Testing the nature of astrophysical black hole candidates

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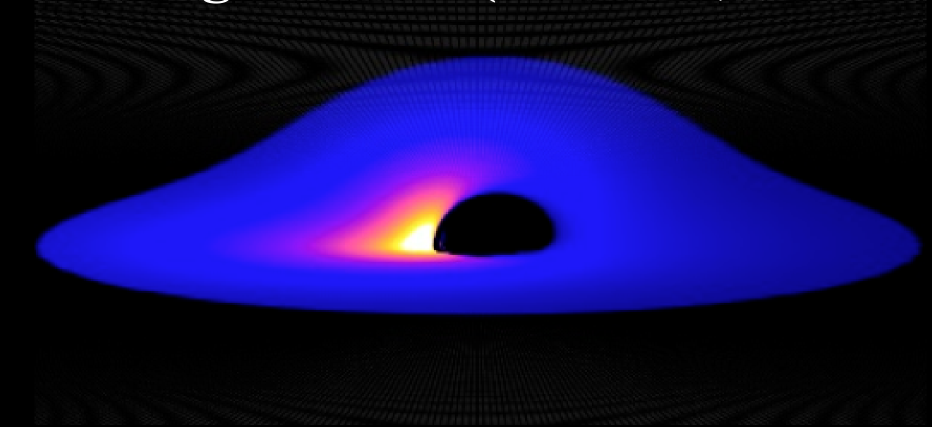
7th FERO Meeting
28-30 August 2014 (Krakow, Poland)



Plan of the talk

- Motivations
- Theoretical and observational facts
- How can we test the nature of astrophysical BH candidates?
- Continuum-fitting method (only for stellar-mass BH candidates)
- K-alpha iron line analysis and reverberation mapping
- Are jets powered by the spin?
- Testing the nature of SgrA*

Motivations

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

Tests of General Relativity

- **Earth's gravitational field:**

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

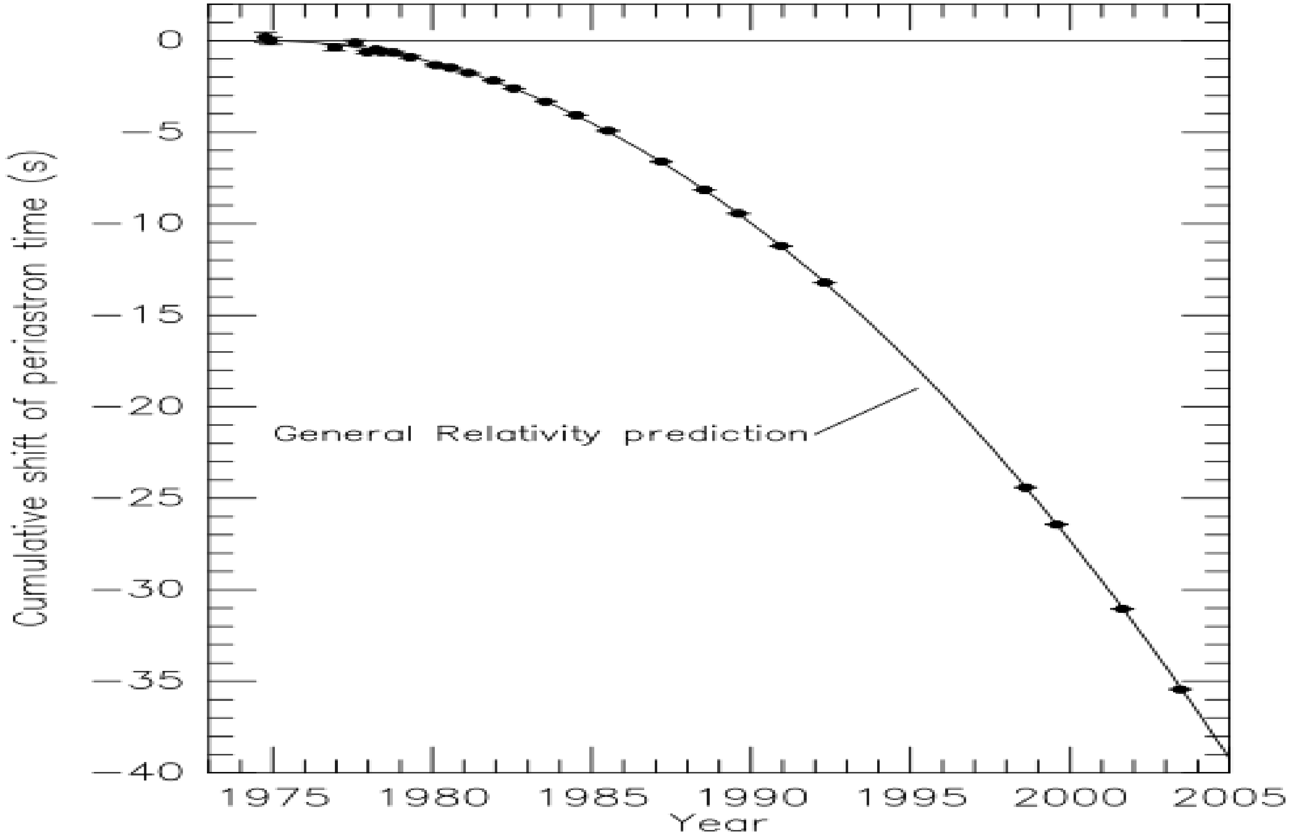
- **Solar System:**

  Cassini mission, . . .

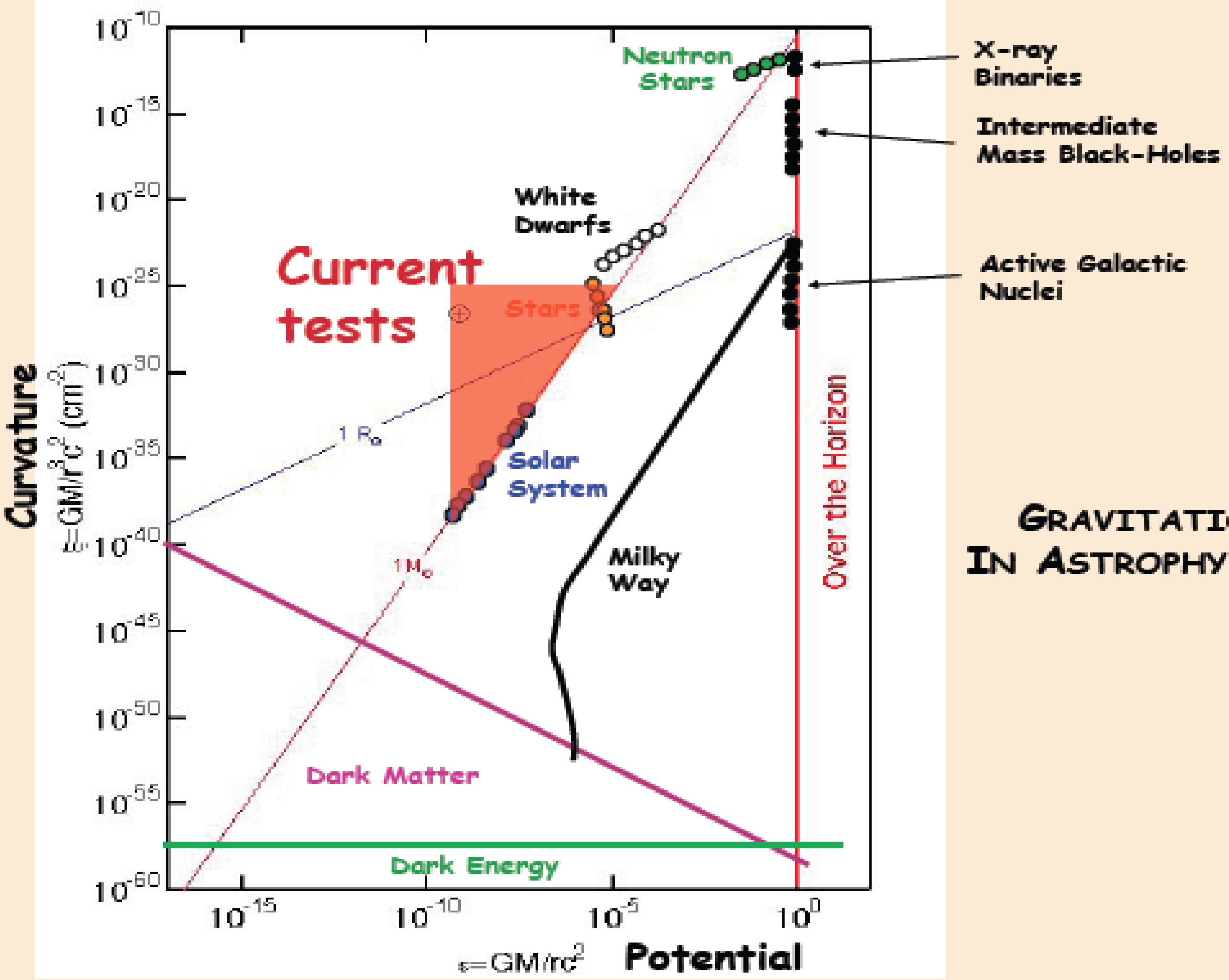
- **Observation of binary pulsars:**

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

Orbital decay of PSR B1913+16



From Weisberg & Taylor 2005



GRAVITATIONAL FIELDS IN ASTROPHYSICAL SYSTEMS

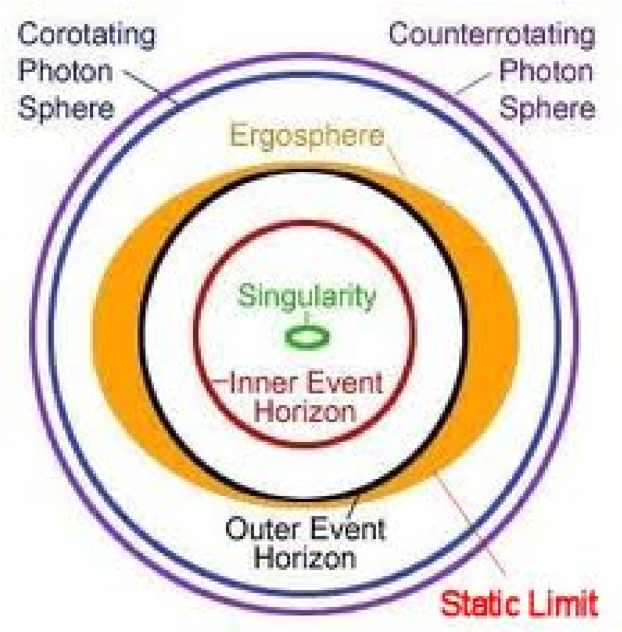
Psaltis 2008

Theoretical and observational facts

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

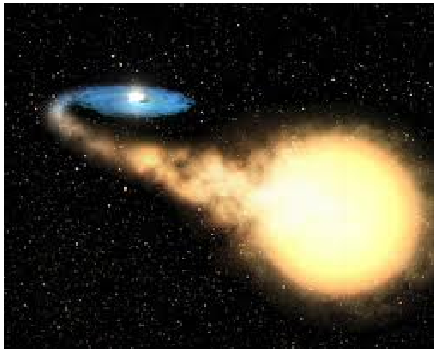
Black holes in GR (Theory)

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

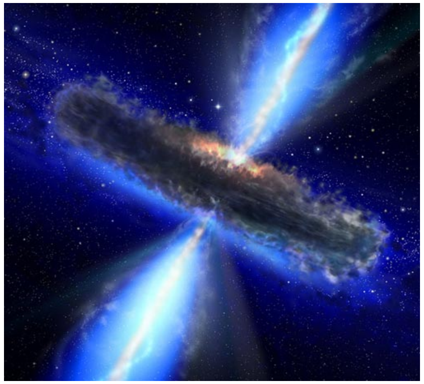


Black hole candidates (Observations)

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



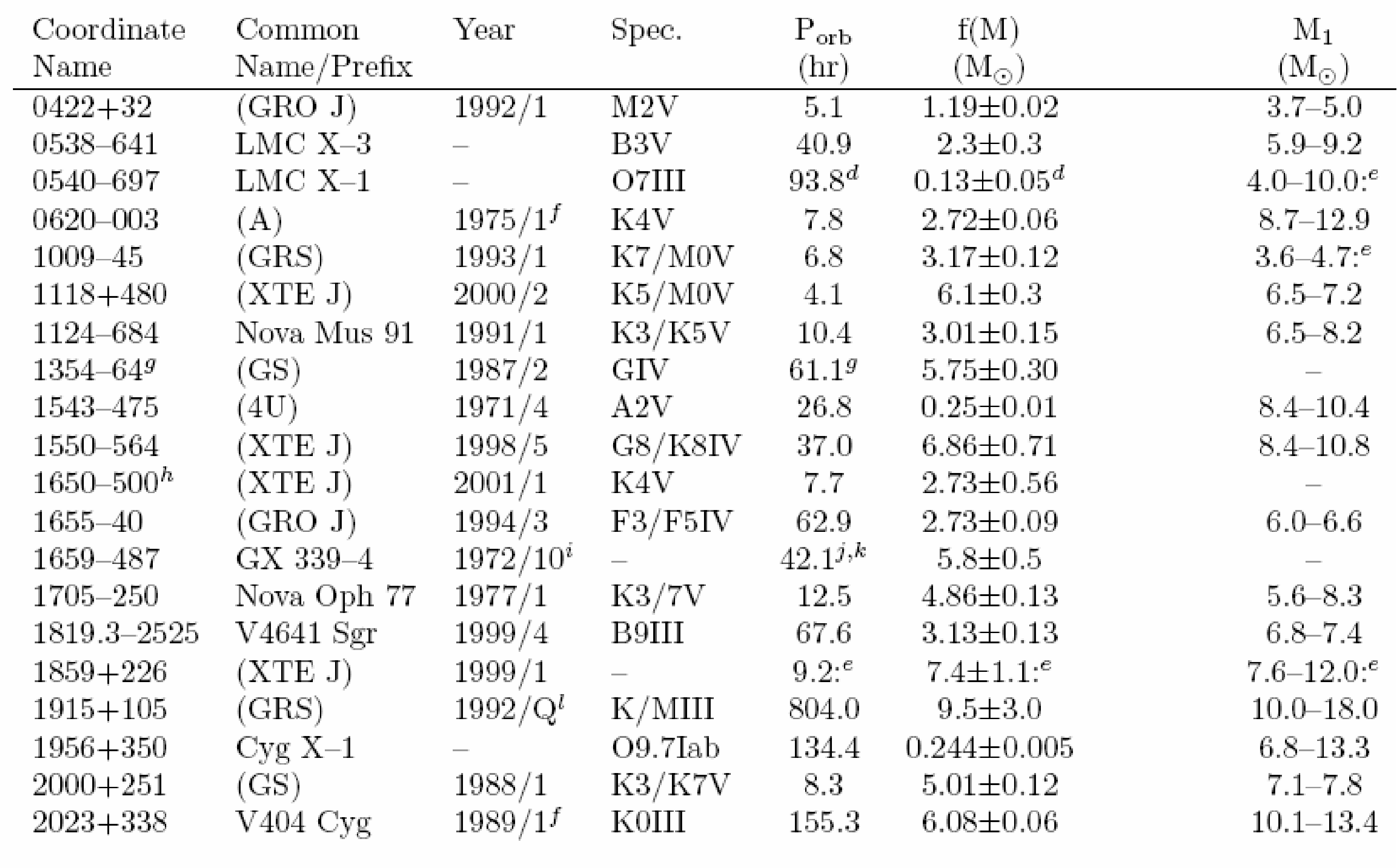
- **Super-massive BH candidates in galactic nuclei (10^5 – 10^{10} Solar masses)**



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

Stellar-mass BH candidates

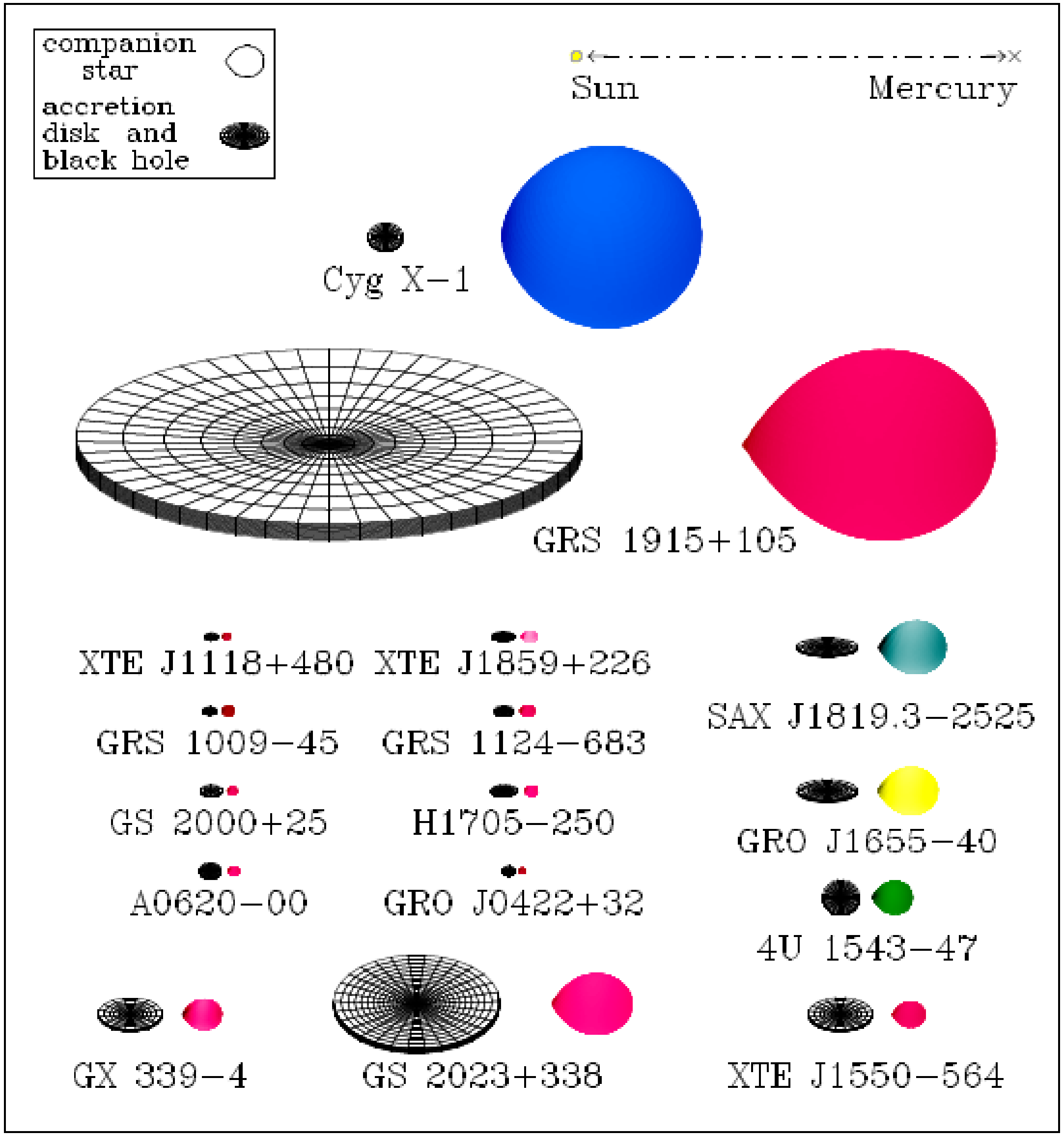
- **Dark objects in X-ray binary systems**
- **Mass function:** $f(M_{BH}) = \frac{K^3 T}{2\pi G_N} = \frac{M_{BH}^3 \sin^3 i}{(M_{BH} + M_c)^2}$ $K = v \sin i$
- **In general, a good estimate of M_C and *i* is necessary**
- **Maximum mass for relativistic stars about 3 Solar masses (see Rhoades & Ruffini 1974 and Kalogera & Baym 1996)**



Coordinate Name	Common Name/Prefix	Year	Spec.	$P_{\rm orb}$ (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

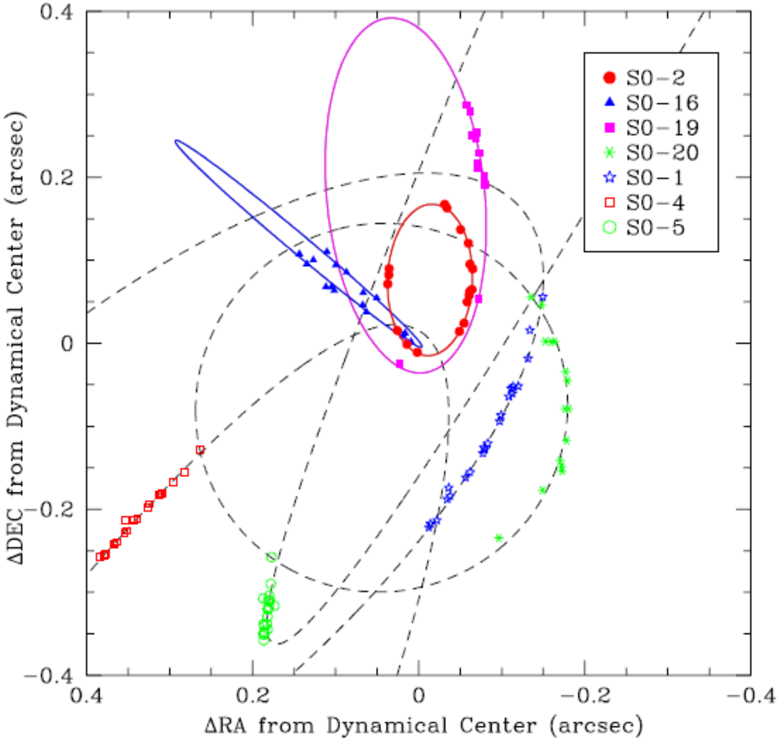
Black Hole Binaries in the Milky Way



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 nature of astrophysical black hole candidates?

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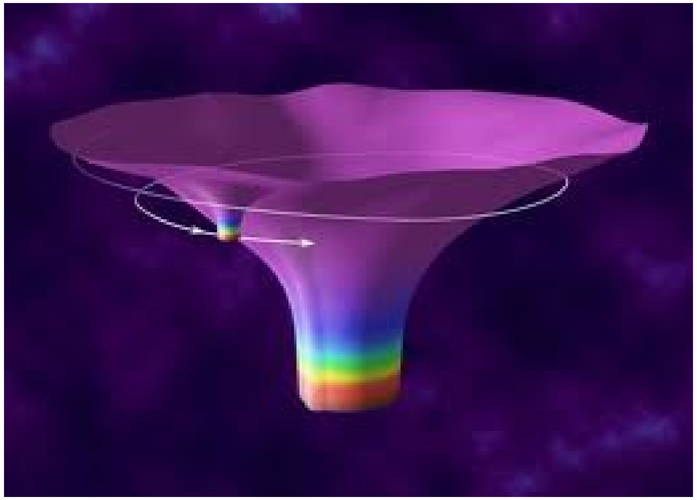
- **Jet power**
- **SgrA***

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 facilities with unprecedented high-resolution imaging capabilities (EHT, GRAVITY, etc.)

Important remarks

- The study of the properties of the electromagnetic radiation emitted by the gas in the accretion disk can test the Kerr metric, not the Einstein equations
- The Kerr metric is the unique uncharged BH solution of GR, but it is a solution of many other theories of gravity
- If we want to test the Einstein equations, we need to study the perturbations around the Kerr background
- It is not enough to observe relativistic features absent in Newtonian gravity (common misunderstanding in the literature). In order to test the Kerr BH hypothesis it is necessary to check that observational data exclude deviations from the Kerr solution. Non-Kerr BHs typically look like Kerr BHs with different spin

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Correlated important remarks

- **Technically, a black hole is a region causally disconnected to future null infinity and the event horizon is its boundary**
- **Observationally, we can test the existence of an apparent horizon. To test the existence of an event horizon we should know the future, which is impossible. A long-living apparent horizon behaves like an event horizon**

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Strategy

- **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

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

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

Continuum-fitting method

- **Motivations**
- **Theoretical and observational facts**
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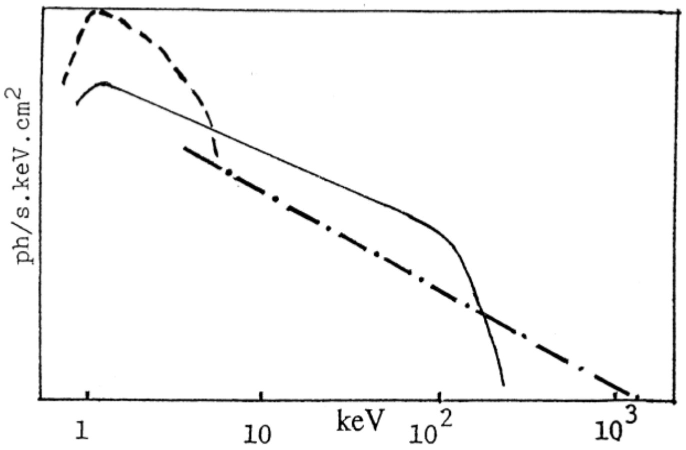
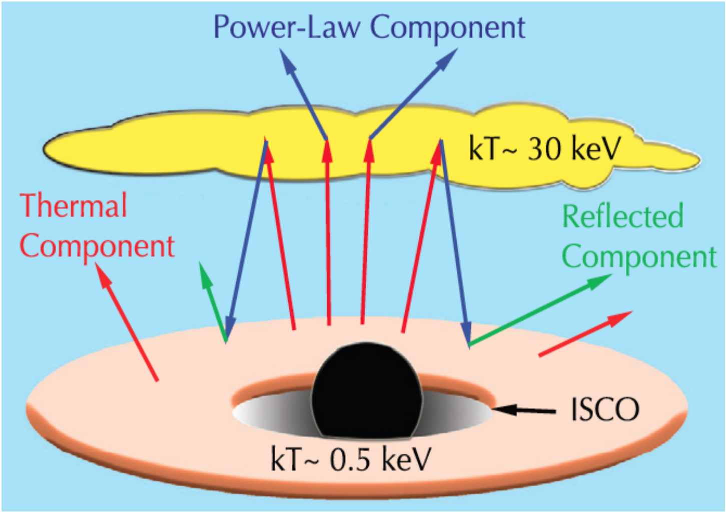
- **Continuum-fitting method**
- **K-alpha iron line and reverberation mapping**
- **Jet power**
- **SgrA***

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**





From Gou et al., ApJ 742 (2011) 85

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

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- **Relativistic generalization of the Shakura-Sunyaev model**

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

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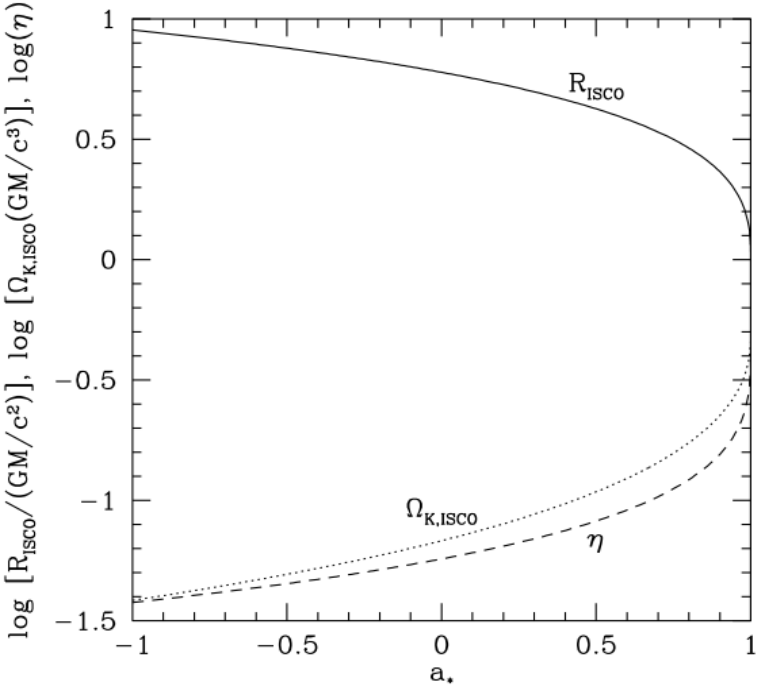
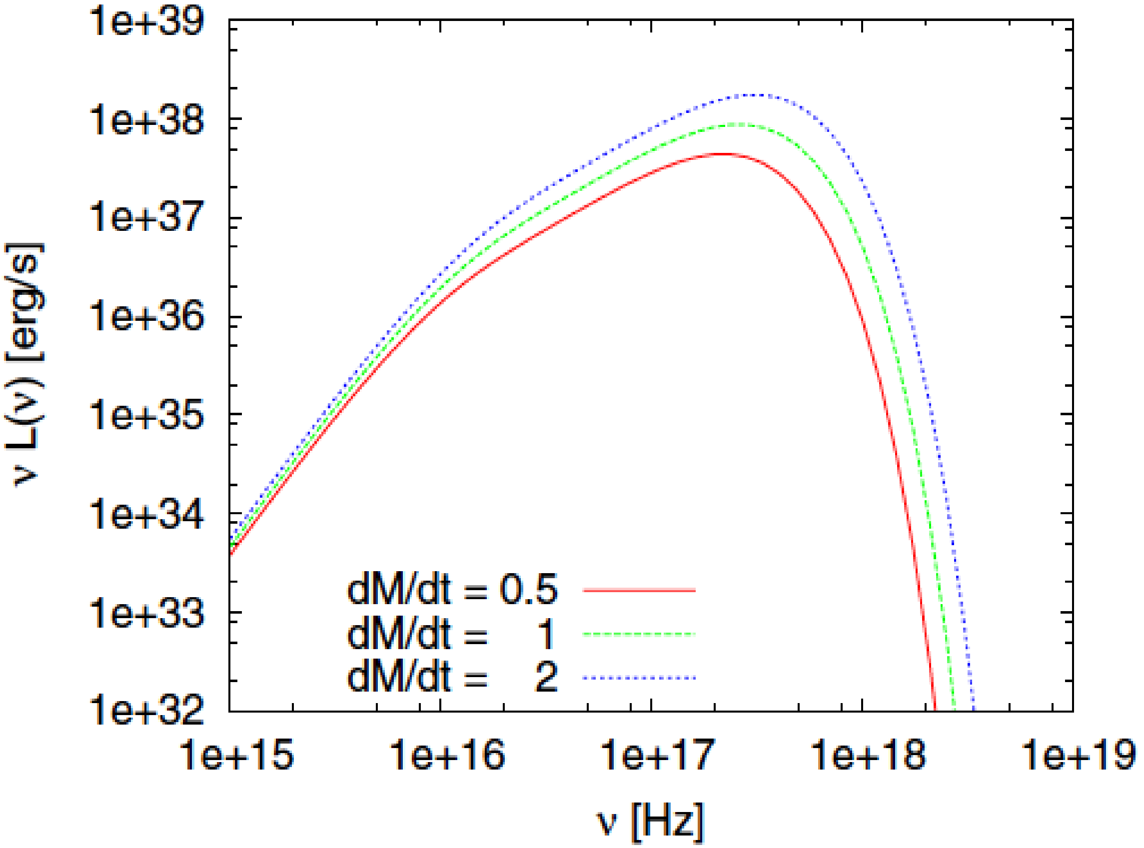
Continuum-fitting method in Kerr background

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

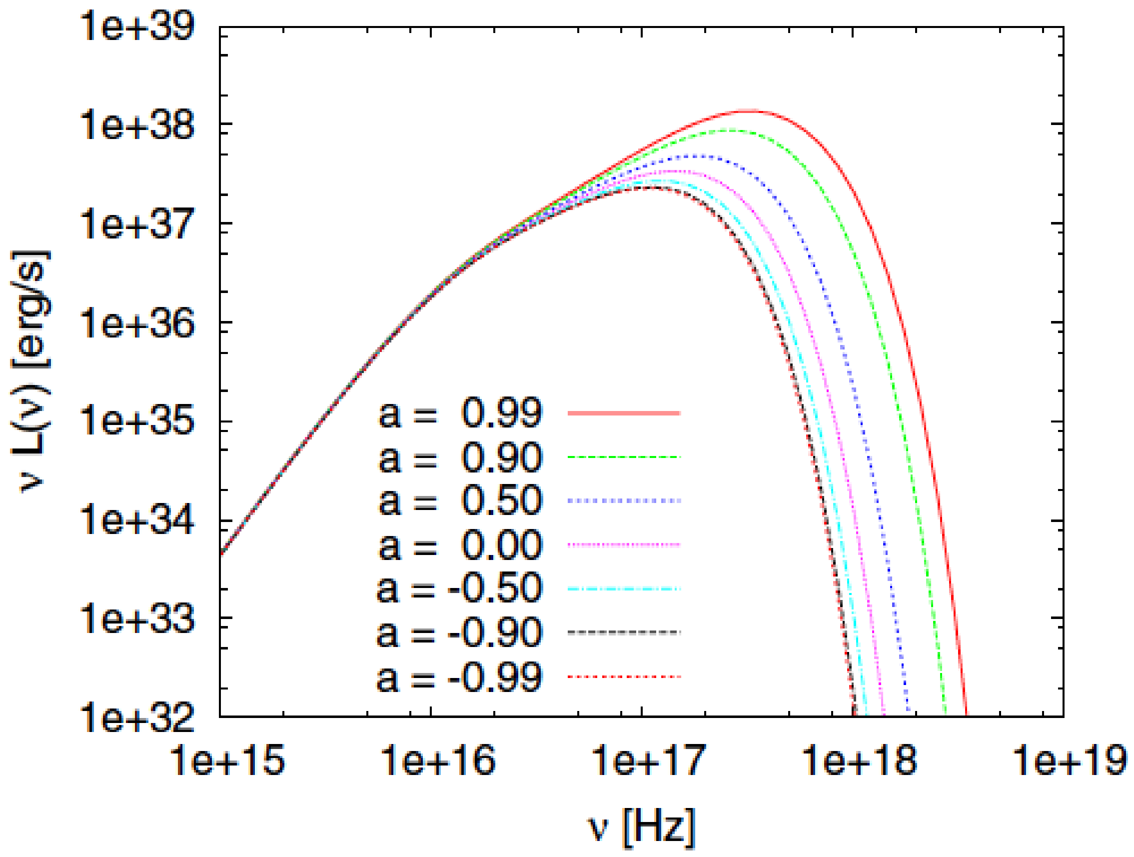


Mass accretion rate (Kerr background)



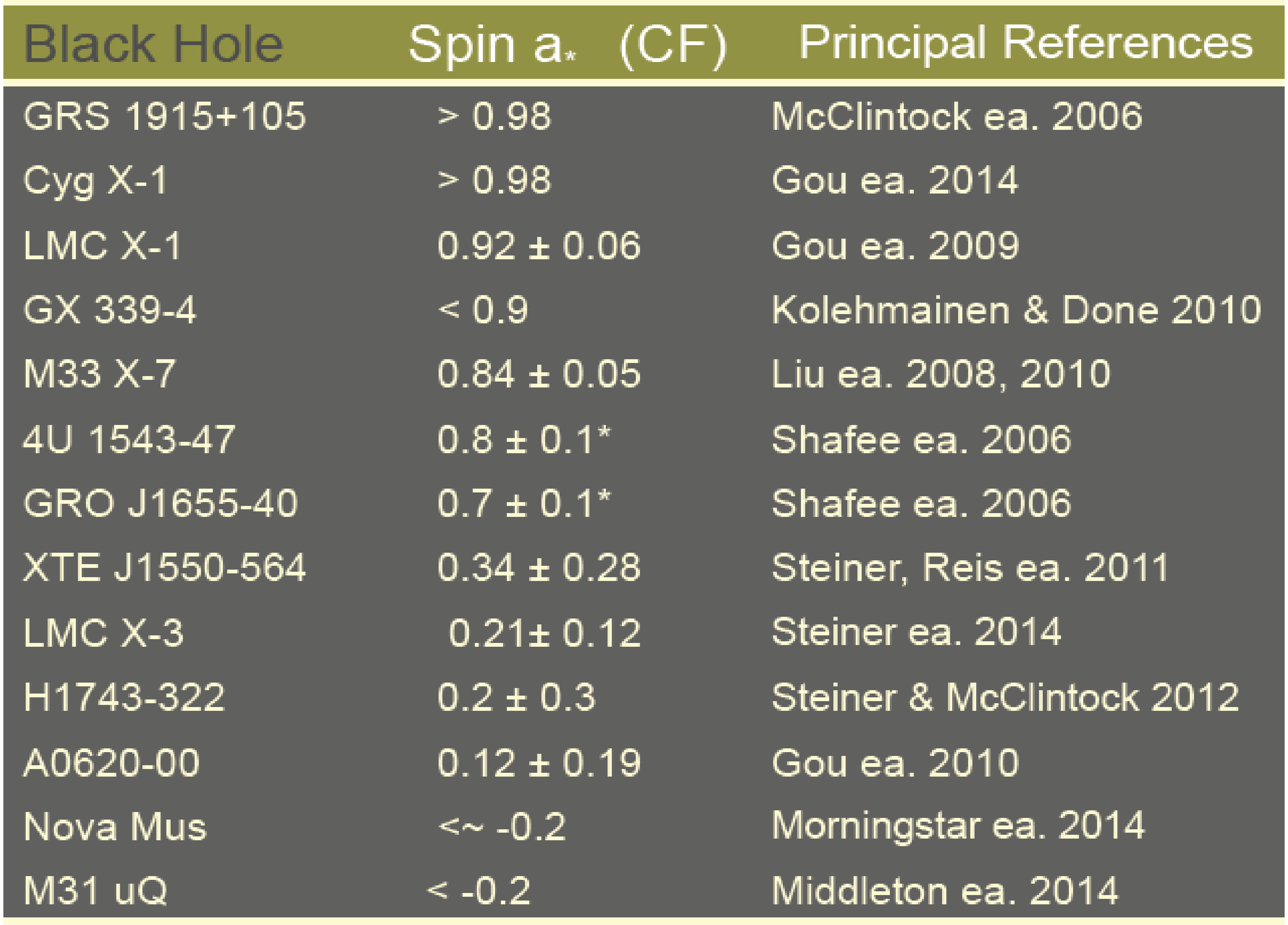
From Bambi & Barausse 2011

BH spin (Kerr background)



From Bambi & Barausse 2011

Continuum-fitting method results to date



Black Hole	Spin a_* (CF)	Principal References
GRS 1915+105	> 0.98	McClintock ea. 2006
Cyg X-1	> 0.98	Gou ea. 2014
LMC X-1	0.92 ± 0.06	Gou ea. 2009
GX 339-4	< 0.9	Kolehmainen & Done 2010
M33 X-7	0.84 ± 0.05	Liu ea. 2008, 2010
4U 1543-47	0.8 ± 0.1*	Shafee ea. 2006
GRO J1655-40	0.7 ± 0.1*	Shafee ea. 2006
XTE J1550-564	0.34 ± 0.28	Steiner, Reis ea. 2011
LMC X-3	0.21± 0.12	Steiner ea. 2014
H1743-322	0.2 ± 0.3	Steiner & McClintock 2012
A0620-00	0.12 ± 0.19	Gou ea. 2010
Nova Mus	<~ -0.2	Morningstar ea. 2014
M31 uQ	< -0.2	Middleton ea. 2014

Step 1: computation of the image

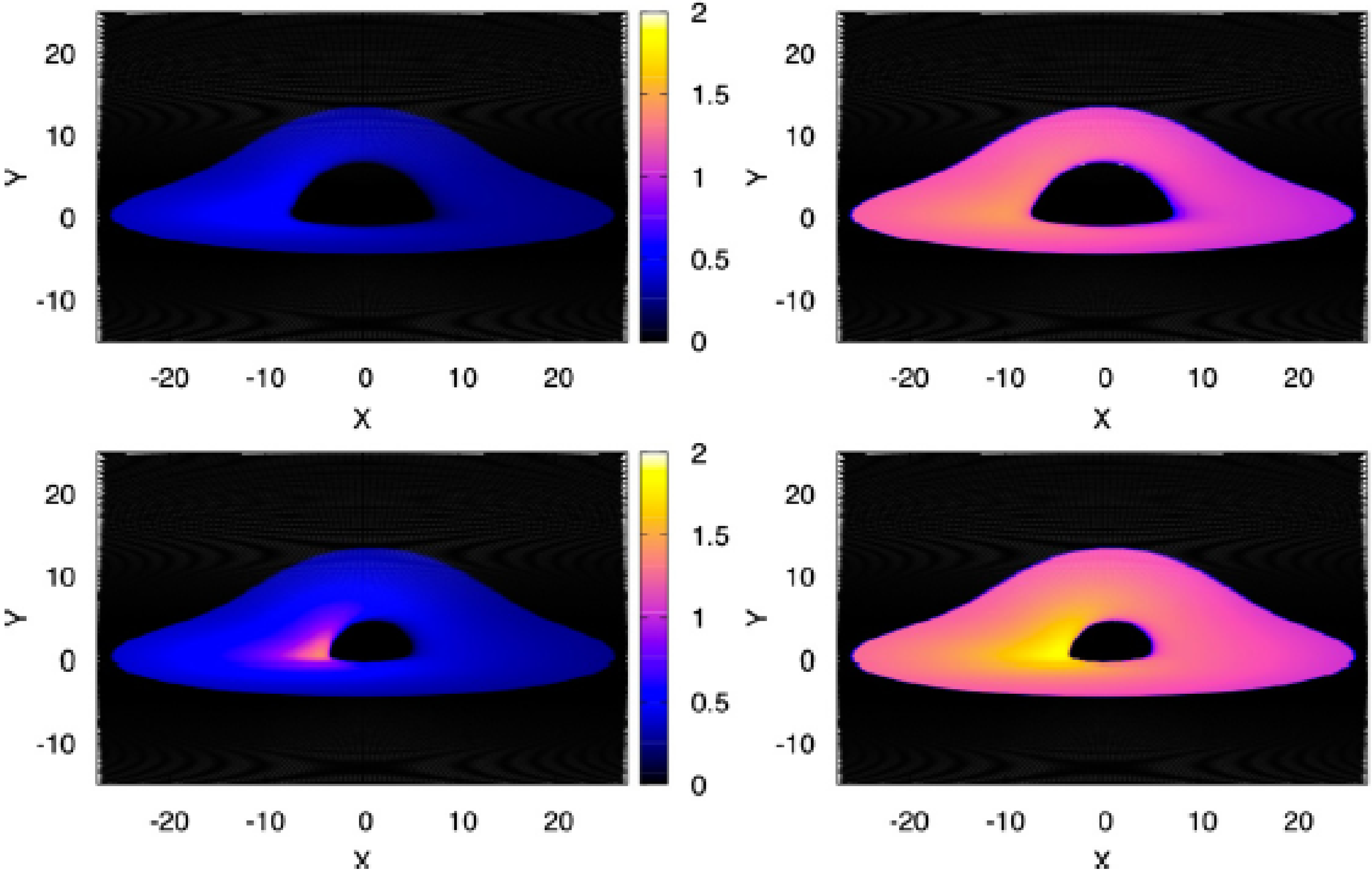
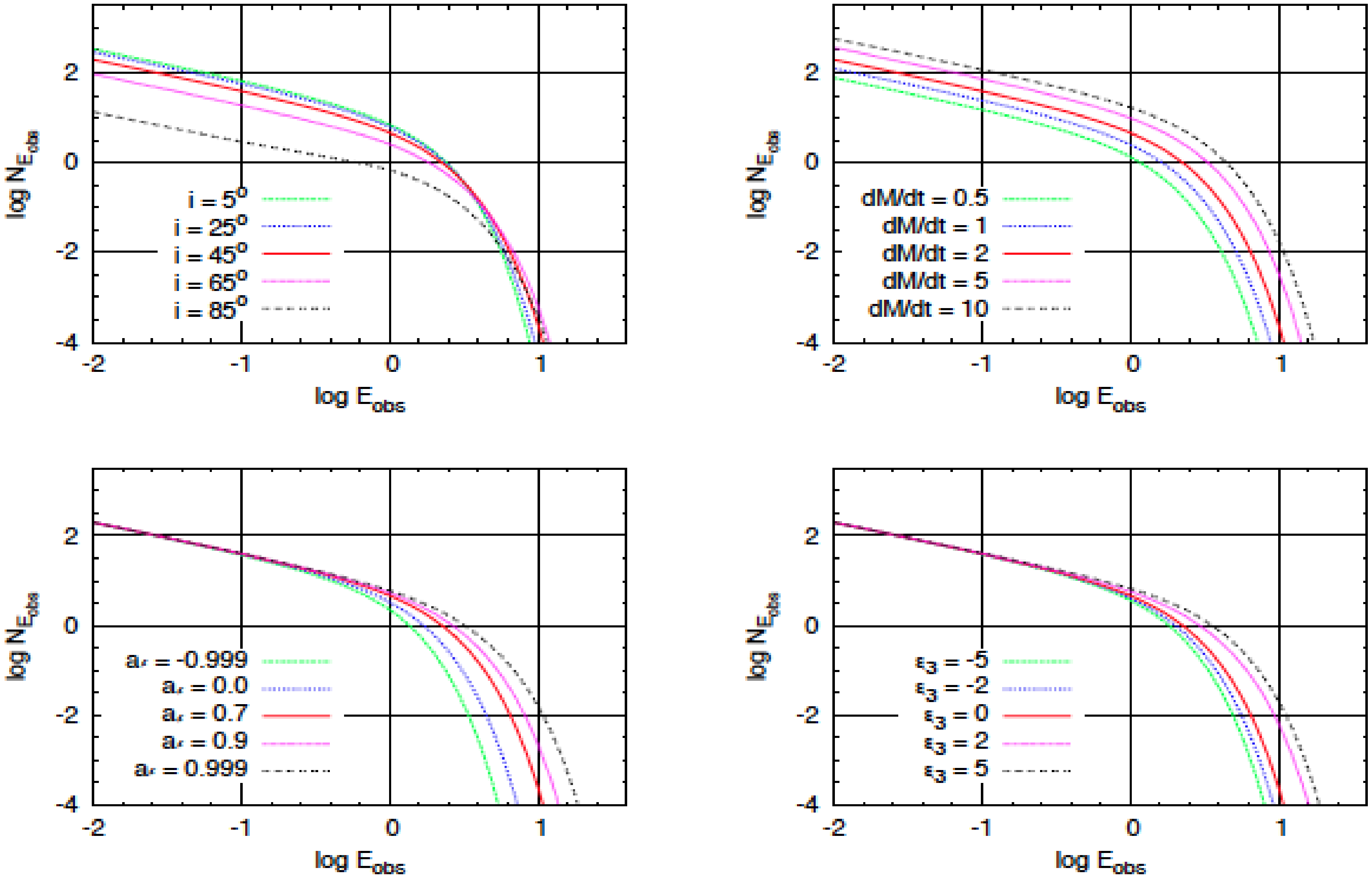


Figure 5. Direct image of the accretion disk. Observed blackbody temperature $T_{\rm obs}$ (left panels) and observed flux $\mathcal{F}_{\rm obs}$ (right panels) in Kerr spacetime with spin parameter $a/M = 0$ (top panels) and 0.9 (bottom panels). The other parameters are $M = 10\ M_\odot$, $\dot{M}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

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

Step 2: calculation of the disk's spectrum



Constraints from the continuum-fitting method

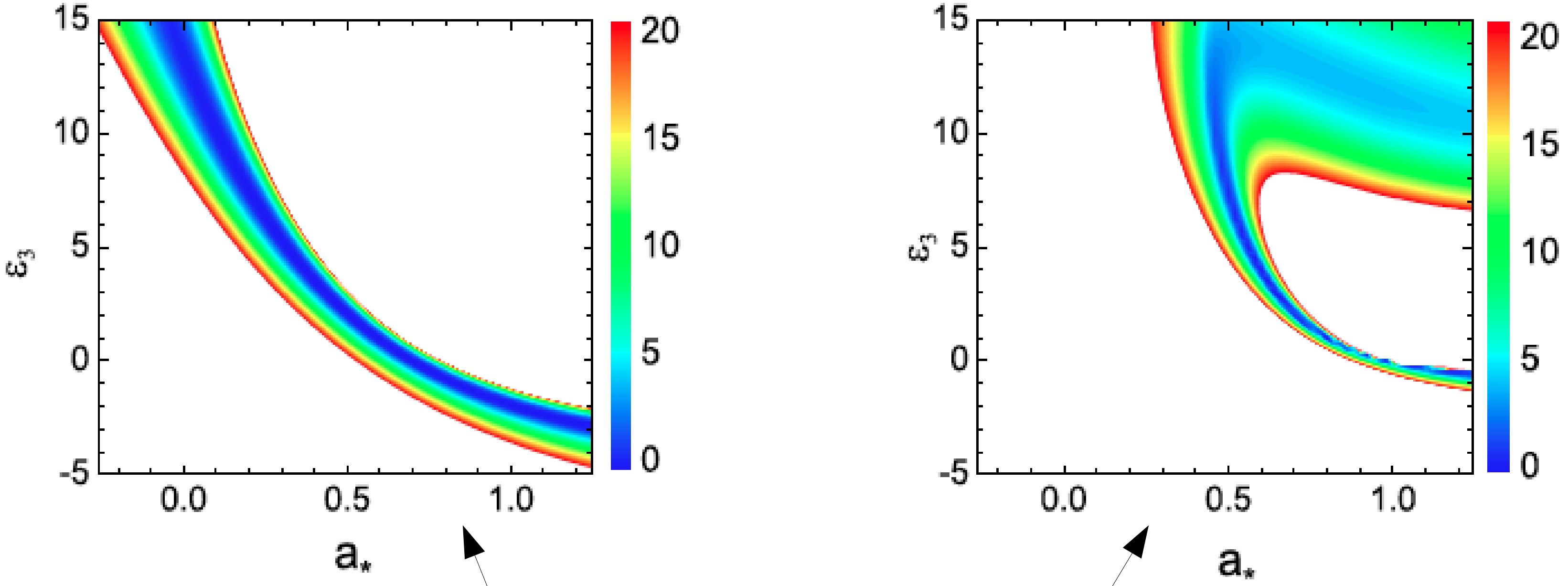
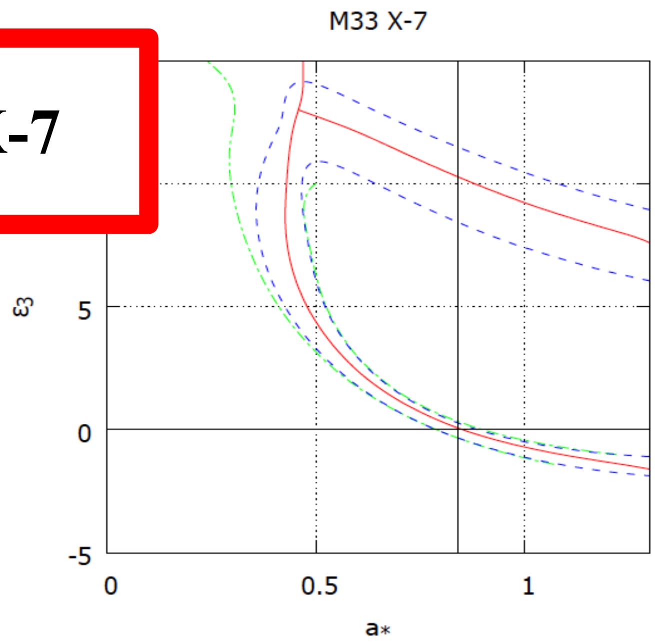


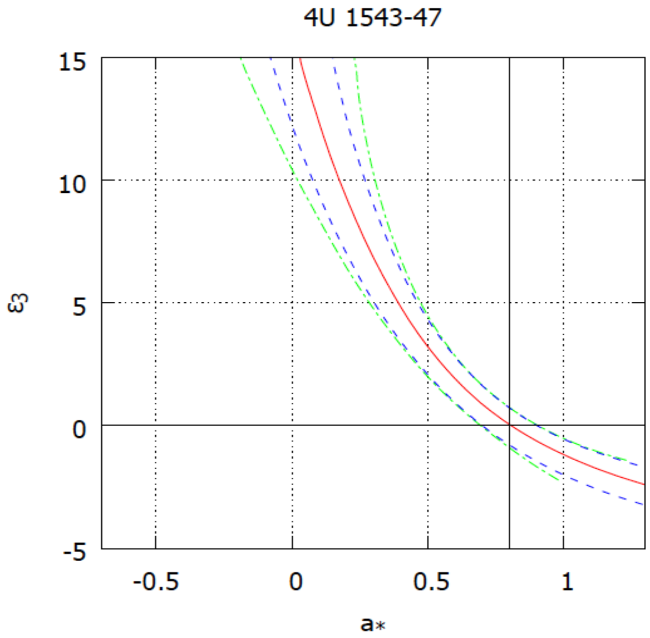
Fig. 4.— $\chi^2_{\rm red}$ from the comparison of the thermal spectrum of a thin accretion disk around a Kerr BH with spin parameter $\tilde{a}_*$ and a JP BH with spin parameter a_* and deformation parameter ϵ_3. Left panel: $\tilde{a}_* = 0.7$. Right panel: $\tilde{a}_* = 0.98$. See text for details.

Constraints from the continuum-fitting method

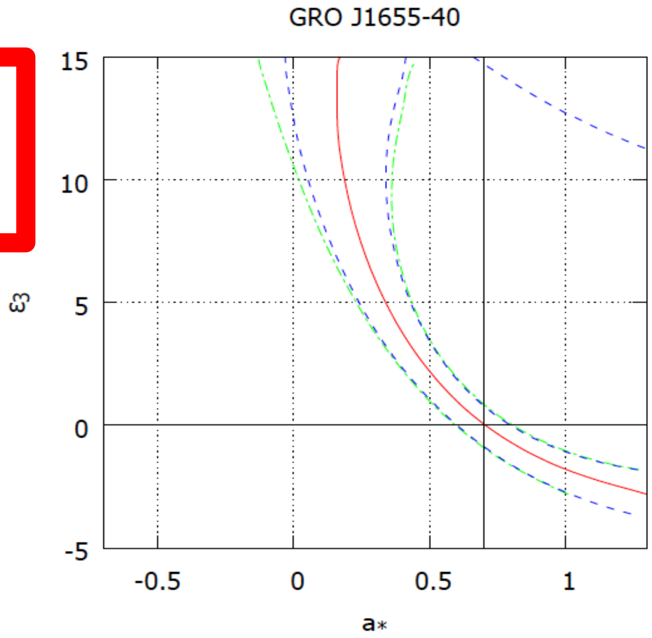
M33 X-7



4U 1543-47



GRO J1655-40



Kong, Li & Bambi, arXiv:1405.1508

K-alpha iron line

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- **Theoretical and observational facts**
- **How can we test the nature of astrophysical BH candiudates?**
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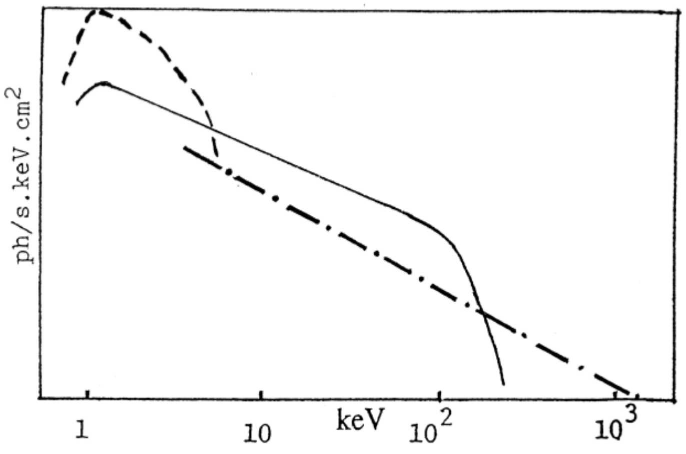
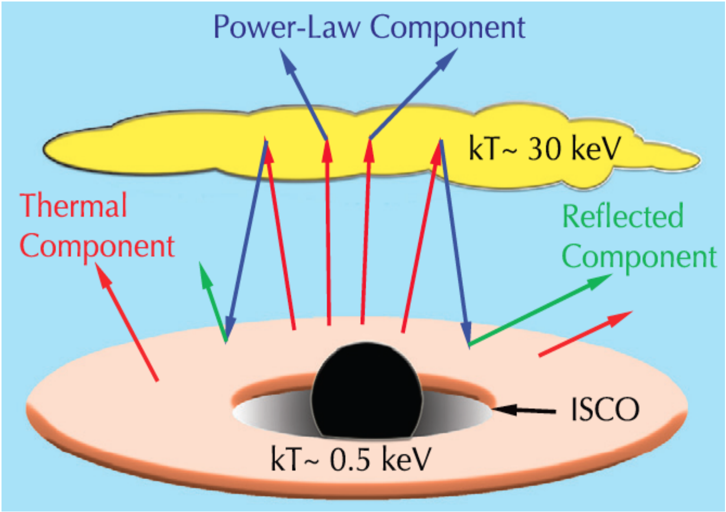
K-alpha iron line

- **The illumination of the cold disk by the primary component produces spectral lines by fluorescence. The strongest line is the K-alpha iron line at 6.4 keV**

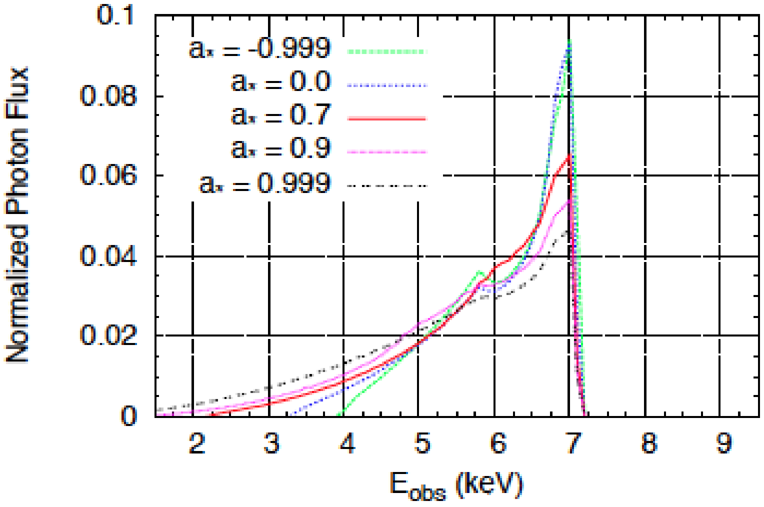


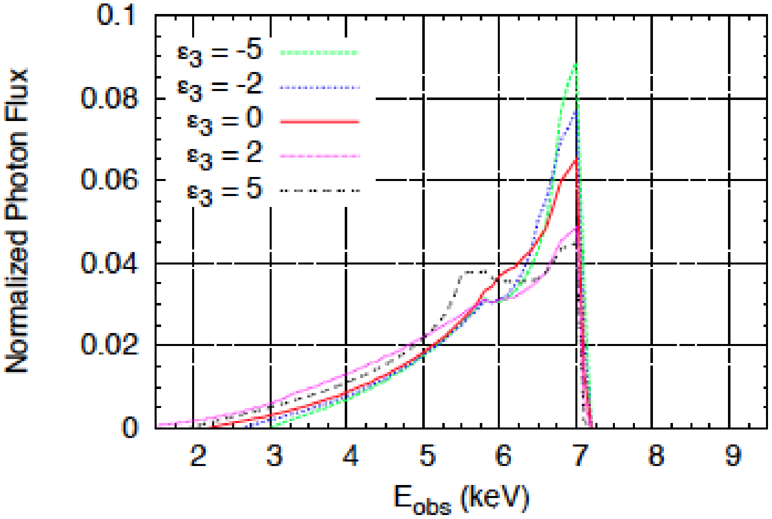


From Gou et al., ApJ 742 (2011) 85

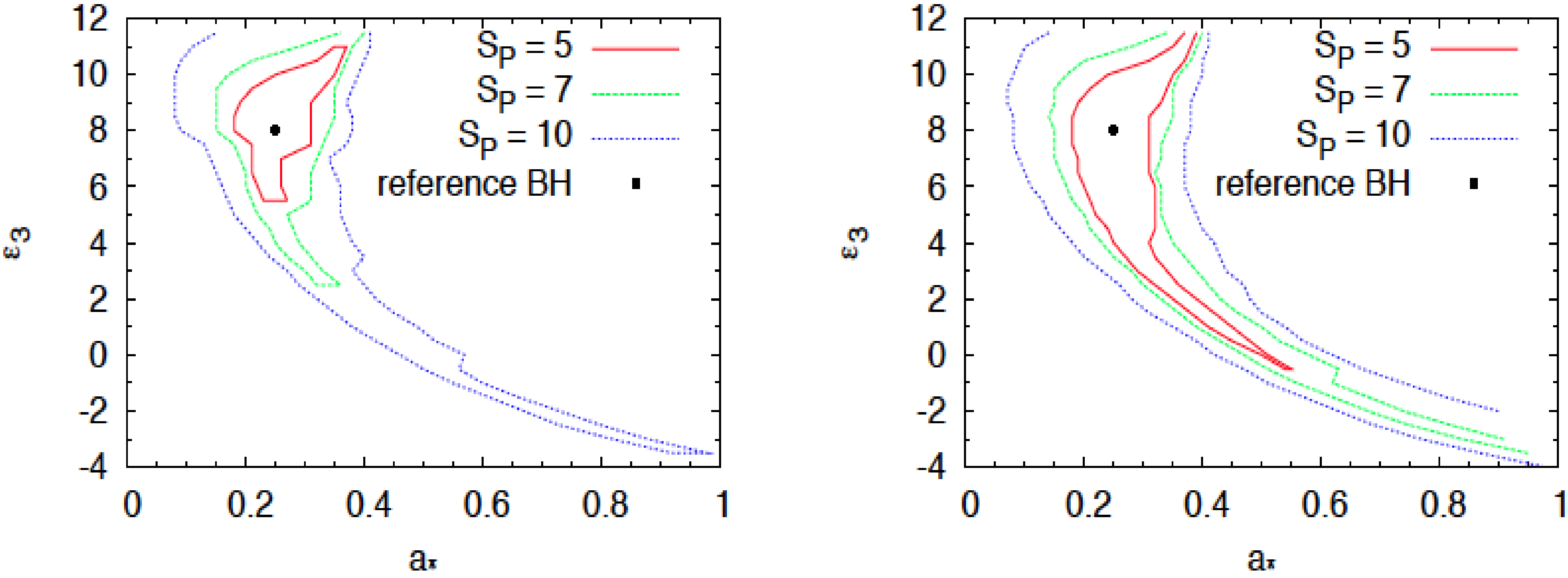
K-alpha iron line analysis

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



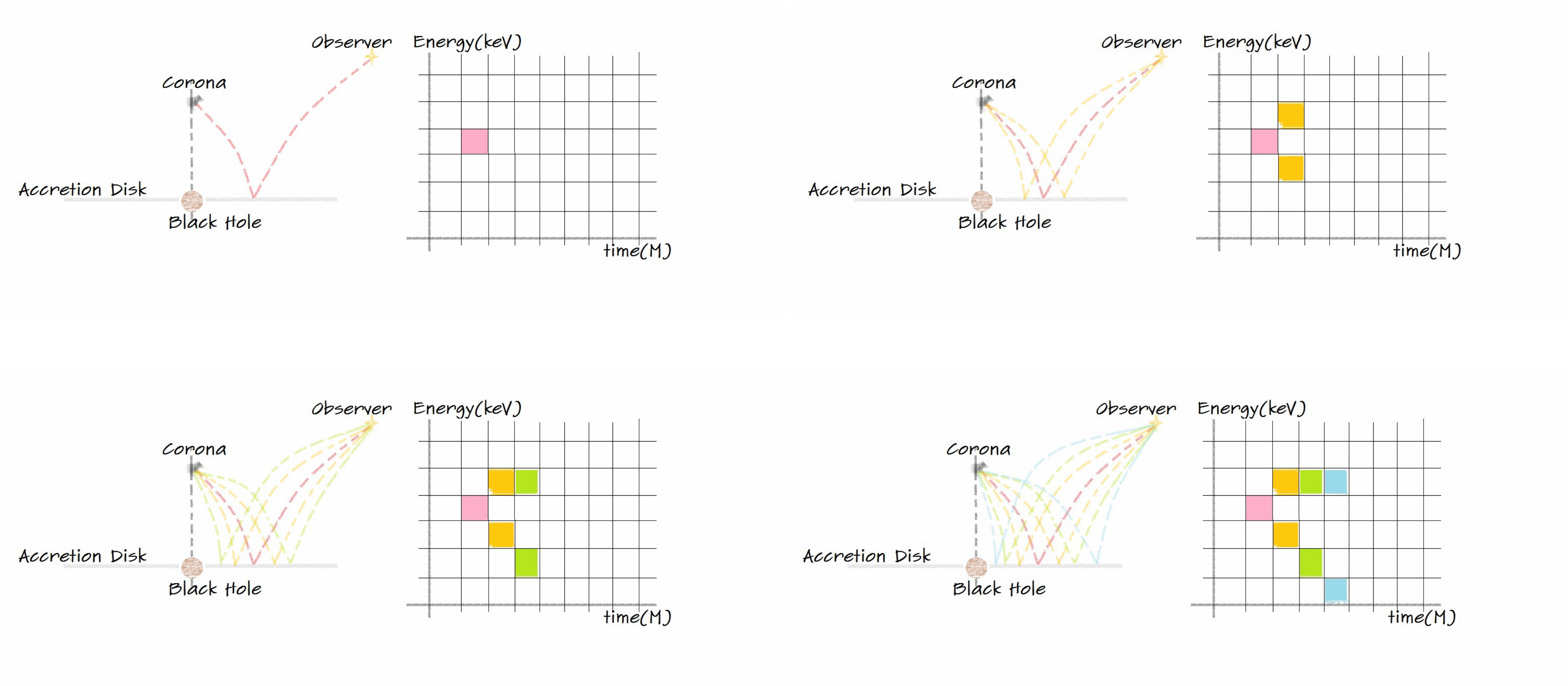


Example of non-Kerr BH: iron line



Jiang, Bambi & Steiner, arXiv:1406.5677

Iron line reverberation



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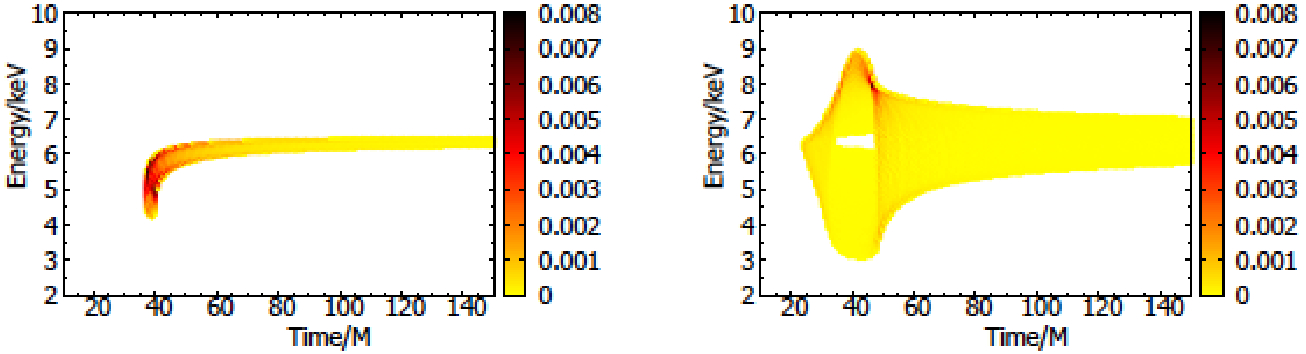


Figure 2. Transfer functions for a Schwarzschild BH ($a_* = 0$). The inclination angle is $i = 10°$ (left panel) and $i = 80°$ (right panel). The height of the source is $h = 10\,M$ and the emissivity index of the intensity profile is $q = 3$. See the text for more details.

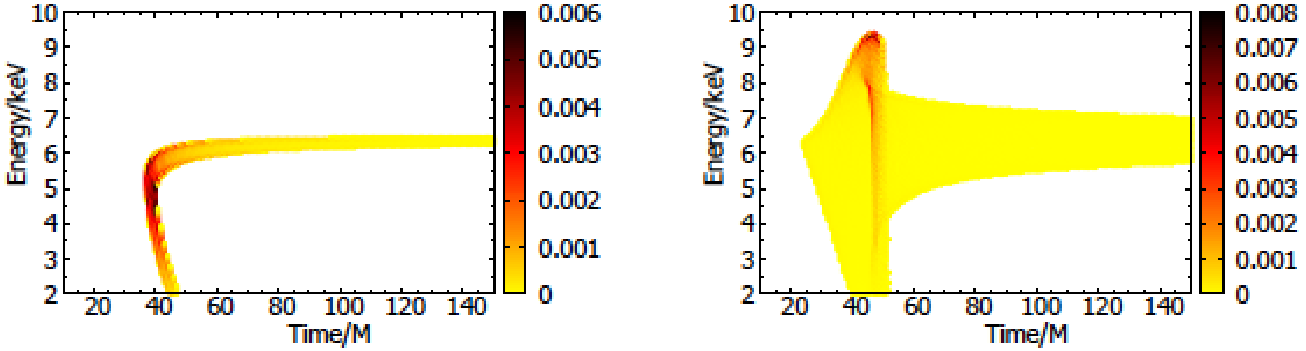
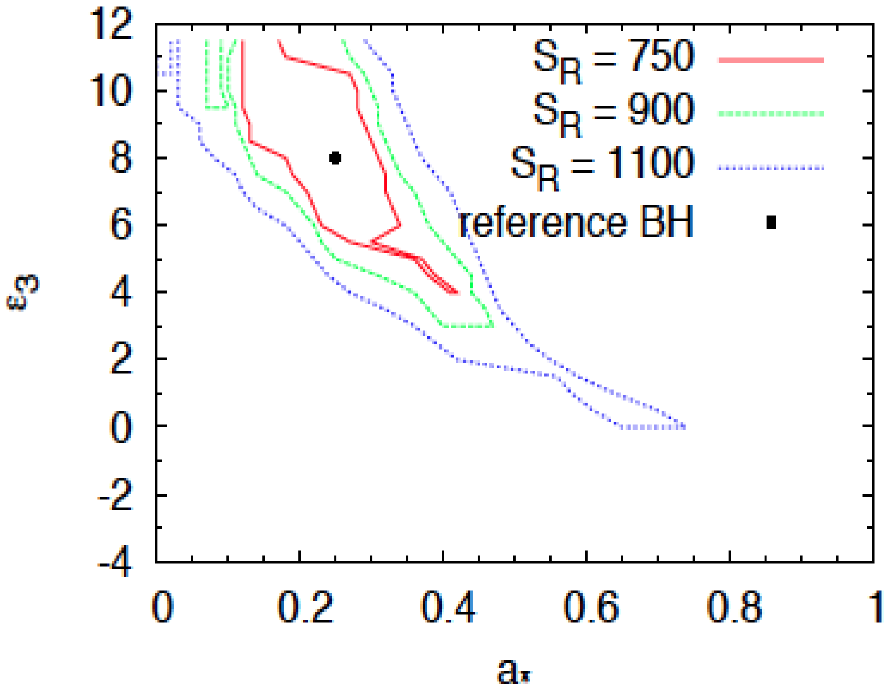
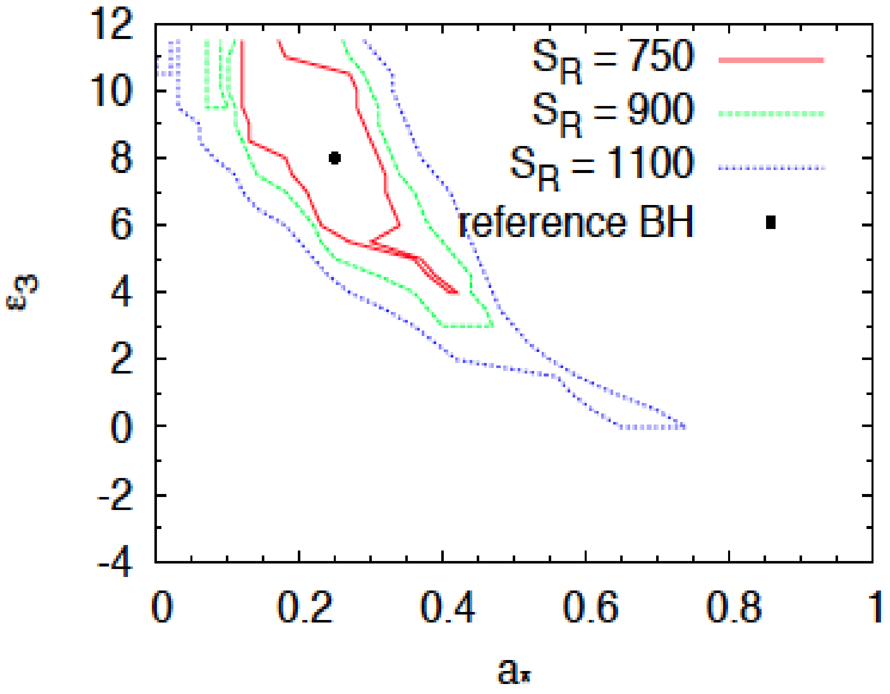


Figure 3. Transfer functions for a Kerr BH with spin parameter $a_* = 0.95$. The inclination angle is $i = 10°$ (left panel) and $i = 80°$ (right panel). The height of the source is $h = 10\,M$ and the index of the intensity profile is $q = 3$. See the text for more details.

Example of non-Kerr BH: reverberation



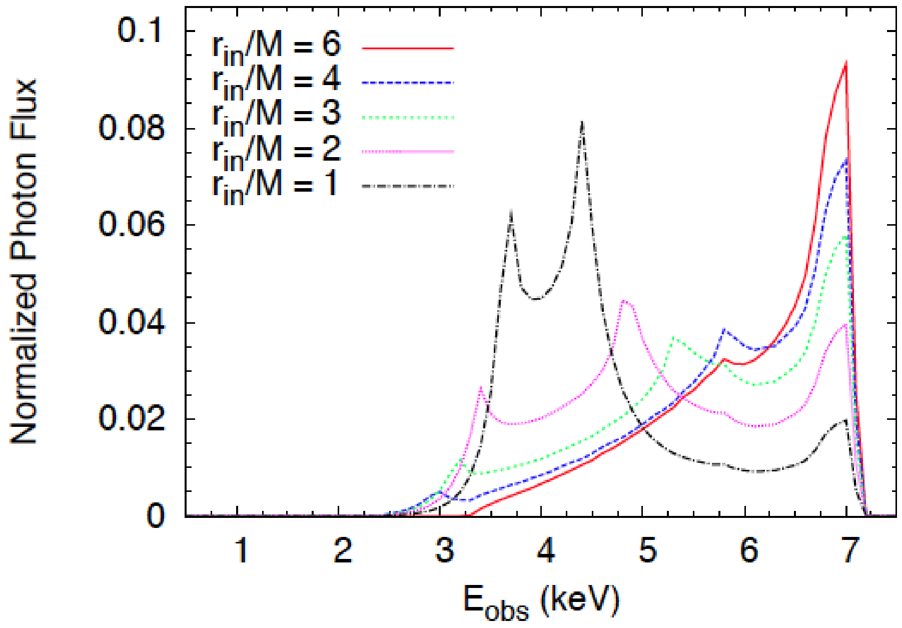


Jiang, Bambi & Steiner, arXiv:1406.5677

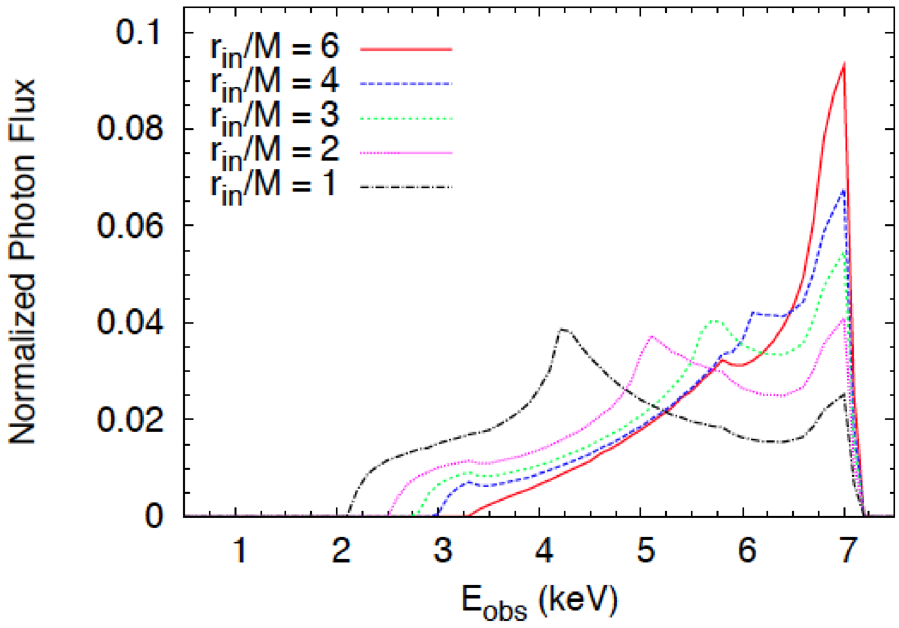
Constraints

K-alpha iron line
(Interior solutions or Boson stars)

Regular solution



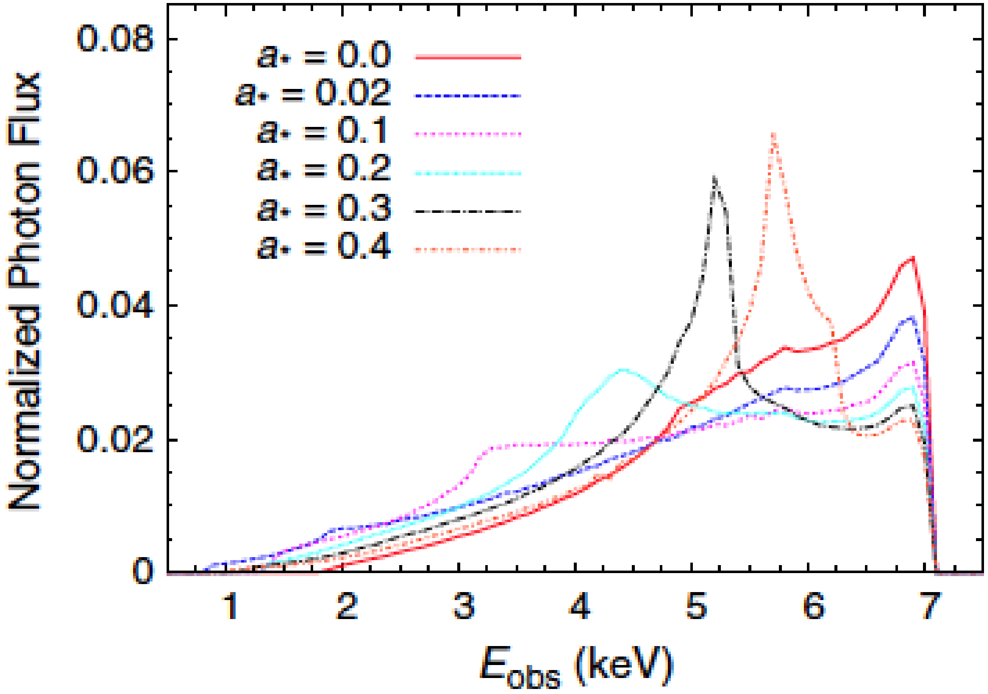
Singular solution



K-alpha iron line
(Traversable wormholes)

Metric

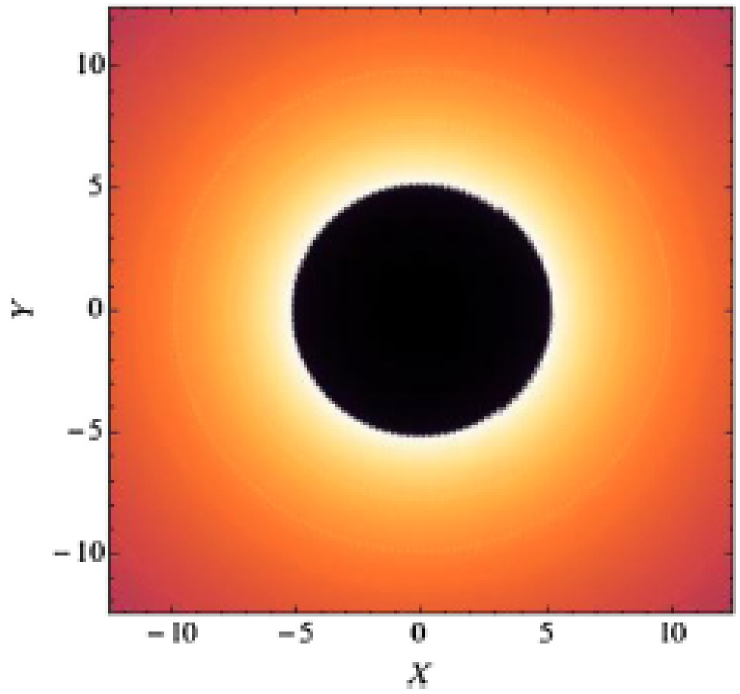
$$ds^2 = -e^{2\Phi}dt^2 + \frac{dr^2}{1-b} + r^2[d\theta^2 + \sin^2\theta(d\phi - \omega dt)^2],$$



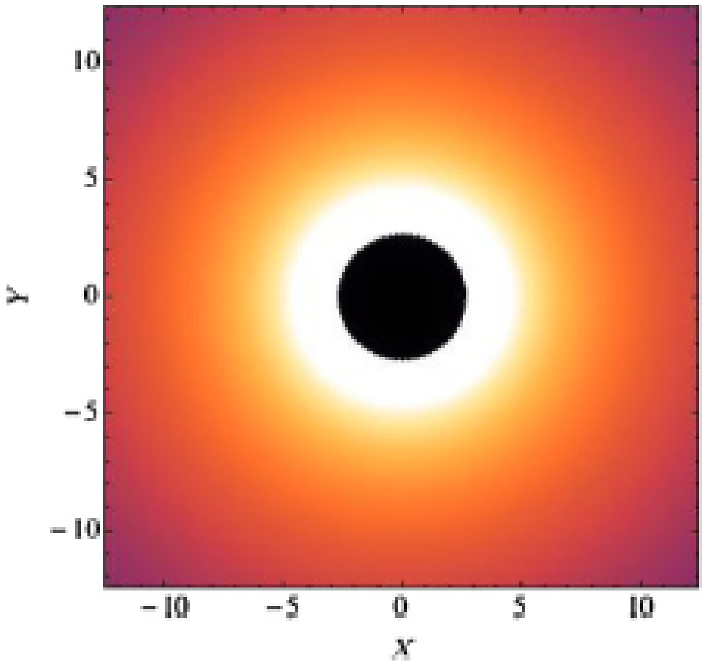
Constraint: a < 0.02

Shadow
(Non-rotating traversable wormholes)

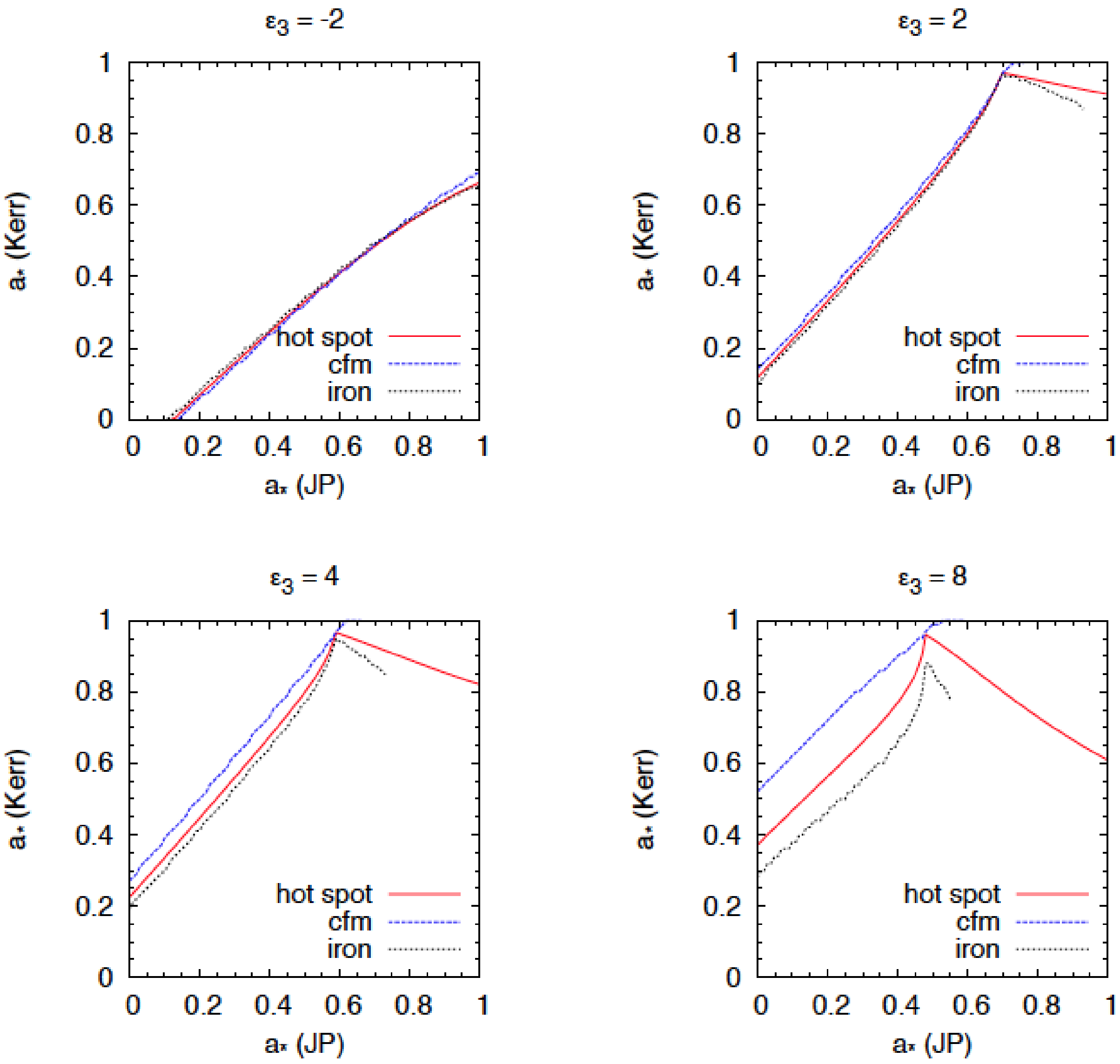
Schwarzschild black hole



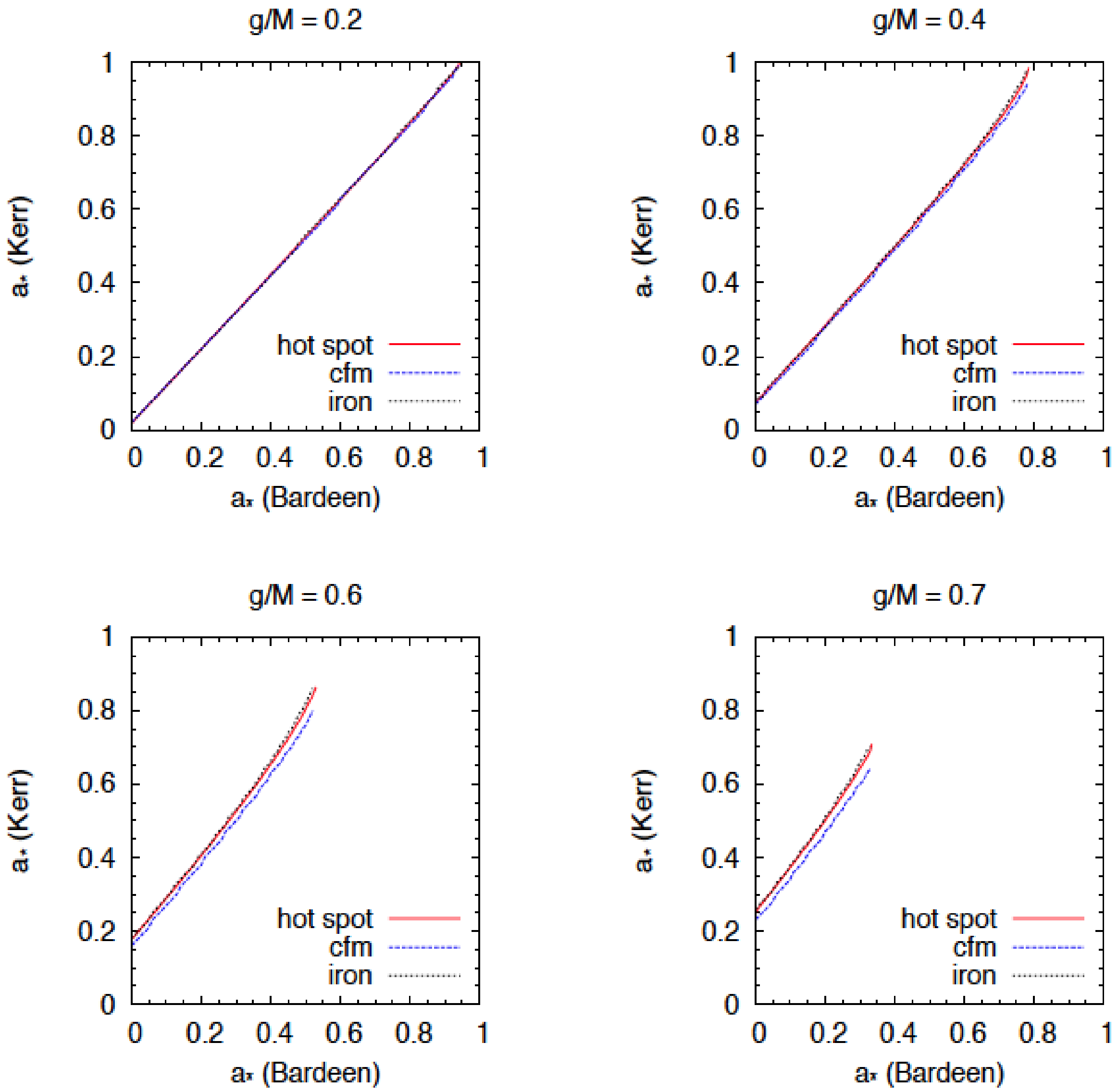
Wormhole



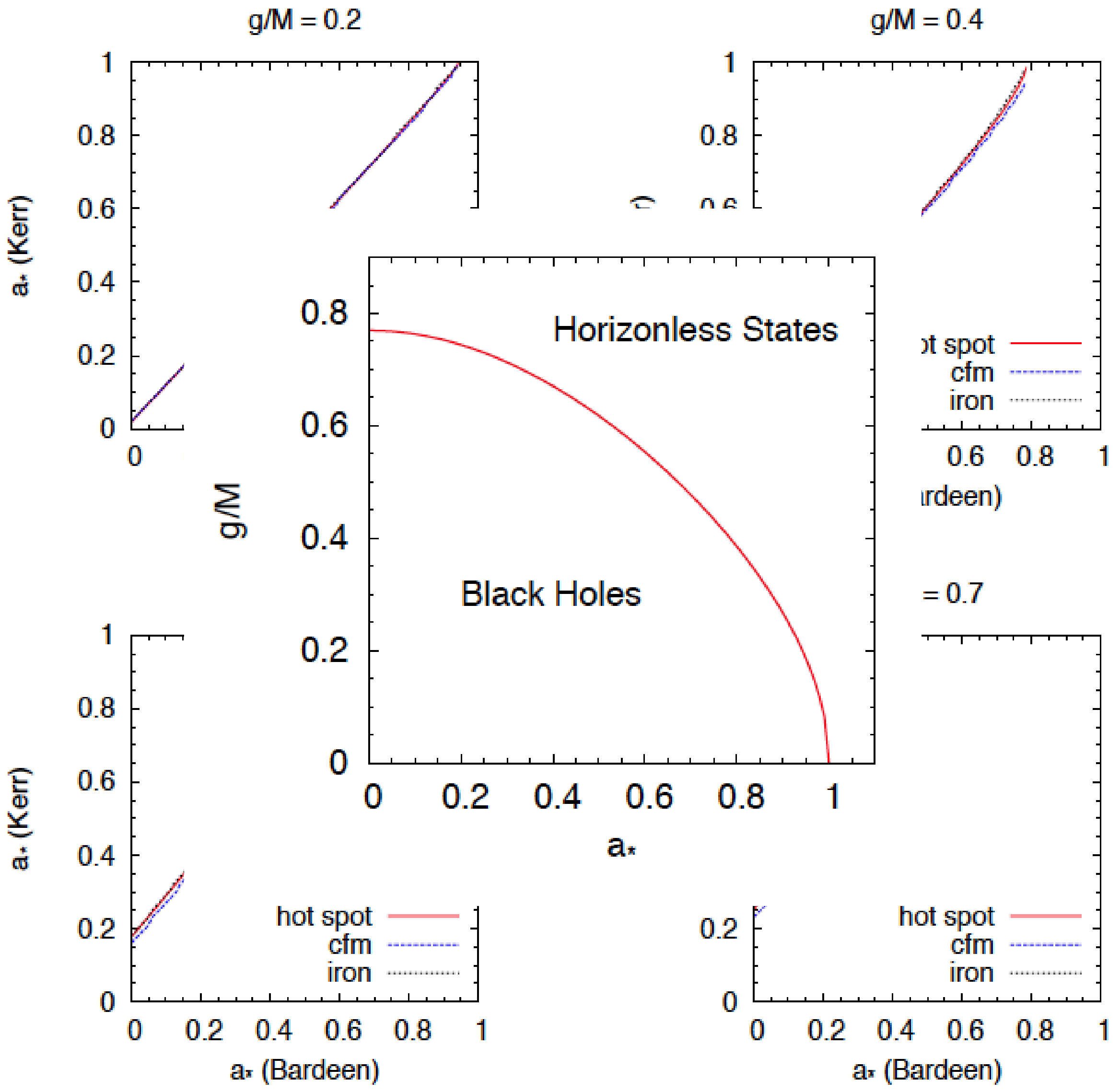
Continuum-fitting method + K-alpha iron line (Johannsen-Psaltis metric)



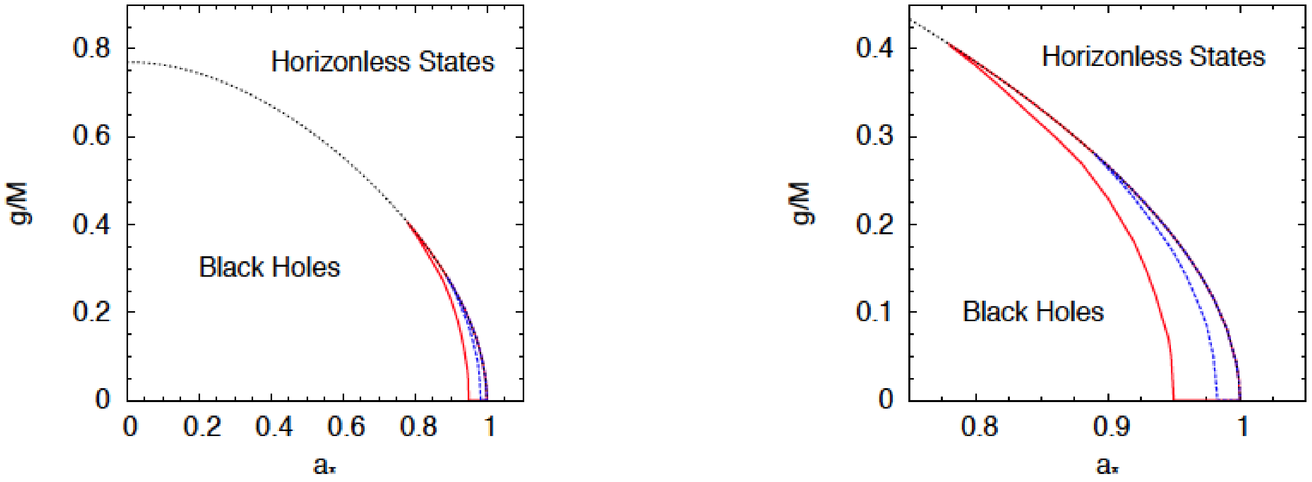
Continuum-fitting method + K-alpha iron line (Rotating Bardeen BHs)



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



Constraints on the Bardeen metric from the BH candidate in Cygnus X-1 (Continuum-fitting method)



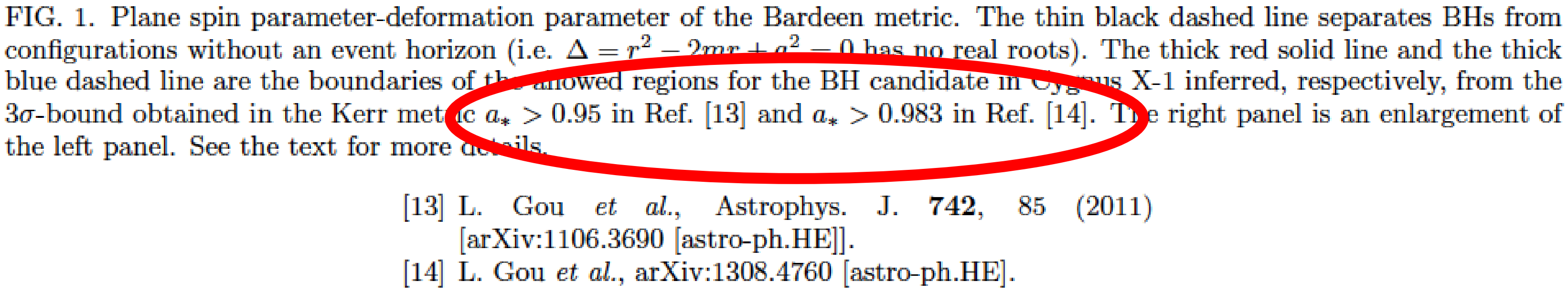


FIG. 1. Plane spin parameter-deformation parameter of the Bardeen metric. The thin black dashed line separates BHs from configurations without an event horizon (i.e. $\Delta = r^2 - 2mr + a^2 = 0$ has no real roots). The thick red solid line and the thick blue dashed line are the boundaries of the allowed regions for the BH candidate in Cygnus X-1 inferred, respectively, from the 3σ-bound obtained in the Kerr metric $a_* > 0.95$ in Ref. [13] and $a_* > 0.983$ in Ref. [14]. The right panel is an enlargement of the left panel. See the text for more details.

[13] L. Gou *et al.*, Astrophys. J. **742**, 85 (2011) [arXiv:1106.3690 [astro-ph.HE]].
[14] L. Gou *et al.*, arXiv:1308.4760 [astro-ph.HE].

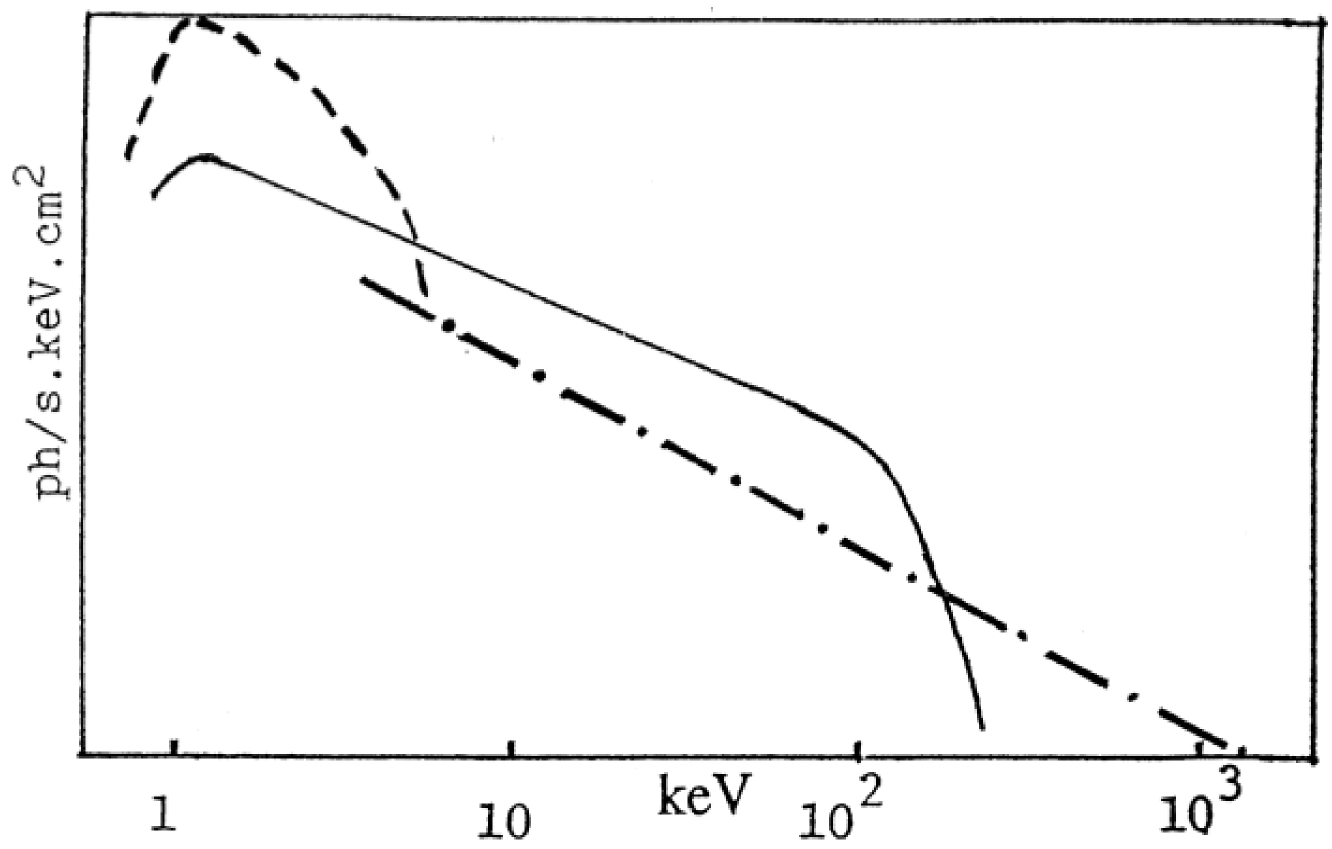
Jet Power

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

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

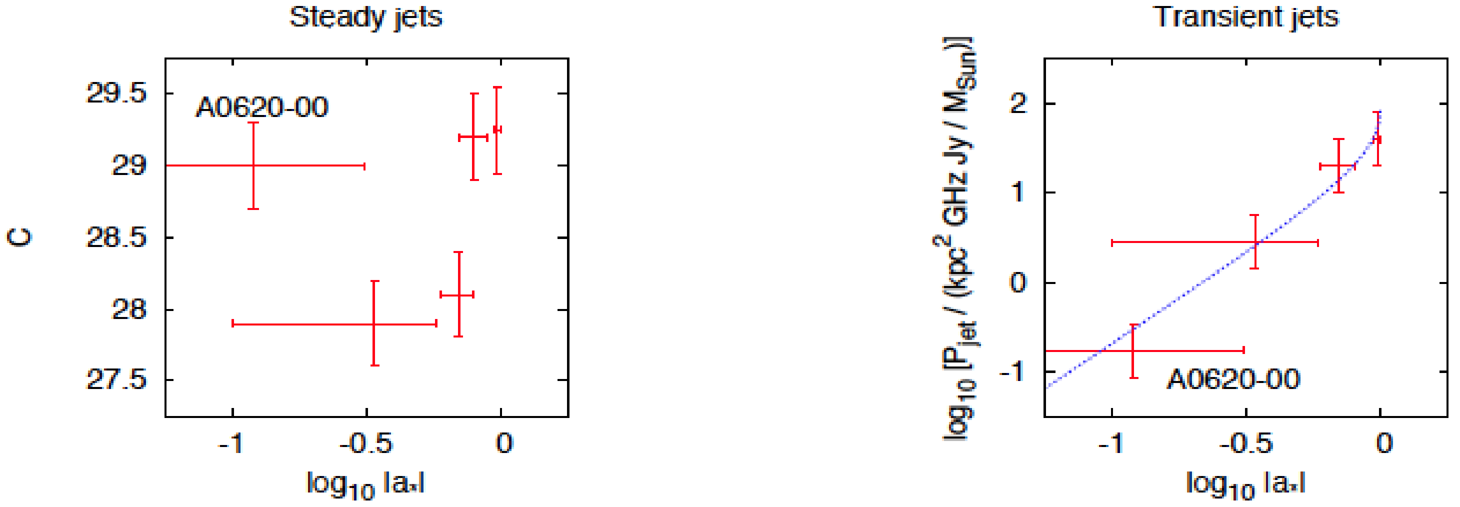


Fig. 9.— Left panel: absence of evidence for a correlation between the jet power and the BH spin for steady jets (Fender et al. 2010). Right panel: evidence for a correlation between the jet power and the BH spin for transient jets (Narayan & McClintock 2012). See text for details.

Non-Kerr background...

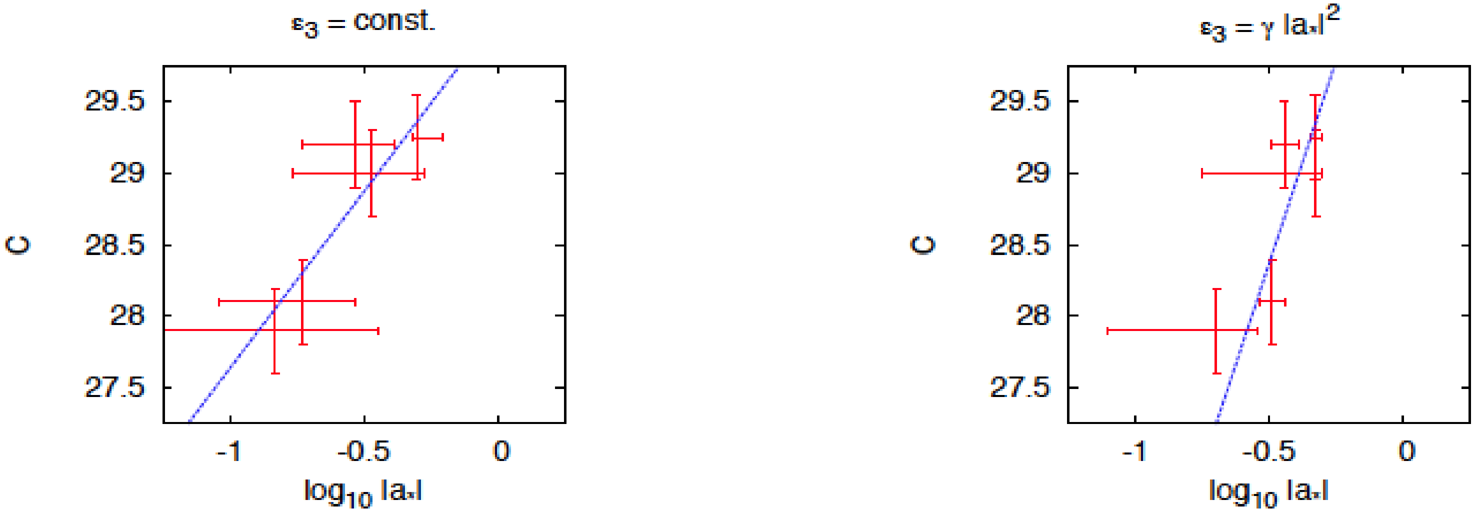


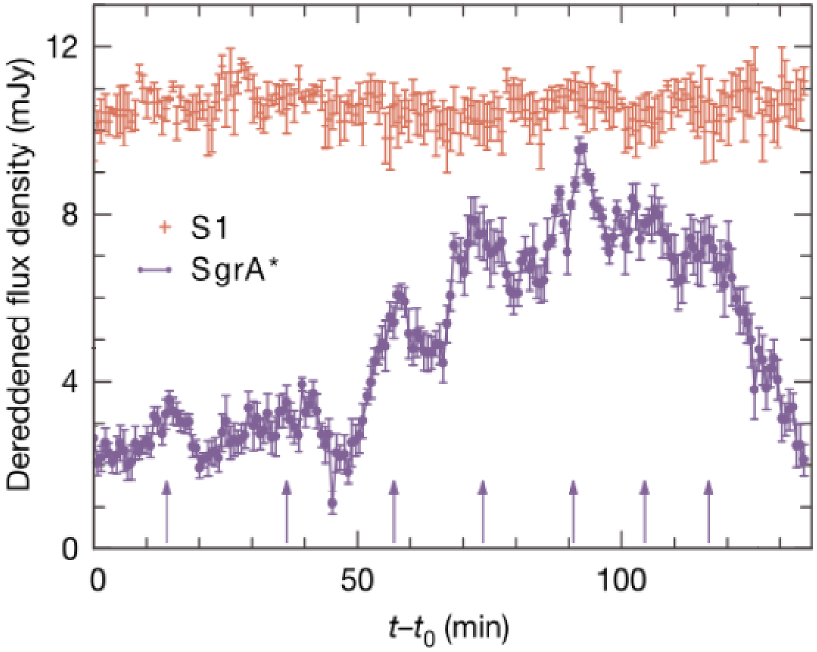
Fig. 10.— Best fit for a possible correlation between the jet power and the spin parameter of BH candidates assuming a non-vanishing deformation parameter ϵ_3. Left panel: ϵ_3 constant for all the objects; the best fit is for $\epsilon_3 = 7.5$. Right panel: $\epsilon_3 = \gamma|a_*|^2$, with γ constant;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

Prospectives for the future

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

Flare activity of SgrA*

- **Flares in the X-ray, NIR, and sub-mm bands**
- **A few per day**
- **Substructures with a timescale of about 20 minutes (observed in the range 13-30 minutes)**



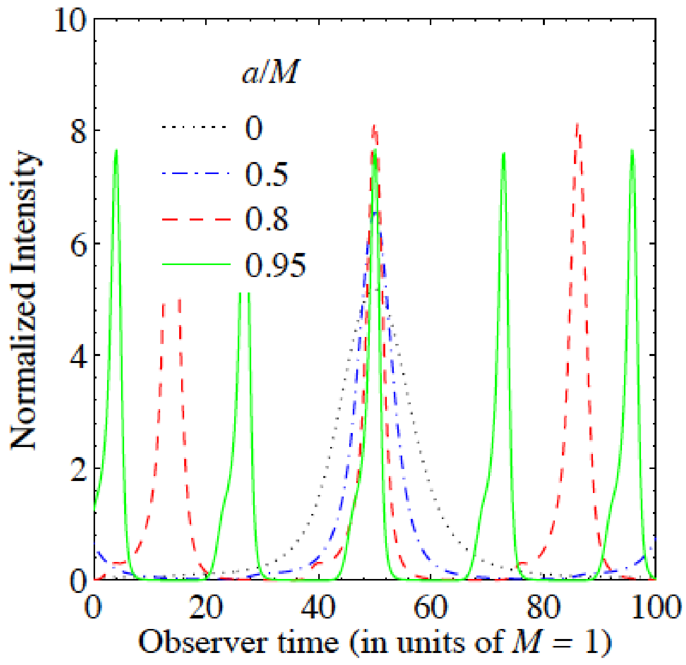
Flare mechanisms

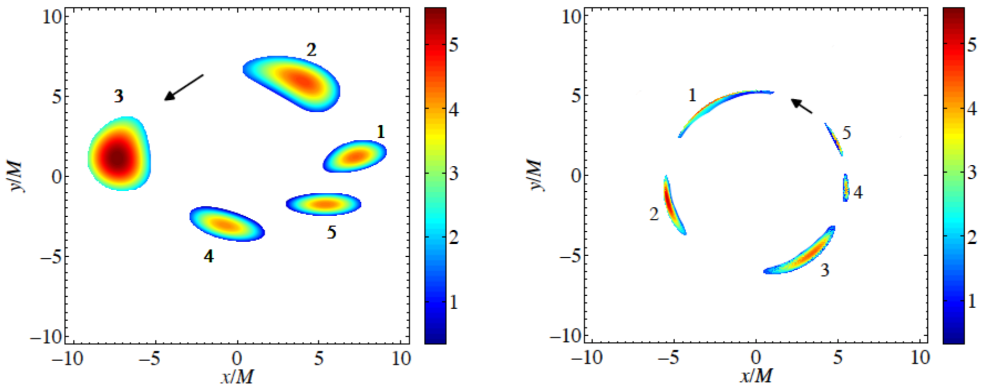
- **Heating of electrons in a jet (Markoff et al. 2001)**
- **Adiabatic expansion of a blob of plasma (Yusef-Zadeh et al. 2006)**
- **Rossby wave instabilility in the disk (Tagger & Melia 2006)**
- **Blob of plasma orbiting the ISCO of SgrA* (Hamaus et al. 2009)**

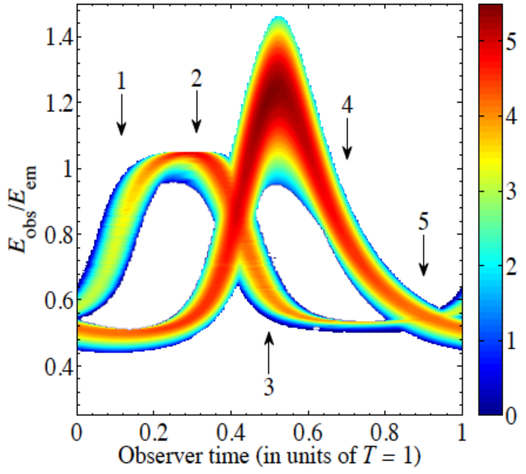
Current data seem to favor the hot spot model near the ISCO, but its confirmation will probably require the GRAVITY instrument for ESO-VLTI

Hot spot model

- **Light curves, spectrograms, images**

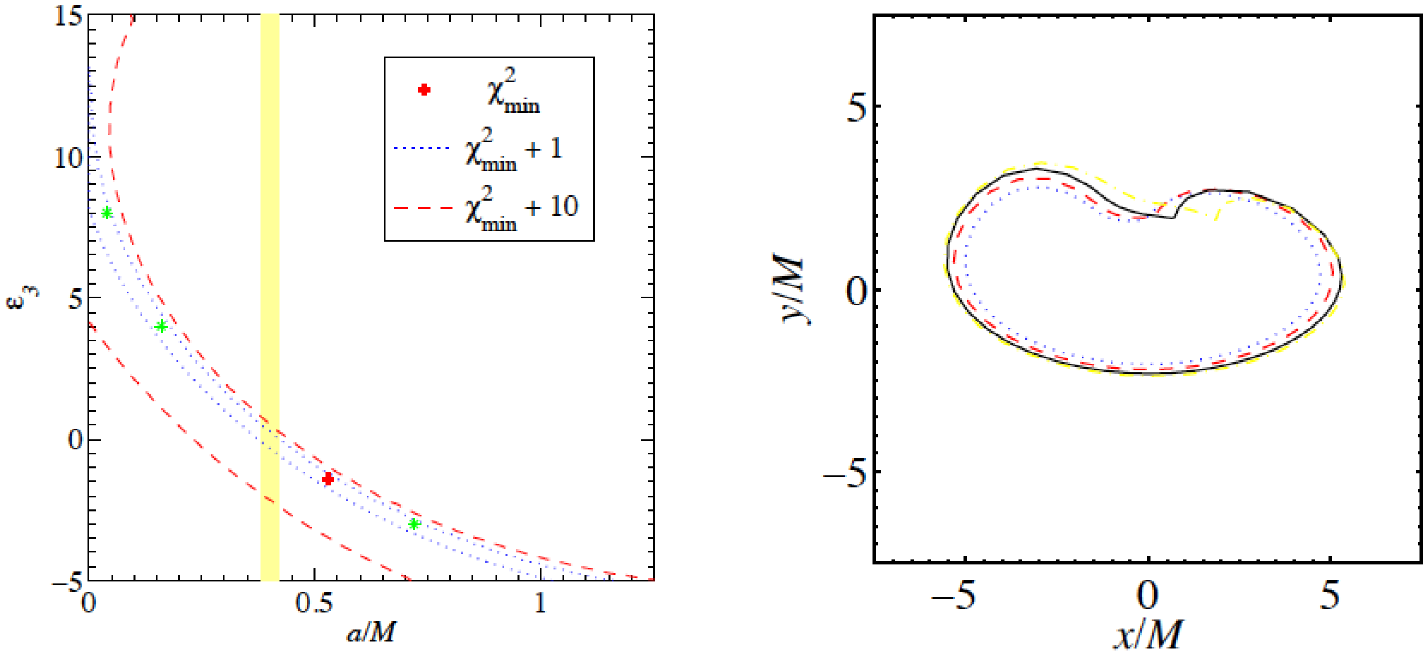






Possible future constraints

- **Light curve**
- **Light curve + centroid track (GRAVITY)**
- **Light curve + pulsar**



Shadow

- **BH shadow + pulsar**

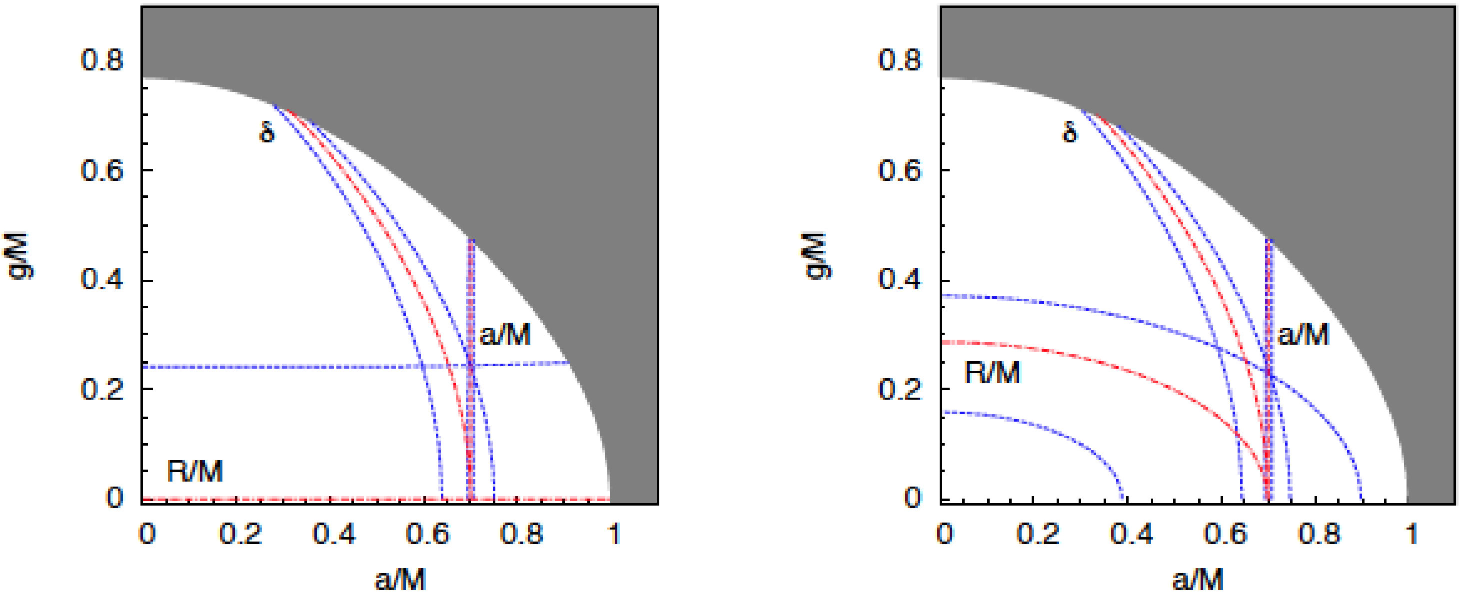


Figure 11. Hypothetical constraints from the measurements of the Hioki-Maeda distortion parameter δ determined with a precision of 20%, of the shadow radius R/M determined with a precision of 1%, and of the spin parameter a/M inferred from the orbital motion of a pulsar in a compact orbit and determined with a precision of 1%, assuming that the object is a Kerr BH with $a/M = 0.7$ and the inclination angle is $i = 90°$ (left panel, in this case $\delta = 0.0668$ and $R/M = 5.20$) and 45° (right panel, in this case $\delta = 0.0371$ and $R/M = 5.12$). The red dashed-dotted lines are the central values of the measurements, while the blue dashed curves correspond to their uncertainties. The gray area is the region of objects without event horizon and can be ignored.

BH shadow + pulsar + hot spot (CPR BHs)

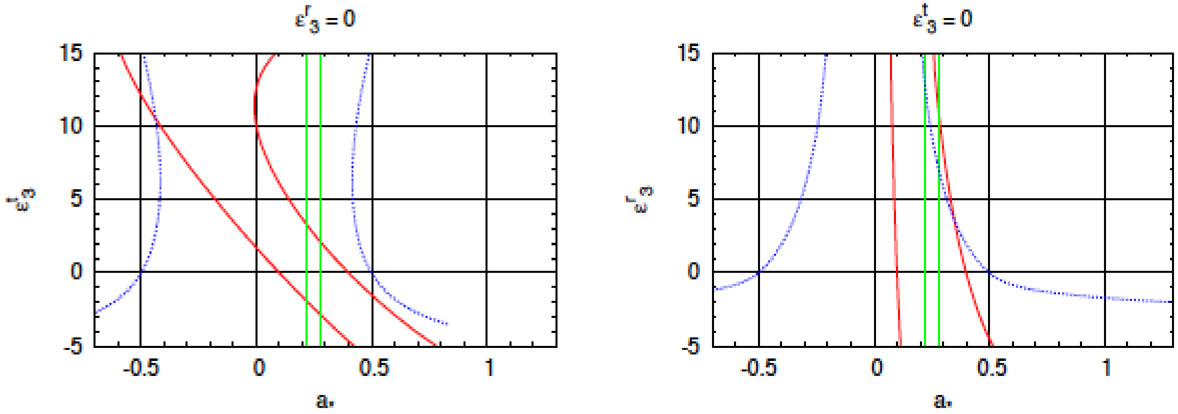


FIG. 1. Allowed regions from the measurement of the ISCO frequency (red solid lines), Hioki-Maeda distortion parameter of the shadow (blue dotted lines) and spin estimate from a radio pulsar (green dashed lines). Left panel: constraints on the spin-ϵ^t_3 plane assuming that all the other deformation parameters vanish. Right panel: constraints on the spin-ϵ^r_3 plane assuming that all the other deformation parameters vanish. These constraints are obtained by assuming "reasonable" measurements of a Kerr BH with spin parameter $a_* = 0.25$. See the text for more details.

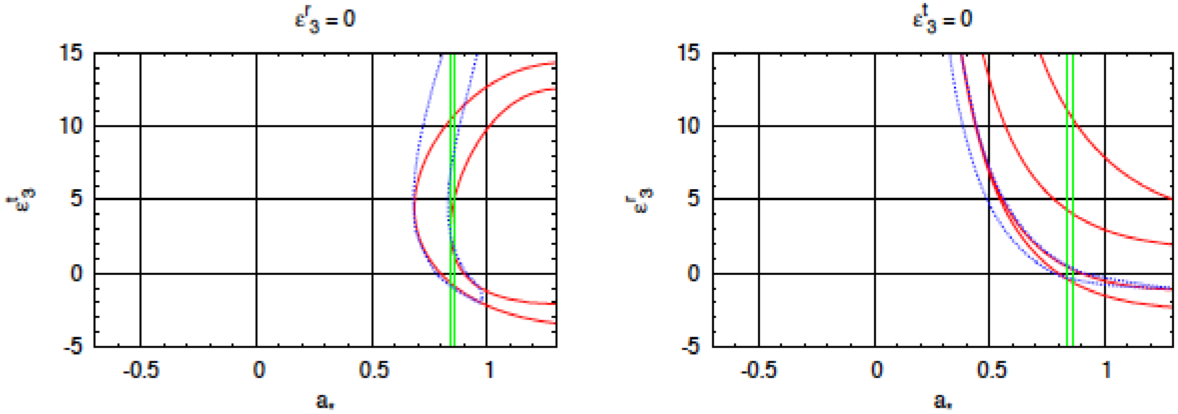


FIG. 2. As in Fig. 1, with the constraints obtained by assuming "reasonable" measurements of a Kerr BH with spin parameter $a_* = 0.85$. See the text for more details.

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, but their nature has still to be verified

- At present, we can just exclude some very exotic alternatives (some kinds of wormholes, some boson stars, etc.)

- To distinguish Kerr and non-Kerr black holes, new observational facilities are necessary

Thank you!