Rogers will also participate in MA3.

NSF request: $434,154

B. Other Personnel

We request two months of summer salary support for Dr. Miguel Morales as a visiting professor. Morales is leading the development of the Monitor and Control System for the MWA and has designed several important components of the Real Time System (the MWA's online system for data calibration and mapping). He is leading the power spectrum estimation team of the MWA. His will contribute his expertise to MA2 (Observable Signatures), MA3 (Data Analysis and Signal Extraction), MA4.1 (Testbed Data Archive), MA5 (Design of AIDA), and MA6 (Leveraging the Activity to the Society at Large).

We request three months per year of support for Dr. Edward Morgan. Morgan built and maintained the data archive for the Rossi X-Ray Timing Explorer satellite, and he will be building and maintaining the MWA data archive. His time during years 1 and 2 will be used to expand the MWA archive to accommodate the data collected during MA4.1, to develop software that will allow access to the archive, and to support the users of the archive. During years 3, 4, and 5 he will continue to support the users, and he will take primary responsibility for the software that will model the performance and the cost of the proposed AIDA array (MA5). He will also participate in MA6.

We request 4.6 months per year of support for Dr. Jesus Villasenor. Dr. Villasenor has extensive experience in the design and construction of low frequency radio arrays and single-dish stations, gained in the course of carrying out measurements of the ionosphere and designing and building the ground stations for the High Energy Transient Explorer satellite. Dr. Villasenor will lead the construction and operation of the FFT Test Array (under MA5), and he will assist in MA4.2 (Antenna Development and Testing) and MA6.

We request 2.5 months per year of support for Mr. Mark Hartman. Hartman will work closely with Porro on carrying out the MIT Education and Outreach activities.

We request three months per year in the first three years for support for a technician. The technician will fabricate and test receiver and signal processing boards for the FFT Test Array (MA5) and will build supporting electronics for the antenna testing (MA4.2).

We request support for two graduate students for five years, four summer appointments for undergraduates for five years, and 84 months of postdoc time distributed over the last four years. The students and postdoc will participate in all aspects of the project, contributing their efforts and gaining valuable experience in a broad-range of activities, including field work, data analysis, and simulation, all giving them valuable hands-on experience in experimental radio astrophysics. The undergraduate summer program will be part of the Center's summer internship program, so the students will also benefit from their interaction with the CfA and Haystack participants.

We request $133,951 for allocated laboratory salary support.

NSF request: $1,611,125.

C. Fringe Benefits

Charges for fringe benefits are applied according to MIT standard rates.

NSF request: $528,960

D. Equipment

We request funding to purchase disk storage and computer equipment that we will use create the archive of test MWA data. Our request is based on quotes we obtained for an archive for another MKI project. If we are funded, we will seek competitive bids that might reflect lower prices in the future. The table below summarizes our strawman system.

Item	Quantity	Unit Cost ($)	Total Cost ($)
Disks and computers	10	13,995	139,950
Racks	2	1,250	2,500
Power distribution units	5	129	645
TOTAL			143,095

Costs associated with cooling and supplying electricity to the racks will be borne by the MIT Kavli Institute.

We request $25,000 for the hardware for setting up a beowulf cluster. This is necessary for the extensive computation required for testing calibration and foreground algorithms, and for modeling the performance of arrays.

We request funding to build a small test array that we will use to demonstrate (or refute) the FFT concept for the frequency ranges and configuration that addresses 21cm cosmology requirements. We base our cost estimate on our MWA experience for the antennas, and on catalog prices for all other items. Our costs for a 14×14 test array break down as follows:

Item	Quantity	Unit Cost ($)	Total Cost ($)
Dipole antennas	196	75	14,700.00
including low-noise amplifiers and cables			
Receiver boards (2 polarizations)	392	141	55,272.00
Memory boards	49	229	11,221.00
Controller board	1	622.50	622.50
I/O Card	1	2,000	2,000.00
Computer	1	2,500	2,500.00
Ground plane	1	800	800.00
30% contingency			26,134.65
TOTAL			113,250.15

NSF request: $281,345

E. Travel

We request domestic travel support at a level of $10,000 per year for five trips to attend conferences and support visitors. We request domestic travel support at a level of $3,000 per year for U.S. members of the review panel.

We request foreign travel support for participant travel to the Western Australian site and to meet with our collaborators in Australia at a level of $12,000 per year for 4 trips per year. We request foreign travel support at a level of $2,000 per year for a foreign member of the review panel.

NSF request: $135,000

F. Participant Support Costs

We request $10,000 per year to support workshop participants, and $83,457 distributed over the five years to support the participants in the MIT Education and Outreach program. The Education and Outreach support includes $5,000 per year for stipends. The remainder (Year 1: $14,457, Year 2: $14,000, Year 3: $12,000, Year 4: $10,000, and Year 5: 8,000) is budgeted for materials, supplies and services for training of undergraduate students and youth workers to facilitate education activities at after-school centers, and for the implementation of the after-school centers and community wide events.

NSF request: $133,457

G. Other Direct Costs

We request support for graduate tuition expenses, for materials for building prototype antennas, for shipping antennas from the fabrication plant in China to the United States, for publication costs, for communications and computer facility costs, to support consultants in the MIT Education and Outreach program and for allocated lab expenses. We request support for miscellaneous materials and services. We request $10,000 to pay technician's fees at Lincoln Laboratory for antenna test; this is much less than the operating cost of the facility so this activity is highly leveraged.

NSF request: $348,100

I. Indirect Costs

Indirect costs are applied according to standard MIT rates.

NSF request $1,527,857

Current and Pending Support - ABRAHAM LOEB
Harvard University

PI Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

<u>Current</u>
Title: Mileura Wide-Field Array
Sponsor/Award #: Foundational Questions Institute (FQXi)/RFP1-06-22
Award Amount: $47,370
Period of Performance: 9/1/06-8/31/07
PI Months/Year: 1 (summer)

Title: Gamma-Ray Bursts from the First Stars
Sponsor/Award #: NASA/NNX07AJ63G
Award Amount: $44,746
Period of Performance: 5/1/07-4/30/08
PI Months/Year: 0.75 (summer)

Title: Forecast the Future of the Local Group of Galaxies
Sponsor/Award #: FQXi /MGA-07-009
Award Amount: $6,000
Period of Performance: 7/1/07-6/30/08
PI Months/Year: 0

Title: Dynamical Detection and Migration of Multiple-Body Planetary Systems
Sponsor/Award #: JPL/1301914
Award Amount: $289,350
Period of Performance: 7/18/07-9/30/10
PI Month/Year: 0 (Michelson Fellowship for D. Fabrycky)

Title: Probing the End of the Dark Ages and the Epoch of Reionization with the 21cm Line
Sponsor/Award #: StScI/HF-01211.01-A
Award Amount: $115,557
Period of Performance: 9/1/07-8/31/10
PI Month/Year: 0 (Hubble Fellowship for J. Pritchard)

Current and Pending Support - ABRAHAM LOEB

Pending

Title: Simulating the Physics of Feedback Processes in Galaxies
Sponsor/Proposal #: NSF/0805816
Amount: $496,350
Period of Performance: 7/1/08-6/30/11
PI Month/Year: 1 (summer)

Title: Simulating the Physics of Feedback Processes in Galaxies
Sponsor/Proposal #: NASA/07-ATFP07-0004
Amount: $332,130
Period of Performance: 1/1/08-12/31/09
PI Month/Year: 1 (summer)

Title: Testing Accretion Physics and Strong Gravity by Imaging Accreting Black Holes
Sponsor/Proposal #: NASA/07-ATFP07-0013
Amount: $342,130
Period of Performance: 1/1/08-12/31/09
PI Months/Year: 2 (summer)

Title: Gamma Ray Bursts from the First Stars
Sponsor/Proposal #: University of Texas (NASA Prime)/07-ATFP07-0137 (NASA)
Sub Amount: $153,751
Period of Performance: 7/1/08-6/30/10
PI Month/Year: 1 (summer)

Title: Toward a Dark Ages Lunar Observatory
Sponsor/Proposal #: MIT (NASA Prime)/07-LASER07-0137 (NASA)
Sub Amount: $126,990
Period of Performance: 5/1/08-4/30/11
PI Months/Year: 1 (summer)

<u>Pending (Cont'd)</u>

Title: A Lunar Array for Radio Cosmology: Reionization, the Dark Ages, and More
Sponsor/Proposal #: MIT (NASA Prime)/07-ASMCS07-0005 (NASA)
Sub Amount: $40,751
Period of Performance: 4/1/08-3/31/08
PI Month/Year: 0.5 (summer)

Title: Baryonic Acoustic Oscillations in 21cm Emission: A Precise Probe of Dark Energy Out to High Redshifts
Sponsor/Proposal #: DOE/ER08-06-27408-46624-33987
Total Amount: $158,572
Period of Performance: 7/1/08-6/30/09
PI Months/Year: 2 (summer)

Title: Modeling the Power Spectrum of Galaxies in High-Redshift Surveys (Co-I)
Sponsor/Proposal #: NASA/07ATFP07-0136
Co-I Amount: $29,655
Period of Performance: 7/1/08-6/30/11
Co-I Months/Year: 0.5 (summer)

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
PI Months/Year: 0

Current and Pending Support - CHARLES ALCOCK
Harvard University

Co-I Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current Support

Title	Sponsor	Sponsor Number	Award	Dates	Months /Year
New Methods in Data Mining for Time-Domain Astronomy	NASA	NNX07AV75G	125,000	9/1/07-8/31/08	0.1 cal
Collaborative Research: SEI: Discovering Unexpected Planets and Other Astronomical Oddities	NSF	IIS-0713273	182,632	9/15/07-8/31/10	0
Studies of Solar System Planetesimals and Extra-Solar Planets: Occultations and Transits Enabled by Novel Fast CCD Cameras	NSF	AST-0501681	397,063	10/1/04-9/30/08	0
Multi-Object High Speed Spectro-Photometer Technology Demonstration Program	NASA-GSFC	NNG05GA28G	728,297	10/1/04-9/30/08	0.1 cal
The Bizarre Young Supernova Remnant G350.1-0.3	NASA-GSFC	NNX06AH60G	45,947	9/18/06-9/17/08	0.1 cal
Detection of Very Small Kuiper Belt Objects with Taiwanese-American Occultation Society	NASA-OSSP	NNG04G113G	226,000	9/1/05-8/31/08	0.1 cal
Galaxy Assembly in a Hierarchical Universe	Keck Found.		1,400,000	8/1/06-7/30/10	0.1 cal
A new Magnetar in a Young Supernova Remnant	SAO	GO7-8002X	24,265	8/7/06-9/30/08	0.1 cal

Current Support (Cont'd)

Title	Sponsor	Sponsor Number	Award	Dates	Months /Year
In a Spin: The Origin and Fate of Neutron Star Rotation	NASA	NAG5-13032	484,997	5/1/03-4/30/08	0.1 cal
Probing the X-ray Emission from Dueling Magnetospheres	SAO/ CHANDRA	GO5-6046X	38,278	3/2/06-3/1/08	0.5 sum
Binary Lenses: The Power of Two (Co-I)	NSF	AST-0708924	365,234	7/1/07-6/30/10	0

Pending Support

Accurate Estimates of the Intrinsic Abundances of Different TNO Populations with Pan-STARRS-1	NSF	AAG 05-608	461,361	7/1/08-6/30/11	0
Employing the Power of Lensing in the Solar Neighborhood	NSF	AAG 05-608	367,748	7/1/08-6/30/11	0
Spectroscopic Investigations of Exotic Carbon, Silicon, and Sulfur Molecules	NSF		455,000	10/1/07-9/30/10	0
Precision High-Speed Crowded-Field Image Analysis in Space (Co-I)	NASA		752,239	9/1/07-8/31/10	0.1 cal
Surveying the Outer Solar System by Stellar Occultations with the Taiwanese-American Occultation Survey and the Multiple Mirror Telescope	NASA		401,441	10/1/07-9/30/10	0.1 cal
This Proposal: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation	NSF	07-567	4,995,979	8/01/08-7/31/13	0

Current and Pending Support - LARS HERNQUIST
Harvard University

Co-I Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current

Title: Probing the End of the Dark Ages (Co-I)
Sponsor: NASA
Sponsor Award #: NNG05GJ40G
PI: Zaldarriaga
Award Amount: $442,757
Period of Performance: 7/1/05-6/30/08
Co-I Months/Year: 1 (summer)

Title: Theoretical Studies of Fluctuations in the Redshifted 21cm Line (Co-I)
Sponsor: NSF
Sponsor Award #: AST-0506556
PI: Zaldarriaga
Award Amount: $375,880
Period of Performance: 7/15/05-6/30/08
Co-I Months/Year: 1 (summer)

Pending

Title: Simulating the Physics of Feedback Processes in Galaxies (Co-I)
Sponsor: NSF
Proposal #: 0805816
PI: Loeb
Amount: $496,350
Period of Performance: 7/1/08-6/30/11
Co-I Months/Year: 1 (summer)

Current and Pending Support - LARS HERNQUIST
2/2

Title: Simulating the Physics of Feedback Processes in Galaxies (Co-I)
Sponsor/Proposal #: NASA/07-ATFP07-0004
PI: Loeb
Amount: $332,130
Period of Performance: 1/1/08-12/31/09
Co-I Months/Year: 1 (summer)

Title: Theoretical Studies of Fluctuations in the Red-shifted 21cm Line (Co-I)
Sponsor: NSF
Proposal #: 0805866
PI: Zaldarriaga
Amount: $570,220
Period of Performance: 7/1/08-6/30/11
Co-I Months/Year: 1 (summer)

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support -- CHRISTOPHER STUBBS
Harvard University

Co-I Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current

DOE Research in High Energy Physics: Dark Energy Science
Source: DOE
Award: $303,819
Period: 11/01/05 - 10/31/07
Person-Months Committed: 1 (summer)

Collaborative Research: Coordinated Survey to Study the Nature of the Dark Energy
Source: NSF
Award: $25,000
Period: 07/15/05-06/30/09
Person-Months Committed: 0

LSST - Calibration of Atmospheric Transmission and Instrumental Sensitivity
Source: Research Corporation
Award: $316,000
Period: 11/01/05-10/31/08
Person-Months Committed: 0.5 (summer)

ESSENCE II: Probing the Equation of State of the Dark Energy with Supernovae
Source: NSF
Award: $1,881,654
Period: 10/01/05-09/30/08
Person-Months Committed: 0

Current and Pending Support -- CHRISTOPHER STUBBS

Testing the Preposterous Universe
Source: JPL
Award: $41,505
Period: 03/30/06-06/30/08
Person-Months Committed: 0.5

LMC Microlensing Puzzle
Source: STScI
Award: $32,665
Period: 09/01/07-08/31/09
Person-Months Committed: 0

REU: Collaborative Research: Coordinated Survey to Study the Nature of the Dark Energy
Source: NSF
Award: $5,000
Period: 07/15/05-06/30/09
Person-Months Committed: 0

A Comprehensive Probe of Gravity via Lunar Laser Ranging
Source: UCAL, San Diego - NSF prime
Requested: $137,289
Period: 03/1/07-02/28/2010
Person-Months Committed: 0

A Mid-infrared study of Hickson Compact Groups: Probing the Effect of Environment in Galaxy Interactions
Source: JPL
Award: $5,000
Period: 07/01/07-06/30/10
Person-Months Committed: 0

Current and Pending Support -- CHRISTOPHER STUBBS

Developing the Optimal Technique for Cluster Photometric Redshift Determination: an Essential Ingredient in Measuring Dark Energy with Cluster Abundances
Source: DOE
Award: $50,000
Period: 06/1/2007-05/31/2008
Person-Months Committed: 0

Pending:

Collaborative Research: Cosmology from Precision Photometry of Supernovae
Source: University of Hawaii
Prime: NSF
Requested: $172,411
Period: 06/01/2008-05/31/11
Person-Months Committed: 0

Attaining the Photometric Precision Required by Future Dark Energy Projects
Source: DOE
Requested: $368,773
Period: 06/01/2008-05/31/09
Person-Months Committed: 0

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support - MATIAS ZALDARRIAGA
Harvard University

Co-I Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current

Title: Packard Fellowship
Sponsor: David & Lucile Packard Foundation
Sponsor Award #: 2001-19070A
Award Amount: $610,459
Period of Performance: 03/03/03-09/30/08
PI Months/Year: 1 (summer)

Title: Probing the End of the Dark Ages
Source: NASA
Sponsor Award #: NNG05GJ40G
Award Amount: $442,757
Period of Performance: 07/01/05-06/30/08
PI Months/Year: 1 (summer)

Title: Theoretical Studies of Fluctuations in the Redshifted 21cm Line
Sponsor: NSF
Sponsor Award #: AST-0506556
Award Amount: $375,880
Period of Performance: 07/15/05-06/30/08
PI Months/Year: 1 (summer)

Pending

Title: Theoretical Studies of Fluctuations in the Redshifted 21cm Line
Sponsor: NSF
Proposal #: 0805866
Amount: $570,220
Period of Performance: 07/01/08-06/30/11
PI Months/Year: 1 (summer)

Current and Pending Support - MATIAS ZALDARRIAGA
2/2

Title: A Lunar Array for Radio Cosmology: Reionization, the Dark Ages, and More (Co-I)
Sponsor: MIT (NASA prime)
Proposal #: 07-ASMCS07-0005
PI: Loeb
Sub Amount: $40,751
Period of Performance: 04/01/08-03/31/09
PI Months/Year: 1/2 (summer)

Title: A Study for a CMB Probe of Inflation
Sponsor: U Chicago (NASA prime)
Proposal #: 07-ASMCS07-012
Sub Amount: $78,714
Period of Performance: 02/01/08-01/31/09
PI Months/Year: 1 (summer)

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support - ALEXANDER DALGARNO
Harvard University

PI Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current Support

Theoretical Investigations of Atomic Collision Physics
Agency: DOE
Award Amount: $374,018
Period of Performance: 4/1/2006 - 3/31/2009
Months/Year: 0

Basic Ionization, Airglow and Auroral Processes
Agency: NSF
Award Amount: $420,000
Period of Performance: 12/1/2004 - 11/30/2008
Months/Year: 0

Collaborative Research: Bringing Primordial Microphysics out of the Dark Ages: Advanced Chemistry and Cooling Calculations for First Star Formation and Evolution
Agency: NSF/UNLV
Award Amount: $105,805
Period of Performance: 8/1/2006 - 7/31/2009
Months/Year: 0

Pending Support

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Senior Investigator Months/Year: 0

Current and Pending Support - DOUGLAS FINKBEINER
Harvard University

Senior Investigator Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current

Title: Exploring the ISM with WMAP: the microwave emission from spinning dust
Sponsor/Program: NASA/LTSA Junior Researcher
Award #: NNX07AH86G
Period: 2/27/07-2/26/09
Amount: $74,764
PI Months/Year: 2 (summer)

Pending

Title: Astrophysical Consequences of WIMPS with an Excited State
Sponsor/Program: DOE Outstanding Junior Investigator Program
Period: 7/1/08-6/30/13
Amount: $414,410
PI Months/Year: 1 (summer)

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support - ROY GOULD
Smithsonian Astrophysical Observatory

Current
Title: NASA Education Forum at SAO on the Structure and Evolution of the Universe
Sponsor/Award #: National Aeronautics and Space Administration-NCC5-706
Award Amount: $8,350,000
Period of Performance: 9/15/03-9/14/08
PI Months/Year: 1 calendar

Title: Exploring Frontiers of Science with Online Telescopes
Sponsor/Award #: National Science Foundation - NSF- 0733252
Award Amount: $1,191,143
Period of Performance: 9/15/07–8/31/10
PI Months/Year: 6 calendar

Title: Black Hole Experiment Gallery
Sponsor/Award #: National Science Foundation - 0638963
Award Amount: $1,664,884
Period of Performance: 7/1/07-6/30/08
PI Months/Year: 4 calendar

Pending
This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08-7/31/13
Amount: $4,995,979
Senior Inv. Months/Year: 1.2 calendar

Current and Pending Support - LINCOLN GREENHILL
Harvard University

Grant: AST-0457585
Agency: NSF
Title: Mileura Wide-Field Array Science and Technology Demonstrator
PI: Lonsdale; coPI: Greenhill
Period of Performance: 06/1/06 - 05/31/10
Award: $613,097 (total: $4,898,882)
Months/Year: 2.4

Grant: G07-8117B
Agency: NASA
Title: The Definitive Chandra Observations of NGC4258
PI: Nowak, coPI: Greenhill
Period of Performance: 10/11/07 – 10/10/09
Award: $48,286
Months/Year: 0.6

Grant: AST-0507478
Agency: NSF
Title: What Does High Mass Star Formation "Look" Like? Movies of Accretion and Outflow 10-1000 AU from a Massive YSO
PI: Humphreys, coPI: Greenhill
Period of Performance: 10/1/05 – 09/30/08
Award: $532,294
Months/Year: 1.2

Grant: NNG05GK24G
Agency: NASA
Title: Masers as Beacons of Compton Thick AGN-Implications for X-ray Background Studies
PI: Greenhill
Period of Performance: 05/15/05 - 05/14/07
Award: $75,911
Months/Year: 0.6

Current and Pending Support - LINCOLN GREENHILL
2/3

Grant: GO-10399.01-A
Agency: NASA
Title: Accurate and Robust Calibration of the Extragalactic Distance Scale with the Maser Galaxy NGC4258 II
PI: Greenhill
Period of Performance: 03/01/05 - 02/28/07
Award: $69,892 (total: $184,130)
Months/Year: 2.4

Grant: HRD- 0726032
Agency: NSF
Title: RDE-FRI: The Effects of Dyslexia on Scientists' Analysis of Astrophysical Data
PI: Schneps, coPI: Greenhill
Period of Performance: 09/01/07 – 01/31/09
Award: $299,999
Months/Year: 1.2

Pending Support

Proposal: CCF-815314
Agency: NSF
Title: CDI Type II: Scientific Computation for Astronomy, Neurobiology and Chemistry using Graphics Processing Units and Solid-State Storage
PI: Pfister, coPI: Greenhill
Period of Performance: TBD
Award: $2,139,091

Proposal: AST-807877
Agency: NSF
Title: Maser GEODESIC - Maser Geometric Distance Estimation to Seyferts and Inference for Cosmology
PI: Humphreys coI: Greenhill
Period of Performance: 10/01/08 – 09/30/09
Award: $211,146

Current and Pending Support - LINCOLN GREENHILL
3/3

Proposal: AST-807877
Agency: NSF
Title: Constraint on Dark Energy through Measurement of Maser Distances and H0
PI: Alcock coPI: Greenhill
Period of Performance: TBD
Award: $680,429

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support - KATE KIRBY
Harvard University

Senior Investigator Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current Support

Institute for Theoretical Atomic Molecular and Optical Physics (ITAMP) Grants from the National Science Foundation (NSF)

Grant: PHY-0140320
Project Title: *The Institute for Theoretical Atomic, Molecular and Optical Physics*
Awardee: Smithsonian Astrophysical Observatory
Amount of Award: $2,497,303
Period of Performance: 1 April 2002 – 31 March 2008
Person-months: 0

Grant: PHY-0653021
Project Title: *The Institute for Theoretical Atomic, Molecular and Optical Physics*
Awardee: Smithsonian Astrophysical Observatory
Amount of Award: $195,257 (first year funding only) [full proposal = $1,419,463]
Period of Performance: 1 June 2007 – 31 May 2011
Person-months: 0

Sponsoring Agency: National Science Foundation
Grant: PHY-0140217
Project Title: *The Institute for Theoretical Atomic, Molecular and Optical Physics*
Awardee: Harvard University
Amount of Award: $1,063,980
Period of Performance: 1 May 2002 – 30 April 2008
Person-months: 0

Current and Pending Support - KATE KIRBY
Page 2/2

Sponsoring Agency: National Science Foundation
Grant: PHY-0653575
Project Title: *The Institute for Theoretical Atomic, Molecular and Optical Physics*
Awardee: Harvard University
Amount of Award: $304,744 (first year funding only) [full proposal = $1,330,537]
Period of Performance: 1 June 2007 – 31 May 2011
Person-months: 0

Pending Support

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support - RAMESH NARAYAN
Harvard University

Senior Investigator Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current

None

Pending (approved for funding)

Sponsor: NASA
Proposal #: 07-ATFP07-0009
Title: Measuring Black Hole Spin: Physics of the Inner Region of an Accretion Disk
Period: 1/1/08-12/31/09
Amount: $183,816
PI Months/Year: 0

Pending

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support - GEORGE RYBICKI
Harvard University

Senior Investigator Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current

None

Pending

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support - HOSSEIN SADEGHPOUR
Smithsonian Astrophysical Observatory

Current

Title: U.S.-Japan Seminar: Field Effects in Cold Atomic and Molecular Reactions
Sponsor/Program: NSF
Award #: 0729562
Period: 9/06/07-9/06/09
Amount: $40,000
PI Months/Year: 0.6 calendar

Title: The Institute for Theoretical Atomic, Molecular and Optical Physics (one of six PIs and Co-Is)
Sponsor/Program: NSF
Award #: 065302
Period: 4/01/07-3/31/11
Amount: ~$2,600,000
PI Months/Year: 6.0 calendar

Pending

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0.1 calendar

Current and Pending Support - IRWIN SHAPIRO
Harvard University

Senior Investigator Time Commitment: The full academic year salaries of members of the Faculty of Arts and Sciences are paid by the University with the understanding that they will ordinarily teach and conduct research freely and flexibly and not make substantial, specific quantified commitments of time and effort to specific organized research projects.

Current
None

Pending
Title: Portable Data Analysis Software for Solar System Dynamics
Sponsor: NASA
Period: 1/1/07-12/31/07
Amount: $75,000
PI Months/Year: 0

Title: Testing the Equivalence Principle via an Einstein Elevator Experiment
Sponsor: NSF
Period: 7/1/08-6/30/11
Amount: $2,212,414
PI Months/Year: 0

Title: Earth Impact! A Large Format Film
Sponsor: NSF
Period: 7/1/08-6/30/11
Amount: $3,000,000
PI Months/Year: 0

This Proposal:
Sponsor: NSF
Solicitation: 07-567 Physics Frontiers Centers (PFC)
Title: Collaborative Research: 21cm Imaging of the Dark Ages: Probing Inflation and the Dark Matter before Galaxy Formation
Period of Performance: 8/01/08 - 7/31/13
Amount: $4,995,979
Person-months/year: 0

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Jacqueline Hewitt

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF
Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Mileura Wide-Field array Science and Technology Demonstrator

Source of Support: NEROC (Prime: NSF)
Total Award Amount: $ 2,151,194 Total Award Period Covered: 06/01/06 - 05/31/10
Location of Project: MIT/Haystack
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Toward a Dark Ages Lunar Observatory

Source of Support: NASA
Total Award Amount: $ 589,030 Total Award Period Covered: 05/01/08 - 04/30/11
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: A Lunar Array for Radio Cosmology: Reionization, the Dark Ages, and More

Source of Support: NASA
Total Award Amount: $ 701,932 Total Award Period Covered: 04/01/08 - 03/31/09
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: MRI: Acquisition of an Archive for the Murchison Widefield Array

Source of Support: NSF
Total Award Amount: $ 425,366 Total Award Period Covered: 09/01/08 - 08/31/11
Location of Project: MIT/NEROC
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Summ: 0.00

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Other agencies (including NSF) to which this proposal has been/will be submitted.

Investigator: Angelica de Oliveira-Costa

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF
Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:4.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: CMB and 21 cm Cosmology in the Presence of Foregrounds

Source of Support: NSF
Total Award Amount: $ 437,789 Total Award Period Covered: 06/01/06 - 05/31/09
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:11.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

Colin J. Lonsdale
Current & Pending Support

Current

Title:	**Mileura Wide-Field Array Science and Technology Demonstrator**
Sponsor:	NEROC (NSF Prime) (multi PI award)
Location:	Massachusetts Institute of Technology
Dates:	06/01/2006 - 05/31/2010
Amount:	$4,898,882
Person Months:	4.25 Person Months

Title:	**DURIP: Augmentation of the Mileura Widefield Array for Solar and Space Weather Applications**
Sponsor:	Air Force Office of Scientific Research
Location:	Massachusetts Institute of Technology
Dates:	06/01/2006 - 05/31/2008
Amount:	$284,635
Person Months:	0 Person Month

Title:	**Advanced Correlation Techniques for Next Generation Radio Arrays**
Sponsor:	NEROC (Prime: NSF)
Location:	Massachusetts Institute of Technology
Dates:	06/01/2006 - 05/31/2009
Amount:	$400,000
Person Months:	0.67 Person Month

Title:	**A Technology Development Project for the Large-N / Small-D Square Kilometer Array Concept**
Sponsor:	Cornell University (Prime: NSF)
Location:	Massachusetts Institute of Technology
Dates:	11/01/2007 - 10/31/2011
Amount:	$394,000
Person Months:	1 Person Month

Pending

Title:	**Collaborative Research PFC: Fundamental Physics from 21cm Cosmology (this proposal)**
Sponsor:	NSF (PI: Hewitt)
Location:	Massachusetts Institute of Technology
Dates:	07/01/2008 - 06/30/2013
Amount:	$4,999,995
Person Months:	2.8 Person Months

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Max Tegmark

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF
Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: David and Lucille Packard Foundation Fellowship Grant

Source of Support: David and Lucille Packard Foundation
Total Award Amount: $ 301,274 Total Award Period Covered: 09/01/04 - 11/30/08
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: CMB and 21 cm Cosmology in the Presence of Foregrounds (PI: de Oliveira-Costa)

Source of Support: NSF
Total Award Amount: $ 437,789 Total Award Period Covered: 06/01/06 - 05/31/09
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: CAREER: Beyond Cosmological Parameters

Source of Support: NSF
Total Award Amount: $ 251,088 Total Award Period Covered: 09/01/05 - 08/31/08
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 1.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Precision cosmology with galaxies, CMB and 21 cm tomography

Source of Support: NSF
Total Award Amount: $ 386,037 Total Award Period Covered: 09/01/07 - 08/31/10
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Summ: 1.00

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Max Tegmark

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Beyond Cosmological Parameters

Source of Support: Research Corporation
Total Award Amount: $ 8,826 Total Award Period Covered: 10/01/06 - 06/30/08
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: FQX Release Time Grant

Source of Support: John Templeton Foundation
Total Award Amount: $ 40,000 Total Award Period Covered: 03/14/06 - 12/31/09
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Edmund Bertschinger

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: New Tests for Dark Energy and Modified Gravity

Source of Support: NSF
Total Award Amount: $ 321,171 Total Award Period Covered: 09/01/07 - 08/31/10
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Indirect and direct Detection of Dark Matter

Source of Support: NASA
Total Award Amount: $ 274,643 Total Award Period Covered: 06/01/06 - 05/31/09
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF
Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Bernard Burke

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF
Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title: Astrometric Search for Exoplanets

Source of Support: NSF
Total Award Amount: $ 280,863 Total Award Period Covered: 07/01/05 - 06/30/08
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support
Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Alan Guth

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Theoretical Physics portion of the Laboratory for Nuclear Science (PI: Edward Farhi)

Source of Support: DOE

Total Award Amount: $ 4,740,000 Total Award Period Covered: 11/01/07 - 10/31/10

Location of Project: MIT

Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 2.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: A Meteorological "Slow Manifold" for Coherent Structures in the Early Universe (PI: J. Tribbia)

Source of Support: NSF

Total Award Amount: $ 422,143 Total Award Period Covered: 06/01/08 - 05/31/11

Location of Project: The University Corporation for Atmospheric Research

Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF

Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13

Location of Project: NSF

Person-Months Per Year Committed to the Project. Cal: 0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

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*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Irene Porro

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF

Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13

Location of Project: MIT

Person-Months Per Year Committed to the Project. Cal:2.50 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Community Science Learning through Youth Astronomy Appreticeships (YAA)

Source of Support: NSF

Total Award Amount: $ 2,208,077 Total Award Period Covered: 10/01/06 - 09/30/10

Location of Project: MIT

Person-Months Per Year Committed to the Project. Cal:6.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Kids Question the Cosmos (PI: Chakrabarty)

Source of Support: SAO

Total Award Amount: $ 49,930 Total Award Period Covered: 03/26/07 - 05/28/09

Location of Project: MIT

Person-Months Per Year Committed to the Project. Cal:3.00 Acad: 0.00 Sumr: 0.00

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Monitoring Faint X-ray Transients in the Galactic Center (PI: Baganoff)

Source of Support: SAO

Total Award Amount: $ 50,000 Total Award Period Covered: 02/11/07 - 03/25/09

Location of Project: MIT

Person-Months Per Year Committed to the Project. Cal:3.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Argos-X: A Panoptic X-ray Observatory (PI: Remillard)

Source of Support: NASA

Total Award Amount: $ 72,271,492 Total Award Period Covered: 06/01/08 - 06/30/17

Location of Project: MIT

Person-Months Per Year Committed to the Project. Cal:1.00 Acad: 0.00 Summ: 0.00

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

 USE ADDITIONAL SHEETS AS NECESSARY

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Irene Porro

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Chandra Astrophysics Institute (PI: Baganoff)

Source of Support: SAO

Total Award Amount: $ 49,995 Total Award Period Covered: 01/01/08 - 12/31/09

Location of Project: MIT

Person-Months Per Year Committed to the Project. Cal:0.50 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:

Total Award Amount: $ Total Award Period Covered:

Location of Project:

Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

Current & Pending Support
Alan E. Rogers

Current

Title:	**Science and Technology through Radio Astronomy Experimentation for Community Colleges**
Sponsor:	NSF
Amount:	$199,000
Period:	06/01/2006 - 05/31/2008
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	1 Calendar Month

Title:	**Development of a Wideband Digital Spectrometer for the Upgraded Haystack Telescope**
Sponsor:	NEROC (Prime: NSF) (PI: A. Whitney)
Amount:	$372,924
Period:	07/15/2006 - 06/30/2008
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	0.5 Calendar Month

Title:	**Development of Wideband Burst Mode Data Recorder for Radio Astronomy**
Sponsor:	NEROC (Prime: NSF) (PI: A. Whitney)
Amount:	$540,334
Period:	06/15/2007 - 05/31/2010
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	0 Calendar Month

Title:	**Development of a Flexible Wideband Digital Backend for Radio Interferometry**
Sponsor:	NEROC (Prime: NSF) (PI: A. Whitney)
Amount:	$639,262
Period:	04/15/2006 - 03/31/2009
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	0.5 Calendar Month

Title:	**MRI Development of a Cooled Sapphire Oscillator Frequency Standard for VLBI**
Sponsor:	NEROC (Prime: NSF) (PI: A. Whitney)
Amount:	$459,568
Period:	08/01/2007 - 07/31/2010
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	0.75 Calendar Month

Pending

Title:	**High Sensitivity VLBI Arrays: Imaging the Event Horizon**
Sponsor:	NSF (PI: A. Whitney)
Amount:	$2,300,000

Period:	04/01/2008 - 03/31/2012
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	0 Calendar Month

Title:	**A Direct Constraint on the Duration of the Cosmological Reionization**
Sponsor:	California Institute of Technology (Prime: NSF)
Amount:	$67,930
Period:	06/01/2008 - 05/31/2010
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	0 Calendar Month

Title:	**Techniques of Submm-VLBI: Observing an Event Horizon**
Sponsor:	NSF (PI: S. Doeleman)
Amount:	$335,400
Period:	07/01/2008 - 06/30/2011
Location of Project:	Massachusetts Institute of Technology, Westford, MA
Person Months:	0 Calendar Month

Title:	**Collaborative Research PFC: Fundamental Physics from 21cm Cosmology (this proposal)**
Sponsor:	NSF (PI: Hewitt)
Location:	Massachusetts Institute of Technology
Dates:	07/01/2008 - 06/30/2013
Amount:	$4,999,995
Person Months:	0 Person Month

Current and Pending Support

(See GPG Section II.C.2.h for guidance on information to include on this form.)

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Frank Wilczek

Other agencies (including NSF) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Theoretical Physics portion of the Laboratory for Nuclear Science (PI: Edward Farhi)

Source of Support: DOE
Total Award Amount: $ 4,740,000 Total Award Period Covered: 11/01/07 - 10/31/10
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 2.00

Support: ☐ Current ☒ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title: Collaborative Research: Fundamental Physics from 21cm Cosmology (this proposal; PI: Hewitt)

Source of Support: NSF
Total Award Amount: $ 4,999,998 Total Award Period Covered: 08/01/08 - 07/31/13
Location of Project: MIT
Person-Months Per Year Committed to the Project. Cal:0.00 Acad: 0.00 Sumr: 0.00

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Sumr:

Support: ☐ Current ☐ Pending ☐ Submission Planned in Near Future ☐ *Transfer of Support

Project/Proposal Title:

Source of Support:
Total Award Amount: $ Total Award Period Covered:
Location of Project:
Person-Months Per Year Committed to the Project. Cal: Acad: Summ:

*If this project has previously been funded by another agency, please list and furnish information for immediately preceding funding period.

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory:

Clinical:

Animal:

Computer:

Office: Harvard Office space will be provided for all faculty and their postdocs and students; as well as for the visitor and internship programs budgeted in the proposal. Harvard will also provide infrastructure as needed for workshops and meetings.

Other:

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

Harvard University is providing seed funds to support the Institute for Theory and Computation (ITC) in which much of the theoretical work on 21cm cosmology was done over the past five years. All Harvard affiliated co-Is are members of the ITC. The proposed data analysis and cosmological simulations will be performed in the ITC high-performance computational facility. and will enable us to carry out the proposed work. In particular, we have recently acquired a 4096 processor IBM BlueGene.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

FACILITIES, EQUIPMENT & OTHER RESOURCES

Continuation Page:

MAJOR EQUIPMENT (continued):

Moreover, in the coming months, we will acquire a new Beowulf cluster that will be dedicated to research in numerical cosmology. This machine will likely consist of roughly 1000 processors and have a total memory of several Tbytes. The IBM BlueGene and the new cluster will be essential for the numerical simulations and data analyses described in MA2 and MA3.

FACILITIES, EQUIPMENT & OTHER RESOURCES

FACILITIES: Identify the facilities to be used at each performance site listed and, as appropriate, indicate their capacities, pertinent capabilities, relative proximity, and extent of availability to the project. Use "Other" to describe the facilities at any other performance sites listed and at sites for field studies. USE additional pages as necessary.

Laboratory: For MA4.2 and MA5, the MIT Kavli Institute (MKI) will provide laboratory space on campus, technical support, and laboratory instruments for testing antennas. MIT's Lincoln Laboratory (LL) will make available anechoic chambers for antenna testing. We have budgeted for the technician time

Clinical: N/A

Animal: N/A

Computer: For MA4.1, the MKI will supply laboratory space on campus, cooling and electrical capacity for the 200-Tbyte archive. The MKI 100Mbit/second connection to the internet will be used to transfer the data, limiting the data rate to 10Mbit/second to prevent interference with other activities.

Office: MKI will provide office space on campus to all participants.

Other:

MAJOR EQUIPMENT: List the most important items available for this project and, as appropriate identifying the location and pertinent capabilities of each.

If field testing of the antennas is necessary, we will carry out these measurements at the Murchison Widefield Array (MWA) site, making use of existing MWA infrastructure.

OTHER RESOURCES: Provide any information describing the other resources available for the project. Identify support services such as consultant, secretarial, machine shop, and electronics shop, and the extent to which they will be available for the project. Include an explanation of any consortium/contractual arrangements with other organizations.

MKI has a small machine shop which will be made available for construction of antenna prototypes. MKI has on staff electronics technicians for populating and testing boards; the support needed has been budgeted.

FACILITIES, EQUIPMENT & OTHER RESOURCES

Continuation Page:

LABORATORY FACILITIES (continued):

needed to run the LL facility.

COMPUTER FACILITIES (continued):

PHONE 617.253.7501
FAX 617.253.3111
jhewitt@mit.edu

Massachusetts Institute of Technology
Kavli Institute for Astrophysics and Space Research
77 Massachusetts Avenue, Building 37-Room 241
Cambridge, Massachusetts 02139-4307

MKI

Office of the Director

January 21, 2008

To Whom It May Concern:

This letter confirms that I, as Director of the MIT Kavli Institute (MKI) for Astrophysics and Space Research, fully support MKI's involvement in the proposed Physics Frontier Center (PFC), "Fundamental Physics from 21cm Cosmology." MKI's computing and laboratory facilities will be made available to the PFC to carry out the activities described in the proposal. Financial management, project oversight and administrative support will also be provided. Office space has been been made available to all current participants and their students, and we will fully support the students and postdocs that we plan to hire. The resources of our office of Education and Outreach will also be made fully available to the PFC.

We at MKI are enthusiastic about the proposed PFC and look forward to our involvement in this forefront area of research.

Sincerely,

Jacqueline N. Hewitt
Director
Professor of Physics

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

244 WOOD STREET
LEXINGTON, MASSACHUSETTS 02420-9108

Area Code 781
981-1052

22 January 2008

Professor Jacqueline N. Hewitt
MIT Kavli Institute for Astrophysics and Space Research Room 37-241
77 Massachusetts Avenue
Cambridge, MA 02139

Dear Jackie:

I am writing to confirm that Lincoln Laboratory is pleased to collaborate with your group and others involved in the proposed Physics Frontier Center that has as its purpose "Fundamental Physics from 21cm Cosmology." We will provide you access to the Laboratory's anechoic chamber, and we will continue to work with you and your students in exploring low-frequency antenna design.

We look forward to our continued collaboration.

Sincerely,

Jeffrey S. Herd
Assistant Group Leader
MIT Lincoln Laboratory
Group 105, Advanced Sensing and Exploitation

Harvard-Smithsonian Center for Astrophysics
60 Garden Street, Cambridge, MA 02138-1516 (617) 495-7000
Charles Alcock, *Director*
Tel: (617) 495-7100 Fax: (617) 495-7105 calcock@cfa.harvard.edu

January 25, 2008

Dear NSF Physics Frontiers Centers (PFC) Review Committee,

The Harvard-Smithsonian Center for Astrophysics (CfA) is a joint facility of Harvard University and the Smithsonian Institution. The CfA combines the resources, staff, and research facilities of the Harvard College Observatory (HCO) and the Smithsonian Astrophysical Observatory (SAO).

Should this proposed Physics Frontiers Center be selected by NSF, the CfA will provide the resources and support necessary for the PFC team members to uphold their responsibilities as defined in this PFC proposal.

Sincerely,

Charles Alcock

Australia Telescope National Facility
PO Box 76
Epping, NSW 1710
Australia
Telephone: (02) 9372 4100 • Facsimile: (02) 9372 4310

CSIRO

Ref:

Professor Jacqueline Hewitt
Director, MIT Kavli Institute
for Astrophysics and Space Research
77 Massachusetts Avenue, 37-287
Cambridge, MA 02139

29 January 2008

Dear Professor Hewitt:

This letter serves as an expression of the firm commitment of the Australia Telescope National Facility (ATNF) to support the activities of the proposed Harvard-MIT Physics Frontier Center (PFC). The goal of the PFC is to study ways in which the capability of low-frequency radio arrays, currently focussed on studies of the first galaxy formation and the Epoch of Reionization, may be extended to enable studies of inflation and dark energy. A specific activity of the PFC will be research and development that might improve the performance of the Murchison Widefield Array (MWA) in its 80-300 MHz band, and possibly extend the MWA operating band down to 30 MHz.

As part of the research and development effort, MIT and Harvard will need to carry out tests of antenna elements in the field at the Murchison Radio Observatory (MRO) and monitor the RFI environment in the 30-100 MHz band. So that MIT and Harvard can carry out these tasks, ATNF will allow the PFC group access to the MRO site and its infrastructure.

We look forward to a continued productive collaboration with the MIT and Harvard groups.

Best regards.

David DeBoer
ATNF Assistant Director
ASKAP Project Director
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
HAYSTACK OBSERVATORY
WESTFORD, MASSACHUSETTS 01886

January 29, 2008

Telephone: 781-981-5407
Fax: 781-981-0590

Prof. Avi Loeb
Department of Astronomy
Harvard University
60 Garden St
Cambridge MA 02138

Dear Avi,

I am writing this letter in support of the proposed educational activities in your proposal. Haystack Observatory has a long-standing undergraduate education and research program – our REU program is currently in its 21st year. Haystack will be pleased to collaborate with the proposed "Center for 21cm Cosmology". As discussed, we will coordinate the summer intern program at the PFC and the existing REU program at Haystack Observatory. We will use the REU program to host students who will work specifically on PFC related projects and host students from the PFC to work at Haystack. We are very enthusiastic about the possibility of this Center being established, and the opportunities it would afford for both hands-on student education and enhanced interaction between Haystack Observatory and the groups in Cambridge.

We look forward to collaborating with you.

Thank you,

Alan R Whitney

Alan Whitney
Director, MIT Haystack Observatory