復旦大學
Fudan University

Testing black holes using X-ray reflection spectroscopy

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Contributors

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FUDAN UNIVERSITY 1905

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

ACADEMIAE FRIDERICO ALEXANDRINAE SIGILLVM

UNIVERSITY OF CAMBRIDGE

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Motivations

Tests of general relativity

- **1915 → General relativity (Einstein)**
- **1919 → Deflection of light by the Sun (Eddington)**
- **1960s-present → Solar System experiments**
- **1970s-present → Binary pulsars**

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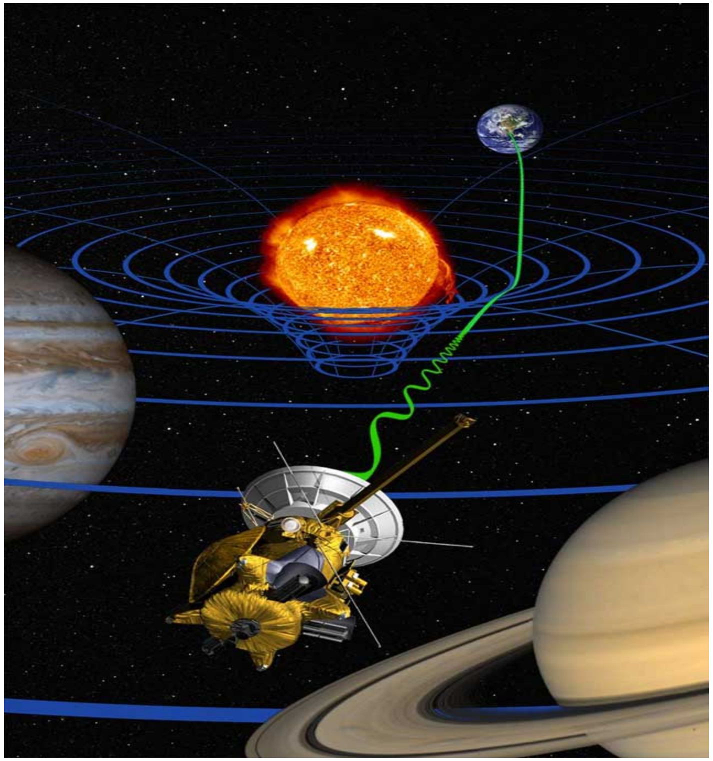

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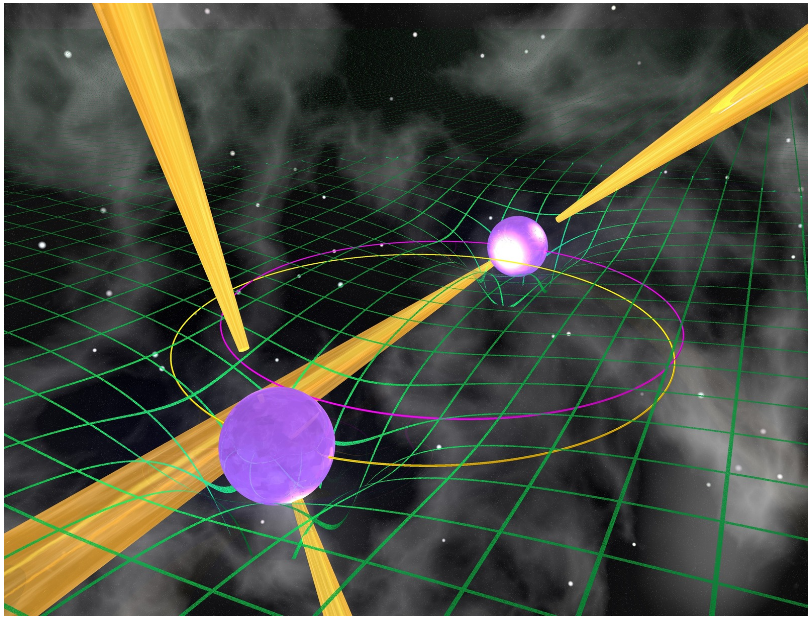

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- **Today → Black holes**

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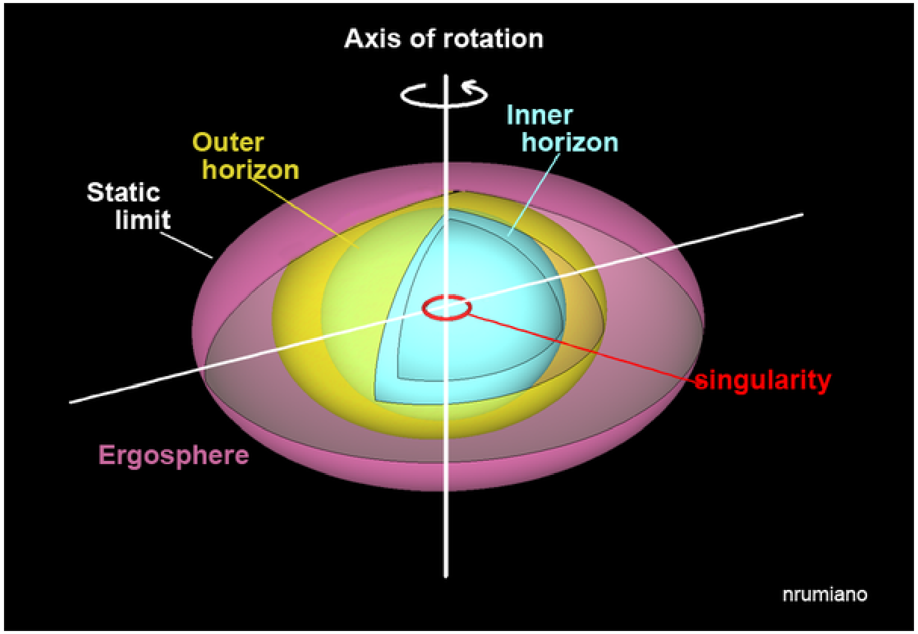
- **Today → Black holes**

→ **Strong fields**

Black holes in Einstein's Gravity

- **"No-Hair Theorem" → M, J, Q ($a_* = J/M^2$)**
- **Uncharged black holes → Kerr solution**
- **Clear predictions on the particle motion**



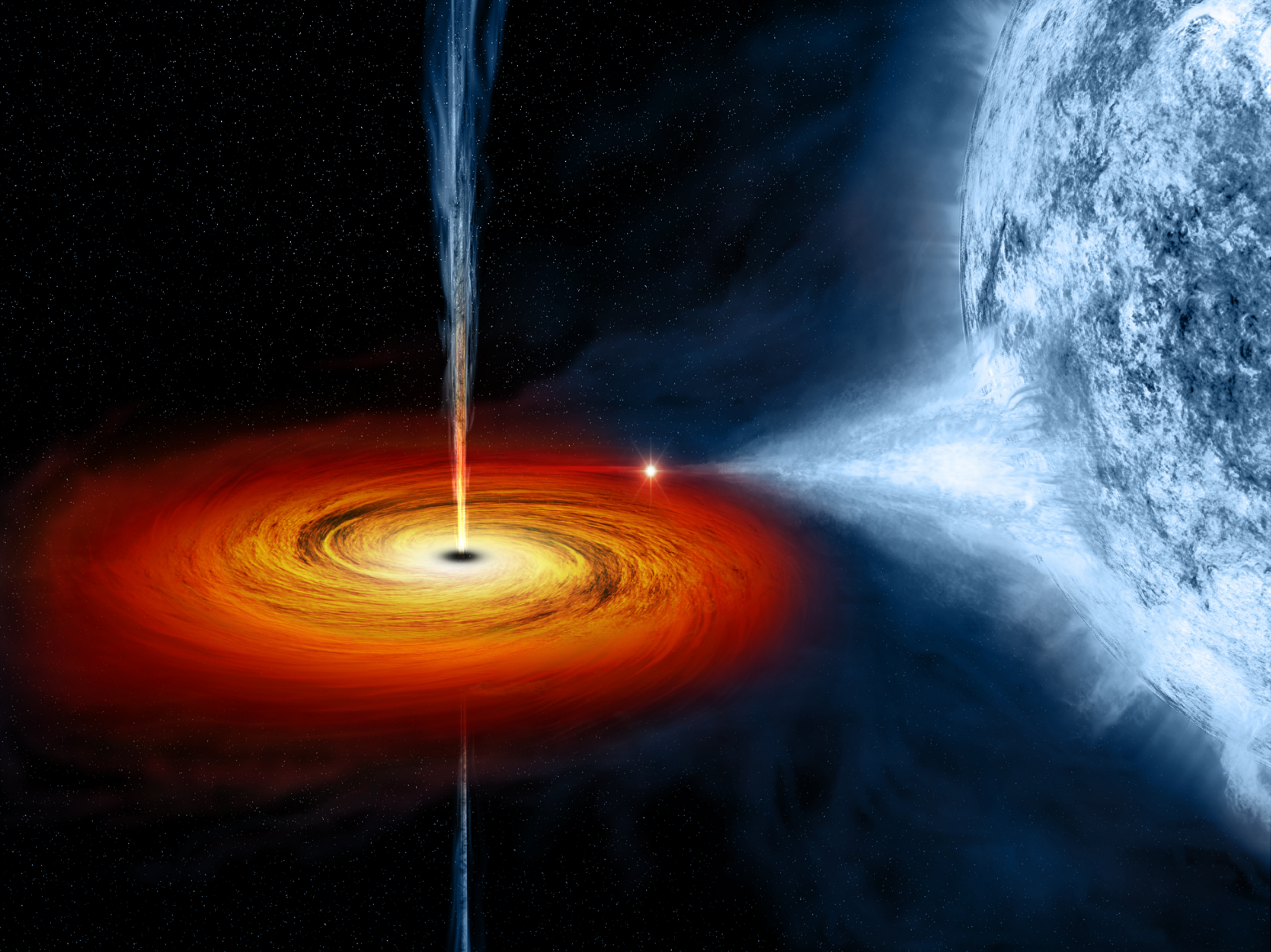
Astrophysical black holes

The spacetime metric around astrophysical black holes formed from gravitational collapse should be well approximated by the Kerr solution:

- **Initial deviations are radiated away by gravitational waves**
- **Equilibrium electric charge is negligible**
- **Mass of the accretion disk is negligible**

Black hole "candidates"

- **Stellar-mass black holes (3 – 100 Solar masses)**
- **Supermassive black holes (10^5 – 10^{10} Solar masses)**
- **Intermediate-mass black holes (10^2 – 10^4 Solar masses?)**



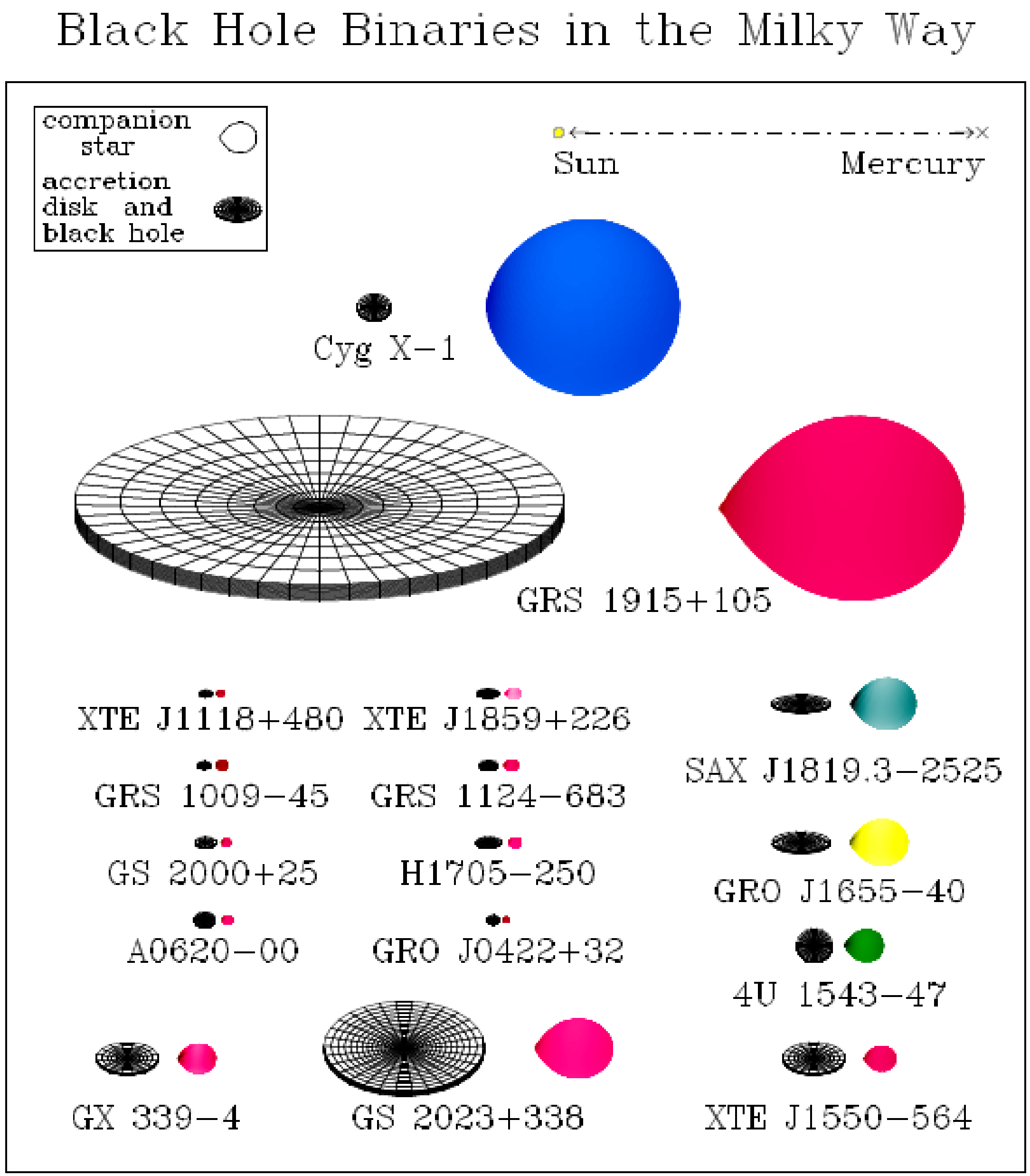
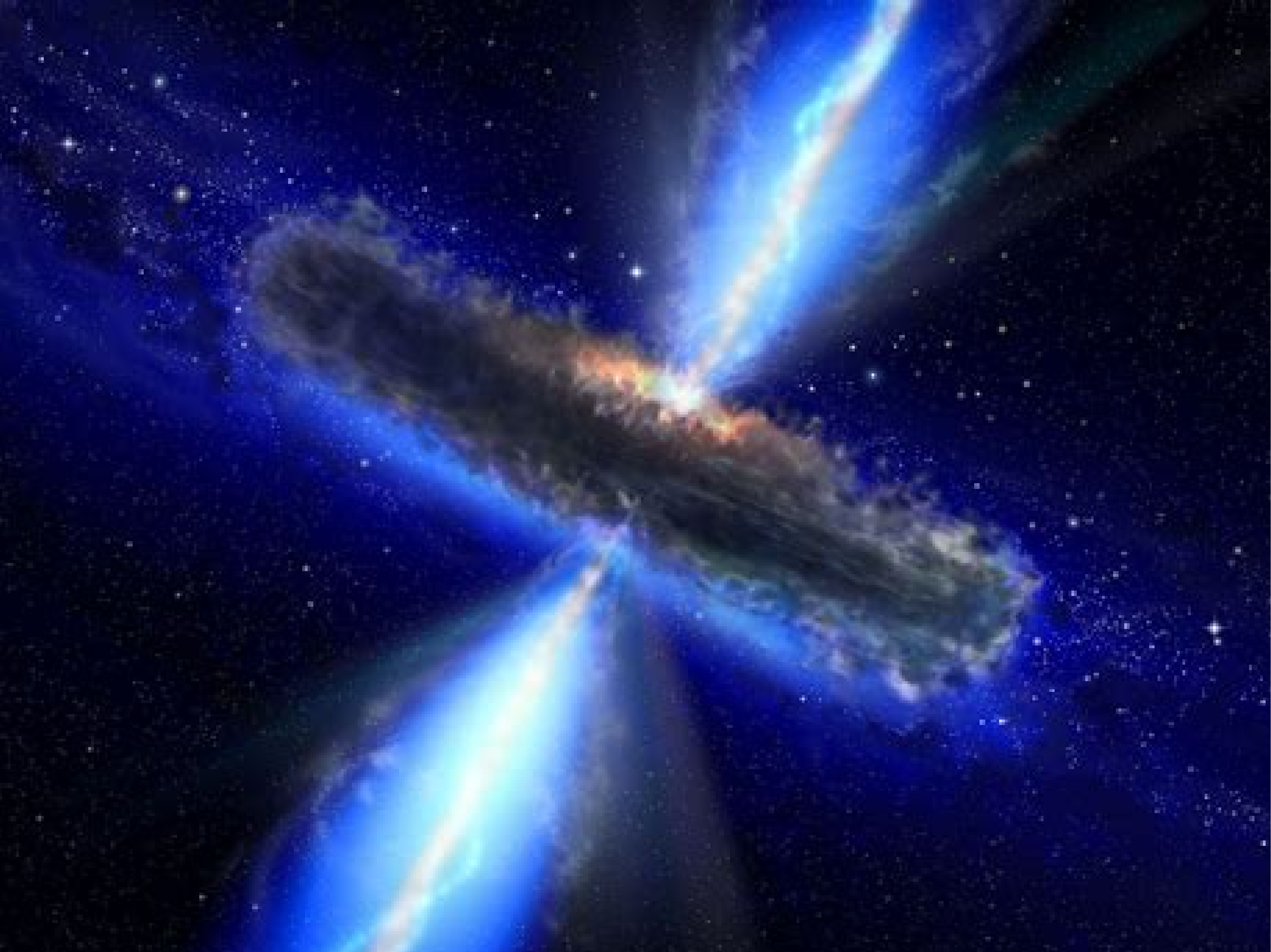
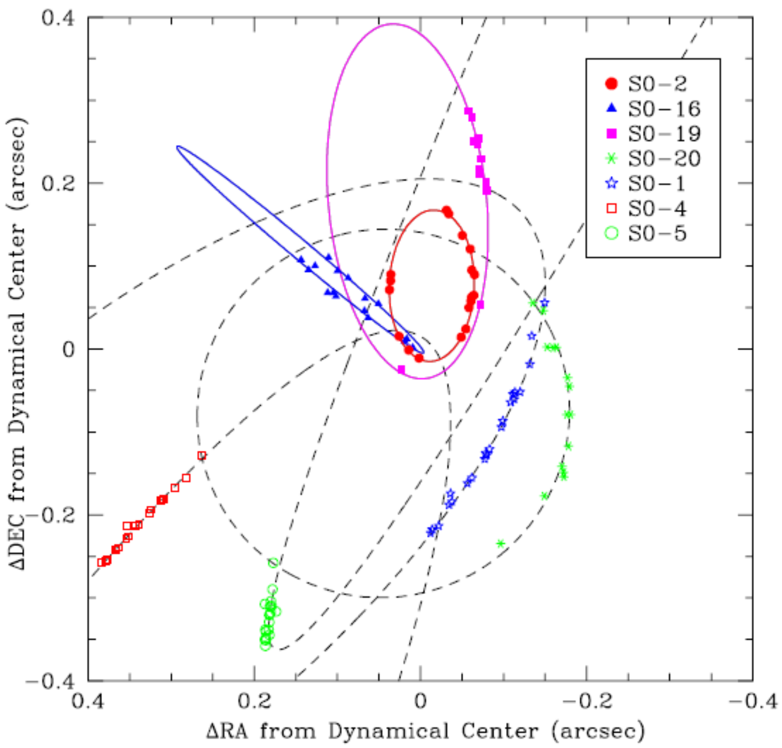


Figure courtesy of Jerome Orosz



Supermassive BH candidate in the Galaxy

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



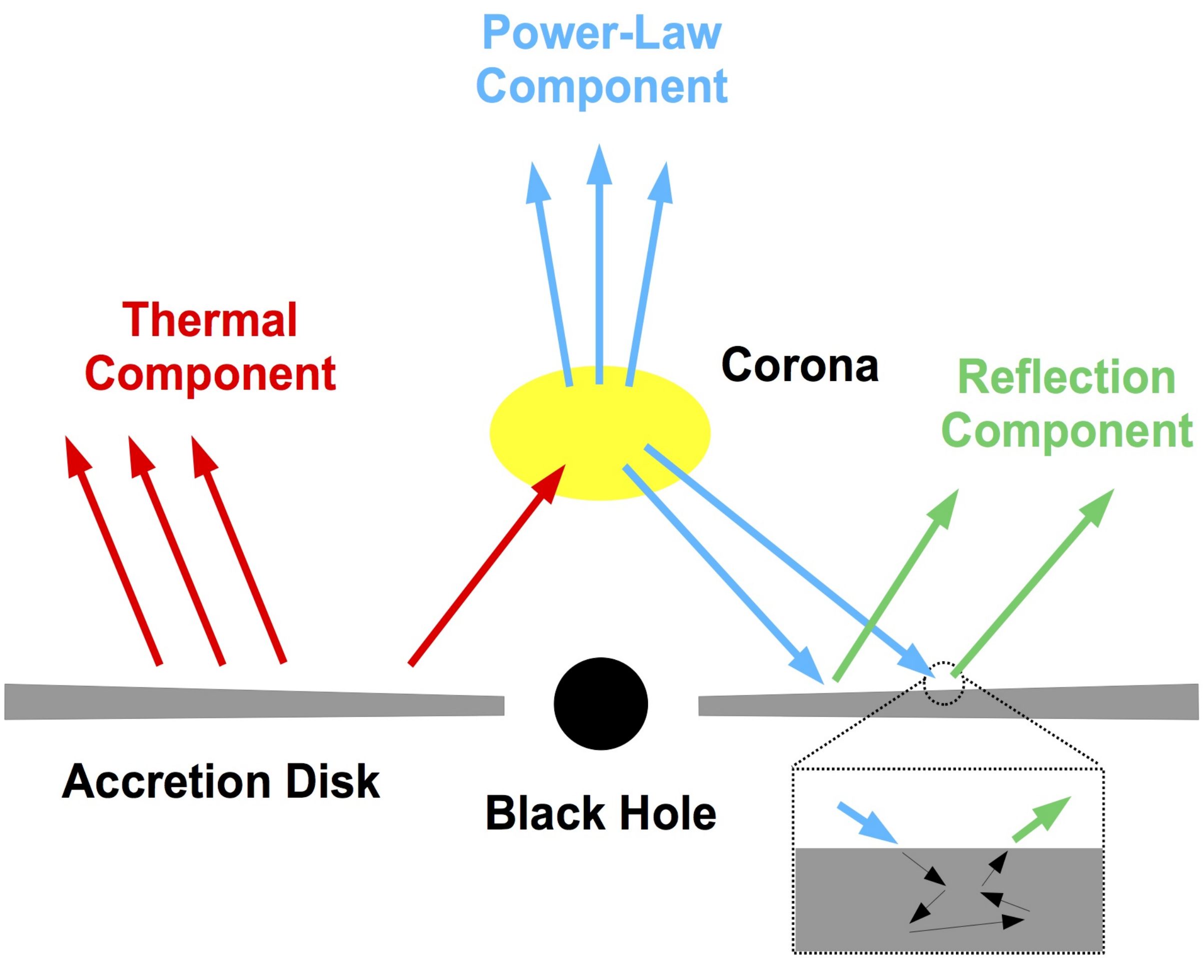
From Ghez et al. 2005

Black holes "candidates" → Dark and compact objects that can be naturally interpreted as the Kerr black holes predicted in General Relativity

We want to observationally test whether the spacetime metric is described by the Kerr solution

Method

Disk-corona model



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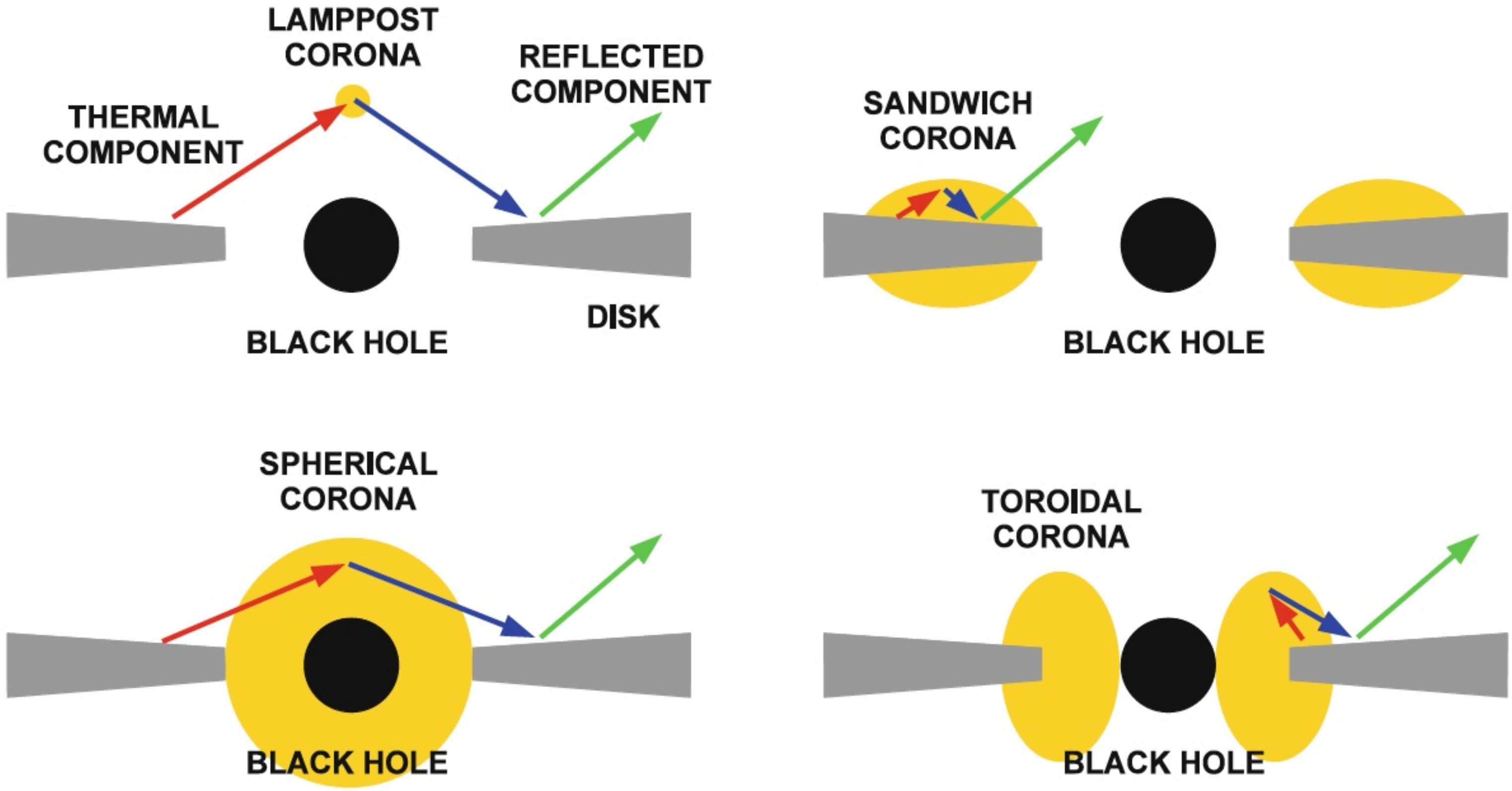

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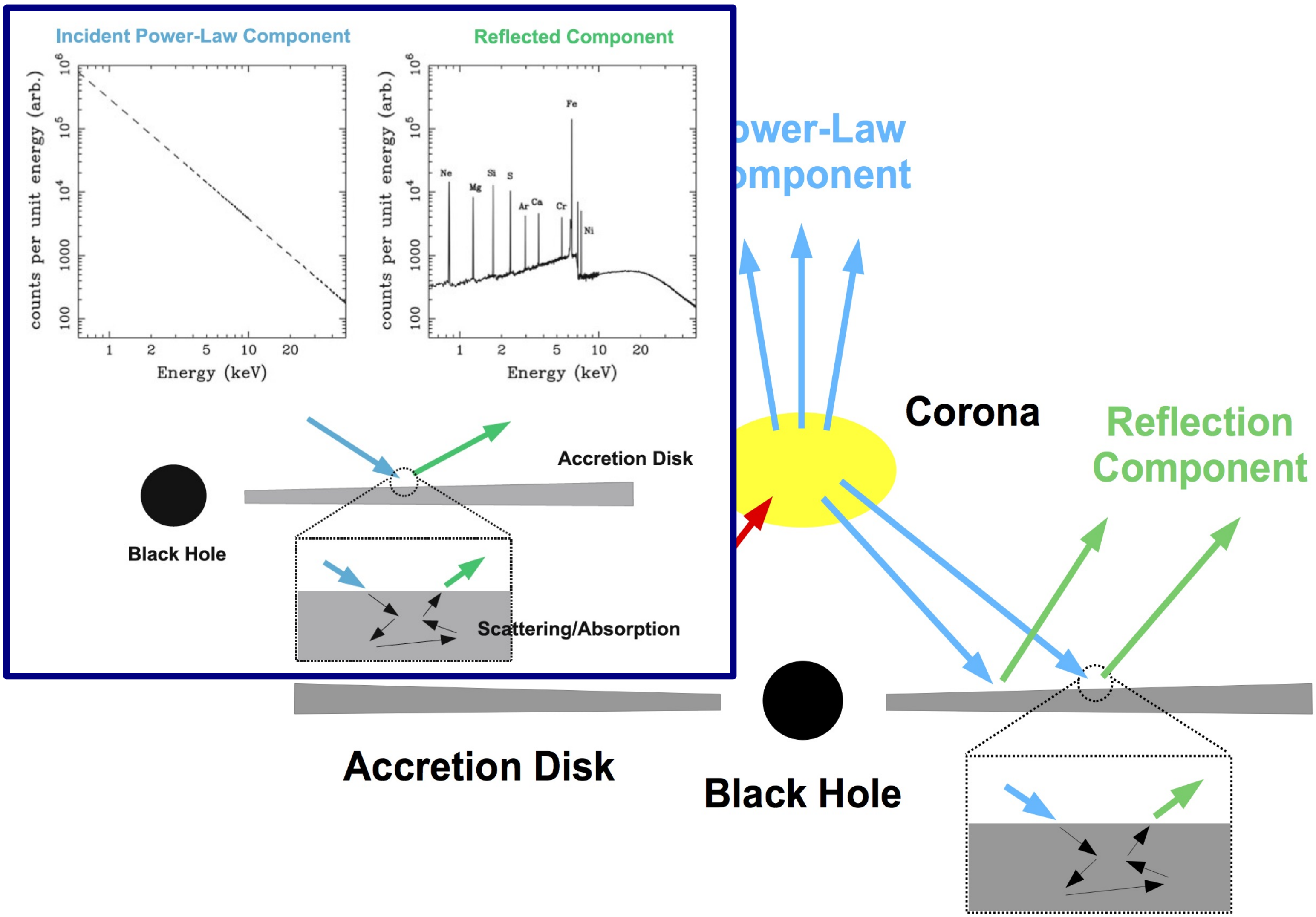
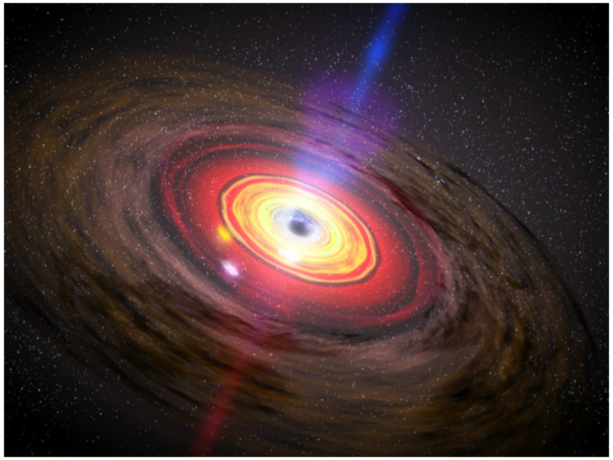
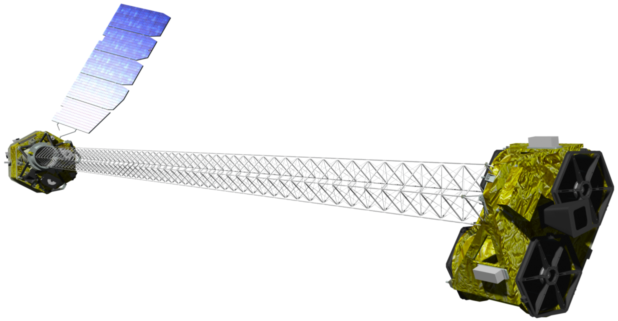
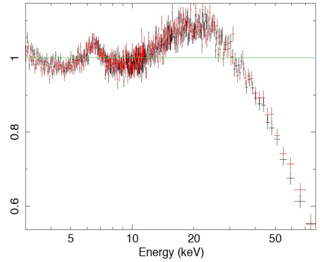


Reflection spectrum

- **Reflection spectrum at the emission point → Atomic physics**
- **Reflection spectrum far from the source → Einstein's gravity**







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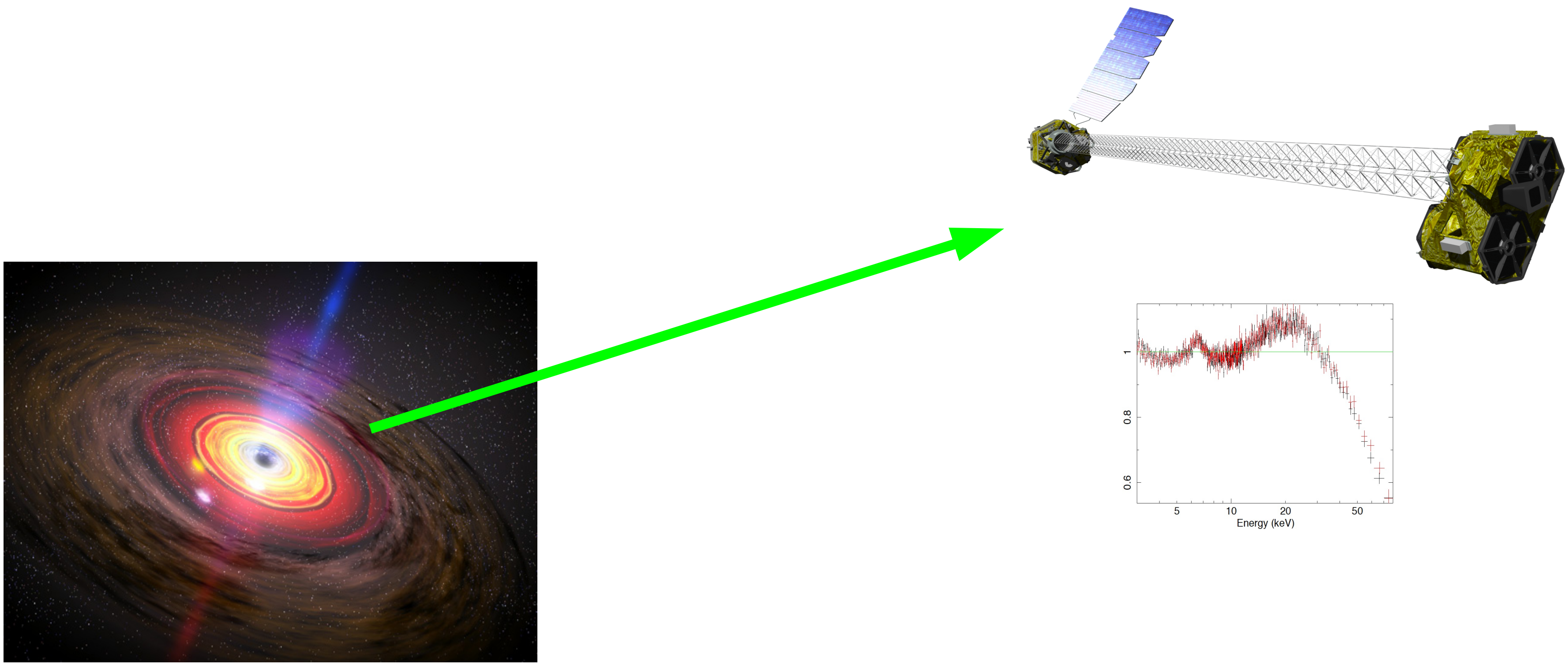


Model

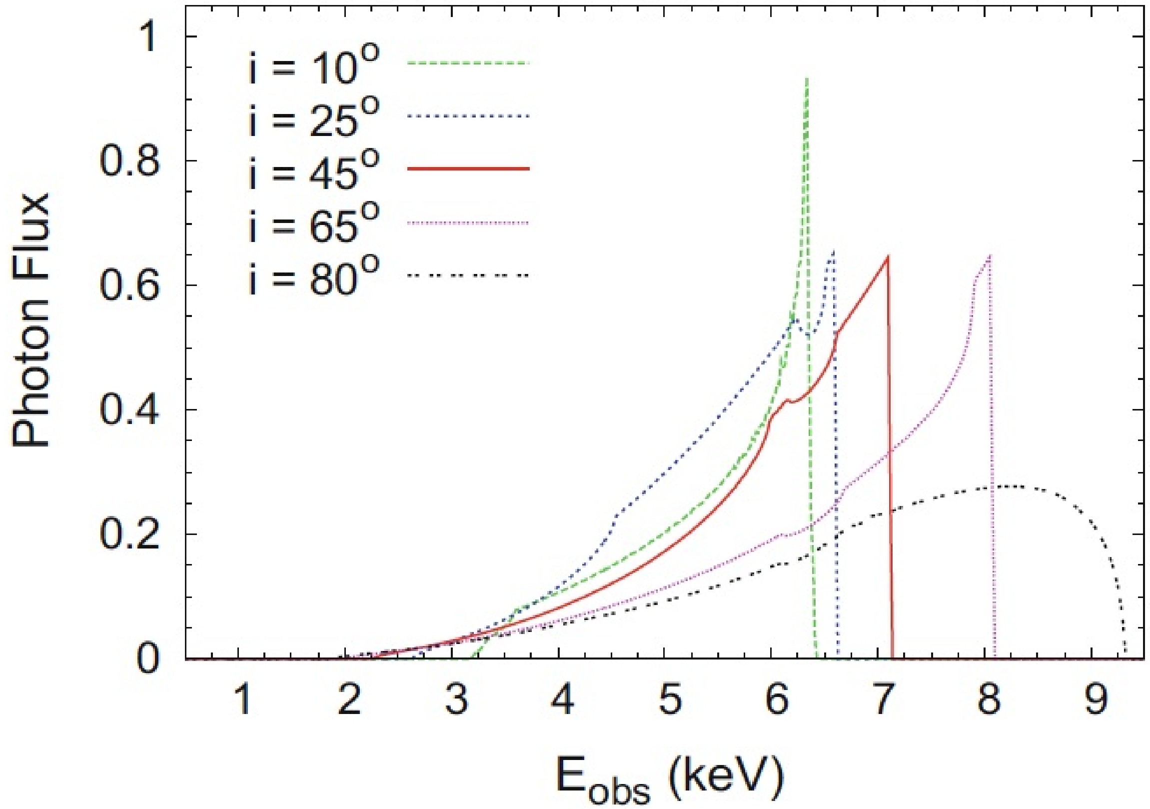
RELXILL

- **RELXILL is currently the most advanced X-ray reflection model for Kerr spacetimes**
- **Reflection spectrum at the emission point → XILLVER**
- **Reflection spectrum far from the source (assuming Einstein's gravity)**

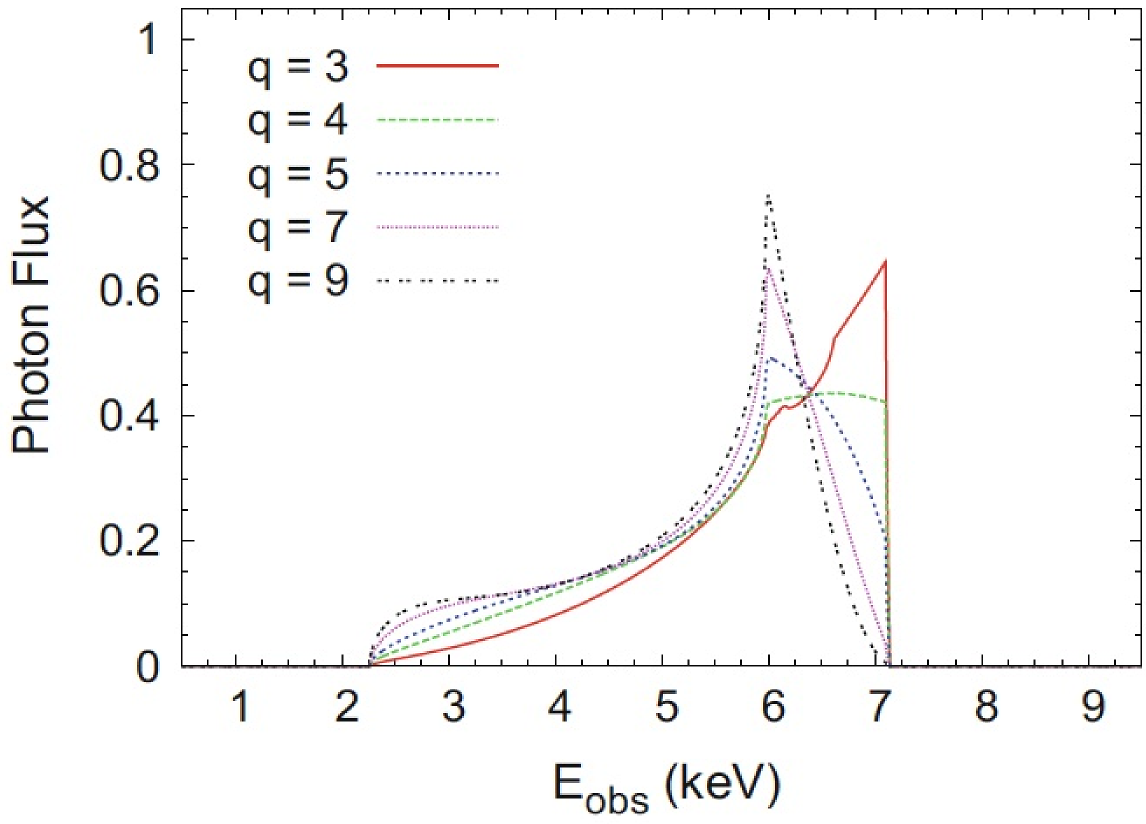
  → RELXILL ~ RELCOV*XILLVER

- **RELXILL can be employed to measure black hole spins**

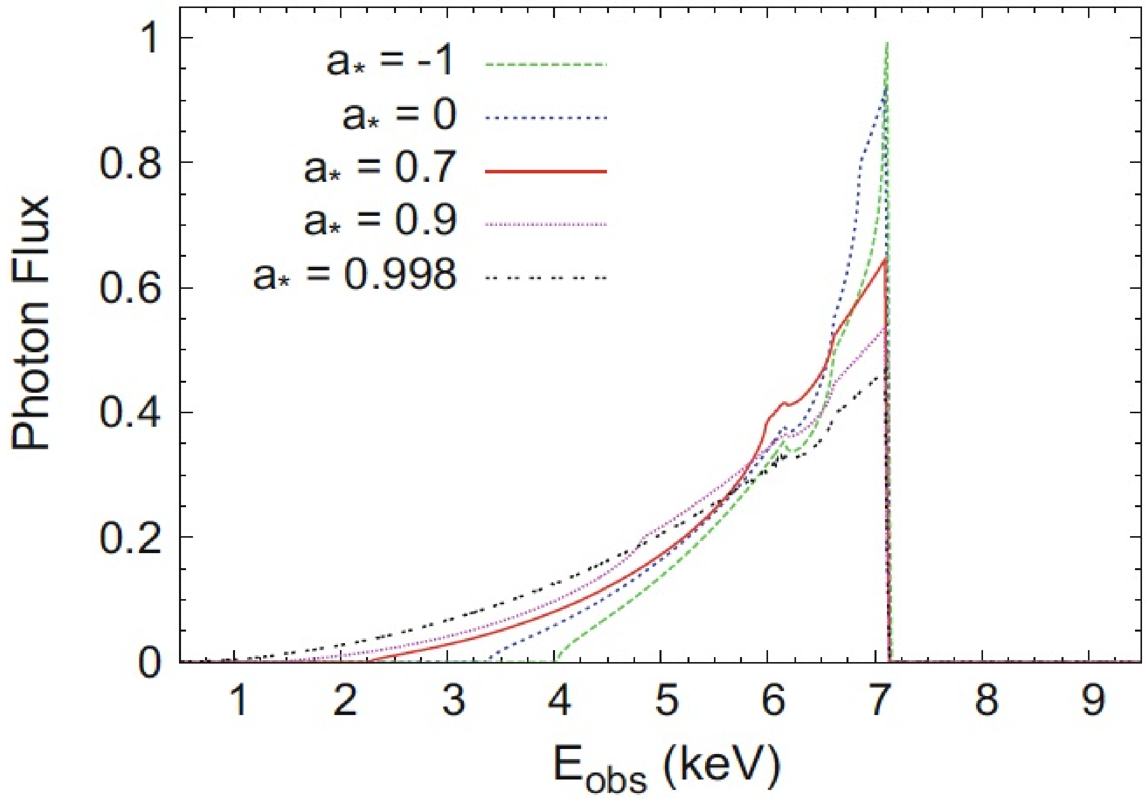
Impact of the inclination angle



Impact of the emissivity index



Impact of the spin parameter



Current spin measurements

BH Binary	a_* (continuum)	a_* (iron)	Principal References
GRS 1915-105	> 0.98	0.98 ± 0.01	[21, 23]
Cyg X-1	> 0.98	$0.97^{+0.014}_{-0.02}$	[12, 13, 8, 25]
LMC X-1	0.92 ± 0.06	$0.97^{+0.02}_{-0.25}$	[10, 36]
GX 339-4	< 0.9	0.95 ± 0.03	[14, 27, 9]
MAXI J1836-194	—	0.88 ± 0.03	[28]
M33 X-7	0.84 ± 0.05	—	[18]
4U 1543-47	$0.80 \pm 0.10^{\star}$	—	[31]
IC10 X-1	$\gtrsim 0.7$	—	[34]
Swift J1753.5	—	$0.76^{+0.11}_{-0.15}$	[26]
XTE J1650-500	—	$0.84 \sim 0.98$	[37]
GRO J1655-40	$0.70 \pm 0.10^{\star}$	> 0.9	[31, 26]
GS 1124-683	$0.63^{+0.16}_{-0.19}$	—	[4, 24]
XTE J1752-223	—	0.52 ± 0.11	[29]
XTE J1652-453	—	< 0.5	[5]
XTE J1550-564	0.34 ± 0.28	$0.55^{+0.15}_{-0.22}$	[35]
LMC X-3	0.25 ± 0.15	—	[32]
H1743-322	0.2 ± 0.3	—	[33]
A0620-00	0.12 ± 0.19	—	[11]
XMMU J004243.6	< -0.2	—	[22]

Table 6.1 Summary of the continuum-fitting and iron line measurements of the spin parameter of stellar-mass black hole candidates under the assumption of the Kerr background. See the references in the last column for more details. *These sources were studied in an early work of the continuum-fitting method, within a more simple model, and therefore here the published 1σ error estimates are doubled.

Current spin measurements

AGN	a_* (iron)	$L_{\rm Bol}/L_{\rm Edd}$	Principal References
IRAS 13224-3809	>0.995	0.71	[36]
Mrk 110	>0.99	0.16 ± 0.04	[36]
NGC 4051	>0.99	0.03	[24]
MCG-6-30-15	>0.98	0.40 ± 0.13	[4, 22]
1H 0707-495	>0.98	~ 1	[26, 36, 39]
NGC 3783	>0.98	0.06 ± 0.01	[5, 24]
RBS 1124	>0.98	0.15	[36]
NGC 1365	$0.97^{+0.01}_{-0.04}$	$0.06^{+0.06}_{-0.04}$	[29, 30, 6]
Swift J0501.9-3239	>0.96	—	[36]
Ark 564	$0.96^{+0.01}_{-0.06}$	>0.11	[36]
3C 120	>0.95	0.31 ± 0.20	[18]
Ark 120	0.94 ± 0.01	0.04 ± 0.01	[25, 23, 36]
Ton S180	$0.91^{+0.02}_{-0.09}$	$2.1^{+3.2}_{-1.6}$	[36]
1H 0419-577	>0.88	1.3 ± 0.4	[36]
Mrk 509	$0.86^{+0.02}_{-0.01}$	—	[36]
IRAS 00521-7054	>0.84	—	[33]
3C 382	$0.75^{+0.07}_{-0.04}$	—	[36]
Mrk 335	$0.70^{+0.12}_{-0.01}$	0.25 ± 0.07	[25, 36]
Mrk 79	0.7 ± 0.1	0.05 ± 0.01	[9, 10]
Mrk 359	$0.7^{+0.3}_{-0.5}$	0.25	[36]
NGC 7469	0.69 ± 0.09	—	[25]
Swift J2127.4+5654	0.6 ± 0.2	0.18 ± 0.03	[21, 25]
Mrk 1018	$0.6^{+0.4}_{-0.7}$	0.01	[36]
Mrk 841	>0.56	0.44	[36]
Fairall 9	$0.52^{+0.19}_{-0.15}$	0.05 ± 0.01	[25, 17, 31, 36]

Table 7.1 Summary of the iron line measurements of the spin parameter of supermassive black hole candidates under the assumption of the Kerr background. See the references in the last column and [3] for more details.

RELXILL_NK

- **RELXILL_NK is the natural extension of RELXILL for non-Kerr spacetimes**

  → RELXILL_NK ~ RELCOV_NK*XILLVER

- **“Deformation parameters”**

- **RELXILL_NK can be employed to test the Kerr black hole hypothesis**

How can we test the Kerr nature of astrophysical black holes?

- **Top-down approach:**

  We test a specific alternative theory of gravity against Einstein's gravity

  Problems:

  1) A large number of alternative theories...

  2) We do not have rotating black hole solutions...

- **Bottom-up approach:**

  See PPN formalism

Solar System experiments:
Schwarzschild solution in the weak field limit

- **Parametrized Post-Newtonian formalism (PPN formalism)**
- **Weak field limit (M/r << 1)**
- **Solar System experiments**

$$ds^2 = -\left(1 - \frac{2M}{r} + \beta \frac{2M^2}{r^2} + ...\right) dt^2 + \left(1 + \gamma \frac{2M}{r} + ...\right) (dx^2 + dy^2 + dz^2)$$

$$|\beta - 1| < 2.3 \cdot 10^{-4} \quad \text{(Lunar Laser Ranging experiment)}$$
$$|\gamma - 1| < 2.3 \cdot 10^{-5} \quad \text{(Cassini spacecraft)}$$

In general relativity $\beta = \gamma = 1$

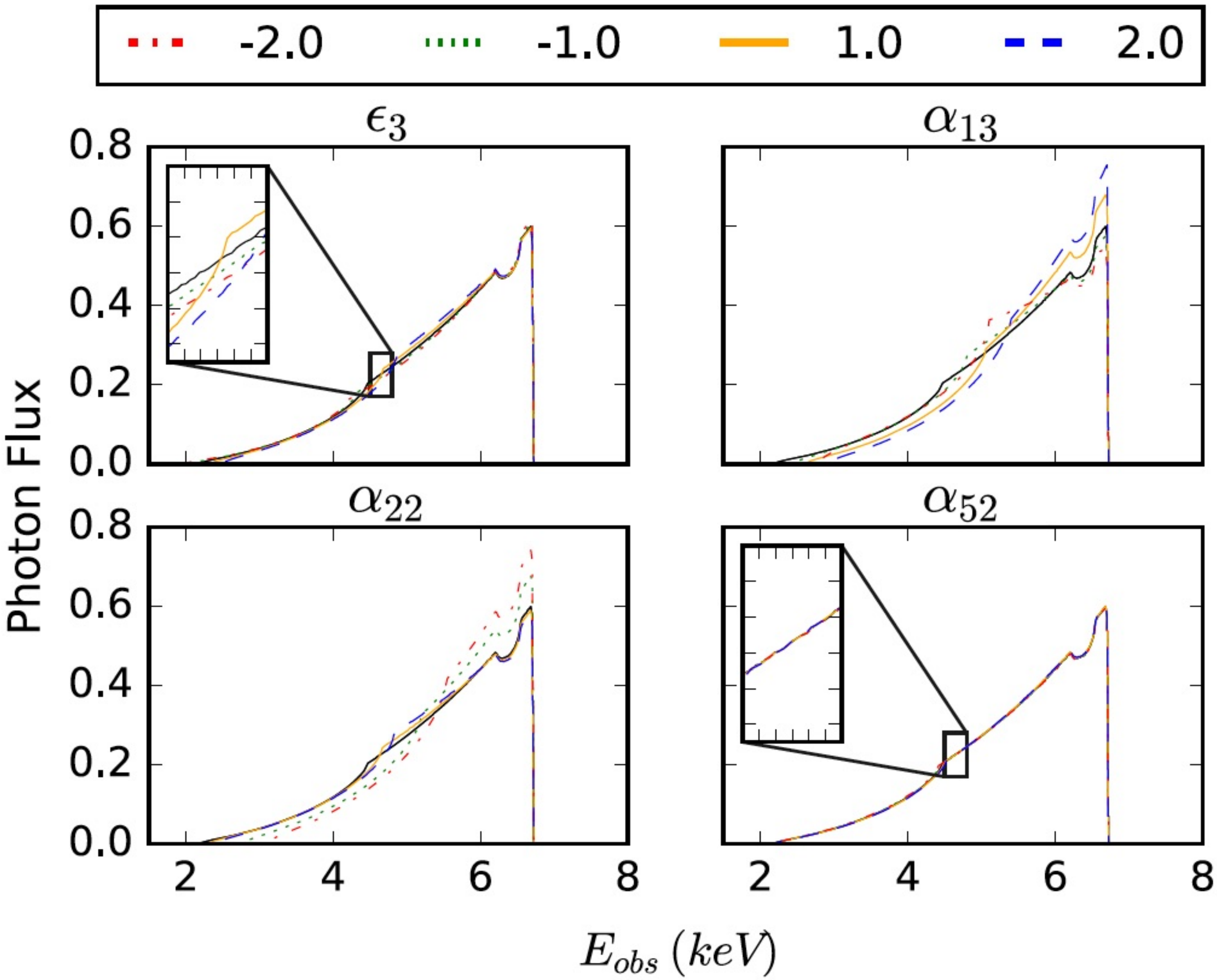
Johannsen metric
[Johannsen, PRD 88, 044002 (2013)]

$$ds^2 = -\frac{\tilde{\Sigma}(\Delta - a^2 A_2^2 \sin^2\theta)}{B^2}\, dt^2$$
$$-\frac{2a\,[(r^2 + a^2)A_1 A_2 - \Delta]\,\tilde{\Sigma}\sin^2\theta}{B^2}$$
$$\times\, dt\, d\phi + \frac{\tilde{\Sigma}}{\Delta A_5}\, dr^2 + \tilde{\Sigma}\, d\theta^2$$
$$+ \frac{[(r^2 + a^2)^2 A_1^2 - a^2 \Delta \sin^2\theta]\,\tilde{\Sigma}\sin^2\theta}{B^2}\, d\phi^2,$$

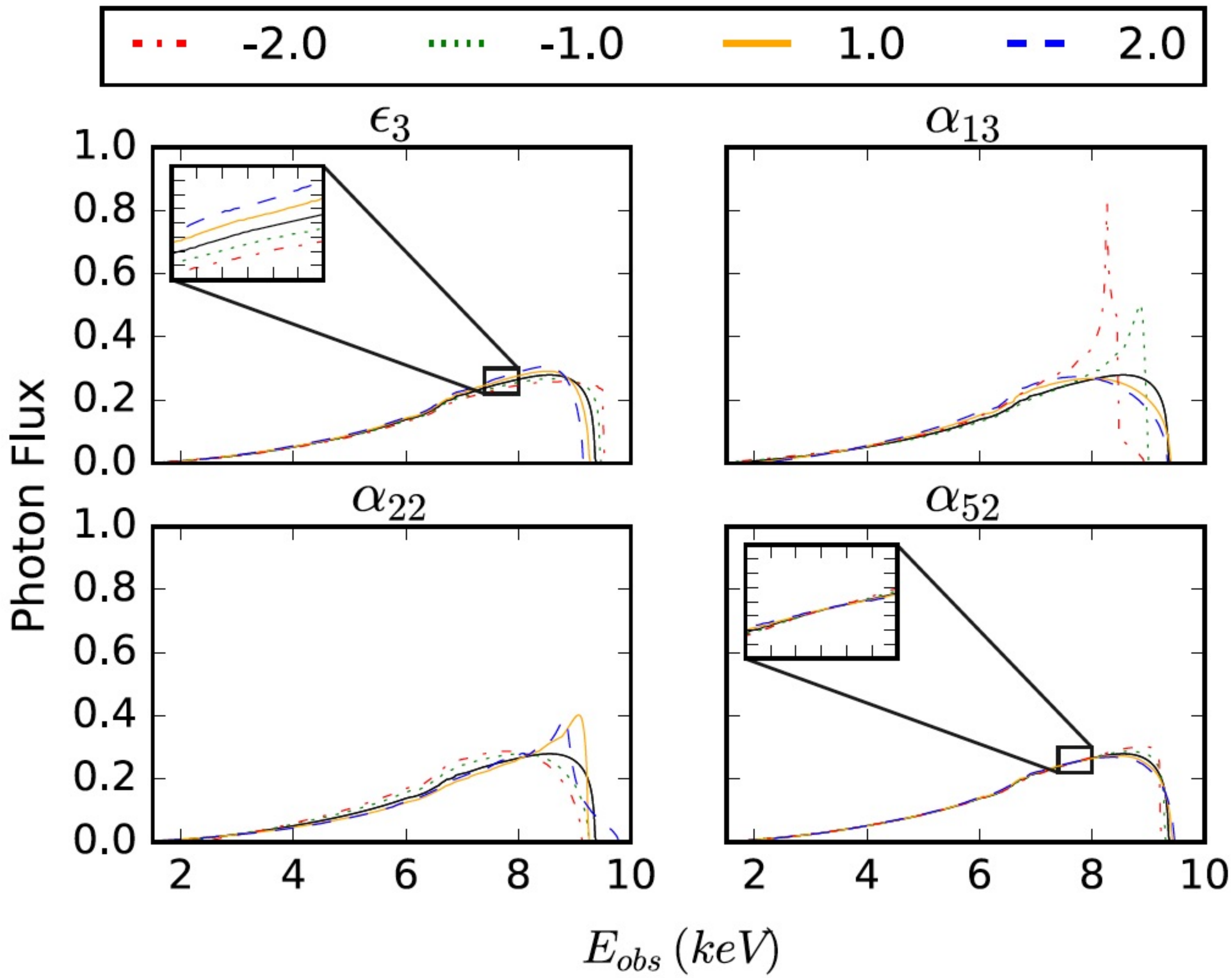
$$B = (r^2 + a^2)A_1 - a^2 A_2 \sin^2\theta, \quad \tilde{\Sigma} = \Sigma + f,$$
$$\Sigma = r^2 + a^2\cos^2\theta, \quad \Delta = r^2 - 2Mr + a^2,$$

$$f = \epsilon_3 \frac{M^3}{r}, \quad A_1 = 1 + \alpha_{13}\left(\frac{M}{r}\right)^3,$$
$$A_2 = 1 + \alpha_{22}\left(\frac{M}{r}\right)^2, \quad A_5 = 1 + \alpha_{52}\left(\frac{M}{r}\right)^2.$$

Impact of the deformation parameters (i = 30 deg)



Impact of the deformation parameters (i = 80 deg)



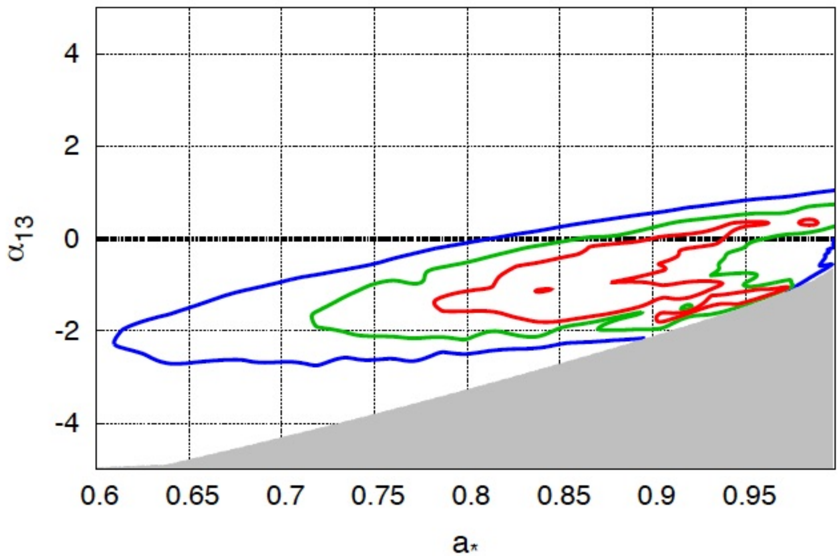
Results

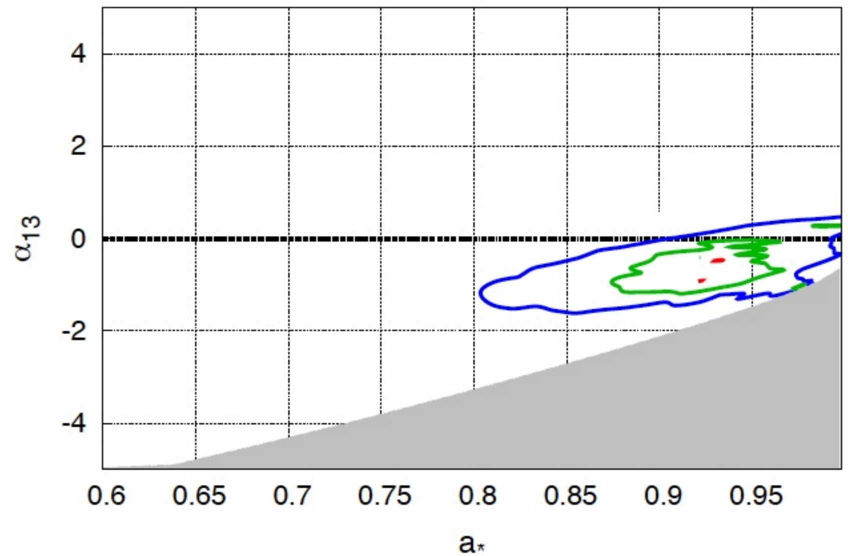
Sources

- **1H0707-495 (Cao et al., PRL 120, 051101, 2018; Zhou et al. PRD 024007, 2018)**
- **Ark 564 with Suzaku data (Tripathi et al., PRD 98, 023018, 2018)**
- **GX339-4 with RXTE data (Wang-Ji et al., arXiv:1806.00126)**
- **GS 1354-645 with NuSTAR (Xu et al., ApJ, 865, 134, 2018)**
- **Mrk 335 with Suzaku (Choudhury et al., arXiv:1809.06669)**

- **Cygnus X-1 with NuSTAR data (in preparation)**
- **MCG-6-30-15 with XMM-Newton+NuSTAR (in preparation)**
- **...**

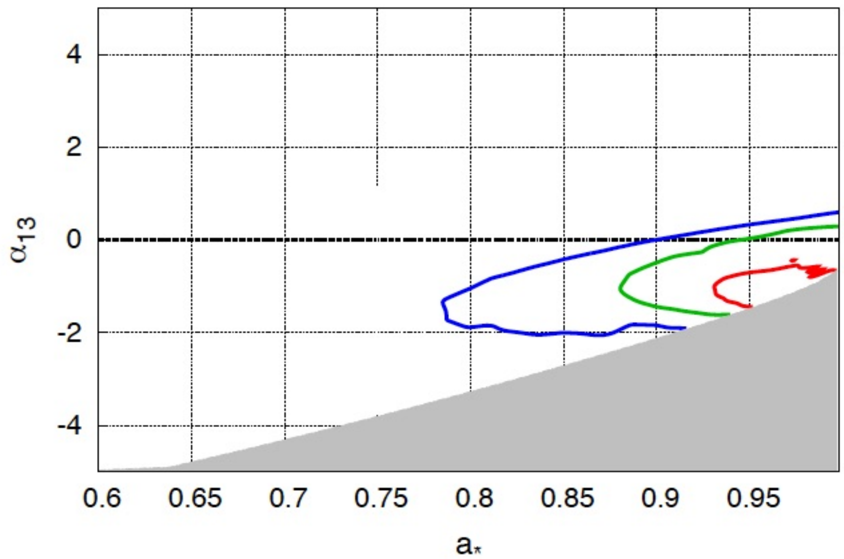
1H0707-495: XMM-Newton data of 2011





Cao et al., PRL 120, 051101 (2018)

1H0707-495: NuSTAR+Swift



Cao et al., PRL 120, 051101 (2018)

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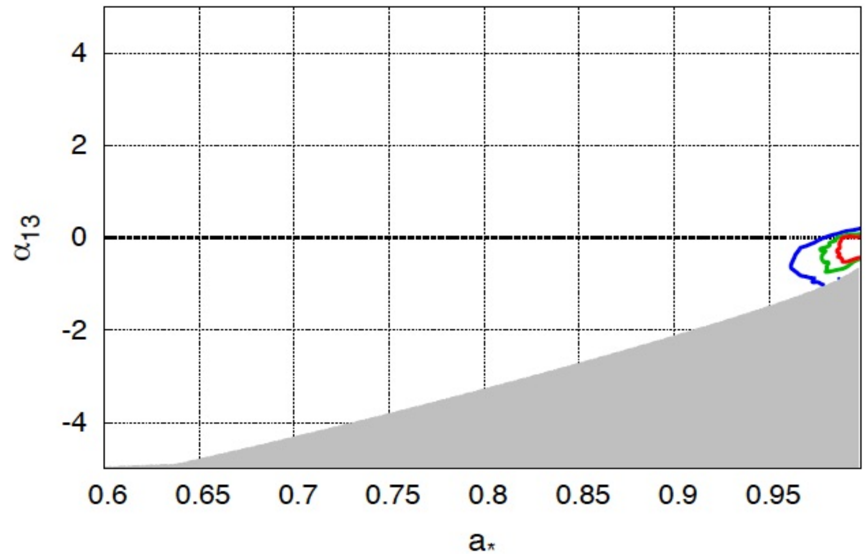
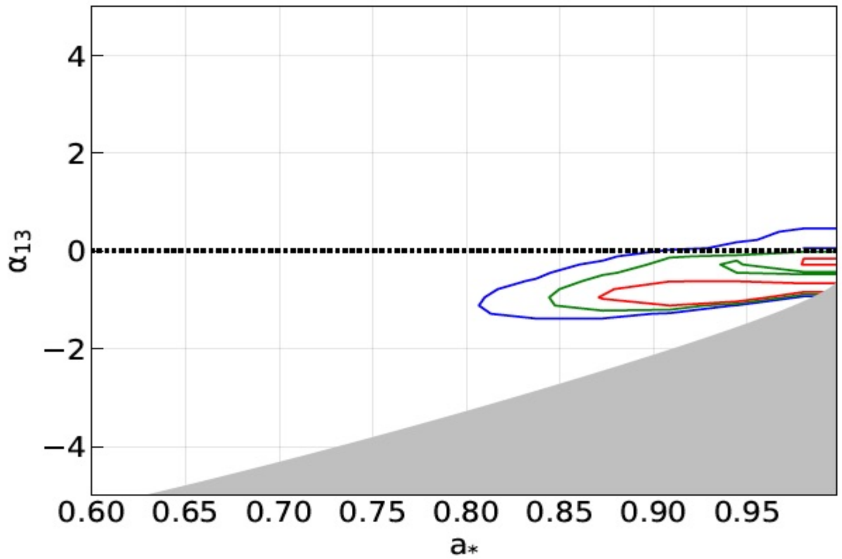


Tripathi et al., PRD 98, 023018 (2018)

GX 339-4: RXTE



Wang-Ji et al., arXiv:1806.00126

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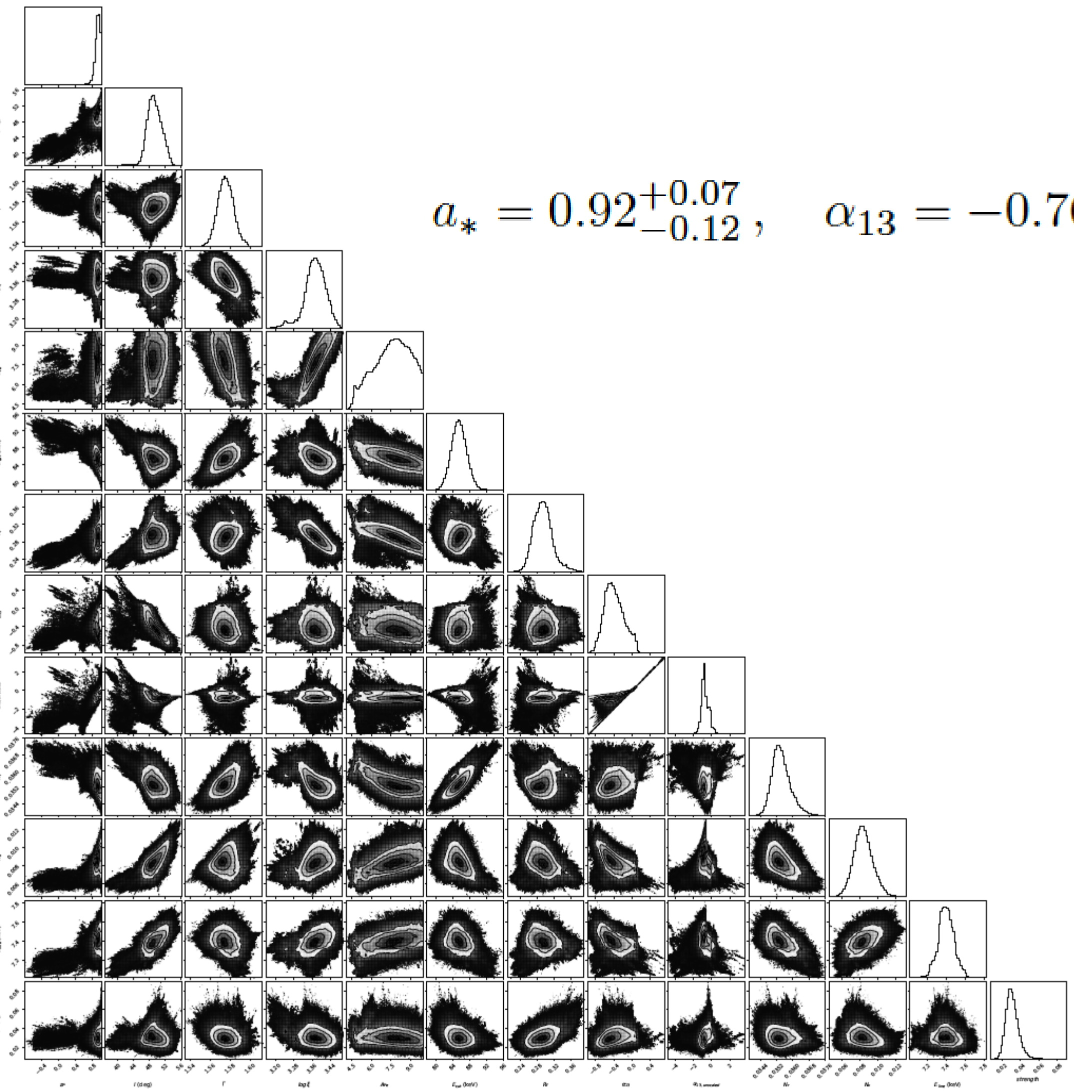
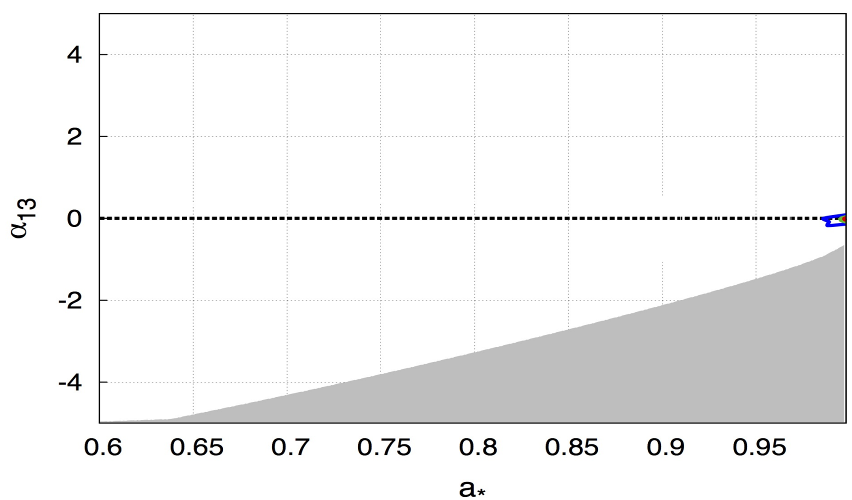


$$a_* = 0.92^{+0.07}_{-0.12}\,, \quad \alpha_{13} = -0.76^{+0.78}_{-0.60}$$

GS 1354: NuSTAR



Xu et al., ApJ 865, 134 (2018)

Conclusions

Road map

Last 3 years (2016-2018):

- **Astrophysical model (RELXILL_NK, Bambi et al. ApJ 842, 76, 2017)**
- **Preliminary observational constraints (Cao et al. PRL 120, 051101, 2018 etc. + papers under review or in preparation)**

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- **Analyzing more data**
- **Testing new gravity models**

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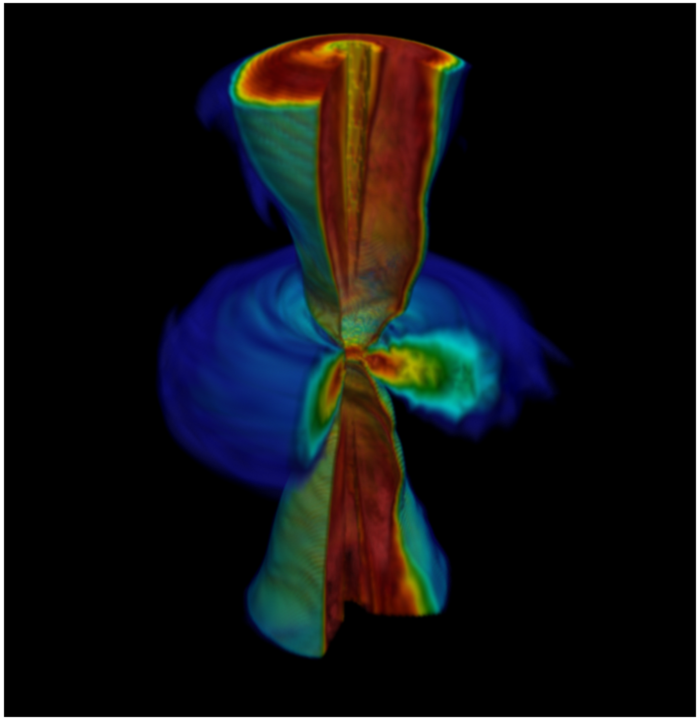

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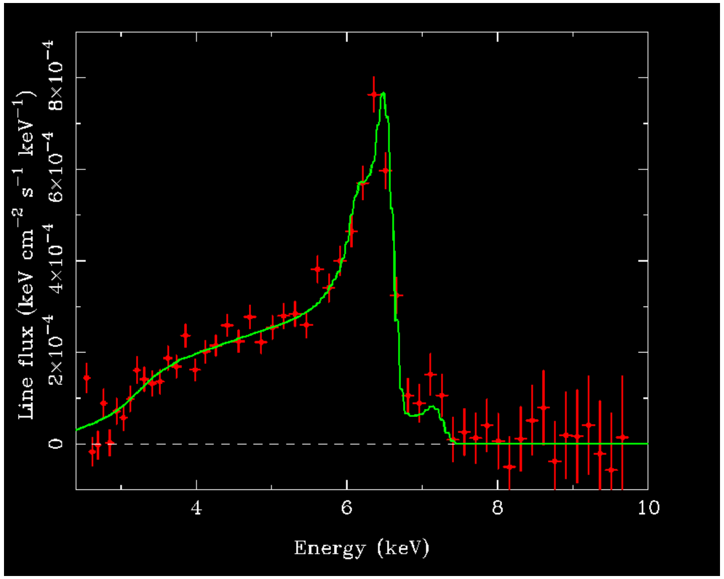

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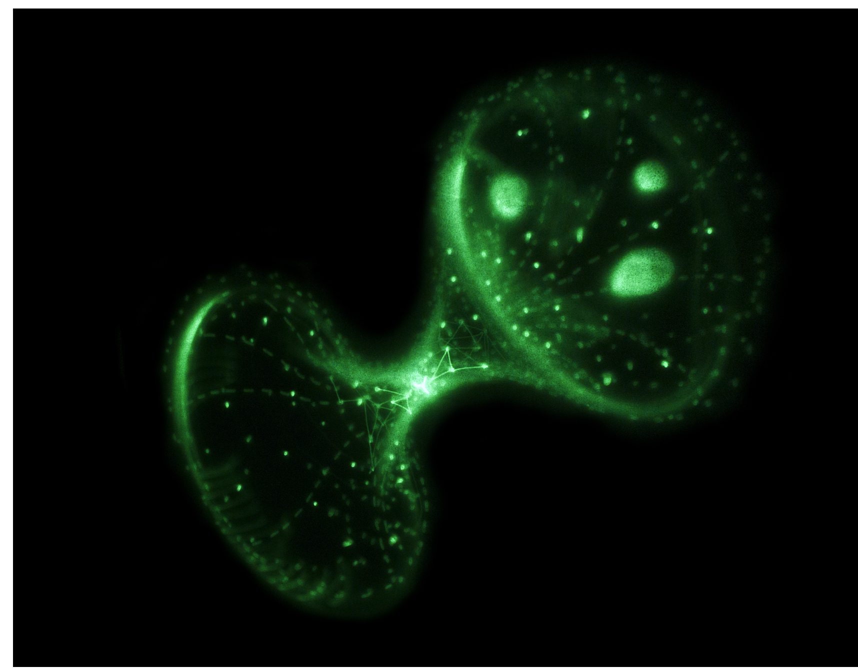

Thank you!

PhD positions at Fudan University

- **Fudan University (Shanghai, China)**

  3rd in China, 44th in the world (QS World University Ranking 2019)

- **International PhD students**

  Application deadline: November 30

  Requirements: Master degree before September 2019

  Application procedure: CV, at least 2 recommendation letters
  bambi@fudan.edu.cn

  https://hyperspace.uni-frankfurt.de/2018/10/01/phd-positions-in-astrophysics-gravity-at-fudan-university-shanghai-china/