Testing Fundamental Physics with Black Holes

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- 1915 $\rightarrow$ General Relativity (Einstein)

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

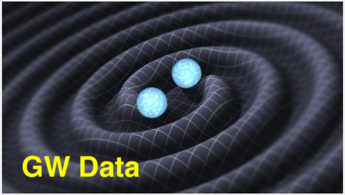
Tests in the weak field regime

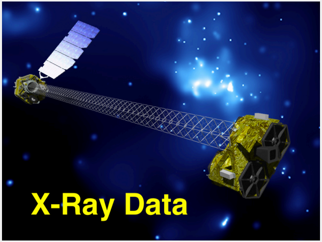
- 2000s-Present $\rightarrow$ Cosmological Tests

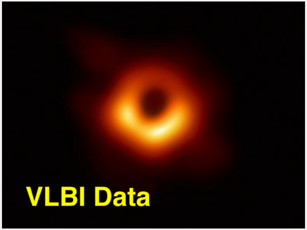
Tests on large scales

- 2010s-Present → Black Holes, Neutron Stars

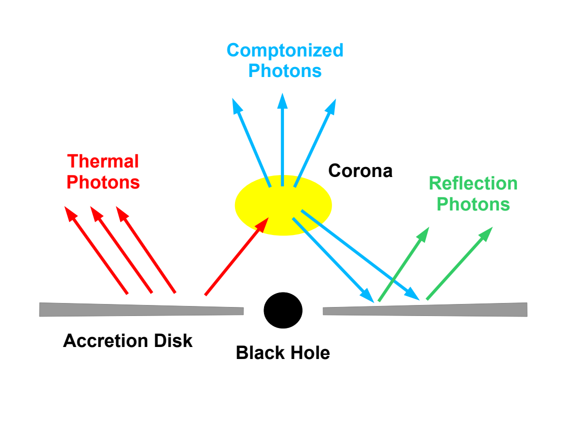
Tests in the strong field regime



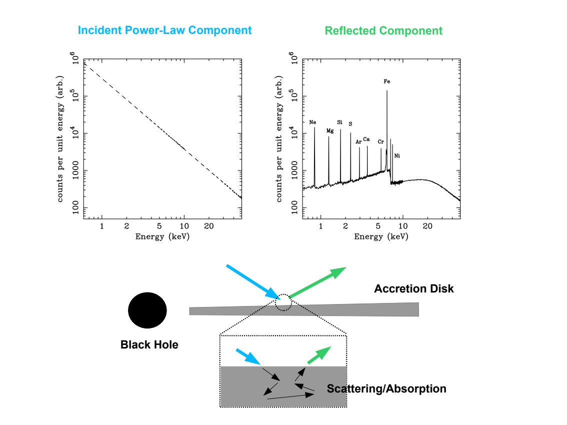




Disk-Corona Model



Reflection Spectrum



THEORETICAL MODELS

Fundamental Physics

1) Spacetime Metric
2) Particle Motion
3) Fundamental Constants
4) Atomic Energy Levels
5) ...

Astrophysical Model

1) Accretion Disk
2) Coronal Geometry

Theoretical Predictions of the Properties of the Reflection and Thermal Photons

Theoretical Models

Standard Physics

Fundamental Physics

1) Kerr Spacetime
2) Geodesic Motion
3) Same Atomic Physics
   as in our Laboratories
   on Earth

Astrophysical Model

1) Accretion Disk
2) Coronal Geometry

Theoretical Predictions of the Properties of the Reflection and Thermal Photons

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

Tests of Fundamental Physics:

- Kerr spacetime $\Rightarrow$ **Kerr hypothesis**
- Geodesic motion $\Rightarrow$ **Weak Equivalence Principle**
- Atomic physics
  $\Rightarrow$ **Local Lorentz Invariance and Local Position Invariance**

How Can We Test General Relativity?

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

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

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

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

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

- “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

Black Holes Beyond General Relativity

Macroscopic deviations from the Kerr metric are predicted in many models

- Quantum gravity effects (information paradox)
  - Mathur (Fuzzballs)
  - Dvali & Gomez
  - Giddings
  - ...

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

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

There are several parametric 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

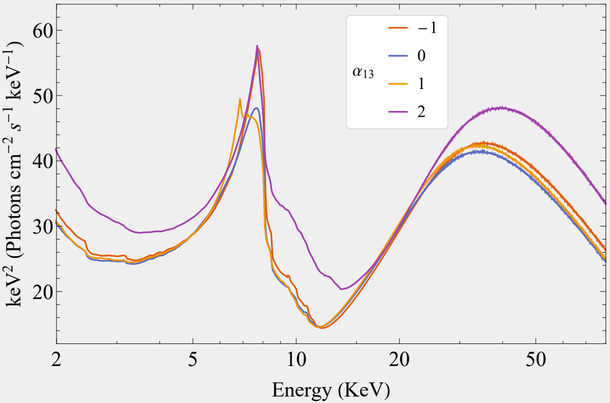
$$\begin{aligned} f &= \sum_{n=3}^{\infty} \epsilon_n \frac{M^n}{r^{n-2}} \,, \quad A_1 = 1 + \sum_{n=3}^{\infty} \alpha_{1n} \left(\frac{M}{r} \right)^n \,, \\ A_2 &= 1 + \sum_{n=2}^{\infty} \alpha_{2n} \left(\frac{M}{r} \right)^n \,, \quad A_5 = 1 + \sum_{n=2}^{\infty} \alpha_{5n} \left(\frac{M}{r}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

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

Impact of the deformation parameter α_{13}



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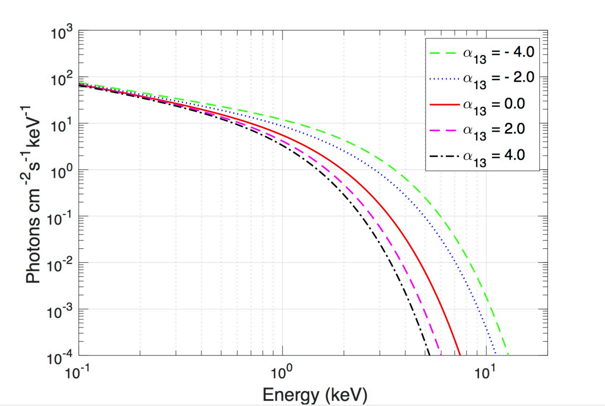


Results

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., ApJ 924, 72 (2022)
- **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., JCAP 01 (2022) 019
- **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

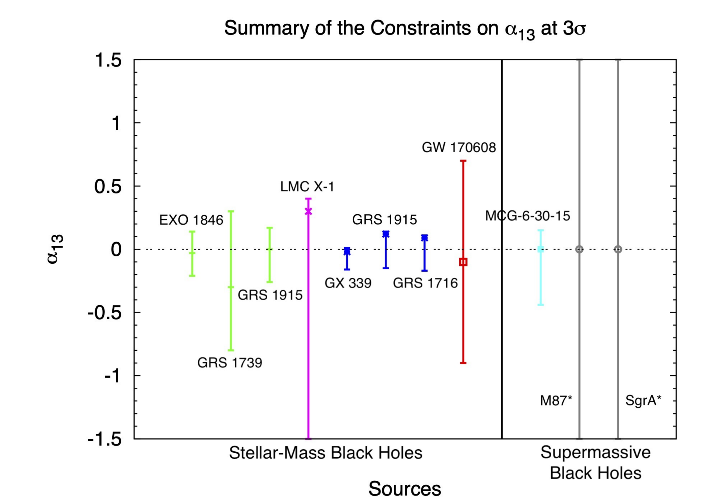
- **1H0419–577**: Tripathi et al., ApJ 874, 135 (2019)
- **1H0707–495**: Cao et al., PRL 120, 051101 (2018)
- **Ark 120**: Tripathi et al., ApJ 874, 135 (2019)
- **Ark 564**: Tripathi et al., PRD 98, 023018 (2018)
- **Fairall 9**: Liu et al., ApJ 896, 160 (2020)
- **MCG–6–30–15**: Tripathi et al., ApJ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

Theories constrained with RELXILL_NK

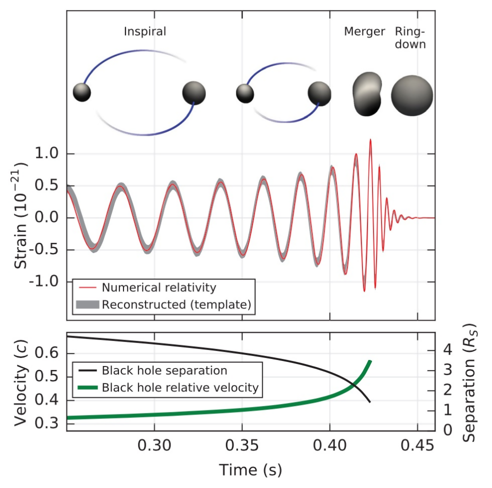
- **Einstein-Maxwell-Dilaton-Axion Gravity**:
  Tripathi et al., JCAP 07 (2021) 002
- **Asymptotically Safe Quantum Gravity**:
  Zhou et al., JCAP 01 (2021) 047
- **Kaluza-Klein Gravity**:
  Zhu et al., EPJC 80, 622 (2020)
- **Conformal Gravity**:
  Zhou et al., PRD 98, 024007 (2018); EPL 125, 30002 (2019)

Agnostic Tests

Constraints on the Johannsen deformation parameter α_{13}



GW Tests



Abbott et al. PRL 116, 061102 (2016)

EM Tests:

- Particle motion
- Non-gravitational physics in strong gravitational fields

EM tests are more suitable to study the interactions between the matter and gravity sectors

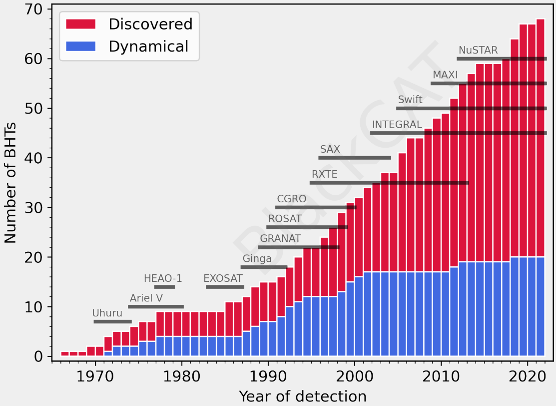
GW Tests:

- Dynamical regime

GW tests are more suitable to study the gravity sector itself

Number of Sources: Stellar-Mass BHs in XRBs

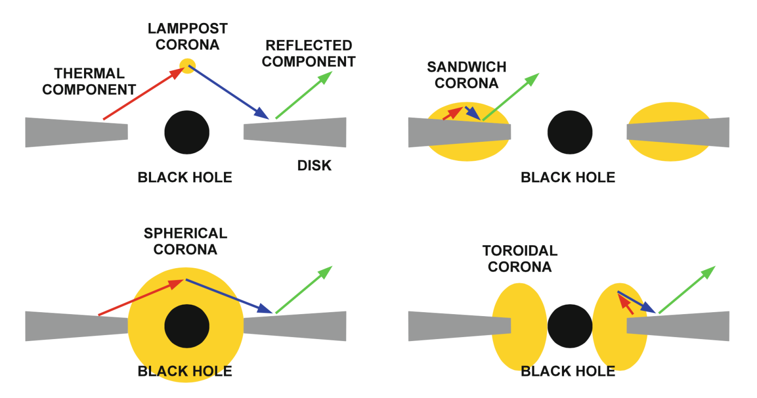
- $10^8 - 10^9$ stellar-mass black holes in the Galaxy (estimate)
- We know less than 100 objects
- We have a spin measurement from about 30 objects



- Source selection for X-ray Reflection Spectroscopy
    1. Prominent iron line
    2. High spin ($a_* > 0.9$)
    3. Compact corona close to the black hole
    4. Bright source
    5. $L \sim 0.05 - 0.30\, L_{\rm Edd}$ ($R_{\rm in} = R_{\rm ISCO}$)
    6. High resolution at the iron line + Data up to 50-100 keV (e.g. *XMM-Newton* + *NuSTAR*)
    7. Constant flux

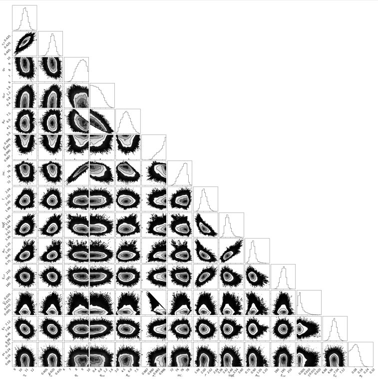
Thank You!

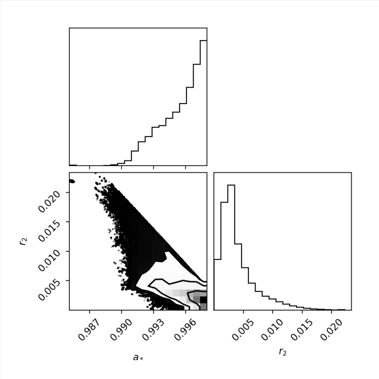
Coronal Models



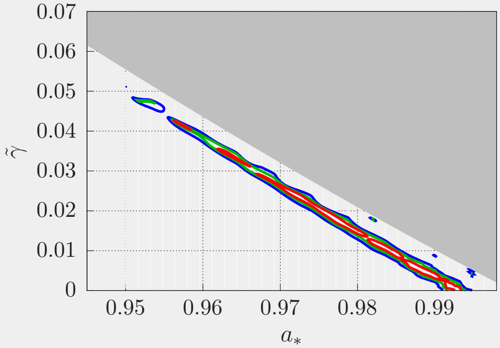
Einstein-Maxwell-Dilaton-Axion Gravity

NuSTAR observation of EXO 1846–031
Constraint: $r_2 < 0.011$ (90% CL)





Suzaku observation of GRS 1915+105
Constraint: $\tilde{\gamma} < 0.047$ (90% CL)



NuSTAR observation of GS 1354–645
Constraint: $L/M < 0.12$ (99% CL)