Title: Testing the Nature of Black Hole Candidates

Date: Jul 21, 2011 01:00 PM

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Abstract: Today there is robust observational evidence of dark and compact objects in X-ray binary systems with a mass of 5-20 $M_\odot$ and in galactic nuclei with a mass of $10^5 - 10^9$ $M_\odot$. The conjecture is that all these objects are the Kerr black holes predicted by General Relativity, as they cannot be explained otherwise without introducing new physics. However, there are no directs observational evidences. In this talk, I discuss how the Kerr black hole hypothesis can be tested with present and future X-ray data and the current constraints on the nature of this objects.

Plan of the Talk

- Observational evidences of black holes
- How can we test the Kerr black hole hypothesis?
- Results

- References:

Cosimo Bambi & Enrico Barausse, ApJ 731, 121 (2011)

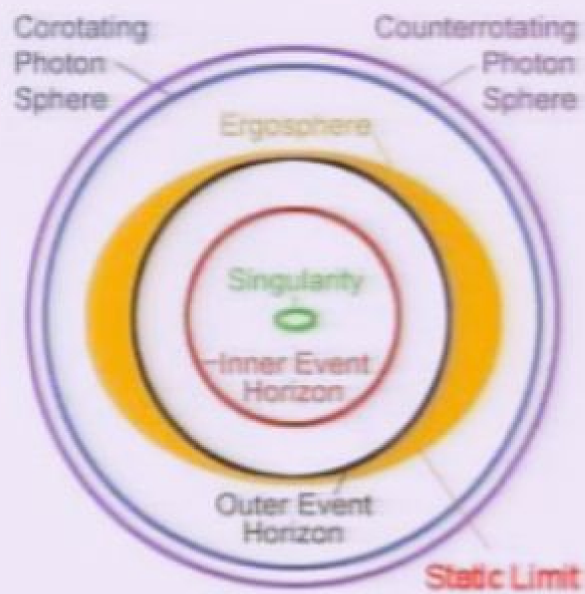
Cosimo Bambi, EPL 94, 50002 (2011)

Cosimo Bambi, PRD 83, 103003 (2011)

Cosimo Bambi, JCAP 05 (2011) 009

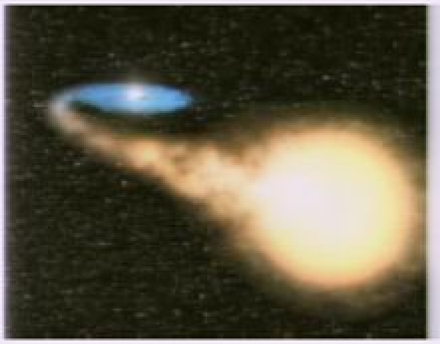
Black Holes in General Relativity

- Final product of the gravitational collapse → Black hole
- 4D → Kerr black hole
- Only 2 parameters: the mass M and the spin J ($a_* = J/M^2$)
- Kerr bound: $|a_*| < 1$
- Thorne bound: $|a_*| < 0.998$

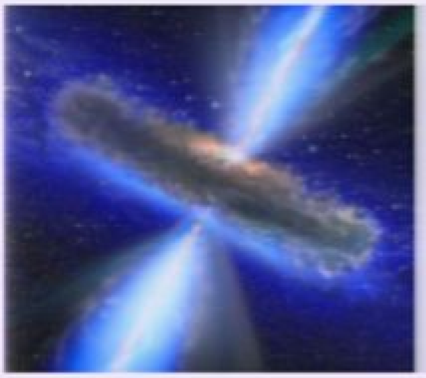


Astrophysical black hole candidates

- Stellar-mass BH candidates in X-ray binary systems (5 – 20 Solar masses)



- Super-massive BH candidates in galactic nuclei (10^5 – 10^9 Solar masses)



- Intermediate-mass BH candidates in ULXS (10^2 – 10^4 Solar masses?)

Stellar-mass BH candidates

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

- **Mass function:** $f(M_{BH}) = \frac{K^3 T}{2\pi G_N} = \frac{M_{BH}^3 \sin^3 i}{(M_{BH} + M_c)^2}$ $\quad K = v \sin i$

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

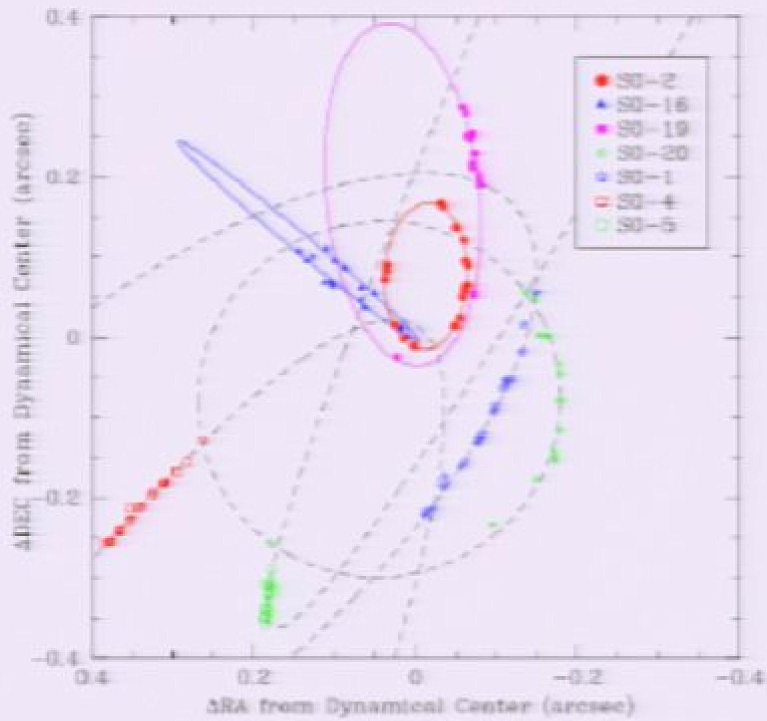
- **Maximum mass for relativistic stars about 3 Solar masses (see Rhoades & Ruffini 1974 and Kalogera & Baym 1996)**

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

Super-massive BH candidate in the Galaxy

- We study the orbital motion of individual stars
- Point-like central object with a mass of 4×10^6 Solar masses
- Radius < 45 AU (600 R_{Sch})



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

How can we test the Kerr BH hypothesis?

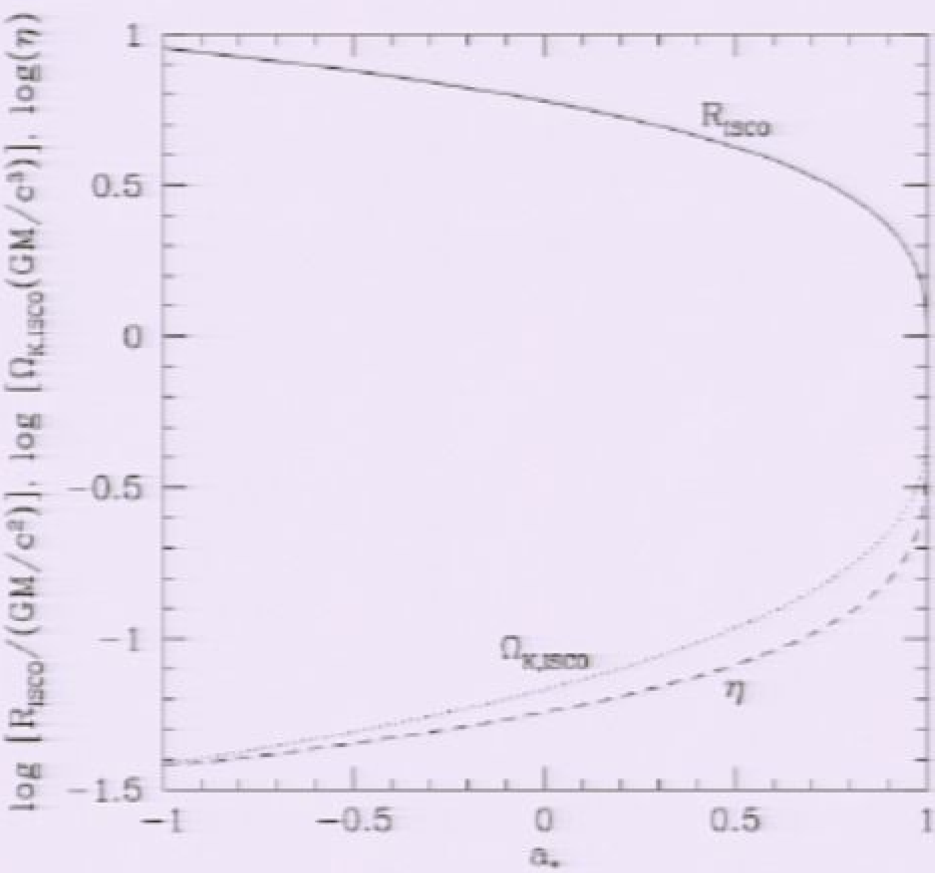
- We can consider a more general object described by three or more parameters. For example: mass M, spin J, deformation parameter D ($D = 0 \rightarrow$ Kerr metric)

- We check that astrophysical data favor $D = 0$

- The Kerr bound does not hold and a_* may exceed 1

Current approaches to estimate the spin

- Continuum fitting method
- Relativistic iron line
- Radiative efficiency



Accretion luminosity

- Energy radiated by a compact object as a consequence of the accretion process: $L = \eta\, dM/dt\, c^2$
- $\eta < 1 - E_{ISCO}$
- A reliable estimate of dM/dt is usually quite problematic

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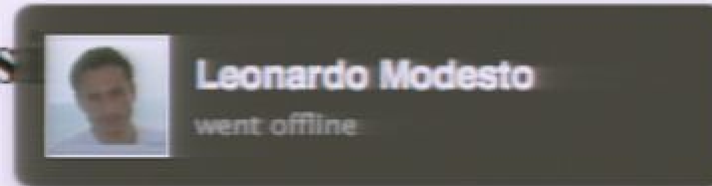

- Energy radiated by a compact object as a consequence of the accretion process: $L = eta\ dM/dt\ c^2$
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Mean radiative efficiency of AGN

- Observed X-ray background at 30 keV + Quasar spectral energy distribution → Total contribution of quasar luminosity to the mean energy density of the Universe (u)
- Study of super-massive black hole candidates in nearby galaxies → Mean energy density of black holes in the contemporary Universe (rho)
- These objects aquire most of their mass through the accretion process: eta = u/rho

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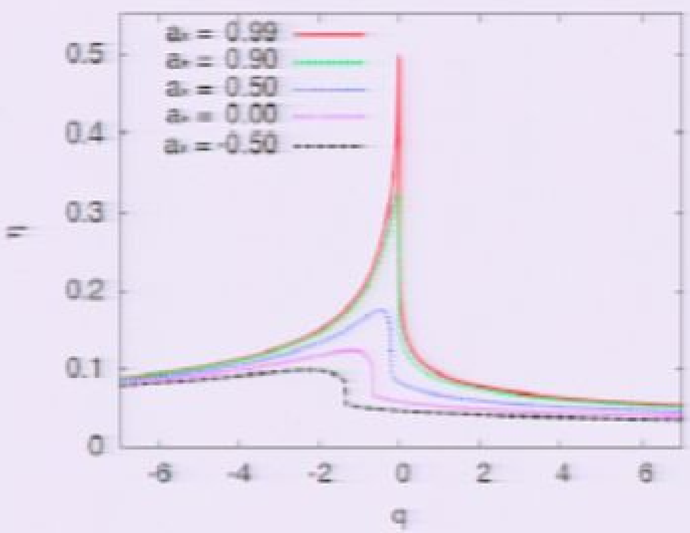
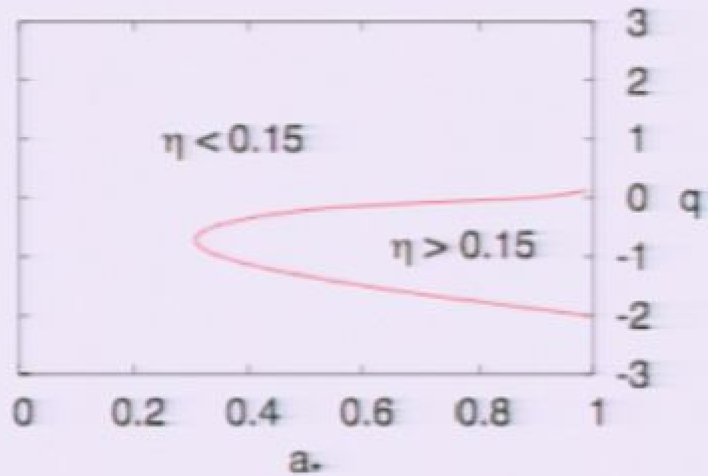
Constraint on the quadrupole moment of super-massive black hole candidates





$-2.00 < q < 0.14$

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Processes determining the value of the spin parameter

- Process of BH formation (irrelevant for super-massive BHs)
- Minor merger
- Major merger
- Gas accretion

Spin-up from gas accretion

- **Accretion from a thin disk**

$$\frac{da_*}{d\ln M} = \frac{1}{M}\frac{L_{\rm ISCO}}{E_{\rm ISCO}} - 2a_*$$

- **Black Hole: $a_* \to 1$ (Bardeen)**

$$a_* = \sqrt{\frac{2}{3}}\frac{M_0}{M}\left[4 - \sqrt{18\frac{M_0^2}{M^2} - 2}\right] \quad \text{for } M \le \sqrt{6}M_0\,,$$

$$a_* = 1 \quad \text{for } M > \sqrt{6}M_0\,,$$

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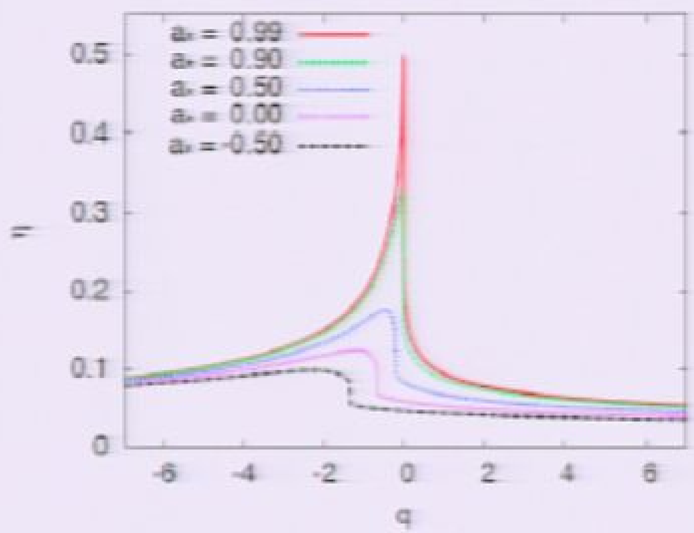

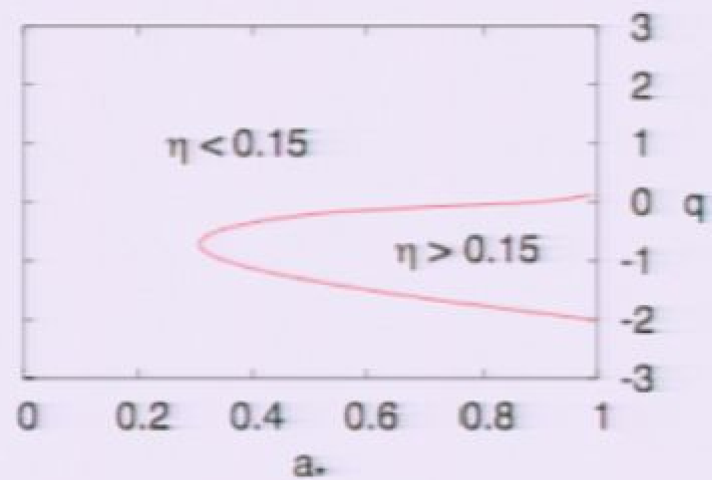

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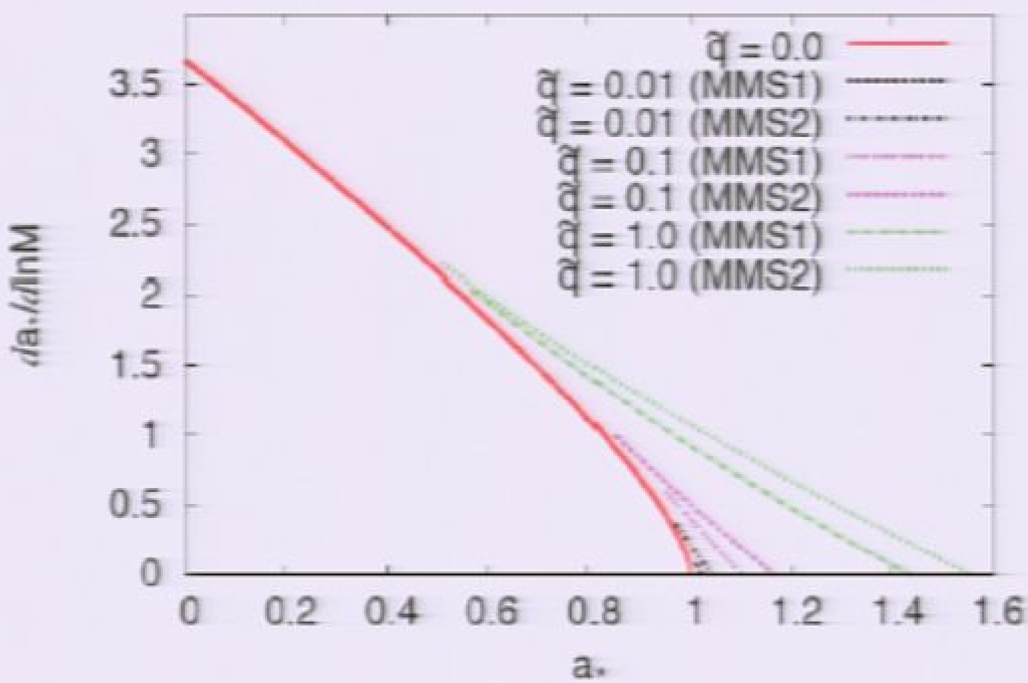
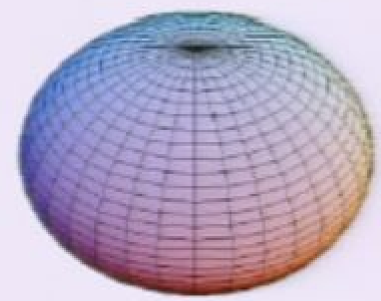
Objects more oblate than a black hole

- **Anomalous quadrupole moment:** $Q = -(1+\tilde{q})a^2 M$





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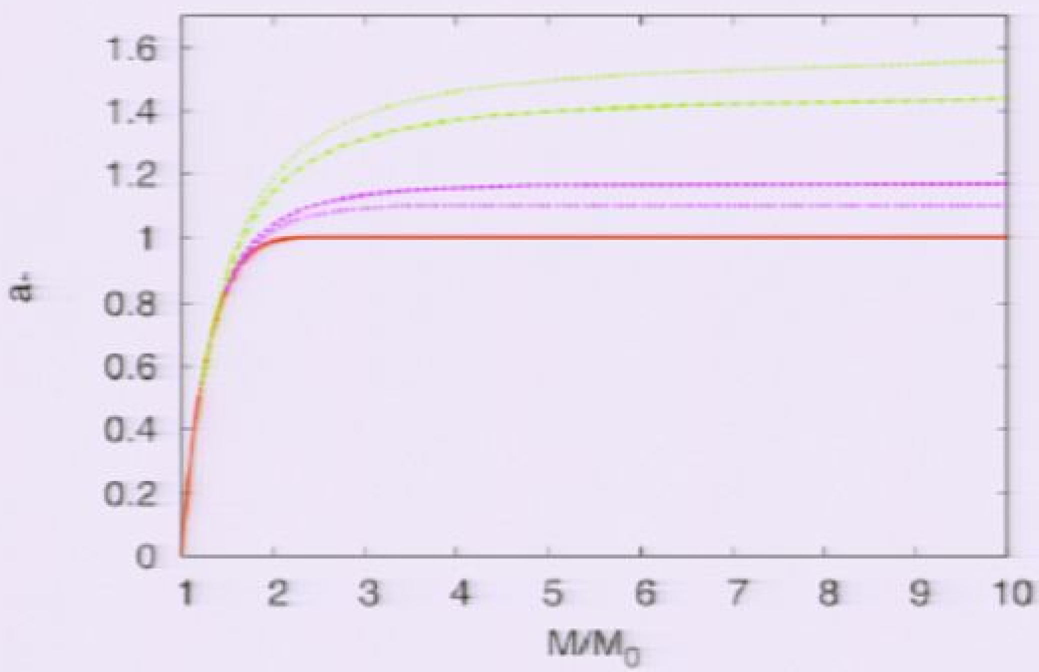

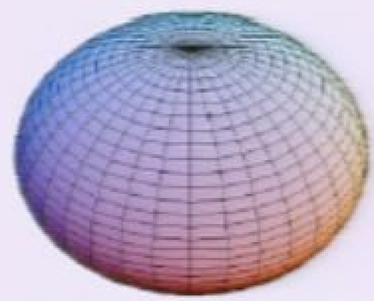

Objects more prolate than a black hole

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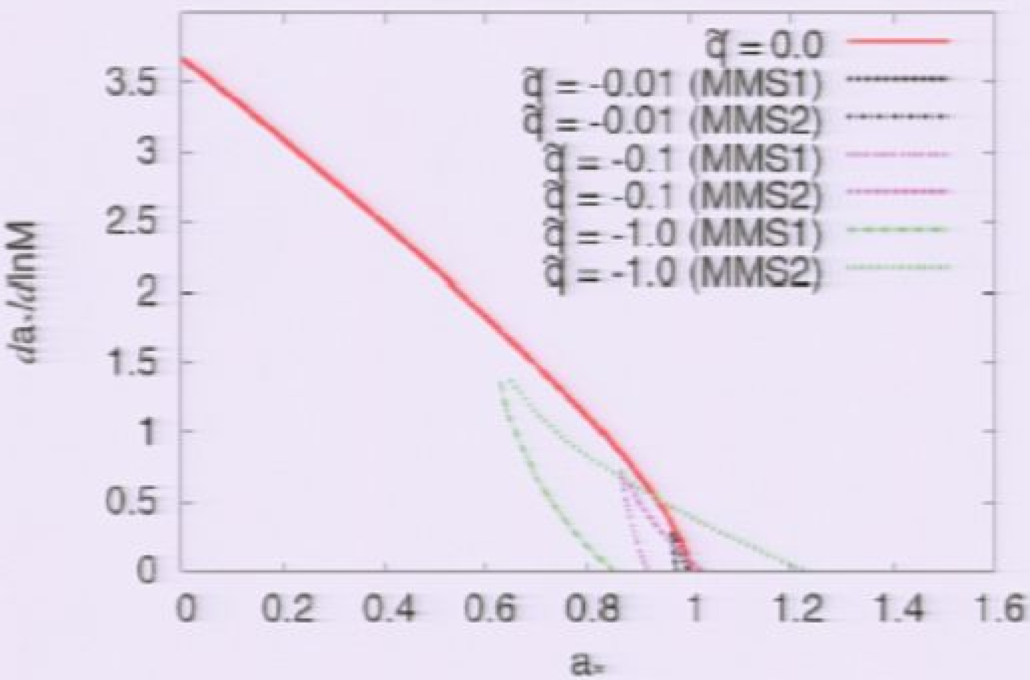

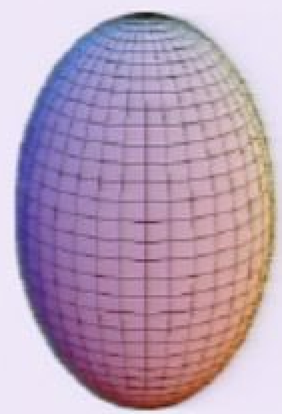

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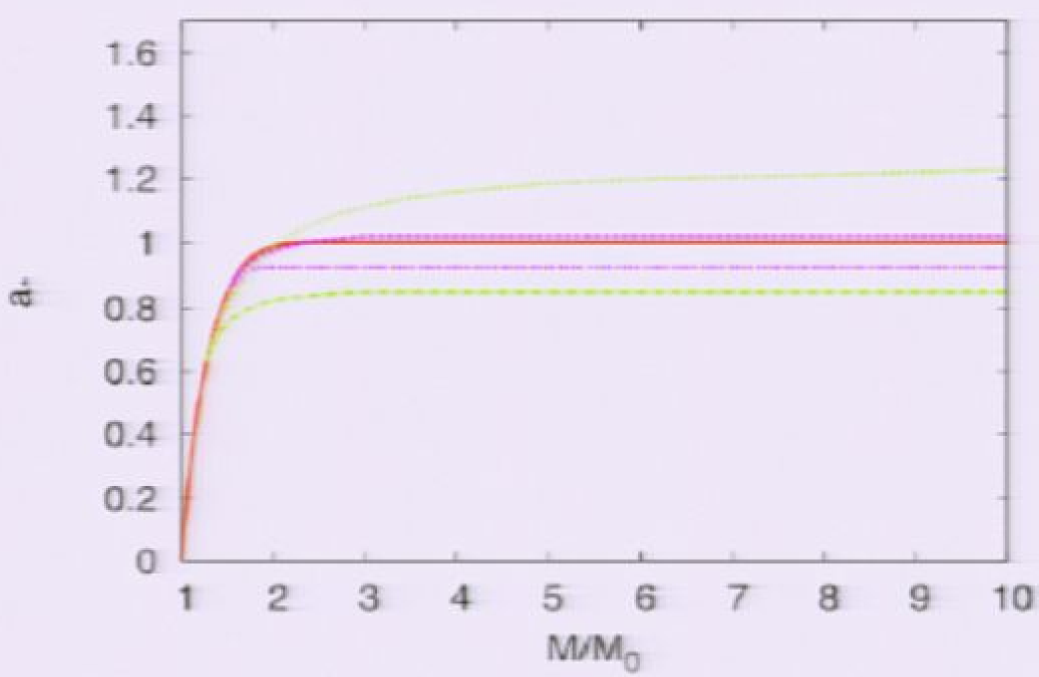
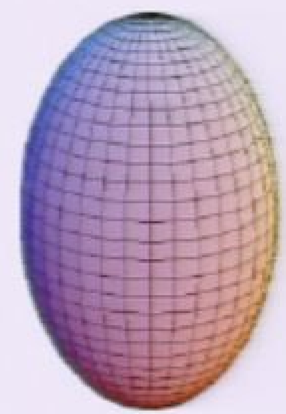
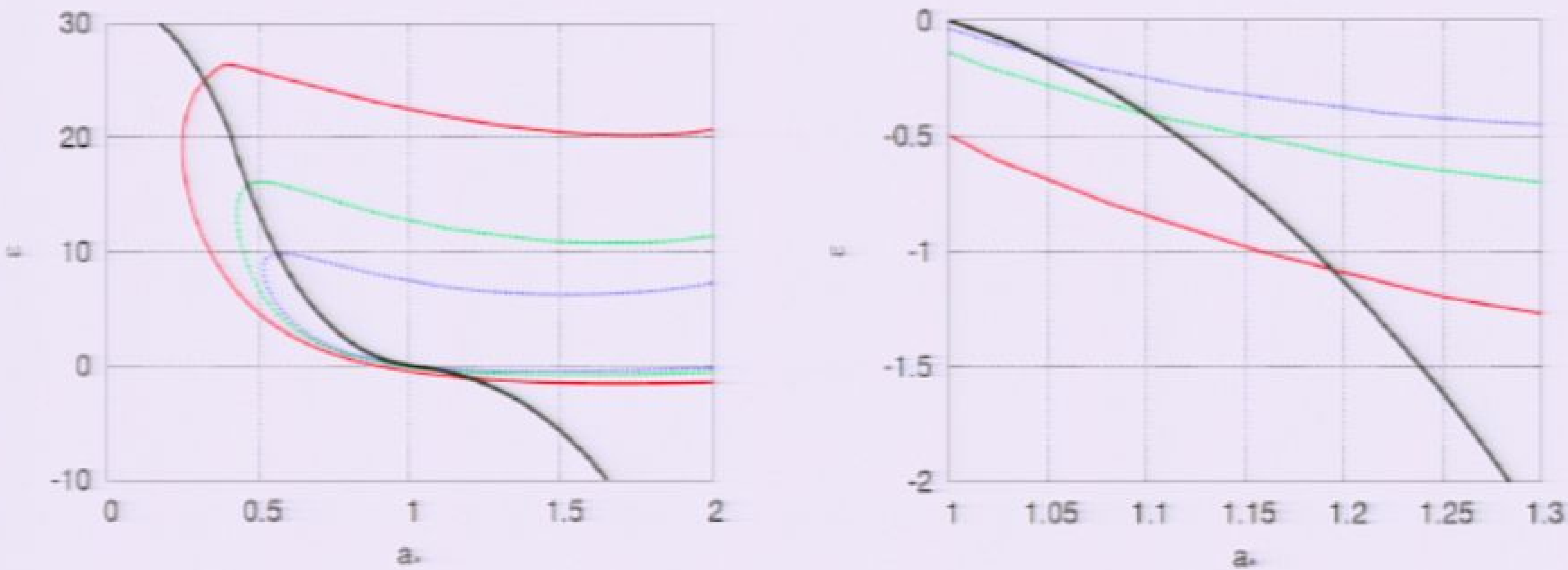




Equilibrium spin parameter of compact objects with non-Kerr quadrupole moment

$\tilde{q}$	a_*^{eq} (MMS1)	a_*^{eq} (MMS2)	a_*^{eq} (Kerr)
1.0	1.44	1.56	–
0.1	1.10	1.17	–
0.01	1.02	1.04	–
0.0	–	–	1.00
-0.01	0.97	0.997	–
-0.1	0.92	1.02	–
-1.0	0.85	1.23	–

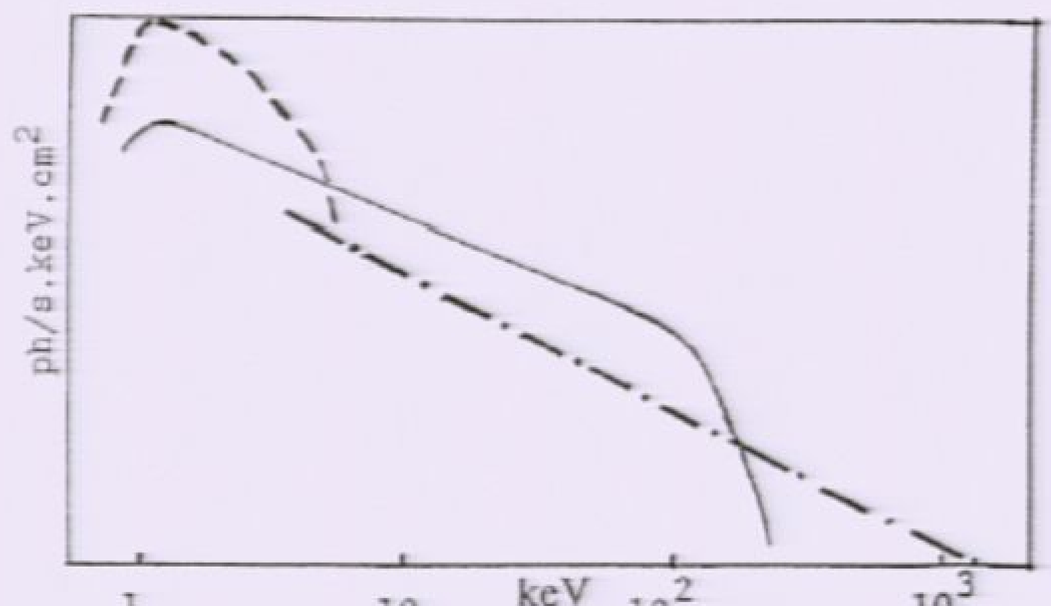
Maximum value for the spin parameter of the super-massive black hole candidates



Observational bound : $|a_*| < 1.19$ (< 1.10, < 1.04)

Continuum fitting method

- The soft X-ray component of the spectrum of stellar-mass BH candidates is the thermal spectrum of a geometrically thin and optically thick accretion disk
- The thin disk is on the equatorial plane
- The inner radius of the disk is equal to the radius of the ISCO
- Efficient cooling mechanism ($L < 0.3\ L_{Edd}$)



Effective temperature and spectrum (Kerr BH)

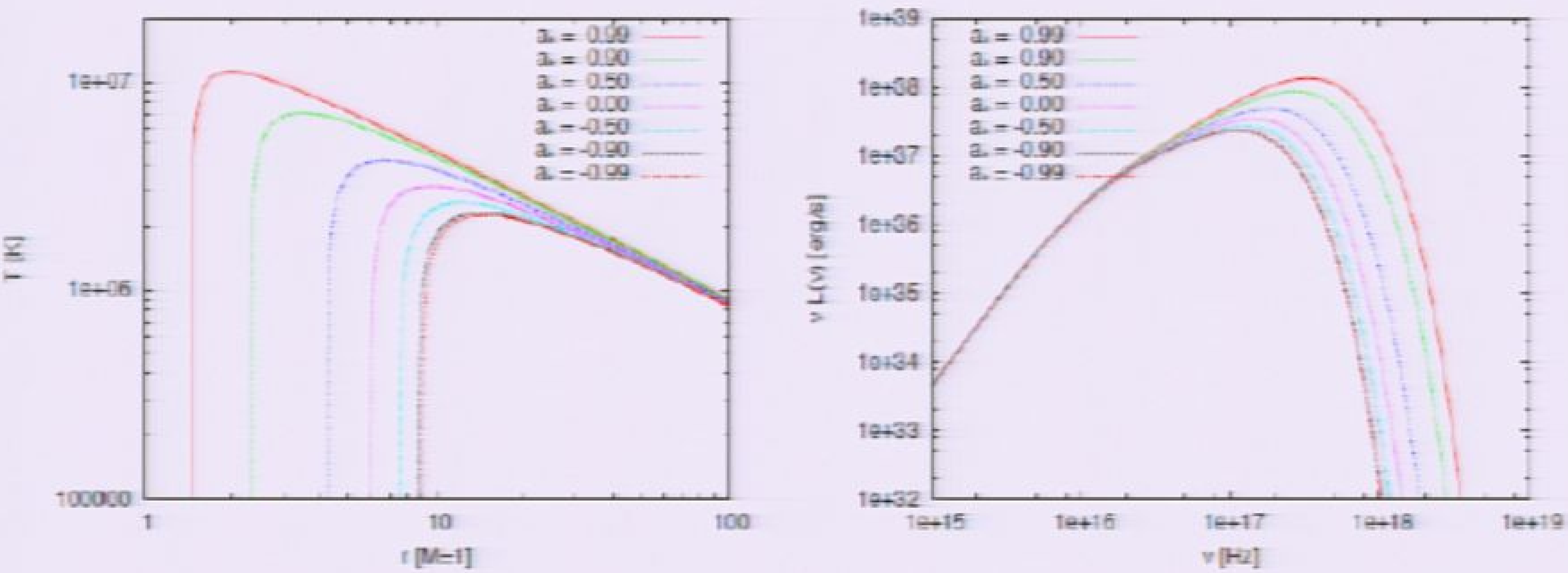
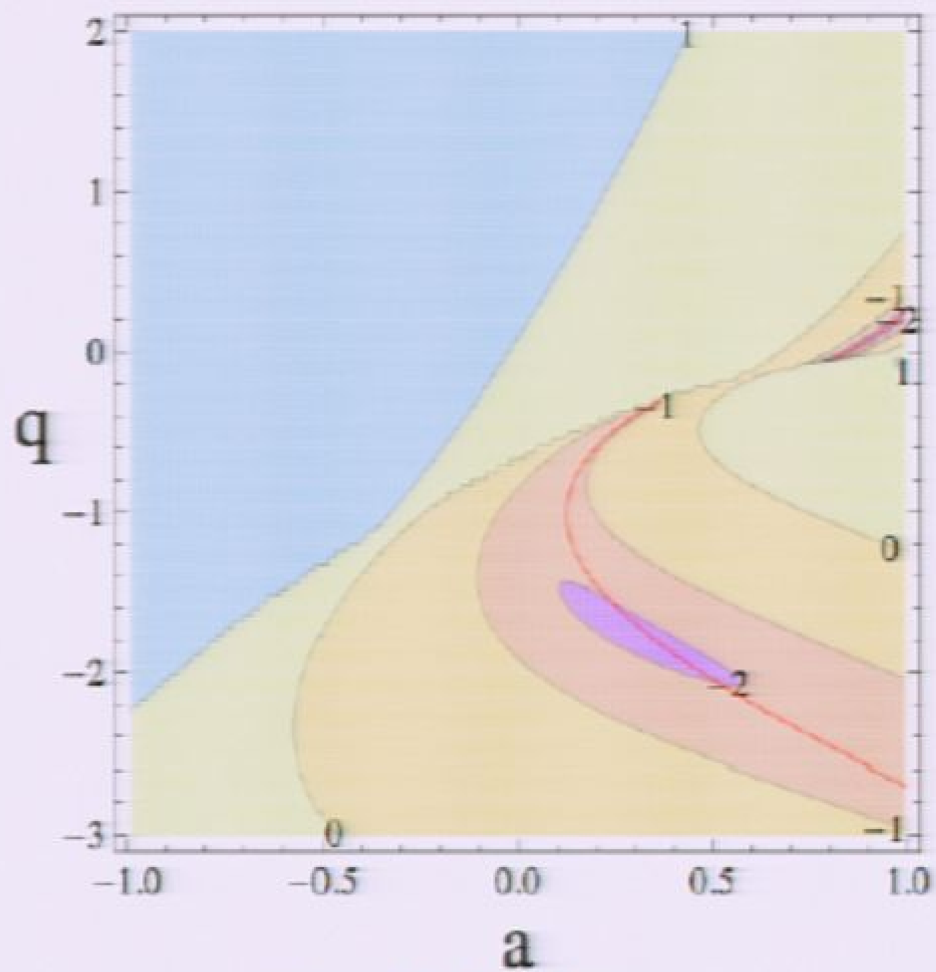


FIG. 1. Radial profile of the effective temperature (left panel) and spectrum $\nu L(\nu)$ (right panel) of a thin accretion disk in Kerr space-time for different value of the spin parameter a_*. Here we take the mass $M = 10\ M_\odot$, the mass accretion rate $\dot{M} = 10^{18}$ g/s, and the inclination angle $i = 45°$.

M33 X-7: Reduced Chi2



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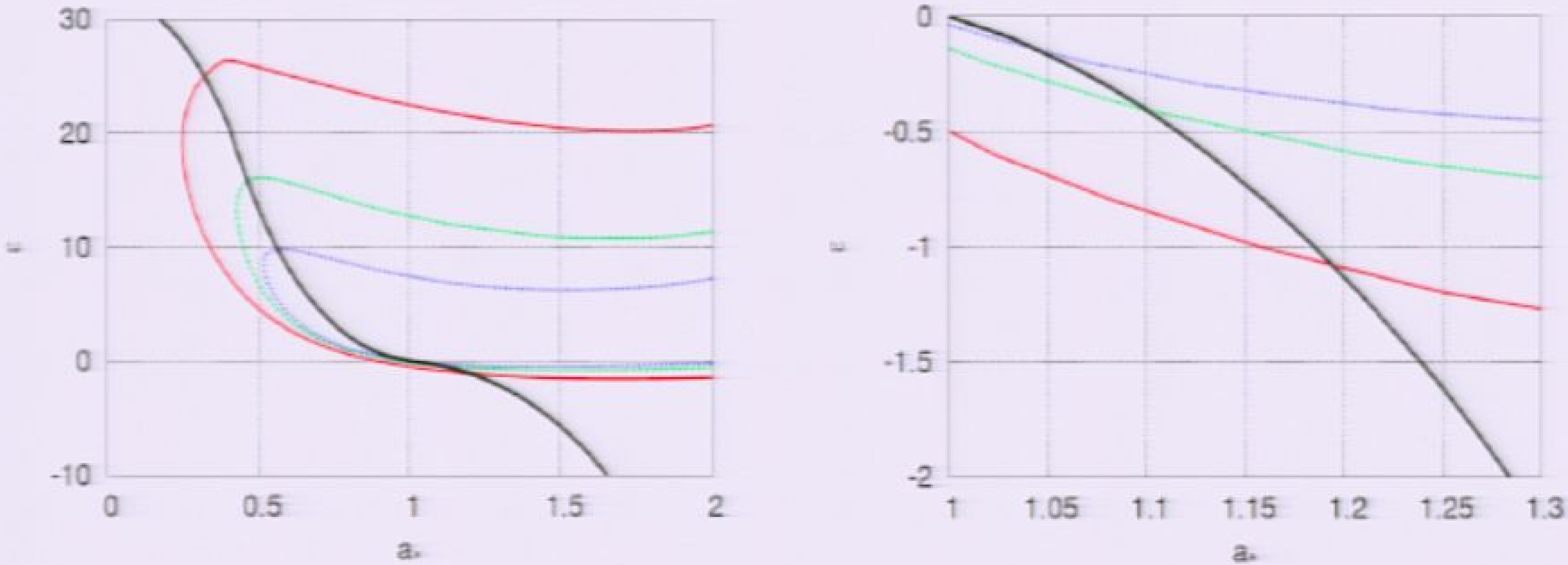
Maximum value for the spin parameter of the super-massive black hole candidates



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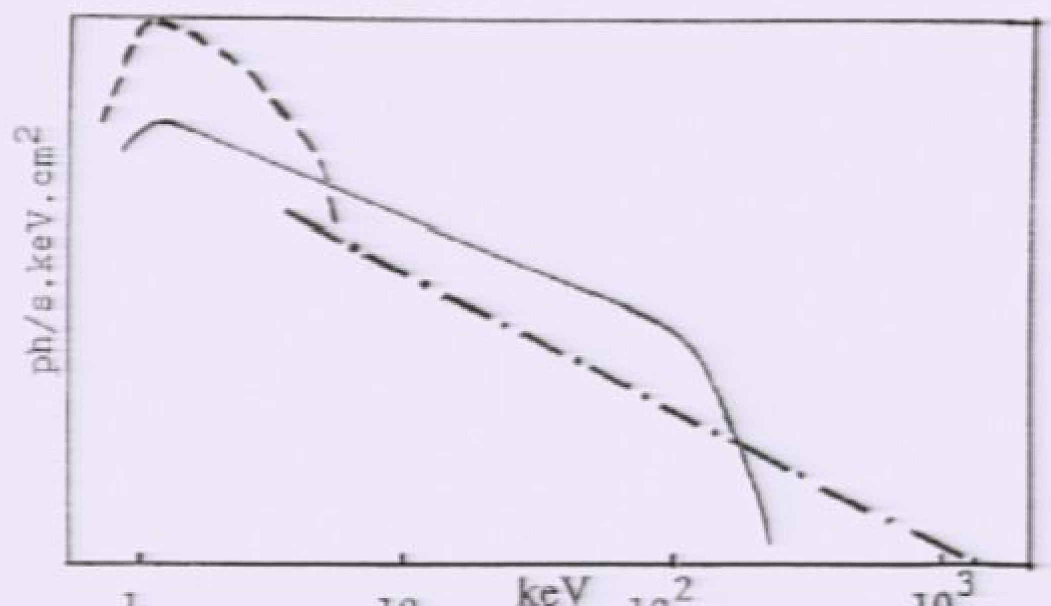

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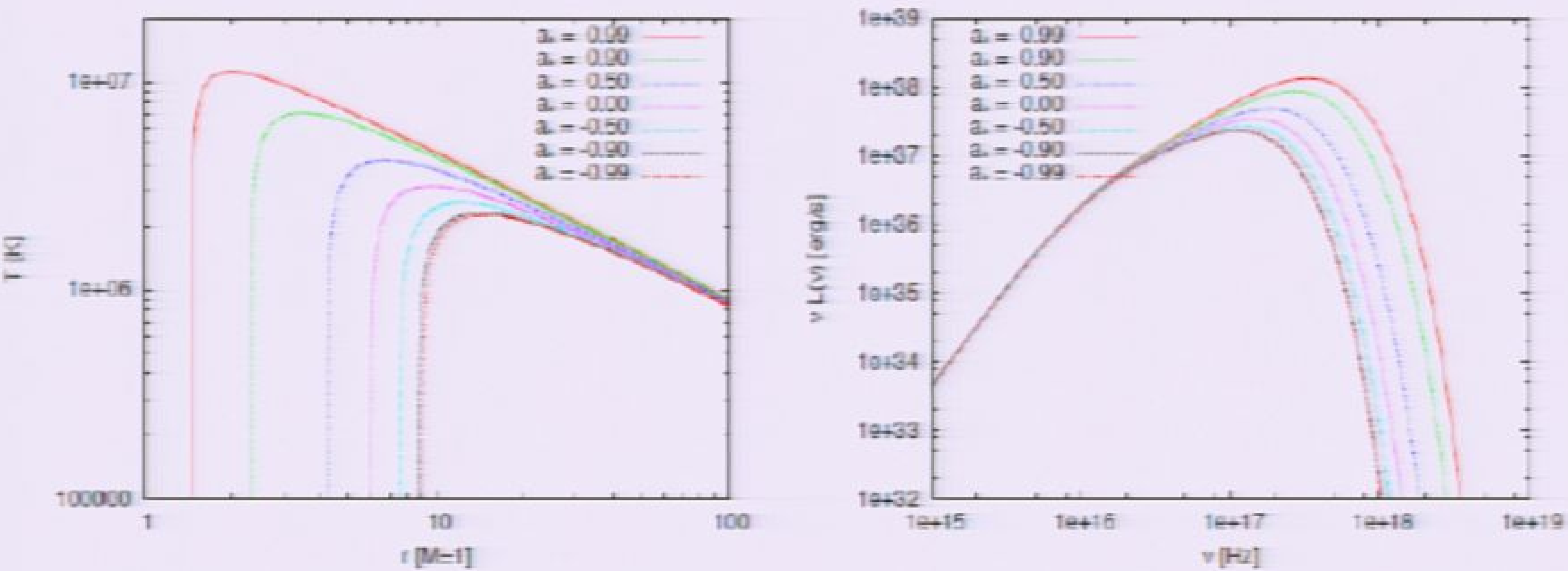

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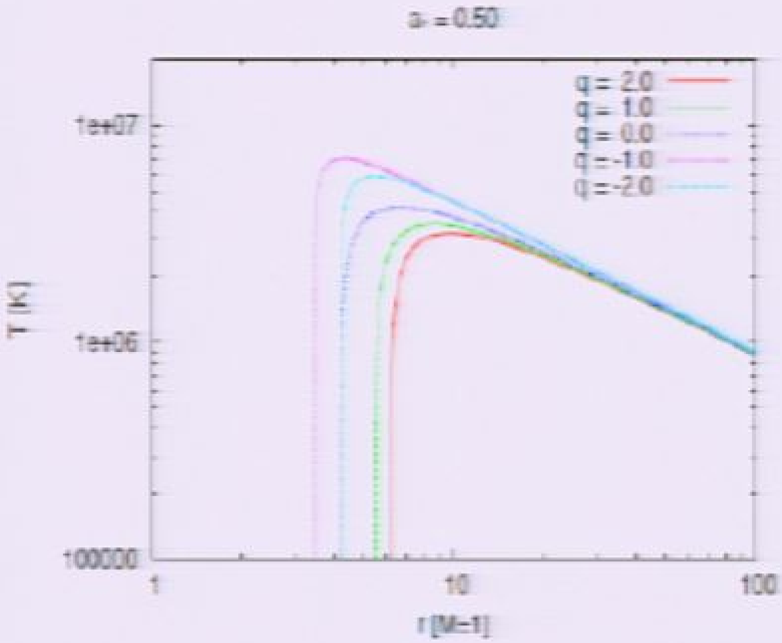
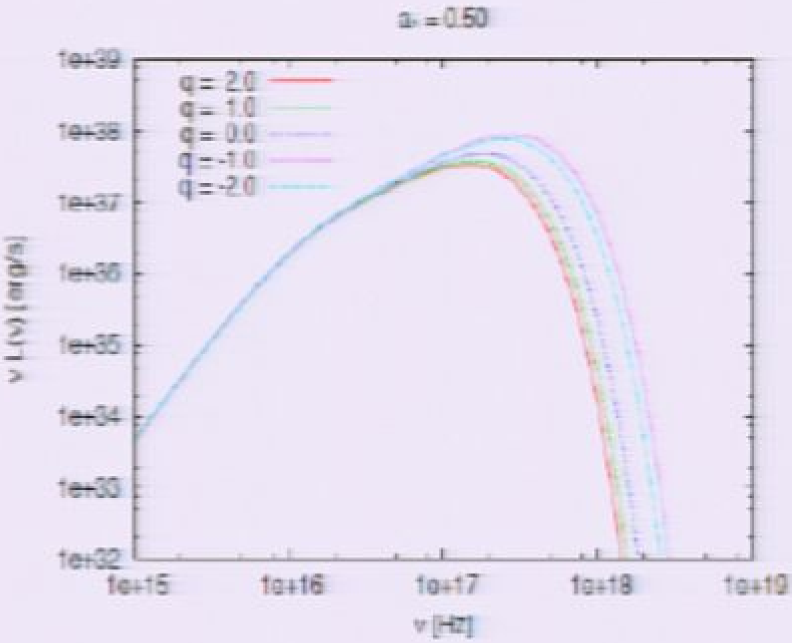
Generic compact object with a/M = 0.50





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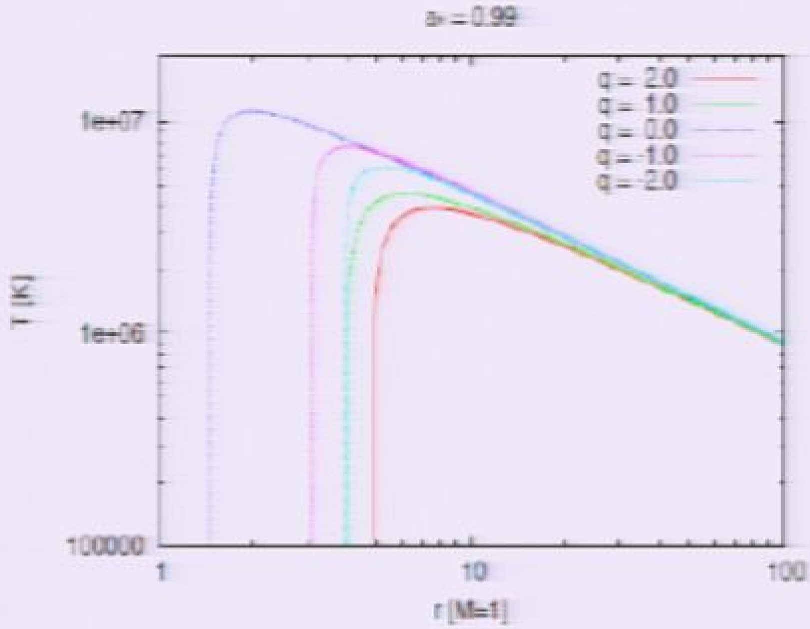
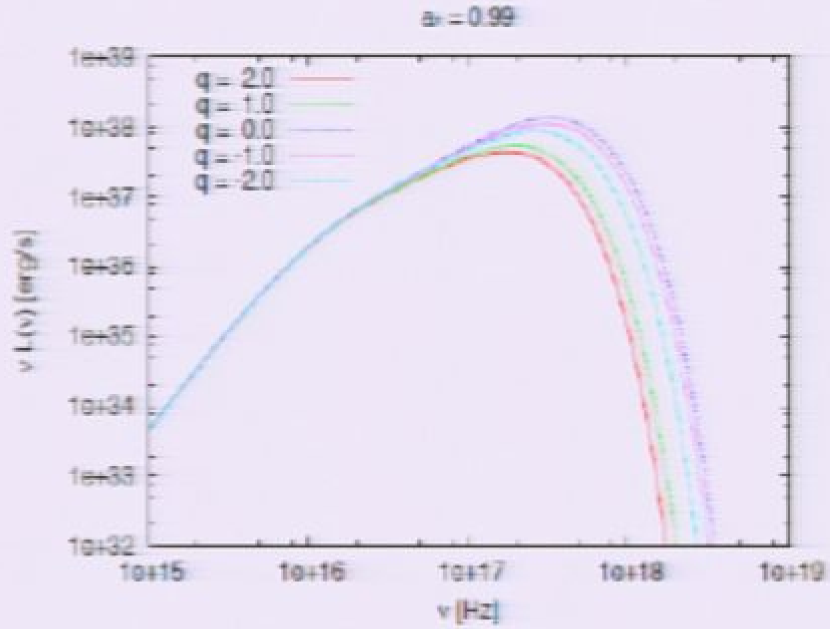
Generic compact object with a/M = 0.99





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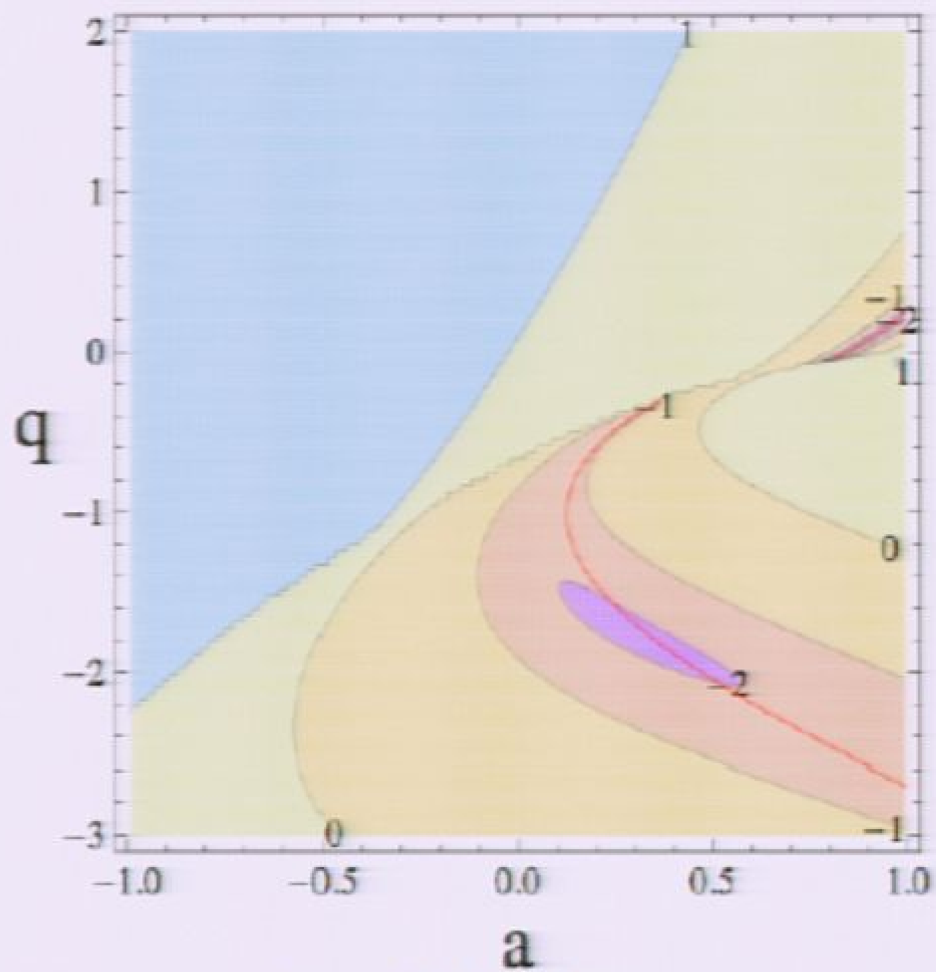

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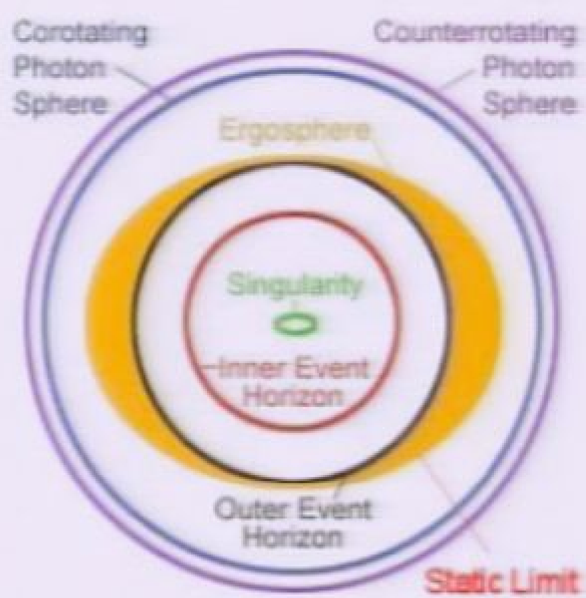
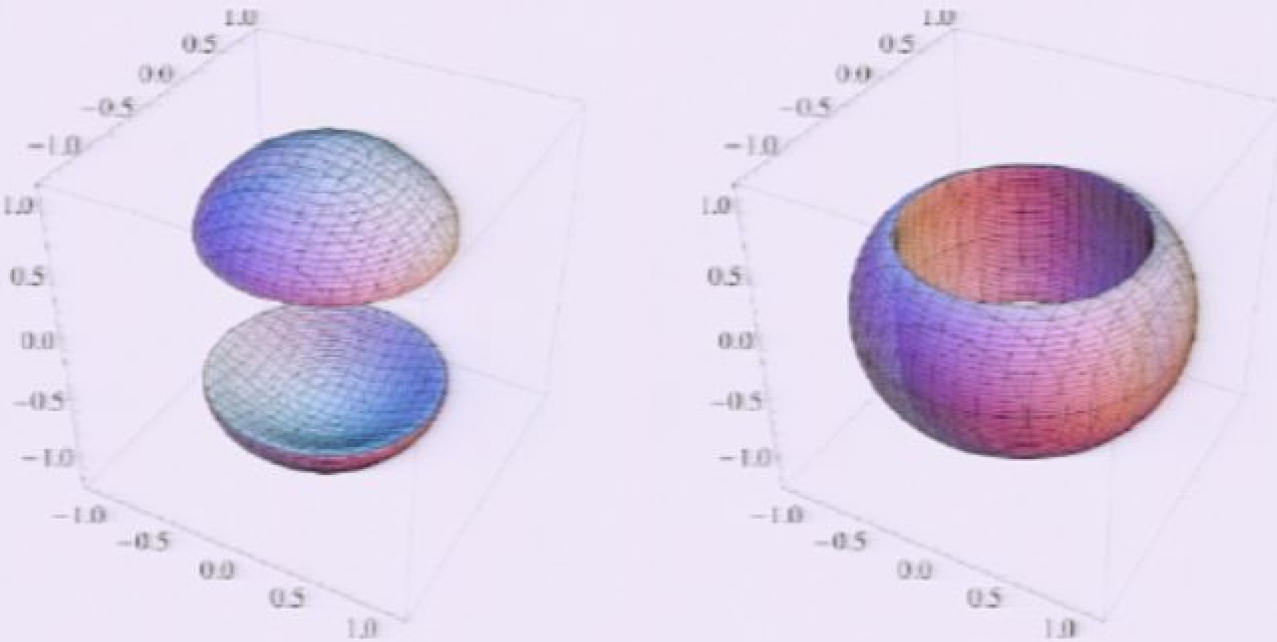
Black Holes with non-trivial topology (in collaboration with Leonardo Modesto)

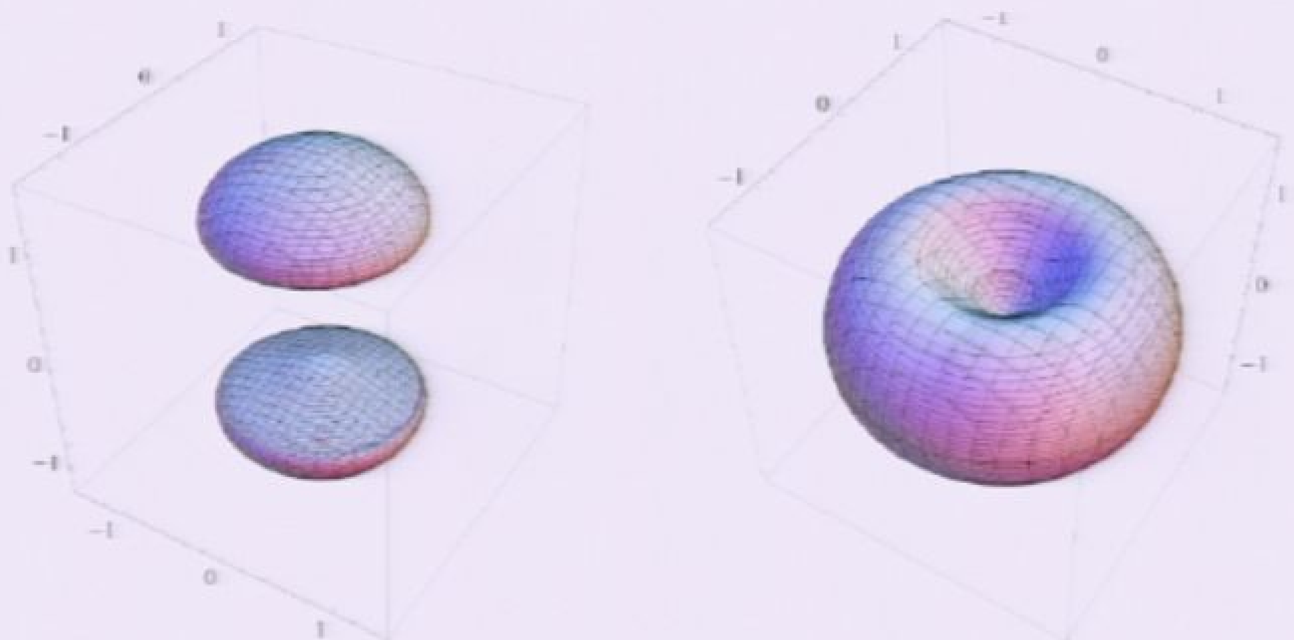
- 4D GR → in the stationary case, the spatial topology of the event horizon of a BH must be a 2-sphere, under the main assumptions of asymptotically flat space-time and validity of the dominant energy condition
- Toroidal BHs can exist for a short time



Black Holes motivated by Loop Quantum Gravity



Black Holes in possible alternative theories of gravity



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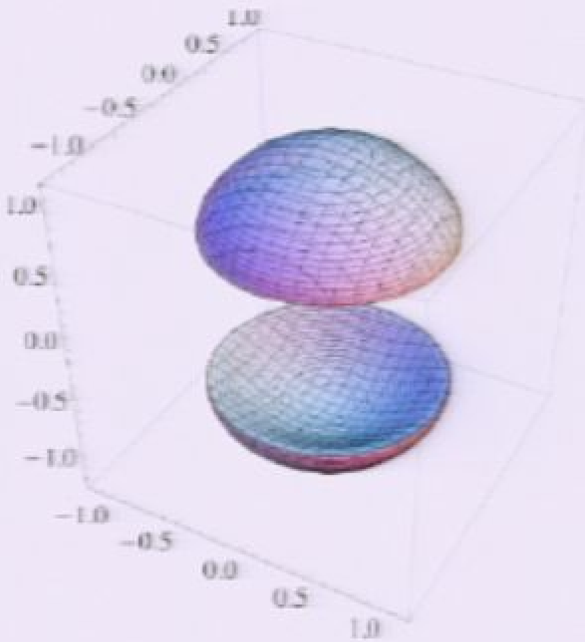

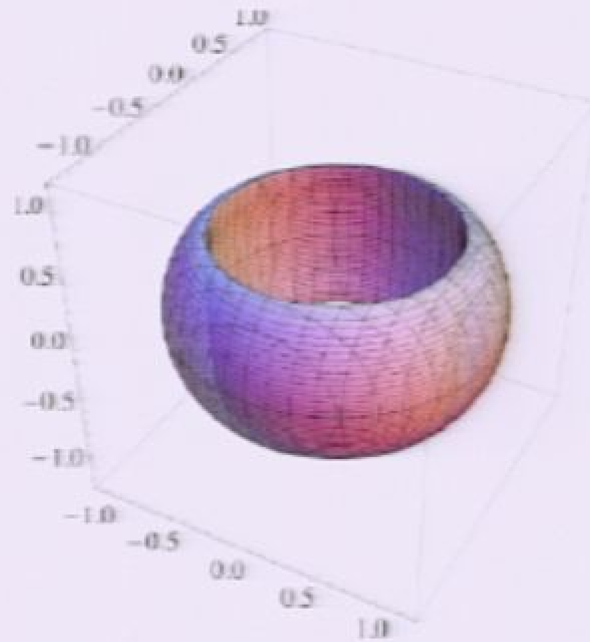

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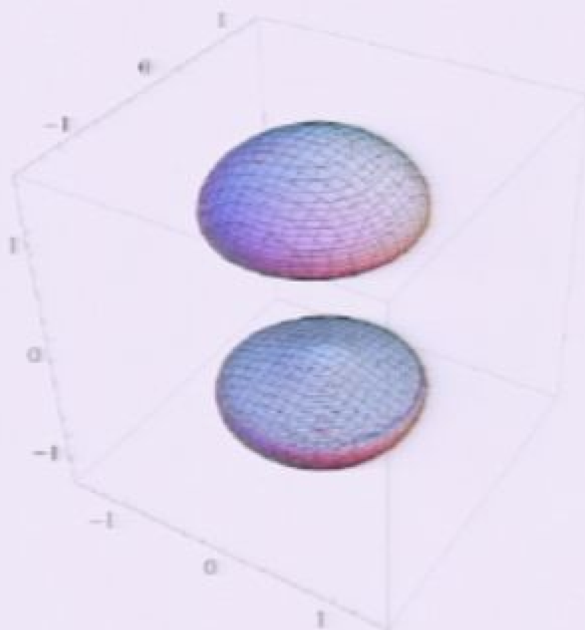

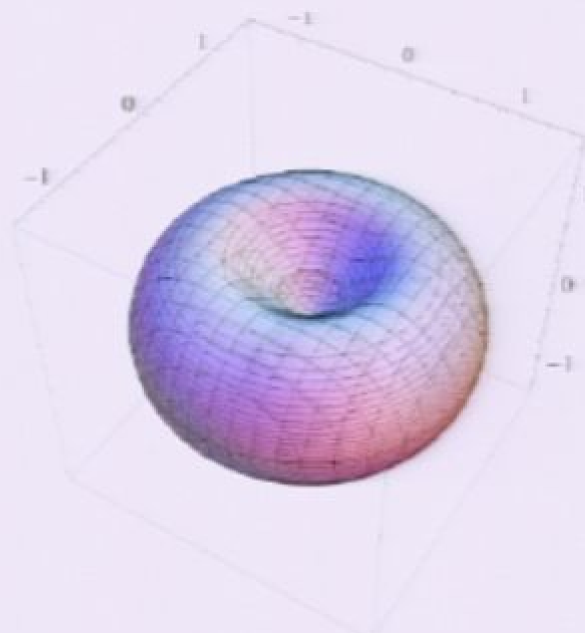

Conclusions

- Robust observational evidences of dark and compact objects. They are thought to be the Kerr black holes predicetd by General Relativity because they cannot be explained otherwise without introducing new physics
- To test the Kerr black hole paradigm, we have to consider more general objects and check that observational data favor the Kerr solution
- Preliminary results. In particular, $|a_+| < 1.2$ for the super-massive objects in galactic nuclei
- Near future: continuum fitting method, relativistic iron line
- More distant future: gravitational waves (QNMs, EMRIs)

Equilibrium spin parameter of compact objects with non-Kerr quadrupole moment

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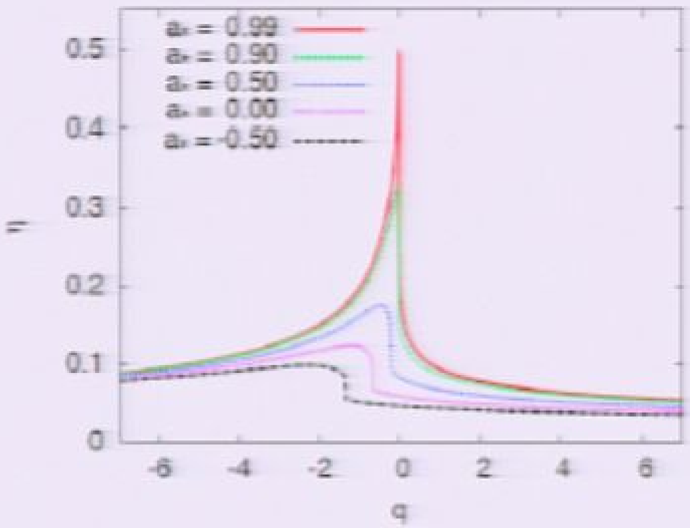
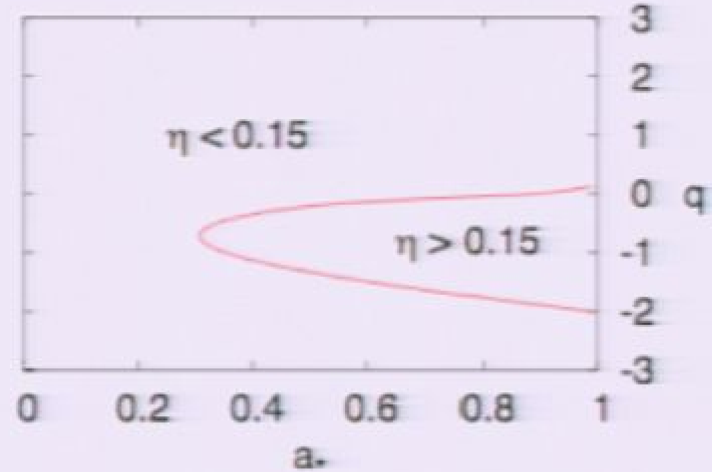
Constraint on the quadrupole moment of super-massive black hole candidates





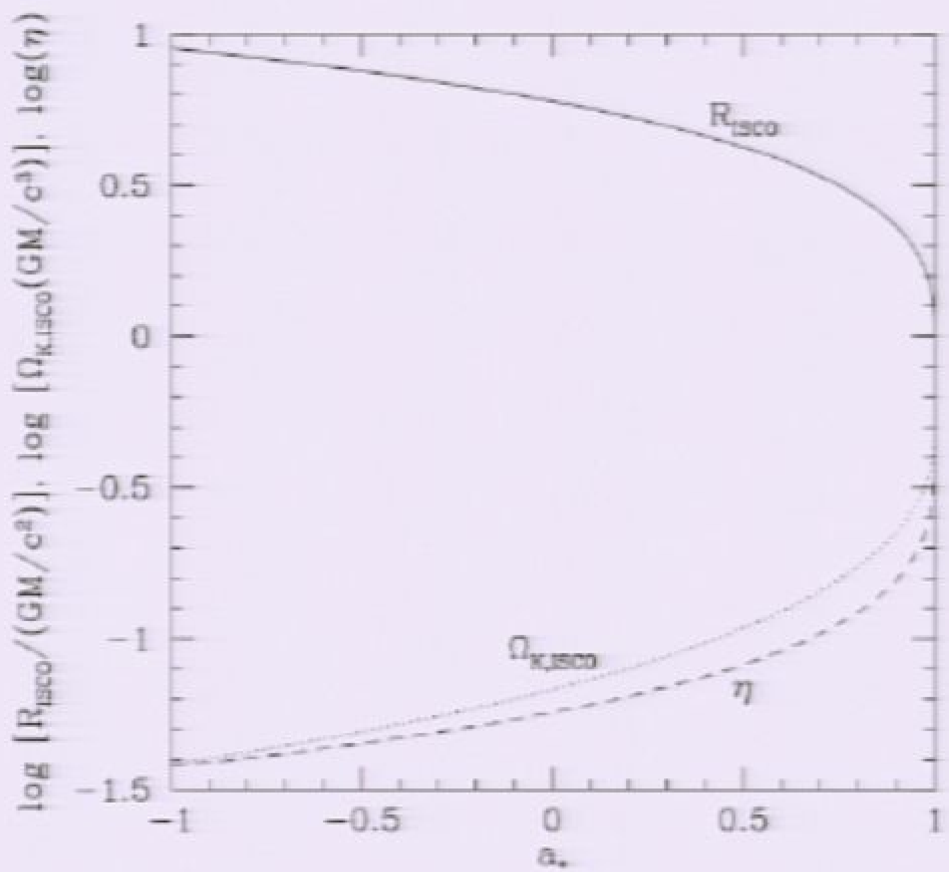
$-2.00 < q < 0.14$

Processes determining the value of the spin parameter

- Process of BH formation (irrelevant for super-massive BHs)
- Minor merger
- Major merger
- Gas accretion

Current approaches to estimate the spin

- Continuum fitting method
- Relativistic iron line
- Radiative efficiency



Current approaches to esti

- Continuum fitting method
- Relativistic iron line
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