Black Hole Physics on Horizon Scales

Thematic Areas:
Cosmology and Fundamental Physics, Formation and Evolution of Compact Objects, Galaxy Evolution, Multi-Messenger Astronomy and Astrophysics

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White Paper Description:
High-resolution imaging of supermassive black holes can test general relativity and elucidate processes of accretion/jet formation on scales of the event horizon. Enhancements achievable within the decade would provide high-fidelity, time-resolved observations of Sgr A*, M87, and other black holes, enabling breakthroughs in black hole astrophysics.
1 Introduction

It is generally accepted that accretion onto supermassive black holes powers active galactic nuclei (AGN), producing luminosity that can outshine the combined starlight from entire galaxies [36]. Relativistic jets produced by some of these central engines extend for tens of thousands of light years, often well beyond the extent of the host galaxy [7]. The accretion flows feeding these black holes are expected to become optically thin at millimeter wavelengths [6], allowing emission in this waveband to serve as a probe of physical processes, dynamics, and General Relativistic effects that hold near the event horizon.

High frequency very-long-baseline interferometry (VLBI) on Earth-sized baselines can resolve the immediate vicinity of nearby supermassive black hole event horizons. The detection of horizon-scale structure (defined here as the black hole photon orbit) in Sgr A* [16], the $\sim 4 \times 10^6 M_\odot$ black hole at the Galactic Center [25, 26, 28], confirmed that imaging a black hole was possible in principle. The Event Horizon Telescope (EHT) project formed at the outset of the Astro2010 review [18] to implement a program of development aimed at building a global 1.3 mm VLBI network to observe Sgr A* and M87, the much larger $\sim 3 - 6 \times 10^9 M_\odot$ black hole in the Virgo A galaxy [24, 45]. Over the ensuing decade, continued observations of both Sgr A* and M87 [16, 20, 17, 1, 33, 37], have made more detailed measurements of these sources through expansion to new VLBI sites and full polarimetric observations. In April 2017, the EHT made first observations with a full array capable of imaging (Figure 1), and data analysis is proceeding with the expectation that results will be released this year.

![Figure 1: A map of the EHT. Stations active in 2017 and 2018 are shown with connecting lines and labeled in yellow, sites in commission are labeled in red, and legacy sites are labeled in gray. Nearly-redundant baselines are overlaying each other, i.e. to ALMA/APEX and SMA/JCMT.](image)

For the purposes of this white paper, we will assume that such horizon-scale imaging is
possible and describe what might be achieved scientifically over the coming decade with anticipated enhancement of the EHT capabilities. Higher resolution (e.g., through space-VLBI or expansion to 0.87 mm wavelength), higher sensitivity through larger recorded bandwidth, and addition of new VLBI sites leading to faster accumulation of Fourier spacings will bring new science possibilities into range. Real-time movies of accretion and jet launching may become possible [32, 8], linking physics processes near the black hole with relativistic outflows, and new tests of General Relativity that focus on matter orbits rather than light bending can be made.

2 Testing GR

Detecting a black hole shadow in M87 or Sgr A* [4, 38, 19, 44, 10] would demonstrate that the central massive objects in these galaxies lie within their photon orbits—a mere 1.5 times the event horizon radius for a non-spinning black hole—providing strong evidence for an event horizon [11, 13]. For Sgr A*, the mass-to-distance ratio is accurately measured from stellar orbits [25, 26, 27], predicting a shadow diameter of 48-52 µas depending upon the spin and inclination of the black hole. Thus, measuring the shadow shape and diameter provides a null hypothesis test of GR [43]. The combination of temporally and spatially resolved movies of black holes, possible in principle for both Sgr A* and M87 [e.g., 32, 8, 42], will enable tracking of luminous matter orbits (Figure 3). These orbits can be used to map the black hole spacetime, leading directly to estimation of black hole spin and tests of the “no hair” theorem [31, 30, 29, 12].
3 Jet Formation

M87 harbors a radio jet that originates near the central black hole and extends for thousands of light years [34, 41]. While the current EHT capability is matched to imaging the bright emission in the photon ring near the black hole in M87, it lacks a dense network of short baselines that would be sensitive to extended emission from the jet on scales \( \gtrsim 100 \mu\text{as} \). Consequently, images produced using the current EHT are unlikely to be sufficient to reveal how the black hole launches and powers the jet close to the event horizon.

Figure 4 shows reconstructions of a 3D general relativistic magnetohydrodynamic (GRMHD) simulation of the M87 accretion flow and jet [14]. The EHT 2017 array is in principle capable of providing access to bright horizon-scale features such as the black hole shadow, but it cannot link these to the jet structure or dynamics in the launching region due to insufficient dynamic range. The addition of short baselines anchored to existing large apertures, combined with observations at \( \lambda = 0.87 \text{mm} \) (Figure 2), will improve the imaging dynamic range by an order of magnitude, and should reveal extended emission from the jet base. These images of the black hole and jet will enable detailed study of how black holes throughout the universe launch and power their relativistic jets. Further extending the EHT into space would provide the increased angular resolution necessary to image the narrow filamentary structures near the shadow [22, 35]. Multi-frequency space-VLBI including longer wavelengths would also open up spectral index and rotation measure studies and may help distinguish achromatic lensing effects from intrinsic plasma physics.
4 Black Hole Accretion

Black hole accretion almost certainly powers the brightest objects in the universe, from quasars to $\gamma$-ray bursts. But black hole accretion flows are still poorly constrained [5, 46], and observations have not yet been able to image the innermost accretion structure. EHT observations can resolve the instabilities that drive disk turbulence [2, 3], with particularly rich time-domain information from Sgr A*, whose innermost stable circular orbit (ISCO) period is between 4 and 30 minutes, depending on the black hole spin [15, 21, 23, 40].

The expanded coverage of future EHT arrays would enable movie reconstructions of Sgr A* over individual observing epochs. Moreover, in addition to monitoring accretion dynamics, studies can be made of the evolution of Sgr A* flares, which occur approximately daily at all wavelengths from radio to x-rays [39, 47]. Recently, the near-infrared interferometer GRAVITY has provided tantalizing evidence for orbits of ‘hot-spots’ in the accretion flow of Sgr A* [27]. Figure 3 shows individual frames of a movie reconstructed from simulated data of such an orbiting hot spot.

5 Resolving Other Supermassive Black Holes

The two prime targets of the EHT, Sgr A* and M87, are the only known black hole sources for which terrestrial VLBI at $\sim 1$ mm can resolve the shadow and horizon-scale structure around the black hole. These two sources have significant differences in black hole mass, accretion and jet power, and host galaxy type. Nearby low-luminosity AGN could fill these gaps with improvements in angular resolution.
Figure 5: (Left panel) Typical 230 GHz flux density versus predicted black hole shadow diameter for a number of current and potential future EHT targets; the size of each point scales with the estimated SMBH mass. The primary science targets, Sgr A* and M87, are plotted in green. Nominal resolutions for a variety of possible EHT array configurations are indicated using vertical lines. (Right panel) Simulated image reconstruction of the M104 black hole shadow with satellites in MEO and GEO orbits [22]. The yellow line indicates a typical ground-array resolution ($\sim 20\ \mu$as), while the white ellipse shows the resolution of an array with MEO/GEO satellites. Improvement in angular resolution with space-borne elements would resolve horizon-scale structures in nearby radio-loud LLAGN.

Adding satellites in medium or geosynchronous Earth orbits (MEO and GEO, respectively) would significantly expand the range of sources that can be probed at horizon-scale resolution [22]. As shown in Figure 5, the black hole shadow may be resolved in nearby radio-loud sources such as the Sombrero Galaxy (M104, NGC4594), IC1459 and M84 (NGC4374), which would fill the significant gap between Sgr A* and M87. Horizon-scale observations of these new sources will provide further unique clues to understand the nature of the black hole accretion and jet genesis. For instance, it is unknown whether the stark difference in jet power is due to differences in the black hole spin, the accretion rate, or other properties of the accretion flow.

6 Summary

Over the coming year, the first EHT results will clarify the state of the art in black hole imaging on horizon scales, bringing into focus the full science potential of this new field. Expected enhancements to the EHT would enable time-resolved videos of black hole jet launching and accretion, with potential significant expansion of black hole physics in Sgr A*, M87 and other sources that require high angular resolution.
References


