Project Description

Project Title: *BHEX Mini: Black Hole Explorer SmallSat*

Executive Summary:

On April 10, 2019, the Event Horizon Telescope imaged M87, directly confirming the existence of black holes. BHEX Mini (Black Hole Explorer Mini) is a satellite which seeks to take the next leap by capturing the first video of a black hole, enabling the first measurement of a black hole's spin.

To capture the first video of a black hole, BHEX Mini must escape the confines of the Earth, where the temporal resolution of ground telescopes is limited by the 24-hour rotational period of the Earth. BHEX Mini will thus launch into a Low-Earth Orbit with a 90-minute orbital period, rapidly imaging black hole targets every 22 minutes at 86 GHz. BHEX Mini will enable black hole movies by resolving accretion disk dynamics on orbital timescales, heralding a new frontier in time domain astronomy. This would enable advancements on black hole spin, jet mechanisms, and binary black hole systems.

To transform this audacious vision into a credible proposal, I trained students at Brown & Columbia University to constrain BHEX Mini's SWaPC requirements, obtain support from Brown's Nelson Center, and establish collaborations with Orion, TU Delft, Texas A&M, and STScI. If funded, BHEX Mini will advance to Phase D of NASA's Program Life Cycle (System Assembly, Integration, Test, and Launch).

Project Description:

See attached document.

Project Description Attachment: *BHEX_Mini_Project_Description.pdf*

Statement of Significance:

BHEX Mini can operate in three distinct roles: (1) A standalone satellite, (2) A partner mission to BHEX, and (3) A pathfinder mission for low-cost space VLBI. We now elaborate on each of these roles.

The spin of a black hole has never been measured. The physical mechanism behind relativistic jets is unknown. Binary black hole systems have never been directly radio-imaged in conjunction with a gravitational wave detector. BHEX Mini would address all three of these major astrophysical problems – leveraging its sub-microarcsecond angular resolution and sub-ISCO temporal resolution to advance our understanding of accretion disk dynamics, black hole formation mechanisms, and active galactic nuclei flaring.

BHEX Mini can also co-observe radio targets with BHEX, creating a first-of-its-kind space-space VLBI system. Operating at 86 GHz from LEO enables BHEX Mini to time-resolve the accretion disk of Sgr A* & M87 and resolve extended jet structure from active galactic nuclei (AGN) targets. By surveying >25 additional radio targets, BHEX Mini will also enable population-level modeling of black hole spin, mass, and luminosity. This would enable the first population-scale parameter estimations on black hole targets, advancing theoretical understanding of black hole formation mechanisms.

Outputs:

As BHEX Mini's science and engineering teams advance our systems architecture and primary science objectives, we expect to publish several papers.

The BHEX Mini engineering team will develop and model each major component of the satellite, including: (1) Instrumentation System Overview, (2) Preliminary Antenna Design, (3) Cryocooler Design & Integration, (4) Primary Receiver for BHEX Mini, (5) LISA Atomic Clock for BHEX Mini, (6) Back-End Electronics for BHEX Mini, (7) Data Uplink from LEO to MEO, and (8) Optimal Orbital VLBI Sandwich Architecture for BHEX Mini + BHEX.

The BHEX Mini science team will establish the feasibility of each PSO, including: (1) Temporally-Resolving Sgr A* & M87 on sub-ISCO Timescales; ISCO defines the last stable circular orbit of a black hole (2) Directly Imaging OJ 287 in tandem with PTA; OJ 287 is a famous binary black hole candidate which has a luminous optical outburst every 12 years. The next outburst is predicted to occur within BHEX Mini's operational lifetime; (3) 86 GHz Targeted Survey of AGN + BBH Science Targets.

The BHEX Mini outreach team will also maintain a public-facing YouTube channel to popularize black hole astronomy. In

BHEX Mini Project Description

By Ref Bari

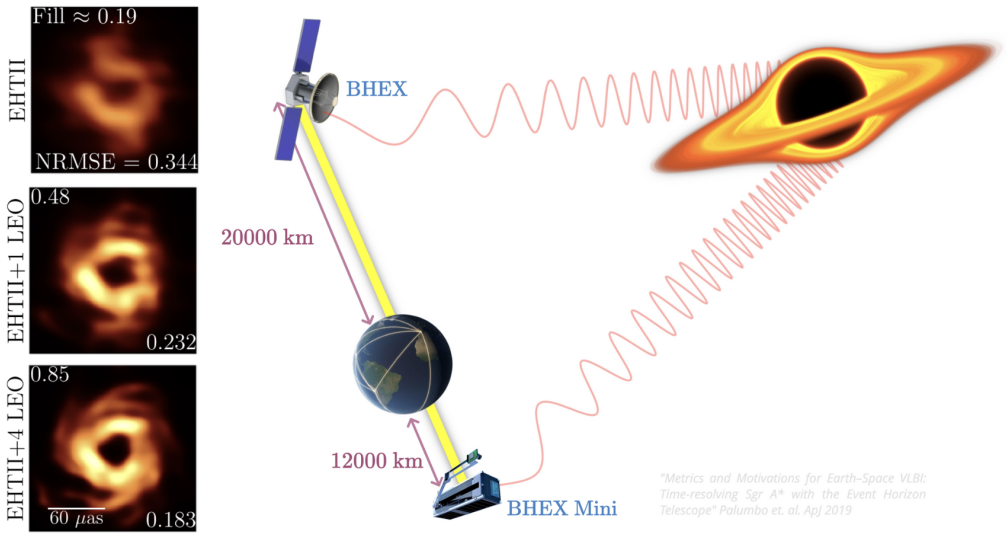

Figure 1. Capturing the first video of a black hole

BHEX Mini is a proposed SmallSat Mission which seeks to capture high resolution videos of black holes. At 87 kg, 500 W, and $25 million, BHEX Mini meets the constraints of a NASA Astrophysics Pioneers Program mission. Unlike the $300 million, 175 kg BHEX mission (under development by Harvard CfA & JAXA), BHEX Mini operates at a lower observing frequency with a fundamentally different primary science objective: capturing the first video of a black hole, as opposed to resolving the photon ring. BHEX Mini seeks to accomplish the following four primary science objectives:

1) Capture first direct video of a black hole using Very-Long Baseline Interferometry (VLBI), combining radio signals with the Event Horizon Telescope.

2) Enable time-resolved multi-messenger astronomy on binary black hole systems by simultaneously co-observing targets with Pulsar Timing Arrays.

3) Conduct a targeted survey of >25 radio targets (e.g., quasars, blazars, relativistic jets, accretion disks, binary black holes, etc.), enabling population modeling of black hole mass, spin, and luminosity distributions.

4) Achieve Space-Space VLBI for the first time by correlating interferometric fringes between BHEX & BHEX Mini.

To achieve the above objectives, the BHEX Mini team will pursue the following work plan for the duration of the 5 year Templeton grant:

1) The Science Team will create simulated observations of targets at 86 GHz from LEO after accounting for all mission parameters and adverse effects (i.e., interstellar scattering, atmospheric decoherence, thermal noise, etc.)

2) The Engineering Team will finalize systems and mission architecture. The Technology Readiness Level (TRL) for all satellite components will be advanced to TRL 7-8. BHEX Mini will advance to Phase D of NASA's Life-Cycle Phases (System Assembly, Integration, Test, Launch & Checkout).

3) The BHEX Mini Team will leverage its extensive social media following (which includes a YouTube channel with 1.4 million YouTube subscribers) to engage in science outreach and popularize black hole astronomy.

To capture the first video of a black hole, BHEX Mini must directly image the target on accretion disk timescales. This is challenging for ground-based telescopes because their temporal resolution is restricted by the Earth's rotational velocity of 0.465 km/s. Thus, to capture the first video of a black hole, BHEX Mini must be launched into low-earth orbit (LEO), where it will orbit the Earth at 7.2 km/s, imaging Sgr A* every 22 minutes. The resulting images will be sequenced together to create a video, enabling the tracking of hotspots within the accretion disk, constraints on the spin of Sgr A*, and testing of the Blandford-Znajek mechanism (which predicts that relativistic jets are powered by black hole spin). The orbital period of the accretion disk of Sgr A* is intimately related to its spin, varying anywhere from 4-30 minutes depending on whether Sgr A* is an extremal Kerr black hole (with Spin Parameter $J = 1$) or static, Schwarzschild black hole ($J = 0$), respectively. BHEX Mini's orbital architecture enables a unique dual short-long baseline capability which permits the satellite to simultaneously probe both small and large-scale morphology in black hole targets.

The success of BHEX Mini's primary science objectives are not contingent upon the existence of the BHEX satellite. Even if BHEX failed to launch, BHEX Mini could still create videos of black holes. Over the next year, the BHEX Mini team will advance the technology readiness level (TRL) for each satellite component, create simulated observations of black hole targets, and determine strategies for mitigating interstellar scattering, atmospheric drag, and thermal noise. If funded under a Templeton Grant, BHEX Mini will advance to Phase D of NASA's Mission Life-Cycle Stages.

addition, team members will engage in public talks, colloquiums, and symposia to promote black hole imaging.

Outcomes:

If funded by a Templeton Grant, the BHEX Mini team expects the following deliverables:
(1) Initiate AIT (Assembly, Integration, and Testing) for satellite instrumentation
(2) Secure a satellite bus provider for BHEX Mini's power systems, solar panels, microcomputers, and satellite gyroscopes.
(3) Secure Memorandum of Understanding (MOU) with Event Horizon Telescope sites to enable co-observing radio targets with BHEX Mini
(4) Secure agreement with BHEX & EHT collaborations to co-observe black hole targets and correlate interferometric fringes between BHEX, EHT, & BHEX Mini.
(5) Simulated observations of black hole targets with BHEX Mini and supporting observatories (i.e., BHEX, ALMA, VLBA, and more).
- Determine temporal-resolution of BHEX Mini's movies of Sgr A* / M87
- Determine feasibility of BHEX Mini constraining spin of Sgr A* / M87

Capacity for Success:

BHEX Mini's leadership structure is as follows: The Lead PI (Ref Bari) is a Physics MS at Brown University. BHEX Mini (TBD) will consist of 12-15 researchers, evenly split between a science and engineering team. Currently, the team includes Prof. Suvi Gezari (University of Maryland) as Co-PI on BHEX Mini's Science Team and Dr. Lucas Anderson (Orion Space Systems) as Co-PI on the engineering team. Prof. Rick Fleeter (Brown University) is the faculty advisor for undergraduate students on the mission. The team currently consists of ~10 students, divided between Brown and Columbia University.

Despite no formal funding to date, and donated time from a diverse set of members and collaborators, the BHEX Mini team has transformed an ambitious vision into a credible proposal. In the last six months, the BHEX Mini team has constrained SWaPC requirements; established collaborations with JPL, Orion & Delft University; and delivered talks on BHEX Mini at Princeton's IAS (09/2025), Ivy Space Conference (04/2025), and SmallSat Europe (05/2026).

With funding and technical support, the BHEX Mini team will advance from conceptual studies to hardware development, building functional prototypes of instrumentation, securing satellite bus providers, and securing a dedicated engineering team.

Relation to Sir John Templeton's Donor Intent:

Sir John Templeton was a philanthropist dedicated to advancing risky, ambitious scientific endeavors. The Templeton Foundation emphasizes research which seeks to answer longstanding, fundamentals questions in the physical sciences. The Templeton Foundation's highest-priority sustaining activity is to fund science projects which (1) Raise Questions of Human Reasoning, (2) Illuminate Cultural and Social Perspectives, and (3) Inspire Awe and Wonder. BHEX Mini is directly aligned with these aims. Capturing the first video of a black hole would not only answer longstanding scientific questions but also transcend cultural and linguistic boundaries, offering humanity a shared glimpse into a profound cosmic reality. The project's ambitious vision embodies the spirit of Templeton's call for risk-taking science: it seeks to inspire global curiosity, foster international scientific collaboration, and achieve a milestone that will revolutionize black hole astronomy.

Project Relationship to Previous Grants: *No*

Proposed Project Start Date: *12/15/2025*

Proposed Project End Date: *12/15/2028*

Personnel

Primary Contact Information

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Project Leader

- *Primary Contact is also the Project Leader*
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Project Co-Leader

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- **Project Co-Leader's CV/Resume Upload:** *SuviGezariCV.pdf*

To the best of your knowledge, is the Project Leader or Project Co-Leader a JTF Trustee, Officer or staff member or related to a JTF Trustee, Officer or staff member as a spouse, sibling, child, or parent?: *No*

Additional Personnel:

Ref Bari, Brown University, Department of Physics (Lead PI)
Prof. Suvi Gezari, Professor (University of Maryland) (Co-PI)
Dr. Lucas Anderson, Cryocooler Engineer, Orion Space Systems (Co-I)
Prof. Rick Fleeter, Faculty Advisor, Brown Satellite Development Team
Dr. Joseph Lazio, Chief Scientist, NASA Deep Space Network (Satellite Communications Advisor)
Ben Hudson, Space Systems Engineering Advisor, KISPE & BHEX (Advisor)
Amelia Frickey, Brown University, Department of Applied Mathematics (Undergrad)
Graham Neely, Brown University, Department of Physics (Undergrad)
Kaylee DeGennaro, Brown University, Department of Physics (Undergrad)
Alexander Khosrowshahi, Brown University, School of Engineering (Undergrad)
Gayda Mohamed, Brown University, Department of Physics (Fulbright Scholar, UAE)
Noah Barton, Brown University, Department of Physics (Grad)
Sebastian Abreu, Columbia University, Department of Mechanical Engineering (Grad)
Tsogt Enkhbat, Columbia University, Department of Astronomy

History with the Foundation:

BHEX Mini's team has no prior Foundation-sponsored grants or event participation. However, we are inspired by the Templeton Foundation's support for ambitious, risky science that advances the frontier of human knowledge. In particular, the Foundation's support for the Event Horizon Telescope (EHT) and Black Hole Initiative (BHI) at Harvard demonstrated a willingness to take risks on transformative astrophysics, ultimately resulting in the first image of a black hole. BHEX Mini builds directly on this legacy—advancing from still pictures to time-resolved black hole movies. This alignment between the Foundation's vision and our scientific objectives motivates our application and represents a natural continuation of the Foundation's prior investments in reshaping our understanding of the universe.

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Organization

Applicant Country & Area: *United States*

Are you seeking funding as an individual: *No*

Organization Name: *Brown University*

Also Known As:

Did this organization receive 50% or more of its annual funding in any one of the last three years from any combination of the John Templeton Foundation, Templeton World Charity Foundation, Inc or Templeton Religion Trust?: *No*

JOHN TEMPLETON FOUNDATION
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Budget

In what currency are you requesting support from the Foundation?: *USD*

Request Amount: *4000000*

Total Project Amount: *25000000*

Brief Budget explanation and Sources of Additional Funding:

We propose spending in the following categories:
(1) Science Objectives
- Videos detailing black hole accretion disk (Sgr A, M87): Receiver backend/digitizers — $240,000.
- Jet morphology & AGN survey (>25 sources): Antenna design, modeling, prototyping — $360,000.
(2) Systems Engineering
- Spacecraft bus procurement/integration — $2 million.
- Cryocooler (4–5 K) R&D — $180,000.
- Orbital configuration simulations — $200,000.
- High-rate downlink trade studies — $440,000.
(3) Team Support
- PI, Co-PIs, Co-Is: $1.4 million of $4 million over 3–5 years (~12–14 senior scientists), ensuring leadership continuity.
- Student research (PhD, MS, UG): In all categories, supporting hands-on work.

Additional Funding:
- NASA NIAC (Req.; $175,000, Sept 2025), NASA Pioneers (Planned; $20 million, June 2026), Moore Foundation, Simons MPS, CSA FAST (Planned).

A $4 million award advances key subsystems to TRL 4–5 and supports a team to deliver a $25 million flagship-class mission.

The proposed project is Fundamental Research, having civilian and military applications. Brown University will be conducting Fundamental Research and therefore expects that it will be exempt from publication restrictions or controls.