Mid-Range Science Objectives for the Event Horizon Telescope

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Mid-Range Science Objectives for the Event Horizon Telescope

The Event Horizon Telescope Collaboration

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ABSTRACT

The first images of the black holes in Sgr A* and M87* have created a wide range of new scientific opportunities in gravitational physics, compact objects, and relativistic astrophysics. We discuss here the scientific opportunities that arise from the rich data sets that have already been obtained and the new data sets that will be obtained, exploiting a wide range of technical advances, including observational agility, receiver upgrades, and the addition of new stations. This document provides a 5-year framework for Event Horizon Telescope (EHT) science structured around four fundamental questions that are used to prioritize the analysis of existing data, guide technical upgrades, and determine the optimal use of future observational opportunities with EHT, ALMA, and multi-wavelength facilities. Through enhancements over this period, the EHT will create the first movie of M87* connecting black hole and jet physics, provide detailed studies of the structure and dynamics of Sgr A*, characterize the magnetospheres of both systems through polarimetric imaging, and explore the spacetime properties of black holes with greater precision and range.

1. INTRODUCTION

The EHT Collaboration (EHTC) has published total intensity and polarized images of the supermassive black holes (SMBHs) in M87* (Event Horizon Telescope Collaboration et al. 2019a,b,c,d,e,f, 2021a,b, 2023, 2024c) and Sgr A* (Event Horizon Telescope Collaboration et al. 2022a,b,c,d,e,f, 2024a,b), providing the first direct visual evidence for the existence of black holes as predicted by general relativity. These images have enabled precise mass measurements for M87*, resolving a discrepancy between stellar and gas-dynamics based mass estimates, and confirmed the stellar orbit mass measurements for Sgr A*. Additionally, these observations have constrained the black hole inclination, plasma parameters, and magnetic field structure. These results have provided a powerful new laboratory to study both gravitational physics and the accretion environment for SMBHs in the context of extensive multi-wavelength campaigns on these objects (EHT MWL Science Working Group et al. 2021). They have also enabled the highest resolution studies of several bright AGN, including the nearby radio galaxies Centaurus A (Janssen et al. 2021) and 3C 84 (Paraschos et al. 2024) and the powerful blazars 3C279 (Kim et al. 2020), J1924-2914 (Issaoun et al. 2022), and NRAO 530 (Jorstad et al. 2023). In total, the EHTC has published over 200 refereed papers on observational, technical, and theoretical topics with over 14,000 citations in the past 5 years.[1]

At present, all published EHT results use data from the 2017 and 2018 observing campaigns. The EHT has the opportunity to significantly improve upon its published results through the analysis of more recent data from observing campaigns in 2018, 2021, 2022, 2023, and 2024 (summarized in Table 2). These campaigns have already expanded to new sites (GLT, KP, and NOEMA; see Figure 1), have doubled the recorded bandwidth (to 64 Gb/s), and have demonstrated successful observations at 345 GHz (Crew et al. 2023; Raymond et al. 2024), which was utilized as a standard EHT observing frequency for the first time in the 2023 campaign. Beyond the opportunities available through these existing observations, the EHT has the potential to deliver breakthrough science over the next 5 years (2024−2029) by pursuing a series of technical upgrades and expansions that are coordinated with increasingly ambitious observations.

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[1] https://ui.adsabs.harvard.edu/public-libraries/VFaebic8RGqFB9UuW9corg

In this paper, we describe the major mid-range scientific opportunities for the EHT and the developments that the EHTC is pursuing to achieve them. This is a living document that we expect to update as our strategies evolve with new scientific discoveries and technical capabilities. While the EHTC will continue to produce major results on non-horizon targets obtained as calibrators or PI-led, we focus only on M87* and Sgr A* because they define the collaboration outputs. In particular, we have identified several key science goals in the mid-term, each of which is enabled by a corresponding set of observational advances

1. **Science Question:** What is the origin of relativistic jets from SMBHs?
   Observational Goal: Establish the dynamical relationship between the SMBH and its relativistic jet in M87*.
   Requirements: Improved baseline coverage, especially on scales of $100-500\,\mu$as ($0.4-2\,\mathrm{G}\lambda$), and temporal coverage extending over at least $1-3$ months.
2. **Science Question:** What causes flaring near SMBHs?
   Observational Goal: Measure the ring structure and dynamics of Sgr A*, especially during multi-wavelength flares.
   Requirements: Improved snapshot baseline coverage, with mutual visibility from $6-8$ separate sites and coordinated multi-wavelength observations in the infrared and X-rays.
3. **Science Question:** Do SMBHs have strong magnetospheres that extract their spin energy?
   Observational Goal: Measure the near-horizon magnetic field structure and strength in M87* and Sgr A*.
   Requirements: Full-Stokes imaging of linear polarization, rotation measure, and circular polarization combining separate sidebands and $230+345\,\mathrm{GHz}$ observations.
4. **Science Question:** What are the characteristics of the massive compact objects in galactic nuclei?
   Observational Goal: Measure properties of the emission rings, apparent shadows, and other observables that depend on the spacetime properties for both M87* or Sgr A*.
   Requirements: Full-Stokes, time-averaged imaging at 230 and 345 GHz, with at least 10 epochs separated by $10GM/c^3$ (minutes for Sgr A*; days for M87*) and extending over a total time span of at least $1000GM/c^3$ (6 hours for Sgr A*; 1 year for M87*).

These goals are enabled by improvements along several axes: image fidelity, time domain, multi-frequency VLBI observations, and broadband multi-wavelength observations. In section 2, we describe planned improvements to the EHT. In section 3, we describe the driving scientific goals in more detail. In section 4, we summarize the opportunities for major scientific breakthroughs with the EHT in the coming years.

2. PLANNED EHT DEVELOPMENTS

Technical developments for the EHT are underway and/or planned in multiple areas. The science impact of these developments will be both during and after the 5-year timescale of this science plan, dependent upon the time necessary to implement, commission, and exploit new capabilities.

- **Pipeline software:** The EHT makes use of dedicated software pipelines and libraries for processing its unique data from the observatory (Blackburn et al. 2019; Janssen et al. 2019). There are several efforts underway to standardize and modernize EHT processing and analysis tools to further automate workflows and ultimately reduce the time required to produce science (e.g., Hoak et al. 2022; Tiede et al. 2022; van Bemmel et al. 2022).
- **Agility:** Technological and operational advances are underway to simplify observations and enable more remote control. Improved observing agility will enable movie campaigns, better response to weather, and response to transient events.
- **Receiver upgrades:** The EHT is pursuing development of dual- and tri-band receivers covering ALMA bands 3, 6, and 7. While observations have been successfully conducted in each band separately, sensitivity and atmospheric coherence time decreases at shorter wavelengths. This can be addressed through simultaneous observations in two or more bands and application of the frequency-phase transfer technique to extend coherence times at short wavelengths and, therefore, improve sensitivity (Dodson et al. 2023; Rioja et al. 2023; Pesce et al. 2024). Bandwidths in each receiver will also be doubled to match the ALMA Wideband Sensitivity Upgrade (Carpenter et al. 2023). Shorter wavelength VLBI, i.e. in ALMA Band 9, has been proposed (e.g., Chen et al. 2023) but is not yet a part of the EHT plan.

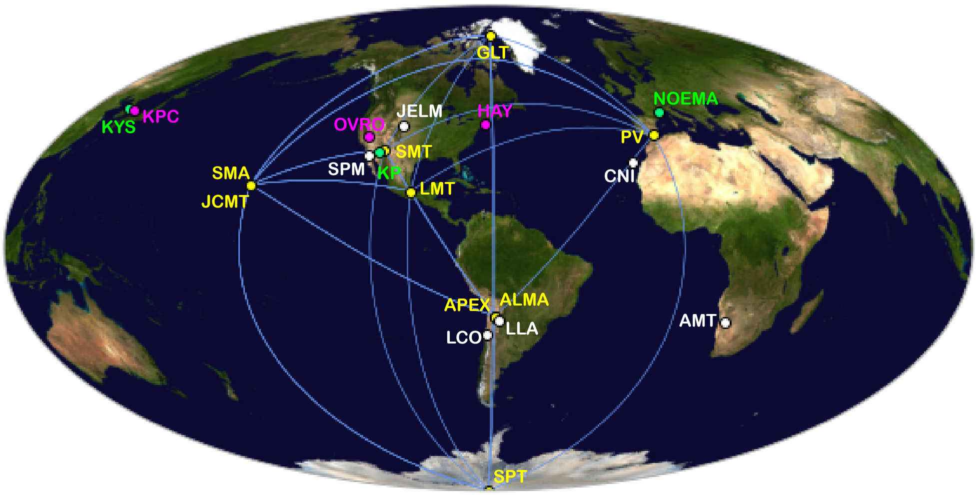

Figure 1. Map of the EHT. Stations active in 2017 and 2018 are shown with connecting lines and labeled in yellow, sites that joined in 2021-2024 are labeled in green, sites expected to join in the next 1-2 years are shown in magenta, sites expected to join over the next 5 years are shown in white. These future additions include the 37-m Haystack Telescope (Kauffmann et al. 2023), a 10.4-m telescope at the Owens Valley Radio Observatory in California, and the 21-m Pyeongchang Radio Observatory of the Korean VLBI Network (Asada et al. 2017). Other potential new sites include the 15-m Africa Millimetre Telescope (Backes et al. 2016), the 12-m Large Latin American Millimeter Array (Romero 2020), and several new antennas proposed to be deployed through the ngEHT program (Canary Islands, Spain; Jelm Observatory, USA; San Pedro Martir, Mexico; and Los Cumbres Observatory, Chile; Doeleman et al. 2023).

- **Bandwidth upgrade:** New developments in digitization, digital signal processing, and high bandwidth recording are necessary to accommodate the increase in number of receivers and broader bandwidths (Jiang et al. 2020).
- **Upgraded and new stations:** Developments are underway with antennas at Haystack Observatory, Owens Valley Radio Observatory, and the Korean VLBI Network to enable their participation in upcoming EHT campaigns (Kauffmann et al. 2023; Shin et al. 2022). Design and development of the Africa Millimeter Telescope in Namibia is underway (Backes et al. 2016; La Bella et al. 2023). Relocation of the Greenland Telescope (GLT) to the summit of Greenland (Chen et al. 2023) and construction of an array of new 9–m dishes as part of the ngEHT project (Doeleman et al. 2023) have been proposed. One longer term vision for an expanded array, including some of the above facilities, has been developed through the ngEHT program and published in a special issue of the journal Galaxies (https://www.mdpi.com/journal/galaxies/special_issues/ngEHT_blackholes). New stations will improve uv-coverage, array sensitivity, and robustness to station-loss due to weather.
- **Spectral line observations:** Spectral line observations provide information on the kinematics, physical and chemical composition of the gas in astronomical objects. Spectral line VLBI with the EHT+ALMA can support core black-hole studies via, e.g., high resolution observations of water megamaser at 321 GHz and 325 GHz[2] (Gray et al. 2016). Absorption studies offer another powerful tool to study and resolve the molecular gas in the vicinity of AGN, allowing to detect diffuse gas even at high redshift, depending only on the background continuum emission and the gas optical depth (see e.g., Kim & Fish 2023).

Similar technical developments are also discussed in Doeleman et al. (2023) which presents a reference array and design considerations from the ngEHT project.

3. SCIENCE OPPORTUNITIES

3.1. *Establish the dynamical relationship between the SMBH and its relativistic jet in M87**

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[2] It is worth noting that more water maser lines are known to emit from AGN disks, e.g. at 183 GHz, but suitable receivers are not uniformly available on all EHT stations.

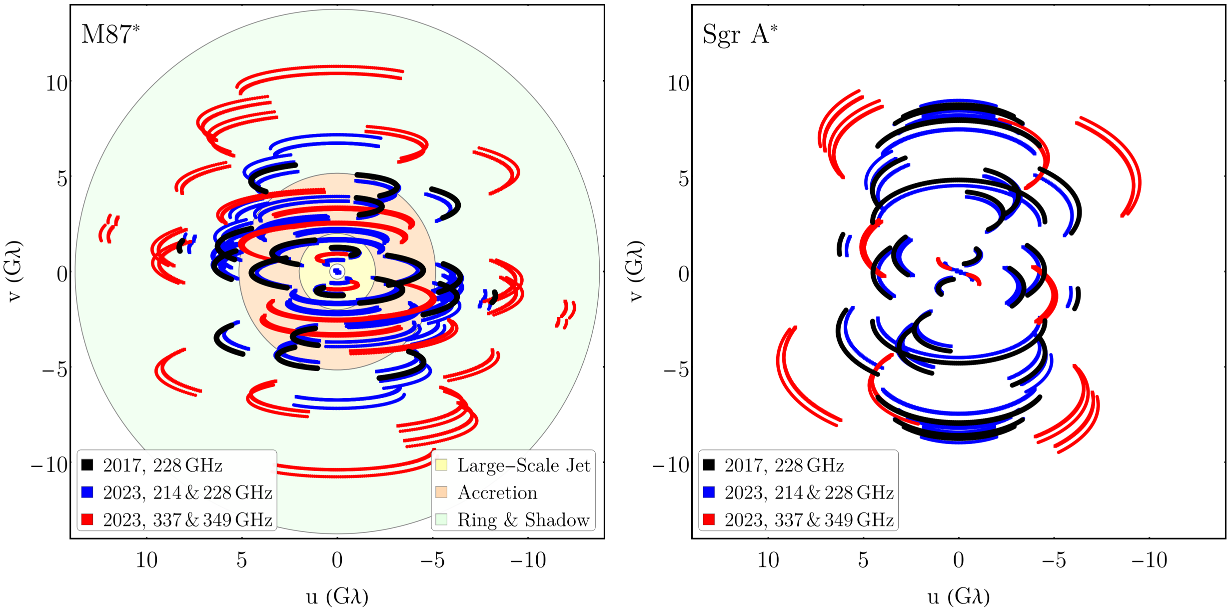

Figure 2. Comparison of EHT geometric baseline coverage over time for M87* (left) and Sgr A* (right). Black curves show the maximal coverage with the 2017 EHT array; blue/red curves show the dual-sideband 214/228 GHz and 337/349 GHz coverage for the 2023 EHT array. All current EHT sites have a telescope with 345 GHz observing capabilities except SPT, Kitt Peak, and LMT. For the M87* coverage, baseline ranges that contribute to the various science goals are colored: scales of $10-40\,\mu$as probe the emission ring and apparent shadow, $40-100\,\mu$as probe the accretion and jet launching regimes, and $100-500\,\mu$as probe the large-scale jet. These figures show the maximal baseline coverage of each array and do not account for detection limitations from finite sensitivity, which can limit the accessible baseline coverage at 345 GHz (see Figure 3; Pesce et al. 2024).

Black holes impart variability on their surrounding environment through channels including circularization of accreting material and frame dragging near a spinning black hole. One of the most exciting (but untested) predictions from current EHT simulations is that the relativistic jet in M87* is powered by drawing its energy from the spin of the SMBH through an analogue of the Penrose process (Penrose 1969; Blandford & Znajek 1977; Event Horizon Telescope Collaboration et al. 2019e, 2021b). This process is considered an extension of the concept initially proposed by Penrose, where energy is extracted from a rotating black hole. In the Blandford-Znajek process, this energy extraction is facilitated by magnetic fields interacting with the black hole's spin, leading to the formation of relativistic jets. In addition, major unresolved questions of particle heating and jet formation have distinctive corresponding dynamical signatures. The jet structure and dynamics of M87* have been extensively studied on scales of 10-1000 Schwarzschild radii using VLBI at frequencies up to 86 GHz (e.g., Kovalev et al. 2007; Mertens et al. 2016; Hada et al. 2016; Walker et al. 2018; Kim et al. 2018; Lu et al. 2023; Cui et al. 2023). These studies have revealed a relativistic outflow with substantial evolution on short (∼days) timescales and a wobbling position angle on long (∼years) timescales. However, these dynamics have never been directly connected to the black hole, and the EHT has the angular resolution necessary to monitor launching and acceleration of the jet and to reveal jet-disk kinematics. Analysis of the near-horizon jet morphology, radial velocity, azimuthal velocity, and polarization structure over time could test the jet-launching mechanism, and constrain black hole parameters such as magnetization and black hole spin (Wong et al. 2021; Cruz-Osorio et al. 2022; Fromm et al. 2022; Chael et al. 2023b; Davelaar et al. 2023; Moriyama et al. 2024). Hence, **full-polarization dynamical studies of M87* are a major priority for continued EHT observations.**

The relativistic jet in M87* is associated with dynamical activity on the scales of ∼weeks, and GRMHD simulations predict that the near-horizon emission should also be variable, with an associated correlation timescale of $\sim 50-100MG/c^3$, or a few weeks. Currently published EHT data can only marginally constrain the structure of the extended jet emission (e.g., Event Horizon Telescope Collaboration et al. 2019d; Arras et al. 2022; Broderick et al. 2022). In addition, while the published set of EHT observations unambiguously identifies the existence of structural evolution near the black hole (Event Horizon Telescope Collaboration et al. 2024c), the published EHT temporal coverage

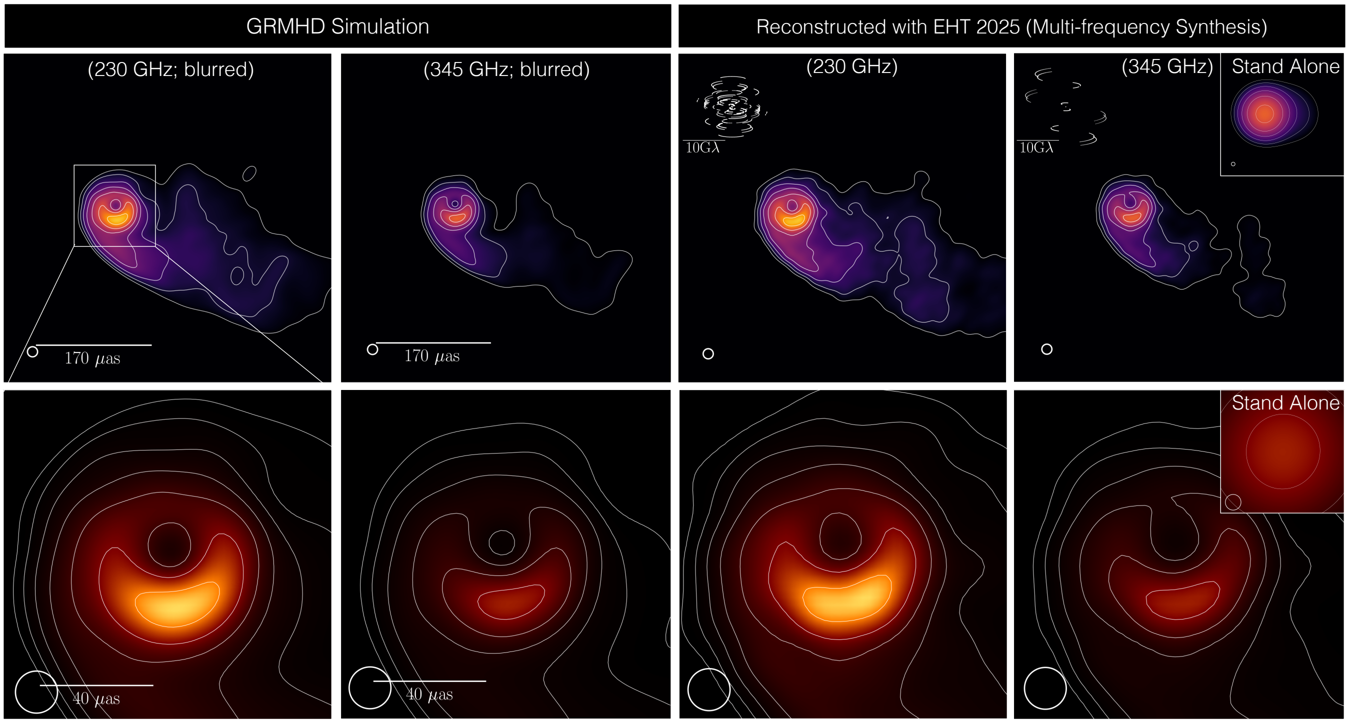

Figure 3. (From left to right) First two columns show images of M87* at 230 and 345 GHz from a GRMHD simulation (Chael et al. 2019). The next two columns show multi-frequency reconstructions (Chael et al. 2023a) using simulated data from the EHT with the projected 2025 array configuration and realistic weather modeling (Pesce et al. 2024). Insets show the baseline coverage in each band as well as reconstructions using 345 GHz data alone. Dual-band observations are necessary to obtain images at 345 GHz. The top row shows large-scale emission with a logarithmic color scale; the bottom row shows the central region with a linear color scale. Contours are set by successive powers of 1/2 from the peak brightness. Enhancements to imaging through inclusion of 345 GHz are a strong function of the underlying source model.

is inadequate to unambiguously identify the structural variability in M87* (e.g., to determine apparent velocity of rotation, inflow, or outflow).

Meaningful studies of M87* dynamics with the EHT will require improved image dynamic range to unambiguously constrain the extended jet structure (see, e.g., Johnson et al. 2023; Conroy et al. 2023). This requires multiple sensitive baselines that sample angular scales of $100 - 500\,\mu$as ($|\vec{u}| = 0.4 - 2\,\mathrm{G}\lambda$), ideally with associated phase information (through closure phase) and full-Stokes information. For comparison, the EHT observations in 2017 included only a single intersite baseline shorter than $2\,\mathrm{G}\lambda$, the LMT-SMT baseline, which sampled the range $1.25 - 1.5\,\mathrm{G}\lambda$ (see Figure 2). However, the improved baseline coverage in the current EHT may allow firm detections of the M87* jet (see Figure 3). To study the dynamics of M87* will also require longer EHT observing campaigns, extending for at least $1 - 3$ months with a sub-week observing cadence, and the study of observations over several years to assess the connection between the evolving jet and the horizon-scale structure. These campaigns can also be coordinated with multi-wavelength facilities to elucidate the mechanisms behind particle acceleration within the jet and the generation of high energy flares.

3.2. *Measure the ring structure and dynamics of Sgr A*, especially during multi-wavelength flares*

Sgr A* is a highly variable source, with a gravitational timescale of only $GM/c^3 \approx 20$ seconds and daily flares in the radio through X-rays (e.g., Baganoff et al. 2001; Genzel et al. 2003; Eckart et al. 2004; Marrone et al. 2008; Haggard et al. 2019; Witzel et al. 2021). The EHT is the only facility that can directly image the evolving emission structure of Sgr A*. Measuring the direction of rotation would enable the EHT to corroborate the measurement of clockwise motion by the GRAVITY collaboration (GRAVITY Collaboration et al. 2018, 2020). Measuring the magnitude of the apparent rotation rate and the pitch angle of orbiting features would enable constraints of inclination, distance-independent constraints on mass, and constraints of spin (Ricarte et al. 2022; Conroy et al. 2023). Movies depicting the near-horizon dynamics of Sgr A* could also constrain different models of flaring events (Ripperda et al. 2020, 2022; Porth et al. 2021; Grigorian & Dexter 2024).

However, the rapid variability renders the standard VLBI approach of Earth-rotation synthesis inapplicable, and the "snapshot" baseline coverage of the published EHT data are inadequate to unambiguously describe the source structure (Event Horizon Telescope Collaboration et al. 2022c).

In the 2017 EHT campaign, the variability of Sgr A* in total intensity was mild on April 6 and 7 and more significant on April 11 (Event Horizon Telescope Collaboration et al. 2022d; Wielgus et al. 2022a). On all days, the polarimetric variability is considerably stronger than that in total intensity alone (Event Horizon Telescope Collaboration et al. 2024a). This is consistent with previous measurements of the 1.3 mm light curve (Marrone et al. 2006; Bower et al. 2018; Goddi et al. 2021) and in interferometry with a precursor EHT array (Johnson et al. 2015).

Analysis of the structural evolution associated with the variability of Sgr A* is a major opportunity for the EHT in near-term analyses. Despite the current limitations in snapshot baseline coverage, variability analysis will be carried out through non-imaging studies that quantify the power spectrum of the variability (e.g., Broderick et al. 2022) or that rely on constraining low-dimensional parametric models (e.g., Event Horizon Telescope Collaboration et al. 2022c,d; Roelofs et al. 2023; Event Horizon Telescope Collaboration et al. 2024a), alongside attempts at dynamic imaging with the available data.

3.3. *Measure the near-horizon magnetic field structure and strength in M87* and Sgr A**

The EHT has published findings on both the linear and circular polarization results for M87* (Event Horizon Telescope Collaboration et al. 2021a,b, 2023) and Sgr A* (Event Horizon Telescope Collaboration et al. 2024a,b). For M87*, the addition of polarization indicated a preference for magnetically arrested accretion flow models and severely restricted the acceptable GRMHD parameter space; for instance, passing models in total intensity had accretion rates $\dot{M}$ that extended over $10^{-4} - 10^{-1} M_{\odot}/\text{yr}$, while the linear polarization constraints reduced the range of passing models to $10^{-4} - 10^{-3} M_{\odot}/\text{yr}$ (Event Horizon Telescope Collaboration et al. 2021b). Consistent with our analyses of M87*, the Sgr A* polarimetric data further supports the preference for GRMHD models characterized by dynamically significant magnetic fields (Event Horizon Telescope Collaboration et al. 2022c). The high degree of spatially resolved linear polarization observed in Sgr A* (ranging from 24% to 28%, with peaks at approximately 40%; Event Horizon Telescope Collaboration et al. 2024a) provides a stringent constraint on the parameter space, effectively ruling out models that exhibit excessive Faraday depolarization. Polarimetric variability also has the potential to characterize turbulence in the accretion flow. Thus, polarimetric information is imperative in guiding astrophysical models for M87* and Sgr A*, and our current analyses have only begun to explore the information encoded in the polarized signals from these SMBHs.

In addition, while linear polarization images primarily constrain the magnetic field *structure*, frequency-dependent Faraday rotation primarily constrains the magnetic field *strength*. Because all the current EHT results are effectively monochromatic, they have not yet integrated information that is accessible through resolved Faraday rotation images that may be possible through dual-sideband (214/228 GHz) observations in 2018 onward, and through dual frequency (230/345 GHz) observations in 2023 onward. Both unresolved measurements with ALMA (e.g., Bower et al. 2018; Goddi et al. 2021; Wielgus et al. 2022b) and GRMHD simulations (e.g., Mościbrodzka et al. 2017; Ricarte et al. 2020) indicate that the EHT observations will show rich frequency structure from internal Faraday rotation, providing crucial astrophysical insights. Moreover, measuring the Faraday rotation will be imperative so that the observed linear polarization can be de-rotated to evaluate the internal magnetic field structure. This is particularly relevant for Sgr A*, where the inferred sense of rotation of the material around the ring depends on whether the Faraday rotation occurs internally within the emitting plasma or in an external screen (Event Horizon Telescope Collaboration et al. 2022c).

3.4. *Estimate the spacetime properties for M87* and Sgr A* through properties of their emission rings and apparent shadows*

The EHT has enabled crucial new constraints on the compact objects in M87* and Sgr A*. For both sources, studies of the emission ring and apparent "shadow" (Falcke et al. 2000) yield estimates of the black hole mass-to-distance ratio to an accuracy of $10 - 20\%$ (Event Horizon Telescope Collaboration et al. 2019f, 2022d,f). For M87*, the EHT measurements of the SMBH mass conclusively resolved a long-standing dispute between estimates of the mass from gas dynamical and stellar dynamical measurements on scales $\sim 10^4 - 10^5$ times larger than those probed by the EHT. For Sgr A*, the EHT measurements showed precise agreement with the measurements from resolved stellar orbits –

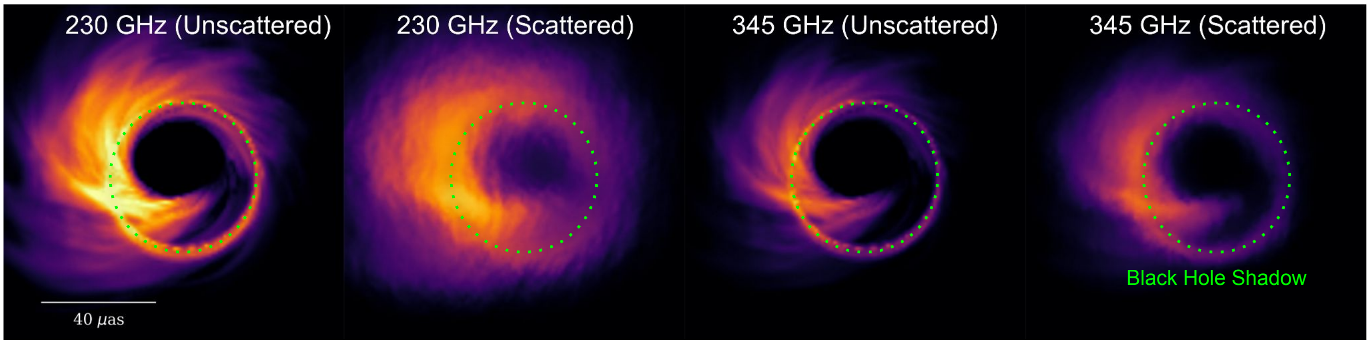

Figure 4. The effects of interstellar scattering on images of Sgr A*. The panels show simulated images of Sgr A* at 230 and 345 GHz both before and after scattering. Even for an array with perfect imaging capabilities, 345 GHz observations of Sgr A* are necessary to reduce the scattering and source opacity sufficiently to access sharp gravitational features.

a powerful confirmation of general relativity. These measurements allow constraints on the spacetime parameters for various non-Kerr spacetimes as well as excluding some families of alternative compact objects (e.g., Mizuno et al. 2018; Psaltis et al. 2020; Kocherlakota et al. 2021; Event Horizon Telescope Collaboration et al. 2022f; Younsi et al. 2023).

Nevertheless, the EHT measurements of both sources have only begun to explore what is possible through VLBI. For M87*, the central brightness depression is only constrained to a contrast of 10:1, our measurements have only given an upper limit on the thickness of the emission ring, and our measurements give only weak constraints on ring ellipticity (Tiede et al. 2022). For Sgr A*, the central brightness depression is only constrained to a contrast of 3:1, and even the most basic azimuthal structure of the emission ring (such as the position angle of peak brightness) and its geometric shape is uncertain. Most importantly, the current EHT measurements have only weakly constrained the spin of the black hole in both sources.

The EHT has the opportunity to substantially enrich its results through improved angular resolution observations of both sources. The most straightforward pathway to sharper images is through higher frequency observations, with 345 GHz coming online as a standard observing mode since 2023. The observations at 345 GHz (0.8 mm) will increase the effective resolution of the array by up to 50%. Higher frequency observations are especially critical for Sgr A* because of its severe interstellar scattering, which diminishes rapidly at higher frequencies (see Figure 4; Shen et al. 2005; Bower et al. 2006; Psaltis et al. 2018; Johnson et al. 2018; Issaoun et al. 2019). The 345 GHz observations will also be imperative for stronger tests of the spacetime properties through comparison with the 230 GHz observations because the strong gravitational lensing that gives rise to features such as the black hole shadow (Falcke et al. 2000), photon ring (Johnson et al. 2020), and inner shadow (Chael et al. 2021) is achromatic, whereas the confounding emission from the nearby plasma is steeply chromatic. In addition to higher frequency observations, combining multiple epochs of observations of M87* will give access to its time-averaged structure. Likewise, combining multiple epochs of observations of Sgr A* will provide stronger constraints on both its variability power spectrum and the time-averaged structure; these must be evaluated together because of the strong effects of intrinsic variability on the modeling and imaging (e.g., Event Horizon Telescope Collaboration et al. 2022c,d; Broderick et al. 2022). This structure may give crucial insights into the black hole spin through polarimetric features (e.g., Palumbo et al. 2020; Mościbrodzka et al. 2021; Ricarte et al. 2021; Chael et al. 2023b). In particular, the angle of linear polarization across position angle and radius has potential to constrain spin (Chael et al. 2023b).

Valuable constraints on the spacetime properties of Sgr A* can also be measured from nearby pulsars (e.g., Psaltis et al. 2016). Expectations are that pulsars should be numerous in this region, although difficult to detect as the result of interstellar scintillation. The EHTC has now conducted the most extensive and sensitive search for Galactic Center pulsars at millimeter wavelengths (Torne et al. 2023). Because pulsar searches can simply "piggyback" on standard EHT observations, we will continue them into the future (also at 345 GHz), as well as combining these searches with searches for Galactic Center pulsars at other frequencies. Combining EHT's high-resolution electromagnetic observations with the rich dataset from gravitational wave observatories, such as LIGO/Virgo, LISA, or ET, enables more accurate determinations of black hole properties, such as mass, spin, and the dynamics of their surrounding accretion disks and jets. These integrated observations are pivotal for enhancing existing models and achieving unprecedented precision in our measurements. Such multi-messenger approaches are not only for corroborating the current predictions of GR but also will provide profound insights into the fundamental forces and interactions that govern our universe.

4. PLANS FOR EXISTING DATA AND FUTURE OBSERVING CAMPAIGNS

In this section, we show how our science questions map onto analysis of existing data sets and will guide future observing campaigns.

4.1. *Opportunities with Existing EHT Data*

The EHT operations and science utilization span at a minimum a 5-year cycle, from the identification of the year-specific science goals to the completion of science utilization and the announcement of results. Archival data is available on the EHT public website[3]. We now briefly summarize the expected merits of unpublished EHT observations of M87* and Sgr A*. Table 1 summarizes the potential for each of these observing campaigns to address the primary goals given above.

2017: Extensive analysis has been carried out on nearly all aspects of M87* and Sgr A* from this campaign. One opportunity that is still under investigation is studies of Sgr A* dynamics during X-ray flaring activity on 11 April 2017 (Event Horizon Telescope Collaboration et al. 2022b), which also shows associated polarimetric variability in the EHT observations (Wielgus et al. 2022b; Event Horizon Telescope Collaboration et al. 2024a).

2018: EHT observations in 2018 provide an incremental technical improvement compared to 2017. The EHTC was enhanced through the inclusion of the GLT for the first time and doubling of the recording bandwidth across all stations. For M87*, we have confirmed the stability of the ring diameter over a one year period while also observing a change in the orientation of the azimuthal brightness distribution (Event Horizon Telescope Collaboration et al. 2024c). For Sgr A*, the baseline coverage is unchanged in 2018 (the GLT cannot observe Sgr A*), but these observations will determine the stability of the image structure over 1-year timescales. In addition, the recorded bandwidth doubled in 2018 through dual-sideband data (from 4 GHz to 8 GHz), resulting in an increase in the spanned bandwidth from 4 GHz to 18 GHz. Because Faraday rotation is proportional to the squared observing wavelength, the effects of rotation measure in 2018 data will be approximately 5× those in 2017 data.

2021: EHT observations in 2021 have significantly improved baseline coverage relative to 2017. Despite the notable omission of the LMT, the number of non-redundant baselines *doubles* in 2021 relative to 2017, increasing from 10 to 21 baselines for M87* and from 15 to 21 baselines for Sgr A*. The 2021 observations also include new short baselines (KP-SMT and PV-NOEMA), which will improve the EHT's sensitivity to extended jet or disk structures in M87* and Sgr A*. This EHT campaign also included 345 GHz observations of M87* on an adjacent day to 230 GHz observations, creating the possibility to combine them for multi-frequency synthesis with up to 50% sharper resolution than the current EHT images. For Sgr A*, the best *snapshot* baseline coverage does not improve in 2021 because the addition of Kitt Peak is offset by the loss of the LMT in the region of time with the best baseline coverage (and NOEMA does not have mutual visibility in this interval).

2022: EHT observations in 2022 created significant new opportunities. For both M87* and Sgr A*, there are 8 participating sites, giving 28 baselines. Moreover, the snapshot baseline coverage for Sgr A* increases from at most 5 sites (10 baselines) in 2017-2021 to 6 sites (15 baselines) in 2022, improving the capacity to constrain the time-variable structure. A limitation of the 2022 observations is that they sample only 3 days in a 9-day interval for M87* (observations in 2021 sampled 6 days in a 10-day interval).

2023: EHT observations in 2023 included for the first time data obtained at 345 GHz on Sgr A* with 5 stations at three geographic locations, Chile, Hawaii, and Arizona. These data will provide the first measurements of the angular size and asymmetry of Sgr A* at these wavelengths in total and polarized intensity. Direct comparison with the 230 GHz epochs from the same campaign will enable construction of a multi-frequency synthesis image. These data also provide the opportunity for the first ALMA 345 GHz search for Galactic Center pulsars. M87* was not observed in this epoch.

2024: EHT observations in 2024 included both Sgr A* and M87* in three different frequency bands centered at 230, 260, and 345 GHz, an array with 11 sites including a limited first-time participation of the Korean VLBI Network (KVN) Yonsei antenna (KYS) on a best-efforts basis, and a significant multi-wavelength campaign.

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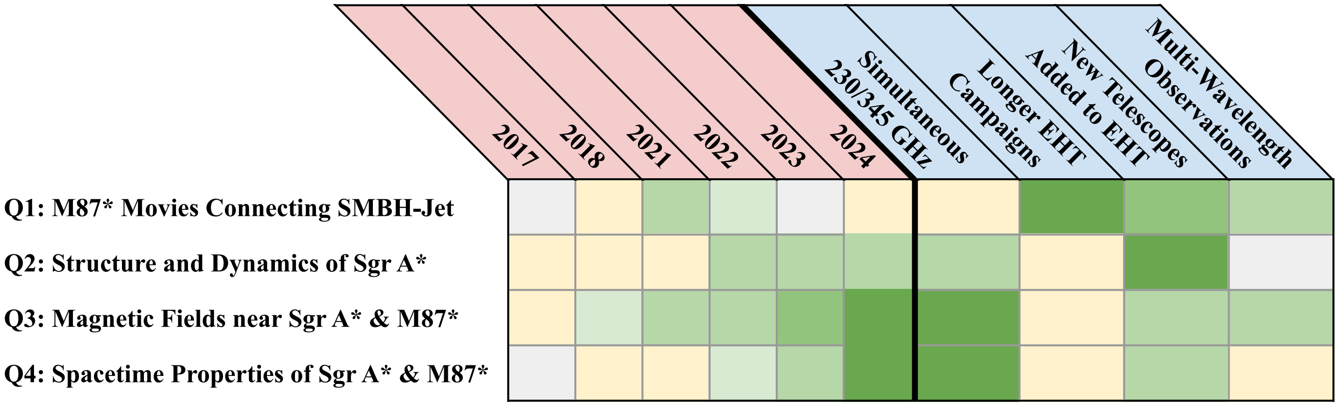
[3] https://eventhorizontelescope.org/for-astronomers/data



	2017	2018	2021	2022	2023	2024	Simultaneous 230/345 GHz	Longer EHT Campaigns	New Telescopes Added to EHT	Multi-Wavelength Observations
Q1: M87* Movies Connecting SMBH-Jet	⬜	🟨	🟩	🟩	⬜	🟨	🟨	🟩	🟩	🟩
Q2: Structure and Dynamics of Sgr A*	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟩	⬜
Q3: Magnetic Fields near Sgr A* & M87*	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩
Q4: Spacetime Properties of Sgr A* & M87*	⬜	🟨	🟨	🟩	🟩		🟩	🟨	🟩	🟨

Table 1. Summary of the primary EHT goals (rows) and the pathway to achieving them (columns). Red headers denote past or scheduled EHT campaigns (see Table 2); blue headers denote potential EHT upgrades (see subsection 4.2). Cells are colored by the likelihood to significantly advance progress on the corresponding science goal (relative to currently published results) through the associated observation or upgrade: gray indicates no advance, yellow is a minor advance, and green is a major advance shaded by significance. Dark green indicates the expectation for a decisive discovery enabled by the corresponding upgrade.

4.2. *Priorities for Mid-Range Science Campaigns and Upgrades*

In the mid-range (2024 – 2029), the EHT has many potential observations, upgrades, and expansions that can be considered. The most significant improvements will likely come in the following areas:

- **Improved image fidelity and sensitivity through simultaneous multi-frequency observations and the use of frequency phase transfer techniques.** The most significant recent new EHT capability is the addition of 345 GHz as a standard observing frequency in 2023 although observations at this frequency are likely to remain limited in both sensitivity and baseline coverage. 345 GHz will be most effective when combined with VLBI observations at other wavelengths through simultaneous dual-frequency 230+345 GHz or triple-frequency 86+230+345 GHz observations. Such observations will enable multi-frequency synthesis as discussed below and, significantly, will also allow the use of frequency phase transfer (FPT) techniques that exploit the fact that atmospheric phase fluctuations at these frequencies are dominated by the troposphere, which is non-dispersive. Hence, phase fluctuations can be tracked at lower frequencies and then corrected at higher frequencies where e.g. phase wrapping can become problematic. This technique has already been demonstrated at frequencies up to 130 GHz using the KVN, extending coherence time from tens of *seconds* to tens of *minutes* (Rioja et al. 2015). Lower-altitude non-345 GHz EHT telescopes will benefit from dual-frequency FPT from 86 to 230 GHz allowing also continued operation under less-than-ideal conditions. High-altitude/low-opacity EHT telescope will benefit from dual-frequency 230 to 345 GHz or triple-frequency FPT to improve the coherence of VLBI at the higher band(s). It is likely that the full angular resolution improvement possible at 345 GHz will require this technique to offset the severe limitations from reduced sensitivity and rapid atmospheric phase fluctuations (Issaoun et al. 2023; Pesce et al. 2024). These improvements will be necessary to mitigate the strong interstellar scattering of Sgr A* and to use this source to obtain tighter constraints on potential deviations from the Kerr metric (leveraging the precise measurements of mass and distance from resolved stellar orbits), and they will enable spectral studies of the emission near M87* that can clarify what image features are associated with strong gravitational lensing (which is achromatic). The potential merits of FPT for 230 and 345 GHz VLBI have been extensively explored and simulated (through the ngEHT program), and the first FPT experiment between 86 and 230 GHz took place in November 2022 (led by the KVN).[4]
- **Longer EHT observing windows enabled through agile observations, to produce horizon-scale movies of M87*.** Even through 2024, EHT campaigns of M87* are still effectively within a "snapshot" regime.

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[4] In 2022, a dedicated workshop exploring multi-band capabilities for VLBI was convened, with most presentations available online (https://www.ngeht.org/broadening-horizons-2022).

The source coherence timescale is expected to be $50 - 100\ GM/c^3 \approx 20 - 40$ days, while the longest span of existing EHT observations is only 10 days. An EHT campaign extending over 2-3 months, even with a limited observing cadence, would have immense value in constraining the source dynamics. It may be possible to study ring dynamics with relatively sparse uv-coverage but more detailed studies of disk-jet dynamics may require long-duration, high-cadence studies. Detailed trade-off studies are required to optimize movie observing campaigns with scientific goals.

- **Improved dynamic range and snapshot coverage through the integration of new telescopes.** Many scientific objectives with submillimeter VLBI are simply not possible without improved baseline coverage. Additional baseline coverage is necessary to produce movies of Sgr A*, and to detect the jet and counter-jet in M87*. Some existing sites could potentially join EHT observations (e.g., the 21-m Pyeongchang Radio Observatory; Asada et al. 2017) and several are being developed through the ngEHT program (e.g., the Haystack 37-m and the OVRO 10.4-m; Doeleman et al. 2019; Raymond et al. 2021; Doeleman et al. 2023). Other potential forthcoming sites include the 15-m Africa Millimetre Telescope (Backes et al. 2016) and the 12-m Large Latin American Millimeter Array (Romero 2020).
- **Coordinated multi-wavelength observations to enable multi-frequency synthesis.** For M87*, quasi-simultaneous observations with a global 86 GHz array (the GMVA or VLBA) would enable multi-frequency synthesis across an order of magnitude wider bandwidth than is currently sampled by the EHT. Moreover, it would allow the EHT to leverage the substantially higher image dynamic range at 86 GHz, 1-2 orders of magnitude better than the EHT alone (e.g., Kim et al. 2018; Lu et al. 2023; Cui et al. 2023), to improve the fidelity of EHT images (see, e.g., Chael et al. 2023a). For M87*, these observations would ideally be scheduled within 1-2 days of each other to ensure that the source was effectively static. For Sgr A*, coordinated simultaneous 86 GHz observations can provide constraints on the severe interstellar scattering as well as characterize multi-frequency light-curves during flares, which are an important aspect of EHT multi-frequency analyses.
- **Expansion of the sample of horizon-scale objects.** Observations are already underway to detect and characterize objects with predicted photon ring diameters that are a factor of a few smaller than that of Sgr A* and M87* (Ramakrishnan et al. 2023). Given the large systematic uncertainty in black hole masses, the photon rings in these objects are potentially resolvable with the current EHT at 230 or 345 GHz. Characterization of these objects also explores accretion flows and jet formation on compact scales as well as establishes their suitability for photon ring imaging through high dynamic range imaging, higher frequency VLBI, and space VLBI (e.g., Pesce et al. 2021, 2022; Ricarte et al. 2023).

We will prioritize efforts and funding that are in support of these objectives. Additional areas of development such as observations at frequencies higher than 345 GHz and real-time data transport and correlation offer further possibilities but should not be pursued at the expense of these primary goals.

While this document has focused on science objectives related to M87* and Sgr A*, these array enhancements would also significantly improve our understanding of relativistic jets from AGN, particularly in terms of jet formation, collimation, and acceleration, the role of magnetic fields in jet dynamics, and the processes and locations of high energy emission production. Currently, EHT observing campaigns are limited to capturing snapshot images of blazar jets with the highest possible angular resolutions. The EHT's imaging of the blazar 3C279 has uncovered an unexpected, twisted, and bent jet structure near the central black hole (Kim et al. 2020). Similarly, observations of Centaurus A have provided detailed insights into jet collimation and its relationship with the supermassive black hole (Janssen et al. 2021), advancing our understanding of how jets form and accelerate. These findings underscore the EHT's transformative impact on our comprehension of relativistic jets in AGN, and while these initial results from the EHT are groundbreaking, the potential for further advancements is substantial. The planned longer observing windows will enable the creation of the first movies of blazar jets at the remarkable 20 microarcsecond resolution of the EHT. This enhancement will provide a 10-fold increase in resolution, allowing us to map the jet dynamics and evolving magnetic field structures closer to the central engine than ever before. Multi-frequency phase transfer and multi-frequency imaging will also enable higher image dynamic range, revealing detailed internal structure and dynamics within the jets (e.g., Lobanov & Zensus 2001; Gómez et al. 2016, 2022; Okino et al. 2022; Chael et al. 2023a; Fuentes et al. 2023), including regions 10 times closer to the SMBH than is possible at cm wavelengths because of synchrotron self-absorption. These studies will also have multi-wavelength and multi-messenger components, with the potential to study the connection to high energy emission, including neutrinos.

Source	Year	Day	Freq	ALMA	APEX	LMT	SMT	PV	SMA	JCMT	SPT	GLT	NOEMA	KP	Sites	MWL Notes
M87*	2017	April 5	228	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	5 (7)	EVN, EAVN, VLBA, GMVA, KVN, HST, Swift, Chandra, NuSTAR, Fermi, HESS, MAGIC VERITAS. Nucleus in low state
		April 6	228	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	5 (7)	
		April 10	228	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	5 (7)	
		April 11	228	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	5 (7)	
	2018	April 21	214, 228	✓	✓	✓	✓	✓	✓	✓	-	✓	-	-	6 (8)	EAVN, VLBA, KVN, GMVA, Kanata, Swift, Astrosat, Chandra, NuSTAR, Fermi, HESS, MAGIC, VERITAS. TeV flare during EHT campaign
		April 22	214, 228	✓	✓	✓	✓	-	-	-	-	✓	-	-	4 (5)	
		April 25	214, 228	✓	✓	-	✓	✓	✓	✓	-	✓	-	-	5 (7)	
		April 28	214, 228	-	-	-	✓	✓	✓	✓	-	✓	-	-	4 (5)	
	2021	April 9	214, 228	-	✓	-	✓	-	✓	✓	-	✓	✓	✓	6 (7)	EAVN, VLBA, KVN, GMVA, NuSTAR, Kanata, Swift, Chandra, Fermi, MAGIC, HESS, VERITAS
		April 13	214, 228	✓	✓	-	✓	✓	✓	✓	-	✓	-	✓	6 (8)	
		April 14	214, 228	✓	✓	-	✓	✓	-	-	-	✓	✓	✓	6 (7)	
		April 17	214, 228	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓	7 (9)	
		April 18	214, 228	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓	7 (9)	
		April 19	337, 349	✓	-	-	✓	✓	✓	✓	-	✓	✓	-	6 (7)	
	2022	March 18	214, 228	-	-	✓	✓	✓	✓	✓	-	✓	✓	✓	7 (8)	EAVN, VLBA, KVN, GMVA, Lowell, Kanata, HST, Swift, NuSTAR, Chandra, Fermi, MAGIC, HESS, VERITAS.
		March 22	214, 228	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	8 (10)	
		March 27	214, 228	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	8 (10)	
	2024	April 4	253, 267	✓	✓	-	✓	✓	✓	✓	-	✓	✓	✓	7 (9)	EAVN/EATING, VLBA, KVN, GMVA, Kanata, Swift, NuSTAR, Chandra, Fermi, MAGIC, HESS, VERITAS.
		April 8	214, 228	✓	✓	✓	✓	-	✓	✓	-	✓	✓	✓	7 (9)	
		April 9	337, 349	✓	✓	-	✓	✓	✓	✓	-	✓	-	-	5 (7)	
Sgr A*	2017	April 5	228	-	✓	✓	✓	-	✓	✓	✓	-	-	-	5 (6)	EAVN, GMVA, VLT, Swift, Chandra, NuSTAR, Fermi, HESS, MAGIC. Chandra flare on Apr 11
		April 6	228	✓	✓	✓	✓	-	✓	✓	✓	-	-	-	5 (7)	
		April 7	228	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	6 (8)	
		April 10	228	-	✓	✓	✓	-	✓	✓	✓	-	-	-	5 (6)	
		April 11	228	✓	✓	✓	✓	-	✓	✓	✓	-	-	-	5 (7)	
	2018	April 21	214, 228	✓	✓	✓	✓	-	✓	✓	✓	-	-	-	5 (7)	EAVN, VLBA, GMVA, VLT, NuSTAR, Swift, Chandra, Fermi, VERITAS, MAGIC, HESS
		April 22	214, 228	✓	✓	✓	✓	-	✓	✓	✓	-	-	-	5 (7)	
		April 24	214, 228	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	6 (8)	
		April 25	214, 228	✓	✓	-	✓	-	✓	✓	✓	-	-	-	5 (7)	
	2021	April 9	214, 228	-	✓	-	✓	✓	✓	✓	✓	-	✓	✓	7 (9)	VLA, KVN, EAVN, NuSTAR, Swift, Chandra, Fermi, MAGIC, HESS, VERITAS
		April 14	214, 228	✓	✓	-	✓	✓	✓	✓	✓	-	✓	✓	7 (9)	
		April 15	214, 228	✓	✓	-	✓	-	✓	✓	✓	-	-	✓	5 (7)	
		April 16	214, 228	✓	✓	-	✓	✓	✓	✓	✓	-	✓	✓	7 (9)	
		April 17	214, 228	✓	✓	-	✓	✓	✓	✓	✓	-	✓	✓	7 (9)	
	2022	March 20	214, 228	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	8 (10)	VLA, EAVN, KVN, VLBA+GBT, VLT-Gravity, NuSTAR, XMM-Newton, Chandra, IXPE, Fermi, MAGIC, INTEGRAL, HESS.
		March 22	214, 228	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	8 (10)	
		March 23	214, 228	✓	✓	✓	✓	-	✓	✓	✓	-	✓	✓	7 (9)	
	2023	April 15	337, 349	✓	✓	-	✓	-	✓	✓	-	-	-	-	3 (5)	VLA, EAVN, VLBA+GBT, JWST, NuSTAR, Chandra, INTEGRAL, HESS.
		April 16	214, 228	✓	✓	✓	✓	-	✓	✓	✓	-	✓	✓	7 (9)	
		April 18	214, 228	✓	✓	-	✓	-	✓	✓	✓	-	✓	✓	7 (9)	
	2024	April 4	253, 267	✓	✓	-	✓	✓	✓	✓	-	-	✓	✓	6 (8)	VLA, EAVN, VLBA+GBT, JWST (MIRI/Nircam), NuSTAR, Chandra, XMM, INTEGRAL, HESS.
		April 8	214, 228	✓	✓	✓	✓	-	✓	✓	✓	-	✓	✓	7 (9)	
		April 9	337, 349	✓	✓	-	✓	✓	✓	✓	-	-	-	-	4 (6)	

Table 2. Summary of existing EHT observations of M87* (top) and Sgr A* (bottom) from 2017 – 2024, with participating observatories noted with a ✓ (✓ indicates that participation was severely limited by weather or technical difficulties). Observations of M87* and Sgr A* have primarily been conducted in the 230 GHz band with one observation for each source at 345 GHz. Sites joining these 345 GHz observations are marked with a ✓; the SMT for 2021 M87* observations is denoted using a faint marker because it only joined for one partial and one full scan because of bad weather. The "Sites" column lists the total number of geographic locations, with the total number of participating telescopes in parenthesis. The EHT operations and analysis process are discussed in Section 4. KVN Yonsei observations with the EHT at 230 GHz were performed on a best-efforts basis for the first time in 2024.

APPENDIX

A. EHT OBSERVING CAMPAIGN DATA SUMMARY

In this appendix, we summarize the existing EHT observations (Table 2) and describe the data handling process and associated timelines. The table details all observations of M87* and Sgr A*, including the antennas involved, the MWL resources used as part of the campaign, and the release date of basic data products.

The EHT operations and science utilization typically span a multi-year cycle, from the identification of the year-specific science goals to the completion of science utilization and the announcement of results. Observations are proposed a year before the planned observing epoch. Assembling the full set of recorded data at the correlator sites takes nearly a year due to the limits on shipping from the South Pole station. Fringe-finding, production correlation, metadata collection, calibration, and data validation typically span an additional year. The duration of scientific analysis and paper writing is highly variable dependent on the complexity of the project, collaboration priorities, and available resources. Data issues can appear at this stage, requiring re-calibration and sometimes re-correlation. Data issues most commonly occur as the result of the introduction of new stations or new instrumental capabilities into the array.

Raw visibility data and associated metadata are posted to the ALMA data archive 1 year after they have passed internal validation. Calibrated visibility data and accompanying analysis routines are posted to the Cyverse archive at the time of publication. All archival data are available on the EHT public website: https://eventhorizontelescope.org/for-astronomers/data.

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