"Multi-wavelength studies of micro-quasars and ULXs"

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What is an ULX ?

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

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

  with a couple of outstanding cases…

How can we power an ULX ?

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

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

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

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

Strong beaming unlikely (X-ray ionized nebulae)

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

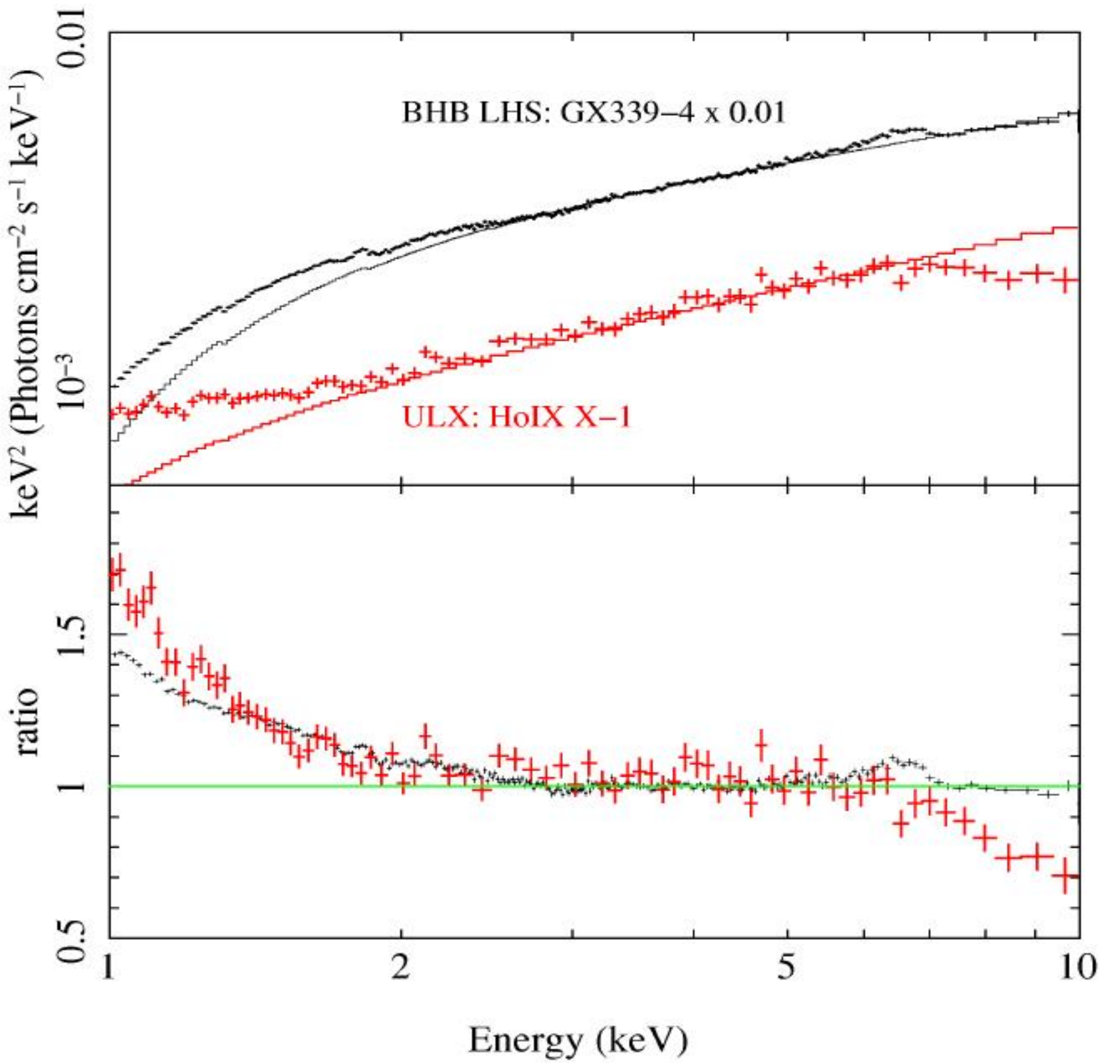
Why do we care ?

- Stellar mass BHs:
  - what make them different from Galactic BHs ? Evolutionary paths not seen in the Milky Way ?
  - laboratories to study accretion physics at near or super Eddington accretion rates.
- IMBHs:
  - constrain formation mechanism (extreme environment, low Z).
  - role in forming super-massive BHs in the early universe.

ULX X-ray spectra

- Phenomenology in two groups (Makishima 2007):
  - "Simple" power law energy distributions with a broad Γ distribution (1-3) peaking at $\Gamma \approx 1.8\text{-}2.0$
  - "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 behaviours reminiscent of Galactic BHs

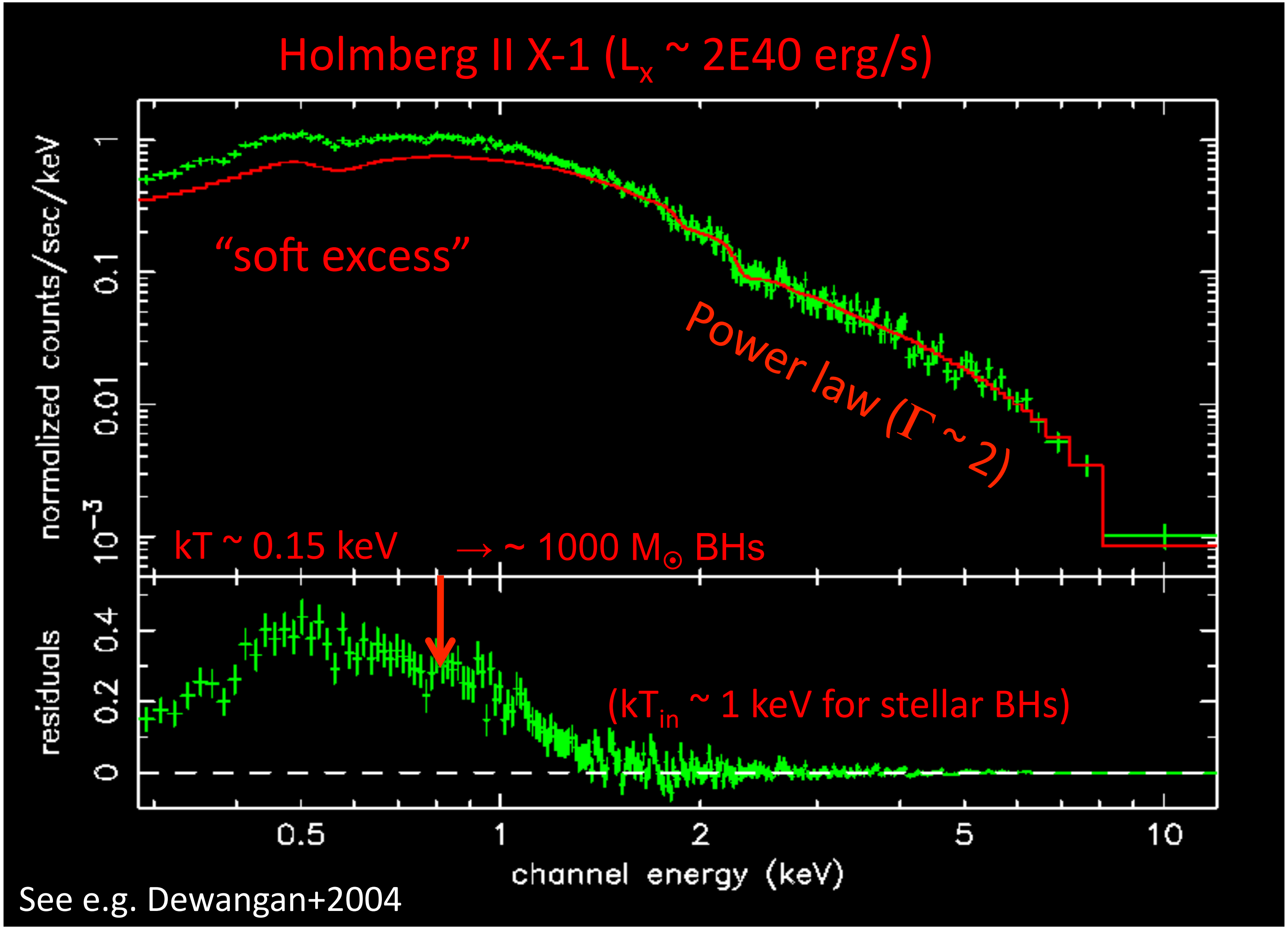
"Complex" spectra



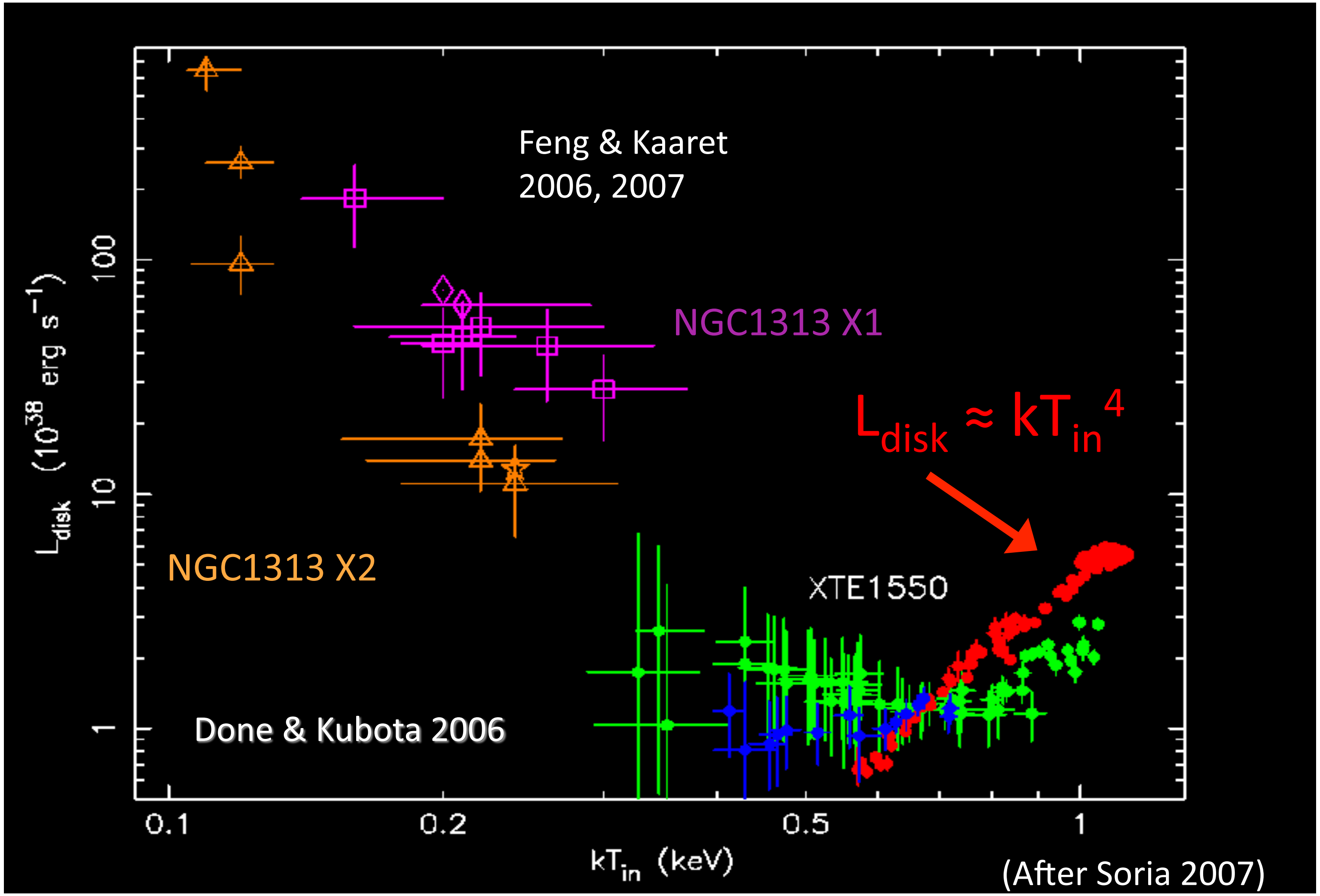
- X-ray state not seen in Galactic BHs ($L_X < L_{Edd}$)
- Identified as a new "Ultraluminous" state (Roberts 2007, Gladstone +2009)

(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

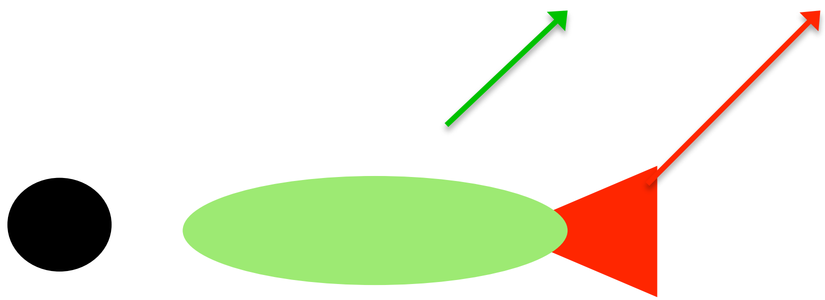


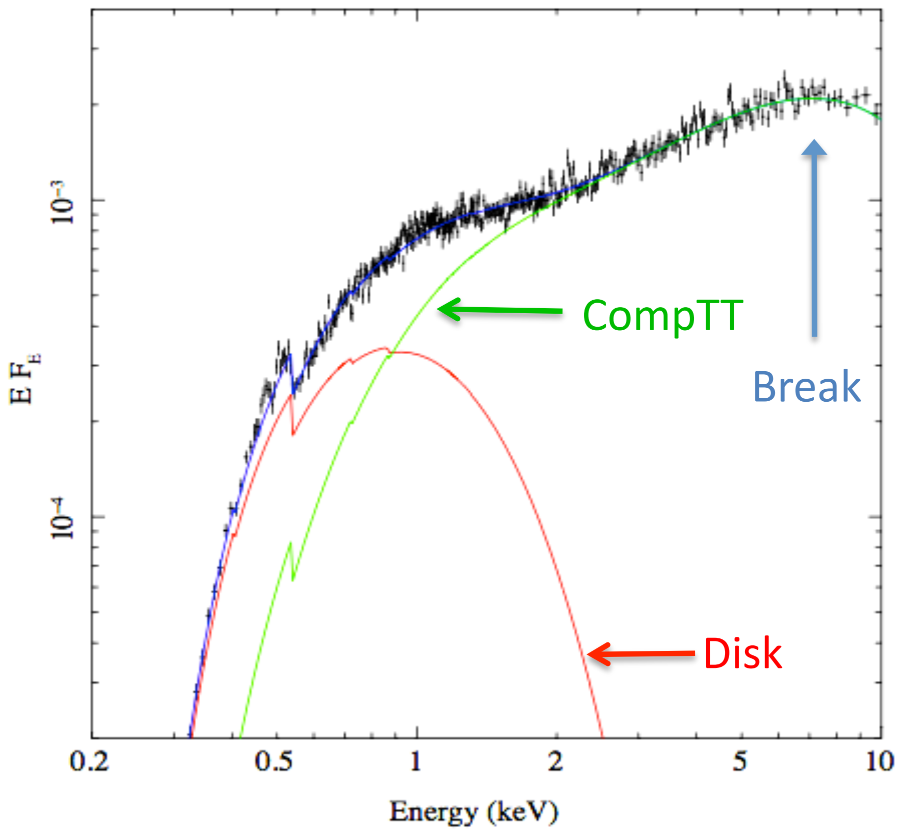
High energy spectral break

A common feature in high S/N spectra.

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

- $kT_e \sim$ 1-3 keV
- $\tau \sim 6 - 80$
- T_{max} disk ~ 0.2-0.3 keV



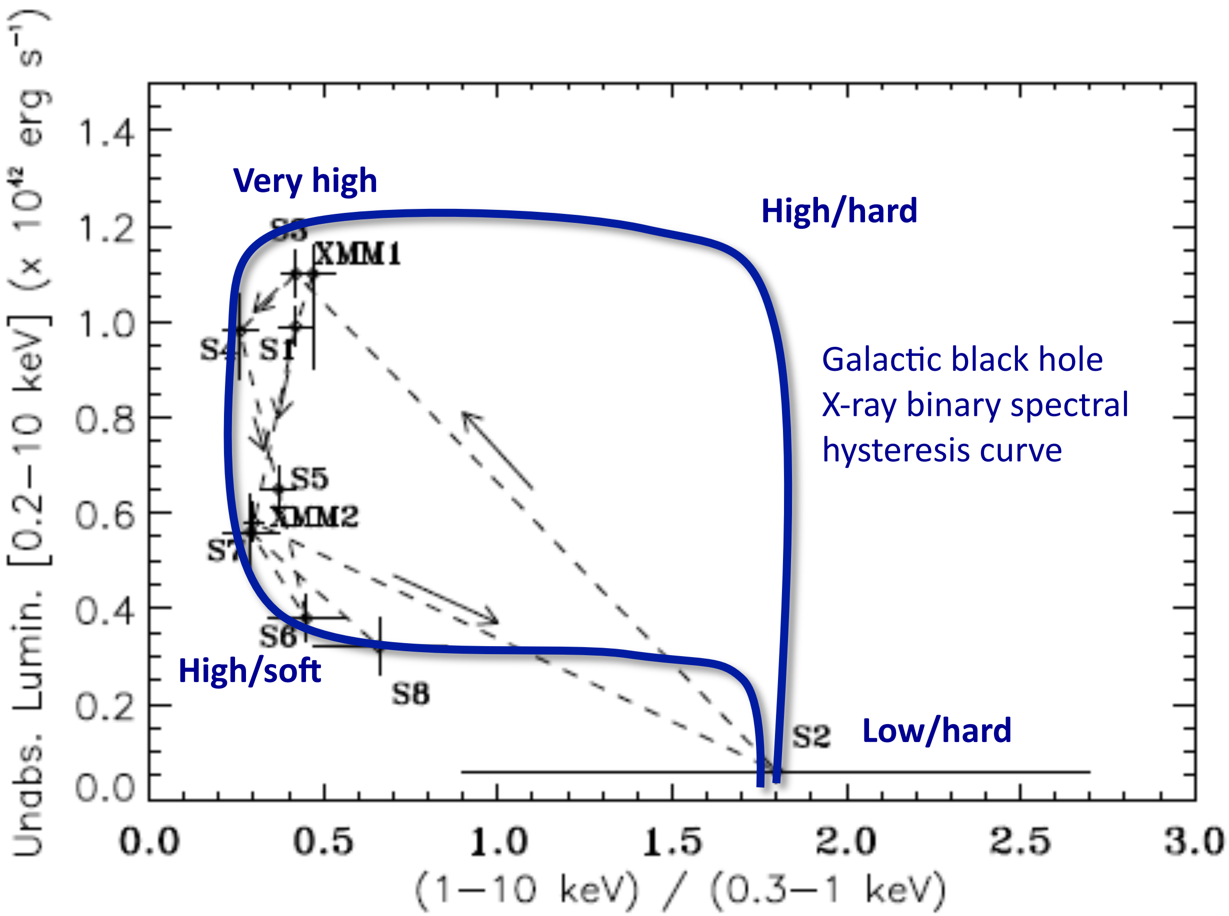


(After Gladstone 2011)

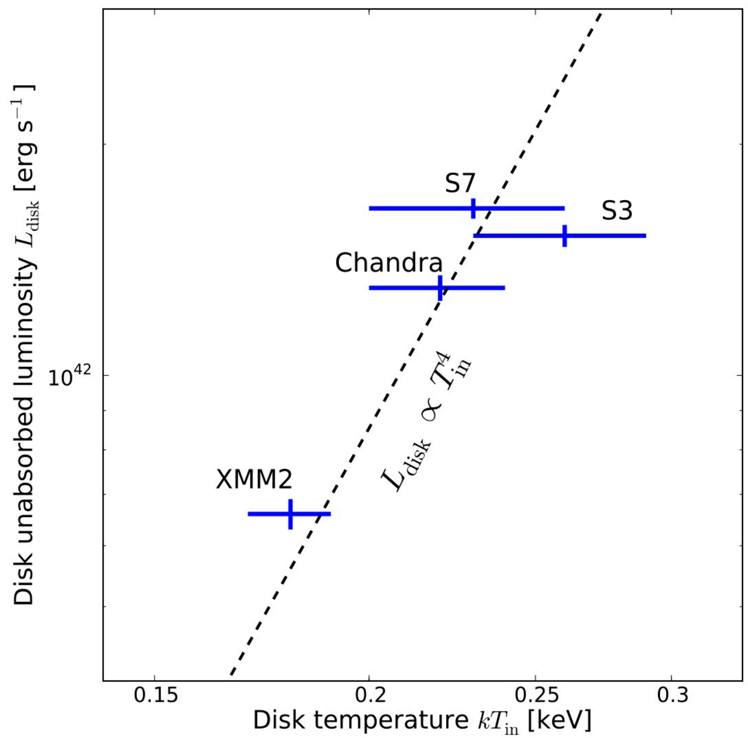
ESO 243-49 HLX-1:

Lx $_{max}$ ~ 10^{42} $ergs^{-1}$ (Farrell+2009)

X-ray state transitions similar to Galactic BH



Farrell+2011; Godet+2009



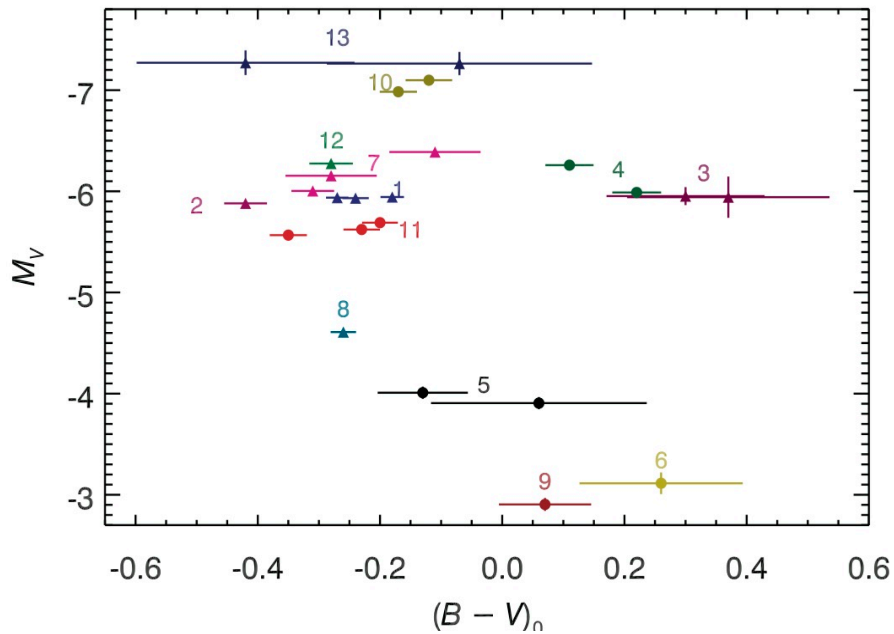
Servillat+2011

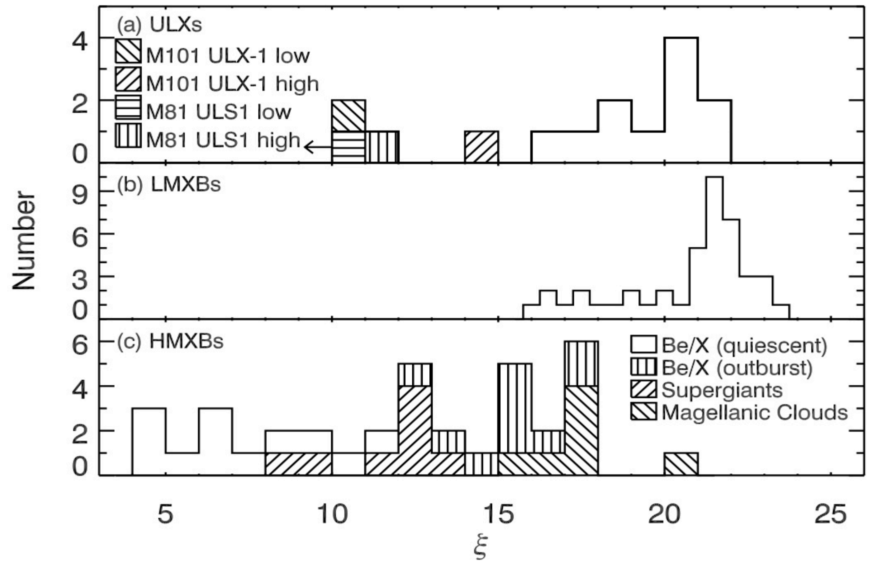
ULX X-ray spectra – a summary

- Evidence for strong Comptonization defining a new "Ultraluminous" X-ray state
  - static corona or dense wind created by super-critical accretion ?
  - Importance of reflection ?
- Favours 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) indicating sub-Eddington regime and hence the likely presence of an IMBH.

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





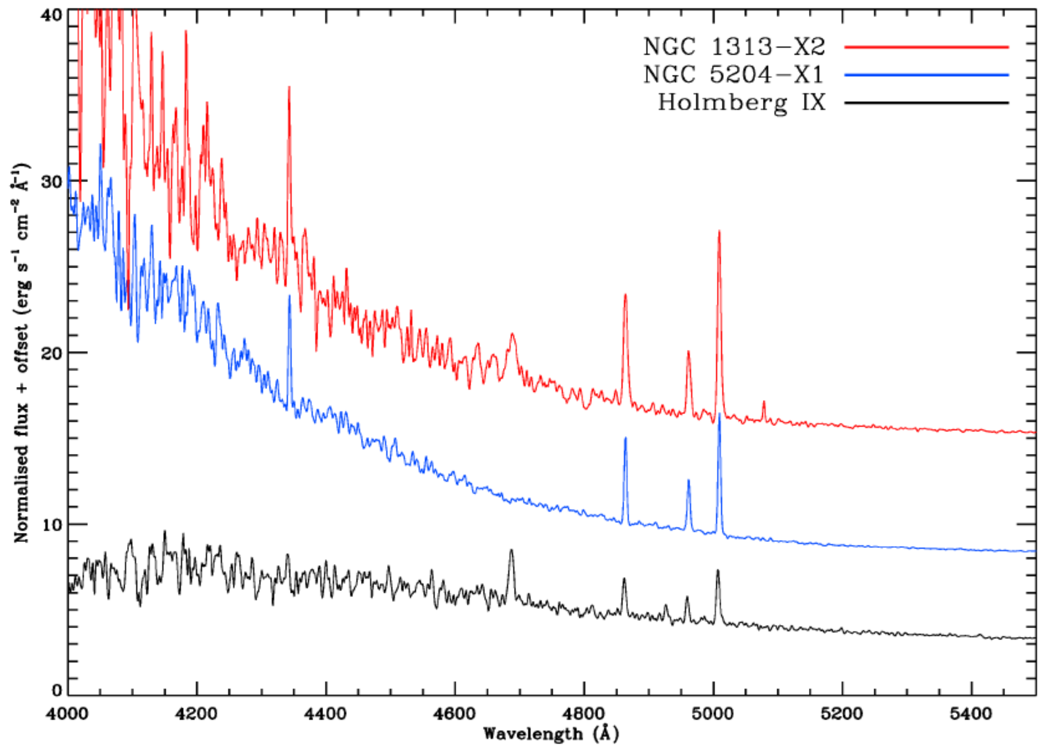
Tao+2011

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*

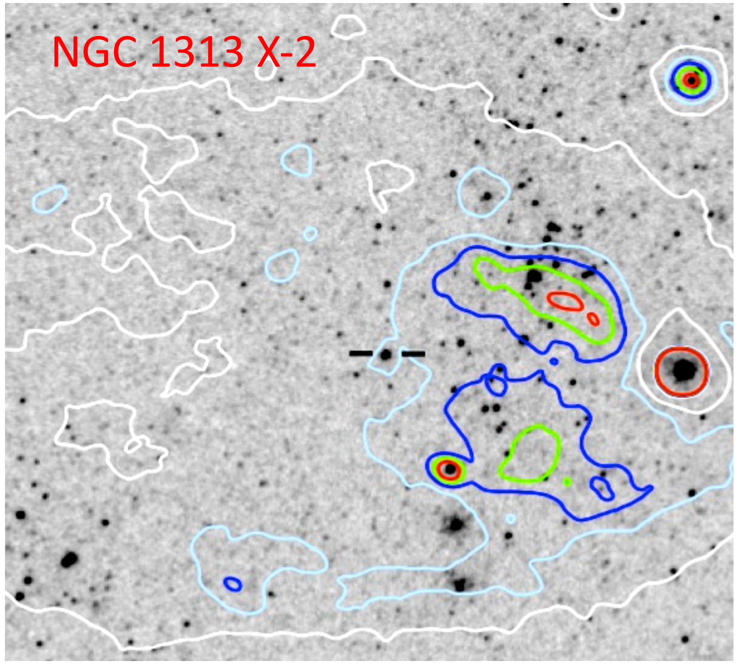
Field crowding + nebulae makes observations challenging

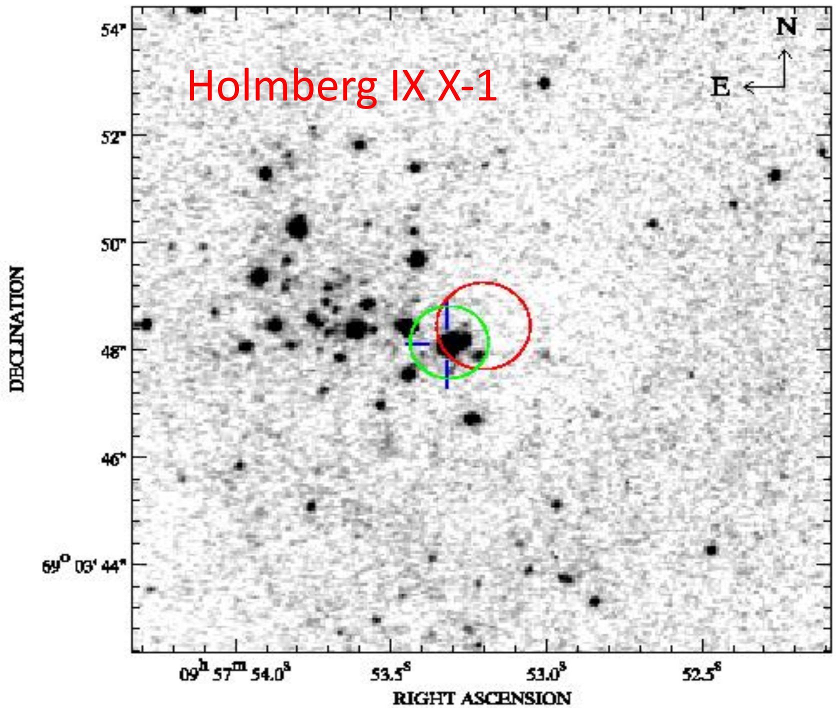


Roberts 2011

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 $10^3 M_\odot$ (too small to yield an IMBH)
  - ages in the range of 10 -20 Myr (Grisé+2008, 2011)

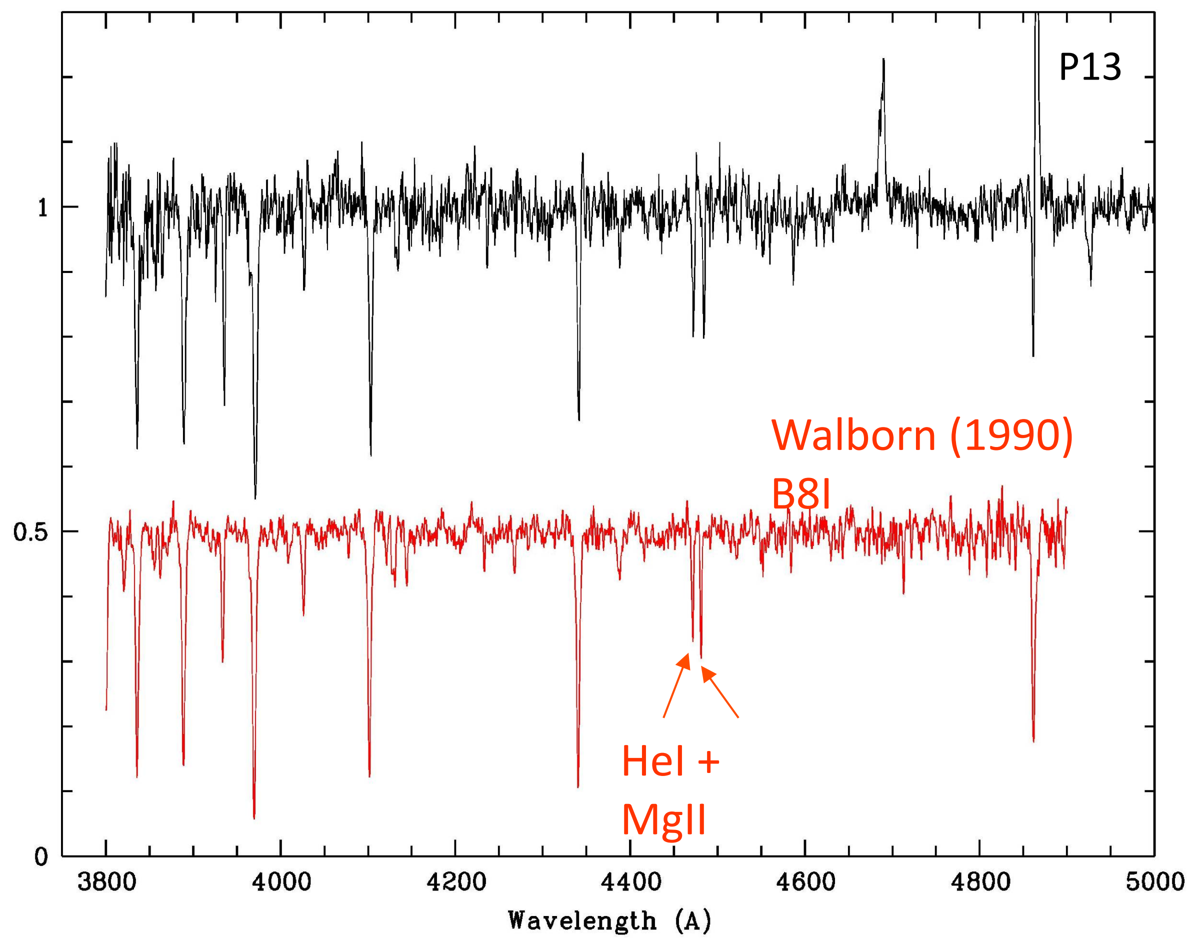




ULX P13 in NGC 7793

The optically brightest ULX counterpart (V ~20.5)

- Photospheric lines from the mass donor star are well detected
- Strong HeII + Bowen line complex in emission
- Lines + SED consistent with a B8I supergiant (Mv ~ -7, Lbol 5 10^{38} erg s^{-1}, M ~ 20M☉)
- Lx ~ 4 10^{39} erg s^{-1}
- Preliminary radial velocity curve suggests M_{BH} ~ 10 M☉

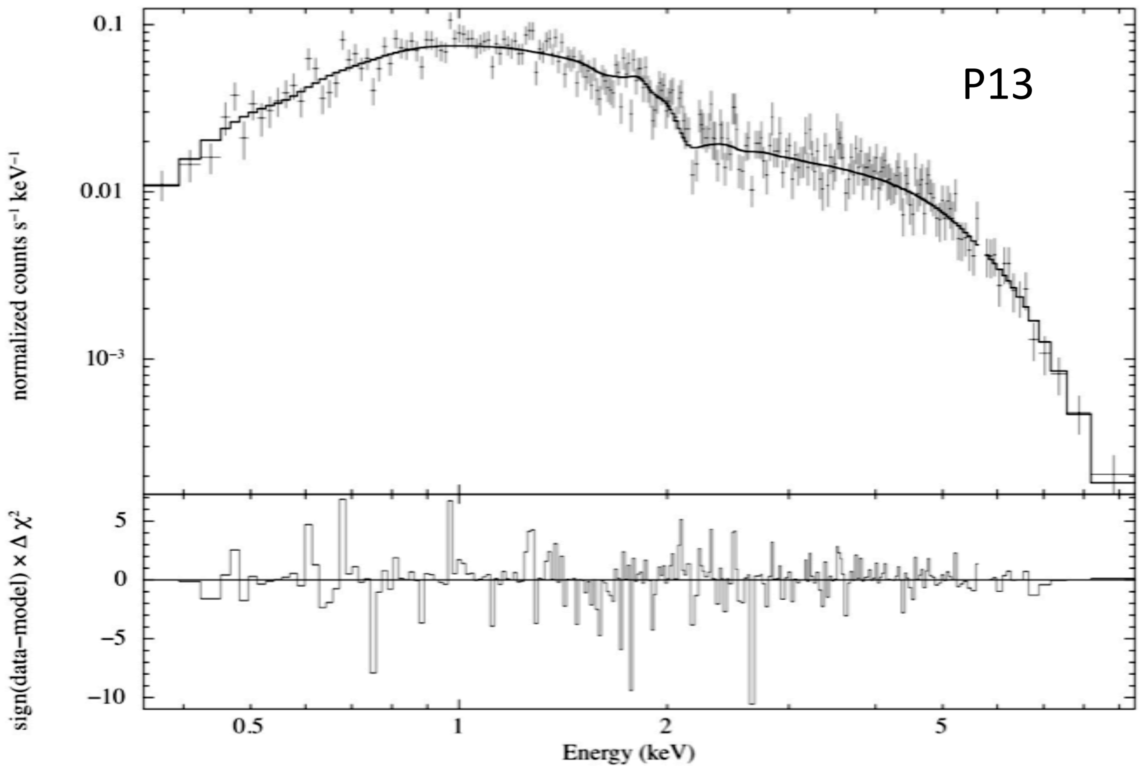


(Motch+2011,2012)

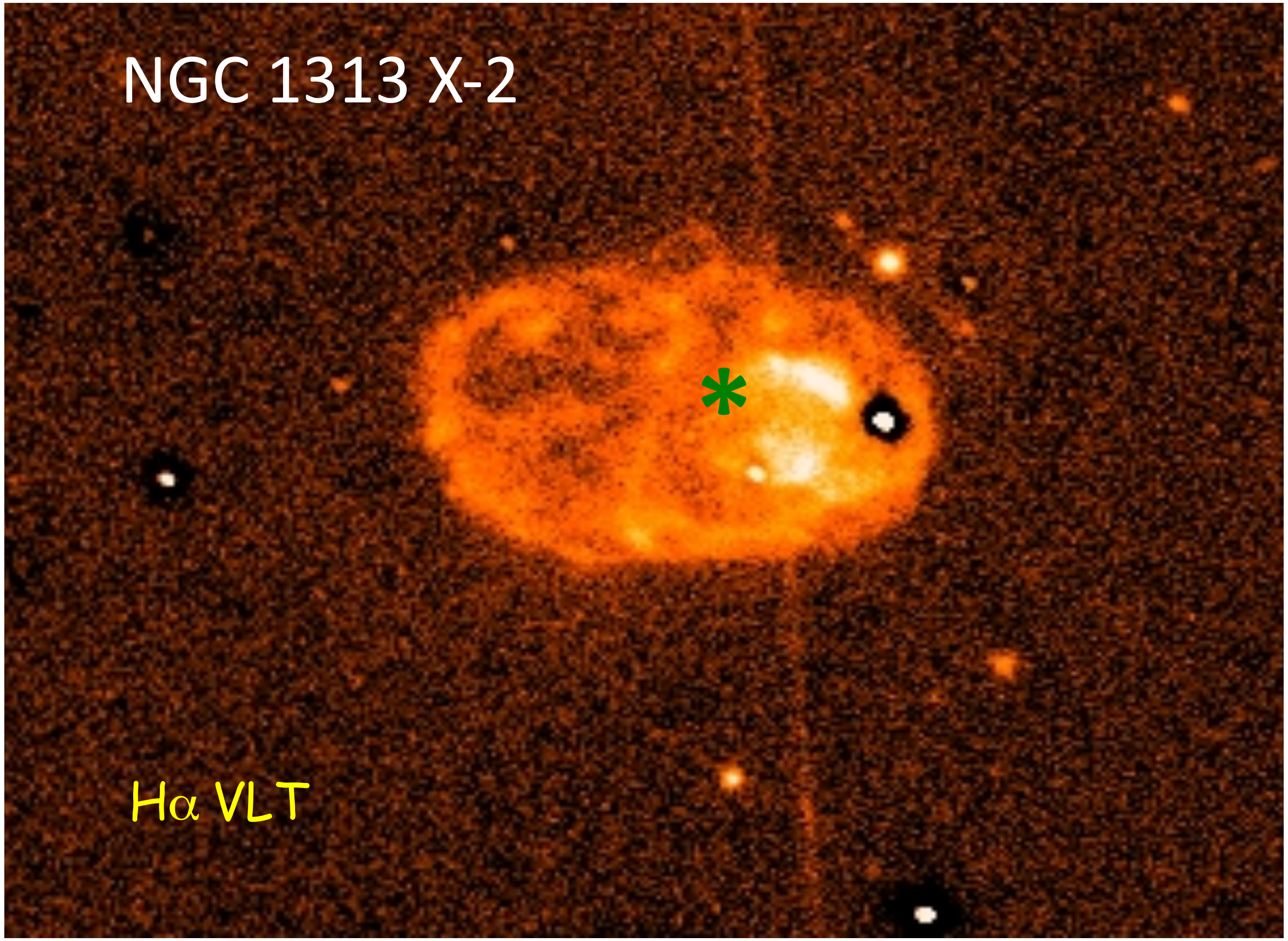
X-ray spectrum of P13

- Lx ≈ 3 L_{edd} -> ULX P13 is a bona fide near or super Eddington accreting black hole
- Chandra spectrum best fitted by a simple Comptonized energy distribution with:
  - kTe ~ 2.3 keV and τ ~ 11
  - No need for a soft component
- Fitting high energy part only (E>2 keV) seems to require a broken power law with E_b ~ 4 keV

Consistent with an "Ultraluminous" state



ULX bubbles, jets & micro-quasars



Pakull & Mirioni 2002, Pakull+2006

Bubble diameter
~ 26'' = 400 pc (!)

Optical spectra:
shock ionised

Vs ~ 100 km/s

ULX bubbles, jets & micro-quasars

About 25% ULX blow observable bubbles.

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

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

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

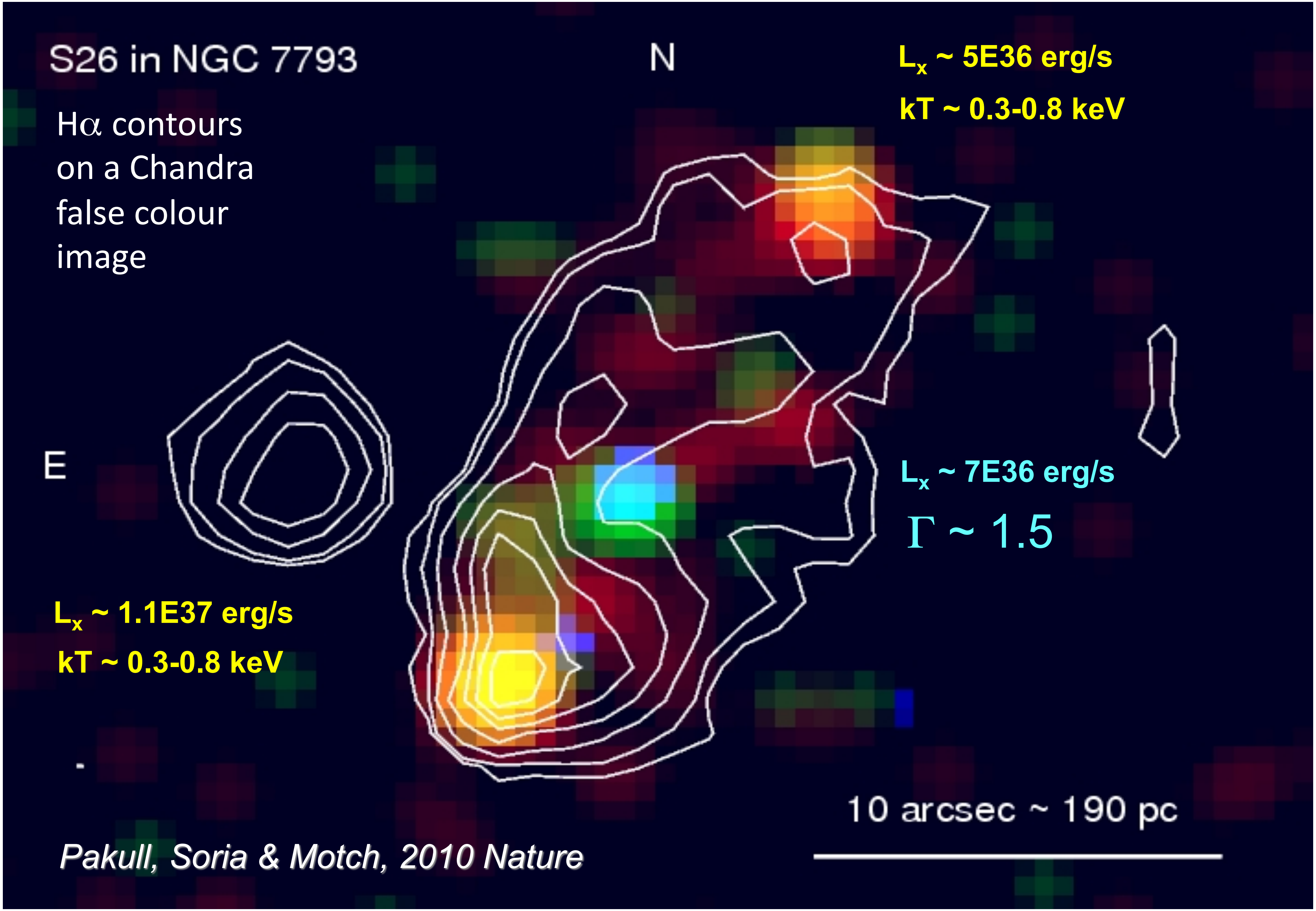
$L_w = 5\ 10^{39}$ erg/s $R_{100}^2 \times v_{100}^3 \times n \approx$ Lx !

Fully radiative shock with v_s implies for total radiative luminosity & Hβ Luminosity

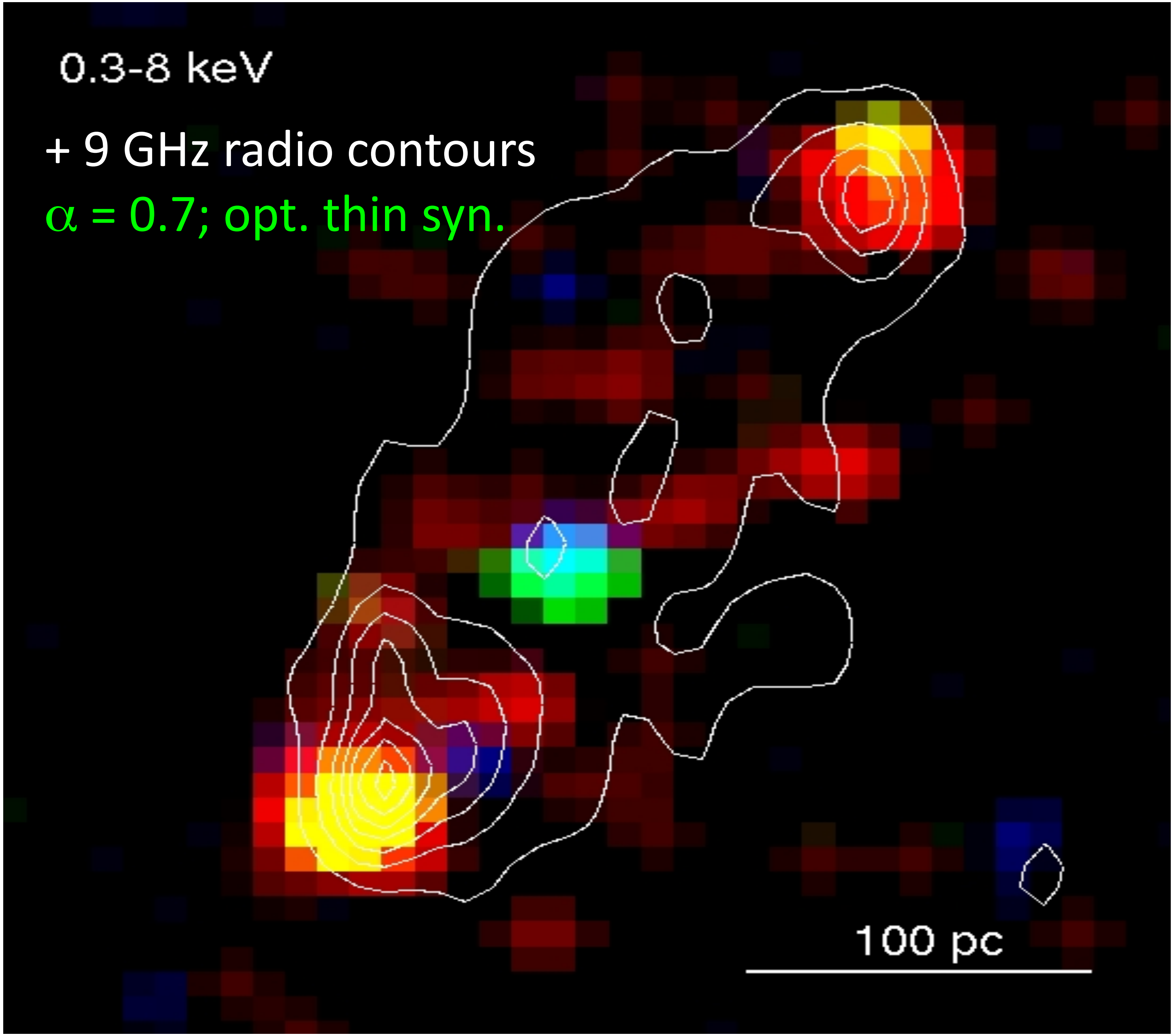
$L_{rad} = 27/77 \times L_w$; $L_{H\beta} = f(v_s) \times L_w$

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

(Pakull & Mirioni 2002; Pakull & Grisé 2006)


S26 in NGC 7793
N
E
Hα contours
on a Chandra
false colour
image
Lx ~ 5E36 erg/s
kT ~ 0.3-0.8 keV
Lx ~ 7E36 erg/s
Γ ~ 1.5
Lx ~ 1.1E37 erg/s
kT ~ 0.3-0.8 keV
10 arcsec ~ 190 pc
Pakull, Soria & Motch, 2010 Nature

S26: X-ray/ radio image



S26 in NGC 7793:
a super-SS433/W50 micro-quasar

Largest and most powerful micro-quasar system (160 x 290 pc)

- Vexp ~ 250 km s^{-1}
- Linear size ~ 2.5 that of SS433/W50
- Jet power ~ a few 10^{40} erg/s (>> Ledd of accr. BH.)
- Characteristic age ~ 2 x 10^{5} yrs
- Low persistent X-ray luminosity Lx = 7 10^{36} $ergs^{-1}$
- Total energy E ~ 10^{53} erg
  - most of it is thermal and kinetic energy
  - only ~ 1% goes into synchrotron-emitting electrons

First evidence of collimated jets at super Eddington rates ?

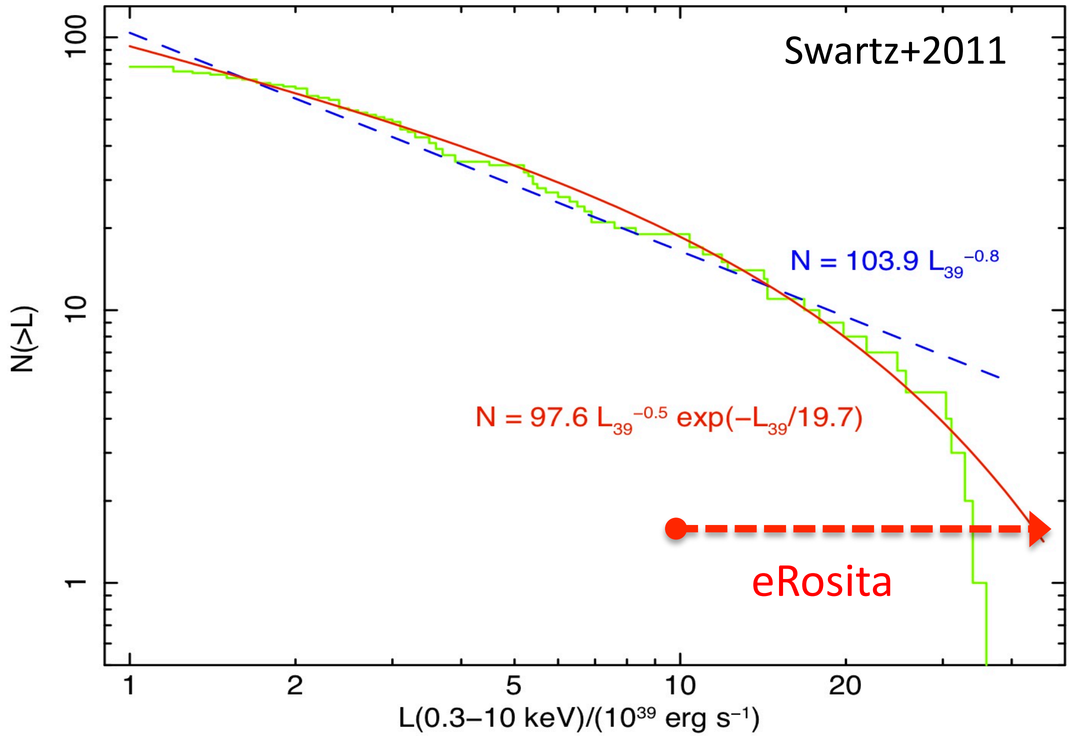
Prospects for eRosita

- Current ULX surveys are complete up to 15Mpc (northern sky only, Swartz +2011)
- eRosita all-sky ULX survey will be complete up to ≈ 10Mpc.
- eRosita somewhat hampered by spatial resolution (30" = 5kpc at 35Mpc), but excellent in finding the most luminous ULXs.
- Modelling by Prokopenko & Gilfanov (2009):

  d_{max} = 35 Mpc, Lx_{min} ~ 1 x 10^{40} $ergs^{-1}$

  About 85 high Lx ULXs will be found in the eRosita survey compared to

  10 – 15 in Chandra (Swartz+2011) and 2XMM (Walton+2011) surveys.



- Is there a break at Lx = 2x10^{40} erg s^{-1} ? (corresponding to ~ Ledd of the most massive stellar BHs)
- Is there evidence of a more luminous and distinct (IMBH) ULX population ? (eg HLX-1; Lx ~10^{42} erg s^{-1})

Conclusions

- "Complex" X-ray spectra indicate the presence of large warm Comptonizing regions (static coronae or massive winds), possibly related to super-Eddington accretion => likely "normal" or "massive" **stellar mass black holes**…
- Some ULXs display X-ray spectral states consistent with sub-critical accretion (e.g. HLX-1) and are good **IMBH** candidates.
- Bubbles show that ULXs may radiate as much mechanical energy as Lx and should thus produce strong massive winds (or jets).
- Some black holes (S26, SS433) seem able to radiate most of their energy in the jets (alternatively, we observe them in a low state or view them at high inclination) => introduce the concept of "Ultrapowerful sources" (UPSs) (Feng & Soria 2011).
- BH feedback also important in the near to or super Eddington regime.
- eRosita will likely discover several more Lx ≈ 10^{41-42} erg/s IMBH candidates and determine the shape of the high Lx ULX luminosity function.

Thank You