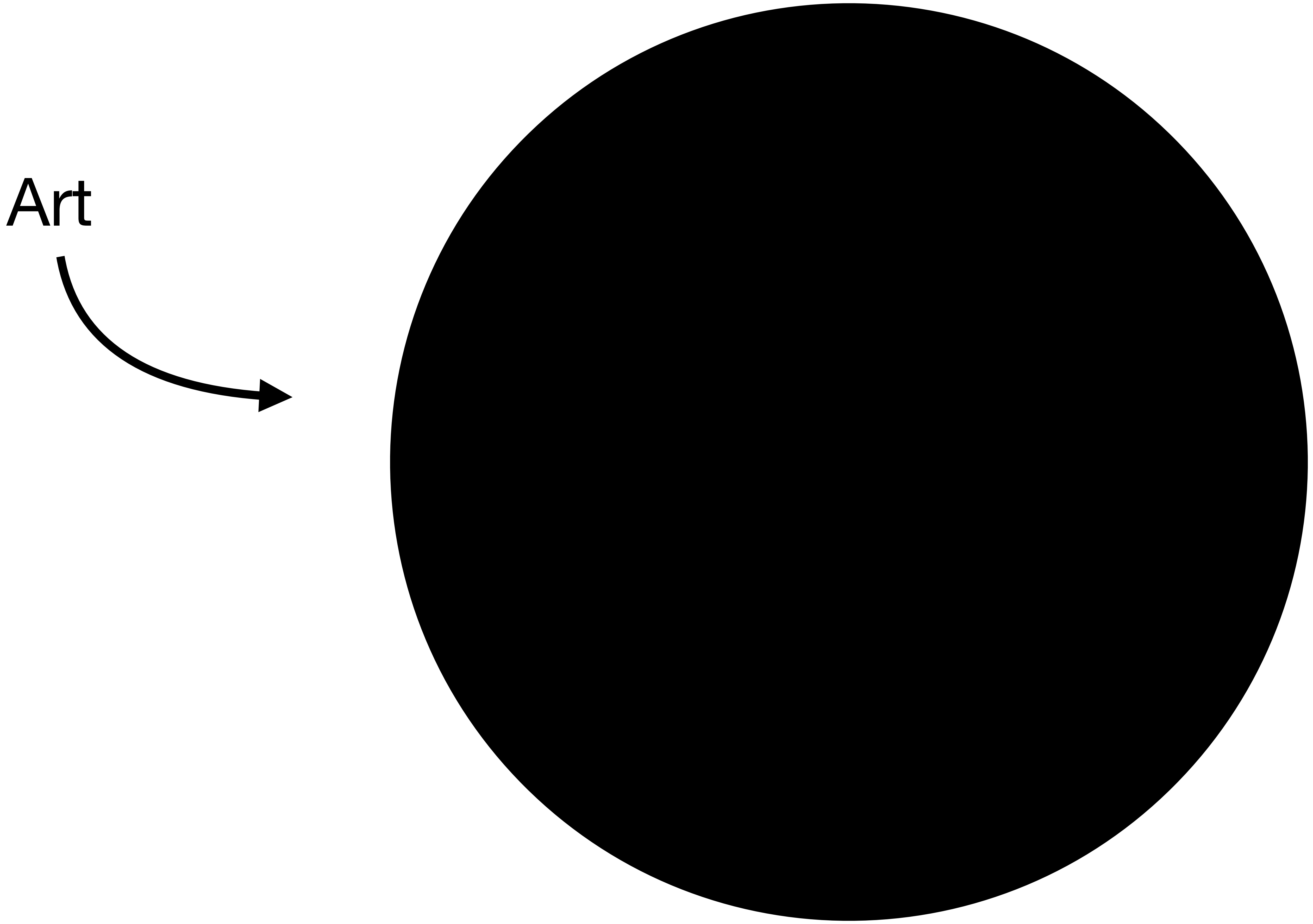
Variability of black hole outflows

Michael Parker
Zsofi Igo, Amy Joyce, Gabi Matzeu, Will Alston

ESAC virtual seminar, 7/5/20

Black holes 101



Black holes 101

Consider escape velocity:

Kinetic energy $$\frac{1}{2}mv^2 = \frac{GMm}{r}$$ Gravitational binding energy

Black holes 101

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Kinetic energy $$\frac{1}{2}mv^2 = \frac{GMm}{r}$$ Gravitational binding energy

$$v = \left(\frac{2GM}{r}\right)^{\frac{1}{2}}$$

Black holes 101

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$v_{\mathrm{esc}} = \sim 11$ km/s

$v_{\mathrm{esc}} = \sim 1$m/day

Black holes 101

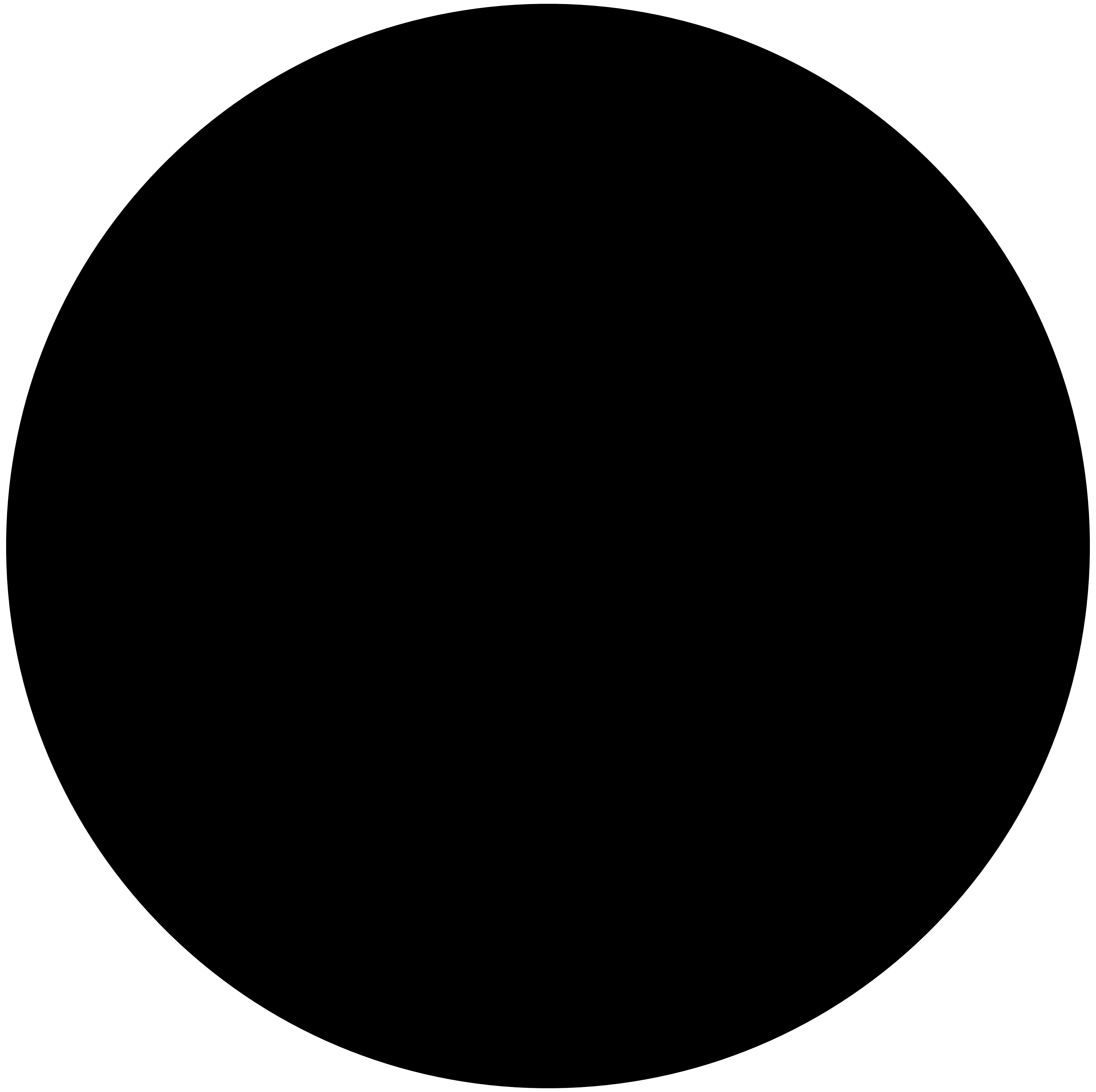
Consider escape velocity:

Kinetic energy $$\frac{1}{2}mv^2 = \frac{GMm}{r}$$ Gravitational binding energy

as v -> c $$\frac{1}{2}c^2 = \frac{GM}{r}$$

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

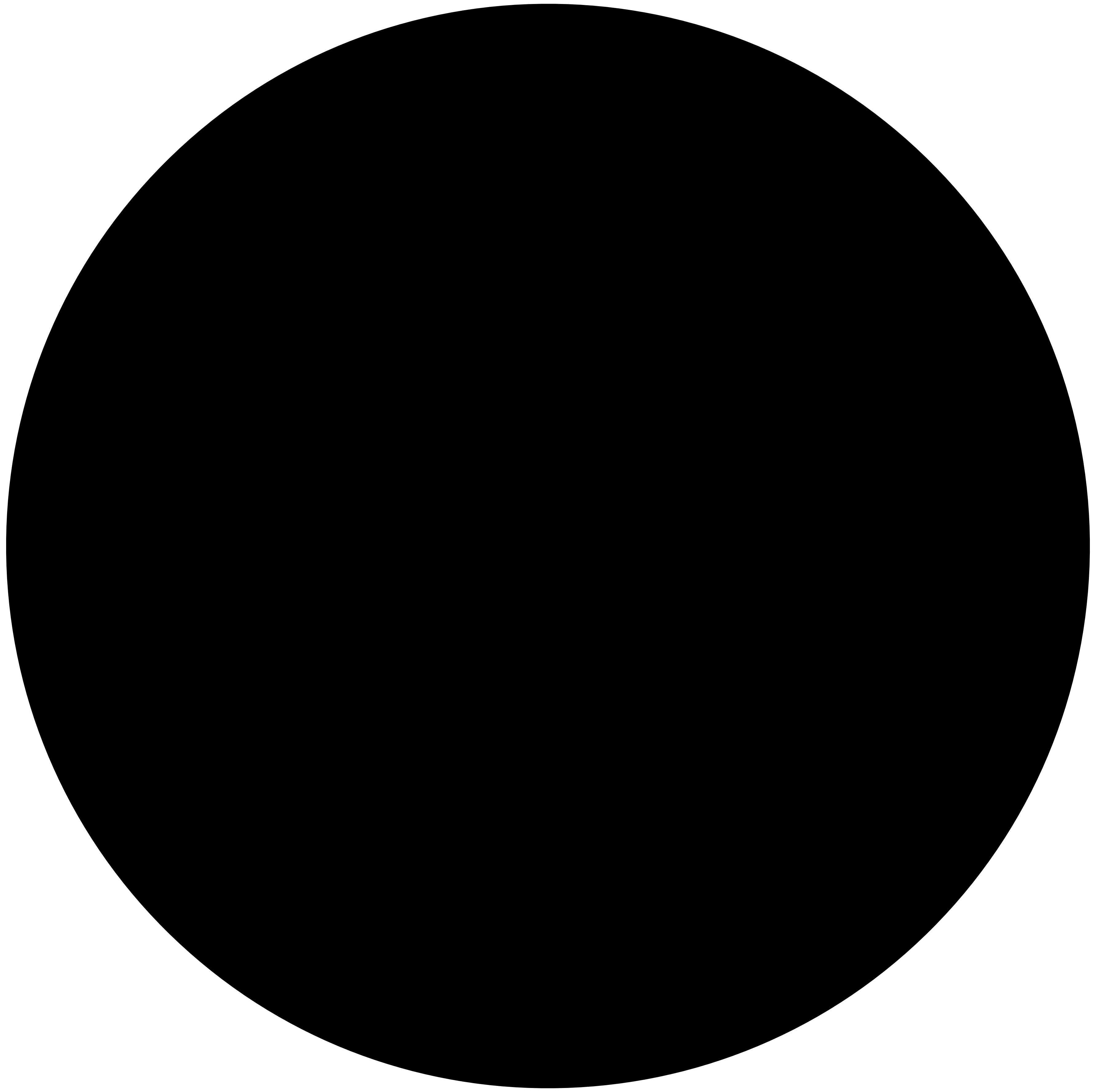
Black holes 101



Black holes 101

$r \sim 5 \text{ cm}$

$r = GM/c^2$

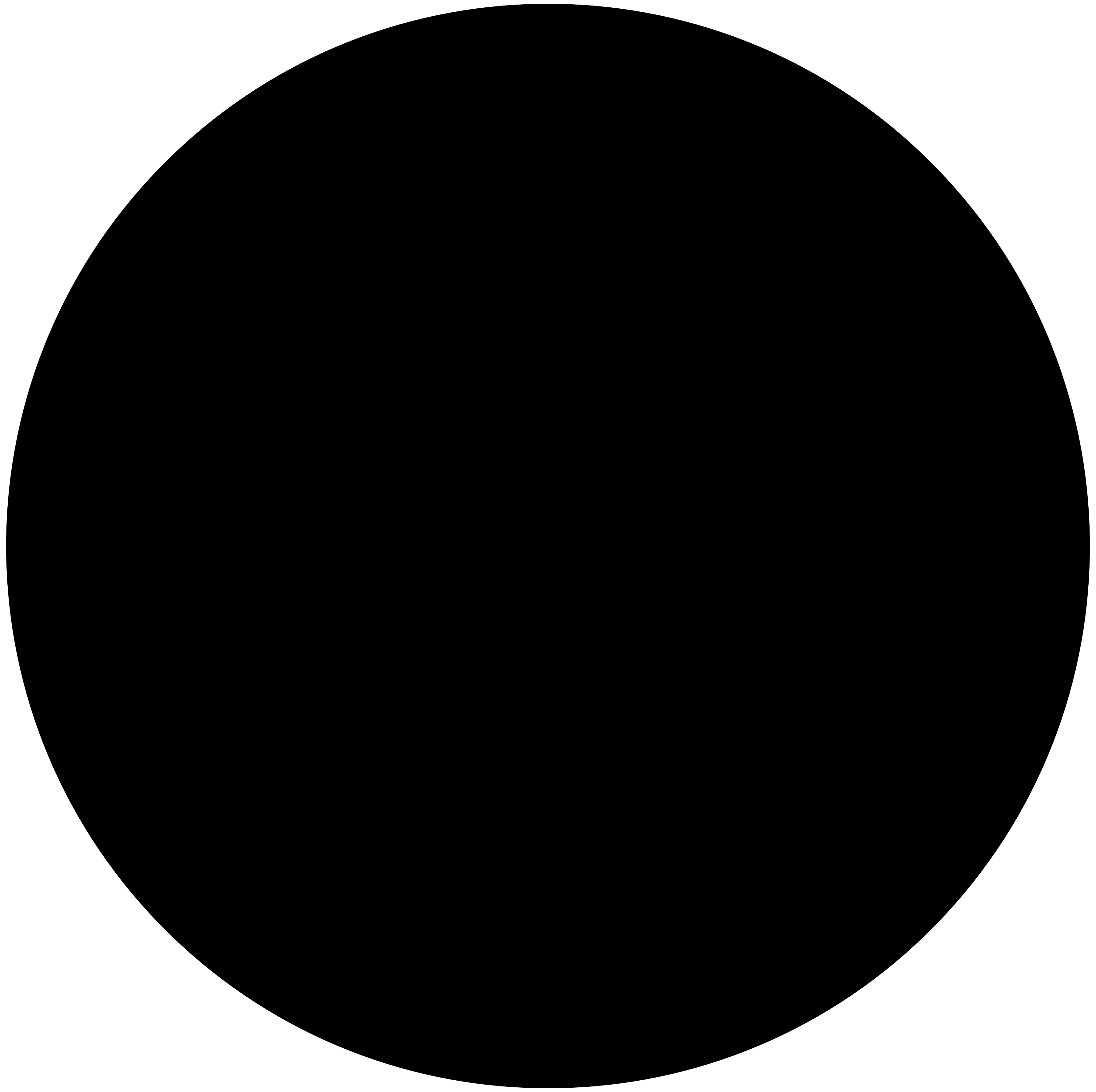


Black holes 101

$r \sim 5\ \text{cm}$

$r = GM/c^2$

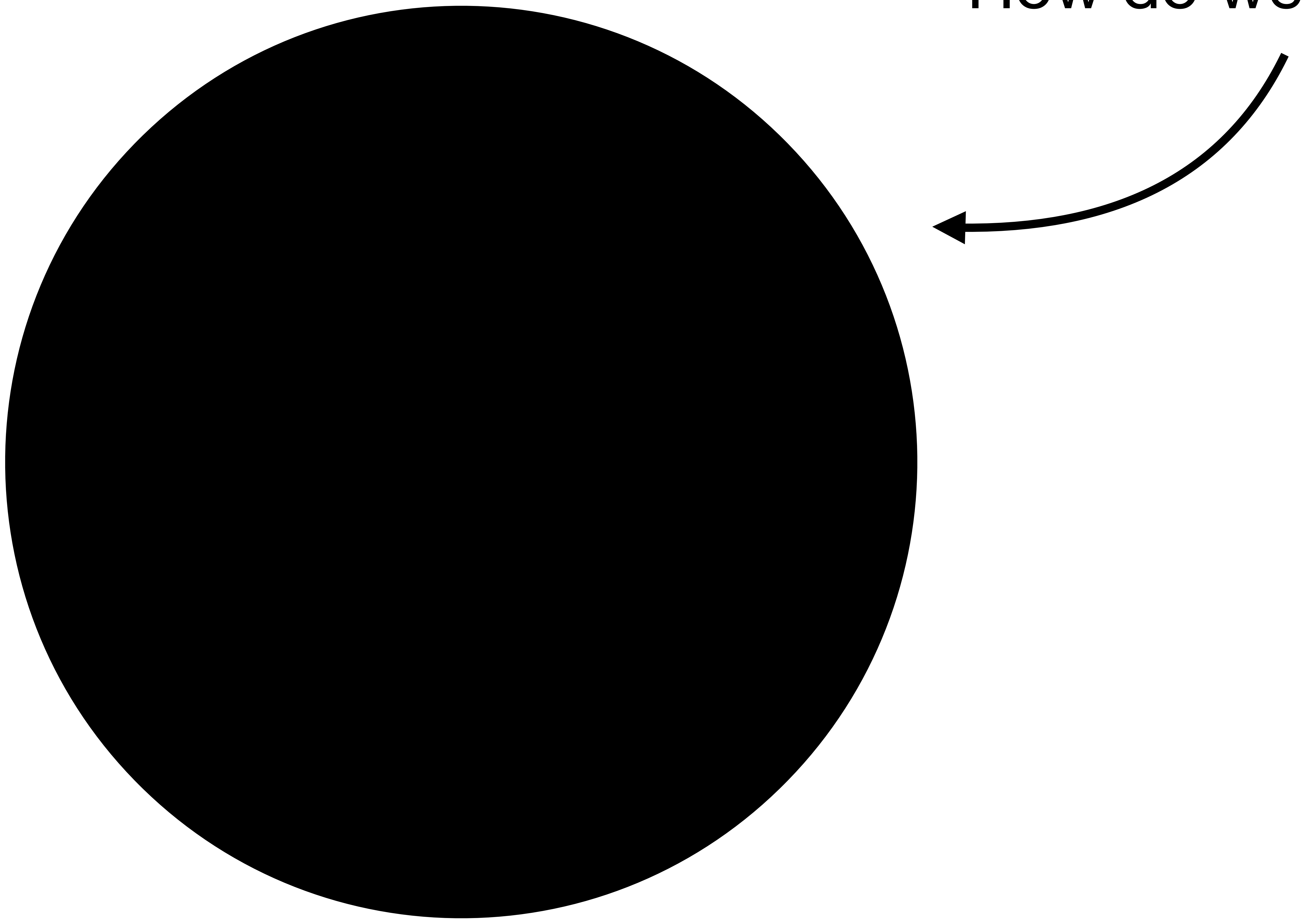
$$M \sim \frac{0.05 \times 9 \times 10^{16}}{6.67 \times 10^{-11}}$$



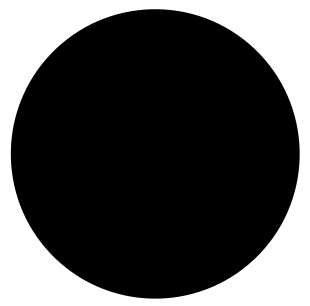
$$M \sim 7 \times 10^{25}\ \text{kg} \sim 10\ M_{\text{Earth}}$$

Accretion

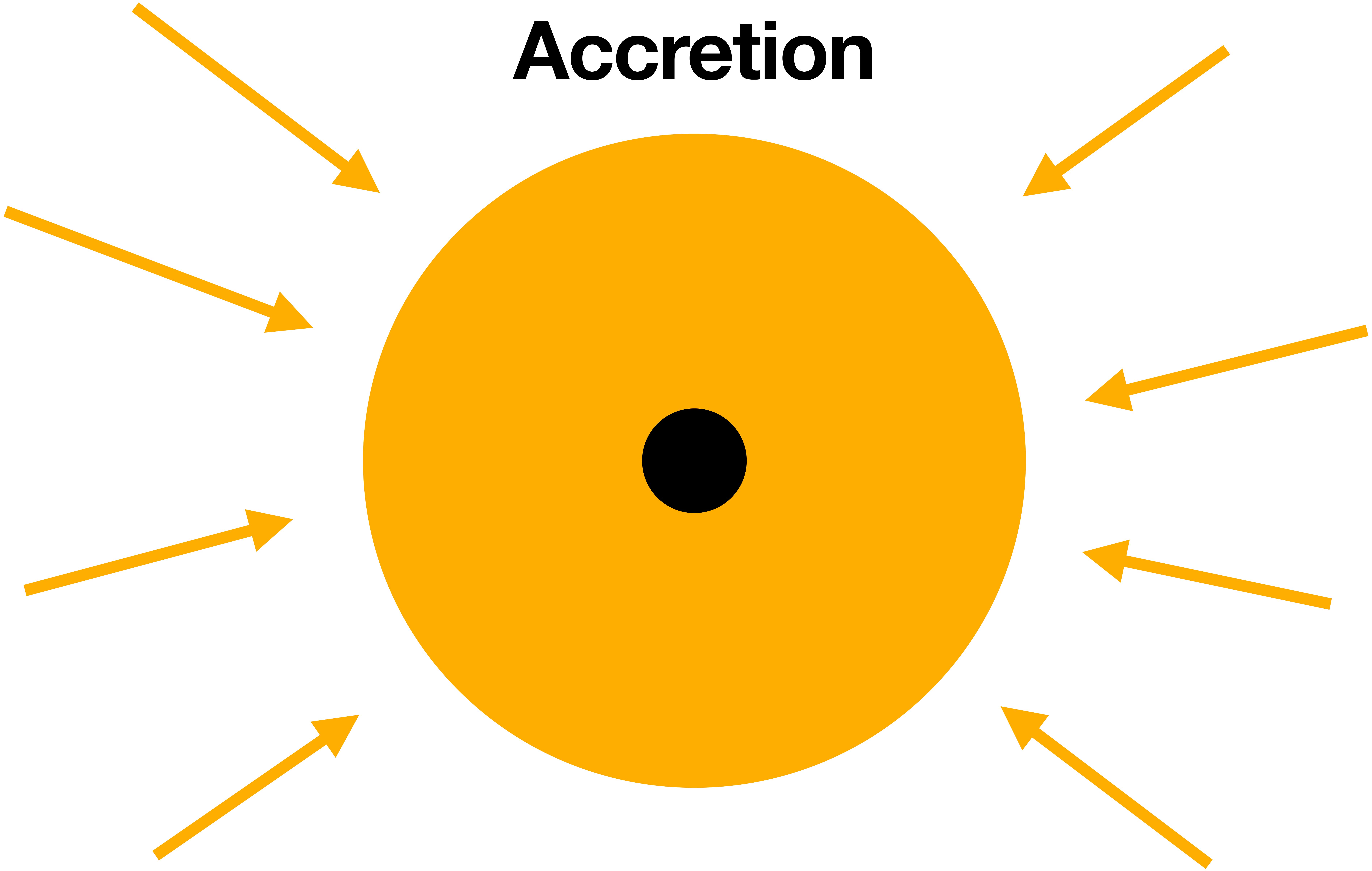
How do we see this?



Accretion



Accretion



Accretion

Accretion

As a particle spirals inwards, it loses energy:

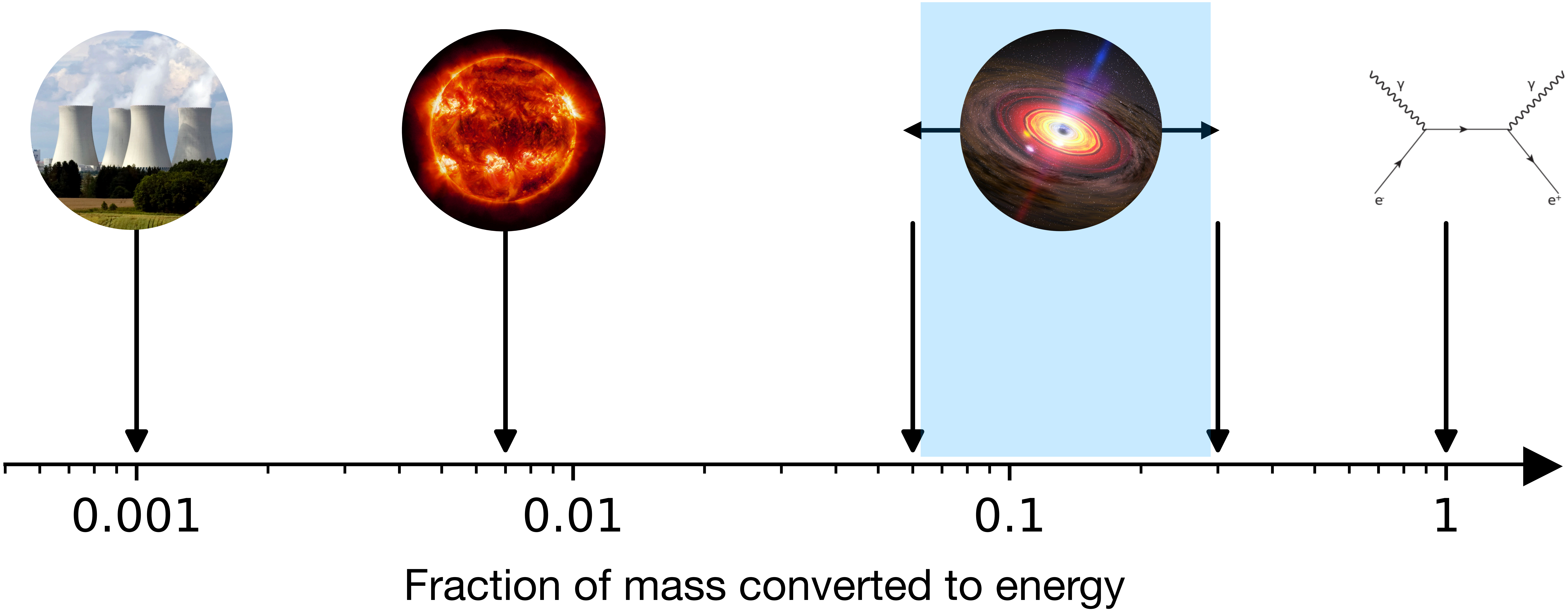
$$E = mc^2 - GMm/r$$

$$r = 2GM/c^2$$

$$E = \frac{1}{2}mc^2$$

A large fraction of the rest mass energy is lost as radiation

Accretion

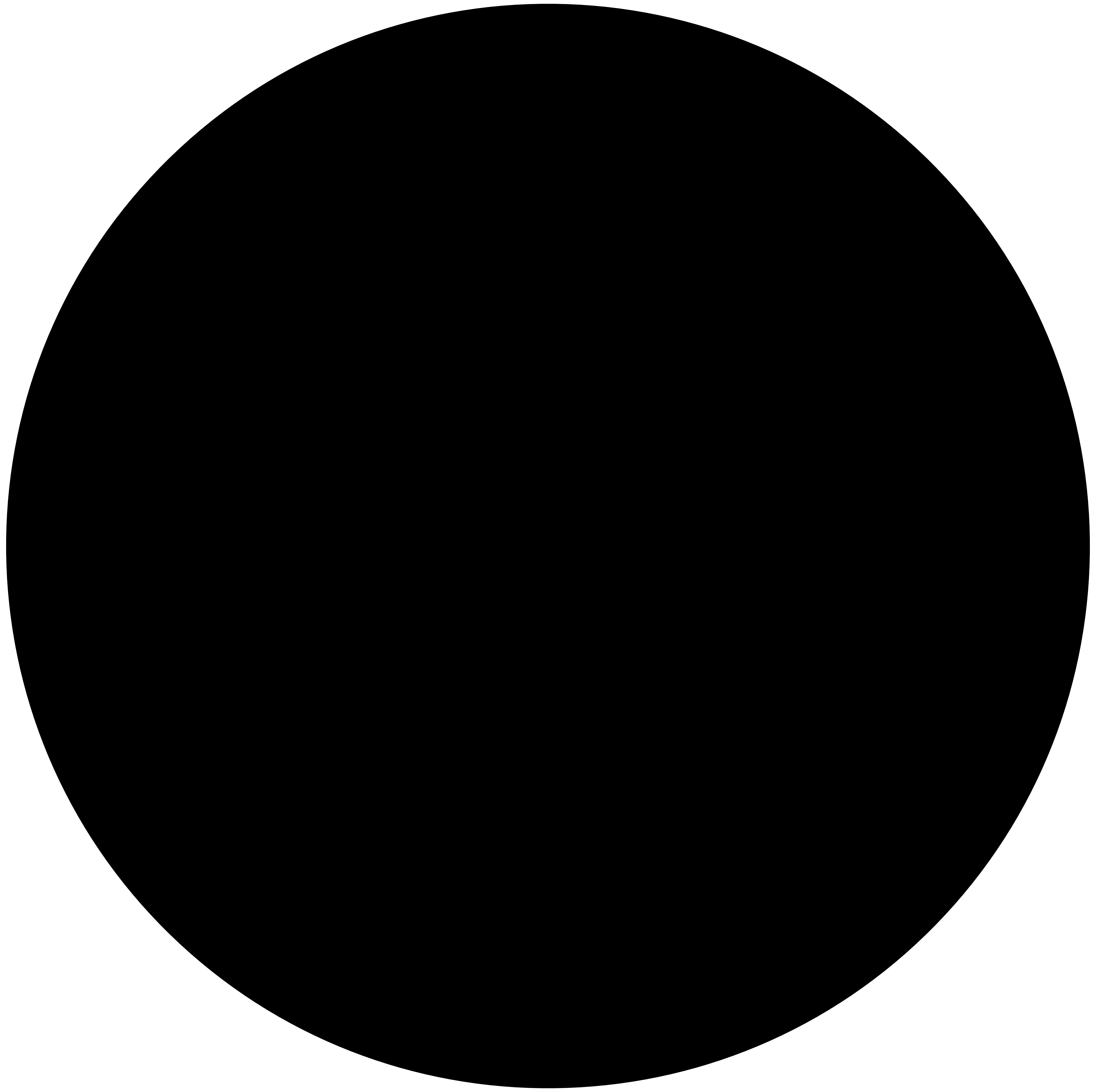


Total energy release

$$M = 10^8 M_\odot$$

$$r \sim 1.5 \times 10^{11}\ \text{m}$$

$$r \sim 1\ \text{AU}$$



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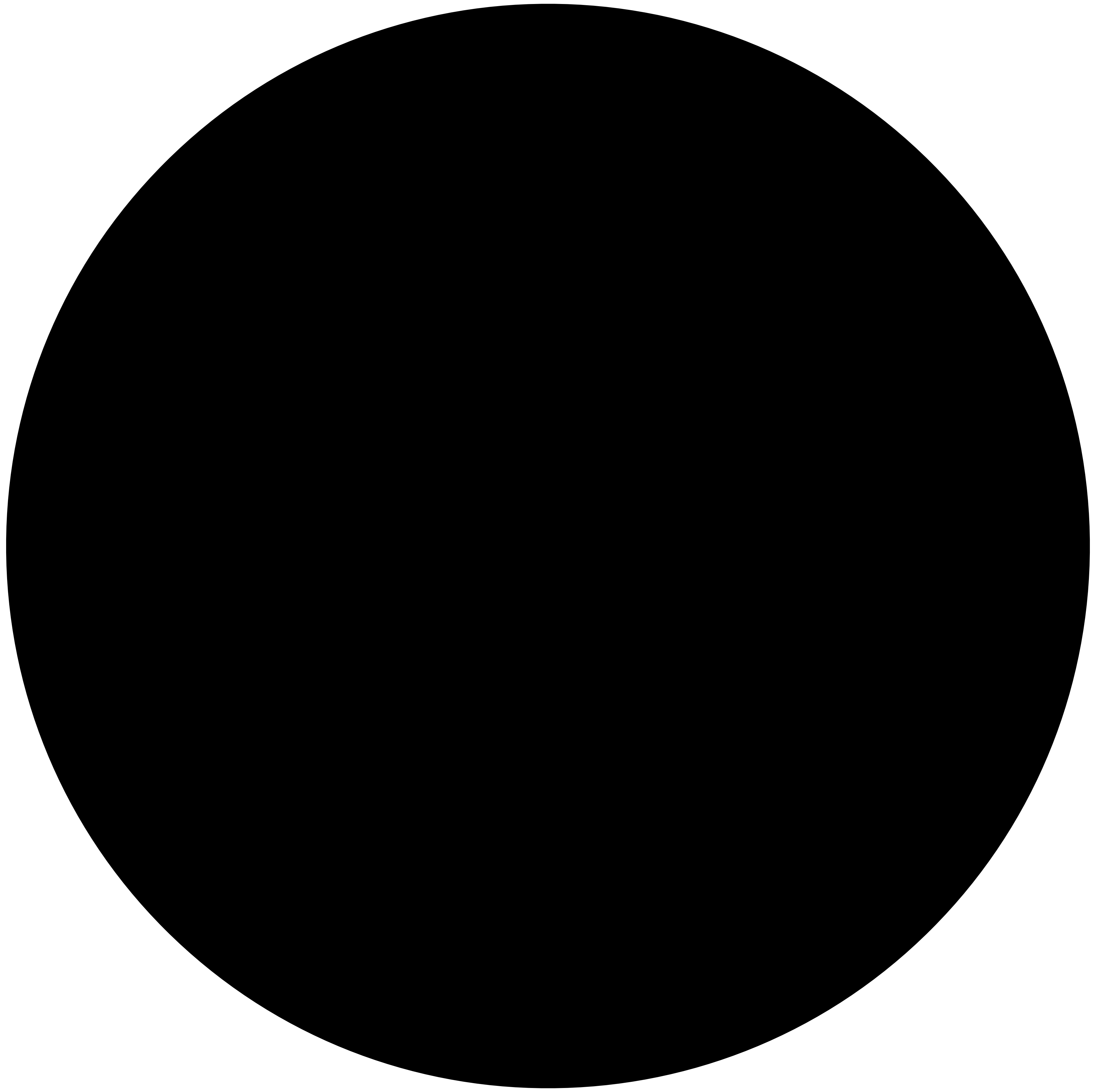

$$E = M\eta c^2$$

$$(\eta \sim 0.1)$$

$$E = 2 \times 10^{55} \; J$$

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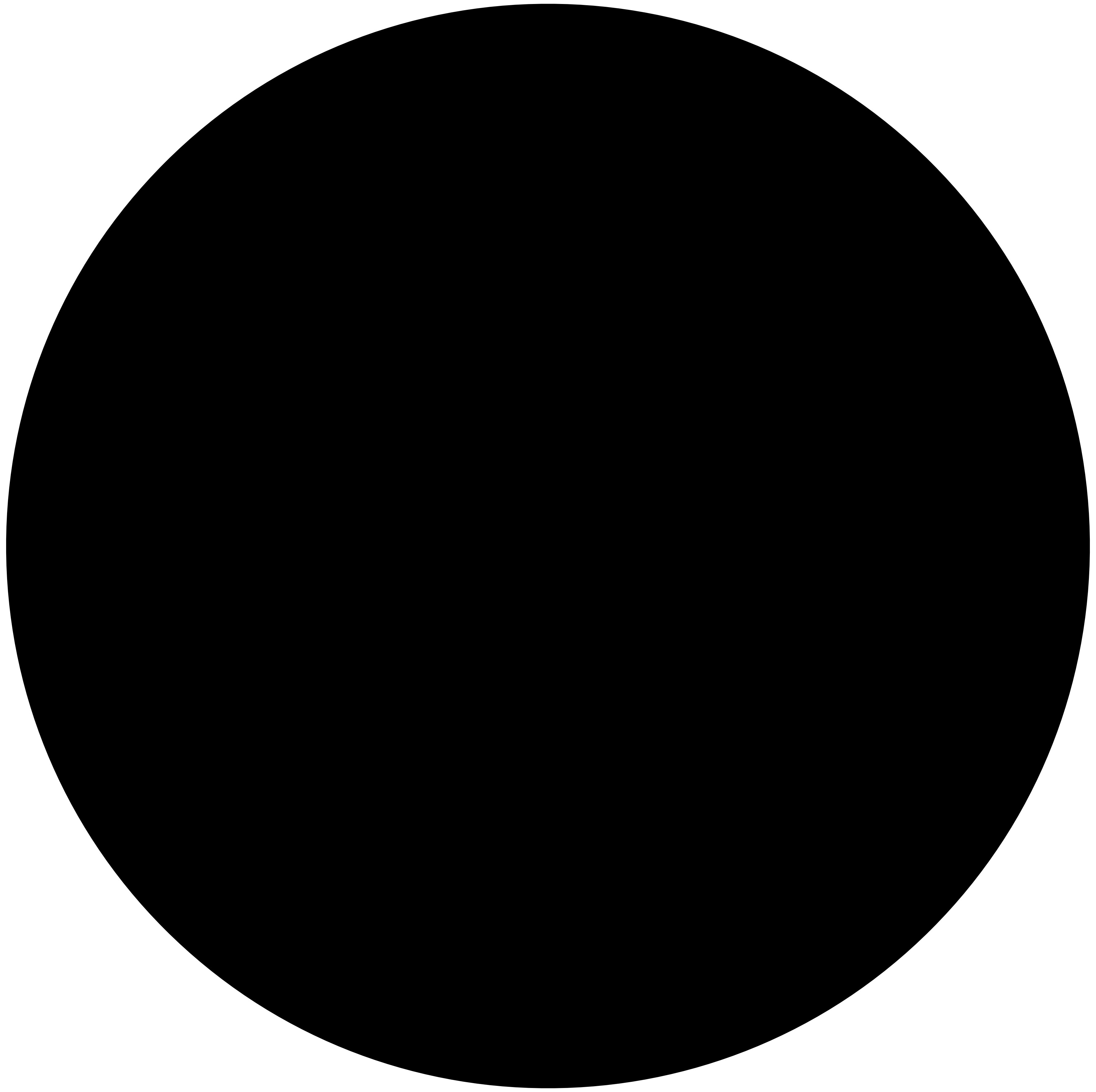

$$E = M\eta c^2$$

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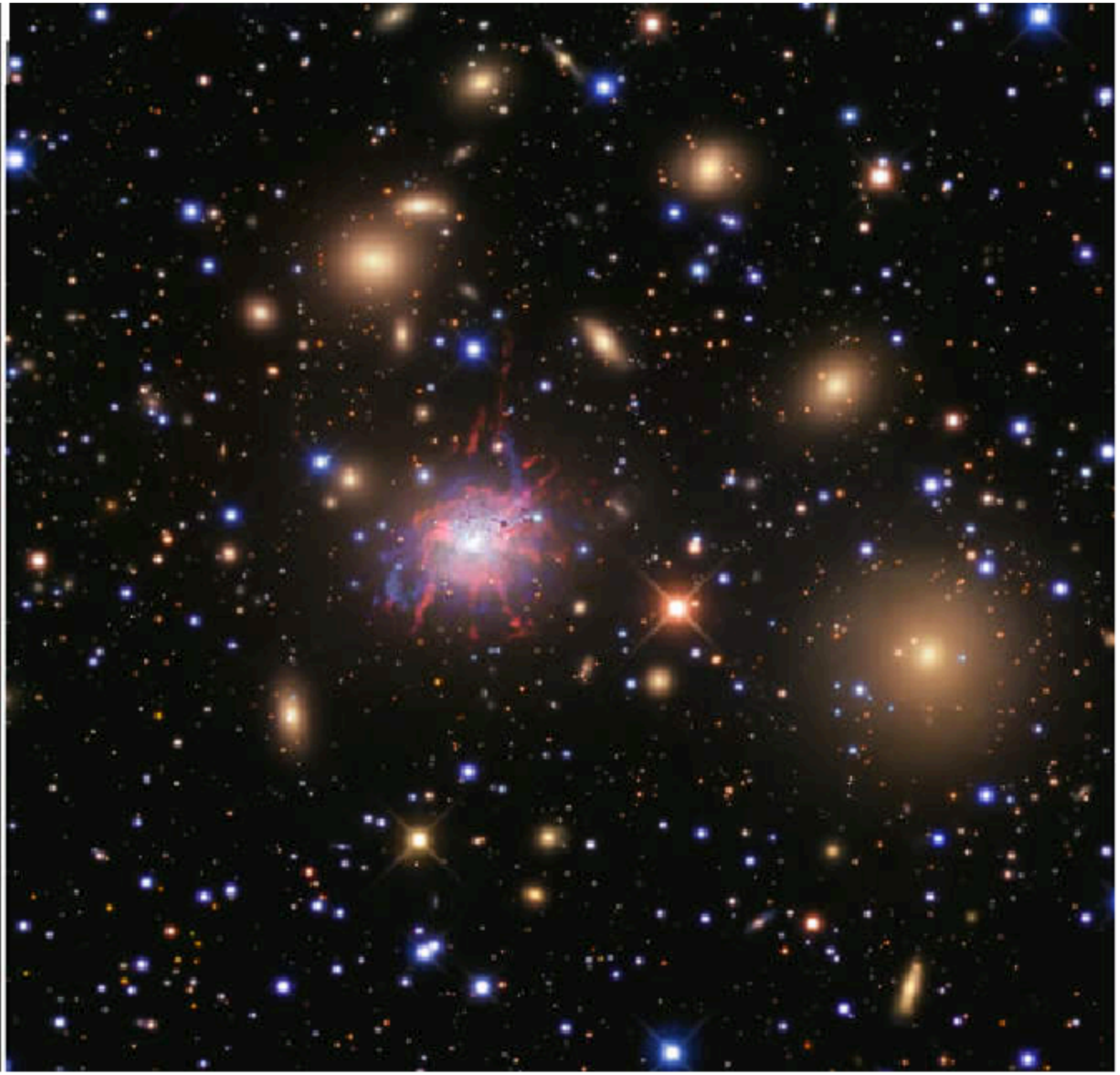
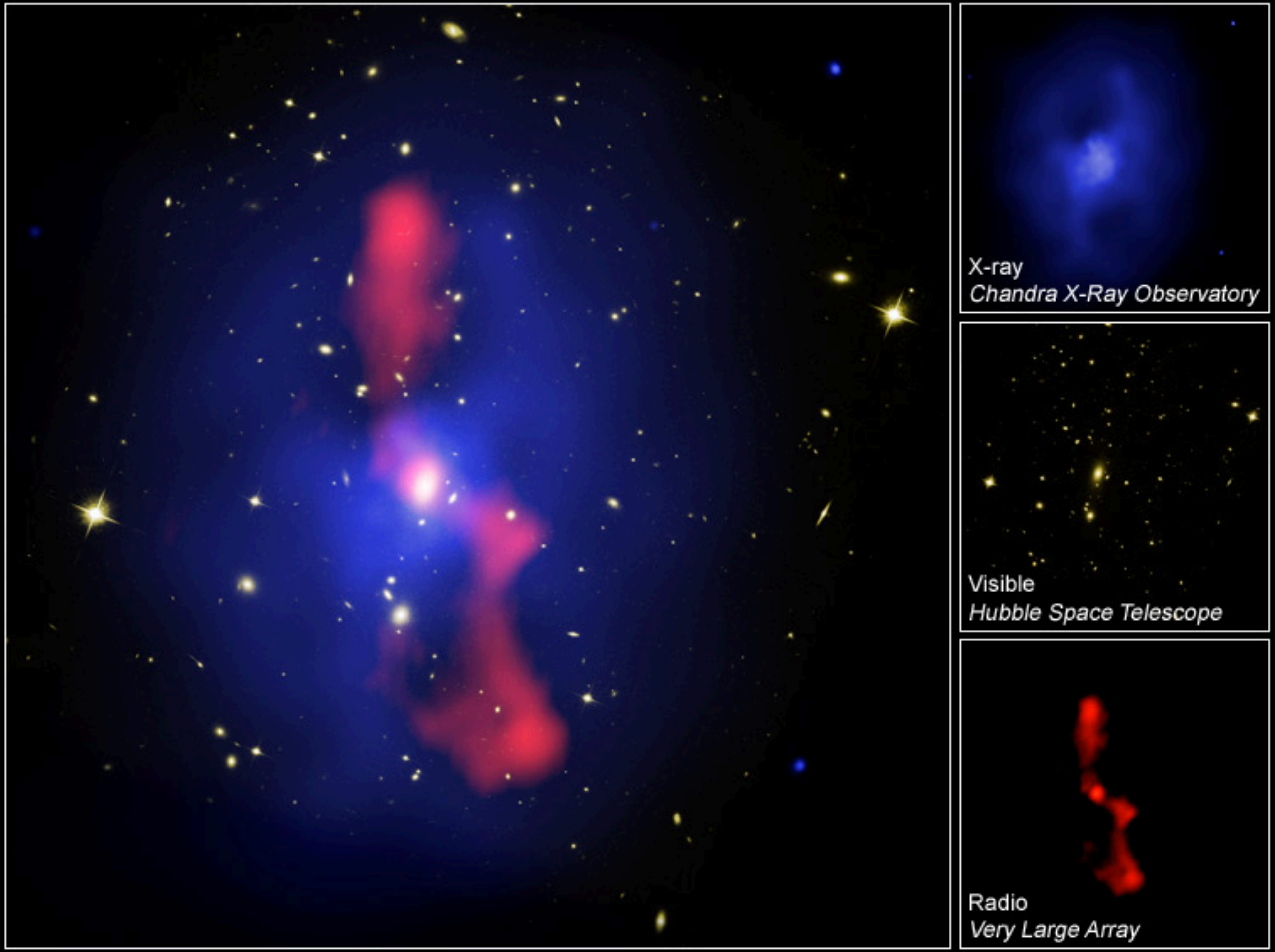
$$E = 2 \times 10^{55}\ J$$

The energy radiated by 100 billion stars over 14 billion years



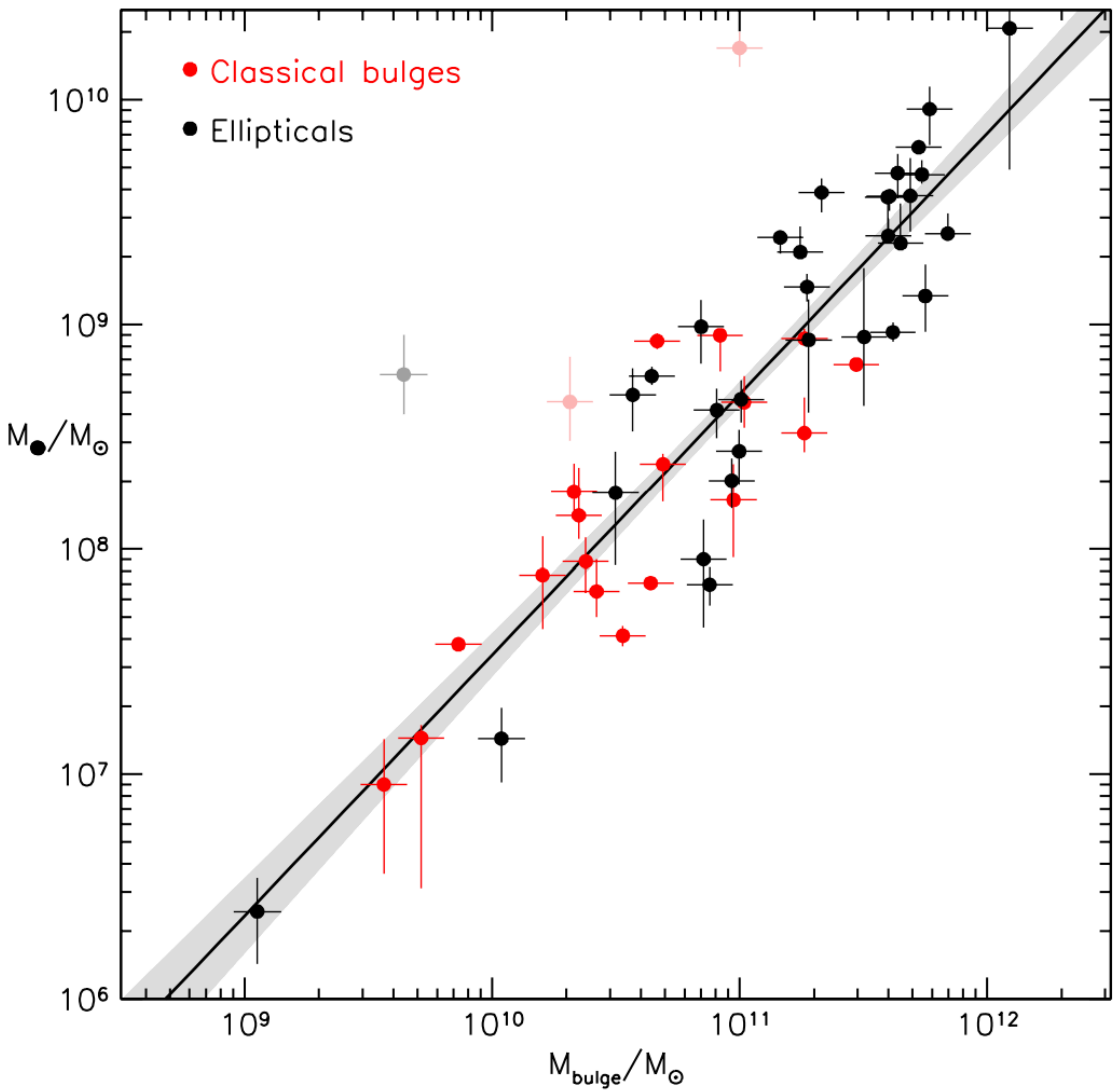
Galaxy Cluster MS 0735.6+7421

CXO ▪ HST ▪ VLA



NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University) STScI-PRC06-51

Black Hole Mass

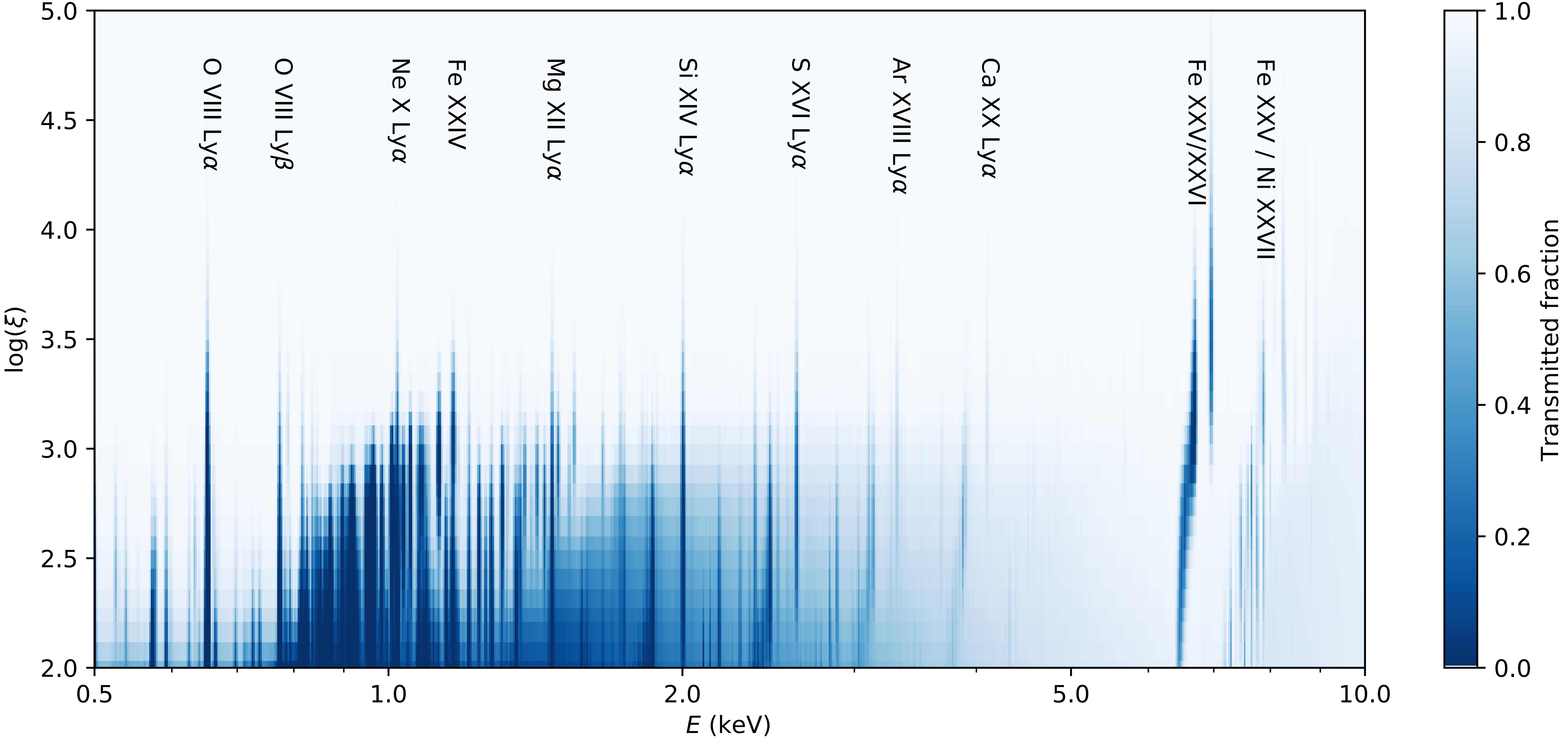


Galactic Bulge Mass

Kormendy & Ho, ARA&A, 2013

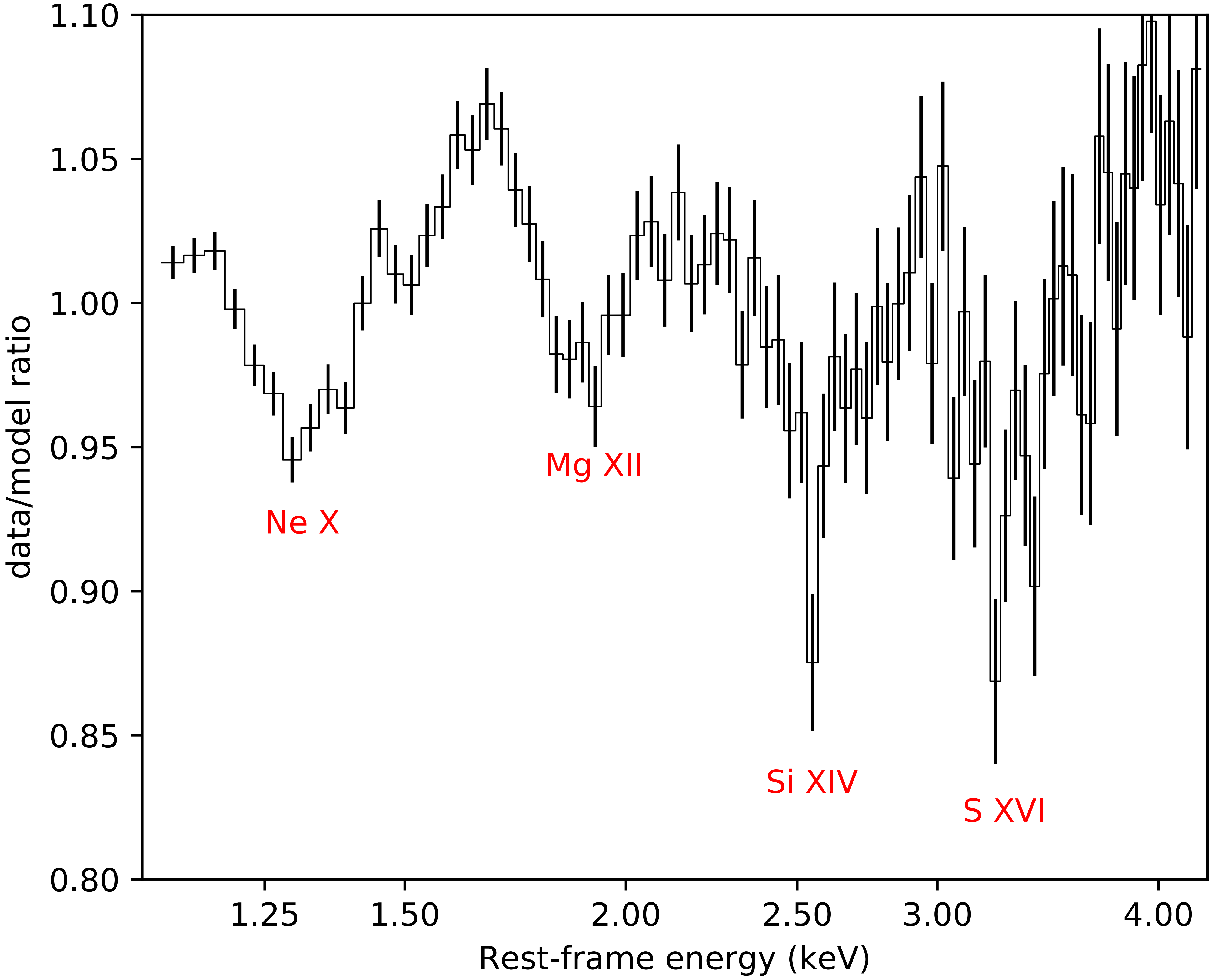
Black holes must be regulating galaxy growth…

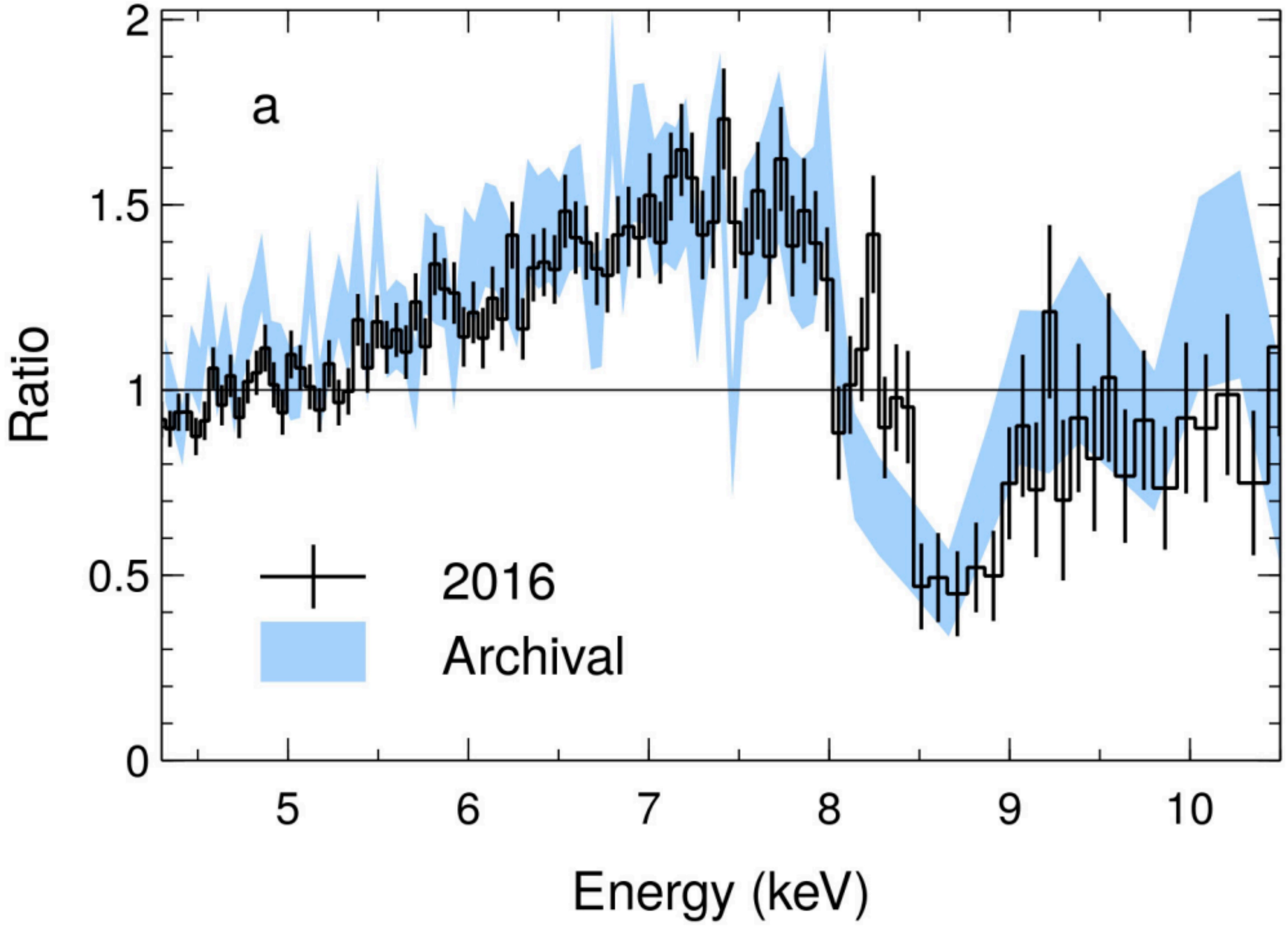
Observational signatures



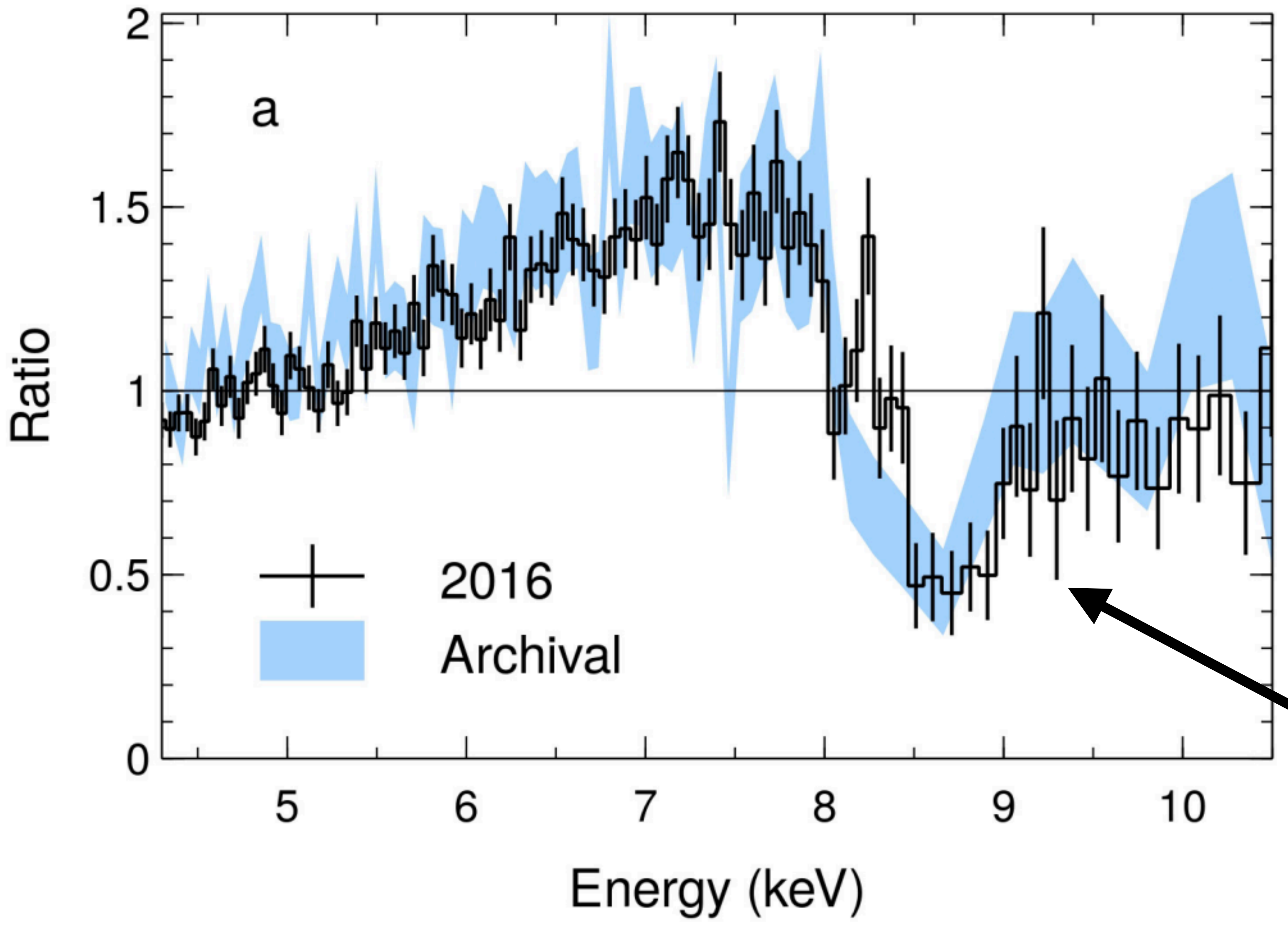
Parker et al, MNRAS, 2018

X-ray Spectroscopy

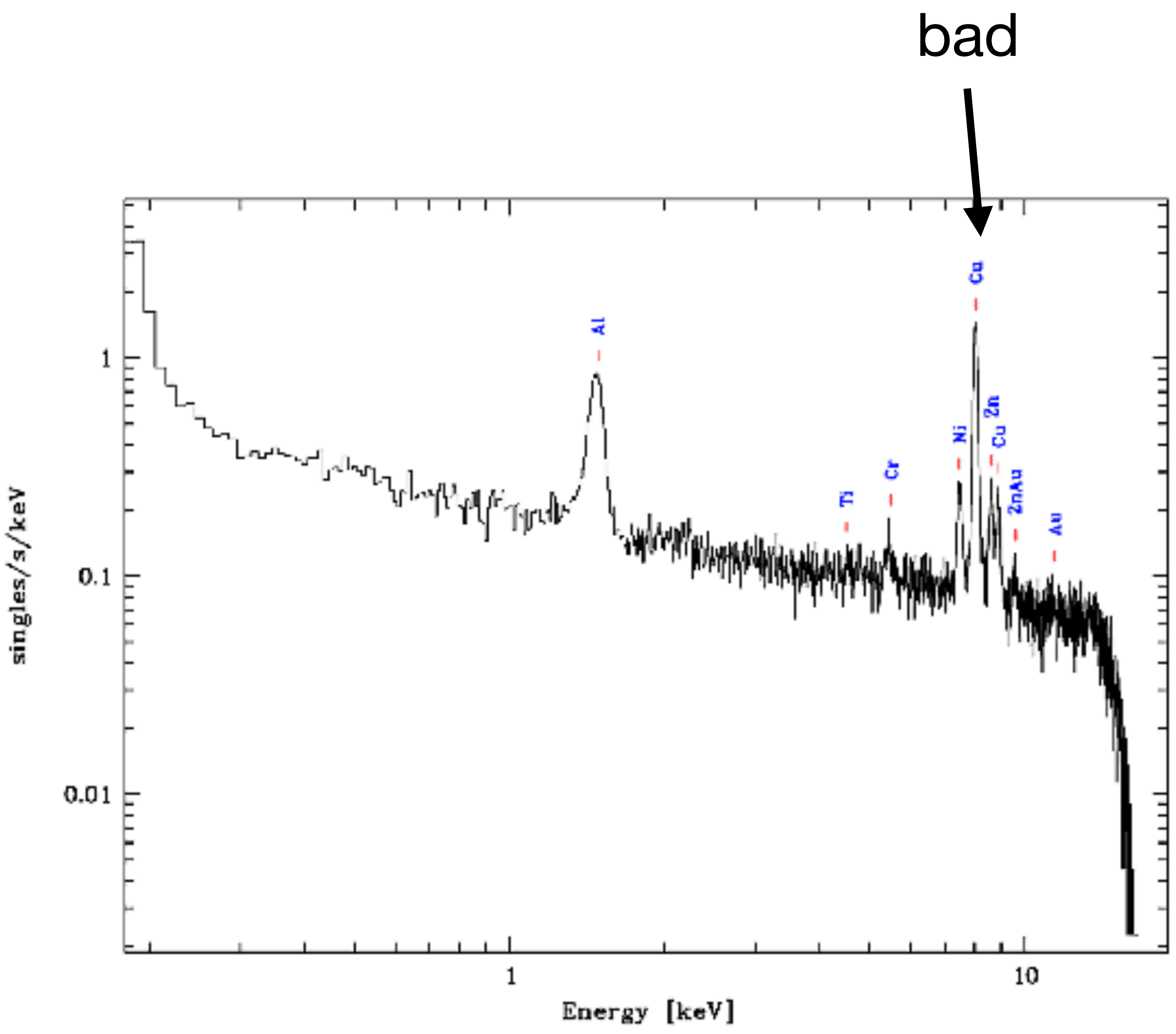


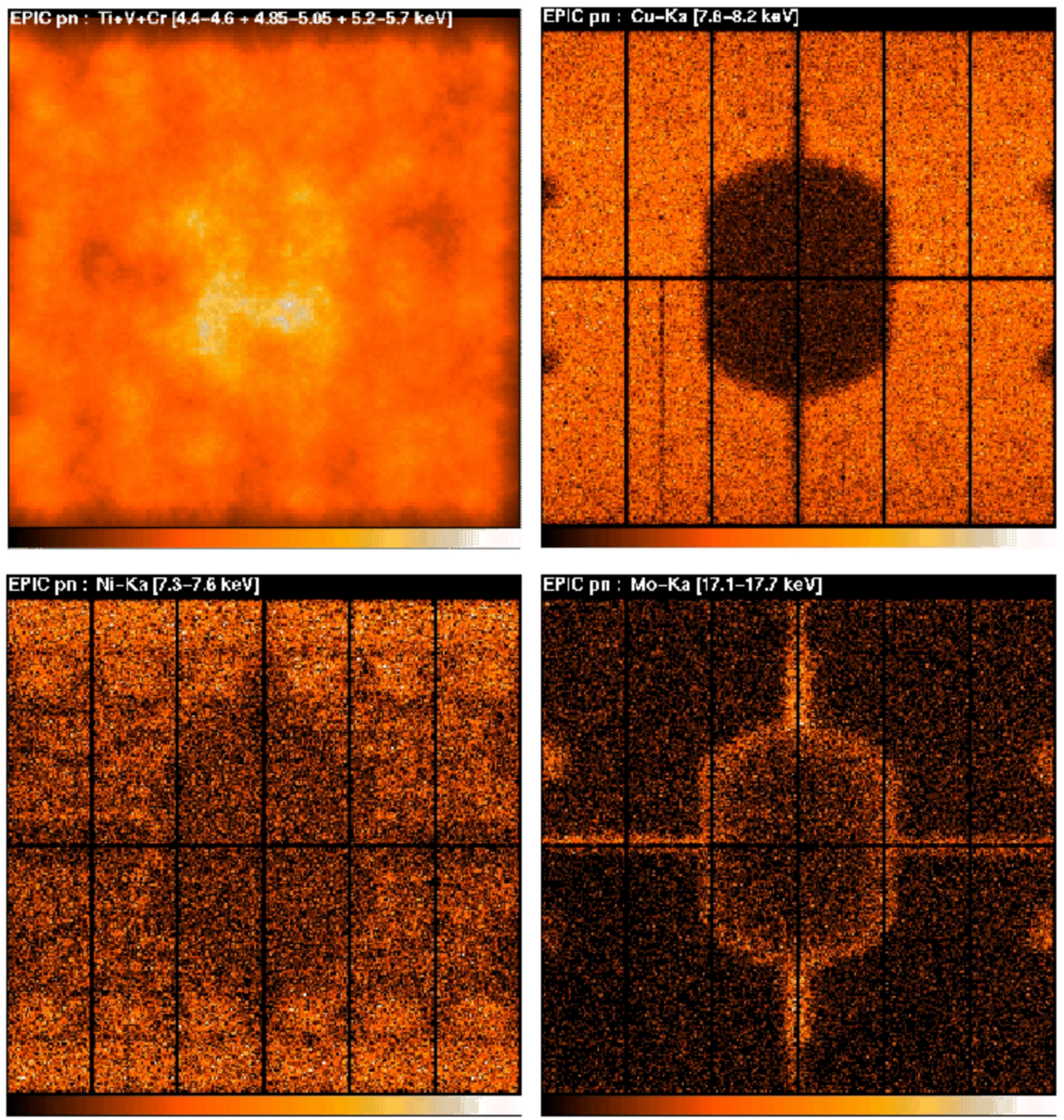


Parker et al., Nature, 2017



This is frequently the only observed spectral feature, and spectroscopy here is hard.


bad
Cu
Al
Zn
Ni
Cu
Cr
Ti
ZnAu
Au
1
0.1
0.01
singles/s/keV
1
10
Energy [keV]


EPIC pn : Ti+V+Cr [4.4–4.6 + 4.85–5.05 + 5.2–5.7 keV]
EPIC pn : Cu-Ka [7.6–8.2 keV]
EPIC pn : Ni-Ka [7.3–7.6 keV]
EPIC pn : Mo-Ka [17.1–17.7 keV]

Background Summary:

- Supermassive black holes live in centers of galaxies, feeding on gas
- They release huge quantities of energy, which can regulate galaxy growth
- One of the leading candidates for this is powerful winds, launched from the accretion disk
- Winds are hard to detect - only a few absorption lines in the X-ray band
- X-ray spectroscopy is hard, limited by poor photon counts, calibration and contamination at high energies

Optical and X-ray detectors

- Lots of photons
- No individual information

- Hardly any photons
- Lots of individual information

File Edit Tools Help

Select	TIME	RAWX	RAWY	DETX	DETY	X	Y	PHA	PI	FLAG	PATTERN	PAT_ID	PAT_SEQ	CCDNR	TIME_RAW
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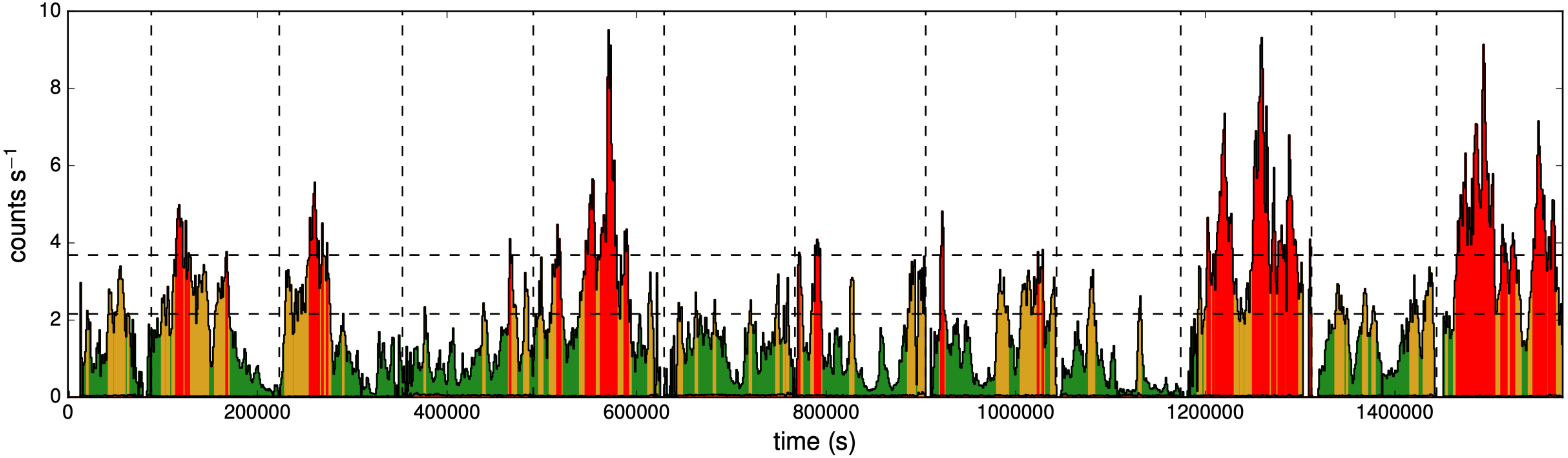
1	7.041516543611E+08	22	145	1403	3497	28872	24666	555	2944	0	3	5121	1	4	7.041516543595E+08
2	7.041516543700E+08	38	191	80	-294	26533	27929	58	528	0	3	5121	1	4	7.041516543708E+08
3	7.041516545315E+08	35	189	308	-115	26802	27822	82	429	0	0	0	0	4	7.041516545296E+08
4	7.041516545512E+08	38	191	35	-296	26489	27918	173	948	0	0	0	0	4	7.041516545523E+08
5	7.041516545650E+08	38	190	44	-167	26534	27797	166	905	0	0	0	0	4	7.041516545637E+08
6	7.041516545793E+08	38	188	54	-51	26576	27688	53	530	0	4	5121	0	4	7.041516545807E+08
7	7.041516545862E+08	21	180	1473	611	28124	27454	80	629	0	3	5121	1	4	7.041516545863E+08
8	7.041516546779E+08	36	189	212	-105	26713	27785	28	151	0	0	0	0	4	7.041516546771E+08
9	7.041516549569E+08	37	192	163	-328	26603	27985	98	535	0	0	0	0	4	7.041516549550E+08
10	7.041516549621E+08	38	190	80	-189	26562	27828	159	867	0	0	0	0	4	7.041516549607E+08
11	7.041516549964E+08	35	190	285	-233	26746	27928	38	203	0	0	0	0	4	7.041516549947E+08
12	7.041516550557E+08	35	190	292	-204	26761	27902	34	177	0	0	0	0	4	7.041516550571E+08
13	7.041516551178E+08	36	190	212	-213	26682	27889	220	1218	0	0	0	0	4	7.041516551195E+08

Each row = 1 photon

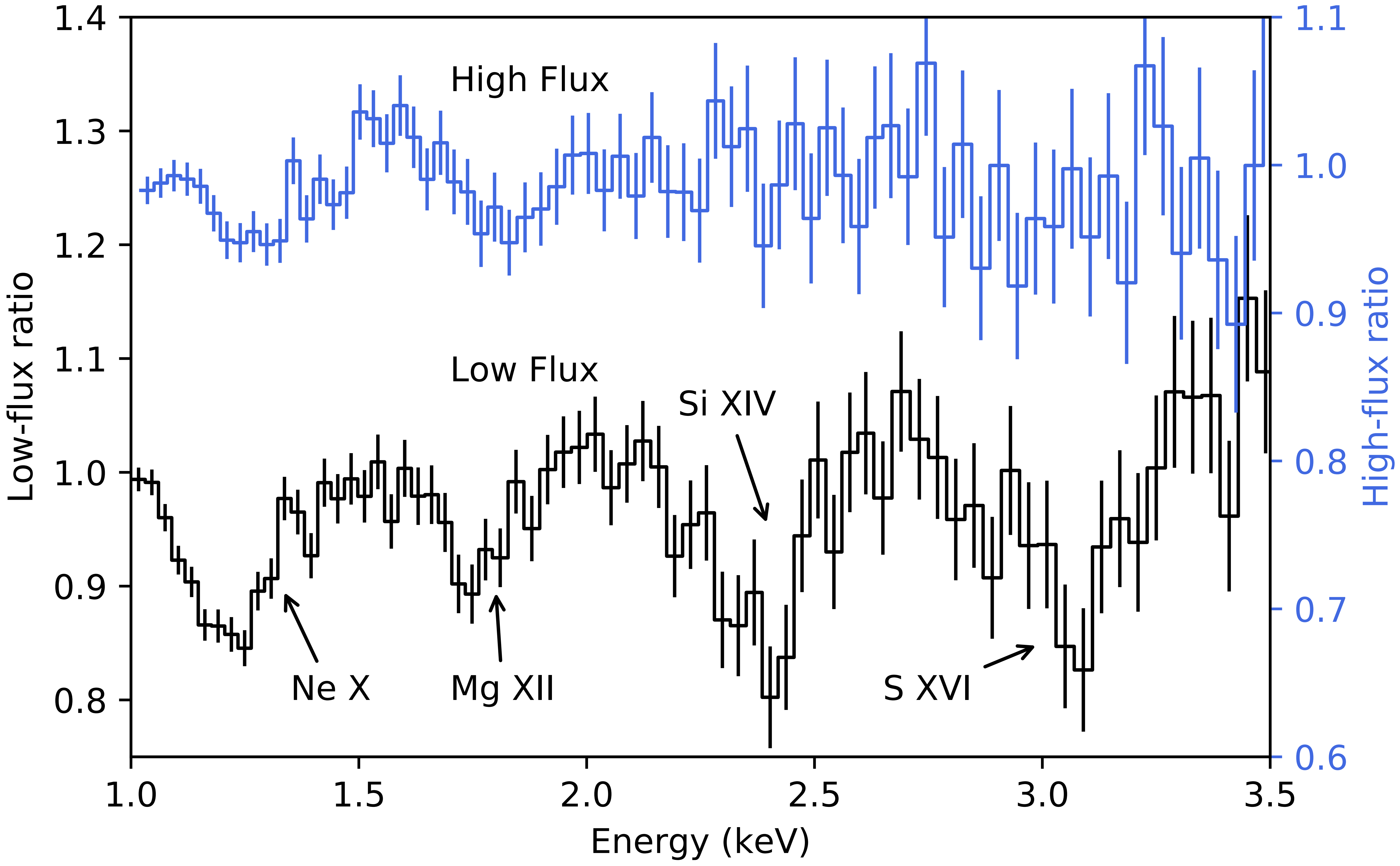
X-ray Timing



Parker et al., Nature, 2017

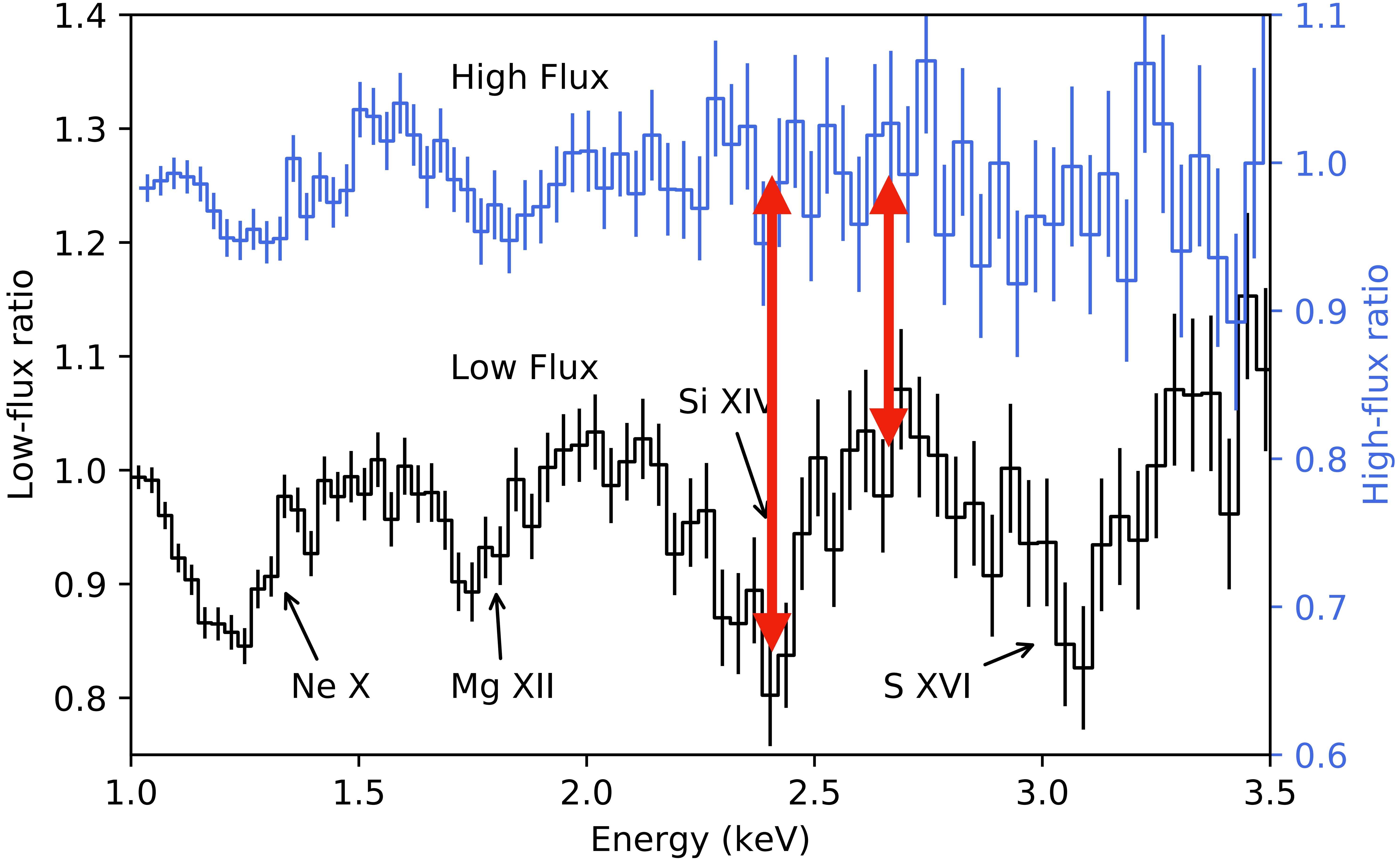
Flux-resolved spectra

We don't really know why this happens…

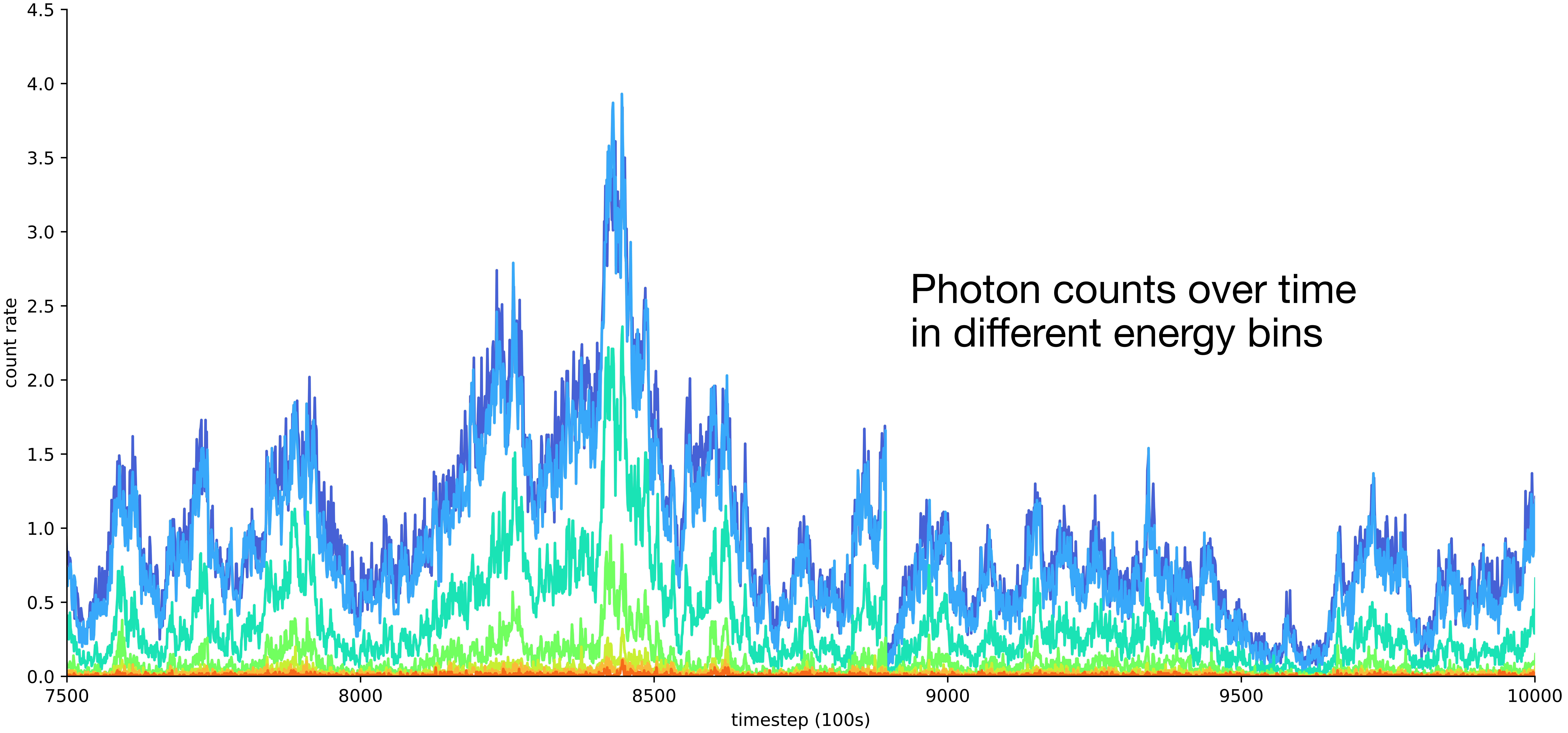


Parker et al. 2017a,b, Pinto et al. 2018, Jiang et al. 2018

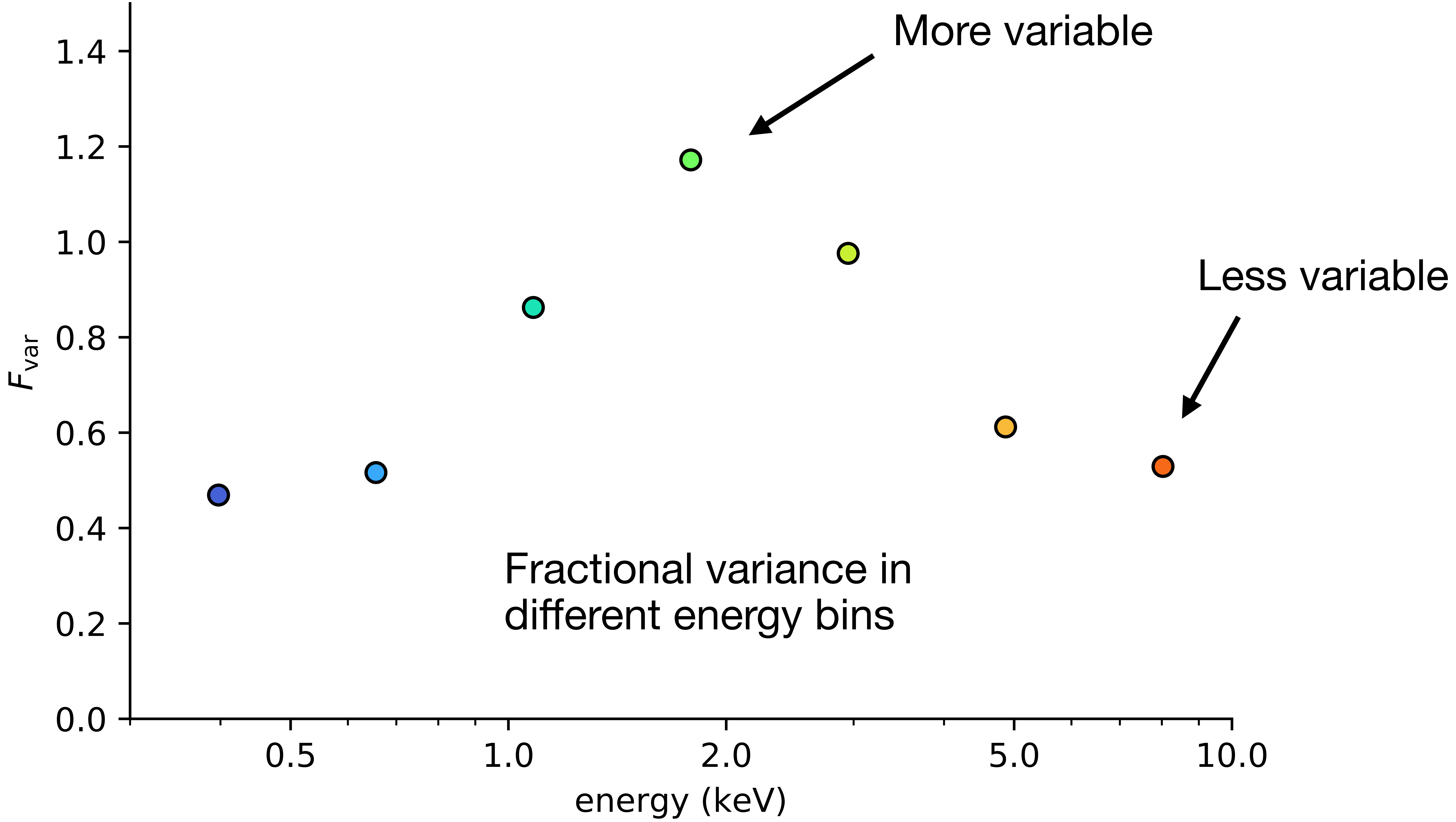
Flux-resolved spectra

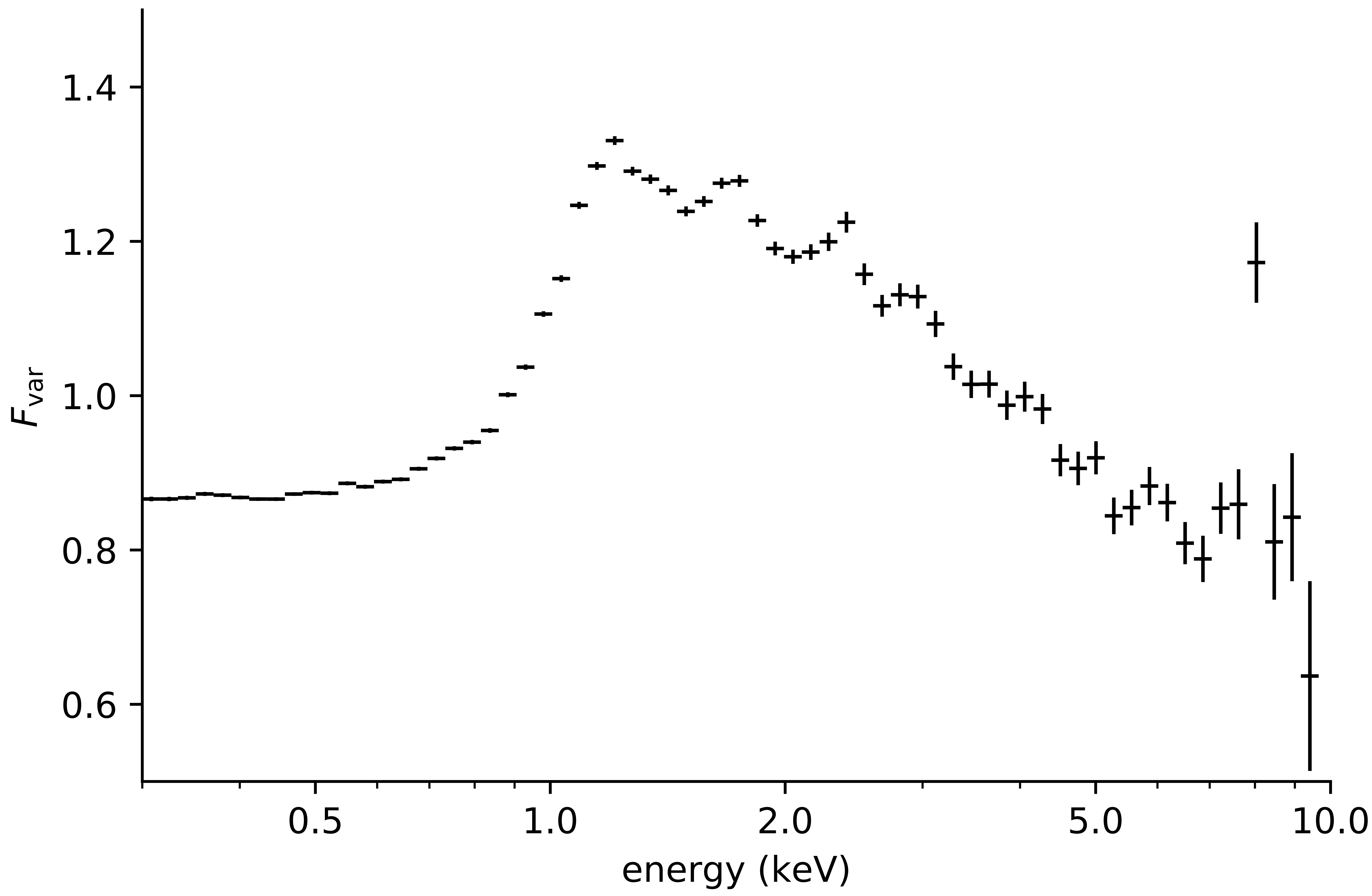


Parker et al. 2017a,b, Pinto et al. 2018, Jiang et al. 2018



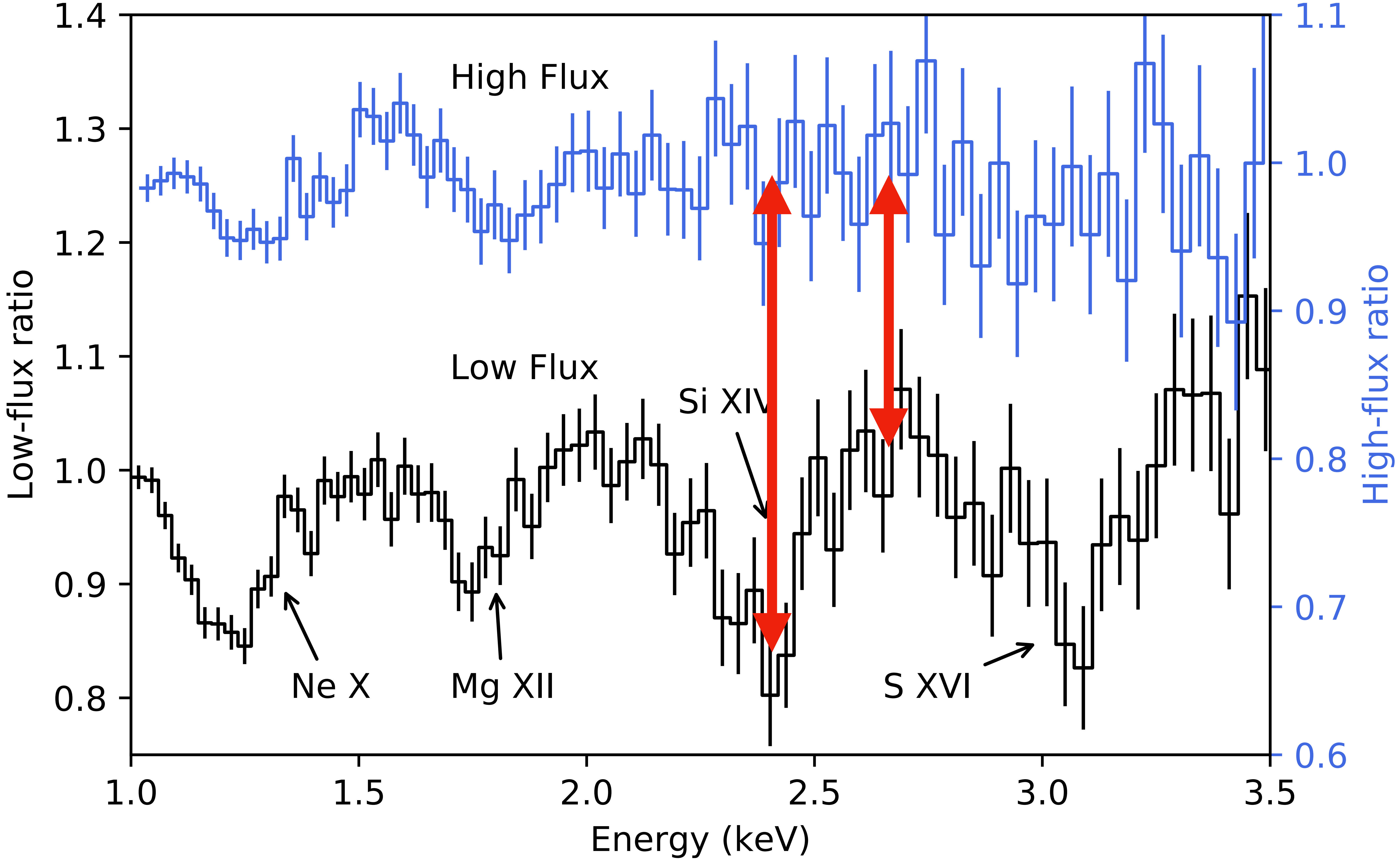
Photon counts over time
in different energy bins
count rate
timestep (100s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
7500
8000
8500
9000
9500
10000


More variable
Less variable
Fractional variance in different energy bins
F_{var}
energy (keV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0.5
1.0
2.0
5.0
10.0

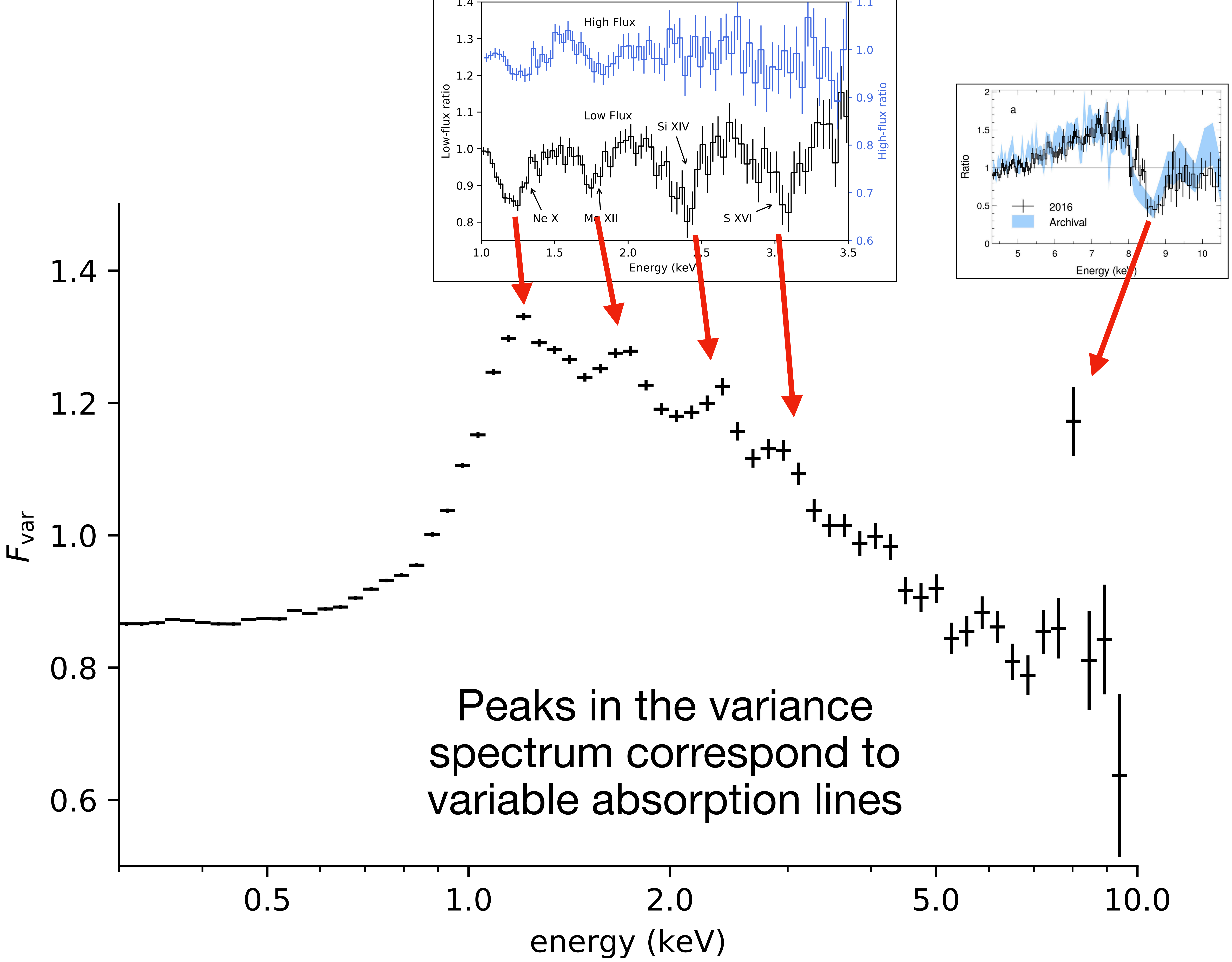


1.4
1.2
1.0
0.8
0.6
F_{var}
0.5
1.0
2.0
5.0
10.0
energy (keV)

Flux-resolved spectra



Parker et al. 2017a,b, Pinto et al. 2018, Jiang et al. 2018

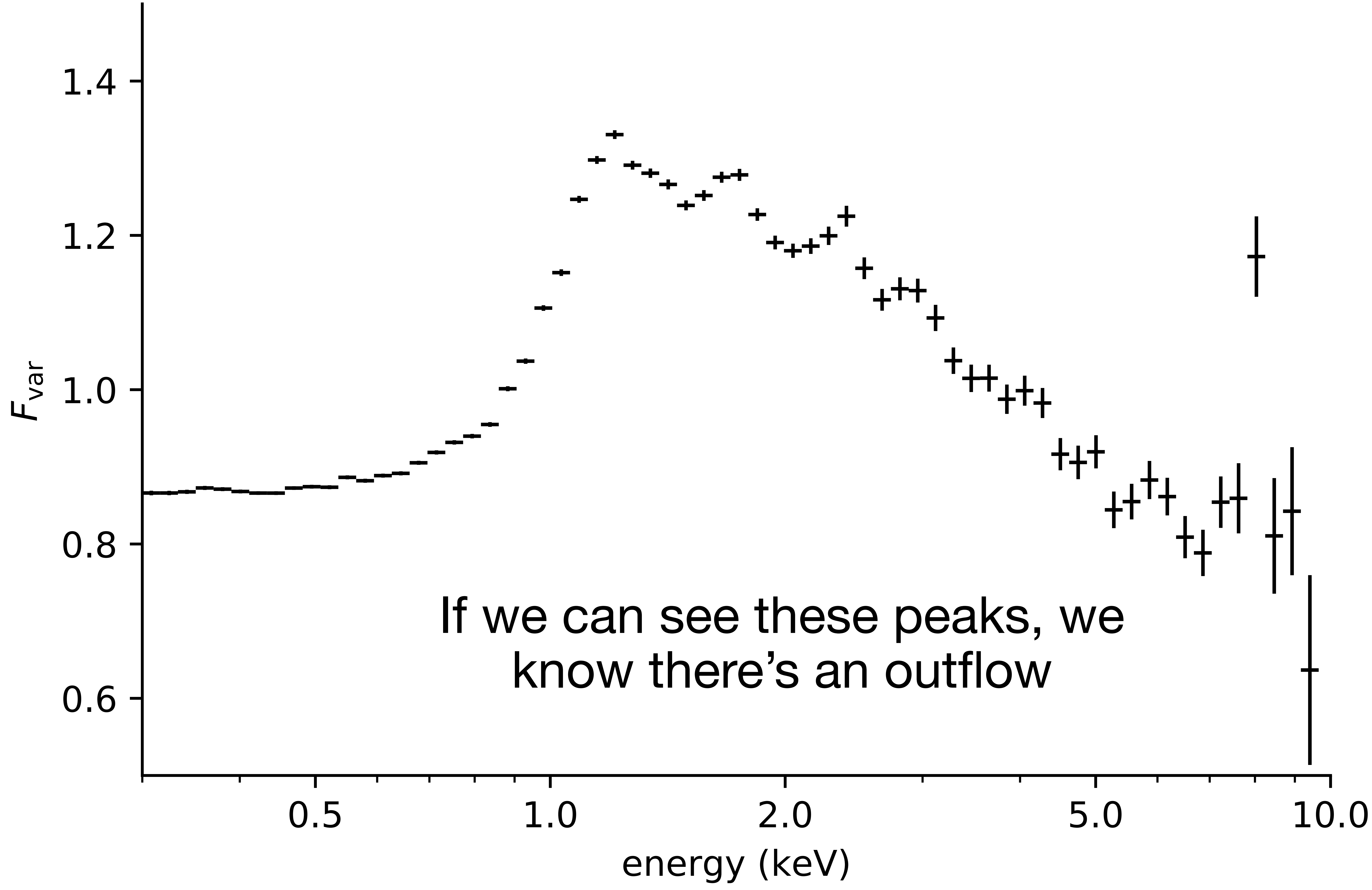


High Flux
Low Flux
Ne X
Mg XII
Si XIV
S XVI
Low-flux ratio
High-flux ratio
Energy (keV)
a
2016
Archival
Ratio
Energy (keV)
F_{var}
energy (keV)
Peaks in the variance
spectrum correspond to
variable absorption lines

Variability spectra → **Outflow Detection**

Variability spectra → **Outflow Physics**

Outflow detection



If we can see these peaks, we know there's an outflow

Outflow detection

Searching for Ultra-fast Outflows in AGN using Variability Spectra

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Accepted XXX. Received YYY; in original form ZZZ

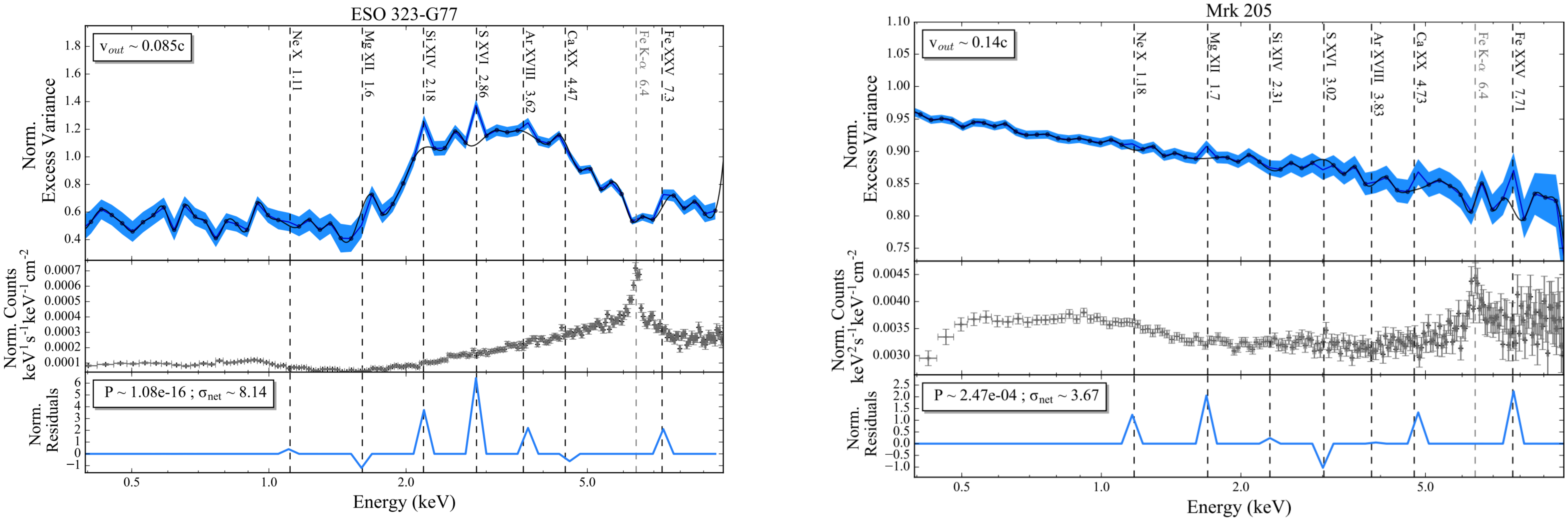
Variance analysis of 58 bright, variable black holes

ABSTRACT

We present a qualitative search for ultra-fast outflows (UFOs) in excess variance spectra of radio-quiet active galactic nuclei (AGN). We analyse 42 sources from the Tombesi et al. (2010) spectroscopic UFO detection sample, and an additional 22 different sources from the Kara et al. (2016) variability sample. A total of 58 sources have sufficient observational data from *XMM-Newton* EPIC-pn and variability for an excess variance spectrum to be calculated. We examine these spectra for peaks corresponding to variable blue-shifted H- and He-like ion absorption lines from UFOs. We find good evidence for such outflows in 28% of the AGN sample and weak evidence in a further 31%, meaning that ~ 30–60% of the AGN sample hosts such UFOs. The mean and median blue-shifted velocity is found to be ~ 0.14c and 0.12c, respectively. Current variability methods allow for a fast, model-independent determination of UFOs, however, further work needs to be undertaken to better characterize the statistical significance of the peaks in these spectra by more rigorous modelling. Detecting good evidence for variable UFO lines in a large number of sources also lays the groundwork for detailed analysis of the variability timescales of the absorbers. This will allow us to probe their densities and hence distances from the central super-massive black hole.

Key words: accretion, accretion discs – galaxies: active – black hole physics

Igo et al., MNRAS, 2020

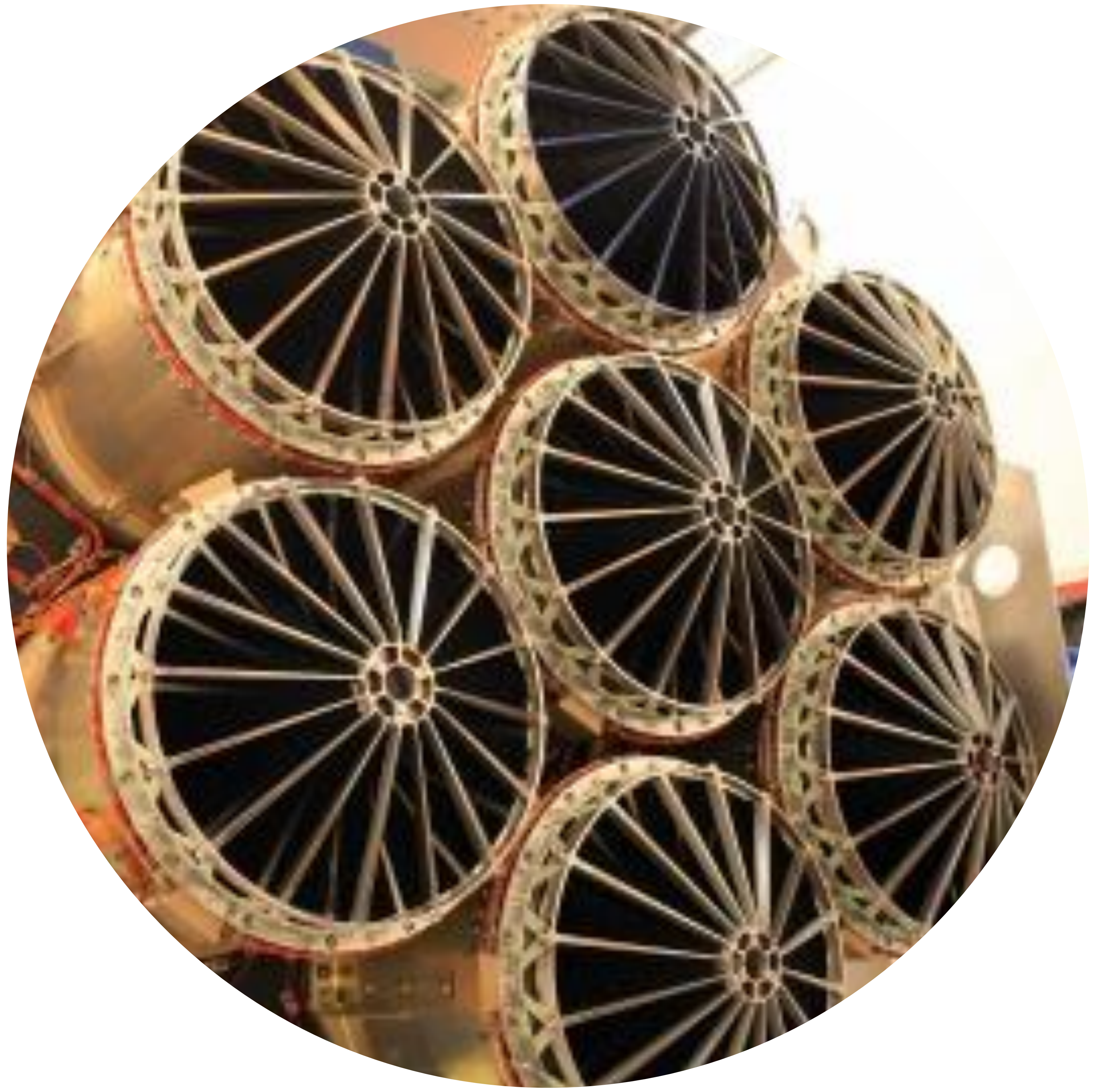


Much faster than conventional spectral fitting, scalable to arbitrarily large datasets, less vulnerable to contamination…

Igo et al., MNRAS, 2020

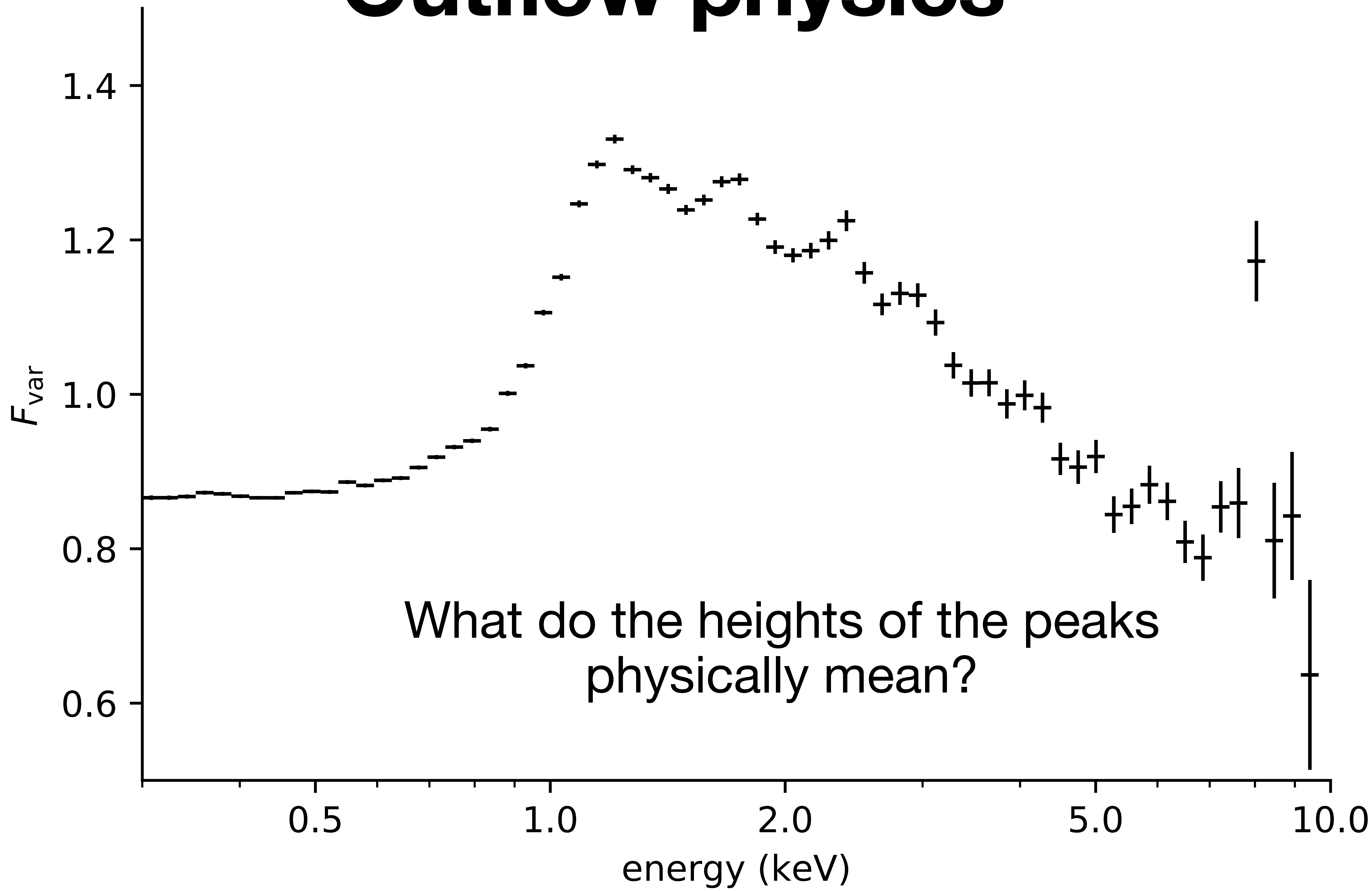
“We find good evidence for such outflows in 28% of the AGN sample and weak evidence in a further 31%, meaning that ~ 30–60% of the AGN sample hosts such UFOs”

Igo et al., MNRAS, 2020



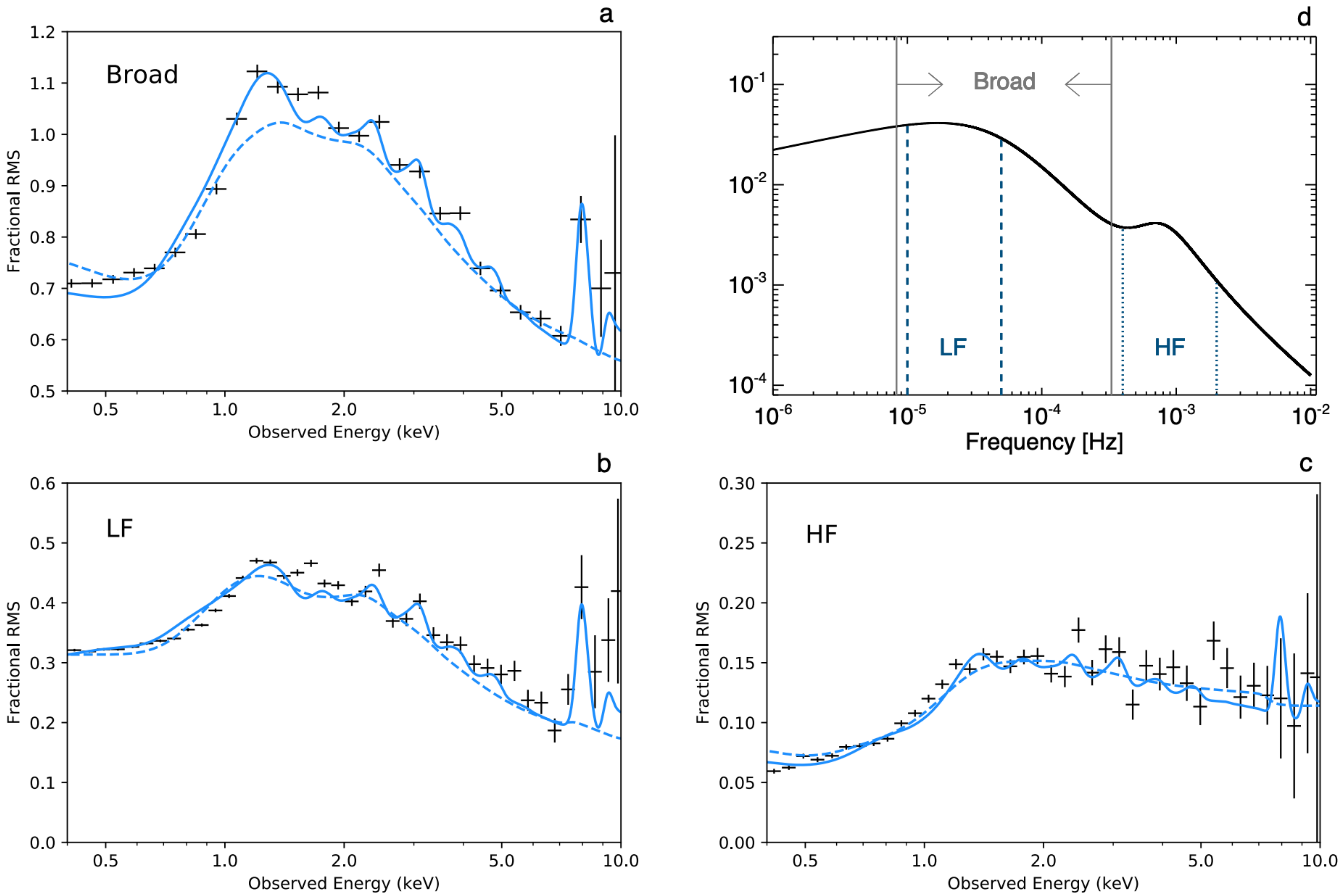
Particularly powerful with the next generation of telescopes

Outflow physics



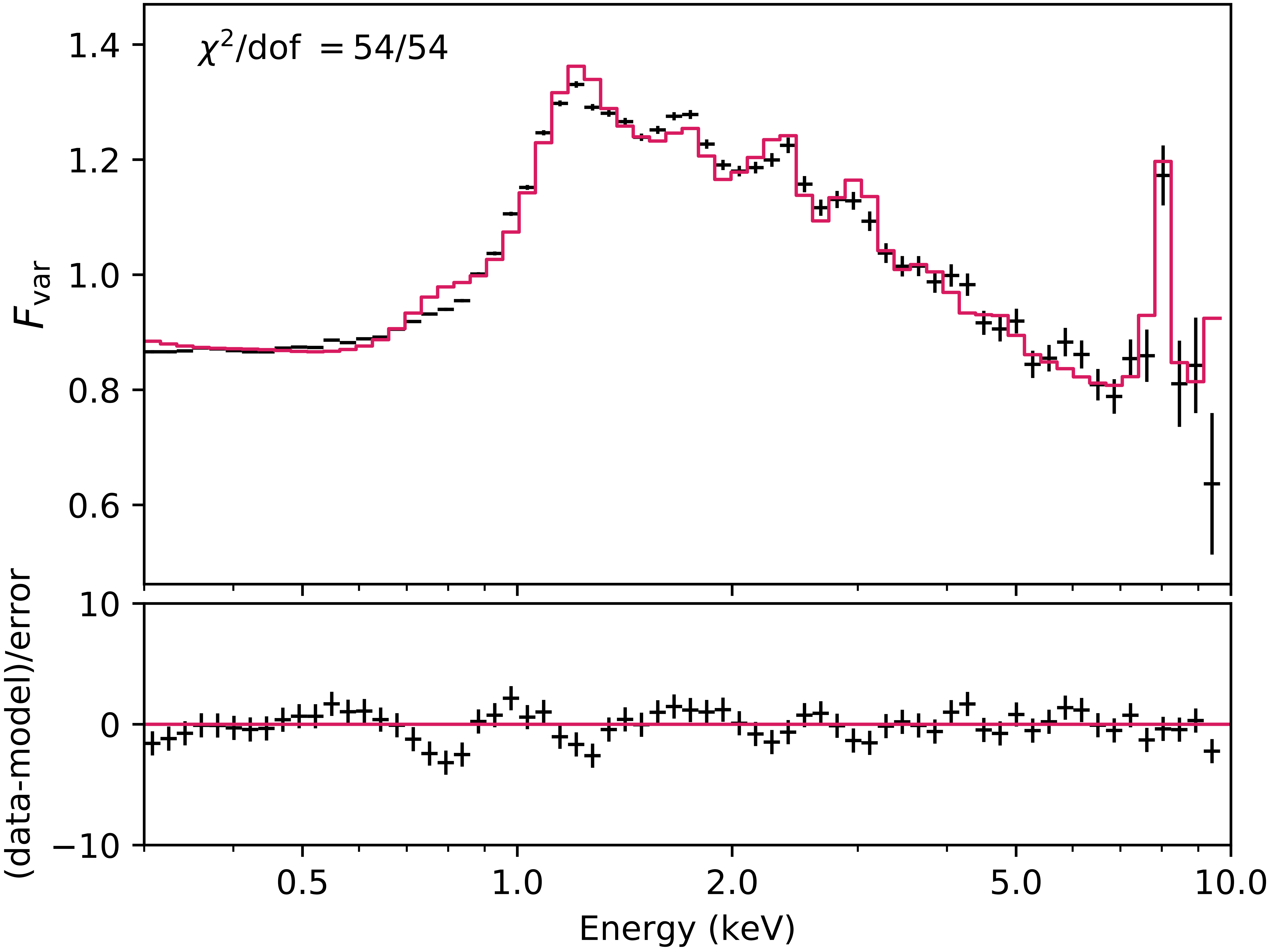
What do the heights of the peaks physically mean?

Outflow physics



Simulated variance spectra, smoothed to match data

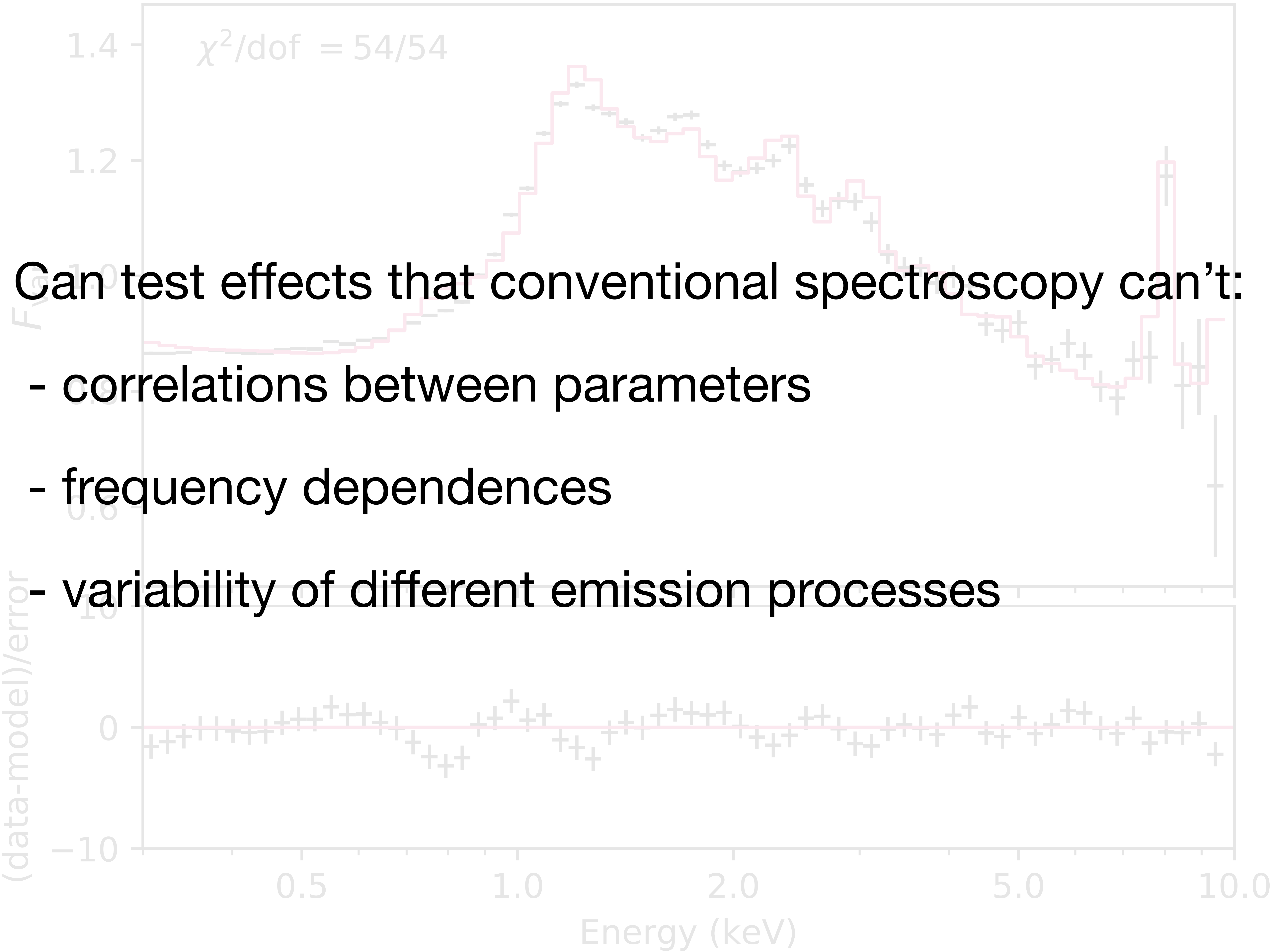
Alston et al, Nature Astro, 2020



Parker et al, MNRAS, 2020

Can test effects that conventional spectroscopy can’t:

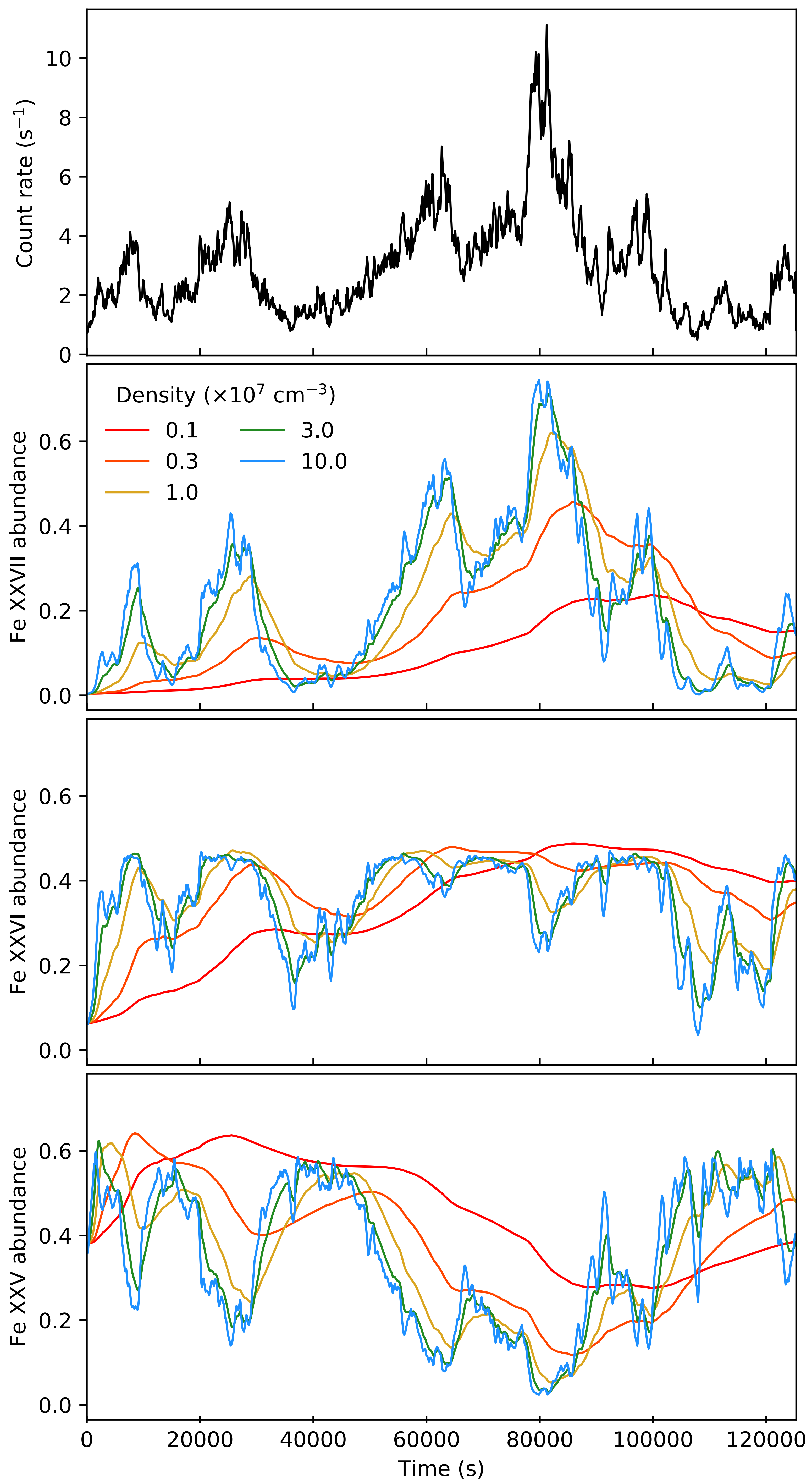
- correlations between parameters
- frequency dependences
- variability of different emission processes



Parker et al, MNRAS, 2020

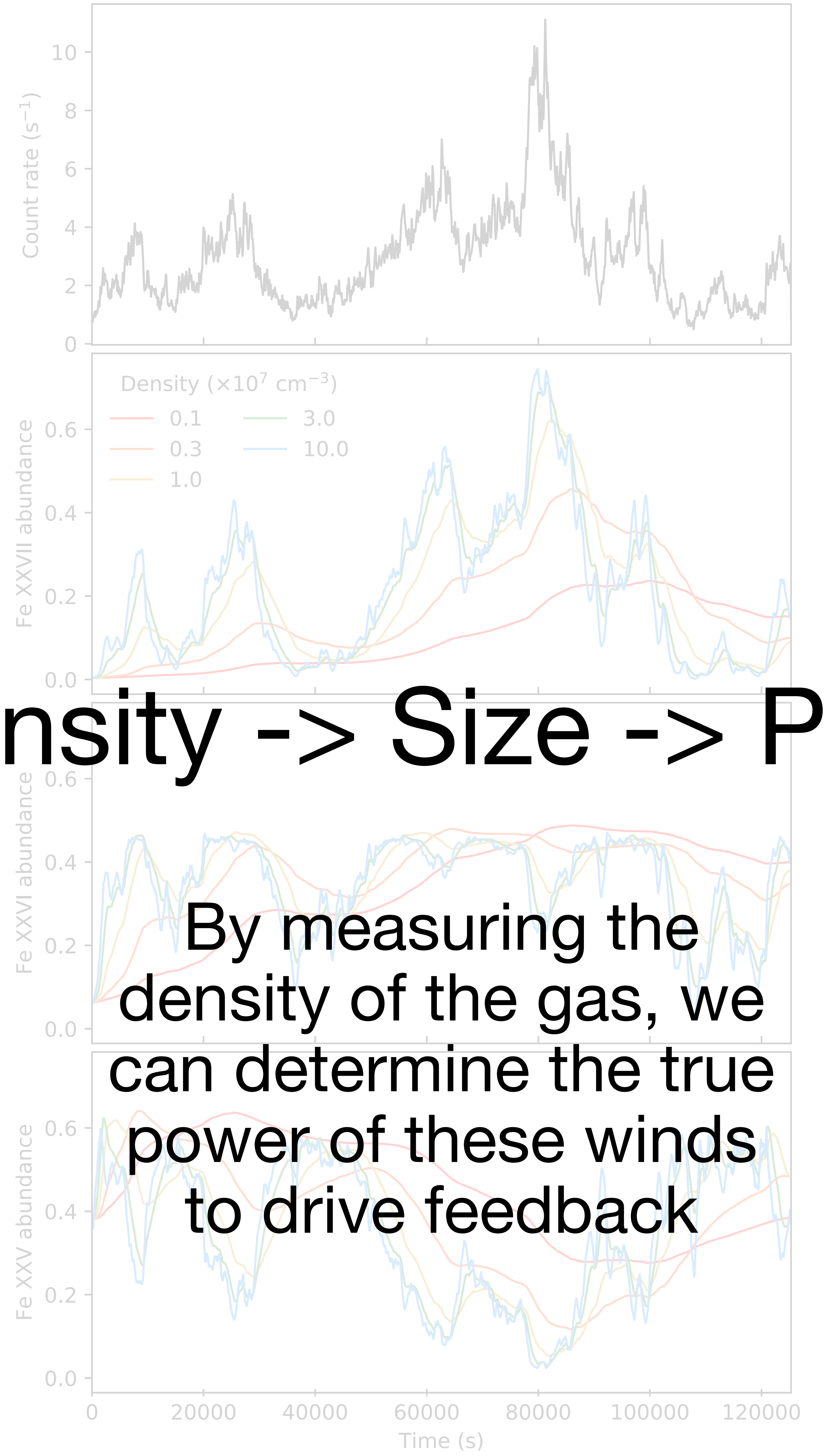
How do we distinguish between this…


Disk wind
...and this?
Absorbed
X-rays
X-ray Corona
Accretion Disk



Variability can serve as a density diagnostic

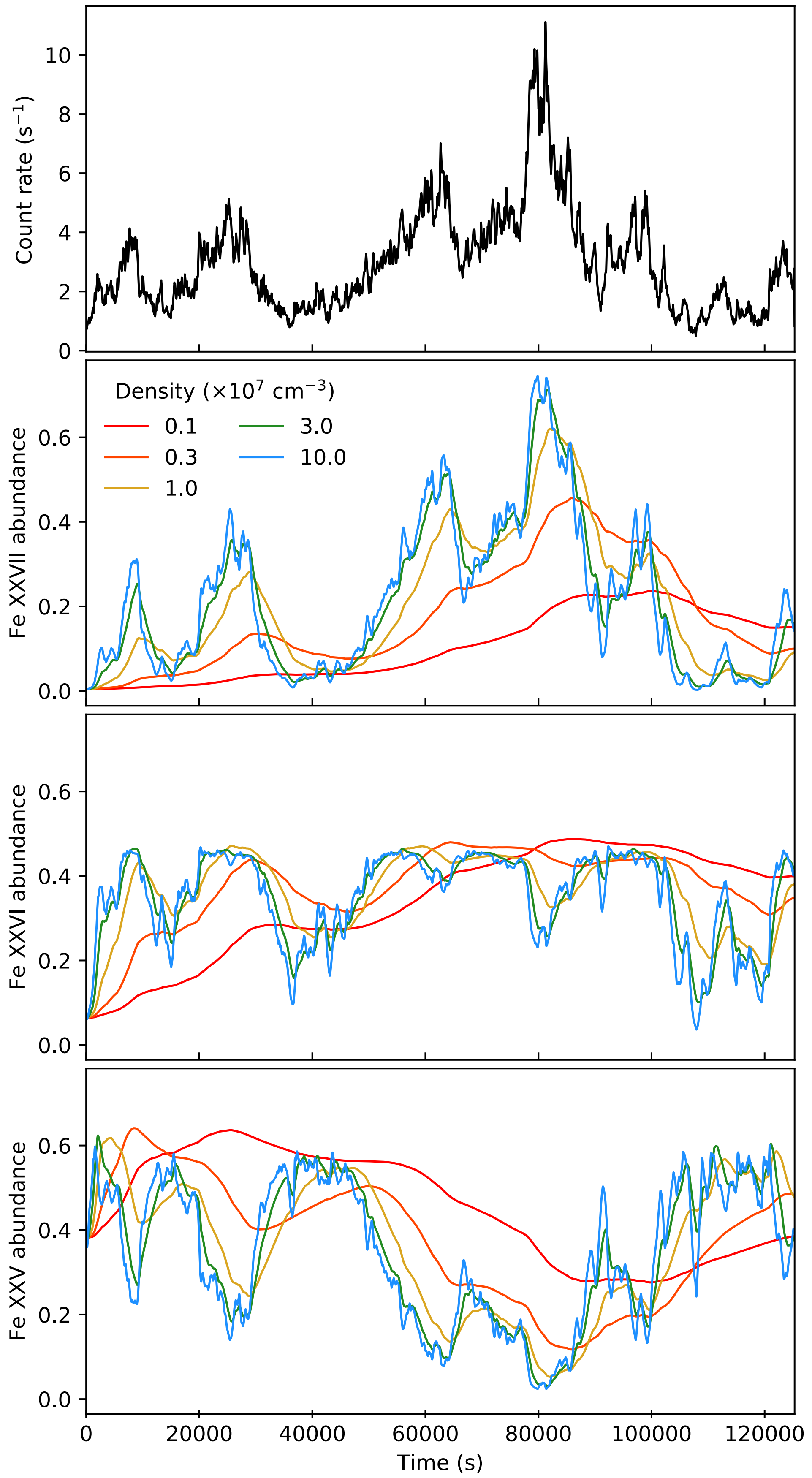
Density -> Size -> Power



By measuring the density of the gas, we can determine the true power of these winds to drive feedback

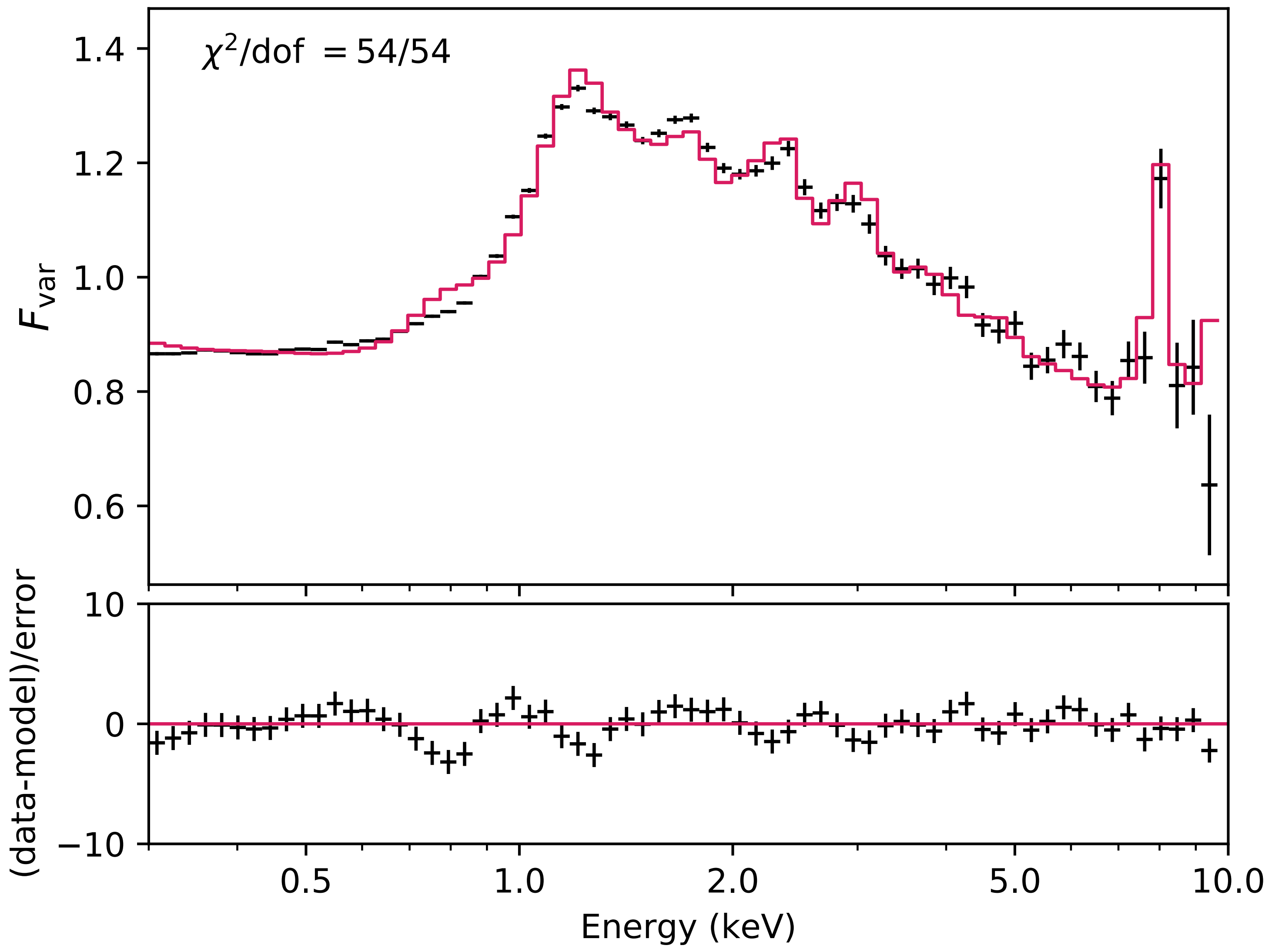
Future work

Detailed density predictions



Simulations for future instrumentation

Expand and enhance modelling



Summary

- Supermassive black holes launch powerful outflows that potentially control galaxy growth
- We don’t know exactly how powerful they really are
- They can usually only be detected in X-rays, and conventional X-ray spectroscopy is difficult, slow, and limited
- The absorption lines from outflows respond to continuum variability, enhancing variance in specific energy bands
- We can use this to detect and study outflows with variance spectra
- This circumvents many of the problems with conventional spectroscopy, and could finally answer the question of how powerful outflows are