Testing Black Holes Using X-ray Reflection Spectroscopy

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2019 CCNU-USTC Junior Cosmology Symposium
Wuhan, China (26-29 April 2019)

Tests of General Relativity

- 1915 $\rightarrow$ General Relativity (Einstein)
- 1919 $\rightarrow$ Deflection of light by Sun (Eddington)
- 1960s-Present $\rightarrow$ Solar System Experiments
- 1970s-Present $\rightarrow$ Binary Pulsars

These are all tests in the weak field regime!

- Today $\rightarrow$ Black Holes

Strong field regime

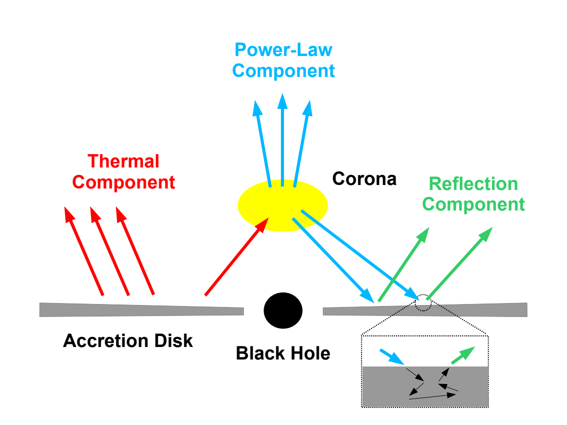
- "No-Hair Theorem" $\rightarrow$ M, J, Q ($a_* = J/M^2$)
- Uncharged black holes $\rightarrow$ Kerr solution
- Clear predictions on particle motion

Astrophysical Black Holes

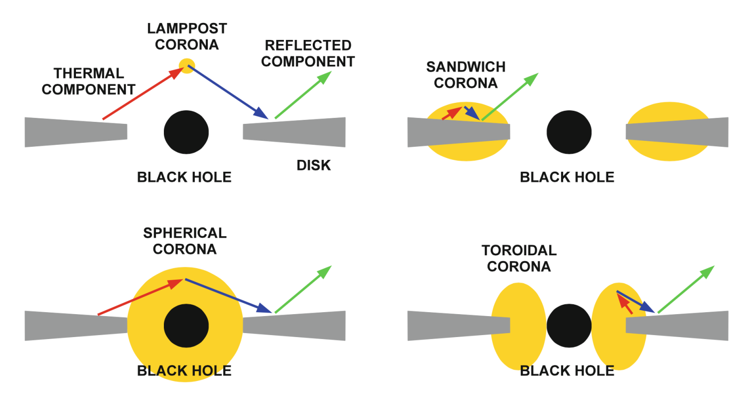
It is remarkable that the spacetime metric around astrophysical black holes formed from gravitational collapse of stars/clouds should be well approximated by the “ideal” Kerr metric

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

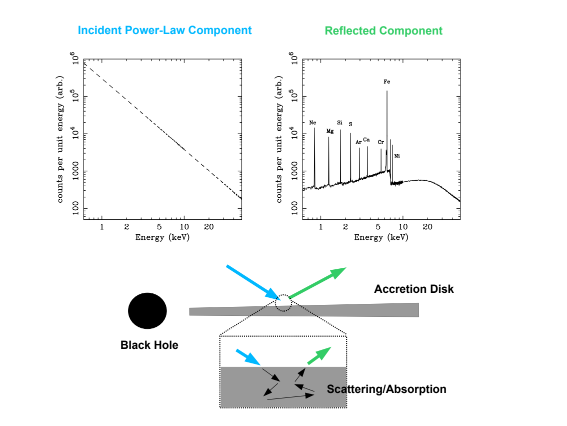
Disk-corona model



Corona models



Reflection spectrum



- Atomic physics $\rightarrow$ We can calculate the reflection spectrum at the emission point in the rest-frame of the gas in the disk
- Observations $\rightarrow$ We measure the reflection spectrum affected by relativistic effects (Doppler boosting, gravitational redshift, light bending)
- With the correct astrophysical model, we can learn about the spacetime metric in the strong gravity region

- RELXILL[1] is currently the most advanced relativistic reflection model for Kerr spacetimes
- RELXILL $\sim$ RELCONV $\times$ XILLVER
- XILLVER: non-relativistic reflection model
- RELCONV: convolution model for the Kerr spacetime and a Novikov-Thorne accretion disk
- RELXILL $\rightarrow$ Black hole spin measurements

[1] Dauser et al., MNRAS 430, 1694 (2013); Garcia et al., ApJ 782, 76 (2014)

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"

Bottom-Up Approach

- 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[2]:

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

[2] 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

- RELXILL_NK[3] is the natural extension of RELXILL to non-Kerr spacetimes
- RELXILL_NK $\sim$ RELCONV_NK $\times$ XILLVER
- We assume that atomic physics is the same (XILLVER) but we employ a metric more general than the Kerr solution and that includes the Kerr solution as a special case
- RELXILL_NK $\rightarrow$ Tests of the Kerr metric

[3] Bambi et al., ApJ 842, 76 (2017); Abdikamalov et al., arXiv:1902.09665

RELXILL_NK

A public version[4] of RELXILL_NK and its manual can be found at:

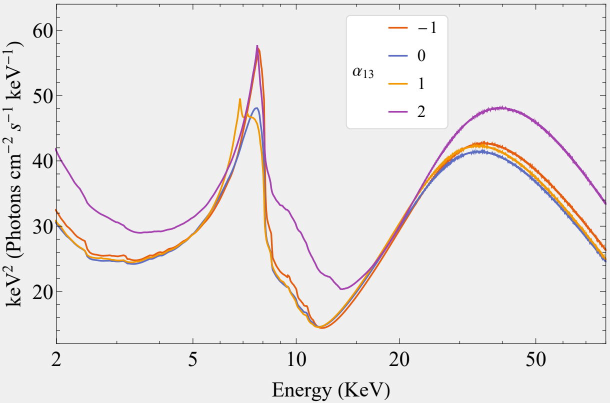
Johannsen metric with the deformation parameters α_{13} and α_{22}

[4]Current version is 1.3.2

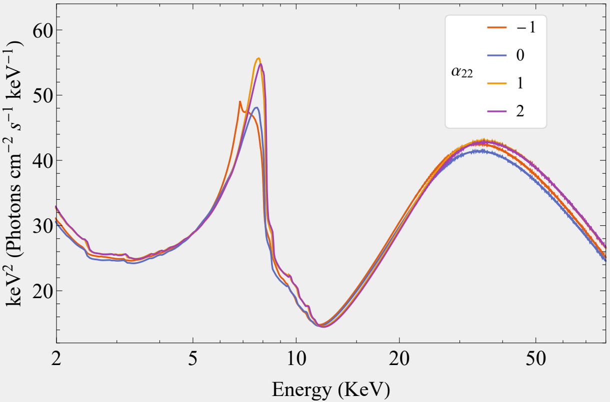
List of flavors:

1. RELLINE_NK
2. RELCONV_NK
3. RELXILL_NK
4. RELXILLCP_NK
5. RELXILLD_NK
6. RELLINELP_NK
7. RELXILLLP_NK
8. RELXILLLPCP_NK
9. RELXILLLPD_NK

Impact of the deformation parameter α_{13}



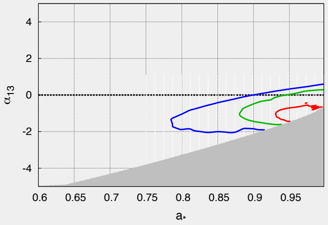
Impact of the deformation parameter α_{22}

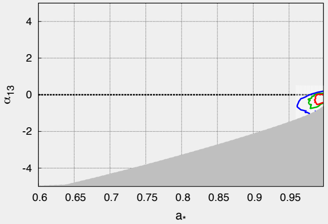


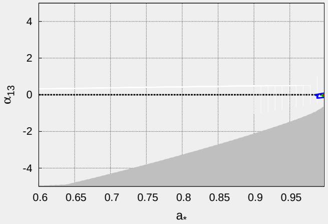
- 1H0707−495; Cao et al., PRL 120, 051101 (2018)
- Ark 564; Tripathi et al., PRD 98, 023018 (2018)
- GS 1354−645; Xu et al., ApJ 865, 134 (2018)
- Ton S180, RBS 1124, Swift J0501.9−3239, Ark 120, 1H0419−577, PKS 0558−504, Fairall 9; Tripathi et al., ApJ 874, 135 (2019)
- MCG−6−30−15; Tripathi et al., ApJ 875, 56 (2019)
- etc.

1H0707–495, Ark 564, GS 1354–645

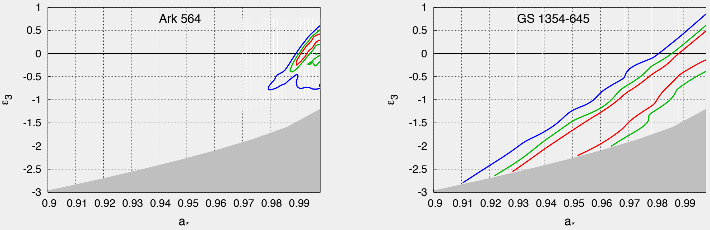
Constraints on a_* and α_{13} from 1H0707–495, Ark 564, and GS 1354–645



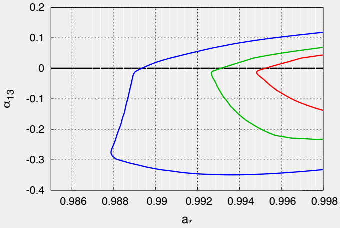


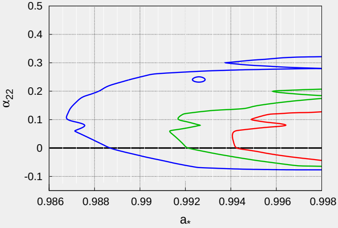


Constraints on a_* and ϵ_3 from Ark 564 and GS 1354–645



Constraints on a_* and α_{13}/α_{22} from 1H0419−577



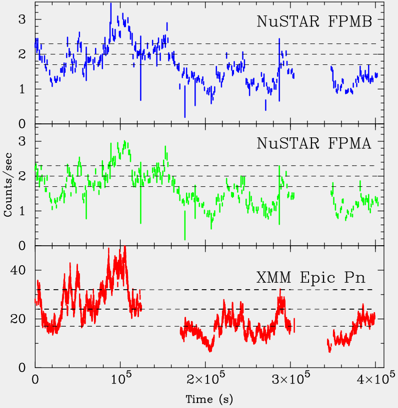


Observations

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

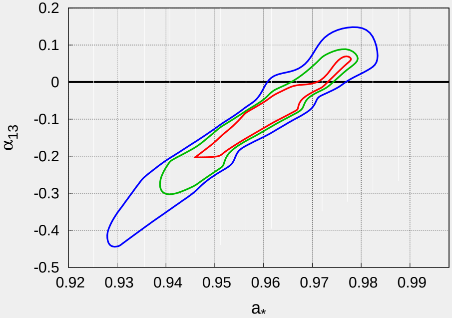
MCG–6–30–15

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

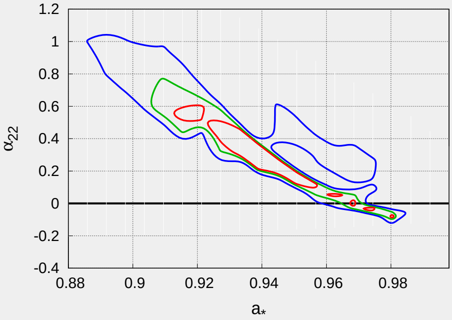


MCG–6–30–15

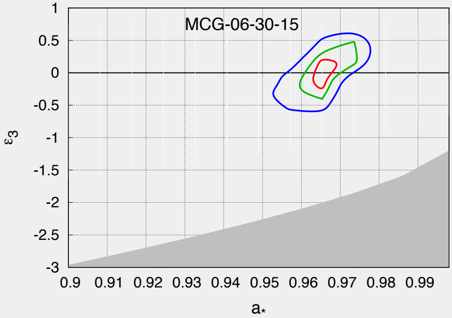
Constraints on a_* and α_{13}



Constraints on a_* and α_{22}



Constraints on a_* and ϵ_3



Past Work

- RELXILL_NK (with public version)
- "Preliminary" observational constraints on some deformation parameters

- Developing RELXILL_NK
    1. Atomic physics calculations
    2. Accretion disk model
    3. Corona model
    4. Minor relativistic effects
- Selecting the most suitable sources/data for our tests
- Testing more deviations from standard predictions

- Source Selection
  1. AGN probably better than binaries
  2. Very high spin ($a_* > 0.9$)
  3. No absorbers
  4. High resolution at the iron line + Data up to 50-100 keV (e.g. *XMM-Newton* + *NuSTAR*)
  5. Prominent iron line
  6. $L \sim 0.05 - 0.30\ L_{\rm Edd}$ ($R_{\rm in} = R_{\rm ISCO}$)
  7. Lamppost coronas?

Thank You!

MCG–6–30–15

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