Title: Testing General Relativity with black hole X-ray data

Speakers: Cosimo Bambi

Series: Strong Gravity

Date: February 01, 2024 - 1:00 PM

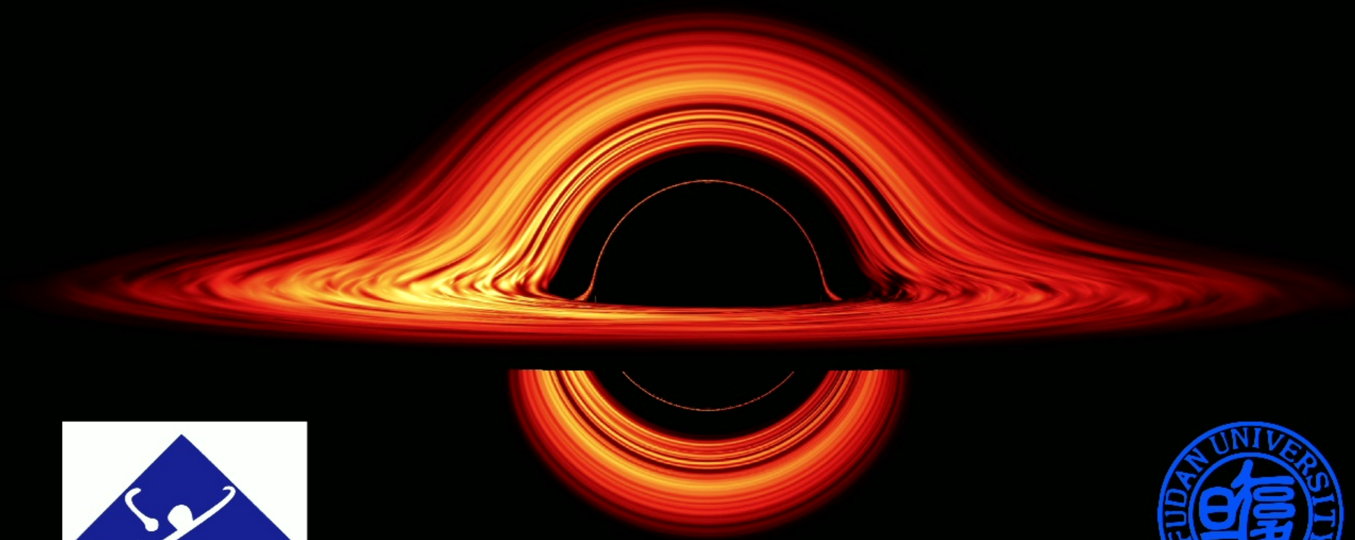
URL: https://pirsa.org/24020044

Abstract: The theory of General Relativity has successfully passed a large number of observational tests. The theory has been extensively tested in the weak-field regime with experiments in the Solar System and observations of binary pulsars. The past 7-8 years have seen significant advancements in the study of the strong-field regime, which can now be tested with gravitational waves, X-ray data, and mm Very Long Baseline Interferometry observations. In my talk, I will summarize the state-of-the-art of the tests of General Relativity with black hole X-ray data, discussing its recent progress and future developments.

Zoom link

Testing General Relativity with Black Hole X-ray Data

Cosimo Bambi
Fudan University



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Perimeter Institute (1 February 2024)

Motivations

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Tests of General Relativity

- 1915 → General Relativity (Einstein)

- 1919 → Deflection of light by the Sun (Eddington)
- 1960s → Solar System experiments
- 1970s → Binary pulsars

- 2000s → Cosmological tests

Tests in weak gravitational fields

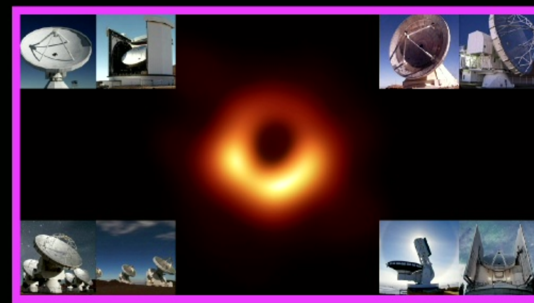
Tests on large scales

Tests of General Relativity

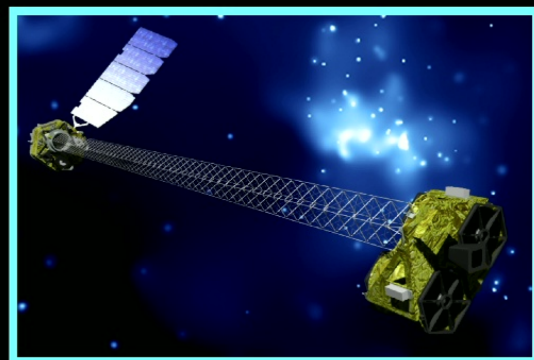
- 2010s → Black holes, neutron stars

Tests in strong gravitational fields

GW Data



VLBI Data



X-ray Data

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Black Holes

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Black Holes in General Relativity

- No-Hair Theorem: in 4D General Relativity, black holes are fully characterized by a small number of parameters: M, J, Q
- Uniqueness Theorem: in 4D General Relativity, black holes are only described by the Kerr-Newman solution
- Uncharged black holes are described by the Kerr solution

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Astrophysical Black Holes

It is remarkable that the spacetime metric around astrophysical black holes formed from gravitational collapse of stars/clouds should be approximated well by the "ideal" Kerr metric

- Initial deviations → Quickly radiated away by GWs
- Accretion disk, nearby stars → Negligible
- Electric charge → Negligible

Beyond General Relativity

- Modified theories of gravity:
  - Einstein-dilaton-Gauss-Bonnet gravity
  - Chern-Simons gravity
  - Lorentz-violating theories
  - ...

- Macroscopic quantum gravity effects (information paradox):
  - Mathur (Fuzzballs)
  - Dvali & Gomez
  - Giddings
  - ...

- Presence of exotic matter:
  - Hairy black holes (Herdeiro & Radu)
  - ...

Disk-Corona Model

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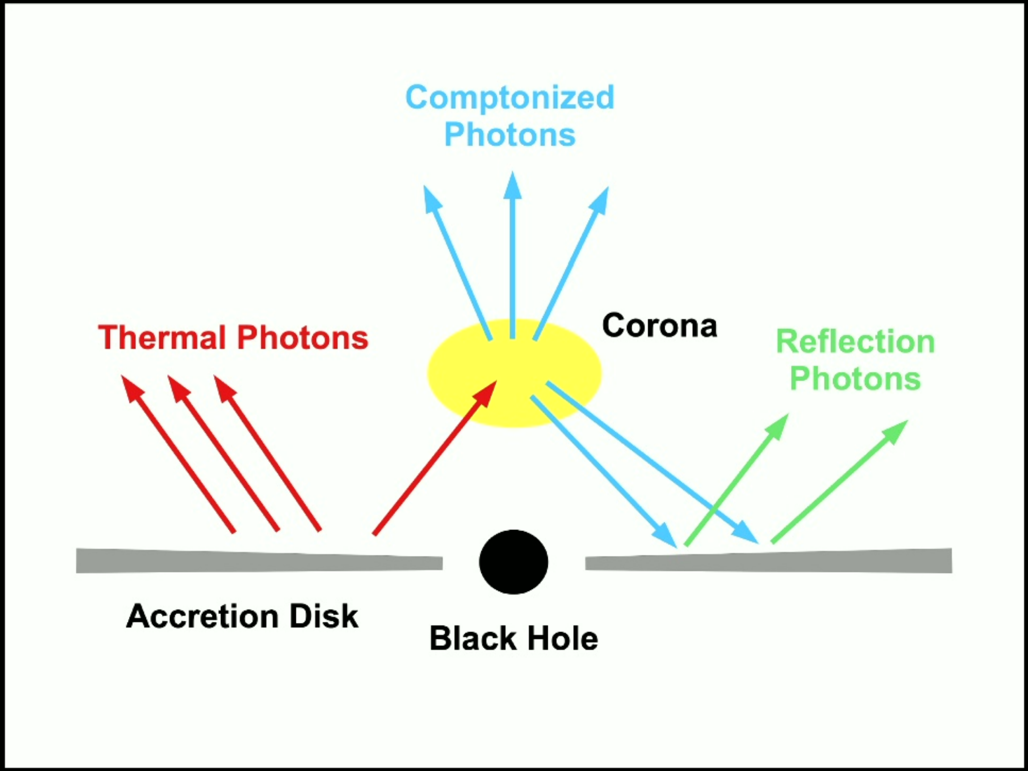
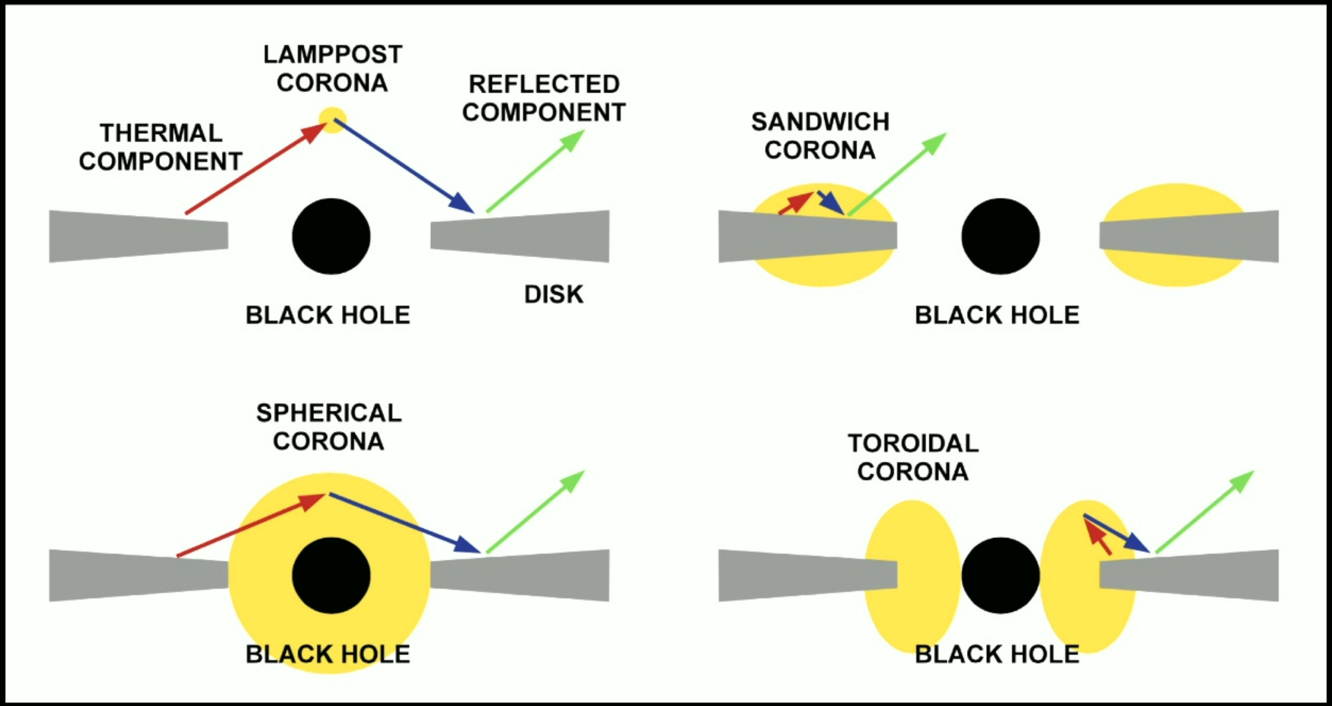
Disk-Corona Model



Coronal Geometries



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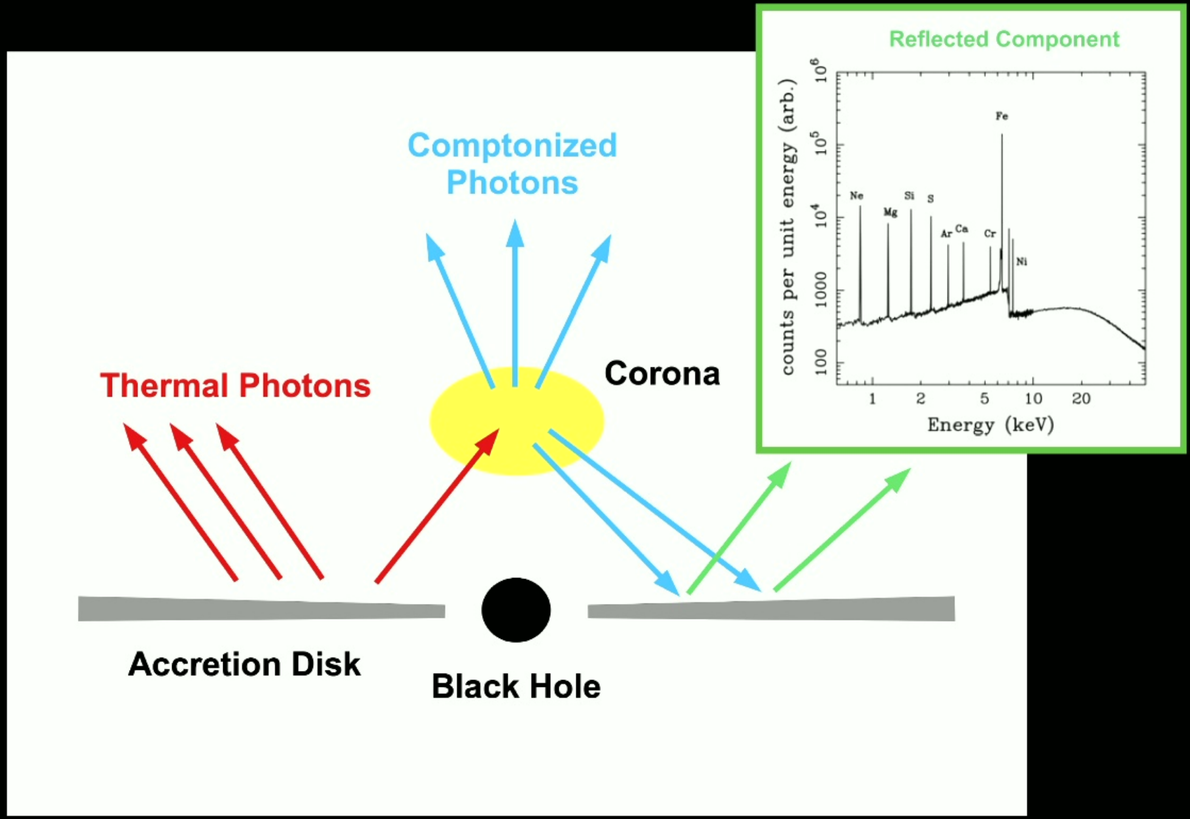
Disk-Corona Model



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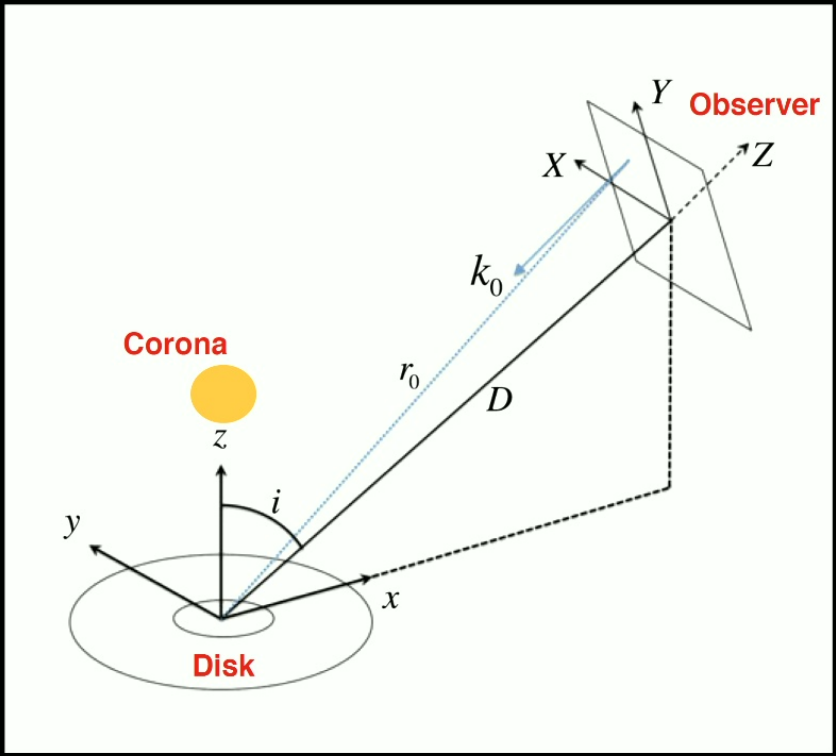
Synthetic Spectra



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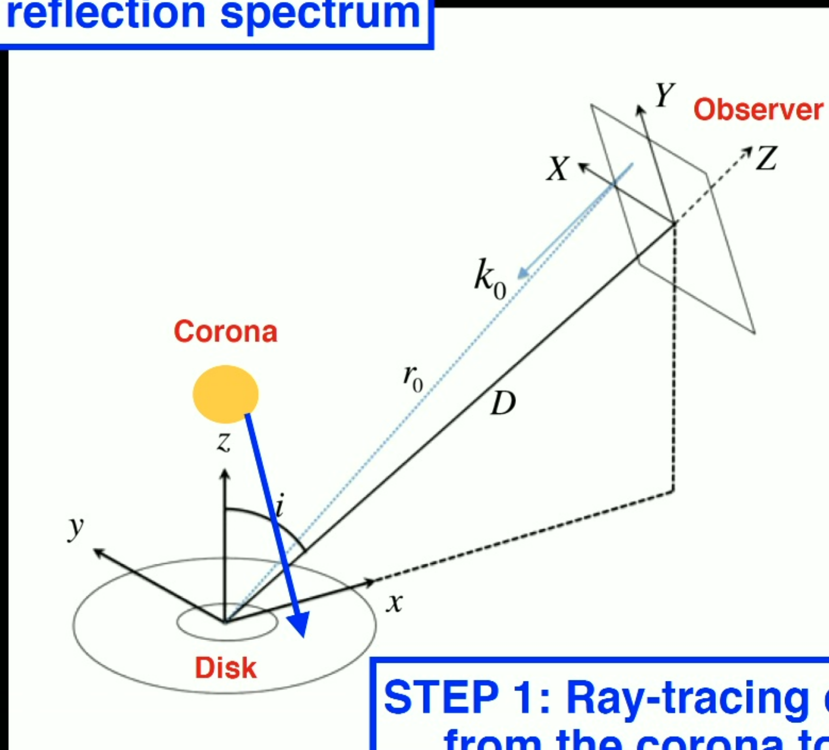
Synthetic Spectra

For reflection spectrum



STEP 1: Ray-tracing calculations from the corona to the disk

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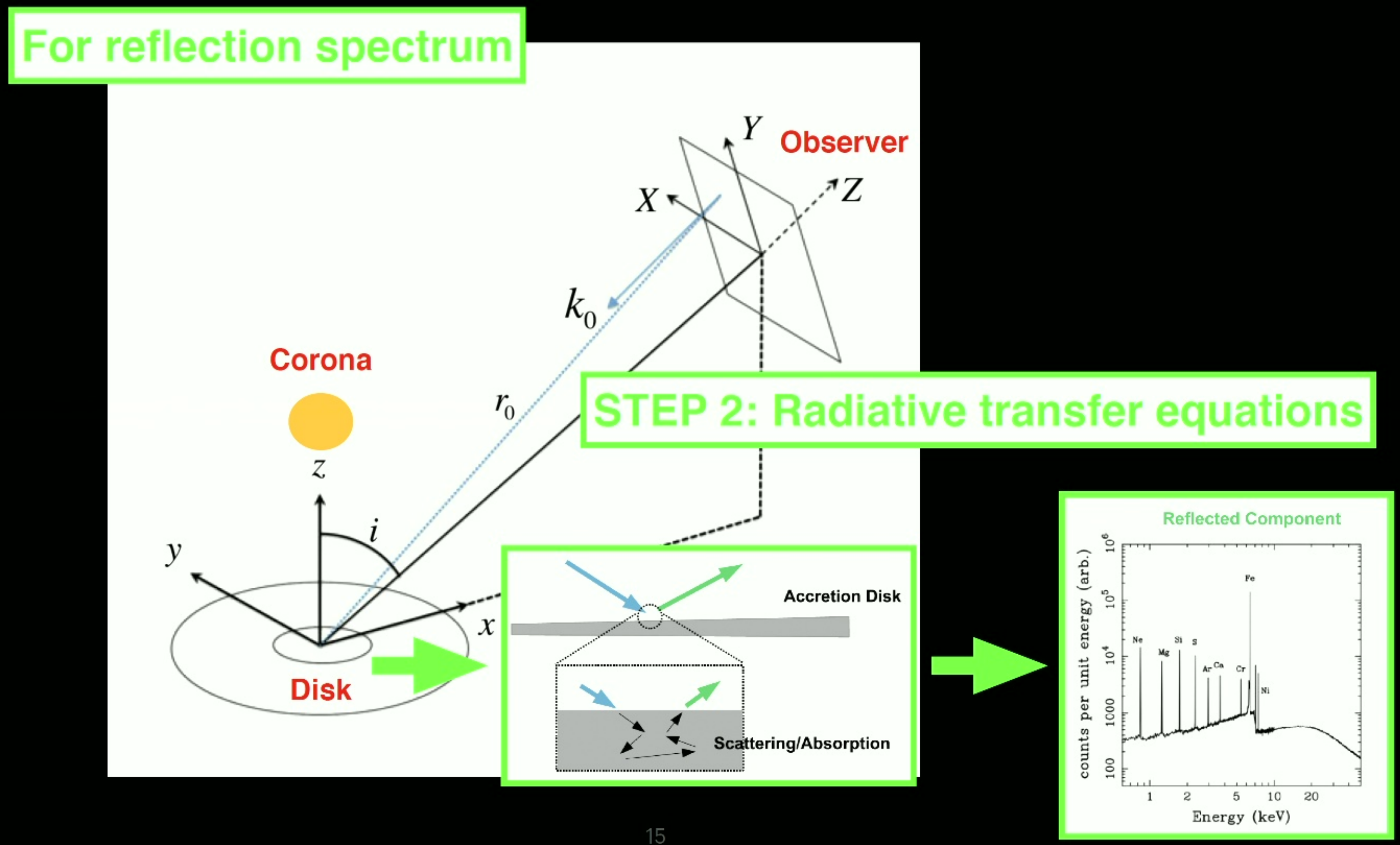
Synthetic Spectra



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Synthetic Spectra

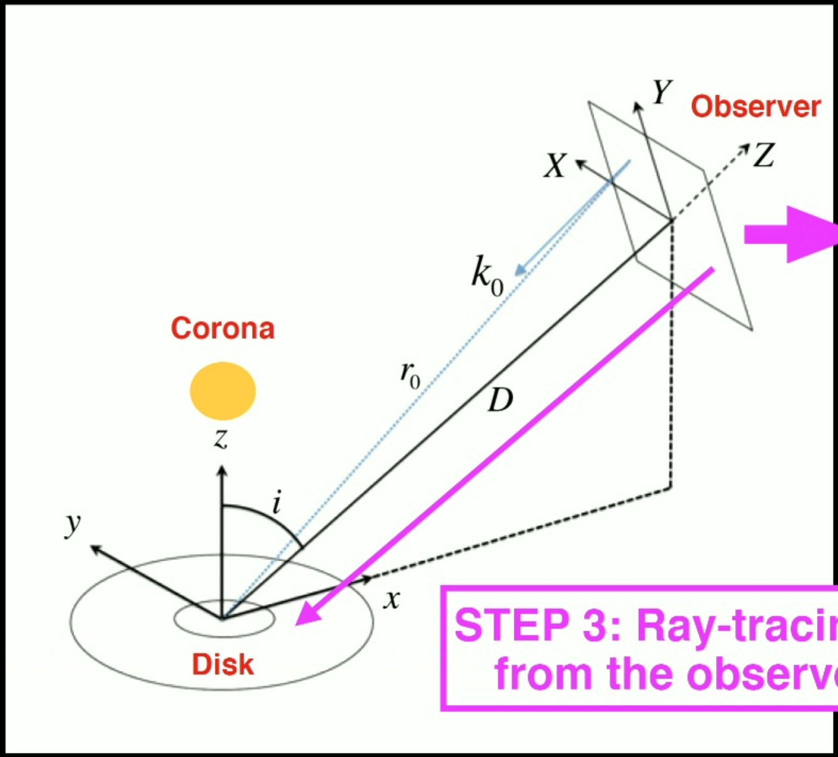
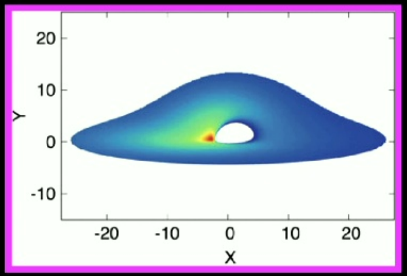


Image of the accretion disk



Every point on the image is characterized by its redshift factor *g*

STEP 3: Ray-tracing calculations from the observer to the disk

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Synthetic Spectra

- Photon motion (from the corona to the disk)
- Particle motion on the disk
- Radiative transfer equations (atomic physics, fundamental constants)
- Photon motion (from the observer to the disk)
- Particle motion on the disk

- Accretion disk model
- Corona model

Testing Black Holes with X-ray Data

Synthetic Spectra

- Photon motion (from the observer to the disk)
- Particle motion on the disk
- Radiative transfer equations (atomic physics, fundamental constants)
- Photon motion (from the observer to the disk)
- Particle motion on the disk

- Accretion disk model
- Corona model

We can test the Kerr metric

We can test the geodesic motion

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Synthetic Spectra

- Photon motion (from the observer to the disk)
- Particle motion on the disk
- Radiative transfer equations (atomic physics, fundamental constants)
- Photon motion (from the observer to the disk)
- Particle motion on the disk

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We can test atomic physics and the values of fundamental constants in strong gravitational fields

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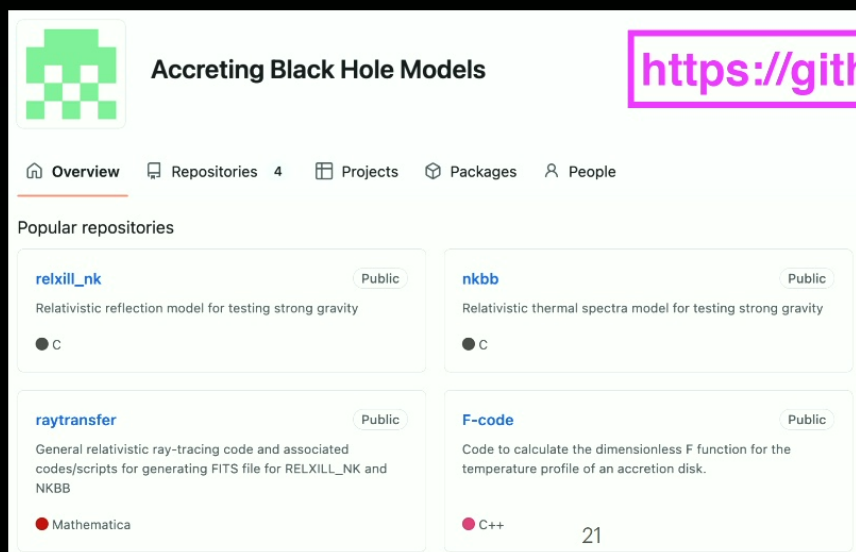
XSPEC Models

- `relxill_nk` (Bambi et al. 2017; Abdikamalov et al. 2019)

  Reflection spectrum for thin accretion disks in stationary, axisymmetric, and asymptotically-flat spacetimes

- `nkbb` (Zhou et al. 2019)

  Thermal spectrum for thin accretion disks in stationary, axisymmetric, and asymptotically-flat spacetimes



https://github.com/ABHModels

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Strategies

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Strategies

- Top-down approach: we test a specific alternative theory of gravity against Einstein's theory of General Relativity. Problems:
  - There are many theories of gravity...
  - Usually we do not know their rotating black hole solutions...

- Bottom-up approach: we parametrize possible deviations from General Relativity with a number of phenomenological "deformation parameters"

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Example: PPN Formalism

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

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

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

- In General Relativity (Schwarzschild metric): $\beta = \gamma = 1$

Example: Johannsen Metric

- Several parametric black hole spacetimes proposed in the literature
- Johannsen metric (Johannsen 2013):

$$
\begin{aligned}
ds^2 &= -\frac{\tilde{\Sigma}\left(\Delta - a^2 A_2^2 \sin^2\theta\right)}{B^2} dt^2 + \frac{\tilde{\Sigma}}{\Delta A_5} dr^2 + \tilde{\Sigma} d\theta^2 \\
&\quad - \frac{2a\left[(r^2+a^2) A_1 A_2 - \Delta\right] \tilde{\Sigma} \sin^2\theta}{B^2} dt d\phi \\
&\quad + \frac{\left[(r^2+a^2)^2 A_1^2 - a^2 \Delta \sin^2\theta\right] \tilde{\Sigma} \sin^2\theta}{B^2} d\phi^2 , \\
\tilde{\Sigma} &= r^2 + a^2 \cos^2\theta , \quad \Delta = r^2 - 2Mr + a^2 , \\
B &= \left(r^2 + a^2\right) A_1 - a^2 A_2 \sin^2\theta \\
f &= \sum_{n=3}^{\infty} \epsilon_n \frac{M^n}{r^{n-2}} , \quad A_1 = 1 + \sum_{n=3}^{\infty} \alpha_{1n} \left(\frac{M}{r}\right)^n , \\
A_2 &= 1 + \sum_{n=2}^{\infty} \alpha_{2n} \left(\frac{M}{r}\right)^n , \quad A_5 = 1 + \sum_{n=2}^{\infty} \alpha_{5n} \left(\frac{M}{r}\right)^n
\end{aligned}
$$

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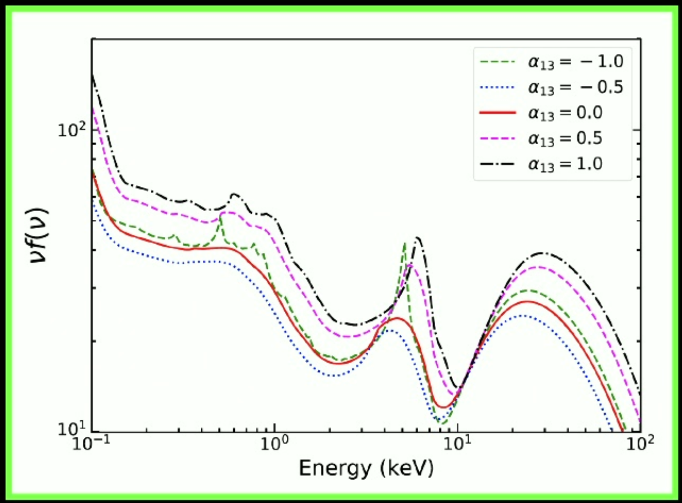
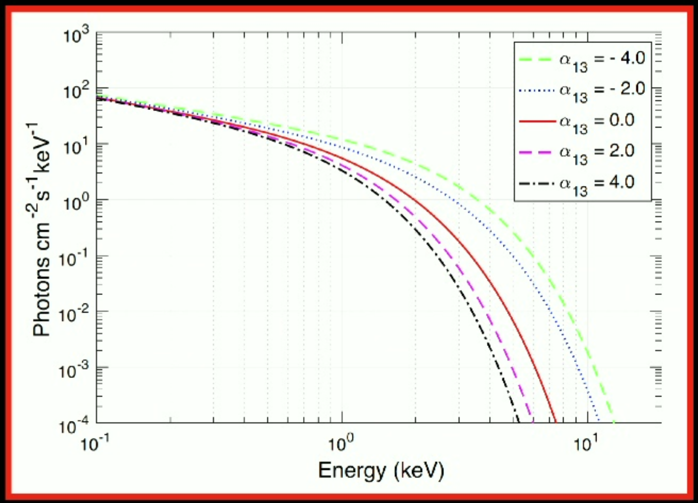
Example: Johannsen Metric





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Results:
Agnostic Tests

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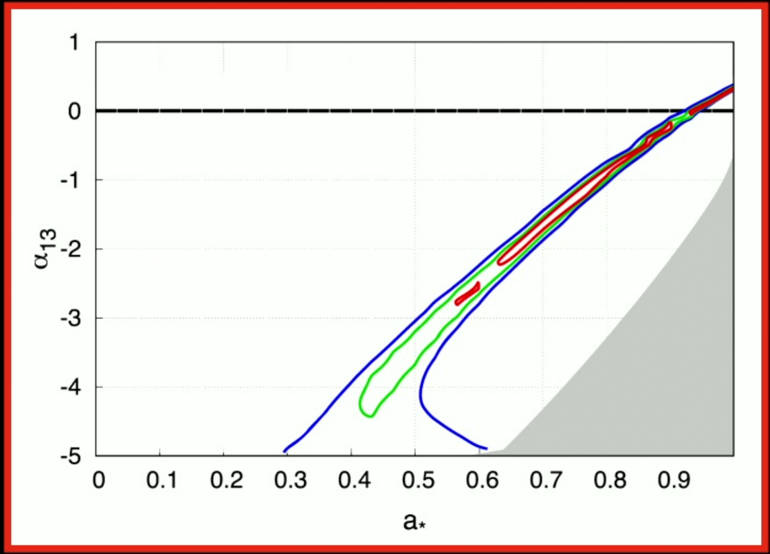
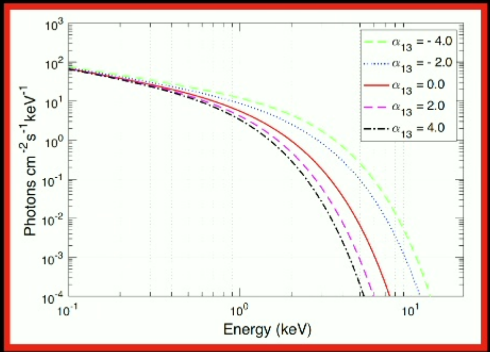
Analysis of Thermal Spectra

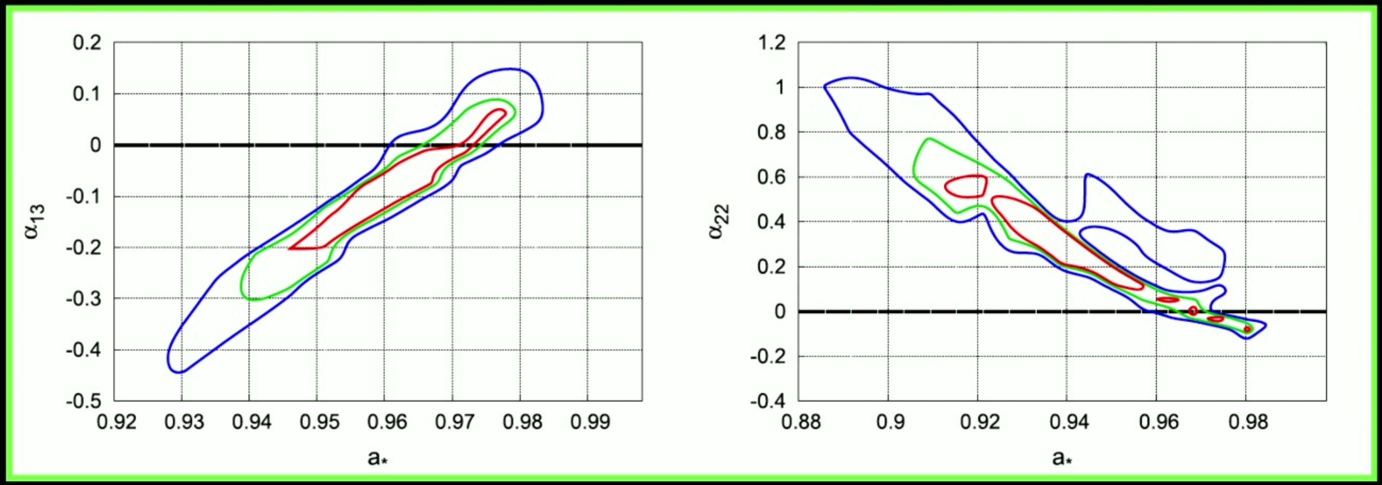
- LMC X-1 (Tripathi et al. 2020), RXTE



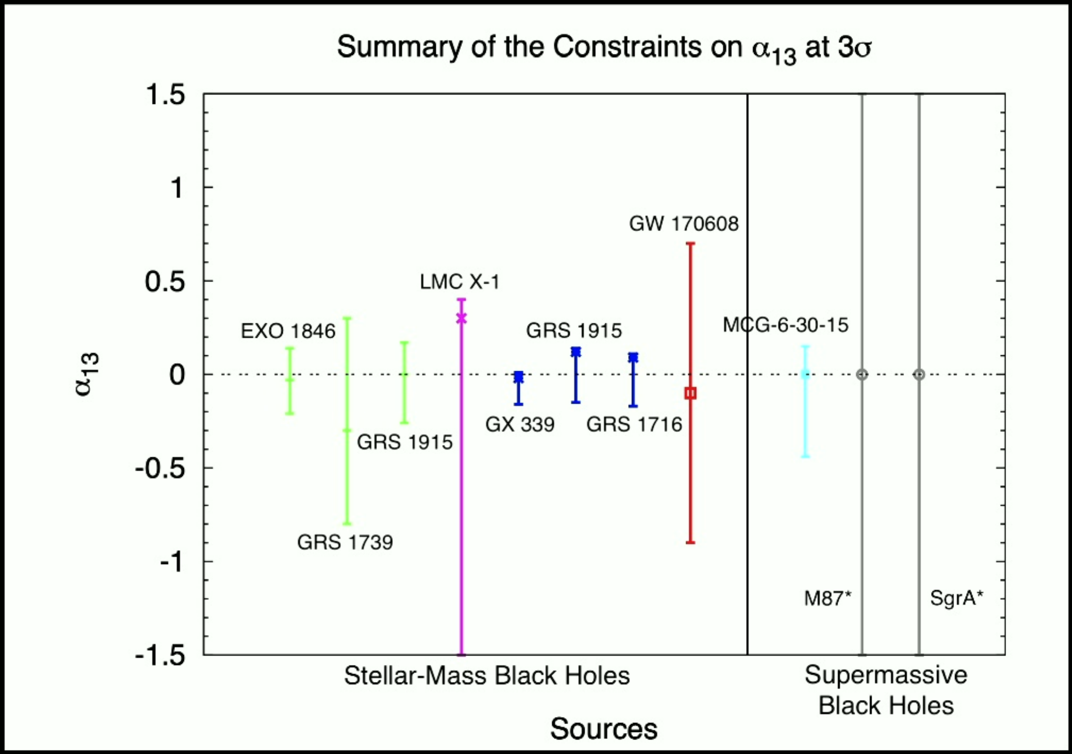


Analysis of Reflection Features

- MCG-6-30-15 (Tripathi et al. 2019), XMM+NuSTAR



Summary: X-ray, GWs, VLBI



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Results:
Tests of Specific Gravity Models

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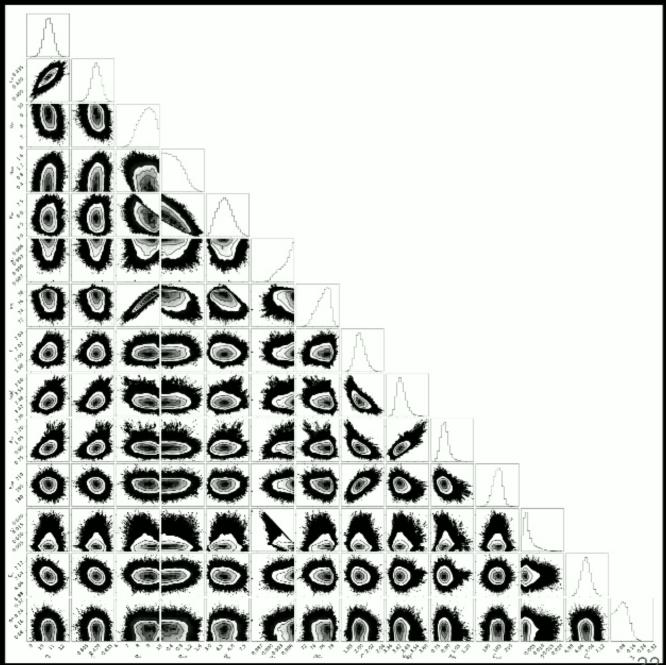
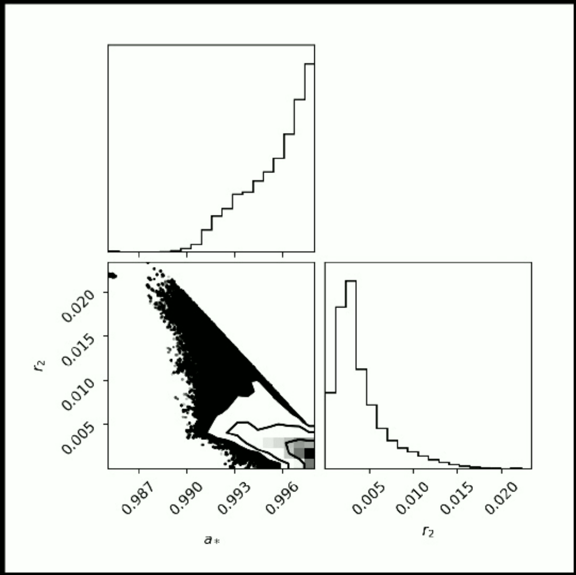
Einstein-Maxwell-Dilaton-Axion Gravity

- Tripathi et al. 2021
- EXO 1846-031 (NuSTAR)
- Constraint: $r_2 < 0.011$ (90% CL)





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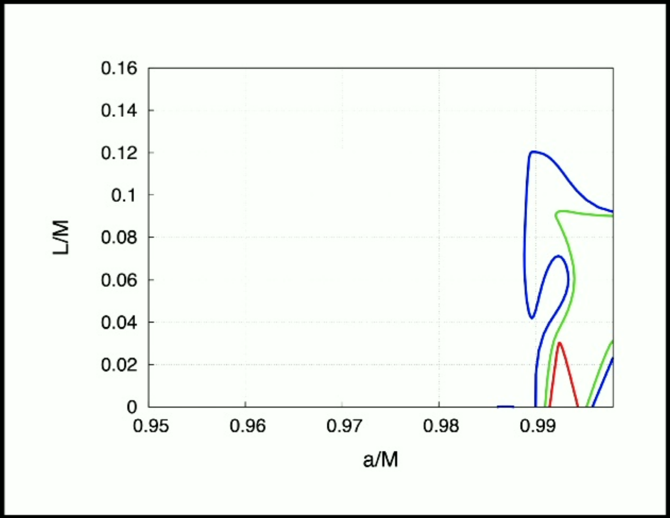
Conformal Gravity

- Zhou et al. 2018, 2019
- GS 1354-645 (NuSTAR)
- Constraint: L/M < 0.12 (99% CL)



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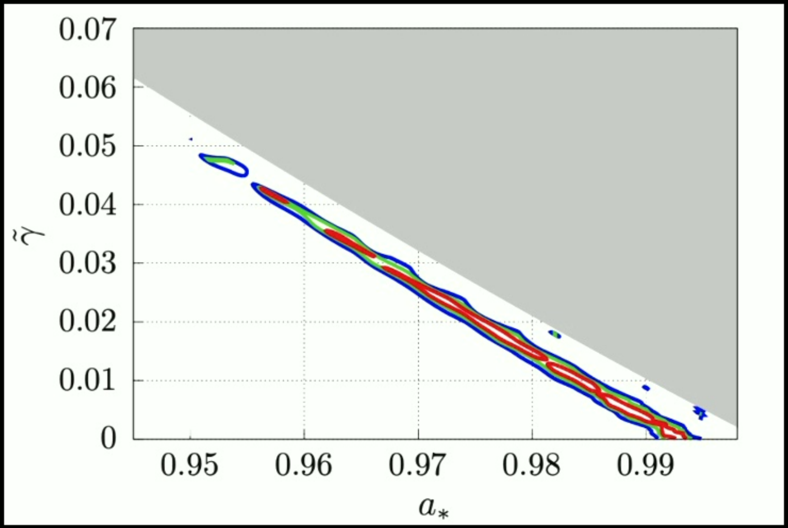
Asymptotically Safe Quantum Gravity

- Zhou et al. 2021
- GRS 1915+105 (Suzaku)
- Constraint: $\gamma < 0.047$ (90% CL)



Accuracy of GR Tests with X-ray Data

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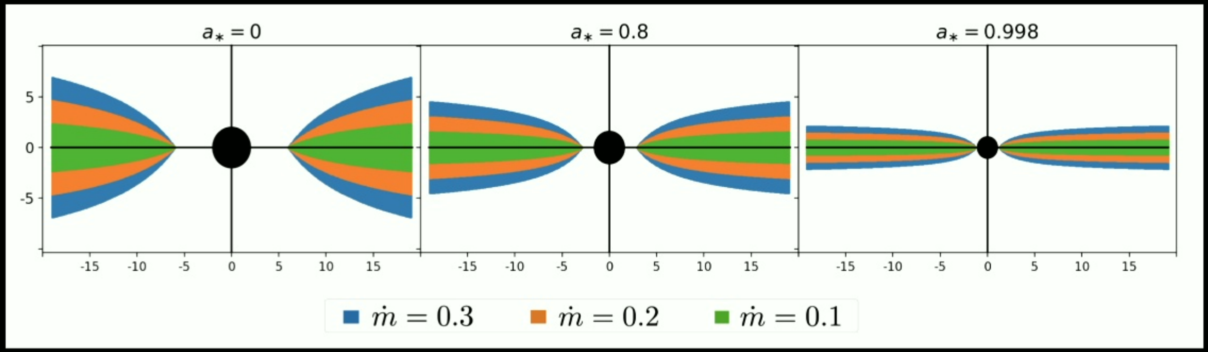
Are Current XRS Measurements of Black Holes Accurate?

Quick (and personal) answer: yes, but only if we select the right sources and observations

- High spin ($a > 0.9$)
- Compact corona close to the black hole
- Prominent and broadened iron line
- $L \sim 0.05$-$0.30\ L_{Edd}$
- High resolution at the iron line + hard X-ray band

Thickness of the Disk

- Thin disks of finite thickness
- Abdikamalov et al. 2020 (model, GRS 1915+105)
- Tripathi et al. 2021 (MCG-6-30-15, EXO 1846-031)
- Jiang et al. 2022 (lamppost corona, MCG-6-30-15)



Conclusion: no significant impact on the parameter estimate for disks with high radiative efficiency

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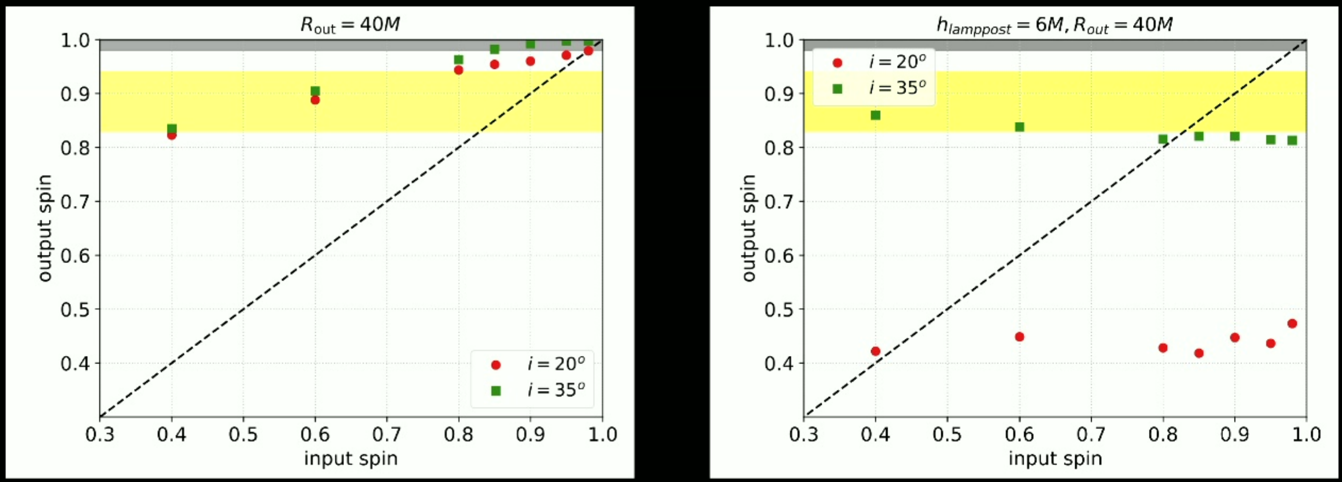
Thickness of the Disk

- Thick disks
- Riaz et al. 2020a, 2020b



Conclusion: large systematic uncertainties, wrong measurements

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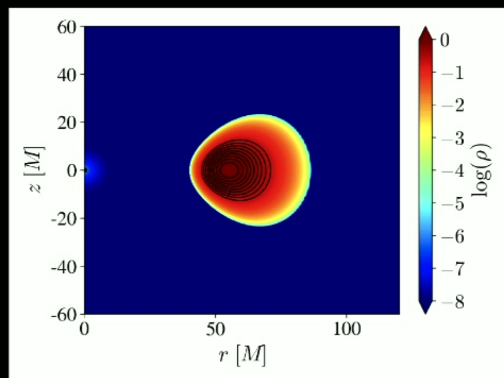
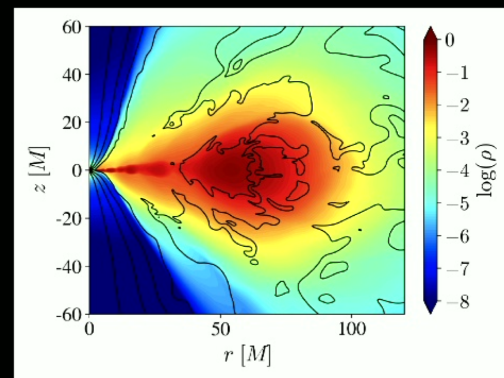
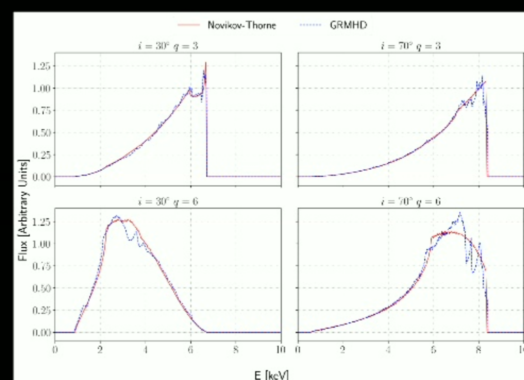
GRMHD-Simulated Thin Disks

- Shashank et al. 2022







Conclusion: we recover well the input parameters

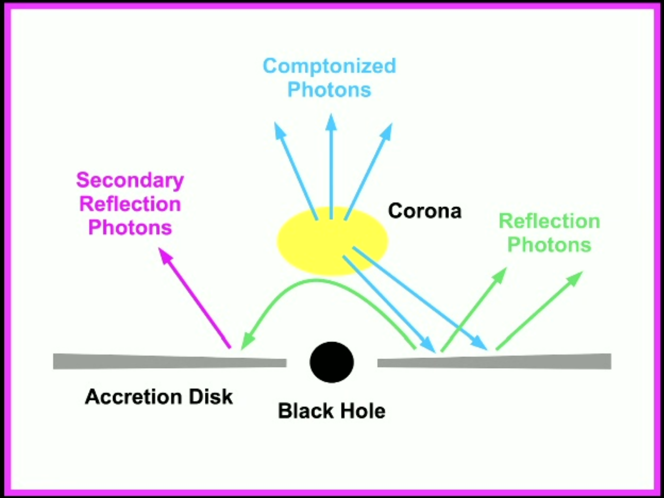
Plunging Region

- Plunging region is optically thin:
  - Higher order disk images (Zhou et al. 2020)
- Plunging region is optically thick:
  - Reflection spectrum from the plunging region (Cardenas-Avendano et al. 202)

Conclusion: no significant impact on the parameter estimate, especially for fast-rotating black holes

Returning Radiation

- Mirzaev et al. 2024



Conclusion: we can have large systematic uncertainties when:
1) The black hole spin is high
2) The corona is compact and close to the black hole
3) The ionization parameter is not high

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Concluding Remarks

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Past/Present Work

- Models: `relxill_nk`, `nkbb`
- Public on GitHub: https://github.com/ABHModels
- Agnostic tests
- Tests on specific theories of gravity

Future Work

- More sophisticate astrophysical model (necessary to analyze the data of the next generation of X-ray missions)

- Tests of atomic physics and values of fundamental constants in the strong gravitational fields of black holes