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Testing the Kerr black hole hypothesis using X-ray reflection spectroscopy

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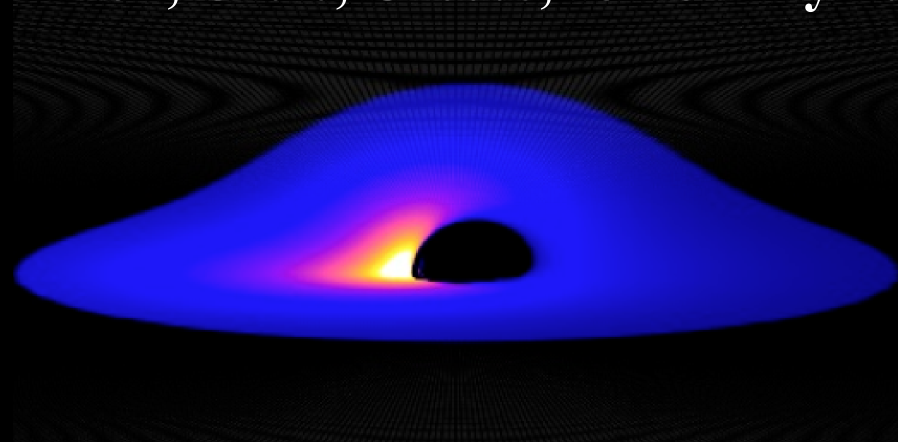
9th FERO Meeting
Heraklion, Crete, Greece, 23-25 May 2018



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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Today:

- Cosmological tests (dark matter/dark energy)
- Black holes

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Weak fields

Today:

- Cosmological tests (dark matter/dark energy)

Large scales

- Black holes

Strong fields

Black holes in Einstein's Gravity

- **Uncharged black holes in 4-dimensional Einstein's Gravity**

  → Kerr black holes

- **Only 2 parameters: the mass M and the spin J ($a_* = J/M^2$)**

- **Note: Einstein's Gravity makes very clear predictions about the motion of particles around Kerr black holes → This is what we can test**

Astrophysical black holes

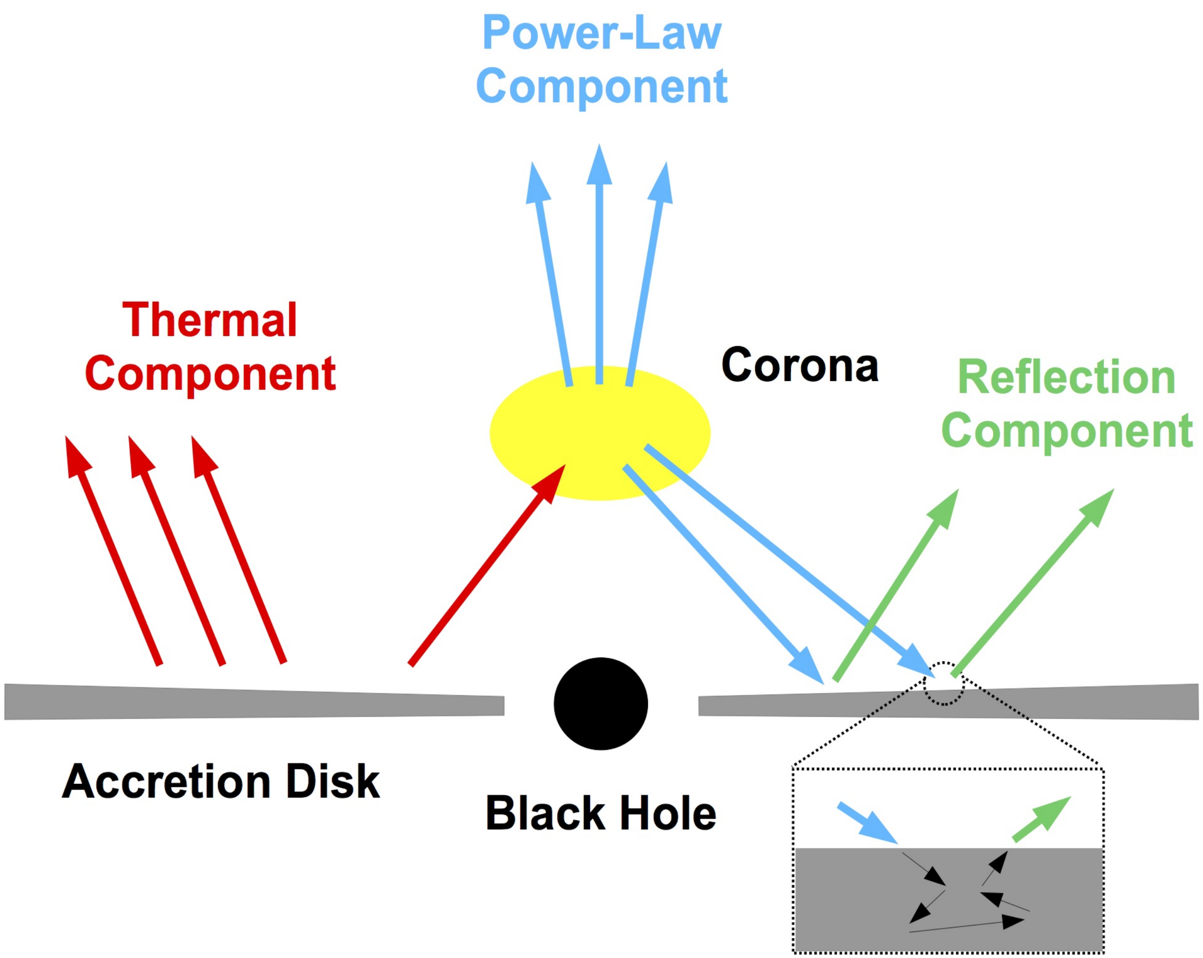
The spacetime metric around astrophysical black holes formed from gravitational collapse should be well approximated by the Kerr solution:

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

Black holes in the Universe → 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

Disk-corona model



Reflection spectrum

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

  Gravitational redshift

  Doppler boosting

  Light bending

- **We can predict the reflection spectrum at the emission point**

  → We observe the reflection spectrum far from the source

  → We can test the strong gravity region

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**

RELXILL_NK

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

  → RELXILL_NK ~ RELCOV_NK*XILLVER

- Transfer function table for non-Kerr metrics
- "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

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

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

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

$$
\Sigma = r^2 + a^2\cos^2\theta, \quad \Delta = r^2 - 2Mr + a^2,
$$

$$
f = \epsilon_3 \frac{M^3}{r}, \quad A_1 = 1 + \alpha_{13}\left(\frac{M}{r}\right)^3,
$$

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

Sources

- **1H0707-495 with XMM-Newton and NuSTAR+Swift**
- **Ark 564 with Suzaku**
- **GX339 with RXTE**

- **Cygnus X-1 with NuSTAR data (in preparation)**
- **GS1354 with NuSTAR data (in preparation)**
- **MCG-6-30-15 with XMM-Newton+NuSTAR (in preparation)**
- **...**

1H0707-495: XMM-Newton constraints

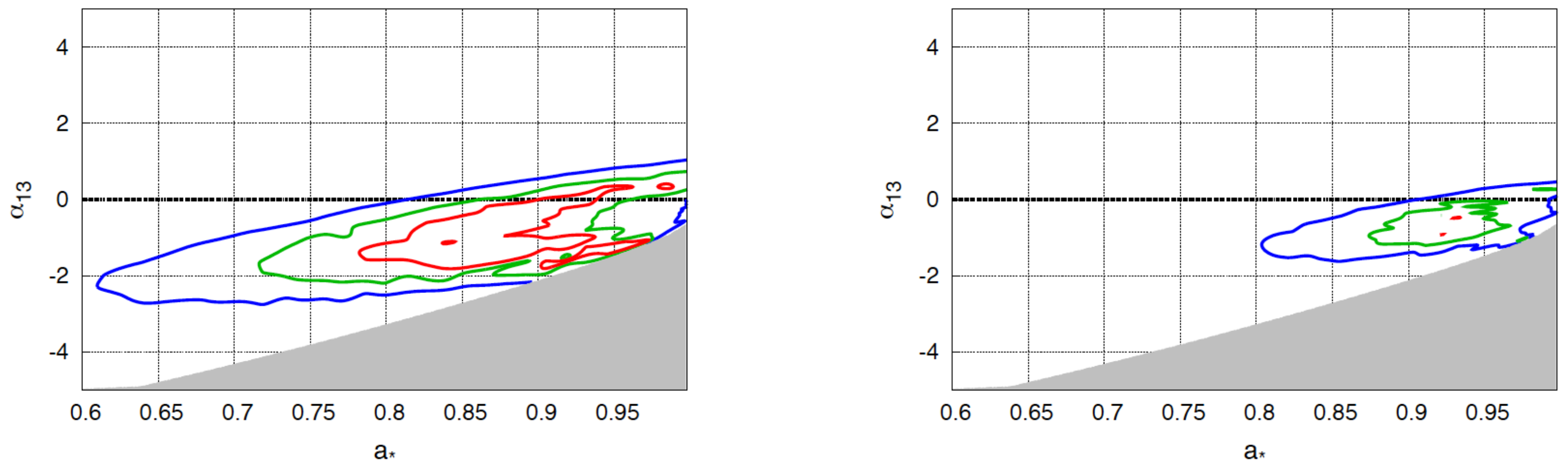


FIG. 2. Constraints on the spin parameter a_* and the Johannsen parameter α_{13} from the study in Ref. [52] of the 2011 *XMM-Newton* data of 1H0707–495 if we fit the "soft excess" around 1 keV with a thermal model (left panel) or if we employ a double reflection model (right panel). The red, green, and blue lines indicate, respectively, the 68%, 90%, and 99% confidence level curves for two relevant parameters. The grayed region is ignored because those spacetimes violate the constraint in Eq. (5). See the text and Ref. [52] for more details. Note that the constraints reported in Ref. [52] are slightly different because that study used an earlier version of RELXILL_NK, and therefore the constraints reported here should be more reliable.

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1H0707-495: NuSTAR+Swift constraints

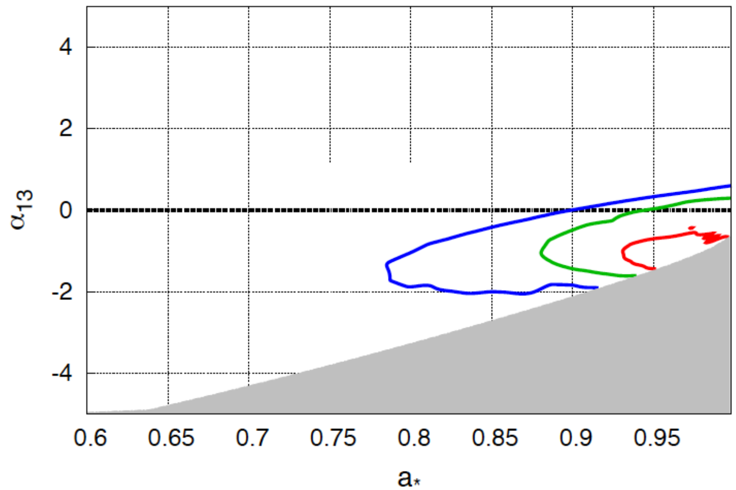

FIG. 3. Constraints on the spin parameter a_* and the Johannsen parameter α_{13} from the study in Ref. [52] of *NuSTAR* and *Swift* data of 1H0707–495. The red, green, and blue lines indicate, respectively, the 68%, 90%, and 99% confidence level curves for two relevant parameters. The grayed region is ignored because those spacetimes violate the constraint in Eq. (5). Note that the constraints reported in Ref. [52] are slightly different because that study used an earlier version of RELXILL_NK, and therefore the constraints reported here should be more reliable.

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Ark 564: Suzaku constraints

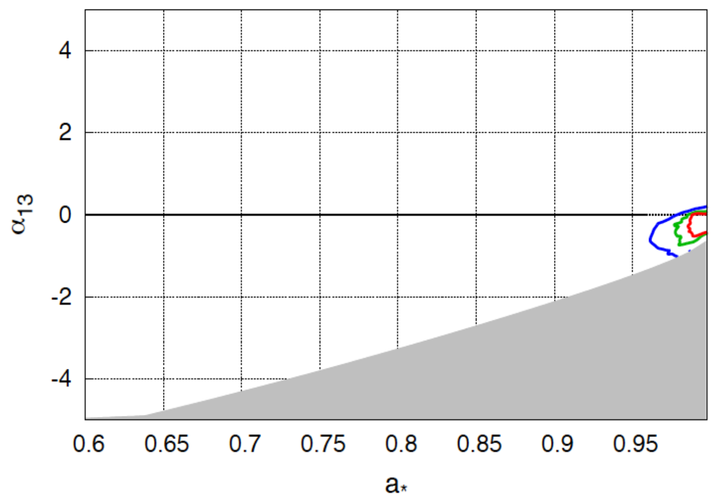

FIG. 4. Constraints on the spin parameter a_* and the Johannsen parameter α_{13} from the study in Ref. [53] of *Suzaku* data of Ark 564. The red, green, and blue lines indicate, respectively, the 68%, 90%, and 99% confidence level curves for two relevant parameters. The grayed region is ignored because those spacetimes violate the constraint in Eq. (5).

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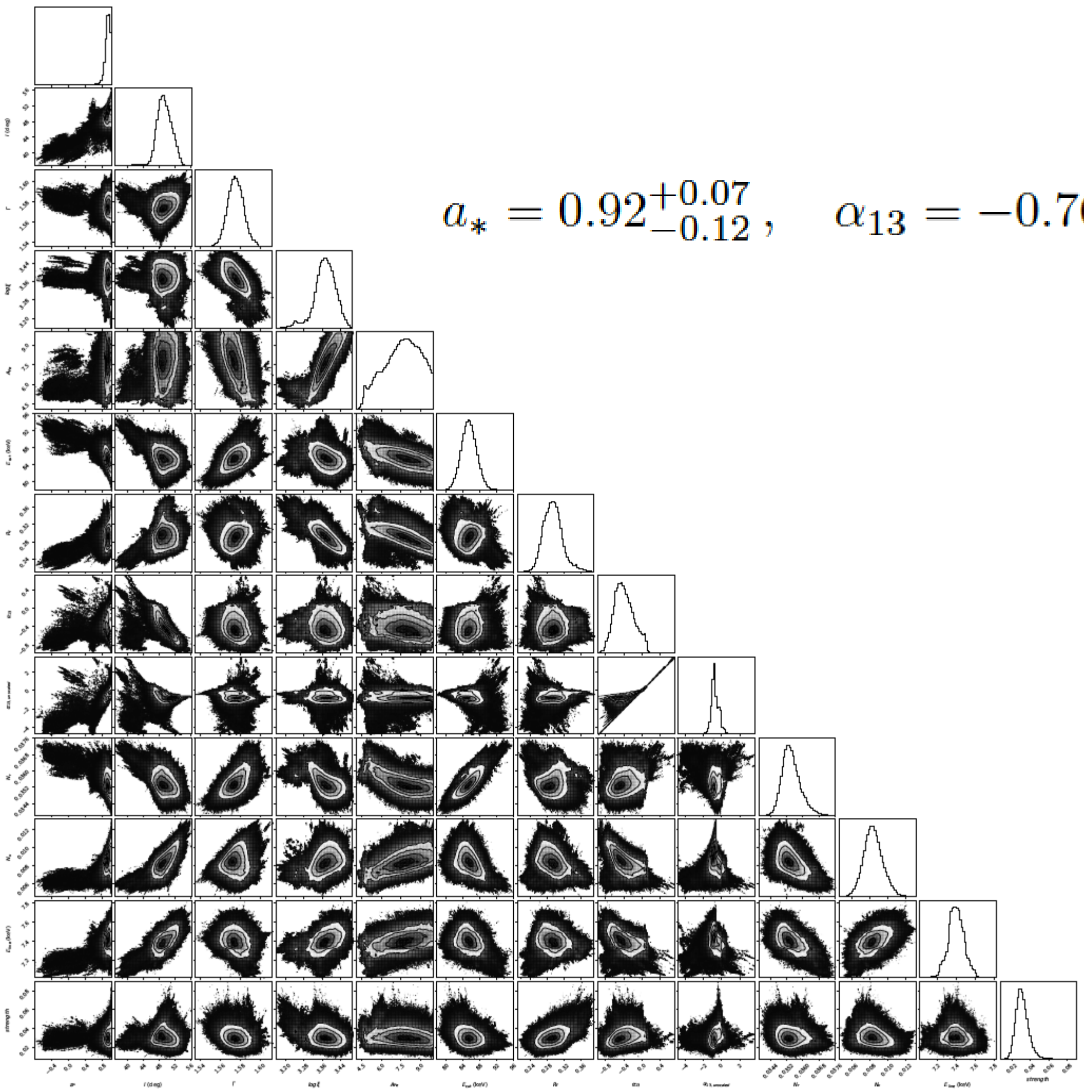
GX 339-4: RXTE constraints

Wang-Ji et al., to appear soon on arXiv



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

GX 339-4: RXTE constraints

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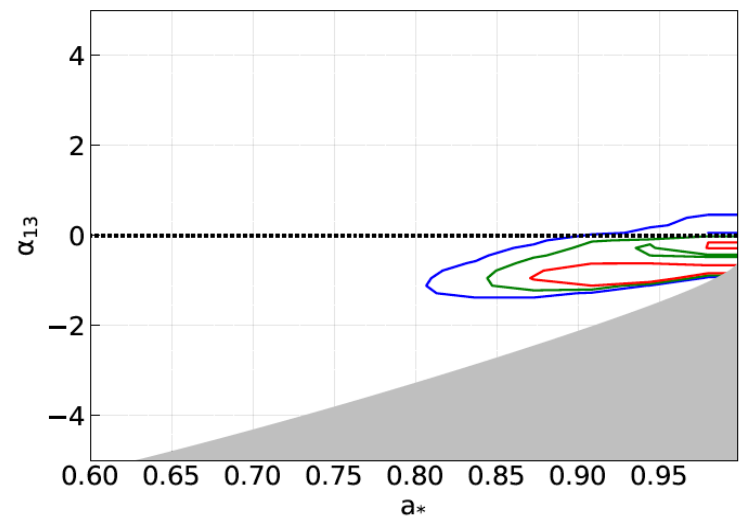

FIG. 5. Constraints on the spin parameter a_* and the Johannsen parameter α_{13} from the study in Ref. [54] of *RXTE* data of GX 339–4. The red, green, and blue lines indicate, respectively, the 1-, 2-, and 3-σ confidence level curves for two relevant parameters after MCMC simulations. The grayed region is ignored because those spacetimes violate the constraint in Eq. (5).

Road map

- **Using RELXILL_NK to analyze available X-ray data**

  Cygnus X-1, GS1354-645, NGC1365,…

- **Improving the model: lamppost model, thick disk, electron density, iron abundance, hot disks, etc.**

- **New background metrics**

Thank you!