# The Milky Way's Supermassive Black Hole: How good a case is it?

## A Challenge for Astrophysics & Philosophy of Science

SEVENTH FRAMEWORK PROGRAMME

Max-Planck-Institut für Radioastronomie

**Andreas Eckart**

*I.Physikalisches Institut der Universität zu Köln*

*Max-Planck-Institut für Radioastronomie, Bonn*

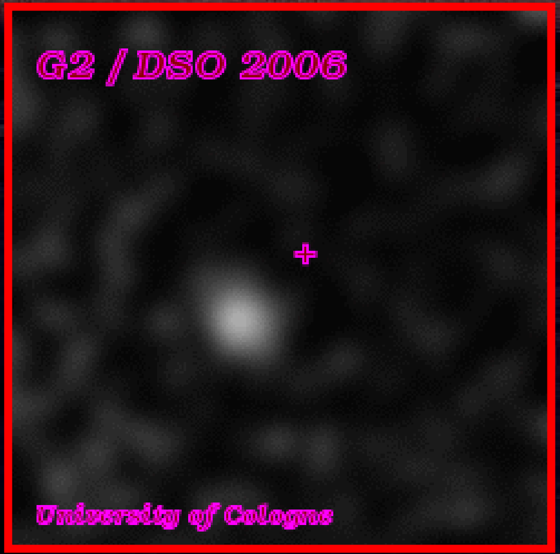
I. Physikalisches Institut Universität zu Köln

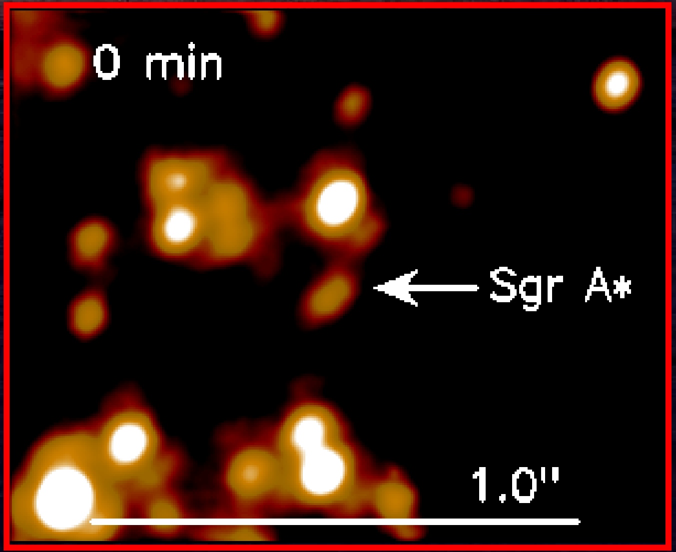
**2nd International Conference on**

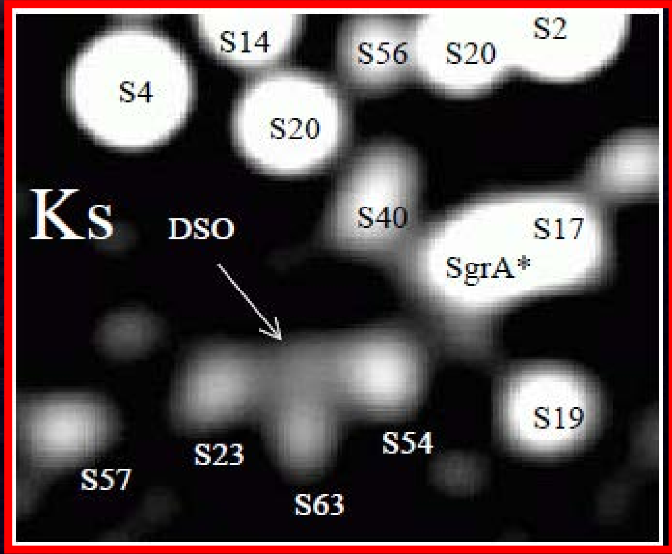
**ASTROPHYSICS and PARTICLE PHYSICS**

**November 13-15, 2017, San Antonio, Texas, USA**

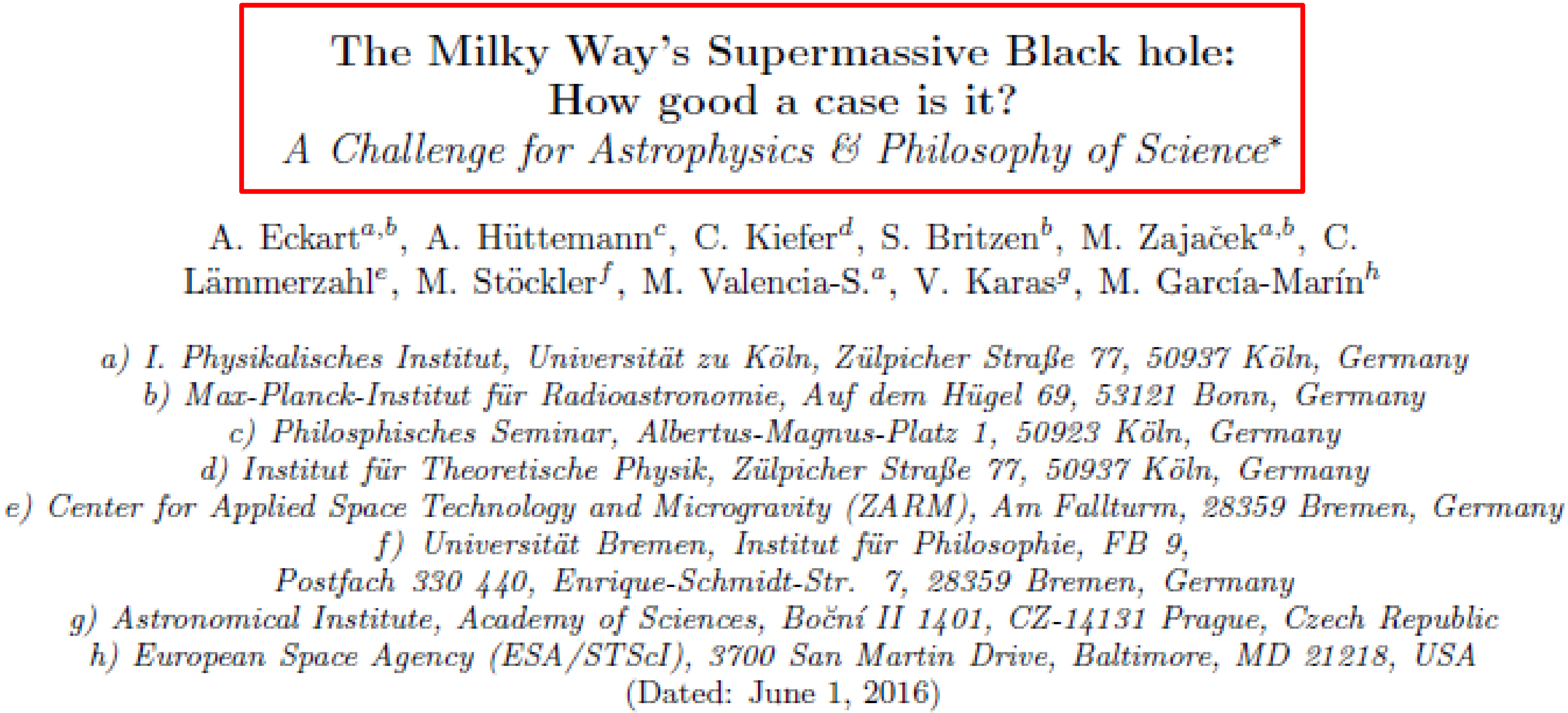
STRONGGRAVITY
EU FP7-SPACE research project 312789 2013 - 2017







# The Milky Way’s Supermassive Black Hole
# How good a case is it?



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

A. Eckart[a,b], A. Hüttemann[c], C. Kiefer[d], S. Britzen[b], M. Zajaček[a,b], C. Lämmerzahl[e], M. Stöckler[f], M. Valencia-S.[a], V. Karas[g], M. García-Marín[h]

*a) I. Physikalisches Institut, Universität zu Köln, Zülpicher Straße 77, 50937 Köln, Germany*
*b) Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany*
*c) Philosphisches Seminar, Albertus-Magnus-Platz 1, 50923 Köln, Germany*
*d) Institut für Theoretische Physik, Zülpicher Straße 77, 50937 Köln, Germany*
*e) Center for Applied Space Technology and Microgravity (ZARM), Am Fallturm, 28359 Bremen, Germany*
*f) Universität Bremen, Institut für Philosophie, FB 9,*
*Postfach 330 440, Enrique-Schmidt-Str. 7, 28359 Bremen, Germany*
*g) Astronomical Institute, Academy of Sciences, Boční II 1401, CZ-14131 Prague, Czech Republic*
*h) European Space Agency (ESA/STScI), 3700 San Martin Drive, Baltimore, MD 21218, USA*

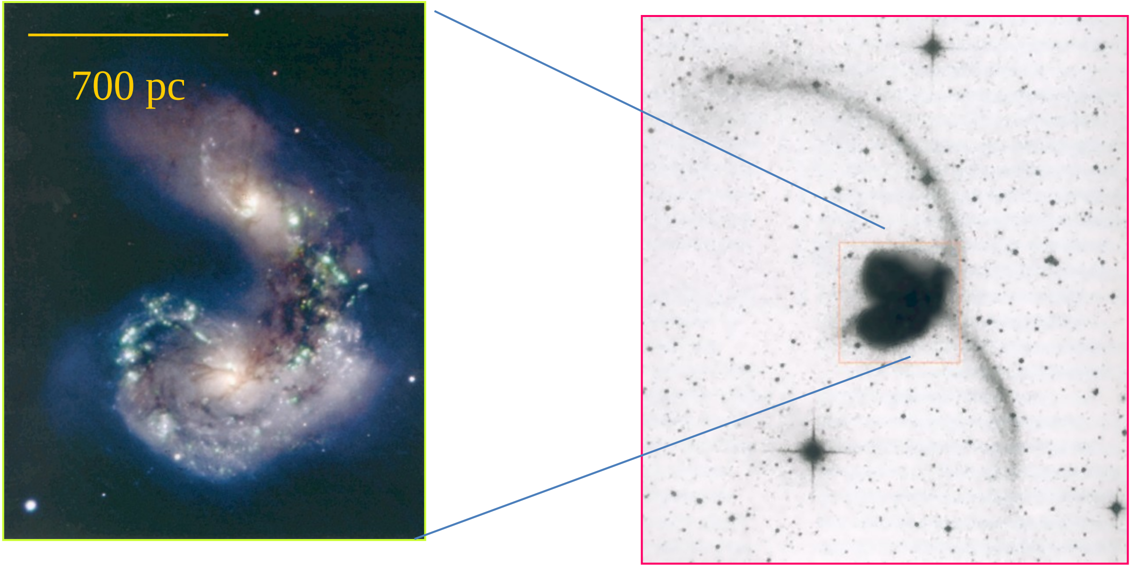
(Dated: June 1, 2016)

Foundations of Physics, 47, 553, Springer, 2017

# Difference between stellar and Galactic black holes

Stellar black holes are formed through the collapse of a massive star: M~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“ = 140 pc

# Investigating Supermassive Black Holes

We are actively involved in investigating SgrA* as a SMBH:

- Radio interferometric **VLB**I observations
- Infrared interferometric observations (**GRAVITY**)
- Multifrequency radio and infrared observations in parallel to the Event Horizon Telecope (**EHT**) observazions

Providing SMBH relevant instrumentation, e.g.:

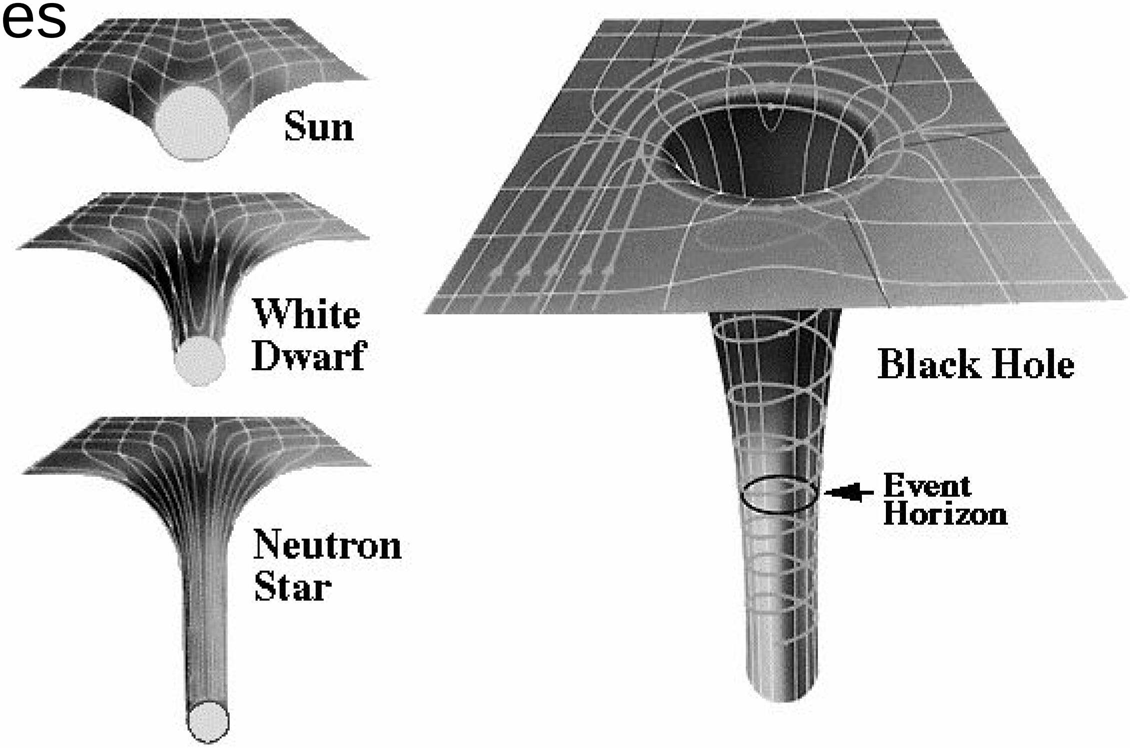
- Imaging beam combinor for the Large Binocular Telescope (**LBT**) in Arizona
- Very Large Telescope beam combiner spectrometer for the **GRAVITY** experiment
- Participation in the **MIRI** imaging spectrometer on board **JWST**

Working definition:
What is a
(supermassive)
black hole?

# Working definition: What is a black hole?

A black hole is a geometrically defined region of spacetime around a compact mass. The gravitational is so strong that nothing can escape from inside the event horizon.

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

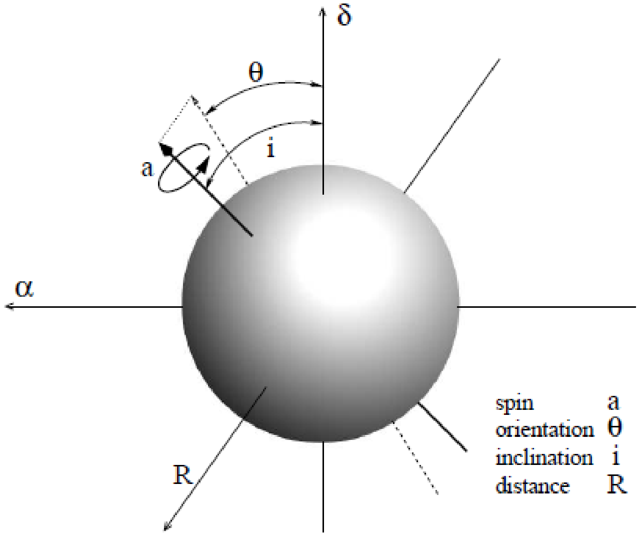


Here we suppress complications like rotation  Bleck Holes and radiation that may come from immediate vicinity

source: https://www.pinterest.com

# Working definition: What is a black hole?

They are characterized by an event horizon that, however, *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.

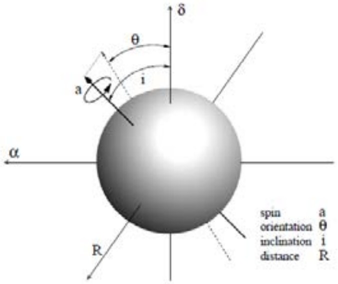


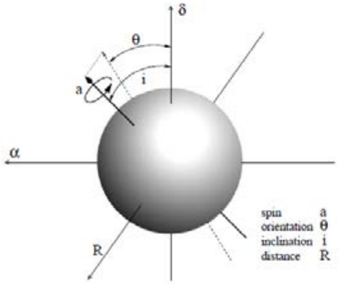
# Working definition: What is a black hole?

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.

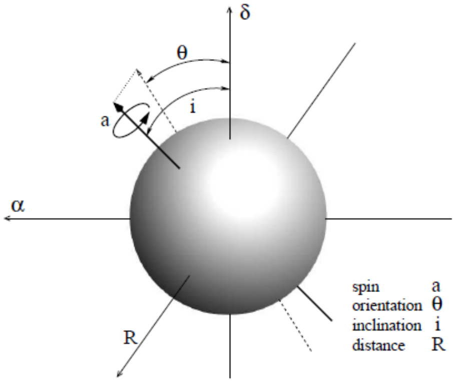




# Working definition: What is a black hole?

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”



# Working definition: What is a black hole?

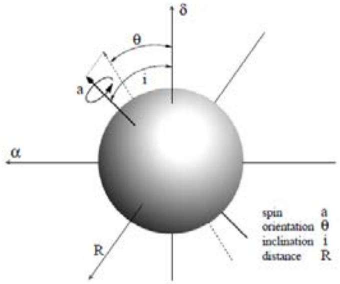
For stationary black holes of mass $M_\bullet$, the apparent horizon coincides with the (time slice of the) event horizon. In the simplest case of the Schwarzschild solution, the horizon size is given by the Schwarzschild radius

$$R_{\rm S} := \frac{2GM_\bullet}{c^2}; \tag{1}$$

for the Kerr black hole, the horizon is located at

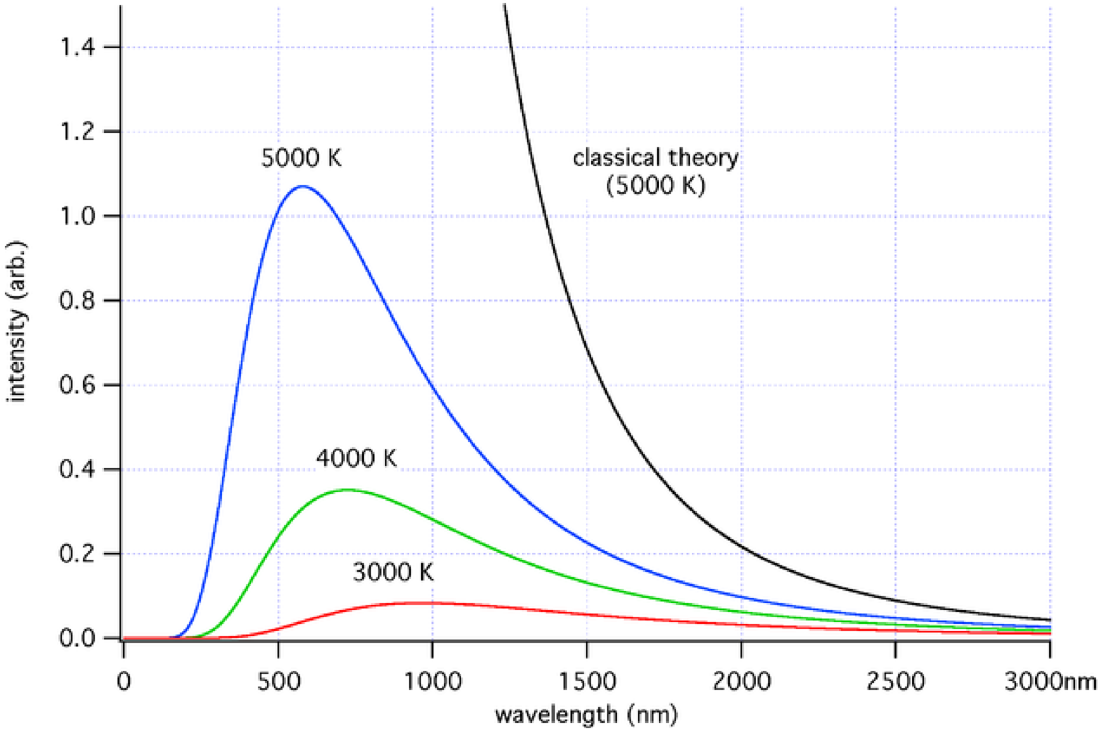
$$R_{\rm Kerr} := \frac{GM_\bullet}{c^2} + \sqrt{\left(\frac{GM_\bullet}{c^2}\right)^2 - a^2}. \tag{2}$$

Quite generally,[13] the apparent horizon lies *within* the event horizon or coincides with it.



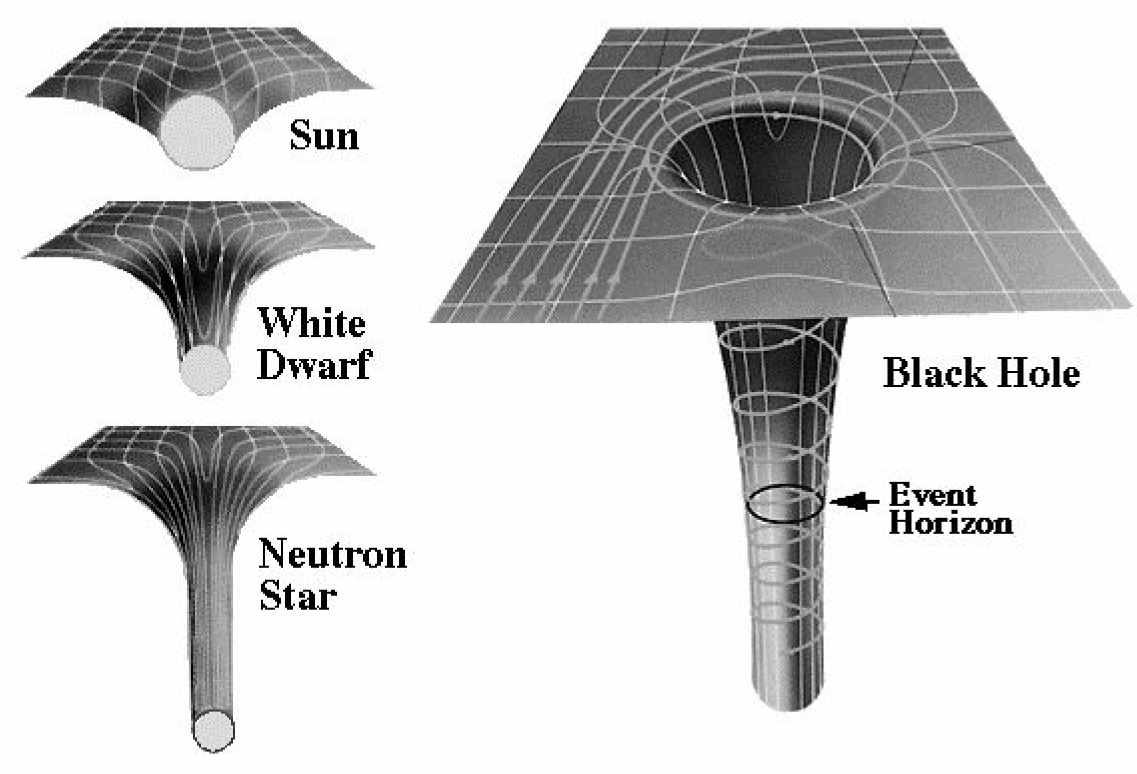
# Black Body Radiation – is only relevant for micro-black holes

$$\begin{aligned} T_H &= \frac{\hbar c^3}{8\pi k_B G M} \\ &\boxed{\simeq\ 6.2 \times 10^{-14}\ \mathrm{K} \left(\frac{10^6\,\mathrm{M}_\odot}{M}\right)} \\ &\simeq\ 6.2 \times 10^{-8}\ \mathrm{K} \left(\frac{1\,\mathrm{M}_\odot}{M}\right) \\ &\simeq\ 1.2 \times 10^{11}\ \mathrm{K} \left(\frac{10^{15}\,\mathrm{g}}{M}\right) \\ &\simeq\ 7.7 \times 10^{29}\ \mathrm{K} \left(\frac{1\ \mathrm{TeV}}{M}\right) \end{aligned}$$



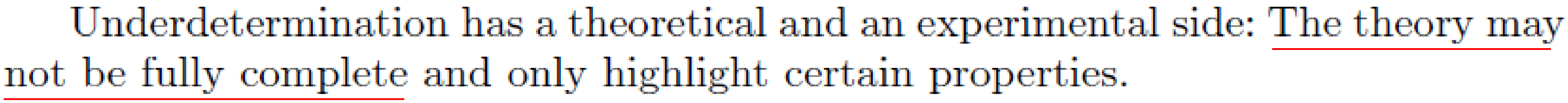
(Hawkingstrahlung)

# How can we ‘proof‘ the existance of supermassive black holes?

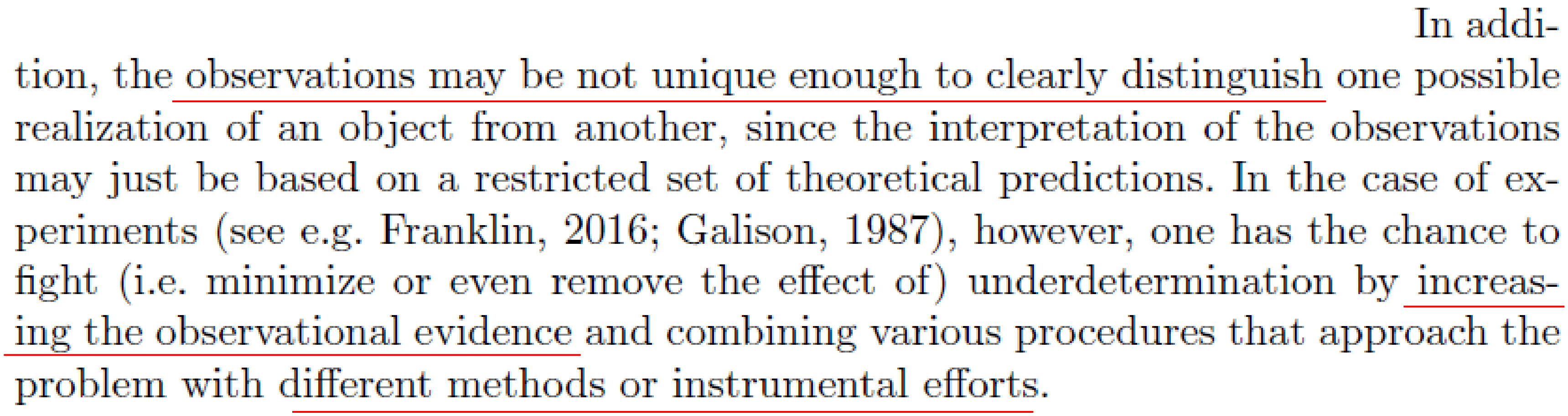


# Philosophical Concepts

# Underdetermination …..

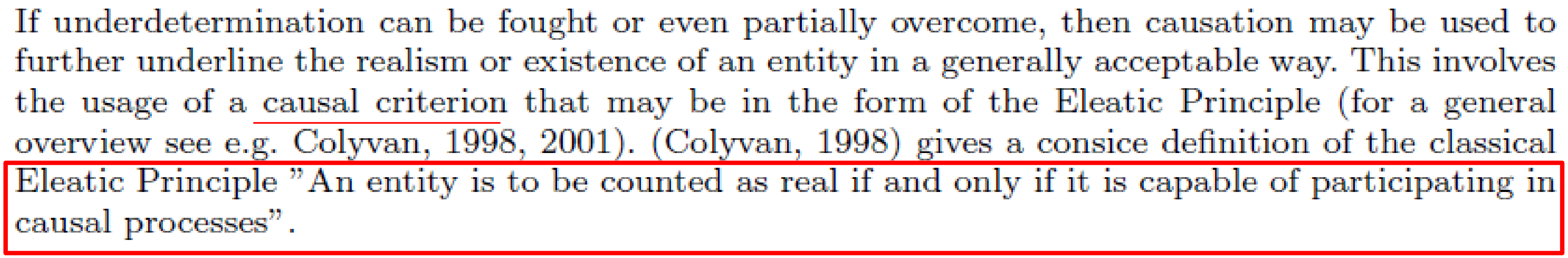


Underdetermination has a theoretical and an experimental side: The theory may not be fully complete and only highlight certain properties.



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.

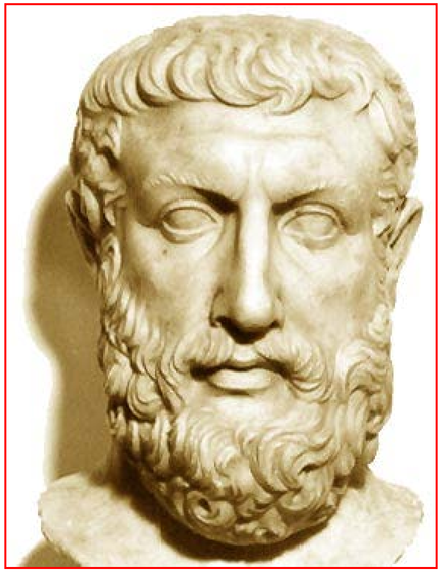
# ….. and Causation



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 consice 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".

# Eleatic Principle

Named after a Greek school in lower Italy Elea (Ἐλέα) closely linked to the philosophers Parmenides, Zeno and Xenophanes of Colophon.



Parmenides

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 <u>logical statements</u> or objects in order to <u>be accepted by the researchers ontology</u>, i.e. the study of the nature of being, becoming, existence, or reality.

source: internet

# Historic example for such a test

## Acceptance of the existance of molecules and atoms

Aa 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.

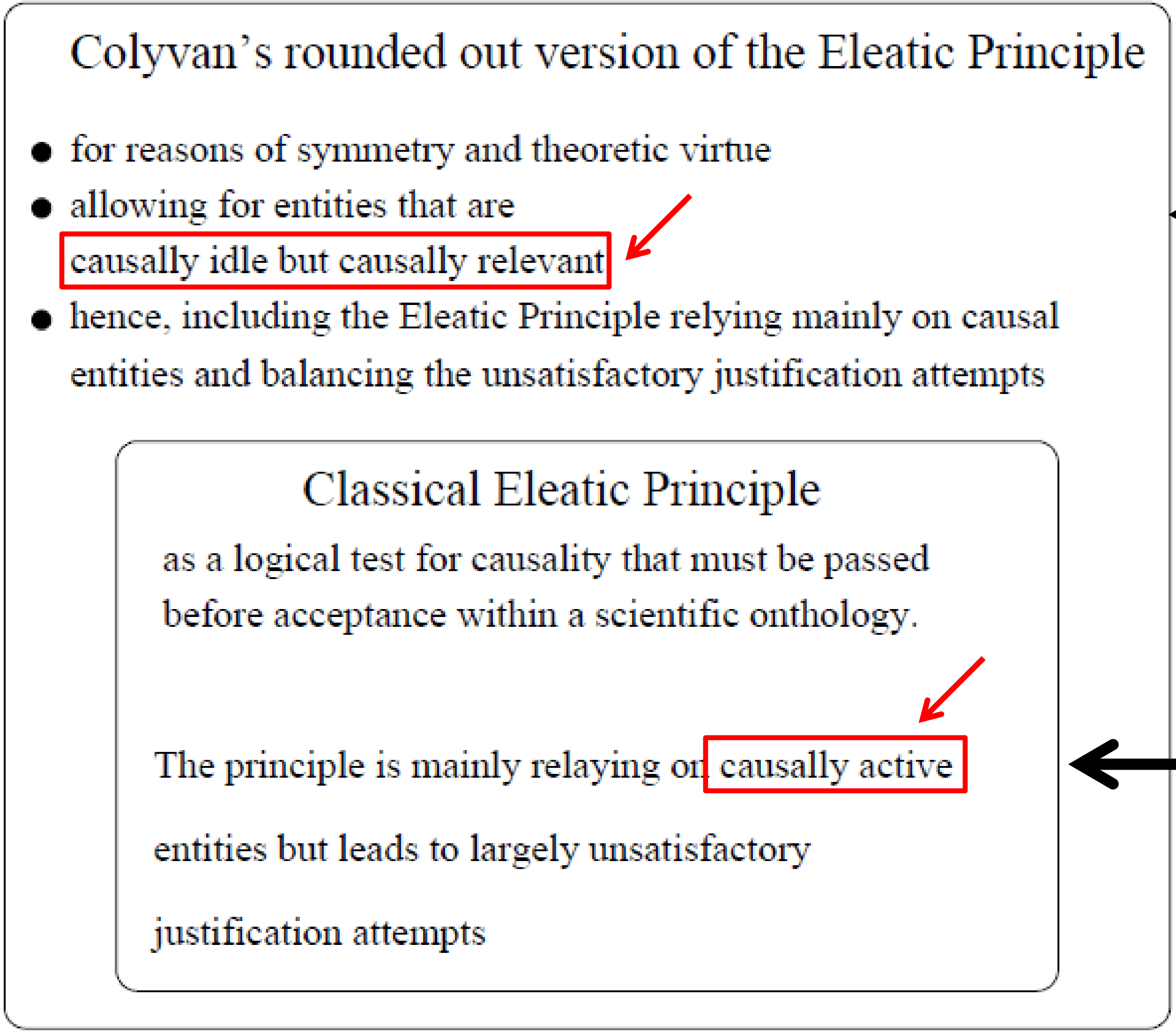
If the effect is successfully brought about we have sufficient evidence for the claim that there is something with this particular profile.

**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 onthology.

The principle is mainly relaying 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

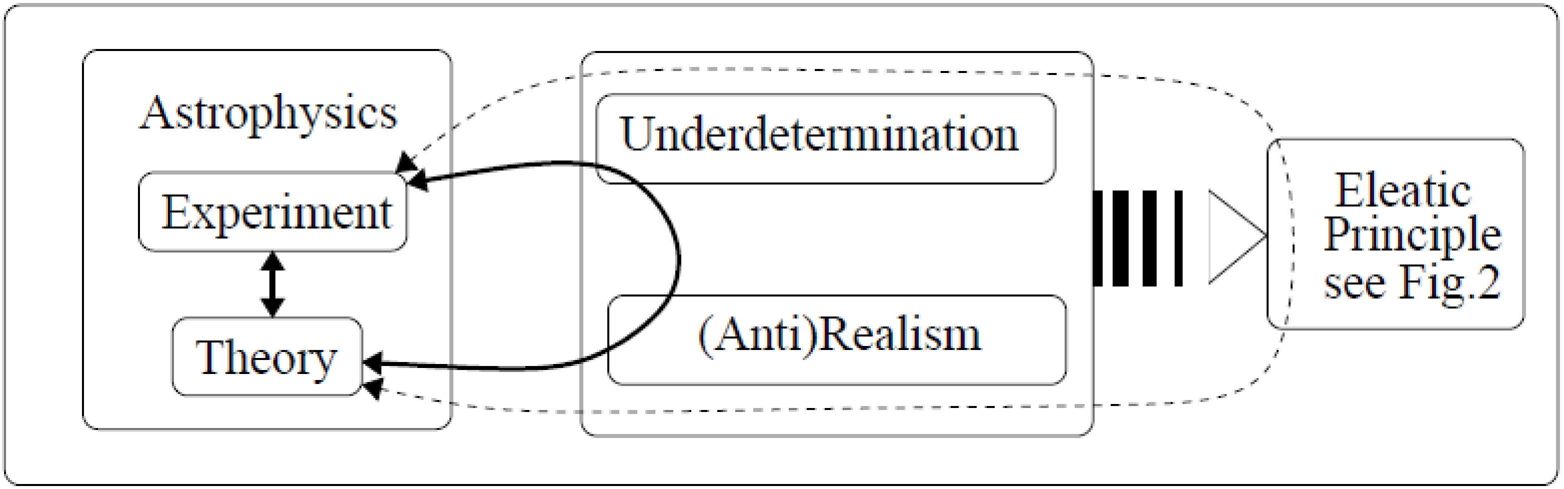


**Fig. 1** Linkage between experiment and theory interpreted via the concept of realism and underdetermination finally allowing us to discuss the question of realism and existence in the framework of causation, making use of a form of the Eleatic Principle.

This structure must be filled for the Galactic Center

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 consice 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".

# Connecting Necessary and Sufficient Conditions

necessary conditions: $S \Longrightarrow \forall \mu N_\mu \Longleftrightarrow N_1 \wedge N_2 \wedge N_3 \wedge \ldots \wedge N_\mu$

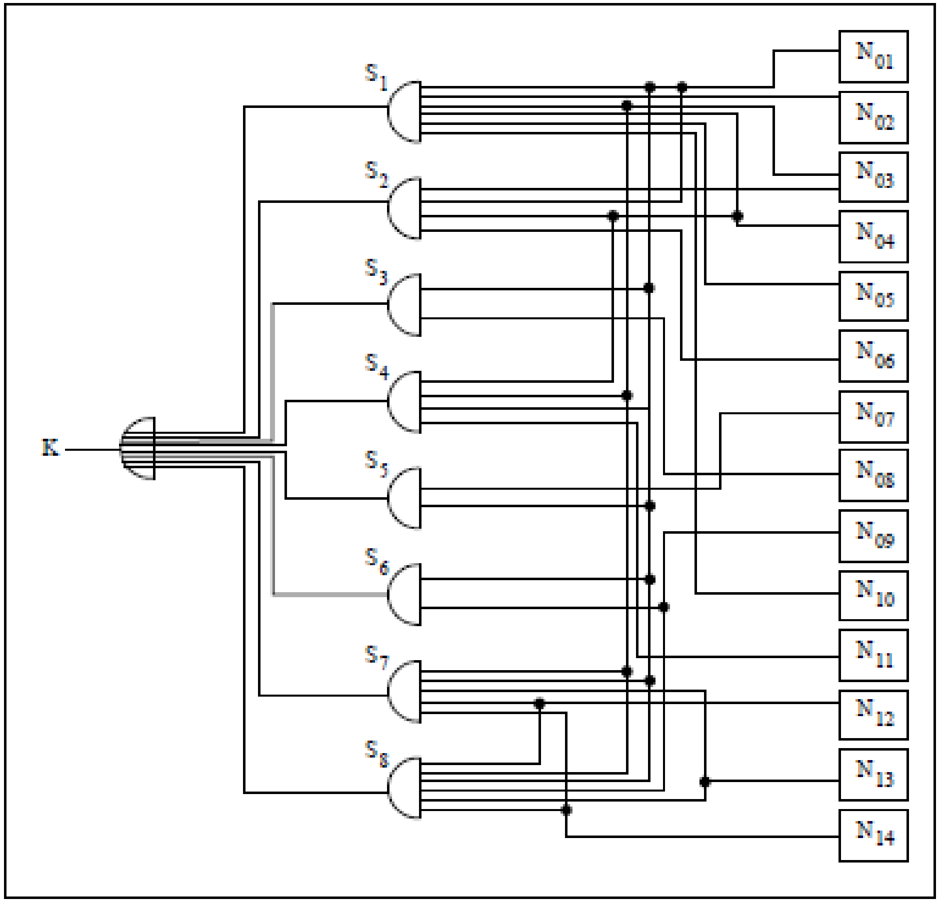
sufficient conditions: $K \Longrightarrow \exists \nu S_\nu \Longleftrightarrow S_1 \vee S_2 \vee S_3 \vee \ldots \vee S_\nu$

necessary and sufficient conditions:

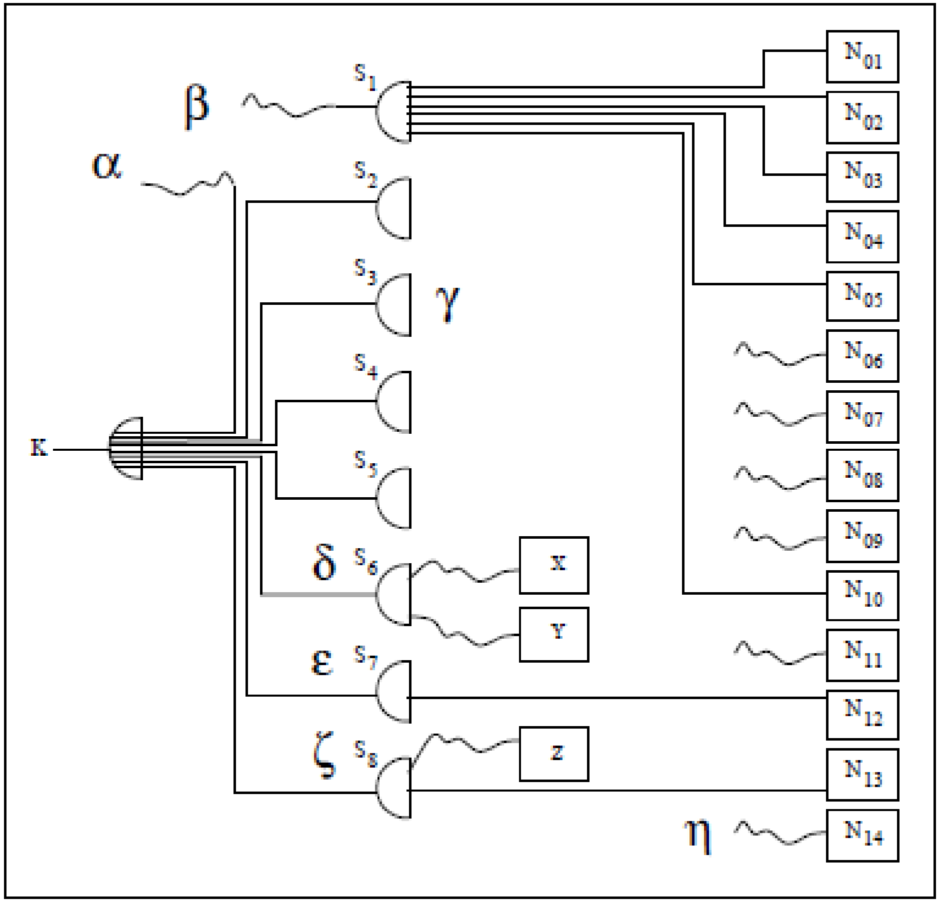
$$K \Longrightarrow \exists \nu S_\nu \Longleftrightarrow \exists \nu \forall \mu(\nu) N_{\nu,\mu(\nu)}$$

$$\begin{aligned}\exists \nu \forall \mu(\nu) N_{\nu,\mu(\nu)} \Longleftrightarrow\ & (N_{\kappa_{1,1}} \wedge \ldots \wedge N_{\kappa_{1,\mu(1)}})_1 \vee \\ & (N_{\kappa_{2,1}} \wedge \ldots \wedge N_{\kappa_{2,\mu(1)}})_2 \vee \ldots \\ & \vee (N_{\kappa_{\nu,1}} \wedge \ldots \wedge N_{\kappa_{\nu,\mu(\nu)}})_\nu\end{aligned}$$

# Connection necessary and sufficient conditions

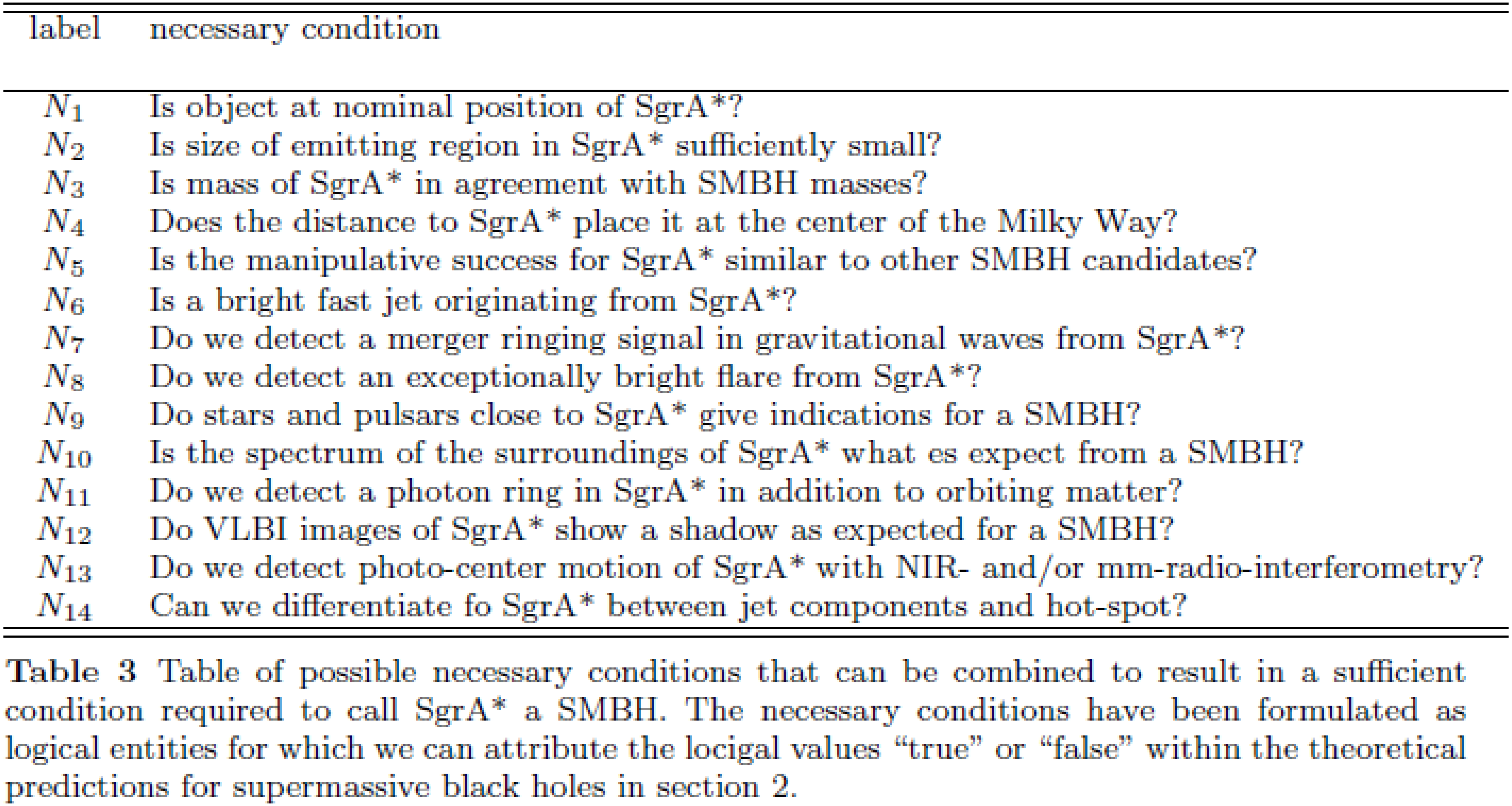


**Yes**



**No**

# 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 fo SgrA* between jet components and hot-spot? |

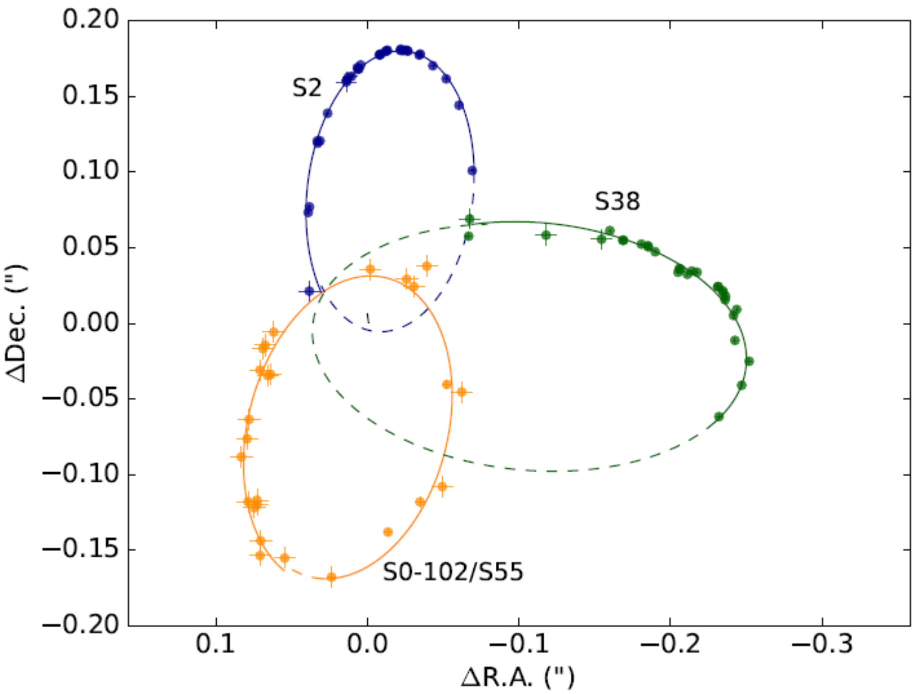
**Table 3** Table of possible necessary conditions that can be combined to result in a sufficient condition required to call SgrA* a SMBH. The necessary conditions have been formulated as logical entities for which we can attribute the locigal values "true" or "false" within the theoretical predictions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

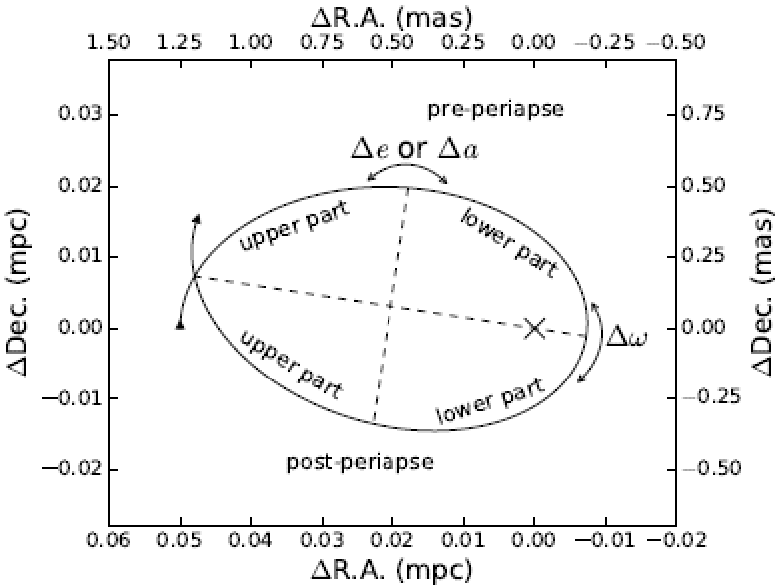
# Example 1

Proving that we indeed probe a relativistic regime:

Relativistic orbtis of stars

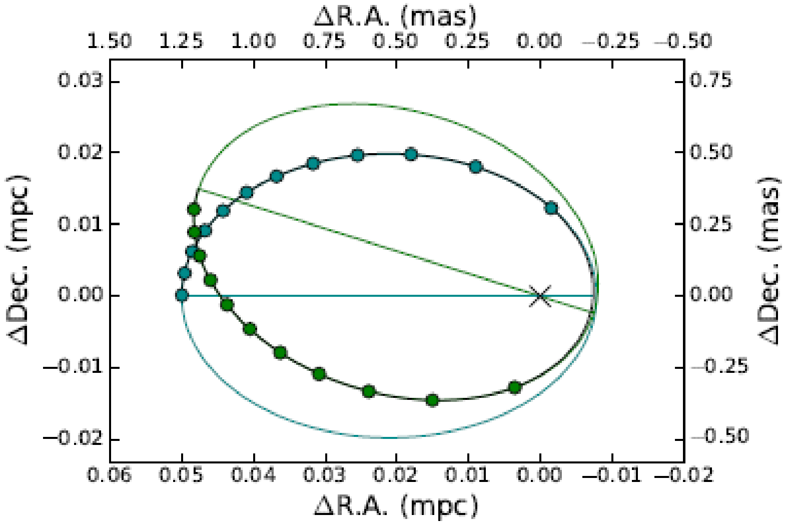
Parsa et al. 2017, ApJ 845, 22



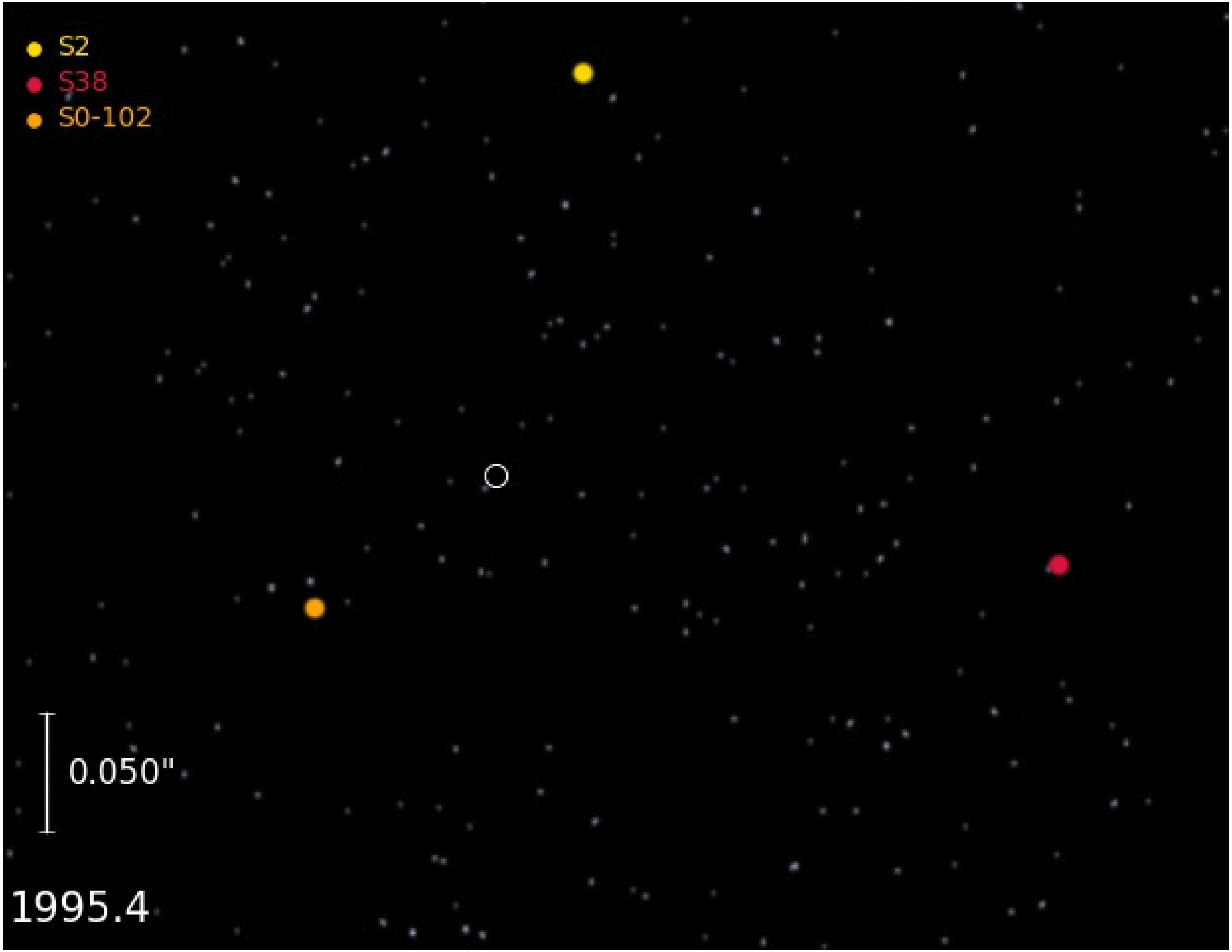


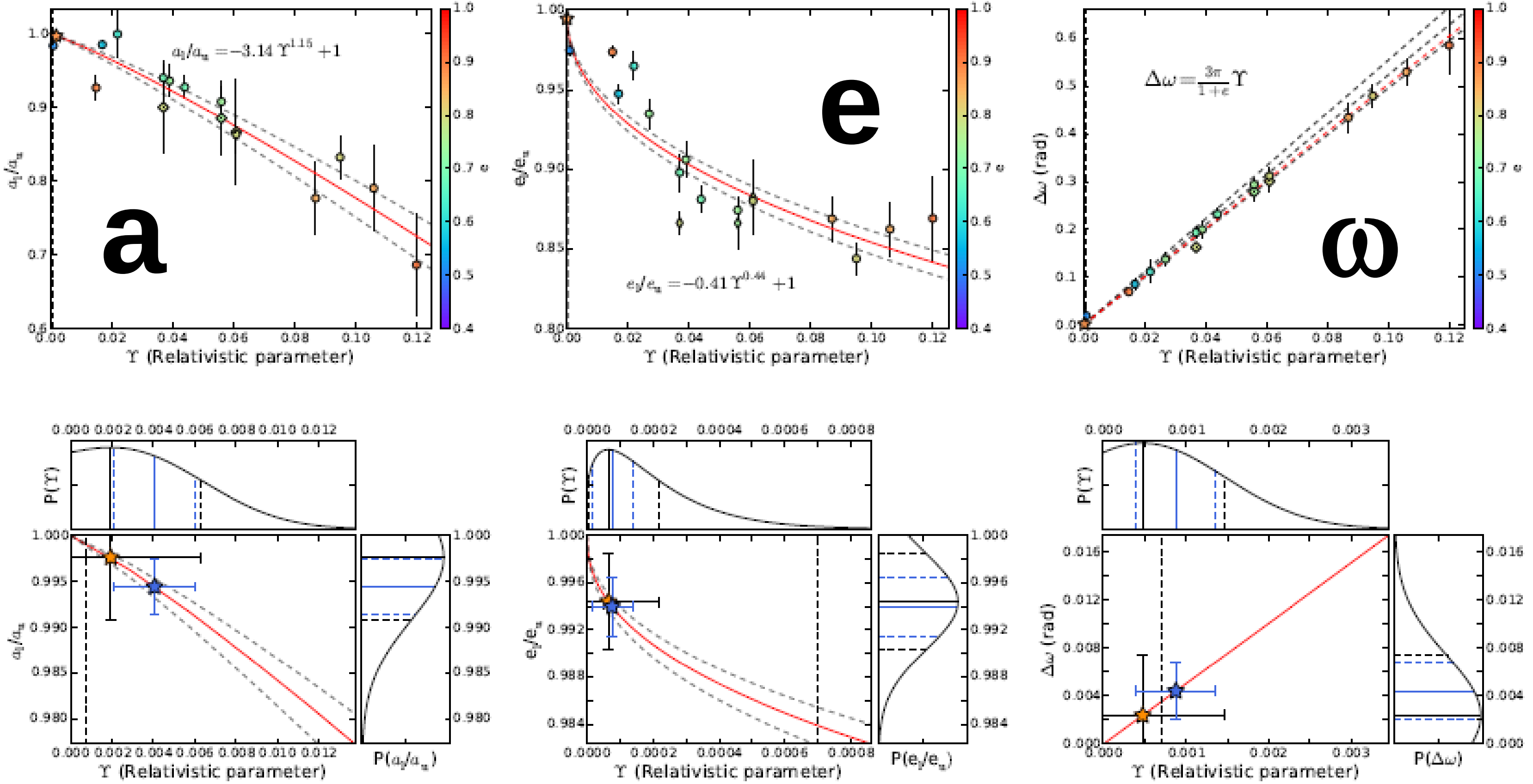
First relativistic analysis
using three stars orbiting SgrA*!

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



Parsa et al. 2017, ApJ 845, 22


S2
S38
S0-102
0.050"
1995.4



relativistic parameter defined as $\Upsilon \equiv r_s/r_p$

$r_s$ Schwarzschild radius; $r_p$ periapse distance

expected value of $\Upsilon = 0.00065$

derived from $M_{BH}$ and the orbit of S2

$\Upsilon = 0.00088 \pm 0.00080$

First time that the investigation of a resolved stellar orbit around an SMBH has been carried out in detail.

The result is consitent with the SMBH hypothesis.

**For $\Delta\omega$ a 3-4 $\sigma$ result**

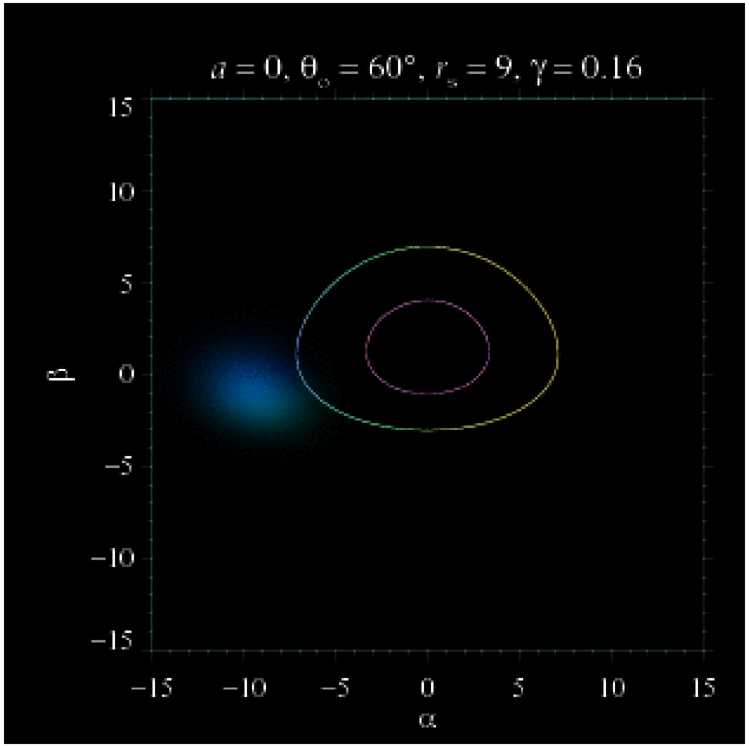
# Example 2

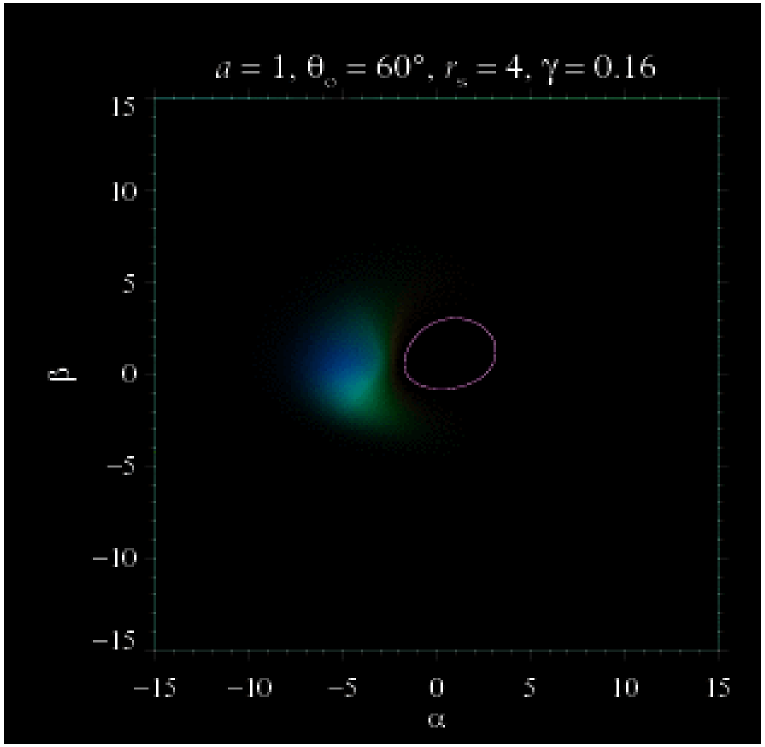
Proving that we indeed probe a relativistic regime:

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

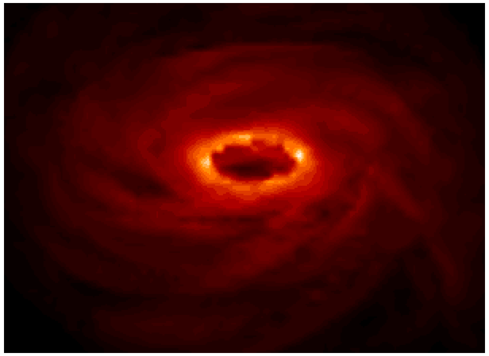
Karssen et al. 2017, MNRAS 472, 4422

# Polarized Light from SgrA* in the Infrared





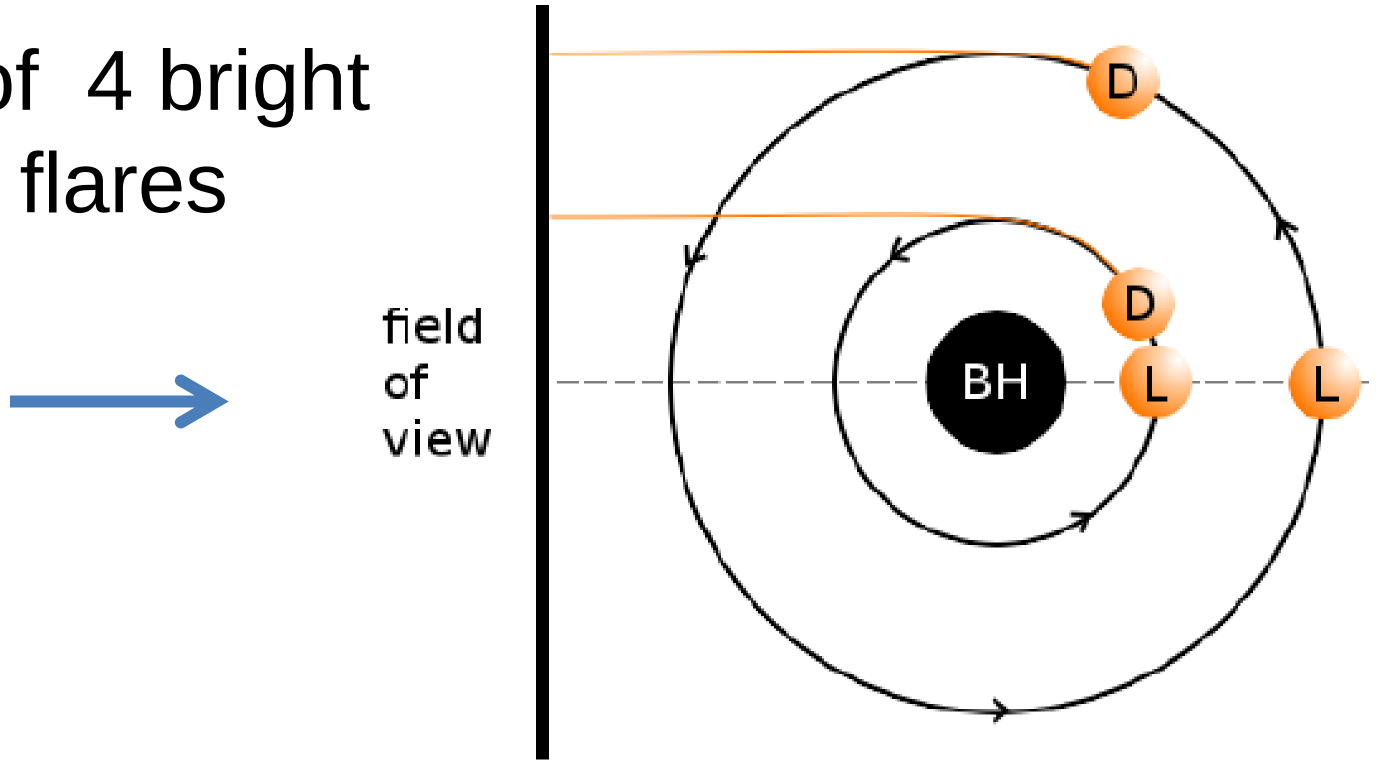
Dovciak, Karas & Yaqoob 2004, ApJS 153, 205
Dovciak et al. 2006



S. Karssen, M. Valencia-S., M. Bursa,
M. Dovciak, , V. Karas, A. Eckart

# Analysis of 4 bright X-ray flares

observer



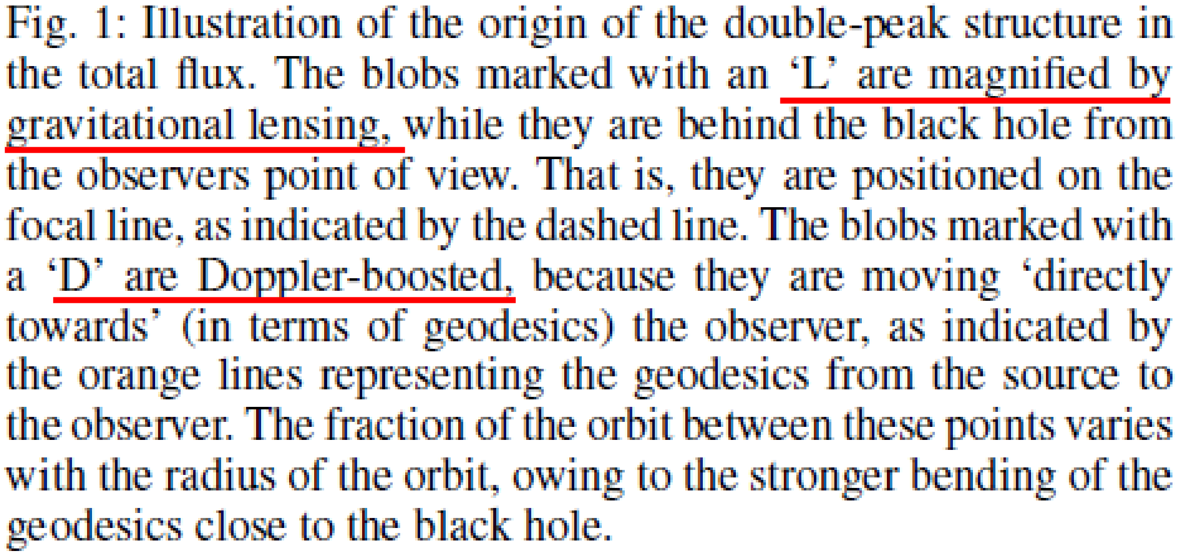
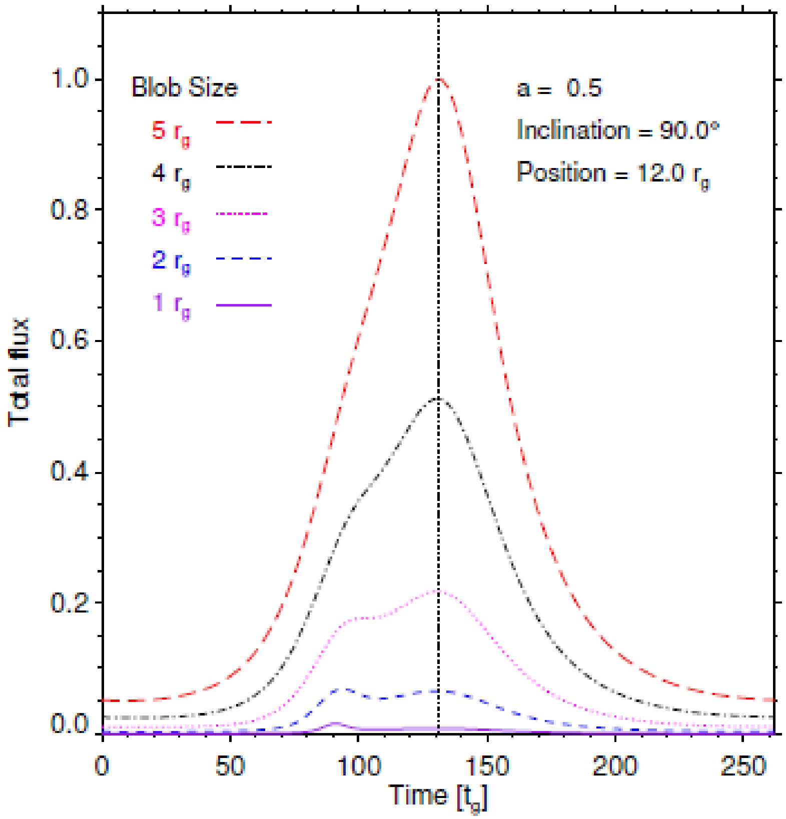
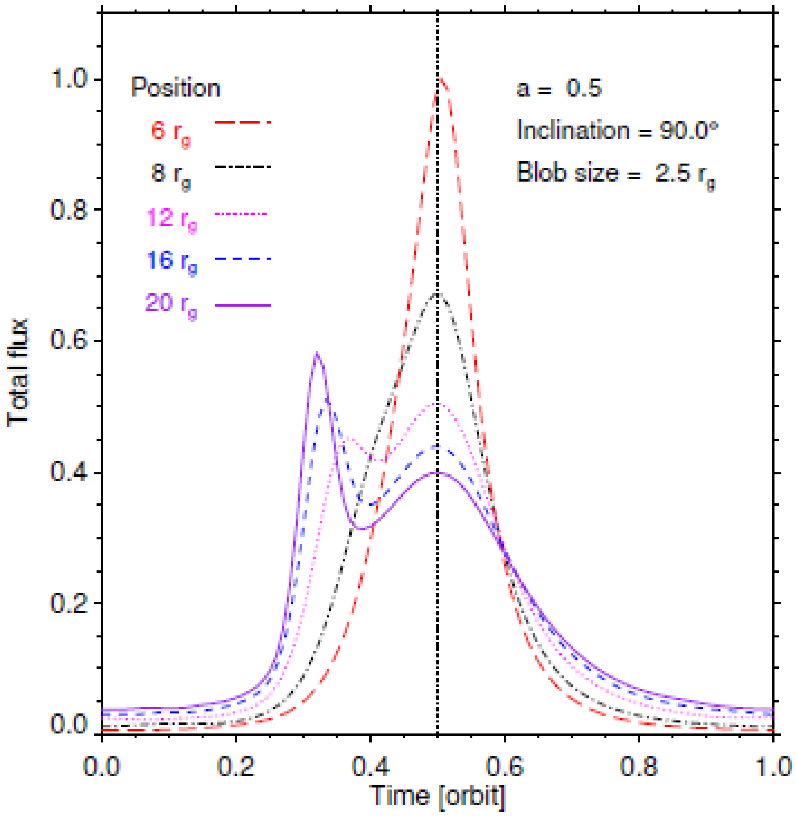


Fig. 1: Illustration of the origin of the double-peak structure in the total flux. The blobs marked with an ‘L’ are magnified by gravitational lensing, while they are behind the black hole from the observers point of view. That is, they are positioned on the focal line, as indicated by the dashed line. 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

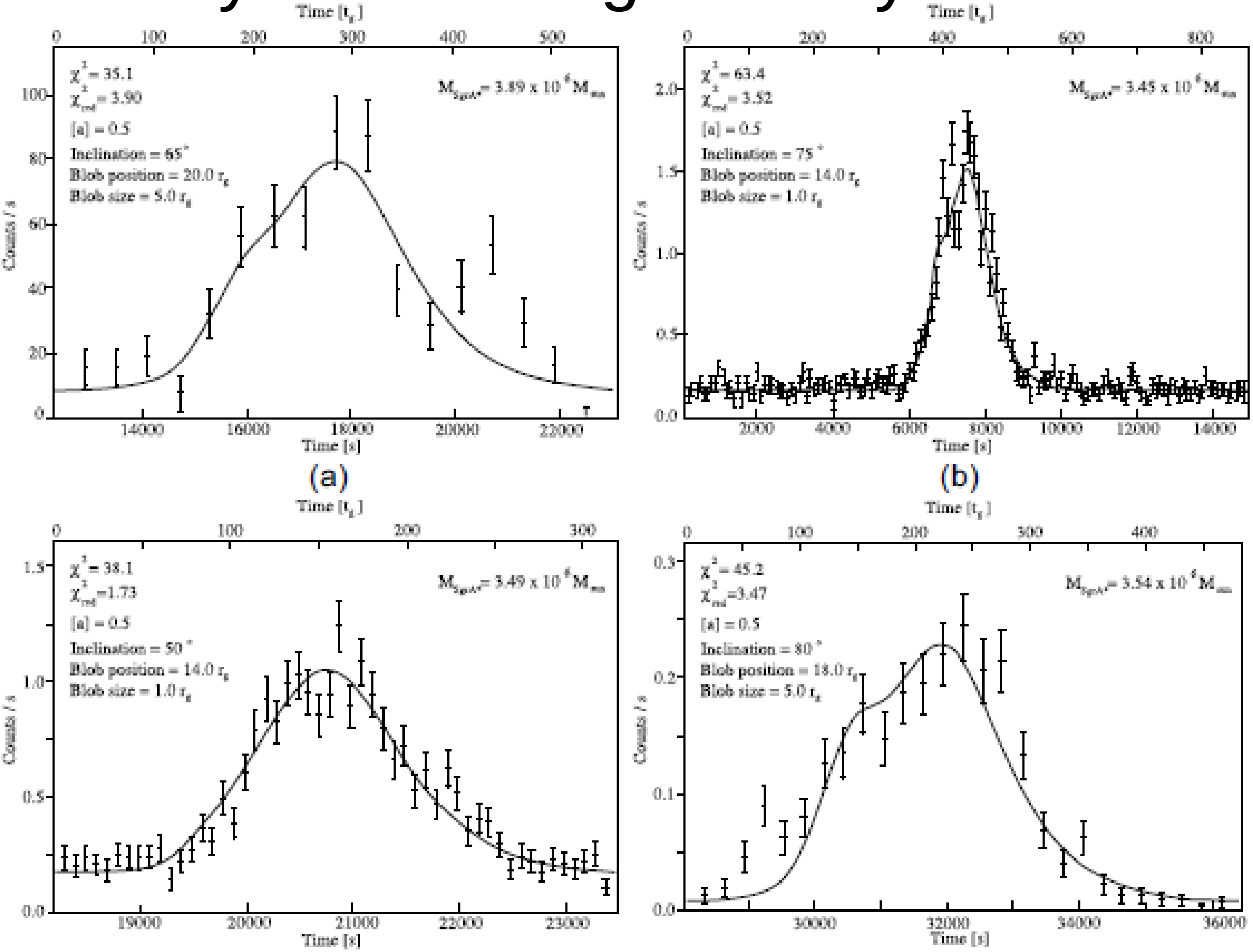


(a) Illustrates the influence of the blob's size on the shape of the light curve. The blobs of different sizes (5 $r_g$ red long dashed, 4 $r_g$ black dash-dotted, 3 $r_g$ magenta dotted, 2 $r_g$ blue short dashed and 1 $r_g$ solid purple line) are orbiting at a radial position of 12 $r_g$ around a black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



(b) Illustrates the influence of the blob's position on the shape of the light curve. The blobs are orbiting at different positions (6 $r_g$ red long dashed, 8 $r_g$ black dash-dotted, 12 $r_g$ magenta dotted, 16 $r_g$ blue short dashed and 20 $r_g$ solid purple line) and have a size of 2.5 $r_g$ around a black hole with spin 0.5, the viewing angle is 90 ° (edge on). The light curves are normalized to the maximum of the peak value of the light 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

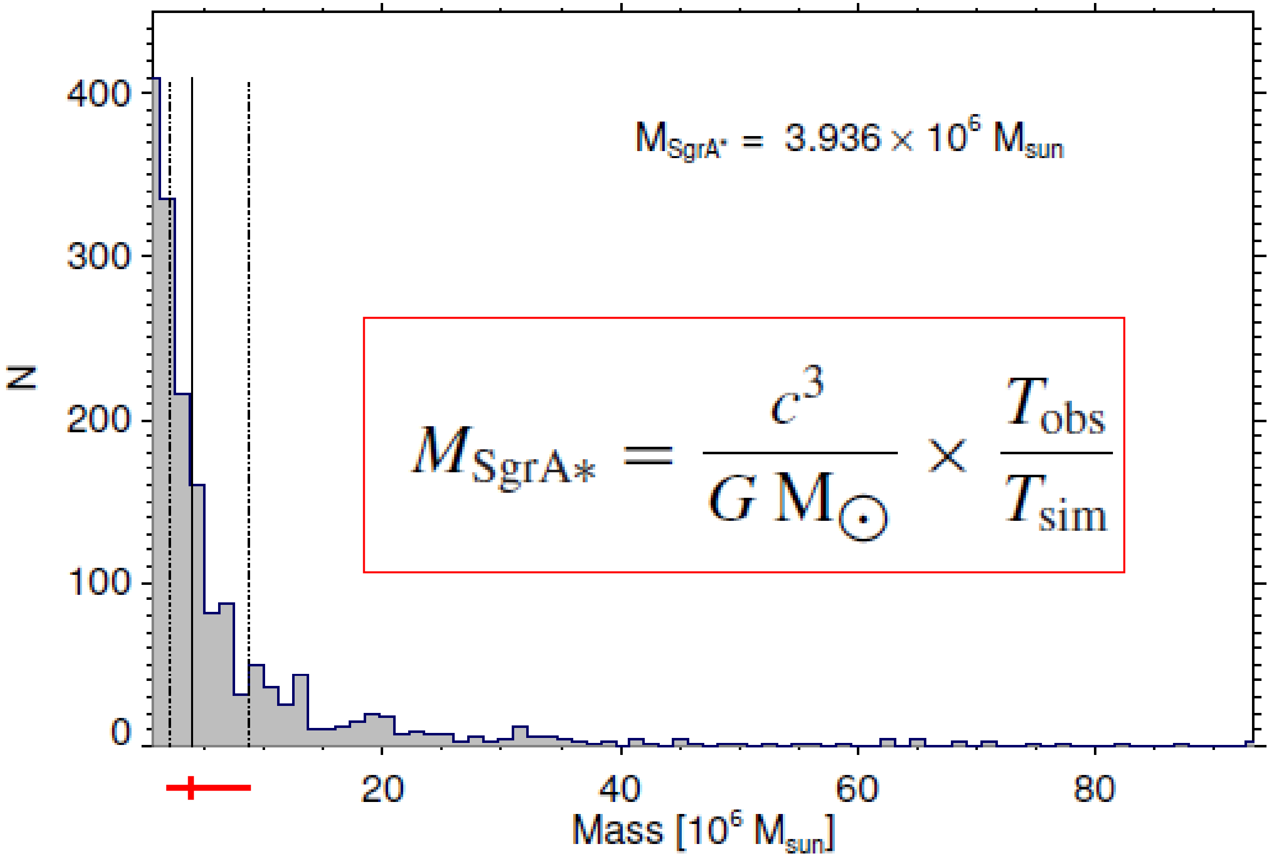


(a) (b)

(c) (d)

Karssen et al. 2017, MNRAS 472, 4422

# Analysis of 4 bright X-ray flares



$$M_{\mathrm{SgrA*}} = \frac{c^3}{G\,\mathrm{M}_\odot} \times \frac{T_{\mathrm{obs}}}{T_{\mathrm{sim}}}$$

(g) All flares together give a median mass of $3.936 \times 10^6 M_\odot$.

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

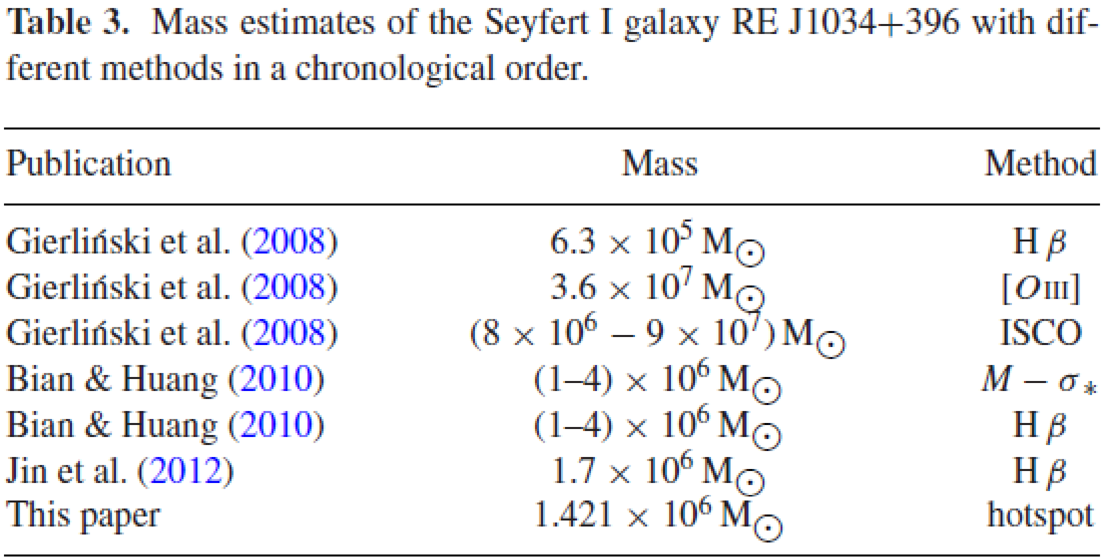


**Table 3.** Mass estimates of the Seyfert I galaxy RE J1034+396 with different methods in a chronological order.

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

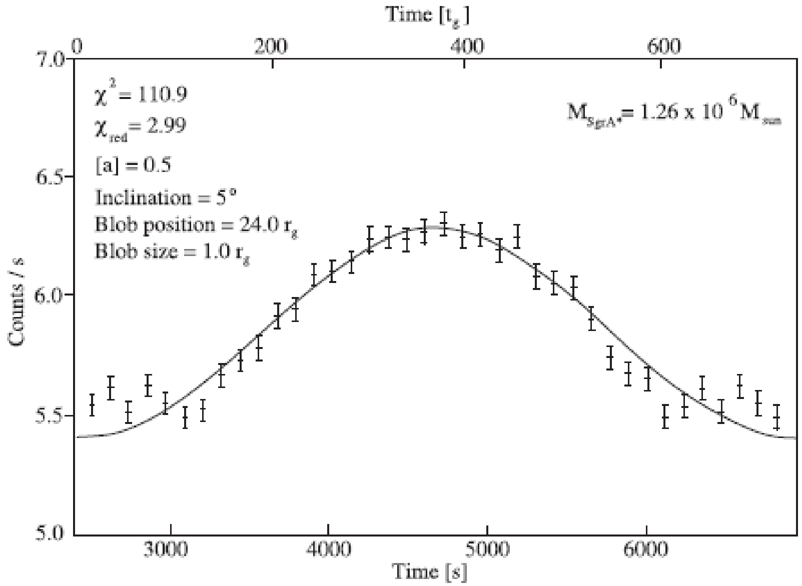


**Figure 9.** Best fit for the QPO of J1034-396 show for data of the folded light curve as published by Gierliński et al. (2008).

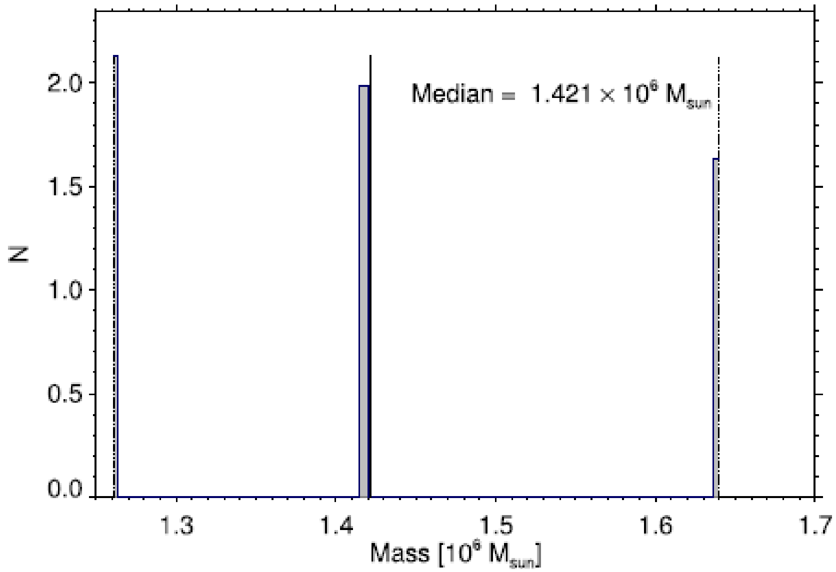


**Figure 8.** Weighted histogram for the QPO of J1034-396 as published by Gierliński et al. (2008).

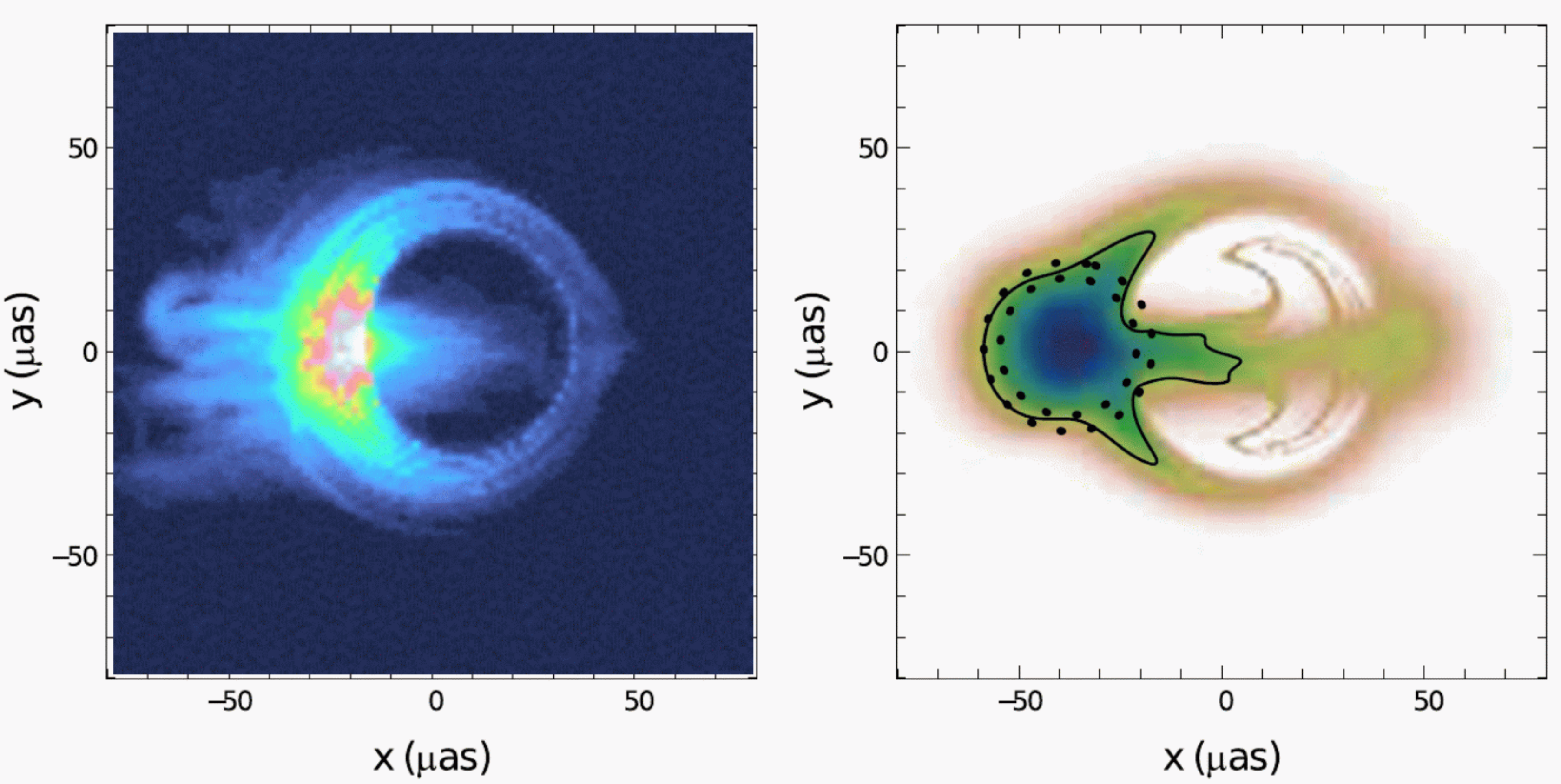
# Example 3

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 Black Hole



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

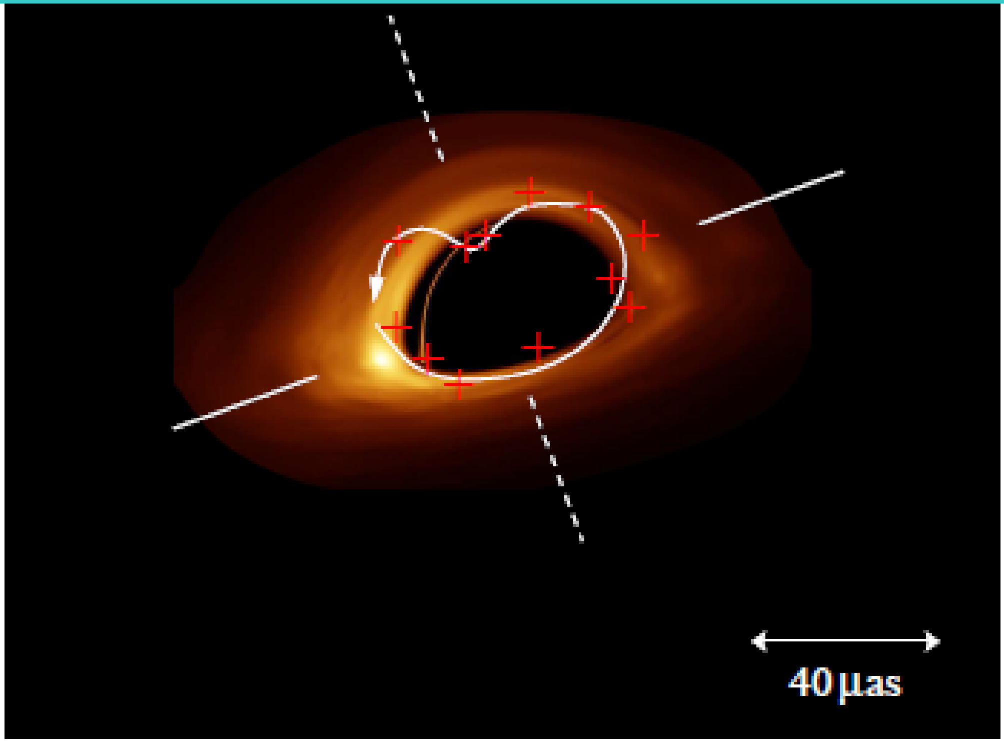
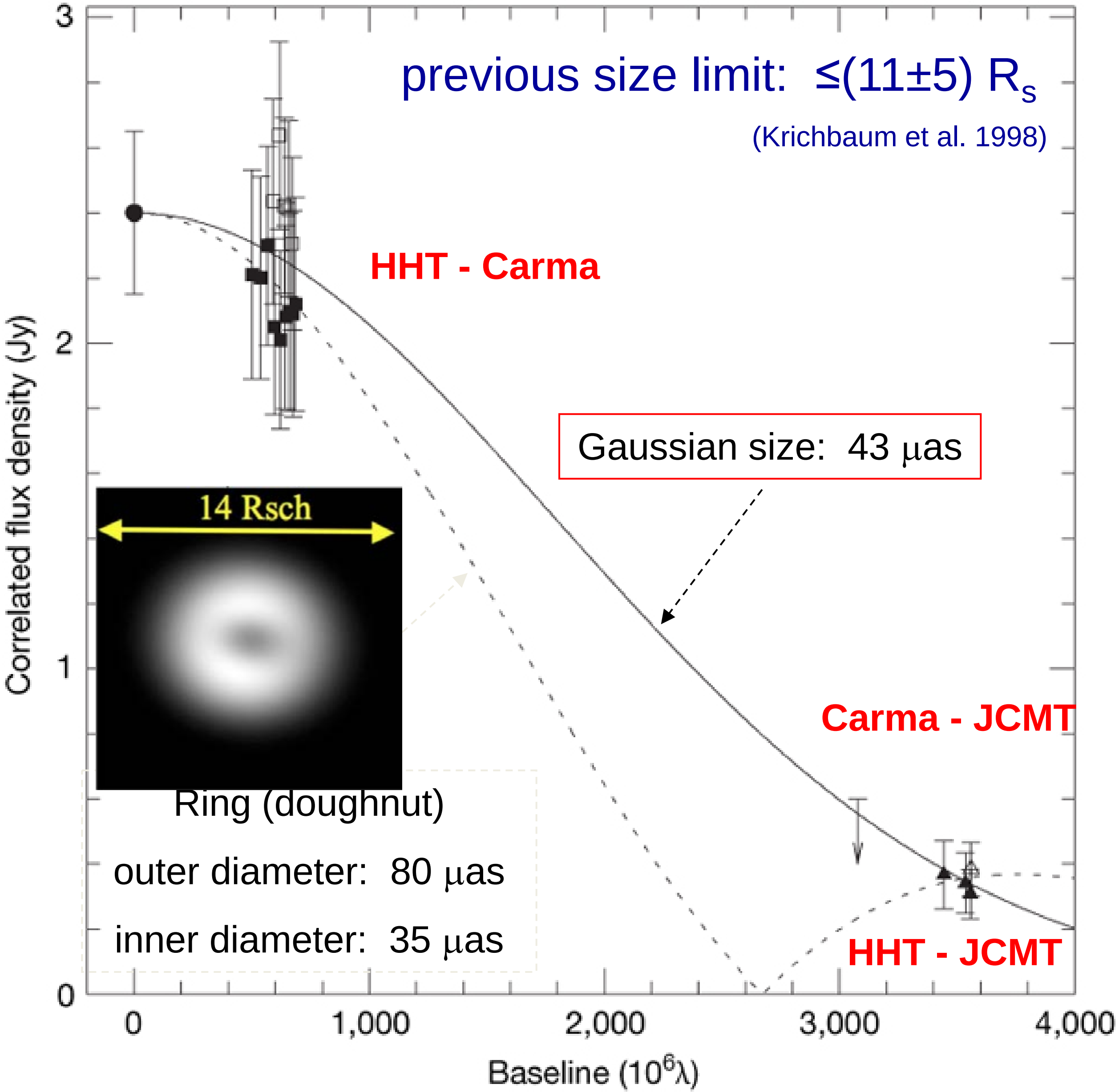


FIG. 10. Photocenter motion compared to a disk model. The example of a NIR photo-center motion as planned to be measured with the GRAVITY interferometer at the VLTI is taken from [256] and [257]. The simulation describes the apparent trajectory of flare events assuming material orbiting a non-rotation black hole at an inclination of 45° on the last stable orbit at a distance of 3 $R_S$ 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)



previous size limit: ≤(11±5) $R_s$

(Krichbaum et al. 1998)

**HHT - Carma**

Gaussian size: 43 μas

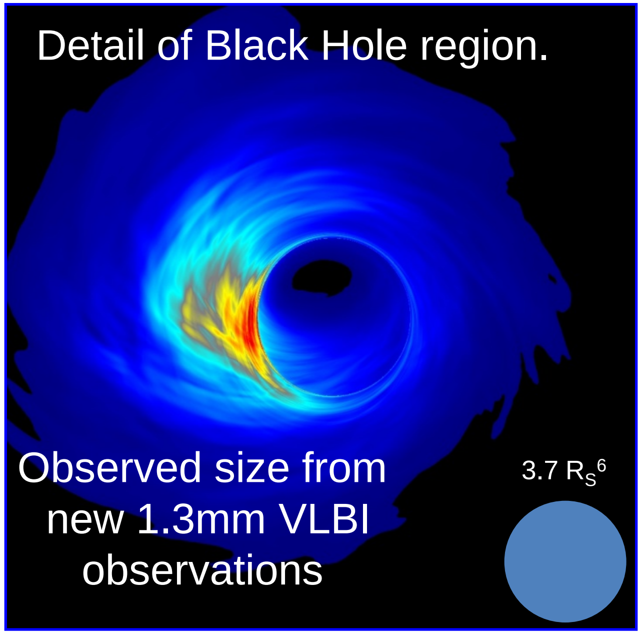
**Carma - JCMT**

**HHT - JCMT**

Ring (doughnut)

outer diameter: 80 μas

inner diameter: 35 μas



Detail of Black Hole region.

Observed size from new 1.3mm VLBI observations

3.7 $R_S$[6]

observed size:

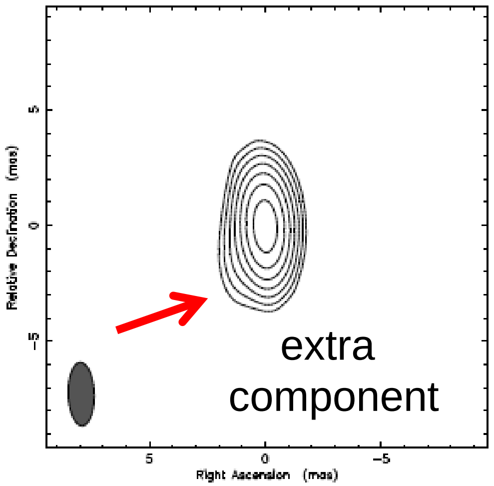
43 (+14/-8) μas

deconvolved :

37 μas (3.7 $R_S$)

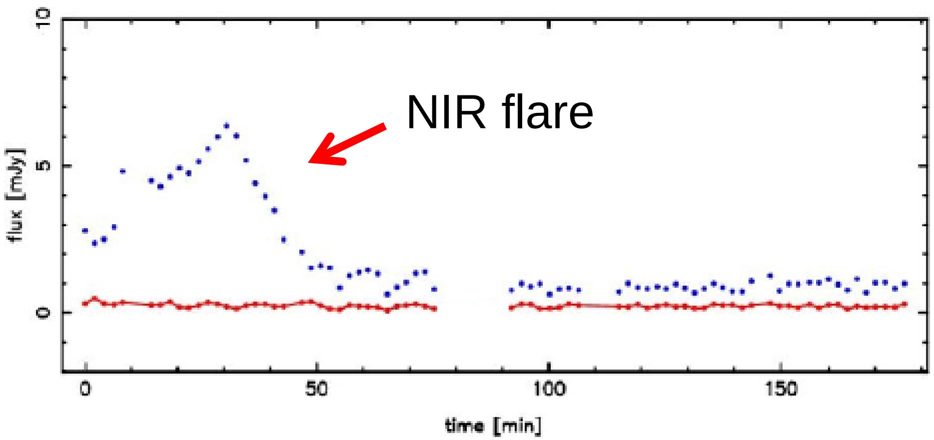
Doeleman *et al. Nature* **455**, 78-80 (2008)

# Nature of some SgrA* radio flares



extra component

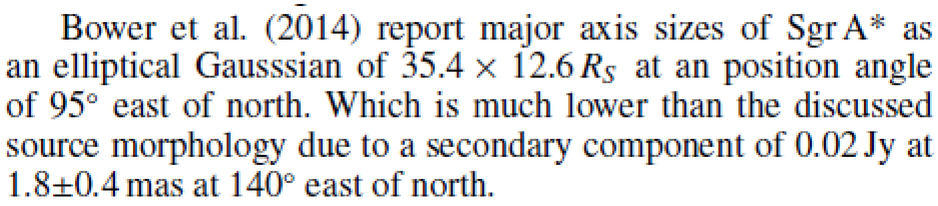
Fig. 7: RCP map of Sgr A* on May 17 2012 (8-10h UT). The map was convolved with a beam of 2.74×1.12 at 1.76°. Contour levels are 1, 2, 4, 8, 16, 32 and 64% of the peak flux density of 1.5 Jy/beam.



NIR flare

Fig. 3: NIR $K_s$-band (2.2 $\mu$m) light curve of Sgr A* observed in polarimetry mode on 17 May 2012. The light curve shown is produced by combining pairs of orthogonal polarization channels: 0° and 90° (taken from Shahzamanian et al. (2015)). Observations started at 4:55 AM UT.

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



Bower et al. (2014) report major axis sizes of Sgr A* as an elliptical Gausssian of 35.4 × 12.6 $R_S$ at an position angle of 95° east of north. Which is much lower than the discussed source morphology due to a secondary component of 0.02 Jy at 1.8±0.4 mas at 140° east of north.

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

See also ‚Asyummetric 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*

**N → a few to 0**

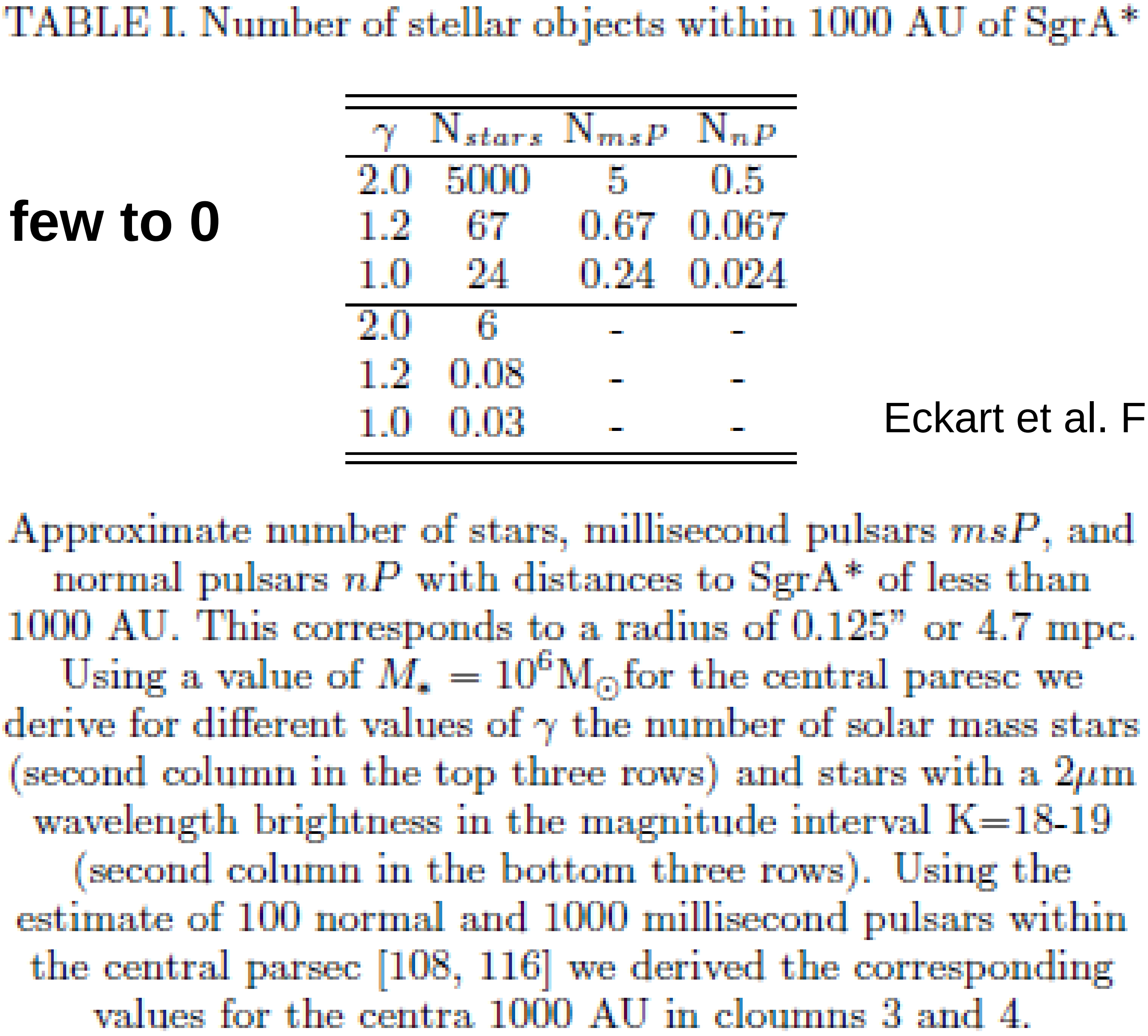


TABLE I. Number of stellar objects within 1000 AU of SgrA*

| $\gamma$ | $N_{stars}$ | $N_{msP}$ | $N_{nP}$ |
|---|---|---|---|
| 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 | - | - |

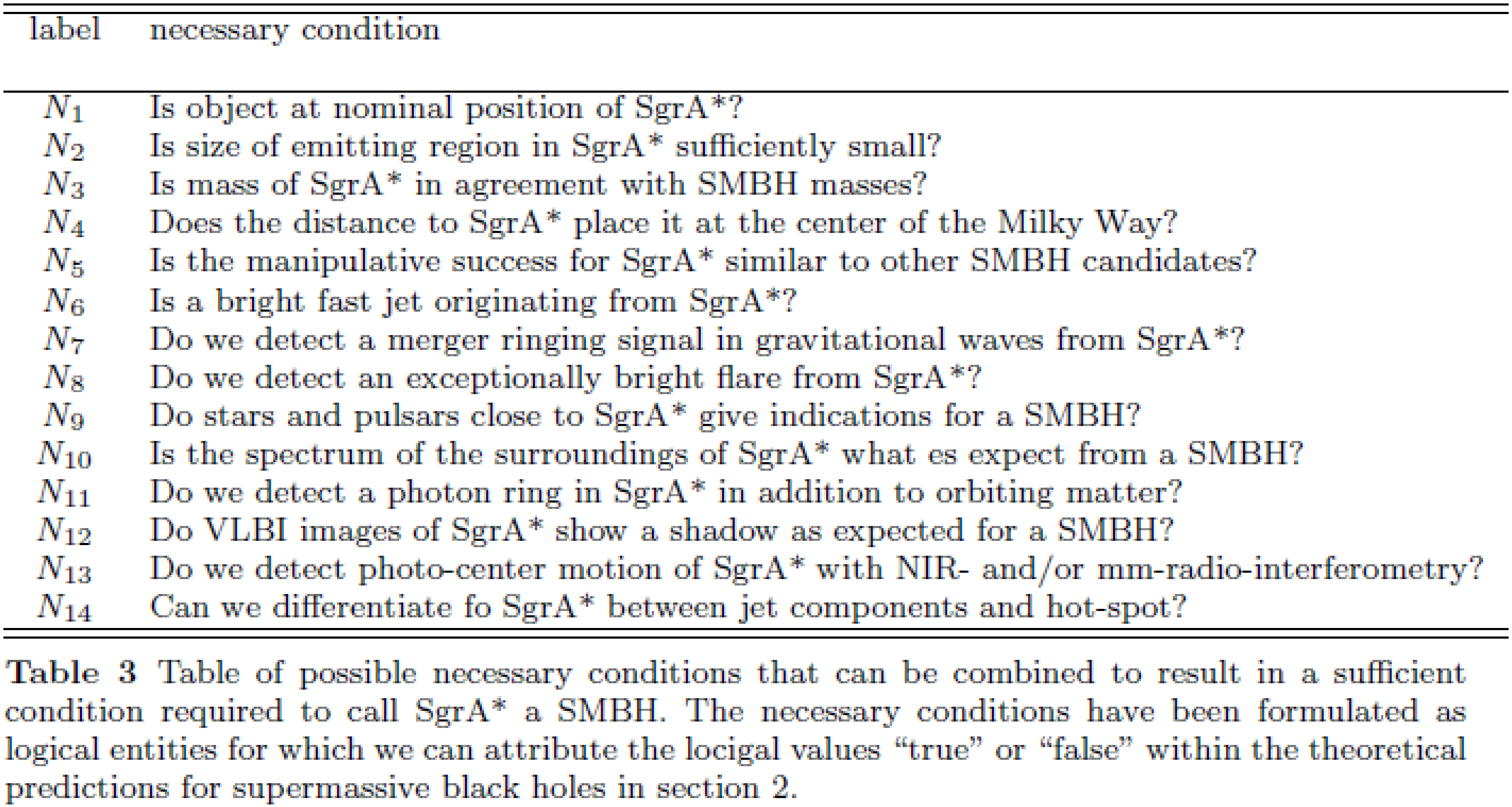
Approximate number of stars, millisecond pulsars $msP$, and normal pulsars $nP$ with distances to SgrA* of less than 1000 AU. This corresponds to a radius of 0.125" or 4.7 mpc. Using a value of $M_* = 10^6 M_\odot$ for the central parsec we derive for different values of $\gamma$ the number of solar 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 centra 1000 AU in cloumns 3 and 4.

Eckart et al. FoPh 47, 553

# Synthesis:

# Combining the Necessary Conditions to Sufficient Conditions

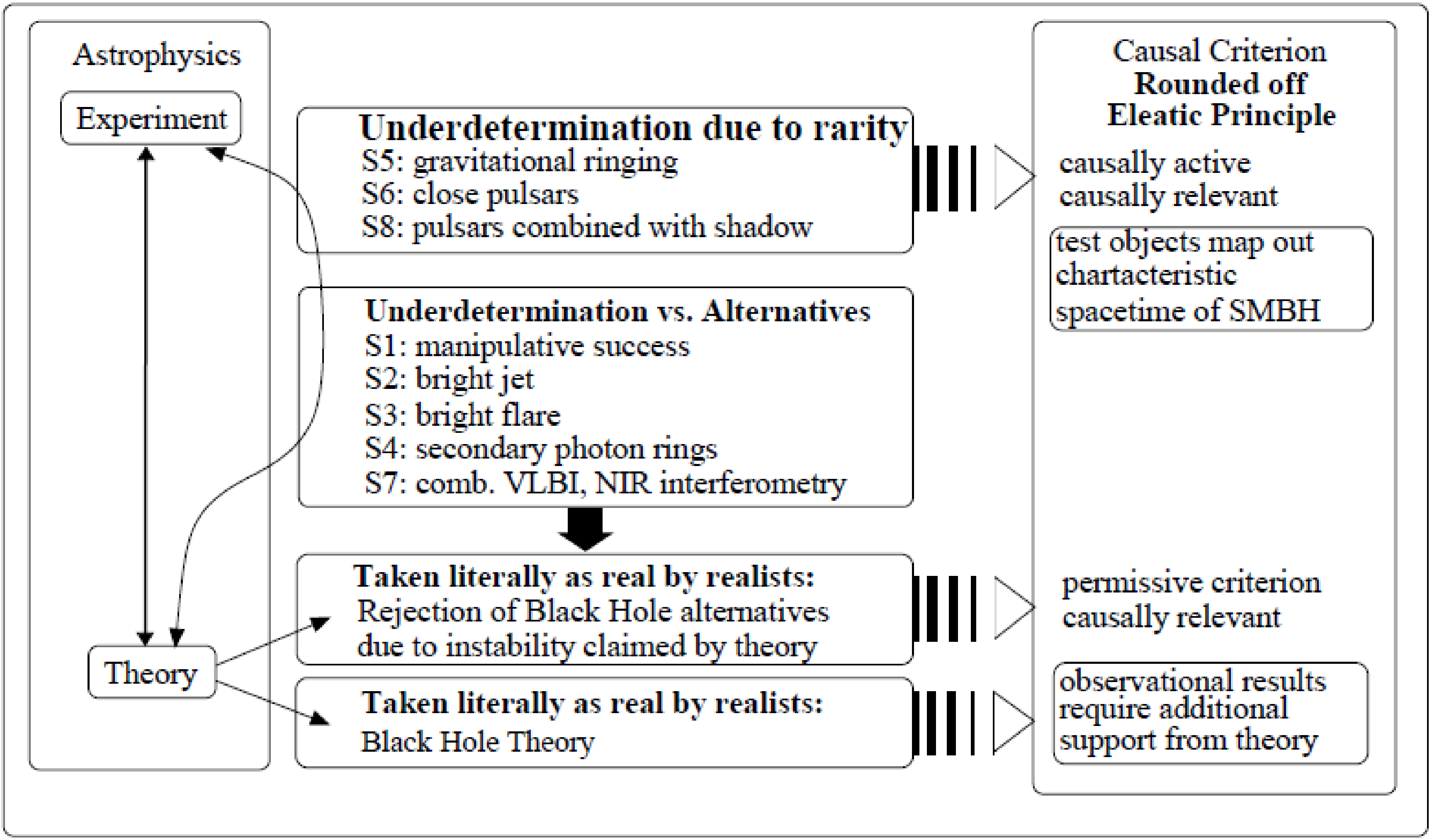
# Necessary Conditions for the presence of a Black Hole



| 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 fo 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.

# Philosphical Concepts layed out for the GC



Astrophysics

Experiment

Theory

**Underdetermination due to rarity**
S5: gravitational ringing
S6: close pulsars
S8: pulsars combined with shadow

**Underdetermination vs. Alternatives**
S1: manipulative success
S2: bright jet
S3: bright flare
S4: secondary photon rings
S7: comb. VLBI, NIR interferometry

**Taken literally as real by realists:**
Rejection of Black Hole alternatives
due to instability claimed by theory

**Taken literally as real by realists:**
Black Hole Theory

Causal Criterion
**Rounded off**
**Eleatic Principle**

causally active
causally relevant

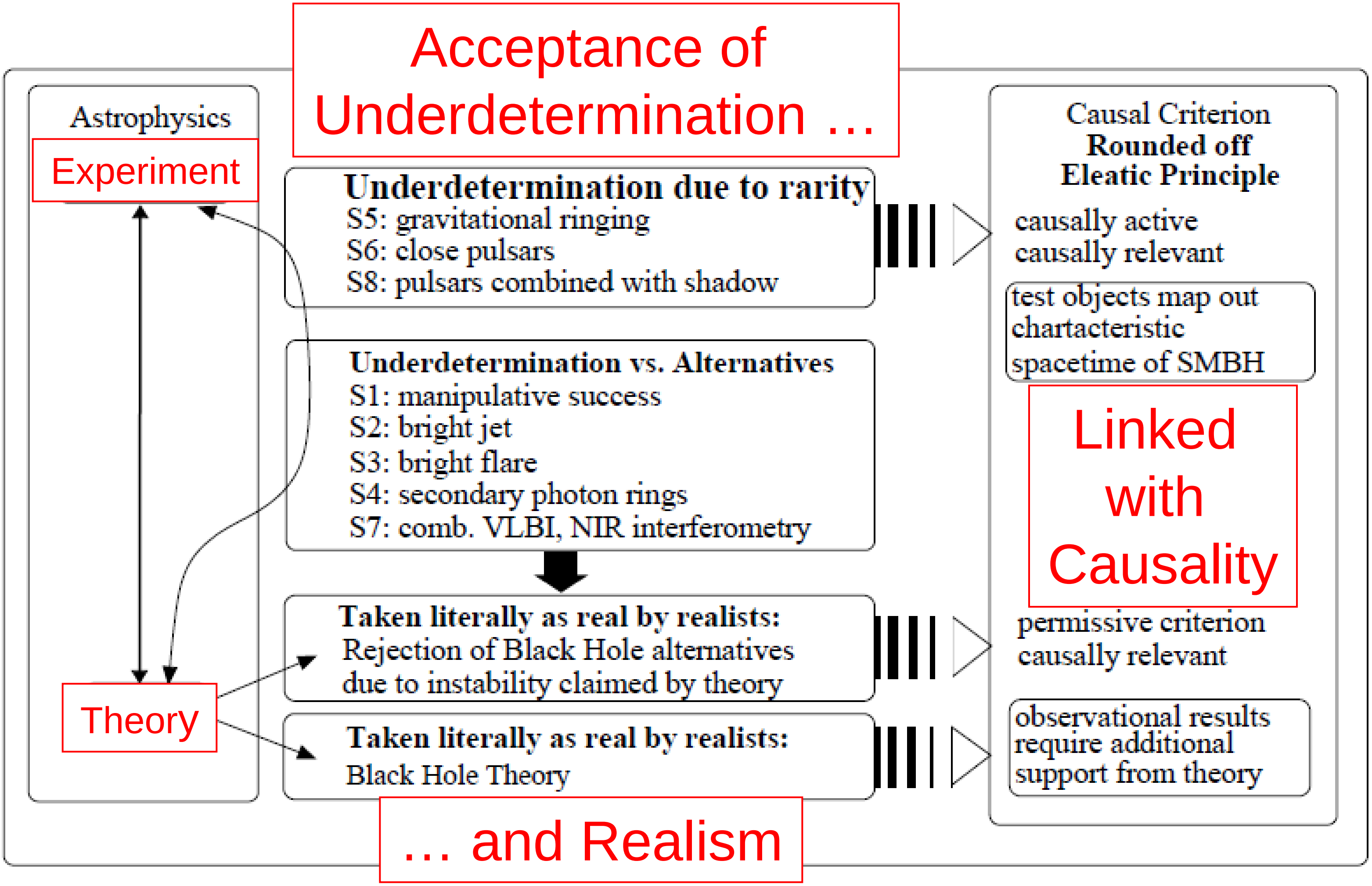
test objects map out
chartacteristic
spacetime of SMBH

permissive criterion
causally relevant

observational results
require additional
support from theory

**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.

# Philosphical Concepts layed out for the GC



Acceptance of Underdetermination …

Astrophysics

Experiment

Theory

**Underdetermination due to rarity**
S5: gravitational ringing
S6: close pulsars
S8: pulsars combined with shadow

**Underdetermination vs. Alternatives**
S1: manipulative success
S2: bright jet
S3: bright flare
S4: secondary photon rings
S7: comb. VLBI, NIR interferometry

**Taken literally as real by realists:**
Rejection of Black Hole alternatives
due to instability claimed by theory

**Taken literally as real by realists:**
Black Hole Theory

… and Realism

Causal Criterion
**Rounded off**
**Eleatic Principle**

causally active
causally relevant

test objects map out
chartacteristic
spacetime of SMBH

Linked with Causality

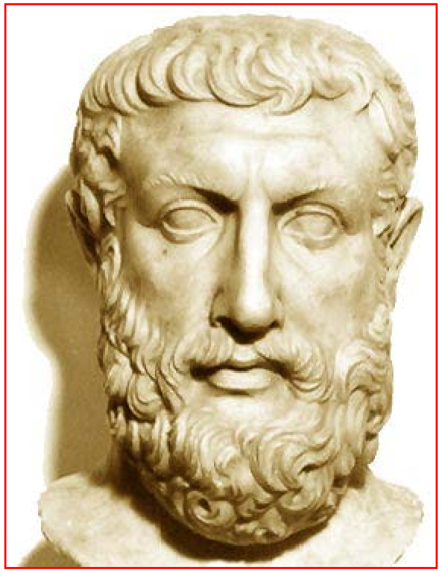
permissive criterion
causally relevant

observational results
require additional
support from theory

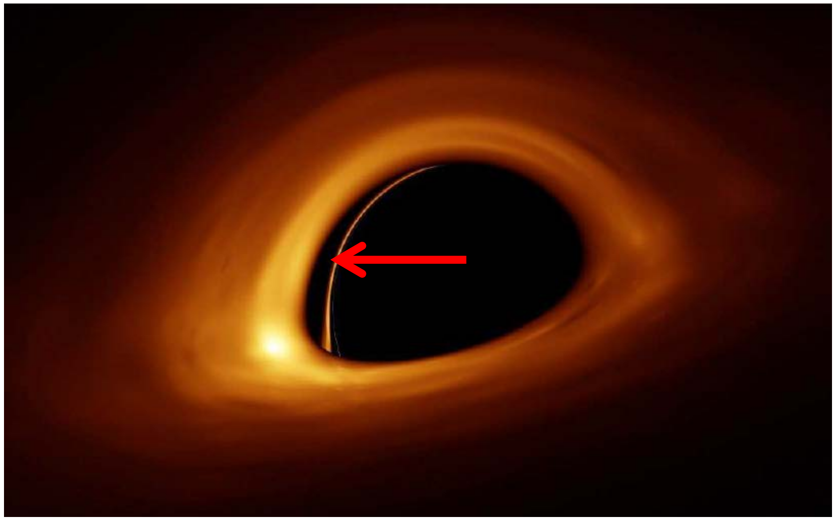
**Fig. 13** Linkage between experiment and theory interpreted via the concept of realism, underdetermination and a "rounded out" version of the Eleatic Principle, here shown with respect to the results of our investigation. For comparison see also Fig.1 which we adopted here for the case of the Galactic Center SMBH.

# Combining all results

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.



Parmenides

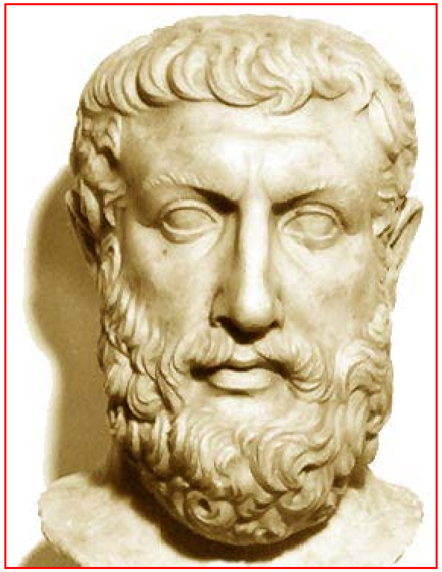


source: internet

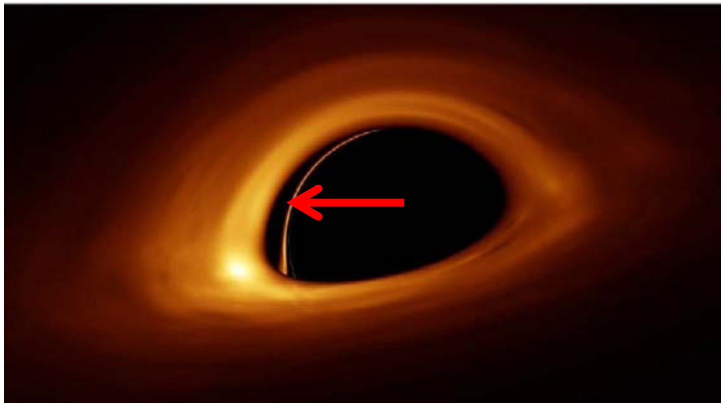
# Combining all results

**Challenge for Astrophysics:** How clean are the obervational 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 existance and are they risky enough?



Parmenides



source: internet

# Philosphical Concepts layed 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)

---------

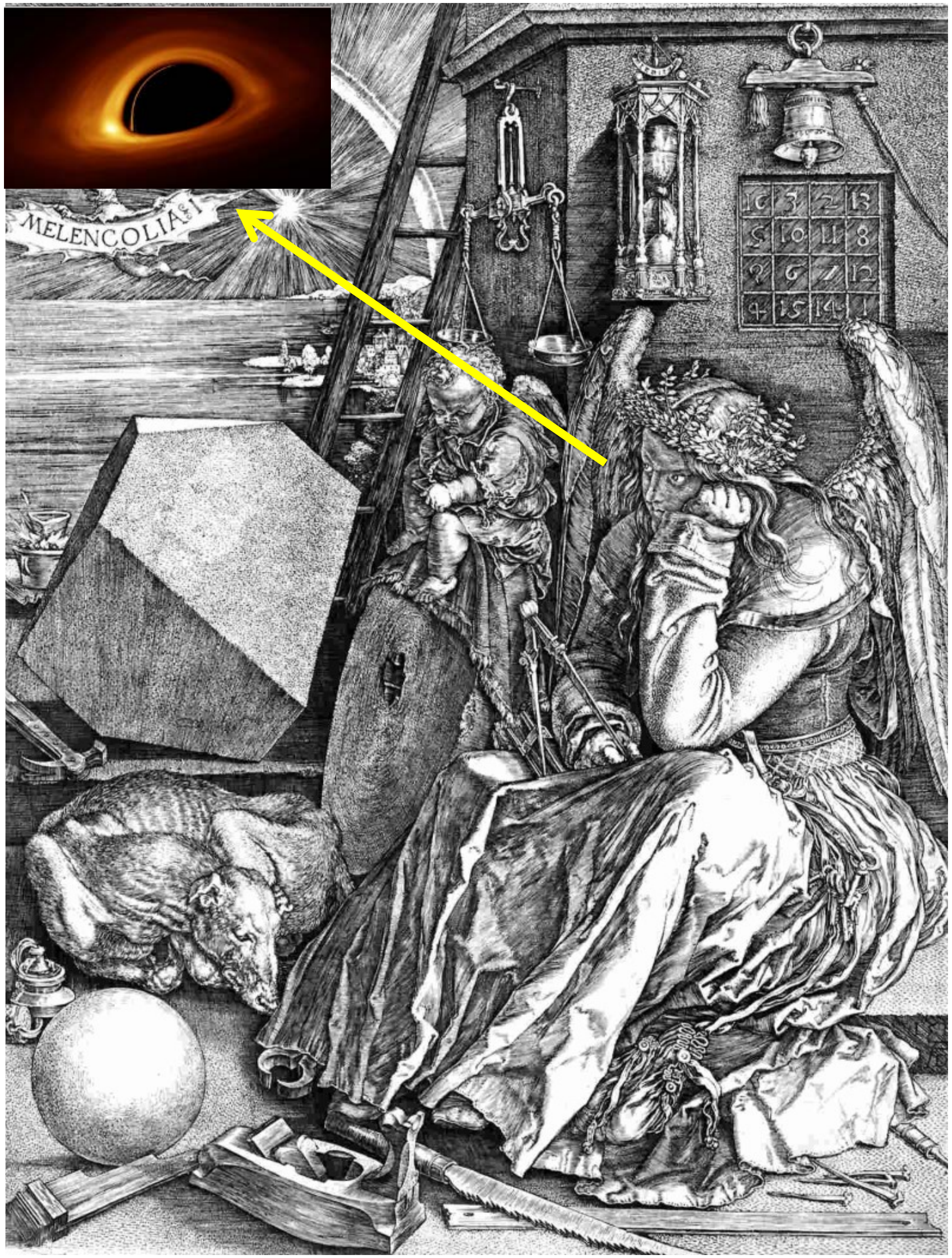
The more meaningful and stringent key obesrvations
are the more difficult and rare they are.
(Pulsar and stellar measurements; gravitational waves)

---------

**A real prove dosen‘t seem to be possible, however,
the acceptance of the idea can be maximized.**

'Melancholia' by
Albrecht Dürer

END



# 'Melancholia' by Albrecht Dürer

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

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

# END