

The Galactic Center with Kilometer-Baseline Interferometry

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The irresistible power of angular resolution

The Galactic Center (GC) is one of the most famous success stories of high angular resolution astronomy [1]. Near-infrared (NIR) observations of individual stellar orbits have established beyond reasonable doubt that the radio source Sgr A* is a massive black hole (MBH) of $4.3 \times 10^6 M_{\odot}$ [2,3]. The angular size of orbits with a period of a decade is around 200 mas , setting thus the scale for the spatial resolution needed to monitor the motions. Spectrally, the observing window is rather narrow: At wavelengths $< 1 \mu\text{m}$ the interstellar extinction blocks the light [4]; at wavelengths $> 20 \mu\text{m}$ Earth's atmosphere becomes intransparent. Much shorter wavelengths (such as in the X-ray regime) or much longer wavelengths (as in the radio band) do allow observing the GC, but stars will remain invisible, as the surface temperatures of $\approx 10000\text{K}$ do not lead to emission in these bands. The best compromise are the NIR H- and K-bands around $1.5 \mu\text{m}$ and $2.2 \mu\text{m}$ respectively (Figure 1 left).

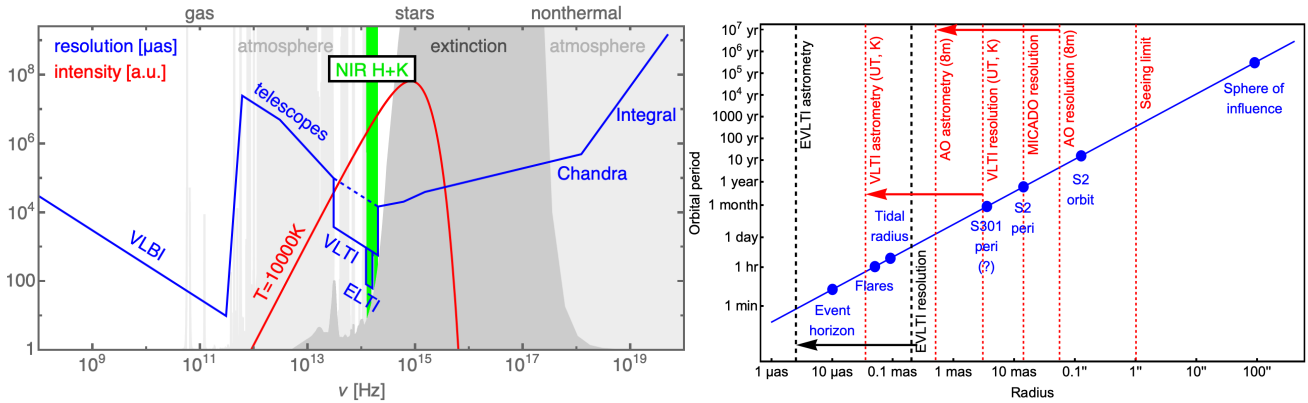


Figure 1: Left: Resolution as a function of observing frequency for the electromagnetic spectrum (blue line). The atmospheric extinction is shown in light gray, the extinction screen towards the GC in dark gray. The red curve shows the black-body emission of a $T = 10000\text{K}$ source. The green band marks the NIR bands around $1 - 2 \mu\text{m}$. Right: Size scales and corresponding orbital periods for the Galactic Center and some prominent objects. The resolution and astrometric accuracies of adaptive optics observations, MICADO, VLT and KBI (“EVLTI”) are marked by vertical lines.

For $\lambda = 2 \mu\text{m}$, and using the 8m aperture available at ESO's VLT, the diffraction limit is 63mas . Achieving this in practice requires using adaptive optics (AO), as the natural seeing limitation in the NIR at a good site is typically a factor 10 worse. Note that the diffraction limit is similar to the size scale for the orbits. Yet, bright, unconfused sources can be localized much better than the resolution limit, and a factor 100 has been achieved (corresponding to 0.5mas , [5]) in the GC, where the main limitation is source confusion.

The NIR band is also preferable for technical reasons: Modern AO systems regularly reach a Strehl ratio of 90% in this regime [6]. Further, in the few- μm regime, one can combine the light interferometrically between different telescopes. This overcomes the diffraction limit of individual telescopes and offers an intrinsic resolution of $\lambda/2B$, where B is the maximum baseline. For the VLTI with UTs this evaluates to 3.4mas . The price to pay for this high resolution is (besides the technical challenges) the comparably lower throughput and the complex optical transfer function. Of the current VLTI instruments GRAVITY is ideally suited for observing the GC. The data since 2017 have delivered many exciting discoveries, such as the gravitational redshift induced by Sgr A* onto stellar light [7], and the relativistic pericenter precession [8]. A detection of a gravitational lensing event should be feasible by 2027, concluding the series of classical tests of general relativity.

The combination of GRAVITY and future MICADO spectroscopy will enable measuring of the spin of Sgr A*. This requires detecting stars that come even closer to the MBH at their pericenter passages than the AO based sample. One first such star already has been found, and following its motion over roughly a decade will yield the spin of Sgr A*. Note that the ELT cannot compete in spatial resolution with the VLTI, but due to its large mirror will contribute via its sensitivity to spectroscopic Doppler shifts.

Looking ahead even further, it is an obvious question, what continuing the avenue of improving the angular resolution will yield for the GC. Going to km-baseline interferometry (KBI) will enable a large number of exciting and fundamental questions. The ultimate resolution an interferometer for faint sources can deliver is given by the condition that the stars needed for fringe-tracking be unresolved. This limits B to $< 20 \text{ km}$. For $B = 2\text{km}$ the angular resolution will be around 0.2mas – only a factor 10 worse than global radio-VLBI. $B = 20\text{km}$ might eventually bring NIR interferometry to the $20 \mu\text{as}$ level. Assuming the factor 100 between resolution and astrometric accuracy, we expect even for $B = 2\text{km}$ to be able to measure stellar positions down to $2 \mu\text{as}$. An overview of the angular size scales in the GC is given in Figure 1, right.

Resolving Sgr A* - live views of the accretion flow and understanding its physics

The event horizon of Sgr A* measures $10\mu\text{as}$, which implies a diameter of the innermost stable circular orbit (ISCO) of $60\mu\text{as}$. The innermost structures around Sgr A* therefore are only slightly smaller than the KBI resolution. Imaging thus might not be quite feasible, yet modeling the complex visibilities will reveal the source structure. Figure 2 shows a set of simulations what to expect for Sgr A*. The first row shows the smallest possible source size – a thin ring with an inner diameter of $d_i = 50\mu\text{as}$ and an outer diameter of $d_o = 55\mu\text{as}$. This model shows a clear decrease of the visibility amplitude at the larger spatial frequencies, indicating that Sgr A* is marginally resolved in this observation. The closure phases are 0 because this model is symmetric. In an optimistic ring model with $d_i = 60\mu\text{as}$ and $d_o = 200\mu\text{as}$ the structures are truly resolved, as the first null is covered by the array (row 2). One is not restricted to look at simple source models like rings, but instead also use a GRMHD simulation of Sgr A*'s accretion disk [9], which again is resolved (row 3). Finally, if there is in addition to the ring a hot spot, the asymmetry leads to non-zero closure phases and temporally varying amplitudes. The motion of the hot spot will be traceable by these variations, easily distinguishing for example a circular orbit from a radially outward motion (which could occur for example along a putative jet axis). KBI thus will be able to resolve the dynamics of the gas swirling around Sgr A*, a regime that is fully dominated by general relativity. The orbital time scale at Sgr A*'s ISCO is around an hour, making NIR observations of such flaring events well suited to study the event-horizon-scale dynamics.

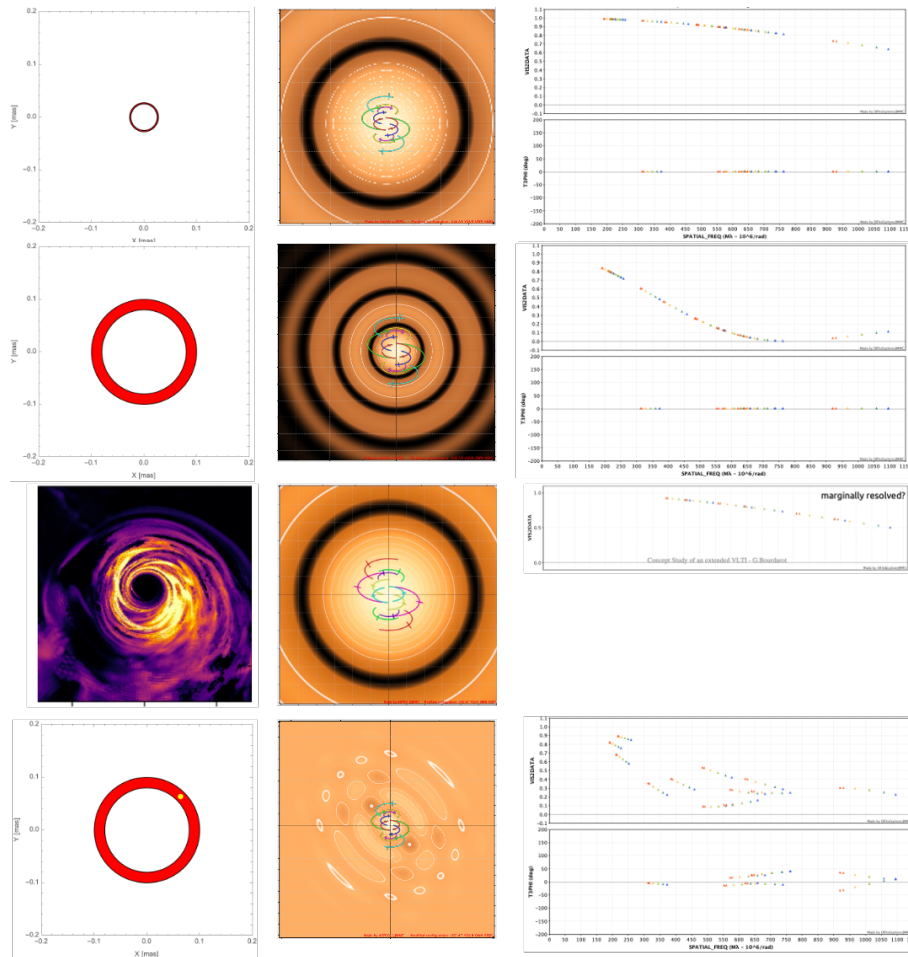


Figure 2: Simulated KBI observations of Sgr A*. The left panels show the model, the middle ones the Fourier transform, and the right ones the interferometrically observable amplitudes and closure phases. For a description of the different models in each row, see the main text.

There are many fundamentally interesting questions that are addressed with that:

- Does the orbital plane of the flares match the orientation of the black hole spin? Or do they align with the clockwise rotating disk of massive stars at radii around $10^5 R_S$, from where the accreting gas ultimately originates? To what extent does the Bardeen-Petterson effect [10] happen in Sgr A*?
- Do the observed flare orbits show the expected signatures of strong gravitational lensing? Sgr A* is truly unique in this respect and the only source in the Universe allowing such tests.

- What is the distribution of flare radii? If they map out the accretion disk, we have a quantitative handle on the accretion flow density structure at the event horizon.
- It is known that energetically flares are significant events for the accretion flow [11], and hence they should have an impact on the morphology of the accretion flow that KBI should be able to detect.
- We should be able to distinguish single hot-spot flares from more extended or multiply peaked emission regions – allowing to filter for those events that astrometrically would give a clean probe.
- The energy source for flares is still open – are they magnetically powered, or are they due to shock-heating? The flaring regions themselves might be resolved with KBI, allowing then for an energy check, namely whether the energy in the flare matches what was lost from the accretion flow’s overall magnetic field. The latter quantity is observed by 22GHz or 44GHz radio measurements.
- Sgr A* flares are highly linearly polarized [12]. A KBI with polarimetric capabilities should thus be able to see the differences in propagation for the two polarization states, probing in yet another way the space-time around Sgr A*.

Ultra-precise stellar orbits and the no-hair theorem

The stellar orbits can be modelled via the post-Newtonian equations of motion. AO data was sensitive to the “OPN”, Newtonian term. Current VLTI did detect the 1PN term, and future GRAVITY@VLTI and MICADO@ELT most likely will be able to determine the spin-sensitive 1.5PN term. Another step more challenging to detect are the 2PN terms, among them the quadrupole term due to the ellipticity of the black hole. An extremely valuable test of general relativity would be to compare the spin and the quadrupole contributions. They are uniquely coupled in general relativity, a consequence of the no-hair conjecture [13]. For being able to execute this no-hair test, one needs either radial velocity data of suitable stars with an accuracy in the 100m/s regime, below the design specification of MICADO@ELT. The other path is via ultraprecise astrometry such as the KBI would provide.

Resolving stars – solving the puzzling presence of stars so close to the black hole

With KBI, many of the current test particles – stars – in the GC will become a topic of research by its own.

- At the resolution of KBI, all late-type stars will be resolved, which would open up the unique GC region to classical stellar astrophysics as the VLTI currently provides in the solar neighborhood.
- All binary or multiple stars will be resolved into the individual components. The semi-major axis of binaries is constrained by demanding stability against tidal disruption from Sgr A*. The tidal radius is $r_t = a (M/M_{MBH})^{1/3}$ for a binary semi-major axis a . This means that for any star on a deep-dive orbit with a pericenter distance around 20mas, one has $a < 300\mu\text{as}$. Binary stars are thus necessarily unresolved for VLTI, but would be resolved with KBI. Multi-epoch astrometry could reveal binaries in a very telescope-time costly manner with the VLTI – or from snapshot imaging with KBI.

Binaries play a crucial role in the history of the GC stars. Most likely the stars observed today came to reside so close to Sgr A* one by one via the Hills mechanism, the tidal break-up of a binary during a close encounter [14, 15]. Finding a binary among the stars reaching close to Sgr A* would be extremely surprising, and would challenge our understanding how stars can be found so close to a MBH. KBI would thus probe a very fundamental process of stellar dynamics in a galactic nucleus, the same branch of theory that is relevant for extreme-mass-ratio in-spiral events as to be detected via the gravitational wave observatory LISA [15].

Strong gravity and boson stars

More speculative are the following two prospects: The photon ring around the MBH, a tell-tale sign for strong lensing, might lead to measurable signatures in the complex visibilities with KBI. And the only source model still being a contender for a black hole alternative, a boson star [16], might also be discernable with KBI. The key difference is that boson stars are transparent to light – and thus besides the general-relativistic multiple images of light emitters in the vicinity of the boson star an additional image would appear from light passing through the boson star.

References

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