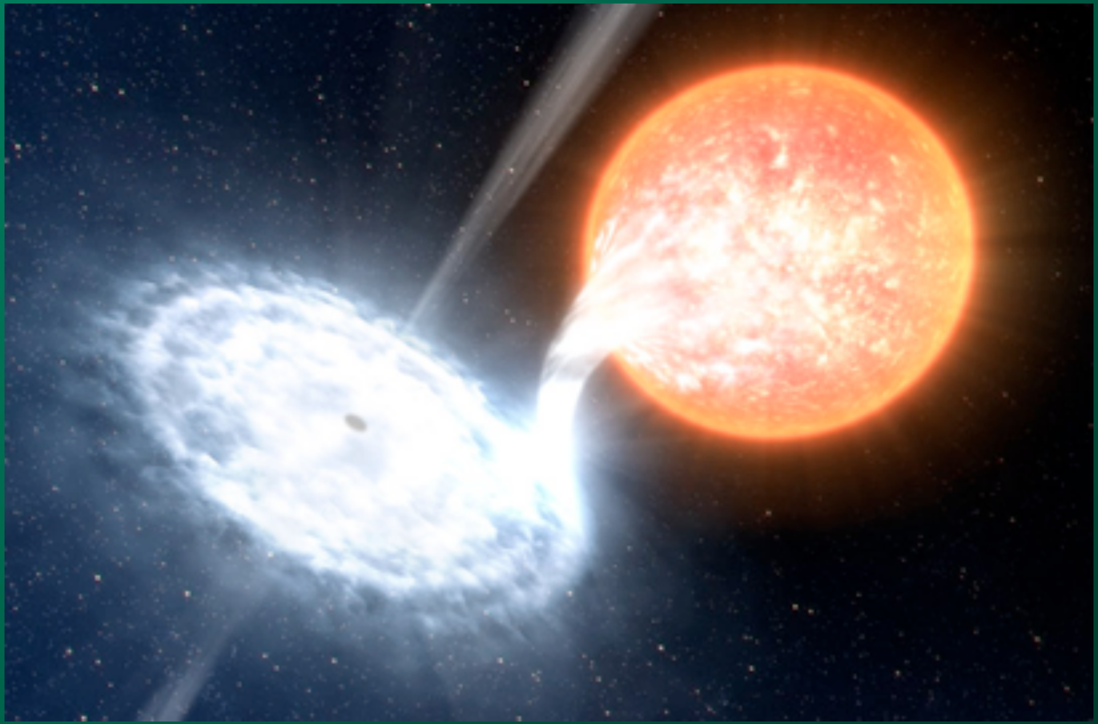


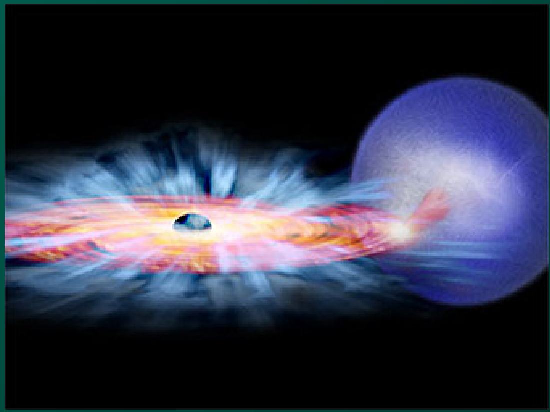
Ultraluminous X-ray sources and the search for intermediate mass black holes

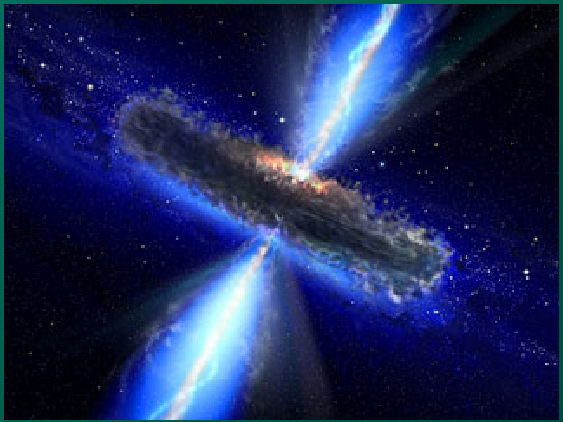
Jeanette Gladstone

UNIVERSITY OF ALBERTA

Black hole masses ...

- ★ Stellar-mass black holes
  - ★ $3\ M_\odot < M_{BH} < 80\ M_\odot$
  - ★ $L_X < 10^{39}$ erg s^{-1}

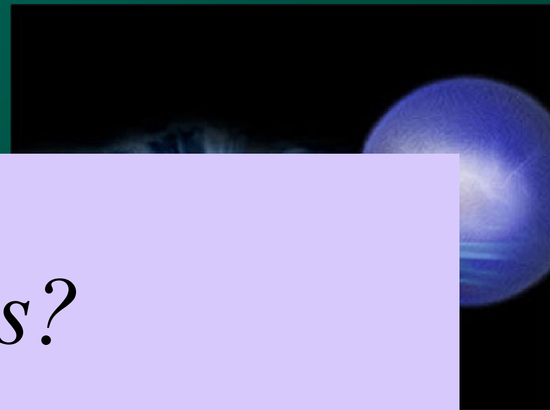




- ★ Super-massive black holes
  - ★ $10^6\ M_\odot < M_{BH} < 10^9\ M_\odot$
  - ★ 10^{42} erg $s^{-1} < L_X$

Black hole masses …

★ Stellar-mass black holes



Intermediate mass?

Basically, the range in between

Something that could not be formed as an end point for any of the current generation of stars

★ $10^6 M_\odot < M_{BH} < 10^9 M_\odot$

★ 10^{42} erg s^{-1} $< L_X$

Formation of these objects

- ★ Pop III remnants - extreme low metallicity allows majority of mass in Pop III stars to collapse to black holes (Madau & Rees 2001; Islam, Taylor & Silk 2003).
- ★ Runaway growth and subsequent collapse of a single stellar object in a young, dense stellar cluster (e.g. Portegies Zwart & McMillan 2002)

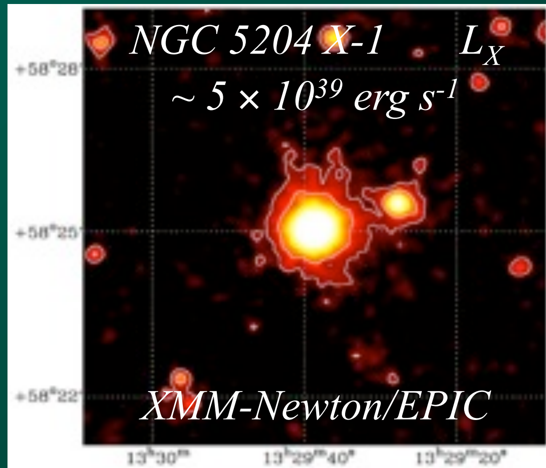
Intermediate mass black holes?

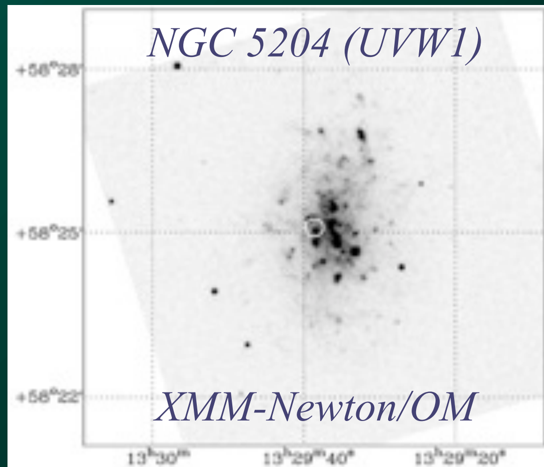
- Provides a formation route to super-massive black holes
  - we understand the formations scenarios for stellar mass but the route to form supermassive black holes has not yet been confirmed
- Could give further info on formations of galaxies
  - formation of galaxies os known to be linked to the formation of the supermassive black holes at their centre, thought to be formed via mergers, in which case we need

Searching for IMBHs ...

The search for IMBHs

- ★ EINSTEIN (~1980) - some galaxies contain unusually luminous extra-nuclear X-ray sources
- ★ Brightest extra-nuclear sources termed ultraluminous X-ray sources (ULXs)





What are Ultraluminous X-ray sources?

- X-ray point source residing outside the nucleus of the galaxy

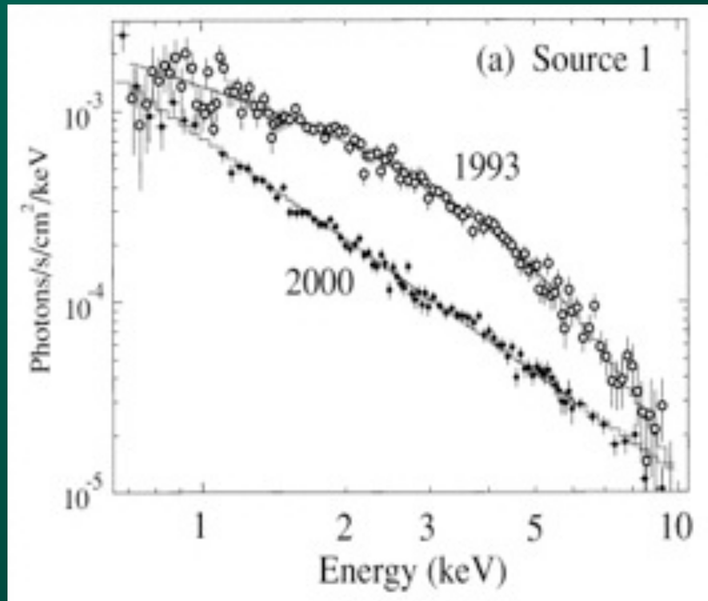
- $L_X > 10^{39}$ erg s^{-1} (above Eddington limit for ~10 solar mass black hole)

- On average, there are less than ~1 per galaxy

composite X-ray (red)/optical (blue & white) image of the spiral galaxy M74 (NASA/CXC/U. Michigan/J. Liu et al.)

Early X-ray observations

- *ASCA* (Makishima et al. 2000, Kubota et al. 2001) :
  - data quality only allowed for single component fitting
  - spectral analyses show accretion disc spectra & spectral transitions
  - ULXs contain black holes (we remove other types of sources from the class)



ASCA spectra of IC 342 X-1, showing convex accretion disc spectrum (top) and power-law-like spectrum (bottom) (from Kubota et al. 2001)

Before we get too carried away ...

- ★ We know this class of objects contain black holes, but are they IMBHs?

- ★ We must test multiple scenarios if we are to trust our findings ...

Before we get too carried away ...

- ★ We know this class of objects contain black holes, but are they IMBHs?

- ★ We must test multiple scenarios if we are to trust our findings ...

... so what is the alternative?

What else could they be?

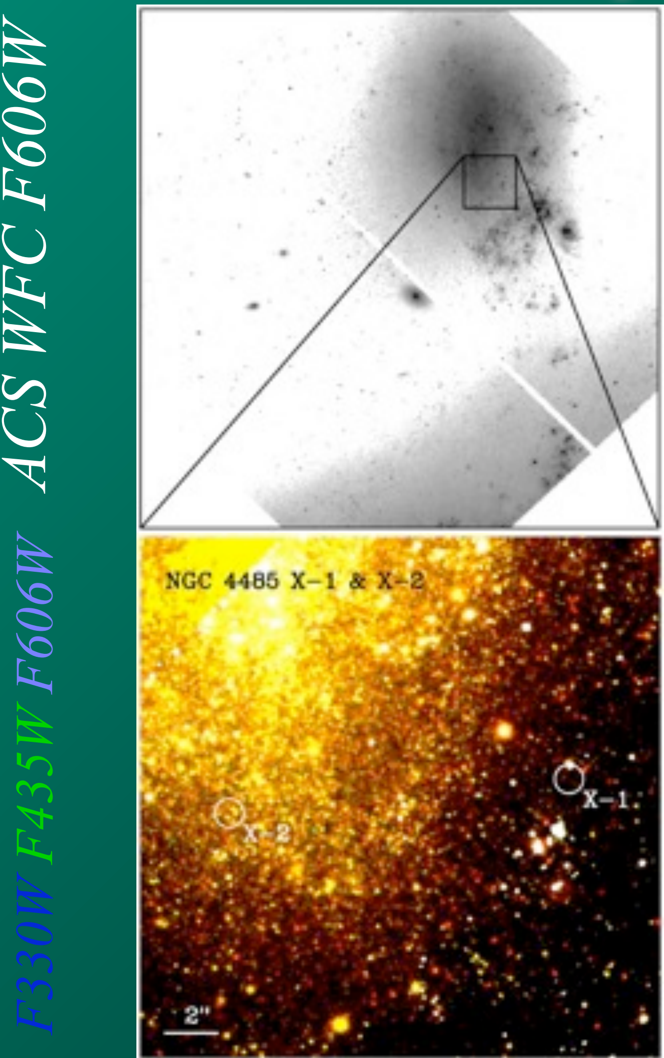
- ★ Stellar mass black hole (<~80 $M_\odot$)?
  - ★ Beamed emission (relativistic jets)? (*e.g.* Körding et al. 2002)
  - ★ Anisotropic system? (King et al. 2001)
  - ★ True super-Eddington accretion?

So what do observations tell us?

Radio emission from ULXs

- By taking detections to date, and using the fundamental radio - X-ray plane
  - $L_X \alpha L_R^{1.38} M^{0.81}$ (in hard state: Flacke et al. 2004)
  - Implies $M_{BH} \approx 10^2$ - 10^5 $M_{\odot}$
- However its unusual to see radio emission from these sources ... very few detections to date. Most recent study (Mezcura & Lobanov 2011) mainly placed limits on objects, with only two strong detections listed.

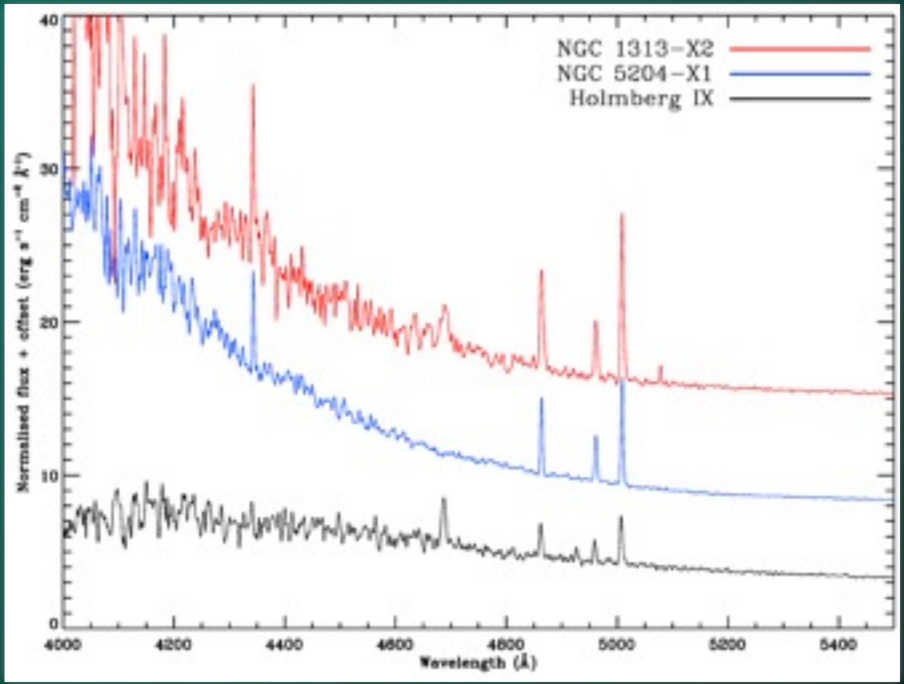
What can the optical counterparts tell us?



- Search has focused on nearby systems (<10 Mpc)
    - $m_V \approx$ 22-26 (Roberts et al. 2008
- Association with OB stars (e.g. Liu et al. 2007, Copperwheat et al. 2007)
    - High mass X-ray binary systems?
    - Blue emission may come from accretion disc emission

Optical spectra of the ULXs

- Gemini Spectra of 3 potential optical counterparts
- Spectra are blue, and mainly featureless (most lines from nebula)
- Slope is non-stellar
- To show evidence of He II 4686 line - association with accretion disc.



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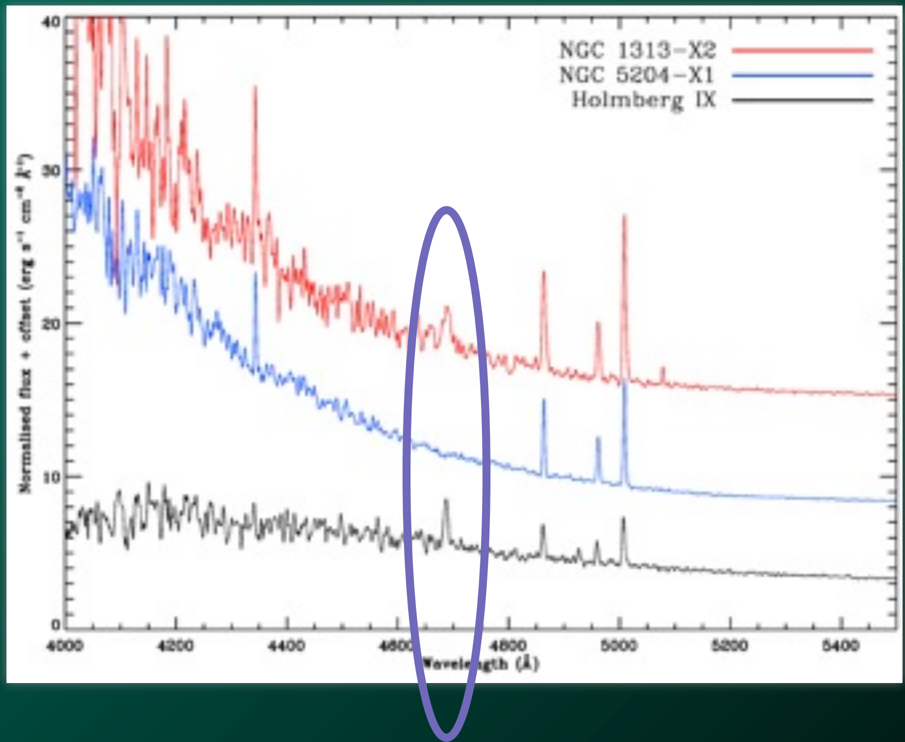

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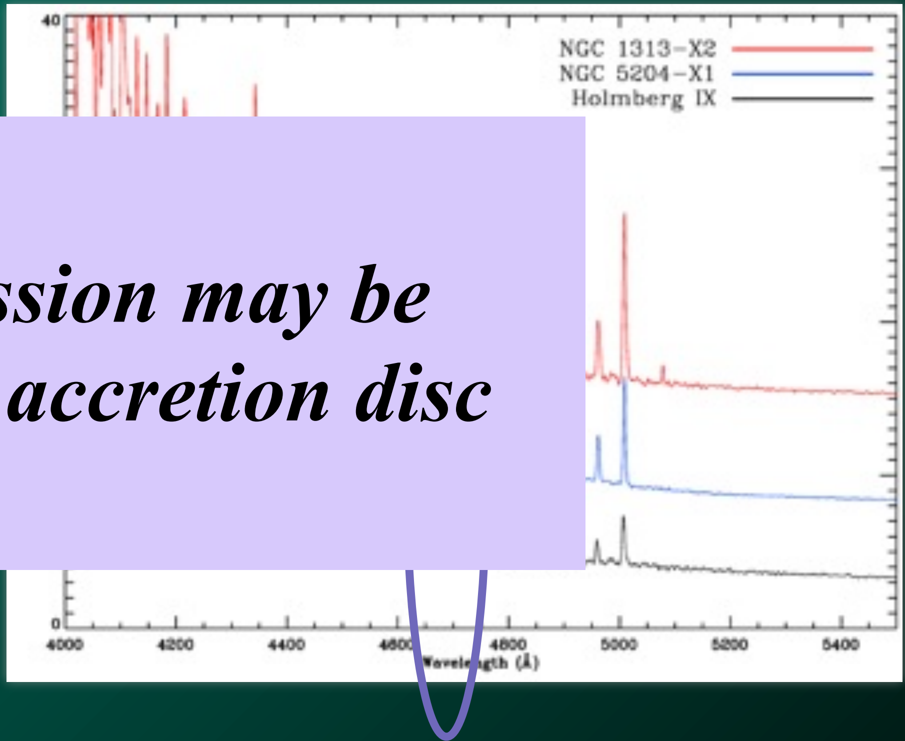
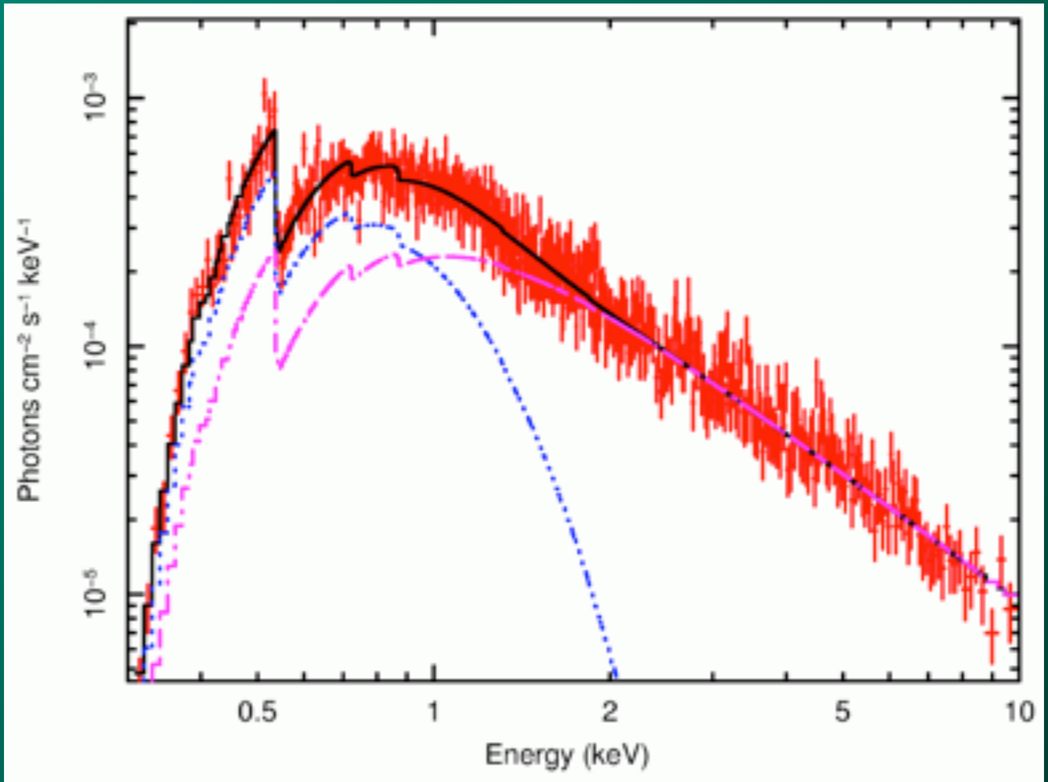


Optical emission may be dominated by accretion disc

X-ray observations

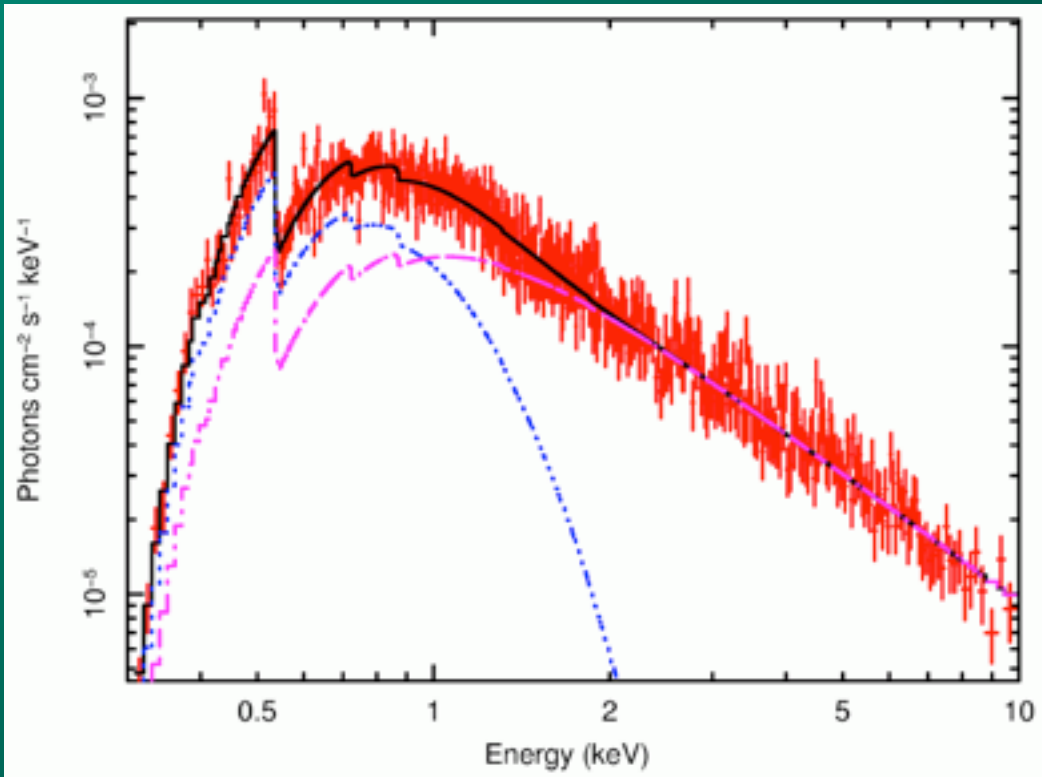


e.g. NGC 1313 X-1 Miller et al. (2003)

$kT_{in} \sim 0.15$, $\Gamma \sim 1.8$ $\sim 1000\ M_{\odot}$ BHs

- Early *XMM-Newton* studies fit with standard disc + power-law (as used in Galactic sources)

X-ray observations



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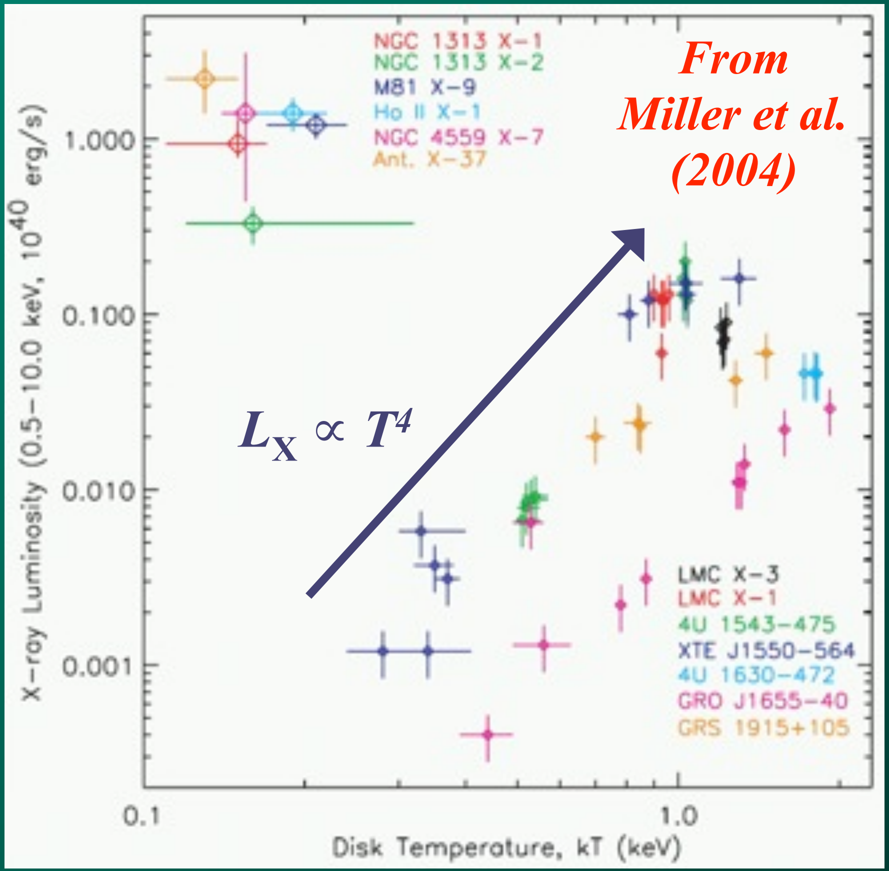
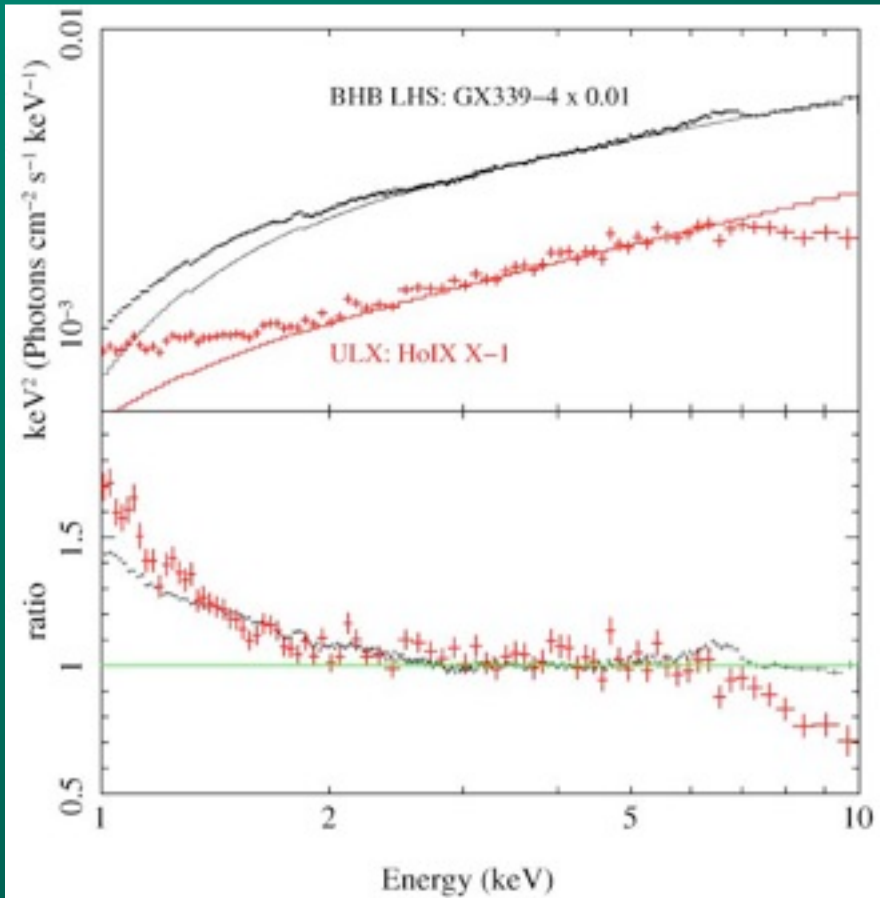


- ★ Early *XMM-Newton* studies fit with standard disc + power-law (as used in Galactic sources)
- ★ Detection of cool disc component suggested IMBH
- ★ IMBH candidates occupy separate part of parameter space to stellar-mass BHs

Higher quality X-ray data



- ★ Spectral features
- ★ Soft excess
- ★ High energy break

  (e.g. Roberts 2007)

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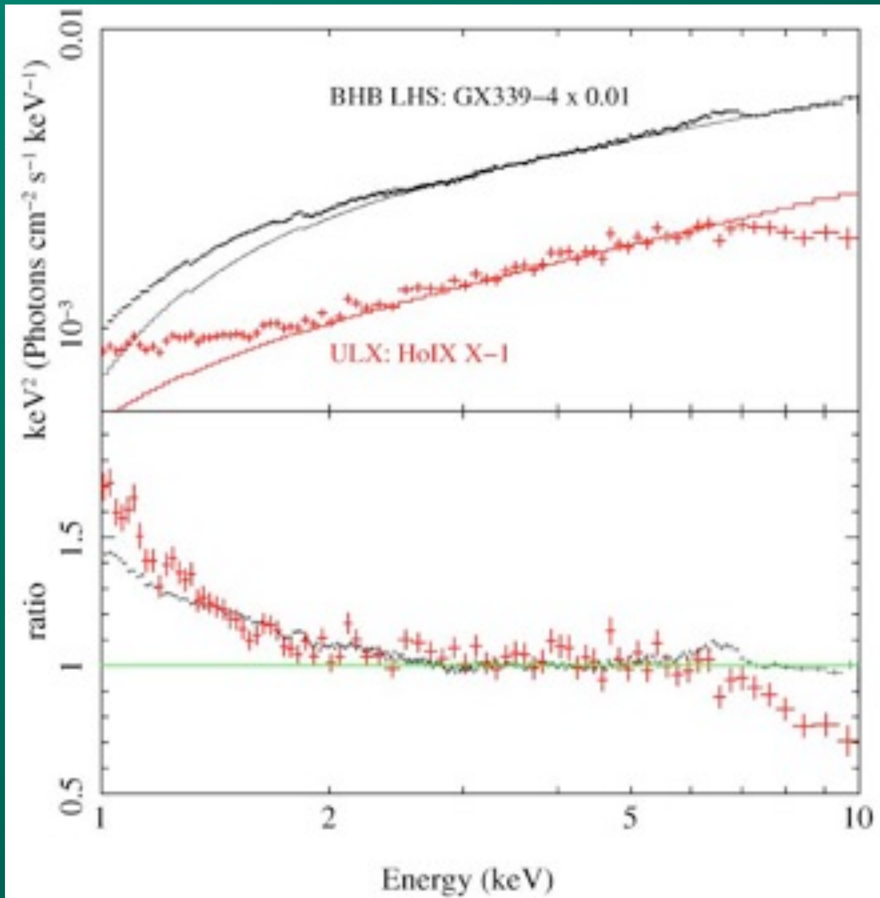

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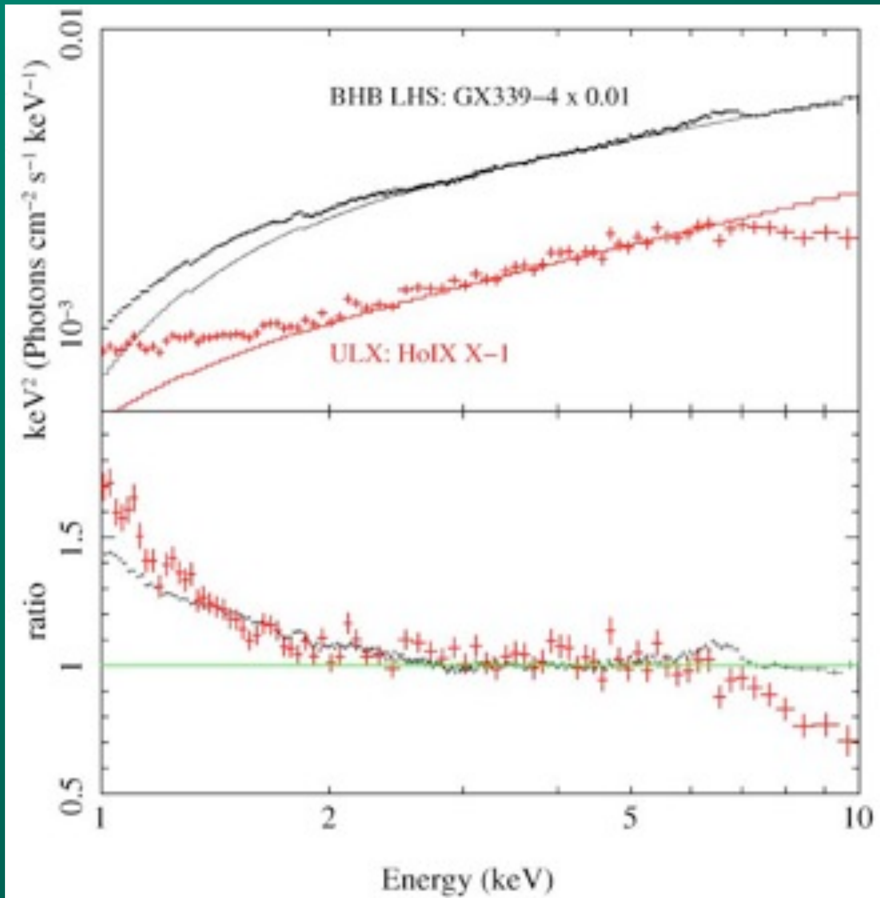

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    (Gladstone, Roberts & Done 2009)

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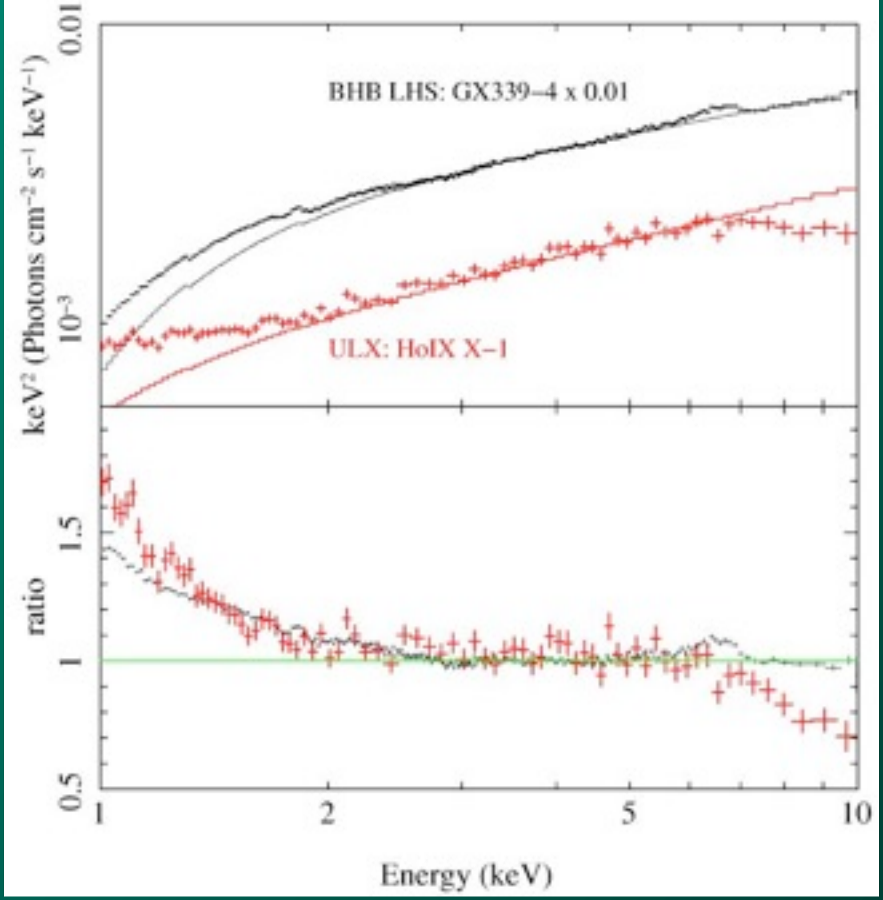

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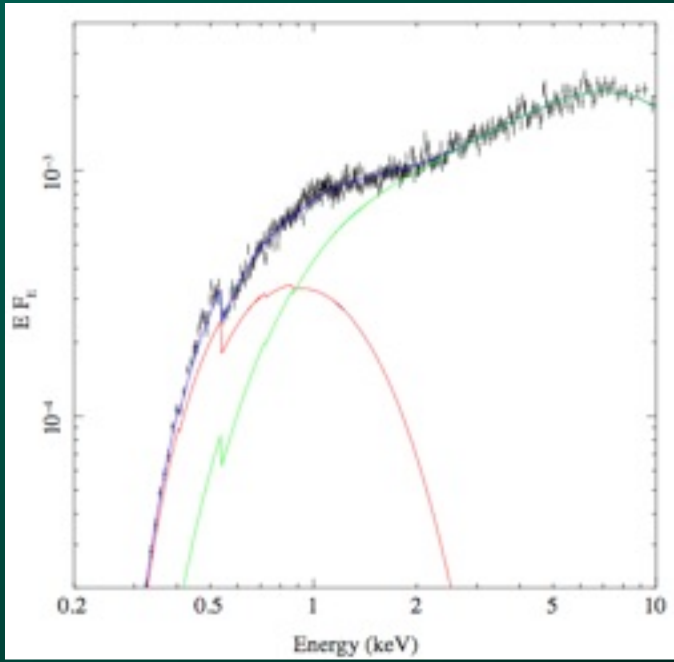
The ultraluminous state

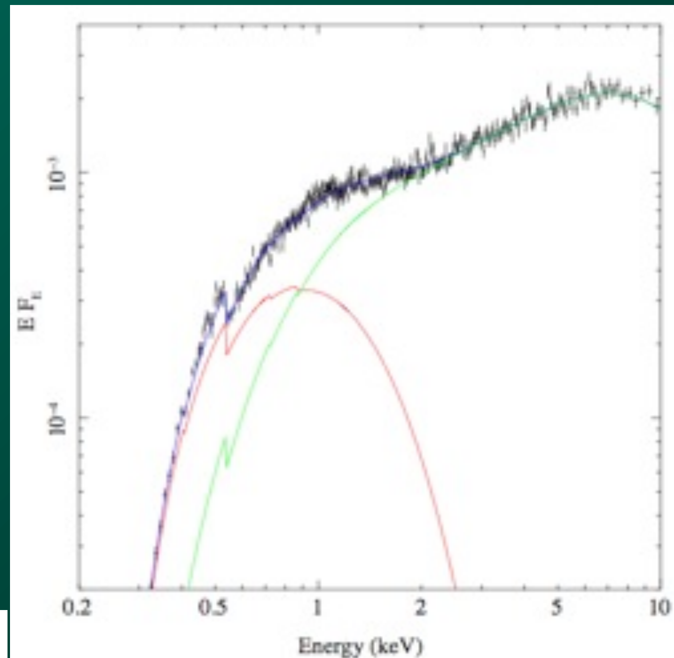
- observationally defined as showing both a soft excess and a break above ~2 keV (Gladstone et al 2009)

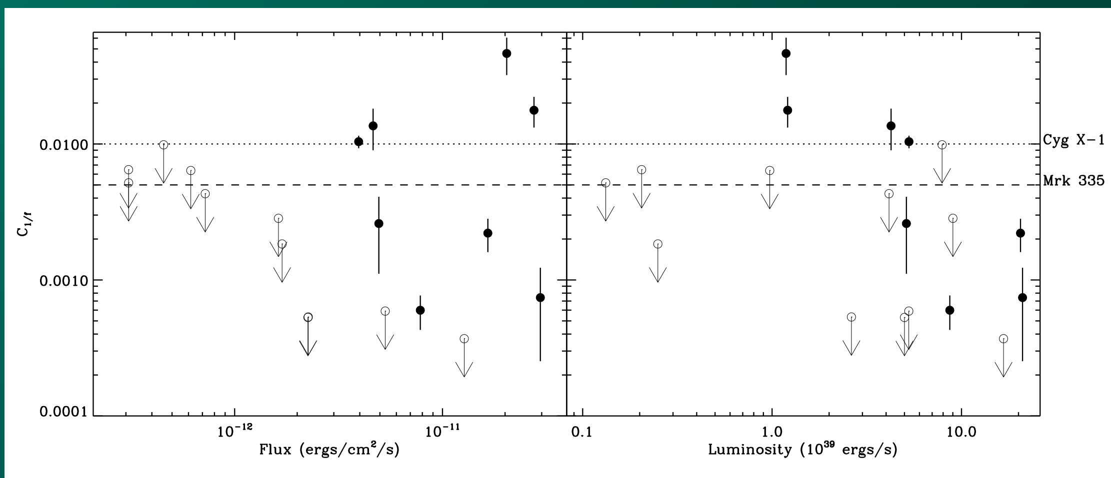


X-ray data of Holmberg IX X-1 fit with DISKPN + COMPTT

The ultraluminous state

- observationally defined as showing both a soft excess and a break above ~2 keV (Gladstone et al 2009)
- also ULXs show suppressed variability (Heil et al. 2009)





Estimated variability amplitudes of ULXs

The ultraluminous state

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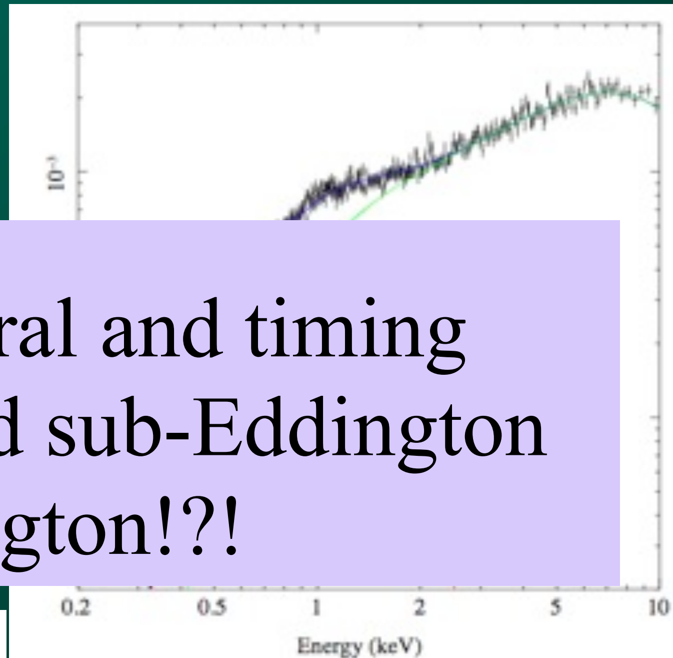
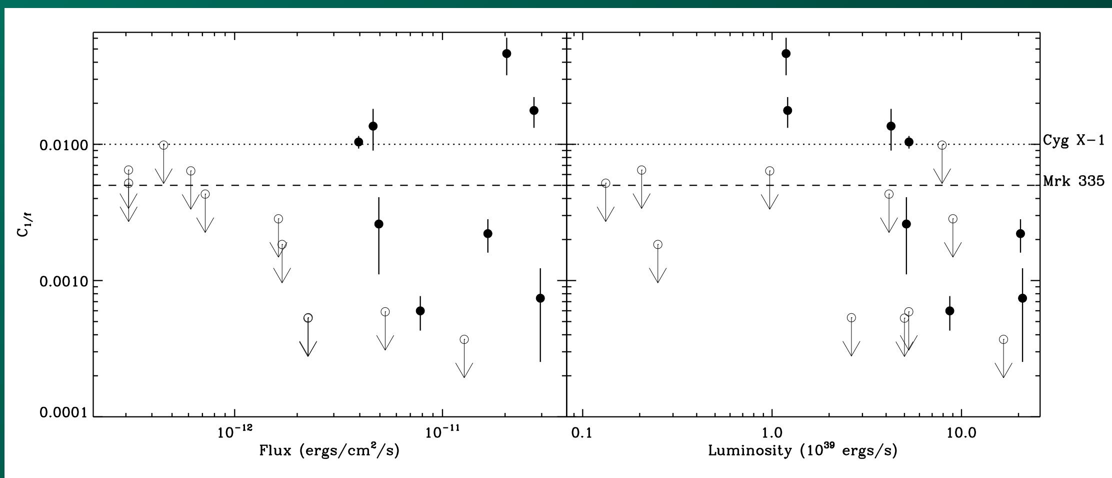
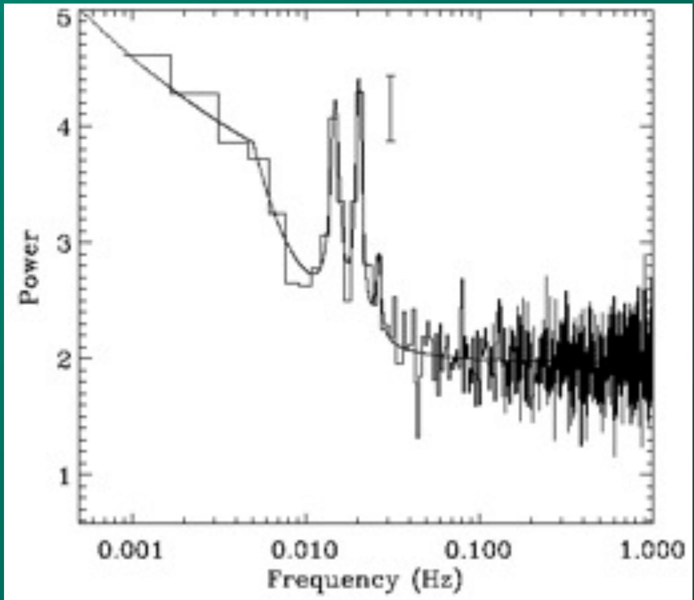


Apparently different spectral and timing features from that of standard sub-Eddington rates ... super-Eddington!?!



Estimated variability amplitudes of ULXs

Still some questions ... (e.g. NGC 5408 X-1)



Double QPO in NGC 5408 X-1 (from Strohmayer et al. 2007)

- ★ Timing studies reveal QPO
  - ★ Scaling from Galactic BHs - $M_{BH} \sim 10^2\text{-}10^4\ M_\odot$ (e.g. Casella et al. 2008), maybe higher (Strohmayer et al. 2009) in LHS
  - ★ Middleton et al. (2010) reanalysed data to show that the power spectral density and variability are a better match to model of super-Eddington accretion than that of the LHS
    - ★ comparable to mHz QPO in GRS 1915+105

Are ULXs IMBHs

- No, at least not the majority of them
  - Recent X-ray analysis suggest that we are looking at stellar mass black holes accreting at around or above the Eddington limit

is there still hope of finding IMBHs?

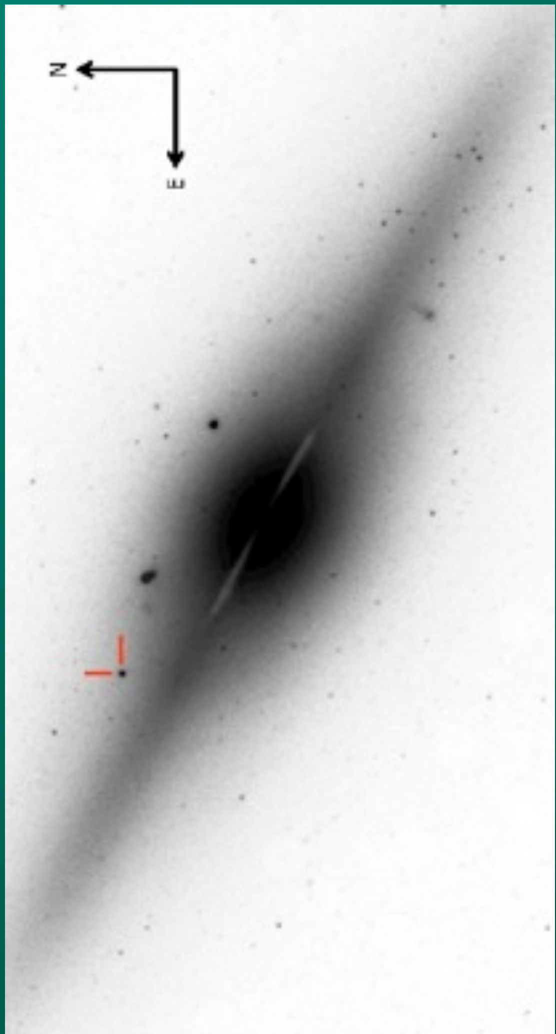
- Yes, combining our new knowledge of possible super-Eddington accretion with moderate beaming, and by invoking larger stellar mass black holes we can explain observed ULXs up to ~few times $10^{40} ergs^{-1}$. If we find brighter objects, then maybe ...

Hyperluminous X-ray sources

- $L_X > 10^{41}$ erg s^{-1}
- < 10 objects of this class known to date
- Brightest is ESO 243-49 HLX-1, reaching ~ 10^{42} erg s^{-1}

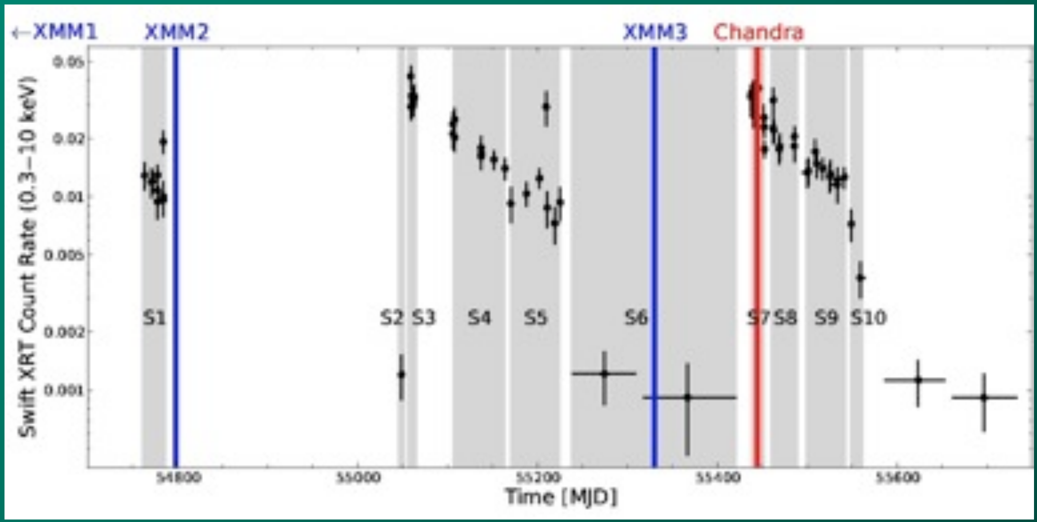
Artist impression of ESO 243-49
by Heidi Sagerud

ESO 243-49 HLX-1



- ★First reported by Farrell et al. (2009) as bright X-ray non-nuclear point source
- ★Resides above galaxy plane
- ★Peak Lx ~ 10^{42} erg/s
- ★Distance (so luminosity) confirmed via optical spectroscopy
- ★One of the strongest candidates for IMBH

ESO 243-49 HLX-1 - X-ray analysis



- Swift monitoring shows possible periodic variations in the luminosity of this source (e.g. Godet et al. 2009)

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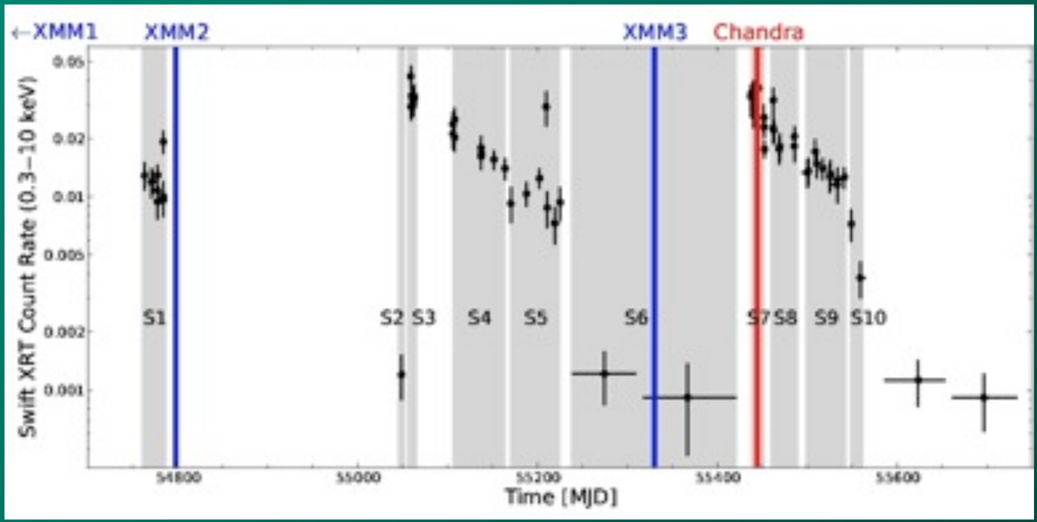

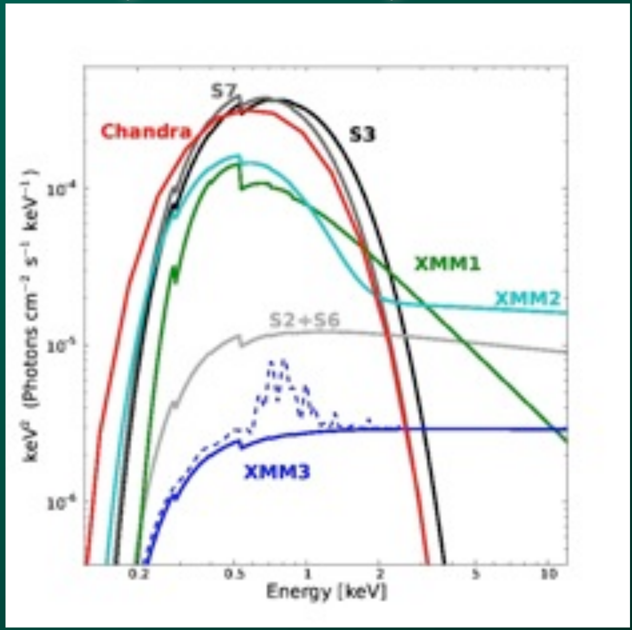

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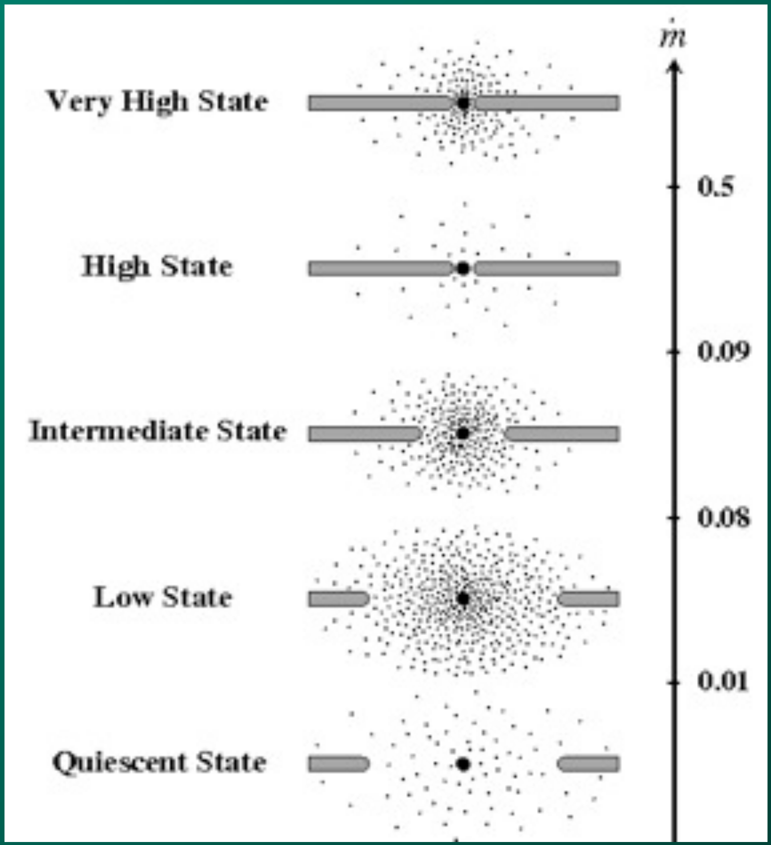
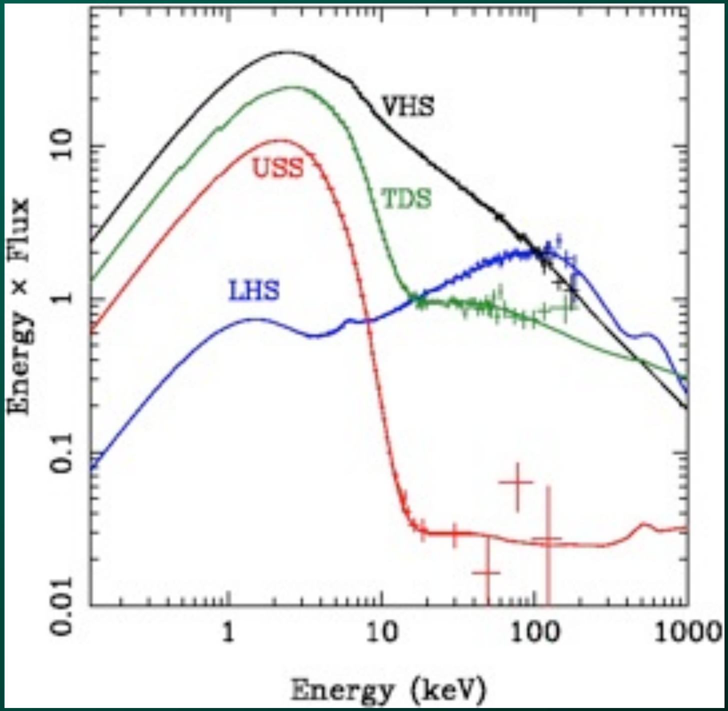
Accretion states





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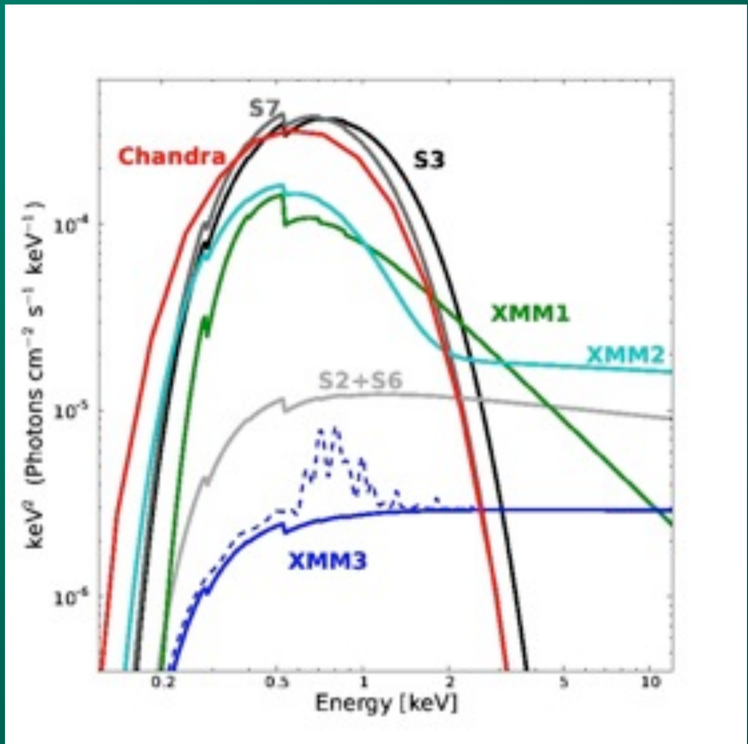

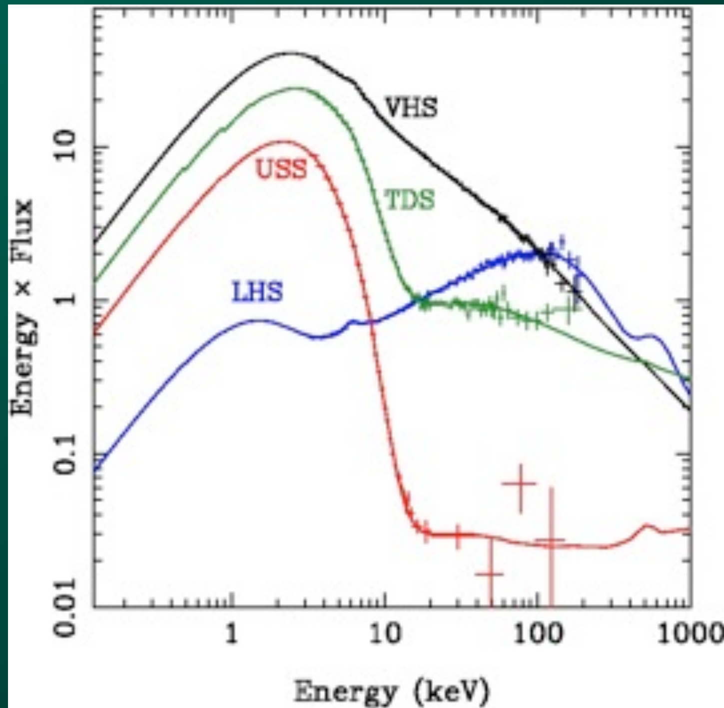

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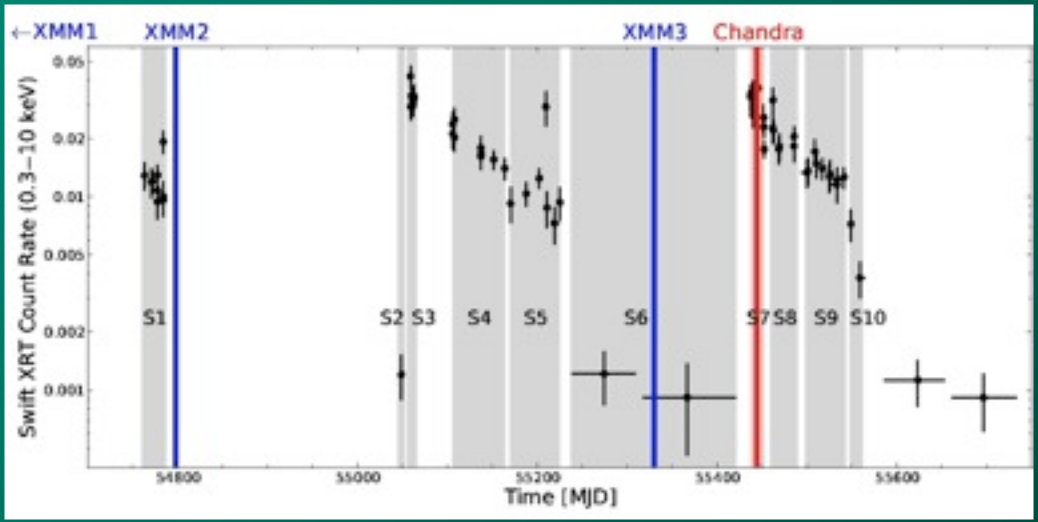
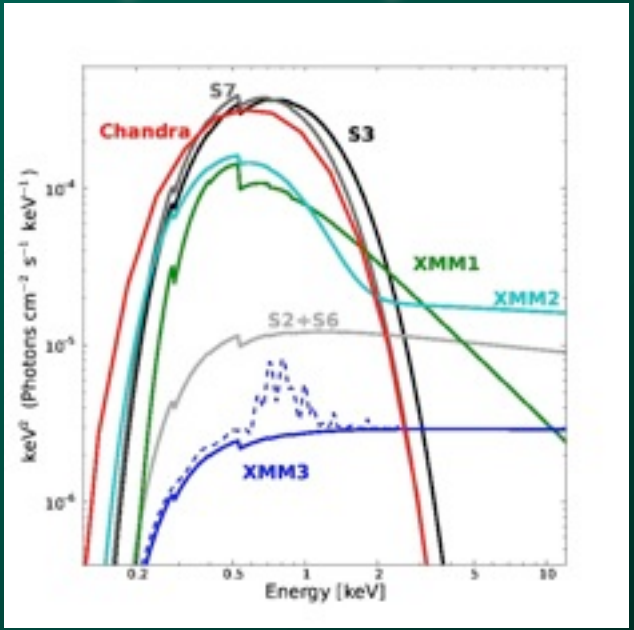




- ★ Swift monitoring shows possible periodic variations in the luminosity of this source (e.g. Godet et al. 2009)
- ★ Peak of the outburst looks similar to TDS/High state & low flux looks like Hard state (Servillat et al. 2011)
- ★ Scaling based on mass accretion rate in each state suggests ~ 10,000 M_{sun}

ESO 243-49 HLX-1

HST Photometry

- HST observations taken shortly after the peak of the outburst in August 2010 (Farrell et al. 2012)
- Data was fit with combination of stellar population and accretion disc.
  - best fit parameters were that of young stellar population plus irradiated accretion disc.

Filter	m (ABmag)
NUV	23.96 +/- 0.04
Wash C	23.92 +/- 0.06
V	23.83 +/- 0.08
I	23.91 +/- 0.08

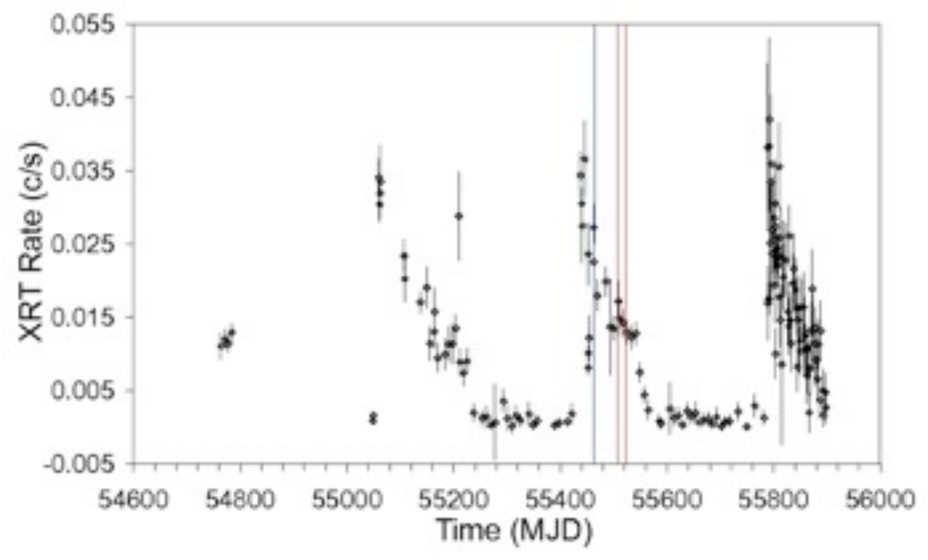
ESO 243-49 HLX-1

VLT Photometry

- VLT observations taken ~3 months after outburst in November 2010 (Soria et al. 2012)
- Data was compared to stellar population and accretion disc.
  - Indicates similarities to truncated irradiated disc or intermediate mass/age population

Filter	m (ABmag)
U	24.7 +/- 0.2
B	25.0 +/- 0.3
V	24.8 +/- 0.3
R	24.9 +/- 0.4
I	>25.0

ESO 243-49 HLX-1 - Optical analysis



- Optical drops by
  - ~ 1 mag
- X-ray drops by
  - ~ factor 2

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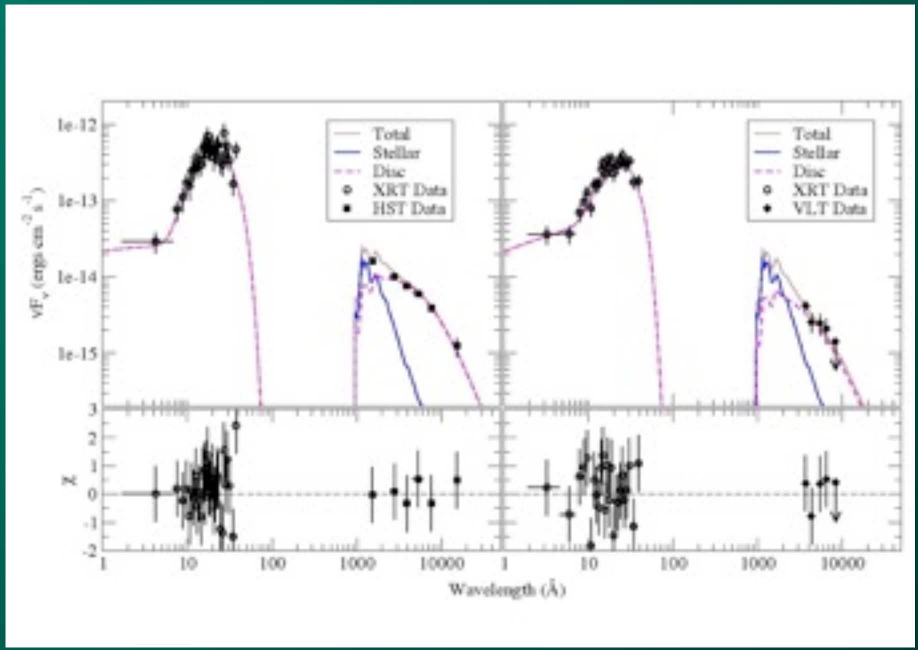
ESO 243-49 HLX-1

combining photometry



- By tying the stellar population while allowing the disc to vary, we find that we get a young (~9 Myr) small ($4*10^5$ M_{sun}) stellar population (*very preliminary!!!*)

ULXs and the search for IMBHs

- ULXs have recently been reclassified
  - Standard ULXs
    - those ranging for 10^{39} to a few * 10^{40} erg s^{-1}
    - thought to be HMXBs
    - *majority* contain (large) stellar mass black holes
    - show that super-Eddington accretion is possible
  - new sub-class called HLXs
    - $L_X < \sim 10^{41}$ erg s^{-1}
    - only a handful known to date
    - early indications show these may contain population of IMBHs
- Still much work to be done in the study of these objects