

Ultra-Luminous X-ray Sources

G. Fabbiano

Harvard-Smithsonian CfA

IMBH?

High luminosity stellar sources?

ULX definition

- Non-nuclear X-ray sources in galaxies with ‘isotropic’

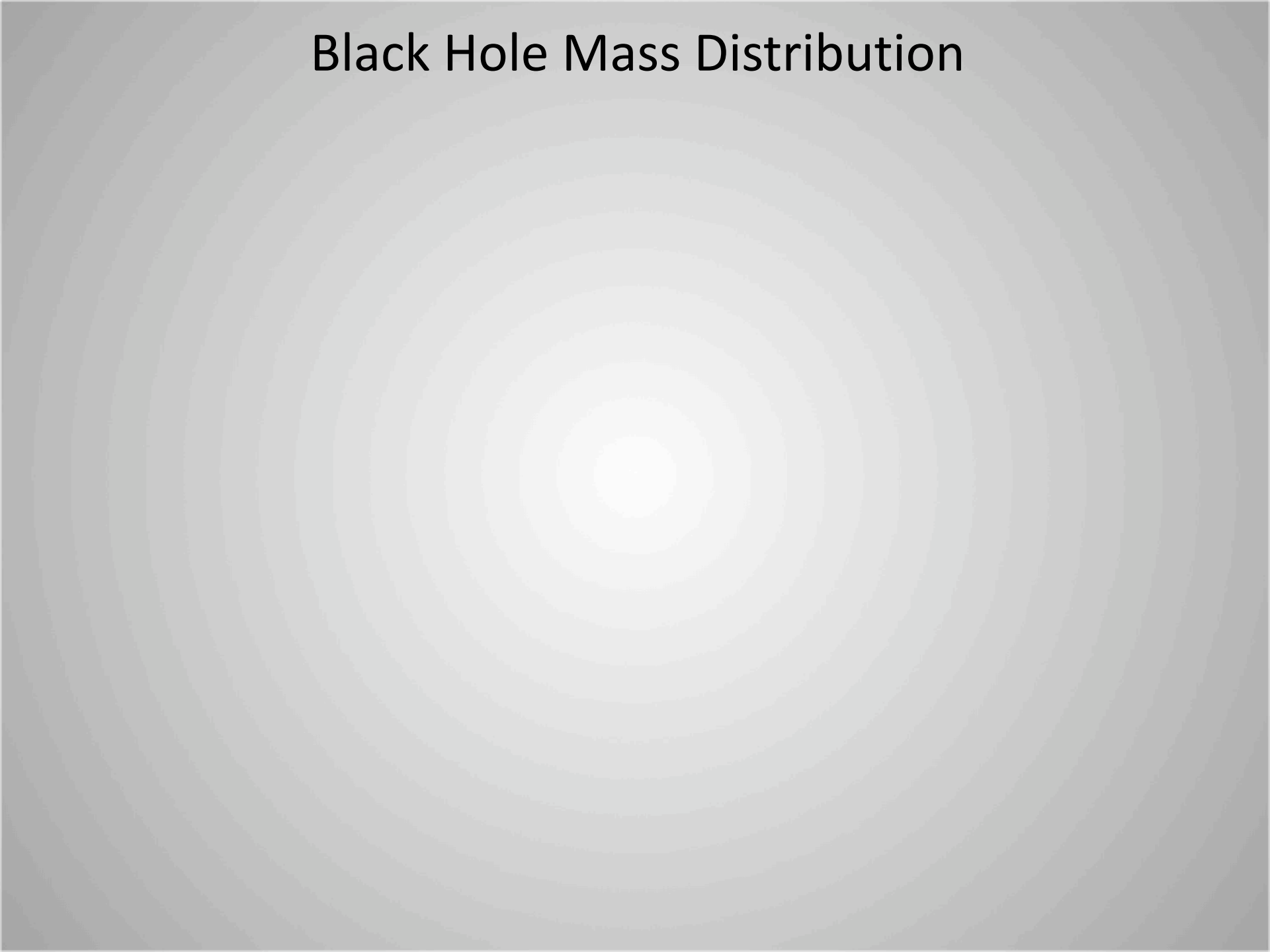
$$L_x > 10^{39} \text{ up to } 10^{41} \text{ erg s}^{-1}$$

- Well above L_E of a neutron star ($\sim 2 \times 10^{38} \text{ erg s}^{-1}$)
- If taken at face value...

$$\text{Mass} > 8 - 500 M_{\odot}$$

ULXs could be IMBHs !

Black Hole Mass Distribution



Black Hole Mass Distribution

SMBH
 $10^7 - 10^{10} M_{\odot}$

Stellar BH masses
 $< 50 M_{\odot}$

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Low-Lum. AGN
 $10^5 - 10^7 M_{\odot}$

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Stellar BH masses
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 $\geq 100 - 10^5 M_{\odot}$

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- Core collapse in Globular Clusters
- Remnants of Pop III stars and subsequent mergers (Λ CDM)

- Something happens to the center of accretion disks models
 - Beamed emission at high accretion rates?
King et al 2001
 - Relativistic jets, microquasars, e.g. SS433?
Mirabel & Rodriguez 1999; Koerding et al 2002; Begelman, King & Pringle 2006; Poutanen et al 2007
 - High accretion rate central Comptonized disks & outflows
several papers by **Chris Done** and collaborators;
also, Soria and collaborators
- Super-Eddington accretion disks
Begelman 2002
- 30-90 M_{\odot} BH binaries formed at very low Z (e.g., Cartwheel, Antennae)
Zampieri & Roberts 2009; Mapelli et al 2009

Observational constraints

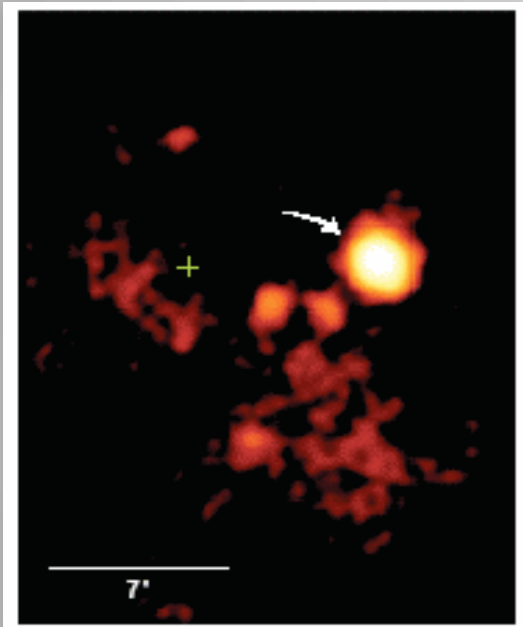
ULX Luminosity

Spectra

Variability

Sample properties

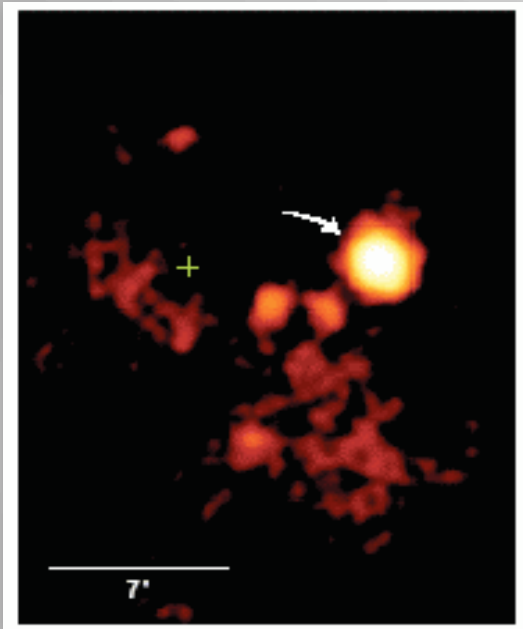
An aside – Beware of crowding!



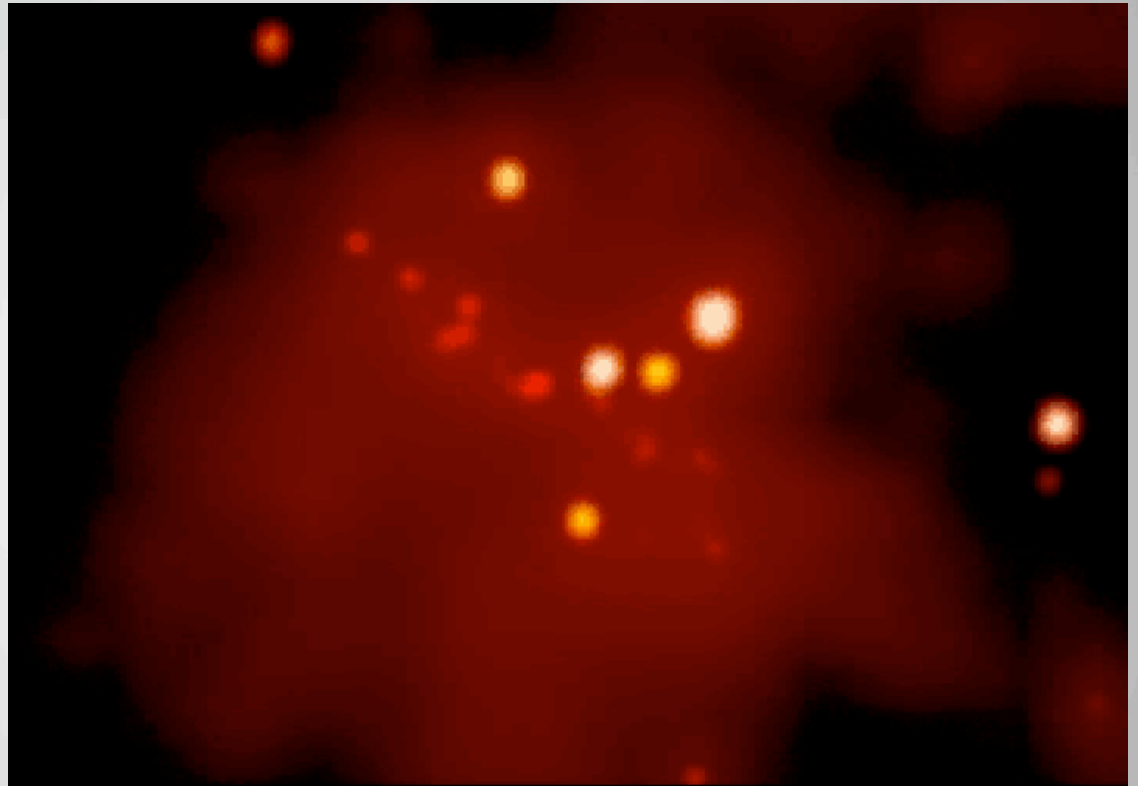
M82 ULX region

Zezas et al

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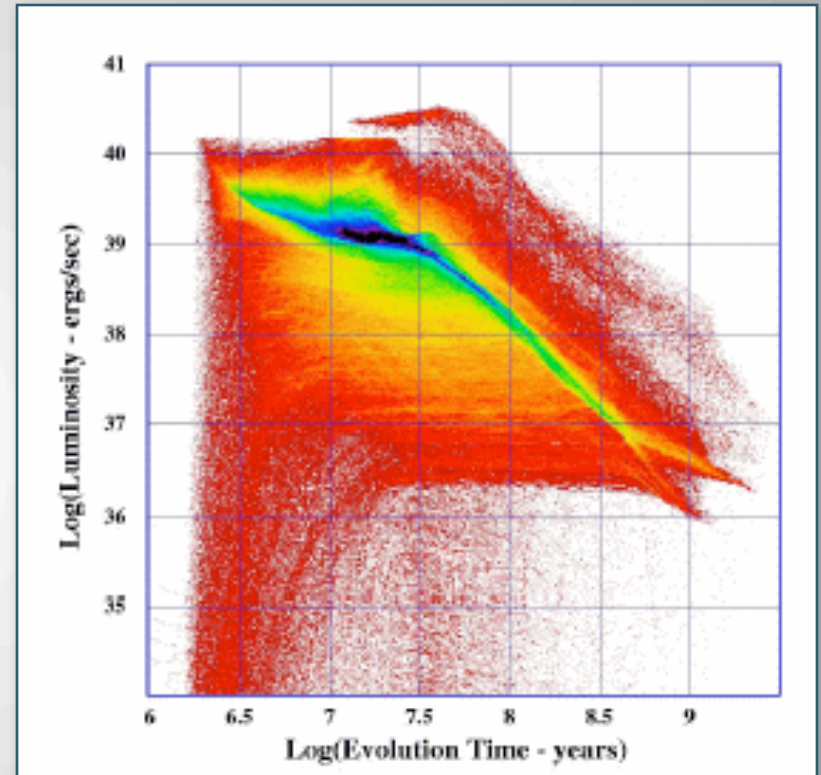
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ULX Luminosity can be reached in stellar BH XRBs

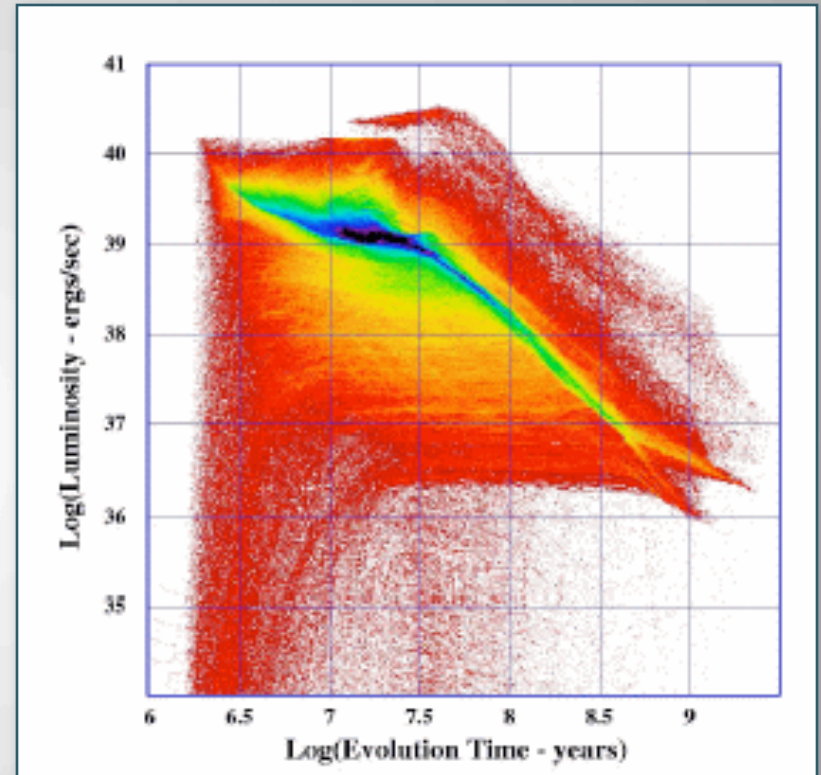
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- *Only* luminosities $L_x > 10^{41}$ erg/s require IMBHs



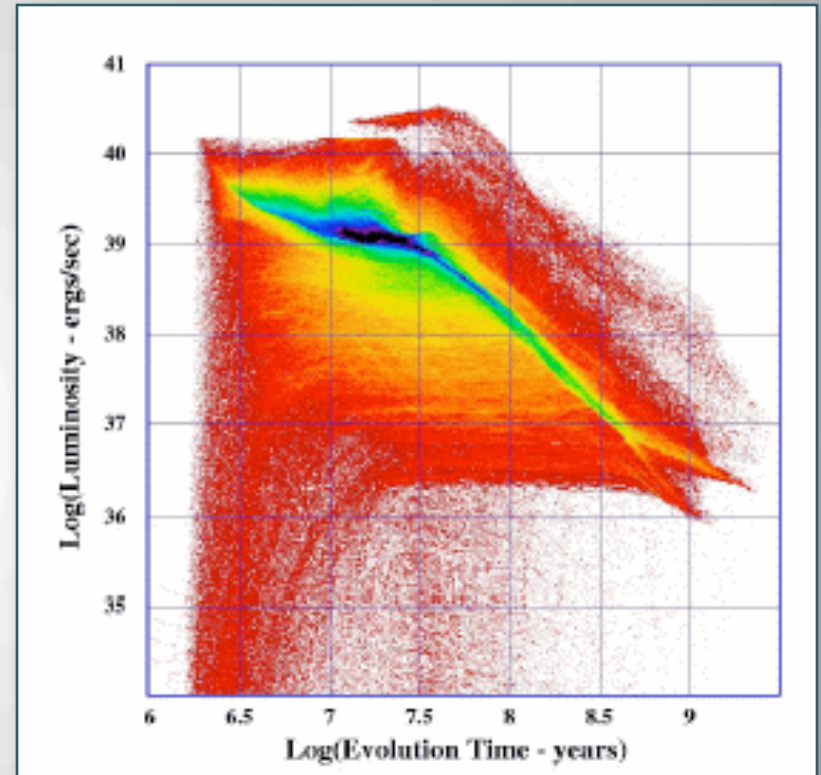
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e.g. Rappaport, Podsiadlowski, Pfahl 2005



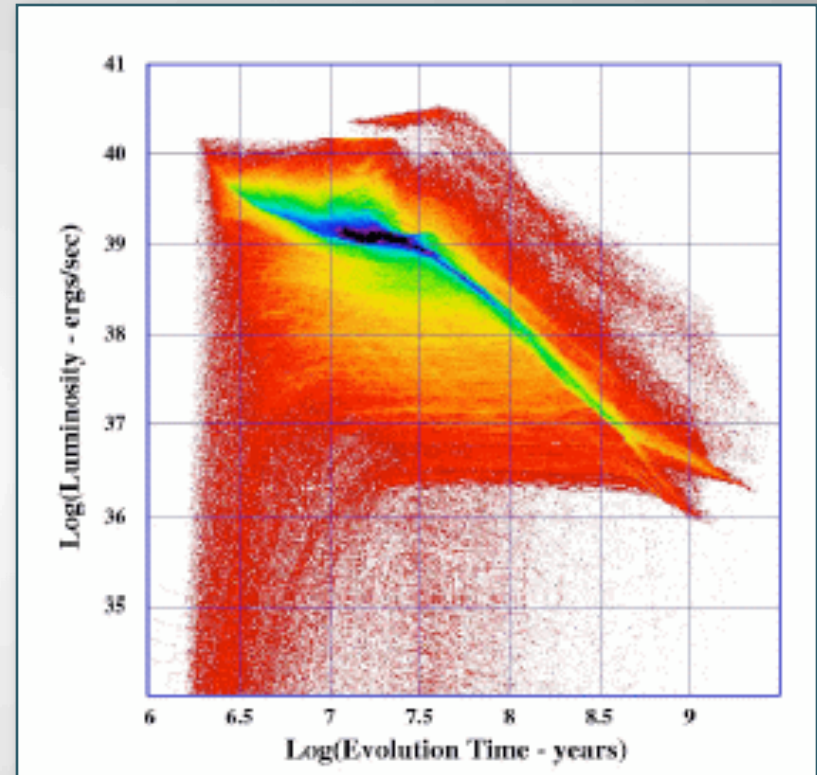
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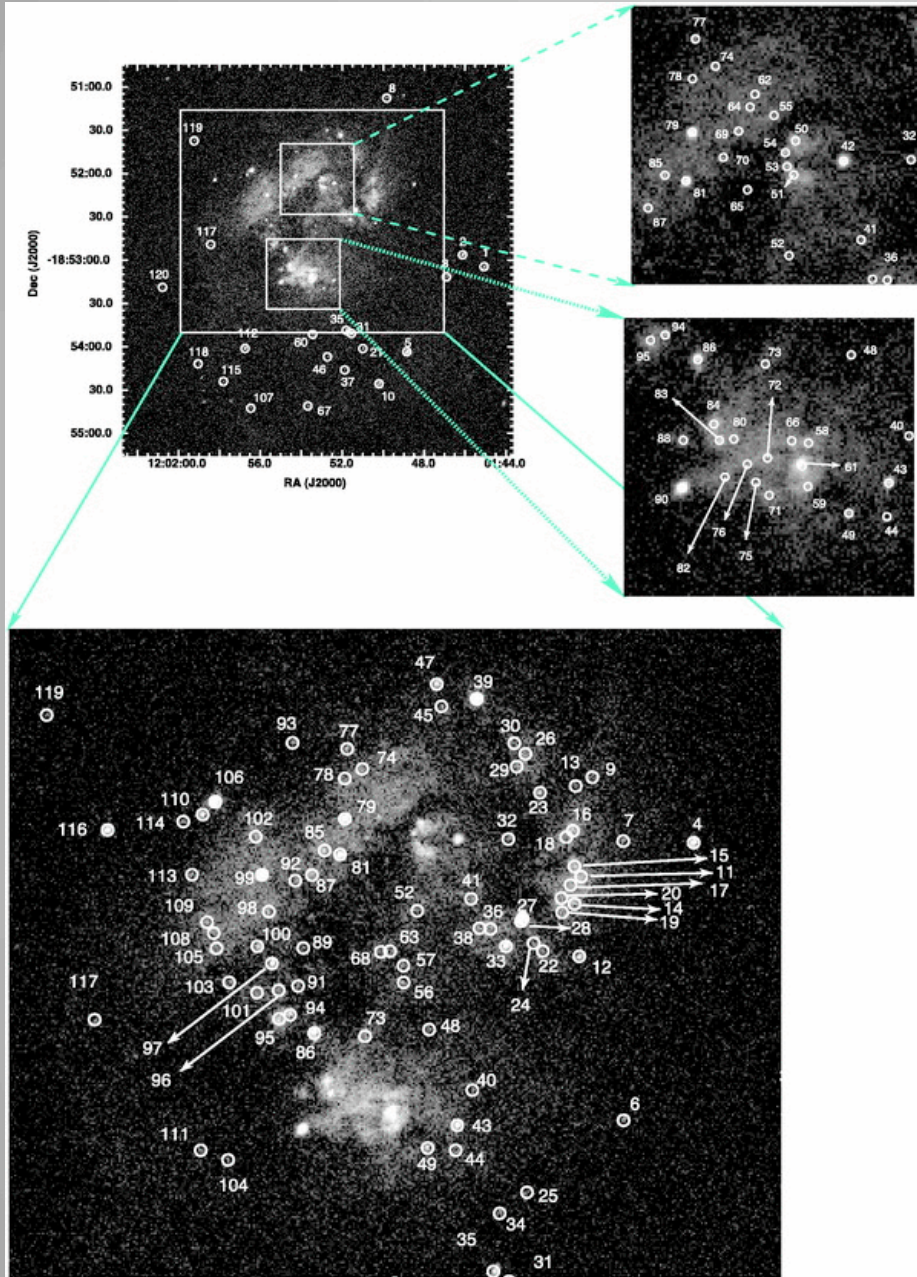


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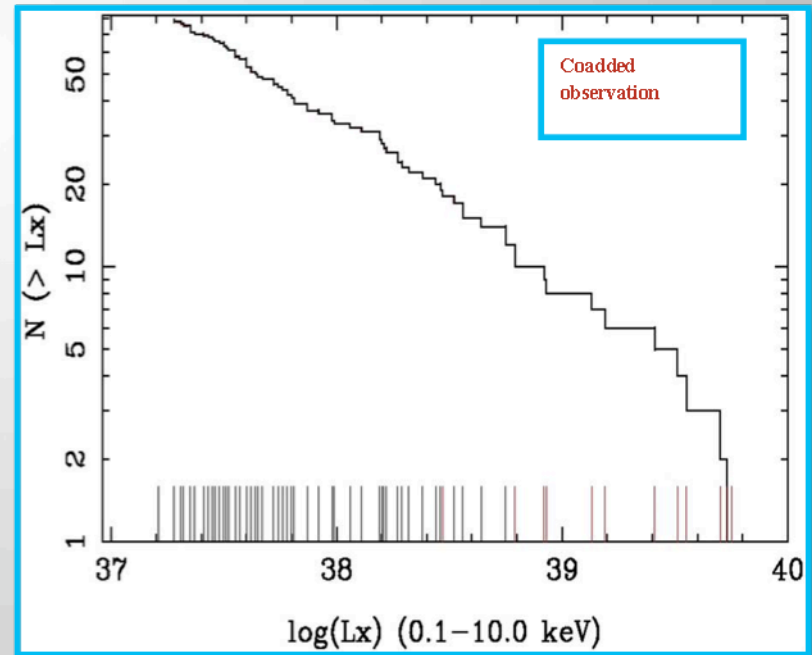
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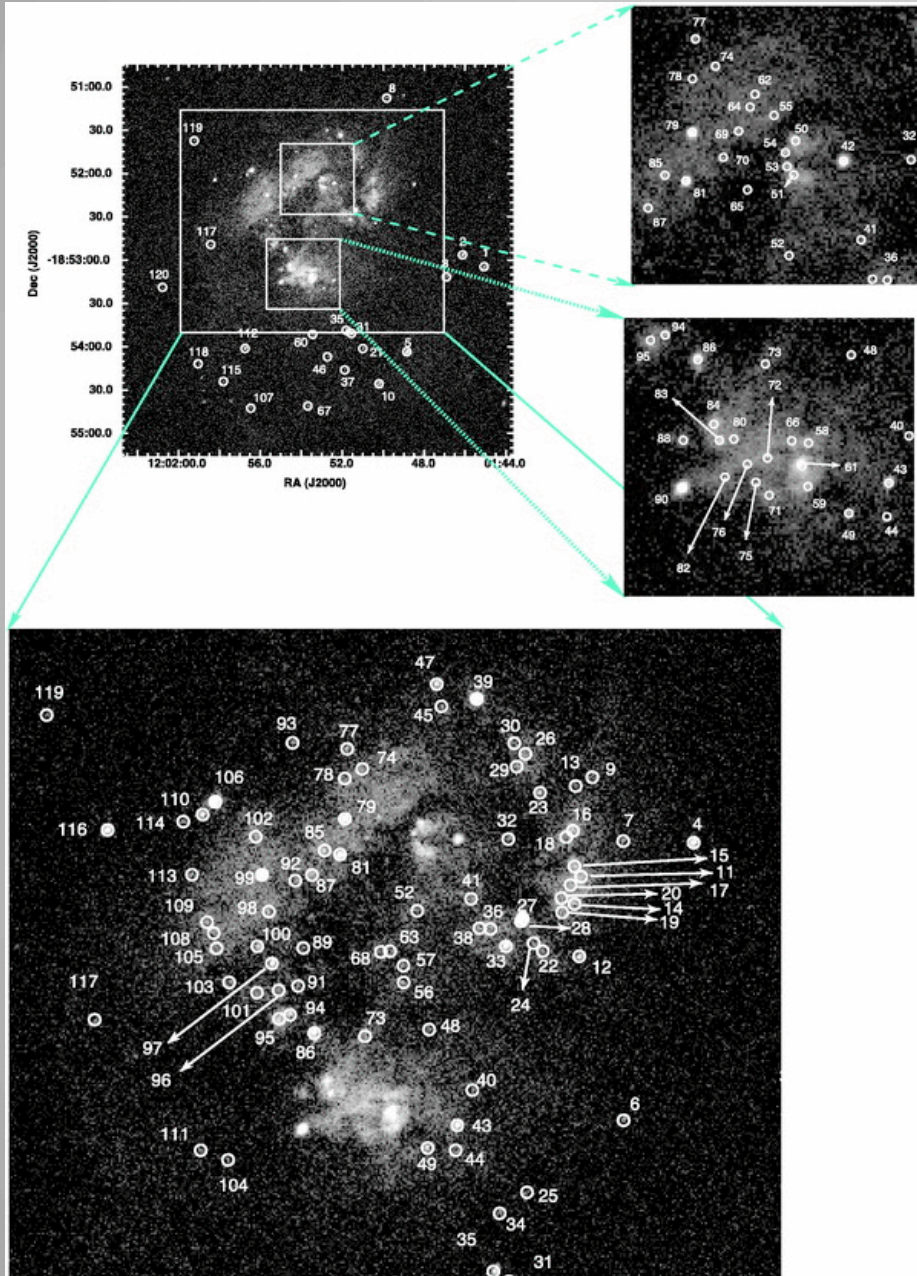
HMXB Luminosity Functions



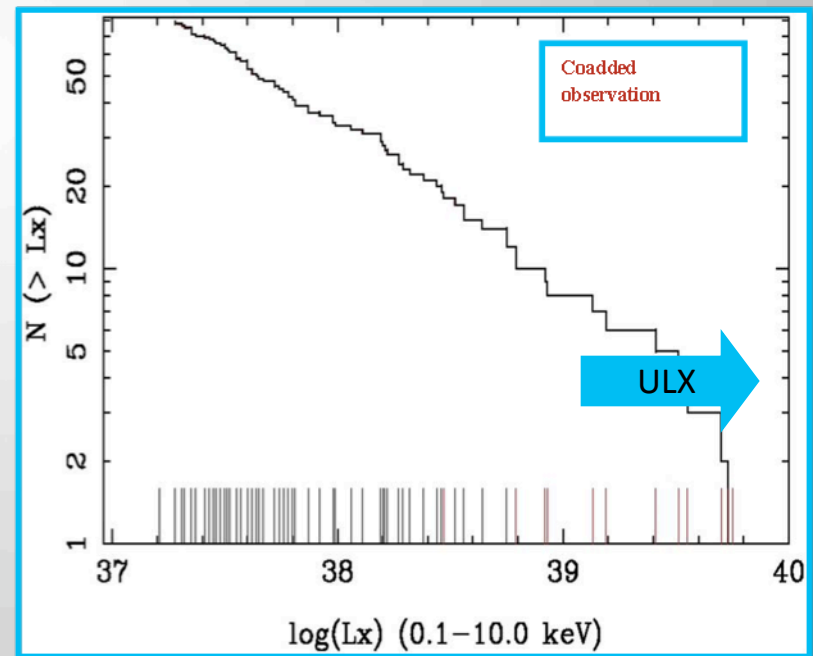
- The Antennae with *Chandra*
 - 480 ks, 7 ACIS-S exposures
- 120 sources (see catalog, [Zezas et al 2006](#))
- ~ 10 ULX - variable
- Cumulative XLF slope ~ -0.5



HMXB Luminosity Functions

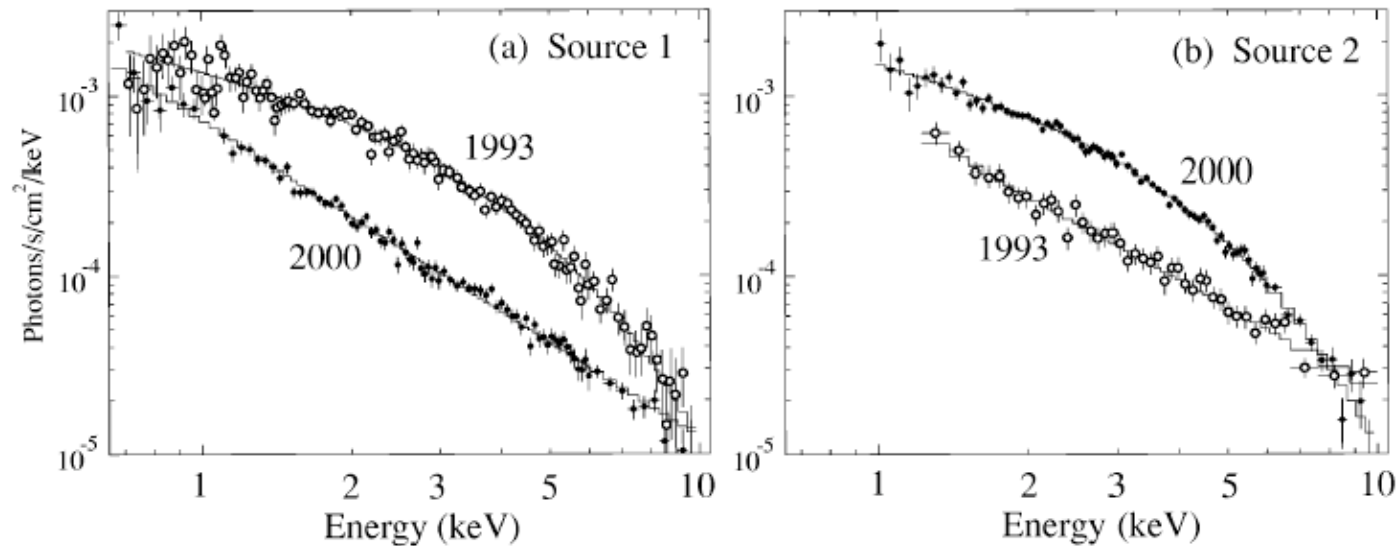


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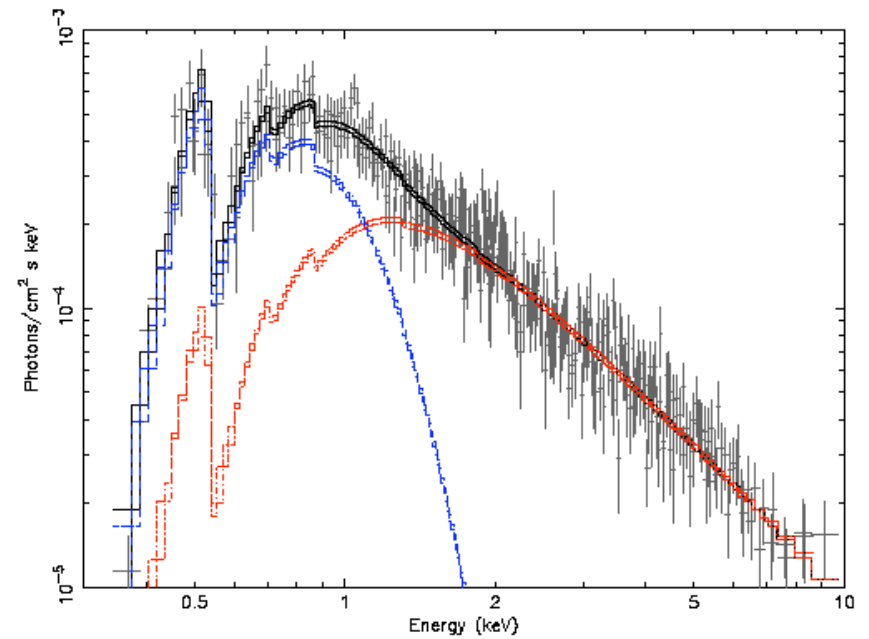
ULX Spectral Variability \rightarrow XRBs

- High/soft – low/hard
 - IC342 ULXs (ASCA – [Kubota et al 2001](#))



Phenomenological model: Miller et al 2003

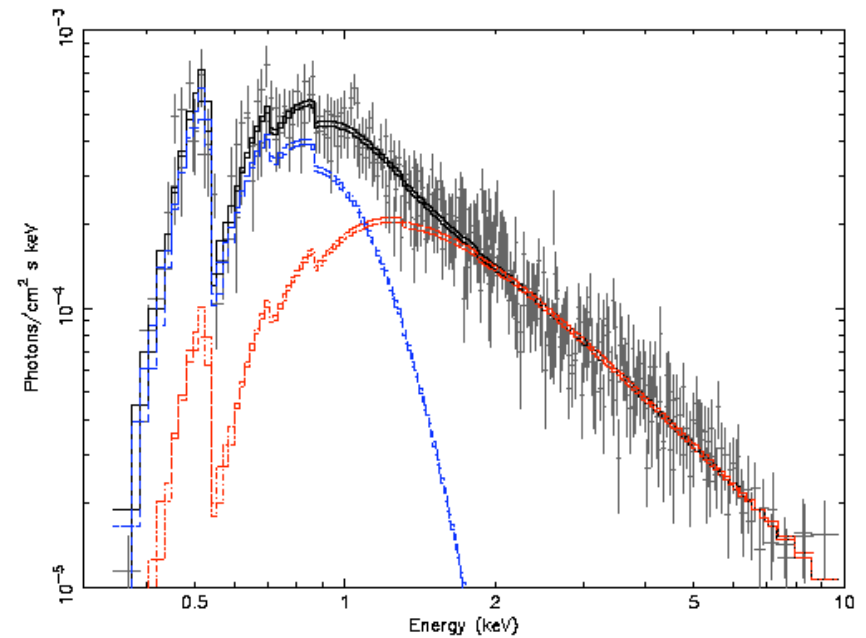
thin disk & decoupled corona



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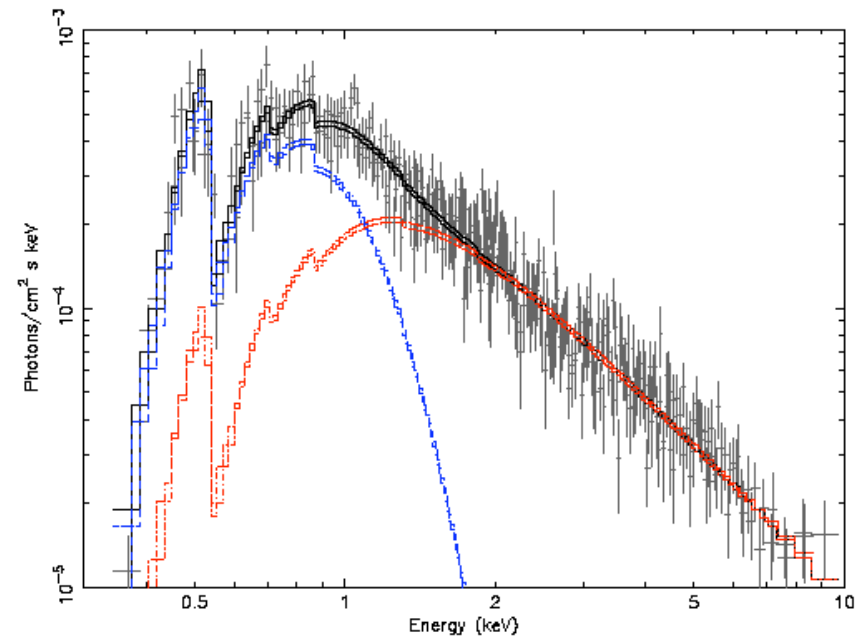
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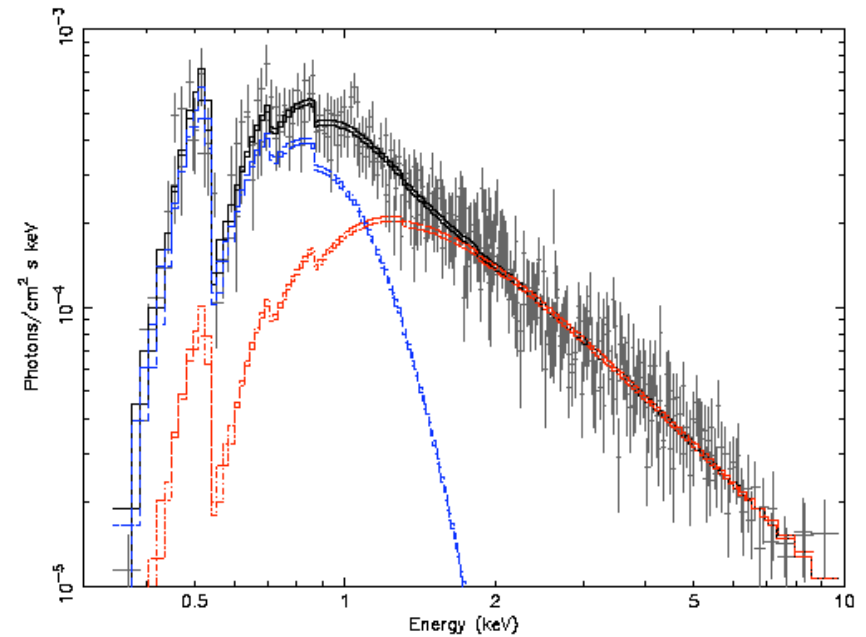
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 - $kT_{\text{in}} \sim 1$ keV for $10 M_{\odot}$ BH
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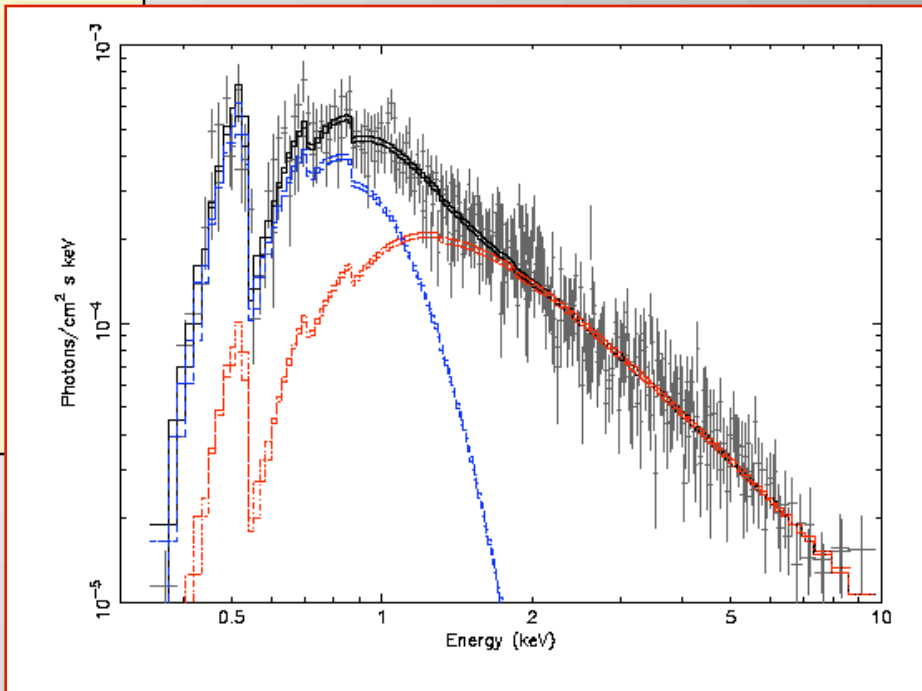


- But is the model correct?

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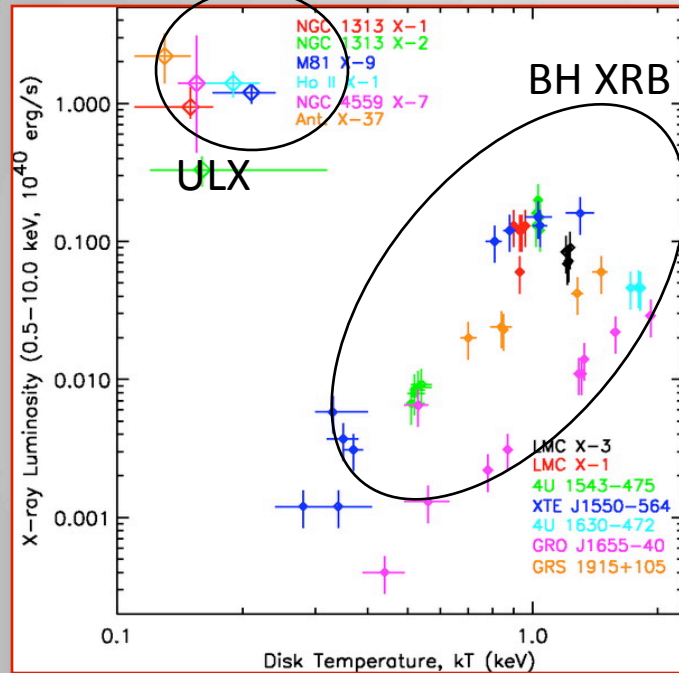


- But is the model correct?
- Is $R_{\text{in}} = R_{\text{isco}}$?

Model dependencies: $L_{disk} - T_{in}$ diagram

Miller, Fabian & Miller 2004

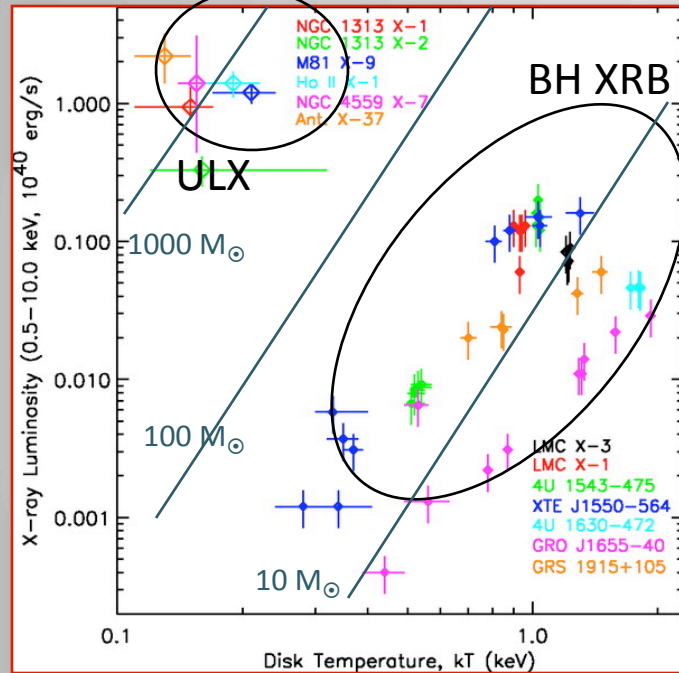
Cool Disk & power-law model



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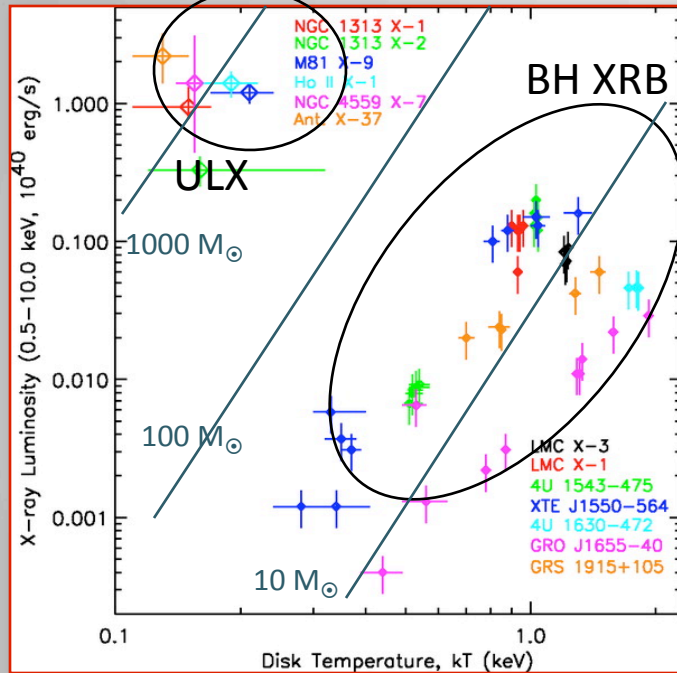
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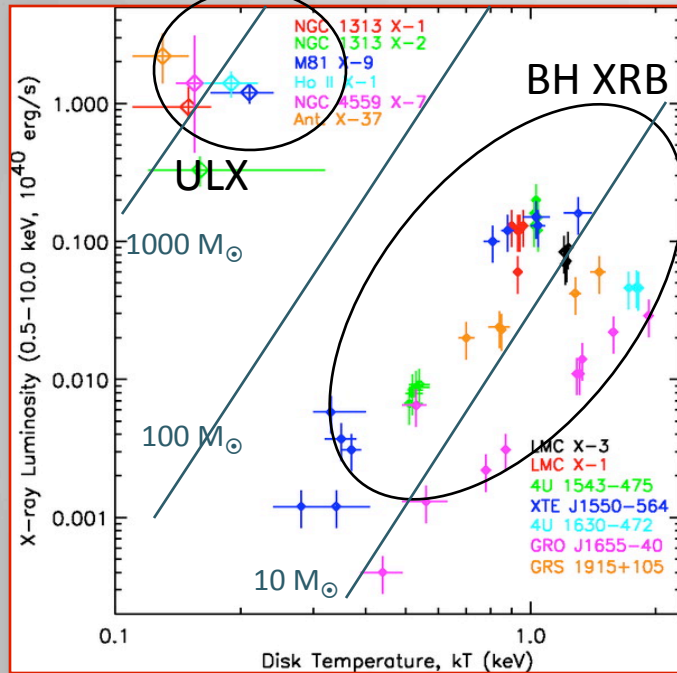


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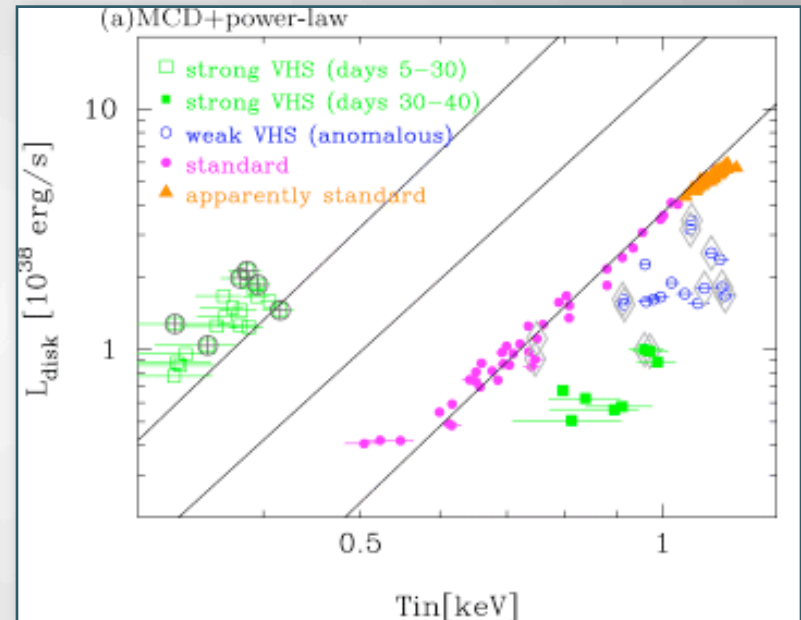
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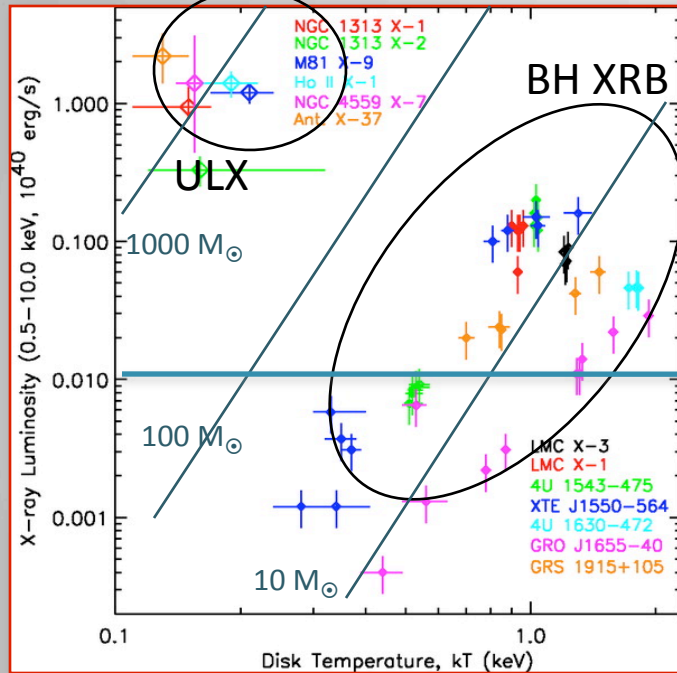
Kubota & Done 2004

XTEJ1550-564 BHB, $M_{BH} \sim 10 M_{\odot}$



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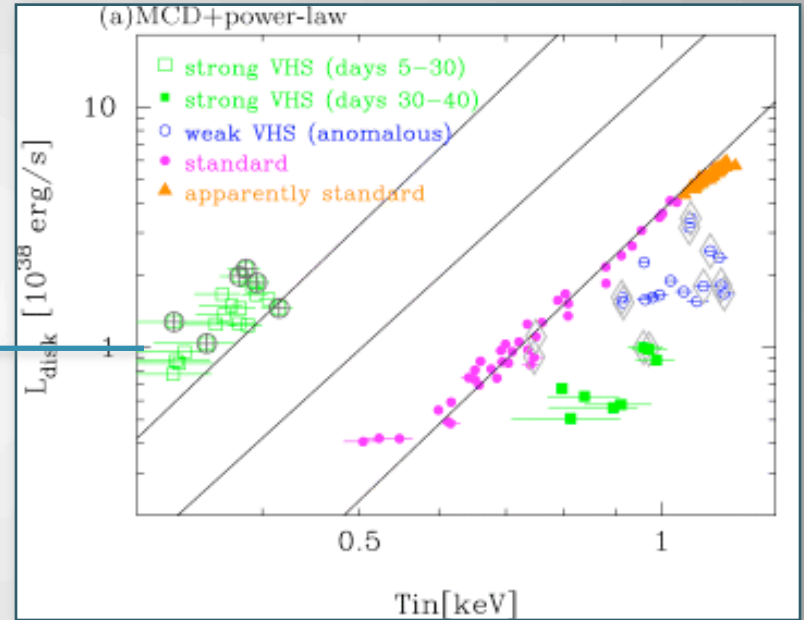


BUT

$L_x = 10^{38}$

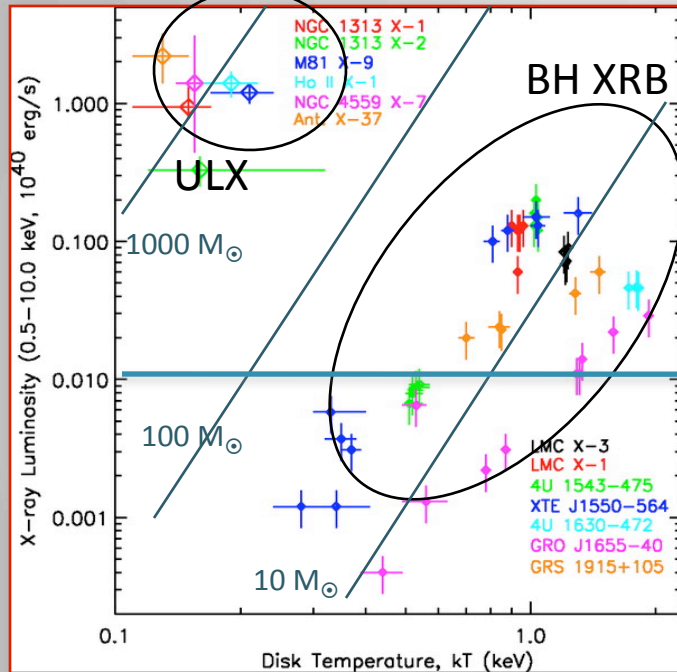
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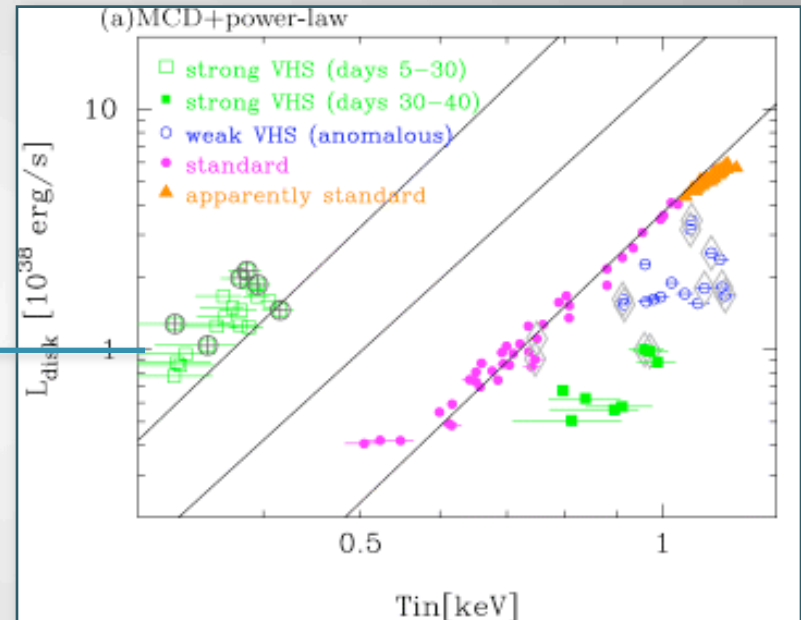


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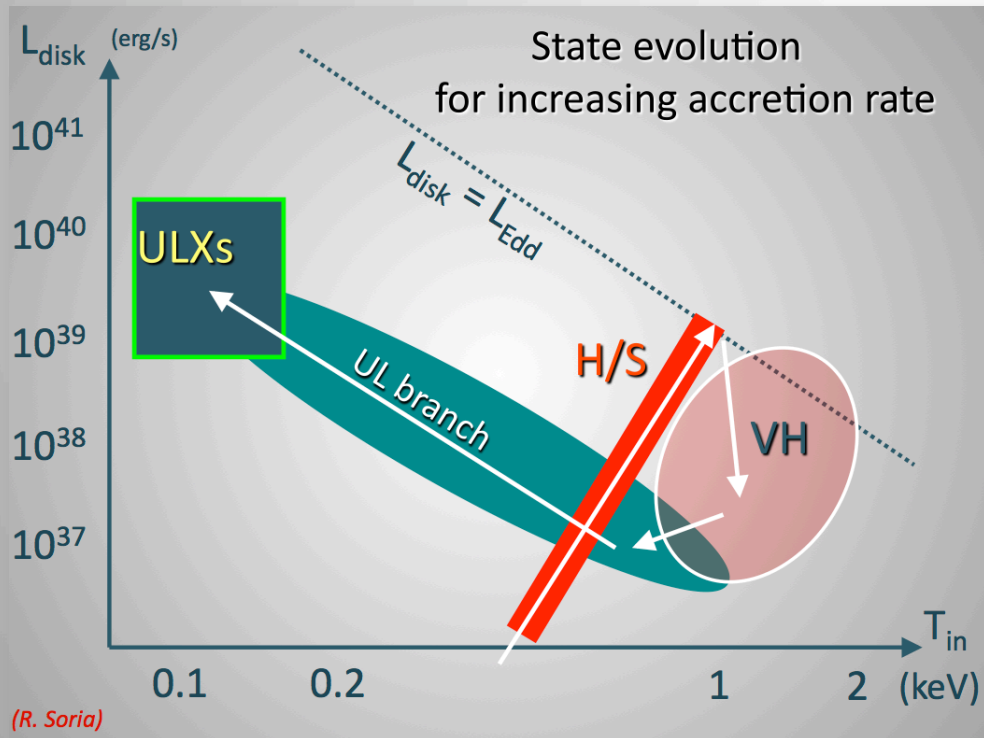
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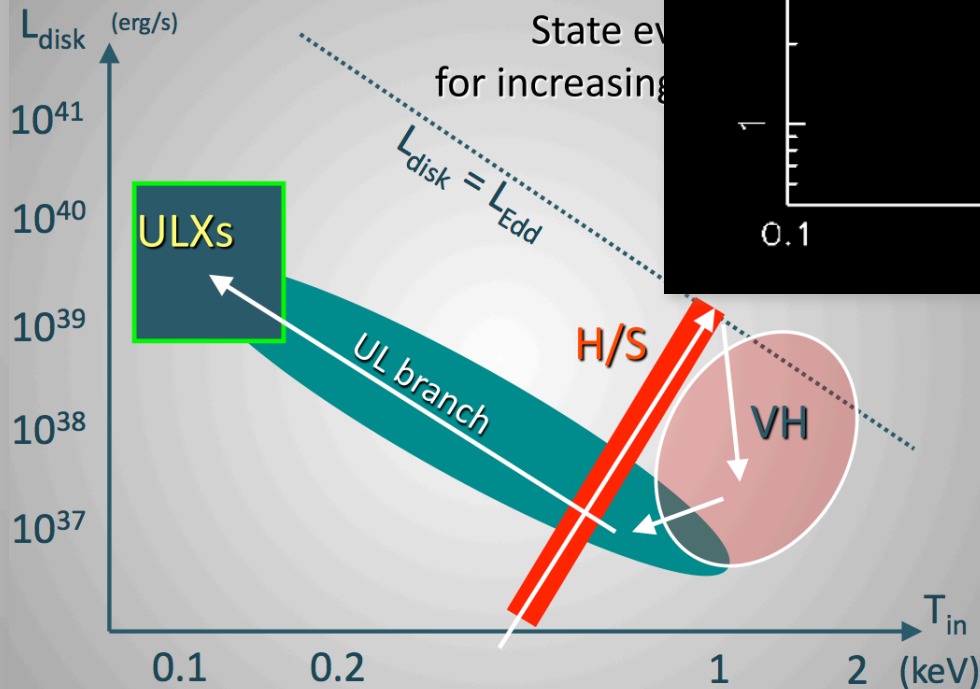
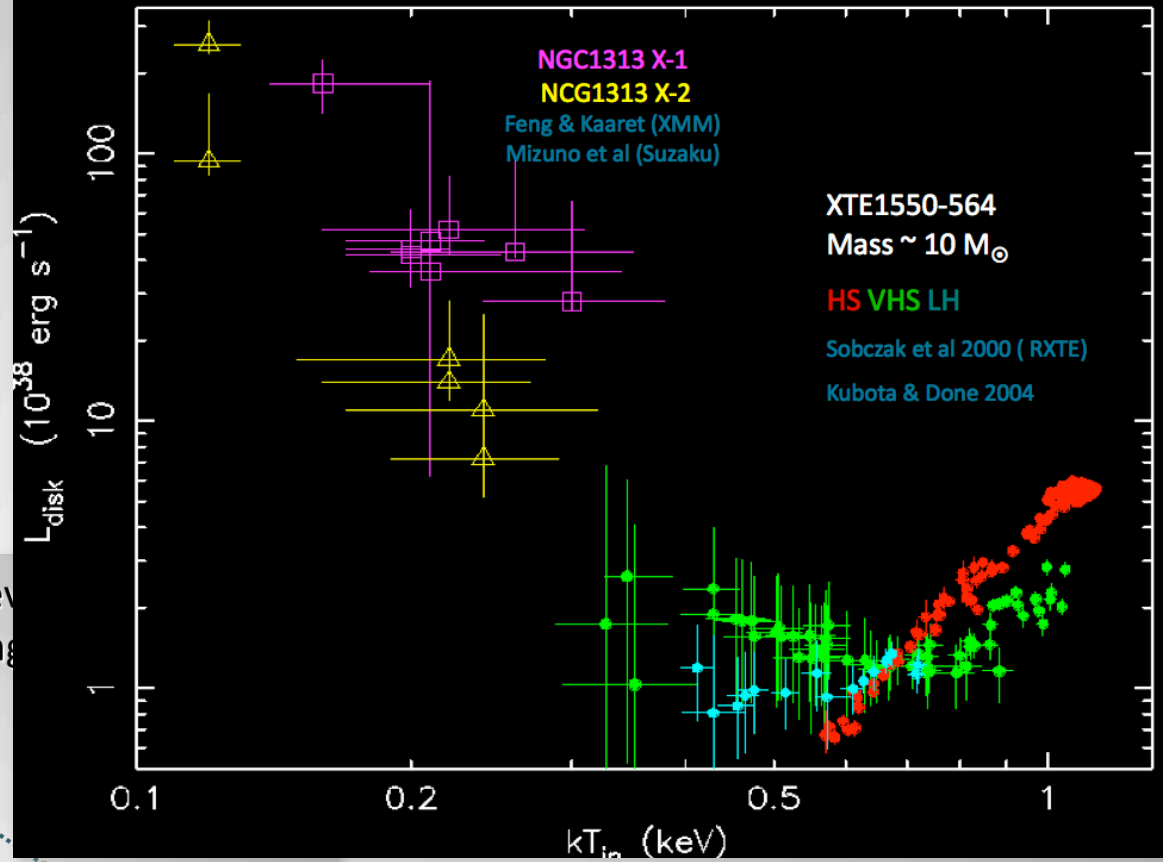


The same BH binary can have L_{disk} and T_{in} 'suggesting' different M_{BH}



Slides from R. Soria
See also, [Kajava & Poutanen 2009](#)

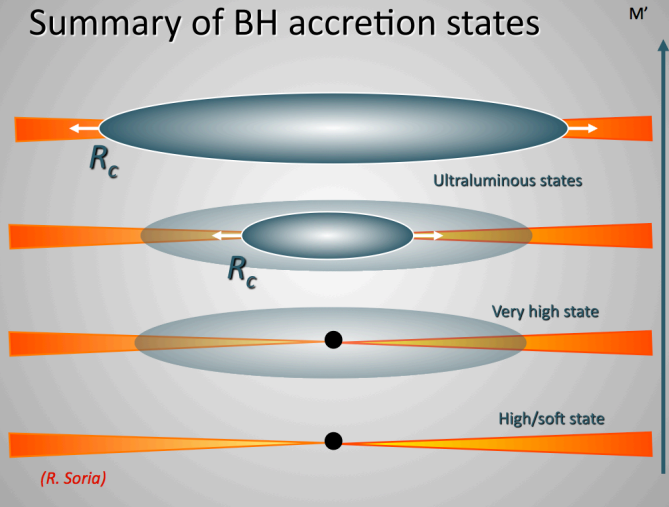
(R. Soria: standard (cold) Disk component)



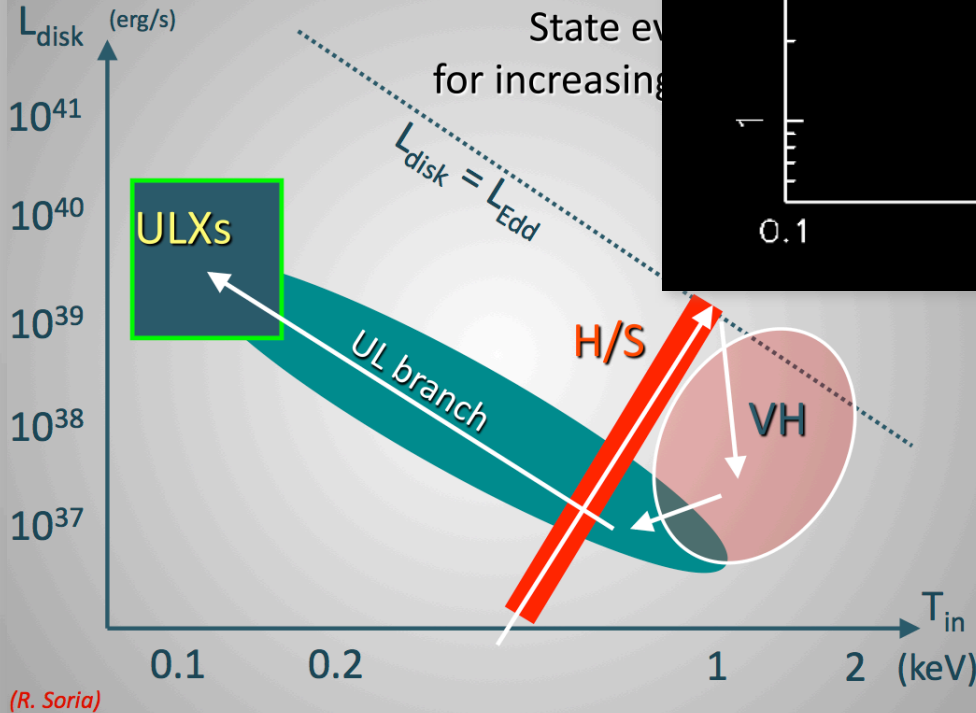
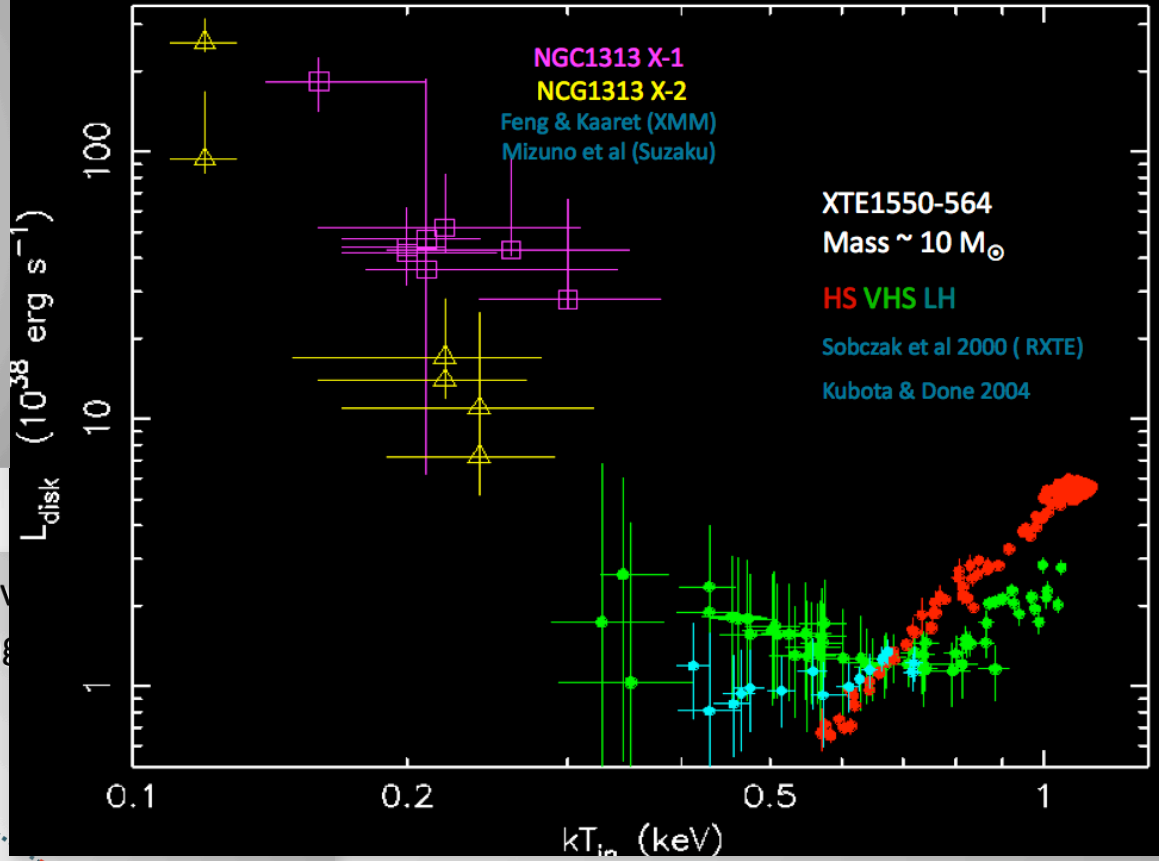
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Summary of BH accretion states



(R. Soria: standard (cold) Disk component)



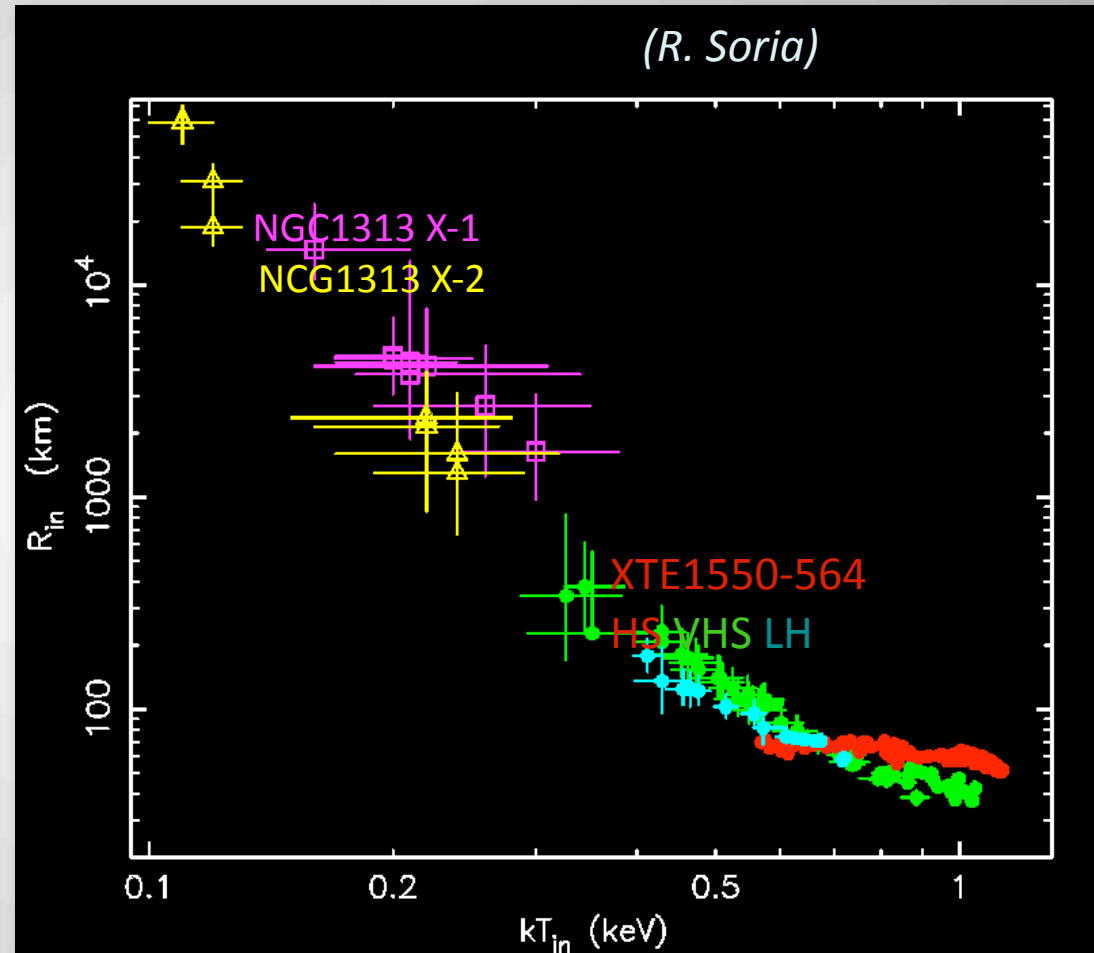
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$R_{in} - kT_{in}$ (from spectral disk fits)

If $R_{in} > R_{isco}$ and

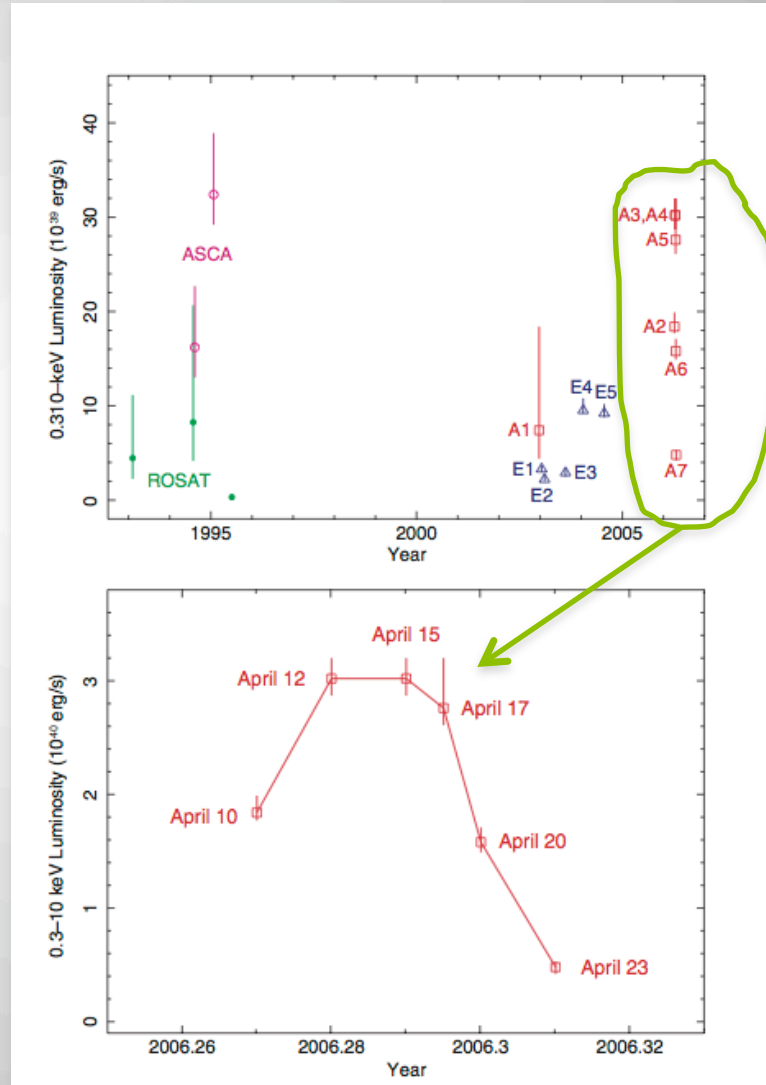
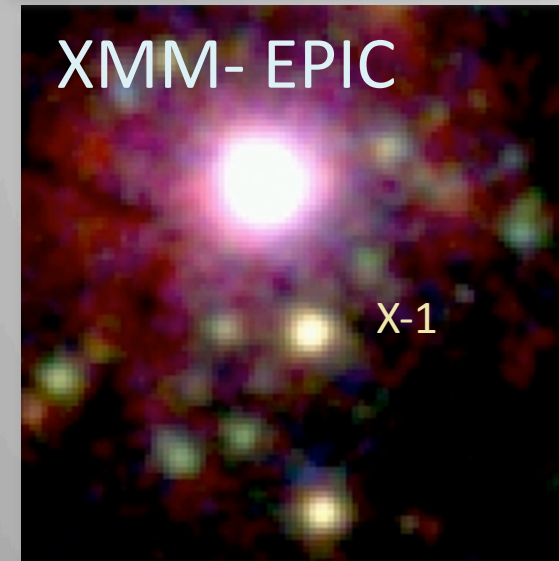
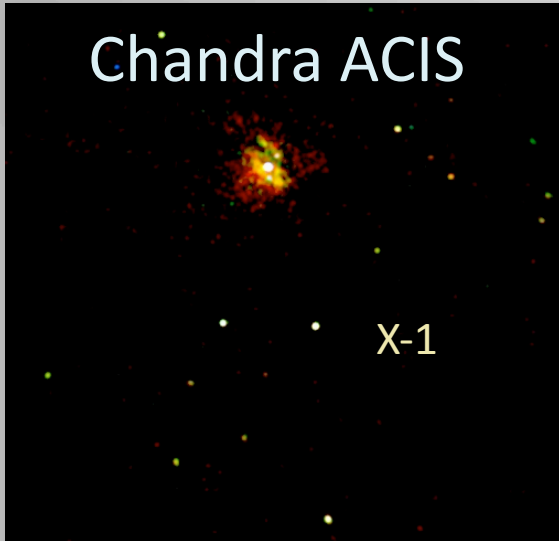
$$R_{in} = f M'$$

- kT does not measure M_{BH}
 - only in disk-dominated **HS** state
- Note: same applies to QPO frequency-mass



ULX NGC1365 X1

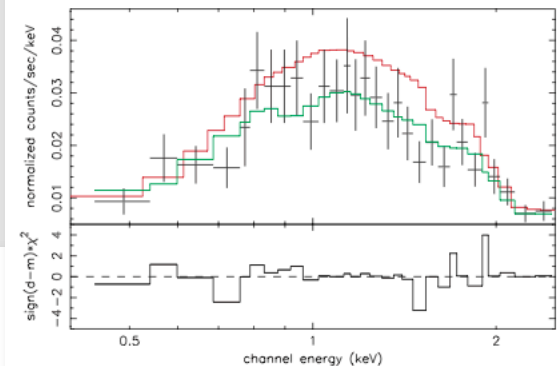
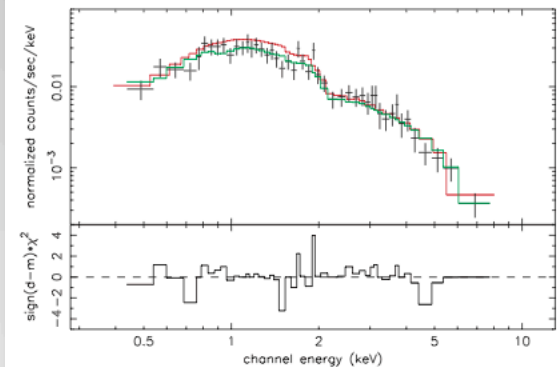
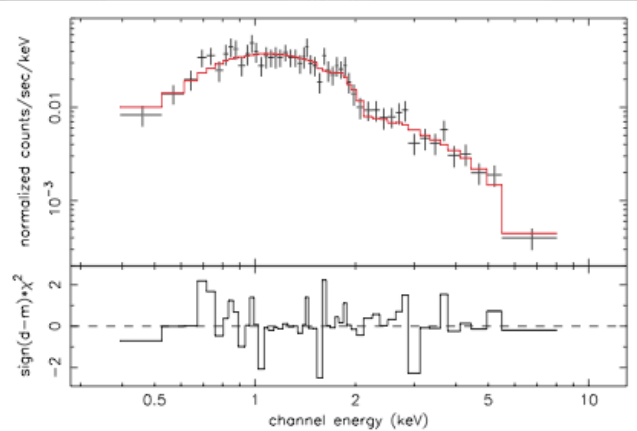
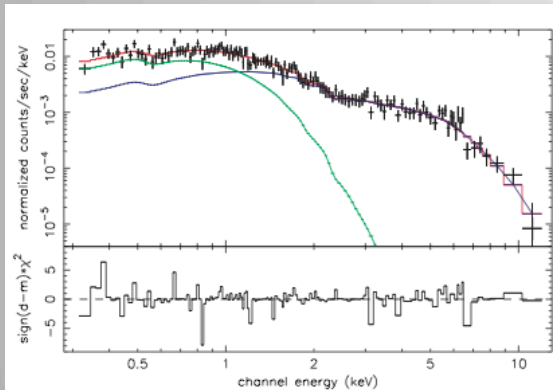
Soria et al 2007



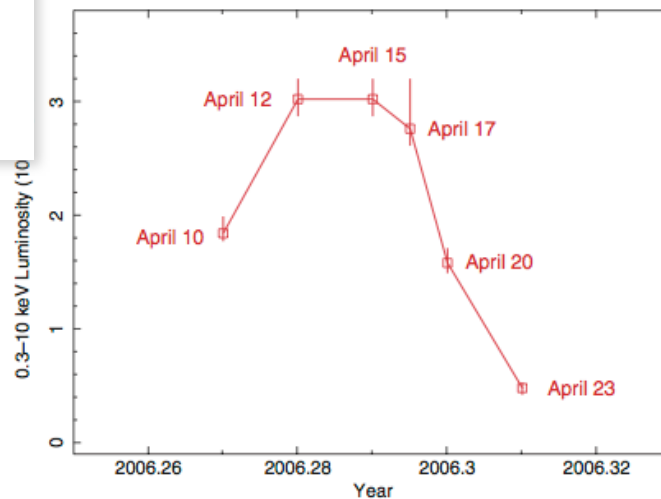
ULX NGC1365 X1

Soria et al 2007

Chandra, peak =>
Power-law, $\Gamma \sim 1.8$



XMM, pre-flare:
Disk, $kT \sim 0.23$ keV
+
Power-law, $\Gamma \sim 1.4$

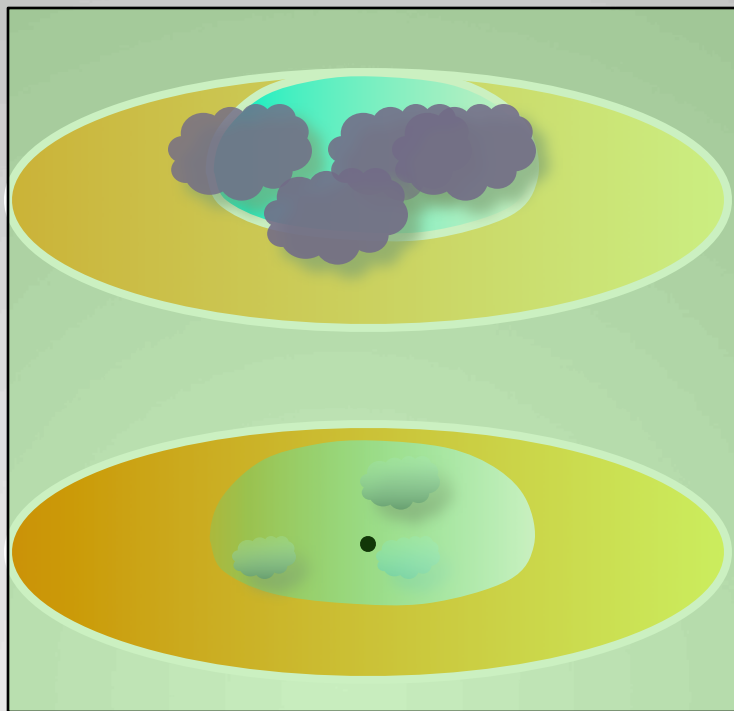


Chandra, Ap. 17
Power-law, $\Gamma \sim 1.8$ +
ionized absorber $N_H \sim 10^{22}$
 cm^{-2}

Outflow: see also NGC 1313 X-2

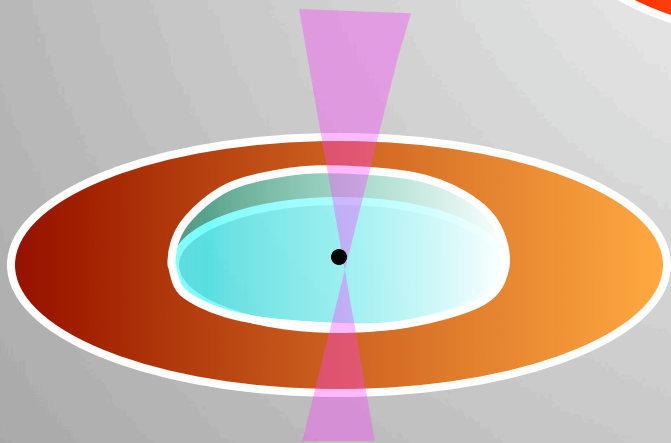
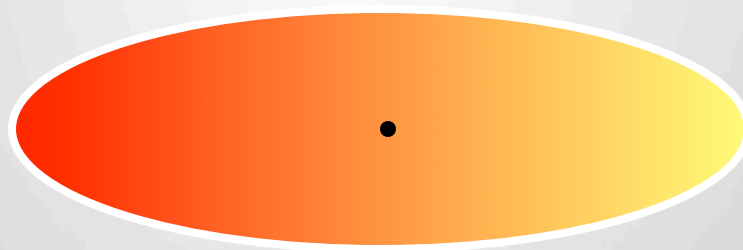
Feng & Kaaret 2007b

Ultraluminous

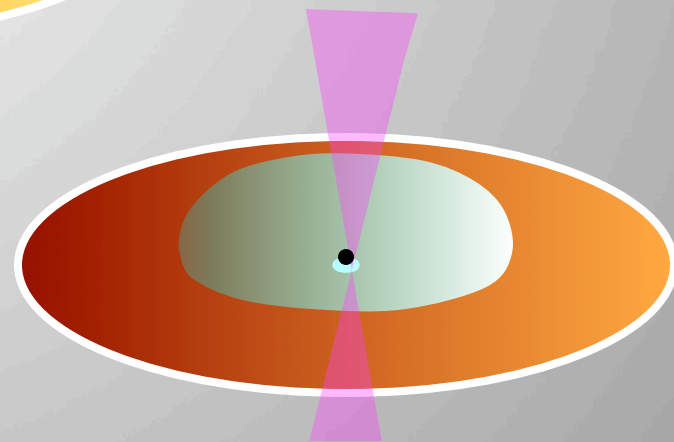


Very high (SPL)

High/soft (TD)



Low/hard



M'/M'_{Edd}



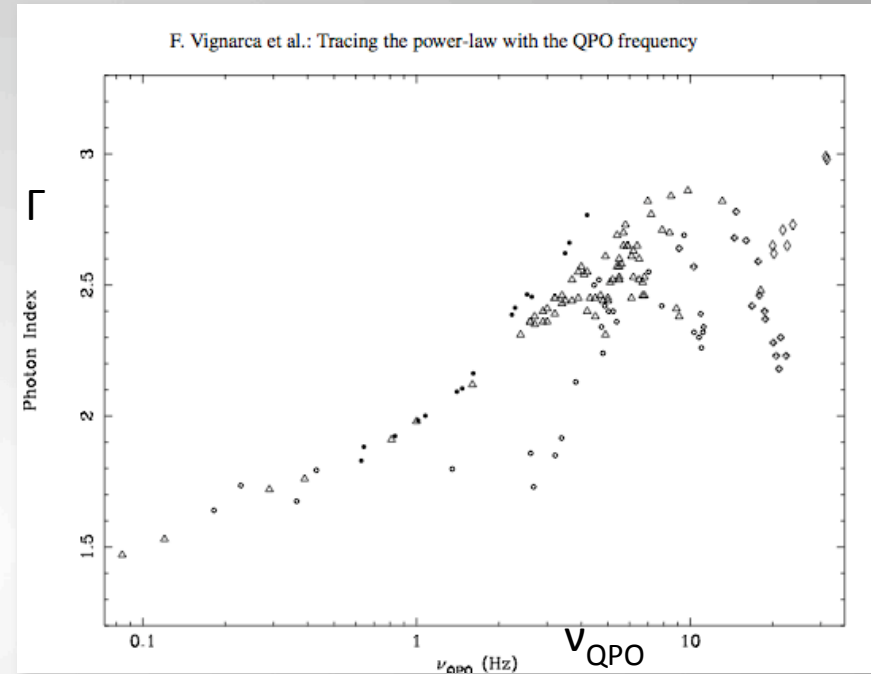
Constraints on M_{BH} for NGC1365 X-1

Soria et al 2007

- 2006 outburst peaked at $L \sim 3 \times 10^{40} \text{ erg s}^{-1}$, soon after which we see the outflow
 - If this is because of Eddington limit,
 $M_{\text{BH}} \leq 200 M_{\odot}$
 - Super-E accretion is possible, with central outflow funnel (King & Pounds 2003; Begelman et al 2006)
 - M_{BH} could be further reduced by mild beaming and be consistent with high values of stellar BHs

QPO Scaling relationships and BH mass

- QPOs with $\nu \sim 10\text{-}100$ mHz have been found in ULXs
 - M82
[Strohmayer & Mushotzky 2003](#); [Fiorito & Titarchuk 2004](#); [Dewangan et al 2006a](#)
 - Ho IX X-1
[Dewangan et al 2006b](#)
 - NGC 5408 X-1
[Strohmayer et al 2007](#); [Strohmayer & Mushotzky 2009](#)
- In BHB there is a clear relation between spectral index Γ and ν_{QPO} (see e.g., [Vignarca et al 2003](#))
- Also, $\nu_{QPO} \sim 1/M_{BH}$ connecting QPOs with R_{in}



QPO Scaling relationships and BH mass

- [Shaposhnikov & Titarchuk 2009](#) in BHB

$$M_t = M_r v_r / v_t$$

where 't' denotes the target system and 'r' the reference system

- Using this scaling law for ULXs with QPO, IMBHs $\sim 1000 M_\odot$
(see [Strohmayer & Mushotzky 2009](#) and refs. therein)

QPO Scaling relationships and BH mass

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(see [Strohmayer & Mushotzky 2009](#) and refs. therein)

- Is this scaling 'legitimate' in the case of ULXs?
- If $R_{in} \gg R_{ISCO}$ because of SE outflows, the scaling would not apply
- See [Ingram & Done 2011](#) – QPO model in hot inner flow disk

The 'hard' spectra of ULX

- Hard power-laws

- $\Gamma \sim 1.2 - 1.8$

- [Zezas et al 2002](#) – in the Antennae

- [Soria et al 2009](#) – NGC 1365 X-1 and X-2

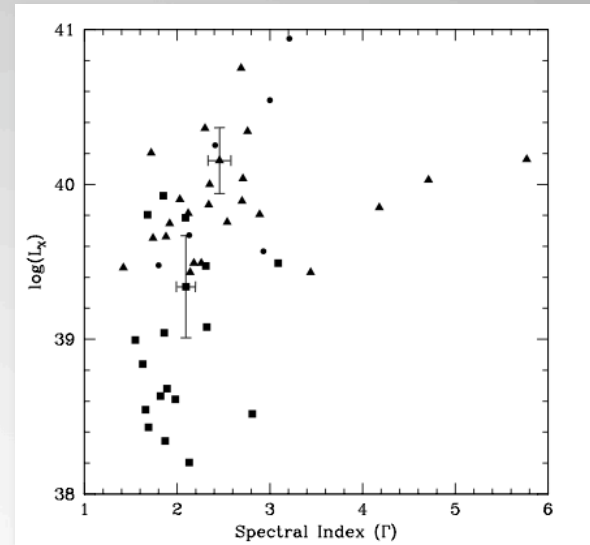
- [Berghea et al 2008](#) – Chandra sample

- [Winter, Mushotzky & Reynolds 2006](#) – XMM survey

- [Winter et al 2006](#)

- Lower L_x is associated with smaller Γ ,
as in Galactic BHBs in low hard state

- If ULXs are in low state and the model
is mass scalable, this would imply
IMBH masses



[Winter et al
2006](#)

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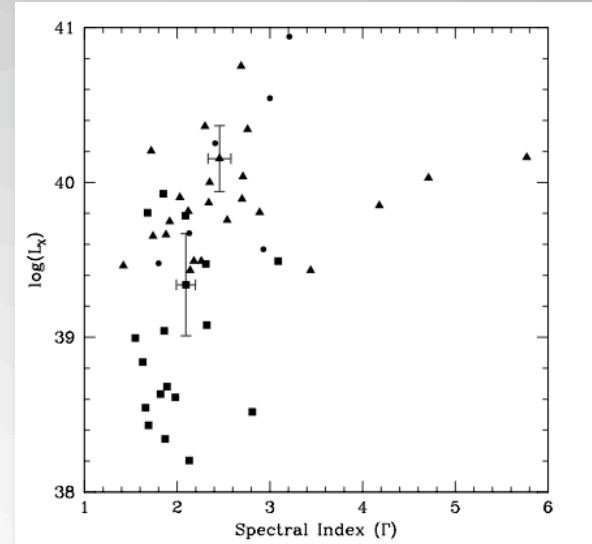
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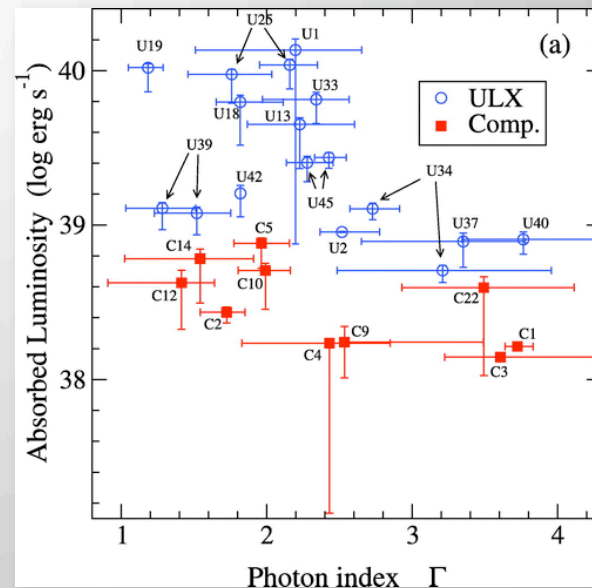
- If ULXs are in low state and the model is mass scalable, this would imply IMBH masses

- Instead.. [Berghea et al 2008](#)

- In 2-component fit finds that higher L_X goes with smaller Γ



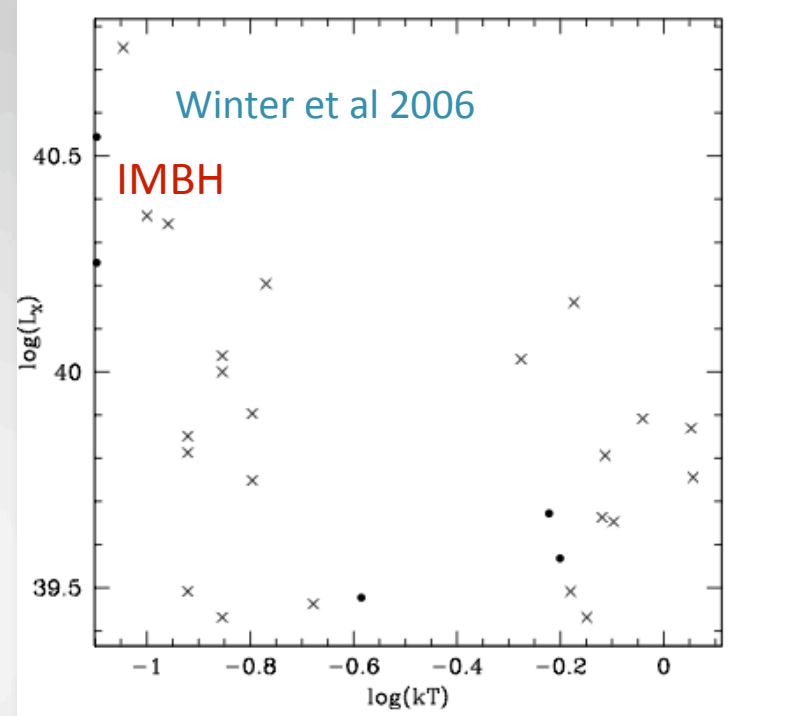
[Winter et al 2006](#)



[Berghea et al 2008](#)

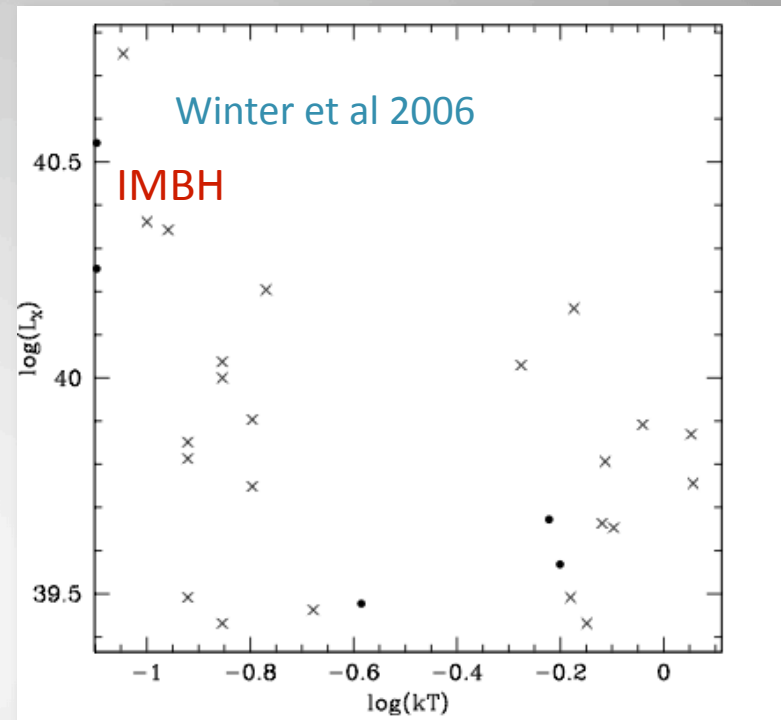
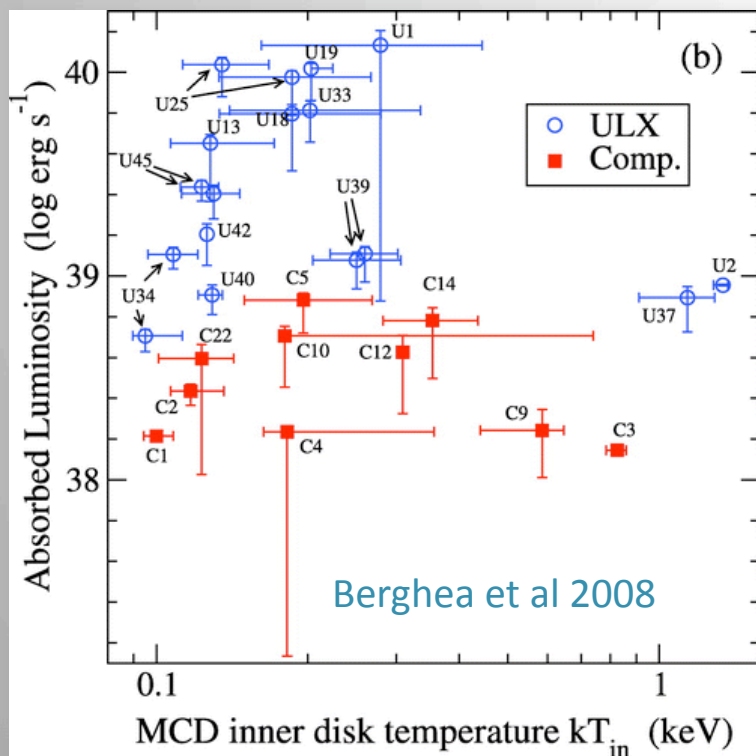
The disk component of ULX

- Winter et al 2006 - 2 regimes of $kT_{in} \sim 1$ and 0.1 keV



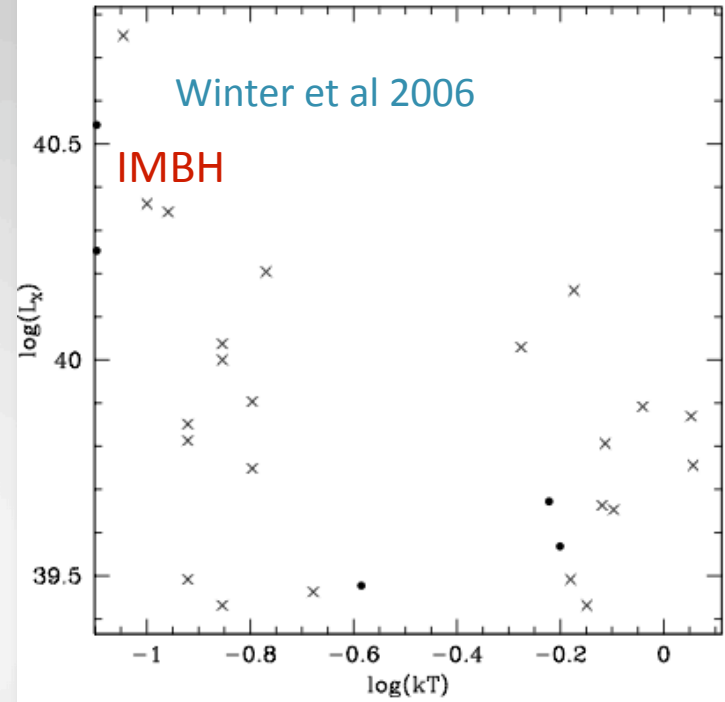
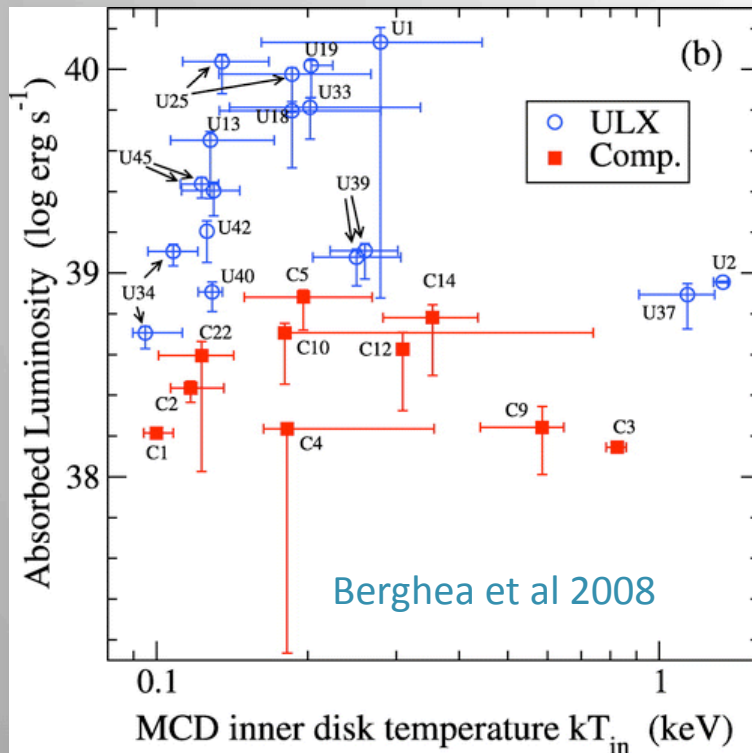
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- Soria et al 2009
 - ULX have SE accretion rates that always impede the formation of a stable disk
 - No direct constraint on BH mass

A list of proposed models: Which model is 'right'?

IMBH

'Phenomenological' model PL with soft component

- Thermal emission from cool optically thick thin accretion disk (BB) + power-law from Comptonized emission from corona (used by [Miller et al 2003](#))

XRB

Slim disk models (hot thicker disk at super-E accretion rates)

(e.g. [Ebisawa et al 2003](#), [Vierdayanti et al 2006](#), see also [Stobbart et al 2006](#))

XRB

Self-consistent Comptonized models, with disk-corona interaction

([Svensson & Zdziarski 1994](#), [Done & Kubota 2005](#), [Socrates & Davis 2006](#))

- Dissipates accretion power in corona, lower flux and kT in inner disk
- Gives reasonable results for VHS BH XRBs

XRB

Semi-phenomenological models with Comptonization, ionized absorber,

outflow (e.g. [Gonsalves & Soria 2006](#), [Soria et al 2007](#))

IMBH??

WD -XRB

QPO – BHB analogy (e.g. [Shaposhnikov & Titarchuk 2009](#))

SS ULXs WD or BH photospheric outflow?

(e.g., [Fabbiano, King et al 2003](#), Antennae SSULX; [Mukai et al 2005](#), M101 supersoft ULX; [Soria & Ghosh 2009](#), NGC 4631 X-1)

XRB

microquasar

SS433 type model: Jet, Eddington columnar outflow, outer disk

([Begelman, King & Pringle 2006](#))

XRB

Low Z

Zampieri & Roberts 2009

But how can we measure the BH
mass?

Iron-clad solution

(if we have an X-ray binary)

- Find optical star and follow up with measurement of mass function (as for Galactic BHs)

$$f = PK^3 / 2\pi G = M_{\bullet} \sin^3 i / (M_p / M_{\bullet} + 1)^2 < M_{\bullet}$$

where P = orbital period

K = 1/2 amplitude of change in radial v

M_p = mass of star with known spectrum

M_{\bullet} = mass of BH

HST may do a few, and future very large area and high resolution optical telescopes

...ASTROSAT

- Not ideal for studying ULXs in galaxies
- Ideal for studying bright Galactic binaries, esp. transients, high lum. Variables
 - Further constrain stellar BH binary option for ULXs