



Space-VLBI Frontier Observatory (SFO)

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Noble, Daniel Palumbo, Hannah Rana, Angelo Ricarte, Paul Tiede, and many others

Technologies & Capabilities Day, Ad ASTRA Workshop

September 2, 2026

Graphic: Hannah Rana



Credit: ESO/L. Calçada, Digitized Sky Survey 2, ESA/Hubble, RadioAstron, De Gasperin et al., Kim et al., EHT Collaboration.

Improved Black Hole Imaging is needed to Address Astro2020 Priorities

Space-VLBI is required to address Fundamental Open Questions:

- How do black holes launch and power relativistic jets?
- How are supermassive black holes formed?
- What is the physical origin of explosive transient events?

Key question: What black hole observations would allow us to decisively answer these questions?

“If we could find evidence that relativistic jets extract power directly from spinning black holes through some combination of theory, simulation, and **ultra-high resolution observations of jet-launching regions**, it would be a spectacular demonstration that black holes do not just consume mass and energy – that they also sometimes return energy to the world outside.”

– Astro2020 B-Q3a

NATIONAL
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Sciences
Engineering
Medicine

SCIENCE GOALS SPACE AND GROUND BASED INITIATIVES PROFESSION, RESEARCH, AND TECH RECENT ACHIEVEMENTS FAQ GET THE REPORT SHARE

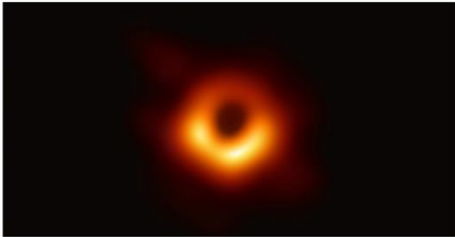
Pathways to Discovery in Astronomy and Astrophysics for the 2020s

Key Scientific Challenges for the Next Decade



Worlds and Suns in Context

Priority Area: Pathways to Habitable Worlds



New Messengers and New Physics

Priority Area: New Windows on the Dynamic Universe



Cosmic Ecosystems

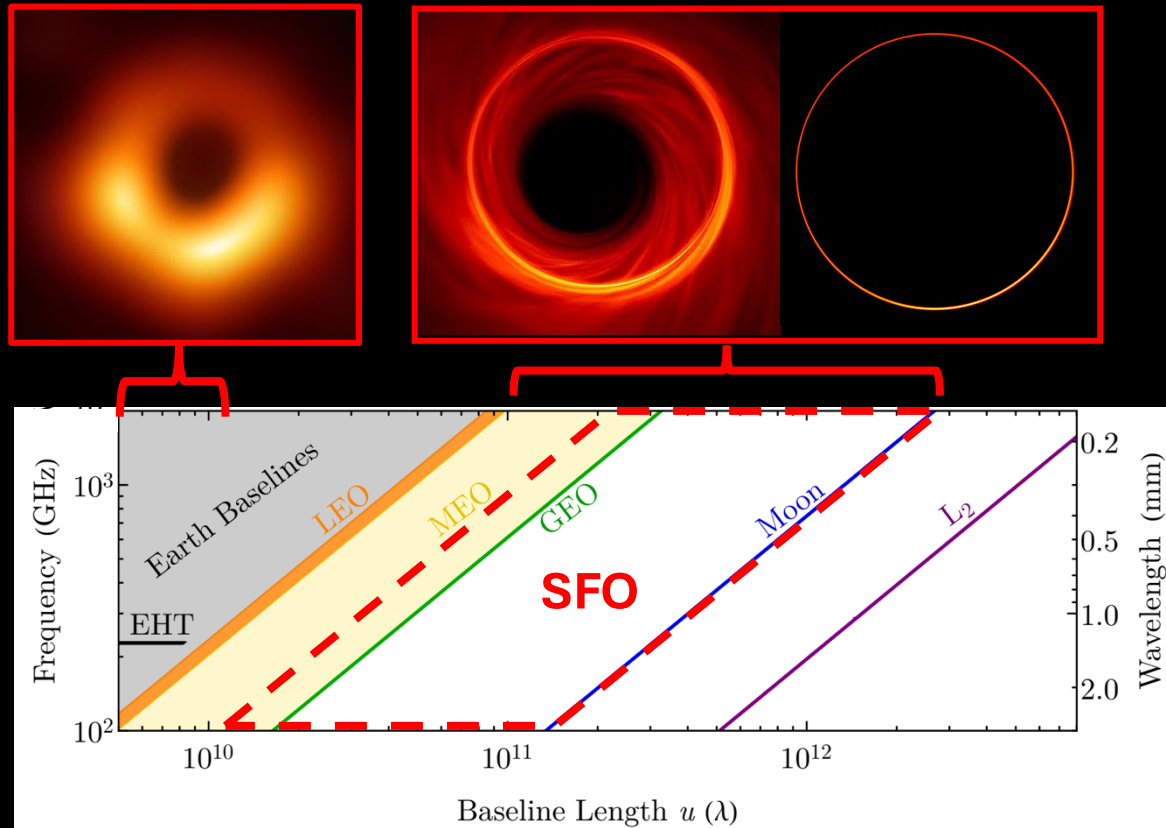
Priority Area: Unveiling the Drivers of Galaxy Growth

Direct Light



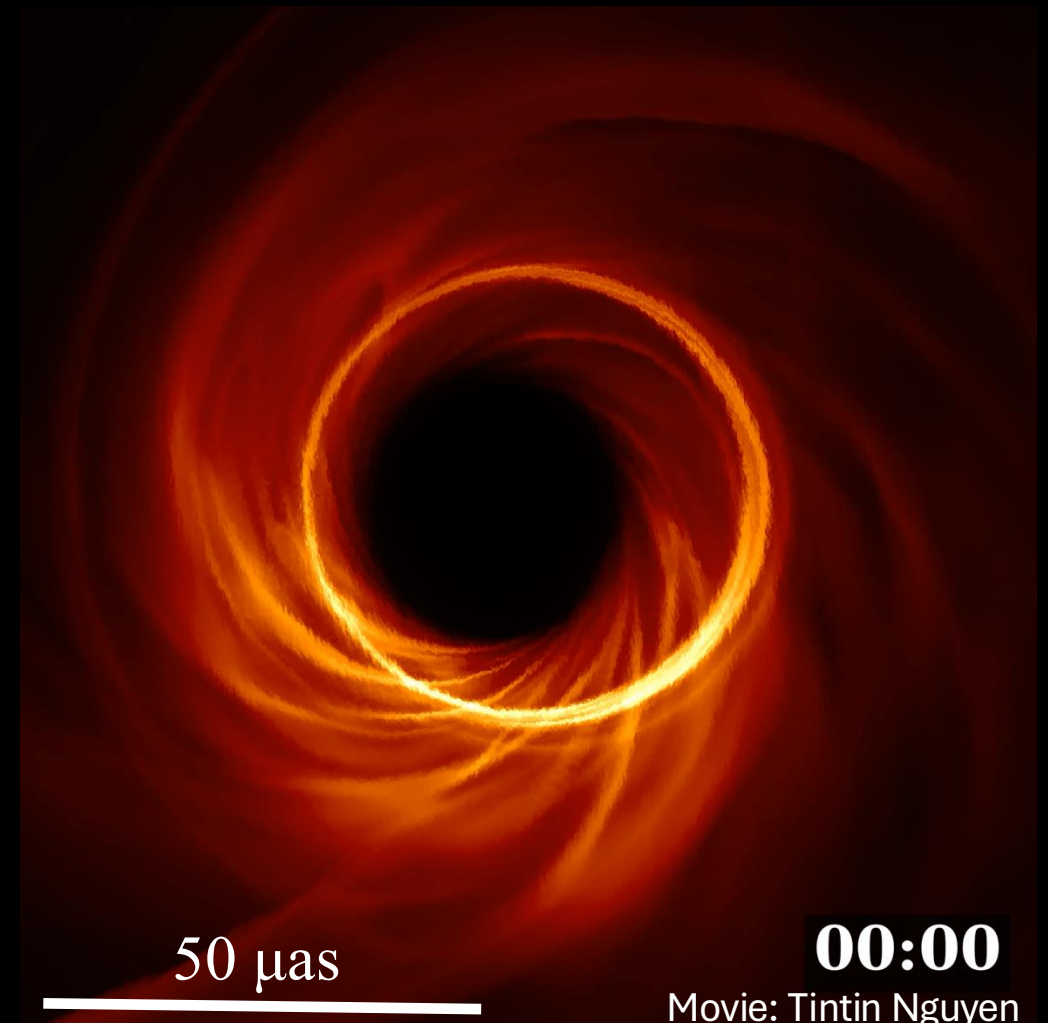
Need Longer Baselines and Higher Frequencies: Photon Rings

Photon Ring Interferometric Response



Adapted from arXiv:1907.04329

Simulated images of Sgr A*

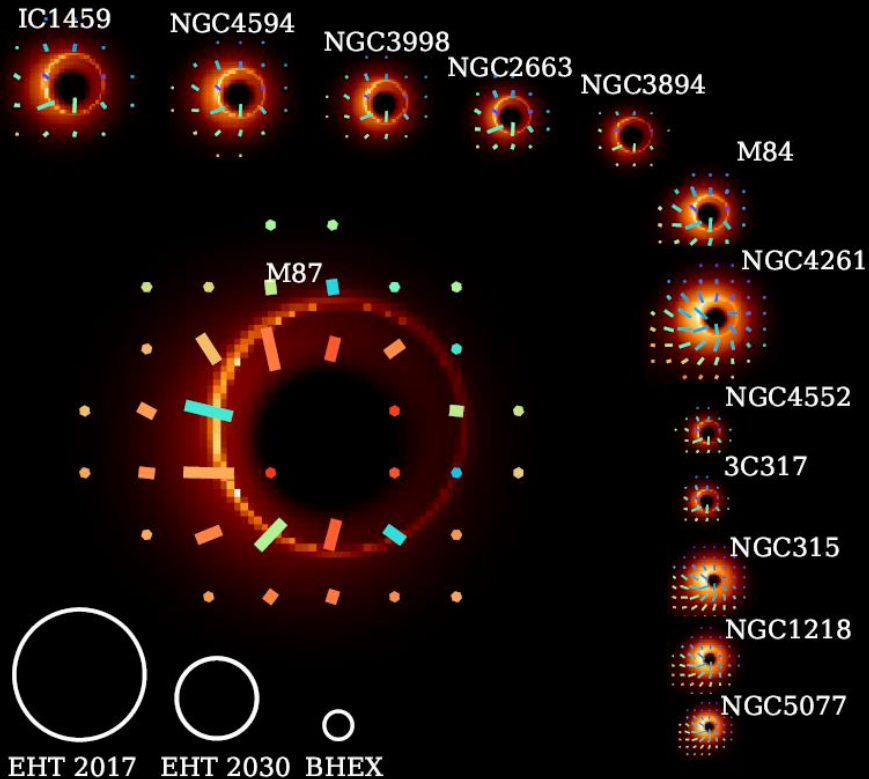


Need Higher Sensitivity: Black Hole Populations

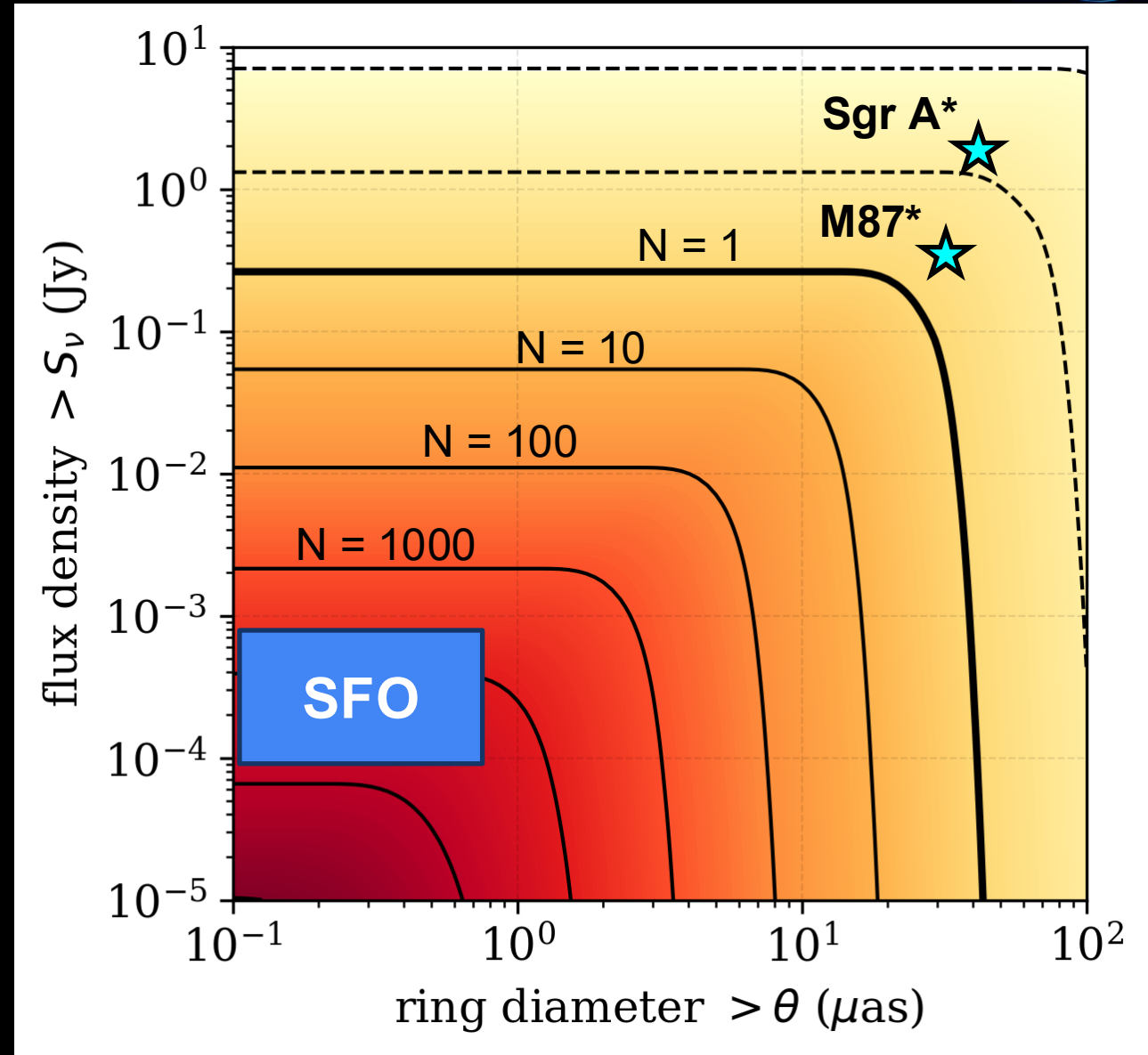


SFO has the combination of angular resolution and sensitivity to study *thousands* of nuclear SMBHs!

Contours show the estimated number of observable, optically-thin black holes that exceed a specified angular size and flux density at 230 GHz (Pesce+ 2021)



Zhang+ 2025



Super Massive Black Hole Binaries: A New Era of Multi-Messenger Astronomy

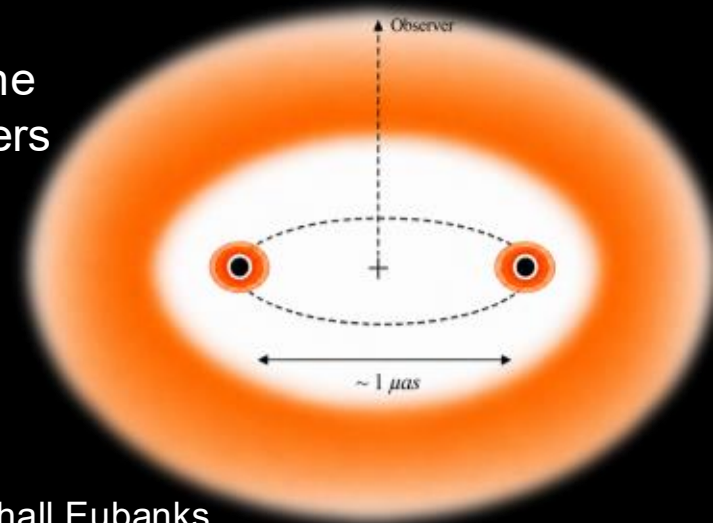


Pulsar timing arrays have provided compelling evidence for a stochastic background of gravitational waves

- The Nanograv 15-year Pulsar Timing Array (PTA) GW strain estimate is 2.4×10^{-15} at a period of 1 year (Agazie et al. 2023)
- If (as is generally expected) the stochastic GW background is due to SMBH binaries, it should be dominated by the larger (order $10^9 M_{\text{Sun}}$) binaries
- ***SFO will be well suited to observing binaries in this mass range***
- Individual SMBH binaries that rise above the stochastic GW background could be searched for by both PTAs and SFO
- Once found, these would multi-messenger tests of both the SMBH binary origin of the GW signal and the highly non-linear physics of black hole binary inspirals and mergers

*See also talk by Joe Lazio

SFO can resolve binaries with separation greater than 1000 AU (0.005 pc) over all of cosmic history



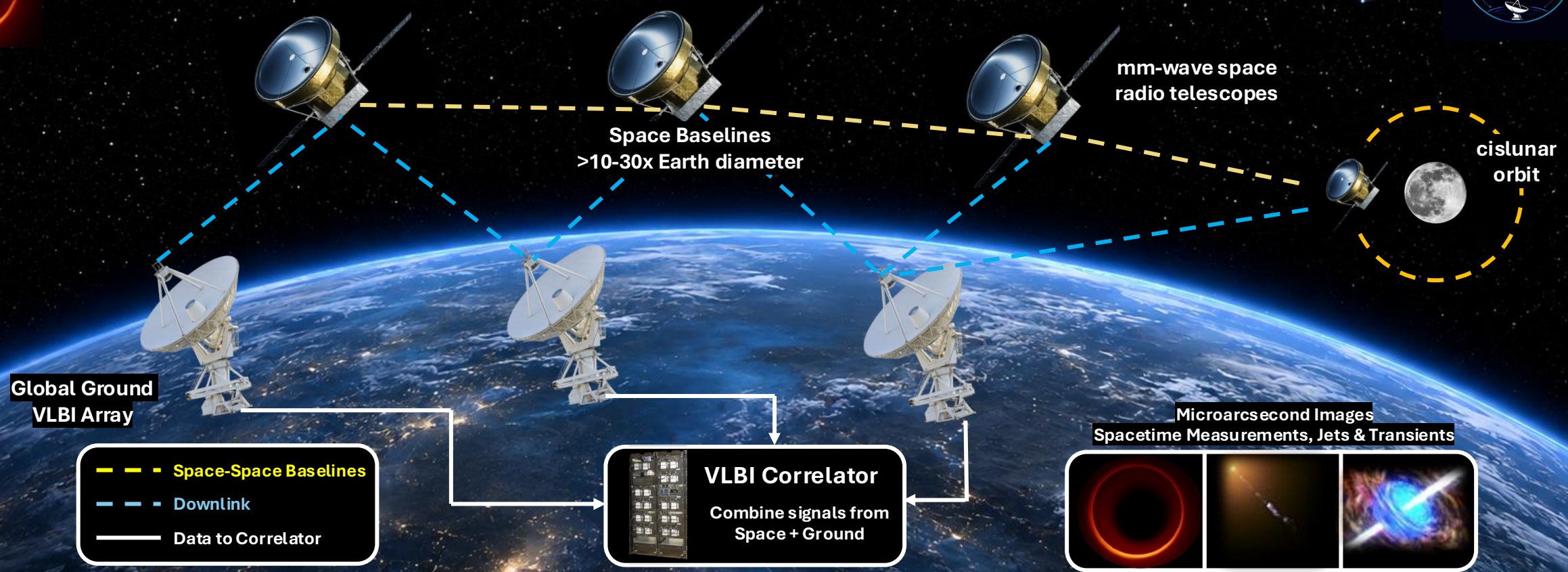
Graphic: Marshall Eubanks



SFO Driving Requirements

- Microarcsecond imaging of SMBHs to enable precision measurements of their spacetimes
Requirement: ≥ 3 spacecraft to form an interferometric array that can form images within the relevant gravitational timescales
- Resolved studies of supermassive black hole binaries together with PTAs
Requirement: 10+ year mission duration
- Studies of a large (1000+) population of supermassive black holes
Requirement: 6-10+ meter apertures to deliver required $< \text{mJy}$ sensitivity
High-Earth / cislunar baselines to deliver microarcsecond resolution
- Studies of black hole magnetospheres and energy outflow
Requirement: Full-Stokes measurement capabilities
- Studies of Sgr A* and nuclear SMBHs in the optically thin regime
Requirement: 345–690 GHz

Space-VLBI Frontier Observatory (SFO) Concept Overview

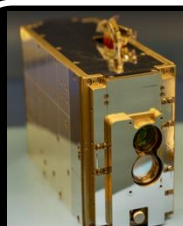


Enabling Technologies



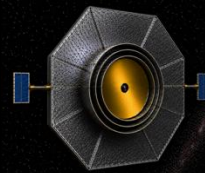
Cryocooler

Mature 4 K space cryocooling technology to maintain low temp of receivers and low noise amplifiers for maximum sensitivity



Laser Comms

High speed laser communications enable multi-Gbps data rates for downlink from space and cislunar orbits to ground



Large Apertures

Precision deployable reflectors, including segmented, CFRP, mesh, or inflatable options in the 6-10 m class



Precision timing

Ultra stable timing references at spacecraft and ground sites ensuring phase coherence across thousands of kilometers



SFO Technology Needs

- **Large Apertures** (main sensitivity driver)

Precision reflectors in the 6-10+ meter class for 345-600 GHz (see, e.g., talk by Chris Walker)

- **Phase coherence** (determines integration time)

Optical-frequency division or comb-based references provide orders of magnitude improvements

- **100+ Gb/s digitization, recording, downlink**

SFO is a computational telescope, generating 10+ PB/day!

- **Long-life 4 K Cryocoolers**

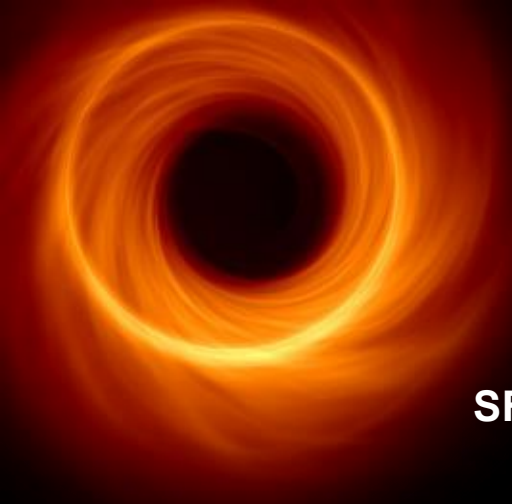
Requires 10+ year demonstrated lifetime for high-performance SIS mixers



SFO Design Study Needs

- Evaluation of (baseline-dependent) **flux sensitivity requirements** to deliver breakthrough science
- Exploration of **orbital configurations** that deliver the required angular resolution and interferometric baseline coverage
 - Evaluation of potential benefits leveraging access to cislunar space through the Artemis/Moon-to-Mars program
 - Evaluation of the potential benefit to extending the SFO to the lunar surface
- Balance between **onboard and ground processing**, including high-speed, robust high-performance space computing and communications capabilities, potentially including the Lunar Communications & Navigation Services (LCRNS)
- Evaluation of the **realistic maturation pathway for large apertures and high-performance frequency references**
- Definition of the **optimum set of observing frequencies**, including considerations of receiver performance, onboard data storage, and sampling necessary for multi-frequency science goals

ASTRA studies will utilize ***ab initio* GRMHD simulations** of black holes, **space-VLBI simulation tools** that have already been developed (e.g., Palumbo+ 2019), as well as **extensive existing exploratory studies of submillimeter VLBI** (e.g., Roelofs+ 2019; Haworth+ 2019; Pesce+ 2019; Lazio+ 2020; Gurvits+ 2022; Kurczynski+ 2022; Johnson+ 2024; Faggert+ 2026)



Summary



SFO will be the first space-VLBI network, exploring a vast new parameter space

SFO will study thousands of black holes, linking a broad population to their relativistic jets and host galaxies

Rich source of multi-messenger science through binary supermassive black holes, jointly studied with pulsar timing arrays

Synergies with CMB studies, studies of O_2 and H_2O , masers, and millimeter transients

Leverages commercial advances in data storage and transmission, optical communications, and low-cost cryogenic systems

ASTRA is an opportunity to secure US leadership in this new frontier, coincident with an explosion of global community interest in space-VLBI and leveraging pathfinder studies including RadioAstron and BHEX



Technology Development Plan

Technology	Present Capabilities	SFO Requirements	ASTRA Development
Precision aperture	3-4 m space antennas (TRL 5)	6-10 m, thermally stable sub-mm surface (TRL 2-3)	Deployment for larger antenna; surface finishing, thermal stability
Cryogenic receiver	~3 year operation 4K space cryocooler; dual-band receivers (TRL 9)	Multi band 345-690+ GHz; low cryocooler vibration; 5-10+ year 4K cryocooler operation (TRL 3-4)	Ground-based 4K cryocooler testing for >5+ year demonstrated operation; develop low vibration cryo technologies
Timing coherence	Ultra-stable referencing, optical links, ground VLBI calibration (TRL 6)	Space-space phase transfer in motion (TRL 2-3 for space-space)	2 node dynamic hardware testing; clock, orbit & delay reconstruction studies
Data	100 Gbps lasercomm demonstrations and high rate recording (TRL 9 – TBIRD)	Hundreds of Gbps per node; storage/onboard versus downlink trades (TRL 2-3)	End-to-end recording tests; storage and onboard processing studies; sustained testing for thermal/power/error accounting
Orbit & operations	Precision orbit and ground array hybrid operations plan developed for BHEX	Dynamic cislunar baselines; rapid target response	Trade study on cislunar orbit versus lunar surface; systematic scenario study for various satellite locations and orbital operation

→ High TRL critical technology exists: SFO must mature their scale, interfaces, and verification to TRL 6