# NSF Center for Black Hole Physics

Black holes (BHs) play a central role in fundamental physics and astrophysics. They exist at the center of most galaxies and are the end state in the evolution of the most massive stars. The defining characteristic of a BH is the event horizon, a space-time surface surrounding a region disconnected from the rest of the universe, where gravity is so strong that even light cannot escape. The physics associated with this most extreme environment holds keys to our understanding of General Relativity (GR) in the strong gravity regime, accretion and outflow in active galactic nuclei (quasars), the brightest explosions in the Universe (gamma-ray bursts - GRBs), and the interplay between quantum mechanics and gravity.

New observational, computational and theoretical approaches to understanding BHs on all cosmic scales have opened a rich discovery space with extraordinary potential for transformative advances. We have developed technology capable of imaging the silhouette of the BH at the center of our own galaxy, based on Very Long Baseline Interferometry (VLBI) at millimeter wavelengths. New theoretical frameworks for exploring BH environments have been developed, including peta-scale computational platforms for full 3-D simulations of relativistic magnetized flows near a BH. This work is underway at Harvard and collaborating institutes, and the combination of such developments within a center environment presents a special opportunity to focus on several frontier areas in physics, astronomy and mathematics. We propose a Harvard-led Science and Technology Center (STC), which will leverage the proximity of local and collaborating institutions such as MIT and NASA/GSFC, and make use of the deep synergy of research by several prominent groups, and the timely nature of recent experimental and instrumental advances, to bring us closer to the horizon of a BH than ever attempted before.

The unifying theme of the center will be exploration of BH physics on all cosmic scales, and efforts will focus on addressing the following questions:

- *Does Einstein's theory of GR hold near a BH?*
- *What are the fundamental properties of BHs: Do Event Horizons exist? How fast do BHs spin? What are the quantum properties of BHs?*
- *How do BHs accrete matter, create powerful jets, and influence their surroundings?*
- *How do BHs cause the most powerful explosions in the Universe?*

Work within the center will be organized into several Major Activities (MAs), which are themselves the results of ongoing work within, and collaborations between, the proposing groups.

**MA1: Developing a submm-VLBI Event Horizon Telescope.** The MIT Haystack Observatory and SAO are collaborating on developments aimed at extending VLBI to the shortest wavelengths possible. This technique creates an Earth-sized virtual telescope with the highest angular resolution ever obtained, and has recently been used to resolve the emission surrounding the 4 million solar mass BH at the center of the Milky Way, SgrA*, on the scale of its event horizon. Advanced instrumentation efforts within the STC will increase the capabilities of this long baseline array by more than an order of magnitude to form an Event Horizon Telescope (EHT), to enable imaging of the BH 'shadow', a signature of light bending in the strong gravity environment of the event horizon. The EHT will also time-resolve the orbits of matter as it inspirals to the event horizon.

**MA2: Modeling accretion and emission at the Event Horizon.** VLBI observations on event horizon scales need sophisticated models and simulations for context and interpretation. The BH theory group at Harvard has developed GR ray tracing and radiative transfer algorithms that meld space-time effects with emission mechanisms. Collaborative work has demonstrated that parameters such as the inclination of SgrA*'s accretion disk and the BH spin can be constrained by VLBI data. This Major Activity will advance this work by incorporating more sophisticated emission models and through adoption of results from 3-D, fully relativistic magnetohydrodynamical simulations of accretion flows.

**MA3: Testing modified theories of Gravity.** The size and shape of the BH 'shadow', and the period of orbits at the Innermost Stable Circular Orbit (ISCO), can be used to test GR in the strong gravity regime. The GR group at MIT has pioneered a formalism for describing deviations from GR through multipole expansion that can be used to devise tests of the famous BH "no-hair" theorem using observations across the electromagnetic spectrum. This theorem states that a BH is essentially a large fundamental particle that can be fully described by only three parameters: its Charge (Q), Mass (M), and Spin (a). Higher order multipoles, such as the quadrupole must be determined by mass and spin (the charge is typically zero), but an anomalous quadrupole component would result in deviations of the 'shadow' size given the well-determined mass of SgrA*.

**MA4: Measuring the Spins of Accreting Black Holes.** Knowledge of spin is crucial for understanding how BHs interact with their environment and ultimately for testing GR in strong fields. The Harvard/SAO group is leading development of two methods to measure the spins of stellar-mass BHs in X-ray binary systems. To date, spins for nine BHs have been determined by fitting the thermal X-ray continuum spectrum, and independent spin measurements are being made through observations of the relativistically broadened Iron emission line. The main goal of this activity will be to use measurements of BH mass and spin for a broad sample of BHs to test models of relativistic jets, BH formation, and GRBs. The group engages in X-ray, optical and radio observations of X-ray binaries, and theoretical modeling of accretion disks in strong gravity.

**MA5: Gamma Ray Bursts (GRBs): The brightest explosions in the Universe.** GRBs are likely the clearest signposts for the birth of stellar mass BHs, through either the core-collapse of massive stars, or the coalescence of compact object binaries. The established observational GRB group at Harvard pursues multi-wavelength investigations for fully characterizing the GRB phenomenon including signatures of accretion in the gamma-ray and afterglow emission, ejecta compositions, progenitor system identities, and the GRB rate over cosmic time. Theoretical work at Harvard and MIT focuses on the formation and composition of relativistic jets from GRBs, and the NASA/GSFC group simulates gravitational wave signals from black hole binaries in GRB models that is detectable by upcoming observatories such as Advanced LIGO. This MA links the observational properties of GRBs with simulations of jet formation and propagation, and calculations of gravitational wave signatures to characterize the formation process of BHs, to study their properties at birth, and to probe the conditions and consequences of extreme accretion rates.

**MA6: Quantum Theory of BHs.** BHs are the simplest and most complex objects in the physical world. They are maximally complex in that the number of possible microstates, or entropy, of a BH is believed to saturate a universal bound. They are maximally simple in that, according to Einstein's theory, they are featureless holes in space characterized only by their mass, charge and angular momentum. This dual relation between simplicity and complexity, as expressed in BHs, has recently been successfully applied to problems in a disparate variety of physical systems. This STC activity, led by the Harvard Physics department, will focus on developing our theoretical understanding of both quantum and classical aspects of BHs and their applications.

**MA7: Education and Public Outreach.** Obtaining an image of a BH would potentially be the most exciting result in astrophysics for decades. BHs capture the imagination of young students and the general public in a unique and compelling way, and are routinely the subject of magazine articles, educational TV programs, and science fiction entertainment. The proposed STC will leverage the intense interest in this topic and the excellent outreach facilities at Harvard, SAO, MIT and NASA to focus on development of a broad based EPO program that will engage K-12 students and the general public. This effort will build on over 20 years of experience in improving science education at the Science Education Department (SED) of the Harvard Center for Astrophysics (CfA). This group specializes in research on learning, creation of innovative audiovisual media, instructional tools for physical sciences, and professional development programs for pre-college science teachers. At the MIT Kavli Center, educational programs that highlight 'out-of-school' activities are specifically aimed at underserved groups, and the STC will build on these established programs to recruit and train undergraduates from STC institutes as instructors. In this way, the proposed STC will focus on enriching STEM (Science, Technology, Engineering and Mathematics) curriculum for primary and secondary students through multiple means. This effort will also include participation by the Boston Museum of Science, and the MIT and Harvard outlets to the public. The CfA has already developed a professional Black Hole museum exhibit that is currently at Yale University's Peabody Museum as part of a national tour. Thanks to the exhibit's new technology, we are already gathering relevant feedback from hundreds of thousands of visitors.

**Budget and Scope**

Though nucleating at Harvard, MIT, and SAO, the Center will include strong participation from institutions across the nation. Existing collaborations already provide natural links to expert groups at NASA/GSFC, University of Illinois at Urbana-Champaign, UC Berkeley, University of Arizona, and the California Institute of Technology. Our group is reaching out to other institutions as well, and the response has been overwhelmingly positive. There is little question that a critical mass of Universities and research centers see a Black Hole STC as a timely and exciting opportunity. We envisage a budget of ~$5M per year. This will allow transformative improvements in observations, modeling and theoretical activities, providing a vibrant center environment for joint work as well as community and educational outreach.