Ultraluminous X-ray Sources

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Outline

Ultraluminous X-ray Sources (ULXs)

I will start from some established and recent observational evidences ...

- First dynamical measurements of mass functions and black hole masses
- X-rays spectra and variability
- Detection of broad optical emission lines

… and try to critically frame them within the framework of super-Eddington accretion onto black holes of stellar origin ...

- Super-Eddington accretion and non-standard discs
- Evolution of the binary system
- Modelling the multiwavelength emission

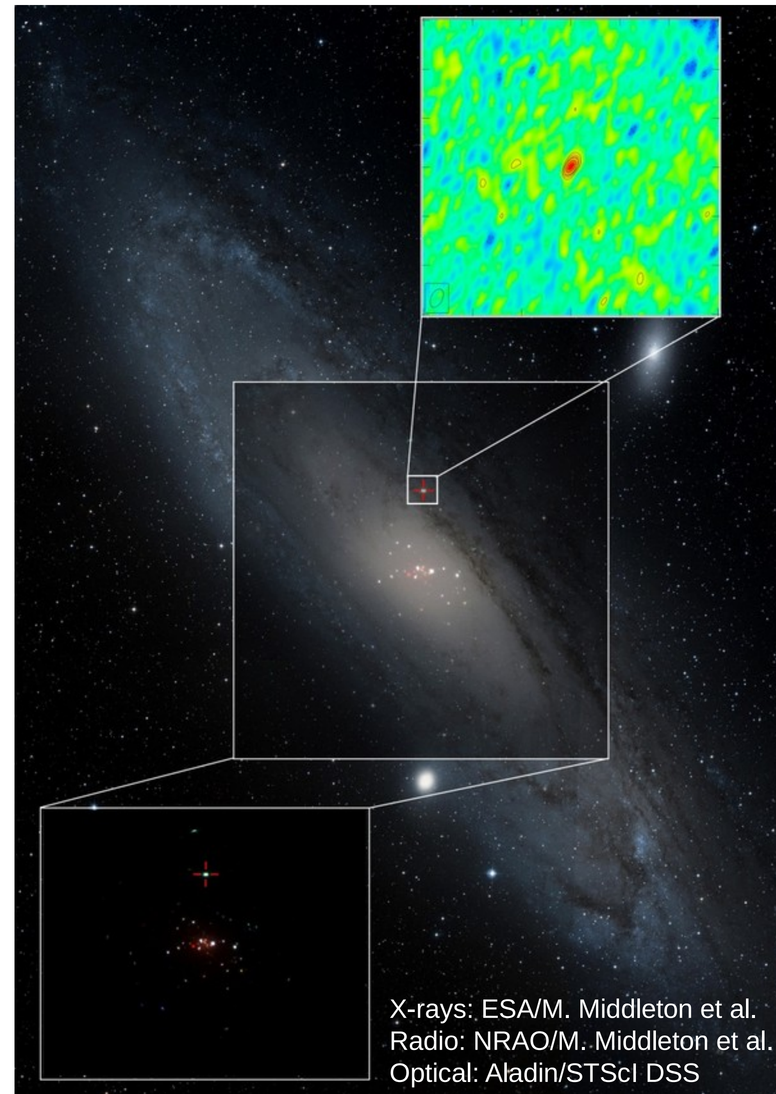
… finishing with some future perspectives and concluding remarks abcdefghijklmnopqrstuvXyz

Ultraluminous X-ray sources (ULXs)

Point-like off-nuclear X-ray sources in nearby
(< 100 Mpc) galaxies
Intrinsically powerful but faint
L exceeds (although not necessarily all the time)
the Eddington limit for spherical accretion
onto a ~10 M black hole (L>1.0e39 erg/s)

Hundreds of sources in various surveys/catalogues:
ROSAT: Roberts & Warwick 2000, Colbert & Ptak 2002
Liu & Bregman 2005, Liu & Mirabel 2005
Chandra: Swartz et al. 2011
XMM-Newton: Walton et al. 2011

~ 20% Background AGNs
~ 5% Supernovae interacting with circumstellar medium
60-70% Accreting binaries



Typifying the compact object: First dynamical masses

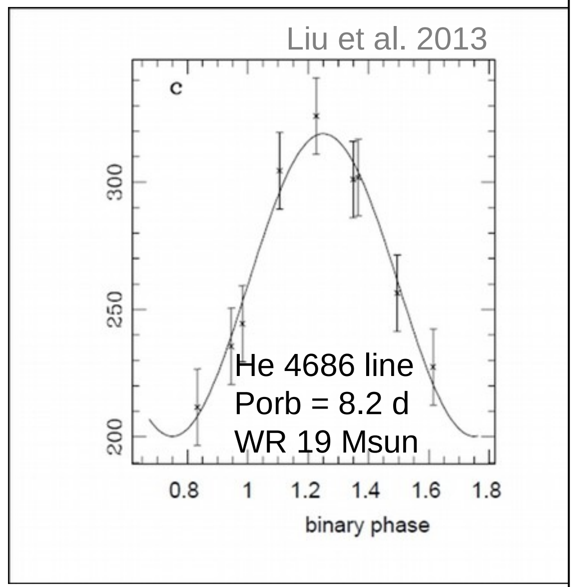
First measurements of a mass function in ULXs gathered in the last couple of years

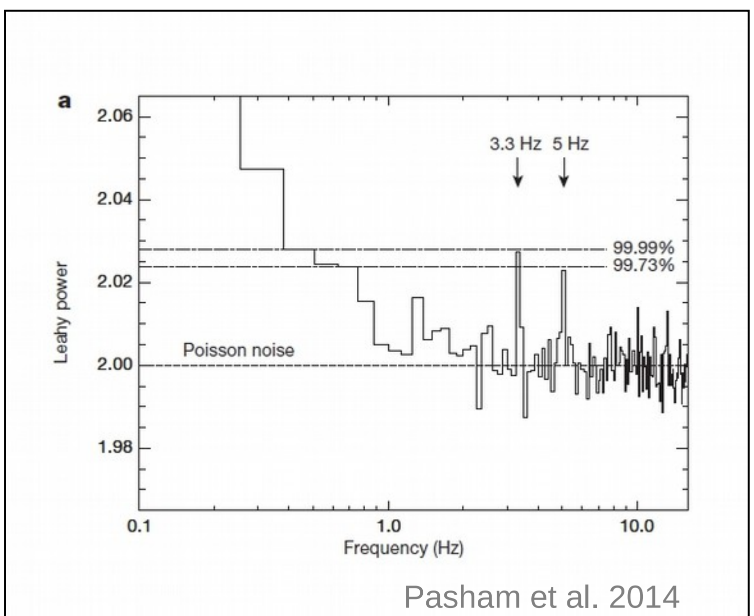
M 101 ULX-1 (Liu et al. 2013):

Mbh>5 Msun

ULX P13 in NGC 7793 (Motch et al. 2014):

Mbh<15 Msun

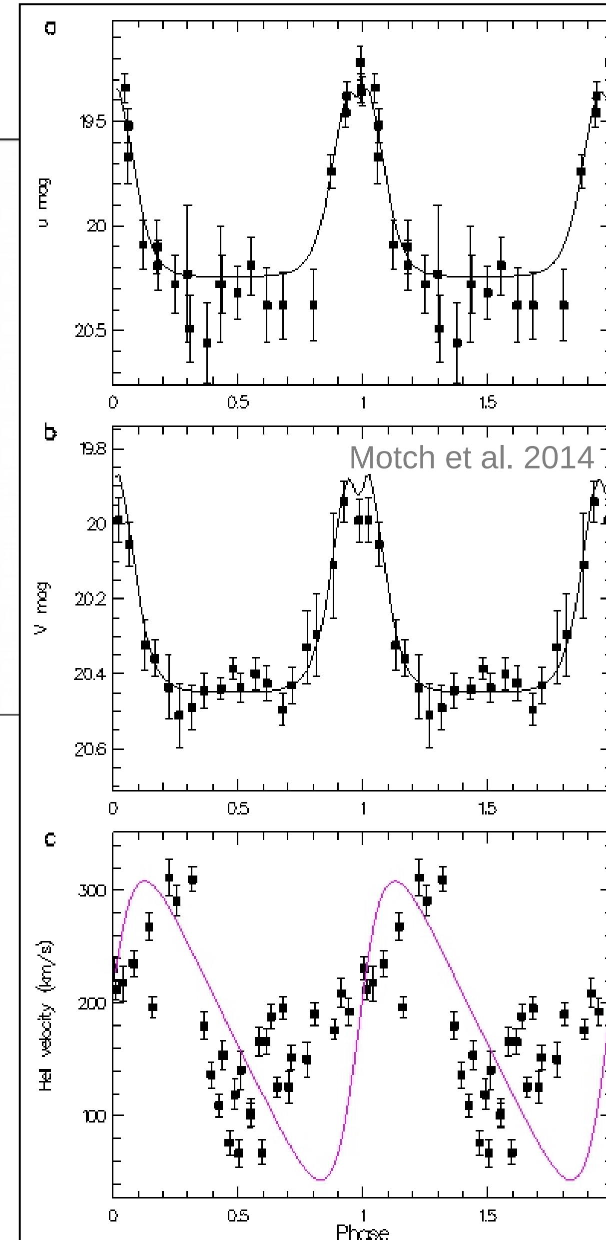




First detection of 3:2 twin QPOs in M82 X-1 (Pasham et al. 2014)

Inverse-mass scaling of the frequencies yields:

Mbh ~ 400 Msun



Typifying the compact object

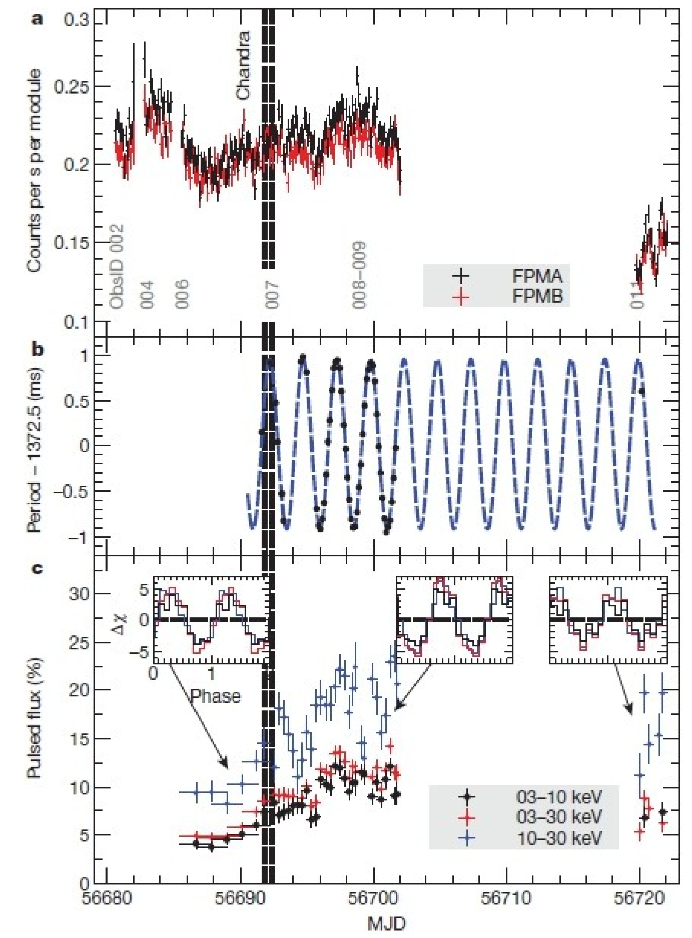
Our present understanding suggests that ULXs are the key to exploring the origin and unknown distribution of BH masses above 10 Msun in the local Universe

Some may even contain the long sought intermediate mass BHs (IMBHs; Colbert & Mushotzky 1999) with mass in excess of 100 Msun (e.g. HLX-1 in ESO 243-49; Farrell et al. 2009)

But … *we now know of a ULX that shows X-ray pulsations and thus contains a neutron star* (*Bachetti et al. 2014*)

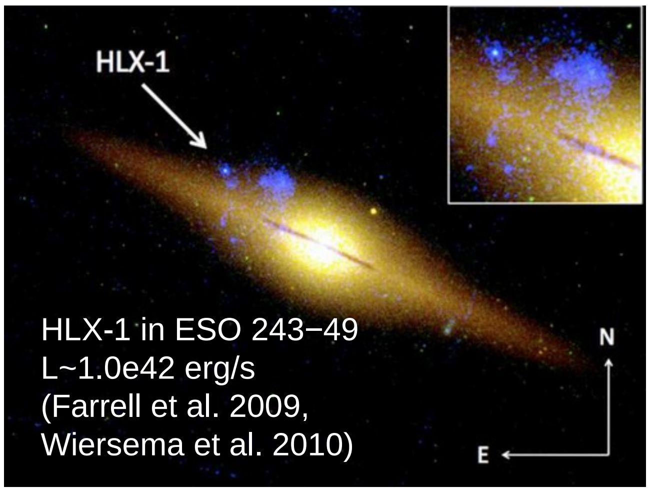
Background-subtracted 3–30 keV light curve detected by NuSTAR from the region containing the transient ULX M 82 X-2 (NuSTAR J09555116940.8) shows a modulated periodicity

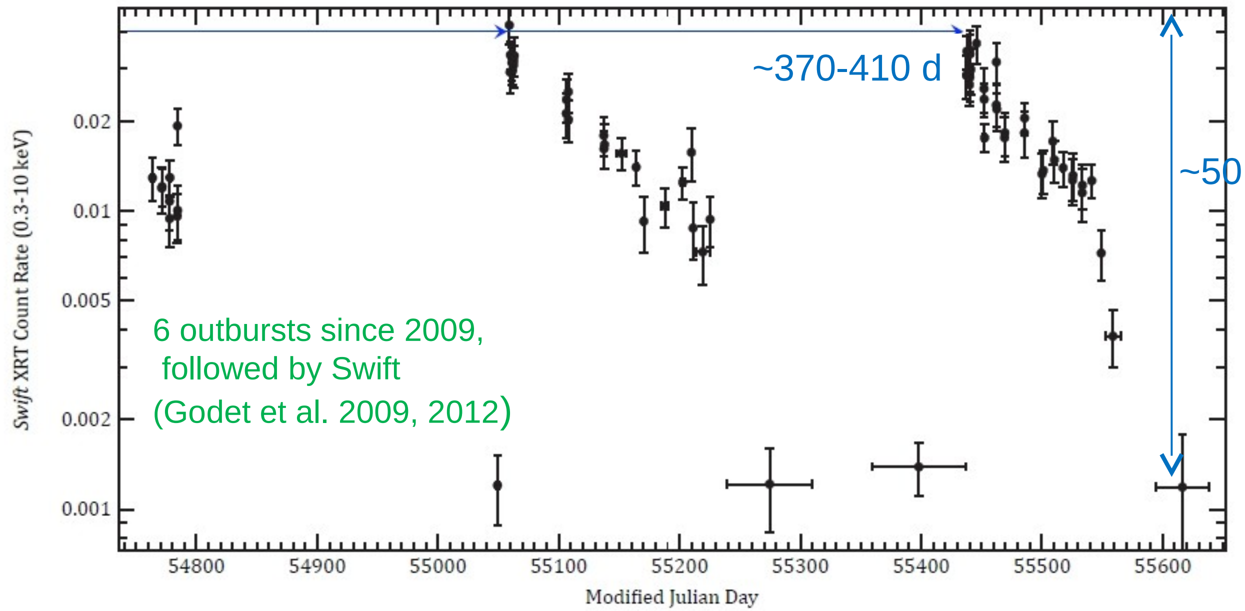
The mean period is 1.37252266(12) seconds, with an orbital modulation period of 2.51784(6) days



Bachetti et al. 2014

IMBH candidates: HLX-1 in ESO 243-49, NGC 2276-3c





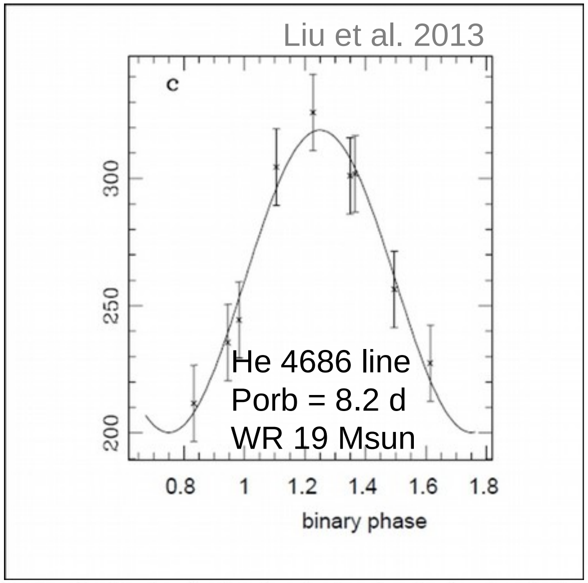
The relatively low disk temperature in the disc-dominated state (0.2-0.3 keV) suggests the presence of an IMBH of a few x 1000 up to a few x 10000 Msun
Detection of ballistic radio jets implies a mass between 9000 and 90000 Msun
(Davis et al. 2011; Godet et al. 2012; Webb et al. 2012)

Light curve timescale difficult to reconcile with thermal-viscous timescale
Interpreted as due to bursts of mass transfer occurring when the donor, in an eccentric orbit, grazes the tidal radius (Lasota et al. 2011)
But disc small for the observed decay time (Soria 2013) and in comparison to that inferred from optical data, and outburst recurrence not strictly periodic

NGC2276-3c (Mezcua et al. 2015)

- 1.8 pc radio jet oriented in the same direction as large-scale (~650 pc) radio lobes
- emission consistent with flat to optically thin synchrotron (1.6-5 GHz)
- Placing the source on the fundamental plane gives: Mbh=50000 Msun

Mass function of M 101 ULX-1 and NGC 7793 ULX P13



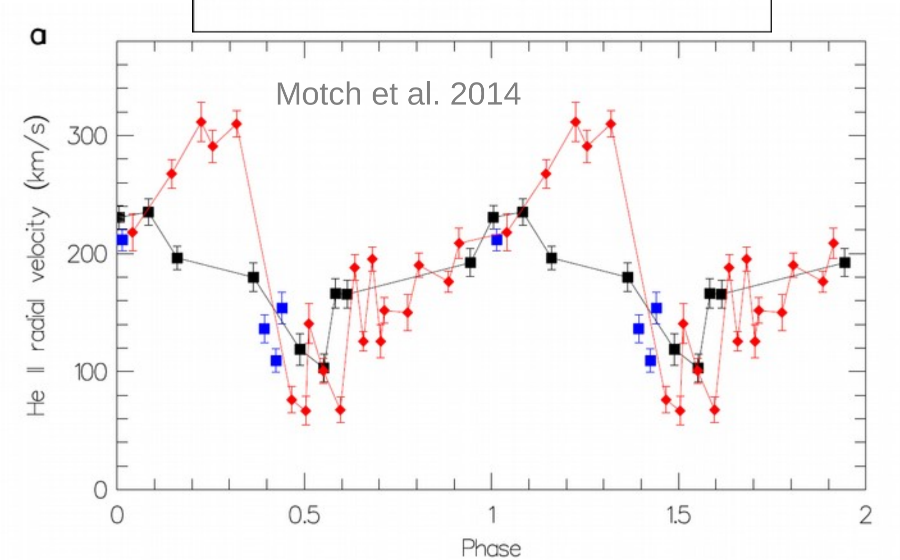
Successful Gemini spectroscopic monitoring of the He II 4686 line in the supersoft source M 101 ULX-1 (Liu et al. 2013):

f=0.18 +/- 0.03 Msun

Mbh>4.6+/- 0.3 Msun

Lmax = 3.0e39 erg/s < 5 Ledd

Warning: Result based on only 9 points

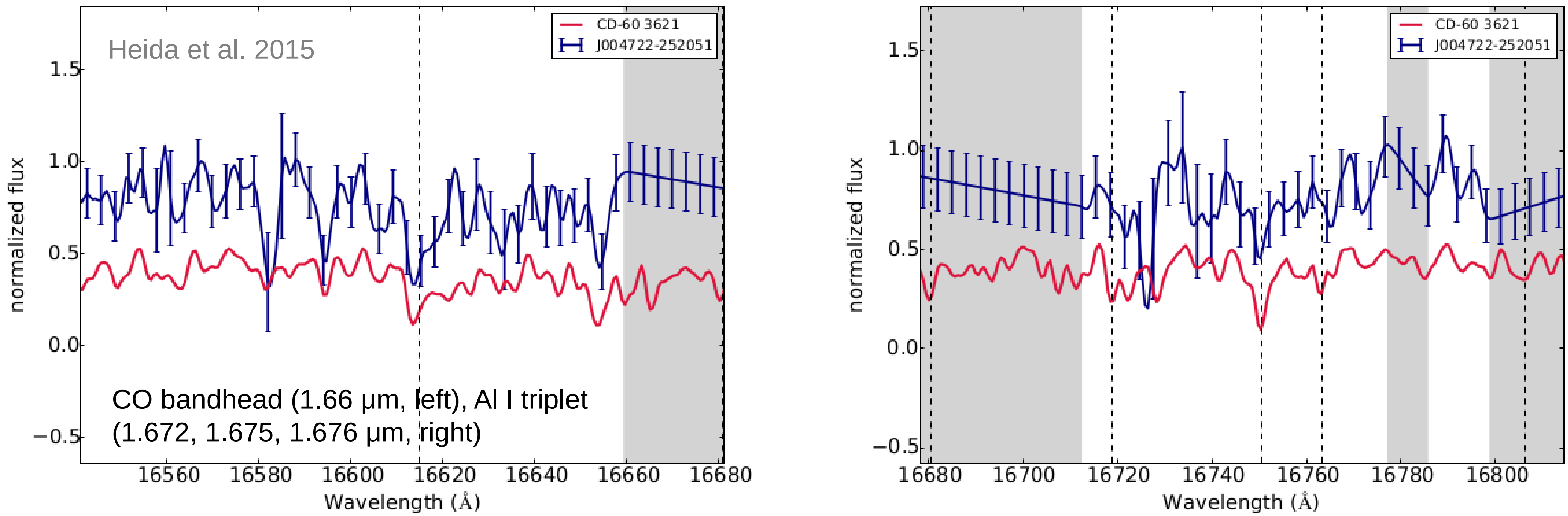


Robust identification of high-order H Balmer absorption lines of the donor and their radial shifts in NGC 7793 ULX P13, but He II 4686 line traces orbital phase better (Motch et al. 2014)
Modelling with the Eclipsing Light Curve code (Orosz & Hauschildt 2000), that takes into account X-ray irradiation, gives

Mbh<15 Msun

Lmax = 5.0e39 erg/s > 2.5 Ledd

Towards a mass function measurement: A red supergiant counterpart to a ULX in NGC 253



NIR spectroscopic follow-up of the ULX with the brightest candidate NIR counterpart (Heida et al. 2014)
VLT/X-shooter spectrum best matched by that of early M-type supergiants (CD-60 3621, red)

- From temperature and absolute K mag, R=600-1600 Rsun
- Assuming M=10 Msun and RLO, P=4.5-20 years

Radial velocity shift: 417 +/- 4 km/s

- confirms that the source is located in NGC 253
- shows an offset with respect to the local bulk motion of the galaxy of 66 +/- 6 km

1) Systemic velocity of the binary → Mbh > 50 Msun
2) Binary motion of the red supergiant → Mbh > 100 Msun (i<60 deg)
Mbh > 50 Msun (i<75 deg; cmp. Pintore et al. 2014)

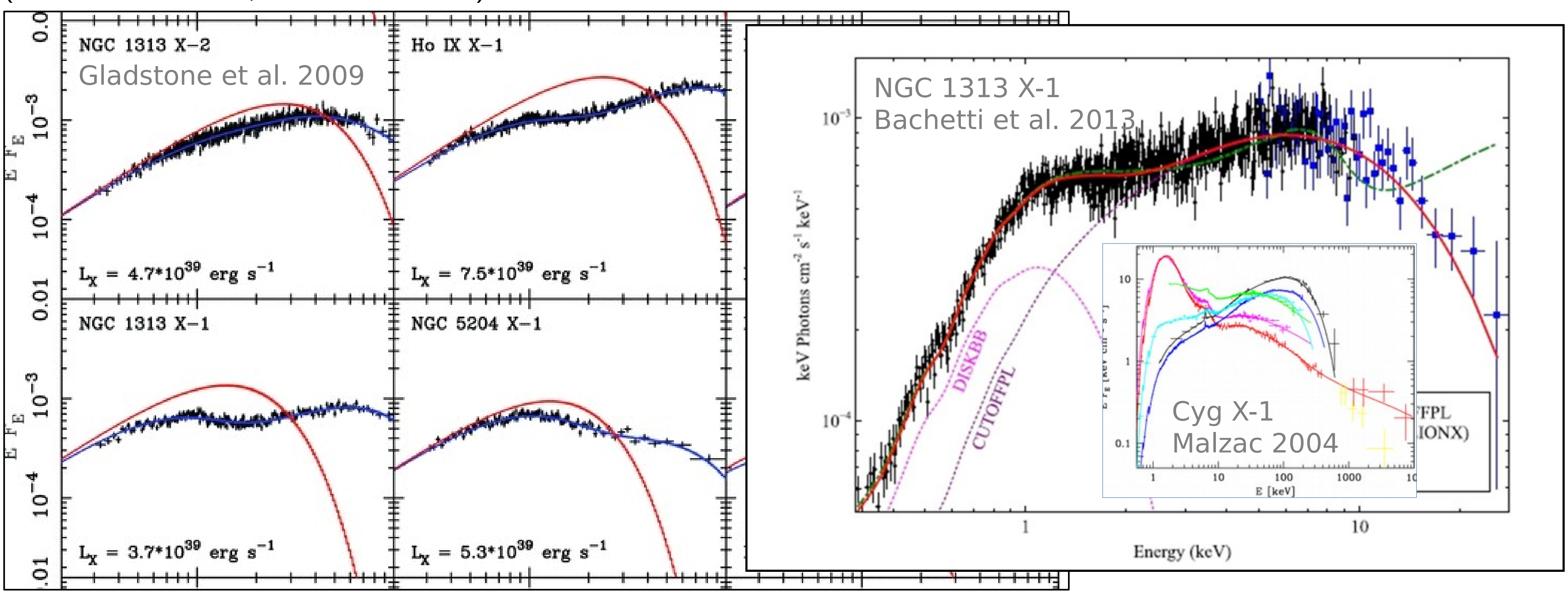
X-ray spectra

Two-thermal component fits of high-counting statistics XMM-Newton data

High quality X-ray spectra essential to clarify subtle but important differences from Galactic BHs
(Goncalves & Soria 2006; Stobbart et al. 2006)

Many ULXs show either curved X-ray spectra or a turnover at ~3-5 keV, sometimes with a soft excess below 1 keV (ultraluminous state; Gladstone et al. 2009)

Two-component thermal models confirmed by broadband XMM+NuSTAR observations
(Bachetti et al. 2013; Walton et al. 2013)

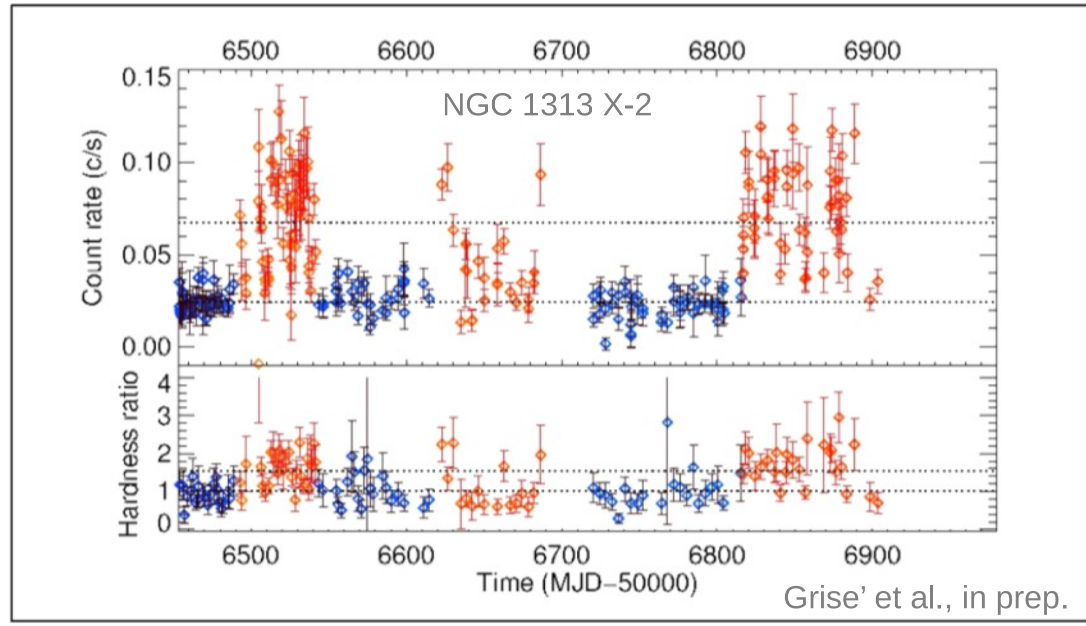


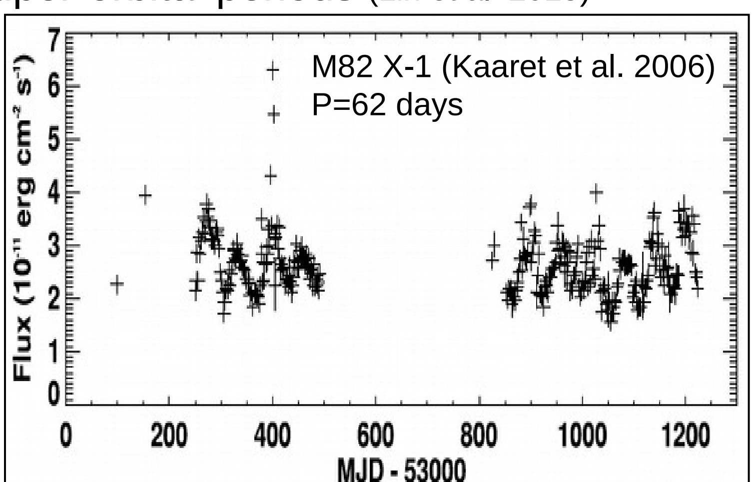
X-ray long-term variability

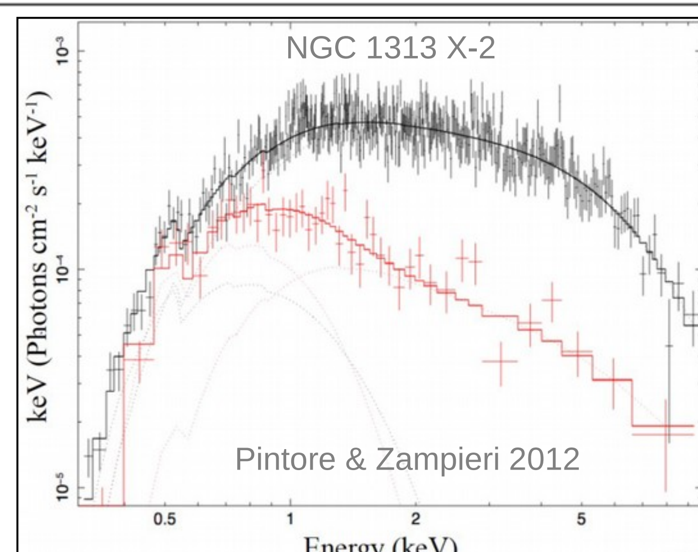
- Hard/soft flux-dependent transitions in Swift, ASCA and XMM data (Kubota et al. 2001; Feng & Kaaret 2006, 2009; Kajava & Poutanen 2009; Kong et al. 2010; Pintore & Zampieri 2012; Pintore et al. 2014, 2015)

- Swift/XRT monitoring clearly identified structured long-term variability by a factor up to 5-10, with flux-dependent flaring activity

- Long term modulations searched in Rossi/RXTE and Swift/XRT data → quasi-periodicities possibly related to super-orbital periods (Lin et al. 2015)







Hard/high to soft/low transitions

X-ray long-term variability

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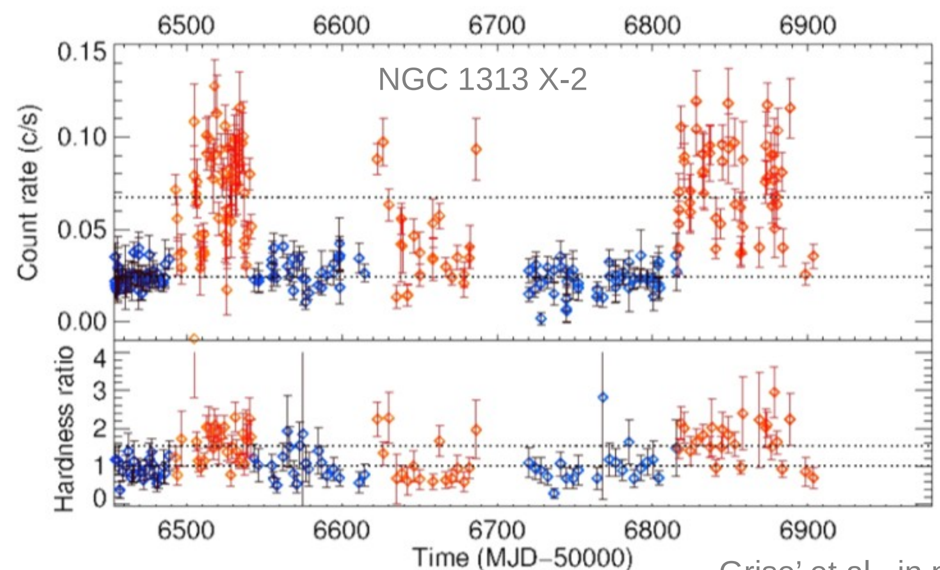
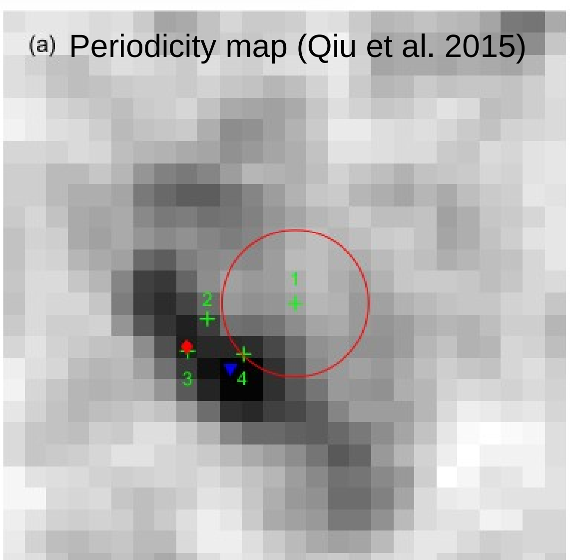
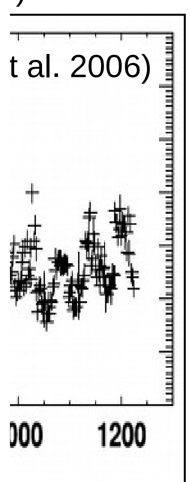
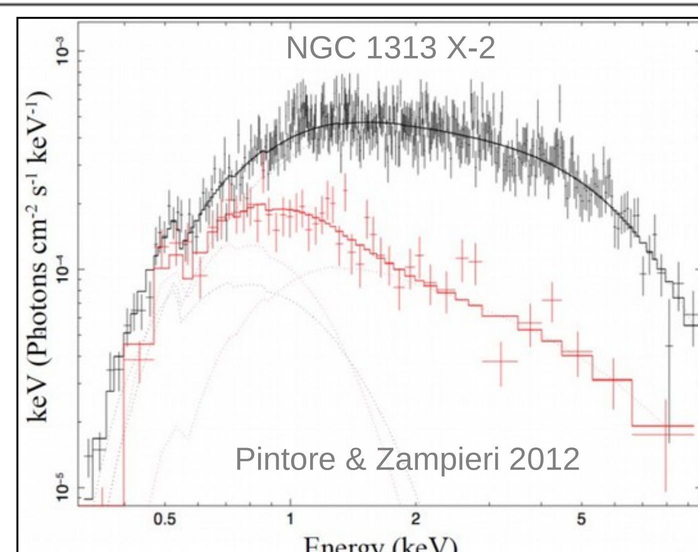


Grise' et al., in prep.







Pintore & Zampieri 2012

Hard/high to soft/low transitions

X-ray long-term variability

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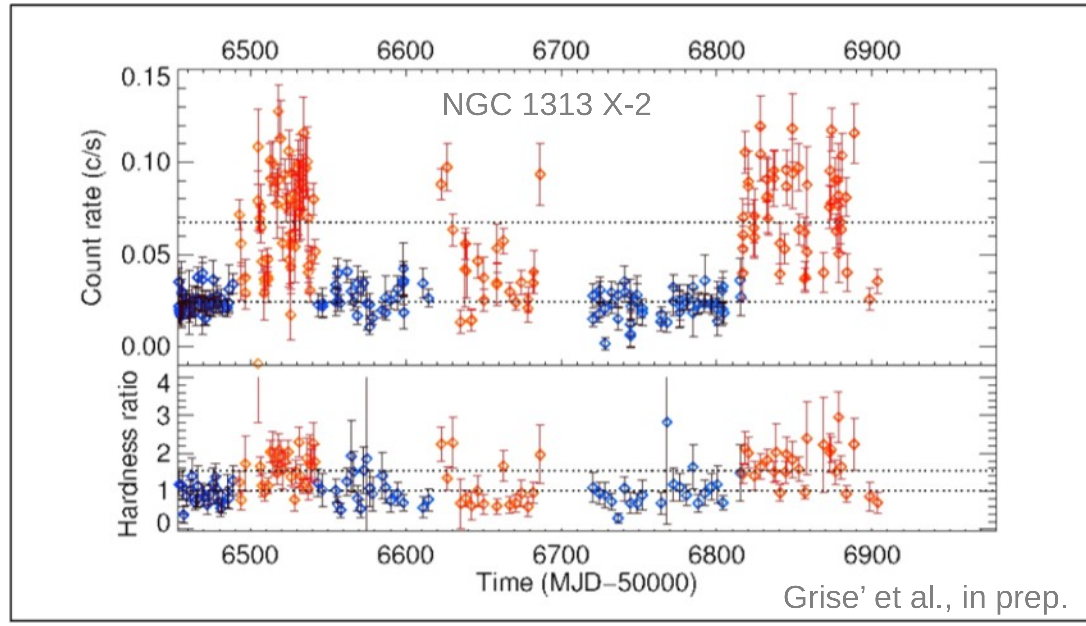

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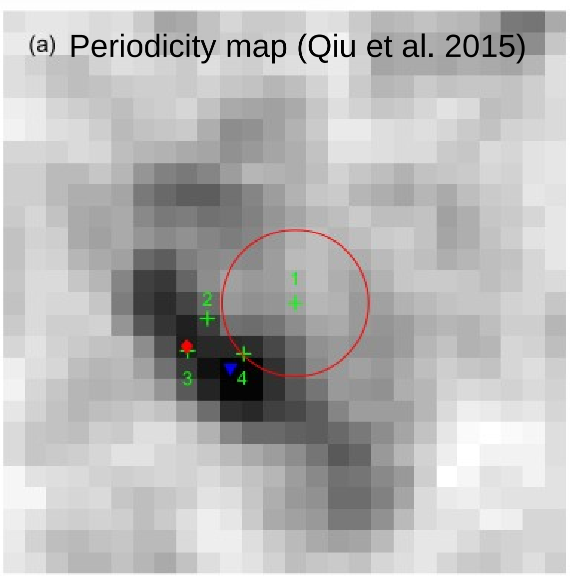
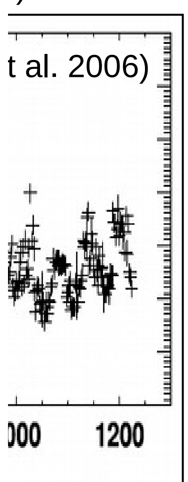
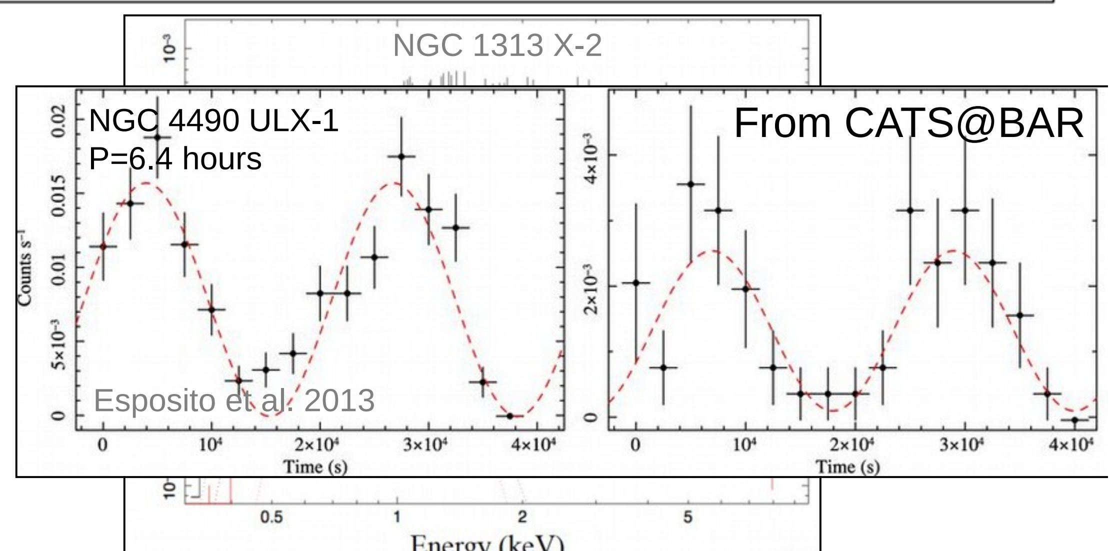
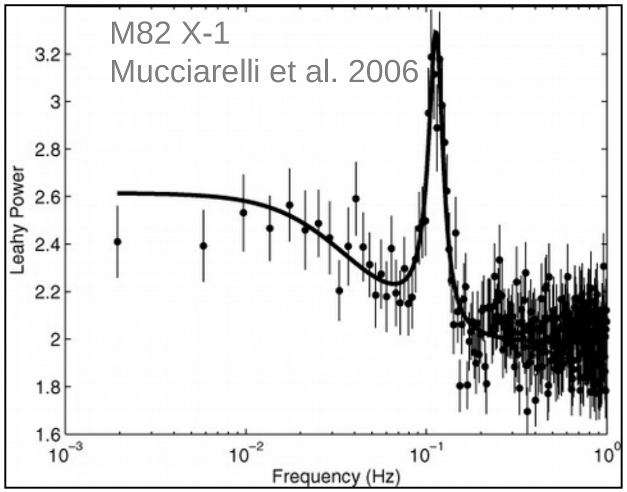






X-ray short term variability

Significant variability (including QPOs and broad band noise) ...

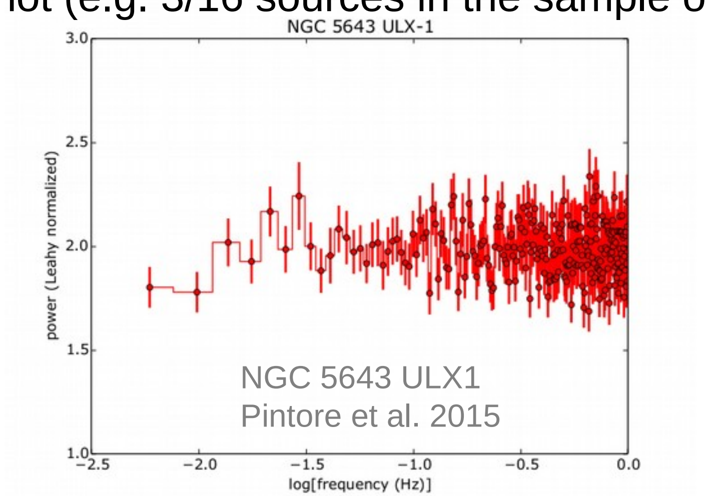


QPOs+broad band noise in 4 ULXs

M82 X-1	54-166 mHz
	3.32 and 5.07 Hz
NGC 5408 X-1	20 mHz
IC 342 X-1	642 mHz (3.6 sigma)
M82 X-2 (X42.3+59 in M82)	3-4 mHz

(Strohmayer & Mushotzky 2003; Pasham et al. 2014; Strohmayer et al. 2007; Agrawal & Nandi 2014; Feng et al. 2010)

… or not (e.g. 3/16 sources in the sample of Heil et al. 2009)?



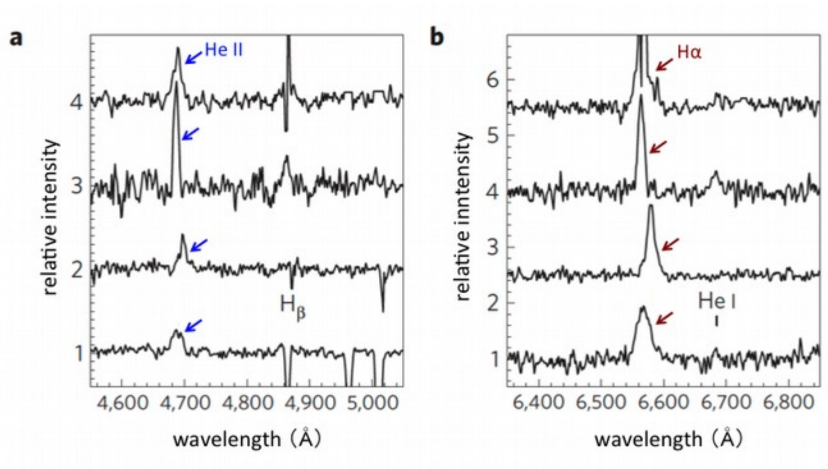
Linear rms-flux relation at E>1 keV

NGC 5408 X-1, NGC 6946 X-1
Accr. rate fluctuations (Hernandez-Garcia et al. 2015)?

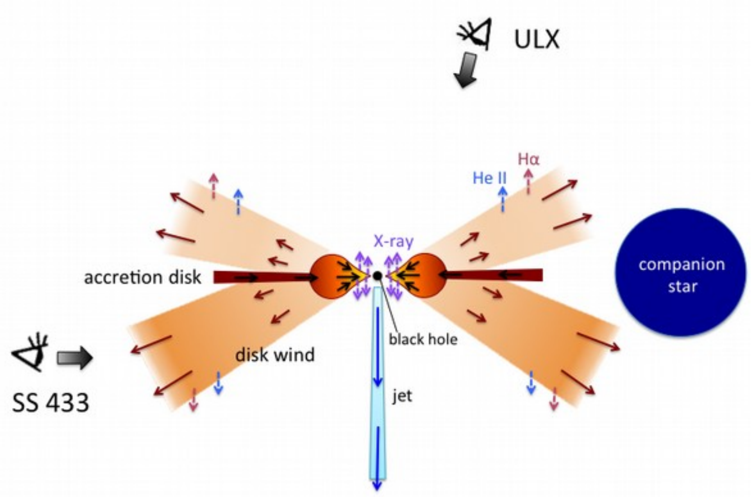
Soft lag (10s) at a few mHz in 5408 X-1
(De Marco et al. 2013)

No signature of reflection in the spectra → not induced by reverberation of coronal emission in the inner disc

Stellar optical counterparts: High-quality spectra with the FOCAS@Subaru



Fabrika et al. 2015



Credit Kyoto University

High-quality spectra with FOCAS at Subaru for 4 nigths
(Fabrika et al. 2015)

Optical counterparts spectroscopically observed exhibit spectra similar to those of WN 9–11 stars

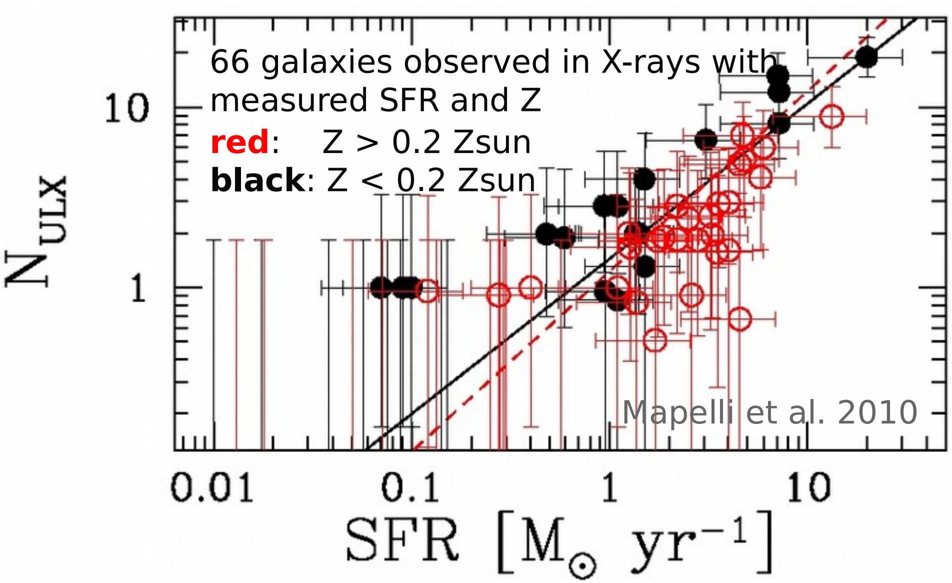
Broad He II 4686 (average FWHM 870 km/s) and
H alpha (average FWHM 1000 km/s) emission lines
are detected

Rapid variability of the He II linewidth in WN 9–11 stars is difficult to explain, because the wind terminal velocity in stars is determined by the surface gravity

Lines are formed in different parts of radiatively accelerated disc winds forming at or above Eddington. Ionized gas located closer to the source has smaller outflow velocities (similar to what observed in SS433)

These findings suggest that the gas must be accelerated outward as a wind from a disc accreting above Eddington, and cools down as it escapes

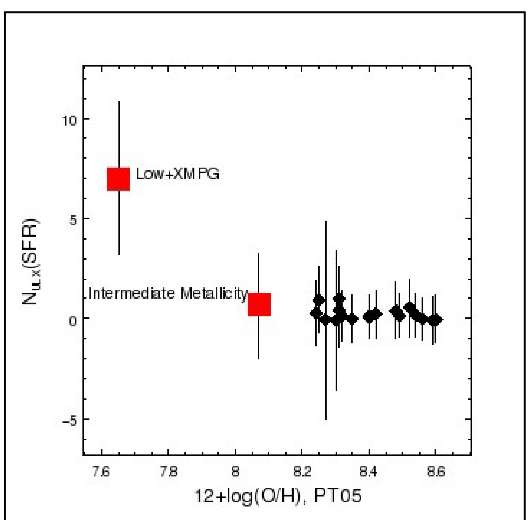
Host galaxy environment: strong dependence on SFR and preferential association to low Z



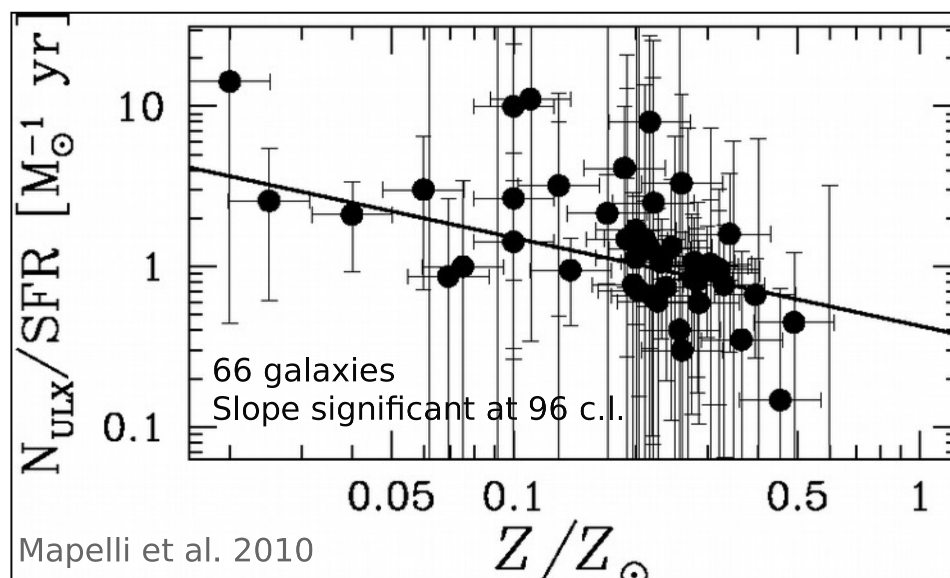
Strong correlation between number of ULXs per galaxy (Nulx) and star formation rate (SFR), as for Galactic high mass X-ray binaries
(Grimm et al. 2003; Mineo et al. 2012)

Specific ULX frequency decreases with increasing host galaxy mass indicating that <u>smaller, lower metallicity systems have more ULXs per unit mass</u>
(Swartz et al. 08; Walton et al. 2011)

Line intensities of HII region give Z=0.1-0.5 Zsun and <u>marginal anticorrelation of Nulxs/SFR vs Z</u>



Compared to a comparison sample of high Z Spitzer IR galaxies, low Z and Extremely Metal Poor galaxies are more likely to host a ULX (at the 2.3 sigma c.l.; Prestwich et al. 2013)



Super-Eddington accretion and non-standard discs

Highest mass of BHs that can form through single-star core-collapse (Heger et al. 2003; Belczynski et al. 2010):

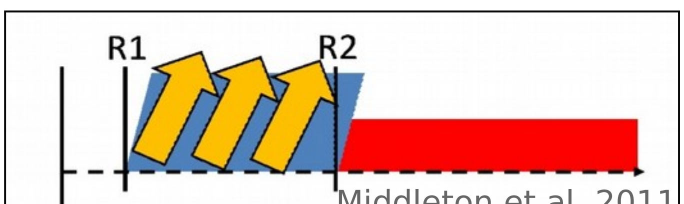
Mbh ~ 25-80 Msun ⇒ Ledd ~ 2.0e39-1.0e40 erg/s (isotropic)

Even allowing for massive BHs up to 80 Msun, ULXs emitting above 1.0e40 erg/s have L > Ledd and hence are accreting in a non-standard way

This is even more true for M82 X-2, the ULX with a NS

The accretion rate needed to sustain the observed luminosity and/or configuration most likely requires accretion to proceed at superEddington rates

The ultraluminous state is interpreted as the characteristic spectral imprint of an unusual accretion state at Mdot >~ MdotEdd (e.g. Gladstone et al. 2009; Sutton et al. 2013, Pintore et al. 2014)



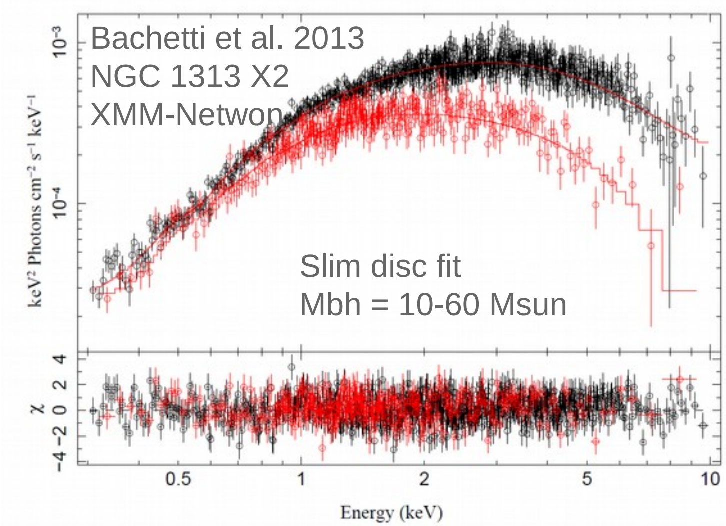
Significant dependence on inclination to line of sight and mass accretion rate (Middleton et al. 2015)

Lab for the study of extreme accretion environments (where photon trapping effects become important), relevant for first generation of Quasars at very high redshift

Super-Eddington accretion and non-standard discs

1D (vertically integrated) model of super-critical accretion discs: *slim discs* (Abramowicz et al. 1988; Begelman 2002; Ebisawa et al. 2003; Kawaguchi 2003)

Mbh = 7.5-75 (L/10^{40} erg/s) **Msun**
L_{slim} = 1-10 Ledd

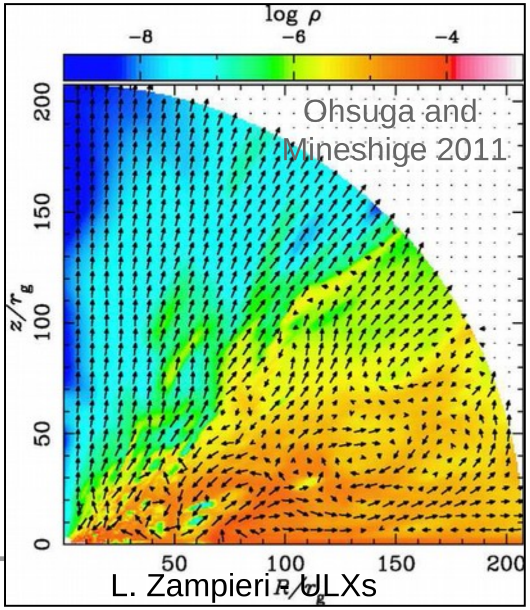


First introduced to account for energy advection and used to explain peculiar evolution of some high L phases of BH transients (e.g. GRS 1915+105)

They work reasonably well in some ULXs

Onset of wind not included in 1D slim disc models

2D magneto-hydro simulations (e.g. Ohsuga and Mineshige 2011)



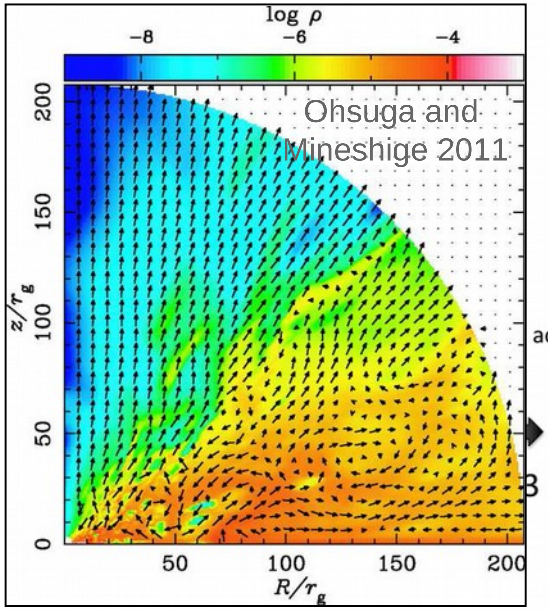
Disc and outflow region, with powerful winds driven by radiation pressure

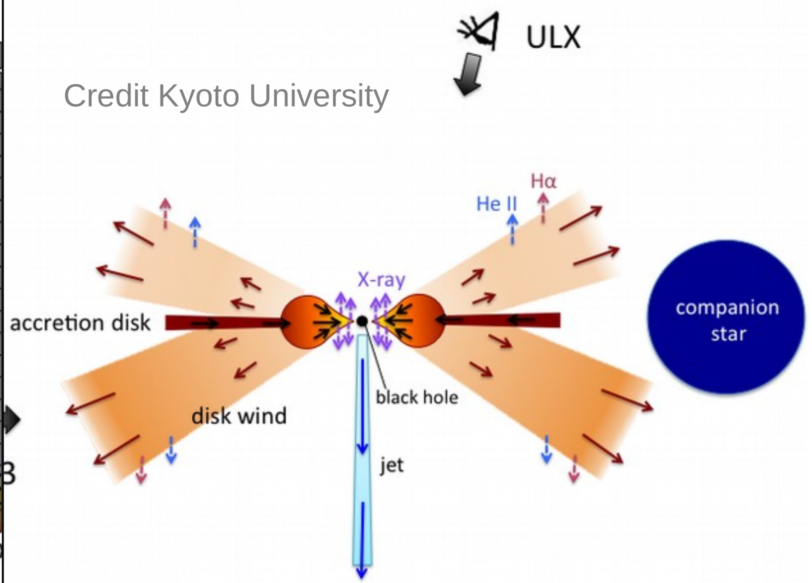
In the inner disk the density is greatly reduced, whereas T hardly changes

(Local) emergent spectra may not sensitively depend on mass outflow

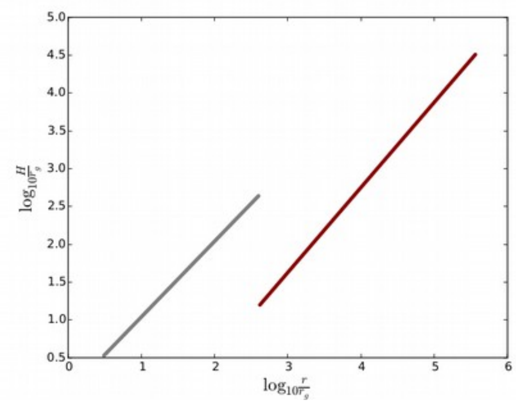
Super-Eddington accretion and non-standard discs

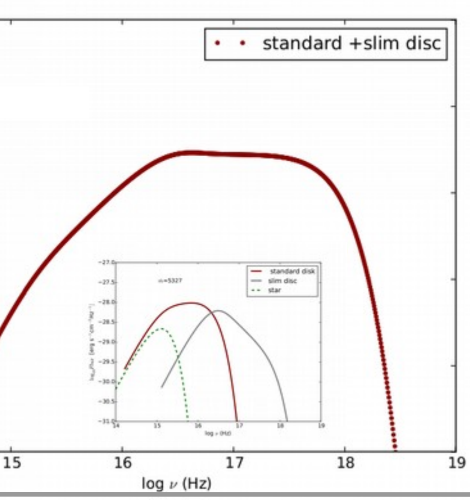
Approximate multiwavelength model of super-Eddington emission (Ambrosi & Zampieri 2015)





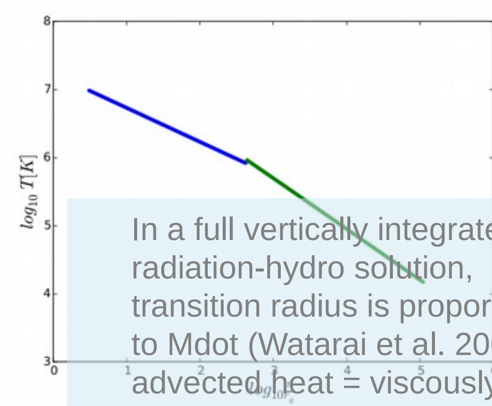
Geometry mimics the innermost part of accretion disc from 2D magneto-hydro simulations





Disc+donor emission with irradiation (Copperwheat et al. 2005; 2007; Mucciarelli et al. 2007; Grise' et al. 2012)

X-ray illuminated plane-parallel atmosphere in radiative equilibrium (e.g. Wu et al. 2001)



In a full vertically integrated radiation-hydro solution, transition radius is proportional to Mdot (Watarai et al. 2000; advected heat = viscously dissipated heat)

Formation and evolution of ULX binary system

Assessing formation of a ULX BH binary

Linden et al. 2010: In isolation through population synthesis codes (StarTrack; Belczynski et al. 2008)

Mapelli et al. 2011, 2013: In a cluster through n-body code (STARLAB; Portegies Zwart et al. 2001)

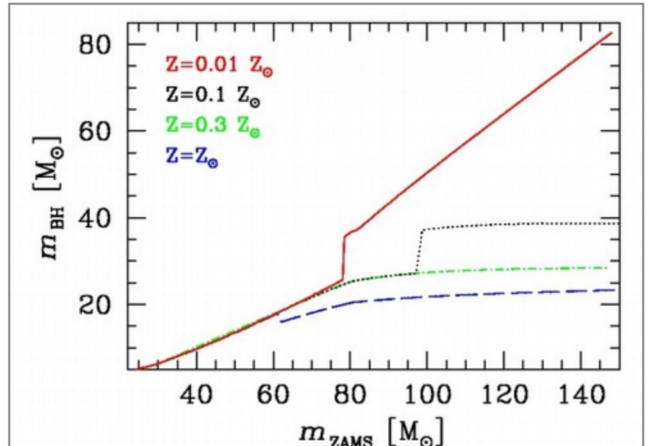
Metallicity dependence of mass loss (Vink et al. 2001) and massive BH formation (Belczynski et al. 2010) included

Difficult to form RLO ULX binaries with massive BHs in isolation

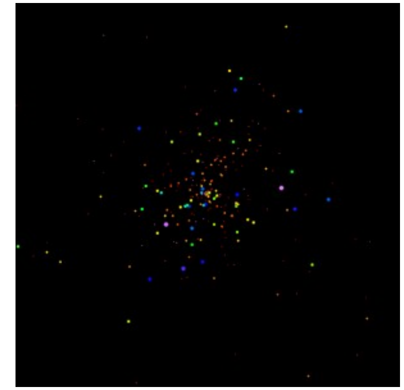
But in young clusters with low-Z, 3-body encounters and dynamical exchanges change the evolution of massive BHs
Both BHs and massive BHs can power RLO ULXs

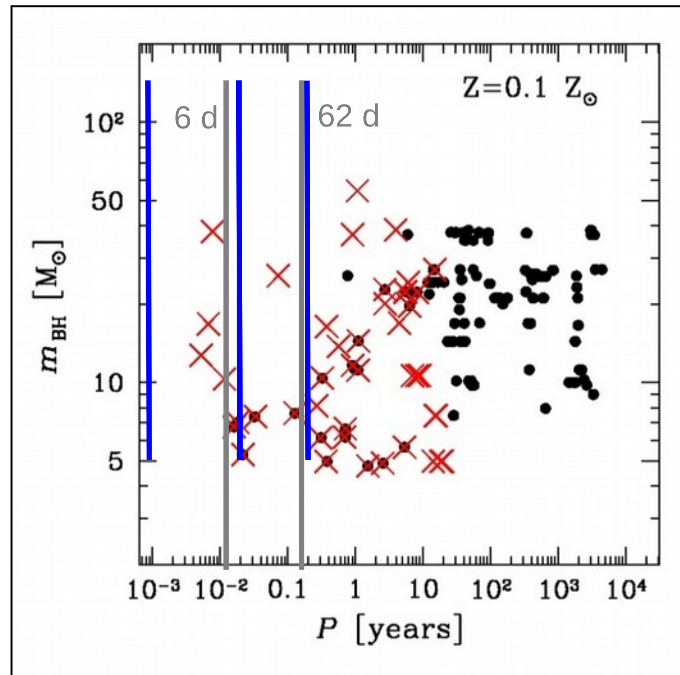
Agreement with observed offset of ULXs from parent clusters (Zezas et al. 2002; Kaaret et al. 2004; Poutanen et al. 2013; Berghea et al. 2013)

Ejected BHs/MSBHs in binaries that undergo RLO: 1%



Mapelli et al. 2013





Modelling the multiwavelength emission of a ULX binary

ULX BH binary models compared to multiwavelength SED of ULXs and their counterparts

Disc+donor emission with irradiation, *standard disc assumed* (Copperwheat et al. 2005; 2007; Mucciarelli et al. 2007; Grise' et al. 2012)

Stellar+binary evolution (Madhusudhan et al. 2008; Patruno & Zampieri 2008, 2010)

ULX binaries are:

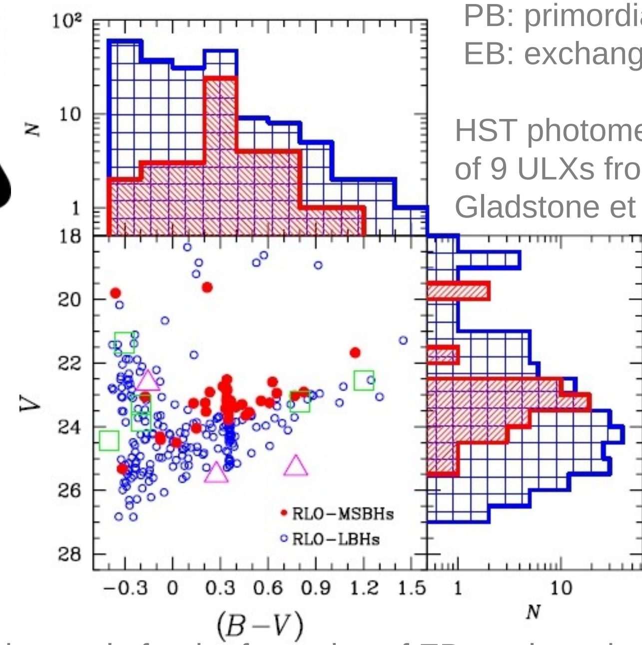
a) Short-period binaries with MS/post-MS donors

b) Long-period binaries with more evolved donors and extended discs

Caveat: Extended emission nebulae observed around many ULXs have kinematic ages of about 1 Myr

They have enough time to form in case (a), but also in case (b) if the system underwent a previous contact phase (during MS) or the donor is burning He in the core

Mapelli & Zampieri 2014
PB: primordial binaries
EB: exchange binaries



HST photometry of 9 ULXs from Gladstone et al. 2009

The timescale for the formation of EBs so long that massive donors are gone when conditions for RLOF occur

Cluster evolution and Z-dependent stellar evolution (Mapelli & Zampieri 2014)

Blue counterparts mostly associated to PBs and stellar-mass BHs

EBs mostly associated to older and less massive donors - Massive BHs are a sub-class of EBs

The future

IR/Optical/UV monitoring

Intensive photometric and spectroscopic monitoring for other measurements of mass function

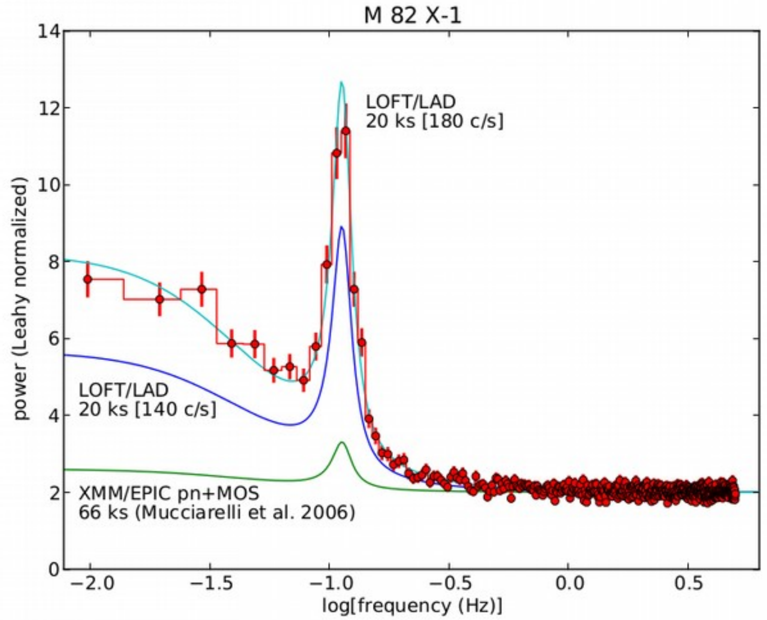
Swift monitoring

Estimate contribution of X-ray irrad.
Characterize long-term variability

LOFT

Transient ULX detection with LOFT/WFM in 50 ks:
L~1.0e41 erg/s
up to D~4 Mpc

1 every few years
(Orlandini et al. 2015)



Athena

Deep high resolution observations will allow to study the energy, power density and rms-energy spectra of at least ~100 ULXs at a level presently attained for the brigthest 10 (Motch et al. 2015)

Unprecedented spectral resolution will be instrumental to detect narrow features produced by winds/outflows

SKA

If they host IMBHs, ULXs should radiate below Eddington, showing accretion states with timing properties similar to Galactic BHs

Synergies between X-ray facilities and SKA to jointly monitor radio/X-ray variability (Wolter et al. 2014)

Conclusions

2 ULXs have dynamical constraints on the mass of the BH:

Mbh < 15 Msun	**Mbh > 5 Msun**
L/Ledd > 2.5	**L/Ledd < 5**

New measurements of the mass function, through a joint IR/optical+X-ray monitoring, deeply needed

BHs of stellar origin with super-Eddington accretion can account for the majority of ULXs (origin of BH and mode of accretion are related)

Only a very limited number of ULXs shows some evidence in favour of an IMBH
But there is one even containing a NS

What next?

Efforts to model emission from non-standard super-Eddington accretion (and to understand the role of low metallicity in BH formation)

Good progress in modelling the evolution of ULX binary systems including dynamical effects in their natal clusters. Accurate predictions of their multiwavelength emission properties under way

Future facilities will hopefully allow us to:

- detect radio counterparts/jets for a characterization of the accretion states
- perform high resolution X-ray spectroscopy to test the existence of winds
- [understand the timing properties and search for periodicities and transient ULXs]