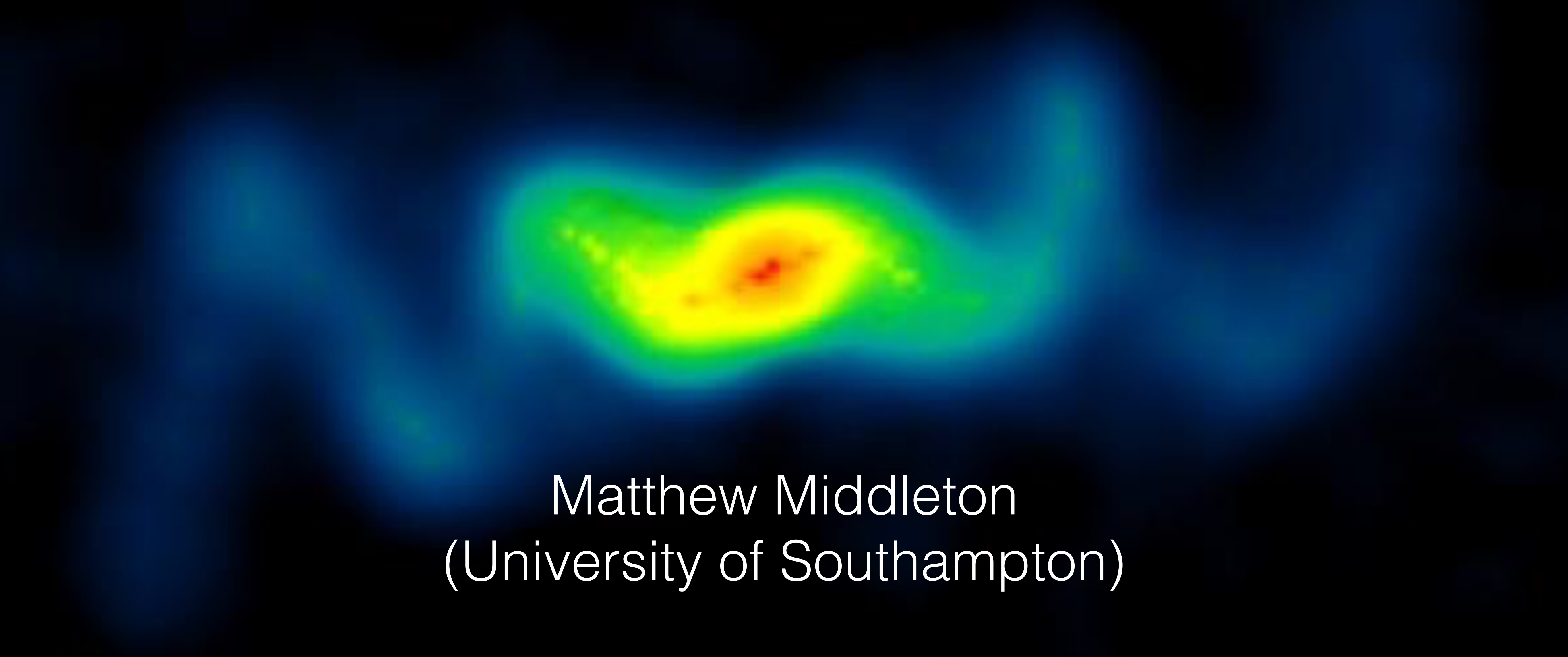
ULXs - our window into the extreme



Matthew Middleton
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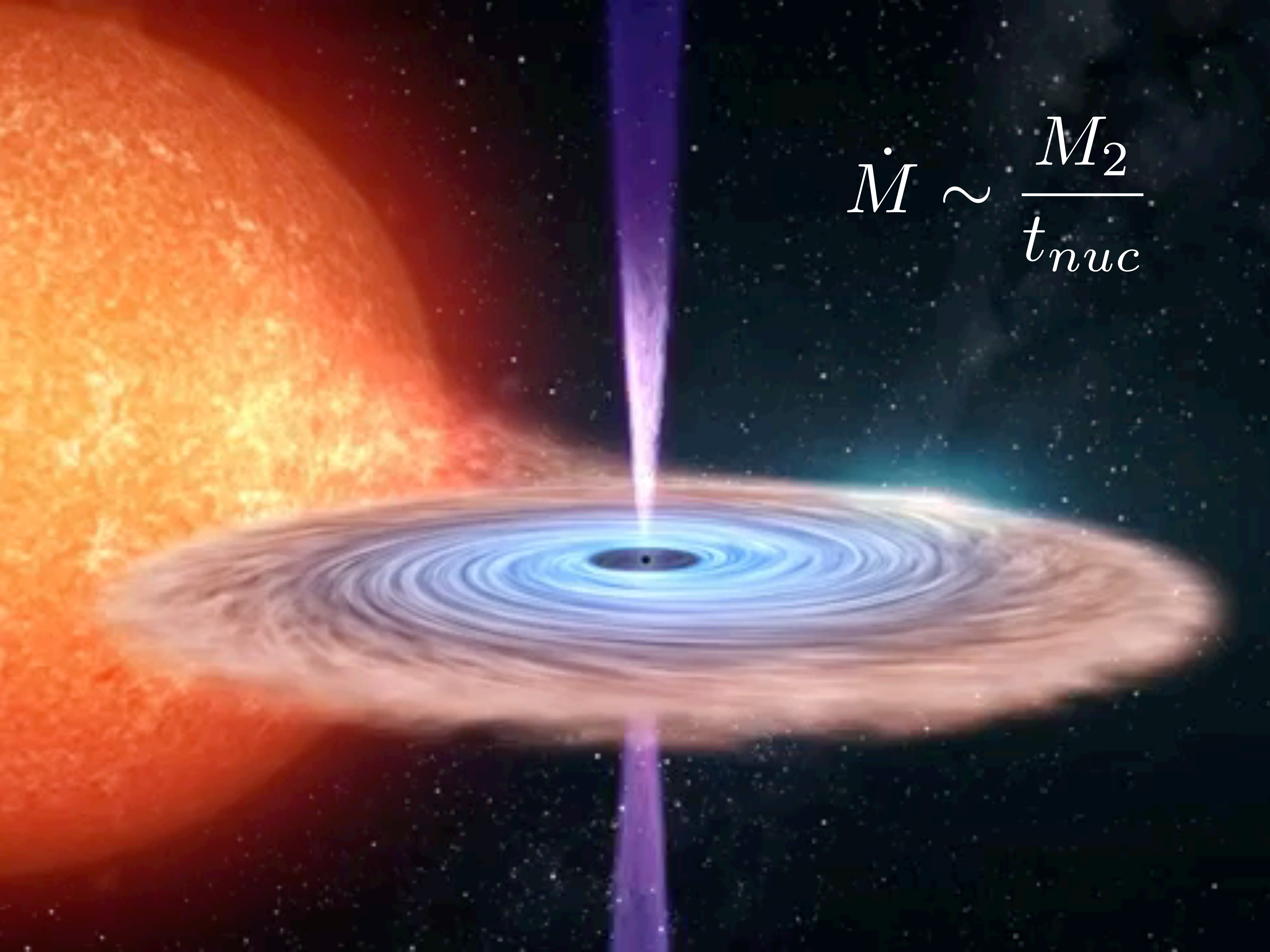
Chris Fragile, Yan-Fei Jiang, Shane Davis, Jim Stone, Wynn Ho, Murray Brightman, Thomas Dauser, Matteo Bachetti, Adam Ingram, Andrew King, Ciro Pinto, Andy Fabian, Tim Roberts, Dom Walton, Felix Fuerst

Science & Technology Facilities Council

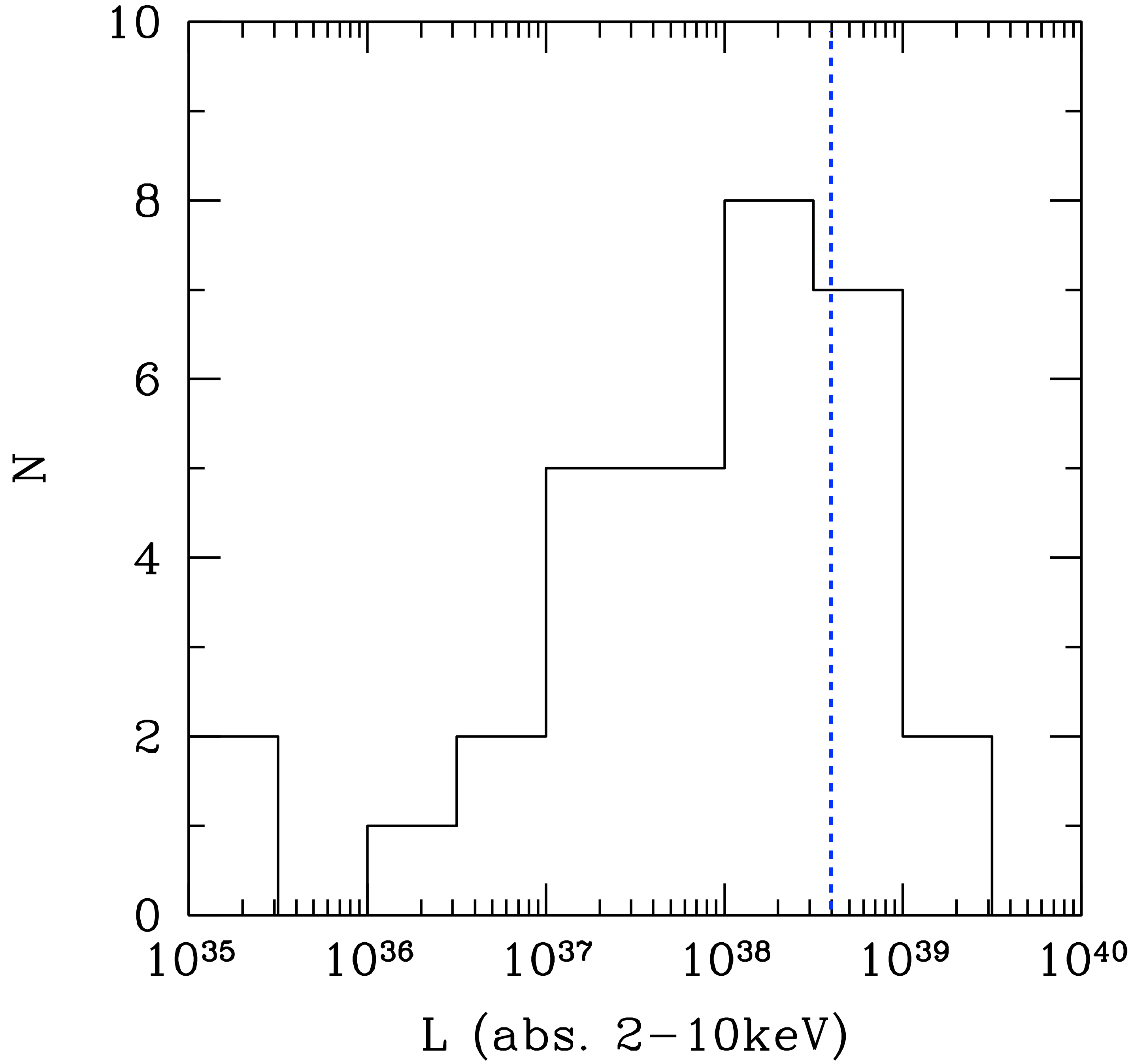


$$\dot{M} \sim \frac{M_2}{t_{nuc}}$$

For context and defining $\dot{m}_0 = \dfrac{\dot{M}}{\dot{M}_{Edd}}$

MT	$<\dot{M}>$	$\dot{m}_0$ (NS)	$\dot{m}_0$ (BH)
Nuclear	$10^{-8} - 10^{-7}\ M_\odot/\mathrm{yr}$	< 10	< 1

Rough distribution of peak luminosity of LM-BHBs



Note that these are subject to distance uncertainties (smaller now that GAIA is on the scene)

Thermal timescale mass transfer

Occurs when $M_2 > M_1$ - as mass is transferred, the Roche Lobe of the star shrinks. The thermal equilibrium radius is larger than the RL so the star expands against the contraction and this drives a period of rapid mass transfer of:

$$\dot{M} \sim \frac{M_2}{t_{KH}}$$

This is very large but short lived and when M2 < M1, nuclear timescale mass transfer restarts - **we're more likely to find accretion in the nuclear regime than thermal.**

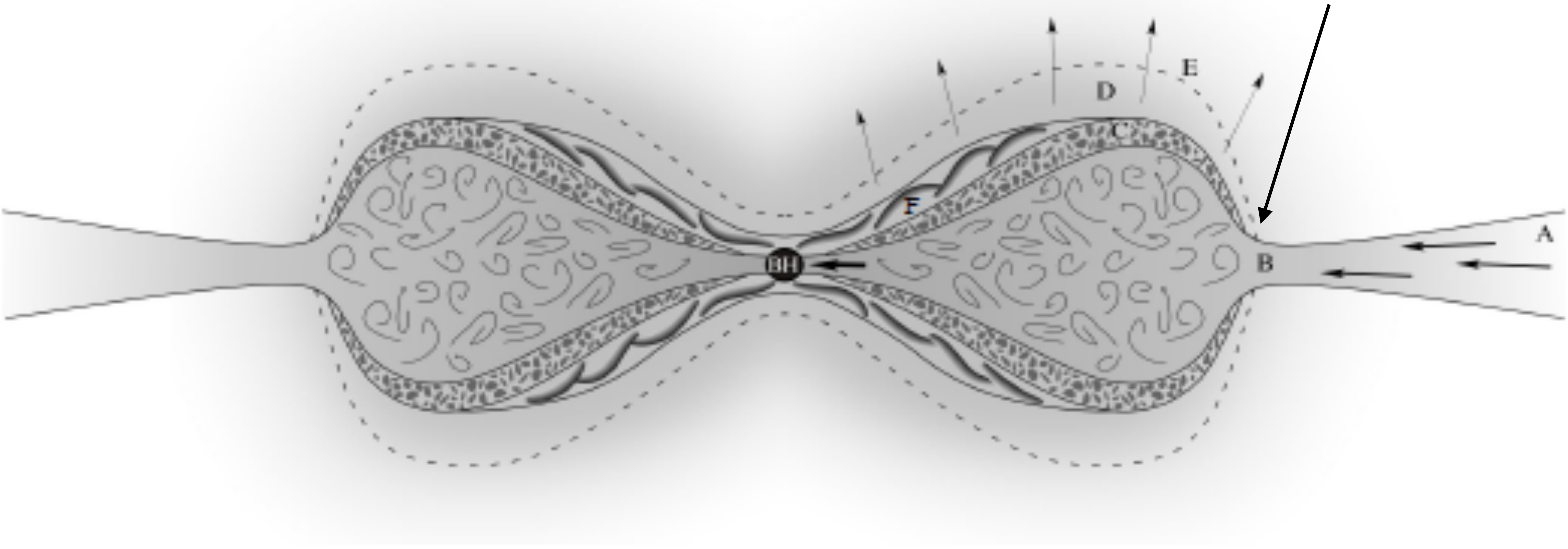
For context and defining $\dot{m}_0 = \frac{\dot{M}}{\dot{M}_{Edd}}$

MT	$<\dot{M}>$	$\dot{m}_0$ (NS)	$\dot{m}_0$ (BH)
Nuclear	10^{-8} - 10^{-7} $M_\odot$/yr	< 10	< 1
Thermal	10^{-5} - 10^{-4} $M_\odot$/yr	$< 1\text{x}10^4$	$< 1\text{x}10^3$

What happens at **highly** Super-Eddington (thermal MT) rates?

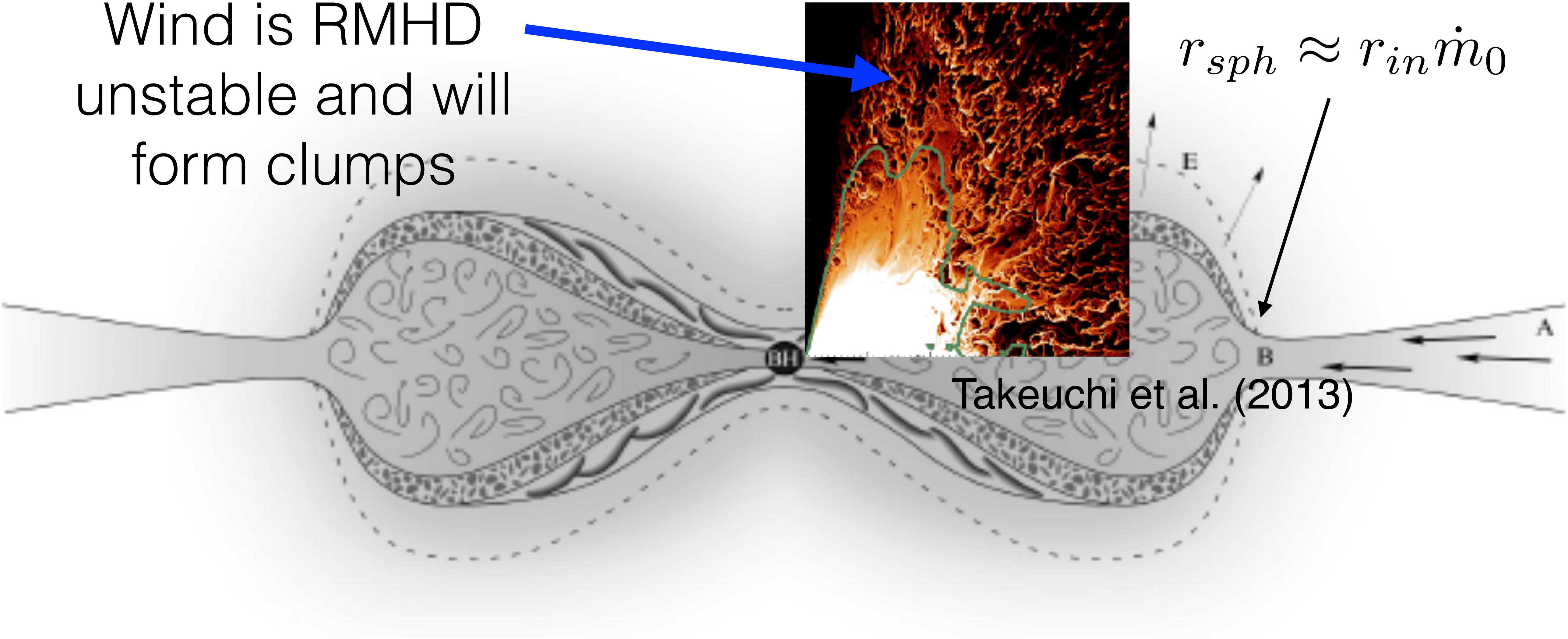
At the ‘spherization radius’ r_{sph} the accretion disc is locally Eddington (Shakura & Sunyaev 1973) - we say that the flow is **super-critical**

$$r_{sph} \approx r_{in} \dot{m}_0$$



Dotan & Shaviv 2011

Disc inflates due to radiation pressure (H/R ~1) - mass is then easily lost via scattering/line-driving/centrifugal/B-centrifugal so that the inflow remains locally Eddington limited - forms a ‘wind-cone’



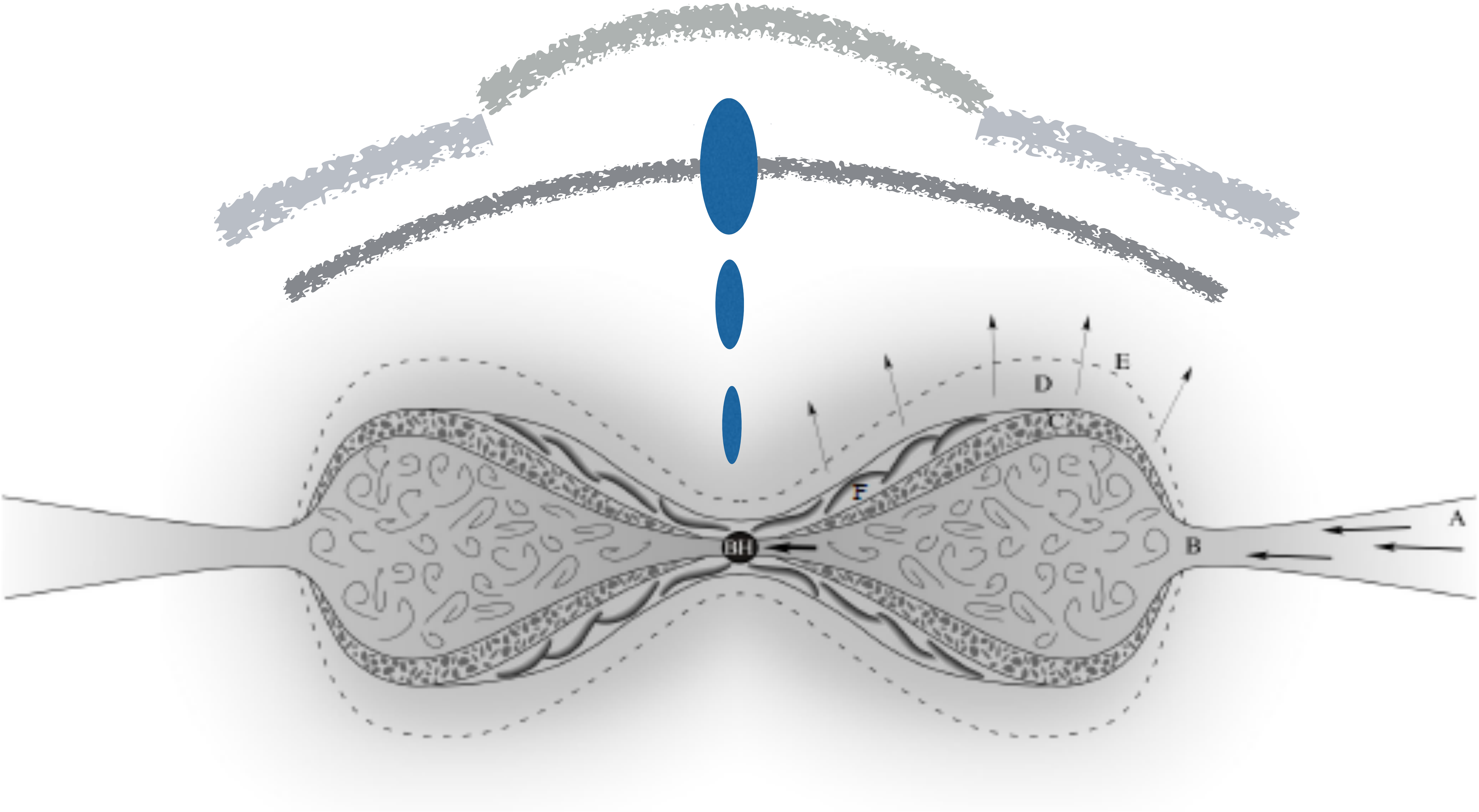
Wind is RMHD unstable and will form clumps

$r_{sph} \approx r_{in}\dot{m}_0$

Takeuchi et al. (2013)

Dotan & Shaviv 2011

Energy and matter deposited into the local environment

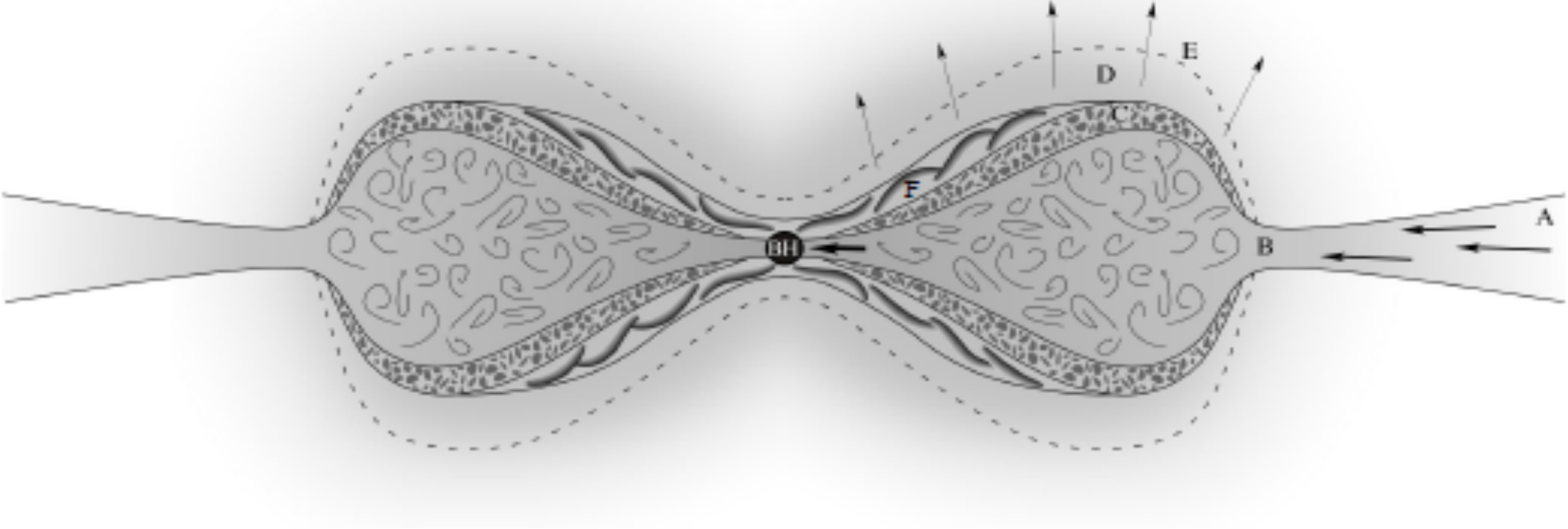


Dotan & Shaviv 2011

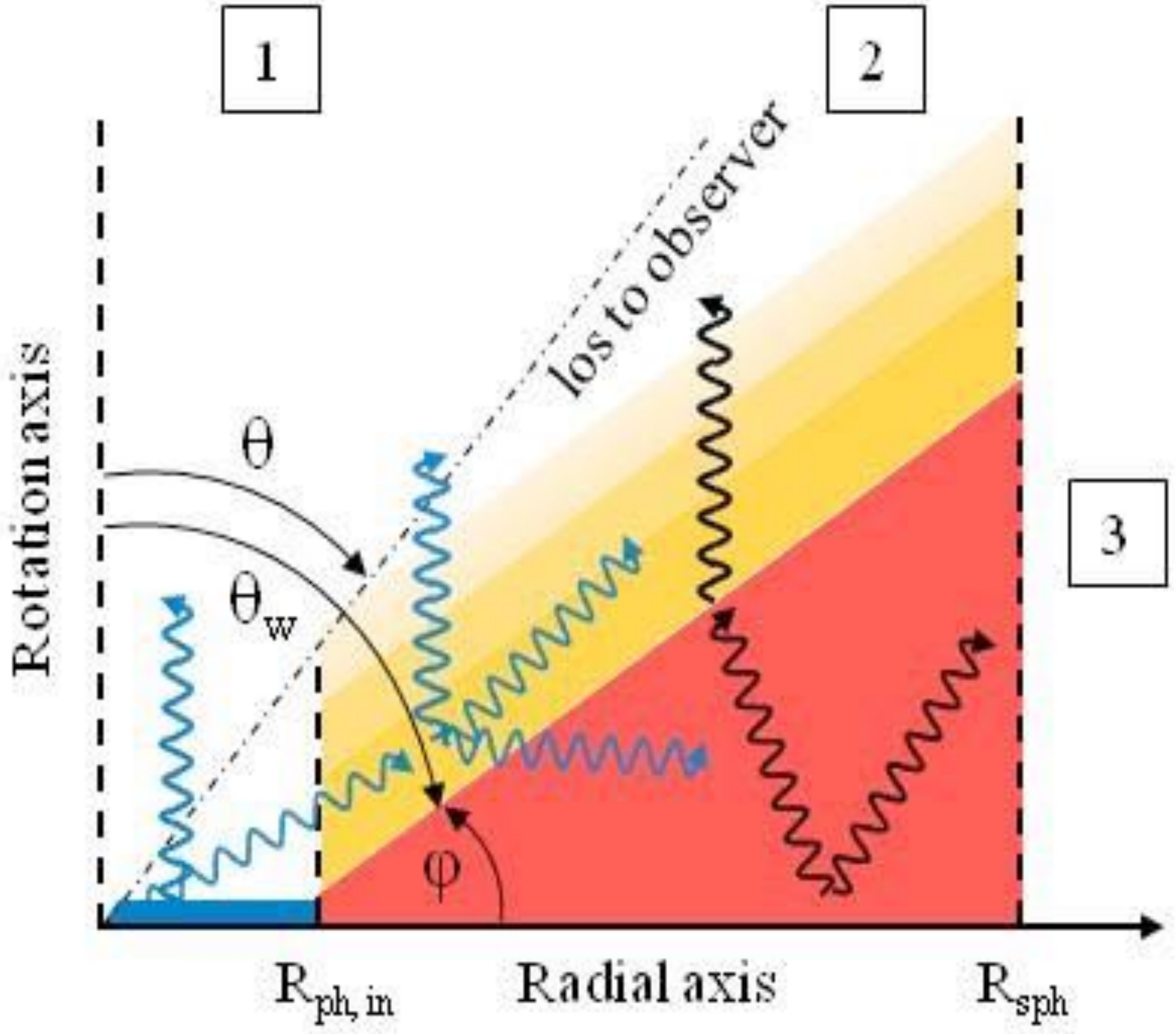
Mass loss keeps flow locally Eddington and leads to $Q_+ \propto R^{-2}$

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

Some of this will emerge as radiation, some will be used to power the outflow (see Poutanen et al. 2007) some can be advected



Dotan & Shaviv 2011



Middleton et al. (2015)

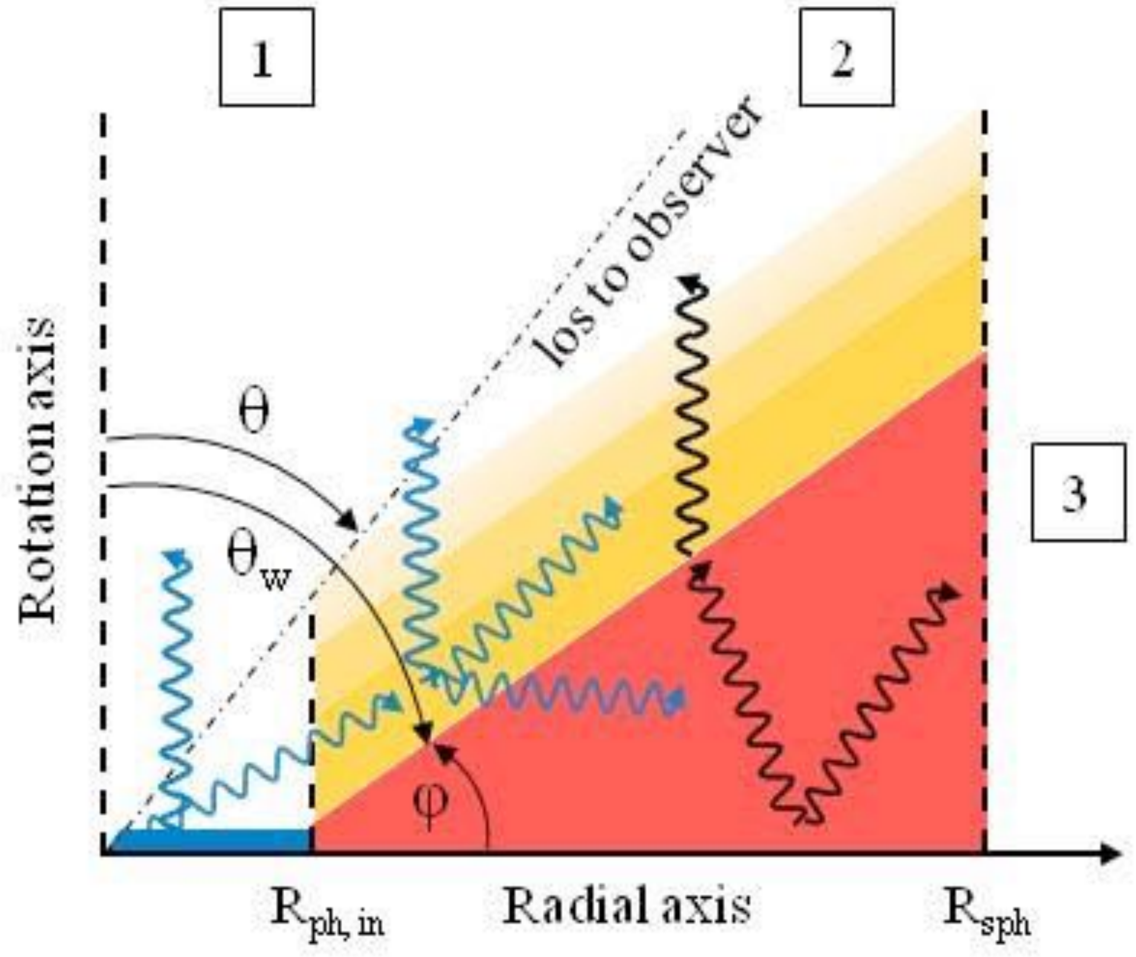
The radiation path isn't straightforward and will be scattered into and off the walls of the wind

Scattering leads to geometric (*not* relativistic) beaming (King 2009)

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

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

The energy spectrum should look roughly thermal with three regions (Poutanen et al. 2007)

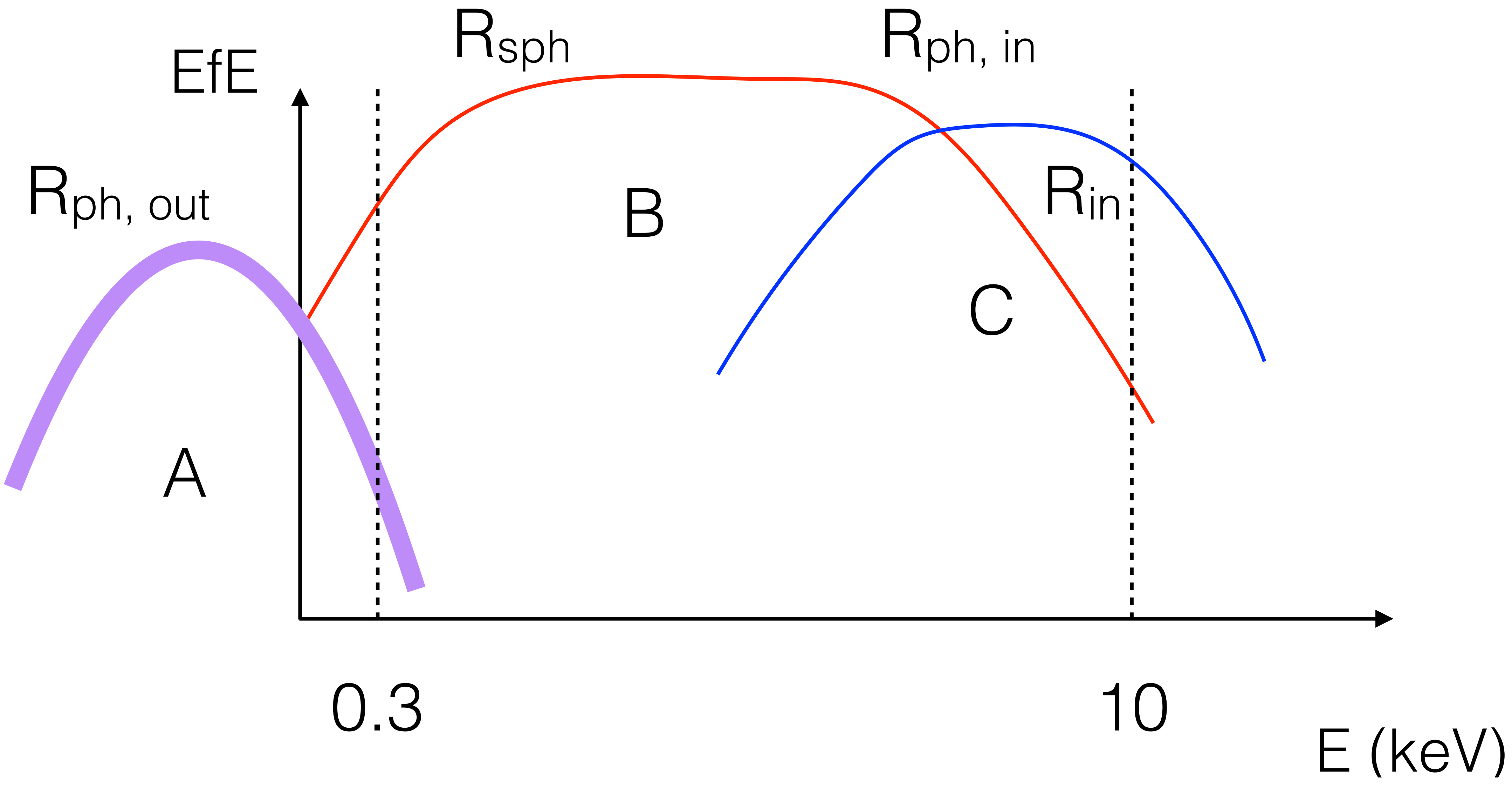


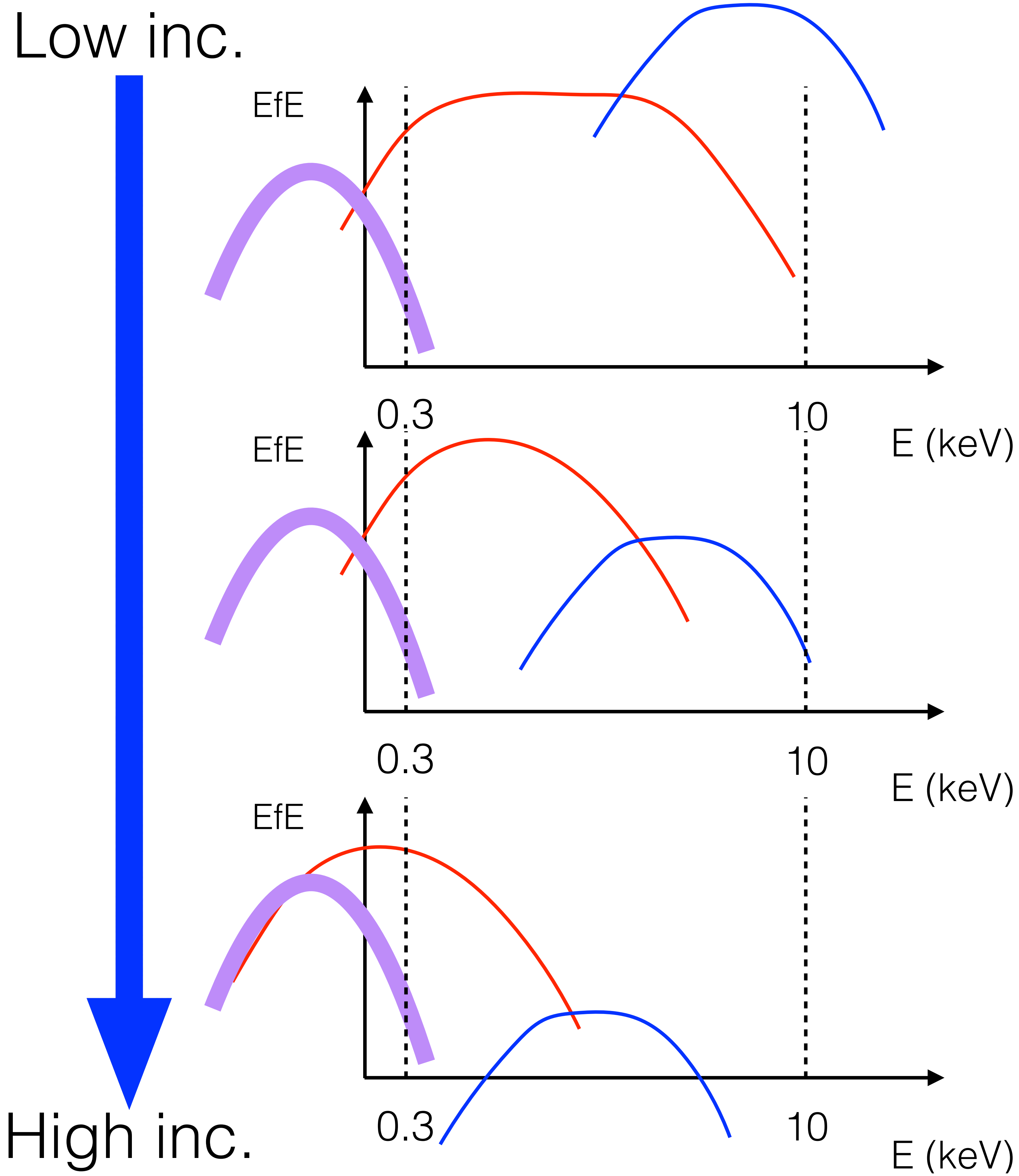
A: $R > R_{sph}$
'thin' disc, any emission may be affected by wind launched from smaller radii

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

C: $R_{in} < R < R_{ph,in}$
thick disc but the wind is optically thin so radiation escapes locally

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



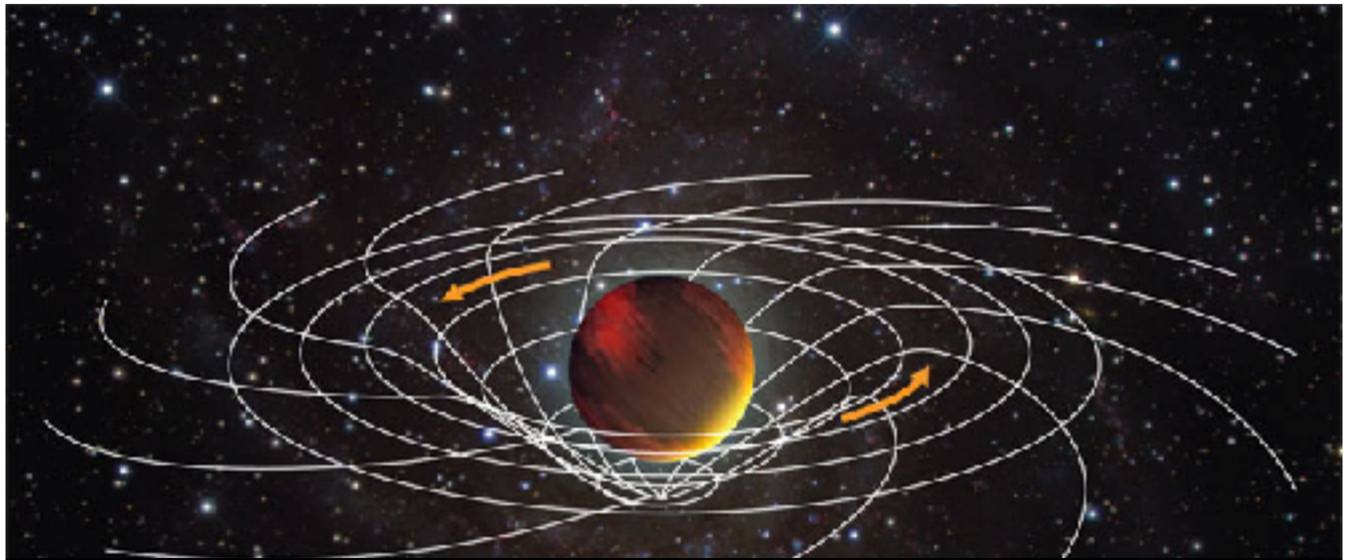


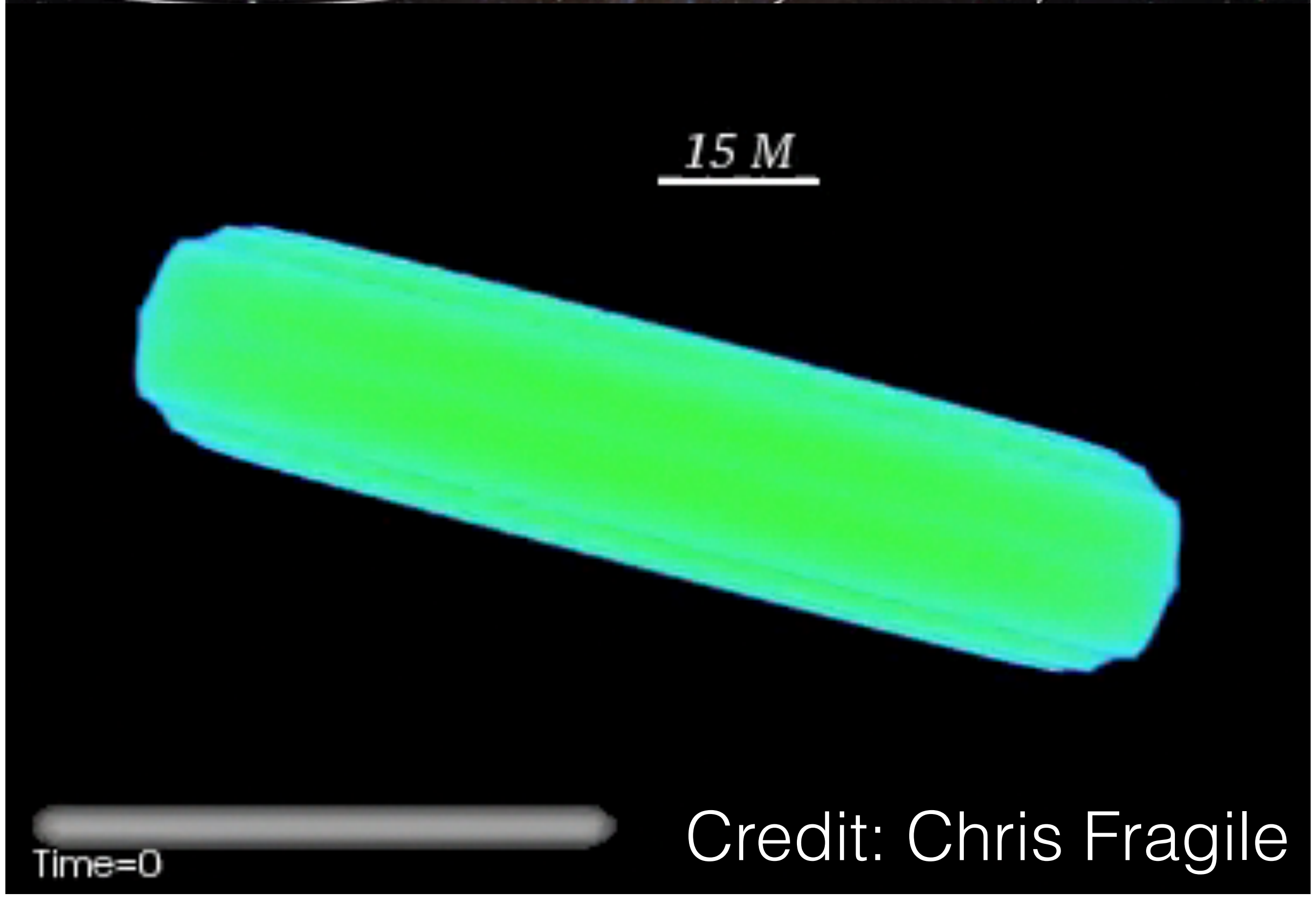
Important: the cooler outer regions ~isotropic and the inner-most regions most geometrically beamed

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

As the wind is clumpy it can also imprint itself on the variability and is a function of inclination (see Middleton et al. 2015)

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')

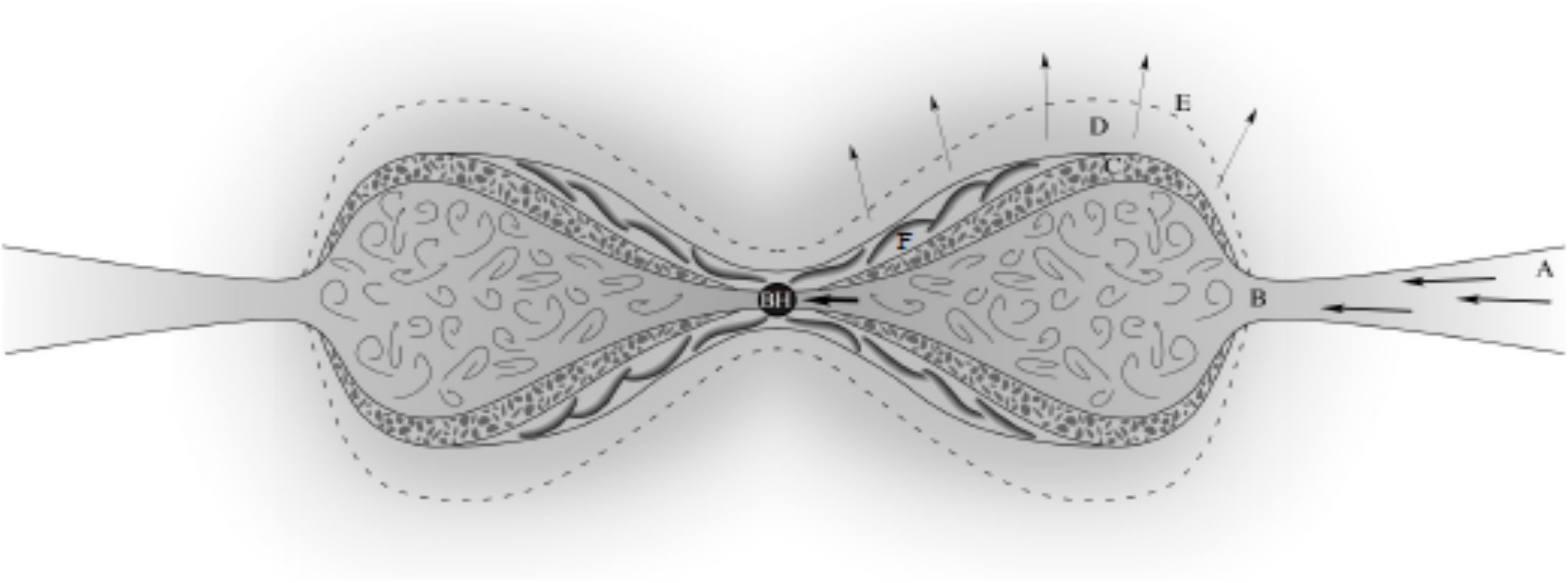
If the compact object's spin axis is tilted with respect to orbit then the frame-dragging induces vertical precession

Conditions that need to be met:

i) Misalignment — asymmetric SN

ii) α < H/R — H/R ~ 1

iii) $T_{prec} \sim T_{sound}$

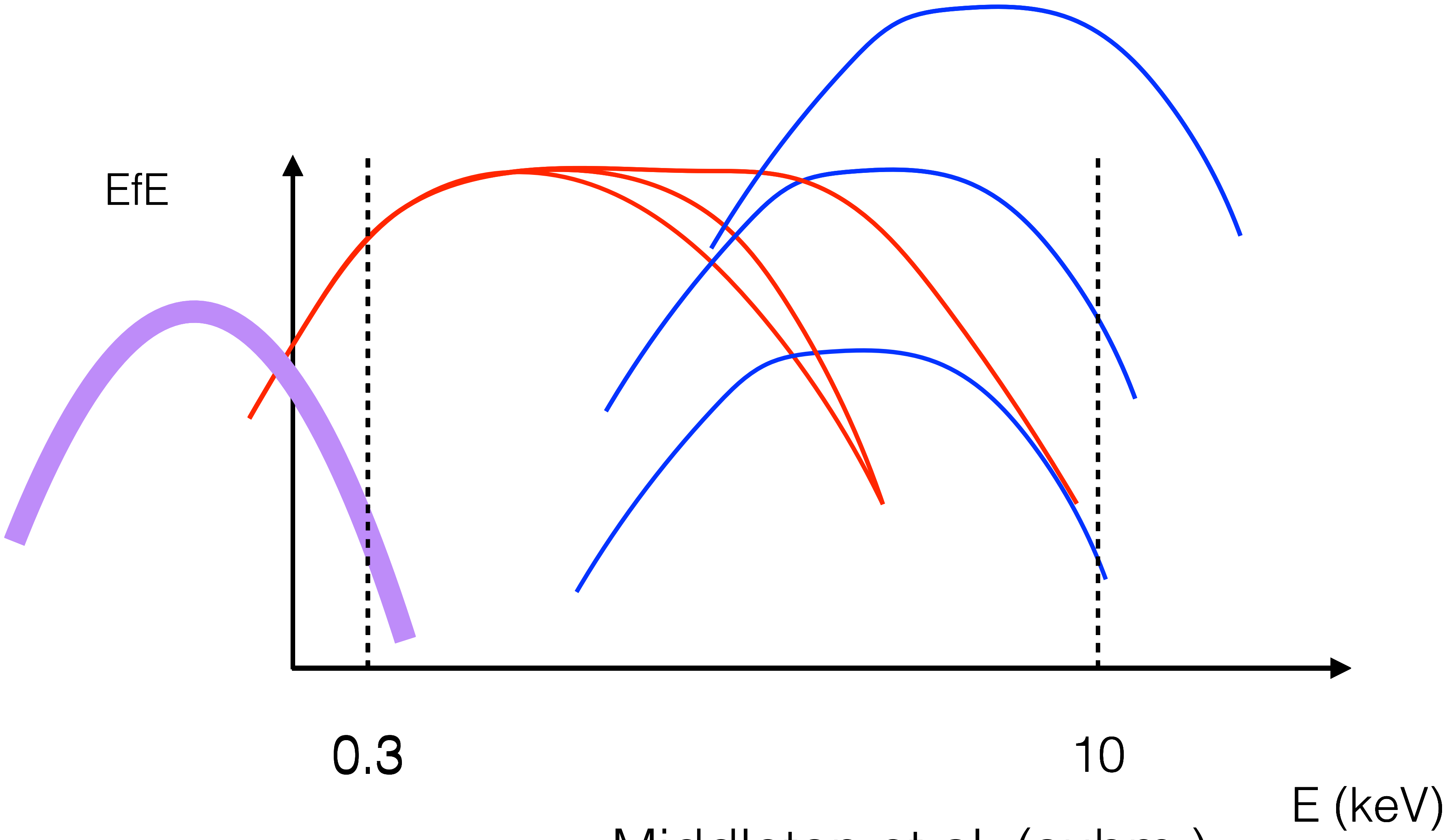


Inflow precesses as:

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

Where r_{in} is the disc inner edge (NB - doesn't have to be the ISCO)

What would this precession 'look' like?



Middleton et al. (subm.)

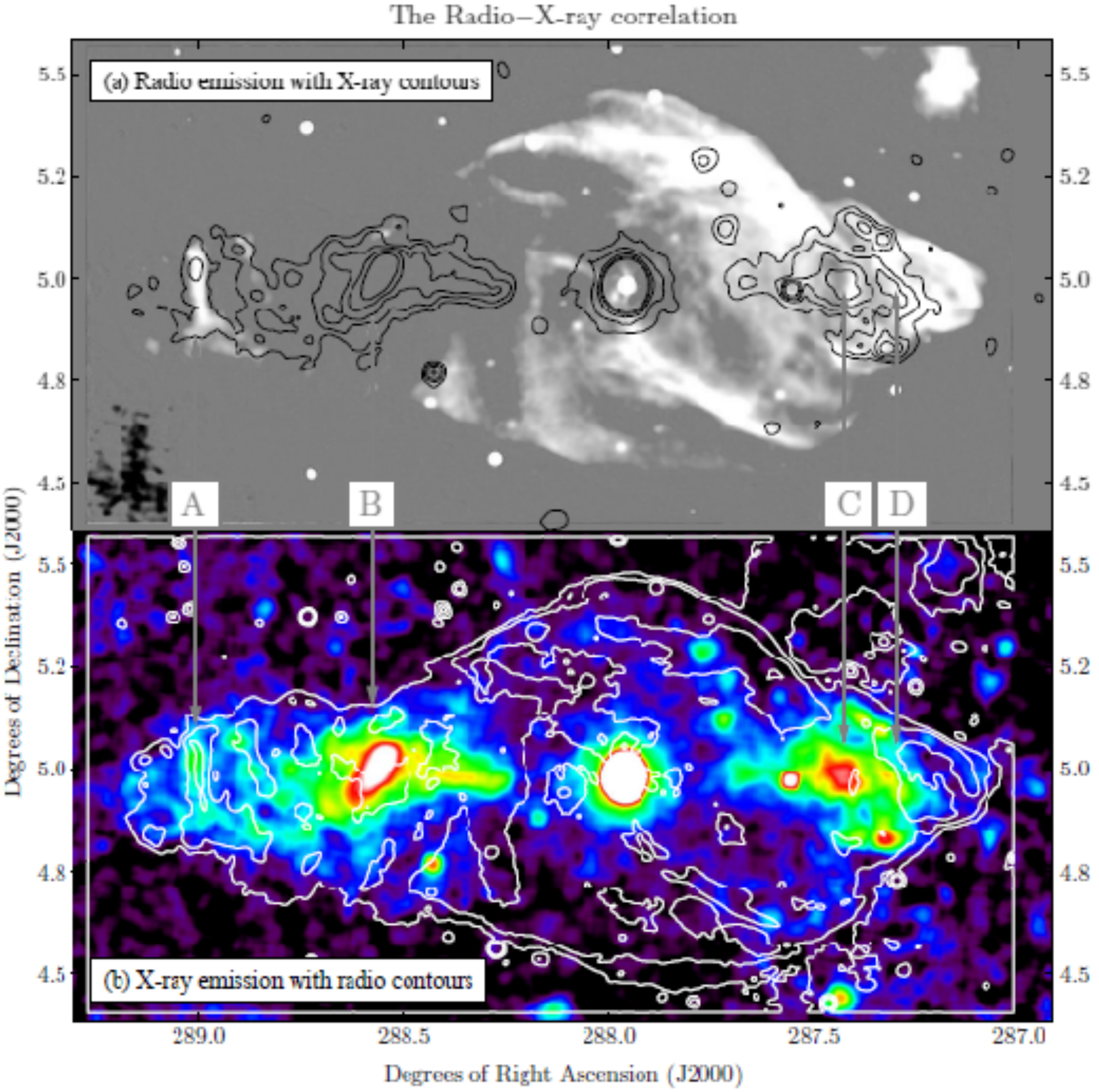
Wind should *also* precess due to inflow precessing but *slower* due to conservation of **J**. Observationally this is relevant out to some radius at which point it no longer obscures the inner regions

$$P_{prec} = \frac{GM\pi}{3c^3 a_*} r_{sph}^3 \left[\frac{1-\left(\frac{r_{in}}{r_{sph}}\right)^3}{ln\left(\frac{r_{sph}}{r_{in}}\right)}\right] \times \boxed{\left(\frac{r_{out}}{r_{sph}}\right)^2}$$

Middleton et al. (2018)

$r_{out} >> r_{sph}$ so if the flow precesses on ~10s of seconds, wind precesses on ~days to 10s of days

Enough theory - what do we see and how does this measure up to expectation?



Good place to start is in our own backyard

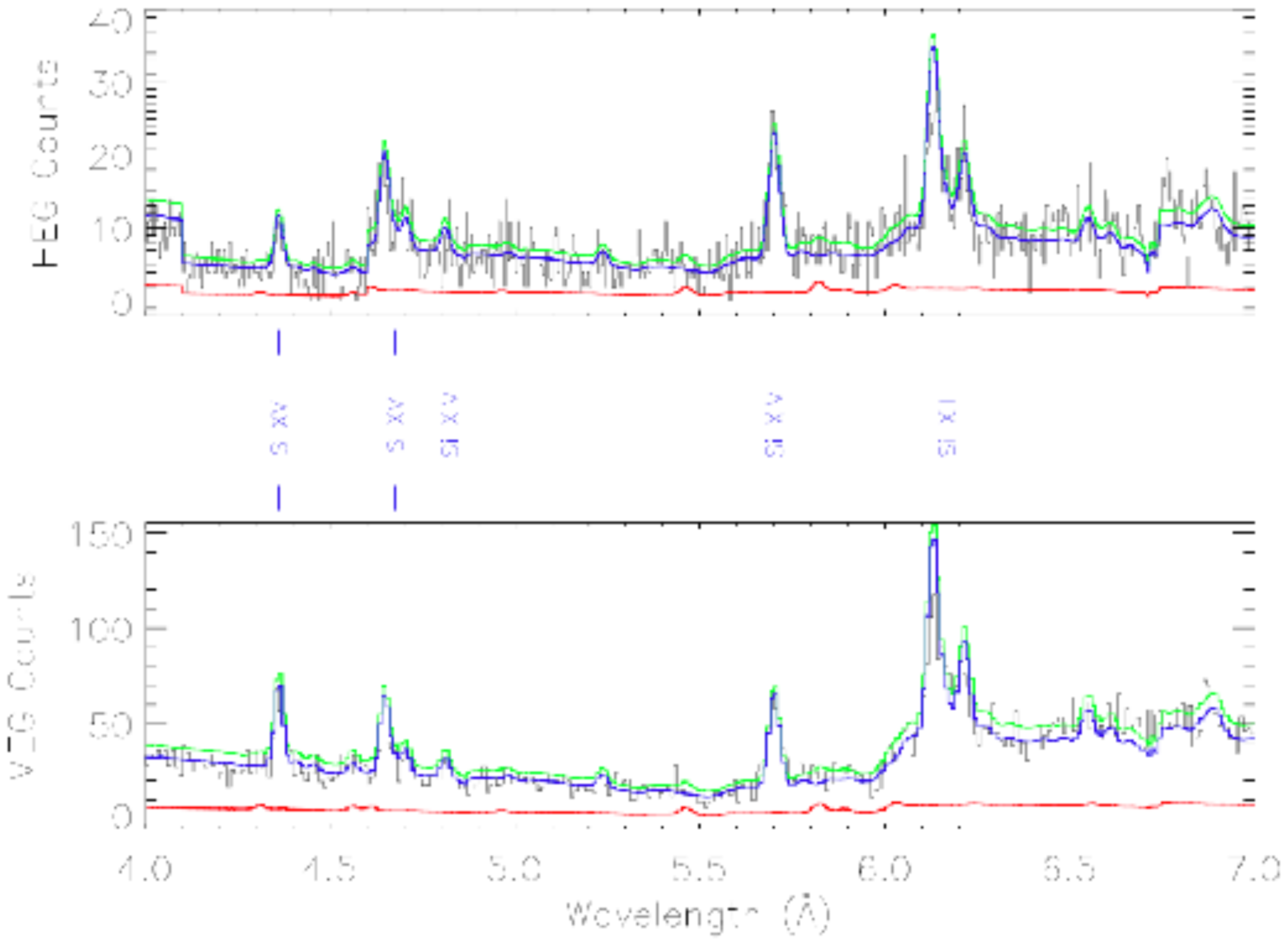
SS433 (W50)

~5kpc away

X-ray faint (<10^{36} erg/s)

Outflows inflating surrounding nebula (W50), 100s of pc across

Baryon jets - revealed through optical/X-ray studies

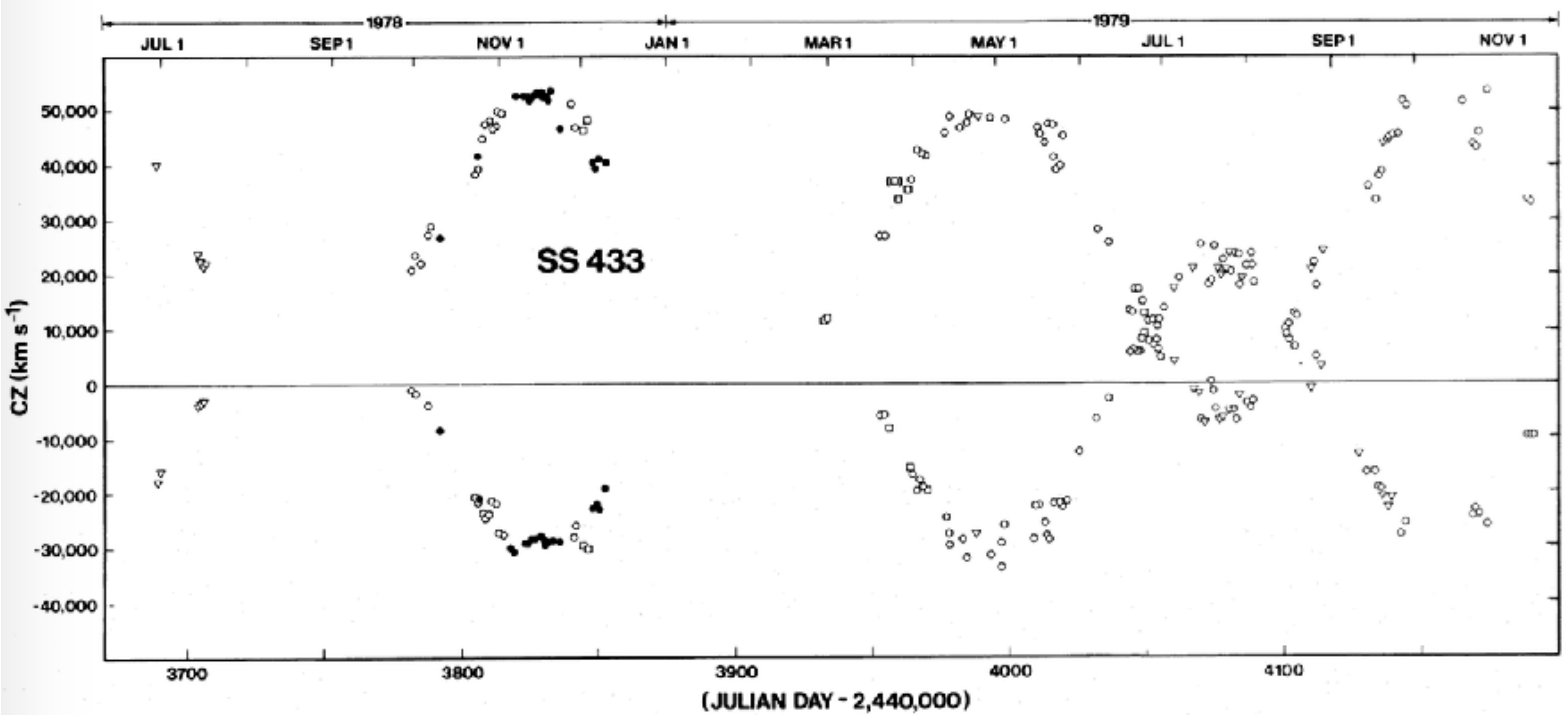


Marshall et al. (2002)

Mass loss measured in the jet ~10^{-7} M⊙/yr

Mass loss measured in the wind ~10^{-4} M⊙/yr

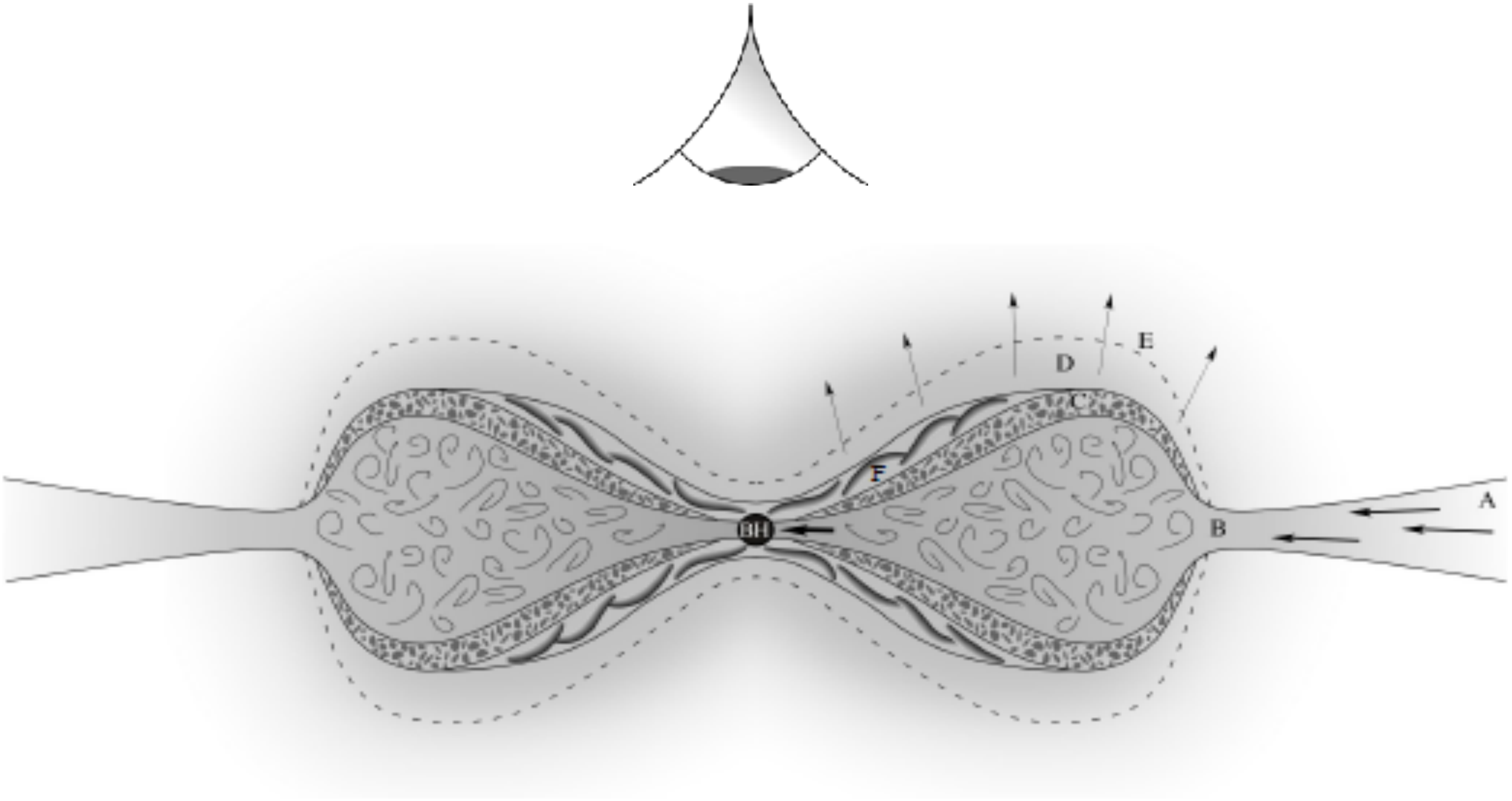
Bona fide super-critical source



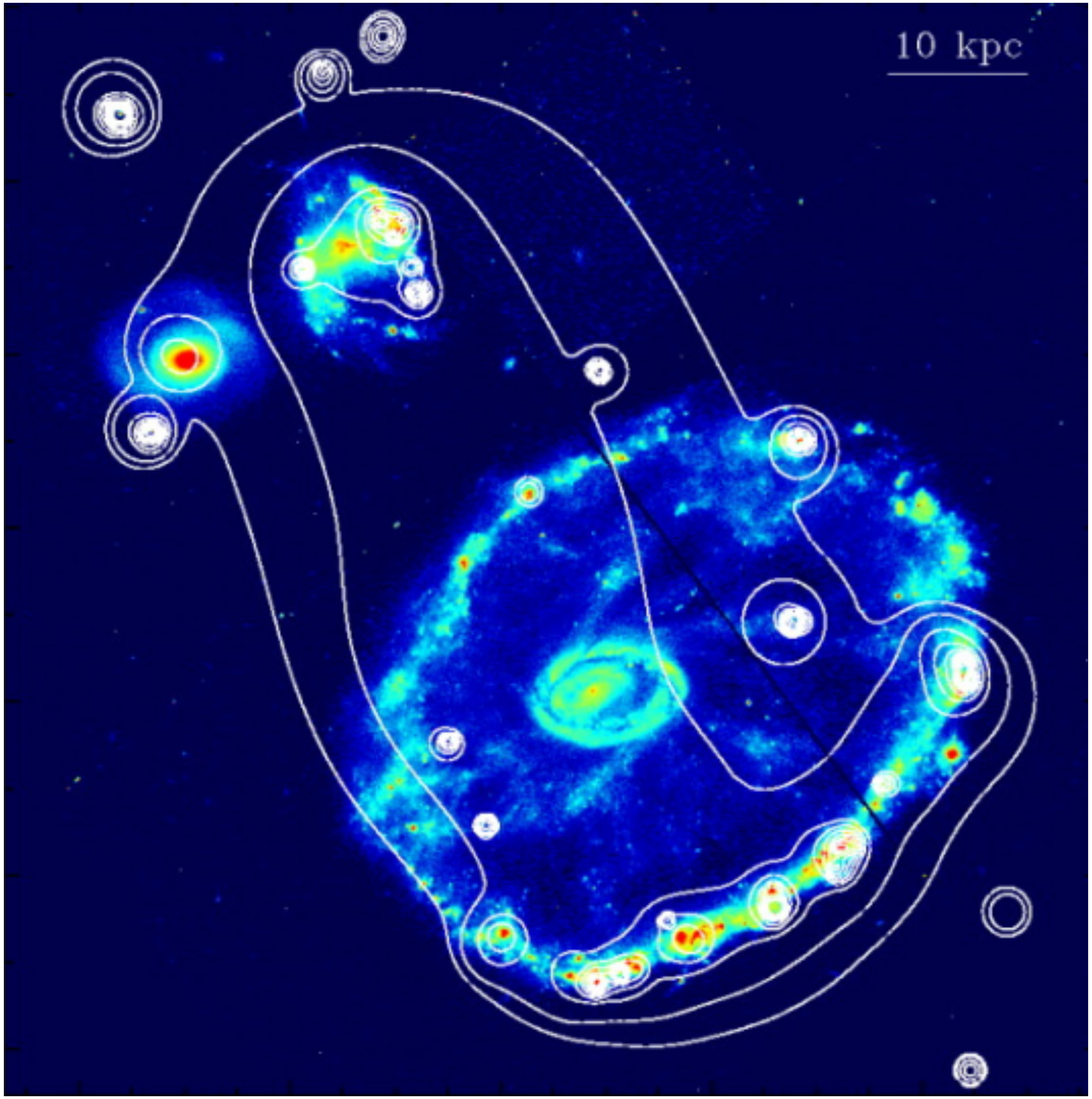
Margon et al. (1980)

The red/blue Doppler shifts of emission lines change in a periodic fashion indicating precession on a period of ~162 days - not LT in this case but tidal

So why do we not see bright X-ray emission?



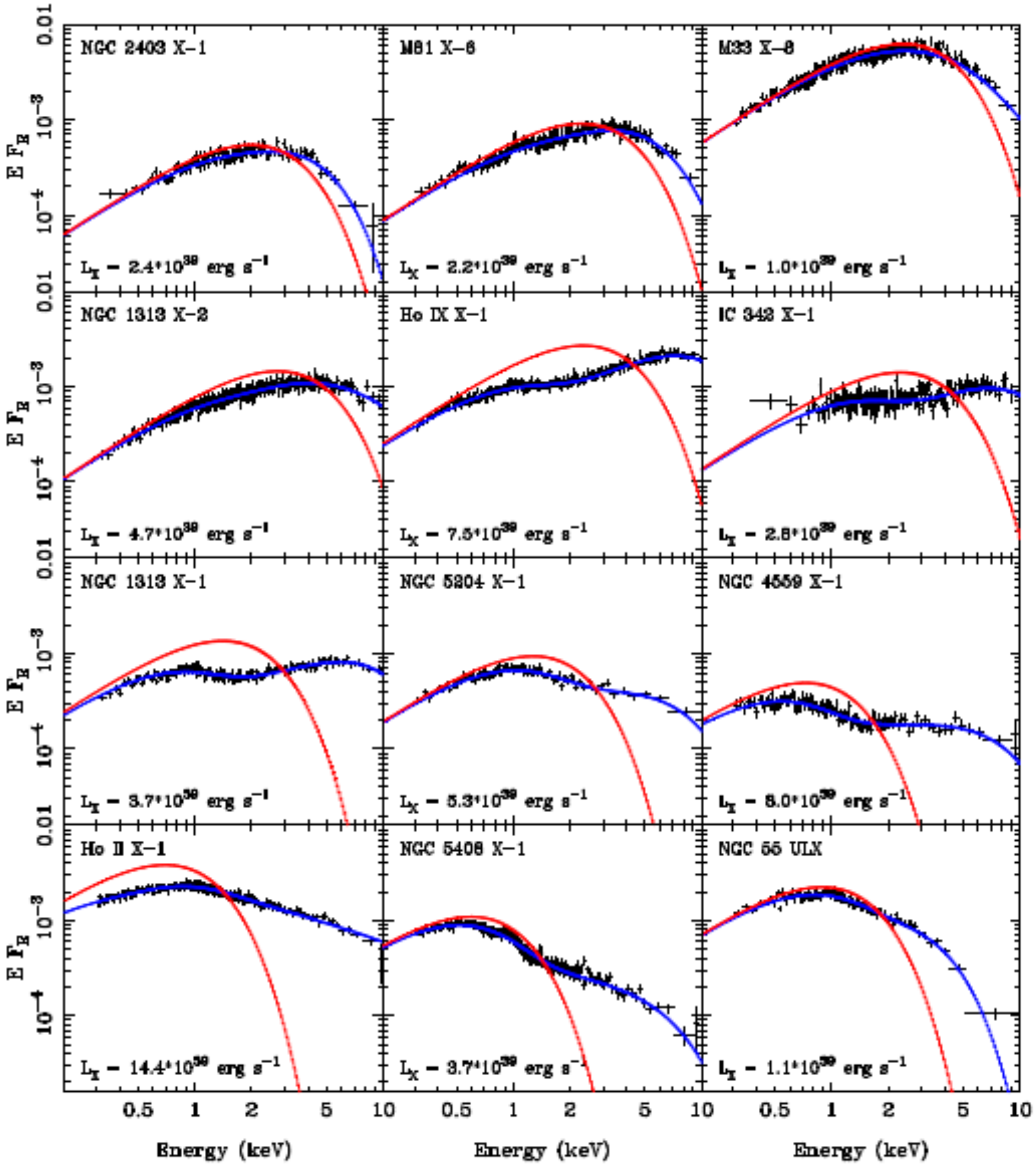
As our Galaxy is pretty normal, shouldn’t we see these types of systems elsewhere but **face-on**? What would they look like?



Ultraluminous X-ray sources (ULXs) which are defined **empirically** as $L_{obs} > 1\text{x}10^{39}$ erg/s

Often associated with star forming regions (e.g. Cartwheel Galaxy)

Typically we *observe* ~1 per galaxy - found in (mostly) spirals and ellipticals

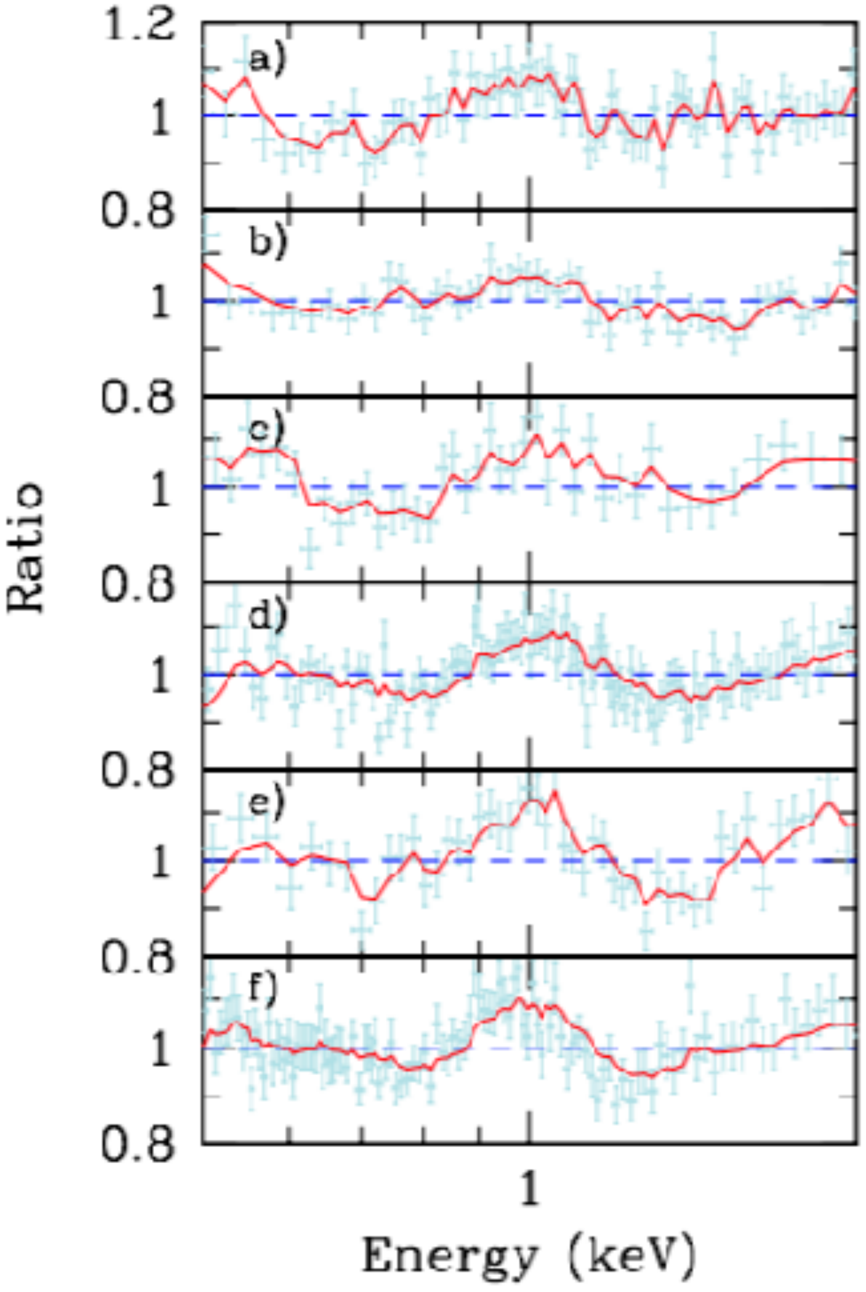


Gladstone et al. (2006)

By definition we see X-ray emission so we should be seeing towards the central engine

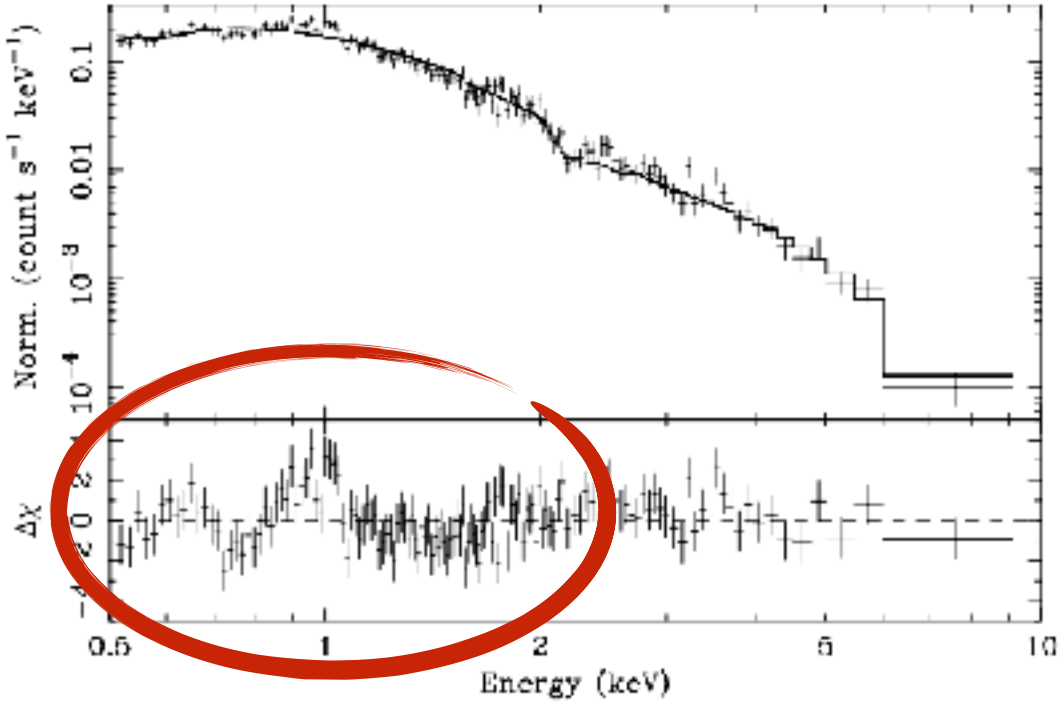
We see the ‘right’ sort of shapes that we might expect from a super-critical flow for objects at a range of inclinations (but not at v high inclinations)

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



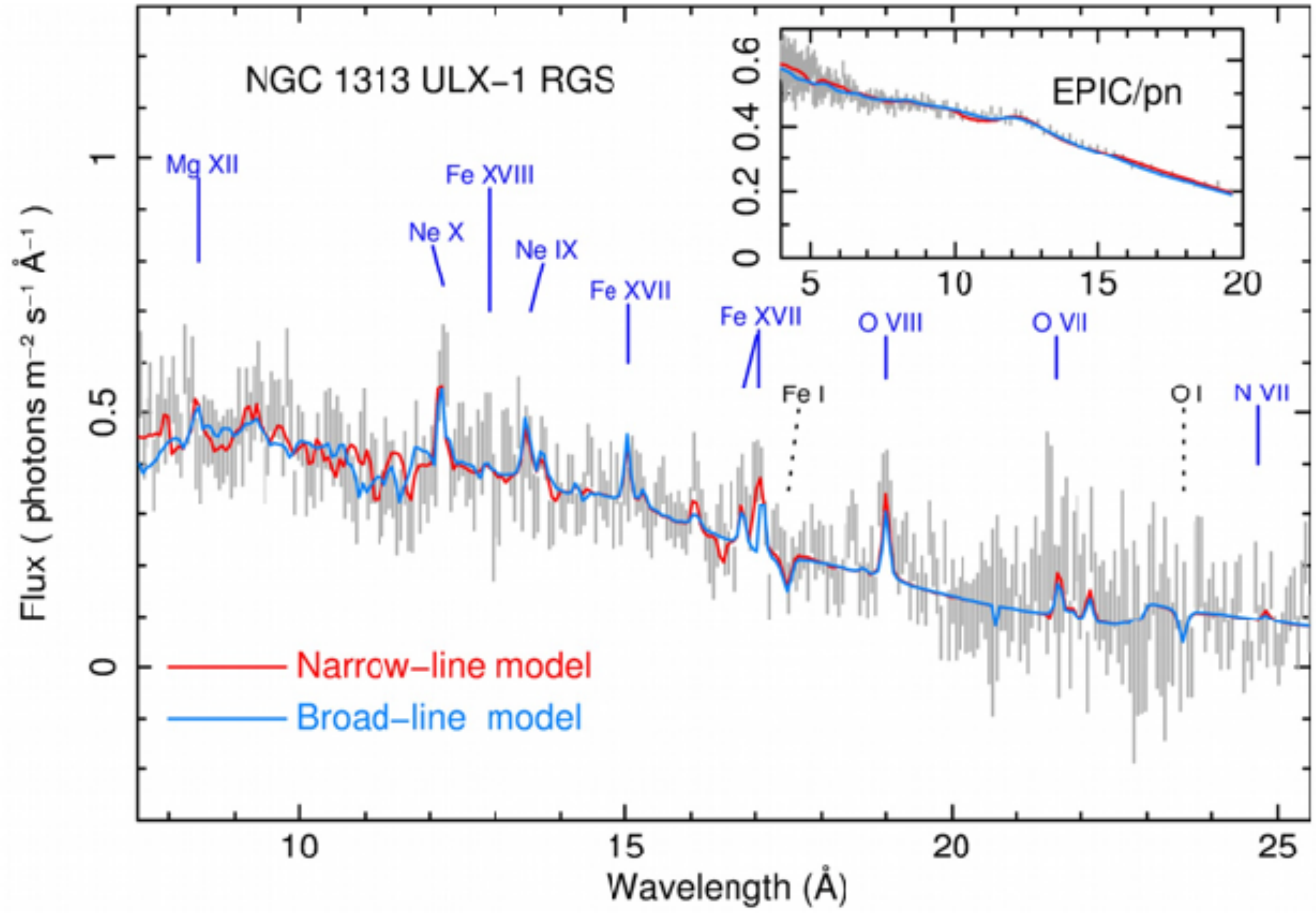
Middleton et al. (2015)

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)

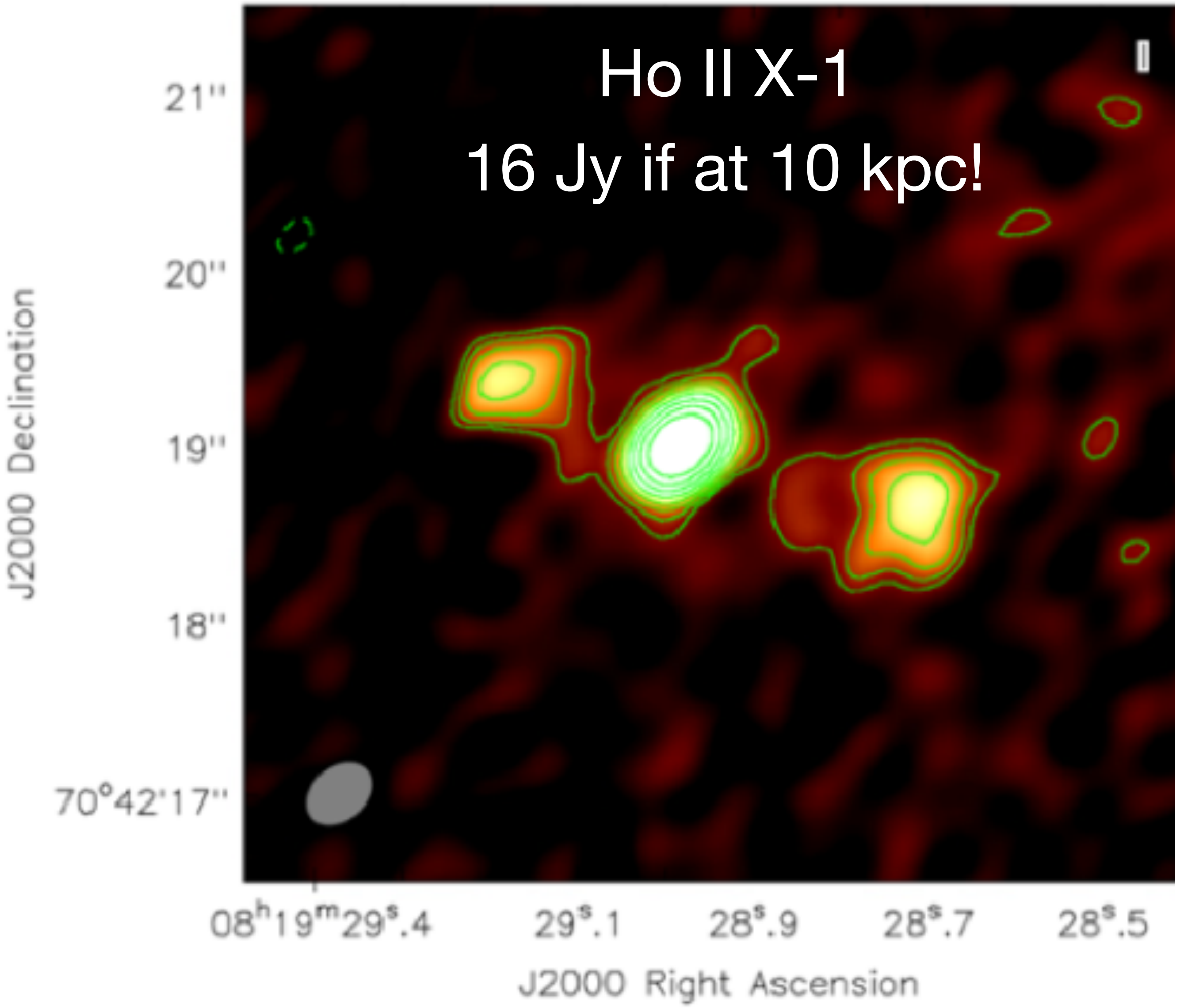
$v = -0.2c$

$N_H \sim 1\times10^{24}$ cm^{-2}

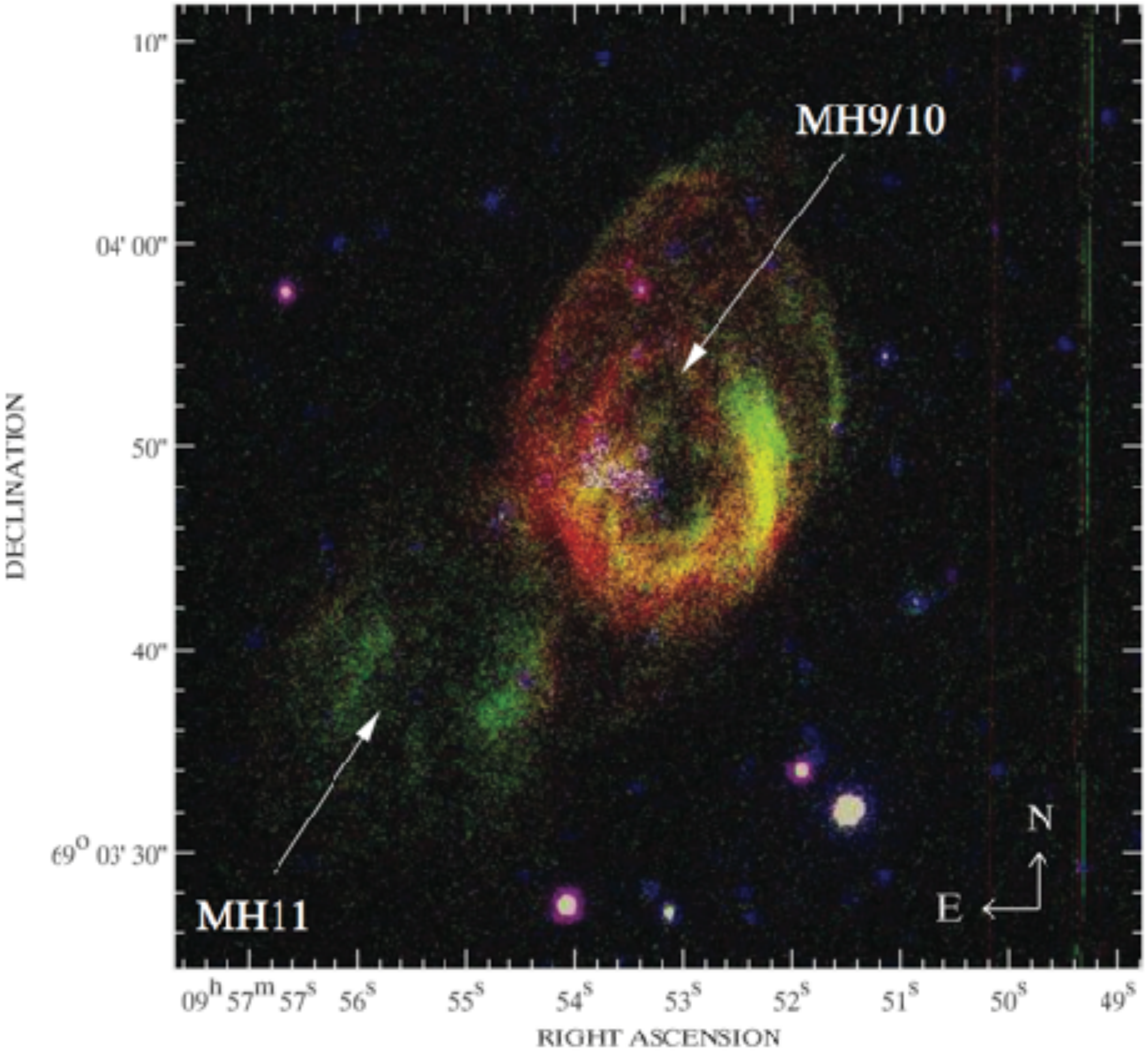
$\log \xi \sim 3\text{-}4$

Emission lines likely associated with collisionally excited plasma

Clearly not just winds but more discrete ejections also occur

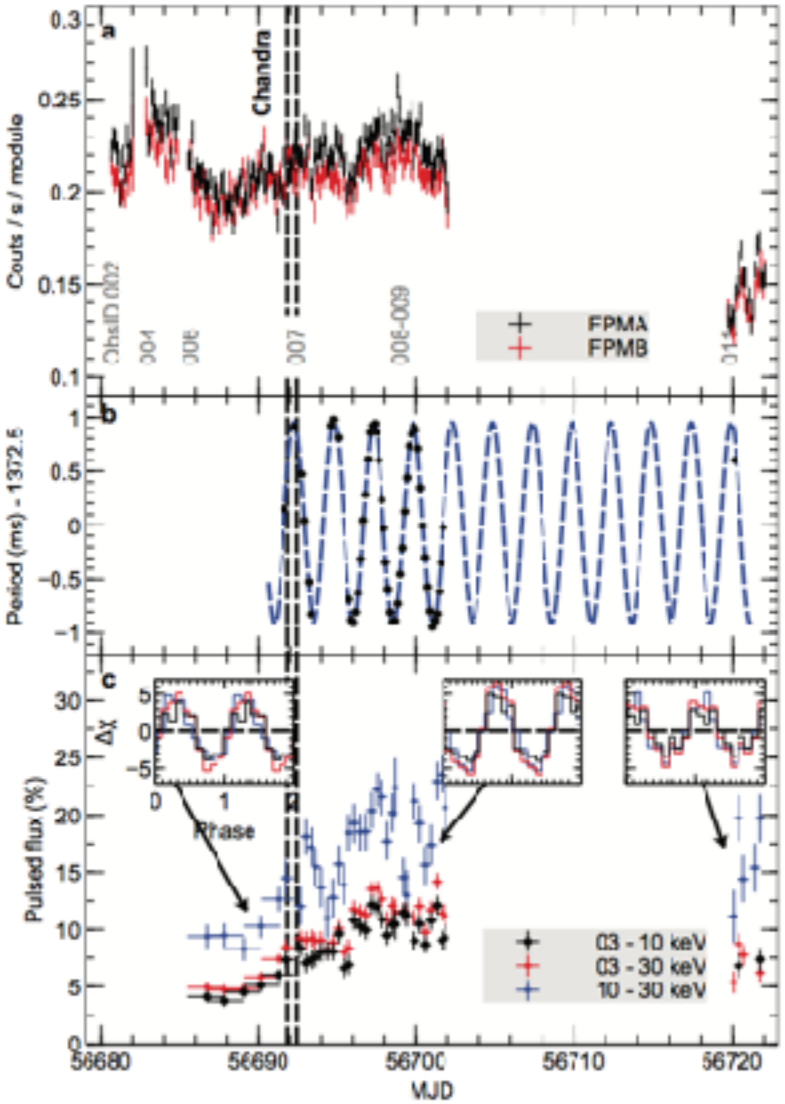


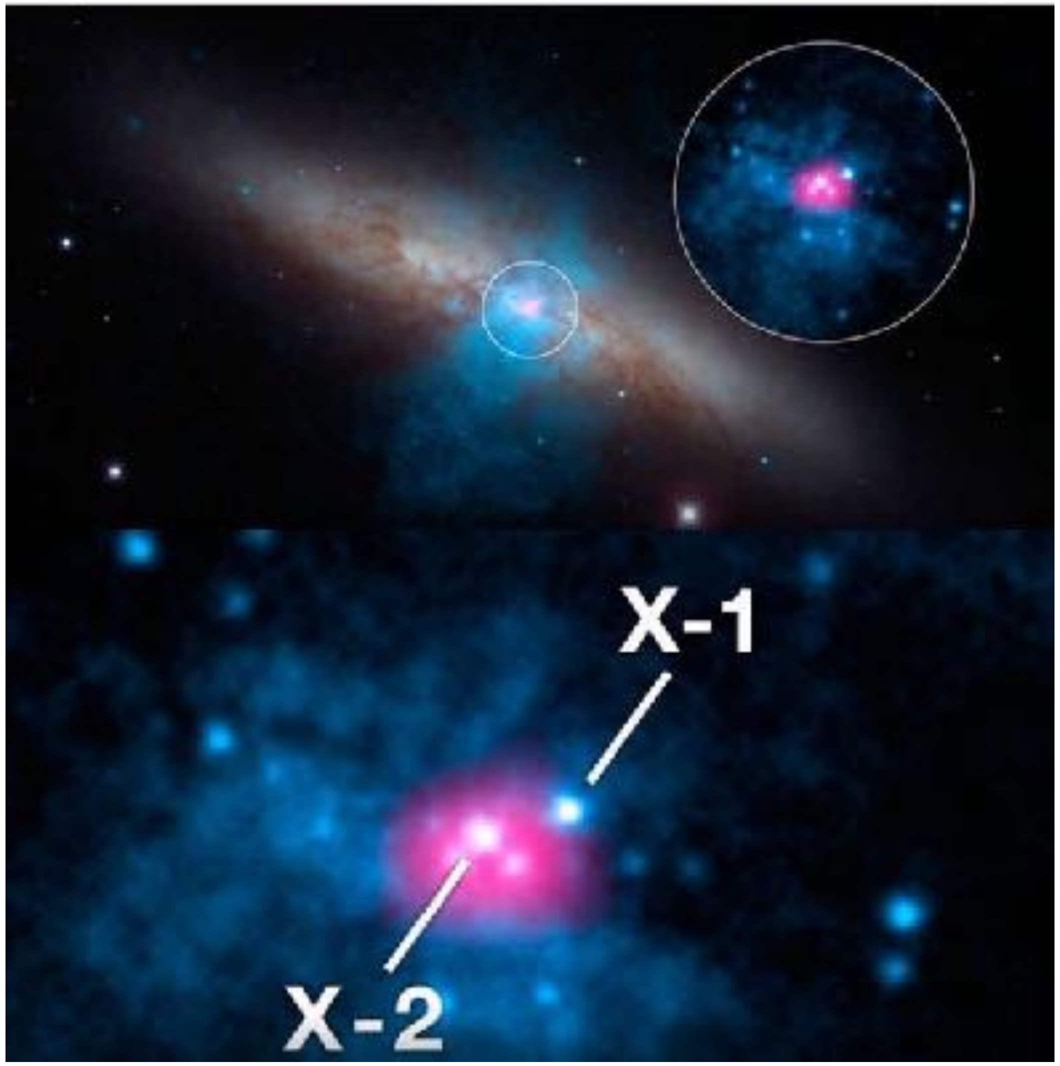
Cseh et al. (2014, 2015)



Grise et al. (2011)

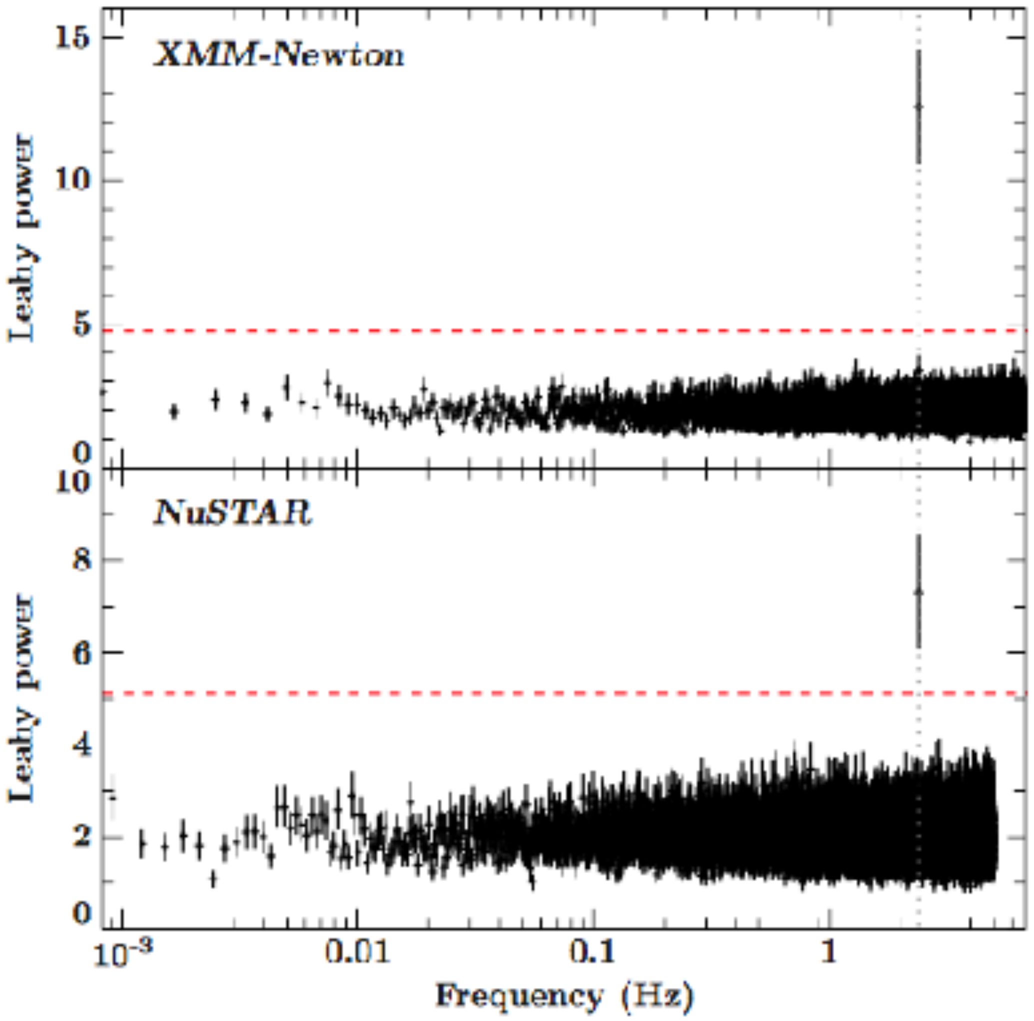
For a long time we *assumed* that ULXs contained stellar mass BHs though there was no reason to (King 2001), after all the secondary star does not know about the primary (caveat: stellar evolution)…..the discovery of ULPs





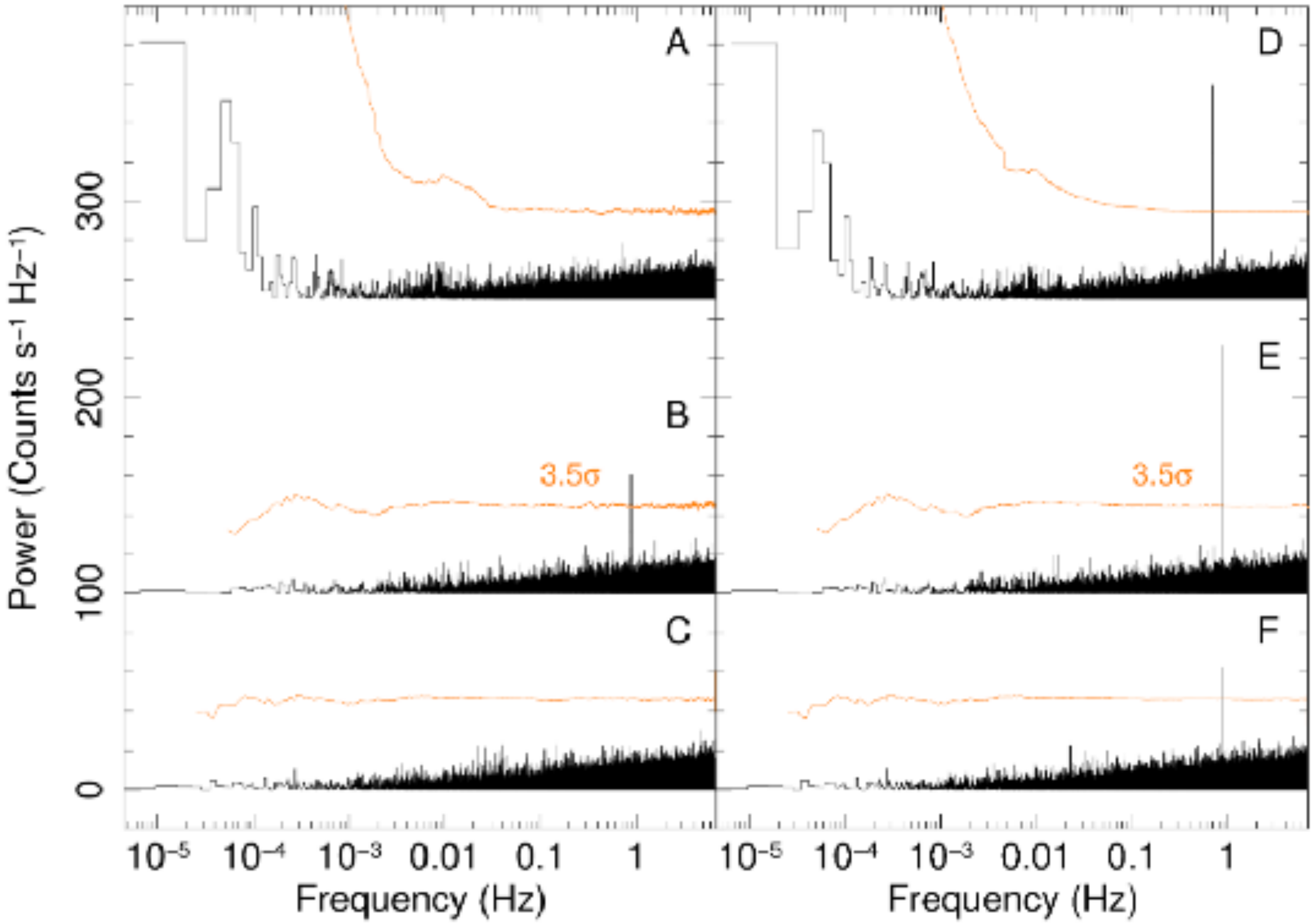
Bachetti et al. (2014)

NGC 7793 P13



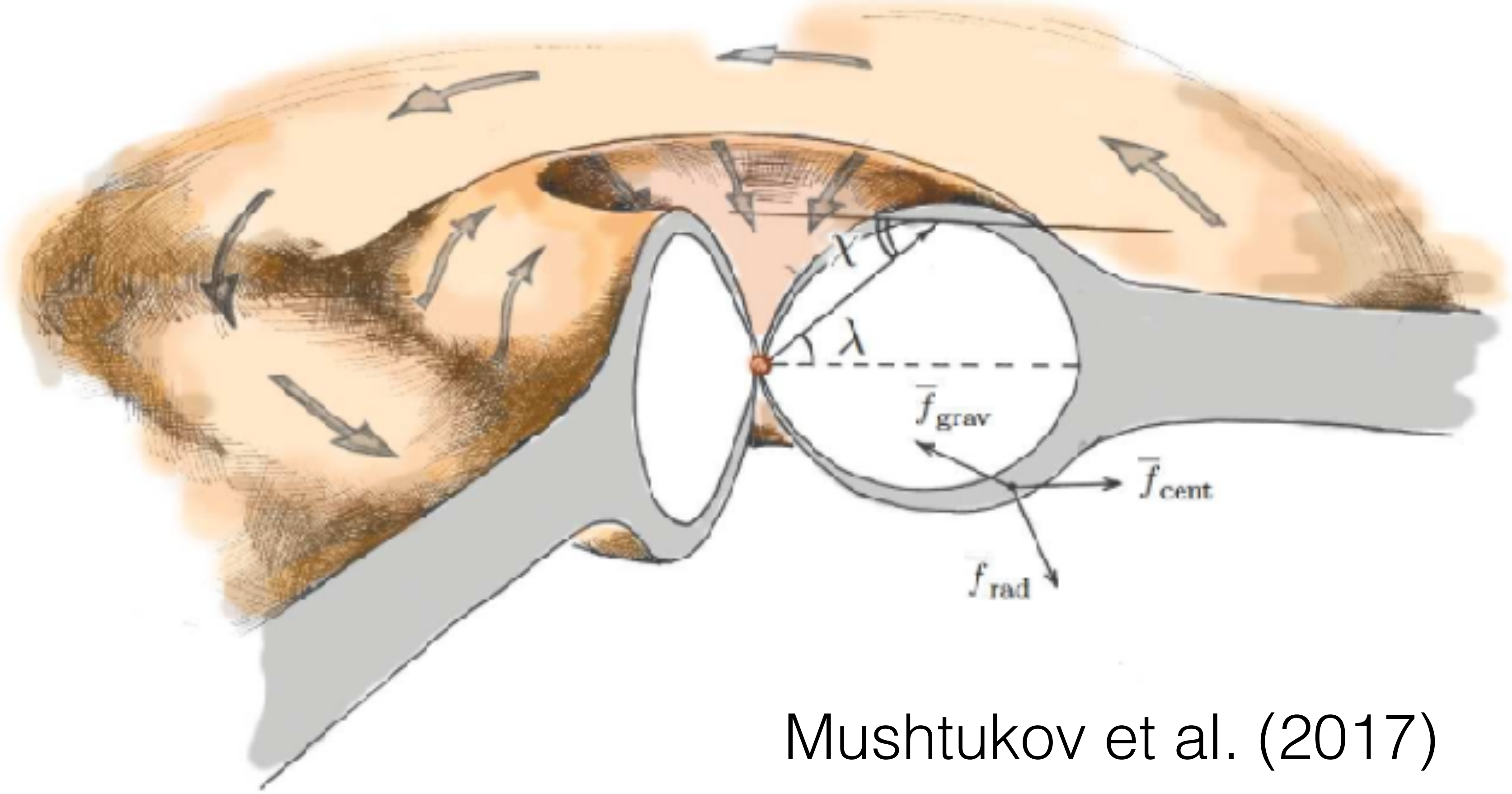
Fuerst et al. (2016)

NGC 5907 ULX-1



Israel et al. (2017)

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 (magnetar).

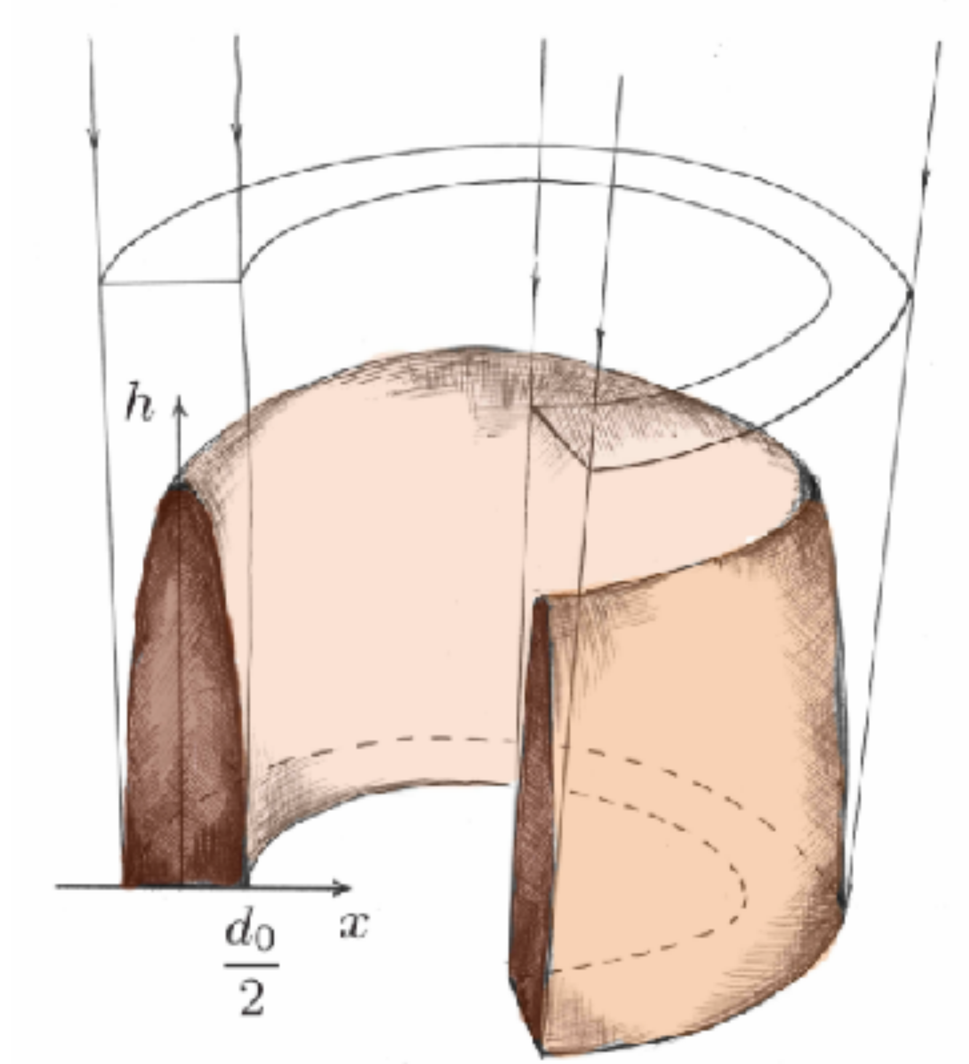


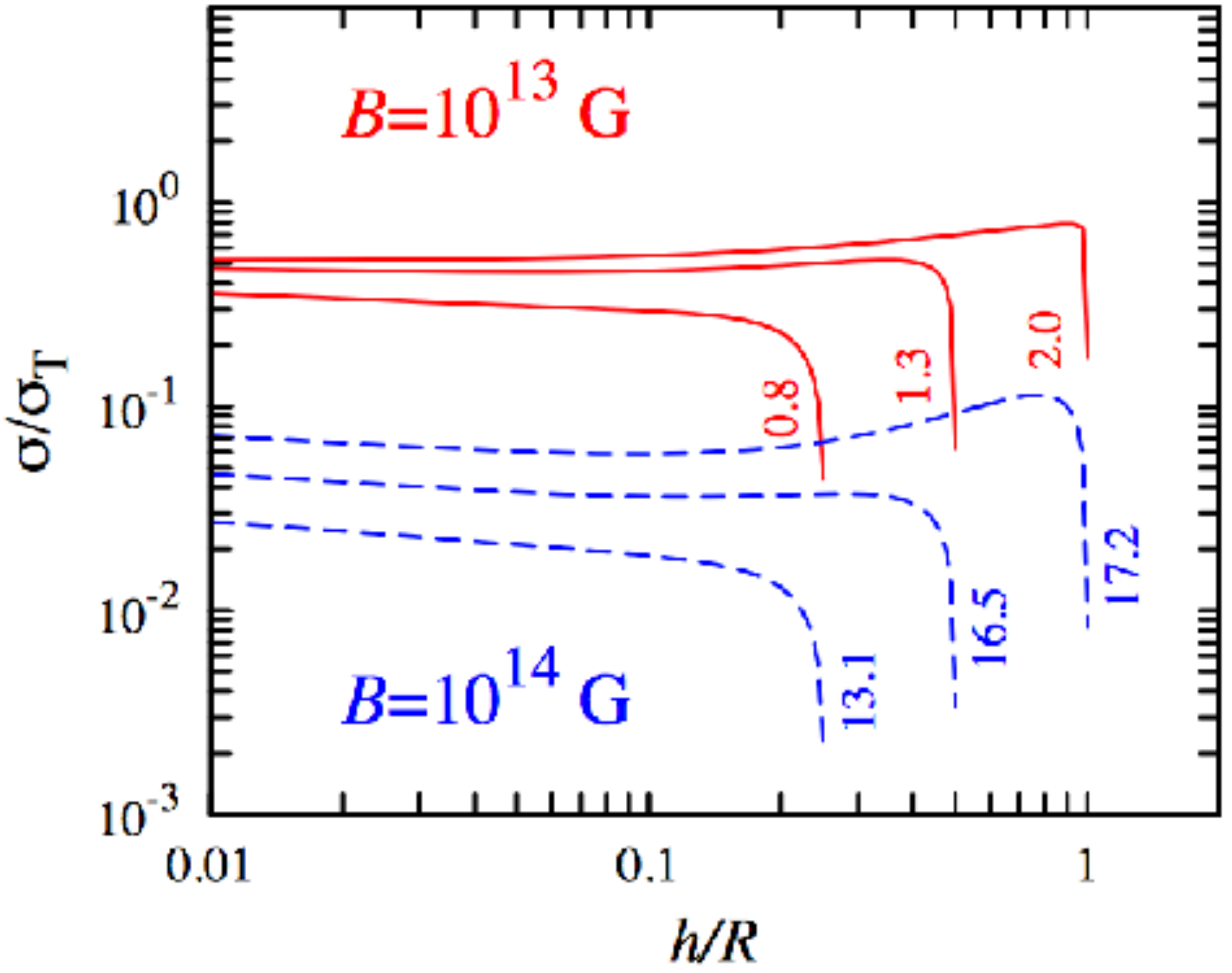
Mushtukov et al. (2017)

If B > 10^{13} G then it may truncate **before** r_{sph} is reached

In which case then we have *no* expectation for radiatively powered relativistic winds

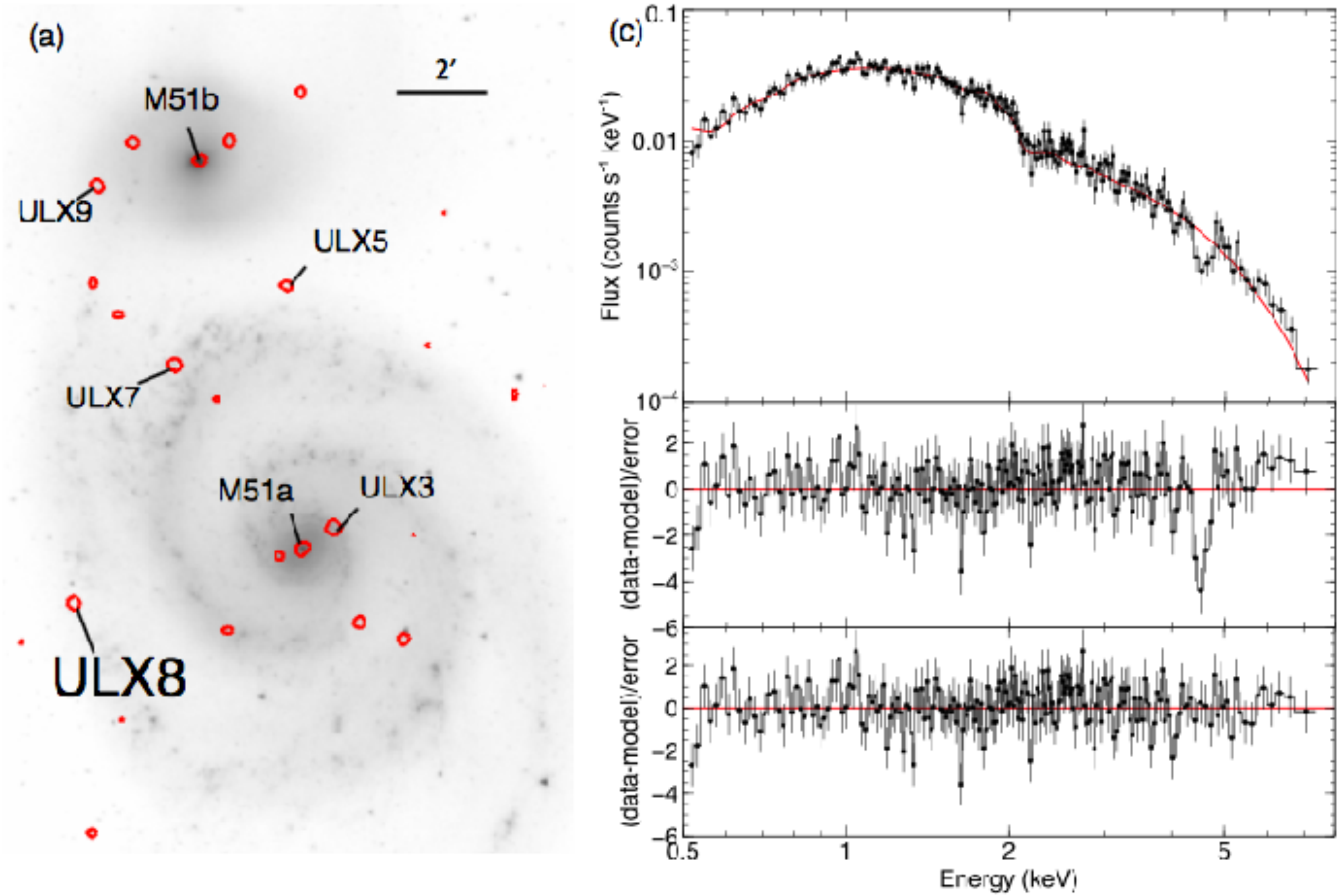
In either case, the observed rate of spin-up (e.g. $-3\text{x}10^{-11}$s/s: Fuerst et al. 2016) demands a large accretion torque and super-Eddington accretion rate **onto** the NS itself. This is ok as the structure of the column can accommodate such rates





Mushtukov et al. (2015)

Getting an *unambiguous* estimate of the field strength is clearly important - we ideally want to find a CRSF

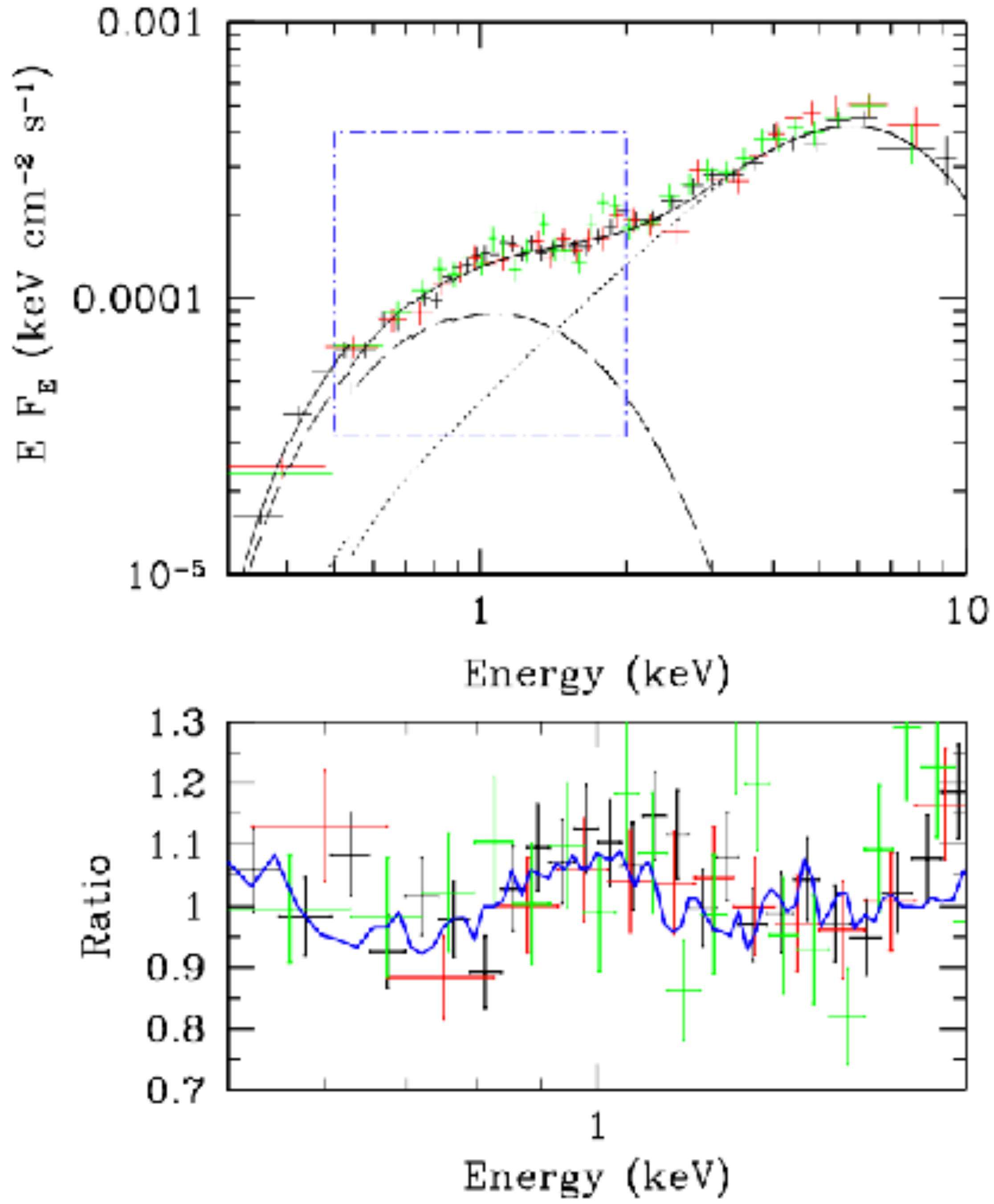


Brightman et al. (2018)

Is it a proton line ($B \sim 10^{14}$ G) or an electron line ($B \sim 10^{12}$ G)?

Is the measured field the dipole (so relevant for the disc structure) or higher order multipole?

We could also look for outflows….

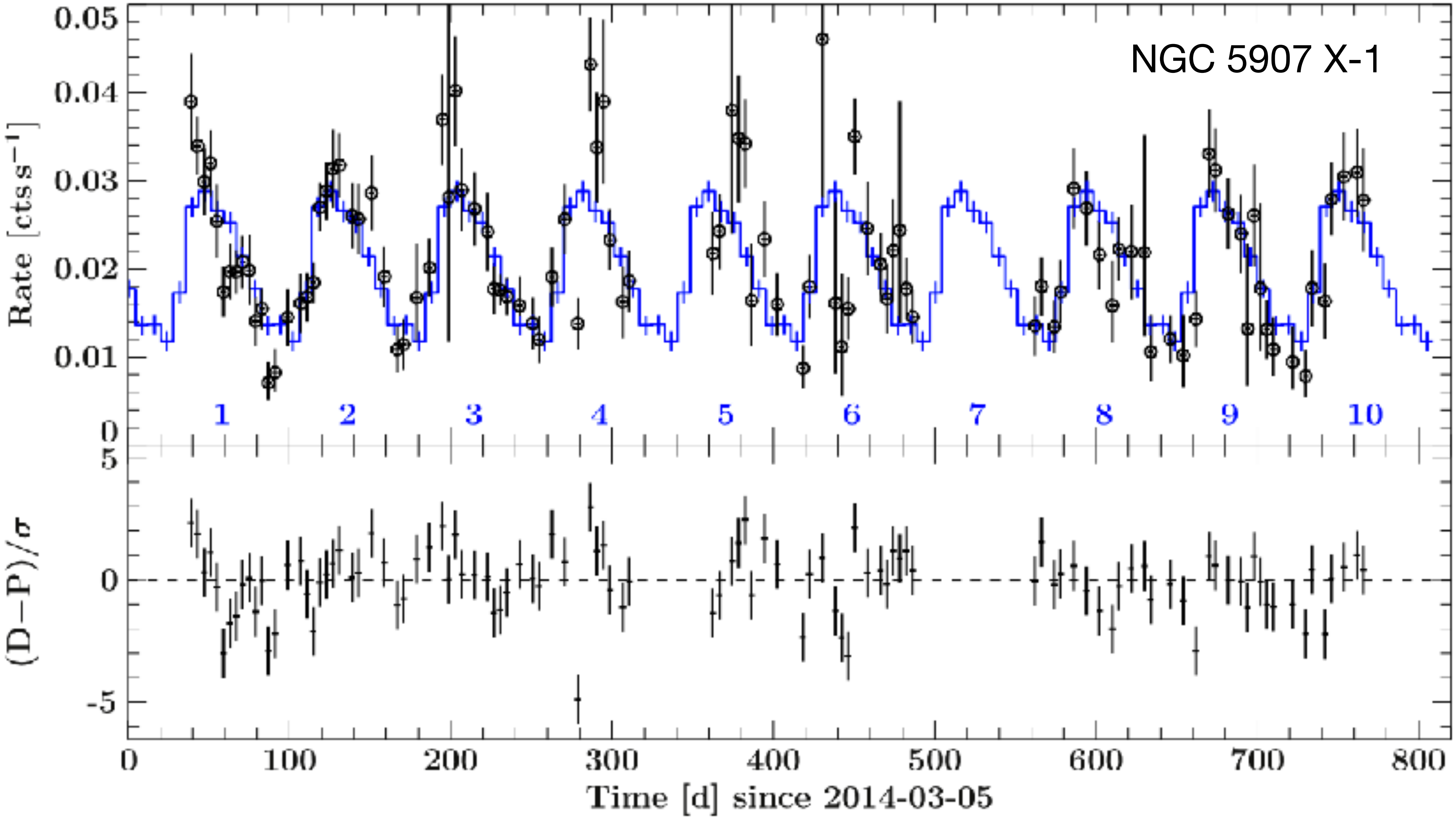


Middleton et al. (2018)

Tentative indications of an outflow in NGC 7792 P13

In the picture where $r_{sph} > r_m$ most ULPs need to be ~ face-on to see the pulsation so the covering fraction of the wind is small and imprint is weak

An increasing number of ULX systems (including ULPs) show super-orbital periods on timescales of ~10s-100 days:



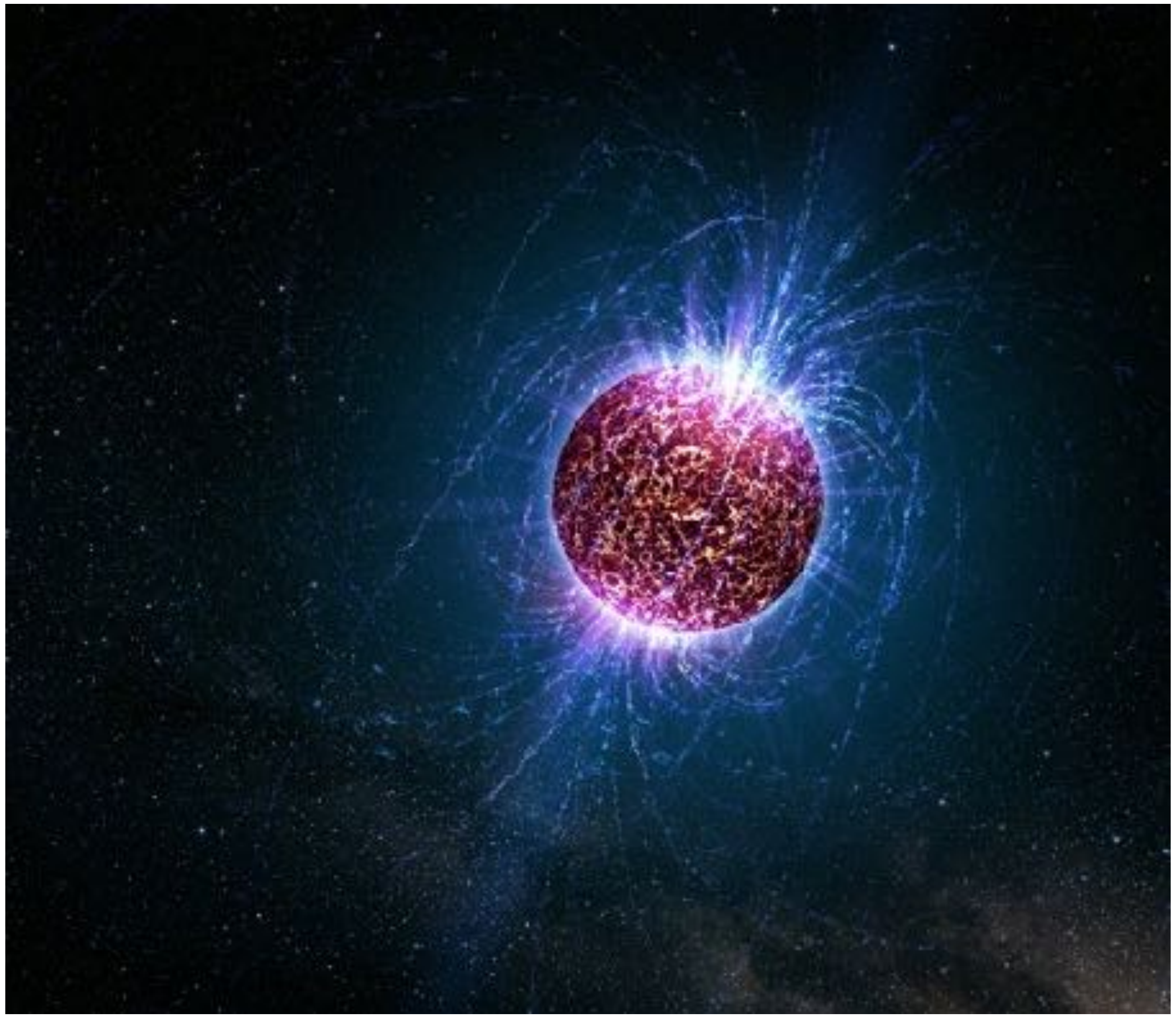
Walton et al. (2016)

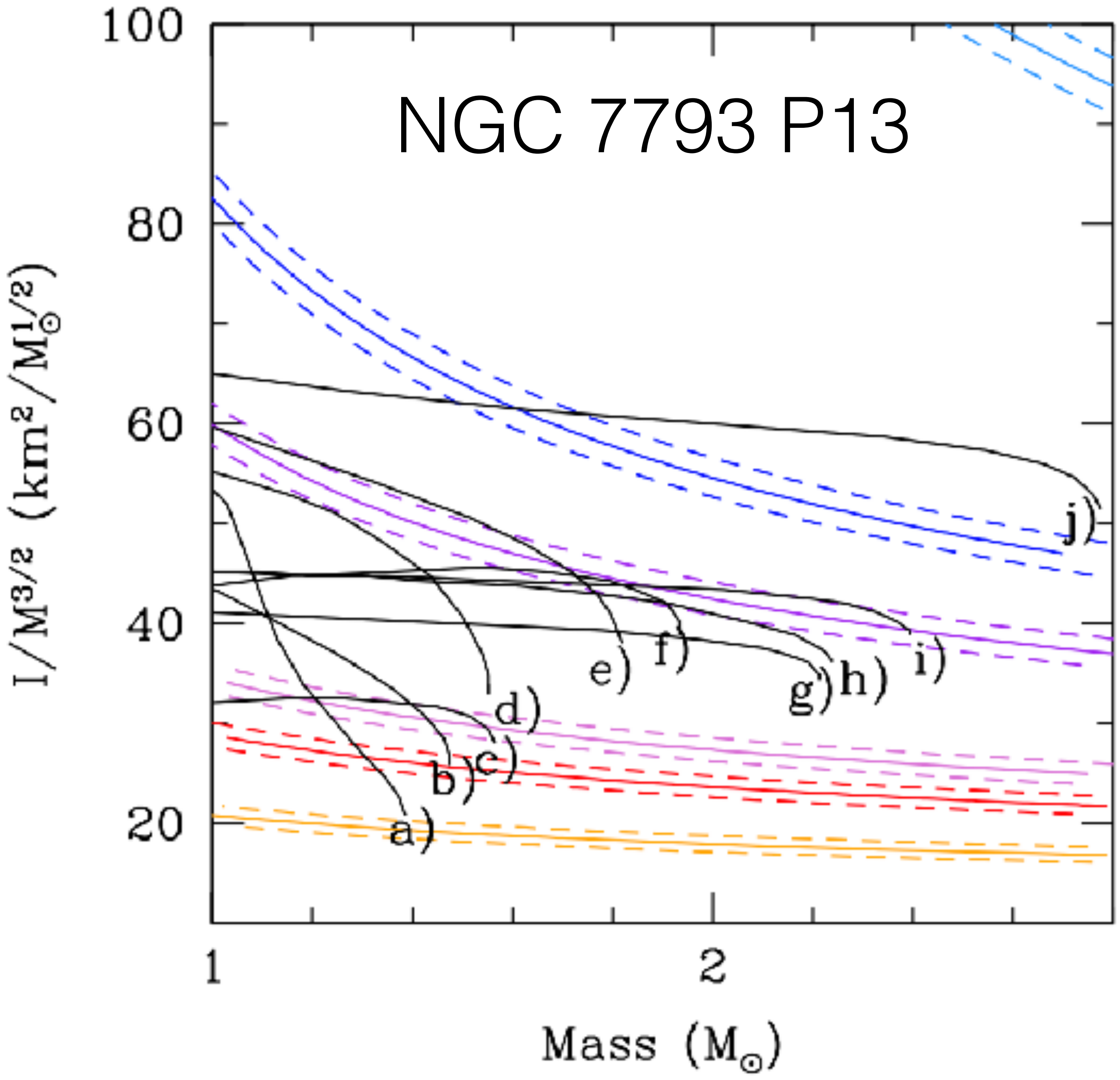
This might take on a whole new relevance when we have a neutron star ULX with pulses **if** driven by Lense-Thirring

The spin of the compact object enters into the precession formula but also:

$$a_* = \frac{2\pi \boxed{I} c}{P_{spin} G M^2}$$

The moment-of-inertia is related to the neutron star equation of state



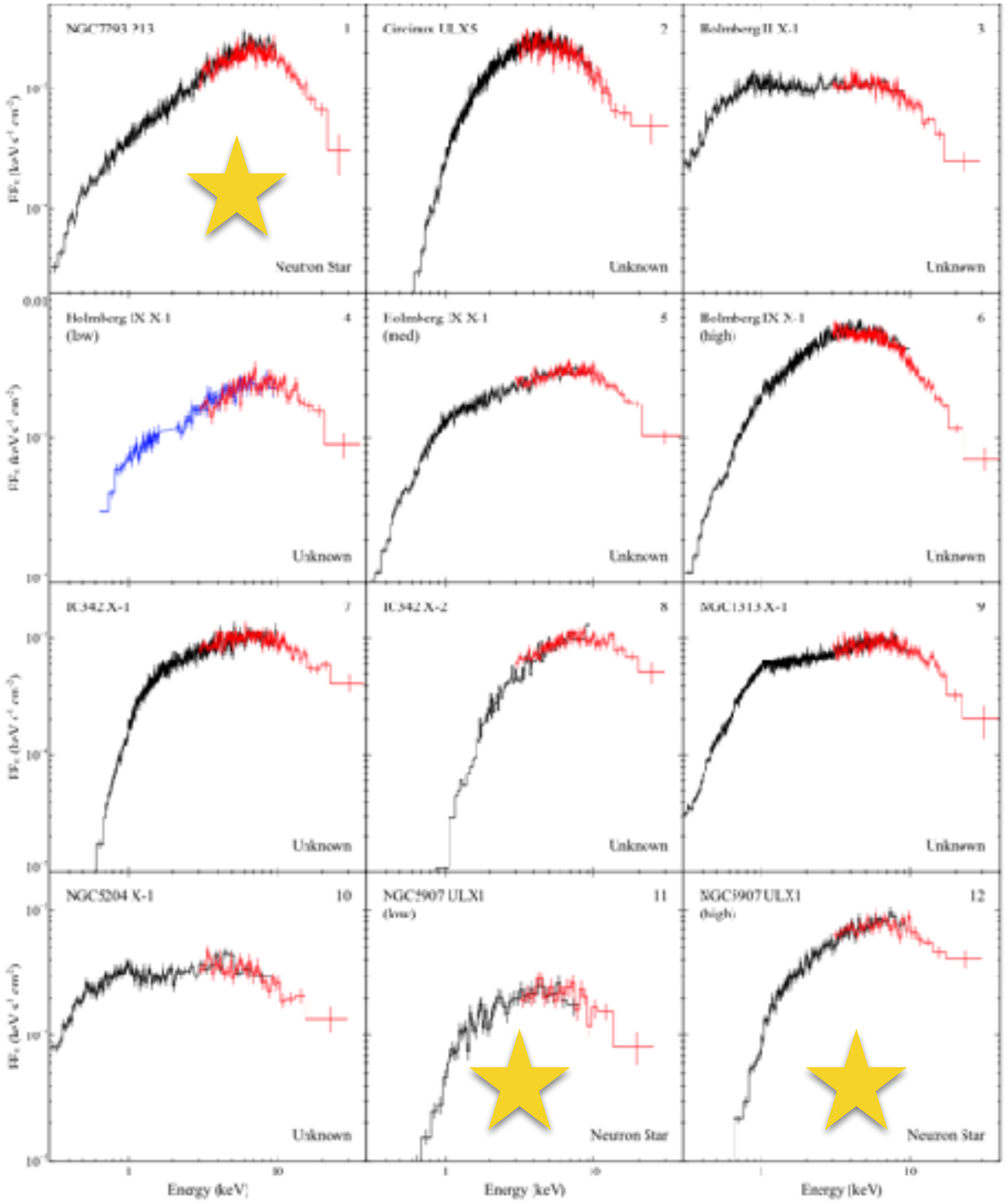


Middleton et al. (2018)

As r_{in} does not sit at the ISCO but at the magnetospheric radius we have a range of solutions with changing dipole field strength

Fuerst et al. (2016) get B ~ 10^{12} G from the rate of spin-up

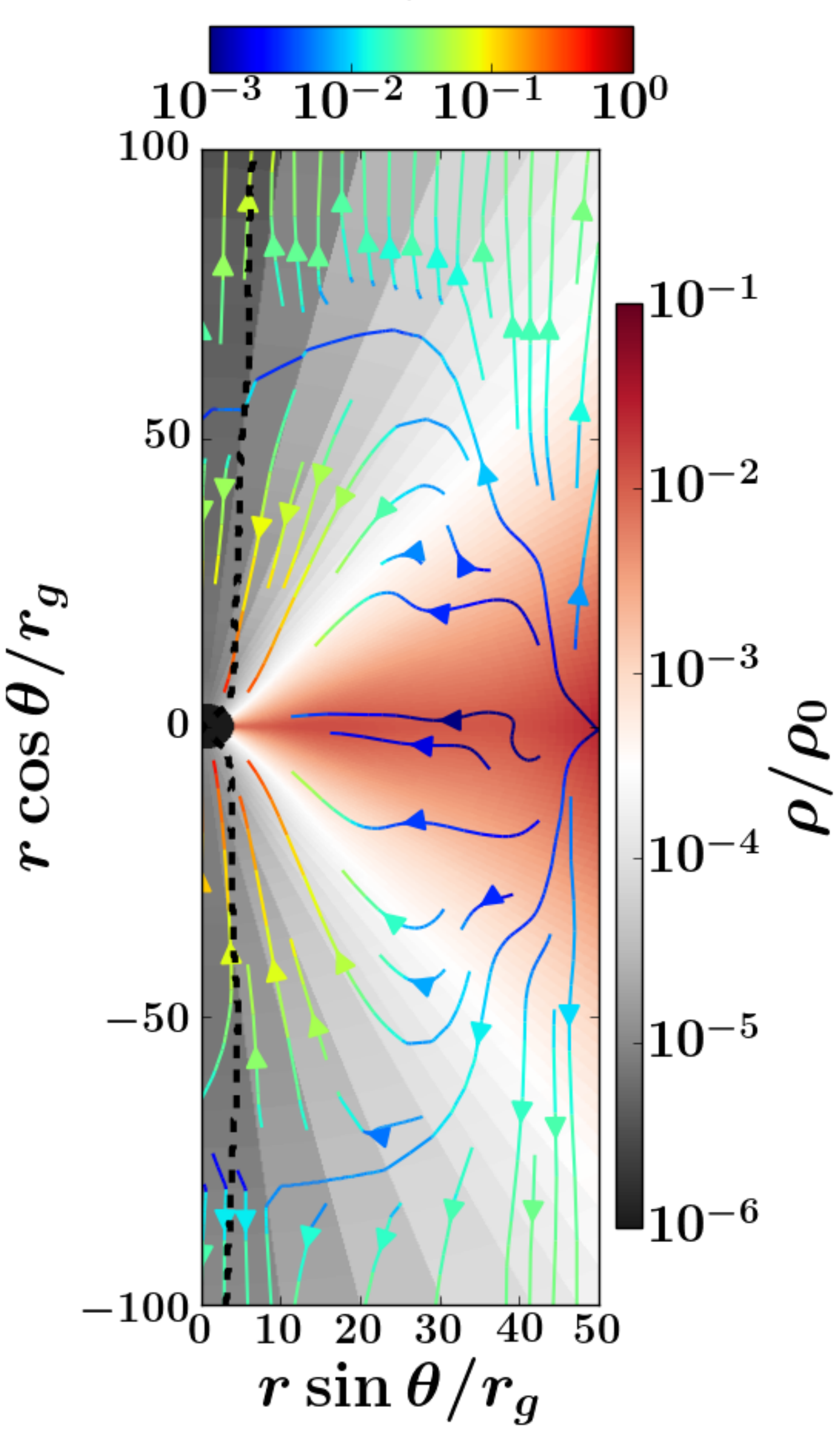
Open questions/future directions: BHs vs NSs?



The spectra of ULPs appear fairly ‘canonical’ but hardly any are found to pulse (4/100s), so how do we know how many neutron star ULXs are out there?

Walton et al. (2017)

Open questions/future directions: BHs vs NSs?



Jiang et al. (2017)

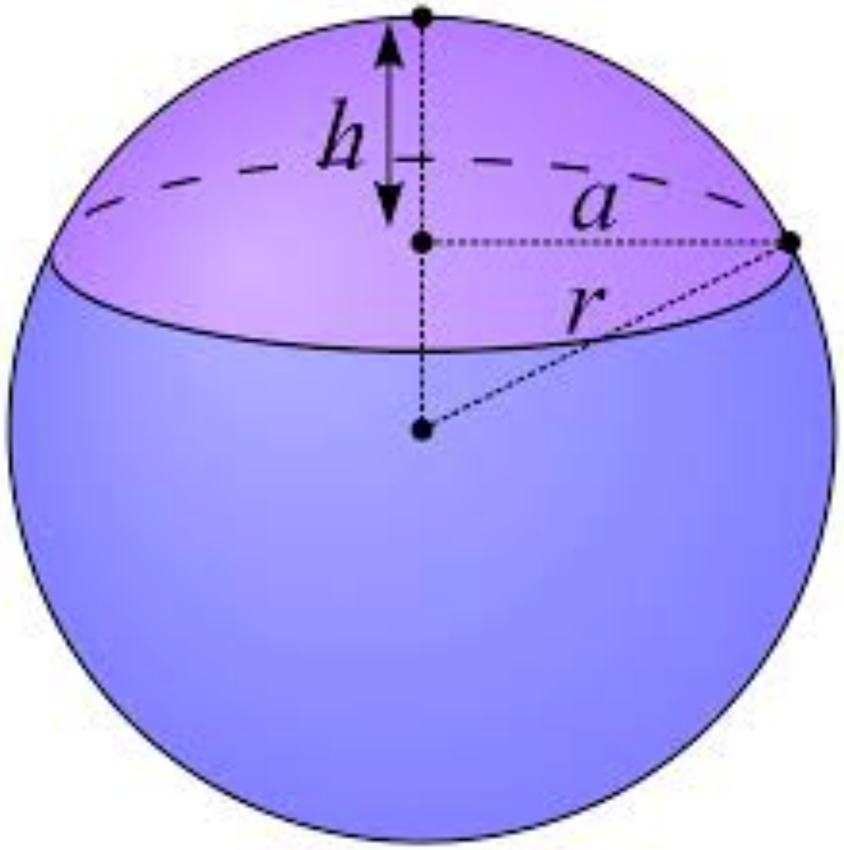
Simulations tell us that the wind cone opening angle is tied to the Eddington ratio (smaller angle for higher rate)

The geometrical beaming is also a function of the opening angle

So face-on ULPs will be the brightest members of the beamed population for the <u>same</u> thermal mass transfer rate (as Eddington ratio is higher)

Open questions/future directions: BHs vs NSs?

BUT the chance of **finding** a new source also depends on the opening angle of the wind cone (assuming random orientations)



A large opening angle means sources can be seen in most orientations

A small opening angle makes it hard to find sources

Open questions/future directions: BHs vs NSs?

So in a flux-limited survey we can determine (roughly) analytically what the observable ratio of neutron star ULXs to black hole ULXs should be for similar mass transfer rates:

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

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

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

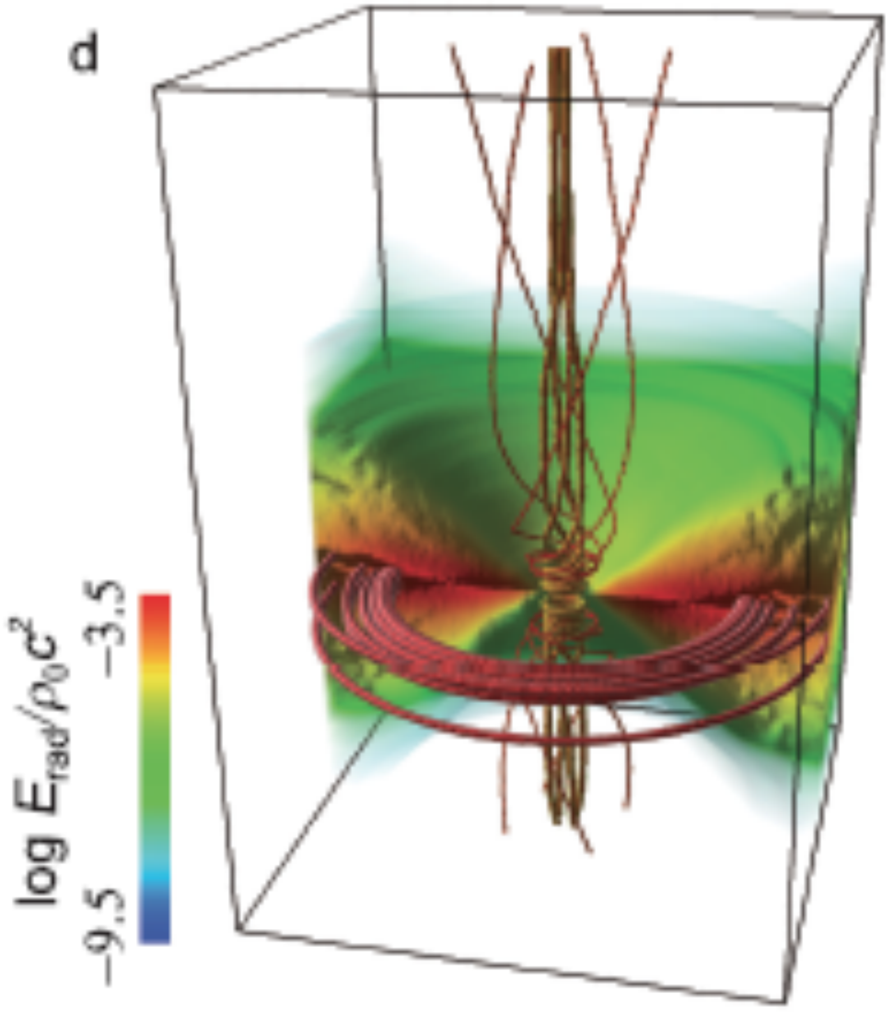
Ratio of species *observed*

Ratio of true spatial densities

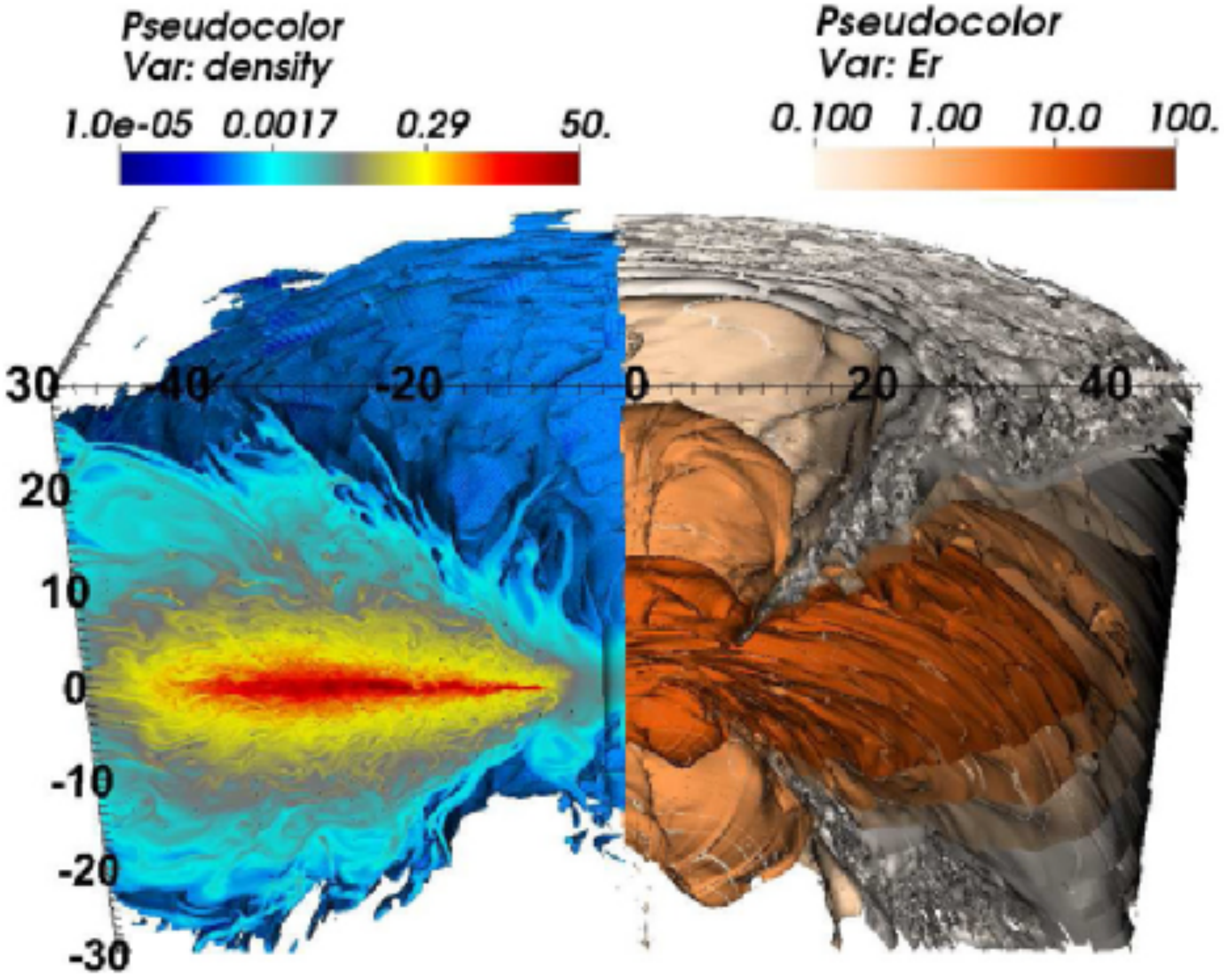
Middleton & King (2017)

Open questions/future directions: new approaches

3D (R) MHD simulations confirm a lot of the classical theory (although internal magnetic effects are important)

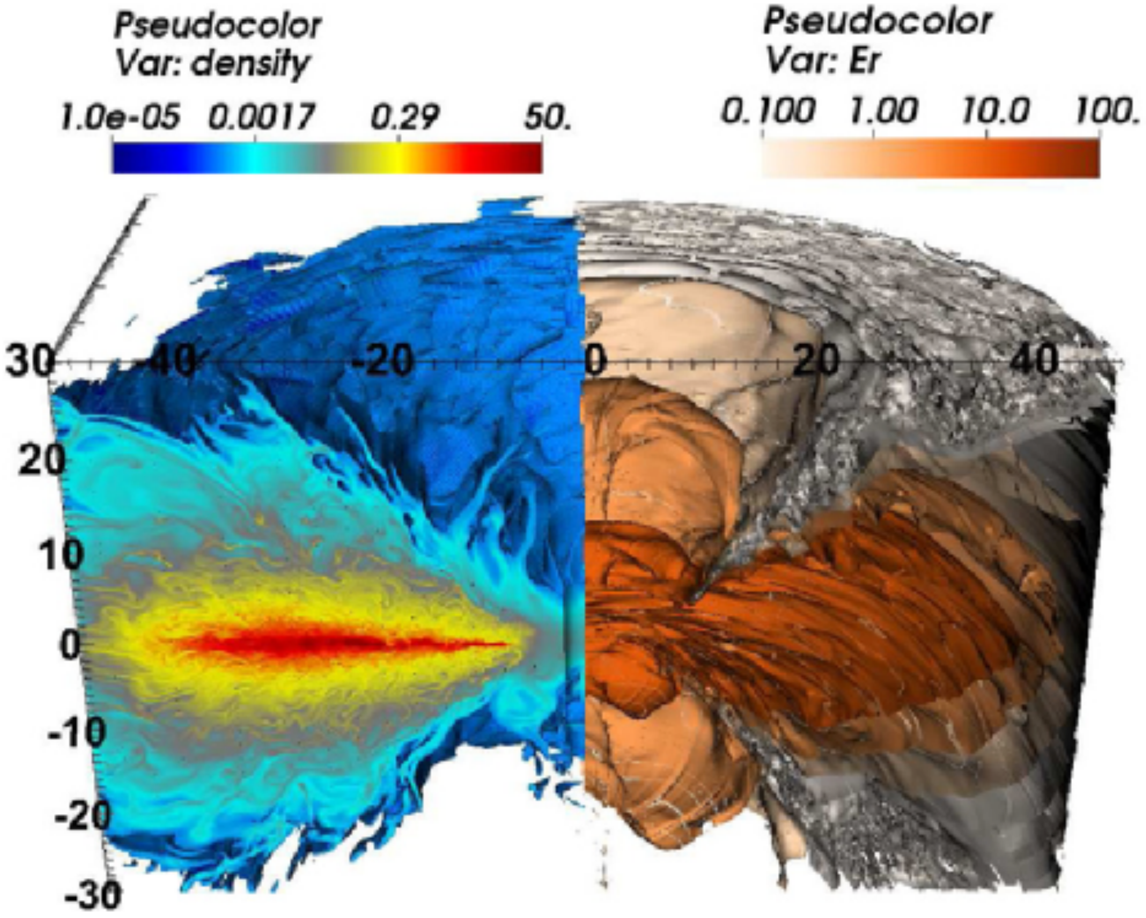


Ohsuga et al. (2011)



Jiang et al. (2014)

Open questions/future directions: new approaches

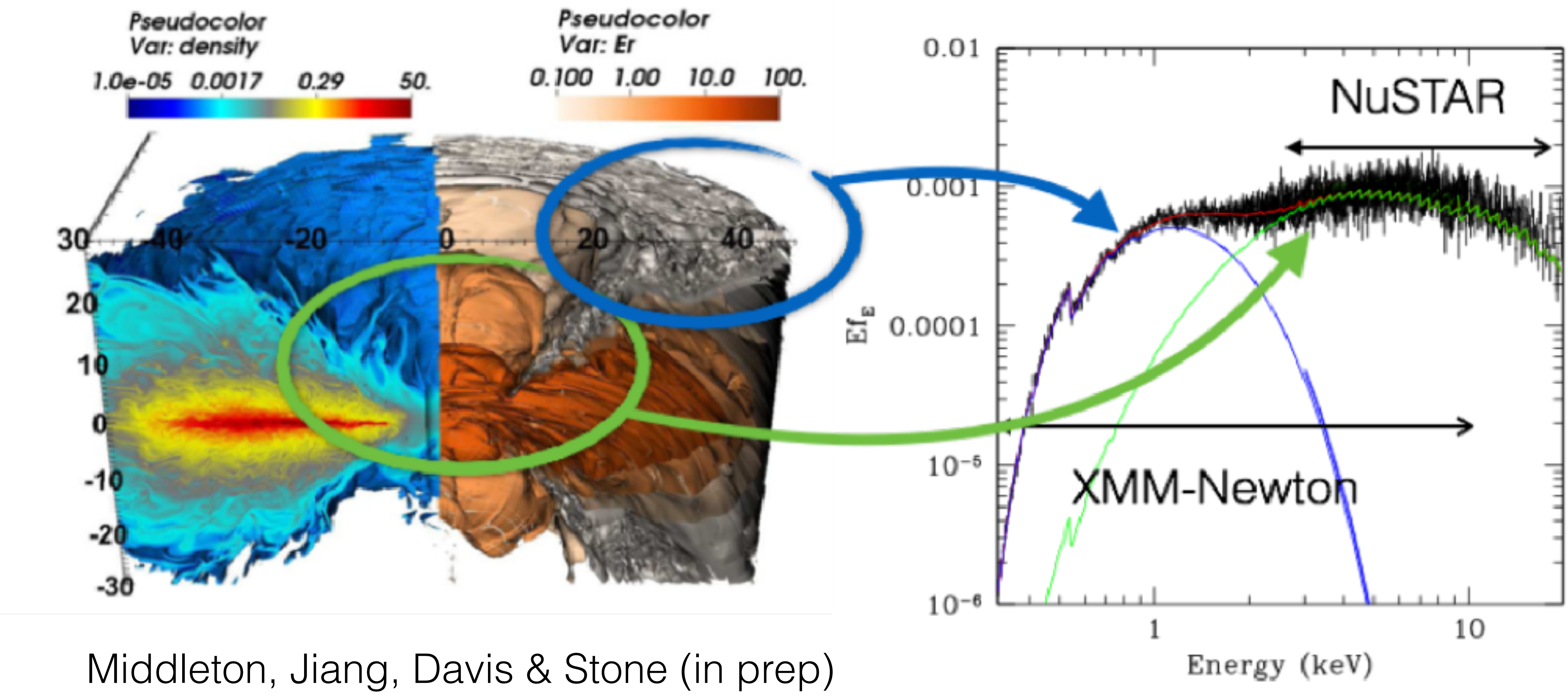


From RMHD simulations we (Shane) can get ‘snapshot’ spectra

e.g. Jiang et al. (2014) assumes a mass of 6.62 $M_\odot$ and a mass accretion rate of 40 $\dot{M}_{Edd}$

Includes MC radiative transfer (includes vertical and radial advection and so accounts for turbulent Compton)

Open questions/future directions: new approaches



Middleton, Jiang, Davis & Stone (in prep)

Fitting these physically motivated models (with atomic lines as well) to data will allow us to constrain the relevant physical parameters and make real progress

Open questions/future directions: new data

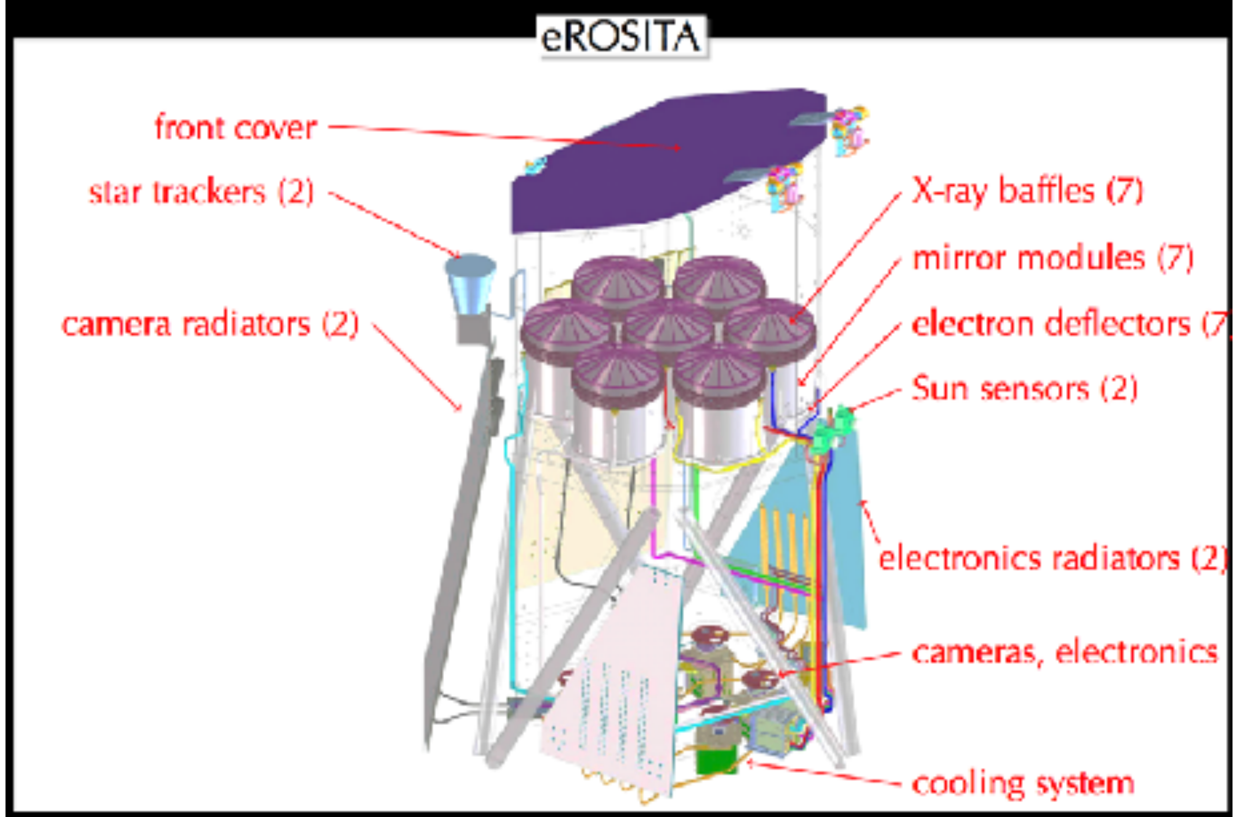
eROSITA

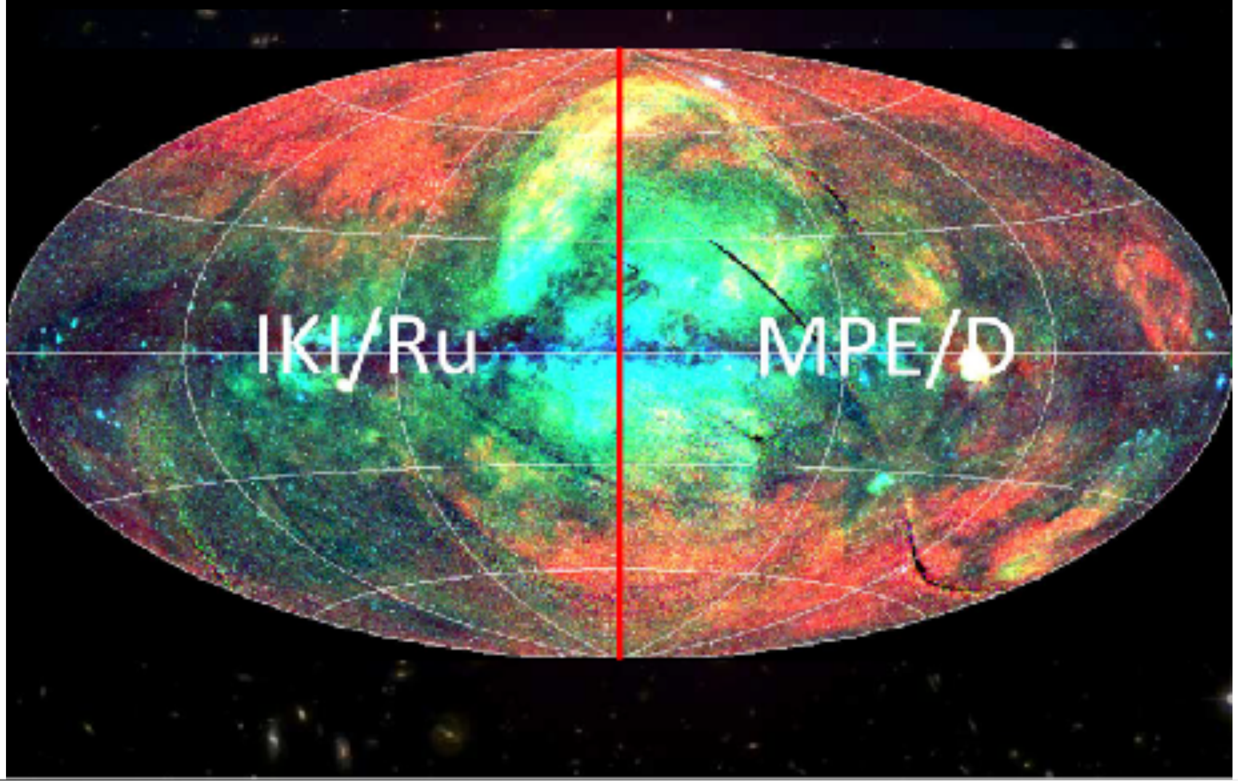
Primary science:

- cluster cosmology (100000 clusters),
- BH evolution (2×10^6 AGN)

Strategy:

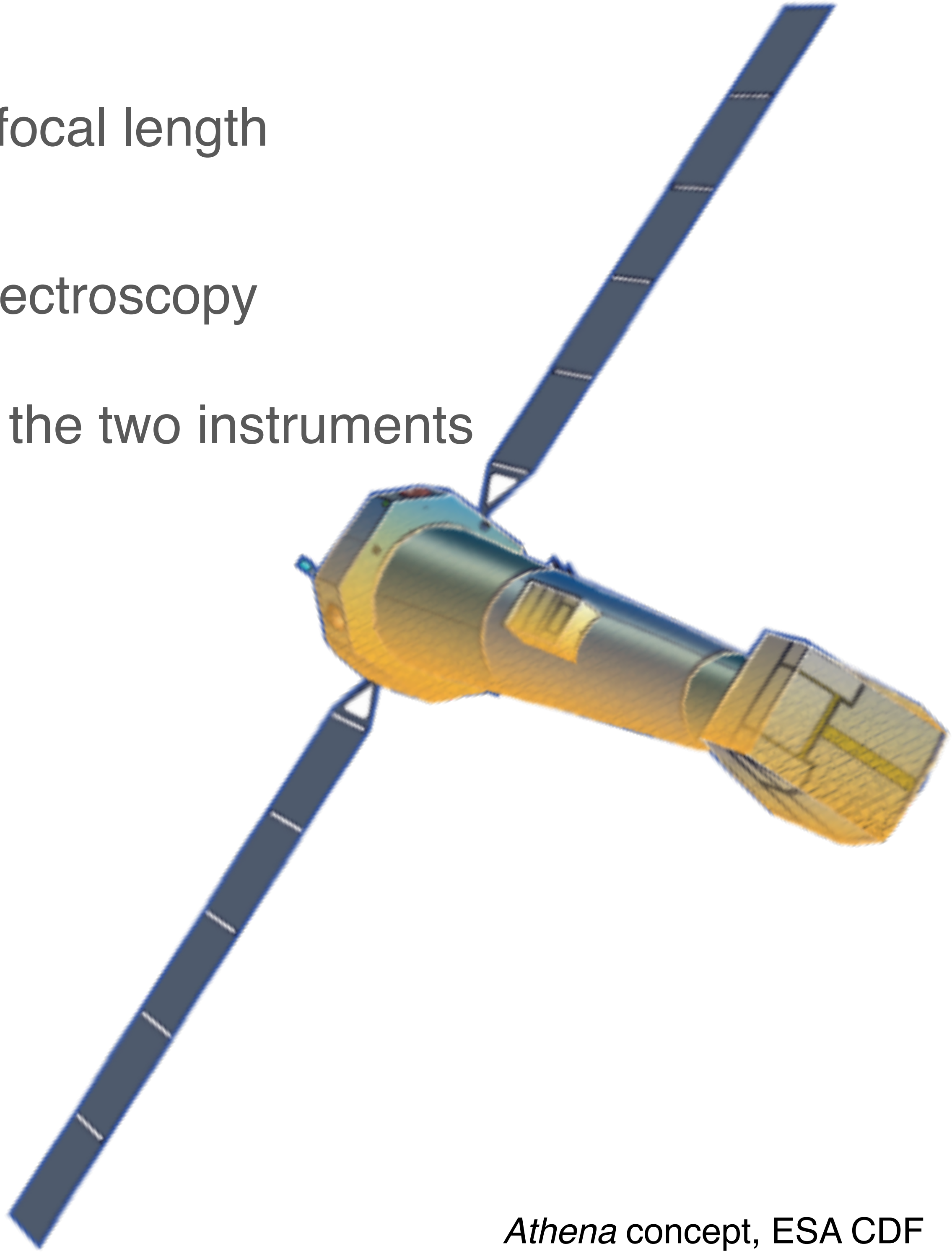
- All Sky Survey to 6×10^{-14} cgs
- Deep survey ($\sim 100\,\square^\circ$) to 10^{-14} cgs
- 1° FoV, moderate angular resolution ($< 28''$ avg.)
- large effective area ($>$2000 cm^2 at 1 keV)
- CCD-type spectral resolution (155 eV at Fe K)





Athena mission concept

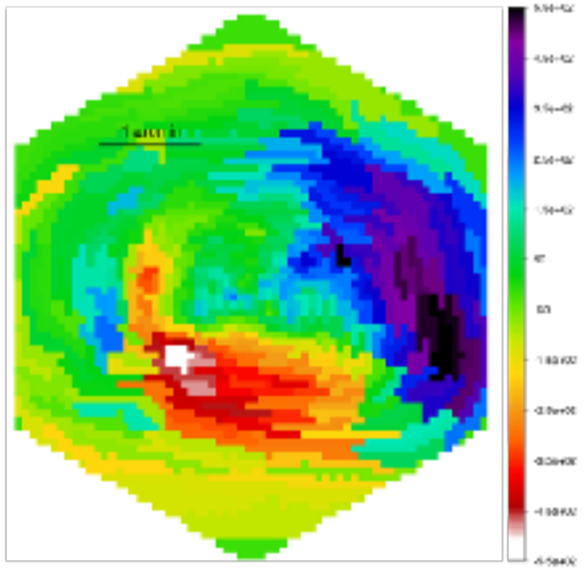
- Single telescope, using Si pore optics. 12m focal length
  - WFI sensitive imaging & timing
  - X-IFU spatially resolved high-resolution spectroscopy
- Movable mirror assembly to switch between the two instruments
- Launch early 2030s, Ariane 6.4
- L2 halo orbit (TBC)
- Lifetime: 4 yr +Possible extensions



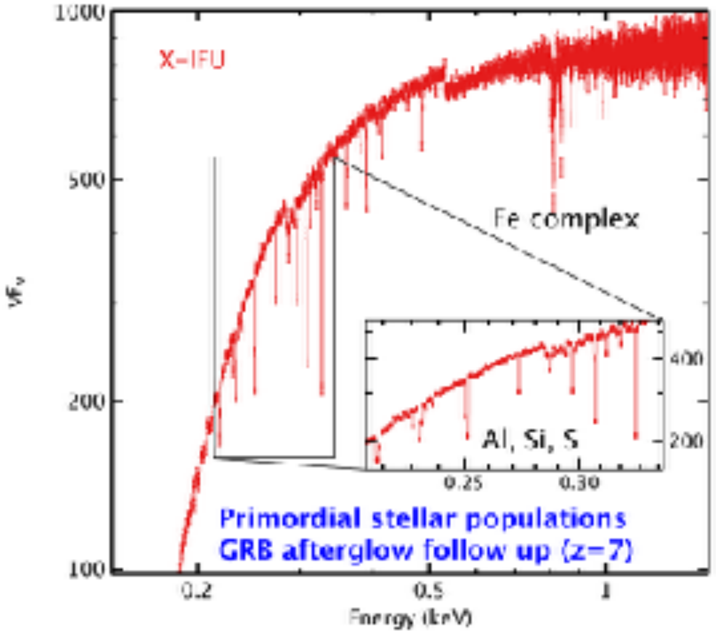
Athena concept, ESA CDF

X-ray Integral Field Unit (X-IFU)

- Cryogenic imaging spectrometer, based on Transition Edge Sensors, operated at 50 mK featuring an active cryogenic background rejection subsystem
- Consortium led by CNES/IRAP-F, with SRON-NL, INAF-IT and other European partners (BE, FI, GE, PL, ES, CH), NASA and JAXA
- Key performance parameters:
  - 2.5 eV energy resolution <7 keV
  - FoV 5´ diameter
  - Pixel size <5´´

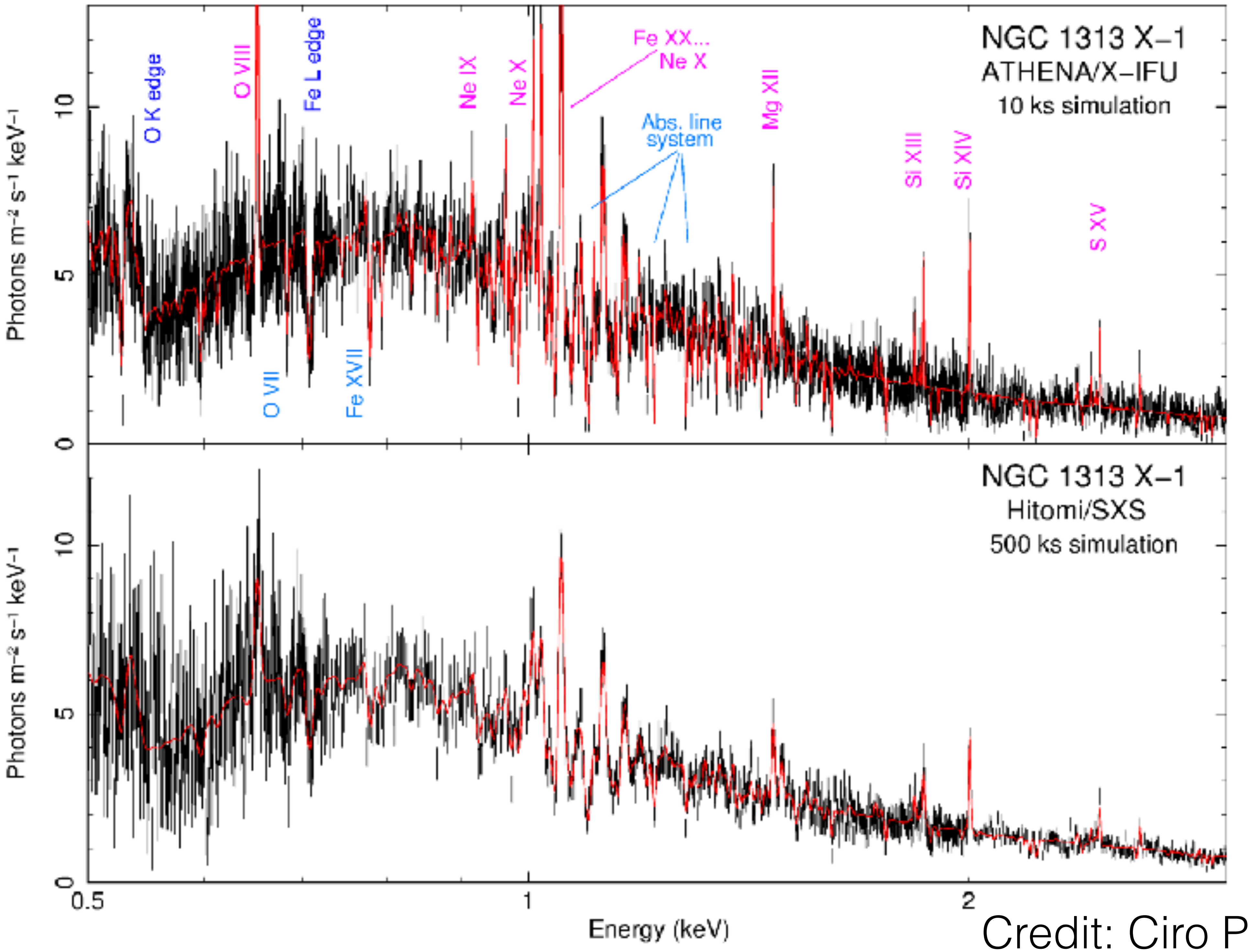


E. Pointecouteau, P. Peille, E. Rasia, V.Biffi, S. Borgani, K. Dolag, J. Wilms



Barret et al. 2013, arXiV: 1308.6784
http://x-ifu.irap.omp.eu/

X-ray Integral Field Unit (X-IFU)



Credit: Ciro Pinto

The bottom line:

ULXs have been around a long time but we’re only now starting to understand what they’re all about

There are lots of open questions (mostly around the magnetic field strength of those with NSs)

Our options for getting more data over the next ~~5~~ ~~10~~ 20 (?) years are looking pretty good