Testing the Kerr Black Hole Hypothesis

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LMU
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

ARNOLD SOMMERFELD CENTER FOR THEORETICAL PHYSICS

Plan of the talk

- **Motivations**
- **Theoretical and observational facts**
- **How can we test the Kerr-nature of astrophysical BH candidates?**
- **Continuum-fitting method (only for stellar-mass BH candidates)**
- **Jet power**

Motivations

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- **Theoretical and observational facts**
- **How can we test the Kerr-nature of astrophysical BH candiudates?**
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Tests of General Relativity

- **Earth's gravitational field:**

  Lunar Laser Ranging experiments, Gravity Probe B, . . .

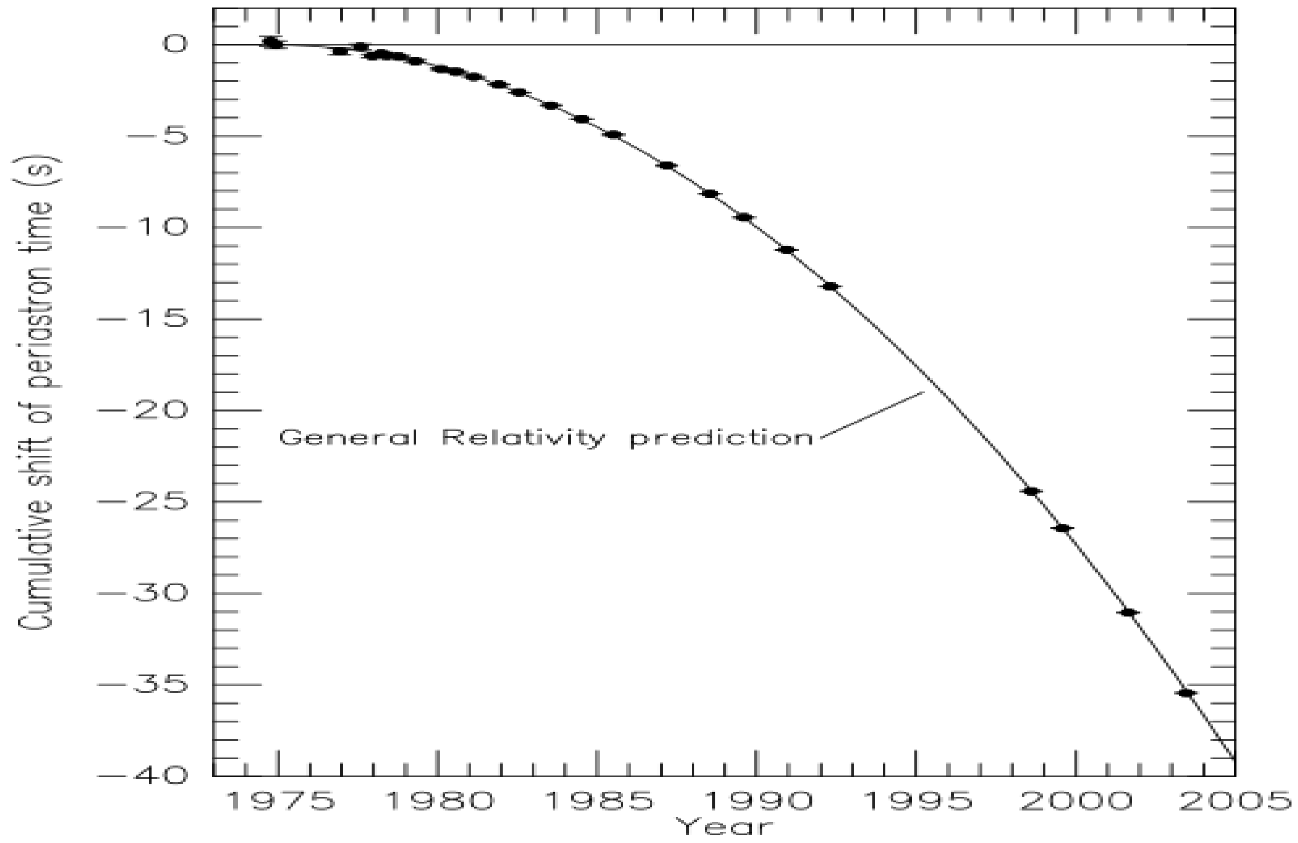
- **Solar System:**

  Cassini mission, . . .

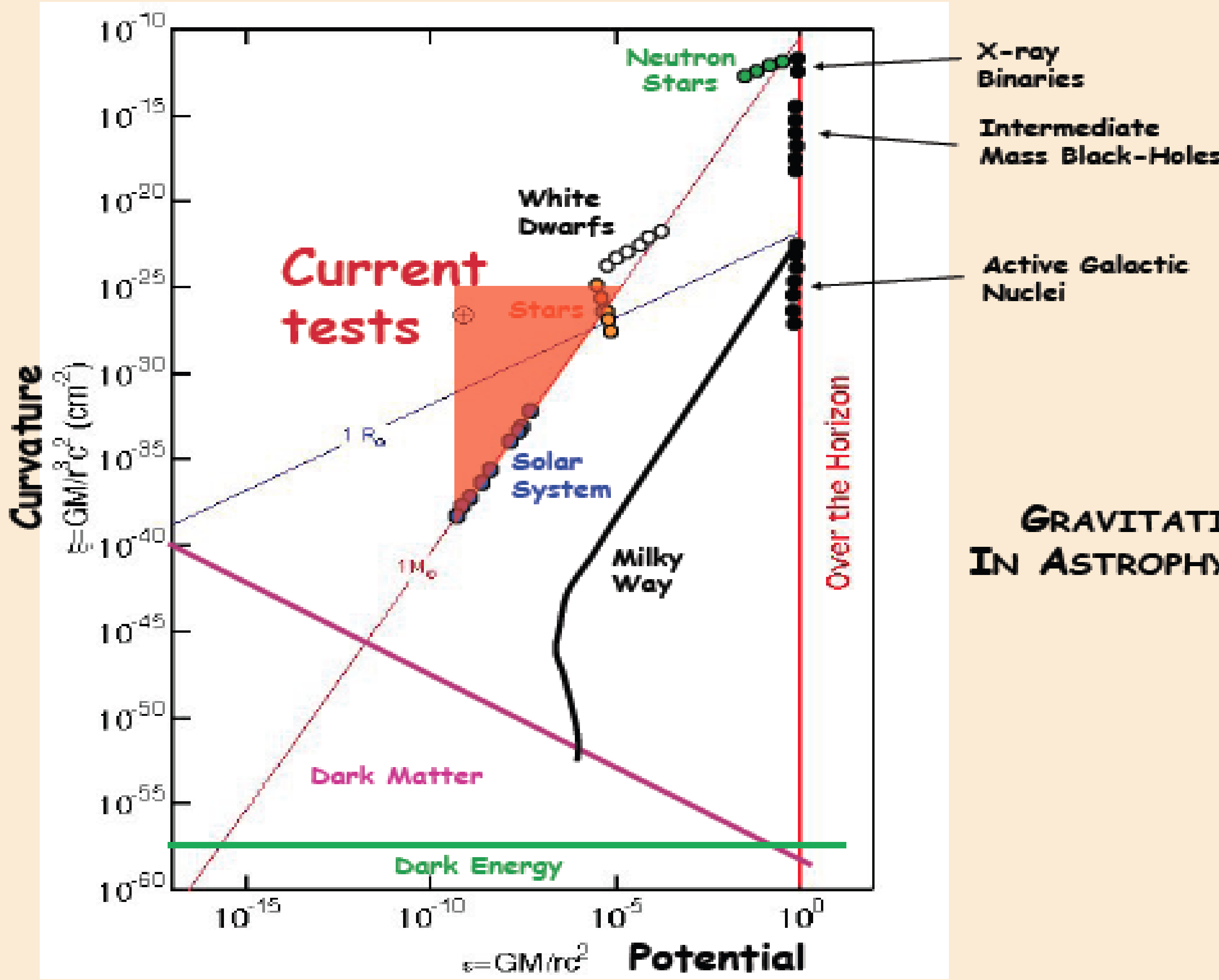
- **Observation of binary pulsars:**

  PSR B1913+16, PSR J0737-3039, . . .

Orbital decay of PSR B1913+16



From Weisberg & Taylor 2005



GRAVITATIONAL FIELDS IN ASTROPHYSICAL SYSTEMS

Psaltis 2008

Theoretical and observational facts

- **Motivations**
- **Theoretical and observational facts**
- **How can we test the Kerr-nature of astrophysical BH candiudates?**
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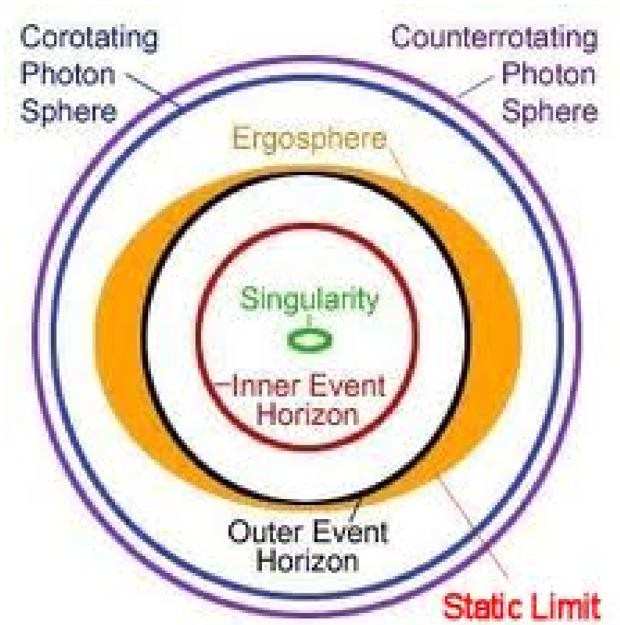
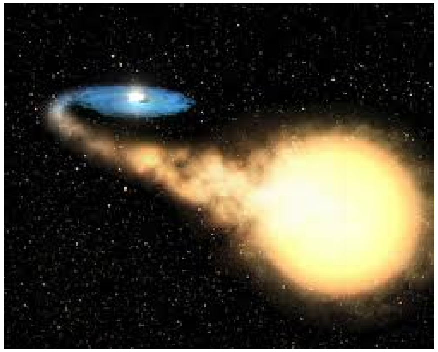
Black holes in GR (Theory)

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

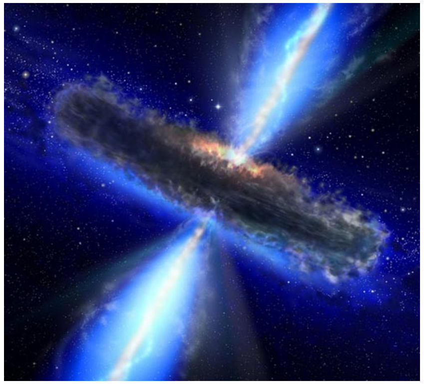


Black hole candidates (Observations)

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



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



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

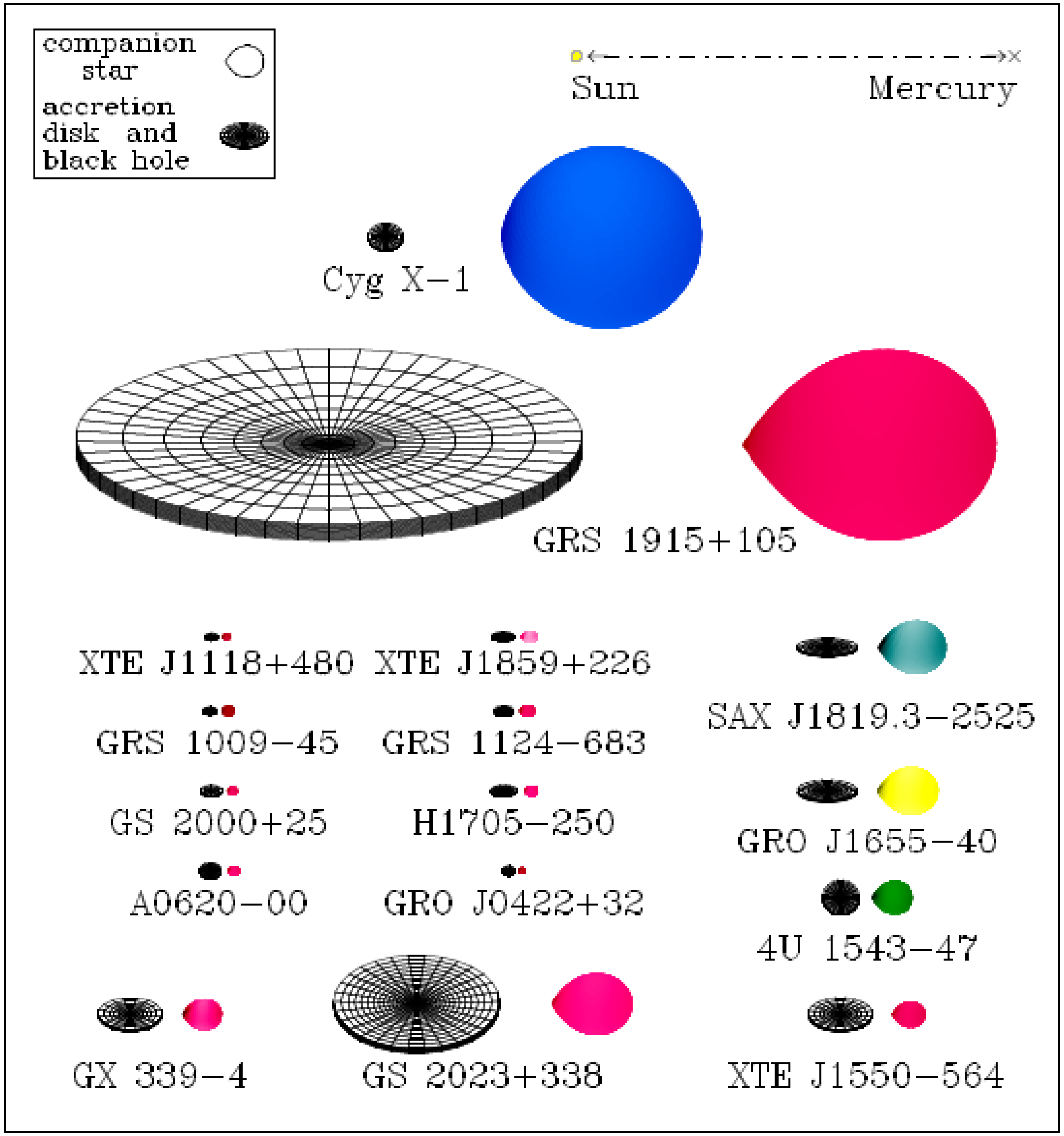
Stellar-mass BH candidates

- **Dark objects in X-ray binary systems**
- **Mass function:** $$f(M_{BH}) = \frac{K^3 T}{2\pi G_N} = \frac{M_{BH}^3 \sin^3 i}{(M_{BH} + M_c)^2} \qquad K = v \sin i$$
- **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 Remillard & McClintock 2006

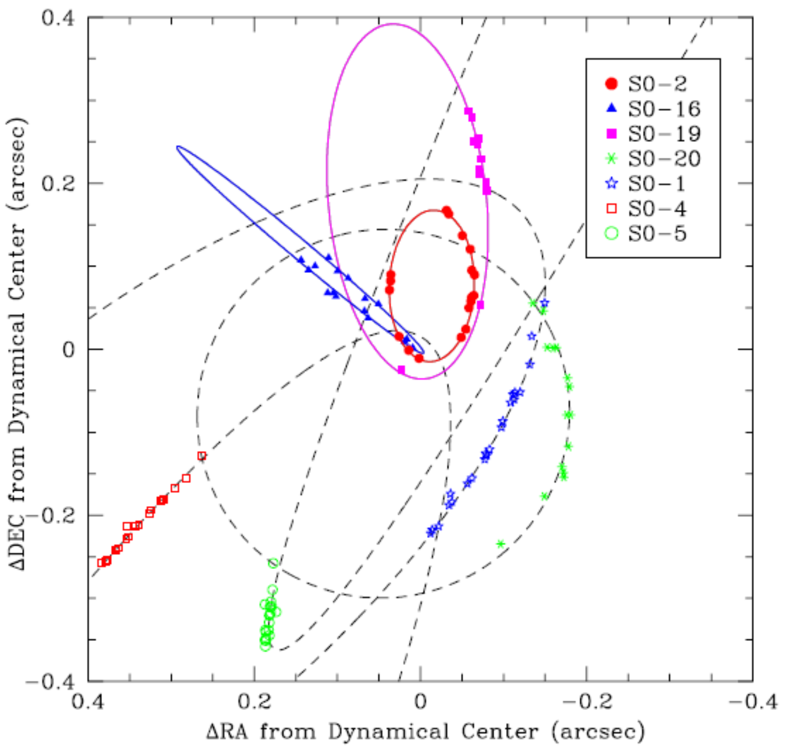
Black Hole Binaries in the Milky Way



From Remillard & McClintock 2006

Super-massive BH candidate in the Galaxy

- We study the orbital motion of individual stars
- Point-like central object with a mass of $4x10^6$ Solar masses
- Radius < 45 AU (600 R_{Sch})



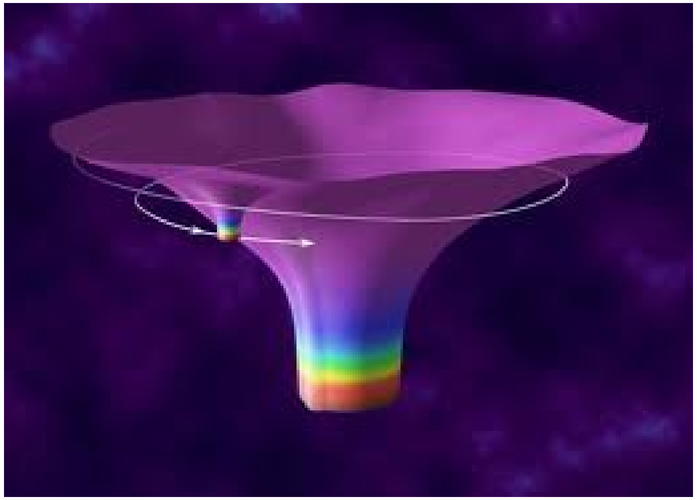
From Ghez et al., ApJ 620 (2005) 744

How can we test the Kerr-nature of astrophysical BH candidates?

- **Motivations**
- **Theoretical and observational facts**
- **How can we test the Kerr-nature of astrophysical BH candiudates?**
- **Continuum-fitting method**
- **Jet power**

Testing the Kerr BH Hypothesis with EMRIs

- **EMRI = Extreme Mass Ratio Inspiral**
- **LISA will be able to observe about 10^4 – 10^6 cycles of GWs emitted by an EMRI while the stellar-mass body is in the strong field region of the super-massive object**
- **The quadrupole moment of the super-massive object can be measured with a precision at the level of 10^{-2} – 10^{-4}**



Testing the Kerr BH Hypothesis with EMRIs

- **Ryan, PRD 52 (1995) 5707**
- **Collins & Hughes, PRD 69 (2004) 124022**
- **Glampedakis & Barak, CQG 23 (2006) 4167**
- **Barack & Cutler, PRD 75 (2007) 042003**
- **Gair, Li & Mandel, PRD 77 (2008) 024035**
- **Apostolatos, Lukes-Gerakopoulos & Contopoulos, PRL 103 (2009) 111101**
- **Vigeland & Hughes, PRD 81 (2010) 024030**
- **etc.**

Testing the Kerr BH Hypothesis with EMRIs

- Ry
- Co
- Gl
- Ba
- Ga
- Ap ... 09) 111
- Vi
- etc

LISA (Laser Interferometry Space Antenna)
was originally scheduled to start working in ~2012
and then postponed to ~2020 or something later

In April 2011, NASA decided to abandon the project

ESA is now revising the mission,
with a smaller antenna
which may not be sensitive to EMRIs

Testing the Kerr BH Hypothesis with the radiation emitted by the gas of accretion

- **Significant progresses in the last ~ 5 years in the understanding of the electromagnetic spectrum of BH candidates**
- **Spin measurements:**

  → Continuum-fitting method (stellar-mass BH candidates)

  → Relativistic iron line (both stellar-mass and super-massive BH candidates)
- **Some data are already available and more data will be available in a near future**
- **New VLBI experiments with unprecedented high-resolution imaging capabilities**

Testing the Kerr BH Hypothesis with the radiation emitted by the gas of accretion

- **BH Shadow:**

  Bambi & Freese, PRD 79 (2009) 043002; Bambi & Yoshida, CQG 27 (2010) 205006; Johannsen & Psaltis, ApJ 718 (2010) 446; Bambi, Caravelli & Modesto, PLB 711 (2012) 10

- **Continuum-fitting method:**

  Bambi & Barausse, ApJ 731 (2011) 212; Bambi, PRD 84 (2012) 043002

- **Relativistic iron line:**

  Johansenn & Psaltis ApJ 745 (2012) 1, arXiv:1202.6069

- **Radiative efficiency:**

  Bambi, PRD 83 (2011) 103003, PLB 705 (2011) 5, PRD 85 (2012) 043001

Testing the Kerr BH Hypothesis with the radiation emitted by the gas of accretion

- **Continuum-fitting method:**

  Bambi & Barausse, ApJ 731 (2011) 212; Bambi, PRD 84 (2012) 043002

Continuum-fitting method

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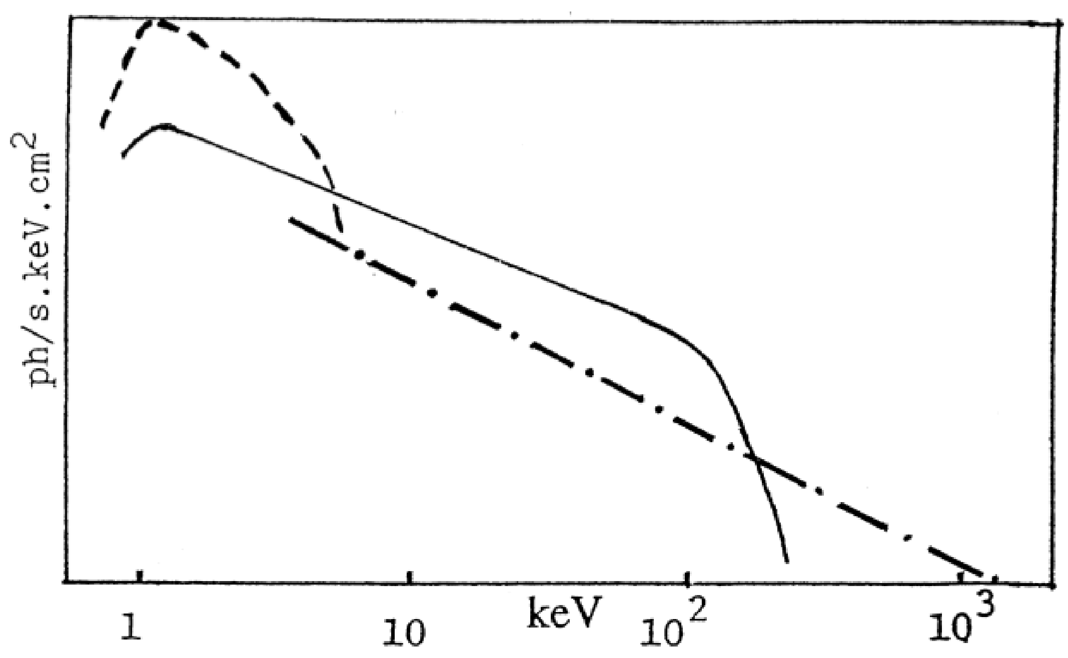
Continuum-fitting method

- **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**



Novikov-Thorne Model

- **Geometrically thin and optically thick accretion disk**
- **Relativistic generalization of the Shakura-Sunyaev model**

Assumptions:

- **Disk on the equatorial plane**
- **Gas's particles move on nearly geodesic circular orbits**
- **No magnetic fields**
- **No heat advection; energy radiated from the disk surface**
- **Inner edge of the disk at the ISCO, where stresses vanish**

→ Efficiency = $1 - E_{ISCO}$

Novikov-Thorne Model

- Geometrically thin and optically thick accretion disk
- Relativistic generalization of the Shakura-Sunyaev model

Selection criterion:
$0.08\ L_{EDD} < L < 0.30\ L_{EDD}$

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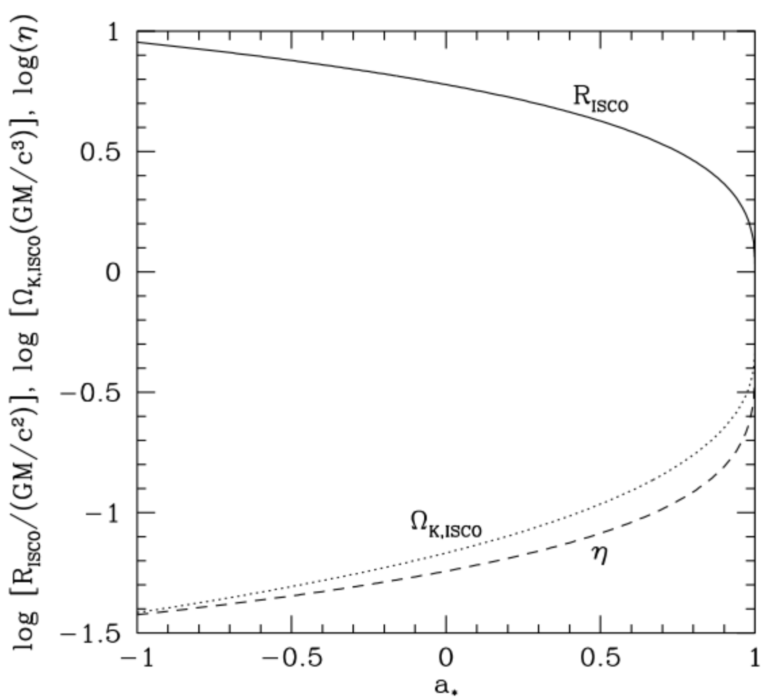
- No heat advection; energy radiated from the disk surface
- Inner edge of the disk at the ISCO, where stresses vanish

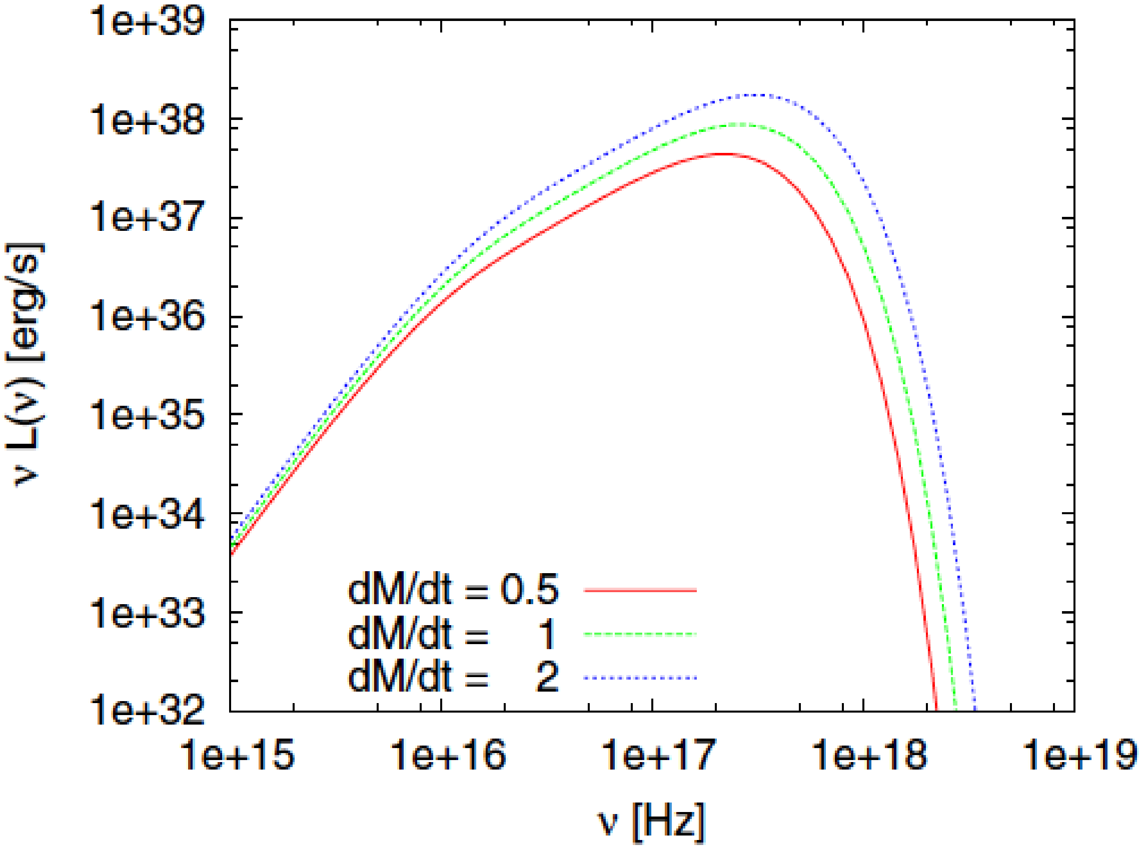
$\rightarrow$ Efficiency = $1 - E_{ISCO}$

Continuum-fitting method in Kerr background

- **5 parameters (BH mass, BH spin, BH distance, viewing angle, mass accretion rate)**
- **BH mass, BH distance, viewing angle → BH spin, mass accretion rate**

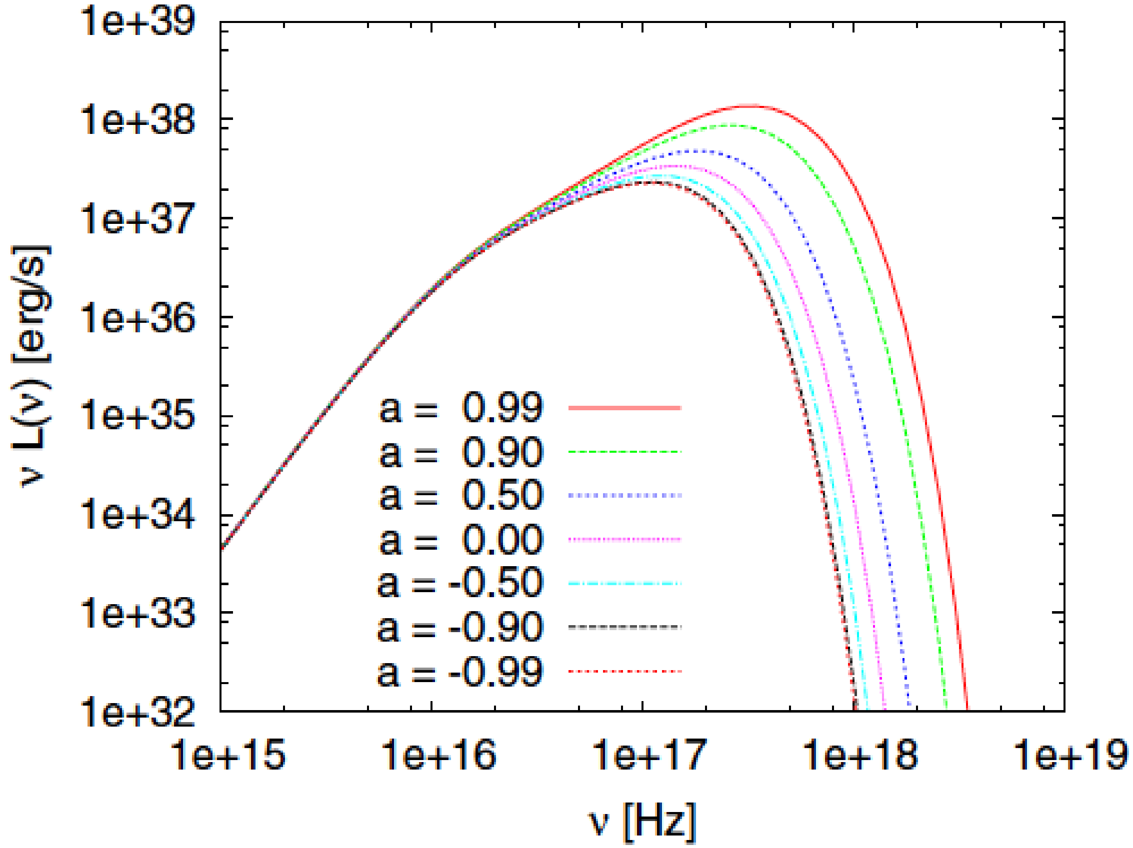


Mass accretion rate (Kerr background)



From Bambi & Barausse 2011

BH spin (Kerr background)



From Bambi & Barausse 2011

Spin measurements from the Harvard group

Black Hole	Spin a_*	Reference
GRS 1915+105	> 0.98	McClintock et al. 2006
Cygnus X-1	> 0.97	Gou et al. 2011
LMC X-1	0.92 ± 0.06	Gou et al. 2009
M33 X-7	0.84 ± 0.05	Liu et al. 2008, 2010
4U 1543-47	0.80 ± 0.05	Shafee et al. 2006
GRO J1655-40	0.70 ± 0.05	Shafee et al. 2006
XTE J1550-564	0.34 ± 0.24	Steiner et al. 2011
LMC X-3	< 0.3	Davis et al. 2006
A0620-00	0.12 ± 0.18	Gou et al. 2009

Testing the Kerr BH Hypothesis

- **To test the Kerr-nature of an astrophysical black hole candidates we need to consider a more general background, which includes the Kerr solution as special case**
- **In addition to the mass and the spin, the compact object will be characterized by one or more "deformation parameters", measuring possible deformations from the Kerr geometry**
- **The Kerr black hole hypothesis is verified if observations require vanishing deformation parameters**

Johannsen-Psaltis metric

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right)(1+h)\,dt^2 + \frac{\Sigma(1+h)}{\Delta + a^2 h \sin^2\theta}\,dr^2 + \Sigma\,d\theta^2 - \frac{4aMr\sin^2\theta}{\Sigma}(1+h)\,dt\,d\phi + \\ + \left[\sin^2\theta\left(r^2 + a^2 + \frac{2a^2 Mr\sin^2\theta}{\Sigma}\right) + \frac{a^2(\Sigma + 2Mr)\sin^4\theta}{\Sigma}h\right]d\phi^2\,,$$

$$\Sigma = r^2 + a^2\cos^2\theta\,,$$
$$\Delta = r^2 - 2Mr + a^2\,,$$
$$h = \sum_{k=0}^{\infty}\left(\epsilon_{2k} + \frac{Mr}{\Sigma}\epsilon_{2k+1}\right)\left(\frac{M^2}{\Sigma}\right)^k$$

Basic features of the code

- **Geometry of the background:**

  Johannsen-Psaltis space-time (Johannsen & Psaltis 2011) with three free parameters – mass, spin parameter, deformation parameter. No restrictions on the values of the spin parameter and of the deformation parameter

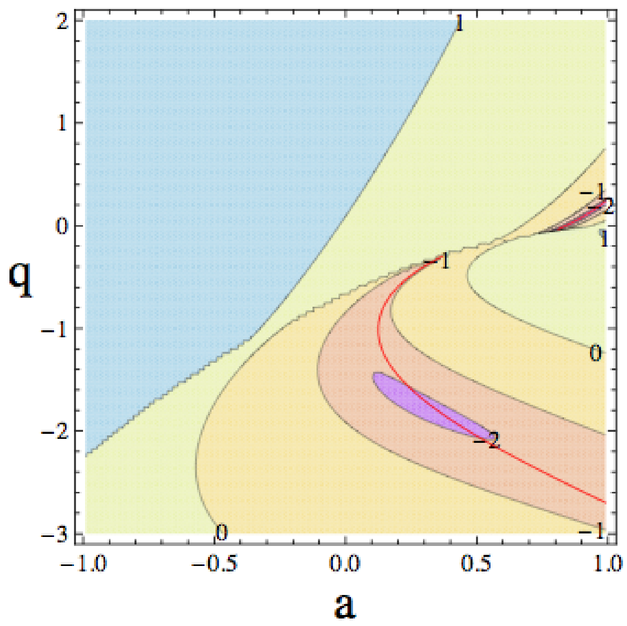
- **Relativistic effects:**

  All relativistic effects are included. Ray-tracing technique used

- **Self-irradiation: Not included**
- **Non-zero torque at the inner edge of the disk: Not included**
- **Color factor: Constant. Set by the user**
- **Radiation emission: Isotropic or limb-darkened**

M33 X-7

- X-ray binary system in the galaxy M33. Mass, distance from us, and inclination angle of the disk are known with good precision
- Chandra and XMM-Newton data in the high-soft state
- Spin parameter: 0.84 ± 0.05 (Liu et al. 2008, 2010)
- Allowed region in the spin parameter – deformation parameter plane: work in progress . . .

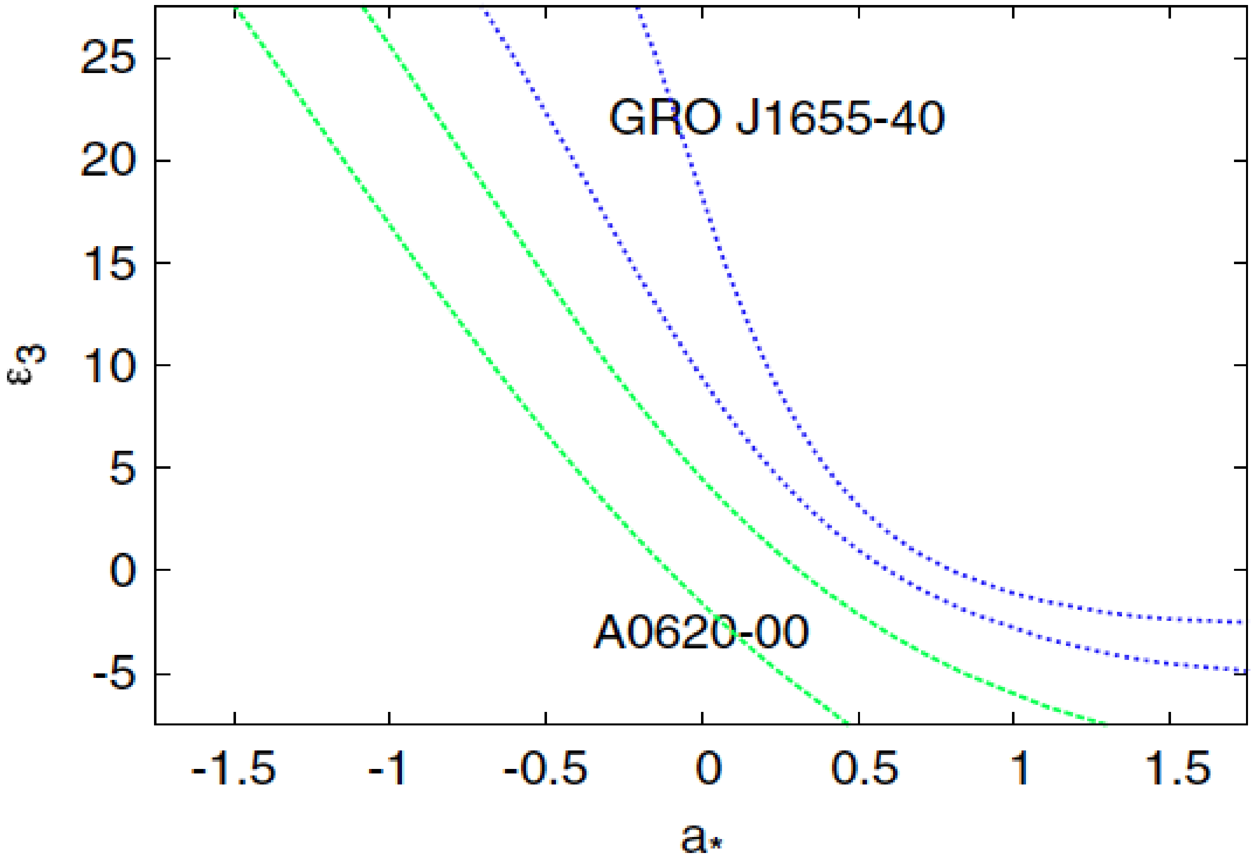


From Bambi & Barausse 2011

Spin parameter – Deformation parameter plane

- **The continuum-fitting method measures the radiative efficiency:**

  Efficiency = 1 – E_{ISCO}



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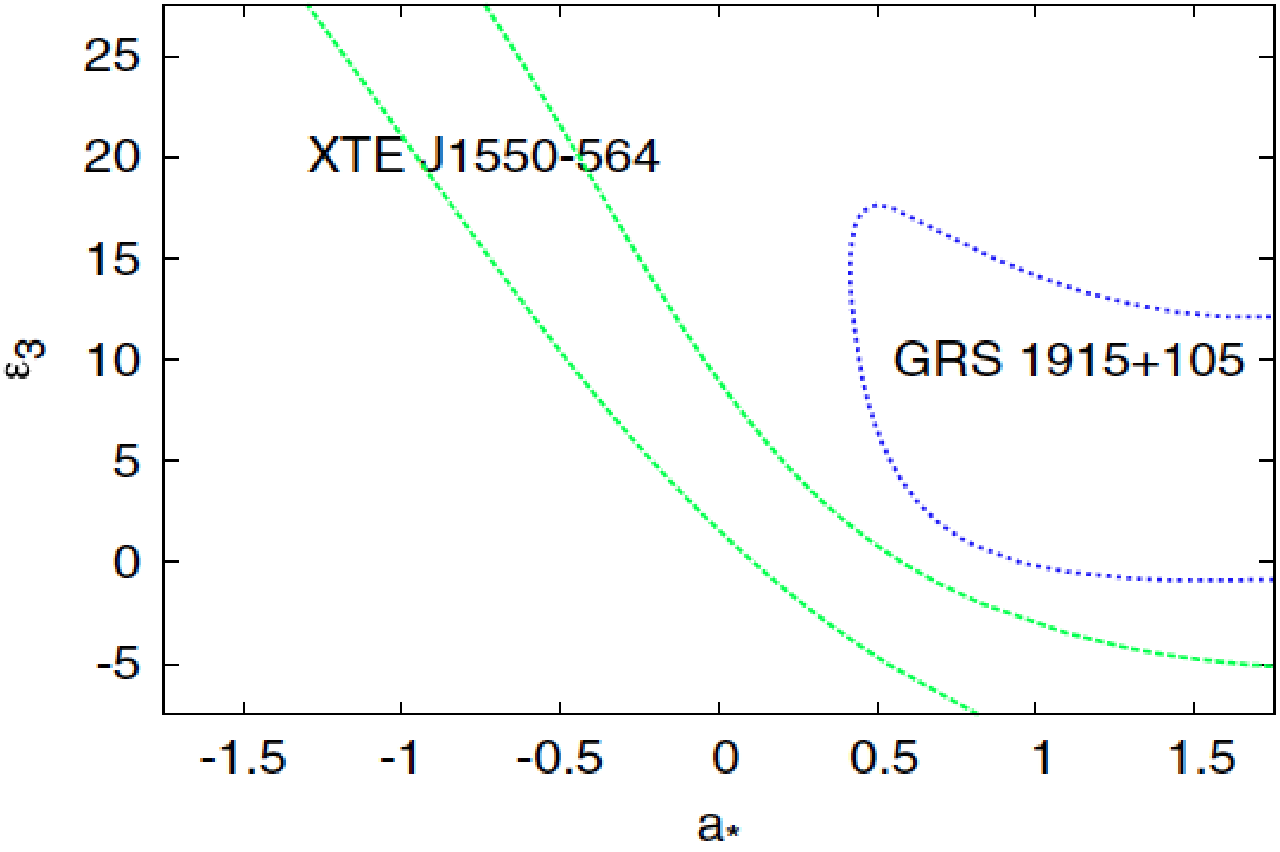

Jet power

- **Motivations**
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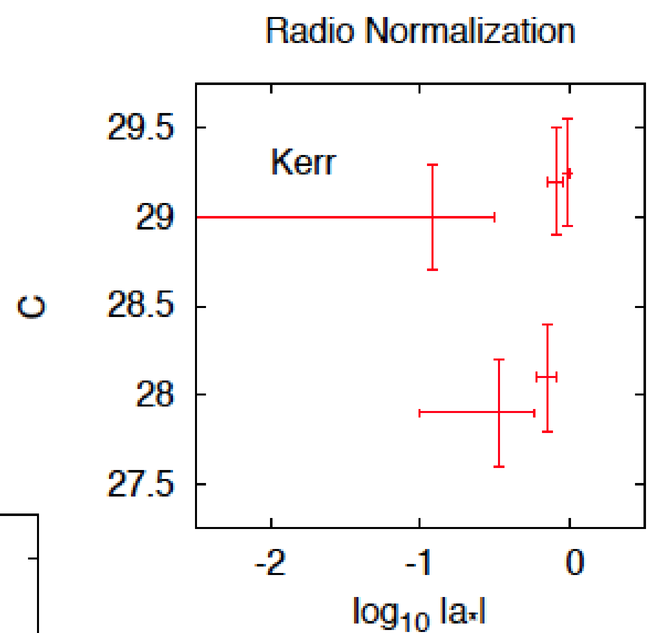
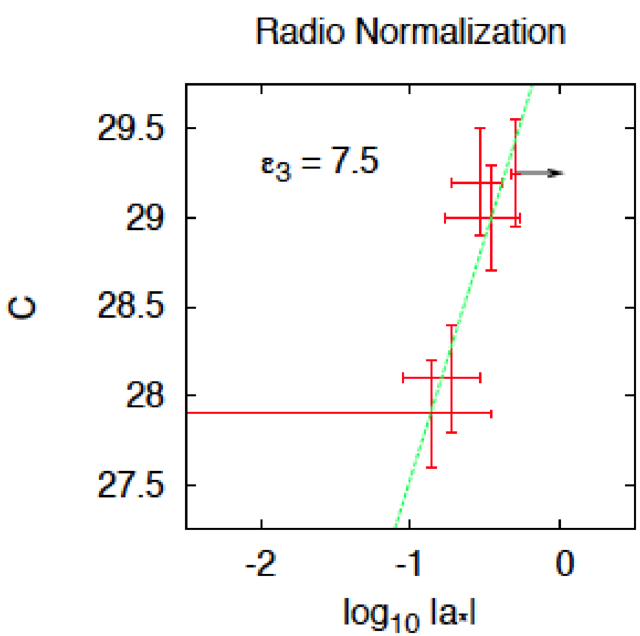
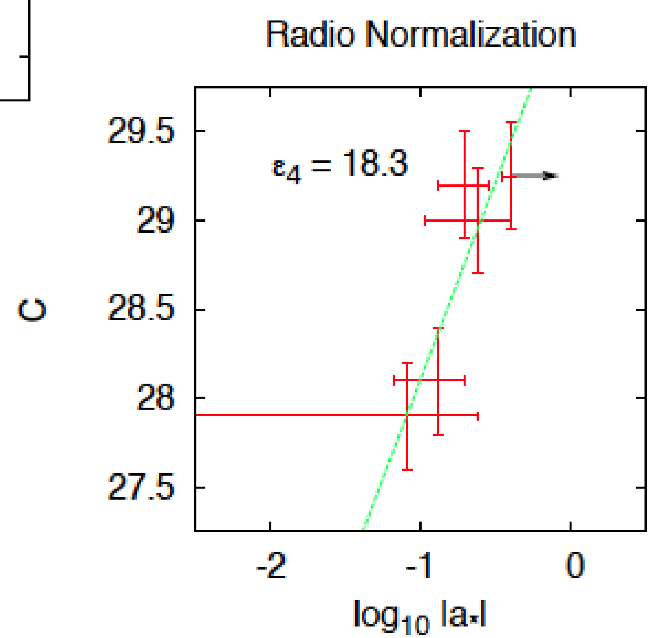
Jets

- **Jets are commonly produced by accreting BH candidates**
- **Two kinds of jets in the case of stellar-mass BH candidates: steady jets (in the hard state) and transient jets (usually when the source switches from the hard to the soft state)**
- **The exact mechanism producing these jets is not known**
- **For steady jets, a quite appealing scenario is the Blandford-Znajek mechanism, in which the jet is powered by the rotational energy of the BH**
- **No observational evidence for a correlation between jet power and BH spin (Fender, Gallo & Russell 2010)**
- **Claim of observational evidence for a correlation between power of transient jets and BH spin (Narayan & McClintock 2012)**

Steady jets

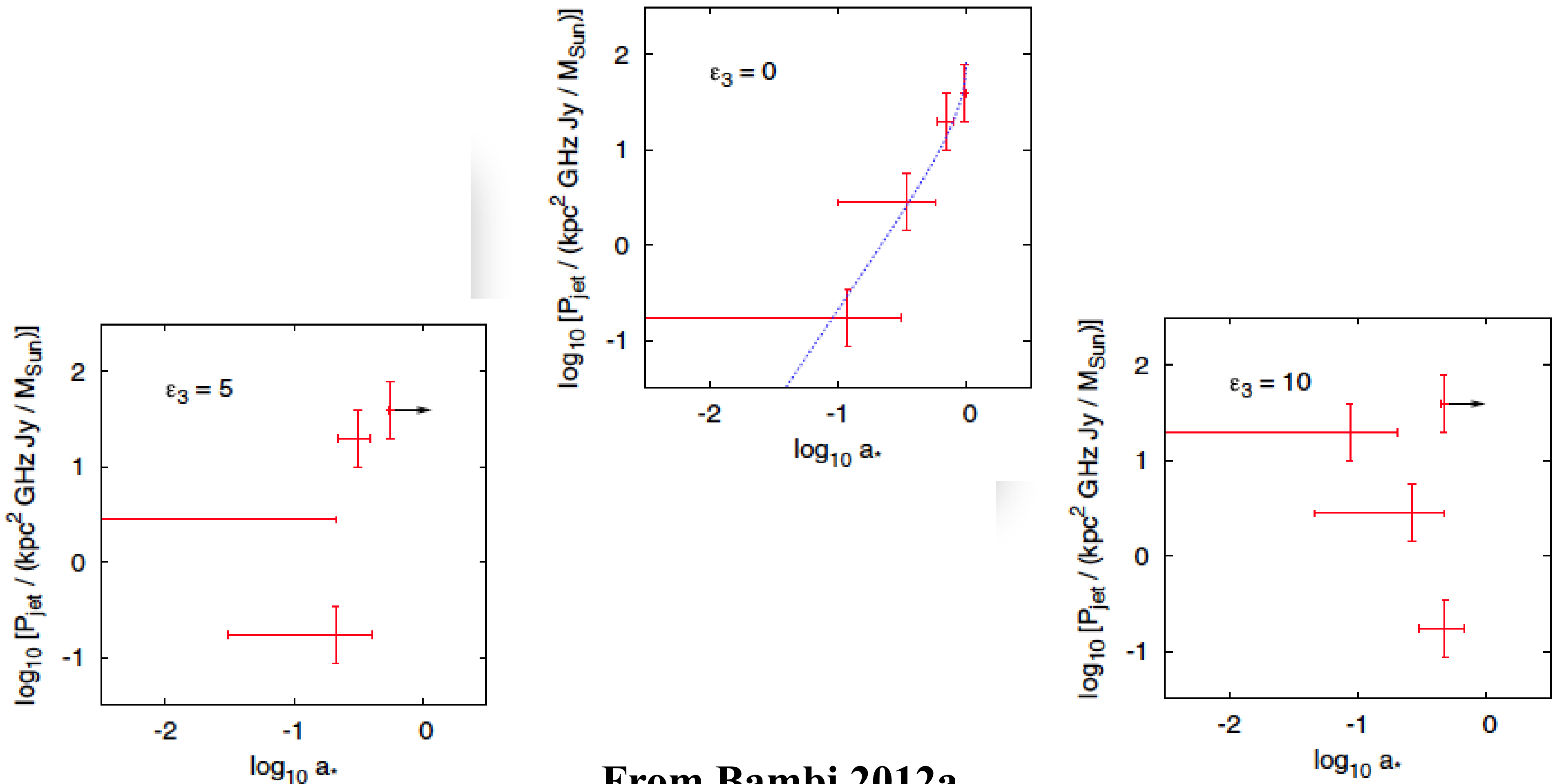






From Bambi 2012b

Transient jets



From Bambi 2012a

Conclusion

- **There is a body of observational evidence supporting the existence of dark and compact objects in the Galaxy and in the Universe. These objects are thought to be Kerr black holes**
- **The Kerr black hole hypothesis can be tested with the already available X-ray data by extending the continuum-fitting method to non-Kerr backgrounds**
- **One typically finds a degeneracy between the spin and the deformation parameter**
- **This degeneracy can be broken by adding another measurement (e.g. the power of steady/transient jets)**