Ultra-Luminous X-ray sources and Intermediate Mass Black Holes

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What is an ULX ?

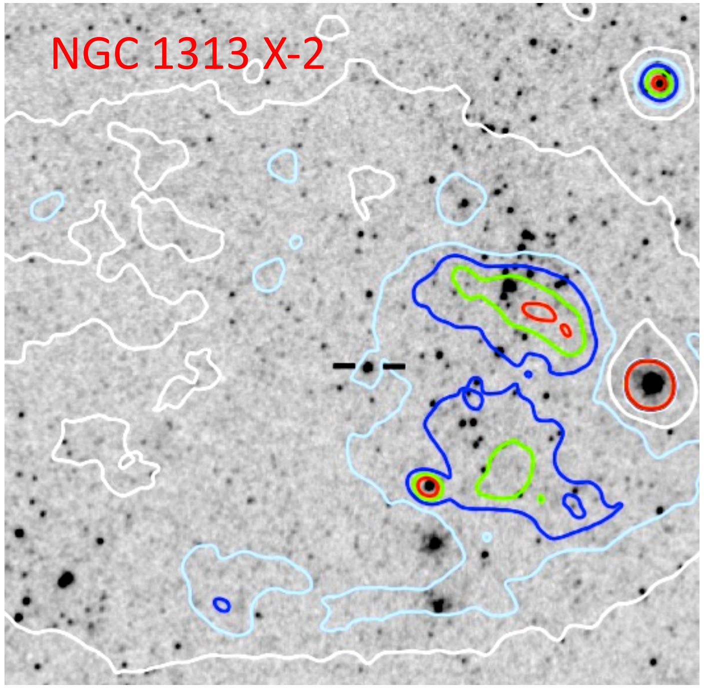
- ULXs defined as non-nuclear unresolved X-ray sources with isotropic Lx ≥ 10^{39} erg s^{-1}
  - Lx higher than that of stellar mass Galactic black holes (peak Lx of ~ 10^{39} erg s^{-1})
  - Lx higher than Eddington luminosity of a typical 10 $M_\odot$ black hole

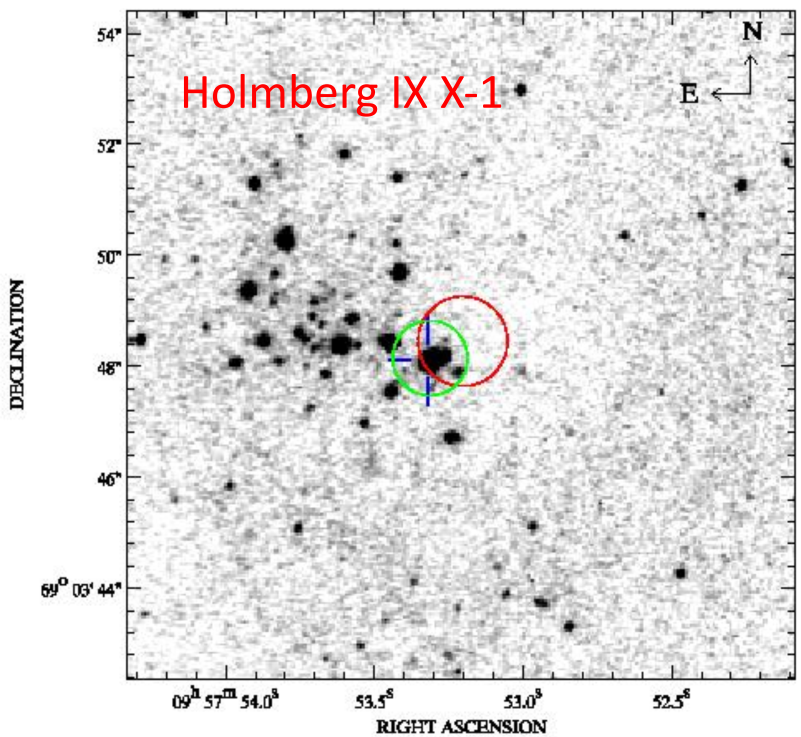
- In practice Lx = 10^{39} -> few 10^{40} erg s^{-1}

  with a couple of outstanding cases…

Stellar environment

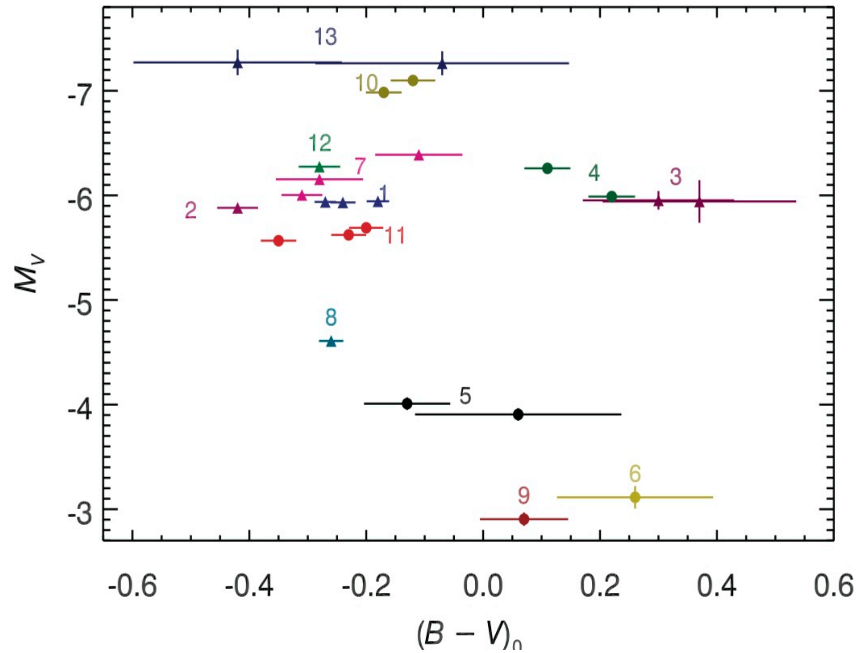
- ULX mostly located in non-elliptical galaxies
- Do not correlate with massive (M > 10^5 M$\odot$) young star clusters (Swartz+2009)
- Often associated with relatively loose star clusters (or OB associations) with:
  - masses of a few 10^3 M$\odot$
  - ages in the range of 10 -20 Myr (Grisé+2008, 2011)





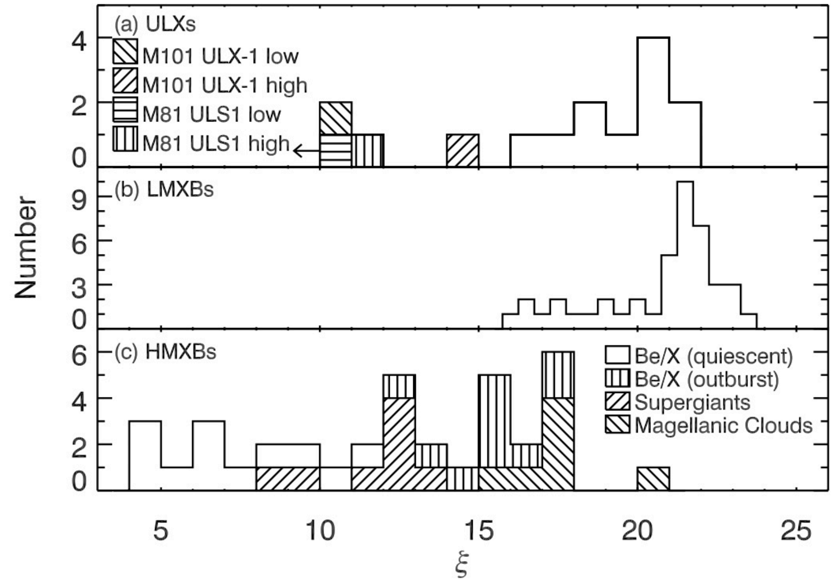
Optical counterparts

- About 13 confirmed optical counterparts (e.g. Tao+2011):
  - faint m> 23 objects (but see below)
  - mostly blue stars, with colours consistent with those of early type stars
  - Mv suggesting giant stars



- Lx/Lopt typical of Low-Mass X-ray Binaries
  - Optical emission dominated by X-ray heating

- Usually strong and random optical variability



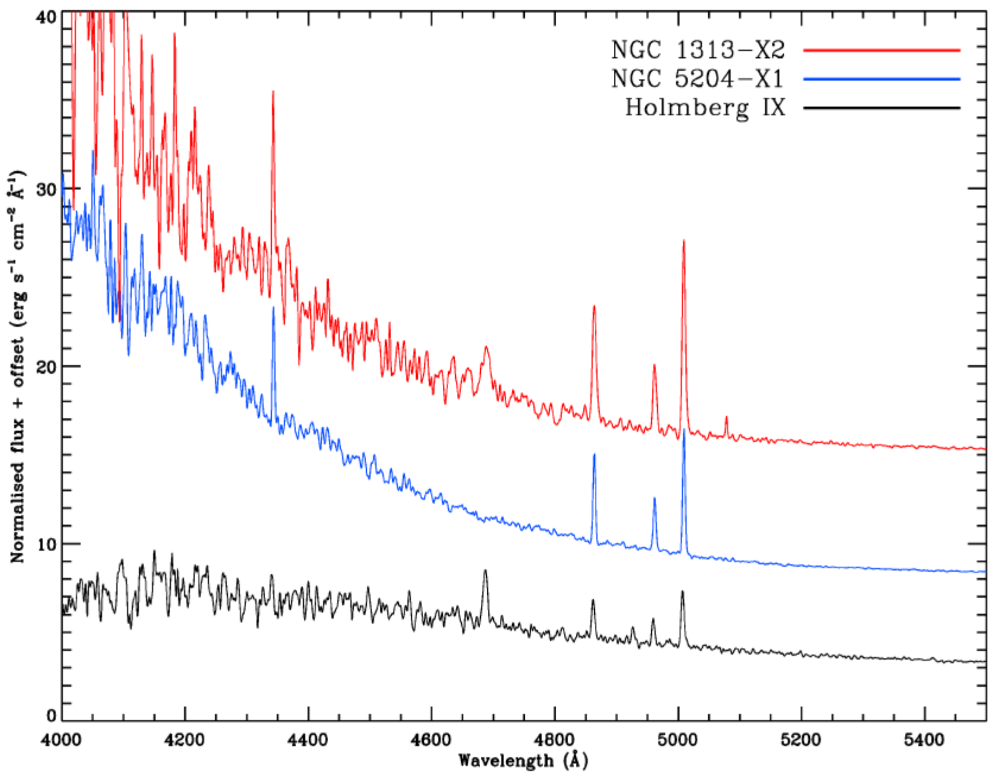
Tao+2011

Optical spectra

- Blue continuum
- HeII in emission, broad and variable profile
- Balmer + other lines sometimes hard to disentangle from nebular emission
- No stellar absorption lines (but see below)
- No periodicity in HeII radial velocities (Roberts 2011)

⇒ *No dynamical BH mass*

Field crowding + nebulae makes observations challenging



Roberts 2011

Powering an ULX

- Use a stellar mass BH ($M \leq 100\ M_\odot$) in super critical accretion regime and/or with beamed radiation:

$$L \approx \frac{1.3 \times 10^{38}}{b}\left(1 + \frac{3}{5}\ln \dot{m}\right)\left(\frac{M}{M_\odot}\right)\ \mathrm{erg\ s^{-1}}, \quad 1 \lesssim \dot{m} \lesssim 100$$

$\dot{m} = \dot{M}/\dot{M}_{Edd}$ $\quad$ b = beaming factor (Poutanen+2007)

Strong beaming unlikely (X-ray ionized nebulae)

May reach $L_x \sim 10^{41}$ erg/s in extreme cases…

Maximum Masses of Stellar Black Holes

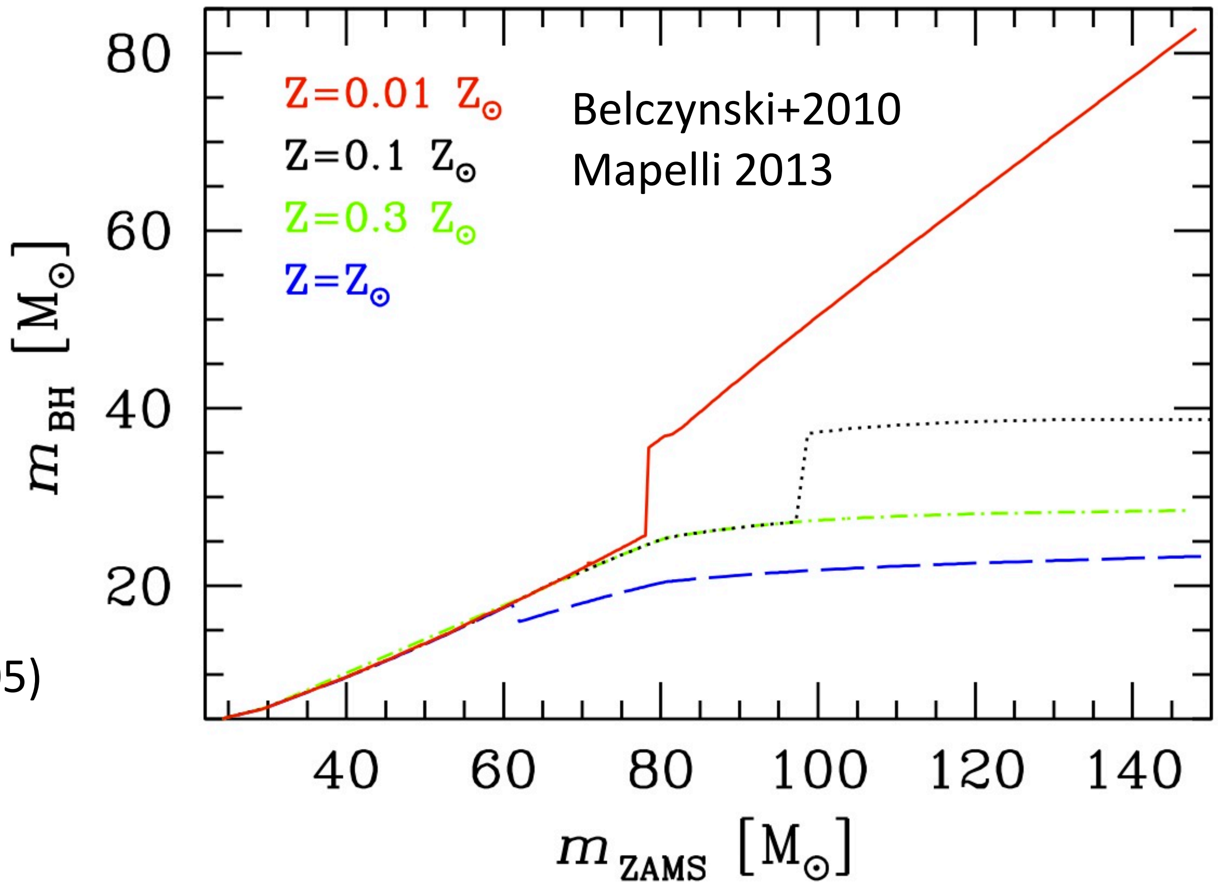
Black holes as massive as ~ 80 $M_\odot$ may be formed at low metallicities

Record breakers:

GRS1915-105: 14+/-4 $M_\odot$
(Greiner+2001)

Cyg X-1: 10-25 $M_\odot$
(Herrero+1995; Ziolkowski+2005)

IC 10 X-1: 23-34 $M_\odot$
(Prestwich+2007) (Z ~0.3 $Z_\odot$)



Powering an ULX

- Use an intermediate mass BH (M ~ 10 $^{2\text{-}4}$ $M_\odot$) in « normal » sub-Eddington regime

$$L \approx \frac{1.3 \times 10^{38}}{b} \dot{m} \left(\frac{M}{M_\odot} \right) \mathrm{erg\ s^{-1}}, \qquad \dot{m} \lesssim 1$$

Astrophysical importance of ULXs

- Stellar mass BHs:
  - what make them different from Galactic BHs ? Evolutionary paths (apparently) not seen in the Milky Way ?
  - laboratories to study accretion/ejection physics at near or super Eddington accretion rates.
- IMBHs:
  - Remnants of BH seeds that through accretion or merging created the super massive BHs in the early universe.
  - constrain formation mechanism (extreme environment, low Z).
- Study wind and jet feedback from accreting black holes

Distinguish between stellar and intermediate mass BHs

- Stellar-mass black holes:
  - ULX parent clusters too poor to generate IMBHs (but could be captured)
  - Undergo (super) Eddington accretion. Spectral behaviour at variance with that of galactic (sub-Eddington) BHs

- Intermediate mass black holes candidates:
  - High X-ray luminosities (Lx > few 10^{41}erg/s)
  - Spectral states similar to those of galactic BHs (ie sub-Eddington)

"Canonical" BH accretion states

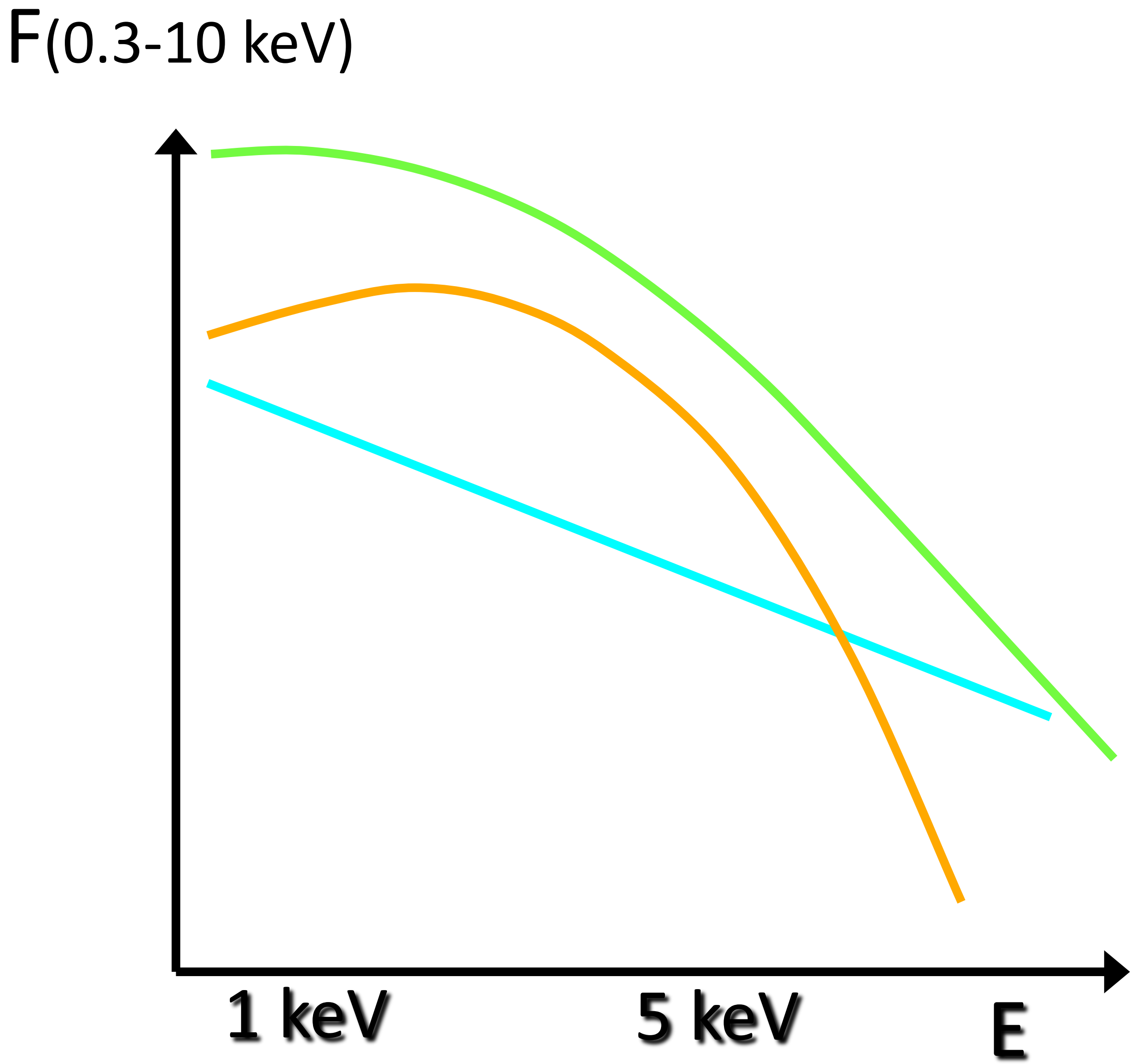
(From the 1980s… eg, Cyg X-1, GX339-4)

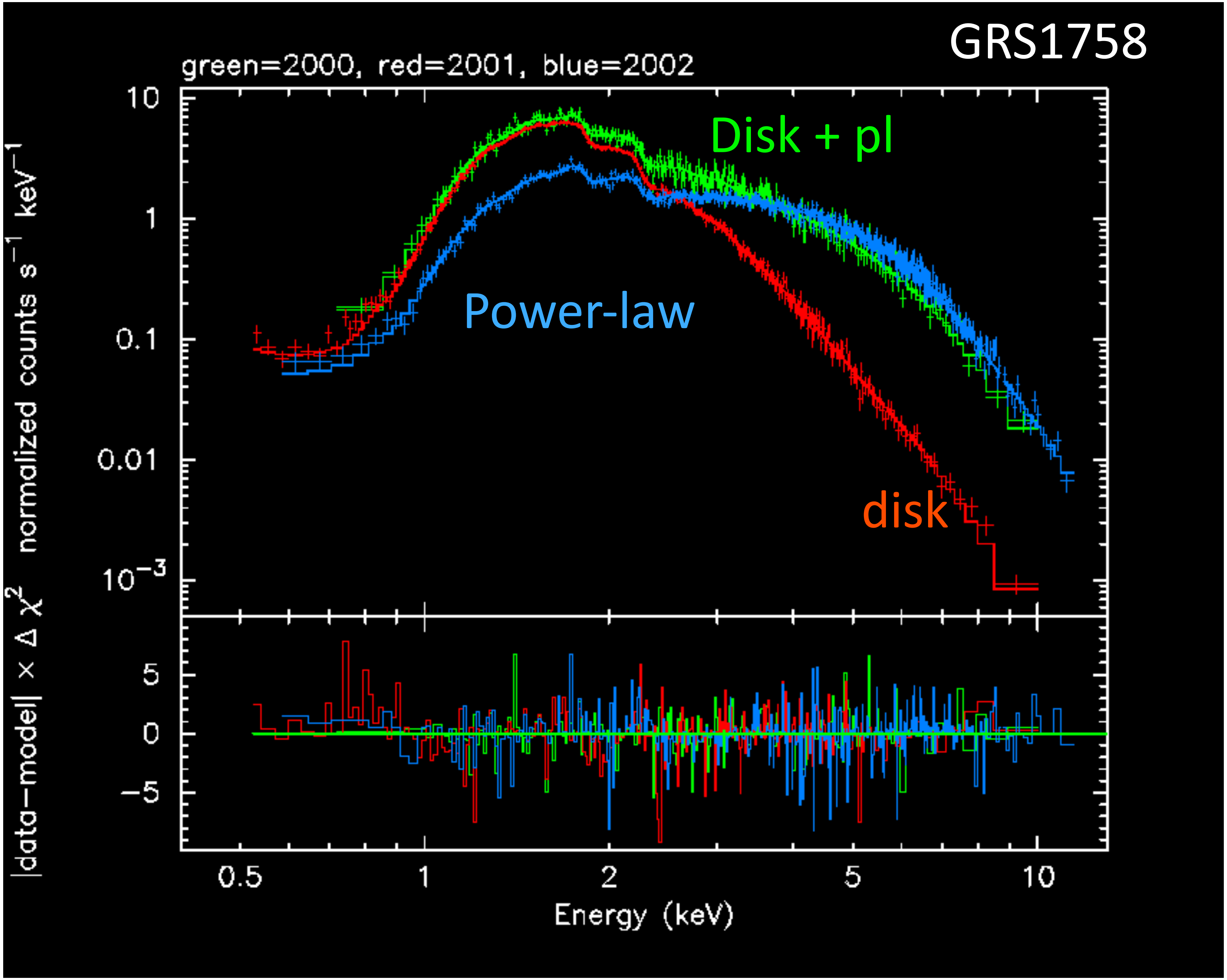
$\dot{m}$

1 — Very high state
Comptonized disk
Radio flaring

0.1 — High/Soft state
Standard disk
Radio quiet

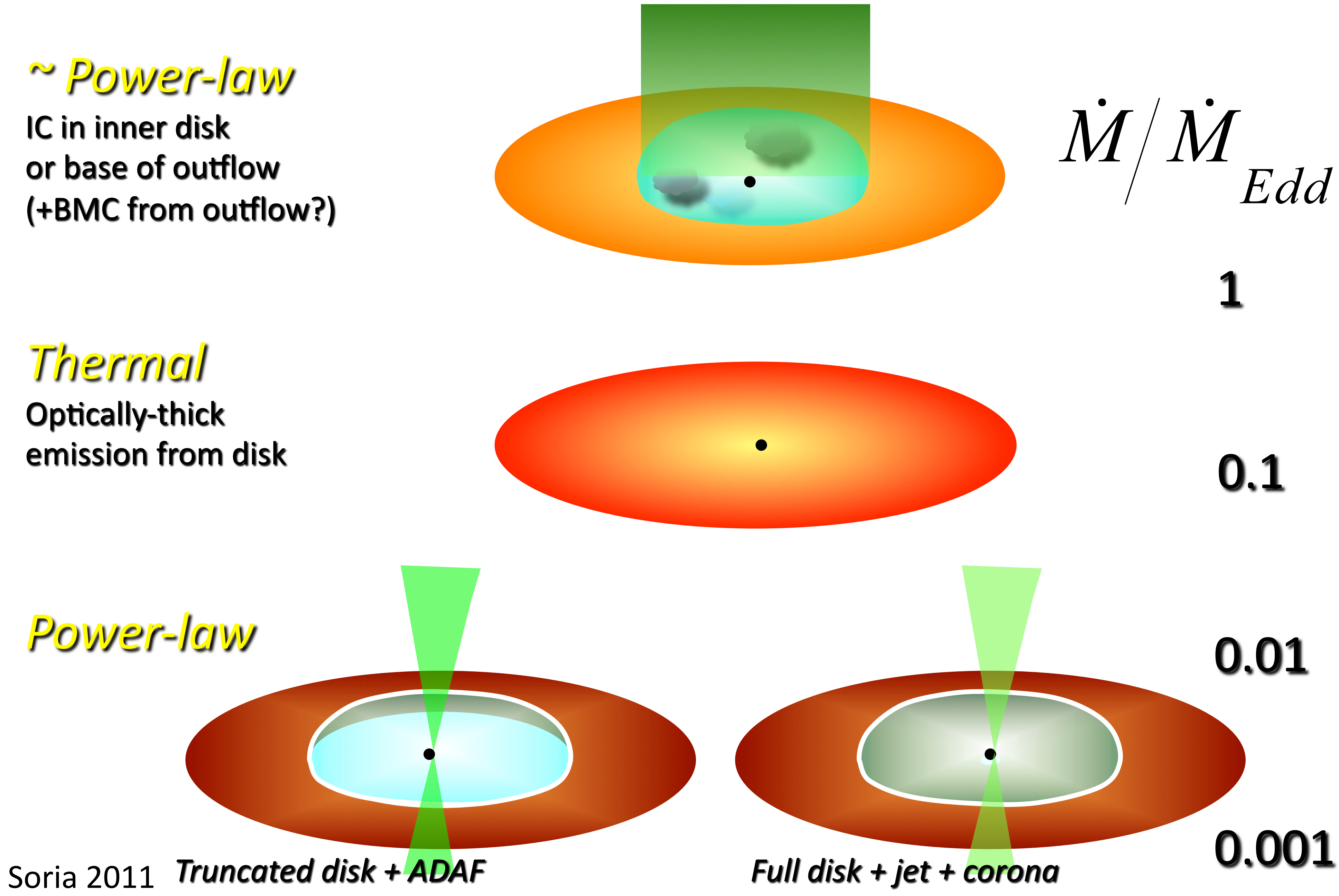
0.01 — Low/Hard state
Jet? Corona?
ADAF?
Radio loud




GRS1758
green=2000, red=2001, blue=2002
Disk + pl
Power-law
disk
normalized counts s^{-1} keV^{-1}
|data−model| × Δ χ^2
Energy (keV)
10
1
0.1
0.01
10^{-3}
5
0
−5
0.5
1
2
5
10

(Hao+2011)

"Canonical" BH accretion states



High/soft state = disk-blackbody spectrum

$$L_{disk} \approx L_X <\sim L_{Edd} \approx 10^{38} M_{BH} \text{ erg/s}$$

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

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

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

In the high soft/state disc extends to the last stable orbit

$$T_{in} \approx (L/L_{Edd})^{1/4} M_{BH}^{-1/4}$$

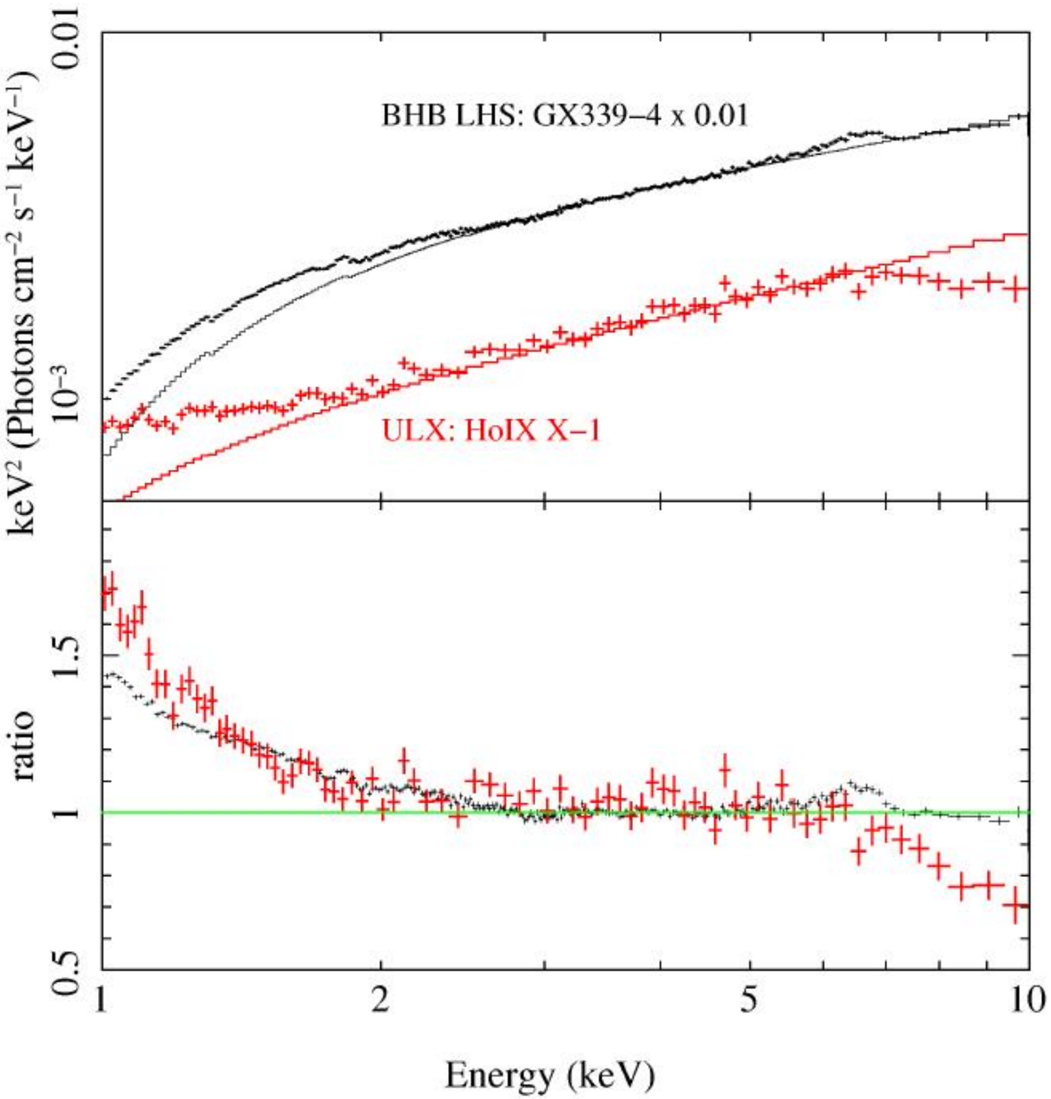
➡ **High/soft states can be used to estimate BH mass**

Soria 2011

ULX X-ray spectra

- Phenomenology in two groups (Makishima 2007):
  - "Simple" power law energy distributions with a broad Γ distribution (1-3) peaking at $\Gamma \approx 1.8$-2.0
  - "Complex" spectra showing a soft excess and a high energy break at $E \approx 5$ keV
- Some ULXs display transitions between "simple" (low Lx) and "high energy break" spectra (high Lx) (e.g. Kubota+2001)
- A few show transitions similars to those of (sub-Eddington) Galactic BHs

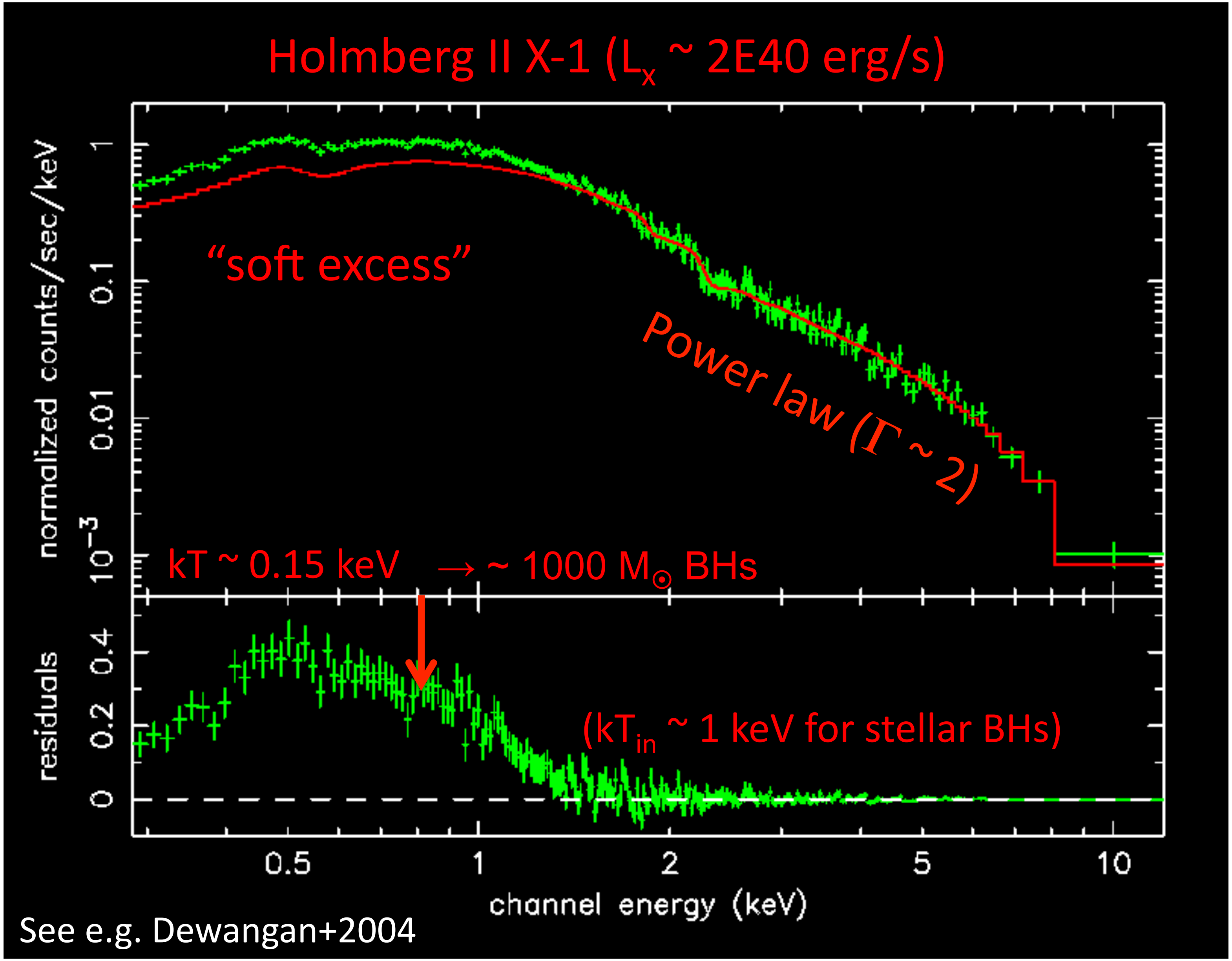
“Complex” spectra



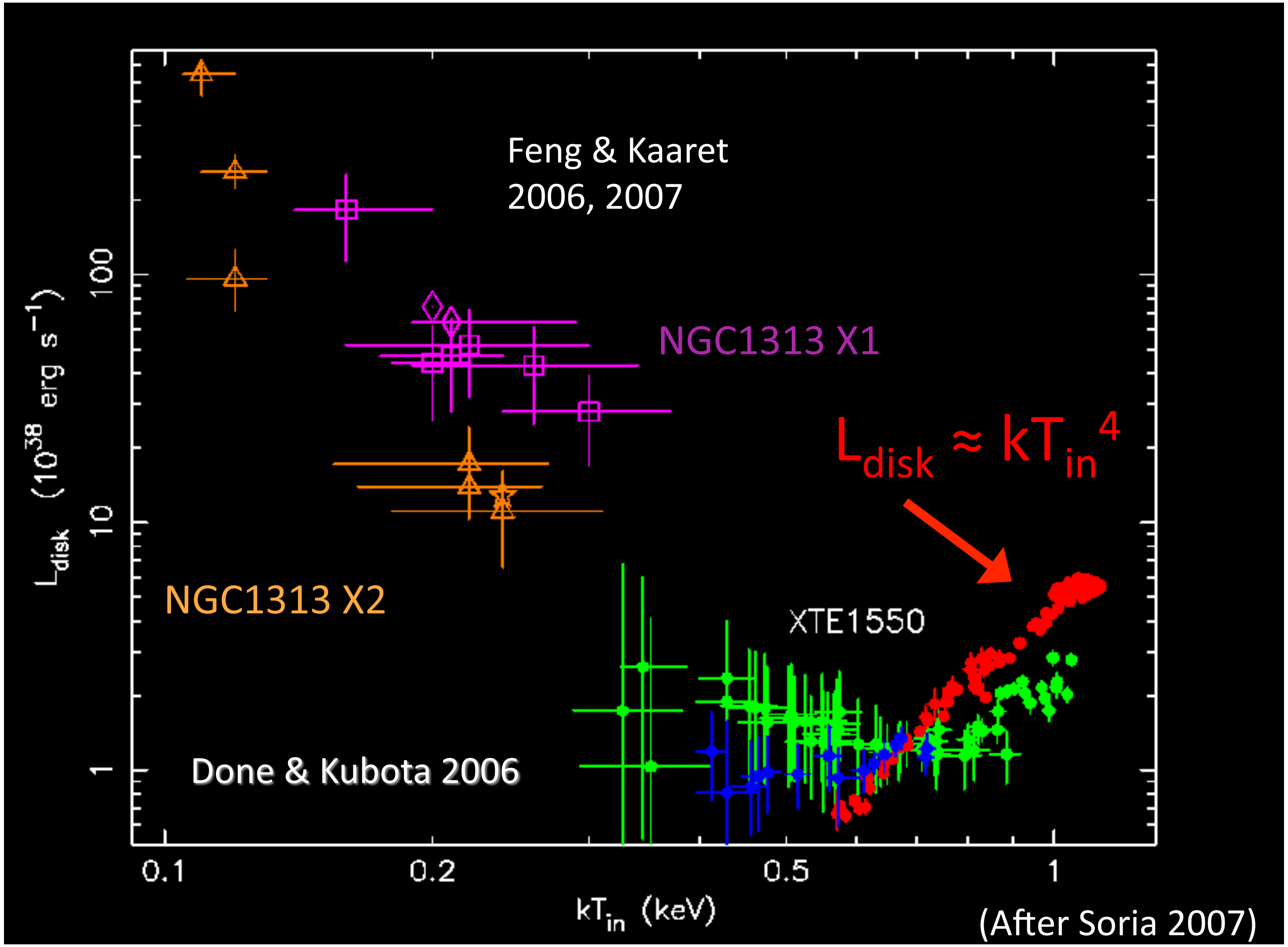
- X-ray state not seen in Galactic BHs ($L_X<L_{Edd}$)
- Identified as a new “Ultraluminous” state (Roberts 2007, Gladstone+2009)

(Roberts 2007)

Soft excess and disk emission



- L disk ~ kT_{in}^{4} in standard Shakura & Sunyaev accretion disk
- L disk ~ $kT_{in}^{-3.5}$ in some ULXs -> The observed disc radius is likely at boundary with an inner corona / outflow

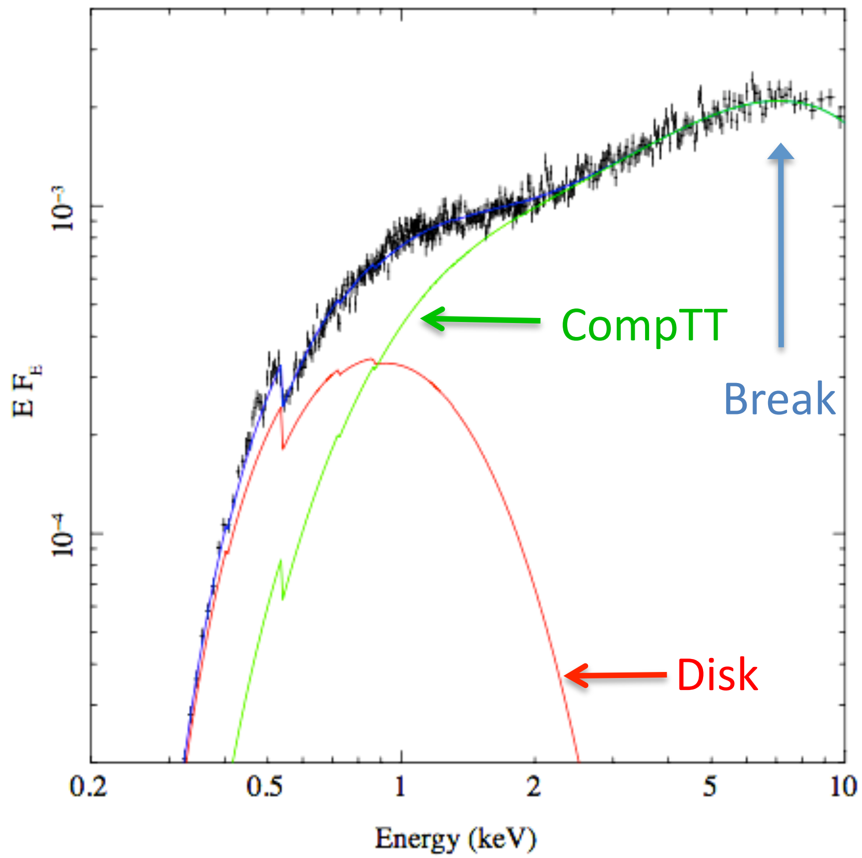


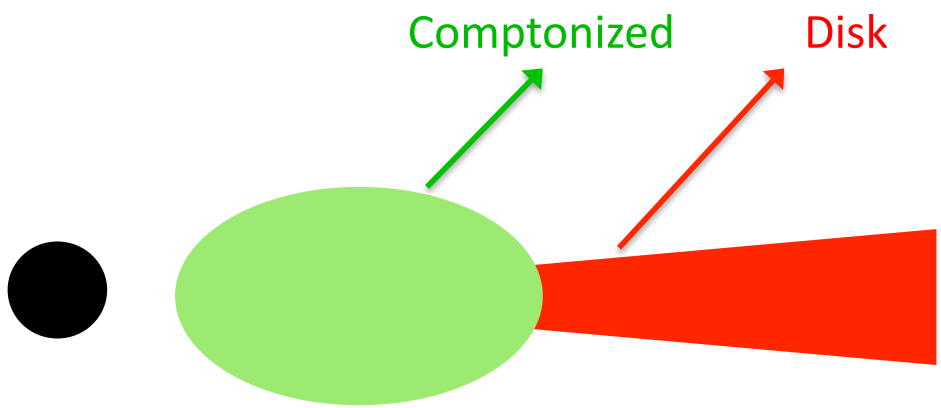
High energy spectral break

A common feature in high S/N spectra.

Main contender: Comptonizing corona
(Stobbart+2006, Gladstone+2009)

- kT_e ~ 1-3 keV
- τ ~ 6 – 80
- T_{max} disk ~ 0.2-0.3 keV





(After Gladstone 2011)

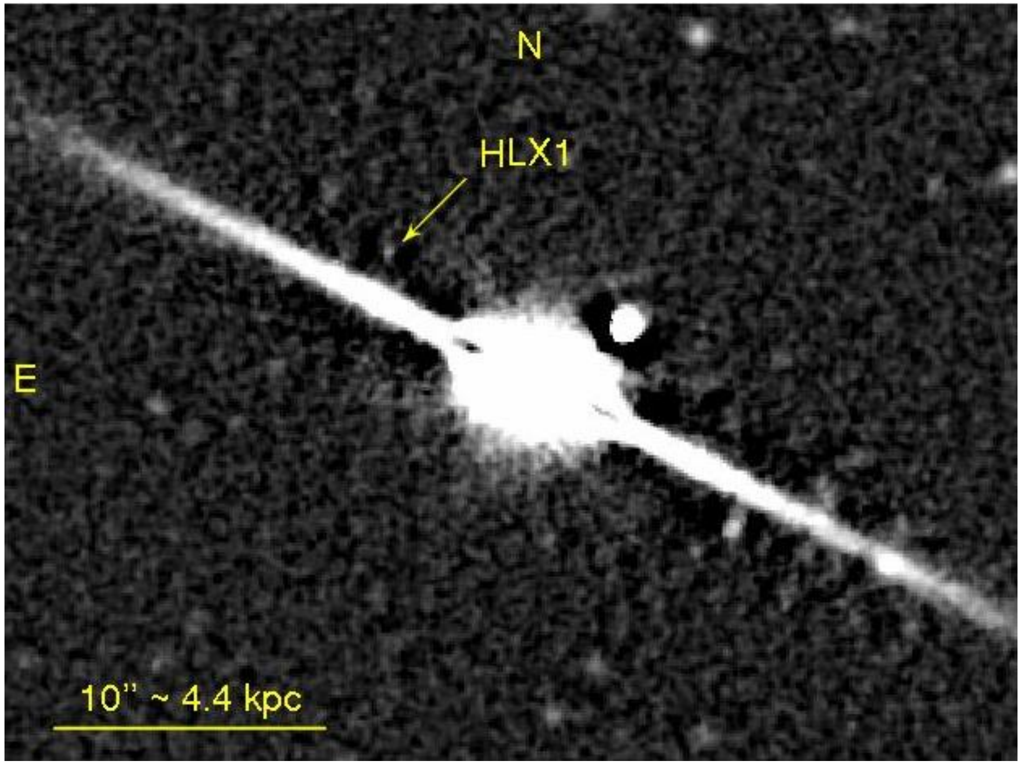
ULX X-ray spectra – a summary

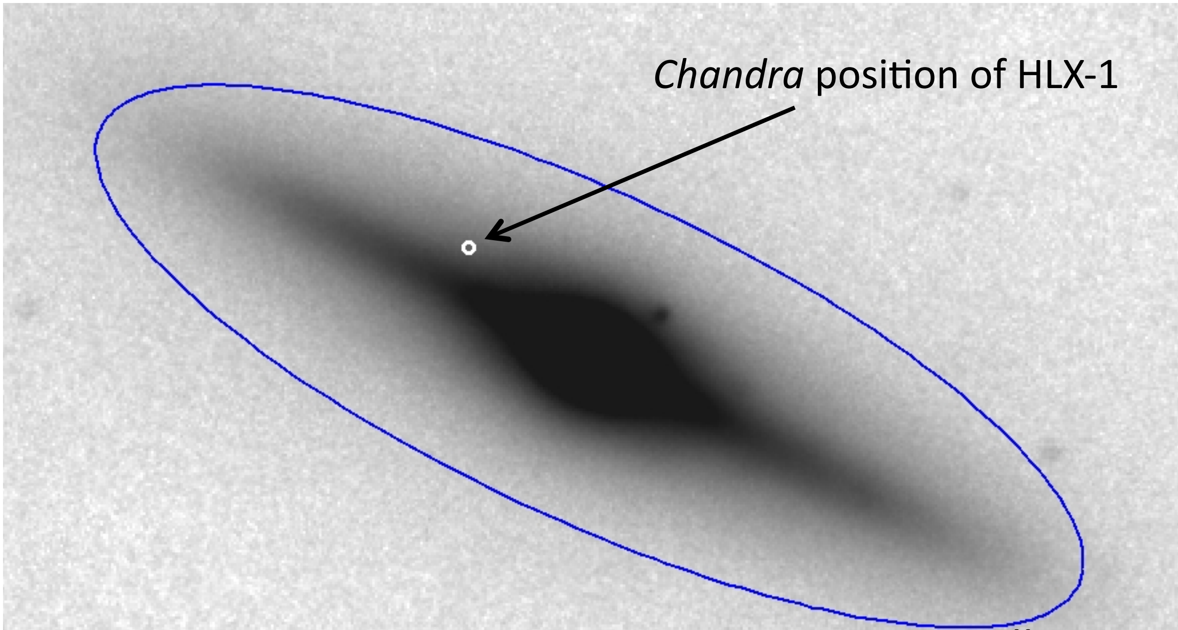
- P13 + environment + X-ray spectral properties favour near to or super Eddington accretion and ordinary ($M < 20\ M_{\odot}$) or massive ($20\ M_{\odot} < M < 100\ M_{\odot}$) stellar mass black holes.
- **However**, some ULXs display typical BH hard/soft transitions (M82 X-1; HLX-1) and low kTin indicating sub-Eddington regimes and hence the likely presence of an IMBH.

ESO 243-49 HLX-1
Best IMBH candidate

- HLX-1 coincident with edge-on S0a spiral galaxy ESO 243-49 at ~100 Mpc
- At galaxy distance, $L_x \sim 10^{42}$ erg/s in the 0.2 – 10 keV band

Farrell+2009

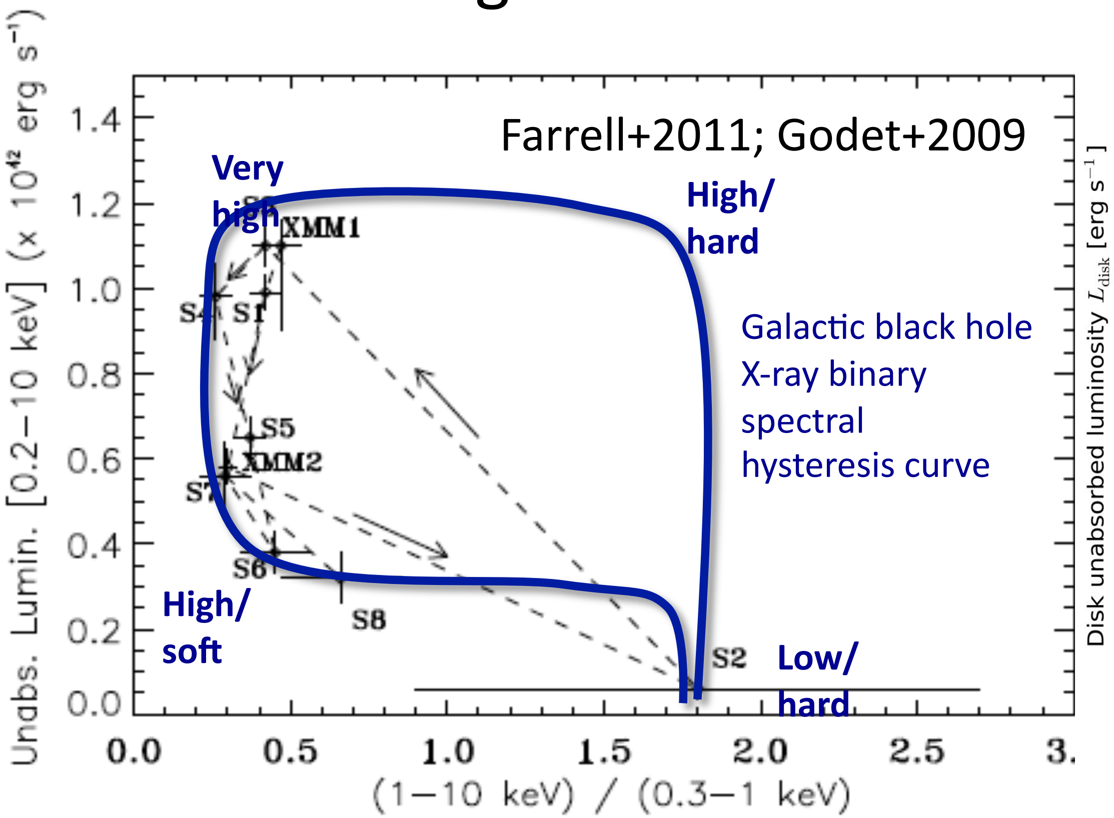


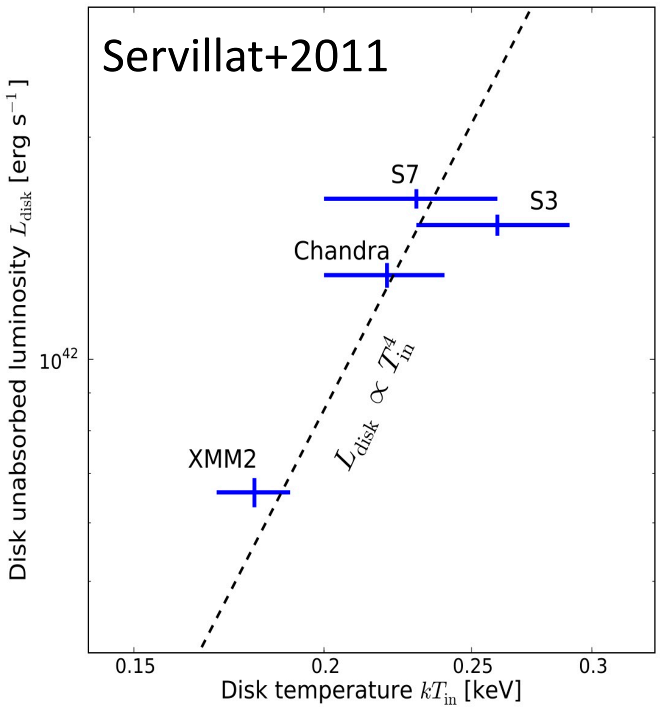


Magellan J-band image of ESO 243-49 Farrell+2010

ESO 243-49 HLX-1

Displays X-ray state transitions similar to sub-Eddington Galactic BH



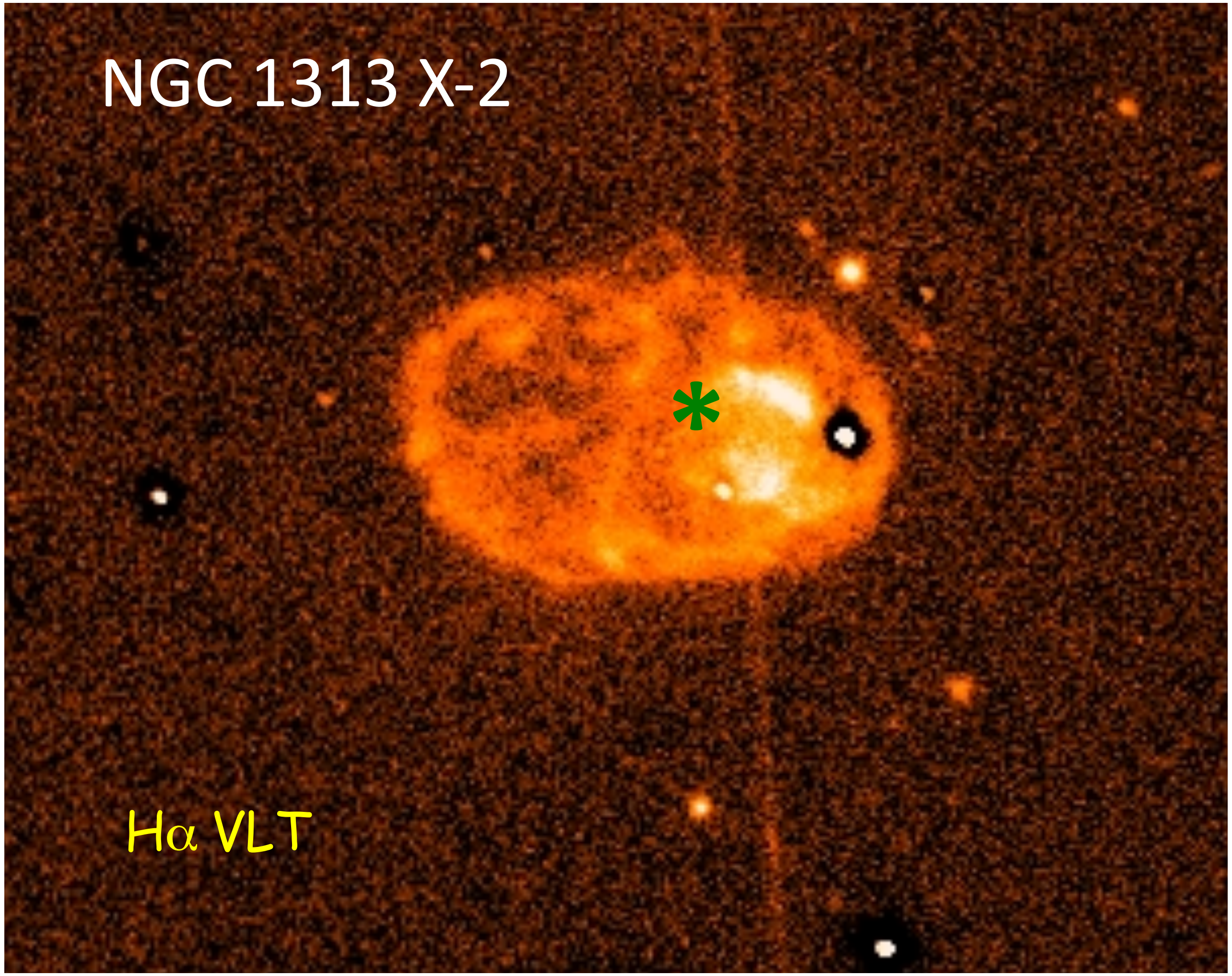


If indeed sub–Eddington then MBH ~ 9000 $M_\odot$

(conservative limit of 500 $M_\odot$ if 10xEddington)

ULX bubbles, jets & micro-quasars

See also F. Mirabel's talk on Saturday



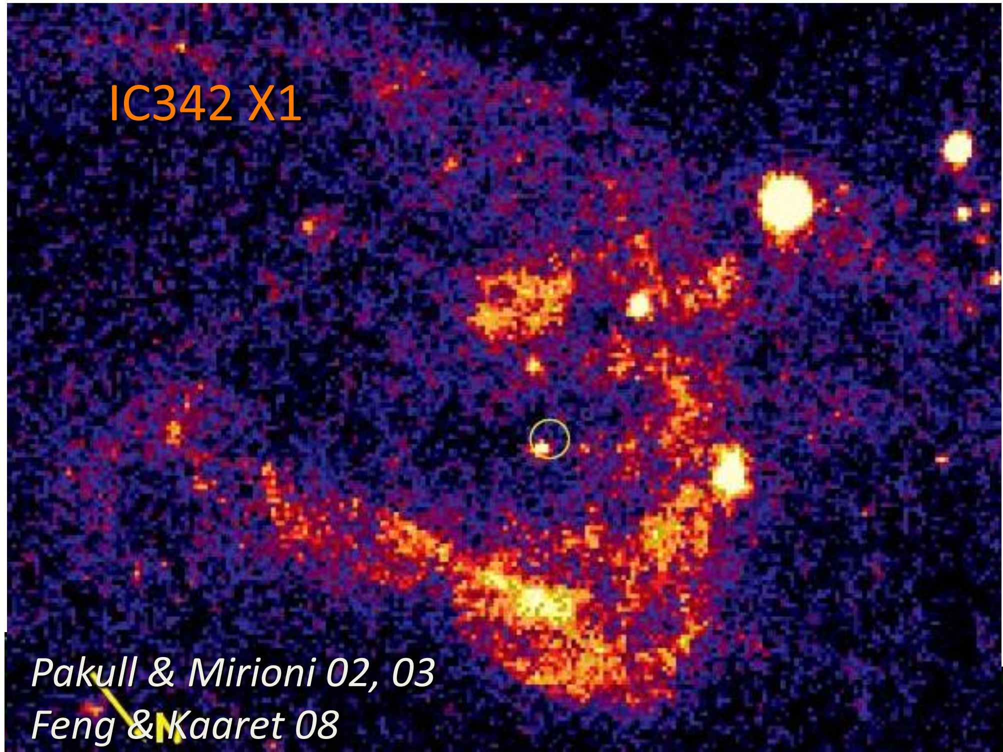
Pakull & Mirioni 2002, Pakull+2006

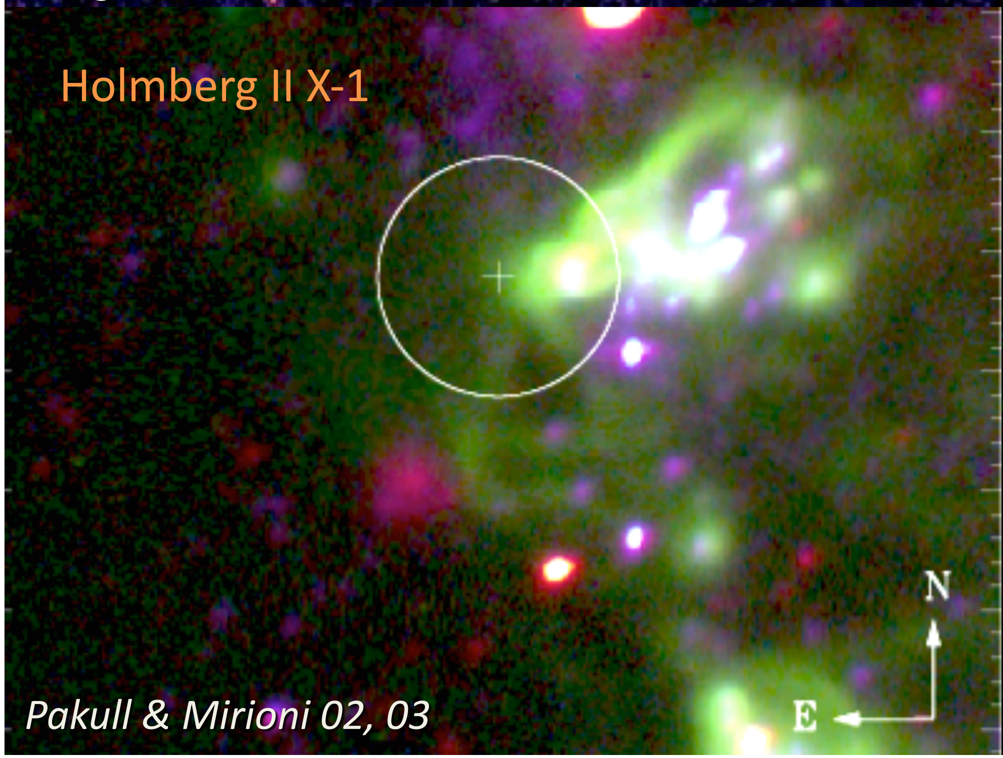
Bubble diameter
~ 26'' = 400 pc (!)
(much larger than any SNR)

Optical spectra: shock ionised

Vs ~ 100 km/s

ULX bubbles


IC342 X1
Pakull & Mirioni 02, 03
Feng & Kaaret 08


Holmberg II X-1
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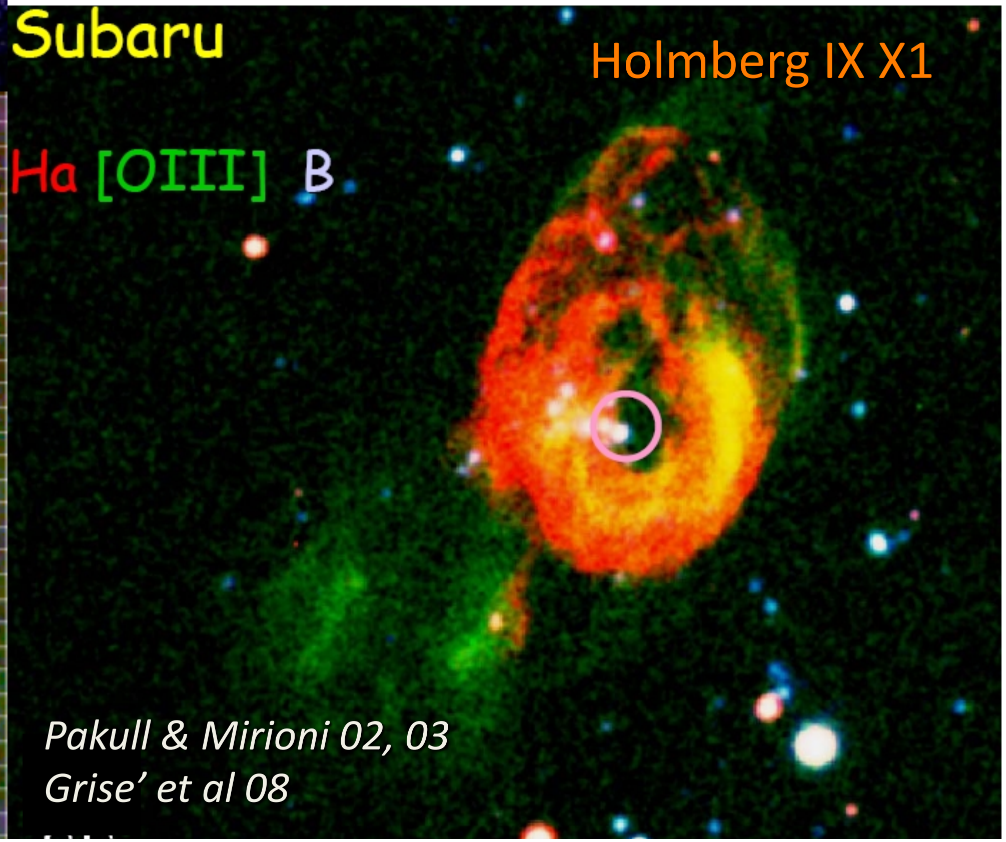
Pakull & Mirioni 02, 03


Subaru
Holmberg IX X1
Ha [OIII] B
Pakull & Mirioni 02, 03
Grise' et al 08

ULX bubbles, jets & micro-quasars

About 25% ULX blow observable bubbles.

The largest ones are most probably shock-ionized nebulae with $E >\sim 10^{52}$ erg, $d >\sim 100$ pc and $V_{exp} = 80 – 150$ km/s (highly supersonic)

Wind/jet driven bubble with power Lw (Weaver+1977*)*

$R = 0.76 \, (L_w/\rho)^{1/5} \, t^{3/5}$; $t = 3/5 \, R/v$

$L_w = 5 \, 10^{39}$ erg/s $R_{100}{}^2 \times v_{100}{}^3 \times n \approx Lx$!

$t \sim 10^6$ yrs**; Lw~10^39-40 erg/s ~ Lx (ULX)** ; $E_o \sim 10^{53}$ erg/s

(Pakull & Mirioni 2002; Pakull & Grisé 2006)

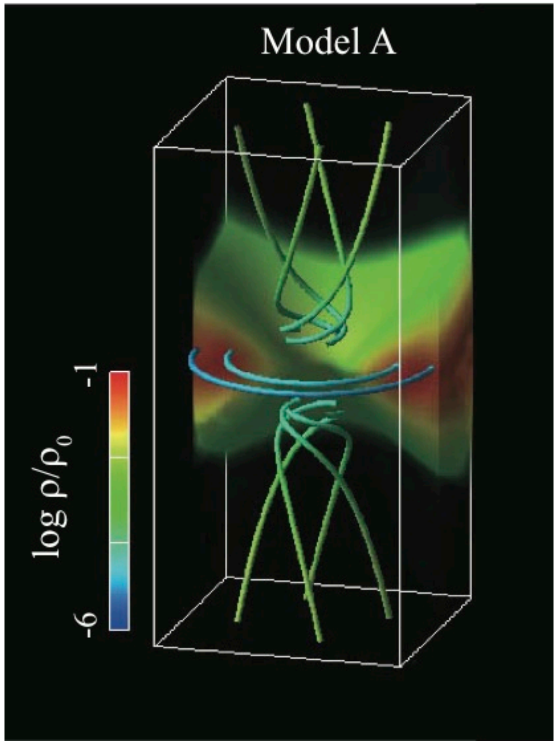
(super) Eddington sources may thus generate highly energetic outflows with mechanical luminosities comparable to those emitted by BH jets (sub Eddington hard state)

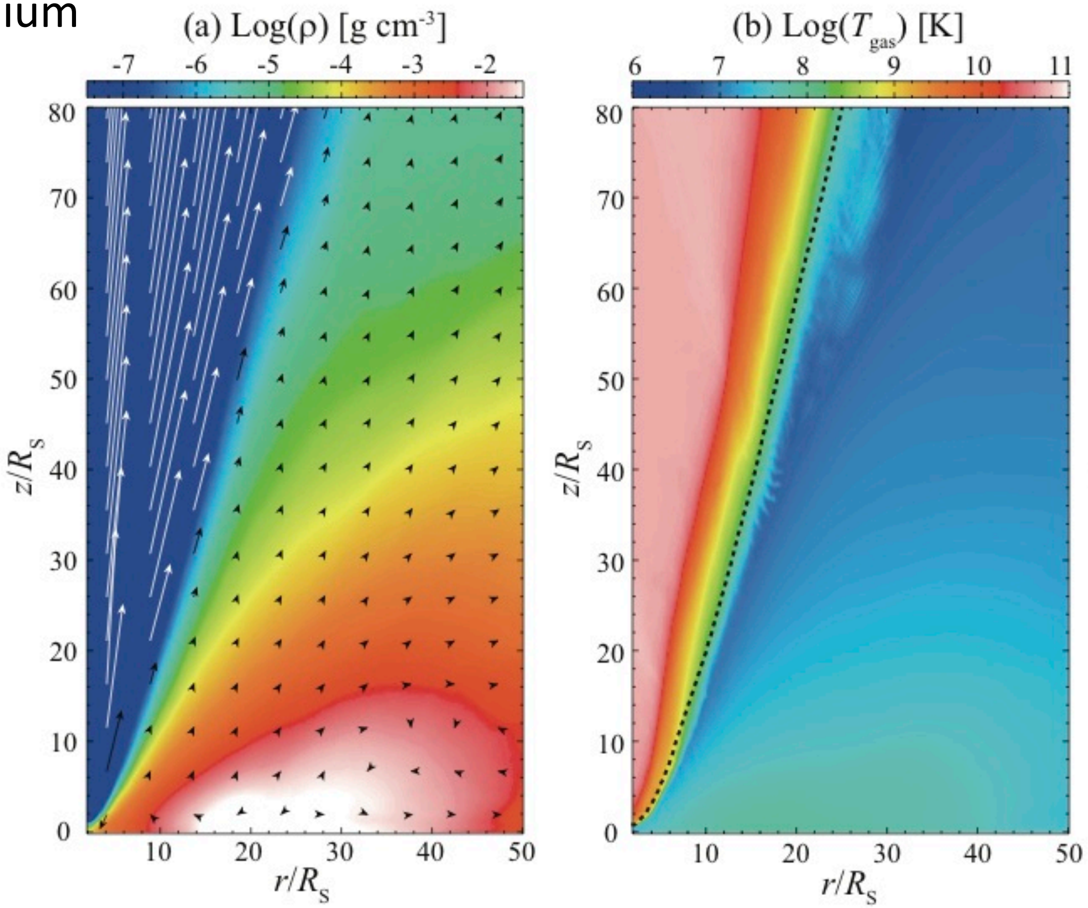
MHD models of super Eddington accretion

Ohsuga+2009/2011

Super Eddington accretion rates

- Geometrically thick disk supported by radiation pressure
- Mild radiation beaming
- High velocity (≈0.25c) collimated and hot outflows ($L_{kin} \approx 0.2$ L)
- Lower velocity dense and cooler disk winds
- Strongly Comptonizing medium



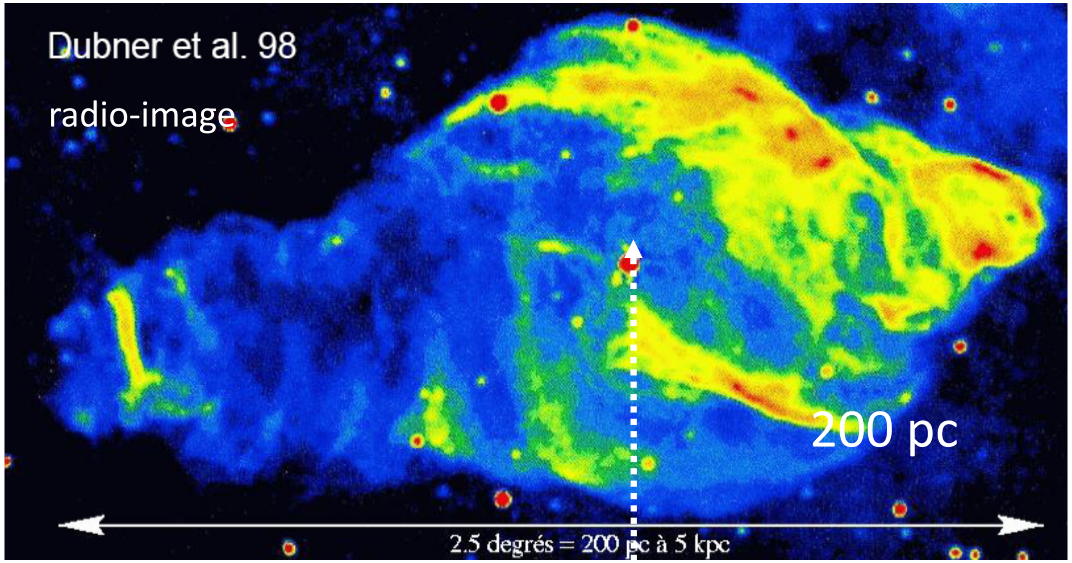


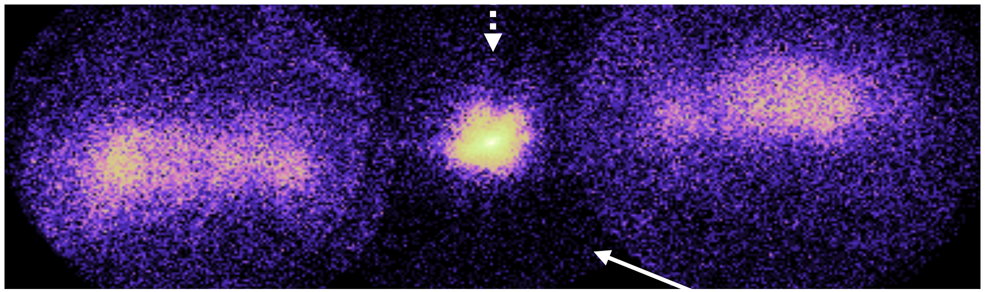
ULX related sources: µQSO SS433 in our Galaxy

- Weak central X-ray source Lx ~ 10^{36} erg/s, v = 0.26c precessing jets (162.5d)
- Radial velocity curve favours a low mass BH
- Mechanically inflated bubble W50 with ‘ears’ due to $L_{mech} = L_J \sim 10^{39}$ ergs

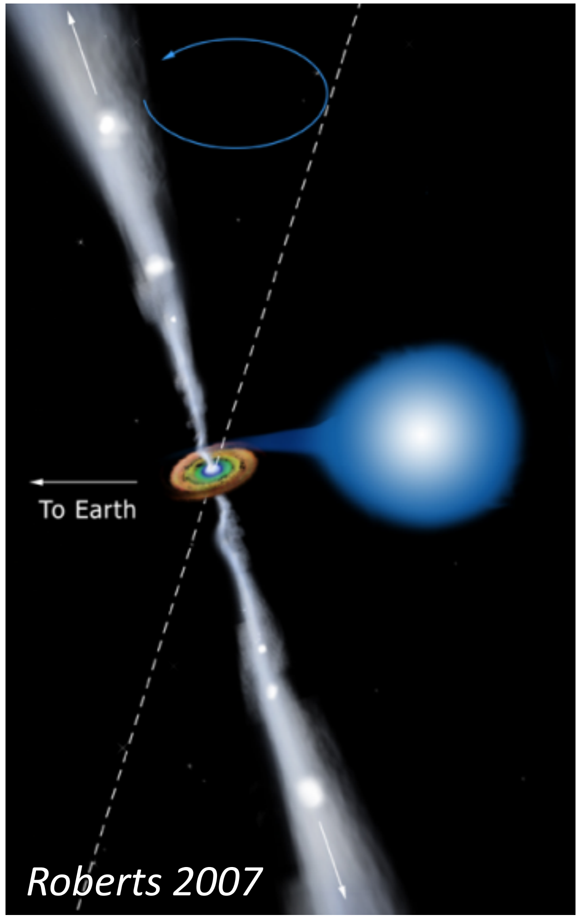
=> SS433 is super-critically accreting

- Would be an ULX if seen face on ? (Begelman+2006, Poutanen+2007)





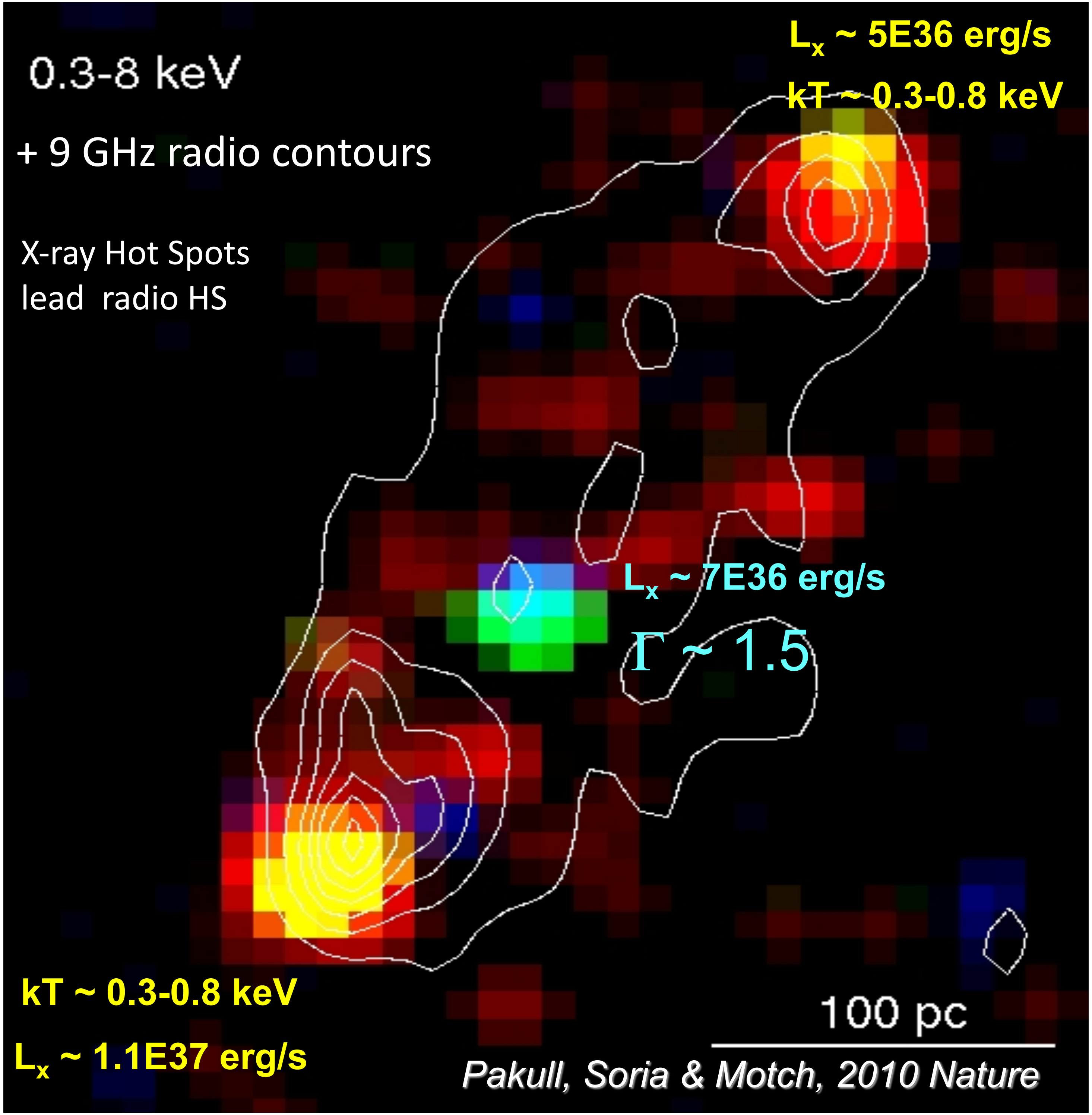
ASCA image (Kotani 1998)



S26 in NGC 7793

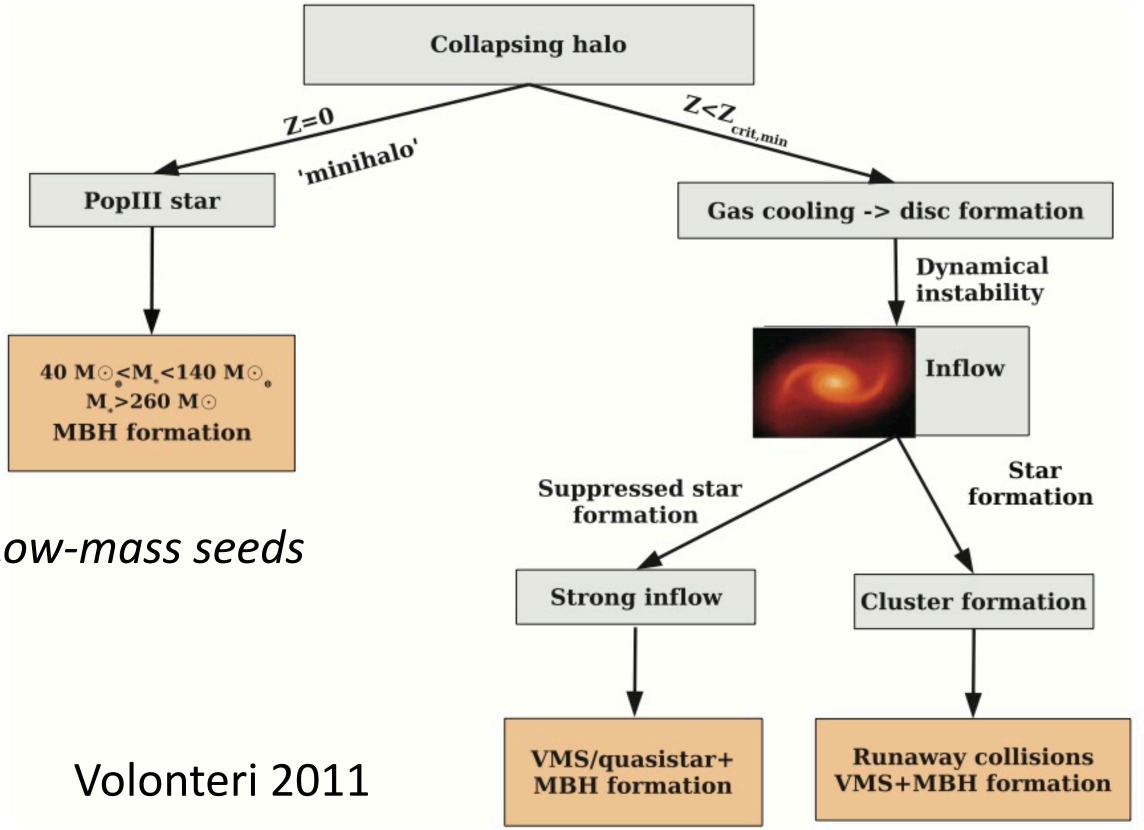
- V_{exp} ~ 250 km s^{-1}
- Linear size ~ 2.5 that of SS433/W50
- Jet power ~ a few 10^{40} erg/s (>> L_{Edd} of accr. BH)
- Age ~ 2 x 10^5 yrs
- Low persistent X-ray luminosity Lx = 7 10^{36} $ergs^{-1}$
- Total energy E ~ 10^{53} erg

Are SS433 & S26 shielded ULXs or “Ultrapowerful sources” (UPSs) ?
(Feng & Soria 2011).



Origin & role of IMBH

- Super massive BH of ~ $10^9\, M_\odot$ already in place in the 1 Gyr old universe.
- Requires Eddington mass accretion rates during 0.5 Gyr for a BH seed mass of $10^2 – 10^5\, M_\odot$.
- Merging may also play a role (test by gravitational waves)
- There could be a lot of "fossil" IMBHs floating around in galaxy clusters, no longer surrounded by a visible galaxy (stripped, ejected, primordial?)



Low-mass seeds

Volonteri 2011

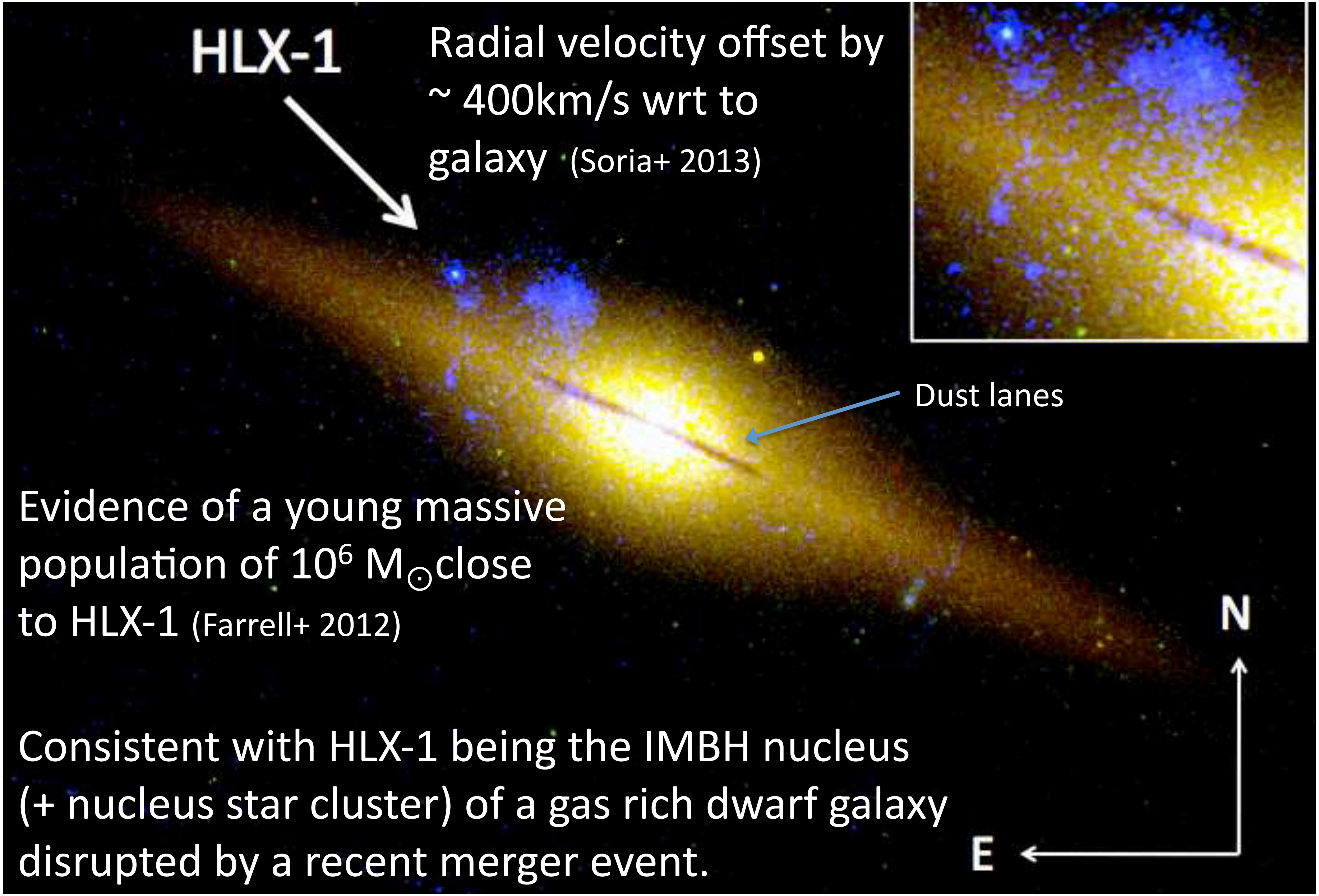
High-mass seed

See reviews in Volonteri 2010 & Greene 2013

See F. Mirabel's talk on importance of BHB for reionization

Latest news from HLX-1

Mapelli+ 2013

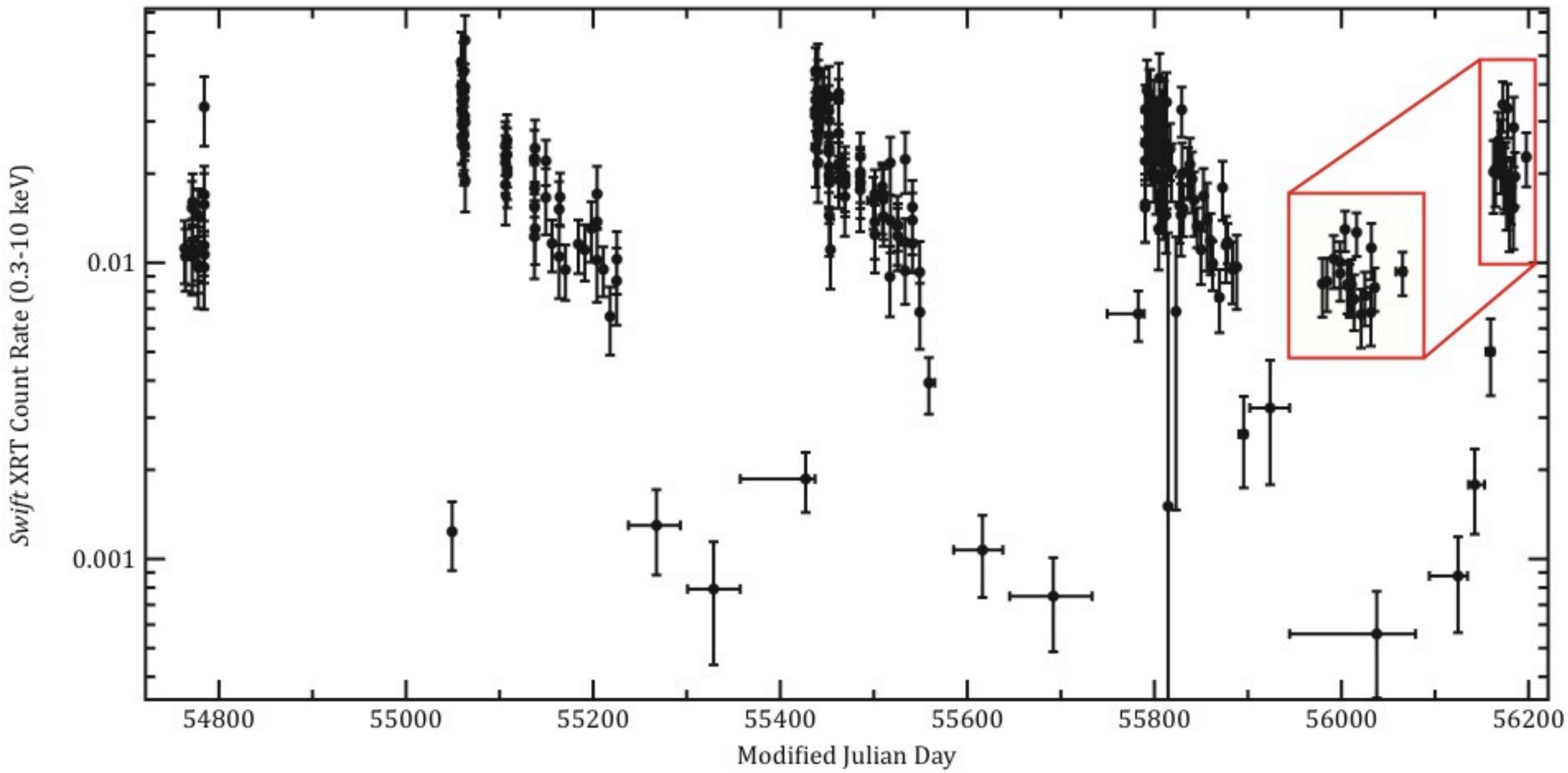


Radial velocity offset by ~ 400km/s wrt to galaxy (Soria+ 2013)

Evidence of a young massive population of 10^6 $M_{\odot}$ close to HLX-1 (Farrell+ 2012)

Consistent with HLX-1 being the IMBH nucleus (+ nucleus star cluster) of a gas rich dwarf galaxy disrupted by a recent merger event.

Swift XRT light curve of HLX-1



Webb+ 2012

One year period: Accretion from a nucleus cluster star on an eccentric orbit ?

Conclusions

- Most ULX are likely (super) Eddington accreting stellar mass BHs.
- Best intermediate mass BH candidates will be found in the high Lx tail of the ULX luminosity function.
- IMBHs may be the left over seeds of SMBH created in the early universe that never grew up. Their nowadays properties may constrain SMBH growth mechanisms.
- ULXs drive strong winds and perhaps jets. Test beds for BH feed back mechanisms (especially in the super Eddington regime believed to dominate in the early universe).
- Is there a class of BH sources transforming most of their accretion energy in jet mechanical energy (no Eddington limit) ?
- Future X-ray facilities (eRosita all sky survey; Athena+ follow up) will discover many IMBH candidates.

Muchas gracias

Thank you

Merci