Testing General Relativity with Black Hole X-ray Data

A Progress Report

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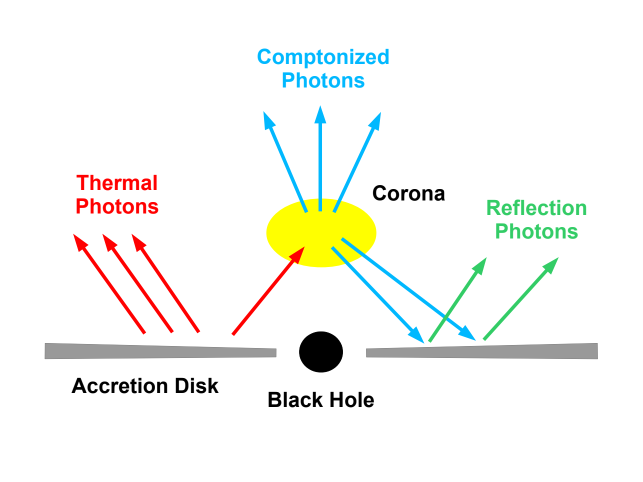
Supermassive Black Hole
and Fundamental Physics
ITP-CAS, Beijing (26 September 2021)

Outline

1. Testing Black Holes with X-ray Data
2. Results
3. Conclusions

Testing Black Holes with X-ray Data

Disk-Corona Model



Our Models

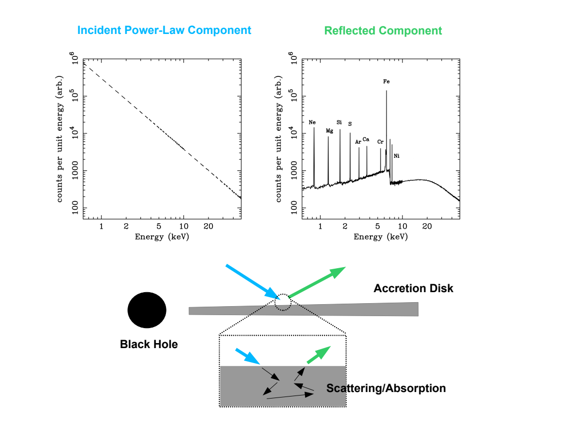
- RELXILL_NK (Bambi et al. 2017; Abdikamalov et al. 2019)
  Reflection spectrum of a thin accretion disk

- NKBB (Zhou et al. 2019)
  Thermal spectrum of a thin accretion disk

Assumptions:

- **Kerr spacetime**
- Geodesic motion (Weak Equivalence Principle)
- Atomic physics as in our laboratories on Earth
  (Local Lorentz Invariance and Local Position Invariance)

Reflection spectrum



How Can We Test the Kerr Metric?

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

- **Bottom-up approach:** parametric black hole spacetimes in which deviations from the Kerr geometry are quantified by a number of "deformation parameters"

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

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

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

In the General Relativity (Schwarzschild metric), $\beta = \gamma = 1$

There are several parametrized black hole spacetimes in the literature. Johannsen metric[1]:

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

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

The functions f, A_1, A_2, and A_5 are defined as

$$
\begin{aligned}
f &= \sum_{n=3}^{\infty} \epsilon_n \frac{M^n}{r^{n-2}} \, , \quad A_1 = 1 + \sum_{n=3}^{\infty} \alpha_{1n} \left(\frac{M}{r} \right)^n \, , \\
A_2 &= 1 + \sum_{n=2}^{\infty} \alpha_{2n} \left(\frac{M}{r} \right)^n \, , \quad A_5 = 1 + \sum_{n=2}^{\infty} \alpha_{5n} \left(\frac{M}{r} \right)^n
\end{aligned}
$$

There are 4 infinite sets of “deformation parameters”:

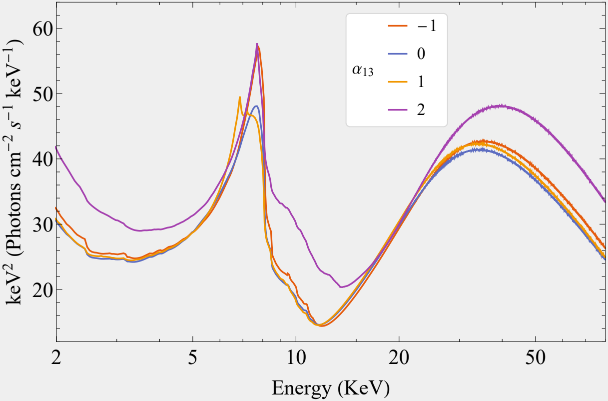
$$
\{\epsilon_n\} \, , \quad \{\alpha_{1n}\} \, , \quad \{\alpha_{2n}\} \, , \quad \{\alpha_{5n}\}
$$

If all deformation parameters vanish, we recover the Kerr solution

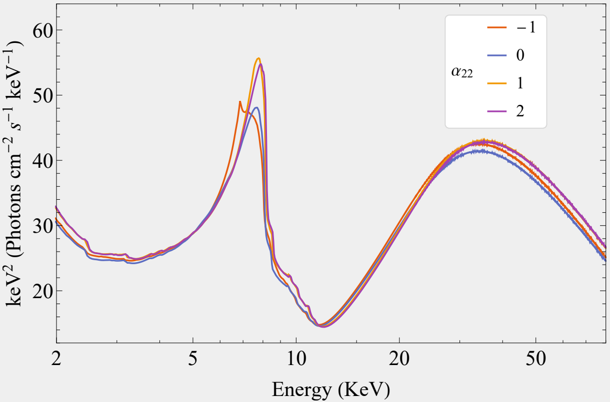
A public version of RELXILL_NK and its manual can be found at:

Johannsen metric with the deformation parameters α_{13} and α_{22}

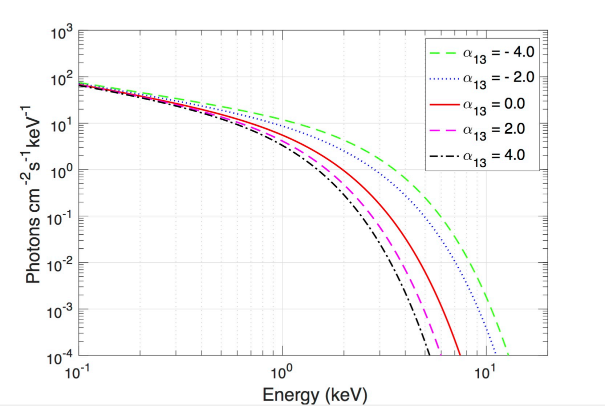
Impact of the deformation parameter α_{13}



Impact of the deformation parameter α_{22}



Impact of the deformation parameter α_{13}



Results

Sources Analyzed (BHBs)

Sources analyzed with RELXILL_NK and NKBB

- **4U 1630–472**: Tripathi et al., ApJ 913, 79 (2021)
- **Cygnus X-1**; Liu et al., PRD 99, 123007 (2019); Zhang et al., PRD 103, 024055 (2021)
- **EXO 1846–031**: Tripathi et al., ApJ 913, 79 (2021)
- **GRS 1716–249**: Zhang et al., arXiv:2106.03086
- **GRS 1739–278**: Tripathi et al., ApJ 913, 79 (2021)
- **GRS 1915+105**; Zhang et al., ApJ 875, 41 (2019); ApJ 884, 147 (2019); Tripathi et al., arXiv:2106.10982
- **GS 1354–645**: Xu et al., ApJ 865, 134 (2018)
- **GX 339–4**: Wang et al., JCAP 05 (2020) 026; Tripathi et al., ApJ 907, 31 (2021)
- **LMC X-1**: Tripathi et al., ApJ 897, 84 (2020)
- **Swift J1658–4242**: Tripathi et al., ApJ 913, 79 (2021)

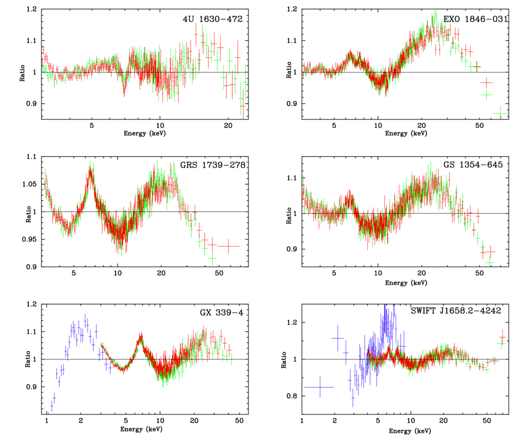
Sources Analyzed (AGN)

Sources analyzed with RELXILL_NK

- **1H0419–577**: Tripathi et al., ApJ 874, 135 (2019)
- **1H0707–495**: Cao et al., PRL 120, 051101 (2018)
- **Ark 120**: Tripathi et al., ApJ 874, 135 (2019)
- **Ark 564**: Tripathi et al., PRD 98, 023018 (2018)
- **Fairall 9**: Liu et al., ApJ 896, 160 (2020)
- **MCG–6–30–15**: Tripathi et al., ApJ 875, 56 (2019)
- **Mrk 335**: Choudhury et al., ApJ 879, 80 (2019)
- **PKS 0558–504**: Tripathi et al., PRD 98, 023018 (2018)
- **Swift J0501.9–3239**: Tripathi et al., PRD 98, 023018 (2018)
- **Ton S180**: Tripathi et al., PRD 98, 023018 (2018)

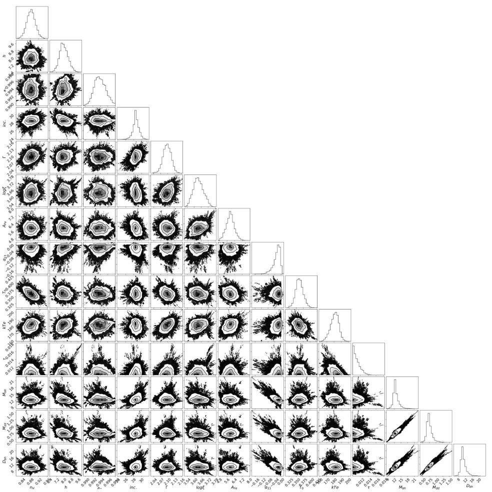
TESTS WITH BHBS WITH *NUSTAR* DATA

- Tripathi et al. ApJ 907, 31 (2021)
- Tripathi et al. ApJ 913, 79 (2021)



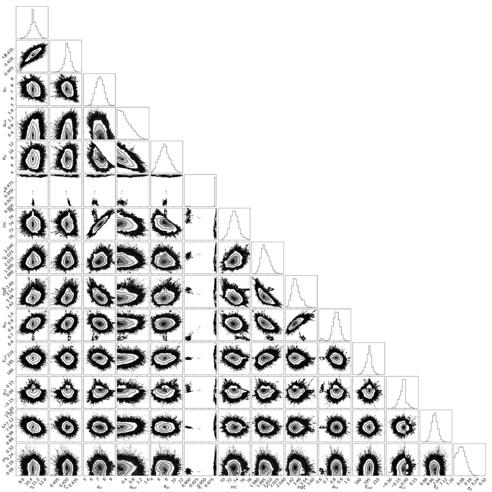
GX 339−4

Results of MCMC analysis (RELXILL_NK + NKBB)

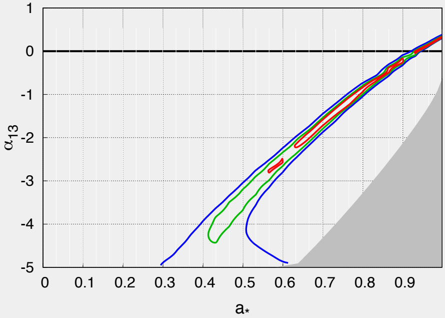


EXO 1846–031

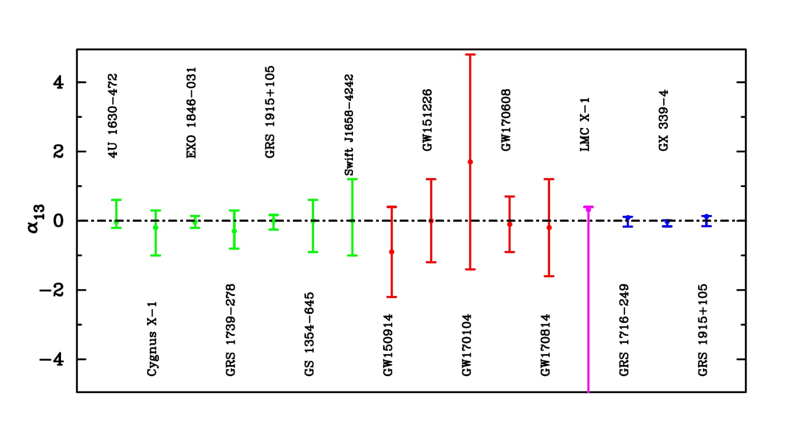
Results of MCMC analysis (RELXILL_NK)



Constraints on a_* and α_{13}



Constraints on the Johannsen deformation parameter α_{13}

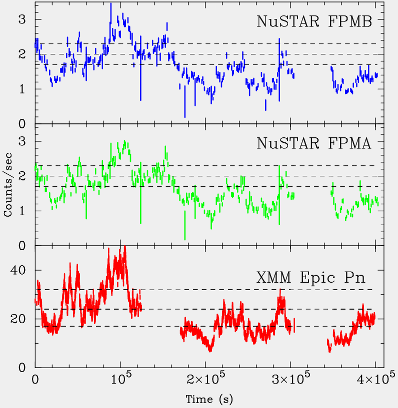


MCG–6–30–15

Observations

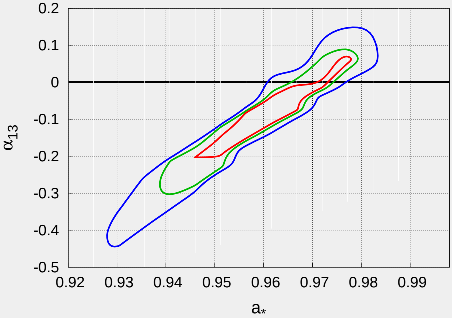
Mission	Observation ID	Exposure (ks)
NuSTAR	60001047002	23
	60001047003	127
	60001047005	30
XMM-Newton	0693781201	134
	0693781301	134
	0693781401	49

Light curves of *NuSTAR*/FPMA, *NuSTAR*/FPMB and *XMM-Newton*/EPIC-Pn

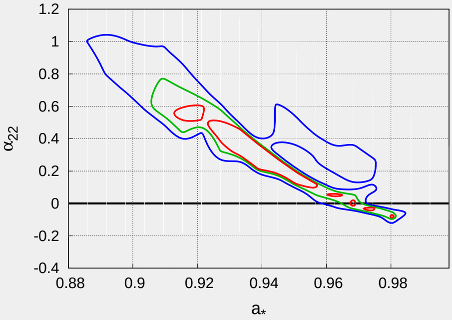


MCG–6–30–15

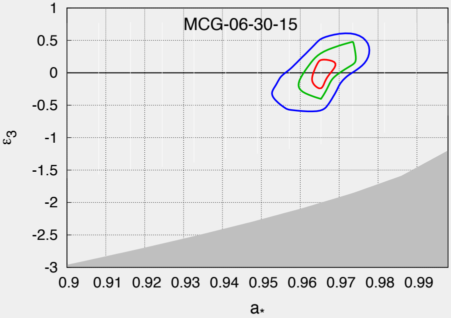
Constraints on a_* and α_{13}



Constraints on a_* and α_{22}



Constraints on a_* and ϵ_3



Conclusions

Past Work

- relxill_nk (with public version)
- nkbb
- Observational constraints on some deformation parameters

Future Work

- Developing RELXILL_NK
  1. Atomic physics calculations
  2. Accretion disk model
  3. Corona model
  4. Minor relativistic effects
- Testing more deviations from standard predictions
- Testing WEP, LLI, and LPI

Future Work

- Source Selection for X-ray Reflection Spectroscopy
    1. Very high spin ($a_* > 0.9$)
    2. No absorbers
    3. High resolution at the iron line + Data up to 50-100 keV (e.g. *XMM-Newton* + *NuSTAR*)
    4. Prominent iron line
    5. $L \sim 0.05 - 0.30\ L_{\mathrm{Edd}}$ ($R_{\mathrm{in}} = R_{\mathrm{ISCO}}$)
    6. Constant flux
    7. Sources with known coronal geometry (?)

Thank You!

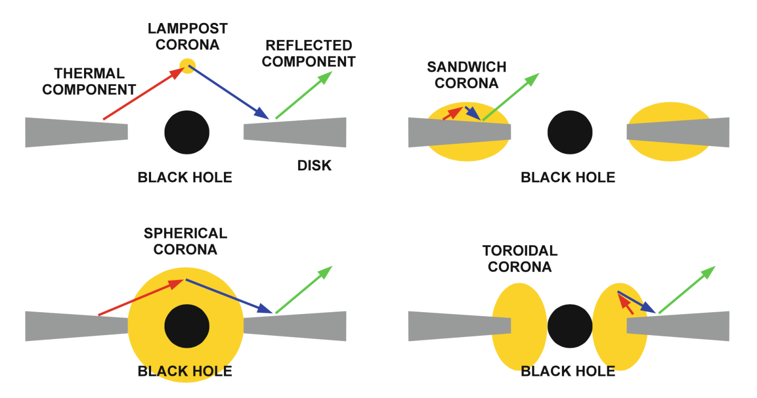
Equations of motion for the proton and electron fluids:

$$\begin{aligned} i) \quad m_p\dot{v}_p &= -\frac{G_\mathrm{N}Mm_p}{r^2} + \frac{\sigma_{\gamma p}L}{4\pi r^2 c} + \frac{eQ}{r^2} \\ ii) \quad m_e\dot{v}_e &= -\frac{G_\mathrm{N}Mm_e}{r^2} + \frac{\sigma_{\gamma e}L}{4\pi r^2 c} - \frac{eQ}{r^2} \end{aligned}$$

Equilibrium electric charge $\Rightarrow \dot{v}_p = \dot{v}_e$

$$\begin{aligned} m_e\, i) - m_p\, ii) \Rightarrow \qquad & m_p m_e \dot{v}_p - m_p m_e \dot{v}_e = \frac{\sigma_{\gamma e}L}{4\pi r^2 c} + \frac{2eQ}{r^2} \\ & \Rightarrow -Q = \frac{\sigma_{\gamma e}L}{8\pi c e} \leq \frac{\sigma_{\gamma e}L_\mathrm{Edd}}{8\pi c e} \sim 10^{21}\left(\frac{M}{M_\odot}\right) e \end{aligned}$$

Coronal Models



Spectra of the best-fit models with the corresponding components and data to best-fit model ratios for a variable ϵ_3