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The Black Hole Explorer: Motivation and Vision

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ABSTRACT

We present the Black Hole Explorer (BHEX), a mission that will produce the sharpest images in the history of astronomy by extending submillimeter Very-Long-Baseline Interferometry (VLBI) to space. BHEX will discover and measure the bright and narrow “photon ring” that is predicted to exist in images of black holes, produced from light that has orbited the black hole before escaping. This discovery will expose universal features of a black hole’s spacetime that are distinct from the complex astrophysics of the emitting plasma, allowing the first direct measurements of a supermassive black hole’s spin. In addition to studying the properties of the nearby supermassive black holes M87* and Sgr A*, BHEX will measure the properties of dozens of additional supermassive black holes, providing crucial insights into the processes that drive their creation and growth. BHEX will also connect these supermassive black holes to their relativistic jets, elucidating the power source for the brightest and most efficient engines in the universe. BHEX will address fundamental open questions in the physics and astrophysics of black holes that cannot be answered without submillimeter space VLBI. The mission is enabled by recent technological breakthroughs, including the development of ultra-high-speed downlink using laser communications, and it leverages billions of dollars of existing ground infrastructure. We present the motivation for BHEX, its science goals and associated requirements, and the pathway to launch within the next decade.

Keywords: Black Holes, AGN, Photon Ring, VLBI, EHT, Jet Launching

1. INTRODUCTION

Black holes are central to questions of stellar evolution, galaxy formation and mergers, astrophysical jets, and the nature of spacetime. They are prodigious energy sources, liberating gravitational energy to power the brightest objects in the Universe.^{1–5} Supermassive black holes are ubiquitous in galactic cores,^{6–9} and their spin can launch and power relativistic jets that extend over thousands of parsecs, ultimately shaping evolution on galactic scales.^{10–12} Yet, the vast influence of black holes originates from their defining property on the smallest scale: a gravitational singularity enshrouded within an event horizon.

Over the past decade, our ability to directly study event-horizon-scale physics using images has been revolutionized by the Event Horizon Telescope (EHT). The EHT is an Earth-spanning very-long-baseline interferometry (VLBI) array that has produced images at ~ 230 GHz (corresponding to a wavelength of $\lambda = 1.3$ mm).^{13–29} The longest baselines of the EHT have a length of $d \approx 11,000$ km, with a corresponding angular resolution $\lambda/d \approx 20 \mu\text{as}$. This resolution is only a few times larger than the angular gravitational scales $\theta_g \equiv GM/(c^2 D)$ of its two primary targets: M87* ($\theta_g \approx 4 \mu\text{as}$), the $M \approx 6 \times 10^9 M_\odot$ black hole at the center of the elliptical galaxy M87, located $D \approx 53$ million light years away, and Sgr A* ($\theta_g \approx 5 \mu\text{as}$), the $M \approx 4 \times 10^6 M_\odot$ black hole at the center of the Milky Way, $D \approx 27,000$ light years away. Previous VLBI studies of M87* and Sgr A*—even those with space VLBI^{30,31}—could not access these scales because they were performed at lower frequencies, where synchrotron self-absorption (for both targets) and interstellar scattering (for Sgr A*) entirely obscure horizon-scale features. The combination of the sharp angular resolution and high observing frequencies with the EHT revealed a dark central region (the “apparent shadow”³²) in each source, with a diameter of about $10\theta_g$.

The EHT images have had a profound influence across the astronomy and physics communities, and they prompted a worldwide explosion of interest in black holes from the general public. The EHT image of M87* features prominently in the Astro2020 Decadal Survey,³⁹ which noted the important role that such observations could play in two of its three organizing science themes—“Cosmic Ecosystems” and “New Messengers and New Physics”—particularly in pursuit of answers to fundamental questions about accretion, jets, galaxy evolution, and strong-field gravity. At EHT resolution, we are beginning to see the structures controlling inflow and outflow around the black hole, but are limited in what we can discern about spacetime itself or the mechanism through which black holes anchor, launch, and power their relativistic jets.⁴⁰ For example, while the EHT images give the masses of M87* and Sgr A* to an accuracy of $\sim 10\%$, they do not directly constrain either black hole’s spin. Finer details in the images of black holes, just beyond the reach of an Earth-bound VLBI array, reflect crisp relativistic features and would enable truly fundamental discoveries.

Recently, we have shown that general relativity predicts a universal feature of black hole images: a sharp ring of light formed by photons that escape after orbiting near the event horizon, known as the “photon ring”.^{41,42}

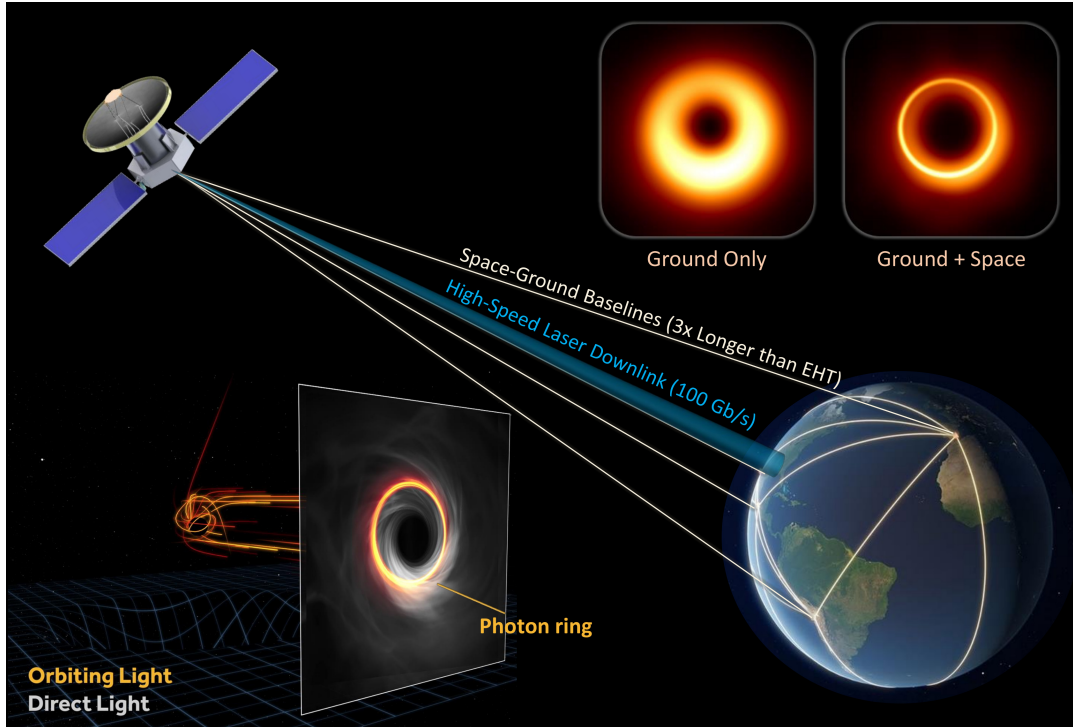


Figure 1. **The BHEX mission concept.** Black hole images display distinctive, universal features such as a sharp “photon ring” that is produced from light that has orbited the black hole before escaping. By extending the Earth-spanning EHT into space, BHEX will be the first mission to make precise measurements of this striking, untested prediction from general relativity, enabling the first direct measurement of a supermassive black hole’s spin.

This photon ring arises from the family of unstable spherical photon orbits near a Kerr black hole.^{43–45} The properties of the black hole, including its spin, are elegantly encoded in the photon ring, as is the origin of black hole feedback power.^{41,42,46–48} For ground-ground VLBI baselines, the photon ring is blended with the more weakly lensed emission,⁴⁹ but it can be isolated using space-ground VLBI baselines where the signal is dominated by the sharpest image features.^{41,50,51} Moreover, it can be studied using a sparse interferometric array because of a telltale “ringing” pattern in interferometric space.^{41,52–59}

Motivated by the promise of such measurements, we have developed a concept for a mission that would extend the EHT to space: the *Black Hole Explorer* (BHEX; see Figures 1 and 2). This work has included contributions from over 100 scientists and engineers, focused workshops on science and engineering,^{60,61} white papers summarizing the potential capabilities of space VLBI and exploring a variety of mission concepts,^{62–67} detailed studies on crucial technologies,⁶⁸ and extensive international contributions that include a burgeoning consortium of scientists and engineers from the Japanese space community.⁶⁹ BHEX will operate as a “hybrid observatory”,^{70,71} combining mission-critical infrastructure on the ground and in space. In particular, these efforts to develop BHEX are catalyzed by intensive parallel efforts to expand the ground-based capabilities of the EHT through higher-frequency observations,^{72,73} major upgrades and expansion of the array,^{33,74–77} frequency phase transfer through simultaneous multi-band observations,^{78–81} and enhancements of the most sensitive ground facilities such as the ALMA Observatory.^{82,83}

In this paper, we describe our vision for BHEX and the technology and instrumentation that makes it possible to launch as a NASA Explorers mission within the next decade. We begin by summarizing the science goals (Section 2) and their associated requirements (Section 3). We then describe the instrument and its associated heritage (Section 4) and the concept of operations (Section 5). We conclude with a summary of the mission status and pathway to launch (Section 6). A series of associated white papers describe the BHEX instrument,⁸⁴ its associated subsystems,^{85–90} the planned coordination with ground networks,⁷¹ as well as several of the primary science drivers for the mission.^{91–93}

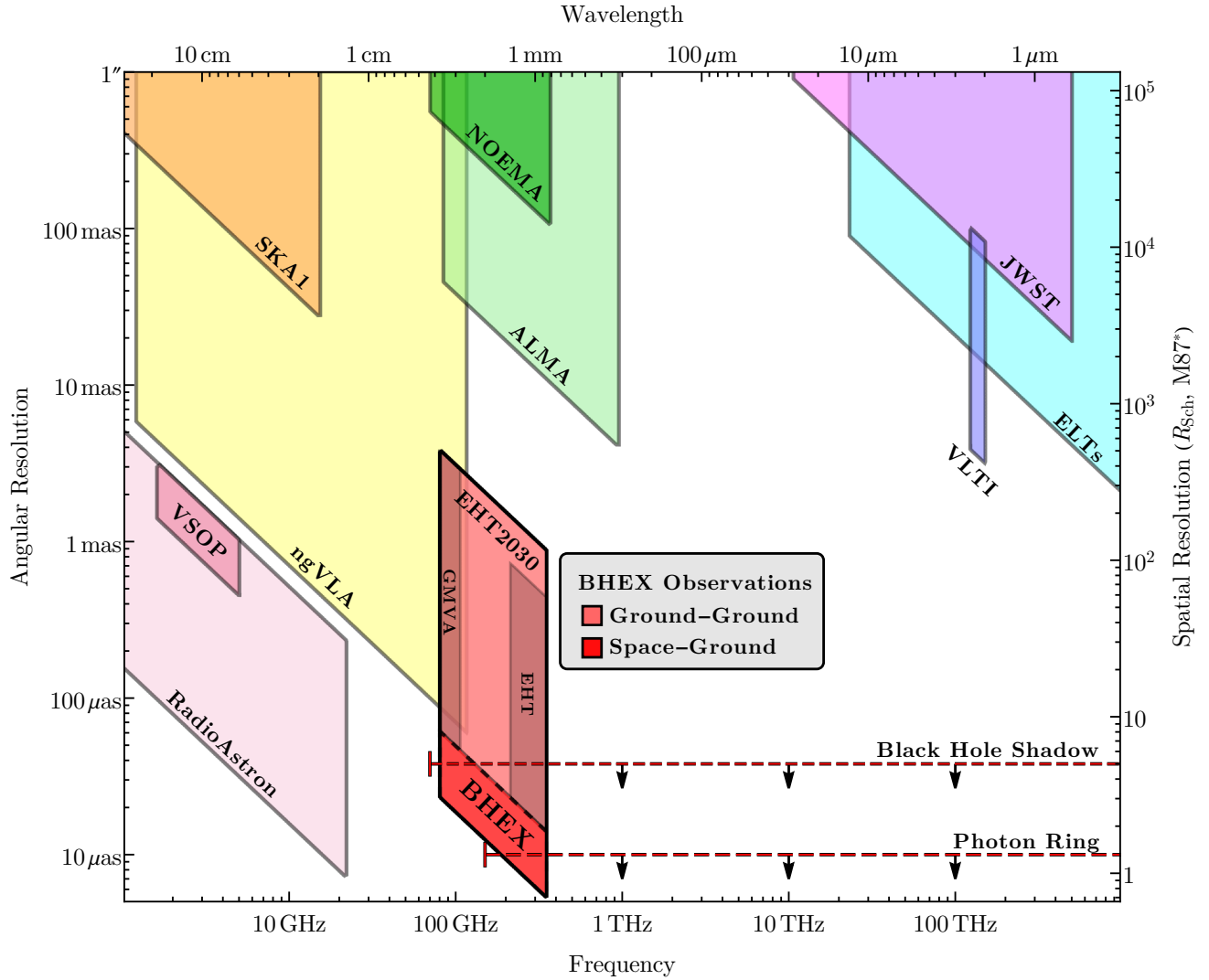


Figure 2. **BHEX: Opening a new window on the Cosmos.** BHEX will deliver the sharpest images in the history of astronomy, accessing structures that no other facility can reach. Ground-based VLBI has steadily improved its capabilities over the past decades, with facilities spanning the globe. At the highest frequencies, the EHT has resolved the apparent shadows of the M87* and Sgr A* black holes and is being significantly enhanced through programs including the next-generation EHT (ngEHT^{33,34}) to include new telescopes and to span frequencies from 80-360 GHz with simultaneous multi-band observations. However, ground-based VLBI cannot produce images at frequencies above ~ 400 GHz because of severe atmospheric turbulence and absorption.³⁵ Past space-VLBI missions (VSOP³⁶ and RadioAstron³⁷) observed only at frequencies below ~ 22 GHz, where relativistic features such as the black hole shadow and photon ring cannot be seen because of synchrotron self-absorption. By working with ground millimeter/submillimeter facilities, BHEX will be the first mission to overcome both limitations, thereby revealing a black hole's photon ring. Figure adapted from Refs. [34, 38].

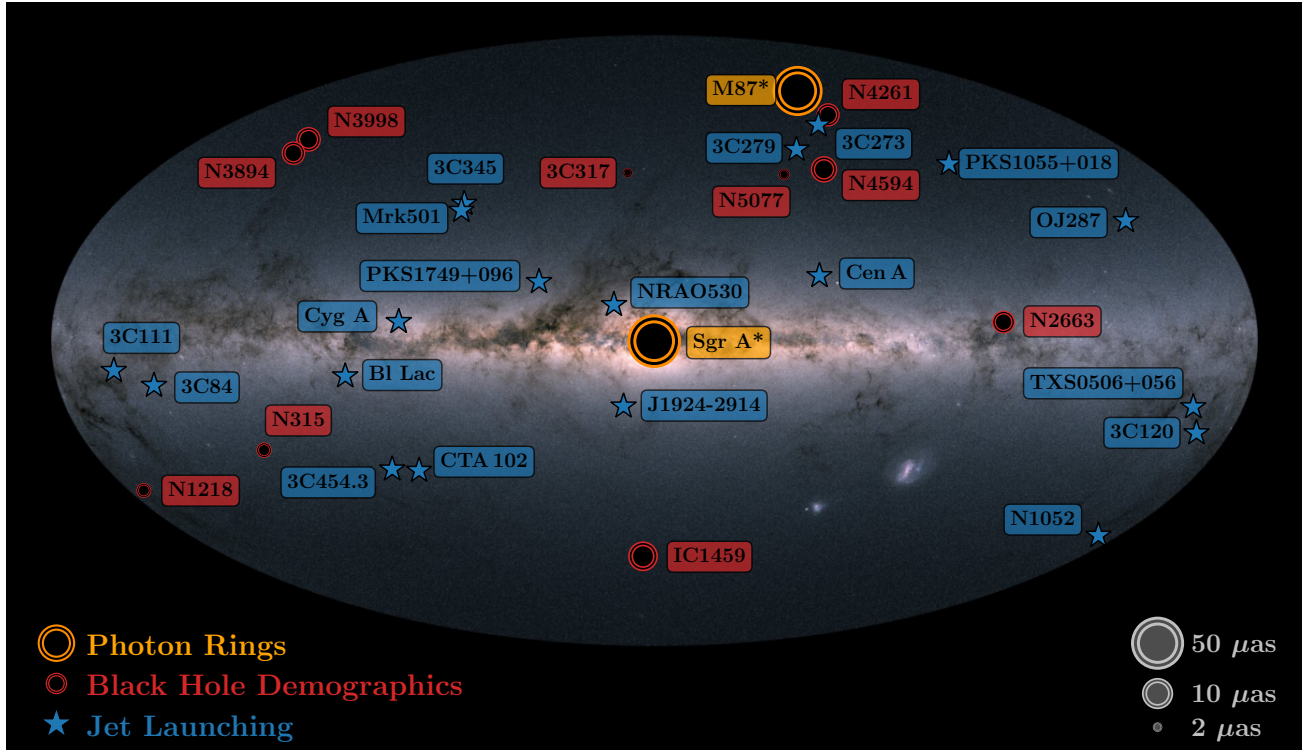


Figure 3. **Potential BHEX targets.** Horizon-scale targets are shown as rings, scaled (logarithmically) by the expected angular size of the black hole shadow. The primary targets for photon ring studies and direct measurements of spin, Sgr A* and M87*, are shown in orange. The remaining horizon-scale targets, shown in red, include a variety of sources in low accretion states, sampling both radio-loud and radio-quiet sources.⁹⁴ In addition, BHEX will study a wide variety of AGN with prominent jets, including potential binary supermassive black holes (e.g., OJ287), sources associated with neutrino emission (TXS0506+056), and bright gamma-ray blazars with superluminal features (e.g., 3C279, CTA102). Many of these sources have already been studied with the EHT.^{95–99} Background image: ESA/Gaia/DPAC.

2. SCIENCE GOALS

We now summarize the primary science goals for BHEX. These goals address some of the most pressing open questions in black hole science across three broad themes. In Section 2.1, we describe how BHEX will reveal fundamental properties of supermassive black holes through studies of the photon rings in M87* and Sgr A*. In Section 2.2, we describe how BHEX will determine how supermassive black holes launch and accelerate relativistic jets through measurements of the jet collimation profile, polarization structure, and dynamics in a sample of active galactic nuclei. Finally, in Section 2.3, we show how BHEX will probe the growth of supermassive black holes by measuring the horizon-scale properties of a population of supermassive black holes in low accretion states across a variety of galaxy morphologies. Figure 3 summarizes potential targets for BHEX across these three science goals. For discussion of additional science opportunities with BHEX, including a potential single-dish mode, see Ref. [69].

2.1 Precision Measurements of Black Holes: the Photon Ring

Photons passing near a black hole can fall in or escape to infinity. Between those two possibilities are unstable orbits that lie on spherical surfaces.^{43,44} For a non-rotating (Schwarzschild) black hole, these orbits have a common radius (defining the “photon sphere”). For a spinning (Kerr) black hole, these orbits lie within a range of radii (defining the “photon shell”).

This shell of unstable spherical photon orbits produces a striking image feature, produced from light that has orbited the black hole before escaping: the photon ring (see Figures 1 and 4).^{41,91} Because the photon ring is

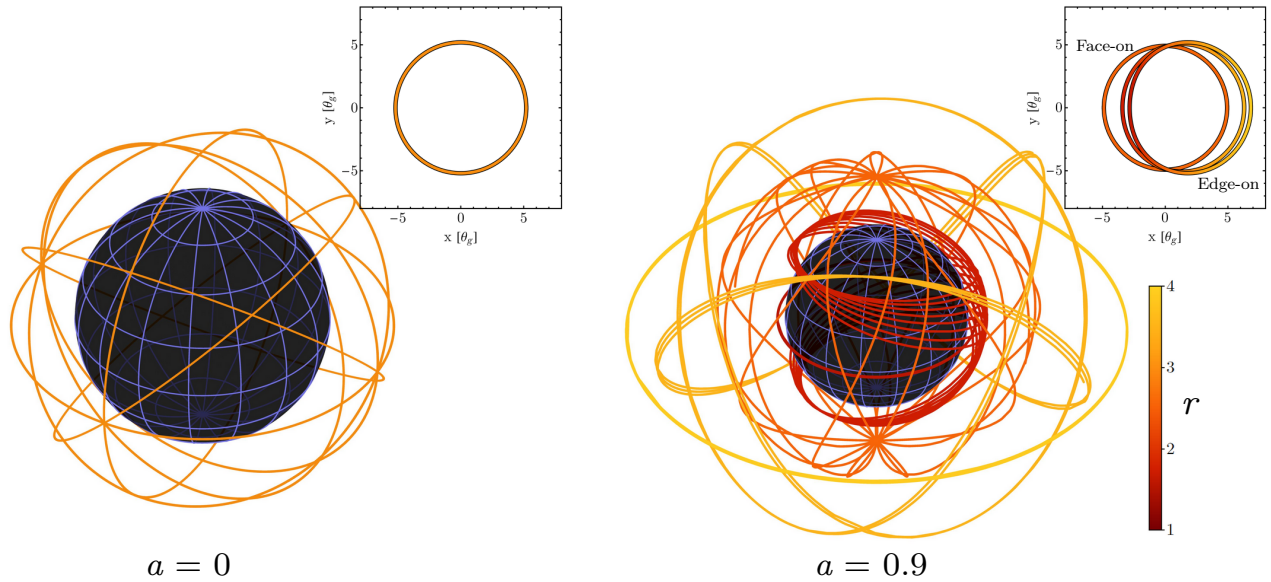


Figure 4. **The photon ring.** A black hole's photon ring arises from the family of unstable photon orbits near a black hole, which are bound on spherical surfaces (in Boyer-Lindquist coordinates).^{43,44} The left panel shows orbits for a non-rotating black hole ($a = 0$; the event horizon is at $r_+ = 2GM/c^2$), which lie at a fixed radius $r \equiv 3GM/c^2$ (defining the photon sphere) and give rise to an asymptotic photon ring that is circular with a radius $\sqrt{27}\theta_g$ (shown as the inset). The right panel shows orbits for a rotating black hole ($a = 0.9$; the event horizon is at $r_+ = 1 + \sqrt{1 - a^2} \approx 1.4GM/c^2$), which span a range of radii (defining the photon shell) and give rise to an asymptotic photon ring that is both smaller and deformed, with a size and shape that are sensitive to the spin and viewing inclination relative to the spin axis.^{41,44,100} Remarkably, the image of the photon shell maps photon orbits at varying emission radius to varying image angle. A [video](#) showing these photon orbits is available online.

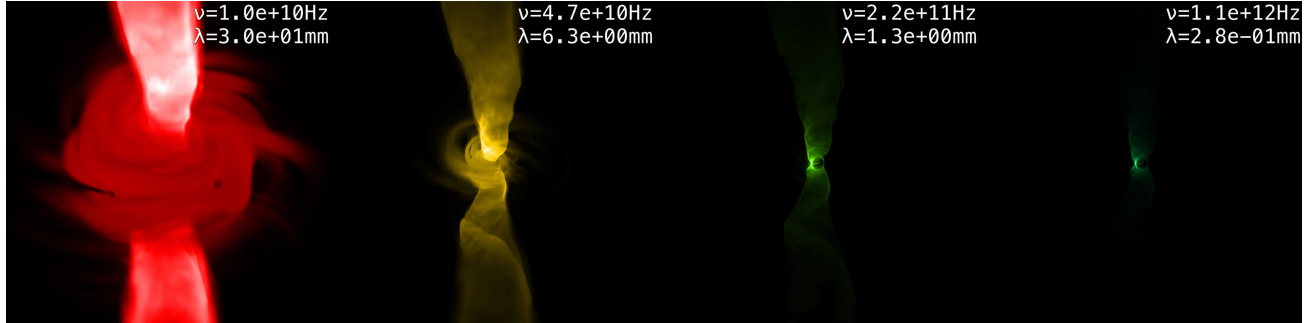


Figure 5. **Model of Sgr A* shown in multiple wavelengths.**¹⁰¹ Two panels on the left: For low frequencies (< 100 GHz), the accretion flow is optically thick and blocks the photon ring. Two panels on the right: For higher frequencies (> 200 GHz), the accretion flow becomes optically thin and the photon ring is visible. A [video](#) showing the opacity with changing frequency is available online.

a result of gravitational lensing, it is generically seen on simulated images,^{41,102,103} including those from state-of-the-art general relativistic magnetohydrodynamic (GRMHD) simulations,^{17,26,104,105} whenever the emission is optically thin (see Figure 5). In addition, the photon ring is a *universal* signature—the surrounding matter has negligible effects on the trajectory of light. Thus, resolved measurements of the photon ring present an extraordinary opportunity for detailed studies of a black hole's spacetime.

The most technically demanding goal of BHEX is to discover the predicted photon rings in M87* and Sgr A*, with measurements that are precise enough to directly measure the black hole spins. In particular, BHEX can provide a firm, model-independent detection of the photon ring by measuring its distinctive interferometric signature for the time-averaged signal on long baselines: a damped periodic signal as a function of baseline length

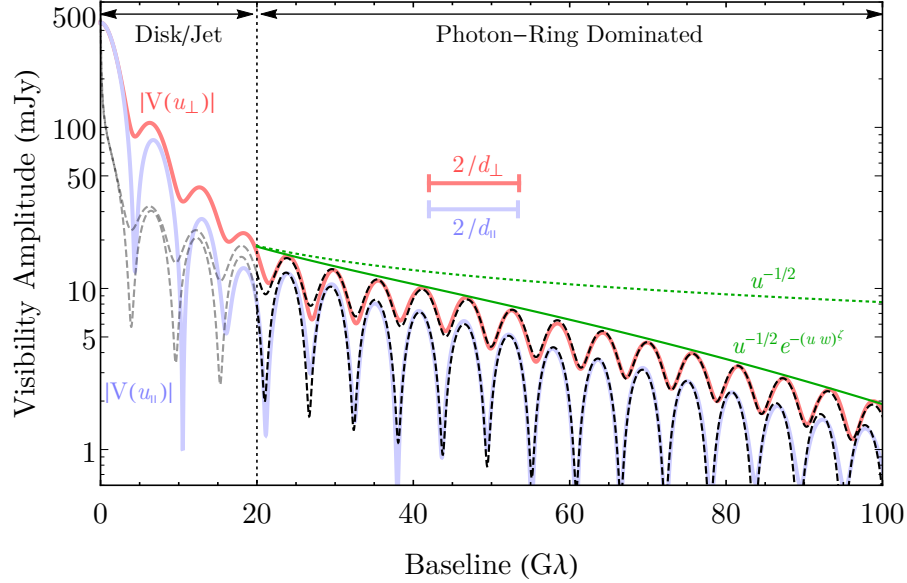


Figure 6. **Universal interferometric signature of the photon ring.** The black hole photon ring produces a strong interferometric signature in the radio visibility of the source. Here, we show the periodic signal produced in a time-averaged GRMHD-simulated image of M87*. This clear ringing dominates the signal on long baselines to space and displays a periodicity that encodes the angle-dependent diameter of the photon ring.^{52–54} Measuring this periodicity on the space baselines targeted with BHEX will provide a clear photon ring detection and measurement of its shape, which encodes information about the black hole mass and spin.⁹¹ Reproduced from Ref. [41].

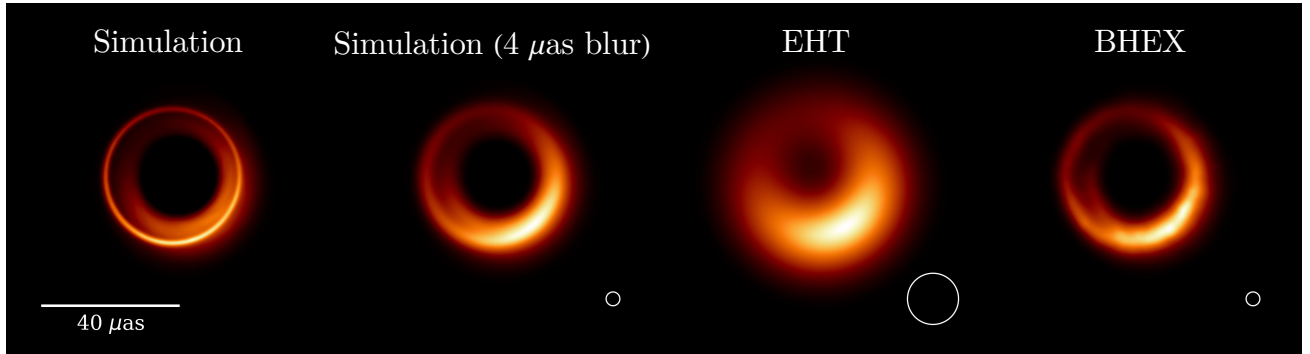


Figure 7. **Black hole imaging with BHEX.** The left panel shows a time-averaged image of M87* from a GRMHD simulation, which displays prominent relativistic features such as the photon ring and inner shadow.¹⁰⁸ The left-center panel shows the simulated image convolved with a $4\mu\text{as}$ Gaussian beam. The right-center panel shows an image reconstruction at the approximate resolution of the current EHT ($15\mu\text{as}$). The right panel shows a reconstruction with BHEX at 240 GHz, averaging 30 simulated observations over a 3-month window ($\approx 240GM/c^3$).¹⁰⁹ These observations used a ground array with 10 existing ground telescopes (but excluding the ALMA array). The improved angular resolution with BHEX accesses the sharp features, which are blended together at the resolution of the EHT.

(see Figure. 6).⁴¹ Because the dimensionless baseline length $u = d/\lambda$ depends on both the physical baseline length d and the observing wavelength, λ , a single ground-space baseline can see the periodic oscillation in u as long as the stations in the baseline instantaneously capture a wide enough range of wavelengths. Thus, BHEX has the ability to uncover this prediction of general relativity through its recently discovered imprint that is only accessible on space-VLBI baselines,^{41,46,49,52,57,106,107} as well as through direct imaging (see Figure 7).

BHEX measurements of the photon ring would provide unambiguous measurements of black hole spin (see Figure 8). Specifically, a spinning black hole has a non-circular photon ring, with a degree of asymmetry that increases with the magnitude of the black hole's spin.^{55,110,111} Thus, precise measurements of the photon ring offer an opportunity to make this fundamental measurement of the spin of M87* and to test whether the

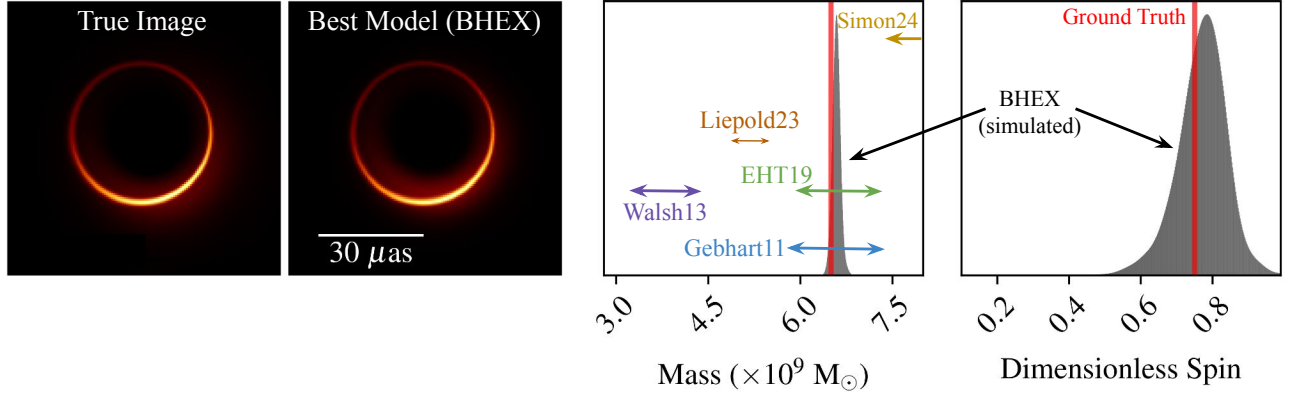


Figure 8. **Measuring black hole spin with BHEX.** These panels show the results of model fits to a simulated image of M87* (left) using software that simultaneously fits for the black hole spacetime and the plasma parameters in a Bayesian framework.¹¹⁵ The marginalized posteriors on the black hole mass and dimensionless spin are shown in the rightmost two panels (the red vertical lines show the correct GRMHD values for this test). The maximum likelihood fitted model is also shown for comparison. These fits indicate that BHEX can make measurements of the black hole mass that are sufficiently precise and accurate to resolve tension among even modern measurements of the M87* mass across a variety of methods.^{18,116–119} More importantly, BHEX can constrain the black hole spin to $\sim 10\%$ accuracy, even accounting for systematic uncertainties from the complex astrophysical environment.

black hole’s spin is indeed the energy source for its powerful jet.^{10,48,112} We note that there are no previous measurements of spin in supermassive black holes that are not strongly dependent on astrophysical assumptions. One of the most relied-upon methods currently uses models of accretion disks and their predicted x-ray reflection spectra to match against observed fluorescent emission lines; the precise shape and width of these emission lines depends on the depth to which the accretion disk’s inner edge lies, which in turn depends on the black hole spin and the assumption that the reflected emission truncates at this inner edge.^{113,114} For additional discussion of the details and scientific opportunities related to photon ring measurements for BHEX, see Refs. [91,92].

The photon ring also provides an avenue to explore exotic alternatives to Kerr black holes. At the resolution of the EHT, these alternatives can effectively mimic the appearance of a Kerr black hole.^{120–124} However, they can produce strikingly different photon rings at scales accessible to BHEX. For instance, boson stars—macroscopic quantum objects with no hard surface, no horizon, and no singularity—may possess no photon shell and thus exhibit no photon ring in the image, depending on their discrete angular momentum and scalar field compactness.¹²⁵ By contrast, images of wormholes can produce multiple photon rings, composed of light bent around photon shells on both sides of the wormhole.¹²⁶ For additional discussion of how extensions of the EHT can be used to constrain fundamental physics, see Ref. [124].

2.2 The Origin of Relativistic Jets from Supermassive Black Holes

One of the most remarkable byproducts of black hole accretion is the production of relativistic jets. These jets are among the most energetic phenomena in our universe, emitting radiation throughout the entire electromagnetic spectrum, from radio wavelengths to the γ -ray regime, and even accelerating particles to the highest measured energies.¹² High-resolution VLBI observations and numerical simulations have advanced our understanding of the accretion processes and the ensuing jet formation. Observations with the EHT have enabled us to probe the innermost regions of the accretion flow and the base of the jet in unprecedented detail, revealing intricate structures and magnetic field configurations crucial for jet launching.⁴⁸ These findings support the hypothesis that the interplay between the black hole spin and the magnetic field topology near the event horizon plays a pivotal role in jet formation. Moreover, GRMHD simulations have demonstrated that the efficiency of jet production is strongly dependent on the black hole spin parameter and the magnetic flux accumulated in the vicinity of the black hole.¹⁰ Despite these advancements, the exact processes governing the conversion of accreted mass and energy into collimated, relativistic outflows remain largely unknown.

Among the various types of active galactic nuclei (AGN), blazars are particularly notable for their highly energetic jets pointed almost directly toward Earth. Mapping the innermost regions of blazar jets to understand

how they are launched, collimated, and accelerated, as well as the role played by magnetic fields in these processes, requires state-of-the-art VLBI observations with the highest possible angular resolution. Space-VLBI observations at centimeter wavelengths with RadioAstron have enabled the mapping of blazar jets with angular resolutions on the order of tens of microarcseconds. These observations have revealed how the jet in the powerful radiogalaxy 3C84 is collimated,¹²⁷ the presence of helical magnetic fields launching powerful relativistic jets in BL Lac,¹²⁸ and how the development of Kelvin-Helmholtz instabilities leads to the formation of filaments in the jet of 3C279,¹²⁹ structures that remain hidden when observed with ground-only arrays. Conversely, ground-based millimeter VLBI observations with the Event Horizon Telescope offer the highest possible angular resolution achievable from the ground, reaching $20\ \mu\text{as}$. These observations operate at wavelengths where the blazar sources are optically thin, allowing us to penetrate the deepest regions of blazars and study areas closest to the black hole, which remain hidden behind an opacity curtain at other wavelengths. The EHT observations of the blazar 3C279 have revealed an unexpected twisted and bent jet structure close to the central black hole,⁹⁵ while observations of Centaurus A have detailed the jet collimation and its connection to the supermassive black hole,⁹⁶ enhancing our understanding of jet formation and acceleration mechanisms. These results (see also Refs. [97–99]) highlight the transformative potential of the EHT in advancing our knowledge of relativistic jets in AGN. The next natural step to obtain the sharpest view of blazar jets as close as possible to the central black hole is to perform space-VLBI observations at millimeter and submillimeter wavelengths with BHEX, capable of achieving angular resolutions of just a few microarcseconds.

Another key aspect to understand the nature of blazar jets is to decipher where and how the high energy emission observed from these objects is produced. Multi-wavelength observations have shown that flares in γ -rays are usually preceded by a rapid rotation of the optical polarization angle at optical and millimeter wavelengths, which provides evidence for the existence of a helical magnetic field in the innermost jet regions, where the plasma is accelerated and collimated.^{130–132} Correlations among the different spectral bands have also allowed to locate the site of the γ -ray emission parsecs away from the central engine in OJ287, AO 0235+164, 3C120, and CTA102.^{133–137}

In recent years, there has been a growing association between flaring activity in blazars and neutrino events. High-energy neutrino detections by telescopes like IceCube have been temporally linked to blazar flares, as exemplified by the case of TXS 0506+056.^{138,139} Further studies have shown a statistically significant association between neutrino sources and the bright cores of blazars, suggesting that these jets are likely sites of neutrino production.¹⁴⁰ The correlation between a sharp gamma-ray and optical flare with the 8 December 2022 neutrino detected toward 0735+178 adds to the evidence supporting this connection.¹⁴¹

Figure. 3 illustrates some of the most promising AGN targets for the BHEX mission. These targets include potential supermassive binary black hole systems, neutrino candidates, nearby AGN where we can study jet formation and dynamics as close as possible to the central engine, and some of the brightest γ -ray sources in the sky.

2.3 Supermassive Black Hole Demographics and Growth

Finally, while BHEX will only be able to probe the photon rings for the most massive and nearby SMBHs (primarily M87* and Sgr A*), it will be able to spatially resolve the horizon-scale emission for black holes that are substantially less massive or more distant, providing images comparable in quality to the current EHT images of M87* and Sgr A*. The ring-like structures seen by the EHT towards M87* and Sgr A* are expected to be ubiquitous for accreting black holes observed in the optically thin regime, and the angular diameter of the emission ring θ_r is proportional to the black hole’s mass-to-distance ratio: $\theta_r \approx 10M/D$.¹¹²

The angular resolution of BHEX will in principle be sufficient to spatially resolve dozens of additional SMBH shadows in the nearby ($z \lesssim 0.1$) Universe.¹⁴² Unlike most AGN samples, which are biased towards (rarer) high-Eddington ratio objects, BHEX targets for horizon-scale studies will be predominantly those with low Eddington ratios, more representative of the typical accretion states of supermassive black holes. Figure. 9 shows the estimated Eddington ratios and black hole masses for a subset of candidate BHEX targets from Ref. [94], selected from the ongoing Event Horizon and Environs (ETHER) survey.^{143,144} Eddington ratios are estimated based on the 230 GHz flux density; black hole masses are typically derived from dynamical modeling.

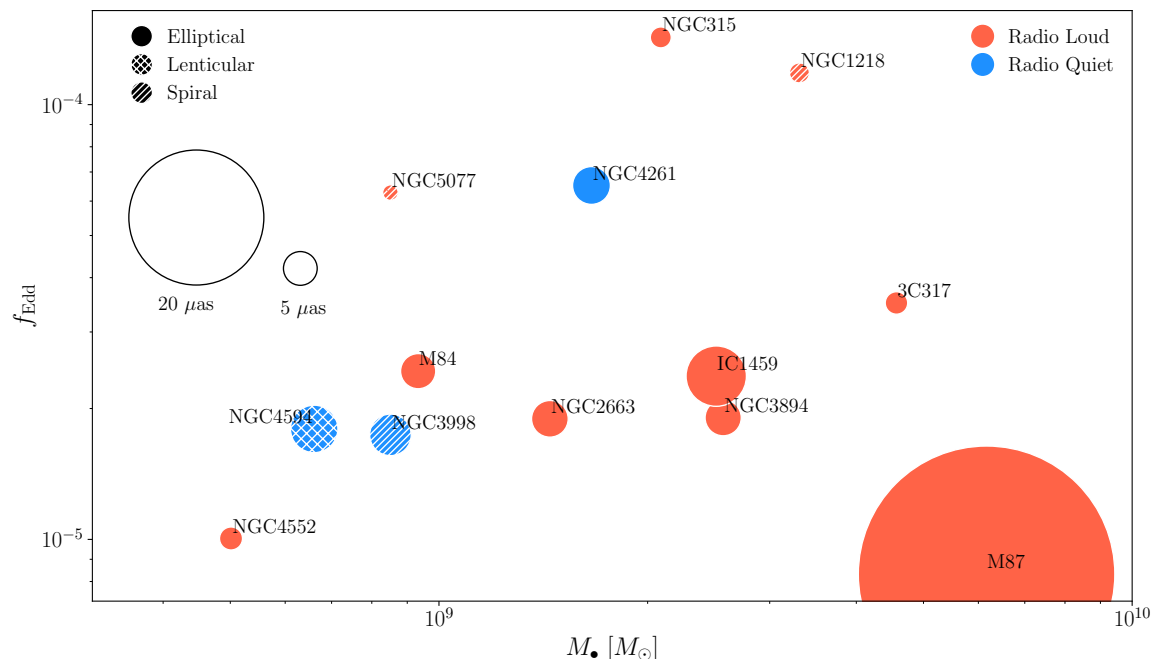


Figure 9. **Candidate BHEX targets for horizon-scale studies.** The increased resolution provided by BHEX will enable access to a population of black holes in a variety of different environments. This figure shows estimated Eddington ratio as a function of black hole mass for M87* and 12 additional sources. The symbol color encodes the radio loudness of each source (based on the 5 GHz to X-ray flux ratio¹⁴⁵), the shading encodes the morphology of the host galaxy, and the size scales linearly with the estimated photon ring diameter. Adapted from Ref. [94].

By expanding the sample of horizon-resolved black holes beyond merely Sgr A* and M87*, BHEX will enable demographic studies in poorly explored regions in parameter space. These dimensions include the following:

- **Black Hole Mass:** By measuring source sizes and applying the techniques already developed and employed for M87*¹⁸ and Sgr A*,^{25,27} BHEX will substantially increase the number of SMBHs with precisely-measured masses. Interestingly, the sample of promising BHEX targets overlaps with the list of objects most likely to produce observable nHz gravitational waves.¹⁴⁶ The large amplitude of the nHz gravitational wave background has motivated scrutiny of the high-mass end of the black hole mass function.^{147,148} Direct mass measurements with BHEX will synergize with gravitational wave science to help resolve these newfound tensions.
- **Eddington Ratio:** The study of Ref. [94] predicts that most new targets should have larger Eddington ratios than those inferred for either M87* or Sgr A* ($\sim 10^{-5}$ and $\sim 10^{-7}$ respectively^{20,29}), up to $\sim 10^{-4}$.⁹⁴ At these higher accretion rates, radiative cooling will become important,¹⁴⁹ which is typically neglected for Sgr A* and M87*.
- **Spin:** If the underlying population of black holes spans a range in spin, then we may observe spin-driven differences in accretion disk and jet activity. The Blandford-Znajek mechanism predicts that the jet power should be proportional to the square of the spin,¹⁰ which can be directly tested using samples such as those presented in Figure. 9 that include both radio-loud and radio-quiet AGN. The distribution of SMBH spins in the local Universe should encode details of their growth histories, including spin-down from jets,^{150,151} SMBH-SMBH mergers,^{152,153} and the relative frequency of prograde versus retrograde accretion.¹⁵⁴
- **Inclination:** Our views of M87* and Sgr A* are close to face-on.^{29,155} The general population should naturally exhibit a uniform distribution of viewing angles. Polarized emission should evolve substantially as a function of inclination due to geometric effects and Faraday rotation.^{29,156} Polarized imaging of the

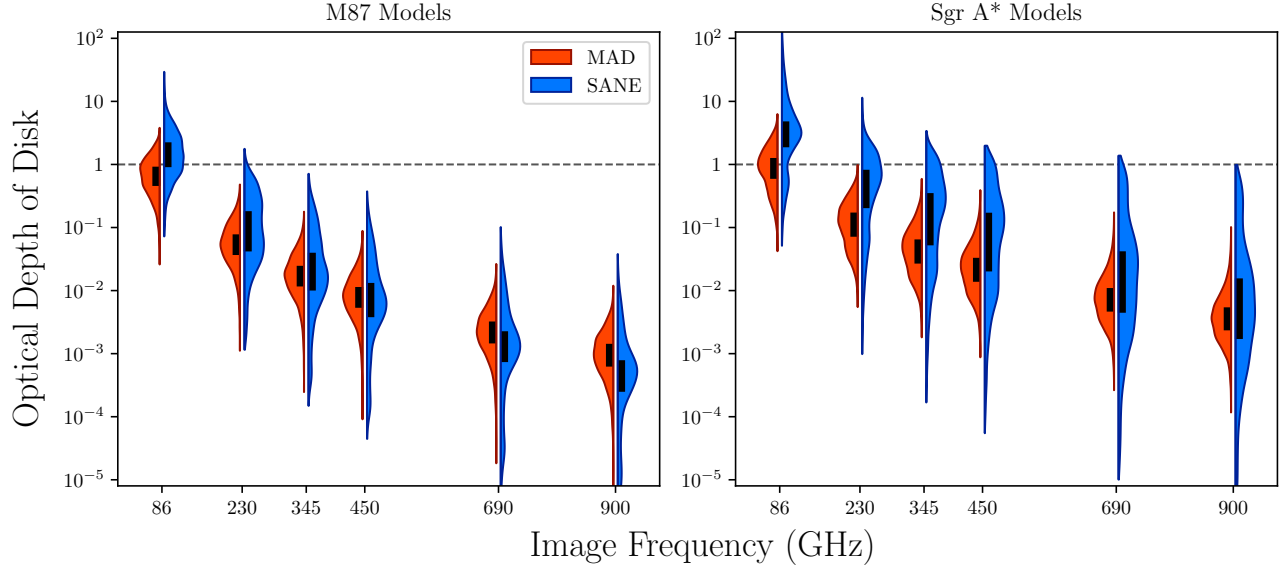


Figure 10. Image-averaged optical depth as a function of observing frequency over a suite of GRMHD models for M87* (left) and Sgr A* (right). The models cover both MAD and SANE configurations, varying black hole spins, and a variety of electron temperature models. For Sgr A*, the images also include varying inclinations. Reproduced from Ref. [158].

expanded BHEX sample will enable inferences of the three-dimensional structure of accretion disks and jets.

- **Environment:** The most promising candidate targets for BHEX include elliptical galaxies, lenticulars, and even spirals (e.g., the Sombrero Galaxy, NGC 4594). Not all ellipticals are central cluster galaxies like M87, and at least one is at the center of a less massive galaxy group (NGC4261; ¹⁵⁷). Thus, studies with BHEX in combination with images on larger scales will connect the accretion and jet launching of black holes to their environment in a variety of intra- and inter-galactic environments.

3. REQUIREMENTS

3.1 General Considerations for Space VLBI

The most demanding requirements for BHEX are those related to detecting and measuring the photon rings in M87* and Sgr A*. This requires both that 1) the photon ring is visible on the sky and that 2) BHEX has sufficient angular resolution and sensitivity to measure the photon ring.

To ensure that the photon ring is visible, BHEX must observe M87* and Sgr A* at high enough frequencies that optical depth to synchrotron self-absorption does not hide the photon ring. General-relativistic magnetohydrodynamic simulations have been extremely successful in producing models that are consistent with EHT observations of M87* and Sgr A* and can generate images with angular resolution of μas or less, providing a firm basis to derive requirements for BHEX. These simulations have been developed for decades and are highly constrained by EHT measurements.^{17,20,21,26,29} As shown in Figure 10, these simulations indicate that BHEX must observe above 200 GHz to ensure that the optical depth is $\tau < 1$, allowing access to the photon rings in M87* and Sgr A*.

In addition, radio observations are affected by lines of sight through the ionized interstellar medium, which has an index of refraction that varies with the local electron density, introducing scattering.^{159,160} While scattering is negligible for most sources at millimeter and submillimeter wavelengths, the scattering toward Sgr A* is approximately 1000 times stronger than typical lines of sight.¹⁶¹ Scattering obscures the photon ring and reduces the flux density on long baselines.¹⁶² Thus, while angular resolution requirements set a lower limit on the length

of BHEX baselines, scattering sets an upper limit on the useful baseline length for a given observing frequency or, equivalently, a lower limit on the observing frequency for a given baseline:

$$\nu \gtrsim 280 \text{ GHz} \left(\frac{b}{20,000 \text{ km}} \right). \quad (1)$$

The scattering has been studied intensively at centimeter wavelengths,^{163–165} giving rise to a detailed predictive model for BHEX.^{166,167} Because of ISM scattering, BHEX must observe above 300 GHz to access the photon ring in Sgr A*. Because the scattering of M87* is 1,000 times weaker than that of Sgr A*, this requirement only affects Sgr A*.

Finally, because the interferometric resolution of BHEX is determined by its separation from the ground-based stations, its orbit is tuned to see spatial scales where the photon ring dominates over smoother, more weakly lensed emission. For M87* and Sgr A*, this transition occurs at approximately $20 \text{ G}\lambda$.

3.2 Key Performance Metrics

BHEX is primarily a mission for continuum VLBI, limited by angular resolution (λ/D) and sensitivity. The angular resolution of a baseline depends only on the length b of the baseline projected orthogonal to the line of sight and on the observing wavelength:

$$\theta \approx 10 \mu\text{as} \times \left(\frac{\lambda}{1 \text{ mm}} \right) \left(\frac{b}{20,000 \text{ km}} \right)^{-1} \quad (2)$$

$$\approx (8 \mu\text{as}) \times \left(\frac{\lambda}{1 \text{ mm}} \right) \left(\frac{\text{Altitude}}{20,000 \text{ km}} \right)^{-1} \quad (3)$$

The sensitivity of a radio telescope is commonly quantified by its system equivalent flux density (SEFD):¹⁶⁸

$$\text{SEFD} = \frac{2k_{\text{B}}T_{\text{sys}}^*}{\eta_{\text{A}}A}. \quad (4)$$

In this expression, k_{B} is the Boltzmann constant, T_{sys}^* is the effective system temperature, η_{A} is the aperture efficiency of the telescope, and A is the geometric area of the dish. The aperture efficiency depends on a number of factors including the reflector design and losses from surface deformations with RMS surface errors of ϵ (Ruze losses):

$$\eta_{\text{A,Ruze}} = e^{-\left(\frac{4\pi\epsilon}{\lambda}\right)^2} \quad (5)$$

For example, to ensure that $\eta_{\text{A,Ruze}} > 0.75$ for the highest observing frequency of BHEX (320 GHz) requires $\epsilon < 40 \mu\text{m}$.

Because BHEX does not have any contribution from atmospheric emission or absorption, T_{sys}^* is approximately equal to the receiver noise temperature, T_{R} . Putting in characteristic values, we obtain

$$\text{SEFD} \approx 20,000 \text{ Jy} \times \left(\frac{T_{\text{R}}}{50 \text{ K}} \right) \left(\frac{D}{3.5 \text{ m}} \right)^{-2} \left(\frac{\eta_{\text{A}}}{0.7} \right)^{-1} \quad (6)$$

$$\approx 10,000 \text{ Jy} \times \left(\frac{\nu}{100 \text{ GHz}} \right) \left(\frac{D}{3.5 \text{ m}} \right)^{-2} \left(\frac{\eta_{\text{R}}}{0.2} \right)^{-1} \left(\frac{\eta_{\text{A}}}{0.7} \right)^{-1}. \quad (7)$$

In the final expression, we have introduced $\eta_{\text{R}} \equiv T_{\text{R}}/T_{\text{Q}}$, which gives the performance of a receiver relative to its quantum limit $T_{\text{Q}} \equiv h\nu/k_{\text{B}} \approx 4.8 \text{ K} \times \left(\frac{\nu}{100 \text{ GHz}} \right)$.^{169,170} To compute the SEFD for dual-sideband (DSB) receivers, the receiver noise temperature must be doubled to account for noise in both sidebands.

For continuum VLBI observations, which will be used for all the primary BHEX science goals, the most important quantity is the ground-space baseline sensitivity (expressed as the RMS thermal noise, σ_{G-S}). This quantity depends on the properties of both the ground and space telescopes:

$$\sigma_{G-S} = \frac{1}{\eta_Q} \sqrt{\frac{\text{SEFD}_G \text{SEFD}_S}{2 \Delta\nu \Delta t}}. \quad (8)$$

Here, $\Delta\nu$ is the averaged bandwidth (single polarization), Δt is the (coherent) integration time, and $\eta_Q \leq 1$ is a factor that accounts for losses in coarse digitization of the electric field (for BHEX baselines, $\eta_Q = 0.75$; see Section 4.4). We note that the baseline length does not affect the baseline sensitivity. For the original EHT observations of M87*, the median SEFD at $\nu = 230$ GHz across all sites was 5,000 Jy, with the best performance of 74 Jy (a phased array of 37 12-m ALMA dishes). Several other EHT sites (e.g., NOEMA and LMT) also achieve $\text{SEFD} < 1,000$ Jy in typical weather conditions for a source at moderately high elevation.

Putting in characteristic values for strong baselines, we obtain

$$\sigma_{G-S} \approx 5 \text{ mJy} \times \left(\frac{\text{SEFD}_G}{1,000 \text{ Jy}} \right)^{1/2} \left(\frac{\text{SEFD}_S}{20,000 \text{ Jy}} \right)^{1/2} \left(\frac{\Delta\nu}{8 \text{ GHz}} \right)^{-1/2} \left(\frac{\Delta t}{100 \text{ s}} \right)^{-1/2}. \quad (9)$$

All elements of the system combine to determine this baseline sensitivity, resulting in a rich trade space.

Frequency phase transfer between the secondary (ν_2) and primary (ν_1) receivers for BHEX will require reaching a signal-to-noise ratio of approximately $S/N \gtrsim \nu_1/\nu_2$ for the signal of the secondary receiver in the coherence time associated with the primary receiver. For instance, if the coherence time at 320 GHz is 10 seconds, frequency phase transfer from 80 to 320 GHz would require reaching a signal-to-noise ratio at 80 GHz of $S/N \gtrsim 4$ in 10 seconds of integration. The signal could then be coherently integrated in both bands for longer times (typically over a full ~ 10 -minute scan). For additional details on frequency phase transfer, including results for a power-law spectrum of phase fluctuations, see Ref. [35].

3.2.1 Requirements for Photon Ring Detections

The precise expected signal from a black hole depends on a multitude of details about the black hole system, many of which are poorly constrained. However, in the optically thin regime (which is appropriate for observations of M87* and Sgr A* at submillimeter wavelengths), the signal on long baselines takes a universal form that is determined solely by basic considerations of the gravitational lensing.⁴¹ Specifically, $\sim 20\%$ of the flux density comes from the black hole's "photon ring," and this flux falls as $u^{-3/2}$ on long baselines as the photon ring is increasingly resolved. Here, u is the baseline length in units of the observing wavelength, with a corresponding angular resolution (or fringe spacing) $\theta = 1/u$.

Because the flux density of the compact components of the sources such as M87* and Sgr A* are known, we can compute the expected photon ring signal on a long baseline. For instance, for M87*,

$$|V| \approx 30 \text{ mJy} \times \left(\frac{u}{10 G\lambda} \right)^{-3/2} \quad (10)$$

$$\approx 0.3 \text{ mJy} \times \left(\frac{\theta}{1 \mu\text{as}} \right)^{3/2}. \quad (11)$$

For Sgr A*, a similar equation holds, accounting for the substantially higher compact flux density and somewhat larger photon ring, but the equation must also be multiplied by the diffractive scattering kernel.^{166,167}

3.2.2 Requirements for Non-Photon-Ring Science and Calibration Targets

For BHEX observations of marginally resolved LLAGN or knots in blazar jets, the flux density is limited by the maximum brightness temperature of incoherent synchrotron emission: $T_b \lesssim 10^{11}$ K.^{173,174} Note that the observed brightness temperature can exceed this limit by an order of magnitude because of relativistic Doppler effects, as is commonly seen in blazar jets. Since bright, marginally resolved sources are also ideal calibration targets for BHEX, this type of source is also useful to define mission requirements for calibrators.

Table 1. **Representative flux densities of primary BHEX targets.** The total (compact) flux densities for M87* and Sgr A* are based on interferometric observations of both targets.^{16,171,172} The BHEX flux densities are based on values measured in GRMHD simulations and simple analytic arguments.

	Total Flux Density	BHEX Flux Density
M87*		
80 GHz	0.6 Jy	40 mJy
240 GHz	0.5 Jy	10 mJy
320 GHz	0.35 Jy	5 mJy
Sgr A*		
80 GHz	3 Jy	3 mJy
240 GHz	3.5 Jy	5 mJy
320 GHz	3.5 Jy	10 mJy
$T_b = 10^{12}$ K	100 mJy 50 mJy 10 mJy	88 mJy 47 mJy 9.9 mJy
$T_b = 10^{11}$ K	100 mJy 50 mJy 10 mJy	29 mJy 27 mJy 8.8 mJy
$T_b = 10^{10}$ K	100 mJy 50 mJy 10 mJy	0 mJy 0.1 mJy 2.9 mJy

For a Gaussian distribution of flux density, the central (peak) brightness temperature is $T_{b,\max} = \frac{2 \ln(2) c^2}{\pi \nu^2 k_B \theta^2} F_0$. Putting in characteristic values,

$$T_{b,\max} = (1.45 \times 10^{10} \text{ K}) \times \left(\frac{\nu}{230 \text{ GHz}} \right)^{-2} \left(\frac{F_0}{1 \text{ Jy}} \right) \left(\frac{\theta}{40 \mu\text{as}} \right)^{-2}. \quad (12)$$

The visibility domain response takes the form:

$$V(u) = F_0 \exp \left(-\frac{\pi b^2 F_0}{2 k_B T_b} \right). \quad (13)$$

Critically, the visibility amplitude depends only on the (projected) *physical* baseline length b (rather than the dimensionless length b/λ). On a fixed baseline b , Equation 13 is maximized when $F_0 = \frac{2 k_B T}{\pi b^2}$. Thus, under the assumption of a Gaussian emitting region, this type of source gives a peak correlated flux density that only depends on the brightness temperature and physical baseline length:

$$|V(b)| \leq (300 \text{ mJy}) \times \left(\frac{T_b}{10^{11} \text{ K}} \right) \left(\frac{b}{10^4 \text{ km}} \right)^{-2}. \quad (14)$$

Hence, BHEX will primarily be sensitive to compact emitting regions with $T_b \gtrsim 10^{11} \text{ K}$ and $F_0 \lesssim 100 \text{ mJy}$ (see Table 1). We note that this limit applies exclusively to marginally resolved emitting regions. For heavily resolved regions, the flux density can be substantially higher than the Gaussian prediction from the overall source morphology (e.g., in the case of the photon ring) or substructure within the image.

4. INSTRUMENT AND TECHNICAL HERITAGE

BHEX builds upon the lessons of space-VLBI missions at centimeter wavelengths: TDRSS,¹⁷⁵ VSOP,³⁶ and RadioAstron³⁷ (for a brief review of space VLBI, see Refs. [168, 176, 177]). The BHEX instrument is a radio

telescope and (heterodyne) receiver system, similar to the corresponding ground systems at all EHT stations [for an overview of these systems, see Ref. [14].

In this section, we briefly summarize each of the six subsystems of the BHEX instrument: the antenna (Section 4.1), the receiver (Section 4.2), the cryocooler (Section 4.3), the digital back end (Section 4.4), the frequency reference (Section 4.5), and the optical data transmission (Section 4.6). Each of these subsystems leverages substantial space heritage and has been designed after considering a broad trade space; see Ref. [61]. A more detailed description of the BHEX instrument is given in Ref. [84].

4.1 Antenna

The BHEX antenna will have a rigid 3.5 m circular aperture. To minimize the mass, the antenna will employ a metallized carbon fiber reinforced plastic (CFRP) sandwich construction. This approach has been successfully used in past missions including Planck.¹⁷⁸ To achieve our required sensitivity at the highest observing frequency (320 GHz), a high surface accuracy with less than 40 μm rms is targeted. The current optical design incorporates a symmetric, dual reflector configuration that achieves an aperture illumination efficiency of $\eta_a \approx 90\%$. Further exploration of design choices and parameter space and reflector shaping studies are in progress.

For additional details on the space heritage, trade space, and design, see Refs. [86, 179].

4.2 Receiver

BHEX includes two dual-polarization receivers together with an optical diplexer that allows them to observe simultaneously. The primary receiver will be double-side-band (DSB) operating over the frequency range 240-320 GHz with a Superconductor-Insulator-Superconductor (SIS) mixer. SIS mixers are standard in ground sub-millimeter telescopes, were used in the Herschel mission,^{180,181} and are being actively developed for a variety of terrestrial and space applications.^{69,85,182} The secondary receiver will be single-side-band (SSB) operating over the frequency range 80-106 GHz with a cryogenic low noise amplifier, which are commercially available.

On baselines from BHEX to ground stations, rapid phase variations are dominated by fluctuations in the troposphere and from errors in reference oscillators. Because all these contributions are non-dispersive delays, measurements at low frequencies can be used to stabilize the phase at high frequencies, substantially increasing the coherence time and, hence, the achievable sensitivity. This technique, known as frequency phase transfer, has been used routinely in centimeter observations,⁷⁸ and is a major focus of ongoing EHT upgrades.⁷⁸⁻⁸¹ The receivers of BHEX are designed to enable this technique, transferring phase measurements from the secondary band to derive phase corrections for the primary band. This design both improves the sensitivity of BHEX and mitigates the requirements for the reference frequency.

For additional details on the space heritage, trade space, and design of the BHEX receivers, see Ref. [85].

4.3 Cryocooler

The BHEX receiver suite requires cryogenic cooling to achieve the required receiver noise temperatures, close to the quantum noise limit $T_Q = h\nu/k$ (see Section 4.2). The SIS mixers of the primary receiver, in particular, must be cooled to 4.5 K (approximately half the critical temperature of the SIS junction), while the low noise amplifier of the secondary receiver performs better when cooled to 20 K. It is worth noting that BHEX only requires a modest heat lift to cool the receiver suite and does not need to cool the dish. BHEX aims to leverage existing cryogenic technology, where the majority of the key cryogenic components within these technologies boast established spaceflight heritage. Recent missions (e.g., SMILES/JEM, ASTRO-H, XRISM) include closed-cycle 4 K cryocoolers that are a good match to the BHEX design and requirements.

For additional details on the space heritage, trade space, and design of the BHEX cryocooler, see Ref. [87].

4.4 Block Downconverter and Digital Back End

Following the receiver, the digital stage of BHEX requires a block downconverter (BDC) and a digital back end that can sample and digitize a combined 32 GHz of analog bandwidth. Because the sampled signal is a zero-mean Gaussian random field (corresponding to band-limited noise from both the source and thermal background noise), no additional data compression can be applied before downlink, aggregation with the data from other participating observatories, and correlation.¹⁶⁸

The BHEX digital back end is informed by state-of-the-art EHT designs, which must operate in harsh terrestrial environments (e.g., at the South Pole or at an altitude of 5000 meters for the ALMA Observatory). These systems use commercial wideband samplers and Field Programmable Gate Arrays (FPGAs) to enable a relatively low-power and low-cost design. The primary difference for the BHEX system is the requirements for space-grade components, which are also commercially available. Another difference is that the BHEX DBE will use a 1-bit quantization scheme, giving a quantization efficiency of $\eta_Q = 0.750$ on baselines from BHEX to ground sites with 2-bit quantization.

For additional details on the space heritage, trade space, and design of the BHEX DBE, see Ref. [89].

4.5 Frequency Reference

VLBI relies on a stable frequency reference to allow coherent integration of the correlated signal between sites in order to find “fringes.” With a sufficiently stable reference, the integration time is limited by fluctuations in optical path length through the troposphere, with typical coherence times of ~ 10 second at wavelengths of $\lambda \approx 1.3$ mm for EHT sites. With sufficient signal-to-noise on short integrations, residual fluctuations can be corrected in post-processing (a procedure sometimes called “ad-hoc phase correction”).^{15,183}

With the use of multi-band observations, using a secondary band for phase corrections, BHEX can use an ultra stable oscillator (USO) based on a temperature-controlled quartz crystal. For example, an exceptionally quiet USO^{184,185} is currently serving as a reference for the European Space Agency’s (ESA) Jupiter Icy Moons Explorer (JUICE) mission.¹⁸⁶ We are also currently evaluating alternative choices of frequency reference that use the stabilization of a continuous wave (CW) laser to an optical atomic or molecular transition. By referencing the output of an optical frequency comb to stabilized CW laser, the coherent optical pulse train output from the comb serves as the clock output and a microwave reference frequency can be generated which preserves the fractional frequency instability of the CW laser. Some of these optical atomic clocks can be quite simple, with performance that exceeds that of an active hydrogen maser over the timescales of interest.¹⁸⁷

For additional details on the space heritage, trade space, and design of the BHEX DBE, see Refs. [61,84].

4.6 Optical Data Transmission

Space optical communications has long been recognized as capable of supporting higher data rates with smaller apertures and lower powers than the incumbent radio-frequency communications methods widely used today. Over the past several decades, these capabilities have been demonstrated over a variety of orbits and mission use cases such as lunar missions for science,¹⁸⁸ geosynchronous relays,^{189–191} and low-earth orbit and lunar missions supporting human exploration.^{192,193} One unique aspect of space optical communications addressed by all missions is the sensitivity of optical frequencies to atmospheric scintillation and fading, requiring atmospheric mitigation techniques to provide error-free data delivery. To support high-fidelity downlink of data captured at up to 64 Gb/s, BHEX requires a 100 Gb/s optical downlink system.

Recently, the TeraByte Infrared Delivery (TBIRD) mission, a small cubesat in low-earth orbit (LEO), demonstrated transmission up to 200 Gb/s from space to ground.^{194,195} We have already explored adaptations to TBIRD that would meet requirements that are more demanding than the present BHEX design; see Ref. [68]. Such a mission can be achieved with technologies which have already been demonstrated today.

For additional details on the space heritage, trade space, and design of the BHEX laser communications downlink design, see Ref. [88].

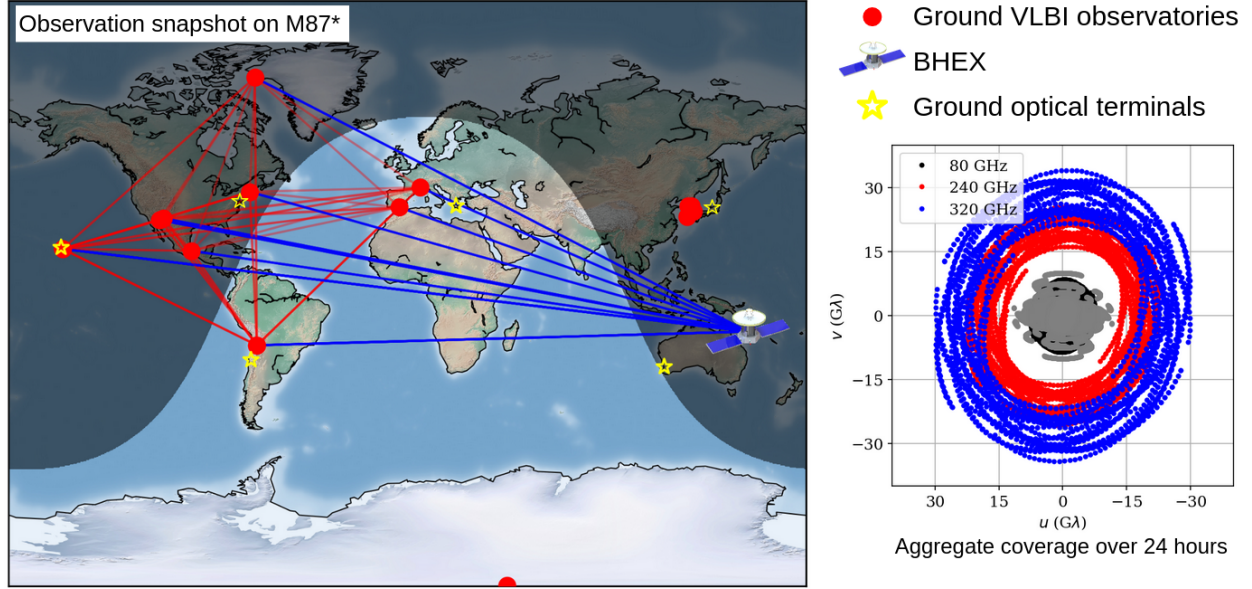


Figure 11. (left) The BHEX concept of operations for M87*. Red and blue lines represent co-observing of the target for ground-only and space-ground telescope pairs, respectively. (right) The geometrical (u, v) coverage on M87* over 24 hours, where BHEX baselines at 80, 240, and 320 GHz are shown in black, red, and blue, respectively. Ground-ground baselines are shown in grey.

5. CONCEPT OF OPERATIONS

The BHEX science goals hinge on building sensitivity from high recording bandwidths and optimal atmospheric conditions at the ground VLBI stations co-observing with the satellite. Weather considerations also need to be taken into account when developing the downlink network receiving the signal from the satellite. The high bandwidth requirements for BHEX necessitate a downlink infrastructure with optical communications, which have demonstrated higher bandwidth rates than radio-frequency methods commonly used in past space-VLBI experiments. The operations concept for BHEX essentially involves a three-part hybrid observatory: satellite operations of the space-based component, coordinated operations of the ground-based VLBI network, and coordinated operations of the ground-based downlink terminals.

BHEX will operate for a nominal two-year mission in a circular, semi-synchronous, near-polar orbit ($\sim 20,200$ km altitude), optimized for multi-directional sampling of the photon ring signal in M87*. Repeated observations are key to aggregate sufficient data to make images of the photon ring. This will provide the required baseline coverage and thus angular resolution of the primary targets, M87* and Sgr A*. Observations of sources will be conducted at the times of year when the angle between the antenna boresight and the Sun is greater than 90 degrees to minimise thermal distortion of the antenna surface due to solar radiation. This requirement, and the favourable times of year for ground station observations, results in observation campaigns of the two main sources during the following months: January - March for M87* and June - August for Sgr A*, respectively. Photon ring campaigns will be interspersed with survey science on demographics of black holes in low accretion states and relativistic jet studies of a range of sources.

Radio emission from distant black holes will be observed by the BHEX and telescopes on the ground simultaneously, including those that currently form the EHT. BHEX will leverage established (sub)millimeter observatories in the EHT to carry out its science goals. Large sensitive apertures (such as ALMA, the LMT, the MIT Haystack 37-m, the IRAM 30-m, and NOEMA telescopes, and the SMA) will provide detections to BHEX and anchor the satellite to the smaller ground dishes filling our coverage for imaging, see Figures 11 and 12 for M87* and Sgr A*, respectively. Partnerships with these facilities are already established within the EHT collaboration, and a path for time allocation is being pursued for BHEX. The observed radio waves will be recorded at

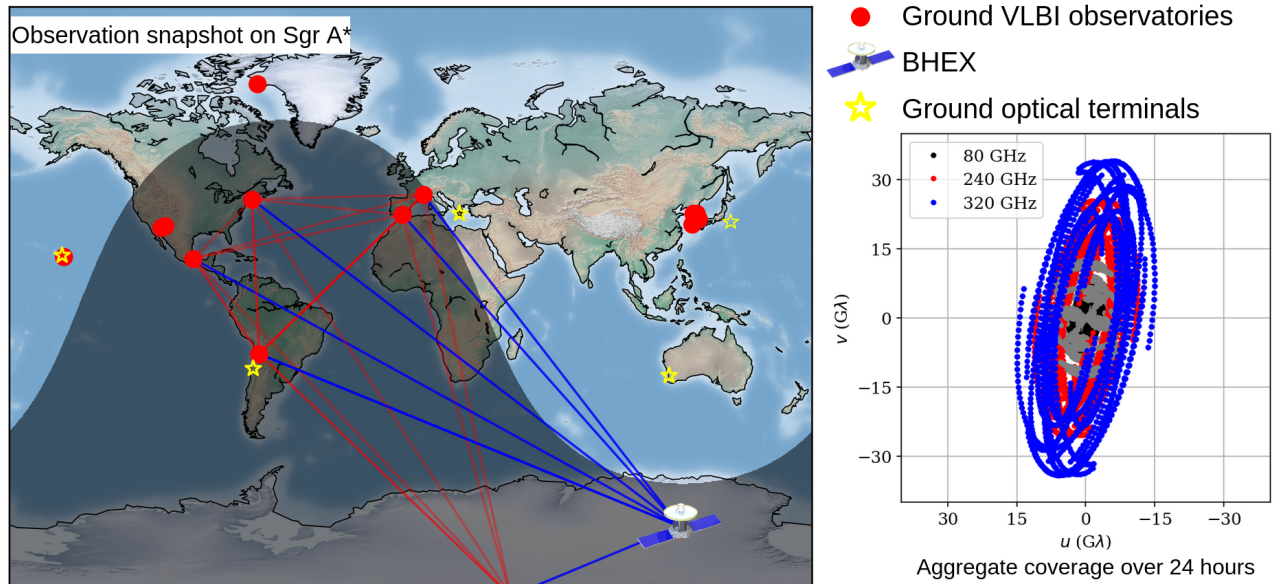


Figure 12. Same as Figure 11, but for Sgr A*. The orbit is selected to provide coverage that is elongated along the minor axis of the scattering kernel, oriented approximately 8° west of north.

the ground-based telescopes and will be computationally combined with the observational data transmitted to the ground from BHEX to generate the highest resolution images of black holes. BHEX will perform real time downlink of data during observations utilising a network of optical ground terminals, distributed across the globe (see section 4.6). The semi-synchronous orbit selection is favourable for this mode of operation as it generates a constant ground track which, alongside a careful selection of ground terminal sites, ensures that a real time downlink can be maintained at all times.

We plan to utilize existing EHT correlation infrastructure, such as the correlator at MIT Haystack Observatory and the Cannon Cluster at the Massachusetts Green High Performance Computing Center (MGHPCC). The correlated data will then be processed using the EHT reference pipeline, and both raw, correlated data products and calibrated, processed data products will be released to a public archive.

6. SUMMARY

The BHEX mission concept, summarized in Table 2, arises from a coincidence of transformational theoretical discoveries, an explosion of community interest in black holes, and technical breakthroughs that enable submillimeter space VLBI. BHEX will produce images that bring us to an edge of the universe, revealing whether spinning black holes are feeding energy back into the universe by powering relativistic jets of emission. And it will reveal a population of unseen black holes, showing how they grow over cosmic timescales.

BHEX is enabled by pioneering work to develop successful space-VLBI missions at centimeter wavelengths and emerging space technologies such as laser communications. It leverages billions of dollars of existing ground infrastructure that has already been combined to deliver the remarkable successes of the EHT. With these advances, we are now at a moment when a critical new science goal—imaging a black hole’s photon ring—is within reach. Guided by this common vision, the BHEX team will submit a Small Explorers mission proposal in 2025 to launch BHEX within the next decade and turn this extraordinary opportunity into a reality.

Table 2. **BHEX Mission Characteristics.**

Antenna	
Diameter	3.5-m
Surface RMS	40 μm
Primary Receiver (SIS; 4.5 K)	
Frequency Range	240-320 GHz
IF	4-12 GHz
Receiver noise temperature (DSB)	23-30 K
SEFD at 240 GHz	16,400 Jy
SEFD at 320 GHz	23,600 Jy
Secondary Receiver (HEMT; 20 K)	
Frequency Range	80-106 GHz
IF	4-12 GHz
Receiver noise temperature (SSB)	45 K
SEFD at 80 GHz	14,700 Jy
Maximum Data Rate	64 Gb/s (both receivers; dual-pol; 1-bit quantization)
Baseline Sensitivity	(RMS Thermal Noise for 8 GHz Bandwidth)
BHEX-ALMA, 10-minute integration	1 mJy
BHEX-ALMA, 10-second integration	7 mJy
BHEX-LMT, 10-minute integration	2 mJy
BHEX-LMT, 10-second integration	15 mJy
Orbit	Semi-synchronous (12-hr; 20,200 km altitude) Circular $\geq 78^\circ$ inclination
Finest Fringe Spacing (λ/D)	
80 GHz	24 μas
240 GHz	8 μas
320 GHz	6 μas
Maximum Baseline Length	32,900 km
80 GHz	9 $G\lambda$
240 GHz	26 $G\lambda$
320 GHz	35 $G\lambda$
Mission Lifetime	2 yr

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REFERENCES

- [1] Schmidt, M., “3C 273 : A Star-Like Object with Large Red-Shift,” *Nature* **197**, 1040 (Mar. 1963).
- [2] Lynden-Bell, D., “Galactic Nuclei as Collapsed Old Quasars,” *Nature* **223**, 690–694 (Aug. 1969).
- [3] Shakura, N. I. and Sunyaev, R. A., “Black holes in binary systems. Observational appearance.,” *A&A* **24**, 337–355 (Jan. 1973).
- [4] Novikov, I. D. and Thorne, K. S., “Astrophysics of black holes.,” in [*Black Holes (Les Astres Occlus)*], 343–450 (Jan. 1973).
- [5] Yuan, F. and Narayan, R., “Hot Accretion Flows Around Black Holes,” *ARA&A* **52**, 529–588 (Aug. 2014).
- [6] Richstone, D., Ajhar, E. A., Bender, R., Bower, G., Dressler, A., Faber, S. M., Filippenko, A. V., Gebhardt, K., Green, R., Ho, L. C., Kormendy, J., Lauer, T. R., Magorrian, J., and Tremaine, S., “Supermassive black holes and the evolution of galaxies.,” *Nature* **385**, A14 (Oct. 1998).
- [7] Magorrian, J., Tremaine, S., Richstone, D., Bender, R., Bower, G., Dressler, A., Faber, S. M., Gebhardt, K., Green, R., Grillmair, C., Kormendy, J., and Lauer, T., “The Demography of Massive Dark Objects in Galaxy Centers,” *AJ* **115**, 2285–2305 (June 1998).
- [8] Fabian, A. C., “Observational Evidence of Active Galactic Nuclei Feedback,” *ARA&A* **50**, 455–489 (2012).
- [9] Kormendy, J. and Ho, L. C., “Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies,” *ARA&A* **51**, 511–653 (Aug. 2013).
- [10] Blandford, R. D. and Znajek, R. L., “Electromagnetic extraction of energy from Kerr black holes.,” *MNRAS* **179**, 433–456 (May 1977).
- [11] Tchekhovskoy, A., Narayan, R., and McKinney, J. C., “Efficient generation of jets from magnetically arrested accretion on a rapidly spinning black hole,” *MNRAS* **418**, L79–L83 (Nov. 2011).
- [12] Blandford, R., Meier, D., and Readhead, A., “Relativistic Jets from Active Galactic Nuclei,” *ARA&A* **57**, 467–509 (Aug. 2019).
- [13] EHTC, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczko, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crew, G. B., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Gómez, J. L., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P.,

- Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, Y., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Ryan, B. R., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Trippe, S., Tsuda, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Wardle, J., Weintroub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Young, K., Young, A., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., Algaba, J.-C., Allardi, A., Amestica, R., Anczarski, J., Bach, U., Baganoff, F. K., Beaudoin, C., Benson, B. A., Berthold, R., Blanchard, J. M., Blundell, R., Bustamente, S., Cappallo, R., Castillo-Domínguez, E., Chang, C.-C., Chang, S.-H., Chang, S.-C., Chen, C.-C., Chilson, R., Chuter, T. C., Córdova Rosado, R., Coulson, I. M., Crawford, T. M., Crowley, J., David, J., Derome, M., Dexter, M., Dornbusch, S., Dudevoir, K. A., Dzib, S. A., Eckart, A., Eckert, C., Erickson, N. R., Everett, W. B., Faber, A., Farah, J. R., Fath, V., Folkers, T. W., Forbes, D. C., Freund, R., Gómez-Ruiz, A. I., Gale, D. M., Gao, F., Geertsema, G., Graham, D. A., Greer, C. H., Grosslein, R., Gueth, F., Haggard, D., Halverson, N. W., Han, C.-C., Han, K.-C., Hao, J., Hasegawa, Y., Henning, J. W., Hernández-Gómez, A., Herrero-Illana, R., Heyminck, S., Hirota, A., Hoge, J., Huang, Y.-D., Impellizzeri, C. M. V., Jiang, H., Kamble, A., Keisler, R., Kimura, K., Kono, Y., Kubo, D., Kuroda, J., Lacasse, R., Laing, R. A., Leitch, E. M., Li, C.-T., Lin, L. C. C., Liu, C.-T., Liu, K.-Y., Lu, L.-M., Marson, R. G., Martin-Cocher, P. L., Massingill, K. D., Matulonis, C., McColl, M. P., McWhirter, S. R., Messias, H., Meyer-Zhao, Z., Michalik, D., Montaña, A., Montgomerie, W., Mora-Klein, M., Muders, D., Nadolski, A., Navarro, S., Neilsen, J., Nguyen, C. H., Nishioka, H., Norton, T., Nowak, M. A., Nystrom, G., Ogawa, H., Oshiro, P., Oyama, T., Parsons, H., Paine, S. N., Peñalver, J., Phillips, N. M., Poirier, M., Pradel, N., Primiani, R. A., Raffin, P. A., Rahlin, A. S., Reiland, G., Risacher, C., Ruiz, I., Sáez-Madaín, A. F., Sassella, R., Schellart, P., Shaw, P., Silva, K. M., Shiokawa, H., Smith, D. R., Snow, W., Souccar, K., Sousa, D., Sridharan, T. K., Srinivasan, R., Stahm, W., Stark, A. A., Story, K., Timmer, S. T., Vertatschitsch, L., Walther, C., Wei, T.-S., Whitehorn, N., Whitney, A. R., Woody, D. P., Wouterloot, J. G. A., Wright, M., Yamaguchi, P., Yu, C.-Y., Zeballos, M., Zhang, S., and Ziurys, L., “First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole,” *ApJ* **875**, L1 (Apr. 2019).
- [14] EHTC, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Bacsko, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crew, G. B., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Friberg, P., Fromm, C. M., Gómez, J. L., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, Y., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V.,

- Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Ryan, B. R., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Trippe, S., Tsuda, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., Algaba, J.-C., Allardi, A., Amestica, R., Bach, U., Beaudoin, C., Benson, B. A., Berthold, R., Blanchard, J. M., Blundell, R., Bustamente, S., Cappallo, R., Castillo-Domínguez, E., Chang, C.-C., Chang, S.-H., Chang, S.-C., Chen, C.-C., Chilson, R., Chuter, T. C., Córdova Rosado, R., Coulson, I. M., Crawford, T. M., Crowley, J., David, J., Derome, M., Dexter, M., Dornbusch, S., Dudevoir, K. A., Dzib, S. A., Eckert, C., Erickson, N. R., Everett, W. B., Faber, A., Farah, J. R., Fath, V., Folkers, T. W., Forbes, D. C., Freund, R., Gómez-Ruiz, A. I., Gale, D. M., Gao, F., Geertsema, G., Graham, D. A., Greer, C. H., Grosslein, R., Gueth, F., Halverson, N. W., Han, C.-C., Han, K.-C., Hao, J., Hasegawa, Y., Henning, J. W., Hernández-Gómez, A., Herrero-Illana, R., Heyminck, S., Hirota, A., Hoge, J., Huang, Y.-D., Impellizzeri, C. M. V., Jiang, H., Kamble, A., Keisler, R., Kimura, K., Kono, Y., Kubo, D., Kuroda, J., Lacasse, R., Laing, R. A., Leitch, E. M., Li, C.-T., Lin, L. C. C., Liu, C.-T., Liu, K.-Y., Lu, L.-M., Marson, R. G., Martin-Cocher, P. L., Massingill, K. D., Matulonis, C., McColl, M. P., McWhirter, S. R., Messias, H., Meyer-Zhao, Z., Michalik, D., Montaña, A., Montgomerie, W., Mora-Klein, M., Muders, D., Nadolski, A., Navarro, S., Nguyen, C. H., Nishioka, H., Norton, T., Nystrom, G., Ogawa, H., Oshiro, P., Oyama, T., Padin, S., Parsons, H., Paine, S. N., Peñalver, J., Phillips, N. M., Poirier, M., Pradel, N., Primiani, R. A., Raffin, P. A., Rahlin, A. S., Reiland, G., Risacher, C., Ruiz, I., Sáez-Madaín, A. F., Sassella, R., Schellart, P., Shaw, P., Silva, K. M., Shiokawa, H., Smith, D. R., Snow, W., Souccar, K., Sousa, D., Sridharan, T. K., Srinivasan, R., Stahm, W., Stark, A. A., Story, K., Timmer, S. T., Vertatschitsch, L., Walther, C., Wei, T.-S., Whitehorn, N., Whitney, A. R., Woody, D. P., Wouterloot, J. G. A., Wright, M., Yamaguchi, P., Yu, C.-Y., Zeballos, M., and Ziurys, L., “First M87 Event Horizon Telescope Results. II. Array and Instrumentation,” *ApJ* **875**, L2 (Apr. 2019).
- [15] EHTC, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Bacsko, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crew, G. B., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Friberg, P., Fromm, C. M., Gómez, J. L., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, Y., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Ryan, B. R., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Trippe, S., Tsuda, S., van Bemmell, I., van Langevelde,

- H. J., van Rossum, D. R., Wagner, J., Wardle, J., Weintroub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., Cappallo, R., Farah, J. R., Folkers, T. W., Meyer-Zhao, Z., Michalik, D., Nadolski, A., Nishioka, H., Pradel, N., Primiani, R. A., Souccar, K., Vertatschitsch, L., and Yamaguchi, P., “First M87 Event Horizon Telescope Results. III. Data Processing and Calibration,” *ApJ* **875**, L3 (Apr. 2019).
- [16] EHTC, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczkowski, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crew, G. B., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Gómez, J. L., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, Y., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Olivares, H., Oyama, T., Özel, F., Palumbo, D. C. M., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Ryan, B. R., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Trippe, S., Tsuda, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Wardle, J., Weintroub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., Farah, J. R., Meyer-Zhao, Z., Michalik, D., Nadolski, A., Nishioka, H., Pradel, N., Primiani, R. A., Souccar, K., Vertatschitsch, L., and Yamaguchi, P., “First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole,” *ApJ* **875**, L4 (Apr. 2019).
- [17] EHTC, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczkowski, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crew, G. B., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Friberg, P., Fromm, C. M., Gómez, J. L., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, Y., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Muller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Olivares, H., Oyama, T., Özel, F., Palumbo, D. C. M., Patel, N., Pen, U.-L., Pesce, D. W., Piétu,

- V., Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Ryan, B. R., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Trippe, S., Tsuda, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., Anczarski, J., Baganoff, F. K., Eckart, A., Farah, J. R., Haggard, D., Meyer-Zhao, Z., Michalik, D., Nadolski, A., Neilsen, J., Nishioka, H., Nowak, M. A., Pradel, N., Primiani, R. A., Souccar, K., Vertatschitsch, L., Yamaguchi, P., and Zhang, S., “First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring,” *ApJ* **875**, L5 (Apr. 2019).
- [18] EHTC, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczkó, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crew, G. B., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Friberg, P., Fromm, C. M., Gómez, J. L., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, Y., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Olivares, H., Oyama, T., Özel, F., Palumbo, D. C. M., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Ryan, B. R., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Trippe, S., Tsuda, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., Farah, J. R., Meyer-Zhao, Z., Michalik, D., Nadolski, A., Nishioka, H., Pradel, N., Primiani, R. A., Souccar, K., Vertatschitsch, L., and Yamaguchi, P., “First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole,” *ApJ* **875**, L6 (Apr. 2019).
- [19] EHTC, Akiyama, K., Algaba, J. C., Alberdi, A., Alef, W., Anantua, R., Asada, K., Azulay, R., Baczkó, A.-K., Ball, D., Baloković, M., Barrett, J., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Boland, W., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Chesler, P. M., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez, J. L., Gómez-Ruiz, A. I., Gu, M., Gurwell, M., Hada, K., Haggard, D., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James,

- D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jimenez-Rosales, A., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Levis, A., Li, Y.-R., Li, Z., Lindqvist, M., Lico, R., Lindahl, G., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Musoke, G., Mejías, A. M., Michalik, D., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Park, J., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Arguelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Traianou, E., Trippe, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G.-Y., and Zhao, S.-S., “First M87 Event Horizon Telescope Results. VII. Polarization of the Ring,” *ApJ* **910**, L12 (Mar. 2021).
- [20] EHTC, Akiyama, K., Algaba, J. C., Alberdi, A., Alef, W., Anantua, R., Asada, K., Azulay, R., Baccko, A.-K., Ball, D., Baloković, M., Barrett, J., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Boland, W., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chan, C.-k., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Chesler, P. M., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Osorio, A., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doleman, S. S., Eatough, R. P., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gelles, Z., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez, J. L., Gómez-Ruiz, A. I., Gu, M., Gurwell, M., Hada, K., Haggard, D., Hecht, M. H., Hesper, R., Himwich, E., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jimenez-Rosales, A., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Levis, A., Li, Y.-R., Li, Z., Lindqvist, M., Lico, R., Lindahl, G., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Musoke, G., Mus Mejías, A., Michalik, D., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Park, J., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Arguelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Traianou, E., Trippe, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G.-Y., and Zhao, S.-S., “First M87

Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon,” *ApJ* **910**, L13 (Mar. 2021).

- [21] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczkowski, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chang, D. O., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Osorio, A., Cui, Y., Dahale, R., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doeleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Foschi, M., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, J. A., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., La Bella, N., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lowitz, A. E., Lu, R.-S., MacDonald, N. R., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Mulaudzi, W., Müller, C., Müller, H., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Romero-Cañizales, C., Ros, E., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satpathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Sosapanta Salas, L. D., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Toscano, T., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bemmelen, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Washington, J. E., Weintroub, J., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yadlapalli, N., Yamaguchi, P., Yfantis, A., Yoon, D., Young, A., Young, K., Younsi, Z., Yu, W., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., and Zhao, S.-S., “First M87 Event Horizon Telescope Results. IX. Detection of Near-horizon Circular Polarization,” *ApJ* **957**, L20 (Nov. 2023).
- [22] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczkowski, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Osorio, A., Cui, Y., Davelaar, J., Laurentis, M. D., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doeleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth,

- K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., Bella, N. L., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lu, R.-S., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintroub, J., Wex, N., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., Zhao, S.-S., Agurto, C., Allardi, A., Amestica, R., Araneda, J. P., Arriagada, O., Berghuis, J. L., Bertarini, A., Berthold, R., Blanchard, J., Brown, K., Cárdenas, M., Cantzler, M., Caro, P., Castillo-Domínguez, E., Chan, T. L., Chang, C.-C., Chang, D. O., Chang, S.-H., Chang, S.-C., Chen, C.-C., Chilson, R., Chuter, T. C., Ciechanowicz, M., Colin-Beltran, E., Coulson, I. M., Crowley, J., Degenaar, N., Dornbusch, S., Durán, C. A., Everett, W. B., Faber, A., Forster, K., Fuchs, M. M., Gale, D. M., Geertsema, G., González, E., Graham, D., Gueth, F., Halverson, N. W., Han, C.-C., Han, K.-C., Hasegawa, Y., Hernández-Rebollar, J. L., Herrera, C., Herrero-Illana, R., Heyminck, S., Hirota, A., Hoge, J., Hostler Schimpf, S. R., Howie, R. E., Huang, Y.-D., Jiang, H., Jinchi, H., John, D., Kimura, K., Klein, T., Kubo, D., Kuroda, J., Kwon, C., Lacasse, R., Laing, R., Leitch, E. M., Li, C.-T., Liu, C.-T., Liu, K.-Y., Lin, L. C. C., Lu, L.-M., Mac-Auliffe, F., Martin-Coche, P., Matulonis, C., Maute, J. K., Messias, H., Meyer-Zhao, Z., Montaña, A., Montenegro-Montes, F., Montgomerie, W., Moreno Nolasco, M. E., Muters, D., Nishioka, H., Norton, T. J., Nystrom, G., Ogawa, H., Olivares, R., Oshiro, P., Pérez-Beaupuits, J. P., Parra, R., Phillips, N. M., Poirier, M., Pradel, N., Qiu, R., Raffin, P. A., Rahlin, A. S., Ramírez, J., Ressler, S., Reynolds, M., Rodríguez-Montoya, I., Saez-Madain, A. F., Santana, J., Shaw, P., Shirkey, L. E., Silva, K. M., Snow, W., Sousa, D., Sridharan, T. K., Stahm, W., Stark, A. A., Test, J., Torstensson, K., Venegas, P., Walther, C., Wei, T.-S., White, C., Wieching, G., Wijnands, R., Wouterloot, J. G. A., Yu, C.-Y., Yu, W., and Zeballos, M., “First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way,” *ApJ* **930**, L12 (may 2022).
- [23] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczko, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doeleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi,

- C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., Bella, N. L., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lu, R.-S., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintroub, J., Wex, N., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., Zhao, S.-S., Agurto, C., Araneda, J. P., Arriagada, O., Bertarini, A., Berthold, R., Blanchard, J., Brown, K., Cárdenas, M., Cantzler, M., Caro, P., Chuter, T. C., Ciechanowicz, M., Coulson, I. M., Crowley, J., Degenaar, N., Dornbusch, S., Durán, C. A., Forster, K., Geertsema, G., González, E., Graham, D., Gueth, F., Han, C.-C., Herrera, C., Herrero-Illana, R., Heyminck, S., Hoge, J., Huang, Y.-D., Jiang, H., John, D., Klein, T., Kubo, D., Kuroda, J., Kwon, C., Laing, R., Liu, C.-T., Liu, K.-Y., Mac-Auliffe, F., Martin-Cocher, P., Matulonis, C., Messias, H., Meyer-Zhao, Z., Montenegro-Montes, F., Montgomerie, W., Muders, D., Nishioka, H., Norton, T. J., Olivares, R., Pérez-Beaupuits, J. P., Parra, R., Poirier, M., Pradel, N., Raffin, P. A., Ramírez, J., Reynolds, M., Saez-Madain, A. F., Santana, J., Silva, K. M., Sousa, D., Stahm, W., Torstensson, K., Venegas, P., Walther, C., Wieching, G., Wijnands, R., and Wouterloot, J. G. A., “First Sagittarius A* Event Horizon Telescope Results. II. EHT and Multiwavelength Observations, Data Processing, and Calibration,” *ApJ* **930**, L13 (may 2022).
- [24] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczko, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doeleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, M.,

- Krichbaum, T. P., Kuo, C.-Y., Bella, N. L., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lu, R.-S., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., and Zhao, S.-S., “First Sagittarius A* Event Horizon Telescope Results. III. Imaging of the Galactic Center Supermassive Black Hole,” *ApJ* **930**, L14 (may 2022).
- [25] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczkowski, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Davelaar, J., Laurentis, M. D., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doeleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., Bella, N. L., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lu, R.-S., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Traianou, E., Trent, T., Trippe, S.,

- Turk, M., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., Zhao, S.-S., and Chang, D. O., “First Sagittarius A* Event Horizon Telescope Results. IV. Variability, Morphology, and Black Hole Mass,” *ApJ* **930**, L15 (may 2022).
- [26] EHTC, Akiyama, K., Alberdi, A., Alef, W., Carlos Algaba, J., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczkowski, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doeleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Violette Impellizzeri, C. M., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., Bella, N. L., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lu, R.-S., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Navarro Fuentes, S., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Filippas Paraschos, G., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., Zhao, S.-S., Chan, T. L., Qiu, R., Ressler, S., and White, C., “First Sagittarius A* Event Horizon Telescope Results. V. Testing Astrophysical Models of the Galactic Center Black Hole,” *ApJ* **930**, L16 (may 2022).
- [27] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczkowski, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doeleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold,

- R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., Bella, N. L., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lu, R.-S., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., and Zhao, S.-S., “First Sagittarius A* Event Horizon Telescope Results. VI. Testing the Black Hole Metric,” *ApJ* **930**, L17 (may 2022).
- [28] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczkowski, A.-K., Ball, D., Balokovic, M., Bandyopadhyay, B., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chang, D. O., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Dahale, R., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Dihingia, I. K., Doeleman, S. S., Dougal, S. T., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Foschi, M., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, J. A., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., La Bella, N., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lowitz, A. E., Lu, R.-S., MacDonald, N. R., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Mulaudzi, W., Müller, C., Müller, H., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D.

- C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Romero-Cañizales, C., Ros, E., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Sosapanta Salas, L. D., Souccar, K., Stanway, J. S., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Toscano, T., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bommel, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Washington, J. E., Weintraub, J., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yadlapalli, N., Yamaguchi, P., Yfantis, A., Yoon, D., Young, A., Young, K., Younsi, Z., Yu, W., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., and Zhao, S.-S., “First Sagittarius A* Event Horizon Telescope Results. VII. Polarization of the Ring,” *ApJ* **964**, L25 (Apr. 2024).
- [29] EHTC, Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Baczkowski, A.-K., Ball, D., Baloković, M., Bandyopadhyay, B., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blackburn, L., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chan, C.-k., Chang, D. O., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Osorio, A., Cui, Y., Dahale, R., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Dihingia, I. K., Doeleman, S. S., Dougall, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Foschi, M., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Jiménez-Rosales, A., Johnson, M. D., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, J. A., Kramer, M., Krichbaum, T. P., Kuo, C.-Y., La Bella, N., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lowitz, A. E., Lu, R.-S., MacDonald, N. R., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Moscibrodzka, M., Mulaudzi, W., Müller, C., Müller, H., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Romero-Cañizales, C., Ros, E., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Sosapanta Salas, L. D., Souccar, K., Stanway, J. S., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Toscano, T., Traianou, E., Trent, T., Trippe, S., Turk, M., van Bommel, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Washington, J. E., Weintraub, J., Wharton, R., Wielgus, M., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yadlapalli, N., Yamaguchi, P., Yfantis, A., Yoon, D., Young, A., Young, K., Younsi, Z., Yu, W., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., Zhao, G.-Y., Zhao, S.-S., and Najafi-Ziyazi, M., “First Sagittarius A* Event Horizon Telescope Results. VIII. Physical Interpretation of the Polarized

- Ring,” *ApJ* **964**, L26 (Apr. 2024).
- [30] Johnson, M. D., Kovalev, Y. Y., Lisakov, M. M., Voitsik, P. A., Gwinn, C. R., and Bruni, G., “First Space-VLBI Observations of Sagittarius A*,” *ApJL*, *in press* (<https://arxiv.org/abs/2111.06423>) (2021).
 - [31] Kim, J.-Y., Savolainen, T., Voitsik, P., Kravchenko, E. V., Lisakov, M. M., Kovalev, Y. Y., Müller, H., Lobanov, A. P., Sokolovsky, K. V., Bruni, G., Edwards, P. G., Reynolds, C., Bach, U., Gurvits, L. I., Krichbaum, T. P., Hada, K., Giroletti, M., Orienti, M., Anderson, J. M., Lee, S.-S., Sohn, B. W., and Zensus, J. A., “RadioAstron Space VLBI Imaging of the Jet in M87. I. Detection of High Brightness Temperature at 22 GHz,” *ApJ* **952**, 34 (July 2023).
 - [32] Falcke, H., Melia, F., and Agol, E., “Viewing the Shadow of the Black Hole at the Galactic Center,” *ApJ* **528**, L13–L16 (Jan. 2000).
 - [33] Doleman, S. S., Barrett, J., Blackburn, L., Bouman, K. L., Broderick, A. E., Chaves, R., Fish, V. L., Fitzpatrick, G., Freeman, M., Fuentes, A., Gómez, J. L., Haworth, K., Houston, J., Issaoun, S., Johnson, M. D., Kettenis, M., Loinard, L., Nagar, N., Narayanan, G., Oppenheimer, A., Palumbo, D. C. M., Patel, N., Pesce, D. W., Raymond, A. W., Roelofs, F., Srinivasan, R., Tiede, P., Weintraub, J., and Wielgus, M., “Reference Array and Design Consideration for the Next-Generation Event Horizon Telescope,” *Galaxies* **11**, 107 (Oct. 2023).
 - [34] Johnson, M. D., Akiyama, K., Blackburn, L., Bouman, K. L., Broderick, A. E., Cardoso, V., Fender, R. P., Fromm, C. M., Galison, P., Gómez, J. L., Haggard, D., Lister, M. L., Lobanov, A. P., Markoff, S., Narayan, R., Natarajan, P., Nichols, T., Pesce, D. W., Younsi, Z., Chael, A., Chatterjee, K., Chaves, R., Doboszewski, J., Dodson, R., Doleman, S. S., Elder, J., Fitzpatrick, G., Haworth, K., Houston, J., Issaoun, S., Kovalev, Y. Y., Levis, A., Lico, R., Marcoci, A., Martens, N. C. M., Nagar, N. M., Oppenheimer, A., Palumbo, D. C. M., Ricarte, A., Rioja, M. J., Roelofs, F., Thresher, A. C., Tiede, P., Weintraub, J., and Wielgus, M., “Key Science Goals for the Next-Generation Event Horizon Telescope,” *Galaxies* **11**, 61 (Apr. 2023).
 - [35] Pesce, D. W., Blackburn, L., Chaves, R., Doleman, S. S., Freeman, M., Issaoun, S., Johnson, M. D., Lindahl, G., Natarajan, I., Paine, S. N., Palumbo, D. C. M., Roelofs, F., and Tiede, P., “Atmospheric limitations for high-frequency ground-based VLBI,” *arXiv e-prints*, arXiv:2404.01482 (Apr. 2024).
 - [36] Hirabayashi, H., Hirosawa, H., Kobayashi, H., Murata, Y., Edwards, P. G., Fomalont, E. B., Fujisawa, K., Ichikawa, T., Kii, T., Lovell, J. E. J., Moellenbrock, G. A., Okayasu, R., Inoue, M., Kawaguchi, N., Kamenoi, S., Shibata, K. M., Asaki, Y., Bushimata, T., Enome, S., Horiuchi, S., Miyaji, T., Umemoto, T., Migenes, V., Wajima, K., Nakajima, J., Morimoto, M., Ellis, J., Meier, D. L., Murphy, D. W., Preston, R. A., Smith, J. G., Tingay, S. J., Traub, D. L., Wietfeldt, R. D., Benson, J. M., Claussen, M. J., Flatters, C., Romney, J. D., Ulvestad, J. S., D’Addario, L. R., Langston, G. I., Minter, A. H., Carlson, B. R., Dewdney, P. E., Jauncey, D. L., Reynolds, J. E., Taylor, A. R., McCulloch, P. M., Cannon, W. H., Gurvits, L. I., Mioduszewski, A. J., Schilizzi, R. T., and Booth, R. S., “Overview and Initial Results of the Very Long Baseline Interferometry Space Observatory Programme,” *Science* **281**, 1825 (Sept. 1998).
 - [37] Kardashev, N. S., Khartov, V. V., Abramov, V. V., Avdeev, V. Y., Alakoz, A. V., Aleksandrov, Y. A., Ananthakrishnan, S., Andreyanov, V. V., Andrianov, A. S., Antonov, N. M., Artyukhov, M. I., Arkhipov, M. Y., Baan, W., Babakin, N. G., Babyshkin, V. E., Bartel’, N., Belousov, K. G., Belyaev, A. A., Berulis, J. J., Burke, B. F., Biryukov, A. V., Bubnov, A. E., Burgin, M. S., Busca, G., Bykadorov, A. A., Bychkova, V. S., Vasil’kov, V. I., Wellington, K. J., Vinogradov, I. S., Wietfeldt, R., Voitsik, P. A., Gvamichava, A. S., Girin, I. A., Gurvits, L. I., Dagkesamanskii, R. D., D’Addario, L., Giovannini, G., Jauncey, D. L., Dewdney, P. E., D’yakov, A. A., Zharov, V. E., Zhuravlev, V. I., Zaslavskii, G. S., Zakhvatkin, M. V., Zinov’ev, A. N., Ilinen, Y., Ipatov, A. V., Kanevskii, B. Z., Knorin, I. A., Casse, J. L., Kellermann, K. I., Kovalev, Y. A., Kovalev, Y. Y., Kovalenko, A. V., Kogan, B. L., Komaev, R. V., Konovalenko, A. A., Kopelyanskii, G. D., Korneev, Y. A., Kostenko, V. I., Kotik, A. N., Kreisman, B. B., Kukushkin, A. Y., Kulishenko, V. F., Cooper, D. N., Kut’kin, A. M., Cannon, W. H., Larionov, M. G., Lisakov, M. M., Litvinenko, L. N., Likhachev, S. F., Likhacheva, L. N., Lobanov, A. P., Logvinenko, S. V., Langston, G., McCracken, K., Medvedev, S. Y., Melekhin, M. V., Menderov, A. V., Murphy, D. W., Mizyakina, T. A., Mozgovoi, Y. V., Nikolaev, N. Y., Novikov, B. S., Novikov, I. D., Oreshko, V. V., Pavlenko, Y. K., Pashchenko, I. N., Ponomarev, Y. N., Popov, M. V., Pravin-Kumar, A., Preston, R. A., Pyshnov, V. N., Rakhimov, I. A., Rozhkov, V. M., Romney, J. D., Rocha, P., Rudakov, V. A., Räisänen, A., Sazankov, S. V., Sakharov,

- B. A., Semenov, S. K., Serebrennikov, V. A., Schilizzi, R. T., Skulachev, D. P., Slysh, V. I., Smirnov, A. I., Smith, J. G., Soglasnov, V. A., Sokolovskii, K. V., Sondaar, L. H., Stepan'yants, V. A., Turygin, M. S., Turygin, S. Y., Tuchin, A. G., Urpo, S., Fedorchuk, S. D., Finkel'shtein, A. M., Fomalont, E. B., Fejes, I., Fomina, A. N., Khapin, Y. B., Tsarevskii, G. S., Zensus, J. A., Chuprikov, A. A., Shatskaya, M. V., Shapirovskaya, N. Y., Sheikhet, A. I., Shirshakov, A. E., Schmidt, A., Shnyreva, L. A., Shpilevskii, V. V., Ekers, R. D., and Yakimov, V. E., ““RadioAstron”—A telescope with a size of 300 000 km: Main parameters and first observational results,” *Astronomy Reports* **57**, 153–194 (Mar. 2013).
- [38] Selina, R. J., Murphy, E. J., McKinnon, M., Beasley, A., Butler, B., Carilli, C., Clark, B., Durand, S., Erickson, A., Grammer, W., Hiriart, R., Jackson, J., Kent, B., Mason, B., Morgan, M., Ojeda, O. Y., Rosero, V., Shillue, W., Sturgis, S., and Urbain, D., “The ngVLA Reference Design,” in [*Science with a Next Generation Very Large Array*], Murphy, E., ed., *Astronomical Society of the Pacific Conference Series* **517**, 15 (Dec. 2018).
- [39] NASEM, [*Pathways to Discovery in Astronomy and Astrophysics for the 2020s: Highlights of a Decadal Survey*], The National Academies Press, Washington, DC (2023).
- [40] Narayan, R. and Quataert, E., “Black holes up close,” *Nature* **615**, 597–604 (Mar. 2023).
- [41] Johnson, M. D., Lupsasca, A., Strominger, A., Wong, G. N., Hadar, S., Kapec, D., Narayan, R., Chael, A., Gammie, C. F., Galison, P., Palumbo, D. C. M., Doeleman, S. S., Blackburn, L., Wielgus, M., Pesce, D. W., Farah, J. R., and Moran, J. M., “Universal interferometric signatures of a black hole’s photon ring,” *Science Advances* **6**, eaaz1310 (Mar. 2020).
- [42] Gralla, S. E. and Lupsasca, A., “Lensing by Kerr black holes,” *Phys. Rev. D* **101**, 044031 (Feb. 2020).
- [43] Bardeen, J. M., “Timelike and Null Geodesics in the Kerr Metric,” in [*Black Holes (Les Astres Occlus)*], Dewitt, C. and Dewitt, B. S., eds., 215, Gordon and Breach Scientific Publishers (1973).
- [44] Teo, E., “Spherical Photon Orbits Around a Kerr Black Hole,” *General Relativity and Gravitation* **35**, 1909–1926 (Nov 2003).
- [45] Yang, H., Nichols, D. A., Zhang, F., Zimmerman, A., Zhang, Z., and Chen, Y., “Quasinormal-mode spectrum of Kerr black holes and its geometric interpretation,” *Phys. Rev. D* **86**, 104006 (Nov 2012).
- [46] Himwich, E., Johnson, M. D., Lupsasca, A., and Strominger, A., “Universal polarimetric signatures of the black hole photon ring,” *Phys. Rev. D* **101**, 084020 (Apr. 2020).
- [47] Palumbo, D. C. M., Wong, G. N., and Prather, B. S., “Discriminating Accretion States via Rotational Symmetry in Simulated Polarimetric Images of M87,” *ApJ* **894**, 156 (May 2020).
- [48] Chael, A., Lupsasca, A., Wong, G. N., and Quataert, E., “Black Hole Polarimetry I. A Signature of Electromagnetic Energy Extraction,” *ApJ* **958**, 65 (Nov. 2023).
- [49] Tiede, P., Johnson, M. D., Pesce, D. W., Palumbo, D. C. M., Chang, D. O., and Galison, P., “Measuring Photon Rings with the ngEHT,” *Galaxies* **10**, 111 (Dec. 2022).
- [50] Gelles, Z., Prather, B. S., Palumbo, D. C. M., Johnson, M. D., Wong, G. N., and Georgiev, B., “The Role of Adaptive Ray Tracing in Analyzing Black Hole Structure,” *ApJ* **912**, 39 (May 2021).
- [51] Cárdenas-Avendaño, A., Lupsasca, A., and Zhu, H., “Adaptive analytical ray tracing of black hole photon rings,” *Phys. Rev. D* **107**, 043030 (Feb. 2023).
- [52] Gralla, S. E., Lupsasca, A., and Marrone, D. P., “The shape of the black hole photon ring: A precise test of strong-field general relativity,” *Phys. Rev. D* **102**, 124004 (Dec. 2020).
- [53] Gralla, S. E. and Lupsasca, A., “Observable shape of black hole photon rings,” *Phys. Rev. D* **102**, 124003 (Dec. 2020).
- [54] Gralla, S. E., Lupsasca, A., and Marrone, D. P., “The shape of the black hole photon ring: A precise test of strong-field general relativity,” *Phys. Rev. D* **102**, 124004 (Dec. 2020).
- [55] Pagnat, H., Lupsasca, A., Vincent, F. H., and Wielgus, M., “Photon ring test of the Kerr hypothesis: Variation in the ring shape,” *A&A* **668**, A11 (Dec. 2022).
- [56] Vincent, F. H., Gralla, S. E., Lupsasca, A., and Wielgus, M., “Images and photon ring signatures of thick disks around black holes,” *A&A* **667**, A170 (Nov. 2022).
- [57] Cárdenas-Avendaño, A. and Lupsasca, A., “Prediction for the interferometric shape of the first black hole photon ring,” *Phys. Rev. D* **108**, 064043 (Sept. 2023).

- [58] Cárdenas-Avendaño, A., Keeble, L., and Lupsasca, A., “Assessing the impact of instrument noise and astrophysical fluctuations on measurements of the first black hole photon ring,” *arXiv e-prints*, arXiv:2404.01083 (Apr. 2024).
- [59] Jia, H., Quataert, E., Lupsasca, A., and Wong, G. N., “Photon Ring Interferometric Signatures Beyond The Universal Regime,” *arXiv e-prints*, arXiv:2405.08804 (May 2024).
- [60] Kurczynski, P., Johnson, M. D., Doeleman, S. S., Haworth, K., Peretz, E., Sridharan, T. K., Bilyeu, B., Blackburn, L., Boroson, D., Brosius, A., Butler, R., Caplan, D., Chatterjee, K., Cheimets, P., D’Orazio, D., Essinger-Hileman, T., Galison, P., Gamble, R., Hadar, S., Hoerbelt, T., Jiao, H., Kauffmann, J., Lafon, R., Ma, C.-P., Melnick, G., Newbury, N. R., Noble, S., Palumbo, D., Paritsky, L., Pesce, D., Petrov, L., Piepmeier, J., Roberts, C. J., Robinson, B., Shieler, C., Small, J., Spellmeyer, N., Tiede, P., Verniero, J., Wang, J., Wielgus, M., Wollack, E., Wong, G. N., and Yang, G., “The Event Horizon Explorer mission concept,” in [*Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*], Coyle, L. E., Matsuura, S., and Perrin, M. D., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12180**, 121800M (Aug. 2022).
- [61] Peretz, E., Kurczynski, P., Johnson, M., Houston, J., Sridharan, T. K., Wang, J., Galison, P., Gamble, R., Marrone, D. P., Noble, S., Melnick, G., Petrov, L., Rana, H., Haworth, K., Doeleman, S. S., Issaoun, S., Hadar, S., Lupsasca, A., Tong, E., Akiyama, K., Srinivasan, R., Boroson, D., Yang, G., Hoerbelt, T., Small, J., Honma, M., Bilyeu, B., Canavan, E., Shtyrkova, K., Lafon, R., Paritsky, L., Sinclair, L. C., Silver, M., Gurvits, L. I., Kovalev, Y., and Lehmensiek, R., “The black hole explorer: Astrophysics mission concept engineering study report,” *Submitted to the SPIE Conference Series* (May 2024).
- [62] Roelofs, F., Falcke, H., Brinkerink, C., Mościbrodzka, M., Gurvits, L. I., Martin-Neira, M., Kudriashov, V., Klein-Wolt, M., Tilanus, R., Kramer, M., and Rezzolla, L., “Simulations of imaging the event horizon of Sagittarius A* from space,” *A&A* **625**, A124 (May 2019).
- [63] Pesce, D., Haworth, K., Melnick, G. J., Blackburn, L., Wielgus, M., Johnson, M. D., Raymond, A., Weintraub, J., Palumbo, D. C. M., Doeleman, S. S., and James, D. J., “Extremely long baseline interferometry with Origins Space Telescope,” in [*Bulletin of the American Astronomical Society*], **51**, 176 (Sept. 2019).
- [64] Lazio, T. J. W., Briskin, W., Bouman, K., Doeleman, S., Falcke, H., Iguchi, S., Kovalev, Y. Y., Lonsdale, C. J., Shen, Z., Zensus, A., and Beasley, A. J., “Space VLBI 2020: Science and Technology Futures Conference Summary,” *arXiv e-prints*, arXiv:2005.12767 (May 2020).
- [65] Gurvits, L. I., Paragi, Z., Casasola, V., Conway, J., Davelaar, J., Falcke, H., Fender, R., Frey, S., Fromm, C. M., Miró, C. G., Garrett, M. A., Giroletti, M., Goddi, C., Gómez, J.-L., van der Gucht, J., Guirado, J. C., Haiman, Z., Helmich, F., Humphreys, E., Impellizzeri, V., Kramer, M., Lindqvist, M., Linz, H., Liuzzo, E., Lobanov, A. P., Mizuno, Y., Rezzolla, L., Roelofs, F., Ros, E., Rygl, K. L. J., Savolainen, T., Schuster, K., Venturi, T., Wiedner, M. C., and Zensus, J. A., “THEZA: TeraHertz Exploration and Zooming-in for Astrophysics,” *Experimental Astronomy* **51**, 559–594 (June 2021).
- [66] Gurvits, L. I., Paragi, Z., Amils, R. I., van Bemmelen, I., Boven, P., Casasola, V., Conway, J., Davelaar, J., Díez-González, M. C., Falcke, H., Fender, R., Frey, S., Fromm, C. M., Gallego-Puyol, J. D., García-Miró, C., Garrett, M. A., Giroletti, M., Goddi, C., Gómez, J. L., van der Gucht, J., Guirado, J. C., Haiman, Z., Helmich, F., Hudson, B., Humphreys, E., Impellizzeri, V., Janssen, M., Johnson, M. D., Kovalev, Y. Y., Kramer, M., Lindqvist, M., Linz, H., Liuzzo, E., Lobanov, A. P., López-Fernández, I., Malo-Gómez, I., Masania, K., Mizuno, Y., Plavin, A. V., Rajan, R. T., Rezzolla, L., Roelofs, F., Ros, E., Rygl, K. L. J., Savolainen, T., Schuster, K., Venturi, T., Verkouter, M., de Vicente, P., Visser, P. N. A. M., Wiedner, M. C., Wielgus, M., Wiik, K., and Zensus, J. A., “The science case and challenges of space-borne sub-millimeter interferometry,” *Acta Astronautica* **196**, 314–333 (July 2022).
- [67] Hudson, B., Gurvits, L. I., Wielgus, M., Paragi, Z., Liu, L., and Zheng, W., “Orbital configurations of spaceborne interferometers for studying photon rings of supermassive black holes,” *Acta Astronautica* **213**, 681–693 (Dec. 2023).
- [68] Wang, J. P., Bilyeu, B., Boroson, D., Caplan, D., Robinson, B., Shieler, C., Johnson, M., Blackburn, L., Doeleman, S., and Haworth, K., “High-rate 256+ Gbit/s laser communications for enhanced high-resolution imaging using space-based very long baseline interferometry (VLBI),” in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], Hemmati, H. and Robinson, B. S., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **12413**, 1241308 (Mar. 2023).

- [69] Akiyama, K., Niinuma, K., Hada, K., Doi, A., Hagiwara, Y., Higuchi, A. E., Honma, M., Kawashima, T., Kolev, D., Koyama, S., Masui, S., Ohsuga, K., Sano, H., Takami, H., Tsunetoe, Y., Uzawa, Y., Akahori, T., Akiyama, Y., Galison, P., Hayashi, T. J., Hirota, T., Inoue, M., Iwata, Y., Johnson, M. D., Kino, M., Kofuji, Y., Mizuno, Y., Moriyama, K., Nagai, H., Nakamura, K., Notsu, S., Ono, F., Oya, Y., Oyama, T., Rana, H., Saida, H., Saito, R., Saito, Y., Sasada, M., Sawada-Satoh, S., Takahashi, M. M., Takamura, M., Tong, E., Tsuji, H., Yoshioka, S., and Watanabe, Y., “The japanese vision for the black hole explorer mission,” *Submitted to the SPIE Conference Series* (May 2024).
- [70] Mather, J., Peretz, E., Kurczynski, P., Albert, J., et al., “Hybrid Observatories,” *in prep.* (2024).
- [71] Issaoun, S., Akiyama, K., Alonso, K., Blackburn, L., Boroson, D., Galison, P., Haworth, K., Houston, J., Johnson, M. D., Kovalev, Y. Y., Kurczynski, P., Lafon, R., Marrone, D. P., Palumbo, D., Peretz, E., Pesce, D., Petrov, L., Plavin, A., and Wang, J., “The black hole explorer: Operating a hybrid observatory,” *Submitted to the SPIE Conference Series* (May 2024).
- [72] Crew, G. B., Goddi, C., Matthews, L. D., Rottmann, H., Saez, A., and Martí-Vidal, I., “A Characterization of the ALMA Phasing System at 345 GHz,” *PASP* **135**, 025002 (Feb. 2023).
- [73] Raymond, A. W., Doeleman, S. S., Asada, K., Blackburn, L., et al. (2024).
- [74] Backes, M., Müller, C., Conway, J. E., Deane, R., Evans, R., Falcke, H., Fraga-Encinas, R., Goddi, C., Klein Wolt, M., Krichbaum, T. P., MacLeod, G., Ribeiro, V. A. R. M., Roelofs, F., Shen, Z. Q., and van Langevelde, H. J., “The Africa Millimetre Telescope,” in [*The 4th Annual Conference on High Energy Astrophysics in Southern Africa (HEASA 2016)*], 29 (Jan. 2016).
- [75] Asada, K., Kino, M., Honma, M., Hirota, T., Lu, R. S., Inoue, M., Sohn, B. W., Shen, Z. Q., Ho, P. T. P., Akiyama, K., Algaba, J.-C., An, T., Bower, G., Byun, D.-Y., Dodson, R., Doi, A., Edwards, P. G., Fujisawa, K., Gu, M.-F., Hada, K., Hagiwara, Y., Jaroenjittichai, P., Jung, T., Kawashima, T., Koyama, S., Lee, S.-S., Matsushita, S., Nagai, H., Nakamura, M., Niinuma, K., Phillips, C., Park, J.-H., Pu, H.-Y., Ro, H.-W., Stevens, J., Trippe, S., Wajima, K., and Zhao, G.-Y., “White Paper on East Asian Vision for mm/submm VLBI: Toward Black Hole Astrophysics down to Angular Resolution of $1R_S$,” *arXiv e-prints*, arXiv:1705.04776 (May 2017).
- [76] Romero, G. E., “Large Latin American Millimeter Array,” *arXiv e-prints*, arXiv:2010.00738 (Oct. 2020).
- [77] Kauffmann, J., Rajagopalan, G., Akiyama, K., Fish, V., Lonsdale, C., Matthews, L. D., and Pillai, T. G., “The haystack telescope as an astronomical instrument,” *Galaxies* **11**(1) (2023).
- [78] Rioja, M. J., Dodson, R., Jung, T., and Sohn, B. W., “The Power of Simultaneous Multifrequency Observations for mm-VLBI: Astrometry up to 130 GHz with the KVN,” *AJ* **150**, 202 (Dec 2015).
- [79] Issaoun, S., Pesce, D. W., Roelofs, F., Chael, A., Dodson, R., Rioja, M. J., Akiyama, K., Aran, R., Blackburn, L., Doeleman, S. S., Fish, V. L., Fitzpatrick, G., Johnson, M. D., Narayanan, G., Raymond, A. W., and Tilanus, R. P. J., “Enabling transformational ngeht science via the inclusion of 86 ghz capabilities,” *Galaxies* **11**(1) (2023).
- [80] Rioja, M. J., Dodson, R., and Asaki, Y., “The transformational power of frequency phase transfer methods for ngeht,” *Galaxies* **11**(1) (2023).
- [81] Jiang, W., Zhao, G.-Y., Shen, Z.-Q., Rioja, M. J., Dodson, R., Cho, I., Zhao, S.-S., Eubanks, M., and Lu, R.-S., “Applications of the Source-Frequency Phase-Referencing Technique for ngeHT Observations,” *Galaxies* **11**, 3 (Jan. 2023).
- [82] Carpenter, J., Brogan, C., Iono, D., and Mroczkowski, T., “The ALMA Wideband Sensitivity Upgrade,” in [*Physics and Chemistry of Star Formation: The Dynamical ISM Across Time and Spatial Scales*], Ossenkopf-Okada, V., Schaaf, R., Breloy, I., and Stutzki, J., eds., 304 (Feb. 2023).
- [83] Navarrini, A., Lambert, J. G., Kerr, A. R., Effland, J., Dindo, P., Saini, K., Lehmensiek, R., Vaselaar, D., Handy, A., Casto, B., Astudillo, P., Lichtenberger, A. W., Cyberey, M., Mena, P., Jarufe, C., and Hawkins, B., “ALMA Band 6v2 receiver development status,” in [*2023 XXXVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*], 45 (Oct. 2023).
- [84] Marrone, D. P., Houston, J., Akiyama, K., Bilyeu, B., Boroson, D., Grimes, P., Haworth, K., Lehmensiek, R., Peretz, E., Rana, H., Sinclair, L. C., Sridharan, T. K., Srinivasan, R., Tong, E., Wang, J., Weintroub, J., and Johnson, M. D., “The black hole explorer: Instrument system overview,” *Submitted to the SPIE Conference Series* (May 2024).

- [85] Tong, E. C., Akiyama, K., Grimes, P., Honma, M., Houston, J., Johnson, M., Marrone, D. P., Rana, H., and Uzawa, Y., “Receivers for The Black Hole Explorer (BHEX) mission,” *Submitted to the SPIE Conference Series* (May 2024).
- [86] Sridharan, T. K., Lehmensiek, R., Cheimets, P., Freeman, M., Houston, J., Johnson, M., Marrone, D. P., and Silver, M., “The black hole explorer (bhcx): Preliminary antenna design,” *Submitted to the SPIE Conference Series* (May 2024).
- [87] Rana, H., Akiyama, K., Canavan, E. R., DiPirro, M. J., Freeman, M., Galison, P., Grimes, P. K., Hada, K., Honma, M., Houston, J., Johnson, M., Kimball, M. O., Marrone, D. P., Niinuma, K., and Tong, E., “The black hole explorer (bhcx) cryocooling instrument,” *Submitted to the SPIE Conference Series* (May 2024).
- [88] Wang, J., Boroson, D., Schieler, C., Bilyeu, B., Shtyrkova, K., Caplan, D., Johnson, M., Weintraub, J., Srinivasan, R., Haworth, K., Houston, J., Blackburn, L., Richards, E., and Marrone, D. P., “High rate laser communications for the black hole explorer,” *Submitted to the SPIE Conference Series* (May 2024).
- [89] Srinivasan, R., Richards, E., Weintraub, J., Test, J., Freeman, M., Haworth, K., Johnson, M., Cheimets, P., Houston, J., Wang, J., Bilyeu, B., Fernandez, M., Mamani, E., Pola, A. L., Gendelman, M., and Marrone, D. P., “The black hole explorer back-end electronics,” *Submitted to the SPIE Conference Series* (May 2024).
- [90] Tomio, H., Numata, K., Yang, G., Attar, A., Lu, W., Xu, X., Leopardi, H. F., Gramling, C., Sridharan, T. K., and Kurczynski, P., “Ultra-low noise laser and optical frequency comb-based timing system for the black hole explorer (bhcx) mission,” *Submitted to the SPIE Conference Series* (May 2024).
- [91] Lupsasca, A., Cárdenas-Avendaño, A., Palumbo, D. C., Johnson, M. D., Gralla, S. E., Marrone, D. P., Galison, P., Tiede, P., and Keeble, L., “The black hole explorer: Photon ring, detection, and shape measurement,” *Submitted to the SPIE Conference Series* (May 2024).
- [92] Galison, P., Lupsasca, A., and Johnson, M., “The black hole explorer: Using the photon ring to visualize spacetime around the black hole,” *Submitted to the SPIE Conference Series* (May 2024).
- [93] Kawashima, T., Tsunetoe, Y., and Ohsuga, K., “Black hole spacetime and properties of accretion flows and jets probed by black hole explorer,” *Submitted to the SPIE Conference Series* (May 2024).
- [94] Zhang, X. A., Ricarte, A., Pesce, D. W., Johnson, M. D., Nagar, N., et al., “Accessing a New Population of Supermassive Black Holes with Extensions to the Event Horizon Telescope,” *under review* (2024).
- [95] Kim, J.-Y., Krichbaum, T. P., Broderick, A. E., Wielgus, M., Blackburn, L., Gómez, J. L., Johnson, M. D., Bouman, K. L., Chael, A., Akiyama, K., Jorstad, S., Marscher, A. P., Issaoun, S., Janssen, M., Chan, C.-k., Savolainen, T., Pesce, D. W., Özel, F., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczko, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Boland, W., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chatterjee, S., Chatterjee, K., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crew, G. B., Cui, Y., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Friberg, P., Fromm, C. M., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., James, D. J., Jannuzi, B. T., Jeter, B., Jiang, W., Jimenez-Rosales, A., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J., Kim, J., Kino, M., Koay, J. Y., Koch, P. M., Koyama, S., Kramer, M., Kramer, C., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Lico, R., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Markoff, S., Marrone, D. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, Y., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Musoke, G., Müller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Palumbo, D. C. M., Park, J., Patel, N., Pen, U.-L., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Ryan, B. R., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Schloerb, F. P., Schuster, K.-F., Shao, L.,

- Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Traianou, E., Trippe, S., Tsuda, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Wardle, J., Ward-Thompson, D., Weintraub, J., Wex, N., Wharton, R., Wong, G. N., Wu, Q., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., Algaba, J.-C., Allardi, A., Amestica, R., Anczarski, J., Bach, U., Baganoff, F. K., Beaudoin, C., Benson, B. A., Berthold, R., Blanchard, J. M., Blundell, R., Bustamente, S., Cappallo, R., Castillo-Domínguez, E., Chang, C.-C., Chang, S.-H., Chang, S.-C., Chen, C.-C., Chilson, R., Chuter, T. C., Rosado, R. C., Coulson, I. M., Crowley, J., Derome, M., Dexter, M., Dornbusch, S., Dudevoir, K. A., Dzib, S. A., Eckart, A., Eckert, C., Erickson, N. R., Everett, W. B., Faber, A., Farah, J. R., Fath, V., Folkers, T. W., Forbes, D. C., Freund, R., Gale, D. M., Gao, F., Geertsema, G., Graham, D. A., Greer, C. H., Grosslein, R., Gueth, F., Haggard, D., Halverson, N. W., Han, C.-C., Han, K.-C., Hao, J., Hasegawa, Y., Henning, J. W., Hernández-Gómez, A., Herrero-Illana, R., Heyminck, S., Hirota, A., Hoge, J., Huang, Y.-D., Violette Impellizzeri, C. M., Jiang, H., John, D., Kamble, A., Keisler, R., Kimura, K., Kono, Y., Kubo, D., Kuroda, J., Lacasse, R., Laing, R. A., Leitch, E. M., Li, C.-T., Lin, L. C. C., Liu, C.-T., Liu, K.-Y., Lu, L.-M., Marson, R. G., Martin-Cocher, P. L., Massingill, K. D., Matulonis, C., McColl, M. P., McWhirter, S. R., Messias, H., Meyer-Zhao, Z., Michalik, D., Montaña, A., Montgomerie, W., Mora-Klein, M., Muders, D., Nadolski, A., Navarro, S., Neilsen, J., Nguyen, C. H., Nishioka, H., Norton, T., Nowak, M. A., Nystrom, G., Ogawa, H., Oshiro, P., Oyama, T., Parsons, H., Peñalver, J., Phillips, N. M., Poirier, M., Pradel, N., Primiani, R. A., Raffin, P. A., Rahlin, A. S., Reiland, G., Risacher, C., Ruiz, I., Sáez-Madaín, A. F., Sassella, R., Schellart, P., Shaw, P., Silva, K. M., Shiokawa, H., Smith, D. R., Snow, W., Souccar, K., Sousa, D., Sridharan, T. K., Srinivasan, R., Stahm, W., Stark, A. A., Story, K., Timmer, S. T., Vertatschitsch, L., Walther, C., Wei, T.-S., Whitehorn, N., Whitney, A. R., Woody, D. P., Wouterloot, J. G. A., Wright, M., Yamaguchi, P., Yu, C.-Y., Zeballos, M., Zhang, S., Ziurys, L., and Event Horizon Telescope Collaboration, “Event Horizon Telescope imaging of the archetypal blazar 3C 279 at an extreme 20 microarcsecond resolution,” *A&A* **640**, A69 (Aug. 2020).
- [96] Janssen, M., Falcke, H., Kadler, M., Ros, E., Wielgus, M., Akiyama, K., Baloković, M., Blackburn, L., Bouman, K. L., Chael, A., Chan, C.-k., Chatterjee, K., Davelaar, J., Edwards, P. G., Fromm, C. M., Gómez, J. L., Goddi, C., Issaoun, S., Johnson, M. D., Kim, J., Koay, J. Y., Krichbaum, T. P., Liu, J., Liuzzo, E., Markoff, S., Markowitz, A., Marrone, D. P., Mizuno, Y., Müller, C., Ni, C., Pesce, D. W., Ramakrishnan, V., Roelofs, F., Rygl, K. L. J., van Bemmell, I., Event Horizon Telescope Collaboration, Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Baczko, A.-K., Ball, D., Ball, D., Barrett, J., Benson, B. A., Bintley, D., Bintley, D., Blundell, R., Boland, W., Boland, W., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chatterjee, S., Chen, M.-T., Chen, Y., Chesler, P. M., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsorio, A., Cui, Y., Cui, Y., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doeleman, S. S., Eatough, R. P., Farah, J., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Friberg, P., Friberg, P., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gelles, Z., Gentaz, O., Georgiev, B., Georgiev, B., Gold, R., Gold, R., Gómez-Ruiz, A. I., Gu, M., Gurwell, M., Hada, K., Haggard, D., Hecht, M. H., Hesper, R., Himwich, E., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Inoue, M., James, D. J., Jannuzi, B. T., Jeter, B., Jiang, W., Jimenez-Rosales, A., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kino, M., Kofuji, Y., Koyama, S., Kramer, M., Kramer, C., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Levis, A., Li, Y.-R., Li, Z., Lindqvist, M., Lico, R., Lindahl, G., Liu, K., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Marchili, N., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Moscibrodzka, M., Musoke, G., Mejías, A. M., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Neilsen, J., Neri, R., Noutsos, A., Nowak, M. A., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Park, J., Patel, N., Pen, U.-L., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Pu, H.-Y., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Rogers, A., Rose, M., Roshanineshat, A., Rottmann, H.,

- Roy, A. L., Ruszczyk, C., Sánchez, S., Sánchez-Arguelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Trent, T., Traianou, E., Trippe, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wharton, R., Wong, G. N., Wu, Q., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G.-Y., and Zhao, S.-S., “Event Horizon Telescope observations of the jet launching and collimation in Centaurus A,” *Nature Astronomy* **5**, 1017–1028 (July 2021).
- [97] Issaoun, S., Wielgus, M., Jorstad, S., Krichbaum, T. P., Blackburn, L., Janssen, M., Chan, C.-k., Pesce, D. W., Gómez, J. L., Akiyama, K., Mościbrodzka, M., Martí-Vidal, I., Chael, A., Lico, R., Liu, J., Ramakrishnan, V., Lisakov, M., Fuentes, A., Zhao, G.-Y., Moriyama, K., Broderick, A. E., Tiede, P., MacDonald, N. R., Mizuno, Y., Traianou, E., Loinard, L., Davelaar, J., Gurwell, M., Lu, R.-S., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Bacsko, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blundell, R., Boland, W., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Osorio, A., Cui, Y., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Doleman, S. S., Dhruv, V., Dzib Quijano, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gu, M., Hada, K., Haggard, D., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., James, D. J., Jannuzi, B. T., Jeter, B., Jiang, W., Jimenez-Rosales, A., Johnson, M. D., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, M., Kuo, C.-Y., La Bella, N., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Lonsdale, C., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Müller, C., Mus, A., Musoke, G., Myerlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötzl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Canizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Arguelles, D., Sanchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Trent, T., Trippe, S., van Bemmell, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wiik, K., Witzel, G., Wondrak, M., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., and Zhao, S.-S., “Resolving the Inner Parsec of the Blazar J1924-2914 with the Event Horizon Telescope,” *ApJ* **934**, 145 (Aug. 2022).
- [98] Jorstad, S., Wielgus, M., Lico, R., Issaoun, S., Broderick, A. E., Pesce, D. W., Liu, J., Zhao, G.-Y., Krichbaum, T. P., Blackburn, L., Chan, C.-k., Janssen, M., Ramakrishnan, V., Akiyama, K., Alberdi, A., Algaba, J. C., Bouman, K. L., Cho, I., Fuentes, A., Gómez, J. L., Gurwell, M., Johnson, M. D., Kim, J.-Y., Lu, R.-S., Martí-Vidal, I., Mościbrodzka, M., Pötzl, F. M., Traianou, E., van Bemmell, I., Alef, W., Anantua, R., Asada, K., Azulay, R., Bach, U., Bacsko, A.-K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blundell, R., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D.-Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chatterjee, K., Chatterjee, S., Chen, M.-T., Chen, Y., Cheng, X., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Osorio, A., Cui, Y.,

- Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fish, V. L., Fomalont, E., Ford, H. A., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gu, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., James, D. J., Jannuzi, B. T., Jeter, B., Jiang, W., Jiménez-Rosales, A., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D.-J., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koyama, S., Kramer, C., Kramer, M., Kuo, C.-Y., La Bella, N., Lauer, T. R., Lee, D., Lee, S.-S., Leung, P. K., Levis, A., Li, Z., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., MacDonald, N. R., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Müller, C., Mus, A., Musoke, G., Myserlis, I., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayan, R., Narayanan, G., Natarajan, I., Nathanail, A., Fuentes, S. N., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares, H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Paraschos, G. F., Park, J., Parsons, H., Patel, N., Pen, U.-L., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Trent, T., Trippe, S., Turk, M., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yamaguchi, P., Yoon, D., Young, A., Young, K., Younsi, Z., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhang, S., and Zhao, S.-S., “The Event Horizon Telescope Image of the Quasar NRAO 530,” *ApJ* **943**, 170 (Feb. 2023).
- [99] Paraschos, G. F., Kim, J. Y., Wielgus, M., Röder, J., Krichbaum, T. P., Ros, E., Agudo, I., Myserlis, I., Moscibrodzka, M., Traianou, E., Zensus, J. A., Blackburn, L., Chan, C. K., Issaoun, S., Janssen, M., Johnson, M. D., Fish, V. L., Akiyama, K., Alberdi, A., Alef, W., Algaba, J. C., Anantua, R., Asada, K., Azulay, R., Bach, U., Bacsko, A. K., Ball, D., Baloković, M., Barrett, J., Bauböck, M., Benson, B. A., Bintley, D., Blundell, R., Bouman, K. L., Bower, G. C., Boyce, H., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Bustamante, S., Byun, D. Y., Carlstrom, J. E., Ceccobello, C., Chael, A., Chang, D. O., Chatterjee, K., Chatterjee, S., Chen, M. T., Chen, Y., Cheng, X., Cho, I., Christian, P., Conroy, N. S., Conway, J. E., Cordes, J. M., Crawford, T. M., Crew, G. B., Cruz-Orsio, A., Cui, Y., Dahale, R., Davelaar, J., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Dexter, J., Dhruv, V., Doleman, S. S., Dougal, S., Dzib, S. A., Eatough, R. P., Emami, R., Falcke, H., Farah, J., Fomalont, E., Ford, H. A., Foschi, M., Fraga-Encinas, R., Freeman, W. T., Friberg, P., Fromm, C. M., Fuentes, A., Galison, P., Gammie, C. F., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gómez-Ruiz, A. I., Gómez, J. L., Gu, M., Gurwell, M., Hada, K., Haggard, D., Haworth, K., Hecht, M. H., Hesper, R., Heumann, D., Ho, L. C., Ho, P., Honma, M., Huang, C. L., Huang, L., Hughes, D. H., Ikeda, S., Impellizzeri, C. M. V., Inoue, M., James, D. J., Jannuzi, B. T., Jeter, B., Jaing, W., Jiménez-Rosales, A., Jorstad, S., Joshi, A. V., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, D. J., Kim, J., Kim, J., Kino, M., Koay, J. Y., Kocherlakota, P., Kofuji, Y., Koch, P. M., Koyama, S., Kramer, C., Kramer, J. A., Kramer, M., Kuo, C. Y., La Bella, N., Lauer, T. R., Lee, D., Lee, S. S., Leung, P. K., Levis, A., Li, Z., Lico, R., Lindahl, G., Lindqvist, M., Lisakov, M., Liu, J., Liu, K., Liuzzo, E., Lo, W. P., Lobanov, A. P., Loinard, L., Lonsdale, C. J., Lowitz, A. E., Lu, R. S., MacDonald, N. R., Mao, J., Marchili, N., Markoff, S., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Michalik, D., Mizuno, I., Mizuno, Y., Moran, J. M., Moriyama, K., Mulaudzi, W., Müller, C., Müller, H., Mus, A., Musoke, G., Nadolski, A., Nagai, H., Nagar, N. M., Nakamura, M., Narayanan, G., Natarajan, I., Nathanail, A., Navarro Fuentes, S., Neilsen, J., Neri, R., Ni, C., Noutsos, A., Nowak, M. A., Oh, J., Okino, H., Olivares,

- H., Ortiz-León, G. N., Oyama, T., Özel, F., Palumbo, D. C. M., Park, J., Parsons, H., Patel, N., Pen, U. L., Piétu, V., Plambeck, R., PopStefanija, A., Porth, O., Pötl, F. M., Prather, B., Preciado-López, J. A., Psaltis, D., Pu, H. Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Rezzolla, L., Ricarte, A., Ripperda, B., Roelofs, F., Rogers, A., Romero-Cañizales, C., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruiz, I., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sánchez-Portal, M., Sasada, M., Satapathy, K., Savolainen, T., Schloerb, F. P., Schonfeld, J., Schuster, K., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Sosapanta Salas, L. D., Souccar, K., Sun, H., Tazaki, F., Tetarenko, A. J., Tiede, P., Tilanus, R. P. J., Titus, M., Torne, P., Toscano, T., Trent, T., Trippe, S., Turk, M., van Bommel, I., van Langevelde, H. J., van Rossum, D. R., Vos, J., Wagner, J., Ward-Thompson, D., Wardle, J., Washington, J. E., Weintraub, J., Wharton, R., Wiik, K., Witzel, G., Wondrak, M. F., Wong, G. N., Wu, Q., Yadlapalli, N., Yamaguchi, P., Yfantis, A., Yoon, D., Young, A., Young, K., Younsi, Z., Yu, W., Yuan, F., Yuan, Y. F., Zhang, S., Zhao, G. Y., and Zhao, S. S., “Ordered magnetic fields around the 3C 84 central black hole,” *A&A* **682**, L3 (Feb. 2024).
- [100] Johannsen, T. and Psaltis, D., “Testing the No-hair Theorem with Observations in the Electromagnetic Spectrum. II. Black Hole Images,” *ApJ* **718**, 446–454 (July 2010).
- [101] Chan, C.-k., Psaltis, D., and Özel, F., “GRay: A Massively Parallel GPU-based Code for Ray Tracing in Relativistic Spacetimes,” *ApJ* **777**, 13 (Nov. 2013).
- [102] Gralla, S. E., Holz, D. E., and Wald, R. M., “Black hole shadows, photon rings, and lensing rings,” *Phys. Rev. D* **100**, 024018 (July 2019).
- [103] Vincent, F. H., Gralla, S. E., Lupsasca, A., and Wielgus, M., “Images and photon ring signatures of thick disks around black holes,” *A&A* **667**, A170 (Nov. 2022).
- [104] Gammie, C. F., McKinney, J. C., and Tóth, G., “HARM: A Numerical Scheme for General Relativistic Magnetohydrodynamics,” *ApJ* **589**, 444–457 (May 2003).
- [105] Porth, O., Chatterjee, K., Narayan, R., Gammie, C. F., Mizuno, Y., Anninos, P., Baker, J. G., Bugli, M., Chan, C.-k., Davelaar, J., Del Zanna, L., Etienne, Z. B., Fragile, P. C., Kelly, B. J., Liska, M., Markoff, S., McKinney, J. C., Mishra, B., Noble, S. C., Olivares, H., Prather, B., Rezzolla, L., Ryan, B. R., Stone, J. M., Tomei, N., White, C. J., Younsi, Z., Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczko, A.-K., Ball, D., Baloković, M., Barrett, J., Bintley, D., Blackburn, L., Boland, W., Bouman, K. L., Bower, G. C., Bremer, M., Brinkerink, C. D., Brissenden, R., Britzen, S., Broderick, A. E., Brogiere, D., Bronzwaer, T., Byun, D.-Y., Carlstrom, J. E., Chael, A., Chatterjee, S., Chen, M.-T., Chen, Y., Cho, I., Christian, P., Conway, J. E., Cordes, J. M., Geoffrey, Crew, B., Cui, Y., De Laurentis, M., Deane, R., Dempsey, J., Desvignes, G., Doleman, S. S., Eatough, R. P., Falcke, H., Fish, V. L., Fomalont, E., Fraga-Encinas, R., Freeman, B., Friberg, P., Fromm, C. M., Gómez, J. L., Galison, P., García, R., Gentaz, O., Georgiev, B., Goddi, C., Gold, R., Gu, M., Gurwell, M., Hada, K., Hecht, M. H., Hesper, R., Ho, L. C., Ho, P., Honma, M., Huang, C.-W. L., Huang, L., Hughes, D. H., Ikeda, S., Inoue, M., Issaoun, S., James, D. J., Jannuzi, B. T., Janssen, M., Jeter, B., Jiang, W., Johnson, M. D., Jorstad, S., Jung, T., Karami, M., Karuppusamy, R., Kawashima, T., Keating, G. K., Kettenis, M., Kim, J.-Y., Kim, J., Kim, J., Kino, M., Koay, J. Y., Patrick, Koch, M., Koyama, S., Kramer, M., Kramer, C., Krichbaum, T. P., Kuo, C.-Y., Lauer, T. R., Lee, S.-S., Li, Y.-R., Li, Z., Lindqvist, M., Liu, K., Liuzzo, E., Lo, W.-P., Lobanov, A. P., Loinard, L., Lonsdale, C., Lu, R.-S., MacDonald, N. R., Mao, J., Marrone, D. P., Marscher, A. P., Martí-Vidal, I., Matsushita, S., Matthews, L. D., Medeiros, L., Menten, K. M., Mizuno, I., Moran, J. M., Moriyama, K., Moscibrodzka, M., Müller, C., Nagai, H., Nagar, N. M., Nakamura, M., Narayanan, G., Natarajan, I., Neri, R., Ni, C., Noutsos, A., Okino, H., Oyama, T., Özel, F., Palumbo, D. C. M., Patel, N., Pen, U.-L., Pesce, D. W., Piétu, V., Plambeck, R., PopStefanija, A., Preciado-López, J. A., Psaltis, D., Pu, H.-Y., Ramakrishnan, V., Rao, R., Rawlings, M. G., Raymond, A. W., Ripperda, B., Roelofs, F., Rogers, A., Ros, E., Rose, M., Roshanineshat, A., Rottmann, H., Roy, A. L., Ruszczyk, C., Rygl, K. L. J., Sánchez, S., Sánchez-Argüelles, D., Sasada, M., Savolainen, T., Schloerb, F. P., Schuster, K.-F., Shao, L., Shen, Z., Small, D., Sohn, B. W., SooHoo, J., Tazaki, F., Tiede, P., Tilanus, R. P. J., Titus, M., Toma, K., Torne, P., Trent, T., Trippe, S., Tsuda, S., van Bommel, I., van Langevelde, H. J., van Rossum, D. R., Wagner, J., Wardle, J., Weintraub, J., Wex, N., Wharton, R., Wielgus, M., Wong, G. N., Wu, Q., Young, K., Young, A., Yuan, F., Yuan, Y.-F., Zensus, J. A., Zhao, G., Zhao, S.-S., Zhu, Z., and Event

Horizon Telescope Collaboration, “The Event Horizon General Relativistic Magnetohydrodynamic Code Comparison Project,” *ApJS* **243**, 26 (Aug. 2019).

- [106] Wielgus, M., “Photon rings of spherically symmetric black holes and robust tests of non-Kerr metrics,” *Phys. Rev. D* **104**, 124058 (Dec. 2021).
- [107] Palumbo, D. C. M. and Wong, G. N., “Photon Ring Symmetries in Simulated Linear Polarization Images of Messier 87*,” *ApJ* **929**, 49 (Apr. 2022).
- [108] Chael, A., Johnson, M. D., and Lupsasca, A., “Observing the Inner Shadow of a Black Hole: A Direct View of the Event Horizon,” *ApJ* **918**, 6 (Sept. 2021).
- [109] Tiede, P., “Comrade: Composable Modeling of Radio Emission,” *The Journal of Open Source Software* **7**, 4457 (Aug. 2022).
- [110] Takahashi, R., “Shapes and positions of black hole shadows in accretion disks and spin parameters of black holes,” *ApJ* **611**, 8 (Nov. 2004).
- [111] Farah, J. R., Pesce, D. W., Johnson, M. D., and Blackburn, L., “On the Approximation of the Black Hole Shadow with a Simple Polar Curve,” *ApJ* **900**, 77 (Sept. 2020).
- [112] EHT Collaboration, Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., Baczko, A.-K., Ball, D., Baloković, M., and Barrett, J., “First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring,” *ApJ* **875**, L5 (4 2019).
- [113] Bambi, C., Brenneman, L. W., Dauser, T., García, J. A., Grinberg, V., Ingram, A., Jiang, J., Liu, H., Lohfink, A. M., Marinucci, A., Mastroserio, G., Middei, R., Nampalliwar, S., Niedźwiecki, A., Steiner, J. F., Tripathi, A., and Zdziarski, A. A., “Towards Precision Measurements of Accreting Black Holes Using X-Ray Reflection Spectroscopy,” *Space Sci. Rev.* **217**, 65 (Aug. 2021).
- [114] Reynolds, C. S., “Observational Constraints on Black Hole Spin,” *ARA&A* **59**, 117–154 (Sept. 2021).
- [115] Palumbo, D. C. M., Gelles, Z., Tiede, P., Chang, D. O., Pesce, D. W., Chael, A., and Johnson, M. D., “Bayesian Accretion Modeling: Axisymmetric Equatorial Emission in the Kerr Spacetime,” *ApJ* **939**, 107 (Nov. 2022).
- [116] Gebhardt, K., Adams, J., Richstone, D., Lauer, T. R., Faber, S. M., Gültekin, K., Murphy, J., and Tremaine, S., “The Black Hole Mass in M87 from Gemini/NIFS Adaptive Optics Observations,” *ApJ* **729**, 119 (Mar. 2011).
- [117] Walsh, J. L., Barth, A. J., Ho, L. C., and Sarzi, M., “The M87 Black Hole Mass from Gas-dynamical Models of Space Telescope Imaging Spectrograph Observations,” *ApJ* **770**, 86 (June 2013).
- [118] Liepold, E. R., Ma, C.-P., and Walsh, J. L., “Keck Integral-field Spectroscopy of M87 Reveals an Intrinsically Triaxial Galaxy and a Revised Black Hole Mass,” *ApJ* **945**, L35 (Mar. 2023).
- [119] Simon, D. A., Cappellari, M., and Hartke, J., “Supermassive black hole mass in the massive elliptical galaxy M87 from integral-field stellar dynamics using OASIS and MUSE with adaptive optics: assessing systematic uncertainties,” *MNRAS* **527**, 2341–2361 (Jan. 2024).
- [120] Vincent, F. H., Meliani, Z., Grandclément, P., Gourgoulhon, E., and Straub, O., “Imaging a boson star at the Galactic center,” *Classical and Quantum Gravity* **33**, 105015 (May 2016).
- [121] Mizuno, Y., Younsi, Z., Fromm, C. M., Porth, O., De Laurentis, M., Olivares, H., Falcke, H., Kramer, M., and Rezzolla, L., “The current ability to test theories of gravity with black hole shadows,” *Nature Astronomy* **2**, 585–590 (Apr. 2018).
- [122] Olivares, H., Younsi, Z., Fromm, C. M., De Laurentis, M., Porth, O., Mizuno, Y., Falcke, H., Kramer, M., and Rezzolla, L., “How to tell an accreting boson star from a black hole,” *MNRAS* **497**, 521–535 (Sept. 2020).
- [123] Vincent, F. H., Wielgus, M., Abramowicz, M. A., Gourgoulhon, E., Lasota, J. P., Paumard, T., and Perrin, G., “Geometric modeling of M87* as a Kerr black hole or a non-Kerr compact object,” *A&A* **646**, A37 (Feb. 2021).
- [124] Ayzenberg, D., Blackburn, L., Brito, R., Britzen, S., Broderick, A. E., Carballo-Rubio, R., Cardoso, V., Chael, A., Chatterjee, K., Chen, Y., Cunha, P. V. P., Davoudiasl, H., Denton, P. B., Doleman, S. S., Eichhorn, A., Eubanks, M., Fang, Y., Foschi, A., Fromm, C. M., Galison, P., Ghosh, S. G., Gold, R., Gurvits, L. I., Hadar, S., Held, A., Houston, J., Hu, Y., Johnson, M. D., Kocherlakota, P., Natarajan, P., Olivares, H., Palumbo, D., Pesce, D. W., Rajendran, S., Roy, R., Saurabh, Shao, L., Tahura, S.,

- Tamar, A., Tiede, P., Vincent, F. H., Visinelli, L., Wang, Z., Wielgus, M., Xue, X., Yakut, K., Yang, H., and Younsi, Z., “Fundamental Physics Opportunities with the Next-Generation Event Horizon Telescope,” *arXiv e-prints*, arXiv:2312.02130 (Dec. 2023).
- [125] Cunha, P. V. P., Grover, J., Herdeiro, C., Radu, E., Rúnarsson, H., and Wittig, A., “Chaotic lensing around boson stars and Kerr black holes with scalar hair,” *Phys. Rev. D* **94**, 104023 (Nov. 2016).
 - [126] Wielgus, M., Horák, J., Vincent, F., and Abramowicz, M., “Reflection-asymmetric wormholes and their double shadows,” *Phys. Rev. D* **102**, 084044 (Oct. 2020).
 - [127] Giovannini, G., Savolainen, T., Orienti, M., Nakamura, M., Nagai, H., Kino, M., Giroletti, M., Hada, K., Bruni, G., Kovalev, Y. Y., Anderson, J. M., D’Ammando, F., Hodgson, J., Honma, M., Krichbaum, T. P., Lee, S. S., Lico, R., Lisakov, M. M., Lobanov, A. P., Petrov, L., Sohn, B. W., Sokolovsky, K. V., Voitsik, P. A., Zensus, J. A., and Tingay, S., “A wide and collimated radio jet in 3C84 on the scale of a few hundred gravitational radii,” *Nature Astronomy* **2**, 472–477 (Apr. 2018).
 - [128] Gómez, J. L., Lobanov, A. P., Bruni, G., Kovalev, Y. Y., Marscher, A. P., Jorstad, S. G., Mizuno, Y., Bach, U., Sokolovsky, K. V., Anderson, J. M., Galindo, P., Kardashev, N. S., and Lisakov, M. M., “Probing the Innermost Regions of AGN Jets and Their Magnetic Fields with RadioAstron. I. Imaging BL Lacertae at 21 Microarcsecond Resolution,” *ApJ* **817**, 96 (Feb. 2016).
 - [129] Fuentes, A., Gómez, J. L., Martí, J. M., Perucho, M., Zhao, G.-Y., Lico, R., Lobanov, A. P., Bruni, G., Kovalev, Y. Y., Chael, A., Akiyama, K., Bouman, K. L., Sun, H., Cho, I., Traianou, E., Toscano, T., Dahale, R., Foschi, M., Gurvits, L. I., Jorstad, S., Kim, J.-Y., Marscher, A. P., Mizuno, Y., Ros, E., and Savolainen, T., “Filamentary structures as the origin of blazar jet radio variability,” *Nature Astronomy* **7**, 1359–1367 (Nov. 2023).
 - [130] Marscher, A. P., Jorstad, S. G., D’Arcangelo, F. D., Smith, P. S., Williams, G. G., Larionov, V. M., Oh, H., Olmstead, A. R., Aller, M. F., Aller, H. D., McHardy, I. M., Lähteenmäki, A., Tornikoski, M., Valtaoja, E., Hagen-Thorn, V. A., Kopatskaya, E. N., Gear, W. K., Tosti, G., Kurtanidze, O., Nikolashvili, M., Sigua, L., Miller, H. R., and Ryle, W. T., “The inner jet of an active galactic nucleus as revealed by a radio-to- γ -ray outburst,” *Nature* **452**, 966–969 (Apr. 2008).
 - [131] Marscher, A. P., Jorstad, S. G., Larionov, V. M., Aller, M. F., Aller, H. D., Lähteenmäki, A., Agudo, I., Smith, P. S., Gurwell, M., Hagen-Thorn, V. A., Konstantinova, T. S., Larionova, E. G., Larionova, L. V., Melnichuk, D. A., Blinov, D. A., Kopatskaya, E. N., Troitsky, I. S., Tornikoski, M., Hovatta, T., Schmidt, G. D., D’Arcangelo, F. D., Bhattarai, D., Taylor, B., Olmstead, A. R., Manne-Nicholas, E., Roca-Sogorb, M., Gómez, J. L., McHardy, I. M., Kurtanidze, O., Nikolashvili, M. G., Kimeridze, G. N., and Sigua, L. A., “Probing the Inner Jet of the Quasar PKS 1510-089 with Multi-Waveband Monitoring During Strong Gamma-Ray Activity,” *ApJ* **710**, L126–L131 (Feb. 2010).
 - [132] Jorstad, S. G., Marscher, A. P., Larionov, V. M., Agudo, I., Smith, P. S., Gurwell, M., Lähteenmäki, A., Tornikoski, M., Markowitz, A., Arkharov, A. A., Blinov, D. A., Chatterjee, R., D’Arcangelo, F. D., Falcone, A. D., Gómez, J. L., Hagen-Thorn, V. A., Jordan, B., Kimeridze, G. N., Konstantinova, T. S., Kopatskaya, E. N., Kurtanidze, O., Larionova, E. G., Larionova, L. V., McHardy, I. M., Melnichuk, D. A., Roca-Sogorb, M., Schmidt, G. D., Skiff, B., Taylor, B., Thum, C., Troitsky, I. S., and Wiesemeyer, H., “Flaring Behavior of the Quasar 3C 454.3 Across the Electromagnetic Spectrum,” *ApJ* **715**, 362–384 (May 2010).
 - [133] Agudo, I., Marscher, A. P., Jorstad, S. G., Larionov, V. M., Gómez, J. L., Lähteenmäki, A., Smith, P. S., Nilsson, K., Readhead, A. C. S., Aller, M. F., Heidt, J., Gurwell, M., Thum, C., Wehrle, A. E., Nikolashvili, M. G., Aller, H. D., Benítez, E., Blinov, D. A., Hagen-Thorn, V. A., Hiriart, D., Jannuzi, B. T., Joshi, M., Kimeridze, G. N., Kurtanidze, O. M., Kurtanidze, S. O., Lindfors, E., Molina, S. N., Morozova, D. A., Nieppola, E., Olmstead, A. R., Reinthal, R., Roca-Sogorb, M., Schmidt, G. D., Sigua, L. A., Sillanpää, A., Takalo, L., Taylor, B., Tornikoski, M., Troitsky, I. S., Zook, A. C., and Wiesemeyer, H., “On the Location of the γ -Ray Outburst Emission in the BL Lacertae Object AO 0235+164 Through Observations Across the Electromagnetic Spectrum,” *ApJ* **735**, L10 (July 2011).
 - [134] Agudo, I., Jorstad, S. G., Marscher, A. P., Larionov, V. M., Gómez, J. L., Lähteenmäki, A., Gurwell, M., Smith, P. S., Wiesemeyer, H., Thum, C., Heidt, J., Blinov, D. A., D’Arcangelo, F. D., Hagen-Thorn, V. A., Morozova, D. A., Nieppola, E., Roca-Sogorb, M., Schmidt, G. D., Taylor, B., Tornikoski, M., and

- Troitsky, I. S., “Location of γ -ray Flare Emission in the Jet of the BL Lacertae Object OJ287 More than 14 pc from the Central Engine,” *ApJ* **726**, L13 (Jan. 2011).
- [135] Casadio, C., Gómez, J. L., Grandi, P., Jorstad, S. G., Marscher, A. P., Lister, M. L., Kovalev, Y. Y., Savolainen, T., and Pushkarev, A. B., “The Connection between the Radio Jet and the Gamma-ray Emission in the Radio Galaxy 3C 120,” *ApJ* **808**, 162 (Aug. 2015).
- [136] Casadio, C., Gómez, J. L., Jorstad, S. G., Marscher, A. P., Larionov, V. M., Smith, P. S., Gurwell, M. A., Lähteenmäki, A., Agudo, I., Molina, S. N., Bala, V., Joshi, M., Taylor, B., Williamson, K. E., Arkharov, A. A., Blinov, D. A., Borman, G. A., Di Paola, A., Grishina, T. S., Hagen-Thorn, V. A., Itoh, R., Kopatskaya, E. N., Larionova, E. G., Larionova, L. V., Morozova, D. A., Rastorgueva-Foi, E., Sergeev, S. G., Tornikoski, M., Troitsky, I. S., Thum, C., and Wiesemeyer, H., “A Multi-wavelength Polarimetric Study of the Blazar CTA 102 during a Gamma-Ray Flare in 2012,” *ApJ* **813**, 51 (Nov. 2015).
- [137] Lico, R., Casadio, C., Jorstad, S. G., Gómez, J. L., Marscher, A. P., Traianou, E., Kim, J. Y., Zhao, G. Y., Fuentes, A., Cho, I., Krichbaum, T. P., Hervet, O., O’Brien, S., Boccardi, B., Myserlis, I., Agudo, I., Alberdi, A., Weaver, Z. R., and Zensus, J. A., “New jet feature in the parsec-scale jet of the blazar OJ 287 connected to the 2017 teraelectronvolt flaring activity,” *A&A* **658**, L10 (Feb. 2022).
- [138] IceCube Collaboration, Aartsen, M. G., Ackermann, M., Adams, J., Aguilar, J. A., Ahlers, M., Ahrens, M., Samarai, I. A., Altmann, D., Andeen, K., Anderson, T., Anseau, I., Anton, G., Argüelles, C., Arsoli, B., Auffenberg, J., Axani, S., Bagherpour, H., Bai, X., Barron, J. P., Barwick, S. W., Baum, V., Bay, R., Beatty, J. J., Becker Tjus, J., Becker, K. H., BenZvi, S., Berley, D., Bernardini, E., Besson, D. Z., Binder, G., Bindig, D., Blaufuss, E., Blot, S., Böhm, C., Börner, M., Bos, F., Böser, S., Botner, O., Bourbeau, E., Bourbeau, J., Bradascio, F., Braun, J., Brenzke, M., Bretz, H. P., Bron, S., Brosteau-Kaiser, J., Burgman, A., Busse, R. S., Carver, T., Cheung, E., Chirkin, D., Christov, A., Clark, K., Classen, L., Coenders, S., Collin, G. H., Conrad, J. M., Coppin, P., Correa, P., Cowen, D. F., Cross, R., Dave, P., Day, M., de André, J. P. A. M., De Clercq, C., DeLaunay, J. J., Dembinski, H., DeRidder, S., Desiati, P., de Vries, K. D., de Wasseige, G., de With, M., DeYoung, T., Díaz-Vélez, J. C., di Lorenzo, V., Dujmovic, H., Dum, J. P., Dunkman, M., Dvorak, E., Eberhardt, B., Ehrhardt, T., Eichmann, B., Eller, P., Evenson, P. A., Fahey, S., Fazely, A. R., Felde, J., Filimonov, K., Finley, C., Flis, S., Franckowiak, A., Friedman, E., Fritz, A., Gaisser, T. K., Gallagher, J., Gerhardt, L., Ghorbani, K., Giommi, P., Glauch, T., Glüsenskamp, T., Goldschmidt, A., Gonzalez, J. G., Grant, D., Griffith, Z., Haack, C., Hallgren, A., Halzen, F., Hanson, K., Hebecker, D., Heereman, D., Helbing, K., Hellauer, R., Hickford, S., Hignight, J., Hill, G. C., Hoffman, K. D., Hoffmann, R., Hoinka, T., Hokanson-Fasig, B., Hoshina, K., Huang, F., Huber, M., Hultqvist, K., Hünnefeld, M., Hussain, R., In, S., Iovine, N., Ishihara, A., Jacobi, E., Japaridze, G. S., Jeong, M., Jero, K., Jones, B. J. P., Kalaczynski, P., Kang, W., Kappes, A., Kappesser, D., Karg, T., Karle, A., Katz, U., Kauer, M., Keivani, A., Kelley, J. L., Kheirandish, A., Kim, J., Kim, M., Kintscher, T., Kiryluk, J., Kittler, T., Klein, S. R., Koirala, R., Kolanoski, H., Köpke, L., Kopper, C., Kopper, S., Koschinsky, J. P., Koskinen, D. J., Kowalski, M., Krammer, B., Krings, K., Kroll, M., Krückl, G., Kunwar, S., Kurahashi, N., Kuwabara, T., Kyriacou, A., Labare, M., Lanfranchi, J. L., Larson, M. J., Lauber, F., Leonard, K., Lesiak-Bzdak, M., Leuermann, M., Liu, Q. R., Lozano Mariscal, C. J., Lu, L., Lünemann, J., Luszczak, W., Madsen, J., Maggi, G., Mahn, K. B. M., Mancina, S., Maruyama, R., Mase, K., Maunu, R., Meagher, K., Medici, M., Meier, M., Menne, T., Merino, G., Meures, T., Miarecki, S., Micallef, J., Momenté, G., Montaruli, T., Moore, R. W., Morse, R., Moulai, M., Nahnauer, R., Nakarmi, P., Naumann, U., Neer, G., Niederhausen, H., Nowicki, S. C., Nygren, D. R., Obertacke Pollmann, A., Olivas, A., O’Murchadha, A., O’Sullivan, E., Padovani, P., Palczewski, T., Pandya, H., Pankova, D. V., Peiffer, P., Pepper, J. A., Pérez de los Heros, C., Pieloth, D., Pinat, E., Plum, M., Price, P. B., Przybylski, G. T., Raab, C., Rädcl, L., Rameez, M., Rawlins, K., Rea, I. C., Reimann, R., Relethford, B., Relich, M., Resconi, E., Rhode, W., Richman, M., Robertson, S., Rongen, M., Rott, C., Ruhe, T., Ryckbosch, D., Rysewyk, D., Safa, I., Sahakyan, N., Sälzer, T., Sanchez Herrera, S. E., Sandrock, A., Sandroos, J., Santander, M., Sarkar, S., Sarkar, S., Satalecka, K., Schlunder, P., Schmidt, T., Schneider, A., Schoenen, S., Schöneberg, S., Schumacher, L., Sclafani, S., Seckel, D., Seunarine, S., Soedingrekso, J., Soldin, D., Song, M., Spiczak, G. M., Spiering, C., Stachurska, J., Stamatikos, M., Stanev, T., Stasik, A., Stettner, J., Steuer, A., Stezelberger, T., Stokstad, R. G., Stöbl, A., Strotjohann, N. L., Stuttard, T., Sullivan, G. W., Sutherland, M., Taboada, I., Tatar, J., Tenholt, F., Ter-Antonyan, S., Terliuk, A., Tilav, S., Toale, P. A., Tobin, M. N., Toennis, C., Toscano, S., Tosi, D.,

- Tselengidou, M., Tung, C. F., Turcati, A., Turley, C. F., Ty, B., Unger, E., Usner, M., Vandenbroucke, J., Van Driessche, W., van Eijk, D., van Eijndhoven, N., Vanheule, S., van Santen, J., Vogel, E., Vraeghe, M., Walck, C., Wallace, A., Wallraff, M., Wandler, F. D., Wandkowsky, N., Waza, A., Weaver, C., Weiss, M. J., Wendt, C., Werthebach, J., Westerhoff, S., Whelan, B. J., Whitehorn, N., Wiebe, K., Wiebusch, C. H., Wille, L., Williams, D. R., Wills, L., Wolf, M., Wood, J., Wood, T. R., Woschnagg, K., Xu, D. L., Xu, X. W., Xu, Y., Yanez, J. P., Yodh, G., Yoshida, S., and Yuan, T., “Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert,” *Science* **361**, 147–151 (July 2018).
- [139] IceCube Collaboration, Aartsen, M. G., Ackermann, M., Adams, J., Aguilar, J. A., Ahlers, M., Ahrens, M., Al Samarai, I., Altmann, D., Andeen, K., Anderson, T., Anseau, I., Anton, G., Argüelles, C., Auffenberg, J., Axani, S., Bagherpour, H., Bai, X., Barron, J. P., Barwick, S. W., Baum, V., Bay, R., Beatty, J. J., Becker Tjus, J., Becker, K. H., BenZvi, S., Berley, D., Bernardini, E., Besson, D. Z., Binder, G., Bindig, D., Blaufuss, E., Blot, S., Böhm, C., Börner, M., Bos, F., Böser, S., Botner, O., Bourbeau, E., Bourbeau, J., Bradascio, F., Braun, J., Brenzke, M., Bretz, H. P., Bron, S., Brostean-Kaiser, J., Burgman, A., Busse, R. S., Carver, T., Cheung, E., Chirkin, D., Christov, A., Clark, K., Classen, L., Coenders, S., Collin, G. H., Conrad, J. M., Coppin, P., Correa, P., Cowen, D. F., Cross, R., Dave, P., Day, M., de André, J. P. A. M., De Clercq, C., DeLaunay, J. J., Dembinski, H., De Ridder, S., Desiati, P., de Vries, K. D., de Wasseige, G., de With, M., DeYoung, T., Díaz-Vélez, J. C., di Lorenzo, V., Dujmovic, H., Dumm, J. P., Dunkman, M., Dvorak, E., Eberhardt, B., Ehrhardt, T., Eichmann, B., Eller, P., Evenson, P. A., Fahey, S., Fazely, A. R., Felde, J., Filimonov, K., Finley, C., Flis, S., Franckowiak, A., Friedman, E., Fritz, A., Gaisser, T. K., Gallagher, J., Gerhardt, L., Ghorbani, K., Glauch, T., Glüsenkamp, T., Goldschmidt, A., Gonzalez, J. G., Grant, D., Griffith, Z., Haack, C., Hallgren, A., Halzen, F., Hanson, K., Hebecker, D., Heereman, D., Helbing, K., Hellauer, R., Hickford, S., Hignight, J., Hill, G. C., Hoffman, K. D., Hoffmann, R., Hoinka, T., Hokanson-Fasig, B., Hoshina, K., Huang, F., Huber, M., Hultqvist, K., Hünnefeld, M., Hussain, R., In, S., Iovine, N., Ishihara, A., Jacobi, E., Japaridze, G. S., Jeong, M., Jero, K., Jones, B. J. P., Kalaczynski, P., Kang, W., Kappes, A., Kappesser, D., Karg, T., Karle, A., Katz, U., Kauer, M., Keivani, A., Kelley, J. L., Kheirandish, A., Kim, J., Kim, M., Kintscher, T., Kiryluk, J., Kittler, T., Klein, S. R., Koirala, R., Kolanoski, H., Köpke, L., Kopper, C., Kopper, S., Koschinsky, J. P., Koskinen, D. J., Kowalski, M., Krings, K., Kroll, M., Krückl, G., Kunwar, S., Kurahashi, N., Kuwabara, T., Kyriacou, A., Labare, M., Lanfranchi, J. L., Larson, M. J., Lauber, F., Leonard, K., Lesiak-Bzdak, M., Leuermann, M., Liu, Q. R., Lozano Mariscal, C. J., Lu, L., Lünemann, J., Luszczak, W., Madsen, J., Maggi, G., Mahn, K. B. M., Mancina, S., Maruyama, R., Mase, K., Maunu, R., Meagher, K., Medici, M., Meier, M., Menne, T., Merino, G., Meures, T., Miarecki, S., Micallef, J., Momenté, G., Montaruli, T., Moore, R. W., Morse, R., Moulai, M., Nahnauer, R., Nakarmi, P., Naumann, U., Neer, G., Niederhausen, H., Nowicki, S. C., Nygren, D. R., Obertacke Pollmann, A., Olivas, A., O’Murchadha, A., O’Sullivan, E., Palczewski, T., Pandya, H., Pankova, D. V., Peiffer, P., Pepper, J. A., Pérez de los Heros, C., Pieloth, D., Pinat, E., Plum, M., Price, P. B., Przybylski, G. T., Raab, C., Rädcl, L., Rameez, M., Rauch, L., Rawlins, K., Rea, I. C., Reimann, R., Relethford, B., Relich, M., Resconi, E., Rhode, W., Richman, M., Robertson, S., Rongen, M., Rott, C., Ruhe, T., Ryckbosch, D., Rysewyk, D., Safa, I., Sälzer, T., Sanchez Herrera, S. E., Sandrock, A., Sandroos, J., Santander, M., Sarkar, S., Sarkar, S., Satalecka, K., Schlunder, P., Schmidt, T., Schneider, A., Schoenen, S., Schöneberg, S., Schumacher, L., Sclafani, S., Seckel, D., Seunarine, S., Soedingrekso, J., Soldin, D., Song, M., Spiczak, G. M., Spiering, C., Stachurska, J., Stamatikos, M., Stanev, T., Stasik, A., Stein, R., Stettner, J., Steuer, A., Stezelberger, T., Stokstad, R. G., Stöfl, A., Strotjohann, N. L., Stuttard, T., Sullivan, G. W., Sutherland, M., Taboada, I., Tatar, J., Tenholt, F., Ter-Antonyan, S., Terliuk, A., Tilav, S., Toale, P. A., Tobin, M. N., Toennis, C., Toscano, S., Tosi, D., Tselengidou, M., Tung, C. F., Turcati, A., Turley, C. F., Ty, B., Unger, E., Usner, M., Vandenbroucke, J., Van Driessche, W., van Eijk, D., van Eijndhoven, N., Vanheule, S., van Santen, J., Vogel, E., Vraeghe, M., Walck, C., Wallace, A., Wallraff, M., Wandler, F. D., Wandkowsky, N., Waza, A., Weaver, C., Weiss, M. J., Wendt, C., Werthebach, J., Westerhoff, S., Whelan, B. J., Whitehorn, N., Wiebe, K., Wiebusch, C. H., Wille, L., Williams, D. R., Wills, L., Wolf, M., Wood, J., Wood, T. R., Woschnagg, K., Xu, D. L., Xu, X. W., Xu, Y., Yanez, J. P., Yodh, G., Yoshida, S., Yuan, T., Fermi-LAT Collaboration, Abdollahi, S., Ajello, M., Angioni, R., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Berenji, B., Bissaldi, E., Blandford, R. D., Bonino, R., Bottacini, E., Bregeon, J., Bruel, P., Buehler, R., Burnett,

T. H., Burns, E., Buson, S., Cameron, R. A., Caputo, R., Caraveo, P. A., Cavazzuti, E., Charles, E., Chen, S., Cheung, C. C., Chiang, J., Chiaro, G., Ciprini, S., Cohen-Tanugi, J., Conrad, J., Costantin, D., Cutini, S., D'Ammando, F., de Palma, F., Digel, S. W., Di Lalla, N., Di Mauro, M., Di Venere, L., Domínguez, A., Favuzzi, C., Franckowiak, A., Fukazawa, Y., Funk, S., Fusco, P., Gargano, F., Gasparrini, D., Giglietto, N., Giomi, M., Giommi, P., Giordano, F., Giroletti, M., Glanzman, T., Green, D., Grenier, I. A., Grondin, M. H., Guiriec, S., Harding, A. K., Hayashida, M., Hays, E., Hewitt, J. W., Horan, D., Jóhannesson, G., Kadler, M., Kensei, S., Kocevski, D., Krauss, F., Kreter, M., Kuss, M., La Mura, G., Larsson, S., Latronico, L., Lemoine-Goumard, M., Li, J., Longo, F., Loparco, F., Lovellette, M. N., Lubrano, P., Magill, J. D., Maldera, S., Malyshev, D., Manfreda, A., Mazziotta, M. N., McEnery, J. E., Meyer, M., Michelson, P. F., Mizuno, T., Monzani, M. E., Morselli, A., Moskalenko, I. V., Negro, M., Nuss, E., Ojha, R., Omodei, N., Orienti, M., Orlando, E., Palatiello, M., Paliya, V. S., Perkins, J. S., Persic, M., Pesce-Rollins, M., Piron, F., Porter, T. A., Principe, G., Rainò, S., Rando, R., Rani, B., Razzano, M., Razzaque, S., Reimer, A., Reimer, O., Renault-Tinacci, N., Ritz, S., Rochester, L. S., Saz Parkinson, P. M., Sgrò, C., Siskind, E. J., Spandre, G., Spinelli, P., Suson, D. J., Tajima, H., Takahashi, M., Tanaka, Y., Thayer, J. B., Thompson, D. J., Tibaldo, L., Torres, D. F., Torresi, E., Tosti, G., Troja, E., Valverde, J., Vianello, G., Vogel, M., Wood, K., Wood, M., Zaharijas, G., MAGIC Collaboration, Ahnen, M. L., Ansoldi, S., Antonelli, L. A., Arcaro, C., Baack, D., Babić, A., Banerjee, B., Bangale, P., Barres de Almeida, U., Barrio, J. A., Becerra González, J., Bednarek, W., Bernardini, E., Berti, A., Bhattacharyya, W., Biland, A., Blanch, O., Bonnoli, G., Carosi, A., Carosi, R., Ceribella, G., Chatterjee, A., Colak, S. M., Colin, P., Colombo, E., Contreras, J. L., Cortina, J., Covino, S., Cumani, P., Da Vela, P., Dazzi, F., De Angelis, A., De Lotto, B., Delfino, M., Delgado, J., Di Pierro, F., Domínguez, A., Dominis Prester, D., Dorner, D., Doro, M., Einecke, S., Elsaesser, D., Fallah Ramazani, V., Fernández-Barral, A., Fidalgo, D., Foffano, L., Pfrang, K., Fonseca, M. V., Font, L., Franceschini, A., Fruck, C., Galindo, D., Gallozzi, S., García López, R. J., Garczarczyk, M., Gaug, M., Giammaria, P., Godinović, N., Gora, D., Guberman, D., Hadasch, D., Hahn, A., Hassan, T., Hayashida, M., Herrera, J., Hose, J., Hrupec, D., Inoue, S., Ishio, K., Konno, Y., Kubo, H., Kushida, J., Lelas, D., Lindfors, E., Lombardi, S., Longo, F., López, M., Maggio, C., Majumdar, P., Makariev, M., Maneva, G., Manganaro, M., Mannheim, K., Maraschi, L., Mariotti, M., Martínez, M., Masuda, S., Mazin, D., Mineev, M., M, J. M., Mirzoyan, R., Moralejo, A., Moreno, V., Moretti, E., Nagayoshi, T., Neustroev, V., Niedzwiecki, A., Nievas Rosillo, M., Nigro, C., Nilsson, K., Ninci, D., Nishijima, K., Noda, K., Nogués, L., Paiano, S., Palacio, J., Paneque, D., Paoletti, R., Paredes, J. M., Pedalletti, G., Peresano, M., Persic, M., Prada Moroni, P. G., Prandini, E., Puljak, I., Rodriguez Garcia, J., Reichardt, I., Rhode, W., Ribó, M., Rico, J., Righi, C., Rugliancich, A., Saito, T., Satalecka, K., Schweizer, T., Sitarek, J., Šnidarić, I., Sobczynska, D., Stamerra, A., Strzys, M., Surić, T., Takahashi, M., Tavecchio, F., Temnikov, P., Terzić, T., Teshima, M., Torres-Albà, N., Treves, A., Tsujimoto, S., Vanzo, G., Vazquez Acosta, M., Vovk, I., Ward, J. E., Will, M., S, Zaric, D., AGILE Team, Lucarelli, F., Tavani, M., Piano, G., Donnarumma, I., Pittori, C., Verrecchia, F., Barbiellini, G., Bulgarelli, A., Caraveo, P., Cattaneo, P. W., Colafrancesco, S., Costa, E., Di Cocco, G., Ferrari, A., Gianotti, F., Giuliani, A., Lipari, P., Mereghetti, S., Morselli, A., Pacciani, L., Paoletti, F., Parmiggiani, N., Pellizzoni, A., Picozza, P., Pilia, M., Rappoldi, A., Trois, A., Vercellone, S., Vittorini, V., ASAS-SN Team, Stanek, K. Z., Franckowiak, A., Kochanek, C. S., Beacom, J. F., Thompson, T. A., Holmbo, S., HAWC Collaboration, Abeysekara, A. U., Albert, A., Alfaro, R., Alvarez, C., Arceo, R., Arteaga-Velázquez, J. C., Avila Rojas, D., Ayala Solares, H. A., Becerril, A., Belmont-Moreno, E., Bernal, A., Caballero-Mora, K. S., Capistrán, T., Carramiñana, A., Casanova, S., Castillo, M., Cotti, U., Cotzomi, J., Coutiño de León, S., De León, C., De la Fuente, E., Diaz Hernandez, R., Dichiaro, S., Dingus, B. L., DuVernois, M. A., Díaz-Vélez, J. C., Ellsworth, R. W., Engel, K., Fiorino, D. W., Fleischhack, H., Fraija, N., García-González, J. A., Garfias, F., González Muñoz, A., González, M. M., Goodman, J. A., Hampel-Arias, Z., Harding, J. P., Hernandez, S., Hona, B., Hueyotl-Zahuantitla, F., Hui, C. M., Hüntemeyer, P., Iriarte, A., Jardin-Blicq, A., Joshi, V., Kaufmann, S., Kunde, G. J., Lara, A., Lauer, R. J., Lee, W. H., Lennarz, D., León Vargas, H., Linnemann, J. T., Longinotti, A. L., Luis-Raya, G., Luna-García, R., Malone, K., Marinelli, S. S., Martinez, O., Martinez-Castellanos, I., Martínez-Castro, J., Martínez-Huerta, H., Matthews, J. A., Miranda-Romagnoli, P., Moreno, E., Mostafá, M., Nayerhoda, A., Nellen, L., Newbold, M., Nisa, M. U., Noriega-Papaqui, R., Pelayo, R., Pretz, J., Pérez-Pérez, E. G., Ren, Z., Rho, C. D., Rivière, C., Rosa-

González, D., Rosenberg, M., Ruiz-Velasco, E., Ruiz-Velasco, E., Salesa Greus, F., Sandoval, A., Schneider, M., Schoorlemmer, H., Sinnis, G., Smith, A. J., Springer, R. W., Surajbali, P., Tibolla, O., Tollefson, K., Torres, I., Villaseñor, L., Weisgarber, T., Werner, F., Yapici, T., Gaurang, Y., Zepeda, A., Zhou, H., Álvarez, J. D., H. E. S. S. Collaboration, Abdalla, H., Angüner, E. O., Armand, C., Backes, M., Becherini, Y., Berge, D., Böttcher, M., Boisson, C., Bolmont, J., Bonnefoy, S., Bordas, P., Brun, F., Büchele, M., Bulik, T., Caroff, S., Carosi, A., Casanova, S., Cerruti, M., Chakraborty, N., Chandra, S., Chen, A., Colafrancesco, S., Davids, I. D., Deil, C., Devin, J., Djannati-Ataï, A., Egberts, K., Emery, G., Eschbach, S., Fiasson, A., Fontaine, G., Funk, S., Füßling, M., Gallant, Y. A., Gaté, F., Giavitto, G., Glawion, D., Glicenstein, J. F., Gottschall, D., Grondin, M. H., Haupt, M., Henri, G., Hinton, J. A., Hoischen, C., Holch, T. L., Huber, D., Jamroz, M., Jankowsky, D., Jankowsky, F., Jouvin, L., Jung-Richardt, I., Kerszberg, D., Khélifi, B., King, J., Klepser, S., Kluz 'niak, W., Komin, N., Kraus, M., Lefaucheur, J., Lemièrre, A., Lemoine-Goumard, M., Lenain, J. P., Leser, E., Lohse, T., López-Coto, R., Lorentz, M., Lypova, I., Marandon, V., Guillem Martí-Devesa, G., Maurin, G., Mitchell, A. M. W., Moderski, R., Mohamed, M., Mohrmann, L., Moulin, E., Murach, T., de Naurois, M., Niederwanger, F., Niemiec, J., Oakes, L., O'Brien, P., Ohm, S., Ostrowski, M., Oya, I., Panter, M., Parsons, R. D., Perennes, C., Piel, Q., Pita, S., Poireau, V., Priyana Noel, A., Prokoph, H., Pühlhofer, G., Quirrenbach, A., Raab, S., Rauth, R., Renaud, M., Rieger, F., Rinchuso, L., Romoli, C., Rowell, G., Rudak, B., Sasaki, D. A., Sanchez, M., Schlickeiser, R., Schüssler, F., Schulz, A., Schwanke, U., Seglar-Arroyo, M., Shafi, N., Simoni, R., Sol, H., Stegmann, C., Steppa, C., Tavernier, T., Taylor, A. M., Tiziani, D., Trichard, C., Tsiros, M., van Eldik, C., van Rensburg, C., van Soelen, B., Veh, J., Vincent, P., Voisin, F., Wagner, S. J., Wagner, R. M., Wiercholska, A., Zanin, R., Zdziarski, A. A., Zech, A., Ziegler, A., Zorn, J., Żywucka, N., INTEGRAL Team, Savchenko, V., Ferrigno, C., Bazzano, A., Diehl, R., Kuulkers, E., Laurent, P., Mereghetti, S., Natalucci, L., Panessa, F., Rodi, J., Ubertini, P., Kanata, K., Teams, S. O., Morokuma, T., Ohta, K., Tanaka, Y. T., Mori, H., Yamanaka, M., Kawabata, K. S., Utsumi, Y., Nakaoka, T., Kawabata, M., Nagashima, H., Yoshida, M., Matsuoka, Y., Itoh, R., Kapteyn Team, Keel, W., Liverpool Telescope Team, Copperwheat, C., Steele, I., Swift/NuSTAR Team, Cenko, S. B., Cowen, D. F., DeLaunay, J. J., Evans, P. A., Fox, D. B., Keivani, A., Kennea, J. A., Marshall, F. E., Osborne, J. P., Santander, M., Tohuvavohu, A., Turley, C. F., VERITAS Collaboration, Abeysekara, A. U., Archer, A., Benbow, W., Bird, R., Brill, A., Brose, R., Buchovecky, M., Buckley, J. H., Bugaev, V., Christiansen, J. L., Connolly, M. P., Cui, W., Daniel, M. K., Errando, M., Falcone, A., Feng, Q., Finley, J. P., Fortson, L., Furniss, A., Gueta, O., Hütten, M., Hervet, O., Hughes, G., Humensky, T. B., Johnson, C. A., Kaaret, P., Kar, P., Kelley-Hoskins, N., Kertzman, M., Kieda, D., Krause, M., Krennrich, F., Kumar, S., Lang, M. J., Lin, T. T. Y., Maier, G., McArthur, S., Moriarty, P., Mukherjee, R., Nieto, D., O'Brien, S., Ong, R. A., Otte, A. N., Park, N., Petrasch, A., Pohl, M., Popkow, A., Pueschel, S. E., Quinn, J., Ragan, K., Reynolds, P. T., Richards, G. T., Roache, E., Rulten, C., Sadeh, I., Santander, M., Scott, S. S., Sembroski, G. H., Shahinyan, K., Sushch, I., Trépanier, S., Tyler, J., Vassiliev, V. V., Wakely, S. P., Weinstein, A., Wells, R. M., Wilcox, P., Wilhelm, A., Williams, D. A., Zitzer, B., VLA/B Team, Tetarenko, A. J., Kimball, A. E., Miller-Jones, J. C. A., and Sivakoff, G. R., "Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A," *Science* **361**, eaat1378 (July 2018).

- [140] Plavin, A., Kovalev, Y. Y., Kovalev, Y. A., and Troitsky, S., "Observational Evidence for the Origin of High-energy Neutrinos in Parsec-scale Nuclei of Radio-bright Active Galaxies," *ApJ* **894**, 101 (May 2020).
- [141] Acharyya, A., Adams, C. B., Archer, A., Bangale, P., Bartkoske, J. T., Batista, P., Benbow, W., Brill, A., Buckley, J. H., Christiansen, J. L., Chromey, A. J., Errando, M., Falcone, A., Feng, Q., Foote, G. M., Fortson, L., Furniss, A., Gallagher, G., Hanlon, W., Hanna, D., Hervet, O., Hinrichs, C. E., Hoang, J., Holder, J., Humensky, T. B., Jin, W., Kaaret, P., Kertzman, M., Kherlakian, M., Kieda, D., Kleiner, T. K., Korzoun, N., Kumar, S., Lang, M. J., Lundy, M., Maier, G., McGrath, C. E., Millard, M. J., Millis, J., Mooney, C. L., Moriarty, P., Mukherjee, R., O'Brien, S., Ong, R. A., Pohl, M., Pueschel, E., Quinn, J., Ragan, K., Reynolds, P. T., Ribeiro, D., Roache, E., Sadeh, I., Sadun, A. C., Saha, L., Santander, M., Sembroski, G. H., Shang, R., Spletstoeser, M., Talluri, A. K., Tucci, J. V., Vassiliev, V. V., Weinstein, A., Williams, D. A., Wong, S. L., Woo, J., Aharonian, F., Aschersleben, J., Backes, M., Martins, V. B., Batzofin, R., Becherini, Y., Berge, D., Bernlöhr, K., Bi, B., Böttcher, M., Boisson, C., Bolmont, J., de Bony de Lavergne, M., Borowska, J., Bouyahiaoui, M., Bradascio, F., Breuhaus, M., Brose, R., Brun,

- F., Bruno, B., Bulik, T., Burger-Scheidlin, C., Caroff, S., Casanova, S., Cecil, R., Celic, J., Cerruti, M., Chand, T., Chandra, S., Chen, A., Chibueze, J., Chibueze, O., Cotter, G., Dai, S., Mbarubucyeye, J. D., Djannati-Ataï, A., Dmytriiev, A., Doroshenko, V., Einecke, S., Ernenwein, J. P., de Clairfontaine, G. F., Filipovic, M., Fontaine, G., Füßling, M., Funk, S., Gabici, S., Ghafourizadeh, S., Giavitto, G., Glawion, D., Glicenstein, J. F., Goswami, P., Grolleron, G., Haerer, L., Hinton, J. A., Holch, T. L., Holler, M., Horns, D., Jamrozy, M., Jankowsky, F., Joshi, V., Jung-Richardt, I., Kasai, E., Katarzyński, K., Khatoon, R., Khélifi, B., Klepser, S., Kluźniak, W., Kosack, K., Kostunin, D., Lang, R. G., Le Stum, S., Lemièrre, A., Lenain, J. P., Leuschner, F., Lohse, T., Luashvili, A., Lypova, I., Mackey, J., Malyshev, D., Marandon, V., Marchegiani, P., Marcowith, A., Martí-Devesa, G., Marx, R., Mitchell, A., Moderski, R., Mohrmann, L., Montanari, A., Moulin, E., Murach, T., Nakashima, K., Niemiec, J., Noel, A. P., O'Brien, P., Olivera-Nieto, L., de Ona Wilhelmi, E., Ostrowski, M., Panny, S., Panter, M., Peron, G., Prokhorov, D. A., Pühlhofer, G., Punch, M., Quirrenbach, A., Reichherzer, P., Reimer, A., Reimer, O., Ren, H., Renaud, M., Rieger, F., Rudak, B., Ruiz-Velasco, E., Sahakian, V., Santangelo, A., Sasaki, M., Schäfer, J., Schüssler, F., Schutte, H. M., Schwanke, U., Shapopi, J. N. S., Specovius, A., Spencer, S., Stawarz, L., Steenkamp, R., Steinmassl, S., Sushch, I., Suzuki, H., Takahashi, T., Tanaka, T., Terrier, R., van Eldik, C., Vecchi, M., Voh, J., Venter, C., Vink, J., White, R., Wiercholska, A., Wong, Y. W., Zacharias, M., Zargaryan, D., Zdziarski, A. A., Zech, A., Zouari, S., Żywucka, N., Mori, K., and H. E. S. S. Collaboration, "Multiwavelength Observations of the Blazar PKS 0735+178 in Spatial and Temporal Coincidence with an Astrophysical Neutrino Candidate IceCube-211208A," *ApJ* **954**, 70 (Sept. 2023).
- [142] Pesce, D. W., Palumbo, D. C. M., Narayan, R., Blackburn, L., Doeleman, S. S., Johnson, M. D., Ma, C.-P., Nagar, N. M., Natarajan, P., and Ricarte, A., "Toward Determining the Number of Observable Supermassive Black Hole Shadows," *ApJ* **923**, 260 (Dec. 2021).
- [143] Ramakrishnan, V., Nagar, N., Arratia, V., Hernández-Yévenes, J., Pesce, D. W., Nair, D. G., Bandyopadhyay, B., Medina-Porcile, C., Krichbaum, T. P., Doeleman, S., Ricarte, A., Fish, V. L., Blackburn, L., Falcke, H., Bower, G., and Natarajan, P., "Event Horizon and Environs (ETHER): A Curated Database for EHT and ngEHT Targets and Science," *Galaxies* **11**, 15 (Jan. 2023).
- [144] Hernández-Yévenes, J., Nagar, N., Arratia, V., and Jarrett, T. H., "WISE2MBH: A scaling-based algorithm for probing supermassive black hole masses through WISE catalogs," *arXiv e-prints*, arXiv:2405.18336 (May 2024).
- [145] Wang, Y., Wang, T., Ho, L. C., Zhong, Y., and Luo, B., "The fundamental plane of black hole activity for low-luminosity radio active galactic nuclei across $1 < z < 4$," *arXiv e-prints*, arXiv:2402.17991 (Feb. 2024).
- [146] Mingarelli, C. M. F., Lazio, T. J. W., Sesana, A., Greene, J. E., Ellis, J. A., Ma, C.-P., Croft, S., Burke-Spolaor, S., and Taylor, S. R., "The local nanohertz gravitational-wave landscape from supermassive black hole binaries," *Nature Astronomy* **1**, 886–892 (Nov. 2017).
- [147] Sato-Polito, G., Zaldarriaga, M., and Quataert, E., "Where are NANOGrav's big black holes?," *arXiv e-prints*, arXiv:2312.06756 (Dec. 2023).
- [148] Izquierdo-Villalba, D., Sesana, A., Colpi, M., Spinoso, D., Bonetti, M., Bonoli, S., and Valiante, R., "Connecting low-redshift LISA massive black hole mergers to the nHz stochastic gravitational wave background," *arXiv e-prints*, arXiv:2401.10983 (Jan. 2024).
- [149] Yoon, D., Chatterjee, K., Markoff, S. B., van Eijnatten, D., Younsi, Z., Liska, M., and Tchekhovskoy, A., "Spectral and imaging properties of Sgr A* from high-resolution 3D GRMHD simulations with radiative cooling," *MNRAS* **499**, 3178–3192 (Dec. 2020).
- [150] Narayan, R., Chael, A., Chatterjee, K., Ricarte, A., and Curd, B., "Jets in magnetically arrested hot accretion flows: geometry, power, and black hole spin-down," *MNRAS* **511**, 3795–3813 (Apr. 2022).
- [151] Ricarte, A., Narayan, R., and Curd, B., "Recipes for Jet Feedback and Spin Evolution of Black Holes with Strongly Magnetized Super-Eddington Accretion Disks," *ApJ* **954**, L22 (Sept. 2023).
- [152] Berti, E. and Volonteri, M., "Cosmological Black Hole Spin Evolution by Mergers and Accretion," *ApJ* **684**, 822–828 (Sept. 2008).
- [153] Ricarte, A., Tiede, P., Emami, R., Tamar, A., and Natarajan, P., "The ngEHT's Role in Measuring Supermassive Black Hole Spins," *Galaxies* **11**, 6 (Jan. 2023).
- [154] King, A. R., Pringle, J. E., and Hofmann, J. A., "The evolution of black hole mass and spin in active galactic nuclei," *MNRAS* **385**, 1621–1627 (Apr. 2008).

- [155] Walker, R. C., Hardee, P. E., Davies, F. B., Ly, C., and Junor, W., “The Structure and Dynamics of the Subparsec Jet in M87 Based on 50 VLBA Observations over 17 Years at 43 GHz,” *ApJ* **855**, 128 (Mar. 2018).
- [156] Qiu, R., Ricarte, A., Narayan, R., Wong, G. N., Chael, A., and Palumbo, D., “Using Machine Learning to link black hole accretion flows with spatially resolved polarimetric observables,” *MNRAS* **520**, 4867–4888 (Apr. 2023).
- [157] Davis, D. S., Mushotzky, R. F., Mulchaey, J. S., Worrall, D. M., Birkinshaw, M., and Burstein, D., “Diffuse Hot Gas in the NGC 4261 Group of Galaxies,” *ApJ* **444**, 582 (May 1995).
- [158] Wong, G., Dhruv, V., and Prather, B. a., “Characteristics of Synchrotron Emission in Radiative Inefficient Flows,” *in prep.* (2024).
- [159] Rickett, B. J., “Radio propagation through the turbulent interstellar plasma,” *ARA&A* **28**, 561–605 (1990).
- [160] Narayan, R., “The Physics of Pulsar Scintillation,” *Royal Society of London Philosophical Transactions Series A* **341**, 151–165 (Oct. 1992).
- [161] Davies, R. D., Walsh, D., and Booth, R. S., “The radio source at the galactic nucleus,” *MNRAS* **177**, 319–333 (Nov. 1976).
- [162] Zhu, Z., Johnson, M. D., and Narayan, R., “Testing General Relativity with the Black Hole Shadow Size and Asymmetry of Sagittarius A*: Limitations from Interstellar Scattering,” *ApJ* **870**, 6 (Jan. 2019).
- [163] Shen, Z.-Q., Lo, K. Y., Liang, M.-C., Ho, P. T. P., and Zhao, J.-H., “A size of ~ 1 AU for the radio source Sgr A* at the centre of the Milky Way,” *Nature* **438**, 62–64 (nov 2005).
- [164] Bower, G. C., Goss, W. M., Falcke, H., Backer, D. C., and Lithwick, Y., “The Intrinsic Size of Sagittarius A* from 0.35 to 6 cm,” *ApJ* **648**, L127–L130 (Sept. 2006).
- [165] Gwinn, C. R., Kovalev, Y. Y., Johnson, M. D., and Soglasnov, V. A., “Discovery of Substructure in the Scatter-broadened Image of Sgr A*,” *ApJ* **794**, L14 (Oct. 2014).
- [166] Psaltis, D., Johnson, M., Narayan, R., Medeiros, L., Blackburn, L., and Bower, G., “A Model for Anisotropic Interstellar Scattering and its Application to Sgr A*,” *arXiv e-prints*, arXiv:1805.01242 (May 2018).
- [167] Johnson, M. D., Narayan, R., Psaltis, D., Blackburn, L., Kovalev, Y. Y., Gwinn, C. R., Zhao, G.-Y., Bower, G. C., Moran, J. M., Kino, M., Kramer, M., Akiyama, K., Dexter, J., Broderick, A. E., and Sironi, L., “The Scattering and Intrinsic Structure of Sagittarius A* at Radio Wavelengths,” *ApJ* **865**, 104 (Oct. 2018).
- [168] Thompson, A. R., Moran, J. M., and Swenson, George W., J., [*Interferometry and Synthesis in Radio Astronomy, 3rd Edition*] (2017).
- [169] Caves, C. M., “Quantum limits on noise in linear amplifiers,” *Phys. Rev. D* **26**, 1817–1839 (Oct. 1982).
- [170] Kerr, A. R., Feldman, M. J., and Pan, S. K., “Receiver Noise Temperature, the Quantum Noise Limit, and the Role of the Zero-Point Fluctuations,” in [*Eighth International Symposium on Space Terahertz Technology*], Blundell, R. and Tong, E., eds., 101–111 (Jan. 1997).
- [171] Lu, R. S., Krichbaum, T. P., Eckart, A., König, S., Kunneriath, D., Witzel, G., Witzel, A., and Zensus, J. A., “Multiwavelength VLBI observations of Sagittarius A*,” *A&A* **525**, A76 (Jan. 2011).
- [172] Bower, G. C., Markoff, S., Dexter, J., Gurwell, M. A., Moran, J. M., Brunthaler, A., Falcke, H., Fragile, P. C., Maitra, D., Marrone, D., Peck, A., Rushton, A., and Wright, M. C. H., “Radio and Millimeter Monitoring of Sgr A*: Spectrum, Variability, and Constraints on the G2 Encounter,” *ApJ* **802**, 69 (Mar. 2015).
- [173] Kellermann, K. I. and Pauliny-Toth, I. I. K., “The Spectra of Opaque Radio Sources,” *ApJ* **155**, L71 (Feb. 1969).
- [174] Readhead, A. C. S., “Equipartition Brightness Temperature and the Inverse Compton Catastrophe,” *ApJ* **426**, 51 (May 1994).
- [175] Levy, G. S., Linfield, R. P., Ulvestad, J. S., Edwards, C. D., Jordan, J. F., di Nardo, S. J., Christensen, C. S., Preston, R. A., Skjerve, L. J., Stavert, L. R., Burke, B. F., Whitney, A. R., Cappallo, R. J., Rogers, A. E. E., Blaney, K. B., Maher, M. J., Ottenhoff, C. H., Jauncey, D. L., Peters, W. L., Nishimura, T., Hayashi, T., Takano, T., Yamada, T., Hirabayashi, H., Morimoto, M., Inoue, M., Shiomi, T., Kawaguchi, N., and Kunimori, H., “Very Long Baseline Interferometric Observations made with an Orbiting Radio Telescope,” *Science* **234**, 187–189 (Oct. 1986).

- [176] Gurvits, L. I., “Space VLBI: from first ideas to operational missions,” *Advances in Space Research* **65**, 868–876 (Jan. 2020).
- [177] Gurvits, L. I., “A Brief History of Space VLBI,” in [*2023 8th IEEE History of Electrotechnology Conference (HISTELCON)*], 171–174 (2023).
- [178] Tauber, J. A., Norgaard-Nielsen, H. U., Ade, P. A. R., Amiri Parian, J., Banos, T., Bersanelli, M., Burigana, C., Chamballu, A., de Chambure, D., Christensen, P. R., Corre, O., Cozzani, A., Crill, B., Crone, G., D’Arcangelo, O., Daddato, R., Doyle, D., Dubruel, D., Forma, G., Hills, R., Huppenberger, K., Jaffe, A. H., Jessen, N., Kletzkine, P., Lamarre, J. M., Leahy, J. P., Longval, Y., de Maagt, P., Maffei, B., Mandolesi, N., Martí-Canales, J., Martín-Polegre, A., Martin, P., Mendes, L., Murphy, J. A., Nielsen, P., Noviello, F., Paquay, M., Peacocke, T., Ponthieu, N., Pontoppidan, K., Ristorcelli, I., Riti, J. B., Rolo, L., Rosset, C., Sandri, M., Savini, G., Sudiwala, R., Tristram, M., Valenziano, L., van der Vorst, M., van’t Klooster, K., Villa, F., and Yurchenko, V., “Planck pre-launch status: The optical system,” *A&A* **520**, A2 (Sept. 2010).
- [179] Lehmensiek, R., Sridharan, T. K., Johnson, M., and Marrone, D. P., “The black hole explorer: Mission overview and antenna concept,” *accepted, in Proc. IEEE Int. Symp. AP & USNC/URSI Nat. Radio Sci. Meet., Florence, Italy* (Jul 2024).
- [180] Pilbratt, G. L., Riedinger, J. R., Passvogel, T., Crone, G., Doyle, D., Gageur, U., Heras, A. M., Jewell, C., Metcalfe, L., Ott, S., and Schmidt, M., “Herschel Space Observatory. An ESA facility for far-infrared and submillimetre astronomy,” *A&A* **518**, L1 (July 2010).
- [181] de Graauw, T., Helmich, F. P., Phillips, T. G., Stutzki, J., Caux, E., Whyborn, N. D., Dieleman, P., Roelfsema, P. R., Aarts, H., Assendorp, R., Bachiller, R., Baechtold, W., Barcia, A., Beintema, D. A., Belitsky, V., Benz, A. O., Bieber, R., Boogert, A., Borys, C., Bumble, B., Caïs, P., Caris, M., Cerulli-Irelli, P., Chattopadhyay, G., Cherednichenko, S., Ciechanowicz, M., Coeur-Joly, O., Comito, C., Cros, A., de Jonge, A., de Lange, G., Delforges, B., Delorme, Y., den Boggende, T., Desbat, J. M., Diez-González, C., di Giorgio, A. M., Dubbeldam, L., Edwards, K., Eggens, M., Erickson, N., Evers, J., Fich, M., Finn, T., Franke, B., Gaier, T., Gal, C., Gao, J. R., Gallego, J. D., Gauffre, S., Gill, J. J., Glenz, S., Golstein, H., Gouloze, H., Gunsing, T., Güsten, R., Hartogh, P., Hatch, W. A., Higgins, R., Honingh, E. C., Huisman, R., Jackson, B. D., Jacobs, H., Jacobs, K., Jarchow, C., Javadi, H., Jellema, W., Justen, M., Karpov, A., Kasemann, C., Kawamura, J., Keizer, G., Kester, D., Klapwijk, T. M., Klein, T., Kollberg, E., Kooi, J., Kooiman, P. P., Kopf, B., Krause, M., Krieg, J. M., Kramer, C., Kruizenga, B., Kuhn, T., Laauwen, W., Lai, R., Larsson, B., Leduc, H. G., Leinz, C., Lin, R. H., Liseau, R., Liu, G. S., Loose, A., López-Fernandez, I., Lord, S., Luinge, W., Marston, A., Martín-Pintado, J., Maestrini, A., Maiwald, F. W., McCoey, C., Mehdi, I., Megej, A., Melchior, M., Meisma, L., Merkel, H., Michalska, M., Monstein, C., Moratschke, D., Morris, P., Muller, H., Murphy, J. A., Naber, A., Natale, E., Nowosielski, W., Nuzzolo, F., Olberg, M., Olbrich, M., Orfei, R., Orleanski, P., Ossenkopf, V., Peacock, T., Pearson, J. C., Peron, I., Phillip-May, S., Piazzi, L., Planesas, P., Rataj, M., Ravera, L., Risacher, C., Salez, M., Samoska, L. A., Saraceno, P., Schieder, R., Schlecht, E., Schlöder, F., Schmölling, F., Schultz, M., Schuster, K., Siebertz, O., Smit, H., Szczerba, R., Shipman, R., Steinmetz, E., Stern, J. A., Stokroos, M., Teipen, R., Teyssier, D., Tils, T., Trappe, N., van Baaren, C., van Leeuwen, B. J., van de Stadt, H., Visser, H., Wildeman, K. J., Wafelbakker, C. K., Ward, J. S., Wesselius, P., Wild, W., Wulff, S., Wunsch, H. J., Tielens, X., Zaal, P., Zirath, H., Zmuidzinas, J., and Zwart, F., “The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI),” *A&A* **518**, L6 (July 2010).
- [182] Kojima, T., Kroug, M., Gonzalez, A., Uemizu, K., Kaneko, K., Miyachi, A., Kozuki, Y., and Asayama, S., “275–500-ghz wideband waveguide sis mixers,” *IEEE Transactions on Terahertz Science and Technology* **8**(6), 638–646 (2018).
- [183] Blackburn, L., Chan, C.-k., Crew, G. B., Fish, V. L., Issaoun, S., Johnson, M. D., Wielgus, M., Akiyama, K., Barrett, J., Bouman, K. L., Cappallo, R., Chael, A. A., Janssen, M., Lonsdale, C. J., and Doeleman, S. S., “EHT-HOPS Pipeline for Millimeter VLBI Data Reduction,” *ApJ* **882**, 23 (Sept. 2019).
- [184] “Accubeat ultra-stable-oscillator recent outstanding results.” <https://www.accubeat.com/uso> (2022).
- [185] “Certain equipment or instruments are identified in this paper in order to specify the experimental procedure adequately. such identification is not intended to imply recommendation or endorsement of any

product by nist, nor is it intended to imply that the equipment identified are necessarily the best available for the purpose..”

- [186] “JUICE.” https://www.esa.int/Science_Exploration/Space_Science/Juice.
- [187] Roslund, J. D., Cingöz, A., Lunden, W. D., Partridge, G. B., Kowligy, A. S., Roller, F., Sheredy, D. B., Skulason, G. E., Song, J. P., Abo-Shaeer, J. R., and Boyd, M. M., “Optical clocks at sea,” *Nature* **628**, 736–740 (Apr. 2024). Publisher: Nature Publishing Group.
- [188] Boroson, D. M. and Robinson, B. S., “The Lunar Laser Communication Demonstration: NASA’s First Step Toward Very High Data Rate Support of Science and Exploration Missions,” *Space Sci. Rev.* **185**, 115–128 (Dec. 2014).
- [189] Caplan, D., Rao, H., Wang, J., Boroson, D., Carney, J. J., Fletcher, A., Hamilton, S., Kochhar, R., Magliocco, R., Murphy, R., Norvig, M., Robinson, B., Schulein, R., and Spellmeyer, N., “Ultra-wide-range multi-rate dpsk laser communications,” in [*CLEO/QELS: 2010 Laser Science to Photonic Applications*], 1–2 (2010).
- [190] Spellmeyer, N. W., Browne, C. A., Caplan, D. O., Carney, J. J., Chavez, M. L., Fletcher, A. S., Fitzgerald, J. J., Kaminsky, R. D., Lund, G., Hamilton, S. A., Magliocco, R. J., Mikulina, O. V., Murphy, R. J., Rao, H. G., Scheinbart, M. S., Seaver, M. M., and Wang, J. P., “A multi-rate DPSK modem for free-space laser communications,” in [*Free-Space Laser Communication and Atmospheric Propagation XXVI*], Hemmati, H. and Boroson, D. M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8971**, 89710J (Mar. 2014).
- [191] Edwards, B. L., Israel, D. J., and Vithlani, S. K., “Latest changes to NASA’s laser communications relay demonstration project,” in [*Free-Space Laser Communication and Atmospheric Propagation XXX*], Hemmati, H. and Boroson, D. M., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10524**, 105240P (Feb. 2018).
- [192] Khatri, F. I., Gonnissen, Z., Wang, J. P., Mikulina, O., Schulein, R. T., Chang, J., Veselka, J., DeVoe, C., Gillmer, S., Han, D., et al., “System level tvac functional testing for the integrated lcrd low-earth orbit user modem and amplifier terminal (illum-a-t) payload destined for the international space station,” in [*Free-Space Laser Communications XXXV*], **12413**, 94–99, SPIE (2023).
- [193] Khatri, F. I., Schulein, R. T., Caplan, D. O., Grein, M. E., DeVoe, C. E., Torres, J., Constantine, S., Wright, M. W., Kovalik, J. M., Biswas, A., et al., “Space-to-ground optical interface verification for the orion artemis ii optical (o2o) communications demonstration,” in [*International Conference on Space Optical Systems*], (2023).
- [194] Riesing, K., Schieler, C., Bilyeu, B., Chang, J., Garg, A., Gilbert, N., Horvath, A., Reeves, R., Robinson, B., Wang, J., et al., “Operations and results from the 200 gbps tbird laser communication mission,” in [*37th Annual Small Satellite Conference*], (SSC23-I-03) (2023).
- [195] Schieler, C. M. et al., “On-orbit demonstration of 100 Gbps optical downlinks from the TBIRD Cube-sat,” in [*Free-Space Laser Communication and Atmospheric Propagation XXXV*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* (2023).