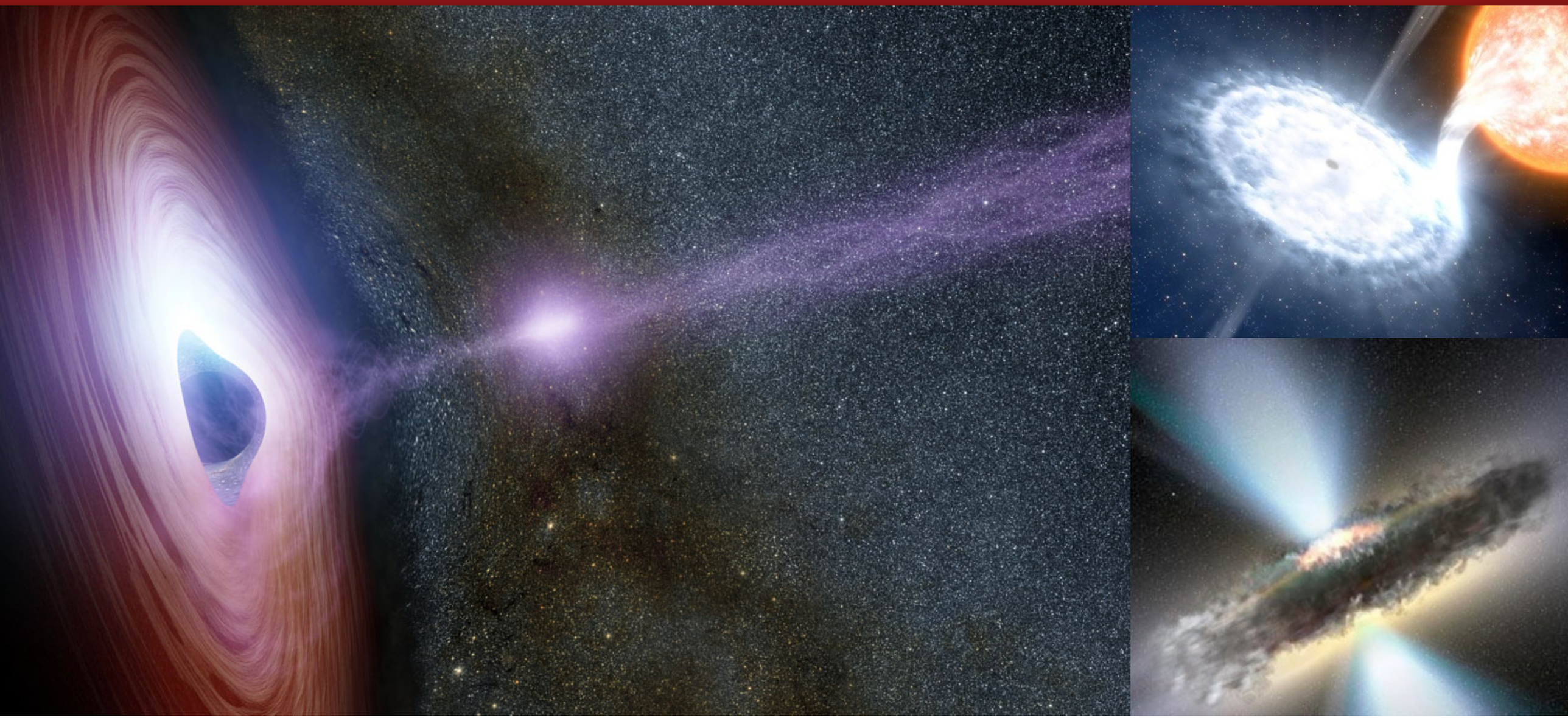

Mapping Supermassive Black Holes with X-ray Reverberation

Dan Wilkins
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The Big Questions

- How does matter falling into black holes power some of the brightest objects in the Universe? What are the processes driving AGN feedback?

- What is the extreme environment like immediately outside the event horizon of a black hole? Does General Relativity provide the correct description?

- What happens to material in its final moments as it plunges into a black hole?

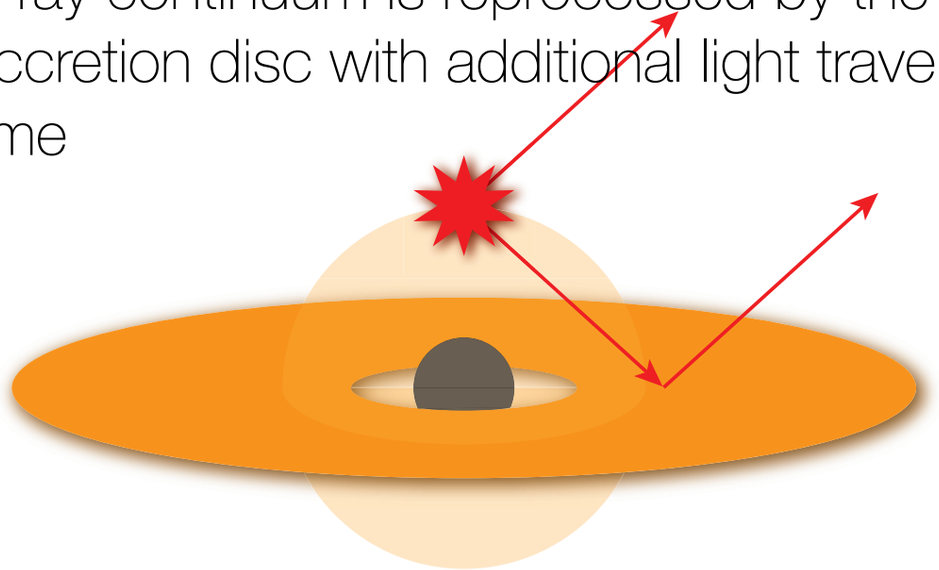
- How are X-ray coronae and jets powered? What is the small-scale physics driving the accretion, ejection & emission processes?

Outline

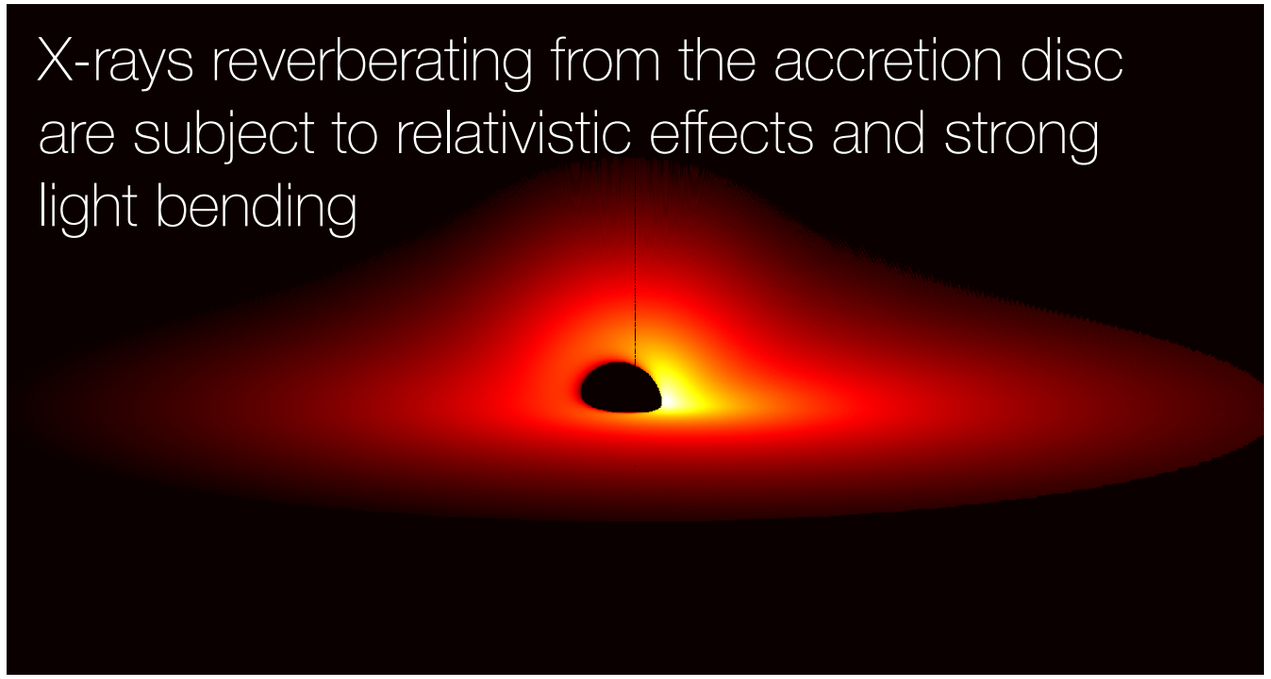
- Observing X-ray reverberation around supermassive black holes
- X-ray reverberation as a probe of the corona and accretion flow
- Beyond the X-rays – multi-wavelength reverberation

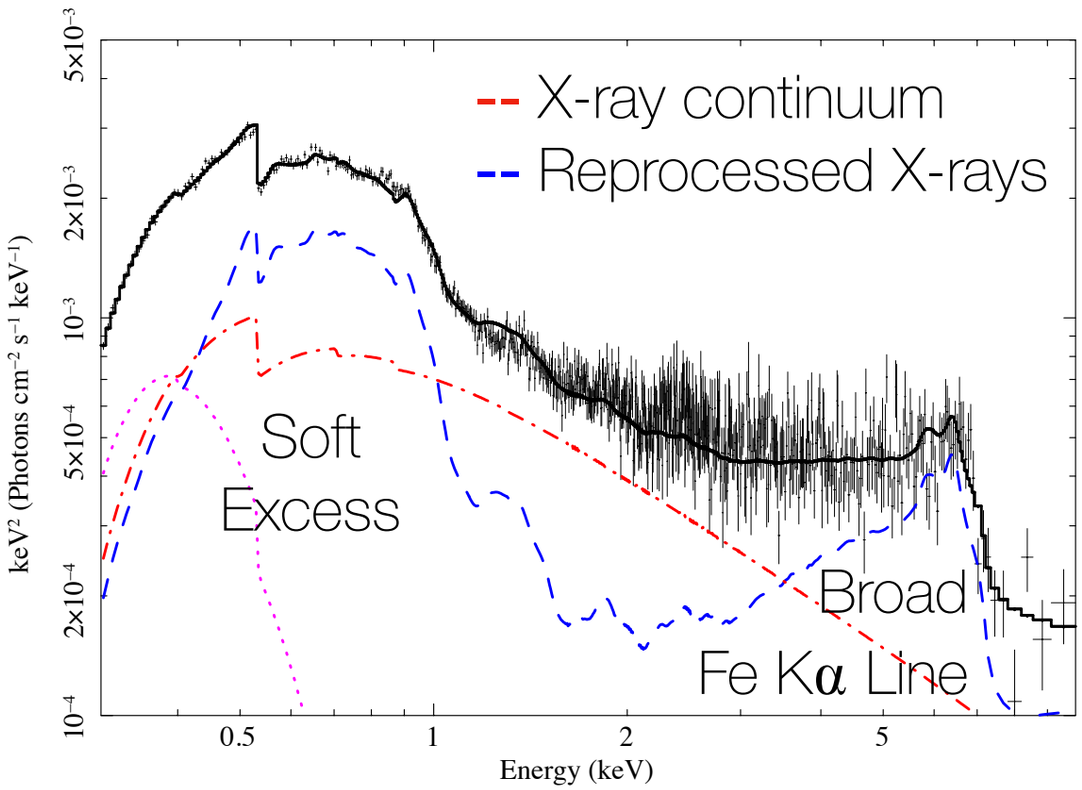
X-ray Reflection & Reverberation

X-ray continuum is reprocessed by the accretion disc with additional light travel time

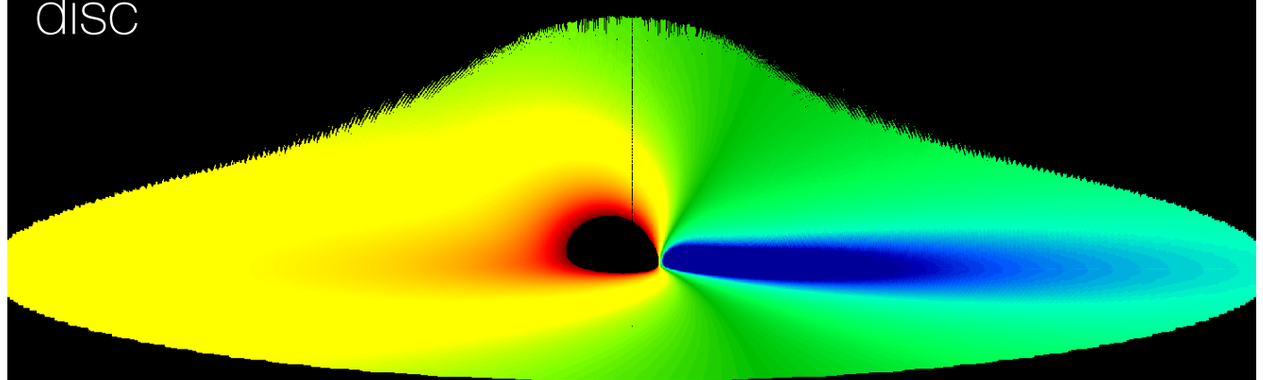


X-rays reverberating from the accretion disc are subject to relativistic effects and strong light bending





Energy shift is a function of location on the disc



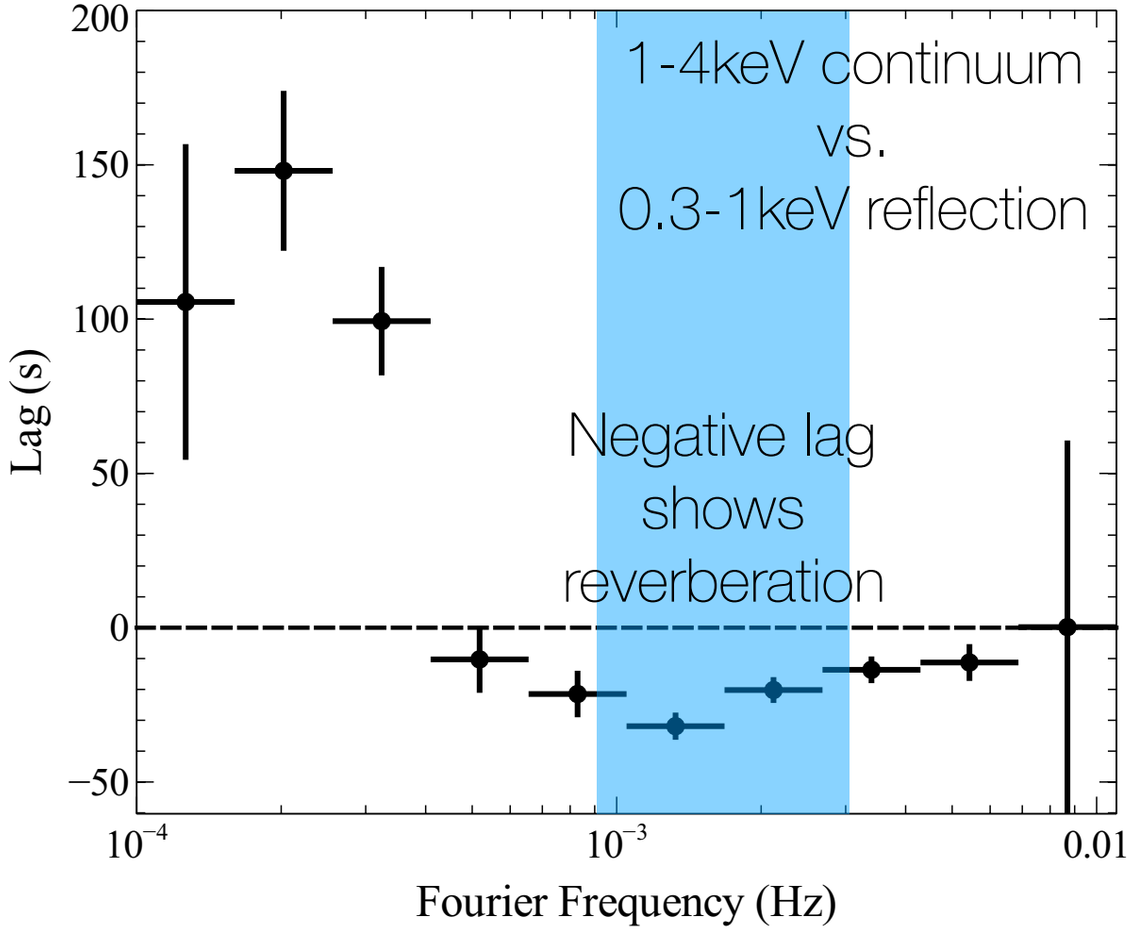
Reverberation time shows distance from corona

Measuring X-ray Reverberation

Work in the Fourier domain – divide the light curve into different Fourier frequency components – fast and slowly varying components of the variability

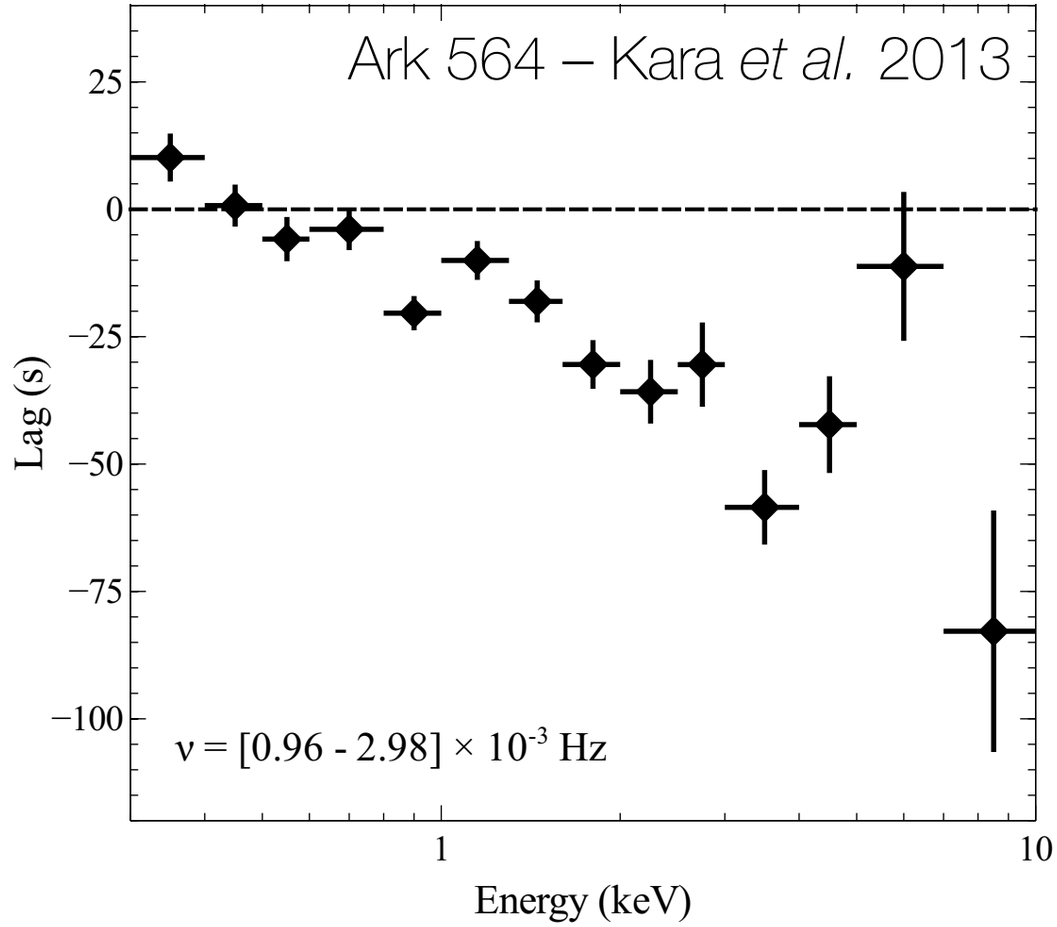
Lag-Frequency Spectrum

Between two energy bands – one dominated by continuum and one dominated by reflection



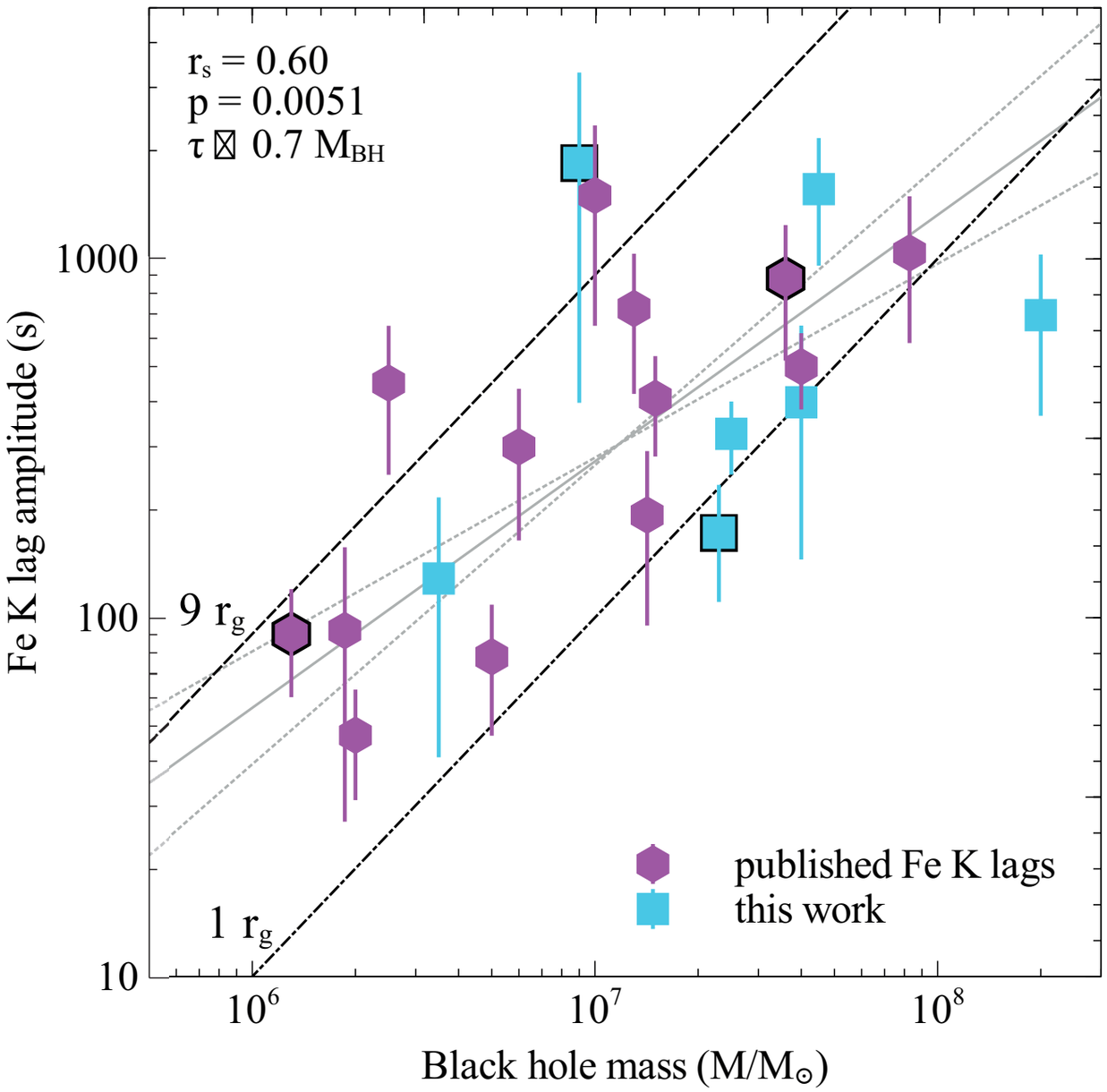
Lag-Energy Spectrum

Average response time of different energies to variability over a chosen range of frequencies



Characteristic Size Scale

Kara *et al.* 2016, also DeMarco *et al.* 2013



- Characteristic length scale around black hole

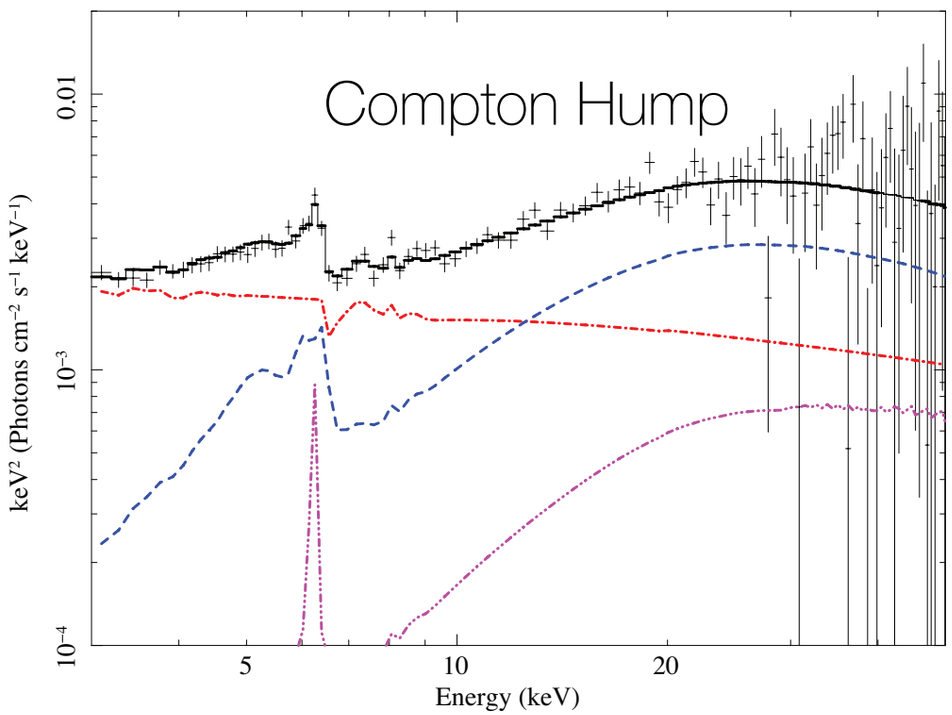
$$r_{\mathrm{G}} = \frac{GM}{c^2}$$

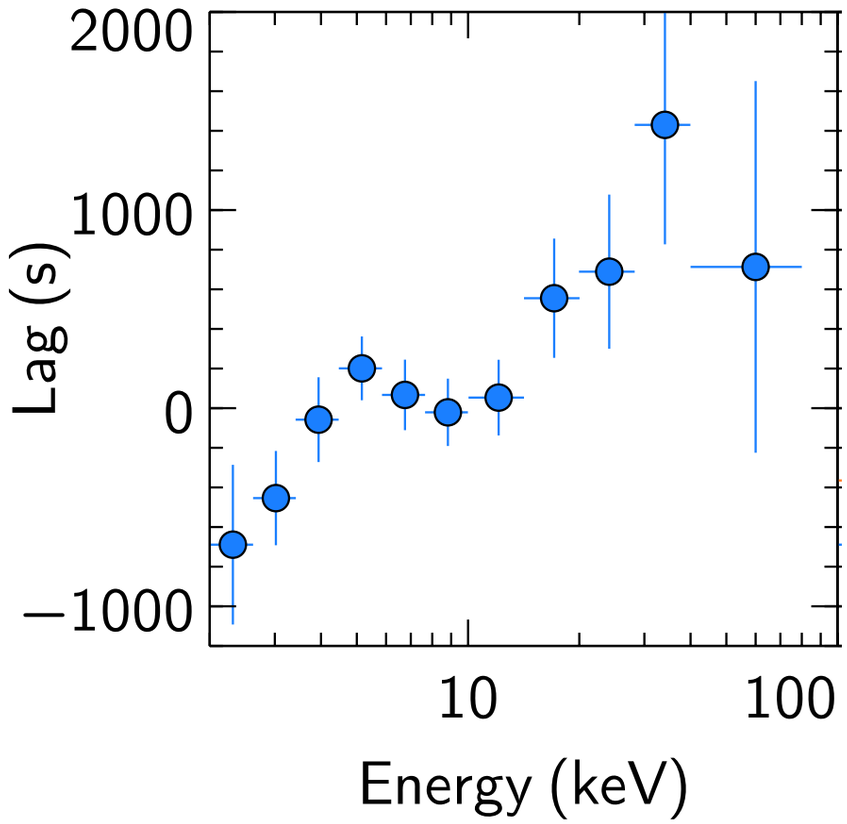
- Reverberation lags scale with black hole mass

- Probing innermost regions of accretion flow

Hard X-ray Reverberation

- Fourier analysis requires continuous light curve segments
- NuSTAR (+ NICER and STROBE-X) are/will be in low Earth orbits – gaps in light curves
- Describe lags in the covariance matrix and fit in the time domain (Zoghbi *et al.* 2013)



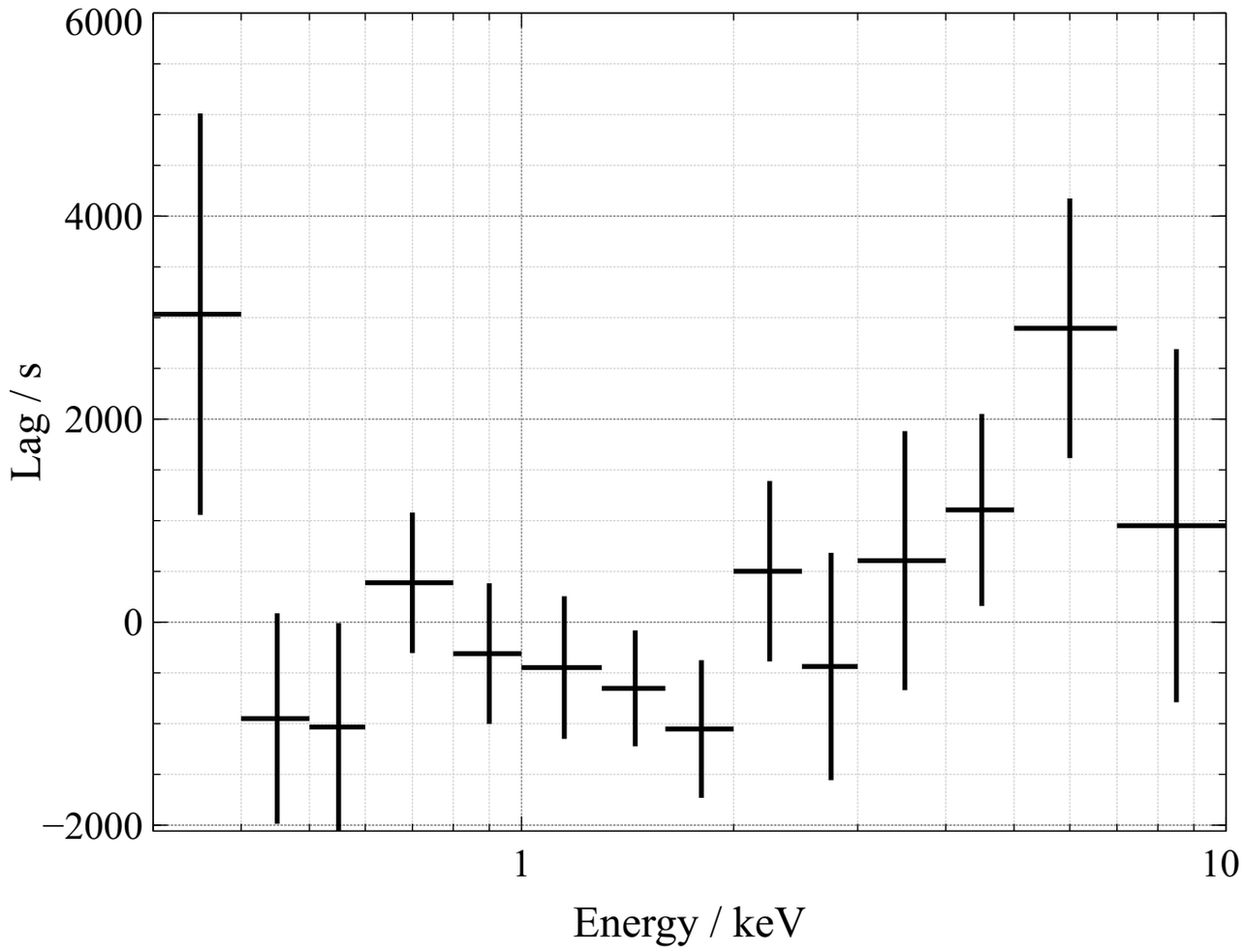


MCG–5-23-16
Zoghbi *et al.* 2014

What about a radio-loud AGN?

Long-Timescale Lags in Radio Galaxy 3C120

Alternative to fitting covariance in the time domain is to model light curves with gaps using a Gaussian process. Sample from probability distribution of underlying light curve and calculate lags across multiple XMM-Newton orbits



3000s ~ $10r_G$ ($M_{BH} = 6x10^7\ M_\odot$)

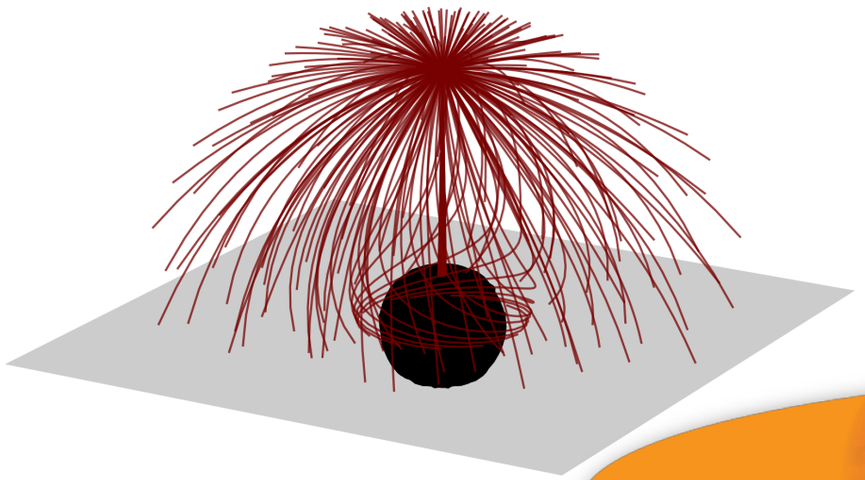
- How are the corona and the jet related?
- Understand the coronal geometry in a radio loud AGN

Wilkins 2019

Probing the corona and accretion flow

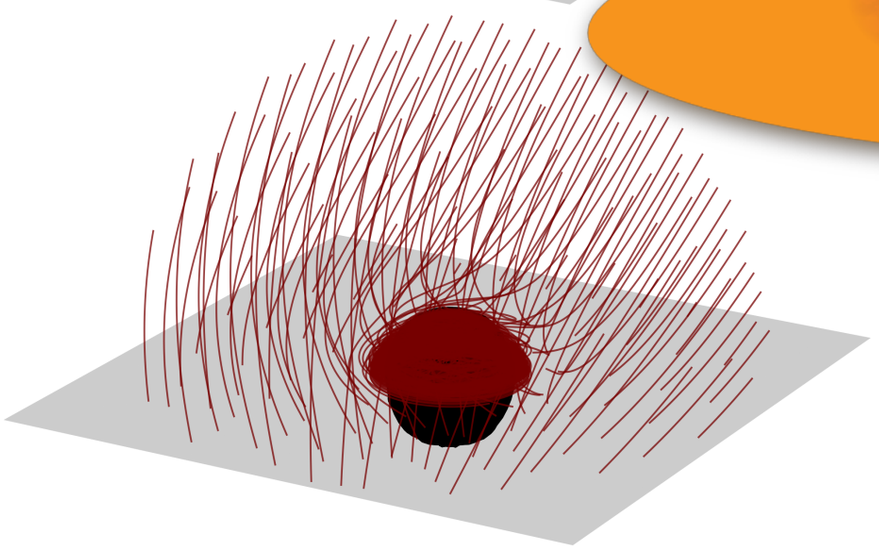
Modelling X-ray Reverberation

- General relativistic ray tracing simulations
- Trace rays from source (corona) to disc to observer in Kerr spacetime
- Understand the effect of the coronal geometry (Wilkins et al. 2012, 2013), propagation of fluctuations (Wilkins et al. 2016, Mastroserio et al. 2018), accretion flow geometry & structure (Taylor & Reynolds 2018)

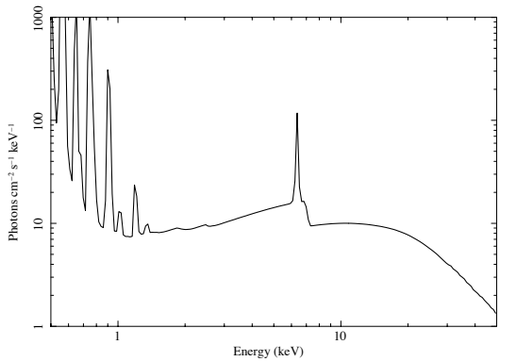


Rays start from either point source or extended corona with propagating fluctuations

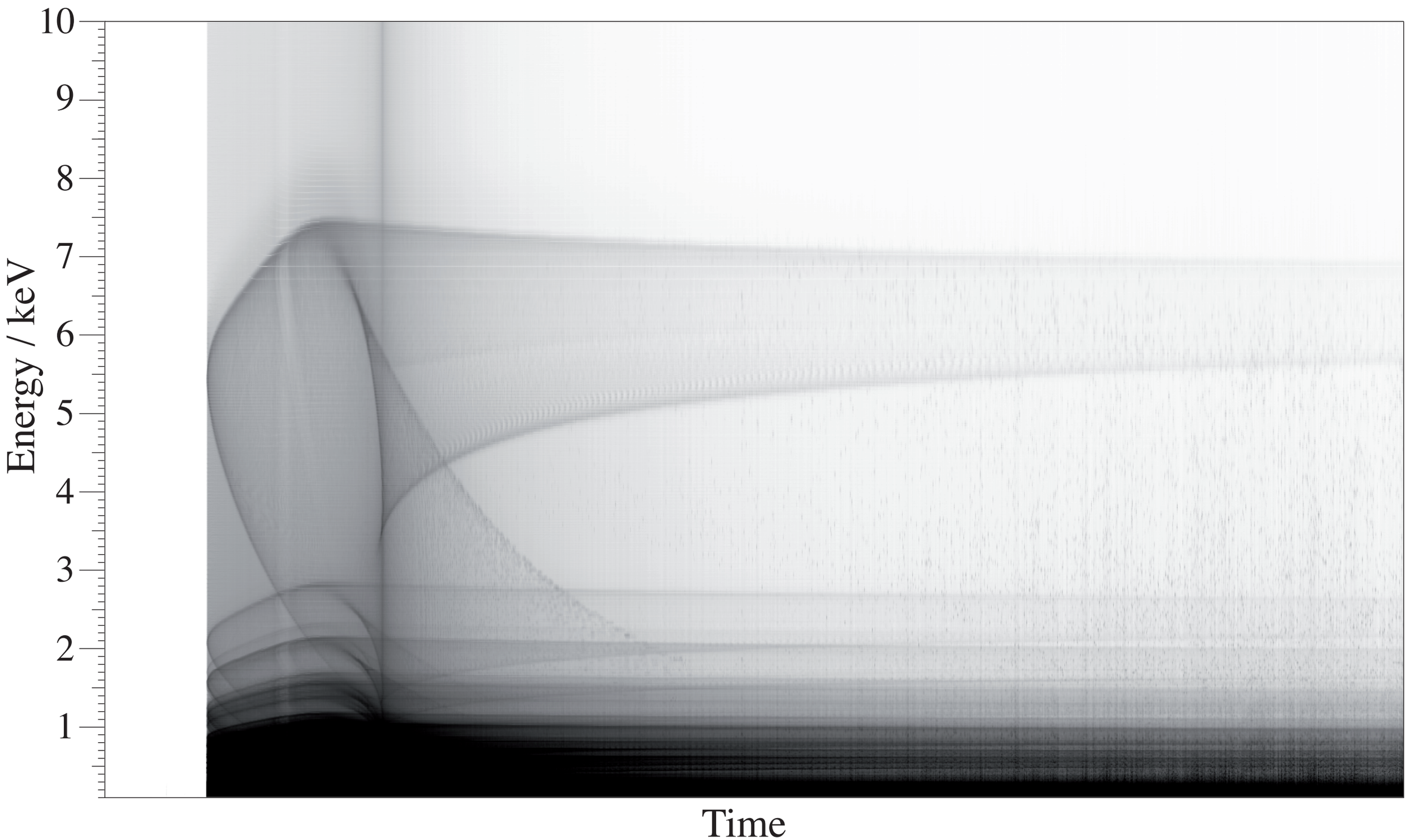
Record redshifted photon energy and time at observer



XILLVER reflection spectrum from illuminated patch on disc according to density & ionisation profile of disc



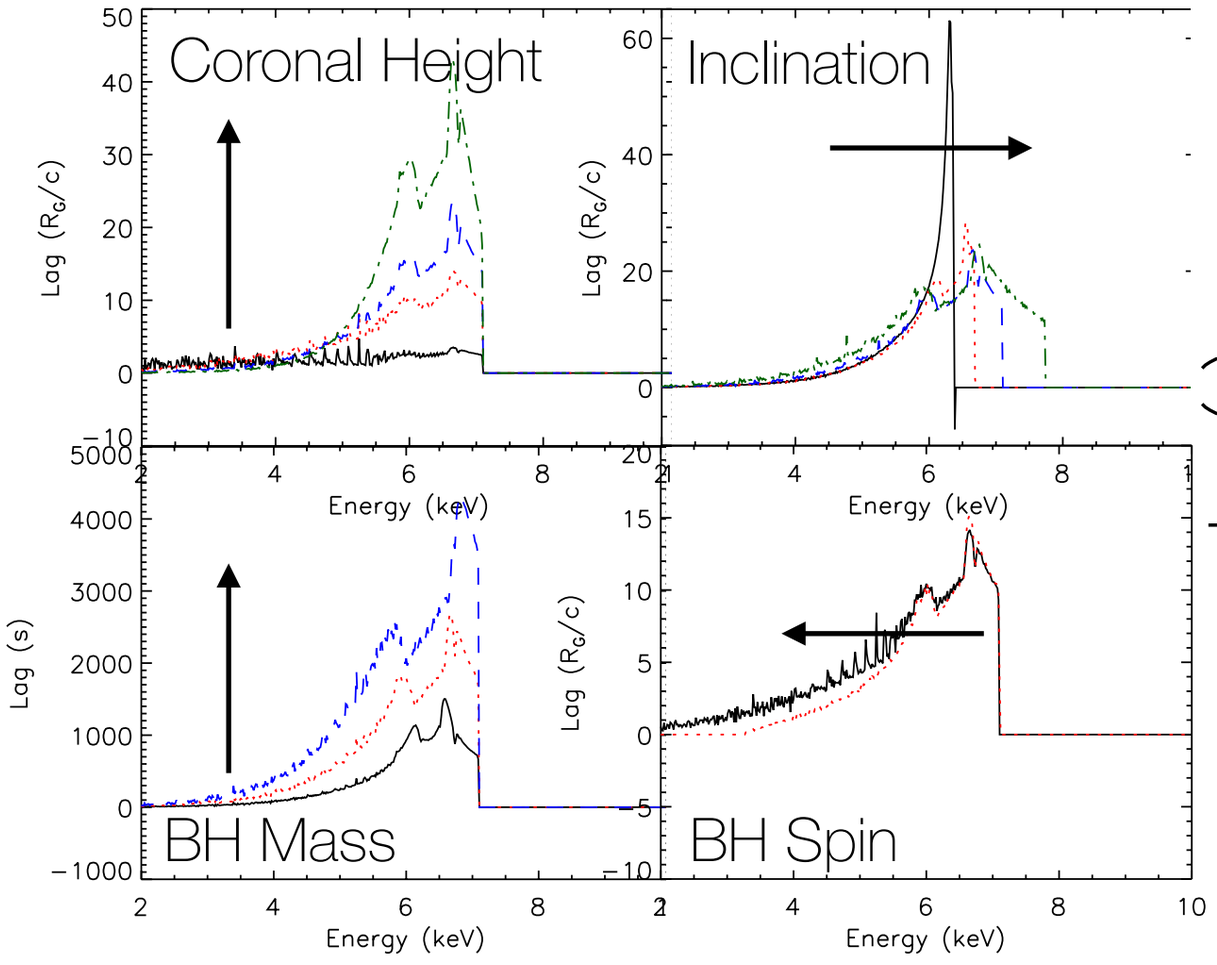
Reverberation Response of Disc

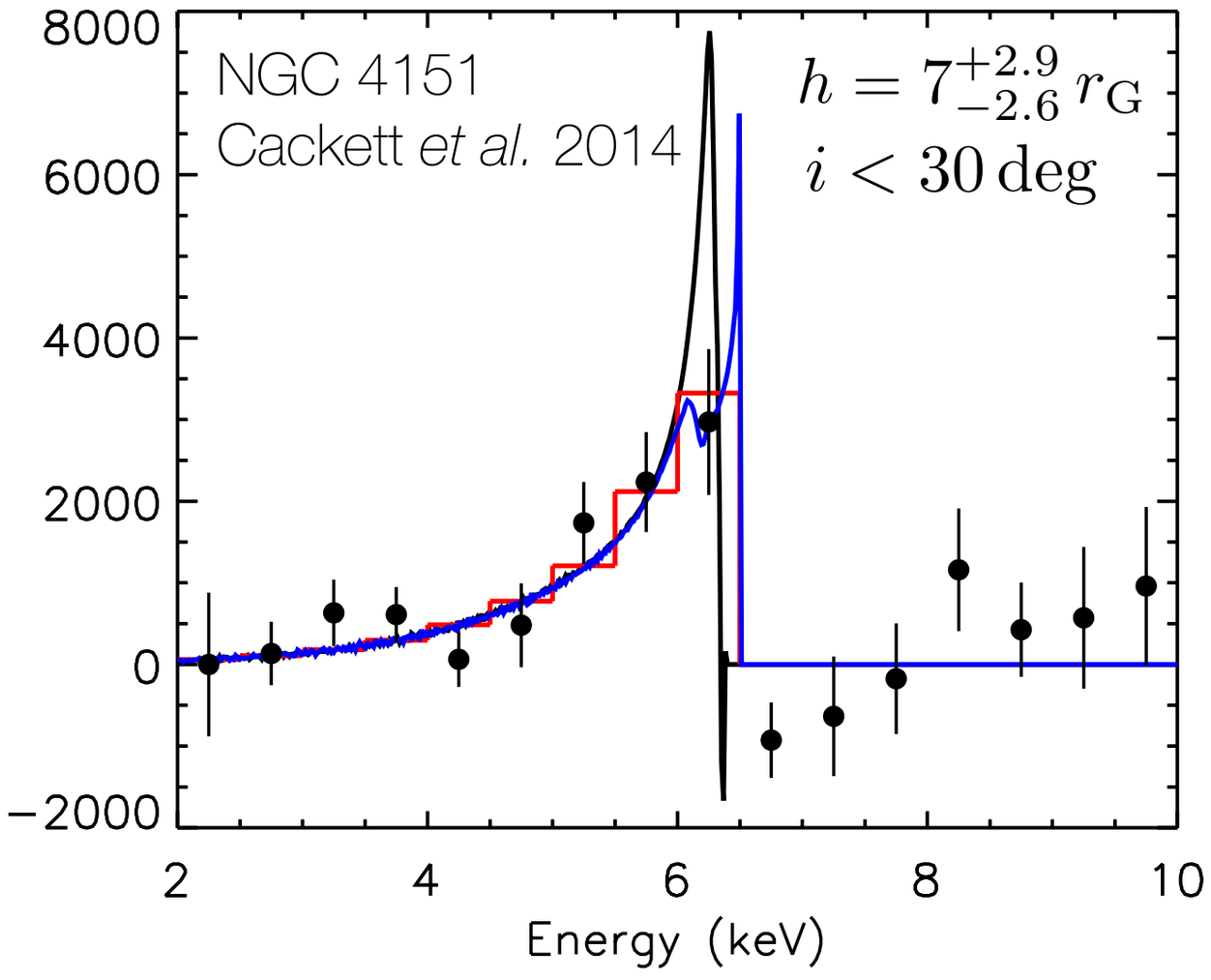


Reynolds *et al.*1999, Wilkins *et al.* 2016

Modelling the Lag-Energy Spectrum

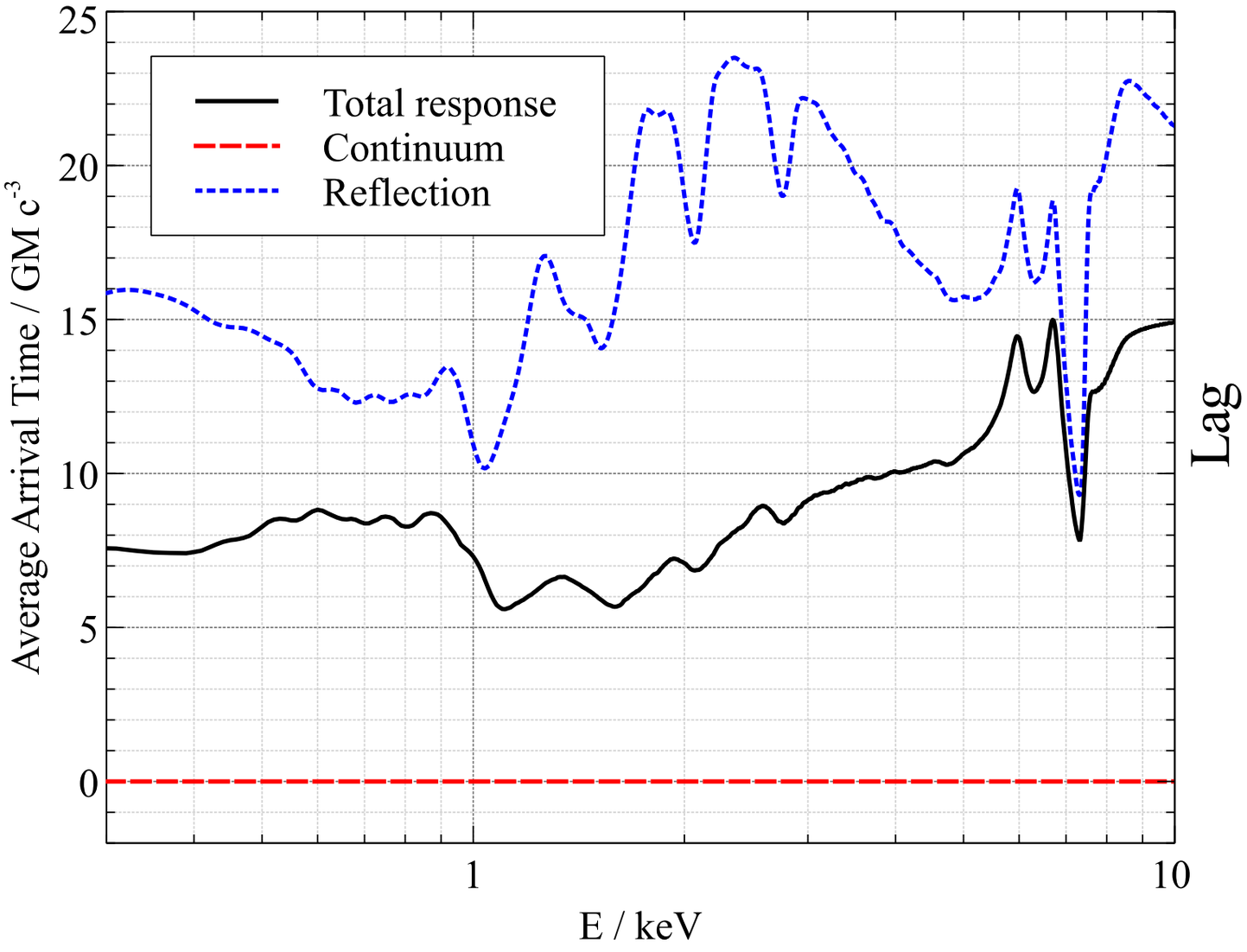
Reverberation response is a function of the corona geometry/scale height, inclination, black hole mass & spin (Wilkins & Fabian 2013, Cackett *et al.* 2014)

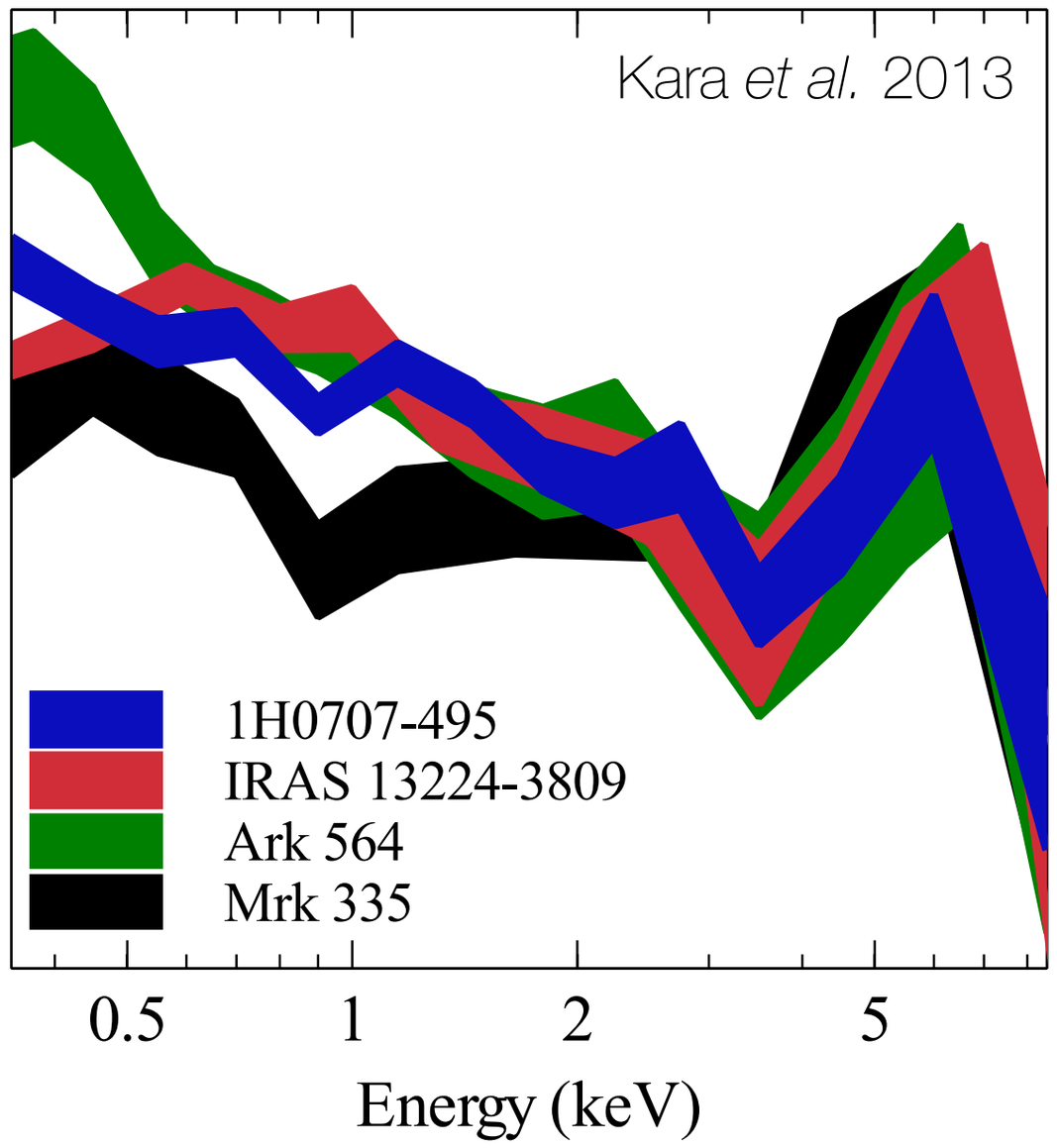




Also sensitive to disc geometry (Taylor & Reynolds 2018) and ionisation Chainakun & Young 2015)

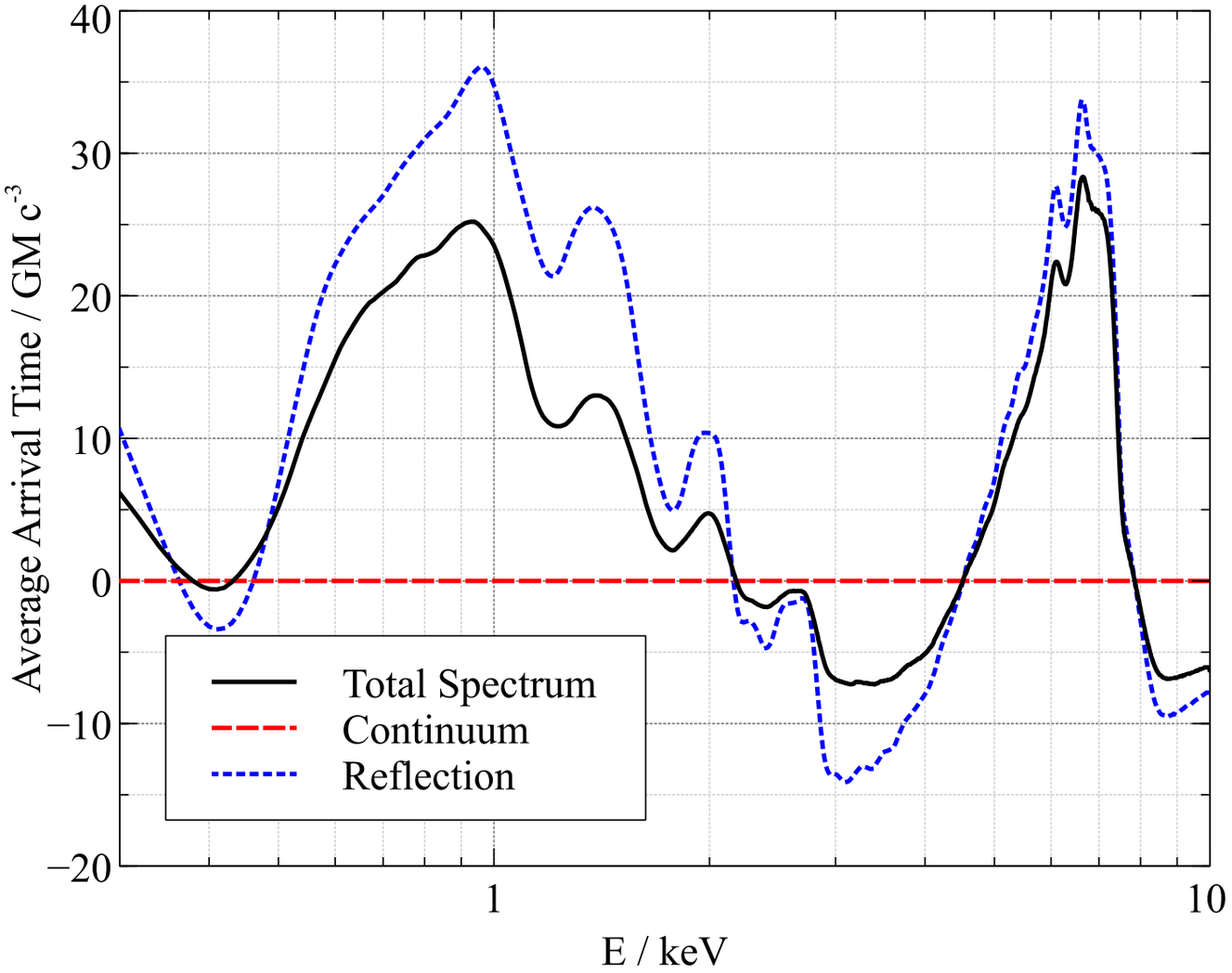
The Lag-Energy Problem

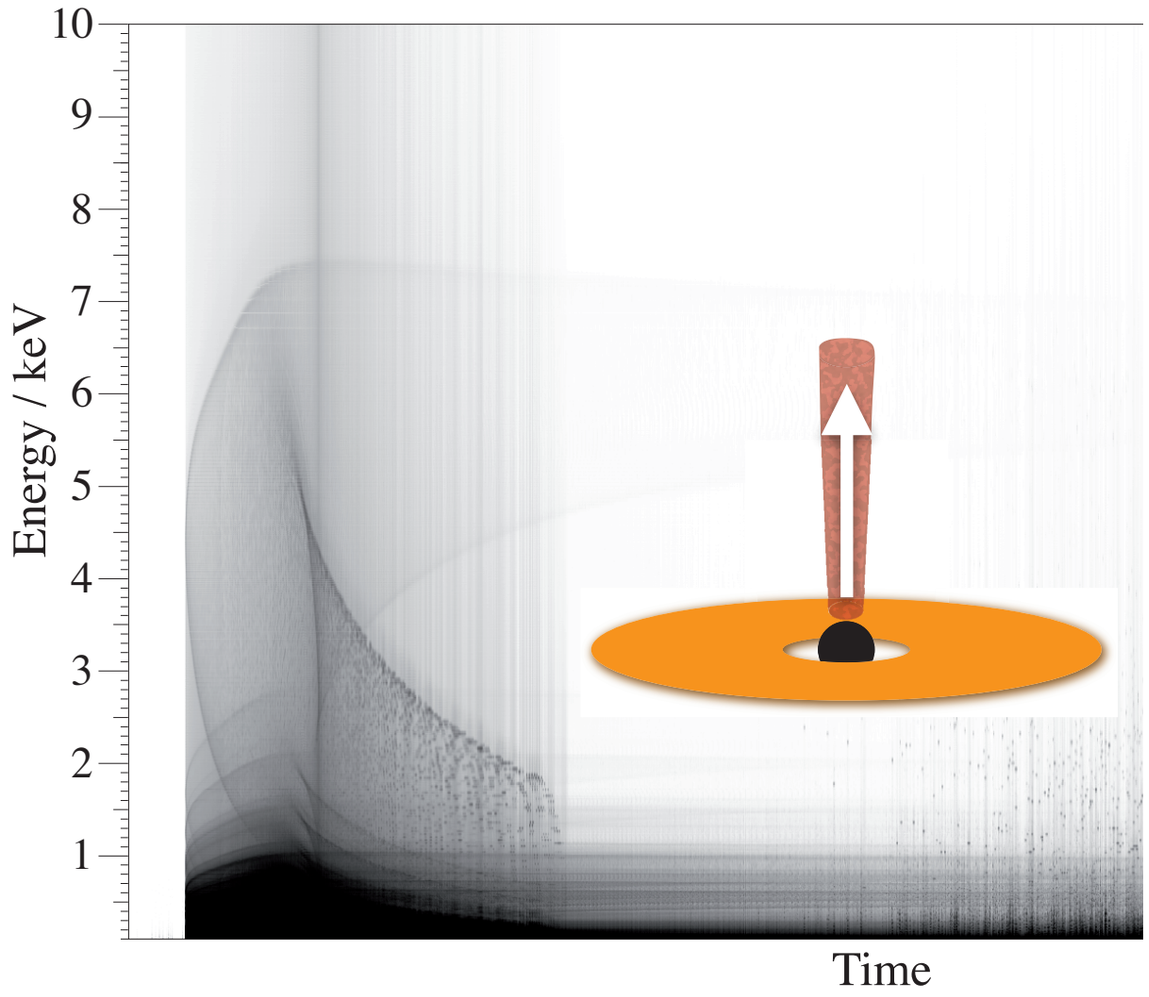




Wilkins *et al.* 2016

What is the Dip at 3keV?

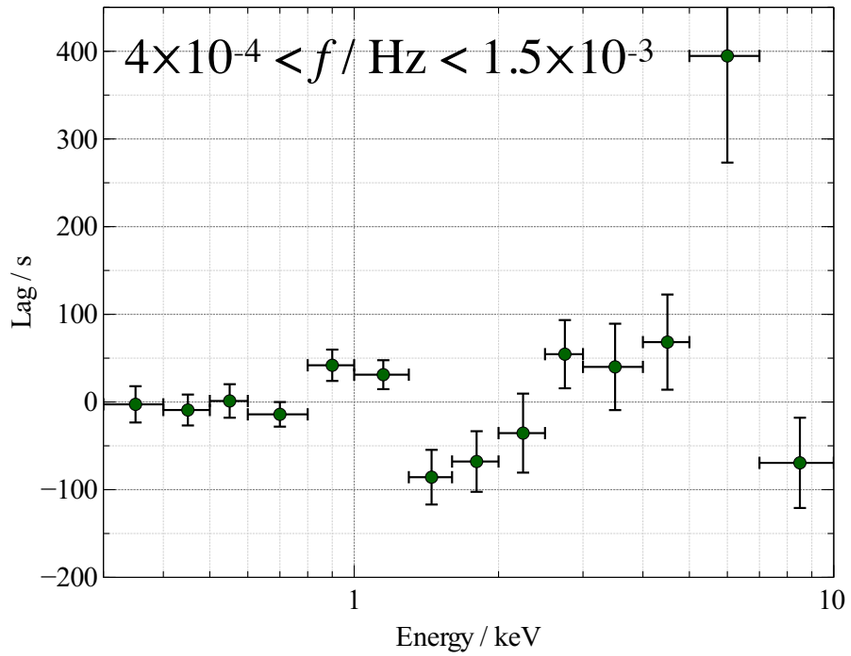


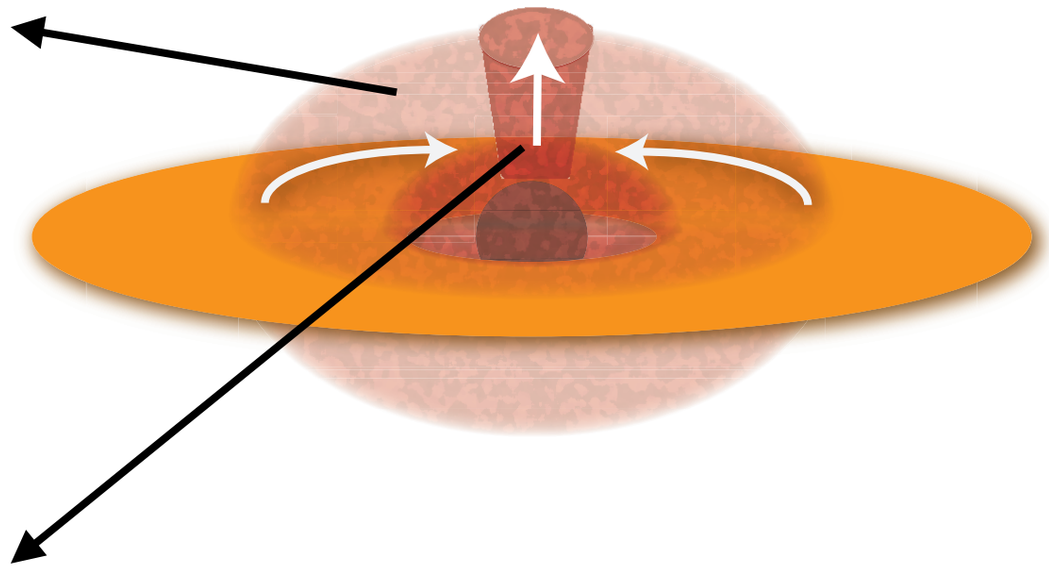


Wilkins *et al.* 2016

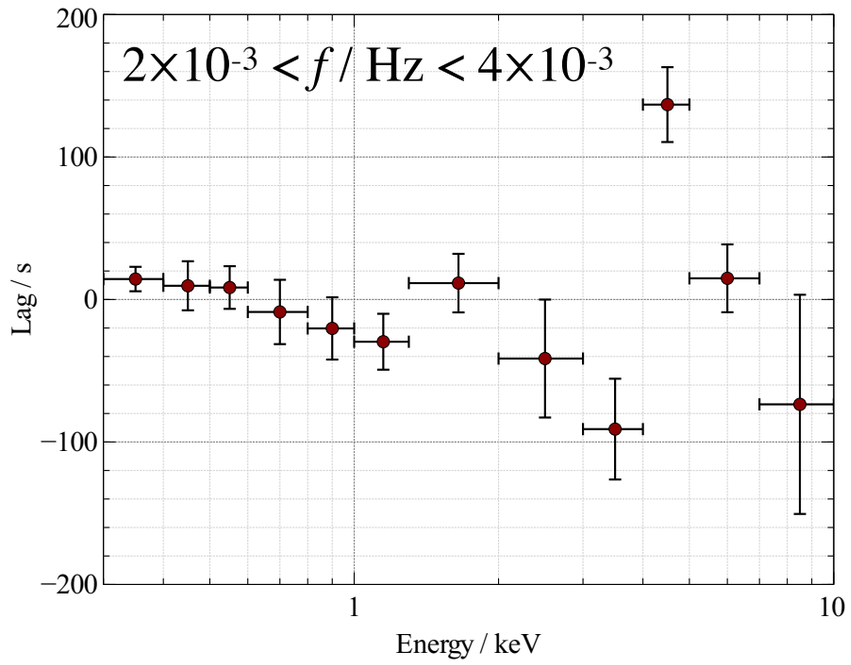
Structure of the Corona in I Zw I

Low Frequency variability dominated by slowly varying disc corona (from disc fields/MRI?)





High Frequency variability dominated by rapidly varying collimated core (like a jet??)



Wilkins *et al.* 2017

Structure of the Corona in I Zw I

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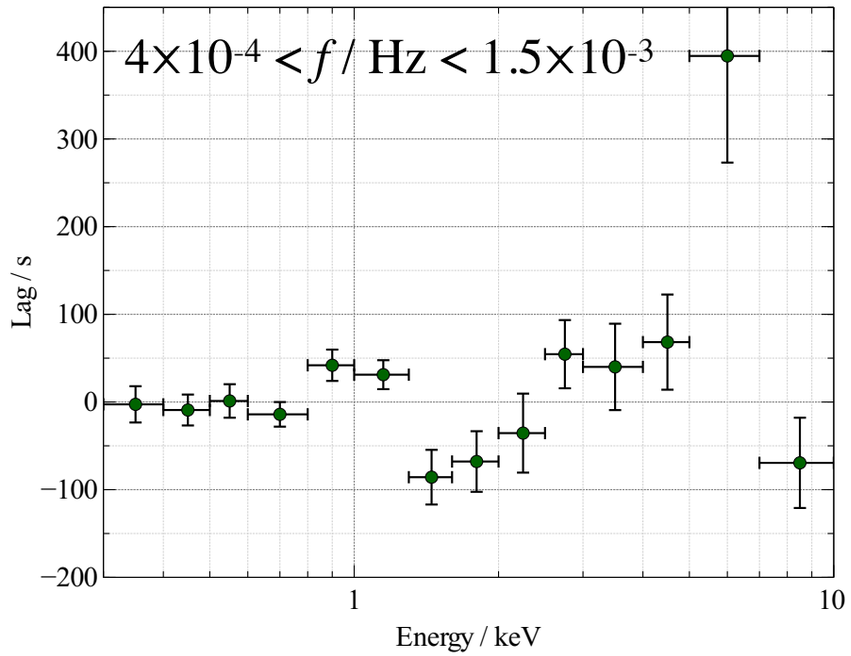

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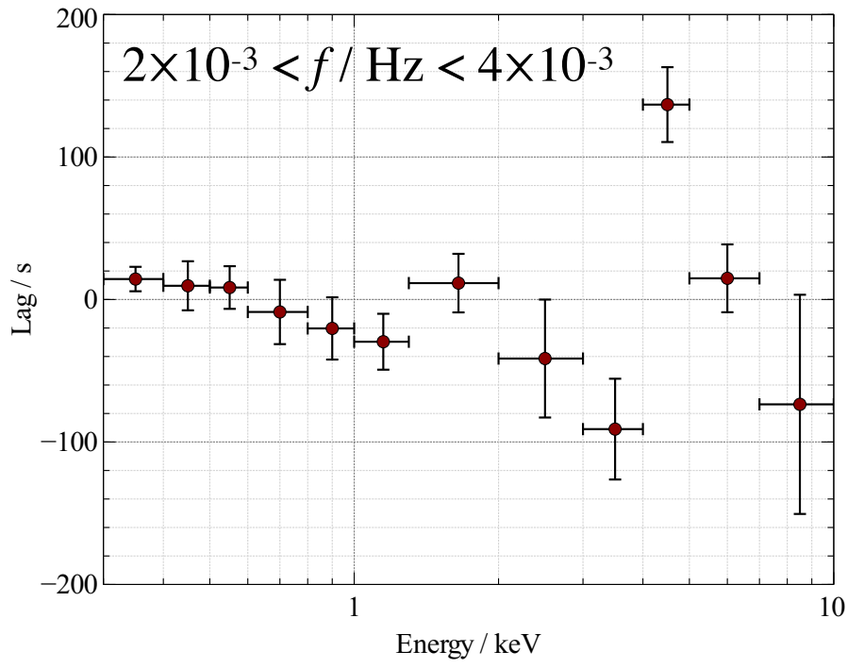
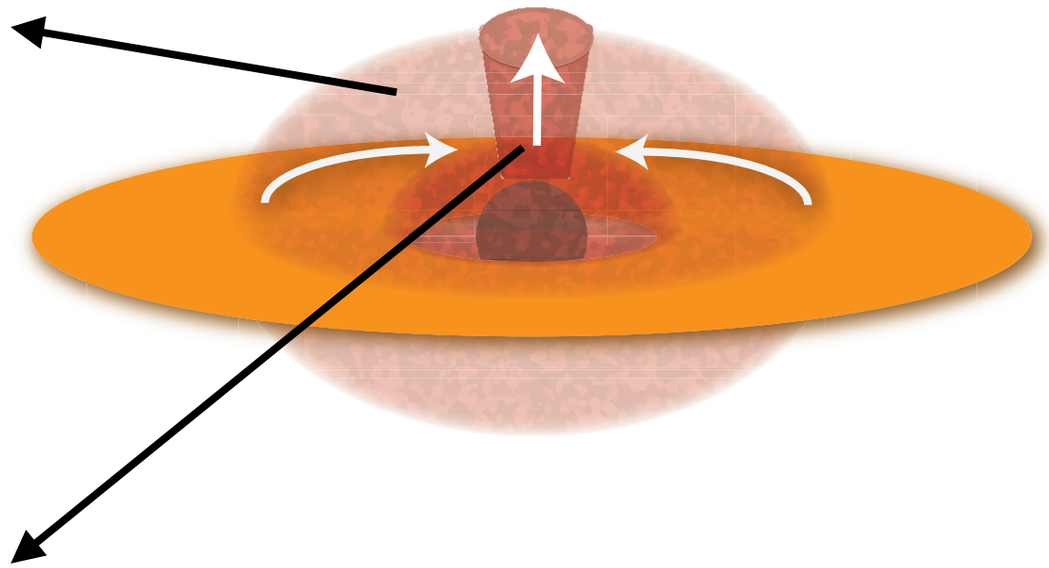


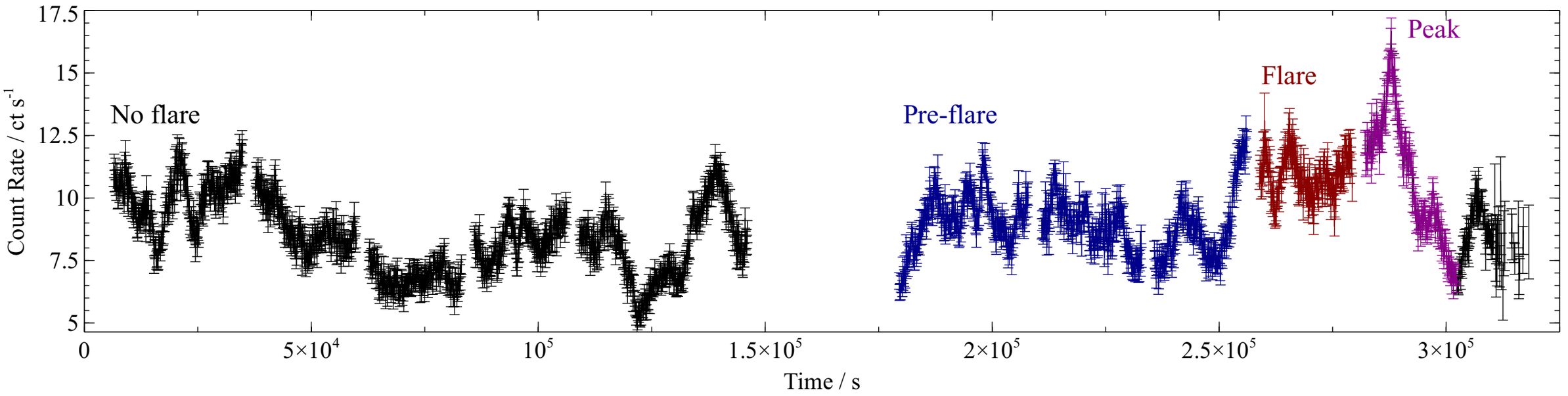


Is the compact 'lamppost' corona in a radio-quiet AGN a jet that has been 'short-circuited'?

Poster 106.46: Yuan, Spitkovsky, Blandford & Wilkins

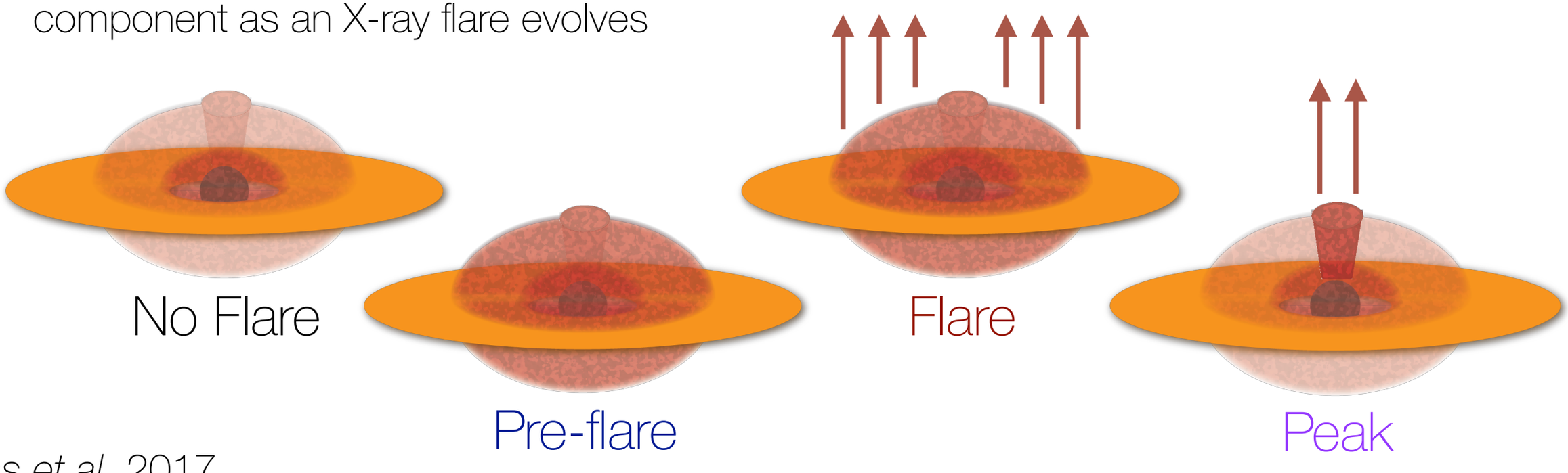
Wilkins *et al.* 2017

The Evolution of a Flare

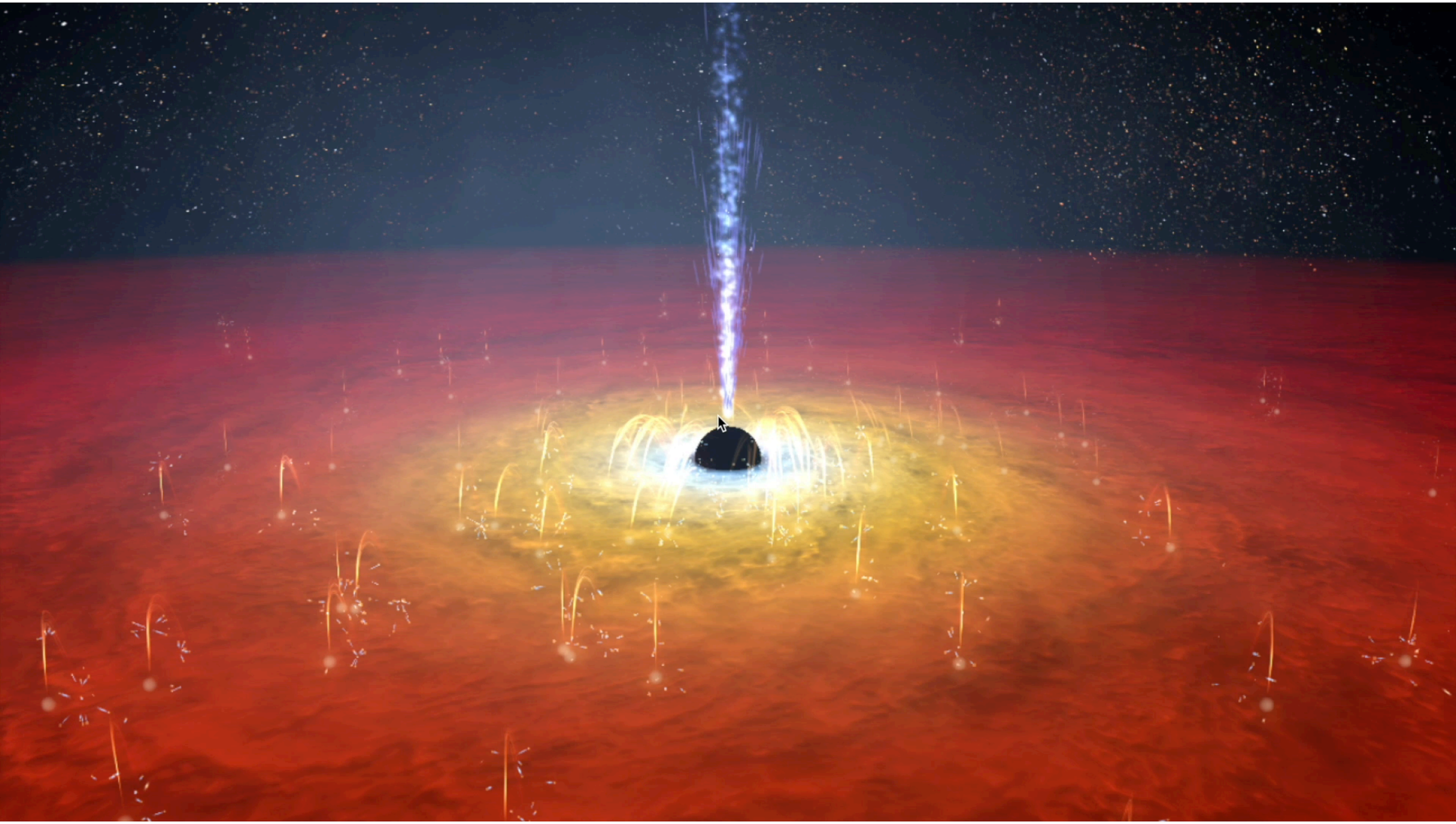


Variability on different timescales distinguishes the extended corona and the core

Covariance over different frequency ranges probes the variability in emission from each component as an X-ray flare evolves

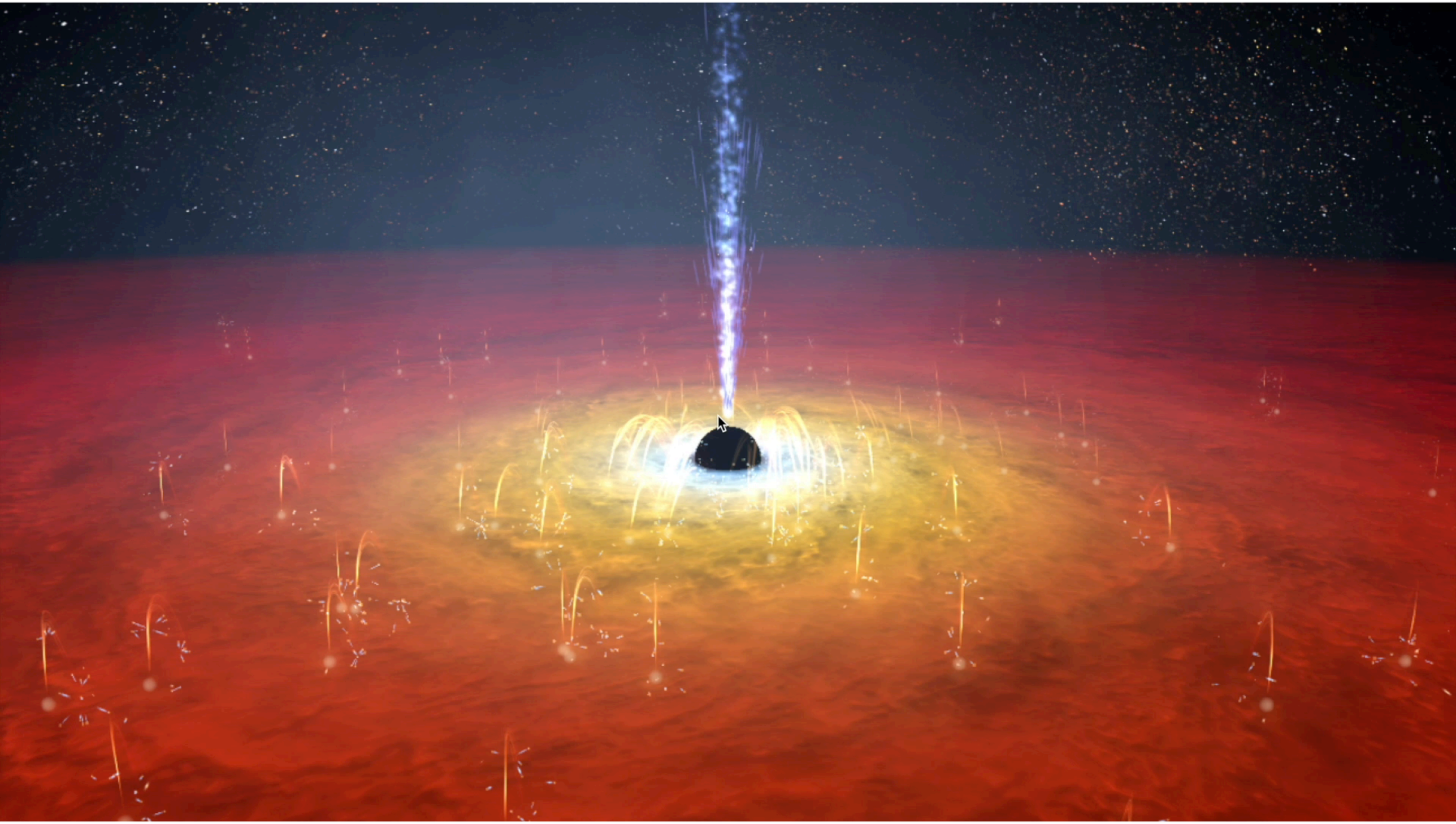


Wilkins *et al.* 2017



Wilkins *et al.* 2017

Animation: Niel Brandt & Nahks Tr'Ehnl

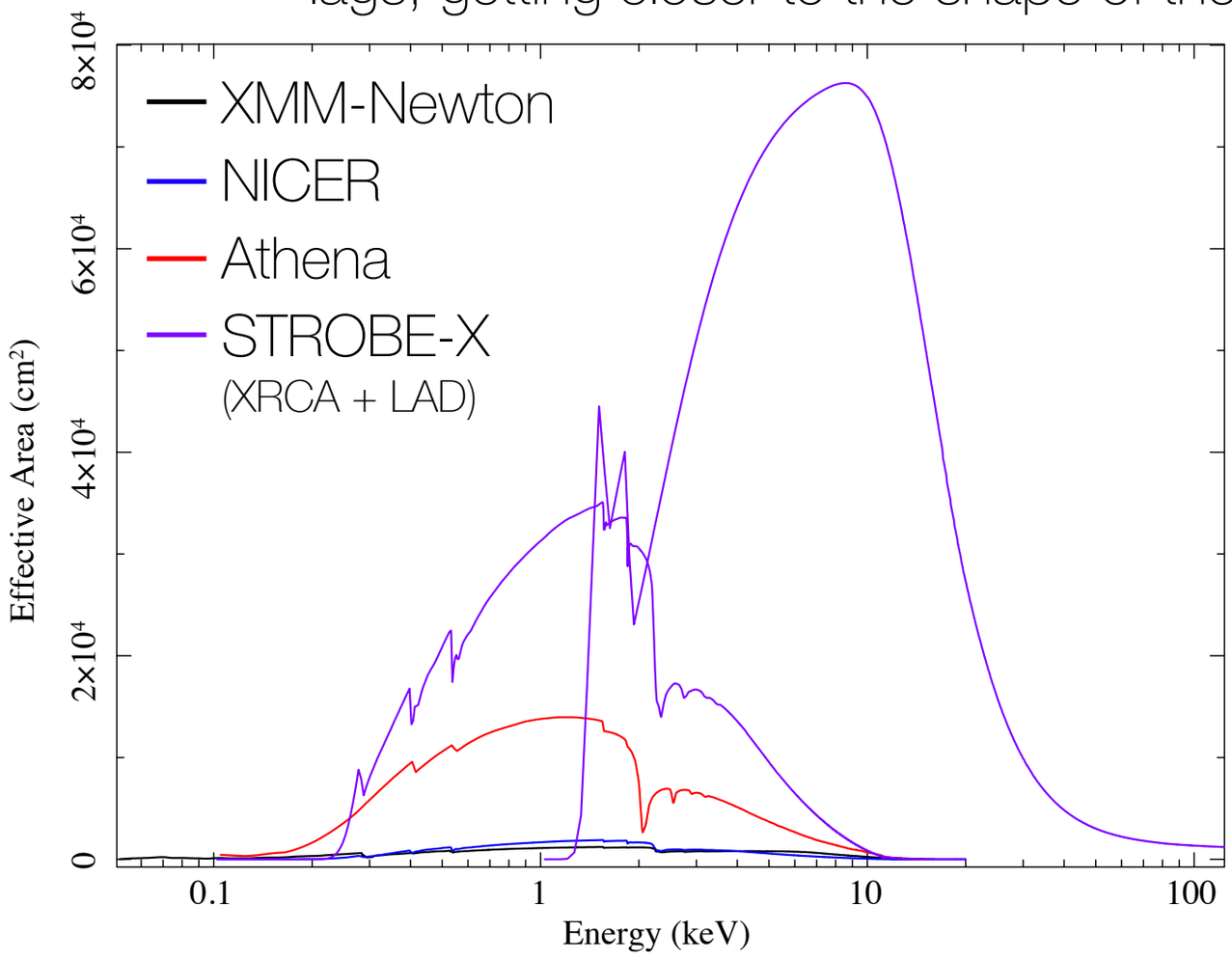


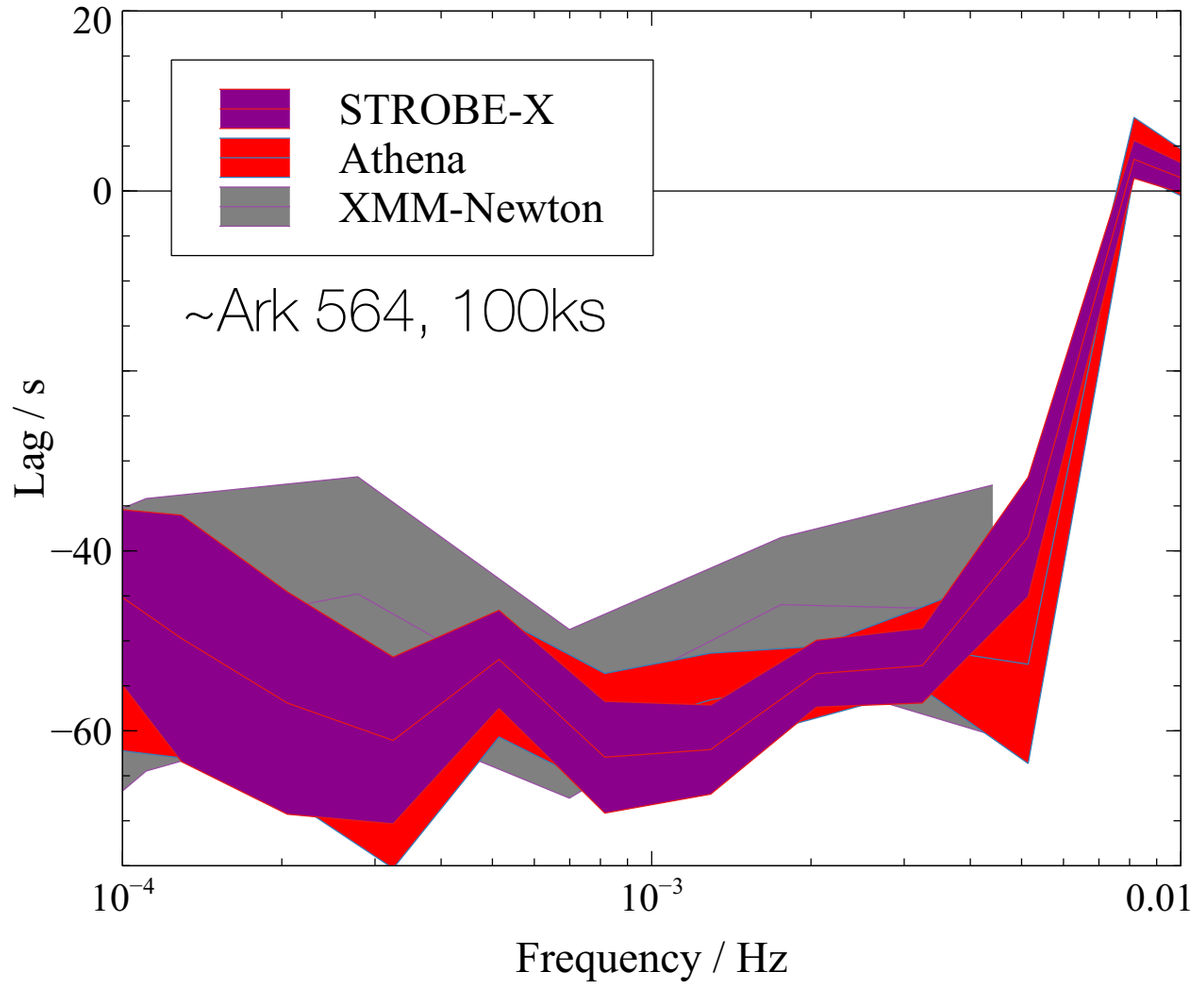
Wilkins *et al.* 2017

Animation: Niel Brandt & Nahks Tr'Ehnl

The Future of X-ray Reverberation

From 1D lag-frequency or lag-energy to lag-energy-frequency. Resolve the high frequency lags, getting closer to the shape of the response function and trace variability

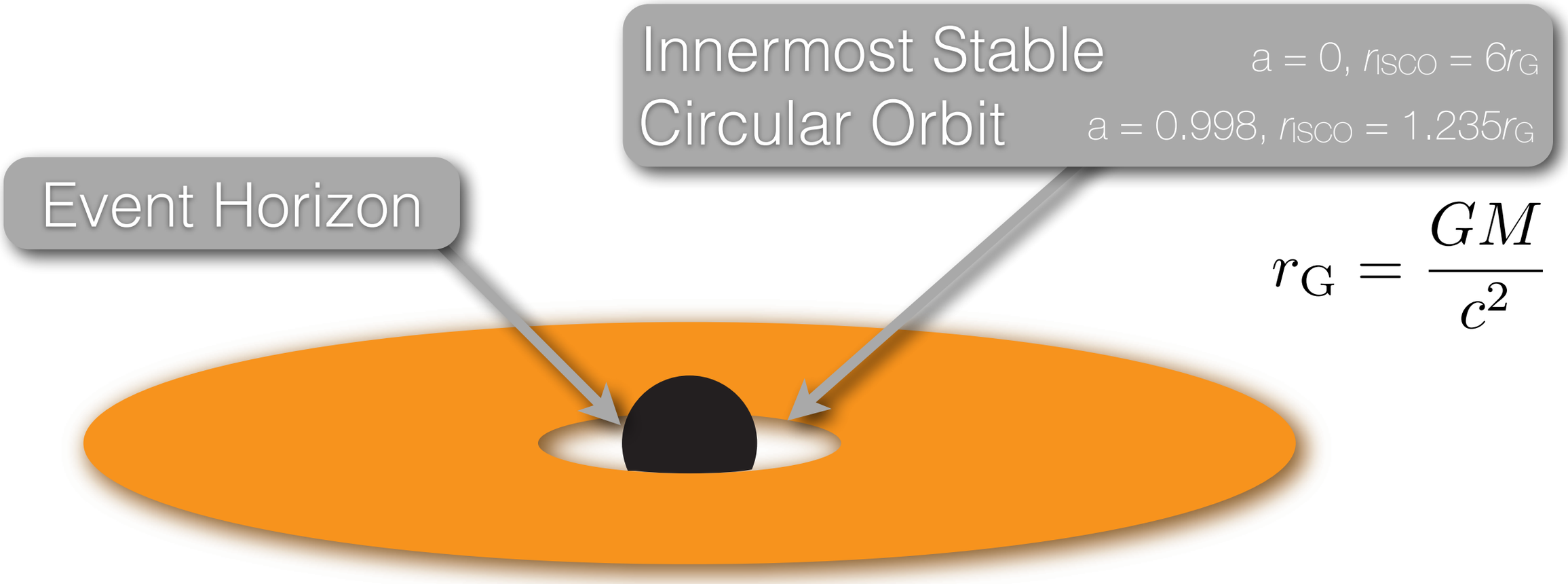




Energy shift – location on disc. Lag time – distance from X-ray source

Build up a 3D picture (movie) of the extreme environment just outside the event horizon

Probing the Plunging Region

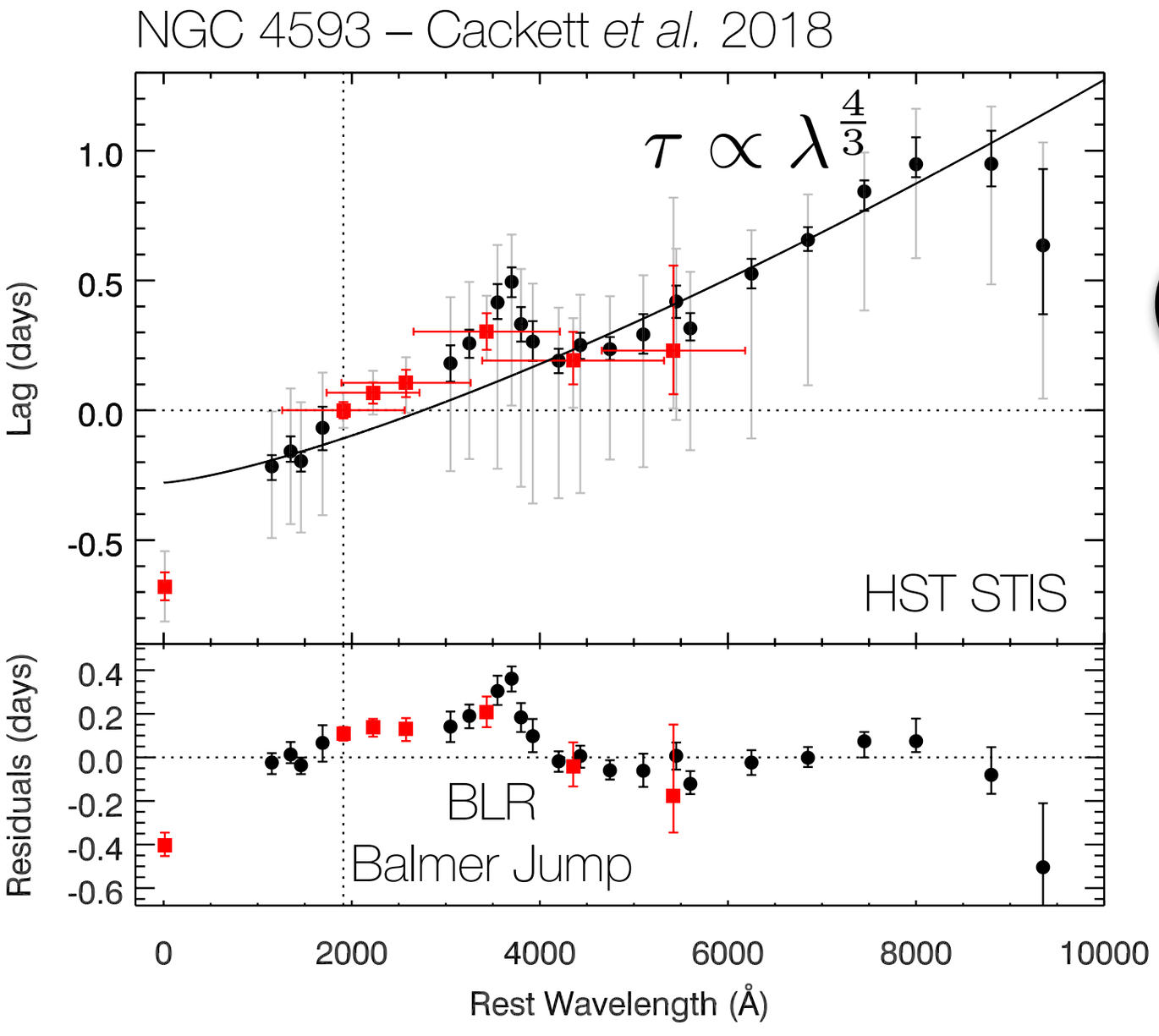


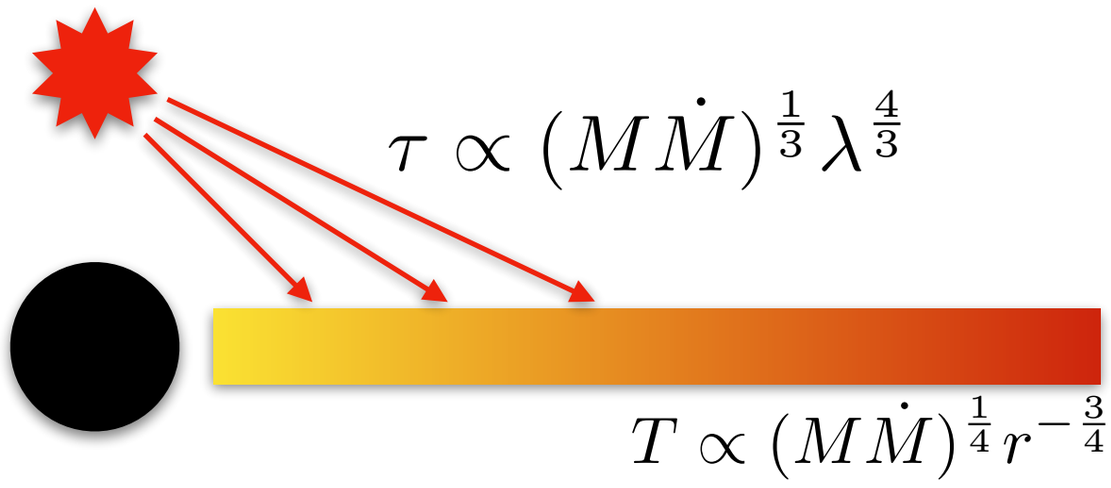
Material in the plunging region is strongly irradiated by the corona
Prospects for probing the plunging region by X-ray reverberation

Talk 301.01: Wilkins
(Wednesday, 10:30am)

Beyond the X-rays

Optical Continuum Reverberation



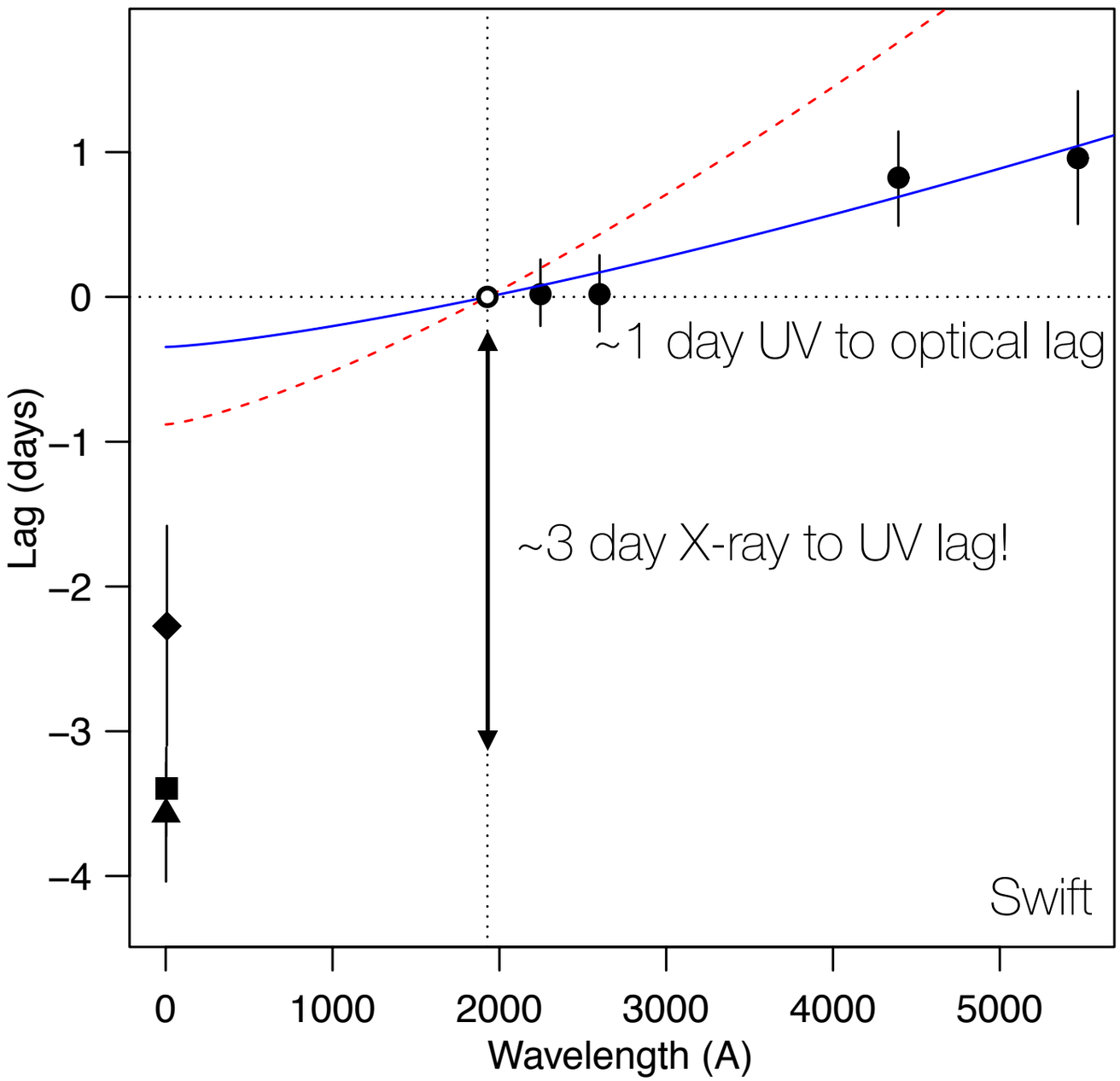


- Time delays as outer disc responds to heating by X-ray source
- Disc appears ~3x bigger than standard accretion disc model
- Vertical structure of disc?
- Disc emissivity and radiative transfer through disc atmosphere?

Poster 106.33: Cackett

Connecting the X-ray and Optical Emission

NGC 4151 – Edelson *et al.* 2017



- Time delay between X-ray and UV is too long to be explained by heating of the disc by a central compact X-ray source
- Evidence for intermediate reprocessing by a warm torus?

How are the innermost regions of the AGN, the corona and jet connected to the fuel supply from the outer disc?

Summary

dan.wilkins@stanford.edu

- X-ray reflection and reverberation probes structure right down to the innermost stable orbit and enables mapping of the inner accretion disc and corona

- X-ray reverberation reveals structure within the corona. Starting to see evidence of a persistent collimated core within an extended corona (the base of a failed jet) and the evolution of coronal components during flares

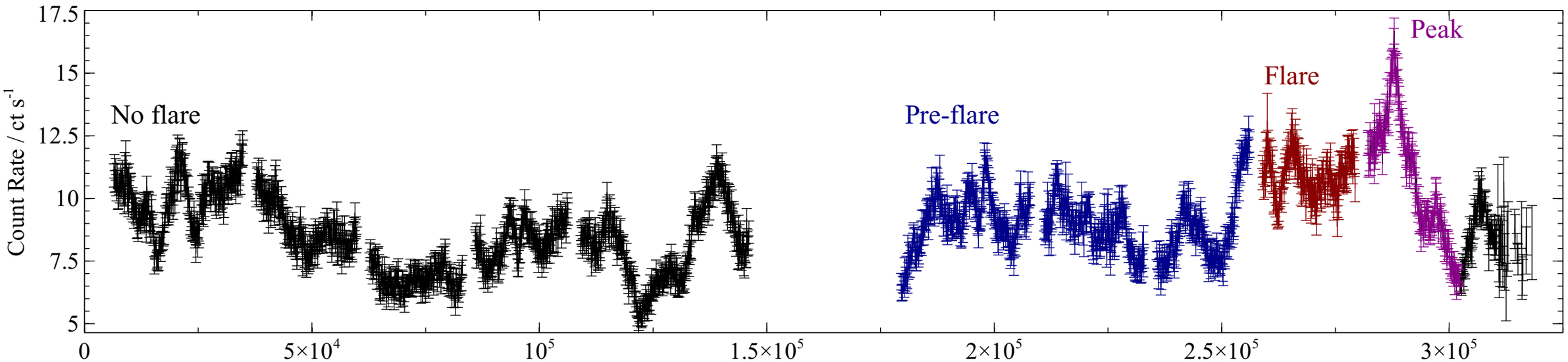
- Great advances with XMM-Newton and NuSTAR. Much more to come with Athena and (hopefully) STROBE-X!

- Multi-wavelength reverberation connects the corona, jet and innermost regions to the fuel supply through the outer disc

- Understand the physics underlying some of the most extreme systems in the Universe

Backup Slides

The Evolution of a Flare



Measure the covariance spectrum at frequencies corresponding to extended corona and core – normalisation is the RMS variability in that component

Left:

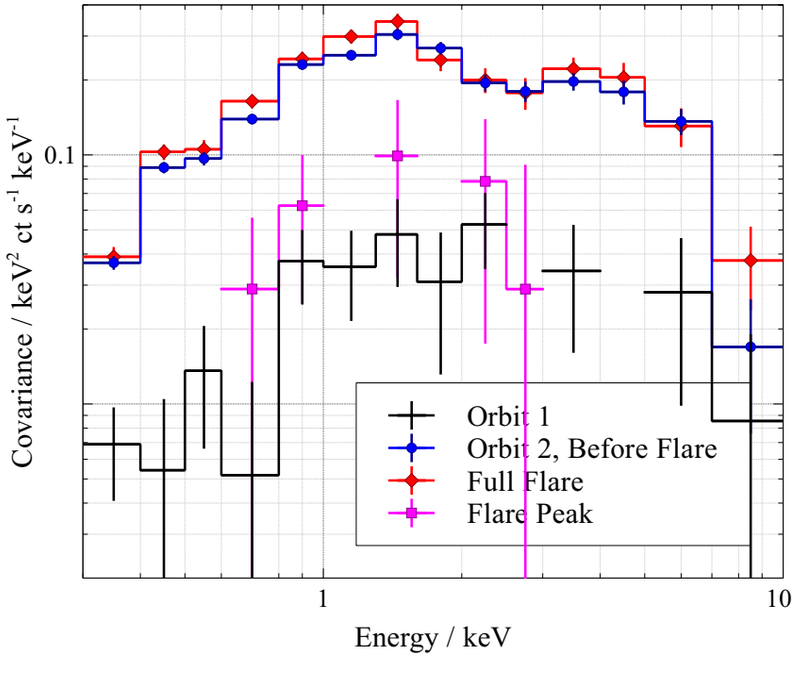
Low Frequency - disc corona

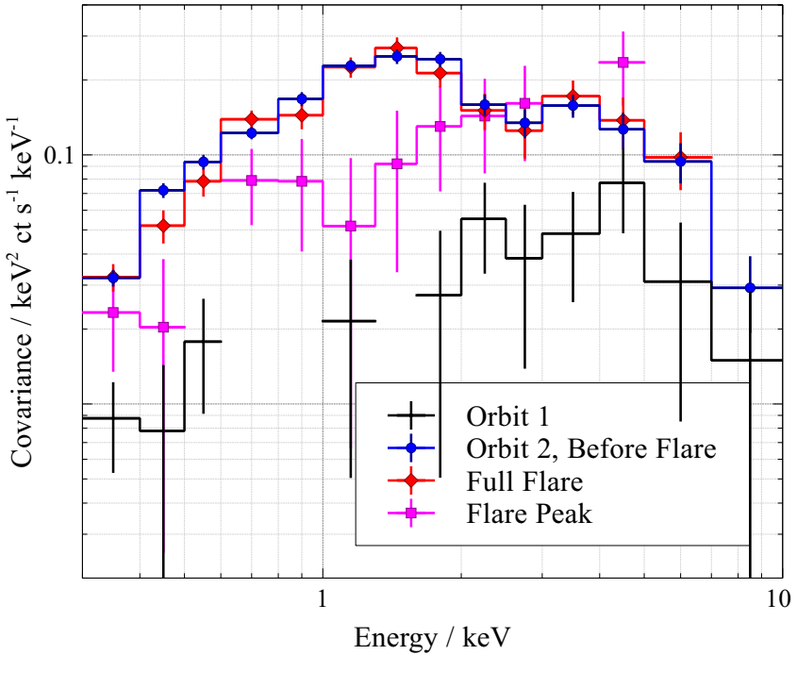
$4\times10^{-4} - 1.5\times10^{-3}$ Hz

Right:

High Frequency - coronal core

$2\times10^{-3} - 4\times10^{-3}$ Hz





Wilkins *et al.* 2017