Testing the Kerr metric using X-ray reflection spectroscopy and continuum fitting method

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Introduction

The theory of general relativity (GR) has been well tested in the weak gravitational regime, e.g. by experiments in the solar system and observations of binary pulsars. Recently, the progress in the detection of the gravitational waves and the black hole imaging by the Event Horizon Telescope (EHT) also made it possible to test GR in the strong gravitational field regime near black holes. We note that, the radiation from the accreting black holes with a geometrically thin and optically thick accretion disk (see below) also contains information about the spacetime geometry near the black holes. Therefore, the spectra of these systems also can be used to test GR in the strong gravitational field.

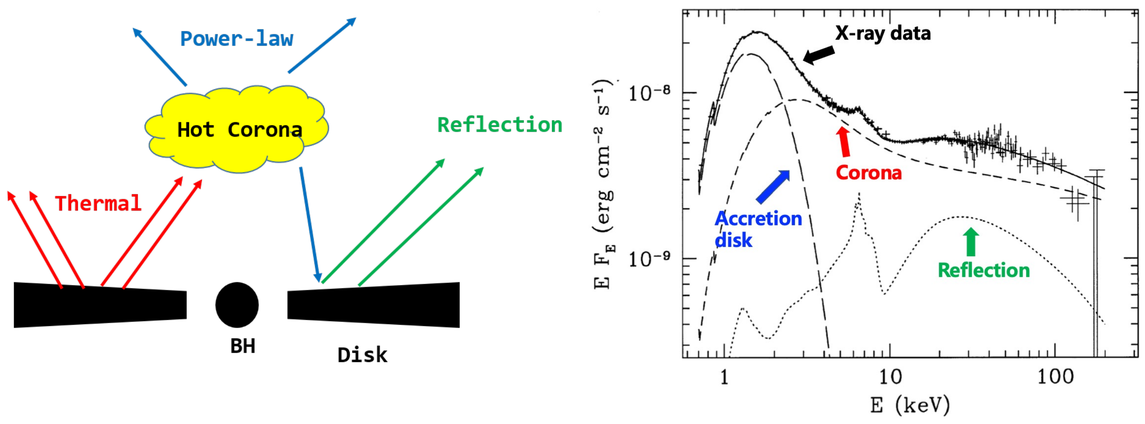

Figure 1. (Left) The sketch of the disk-corona system that is often considered for accreting systems. (Right) The spectral components for black hole X-ray binaries. The picture is adopted from Ref [1].

Method

- **Relativistic reflection**: As shown in Figure 1, photons from the hot corona can be captured and reprocessed by the optically thick accretion disk. This process produces the reflection component in the spectra. The reflection component contains a lot of atomic features, the strongest one of which is the iron Ka emission line at 6.4 keV (for neutral disk). The lines are narrow in the rest-frame of the disk, but will be broadened due to the strong relativistic effects near the black holes (see the plot below). Therefore, we can infer the spacetime geometry through the reflection spectra. We have extended the standard reflection model RELXILL to non-Kerr spacetime and the new model is named RELXILL_NK. This can be used to constrain possible deviation from Kerr spacetime.

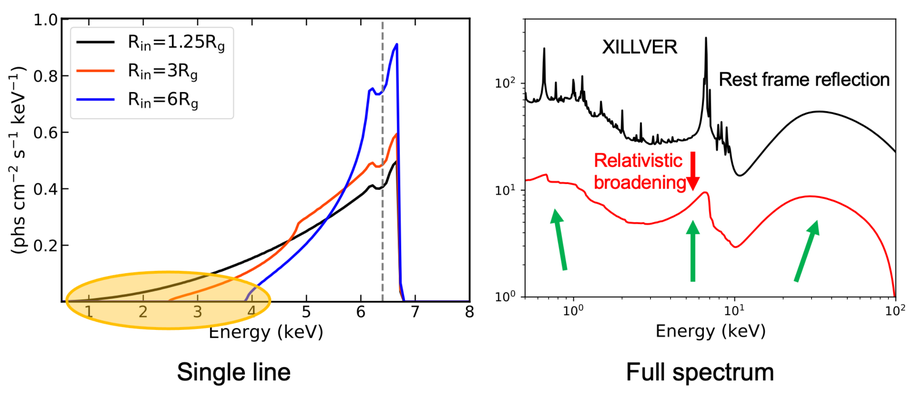

Figure 2. (Left) The broadening of a single line from the accretion disk with different sizes of the inner radius. The spin is fixed at 0.998. (Right) The reflection spectrum in the rest-frame of the disk (black) and that after applying the relativistic broadening kernel (red).

- **Continuum fitting**: The thermal emission from the accretion disk will also be altered by the relativistic effects (see below). The model NKBB[2] has been calculated to analyze the thermal spectra to test the Kerr metric.

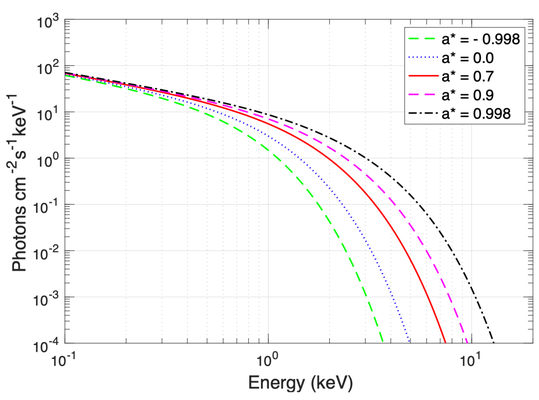

Figure 3. The impact of the black spin on the observed disk thermal emission. The plot is adopted from Ref [2].

Result

- The models RELXILL_NK and NKBB have been applied to a number of XRBs and AGNs to test the Kerr metric. In the contour plot below, the deformation parameter α_{13} quantifies deviation from the Kerr metric. $\alpha_{13} = 0$ means that the spacetime is consistent with Kerr. The reflection analysis provides much stronger constraints on α_{13} compared to the continuum fitting method probably because that the thermal spectra are too simple and featureless (see Figure 1 and 2).

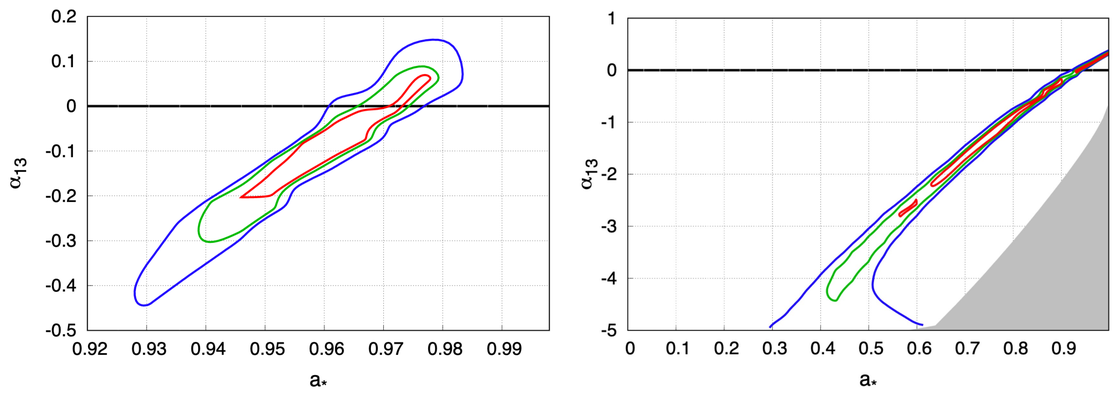

Figure 4. The contours between α_{13} and the spin parameter. The red, green and blue colors represent 68%, 90% and 99% confidence level, respectively. The left plot is from data of MCG-06-30-15 with only reflection analysis[3] and the right plot is from data of LMC X-1 with only thermal spectral analysis[4].

- With proper data, we can also combine the reflection analysis and continuum fitting method.

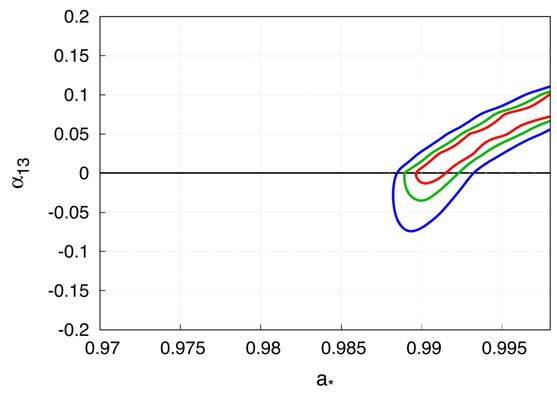

Figure 5. Constraints of α_{13} and the black hole spin after combining the reflection analysis and the continuum fitting method. The data are from Swift+NuSTAR observations of GRS 1716-249 in the intermediate states[5].

- The plot below shows a summary of constraints on α_{13} with different methods. The analysis of combining the reflection and continuum fitting method provides the strongest constraints.

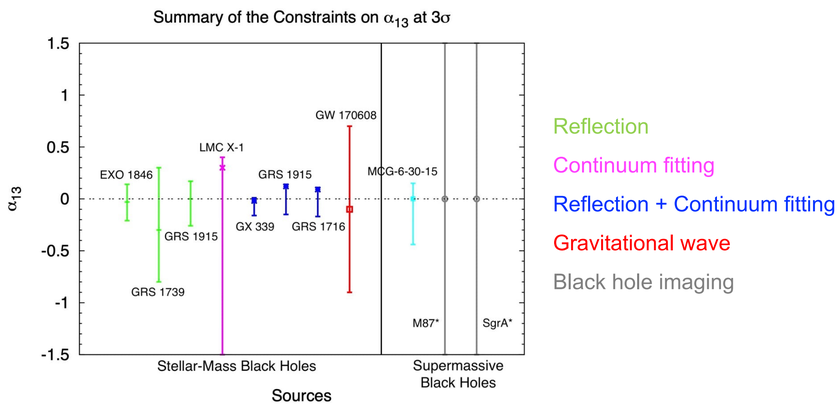

Figure 6. Constraints of α_{13} from different methods. The plot is adopted from https://cosimobambi.github.io/research.html

Conclusion

- The X-ray spectra from accreting black holes can be used to test gravity theories.
- The combination of reflection and continuum fitting method provides by far the strongest constraints on the deformation parameter α_{13}.

References

[1] Gierliński et al., 1999, MNRAS, 309, 496
[2] Zhou et al., 2019, PRD, 99, 104031
[3] Tripathi et al., 2019, ApJ, 875(1), 56
[4] Tripathi et al., 2020, ApJ, 897(1), 84
[5] Zhang et al., 2022, ApJ, 924, 72

The RELXILL_NK model: https://github.com/ABHModels/relxill_nk
The NKBB model: https://github.com/ABHModels/nkbb

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