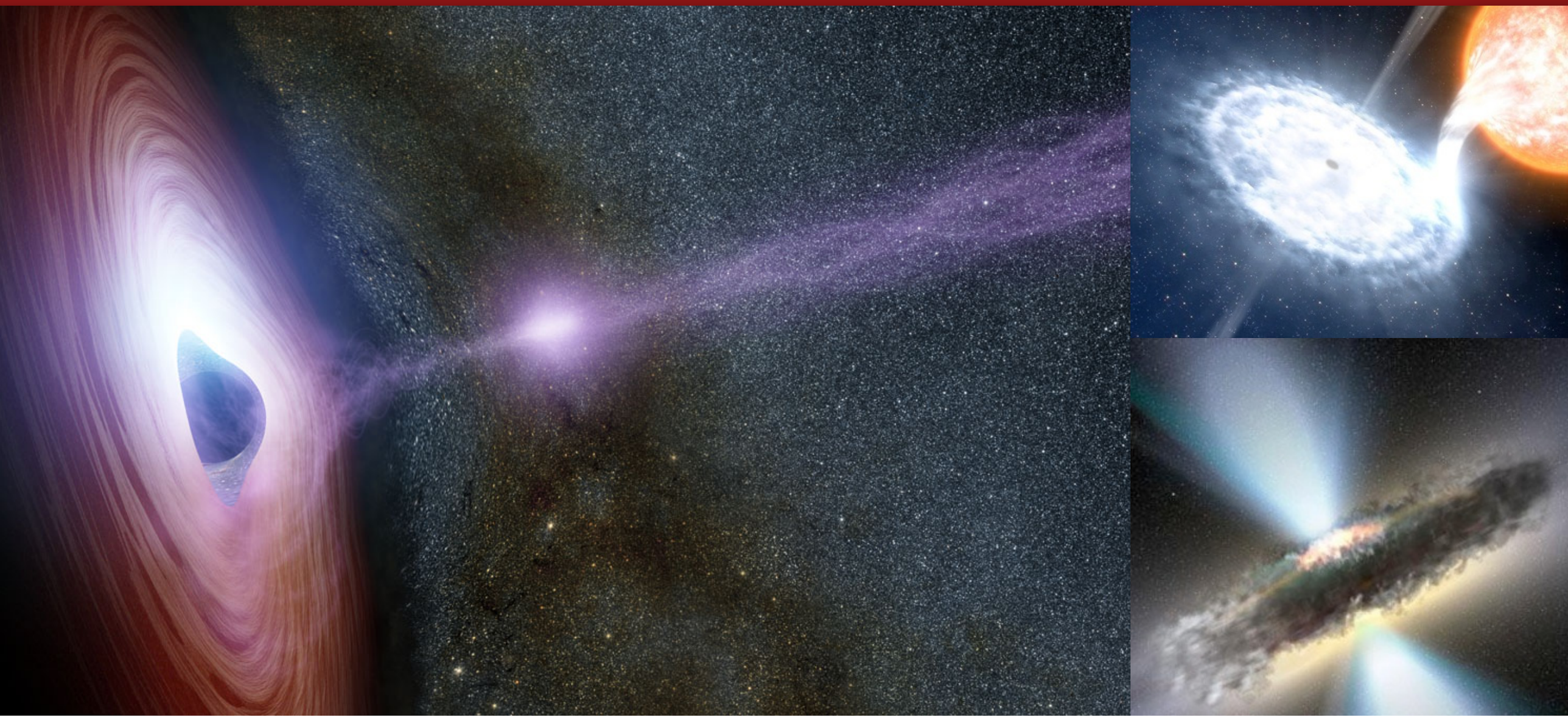


Venturing Beyond the ISCO with X-ray Reverberation

Dan Wilkins
Einstein Fellow
Kavli Institute for Particle Astrophysics & Cosmology, Stanford University

The Big Questions

- How does matter falling into black holes power some of the brightest objects in the Universe?

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

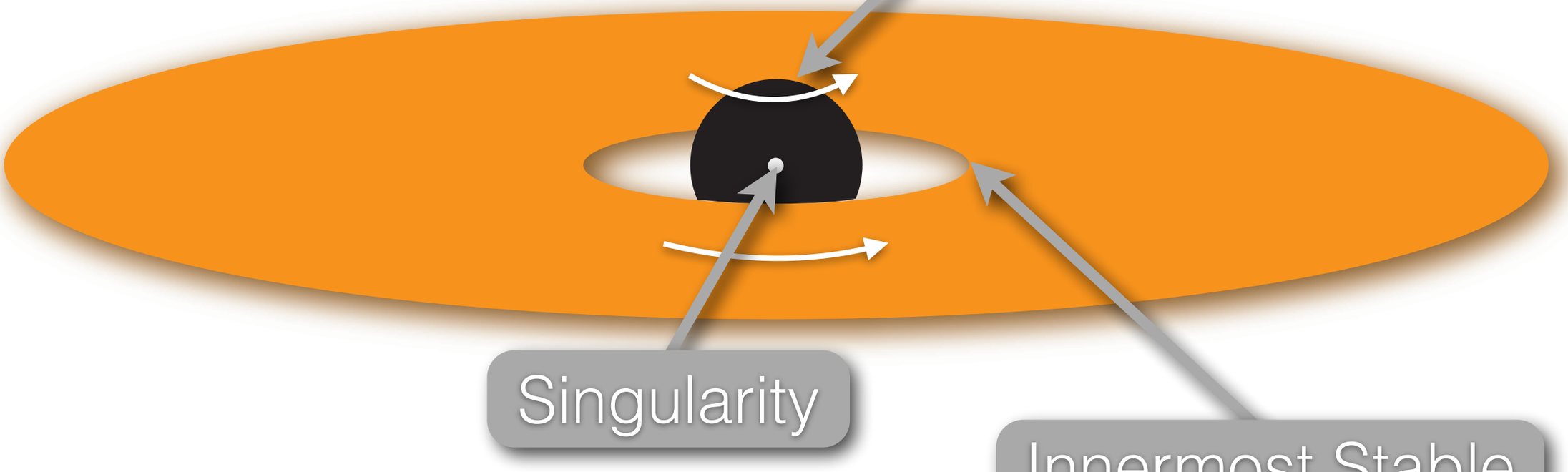
- What is the extreme environment like immediately outside the event horizon of a black hole? Does General Relativity provide the correct description?

Anatomy of an Accreting Black Hole

Spin parameter $a = \dfrac{J}{Mc}$

$$a = 0, r_{\mathrm{H}} = 2\frac{GM}{c^2}$$

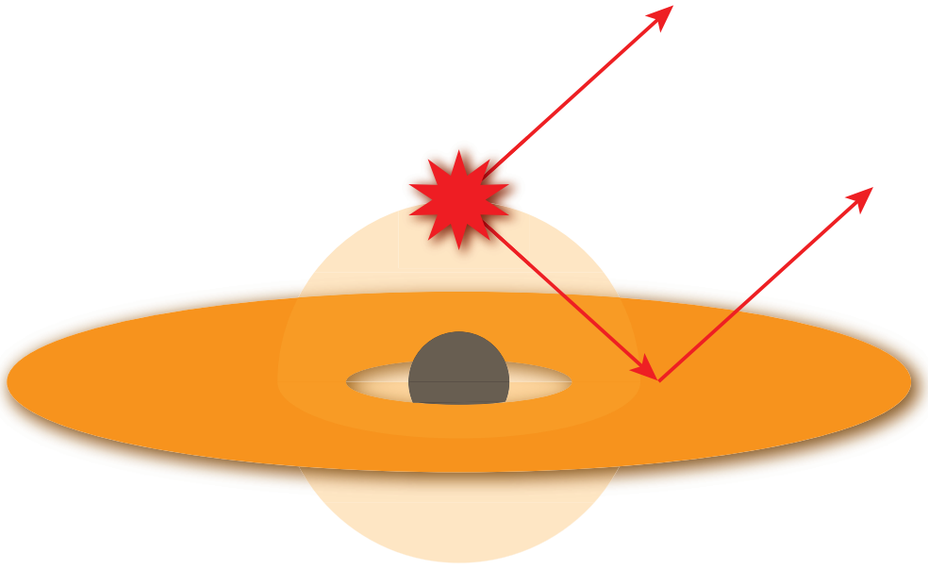
$$a = 0.998, r_{\mathrm{H}} \sim \frac{GM}{c^2}$$

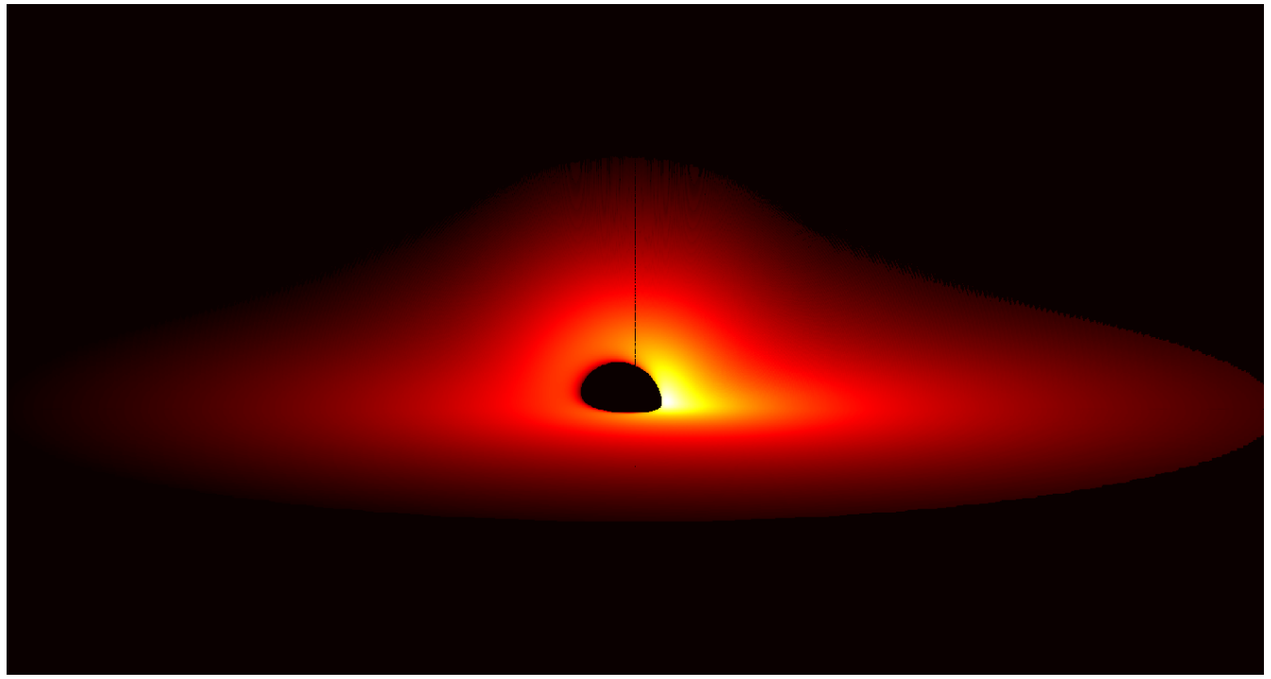


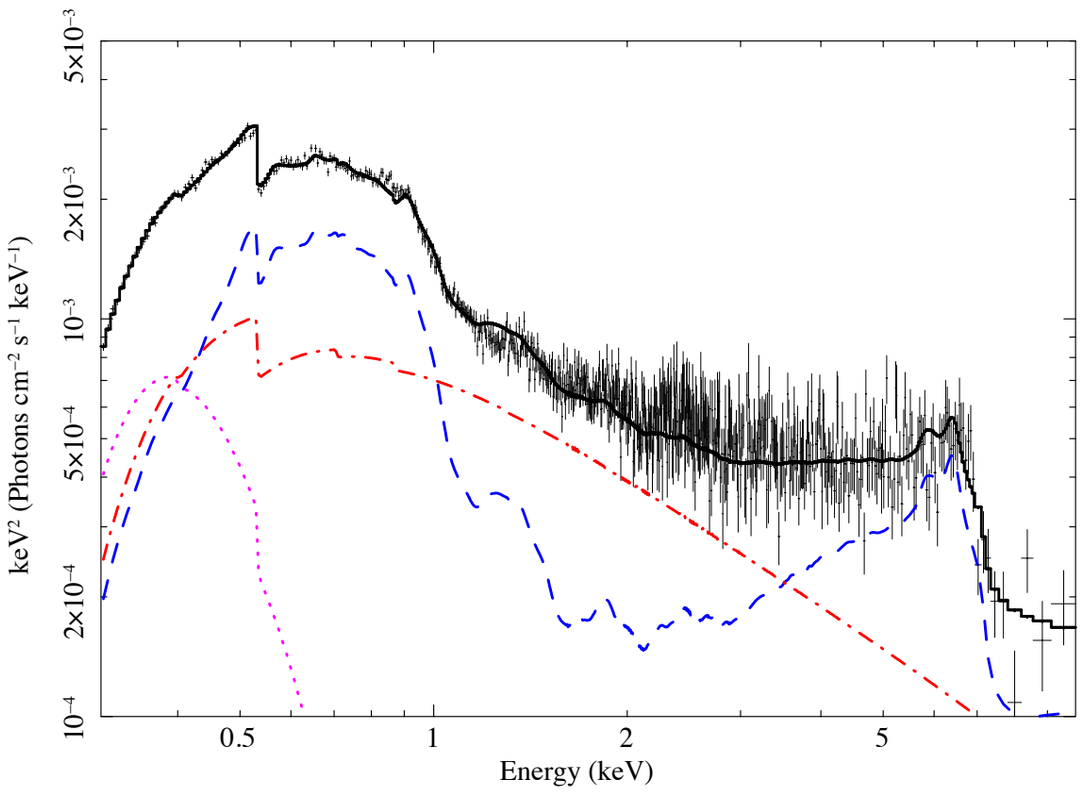
$$a = 0, r_{\mathrm{ISCO}} = 6\frac{GM}{c^2}$$

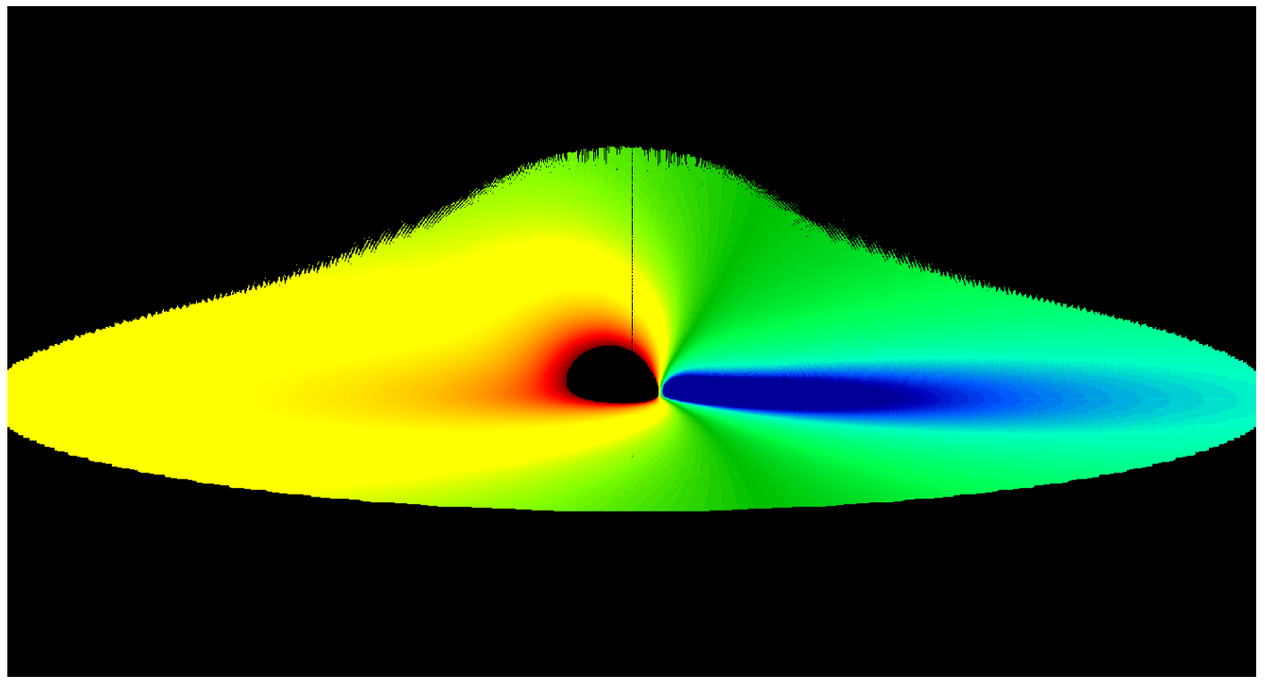
$$a = 0.998, r_{\mathrm{ISCO}} = 1.235\frac{GM}{c^2}$$

X-ray Reflection & Reverberation

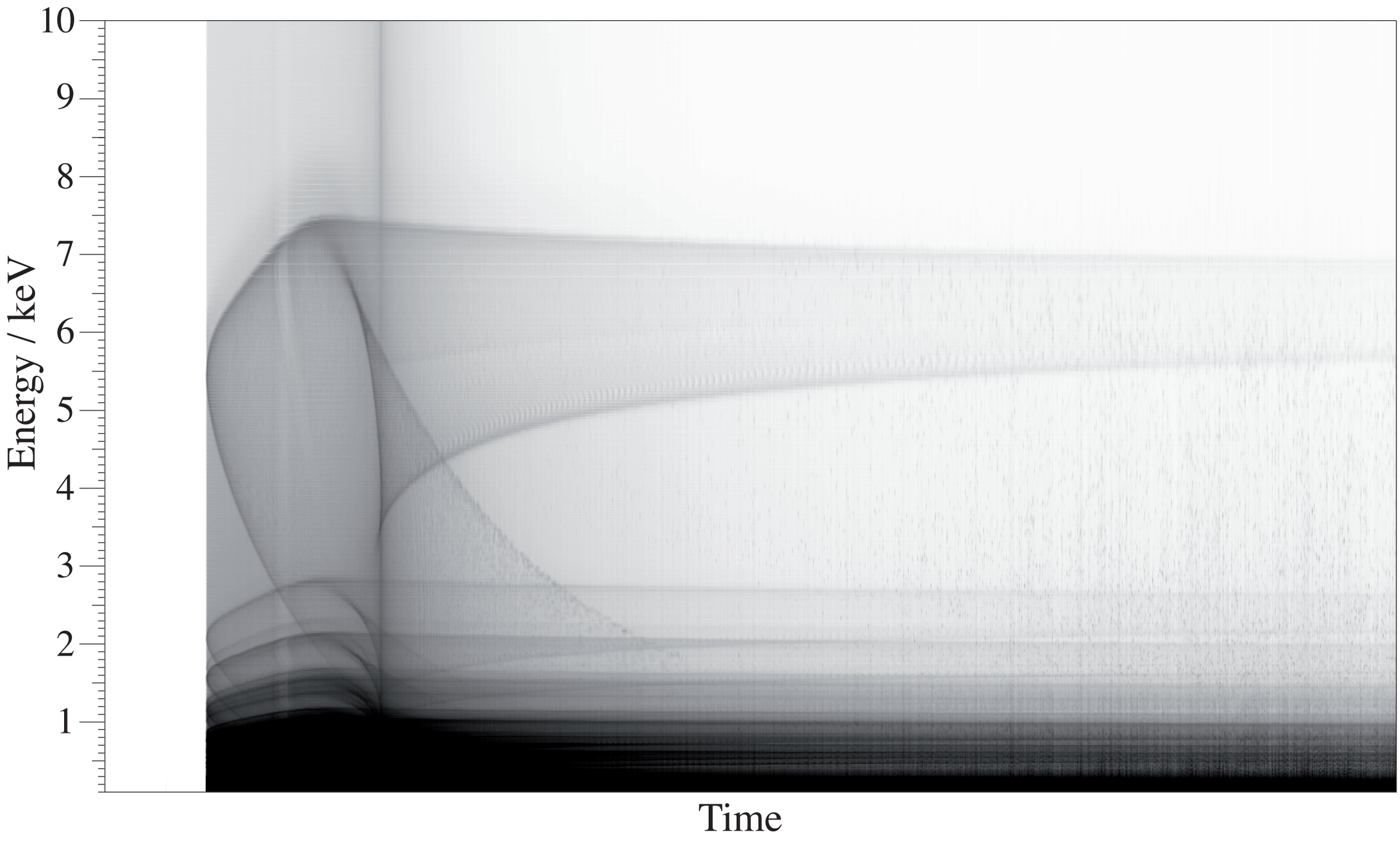






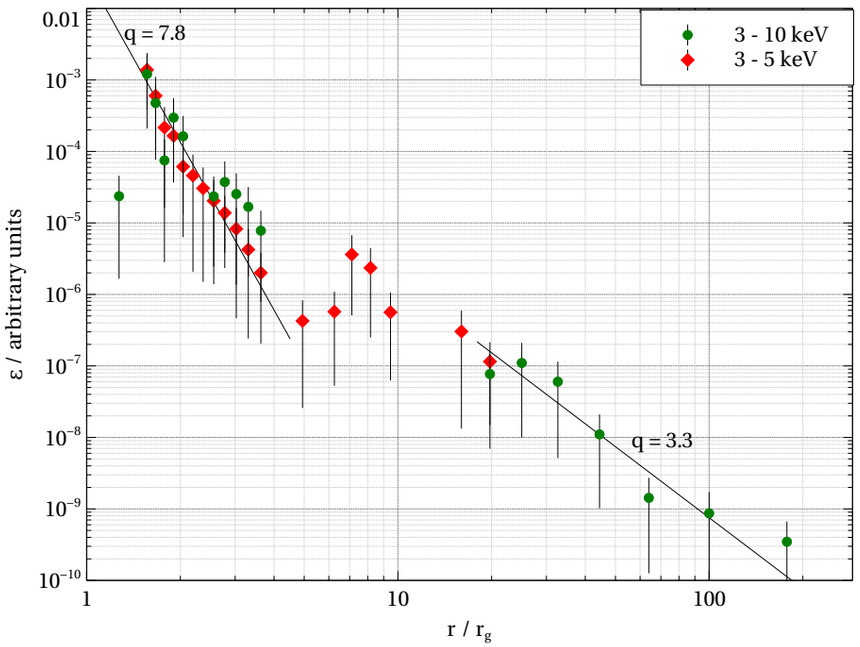


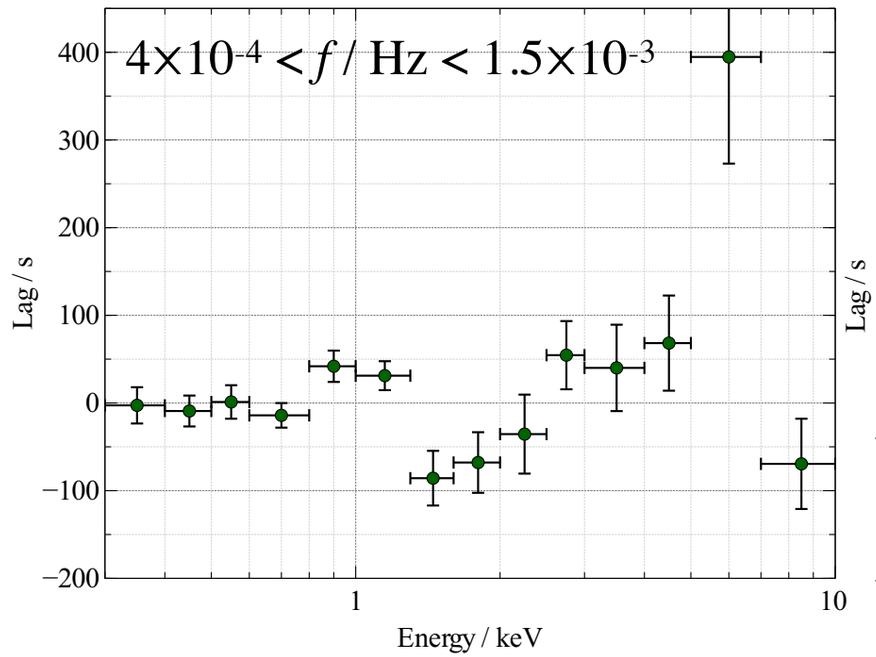
Time-Resolved Response of the Disc

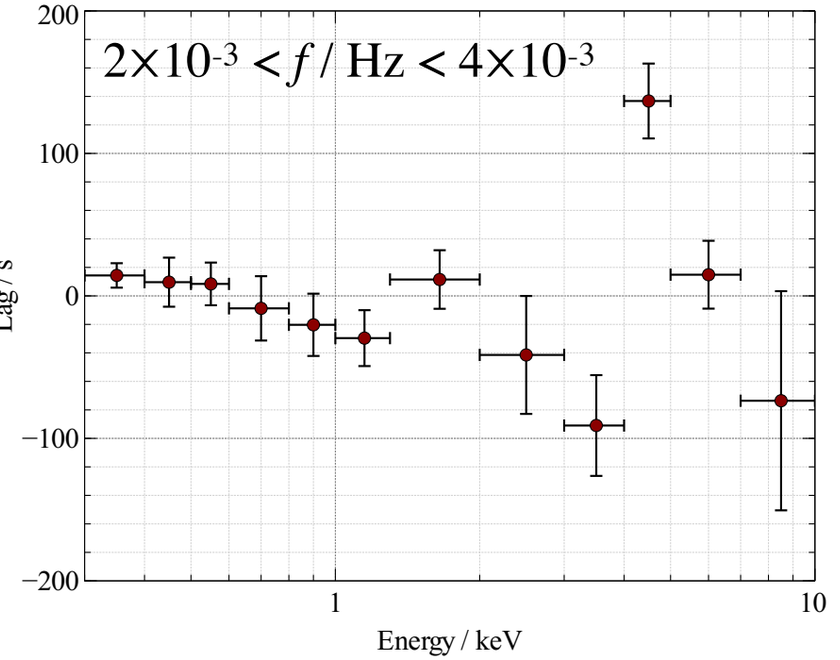


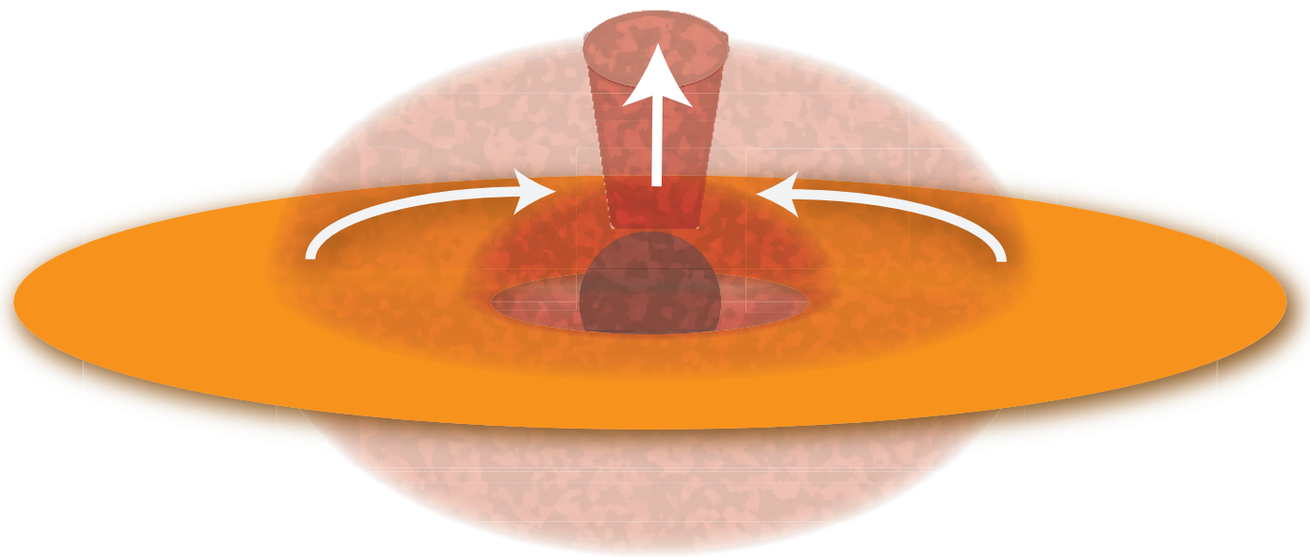
Reynolds et al. 1999, Wilkins et al. 2016

The Structure of the Corona





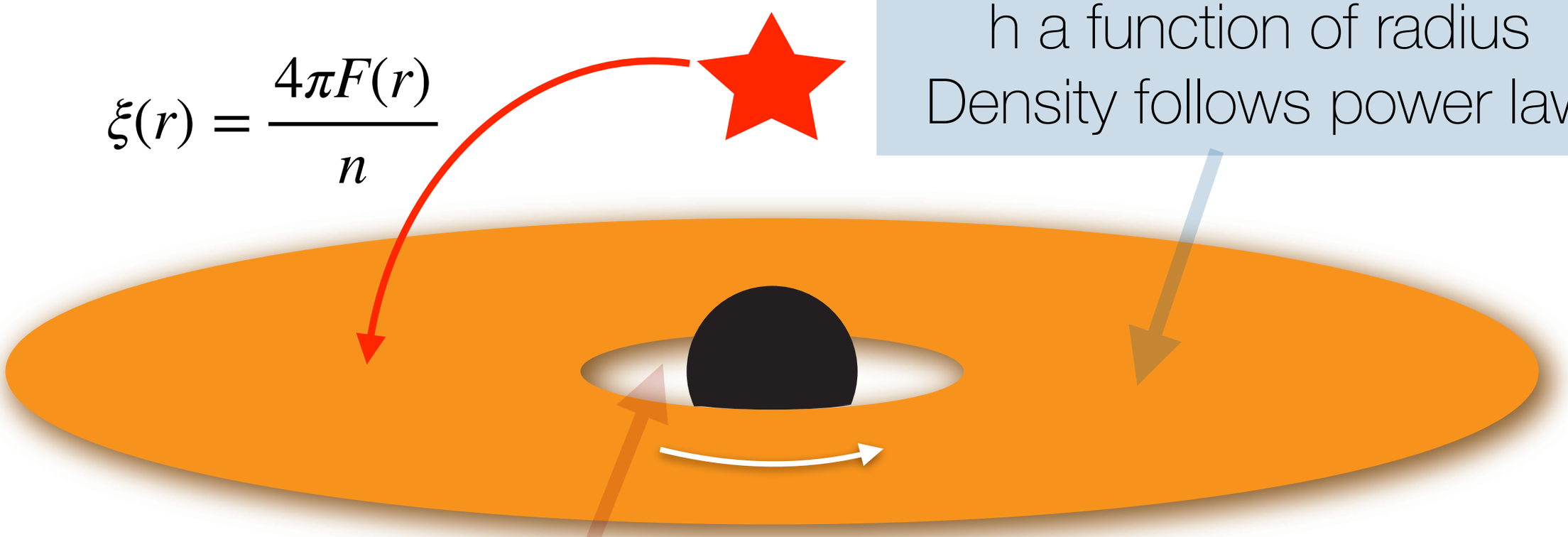




Wilkins et al. 2012, 2013, 2016, 2017

Structure of the Accretion Flow

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



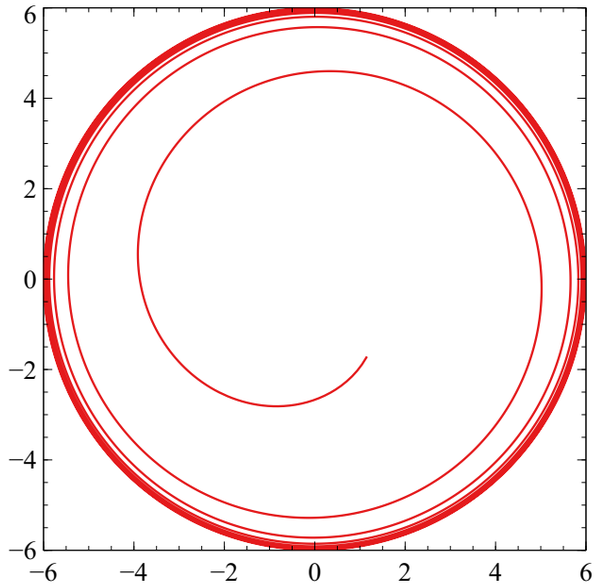
(Relativistic) Keplerian orbits
h a function of radius
Density follows power law

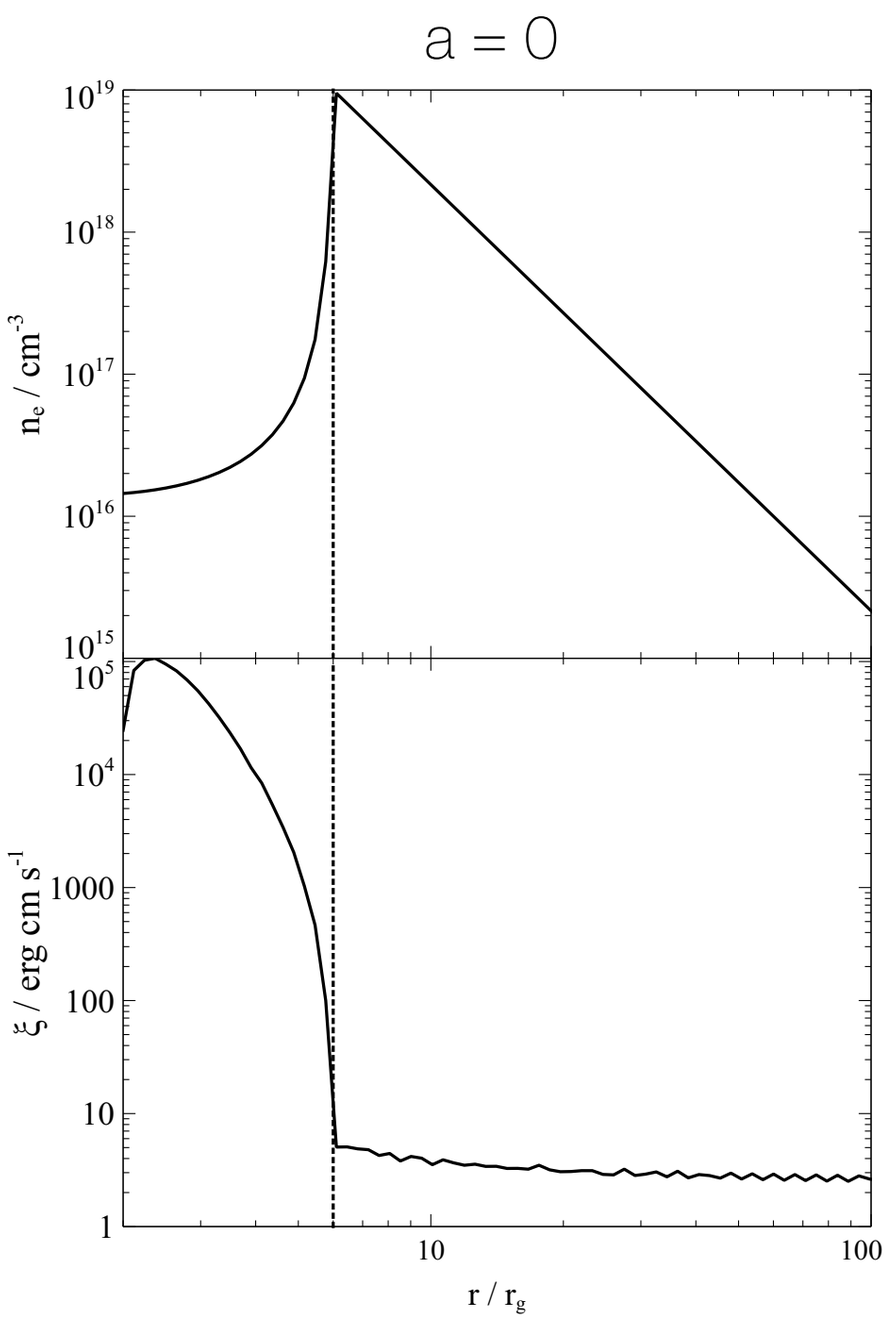
Plunging orbit
Conserve h from ISCO
Density follows mass conservation

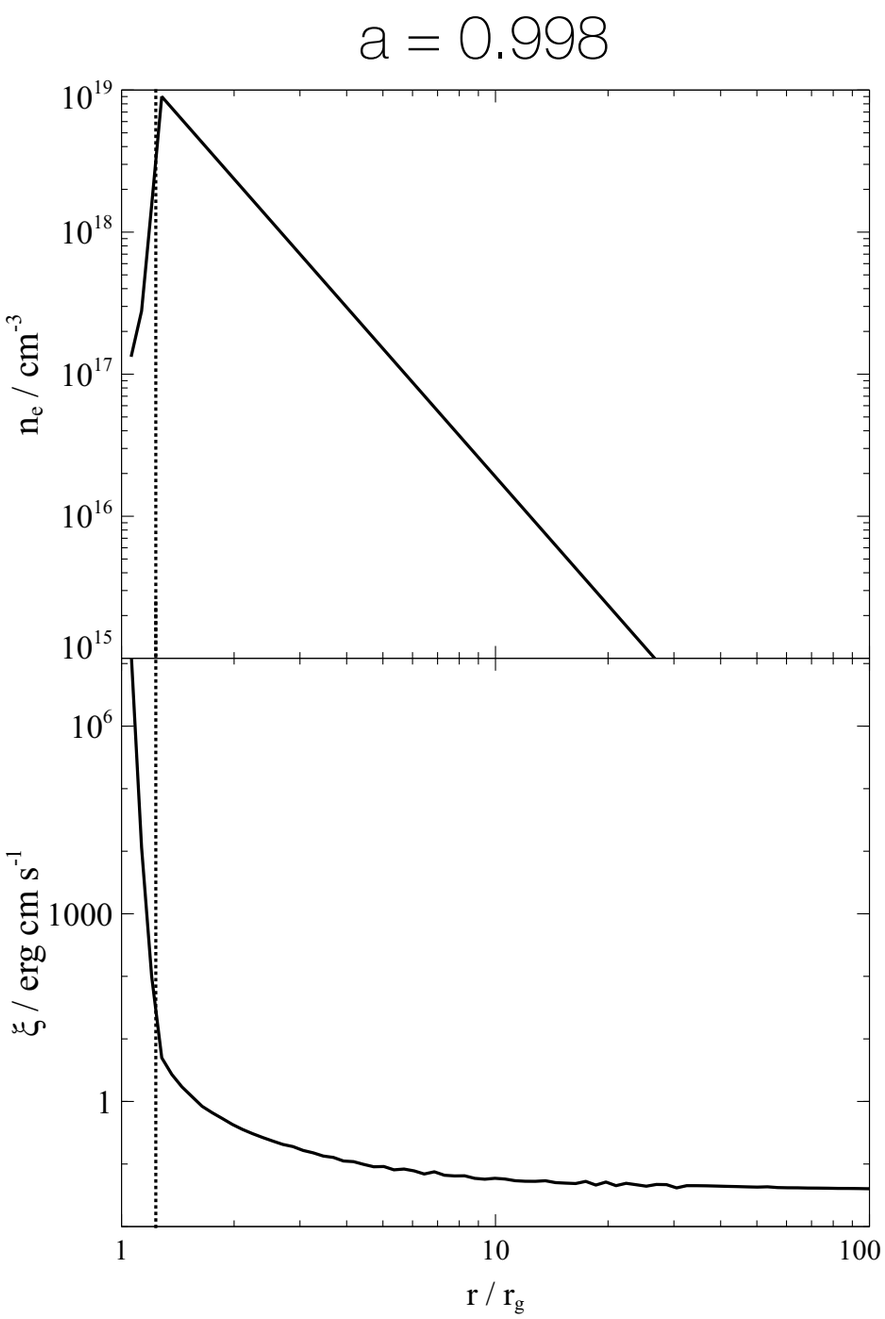
$$r\Sigma u^r = \frac{\dot{m}}{2\pi}$$ For mass continuity

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

What happens to material across the ISCO?





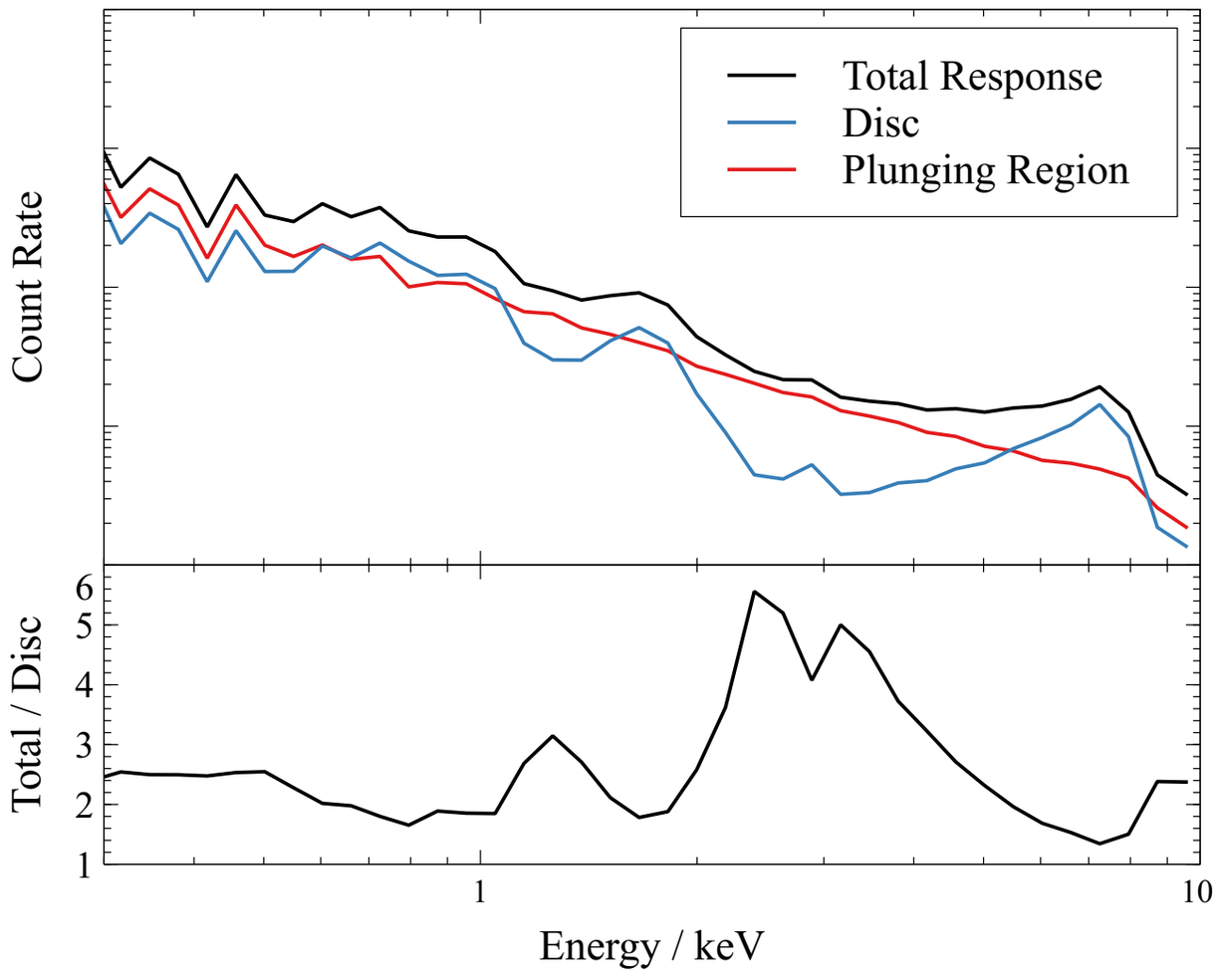


Reynolds & Begelman 1997, Wilkins et al. in prep

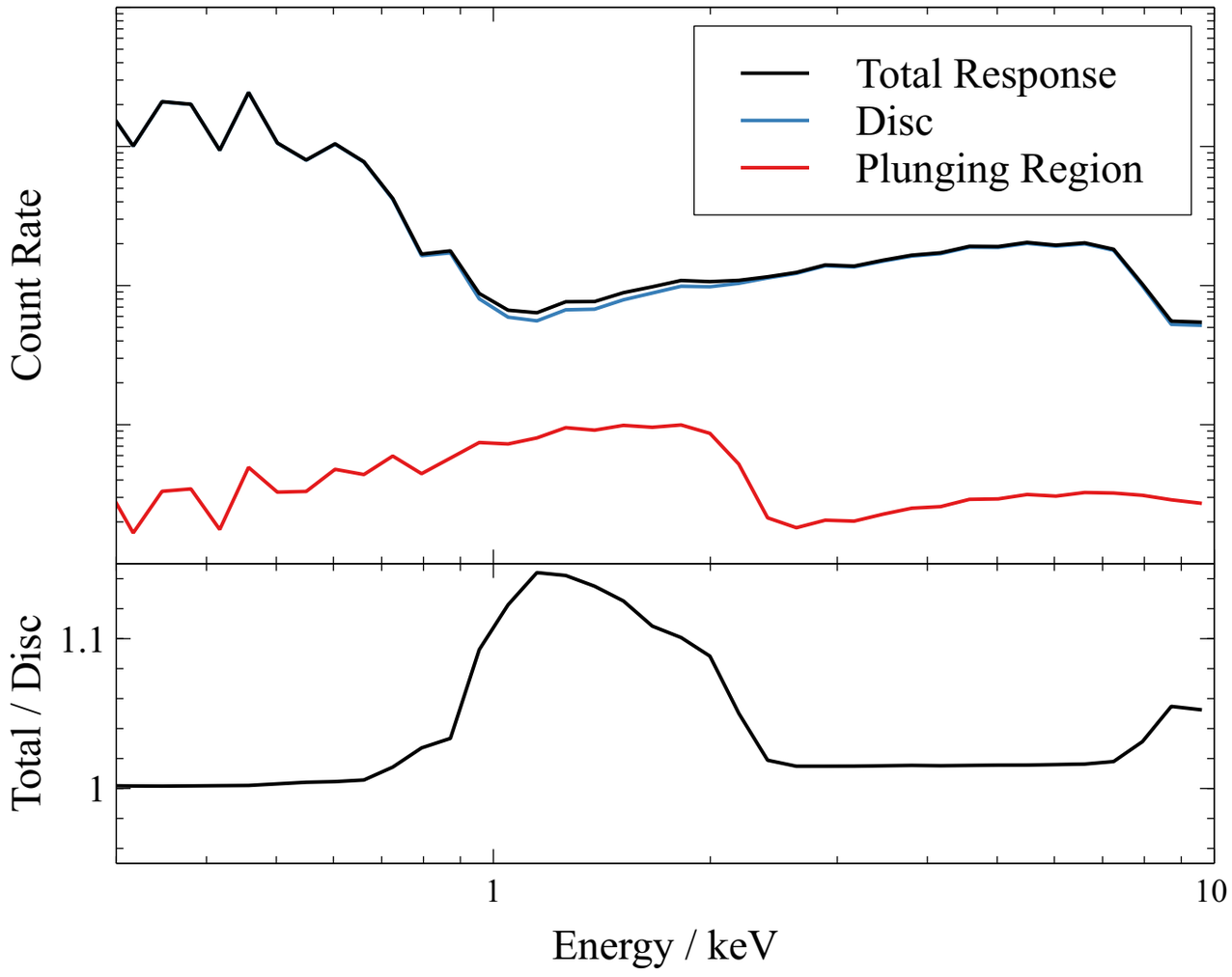
Seeing from Beyond the ISCO

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

a = 0, 45% flux inside ISCO



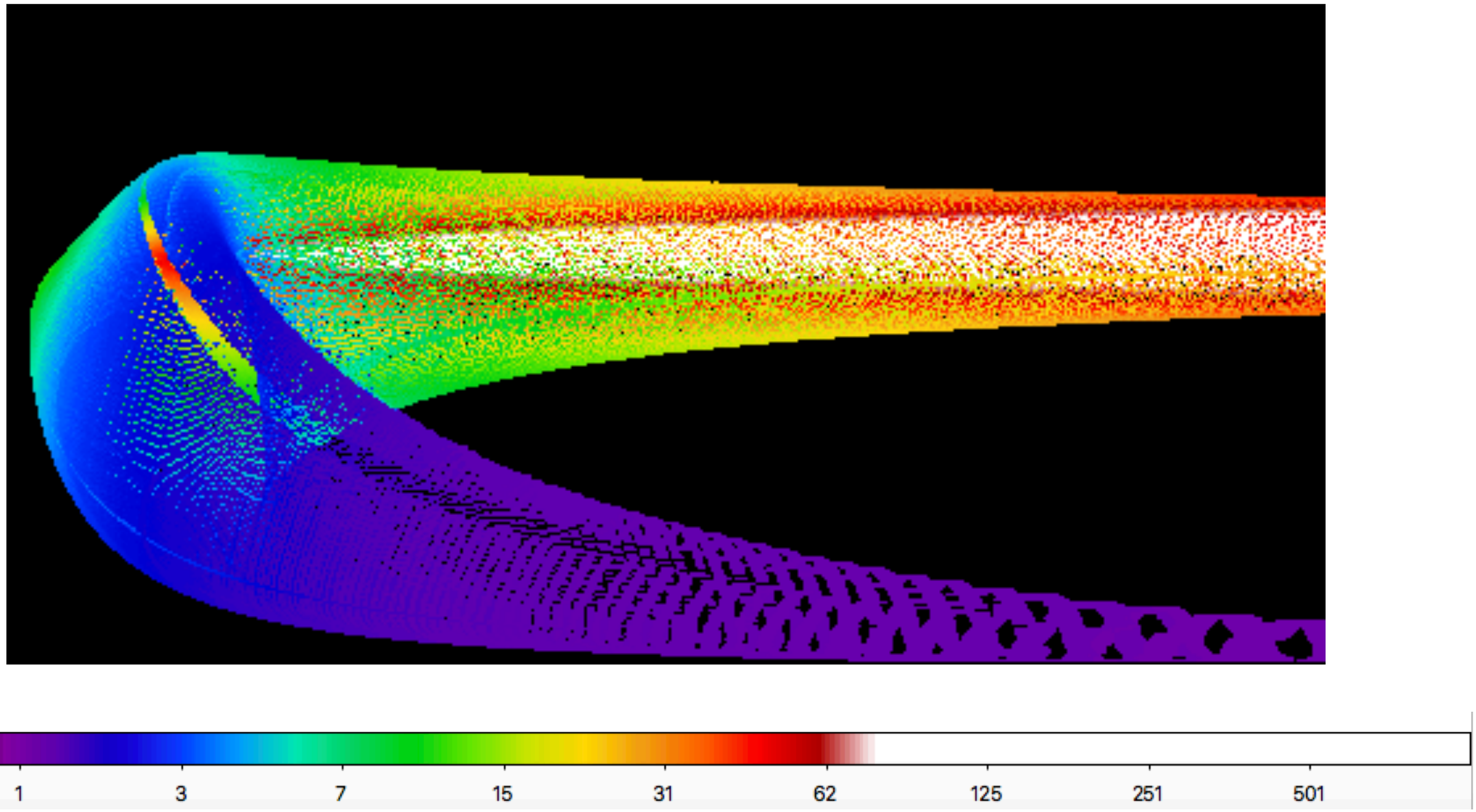
a = 0.998, 8% flux inside ISCO



Wilkins et al. in prep

How would we detect this emission?

X-ray timing - picking out radii in the disc

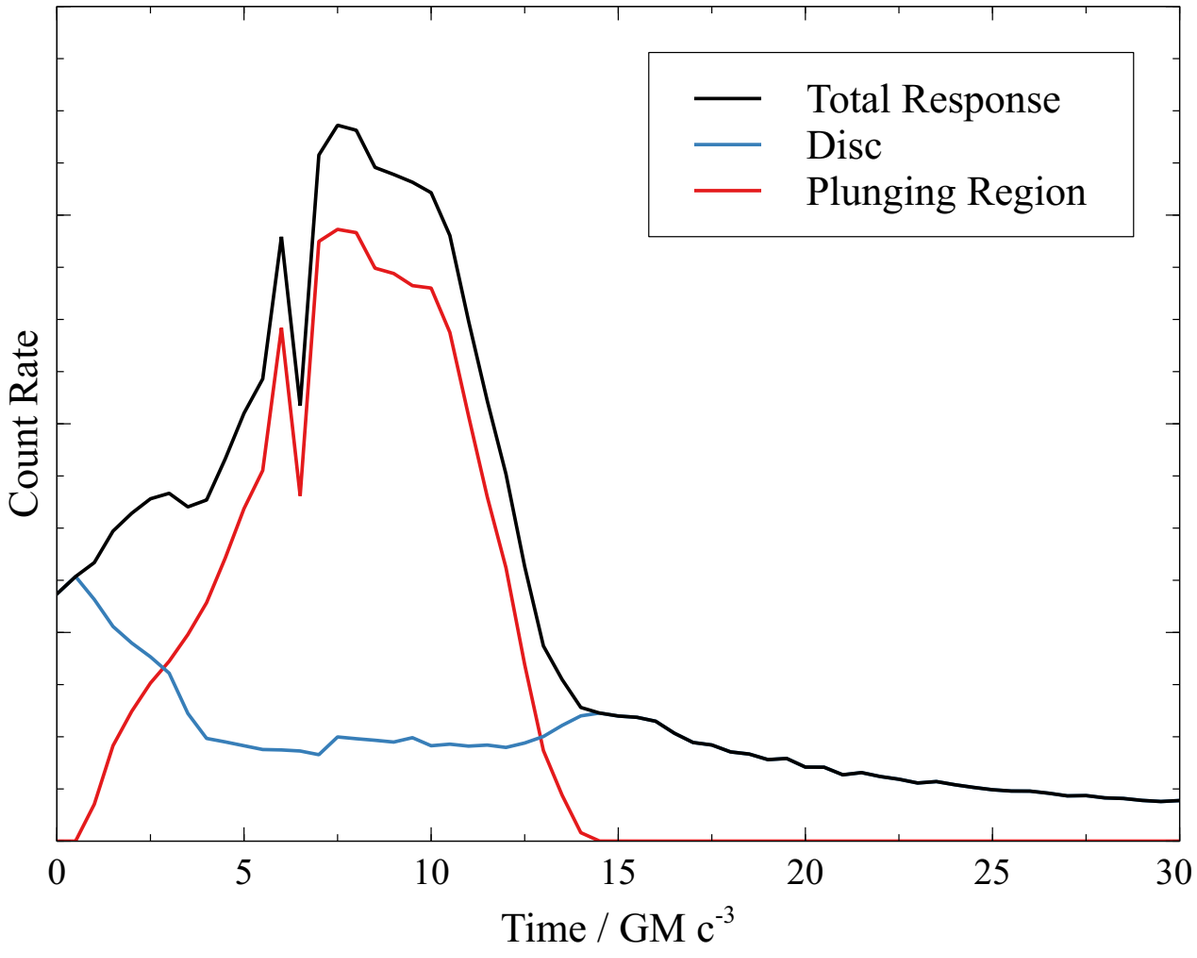


Wilkins et al. in prep

Energy-Resolved Temporal Response

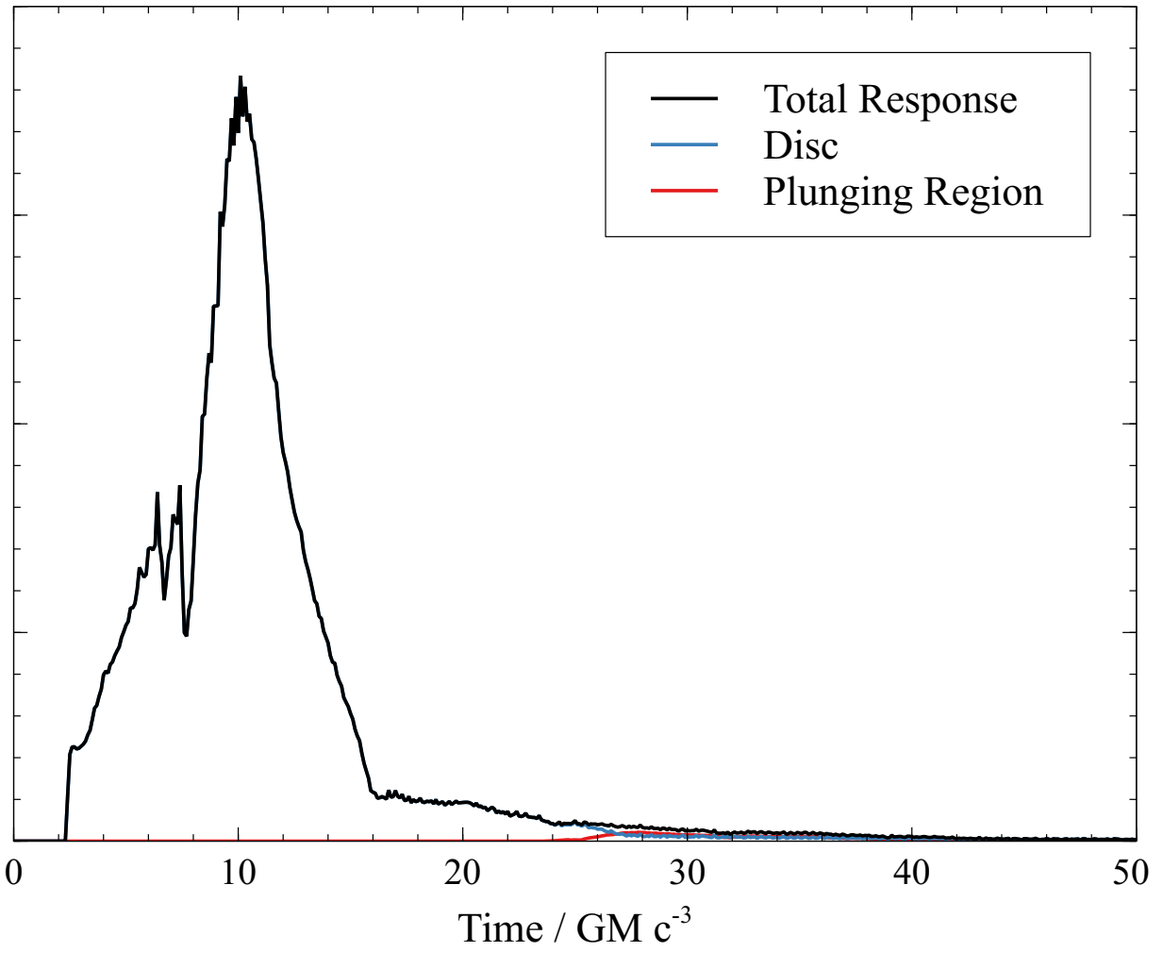
Core of the iron Kα emission line

a = 0, 45% flux inside ISCO



4-7keV

a = 0.998, 8% flux inside ISCO



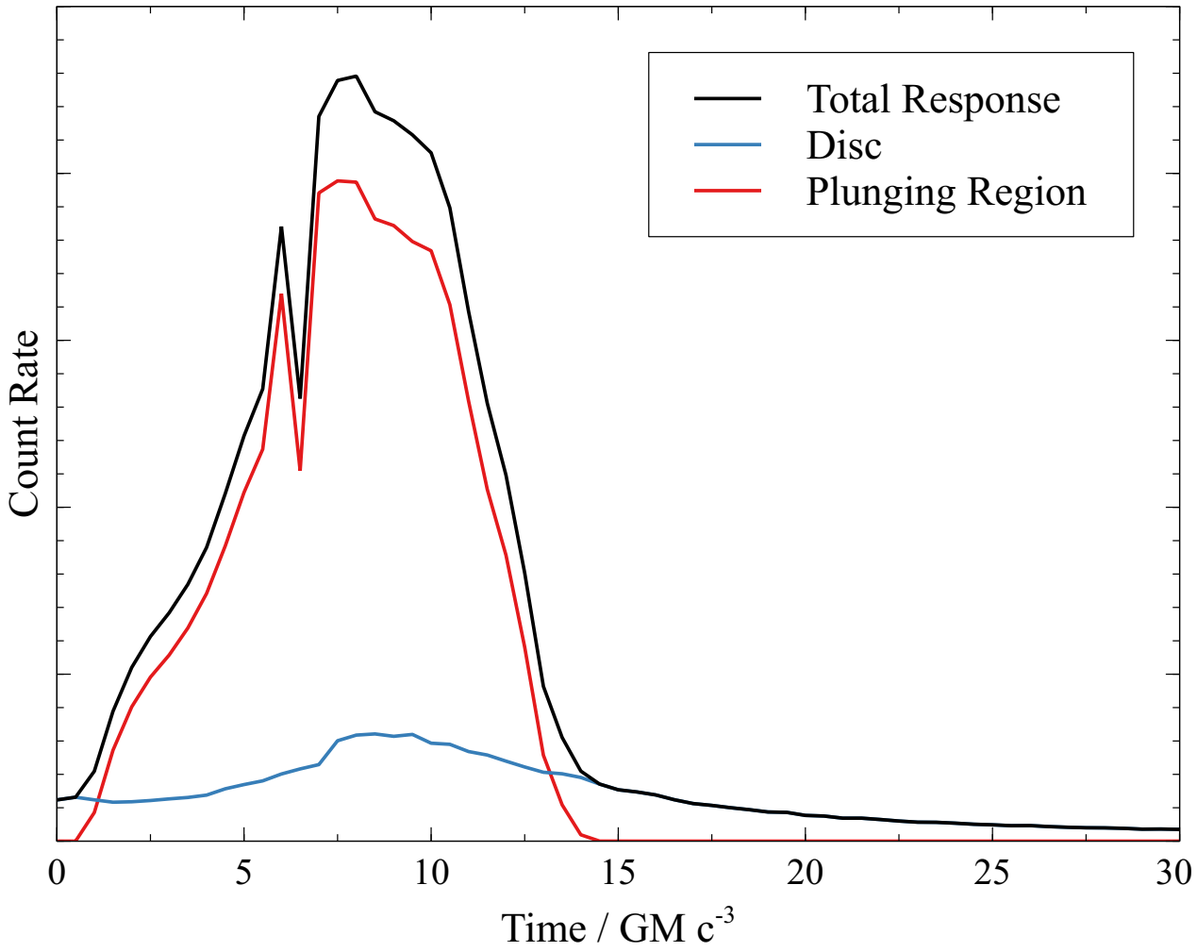
4-7keV

Wilkins et al. in prep

Energy-Resolved Temporal Response

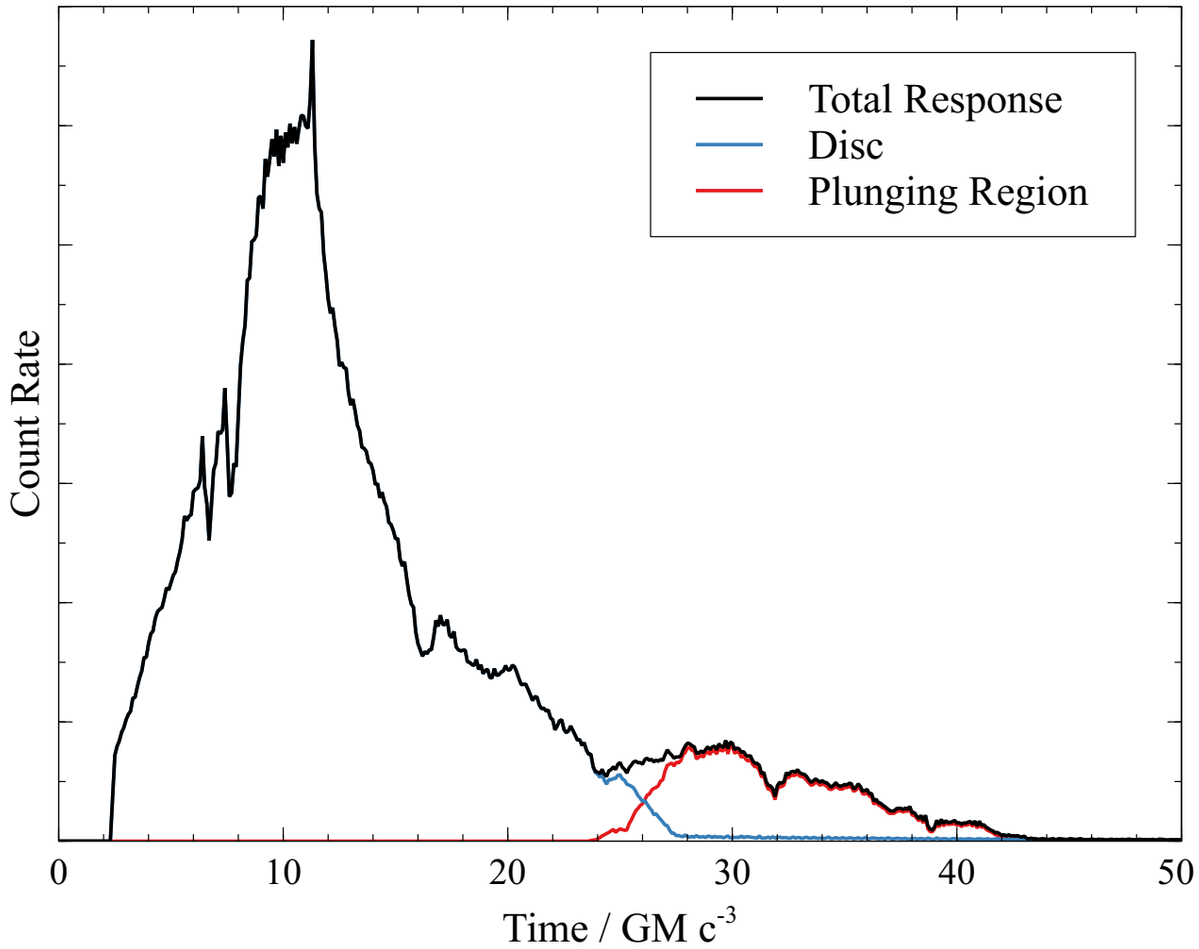
Redshifted wing of the iron Kα emission line

a = 0, 45% flux inside ISCO



2-4keV

a = 0.998, 8% flux inside ISCO

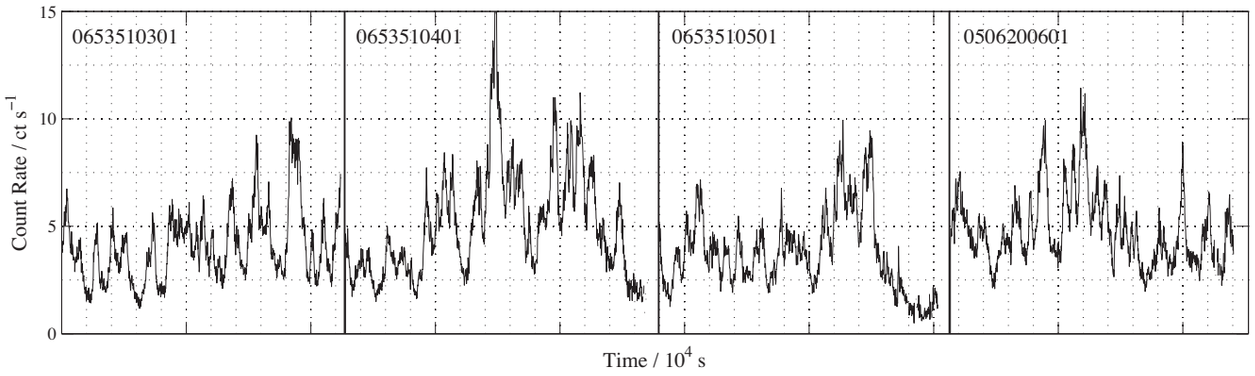


1-2keV

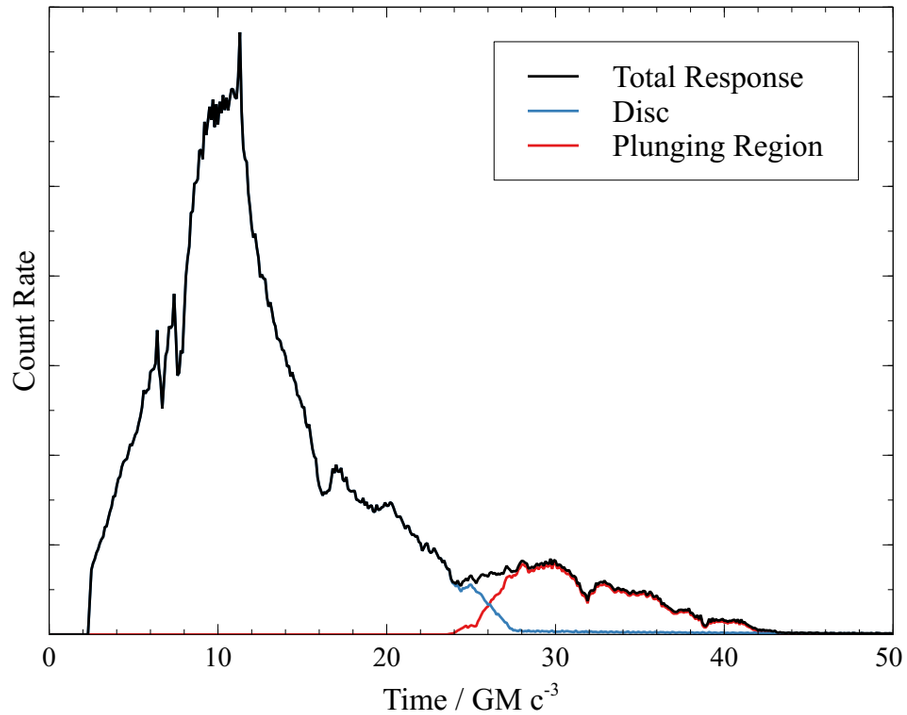
Wilkins et al. in prep

Measuring the Response

$$R(t) = P(t) \otimes T(t)$$



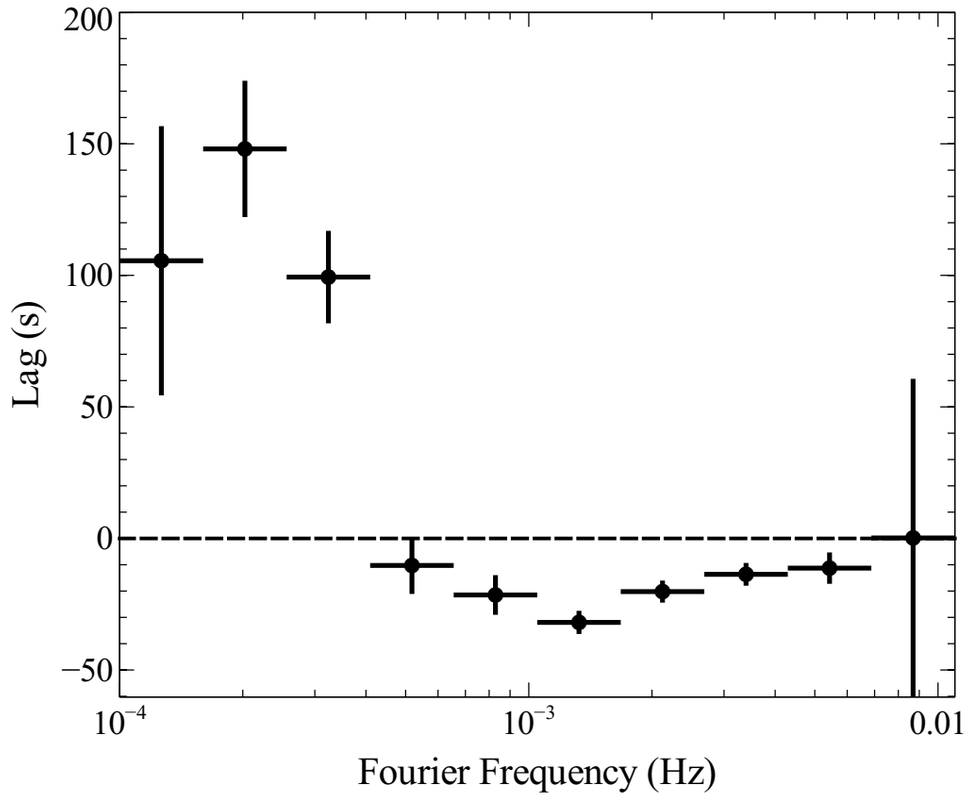
$\otimes$



$$\tilde{C} = \tilde{T}^* \tilde{P}$$

$$\tilde{C}(f) = |\tilde{P(f)}|^2 \tilde{T}^*(f)$$
$$= |\tilde{P}(f)|^2 |\tilde{T}(f)| e^{-i\varphi}$$

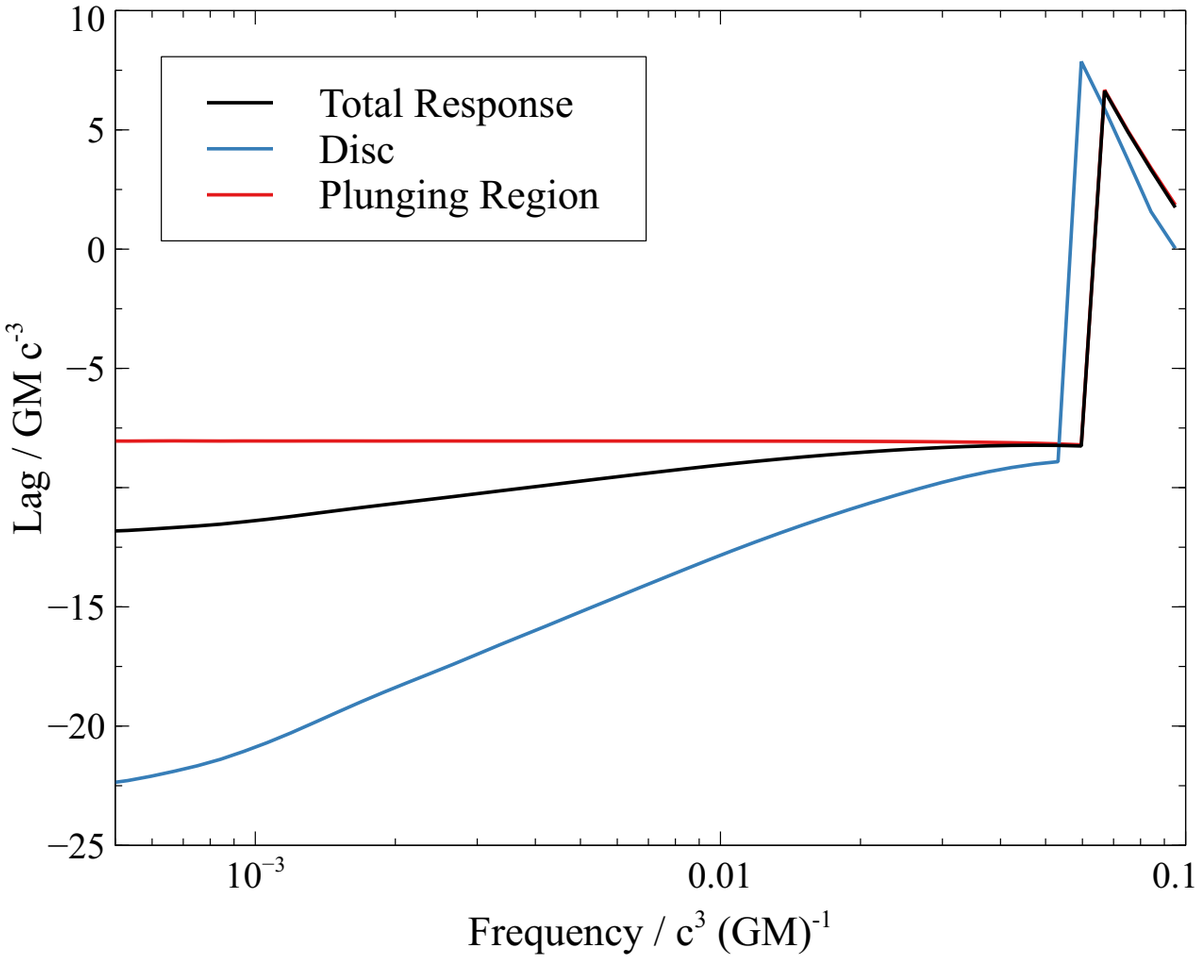
$$\tau(f) = \frac{\arg\left(\tilde{C}(f)\right)}{2\pi f}$$



Lag-Frequency Response

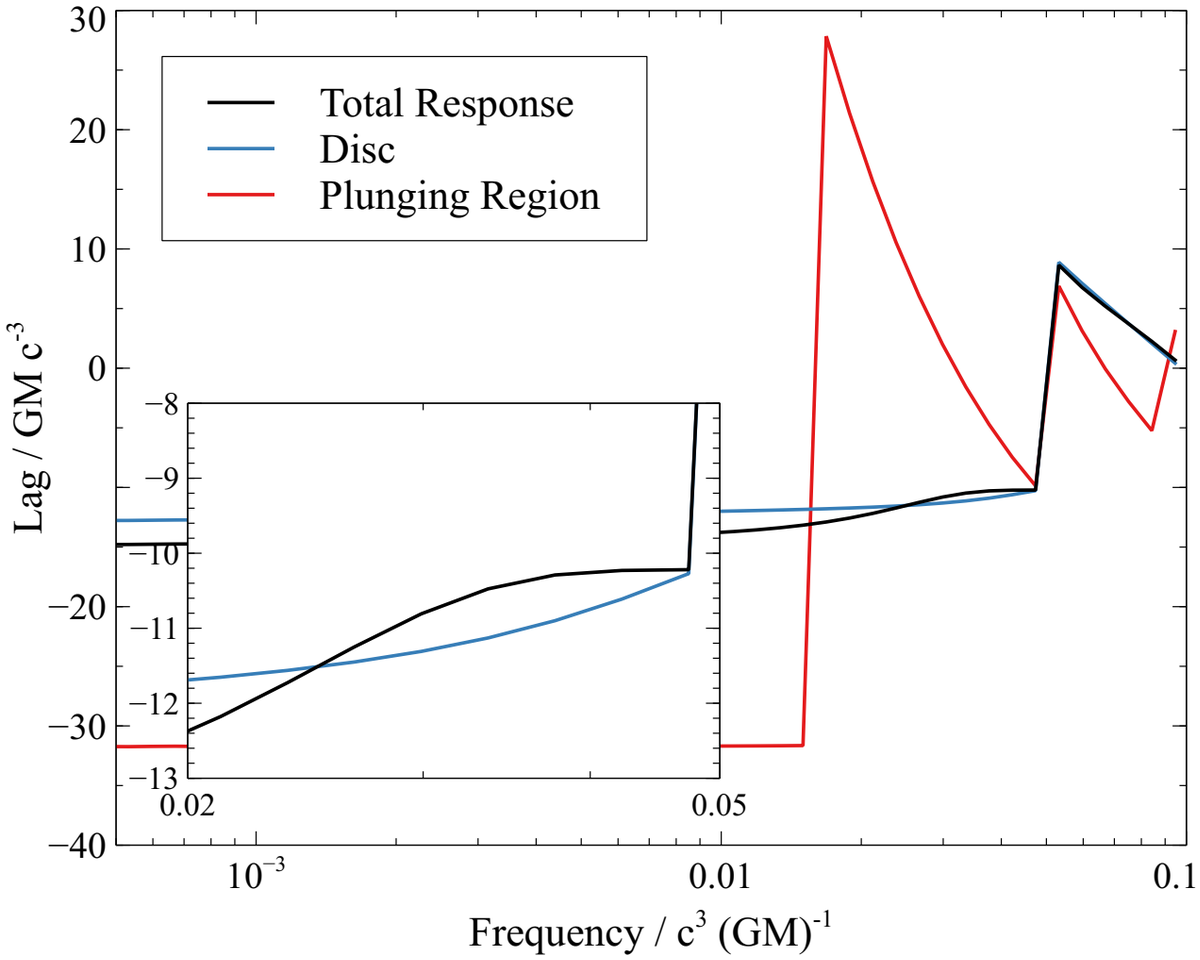
Redshifted wing of the iron Kα emission line

a = 0, 45% flux inside ISCO



2-4keV

a = 0.998, 8% flux inside ISCO

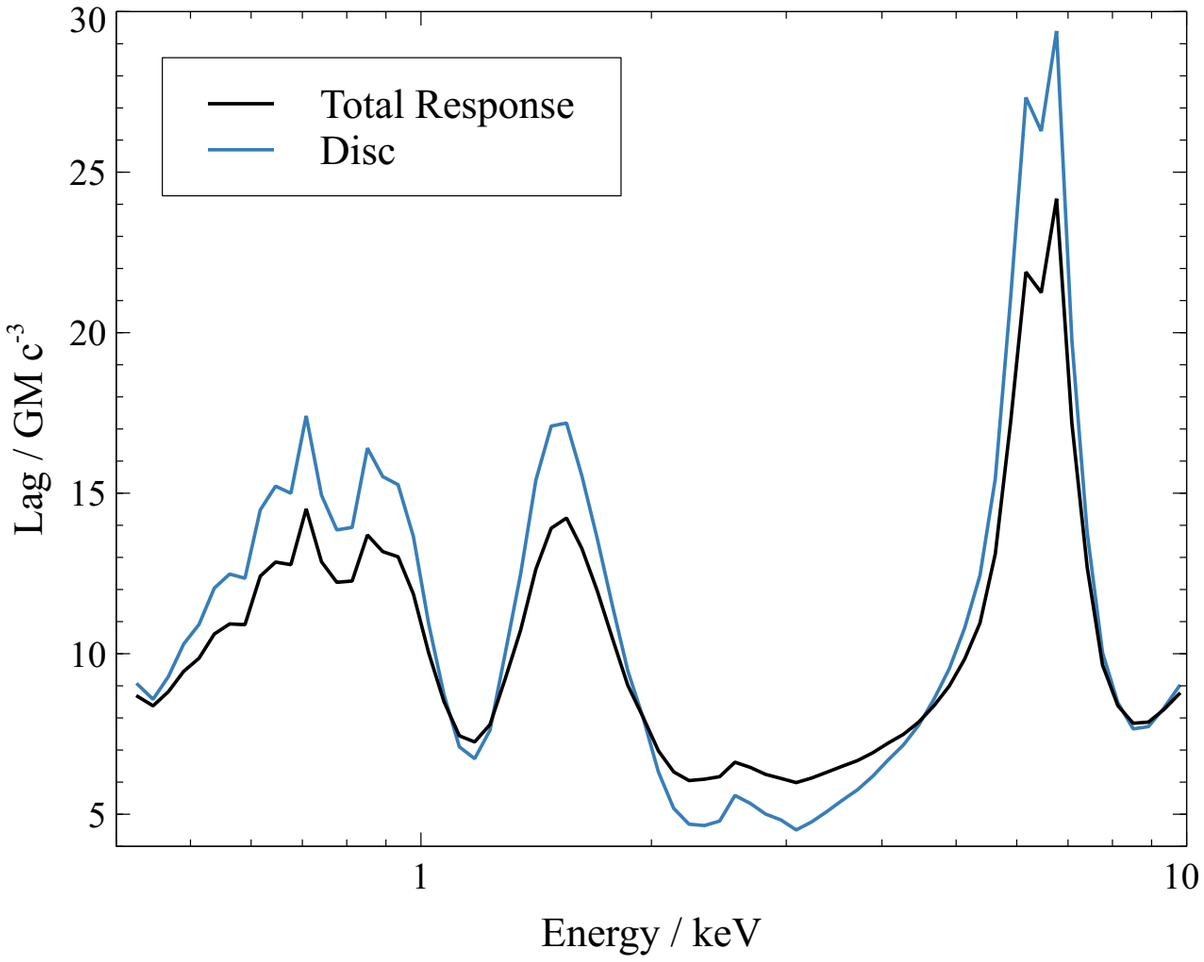


1-2keV

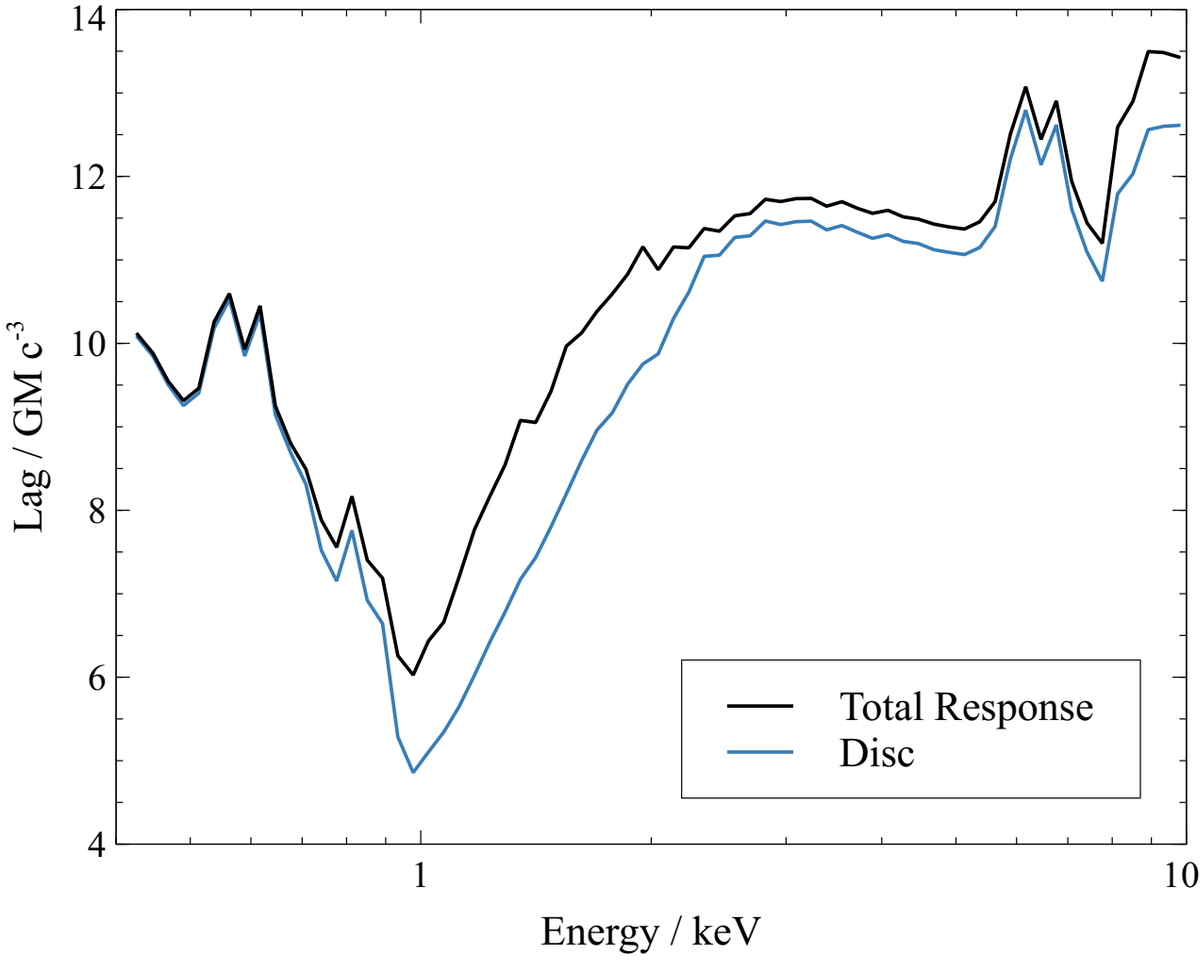
Wilkins et al. in prep

Lag-Energy Response

a = 0, 45% flux inside ISCO



a = 0.998, 8% flux inside ISCO

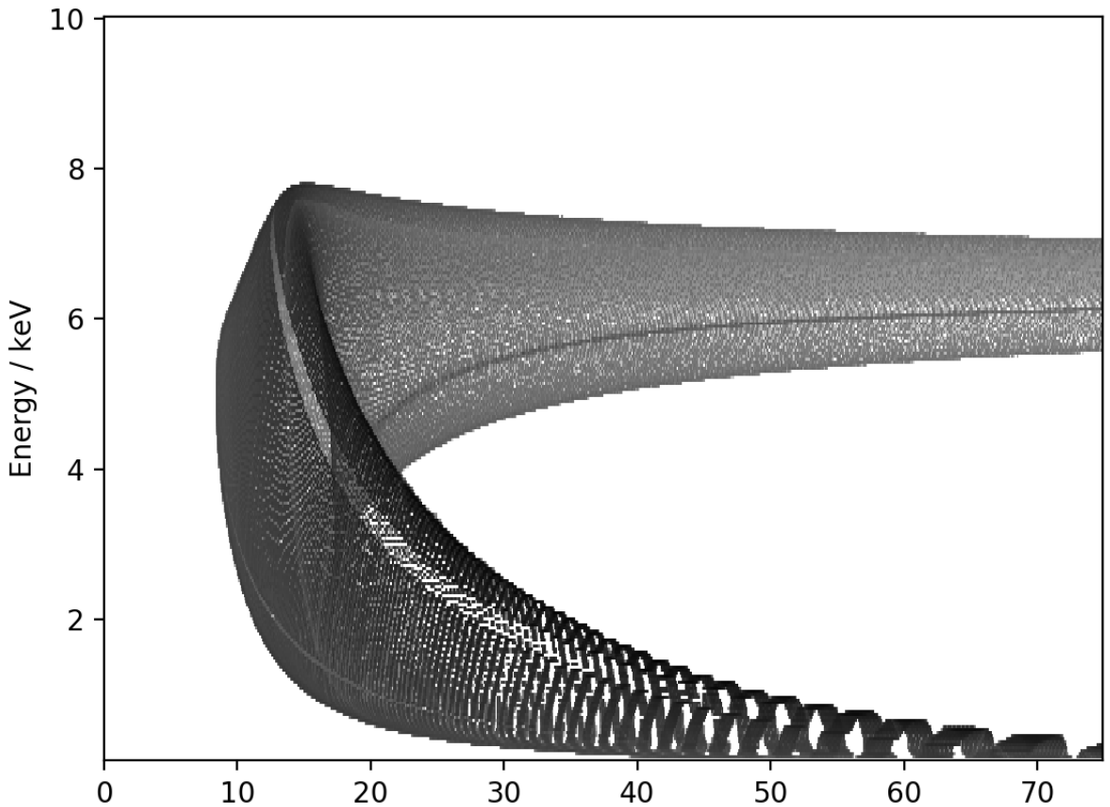


Wilkins et al. in prep

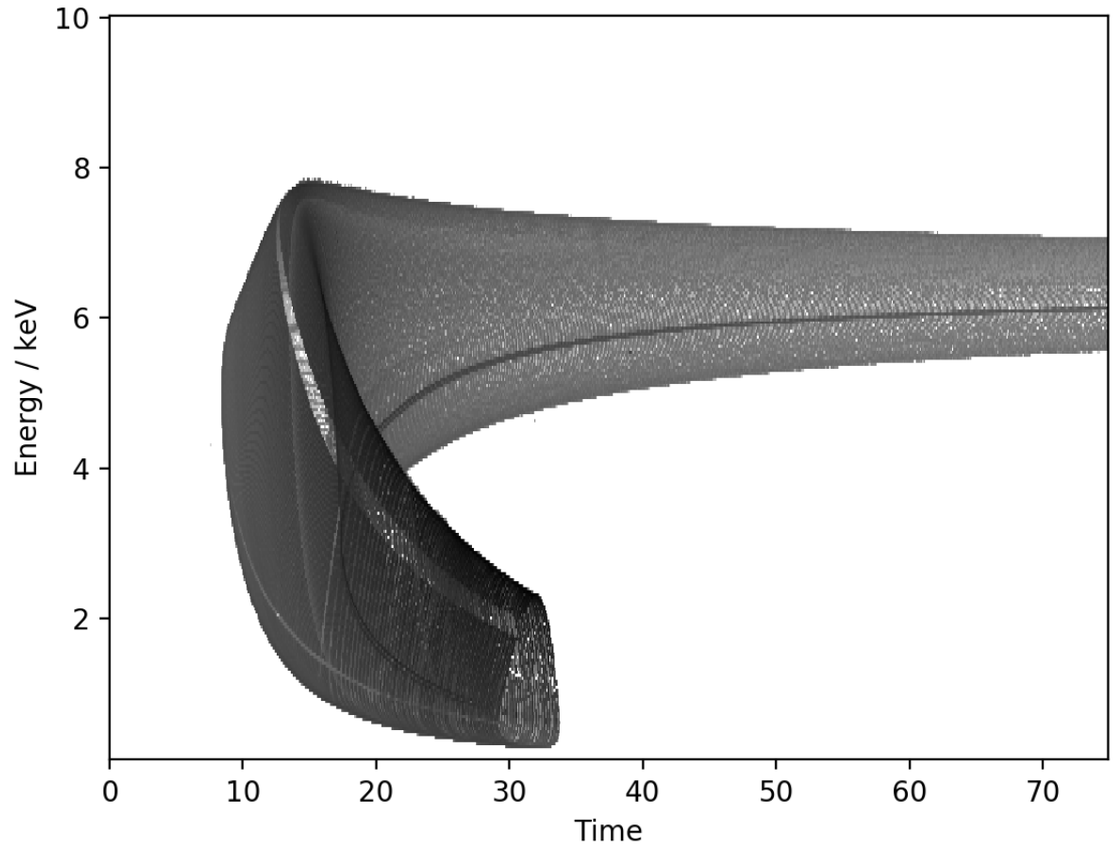
Is the Plunging Region There?

Force disc to maintain Keplerian orbit inside ISCO

With Plunging Region



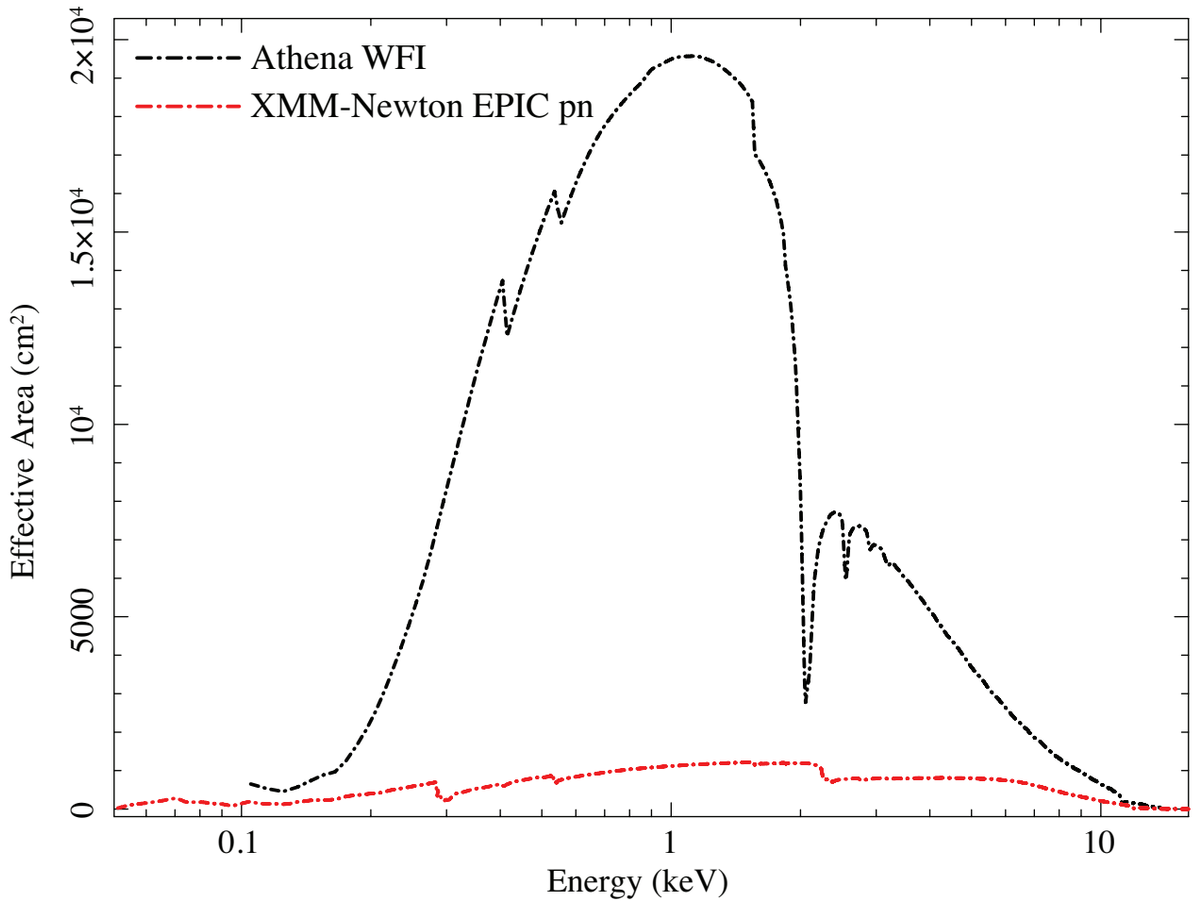
Pseudo-Keplerian Orbits

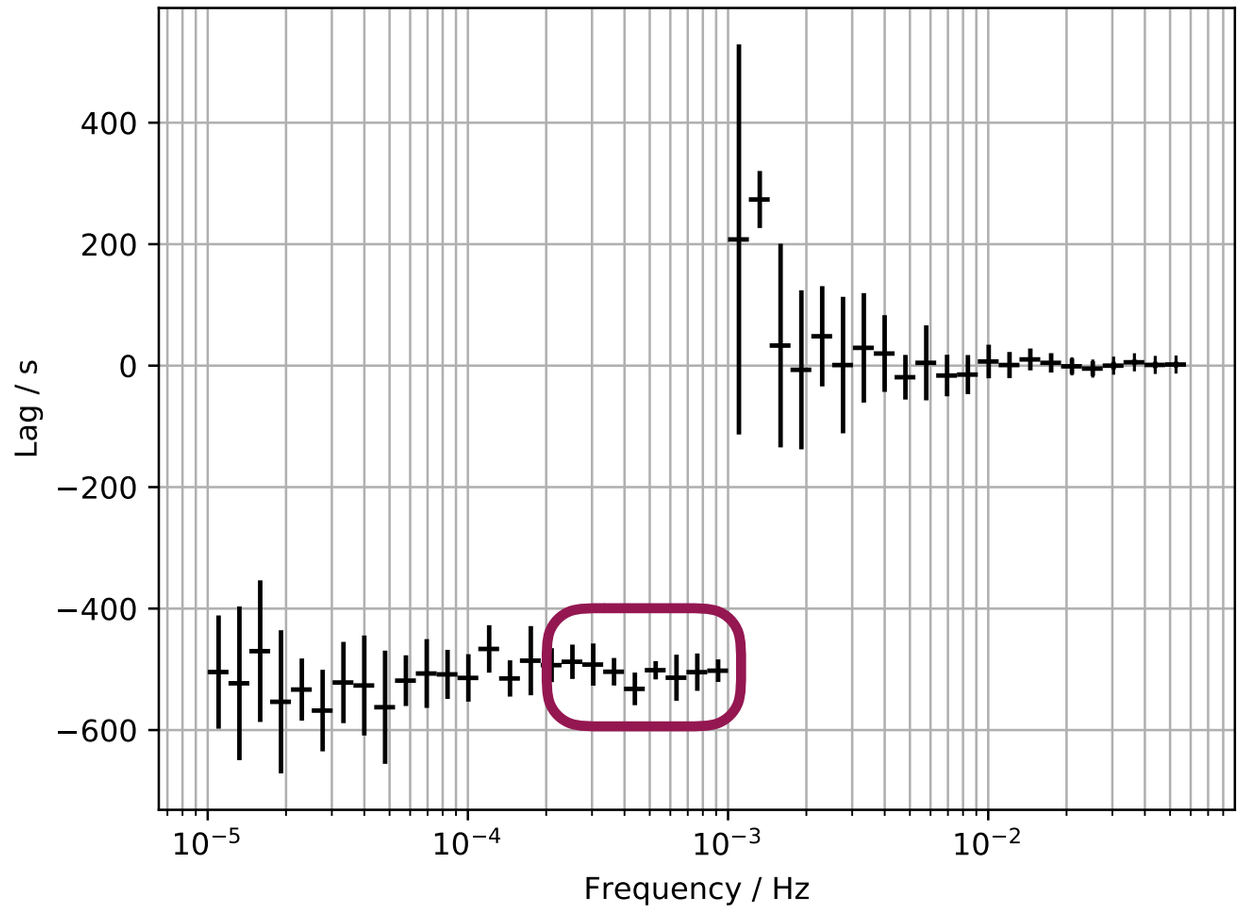


The Future of X-ray Reverberation

The Plunging Region with Athena

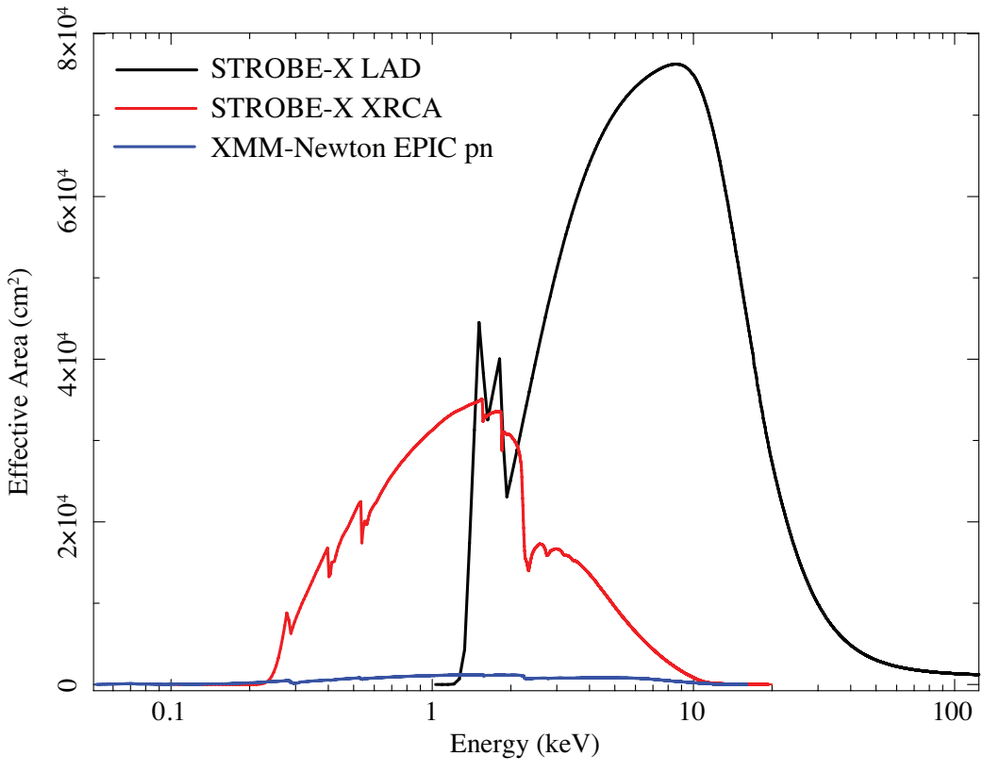
AGN (I Zw 1), XRCA





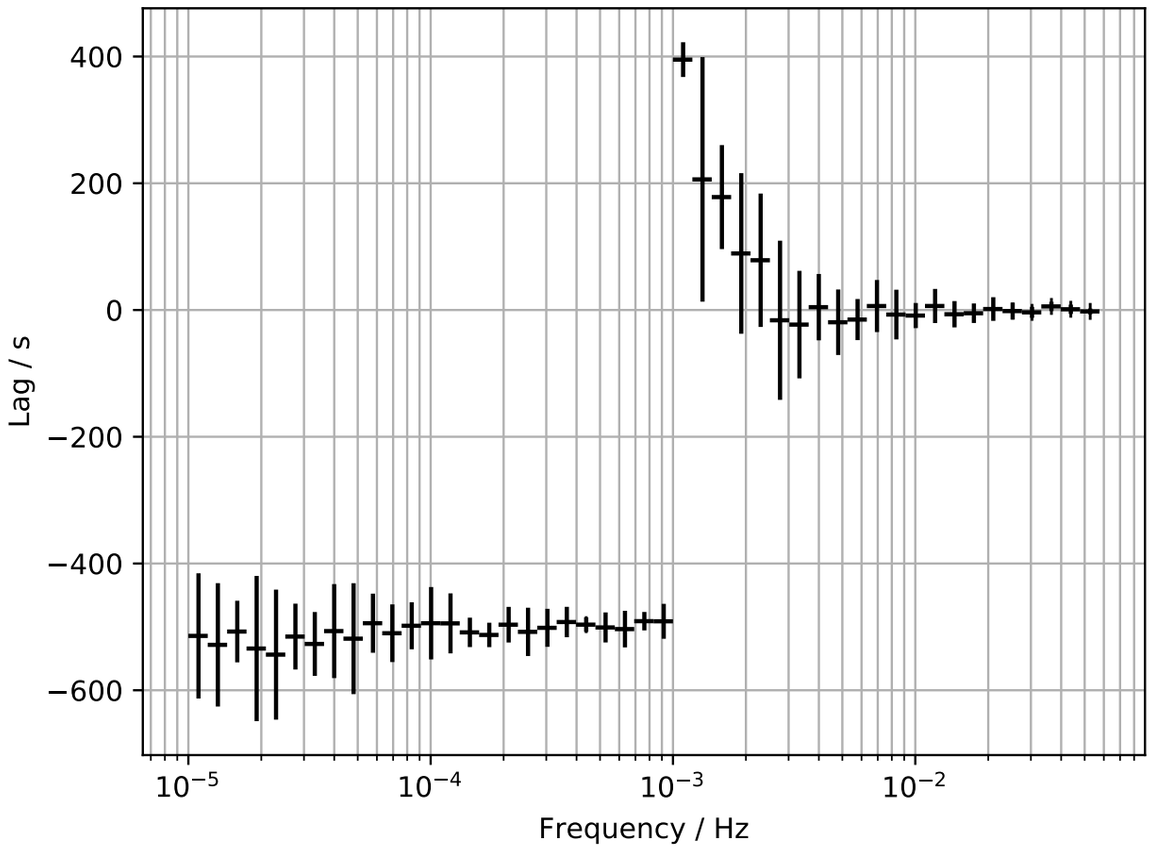
500 ± 30 s $GM/c^3 = 50\,\mathrm{s}$

Strobe-X


STROBE-X LAD
STROBE-X XRCA
XMM-Newton EPIC pn
Effective Area (cm²)
0
2×10⁴
4×10⁴
6×10⁴
8×10⁴
0.1
1
10
100
Energy (keV)

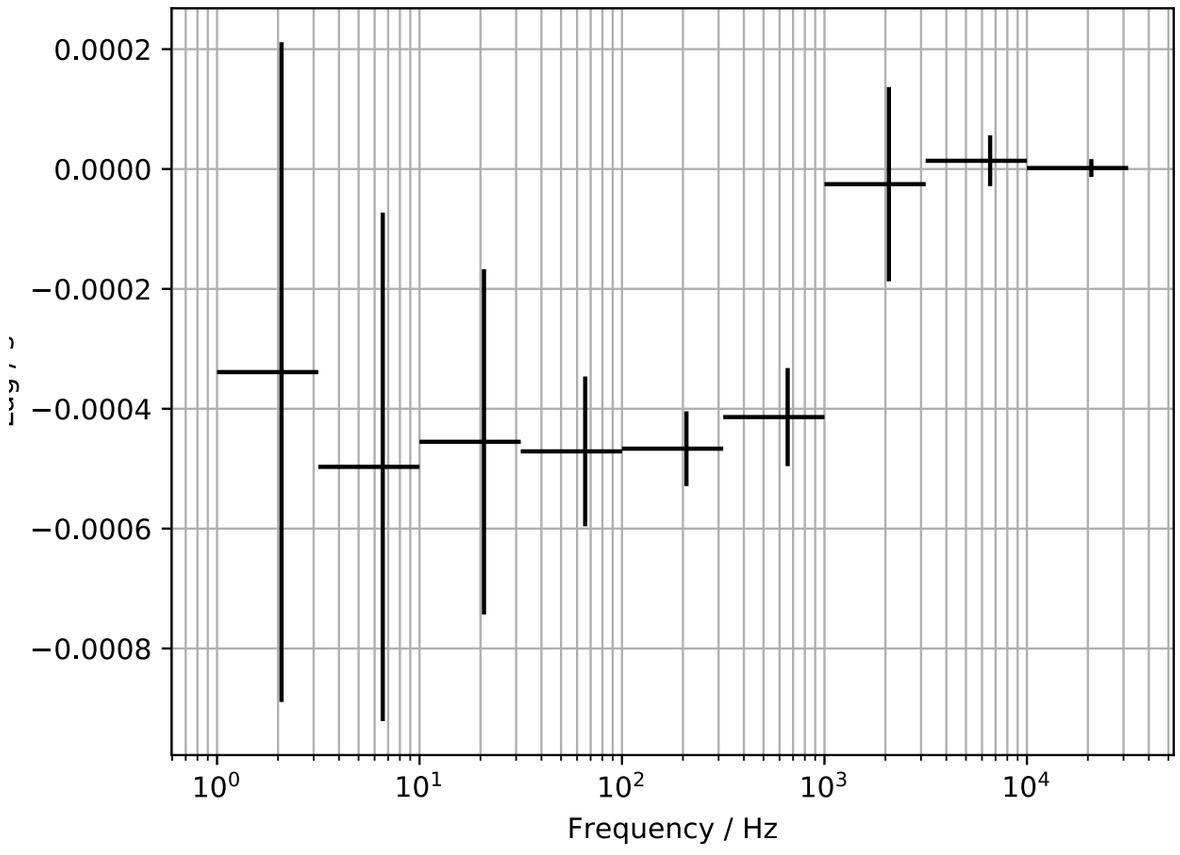
Reverberation with STROBE-X

AGN (I Zw 1), XRCA



500 ± 20 s $GM/c^3 = 50\,\mathrm{s}$

XRB (Cyg X-1), LAD



$GM/c^3 = 50\,\mu\mathrm{s}$

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 can be detected from the plunging region, inside the innermost stable orbit, distinguished by the highly redshifted emission from ionised material

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