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Active Galactic Nuclei (AGN) from an X-ray perspective

Part II

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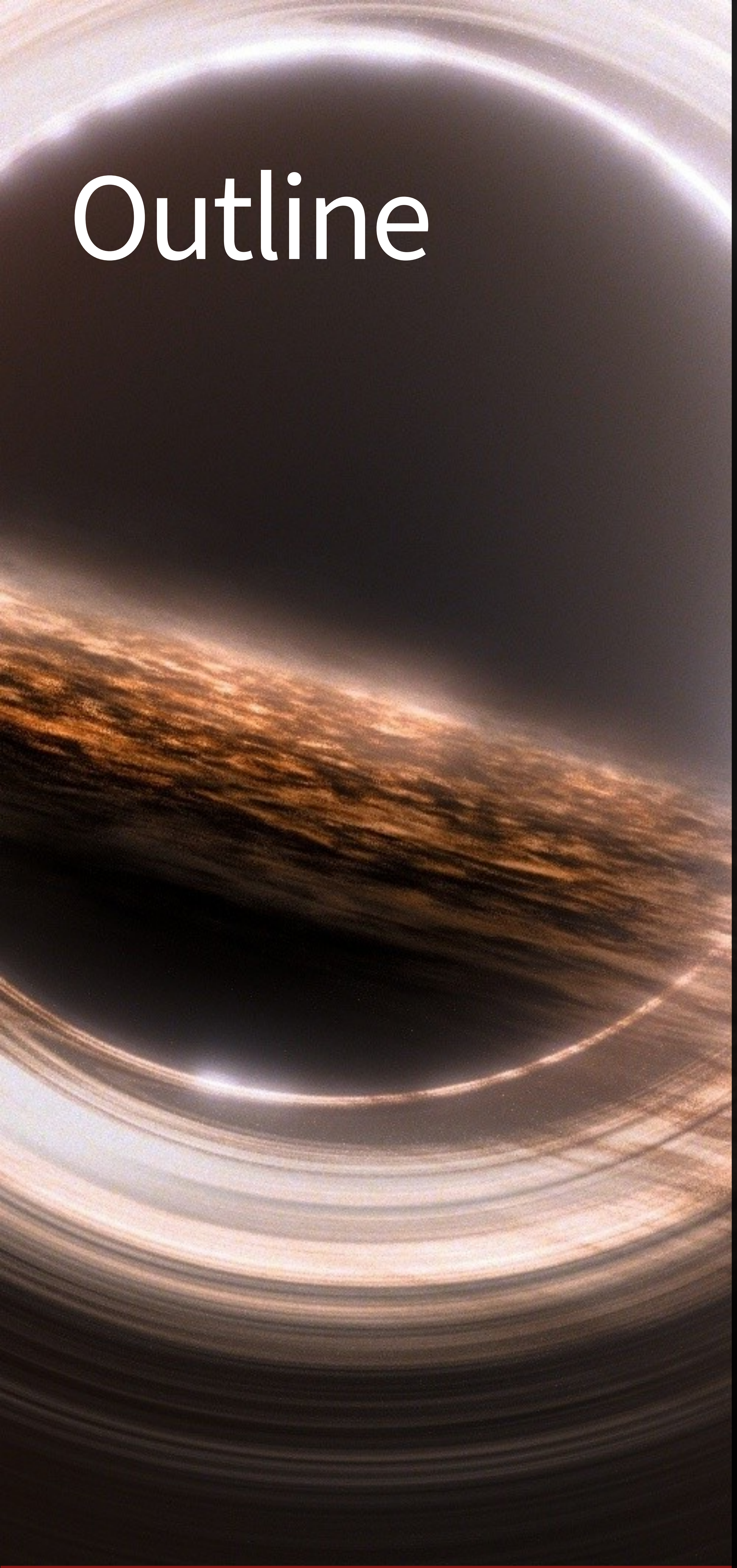


Outline

Lecture 1

- The observable structure of AGN
  - The accretion disc
  - The corona
  - Absorbers and outflows
- AGN feedback

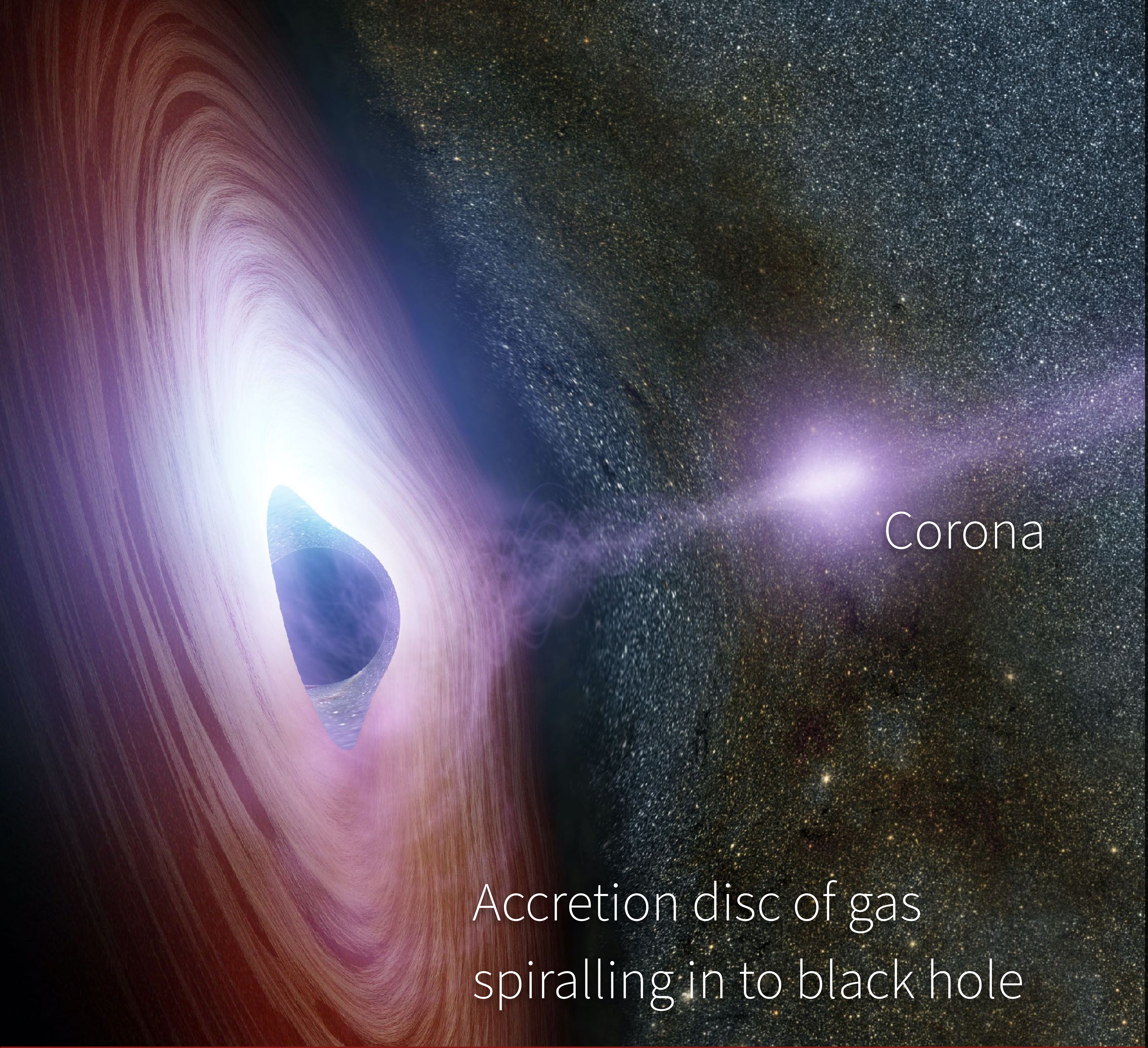
Lecture 2

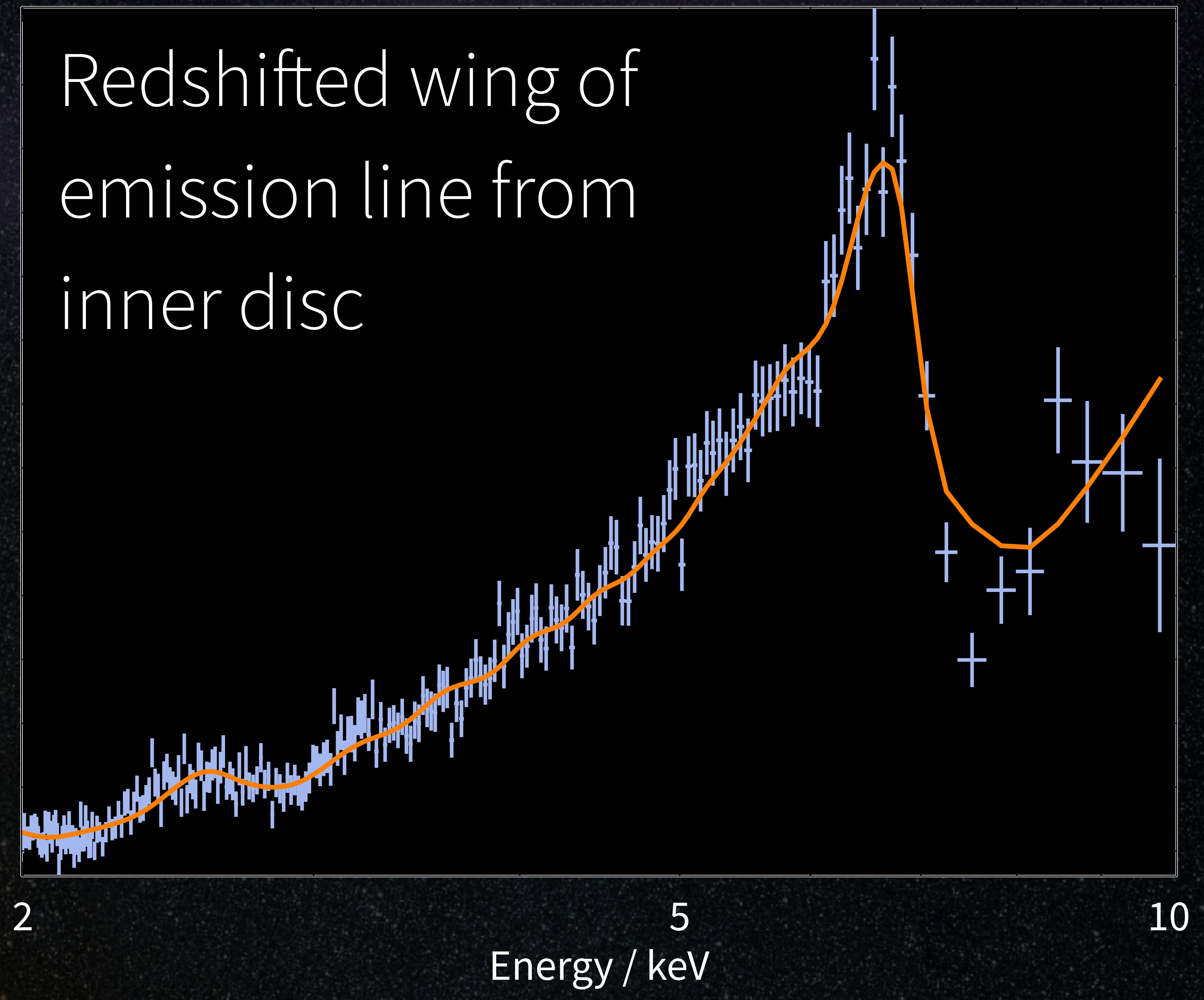
- Seeing to the event horizon of a black hole
  - X-ray reflection
  - X-ray reverberation
- Black hole mass and spin measurements
- The formation of supermassive black holes

X-ray reflection

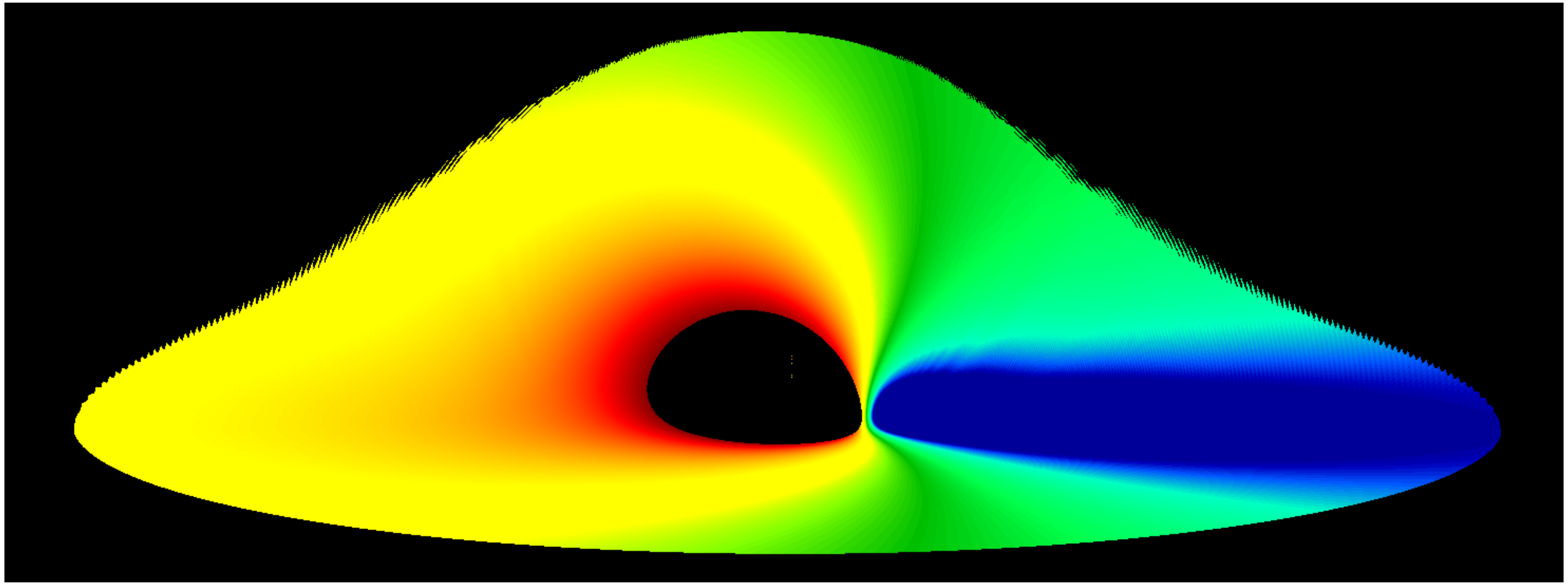
X-ray Reflection

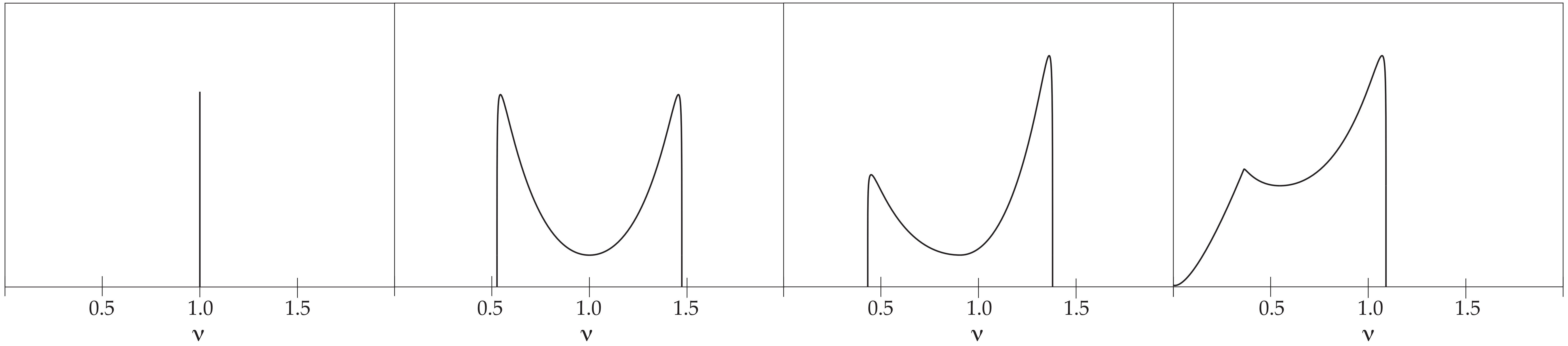
X-ray Reflection





Relativistic reflection and broad emission lines





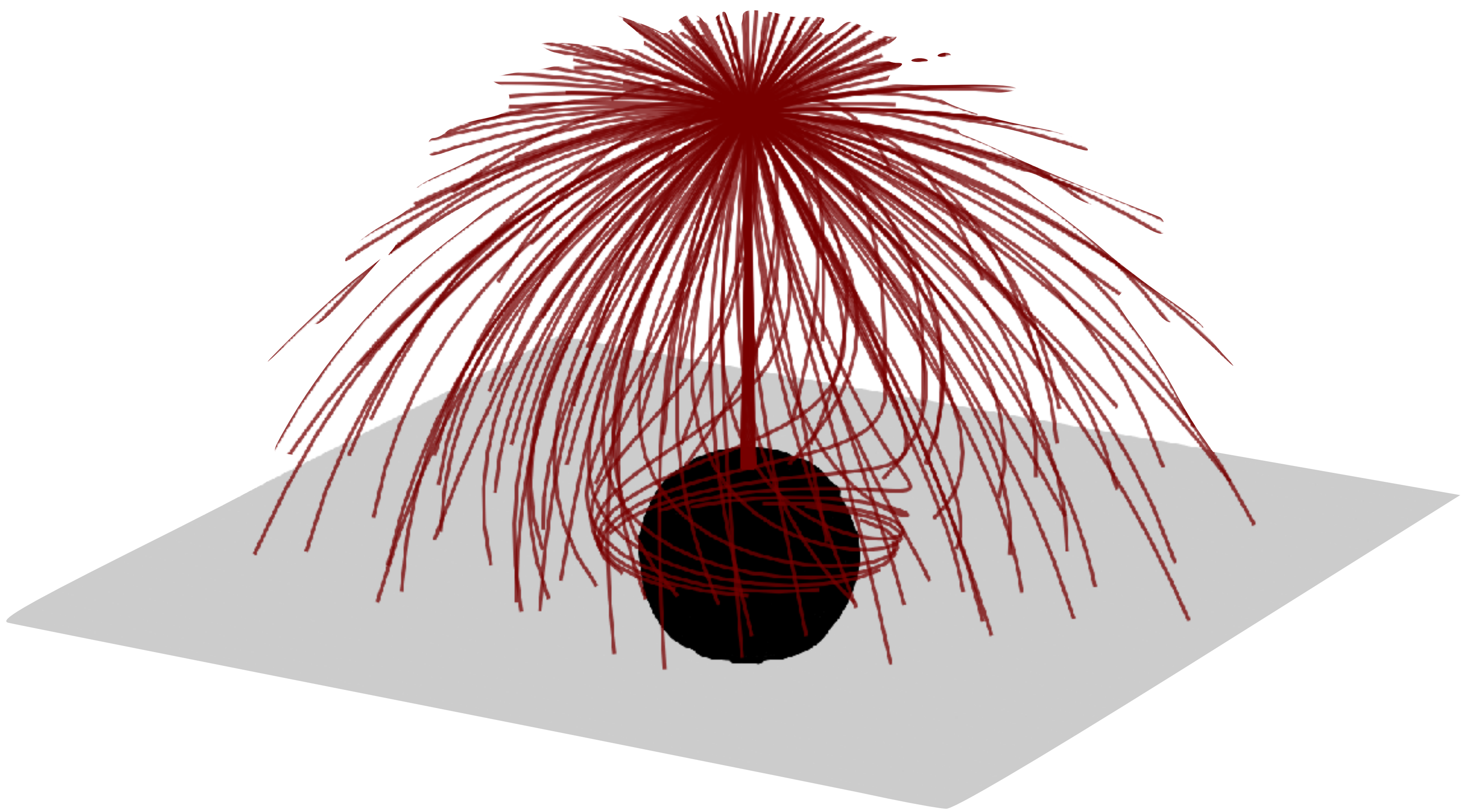
Rest Frame
Emission Line

+ Classical Doppler Shift

+ Special Relativity
Transverse Doppler Shift
Beaming

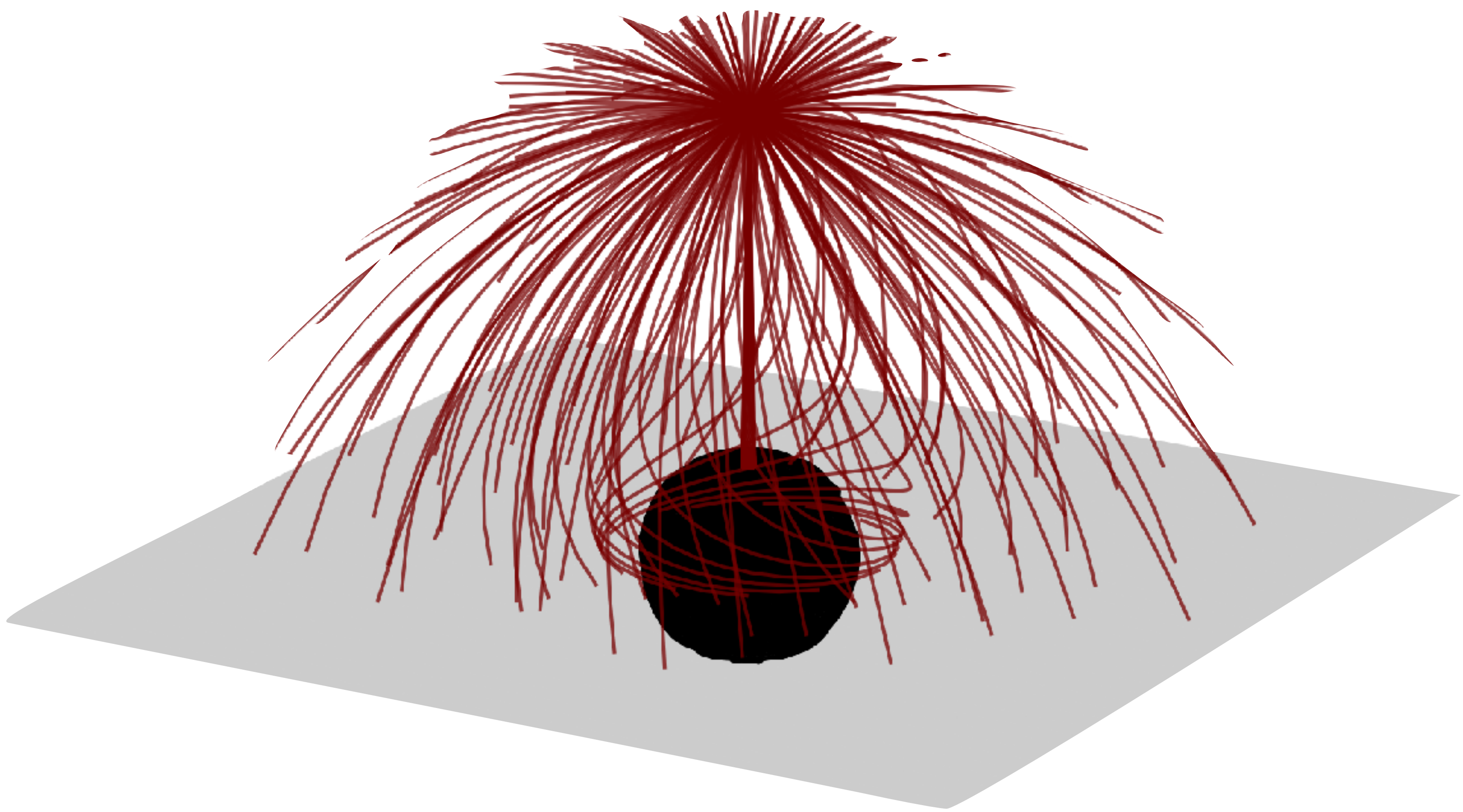
+ General Relativity
Gravitational Redshift

Gravitational light bending

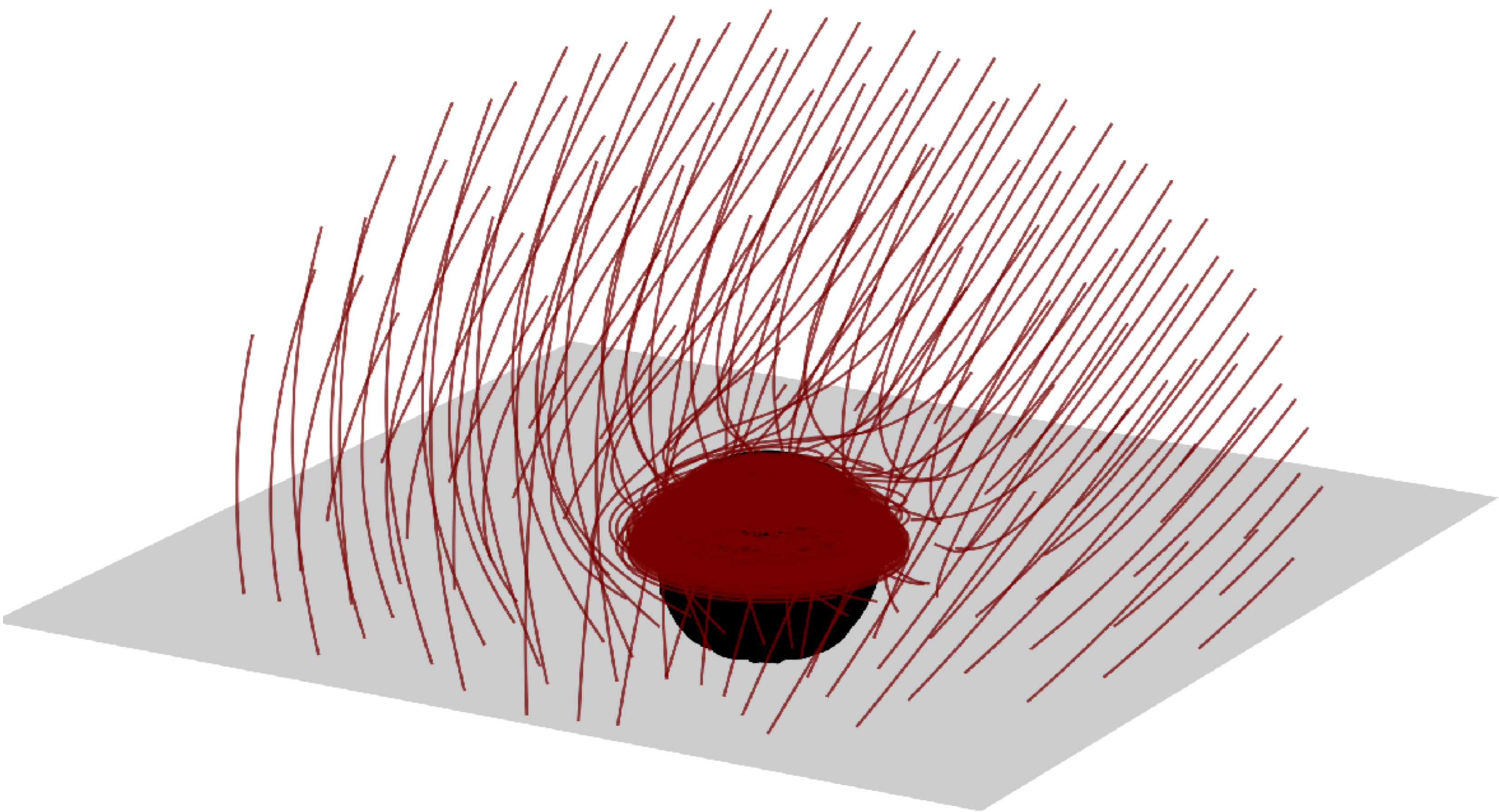


X-rays from corona focused towards black hole — strong illumination of inner disc

Gravitational light bending

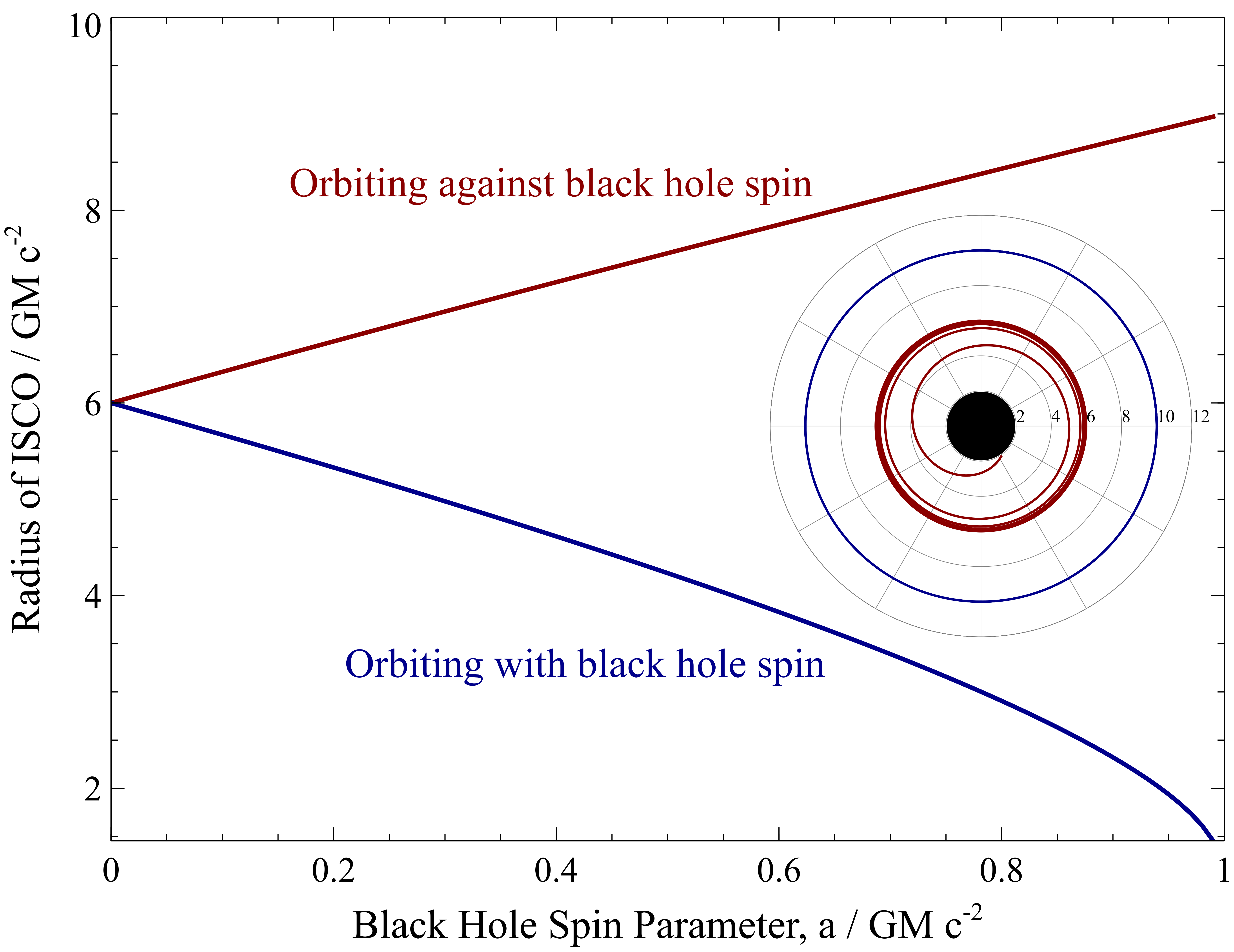


X-rays from corona focused towards black hole — strong illumination of inner disc



Rays bend around black hole, and photons can orbit black hole — back side of disc is visible above the black hole

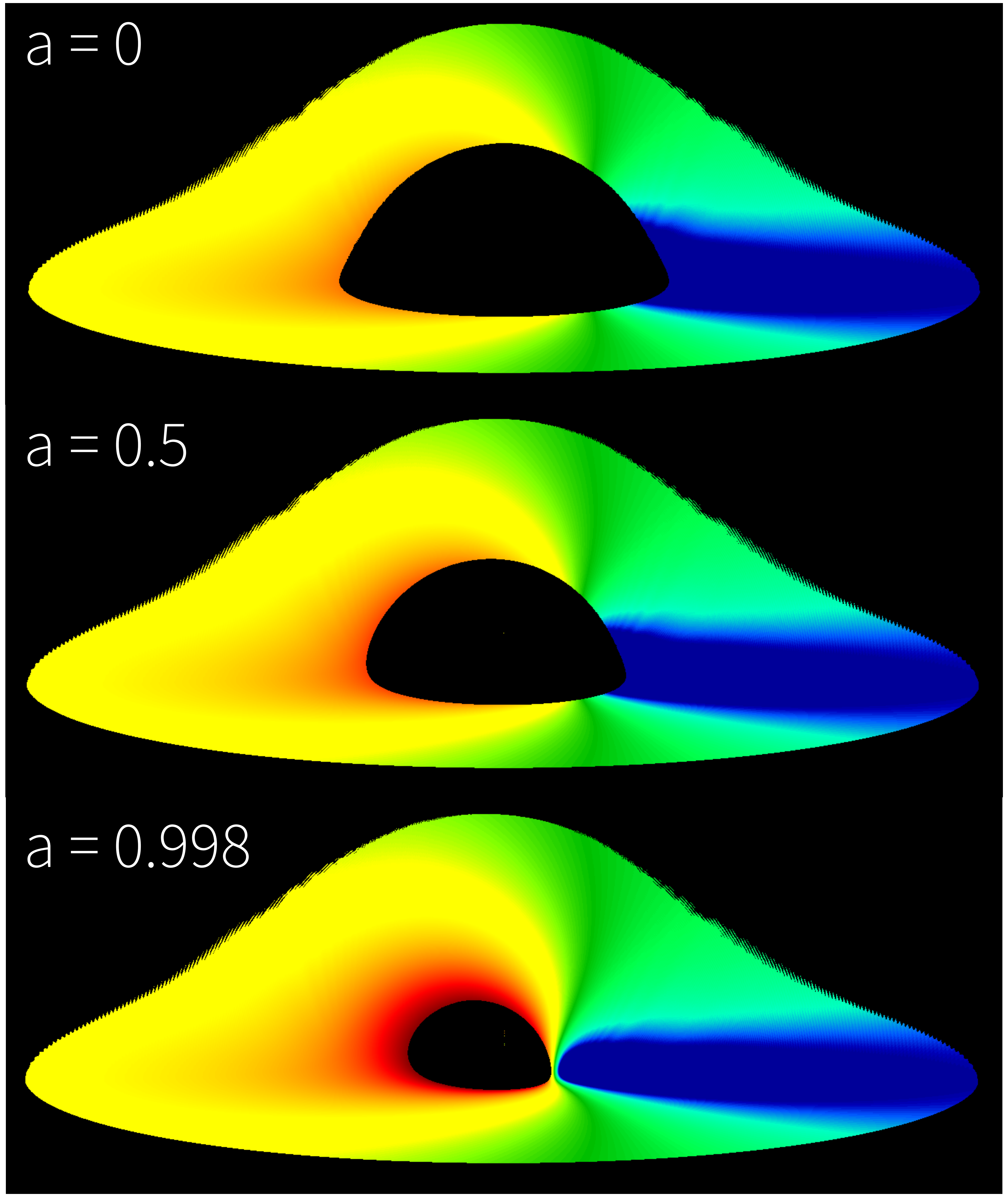
The innermost stable circular orbit

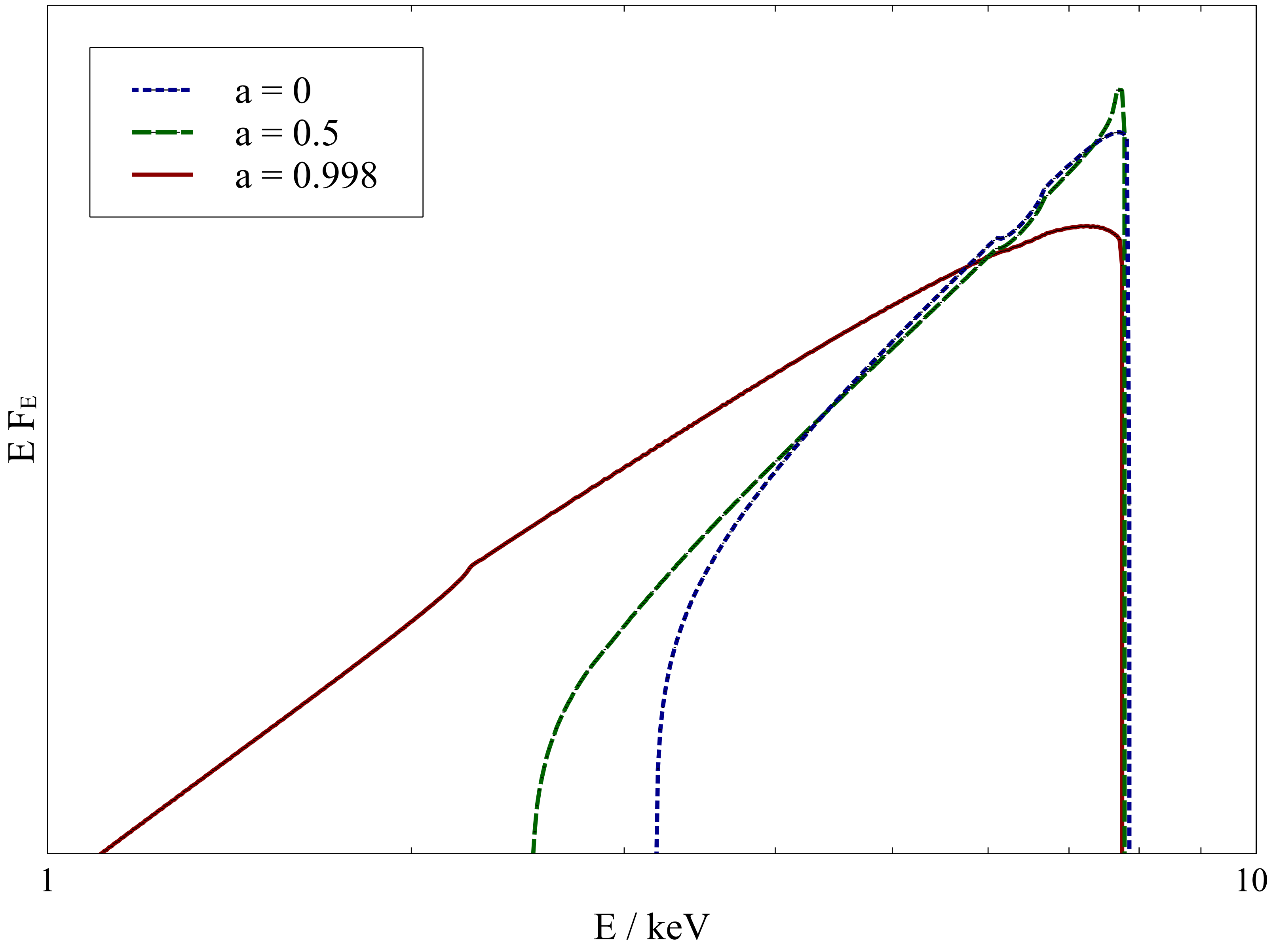


- General Relativity predicts that there is a minimum radius at which a stable orbit can be maintained (the ISCO), which depends on the spin of the black hole
- Inside ISCO, material from disc plunges rapidly into black hole
  - Velocity increases
  - Density drops
  - Reflection from plunging region highly redshifted and beamed into black hole

Brenneman et al. 2006

Measuring black hole spin





Measure extremal redshift in iron K line, to find inner radius of disc

If disc extends down to ISCO, inner radius indicates spin

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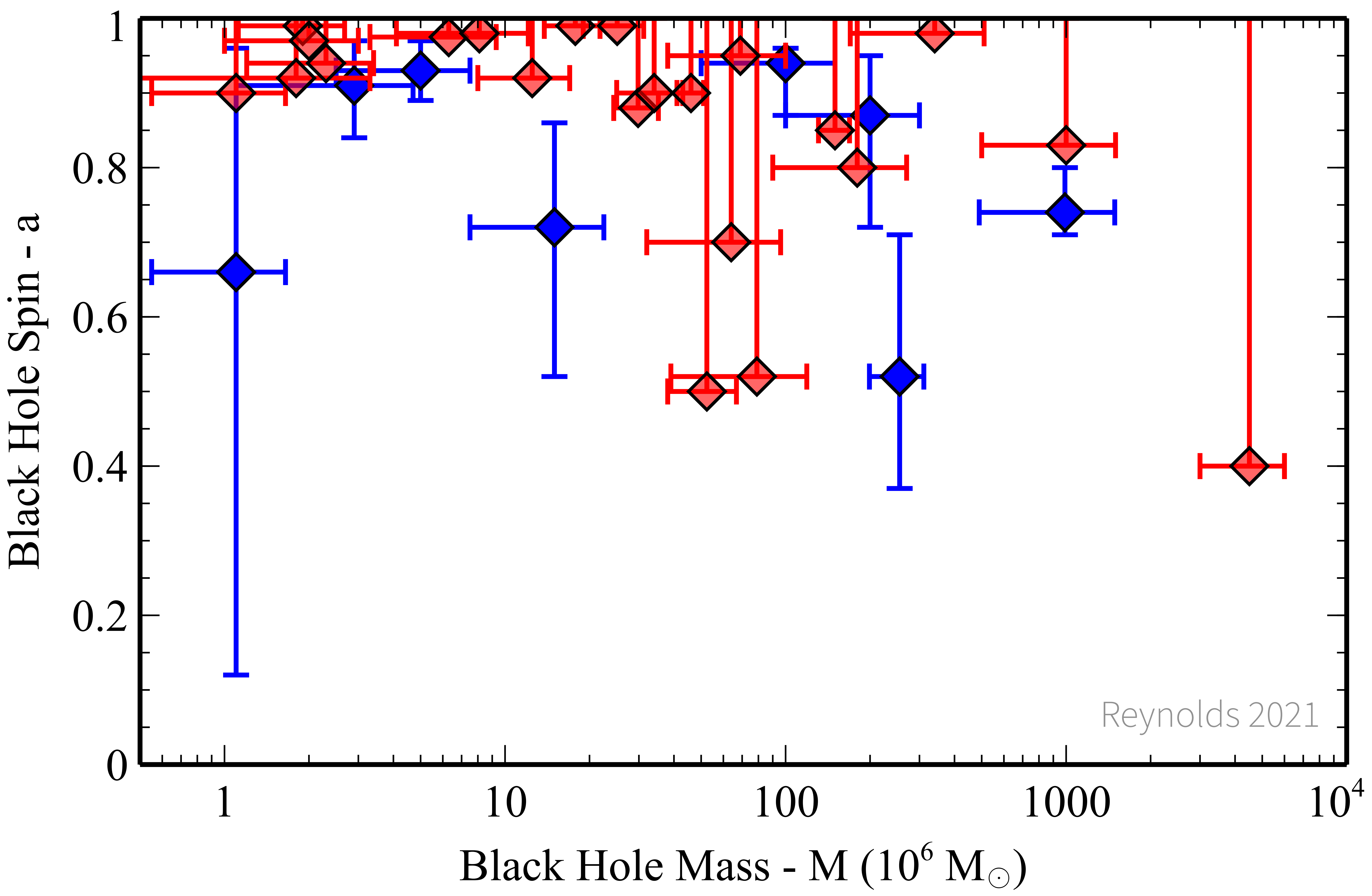
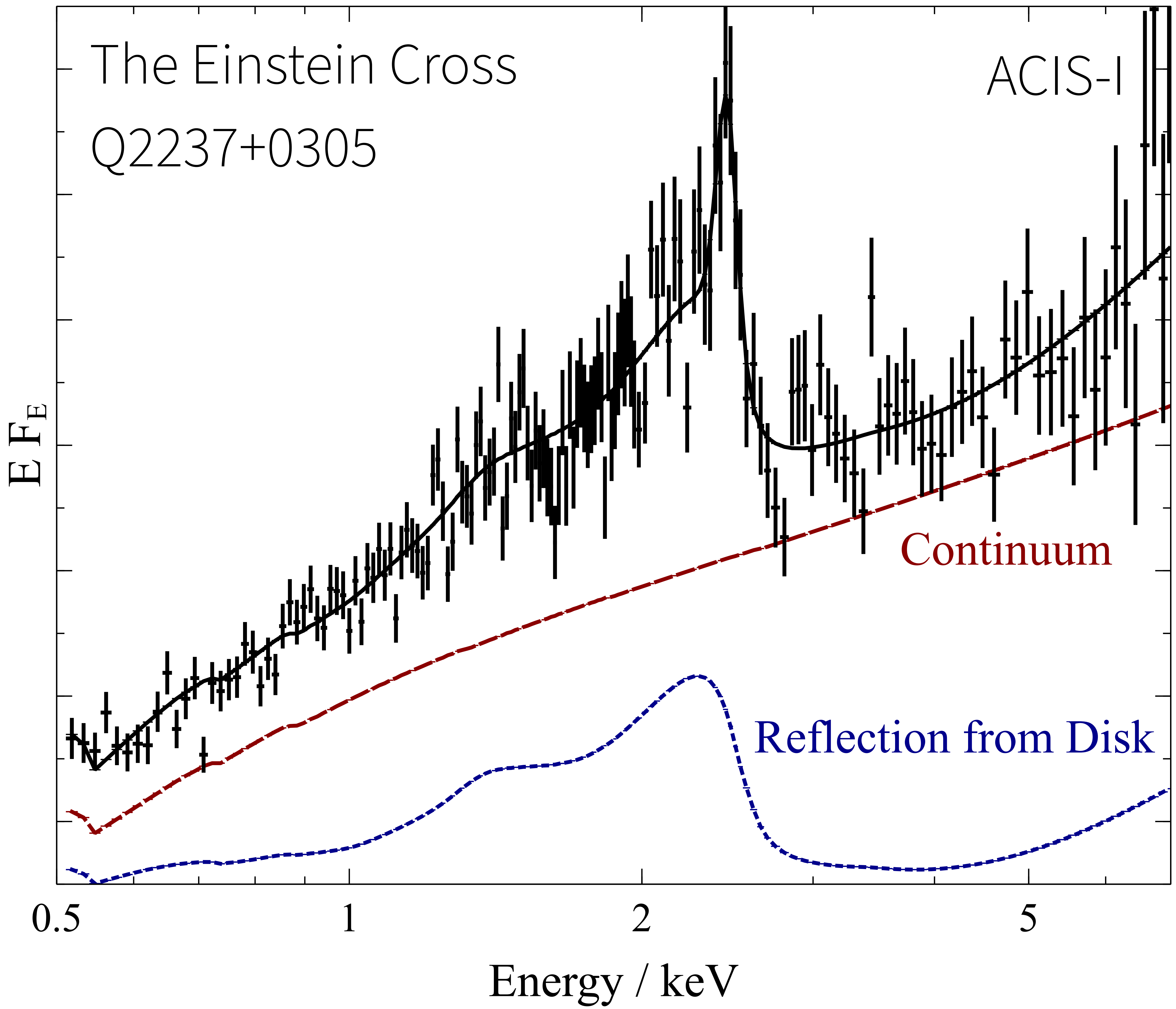
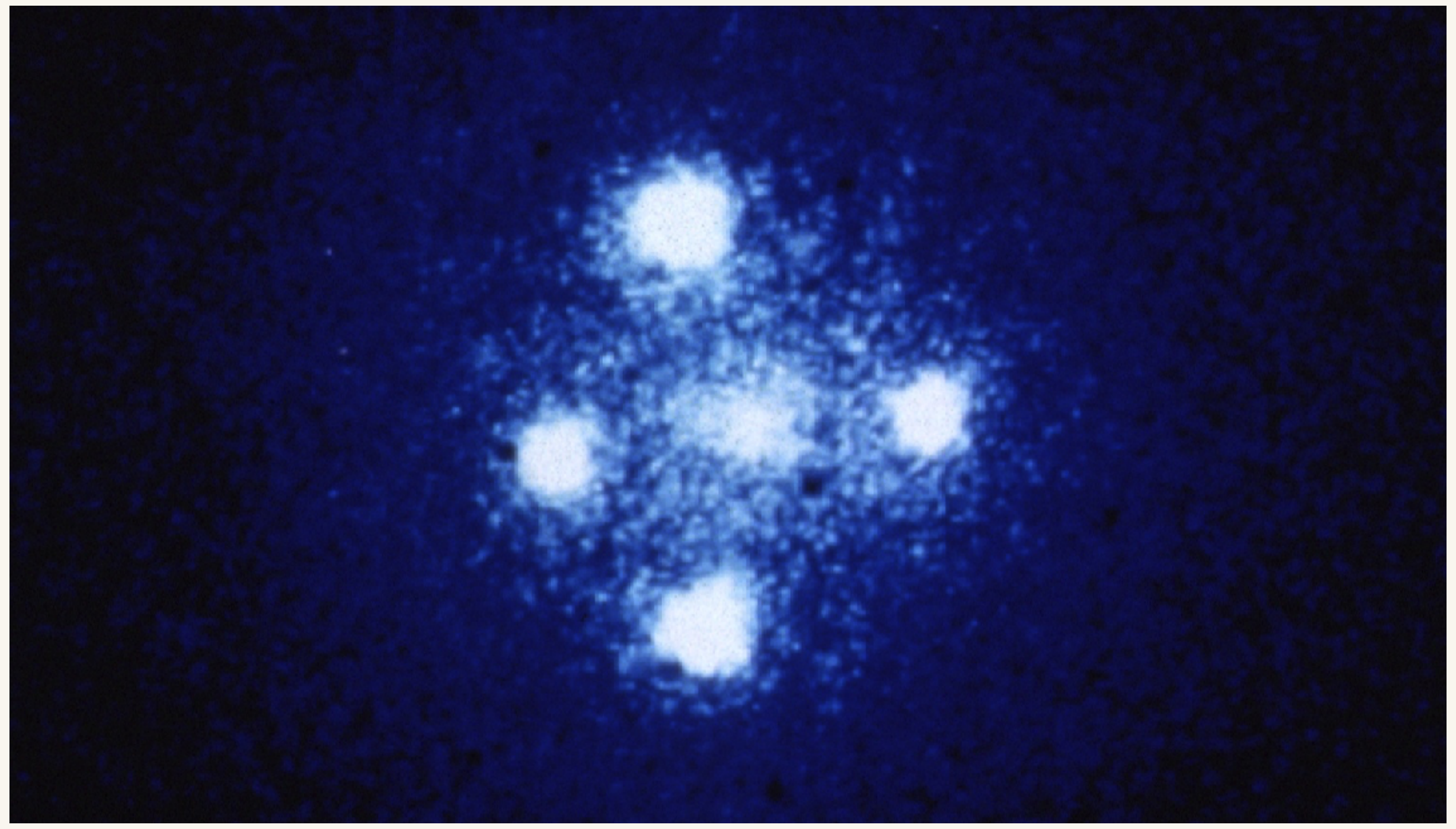
The spins of supermassive black holes

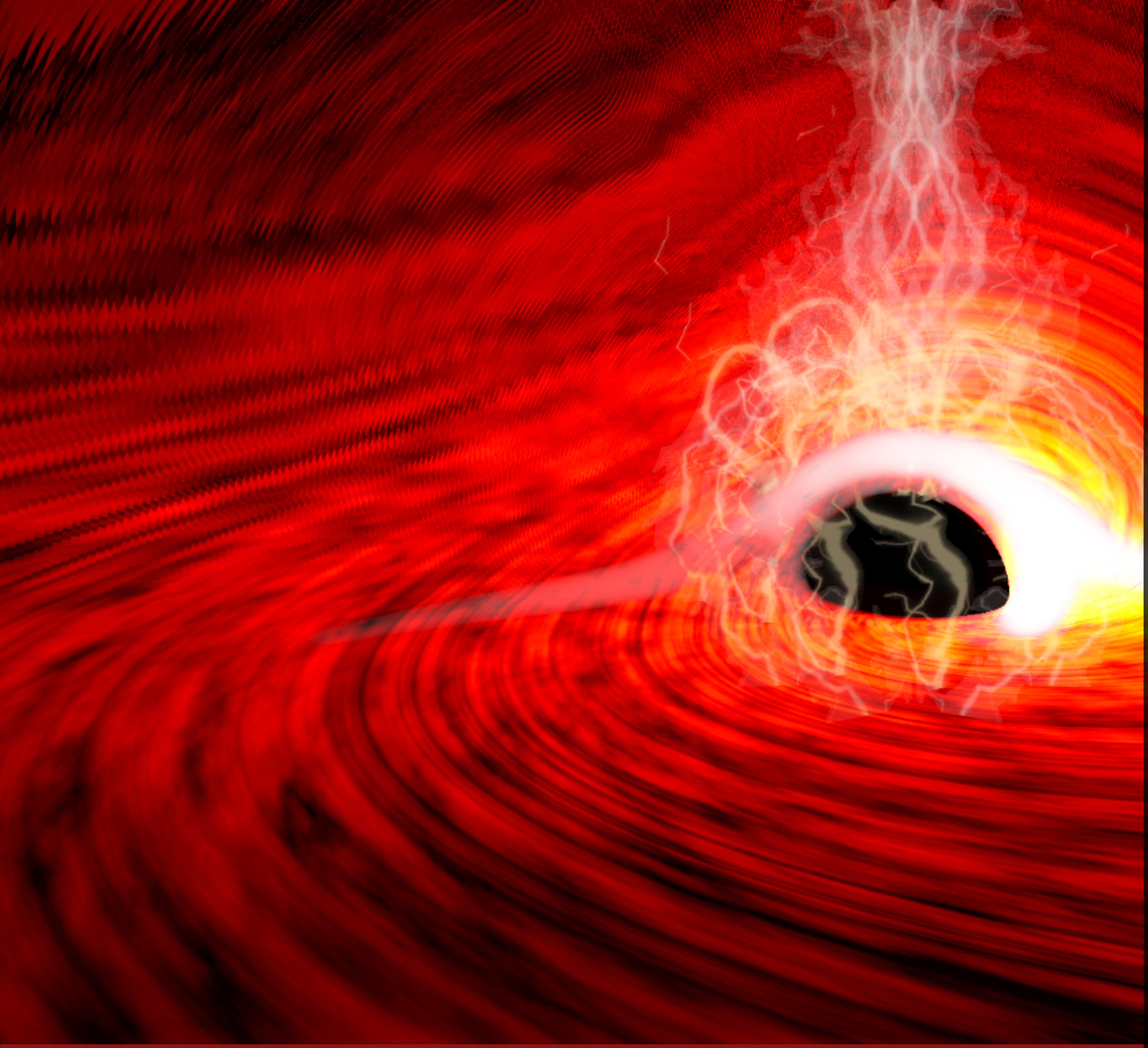


X-ray reflection in lensed quasars





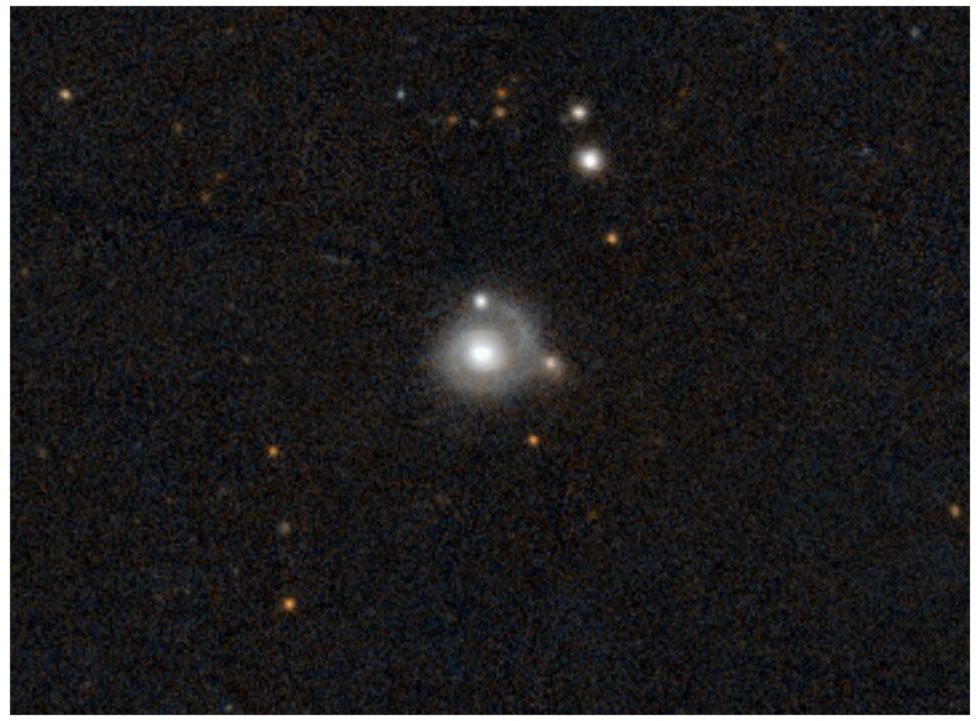
- Strong gravitational lensing magnifies the emission from high(er) redshift quasars, z = 0.5 ~ 2
- Chandra observations of lensed quasars show broad iron K lines, reflected from inner accretion disk around a rapidly spinning black hole — Reis et al. 2014, Reynolds et al. 2014, Walton et al. 2015

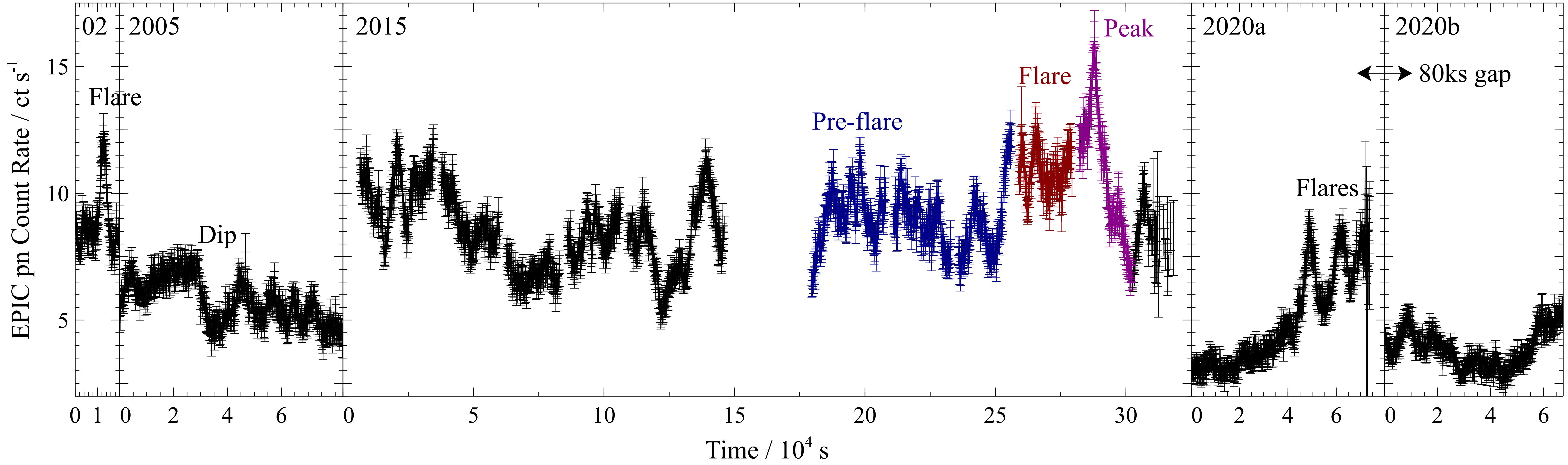


X-ray reverberation

Variable X-ray emission and strong reflection

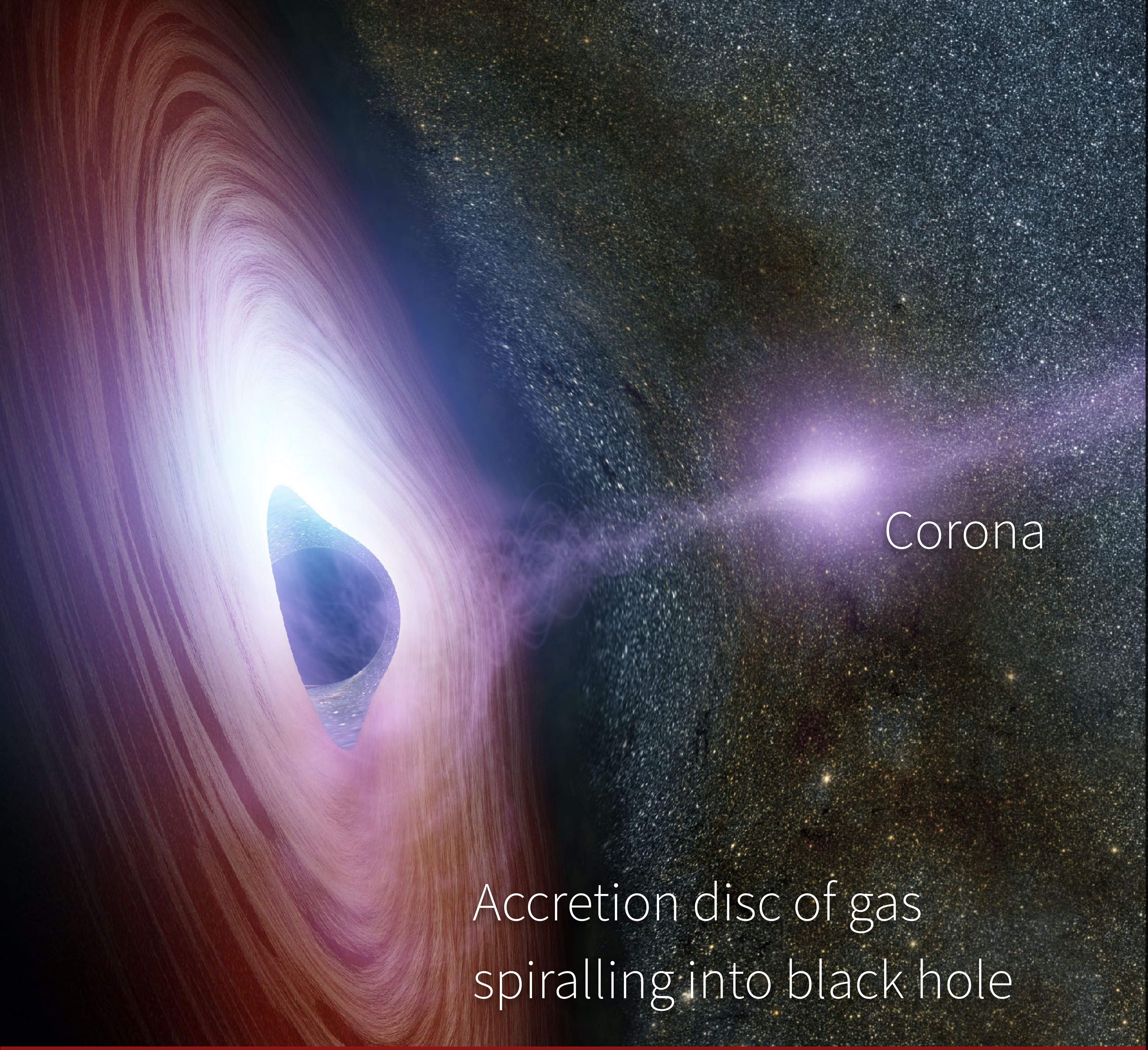
- Nearby narrow-line Seyfert 1 AGN show strong reflection from the accretion disc
- Short time-scale (~few hour) variation in addition to flares, flux drops

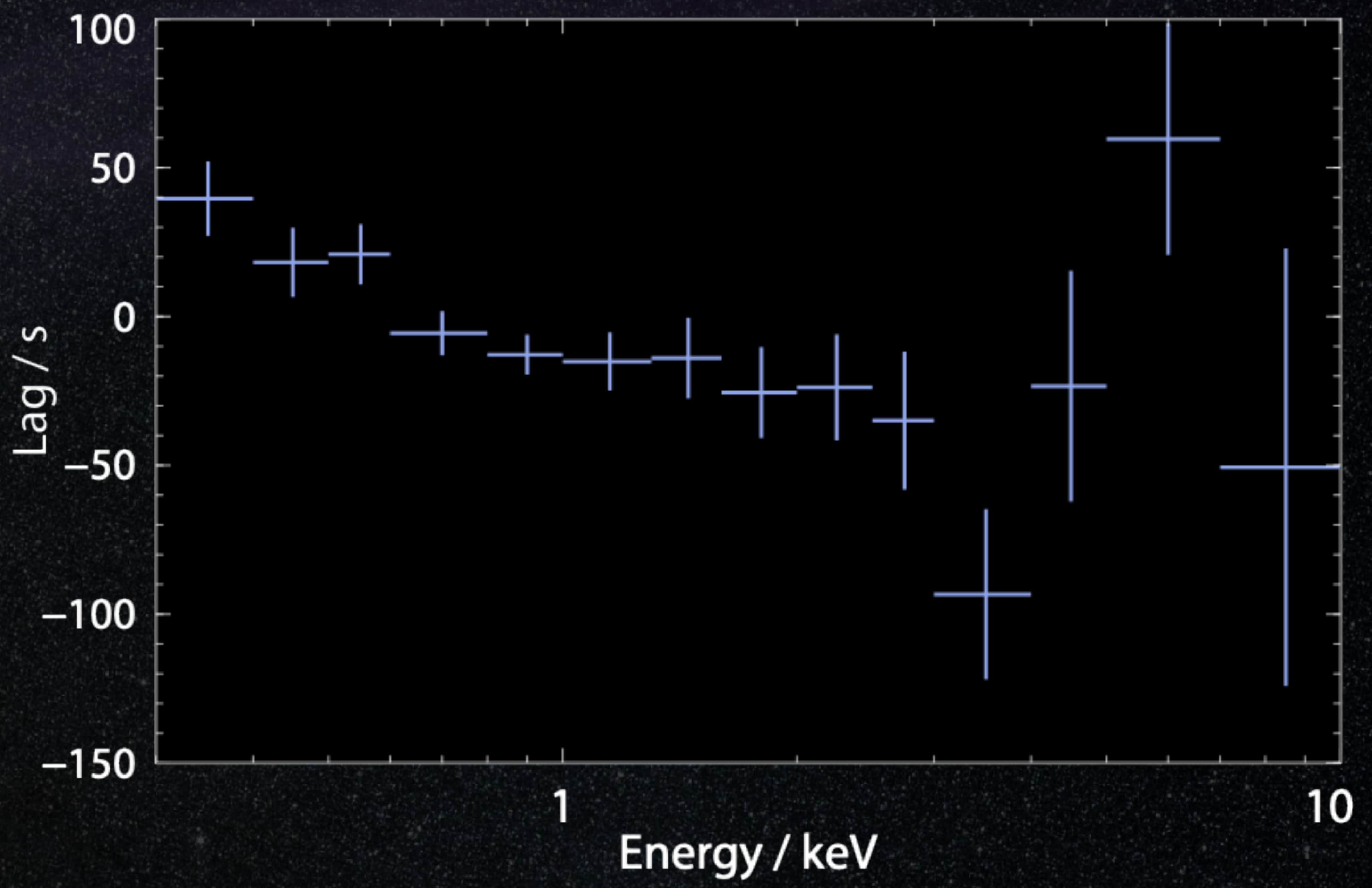




I Zwicky 1 (I Zw1) – narrow-line Seyfert 1 galaxy at $z = 0.06$

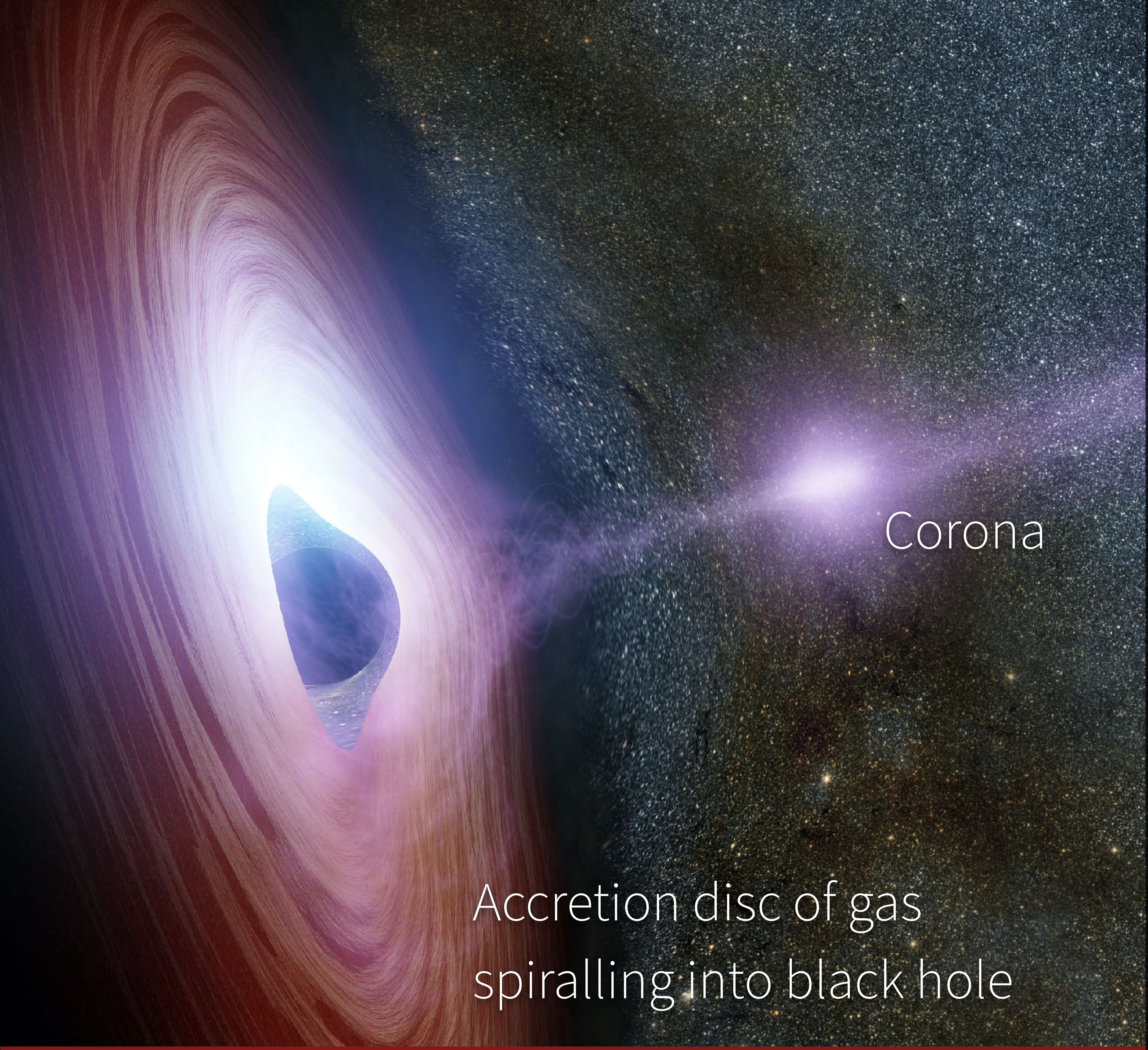
X-ray Reverberation

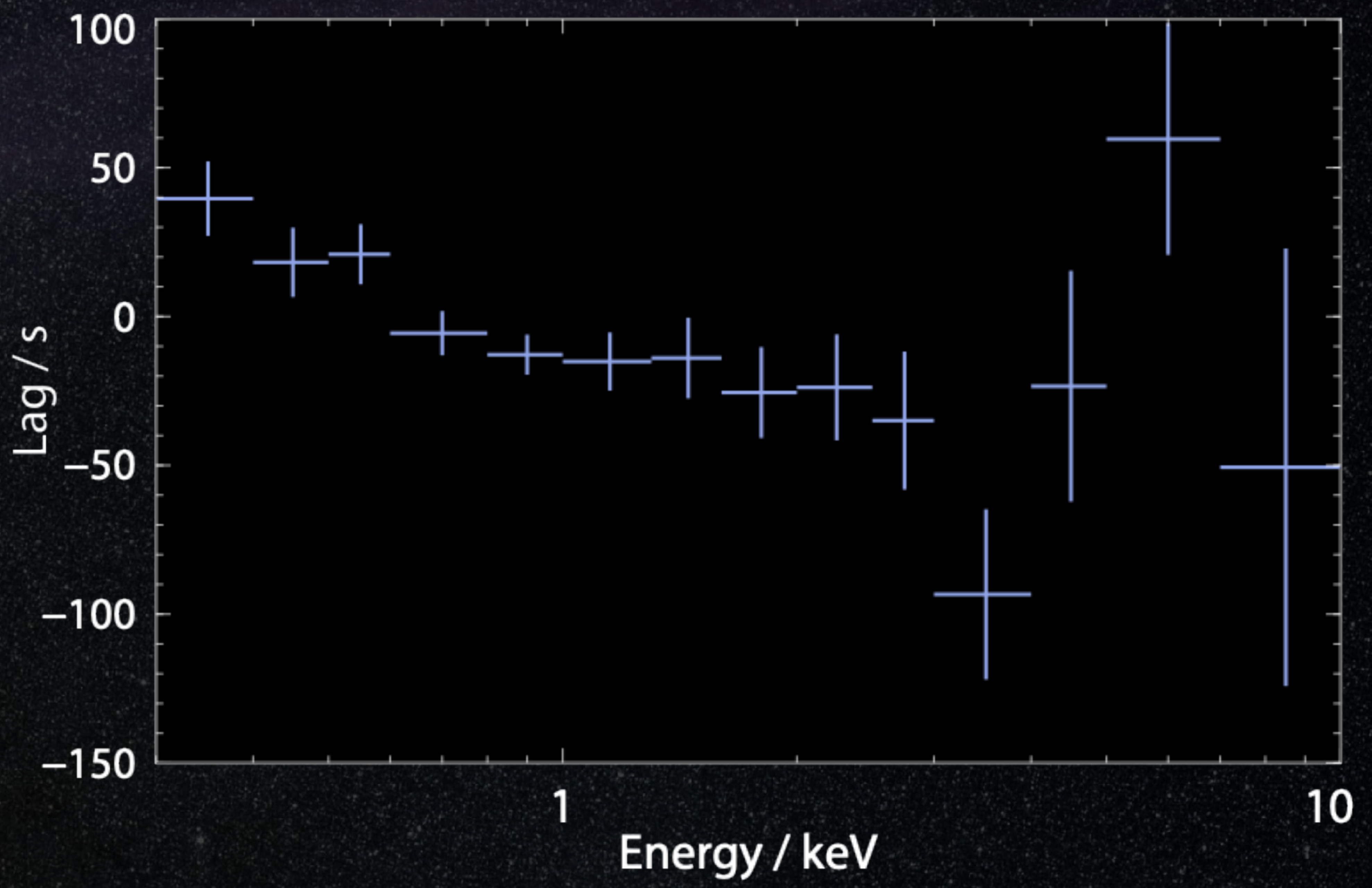




Uttley et al. 2014

X-ray Reverberation





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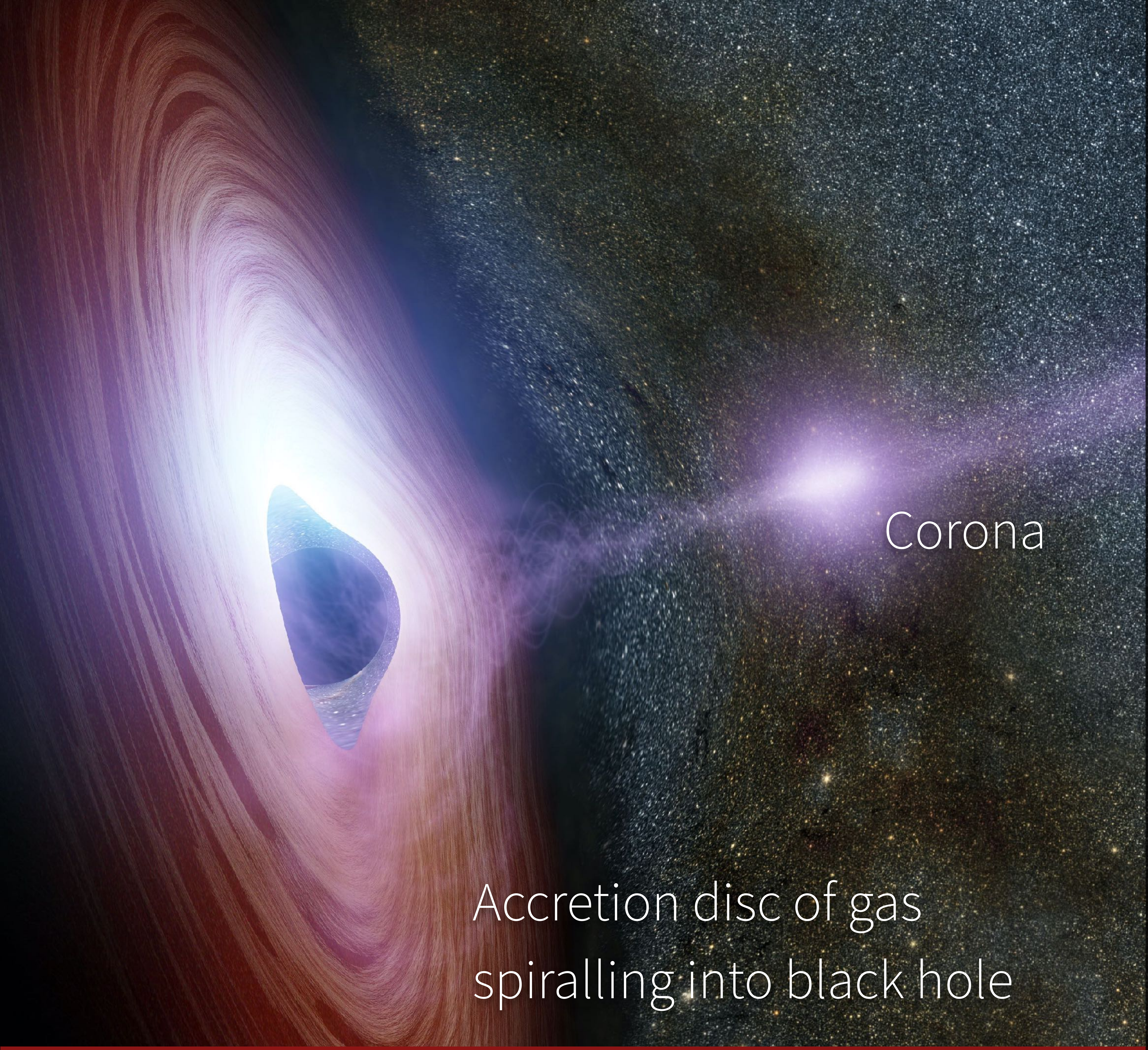

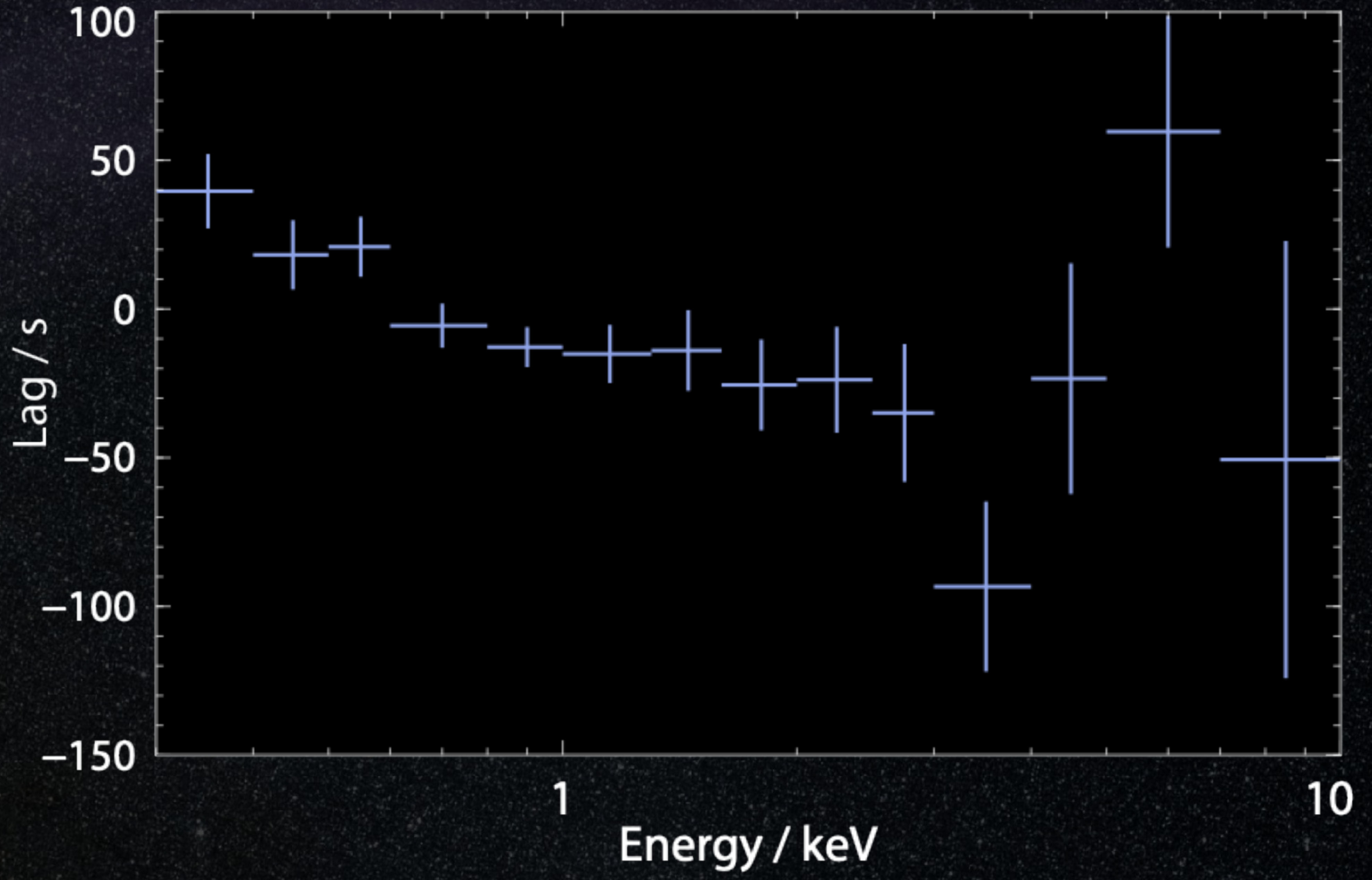

Uttley et al. 2014

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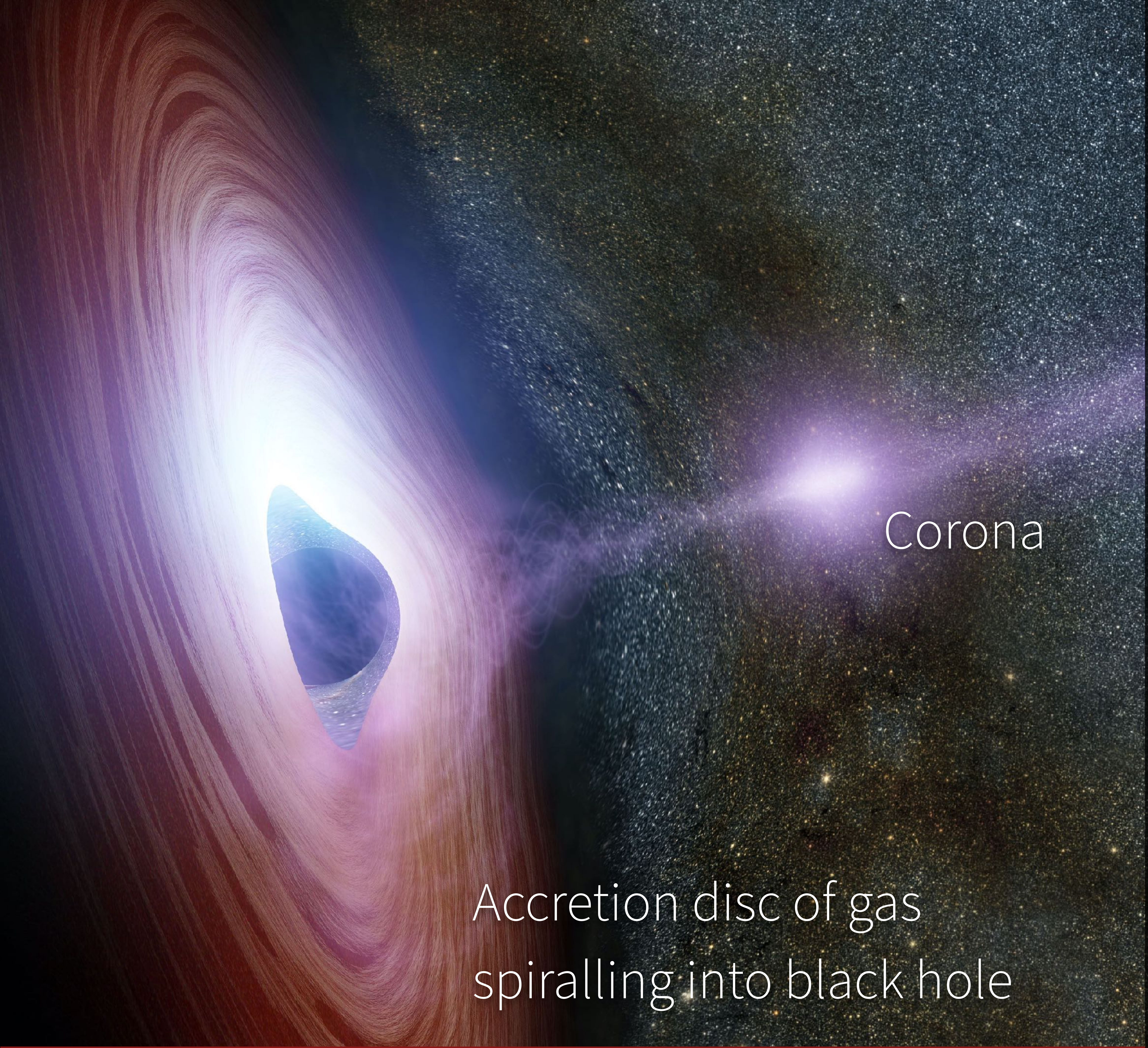
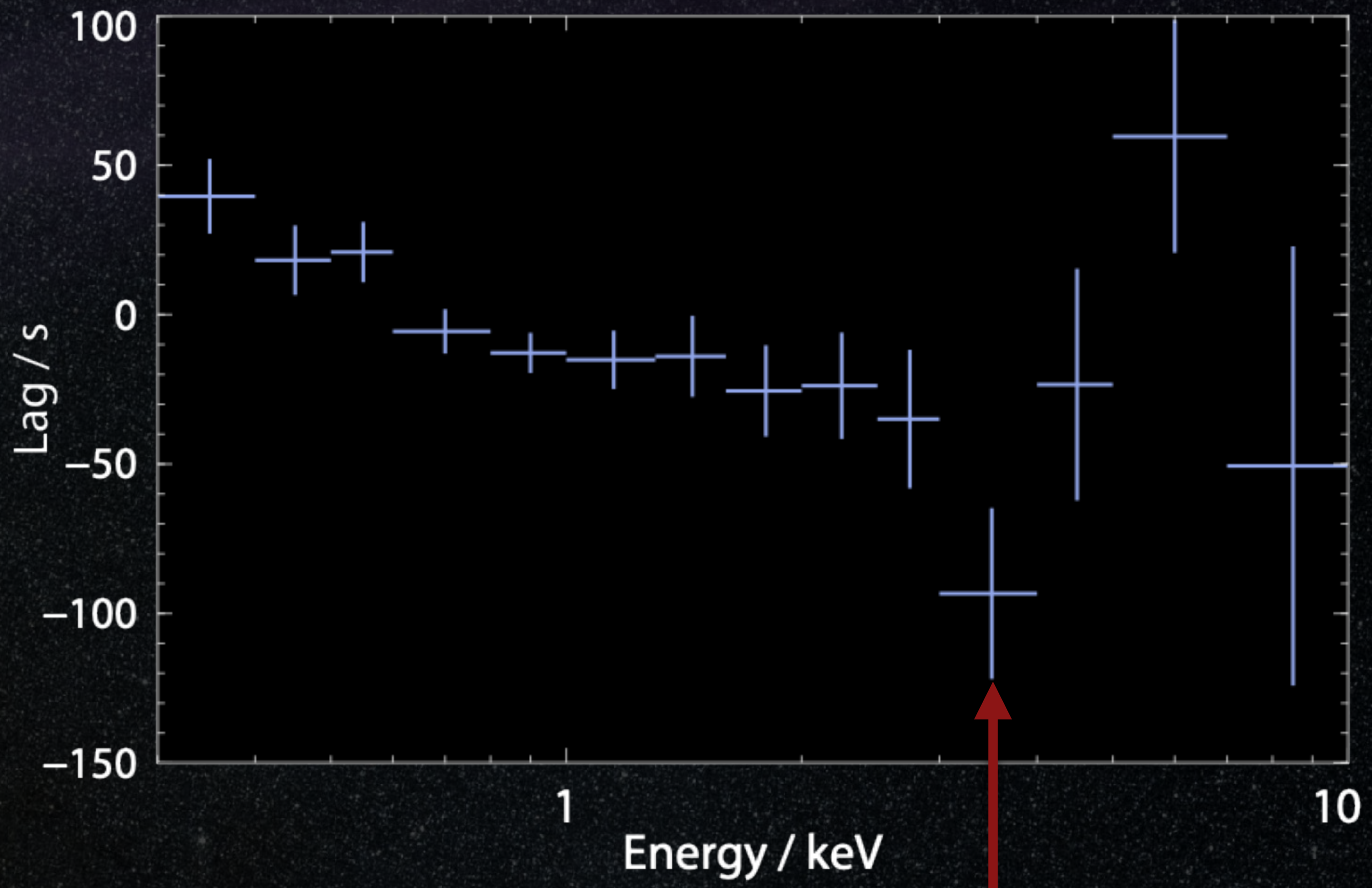
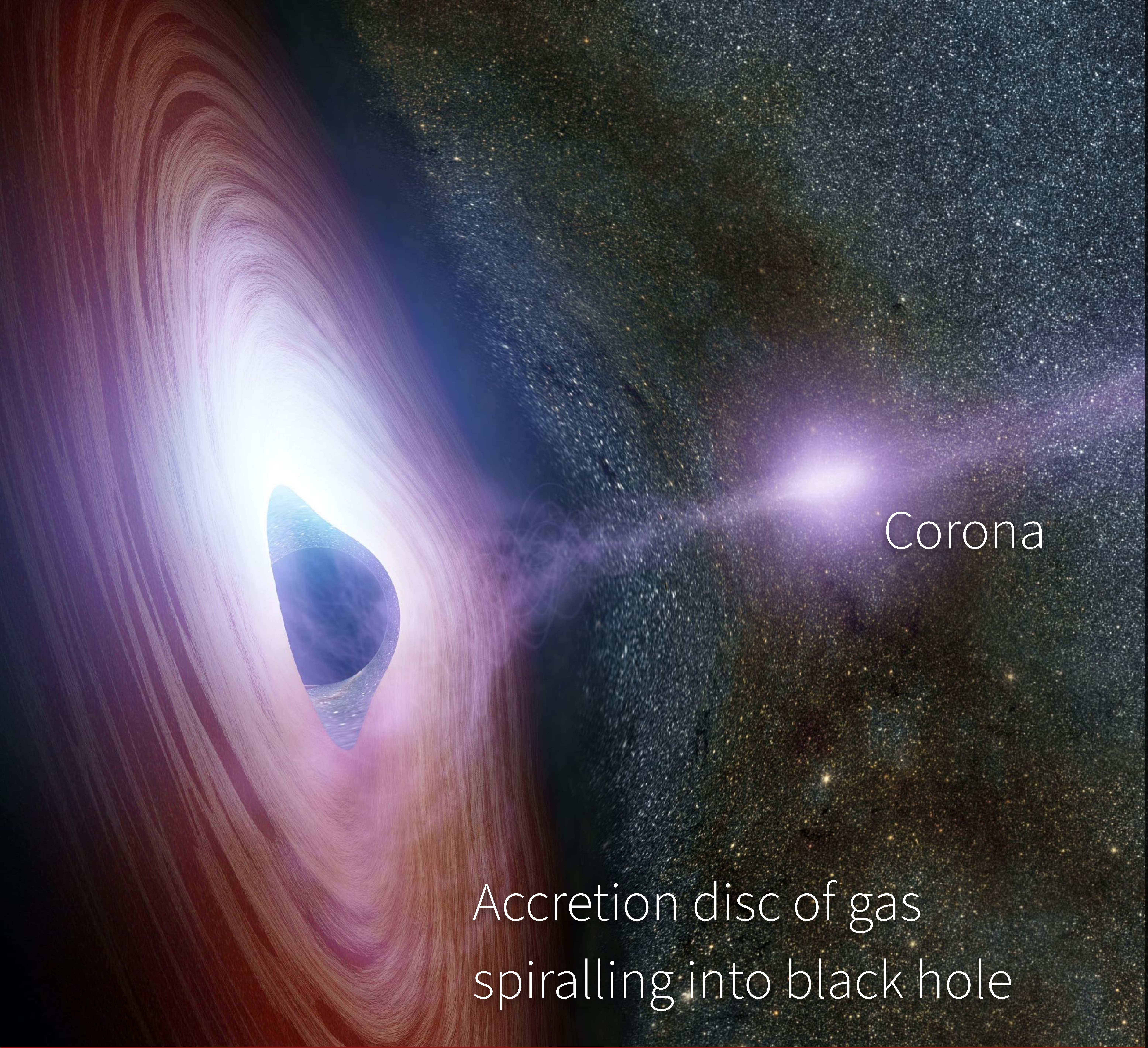


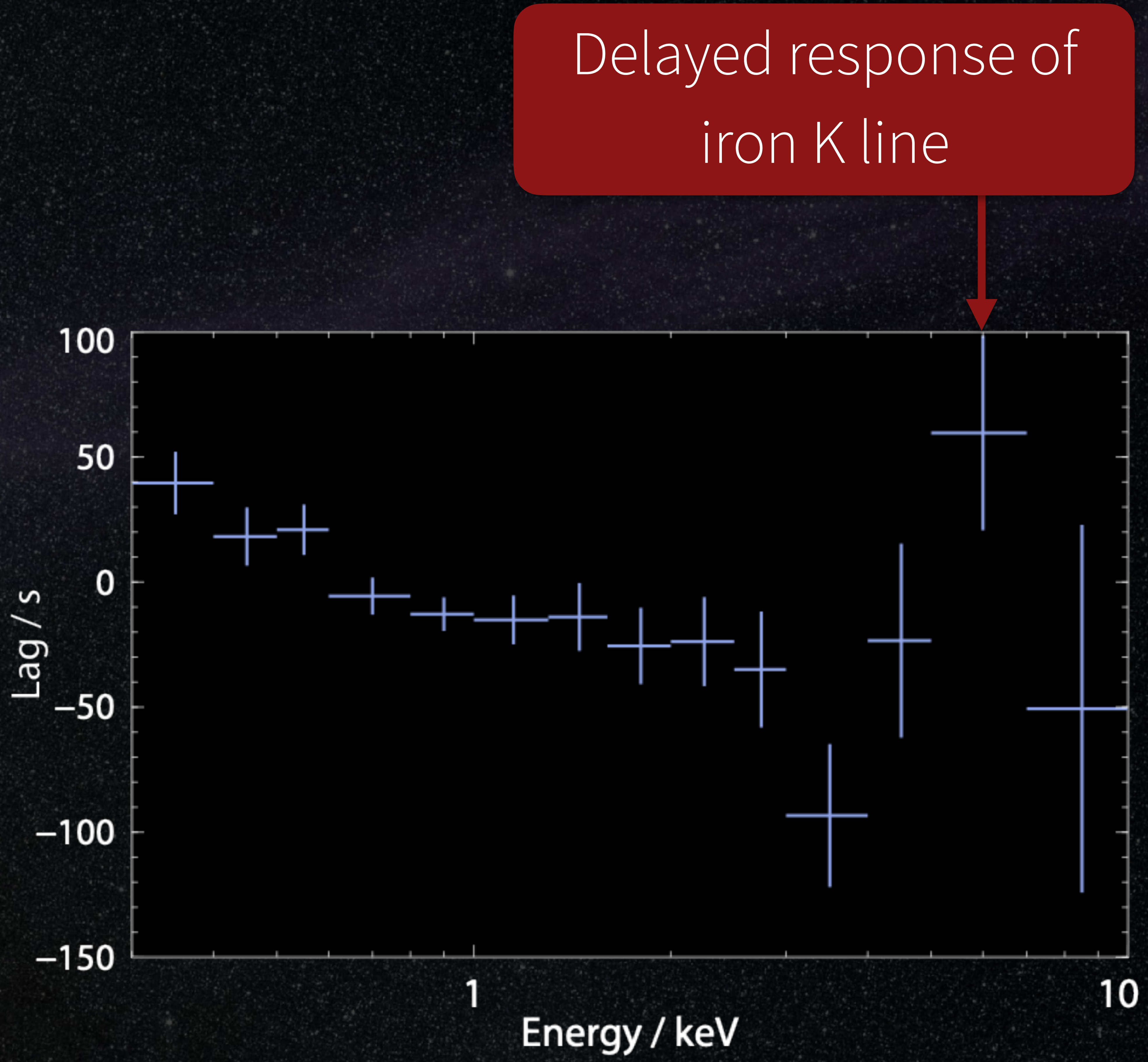


Energy bands dominated by continuum respond first

Uttley et al. 2014

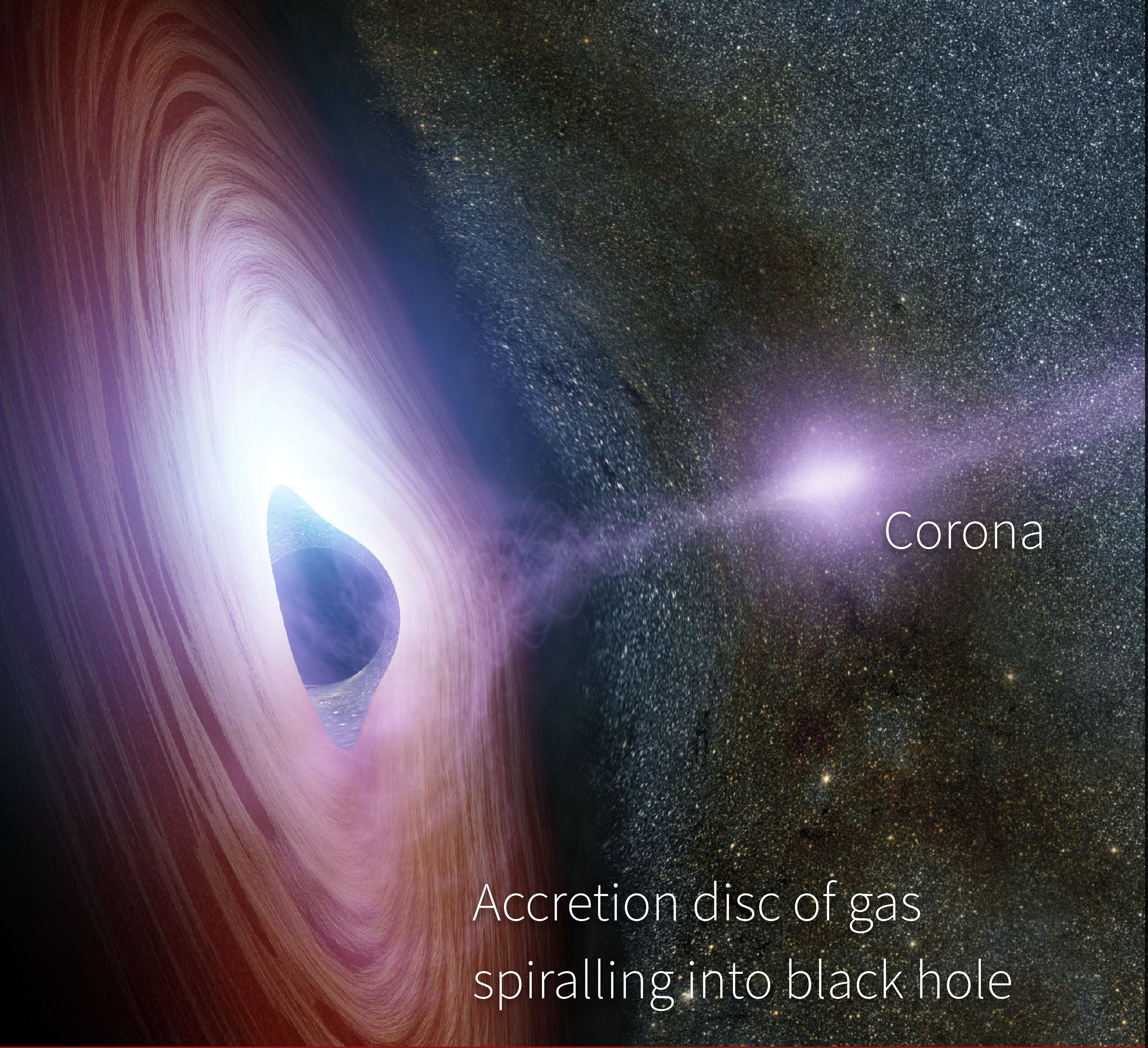


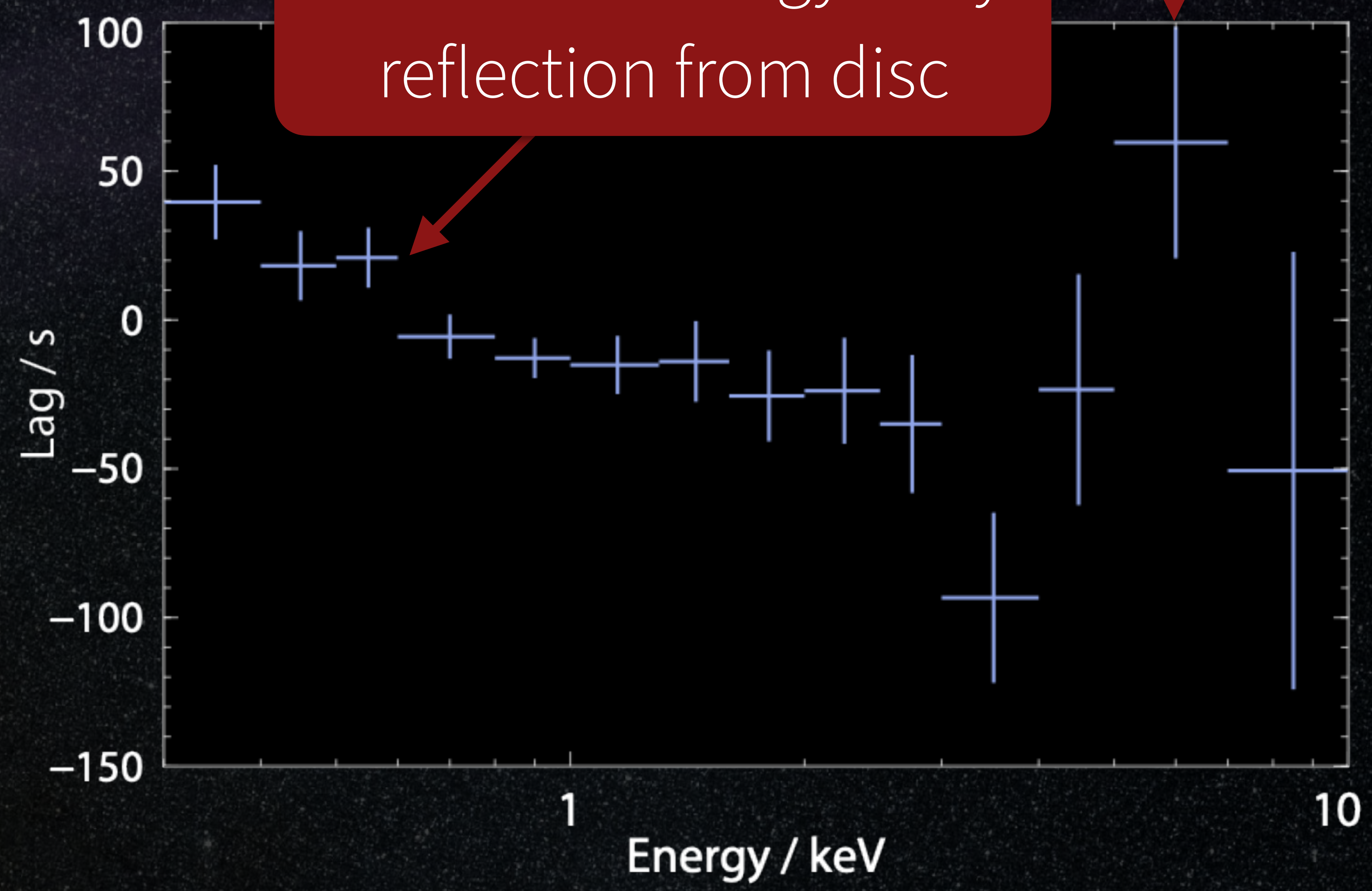
X-ray Reverberation



Uttley et al. 2014

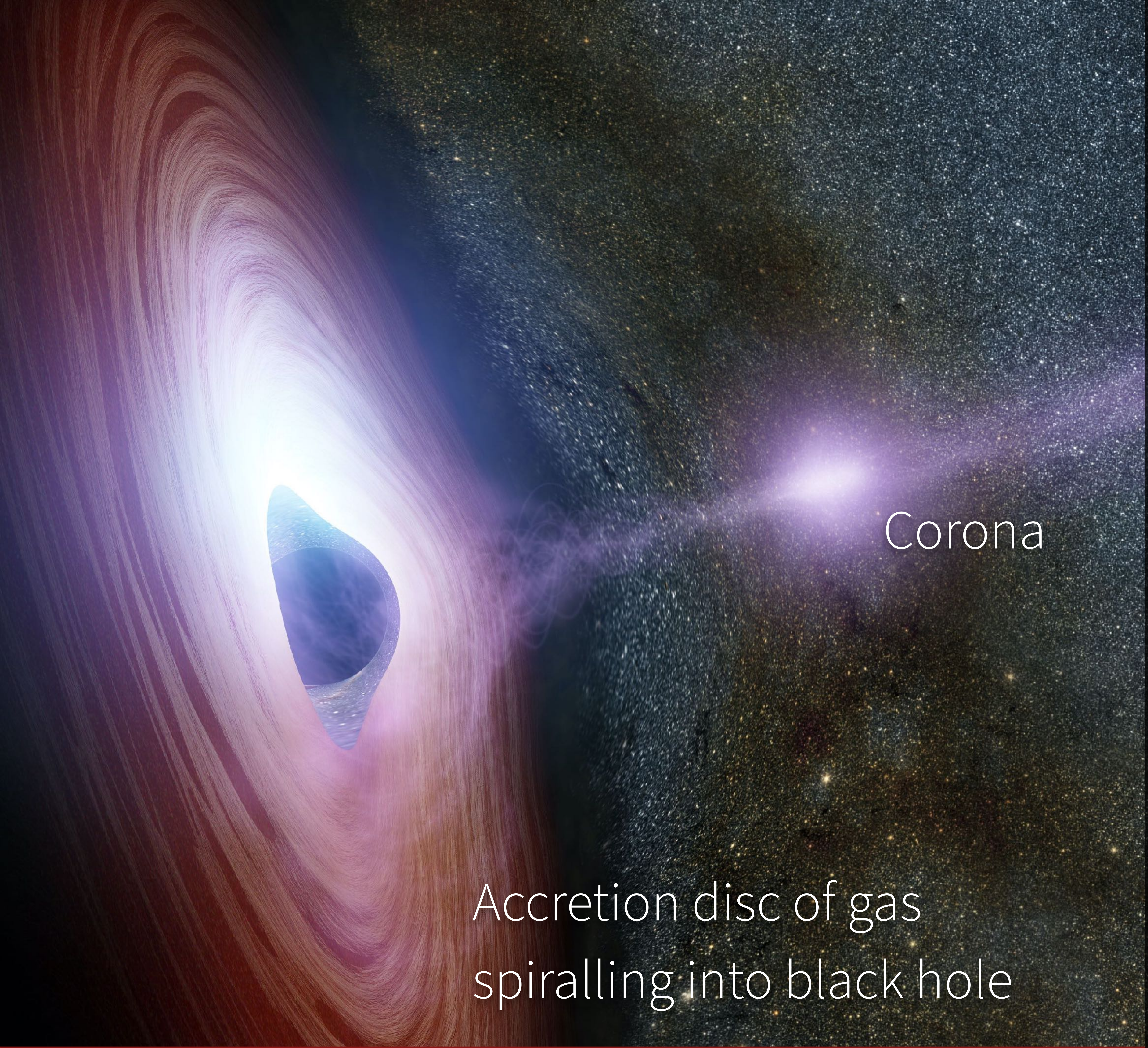
X-ray Reverberation

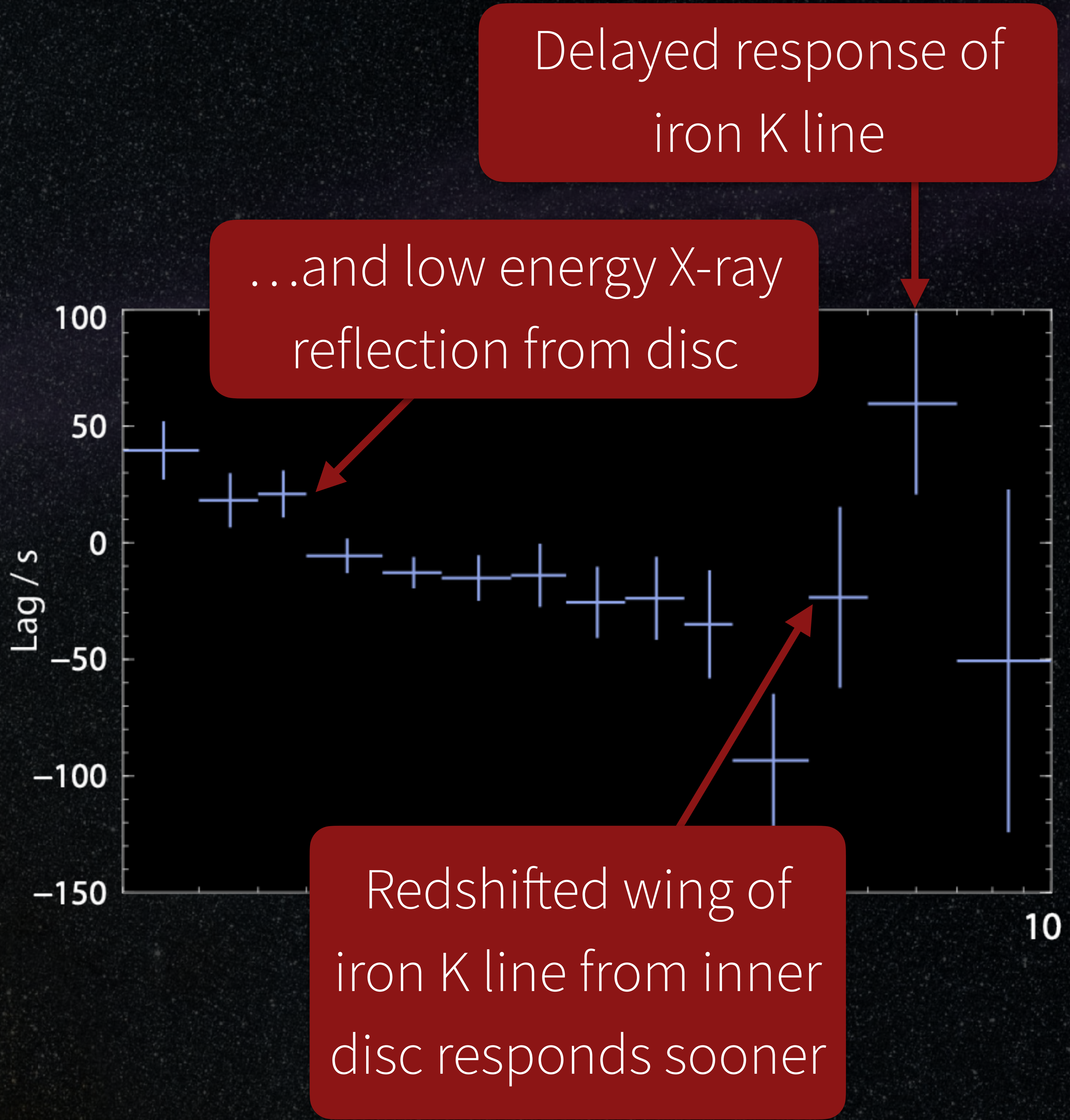




Uttley et al. 2014

X-ray Reverberation

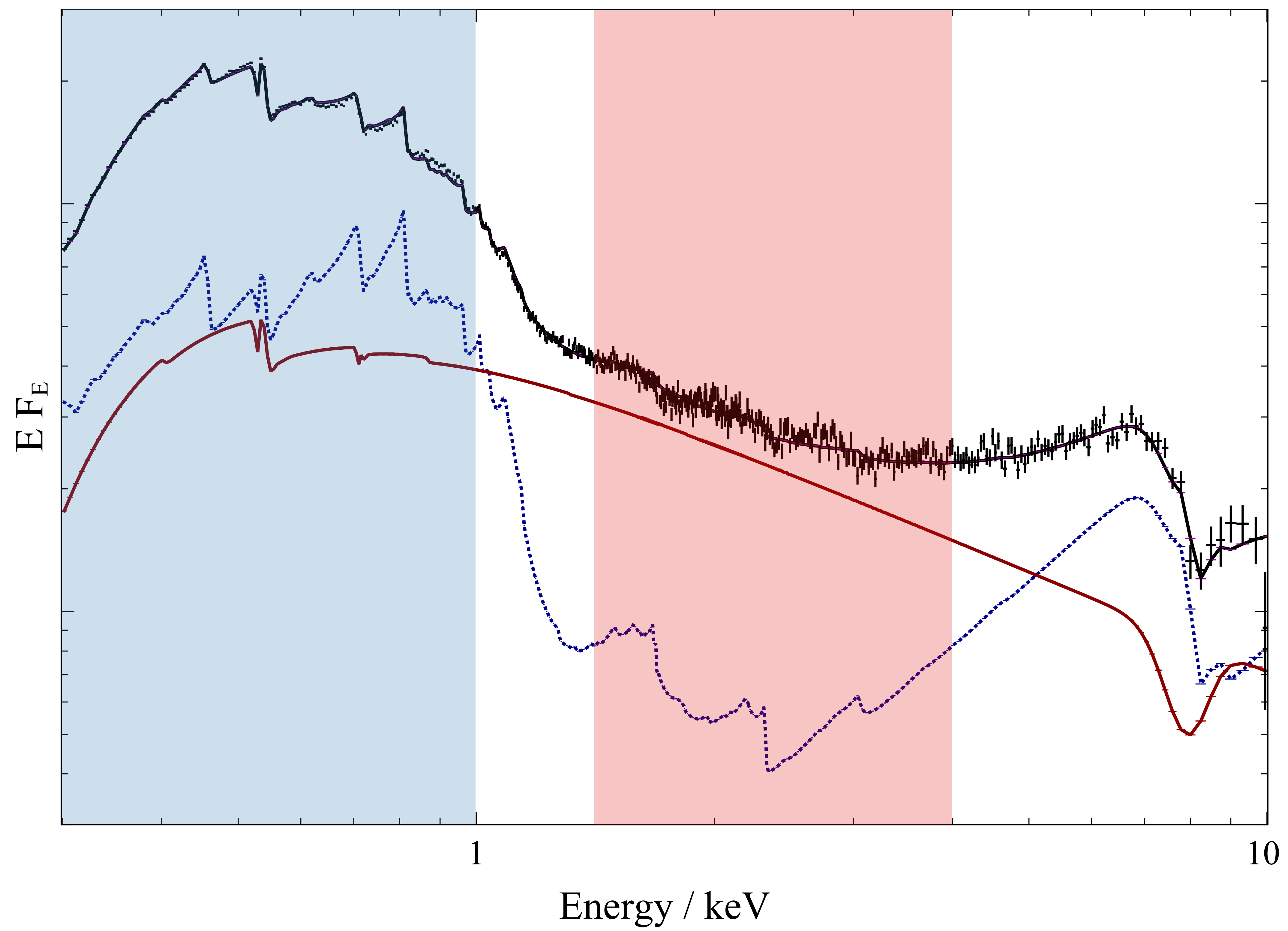


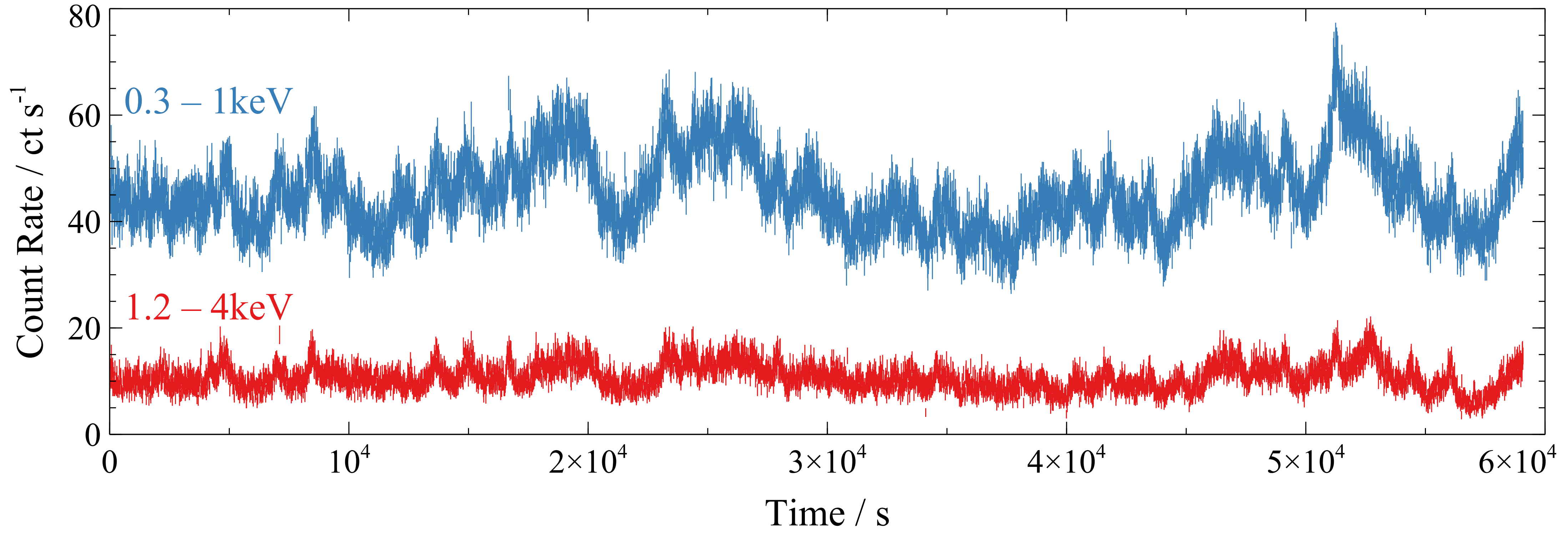


Uttley et al. 2014

A short diversion into Fourier space…

Measuring X-ray reverberation





- Extract light curves in energy bands dominated by continuum (H = 1.2-4keV) and reflection (S = 0.3-1keV soft excess)

- Fourier transform each light curve

$$\tilde{H}(\nu) = |\tilde{H}(\nu)|e^{i\vartheta} \qquad \tilde{S}(\nu) = |\tilde{S}(\nu)|e^{i\varphi}$$

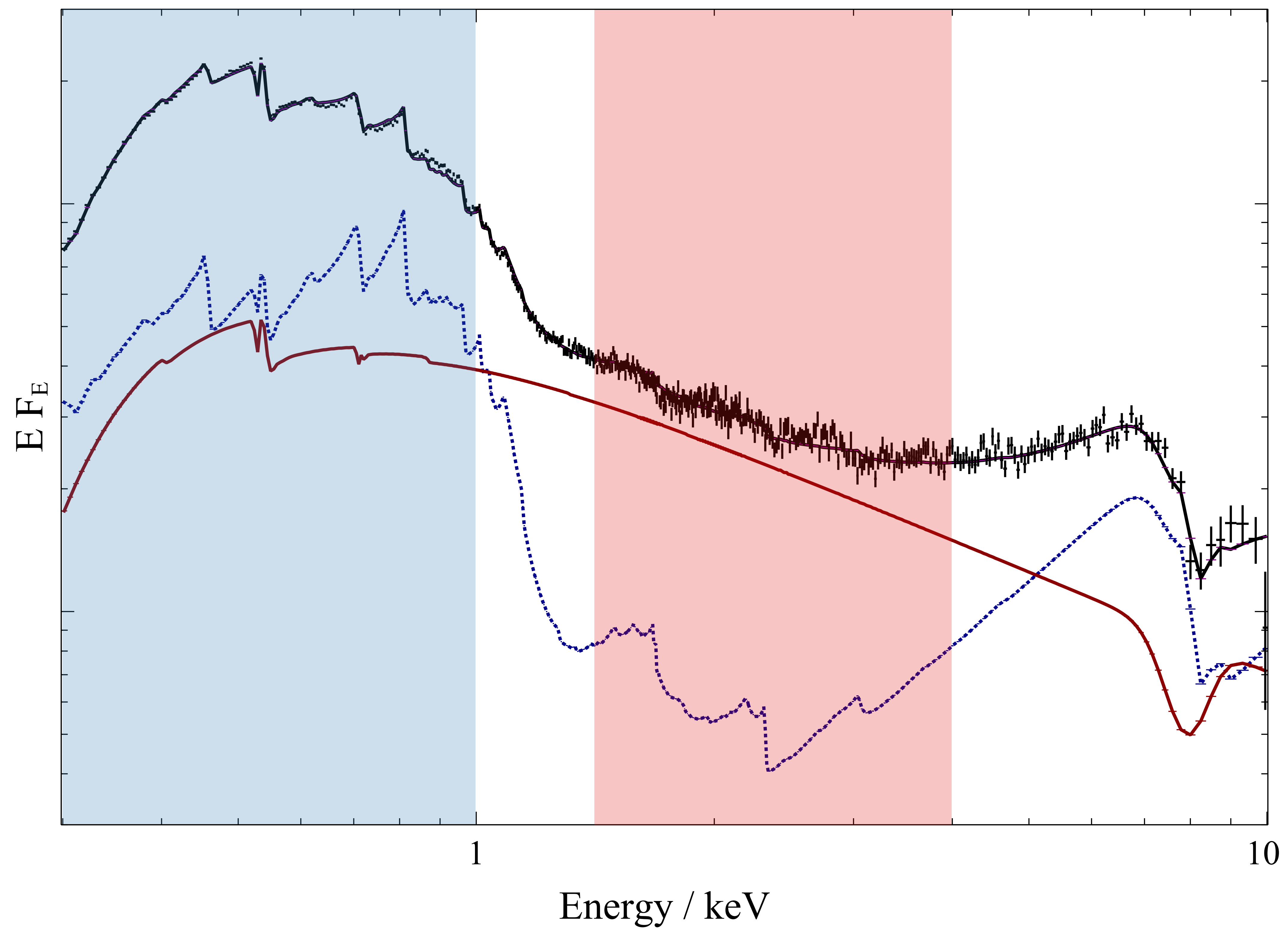
- Calculate the cross spectrum

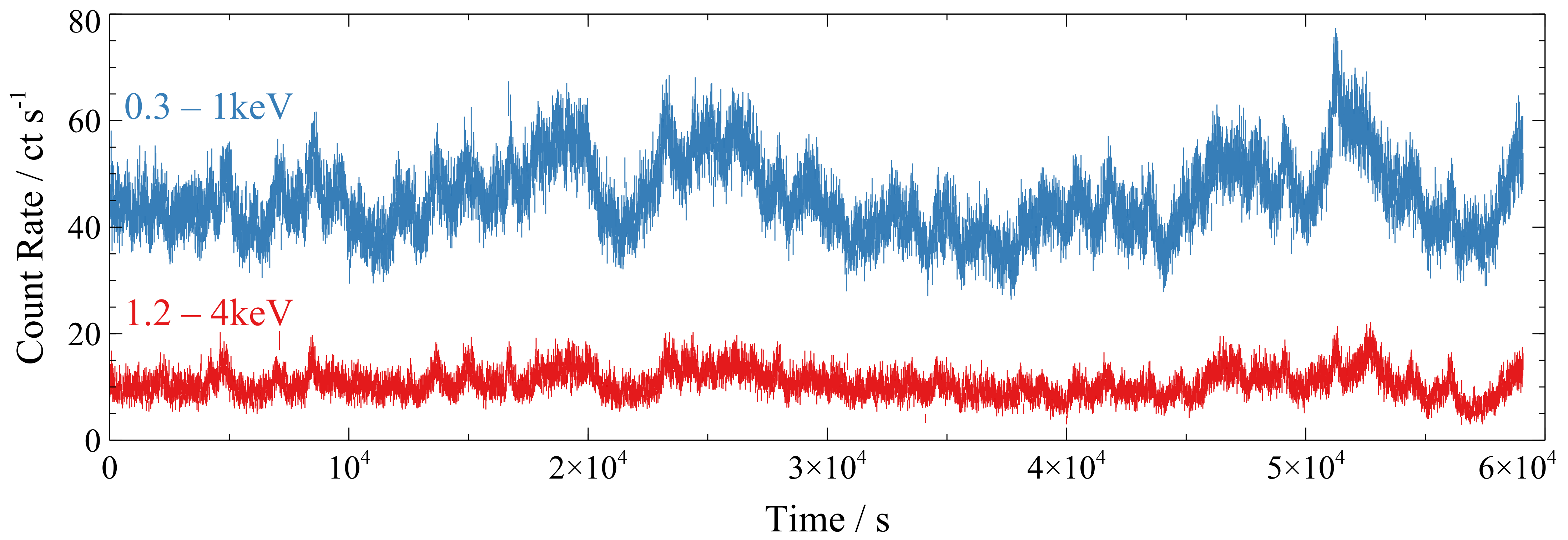
$$\tilde{C}(\nu) = \tilde{H}^*\tilde{S} = |\tilde{C}(\nu)|e^{i(\vartheta-\varphi)}$$

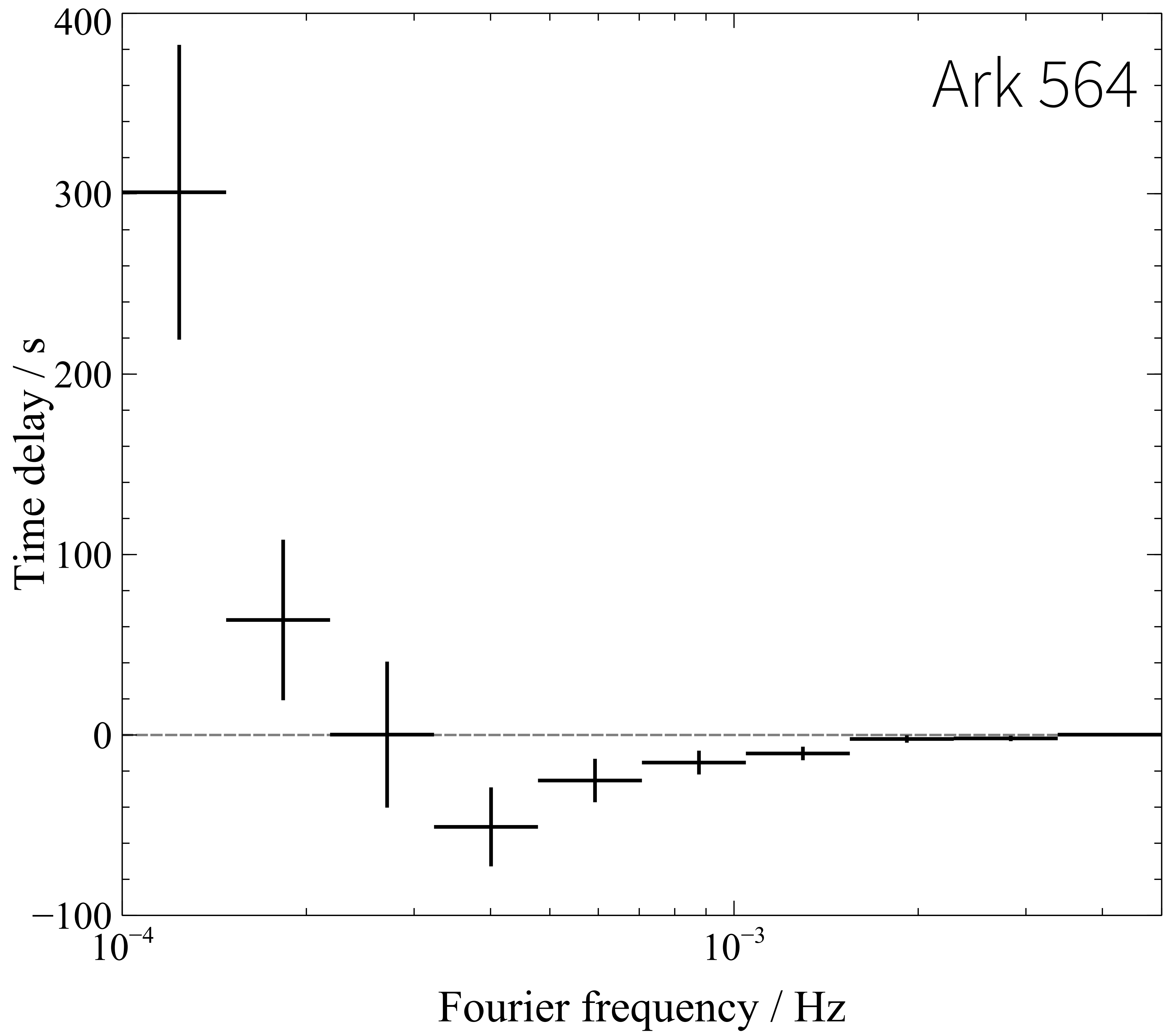
- Time lag is the phase of the cross spectrum

$$\tau(\nu) = \frac{1}{2\pi\nu}\arg\left(\tilde{C}(\nu)\right)$$

Measuring X-ray reverberation







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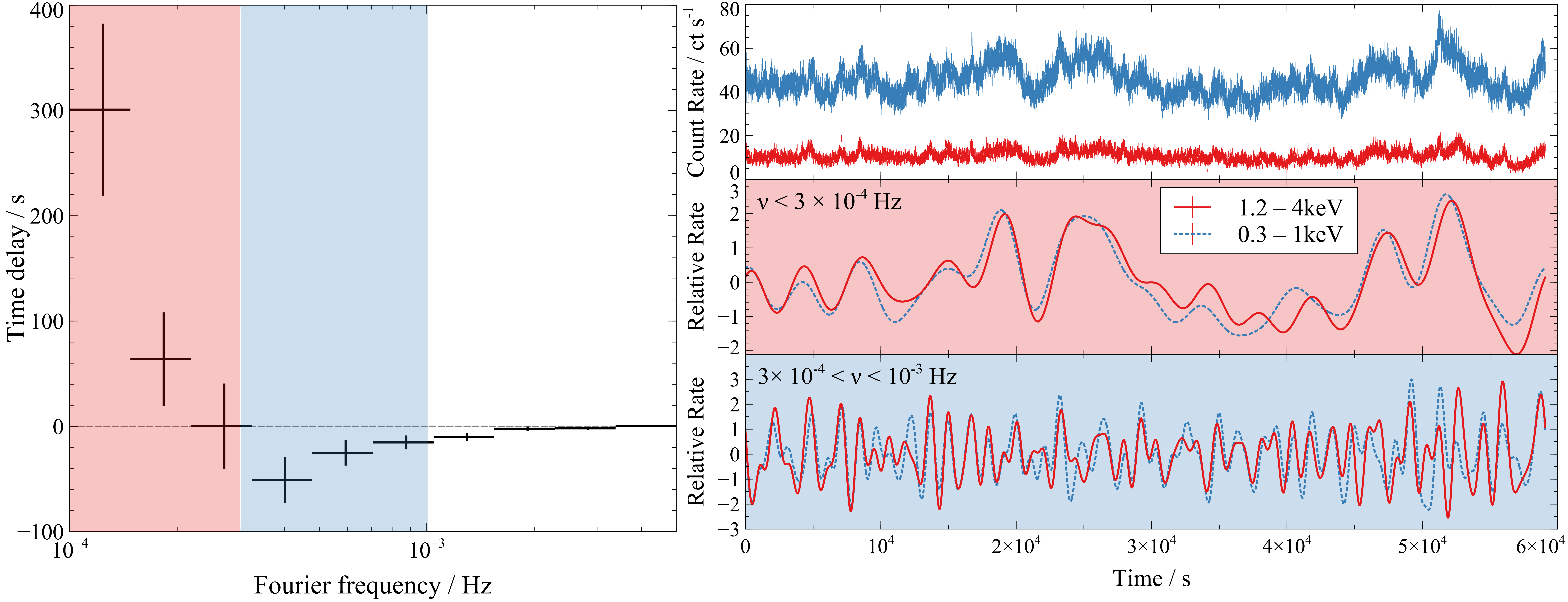

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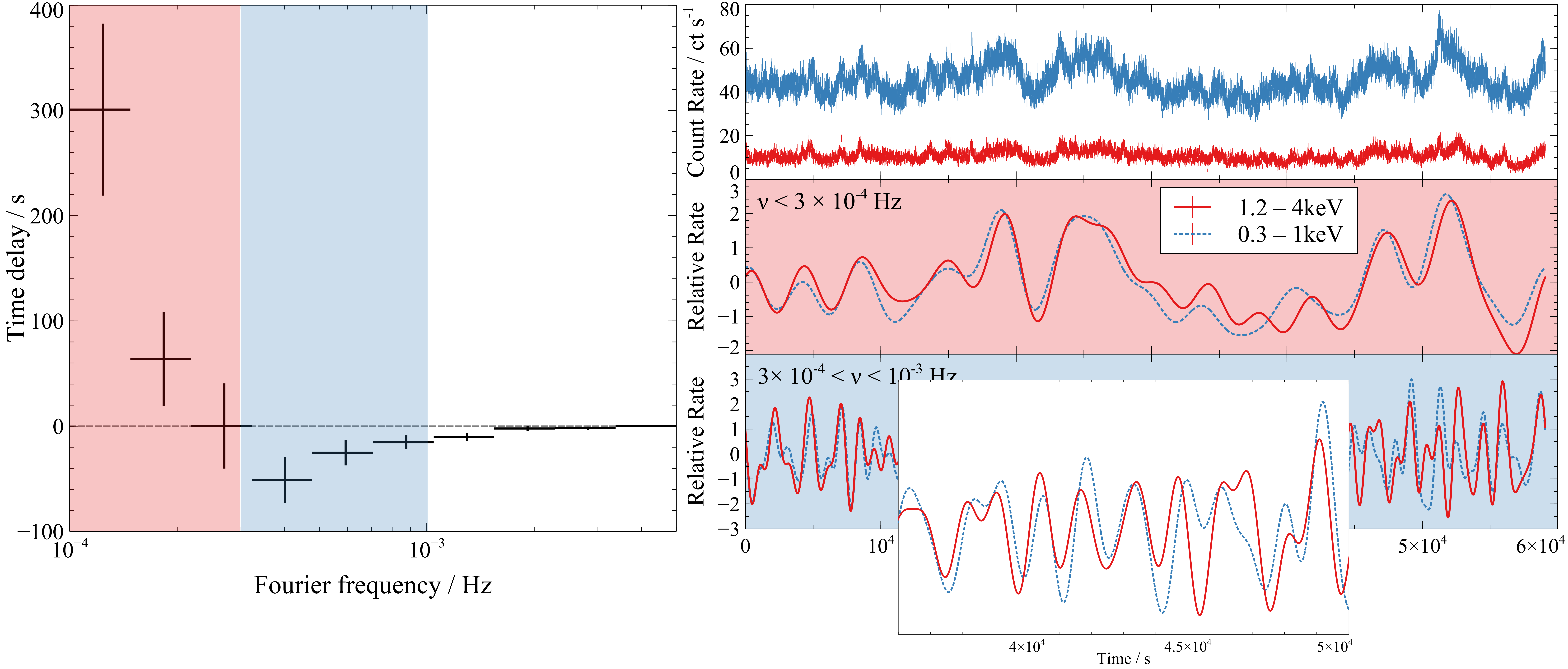
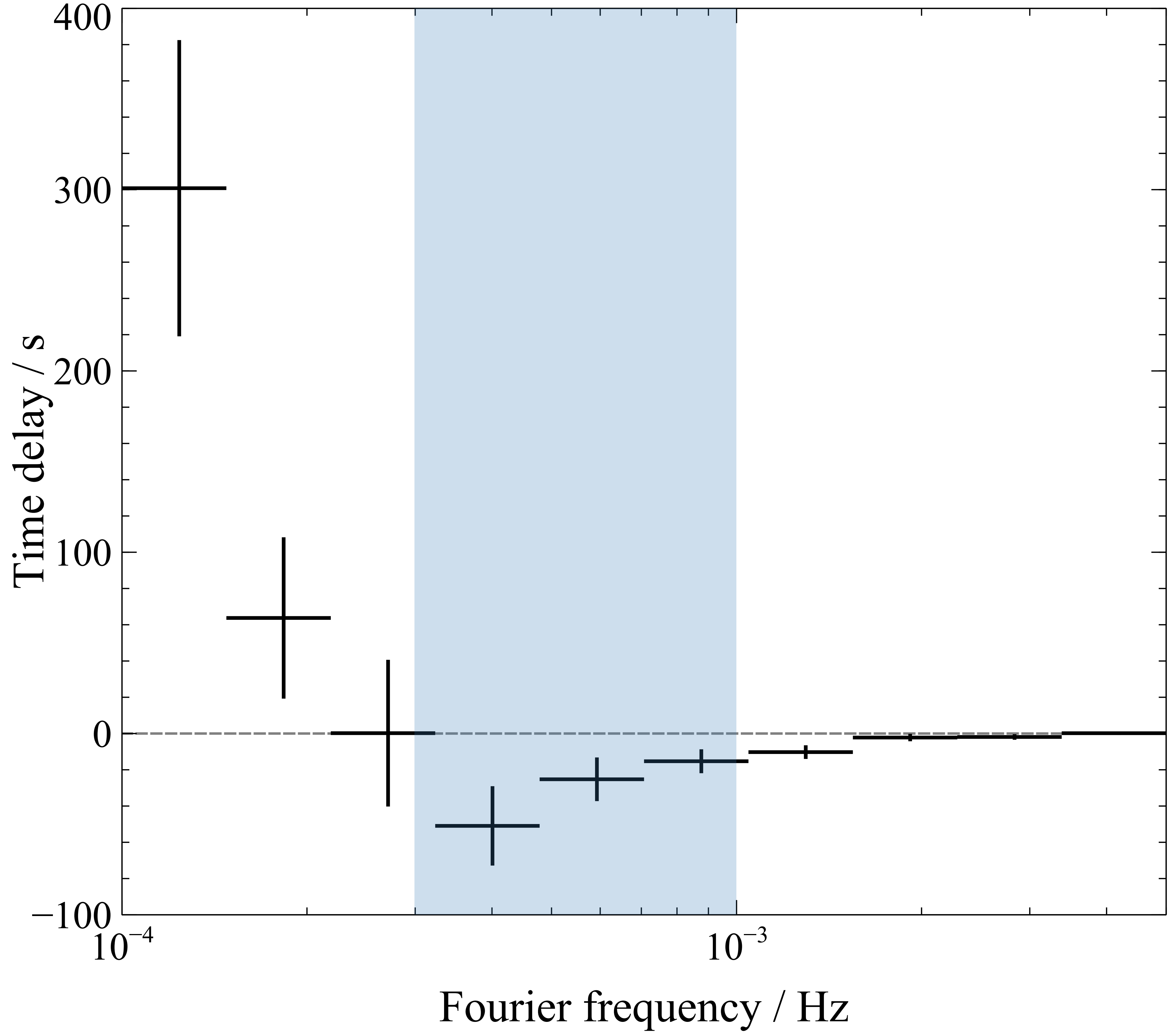
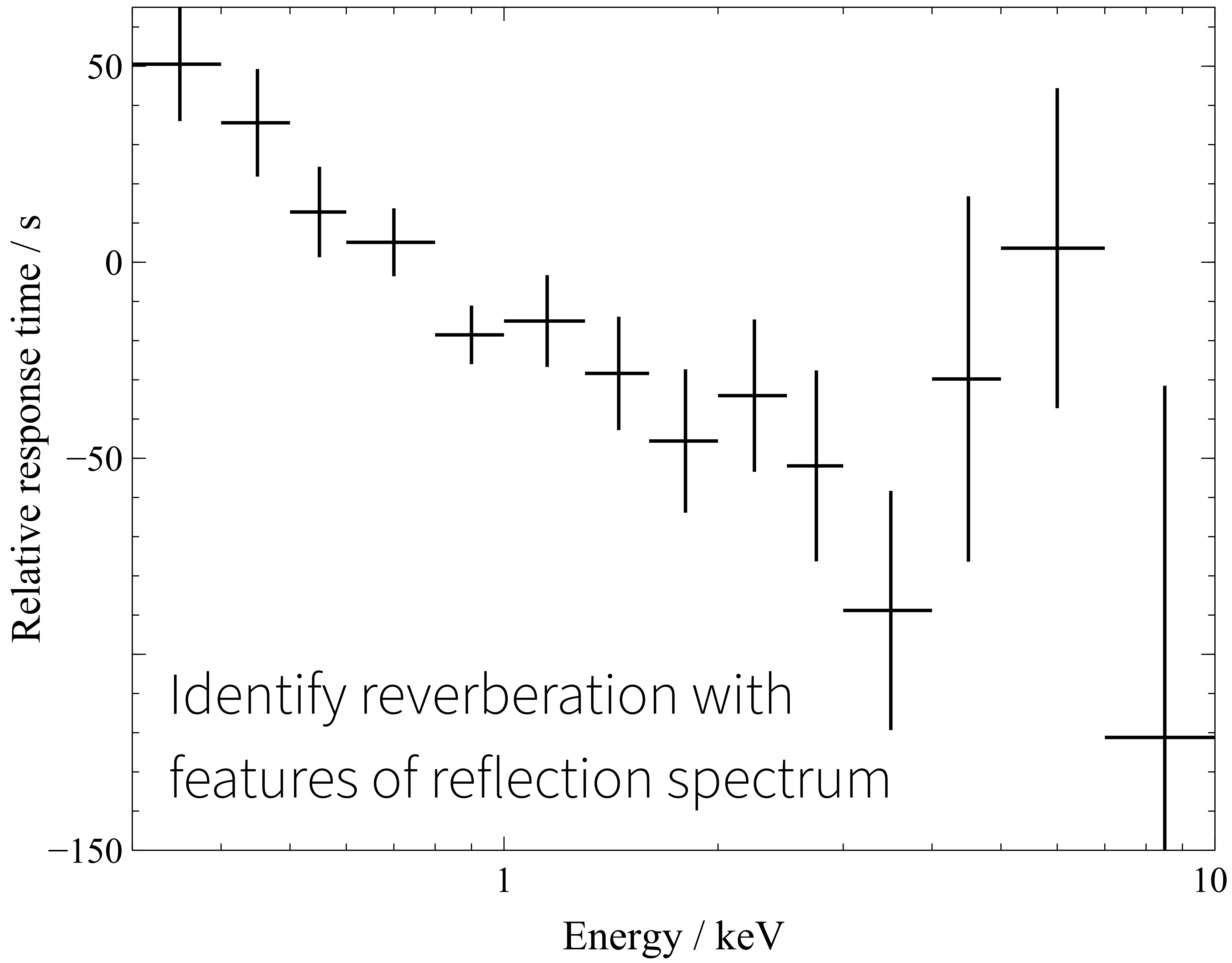


The lag-energy spectrum

Extract light curves in narrow energy bands and calculate time lag of each relative to a reference band. Average over wide range of frequencies.

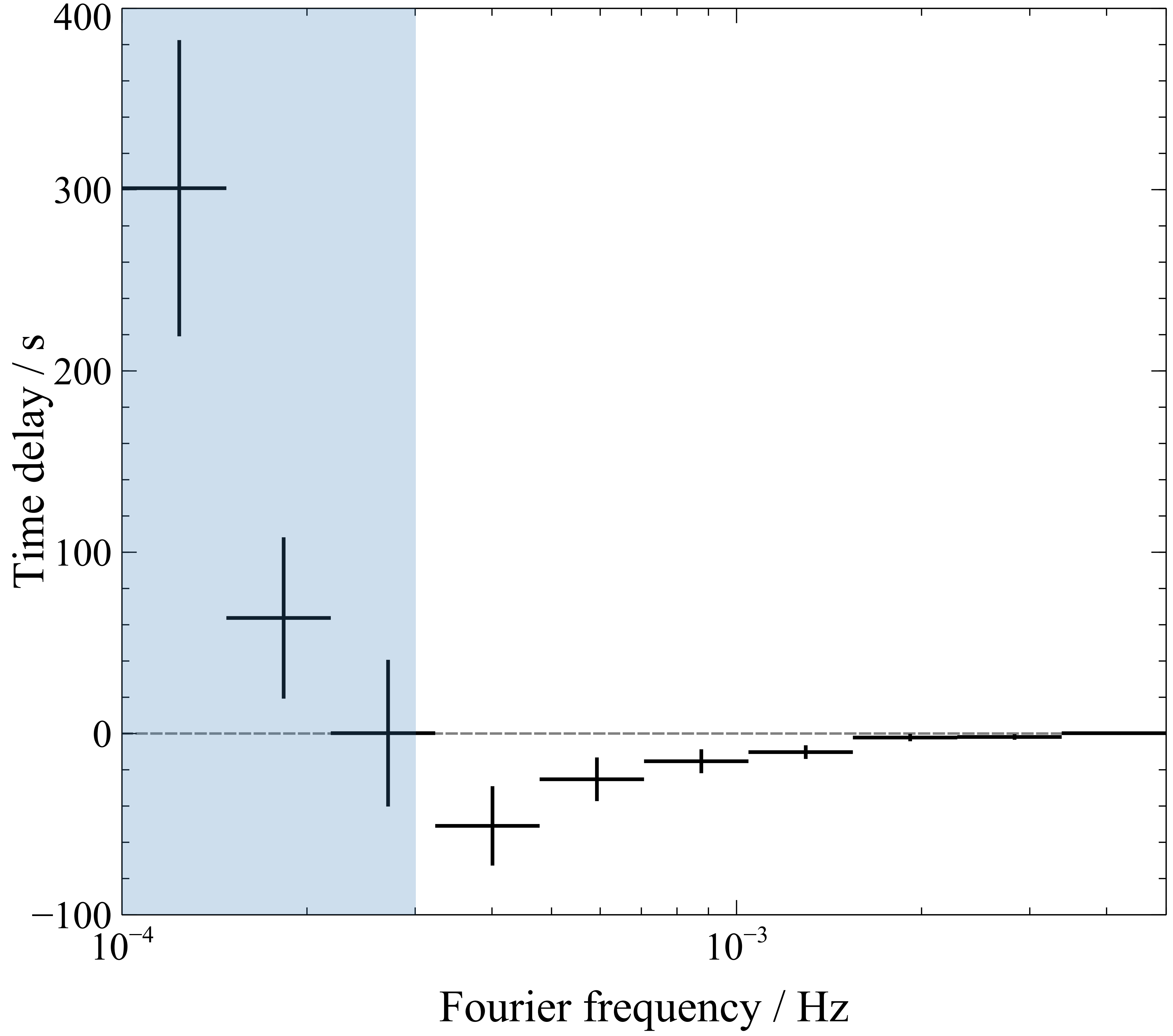


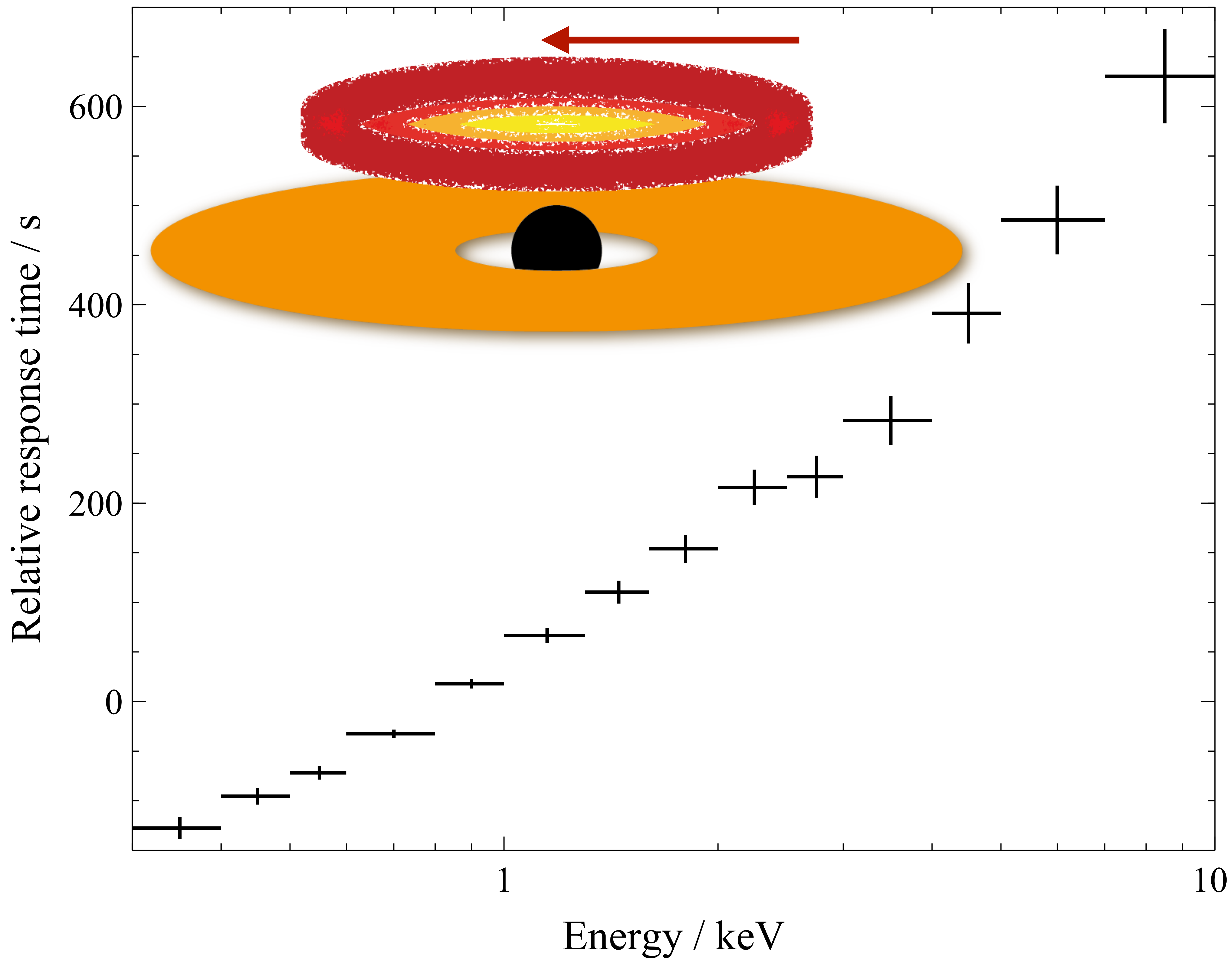


Uttley et al. 2014

The hard lag

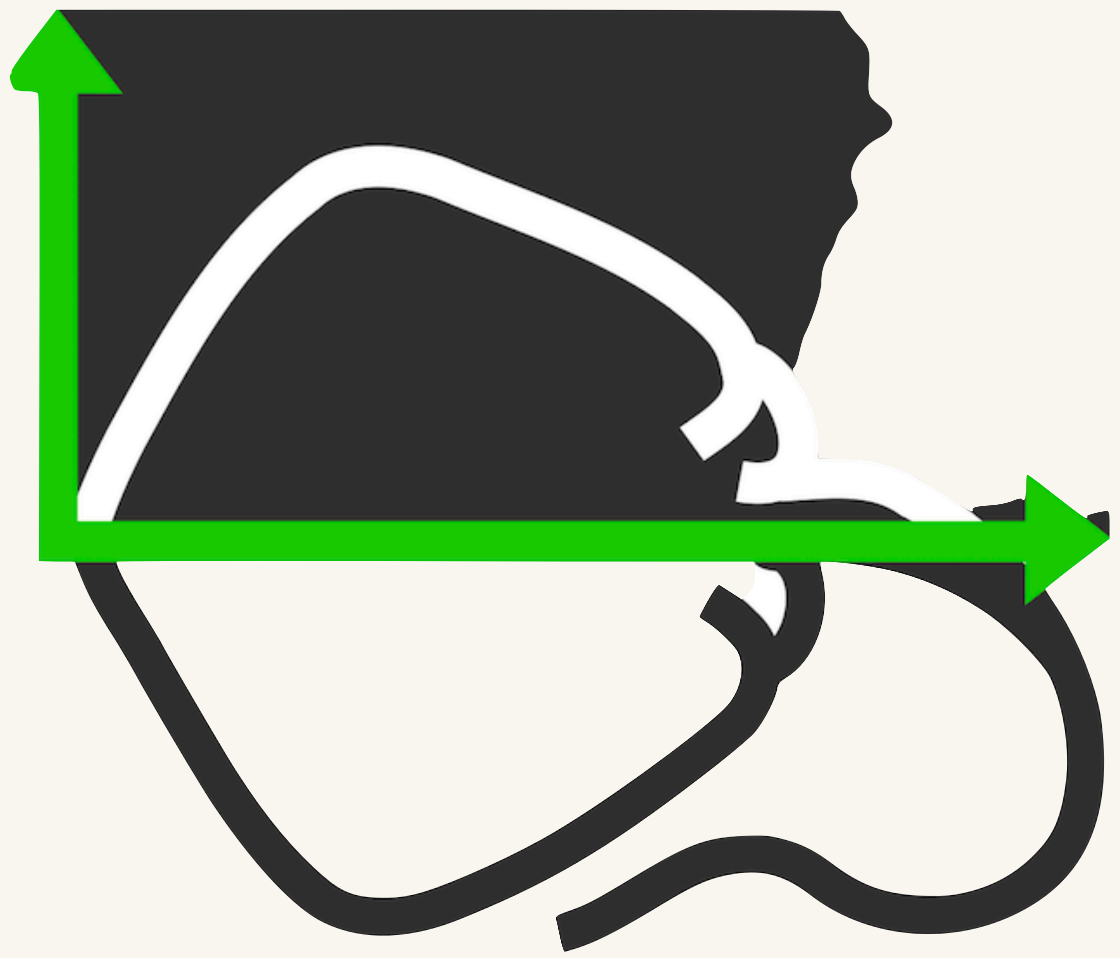
Low frequency variability does not show variation.
High energies delayed with respect to low energies
due to propagation of fluctuations through corona





Uttley et al. 2014

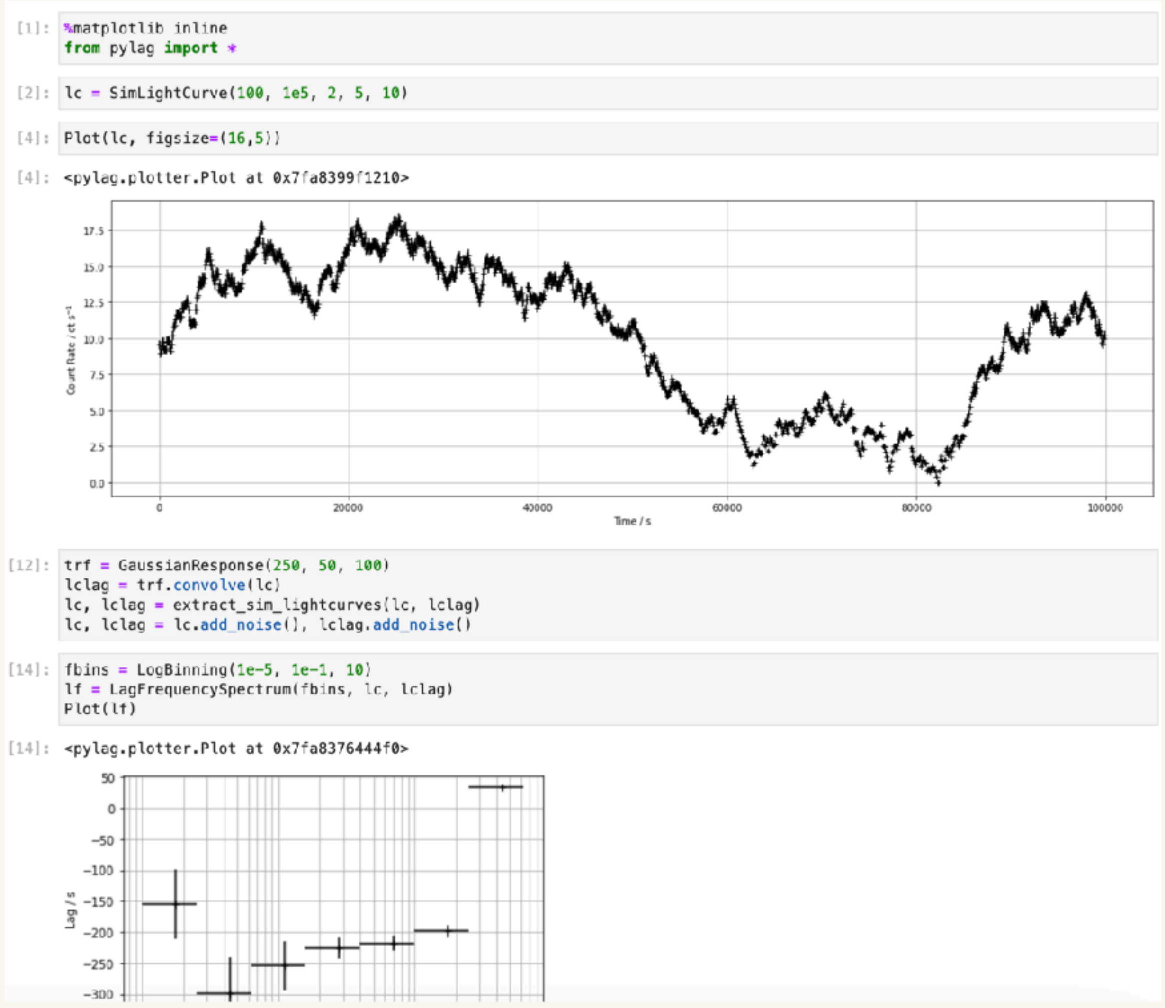
Interested in X-ray spectral timing?



Stingray

- Multi-purpose spectral timing package in Python
- Light curves, power spectra, cross spectra, lags, model fitting, pulsar timing, dead time correction, …

http://stingray.science

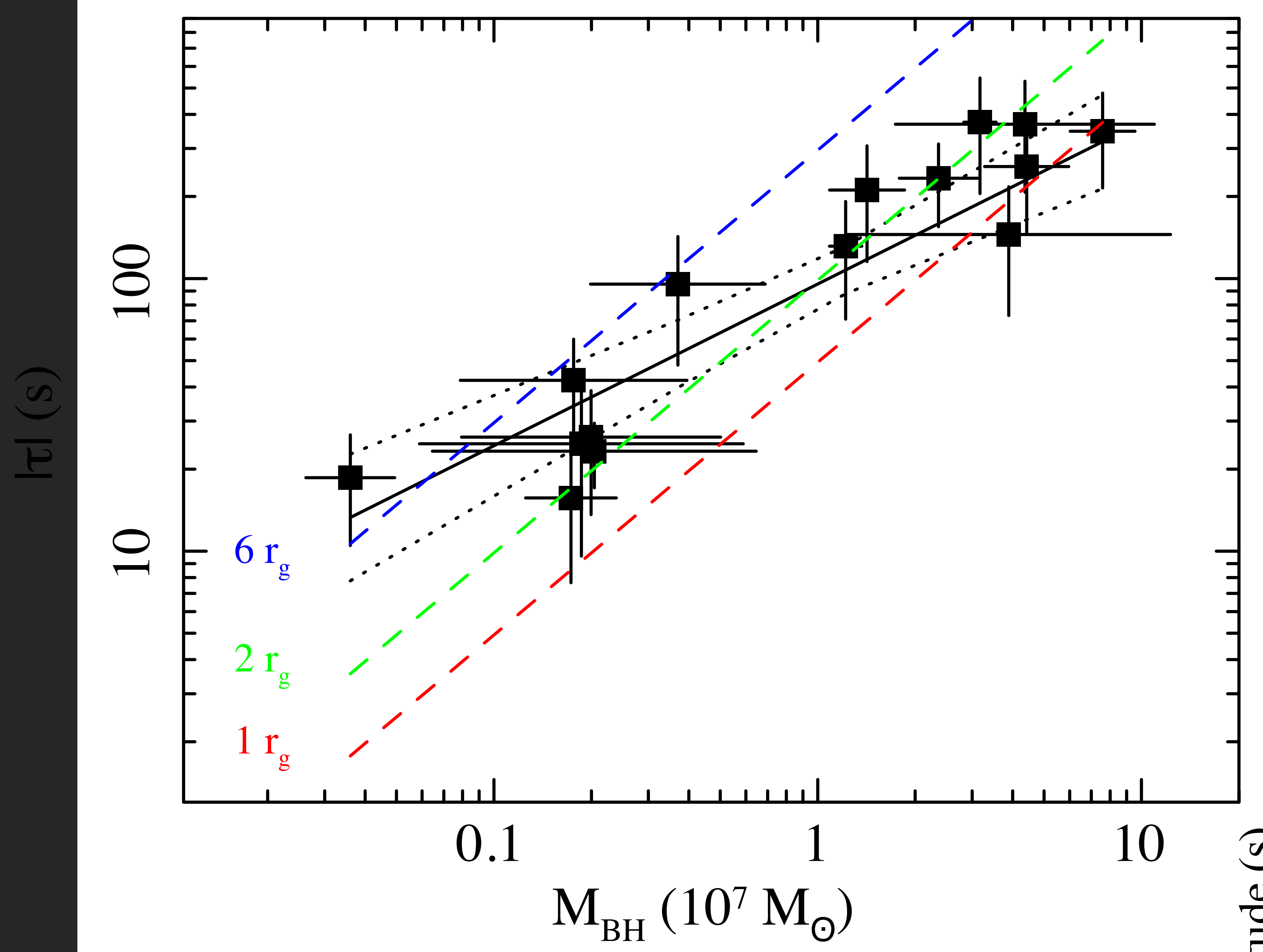


pyLag

- Spectral timing package in Python, specifically designed for X-ray reverberation in AGN/binaries (but other functionality too)
- Light curves, power spectra, cross spectra, lags, covariance, Fvar, model fitting, GR ray tracing, simulating observations, …

http://github.com/wilkinsdr/pyLag

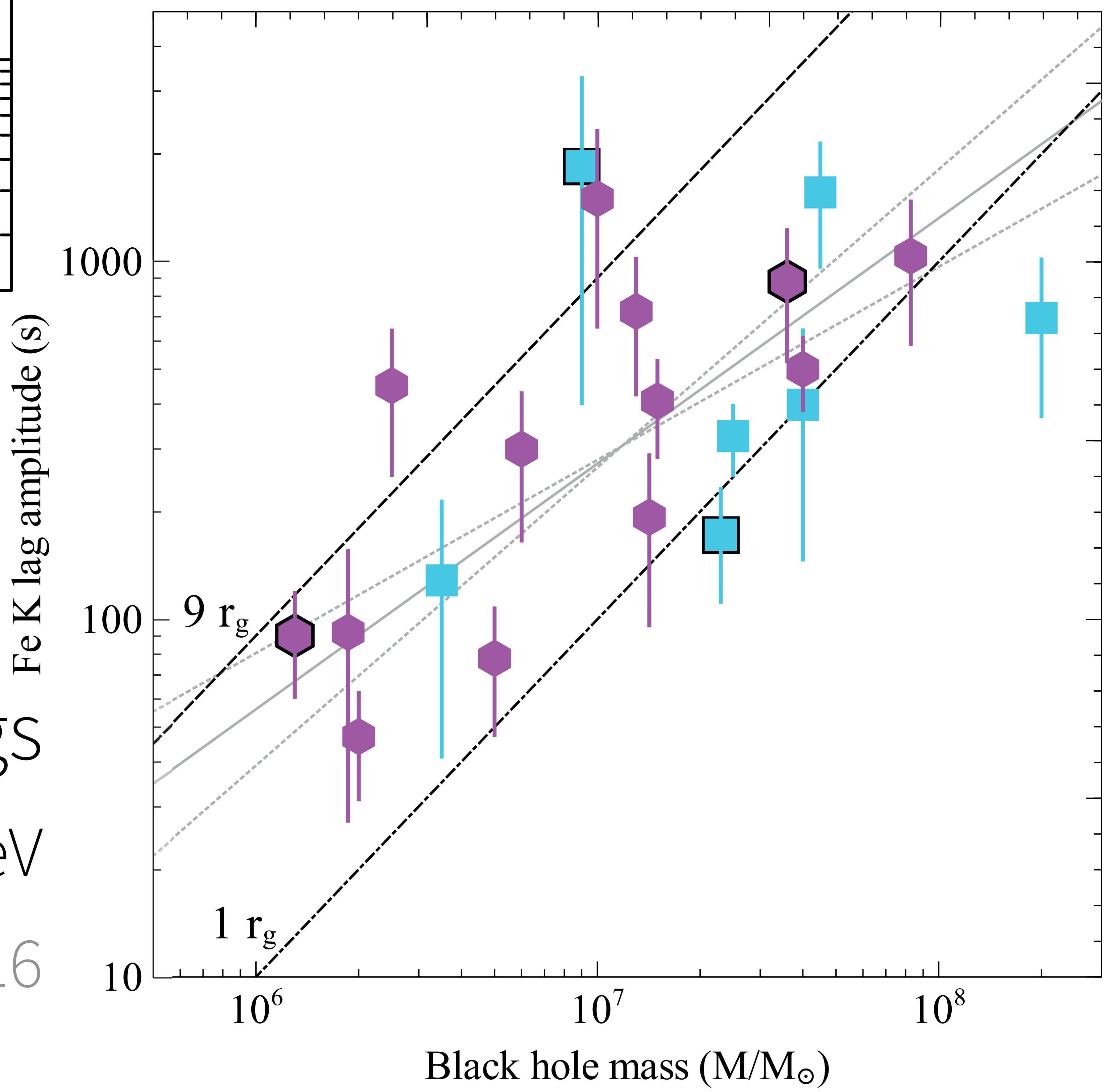
The Height of the Corona



Soft X-ray lags

0.3-1keV vs. 1-4keV

DeMarco et al. 2012



Iron K line lags

4-7keV vs. 1-4keV

Kara et al. 2016

- Reverberation lag times scale with black hole mass — probing a fundamental length scale — height of corona above disc
- Characteristic scale length around black hole is the gravitational radius

$$r_g = \frac{GM}{c^2}$$

- X-ray reverberation probes the innermost parts of the accretion flow

Mapping the Inner Disc and Corona with X-ray Reverberation

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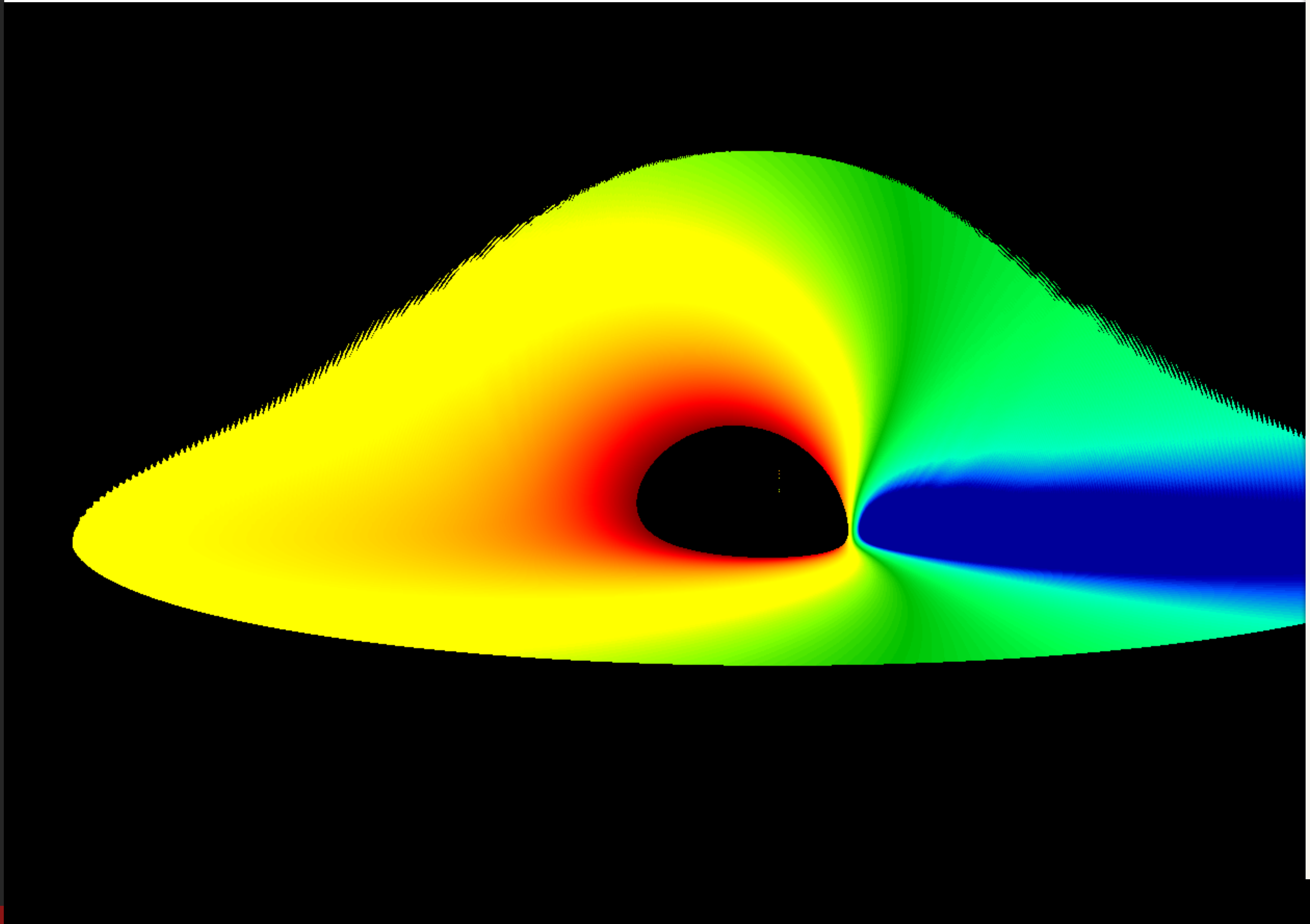

X-rays reverberating from the accretion disc are subject to

- Strong light bending
- Doppler shifts
- Gravitational Redshifts

Energy shifts of line photons are a function of position on the disc

Reverberation time at a given energy shows the distance from corona to each part of the disc

We can build up a 3D picture of the inner disc and corona

Modelling X-ray Reverberation

- General relativistic ray tracing simulation of light paths in curved spacetime around black hole – Wilkins et al. 2012, 2016, 2020a
- Reflection spectrum from disk produced by radiative transfer simulation – García et al. 2013
- Translate measurements of reflection spectrum, line profile and time lags into measurements of location and structure of corona – Wilkins et al. 2012, 2013, 2016
- Detect signatures of strong light bending in vicinity of black hole – Wilkins et al. 2020b, 2021
- Predict emission from gas in its final moments as it plunges into black hole – Wilkins et al. 2020a
- Test deviations from General Relativity – Johanssen & Psaltis 2012, Bambi et al. 2021

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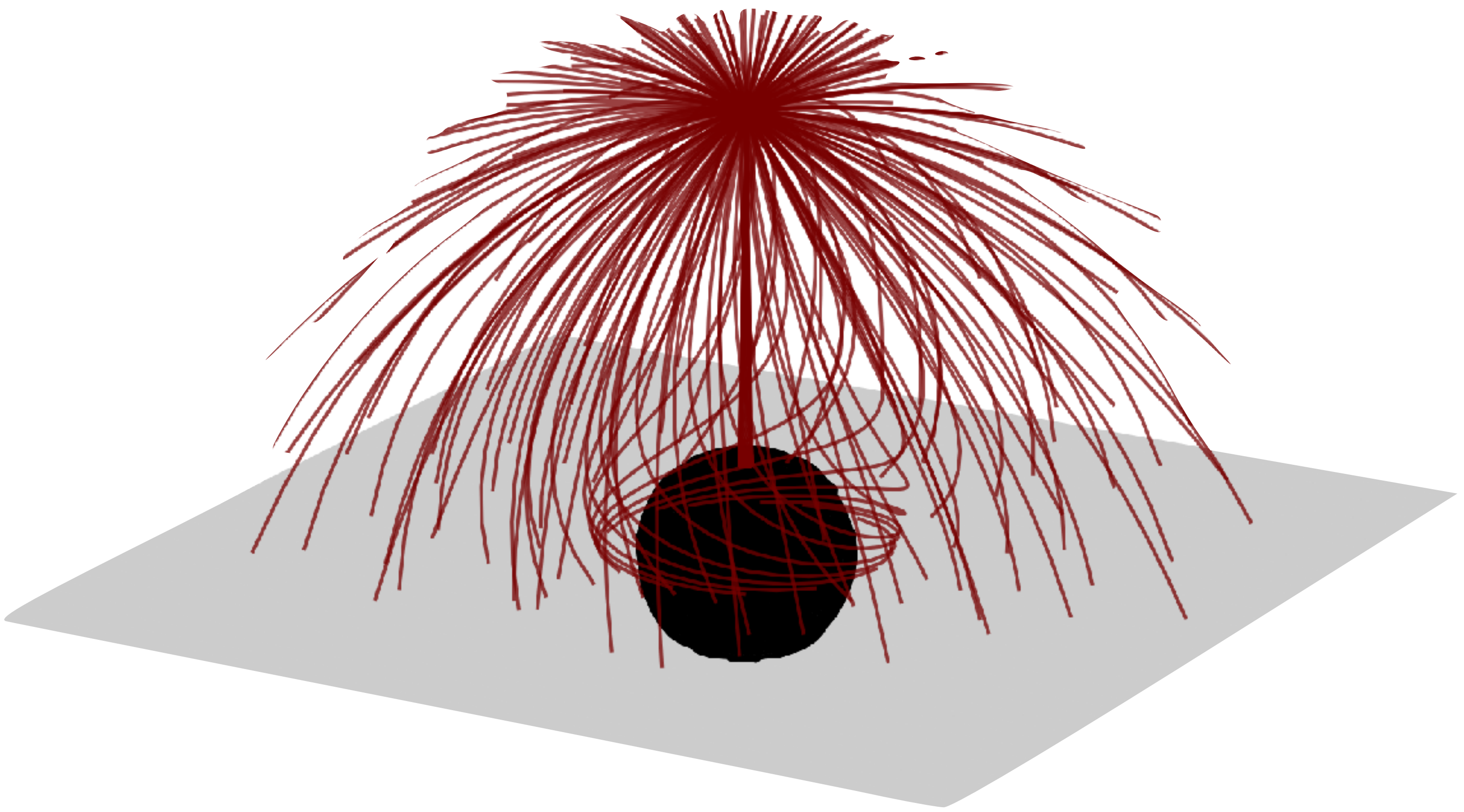
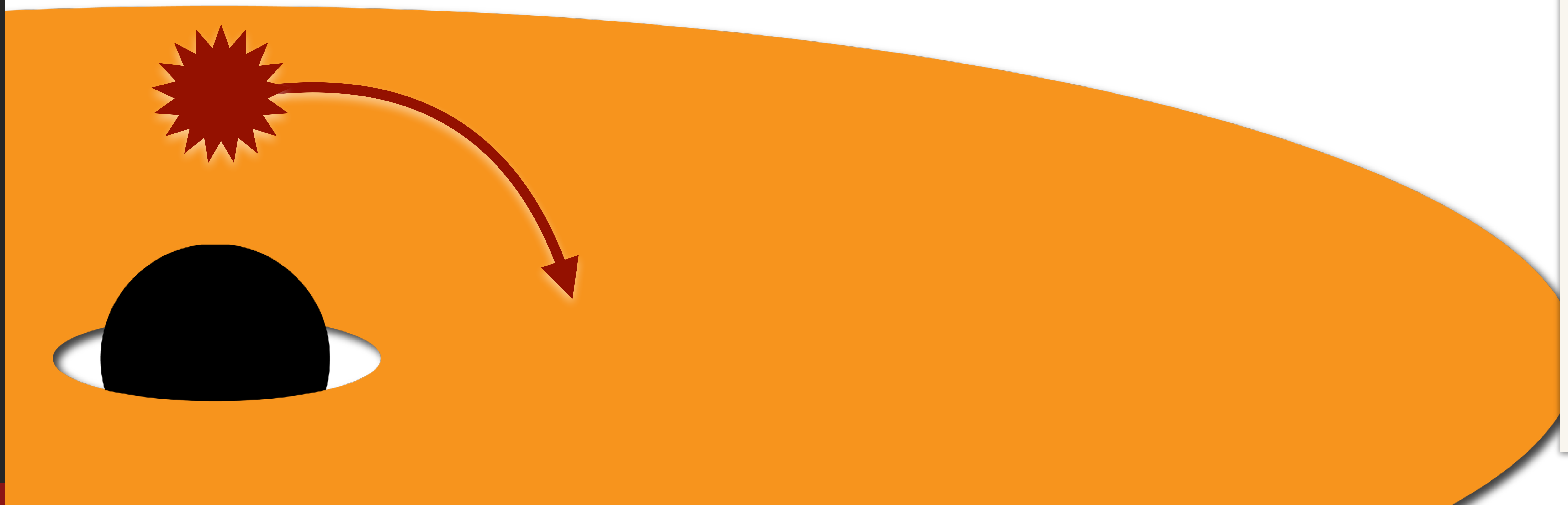
Modelling X-ray Reverberation

1. Trace rays from source to disc





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Modelling X-ray Reverberation

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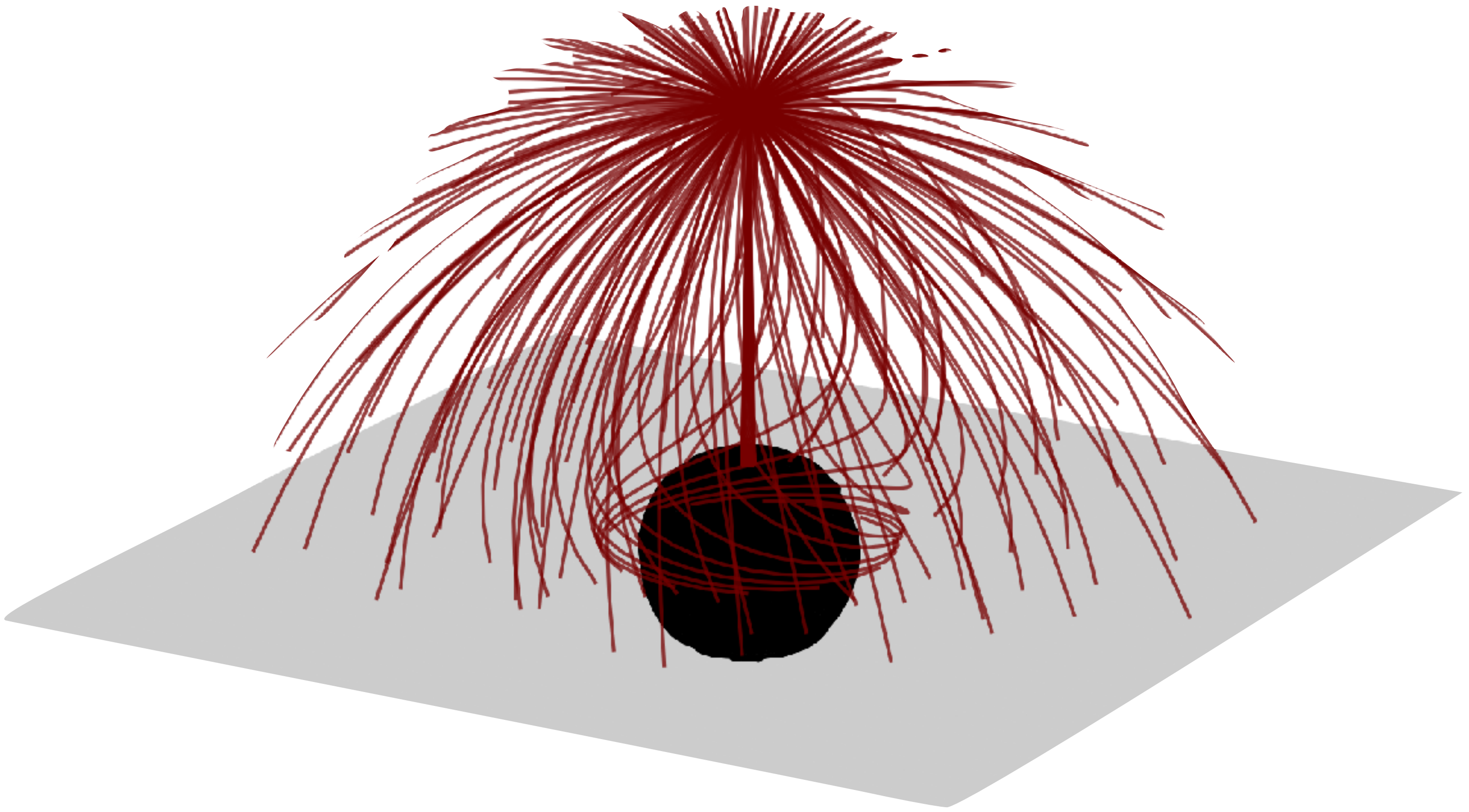

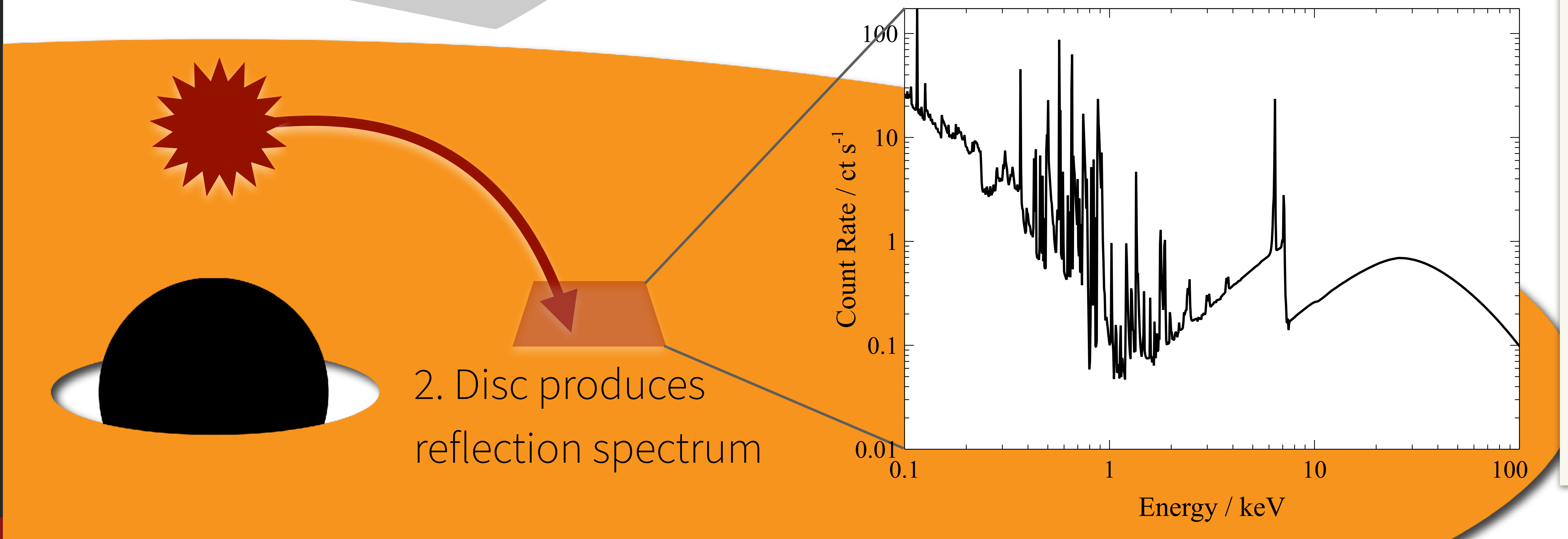

2. Disc produces reflection spectrum

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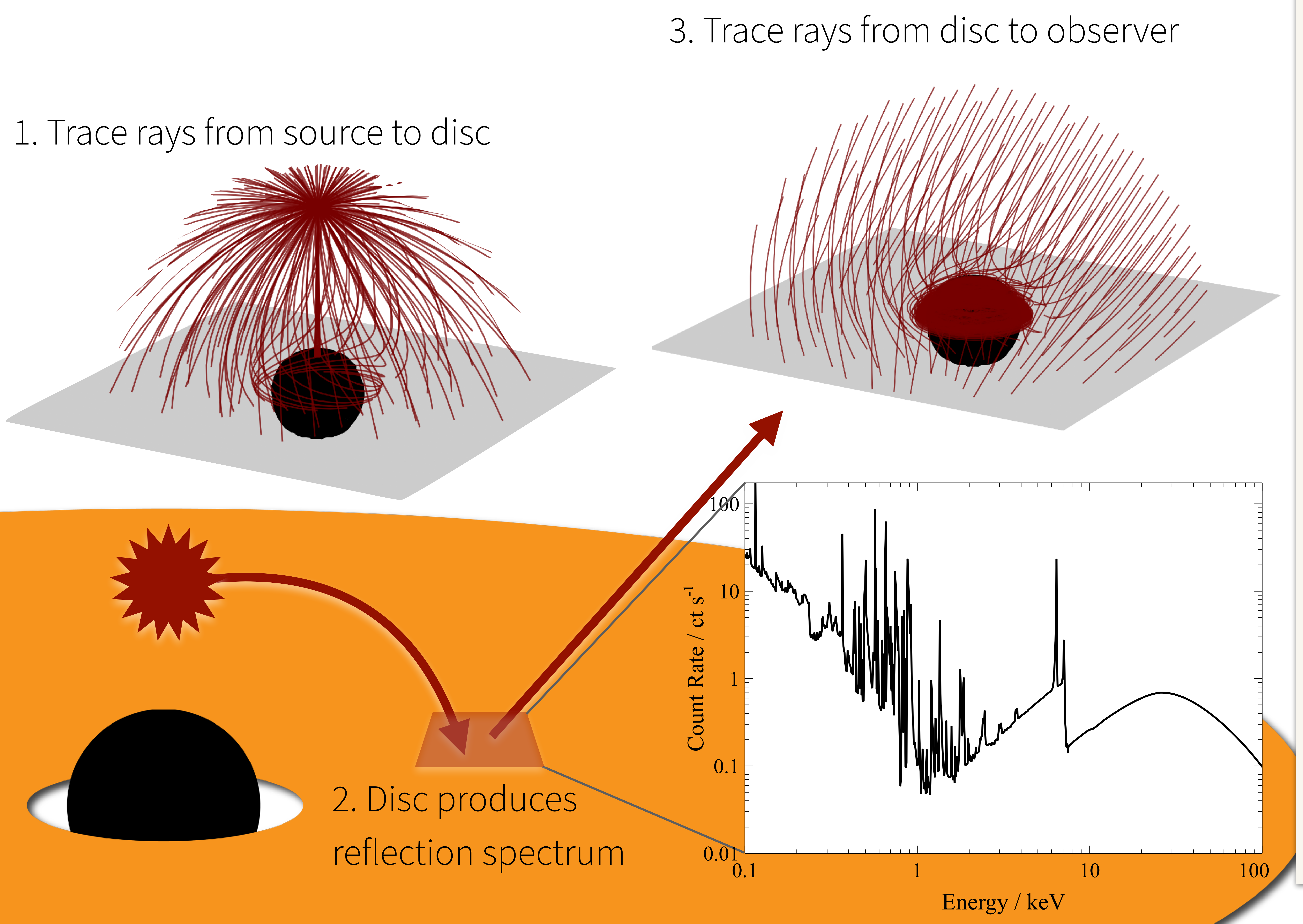
Modelling X-ray Reverberation



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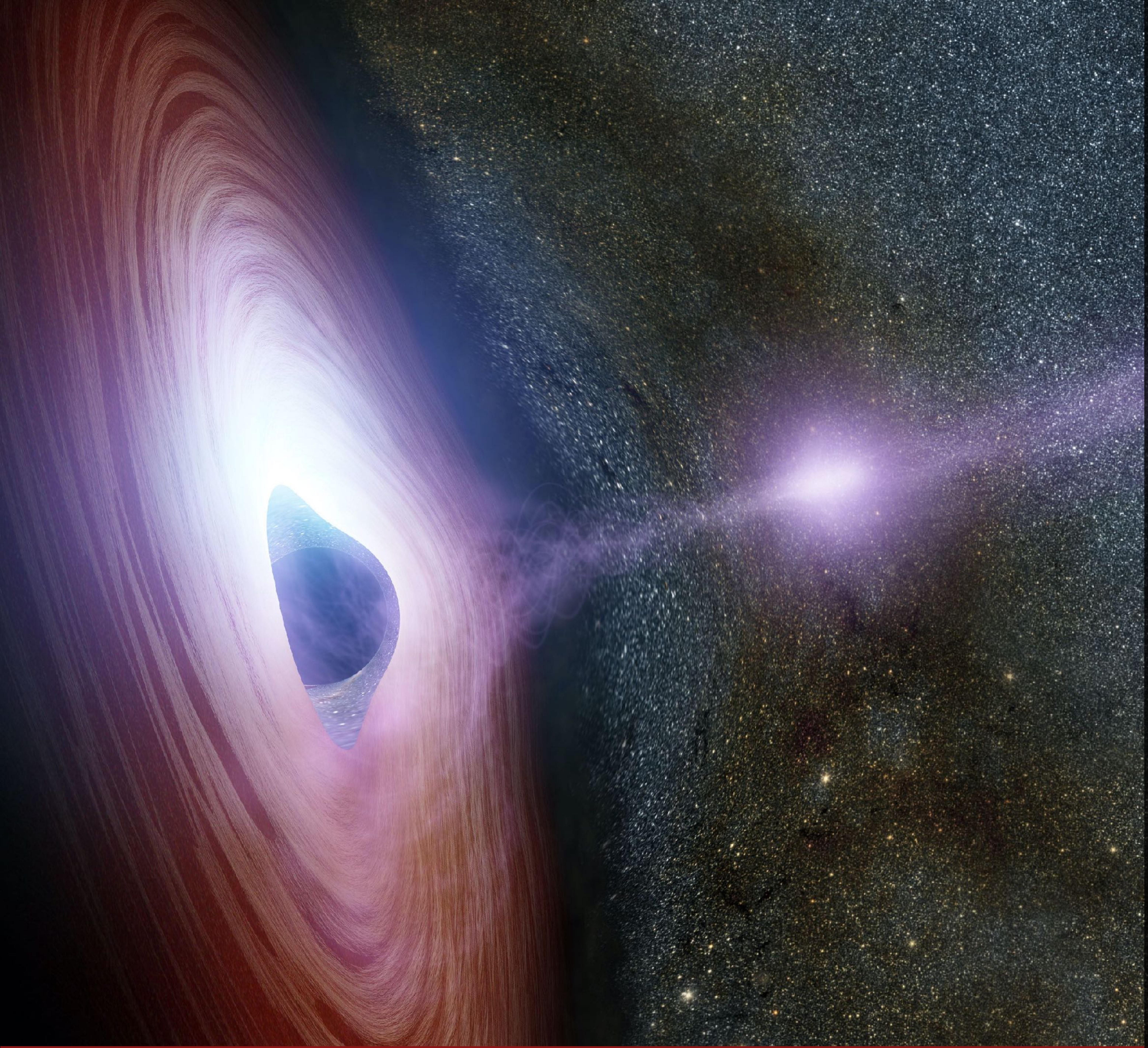
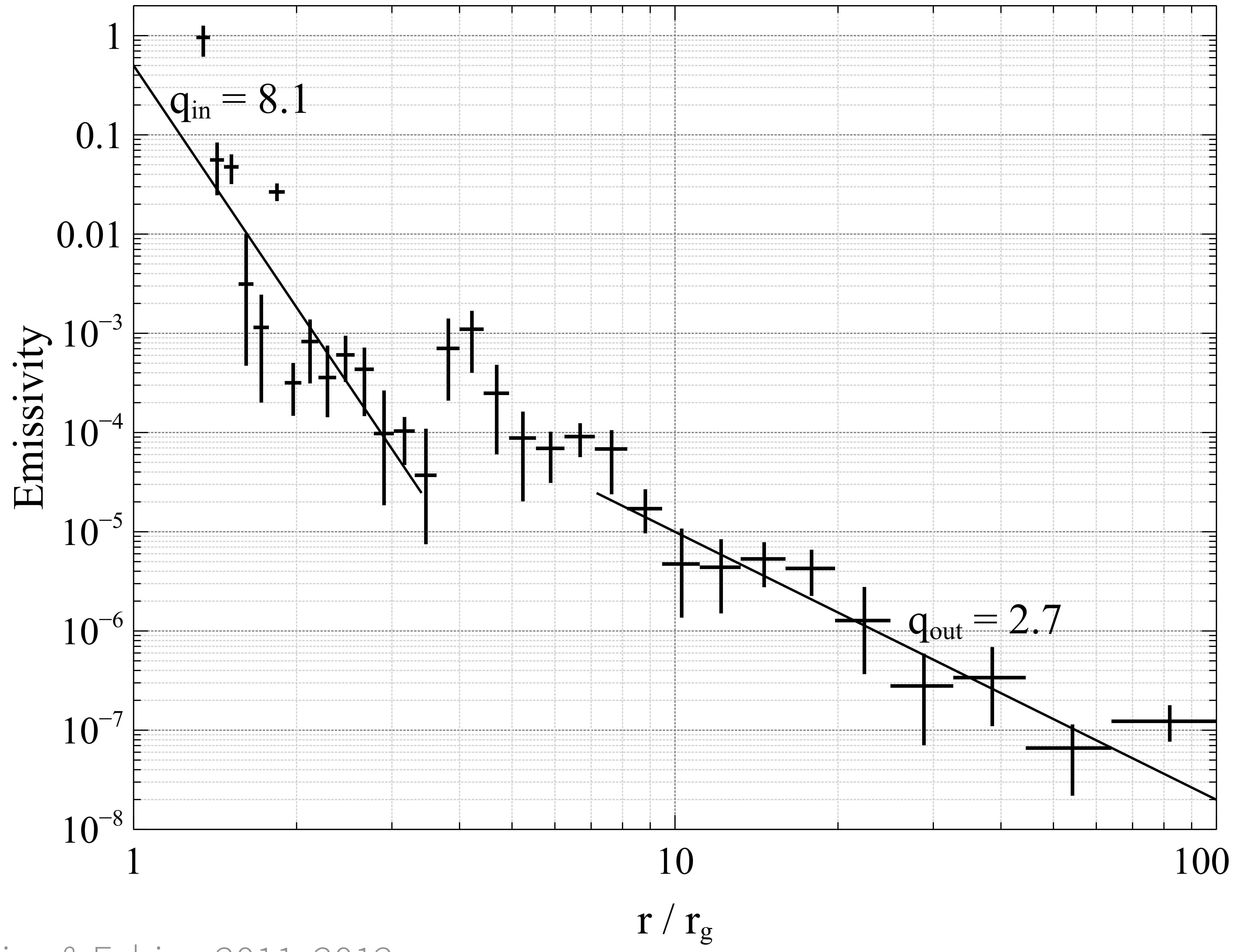
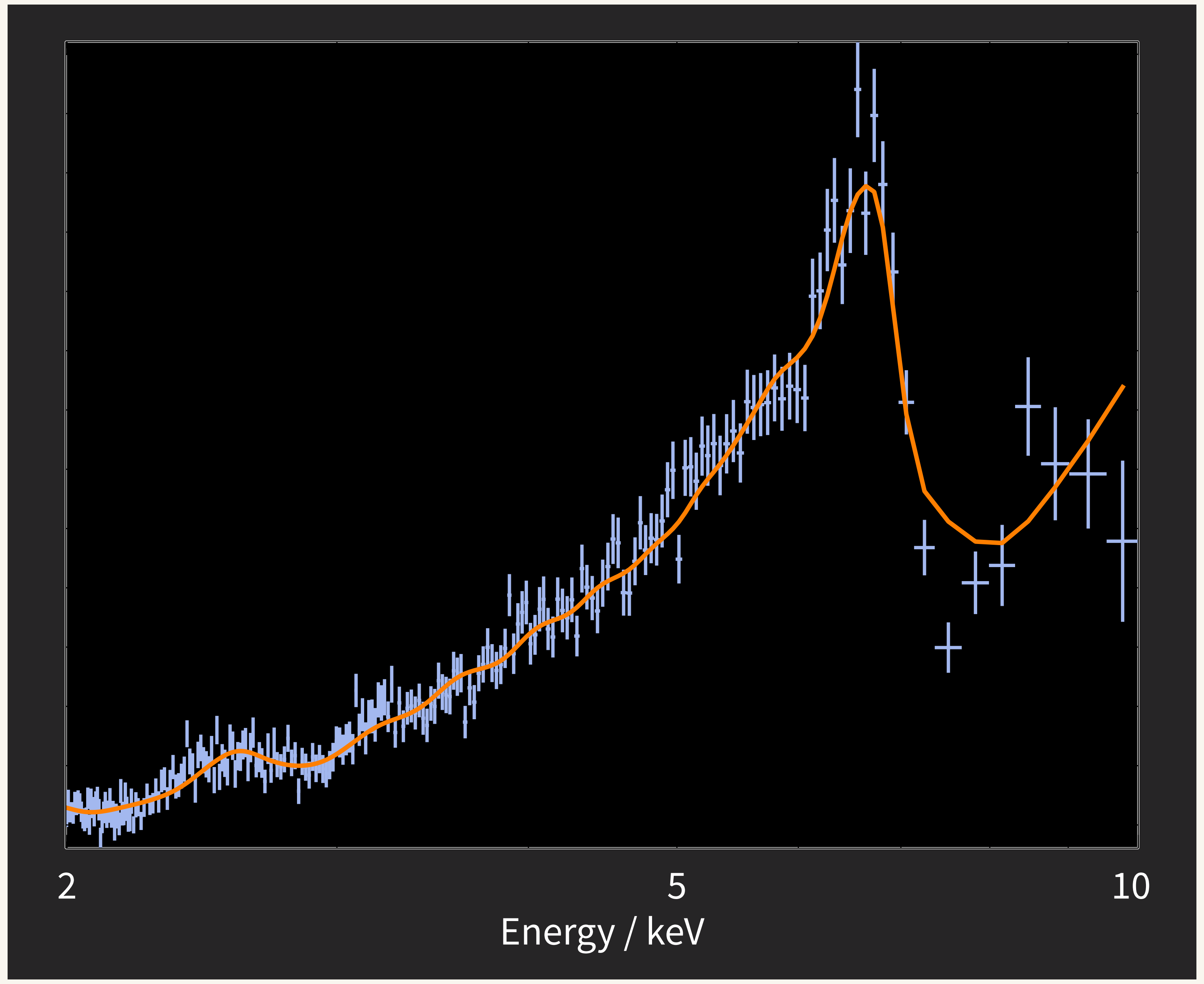


Mapping the Corona

Measuring the Extent of the Corona

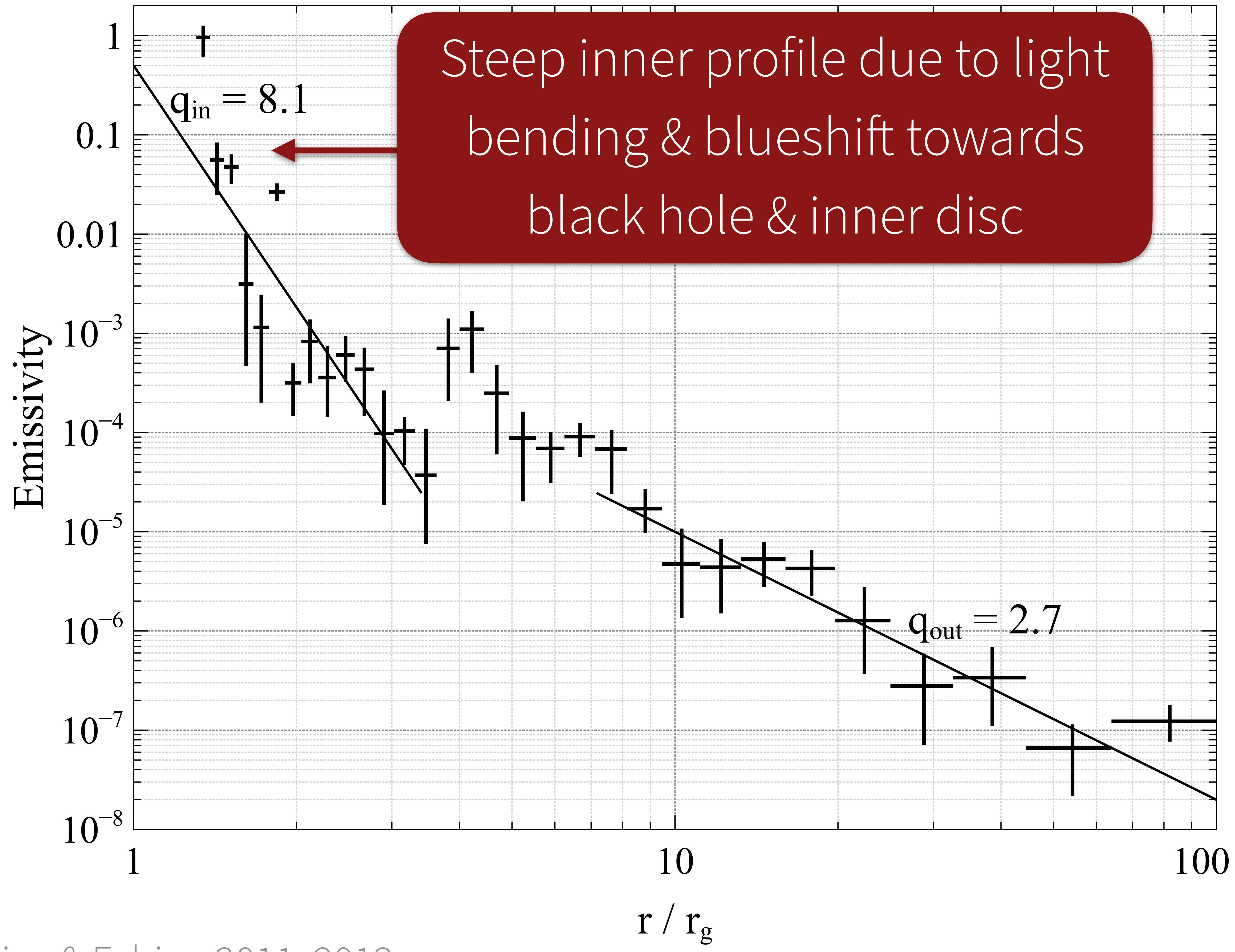


Fit the shape of the emission line to find how much of the reflection arises from each radius



Wilkins & Fabian 2011, 2012

Measuring the Extent of the Corona



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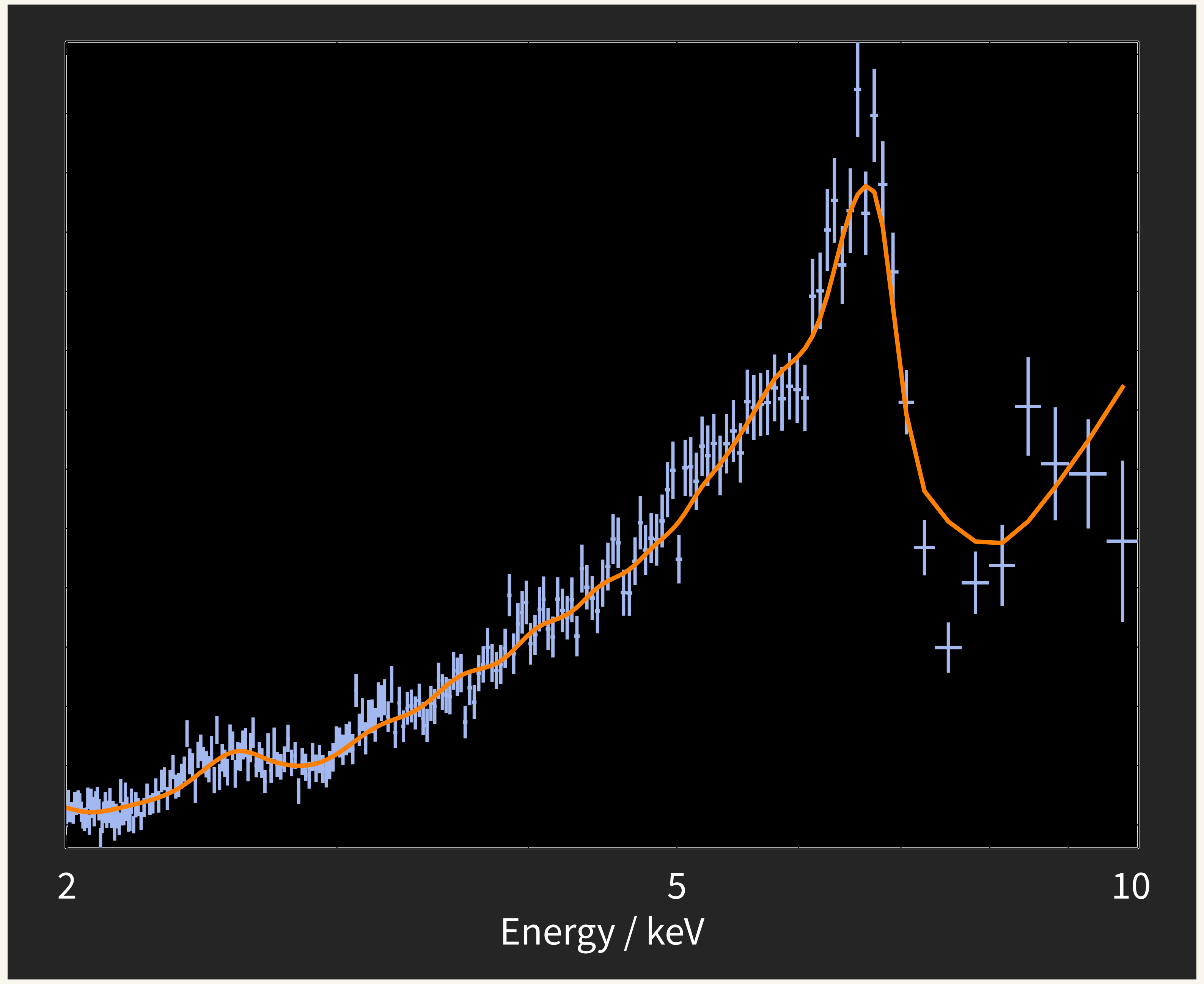
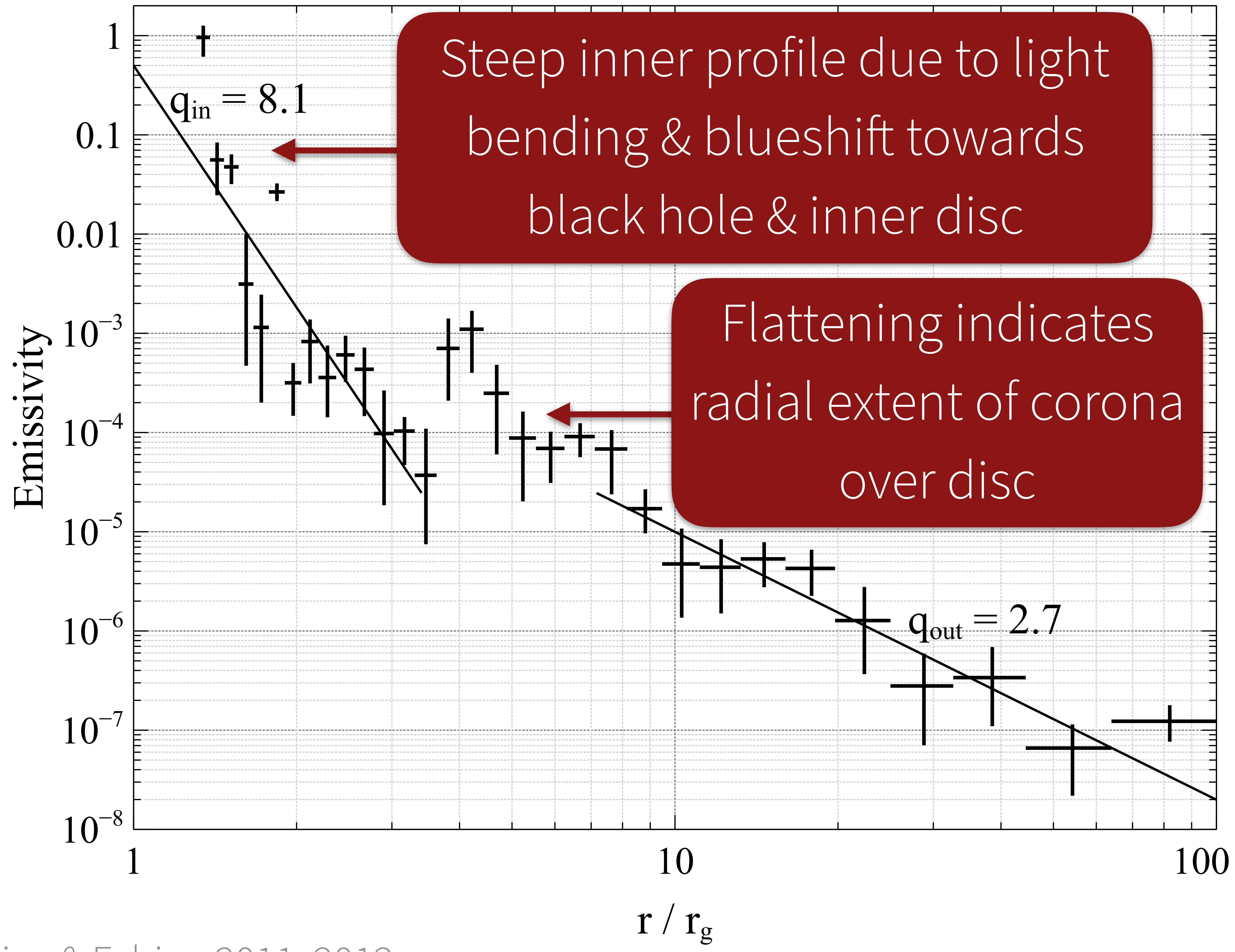
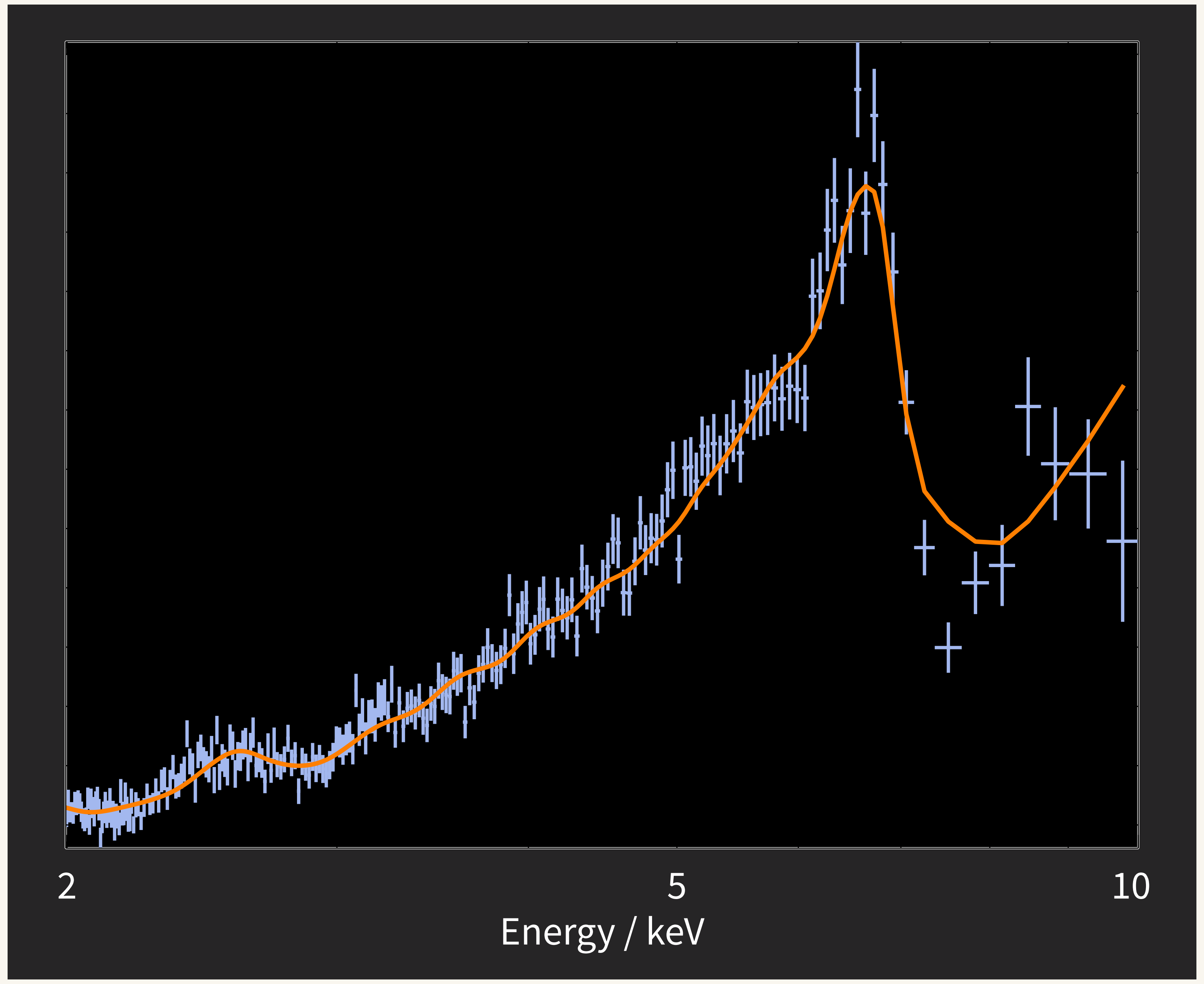


Wilkins & Fabian 2011, 2012

Measuring the Extent of the Corona



Fit the shape of the emission line to find how much of the reflection arises from each radius



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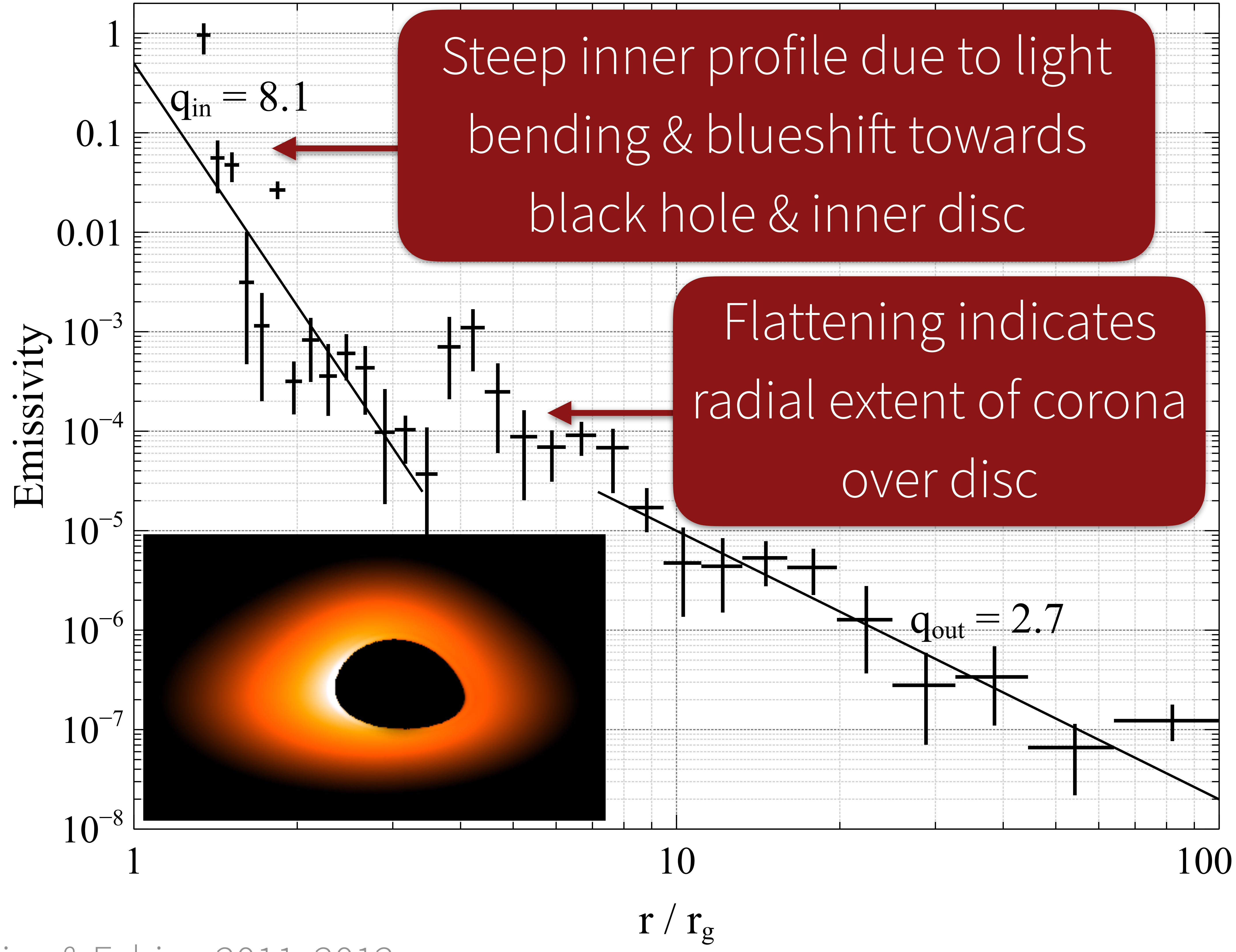

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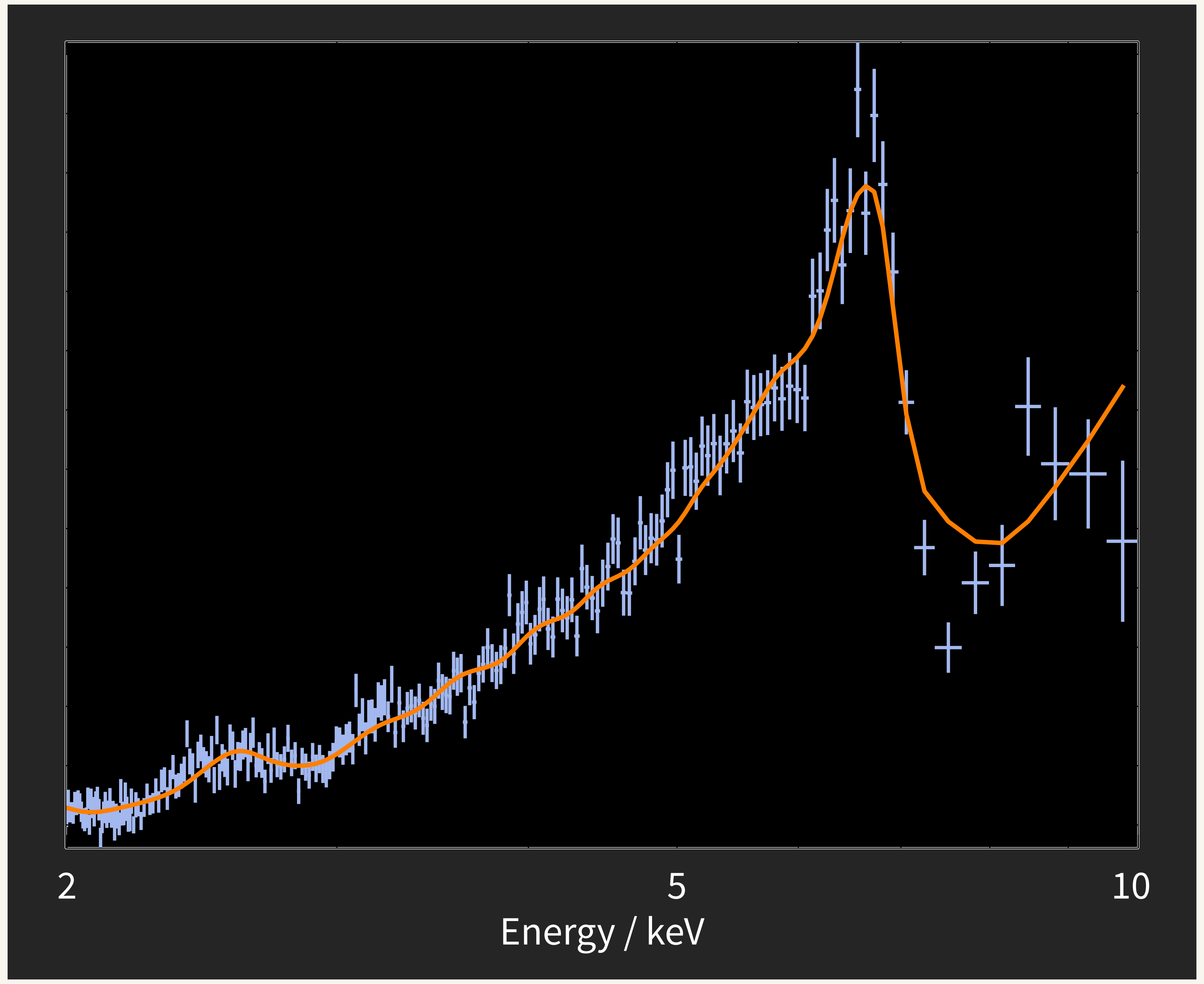
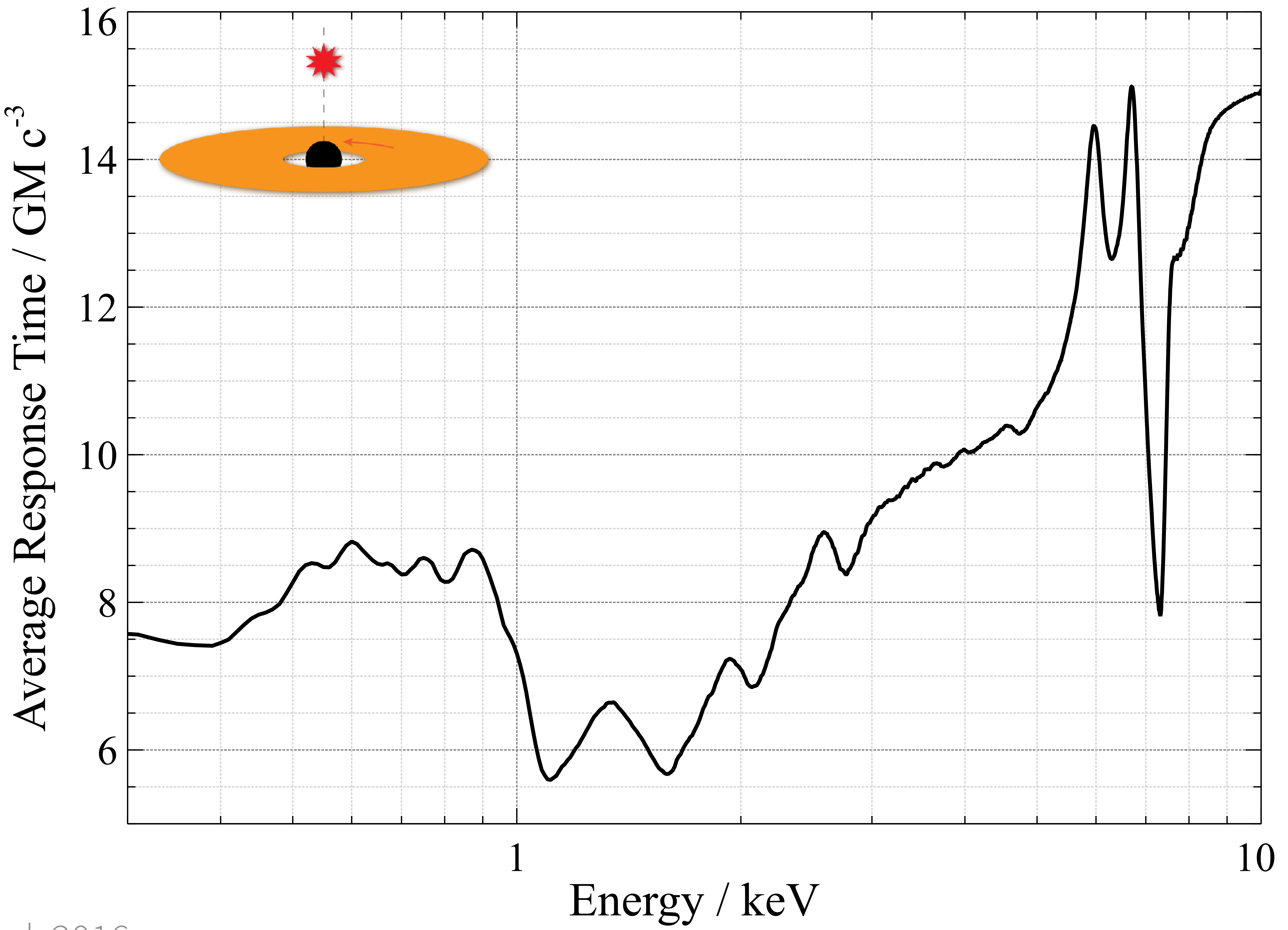


Wilkins & Fabian 2011, 2012

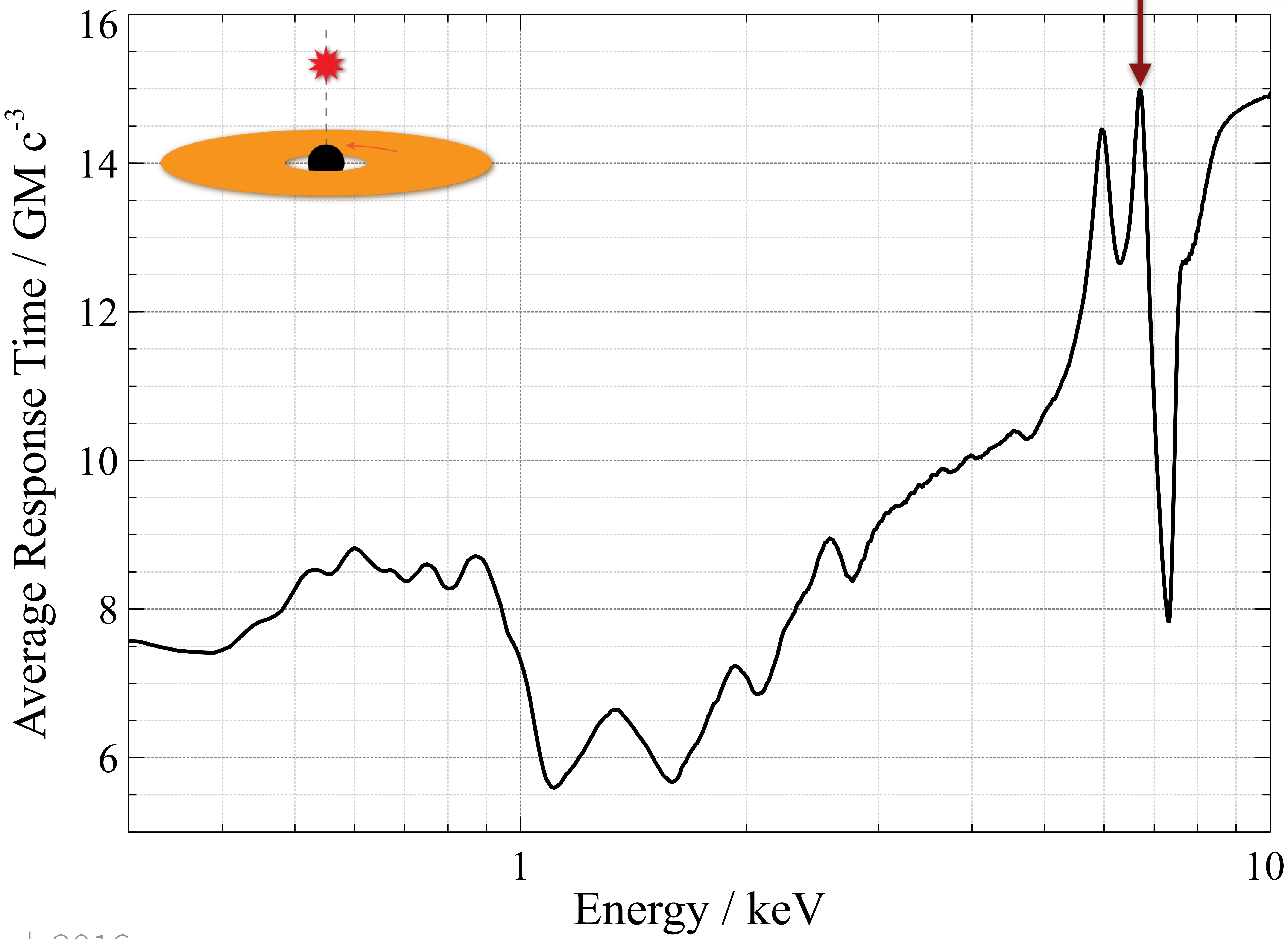
What about the time lags?



Wilkins et al. 2016

What about the time lags?

Delayed response of iron K line



Wilkins et al. 2016

Stanford

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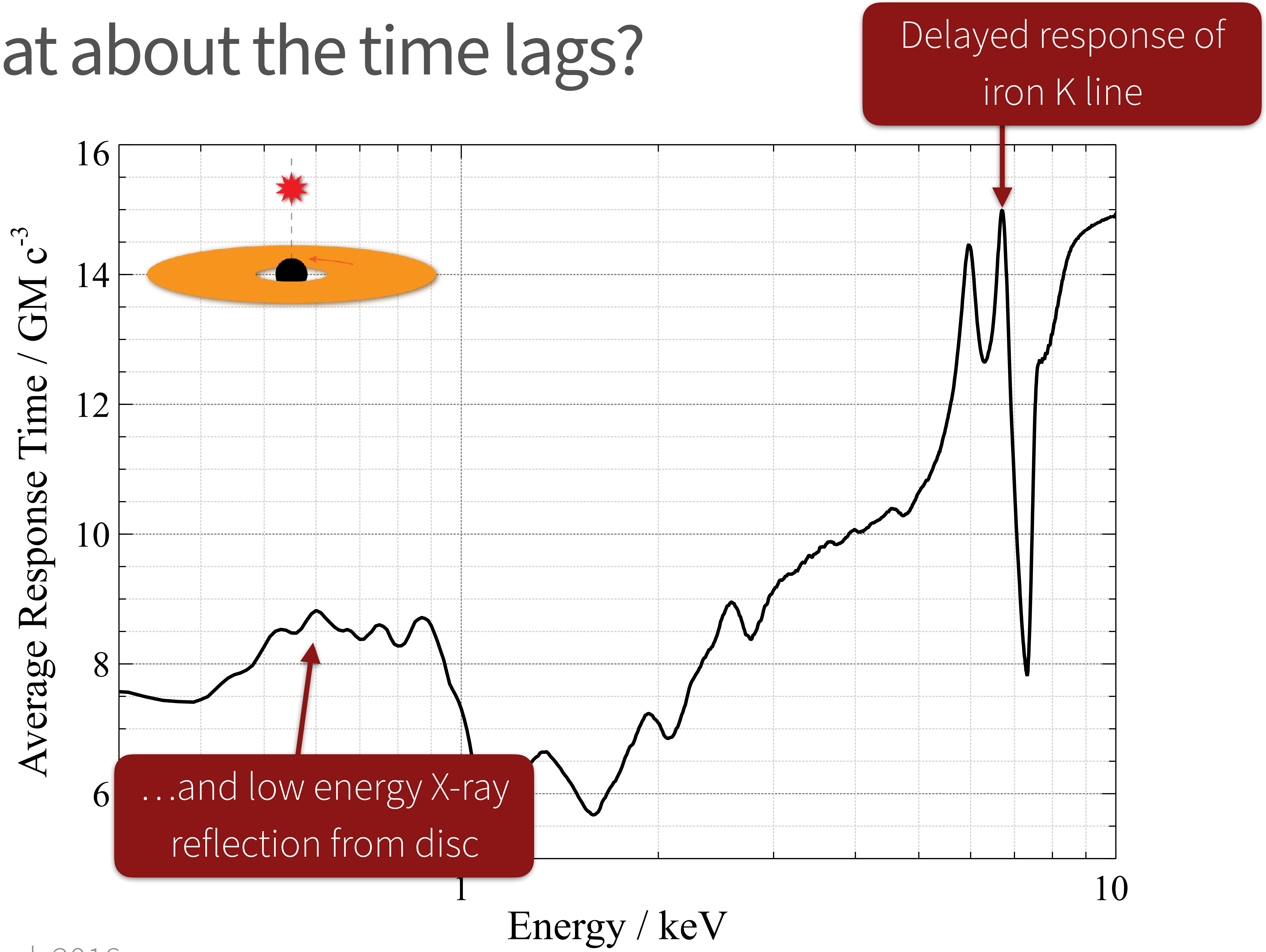

Wilkins et al. 2016

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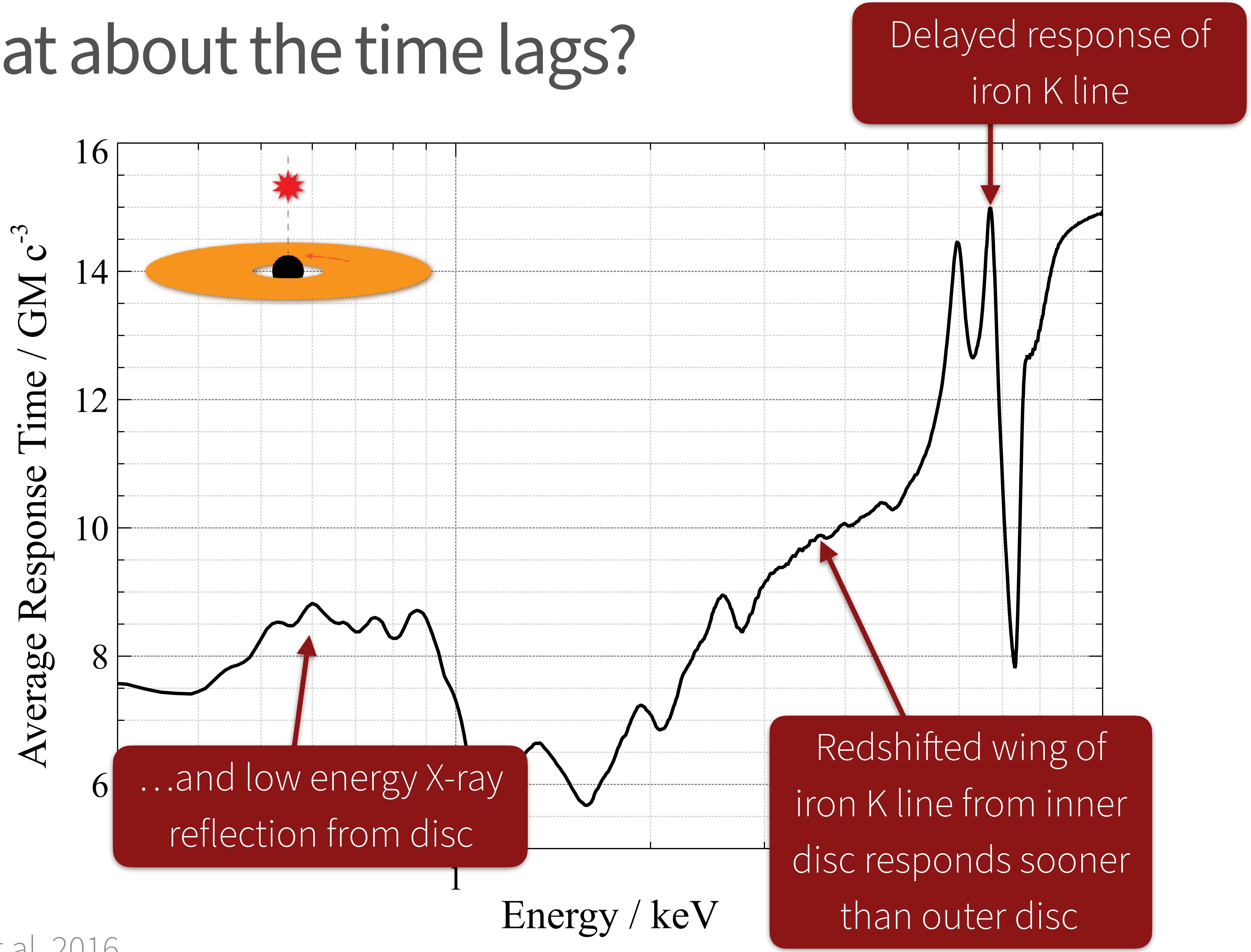

Wilkins et al. 2016

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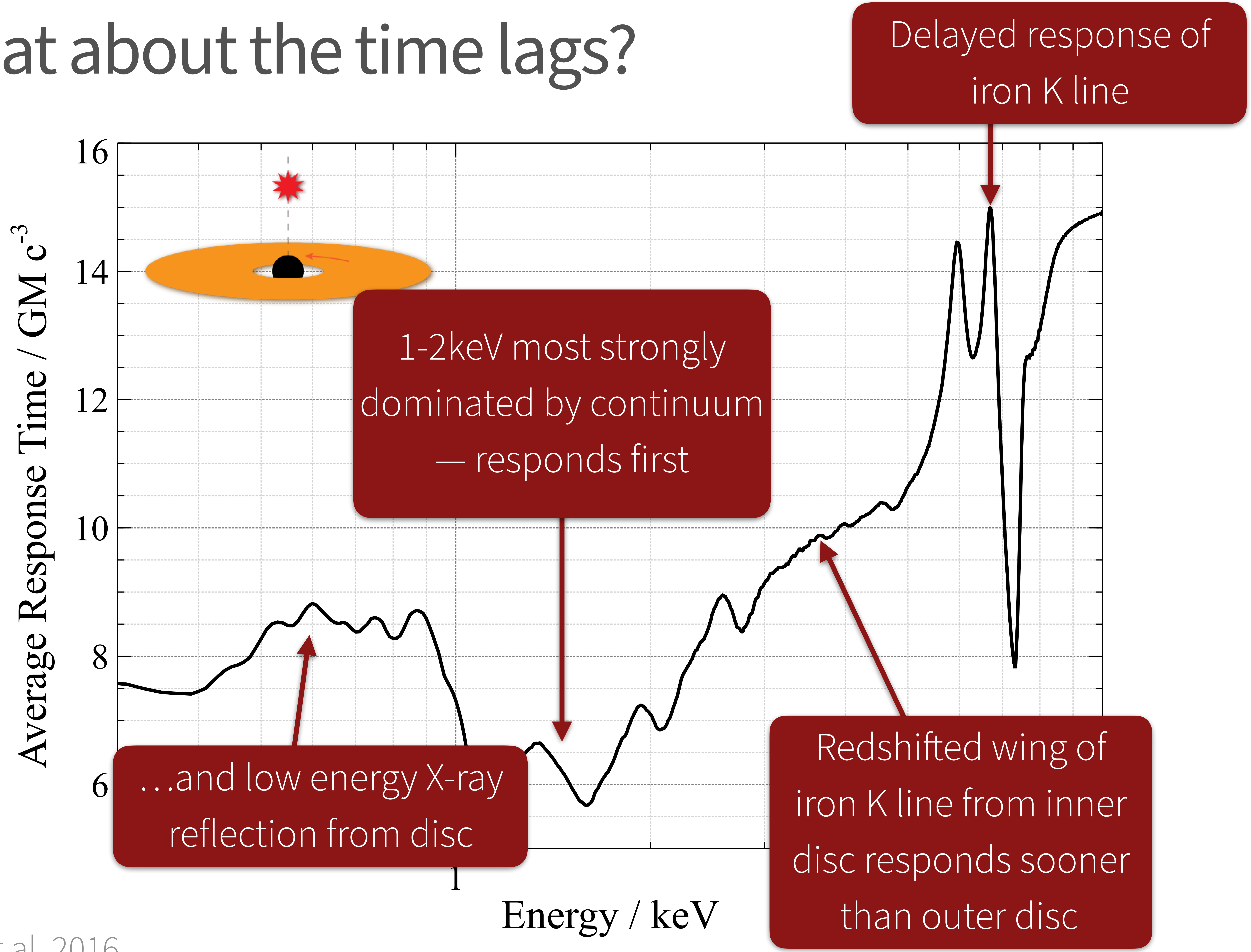

Wilkins et al. 2016

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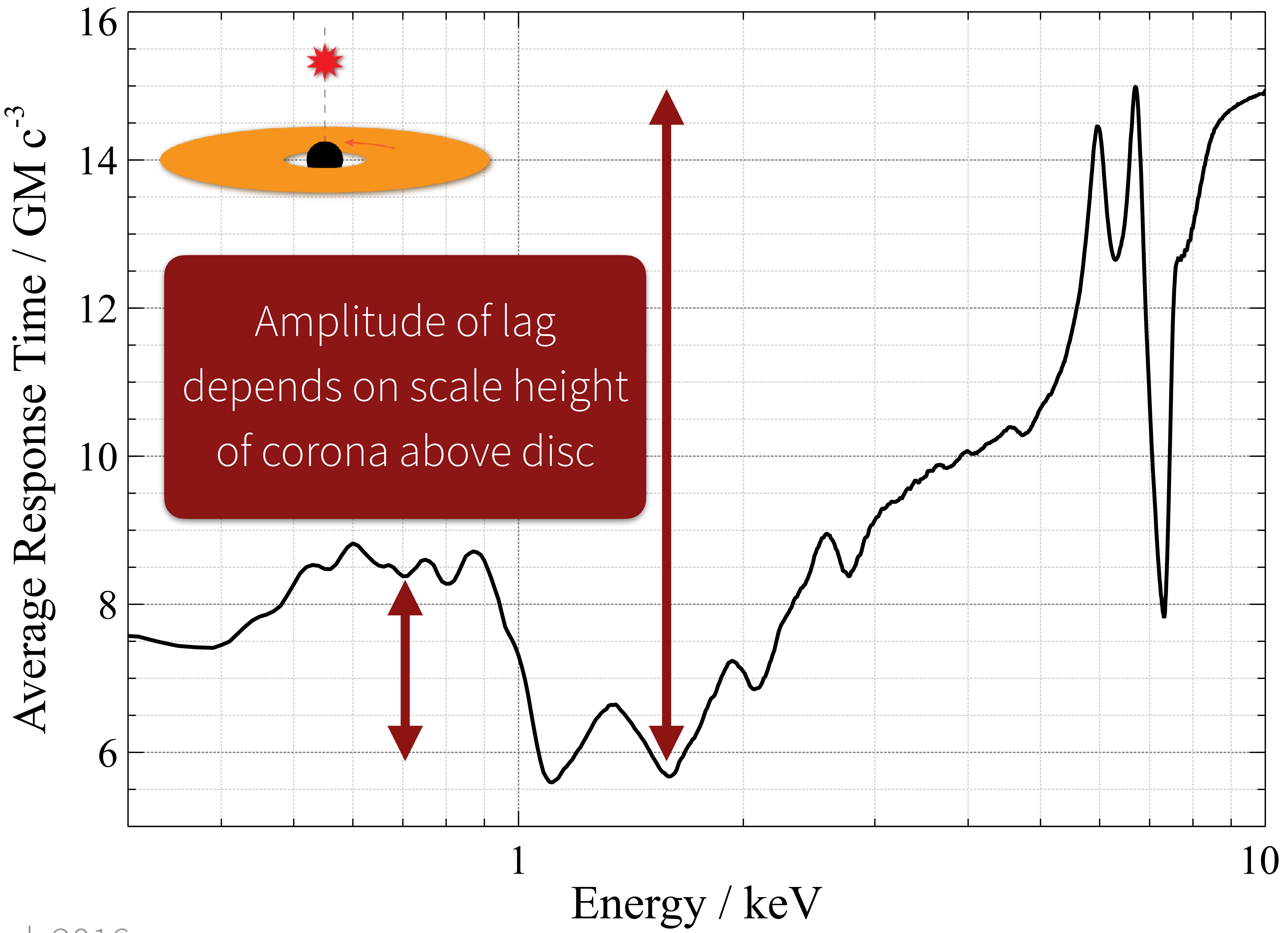
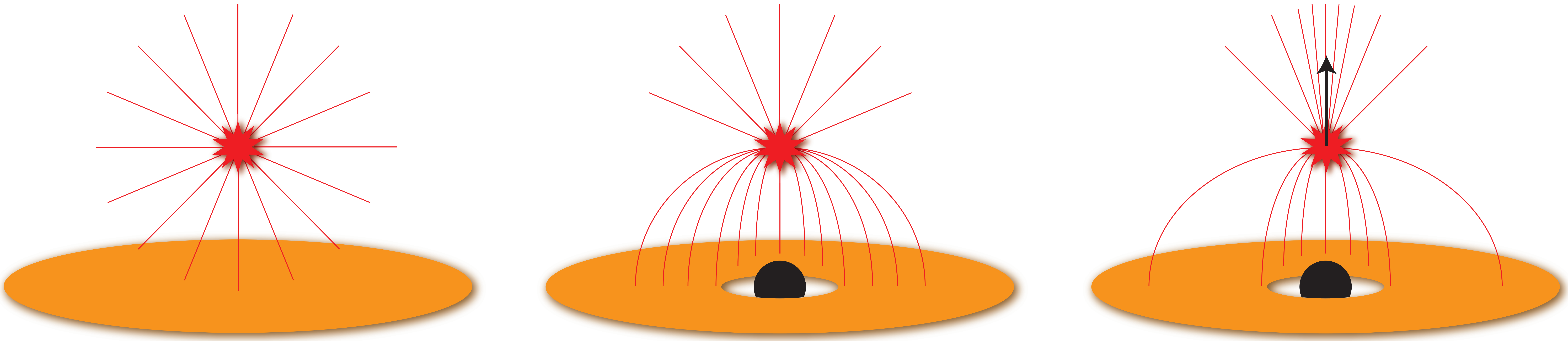


Wilkins et al. 2016

Reflection fraction constrains motion of corona

$$R = \frac{\text{Reflected flux}}{\text{Continuum flux}}$$



$R = 1$

$R > 1$

$R < 1$

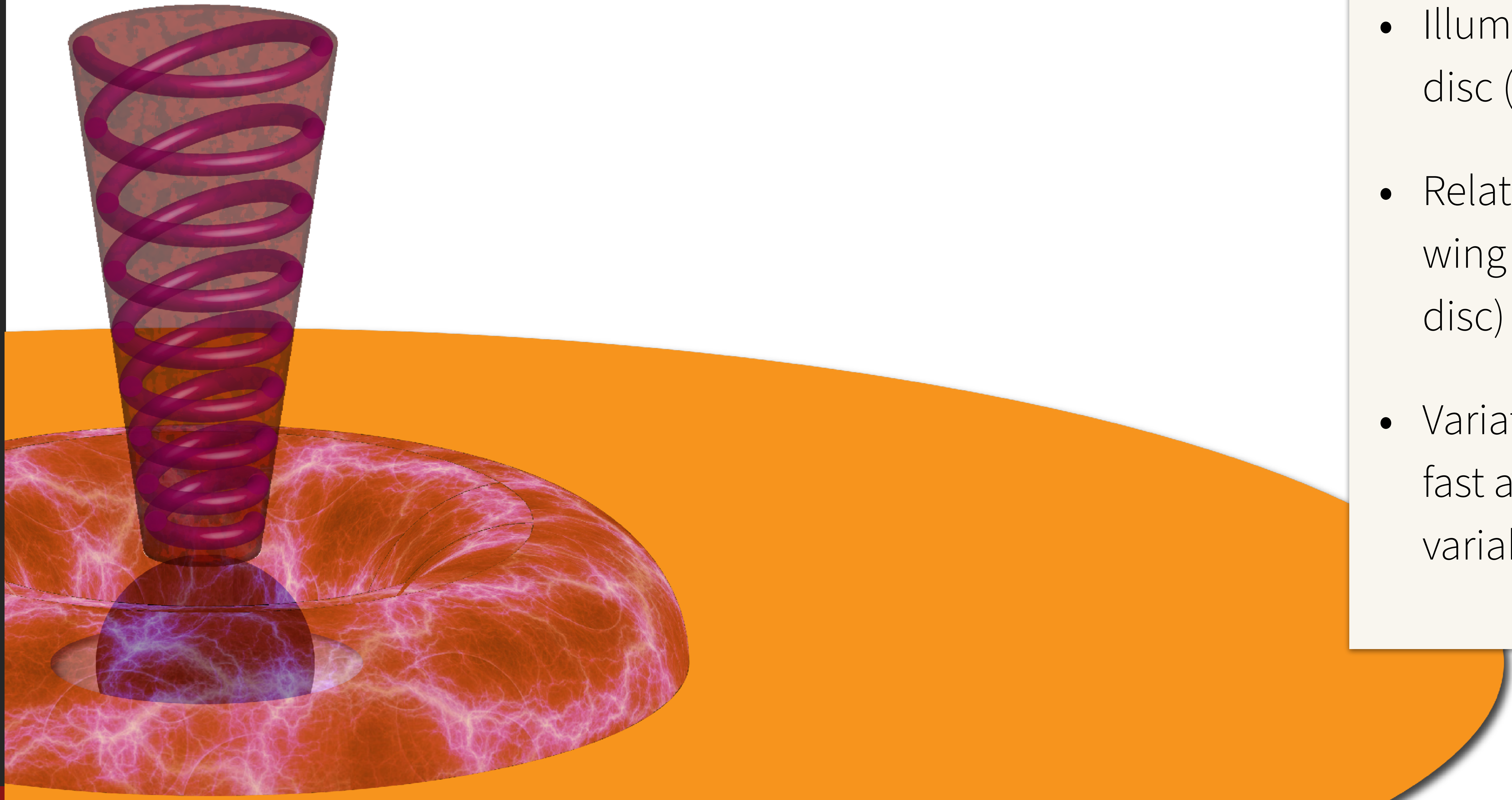
From an isotropic source, equal continuum and reflected flux

Light bending from a source close to the black hole focuses rays onto inner disc, enhancing reflected flux

Relativistic motion of source beams emission away from disc, enhancing continuum

Wilkins 2015, Gonzalez et al. 2018, Beloborodov 1999

Structure of the corona



Piece together structure of corona from

- Illumination pattern of accretion disc (profile of broad iron line)
- Relative time delay of redshifted wing of iron line (from inner disc)
- Variation in time lags between fast and slow components of the variability

Wilkins et al. 2017

Stanford

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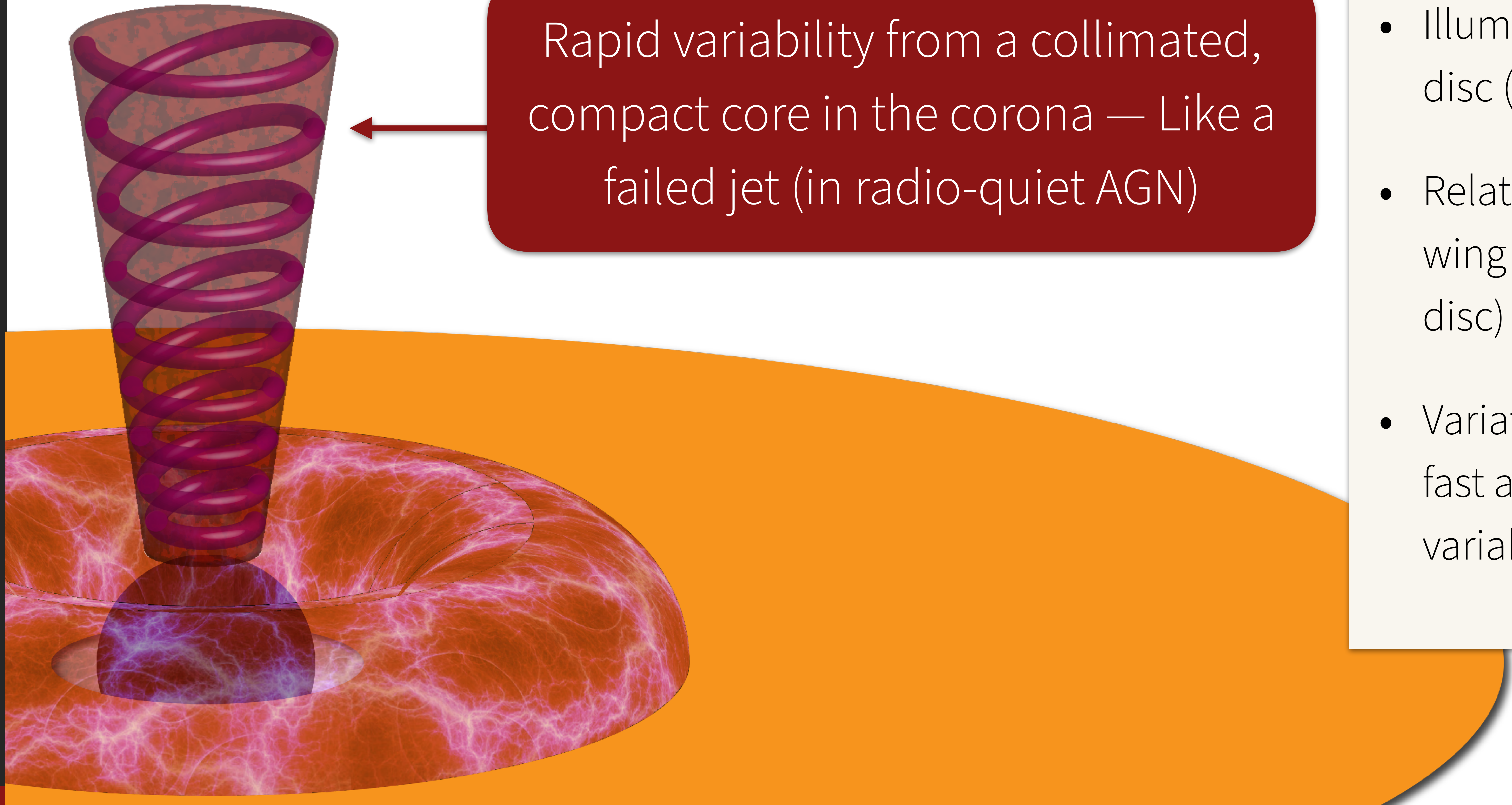

Rapid variability from a collimated, compact core in the corona — Like a failed jet (in radio-quiet AGN)

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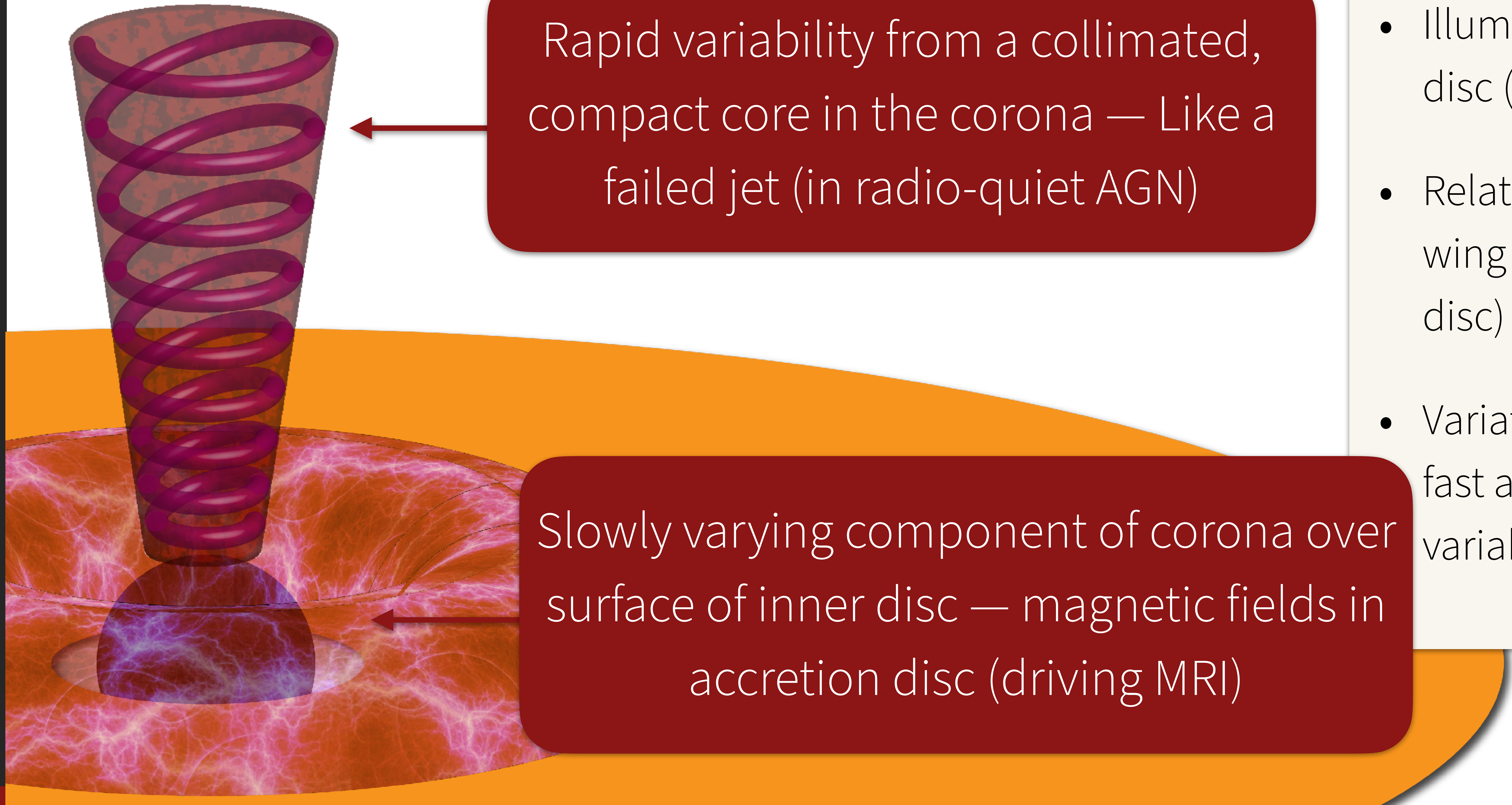


Rapid variability from a collimated, compact core in the corona — Like a failed jet (in radio-quiet AGN)

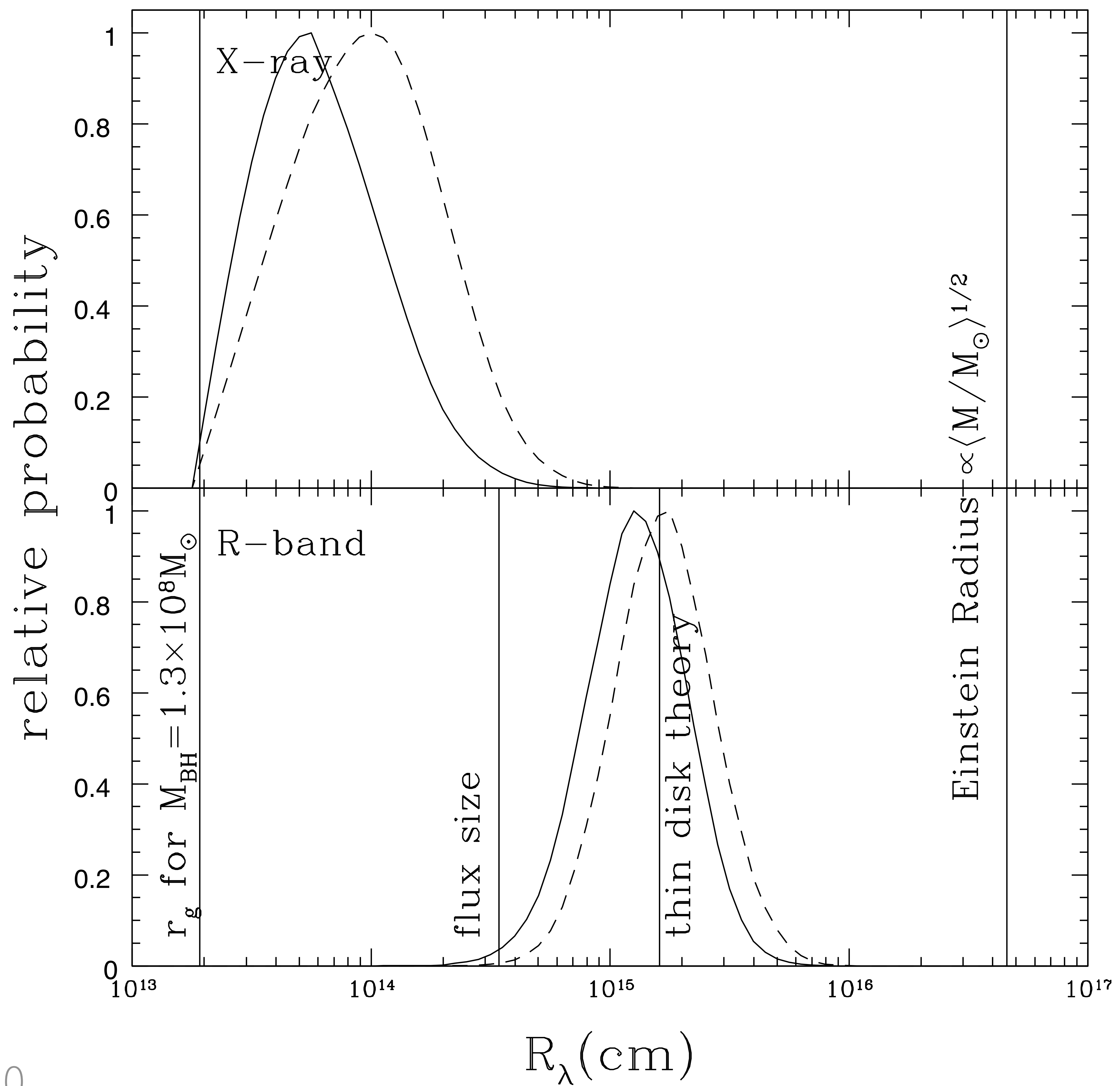
Slowly varying component of corona over surface of inner disc — magnetic fields in accretion disc (driving MRI)

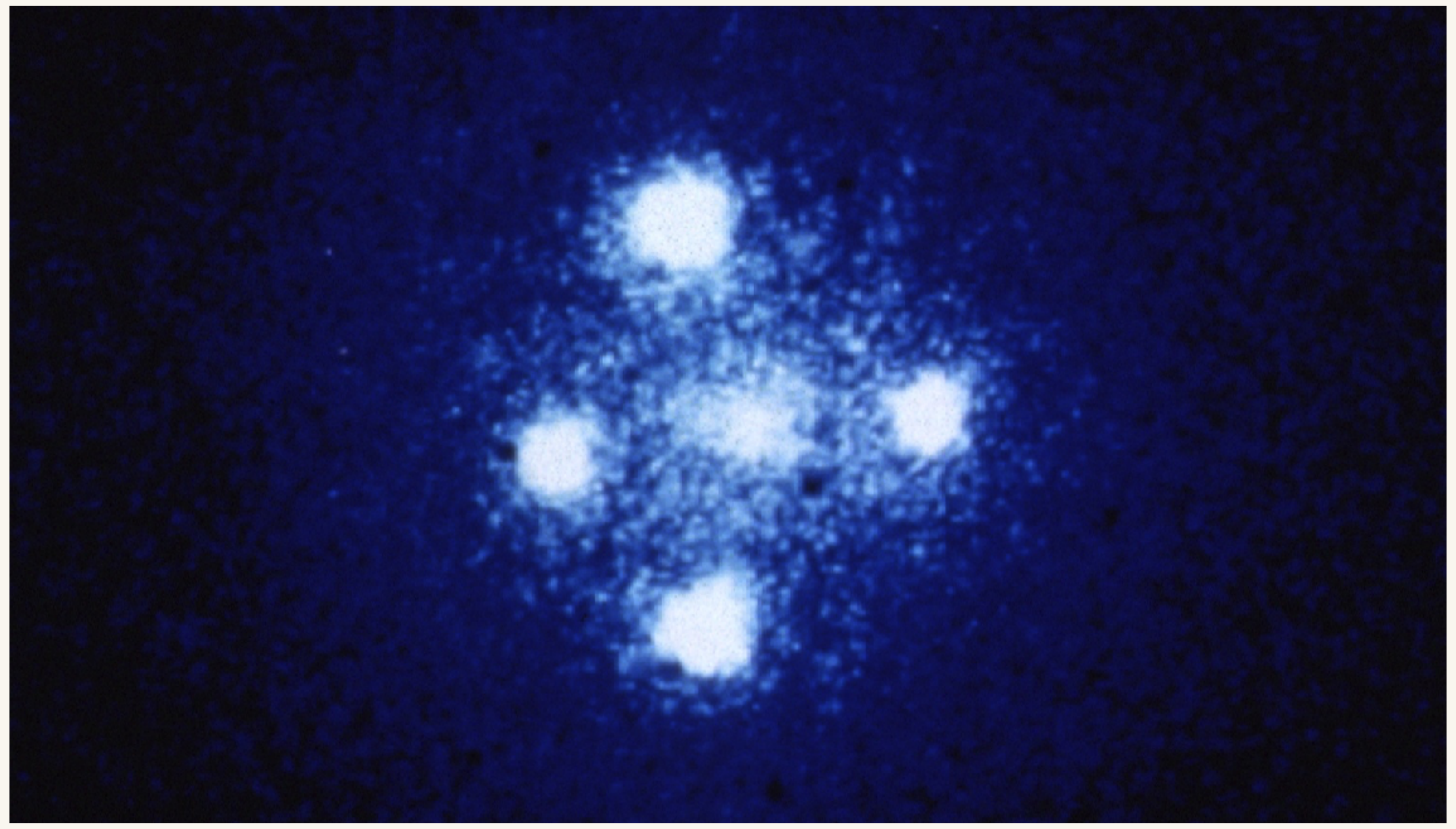
Piece together structure of corona from

- Illumination pattern of accretion disc (profile of broad iron line)
- Relative time delay of redshifted wing of iron line (from inner disc)
- Variation in time lags between fast and slow components of the variability

Wilkins et al. 2017

Microlensing of the corona

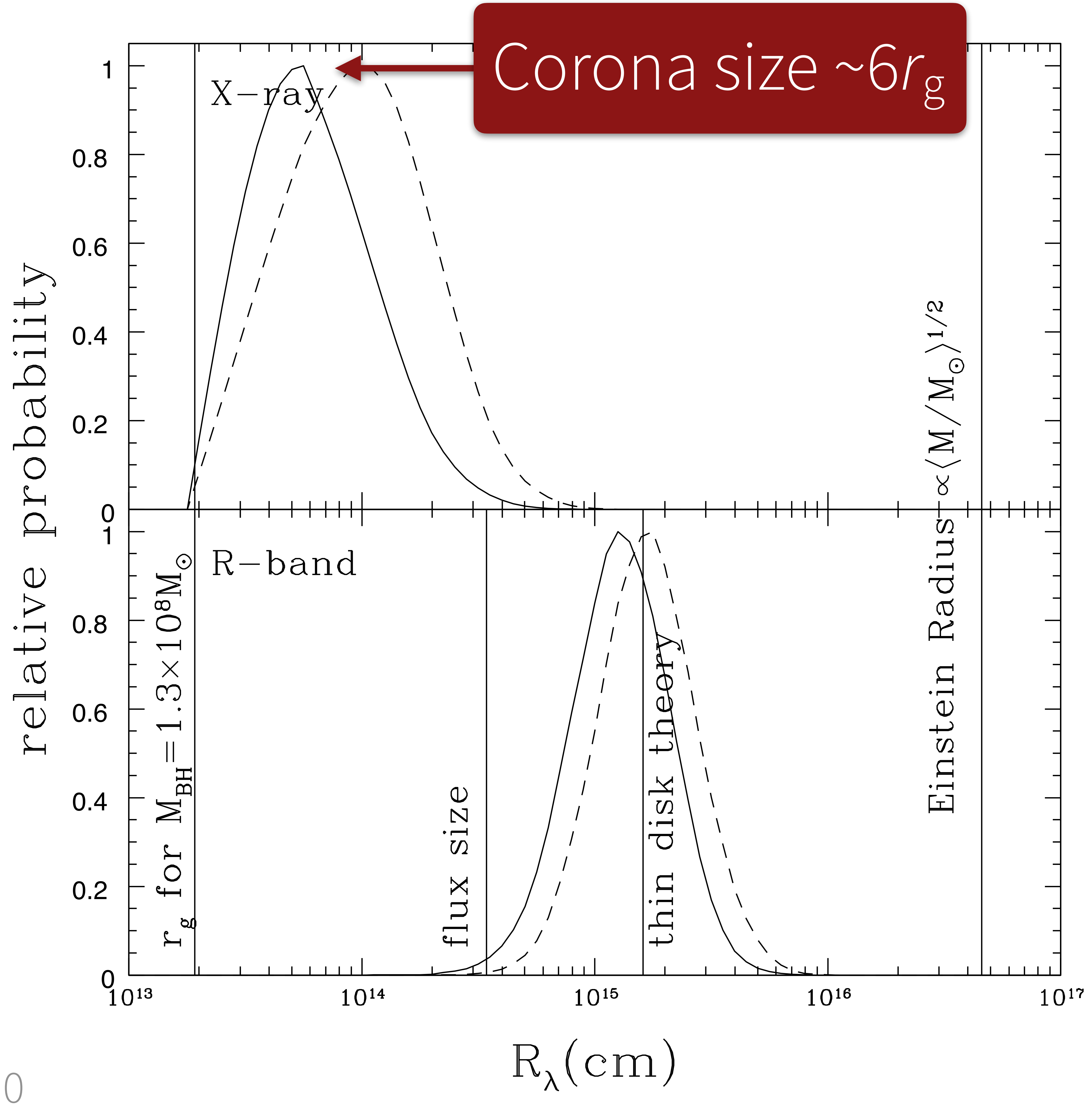




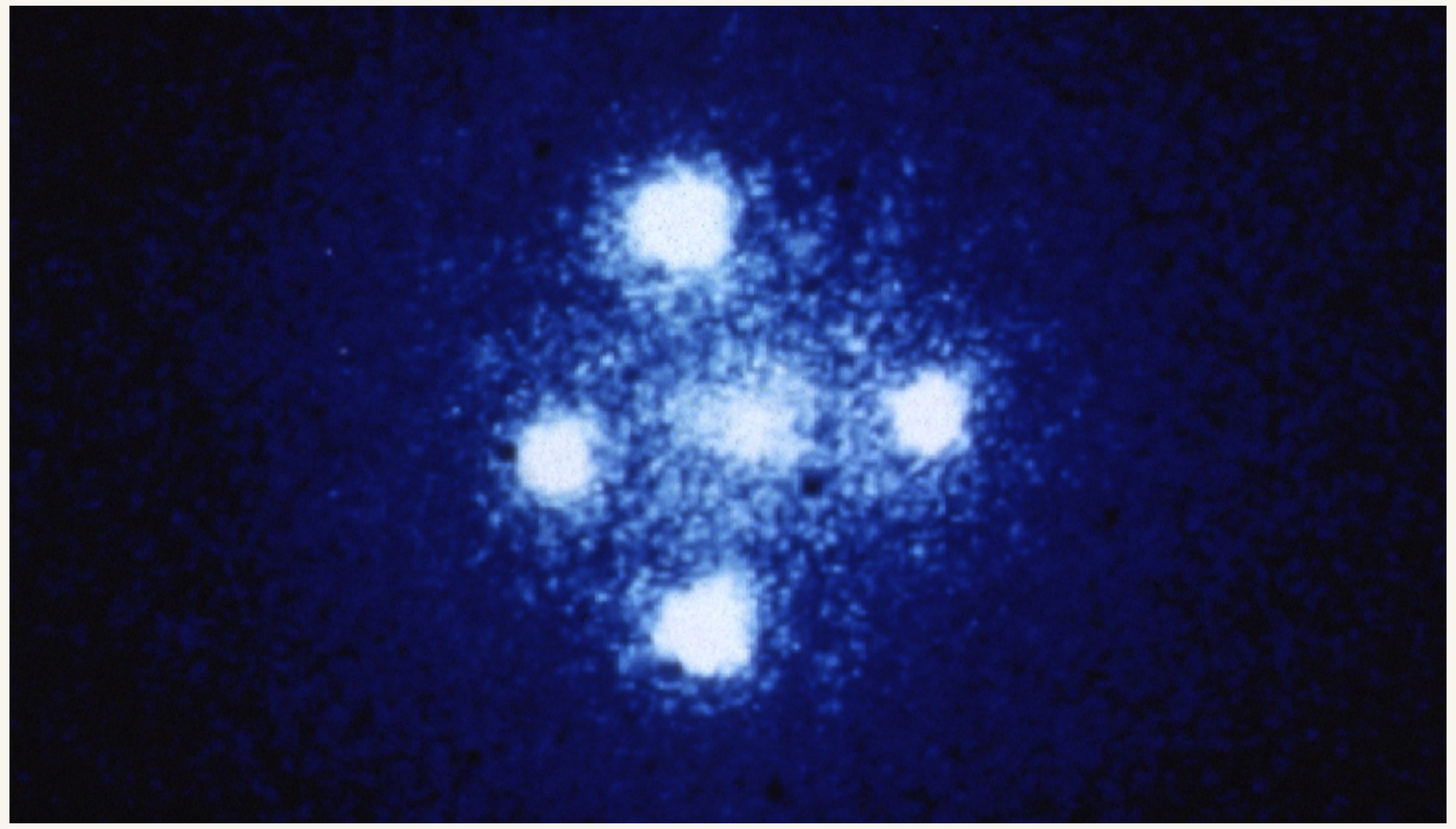
- Gravitational microlensing as stars move in lensing galaxy, causes variation in magnification/flux with time
- Amplitude of microlensing variability constrains size (smaller emitting regions → greater microlensing amplitude)

Dai et al. 2010

Microlensing of the corona



Dai et al. 2010



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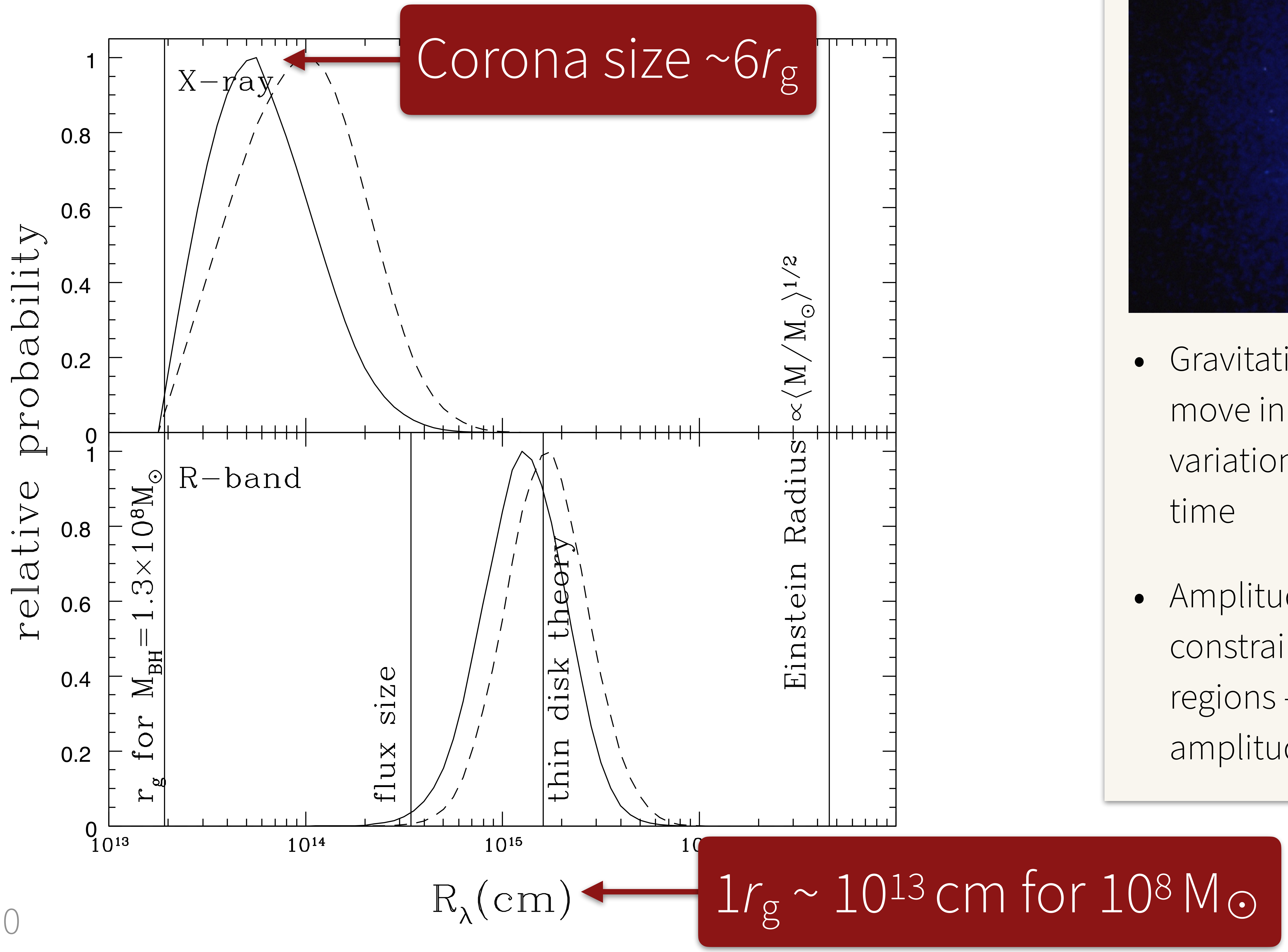

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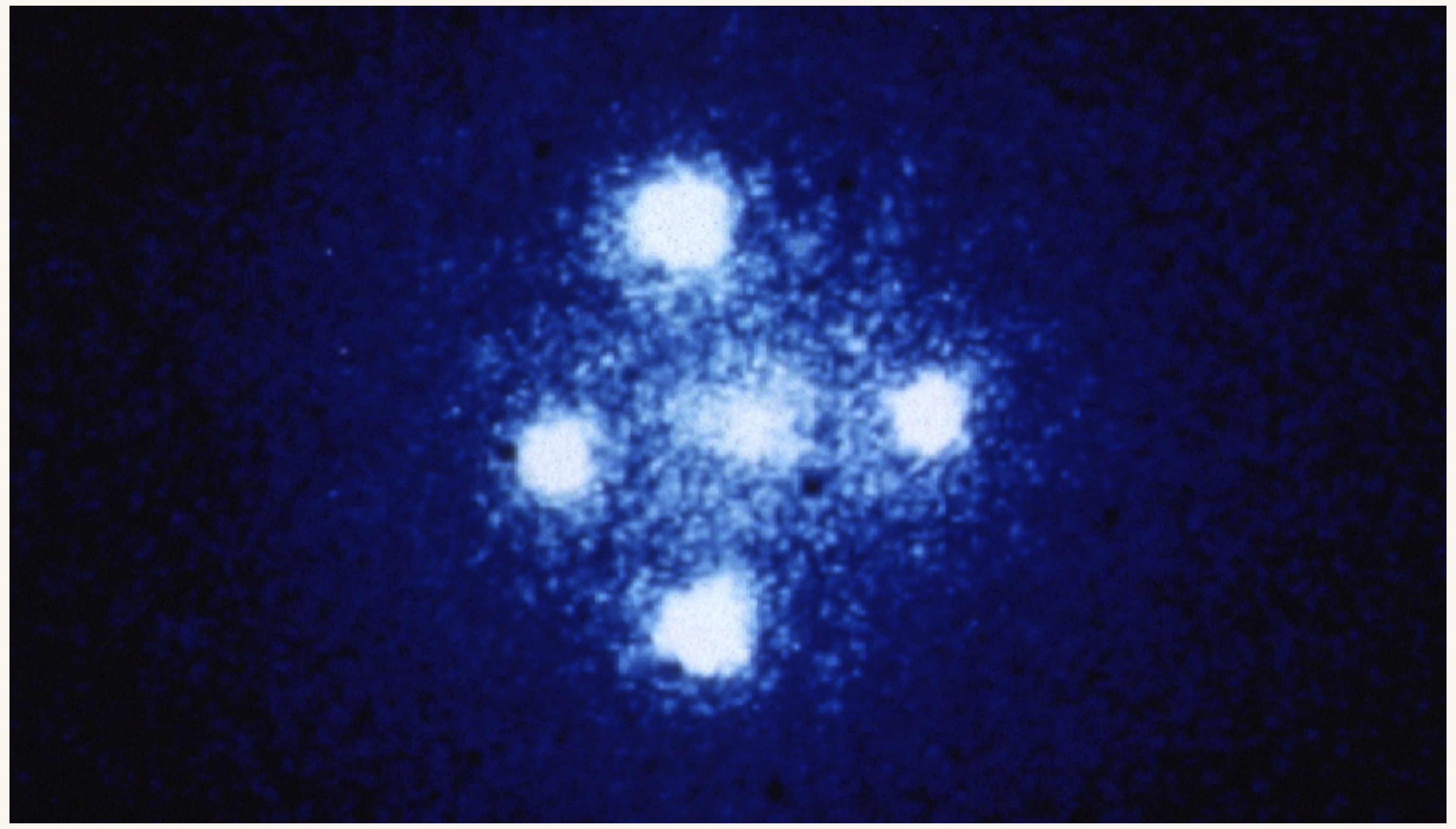

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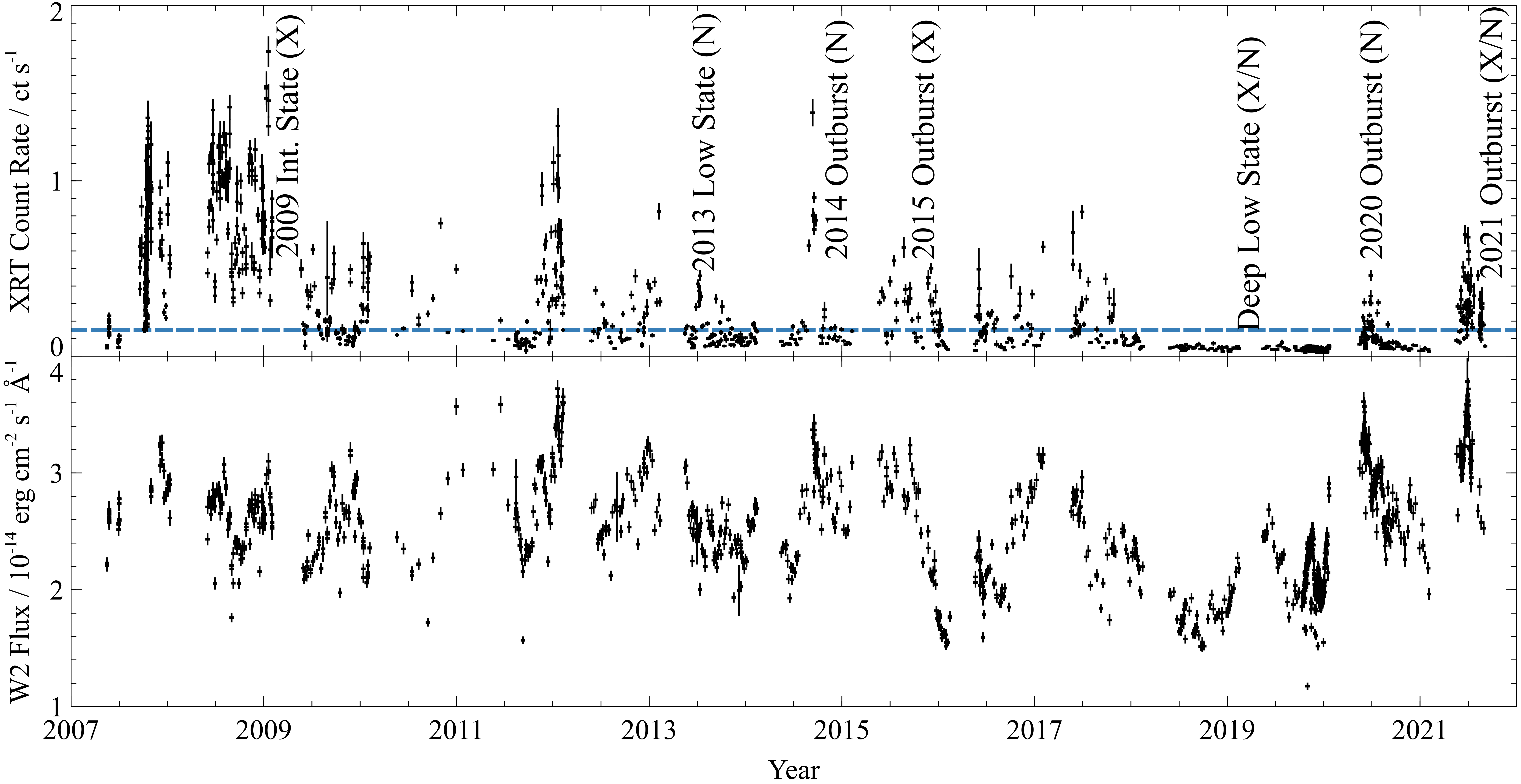
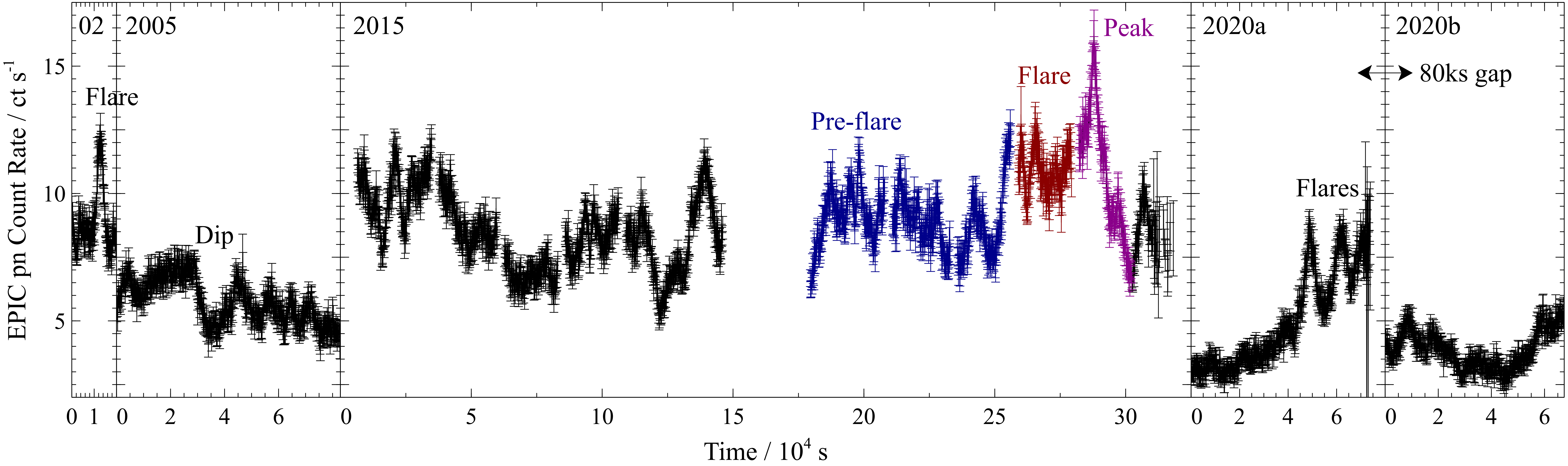
Many AGN are extremely variable!

Mrk 335 Swift monitoring

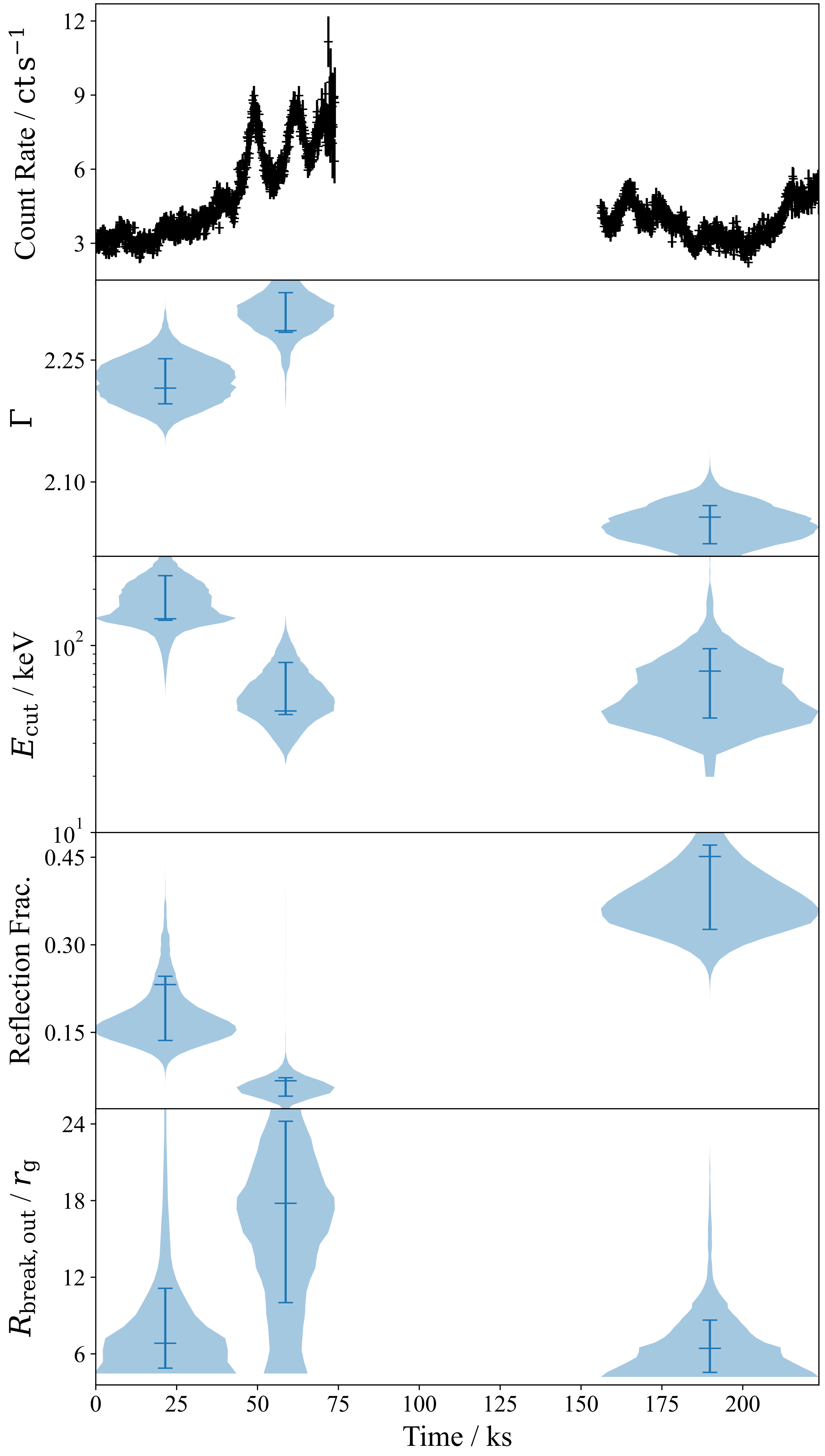


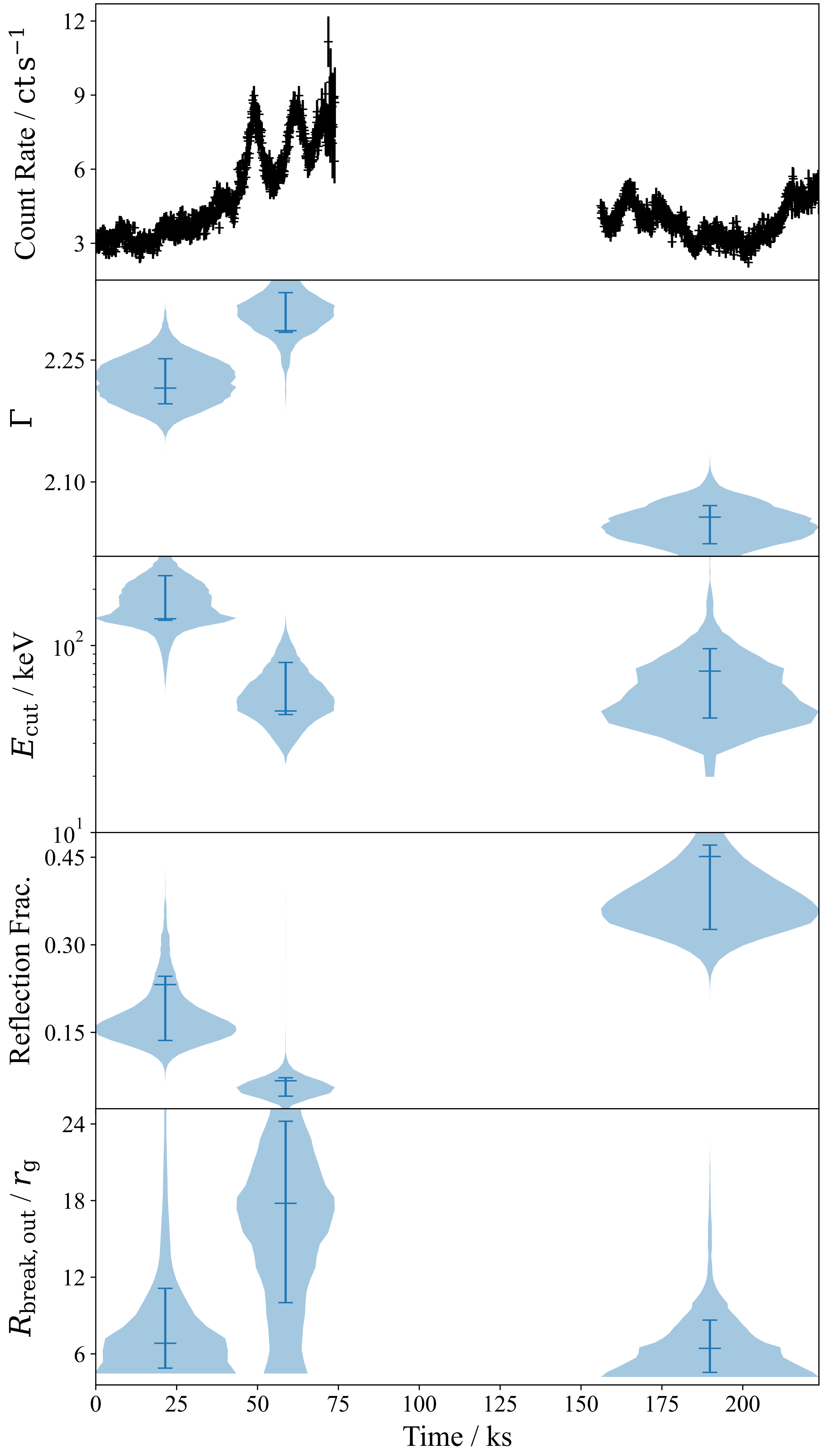
Short term variability and X-ray flares

XMM-Newton light curves of I Zw 1



Evolution of the corona





Evolution of the corona

- X-ray spectrum softens during flares, then hardens after

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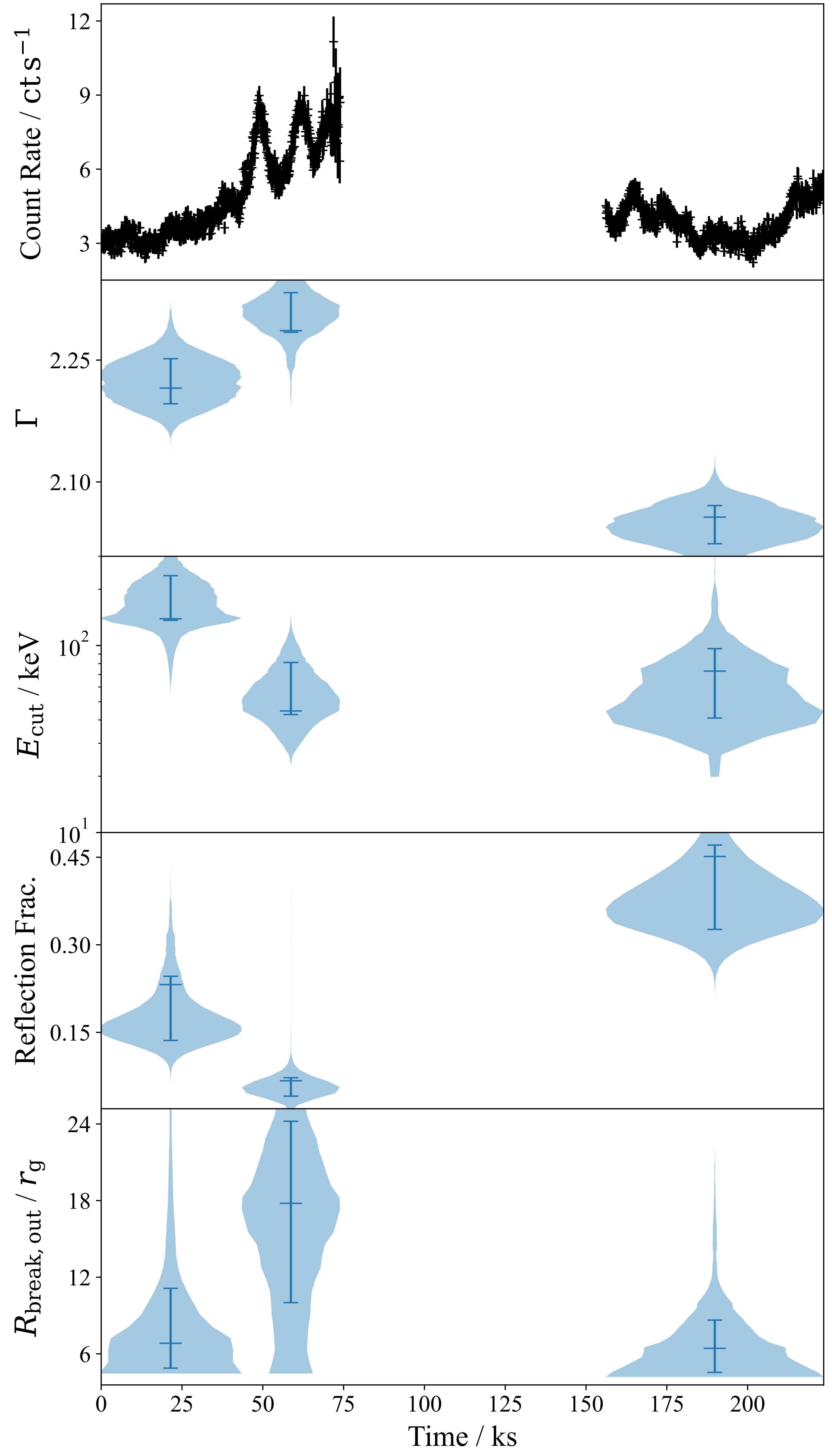
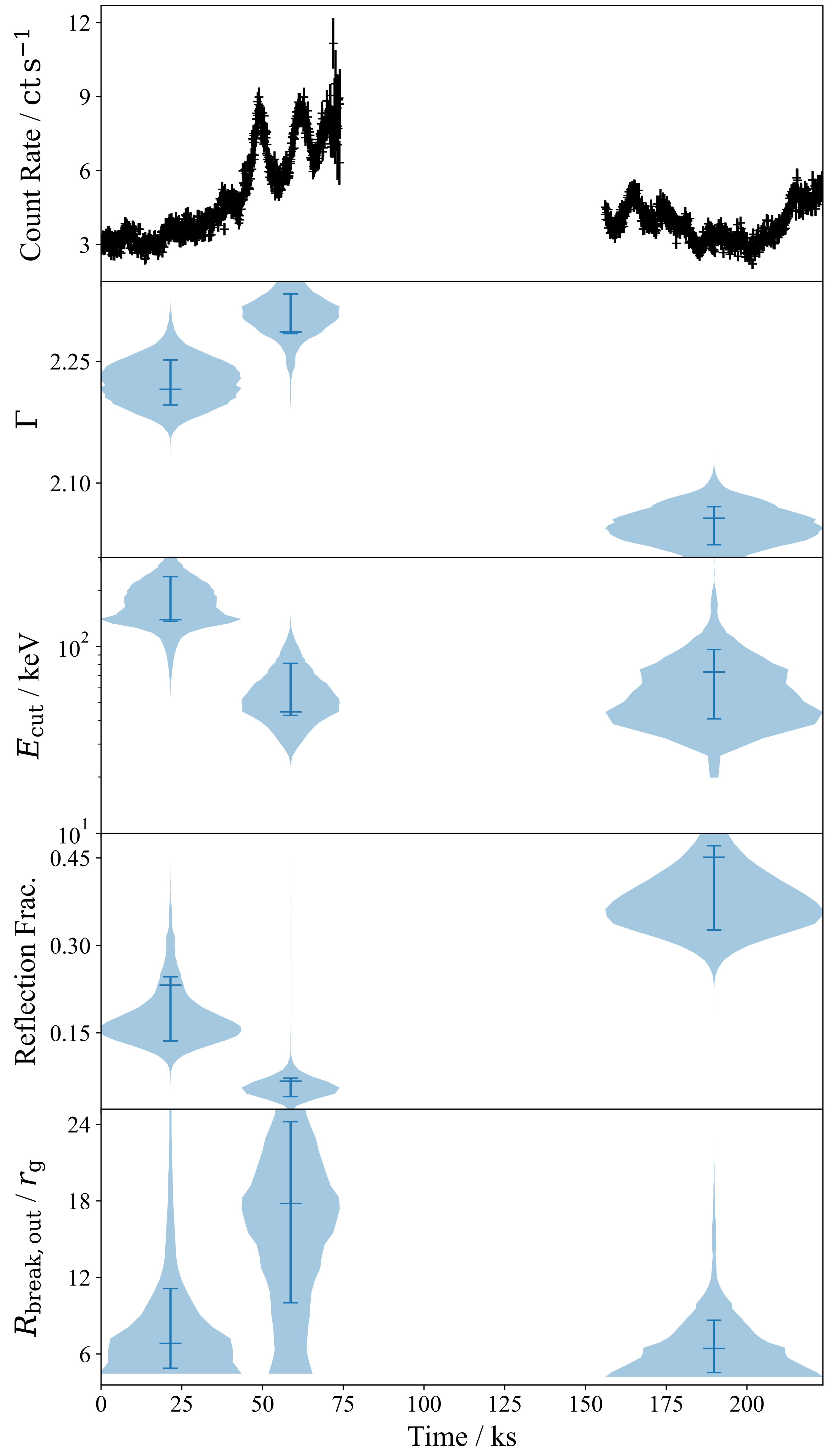


- X-ray spectrum softens during flares, then hardens after
- Drop in temperature of corona during flare

Wilkins et al. 2022



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- X-ray spectrum softens during flares, then hardens after
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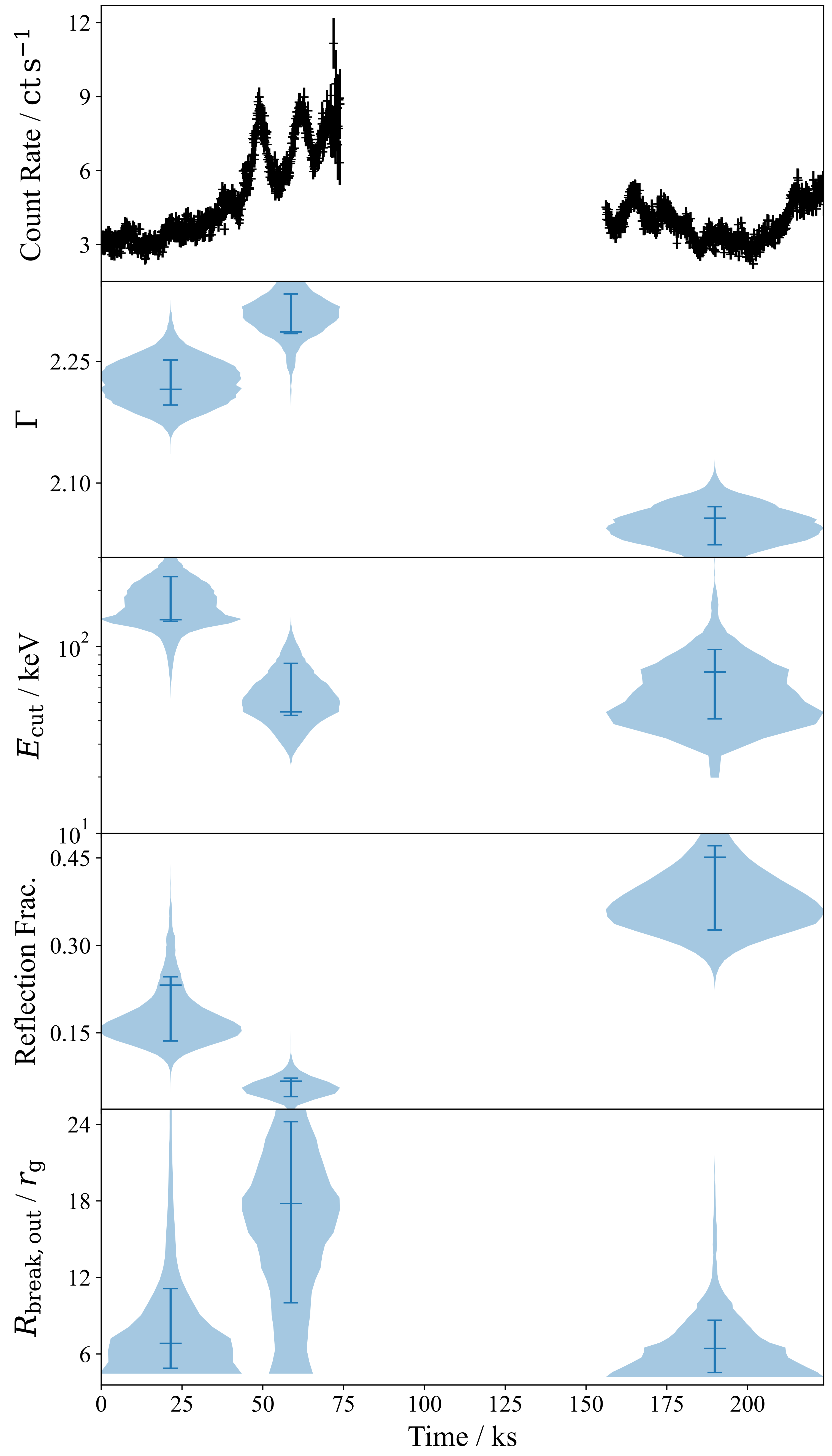
- Drop in reflection fraction during flare, suggesting acceleration of corona away from disc from 0.7c before to 0.9c during, and 0.4c after

Wilkins et al. 2022

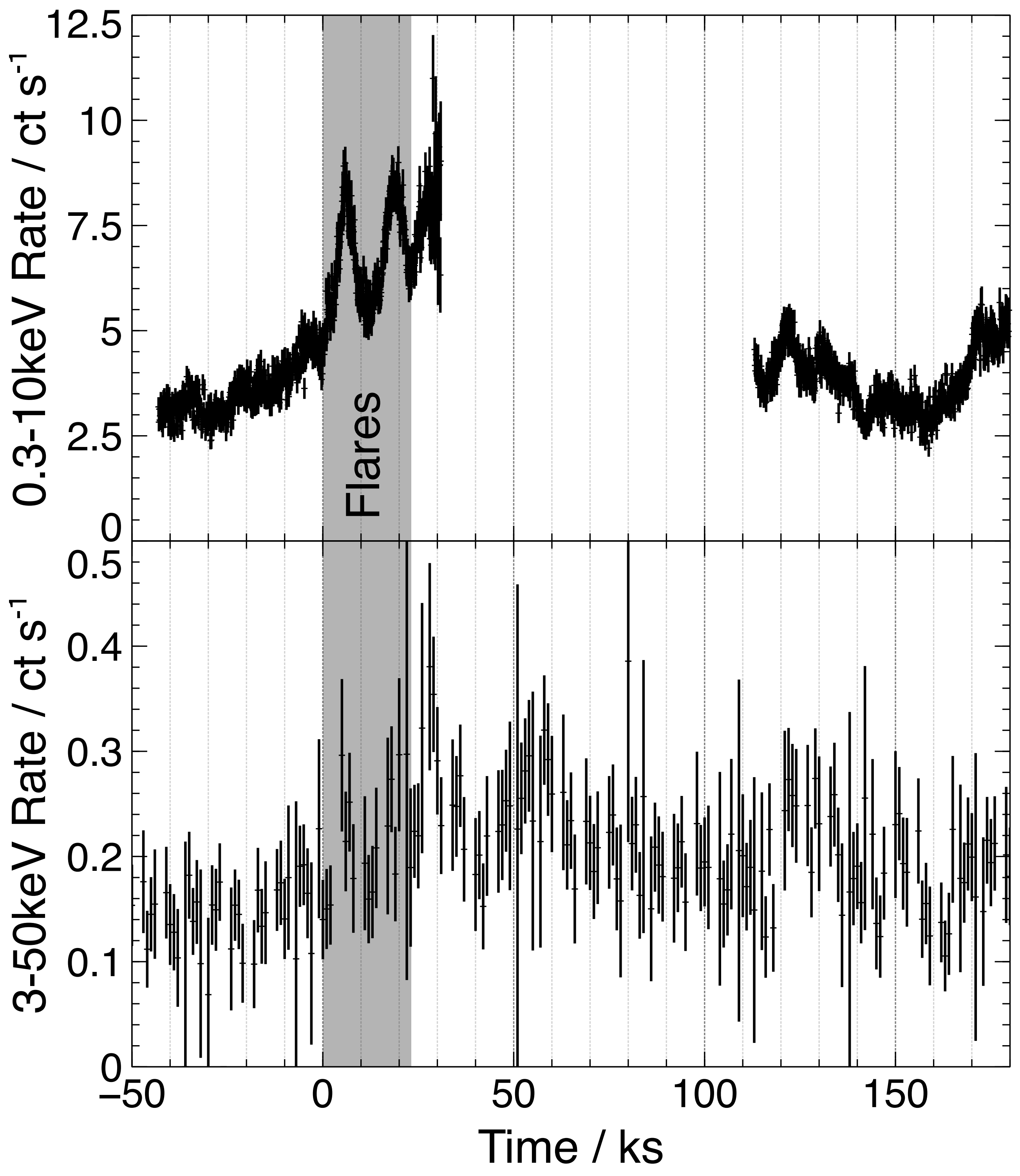


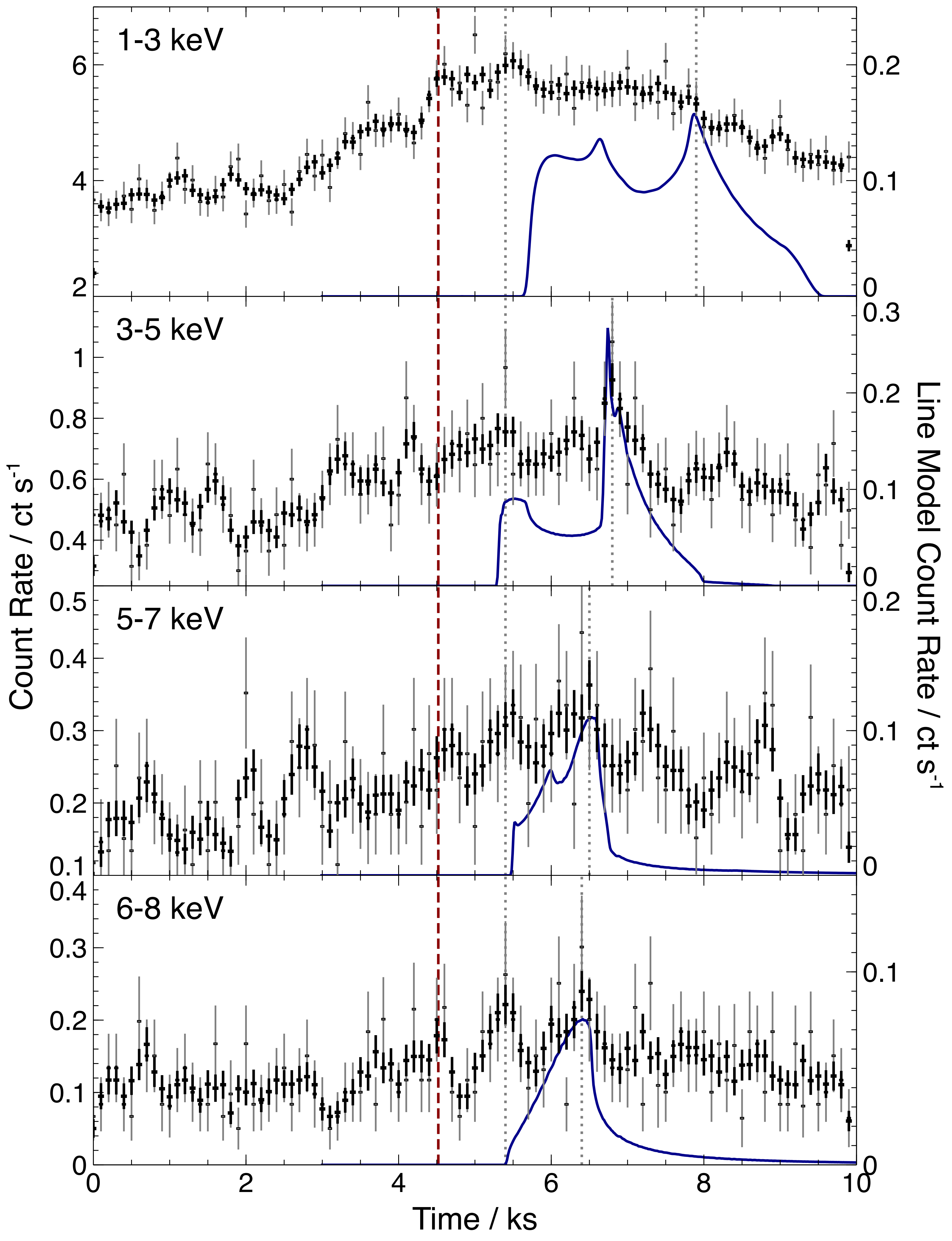
Evolution of the corona

- X-ray spectrum softens during flares, then hardens after
- Drop in temperature of corona during flare
- Drop in reflection fraction during flare, suggesting acceleration of corona away from disc from 0.7c before to 0.9c during, and 0.4c after
- Evidence that the corona expands during flares and contracts after, from variation of accretion disk emissivity profile, measured by profile of iron K line


Wilkins et al. 2015, 2022

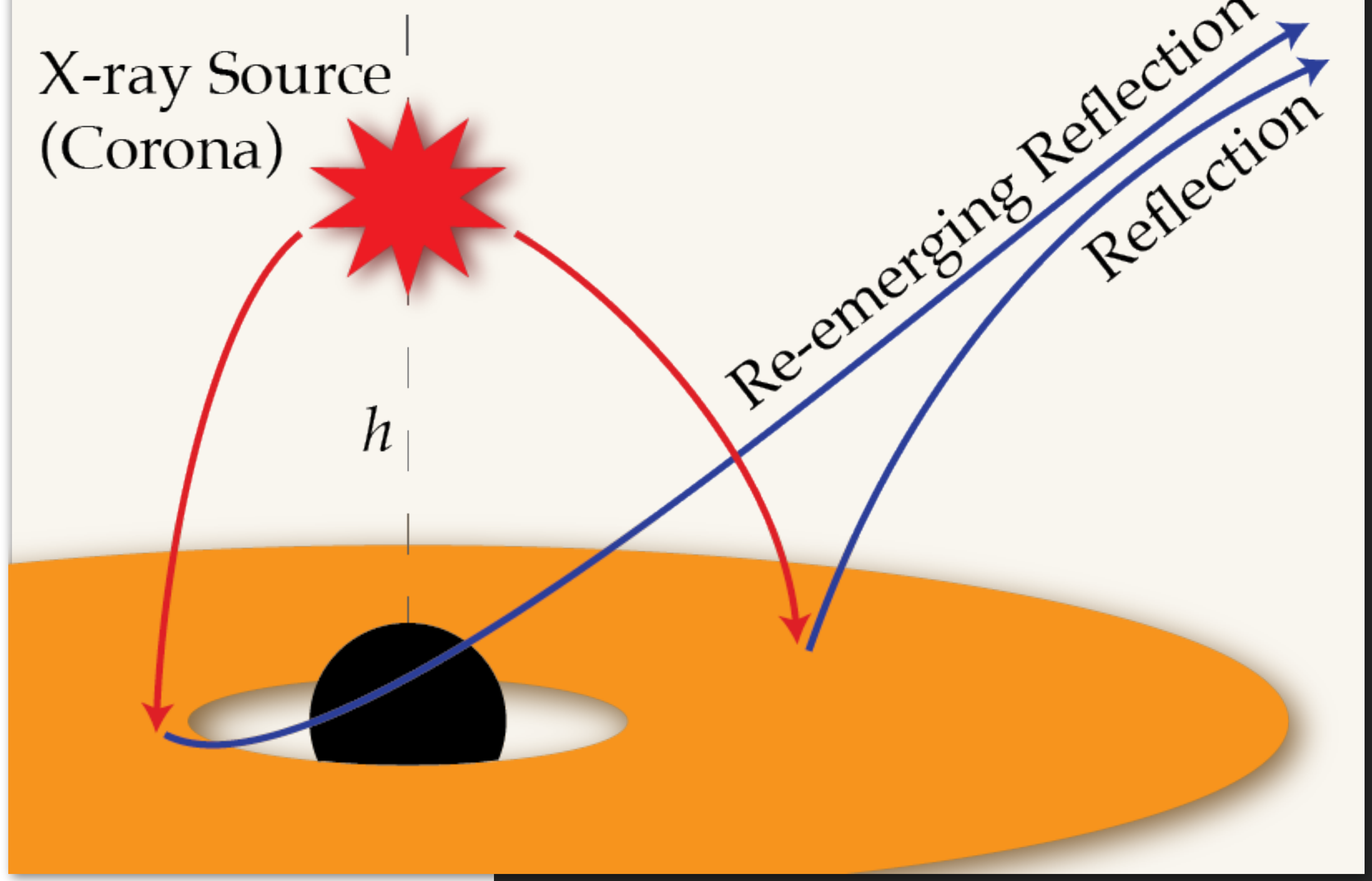
X-ray echoes from behind the black hole



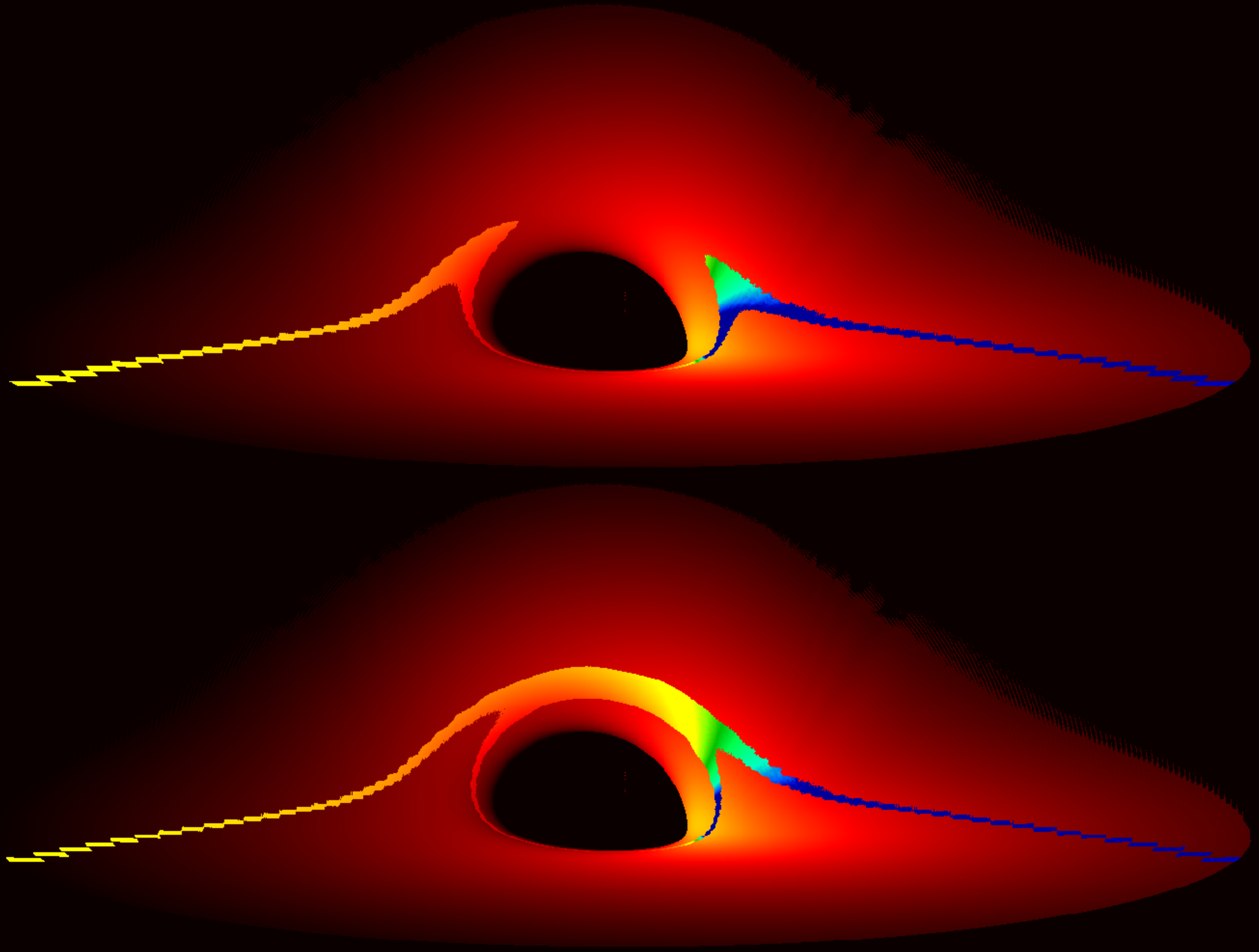


Observe short echoes of X-ray flares due to the re-emergence of X-rays reflected from the back side of the disc

- Classically hidden behind black hole
- Bent around black hole in gravitational field
- Magnified by gravitational lensing



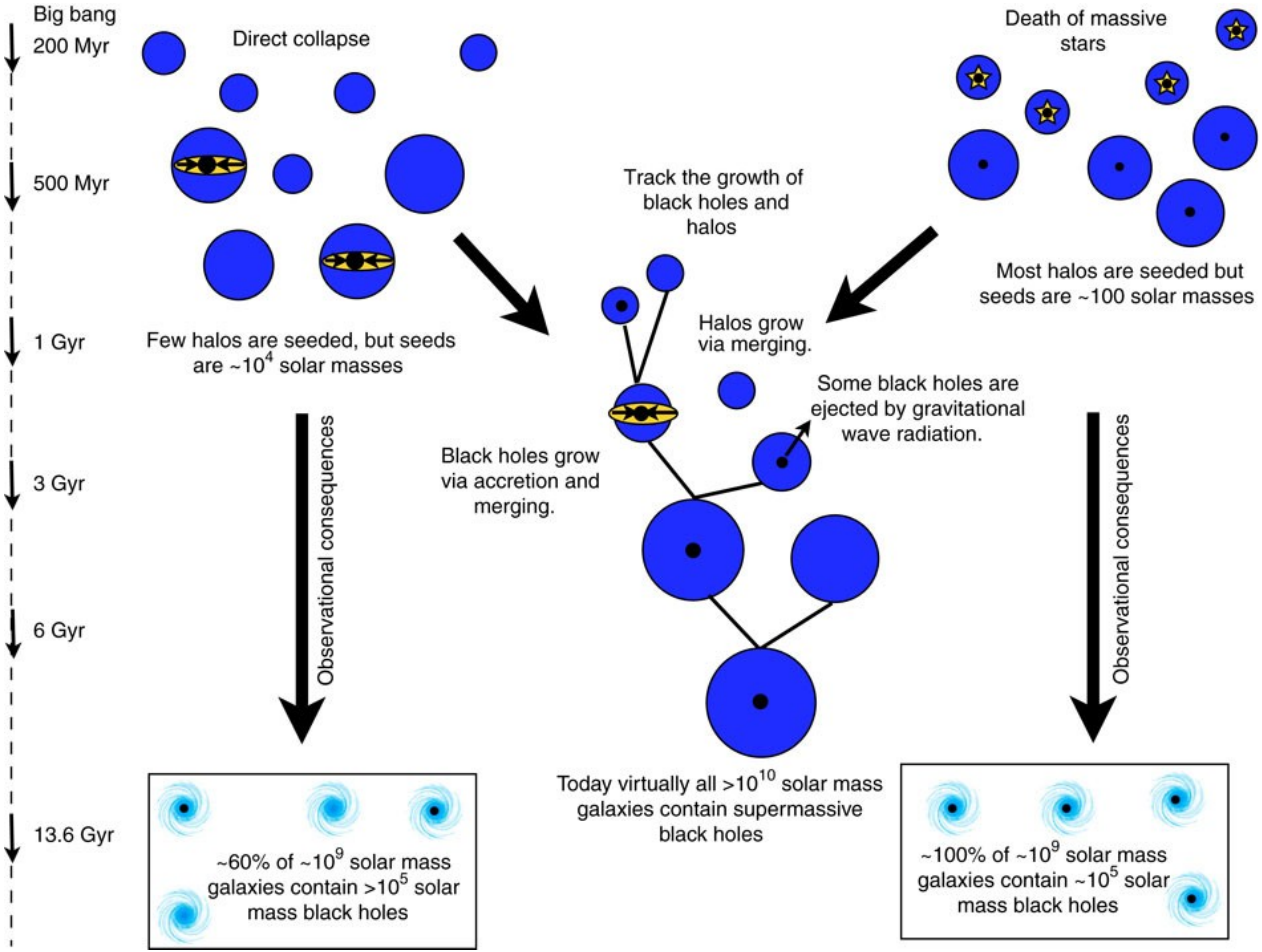
Wilkins et al. 2021



How did supermassive black holes form?

Stanford

The seeds of supermassive black holes



- Origin of supermassive black hole seeds unknown
- Direct collapse of massive gas clouds, vs. death/merger of massive stars predicts different mass distributions (esp. in dwarf galaxies)
- Observational challenges:
  - Quasars with $M_{BH} > 10^9 M_\odot$ at $z > 5$ - must have grown rapidly
  - Massive black holes in small galaxies (NGC 1277)

Stanford

Measuring the black hole mass

$$\frac{GM}{r^2} = \frac{v^2}{r}$$

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Measuring the black hole mass

1. Dynamical masses
   - Measure orbits of resolvable stars or gas clouds in nucleus

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   - Broad optical emission lines (C IV, Mg II, Hβ) from clouds in orbit
   - Velocity from line width, distance from time delay between continuum and line variations
   - Uncertainty in geometry of broad line region – calibration factor that must be calibrated, but may vary (e.g. with Eddington ratio)

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3. Empirical scaling relations
   - Hβ line width vs. mass
   - M-σ relation
   - (BLR) size-luminosity relation (for quasars)

Spin distribution

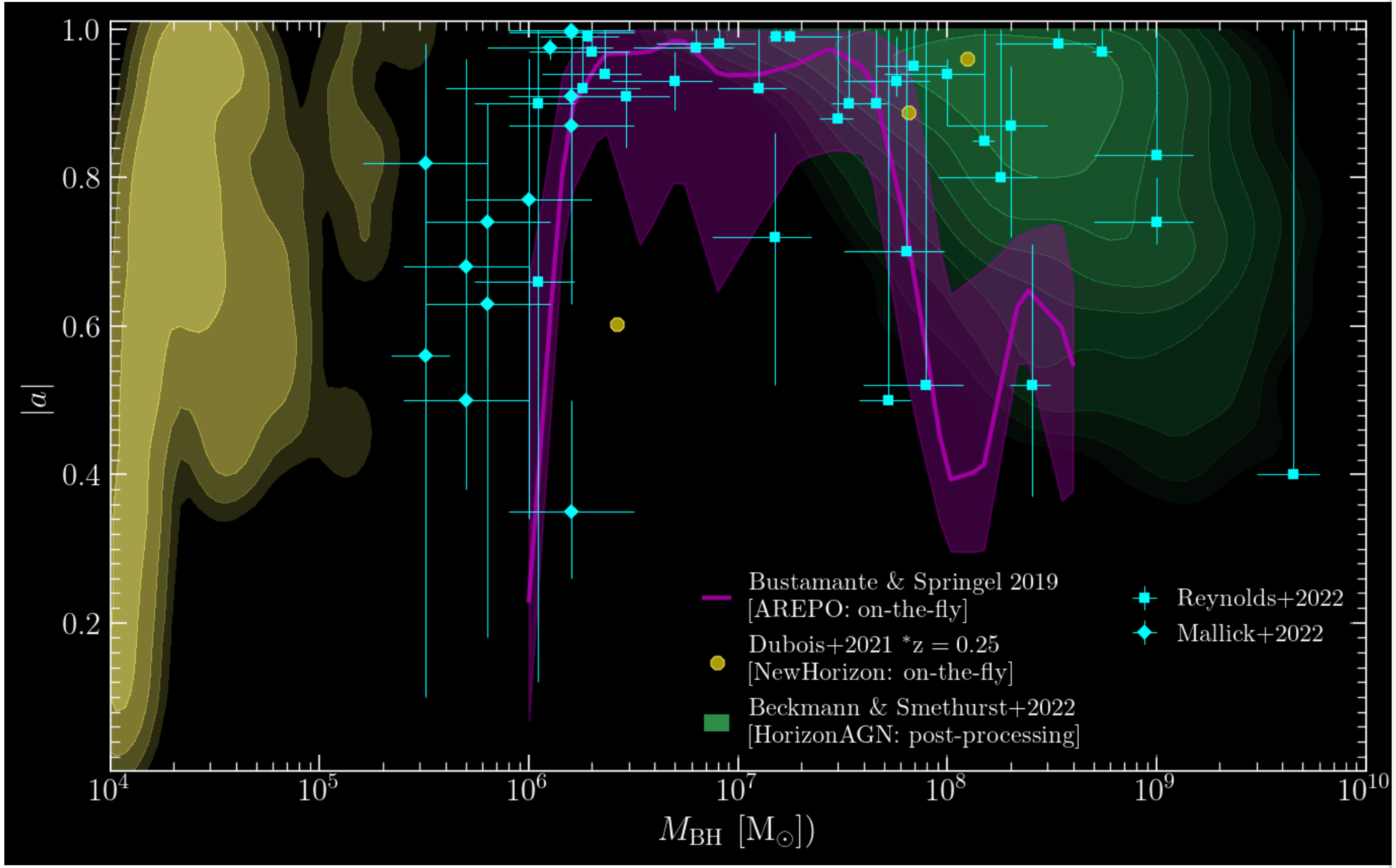
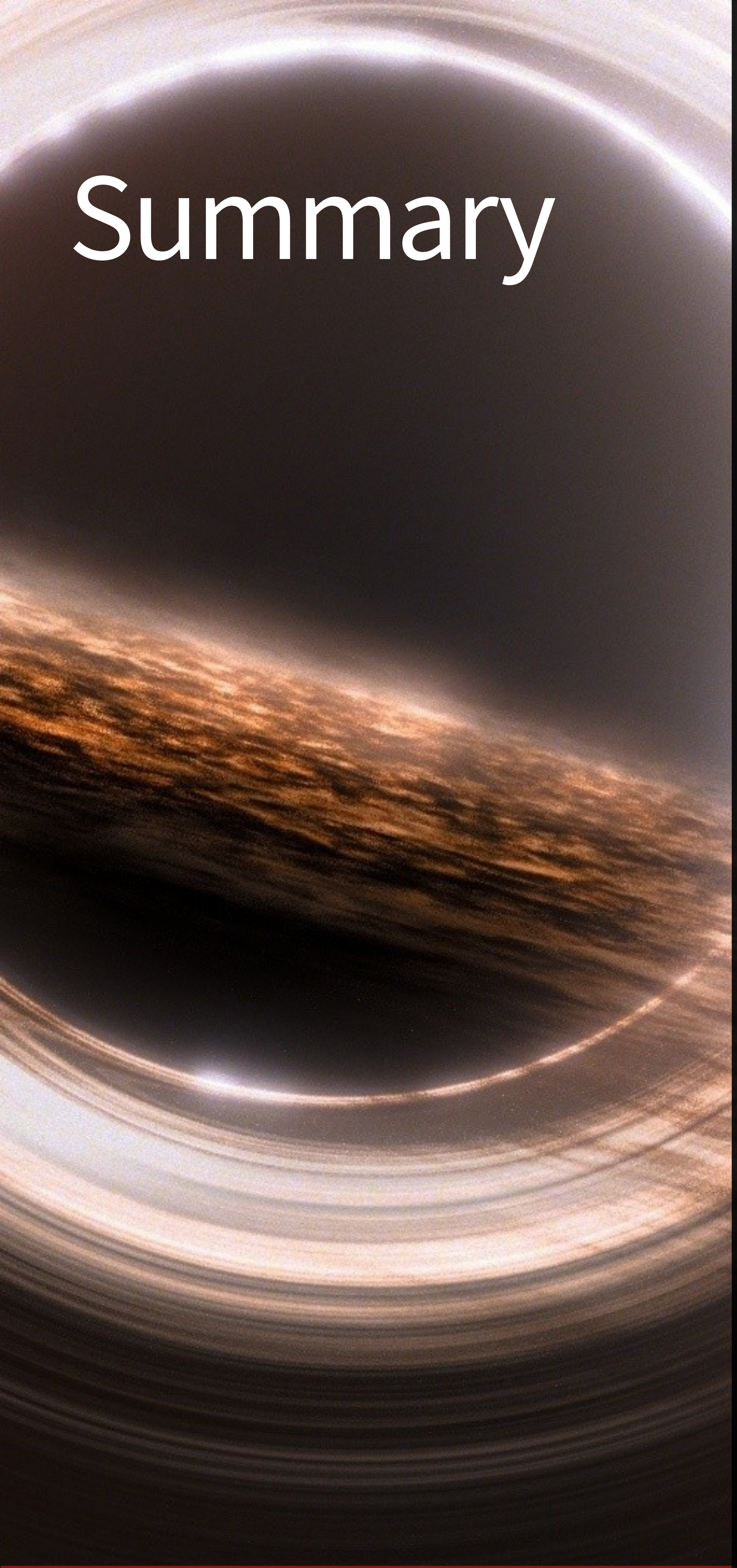


Image credit: J García and J. Piotrowska

- Massive black hole seeds grow via accretion and/or mergers
- Spin of black hole depends on growth history (conservation of angular momentum)
  - Prolonged uniform accretion → rapid spin
  - Chaotic accretion or mergers → low spin
- Measuring spin distribution of supermassive black holes constrains growth history

Summary



- X-ray reflection and reverberation off the inner accretion disc lets us probe the extreme environment just outside the event horizons of black holes
- X-ray reflection enables measurements of the spins of black holes
- Reflection and reverberation allow us to map the structure of the corona, and understand how it evolves, giving rise to the X-ray variability we observe
- Measurements of the mass and spin distributions constrain models of supermassive black hole growth and formation