The Milky Way’s Supermassive Black Hole: How good a case is it?
A Challenge for Astrophysics & Philosophy of Science

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Difference between stellar and Galactic black holes

Stellar black holes are formed through the collapse of a massive star: $M \approx 10$

Galactic black holes are formed in (together with) the central stellar cluster of massive galaxies: $M > 1,000,000$

Antenna-Galaxy NGC 4038/39

20 Mpc distance
$1^\prime = 140$ pc
We are actively involved in investigating SgrA* as a SMBH:

- Radio interferometric VLBI observations
- Infrared interferometric observations (GRAVITY)
- Multifrequency radio and infrared observations in parallel to the Event Horizon Telescope (EHT) observations

Providing SMBH relevant instrumentation, e.g.:

- Imaging beam combiner for the Large Binocular Telescope (LBT) in Arizona
- Very Large Telescope beam combiner spectrometer for the GRAVITY experiment
- Participation in the MIRI imaging spectrometer on board JWST
Working definition: What is a (supermassive) black hole?
A black hole is a geometrically defined region of spacetime around a compact mass. The gravitational field is so strong that nothing can escape from inside the event horizon.

The no-hair theorem states that a black hole is fully described by only three externally observable classical parameters: mass, electric charge, and angular momentum.

Here we suppress complications like rotation, black holes, and radiation that may come from immediate vicinity.
Working definition: What is a black hole?

They are characterized by an event horizon that, however, \textit{cannot} become part of an external observer’s past in a finite time but is an important discriminator against other similarly compact and massive objects.
Working definition: What is a black hole?

But is the event horizon really the most adequate concept for describing observations, as indicated, for example, by the name of the project “Event Horizon Project”?

When observing a black hole such as the SMBH in the Galactic Center now, we cannot know of any amount of matter that will fall into this black hole in the future and will lead to an increase of mass and, consequently, of an increase of the size of its event horizon.

We thus need alternative notions which are of a more local nature.
Working definition: What is a black hole?

Such notions are, in fact, used. The most important one for our case is the notion of an apparent horizon.

For its definition, one considers the boundary between the region where emitted light can reach infinity and the region where it cannot. This three-dimensional boundary is called “trapping horizon”
For stationary black holes of mass $M_\bullet$, the apparent horizon coincides with the (time slice of the) event horizon. In the simplest case of the Schwarzschild solution, the horizon size is given by the Schwarzschild radius

$$R_S := \frac{2GM_\bullet}{c^2};$$  \hspace{1cm} (1)

for the Kerr black hole, the horizon is located at

$$R_{Kerr} := \frac{GM_\bullet}{c^2} + \sqrt{\left(\frac{GM_\bullet}{c^2}\right)^2 - a^2}. \hspace{1cm} (2)$$

Quite generally,\(^{13}\) the apparent horizon lies within the event horizon or coincides with it.
Black Body Radiation – is only relevant for micro-black holes

\[ T_H = \frac{\hbar c^3}{8\pi k_B GM} \]

- \( \lesssim 6.2 \times 10^{-14} \text{ K} \left( \frac{10^6 M_\odot}{M} \right) \)
- \( \lesssim 6.2 \times 10^{-8} \text{ K} \left( \frac{1 M_\odot}{M} \right) \)
- \( \lesssim 1.2 \times 10^{11} \text{ K} \left( \frac{10^{15} g}{M} \right) \)
- \( \lesssim 7.7 \times 10^{29} \text{ K} \left( \frac{1 \text{ TeV}}{M} \right) \)
How can we ‘proof‘ the existence of supermassive black holes?
Philosophical Concepts
Underdetermination has a theoretical and an experimental side: The theory may not be fully complete and only highlight certain properties. In addition, the observations may be not unique enough to clearly distinguish one possible realization of an object from another, since the interpretation of the observations may just be based on a restricted set of theoretical predictions. In the case of experiments (see e.g. Franklin, 2016; Galison, 1987), however, one has the chance to fight (i.e. minimize or even remove the effect of) underdetermination by increasing the observational evidence and combining various procedures that approach the problem with different methods or instrumental efforts.

If underdetermination can be fought or even partially overcome, then causation may be used to further underline the realism or existence of an entity in a generally acceptable way. This involves the usage of a causal criterion that may be in the form of the Eleatic Principle (for a general overview see e.g. Colyvan, 1998, 2001). (Colyvan, 1998) gives a concise definition of the classical Eleatic Principle ”An entity is to be counted as real if and only if it is capable of participating in causal processes”.
Philosophical conceptual aspect:
The School of Elea rejects any epistemological criteria based on sensual experiences. Instead they request logical standards of clarity as criteria of truth.

This is how it is implemented: The Eleatic Principle or causal criterion is a test that must be passed by logical statements or objects in order to be accepted by the researchers ontology, i.e. the study of the nature of being, becoming, existence, or reality.
A further candidate procedure for sufficient evidence:

’if you can spray them, then they are real’ (Hacking 1983):

If you can use entities to manipulate others, then we have sufficient evidence for their reality.

To be used as an instrument in a manipulation of other systems presupposes a quantitative precise causal profile in order to bring about the effects in question.

If the effect is successfully brought about we have sufficient evidence for the claim that there is something with this particular profile.

Historic example for such a test

Acceptance of the existence of molecules and atoms
Realism:
Direct interaction and the possibility of repeatability and manipulation.

Anti-Realism:
The ‘pure’ observational nature of astrophysical research.

(Hacking 1983)
The Eleatic Principle

Colyvan’s rounded out version of the Eleatic Principle

- for reasons of symmetry and theoretic virtue
- allowing for entities that are **causally idle but causally relevant**
- hence, including the Eleatic Principle relying mainly on causal entities and balancing the unsatisfactory justification attempts

Classical Eleatic Principle

as a logical test for causality that must be passed before acceptance within a scientific ontology.

The principle is mainly relying on **causally active** entities but leads to largely unsatisfactory justification attempts

Reality of mathematical sentences, physical laws etc.

Causation with objects in factual time sequence
Underdetermination and Causation

Fig. 1 Linkage between experiment and theory interpreted via the concept of realism and underdetermination finally allowing us to discuss the question of realism and existence in the framework of causation, making use of a form of the Eleatic Principle.

This structure must be filled for the Galactic Center

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Connecting Necessary and Sufficient Conditions

necessary conditions: \[ S \implies \forall \mu N_\mu \iff N_1 \land N_2 \land N_3 \land \ldots \land N_\mu \]

sufficient conditions: \[ K \implies \exists \nu S_\nu \iff S_1 \lor S_2 \lor S_3 \lor \ldots \lor S_\nu \]

necessary and sufficient conditions:

\[ K \implies \exists \nu S_\nu \iff \exists \nu \forall \mu(\nu)N_{\nu,\mu(\nu)} \]

\[ \exists \nu \forall \mu(\nu)N_{\nu,\mu(\nu)} \iff (N_{\kappa_1,1} \land \ldots \land N_{\kappa_1,\mu(1)})_1 \lor (N_{\kappa_2,1} \land \ldots \land N_{\kappa_2,\mu(1)})_2 \lor \ldots \lor (N_{\kappa_\nu,1} \land \ldots \land N_{\kappa_\nu,\mu(\nu)})_\nu \]
Connection necessary and sufficient conditions
Necessary Conditions for the presence of a Black Hole

| label | necessary condition |
|-------|---------------------|
| $N_1$ | Is object at nominal position of SgrA*? |
| $N_2$ | Is size of emitting region in SgrA* sufficiently small? |
| $N_3$ | Is mass of SgrA* in agreement with SMBH masses? |
| $N_4$ | Does the distance to SgrA* place it at the center of the Milky Way? |
| $N_5$ | Is the manipulative success for SgrA* similar to other SMBH candidates? |
| $N_6$ | Is a bright fast jet originating from SgrA*? |
| $N_7$ | Do we detect a merger ringing signal in gravitational waves from SgrA*? |
| $N_8$ | Do we detect an exceptionally bright flare from SgrA*? |
| $N_9$ | Do stars and pulsars close to SgrA* give indications for a SMBH? |
| $N_{10}$ | Is the spectrum of the surroundings of SgrA* what es expect from a SMBH? |
| $N_{11}$ | Do we detect a photon ring in SgrA* in addition to orbiting matter? |
| $N_{12}$ | Do VLBI images of SgrA* show a shadow as expected for a SMBH? |
| $N_{13}$ | Do we detect photo-center motion of SgrA* with NIR- and/or mm-radio-interferometry? |
| $N_{14}$ | Can we differentiate to SgrA* between jet components and hot-spot? |

Table 3 Table of possible necessary conditions that can be combined to result in a sufficient condition required to call SgrA* a SMBH. The necessary conditions have been formulated as logical entities for which we can attribute the locigal values “true” or “false” within the theoretical predictions for supermassive black holes in section 2.
Example 1

Proving that we indeed probe a relativistic regime:

Relativistic orbitis of stars

Parsa et al. 2017, ApJ 845, 22
First relativistic analysis using three stars orbiting SgrA*!

Relativistic distortion of orbits is used to parameterize a relativistic parameter which becomes an observable

Parsa et al. 2017, ApJ 845, 22
First time that the investigation of a resolved stellar orbit around an SMBH has been carried out in detail.
The result is consistent with the SMBH hypothesis.

For $\Delta \omega$ a 3-4 $\sigma$ result
Proving that we indeed probe a relativistic regime:

Fitting flare profiles with blobs moving close to the last stable orbit

Karssen et al. 2017, MNRAS 472, 4422
Polarized Light from SgrA* in the Infrared

Dovciak, Karas & Yaqoob 2004, ApJS 153, 205
Dovciak et al. 2006

S. Karssen, M. Valencia-S., M. Bursa, M. Dovciak, V. Karas, A. Eckart
Analysis of 4 bright X-ray flares

Fig. 1: Illustration of the origin of the double-peak structure in the total flux. The blobs marked with an ‘L’ are magnified by gravitational lensing, while they are behind the black hole from the observers point of view. That is, they are positioned on the focal line, as indicated by the dashed line. The blobs marked with a ‘D’ are Doppler-boosted, because they are moving ‘directly towards’ (in terms of geodesics) the observer, as indicated by the orange lines representing the geodesics from the source to the observer. The fraction of the orbit between these points varies with the radius of the orbit, owing to the stronger bending of the geodesics close to the black hole.
Analysis of 4 bright X-ray flares

(a) Illustrates the influence of the blob’s size on the shape of the light curve. The blobs of different sizes (5 \( r_g \) red long dashed, 4 \( r_g \) black light curve. The blobs are orbiting at different positions (6 \( r_g \) red long dash-dotted, 3 \( r_g \) magenta dotted, 2 \( r_g \) blue short dashed and 1 \( r_g \) solid dashed, 8 \( r_g \) black dash-dotted, 12 \( r_g \) magenta dotted, 16 \( r_g \) blue short purple line) are orbiting at a radial position of 12 \( r_g \) around a black hole dashed and 20 \( r_g \) solid purple line) and have a size of 2.5 \( r_g \) around a with spin 0.5, the viewing angle is 90° (edge on). The light curves are black hole with spin 0.5, the viewing angle is 90° (edge on). The light normalized to the maximum of the peak value of the light curve for curves are normalized to the maximum of the peak value of the light the blob with the size 5 \( r_g \) and shifted such that the dopple peak is at curve for the blob with the size 5 \( r_g \) and shifted such that the dopple peak is at the center.
Analysis of 4 bright X-ray flares

Karssen et al. 2017, MNRAS 472, 4422
Analysis of 4 bright X-ray flares

Fig. 2: Weighted histograms of the predicted masses for all the models for the four flares taken into account.
Application to a different extragalactic SMBH: J1034-396

Table 3. Mass estimates of the Seyfert I galaxy RE J1034+396 with different methods in a chronological order.

| Publication                  | Mass            | Method    |
|------------------------------|-----------------|-----------|
| Gierliński et al. (2008)     | $6.3 \times 10^5 \, M_\odot$ | H $\beta$ |
| Gierliński et al. (2008)     | $3.6 \times 10^7 \, M_\odot$ | [O$\text{III}$] |
| Gierliński et al. (2008)     | $(8 \times 10^6 - 9 \times 10^7) \, M_\odot$ | ISCO |
| Bian & Huang (2010)           | $(1-4) \times 10^6 \, M_\odot$ | $M - \sigma_*$ |
| Bian & Huang (2010)           | $(1-4) \times 10^6 \, M_\odot$ | H $\beta$ |
| Jin et al. (2012)             | $1.7 \times 10^6 \, M_\odot$ | H $\beta$ |
| This paper                   | $1.421 \times 10^6 \, M_\odot$ | hotspot |

Figure 8. Weighted histogram for the QPO of J1034-396 as published by Gierliński et al. (2008).

Figure 9. Best fit for the QPO of J1034-396 show for data of the folded light curve as published by Gierliński et al. (2008).
Example 3

Toward the Event Horizon
Search for the Shadow of the Black Hole

VLBI (EHT) and VLTI (GRAVITY) interferometry

Rauch et al. 2016, A&A 587, 37
Eckart et al. FoPh 47, 553
The shadow of the compact mass at the center of the Milky Way as expected for a **Black Hole (left)** and a **Boson star (right)**.

Goddi, C.; Falcke, H.; Kramer, M.; Rezzolla, L.; et al., 2017, IJMPD (International Journal of Modern Physics D), 2630001, BlackHoleCam: Fundamental physics of the galactic center

Vincent, F. H.; Meliani, Z.; et al., 2016, CQGra 33, 5015, Imaging a boson star at the Galactic center
Expected Photo-Center motion for SgrA*

Probably possible with GRAVITY at the VLTI

FIG. 10. Photocenter motion compared to a disk model. The example of a NIR photo-center motion as planned to be measured with the GRAVITY interferometer at the VLTI is taken from [256] and [257]. The simulation describes the apparent trajectory of flare events assuming material orbiting a non-rotation black hole at an inclination of 45° on the last stable orbit at a distance of \(3R_s\) from the center. Lensing (including multiple images), relativistic beaming and Doppler effect are included in the relative positioning of the resulting data points (red crosses) following the orbital track (white line; further details in [256]). The image [162] is assumed to represent a mm-VLBI data disk model that shows luminous material for radii beyond the last stable orbit. The dashed and straight white arrows indicate the directions perpendicular and along the radio structure that we refer to in the text.

Eckart et al. FoPh 47, 553 and references there in
VLBI at 230 GHz (1.3 mm wavelength)

Observed size:

43 (+14/-8) μas

deconvolved:

37 μas (3.7 Rs)

previous size limit: \( \leq (11 \pm 5) \text{Rs} \)

(Krichbaum et al. 1998)

Doeleman et al. *Nature* 455, 78-80 (2008)

image credit: S. Noble (Johns Hopkins), C. Gammie (University of Illinois)
Central component of 1.55 Jy
secondary component of 0.02 Jy
at 1.5 mas and 140 deg. E-N
with a 4 hout delay relativ to the
NIR flare

Rauch et al. 2016, A&A 587, 37

See also ‘Asyummertic structure in SgrA* …‘
Brinkerink et al. 2016, MNRAS 462, 1382
‘speckle transfer function‘
Example 4

Towards the Event Horizon using stars and pulsars

Psaltis D., Wex N., Kramer M., 2016, A Quantitative Test of the No-hair Theorem with Sgr A*; Using Stars, Pulsars, and the Event Horizon Telescope. ApJ 818, 121

Eckart et al. FoPh 47, 553
**Number of Stars within the Central 1000 AU of SgrA**

| $\gamma$ | $N_{stars}$ | $N_{msP}$ | $N_{nP}$ |
|----------|-------------|-----------|----------|
| 2.0      | 5000        | 5         | 0.5      |
| 1.2      | 67          | 0.67      | 0.067    |
| 1.0      | 24          | 0.24      | 0.024    |
| 2.0      | 6           | -         | -        |
| 1.2      | 0.08        | -         | -        |
| 1.0      | 0.03        | -         | -        |

**Eckart et al. FoPh 47, 553**

Approximate number of stars, millisecond pulsars $msP$, and normal pulsars $nP$ with distances to SgrA* of less than 1000 AU. This corresponds to a radius of 0.125” or 4.7 mpc.

Using a value of $M_*=10^6M_\odot$ for the central parsec we derive for different values of $\gamma$ the number of solar mass stars (second column in the top three rows) and stars with a $2\mu m$ wavelength brightness in the magnitude interval $K=18-19$ (second column in the bottom three rows). Using the estimate of 100 normal and 1000 millisecond pulsars within the central parsec [108, 116] we derived the corresponding values for the central 1000 AU in columns 3 and 4.
Synthesis:
Combining the Necessary Conditions to Sufficient Conditions
### Necessary Conditions for the presence of a Black Hole

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Philosophical Concepts laid out for the GC

Fig. 13 Linkage between experiment and theory interpreted via the concept of realism, underdetermination and a “rounded out” version of the Eleatic Principle, here shown with respect to the results of our investigation. For comparison see also Fig. 1 which we adopted here for the case of the Galactic Center SMBH.
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Fig. 13 Linkage between experiment and theory interpreted via the concept of realism, underdetermination and a “rounded out” version of the Elastic Principle, here shown with respect to the results of our investigation. For comparison see also Fig. 1 which we adopted here for the case of the Galactic Center SMBH.
Combining the observational facts using a causal criterion test may indeed lead to well supported confirmation that SgrA* at the center of the Milky Way can be identified with a super massive black hole.
Combining all results

Challenge for Astrophysics: How clean are the observational cases that may serve as logical entities for the causal criterion test.

Challenge for Philosophy: Are all necessary conditions for the proof of existence known and fulfilled? Is the result a sufficient condition for the existence? Are there individual sufficient conditions that can proof the existence and are they risky enough?
Philosophical Concepts laid out for the GC

Terrible reality:

The ‘easier‘ a key observation can be made the less meaningful and stringent it is. (Radio and infrared interferometry; shadow of the BH)

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The more meaningful and stringent key observations are the more difficult and rare they are. (Pulsar and stellar measurements; gravitational waves)

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A real prove dosen‘t seem to be possible, however, the acceptance of the idea can be maximized.
'Melancholia' by Albrecht Dürer
'Melancholia' by Albrecht Dürer

Are all necessary conditions for the proof of existence known and fulfilled? Is the result a sufficient condition for the existence?

Is there at least one or are there several sufficient conditions for the existence?
