THE OHIO STATE UNIVERSITY

Observing the extreme environments around supermassive black holes

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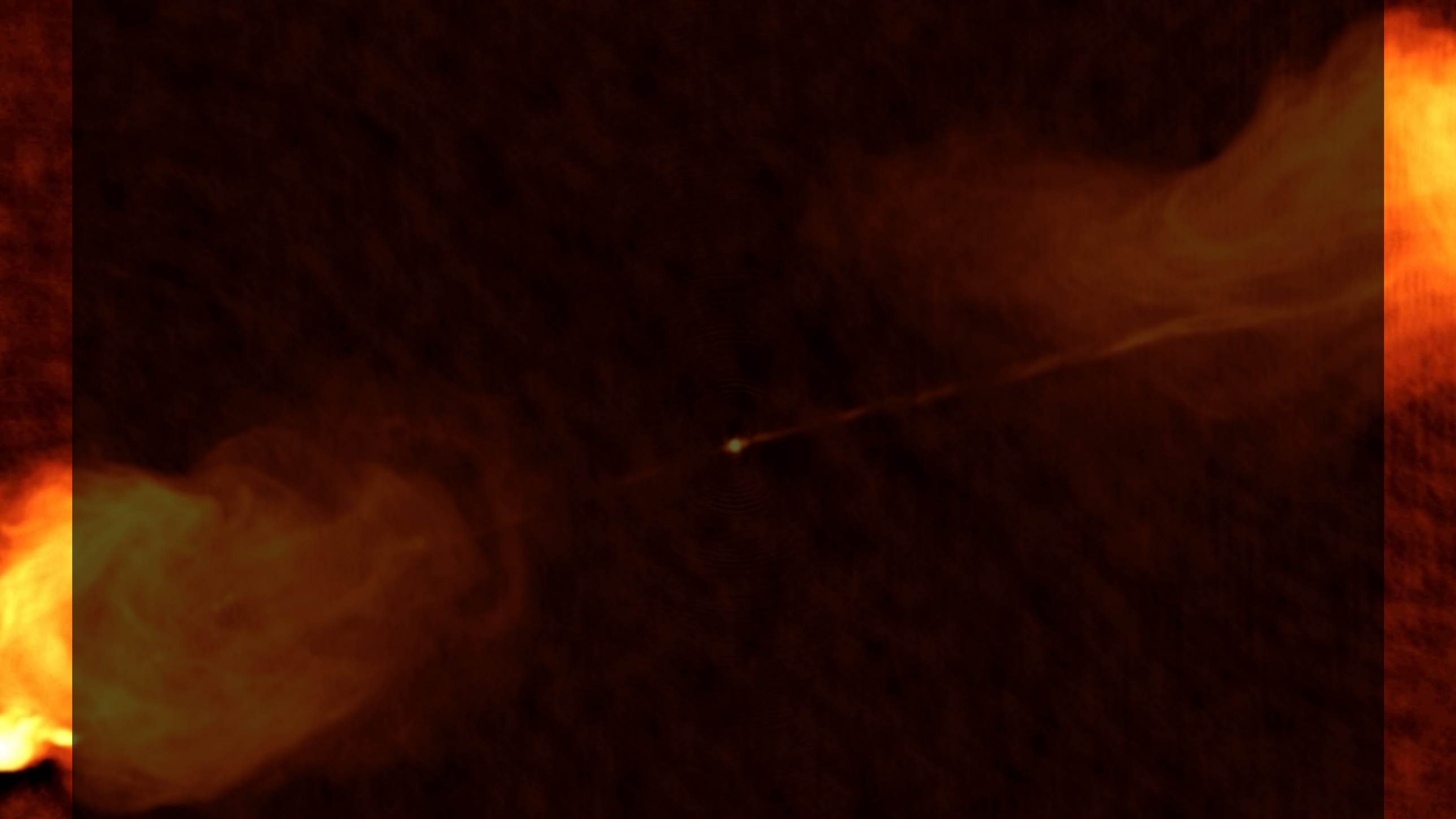

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- How do black holes launch jets? What is the connection between the accretion disc, the corona and the jet?
- Does general relativity accurately describe the extreme gravity just outside the event horizon?

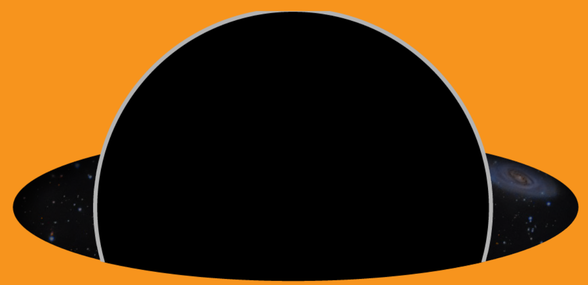
The black hole

- According to General Relativity and the no hair theorem, black holes are described by
  - Mass
  - Spin (angular momentum) $a = \frac{cJ}{GM^2}$
  - (Electrical charge)
- Event horizon for a non-spinning black hole

$$r_{\mathrm{H}} = r_{\mathrm{Sch}} = \frac{2GM}{c^2}$$

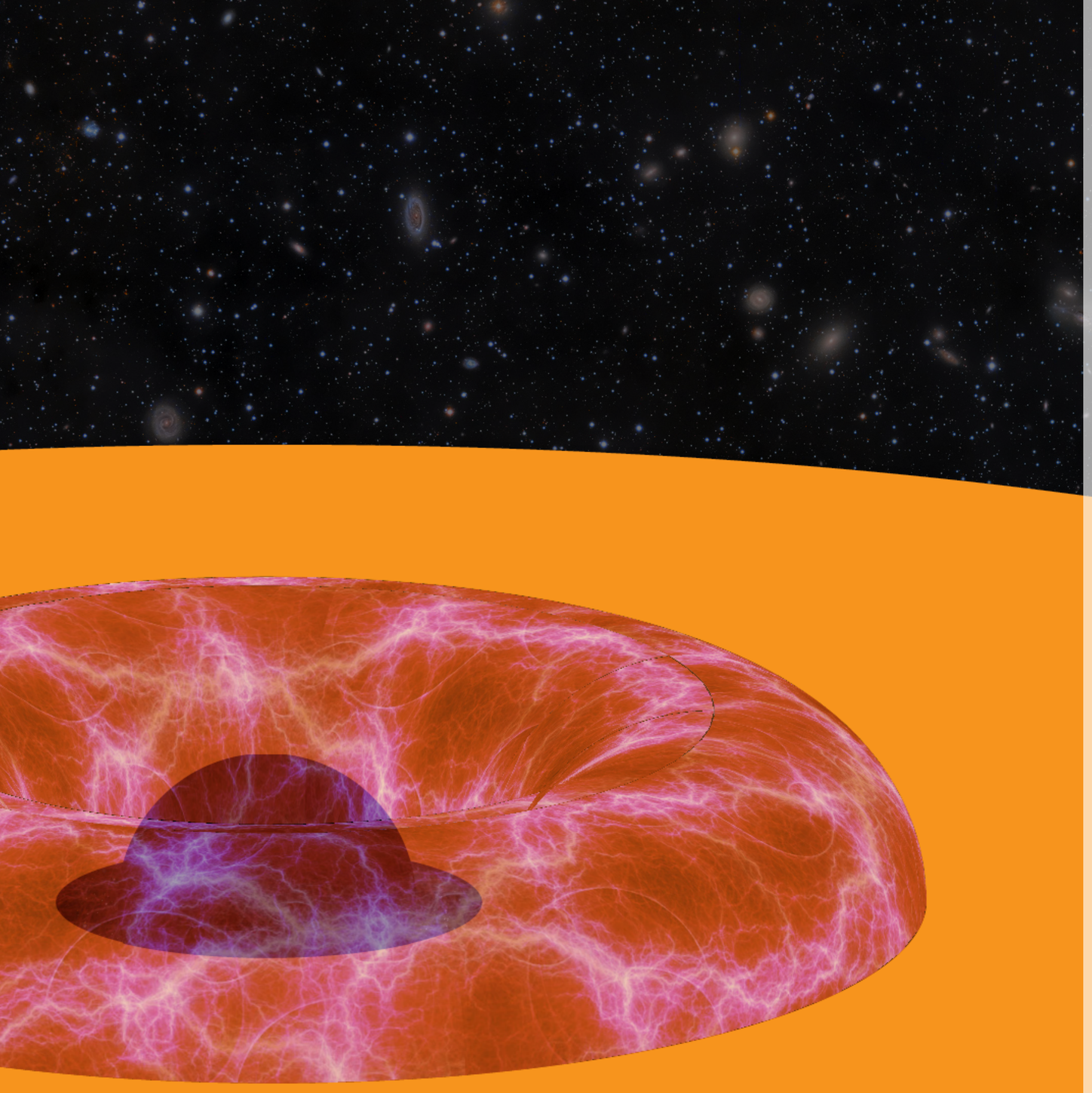
- For a rapidly-spinning black hole

$$r_{\mathrm{H}} = r_{\mathrm{g}} = \frac{GM}{c^2}$$



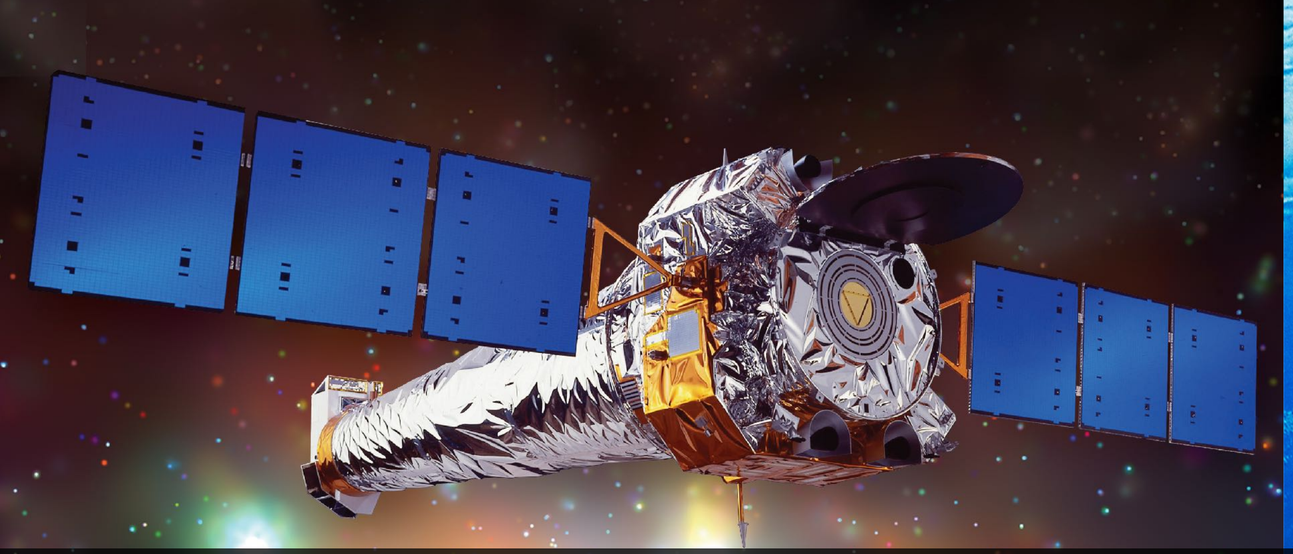
The accretion disc

- Material maintains circular orbits outside the innermost stable orbit, gradually spiralling inwards as viscous friction and magnetic fields transfer angular momentum outwards
- At the innermost stable circular orbit, material transitions to a plunging orbit and falls rapidly into the black hole
- ISCO location depends upon spin:
  - $a = 0$: $r_{\mathrm{ISCO}} = 6r_{\mathrm{g}}$ (or $3r_{\mathrm{s}}$)
  - $a = 0.998$: $r_{\mathrm{ISCO}} = 1.235r_{\mathrm{g}}$

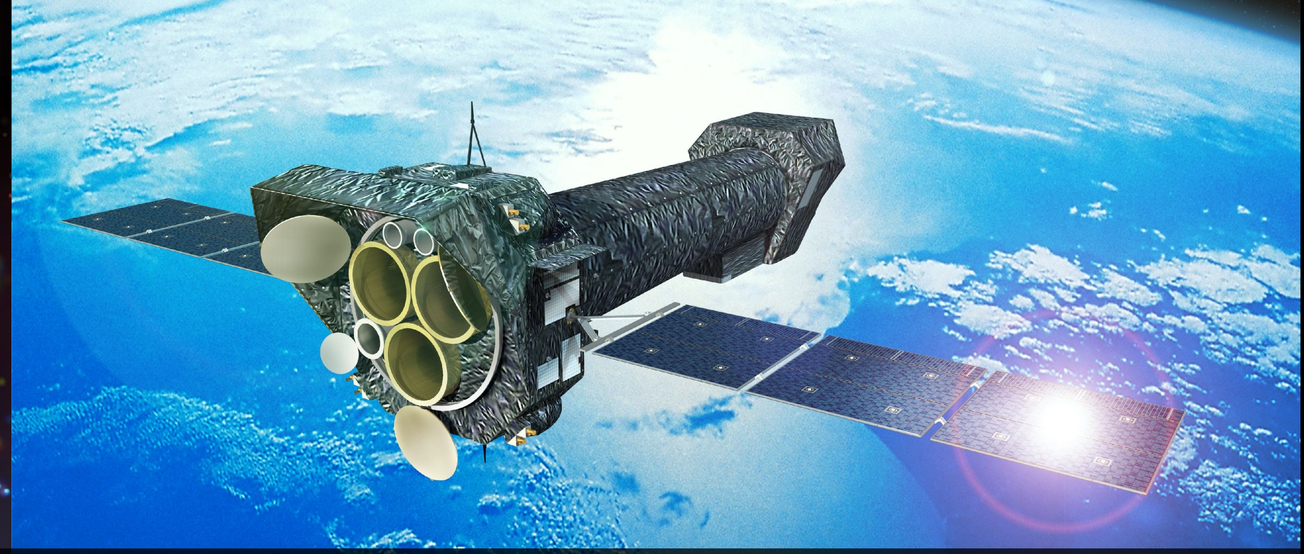


The corona

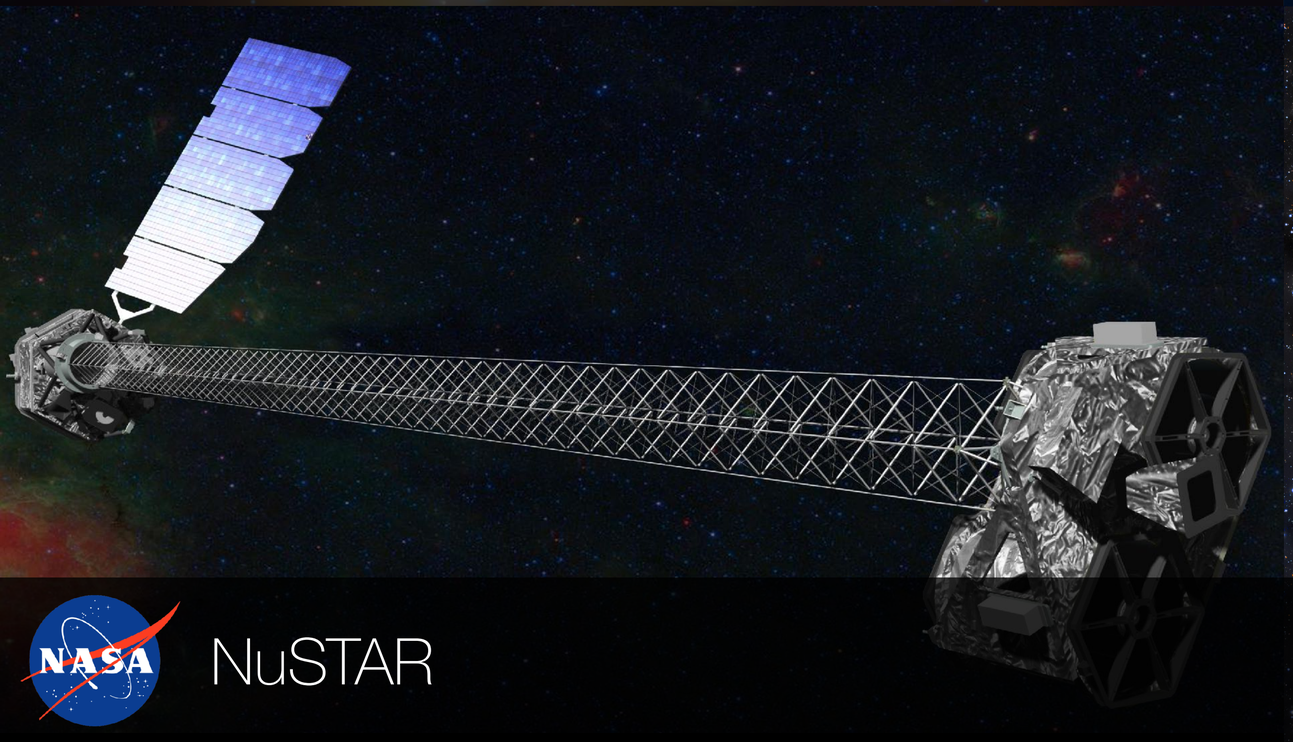
- Particle acceleration, likely by magnetic fields threading inner accretion disc and spinning black hole, produces a corona of energetic particles close to the black hole
- Source of intense X-ray continuum emission
- Illuminates the accretion disc, leading to reprocessing and reflection



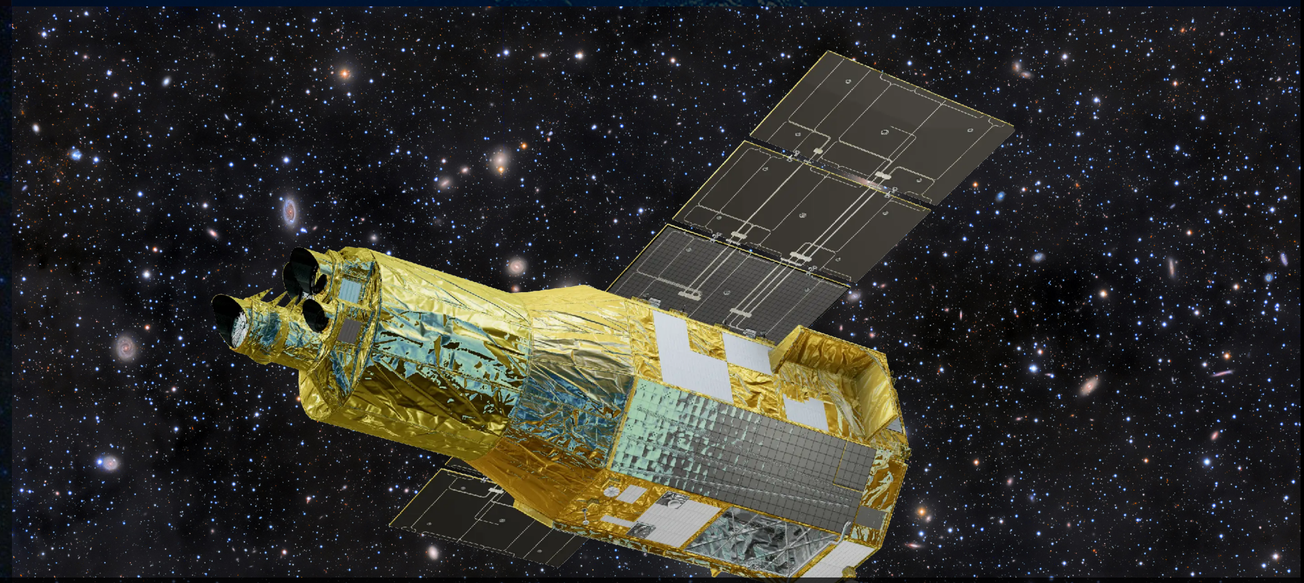
Chandra X-ray Observatory



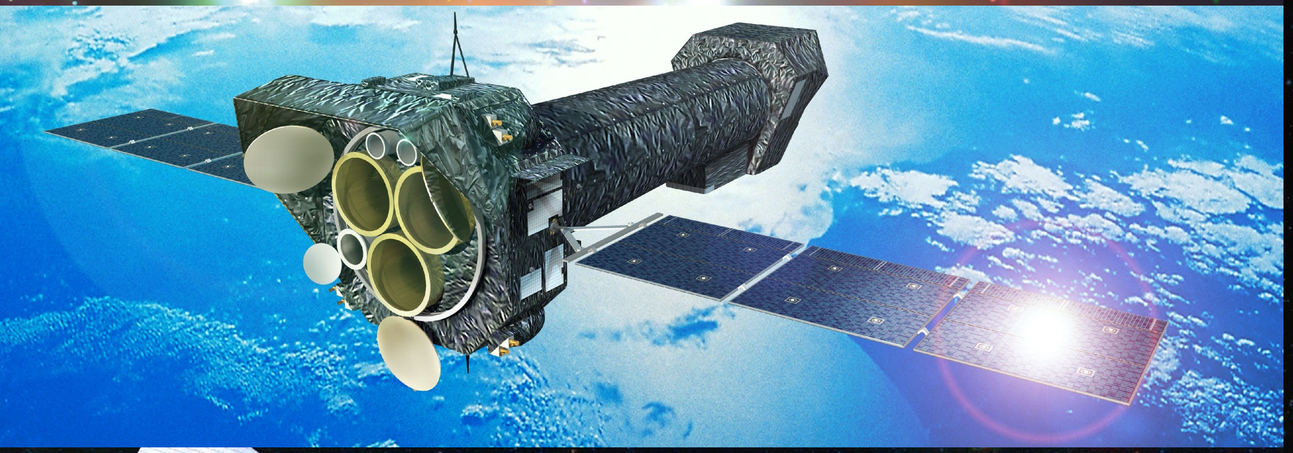
esa XMM-Newton

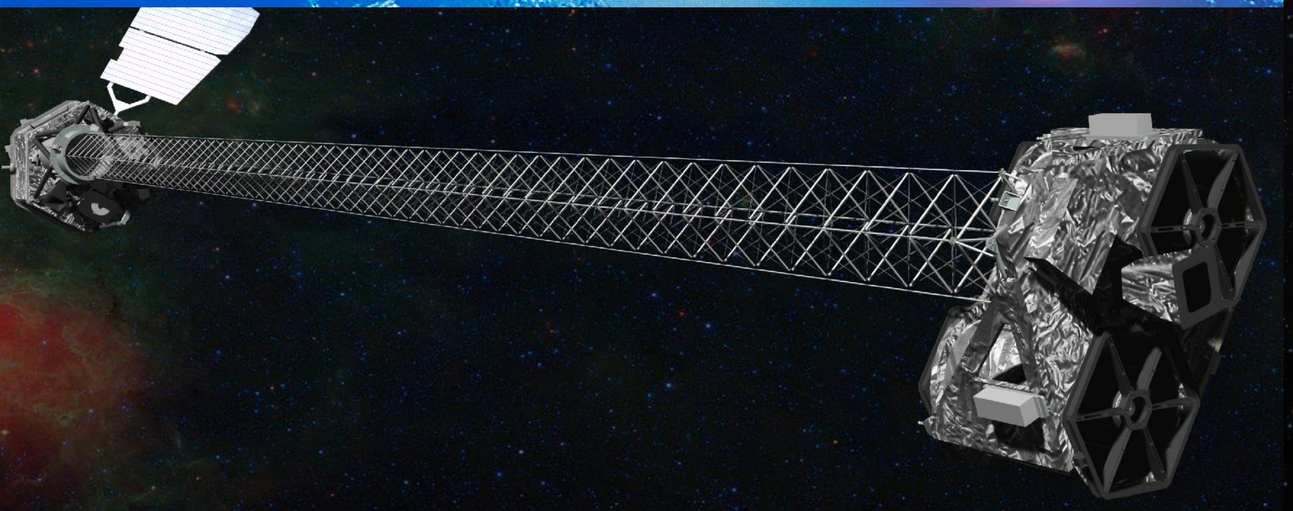


NuSTAR

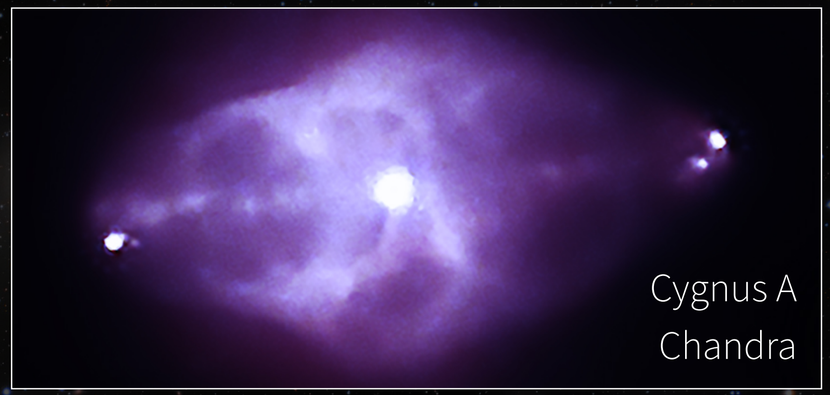


JAXA NASA XRISM

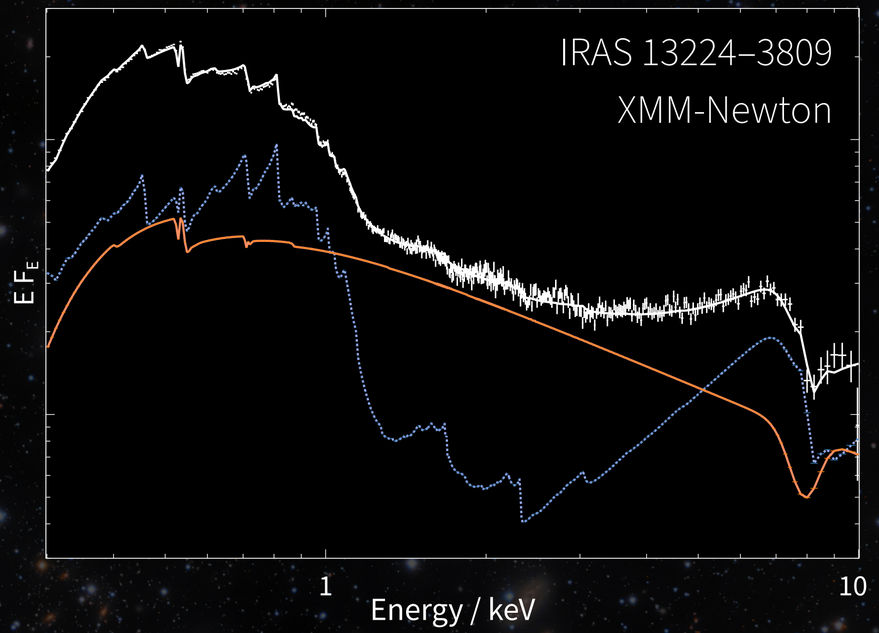




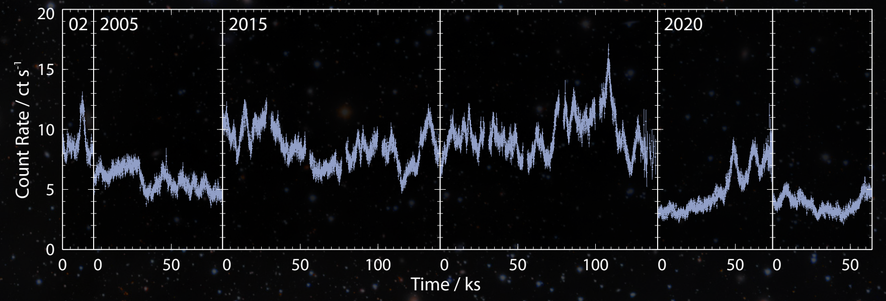
Image



Spectrum



Light Curve

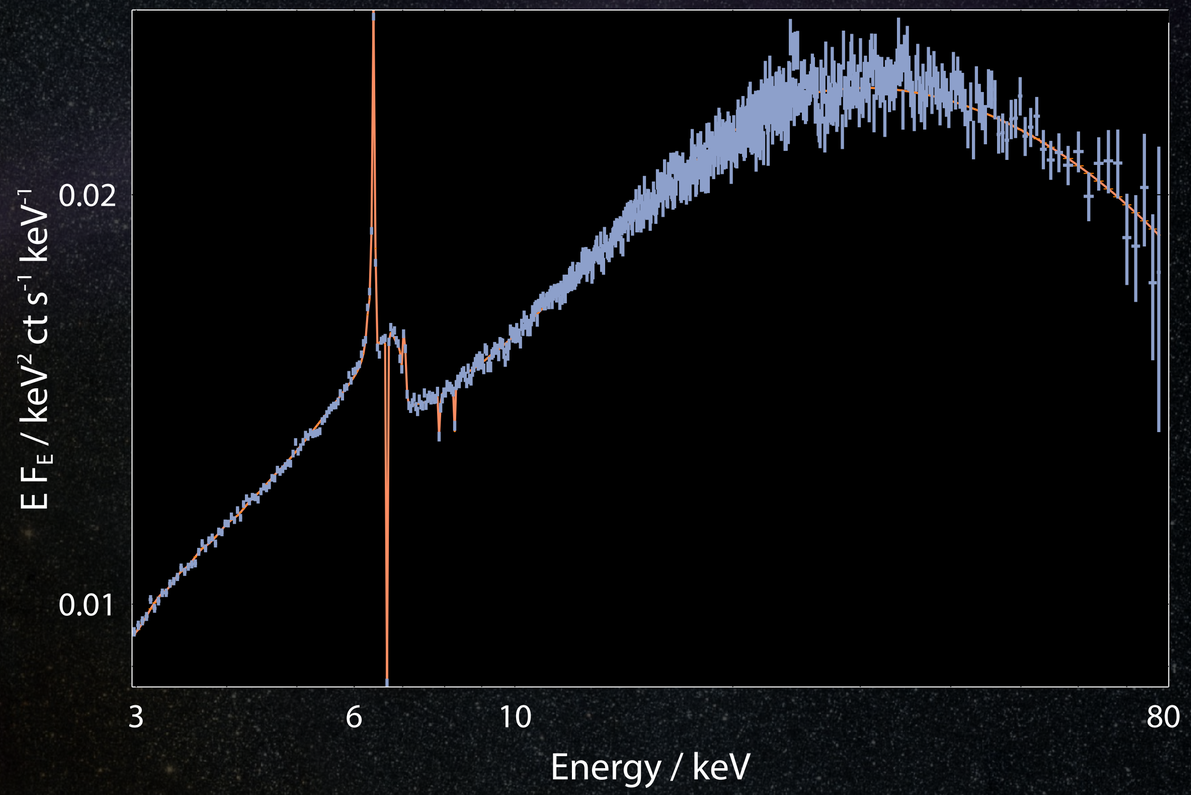


Reflection from the Inner Accretion Disc

X-ray reflection

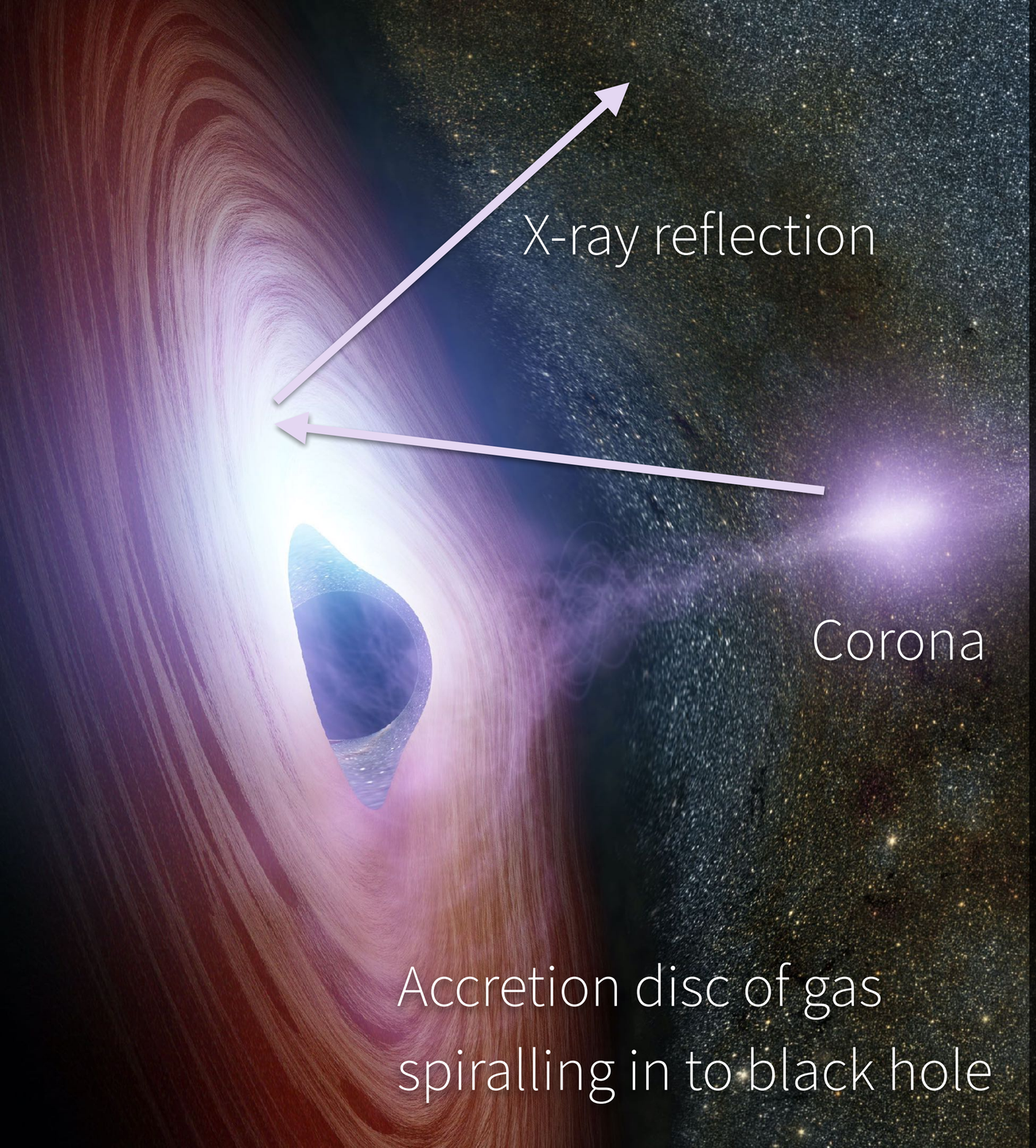
Corona

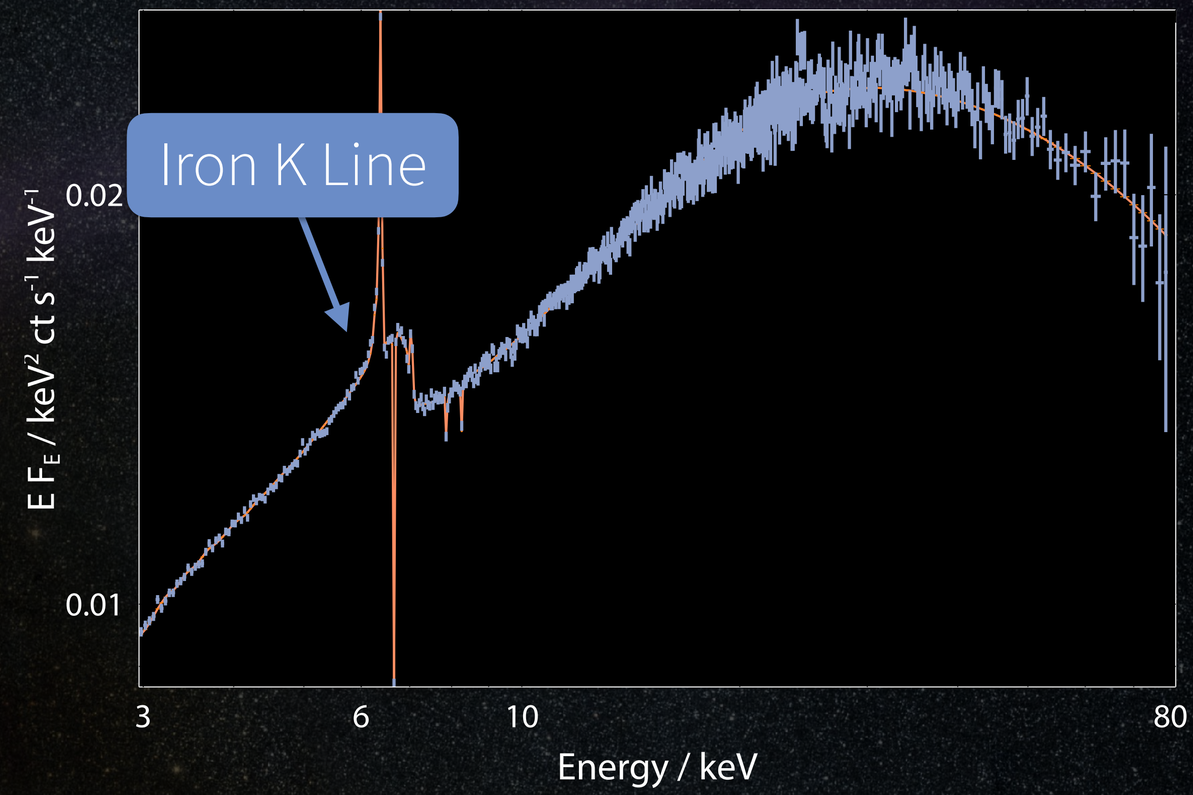
Accretion disc of gas spiralling in to black hole



Stacked NuSTAR spectrum of 18 Seyfert galaxies shows the characteristic features of X-ray reflection from the inner accretion disc

Reflection from the Inner Accretion Disc





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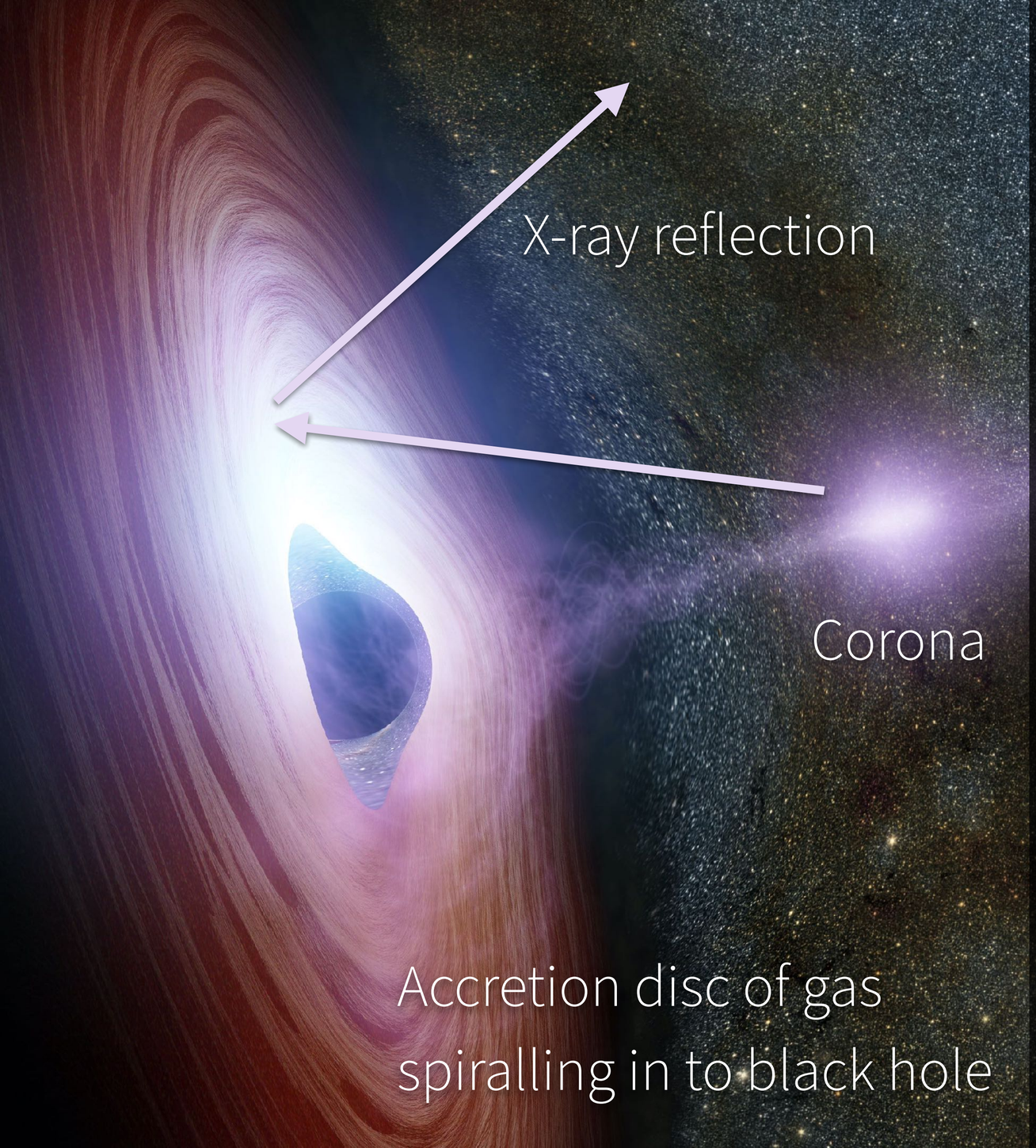
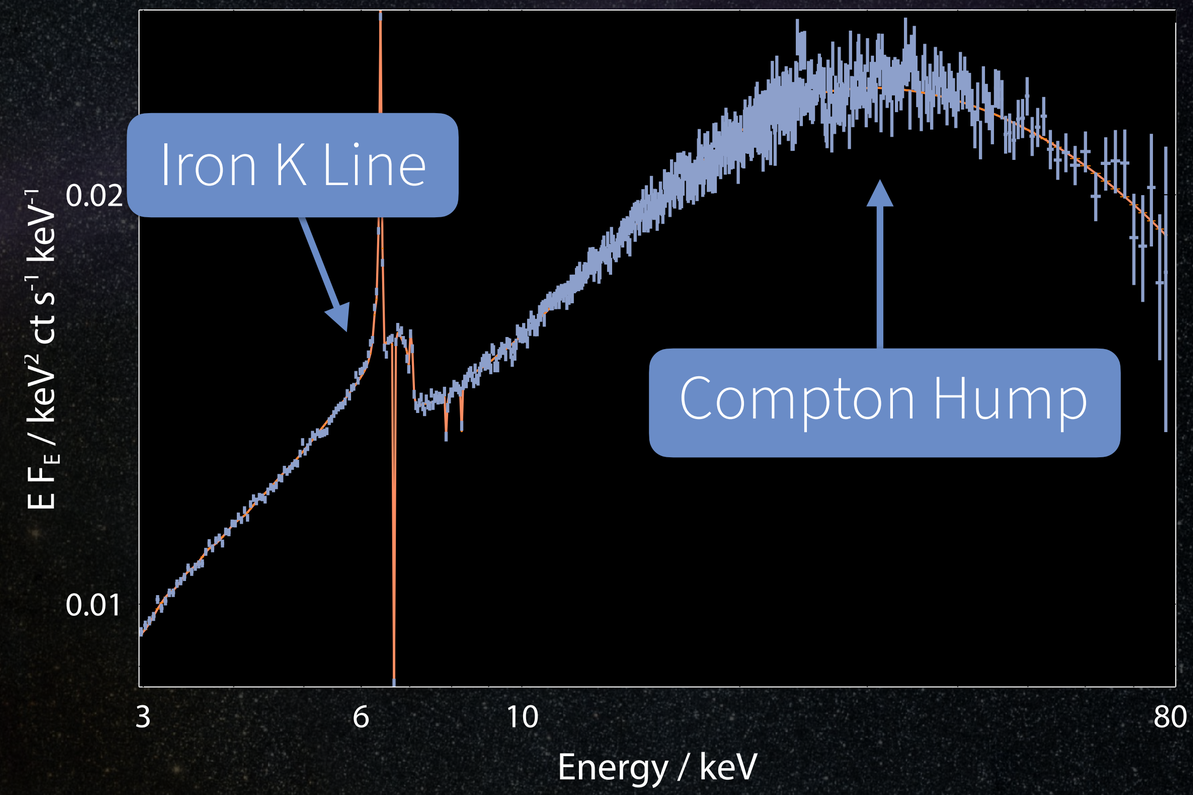
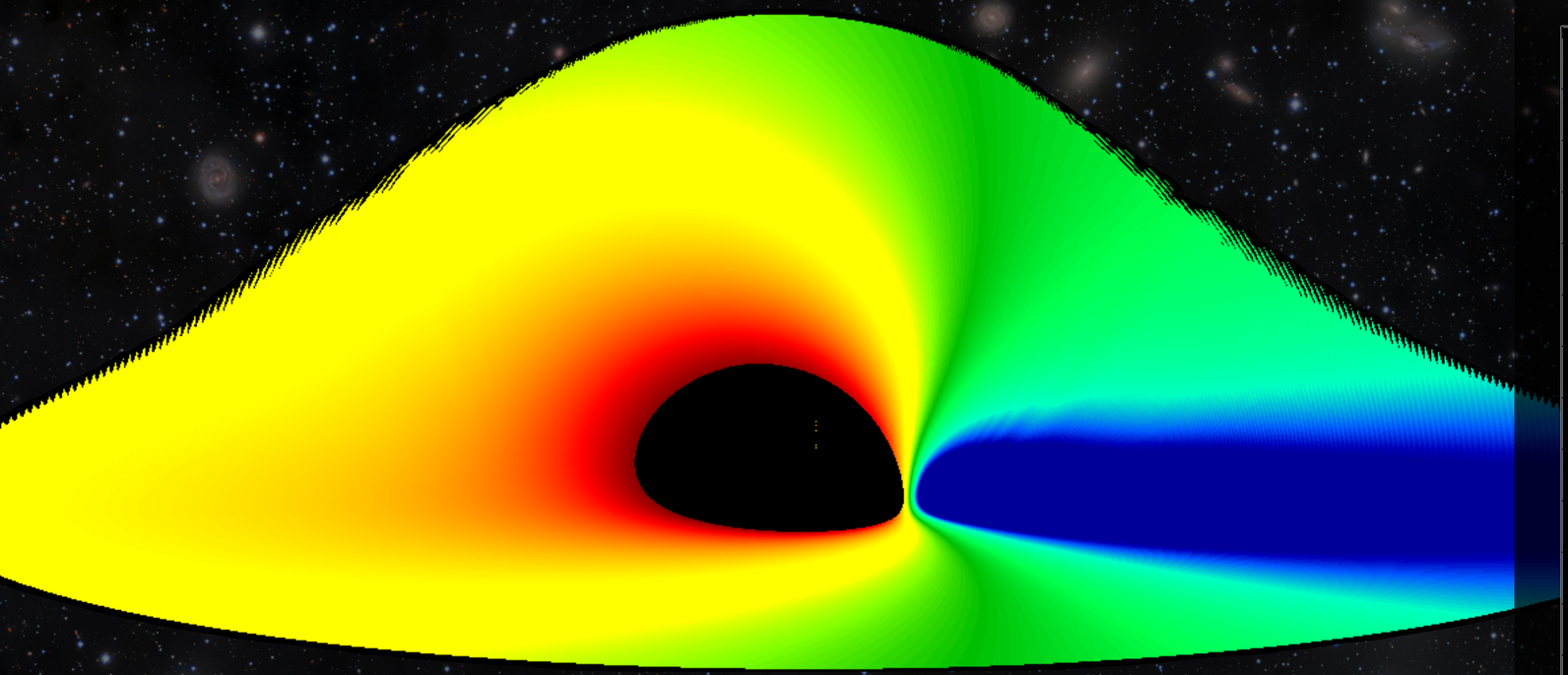


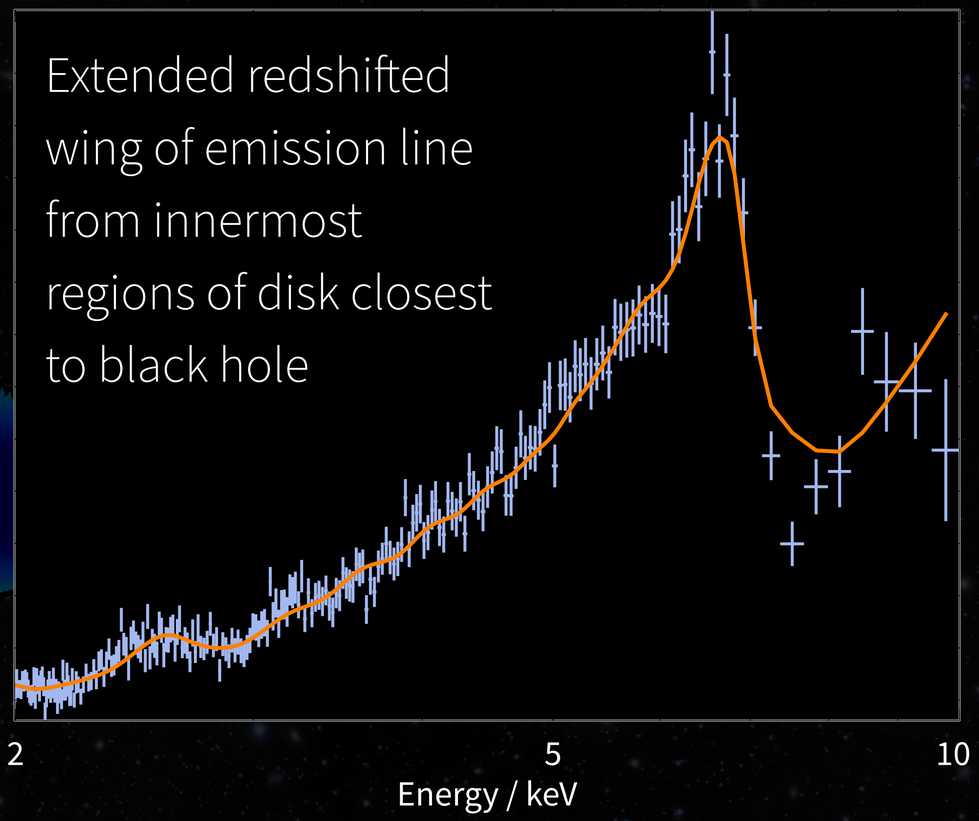


Stacked NuSTAR spectrum of 18 Seyfert galaxies shows the characteristic features of X-ray reflection from the inner accretion disc

The Relativistic Iron K Line



Relativistic effects including Doppler shifts and gravitational redshifts shift the observed energy (or wavelength) of photons emitted or reflected from different locations on the disk

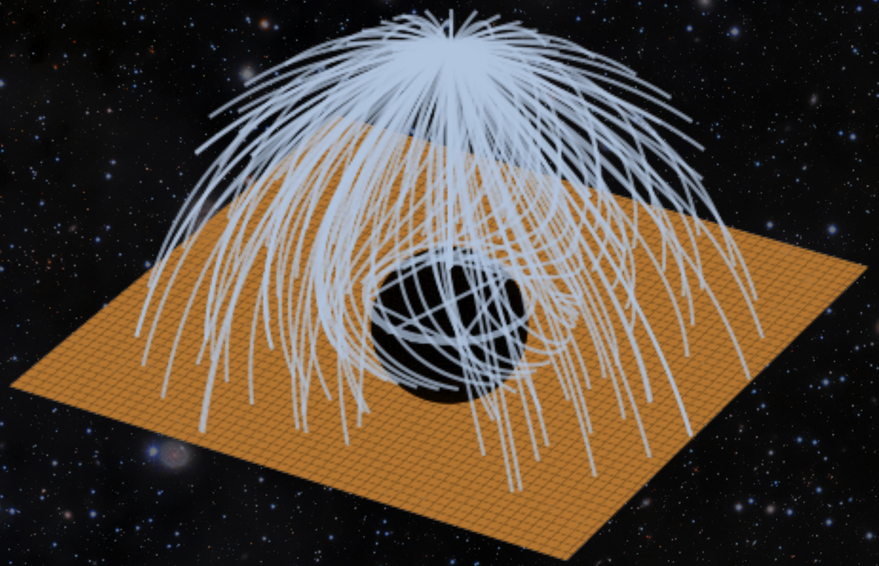


1.5 Ms iron K band spectrum of IRAS 13224–3809 with XMM-Newton

The effects of General Relativity just outside the event horizon

Wilkins et al. 2012, 2016, 2020

The effects of General Relativity just outside the event horizon



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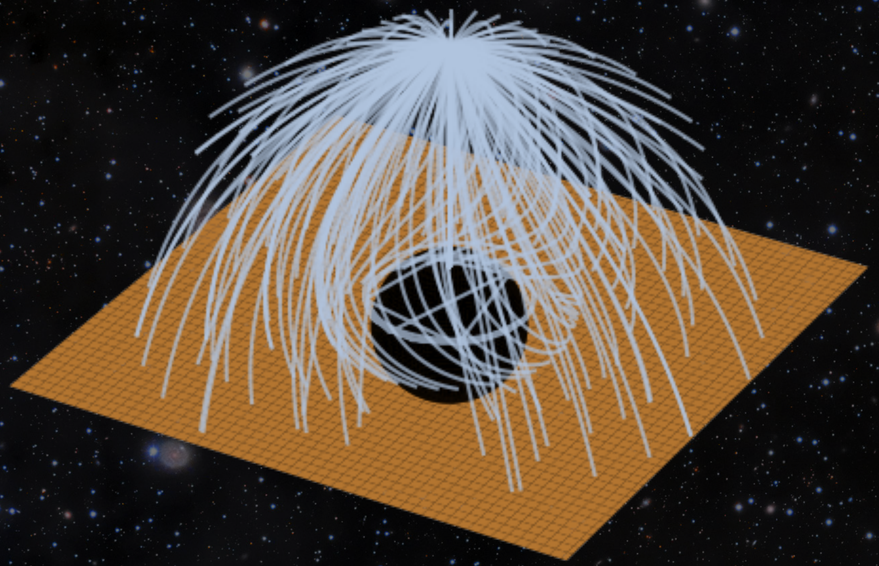

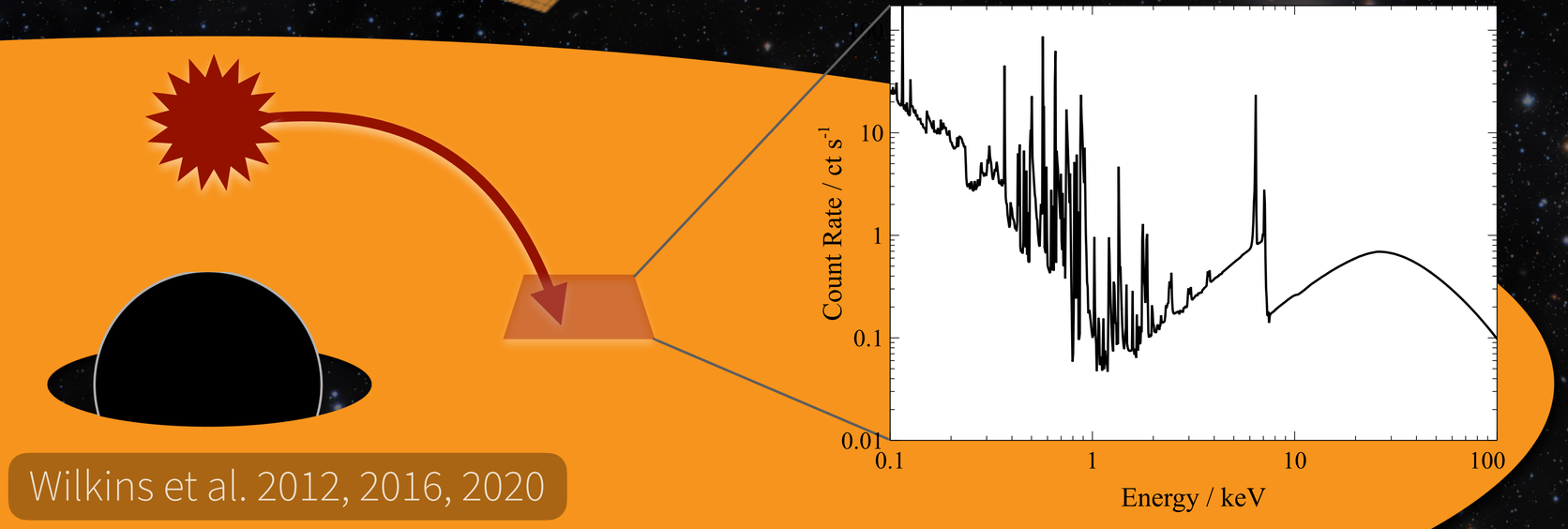

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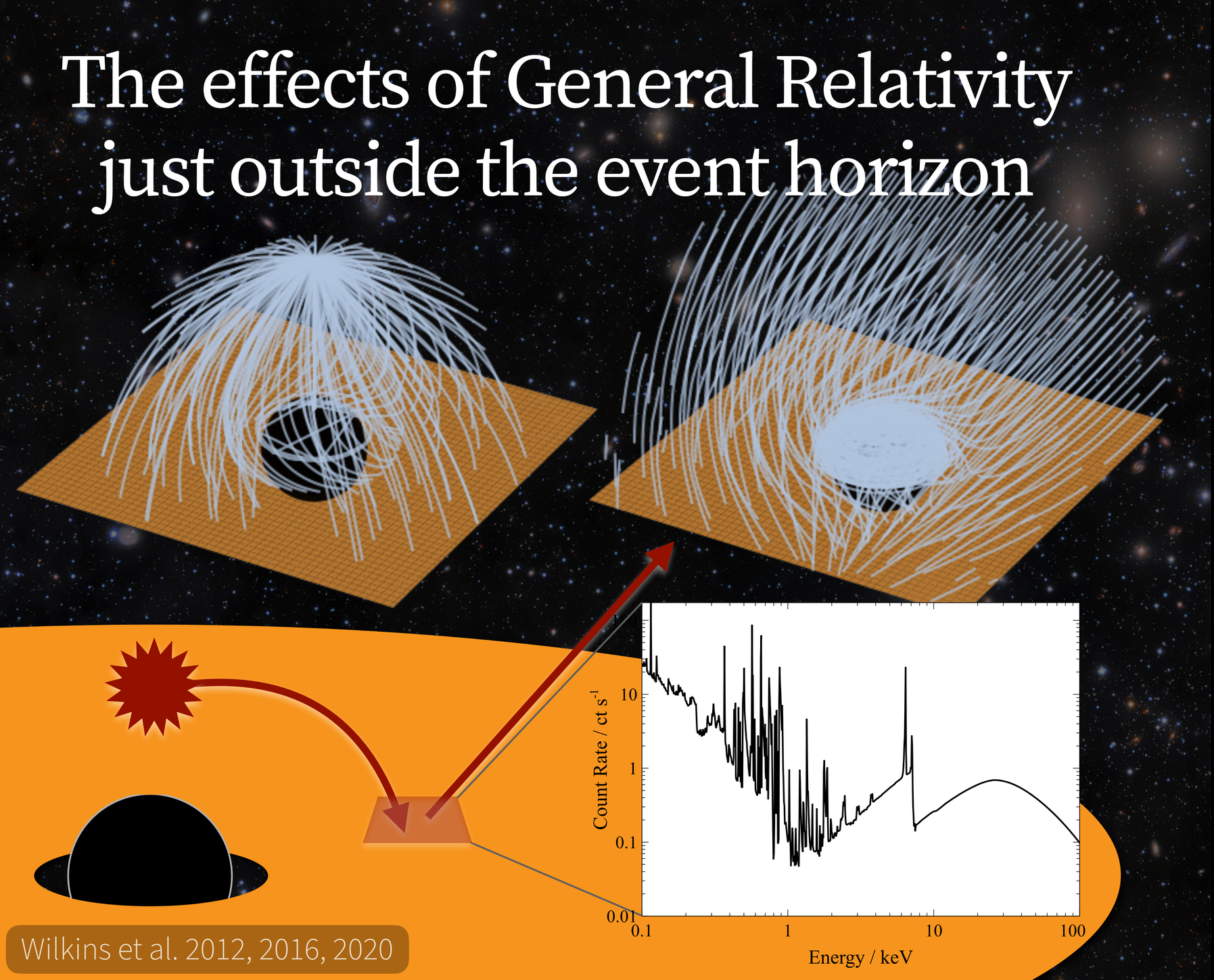

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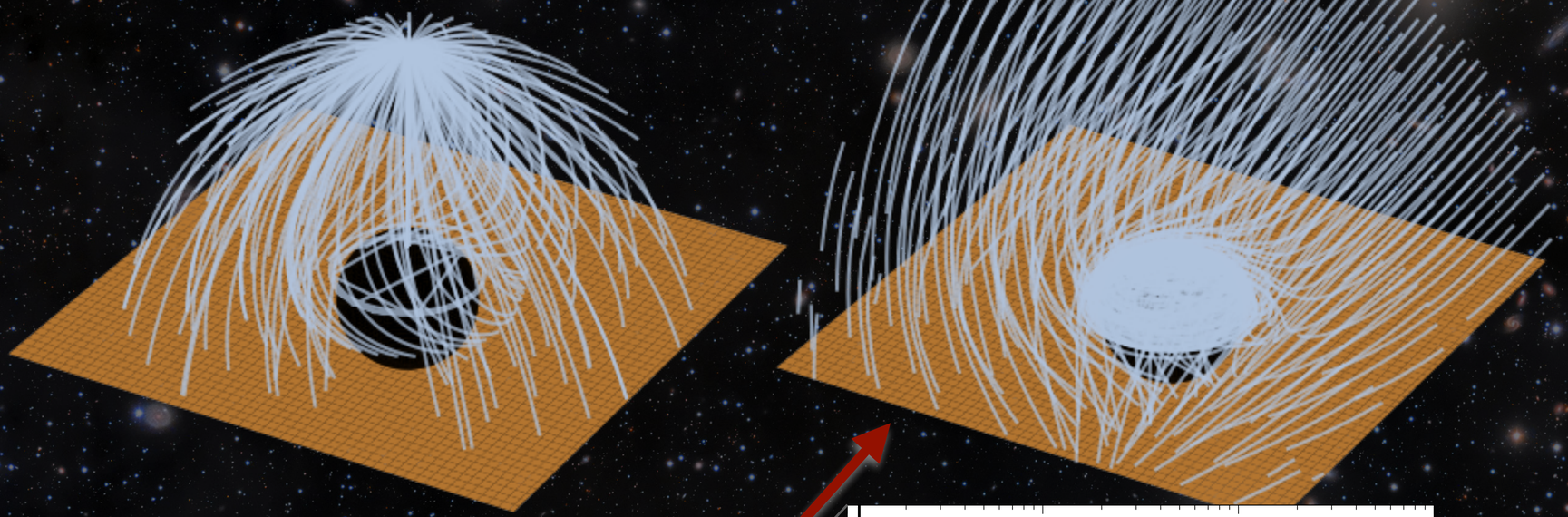

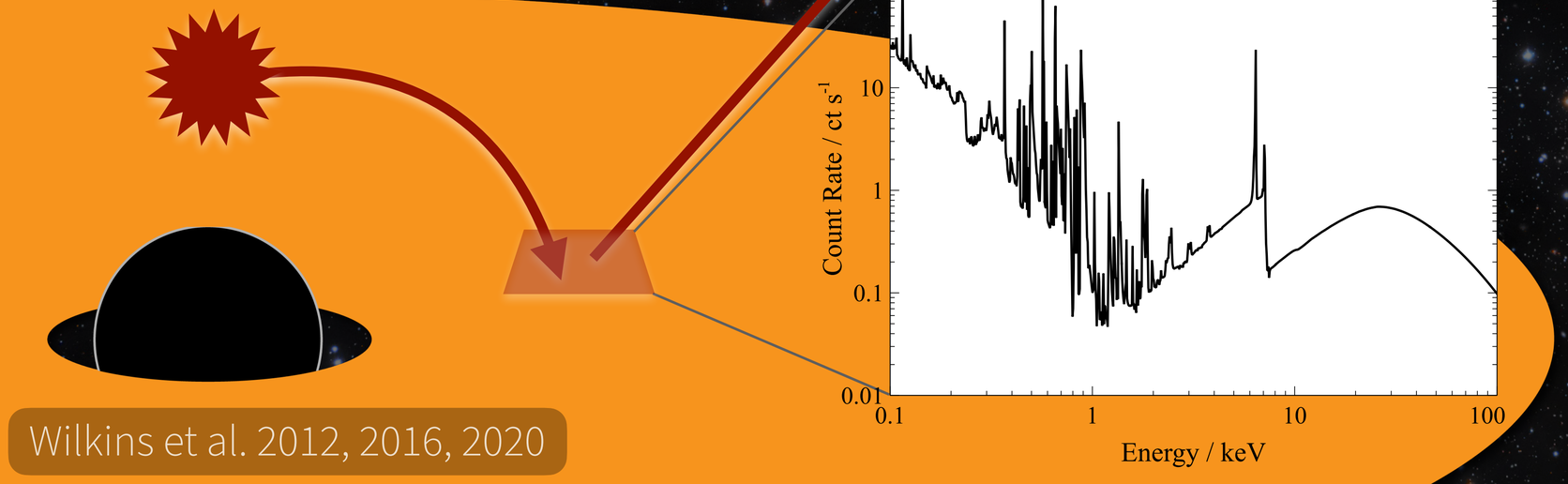

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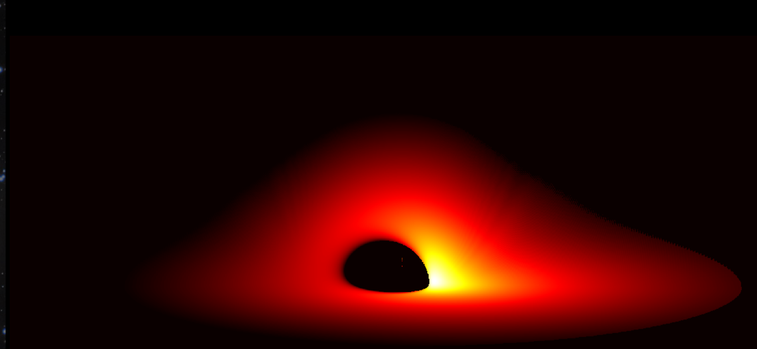
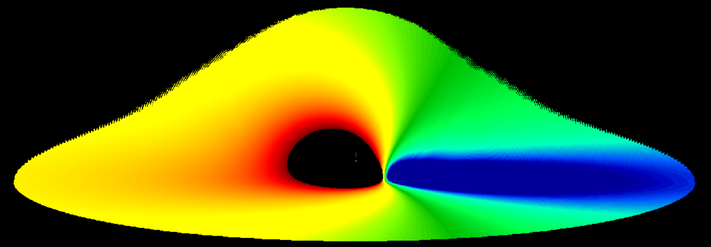
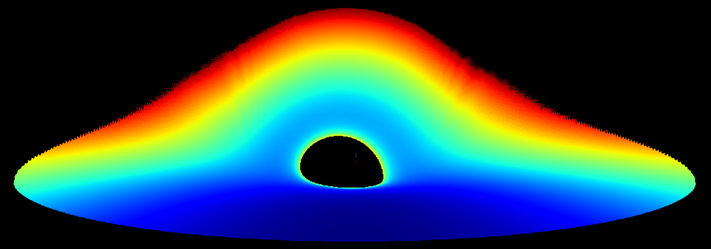


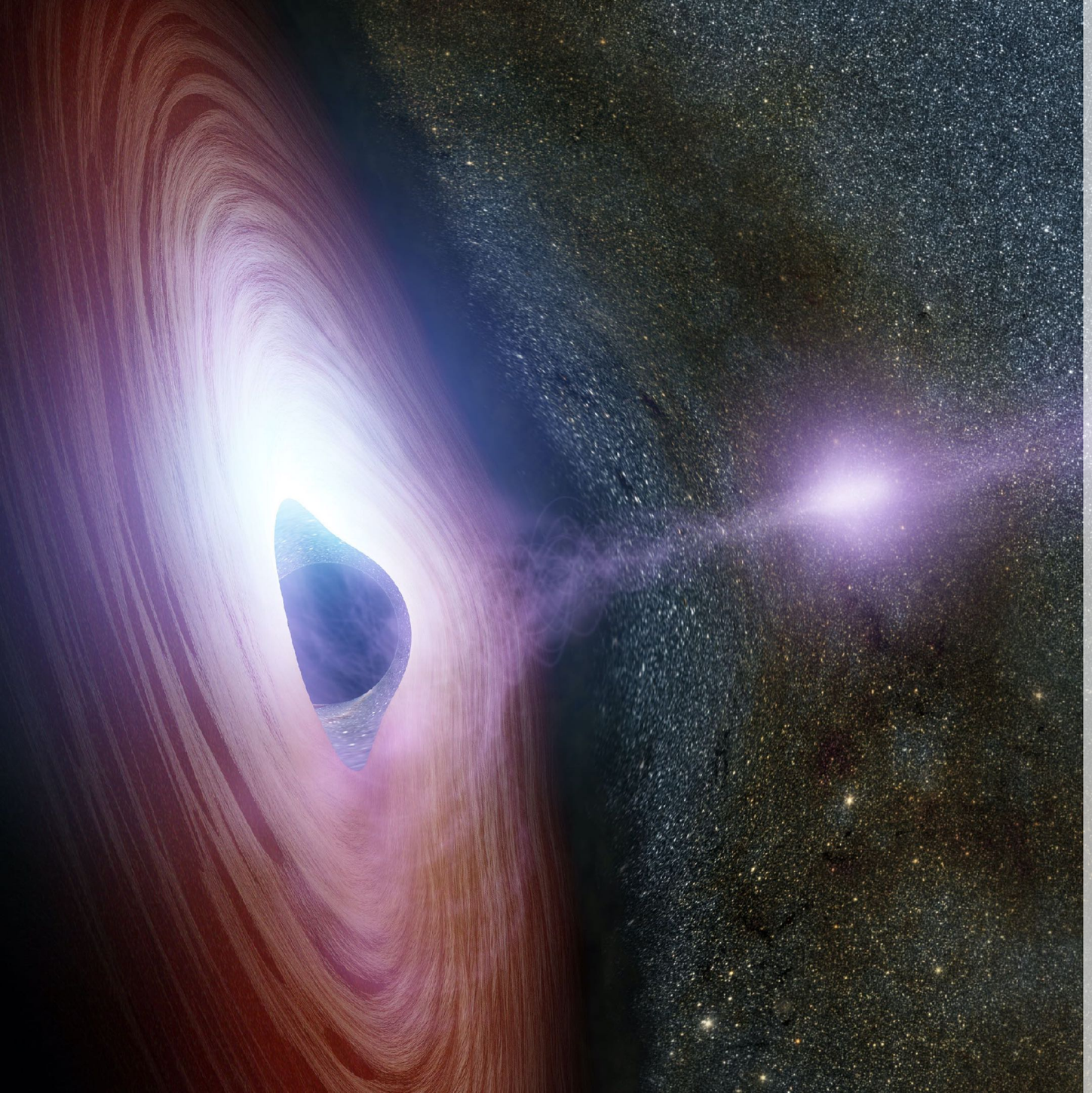
Intensity



Energy shift and spectrum



Light travel time

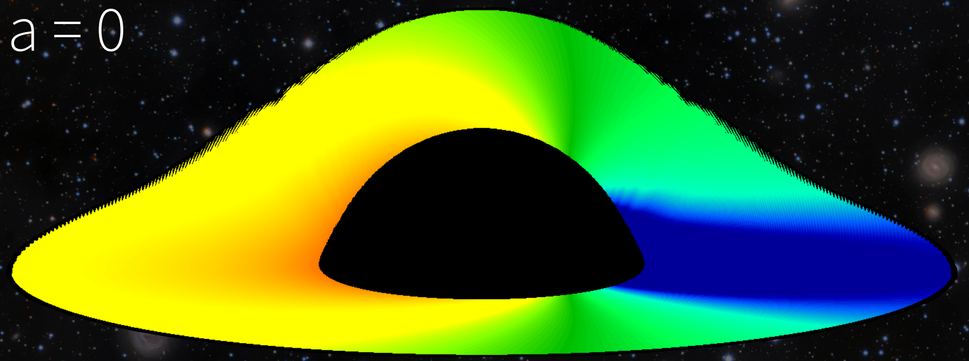


X-ray reflection and reverberation mapping of the inner accretion flow can tell us about…

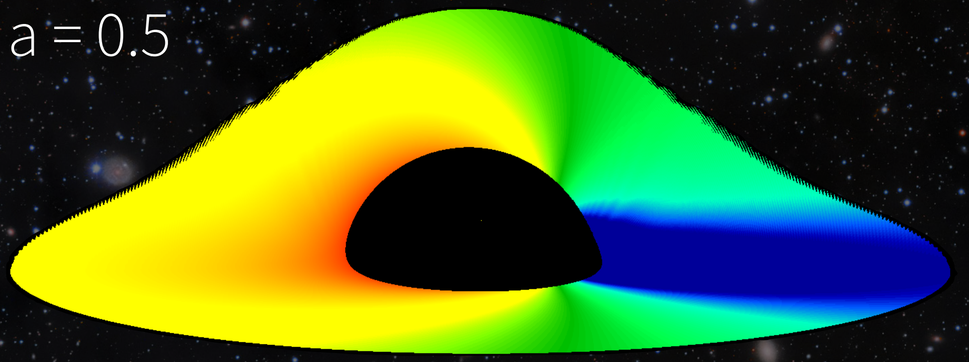
- Geometry of the accretion disc and its inclination to our line of sight
- Spin of the black hole
- Location, geometry and structure of the corona
- The connection between the inner accretion disc, corona and jet

Measuring black hole spin

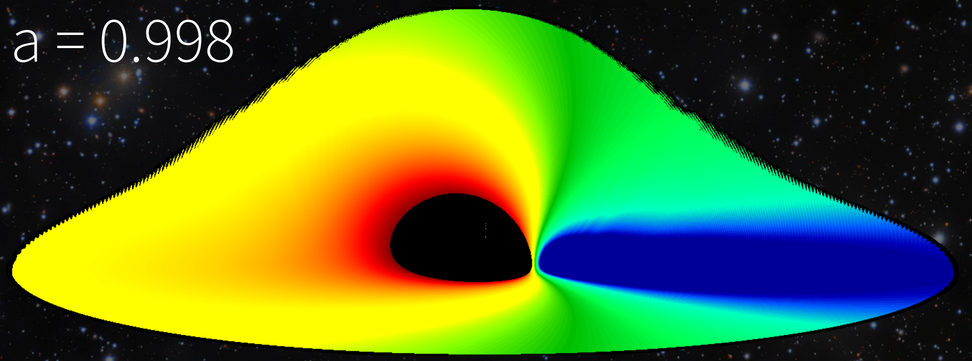
a = 0

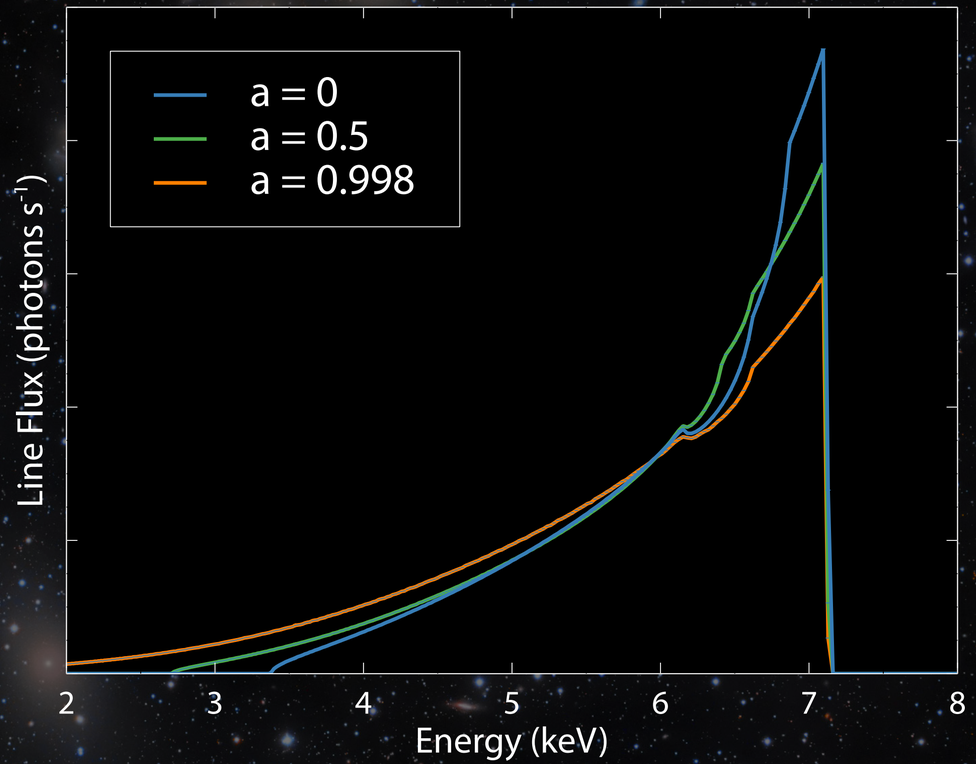


a = 0.5

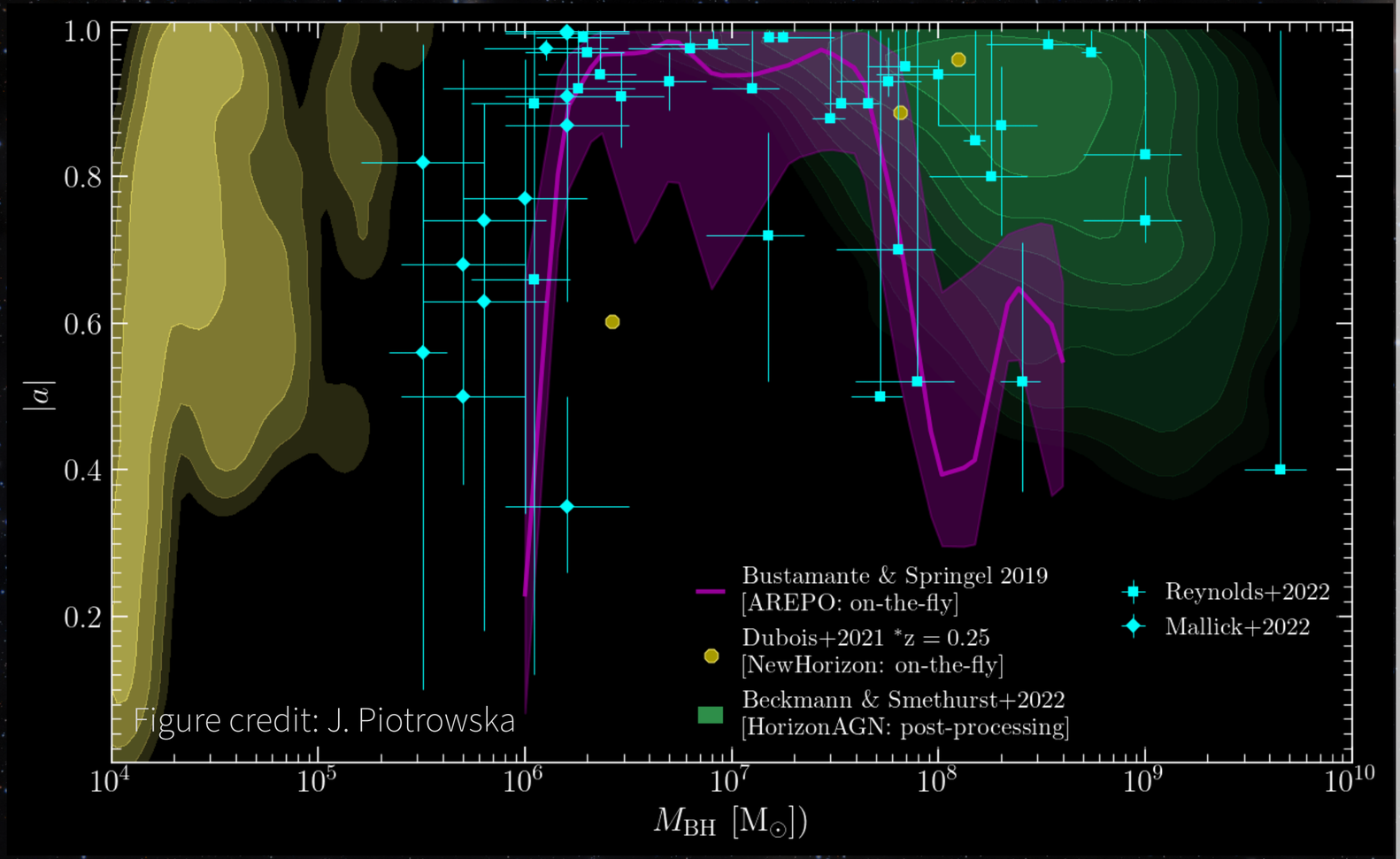


a = 0.998





- As spin increases, ISCO moves to smaller radius and disk can extend closer to black hole
- Inner radius of disk determines extremal redshift of broad iron K emission line in reflection spectrum



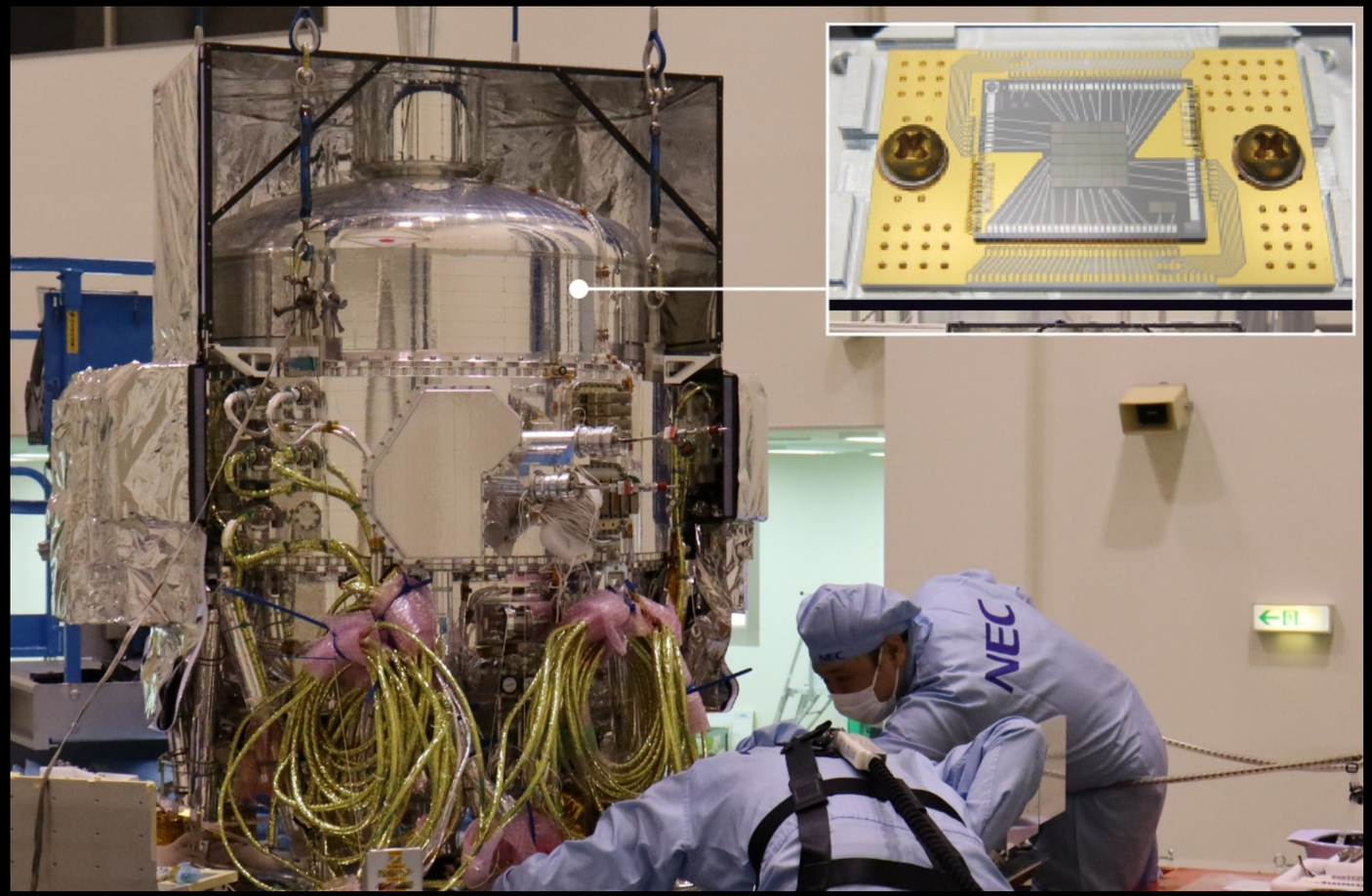
The measured spins of supermassive black holes plotted against their masses, compared to the predictions of models for their growth

And the spin distribution of supermassive black holes encodes their growth histories

- Massive black hole seeds grow via accretion and/or mergers
- Angular momentum must be conserved as gas accretes onto a black hole, and the black hole must retain the angular momentum it accretes
- Spin of black hole depends on growth history
- Prolonged uniform accretion of gas inflowing from the same direction causes the black hole to spin to continuously increase
- Chaotic accretion of gas inflowing from different directions, or mergers between black holes reduce the spin to lower values

High-resolution X-ray spectroscopy with XRISM

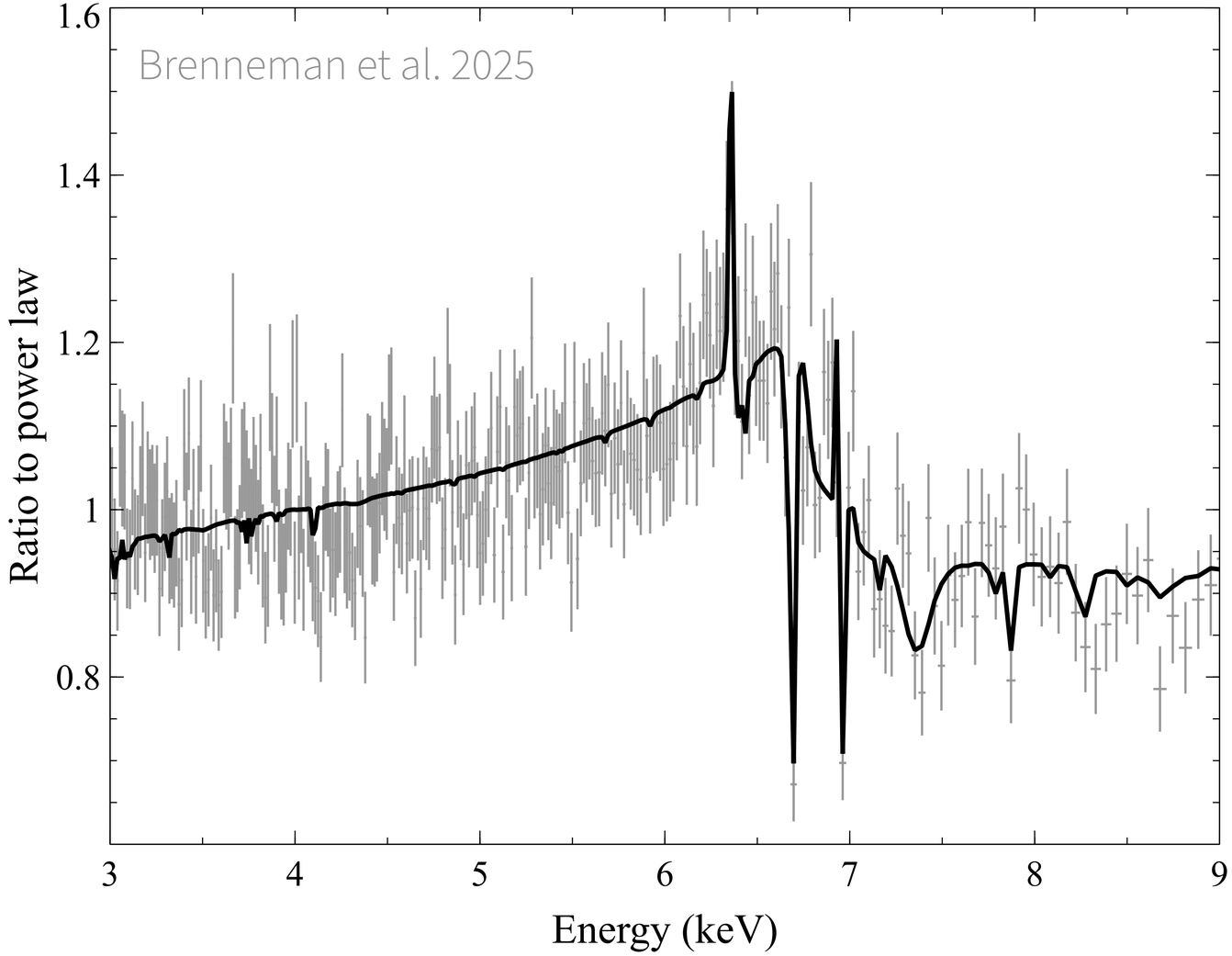
XRISM



The Resolve micro-calorimeter spectrometer measures X-ray photon energies to a resolution of ±4.5eV (E/ΔE = 1500) by measuring the temperature rise as each is absorbed into silicon at T = 50mK

The broad iron K line in MCG–6-30-15

A Seyfert 1 galaxy at z = 0.0077



- XRISM Resolve high-resolution spectrometer separates the broad iron K line from the inner accretion disk from narrow emission and absorption lines
- Narrow lines are blended into the underlying broad line in lower resolution spectra measured by the Xtend CCD

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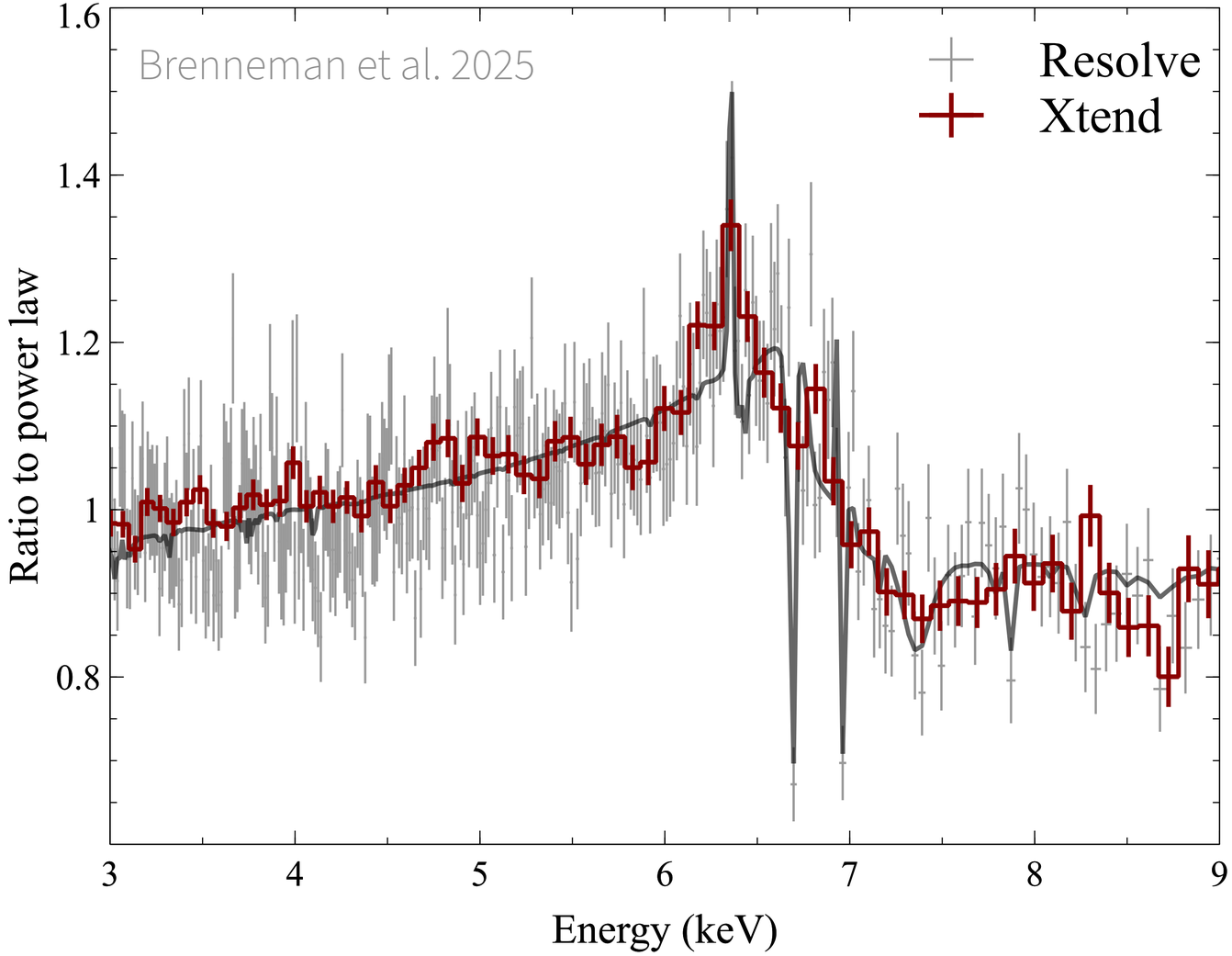

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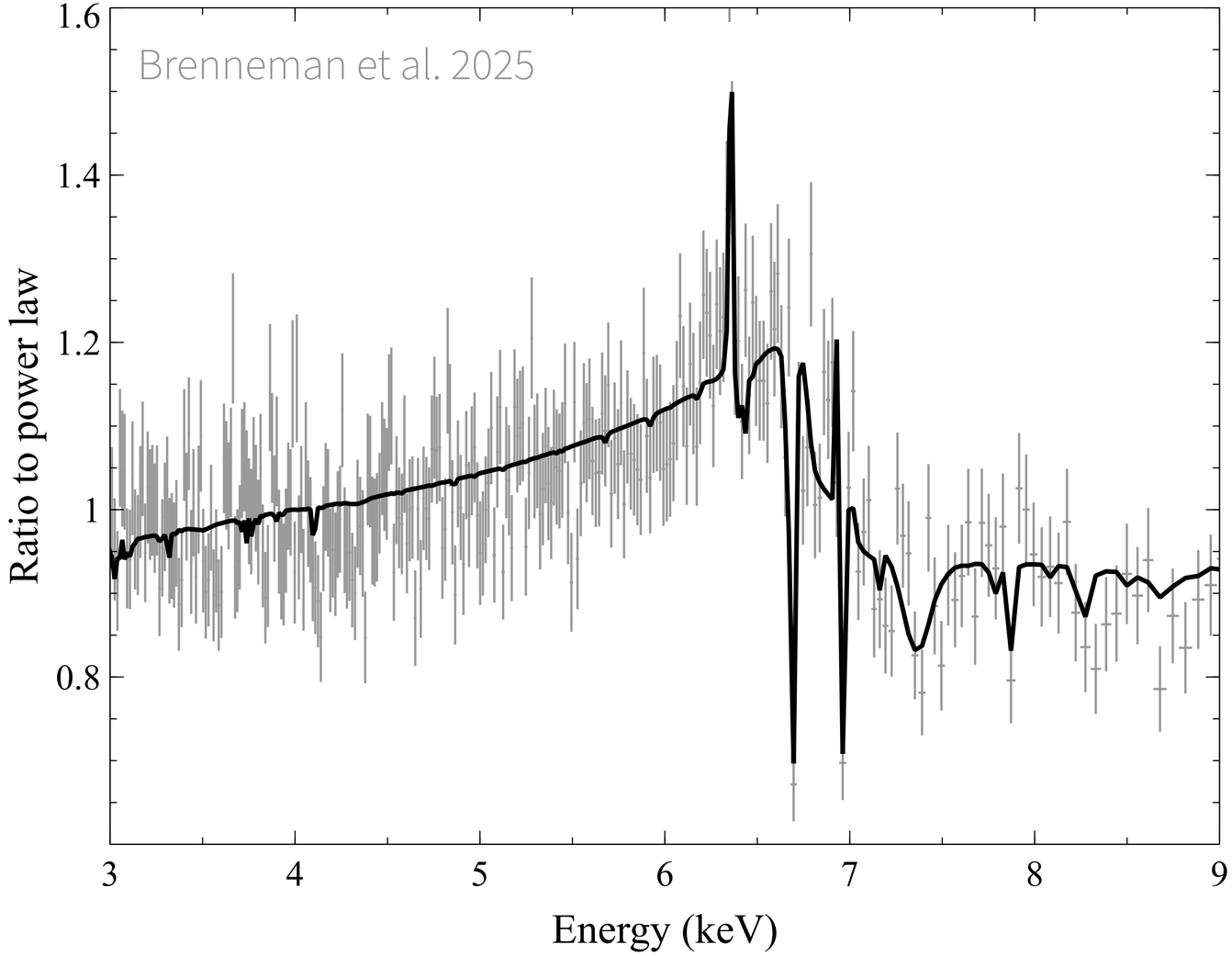

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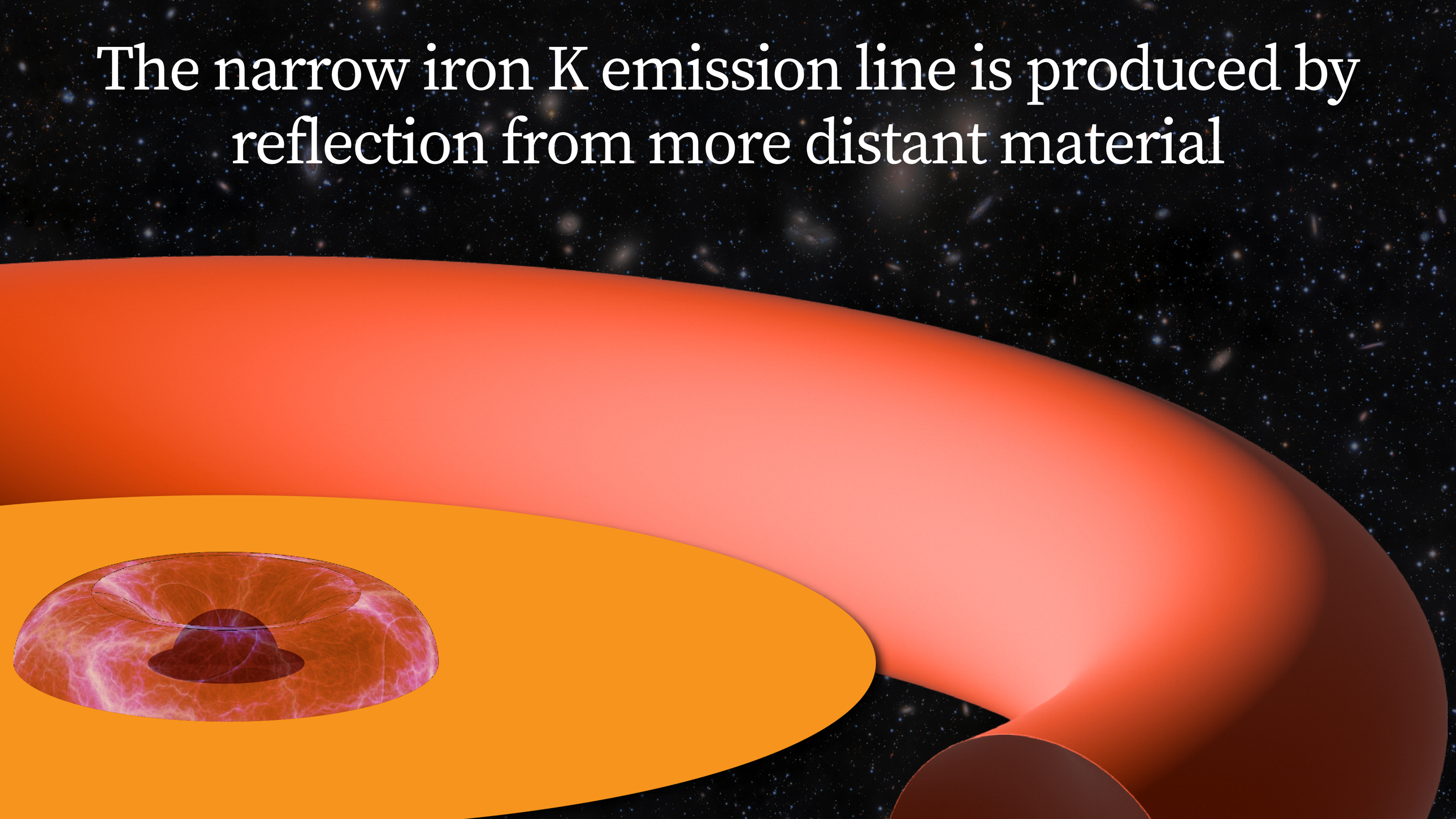
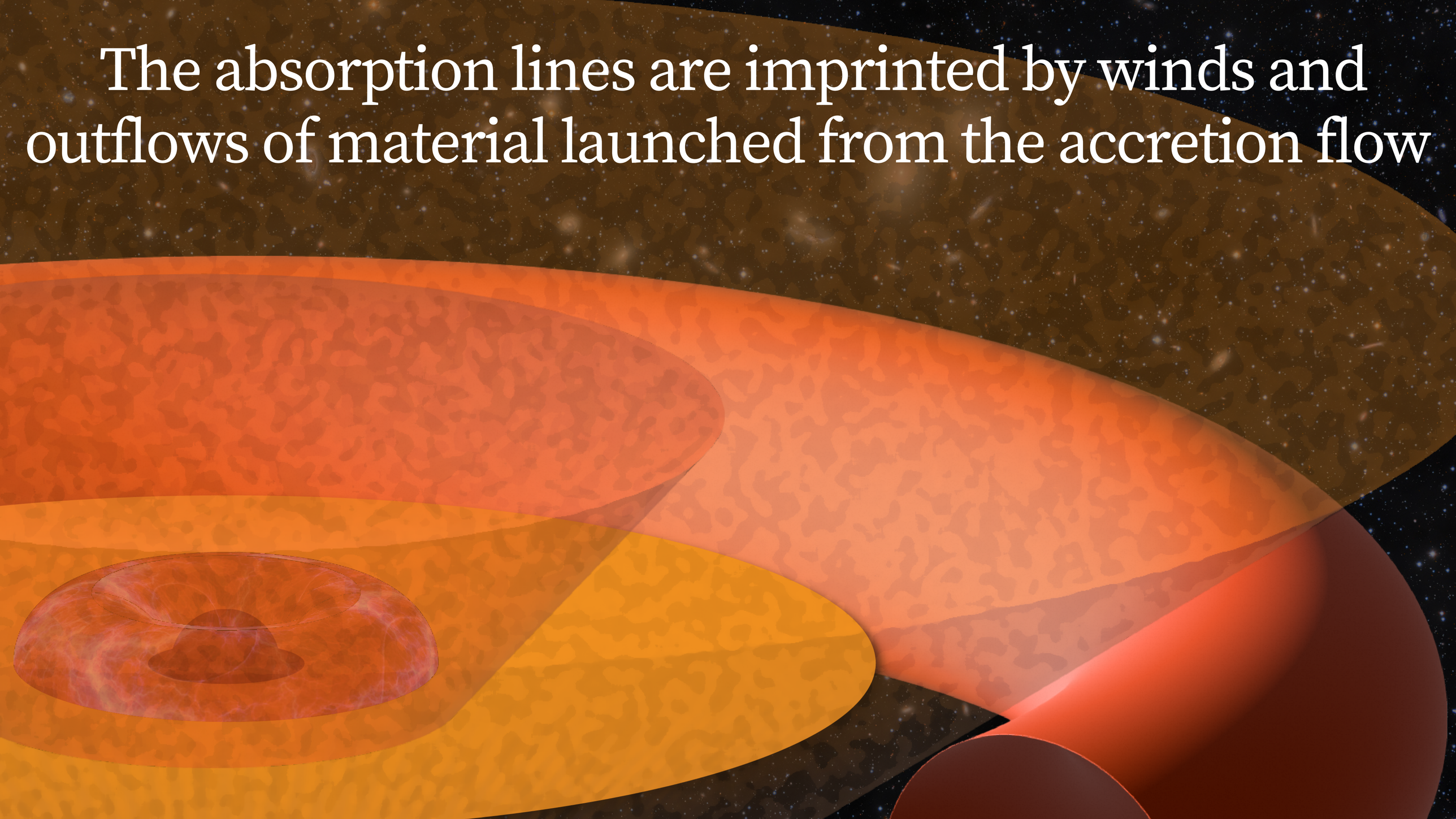
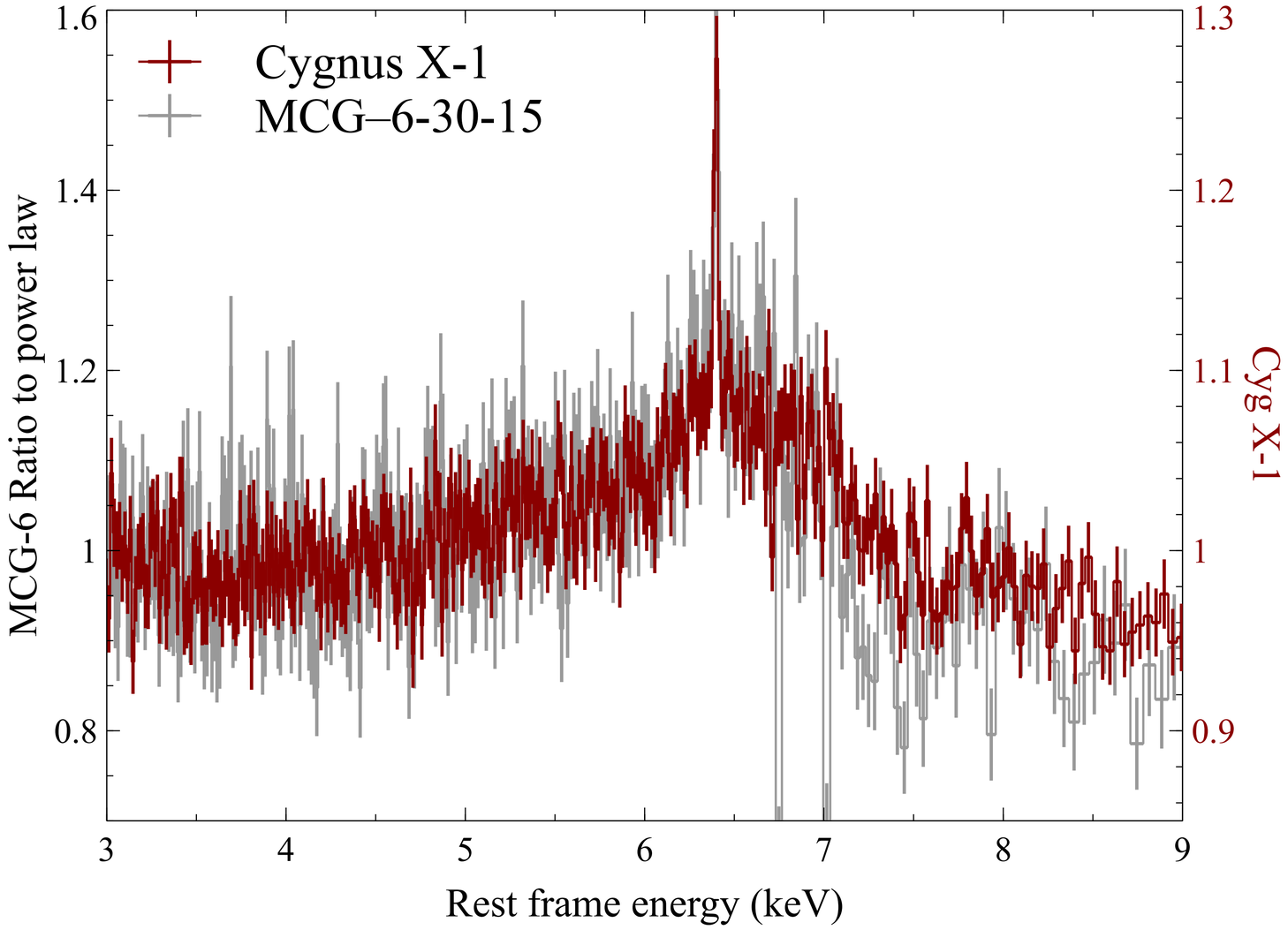
The broad emission line is produced as X-rays from the corona reflect off of the inner accretion disk

The narrow iron K emission line is produced by reflection from more distant material




The absorption lines are imprinted by winds and outflows of material launched from the accretion flow

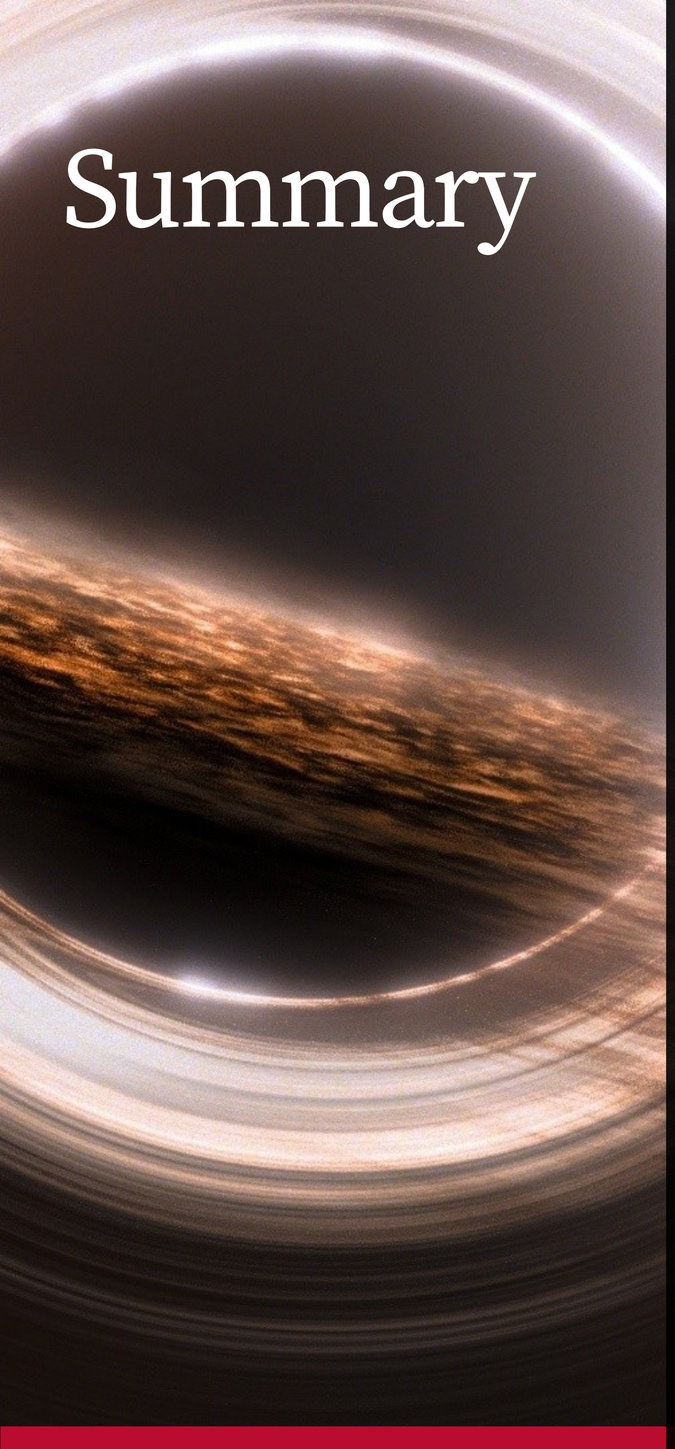
From supermassive to stellar mass black holes



- The shape of the broad iron K line from the inner accretion disk is almost identical between:
  - MCG–6-30-15 - a supermassive black hole in an AGN
  - Cygnus X-1 - a stellar mass black hole in an X-ray binary
- The emission line is generated by the same dynamics of the gas in orbit around a black hole

Brenneman et al. 2025, Draghis et al. 2025

Summary



- X-ray observations allow us to make detailed measurements of the extreme environment just outside the event horizon
- Reflection of X-rays off material falling into the black hole produces emission lines that are broadened by the effects of General Relativity
- We detect relativistically broadened emission lines and X-ray reflection and around black holes across the mass scale from stellar mass to supermassive black holes in active galactic nuclei
- We can make measurements of these lines to reconstruct a map of the inner accretion disk, the particle acceleration region (corona) around the black hole, and to measure fundamental properties of the black hole, including spin
- XRISM is providing the highest-resolution X-ray spectra measured around black holes, allowing us to separate the reflection from the accretion disk, reflection from more distant material and the signatures of winds to high precision