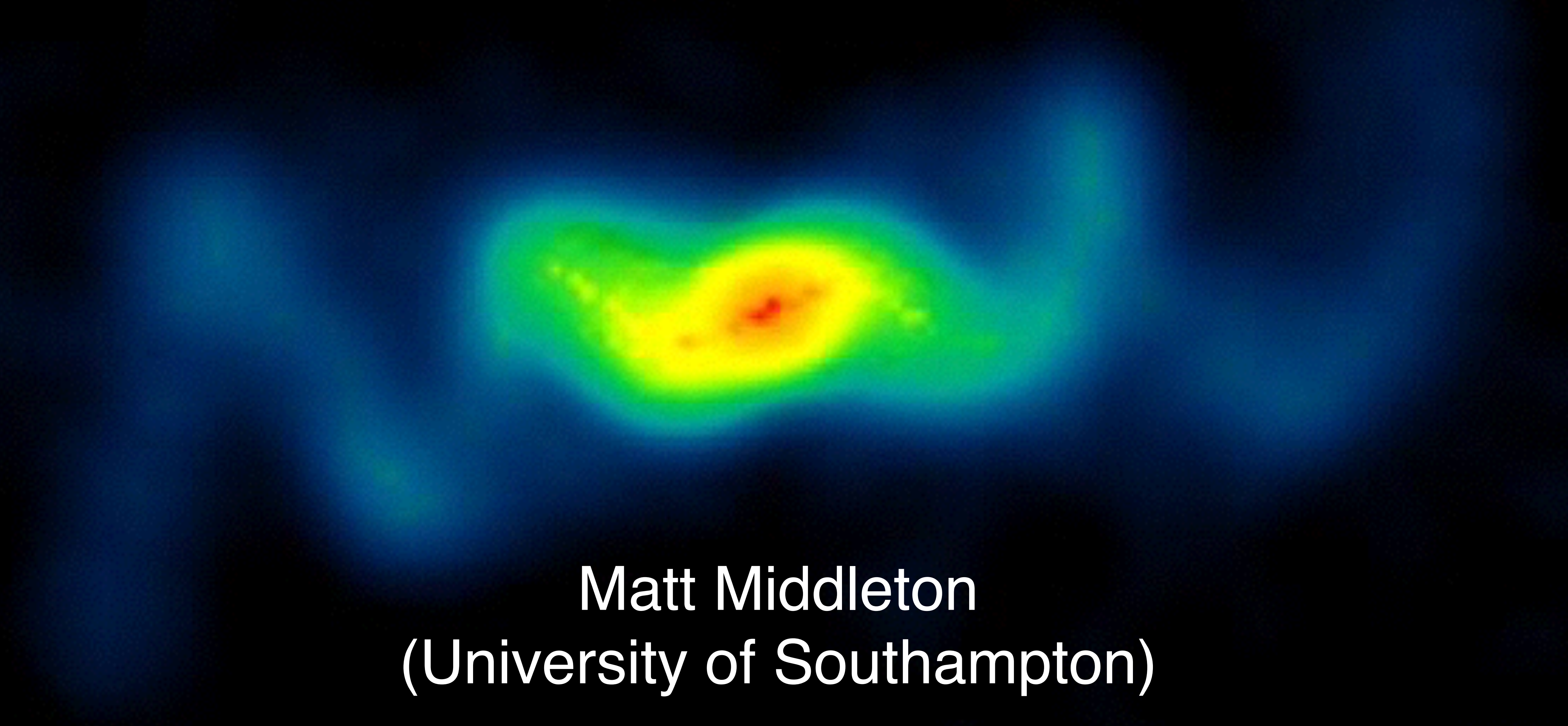
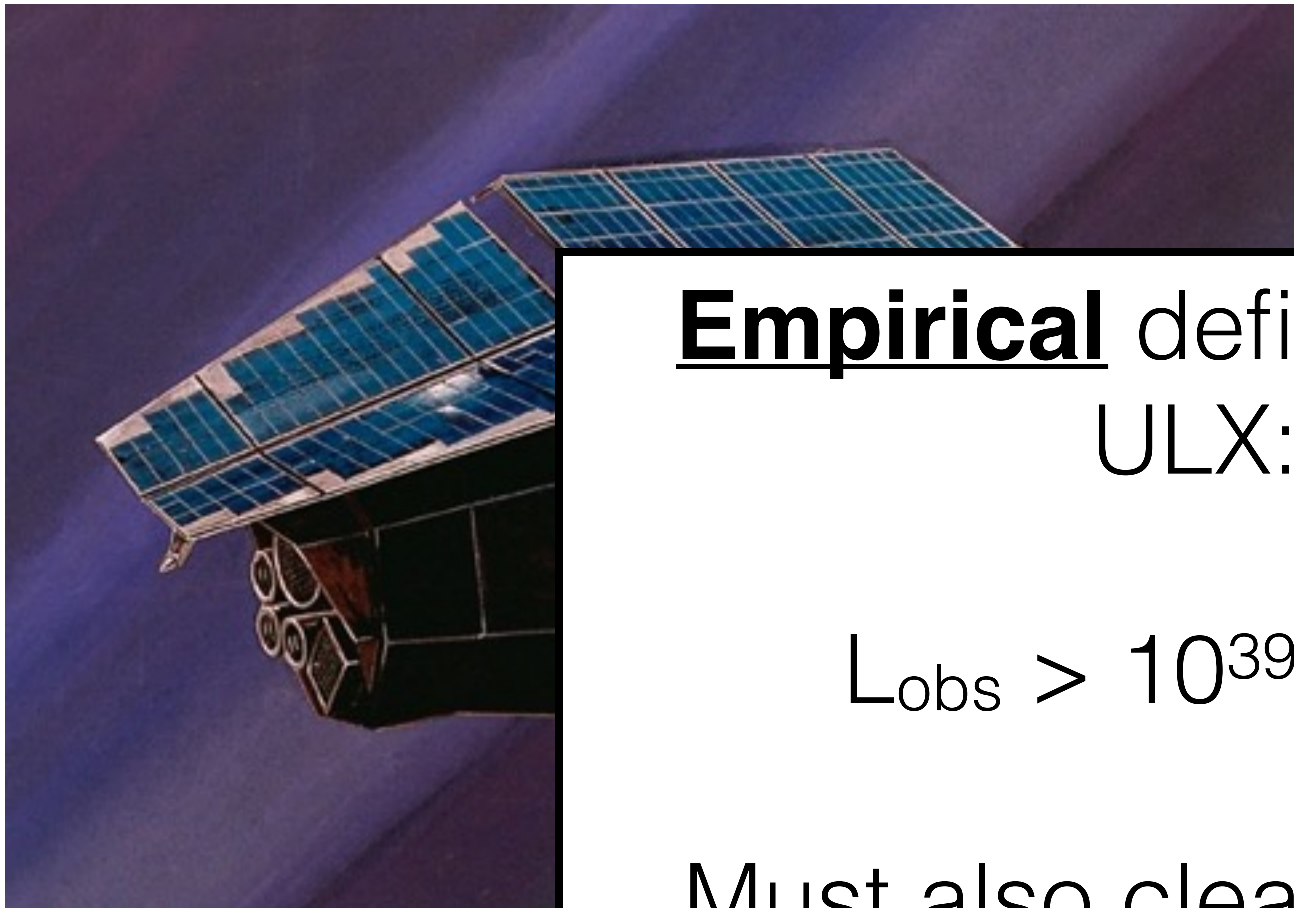
ULXs as observational evidence for super-Eddington accretion

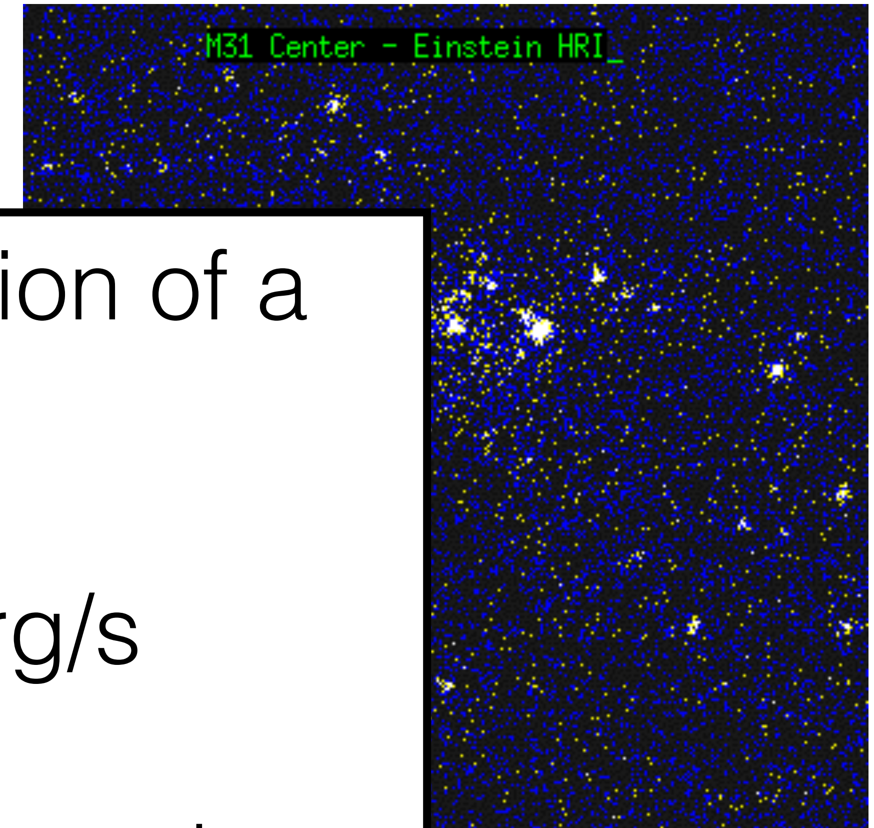


Matt Middleton
(University of Southampton)

A. King, T. Roberts, D. Walton, C. Pinto, P. Fragile, A. Ingram, M. Brightman, A. Fabian, M. Bachetti, F. Fuerst, F. Pintore + many more

Science & Technology Facilities Council

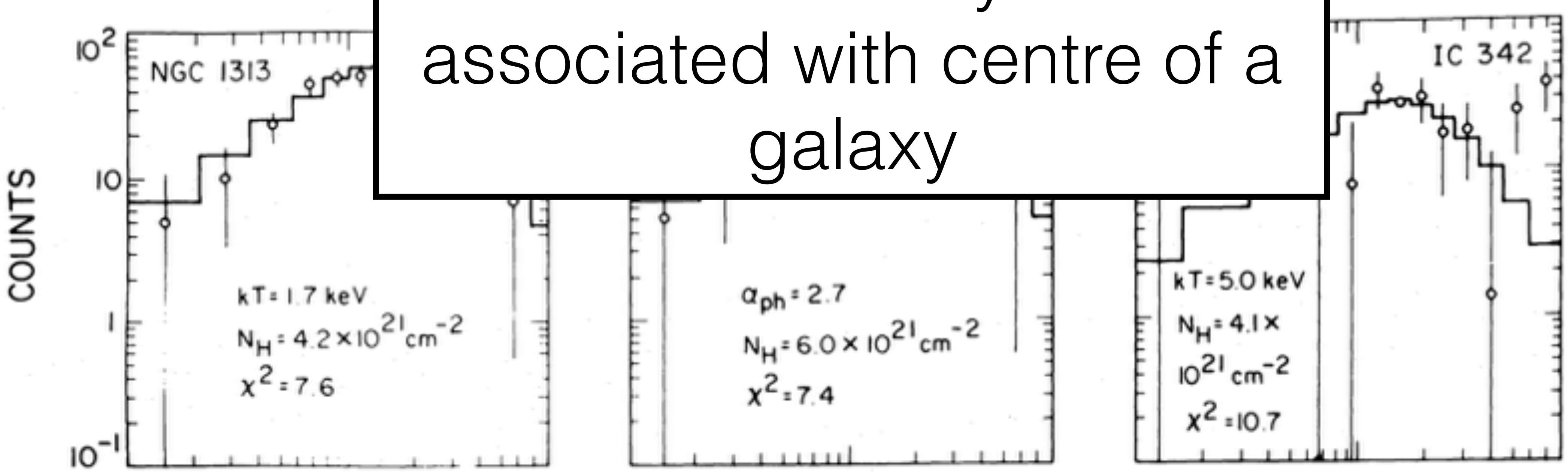




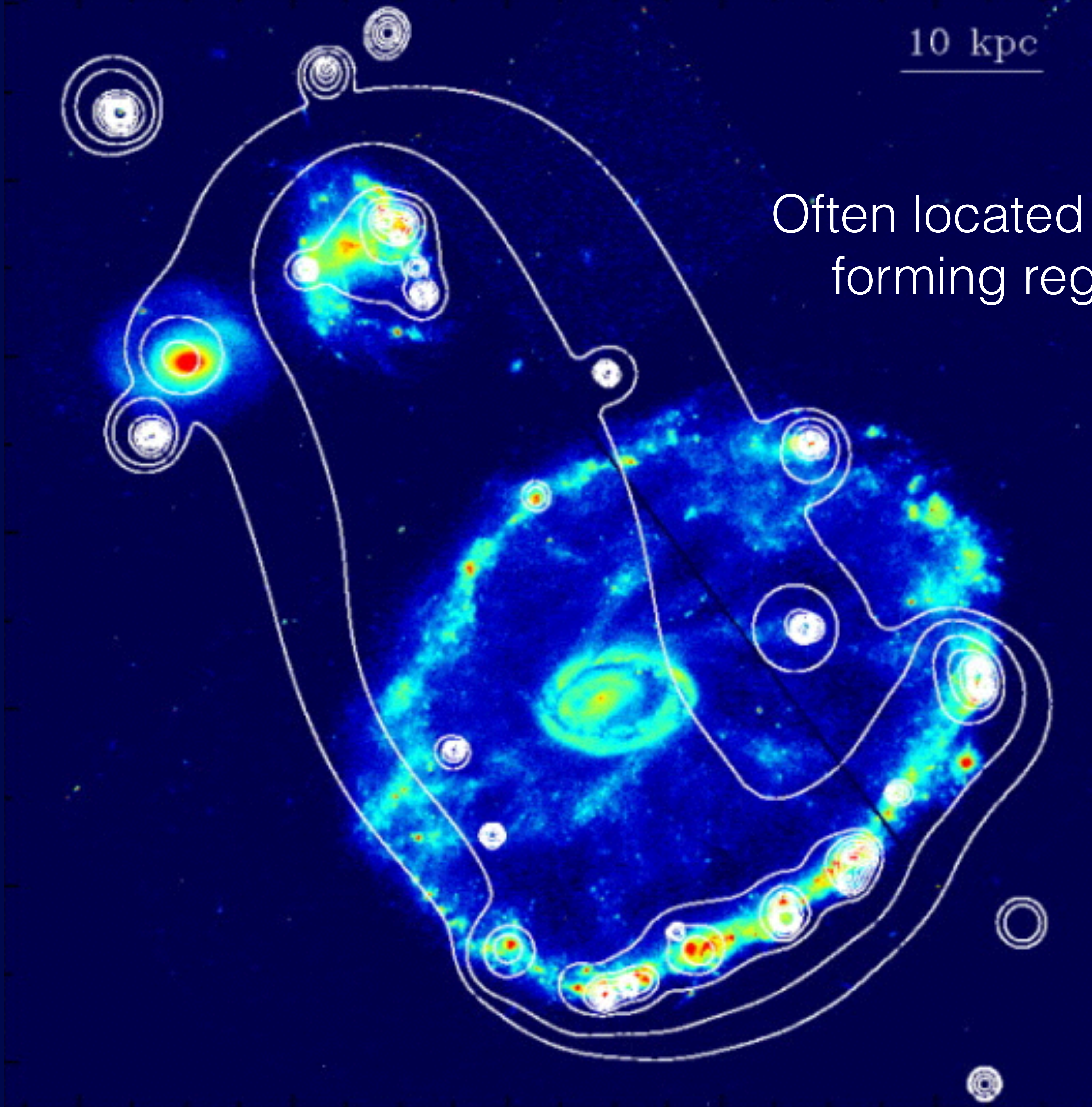
Empirical definition of a ULX:

$L_{obs} > 10^{39}$ erg/s

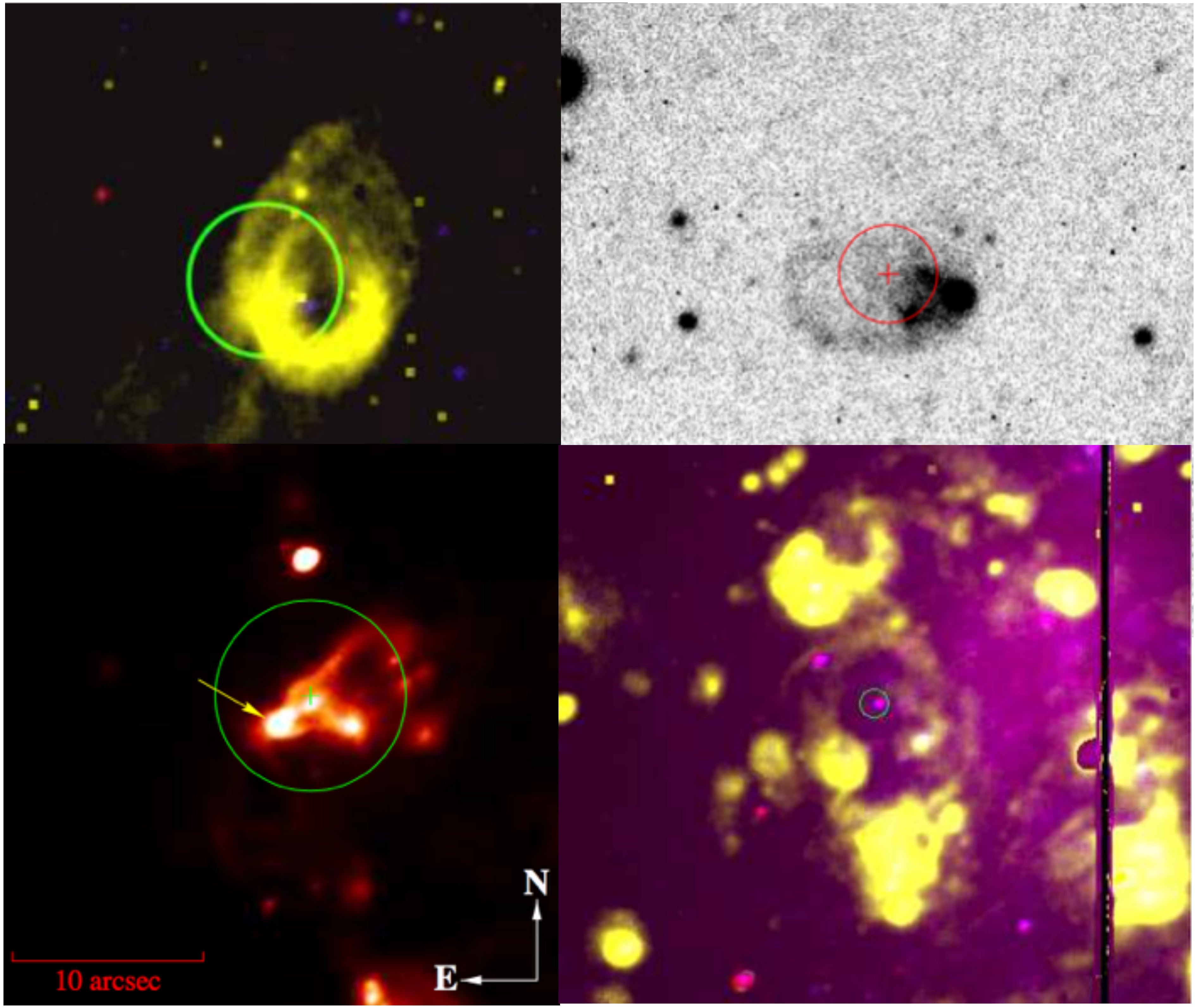
Must also clearly not be associated with centre of a galaxy



Fabbiano & Trinchieri (1987)



Often located in star-forming regions

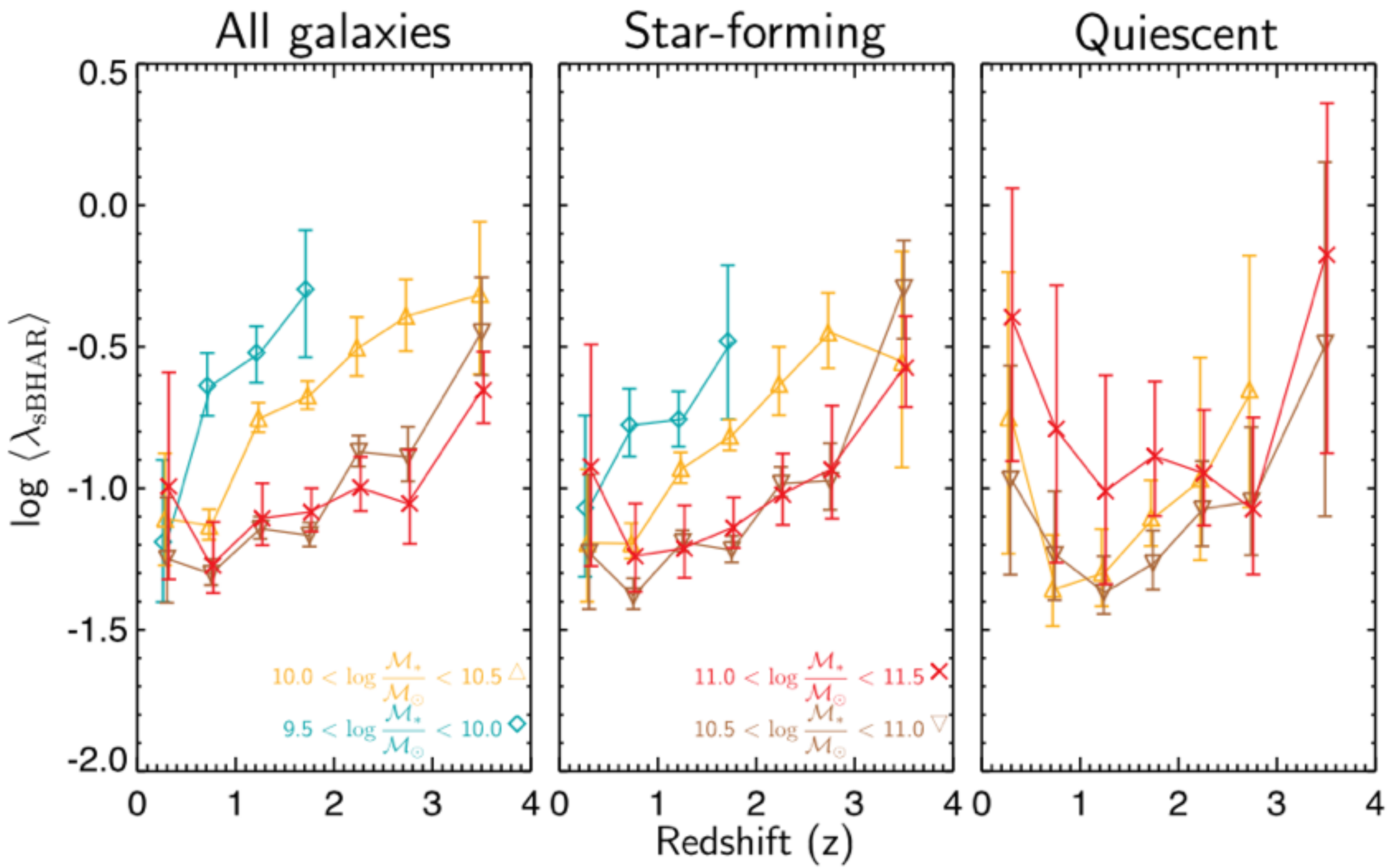


Nebulae, 100s of parsecs across surrounding some of them

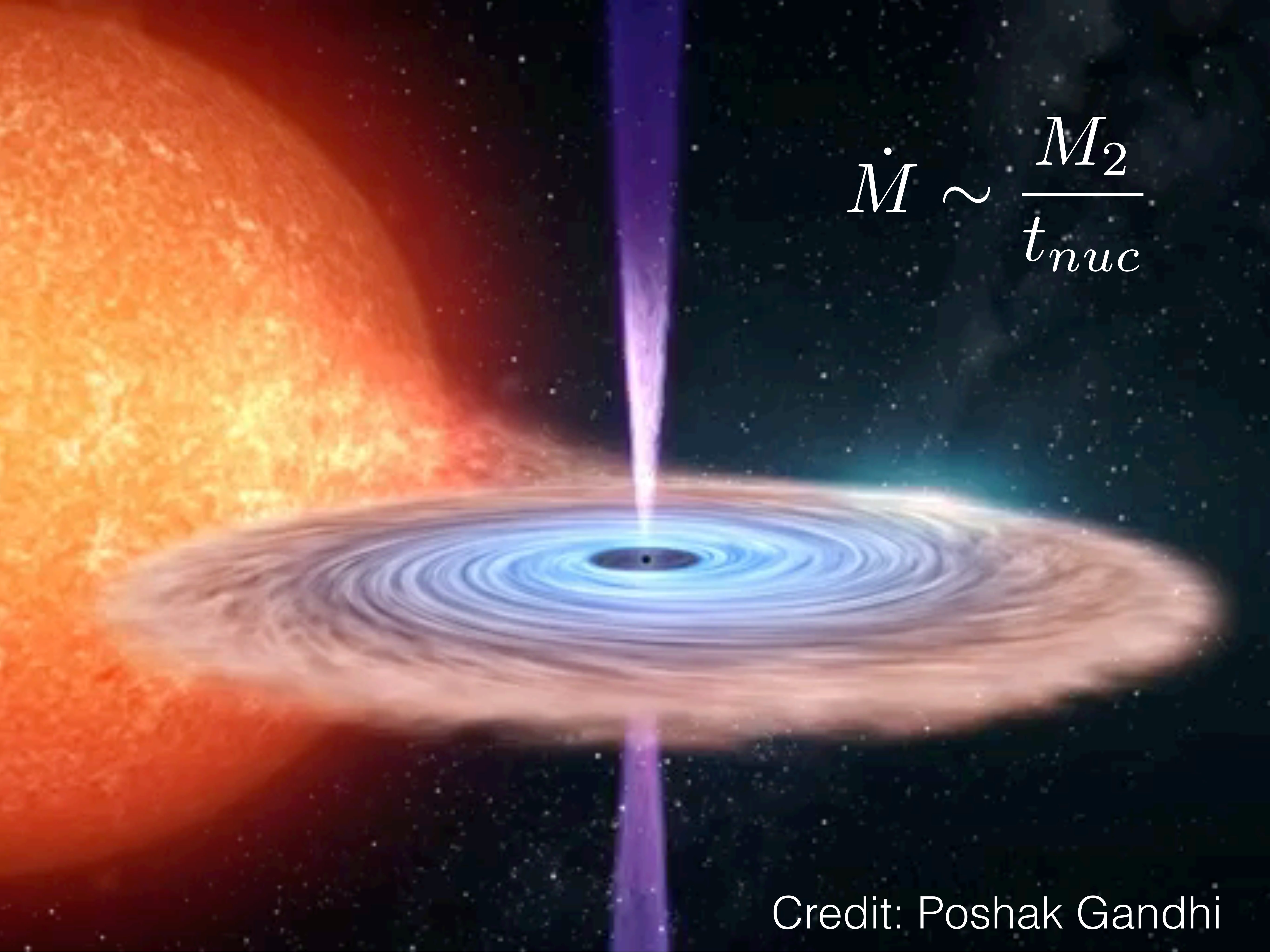
Too big to be the SNR

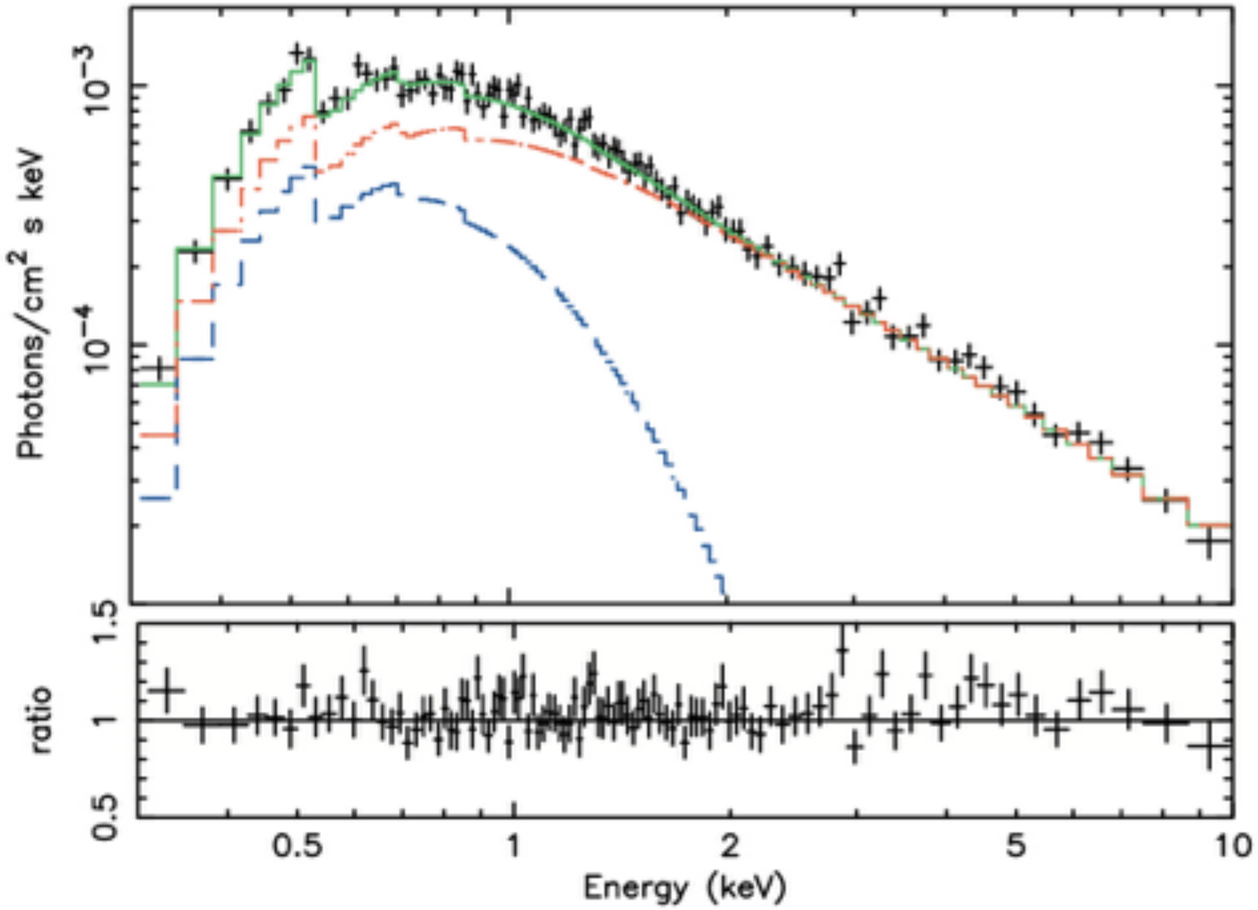
Pakull & Mirioni (2002)

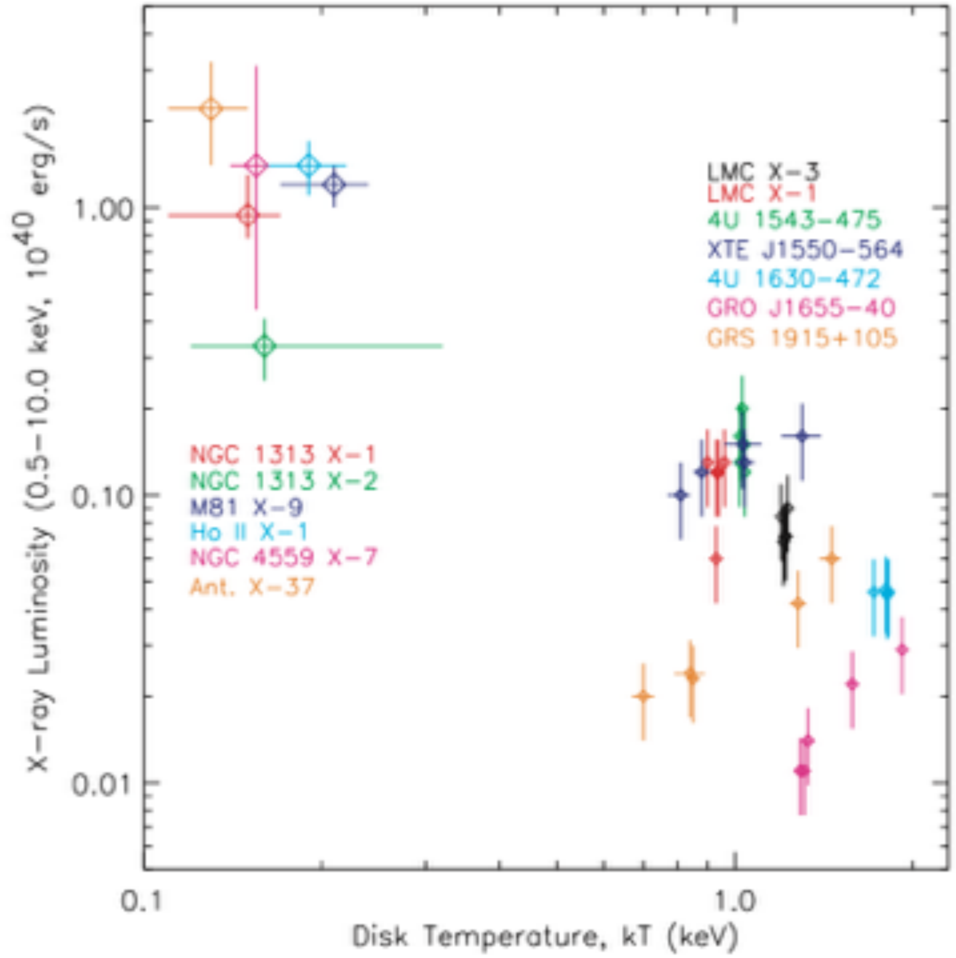
Sub-Eddington accretion is - in the 'local' Universe - commonplace (although there are caveats regarding AGN)



Aird, Coil & Georgakakis (2018)


$$\dot{M} \sim \frac{M_2}{t_{nuc}}$$
Credit: Poshak Gandhi



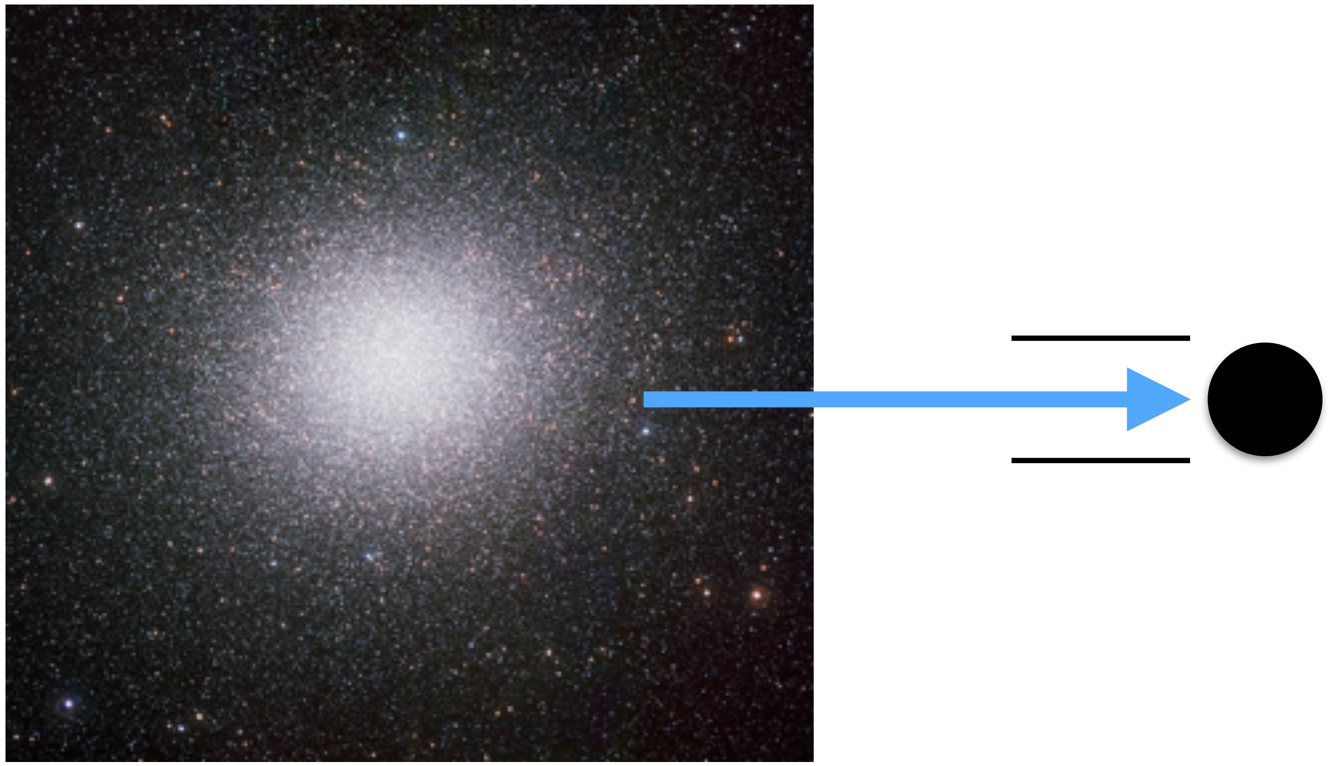


Miller et al. 2004

$$T_{eff} = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma_{SB}} \left[1 - \left(\frac{R_{in}}{R} \right)^{1/2} \right] \right\}^{1/4}$$

→ IMBHs at sub-Eddington accretion rates

IMBHs have been (and still are) proposed to be located in GCs - if these were kicked out of the cluster then they might populate the galaxies.



However, for this to explain **all** ULXs it would require initial stellar masses > 100s M_{solar} as a lot of mass is lost from such massive stars over their lifetimes.

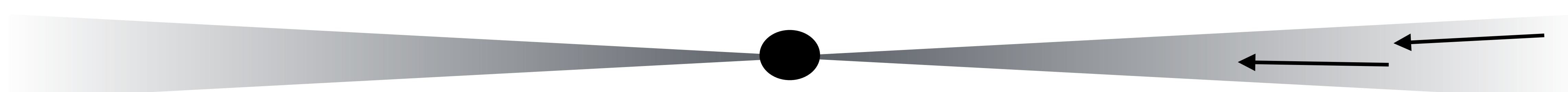
Such a population is <u>not</u> supported by IMFs (King et al. 2001)

So what would ***super-Eddington*** accretion look like onto a stellar remnant $M < 100M_\odot$?

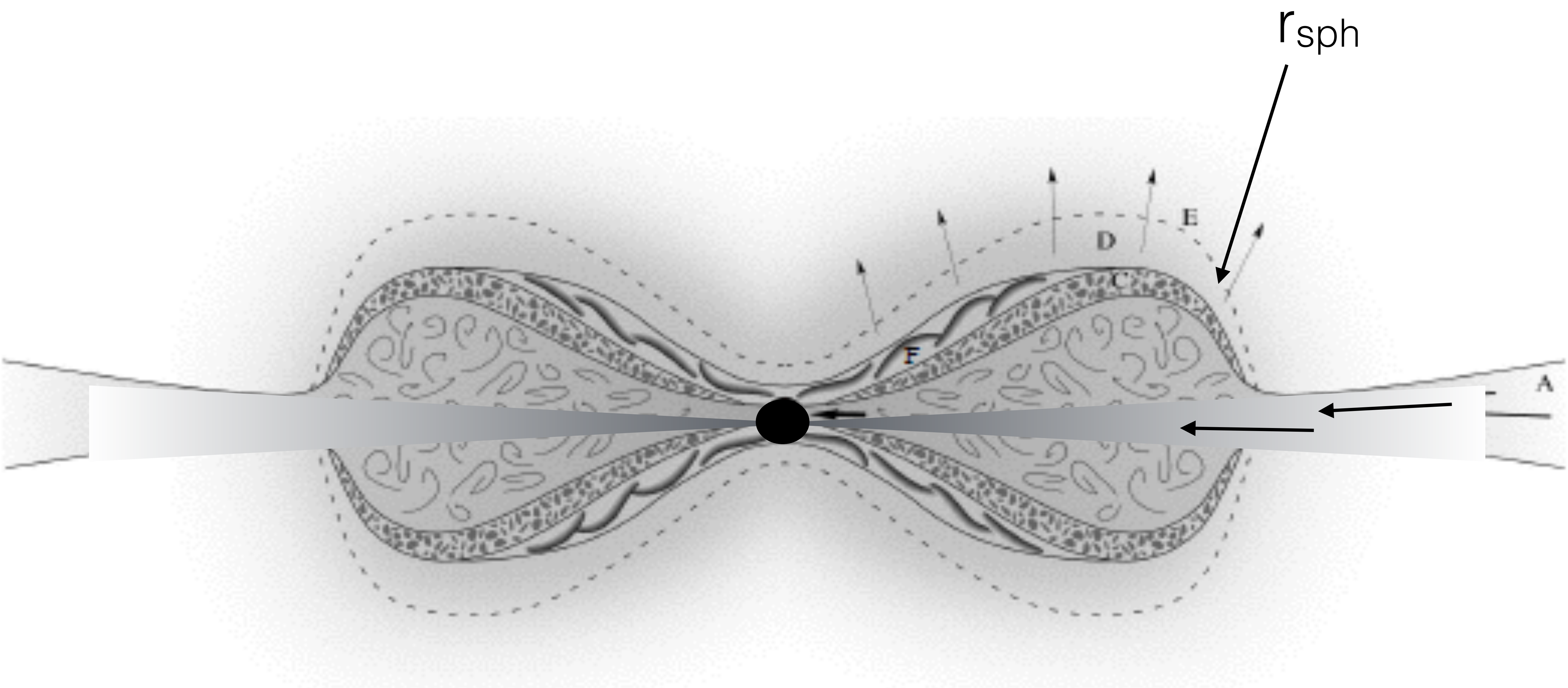
- The disc's radiative efficiency falls as 1/2r
- Lets define $\dot{M}_{Edd} = L_{Edd}/2r_{isco}c^2$

$$\dot{M}/\dot{M}_{Edd} = r/r_{isco}$$

$$\text{or } r_{sph} = \dot{m} r_{isco}$$



if $\dot{m}$ is large, r_{sph} can occur a long way from the compact object



Dotan & Shaviv 2011

To prevent super-Eddington luminosities locally, we can lose mass in a wind so that $\dot{m} \propto r$ and the disc is locally Eddington everywhere. These winds will probably be ~0.1c and will inject energy and matter into the local environment

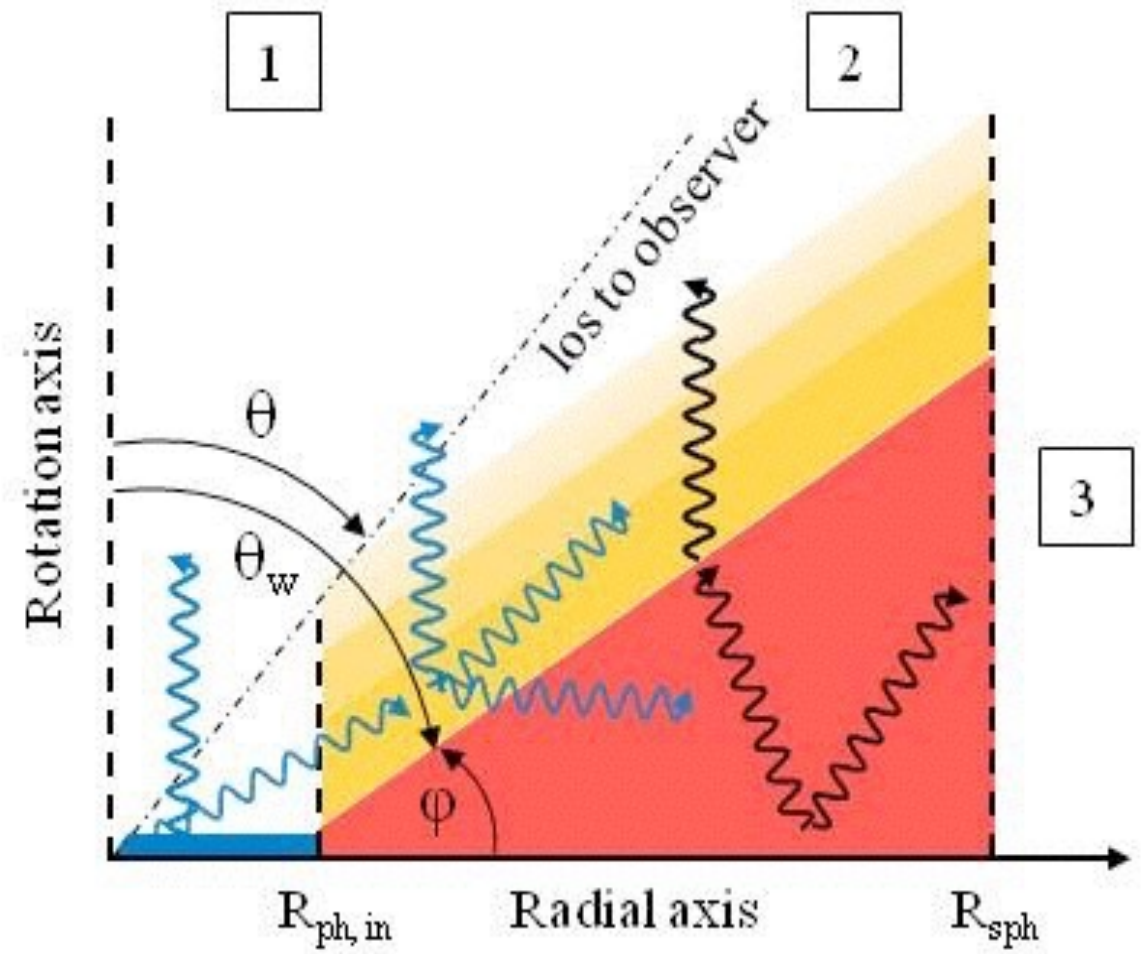
Advection must also be a key ingredient as the scale-height of the disc is large so photon diffusion time is long.

The luminosity we'd get from such flows goes as $L \approx L_{Edd} [1+\ln(\dot{m})]$ with some fraction used to power the outflow, leaving L_{rad}

In 3D, the relative solid angle of the cone is simply $b = \Omega/4\pi$.

The result is *geometric* beaming such that $L_{obs} = L_{rad}/b$ with $b < 1$

In this classical picture the energy spectrum should look roughly thermal with three regions (Poutanen et al. 2007)

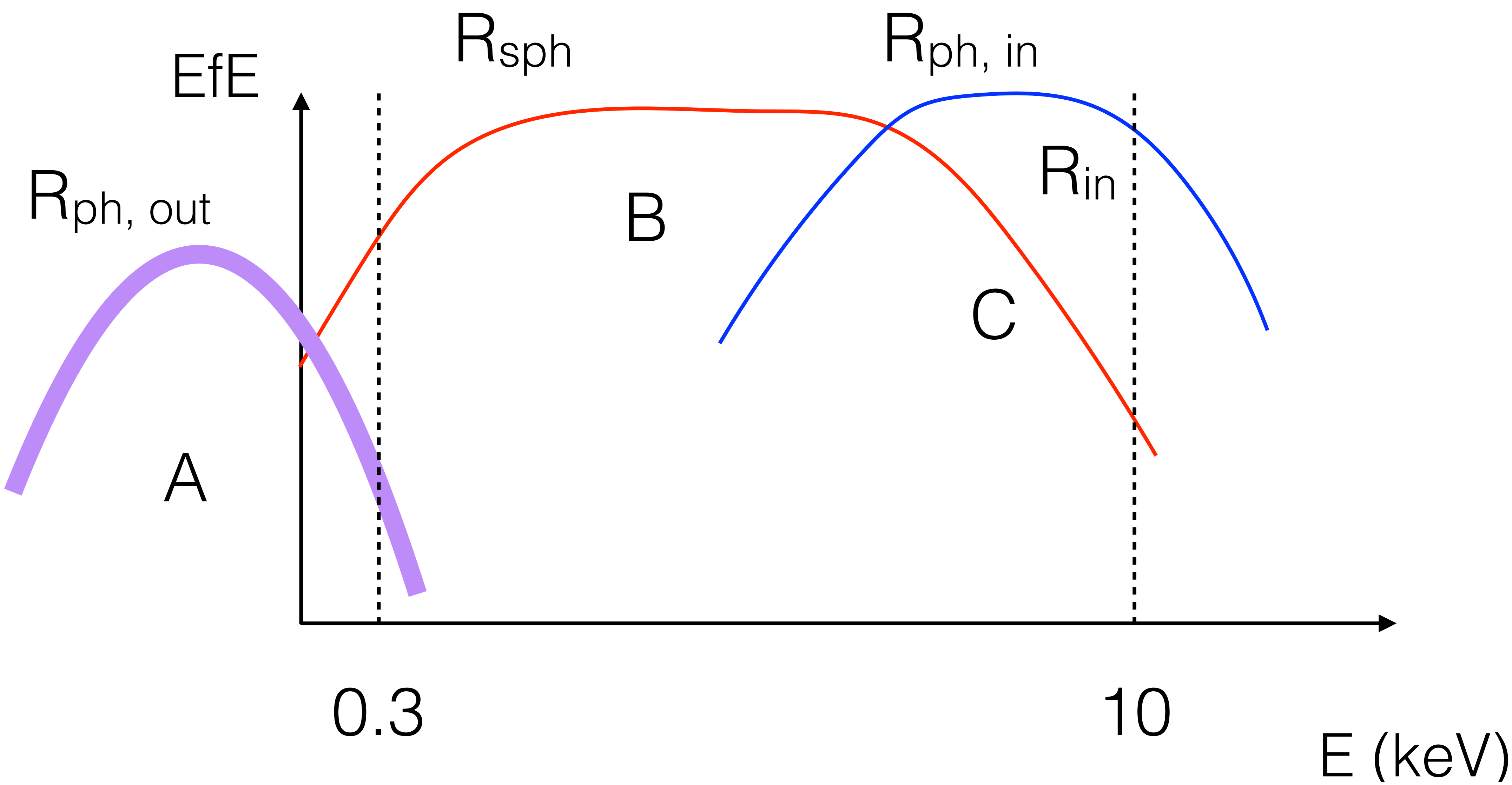


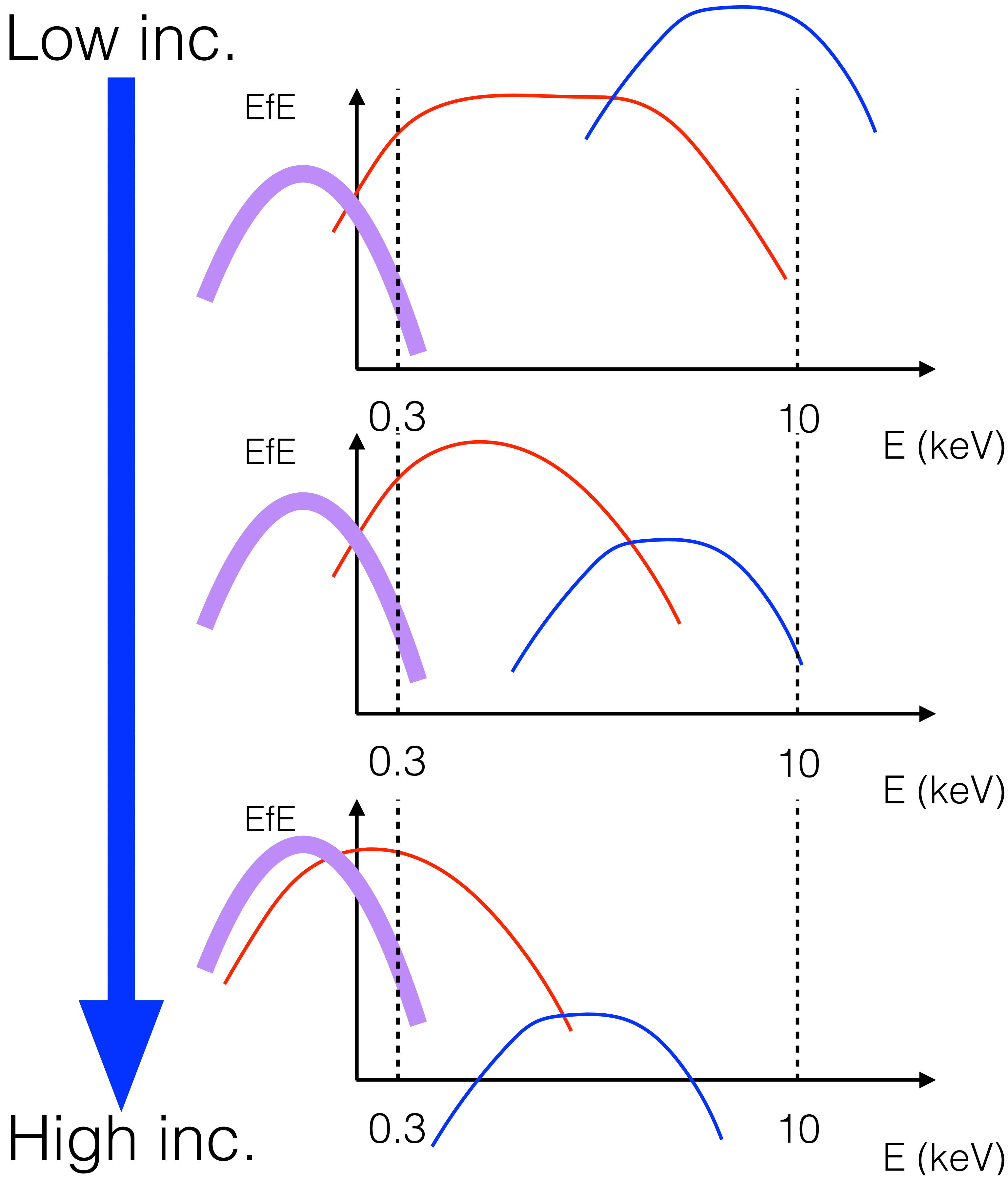
A: $R > R_{sph}$
'thin' disc, any emission may be affected by wind launched from smaller radii

B: $R_{ph,in} < R < R_{sph}$
thick/slim disc with emission modified by passage through the wind and advection

C: $R_{in} < R < R_{ph,in}$
thick/slim disc but the wind is optically thin so radiation escapes locally - **this is the most beamed**

Very crude idea of what this *might* look like intrinsically:

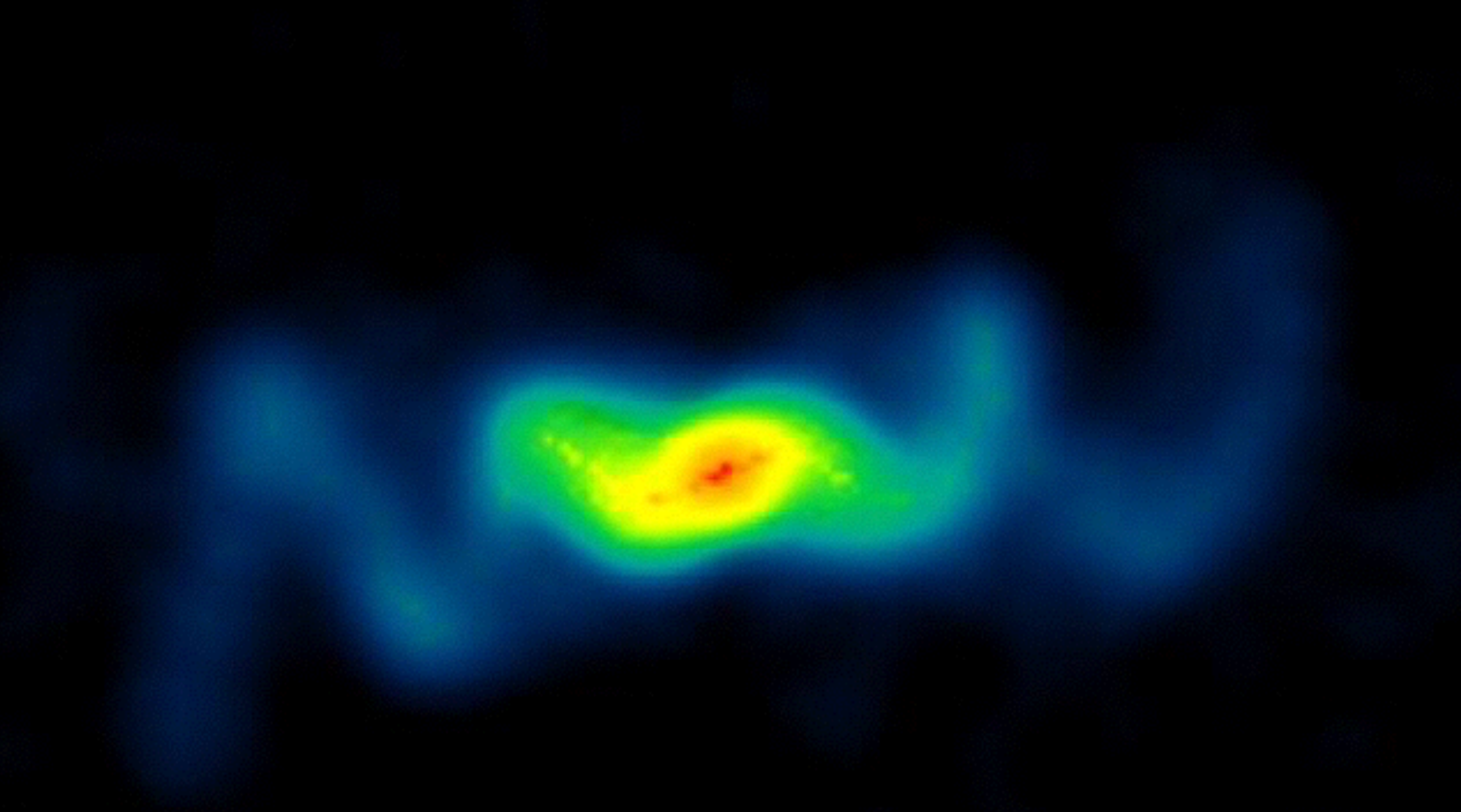




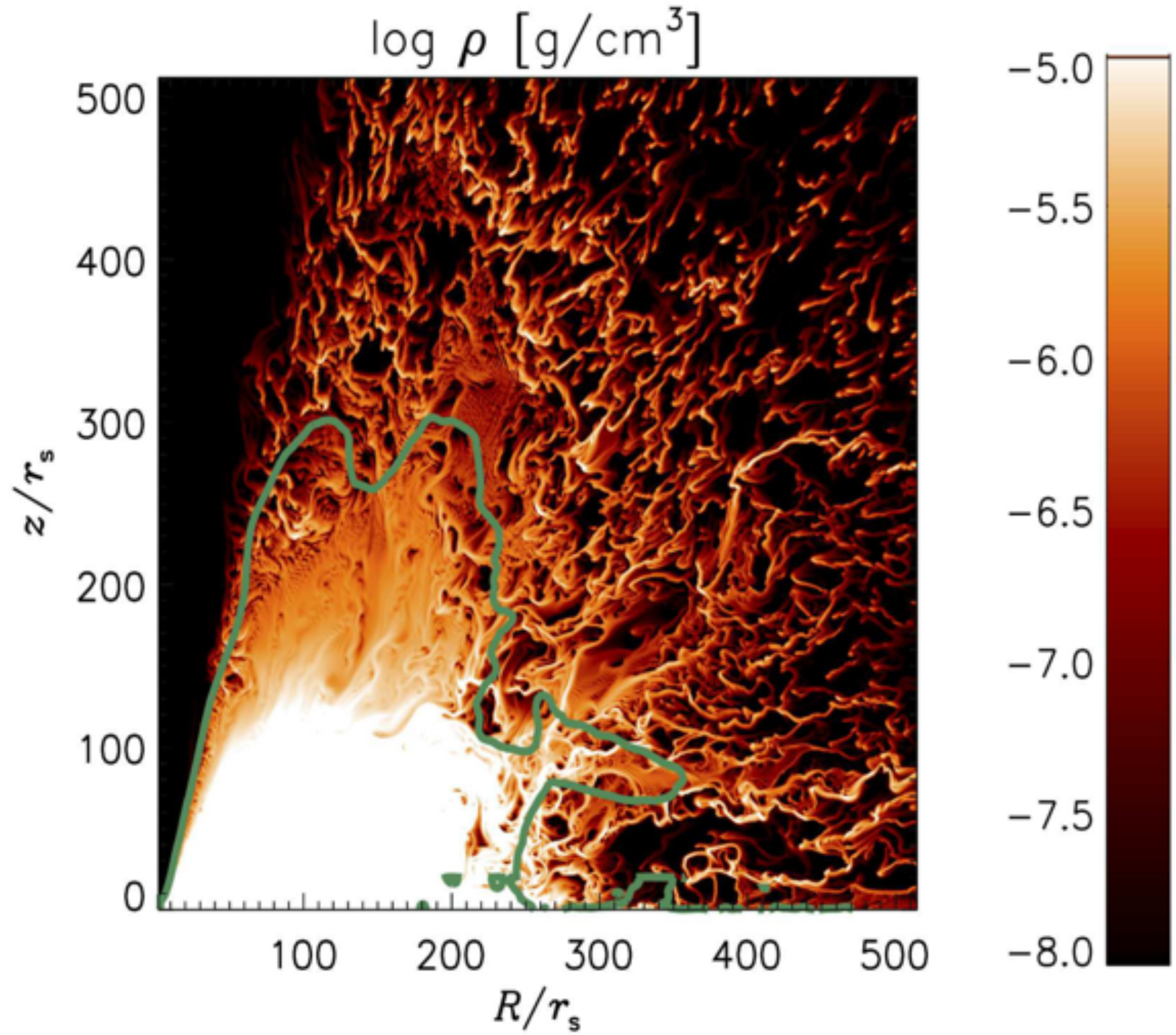
Important: the cooler outer regions ~isotropic and the inner-most regions most geometrically beamed

So appearance is a function of mass accretion rate **and** inclination

NB - edge on these are not technically ULXs - a huge weakness in empirical definitions



SS433 is only observed at $<10^{36}$ erg/s
but is accreting at 10^{-4} $M_{\odot}$/yr

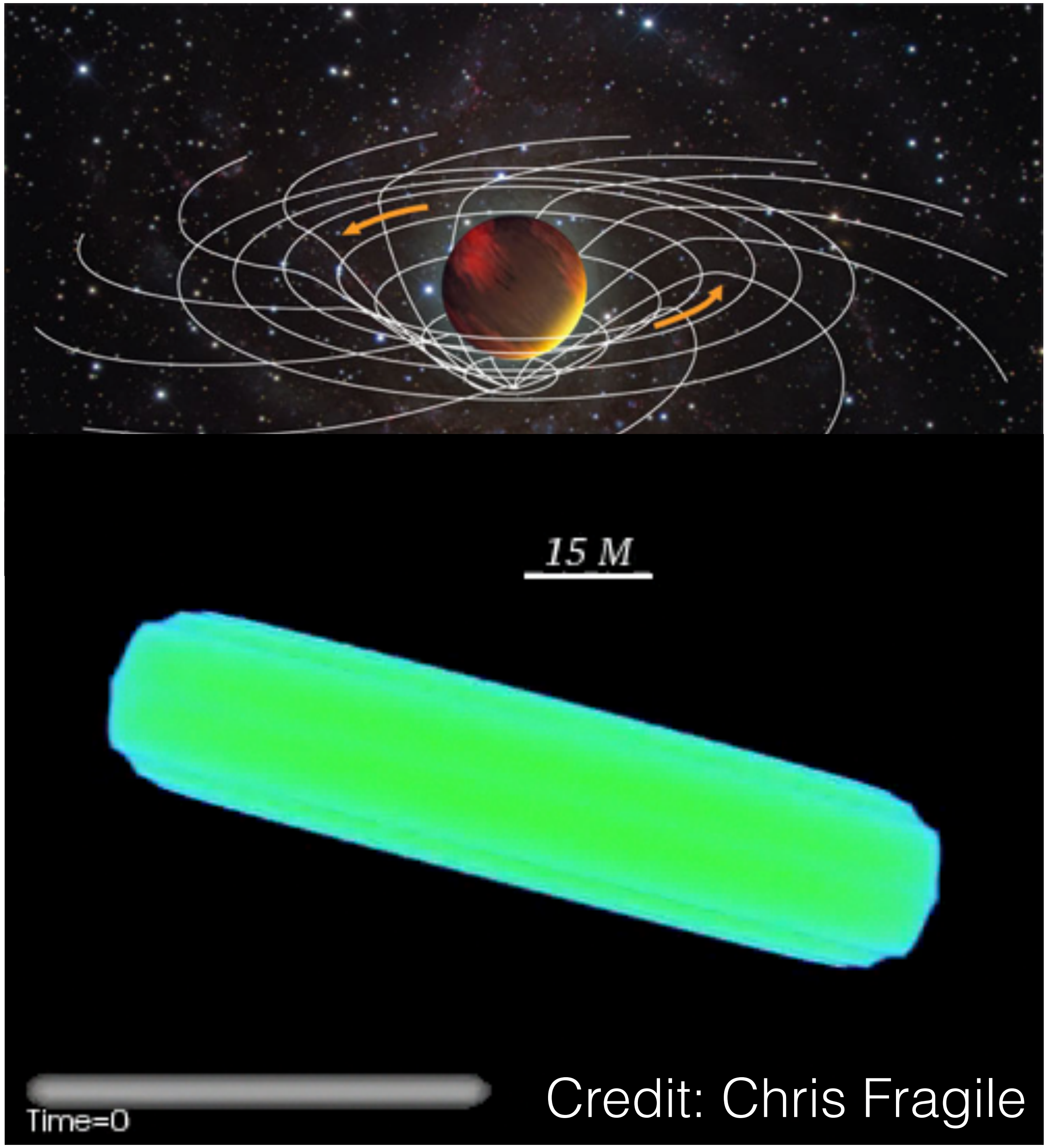


Takeuchi et al. (2013)

Due to density inhomogeneities, the outflow will be Ralyeigh Taylor unstable and the wind will be ‘clumpy’

Optically thick clumps will inject variability **along the line-of-sight**

Frame-dragging and Lense-Thirring precession



Credit: Chris Fragile

ZAMO forced to move with the rotation of the compact object (i.e. for non-zero ‘spin’)

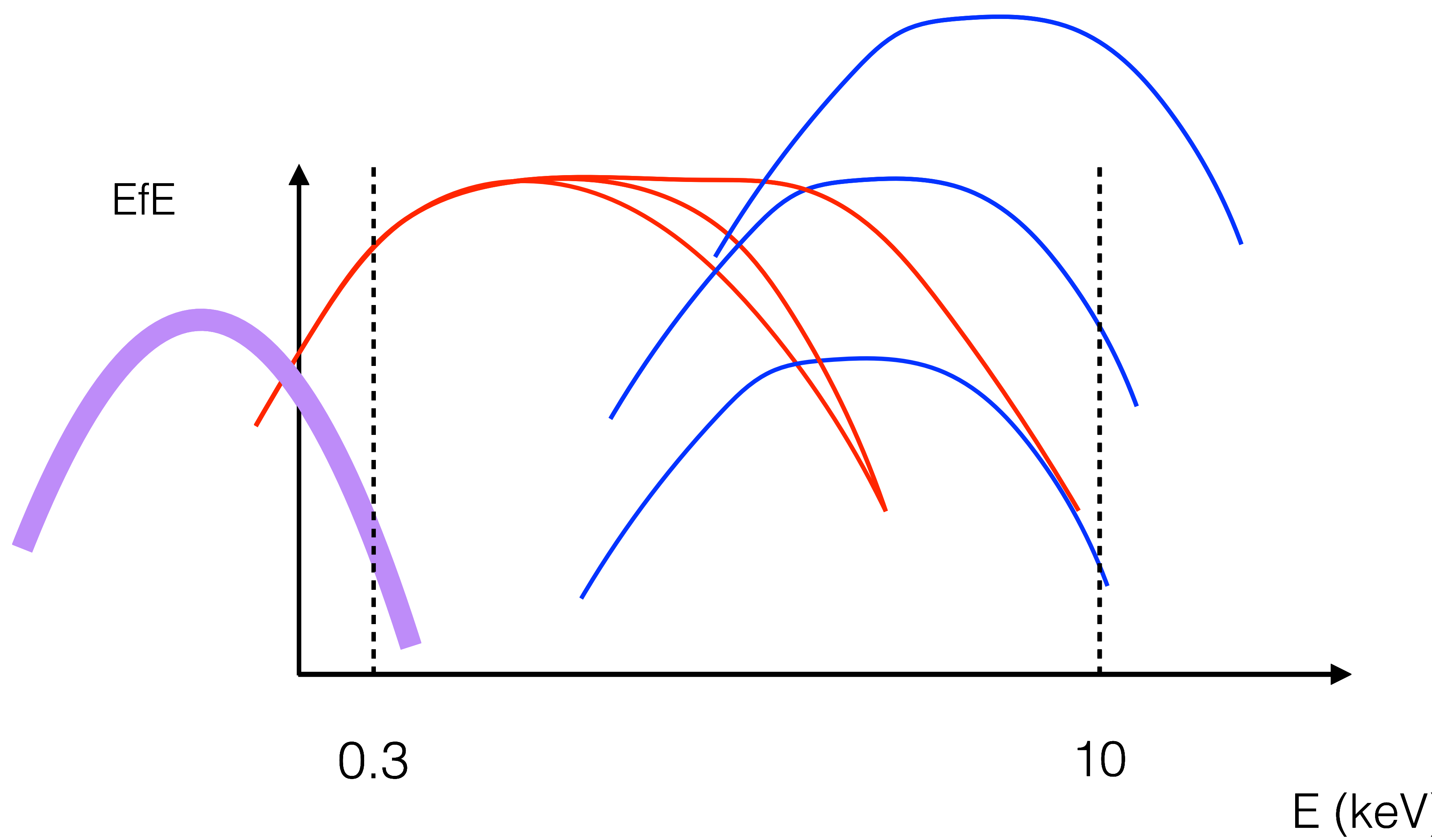
If the compact object’s spin axis is tilted with respect to orbit then the frame-dragging induces vertical precession

Inflow might precess as:

$$P_{\rm prec} = \frac{GM\pi}{3c^3 a_*} r_{\rm sph}^3 \left[\frac{1 - \left(\frac{r_{\rm in}}{r_{\rm sph}}\right)^3}{ln\left(\frac{r_{\rm sph}}{r_{in}}\right)} \right]$$

Middleton et al. (2018)

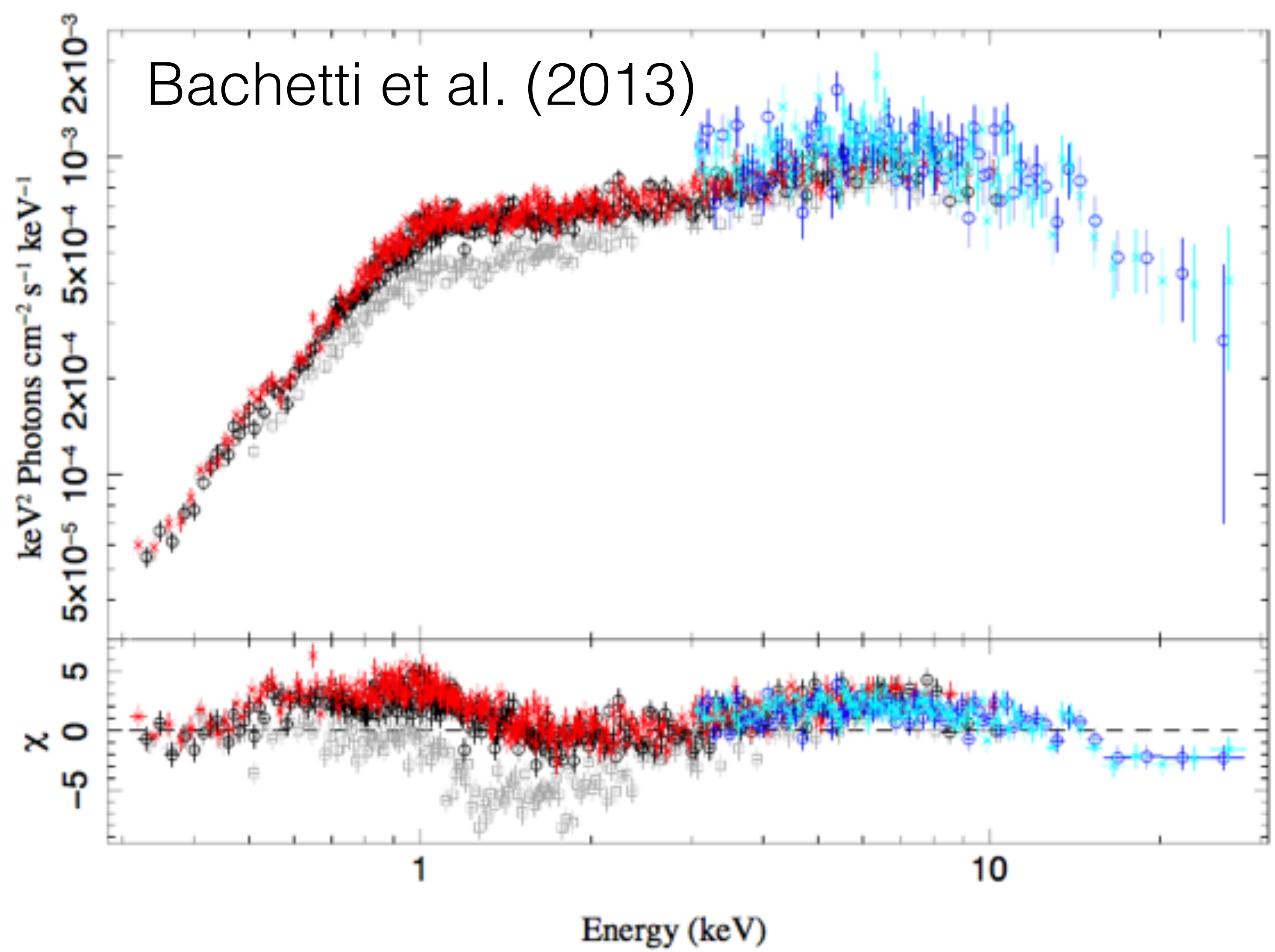
What would this precession 'look' like?



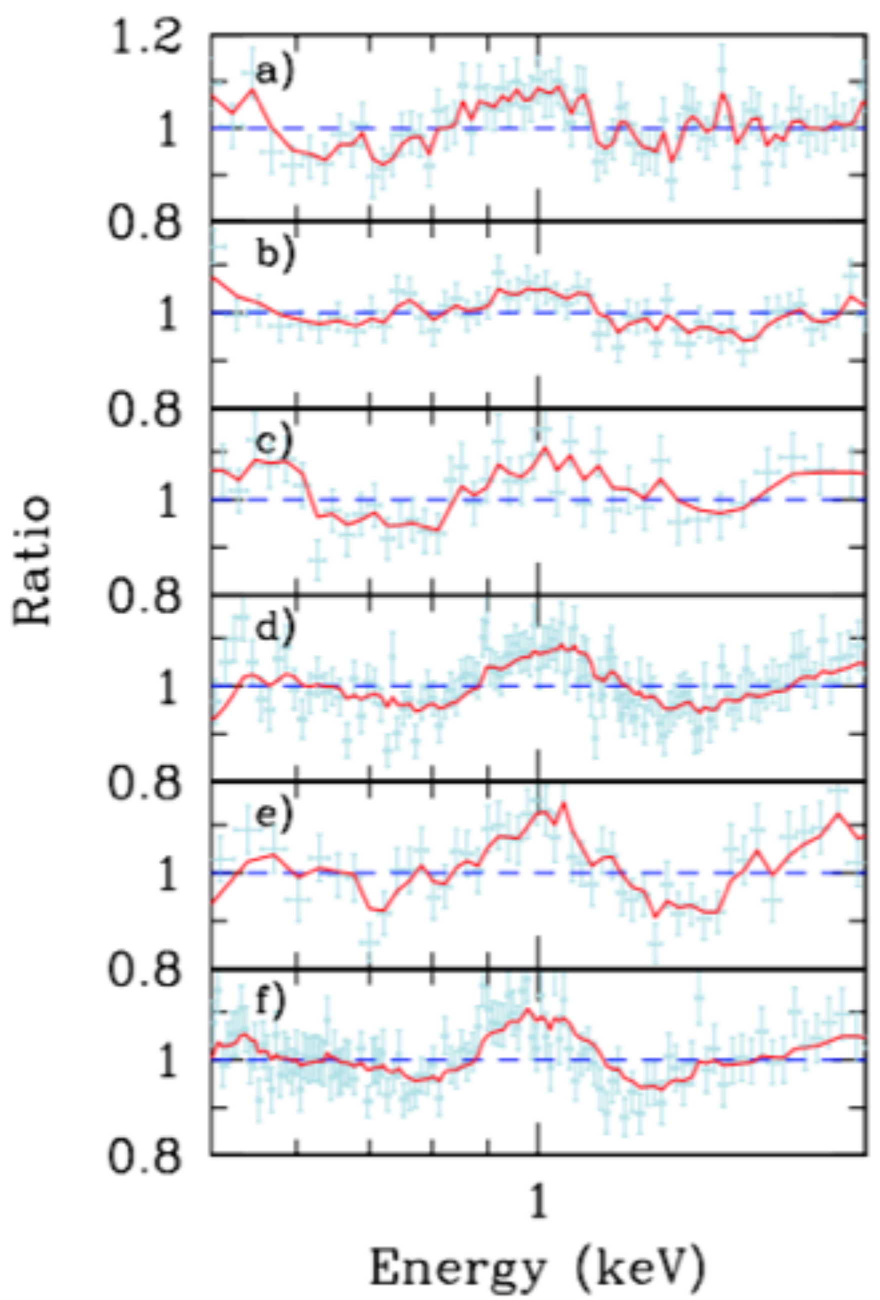
In the picture where we don't care about the compact object, super-critical accretion in ULXs should be evidenced by:

1. A two (perhaps three) component thermal spectrum
2. Winds - seen as absorption features
3. Predictable changes with inclination (beaming, imprints of the wind) and potentially precession

1. The X-ray spectrum appears two-component and doesn't inflect at high energies

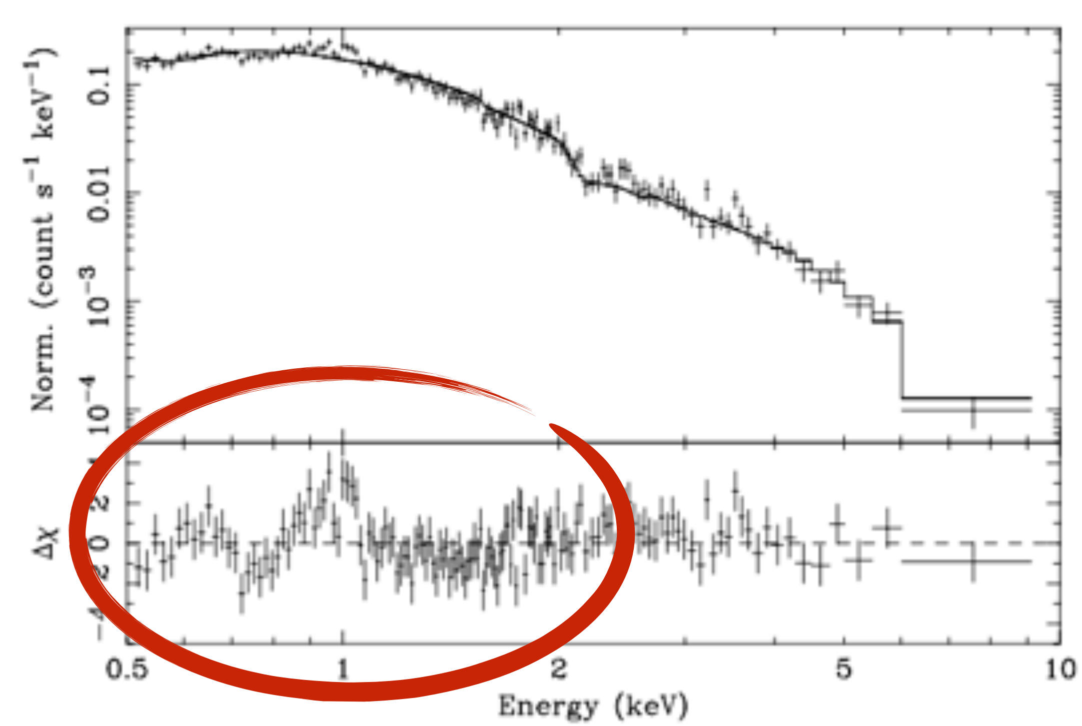


2. Pretty featureless spectra (bad for diagnosing nature of flow) but if we look carefully….



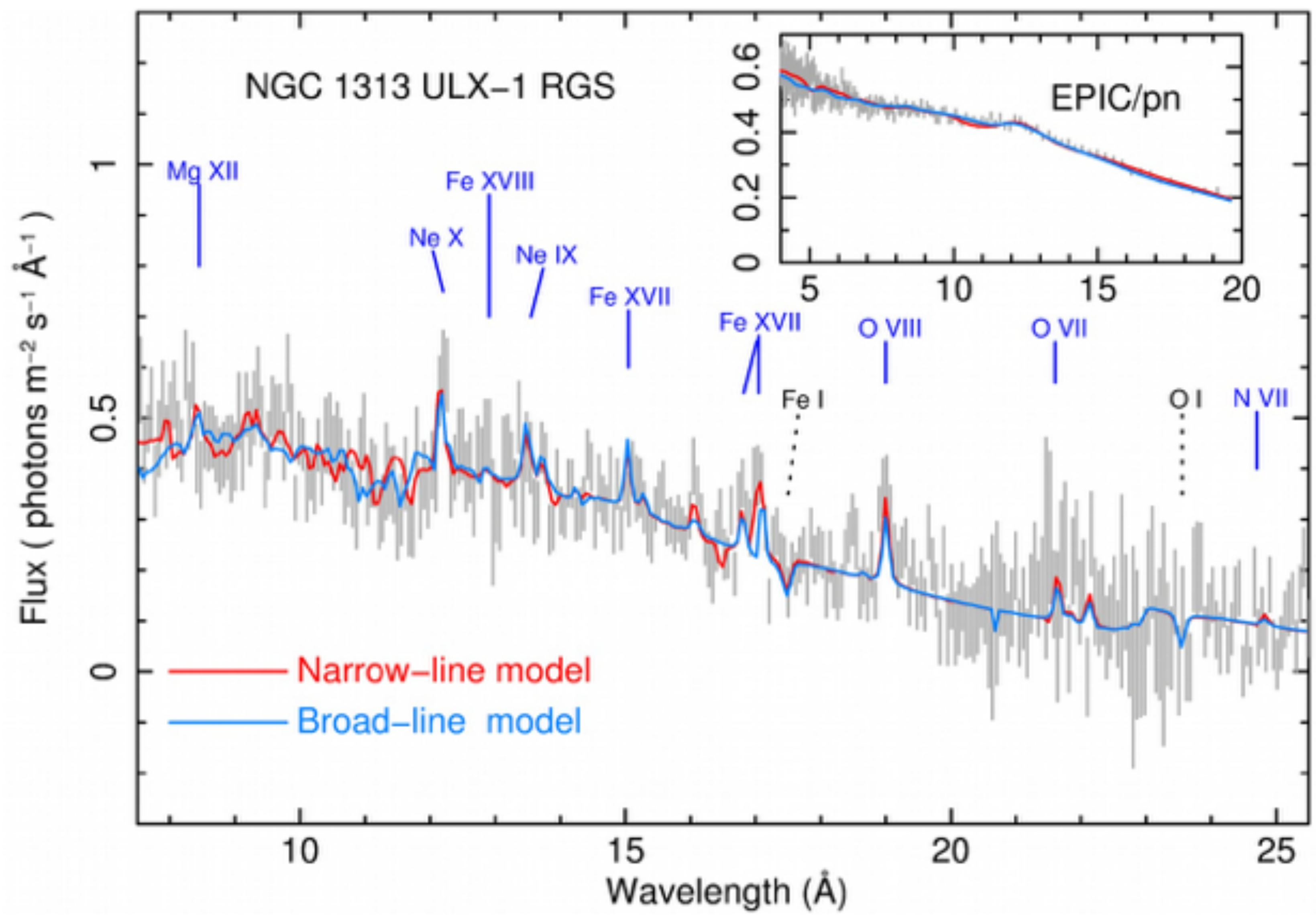
Middleton et al. (2015)

Seen in both XMM and Chandra - could be imprints of a wind, smeared out due to low resolution or intrinsically broad (Middleton et al. 2014; 2015)



Roberts et al. (2006)

Winds have now been *unambiguously* detected in multiple bright ULXs (Pinto et al. 2016; 2017)



Pinto, Middleton & Fabian (2016)

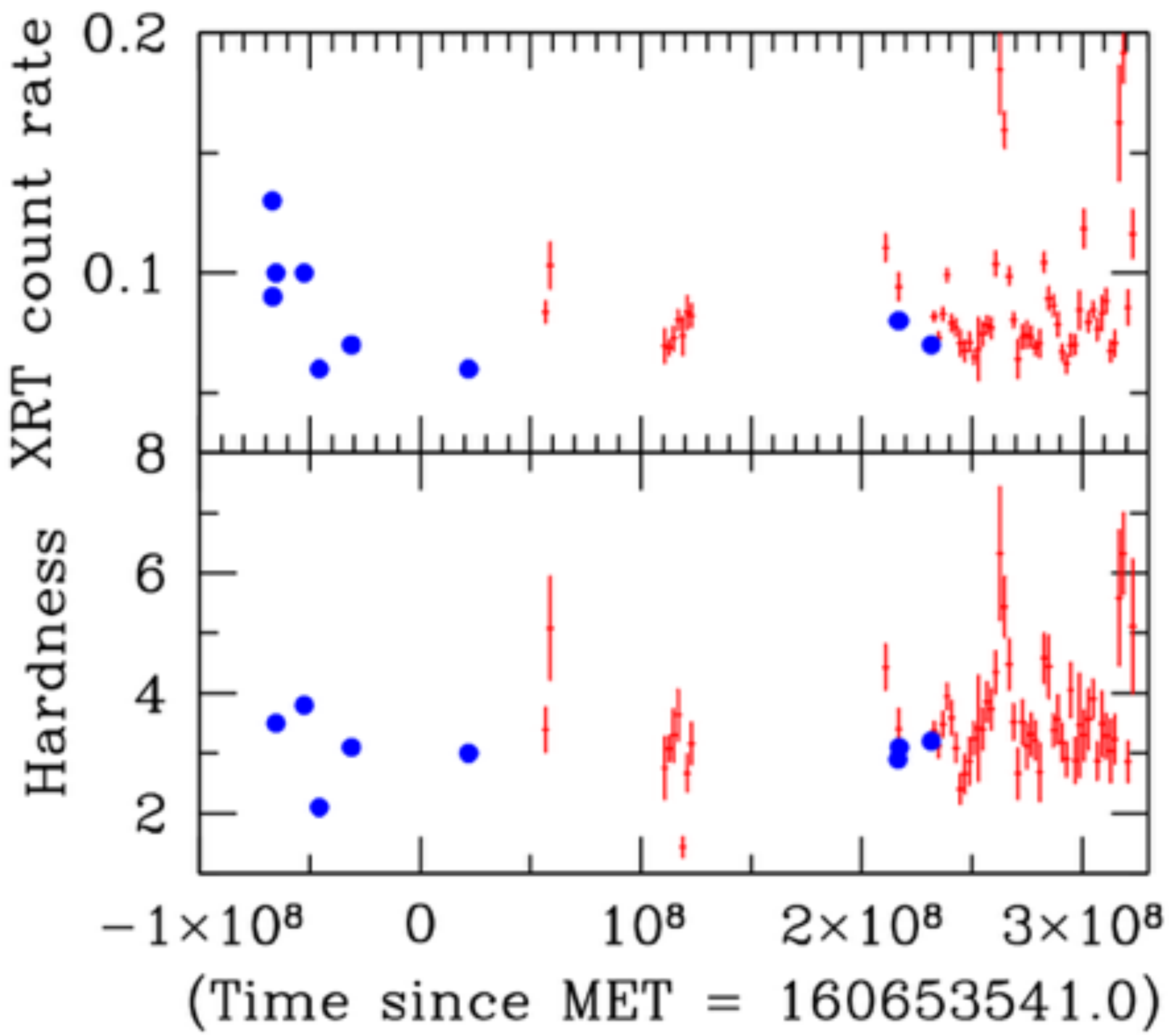
$v = -0.2c$

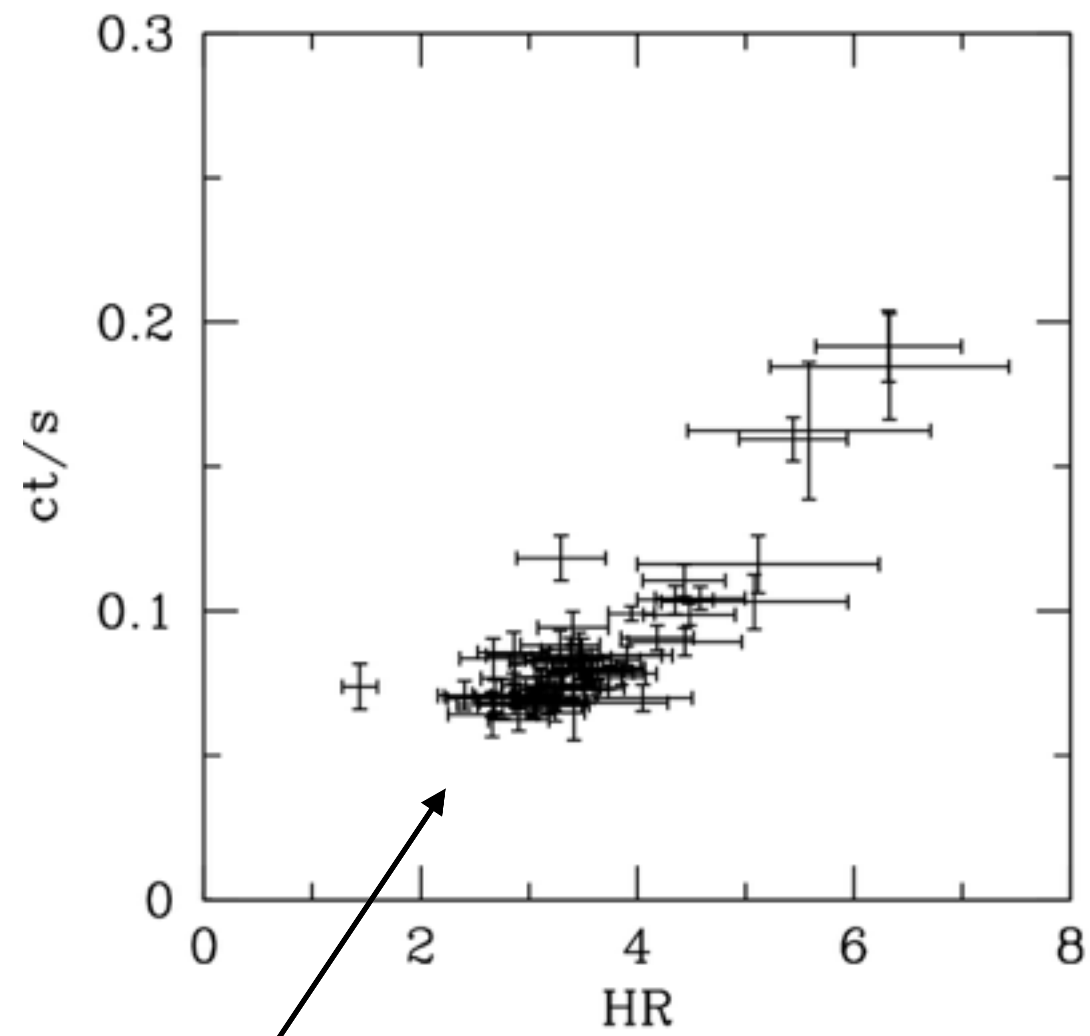
$N_H \sim 1 \times 10^{24}$ cm^{-2}

$\log \xi \sim 3\text{-}4$

Emission lines likely associated with collisionally excited plasma

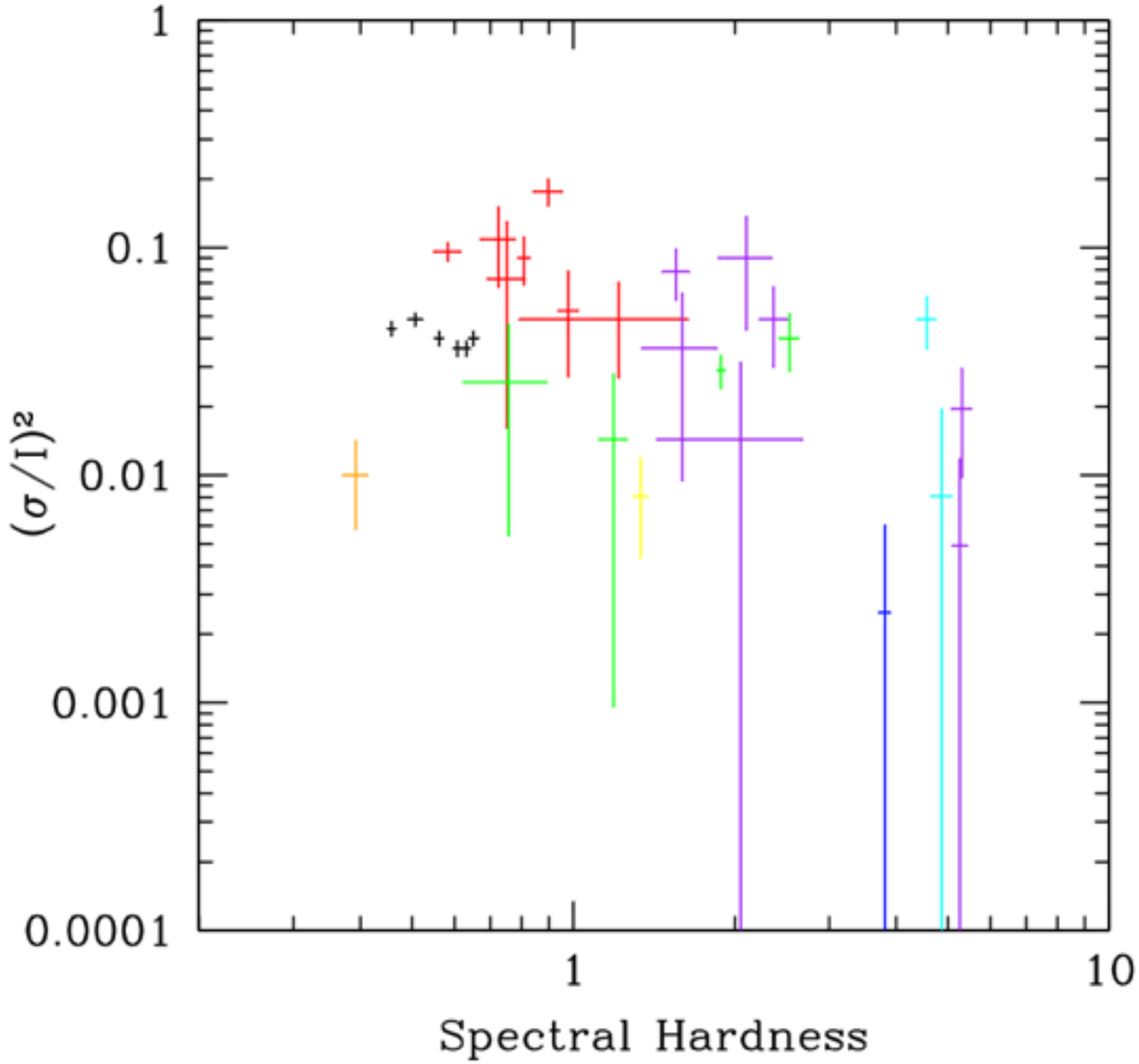
3. When ULXs are bright, they're typically spectrally 'harder', consistent with seeing increased beaming

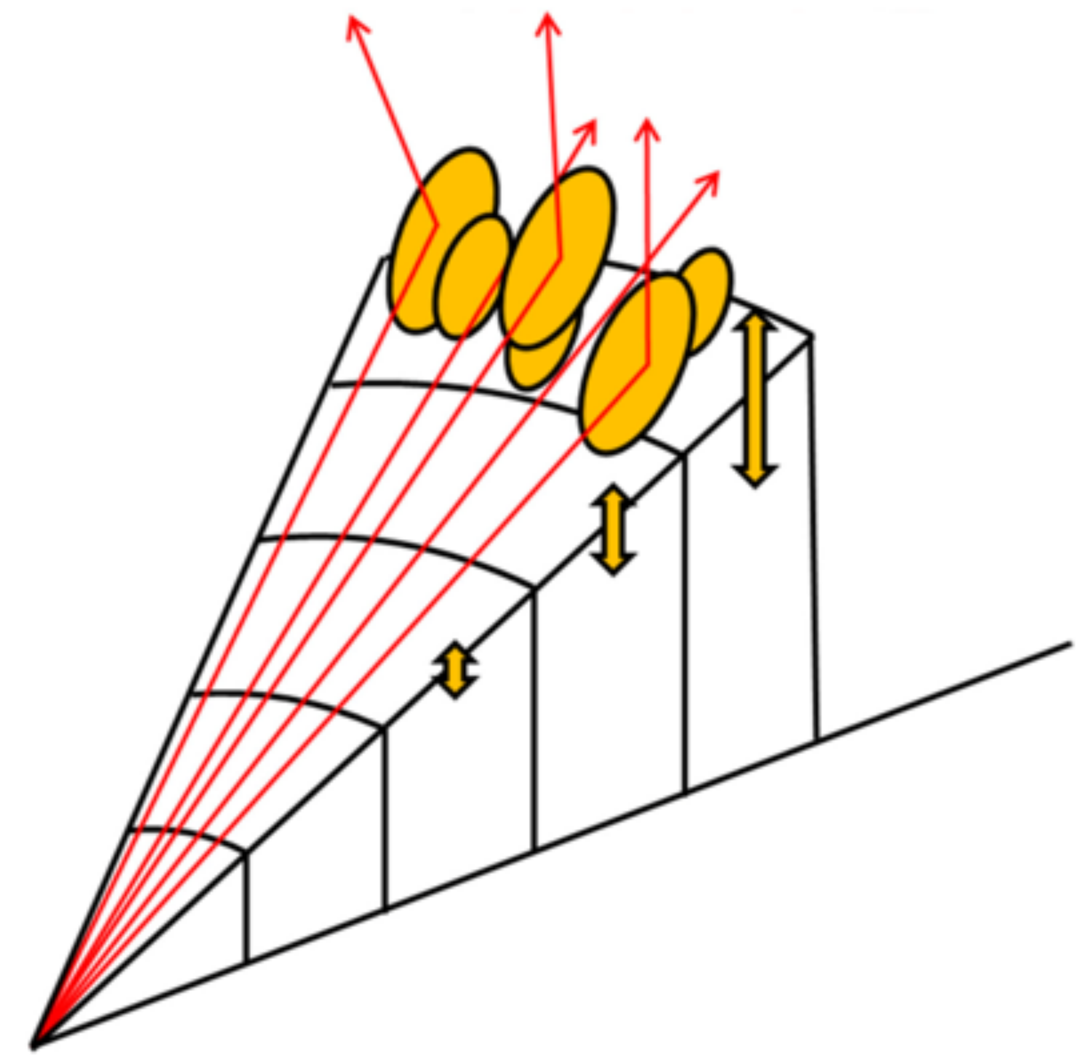




Note - lack of hysteresis

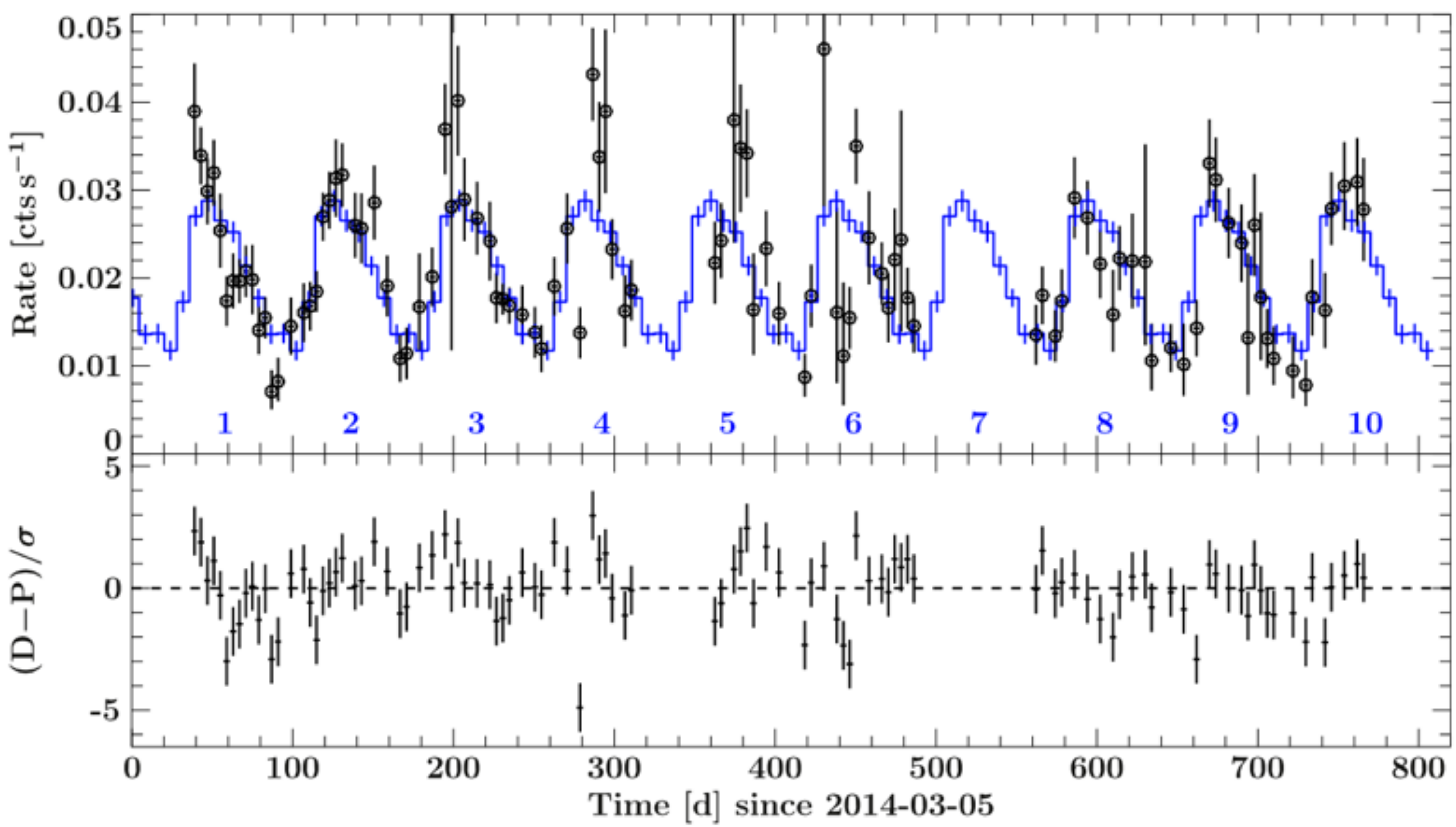
And the presence of variability tends to correlate with spectral hardness - makes sense if part of this is driven by obscuration and range of inclinations





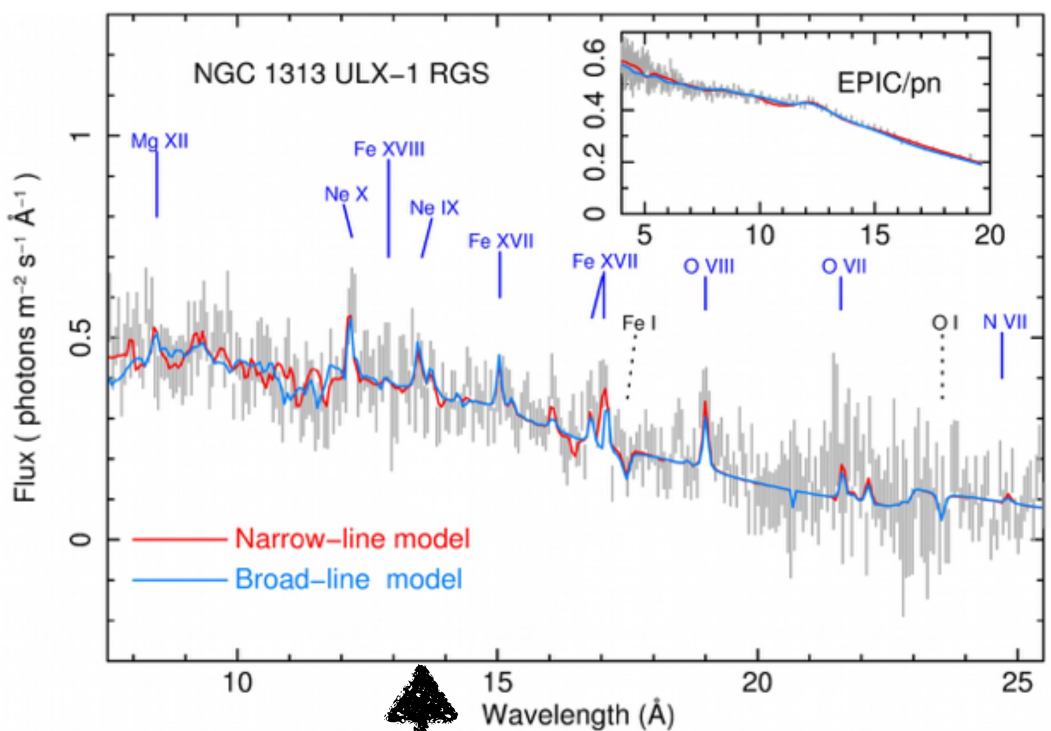
Middleton et al. (2015a)

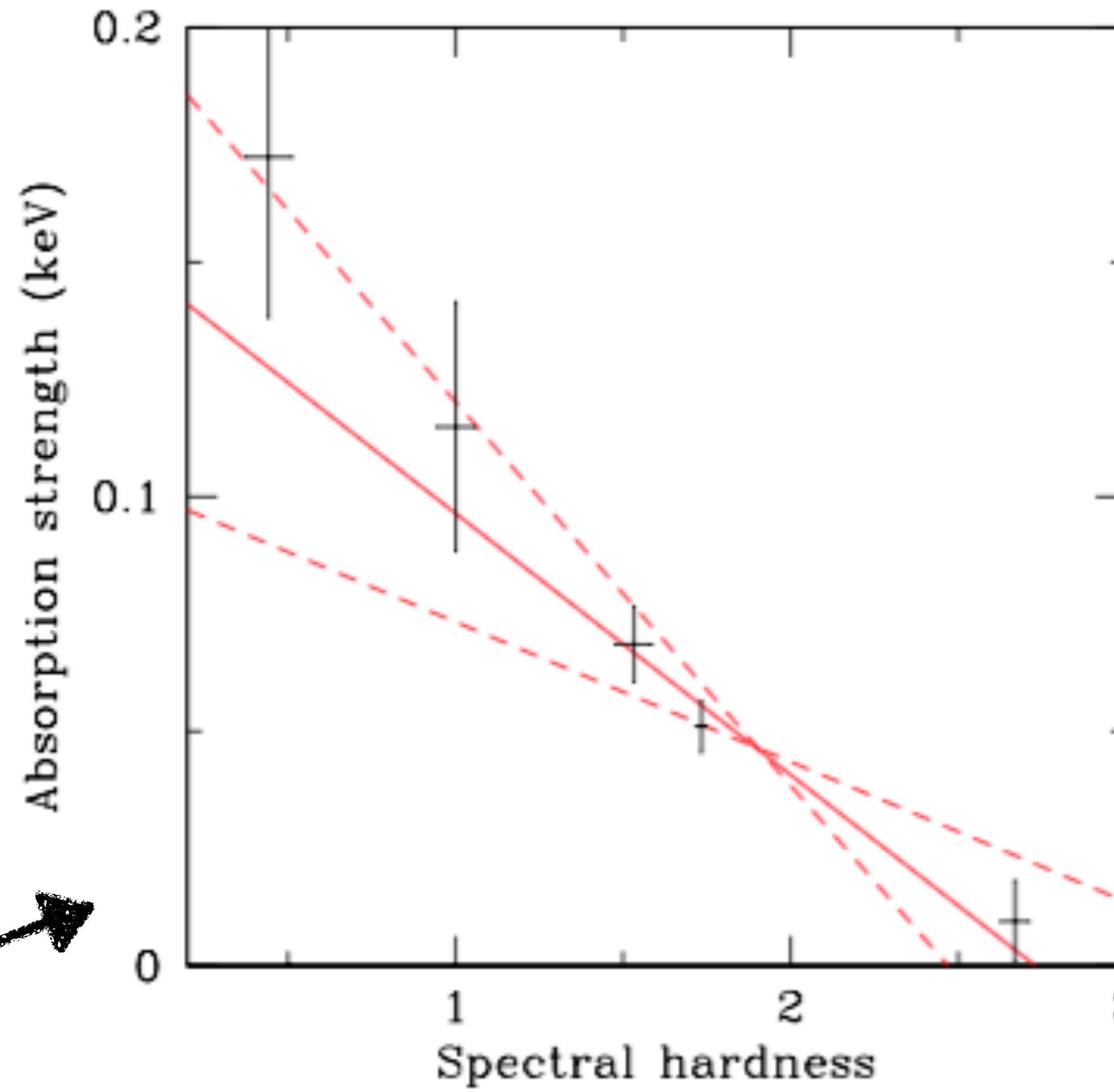
We do see very long periods - these would likely be the the wind (rather than inflow) precessing



Walton et al. (2016)

Where we also see the strength of absorption features change which would make sense if the inclination is changing to the wind (partially degenerate with changes in accretion rate)



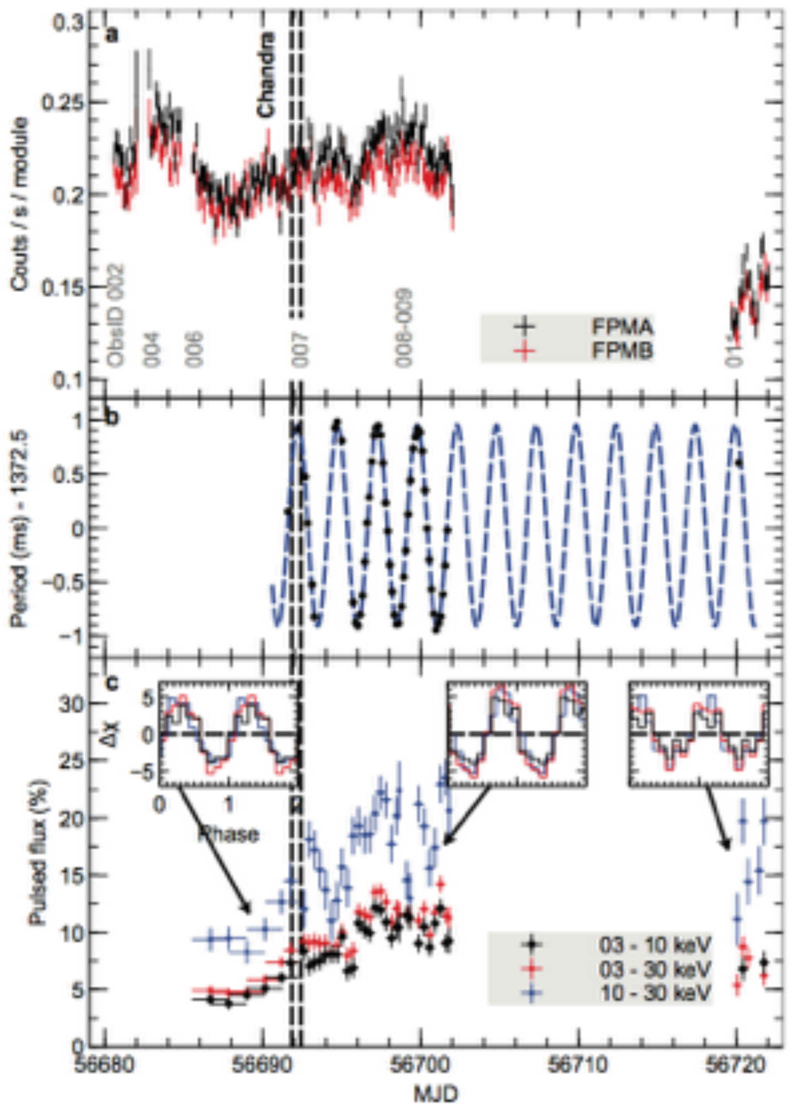


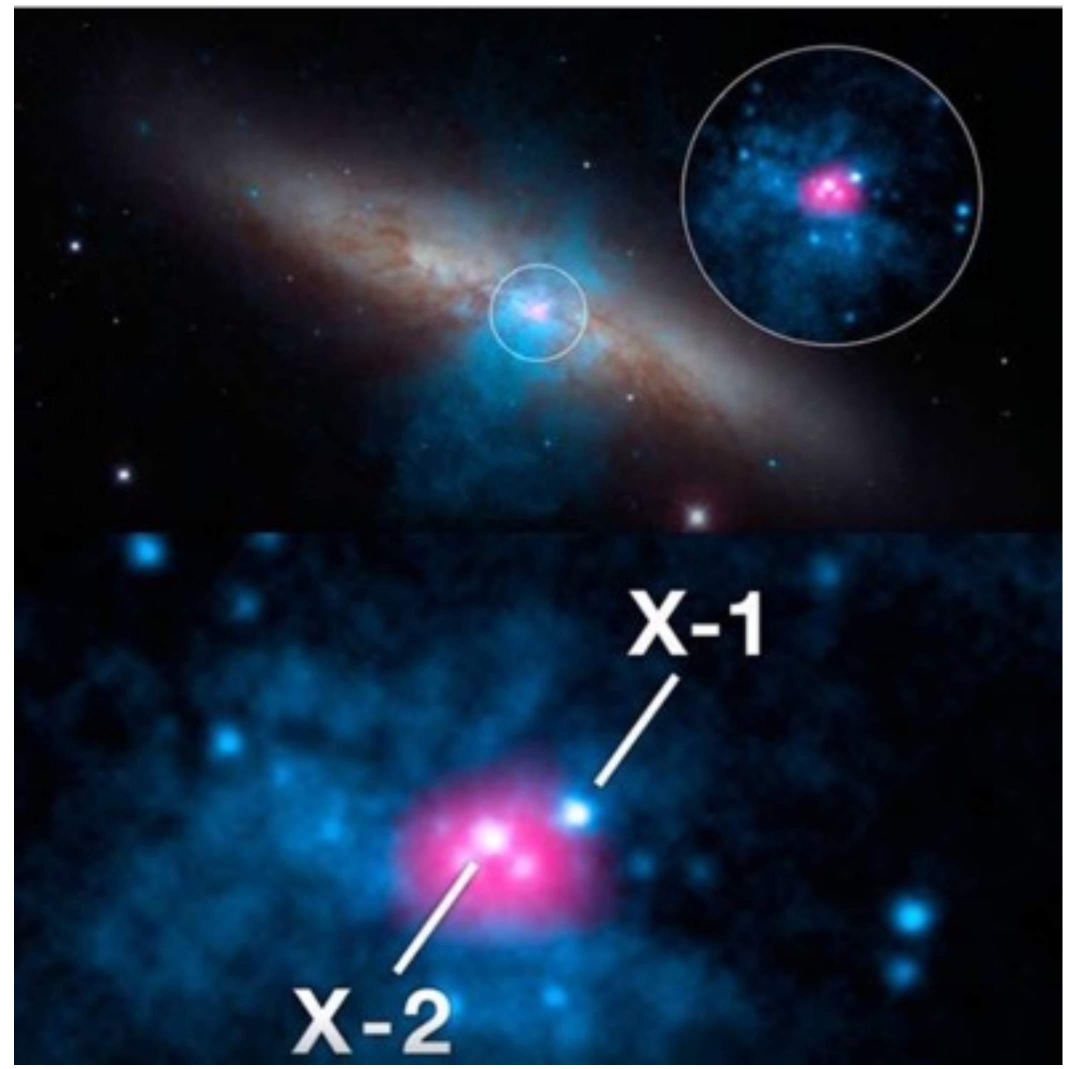
Grating resolution

CCD resolution

Middleton et al. (2015b)

For a long time we *assumed* that ULXs contained stellar mass BHs though there was no reason to (King 2001)…..the discovery of PULXs/ULPs/ULX-Ps…



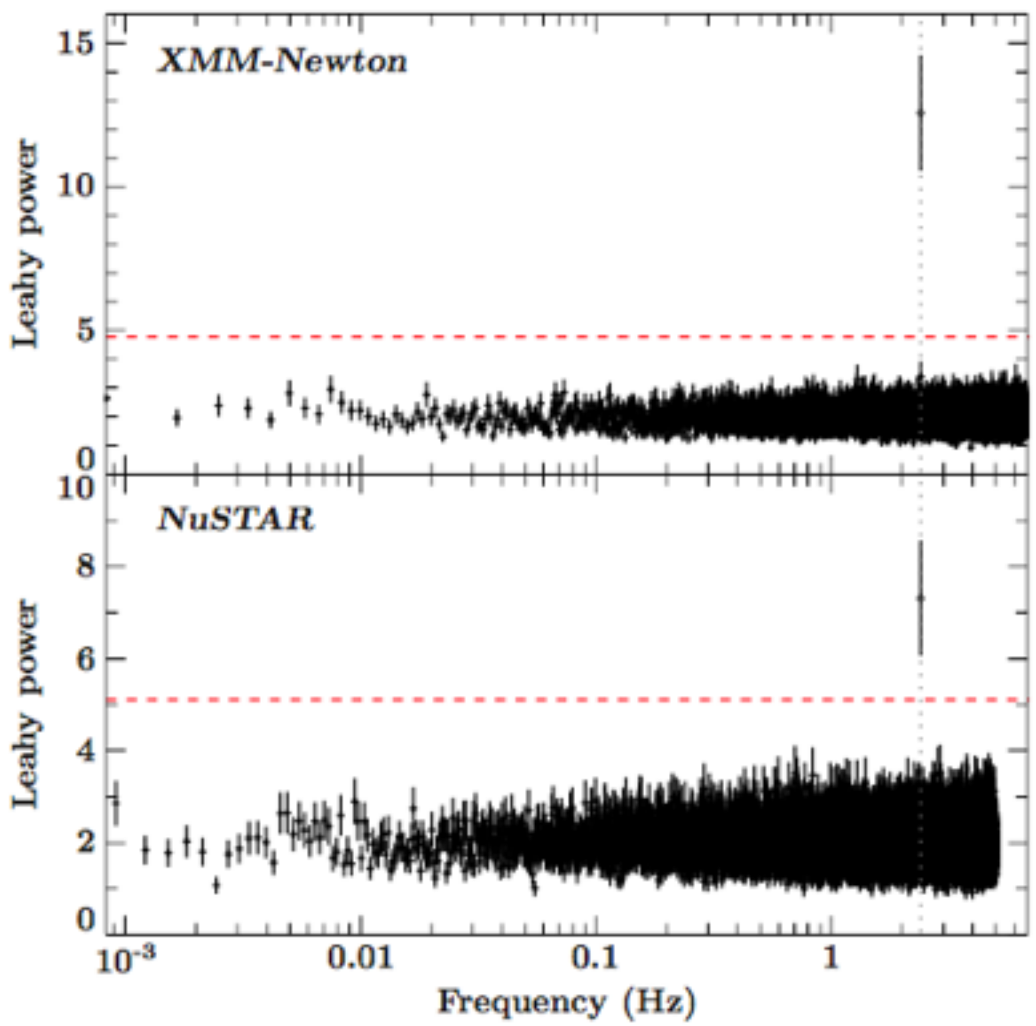


Bachetti et al. (2014)

Pulsations are **transient**

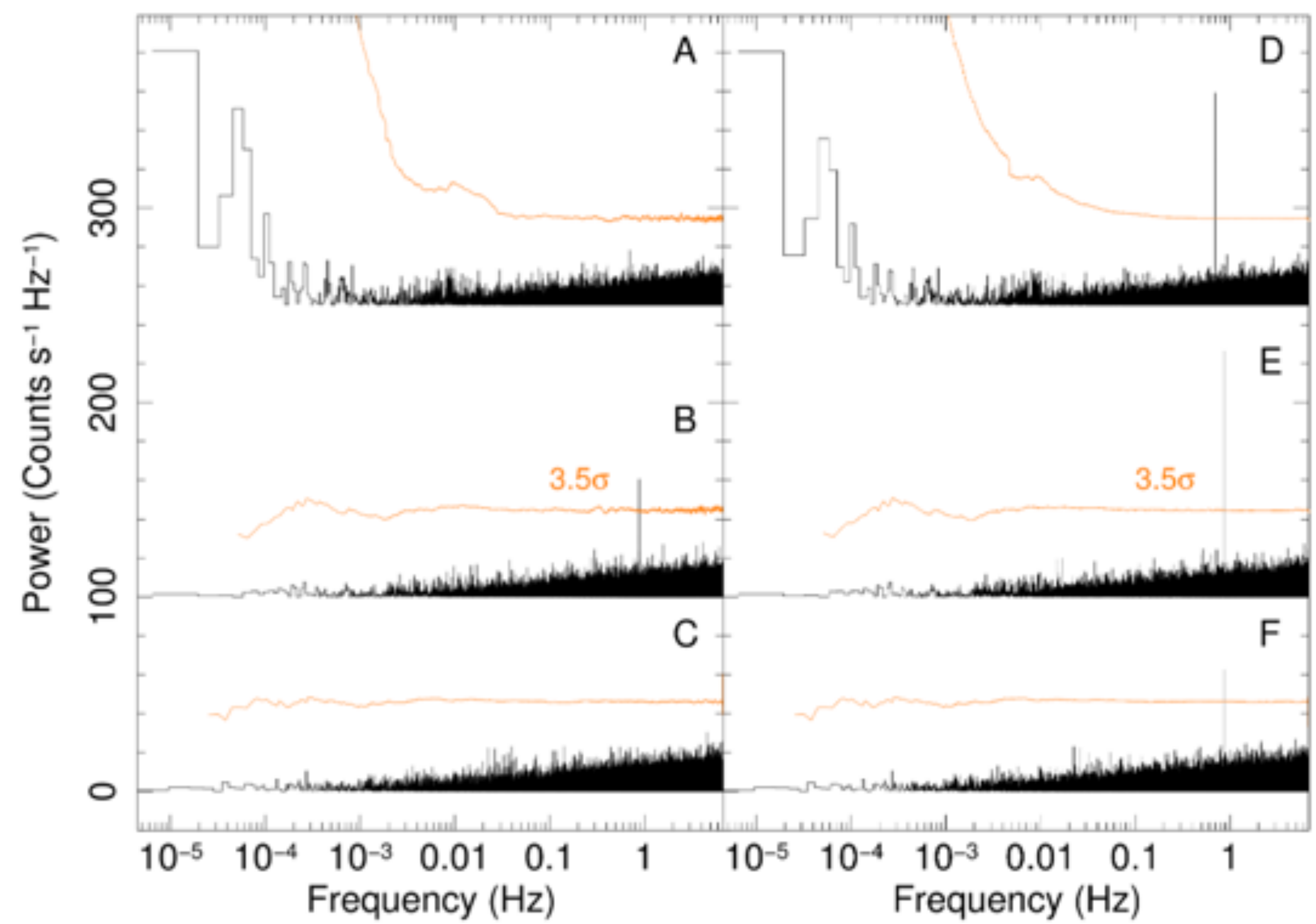
Extremely rare and only a handful of sources out of 100s of ULXs are known to show pulsations

NGC 7793 P13



Fuerst et al. (2016)

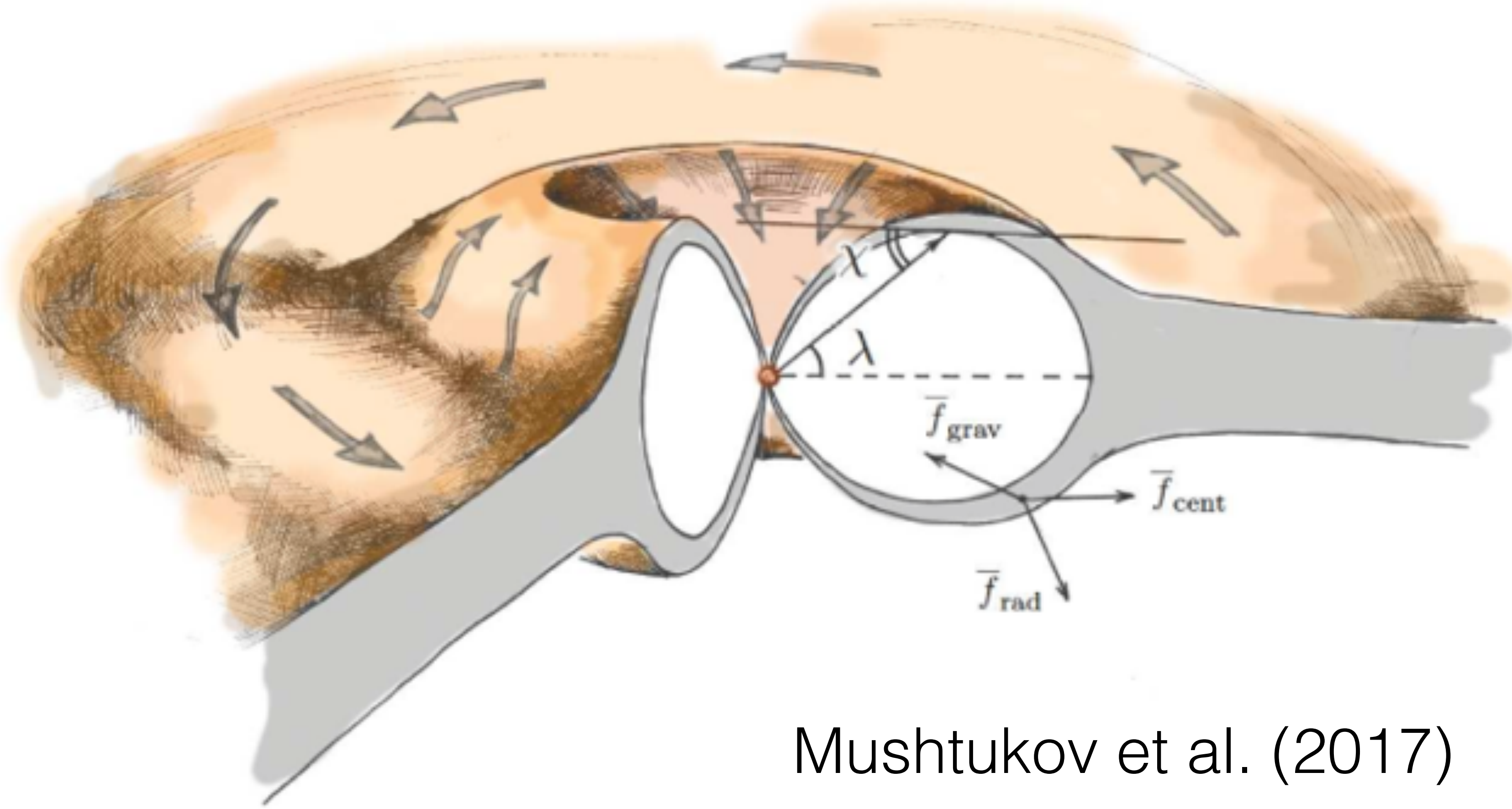
NGC 5907 ULX-1



Israel et al. (2017)

Mass constraint by Motch et al. (2014)

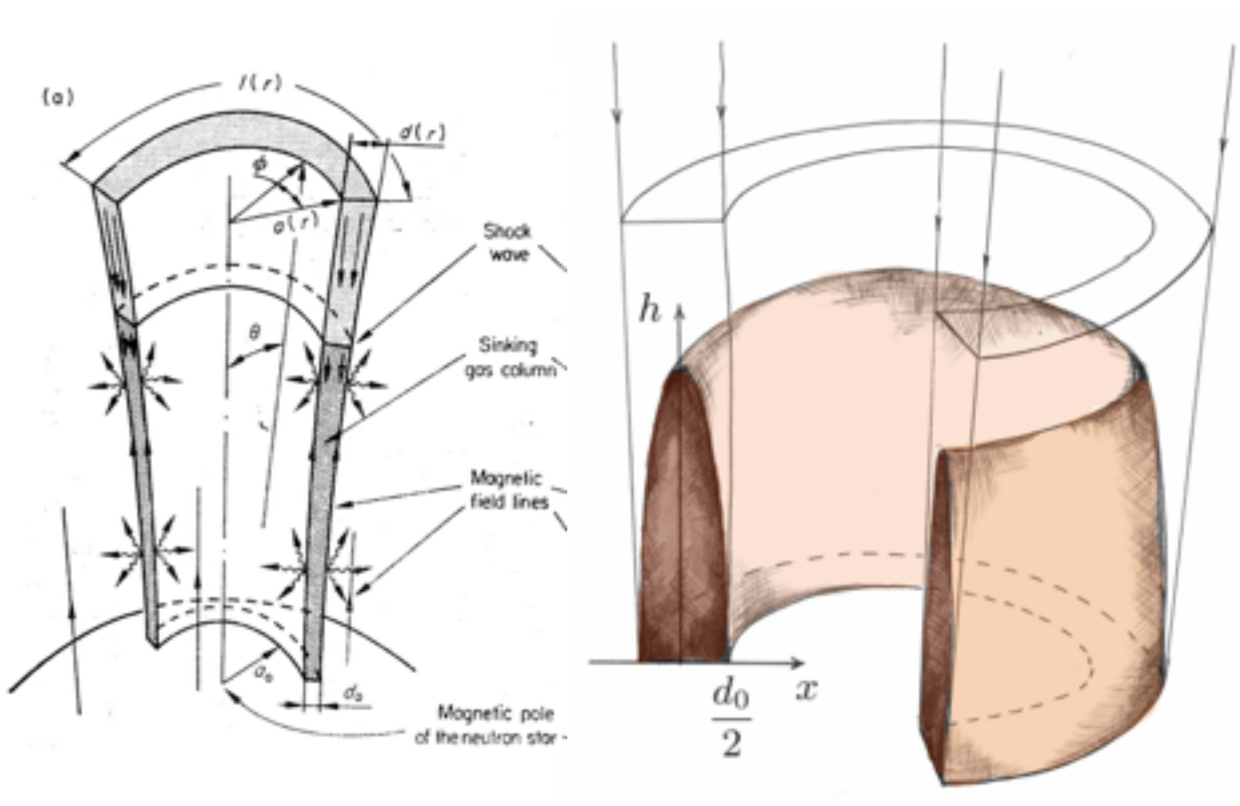
Pulsations indicate that the disc must truncate at r_m (where the magnetic torque dominates over the viscous torque) but there are conflicting ideas for B field strength, moderate ($<10^{11-12}$ G) or very high ($>10^{13}$ G).



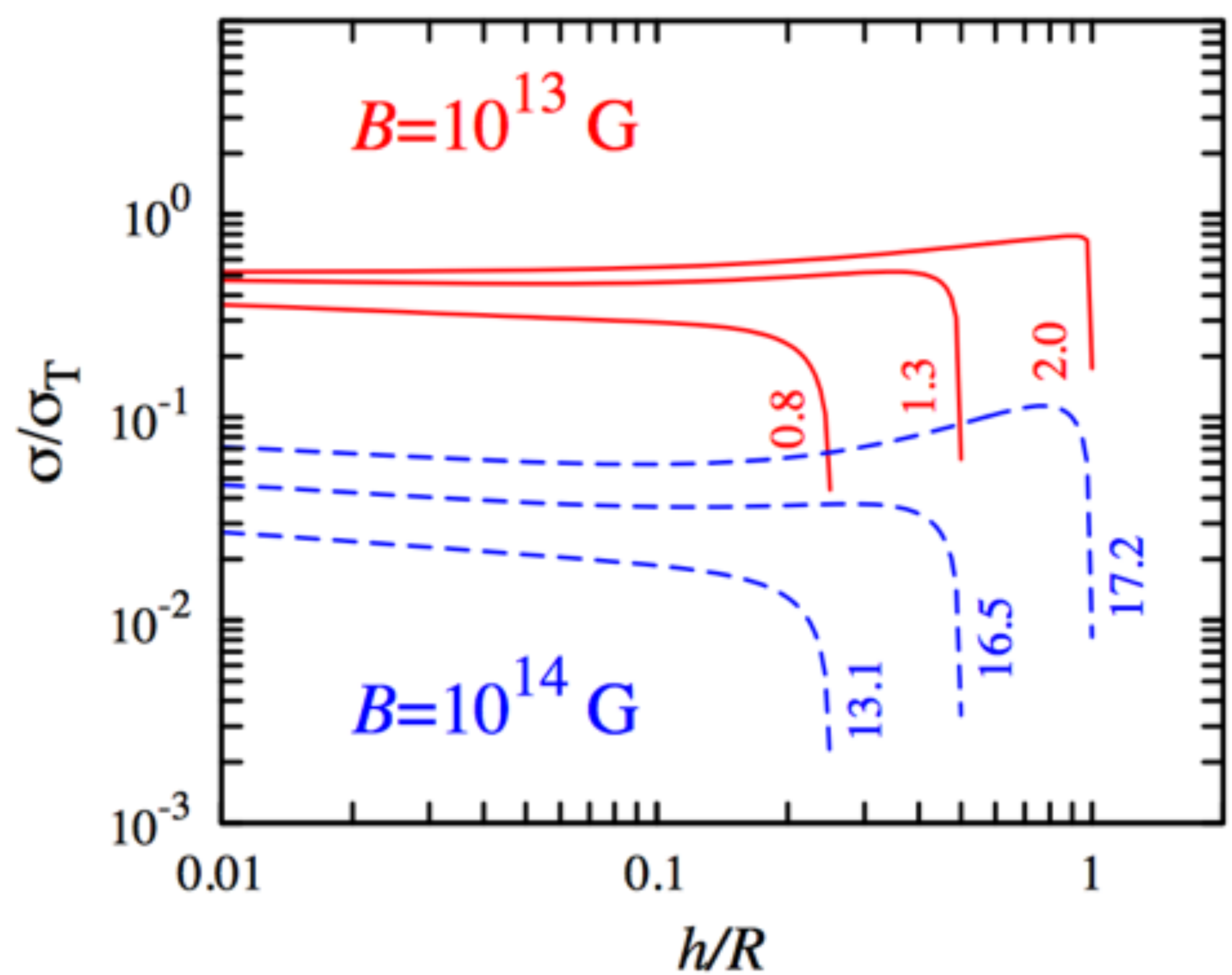
Mushtukov et al. (2017)

If $B > 10^{13}$ G then it may truncate **before** r_{sph} is reached so we have a thin disc and curtain

In either case, the observed rate of spin-up (e.g. -3×10^{-11} s/s: Fuerst et al. 2016) demands a large accretion torque and super-Eddington accretion rate **onto** the NS itself. This is ok as the structure of the column can accommodate such rates



Basko & Sunyaev (1976)/
Mushtukov et al. (2015)



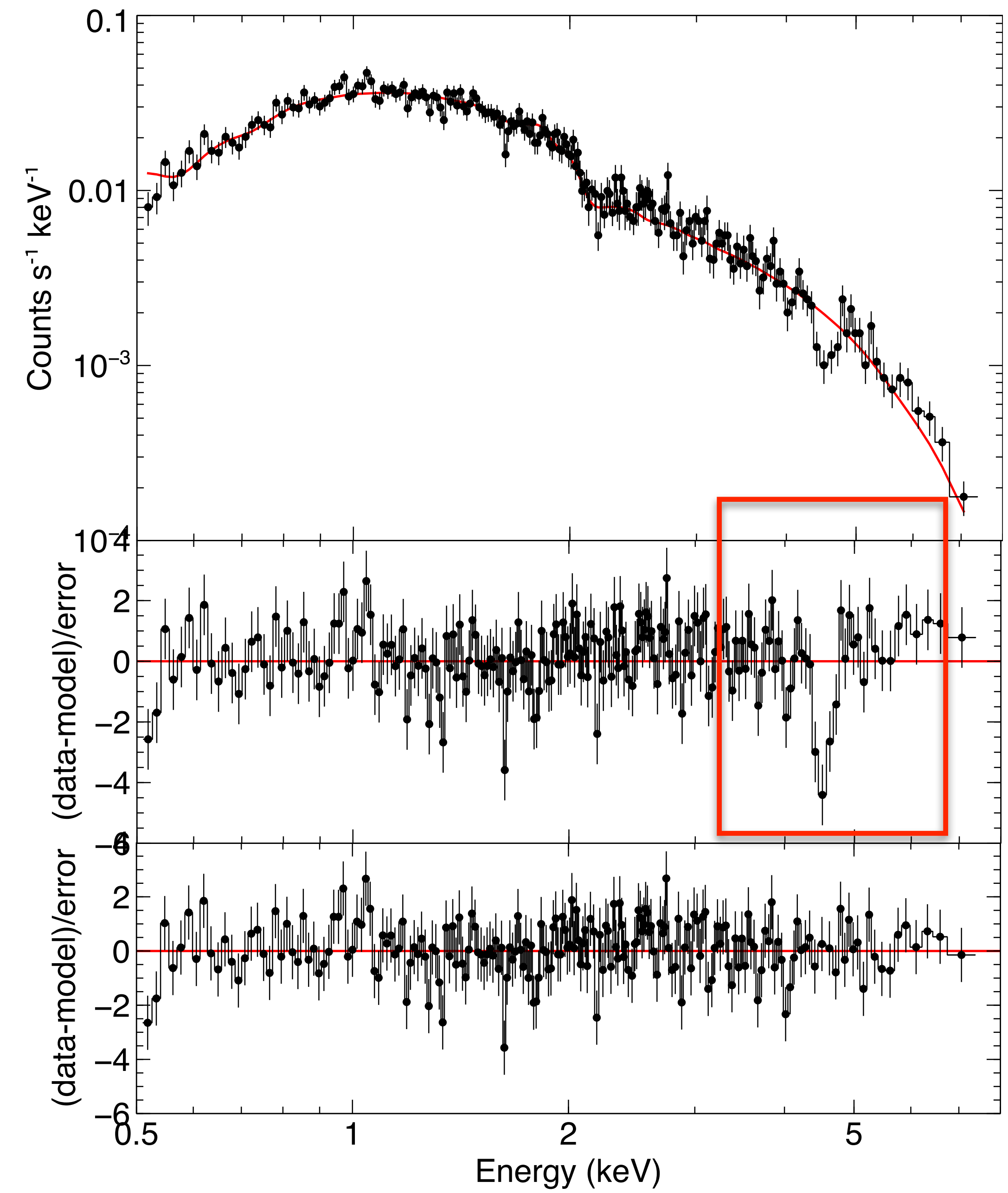
The other option for explaining these sources is to have a lower (close to average the HMXB population) field strength so that $r_M < r_{sph}$ and include the role of beaming on L

Table 3: derived properties of PULXs

Name	M82 ULX2	NGC 7793 P13	NGC5907 ULX1
$\dot{m}_0$	36	20	91
$\mu q^{7/4} m_1^{-1/2} I_{45}^{-3/2}$ [Gcm^3]	9.0×10^{28}	2.3×10^{28}	2.3×10^{31}
$R_{\rm sph} m_1^{-1}$ [cm]	5.9×10^{7}	3.3×10^{7}	1.3×10^{8}
$R_M m_1^{-1/3} I_{45}^{-2/3}$ [cm]	1.6×10^{7}	8.7×10^{6}	1.9×10^{8}
$R_{\rm co} m_1^{-1/3}$[cm]	1.9×10^{8}	8.4×10^{8}	1.6×10^{8}
$P_{\rm eq} q^{-7/6} m_1^{1/3}$ [s]	0.09	0.02	1.86
$t_{\rm eq}$ [yr]	1647	40776	0

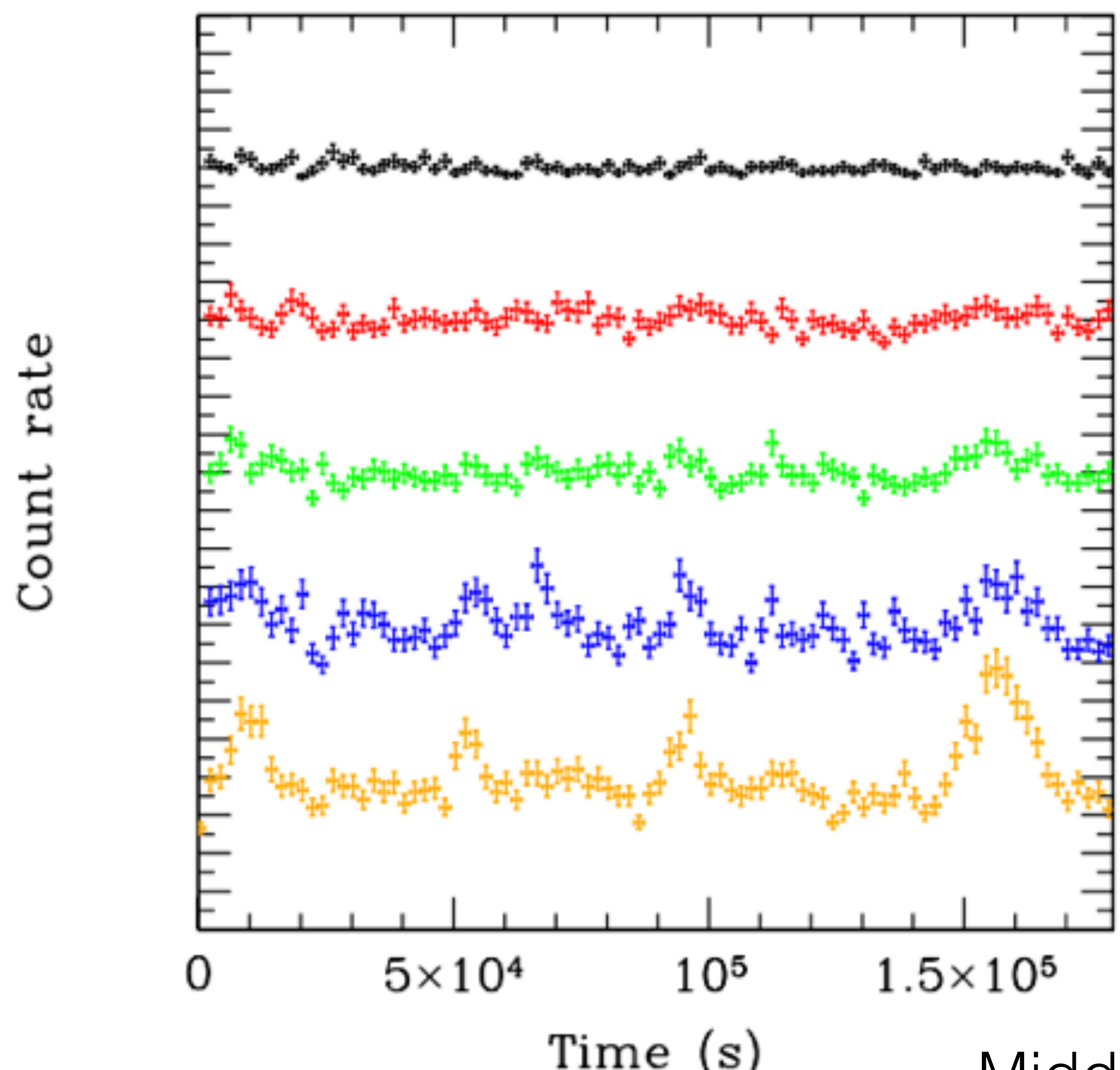
King, Lasota & Kluzniak (2017)

Brightman et al. (2018)



Line energy indicates either a field ~10^{11} or 10^{15} G depending on whether electrons or protons are creating the line

If we see the CRSF then the curtain would have to be optically thin so the spectrum has to be formed of the disc down to r_M and the column but how do we separate them out?



0.5-0.7 keV

0.7-1.0 keV

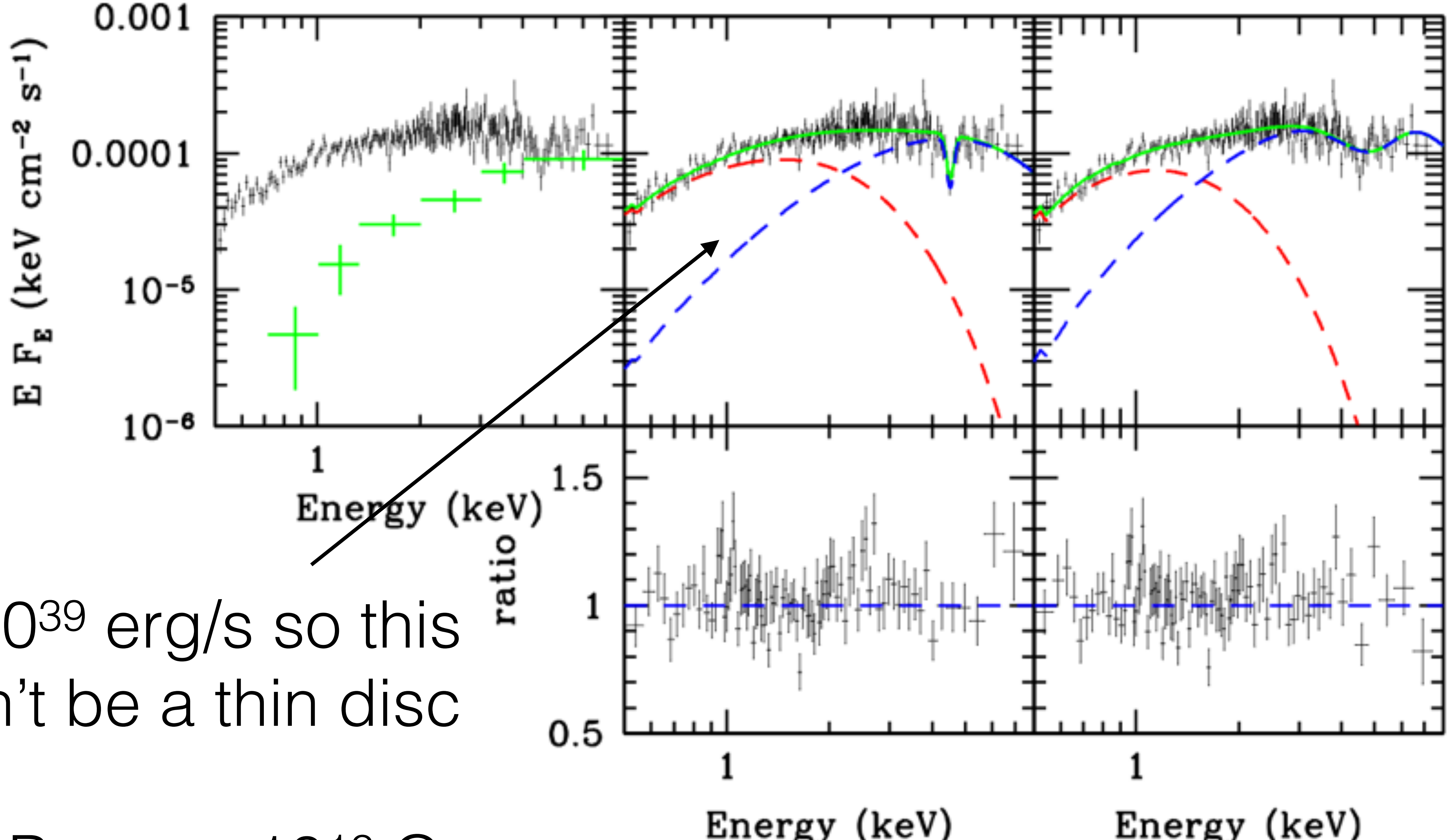
1.0-1.3 keV

1.3-2.0 keV

2.0-8.0 keV

Middleton et al. (subm)

If we see the CRSF then the curtain would have to be optically thin so the spectrum has to be formed of the disc down to r_M and the column but how do we separate them out?



> 10^{39} erg/s so this can't be a thin disc

→ $B_{dipole} < 10^{12}$ G

Middleton et al. (subm)

How many NS ULXs are there? Are there **any** BH ULXs??

In a flux-limited survey we can determine analytically what the observable ratio of neutron star ULXs to black hole ULXs should be for similar mass inflow rates:

$$\frac{P_{NS}}{P_{BH}} \approx \frac{n(NS)}{n(BH)} \left(\frac{M_{NS}}{M_{BH}}\right)^{(3-\beta)/2}$$

$$L \approx \frac{L_{Edd}[1 + ln(\dot{m}_0)]}{b}$$

$$b \propto \dot{m}_0^{-\beta}$$

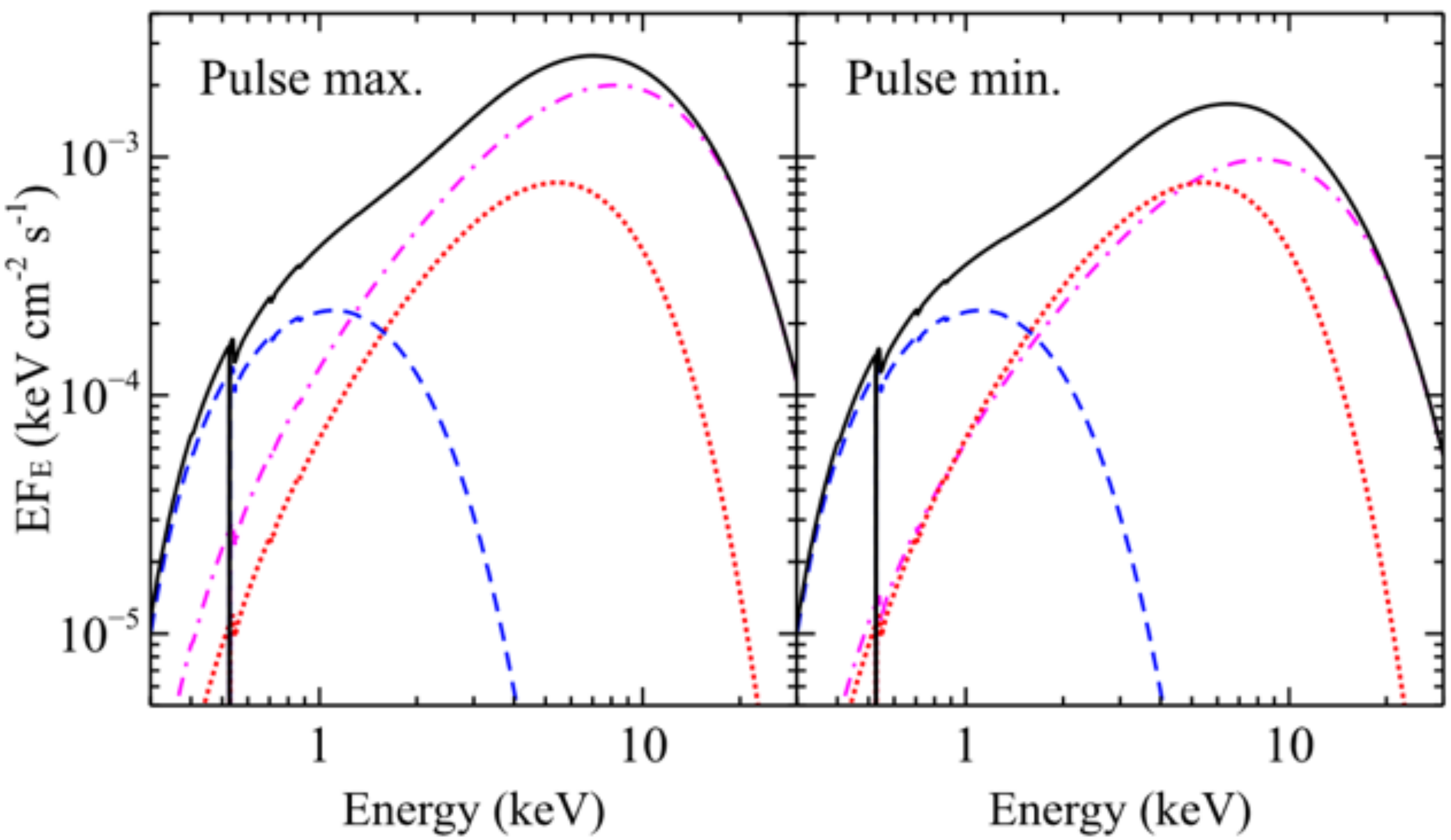
Ratio of species *observed*

Ratio of true spatial densities

Middleton & King (2017)

How can we identify the NS ULXs?

Pulsations will be weak if the inner regions are beamed and the column emission less beamed or we view more edge on.

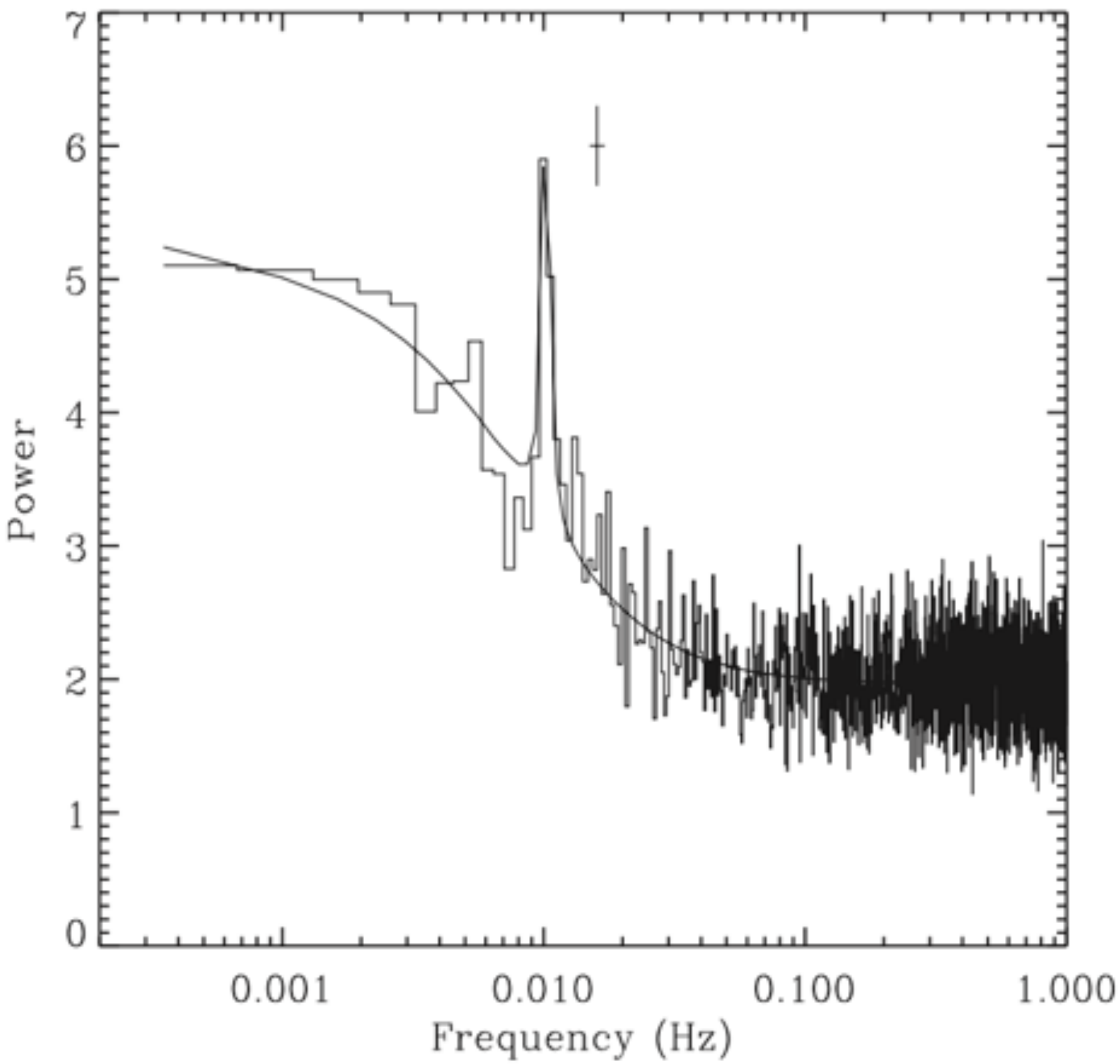


Walton et al. (2018)

Answer - look for longer or with greater sensitivity to pick out CRSFs and weak pulsations

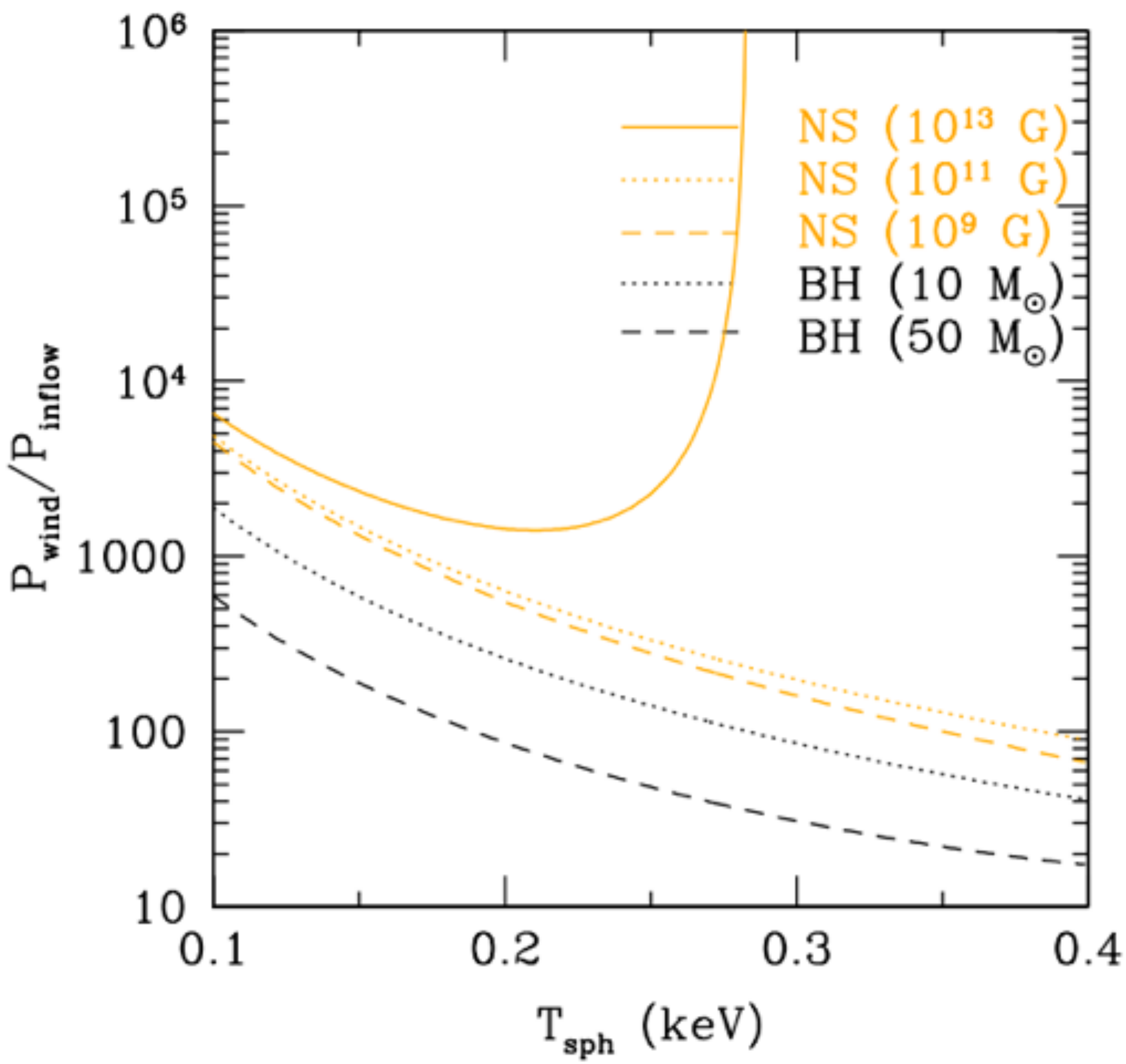
Hyper-Eddington fallback and/or super-critical accretion may **bury** the dipole field so pulsations and CRSFs may be absent

Possible answer….



Strohmayer & Mushotzky (2009)

If the wind is precessing and making the long periods - can we explain the QPOs with an associated mechanism that is tied to the nature of the compact object?

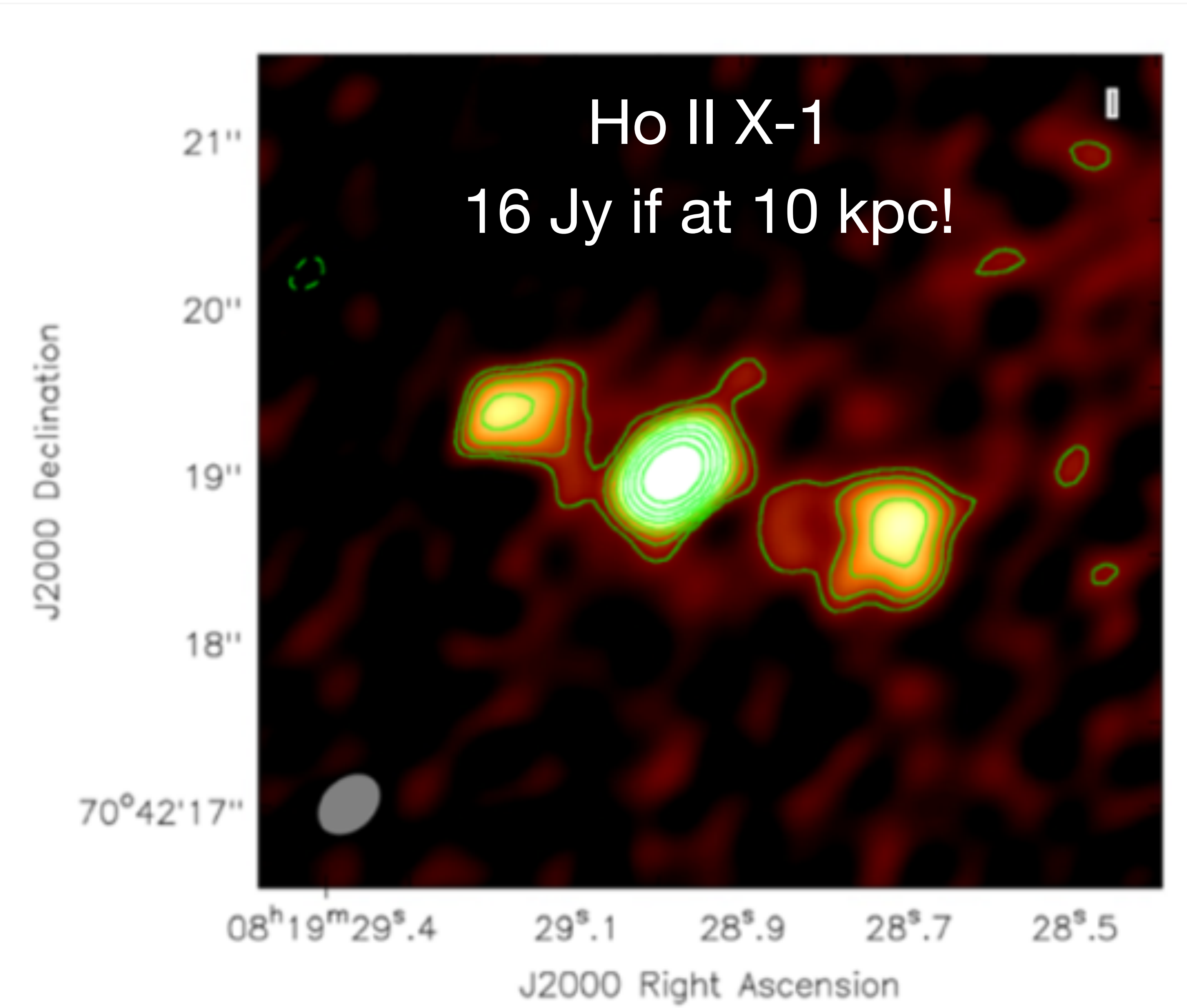


Middleton et al. (in prep)

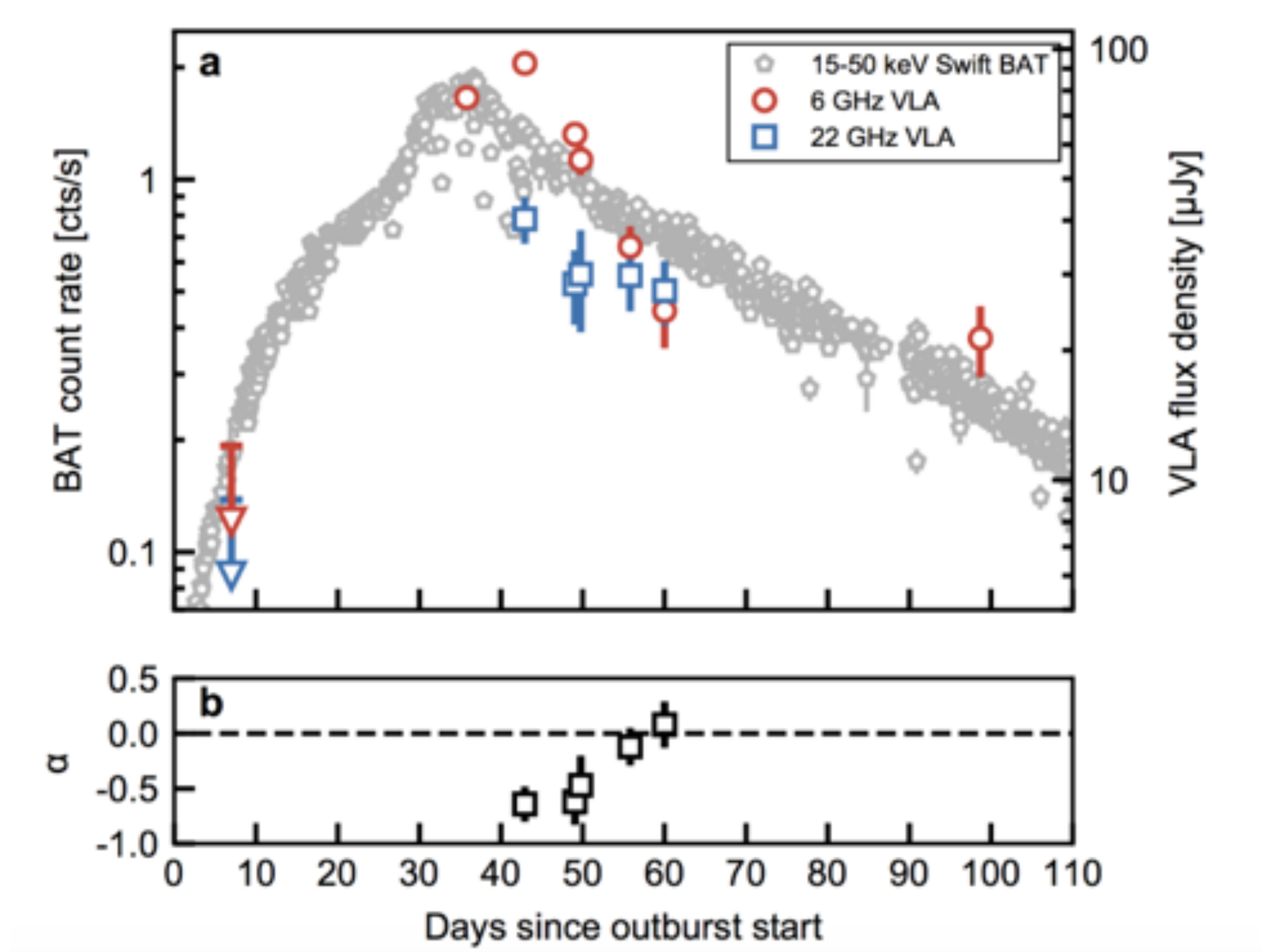
In principle, yes if the mechanism is Lense-Thirring. The QPO is the precessing inflow and the ~day timescale period is the wind

If course, if the precession is actually that of the NS dipole then we should also see secular changes that can't occur in BHs (as it takes longer to spin one up)

How can we identify the NS ULXs?



Cseh et al. (2014, 2015)



Van den Eijnden et al. (2018)

Some take-away points:

- we are certain that **most** ULXs are super-critical accretors but that doesn't mean that accreting IMBHs aren't out there

- pulsating ULXs are consistent with having dipole field strengths around Galactic HMXB mean values

- identifying ULXs containing NS primaries may be hard, especially if the surface dipole field has been suppressed so other techniques are required