Becoming IRAC

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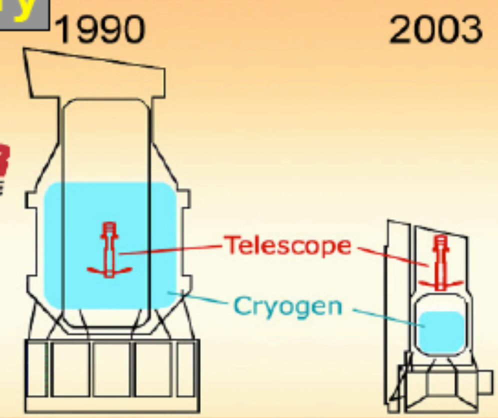
Lab for Observational Cosmology
NASA/GSFC

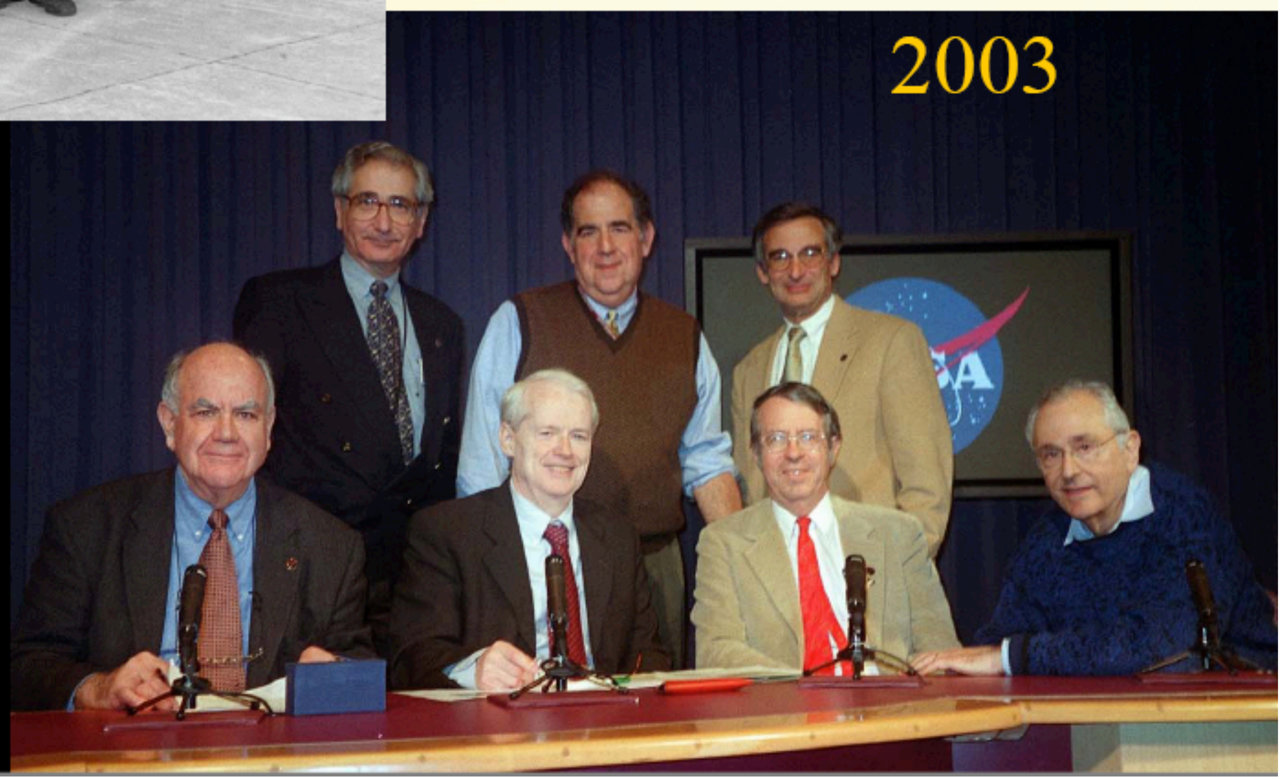
Spitzer – One Slide History

SPITZER SPACE TELESCOPE

DESIGN CHANGES



	COLD LAUNCH (1990)	WARM LAUNCH (2003)
Launch Mass	5700 kg	870 kg
Lifetime	5 years	5 years
Development Cost	~$2.2B	$0.67B
Launch Vehicle	Titan IV	Delta



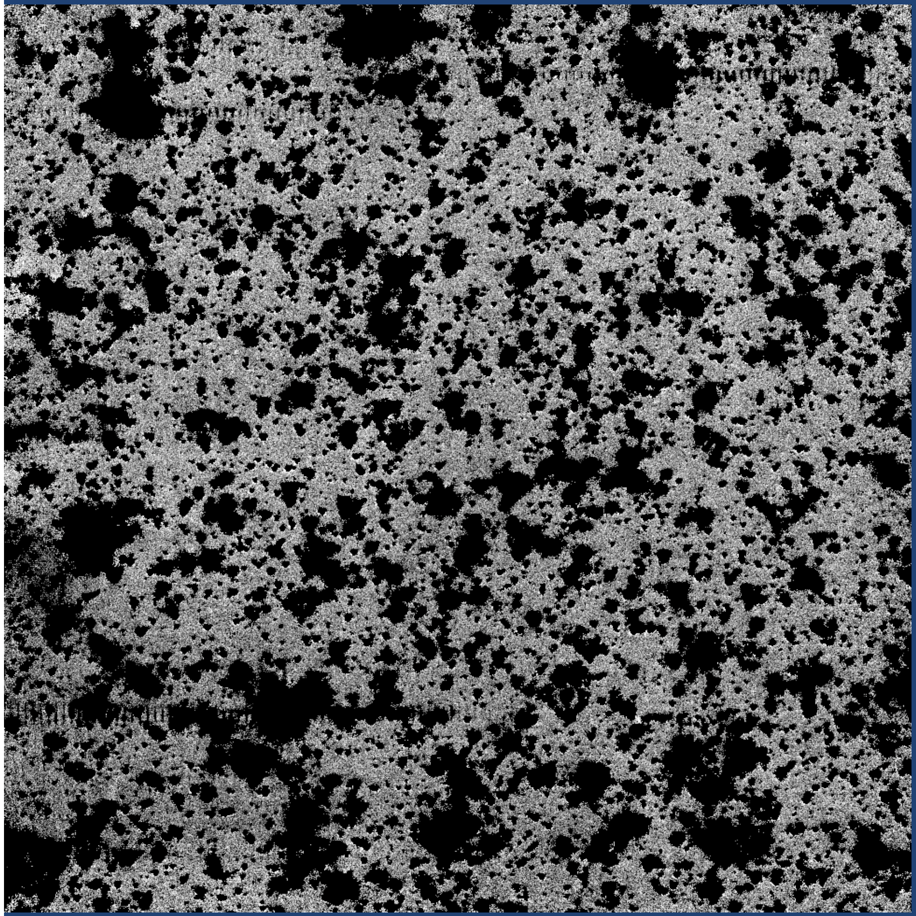
<u>Spitzer Science Team:</u>
Mike Werner, Frank Low, George Rieke, Jim Houck, Giovanni Fazio, Mike Jura, Ned Wright, *Tom Roellig, Marcia Rieke, Tom Soifer, Bob Gehrz, Dale Cruikshank, Charles Lawrence*

A Tale of Woe?

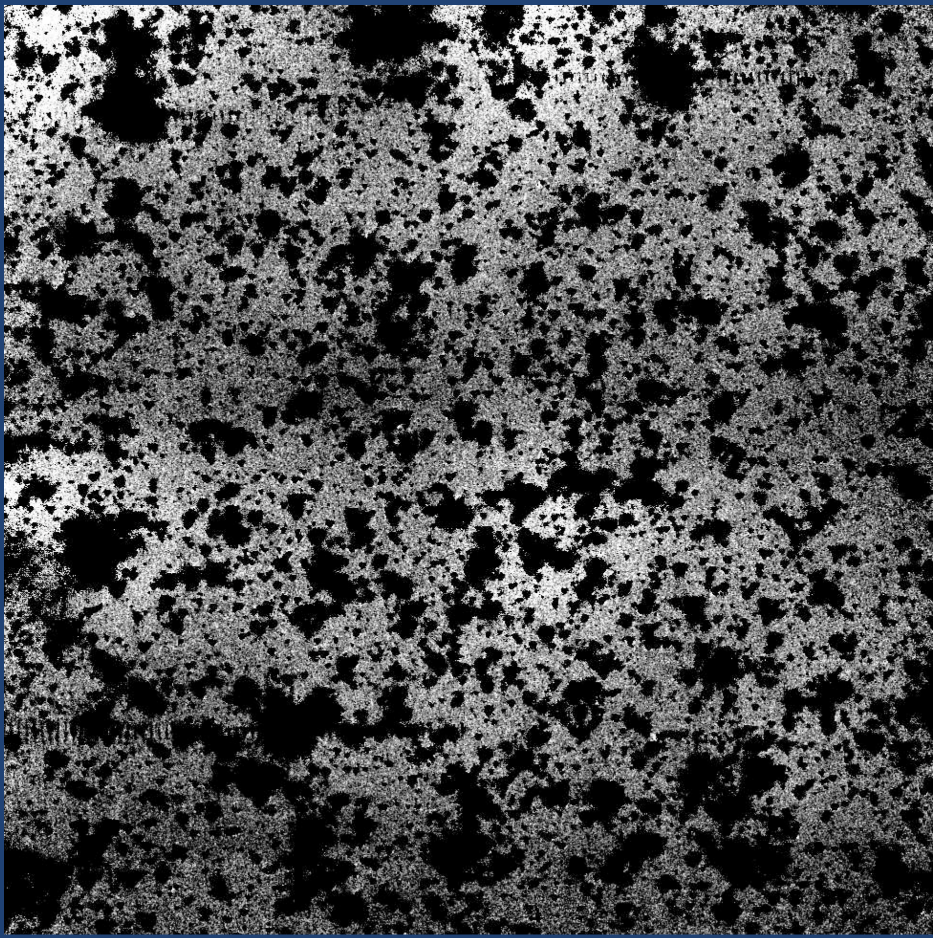
- Reading over the history of IRAC, it seems that it was continually beset by trouble
  - Project went on for a long time.
  - Competitor (ISO) launched earlier.
  - Spent a year in attempting to shoehorn IRAC into Astro-F
  - In fact, it was this history which allowed IRAC to become the spectacular tool it is.

Source-Masked CDFS 4.5μm/3.5μm

AKMM Processing



GOODS Processing



- IRAC has been a major tool for cosmology
  - Number counts, luminosity functions through time, spatial fluctuations
- Galactic astronomy
- These capabilities are far beyond what was envisioned when SIRTF (and IRAC) were originally conceived

IRAC Rev. 1

- IRAC was selected, along with the other instruments, in 1984.
  - IRAS was just launched Jan. '83
  - COBE was beginning development
  - KAO was flying
  - 32 x 32 detector arrays,with 1000 e read noise!
    - Integrating detectors showed promise, but not a lot had been demonstrated.
    - Photoconductors were revealing complex behavior under low light and radiation environments

Science Capability

- The IRAC science was broad:
  - Filter wheels, lots of filters
  - 3 bands, 1-5,5-15, 15-30
  - More defined by a set of capabilities than a focused science program
  - About the size of a large trash can.

Scientific and Technical Evolution

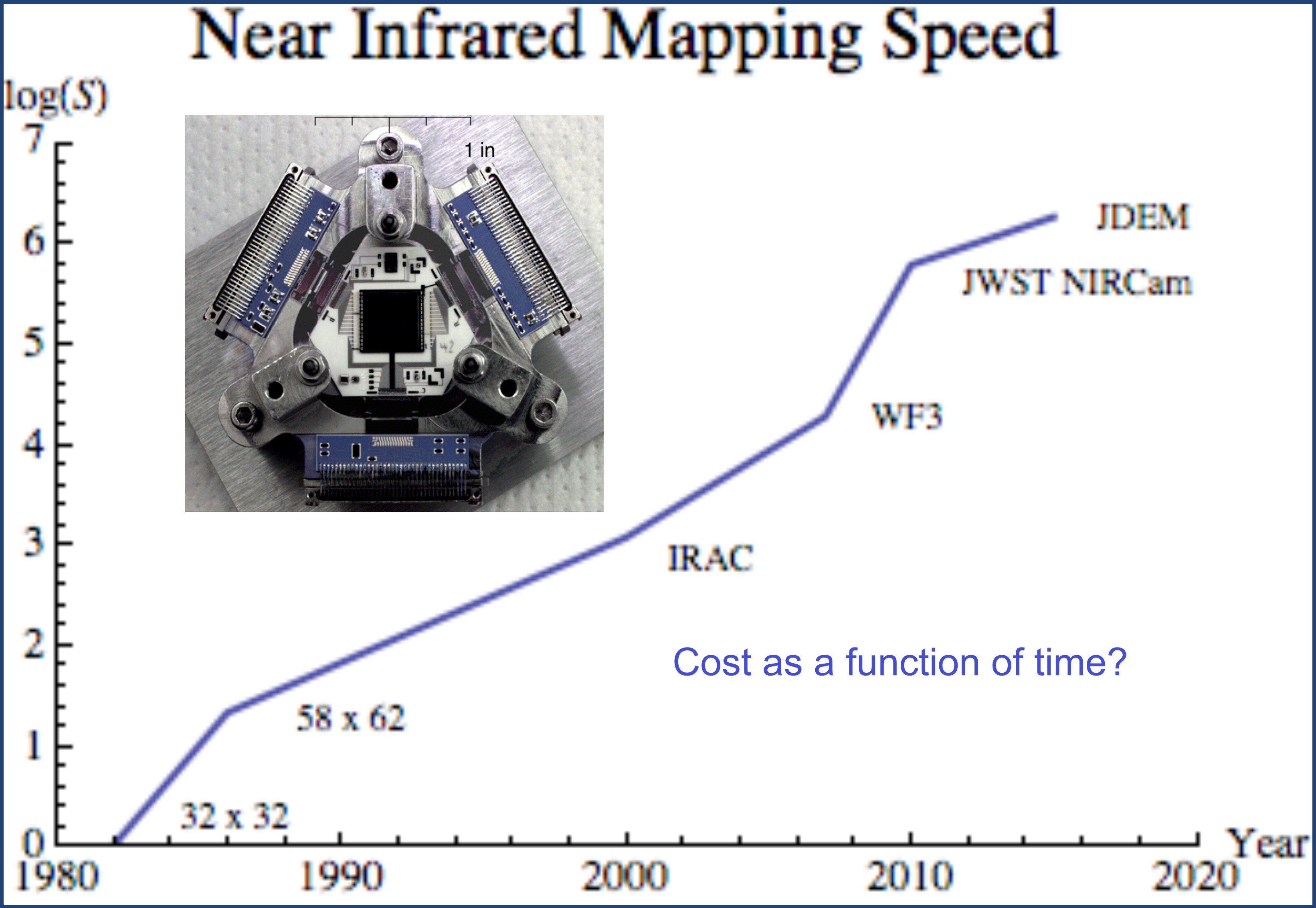
- SIRTF and IRAC evolved into systems very different from those envisioned in 1983.
  - Rapid improvement in detector performance
  - Changes in system architecture, driven by need to reduce system cost.
    - Warm Launch, aggressive radiative cooling
  - Focused science objectives

1980's

- Developing a design for IRAC
- Iterating in increasingly better detectors
  - Greater maturity in InSb, improved thinning, better material, multiplexers
  - IBC (BIB) detectors address the unpleasantness of photoconductors
  - Reduction in read noise, dark currents, better behavior.
- Don't forget WIRE (1990's)

Mapping Speed

Parameter	1986	2003	Speed Ratio
Format	58 x 62	256 x 256	18.2
QE	45%	90%	2
Dark Curr.	~3 e/s	~0.1 e/s	2
Read Noise	160 e/read	~10 e/read	16
Net Speed Gain			1166 (73)


Near Infrared Mapping Speed
log(S)
7
6
5
4
3
2
1
0
1 in
JDEM
JWST NIRCam
WF3
IRAC
58 x 62
32 x 32
Cost as a function of time?
1980
1990
2000
2010
2020
Year

IRAC Protoflight Unit

CRYOGENIC ASSEMBLY

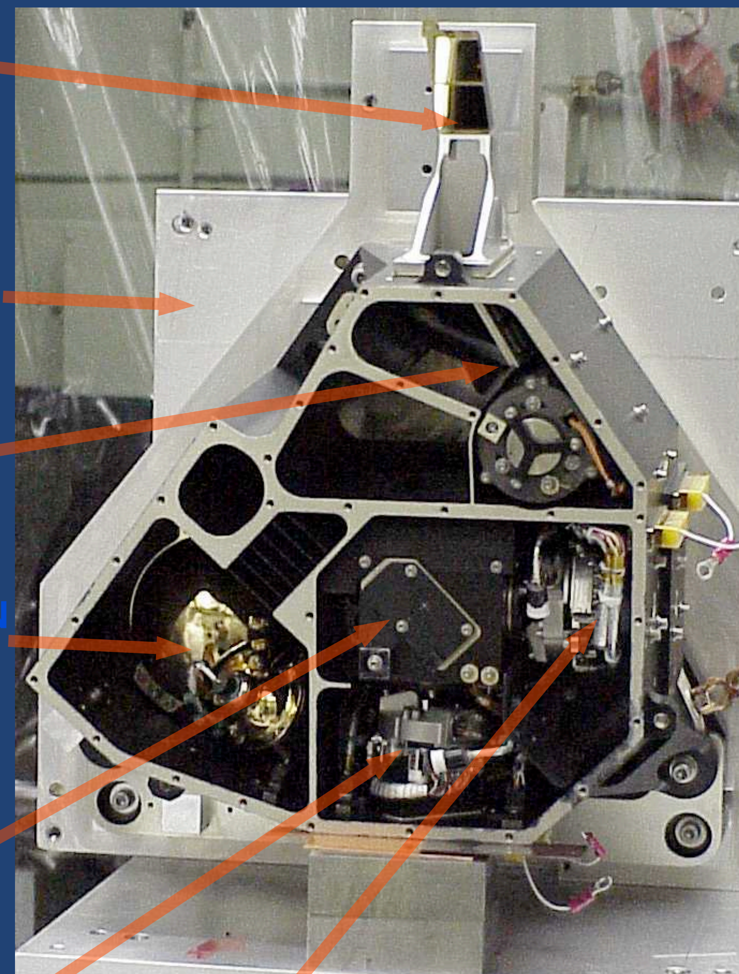
PICKOFF MIRROR

MIC ALIGNMENT PLATE

SHUTTER

TRANSMISSION CALIBRATOR

OPTICAL HOUSING



FPA1

FPA3

The Moral of this Story is….

- "Relax and let Moore's law do the work."
- "Moore's law takes a lot of work."
  - Ask Judy, Bill, and Craig about this
- Persistence and optimism carry the day!
- Note: JDEM will represent a step as large as the one made from the beginning of IRAC development to flight.

Science Beyond 100 μm

- History of star formation and energy release in the universe (neg. K-correction)
- Growth of structure in the universe
- Physics of Star Formation
- Formation of Planetary systems.
- CMB
  - Search for B-modes from earliest instant of BB
  - S-Z
  - Weak lensing of the CMB (small scale)

Basic Detectors Idea Still Works

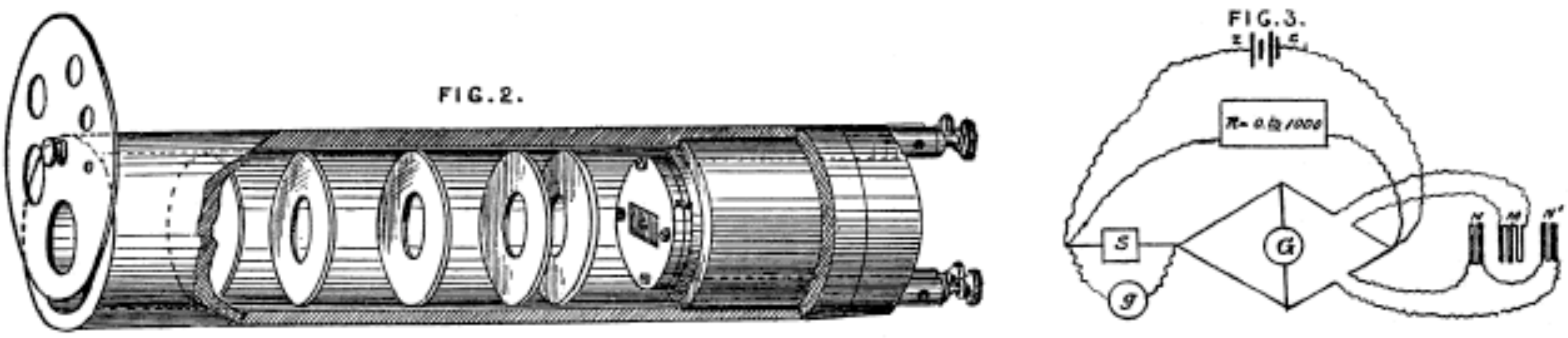
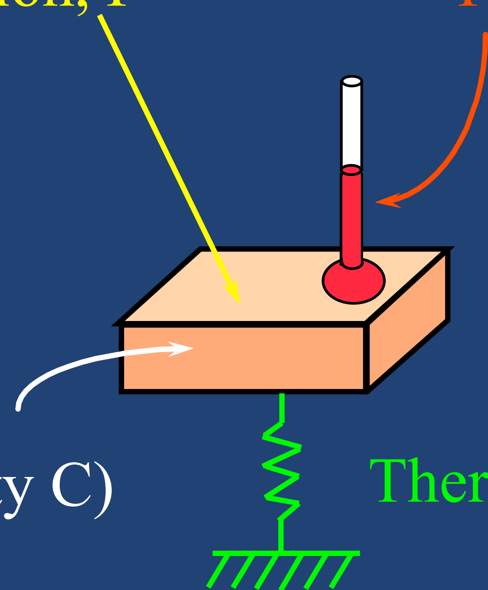


Figure 1. Bolometric instrument of S. P. Langley.

- Except
  - We operate at lower temperature
  - We need a large scale multiplexer

Bolometers



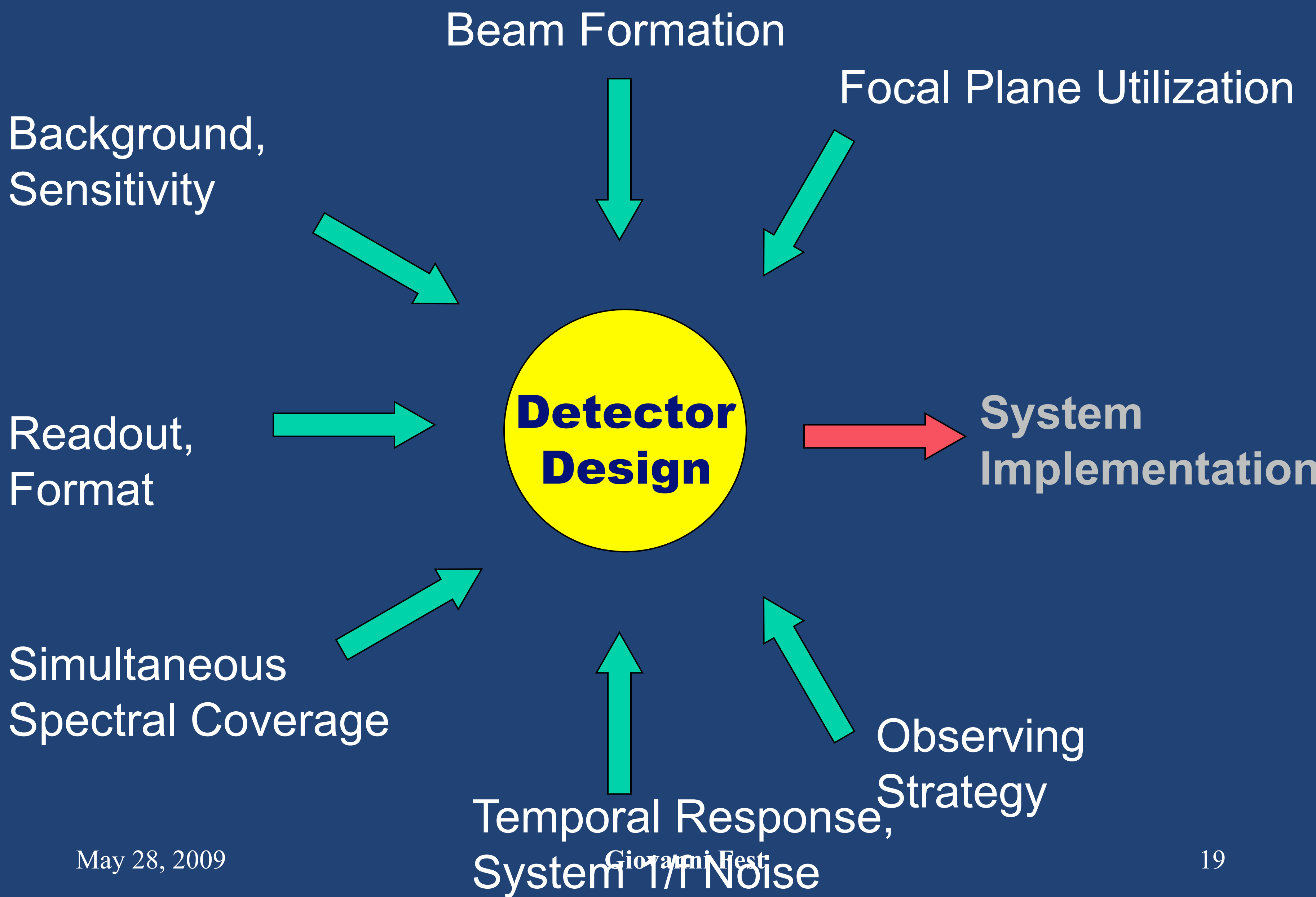
$P = G \times \Delta T$ Bolometer

Thermodynamic power noise:	$NEP^2 = 4k_bT^2G$	$(W/\sqrt{Hz})^2$

Operate at low temperatures (T~ 0.1K to 0.3K) where C, G and thermodynamic fluctuations are small.

Response time:	$\tau \propto C/G$	(s)

Motivation

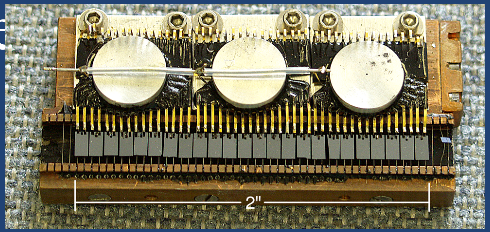


Beam Formation
Focal Plane Utilization
Background,
Sensitivity
Readout,
Format
Detector
Design
System
Implementation
Simultaneous
Spectral Coverage
Observing
Strategy
Temporal Response,
System 1/f Noise

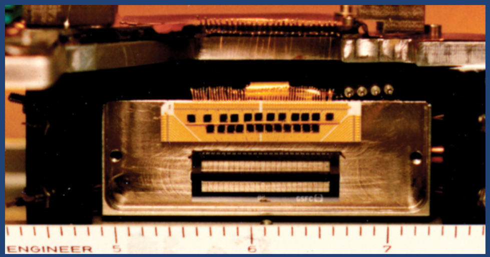
The Old Days

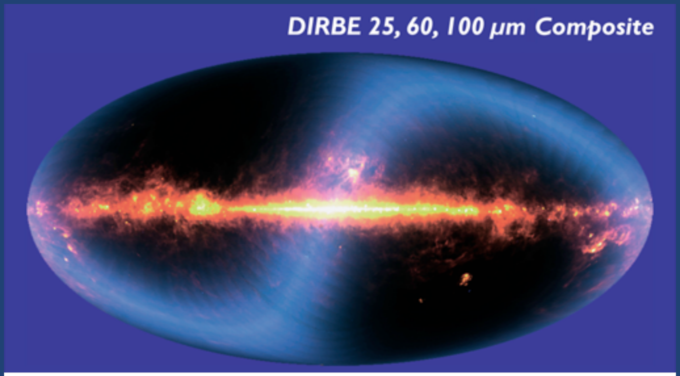
- COBE
  - 1 pixel
  - Handmade

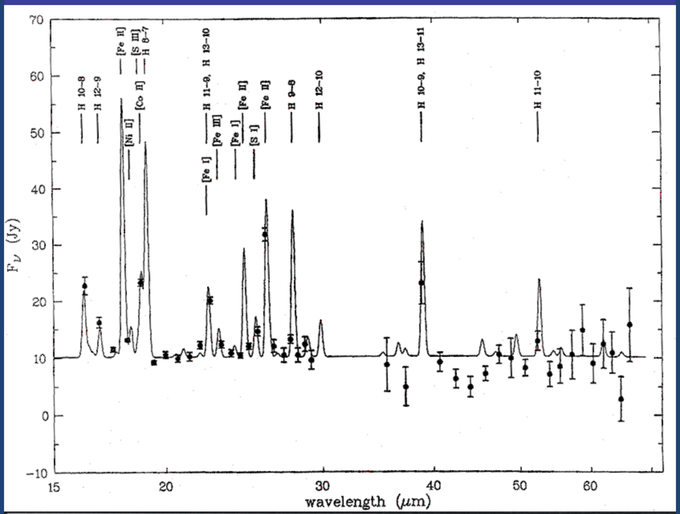
- KAO spe
  - Circa 1987
  - Craft work

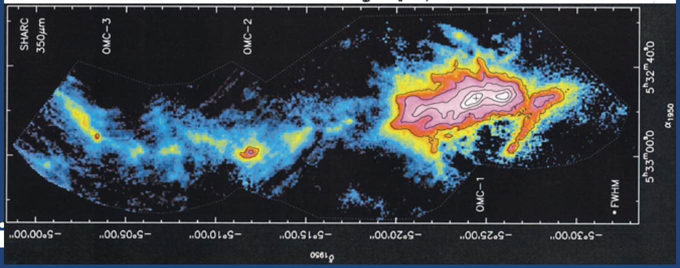


- SHARC I
  - Early 1990s
  - KAO
  - AXAF,
  - Astro-E







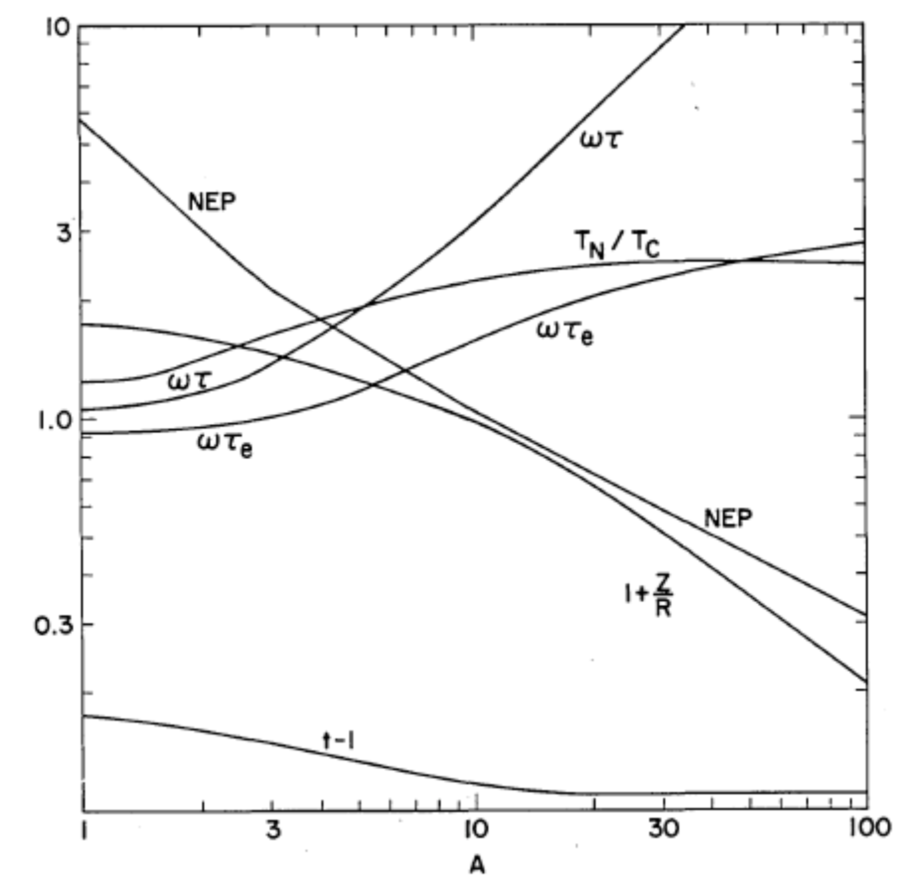


Imaging Arrays Circa 1990

- U. of Chicago produced large arrays in early 1990s
  - Up to 60 elements
- Two 32 element arrays for Hildebrand et al. polarimeter shown; Winston cones

Advances in Theory

- Treats nonequilibrium effects of noise
- Shows benefits of high temperature sensitivity
  - NEP ~ 1/Sqrt[A]
- Focuses on fundamental limits

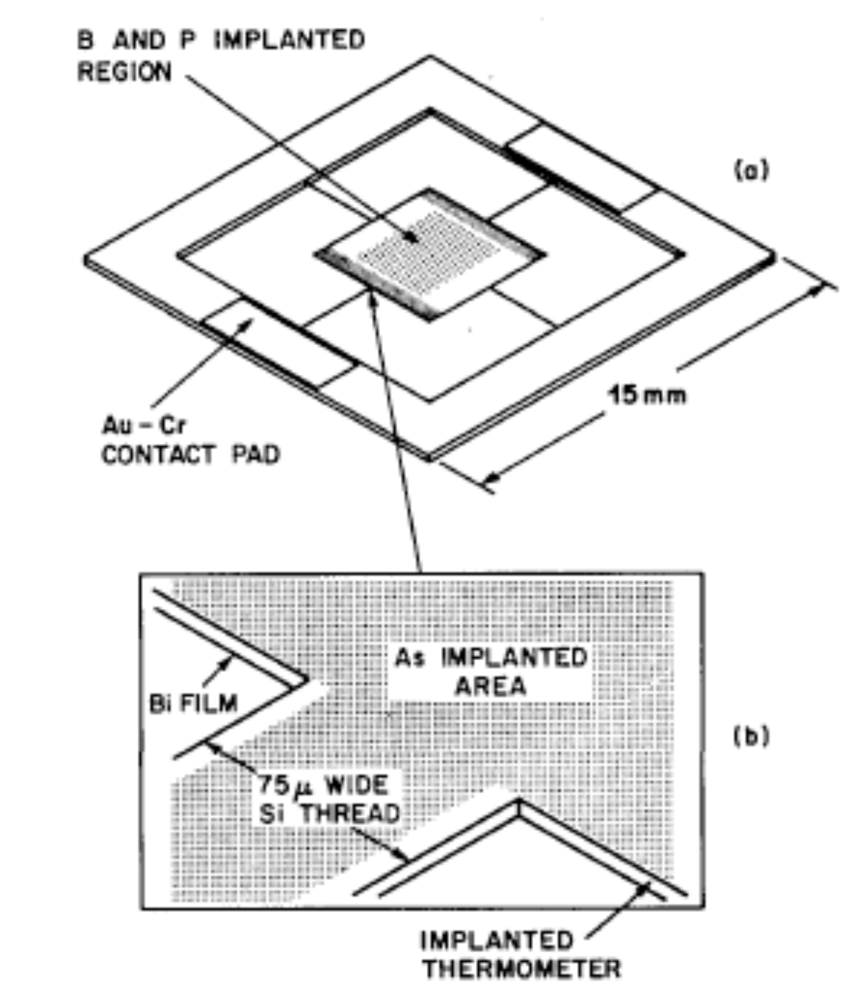


Mather, J. C. Appl. Opt. 23, 584 (1984)

$R(T) = C\,(T/T_0)^A$

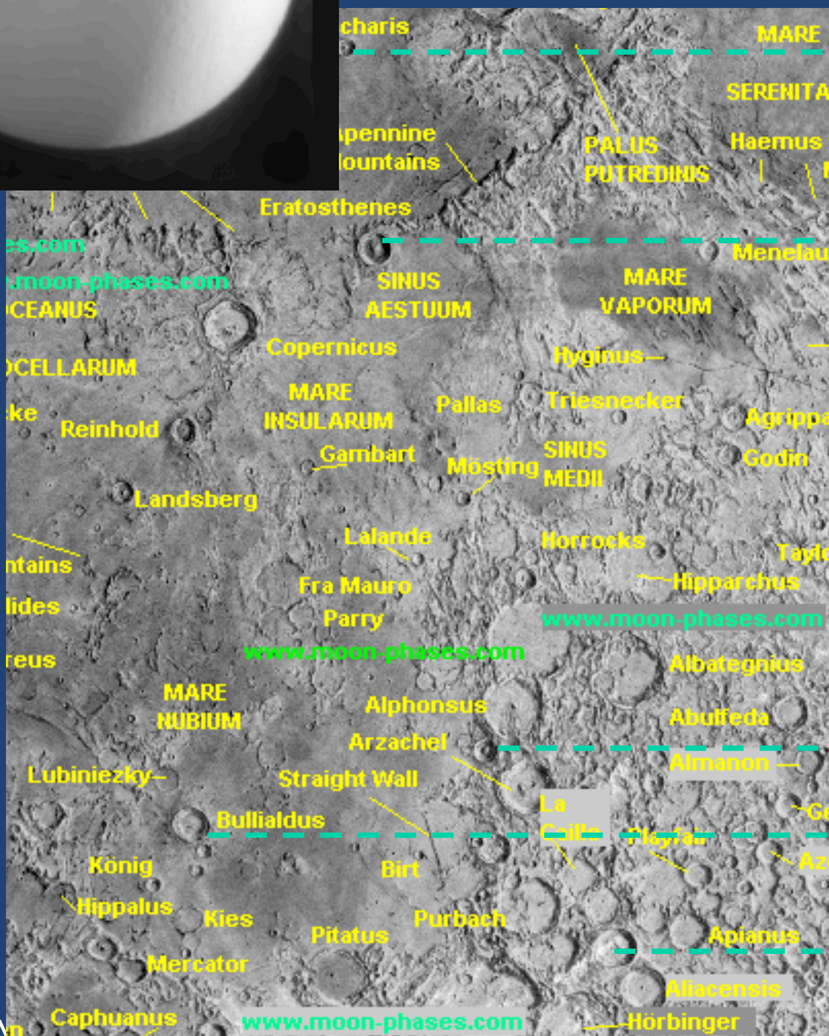
New Fabrication Techniques

- Precision fabrication
- Controlled electrical and thermal properties
  - Predictable response and noise -> Arrays!

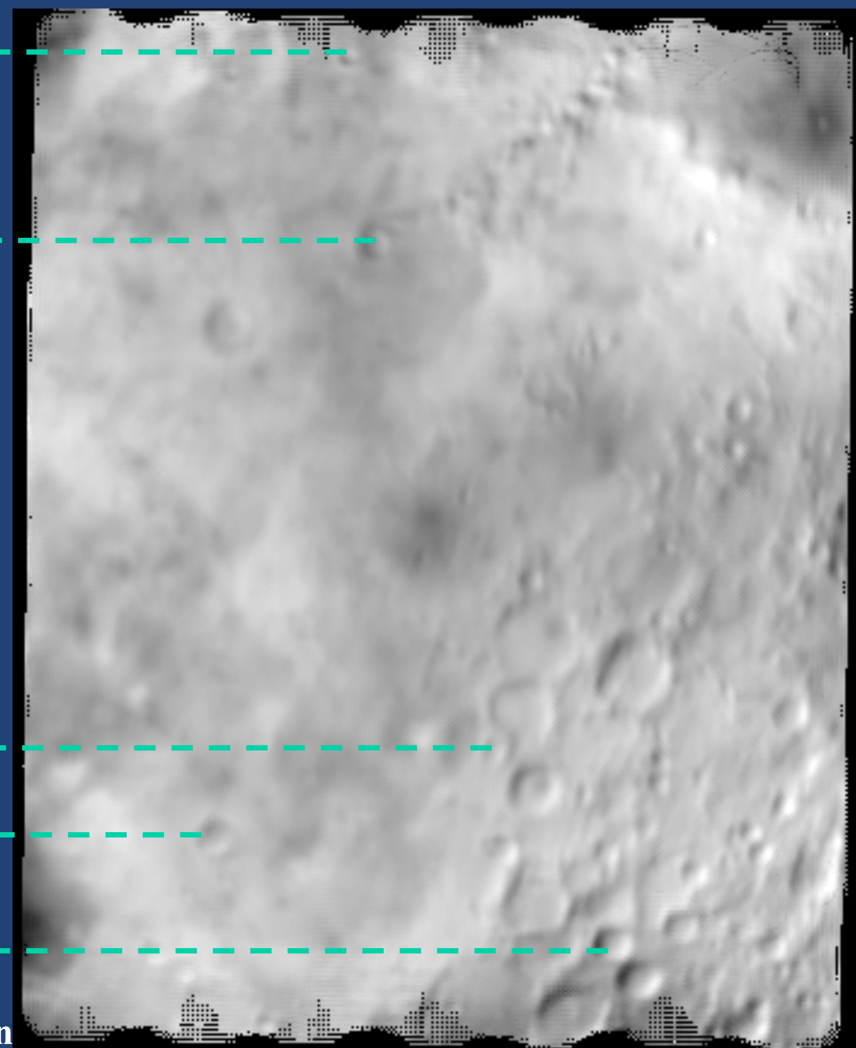


Downey, P. M. Appl. Opt. 23, 910 (1984)

Thermal Emission from the Moon



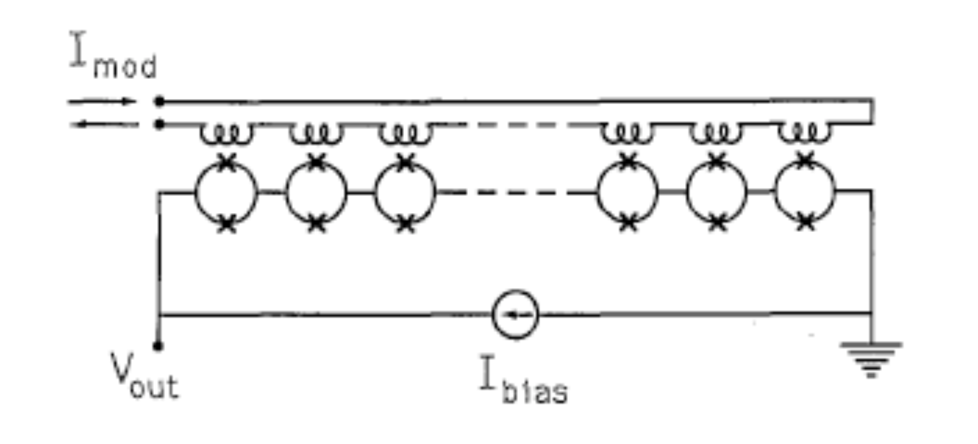
Visual Image



Submillimeter CSO Image

SQUIDs for Everyone

- Series array provides cryogenic amplification, couples to single SQUID front end
  - No transformers, exotic room temp electronics
- A low noise, practical, and easy to use cryogenic amplifier



Welty and Martinis
IEEE Trans. Mag. 27,2924 (1991)

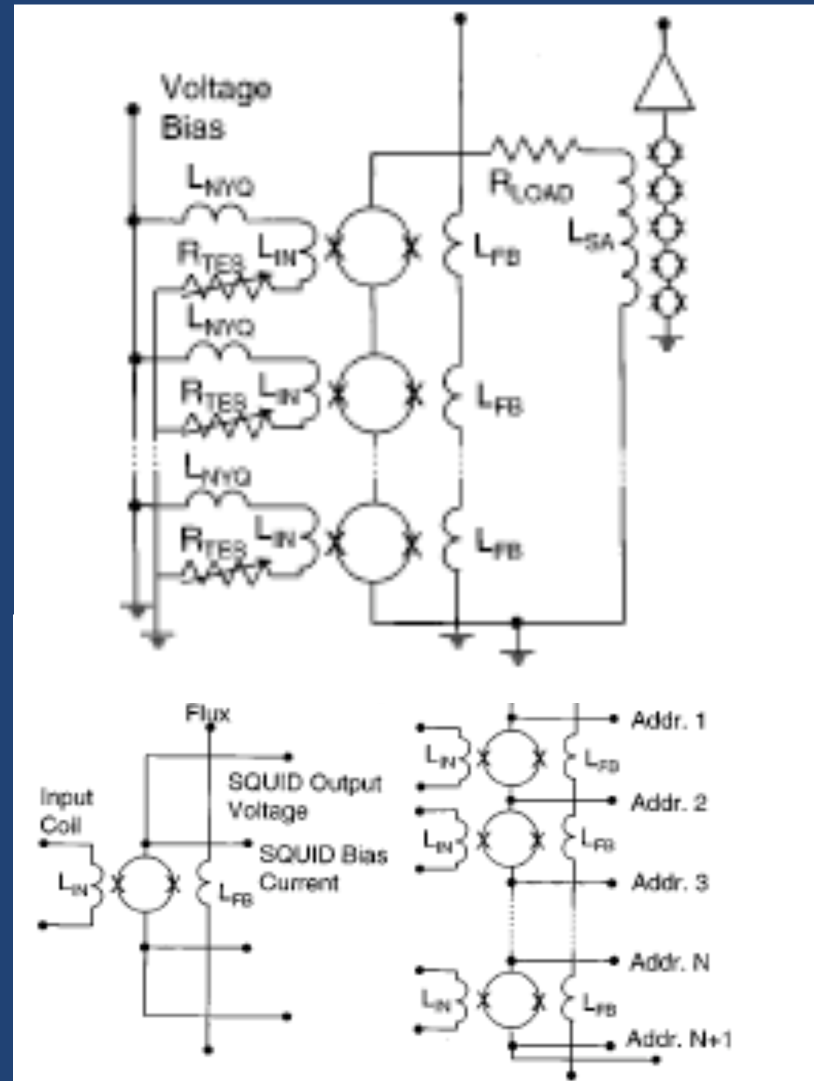
Kautz et al.
IEEE Trans. Mag. 23, 883 (1987)

Multiplexing - the path to large arrays

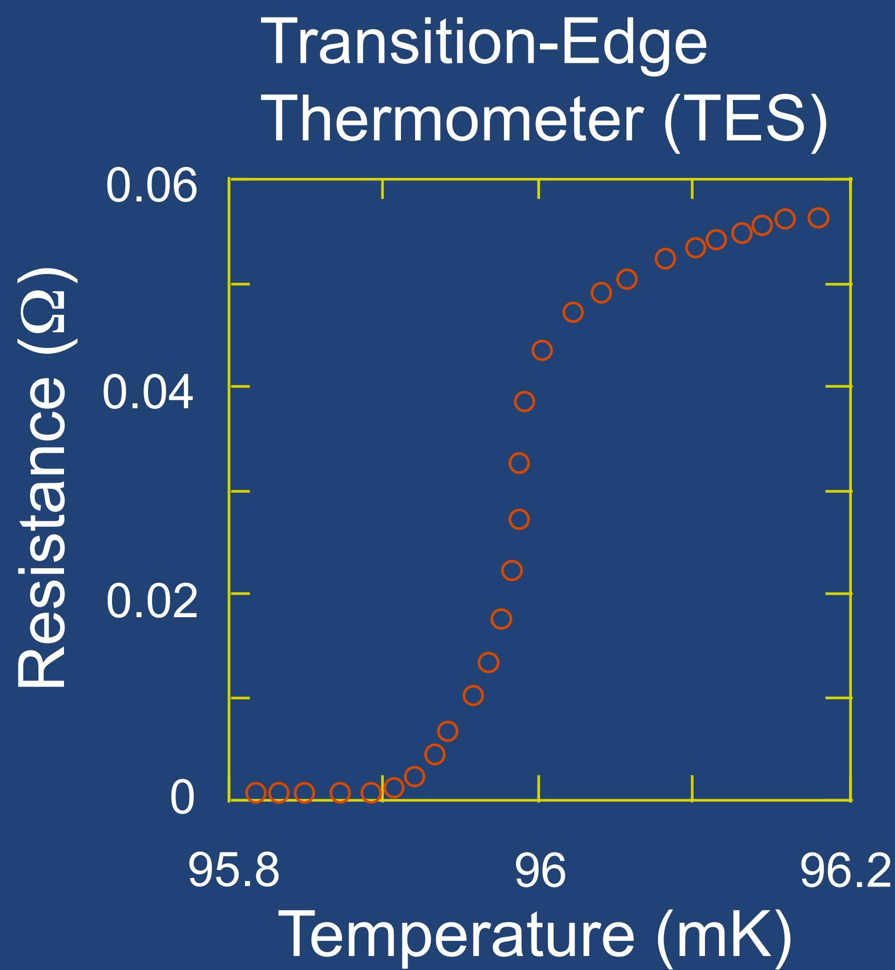
- Time division multiplexing simplifies interfaces

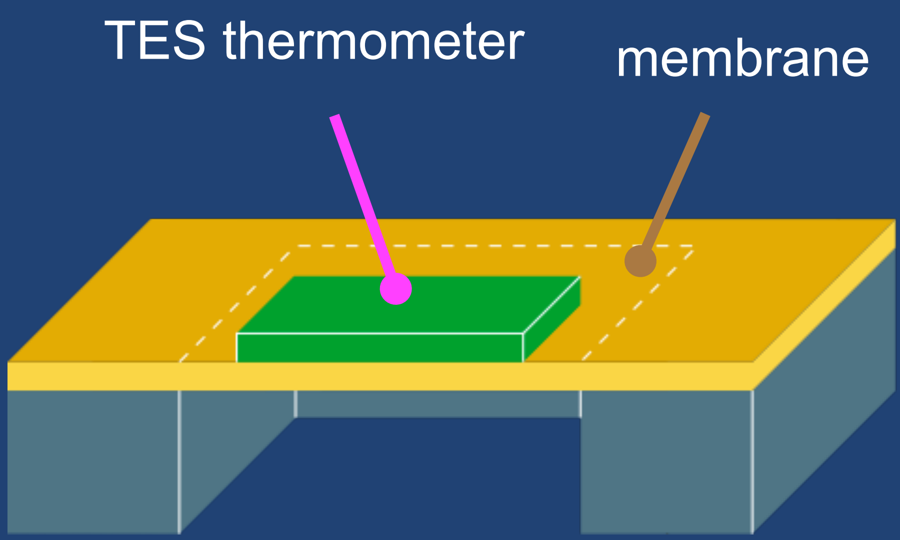
Chervenak et al.

(1999)



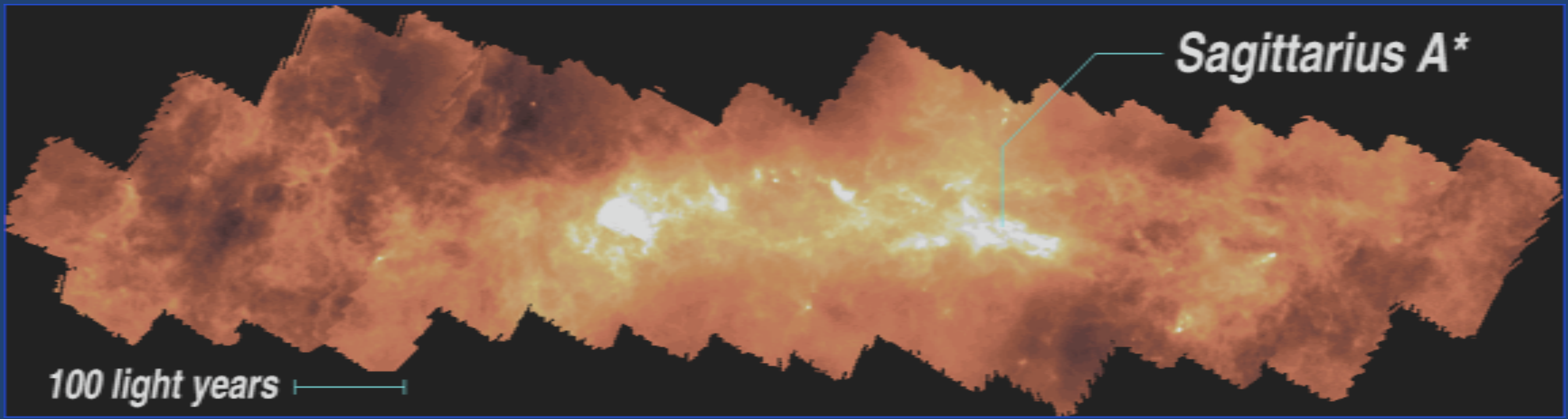
Superconducting Transition-Edge Thermometer



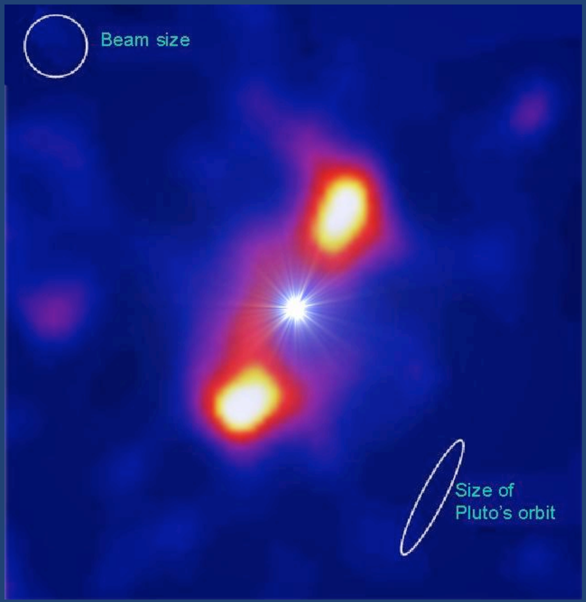


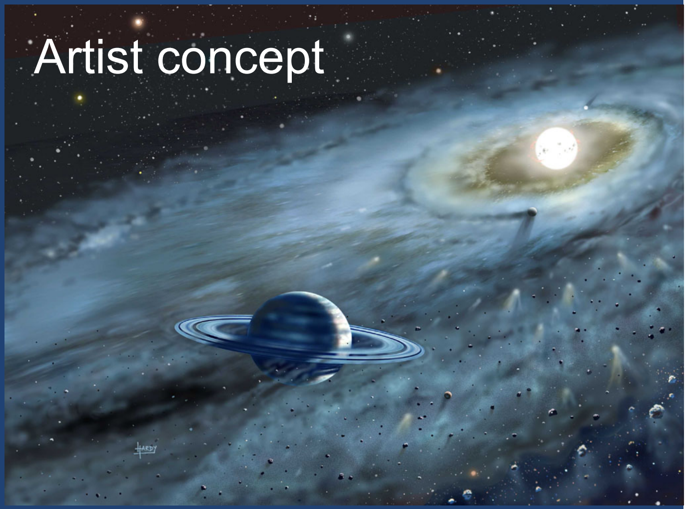
Photon → Heat → Resistance

Submm astronomy: SCUBA-1



Survey of the galactic center





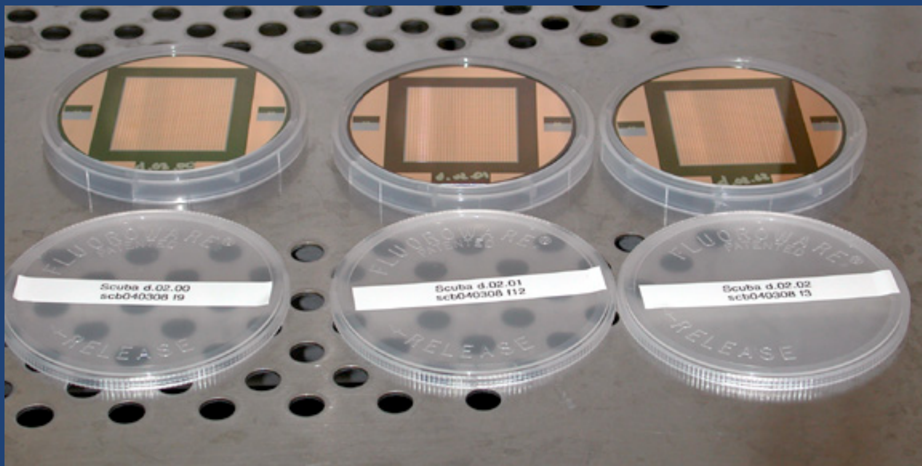
Detection of a gas giant around Fomalhaut

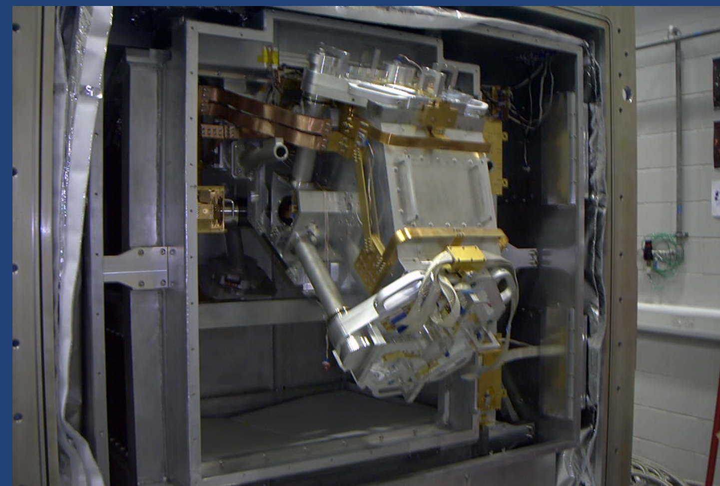
Submm astronomy: SCUBA-2

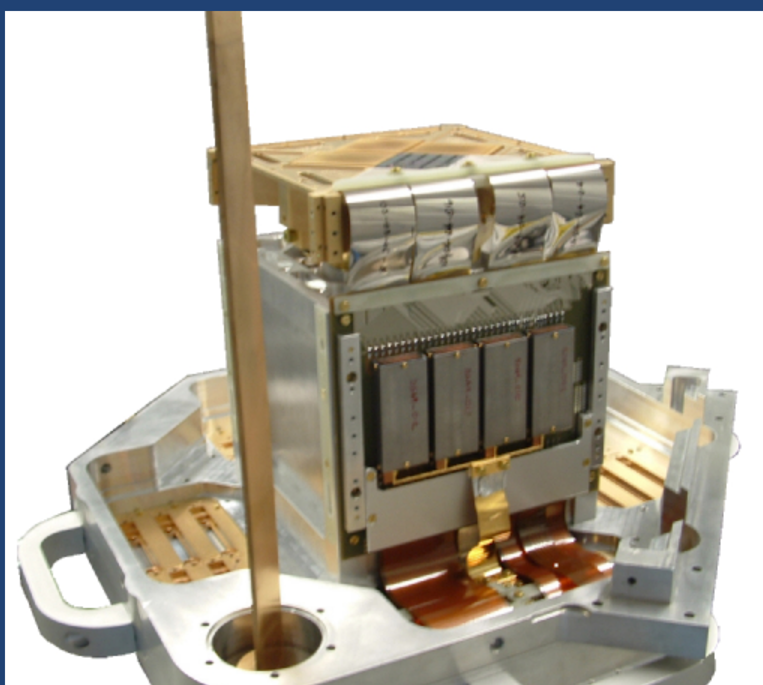
- A collaboration of the UK, Canada, Raytheon, and NIST
- SCUBA-2 will consist of 10,240 TES bolometer pixels (half at 450 μm, half at 850 μm) on the James Clerk Maxwell Telescope in the next months.

James Clerk Maxwell Telescope

THz/submm astronomy: SCUBA-2

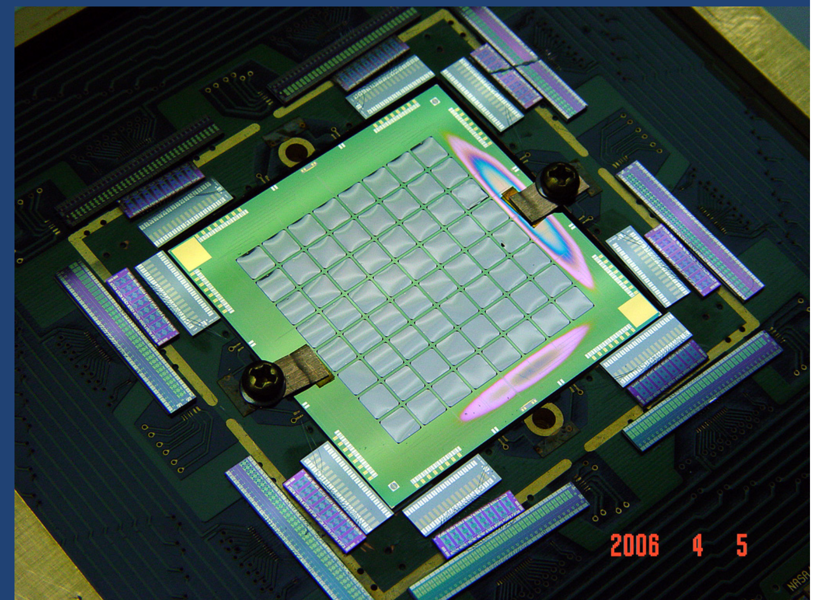


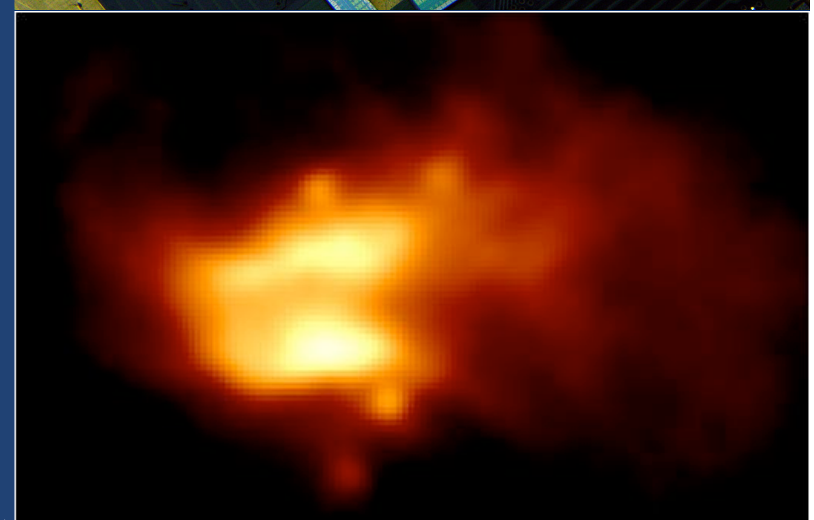




Gio

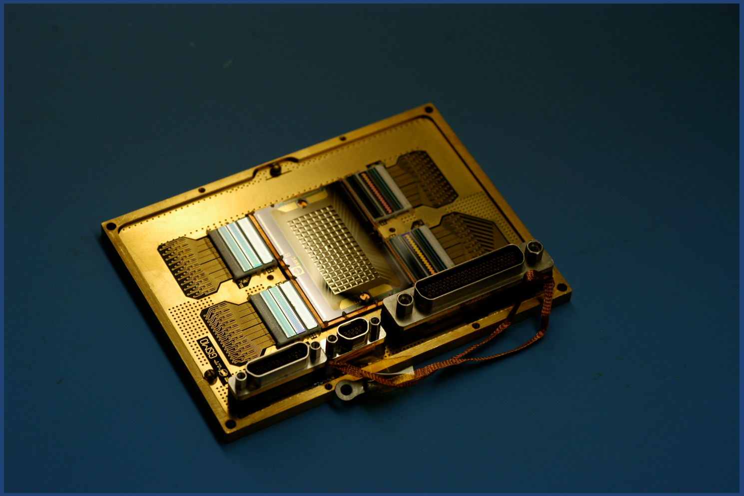
MUSTANG - a 3mm camera for the GBT



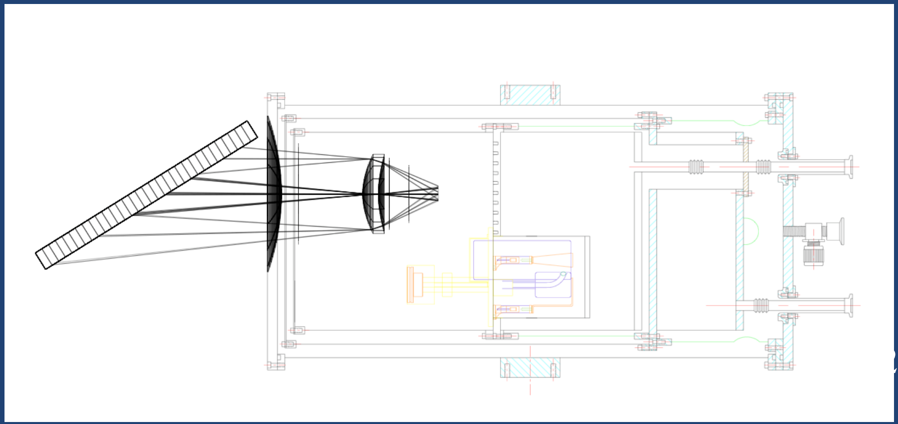


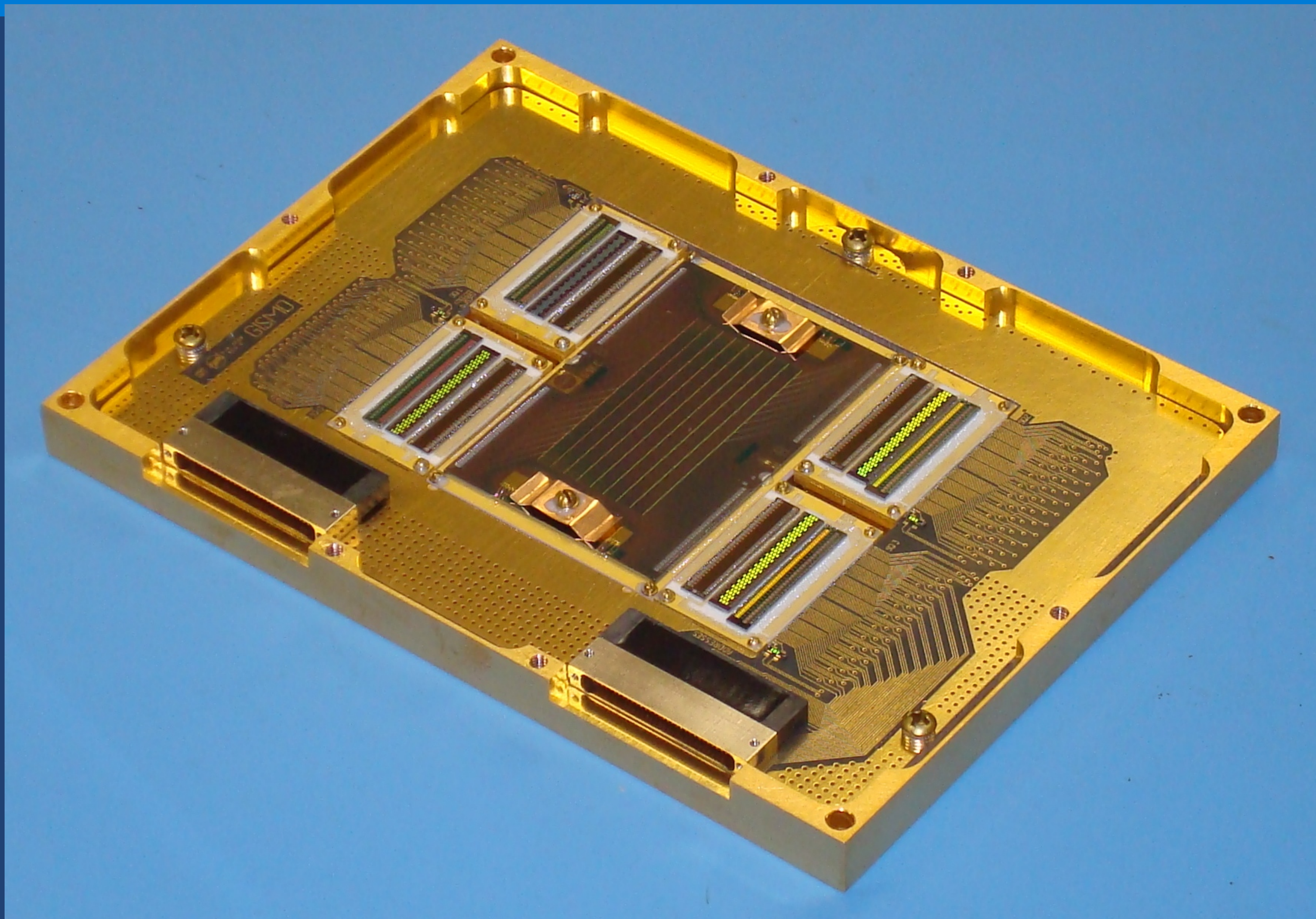
U. Penn, NRAO, GSFC,NIST, UBC

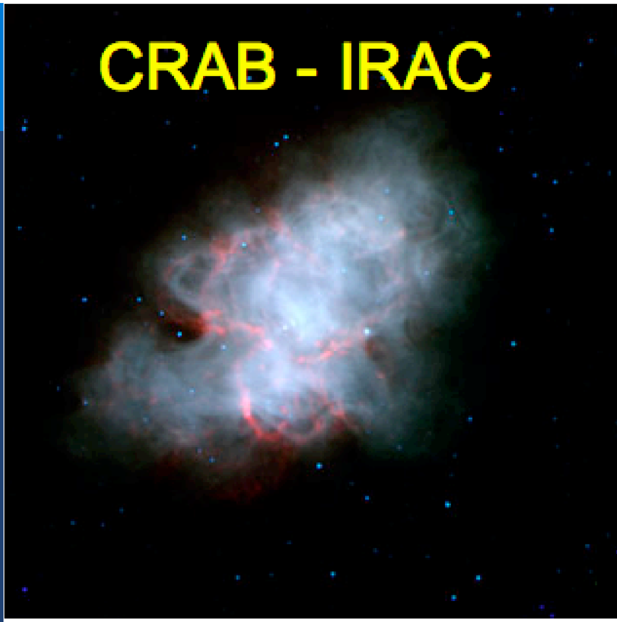
Goddard-Iram Superconducting 2-Millimeter Observer (GISMO)

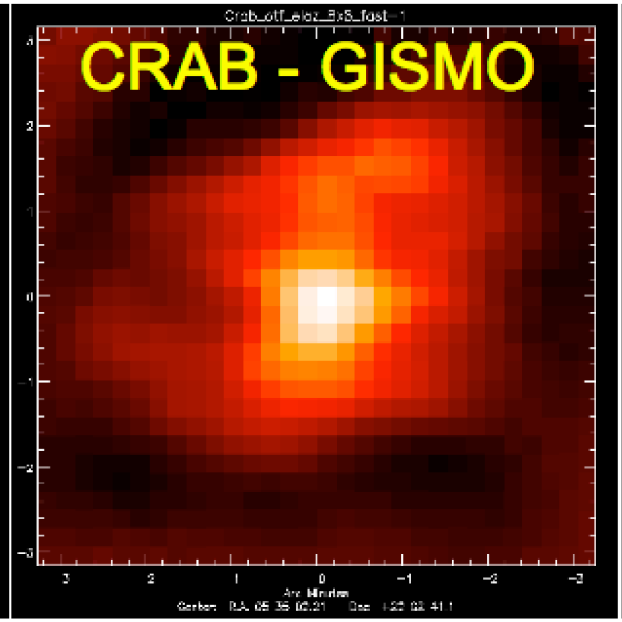


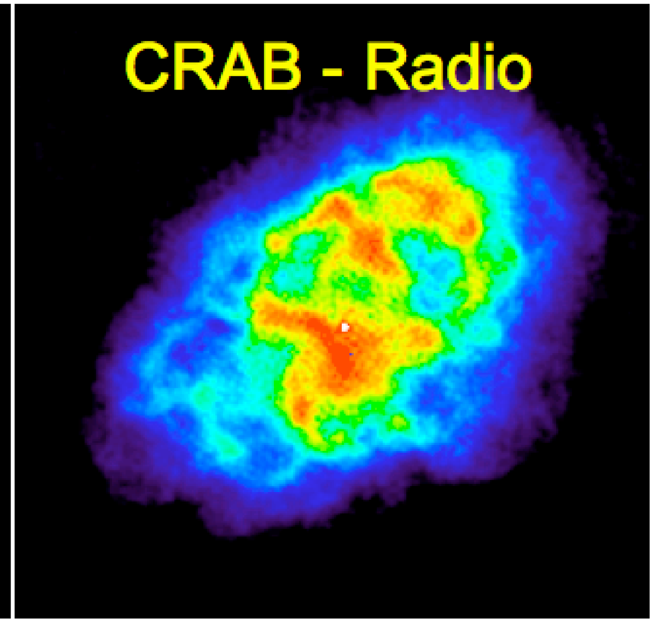
Backshort under Grid (BUG) TES detector array

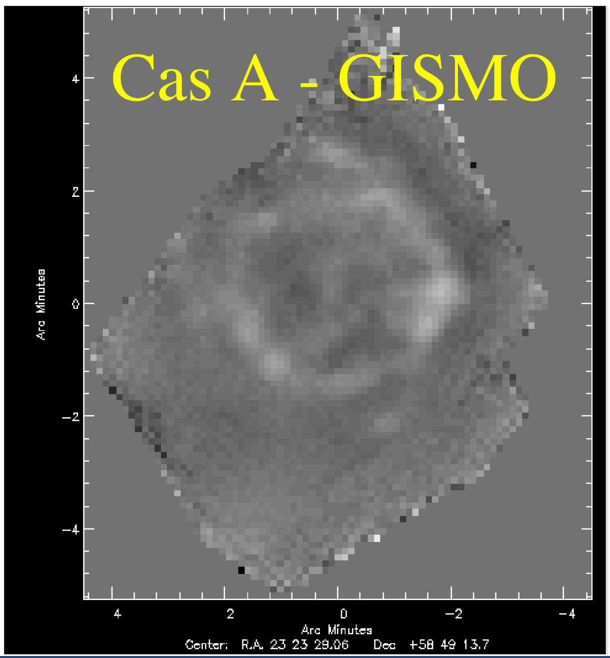


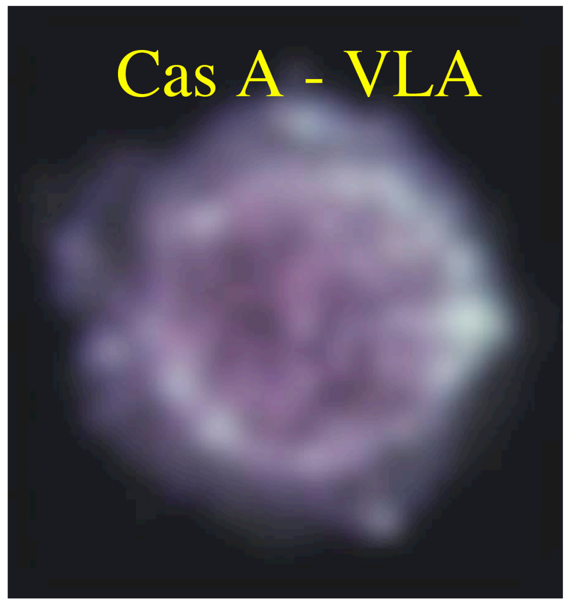

GISMO


CRAB - IRAC


CRAB - GISMO


CRAB - Radio


Cas A - GISMO
Arc Minutes
Arc Minutes
Center: R.A. 23 23 29.06 Dec +58 49 13.7


Cas A - VLA

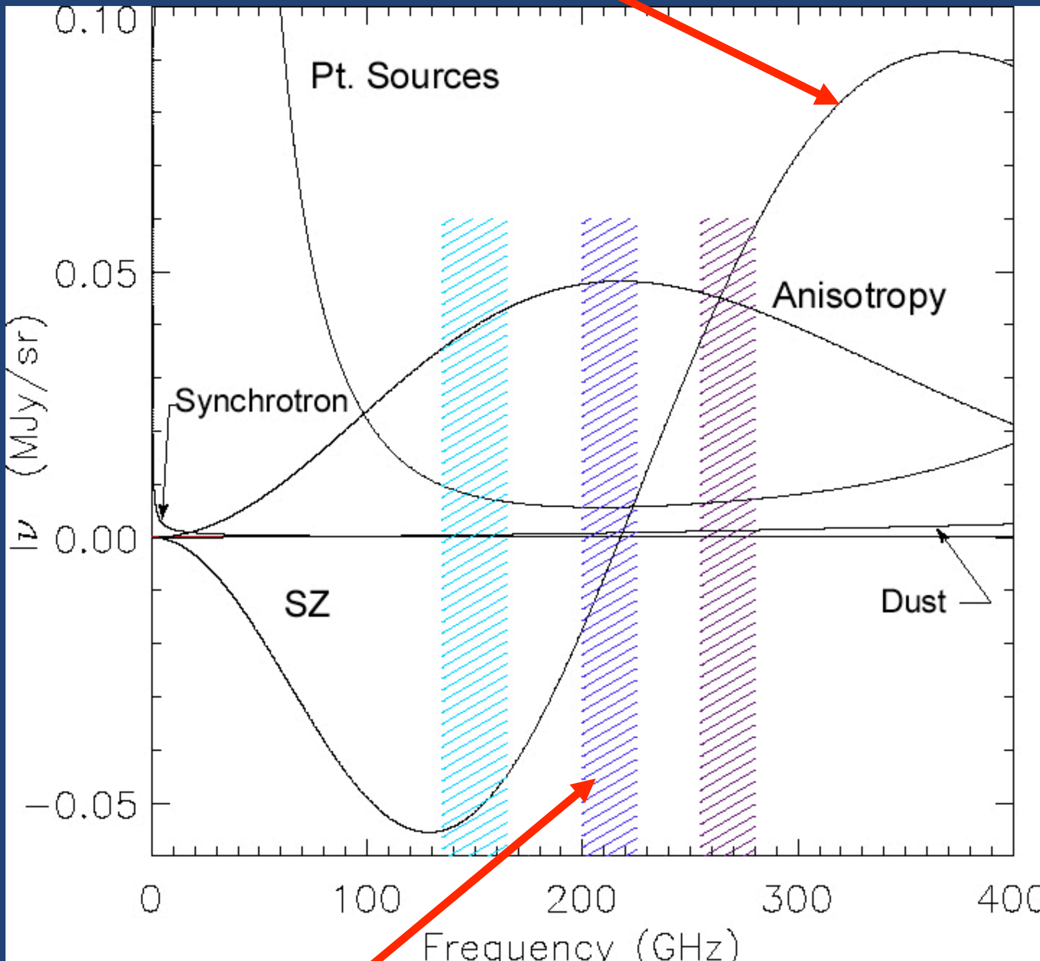
ACT

Three 32x32 arrays.

CMB: SZ Signature

Hot electron gas imposes a unique spectral signature

Z-independent cluster surveys



145 GHz decrement

220 GHz null

270 GHz increment

NO SZ Contribution in Central Band

Devlin, ACT collaboration

1.4°x 1.4°

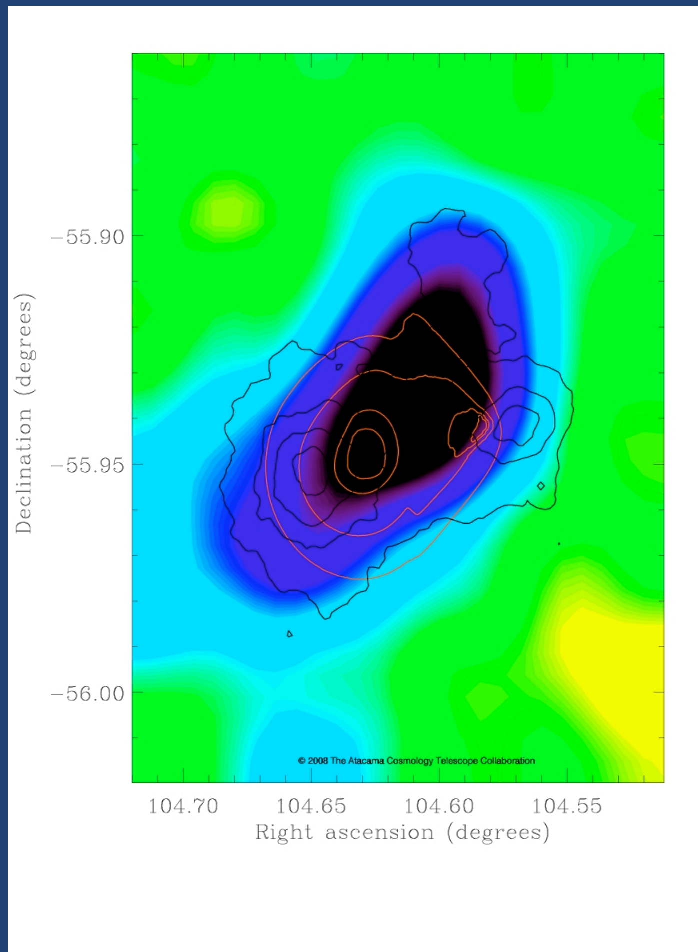
ACT

Three 32x32 arrays.

ACT Works!

- Map of the Bullet cluster, showing the S-Z decrement at 145 GHz.
- The instrument was deployed with a 32 x 32 array of TES detectors

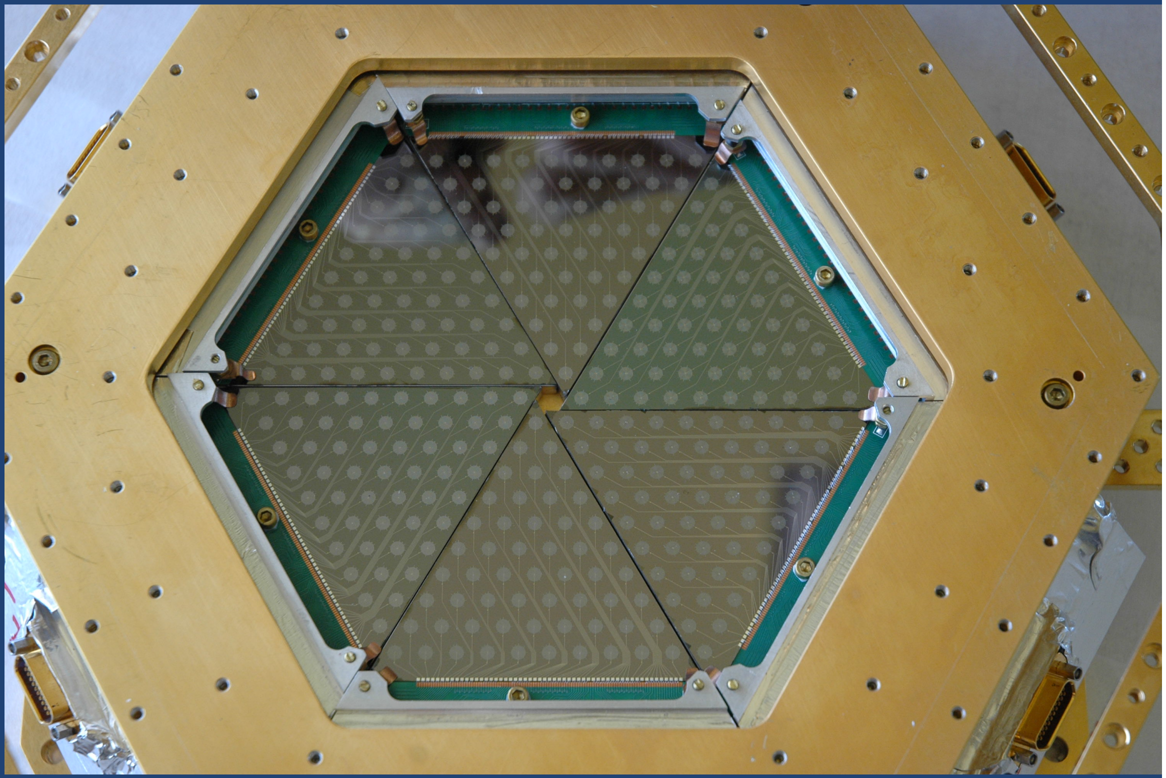
Preliminary Data



South Pole Telescope and APEX-SZ

APEX-SZ, 320 pixels

SPT, 960 pixels



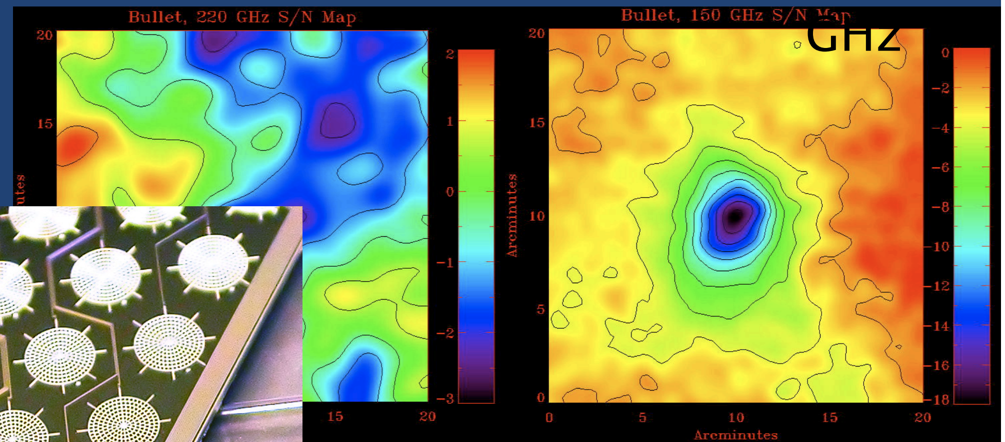
Berkeley, Chicago, etc.

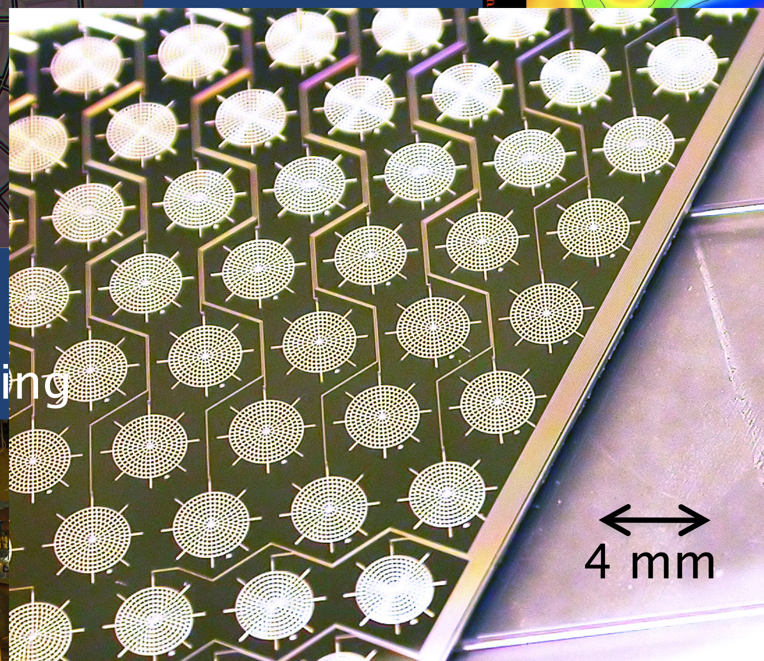
South Pole Telescope Spider TES Arrays

Berkeley, CWRU, Cardiff, Chicago, Colorado, Davis, Illinois, JPL, McGill, SAO

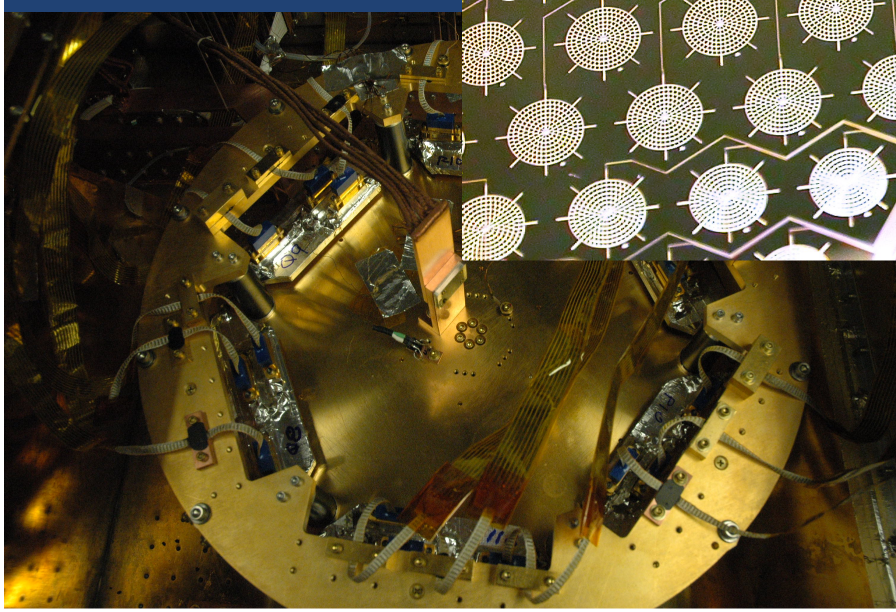
2 mm

220 GHz Bullet Cluster 150 GHz



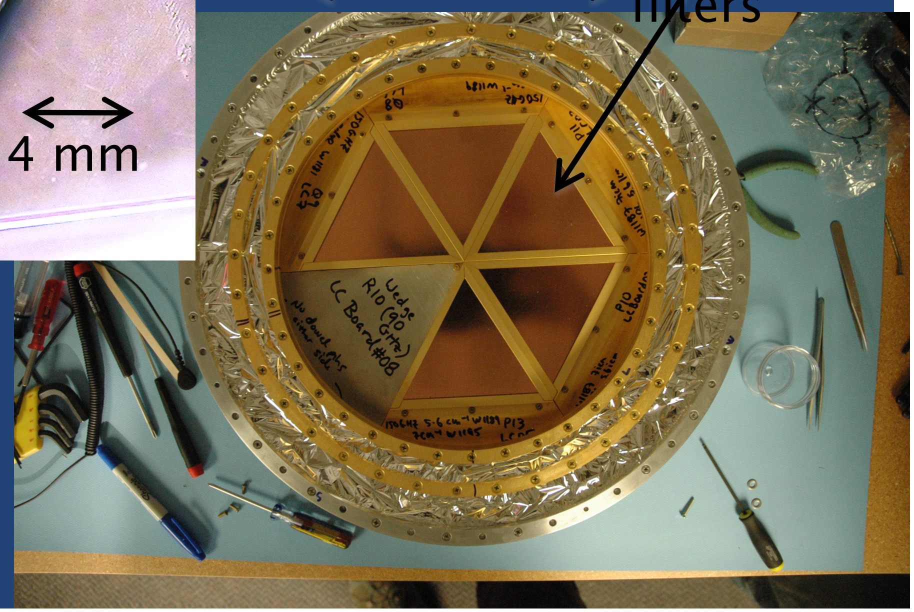


960 Pixel fMUX wiring



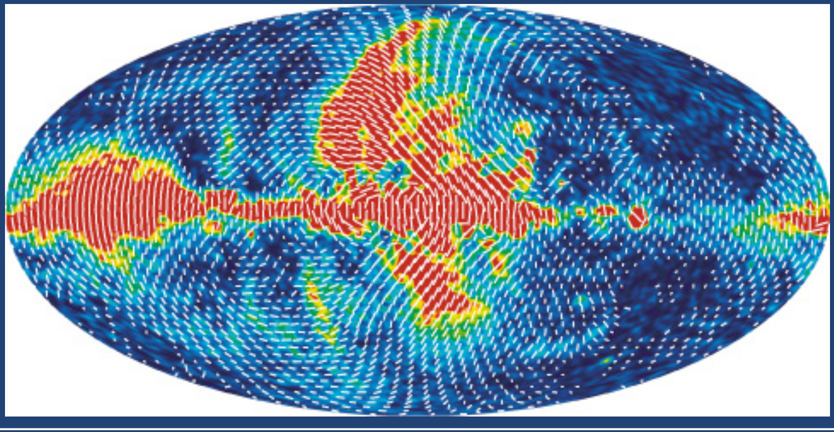
20 cm

Mesh filters



Future: TES CMB polarimeters for cosmology

- Signature of primordial gravitational waves
- CMB polarimetry microlensing: “cosmic shear”
  - Probe of expansion history of universe with different systematics



WMAP EE mode (HEMTs)

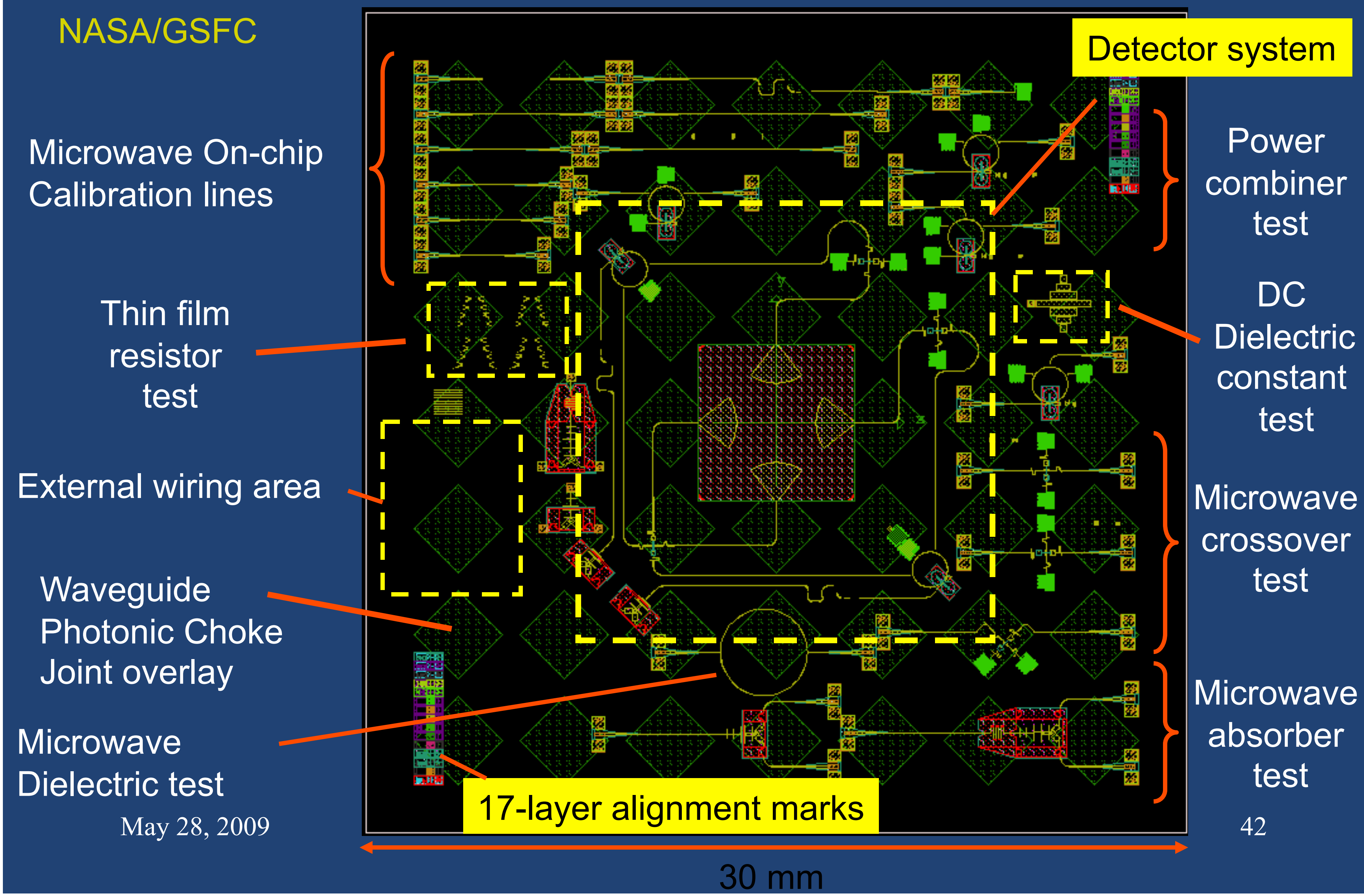
Polarization-sensitive TES provide excellent sensivity
– need good systematic control

Balloons: SPIDER, EBEX

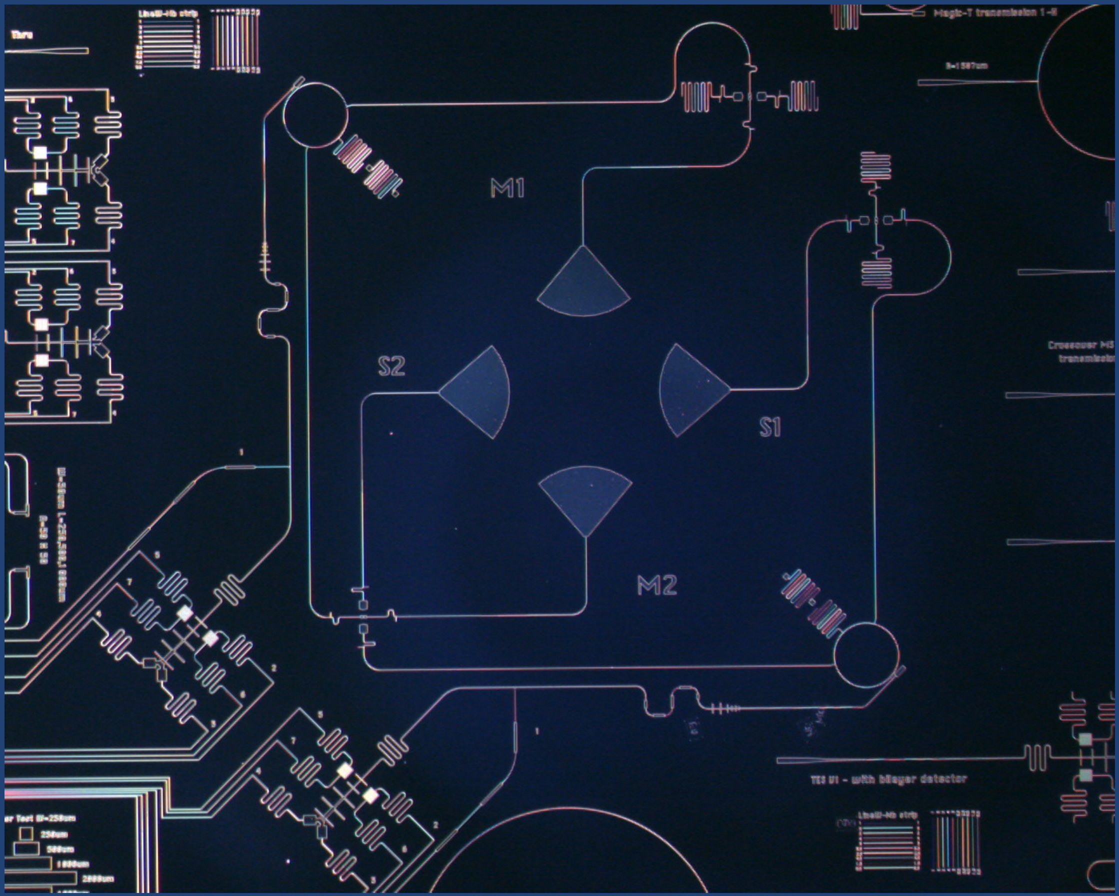
Ground-based: BICEP-2, SPUD, CIOVER, SPT, ACT, …

CMB Polarization Detector Layout

NASA/GSFC

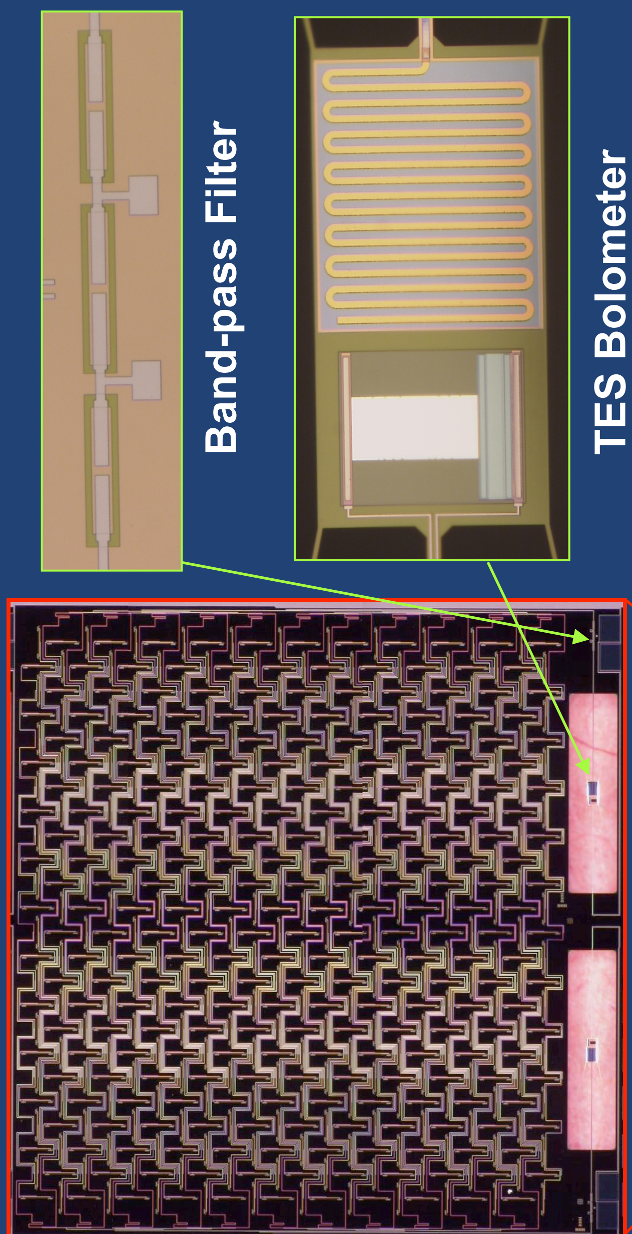


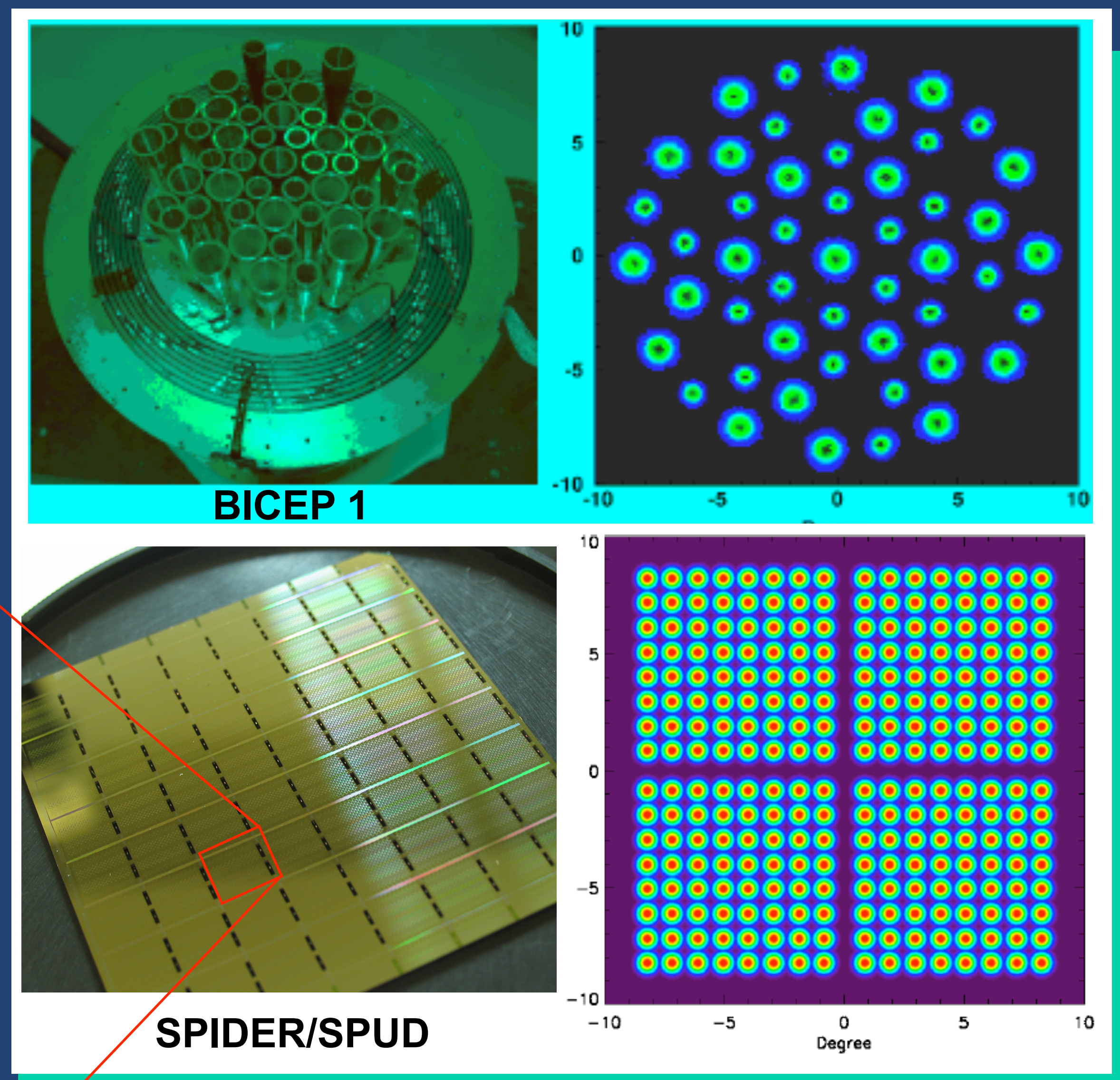
Planar OMT Circuit



Hsieh, NASA/GSFC

Antenna-Coupled TES Bolometer Arrays

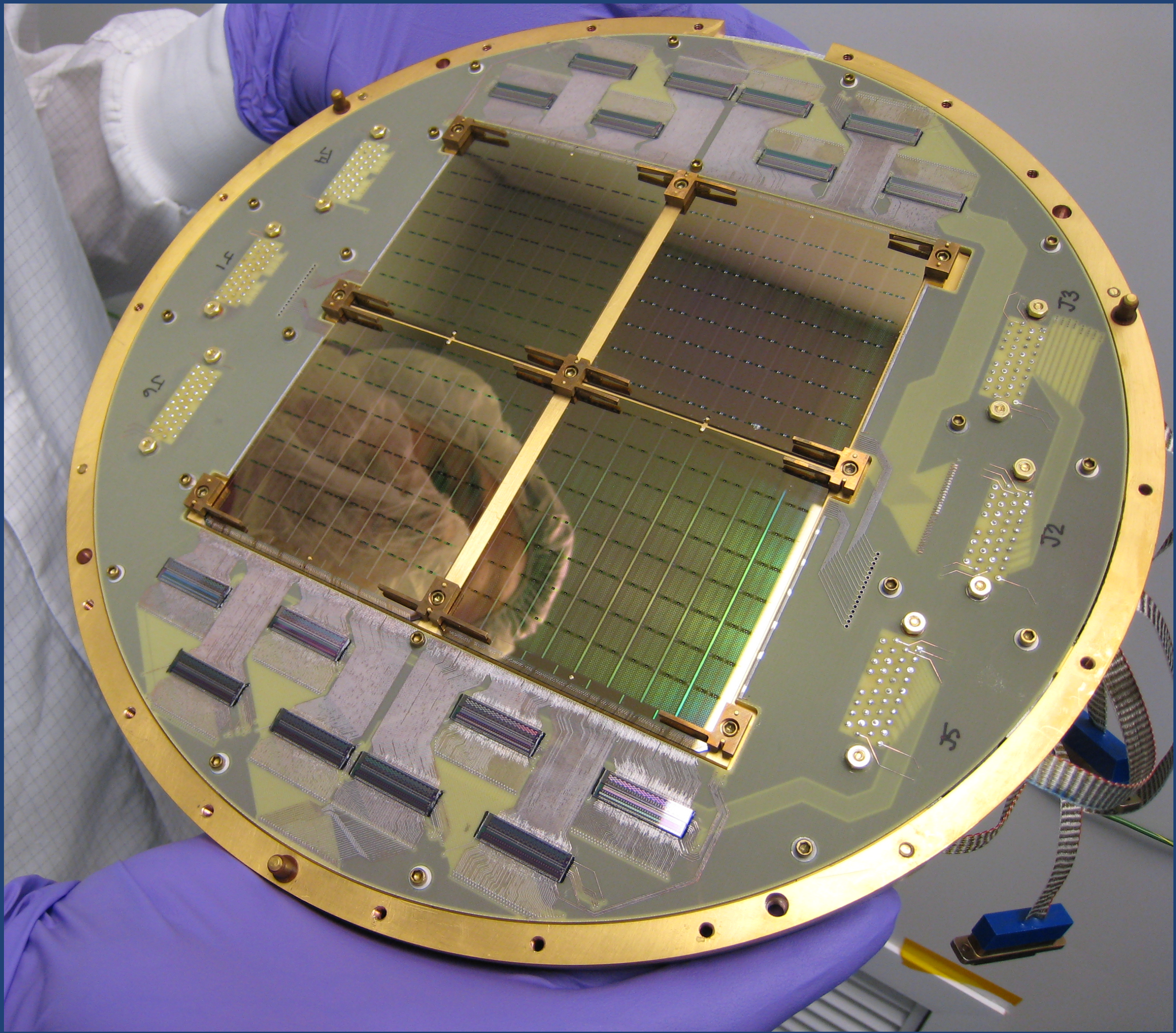




J. Bock, JPL/Caltech

BICEP2 150 GHz Engineering Focal Plane

- 4 wafers
- 2 detectors per pixel
- 512 total detectors
- 16 x 32:1 TD SQUID mux



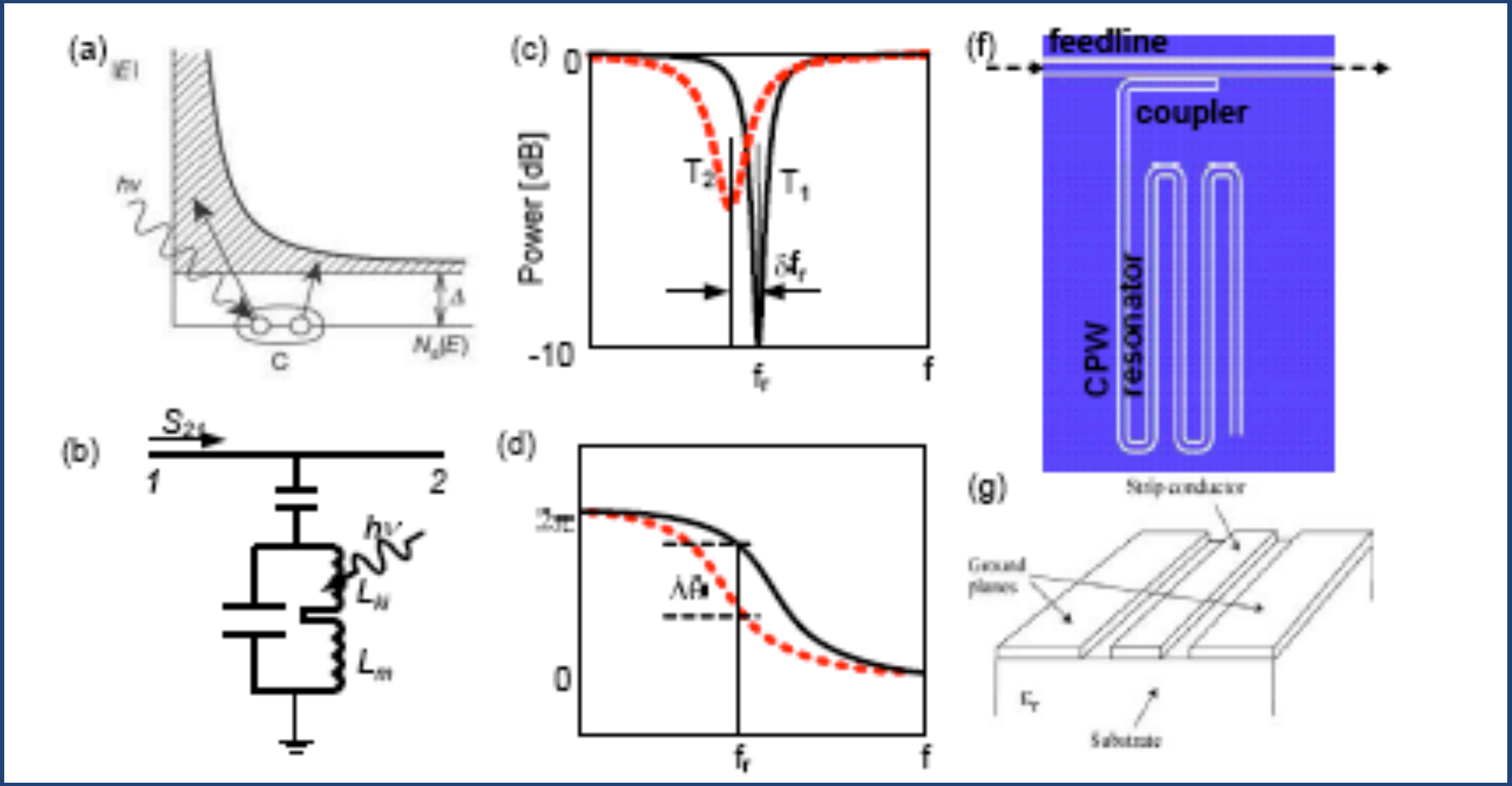
J. Bock, JPL/Caltech

May 28, 2009

Microwave Kinetic Inductance Detectors

- Measures changes in kinetic inductance of a superconductor due to pair breaking.
  - "moral equivalent" of STJ detector
    - Day et al. Nature 2003
- Uses phase or amplitude change in a resonator to sense photon input
- Is a novel twist on McDonald's (1989) thermal kinetic inductance detector
- Readout benefits strongly from microwave infrastructure

MKIDs



(a)
hv
C
Δ
(b)
S21
1
2
hv
L
(c)
0
Power [dB]
T2
T1
δfr
-10
fr
f
(d)
2π
0
fr
f
(f)
feedline
coupler
CPW
resonator
(g)
Strip conductor
Ground planes
Substrate

Summary

- Capabilities over the IR spectrum are growing exponentially
  - >100 Mp in the NIR in the near term
  - 10^3 pixels now, $10^{4\text{-}5}$ in the next decade
- We are moving into an era that will allow unprecedented scientific progress
  - Leveraging tools that others spent a lot of money on
- With such promise, how do we set priorities?