Ultraluminous X-ray sources in the nearby Universe

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NASA
POSTDOCTORAL PROGRAM
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Introduction

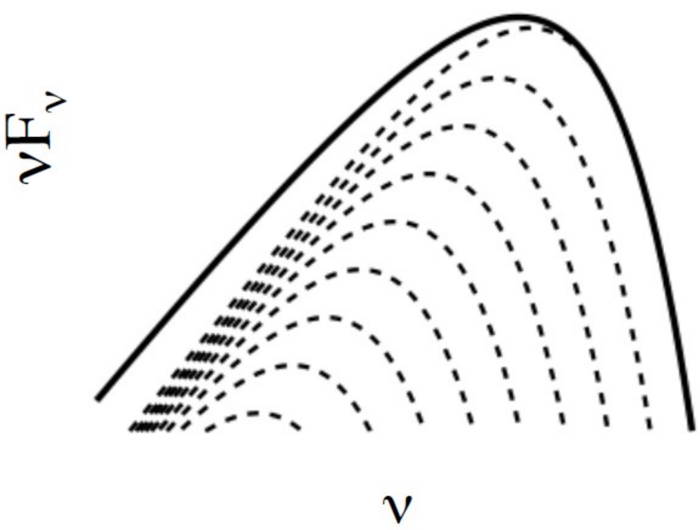
- What are ultraluminous X-ray sources (ULXs)?
- Intermediate mass black holes or super-Eddington accretion?
- A new super-Eddington accretion state: the 'ultraluminous state'

What are ultraluminous X-ray sources?

- Extra-Galactic (distances of ~ 5 – 100 Mpc)
- Non-nuclear - they are not supermassive black holes
- Bright X-ray point sources
  - L_X ~ 10^{39} – 10^{41} erg s^{-1}
    - Exceeds the Eddington limit (~1.3×10^{38} erg s^{-1} $M_\odot^{-1}$) for stellar remnant black holes
- Implying they are intermediate-mass black holes (IMBHs)
  - Which could be the remnant seeds of the SMBHs
- Or, they are in a new, extreme accretion state

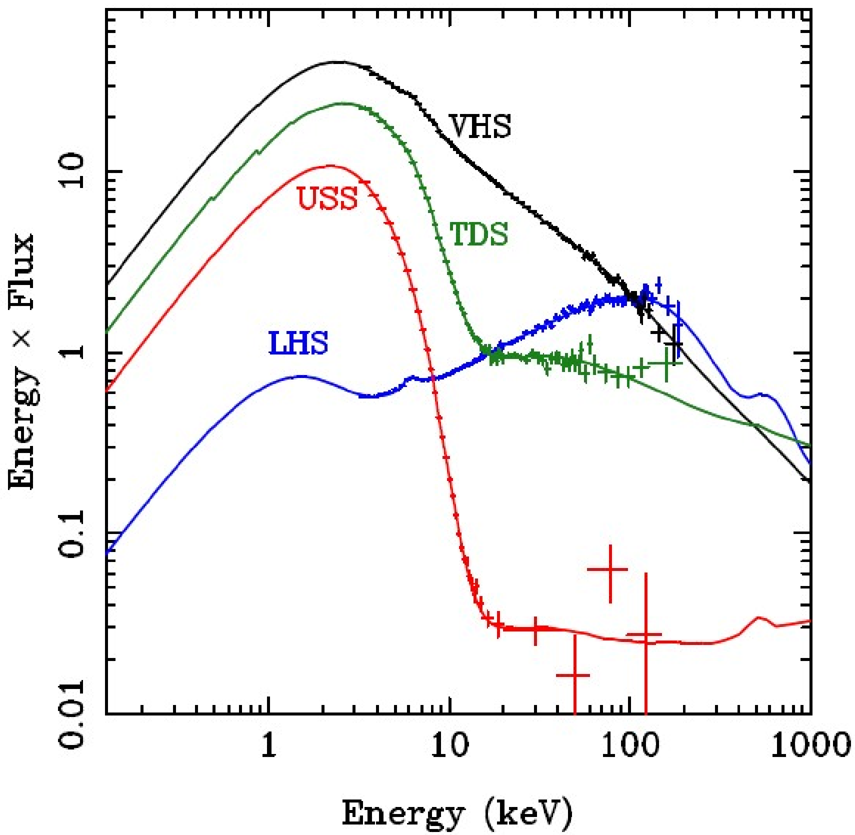
Sub-Eddington disks

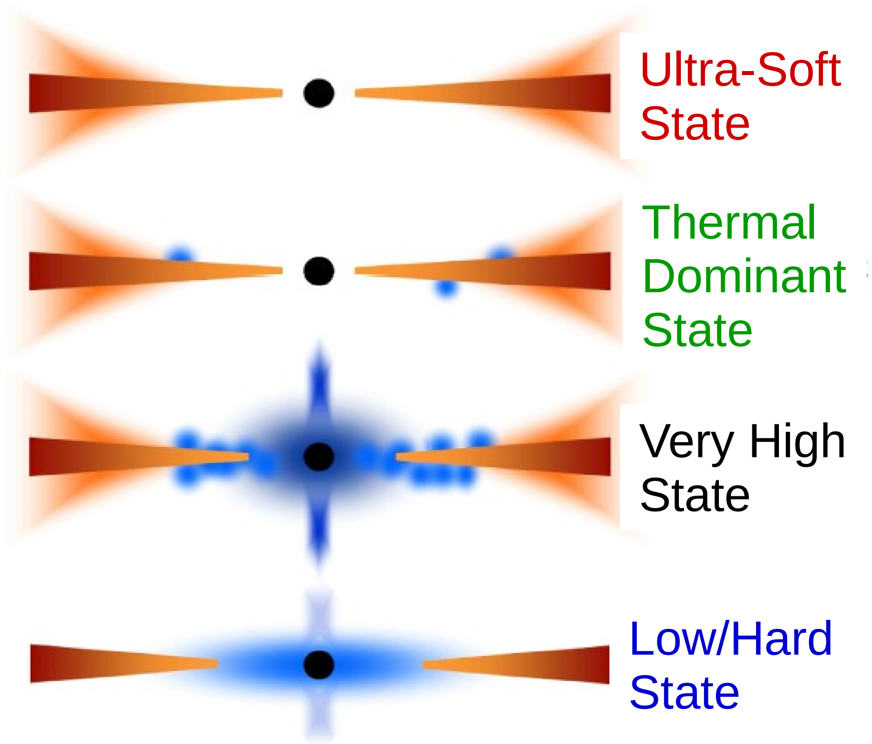
- Sub-Eddington accretion disk spectra can be approximated as a sum of black bodies
- Stellar remnant black holes peak in X-rays
- AGN peak at lower energies



4 classic sub-Eddington states

- Differentiated by mass accretion rate, to first-order
- 2-components: accretion disk and 'power-law': ($kE^{-\alpha}$)

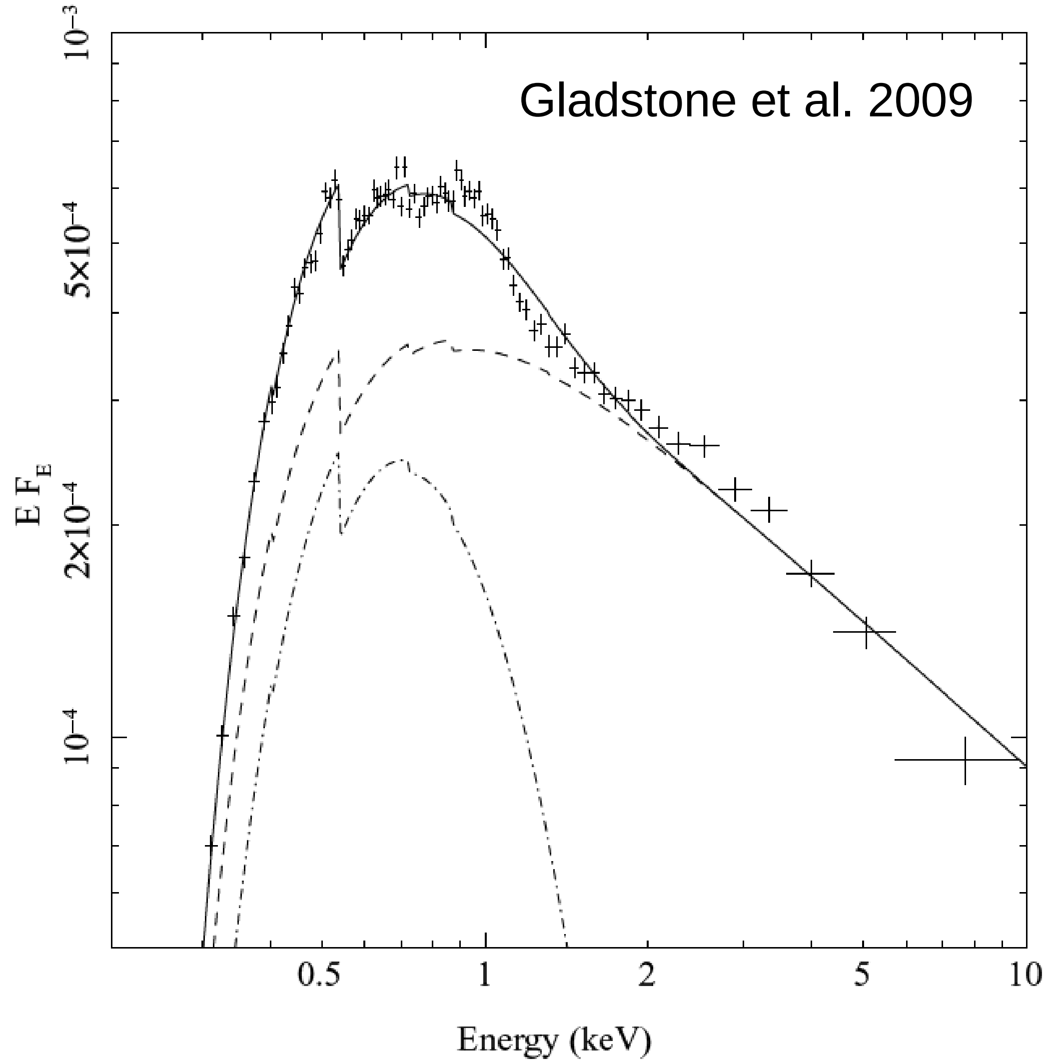




Done et al. 2007

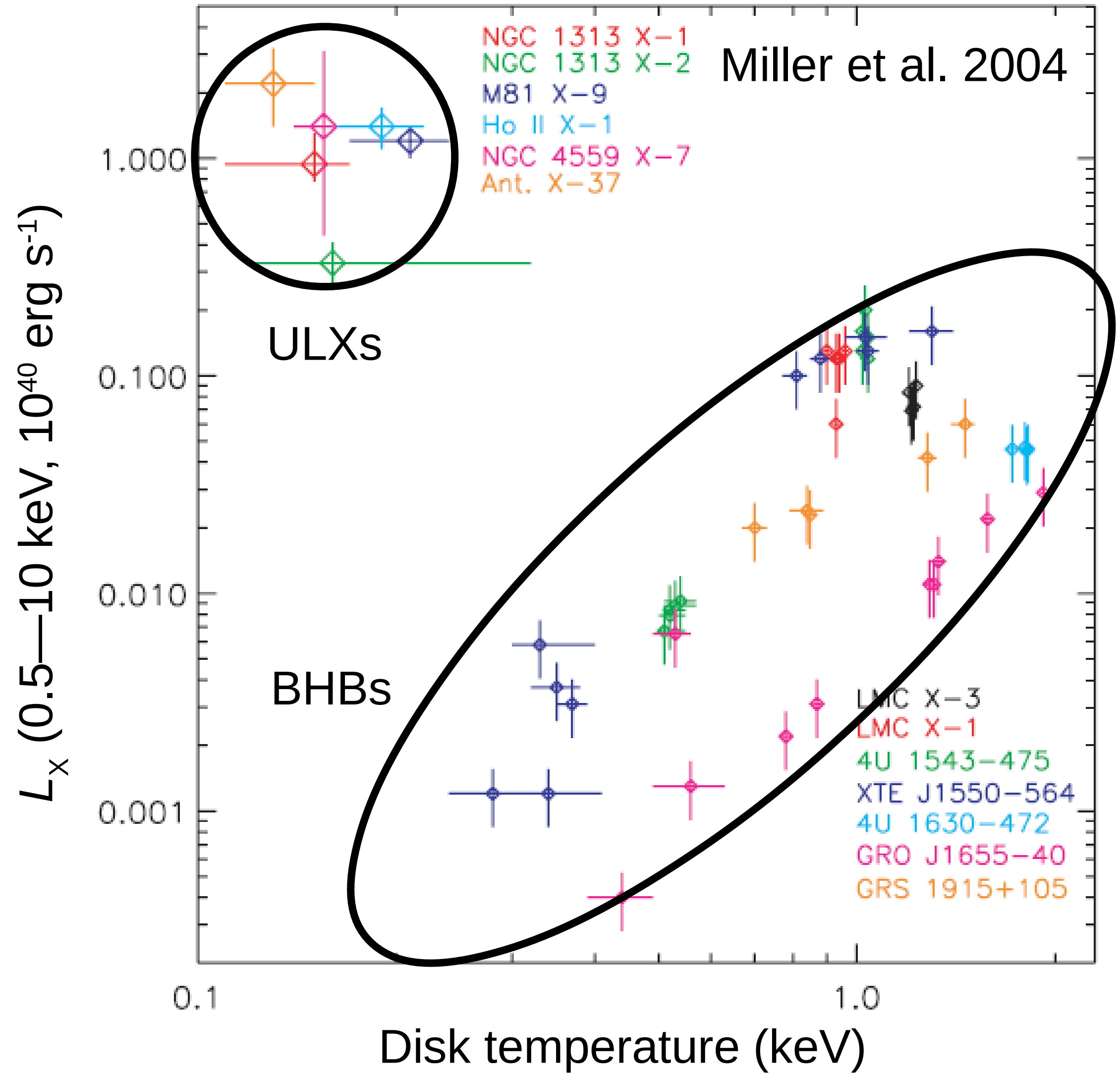
ULX spectra

- Many ULXs are well fitted by the same model
- They have a soft excess
  - Disk emission?
- And a hard power-law



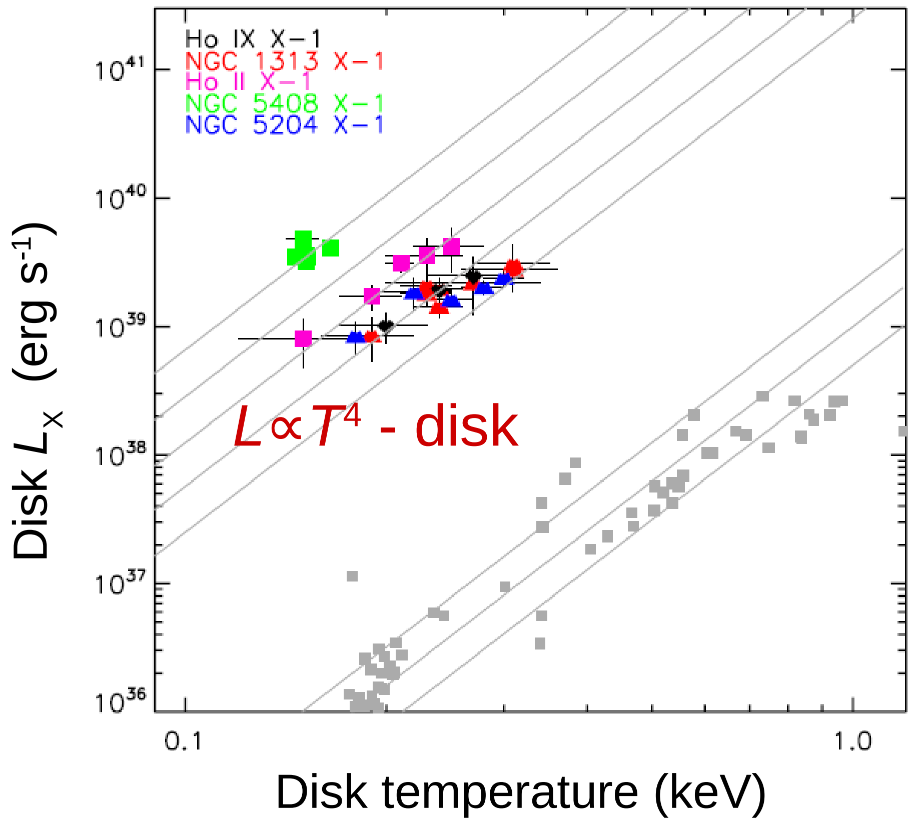
Soft excess: disk emission?

- Accretion disk luminosity - temperature relation:
  - $L \propto MT^4$
- ULXs and BHBs occupy different regions of parameter space
  - Implies $10^3\, M_\odot$ IMBHs

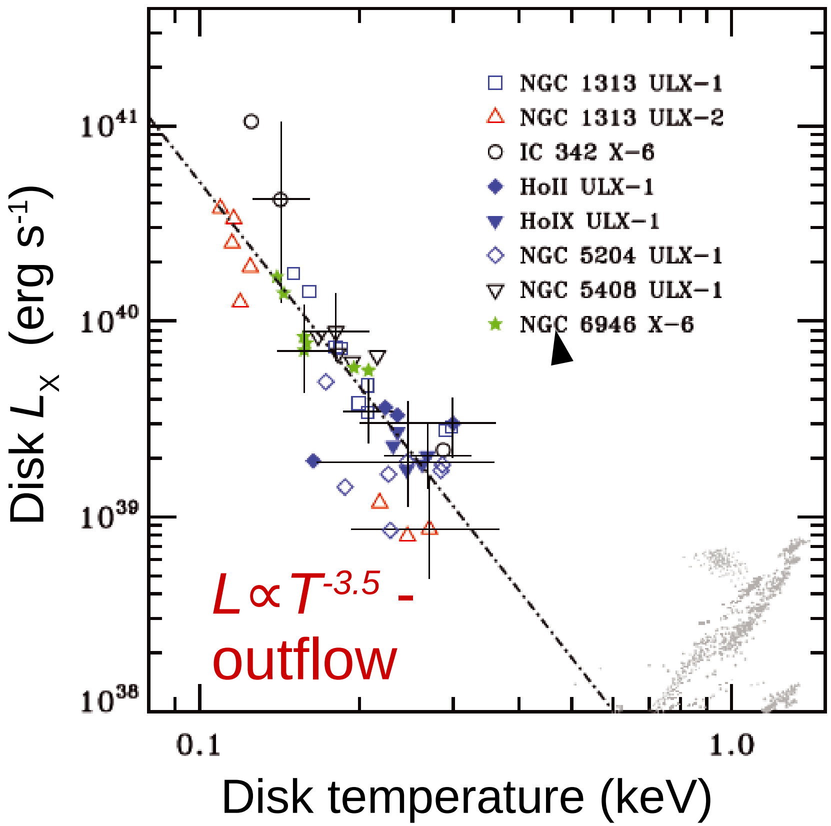


Soft excess: disk emission?

- Inconclusive - ULX *L*-*T* relation depends on assumptions



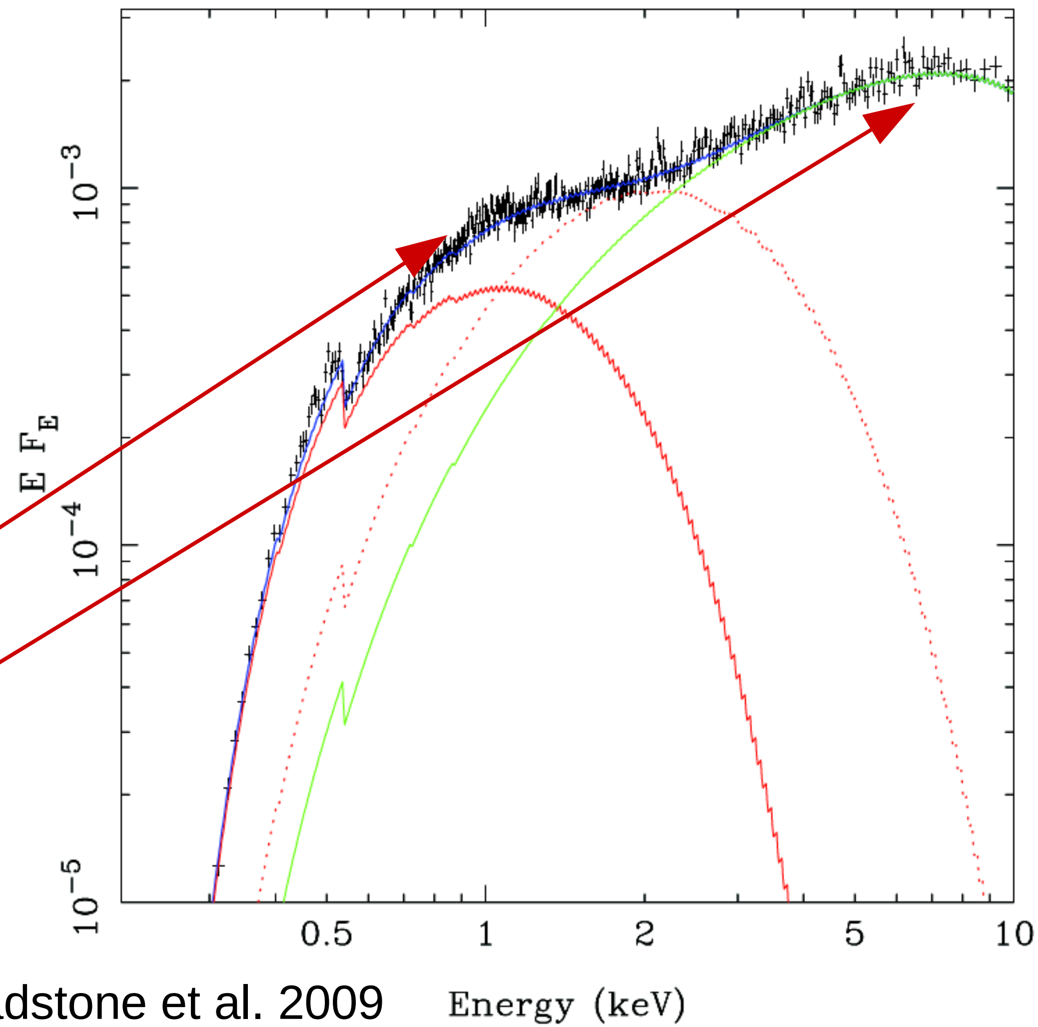
Miller et al. 2013



Kajava & Poutanen 2009

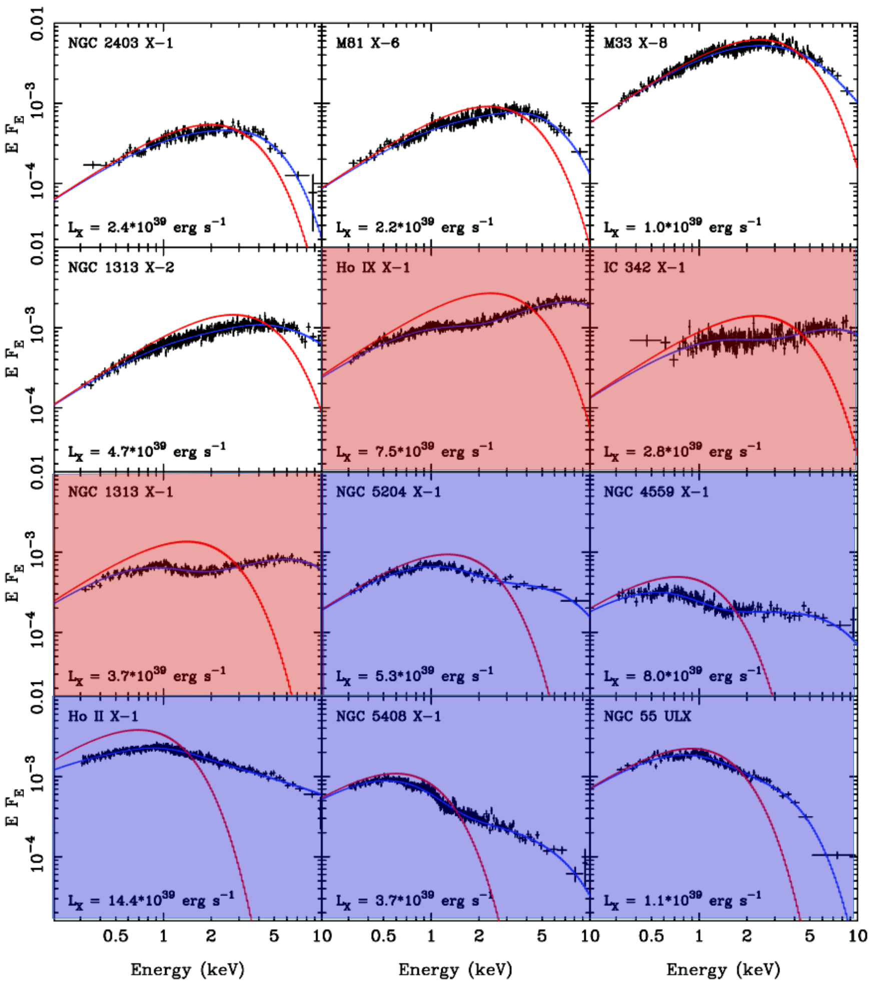
The ultraluminous state

- The highest quality *XMM-Newton* ULX spectra differ from sub-Eddington states
- ULXs are in a new 'ultraluminous' state
  - Characterized by a soft excess
  - And a high energy break



Gladstone et al. 2009

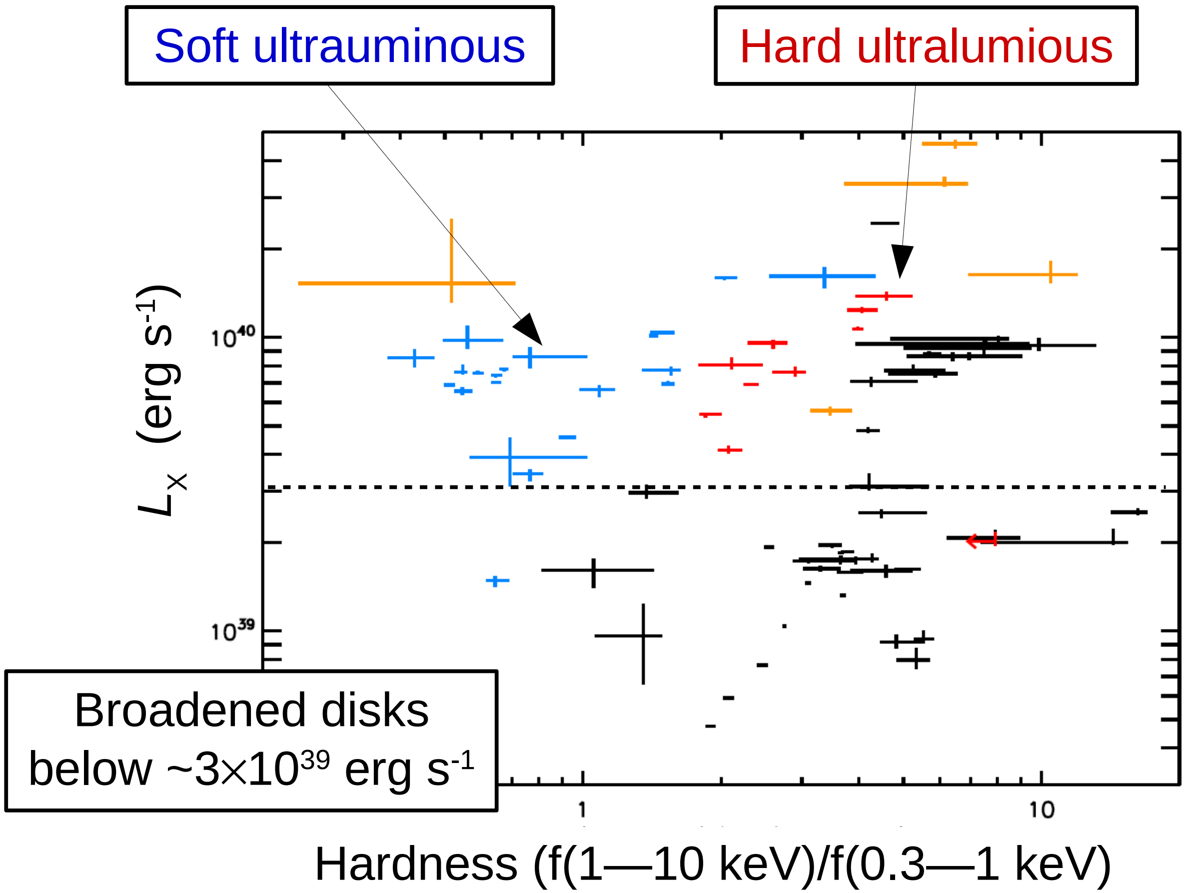
The ultraluminous state

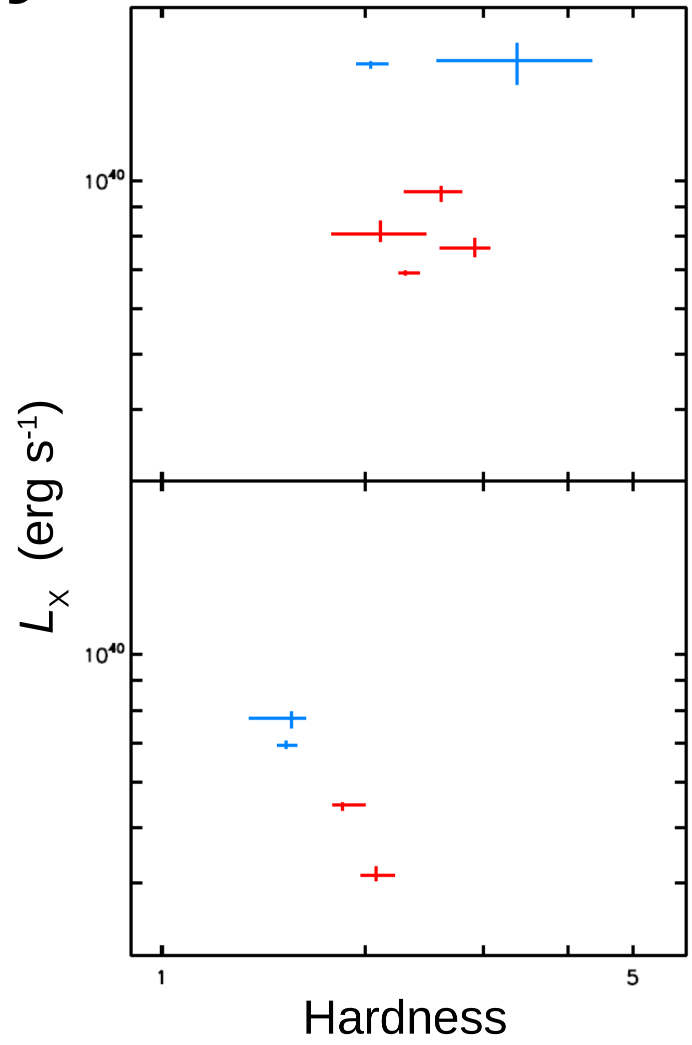


Gladstone et al. 2009

- 3 types of ultraluminous spectra
  - Broadened discs
  - Hard-ultraluminous
  - Soft-ultraluminous

Hardness-luminosity diagram

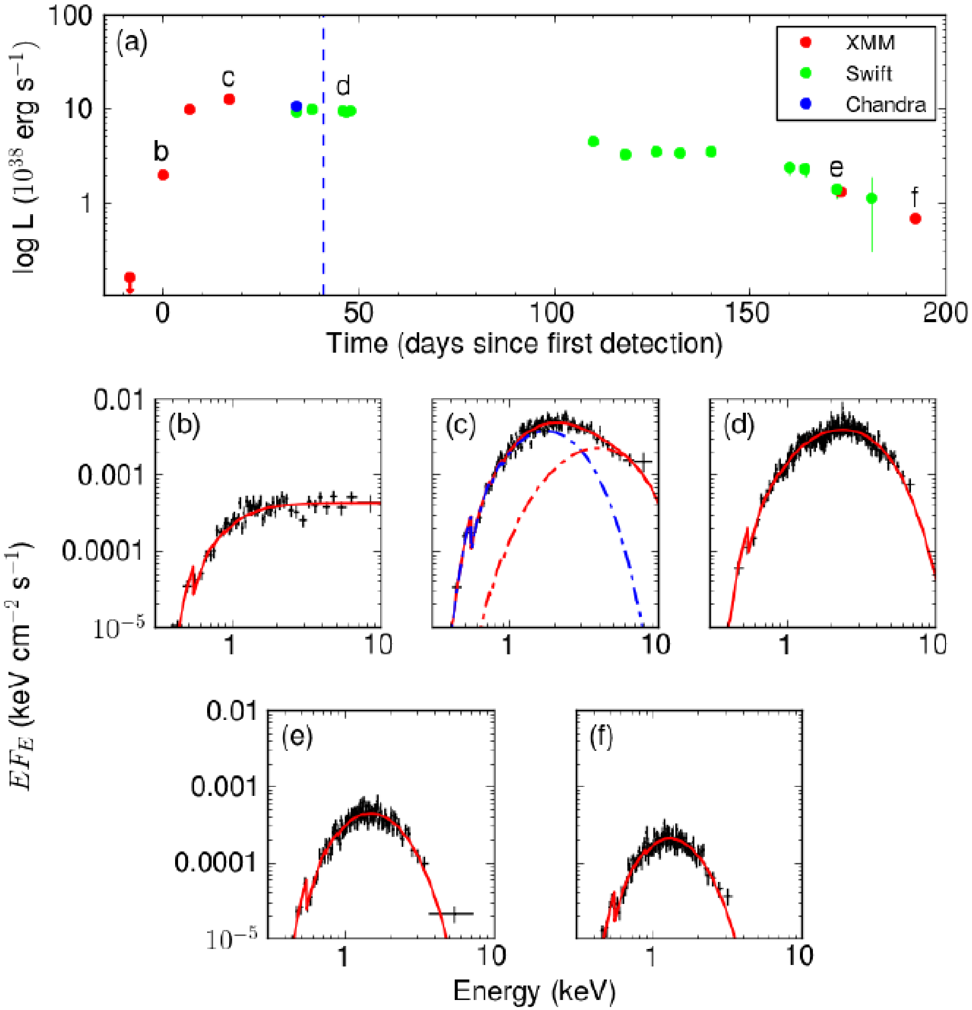




Sutton et al. 2013

Broadened disk ULXs

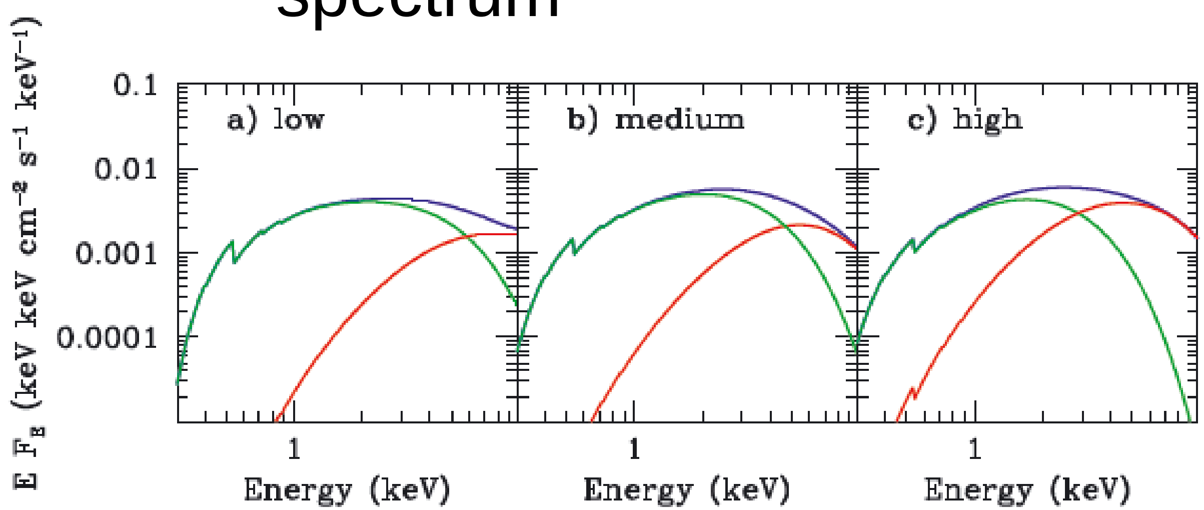
- A few of the faintest ULXs are transients
- A ULX in M31 is seen in a sub-Eddington state when at low L_X
  - Confirmed by radio data
  - $M_{BH} < 17\ M_\odot$



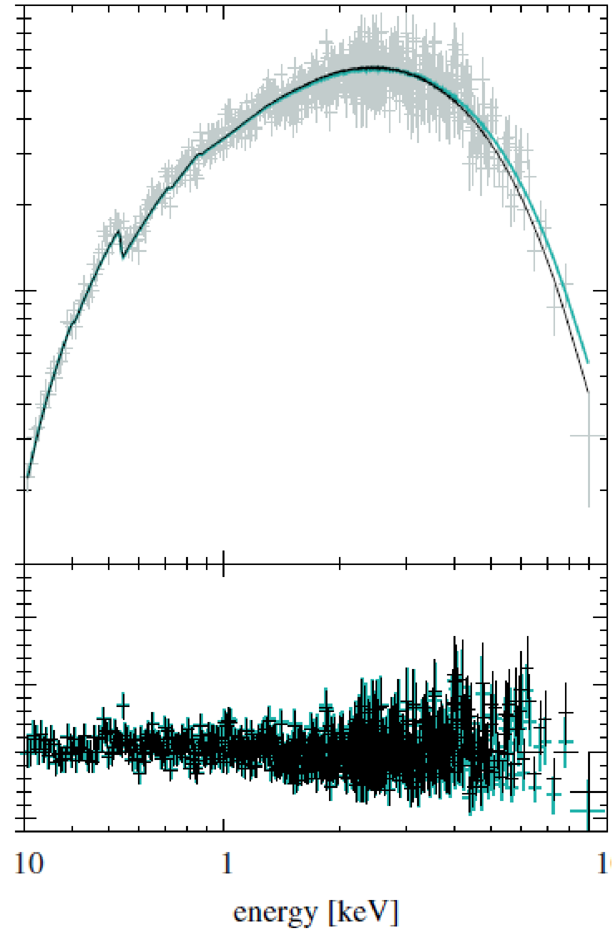
Middleton et al. 2013

Broadened disk spectra

- Another transient: M33 X-8
  - It may have a geometrically slim accretion disk
  - Or an emerging 2-component spectrum

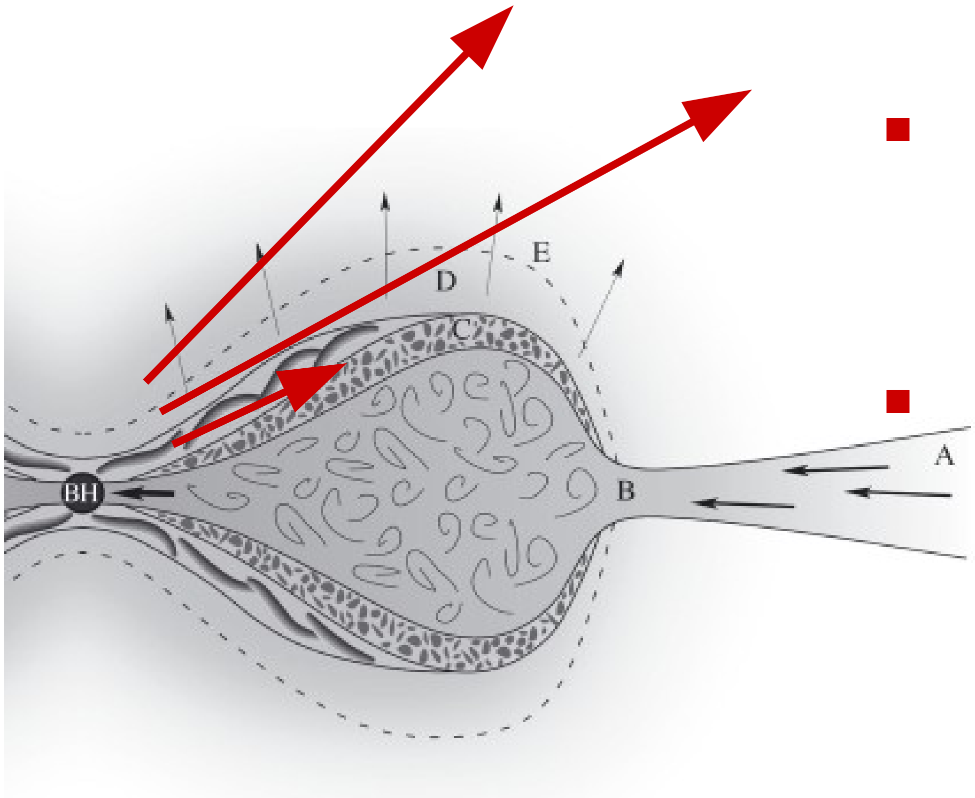


Middleton et al. 2011



Straub et al. 2013

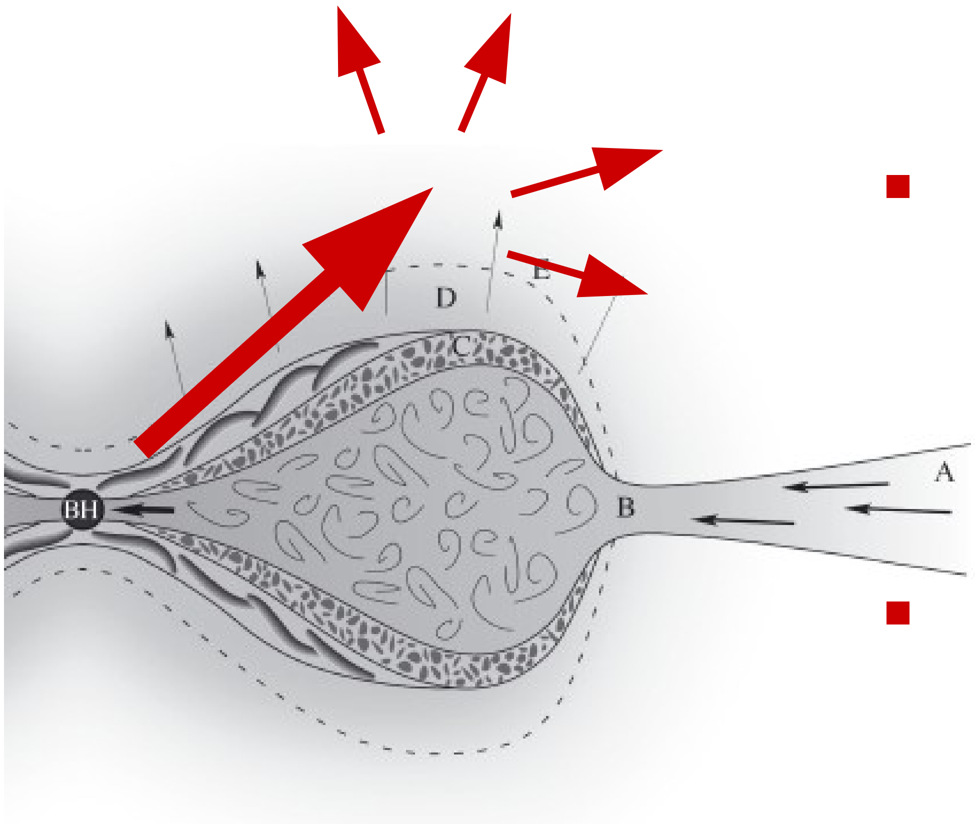
X-ray reprocessing



Modified from Dotan & Shaviv 2011

- X-rays irradiate the outer-disk and are re-emitted as optical/UV photons
- ULX reprocessing fractions are similar to thin disks (Sutton et al. 2014)
  - This may be inconsistent with slim disks

X-ray reprocessing

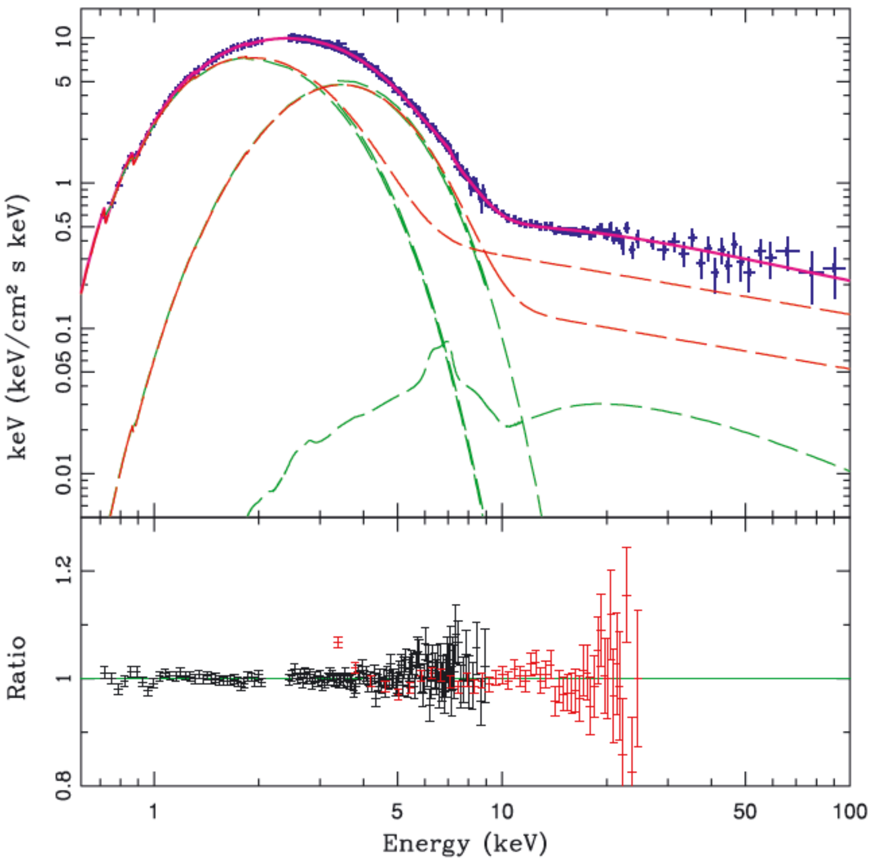


Modified from Dotan & Shaviv 2011

- Scattering in an optically thin phase of an outflow may oppose the obscuration by the disk bulge
- But it seems highly contrived for these effects to cancel out

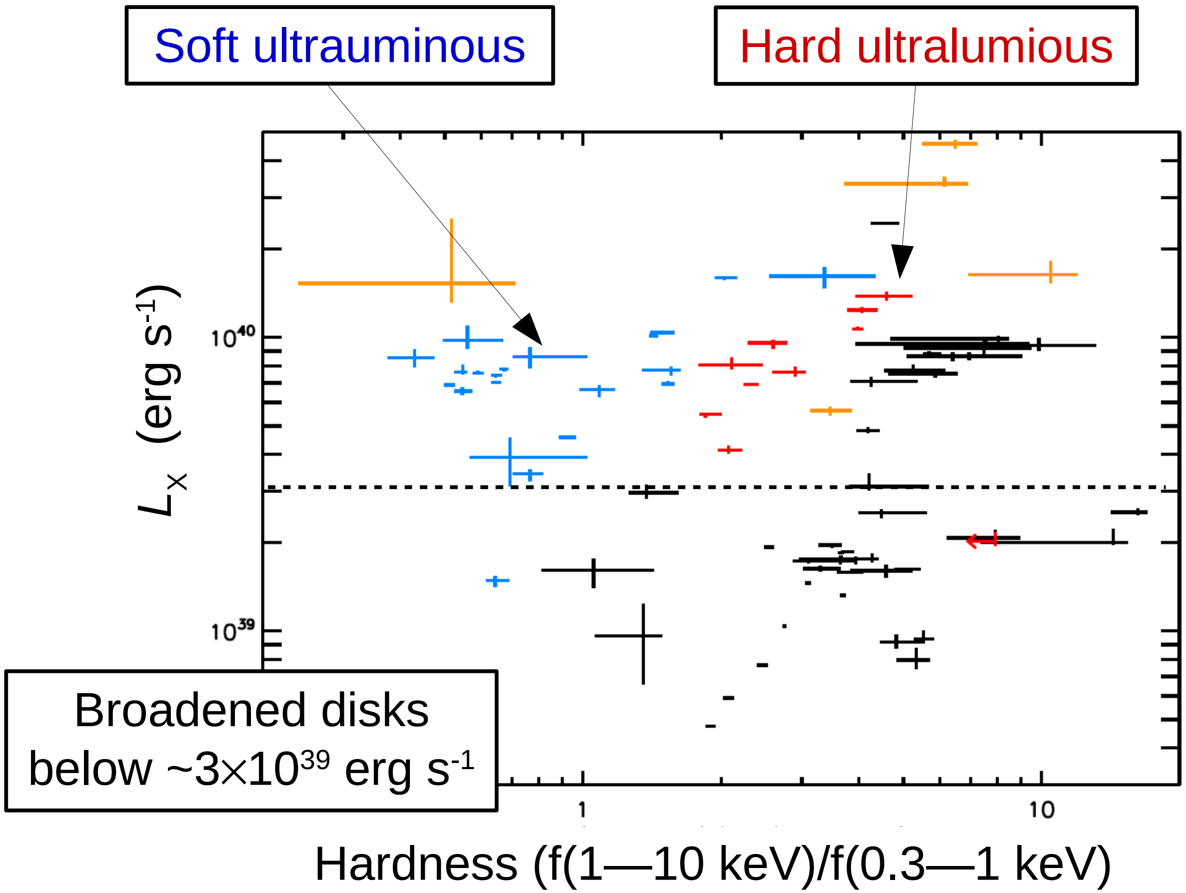
A comparison of BHB and ULX disk spectra

- Sutton et al. In prep.: some sub-Eddington BHB disk spectra are also broader than expected
- ULX-like phenomenological models can reproduce the broad sub-Eddington disk spectra
- Broad disk spectra do not necessarily imply slim disks

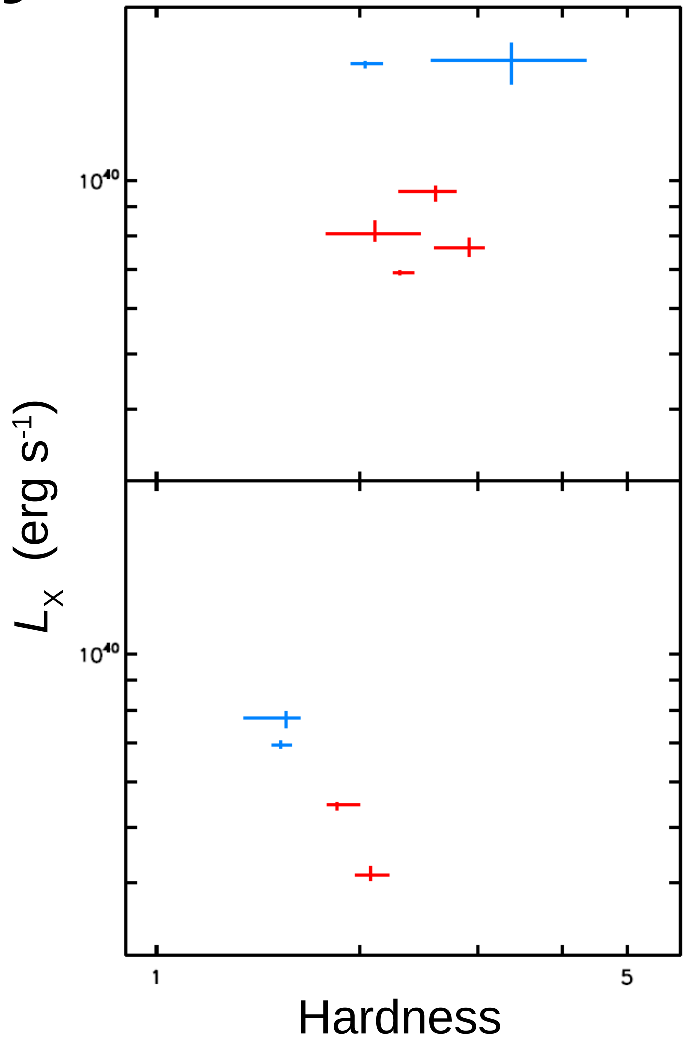


Kolehmainen et al. 2011:
GX 339-4 with *XMM* and *RXTE*

Hardness-luminosity diagram

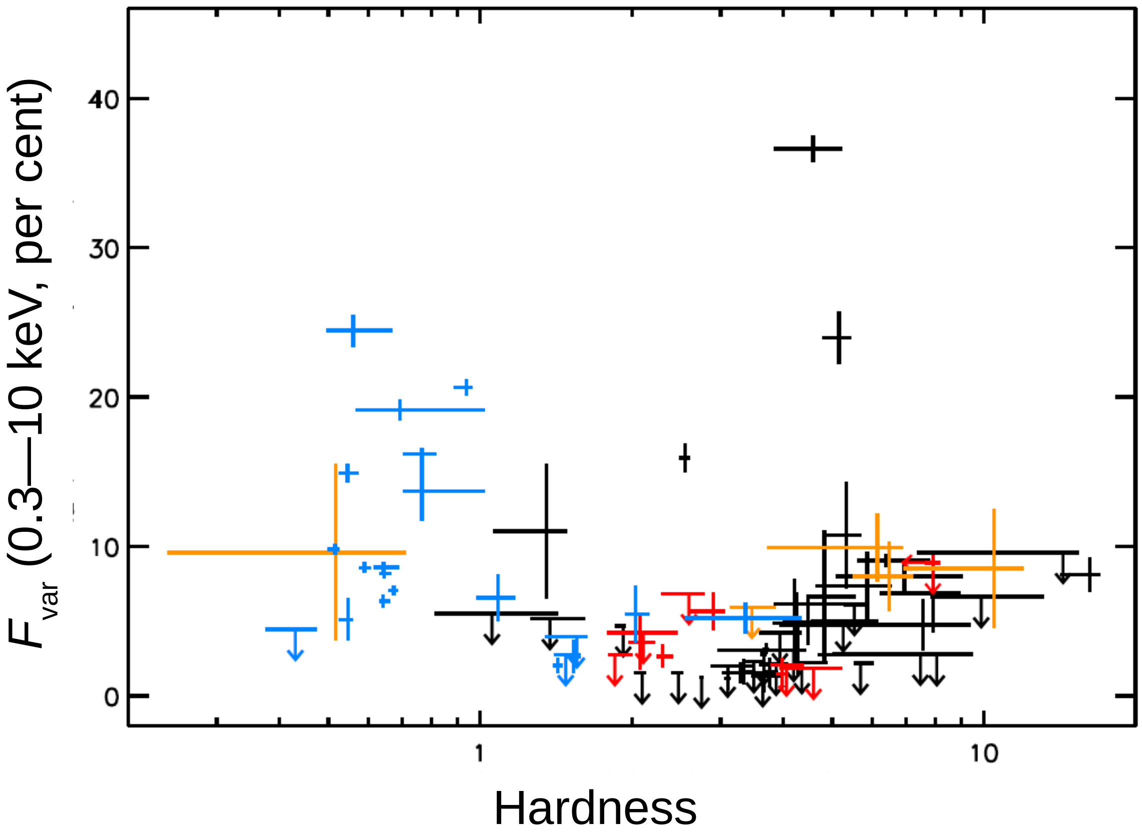


Sutton et al. 2013



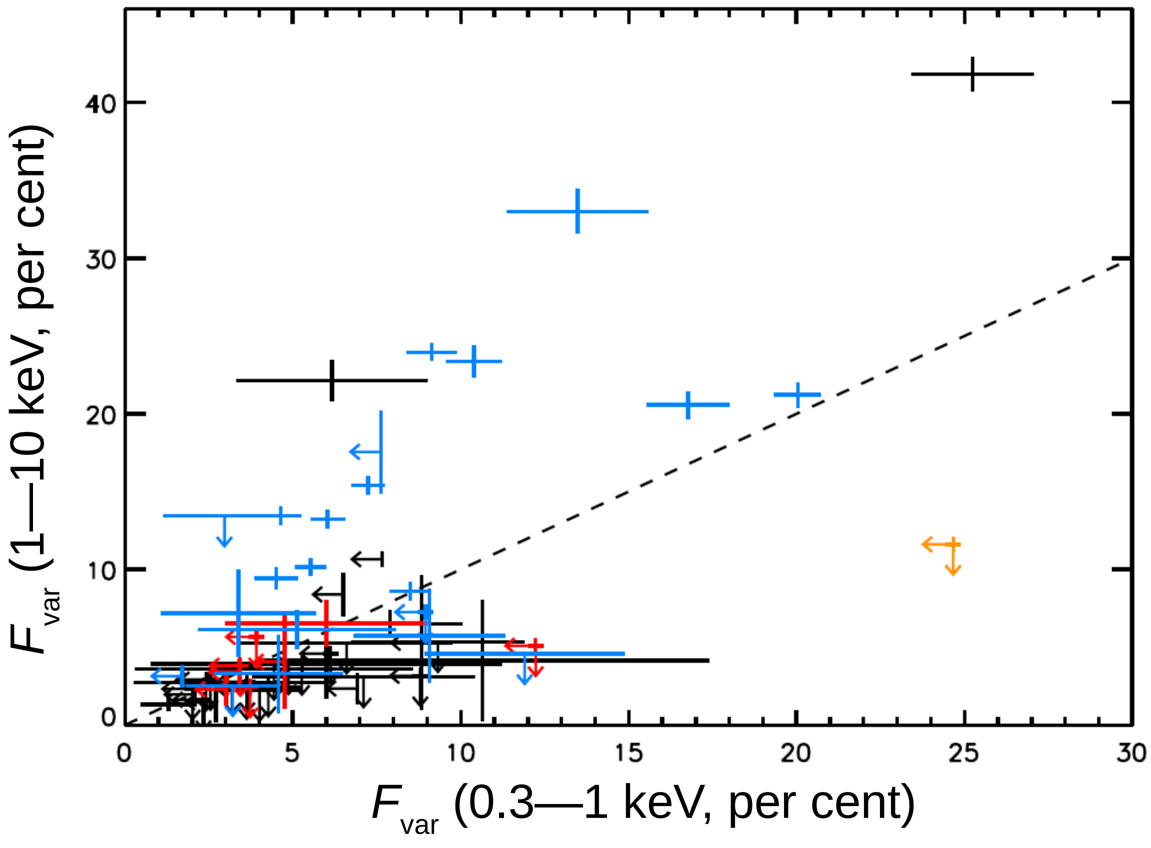
Fractional variability

- High levels of variability seen in soft ultraluminous ULXs
- Variability ≤ 10 % in hard ultraluminous sources



Sutton et al. 2013

Fractional variability

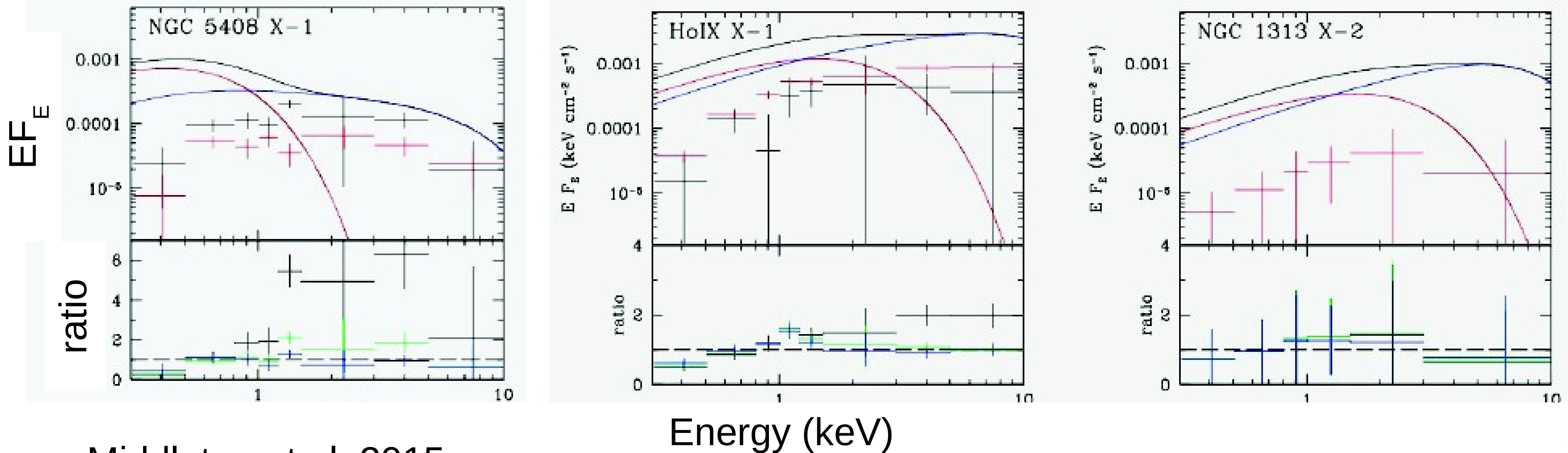


Sutton et al. 2013

- Soft ultraluminous ULXs are more variable
- The variability is significantly greater in the hard band

Covariance

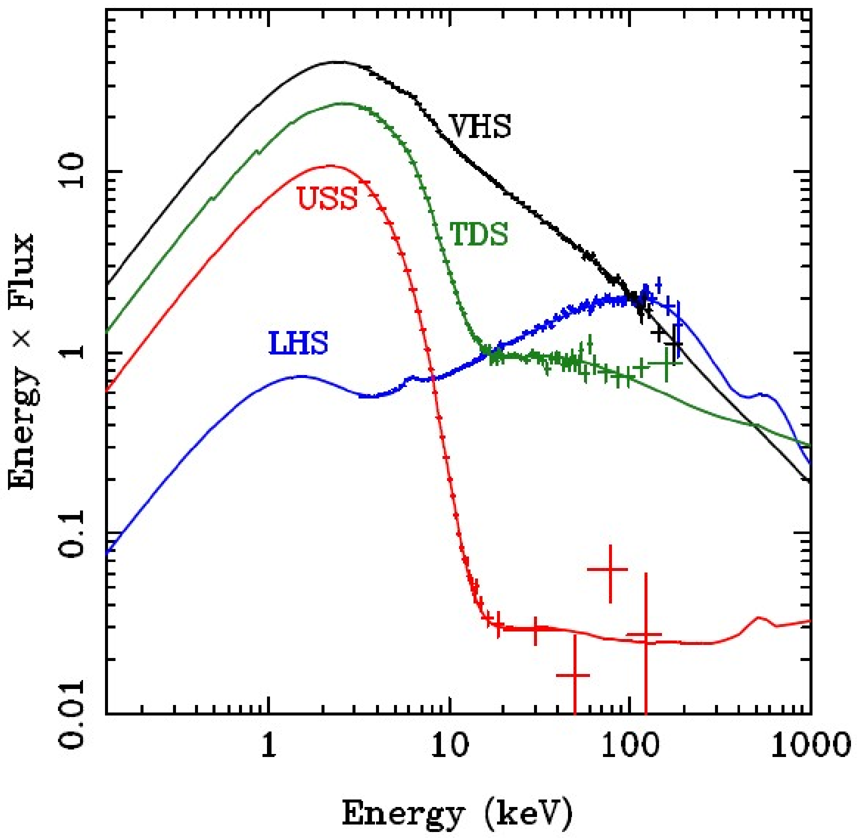
- Confirms that the variability is consistent with originating in the hard spectral component

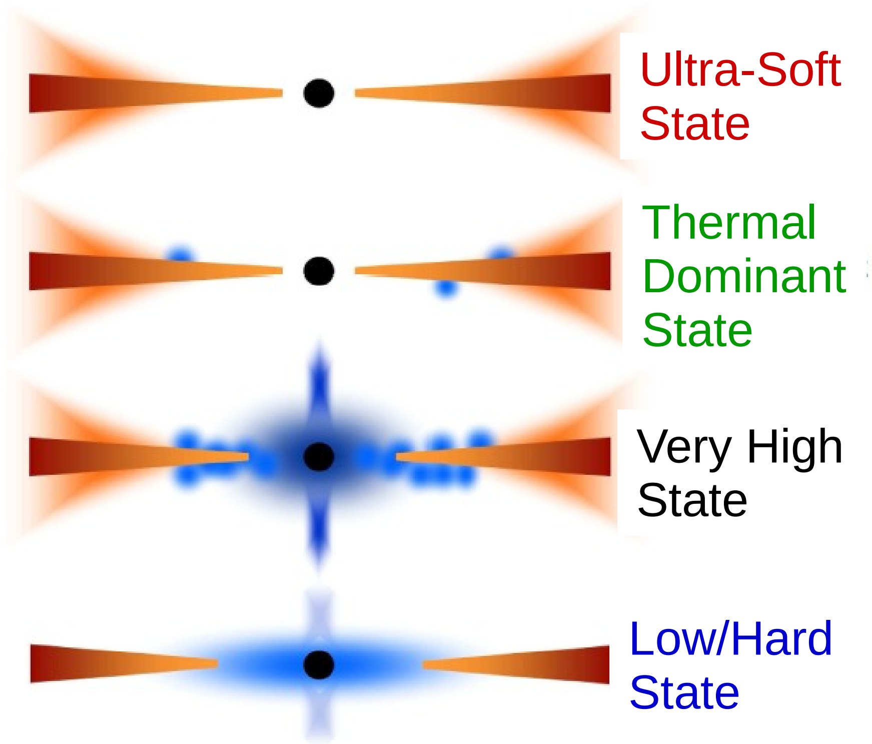


Middleton et al. 2015
Top: spectral model and contributing components (lines), and 3 – 200 mHz (black points) and 0.9 – 3 mHz (red points) covariance relative to 1.5 – 3 keV band; *Bottom:* ratios from re-normalizing the spectral model to the covariance data, with component ratios fixed (black), free (green) and hard component only (blue)

4 classic sub-Eddington states

- Differentiated by mass accretion rate, to first-order
- 2-components: accretion disk and 'power-law': ($kE^{-\alpha}$)



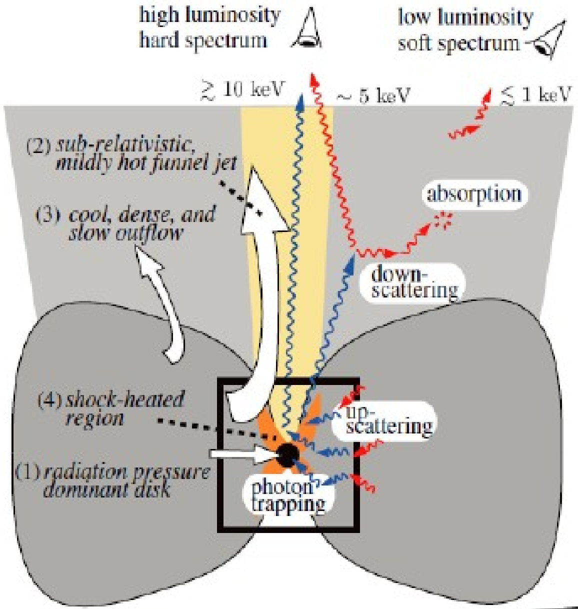


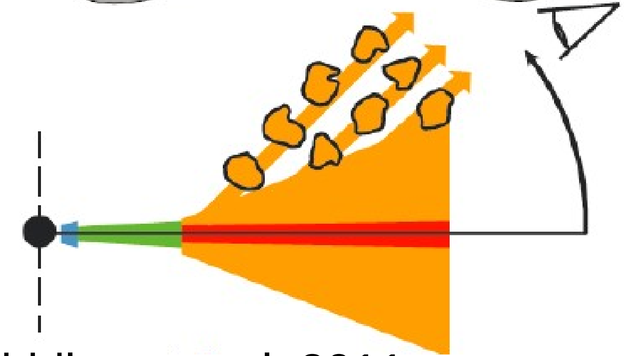
Done et al. 2007

Interpreting the X-ray properties

- Inclination is key in determining the X-ray spectra
  - Funnel shaped wind
  - Face on: hard ultraluminous
  - Off-axis: soft ultraluminous
- Variability supports this
  - Clumpy wind imprints variability
  - Suppressed variability if wind is out of line-of-sight
- State transitions could be due to changes in the wind opening angle

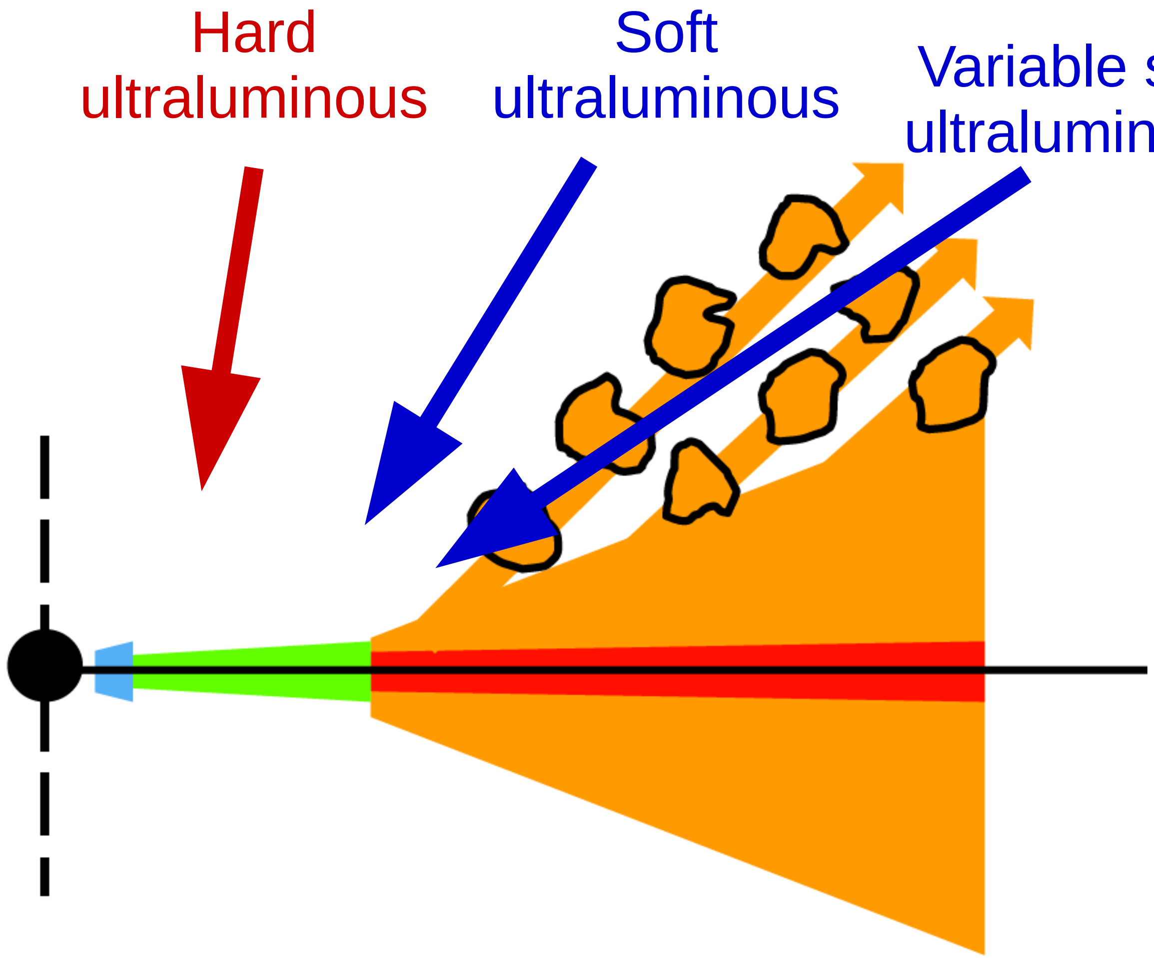
Kawashima et al. 2012

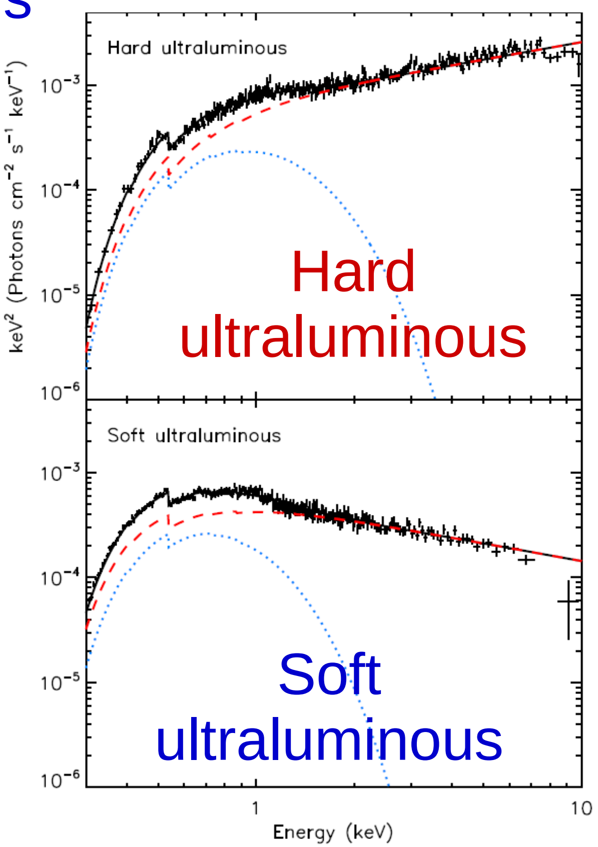




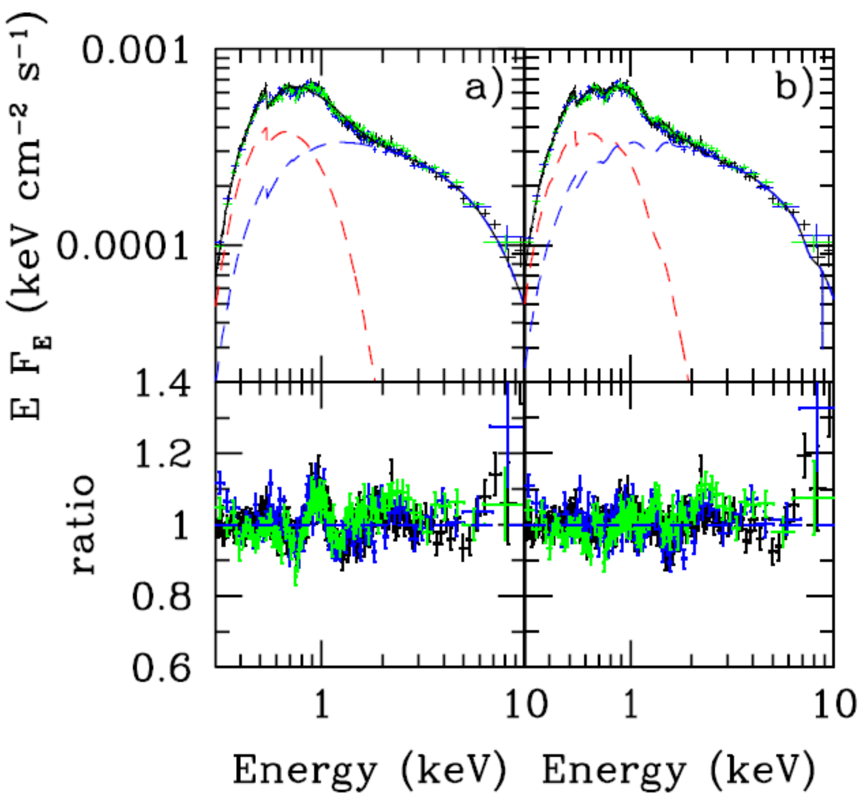
Middleton et al. 2011

Interpreting the X-ray properties





Potential soft absorption features

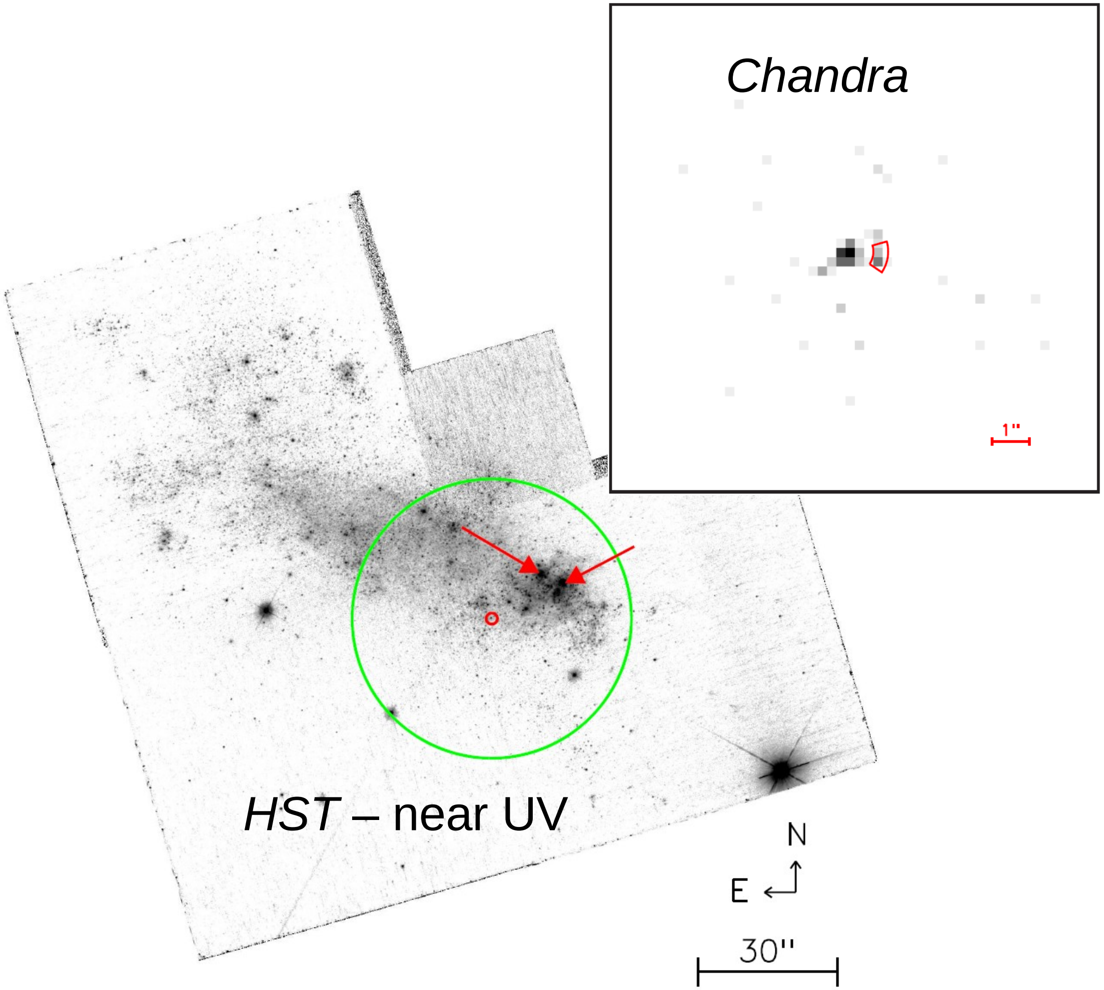


Soft residuals in NGC 5408 X-1
Middleton et al. 2014

- ULXs can have soft residuals
- Absorption by a partially ionised, blue-shifted (0.1 c) material – such as a wind
- But, they can also be well-fitted by thermal plasma emission models
  - Diffuse emission related to star-formation

NGC 5408 X-1 with *Chandra*

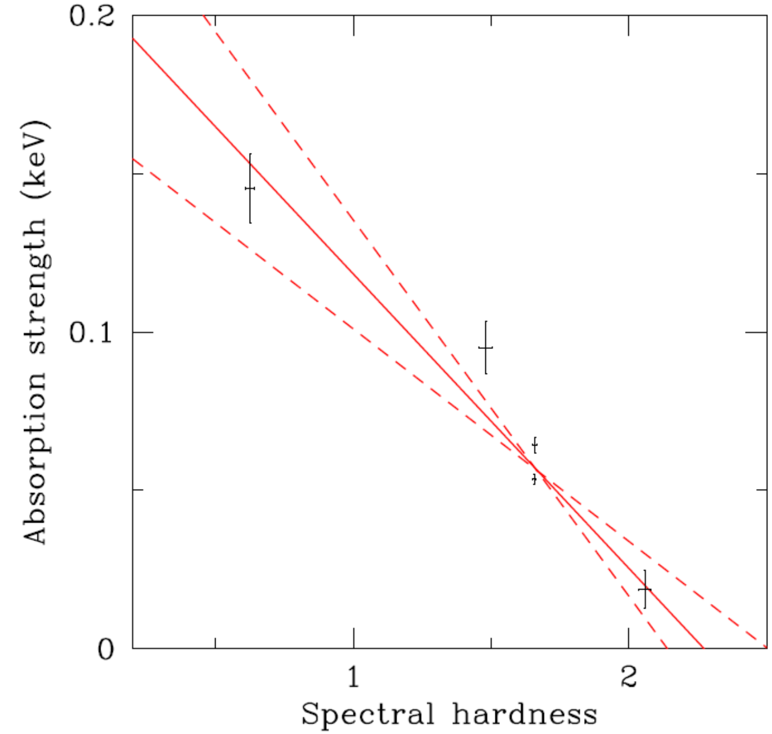
- The ULX is not resolved from star-formation regions with *XMM-Newton*
- But it can be resolved by Chandra
- >2/3 of the putative plasma emission remains unresolved



Sutton et al. 2015

An evolving wind

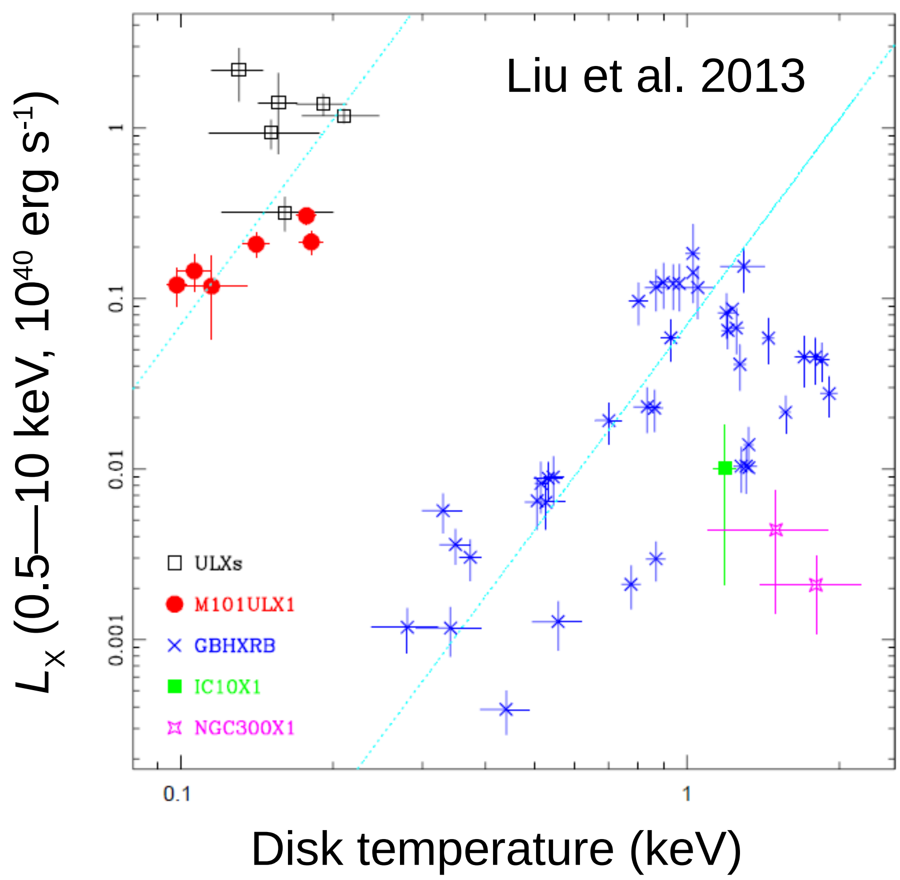
- Residuals are seen in both hard- and soft-ultraluminous sources
- The absorption strength is anti-correlated with spectral hardness in NGC 1313 X-1
  - which is consistent with a wind



Middleton et al. 2015

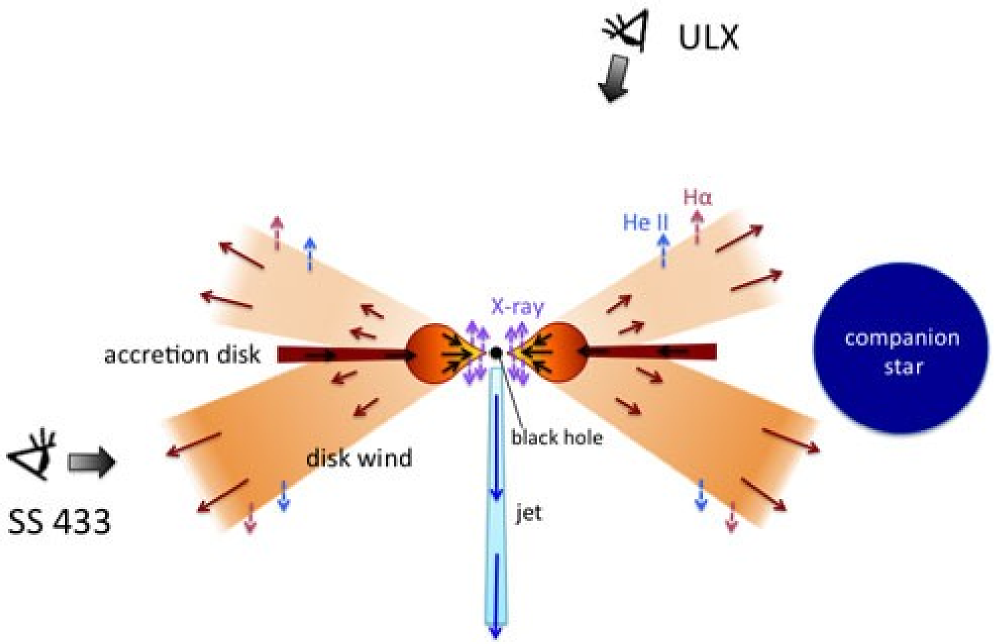
Ultraluminous super-soft X-ray sources (ULSs)

- ULSs have super-soft thermal disk spectra
- A cool disk may imply an IMBH
- Or the photosphere of an edge-on super-Eddington ULXs may peak in soft X-rays (e.g King & Muldew 2015)



A Galactic ULS?

- SS 433 is a Galactic binary with an extreme accretion rate of ~10^4 times the Eddington rate
  - It is edge-on, so we do not see a ULX
  - The photosphere peaks below X-rays so we do not see a ULS



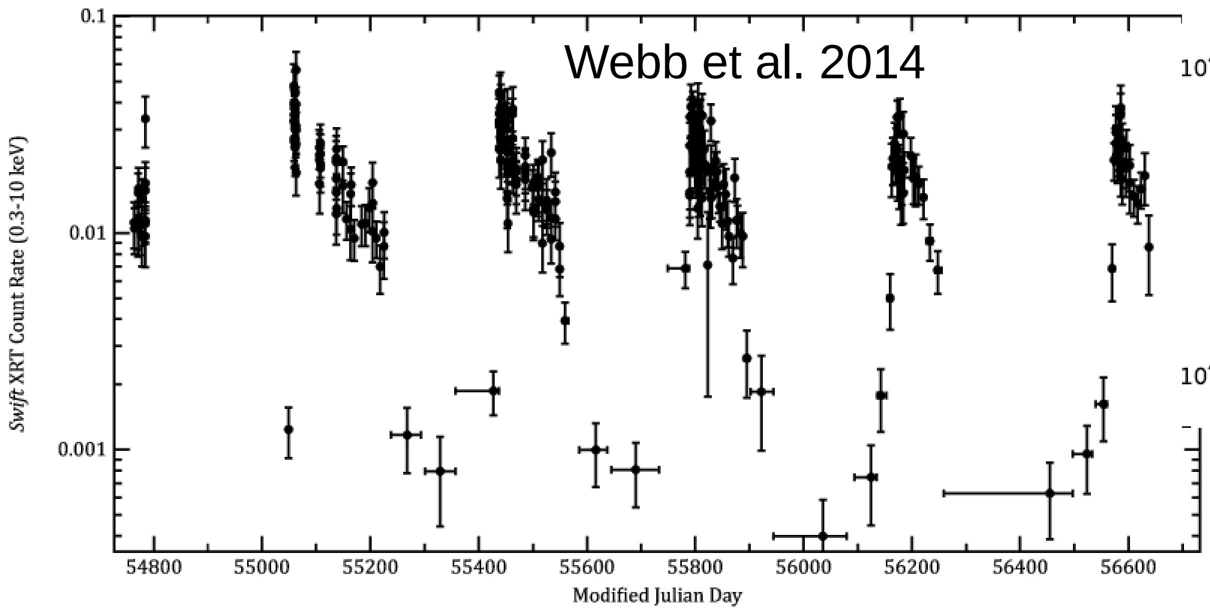
(Kyoto University)

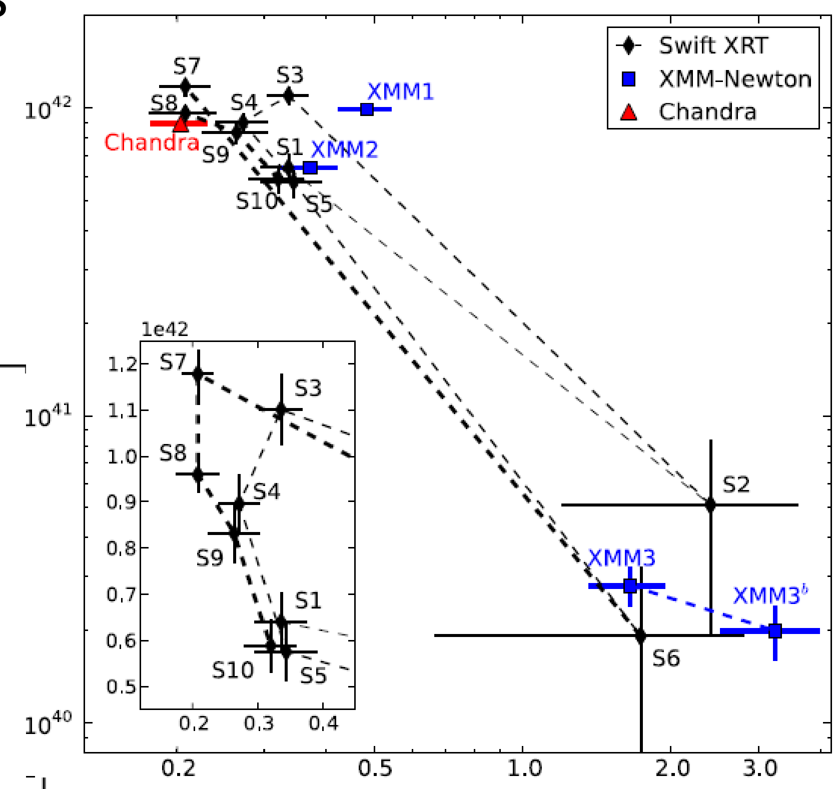
Conclusions

- Most ULXs are stellar remnant black holes in a new, extreme accretion state
- At around the Eddington limit ULXs have broadened disk spectra
- At even higher, super-Eddington accretion rates ULXs are characterized radiatively driven outflows, and inclination is key in determining the observed X-ray properties
- ULSs may be the same class of source, but observed edge-on

IMBH ULXs

- The brightest ULXs may still be IMBHs
- Most famous: ESO 243-49 HLX-1
  - Sub-Eddington state transitions
  - But at $L_X \sim 10^{40} - 10^{42}$ erg s^{-1}

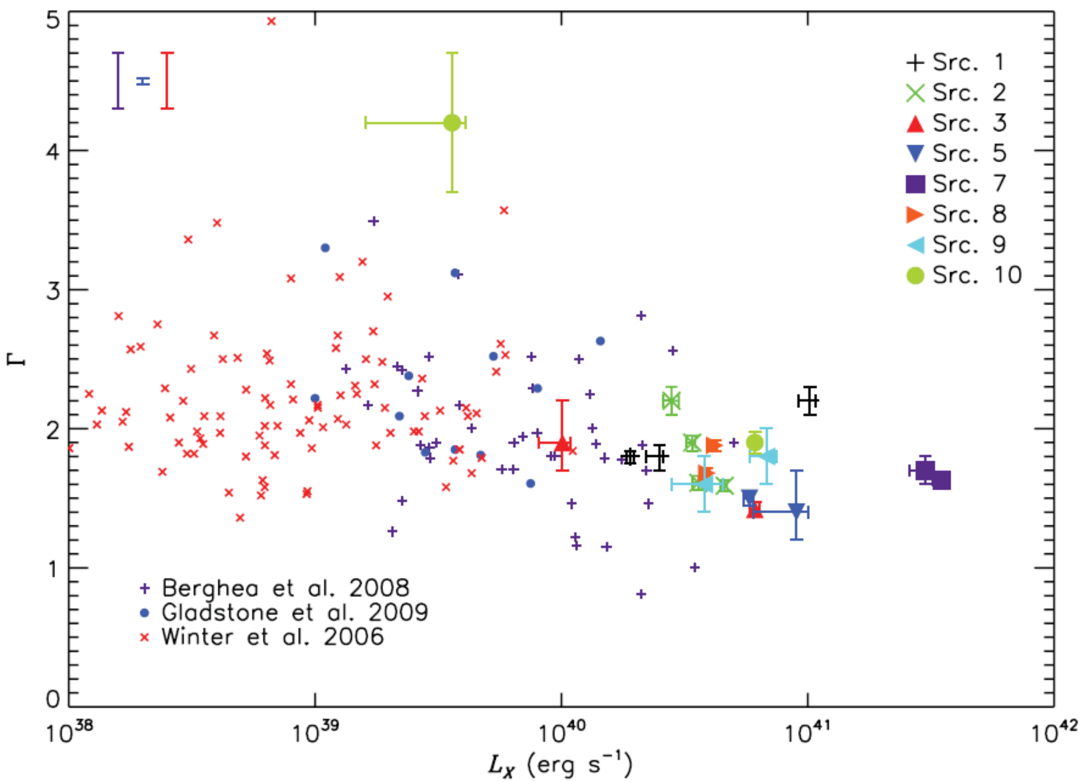




Servillat et al. 2011

IMBH ULXs

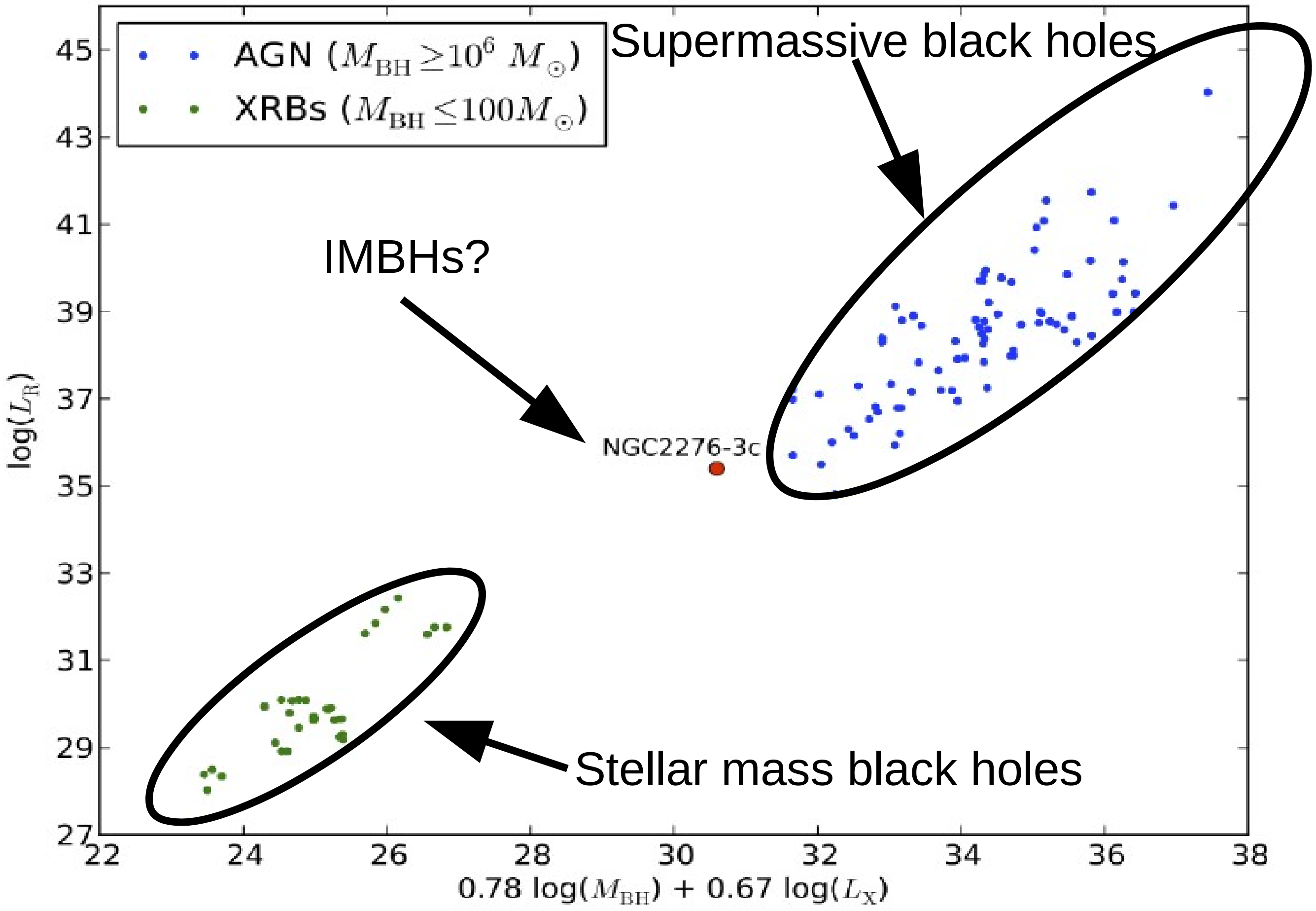
- ULXs more luminous than ~ 5×10^{40} erg s^{-1} have hard power-law spectra and ~ 10% fractional variability
- Reminiscent of the low hard state (L/L_{Edd} ~ 0.1)
  - $10^3 - 10^4\ M_\odot$ IMBHs
- But cannot completely rule out ultraluminous state spectra



Sutton et al. 2012

IMBH ULXs

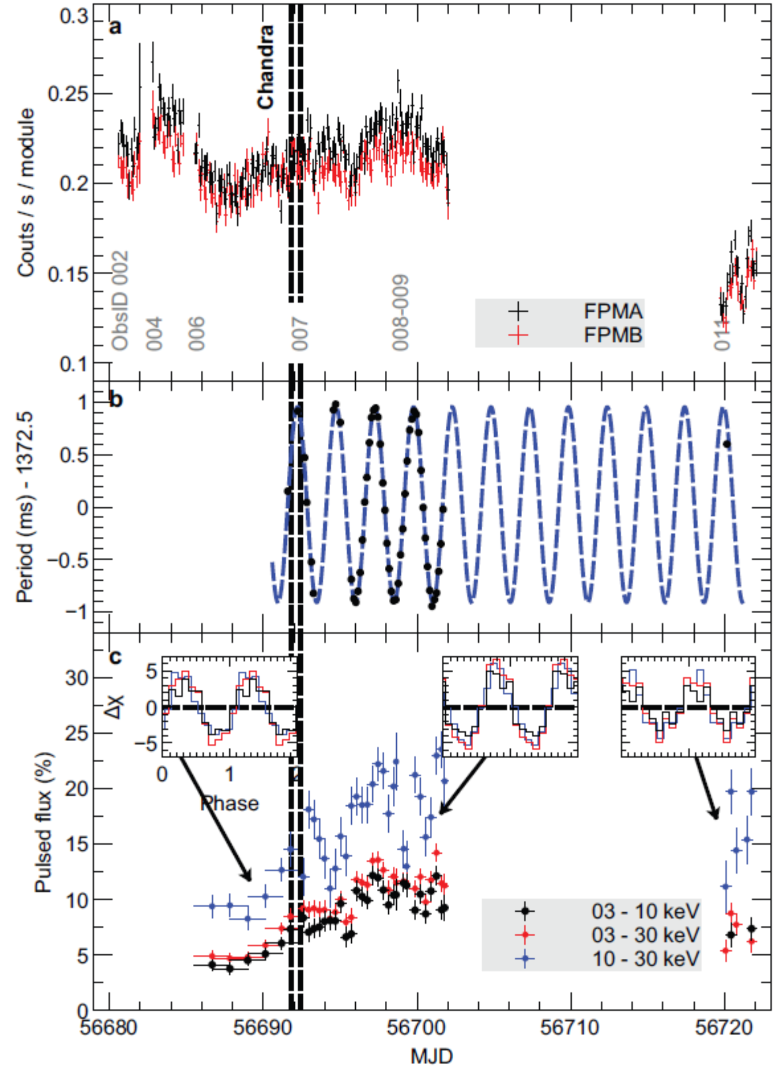
- NGC 2276-3c peaks at $L_X \sim 6\times10^{40}$ erg s^{-1}
- Low/hard state-like in X-rays and radio
- Its position on the X-ray – radio fundamental plane implies a 5×10^4 $M_\odot$ black hole



Mezcua et al. 2015

A neutron star ULX

- 0.7 Hz pulsed flux detected in M82 with *NuSTAR* indicating a pulsar
- Most likely from a ULX M82 X-2
  - With peak $L_X \sim 1.8 \times 10^{40}$ erg s^{-1}
  - Or 100 L_{edd} for a 1.4 $M_{\odot}$ neutron star



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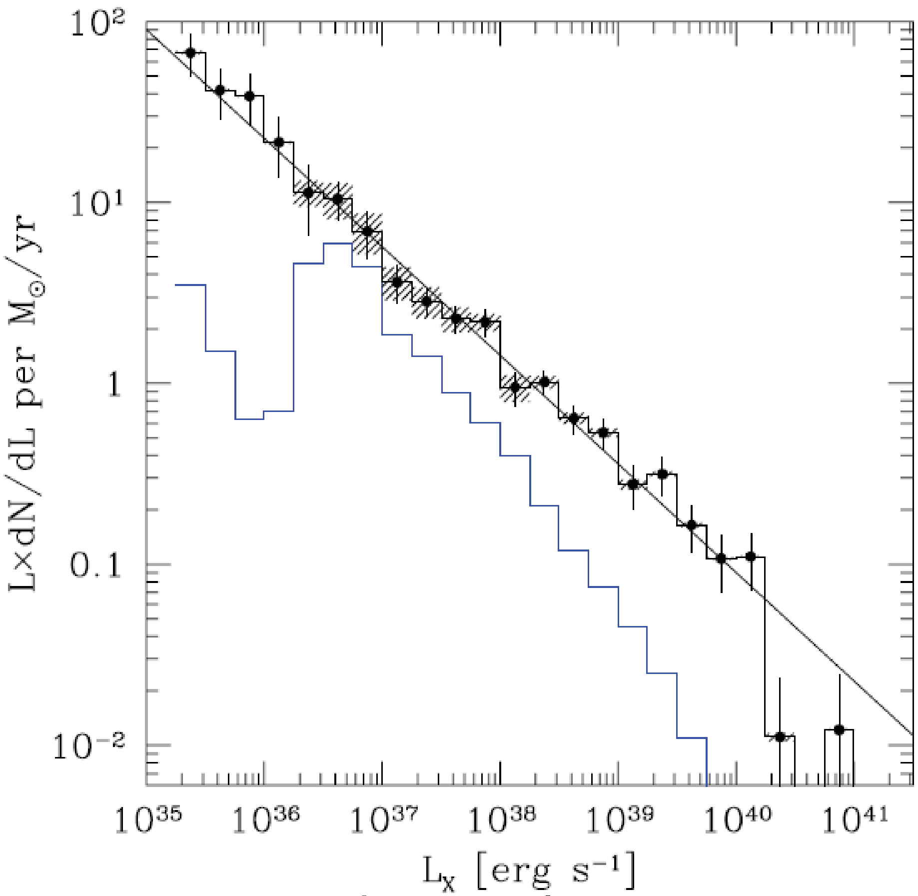
- At even higher, super-Eddington accretion rates ULXs are characterized radiatively driven outflows, and inclination is key in determining the observed X-ray properties
- ULSs may be the same class of source, but observed edge-on
- A sub-set ULXs may still contain IMBHs, and at least one even contains a neutron star primary

Problems with IMBHs 1

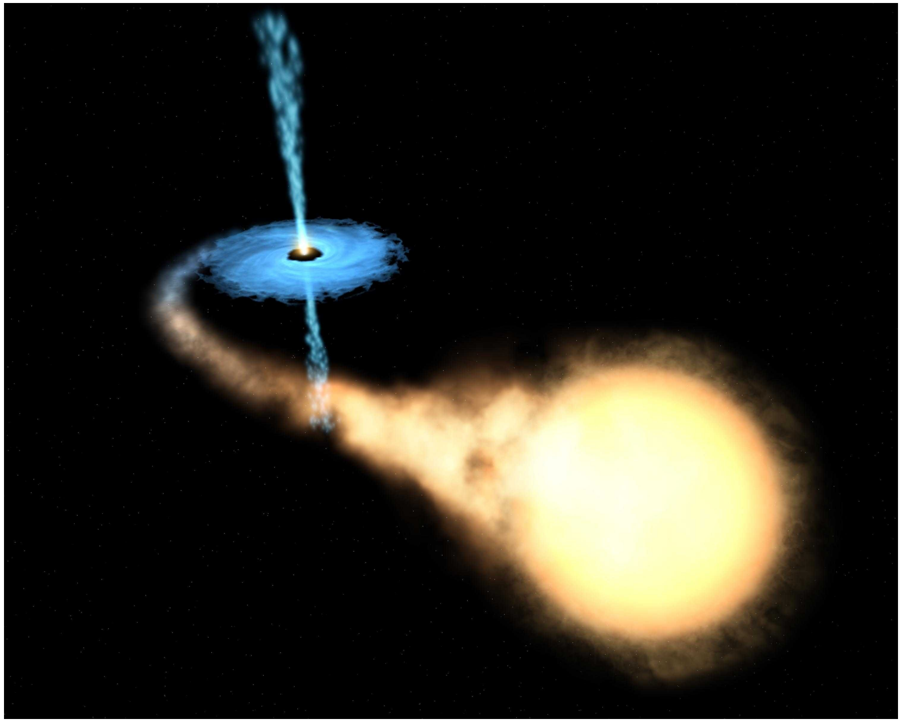
- The X-ray luminosity function normalized by star-formation is a power-law over 5 decades in L_X
- Breaks at ~10^{40} erg s^{-1}
- $10^3\, M_\odot$ IMBHs would have to switch off at ~ 0.1 L_{Edd}



Mineo et al. 2012

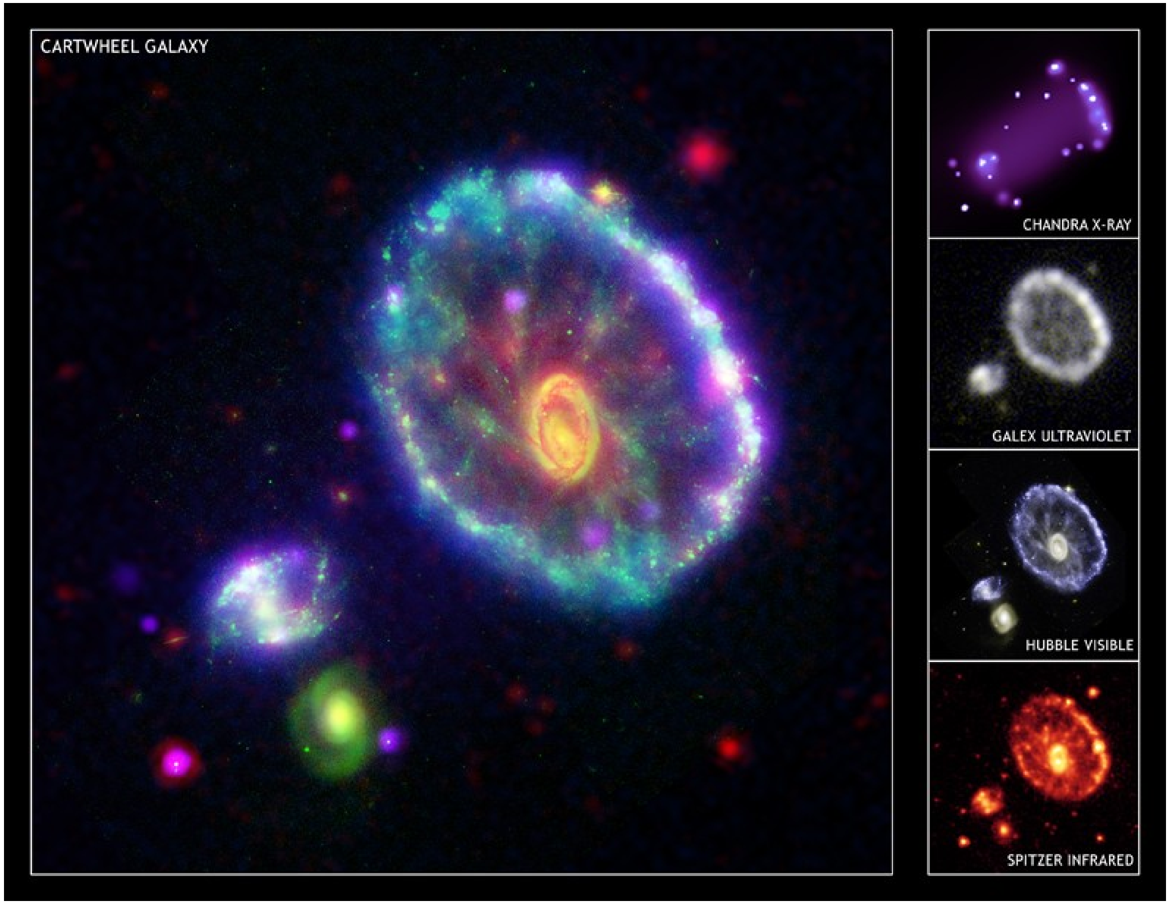
Problems with IMBHs 2

- IMBHs need a supply of mass to accrete
  - The best option: a companion star
- But, models under-predict IMBH ULXs by a factor ~ 10 – 100 (Madhusudhan et al. 2005)



Problems with IMBHs 3

- Cartwheel galaxy
- Unfeasibly high fraction of mass in black holes, if all ULXs are IMBHs
- Most ULXs must contain stellar-remnant black holes



Chandra, GALEX, Hubble, Spitzer - Composite: NASA/JPL/Caltech/P.Appleton et al.