Testing the nature of astrophysical black hole candidates

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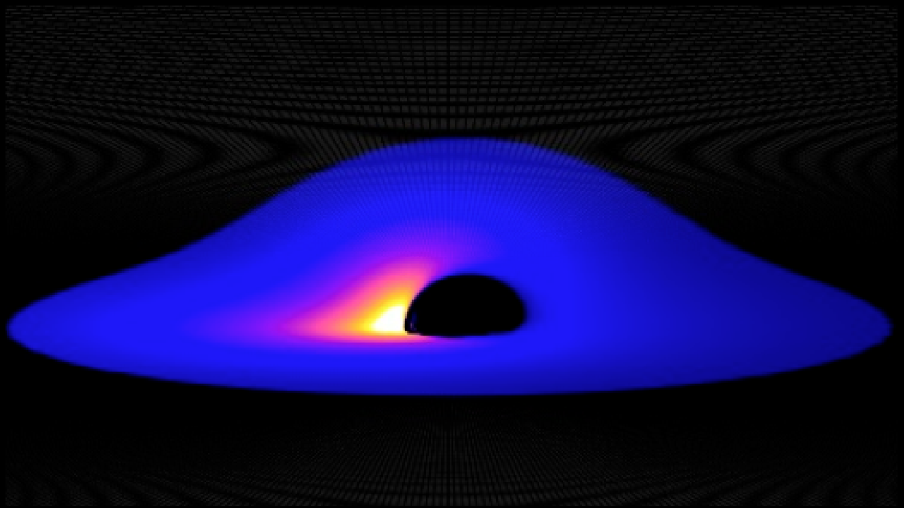


Plan of the talk

- **Motivations**
- **Theoretical and observational facts**
- **How can we test the nature of astrophysical BH candidates?**
- **Rough estimates of possible deviations from the Kerr geometry**
- **Continuum-fitting method (only for stellar-mass BH candidates)**
- **K-alpha iron line analysis**
- **Are jets powered by the spin?**

Motivations

- Motivations
- Theoretical and observational facts
- How can we test the nature of astrophysical BH candiudates?
- Some simple considerations
- Continuum-fitting method
- K-alpha iron line
- Jet power

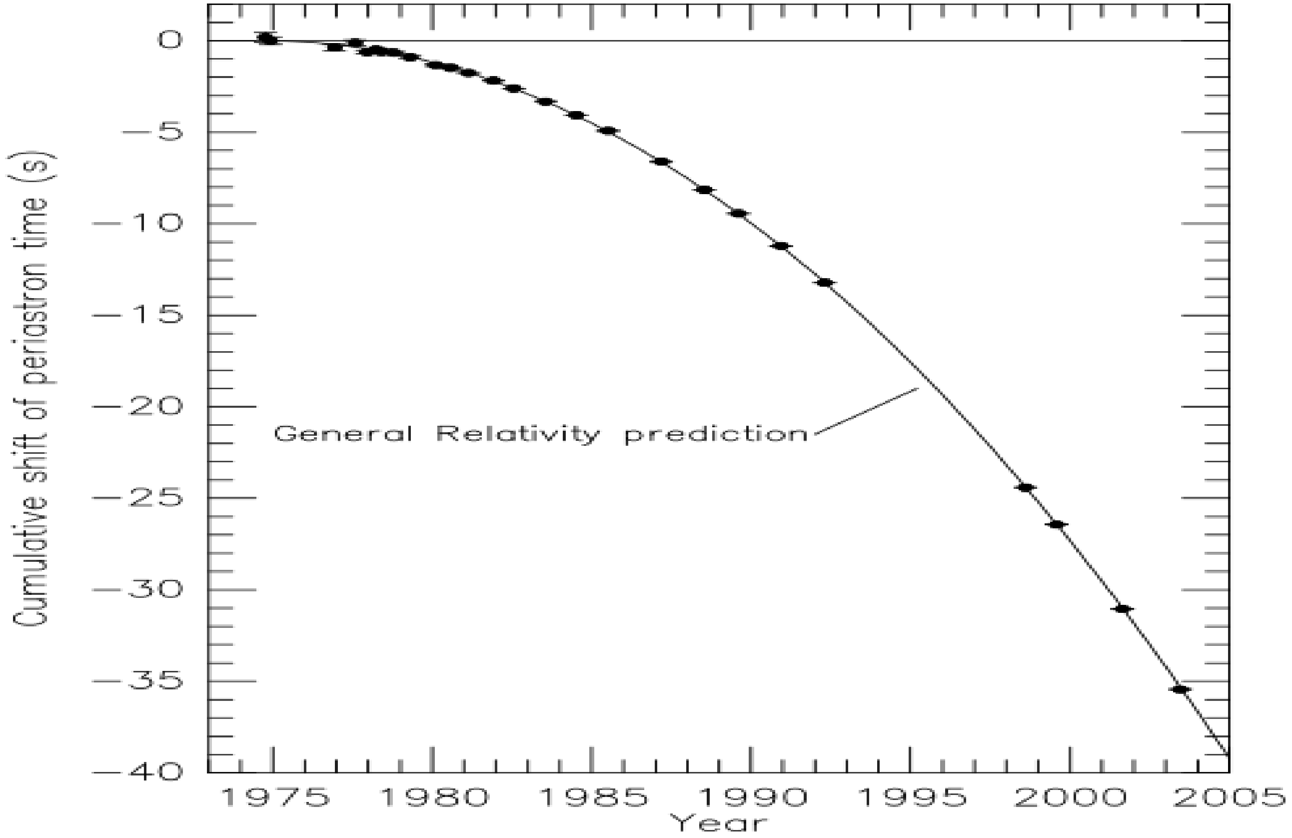
Tests of General Relativity

- **Earth's gravitational field:**
  Lunar Laser Ranging experiments, Gravity Probe B, . . .

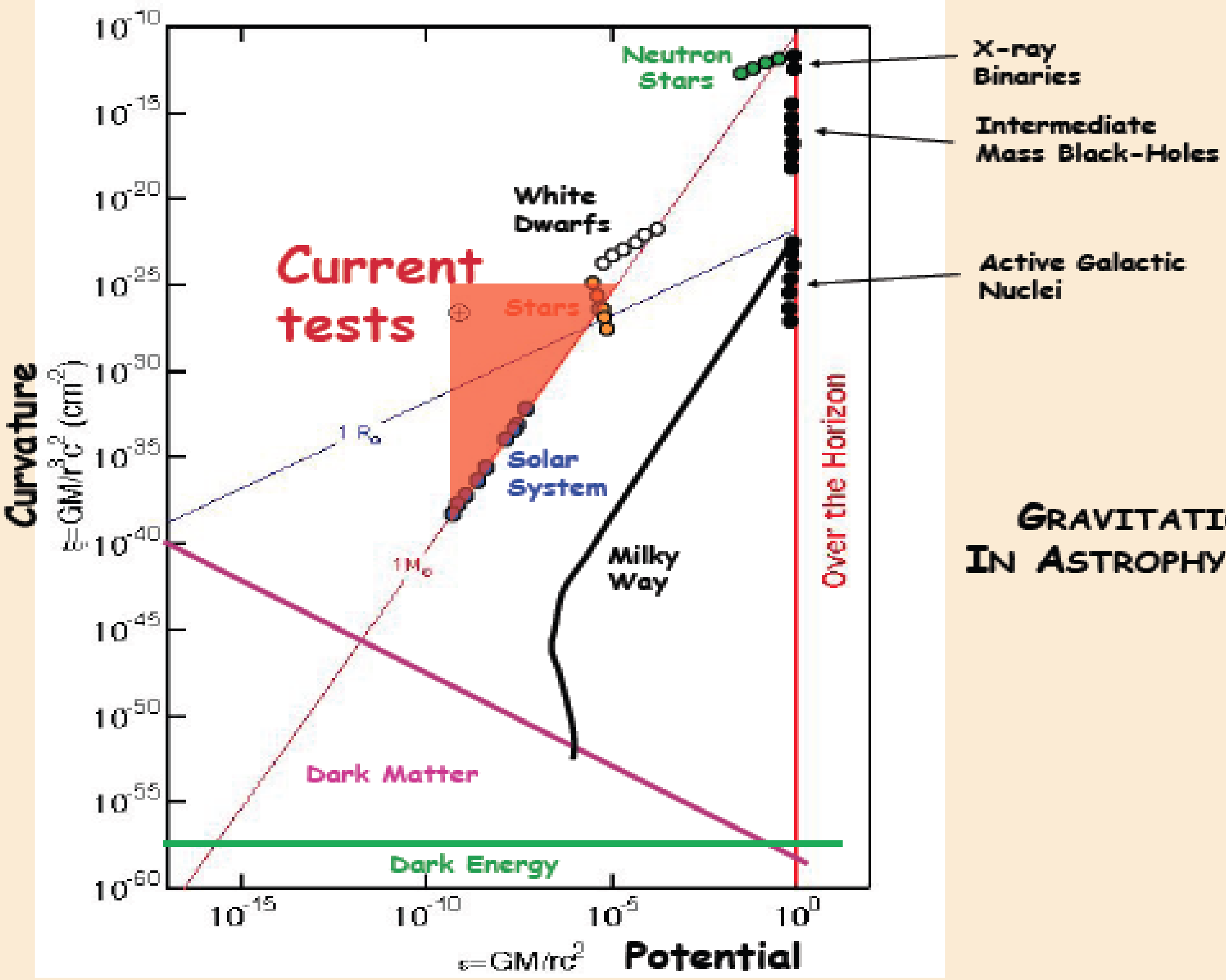
- **Solar System:**
  Cassini mission, . . .

- **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 nature of astrophysical BH candiudates?
- Some simple considerations
- Continuum-fitting method
- K-alpha iron line
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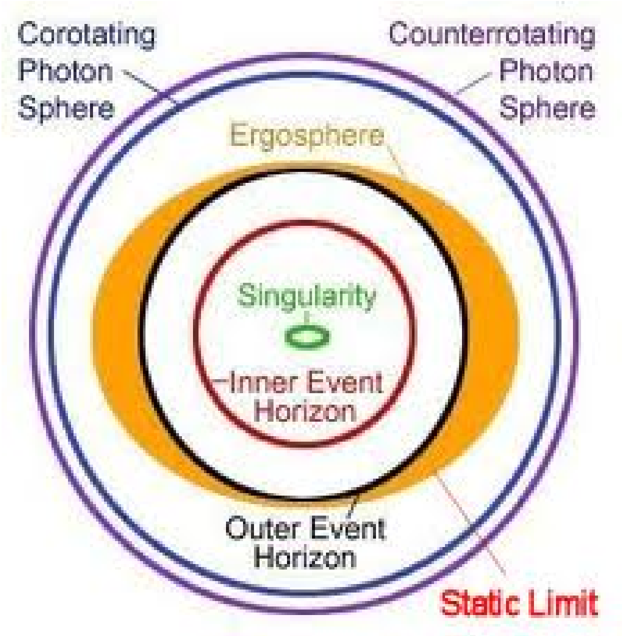
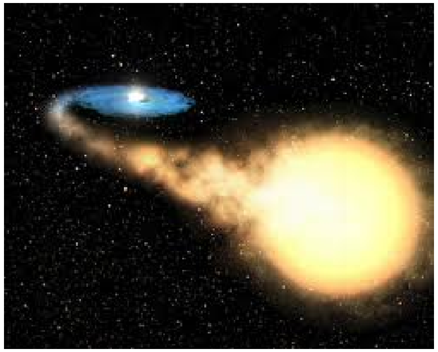
Black holes in GR (Theory)

- **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: $|a_*| < 1$**

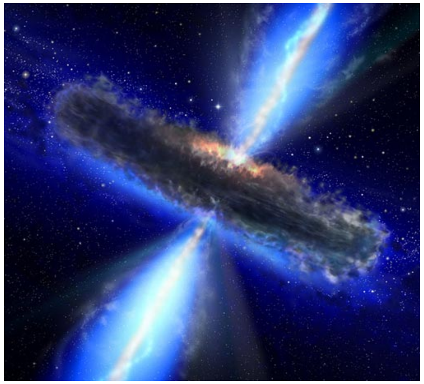


Black hole candidates (Observations)

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



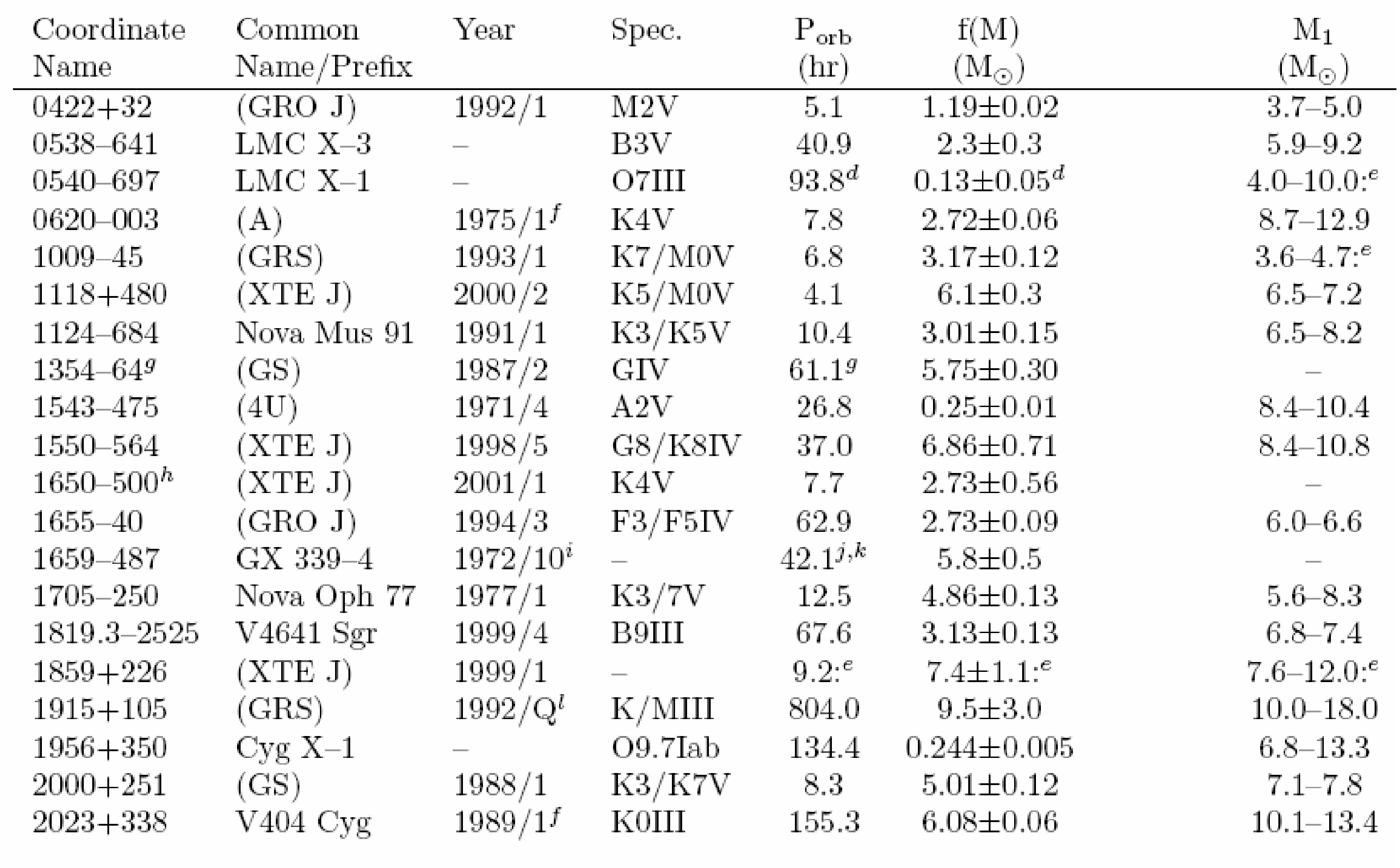
- **Super-massive BH candidates in galactic nuclei (10^5 – 10^{10} Solar masses)**



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

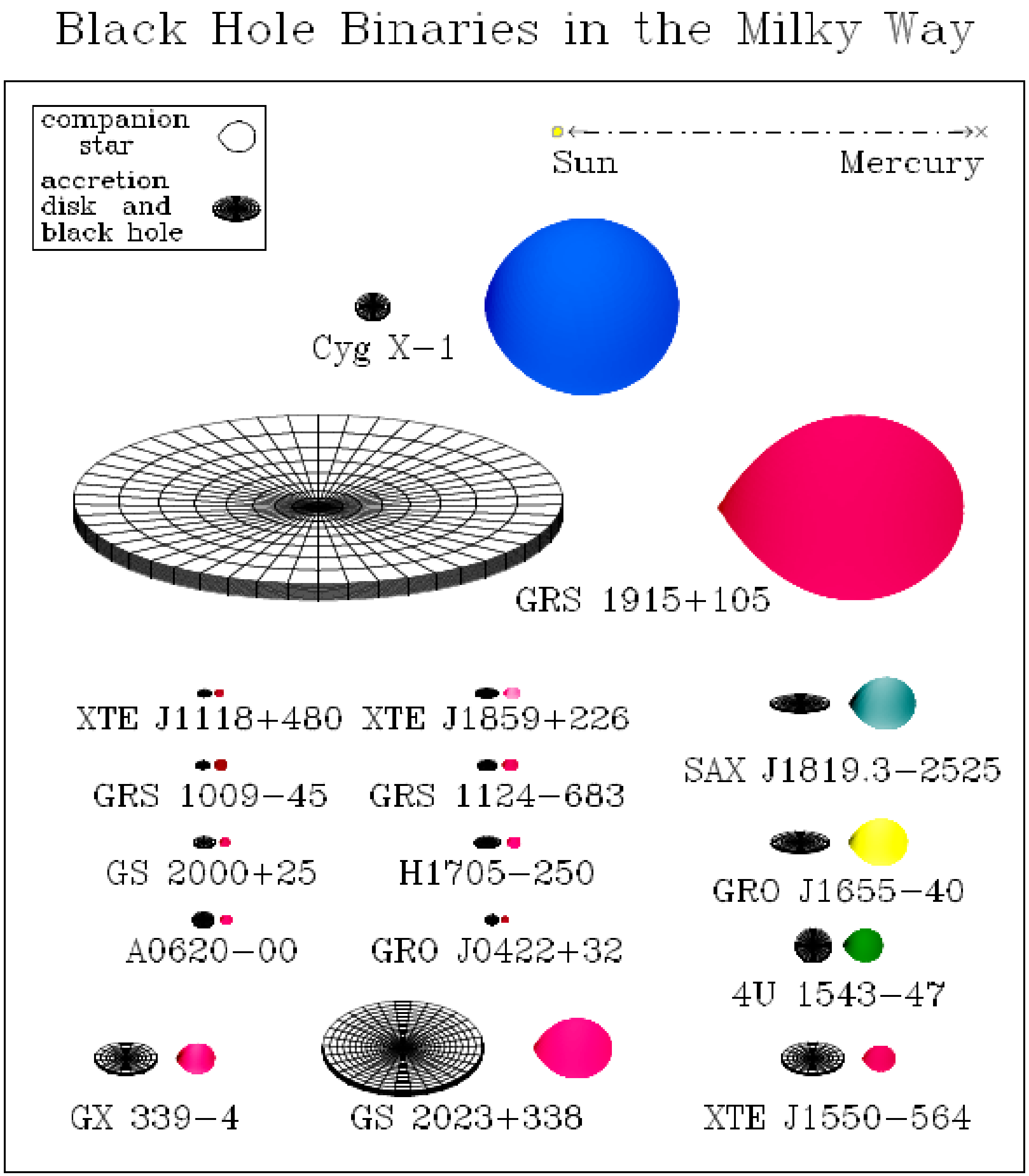
Stellar-mass BH candidates

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

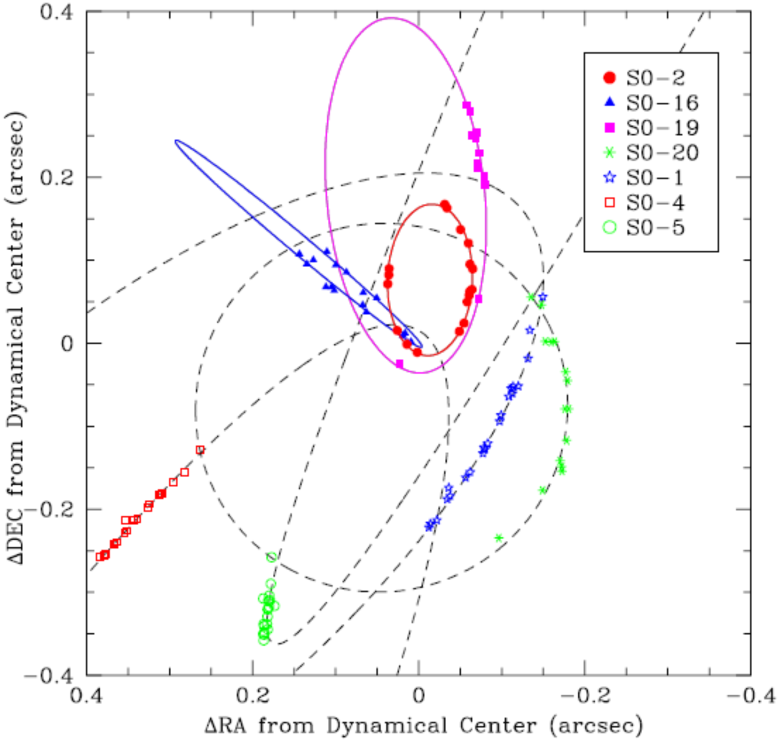
From Remillard & McClintock 2006



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 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-nature of astrophysical BH candidates?

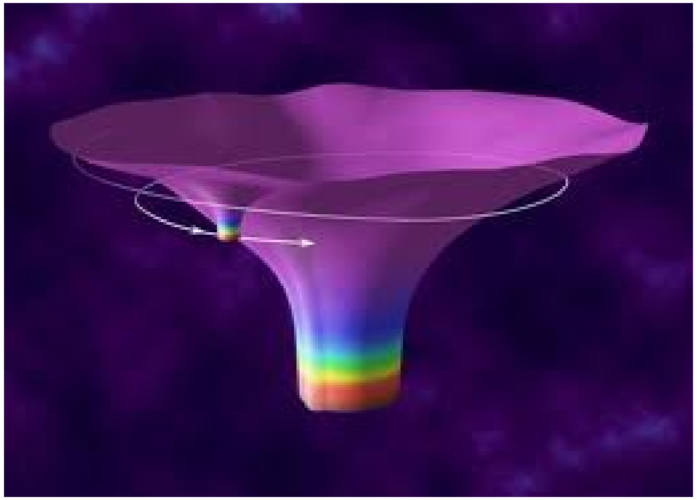
- Motivations
- Theoretical and observational facts
- How can we test the nature of astrophysical BH candiudates?
- Some simple considerations
- Continuum-fitting method
- K-alpha iron line
- Jet power

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**

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 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**

Some simple considerations

- Motivations
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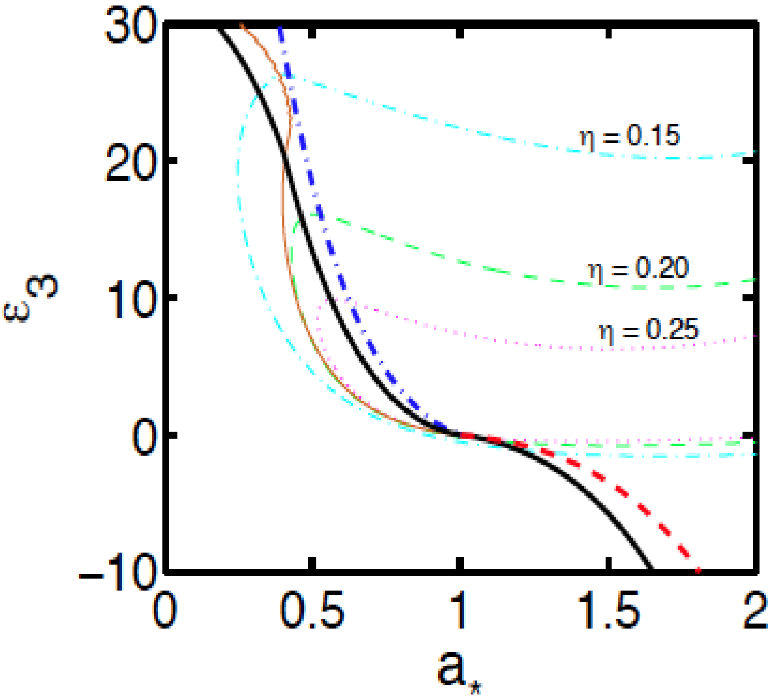
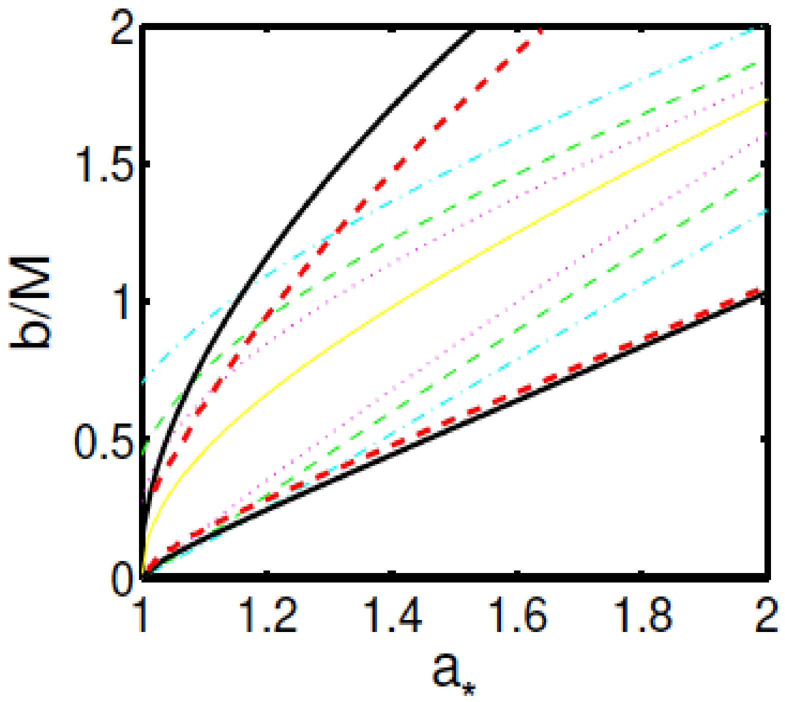
Accretion process + Radiative efficiency





Bound	JP background		MMS background	
	Thin disks	Thick disks	Thin disks	Thick disks
$\eta > 0.15$	$\lvert a_*\rvert < 1.196$	$\lvert a_*\rvert < 1.292$	$\lvert a_*\rvert < 1.179$	$\lvert a_*\rvert < 1.312$
$\eta > 0.20$	$\lvert a_*\rvert < 1.100$	$\lvert a_*\rvert < 1.169$	$\lvert a_*\rvert < 1.090$	$\lvert a_*\rvert < 1.193$
$\eta > 0.25$	$\lvert a_*\rvert < 1.047$	$\lvert a_*\rvert < 1.092$	$\lvert a_*\rvert < 1.040$	$\lvert a_*\rvert < 1.121$

Li & Bambi, JCAP 03 (2013) 031

Continuum-fitting method

- Motivations
- Theoretical and observational facts
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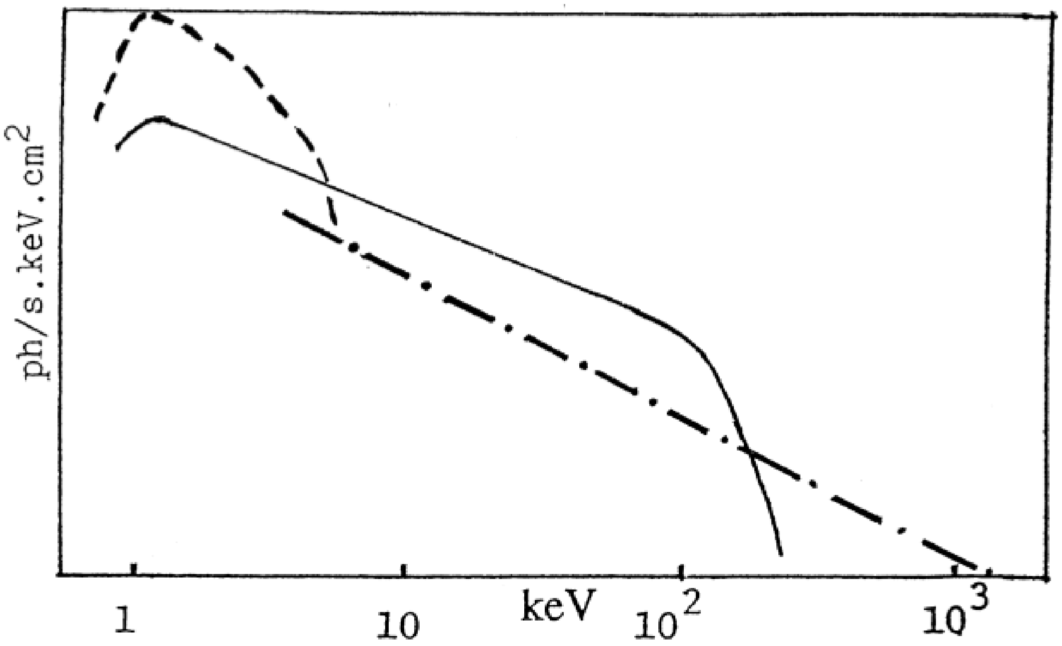
Continuum-fitting method

- **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:
$0.08\, L_{EDD} < L < 0.30\, L_{EDD}$

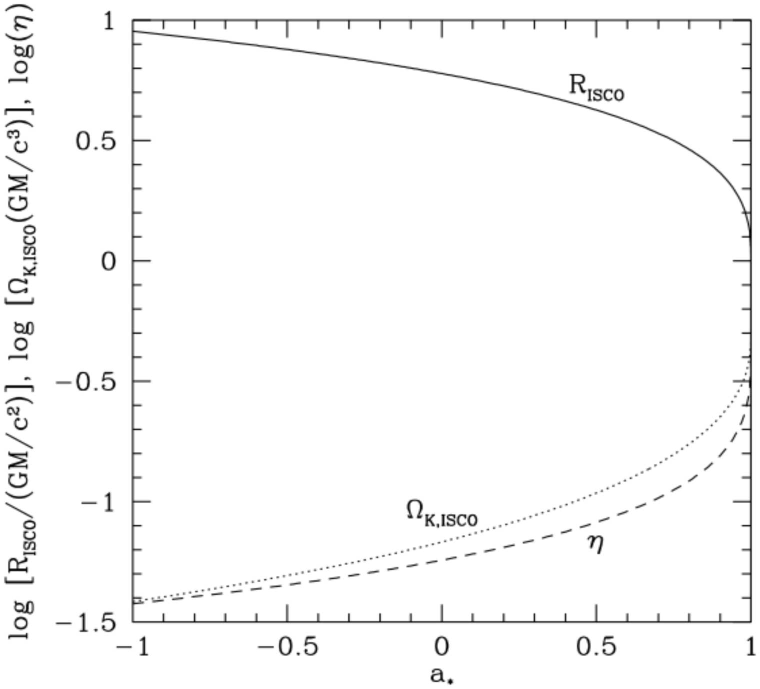
Assumptions:

- **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**

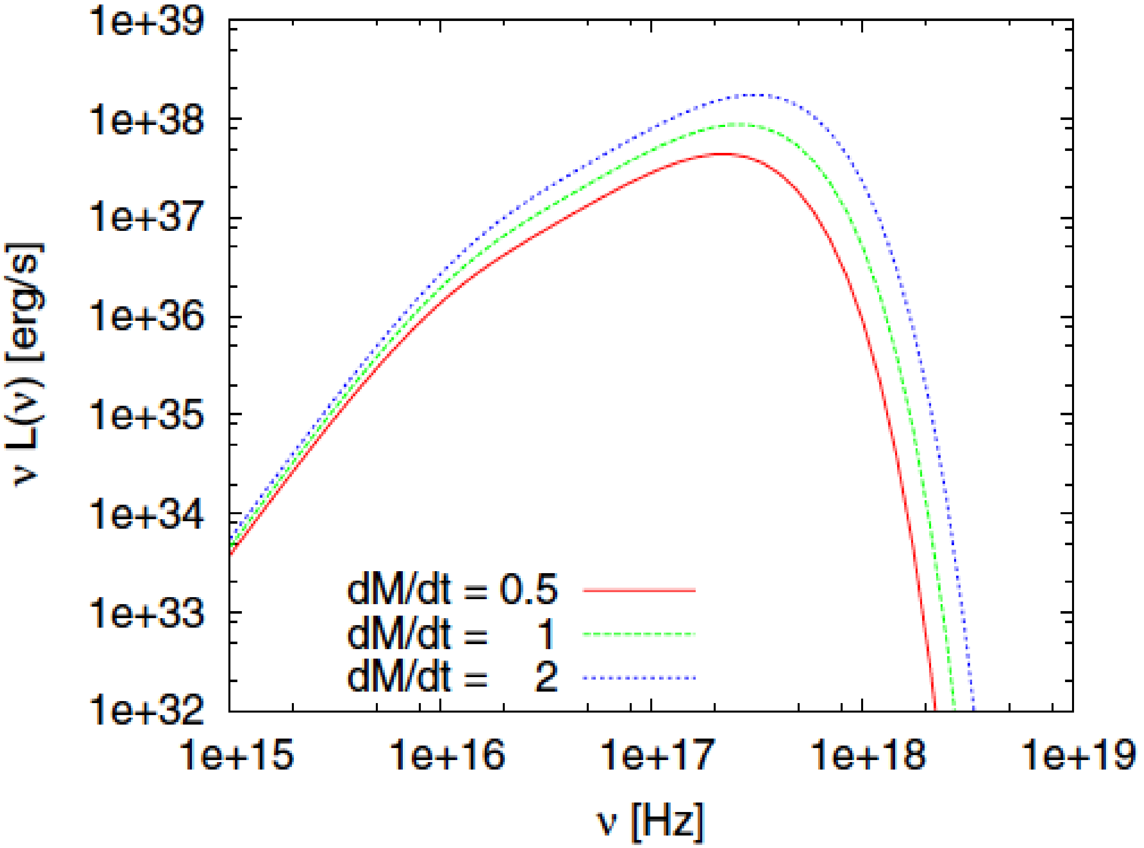
→ **Efficiency** $= 1 - E_{ISCO}$

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**

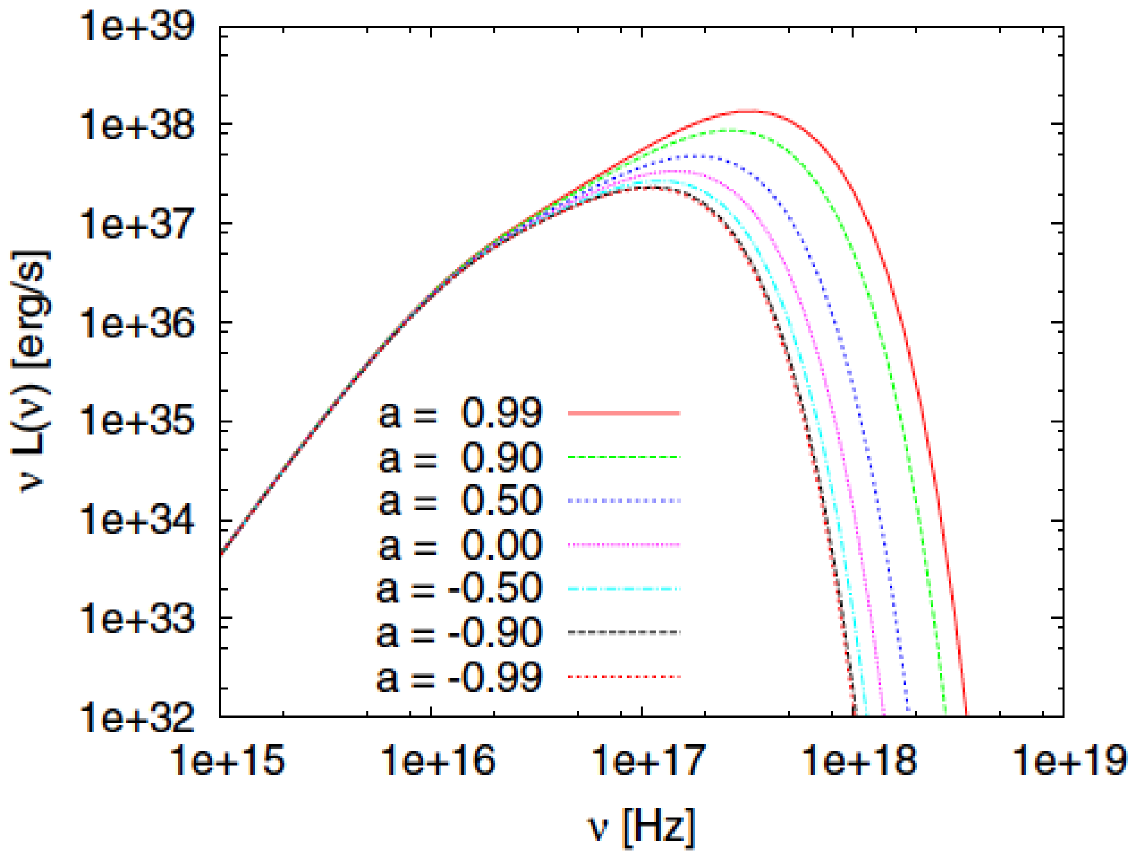


Mass accretion rate (Kerr background)



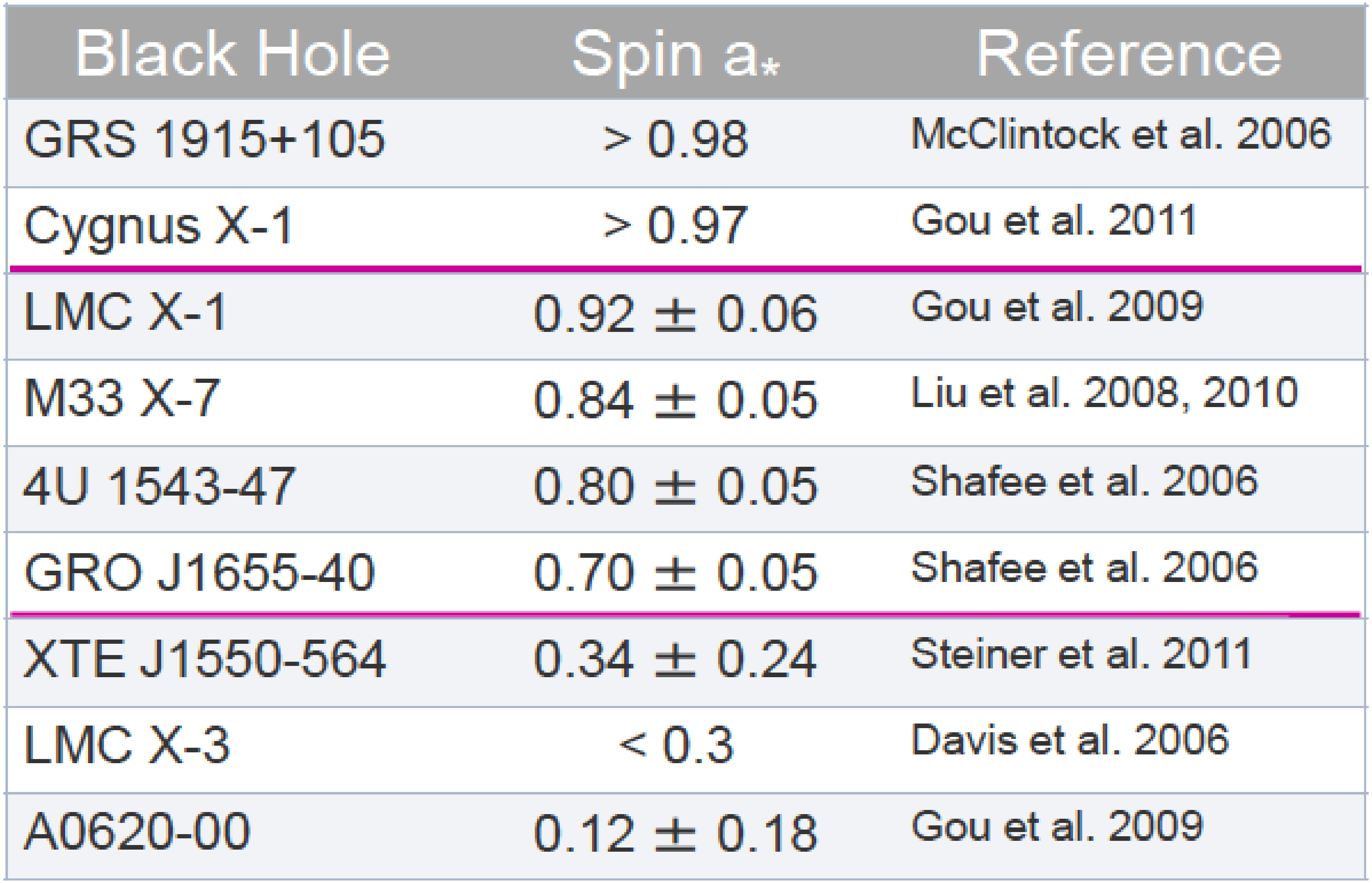
From Bambi & Barausse 2011

BH spin (Kerr background)



From Bambi & Barausse 2011

Spin measurements from the CfA 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

Step 1: computation of the image

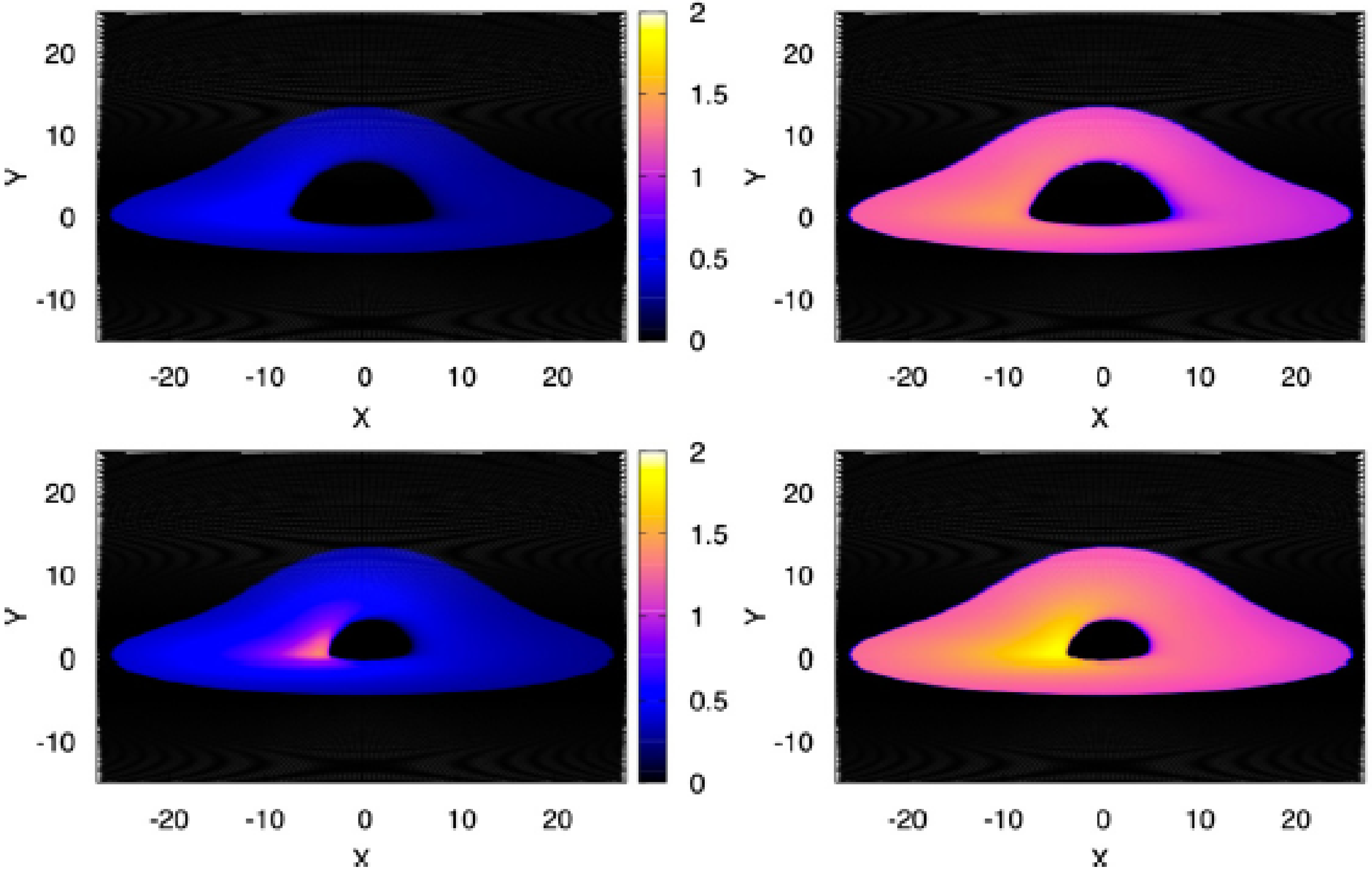
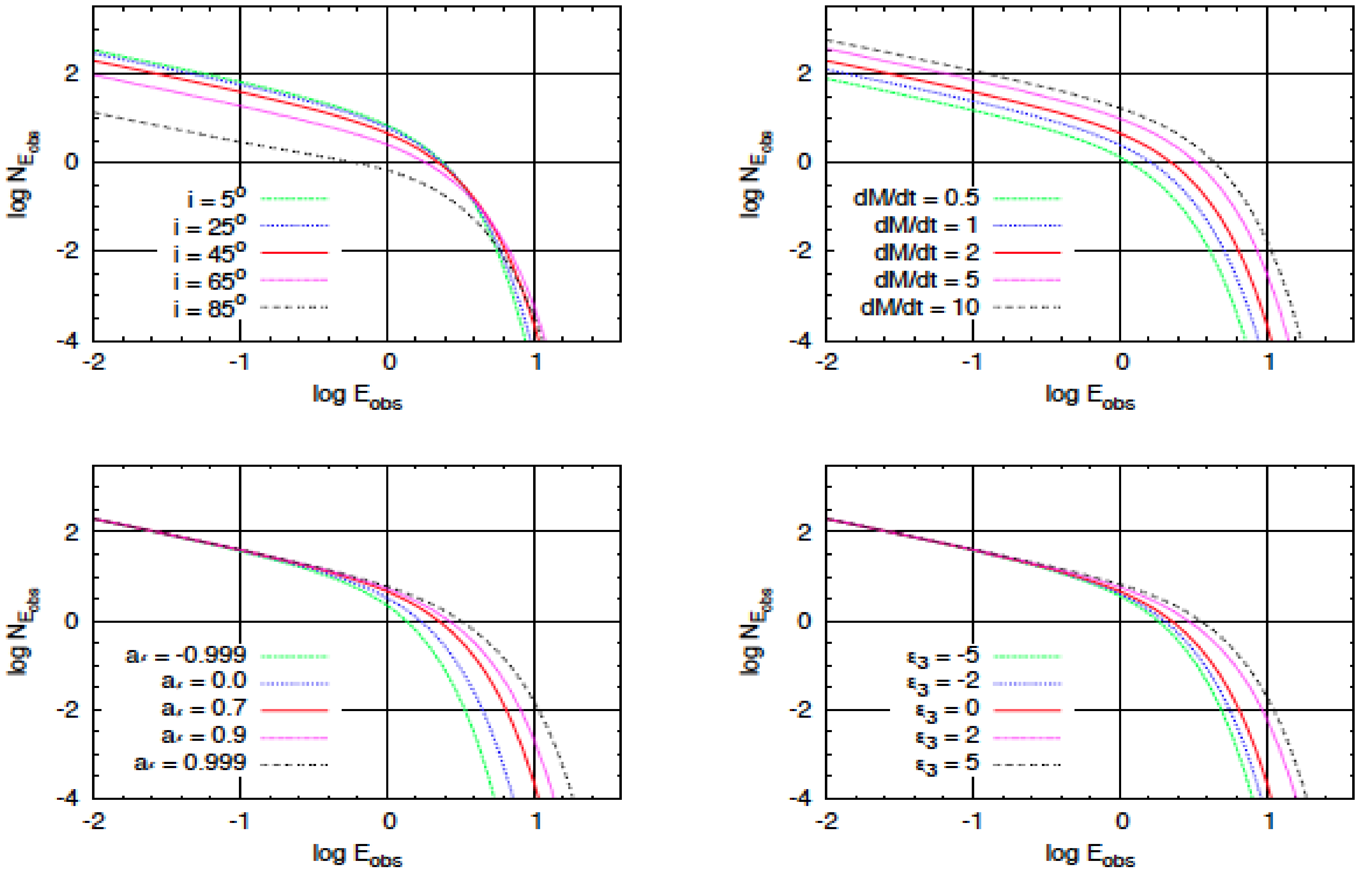


Figure 5. Direct image of the accretion disk. Observed blackbody temperature T_{obs} (left panels) and observed flux $\mathcal{F}_{obs}$ (right panels) in Kerr spacetime with spin parameter $a/M = 0$ (top panels) and 0.9 (bottom panels). The other parameters are $M = 10\ M_\odot$, $\dot{M} = 10^{18}$ g s^{-1}, $i = 80°$, and $f_{col} = 1.6$. The outer radius of the accretion disk is $r_{out} = 25\ M$. T_{obs} in keV; $\mathcal{F}_{obs}$ in arbitrary units and logarithmic scale.

(A color version of this figure is available in the online journal.)

Bambi, ApJ 761 (2012) 174

Step 2: calculation of the disk's spectrum



Bambi, ApJ 761 (2012) 174

Constraints from the continuum-fitting method

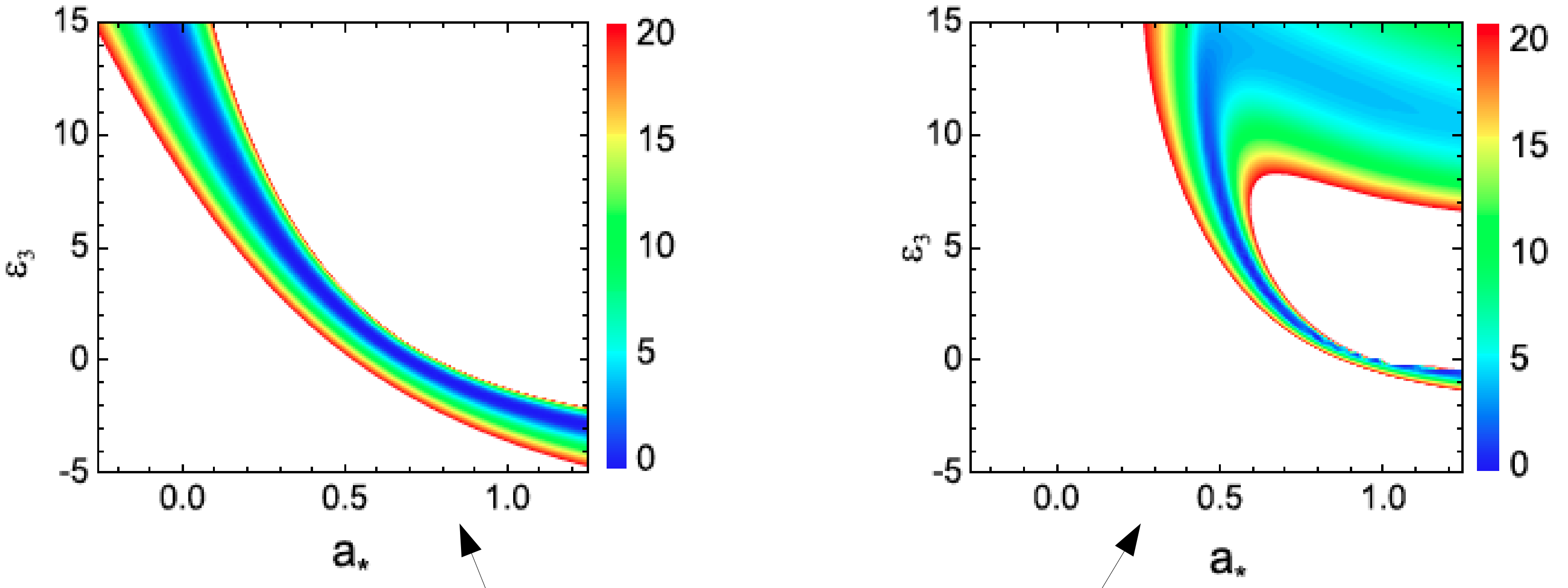
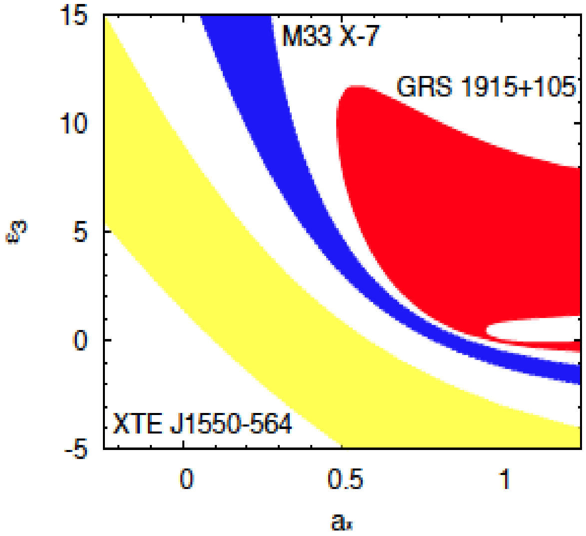


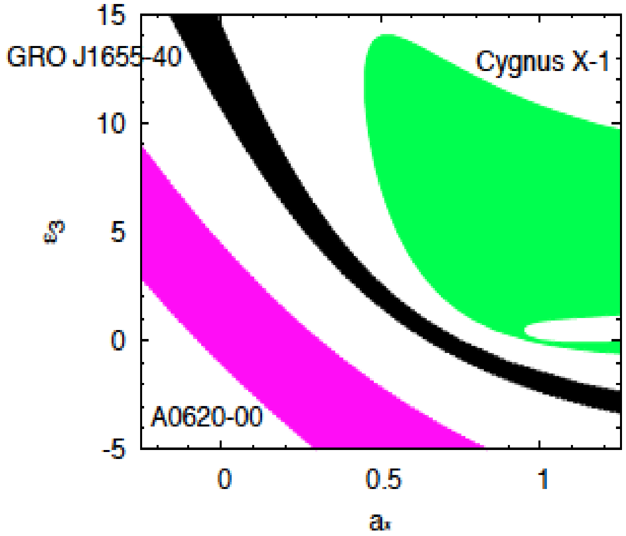
Fig. 4.— $\chi^2_{\rm red}$ from the comparison of the thermal spectrum of a thin accretion disk around a Kerr BH with spin parameter $\tilde{a}_*$ and a JP BH with spin parameter a_* and deformation parameter ϵ_3. Left panel: $\tilde{a}_* = 0.7$. Right panel: $\tilde{a}_* = 0.98$. See text for details.

Bambi, Astrononical Review 8 (2013) 4

Current constraints

BH Binary	$a_*^{\rm Kerr}$	$\eta_{\rm min}$	$\eta_{\rm max}$	Reference
GRS 1915+105	$a_* > 0.98$	0.234	0.423	McClintock et al. (2006)
Cygnus X-1	$a_* > 0.97$	0.215	0.423	Gou et al. (2011)
LMC X-1	0.92 ± 0.06	0.139	0.234	Gou et al. (2009)
M33 X-7	0.84 ± 0.05	0.120	0.151	Liu et al. (2008, 2010)
4U 1543-47	0.80 ± 0.05	0.112	0.136	Shafee et al. (2006)
GRO J1655-40	0.70 ± 0.05	0.097	0.112	Shafee et al. (2006)
XTE J1550-564	0.34 ± 0.24	0.0606	0.0892	Steiner et al. (2011)
LMC X-3	$a_* < 0.3$	0.0365	0.0694	Davis et al. (2006)
A0620-00	0.12 ± 0.19	0.0550	0.0699	Gou et al. (2010)





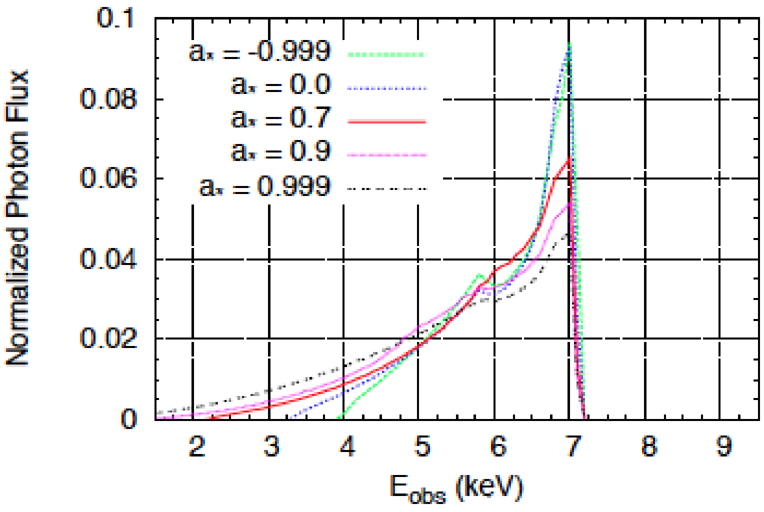
Bambi, Astrononical Review 8 (2013) 4

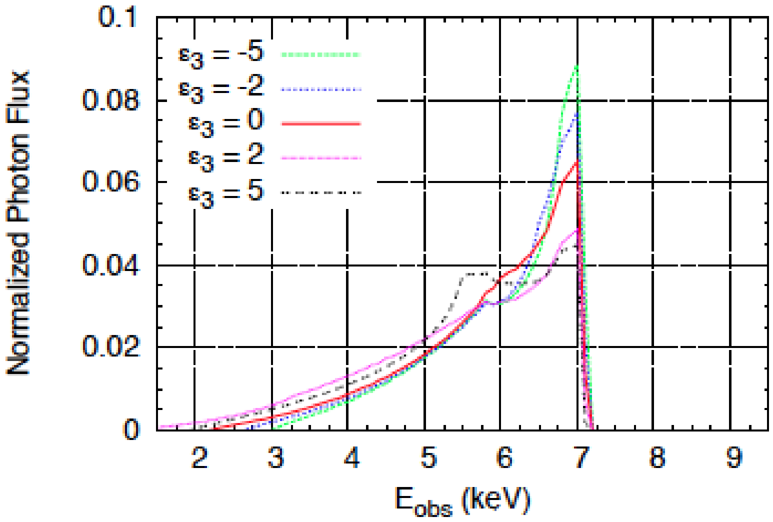
K-alpha iron line

- **Motivations**
- **Theoretical and observational facts**
- **How can we test the nature of astrophysical BH candiudates?**
- **Some simple considerations**
- **Continuum-fitting method**
- **K-alpha iron line**
- **Jet power**

K-alpha iron line analysis

- It is another popular technique used by astronomers to try to estimate the spin parameter of BH candidates





Bambi, PRD 87 (2013) 023007

Constraints from the K-alpha iron line

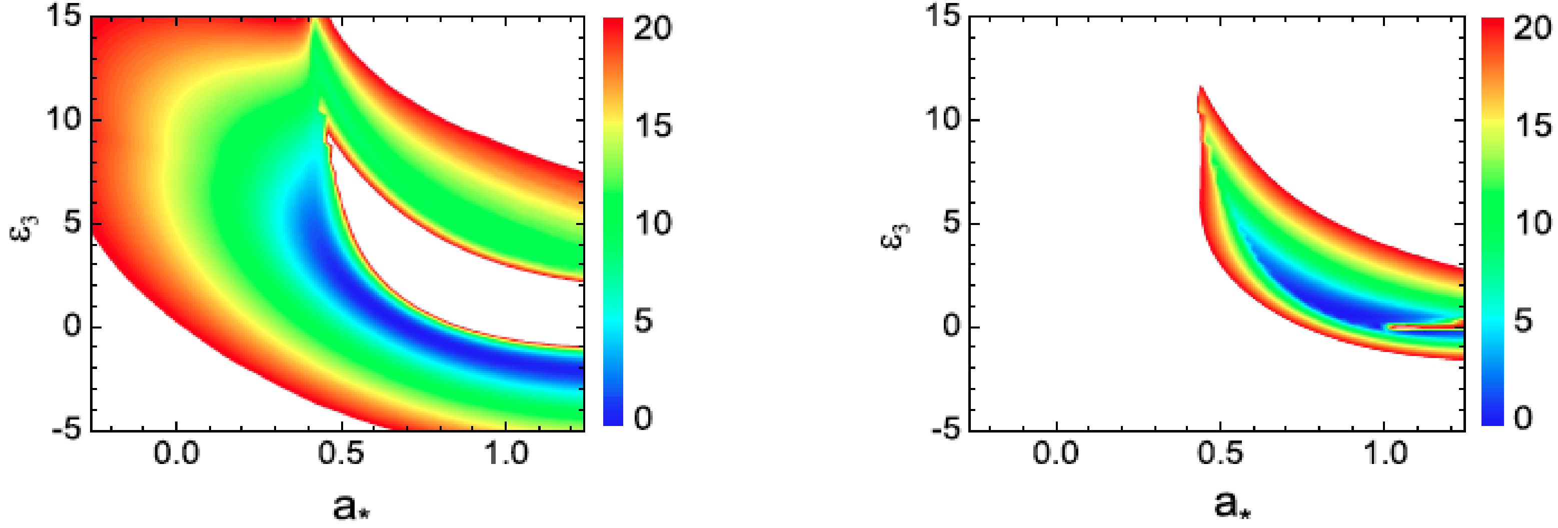
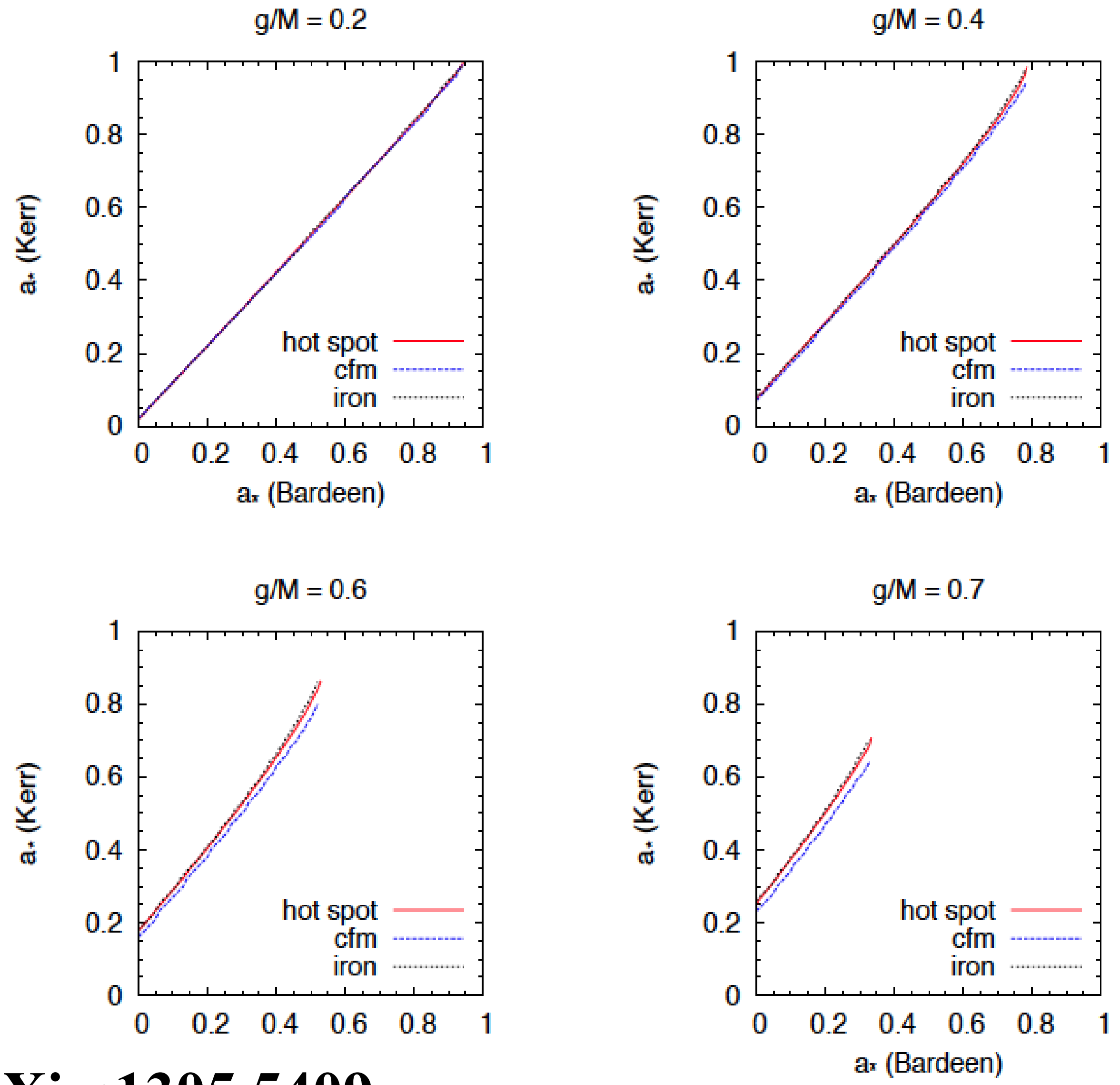


Fig. 7.— $\chi^2_{\rm red}$ from the comparison of the broad Kα iron line generated around a Kerr BH with spin parameter $\tilde{a}_*$ and a JP BH with spin parameter a_* and deformation parameter ϵ_3. Left panel: $\tilde{a}_* = 0.7$. Right panel: $\tilde{a}_* = 0.98$. See text for details.

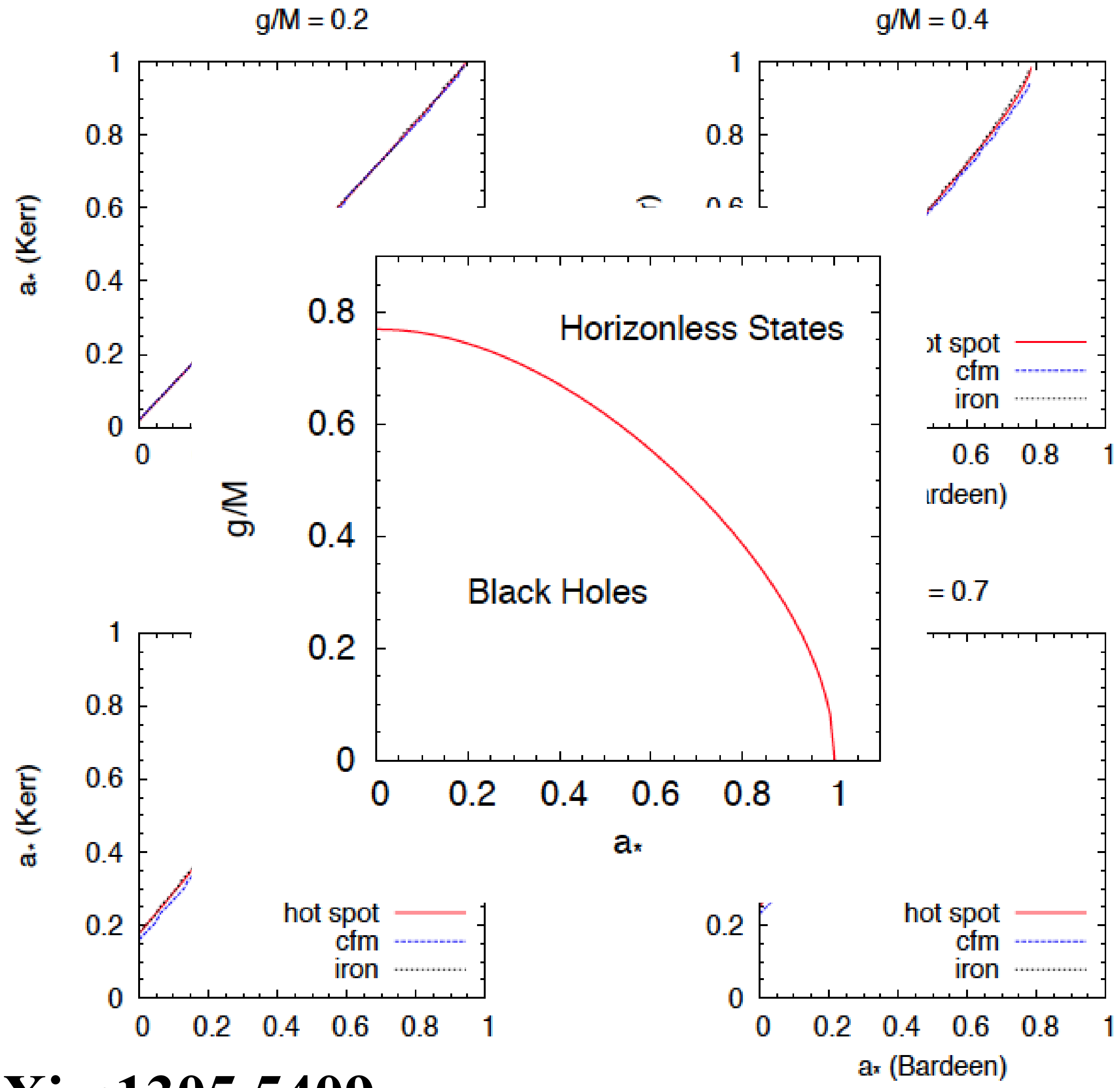
Bambi, Astrononical Review 8 (2013) 4

Continuum-fitting method + K-alpha iron line (Rotating Bardeen BHs)



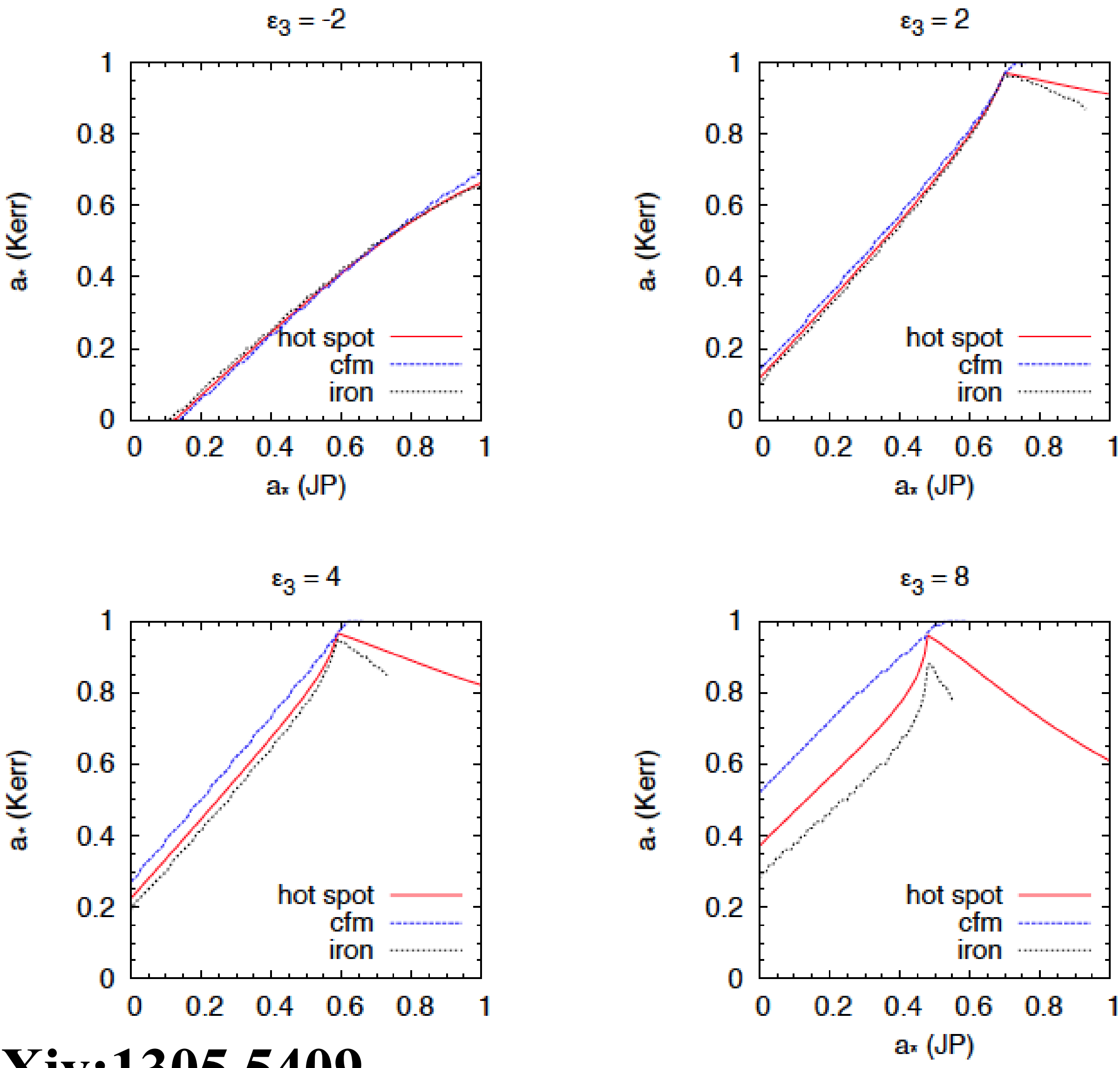
Bambi, arXiv:1305.5409

Continuum-fitting method + K-alpha iron line (Rotating Bardeen BHs)



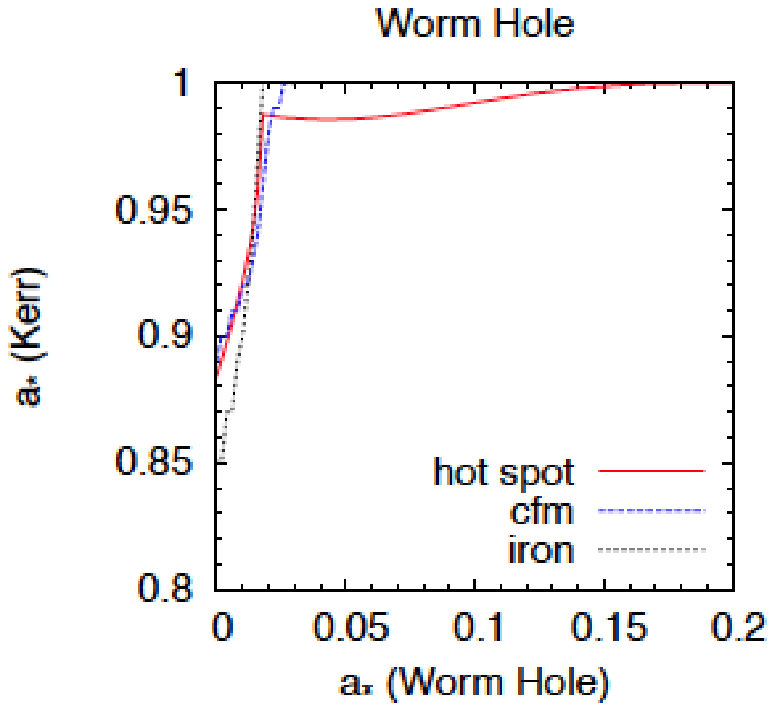
Bambi, arXiv:1305.5409

Continuum-fitting method + K-alpha iron line (Johannsen-Psaltis metric)



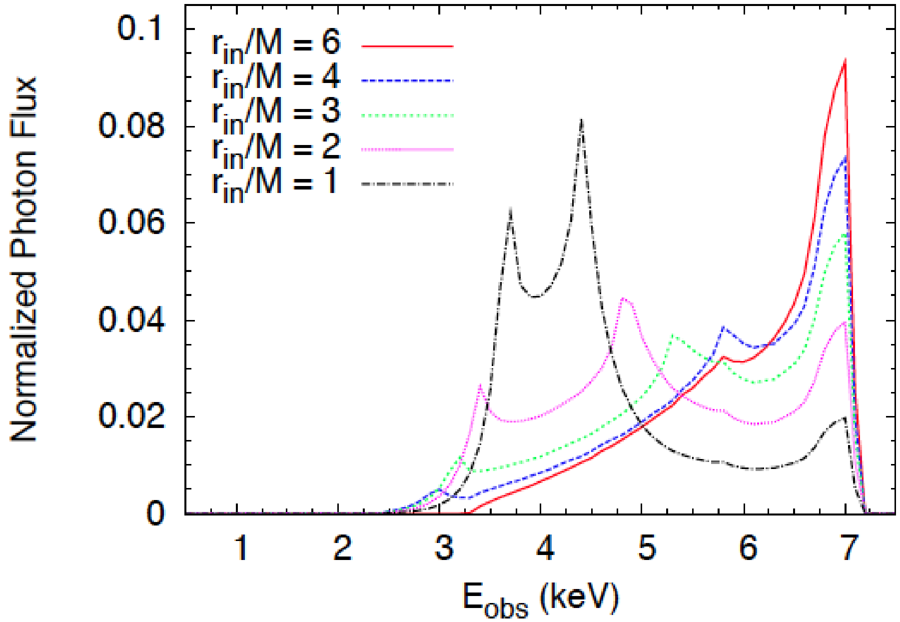
Bambi, arXiv:1305.5409

Continuum-fitting method + K-alpha iron line (Wormholes)

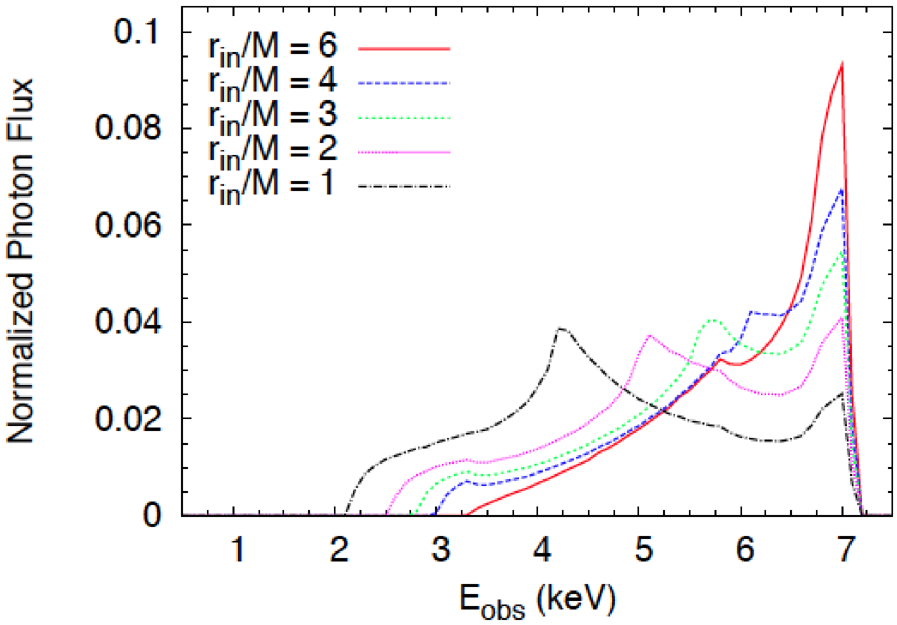


K-alpha iron line (Interior solutions)

Regular solution



Singular solution



Bambi & Malafarina, arXiv:1307.2106

Jet power

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- **Theoretical and observational facts**
- **How can we test the nature of astrophysical BH candiudates?**
- **Some simple considerations**
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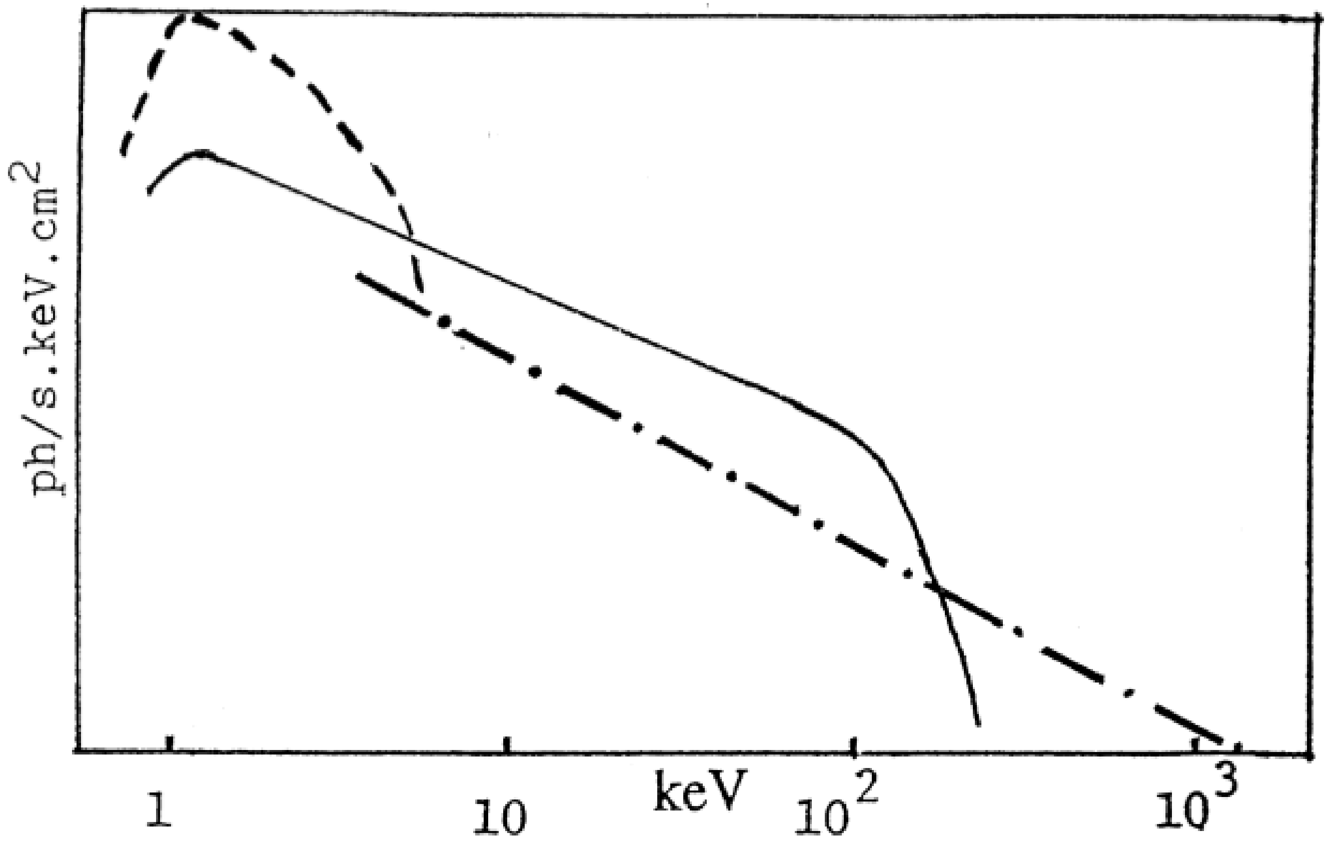
- **Jet power**

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)

X-ray spectrum of stellar-mass BH candidates



Kerr background

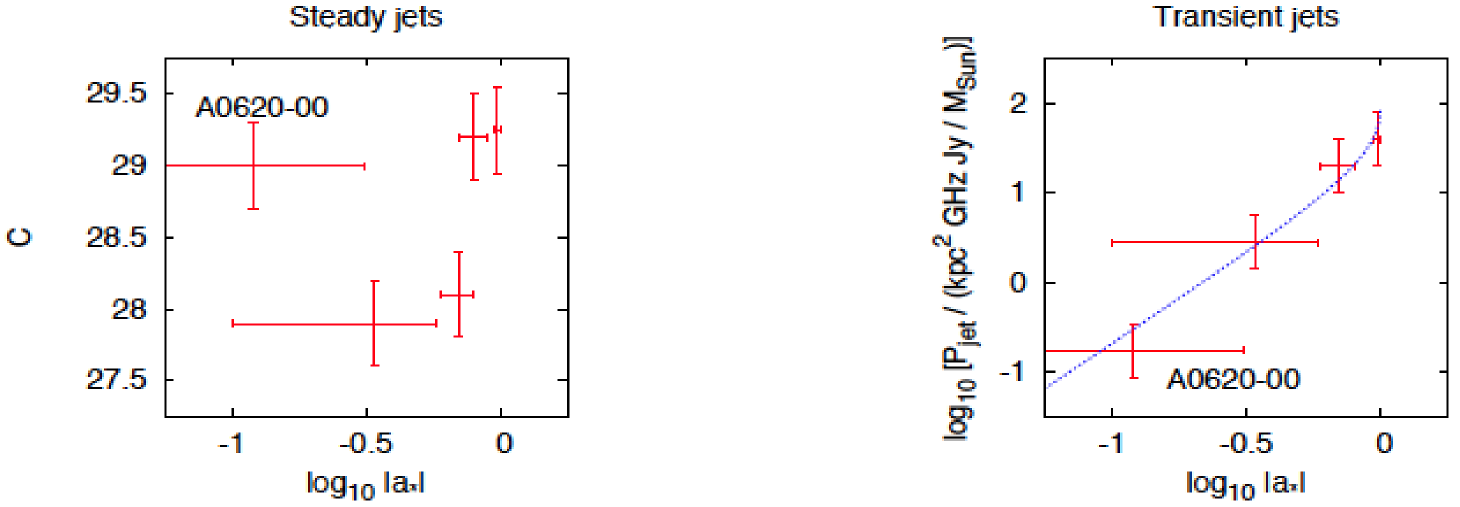


Fig. 9.— Left panel: absence of evidence for a correlation between the jet power and the BH spin for steady jets (Fender et al. 2010). Right panel: evidence for a correlation between the jet power and the BH spin for transient jets (Narayan & McClintock 2012). See text for details.

Bambi, PRD 85 (2012) 043002
Bambi, PRD 86 (2012) 123013

Non-Kerr background...

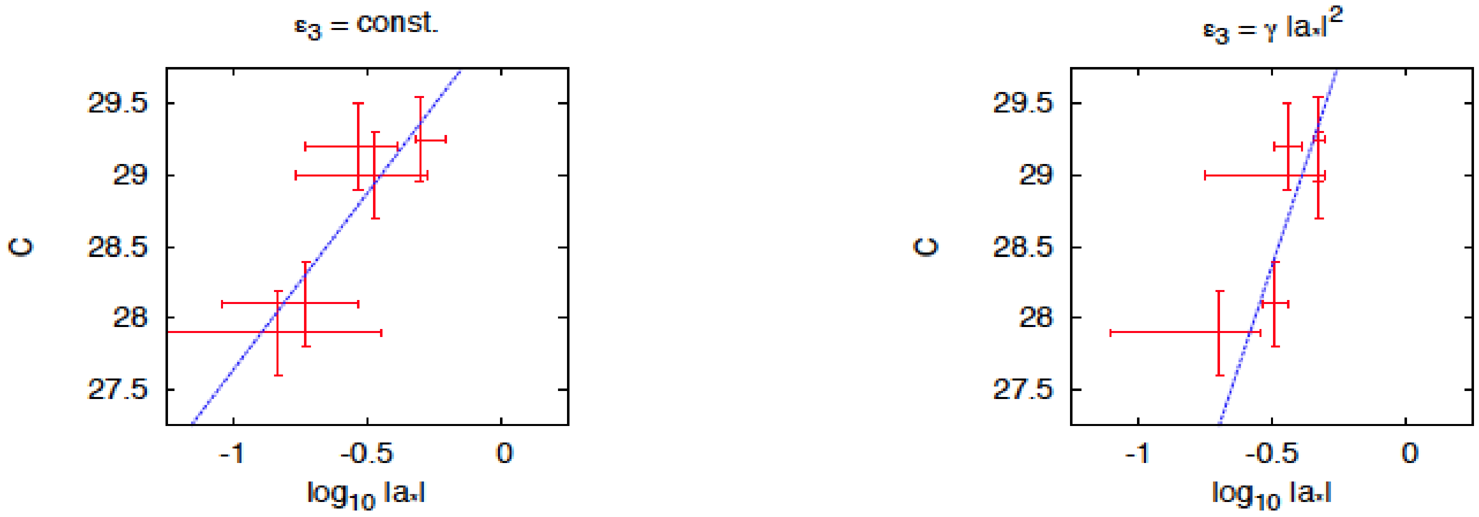


Fig. 10.— Best fit for a possible correlation between the jet power and the spin parameter of BH candidates assuming a non-vanishing deformation parameter ϵ_3. Left panel: ϵ_3 constant for all the objects; the best fit is for $\epsilon_3 = 7.5$. Right panel: $\epsilon_3 = \gamma|a_*|^2$, with γ constant; the best fit is for $\gamma = 45$. See Bambi (2012d) for more details.

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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 and the K-alpha iron line methods to non-Kerr backgrounds**
- **One typically finds a degeneracy between the spin and the deformation parameter**
- **Continuum-fitting method and K-alpha iron line analysis may provide consistent results with a wrong metric!**
- **This degeneracy can be broken by adding another measurement (e.g. the power of steady/transient jets)**

Thank you!