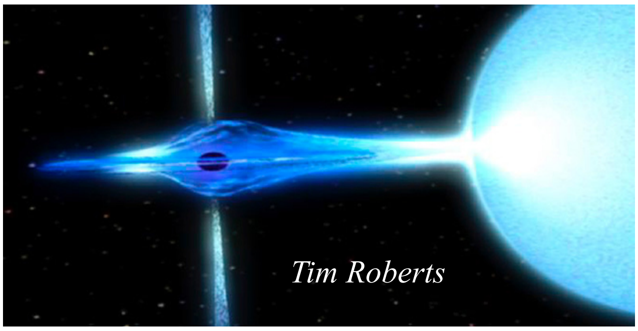
Durham Astronomy Postgraduate Course: Stellar Structure & Evolution lectures

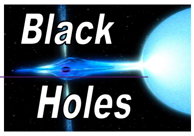
6. Populations of Black Holes



Tim Roberts

Recap

- ☐ Best way of finding stellar black holes is via X-ray emission from accretion of donor star material
  - ■ Presence confirmed by dynamical masses
- ☐ Stellar counterparts define whether HMXBs or LMXBs (latter are soft X-ray transients)
- ☐ Four main classic accretion states: quiescent, hard, thermal-dominated and steep power-law
- ☐ Outbursts follow a common cycle



Aims

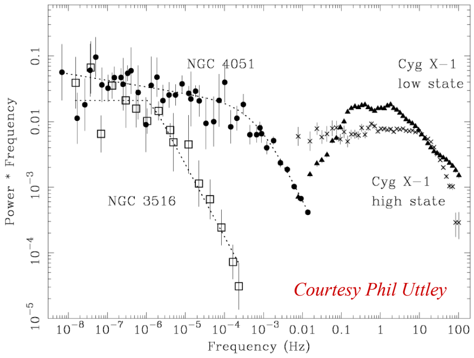
- Discuss whether the behaviour of stellar-mass black holes can be reconciled with the behaviour of super-massive black holes
- What can we say about the populations of black holes in other galaxies?
- What are ultraluminous X-ray sources, and why are they interesting?

Black hole unification

- Question: do black holes of different masses behave in different ways? Or do they behave similarly, with the only differences originating from mass scaling?
  - *E.g.* know that accretion disc temperature scales as $M_{BH}^{-0.25}$ - hence AGN discs peak in UV!
- For example: do they share the same accretion states? Are the variability time scales prop. to black hole mass?

Power spectra - AGNs vs XRBs

- ☐ If in same states, will possess same power spectra - only difference is scaling for physical size of emitting regions - ***SEEN***

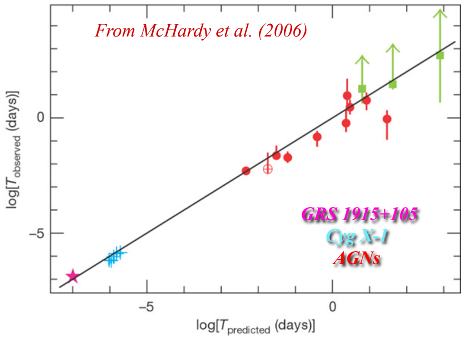


Courtesy Phil Uttley

Comparison of the PSDs of Cyg X-1 in two states, and two AGNs.

PSD break frequencies

- ☐ PSD break frequencies appear to scale with black hole mass, accretion rate as



From McHardy et al. (2006)

$$\log T_B = 2.1 \log M_{BH} - 0.98 \log L_{Bol} - 2.32$$

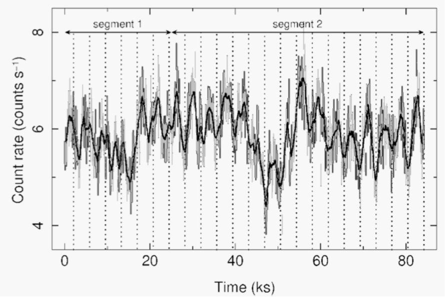
T_B - *break timescale* (days)

M_{BH} - *black hole mass* ($\times 10^6$ M$_\odot$)

L_{Bol} - *bolometric luminosity* ($\times 10^{44}$ erg s^{-1})

QPOs

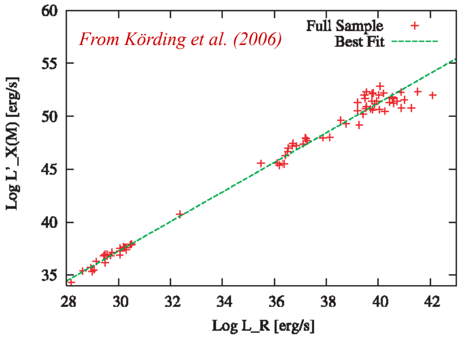
- ☐ Missing link was failure to observe a QPO in an AGN…
- ☐ …until observation of RE J1034+396 by Gierlinski et al. (2008)
- ☐ Timescale correct for ~ $10^7\ M_\odot$ BH
- ☐ Now second detection – MS 2254.9-3712 (Alston et al. 2014)



XMM-Newton EPIC light curve of RE J1034+396 from Gierlinski et al. (2008)

X-ray - radio fundamental plane

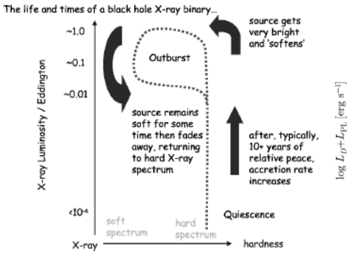
- ☐ For very sub-Eddington emission - in hard state - find relation between L_X, L_R, M_{BH}



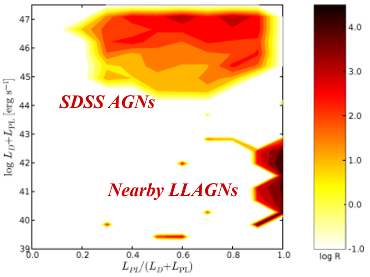
Originally suggested by Falcke, Kording & Markoff (2004); plot of radio luminosity versus X-ray luminosity, with the latter corrected for black hole mass (normalised to a $6M_\odot$ object, and assuming an optically-thin non-thermal jet spectrum) and Doppler boosting effects (etc.) taken out.

AGN outburst cycles?

- ☐ Can't see full outburst cycles from AGNs - but can plot many SDSS AGNs in hardness-intensity style plot - similarities!



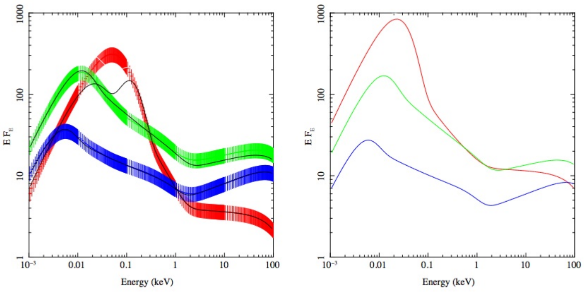
From Fender (2006b)



From Körding, Jester & Fender (2006)

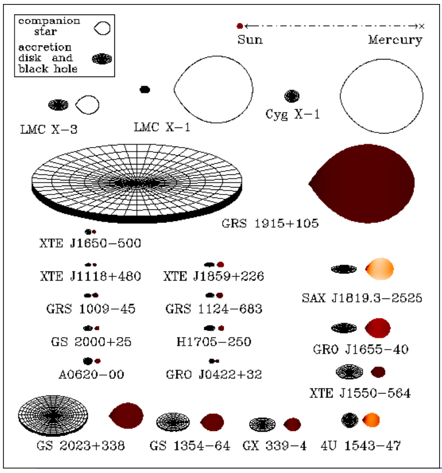
But some issues now appearing…

- ☐ X-ray radio plane: some objects lie off it
- ☐ AGN spectra: presence of a 'soft excess', behaviour inconsistent with stellar BHs



Broad band AGN spectra, from Done et al. (2012). Right hand figure shows template spectra for 10^8 solar mass BHs, accretion rate increases from blue to green to red

Black hole population in our Galaxy



Courtesy Jerome Orosz

- ☐ Our Galaxy (incl. Magellanic Clouds) - dominated (in numbers) by SXTs
    - Note only a fraction in outburst at any time
- ☐ What do we see in other galaxies?

Other galaxies in X-rays

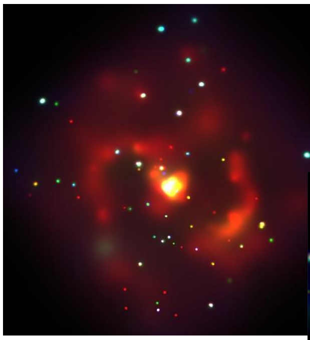
Figures from *chandra.harvard.edu*

Chandra true-colour images of nearby galaxies

red 0.3 - 1 keV (12 - 40Å)

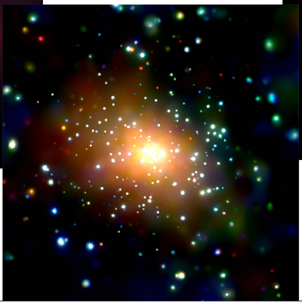
green 1 - 2 keV (6 - 12Å)

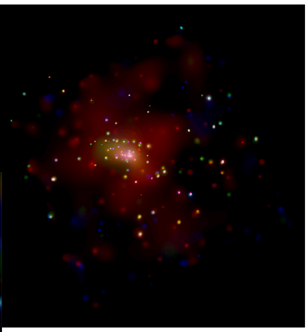
blue 2 - 8 keV (1.5 - 6Å)



↑ *Spiral galaxy M83*

Centre of the nearest major galaxy, M31 →





↑ *Elliptical galaxy NGC 4697*

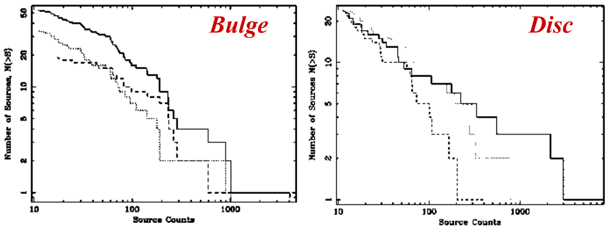
Problems!

- ☐ Remember RXTE animation: our Galaxy dominated by NS X-ray binaries.
- ☐ Cannot currently ID black hole populations in nearby galaxies from mixture of BH, NS, SNRs, background AGN…
  - ■ Only BH IDs (to date) are M33 X-7 & IC 10 X-1
- ☐ However, with *Chandra* (and to a lesser extent *XMM-Newton*) can still extract useful science

---

X-ray luminosity functions

- ☐ Simple calculation: number of X-ray sources seen above a specific luminosity
- ☐ Differences seen between galaxy types, and even within individual galaxies

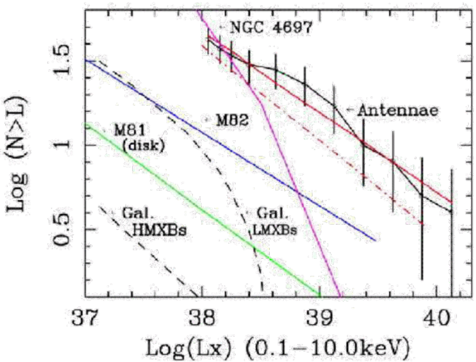


XLFs of disc and bulge regions of M81, from Swartz et al. (2003)

XLFs and star formation

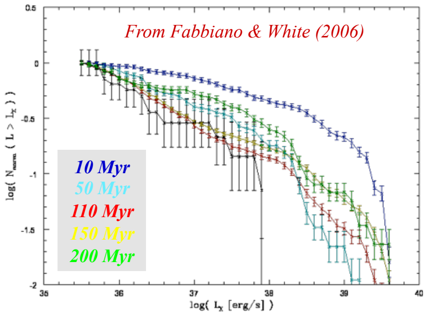
- ☐ Cumulative XLFs of E, SO galaxies (and spiral bulges) have steep slopes, ~ -1 → -2
- ☐ Starburst galaxies (and spiral arms) have flatter slope, ~ -0.6 → -0.8; must be related to presence of HMXBs

From Fabbiano & White (2006)



XLFs: a metric of recent star formation

- ☐ Populations of HMXBs, LMXBs should evolve in a predictable fashion after star formation event
- ☐ Means modelling of XLFs can provide information on the starburst age, metallicity etc.

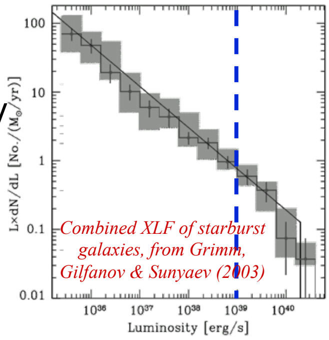


From Fabbiano & White (2006)

Models of XLF from X-ray binaries (coloured lines) compared to data (black) for the dwarf starburst NGC 1569. Based on STARTRACK code (e.g. Belczynski et al. 2008)

Unusually bright sources…

- At top end of XLFs see sources with $L_X > 10^{39}$ erg s^{-1}
- But the Eddington limit is given by **$L_{Edd} \sim 1.3 \times 10^{38} (M/M_\odot)$ erg s^{-1}** hence the brightest sources appear to exceed L_{Edd} for the stellar mass black holes known in our Galaxy
- Ultraluminous X-ray sources (ULXs) defined by $L_X > 10^{39}$ erg s^{-1}



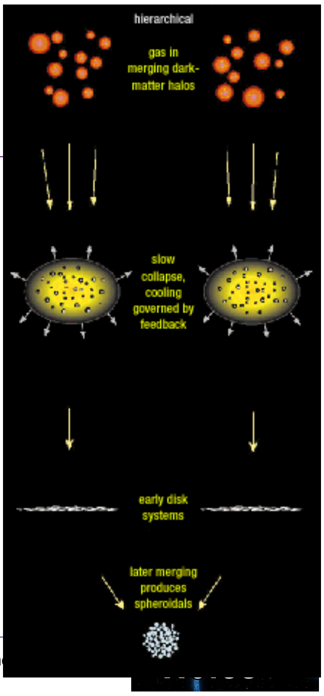
Combined XLF of starburst galaxies, from Grimm, Gilfanov & Sunyaev (2003)

A new class of black hole?

- If accretion in ULXs is sub-Eddington they must contain > 10 $M_\odot$ compact objects – larger still if accretion very sub-Eddington – ***massive black holes***.
  - *Not super-massive BHs* ($M_{BH} \geq 10^6 M_\odot$); fall to Galactic centre in a Hubble time due to effects of dynamical friction.
  - *Too massive for stellar remnants* ($3M_\odot < M_{BH} < 18M_\odot$).
- **Are we observing a new, $10^2 - 10^5 M_\odot$ "intermediate mass" class of accreting black hole (IMBHs; e.g. Colbert & Mushotzky 1999)?**

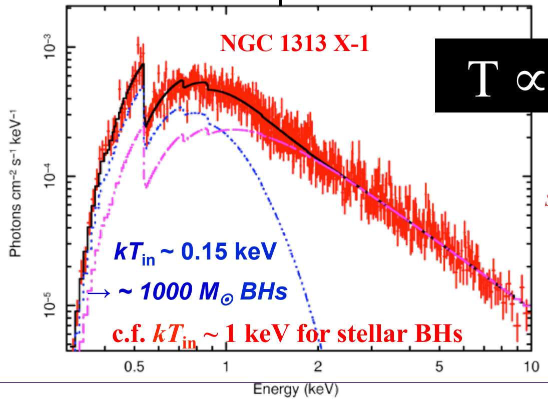
The importance of IMBHs

- ☐ Could be primordial - formed from collapse of Pop III stars
  - Seed proto-SMBHs
  - Primordial IMBHs - relic of the first stars - still present in galaxy halos? (Madau & Rees 2001)
- ☐ Second formation channel - runaway growth and subsequent collapse of a single stellar object in a young, dense stellar cluster (e.g. Portegies Zwart & McMillan 2002).



X-ray evidence for IMBHs

- ☐ X-ray spectroscopic evidence – same spectrum as Galactic BHs - except cool accretion discs.

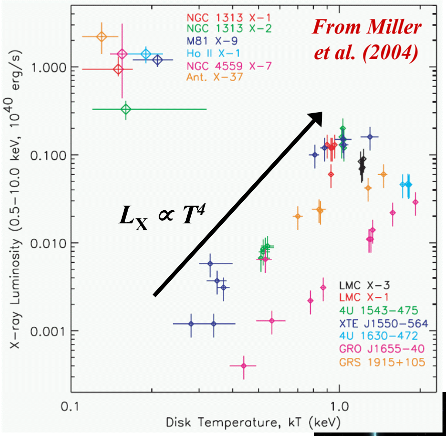


$T \propto M^{-0.25}$

See e.g. Miller et al. (2003)

L_X – kT_{in} relationship

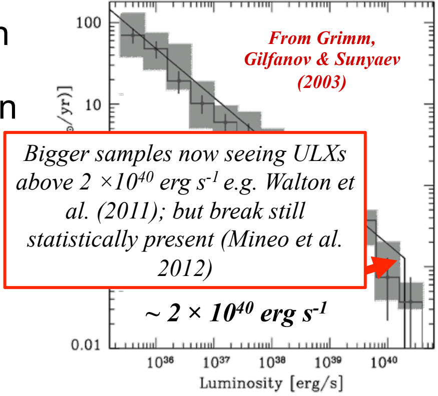
- ☐ IMBH candidates occupy separate part of parameter space to stellar-mass BHs.
- ☐ Strong evidence for IMBHs as new class underlying luminous ULXs.



From Miller et al. (2004)

Vanishing IMBHs problem

- ☐ But some problems with IMBHs, most notably…
- ☐ X-ray luminosity function (XLF), normalised to star formation rate, unbroken over 5 decades,
- ☐ XLF break at ~ 0.1 L_{Edd} for 1000-$M_\odot$ IMBHs.
- ☐ **No other source population switches off at 0.1 L_{Edd} like this.**

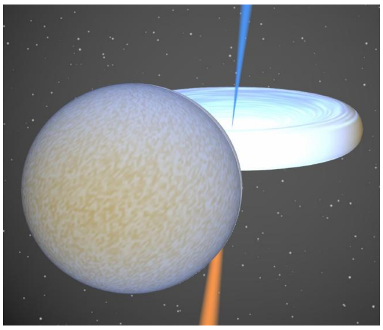


From Grimm, Gilfanov & Sunyaev (2003)

Bigger samples now seeing ULXs above 2×10^{40} erg s^{-1} e.g. Walton et al. (2011); but break still statistically present (Mineo et al. 2012)

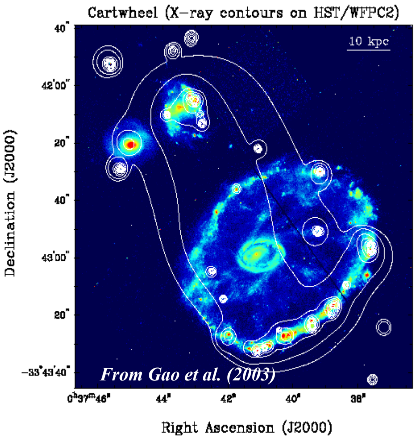
(Re-)fueling problem

- Best way of providing fuel supply: companion star.
- Alternative: molecular cloud disruption (Krolik 2004).
- Modelling – very difficult to form stable IMBH-ULXs, underpredict ULXs by 10-100 (Madhusudhan et al 2006).
- Plausible in dense stellar clusters (Baumgardt et al. 2006); but ULXs found displaced from clusters (Zezas et al. 2002)



A strong steer against IMBHs

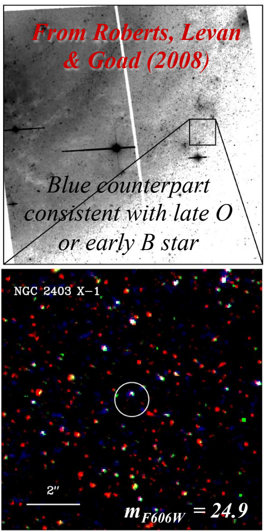
- Early Chandra results: multiple ULXs (10+) are found in Starburst galaxies
- Most ULXs inextricably linked to star formation (e.g. Swartz et al. 2009)
- Ongoing star formation → ULXs are intrinsically short-lived → can't ***ALL*** be IMBHs (King 2004)
- **Alternative: high-mass X-ray binaries (HMXBs)?**



From Gao et al. (2003)

ULXs as HMXBs

- ☐ Super-Eddington mass transfer in HMXBs (Rappaport et al. 2005)
- ☐ Blue stellar counterparts to ULXs – possible high mass donors
- ☐ Still need to break the Eddington limit; possibilities:
  - Relativistic beaming (e.g. Körding et al. 2002)
  - Radiative anisotropy (e.g. King et al. 2001)
  - Truly super-Eddington discs (e.g. Begelman 2002)


From Roberts, Levan & Goad (2008)

Blue counterpart consistent with late O or early B star

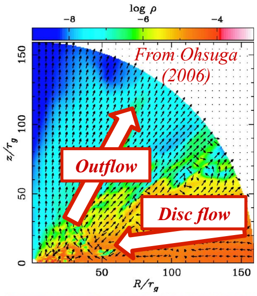
Physical processes

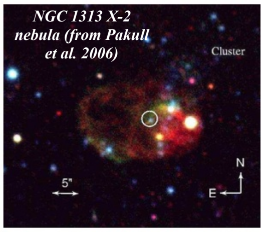
- ☐ Combination of super-Eddington flow & radiative anisotropy, e.g. Poutanen et al. (2007), King (2008)

$$\boxed{L = \frac{L_{Edd}}{b}\left[1 + \ln\frac{\dot{M}}{\dot{M}_{Edd}}\right]}$$

For beaming factor b and super-Eddington rate $\dot{M}/\dot{M}_{Edd}$

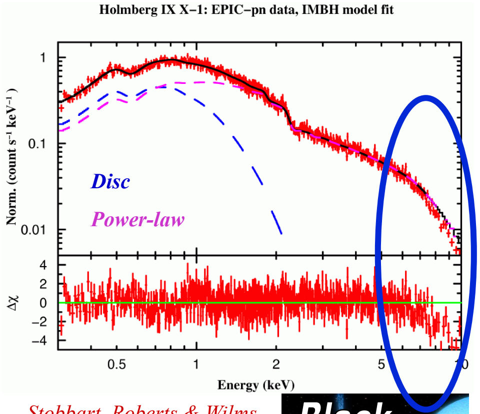
- ☐ ULX nebulae imply outflows
- ☐ Must be possible! Super-Eddington emission seen in many accreting source types – NS (Circinus X-1), BH (GRS 1915+105), AGN (IRAS 13224-3809)…


From Ohsuga (2006)


NGC 1313 X-2 nebula (from Pakull et al. 2006)

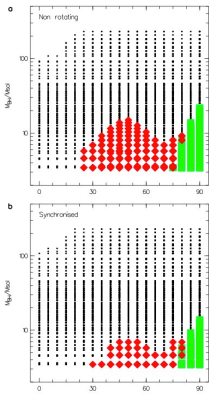
Reconciliation?

- ☐ Highest quality *XMM-Newton* data: X-ray spectral fit is ***NOT*** cool disc + power-law
  - Few keV break
- ☐ This spectrum better described by extreme accretion models
  - Small black holes!
  - See Gladstone et al. (2009) - ULXs as BHBs in *"ultraluminous state"*



Stobbart, Roberts & Wilms (2006)

Coming full circle: RV studies of ULXs

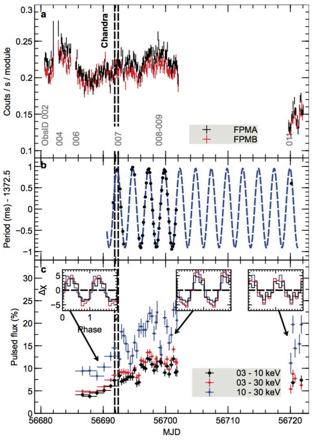


Mass as a function of inclination, red diamonds are allowed values (Motch et al. 2014)

- ☐ Difficult! Faint counterparts, disc reflection features don't work (Roberts et al. 2011)
- ☐ But: now done for two objects
- ☐ M101 ULX-1: $M_{\rm BH}$ 20-30 $M_\odot$ (Liu et al. 2013)
- ☐ NGC 7793 P13: $M_{\rm BH} < 15\ M_\odot$ and X-ray properties consistent with other ULXs (Motch et al. 2014)

But they might not even be BHs…

- ☐ New results in last 2 years: 3 ULXs with detected X-ray pulsations
- ☐ Must be neutron stars!
- ☐ L_X up to 10^{41} erg s^{-1} – very extreme beaming (factor ~ 500)!

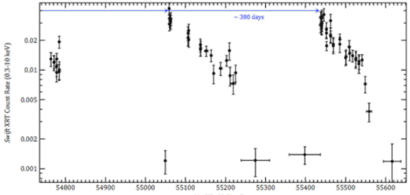


From Bachetti et al. (2014): 1.4 s pulsations on top of a 2.5 day orbital period

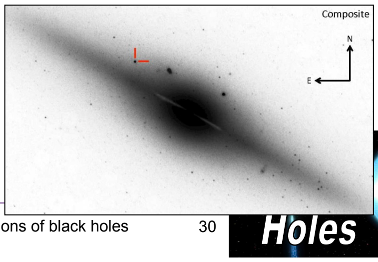
---

Hyperluminous X-ray sources

- ☐ Handful of objects peak at $L_X > 10^{41}$ erg s^{-1}
- ☐ Most luminous is ESO 243-49 HLX-1; shows state changes similar to standard BHBs, but scaled to an IMBH
- ☐ Best remaining IMBH candidates

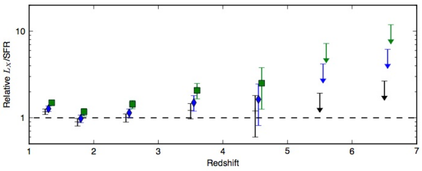


Above: X-ray lightcurve of ESO 243-49 HLX-1 (Lasota et al. 2011). Below: HST image of ESO 243-49, highlighting optical counterpart



Cosmological implications?

- Flat XLFs: ULXs dominate star forming galaxy L_X
- More ULXs formed at low metallicity (Prestwich et al. 2013)
- Kinetic output can exceed radiative (Soria et al. 2013)
- Implication: ULXs may be important factor in primordial galaxy formation? (Kaaret 2013)



Increase in L_X per unit SFR with cosmic look-back time (Kaaret 2013)

Summary

- It appears that both stellar mass and super-massive black holes share some behaviour (particularly timing)
- Cannot resolve black hole populations in nearby galaxies from others (mainly NS)
  - But can use XLFs to investigate recent star formation history
- Ultraluminous X-ray sources are the most extreme X-ray binaries ($L_X > 10^{39}$ erg s^{-1})
  - The majority are probably the most extreme accreting small black holes…
  - …but some are very extreme neutron stars...
  - …and most luminous may yet harbour IMBHs