RELATIVISTIC SPECTROSCOPY OF BLACK HOLES

Michael Parker

ESAC science seminar
24/5/18

BLACK HOLES 101

For an object to just escape a massive body, it needs the sum:

Kinetic energy + gravitational binding energy = 0

$$\frac{1}{2}mv^2 - \frac{GMm}{r} = 0$$

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

At v = c, the speed of light, this gives the Schwarzchild radius:

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

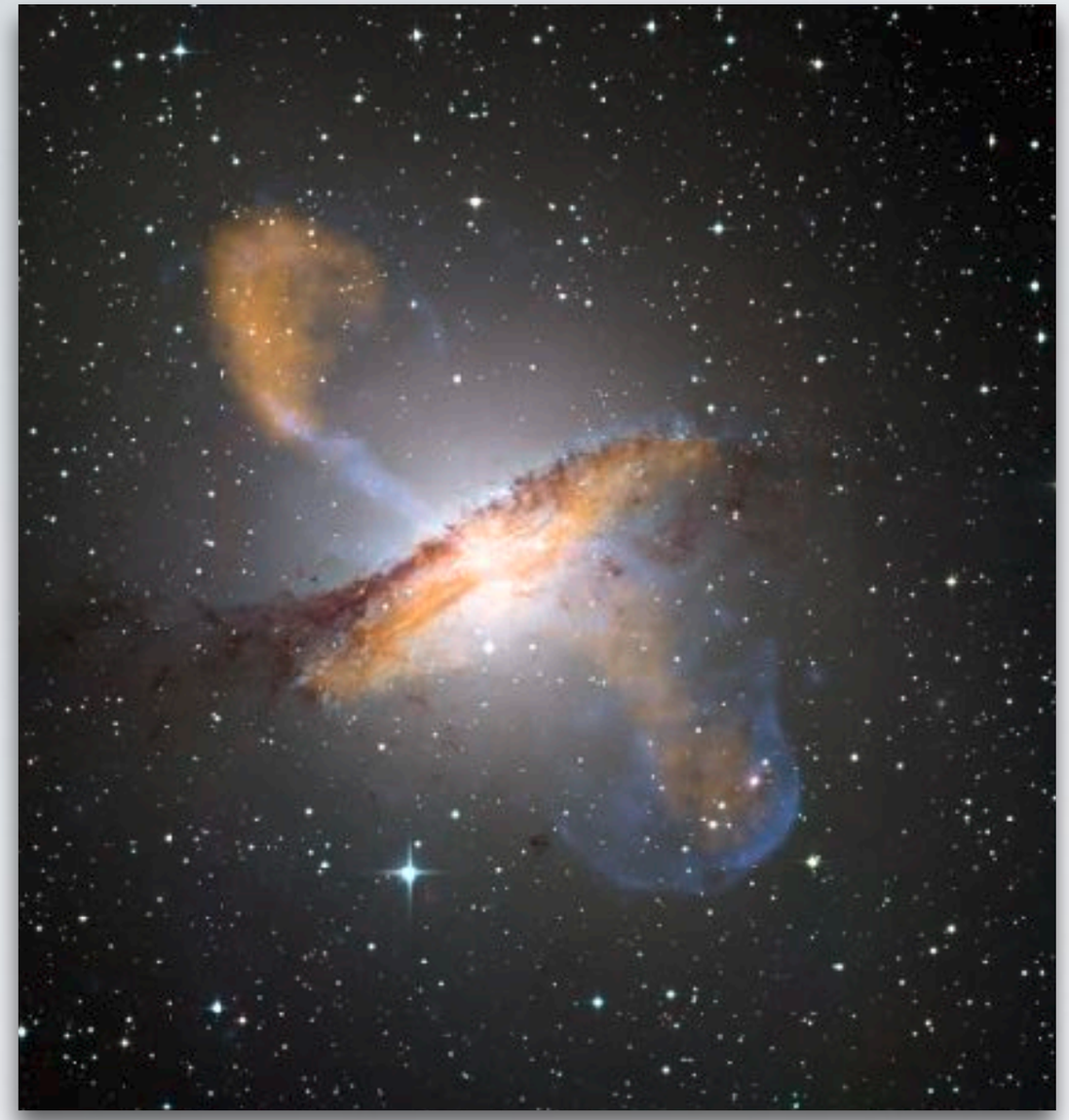
Note that this is linear with mass, whereas for a constant density sphere:

$$M = \frac{4}{3}\pi R^3$$

$$R \propto M^{1/3}$$

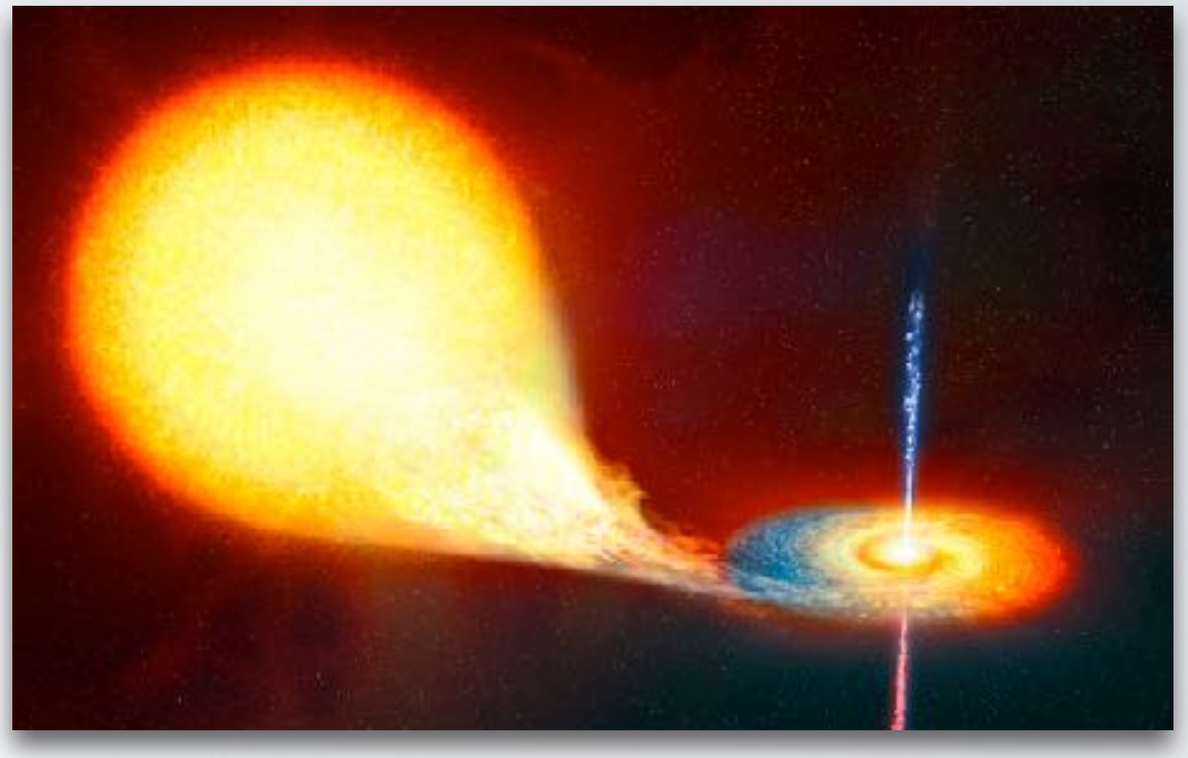
It follows that for a sufficiently massive object of non-zero density, the radius will be smaller than the Schwarzchild radius, so light will not be able to escape.

AGN

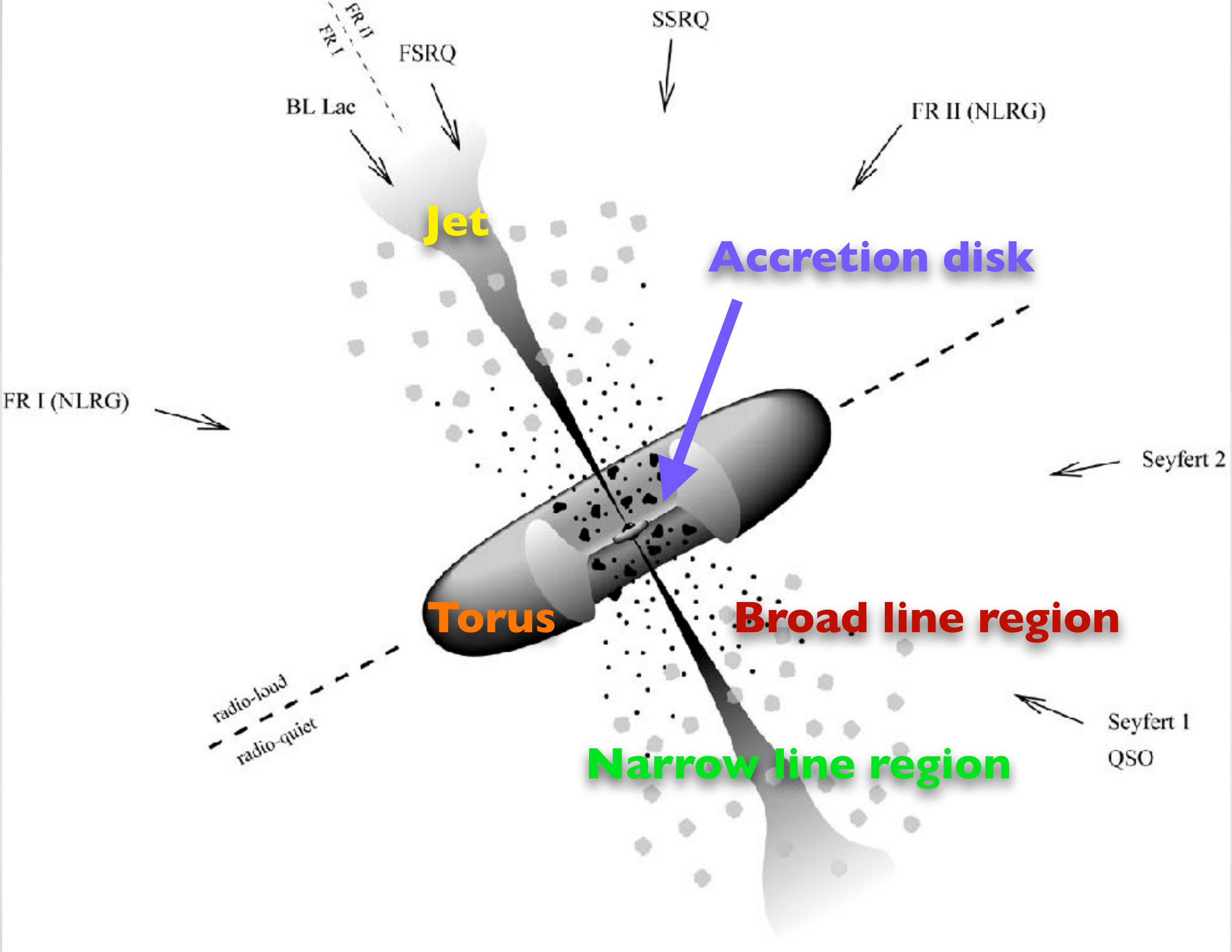


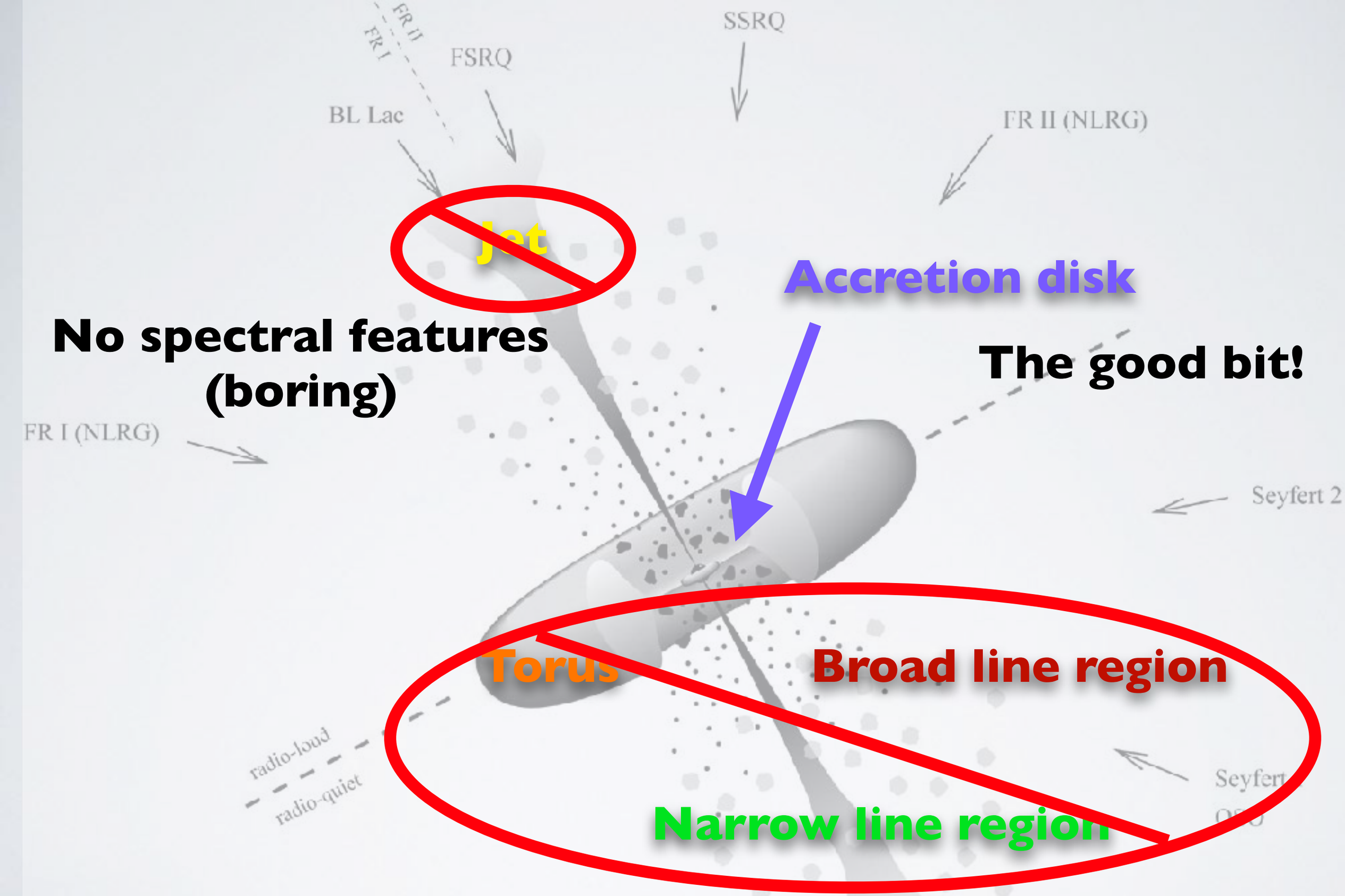
- Big (10^5-10^9 solar masses)
- Formation process uncertain
- Slow
- Cosmologically important

XRB

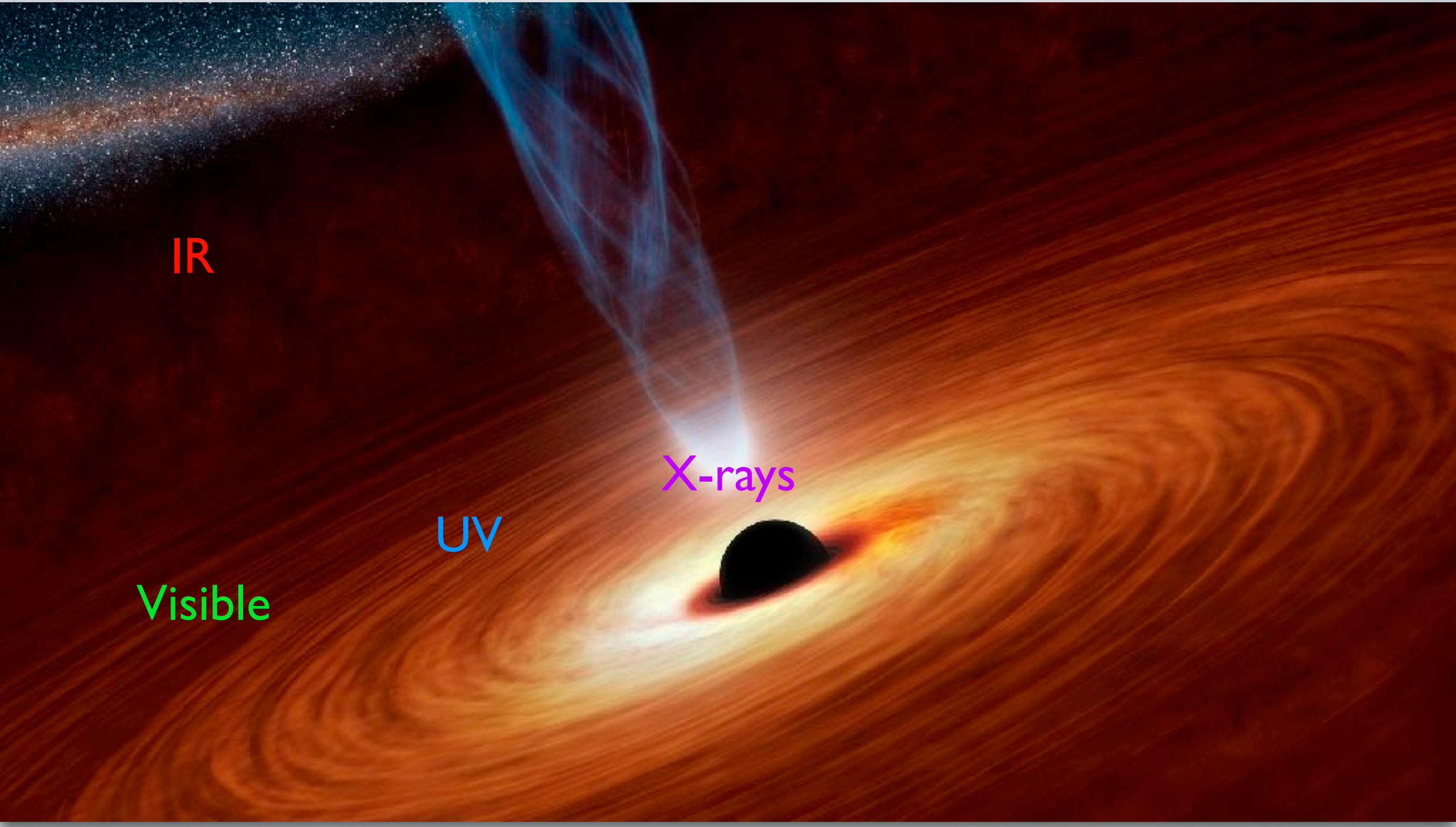


- Small (1-100 solar masses)
- Stellar remnant
- Fast
- Nearby


FR II
FR I
FSRQ
SSRQ
BL Lac
FR II (NLRG)
Jet
Accretion disk
FR I (NLRG)
Seyfert 2
Torus
Broad line region
radio-loud
radio-quiet
Seyfert 1
QSO
Narrow line region



Slow, cold, and messy


IR
X-rays
UV
Visible

X-rays are the most effective way of studying the inner accretion disk, where GR effects are strong.

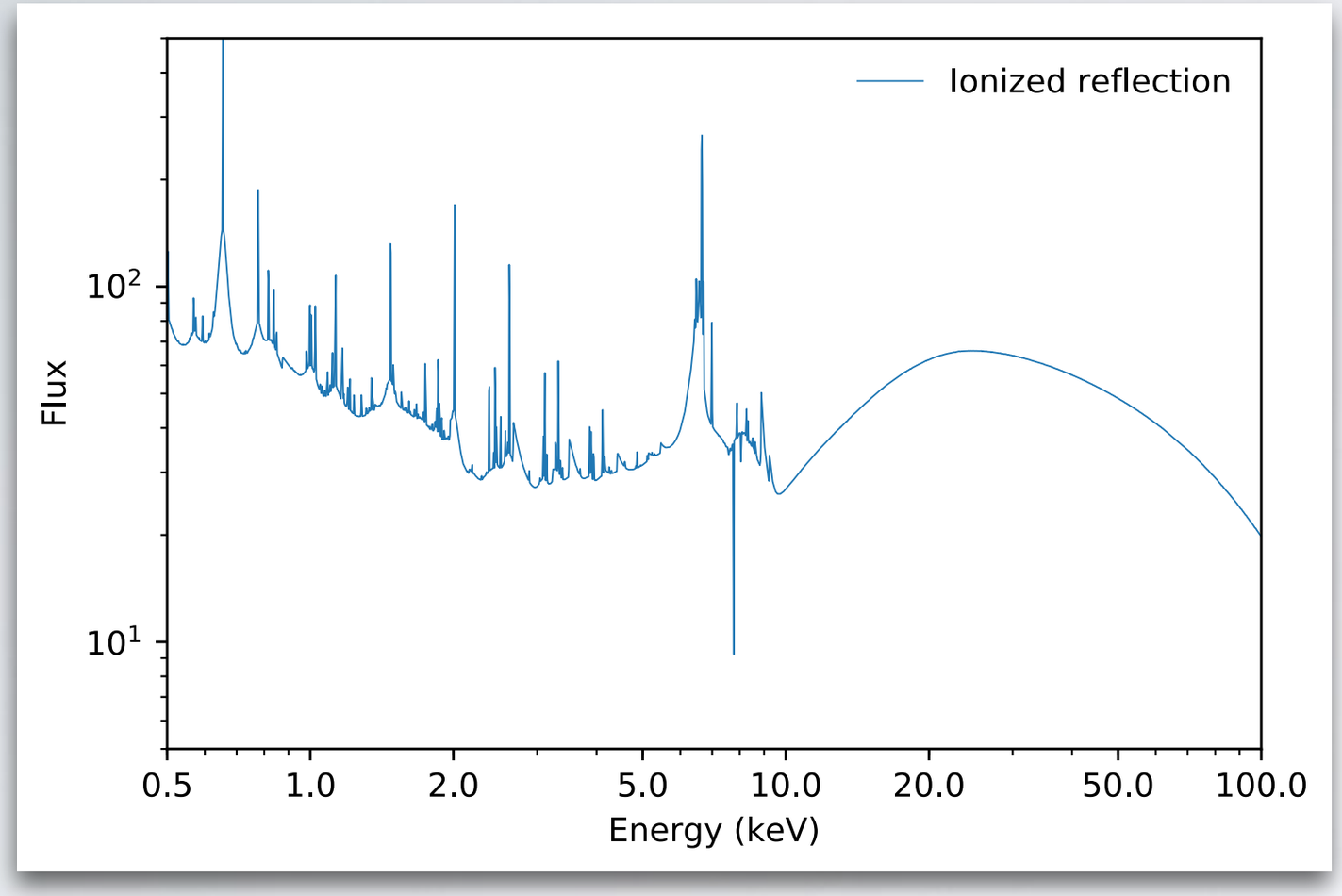
X-ray telescopes, like XMM-Newton (the best telescope) use X-ray CCDs to count individual photons, and measure their energies and arrival times.

This means that we can have lightcurves, spectra, and images simultaneously.

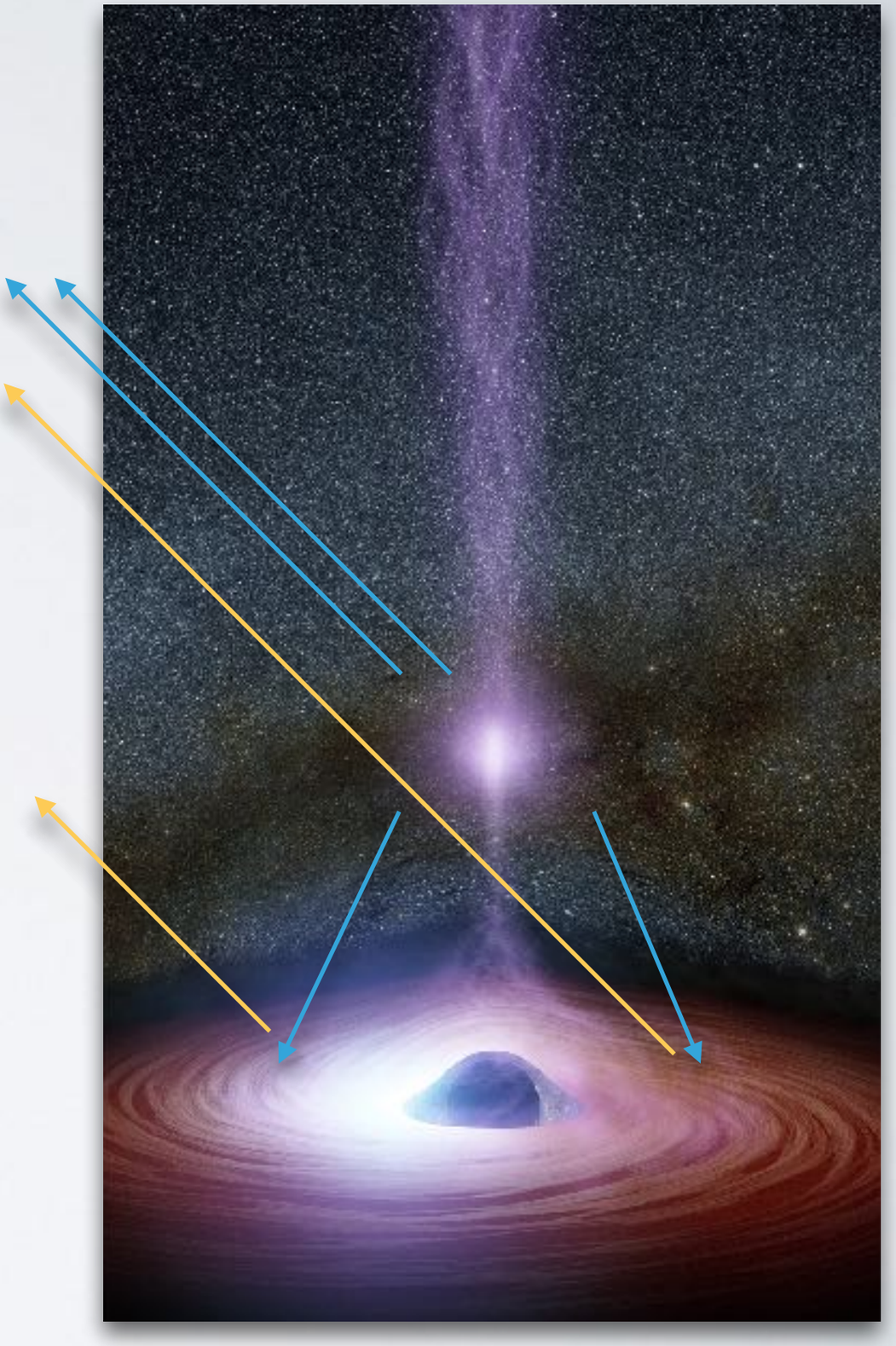
RELATIVISTIC REFLECTION

Spectroscopy of the inner disk

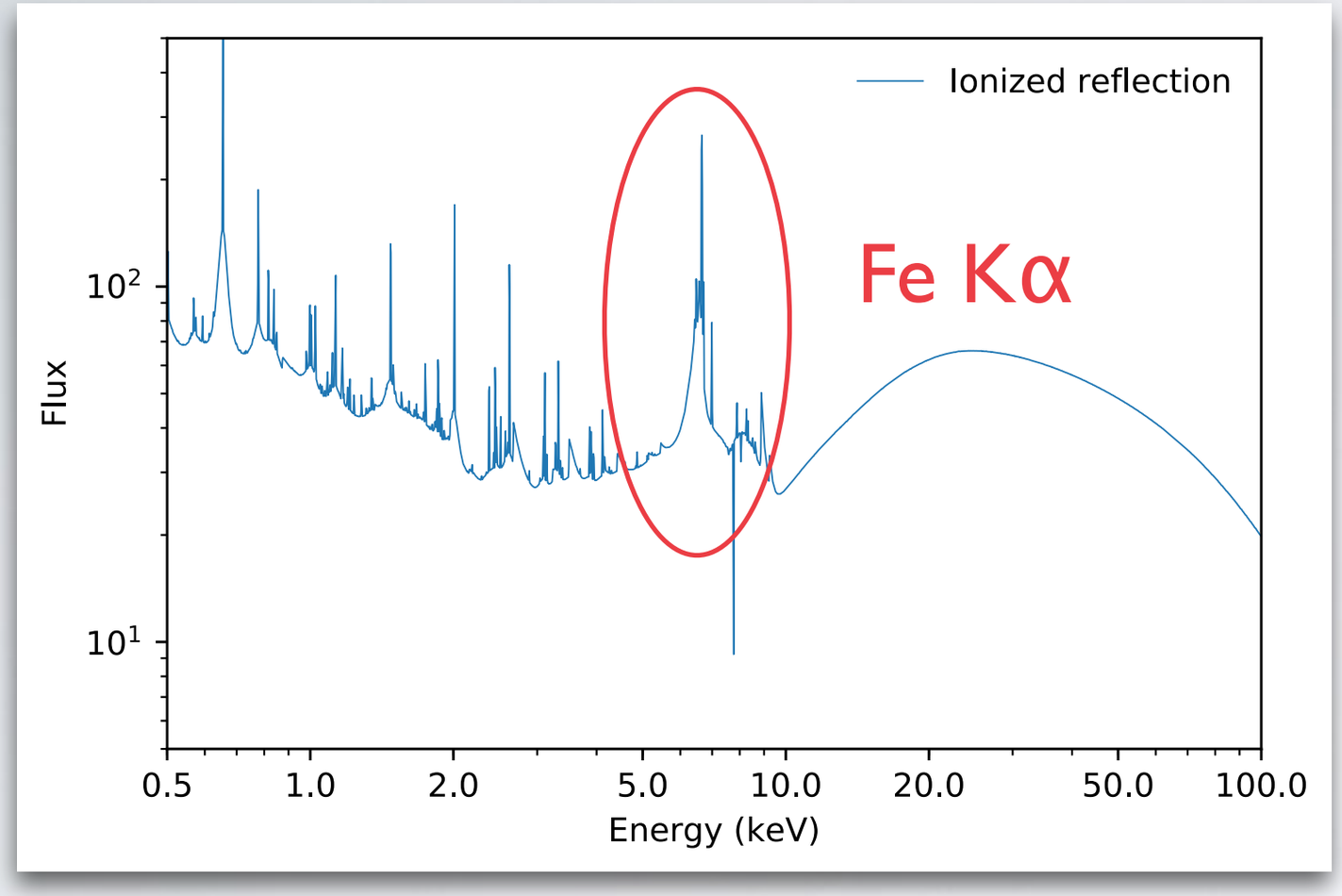
X-ray reflection

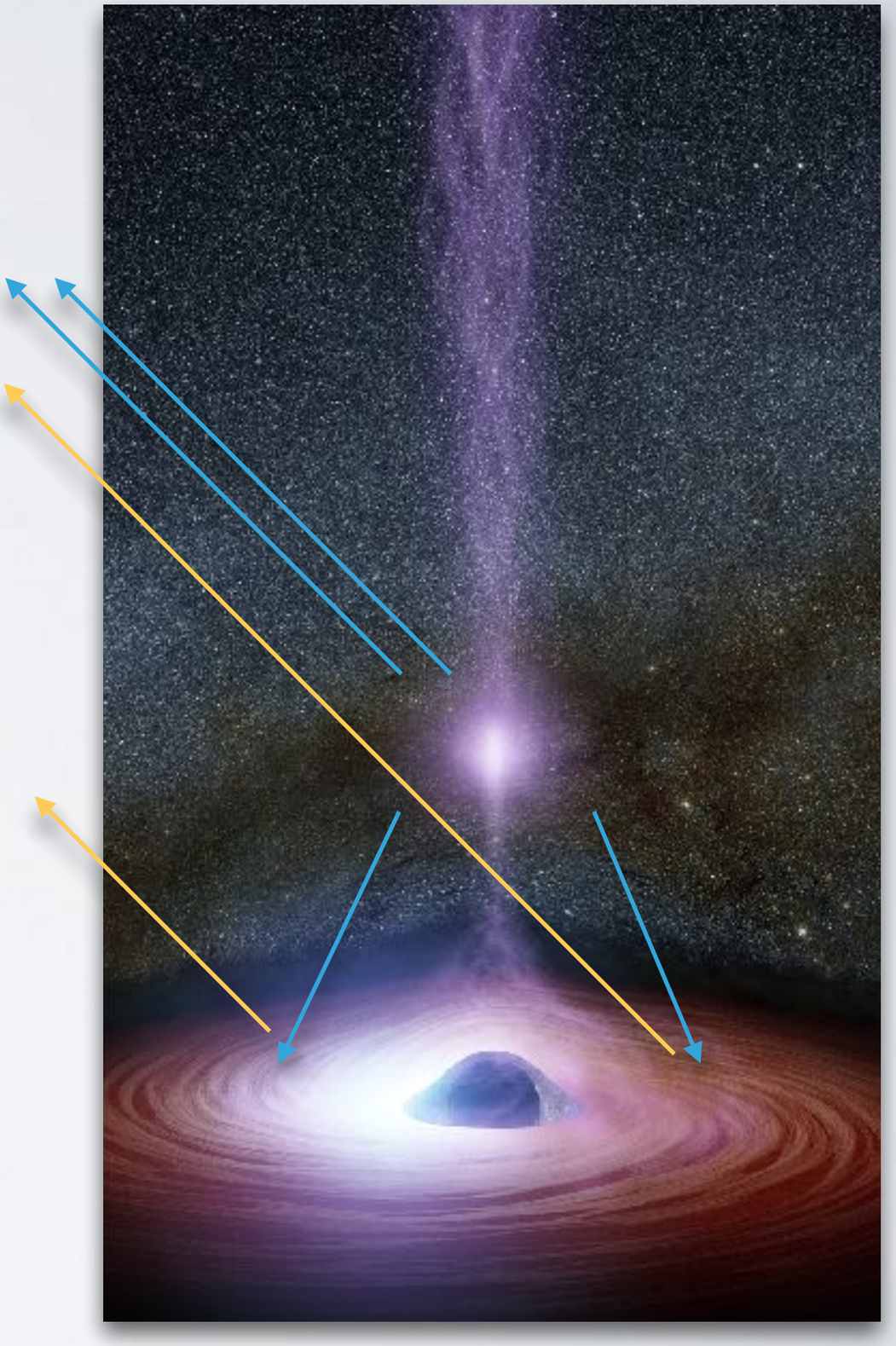


Illumination of dense gas by X-rays produces a characteristic reprocessed emission spectrum

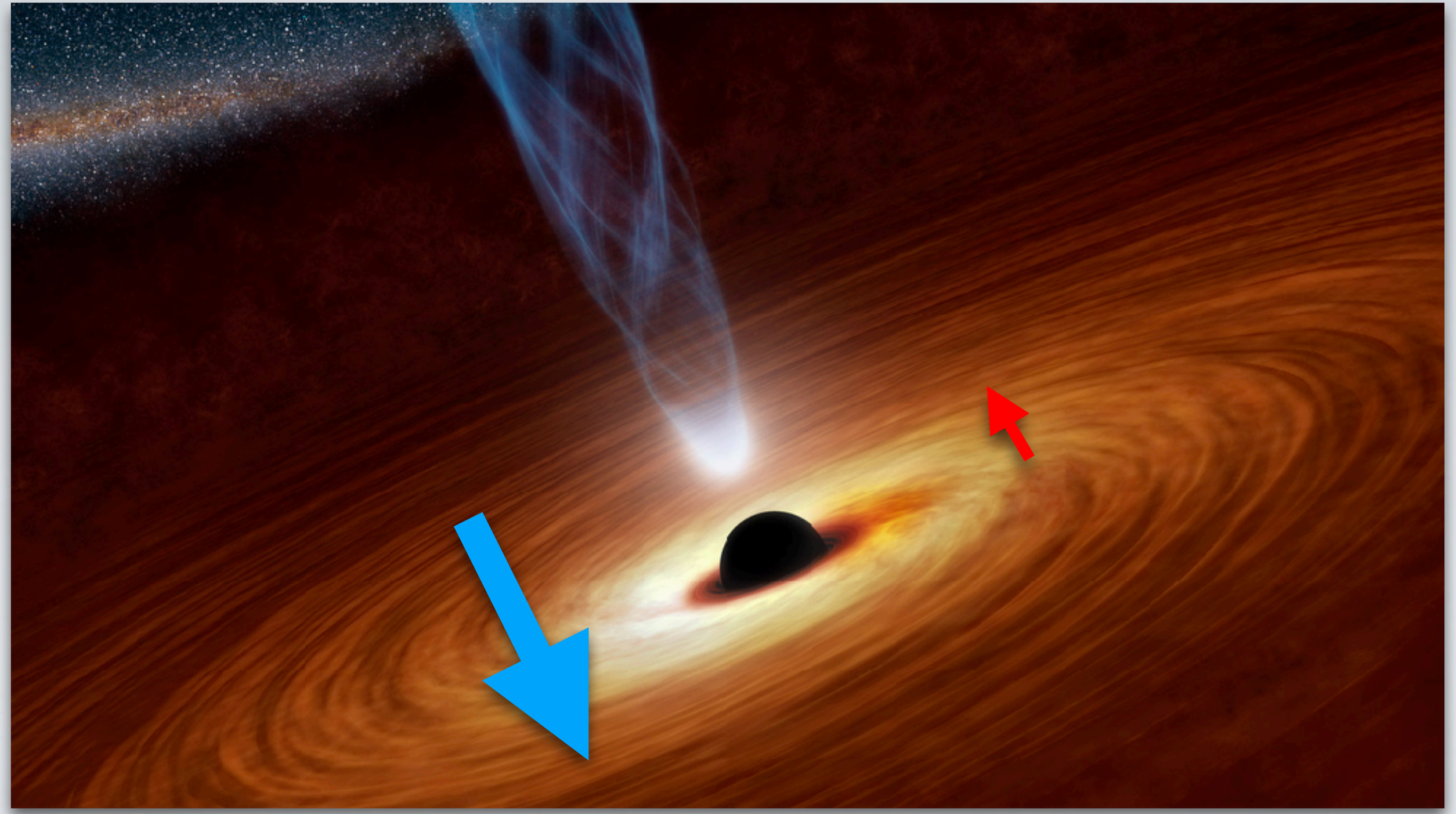


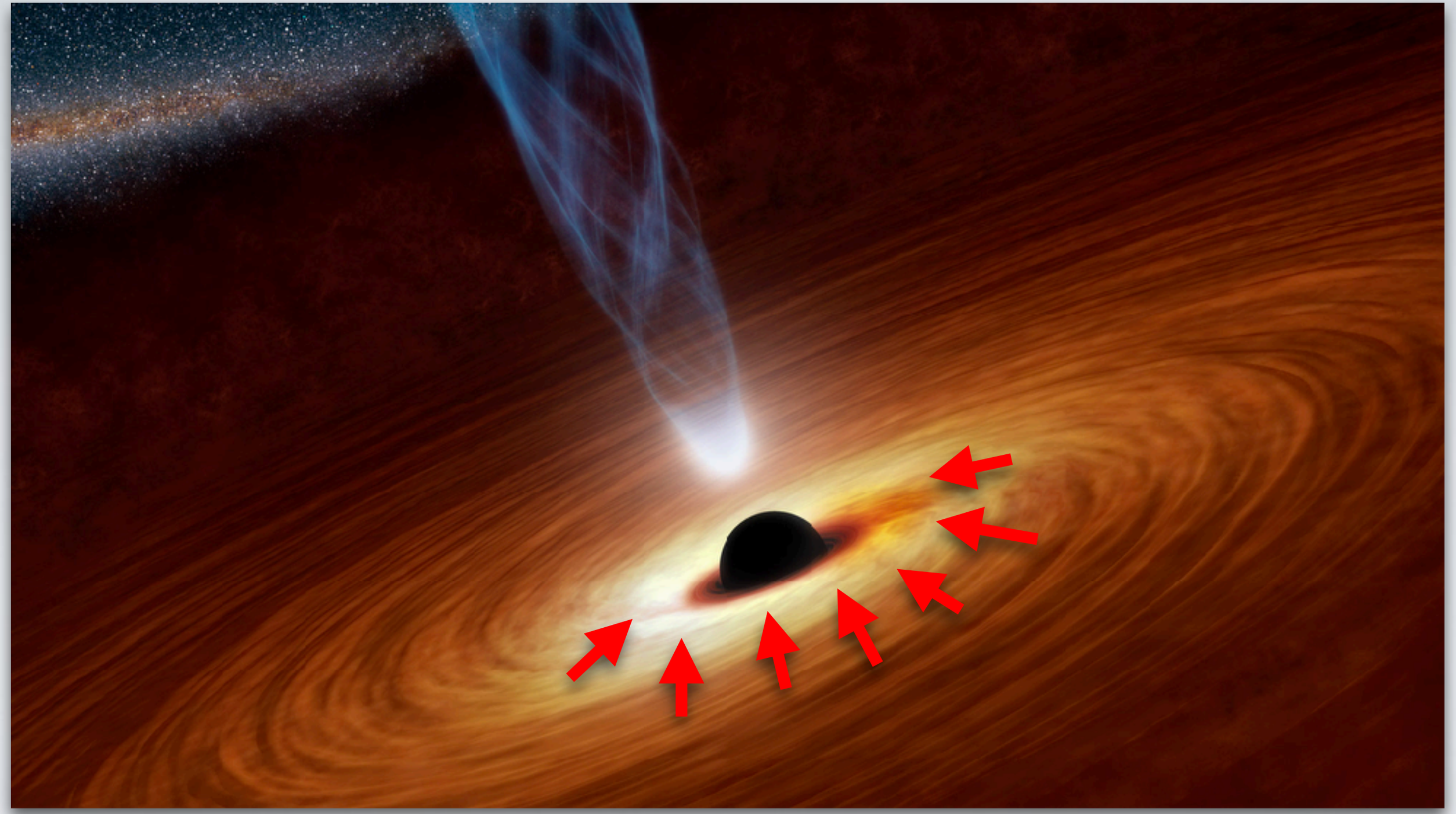
X-ray reflection



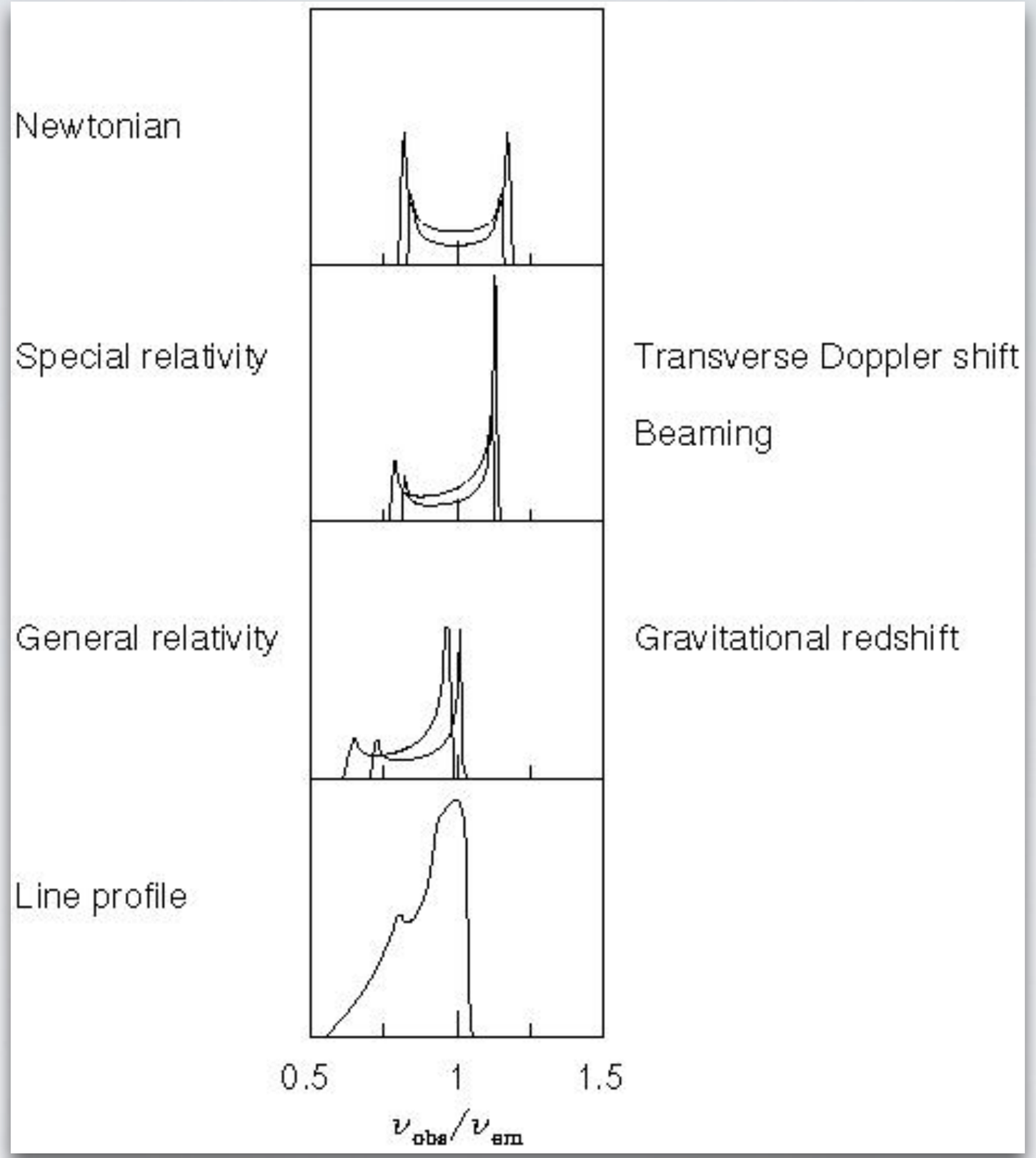


Illumination of dense gas by X-rays produces a characteristic reprocessed emission spectrum

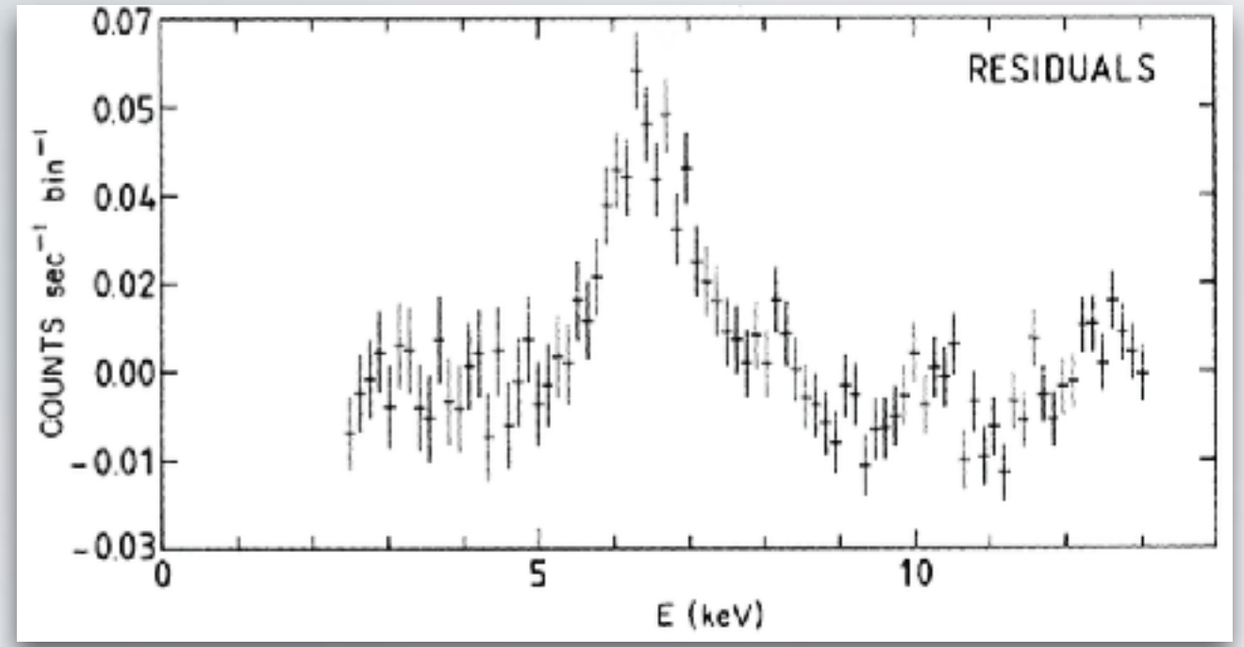




Fabian et al., 1989

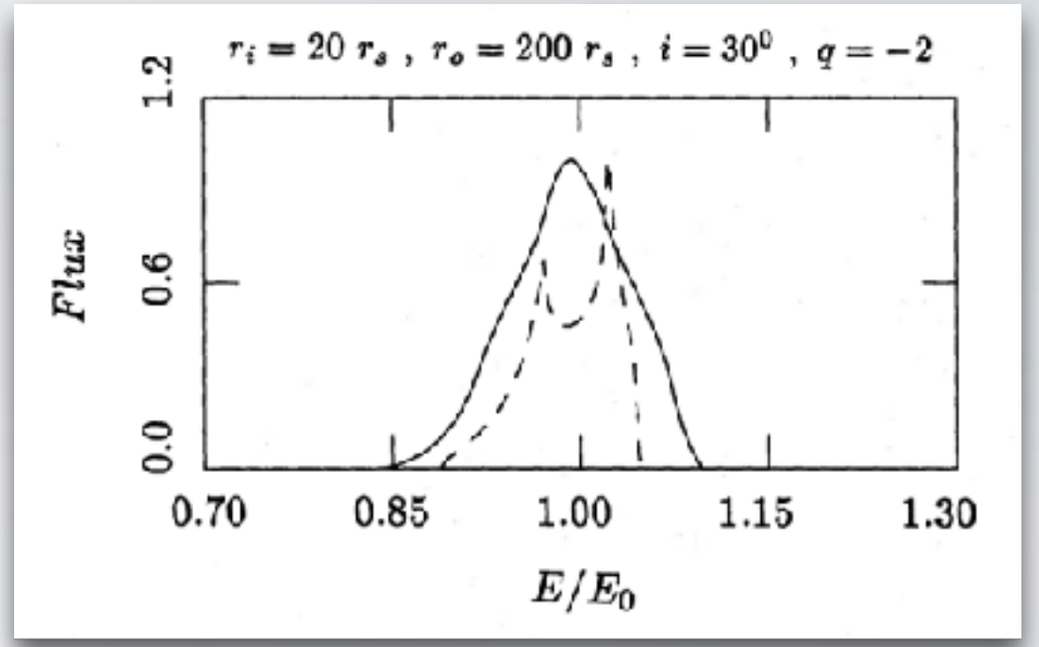


FIRST DETECTIONS



Barr, White & Page, 1985

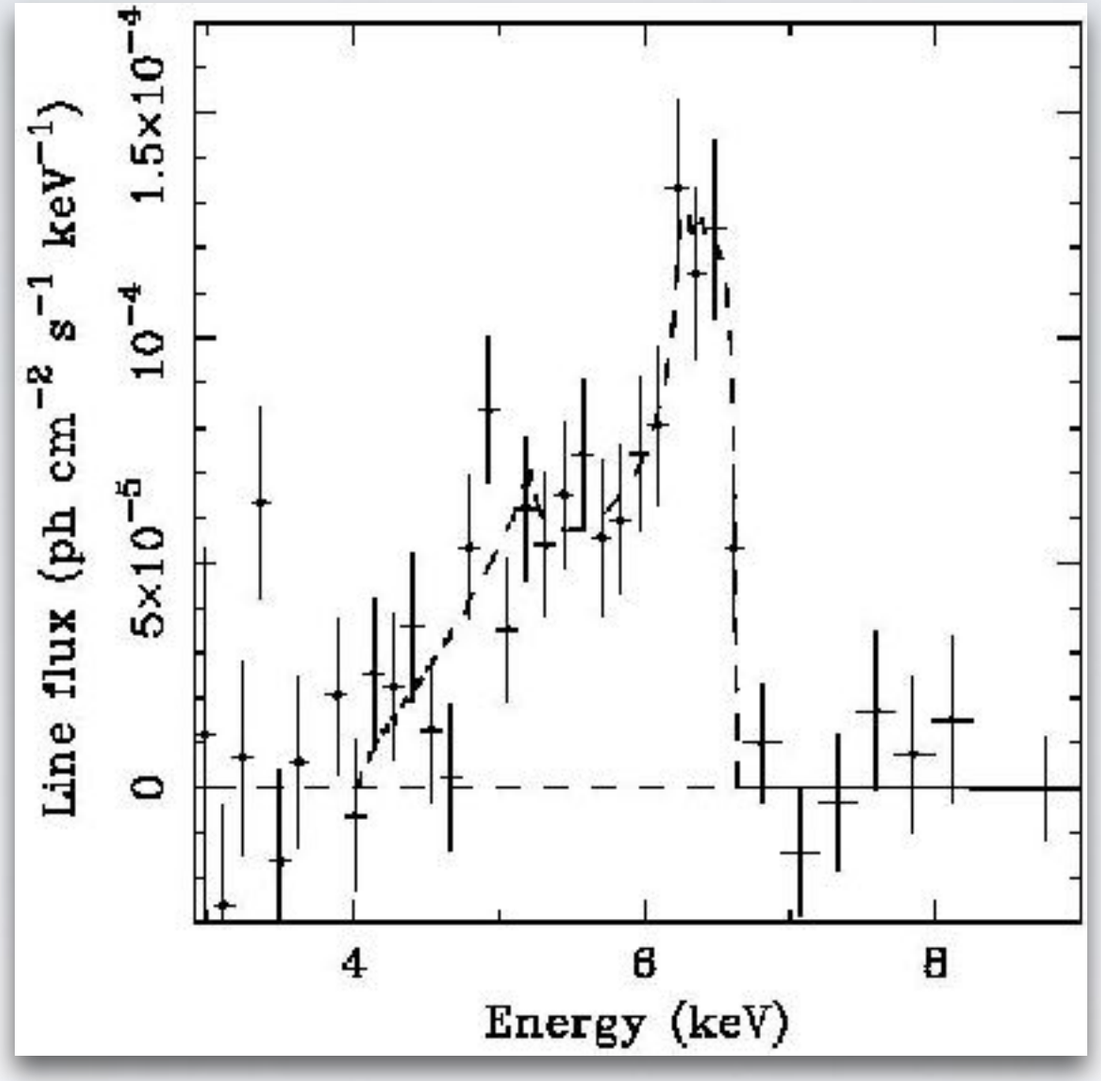
"…a broad emission feature at 6.2 keV is reported with an equivalent width of typically 120 eV."



Fabian et al., 1989

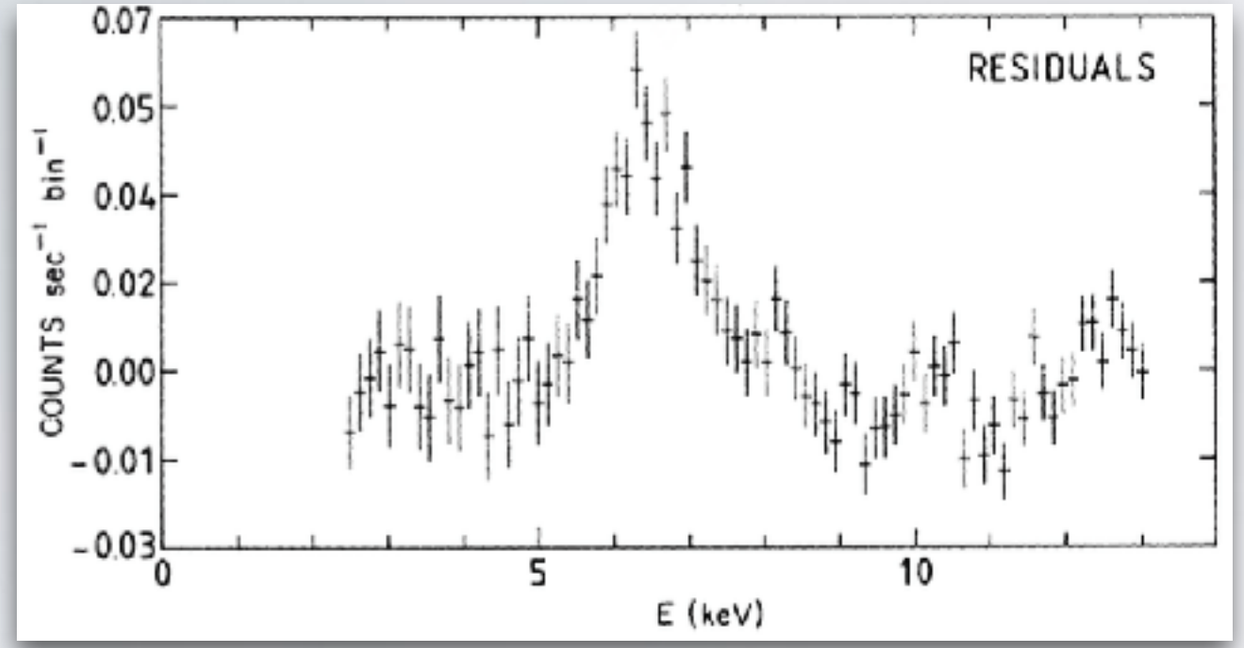
"the broad, iron emission line found in Cyg X-I … is well modelled by fluorescent emission from the inner parts of an accretion disc"

FIRST DETECTIONS

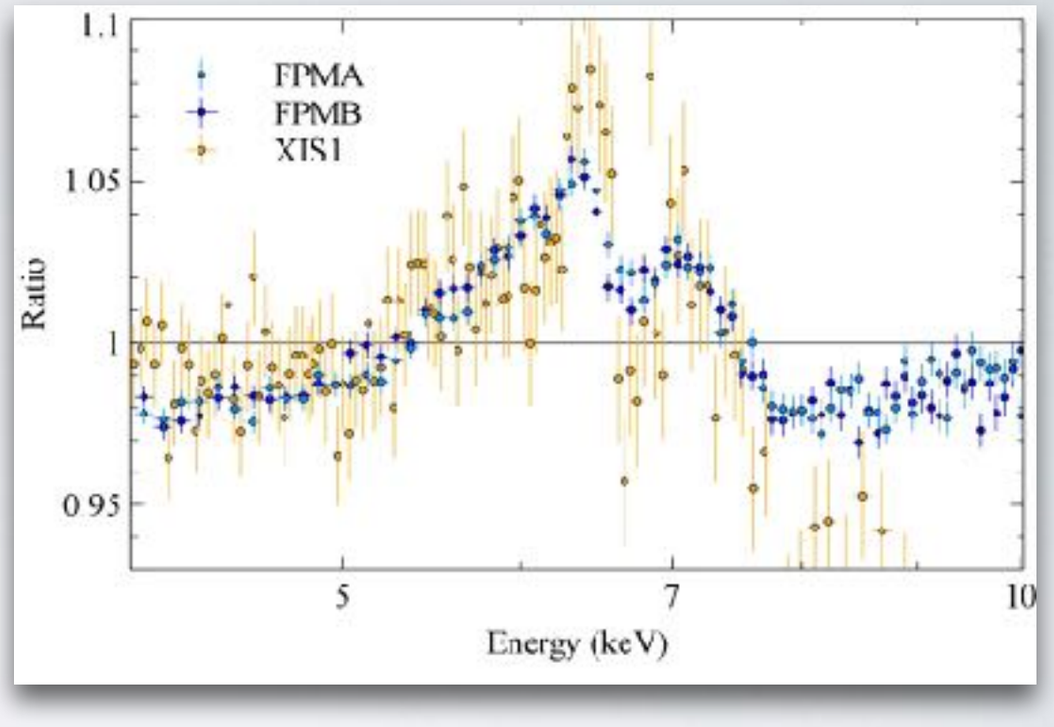


Tanaka et al., 1995

FIRST DETECTIONS

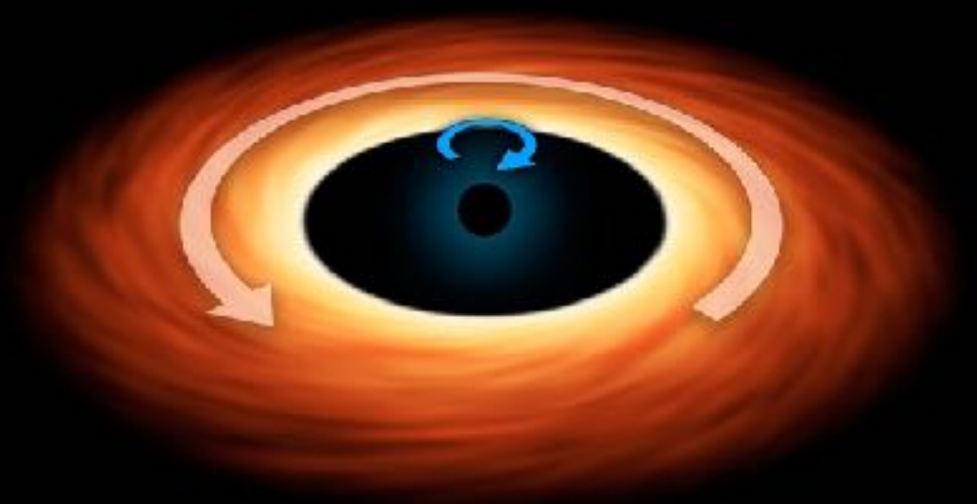


Barr, White & Page, 1985

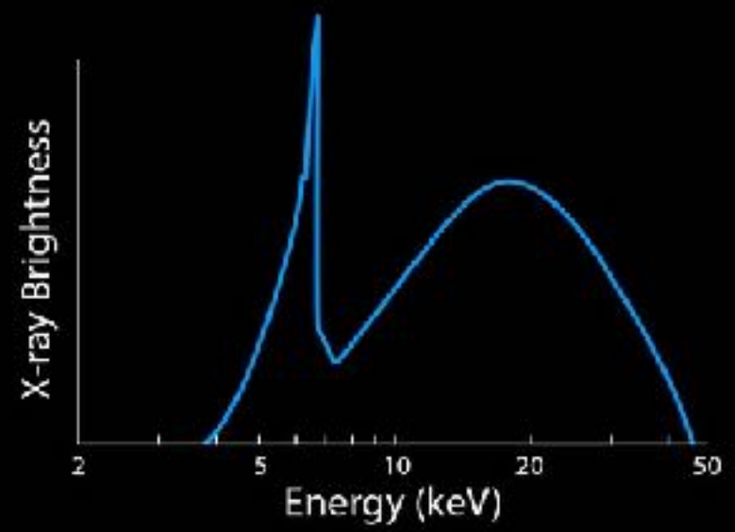


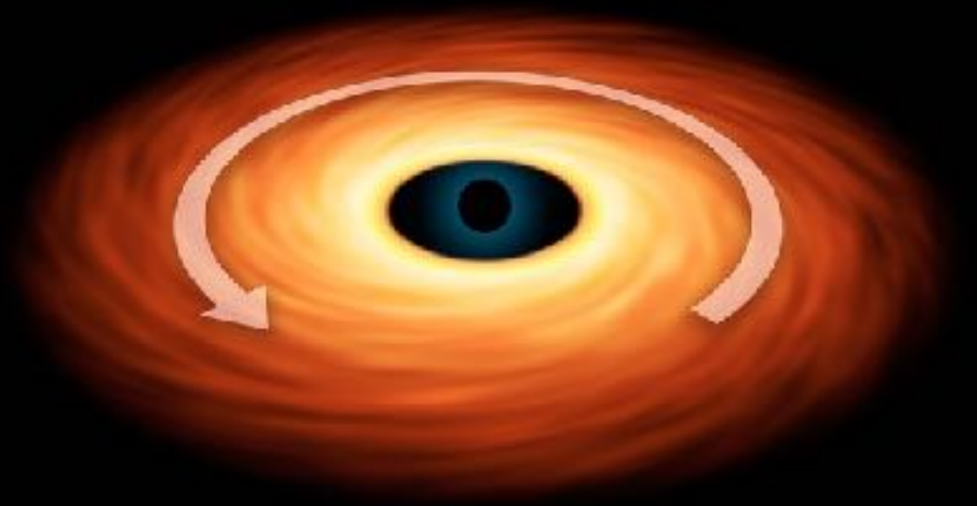
Parker et al., 2015

30 years on, relativistic lines are a powerful tool for measuring the inner accretion disk

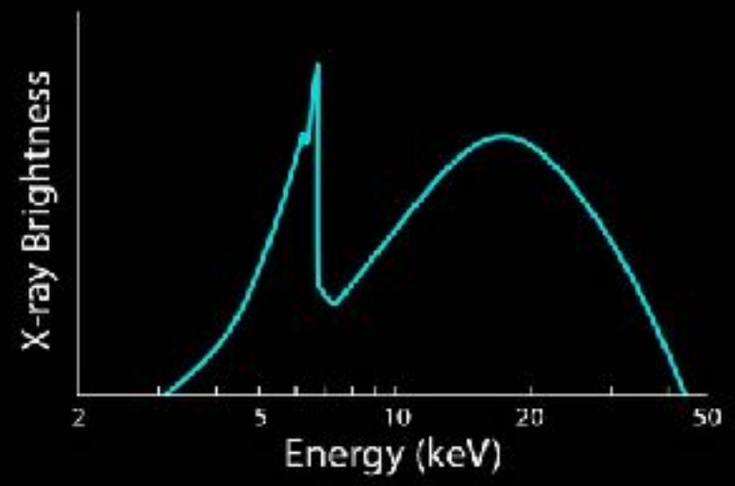


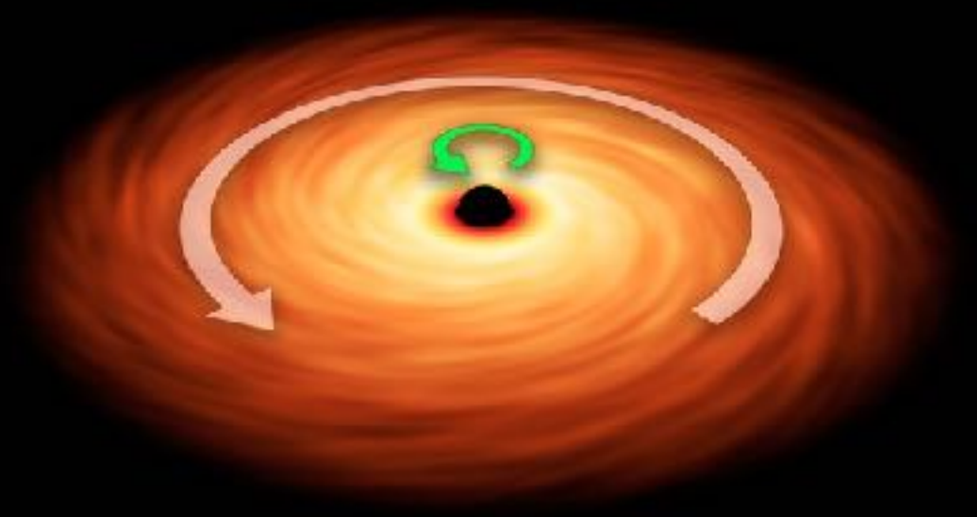
Retrograde
Rotation



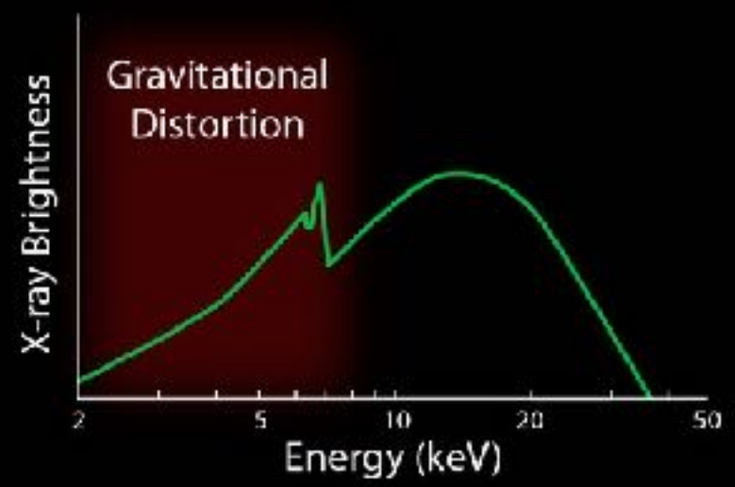


No Black Hole
Rotation

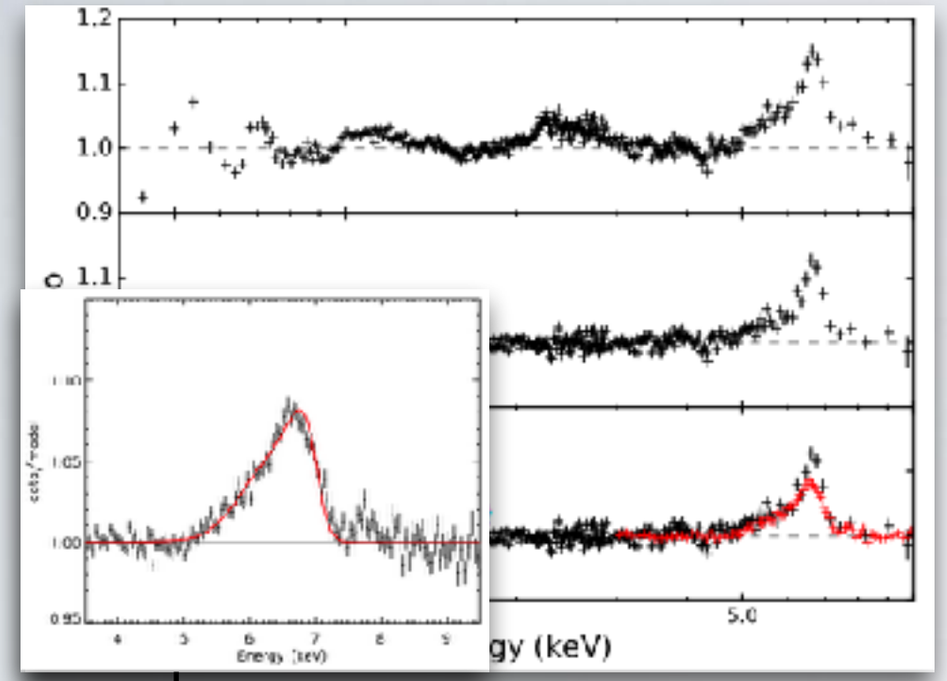




Prograde
Rotation

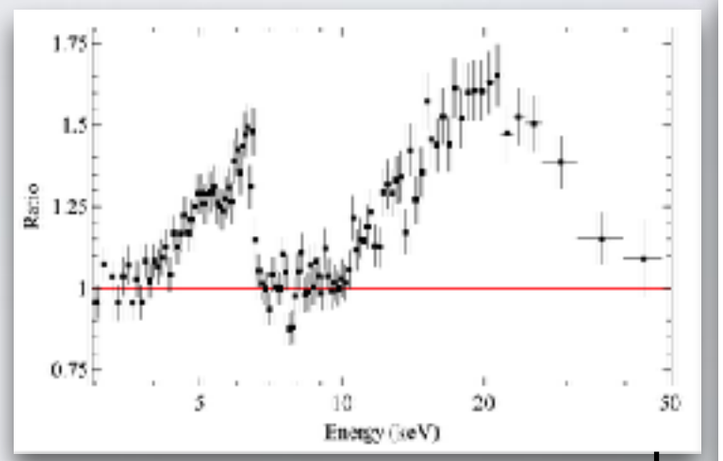


NASA JPL/Caltech

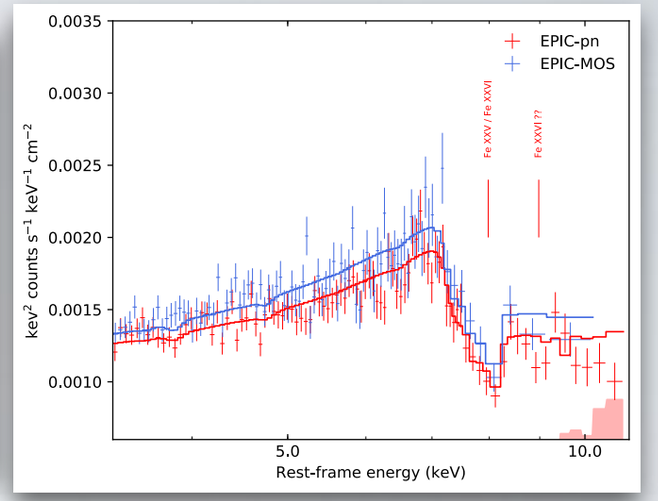


Miller+13, Ludlam+18

MP+14

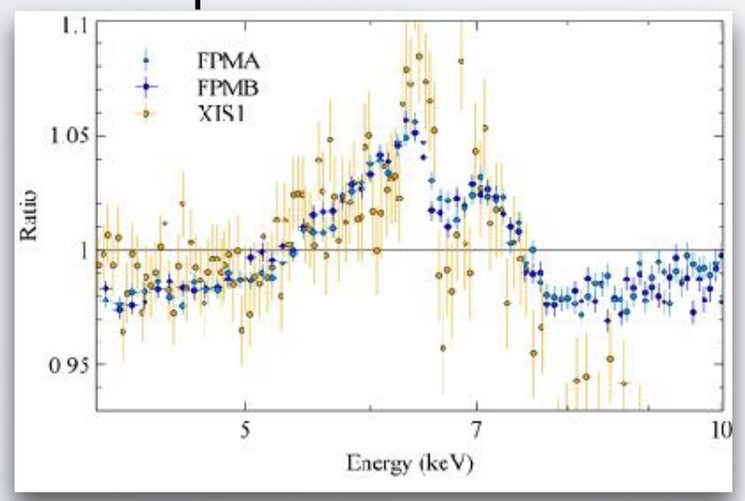


MP+, submitted

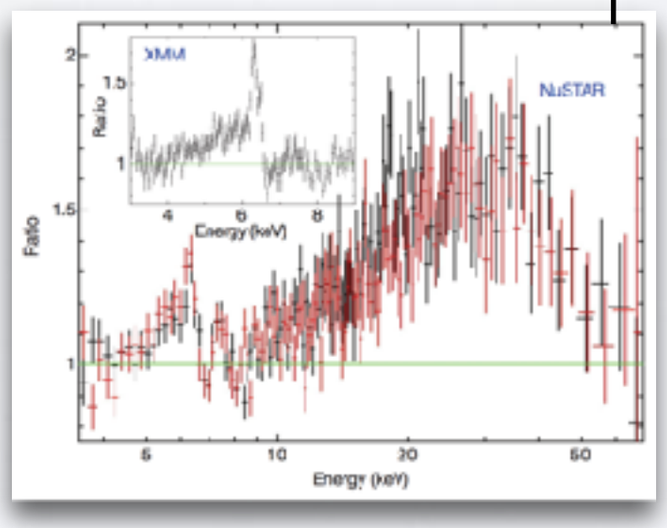


1 10 100 10^3 10^4 10^5 10^6 10^7 10^8 10^9

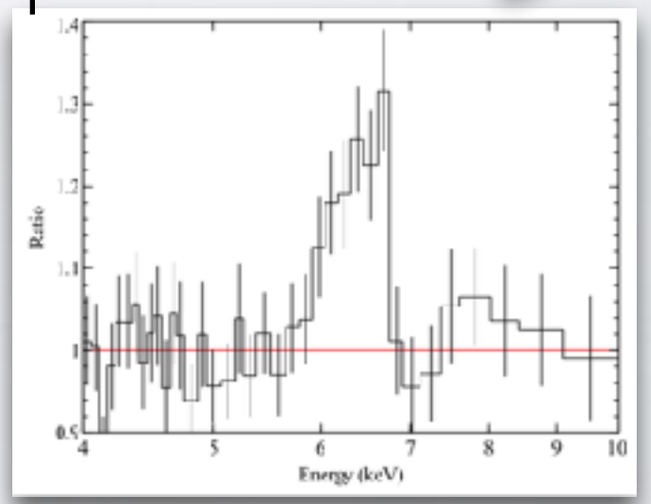
Mass (solar masses)



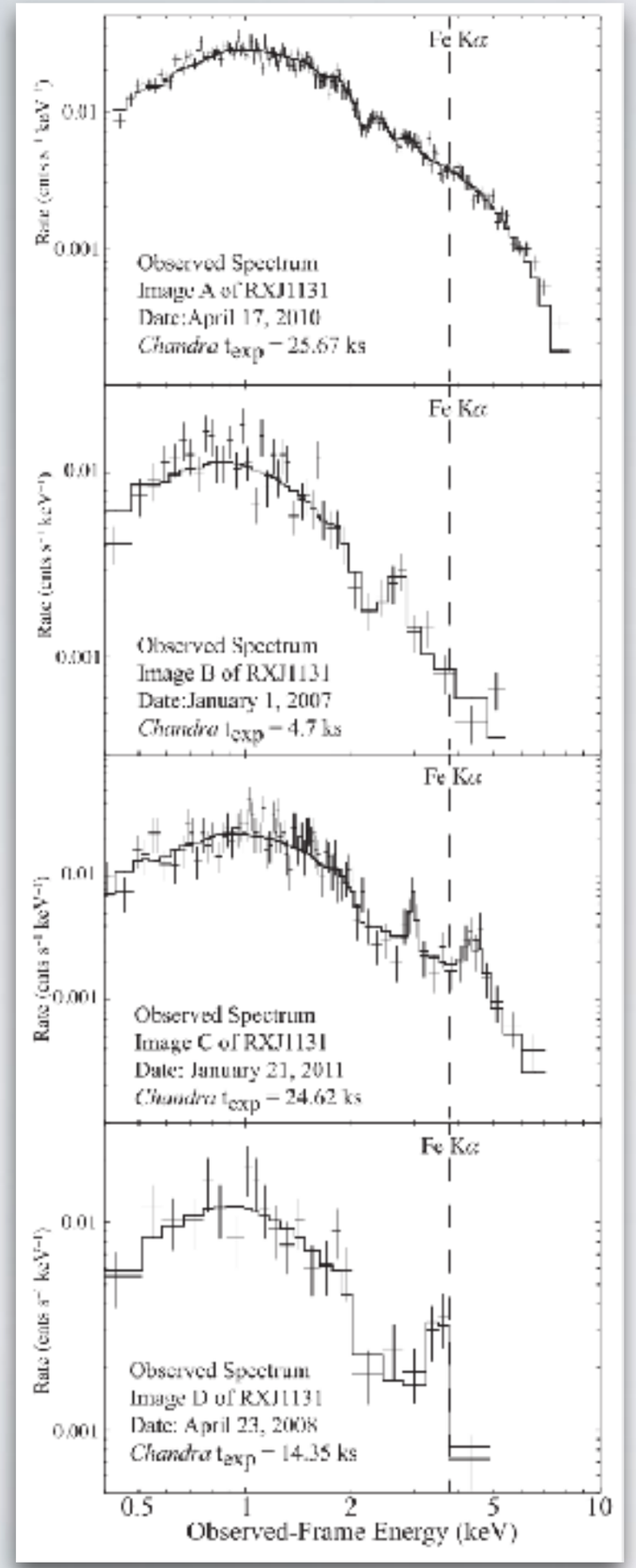
MP+15

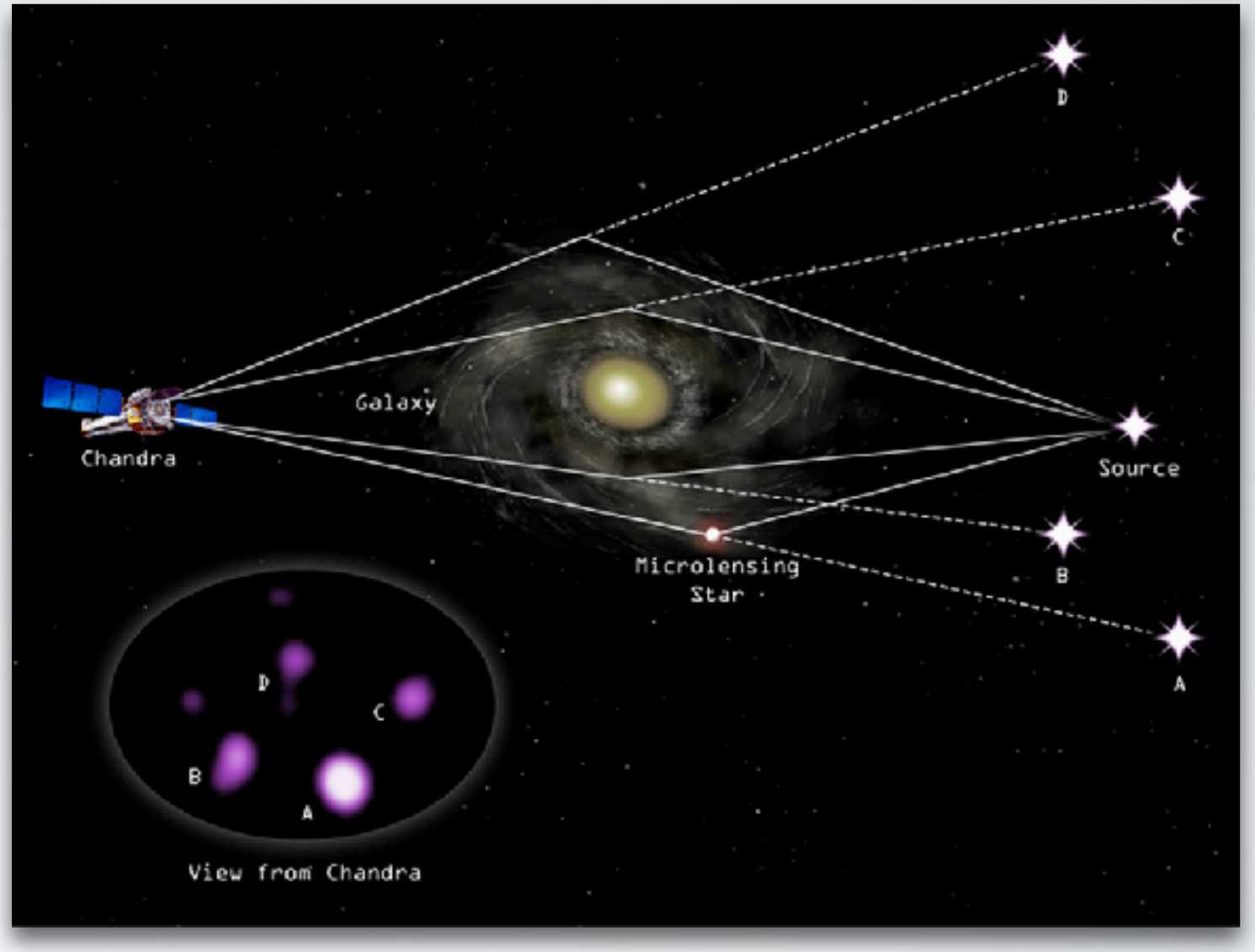


Risaliti+13



MP+18

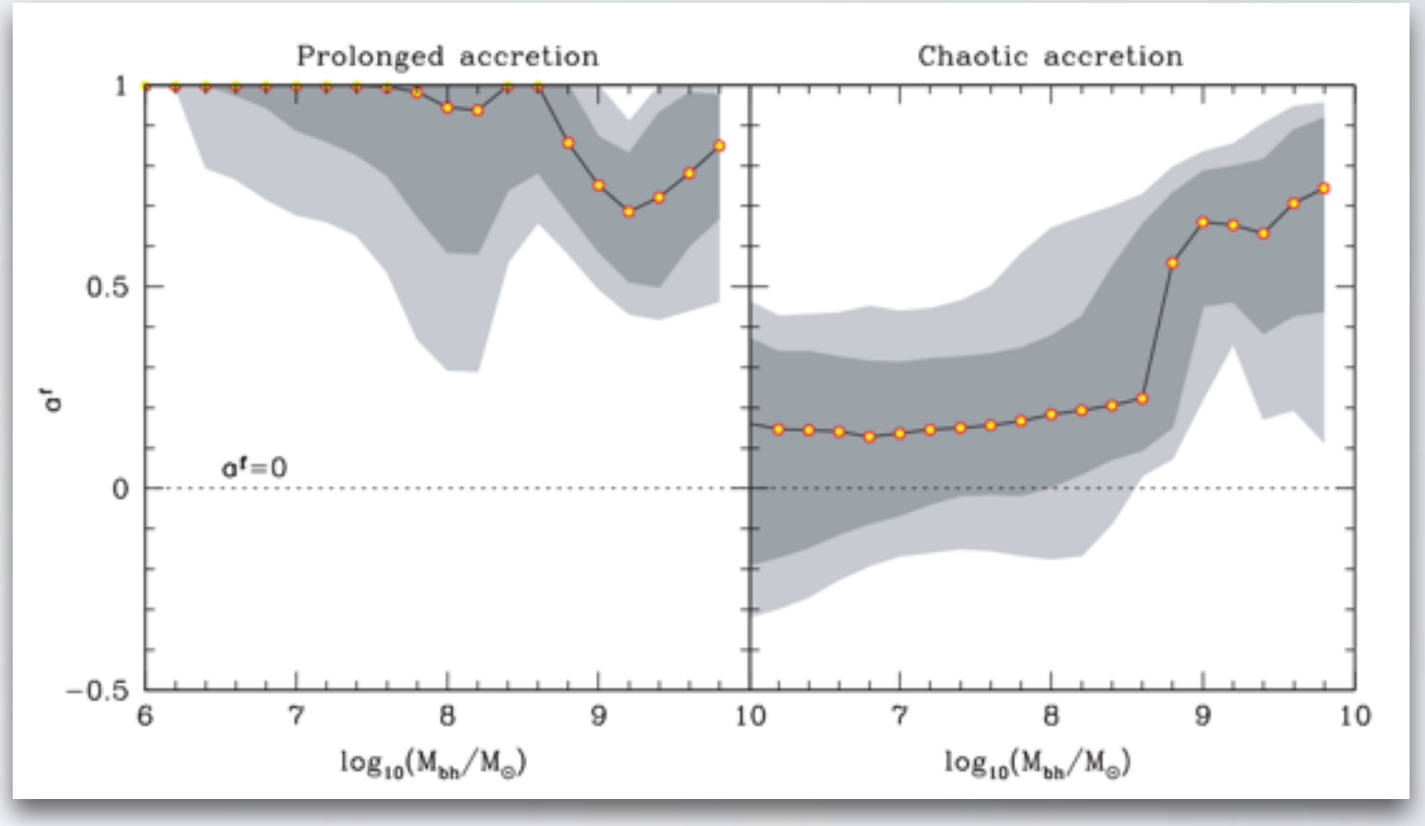

Fe Kα
Observed Spectrum
Image A of RXJ1131
Date: April 17, 2010
Chandra t_{exp} = 25.67 ks
Observed Spectrum
Image B of RXJ1131
Date: January 1, 2007
Chandra t_{exp} = 4.7 ks
Observed Spectrum
Image C of RXJ1131
Date: January 21, 2011
Chandra t_{exp} = 24.62 ks
Observed Spectrum
Image D of RXJ1131
Date: April 23, 2008
Chandra t_{exp} = 14.35 ks
Rate (cnts s^{-1} keV^{-1})
0.01
0.001
0.5
1
2
5
10
Observed-Frame Energy (keV)


D
C
Galaxy
Chandra
Source
Microlensing
Star
B
A
D
C
B
A
View from Chandra

Chartas+17

WHY IS THIS IMPORTANT?

- Powerful probe of strong gravity regime, accretion physics and GR
- Gives information about the BH formation history

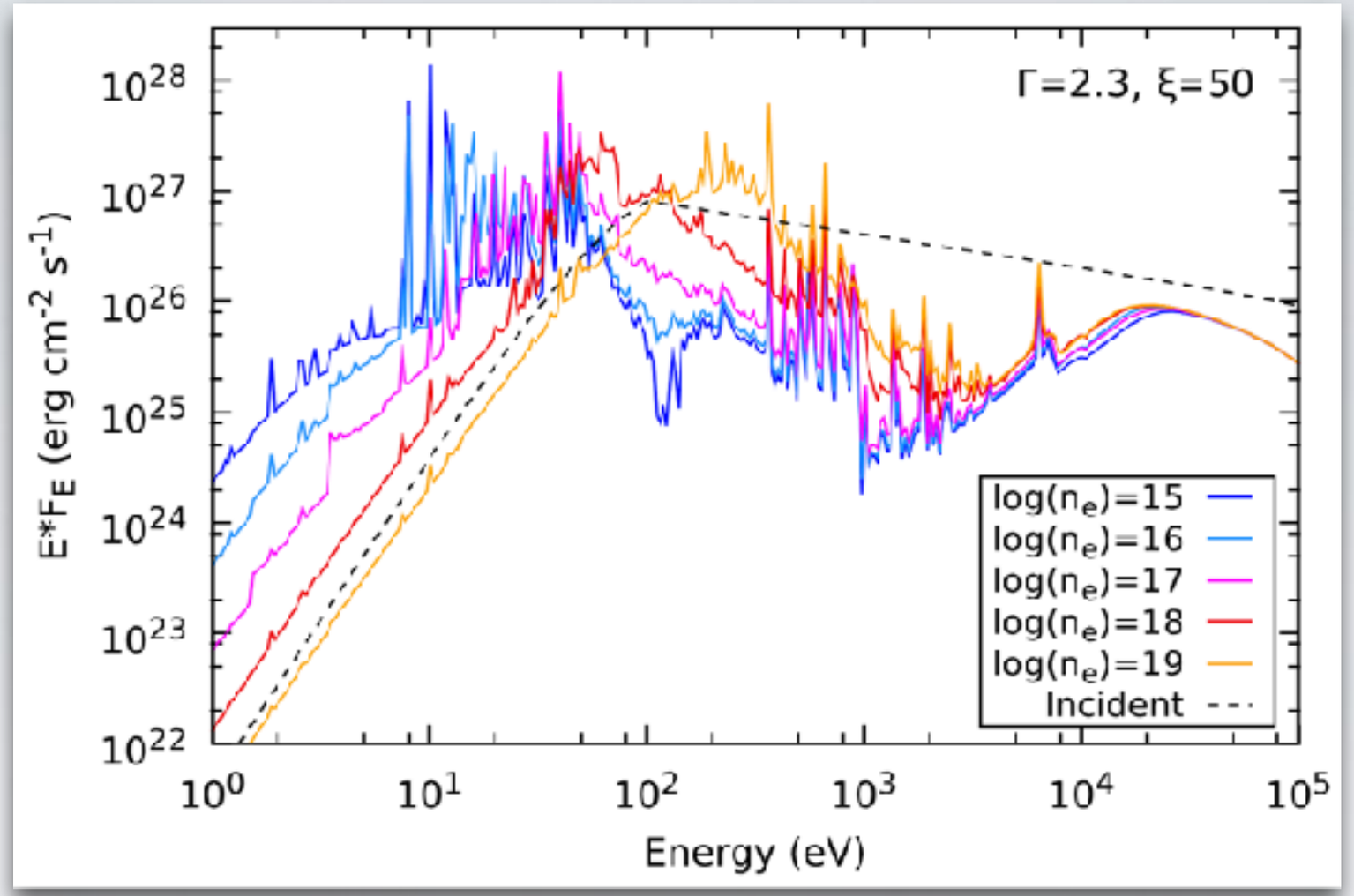


Problems with reflection spectroscopy

- Geometry dependent - some information is encoded in the line shape, but not all

- How much does reflection contribute at low energies?

- Iron abundances found by fitting seem to be highly super-solar

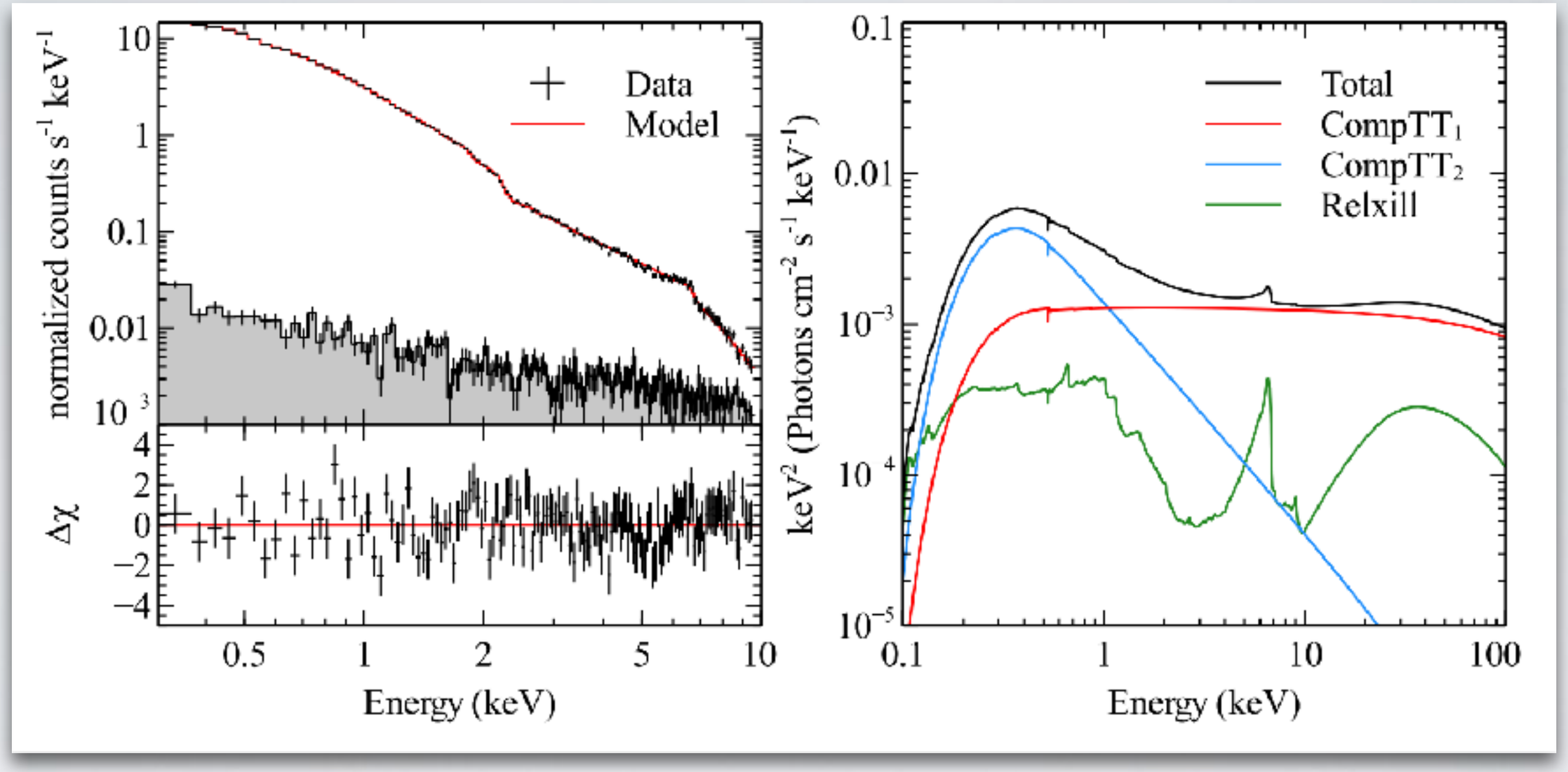


Garcia+17

Most (all) models to date assume a fixed value of the disk density, which is only likely to be accurate for very high mass AGN.

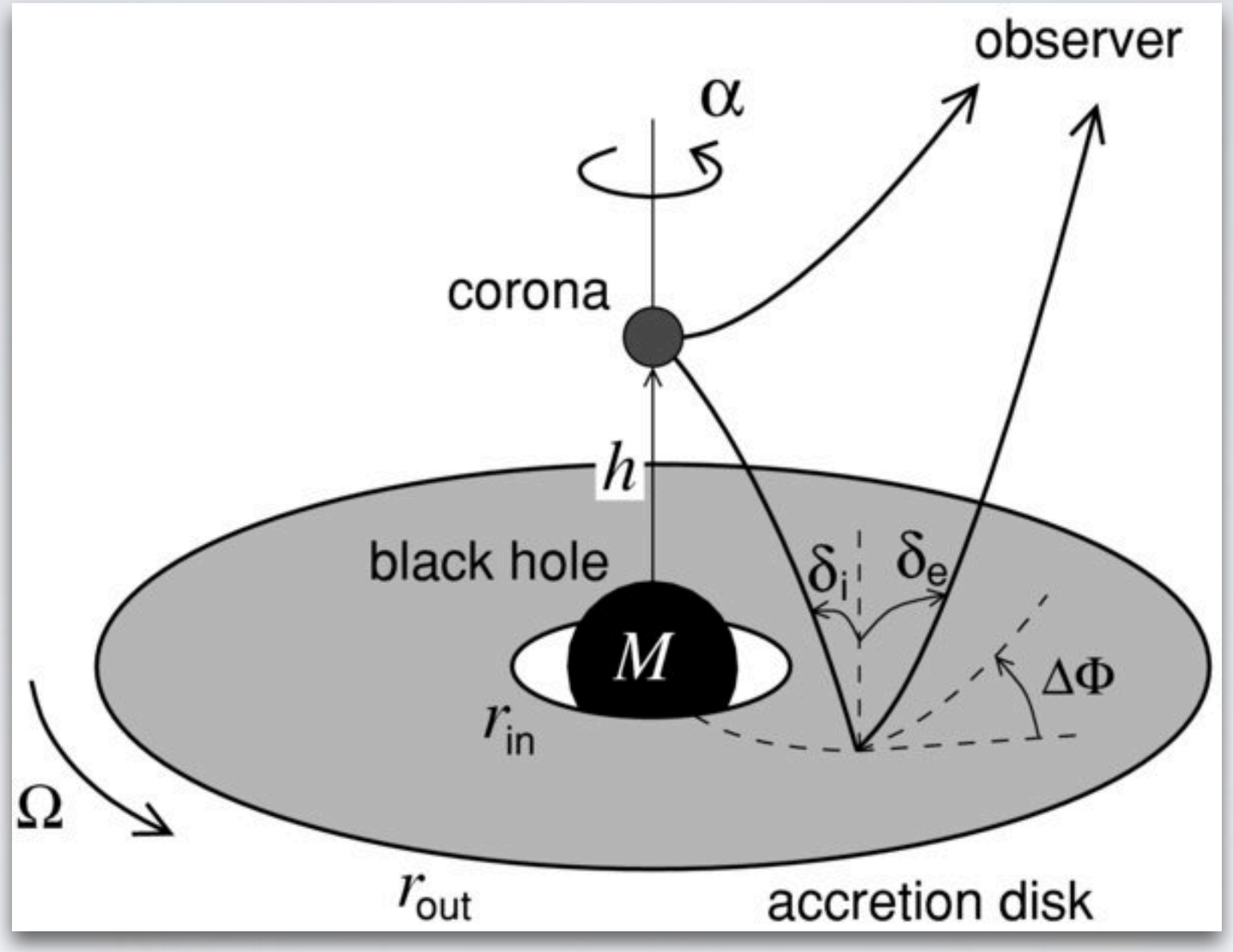
This alters the measured Fe abundance, and the contribution to low energies.

SOFT EXCESS



Parker+18a

GEOMETRY



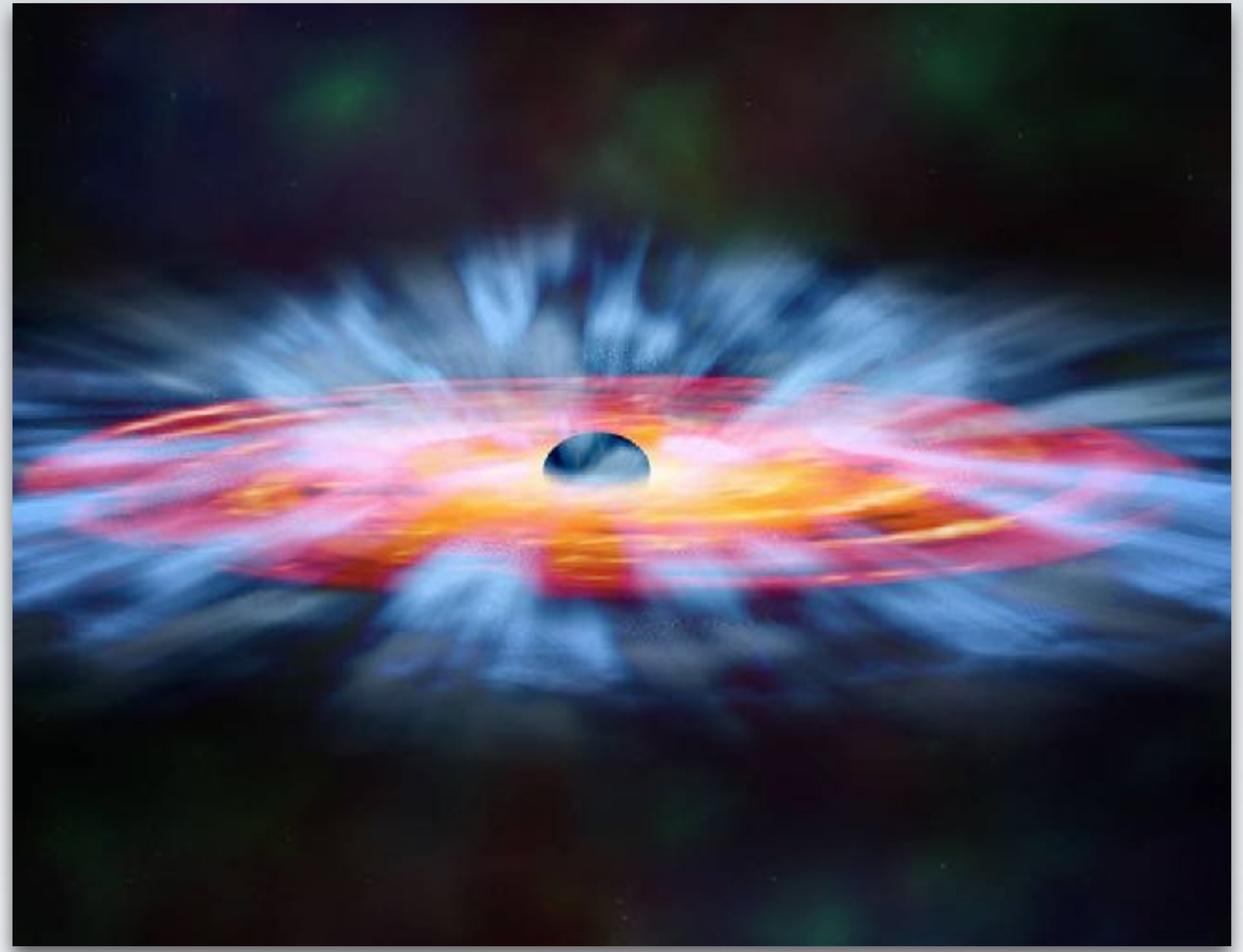
The infamous lamppost

Most of the open questions with relativistic reflection are difficult to answer - they require detailed modelling and simulations.

Most of the big results for reflection with the current generation of instruments have *probably* already happened…

ULTRA-FAST OUTFLOWS (UFOS)

(UFOs = Outflows = Winds)



Highly ionized gas launched from the accretion disk in a wind, accelerated to 0.1-0.4c by magnetic fields in the disk and radiation pressure

WHY IS THIS IMPORTANT?

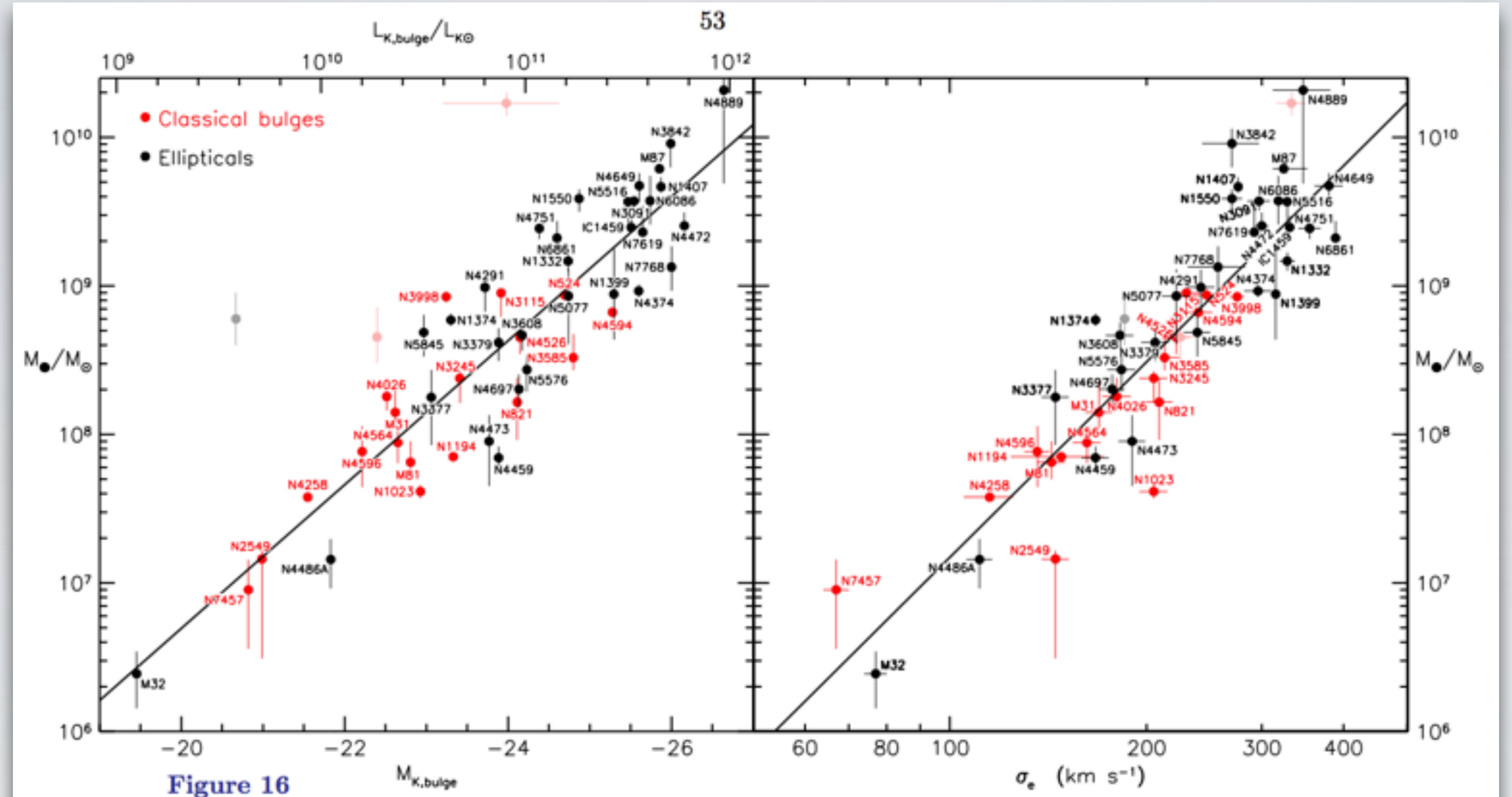
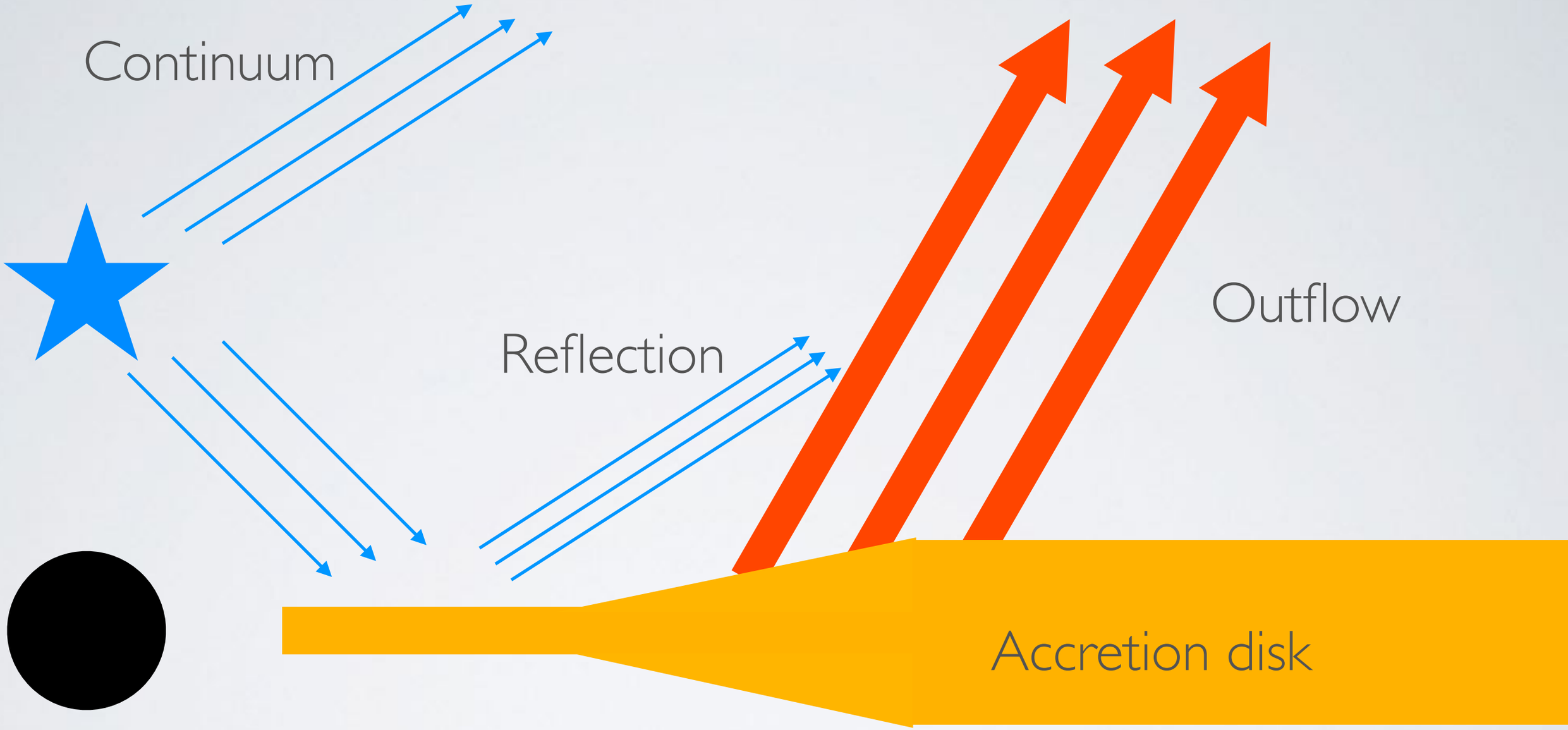


Figure 16

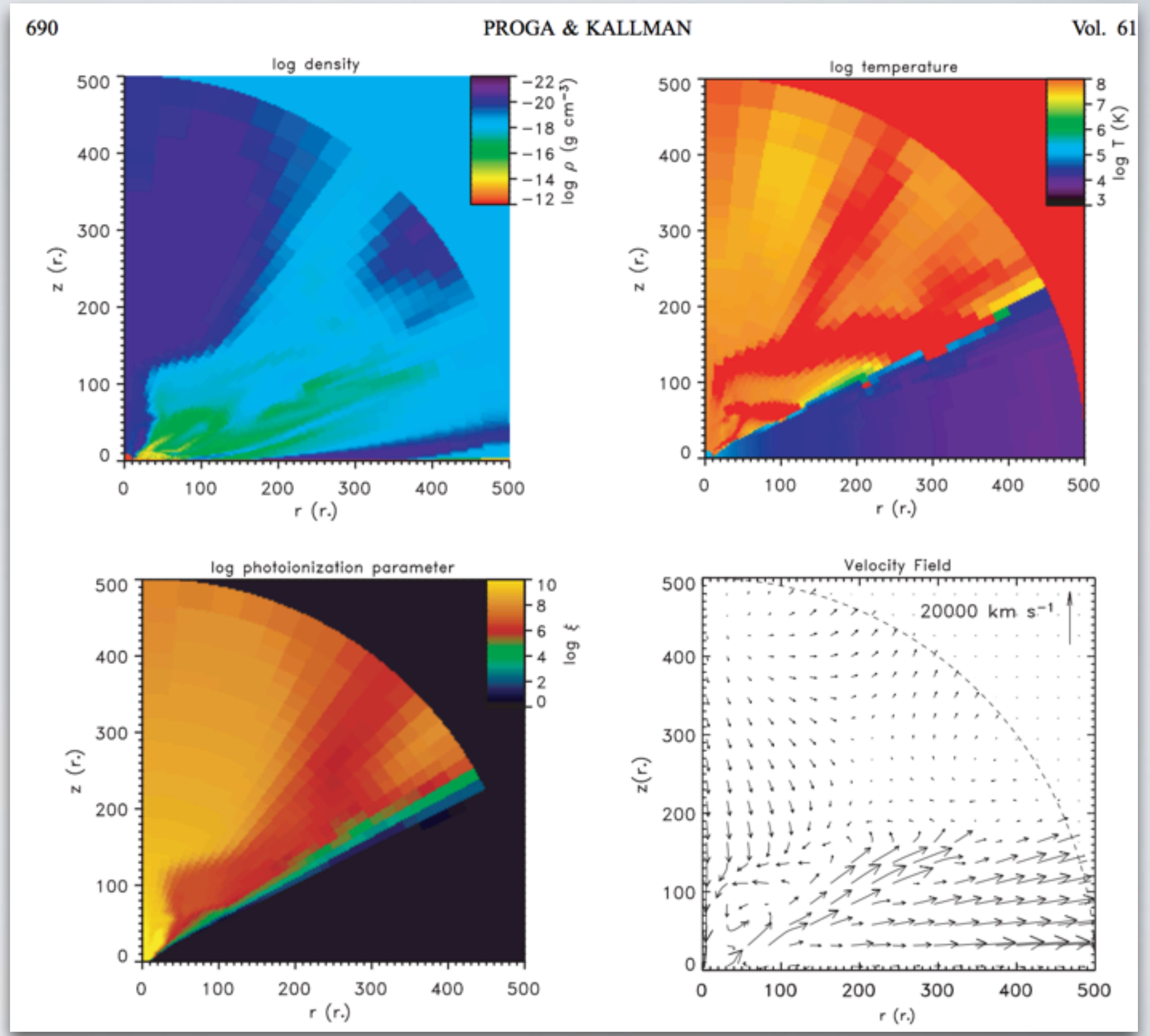
Correlation of dynamically measured BH mass $M_\bullet$ with (*left*) K-band absolute magnitude $M_{\rm K,bulge}$ and luminosity $L_{K,\rm bulge}$ and (*right*) velocity dispersion σ_e for (*red*) classical bulges and (*black*) elliptical galaxies. The lines are symmetric least-squares fits to all the points except the monsters (*points in light colors*), NGC 3842, and NGC 4889. **Figure 17** shows this fit with 1-σ error bars.

Kormendy & Ho, 2013

AGN regulate the growth of their host galaxies, through AGN feedback.
Powerful winds are one way of achieving this.

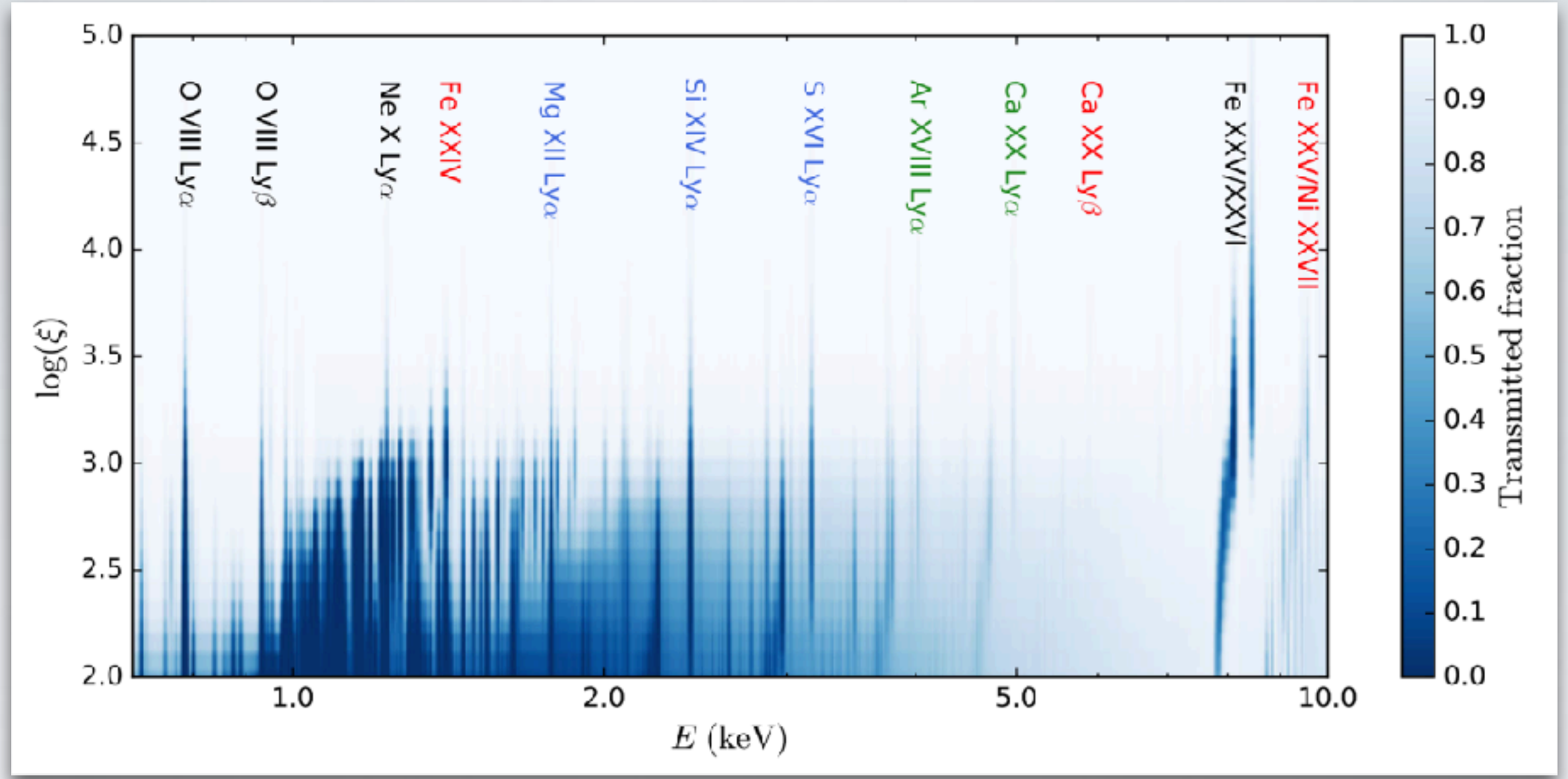

Continuum
Reflection
Outflow
Accretion disk

Gas is very highly ionized, due to low density



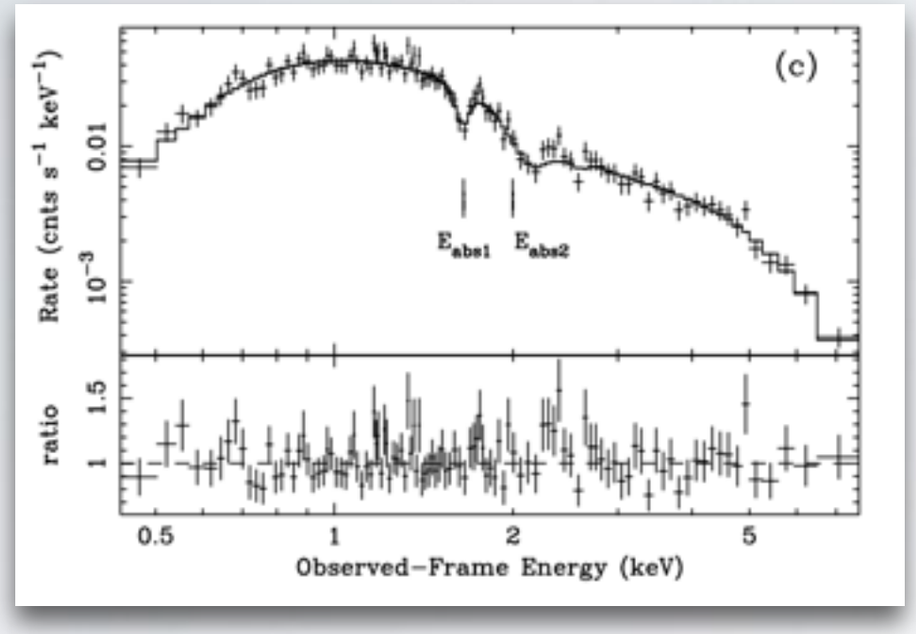
Proga & Kallman, 04

At high ionization, only a few absorption lines exist

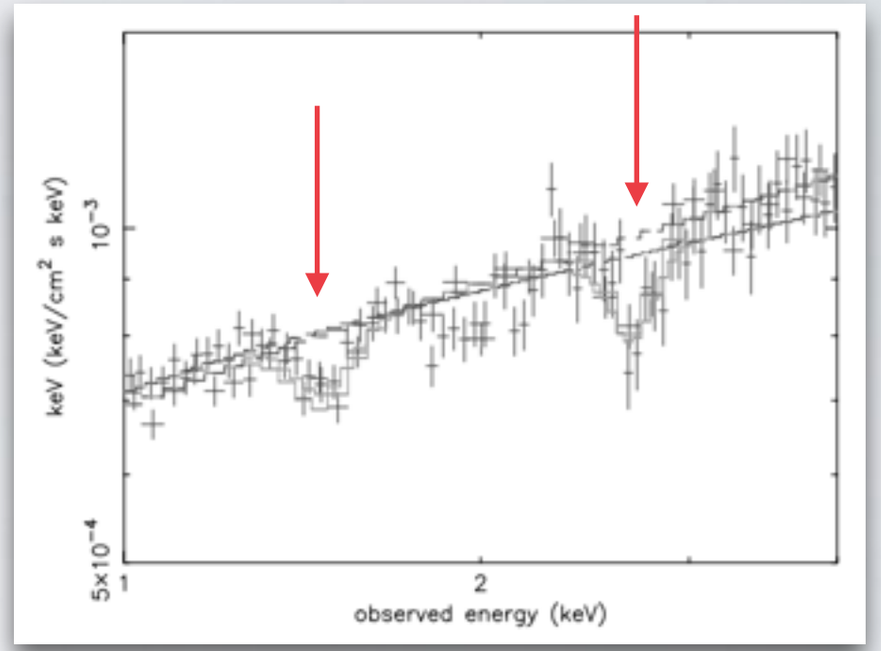


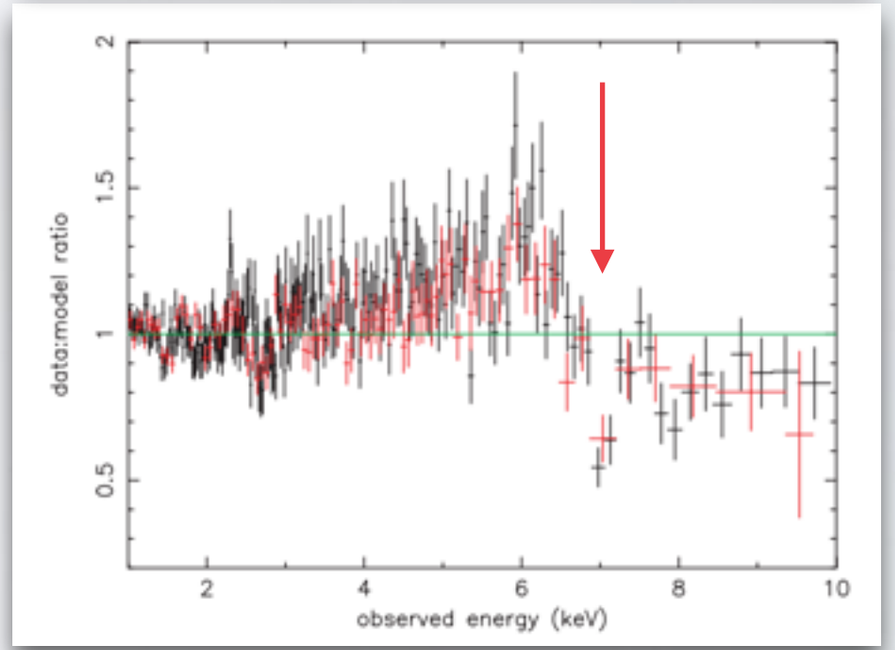
MP+17

FIRST DETECTIONS



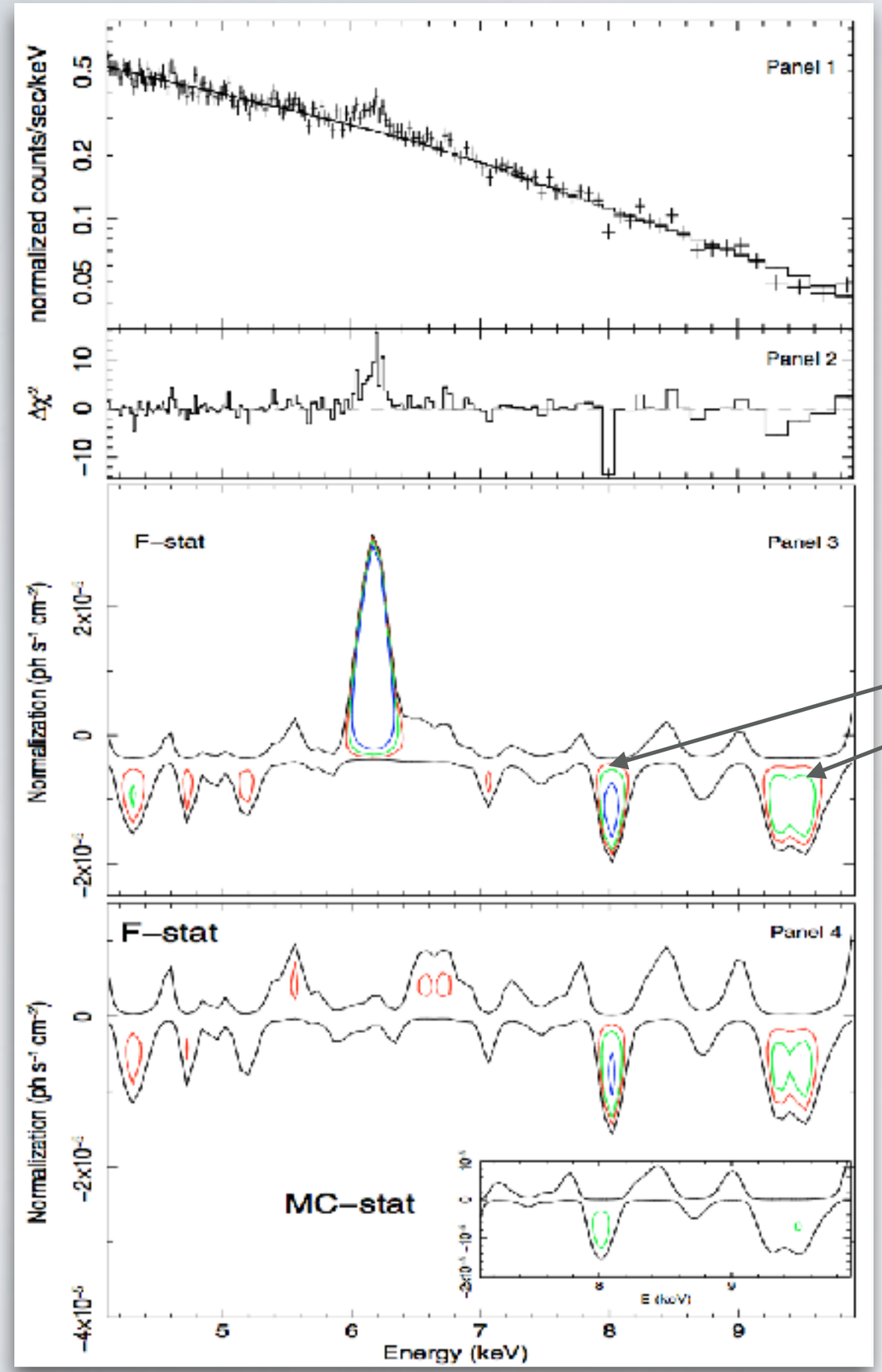
Chartas+02





Pounds+03

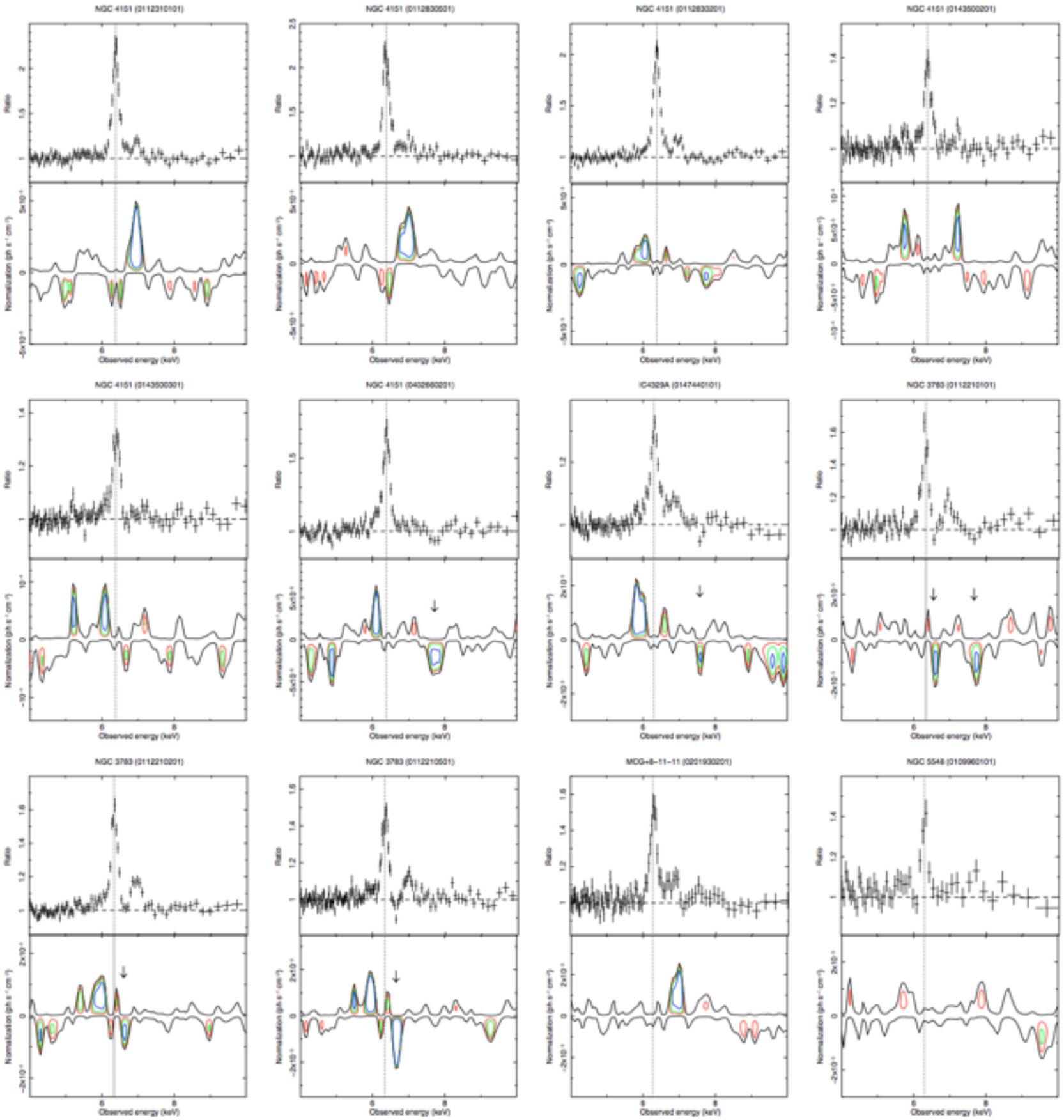
DETECTION



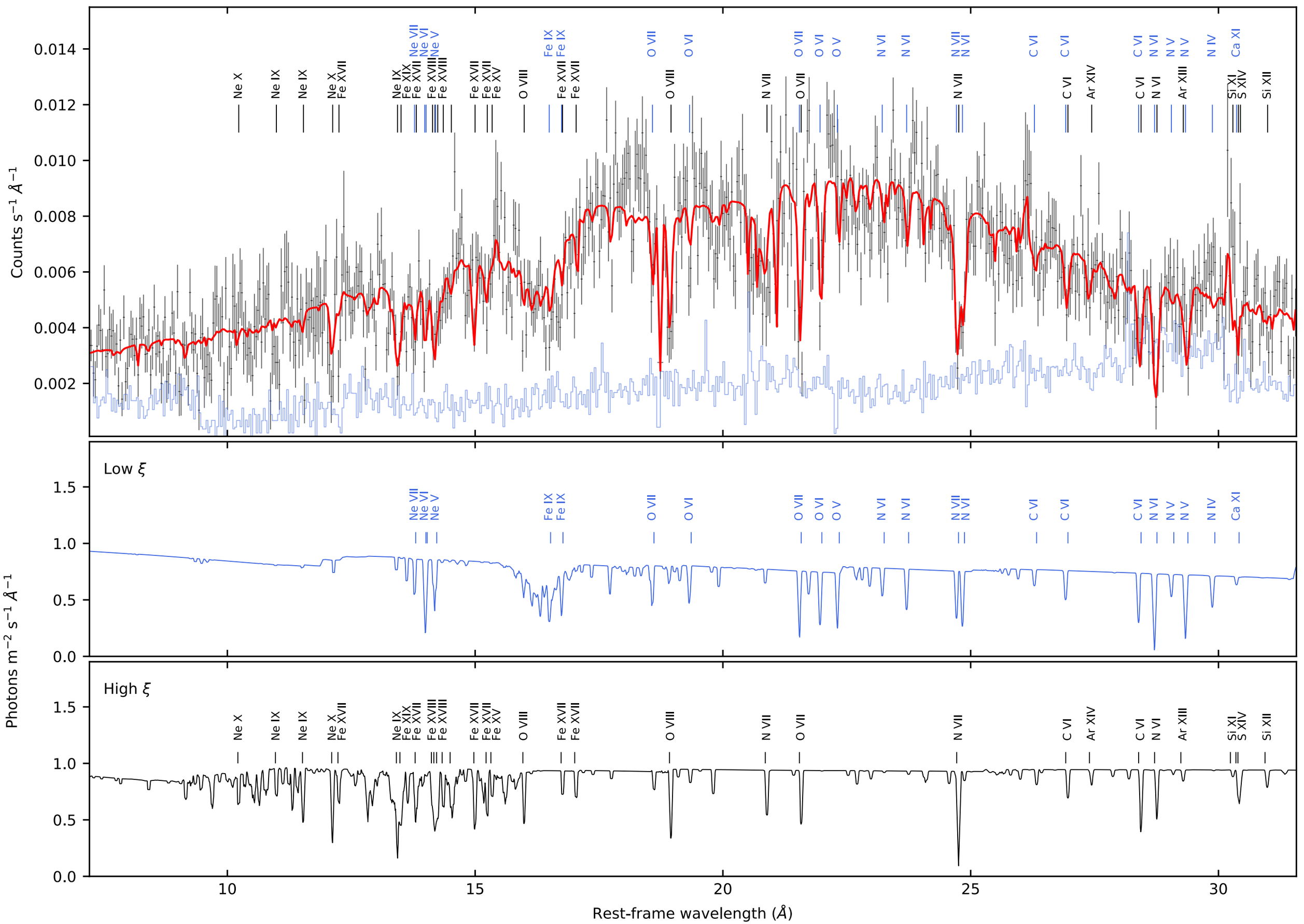
Absorption lines from Fe XXV/XXVI

Easiest at high energies…

Cappi+09


NGC 4151 (0112310101)
NGC 4151 (0112830501)
NGC 4151 (0112830201)
NGC 4151 (0143500201)
NGC 4151 (0143500301)
NGC 4151 (0402660201)
IC4329A (0147440101)
NGC 3783 (0112210101)
NGC 3783 (0112210201)
NGC 3783 (0112210501)
MCG+8-11-11 (0201930201)
NGC 5548 (0109960101)
Ratio
Normalization (ph s⁻¹ cm⁻²)
Observed energy (keV)

Tombesi+11


Counts s^{-1} Å^{-1}
Photons m^{-2} s^{-1} Å^{-1}
Low ξ
High ξ
Rest-frame wavelength (Å)
Ne X
Ne IX
Fe XVII
Ne VII
Ne VI
Ne V
Fe XIX
Fe XVIII
O VII
O VI
O VIII
N VII
O V
N VI
C VI
Ar XIV
Ar XIII
N V
N IV
Ca XI
Si XI
S XIV
Si XII
Fe IX
Fe XV

Counts s^{-1} Å^{-1}

Photons m^{-2} s^{-1} Å^{-1}

Low ξ

High ξ

Rest-frame wavelength (Å)

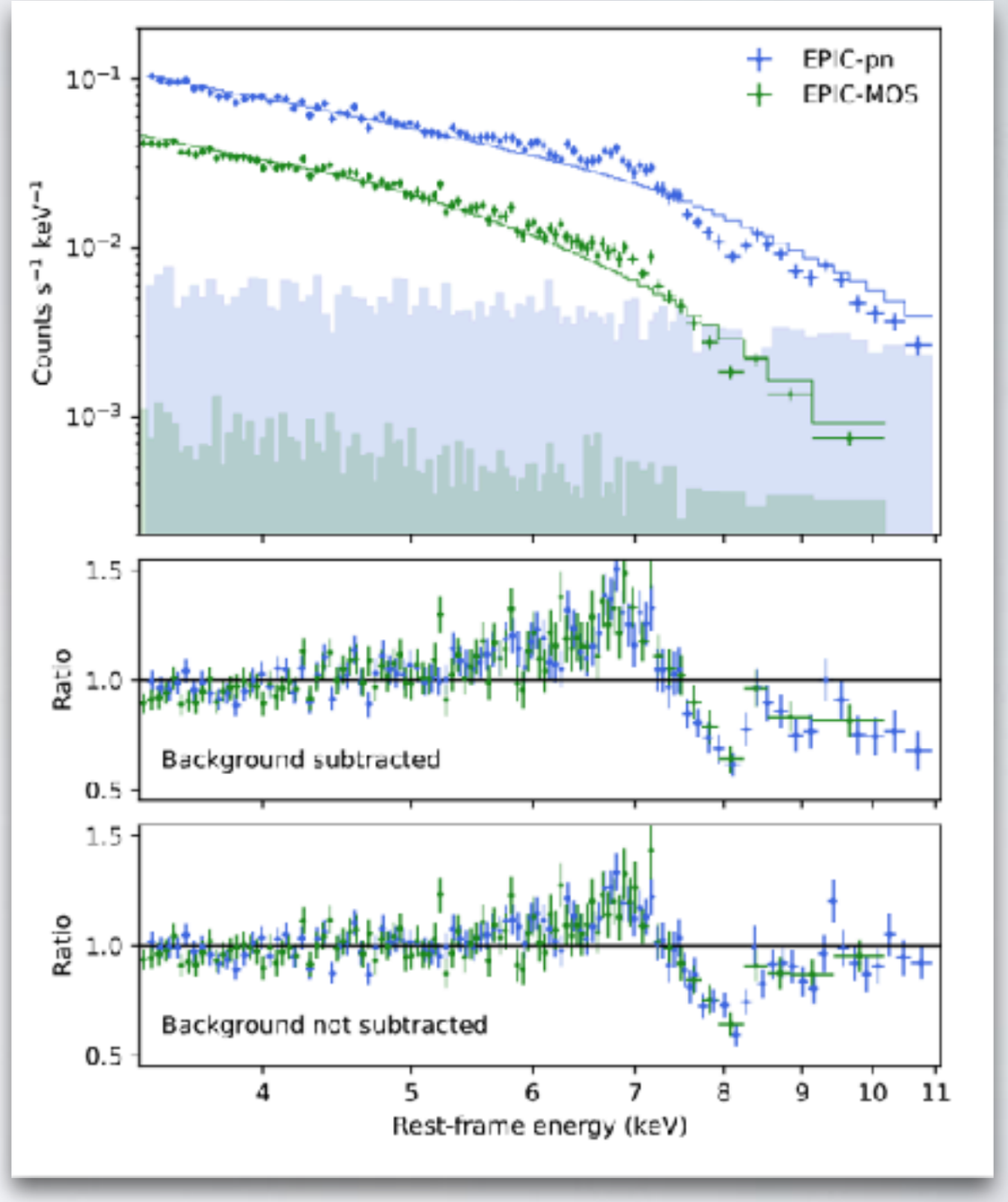
Ne X
Ne IX
Ne IX
Ne X
Fe XVII
Ne IX
Fe XIX
Fe XVII
Ne VII
Ne VI
Ne V
Fe XVIII
Fe XVIII
Fe XVII
Fe XVII
Fe XV
O VIII
Fe IX
Fe XVII
Fe IX
Fe XVII
O VII
O VI
O VIII
N VII
O VII
O VII
O VI
O V
N VI
N VI
N VII
N VI
C VI
C VI
C VI
Ar XIV
C VI
N VI
N V
Ar XIII
N V
N IV
Ca XI
Si XI
S XIV
Si XII

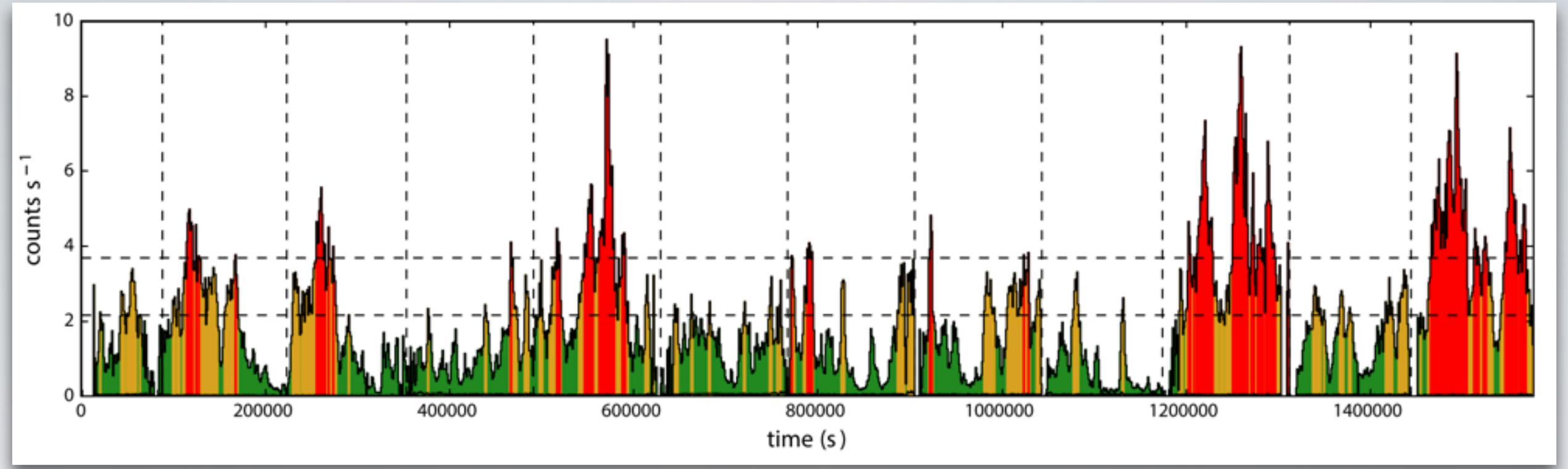
Fe XI
Fe XII
Fe X
Fe XI
Fe IX
Fe X
Fe IX
O VII
O VII
O VIII UFO?
Rest-frame wavelength (Å)

Problems with UFO spectroscopy

MP+18, submitted

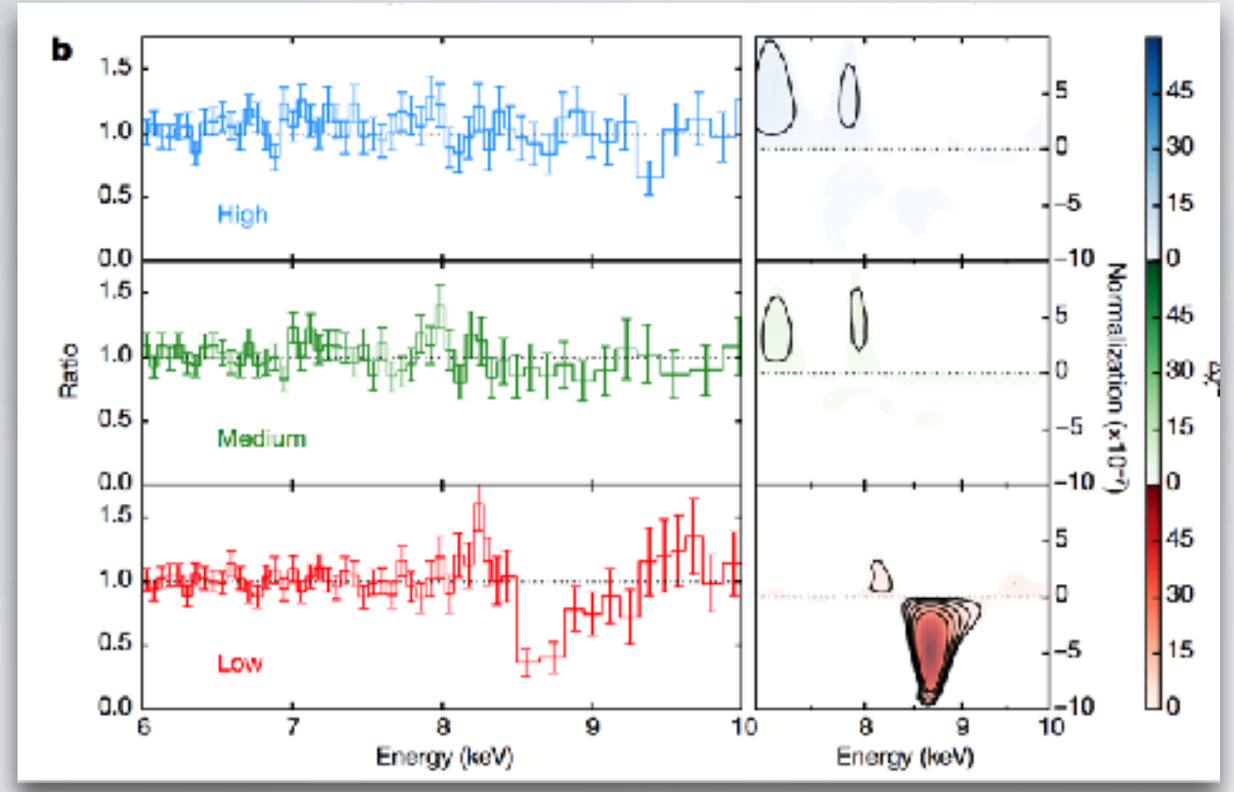
- Detecting only high energy (>7keV) lines introduces biases
- X-ray detectors are generally poorly calibrated and have small collecting area and high background at high energies
- We only see one line of sight through the gas, so cannot establish the density or geometry
- UFO features come and go, and change energies, with little or no explanation

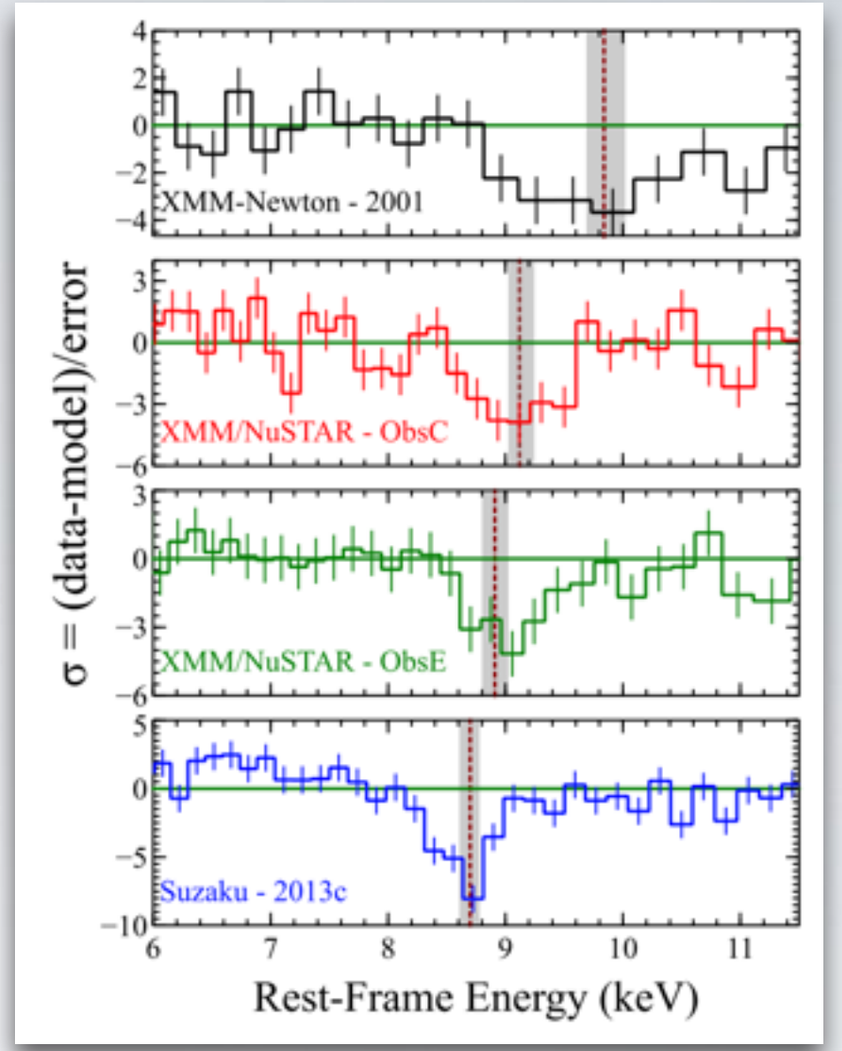


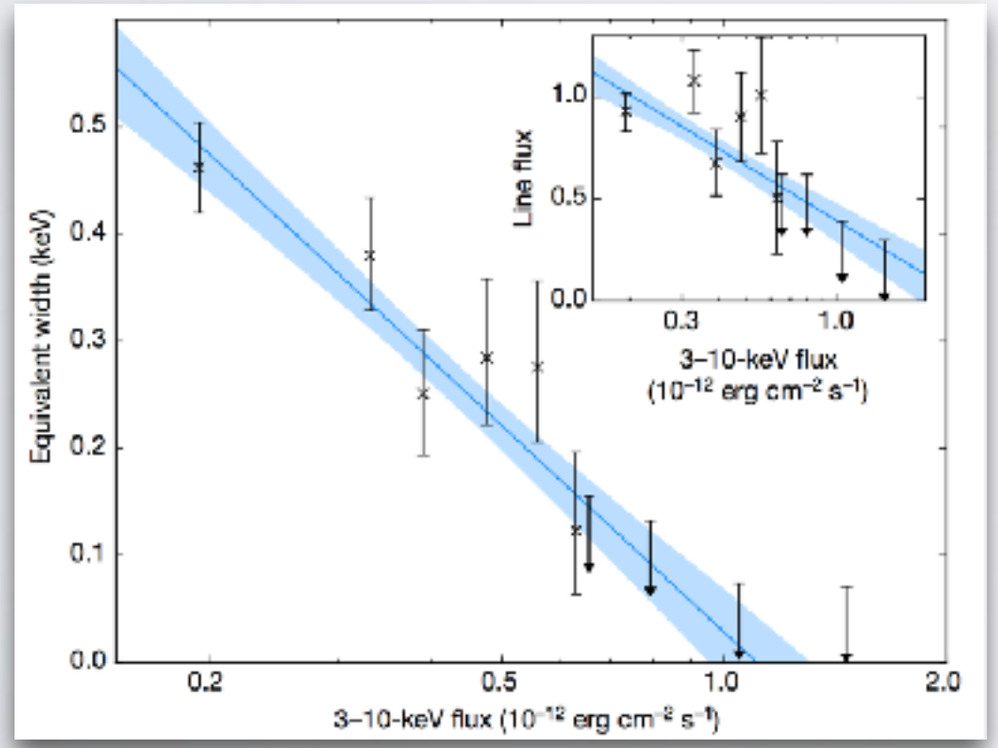


Variability gives one way of addressing these problems.
AGN are very variable!

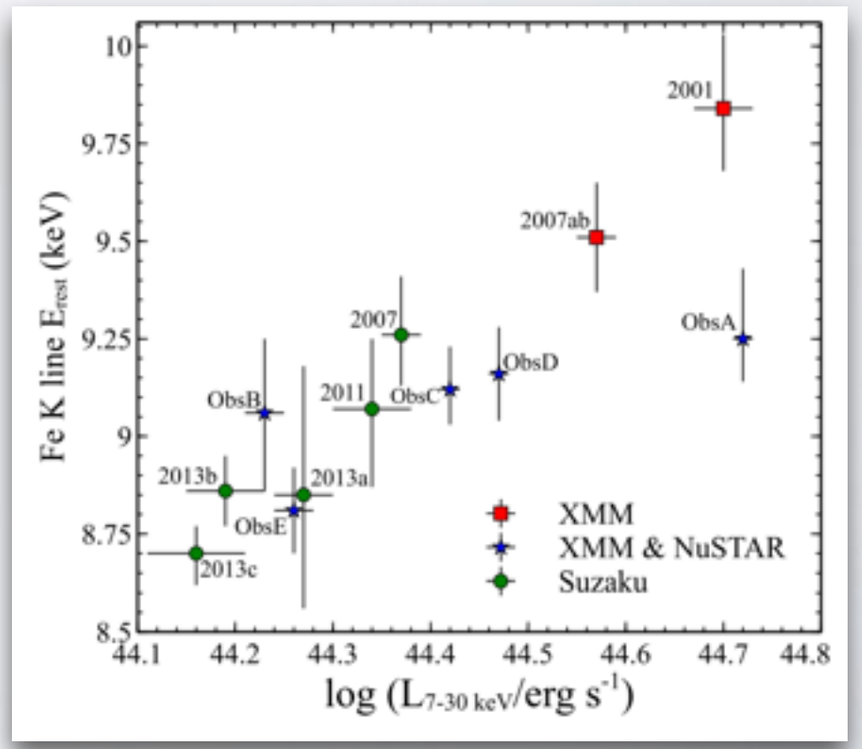
Matzeu+17



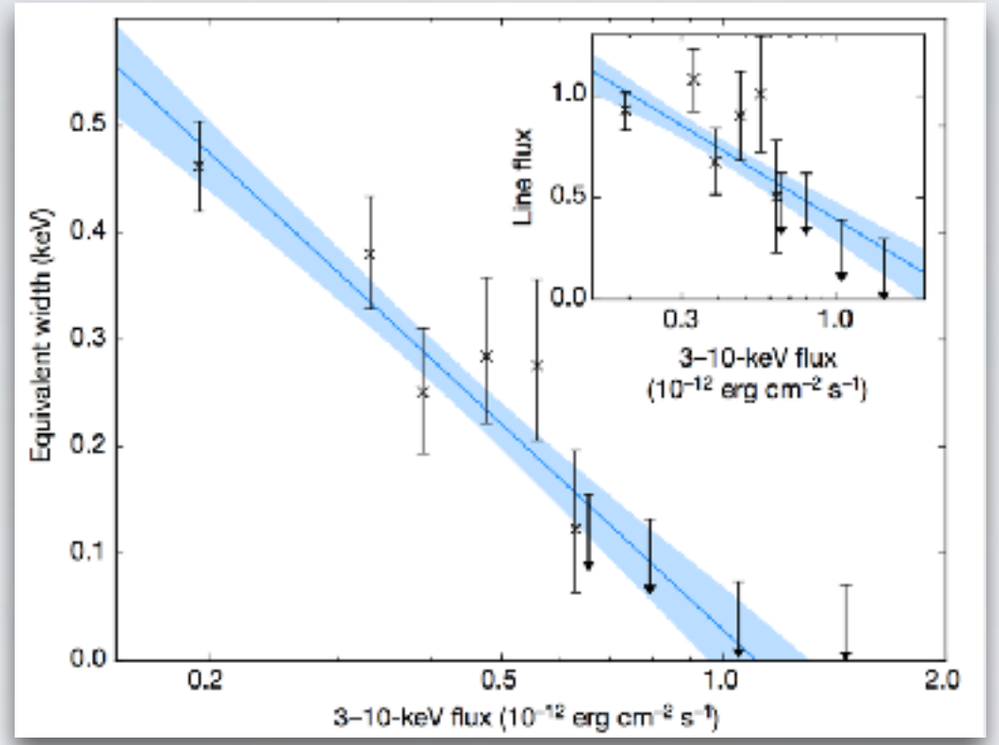




MP+17a

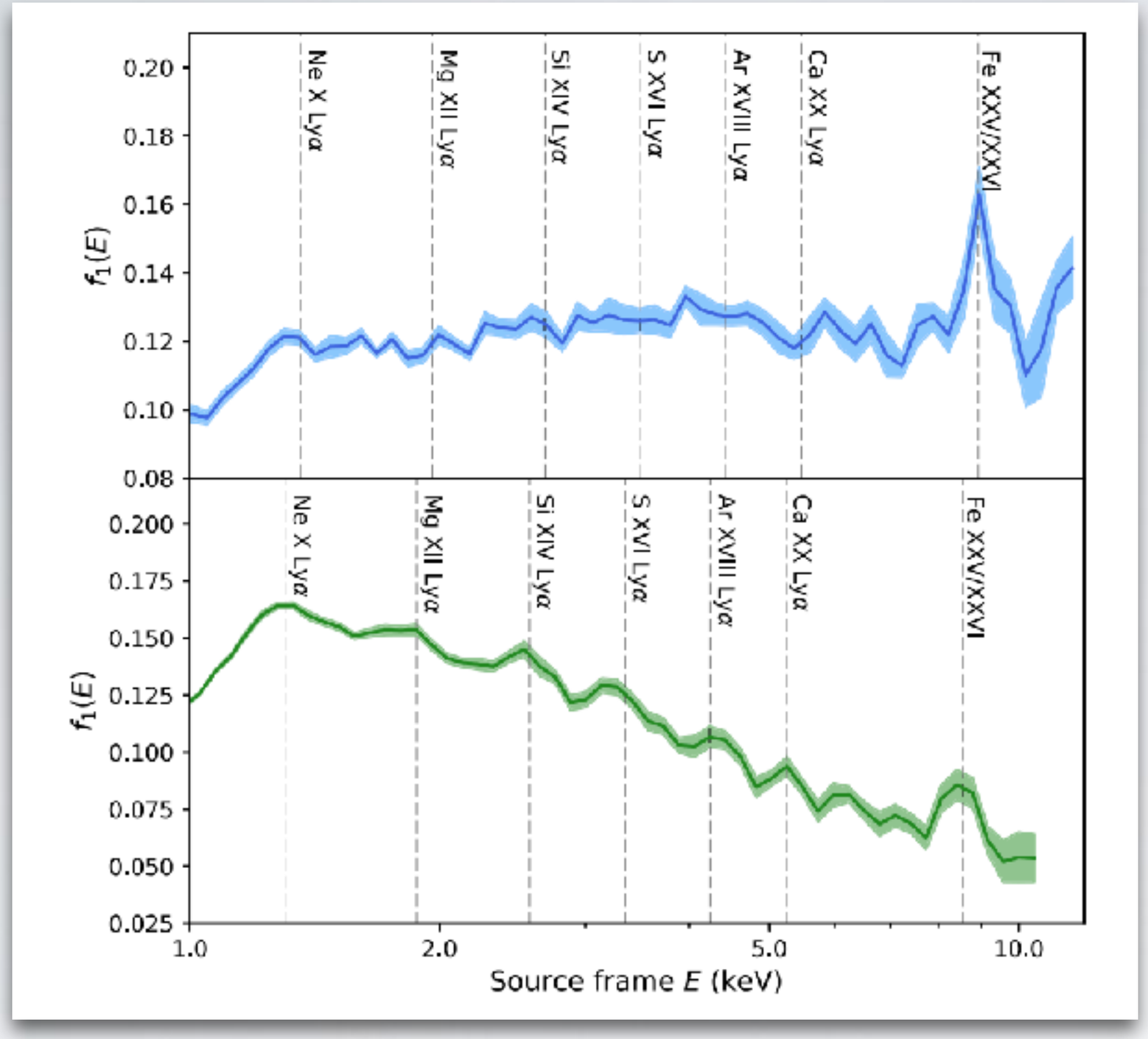


Using variability to search for absorption lines



MP+17a

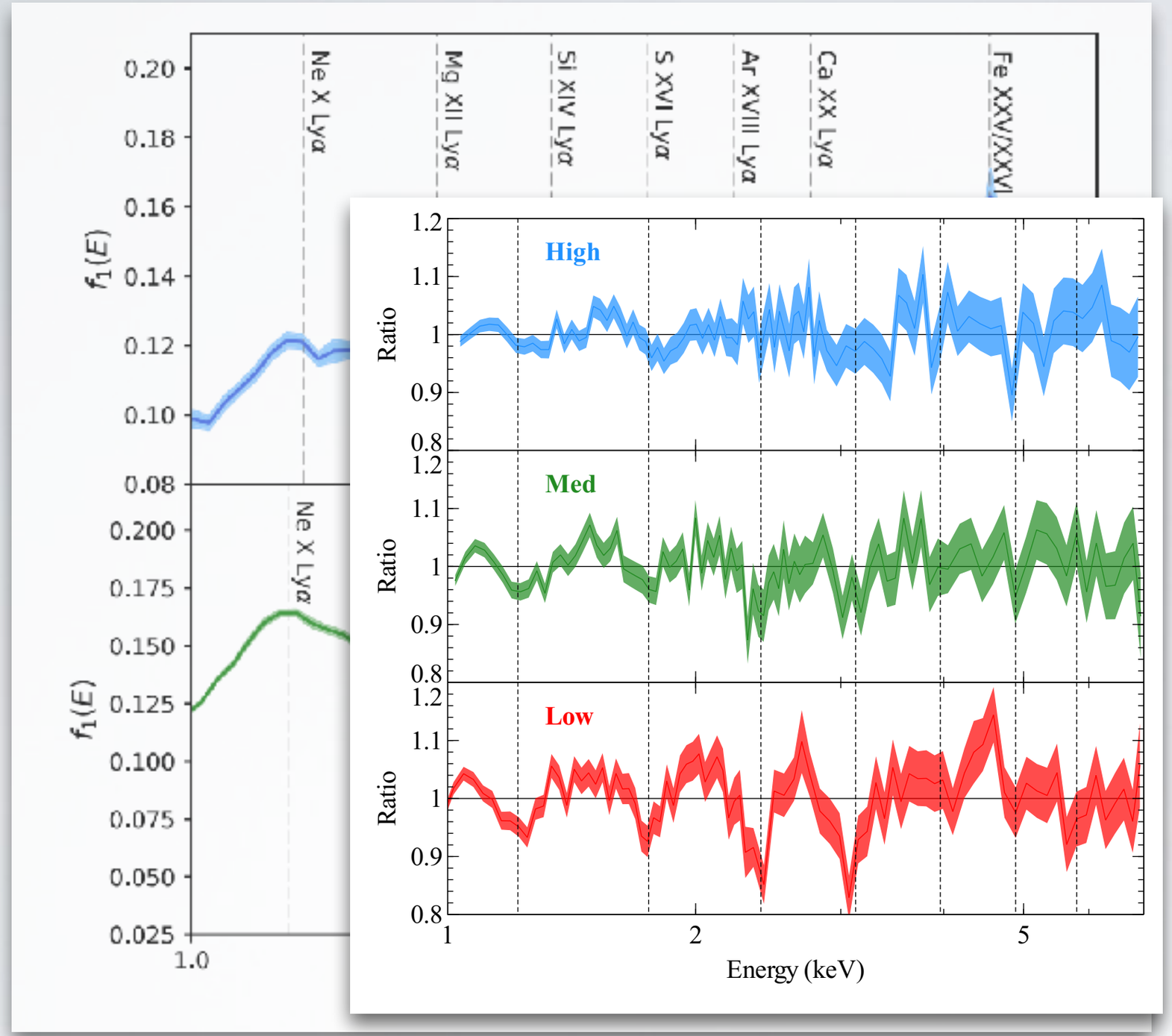
If the strength of absorption features responds to the continuum, then there will be more variability in these energy bands…



High ionization

Low ionization

MP+17b, 18b



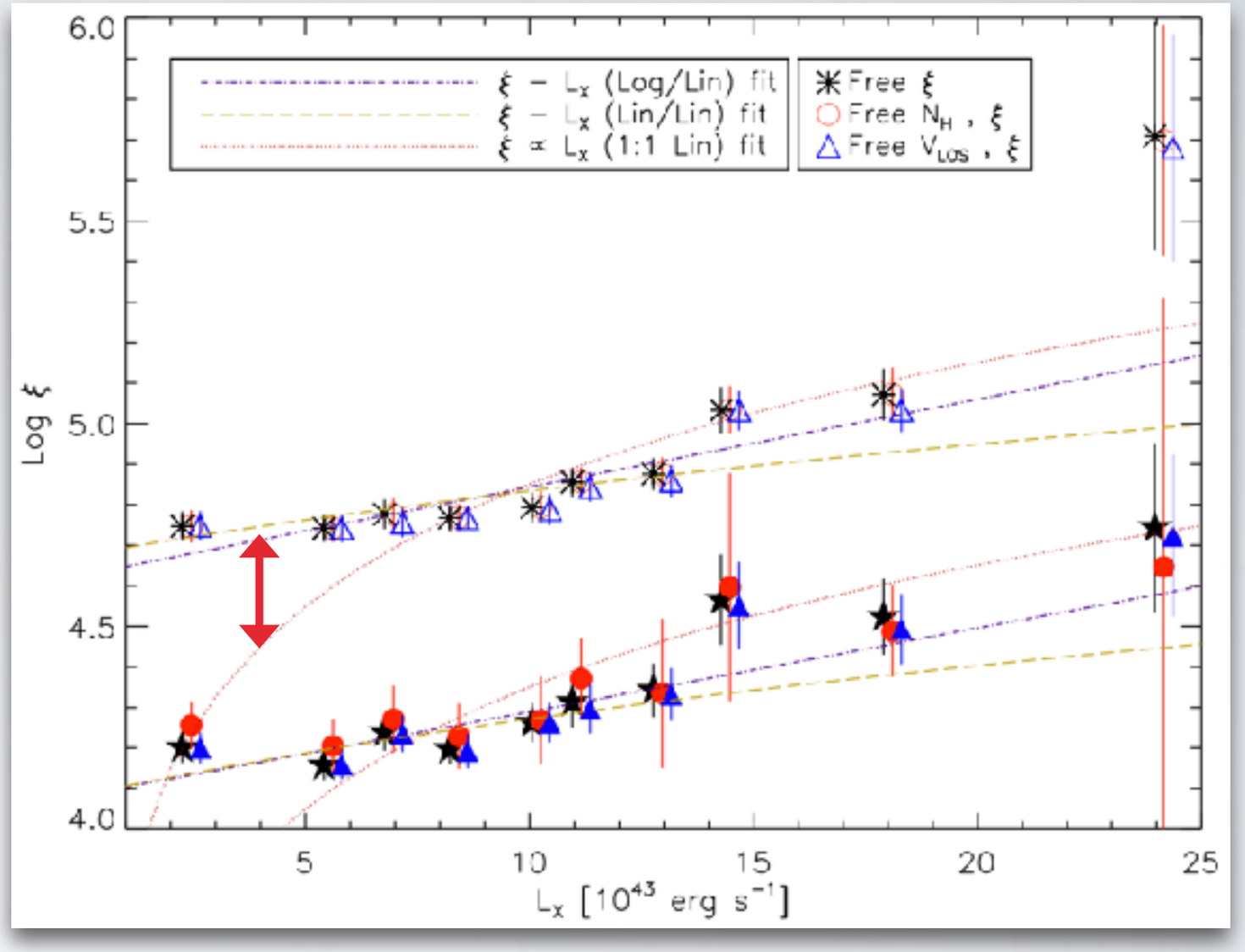
High ionization

Low ionization

MP+17b, 18b

Ionization isn't linear with flux - this could be an indication of a recombination delay

Recombination time is a density dependent effect, so if we can measure this, we get a lot more information about the UFO

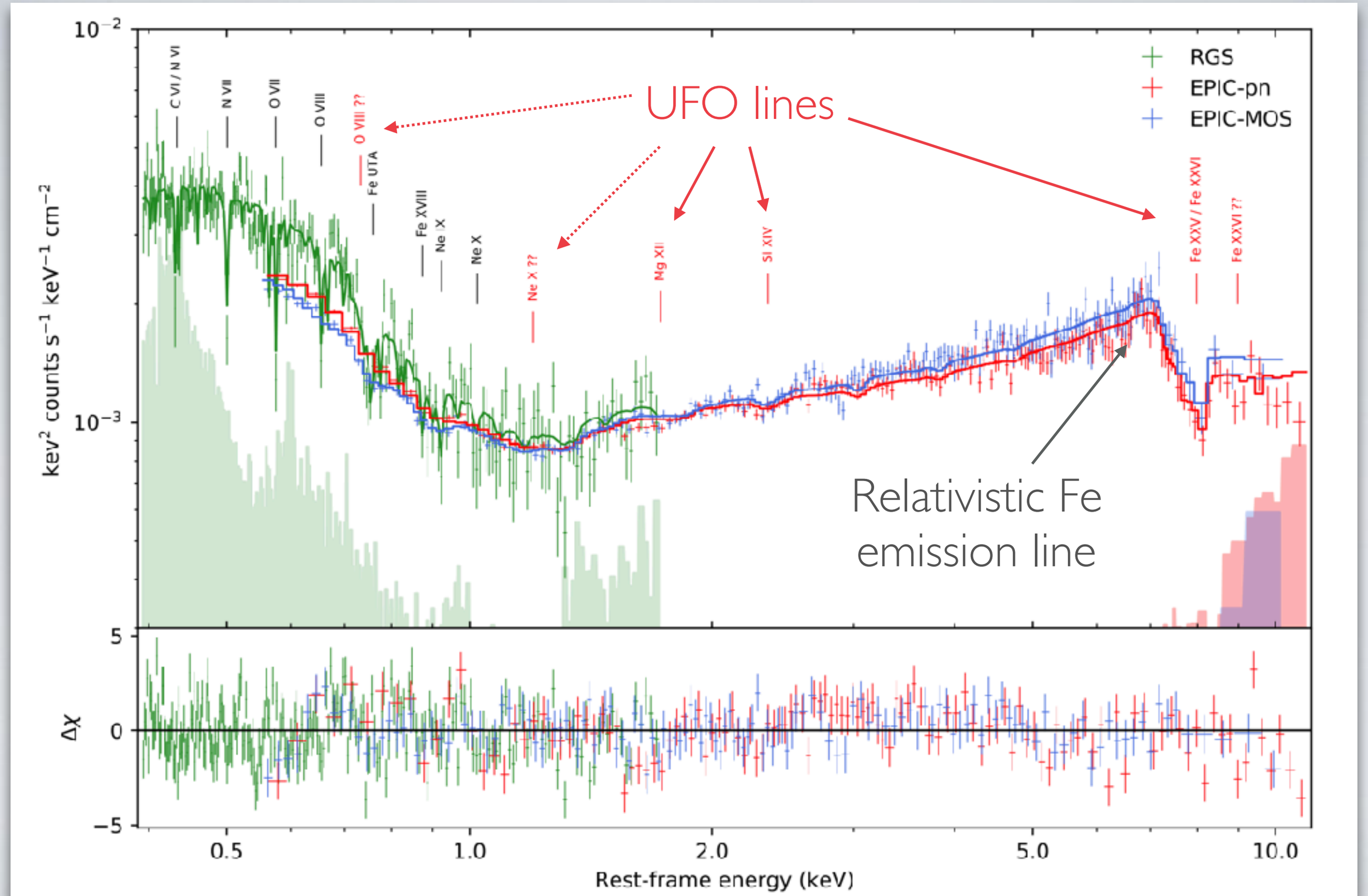


Ionization of gas

X-ray luminosity

COMBINING UFOS AND REFLECTION

MP+18, submitted

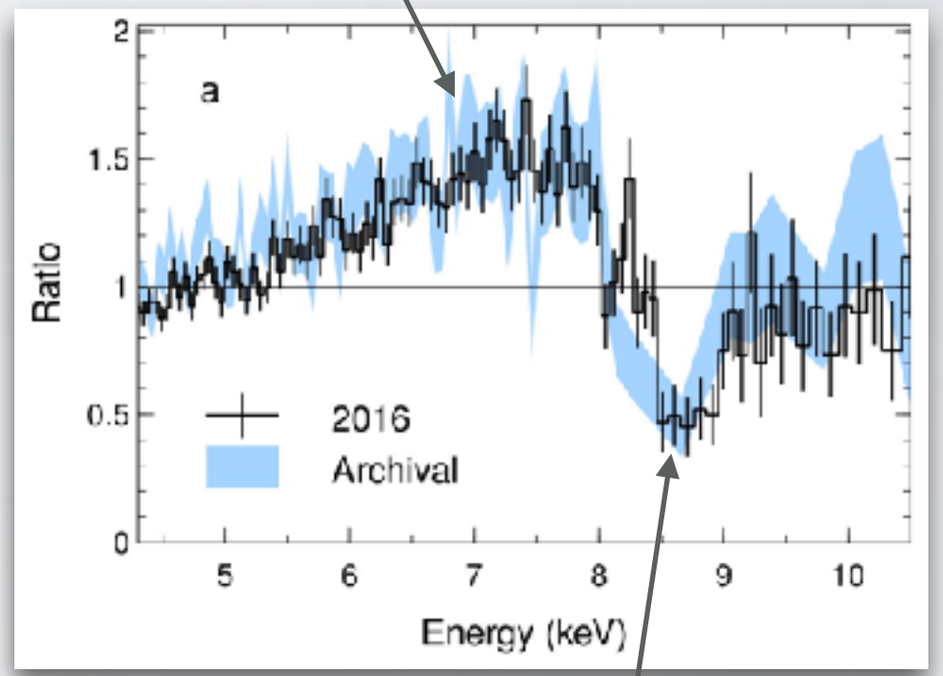


- Very few combined measurements of UFOs and reflection

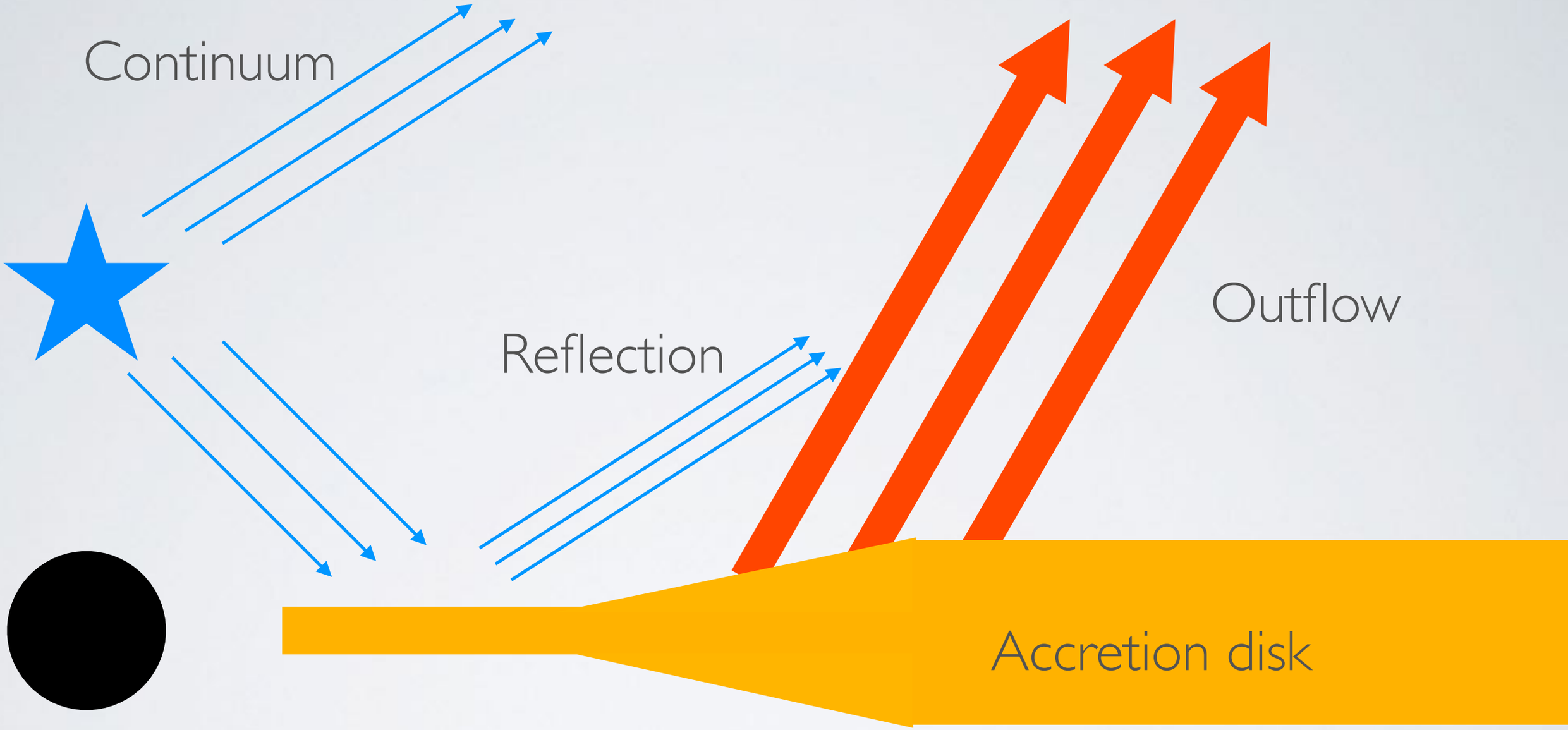
- Potentially a very effective way of mapping UFO structure

Relativistic Fe emission line

MP+17a



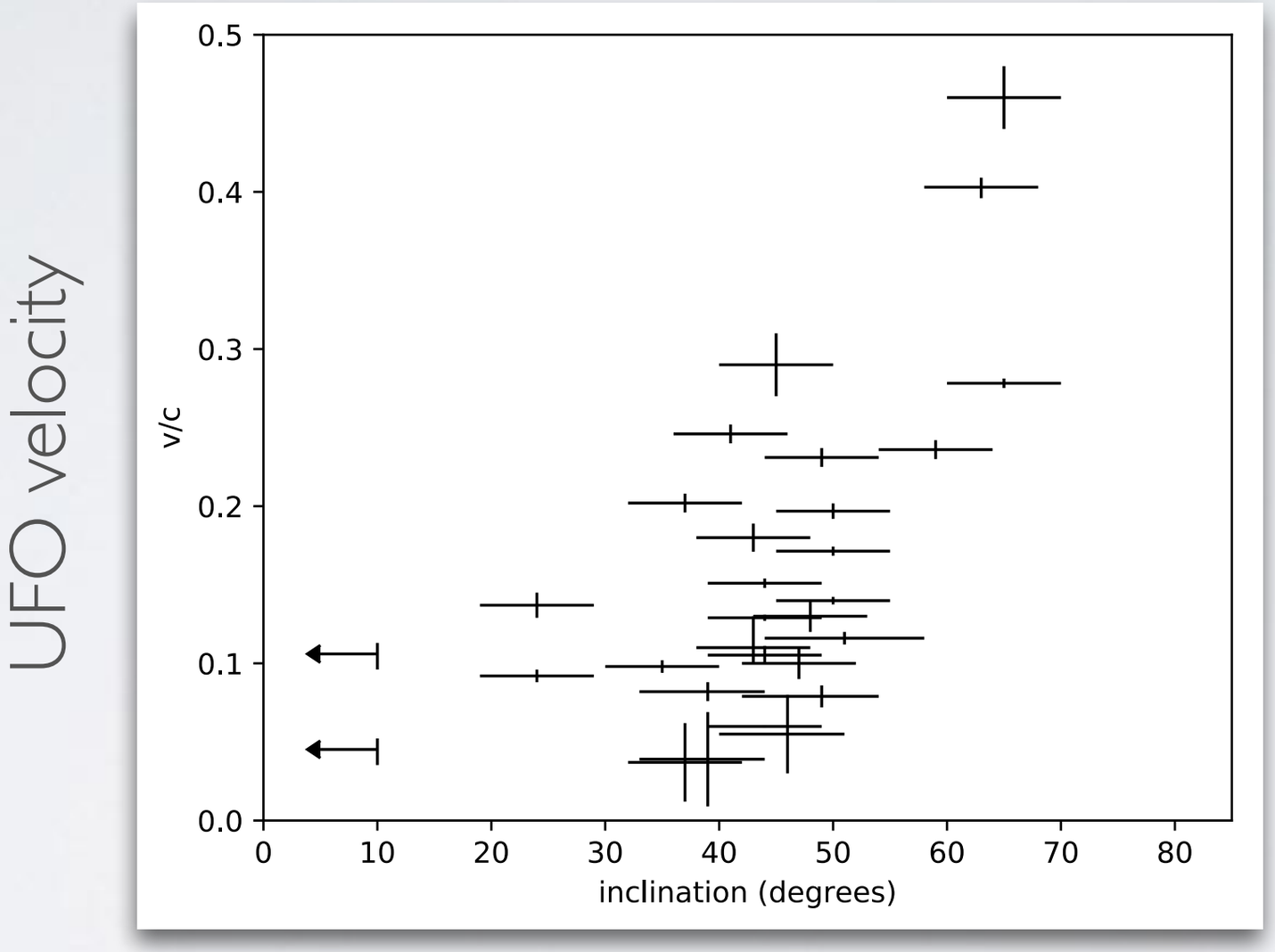
Fe XXV UFO absorption line



Depending on the UFO geometry, we should see some viewing-angle dependence…

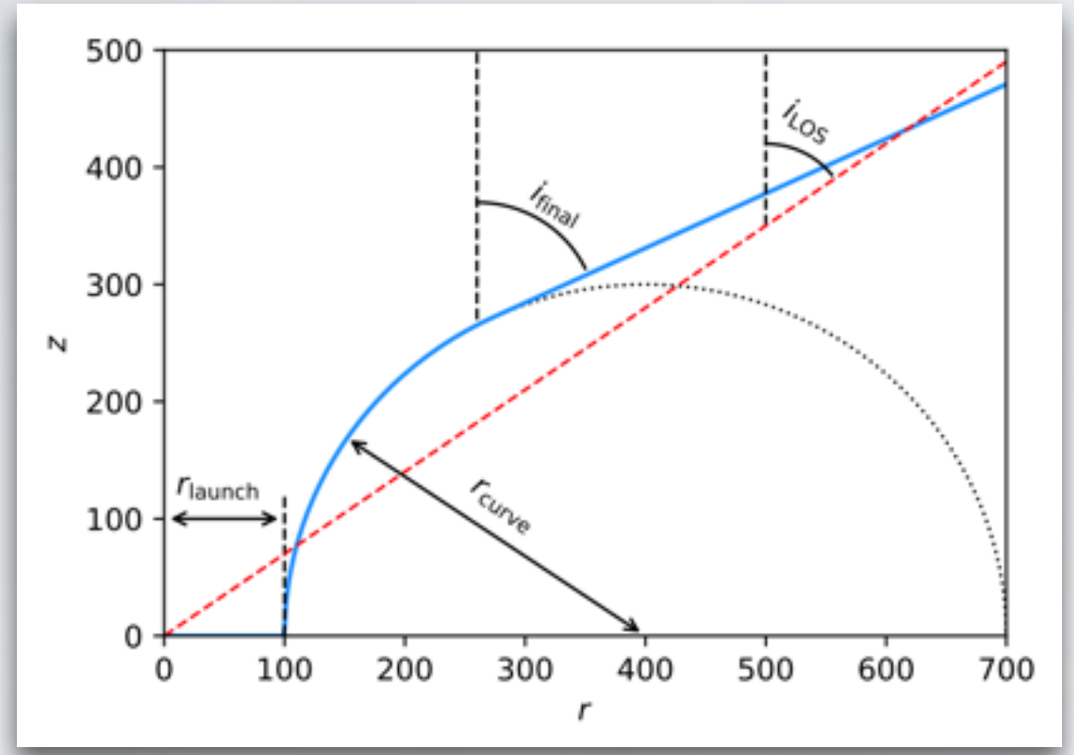
Taking values from literature…

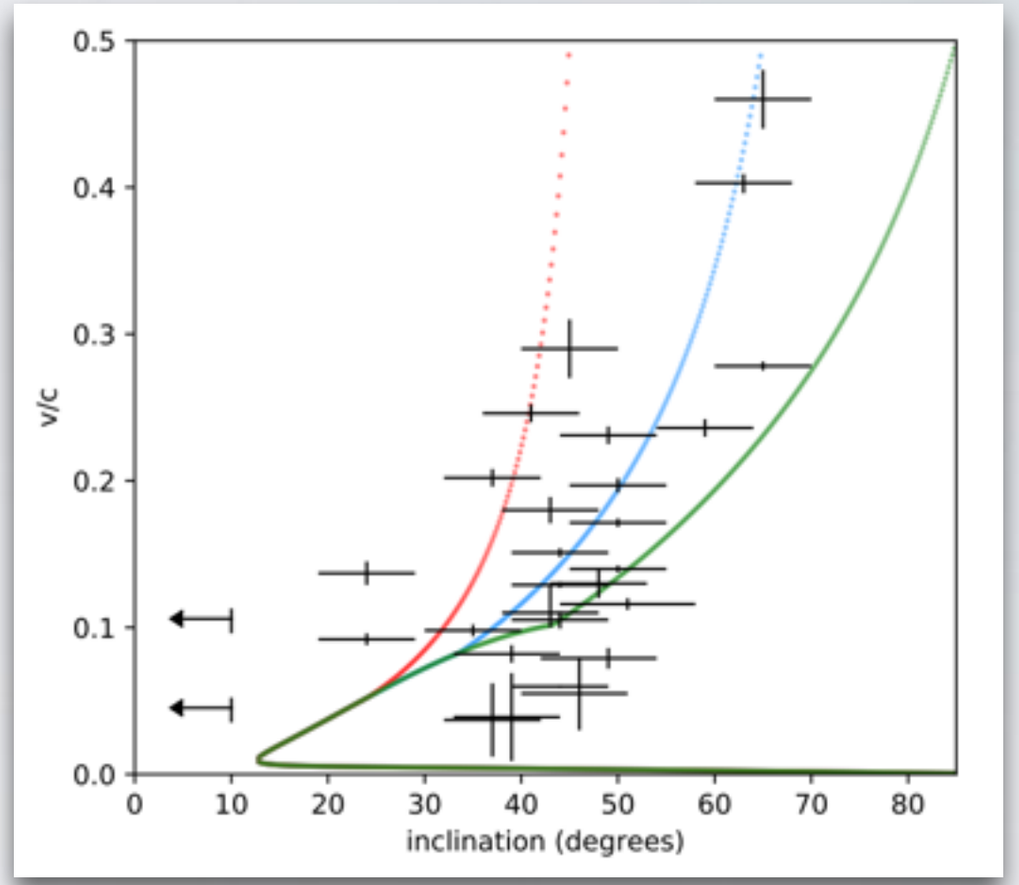
MP+18, submitted



Inclination of the inner accretion disk, taken from relativistic reflection

MP+18, submitted





Simple wind model, predicting observed velocity from viewing angle, gives a reasonable description of the points

Assumes all winds are basically identical. Probably wrong.

TO-DO

- Much more simultaneous spectral fitting
- Larger sample, with consistent models
- More accurate predictions of velocity from simulations/ physical models
- Track other properties of the wind with viewing angle
- Compare other properties of AGN with UFO velocity

SUMMARY

- Relativistic spectroscopy of black holes gives a powerful tool for studying their growth, fundamental physics, and the impact of black holes on cosmology

- Combining reflection from the inner disk with ultra-fast outflows opens up an exciting new area of study, allowing us to map black hole winds