Testing the Carter-Israel Conjecture with Future Observations of SgrA*

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Plan of the talk

Observations:

1. Dynamical measurements of the mass of BH candidates

2. Current approaches to estimate the spin of BH candidates

Super-spinning objects:

1. The nature of the constraint $|a| < M$

2. Observational signatures

3. The case of the BH candidate in the Galactic Center

Black Holes in GR: basic features

- **Horizon: a one-way membrane (at least classically). However, the spacetime is regular there.**

- **"BHs have no hairs": BHs do not have a true internal structure and can be completely characterized by a few parameters (neglecting exotic possibilities, by M, Q and *a*)**

- **BH solutions: Schwarzschild BH, Reissner-Nordstrom BH, Kerr BH, etc.**

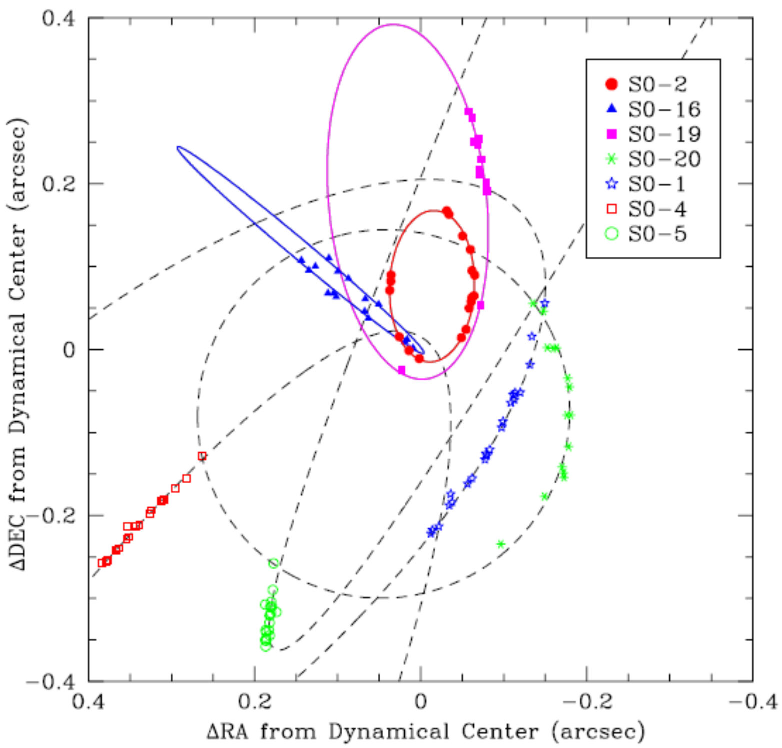
Black Hole candidates

- **Stellar mass Black Hole candidates in X-ray binary systems (5 – 20 Solar masses)**
- **Super-massive Black Hole candidates in galactic nuclei (10^6 – 10^9 Solar masses)**
- **Intermediate mass Black Hole candidates in ultra-luminous X-ray sources (10^3 – 10^4 Solar masses?)**

The BH candidate in the Galaxy

- Study of the orbits of individual stars
- Mass about 4×10^6 Solar masses
- Radius < 45 AU (600 R_{Sch})

The possibility that it is a cluster of some non-luminous bodies sounds very unlikely, because the cluster lifetime due to evaporation or physical collisions is too short (see e.g. Maoz, 1998)



From Ghez et al., ApJ 620 (2005) 744

Stellar mass BH candidates

- **Their existence is essentially suggested by dynamical arguments (X-ray binary systems, Newtonian motion of the companion)**

- **Mass function:**

$$f(M_{BH}) = \frac{K^3 T}{2\pi G_N} = \frac{M_{BH}^3 \sin^3 i}{(M_{BH} + M_c)^2}$$

$$K = v \sin i$$

- **In general, a good estimate of M_C and *i* is necessary**

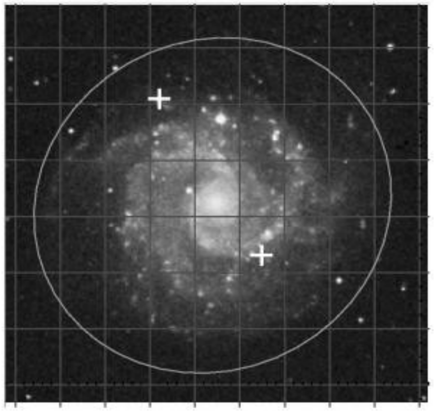
- **Maximum mass of relativistic stars about 3 Solar masses (see Rhoades & Ruffini 1974 and Kalogera & Baym 1996)**

Coordinate Name	Common Name/Prefix	Year	Spec.	P_{orb} (hr)	f(M) ($M_\odot$)	M_1 ($M_\odot$)
0422+32	(GRO J)	1992/1	M2V	5.1	1.19±0.02	3.7–5.0
0538–641	LMC X–3	–	B3V	40.9	2.3±0.3	5.9–9.2
0540–697	LMC X–1	–	O7III	93.8[d]	0.13±0.05[d]	4.0–10.0:[e]
0620–003	(A)	1975/1[f]	K4V	7.8	2.72±0.06	8.7–12.9
1009–45	(GRS)	1993/1	K7/M0V	6.8	3.17±0.12	3.6–4.7:[e]
1118+480	(XTE J)	2000/2	K5/M0V	4.1	6.1±0.3	6.5–7.2
1124–684	Nova Mus 91	1991/1	K3/K5V	10.4	3.01±0.15	6.5–8.2
1354–64[g]	(GS)	1987/2	GIV	61.1[g]	5.75±0.30	–
1543–475	(4U)	1971/4	A2V	26.8	0.25±0.01	8.4–10.4
1550–564	(XTE J)	1998/5	G8/K8IV	37.0	6.86±0.71	8.4–10.8
1650–500[h]	(XTE J)	2001/1	K4V	7.7	2.73±0.56	–
1655–40	(GRO J)	1994/3	F3/F5IV	62.9	2.73±0.09	6.0–6.6
1659–487	GX 339–4	1972/10[i]	–	42.1[j,k]	5.8±0.5	–
1705–250	Nova Oph 77	1977/1	K3/7V	12.5	4.86±0.13	5.6–8.3
1819.3–2525	V4641 Sgr	1999/4	B9III	67.6	3.13±0.13	6.8–7.4
1859+226	(XTE J)	1999/1	–	9.2:[e]	7.4±1.1:[e]	7.6–12.0:[e]
1915+105	(GRS)	1992/Q[l]	K/MIII	804.0	9.5±3.0	10.0–18.0
1956+350	Cyg X–1	–	O9.7Iab	134.4	0.244±0.005	6.8–13.3
2000+251	(GS)	1988/1	K3/K7V	8.3	5.01±0.12	7.1–7.8
2023+338	V404 Cyg	1989/1[f]	K0III	155.3	6.08±0.06	10.1–13.4

From Remillared & McClintock, ARAA 44 (2006) 49

Intermediate mass BH candidates

- Ultra-luminous X-ray sources
- Too bright to be ordinary stellar mass BHs (luminosity larger than 10 times the Eddington limit for a 10 Solar mass object)
- They do not look like low luminosity super-massive BHs
- Their nature is unclear
- The population of ULXRSs is likely not uniform and includes different types of sources (IMBHs, collimated emission from stellar mass BHs, SNRs, etc.)



NGC 3184

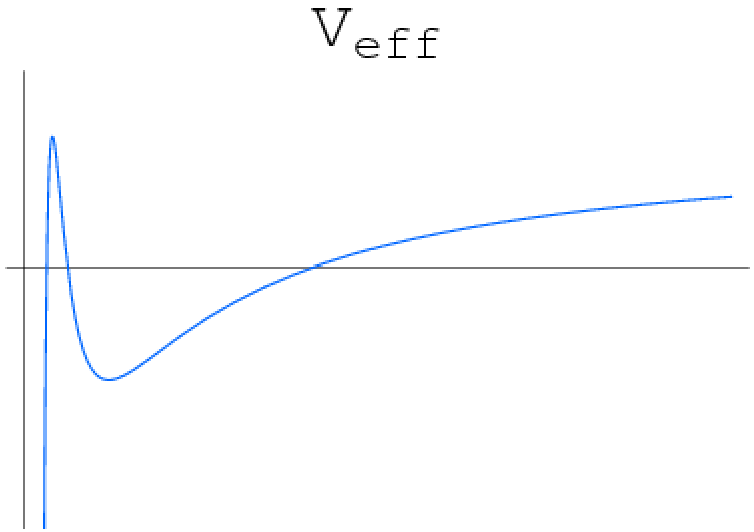
Estimate of the spin of BH candidates

- **The spin has no Newtonian effects on the motion of orbiting bodies. We need test particles on orbits with very small radii!**

- **Basic concept: Innermost Stable Circular Orbit (ISCO)**

- **Schwarzschild case:**

$$V_{eff}(r) = -\frac{m}{r} + \frac{L^2}{2r^2} - \frac{mL^2}{r^3}$$



From Narayan, NJP 7 (2005) 199

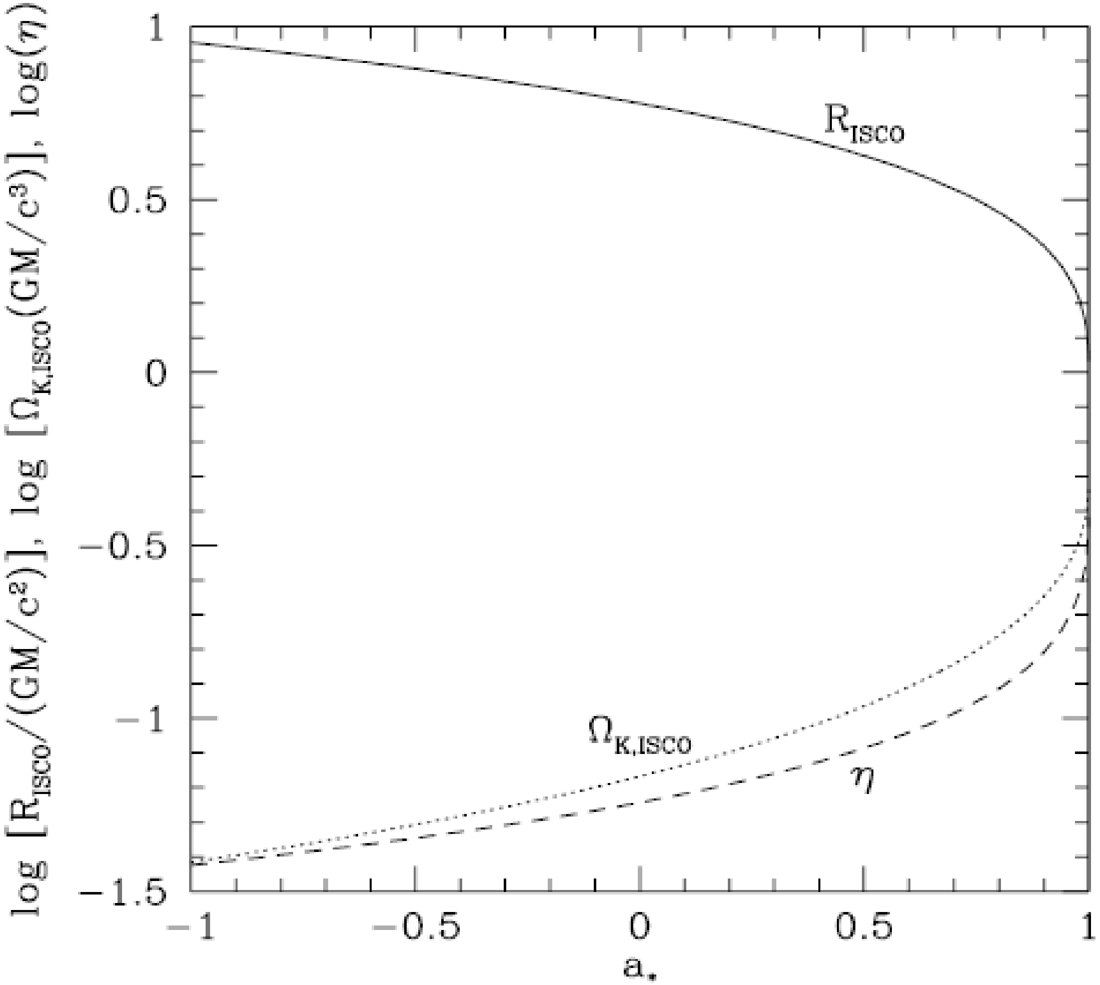


Fig. 2.— The radius of the innermost stable circular orbit $R_{\rm ISCO}$, the Keplerian frequency at this radius $\Omega_{\rm K,ISCO}$, and the binding energy at this radius η, as functions of the BH spin parameter a_*. Positive values of a_* imply that the BH corotates with the orbit and negative values mean that the BH counter-rotates. By measuring the quantity $R_{\rm ISCO}/M$ or $\Omega_{\rm K,ISCO}M$ or η, one could estimate a_*.

Current approaches

- **Spectral fitting method**: measuring the spectral flux received at Earth, one can estimate $R_{in}^2 \cos(i) / D^2$. Reliable estimates of *i*, D and M are necessary in order to infer the spin
- **Quasi-periodic oscillations**: one assumes that the QPO with the highest frequency corresponds to the orbital frequency of gas blobs at the inner edge of the disk
- **Relativistic iron line**: assuming that the radiating gas follows Keplerian orbits with radii larger than the ISCO, one can fit the shape of the line profile and get *a*, *i*, and the emissivity function (usually modeled as $1/r^k$)

All the approaches are questionable and there is no general agreement on their reliability!!!

A few comments...

- **We have a set of observational evidences supporting the existence of BHs in the Universe, but for sure there is no smoking gun**

- **The interpretation that these objects are BHs is just the most conservative possibility**

- **Note that, so far, GR has been tested in the weak field limit only: BHs may not exist or may be very different from the ones predicted by GR!**

Carter-Israel Conjecture

- **The end-state of the gravitational collapse of matter is a Kerr-Newman BH**

- **Kerr-Newman BH: 3 free parameters (mass M, Kerr parameter *a*, and electric charge Q)**

- **Condition for the existence of the horizon: $M^2 > a^2 + Q^2$**

Kerr metric with $|a| > M$

- If $M^2 < a^2 + Q^2$ there is no horizon → Naked singularity!
- Closed time-like curves: we can violate causality
- Cosmic Censorship Conjecture: naked singularity are forbidden

Is the CCC really necessary?

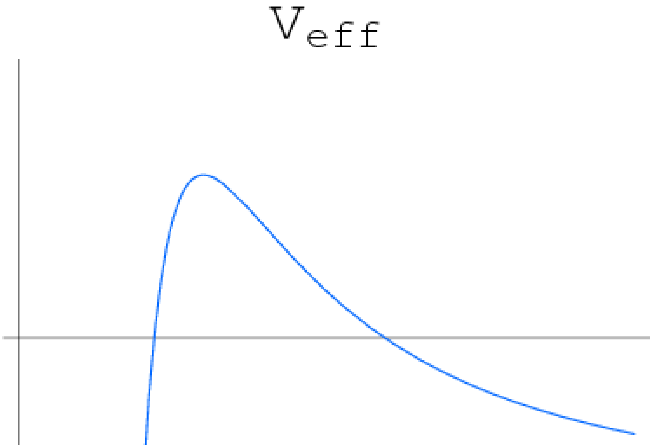
- **What is the "physical meaning" of the singularity at the center of BHs? It may be the symptom of the breakdown of classical GR and be solved at the quantum level/by a higher energy theory. In this case, there would be no reason to impose the bound M > |*a*|**

- **The possibility of violation of the Kerr Bound was first discussed in Horava & Gimon 2007 in the framework of string theories, but actually it may occur in any extension of GR**

Photon Orbits

- **Geodesic equations for massless particles**
- **3 constants of motion (Energy, component of the Angular Momentum parallel to the BH spin and Carter Constant). 2 constants determine the orbit**
- **Effective potential:**

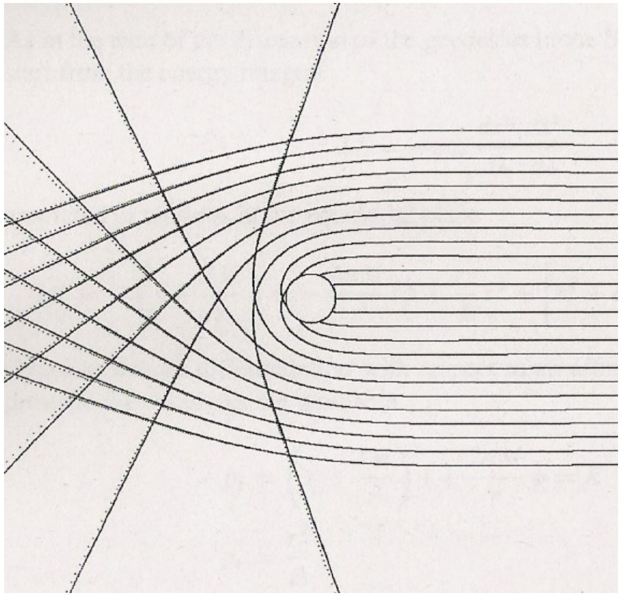
$$V_{eff}(r) = \frac{L^2}{2r^2} - \frac{mL^2}{r^3}$$



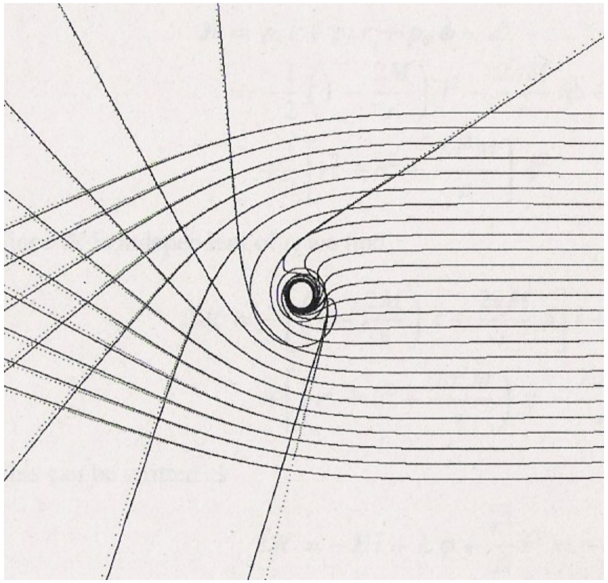
- **3 kinds of photon orbits: capture orbits, scattering orbits and unstable orbits of constant radius**

Null geodesics

Schwarzschild

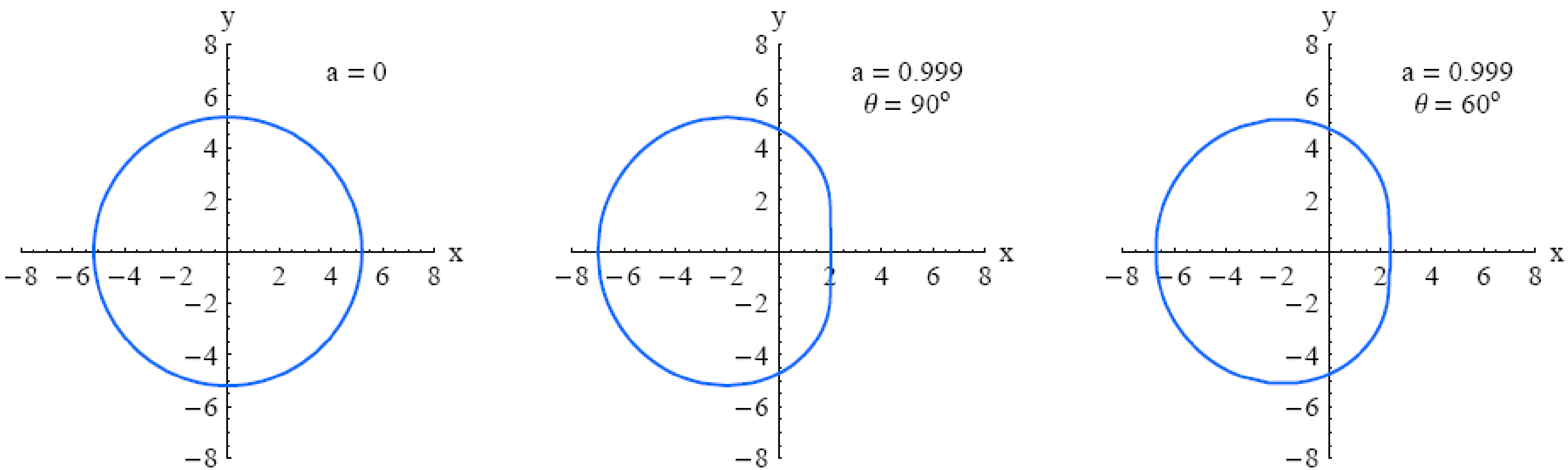


Kerr



Capture cross section

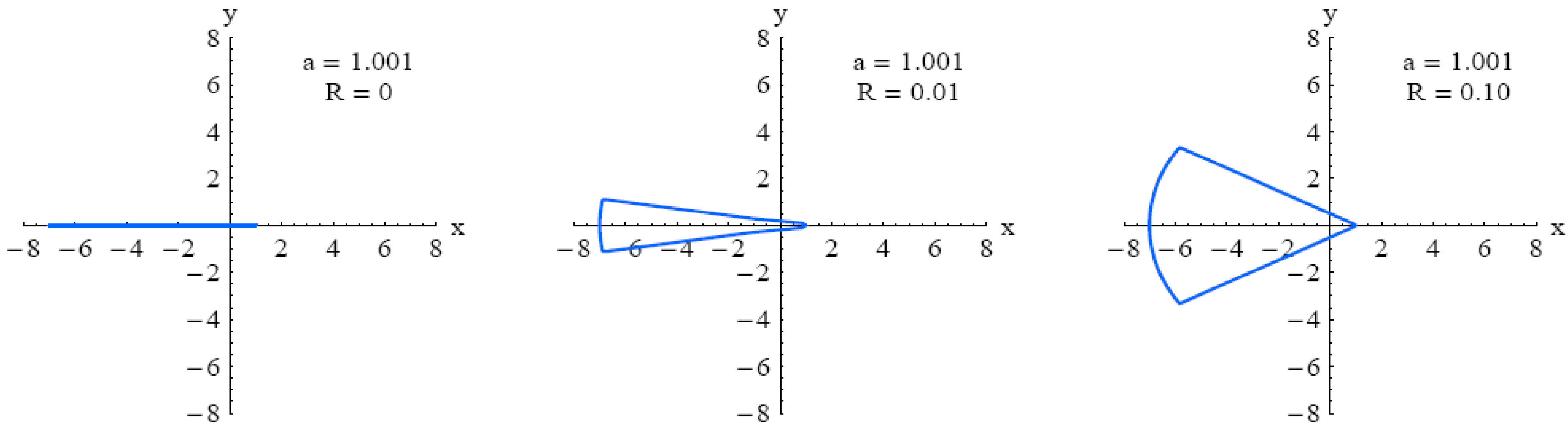
Apparent size:
Schwarzschild BH: about 10.4 M
Extremal Kerr BH: 9 M (for an observer on the equatorial plane)



From Bambi & Freese, PRD 79 (2009) 043002

Capture cross section

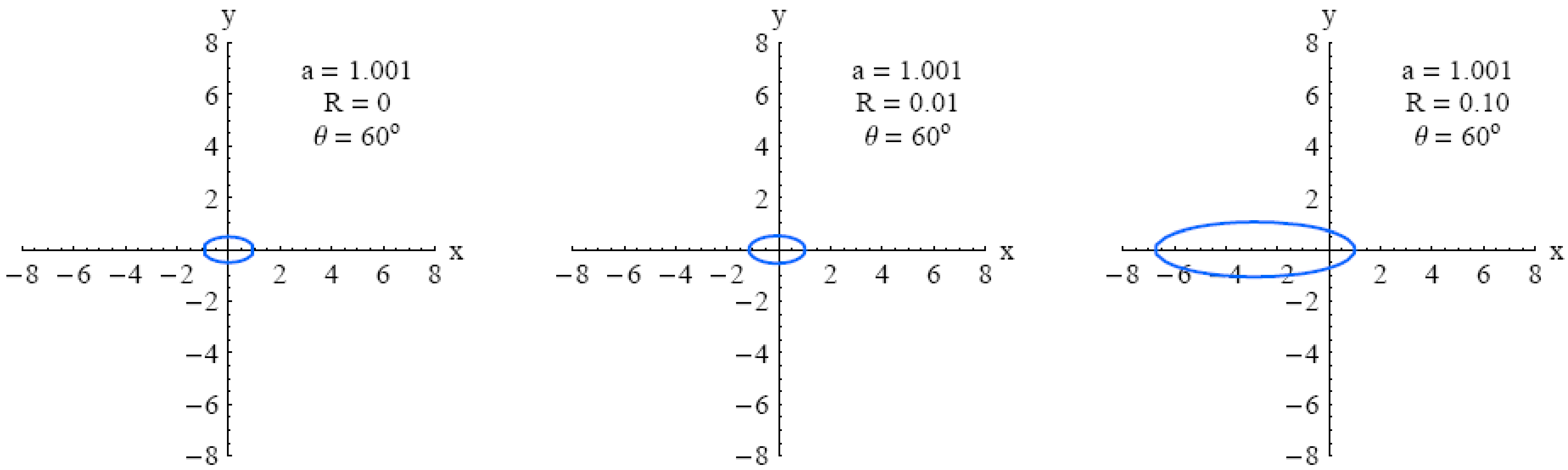
a/M = 1.001 (observer on the equatorial plane)



From Bambi & Freese, PRD 79 (2009) 043002

Capture cross section

a/M = 1.001 (observer not on the equatorial plane)



From Bambi & Freese, PRD 79 (2009) 043002

Connection between capture cross section and observations

- **Optically thick plasma**: we can observe the photosphere centered on the BH. The size of this photosphere cannot be smaller than the capture cross section of the BH
- **Optically (and geometrically) thin plasma**: we can observe the shadow of the BH; that is, a darker area surrounded by the photosphere centered on the BH. The shadow looks like the capture cross section of the BH

Recent Observations of Sgr A*

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LETTERS

Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

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The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation[1]. Sagittarius A* (Sgr A*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun[2,3]. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A*, where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering[4–7]. Here we report observations at a wavelength of 1.3 mm that set a size of 37^{+16}_{-10} microarcseconds on the intrinsic diameter of Sgr A*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of Sgr A* emission may not be centred on the black hole, but arises in the surrounding accretion flow.

The proximity of Sgr A* makes the characteristic angular size scale of the Schwarzschild radius ($R_{Sch} = 2GM/c^2$) larger than for any

uncertainties resulted in a range for the derived size of 50–170 μas (ref. 12).

On 10 and 11 April 2007, we observed Sgr A* at 1.3 mm wavelength with a three-station VLBI array consisting of the Arizona Radio Observatory 10-m Submillimetre Telescope (ARO/SMT) on Mount Graham in Arizona, one 10-m element of the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in Eastern California, and the 15-m James Clerk Maxwell Telescope (JCMT) near the summit of Mauna Kea in Hawaii. A hydrogen maser time standard and high-speed VLBI recording system were installed at both the ARO/SMT and CARMA sites to support the observation. The JCMT partnered with the Submillimetre Array (SMA) on Mauna Kea, which housed the maser and the VLBI recording system and provided a maser-locked receiver reference to the JCMT. Two 480-MHz passbands sampled to two-bit precision were recorded at each site, an aggregate recording rate of 3.84×10^9 bits per second (Gbit s^{-1}). Standard VLBI practice is to search for detections over a range of interferometer delay and delay rate. Six bright quasars were detected with high signal to noise on all three baselines allowing array geometry, instrumental delays and frequency offsets to be accurately calibrated. This calibration greatly reduced the search space for

Results

- **Intrinsic diameter of the radio source: 37^{+16}_{-10} μas at 3 sigma (modelling Sgr A* as a circular Gaussian brightness distribution)**

- **If Sgr A* were a spherically symmetric photosphere centered on the BH, one would expect a larger diameter**

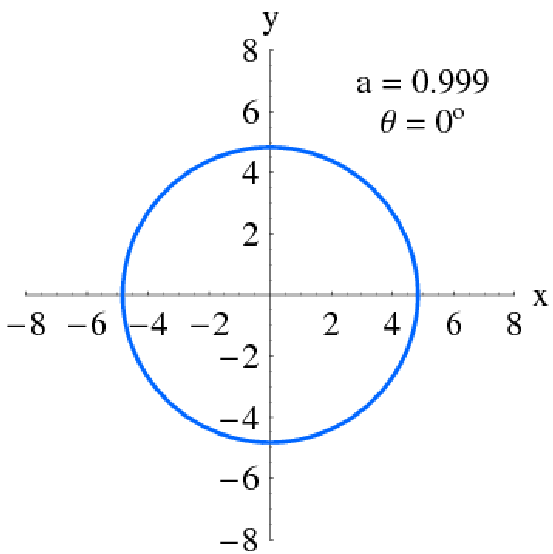
- **Schwarzschild BH: 10.4 M = 52 μas**

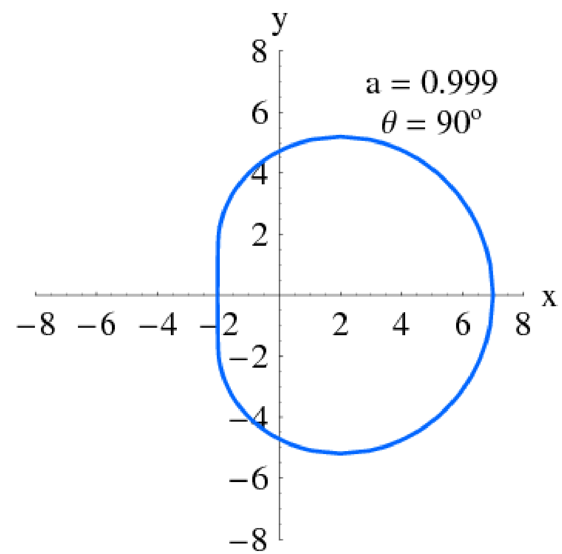
- **Extremal Kerr BH: 9 M = 45 μas**

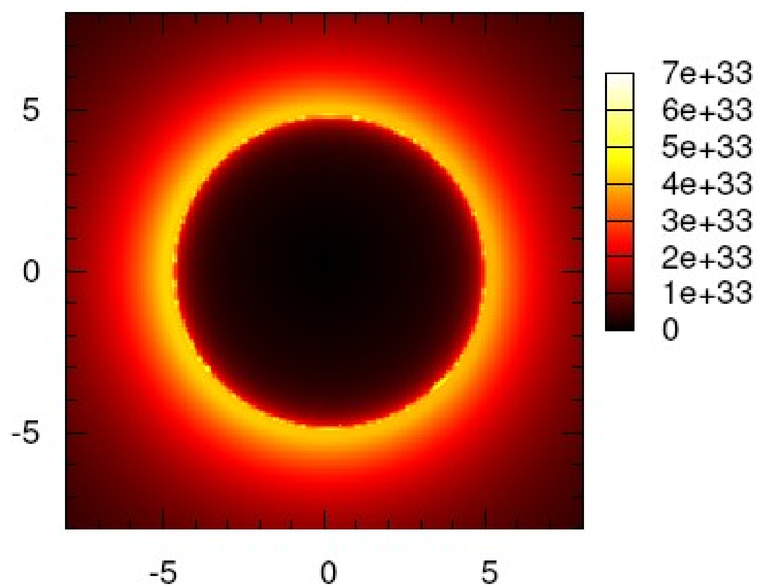
Interpretations

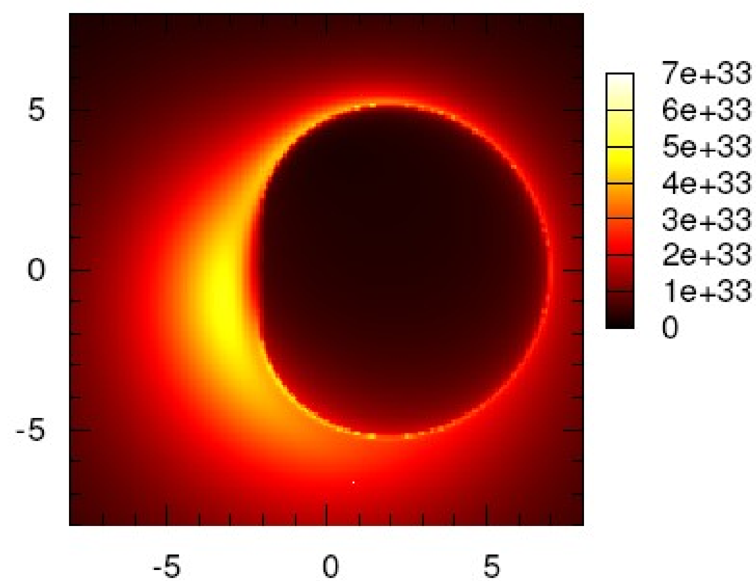
- **Current published data are not capable of absolute confirmation of such a measurement. Nevertheless, let us try to make some speculations...**
- **Doeleman et al.: the radio source is not centered at the BH. There are indeed models which predict an off-set between Sgr A* and the BH position**
- **Our proposal: the radio emission region is a photosphere centered on the BH, but the BH violates the bound M > $|a|$ and Sgr A* may thus have an apparent size smaller than 45 μas**

Direct Image (M > |*a*|)

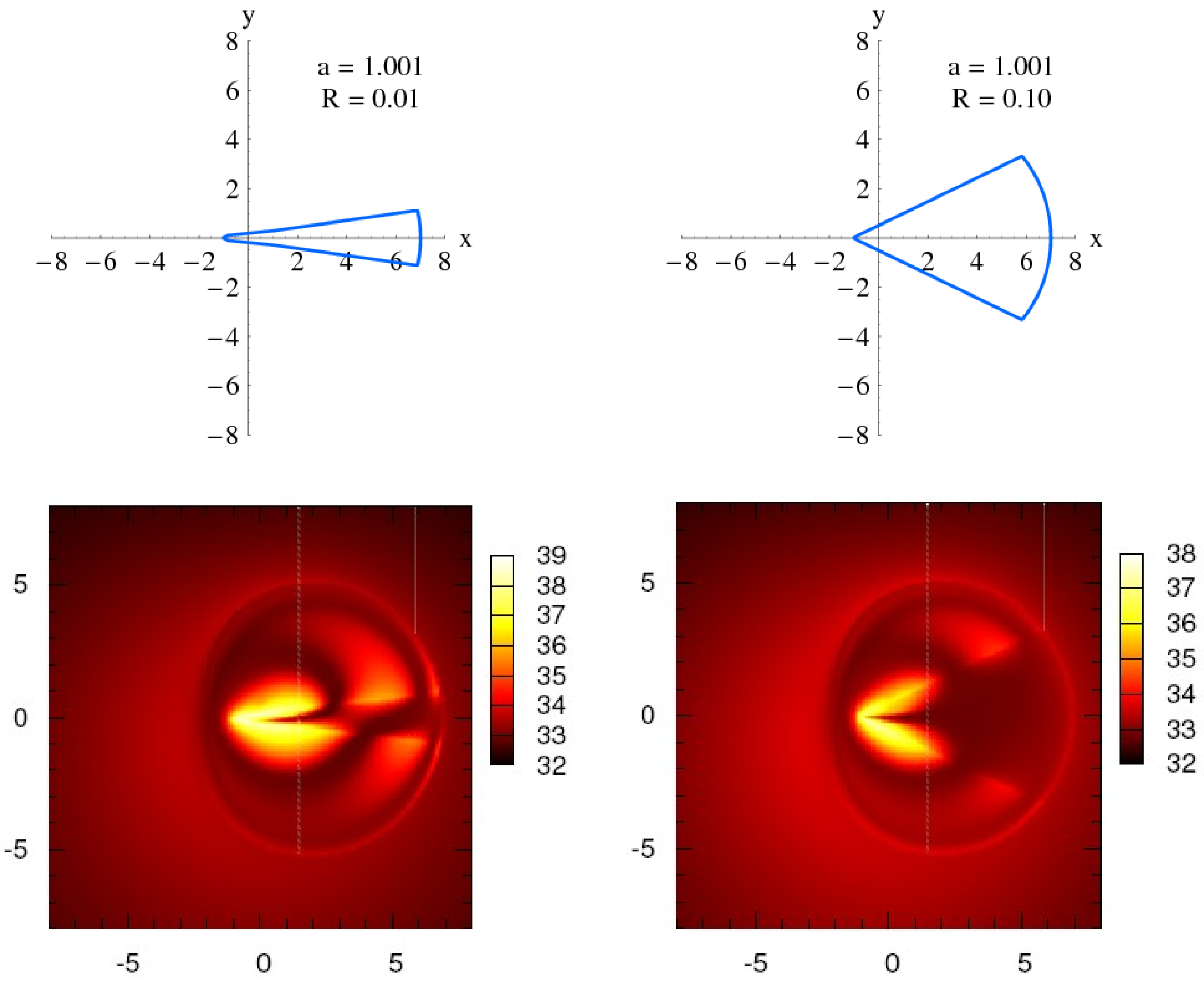




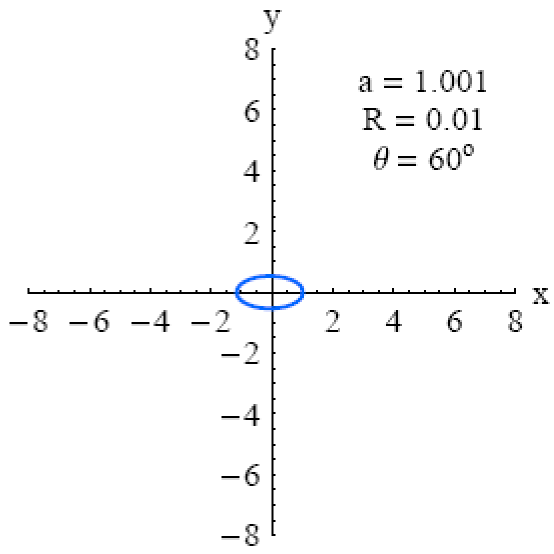


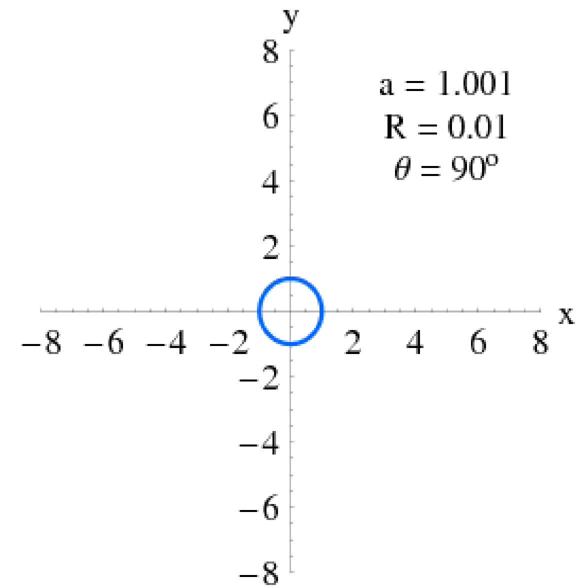


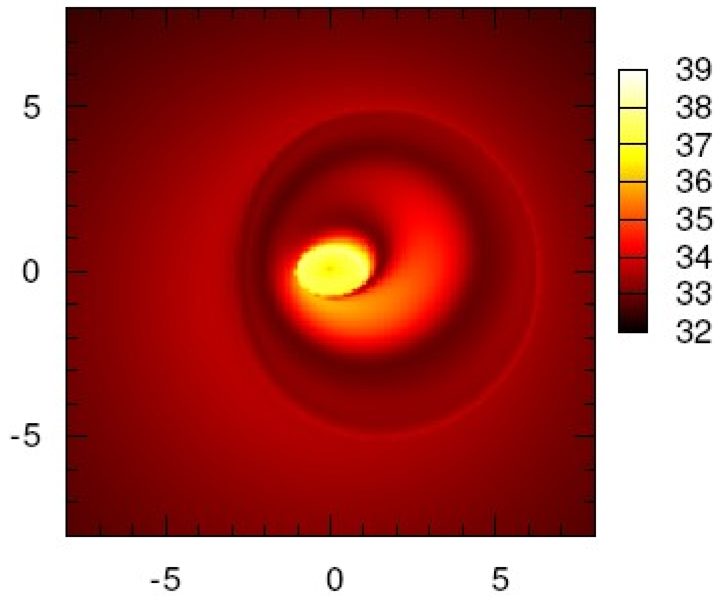
Direct Image ($M < |a|$)

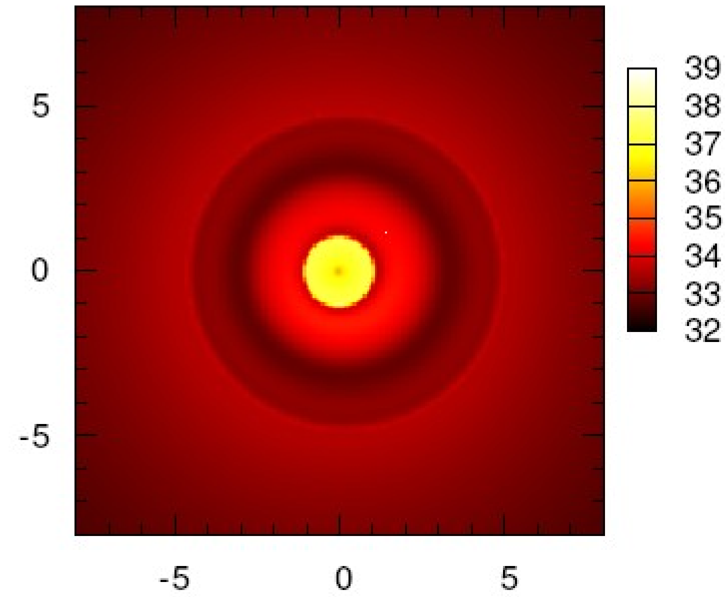


Direct Image (M < |*a*|)









Future Studies

- **Simulations of the accretion flow around a super-spinning objects**

- **Prediction of spectrum and polarization**

- **The spectrum is mainly determined by the accretion model, but standard models of accretion around BHs cannot naturally explain the high energy contribution (see e.g. Pian et al., 2002). Accretion around more compact objects may be more natural!**

- **Polarization features are strongly affected by GR effects**

Conclusions

- **Today we know the existence of objects which are the end-state of the gravitational collapse of matter. They are "normal" BHs if the Carter-Israel Conjecture is correct**

- **The singularity at the center of BHs is likely unphysical. The bound $M > |a|$ may be violated**

- **The relation $M > |a|$ could be tested in the near future, by observing the shadow of the BH candidate in the Galactic Center**