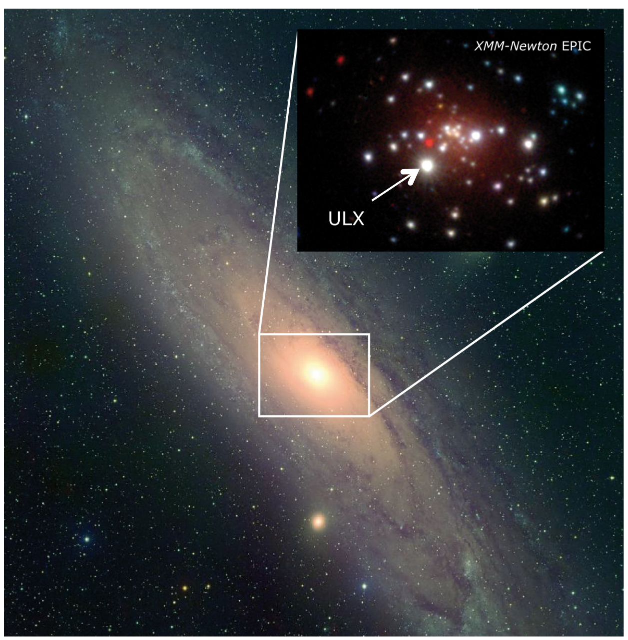
The ultraluminous state refined: *spectral and temporal characteristics of super-Eddington accretion*



Tim Roberts

Andy Sutton (Durham)

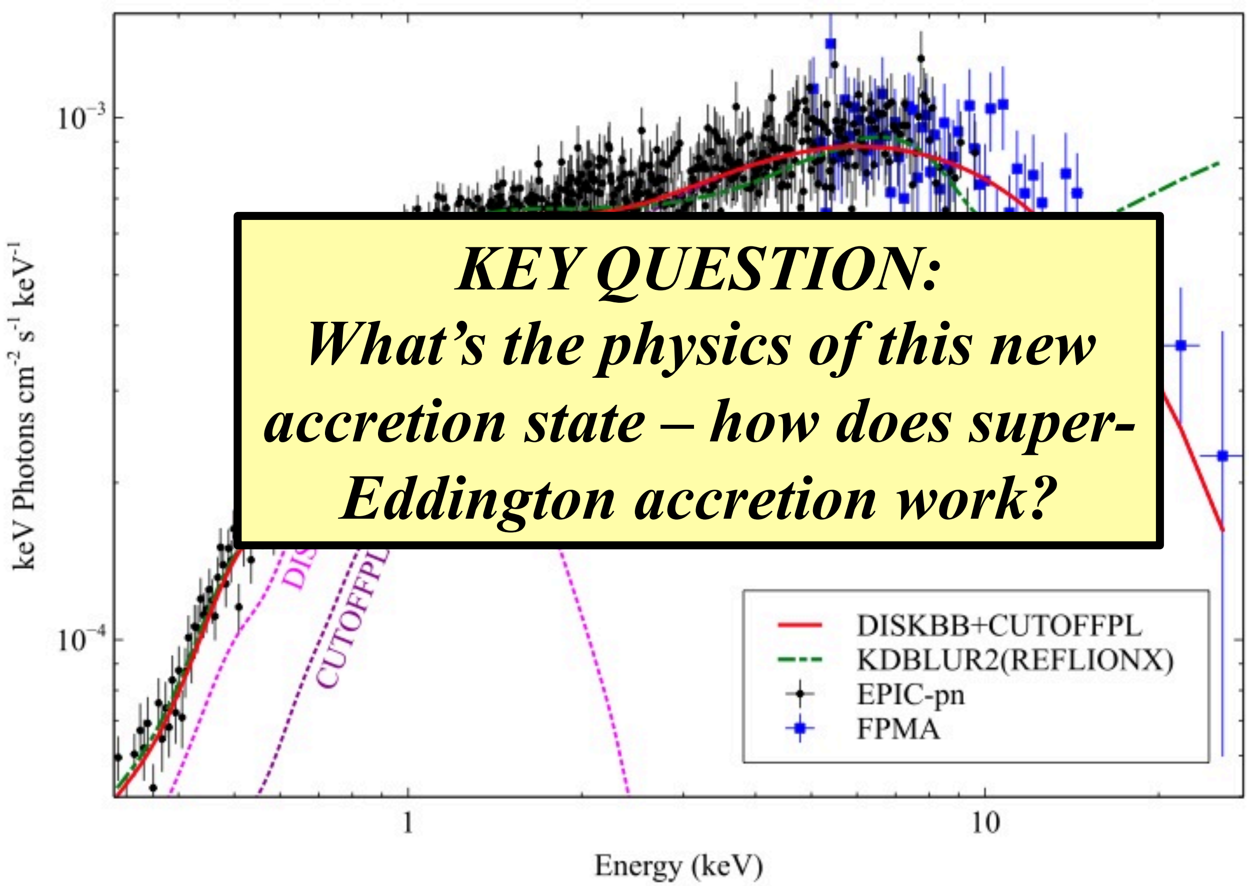
Matt Middleton (Cambridge)

Dom Walton (Caltech)

Lucy Heil (Amsterdam)

et al…

ULXs as super-Eddington accretors



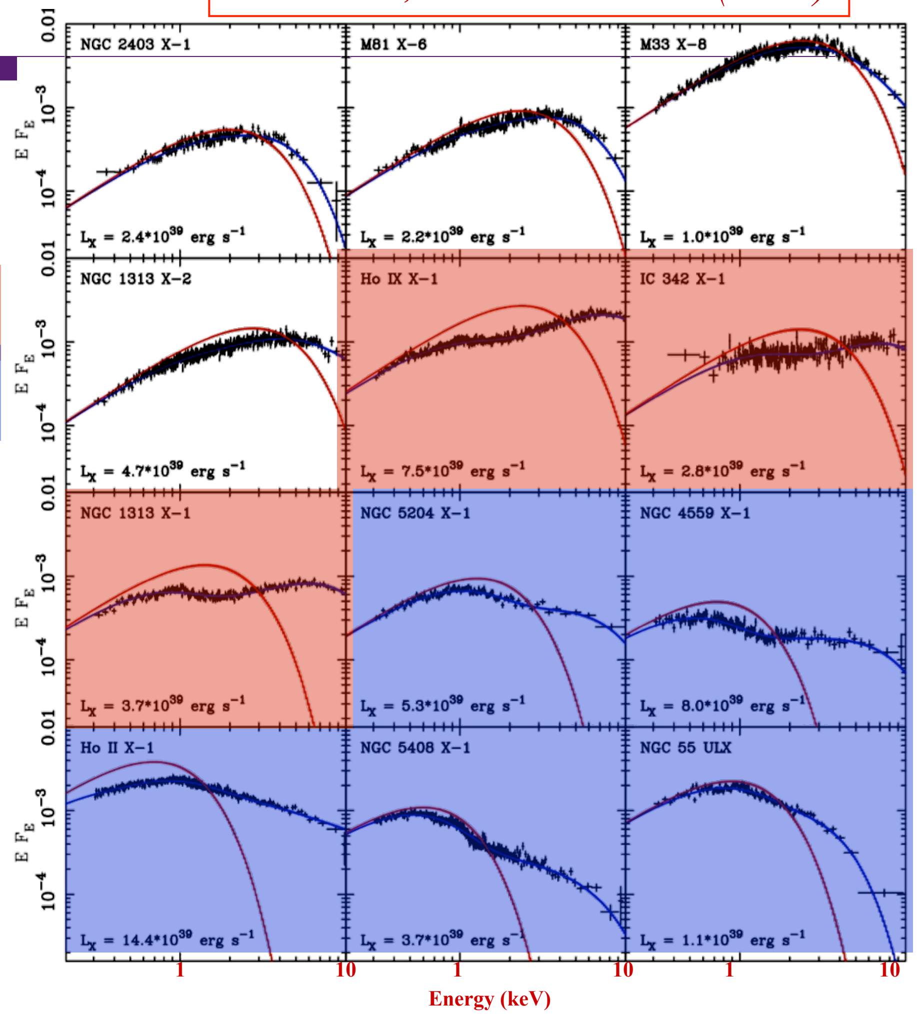
NuSTAR data for NGC 1313 X-1 (Bachetti et al. 2013)

Spectrum is NOT analogous to common sub-Eddington states – implies super-Eddington 'ultraluminous' state (Gladstone et al. 2009)

Starting point

- Spectral sequence:
  - Broadened disc regime
  - Hard ultraluminous regime
  - Soft ultraluminous regime
- In Gladstone et al. we attributed this sequence to increasing accretion rate: is this true? Or are other factors at play?

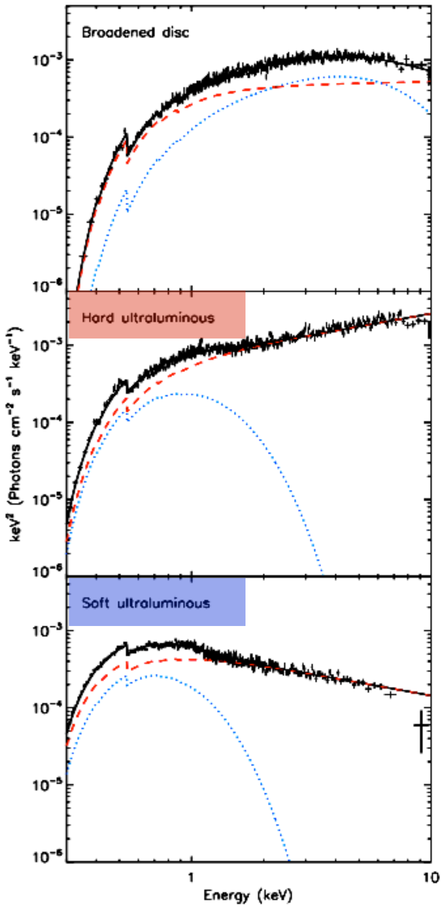
Gladstone, Roberts & Done (2009)

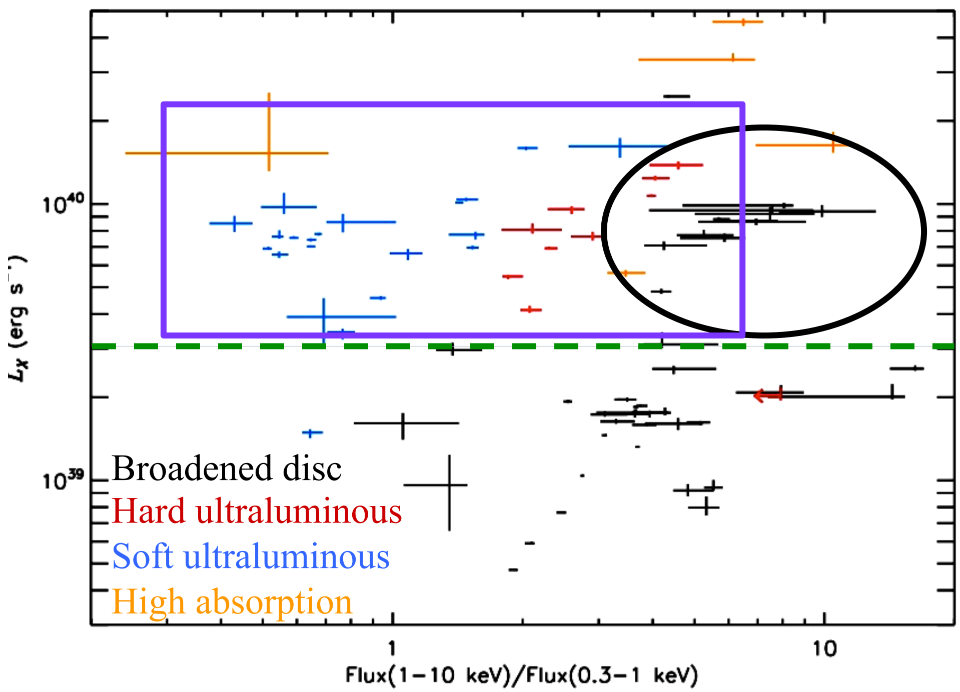


How do we say more about ULX physics?

- X-ray spectral states in BHs show related timing & spectroscopy characteristics
- Is this true of ULXs?
- Empirical study *Sutton, Roberts & Middleton (2013)*
  - Classify 89 obs from 20 ULXs into 3 distinct regimes based on empirical spectral model
  - Recover deabsorbed fluxes, hardness
  - Calculate fractional variability on 200 s timescale in broad, soft & hard bands

Hardness-intensity diagram



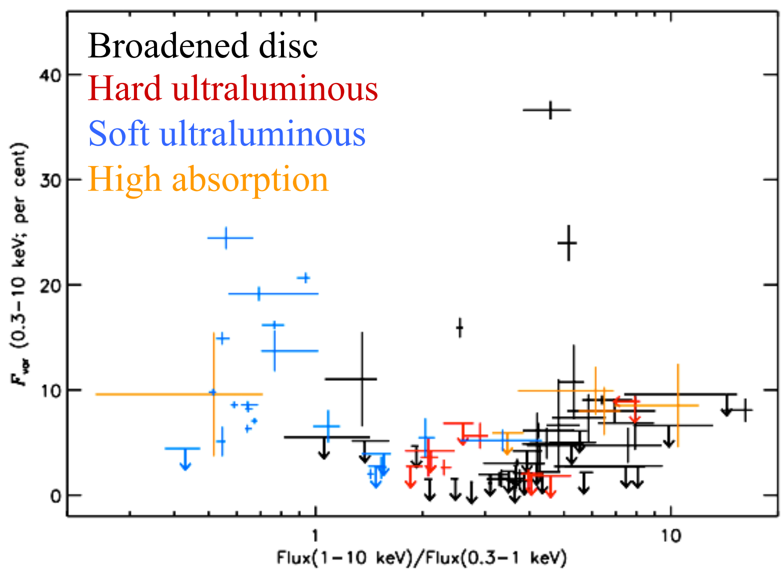


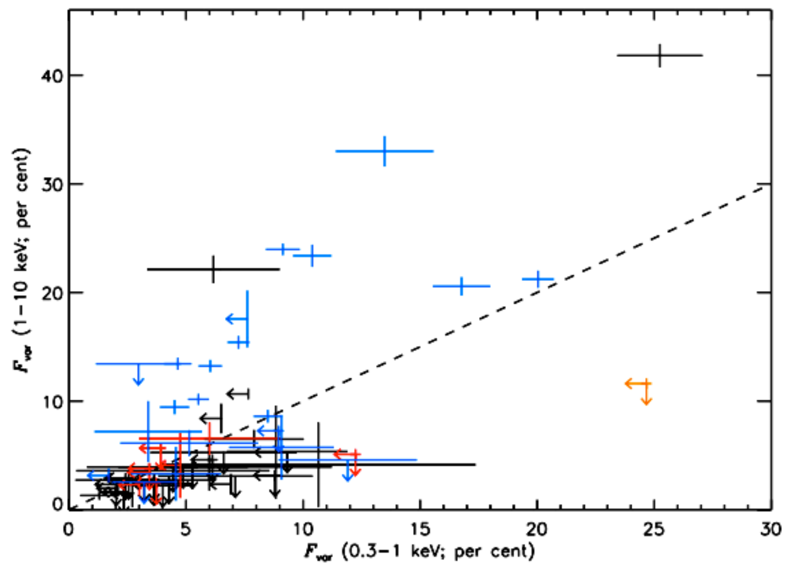
Soft & hard ultraluminous (UL) found at similar L_X

Higher L_X discs – massive stellar BHs or hard UL with weak soft component?

Below ~ 3 $\times 10^{39}$ erg s^{-1} broadened discs dominate: ~ Eddington stellar mass BHs?

Hardness-variability diagrams

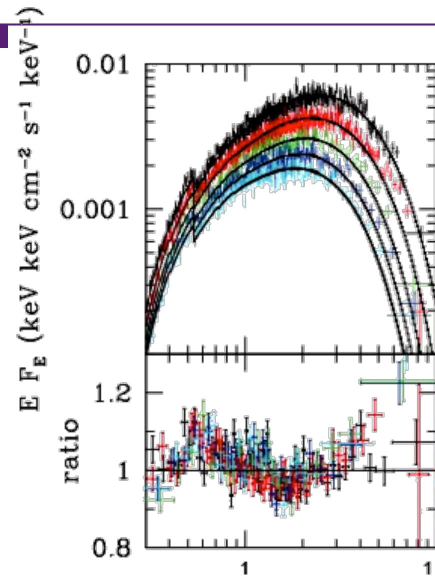




- Low F_{var} (< 10%) in most disc & all hard UL
- High F_{var} mainly seen in some soft UL; stronger above 1 keV; not persistent

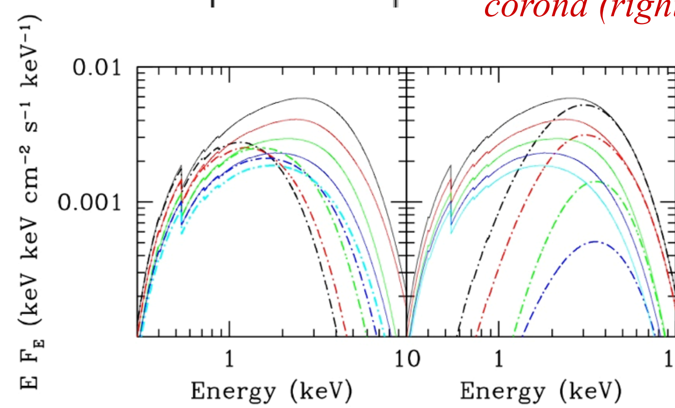
What are the broadened discs?

- Dominate at ~L_{Edd} for 10 $M_{\odot}$ BHs
- Best data: not well fit by disc models
- 2 component models work well, e.g. advective disc plus thick corona
- Same 2 components as UL state – emergent UL spectra?

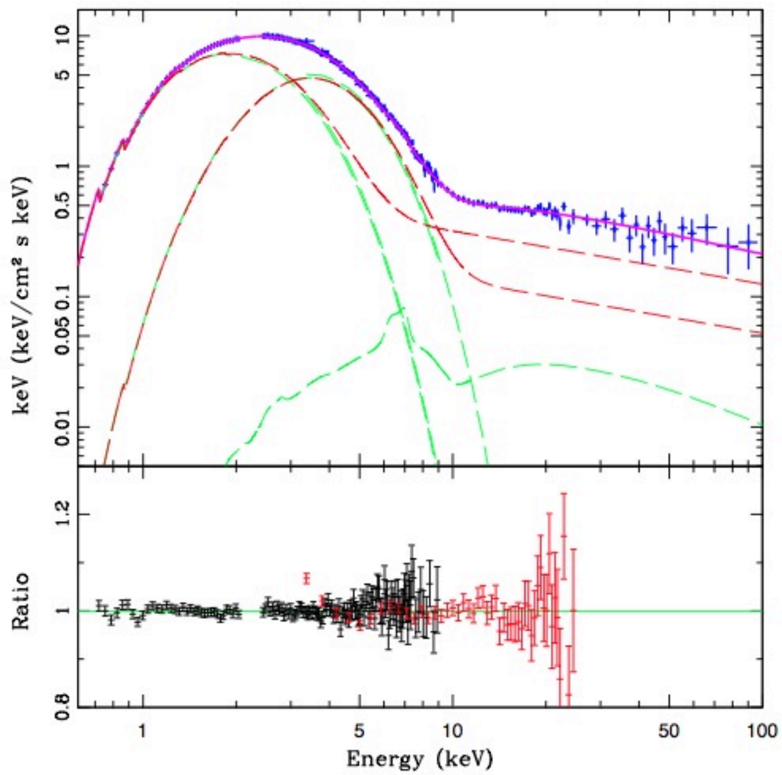


Left: XMM data for M31 ULX, fit with BHSPEC model (Middleton et al. 2012)

Below: 2 component fits to same data – advective disc (left) and cool, thick corona (right)



Do we understand accretion disc spectra?



GX339-4 – EPIC pn & RXTE spectrum at ~ 10% L_{Edd} (Kolehmainen et al. 2011)

- But: similar residuals in TD state CCD spectra of Galactic BHs?
- Sutton et al. (submitted) – reprocessing fraction same as TD state – same geometry?
- Broadened discs simply most luminous TD objects?
- *Are disc spectra well understood?*

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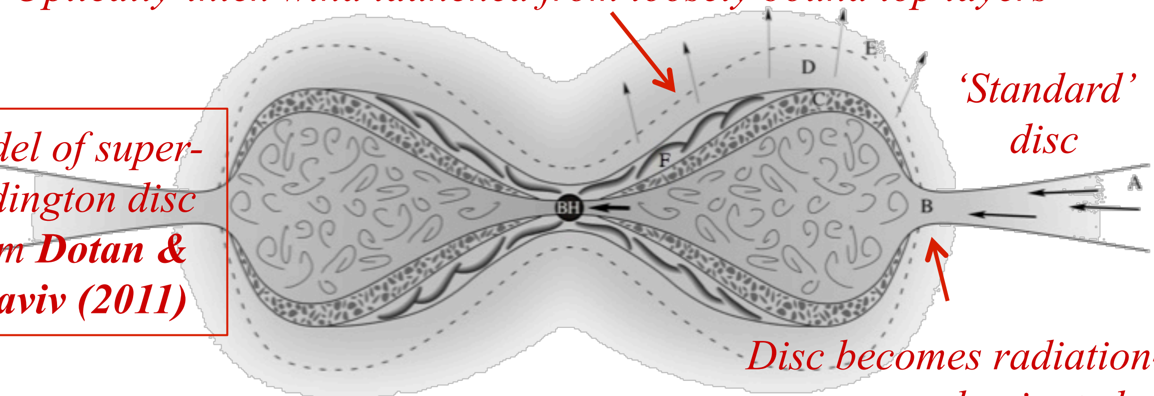
Super-Eddington models

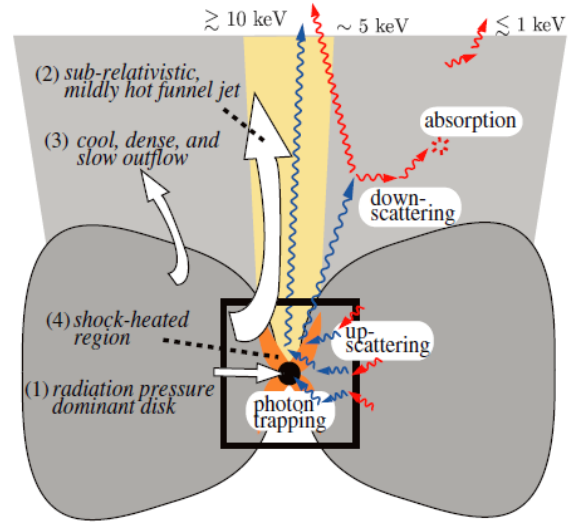
Optically-thick wind launched from loosely bound top layers

Model of super-Eddington disc from ***Dotan & Shaviv (2011)***



'Standard' disc

Disc becomes radiation pressure dominated



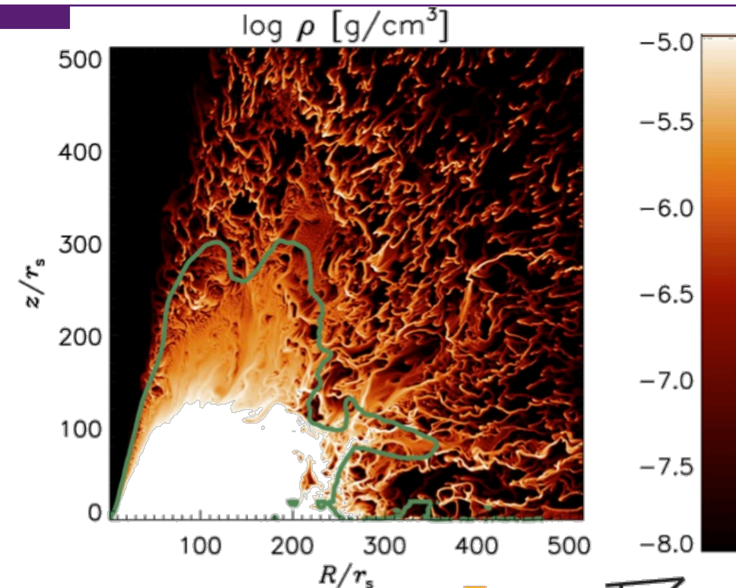
Kawashima et al. (2012)

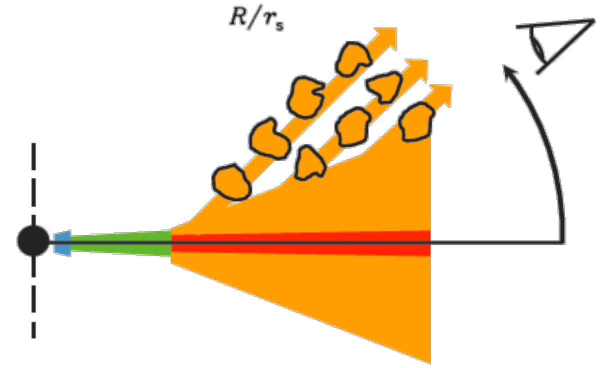
- Super-Edd models naturally explain 2-component spectra as optically thick wind + inner disc
- Poutanen et al. (2007) – inclination critical for observed spectrum: so on-axis HUL, off-axis SUL

Origin of variability

- Variability seen predominantly in wind-dominated ULXs
- Face-on systems show little variability
- Explanation: extrinsic hard variability imprinted by edge of clumpy wind passing through line of sight

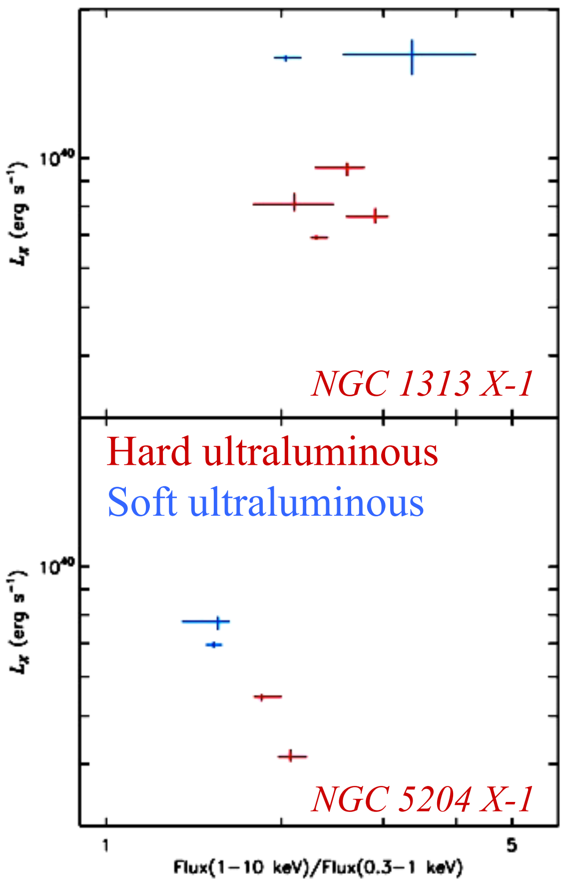
Takeuchi et al. (2013)





Middleton et al. (2011)

Regime change

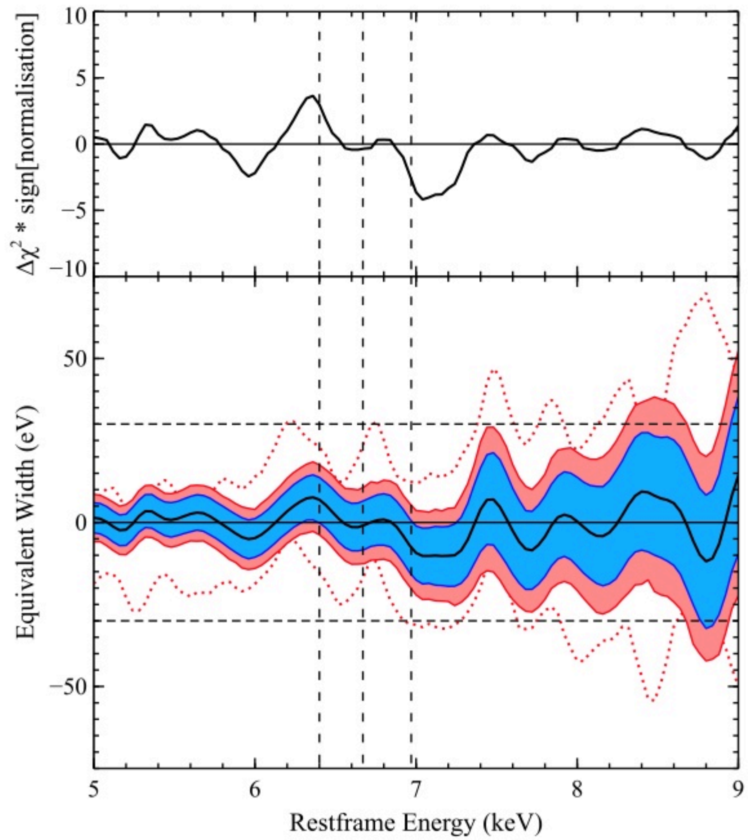


- Do ULXs switch between different regimes?
- King (2009) – $\dot{m}$ goes up, funnel opening angle decreases
- For constant line-of-sight expect to see switch from hard to soft – seen in two ULXs

Winds

Walton et al. (2013)

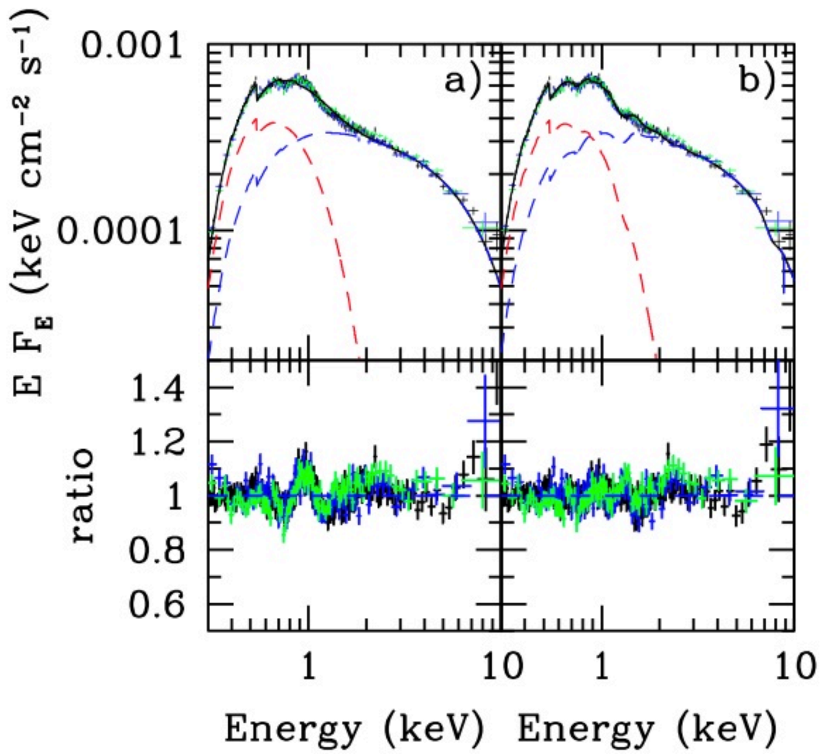
- Interpretation predicated on presence of wind
- Any direct evidence for presence of wind material?
- No narrow emission lines around Fe K in deep *Suzaku* observation of a hard ULX, Ho IX X-1
- But hard – so not viewed through wind!



Top: change in χ^2 statistic for addition of narrow Gaussian feature; bottom: limits on line equivalent width

More winds

Middleton et al. (2014).



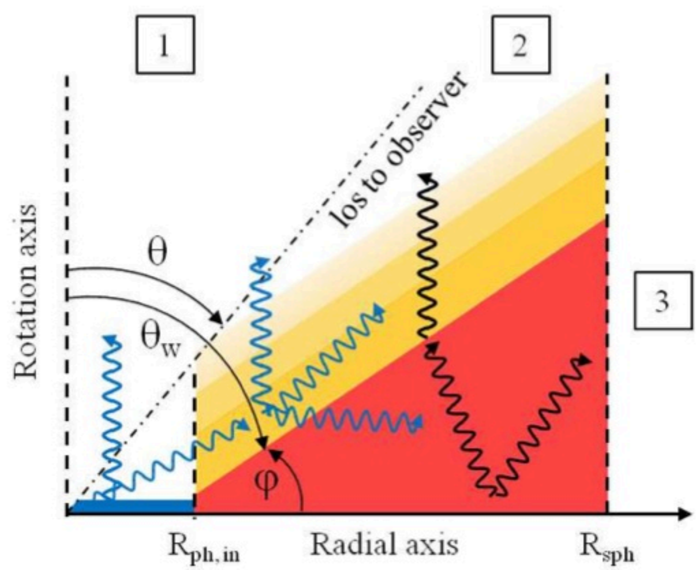
Combined NGC 5408 data – left: continuum model; right: continuum model plus broad, partially ionised absorber

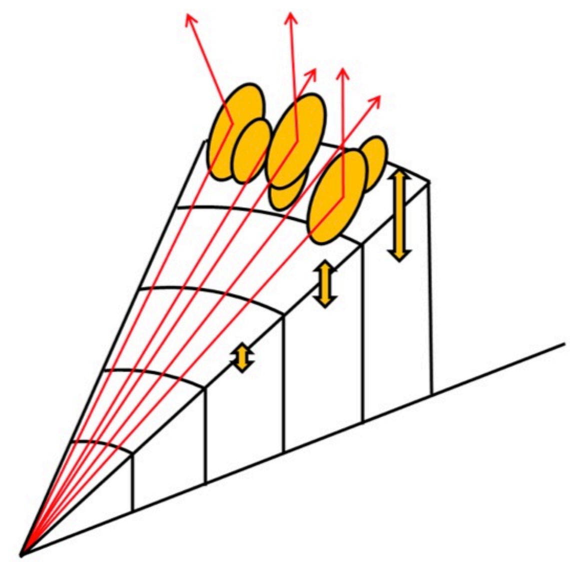
- Long known that soft ULXs can have extensive fit residuals
- Can be fitted by thermal plasma
- But also explained by absorption from broadened, partially ionised and blueshifted ($v \approx 0.1c$) material – outflowing wind!

Refining the UL state

Middleton et al. (submitted).

- Return to model predictions (e.g. Poutanen et al. 2007) to find new tests





Qualitatively consider: effects of inclination on photon propagation; damping of intrinsic disc variability

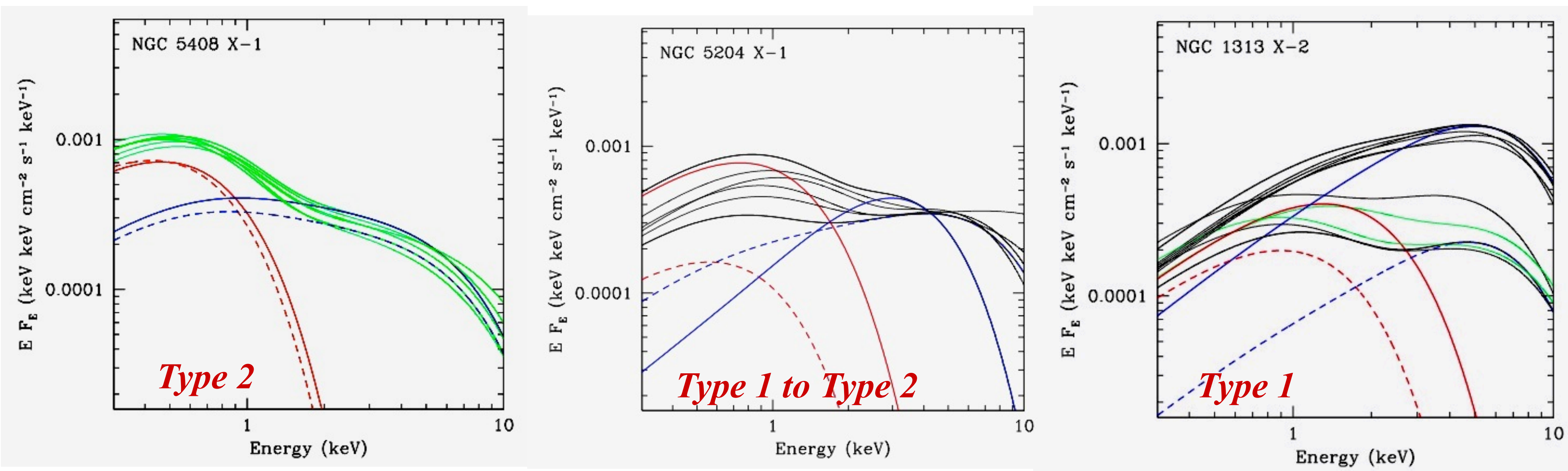
New predictions/better explanations

- Possible dependence of variability on mass accretion rate – at higher rates, increased wind so greater damping of intrinsic variability & effect of clumps averages out
- Evolution of spectra with inclination angle and mass accretion rate better justified; type 1 (HUL) to type 2 (SUL) if off-axis
- Type 3 (close to edge-on): should be faint & spectrally soft, and likely bright UV sources

Some examples of evolution

- Predictions seem to be justified by data

Best fitting models for multiple epochs of XMM data – green spectra when also variable. Red/blue are soft/hard components for least (dotted) and most (solid) luminous epochs



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Conclusions

- Not just spectra: also *behaviour* of most ULXs inconsistent with sub-Eddington IMBHs!
- Can explain properties of most ULXs in framework of super-Eddington accretion
- We can now qualitatively explain the range of ULX spectra in terms of 2 properties: accretion rate and inclination