TESTING GENERAL RELATIVITY WITH X-RAY BINARIES

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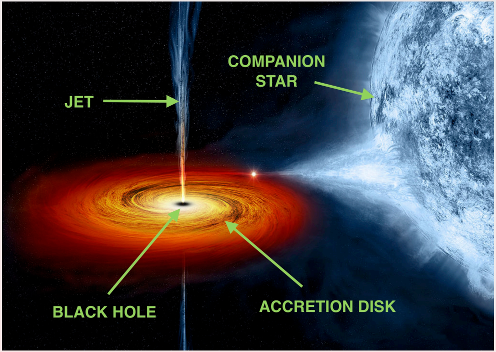
Outline of the talk

- Introduction
- Motivation
- X-ray Reflection Spectroscopy
- Continuum fitting
- Spin measurement with NICER
- Summary and future work

General Relativity and Black Holes

- 1915 $\rightarrow$ General Relativity (GR) by Albert Einstein
- First test of GR $\rightarrow$ Deflection of light by the Sun in 1919
- 1960-present $\rightarrow$ Experiments to test weak field limit (Solar System and Binary Pulsar)
- Experiment to test strong field limit $\rightarrow$ Black holes (BH).
- Black hole $\rightarrow$ strong gravity $\rightarrow$ 4D solutions of Einstein's equation.
- "no-Hair theorems" $\rightarrow$ (M,J,Q) ($a_* = J/M^2$)
- Uncharged spinning BH $\rightarrow$ Kerr solution.
- Describes the spacetime around astrophysical BH.
- Accretion disk, nearby stars, electric charge $\rightarrow$ negligible.

Stellar Mass BH



- Mass $\approx$ 3-100 $M_\odot$.
- Compact → mainly in our Galaxy.
- Spectral states → Hardness Intensity Diagram.
- Disk temperature → soft X-rays.

Why is testing GR important?

- Cosmological observations (Daniel et al. 2010) → dark energy
  - Breakdown of GR at large scales.
  - Existence of some other fields with peculiar properties.
- Increasing interest → deviations from predictions.
  - Kerr BHs → prediction of GR.
  - Direct observational confirmation → testing GR in strong field regime.
- Theoretically, deviations from GR is expected
  - classical extension of GR (Berti et al. 2015).
  - Macroscopic quantum gravity effects (Giddings 2014).
- In Accretion disk physics, the existing models assume GR is correct.
- Kerr metric → photon trajectories around the black hole.

How can the Kerr metric be tested?

- Top-down approach: we test a specific alternative theory of gravity against Einsteins theory of General Relativity.
  - A large number of theories of gravity...
  - Usually we do not know their rotating black hole solutions...
- Bottom-up approach: parametric BH spacetimes in which deviations from the Kerr geometry are quantified by a number of "deformation parameters".

Bottom-up Approach : Johannsen metric

- In Boyer-Lindquist coordinates, the line element reads (Johannsen (2013))

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

$$
\mathrm{a} = \mathrm{J/M}, B = \left(r^2+a^2\right)A_1 - a^2 A_2 \sin^2\theta\,, \quad \tilde{\Sigma} = \Sigma + f\,,
$$

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

- Other components are defined as

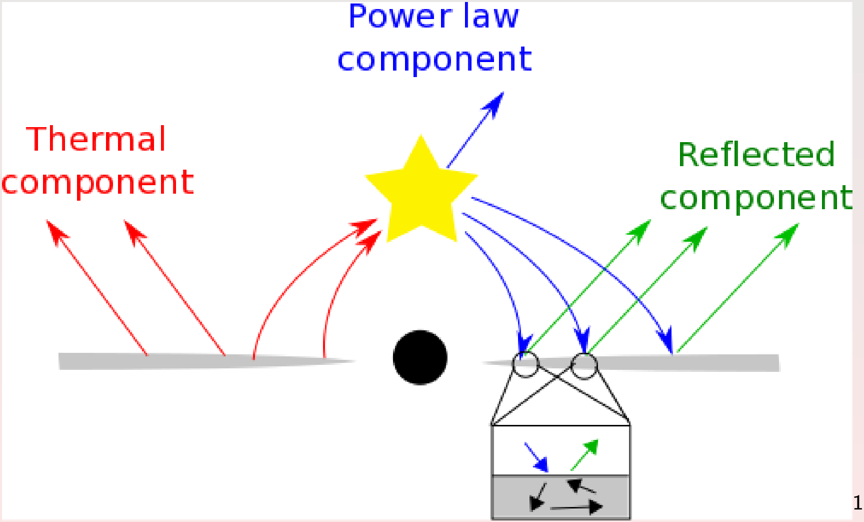
$$A_1 = 1 + \alpha_{13}\left(\frac{M}{r}\right)^3 , \quad A_2 = 1 + \alpha_{22}\left(\frac{M}{r}\right)^2 ,$$
$$f = \epsilon_3 \frac{M^3}{r} \qquad A_5 = 1 + \alpha_{52}\left(\frac{M}{r}\right)^2 .$$

- Deformation parameters → ϵ_3, α_{13}, α_{22}, and α_{52}
- Vanish for Kerr metric.

Electromagnetic Approach to Test General Relativity

- Two leading techniques to probe strong gravity region.
  1. Continuum fitting method
  2. Reflection method
- Continuum fitting → thermal spectrum of thin accretion disk.
  - Depends on BH mass and distance.
- Reflection method → relativistically smeared reflection spectrum of thin accretion disk.
  - Independent of mass and distance.

X-ray Reflection Spectroscopy



[1]

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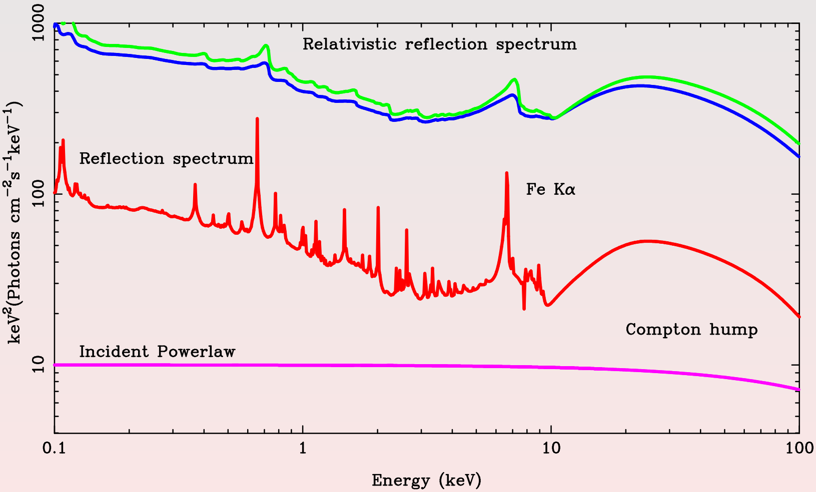
[1] Bambi et al. 2017

Reflection Signatures



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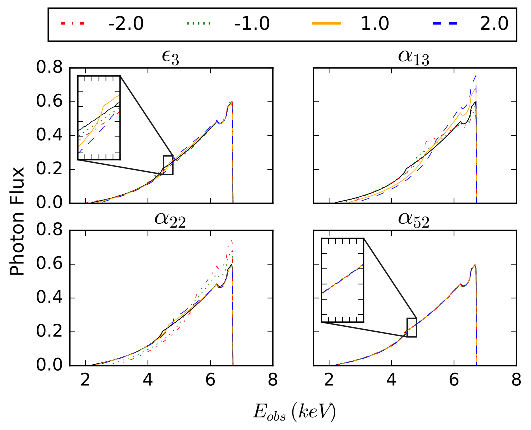
[2] Bambi et al. 2021

Reflection model

- Reflection Component (in rest frame of gas)→ `xillver`.
- `xillver` → radiative transfer → XSTAR.
- Detailed treatment of K-shell atomic properties of ionized ions.
- `relconv` → relativistic convolution code.
- Spectrum measured by distant observer given local spectrum at any emission point in the disk.
- `relxill` ≈ `relconv*xillver` → BH spin measurements.

`relxill_nk`



- `relxill` → Kerr solution.
- `relxill_nk` → Alternate theories of gravity.
- Johannsen metric → α_{13}
- Constraints with observations.

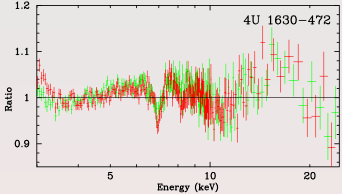
NuSTAR data of Galactic black holes

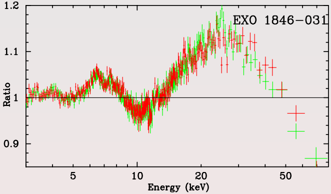
- X-ray Binaries → advantages over AGNs.
- NuSTAR → most suitable for study reflection.
- Not affected by pileup → suitable for bright sources.
- 3-79 keV energy range → Iron line and Compton hump.
- Published spin measurements of NuSTAR → simple spectrum.
- Accepted to ApJ. arXiv:2012.10669

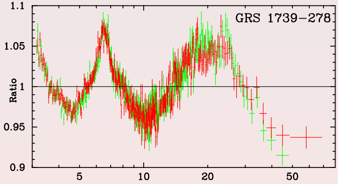
Summary of the sources and the observations analyzed

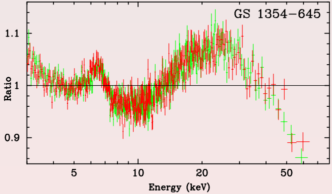
Source	Observation ID	Observation Date	Exposure (ks)	Counts [s^{-1}]
4U 1630–472	40014009001	2013 May 9	14.6	77.5
EXO 1846–031	90501334002	2019 August 3	22.2	148.7
GRS 1739–278	80002018002	2014 March 26	29.7	127.8
GS 1354–645	90101006004	2015 July 11	30.0	51.8
GX 339–4	80001015003	2015 March 11	30.0	208.5
	00081429002	2015 March 11	1.9	35.4
Swift J1658–4242	90401307002	2018 February 16	33.3	34.5
	00810300002	2018 February 16	3.0	4.9

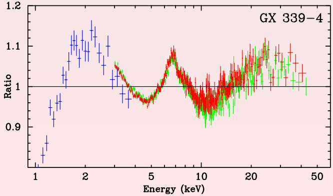
Reflection features present in the observations

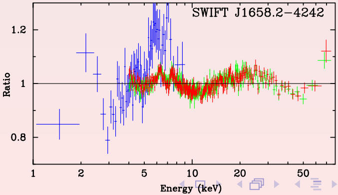




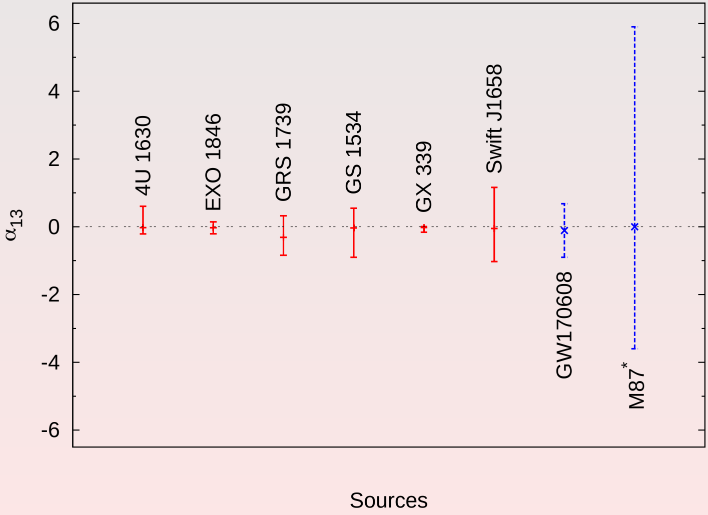




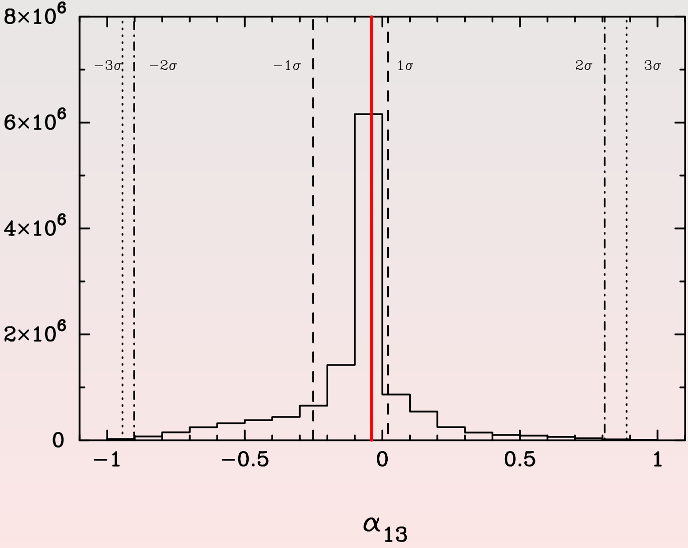




Summary of α_{13} from various sources



Combined α_{13} measurements



$\alpha_{13} = -0.04^{+0.93}_{-0.91}$ (3σ)

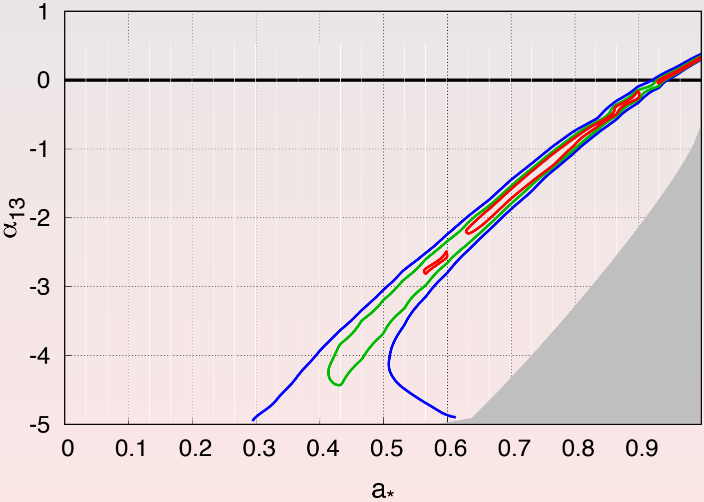
Continuum Fitting Method

- Analysis of thermal spectrum of accretion disk.
- Based on Novikov Thorne model.
- Thin disk $\rightarrow$ L/L_{Edd} is in the range $0.05 - 0.3$.
- Thermal spectrum `Kerrbb` $\rightarrow$ M, $\dot{M}$, i, D, a_*.
- M, i, D $\rightarrow$ independent measurement.
- Simple shape $\rightarrow$ not much information.
- Extended to non-Kerr $\rightarrow$ `nkbb`
- Bottom-up approach, Johannsen metric $\rightarrow$ α_{13}.

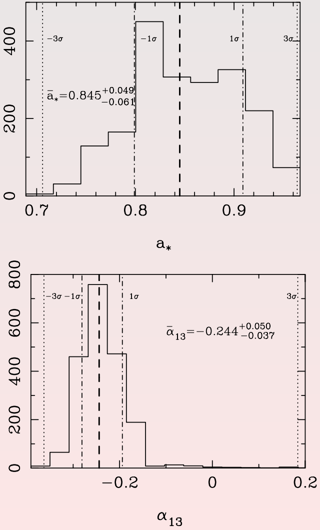
LMC X-1 (Tripathi et al. 2020, ApJ, 907:31)

- Discovered in 1969 as the first extragalactic X-ray binary.
- M $= 10.91 \pm 1.54\ M_\odot$, i $= 36^0 \pm 2^0$, D $= 48 \pm 2$ kpc.
- Stable bolometric luminosity → 16 % of Eddington limit.
- 17 RXTE observations → thermal dominant state.
- `tbabs*simpl*nkbb`
- f → 1.55, returning radiation.
- $a_* = 0.998_{-0.44}$, $\alpha_{13} = 0.32^{+0.04}_{-3.10}$

Constraints in a_*-α_{13} plane

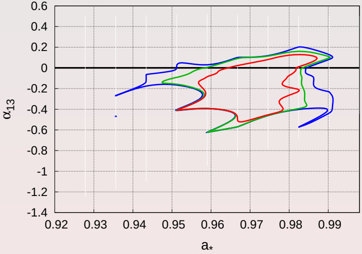


Observational Uncertainties



- statistical uncertainty dominates observational uncertainty.
- Opposite to the Kerr case.
- Strong degeneracy between a_* and α_{13}.
- Can be broken if R_{in} is very close to compact object.

MAXI J1535-571 : Preliminary Results



- NICER observation → 2017 Sept. 13 →Intermediate or very high state.
- broad asymmetric iron line from the ISCO → `relxill_nk`
- Narrow asymmetric line → radii larger than ISCO (Miller et al. 2020).
- Xu et al. 2018 (2017 Sept. 7) → NuSTAR → distant reflection.
- $a_*=0.985^{+0.012}_{-0.029}$, $\alpha_{13}=0.11^{+0.07}_{-0.38}$

- CALDB v20200722
- Energy : 2.3-10 keV.
- Model : `tbabs*(diskbb+relxill_nk+relline_nk)`
- Tripathi et al. (in prep.)

Spin measurement with NICER

- Narrow asymmetric line → NICER resolution → better than NuSTAR.
- The precision in measuring a_* → sensitivity.
- Low energy coverage → absorption and soft excess.
- Simultaneous NuSTAR observations → soft excess, Iron line and Compton hump
- Advantageous for AGNs.
- Successor of RXTE → stacked analysis → a_* from both methods.

Summary and Future Work

- We present constraints on deformation parameter α_{13} using both continuum fitting and reflection spectroscopic methods for various X-ray binaries.
- NICER, RXTE, Swift, NuSTAR, Suzaku etc.
- The results are consistent with Kerr hypothesis.
- Systematic Uncertainties.
- Testing gravity for other modified theories.
- NICER, combined with NuSTAR, would result in coverage of all reflection signatures throughout the broad energy range of 0.25-80 keV.
- Yet to explore more with NICER.

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