Probing the space-time around astrophysical black hole candidates with future VLBI experiments

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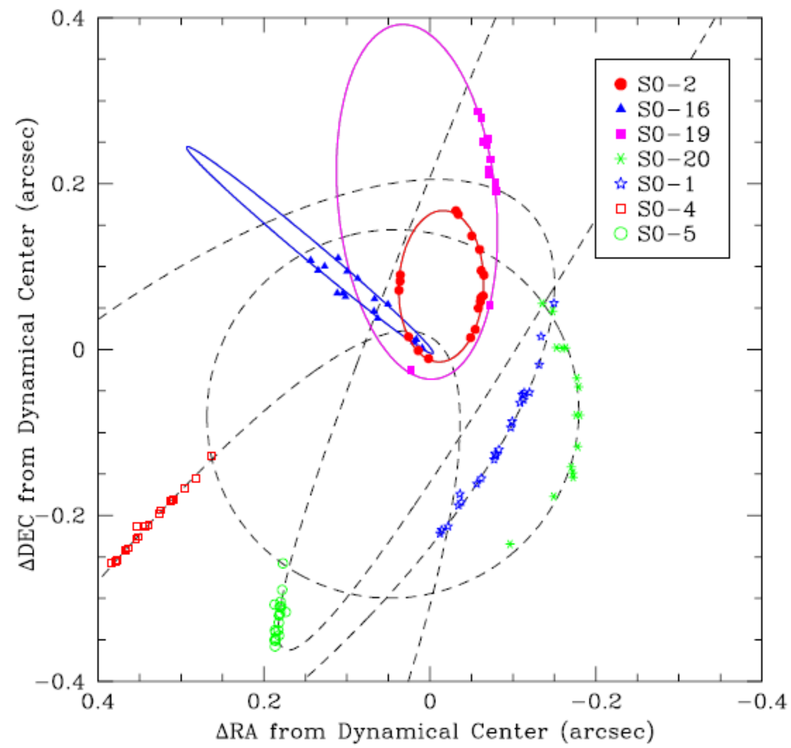
Observational evidences of super-massive black holes

- Super-massive object in the Galactic Center
- 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

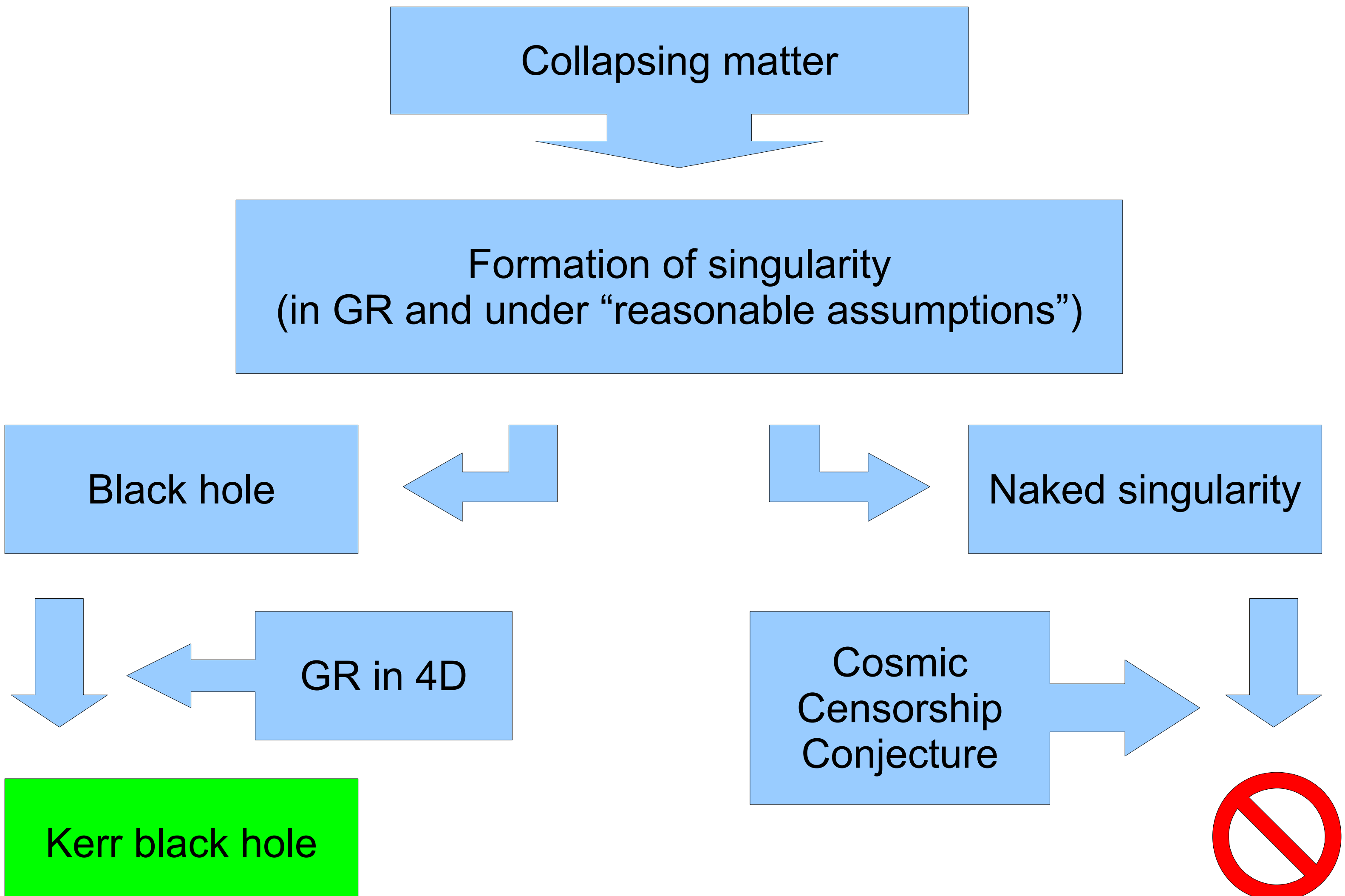
Observational evidences of stellar-mass black holes

- **Dark objects in X-ray binary systems**
- **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

Carter-Israel Conjecture



Counterexamples violating the Cosmic Censorship Conjecture

- D. Christodoulou, Commun. Math. Phys. 93 (1984) 171
- A. Ori & T. Piran, Phys. Rev. D 42 (1990) 1068
- P.S. Joshi & I.H. Dwivedi, Phys. Rev. D 47 (1993) 5357
- D. Christodoulou, Annals Math. 140 (1994) 607
- I.H. Dwivedi & P.S. Joshi, Commun. Math. Phys. 166 (1994) 117
- S.S. Deshingkar, I.H. Dwivedi & P.S. Joshi, Phys. Rev. D 59 (1999) 044018

Chronology Protection in Supergravity

- **E.K. Boyda et al., Phys. Rev. D 67 (2003) 106003**
- **D. Israel, JHEP 01 (2004) 042**
- **N. Drukker, Phys. Rev. D 70 (2004) 084031**
- **E.G. Gimon & P. Horava, arXiv:hep-th/0405019**

CLAIM: Formation of domain wall. Across the domain wall, the metric is non-differentiable and the expected region with closed time-like curves arises from the naive continuation of the metric ignoring the domain wall.

Tomimatsu-Sato space-times [A. Tomimatsu & H. Sato, PTP 50 (1973) 95]

- **3 parameters: mass (M), spin (J), and deformation parameter (delta)**
- **delta = 1 (Kerr space-time)**
- **Quadrupole moment:**

$$Q = \left(q^2 + \frac{\delta^2 - 1}{3\delta^2} p^2 \right) M^3$$

Delta = 2 Tomimatsu-Sato space-time

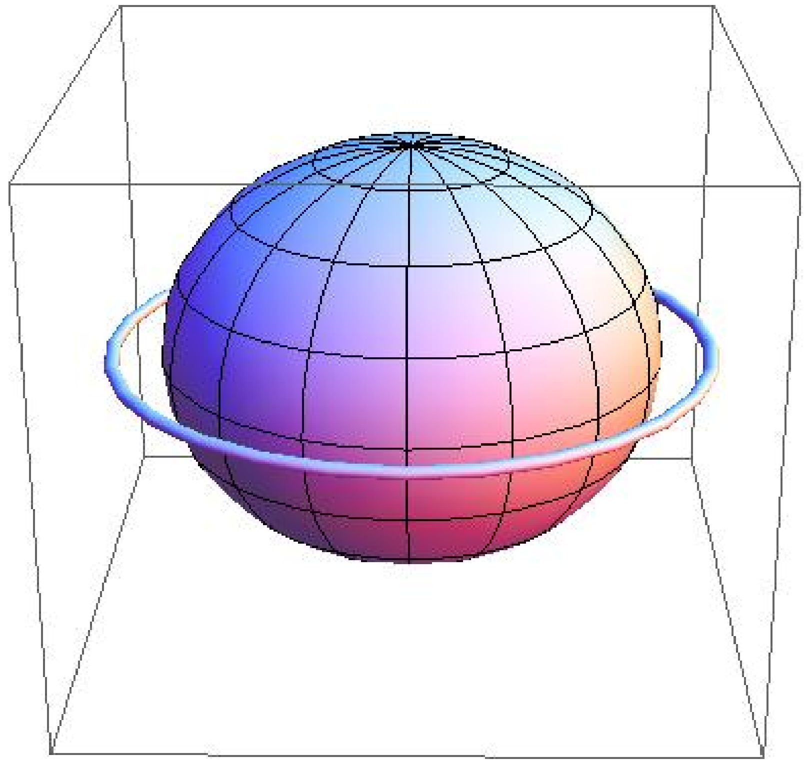
$$ds^2 = -f\left(dt - \omega d\phi\right)^2 + \frac{1}{f}\left[e^{2\gamma}\left(d\rho^2 + dz^2\right) + \rho^2 d\phi^2\right]$$

$$p^2 + q^2 = 1\,, \qquad q = \frac{J}{M^2}\,, \qquad \sigma = \frac{Mp}{\delta}$$

$$f = \frac{A}{B}\,, \qquad \omega = \frac{2Mq(1-y^2)C}{A}\,, \qquad e^{2\gamma} = \frac{A}{p^{2\delta}(x^2-y^2)^{\delta^2}}$$

$$\begin{aligned}
A &= p^4(x^2-1)^4 + q^4(1-y^2)^4 - 2p^2q^2(x^2-1)(1-y^2)\left[2(x^2-1)^2 + 2(1-y^2)^2 + 3(x^2-1)(1-y^2)\right] \\
B &= \left[p^2(x^2+1)(x^2-1) - q^2(1+y^2)(1-y^2) + 2px(x^2-1)\right]^2 + 4q^2y^2\left[px(x^2-1) + (px+1)(1-y^2)\right]^2 \\
C &= -p^3x(x^2-1)\left[2(x^2+1)(x^2-1) + (x^2+3)(1-y^2)\right] - p^2(x^2-1)\left[4x^2(x^2-1) + (3x^2+1)(1-y^2)\right] \\
&\quad + q^2(px+1)(1-y^2)^3\,.
\end{aligned}$$

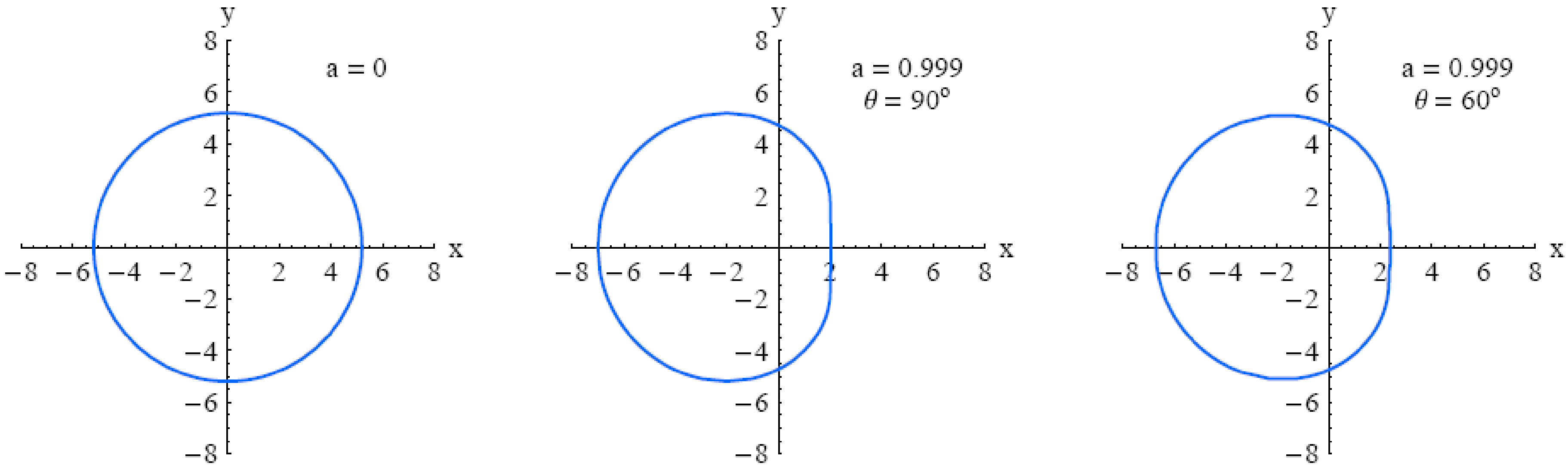
Delta = 2 Tomimatsu-Sato space-time



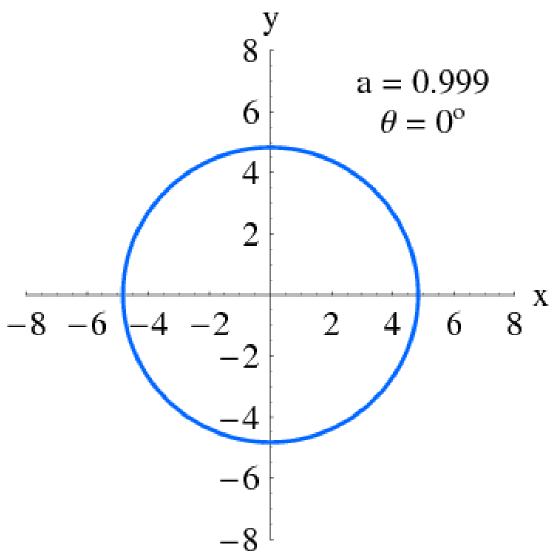
See Kodama & Hikida, CQG 20 (2003) 5121

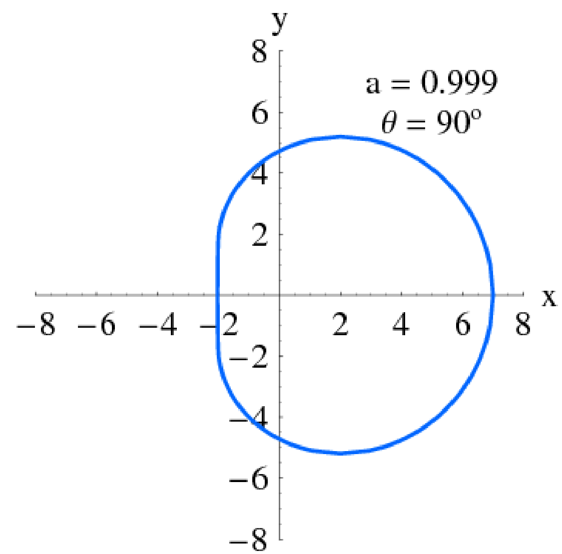
Capture cross section

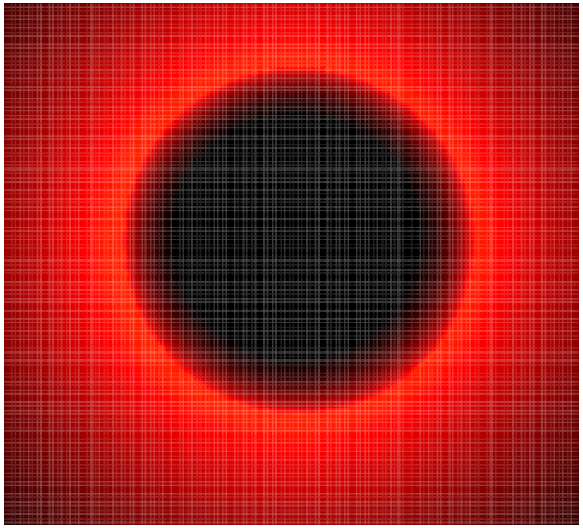
Apparent size:
Schwarzschild BH: about 10.4 M
Extremal Kerr BH: 9 M (for an observer on the equatorial plane)

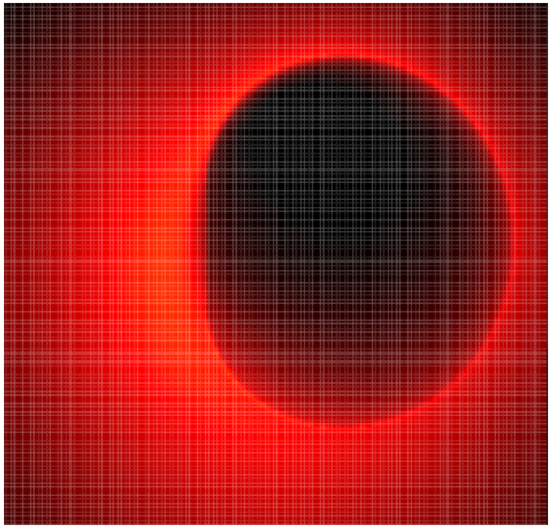


Direct Image

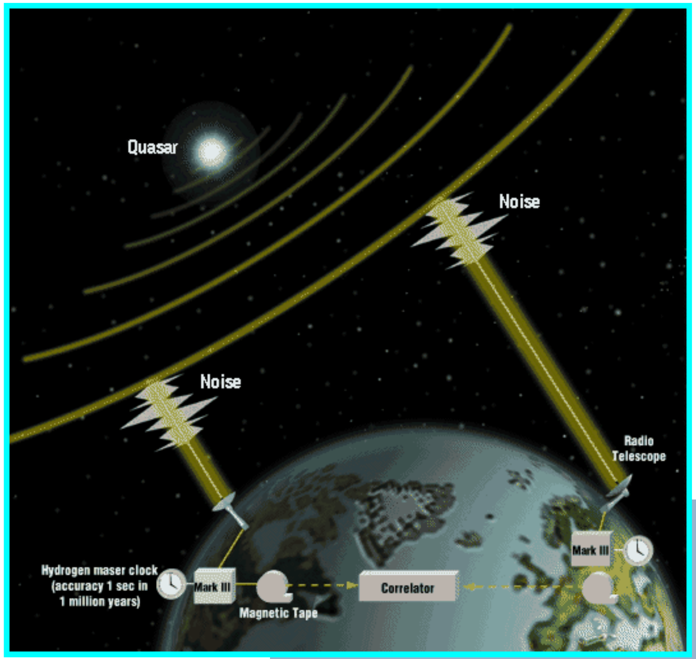


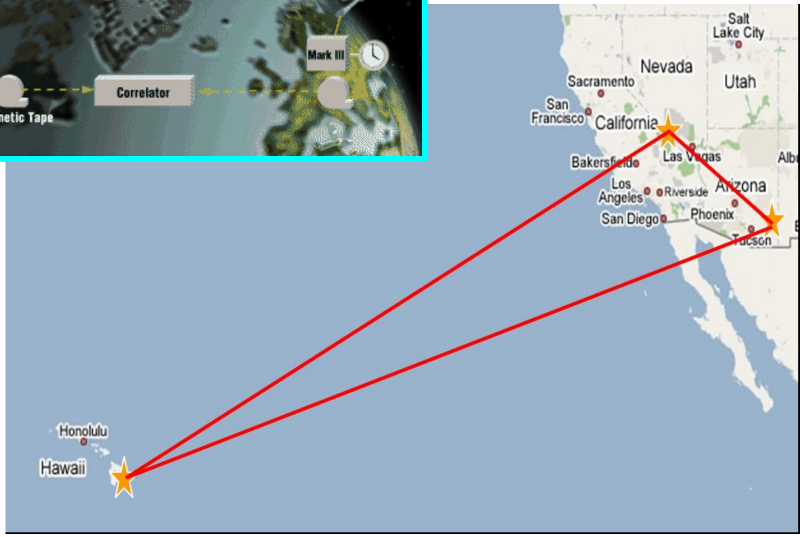


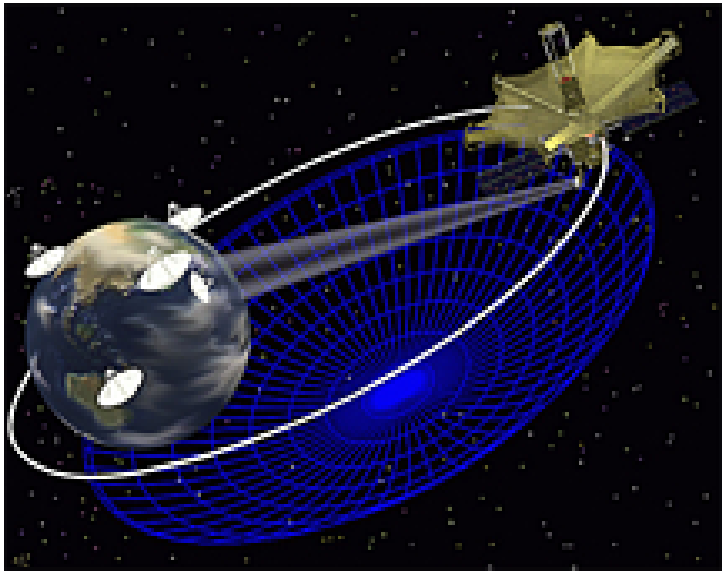




VLBI observatories



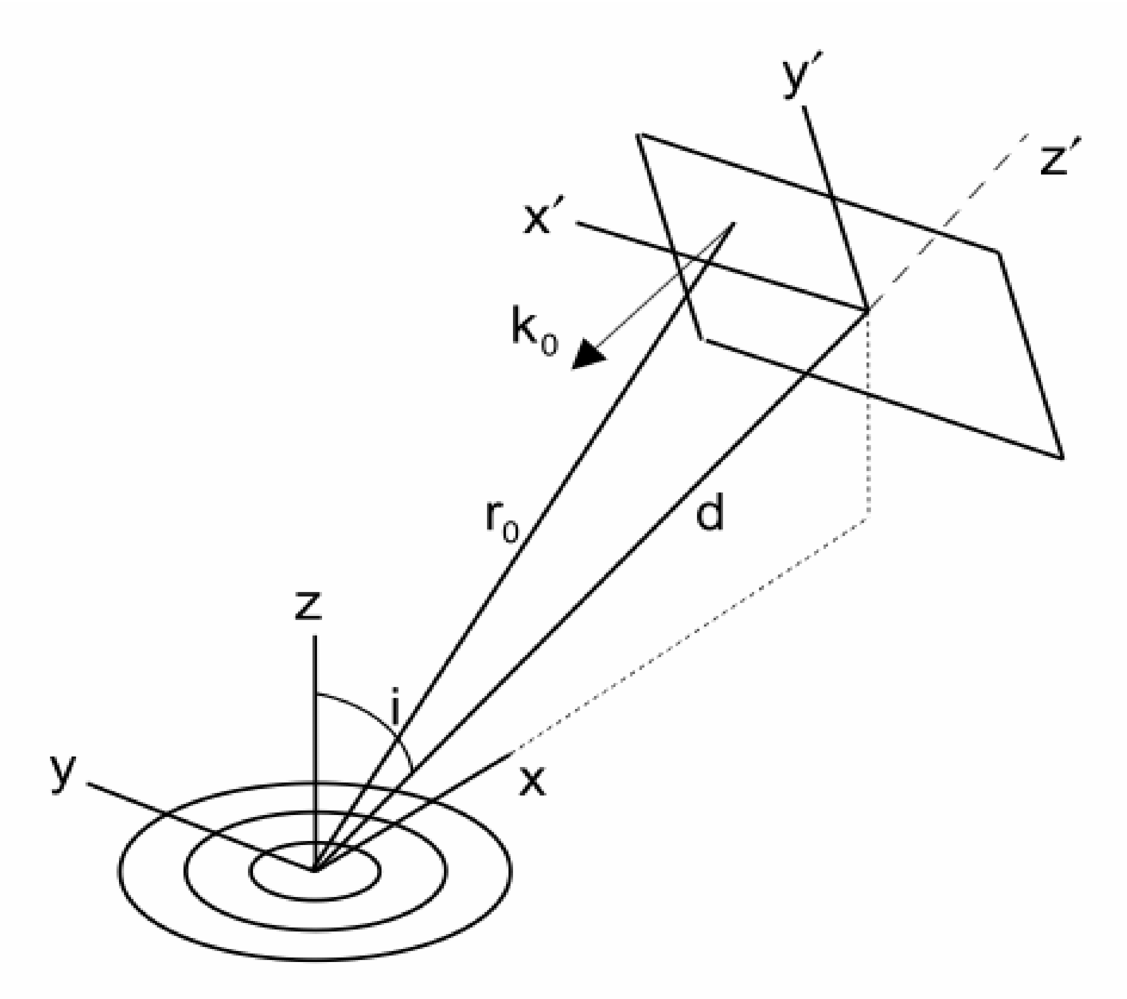




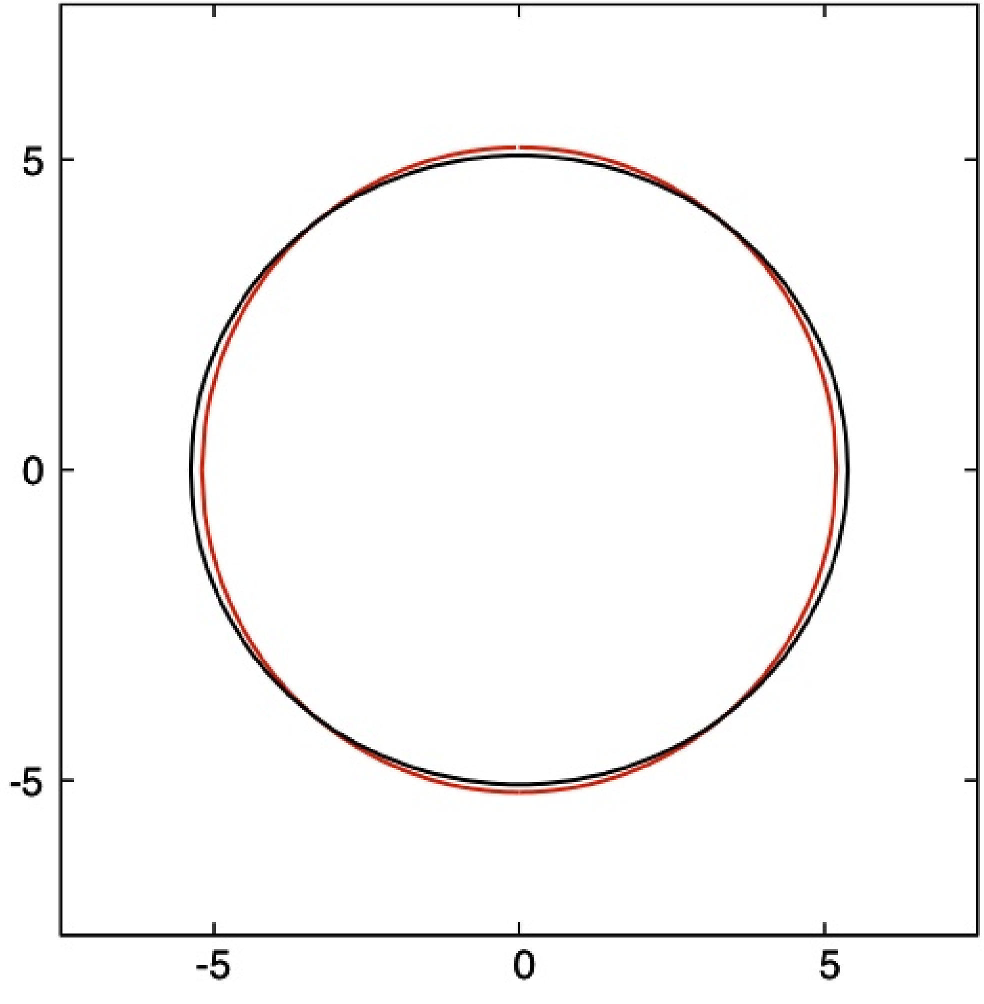
VSOP

Doeleman's group

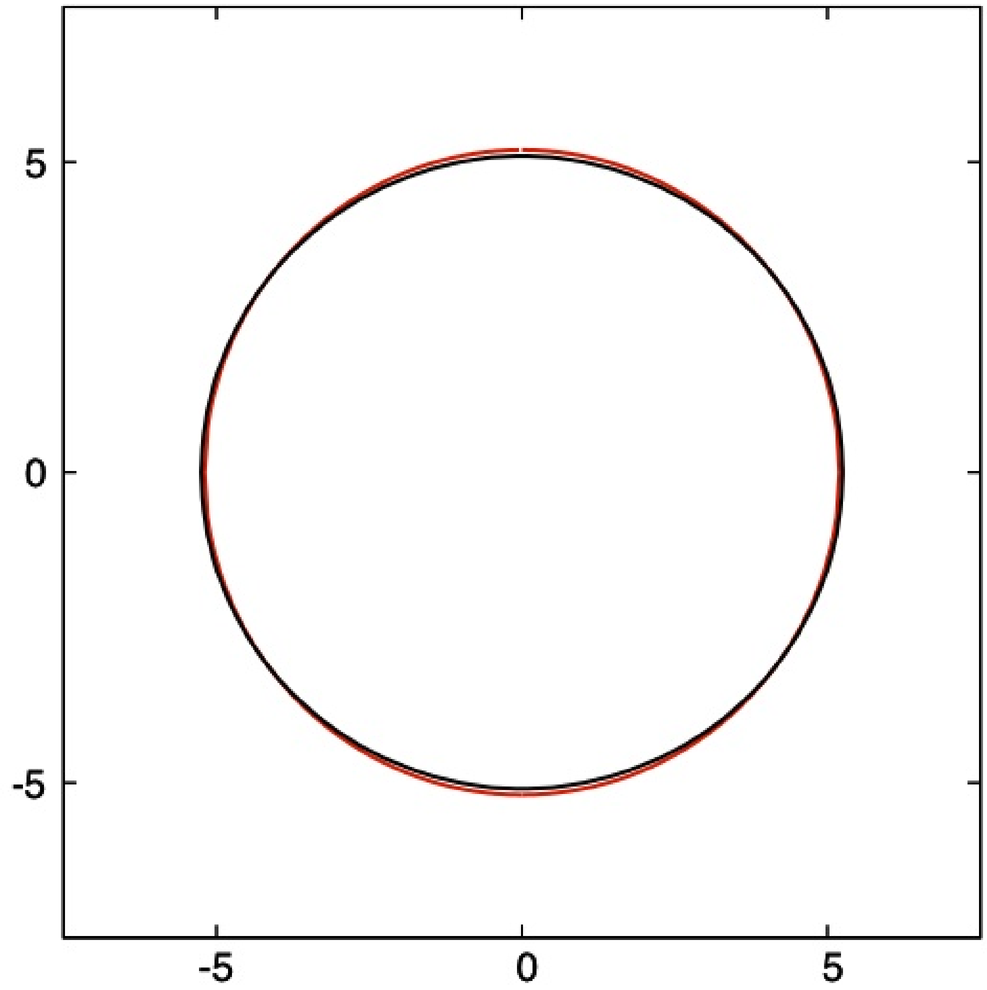
Set-up



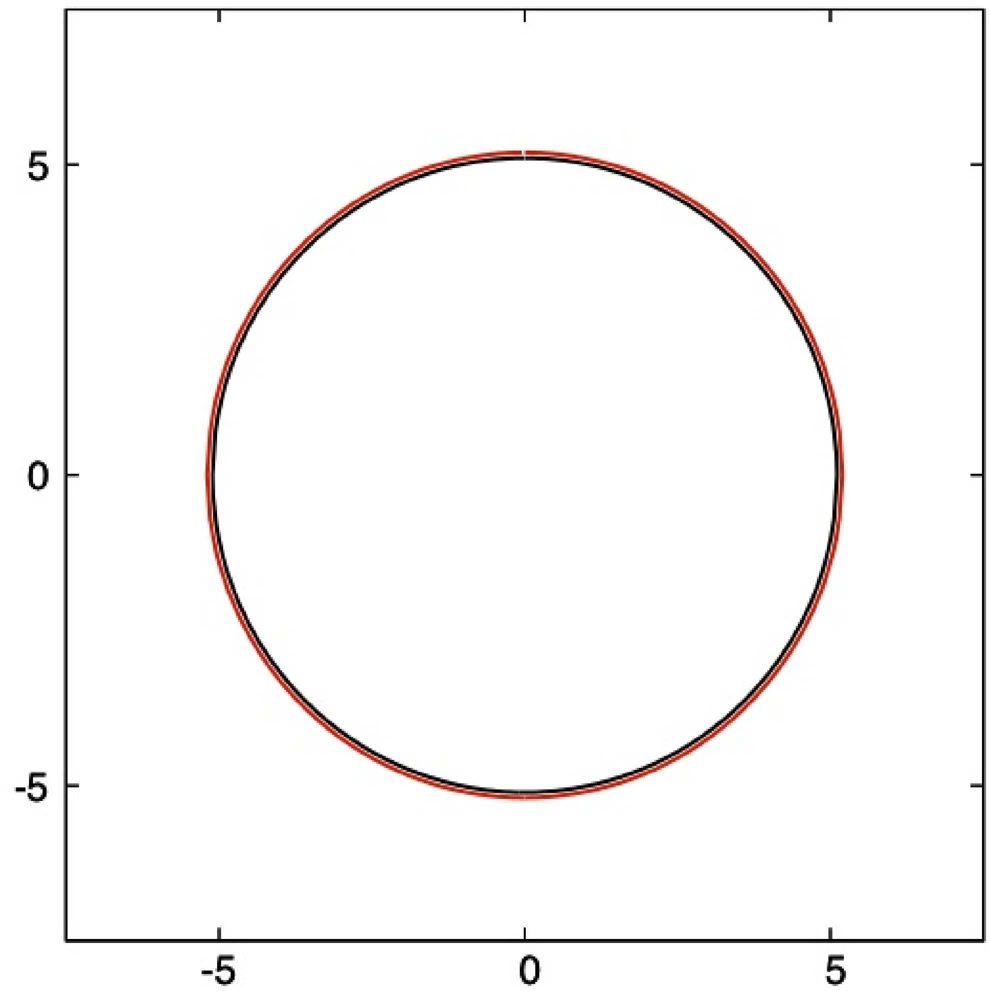
Shadow: q=0, i=90º



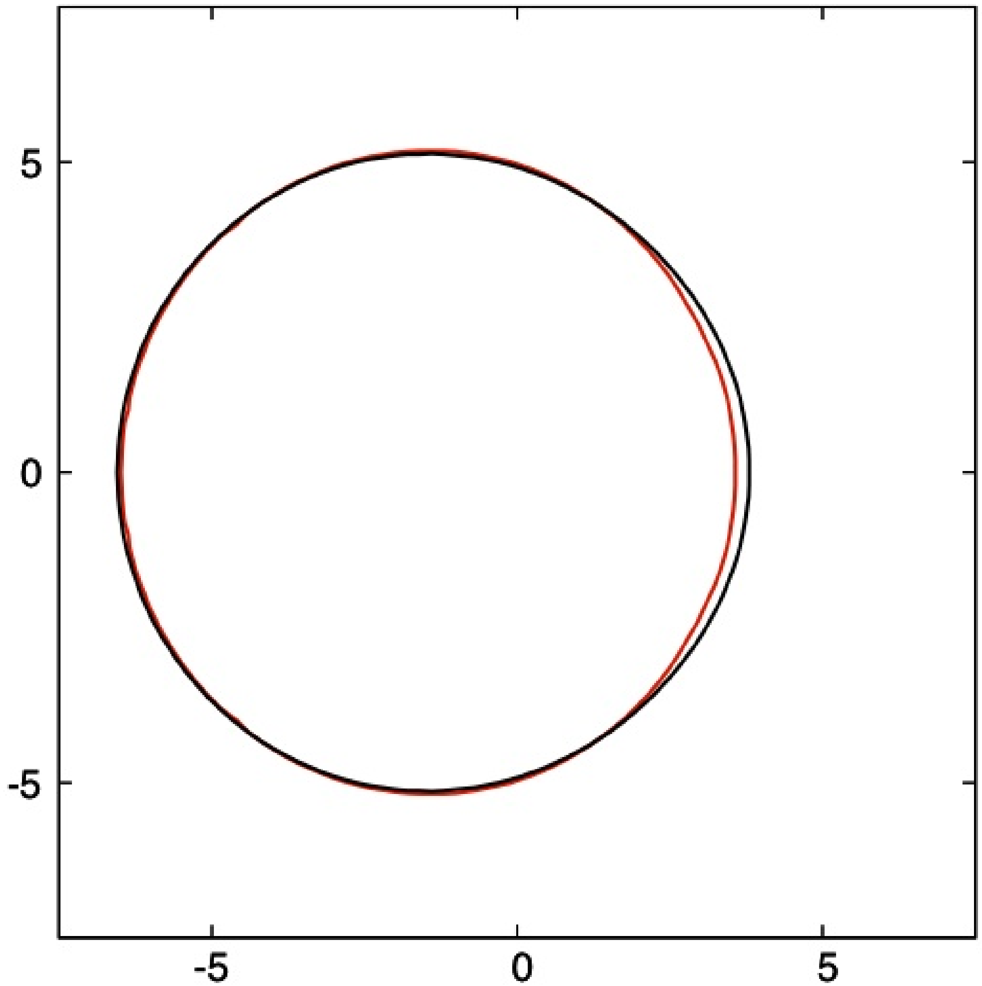
Shadow: q=0, i=45º



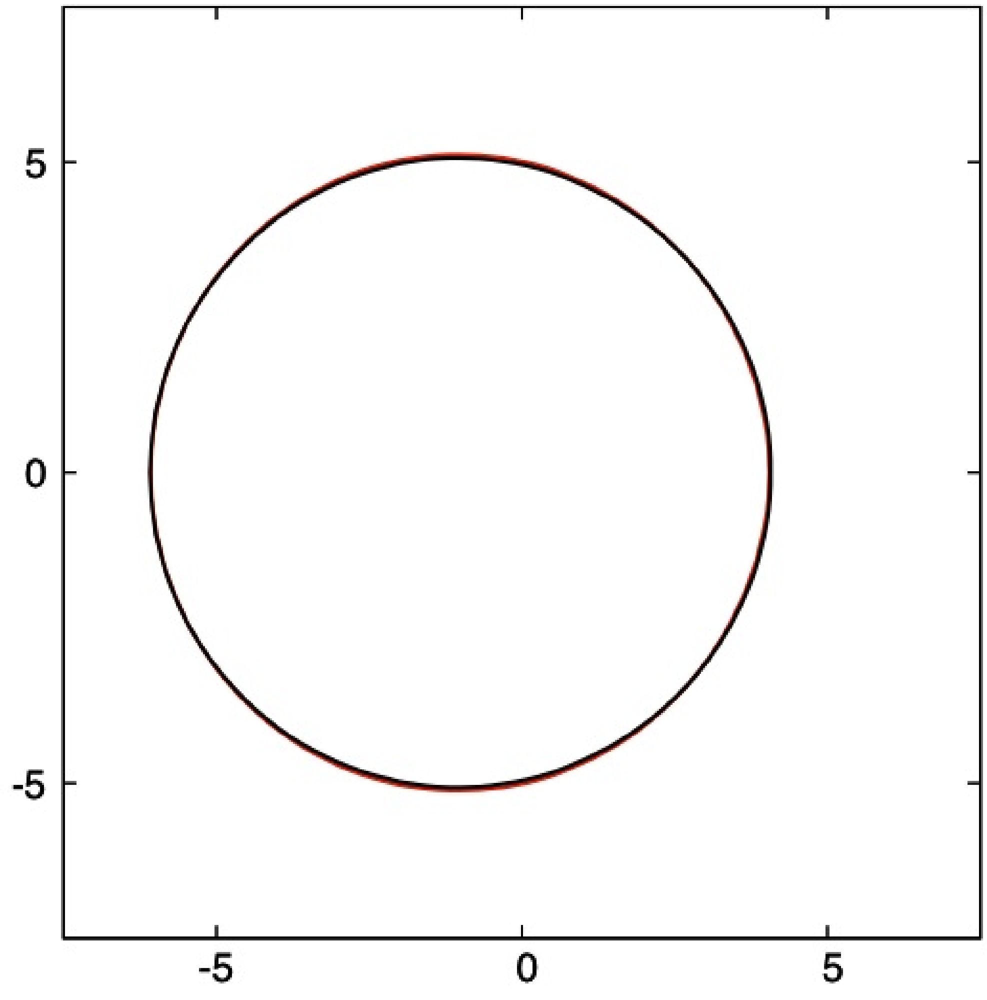
Shadow: q=0, i=0º



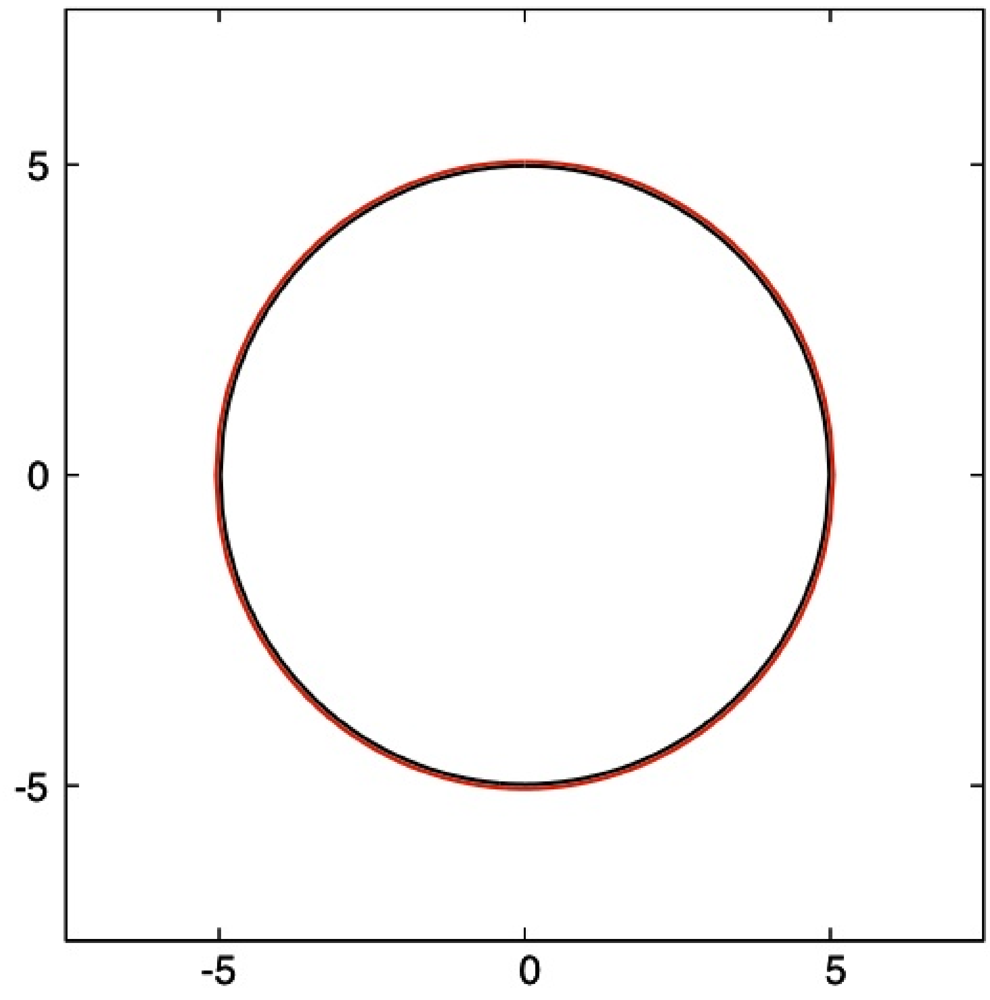
Shadow: q=0.7, i=90º



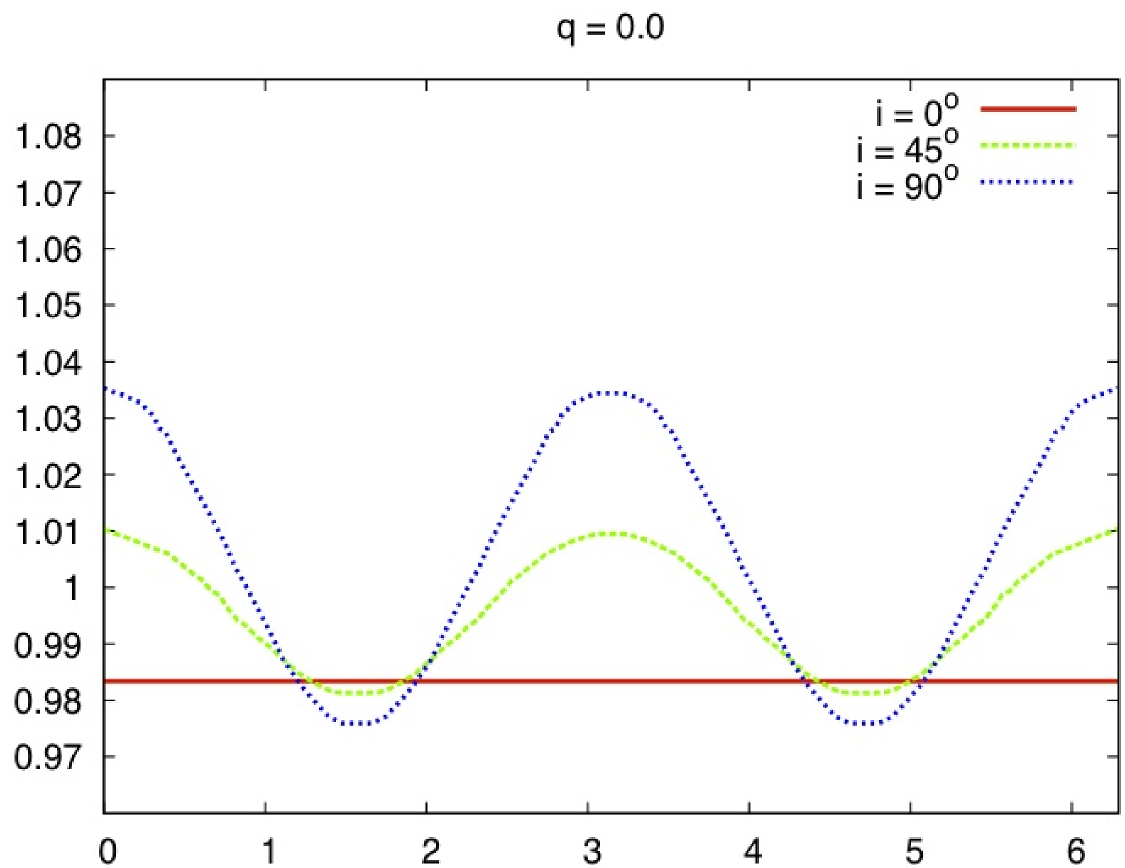
Shadow: q=0.7, i=45º



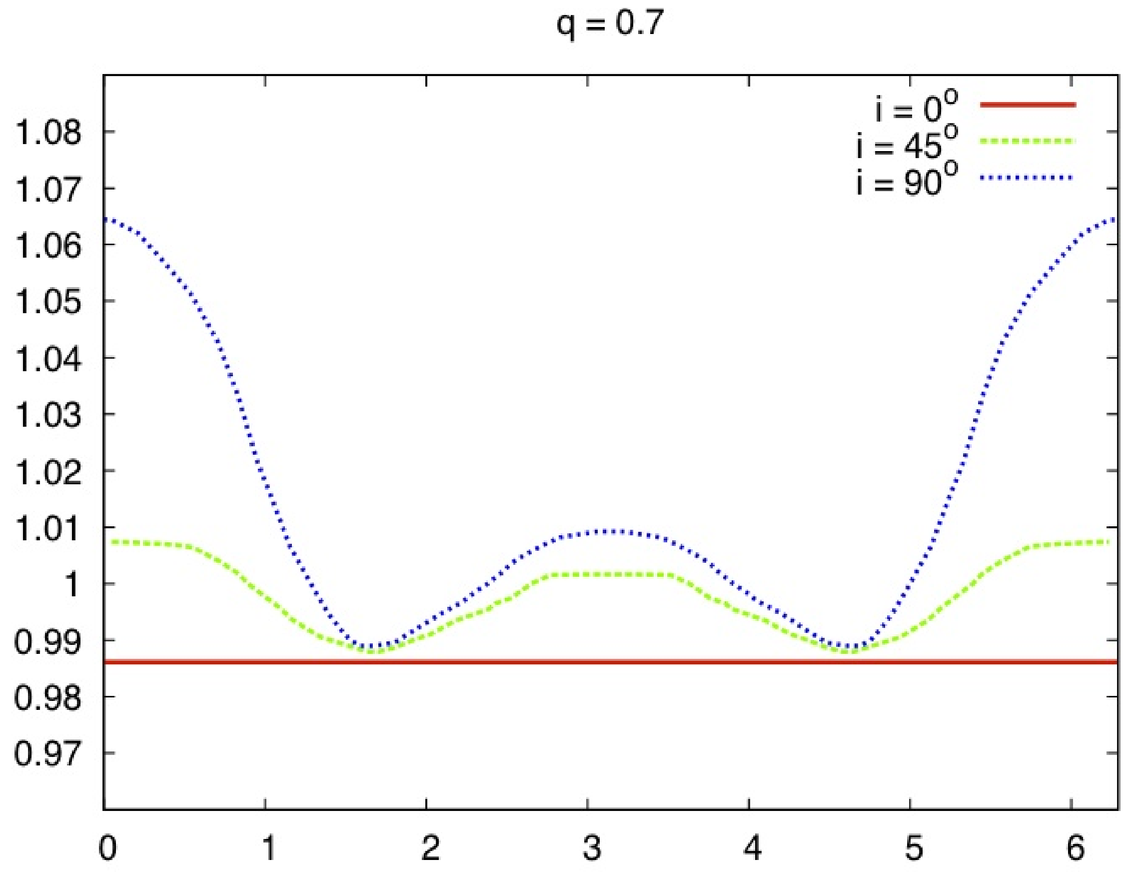
Shadow: q=0.7, i=0º



R_{TS2}/R_{Kerr}


q = 0.0
i = 0°
i = 45°
i = 90°
1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0
1
2
3
4
5
6

R_{TS2}/R_{Kerr}



q = 0.7
i = 0°
i = 45°
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1.08
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
0
1
2
3
4
5
6

A couple of comments

- **The two shadows are quite similar**
- **No features associated to the ring singularity of TS2**
- **Deviations from the Kerr metric at the level of a few per cent**
- **Near future ground based experiments or space missions like VSOP-2 will not be able to detect any difference. With more advanced space missions, like VSOP-3, it is still challenging, but not out of reach**

Conclusions

- **At present there are no evidences that the final product of the gravitational collapse is a Kerr black hole**
- **To test the Kerr metric, we need to probe the space-time very close to the massive object. Deviations from the Kerr metric, if any, are small!**
- **Future VLBI experiments can be used to test strong gravity**
- **The Tomimatsu-Sato space-times are the simplest generalization of the Kerr metric. They represent the gravitational field of spinning and deformed mass**
- **Future space missions like VSOP-3 have the capability of testing the Kerr metric**