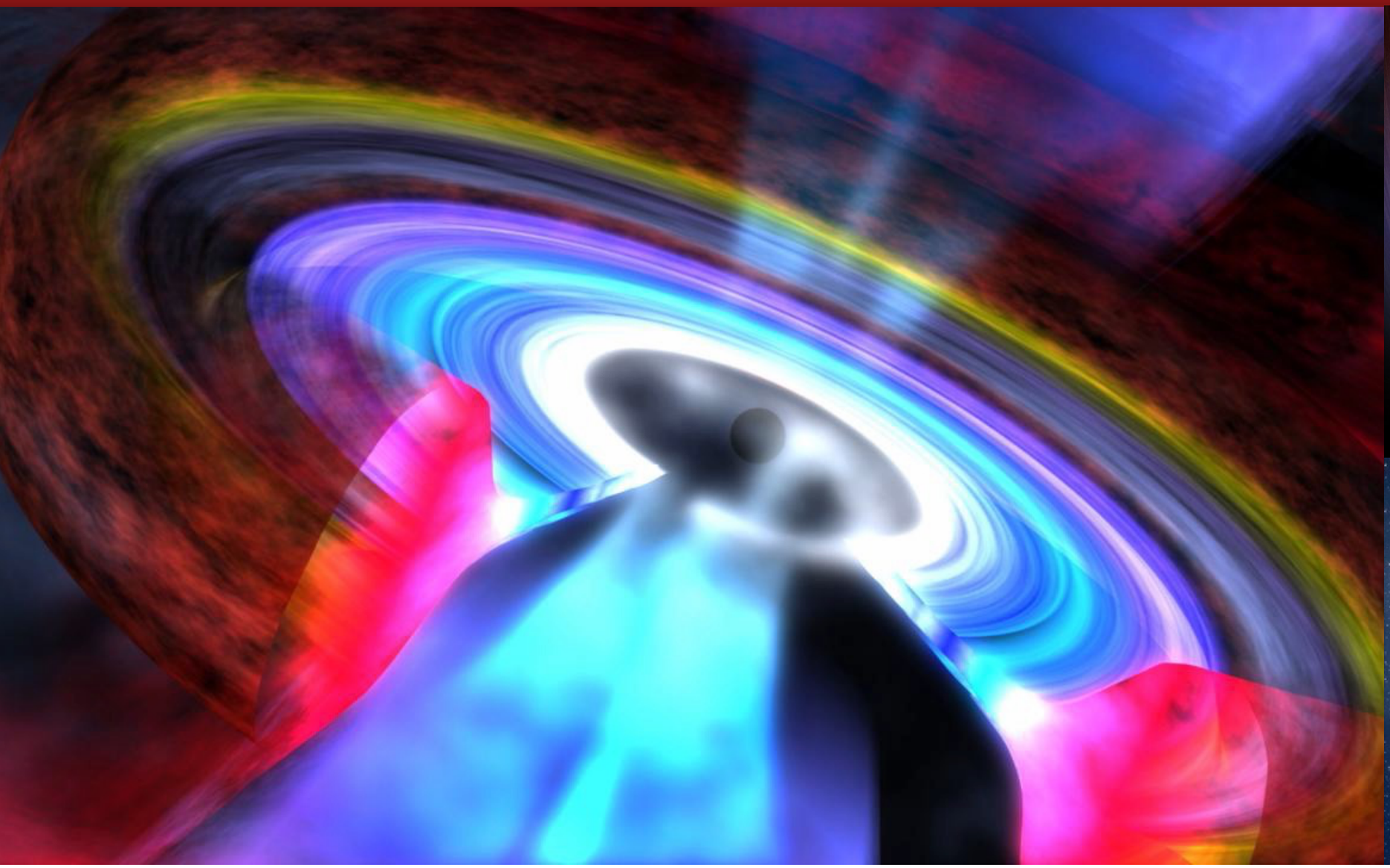
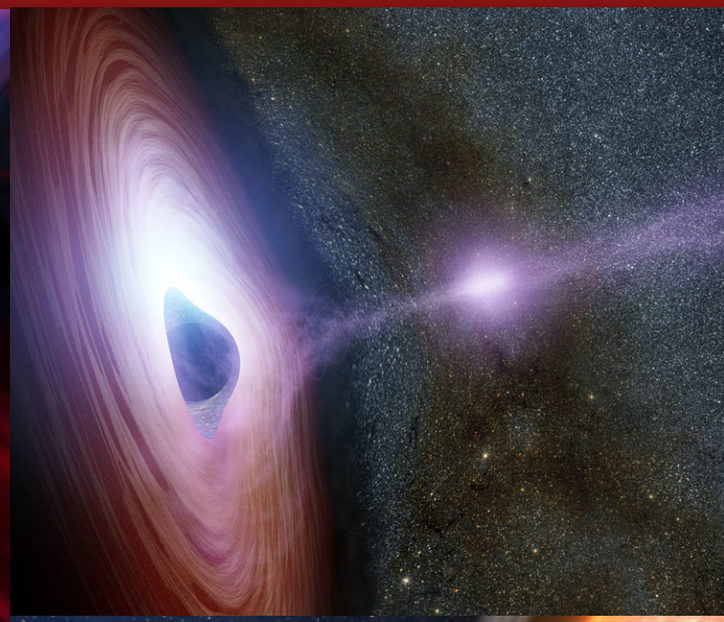
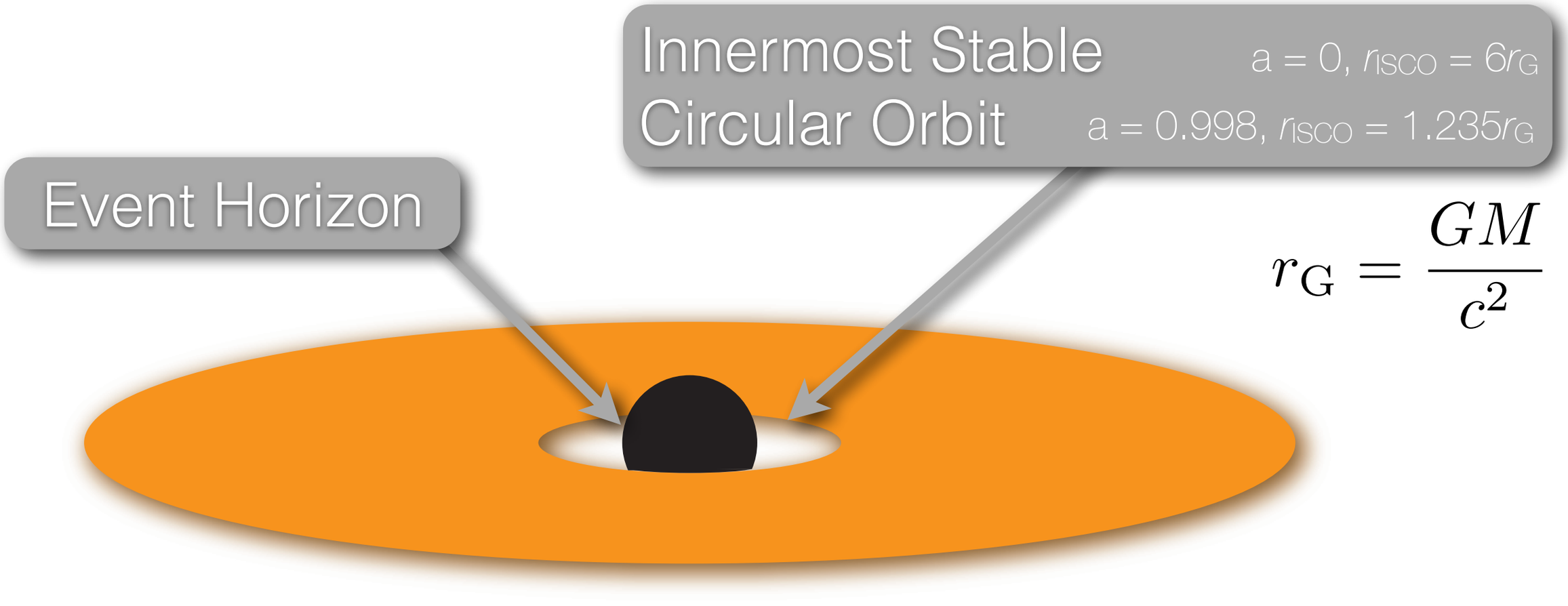




Venturing Beyond the ISCO

Mapping the Extreme Environments Around Black Holes

Dan Wilkins (with Chris Reynolds & Andy Fabian)
Kavli Fellow (2019-20), Einstein Fellow (2016-19)
Kavli Institute for Particle Astrophysics & Cosmology, Stanford University



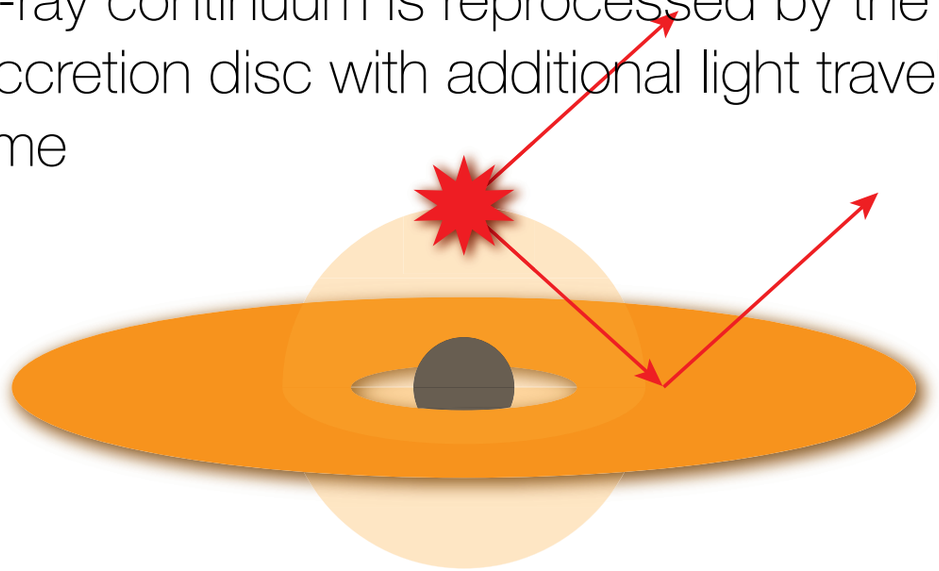
- What happens to material in its final moments as it plunges into a black hole? How does it power some of the most luminous objects in the Universe?

- Does General Relativity accurately describe the extreme environment just outside the event horizon?

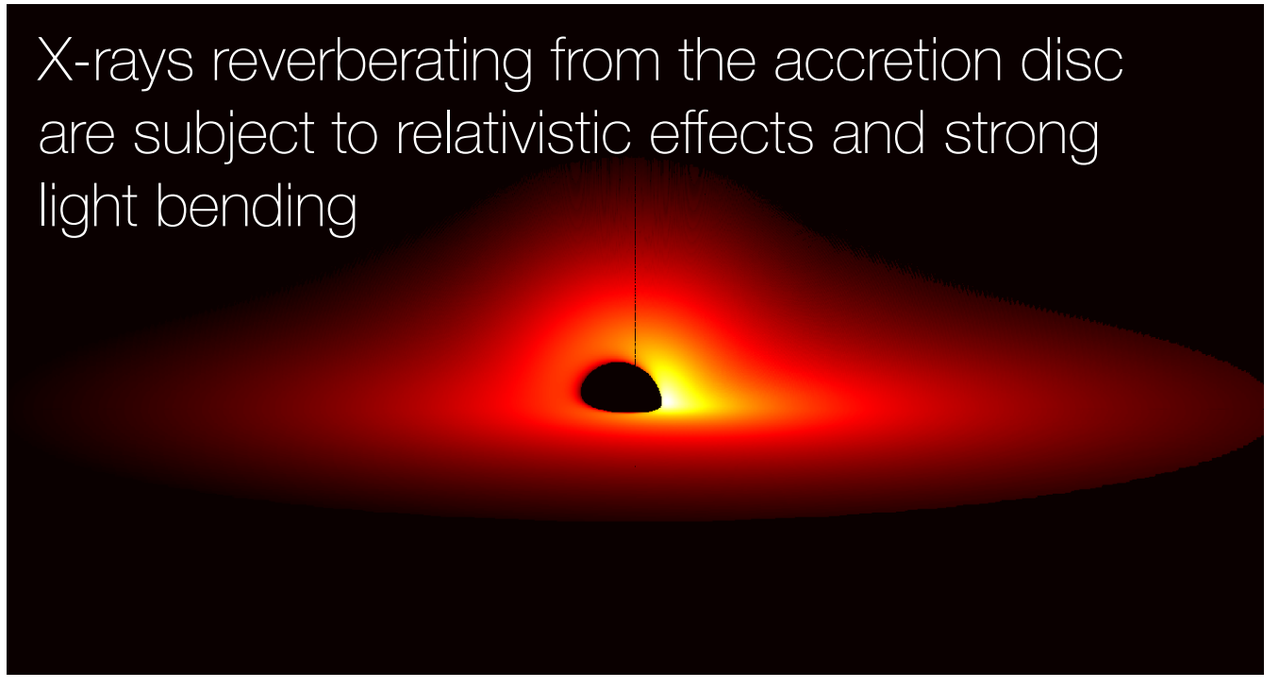
- Can we test the existence of the ISCO and probe the plunging region?

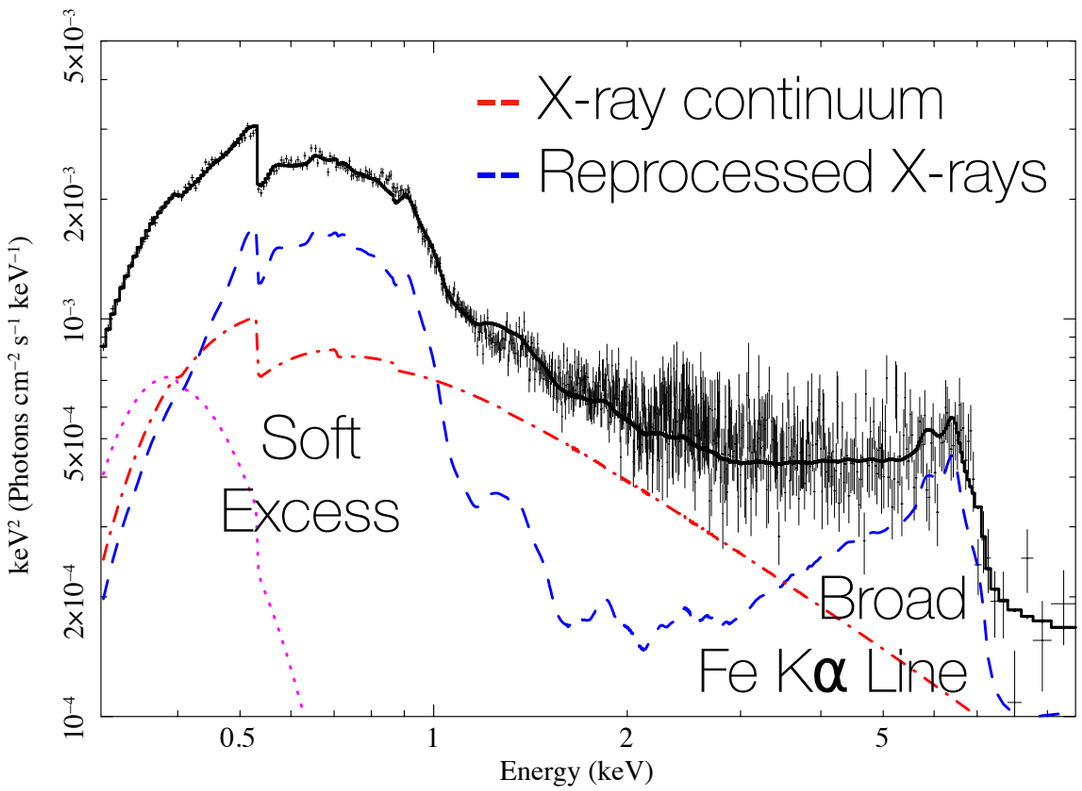
X-ray Reflection & Reverberation

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

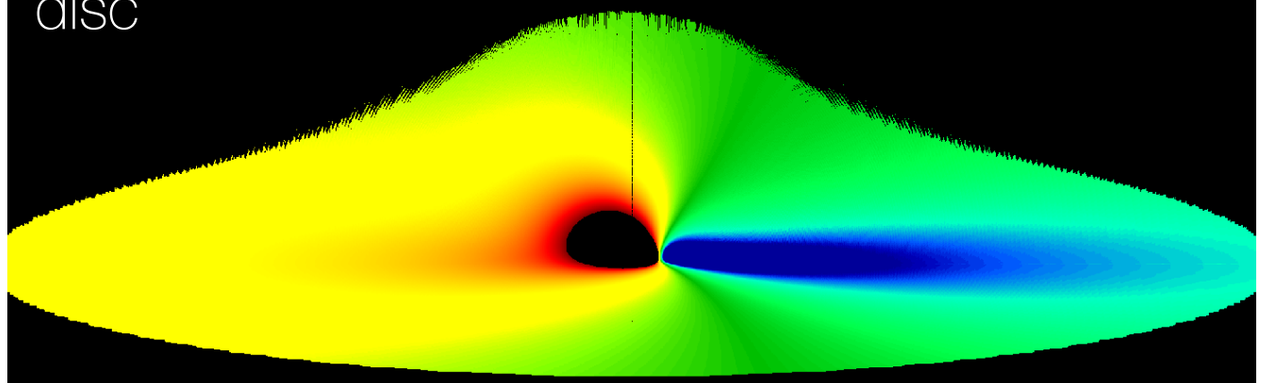


X-rays reverberating from the accretion disc are subject to relativistic effects and strong light bending





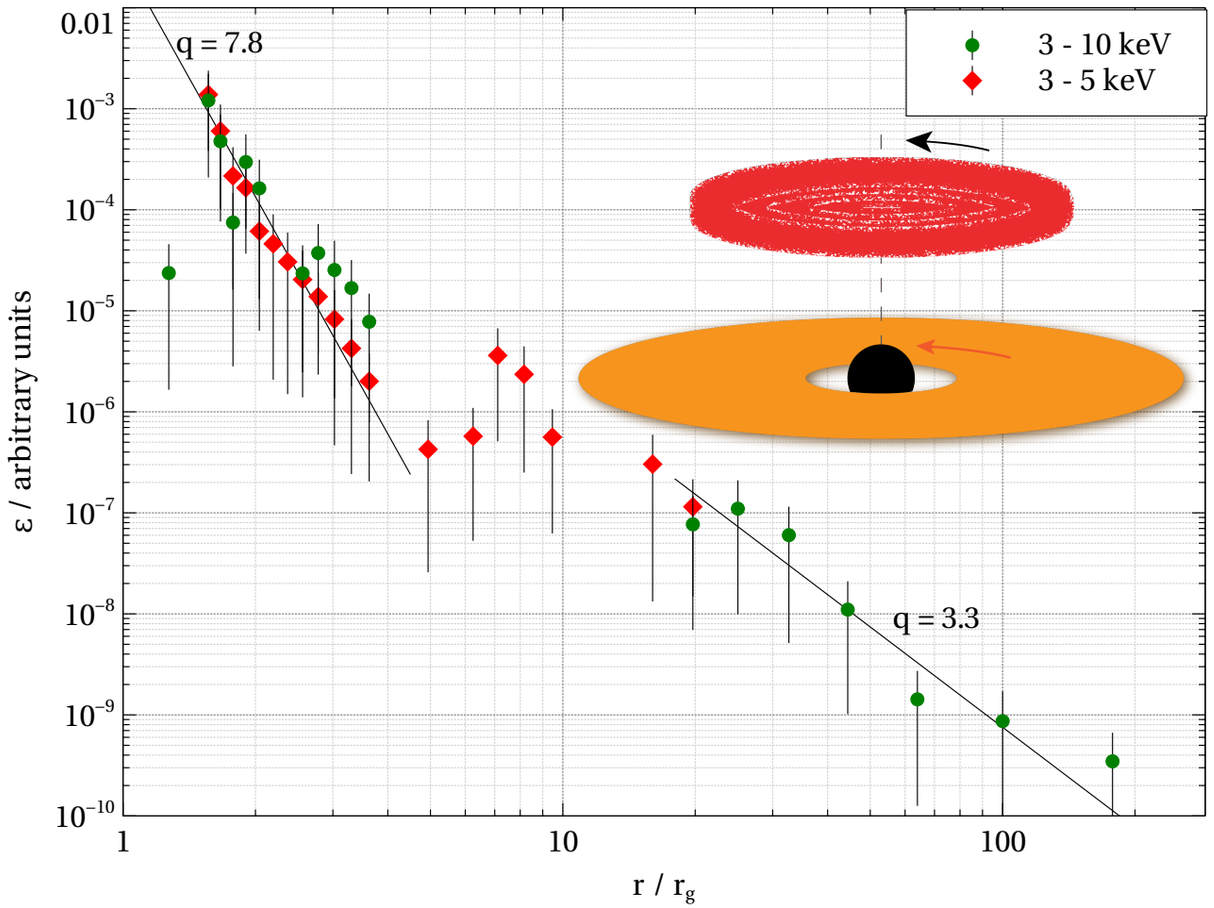
Energy shift is a function of location on the disc



Reverberation time shows distance from corona

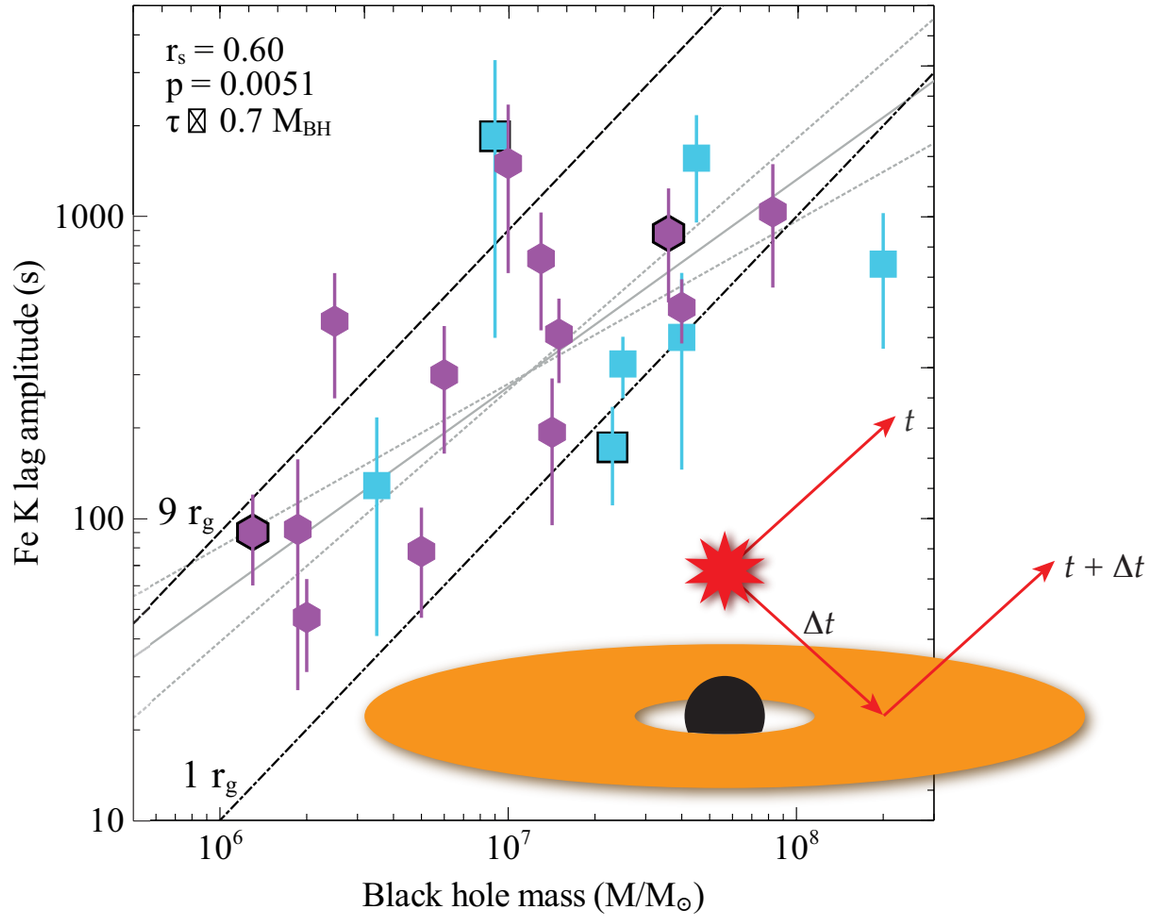
Mapping the Corona

Profile of red wing of line measures emissivity profile
Probes radial extent of corona



Wilkins & Fabian 2011, 2012
Wilkins & Gallo 2015

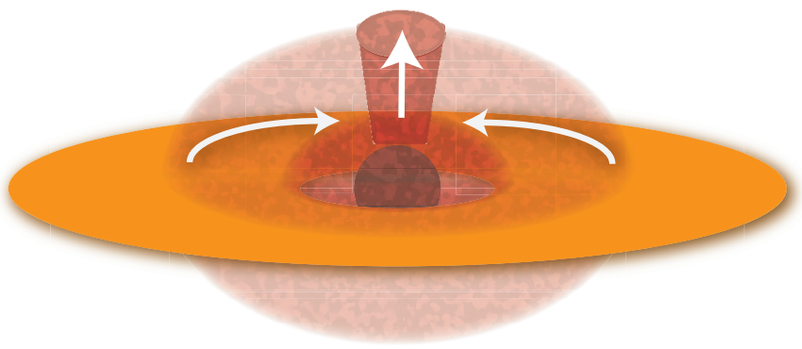
Reverberation time lag between continuum and reflection
Probes vertical scale height

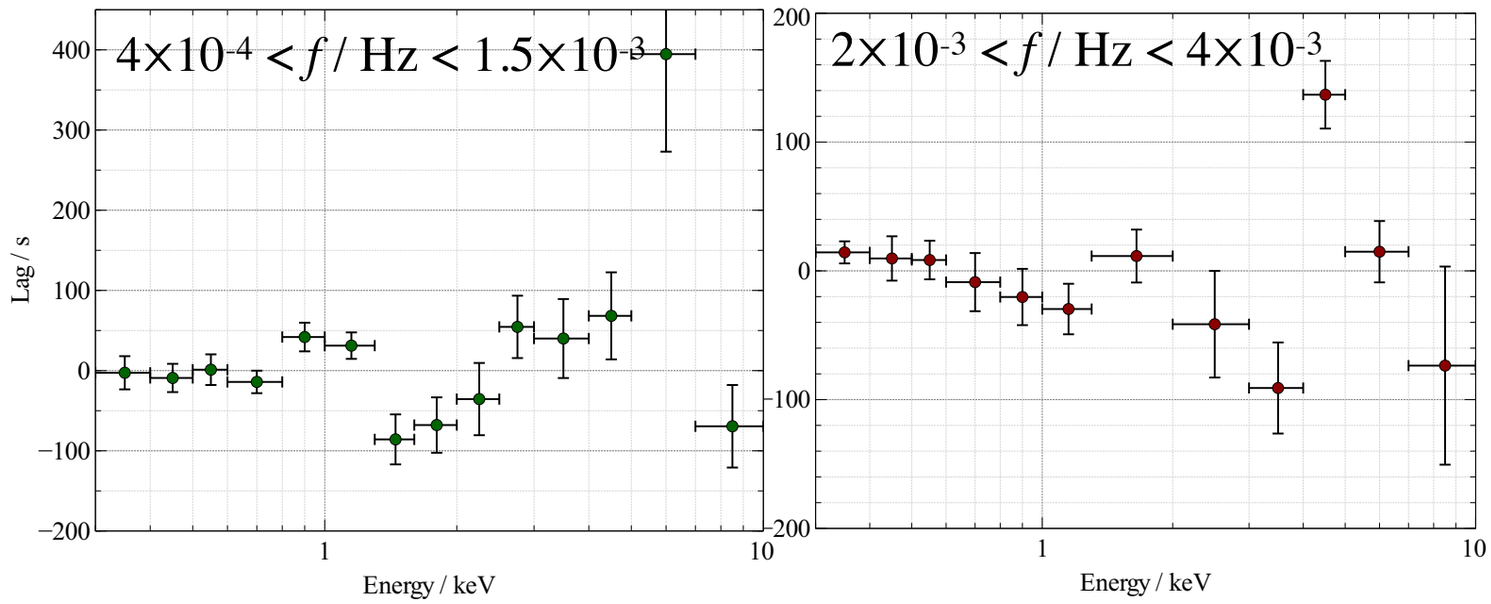


Wilkins & Fabian 2013, Uttley et al 2014
Kara et al 2016, De Marco et al 2013

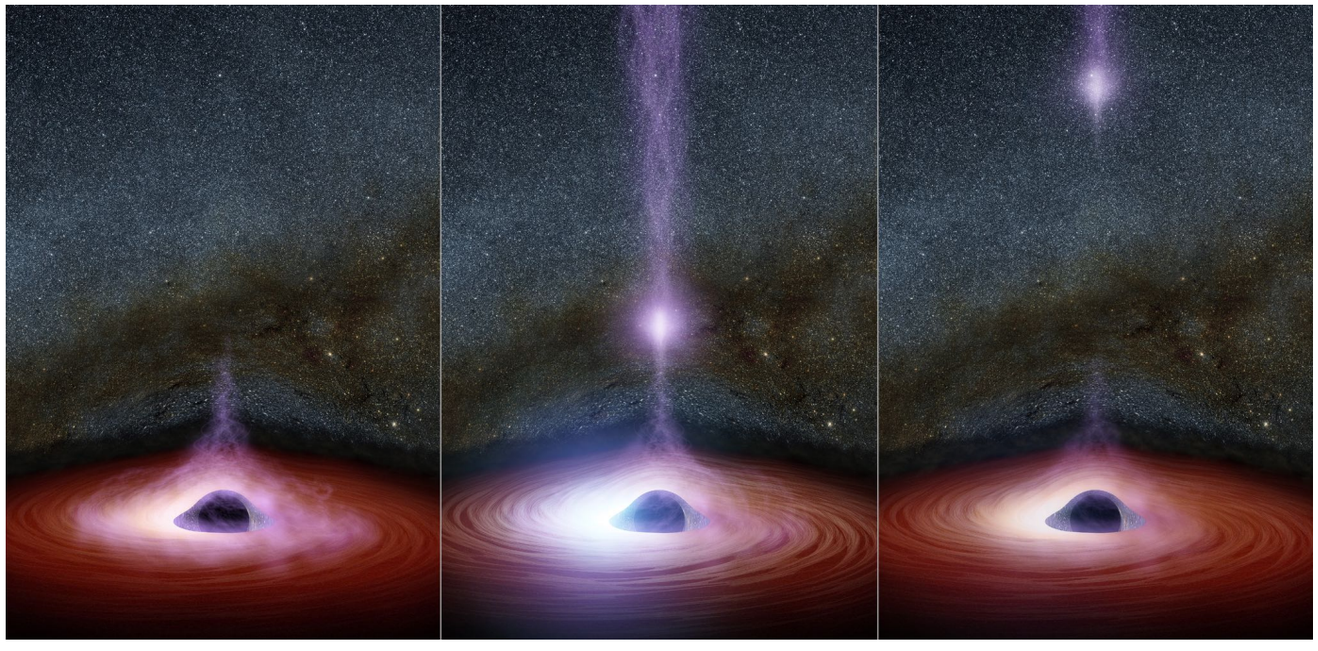
Mapping the Corona (2)

Relative response times of redshifted emission in red wing of line reveal structure of corona and propagation of fluctuations





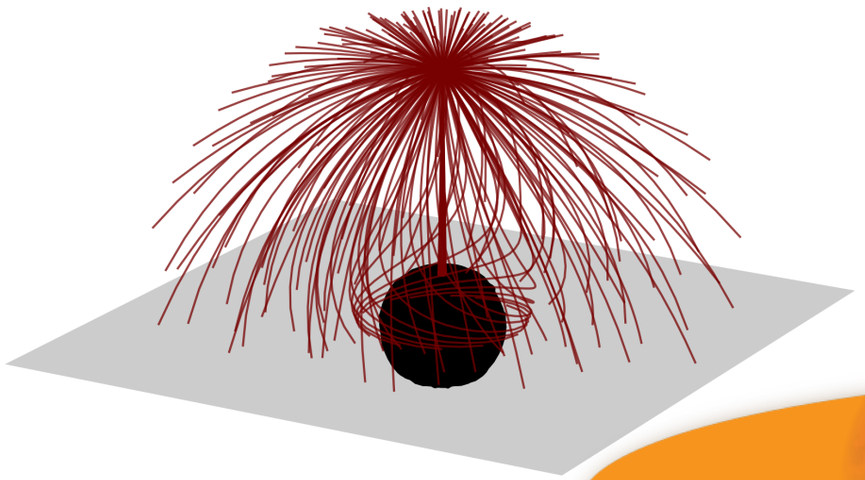
The corona is dynamic
Evolves with luminosity, flares



Wilkins & Gallo 2015
Wilkins et al. 2016, 2017
Kara et al. 2019, Alston et al. 2019

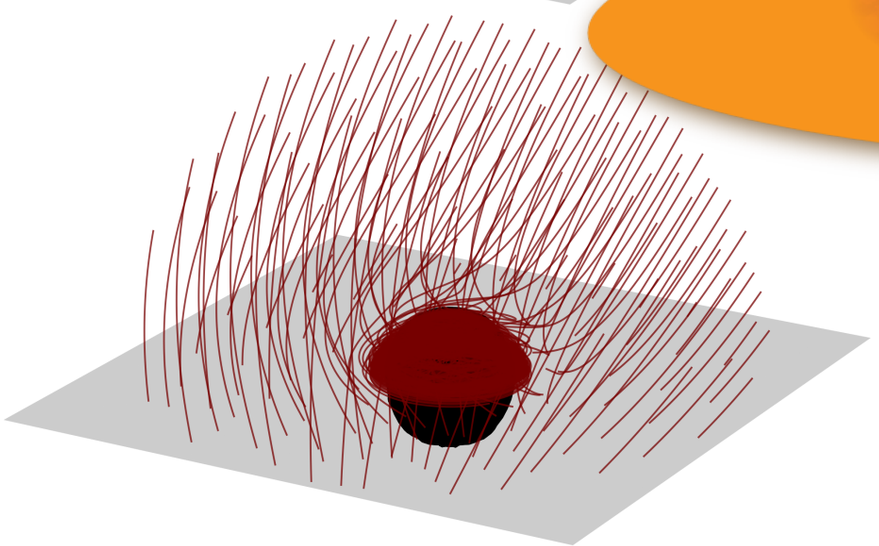
Modelling X-ray Reverberation

- 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)

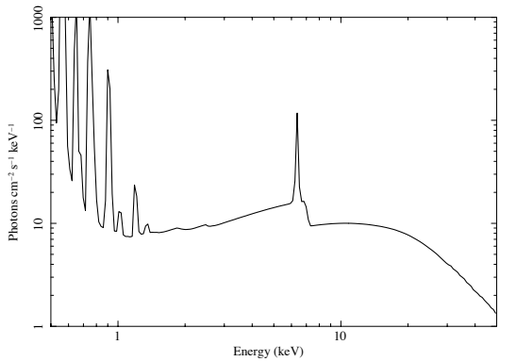


Rays start from either point source or extended corona with propagating fluctuations

Record redshifted photon energy and time at observer

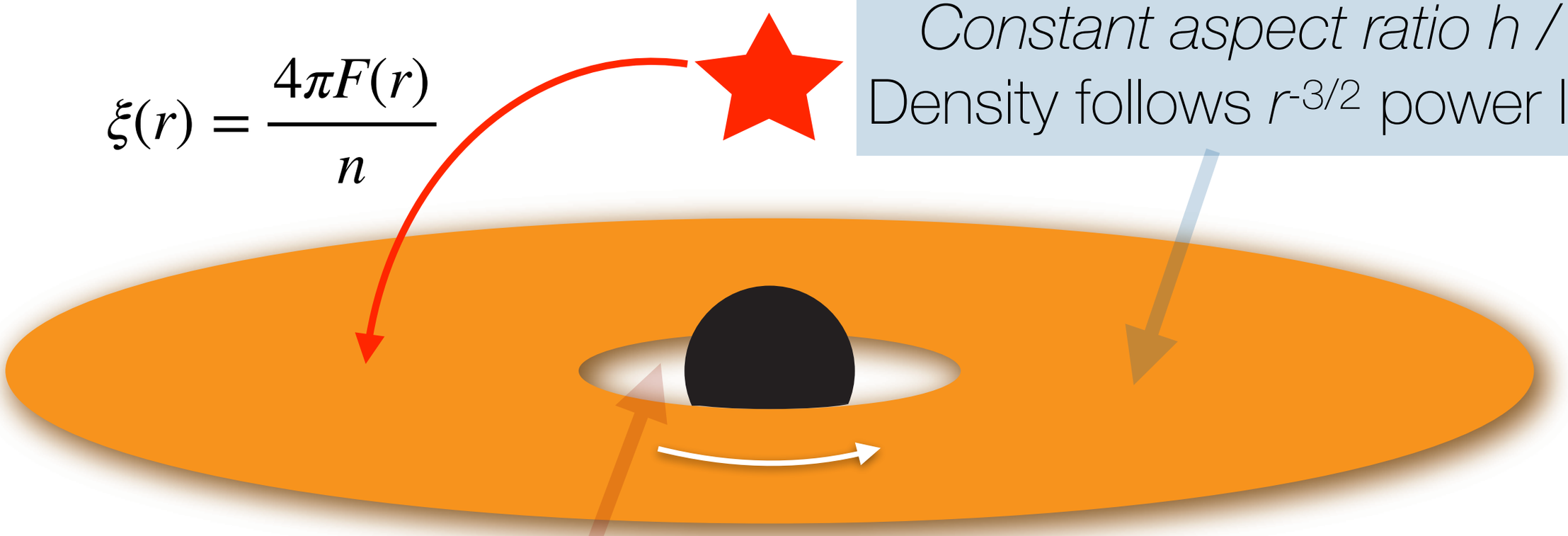


XILLVER reflection spectrum from illuminated patch on disc according to density & ionisation profile of disc



Reverberation from the Plunging Region

$$\xi(r) = \frac{4\pi F(r)}{n}$$



(Relativistic) Keplerian orbits
Constant aspect ratio h / r
Density follows $r^{-3/2}$ power law

Plunging orbit - conserve angular momentum from ISCO
Density follows mass conservation

$$r\Sigma u^r = \frac{\dot{m}}{2\pi}$$ For mass continuity

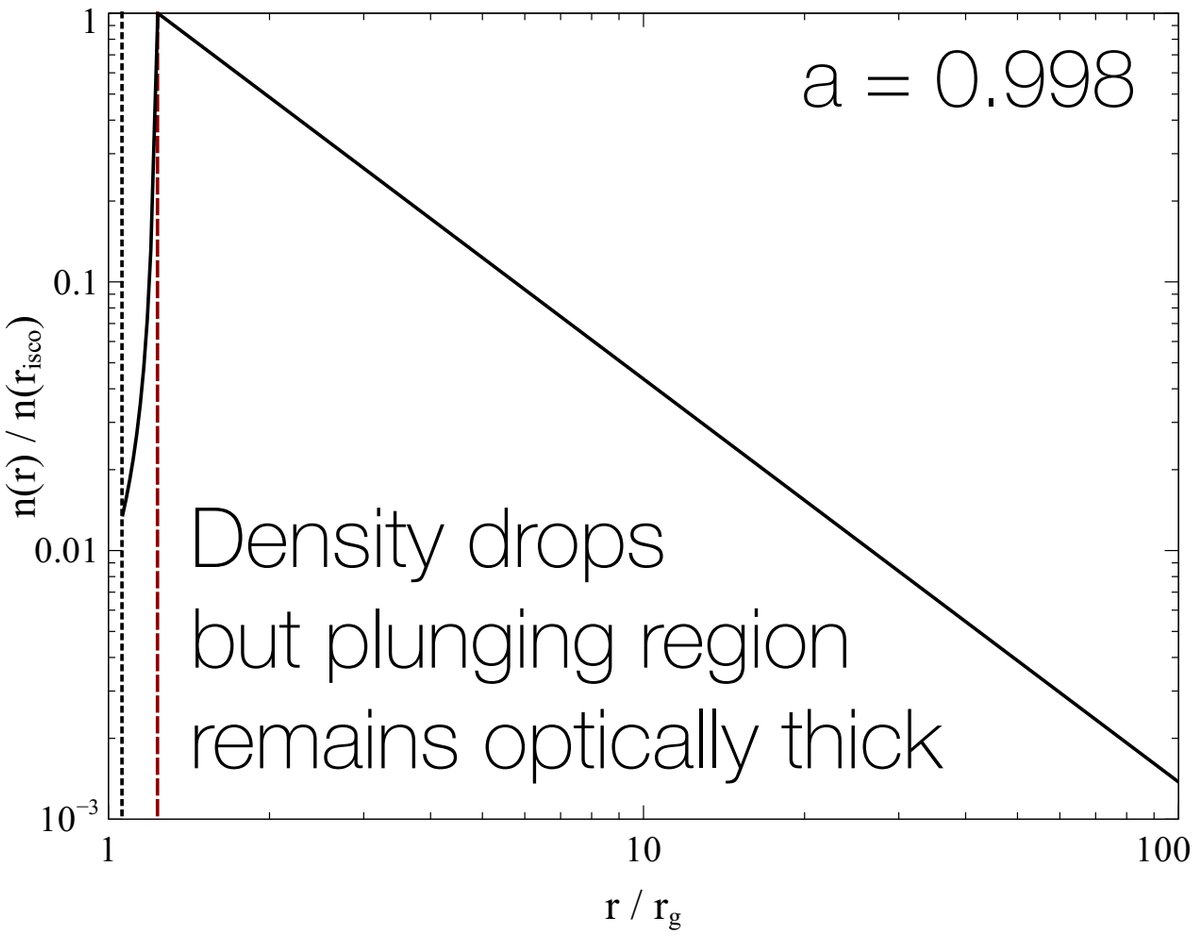
$$\rho(r) \propto \frac{1}{r^2 u^r}$$ Constant *h/r*

What happens to material across the ISCO?

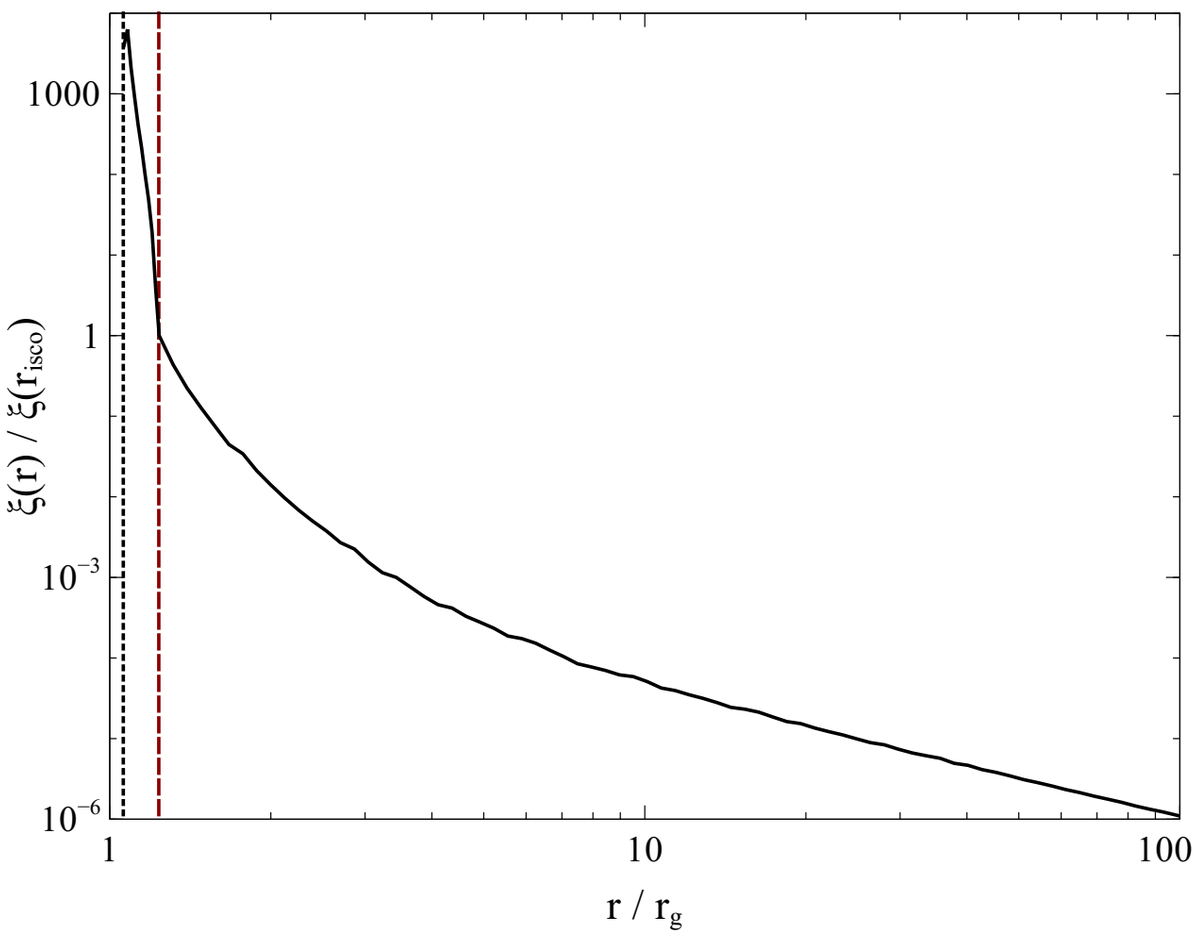
Velocity increases as material enters plunging orbit, density drops

Strongly irradiated by compact central corona, so ionisation increases

Density



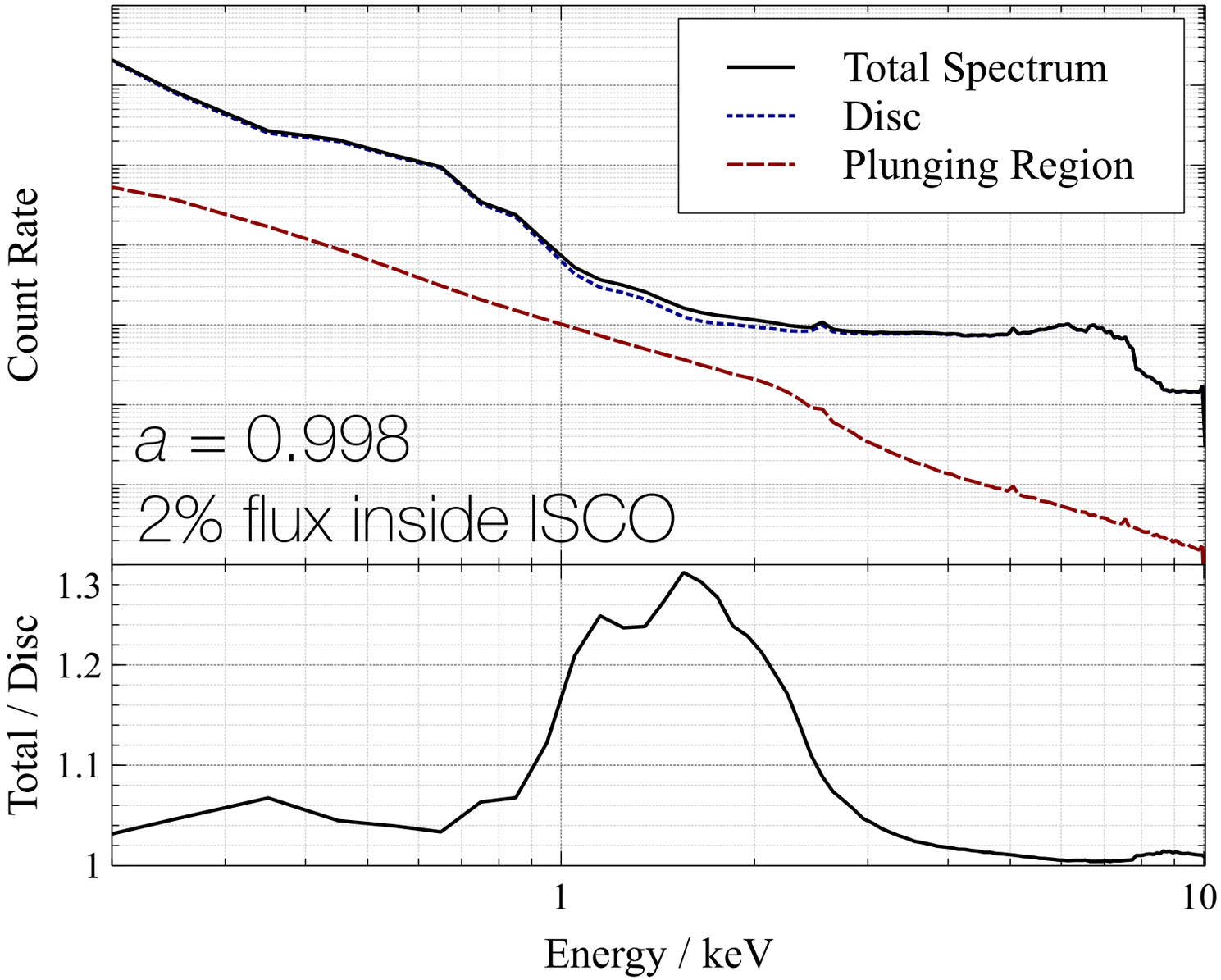
Ionisation



Reynolds & Begelman 1997, Wilkins *et al.* 2019

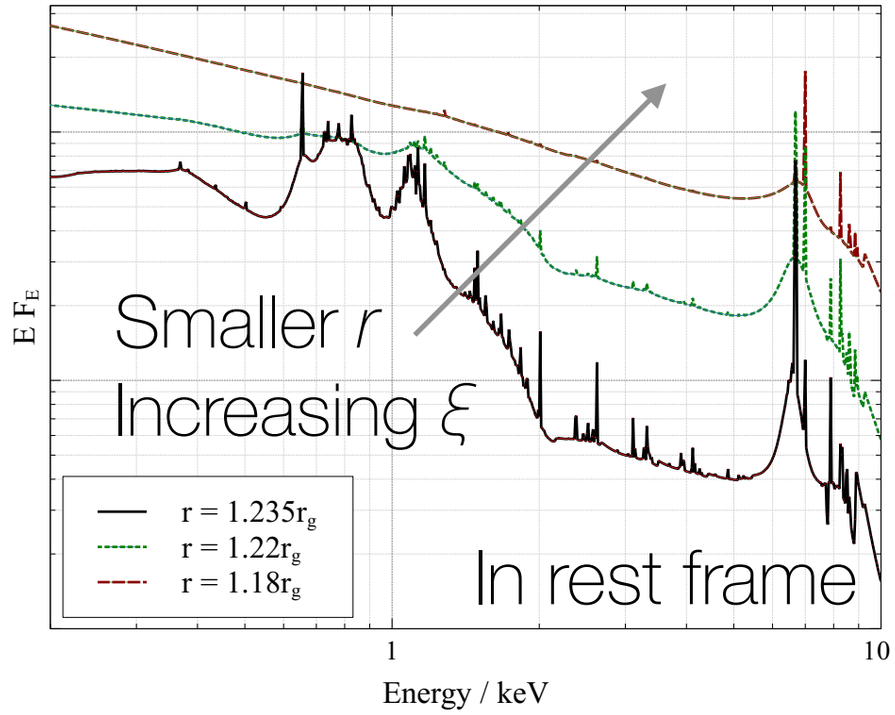
Emission from Beyond the ISCO

Looking for redshifted line emission from highly ionised plunging region



Excess emission in redshifted wing of iron K line

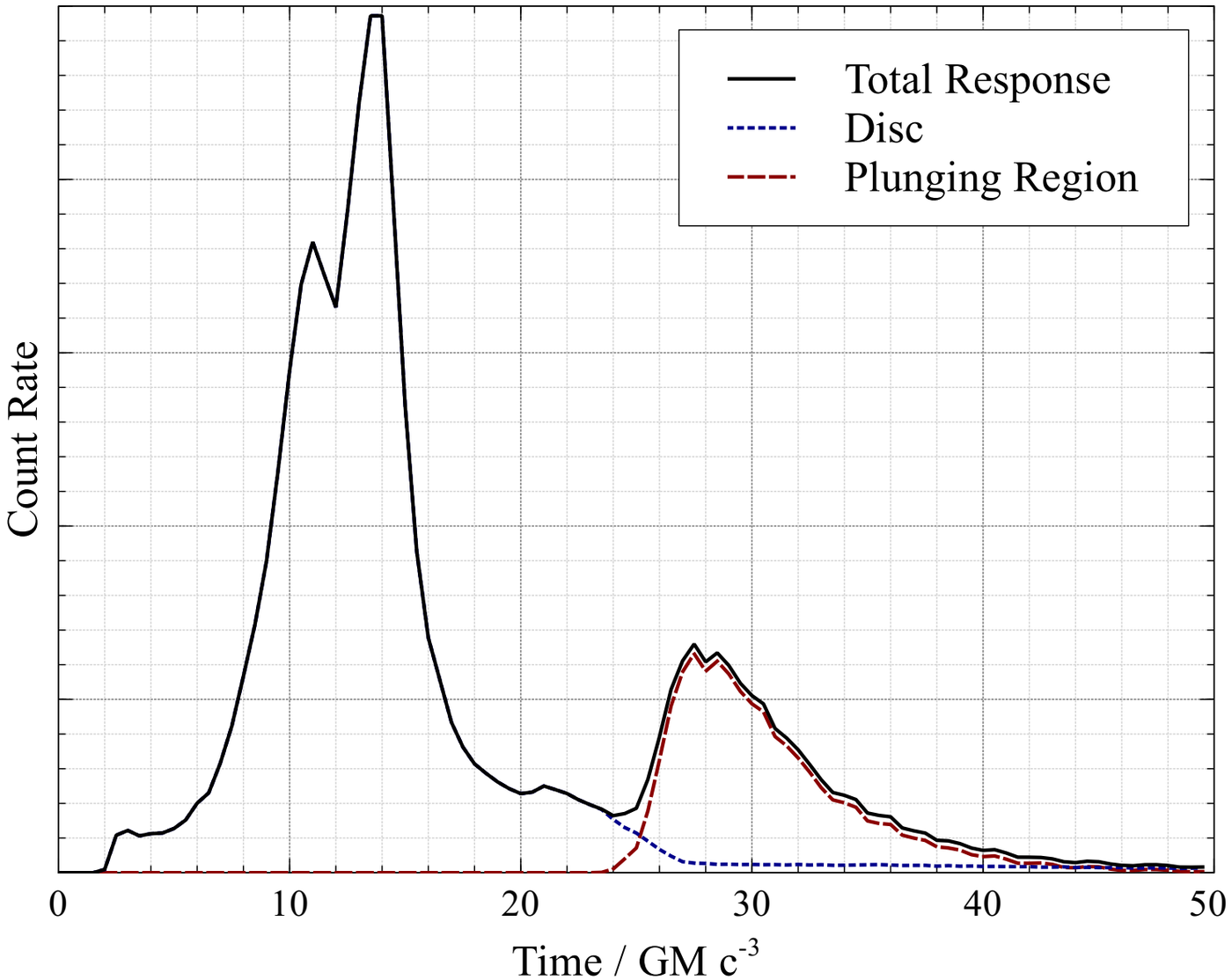
Higher ionisation species closer to black hole



Wilkins *et al.* 2019

Disentangling with Spectral Timing

Separating the redshifted plunging region emission by its response time



Ionised Fe lines from plunging region redshifted to 1-2keV band

Photon passage is delayed in the strong gravitational field close to the black hole, forming a secondary peak

$a = 0.998$, 1-2 keV

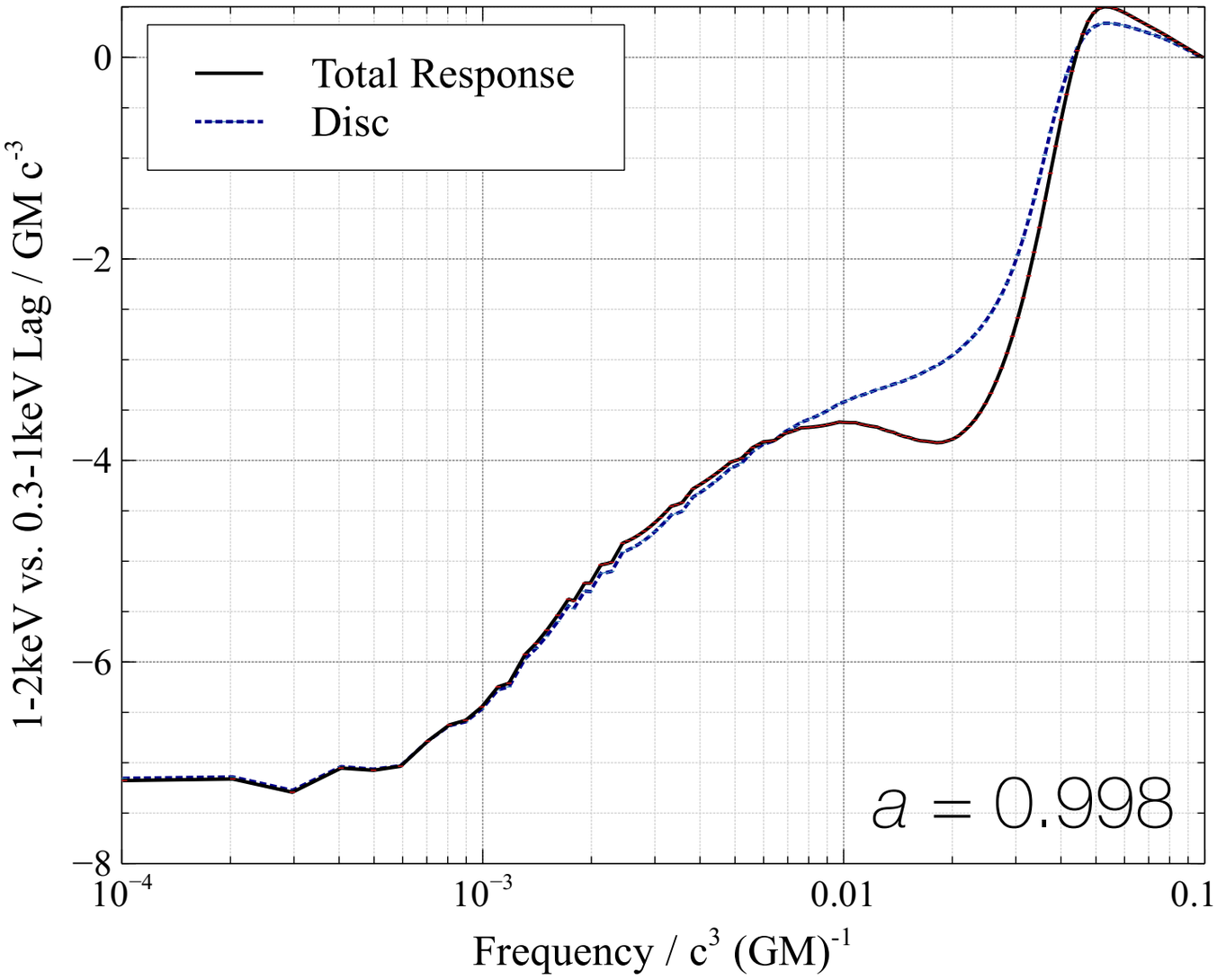
Wilkins *et al.* 2019

GMc^{-3} = Light crossing time over $1r_g$

Observing the Plunging Region

Stochastic variability – measure the response function in the Fourier domain

Lag as a function of Fourier frequency (slow and fast components of the variability)



See reverberation from the plunging region in the high frequency reverberation lags

Can detect the plunging region with 20% uncertainty at in at least 3 frequency bins between 2-6x10^{-3} Hz for $10^6\,M_\odot$ BH

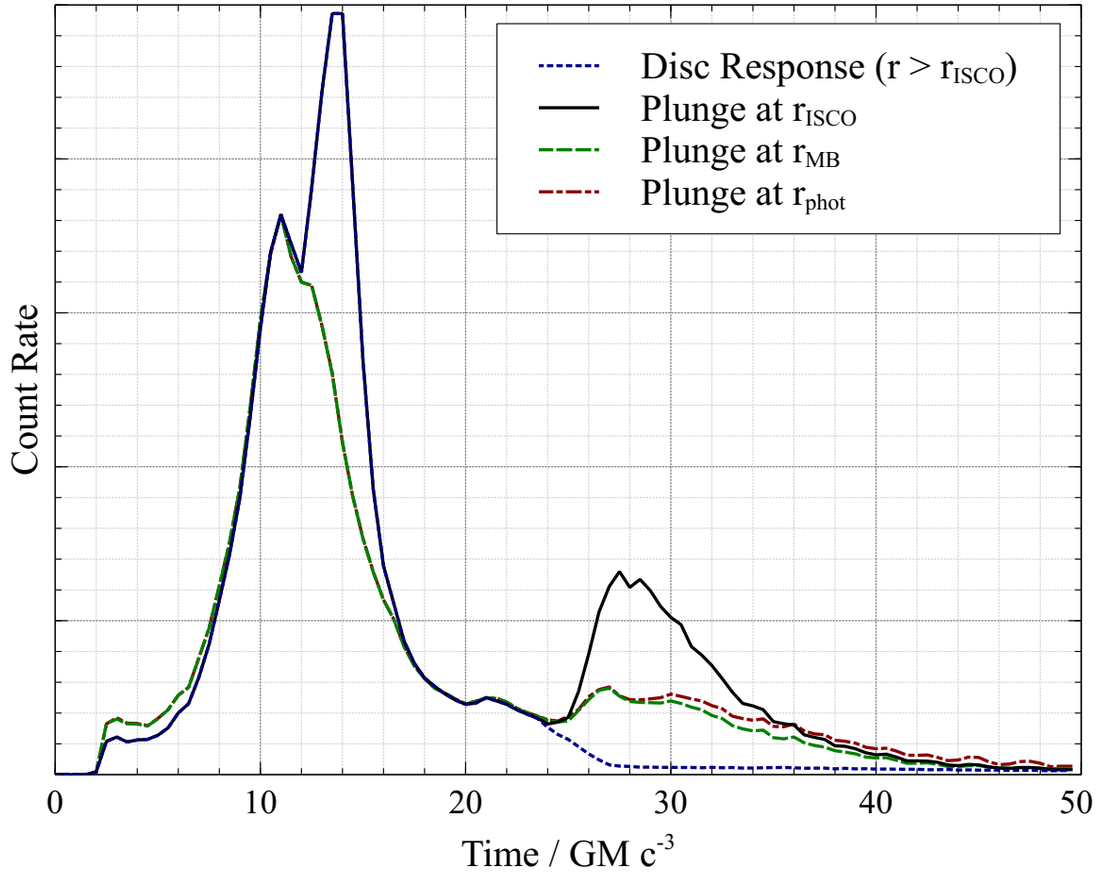
Wilkins *et al.* 2019

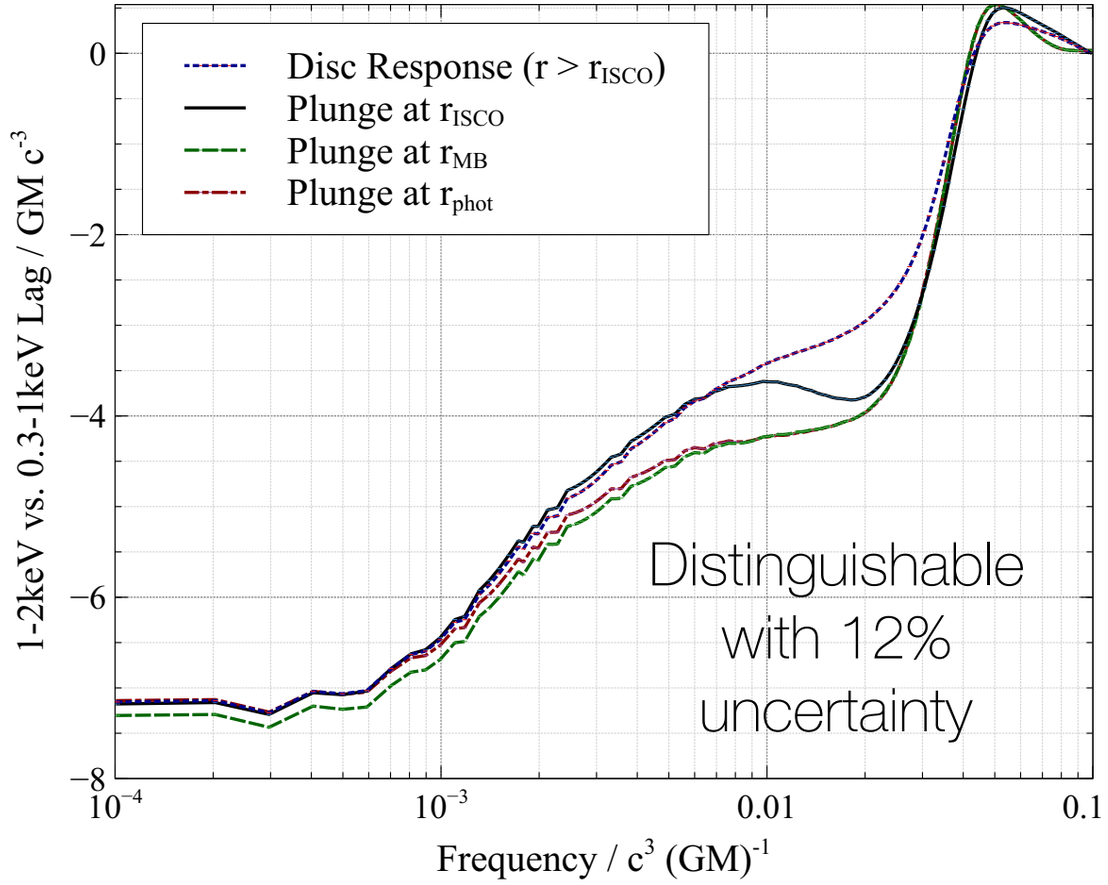
$c^{-3}\,(GM)^{-1}$= 1 cycle per light crossing time over $1r_g$

Is the ISCO really there?

- ISCO is a prediction of general relativity
- Need to be able to probe the dynamics of material in the plunging region
- What if material could maintain circular orbits beyond the ISCO?

  a = 0.998, 1-2 keV



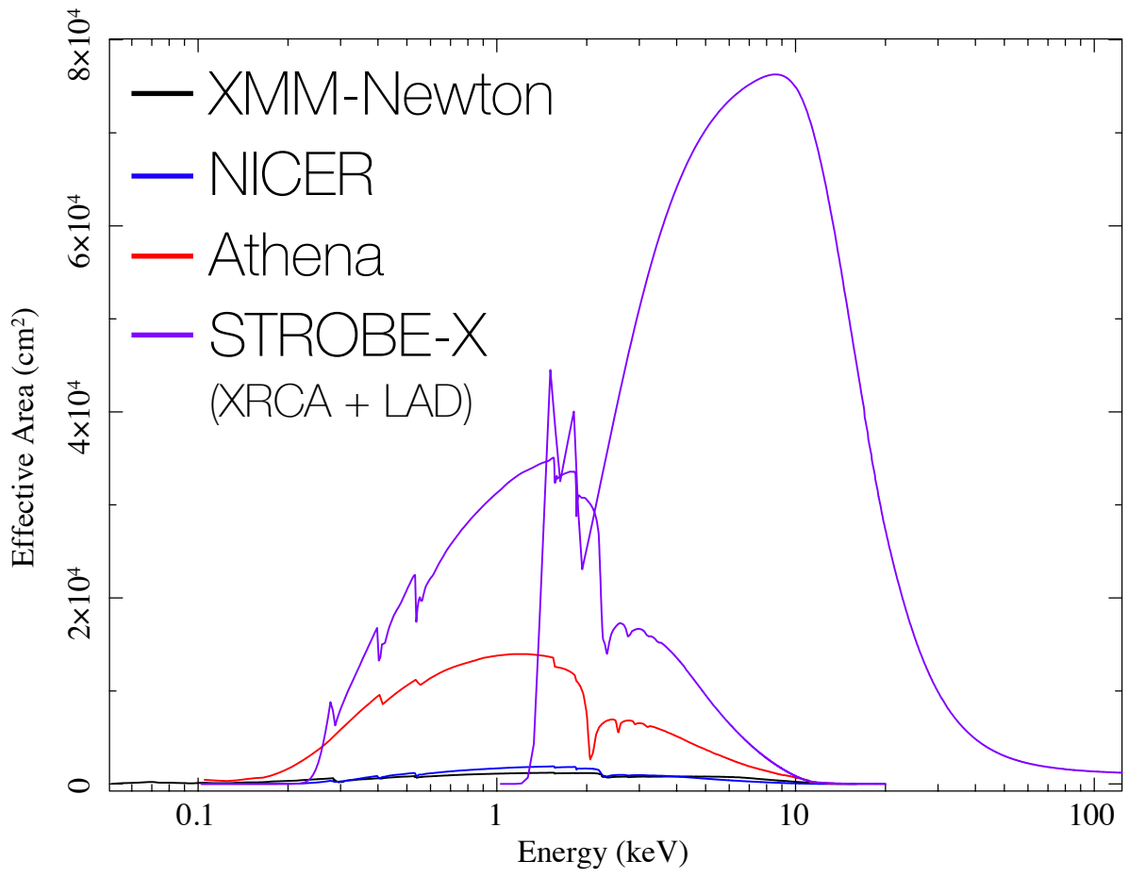


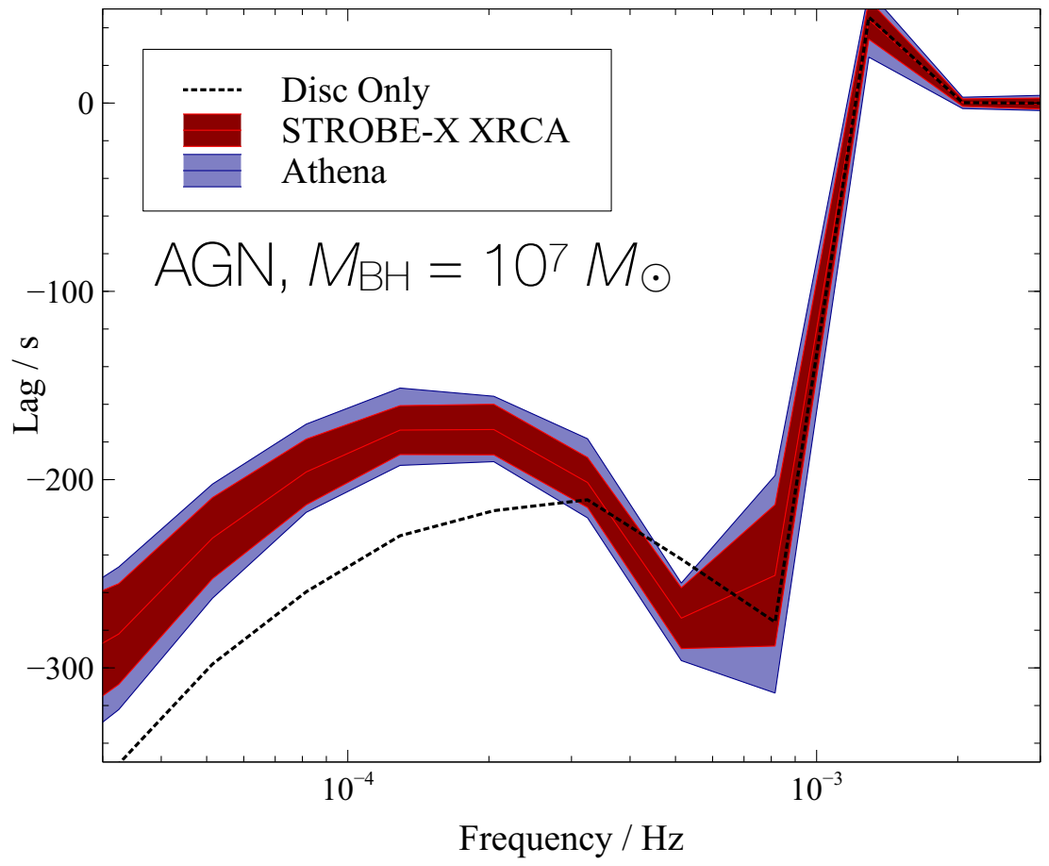
Wilkins *et al.* in prep

What are the prospects?

Large collecting area, high throughput X-ray missions open a new discovery space

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

Summary

dan.wilkins@stanford.edu

- X-ray reflection and reverberation reveals structure right down to the innermost stable orbit and even the event horizon

- X-ray reverberation from the plunging region, inside the innermost stable orbit, is distinguished by the highly redshifted emission from highly ionised material, delayed with respect to the primary continuum and disc response

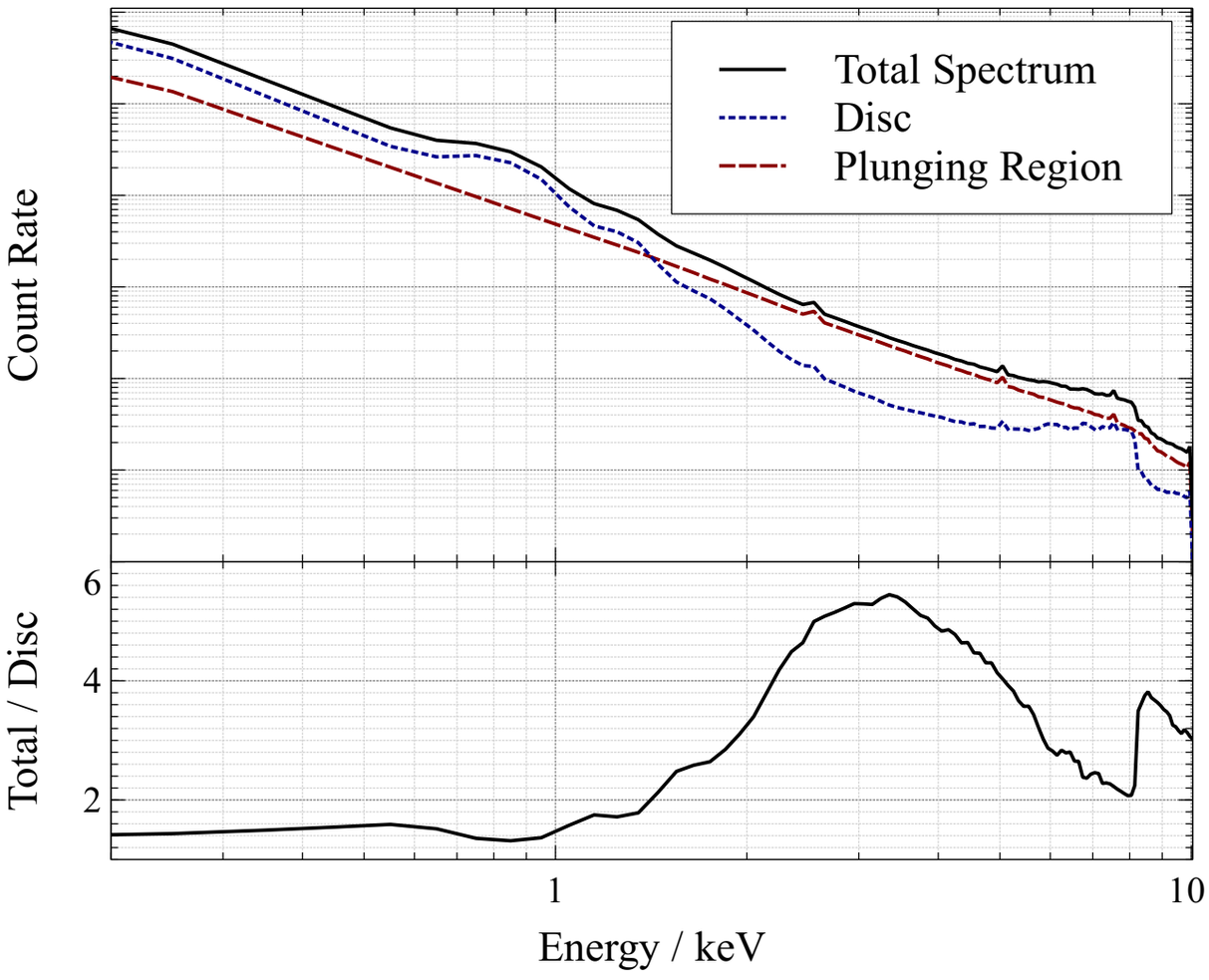
- Future X-ray missions will be able to detect emission from inside the ISCO in AGN and probe its dynamics, presenting a new test of GR and revealing what happens to material in its final moments as it plunges into a black hole

Backup Slides

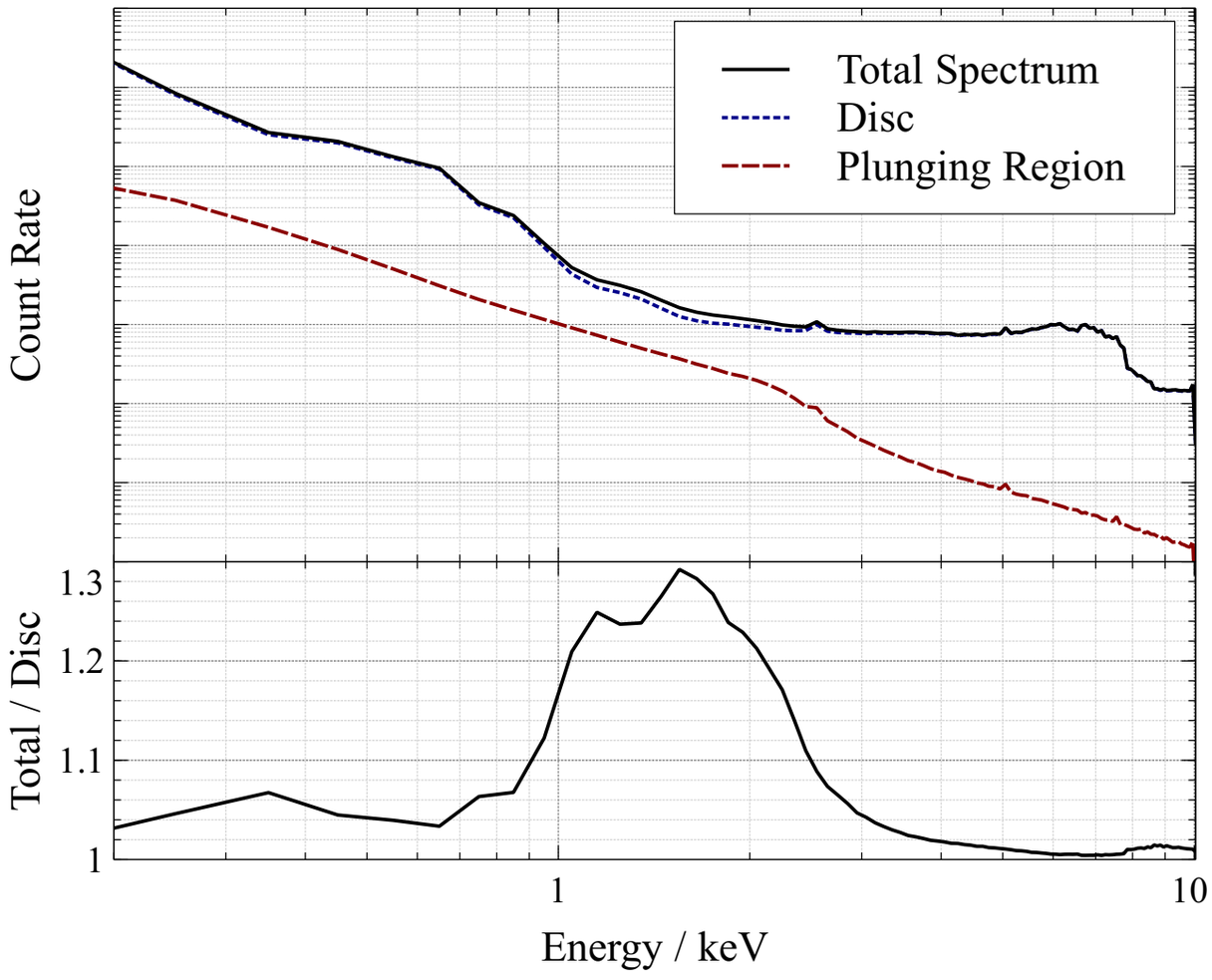
Emission from Beyond the ISCO

Looking for redshifted line emission from highly ionised iron in plunging region

a = 0, 30% flux inside ISCO



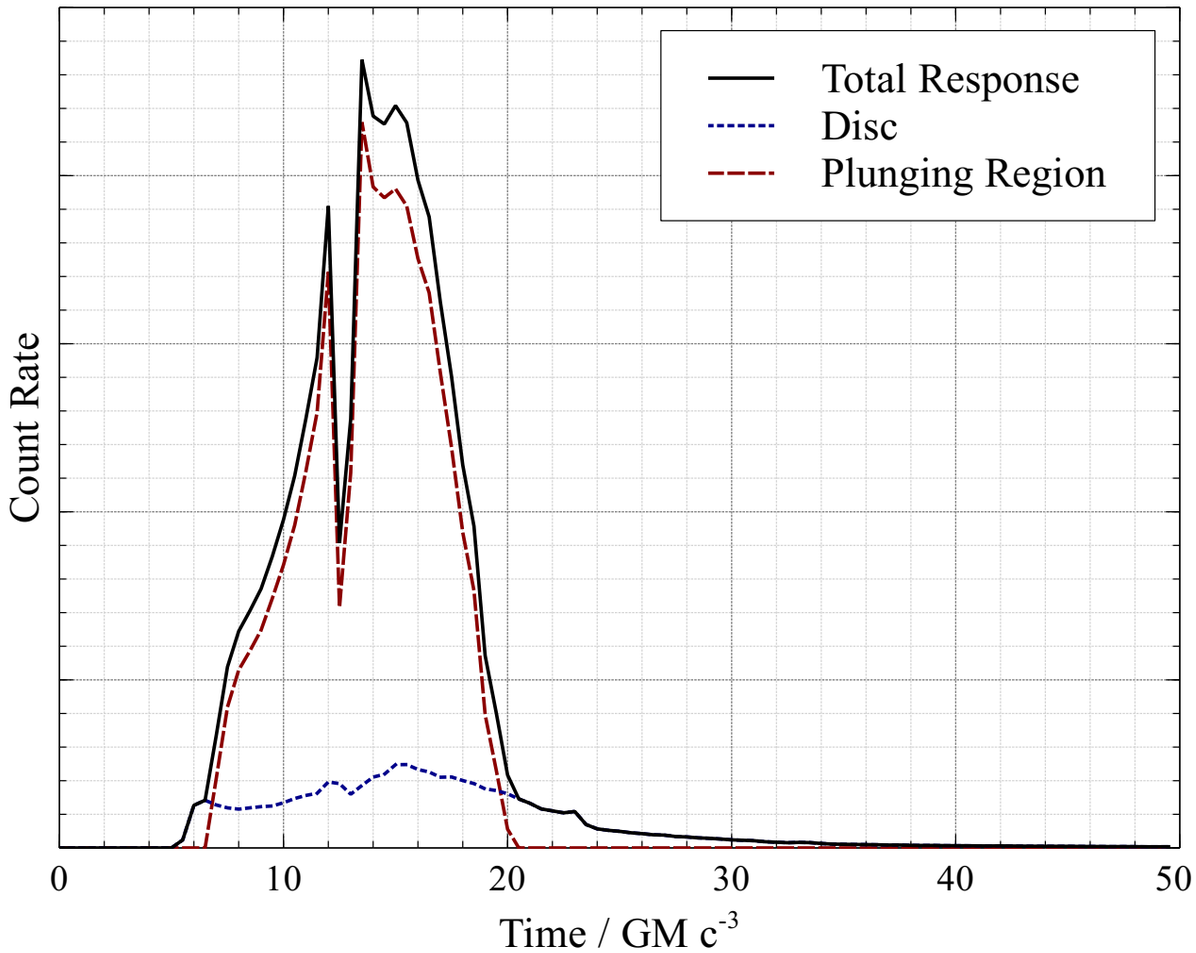
a = 0.998, 2% flux inside ISCO



Wilkins *et al.* in prep

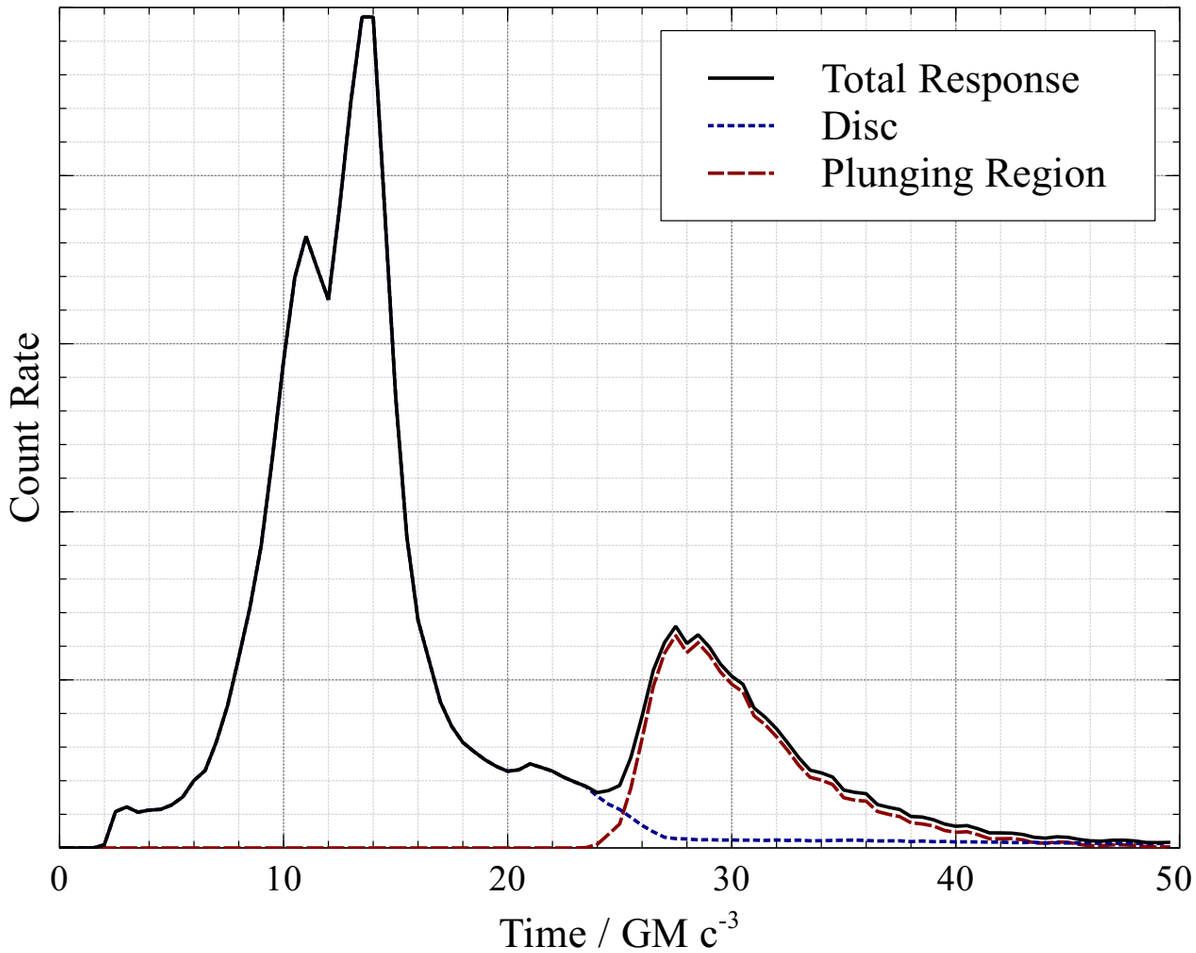
Energy Resolved Temporal Response

a = 0, 2-4 keV



‘False continuum’ from plunging region delayed wrt primary continuum

a = 0.998, 1-2 keV

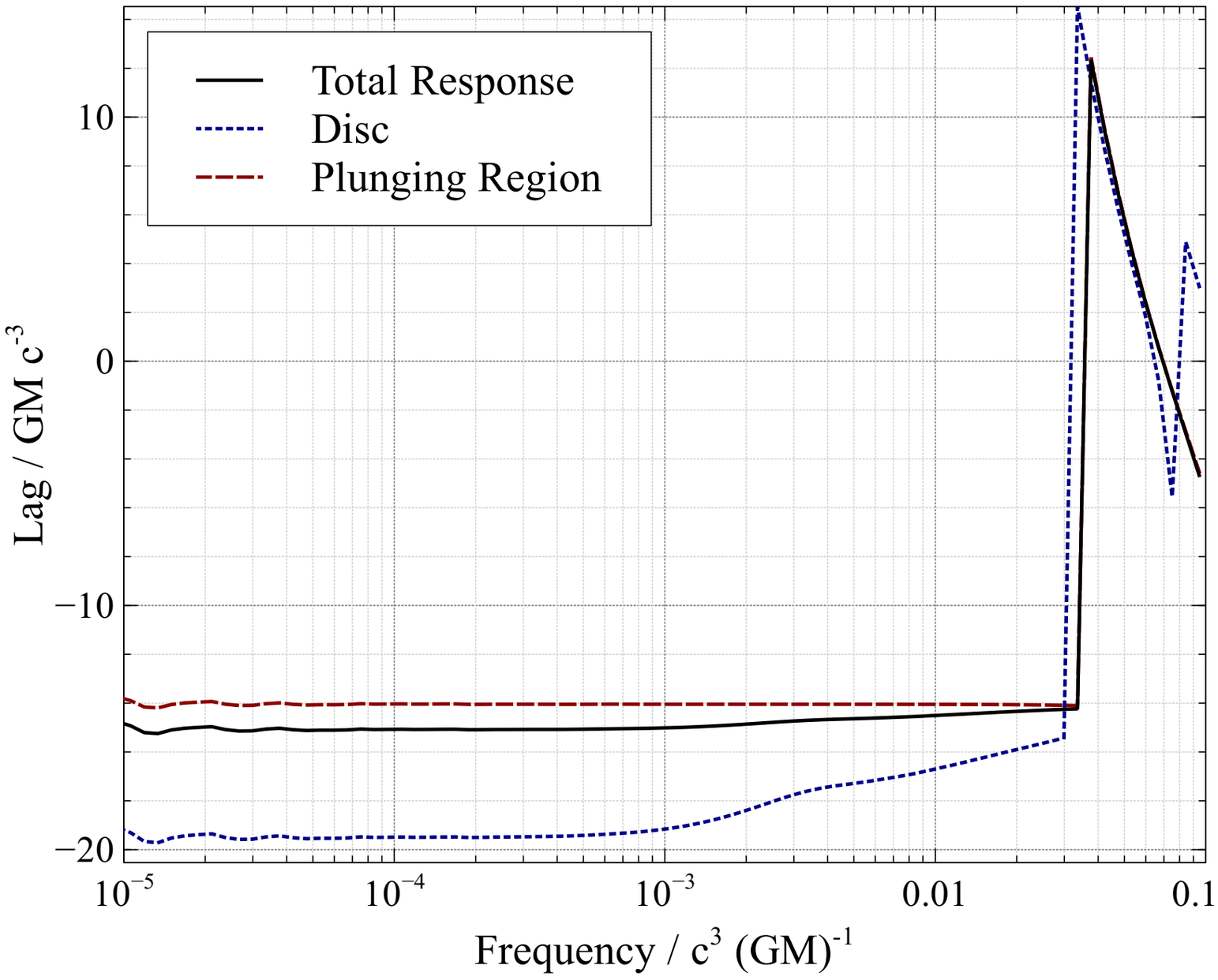


Ionised Fe lines from plunging region redshifted to 1-2keV band form delayed secondary peak

Wilkins *et al.* in prep

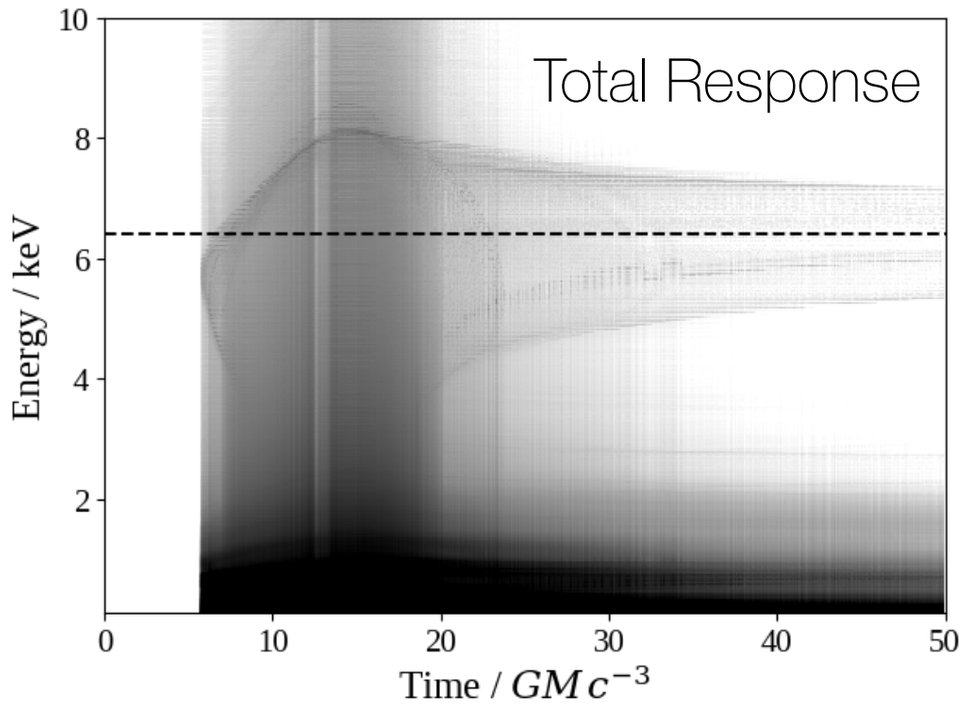
Low Spin Plunging Region Detection

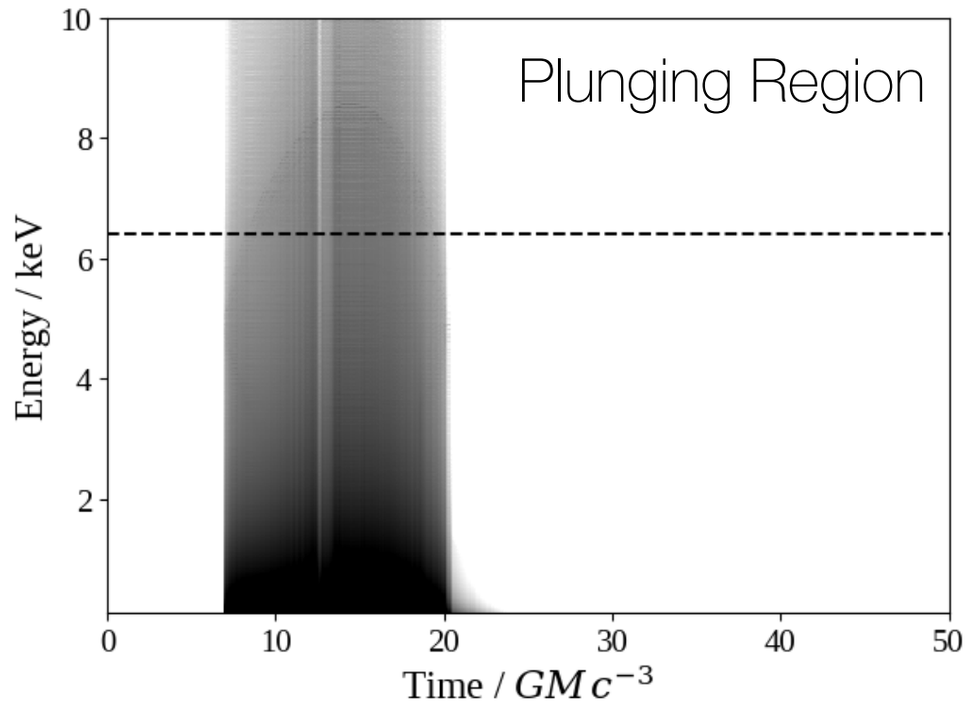
a = 0, 2-4 keV



Plunging Region Response

a = 0





a = 0.998