Fullēohte X-geleomode tungolas

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Kinwah Wu, Mark Cropper, Kip Kuntz,….

Outline

- Introduction & definition
- Population properties
- X-ray spectral and timing properties

  A new physical class of black holes,
  or ordinary black holes in a new state?

- Optical/radio counterparts
- Black hole masses and formation processes

  Stellar/non stellar black holes? IMBHs?

1. Definition of ULX

Accreting, non-nuclear point-like sources (BHs) with apparent X-ray luminosities > 1E39 erg/s

(alternatively: L > 3E39 erg/s)

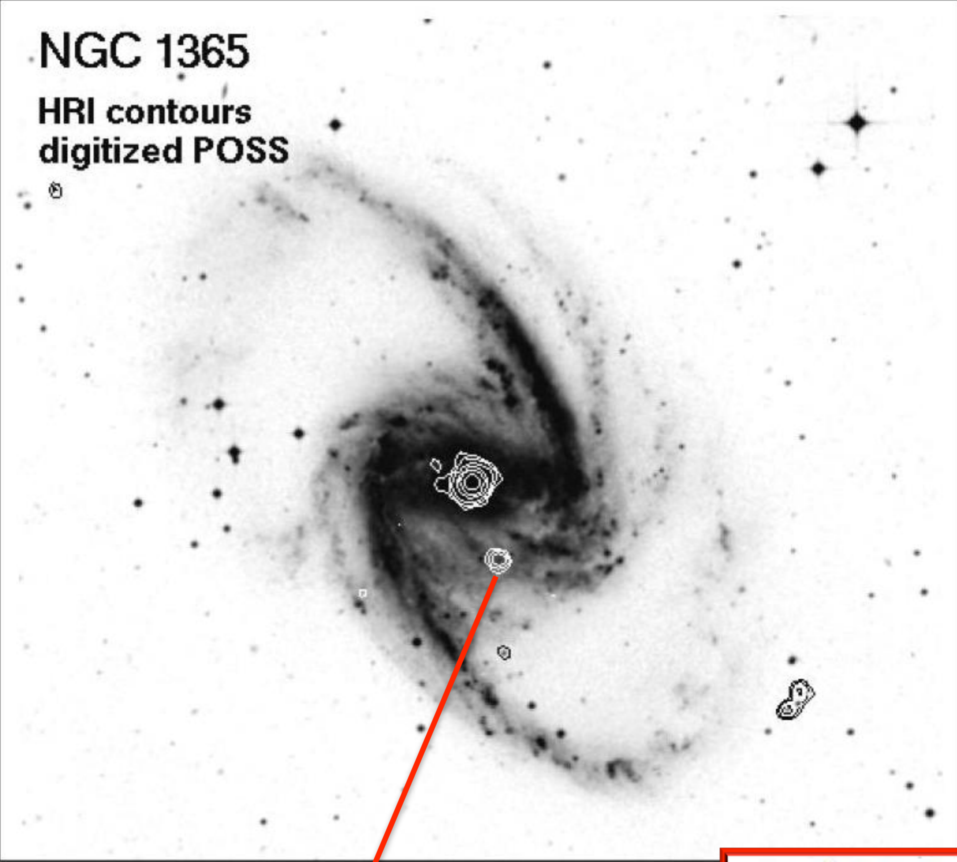
X-ray luminosity of Galactic BHs <~ 1E39 erg/s

X-ray luminosity of Galactic NSs <~ 3E38 erg/s

(both are Eddington limited)

ULX = any source more luminous than Galactic BHs

Or: ULX = any source more luminous than the Eddington limit of a 20 M_{sun} BH



Early detection of non-nuclear sources > 1E39 erg/s with *Einstein*
(Long & van Speybtoeck 1983;
Fabbiano & Trinchieri 1987)

Clearly identified with *ROSAT* + *ASCA* studies in the 1990s
(Okada et al 1998
Colbert & Mushotzky 1999
Roberts & Warwick 2000
Colbert & Ptak 2002
Liu & Bregman 2005)

$L_{0.3\text{-}10}$ ~ 3E40 erg/s

Hard power-law spectrum

At present, the most likely interpretation seems to be an ultra-powerful X-ray binary, with either a highly super-eddington low-mass black hole or a very massive black hole. The hard powerlaw component derived from the ROSAT and ASCA spectral fits is known to be present in Galactic X-ray binaries (see Tanaka 1997 for a recent review); they have soft-excesses added in their high-states. In case the accretion is not super-eddington, a rather high-mass black hole of ~100–200 $M_\odot$ is inferred which may pose a challenge for stellar evolution models.

(Komossa & Shulz 1998)

How can ULXs have apparent luminosities ~ 1E40 erg/s?

$$L \approx \frac{1.3\times10^{39}}{b}\left(\frac{M_{BH}}{10M_{sun}}\right)\left(1+\frac{3}{5}\ln\dot{m}\right)$$

Beaming (b<1)

BH mass >~ 10

Accretion rate (>1?)

Four possible scenarios

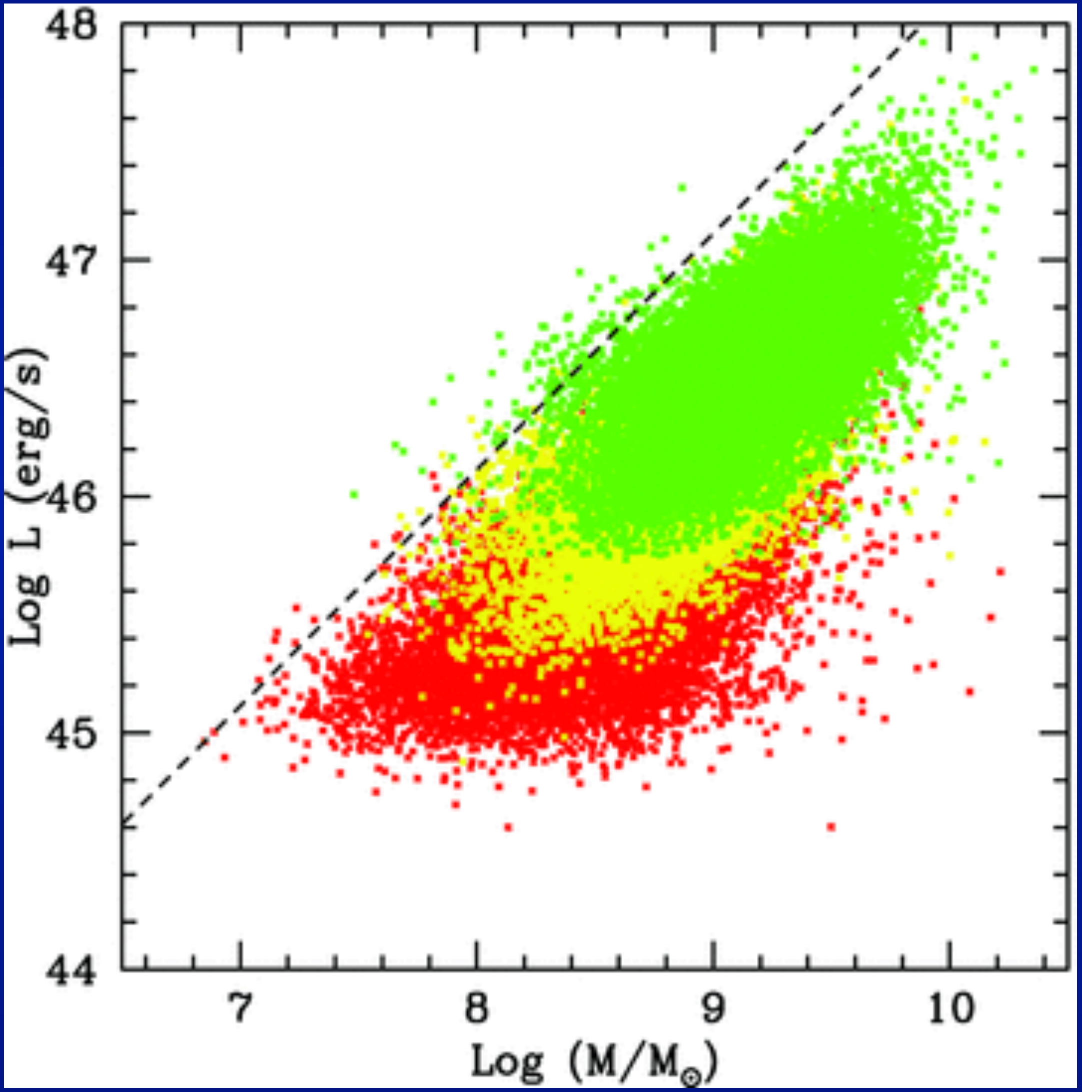
Ordinary stellar-mass BHs ($M <\sim 20\ M_{sun}$)
at very super-Eddington luminosity

Ordinary stellar-mass BHs ($M <\sim 20\ M_{sun}$)
at about Eddington luminosity, beamed by ~ 10

Heavy stellar BHs ($M \sim 30$—$80\ M_{sun}$)
at about Eddington luminosity

Intermediate-mass BHs ($M \sim 1000\ M_{sun}$)
at sub-Eddington luminosity

Eddington limit easy to exceed in theory (Begelman 2002), but not in nature?

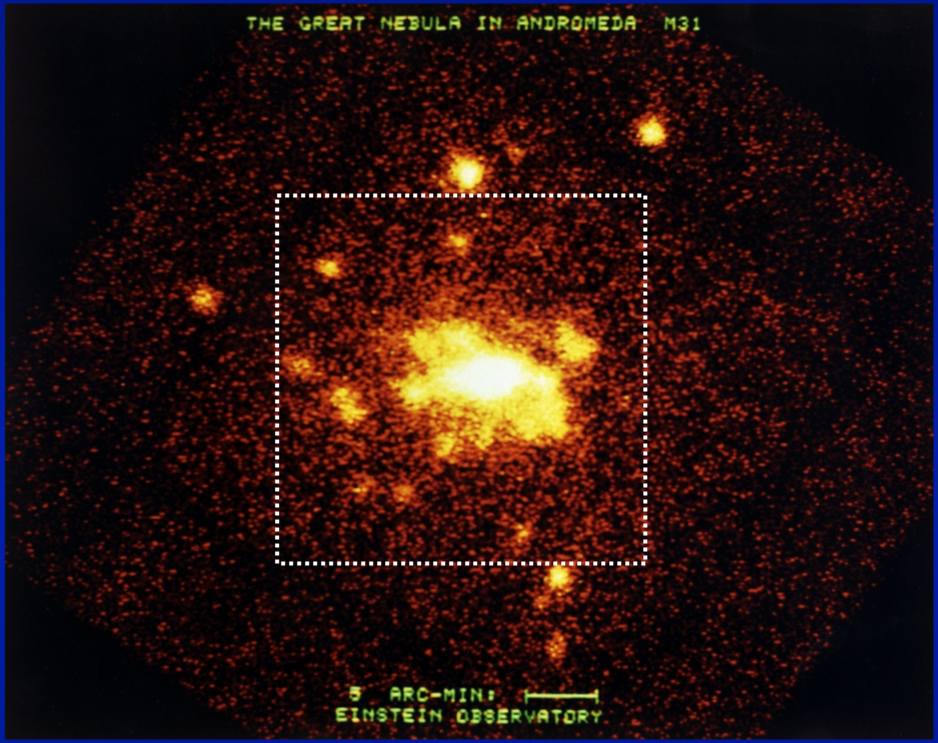


62,000 quasars from the SDSS show L <~ 3 L_{Edd} (Steinhardt & Elvis 2010)

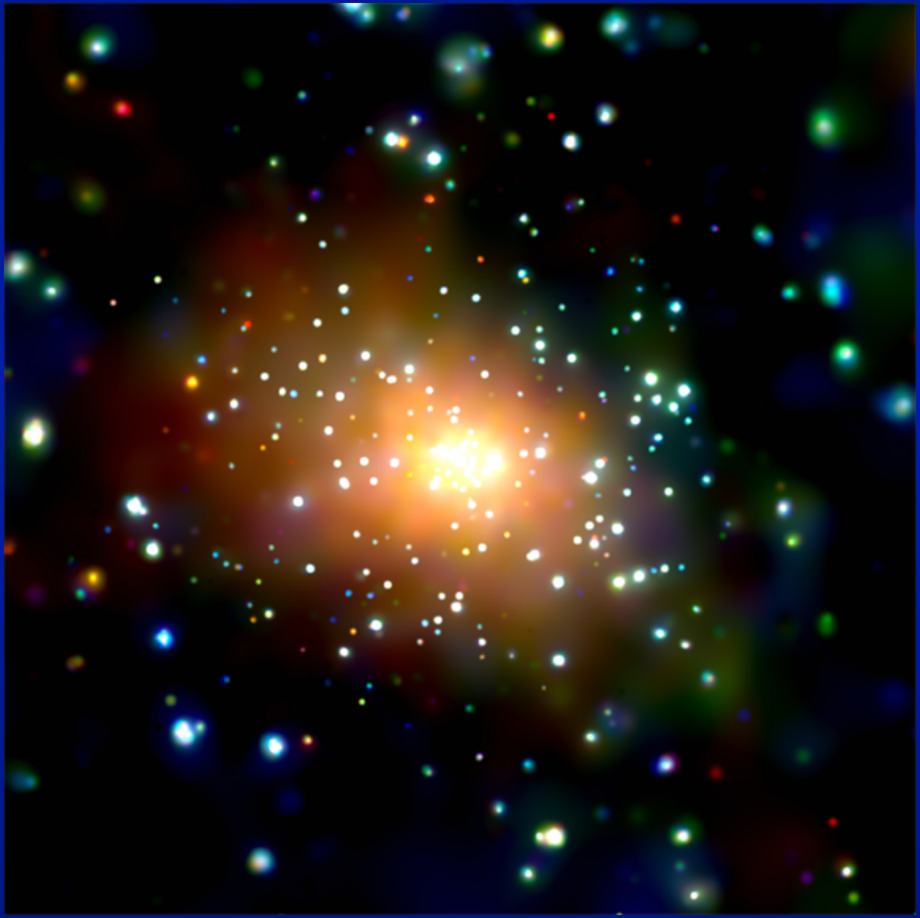
2. Population properties

Chandra & *XMM-Newton* allow statistical studies of X-ray binary populations in nearby galaxies down to $L_X \sim$ 1E36 erg/s

32 years of X-ray imaging (1979—2011)

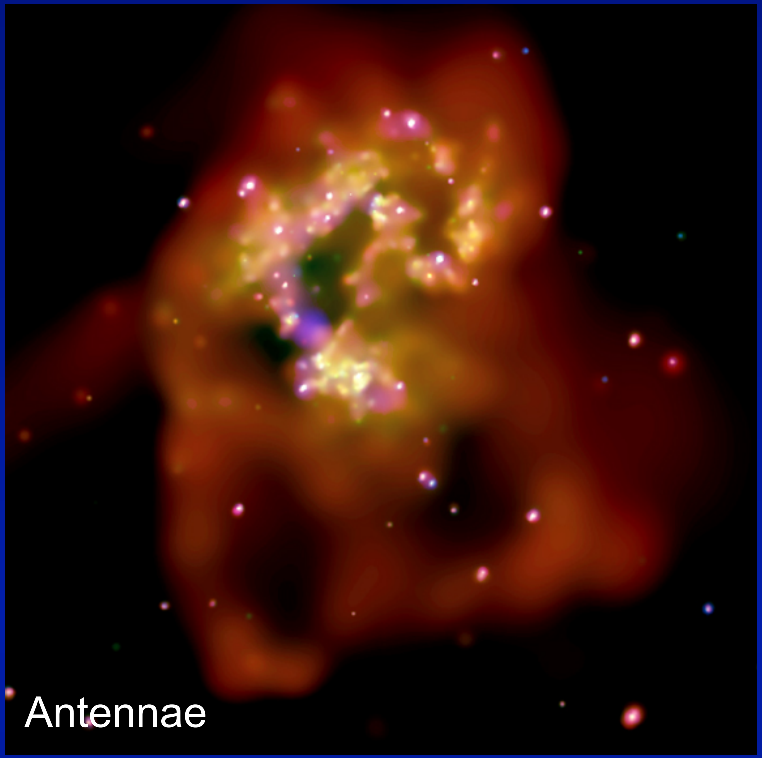


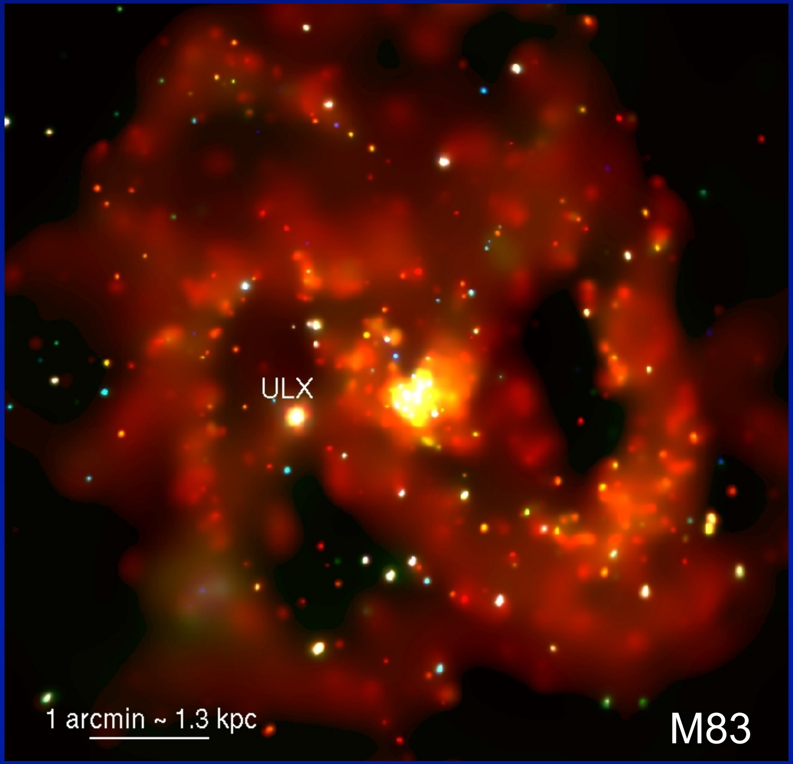
Einstein 1979

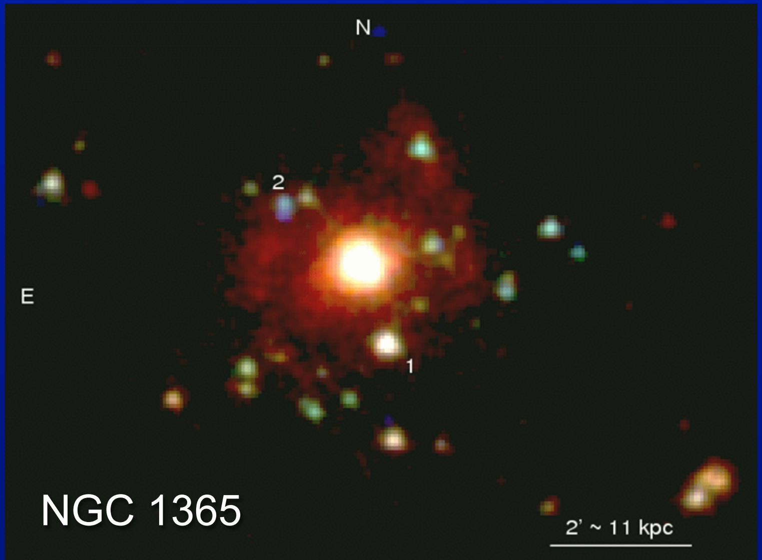


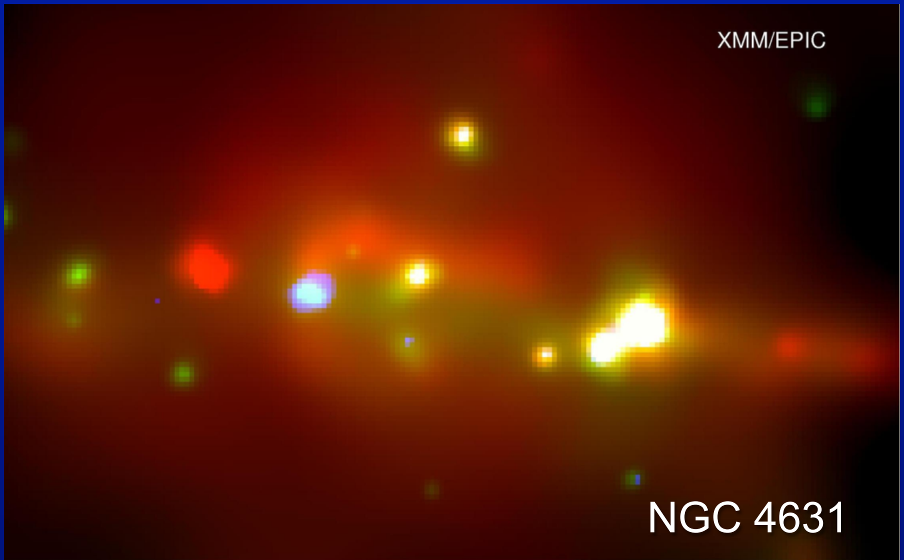
Chandra 2011

ULXs and X-ray binaries in nearby galaxies (*Chandra* and *XMM-Newton*)

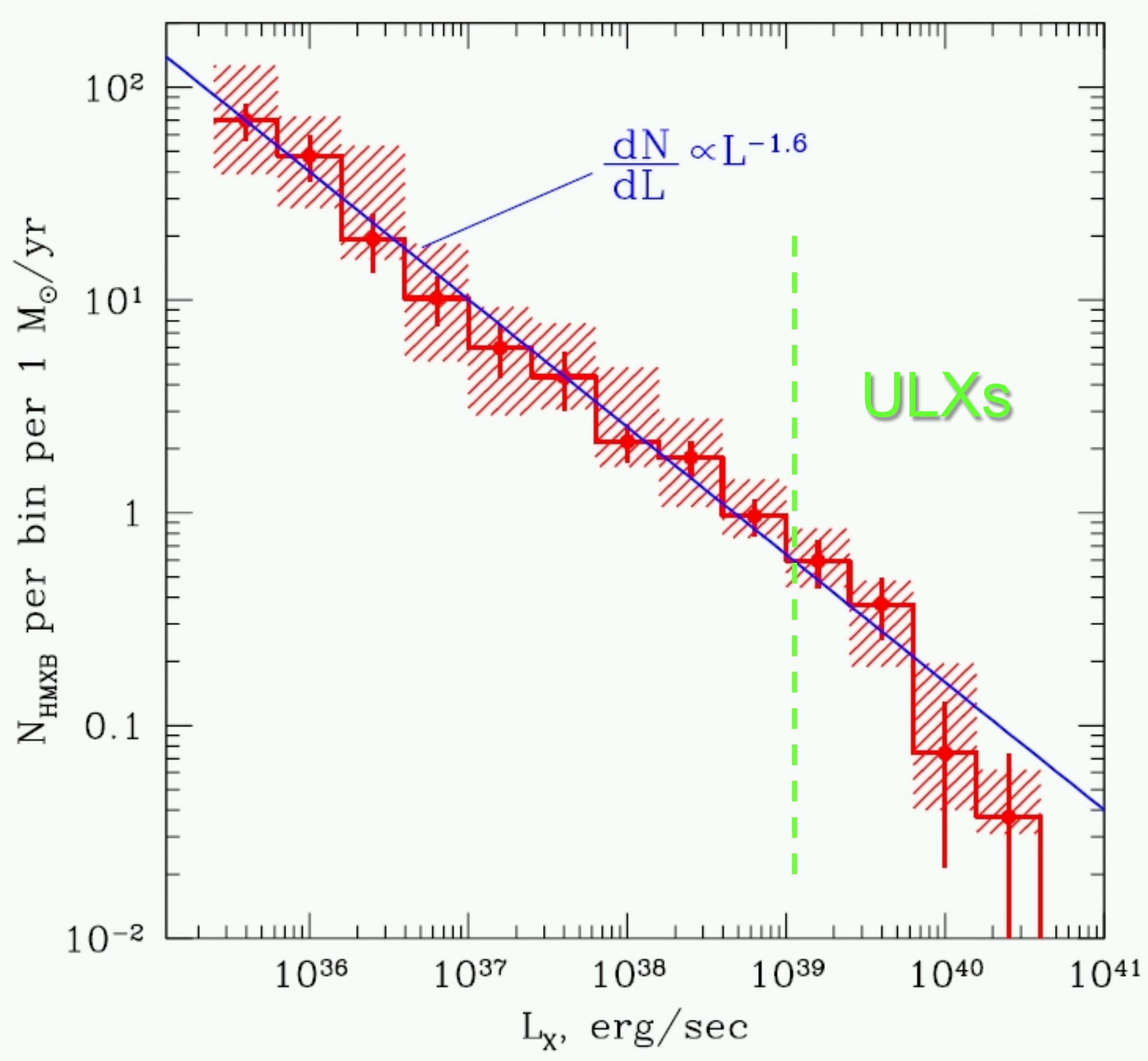






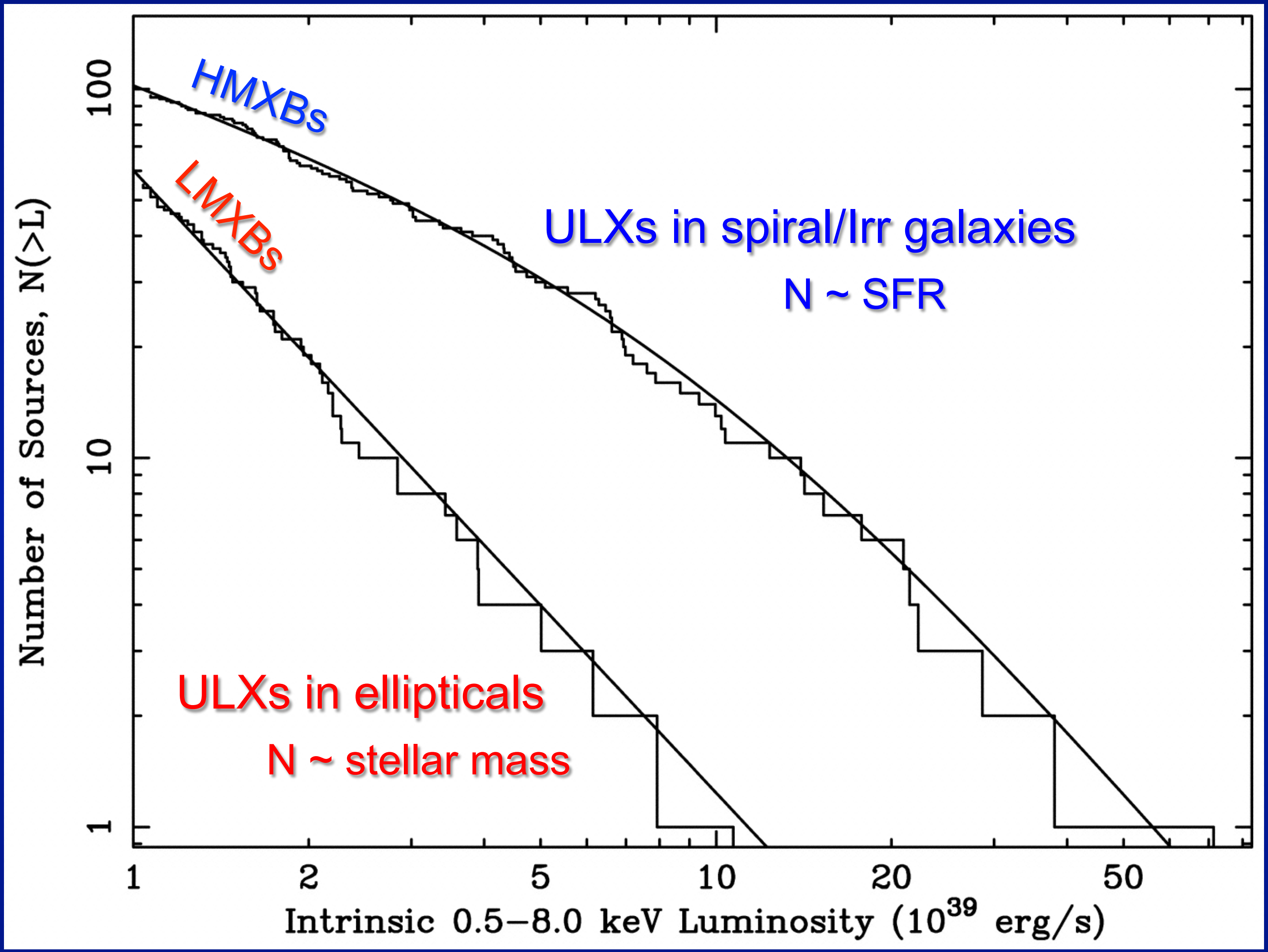


Luminosity function of high-mass X-ray binaries
$N(>L) \sim SFR \times L^{-0.6}$



(Grimm, Gilfanov & Sunyaev 2003)

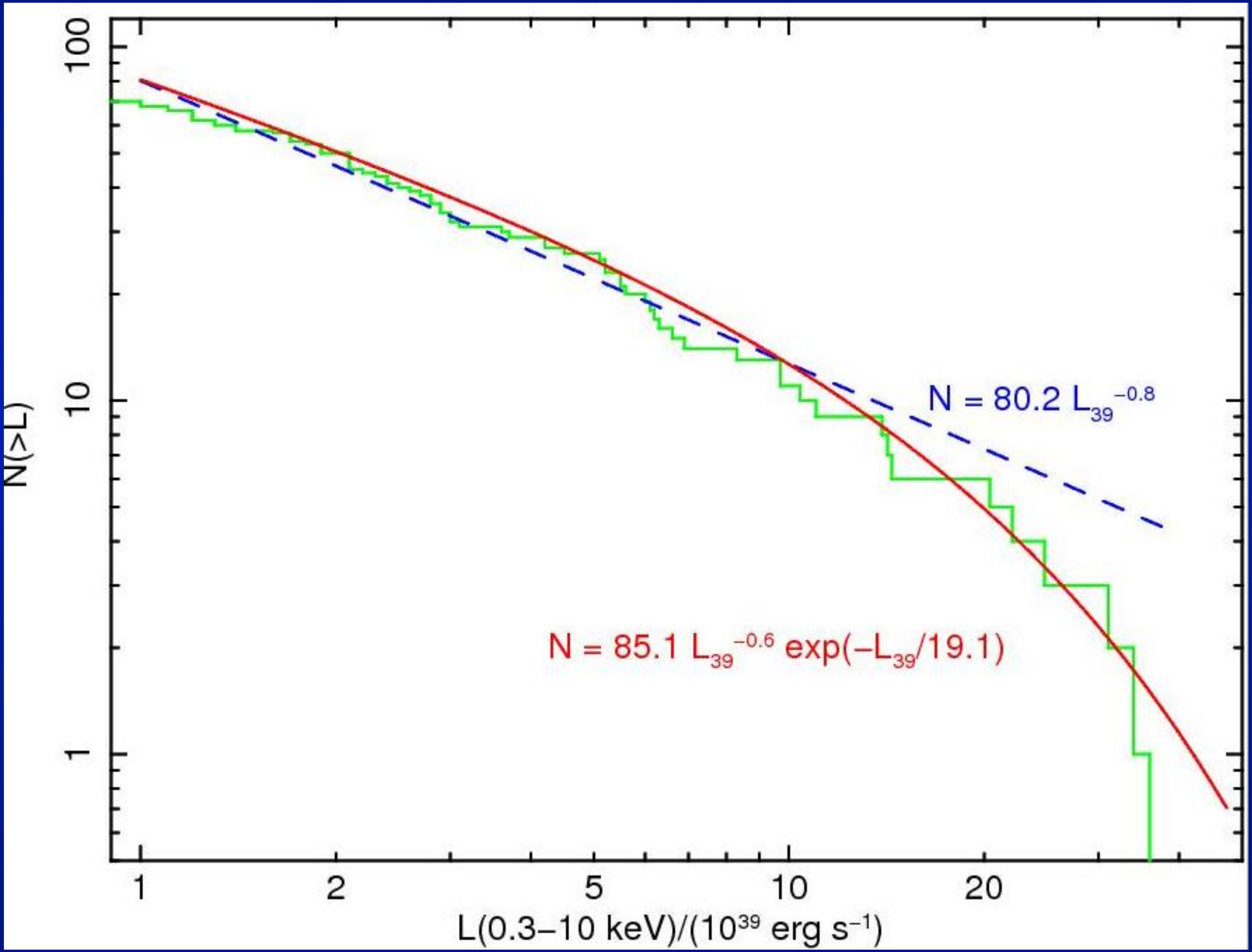
First *Chandra* catalogue of ULXs (Swartz et al 2004)



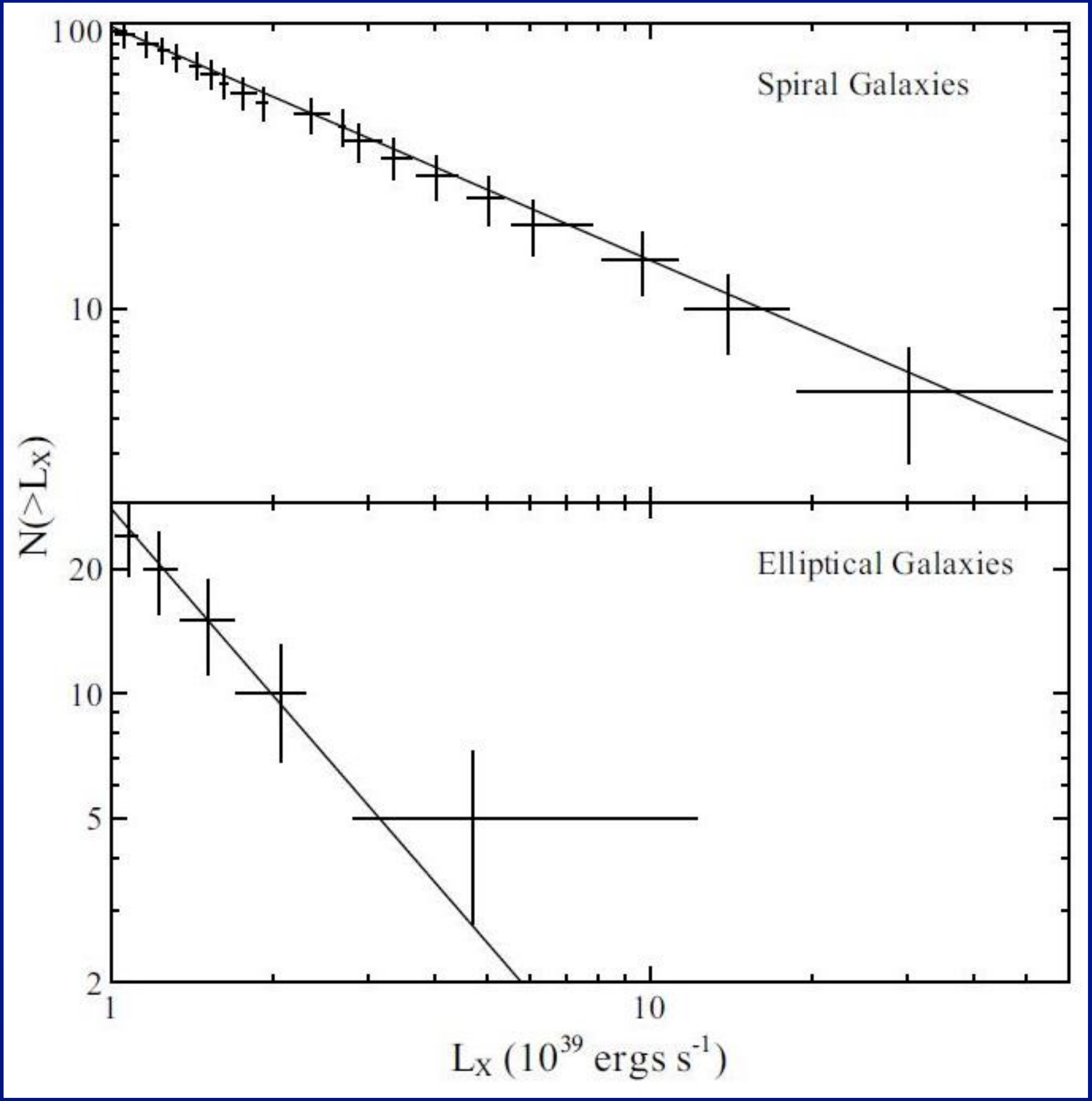
Hints of a break at L ~ 2E40 erg/s

New *Chandra* catalogue of ULXs (Swartz et al 2011)

Complete sample of 127 Northern-sky star-forming galaxies at d < 15 Mpc



XMM-Newton catalogue of ULXs (Walton et al 2011)



How common are ULXs?

~1 ULX per star formation rate ~ 0.5 M_{sun}/yr

~1 ULX per galaxy, for E/Sph with dynamical mass ~ 10^{11} M_{sun}

~1 ULX per galaxy, for S/Irr galaxies with dyn. mass ~ 10^{10} M_{sun}

Low-mass disk galaxies and Irr are the most efficient ULX hosts per unit SFR (low metallicity, higher specific SFR)

3. X-ray spectral properties

Do ULX spectra have the same “states” as Galactic BHs?
Are they mostly thermal (disk) or non-thermal (corona)?

“Canonical” BH accretion states

(From the 1980s… eg, Cyg X-1, GX339-4)

$\dot{m}$

1 **Very high state**

Heavily Comptonized disk

Radio flaring

0.1 **High/Soft state**

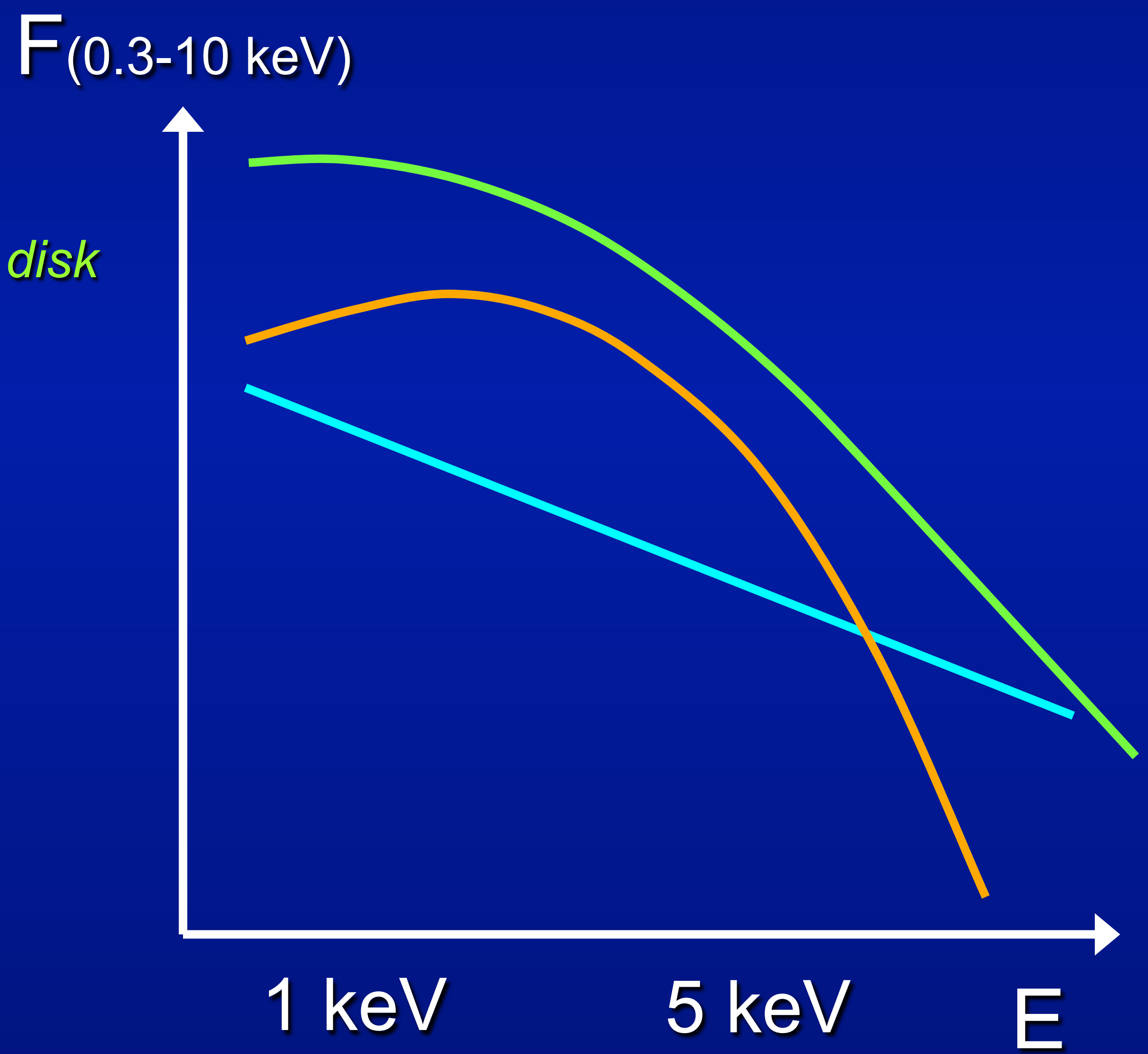
Standard disk

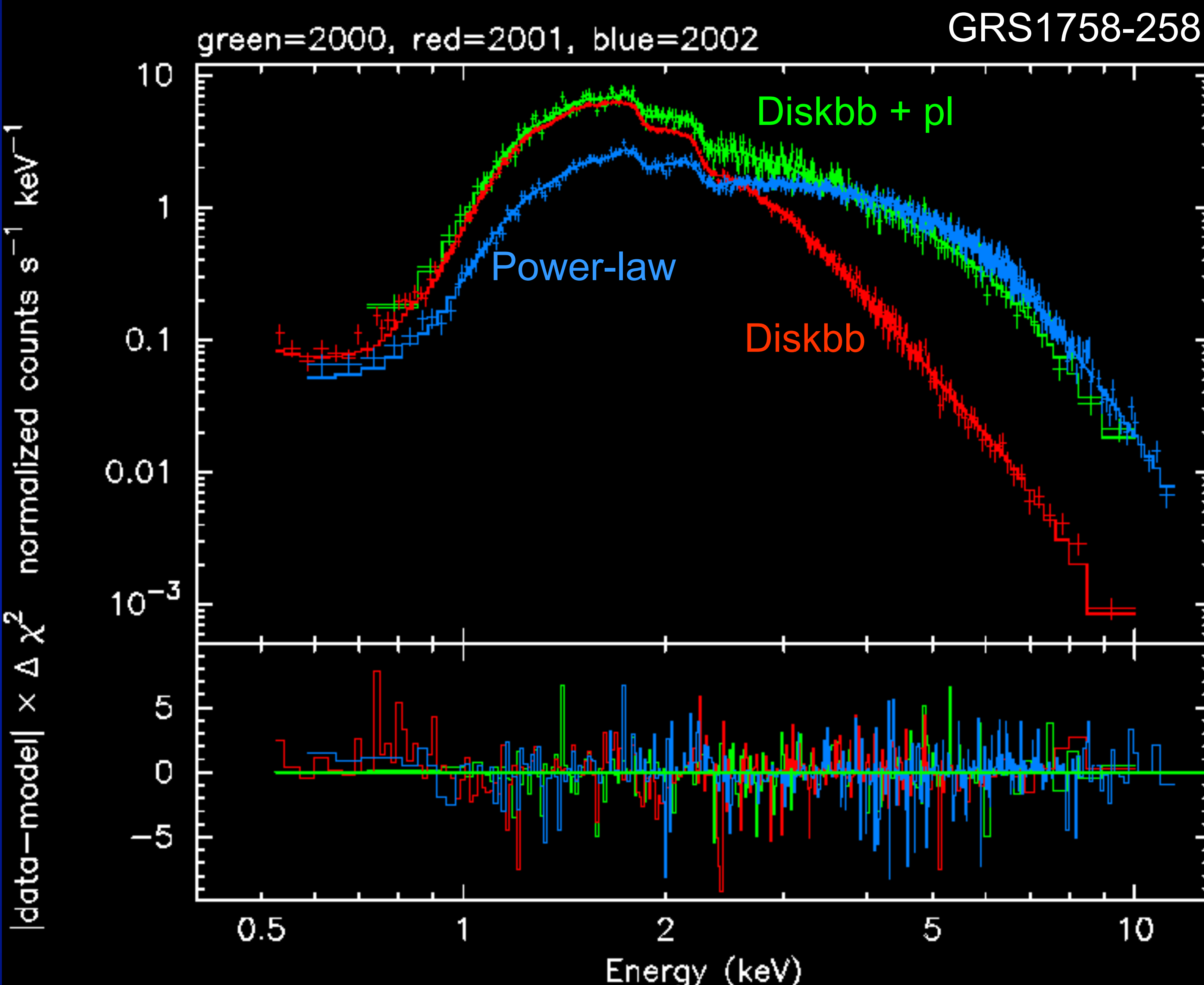
Radio quiet

0.01 **Low/Hard state**

Jet? Corona? ADAF?

Radio loud

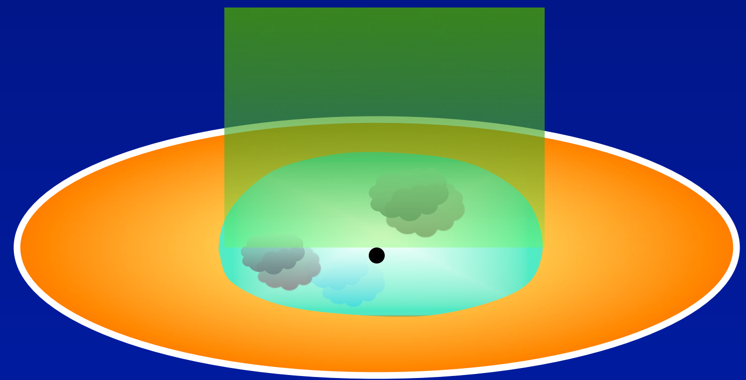




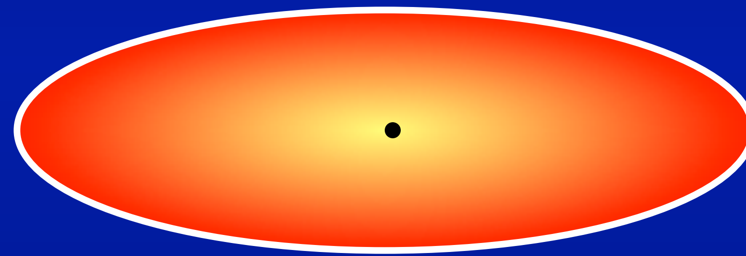
(Soria et al 2011)

“Canonical” BH accretion states

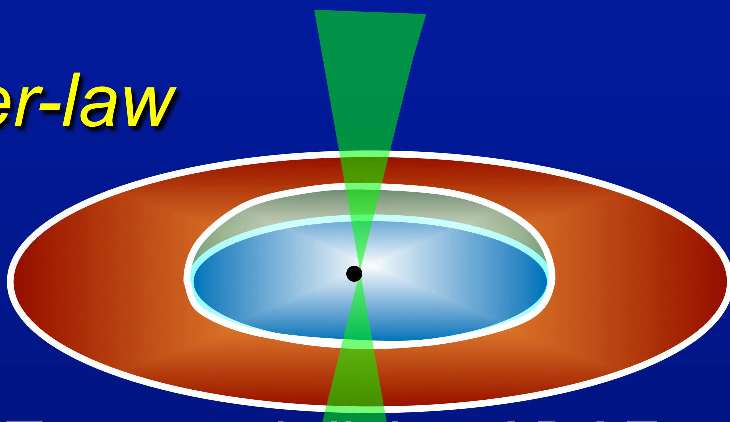
Power-law
IC in inner region
or base of outflow

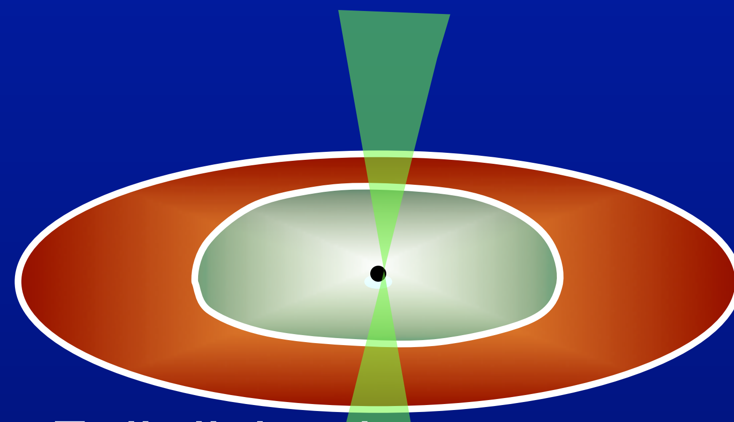


Thermal
Optically-thick
emission from disk



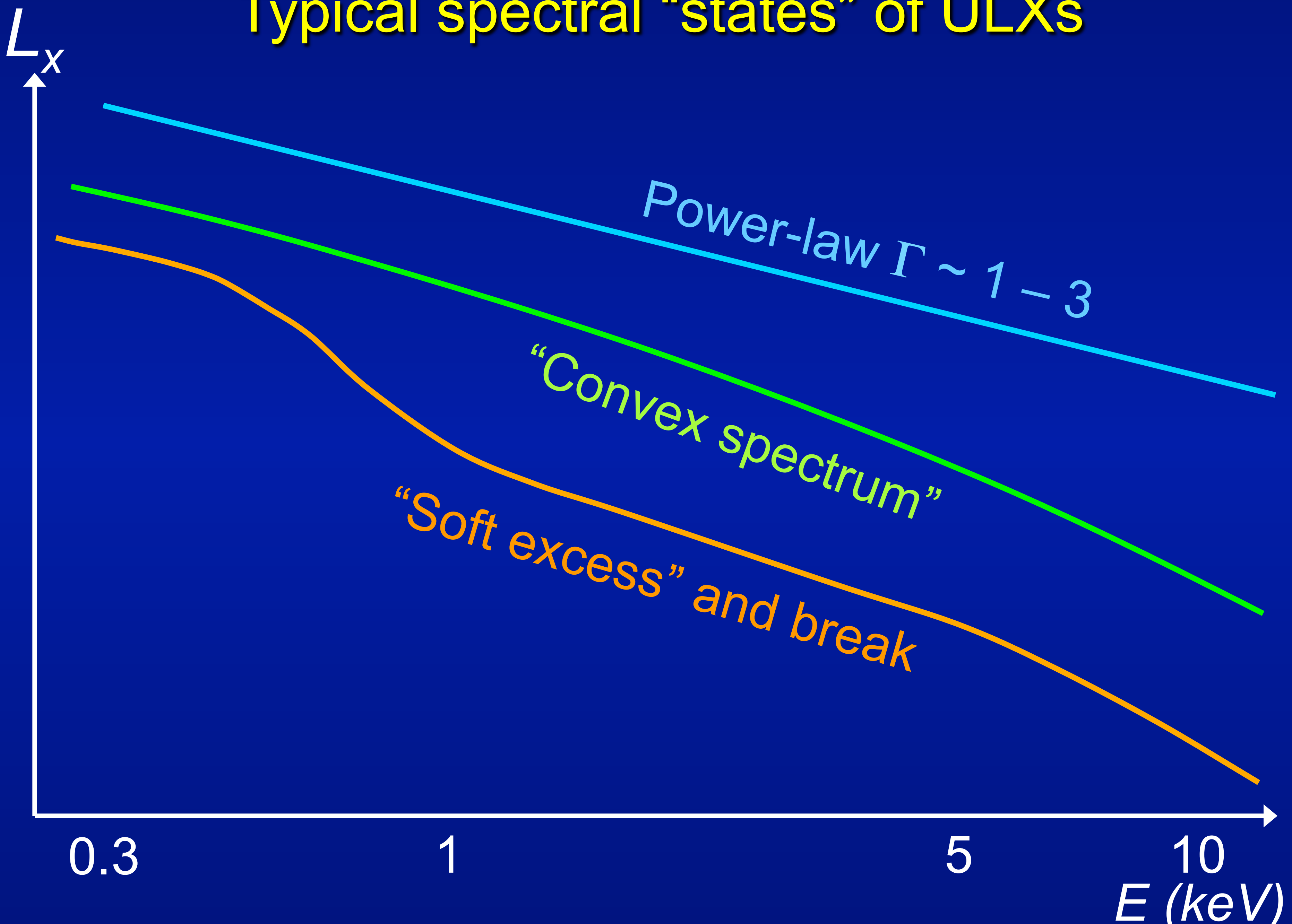
Power-law



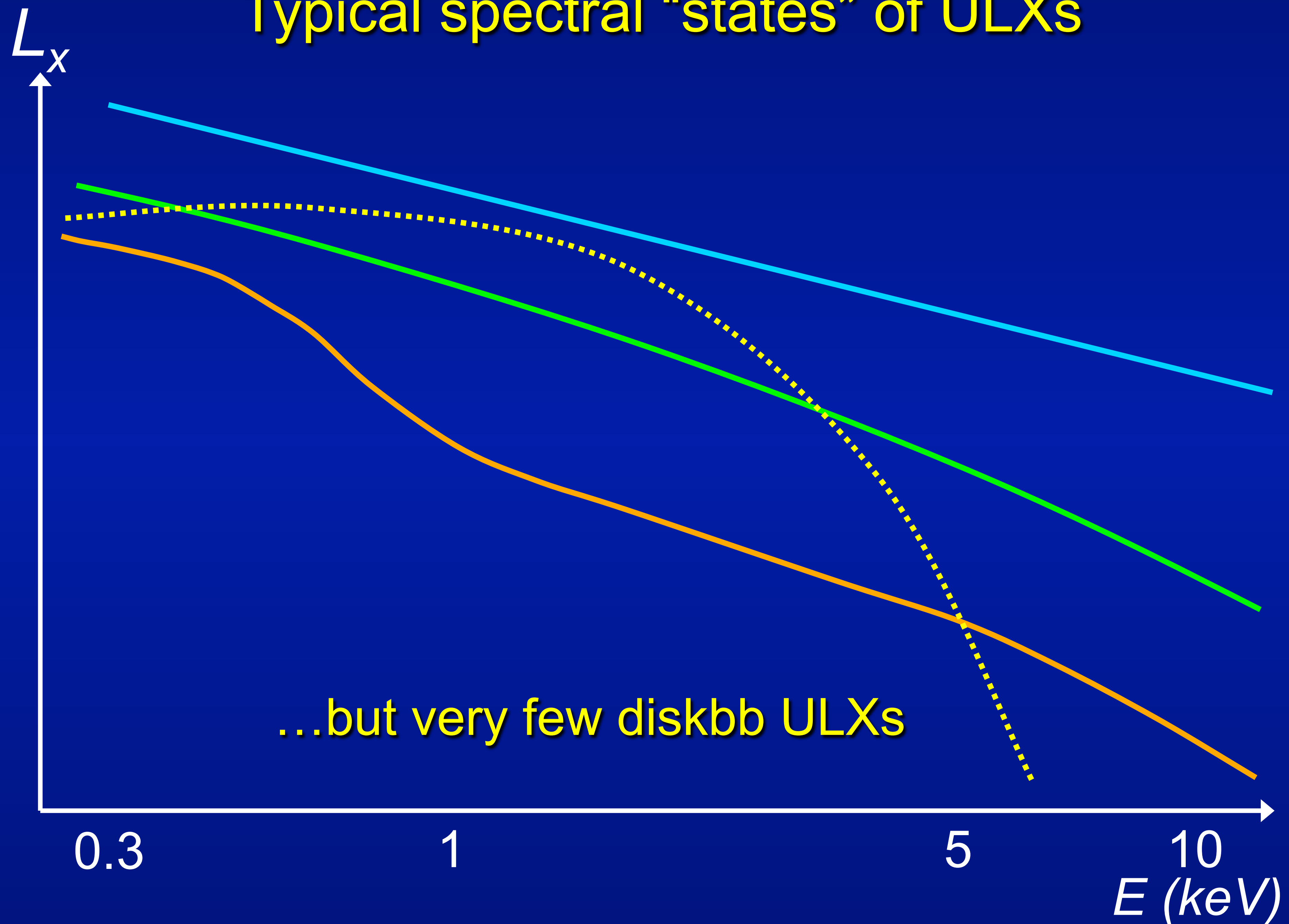


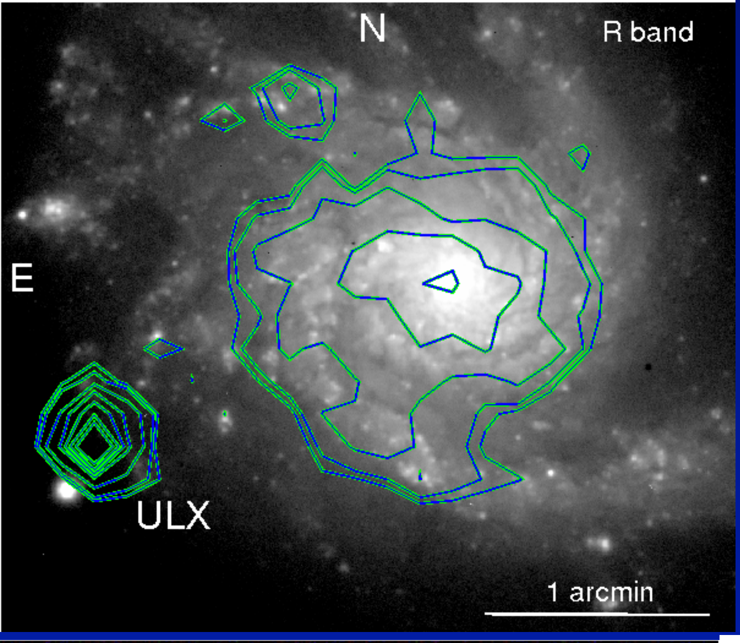
Truncated disk + ADAF　　*Full disk + jet + corona*

Typical spectral “states” of ULXs



Typical spectral “states” of ULXs



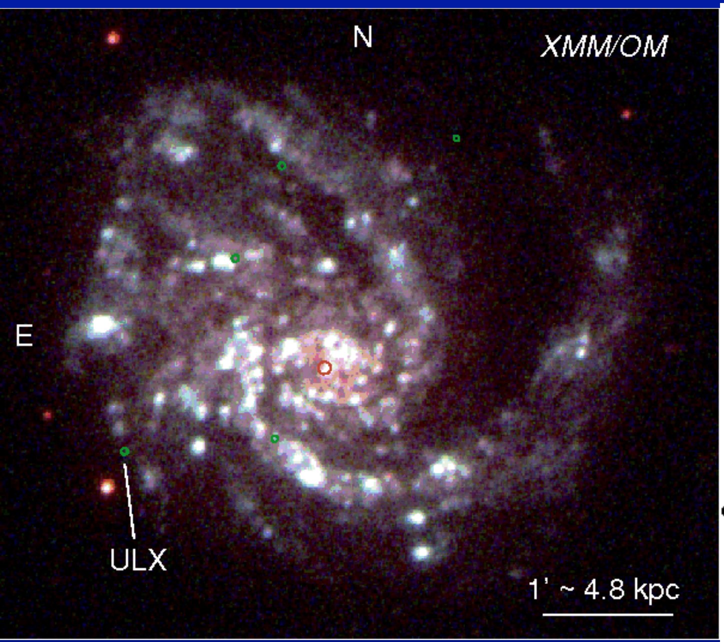


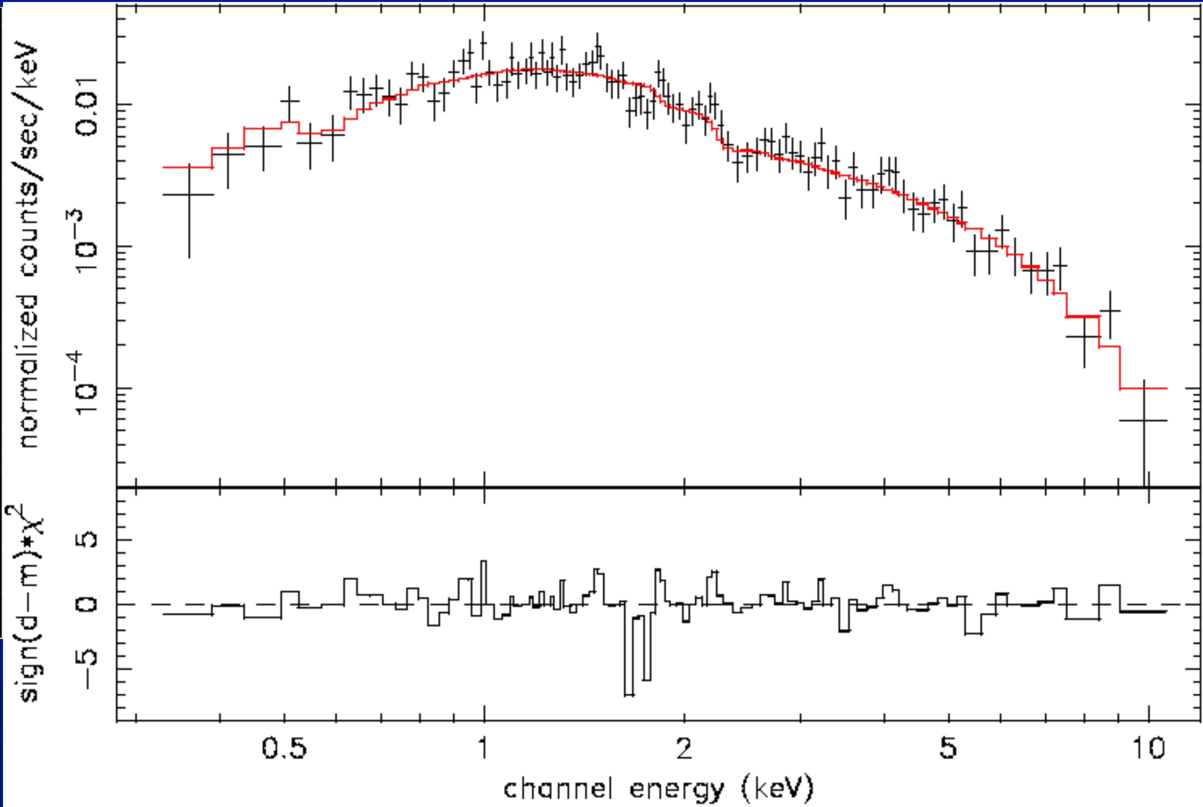
M99 X1

Power-law spectrum

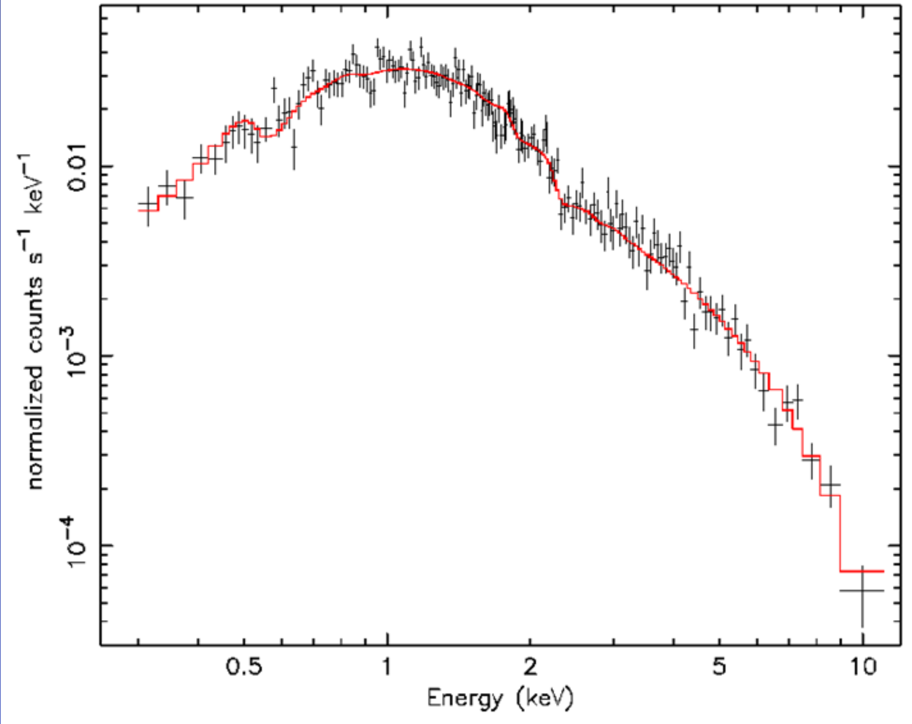
Photon index $\Gamma = 1.6$

$L_x \sim 2$ E 40 erg/s



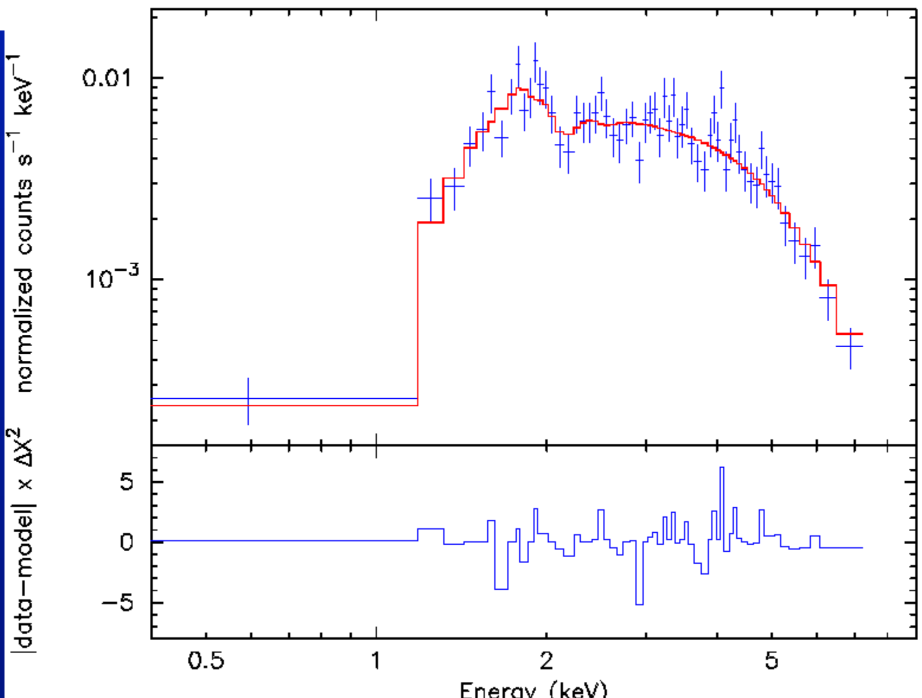


(Soria & Wong 2006)



NGC 4631 X5

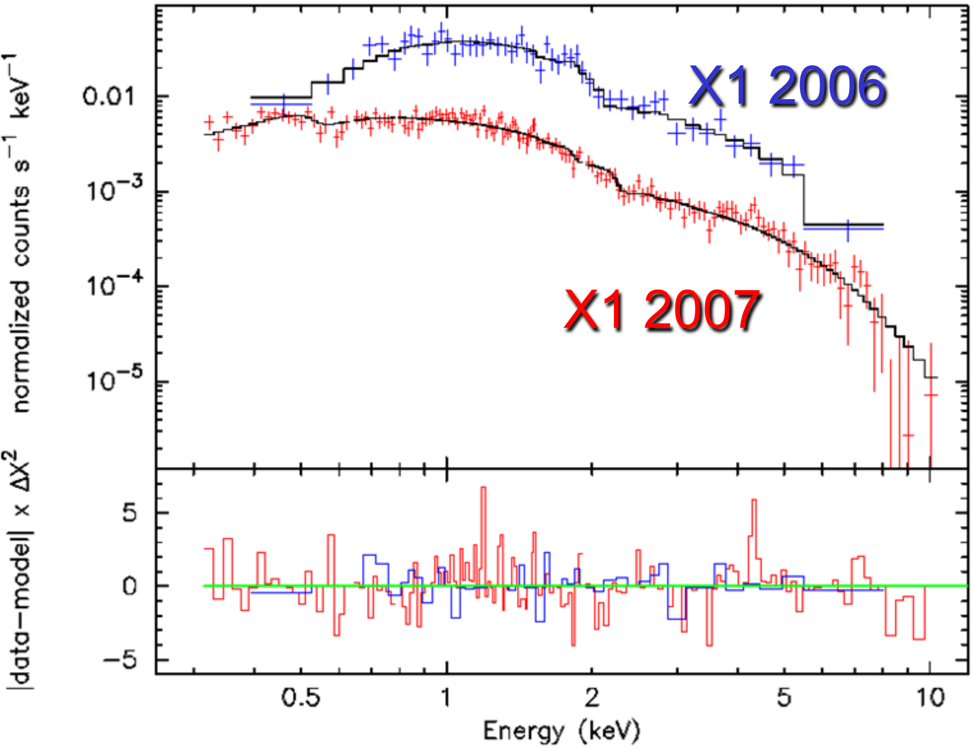
Softer power-law
$\Gamma \sim 2.1$
$L_x \sim$ 5E39 erg/s



NGC 5575 X1

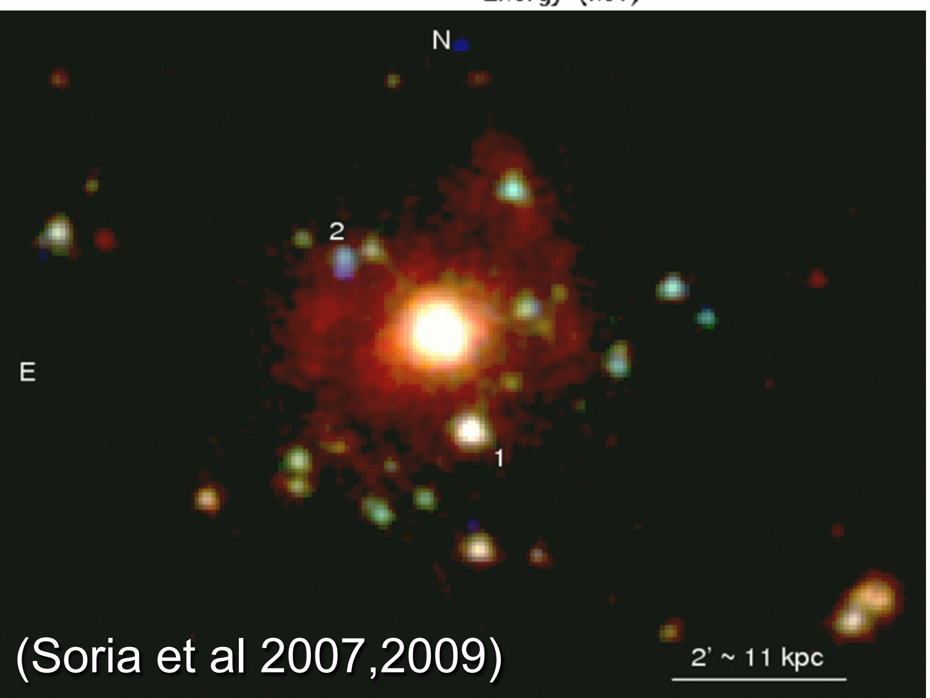
Hard power-law: $\Gamma = 1.5$
$L_x \sim$ 7E40 erg/s

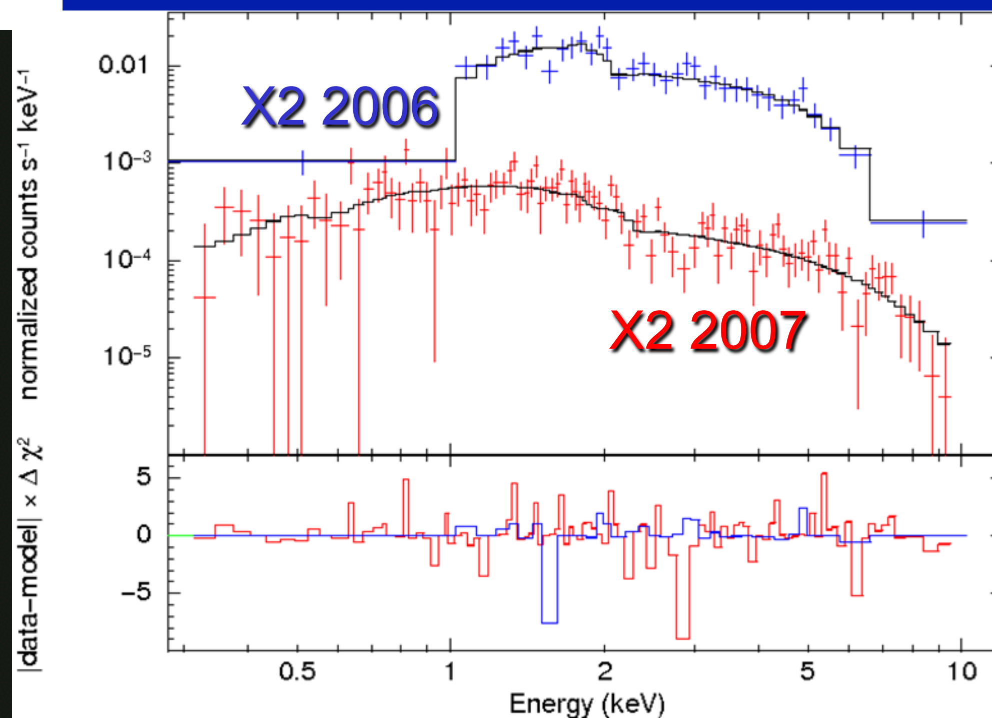
NGC1365 X1, X2

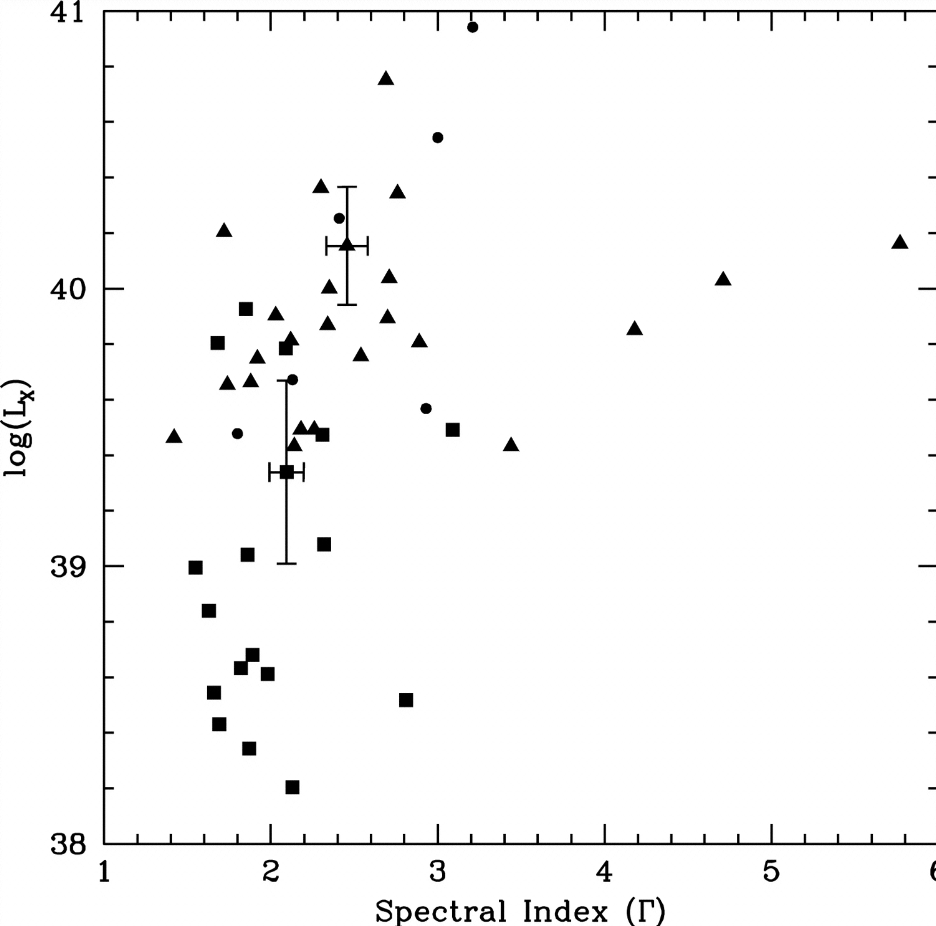


X1: L_x = 3E40 (in 2006)
5E39 (in 2007)
$\Gamma \sim 1.8$

X2: L_x = 4E40 (in 2006)
1.5E39 (in 2007)
$\Gamma \sim 1.2$







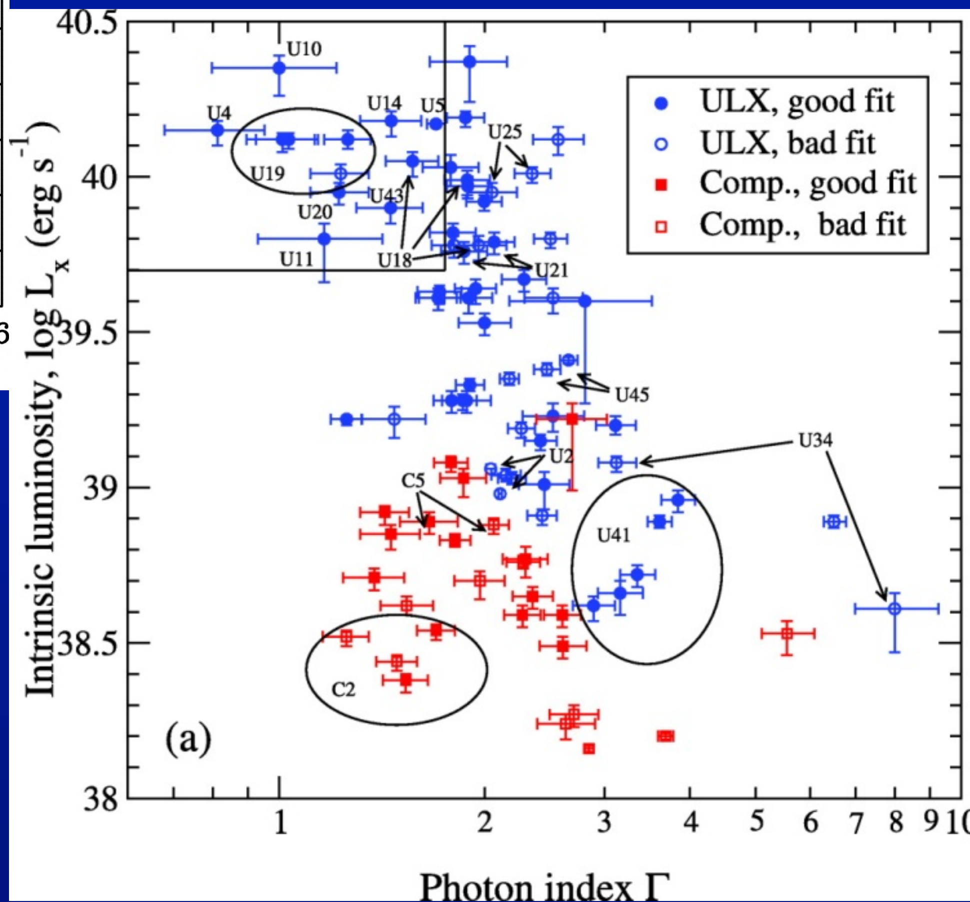
(Winter et al 2006)

↓

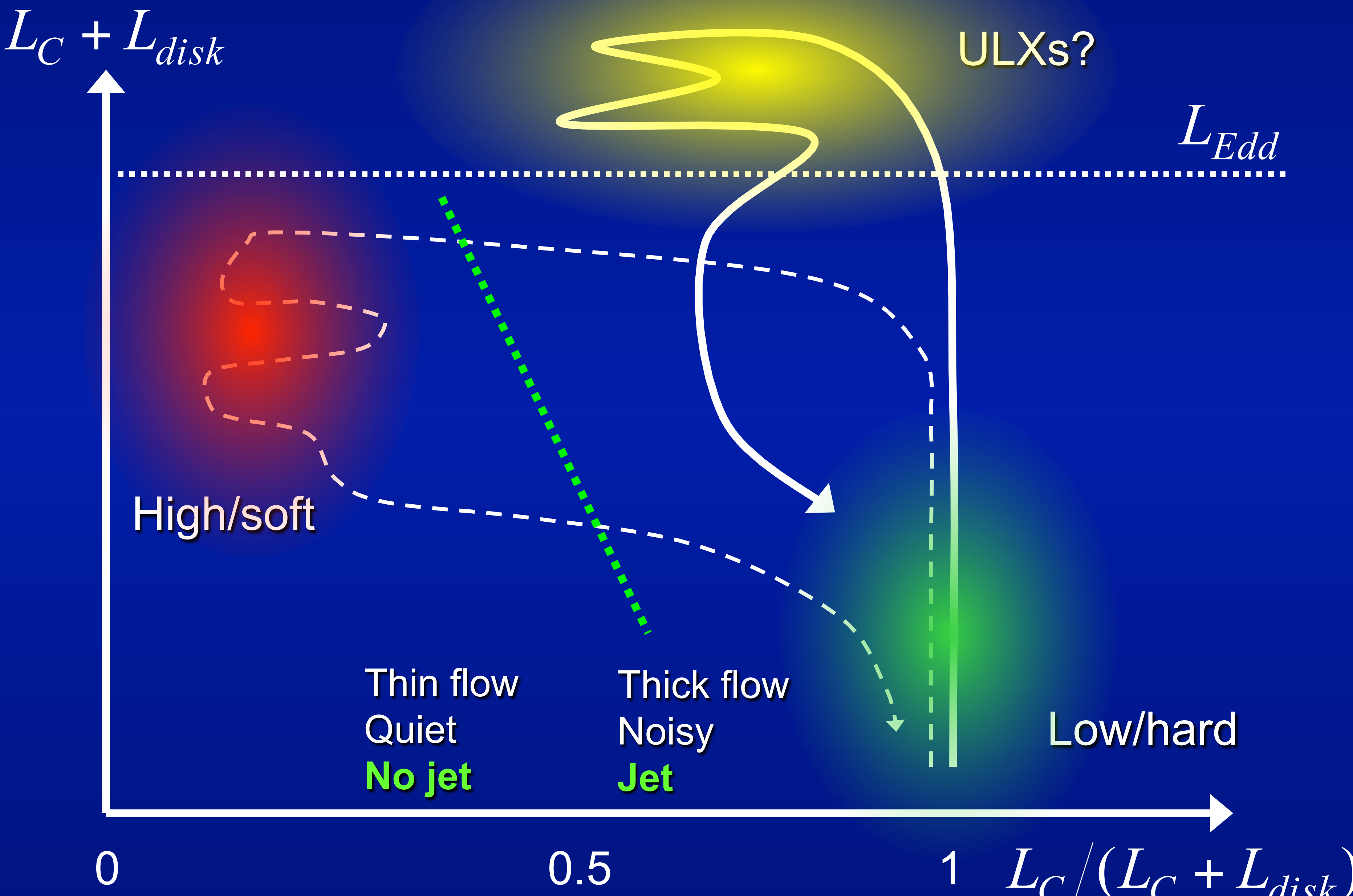
Intermediate-mass BHs
in the low/hard state?
($L_X < 0.1\ L_{Edd}$)

Many ULXs with hard
power-law spectra (Γ <~ 2)

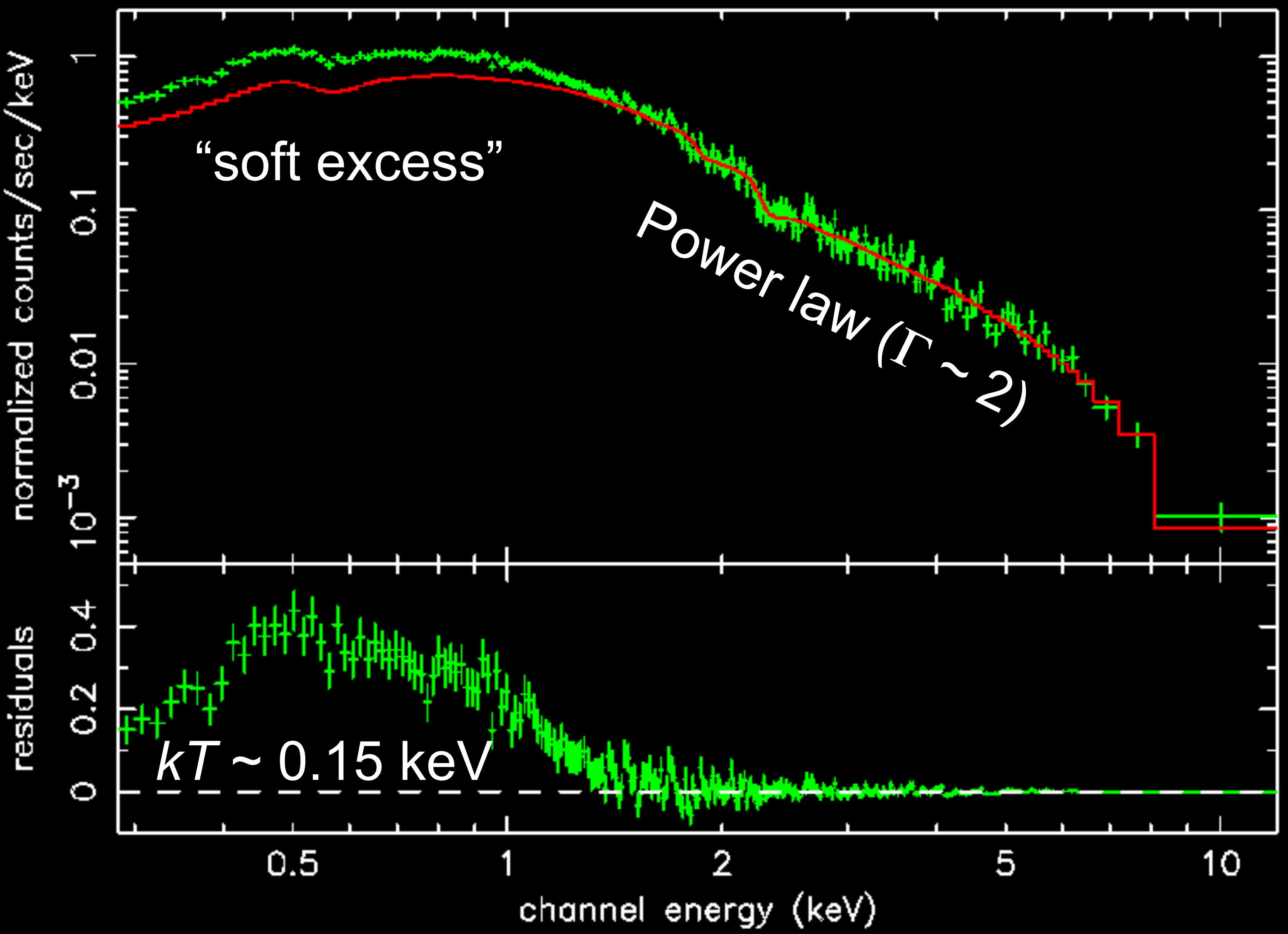
(Berghea et al 2008)



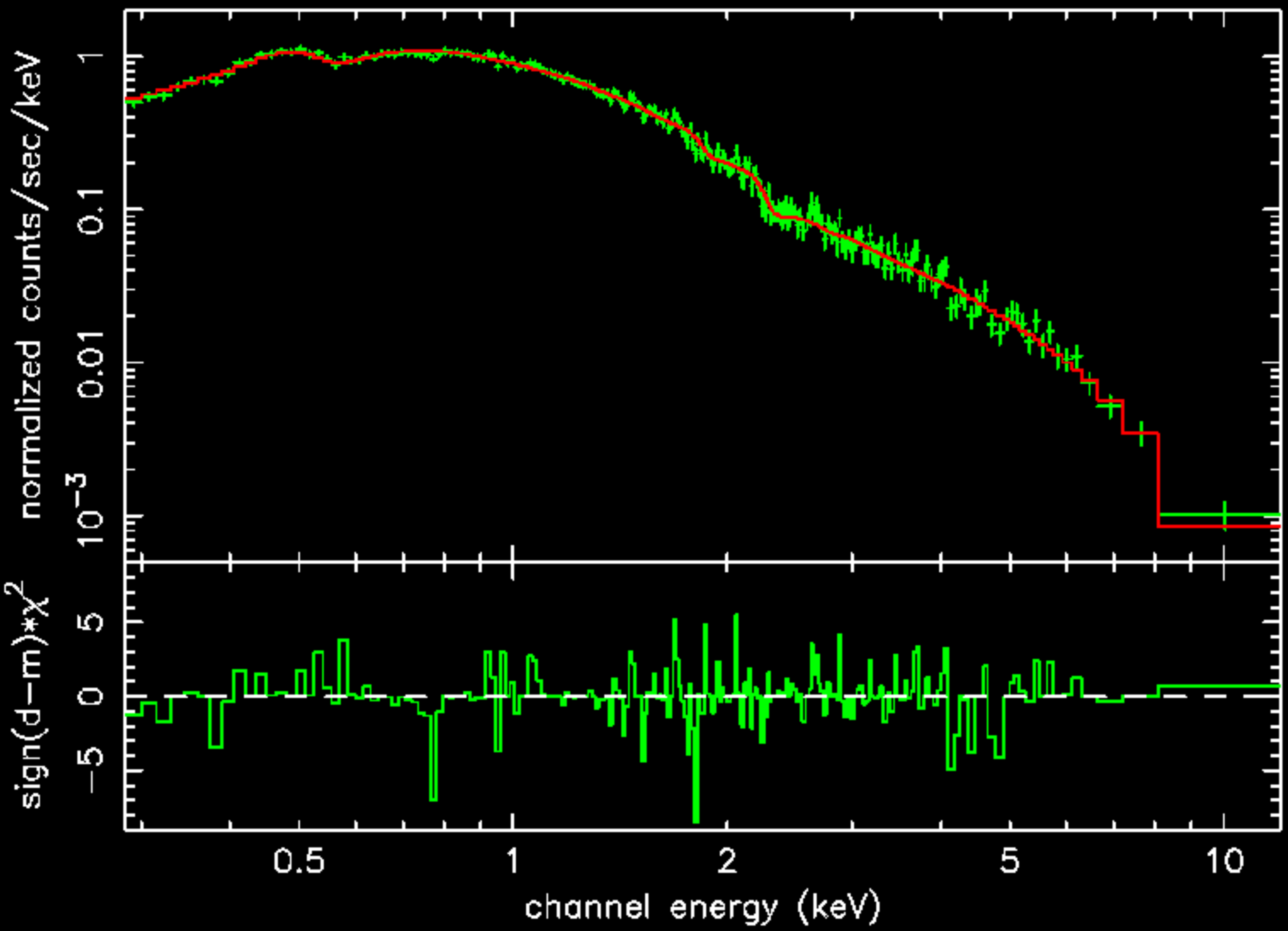
Where are the ULXs?



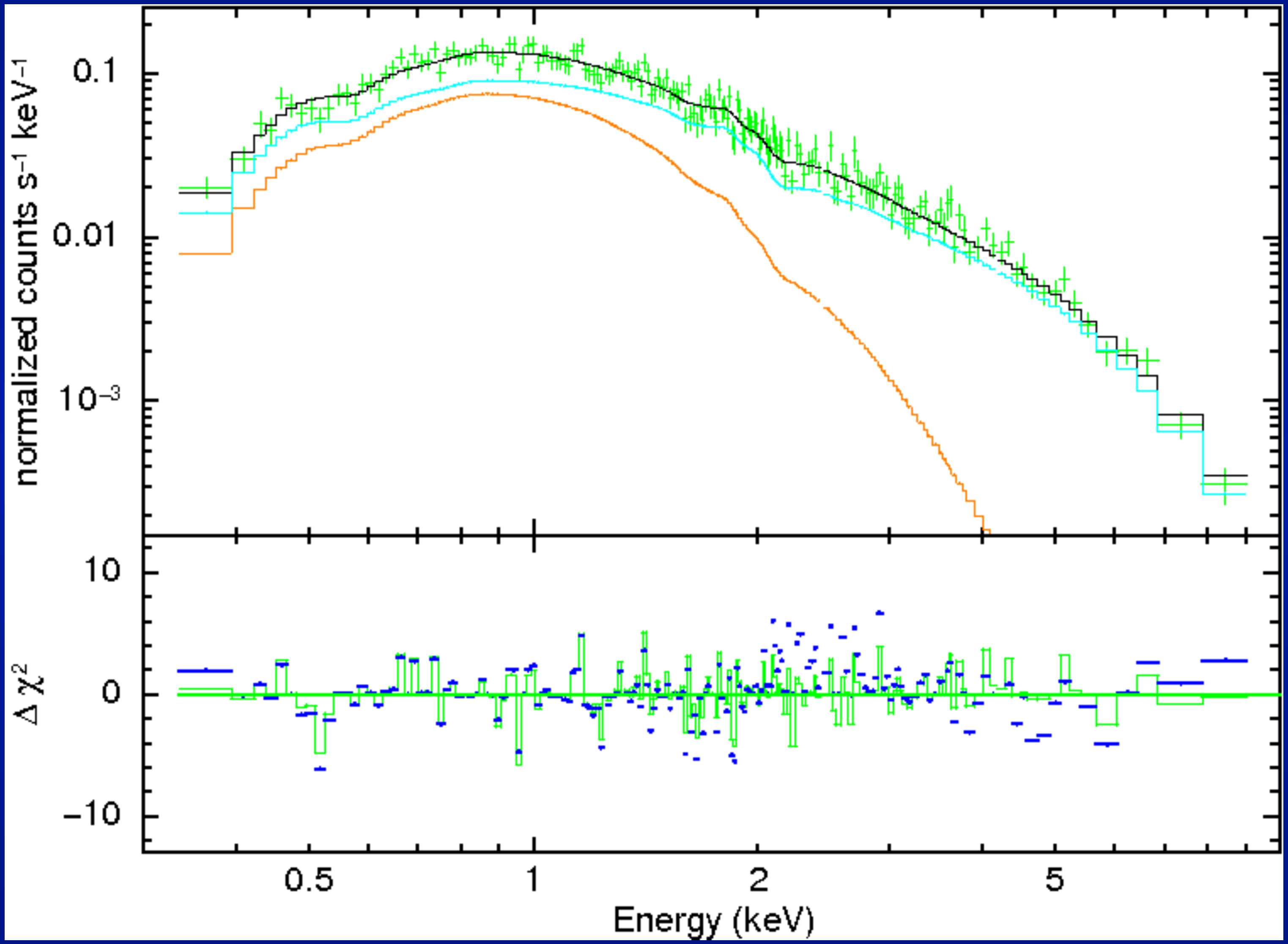
Holmberg II X-1 (L_x ~ 2E40 erg/s)



Holmberg II X-1 (L_x ~ 2E40 erg/s)



M83 X1: power-law ($\Gamma \sim 2.0$) + diskbb ($kT_{in} \sim 0.3$ keV)



Disk-blackbody component is very useful

$$L_{disk} \approx L_X \sim R_{in}^2 T_{in}^4 \sim M_{BH}^2 T_{in}^4$$

$$L_{disk} \approx L_X \sim \dot{m}$$

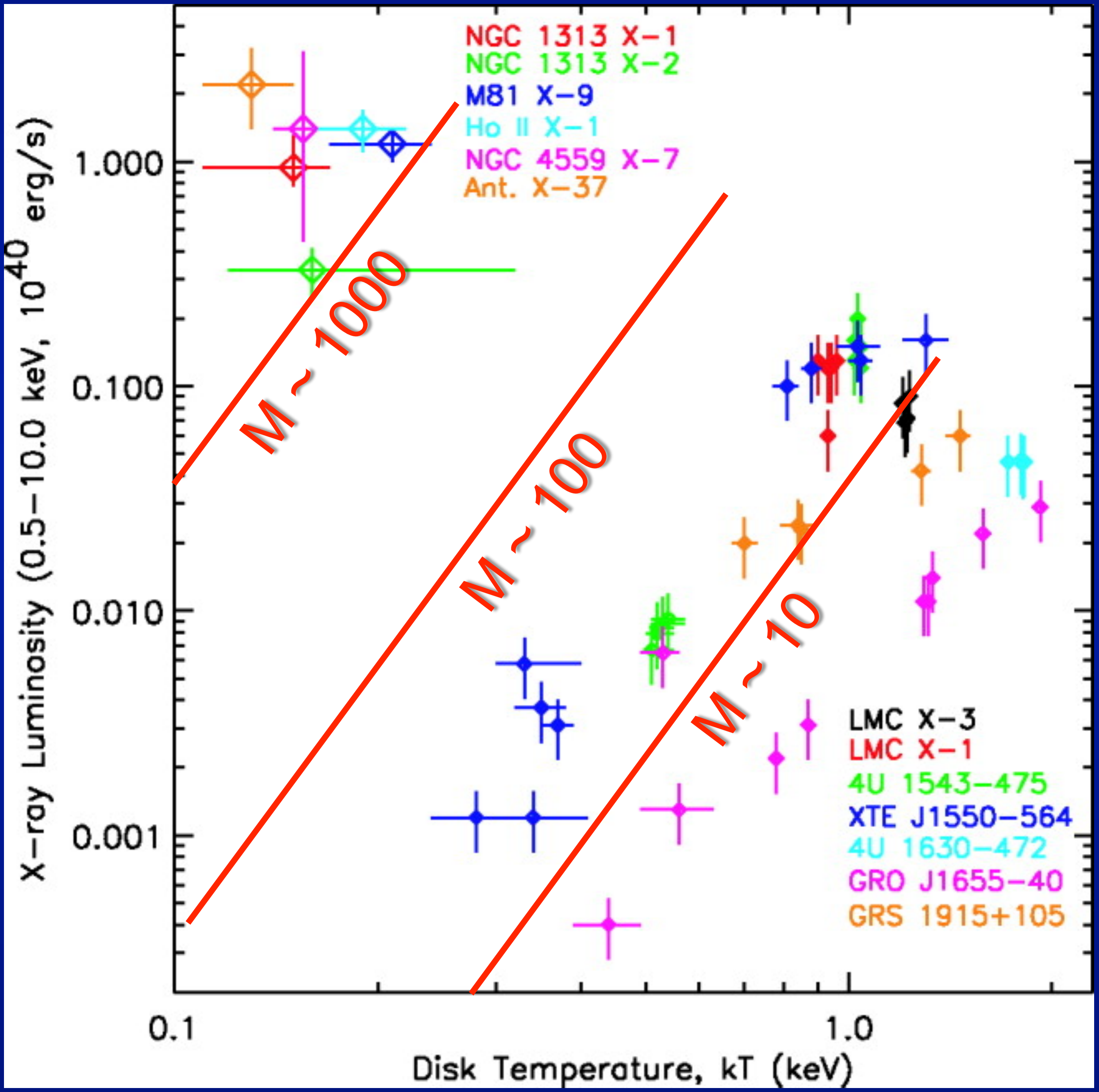
$$T_{in} \sim \dot{m}^{1/4}$$

Can be used to estimate BH mass and accretion rate

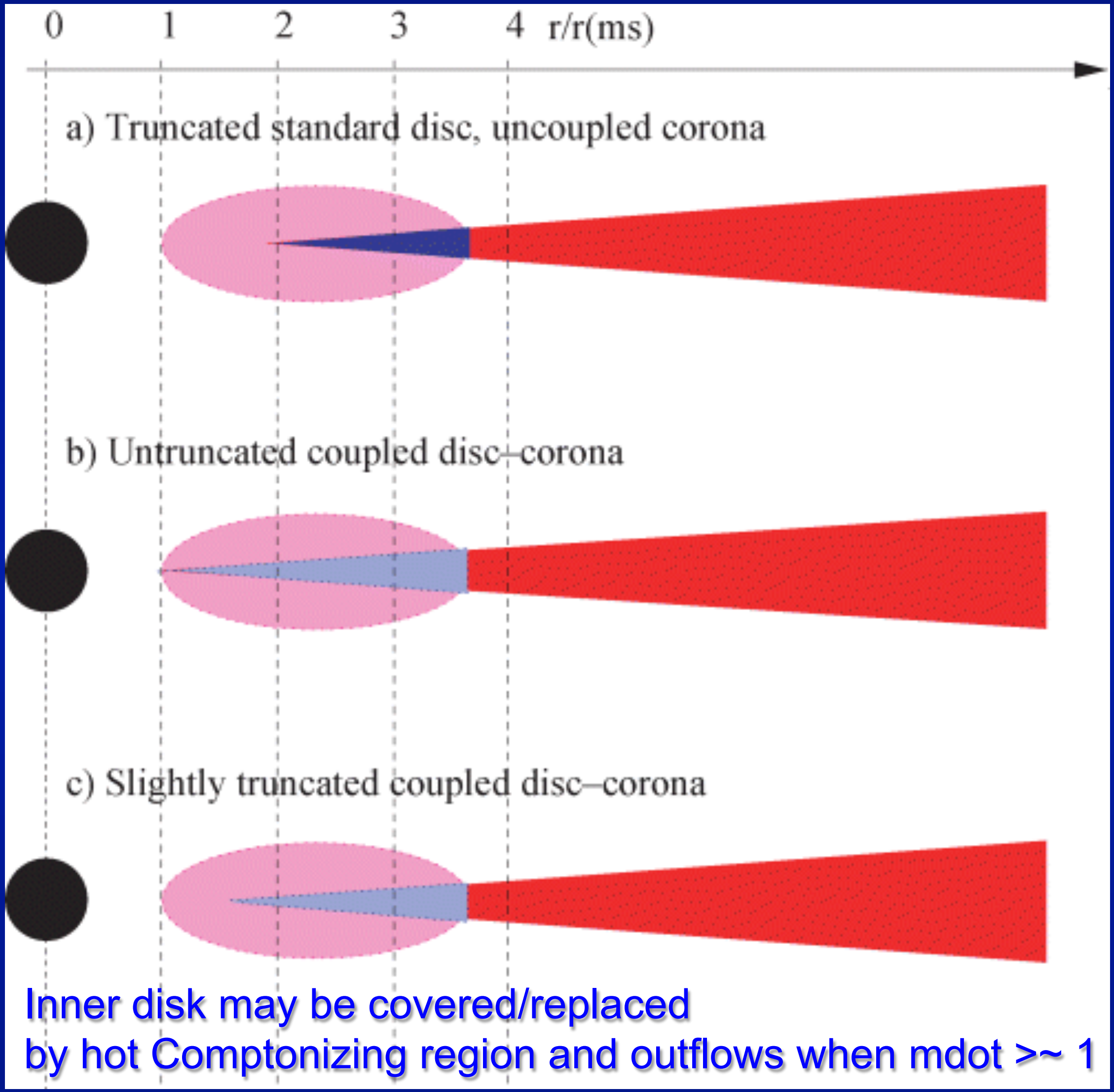
…..but only in certain conditions ($L < L_{Edd}$, $R_{in} \sim R_{ISCO}$)

Large, cool ULX disks as proof of intermediate-mass BHs?

(J M Miller et al 2003; Miller, Fabian & Miller 2004)



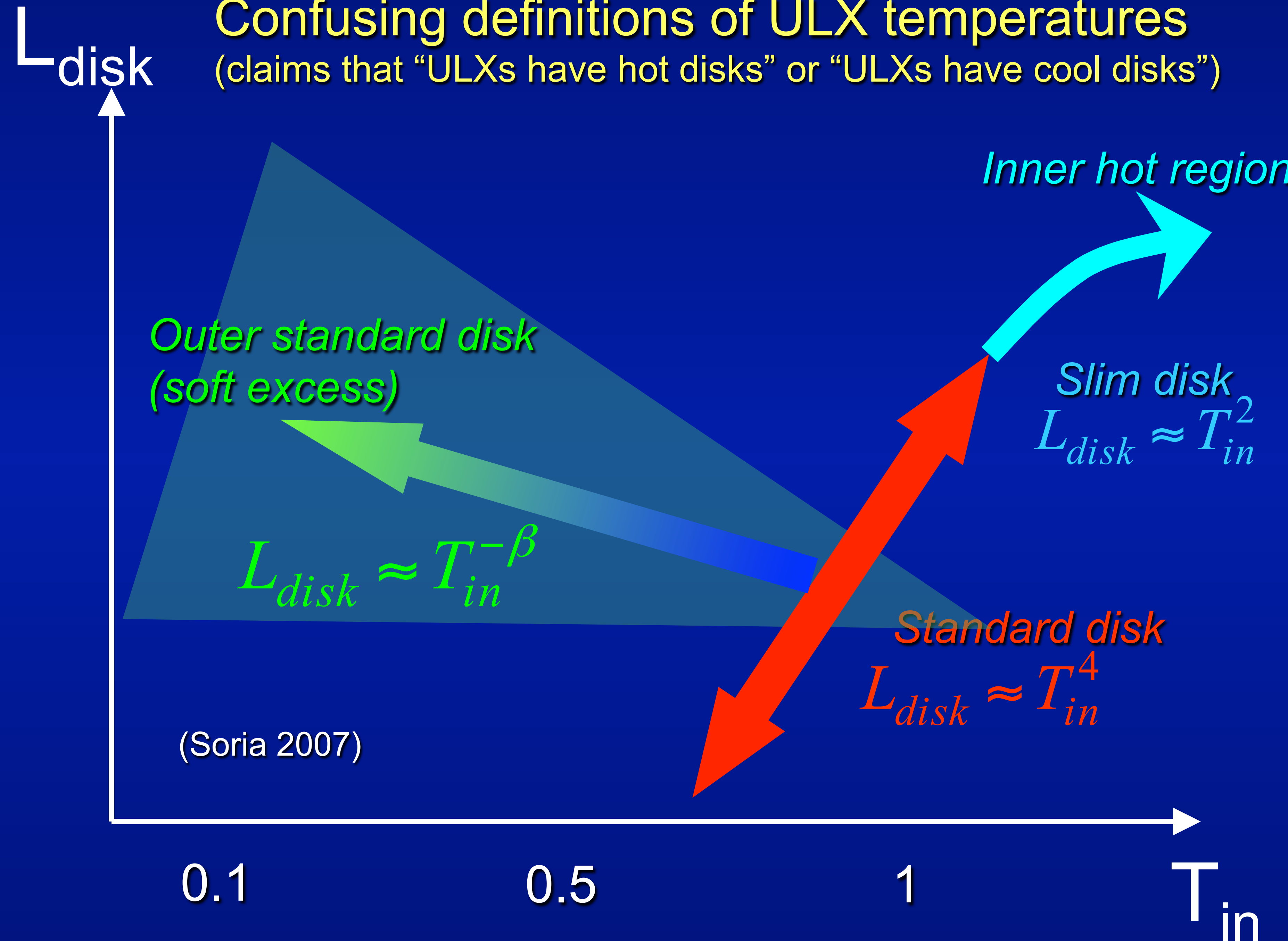
Not true, if the disk does not extend to the ISCO

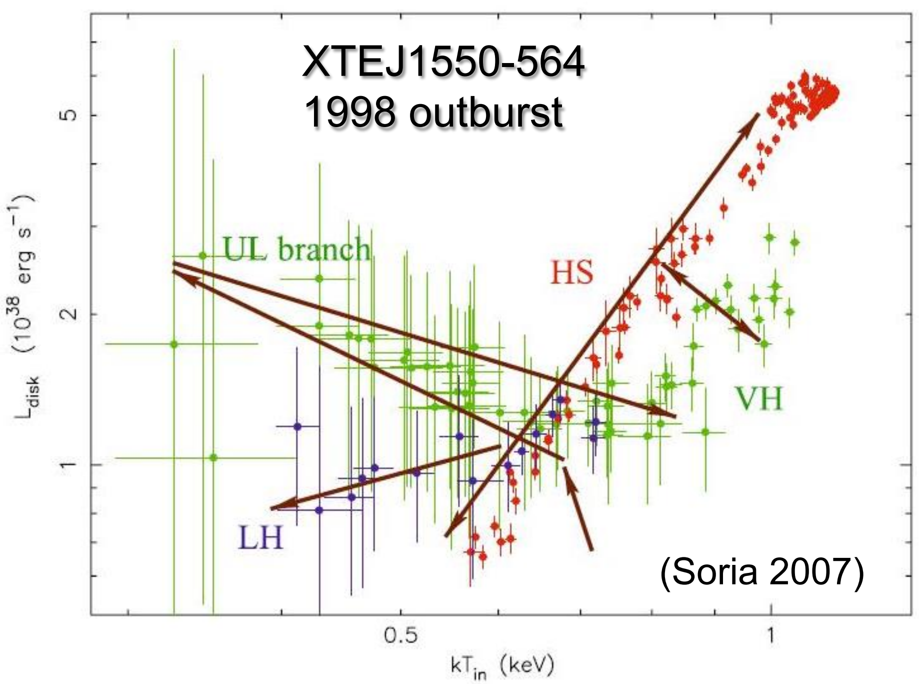


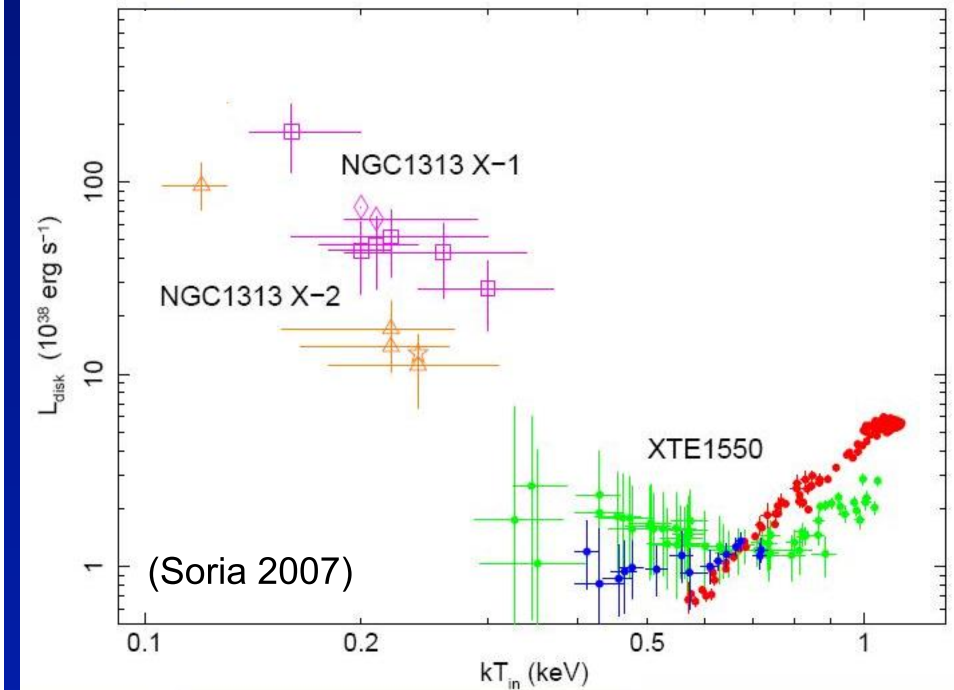
Compare with very high state in the Galactic BH XTEJ1550
(Done & Kubota 2006)

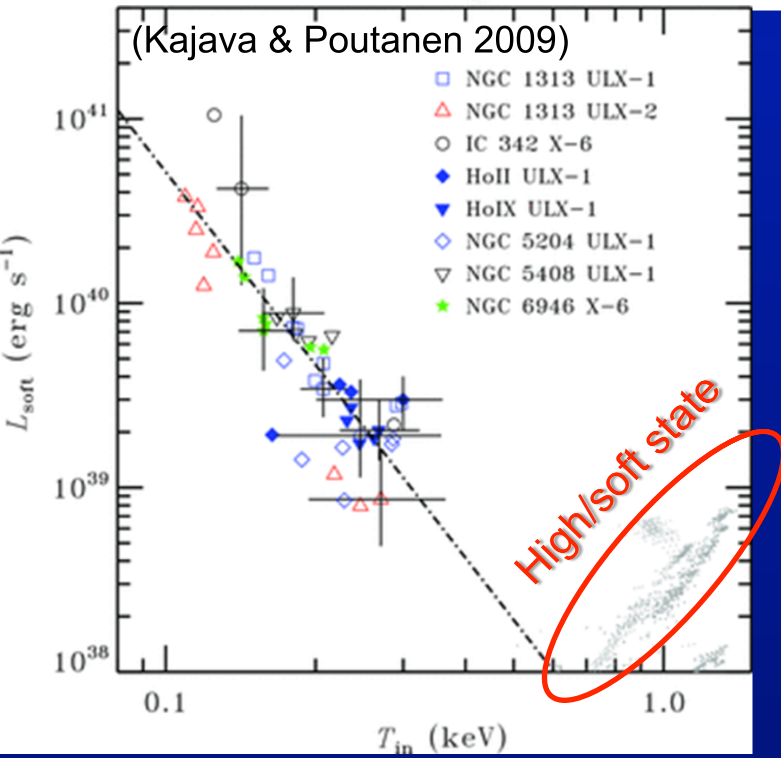
Confusing definitions of ULX temperatures

(claims that “ULXs have hot disks” or “ULXs have cool disks”)





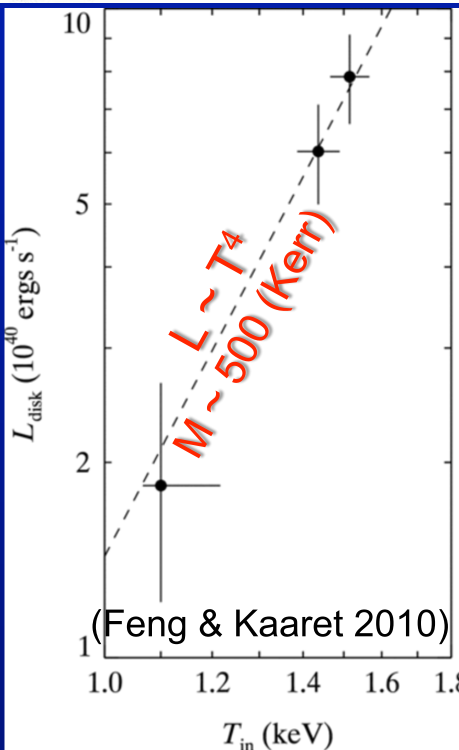


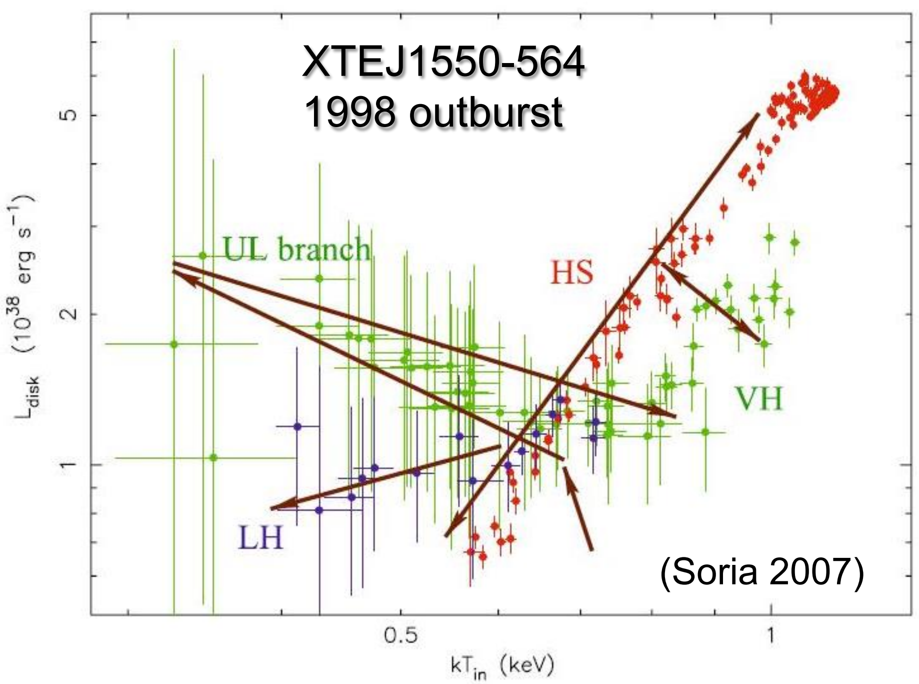


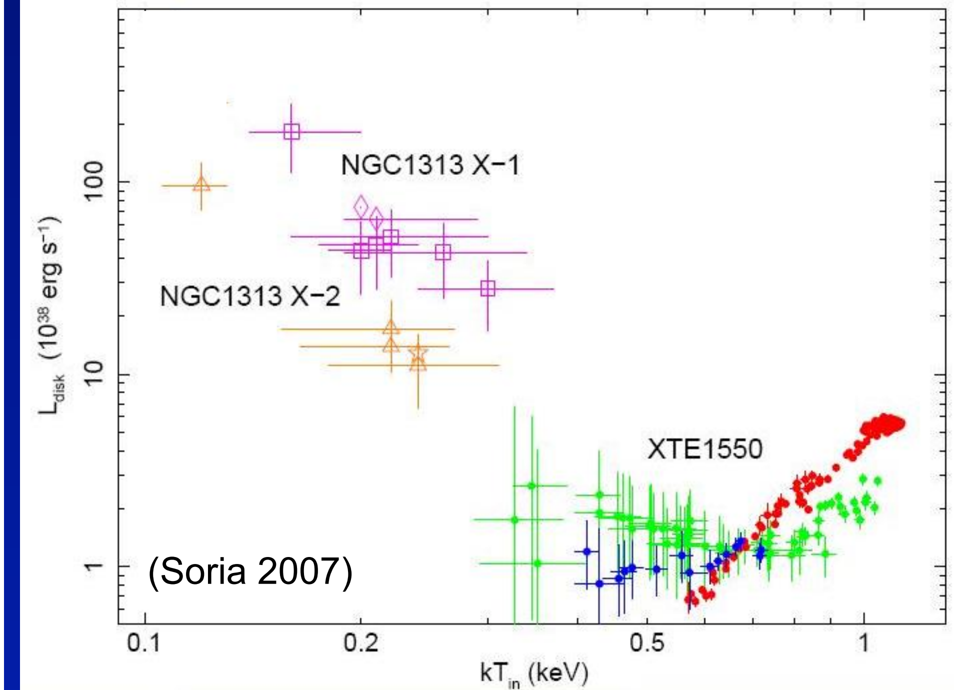
M82 X-1

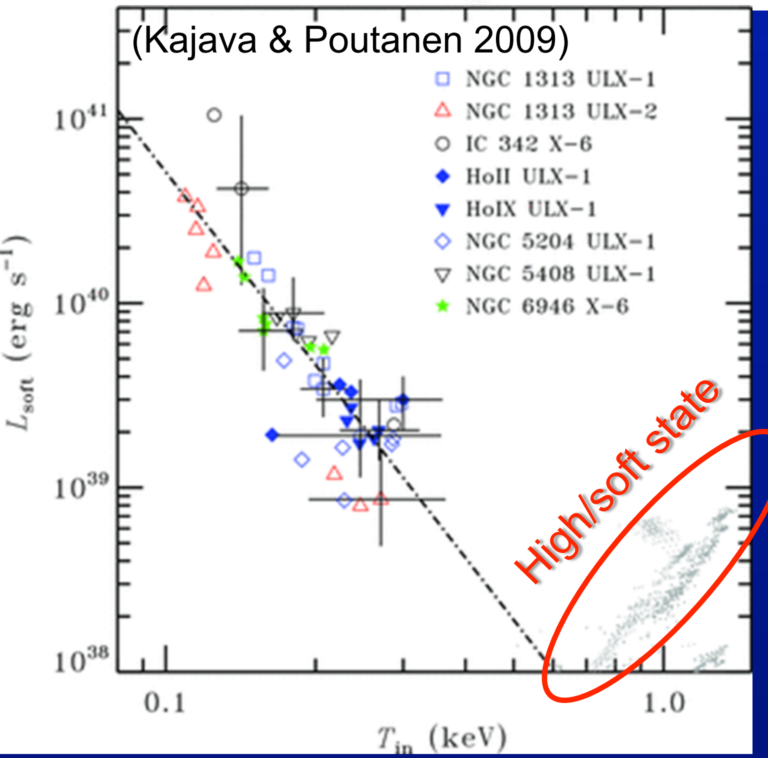
may be in the high/soft state

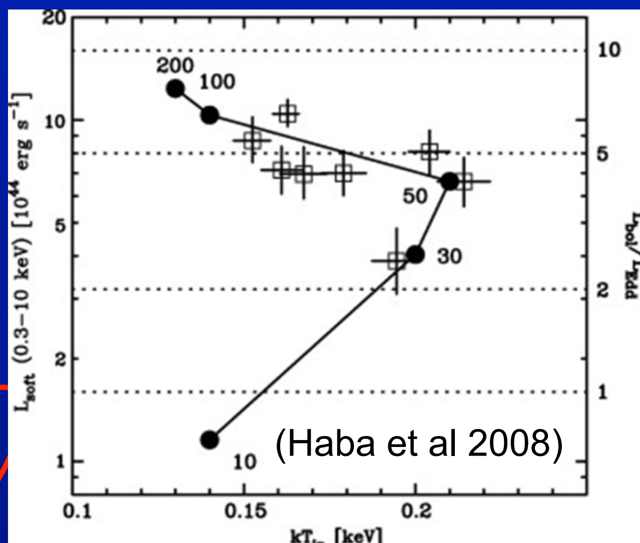
If so, $M \sim 200$—$800\ M_{sun}$ with spin $a \sim 1$



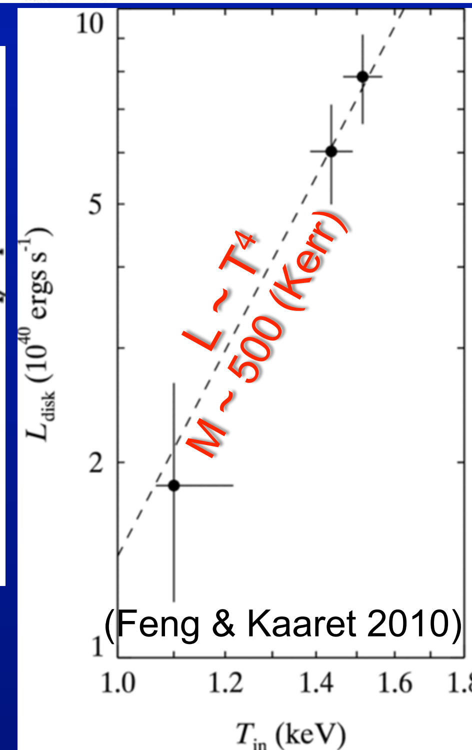


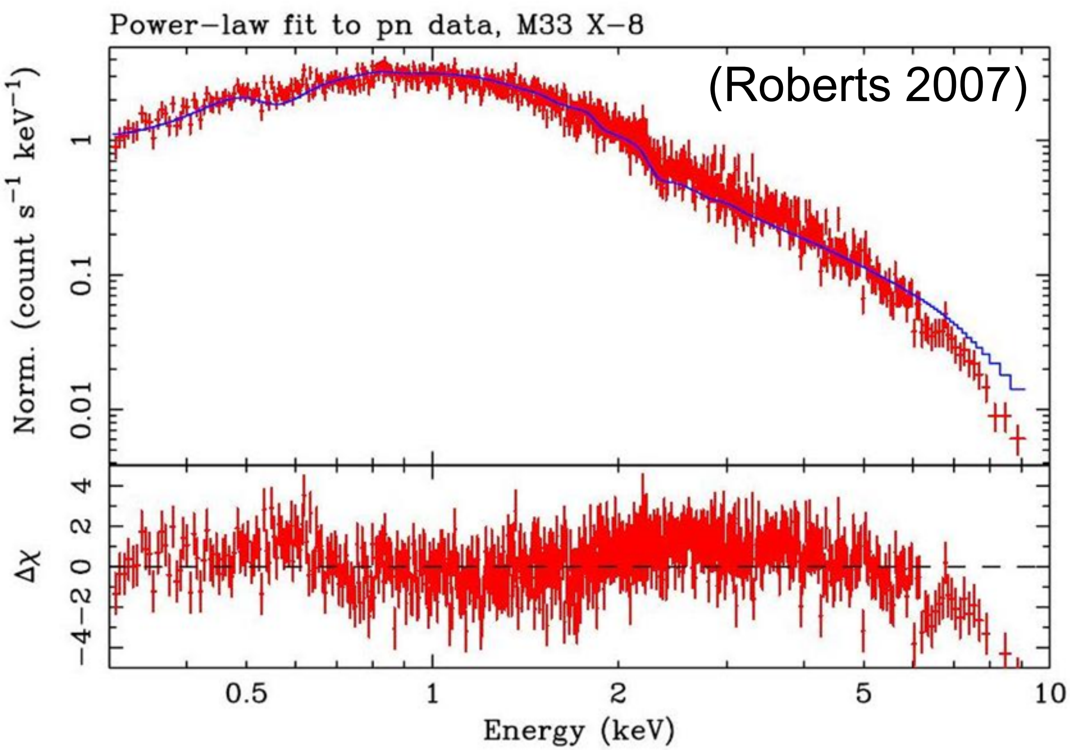






Similar to
PKS 0558-504 (Sy 1)





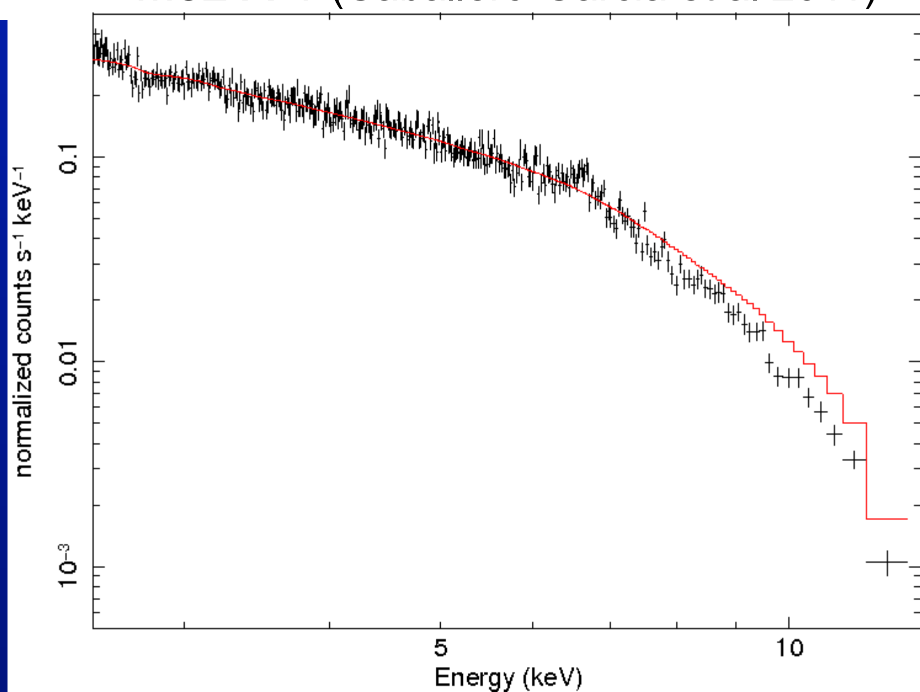
High-energy curvature
depends on T_e
of the Comptonizing region

Typical downturn at E ~ 5 keV

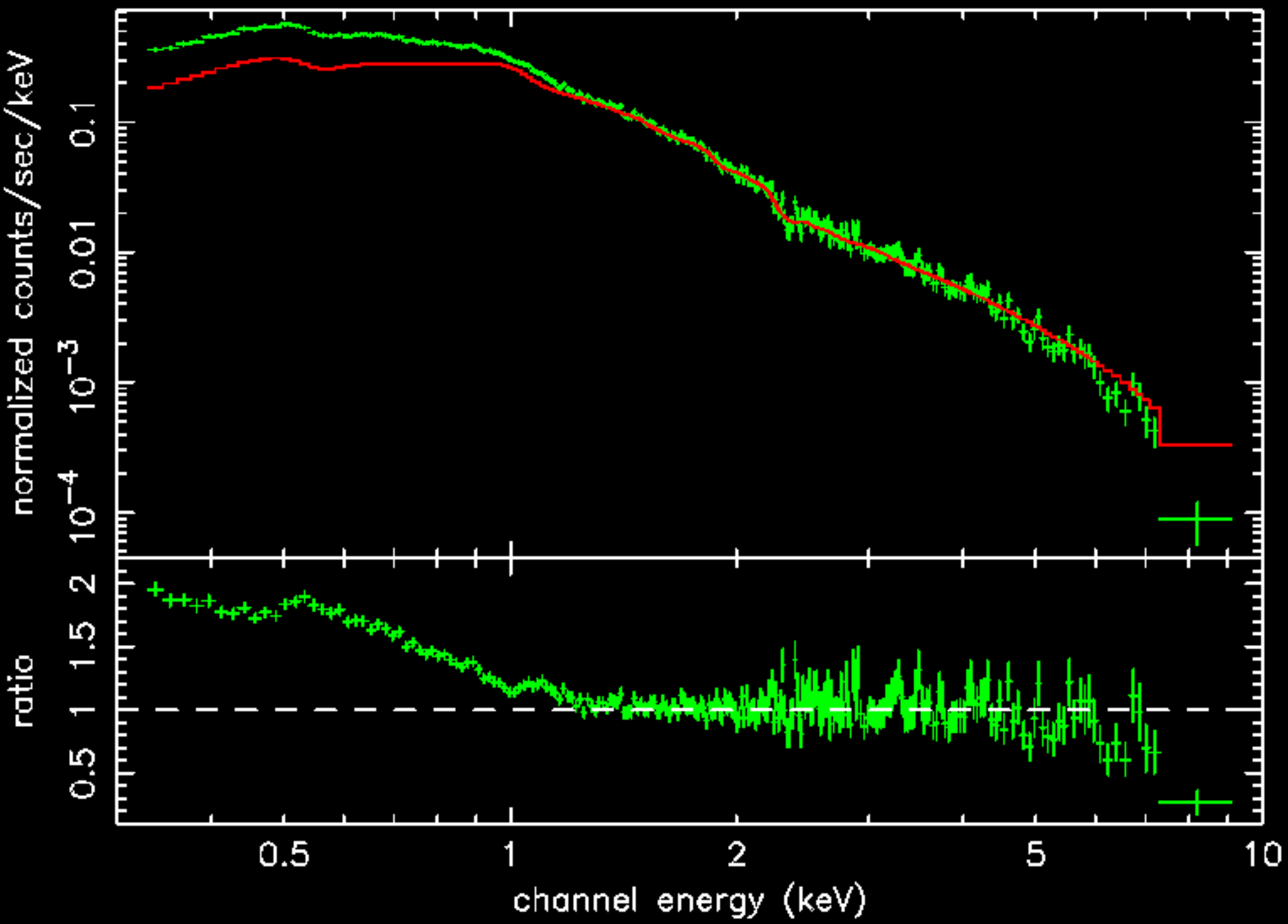
Requires scattering $\tau \sim 10$,
$kT_e \sim 2$—3 keV

"warm, optically thick corona"
in the "ultraluminous state"
(T P Roberts)

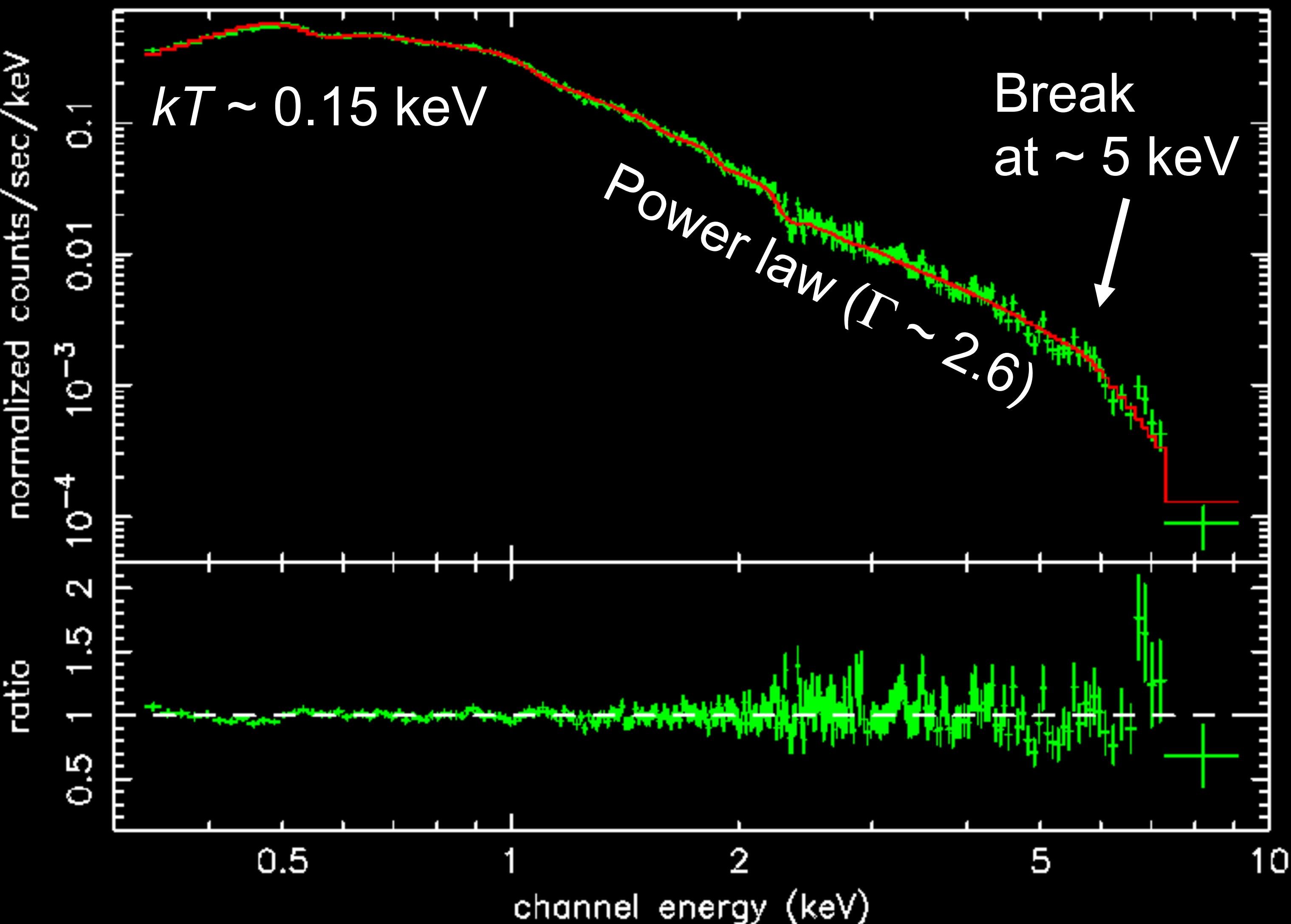
M82 X-1 (Caballero-Garcia et al 2011)



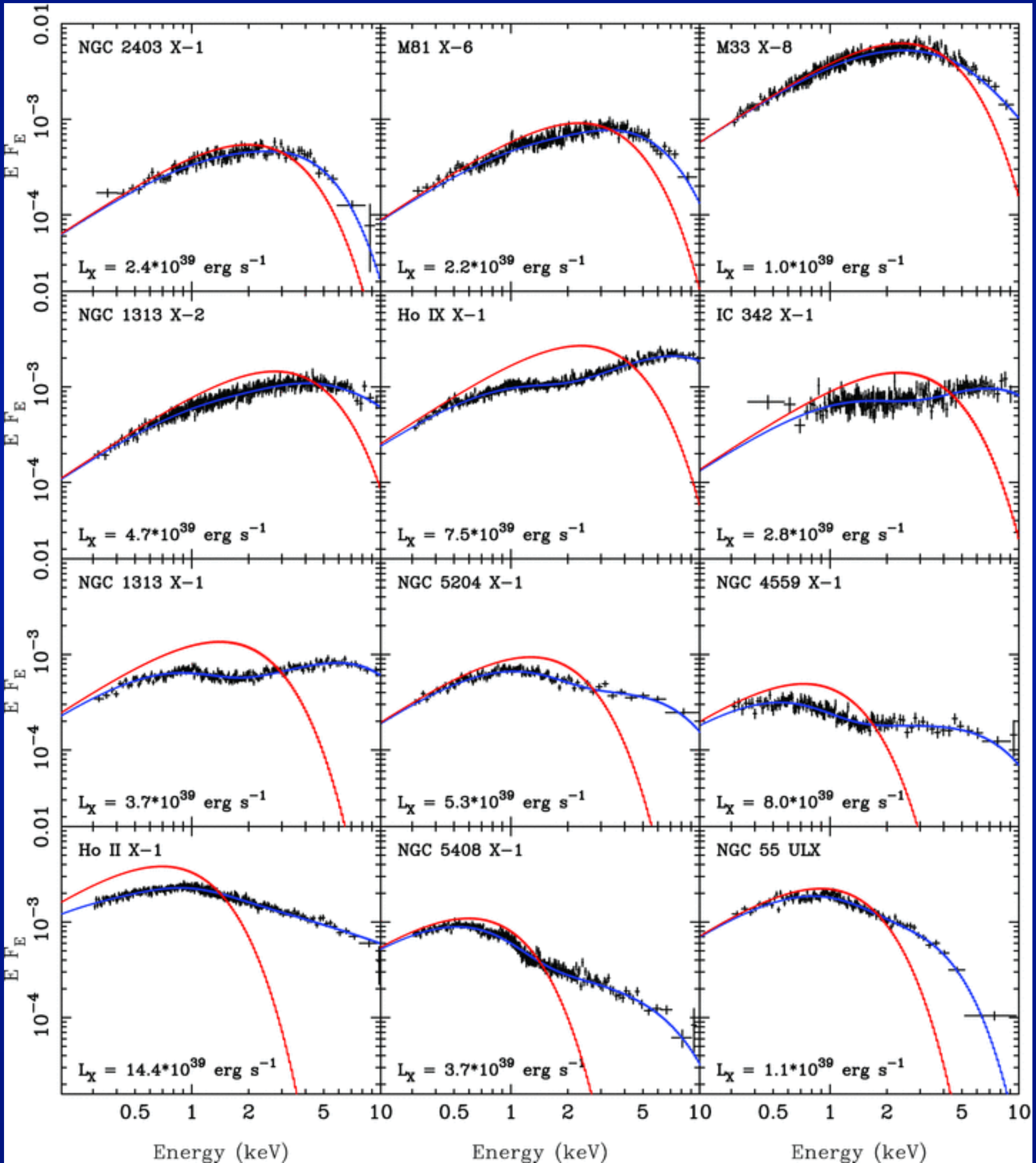
NGC5408 X-1 (L_x ~ 1E40 erg/s)



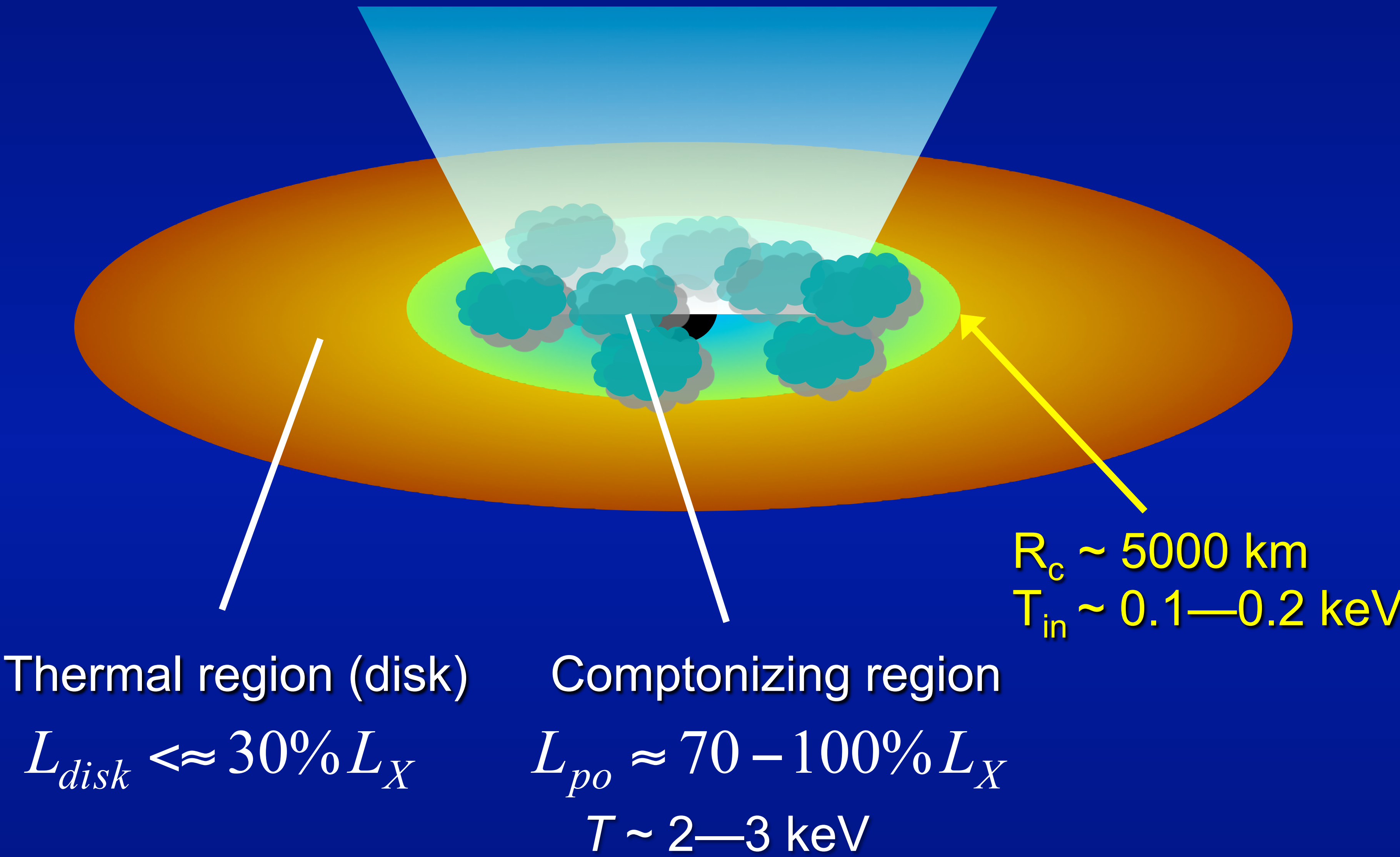
NGC5408 X-1 (L_x ~ 1E40 erg/s)

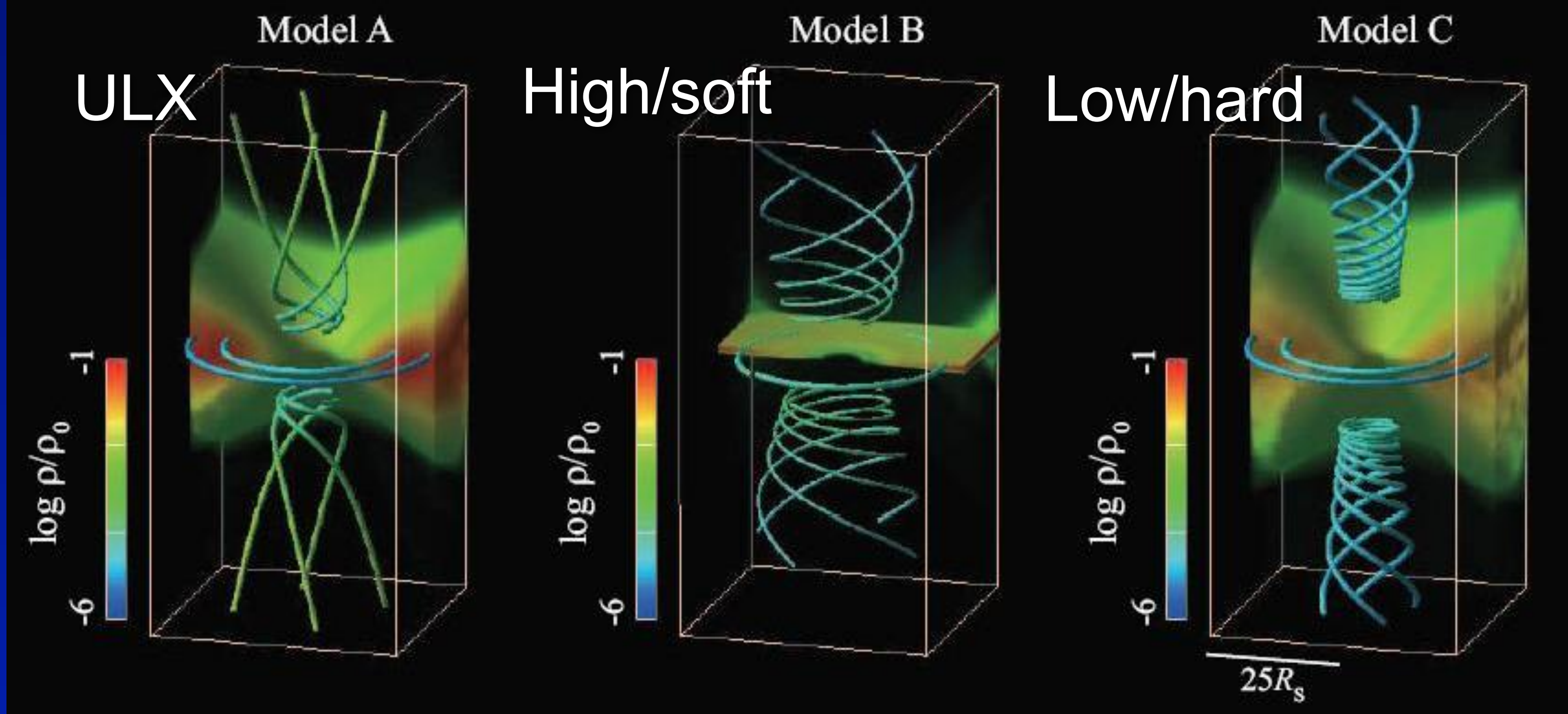


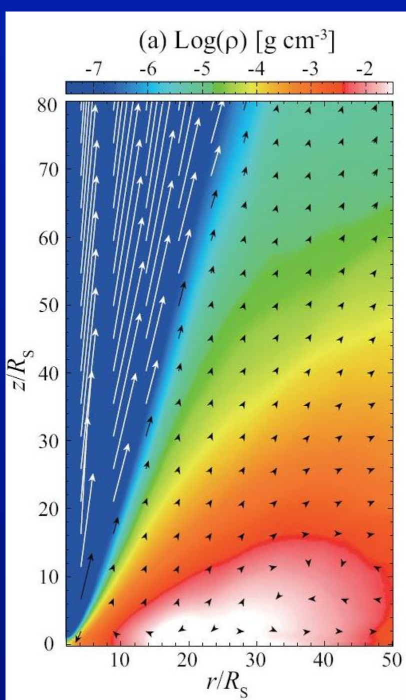
Examples of sources in the ultraluminous state (Gladstone et al 2009)

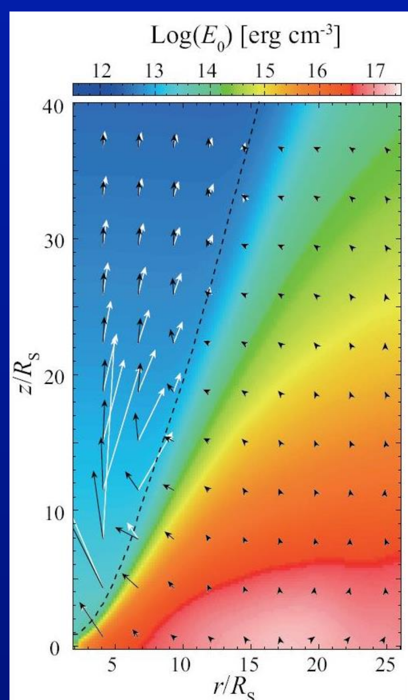


Direct disk emission and scattering regions







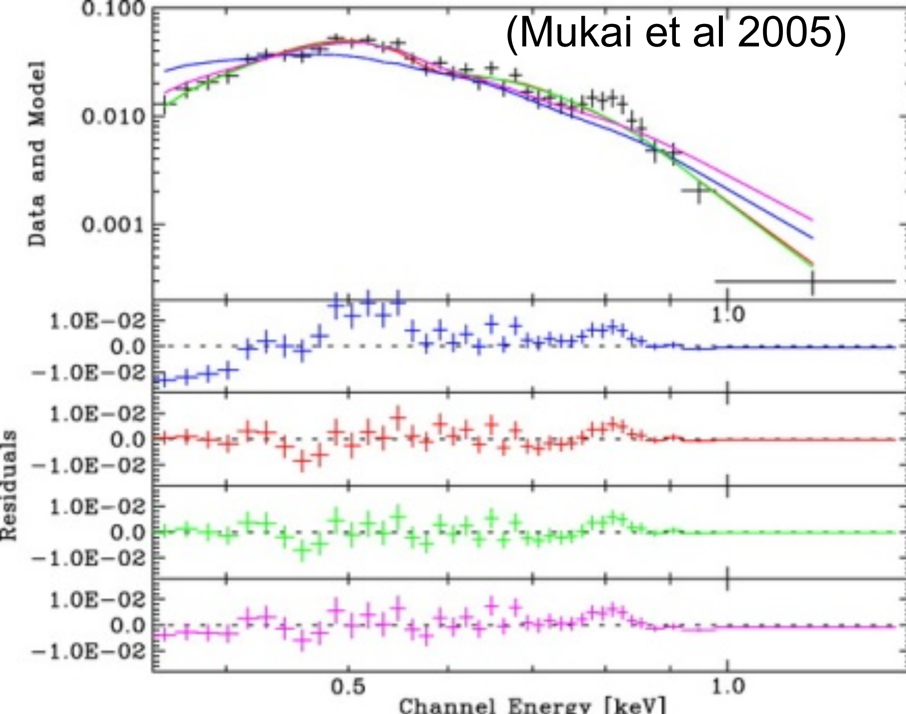


Slim disk model may explain the hot inner region

Radiation-MHD simulations by Ohsuga et al 2009, 2011

Abramowicz et al 1988
Watarai, Mizuno & Mineshige 2001

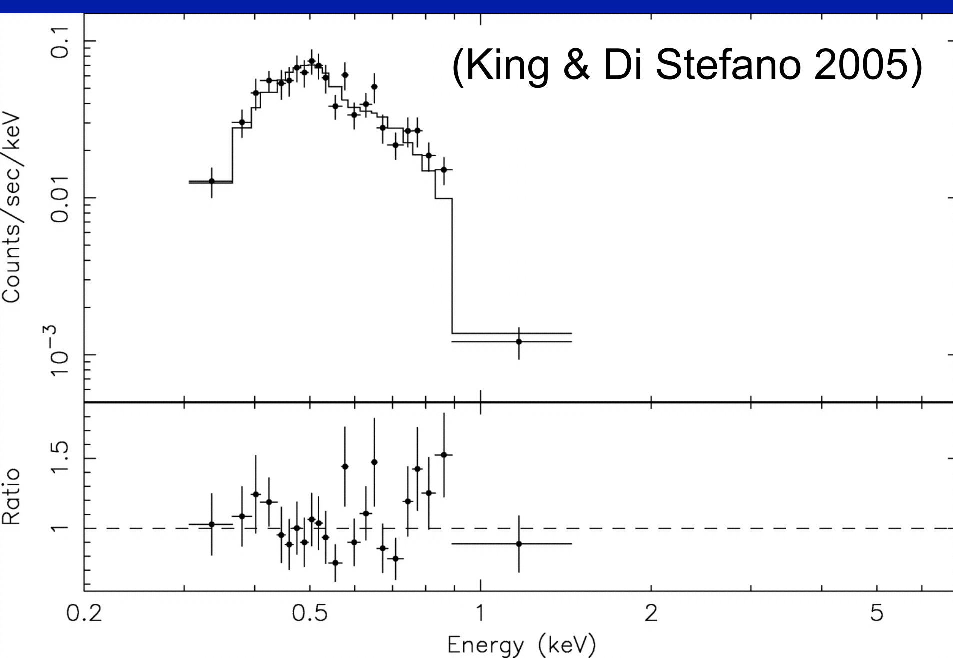
Provides outflows and moderate photon beaming

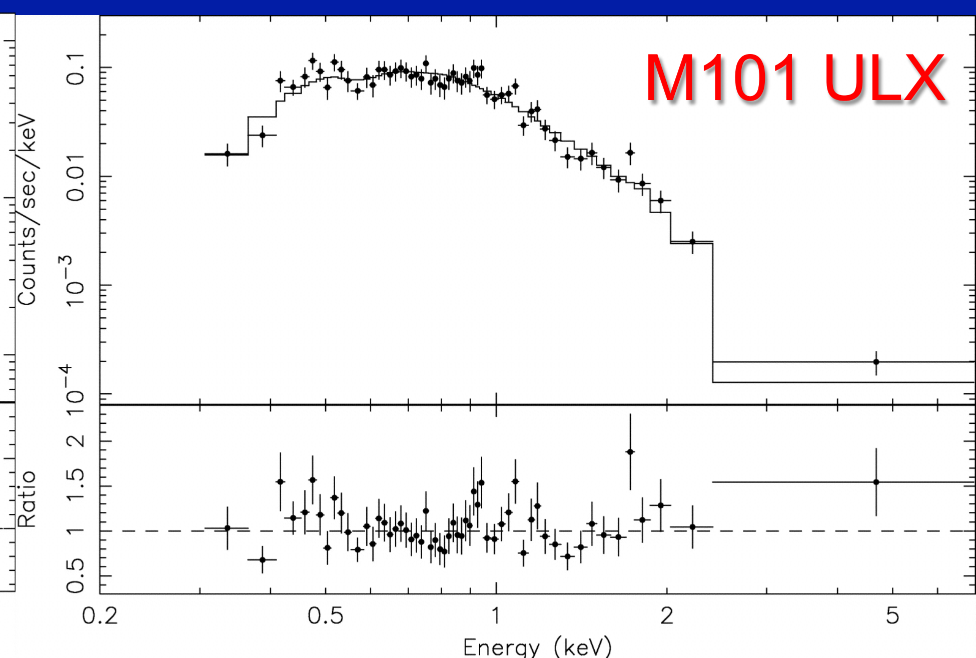


Supersoft ULXs
do not fit this scenario

Blackbody spectra
with kT ~ 0.1—0.2 keV
Photospere size ~ 5000 km

Large photosphere
of super-Edd outflows?



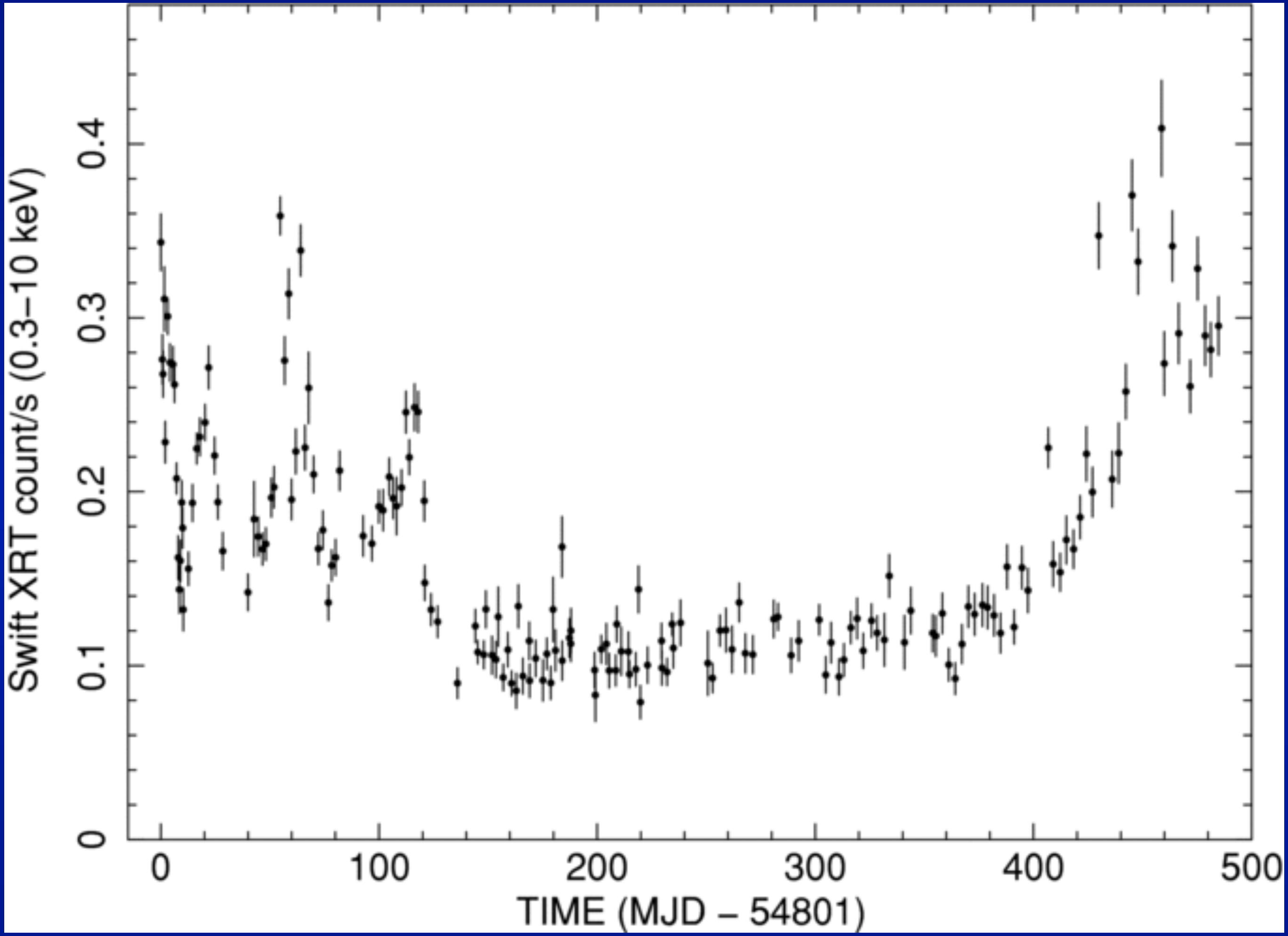


4. X-ray time variability

Sporadic ULX monitoring
with *Chandra*, *XMM-Newton, Swift*

Unfortunately, RXTE is not suitable

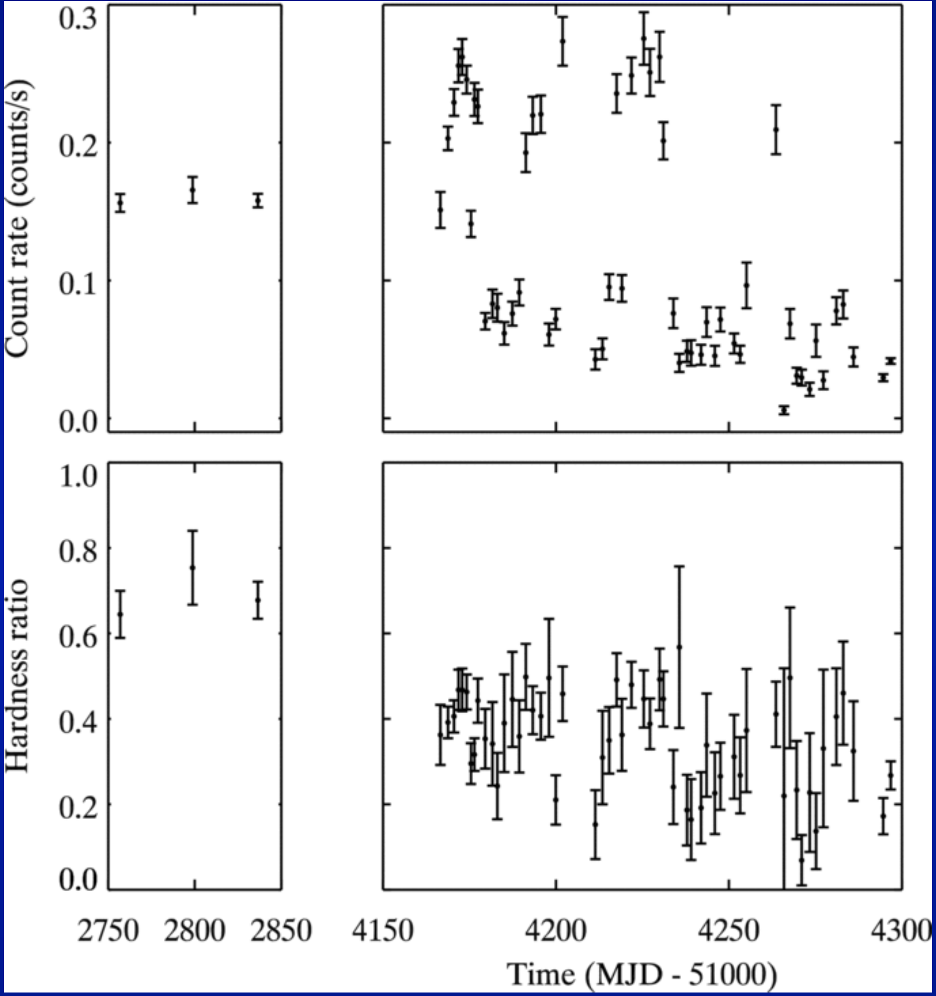
Ho IX X1 (Kong et al 2010) $L_x \sim 1$—$3\ 10^{40}$ erg/s



Most ULXs vary by a factor of a few over months/years

But very rarely in the off state (most *ROSAT* ULXs still on today)

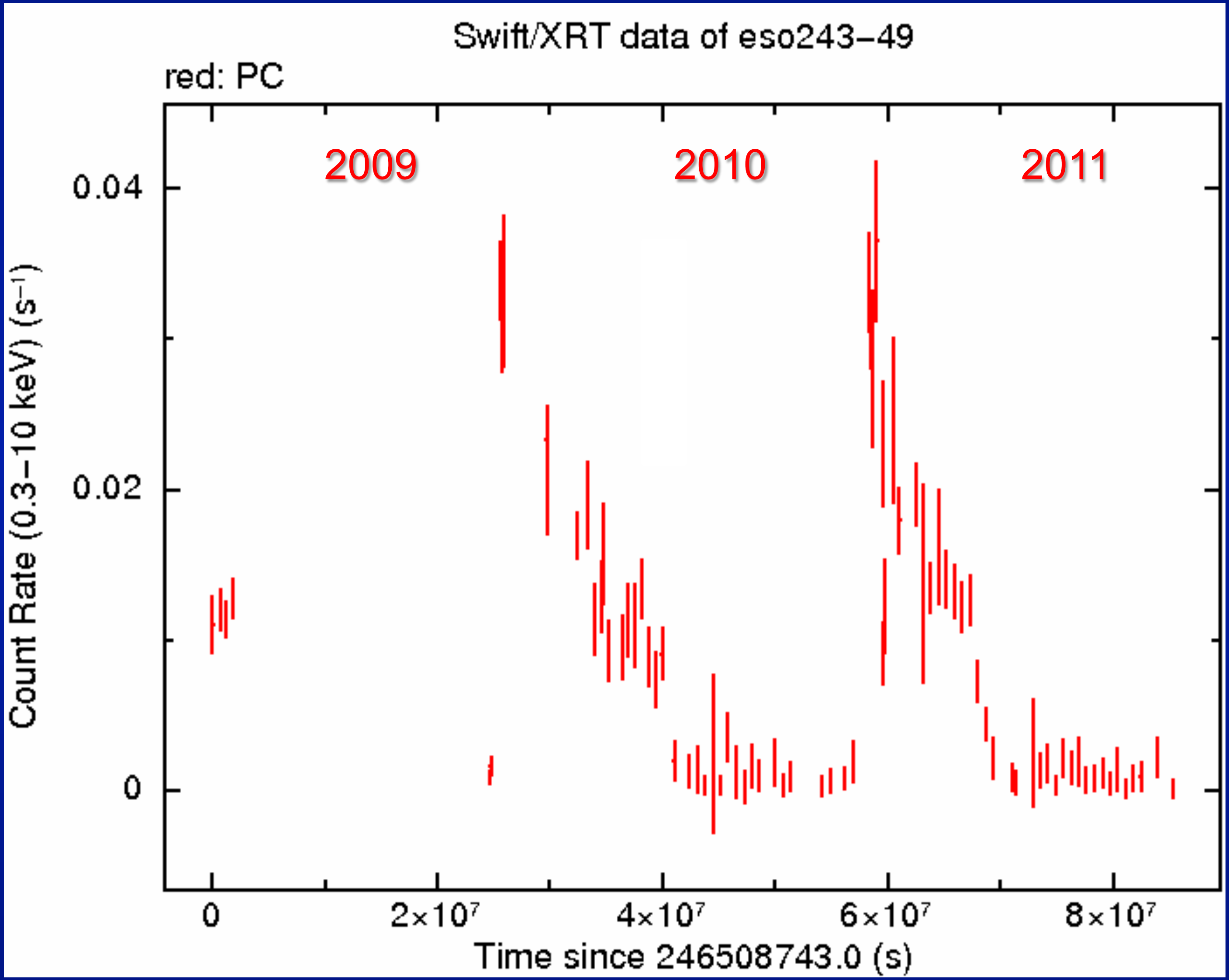
Ho II X1 (Grise' et al 2010) $L_x \sim 1$—$3\ 10^{40}$ erg/s



Count rate changes do not generally correspond to spectral state transitions (unlike Galactic BHs)

Spectral state transitions clearly seen in HLX1

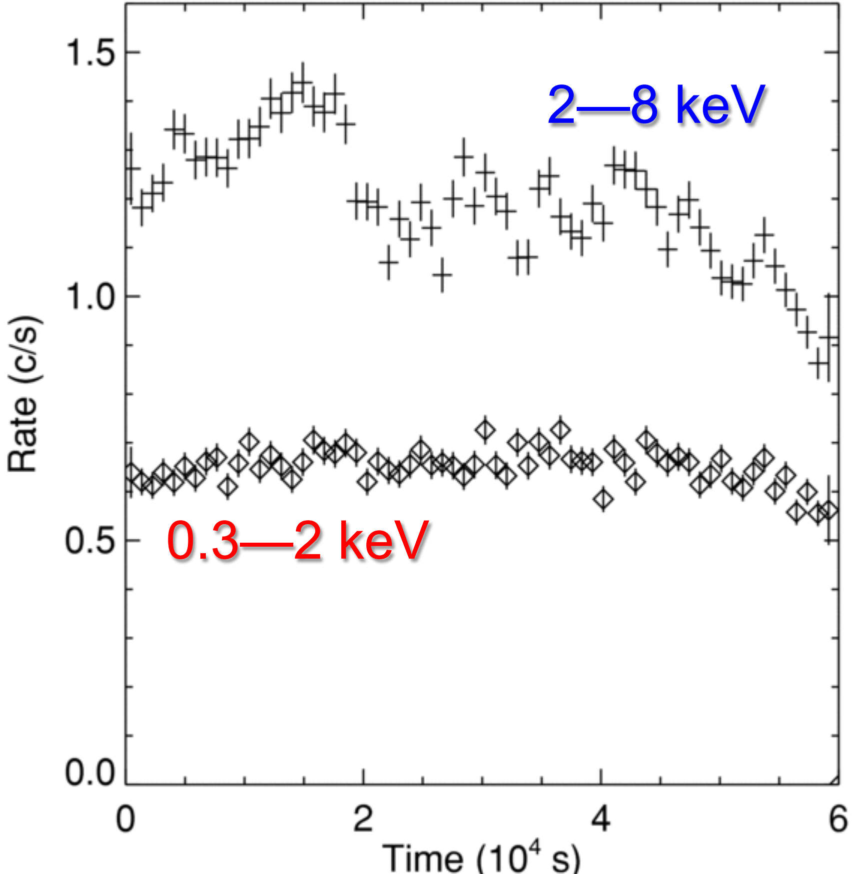
(Farrell et al 2009, Servillat et al 2011) . *See Natalie Webb's talk*



Peak $L_x \sim 1 \times 10^{42}$ erg/s

Hard band much more variable than soft band

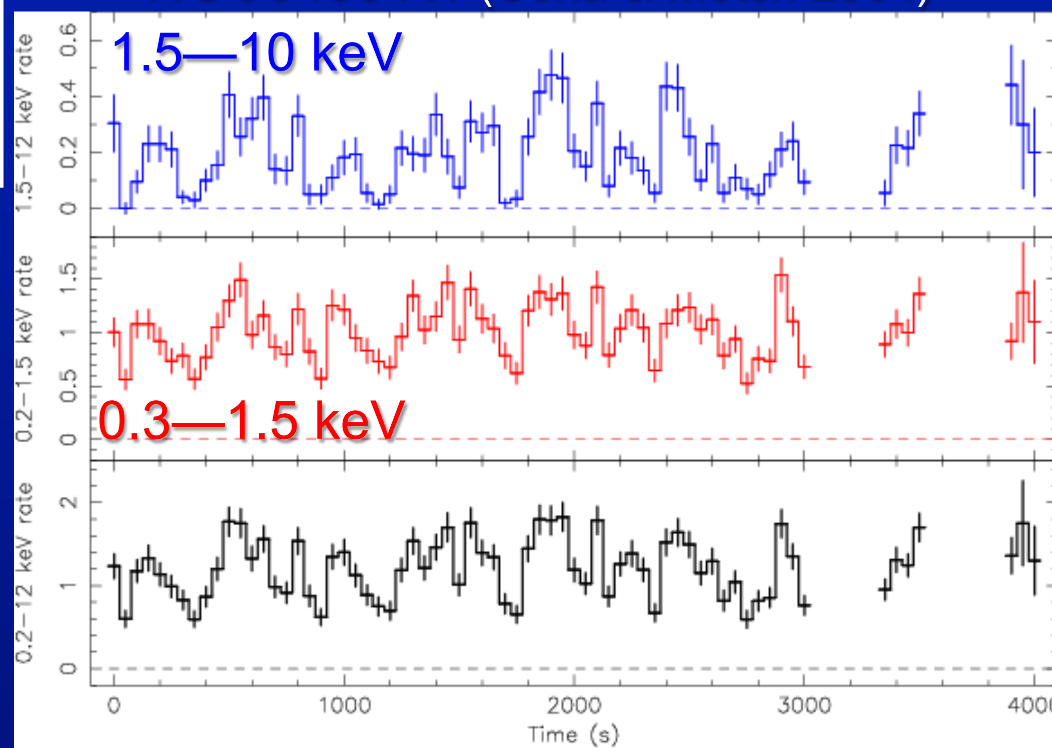
Consistent with interpretation of Comptonized component + soft thermal disk



M82 X1

(Kaaret, Feng & Gorski 2009)

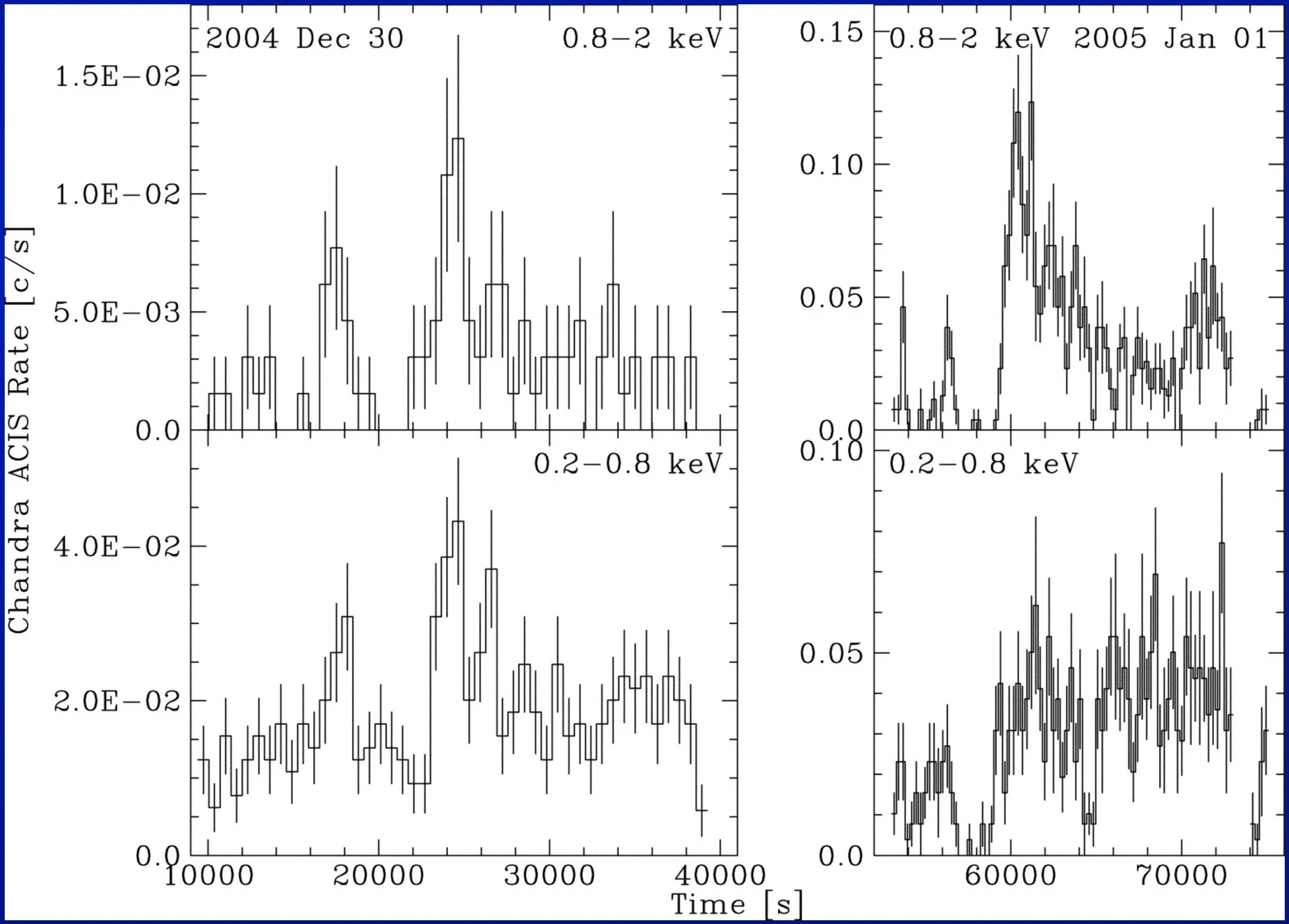
NGC5408 X1 (Soria & Motch 2004)



Supersoft ULXs have the strongest variability

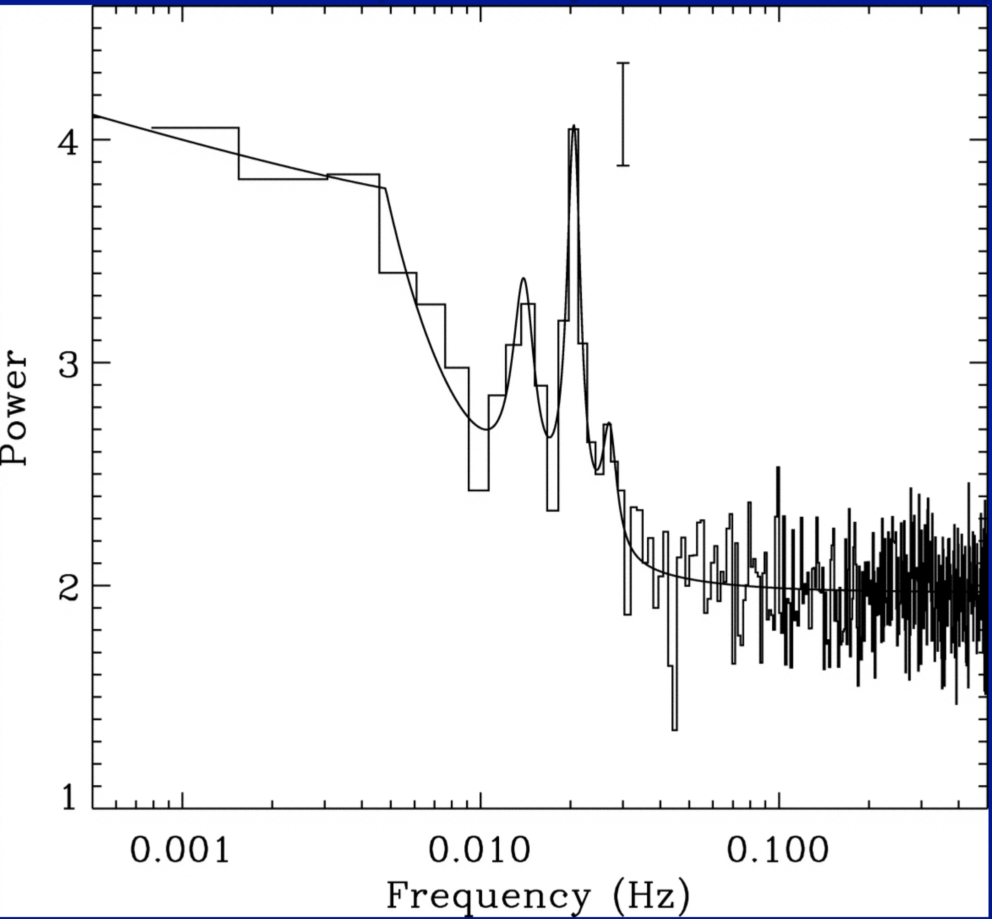
Consistent with outflow scenario
Inconsistent with standard disk around IMBH

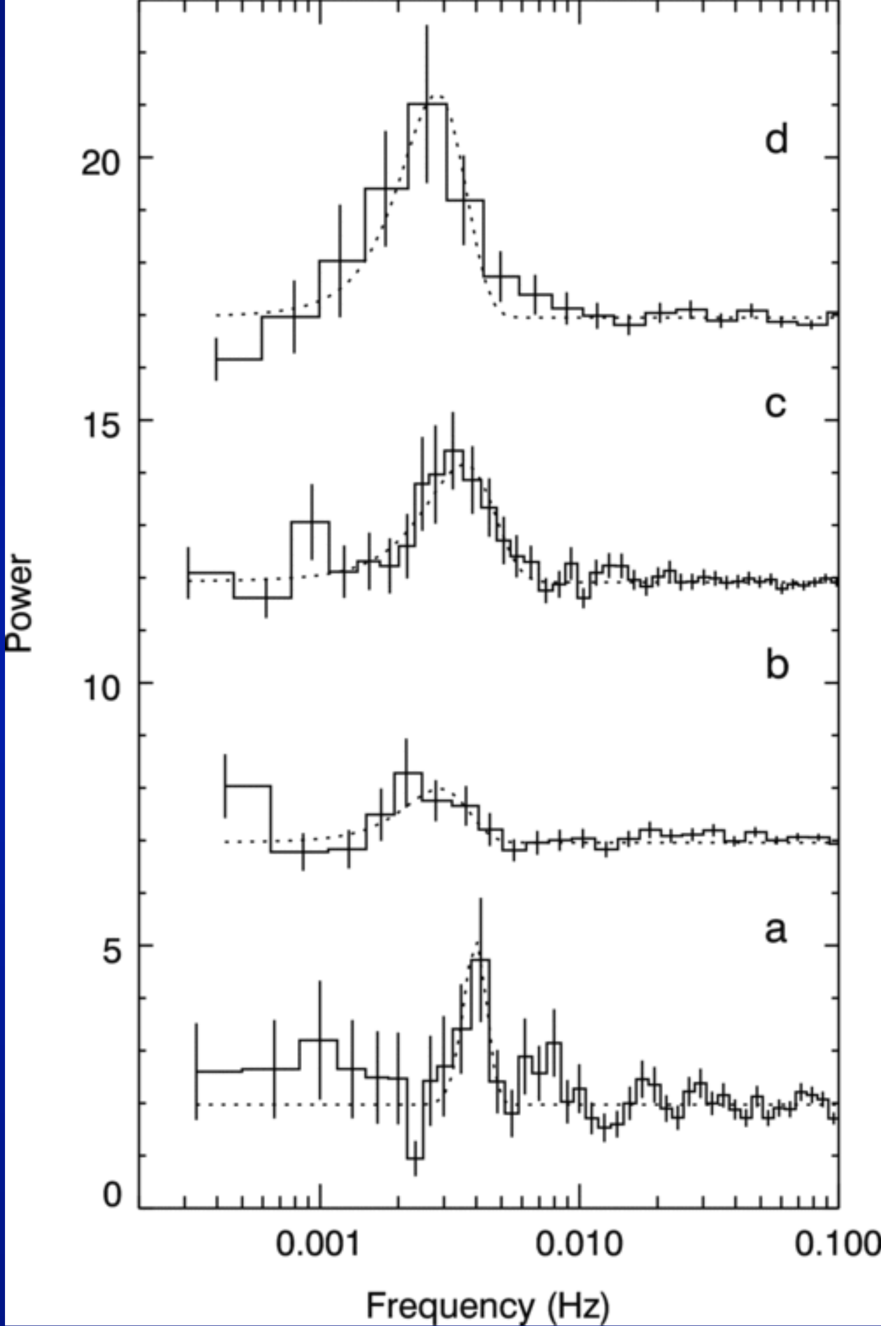
M101 ULX (Mukai et al 2005)



Low-frequency QPOs (~ 10 mHz) detected in several ULXs

NGC5408 X1 (Strohmayer et al 2007,2009)



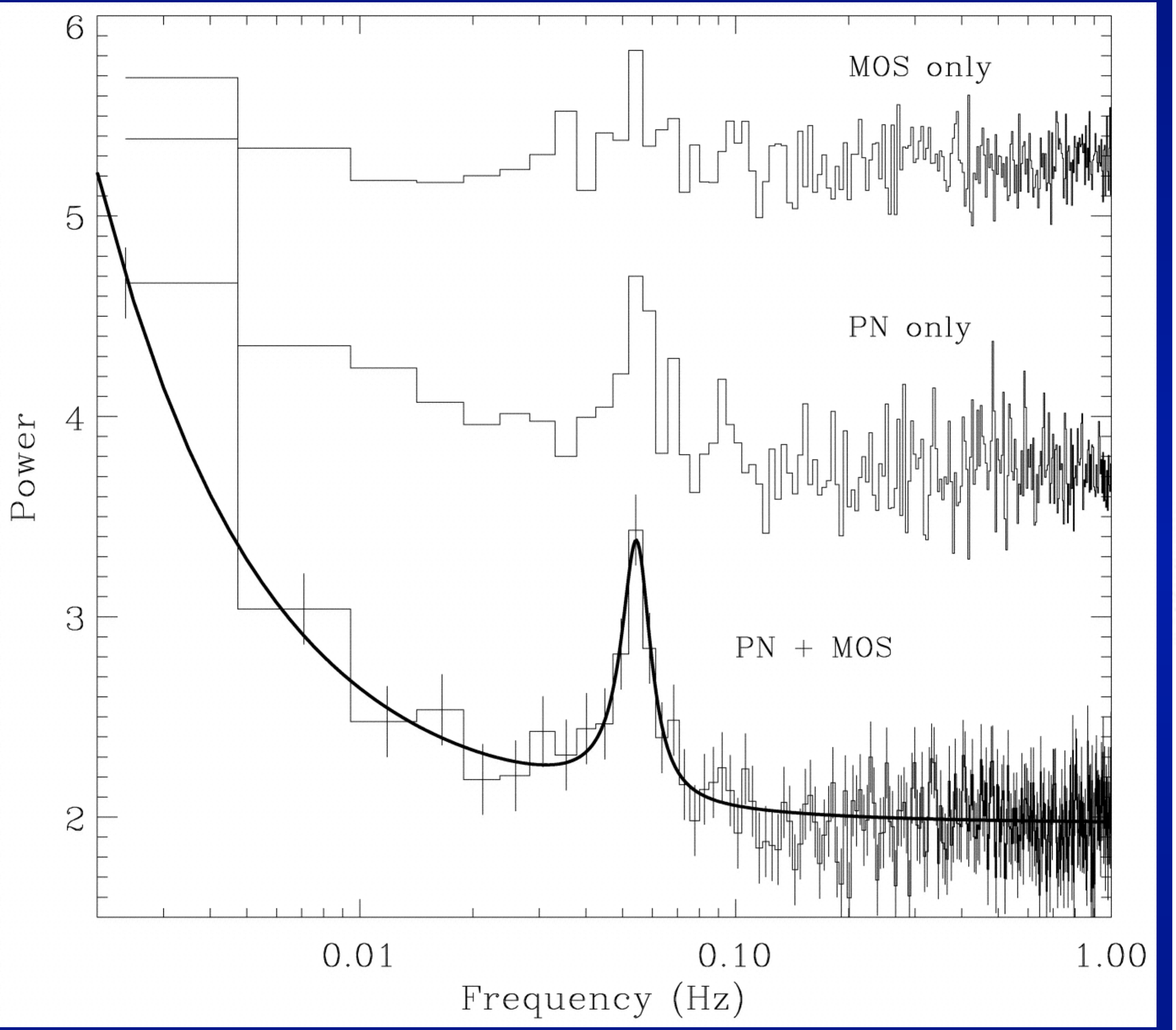


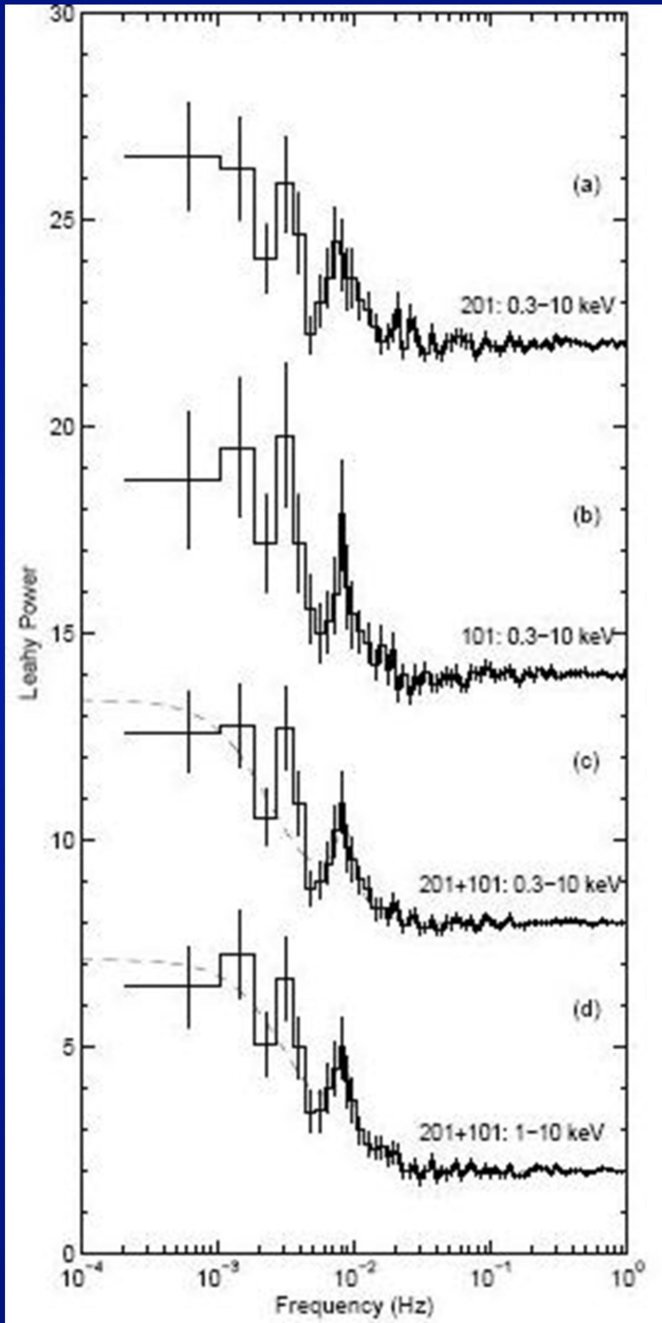
Ho IX X1 (Dewangan et al 2006) ?

M82 X2 (=X42.3+59) (Feng et al 2010)

M82 X1 (Strohmayer & Mushotzky 2003)

NGC6946 X1 (Rao et al 2010)

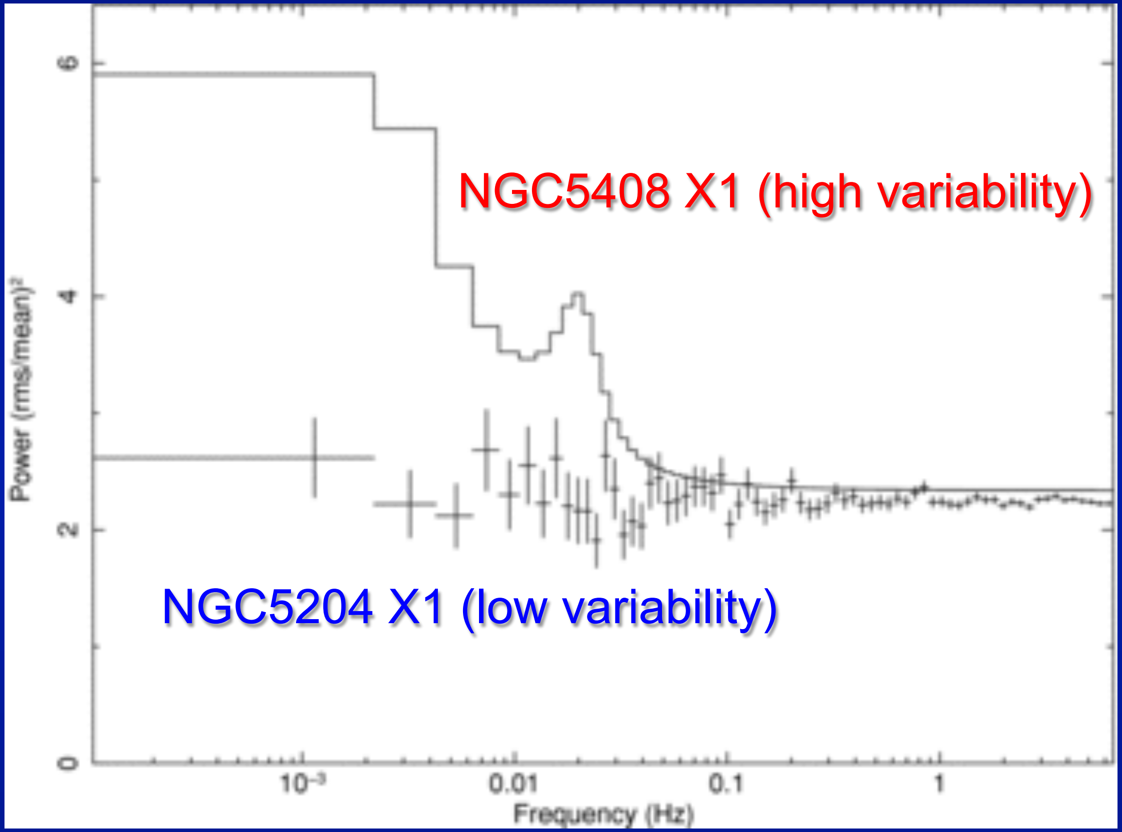




…but unclear how they scale with M and mdot
(may not be mass indicators)

Some ULXs have strong short-term variability, others do not

even if they have similar luminosity and spectra



(Heil, Vaughan & Roberts 2009)

High rms = ULX with jets, low rms = no jets?

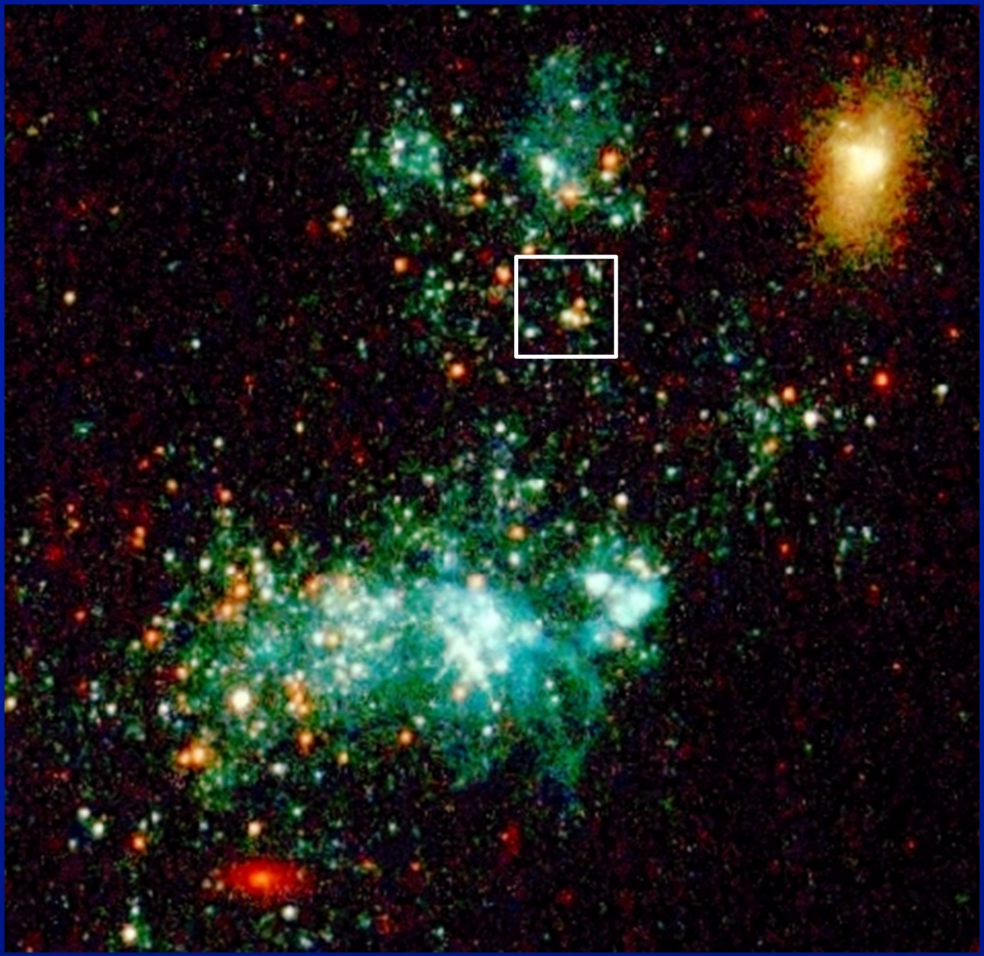
5. Optical counterparts, donor stars

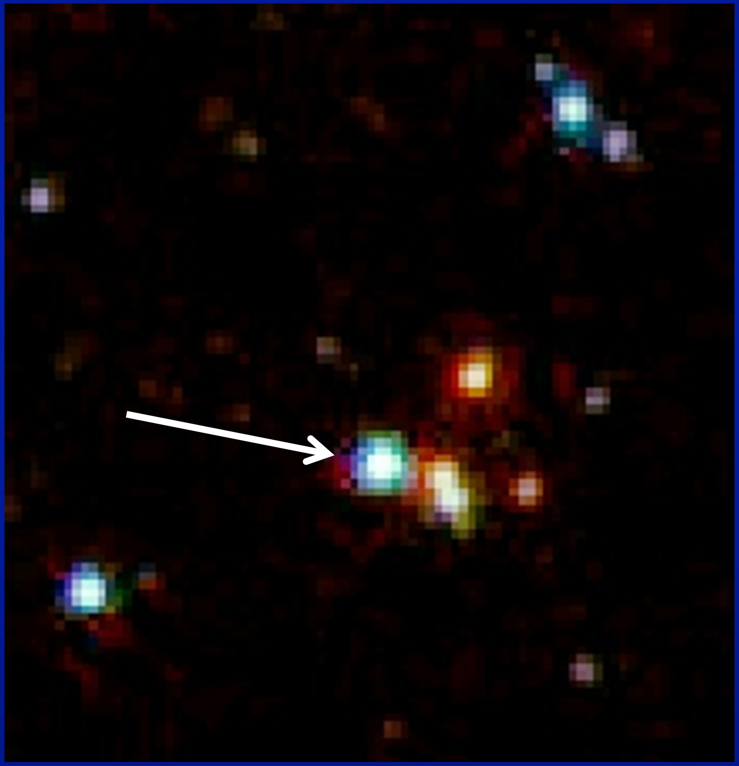
Do ULXs accrete from a low-mass or a high-mass donor?
(compare LMXBs and HMXBs)

Characteristic age, relation with star formation?

Majority of ULXs found near B stars (age ~ 10-30 Myr)

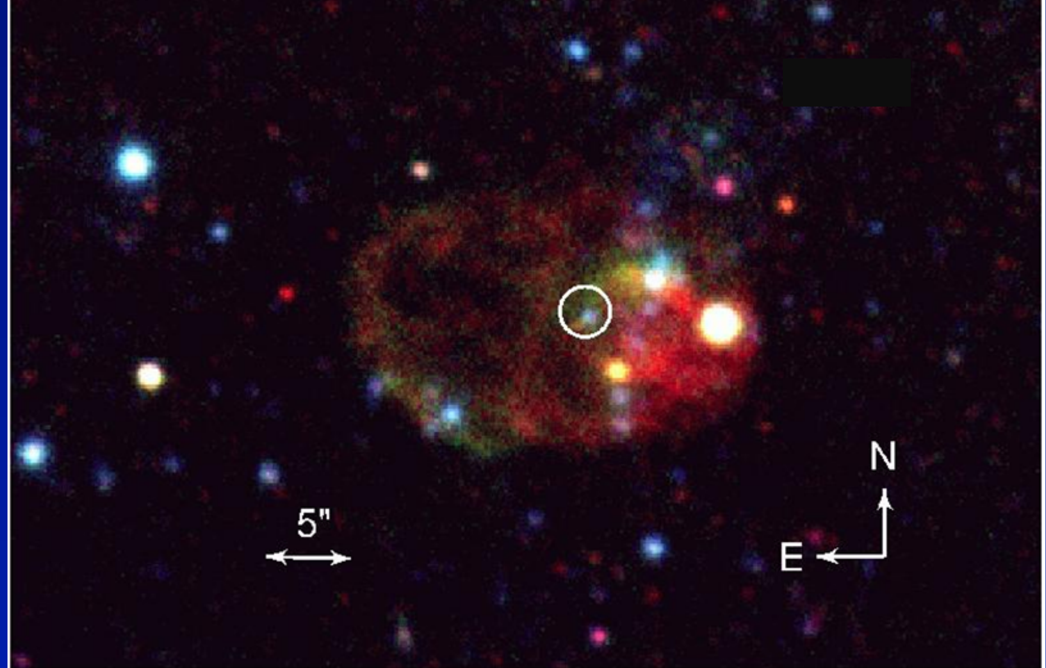
Most likely counterparts tend to be blue stars (eg B0 type)

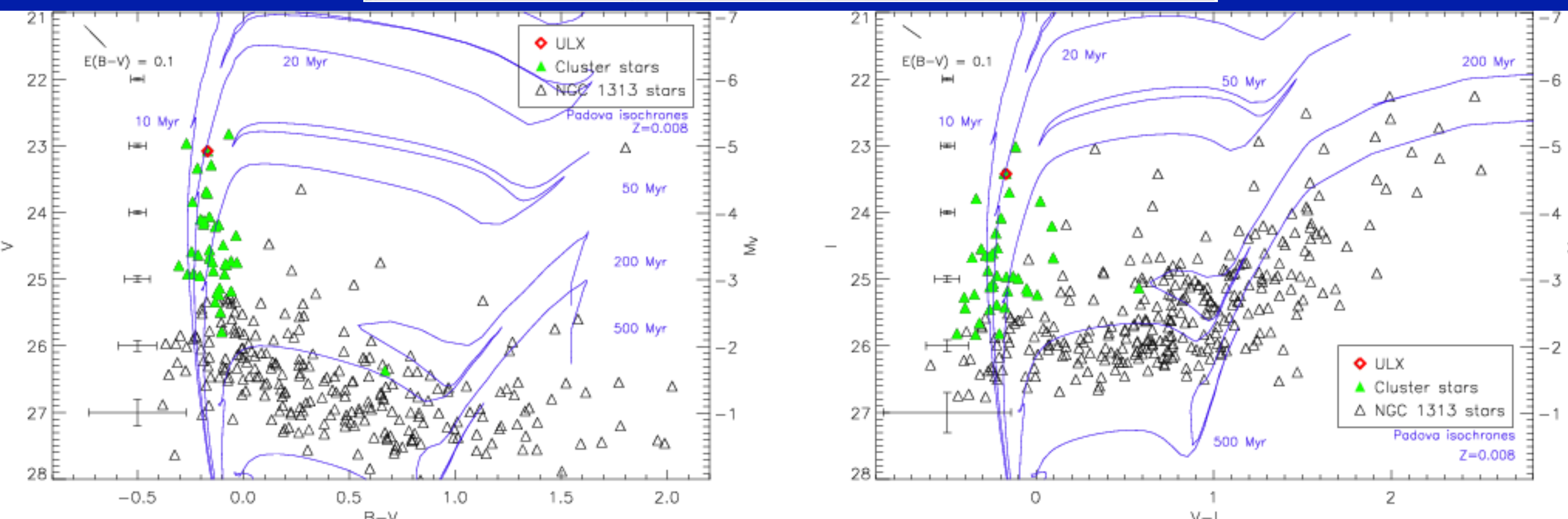




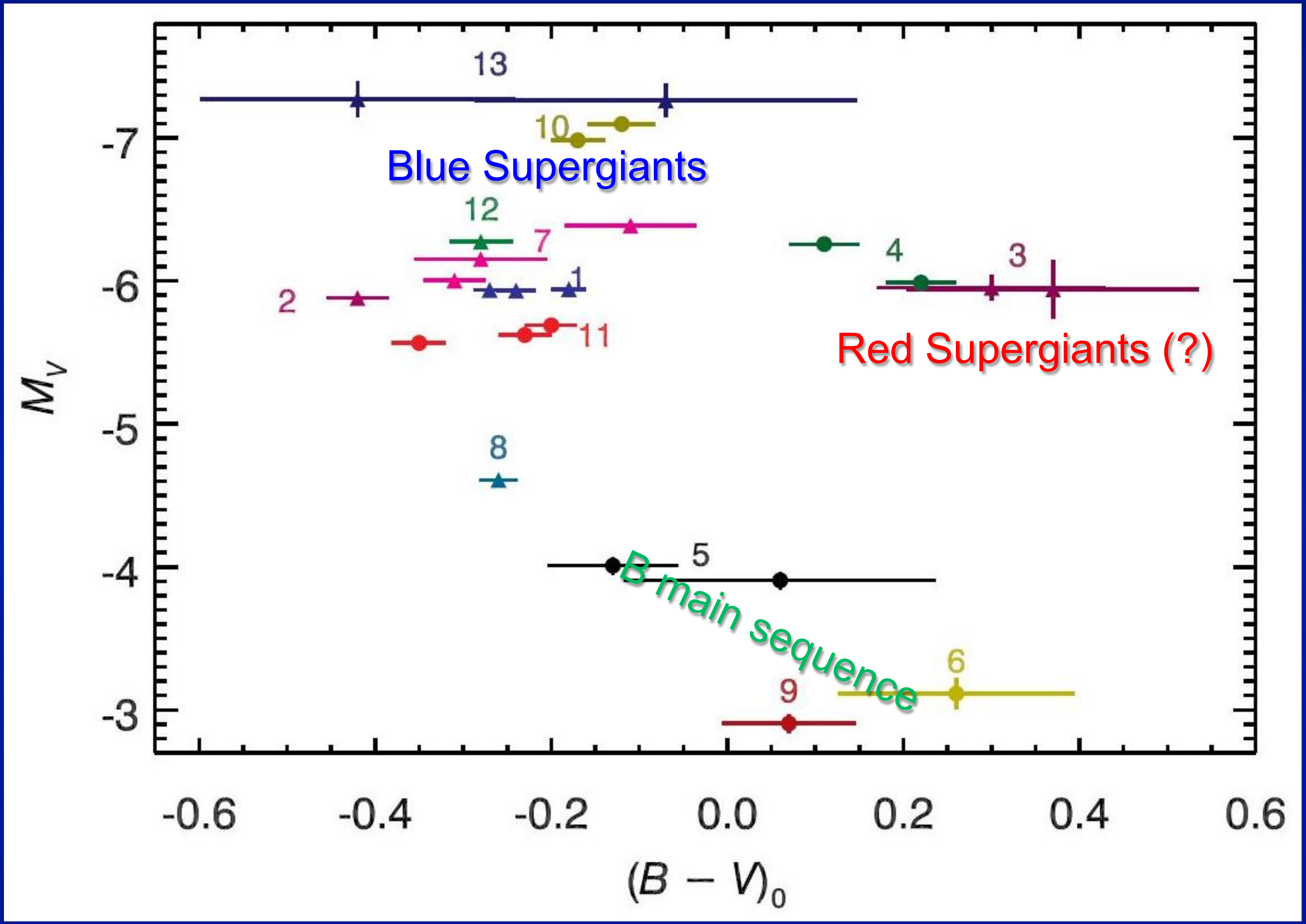
NGC4559 X7 (Soria et al 2005)

NGC1313 X2 (Grise' et al 2008)



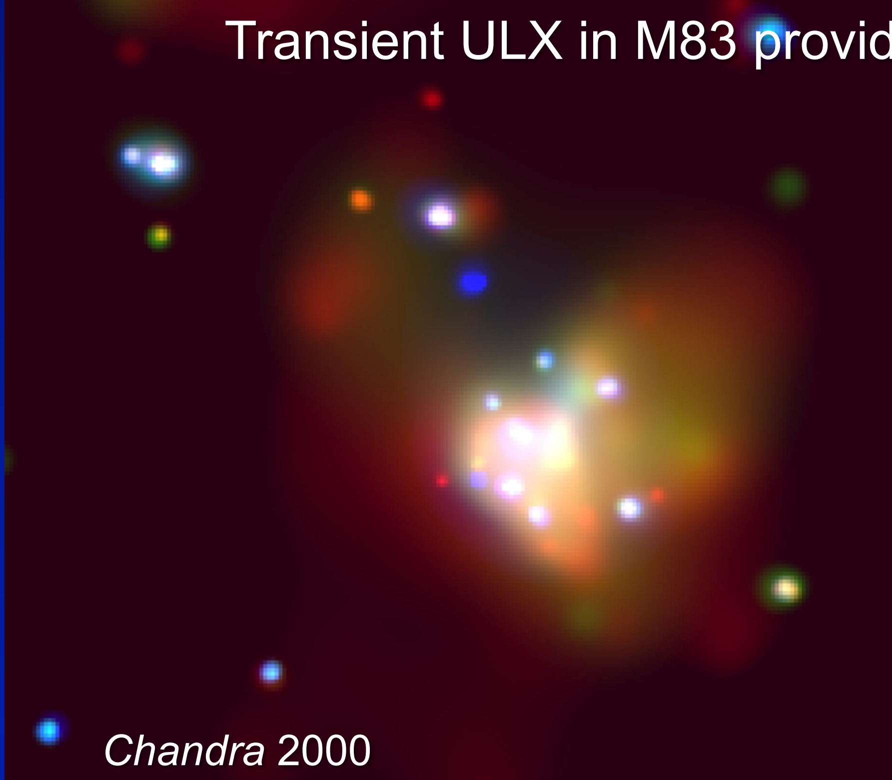


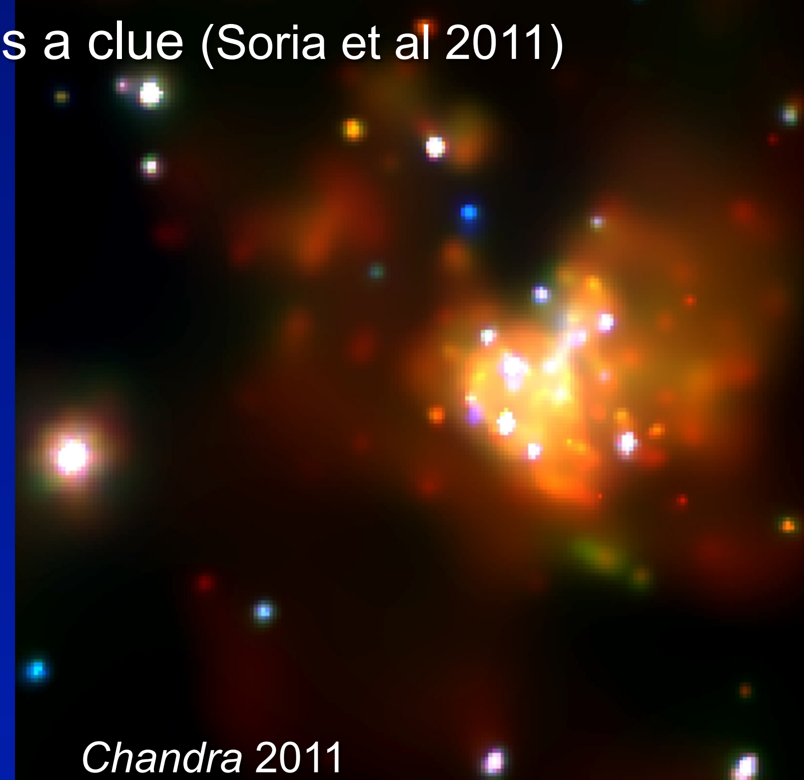
Sample of ULX counterparts with HST imaging (Tao et al 2011)

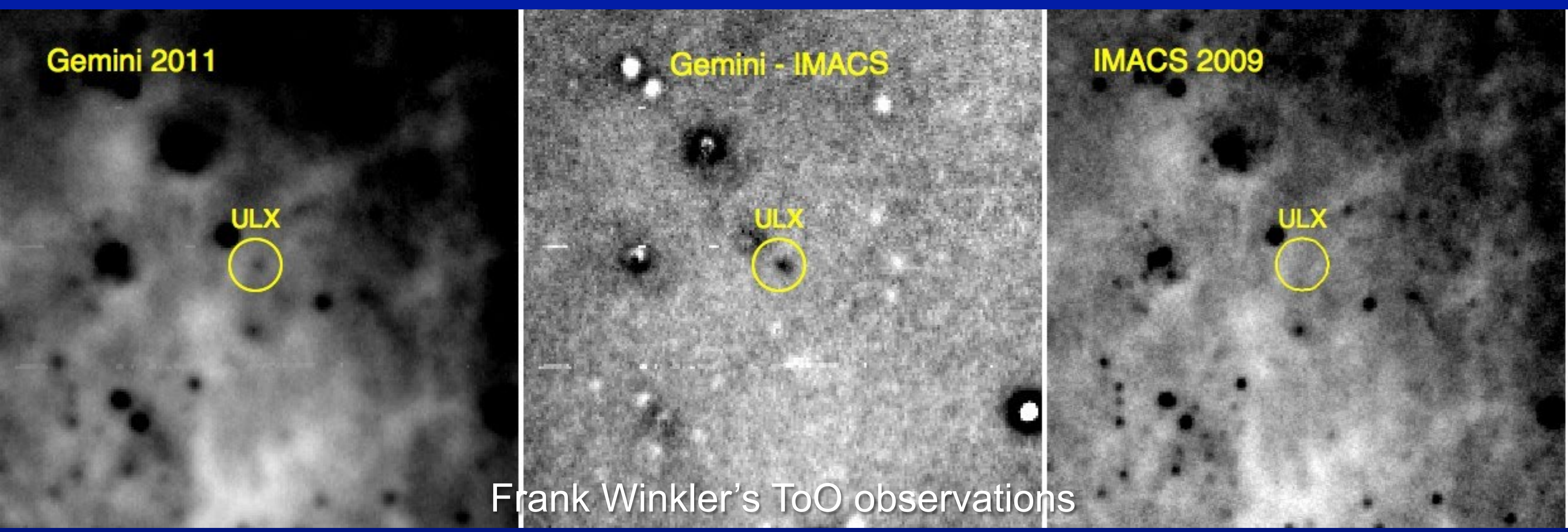


…but are we seeing the true colours of the donor star, or a strongly irradiated donor star, or an irradiated disk?

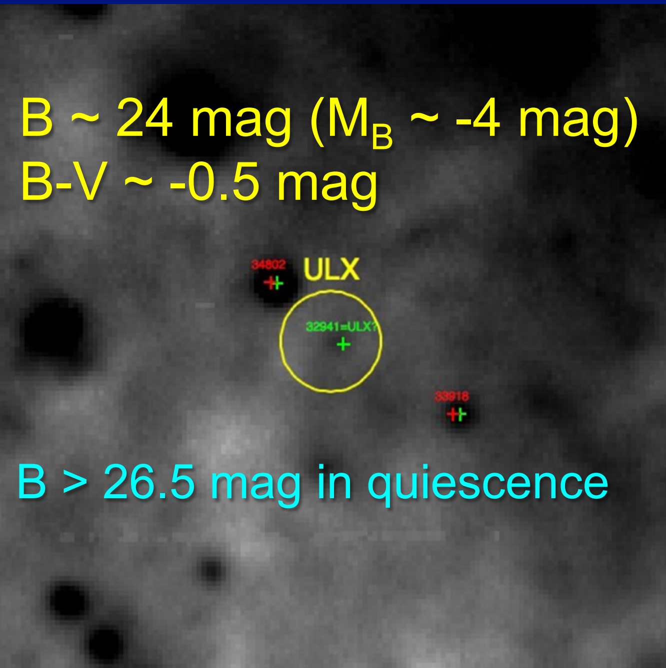
Transient ULX in M83 provides a clue (Soria et al 2011)



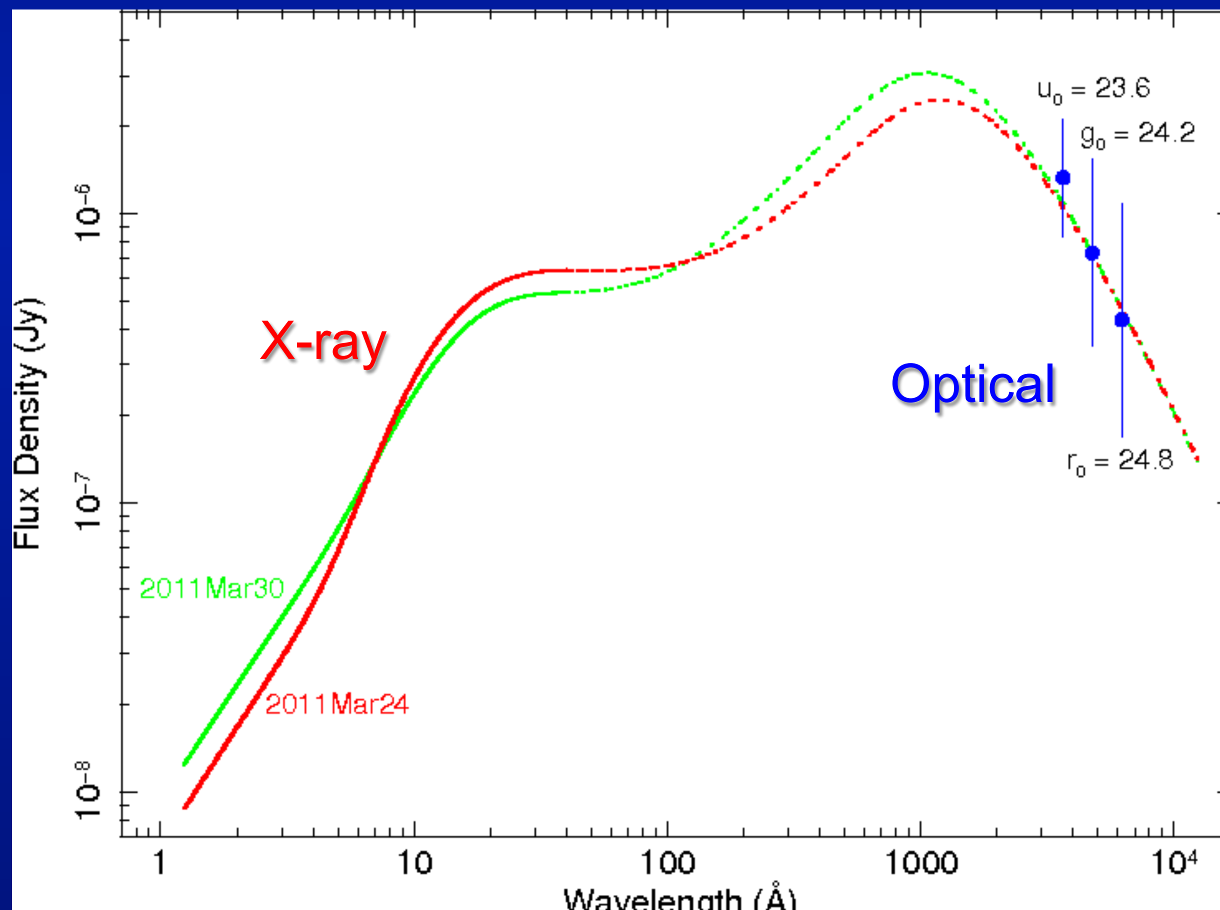




Frank Winkler's ToO observations



Ctp may be irradiated disk, at least for M83 X1



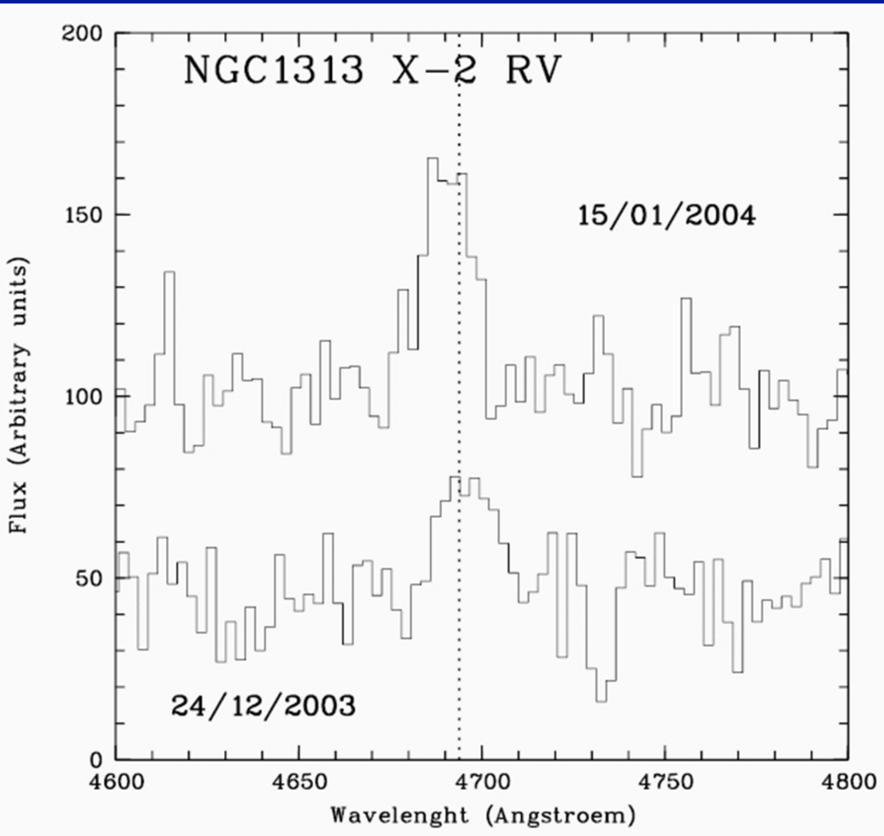
(Soria et al 2011)

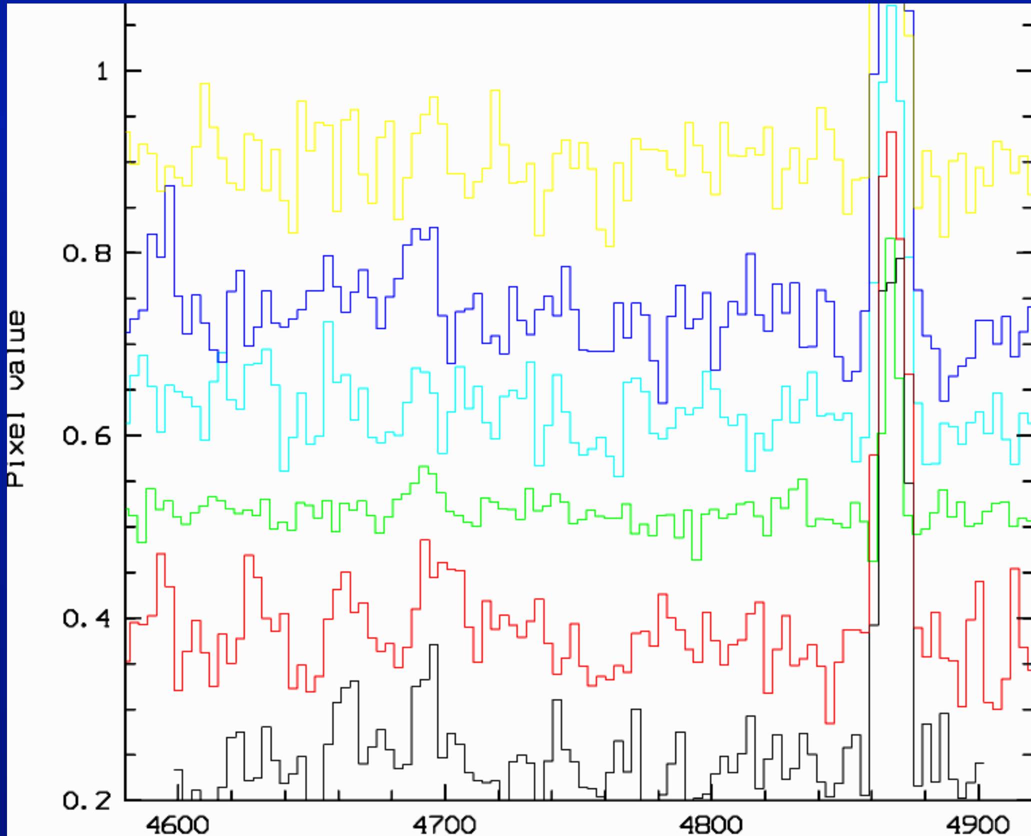
If the optical ctp is an irradiated disk, we may see emission lines

→ We may be able to measure their orbital velocity shifts

→ We may constrain the BH mass function

NGC 1313 X1: several papers by Grise', Pakull & Motch





ULXs often surrounded by large ionized nebulae: ULX bubbles

(Pakull 2002)

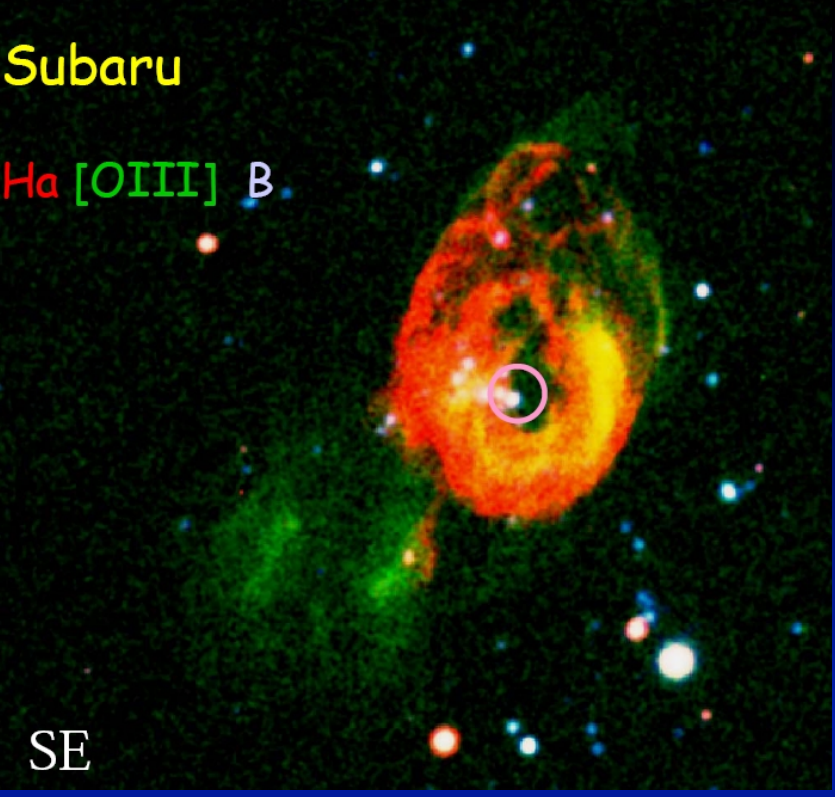
See David Cseh's talk

Characteristic diameter ~ 100—300 pc

Characteristic energy up to ~ 1E52 erg

Some are X-ray photoionized, others shock-ionized

Some have synchrotron radio nebulae, others do not



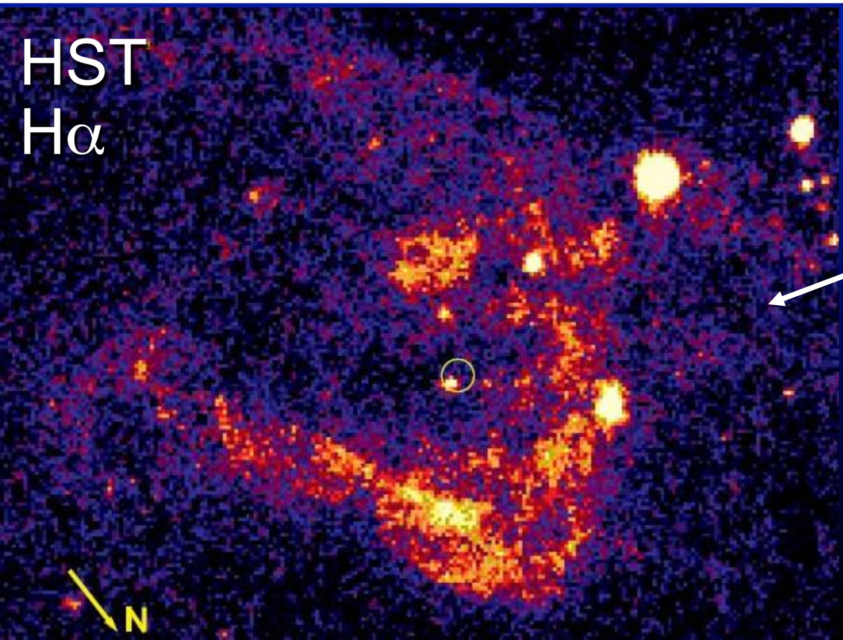
Holmberg IX X1

Pakull & Mirioni 2002
Grise’ et al 2008

No radio nebula (F <~ 0.1 mJy)

L_x ~ 1—2 E 40 erg/s

L_{mech} ~ 1 E 40 erg/s



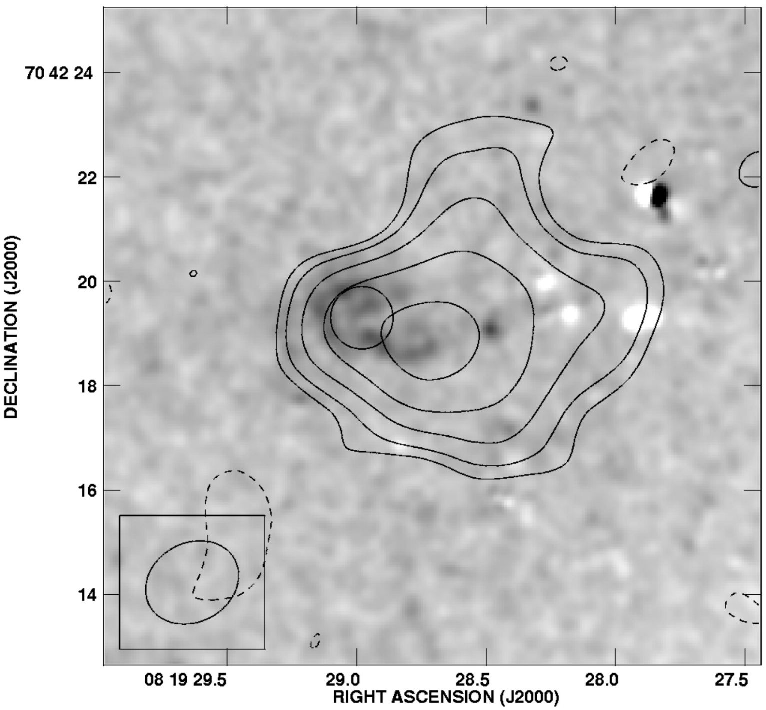
IC342 X1 (“Foot Nebula”)

Pakull & Mirioni 2002
Feng & Kaaret 2008

Radio nebula (Cseh et al 2010)
F ~ 2 mJy, E ~ 1 E 51 erg

L_x ~ 1 E 40 erg/s
L_{mech} ~ few E 39 erg/s

ULX radio bubbles:



Holmberg II X1

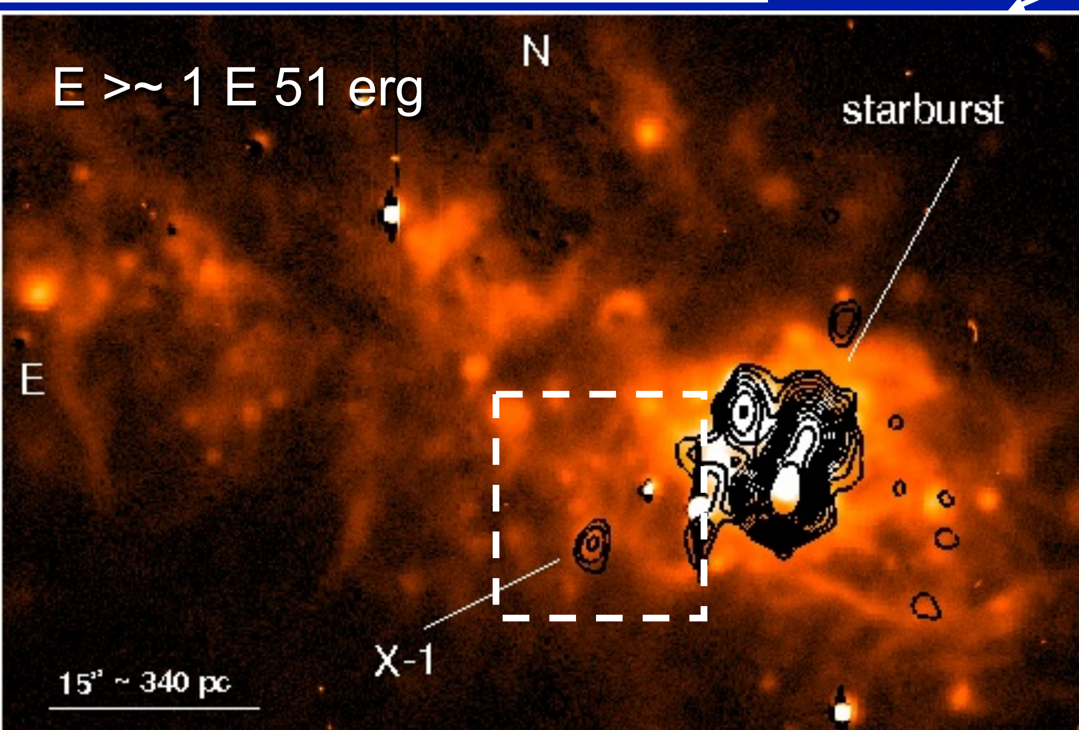
$L_x \sim 2$ E 40 erg/s

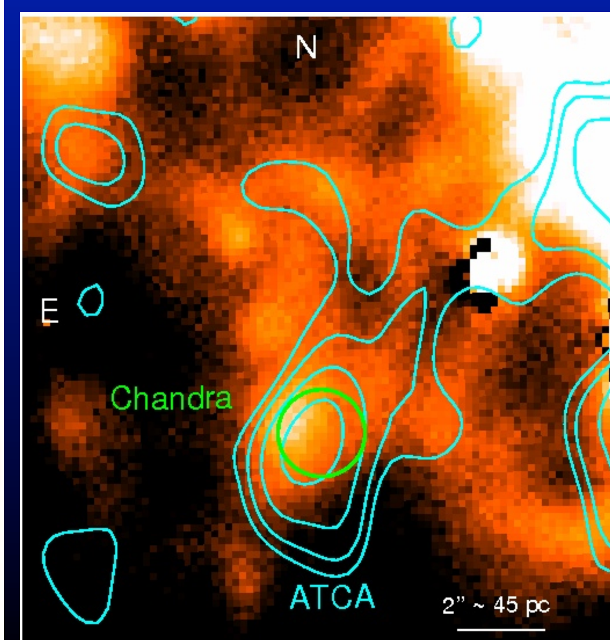
Miller, Mushotzky & Neff 2005

NGC5408 X1

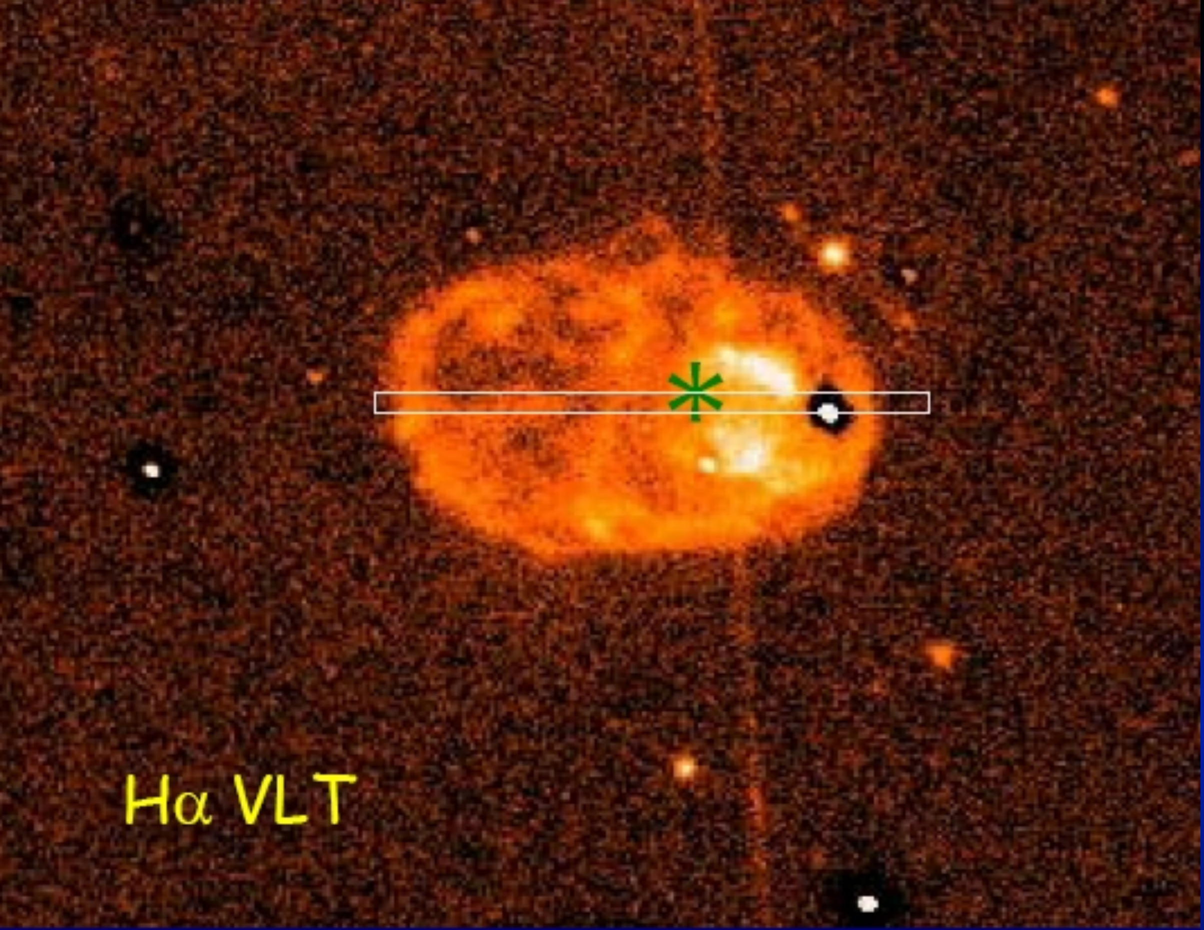
$L_x \sim 1$ E 40 erg/s

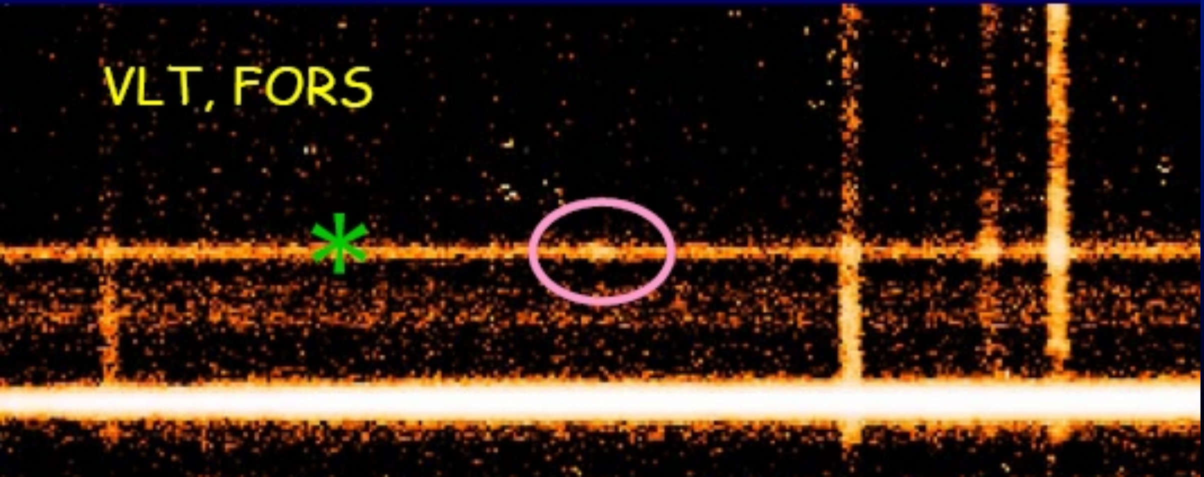
Kaaret et al 2003
Soria et al 2006
Lang et al 2007





NGC1313 X2





Grise' et al 2008

No radio nebula
(F <~ 0.1 mJy)

L_x ~ 0.5—2 E 40 erg/s
L_{mech} ~ few E 39 erg/s

ULX bubbles suggest:

Strong winds (favours near or super-Edd models over IMBHs)

Quasi-isotropic X-ray ionization (rules out strong beaming)

Large bubbles without a ULX are (almost) never seen
(suggests that ULXs are continuously active)

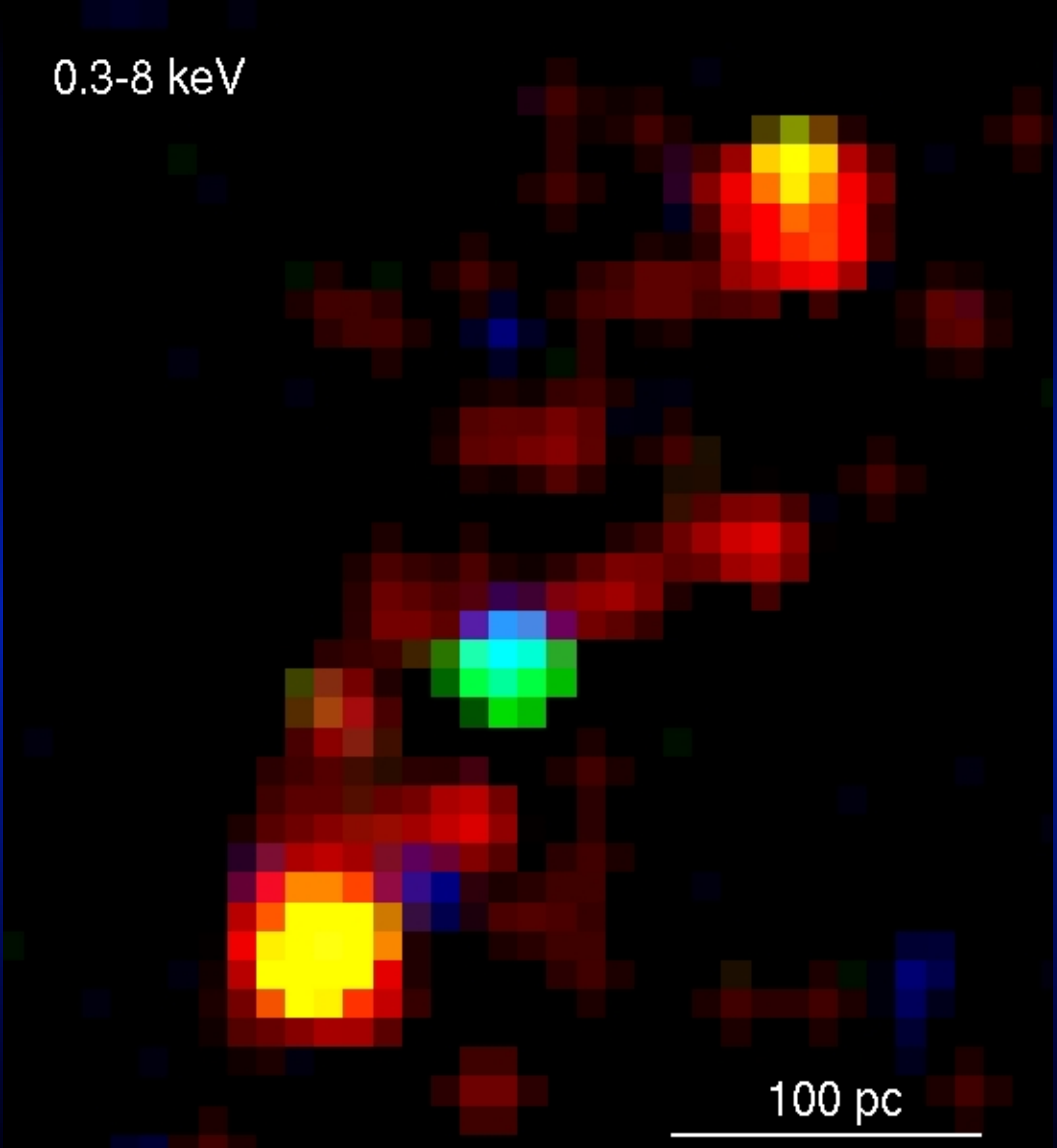
Expansion speed ~ 100—200 km/s, age ~ a few E5 to 1E6 yr

→ Mass transfer rate <~ 1E(-5) M_{sun}/yr

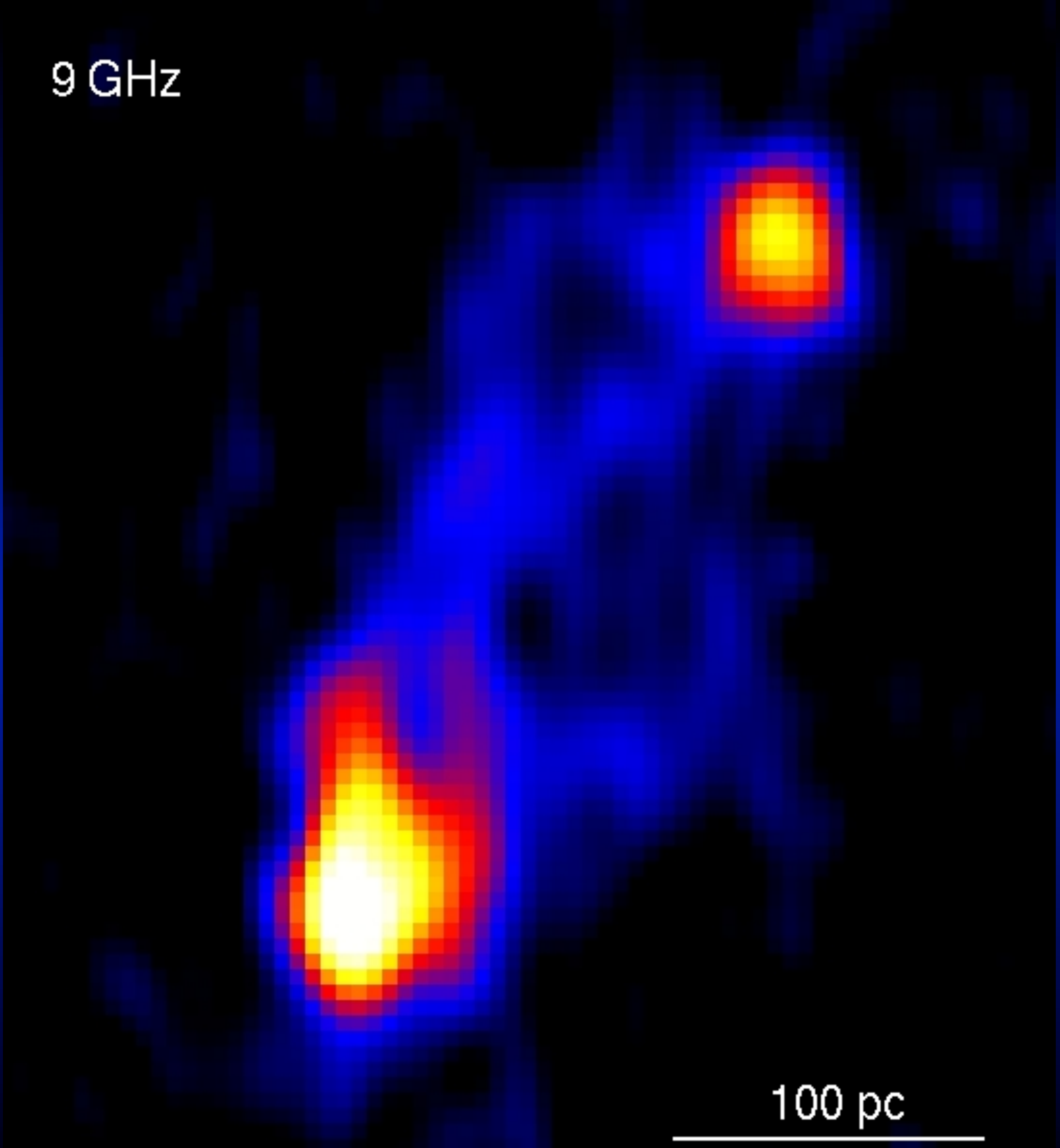
→ More consistent with moderately efficient accretion onto a massive stellar BH, $M \sim 30\text{-}100\ M_{sun}$

(SS433 is similar but younger and with higher mass transfer rate)

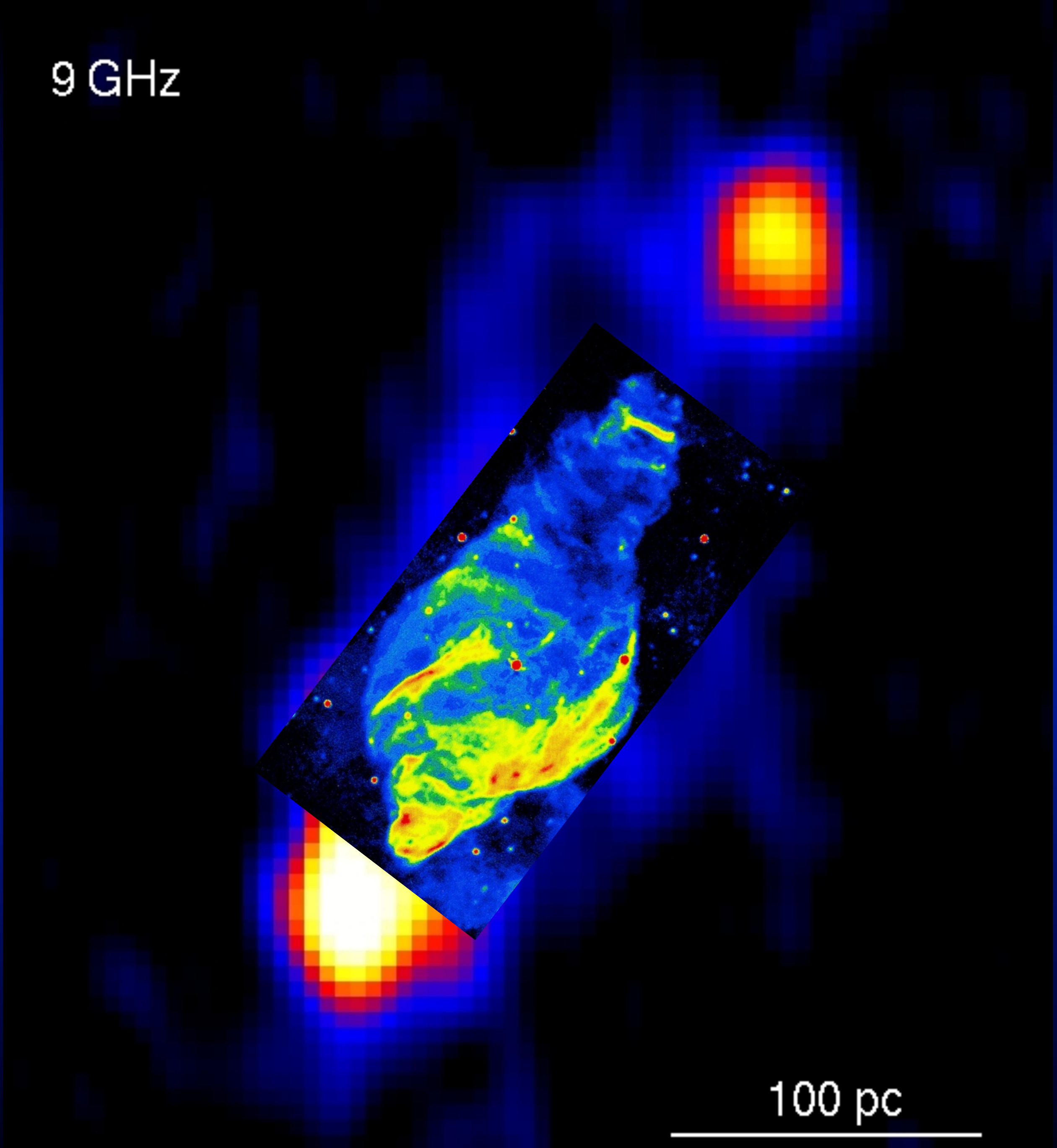
Do ULX bubbles also contain jets? (like SS433)



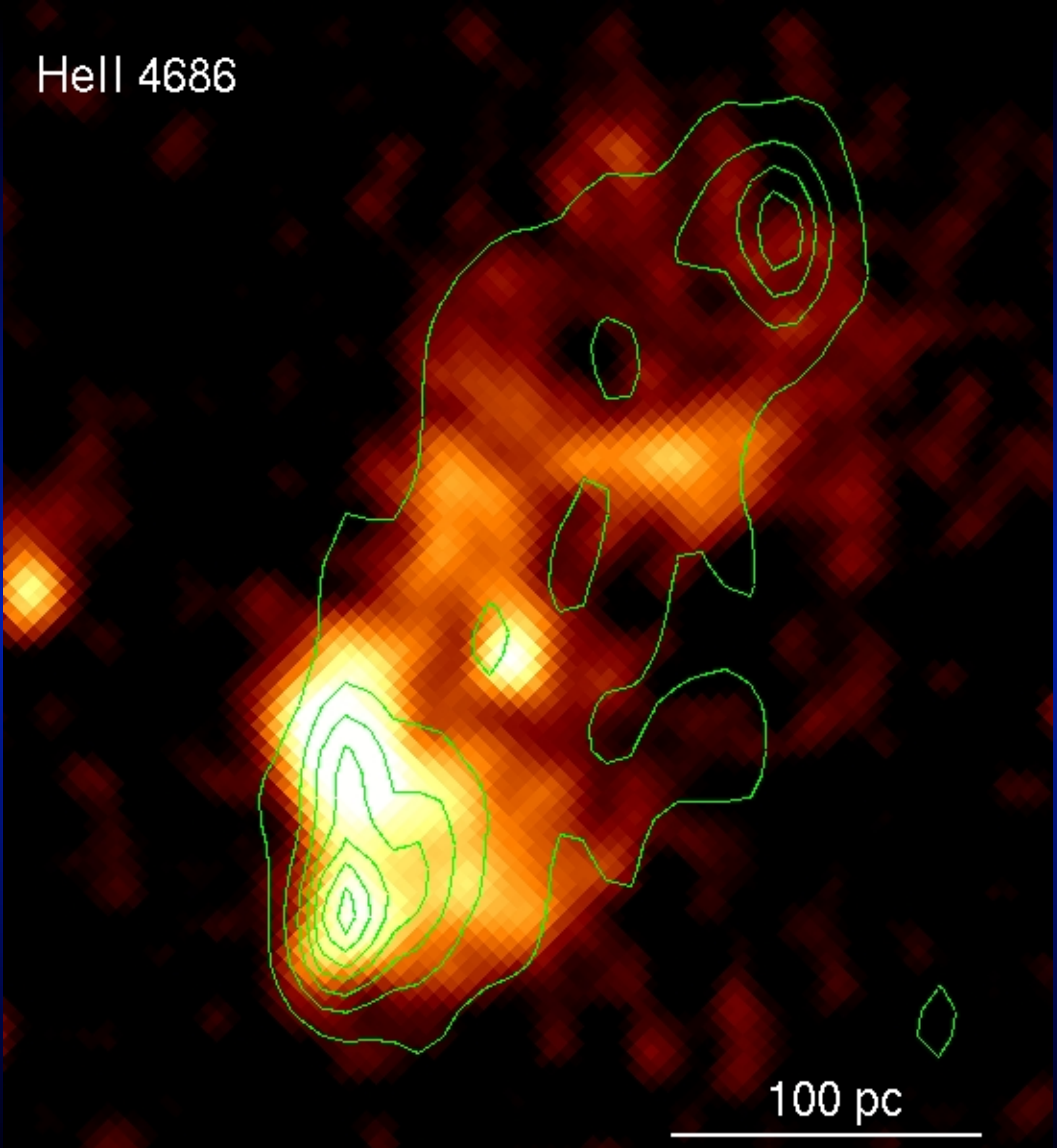
NGC7793 S26 (Pakull et al 2010, Soria et al 2010, Broderick et al 2011 in prep)



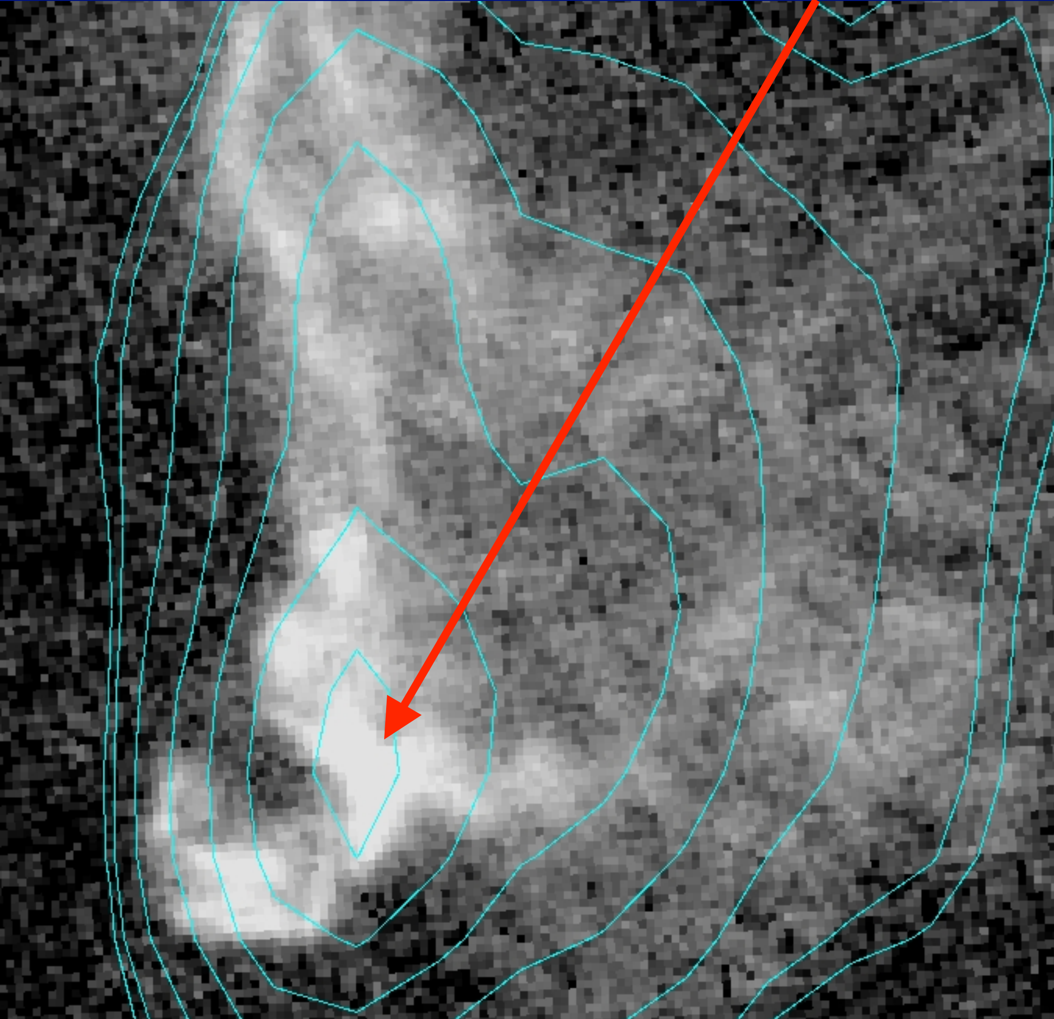
NGC7793 S26 (Pakull et al 2010, Soria et al 2010, Broderick et al 2011 in prep)



NGC7793 S26 (Pakull et al 2010, Soria et al 2010, Broderick et al 2011 in prep)



NGC7793 S26 (Pakull et al 2010, Soria et al 2010, Broderick et al 2011 in prep)



9 GHz contours and
Hα greyscale image

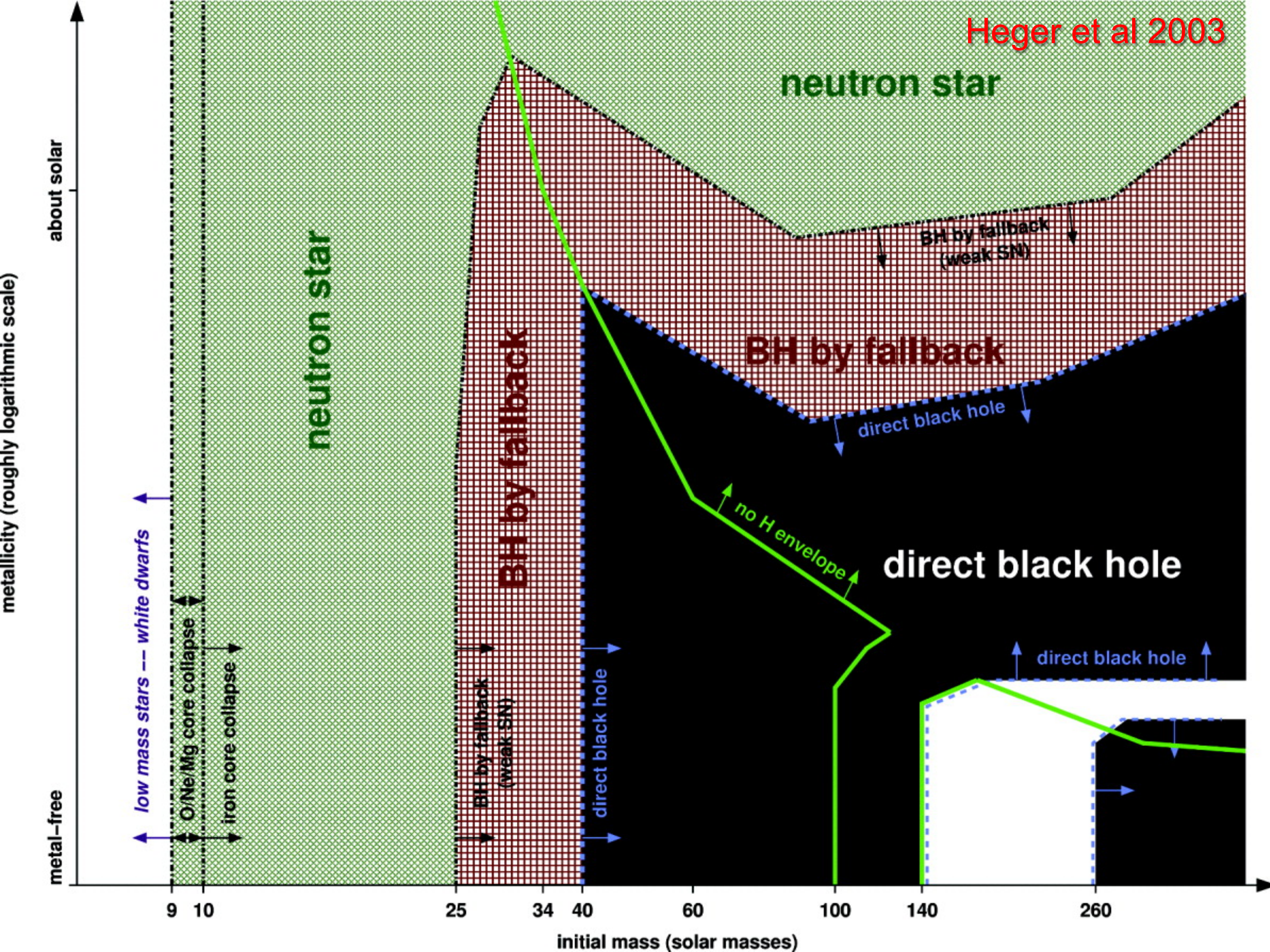
S26 may be a mechanically-dominated BH at super-Edd mdot

Shows that collimated jets can exist in the super-Edd regime

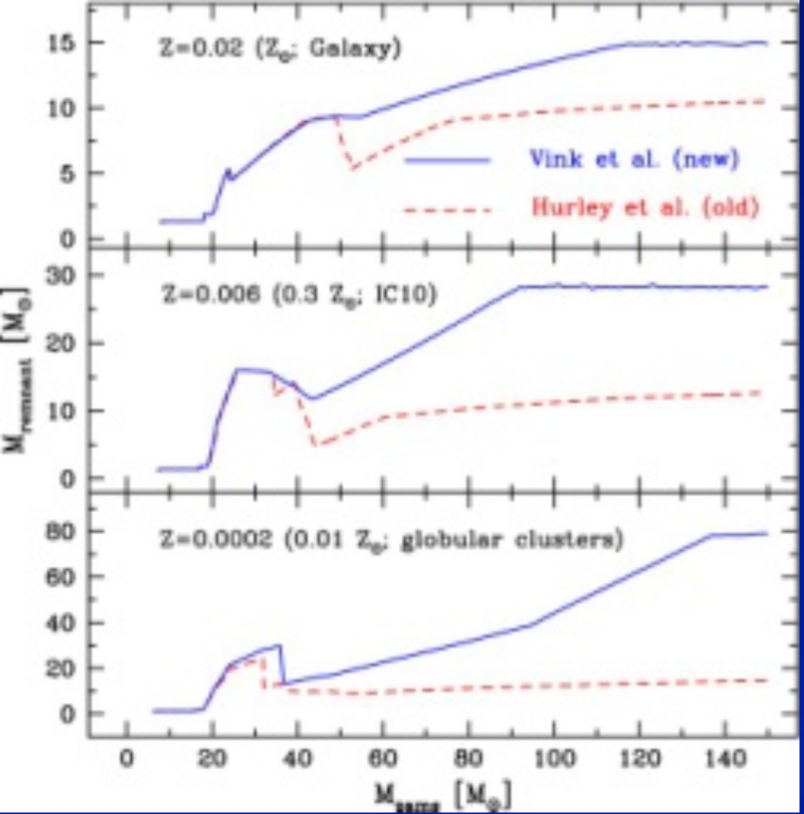
Jet power ~ a few 10^{40} erg/s ~ 10 times SS433

6. BH formation channels

- Ordinary stellar-mass BHs: easy
- Massive stellar BHs (M ~ 30—80 M_{sun}):
  possible, rare….require special conditions
- Intermediate-mass BHs:
  Pop-III remnants?
  nuclei of accreted satellite dwarfs?
  coalescence of stellar BHs in old globular clusters?
  coalescence of O stars in young massive clusters?
  recoiling (small) nuclear BHs?



Heger et al 2003
neutron star
neutron star
BH by fallback
BH by fallback (weak SN)
BH by fallback
direct black hole
no H envelope
direct black hole
direct black hole
direct black hole
low mass stars -- white dwarfs
O/Ne/Mg core collapse
iron core collapse
BH by fallback (weak SN)
direct black hole
about solar
metal-free
metallicity (roughly logarithmic scale)
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

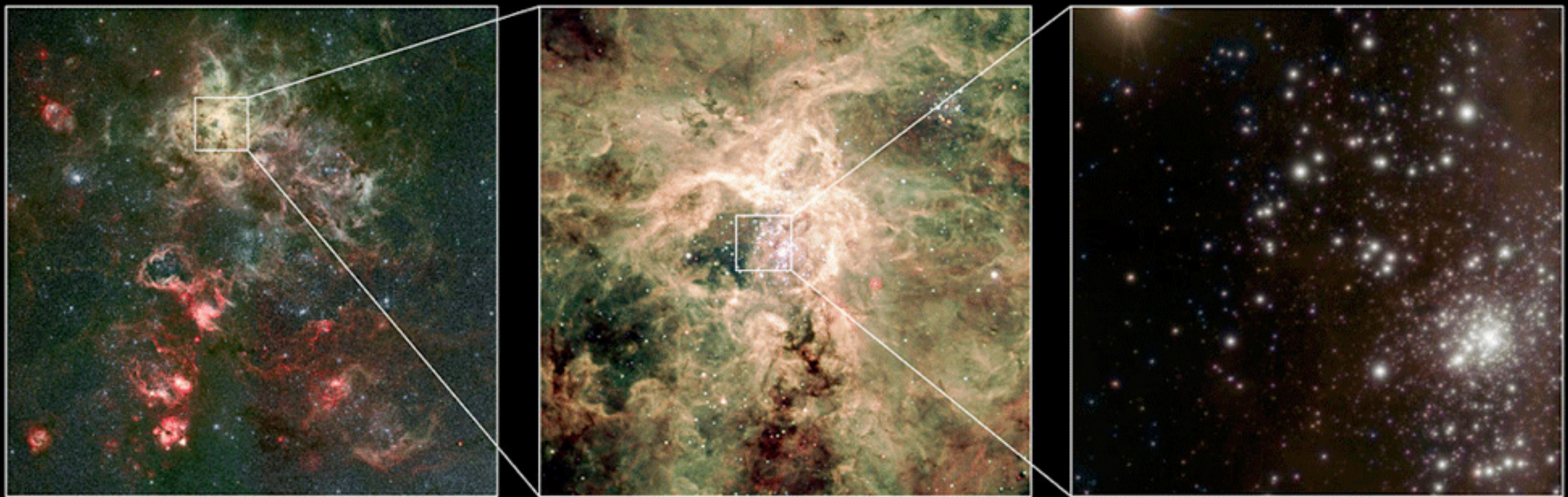


BHs with masses up to 80 M_{sun} can be formed at very low (but not primordial) metallicity

(Belczynski et al 2010)

Stars with initial masses ~ 150—300 M_{sun} do exist (eg, in 30 Doradus, LMC)

(Crowther et al 2010)



Clysung

- BH mass still very uncertain
- Almost all ULXs can be formed with
  BH masses up to 80 M_{sun},
  accretion rates <~ 10 Eddington,
  Luminosity ~ L_{Edd} x (1+ ln mdot) <~ 3 L_{Edd},
  Beaming by a factor of <~ 3
- Very few (2?) may be true IMBHs
- Outflows, slim disk or scattering corona at small radii (near ISCO)
  Standard (irradiated) disk at large radii
- State transitions are different from Galactic BHs
  Why is the high/soft state so rare?
- Mechanical power often similar to radiative power

ULX	$L_{0.3\text{-}10}$	Γ	+ soft x?	curved	HS state
M82 X1	2-10 E 40			(curved)	diskbb?
	2 E 40	1.2 +/- 0.1			
M82 X2	2-3 E 40	1.3-1.5	Y		
NGC925	2.7 E 40	2.0 +/- 0.3			
IC342 X1	2 E 40			comp / sd	
	4-6 E 39	1.6-1.8			
IC342 X2	1.7 E 40			comp / sd	
Ho IX	3 E 40	1.9	Y		
	2 E 40			comp / sd	
	1 E 40	1.6-1.8	Y		
Ho II	2 E 40	2.5 +/- 0.2	Y		
NGC1313 X1	3 E 40	2.4 +/- 0.1	Y		
NGC1313 X2	1-3 E 40	1.7-1.9	Y	sd?	
	4-6 E 39	2.0-2.5	Y		
NGC5055	2 E 40	2.5 +/- 0.1	Y		
	7 E 39	2.3 +/- 0.1	Y		
NGC4559 X1	1.5 E 40	1.8-2.1	Y		
NGC4559 X2	1 E 40	1.8-2.1	Y		
NGC1068	1.5 E 40	0.9 +/- 0.1			
NGC5474	1.3 E 40	(~1)		broken po	
NGC3628	1 E 40	1.8 +/- 0.1	Y	(comp)	
NGC5408	0.7-1 E 40	2.6-2.7	Y	(comp)	

ULX	$L_{0.3-10}$	Γ	+ soft x?	curved	HS state
NGC5775 X1	7 E 40	1.7 +/- 0.2			
	1 E 40	1.9 +/- 0.2			
NGC5775 X2	1 E 40	1.5 +/- 0.1			
NGC1365 X1	3 E 40	1.8 +/- 0.1			
	1 E 40	1.8 +/- 0.1	Y	(curved)	
	5 E 39	1.8 +/- 0.2	Y		
NGC1365 X2	4 E 40	1.2 +/- 0.1			
	1.5 E 39	1.2 +/- 0.2			
M99	2 E 40	1.6 +/- 0.1			
NGC4579	1.5 E 40	1.9 +/- 0.1			
Antennae X11	0.7-2 E 40	1.3-1.8			
Antennae X16	0.7-2 E 40	1.1-1.4			
Antennae X42	1 E 40	1.7 +/- 0.1			
Antennae X35	3 E 40	2.5 +/- 0.5			
Antennae X44	1-1.5 E 40	1.6-2.0			
Antennae X?	1 E 40	1.2 +/- 0.1			
NGC5204	0.7-0.9 E 40	2.1-2.4	Y	comp	
NGC7714	7 E 40	2.1 +/- 0.2			
	4 E 40	(2.6 +/- 0.5)	Y	comp	
Cartwheel N10	4-12 E 40	1.9 +/- 0.2		curved	
Arp240	7 E 40	1.5 +/- 0.5			