Investigating Ultraluminous X-ray Sources through multi-wavelength variability, broadband spectra, and theoretical modelling

Luca Zampieri
INAF-Astronomical Observatory of Padova

In collaboration with:
Elena Ambrosi, Amid Nayerhoda (*University of Padova*)

Outline

- Some basic facts on Ultraluminous X-ray sources (ULXs)
- The compact objects in ULXs
- Black Holes and accretion regime in ULXs
- Model for investigating multi-wavelength variability in ULXs

Ultraluminous X-ray sources (ULXs)

What do we know?

- *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

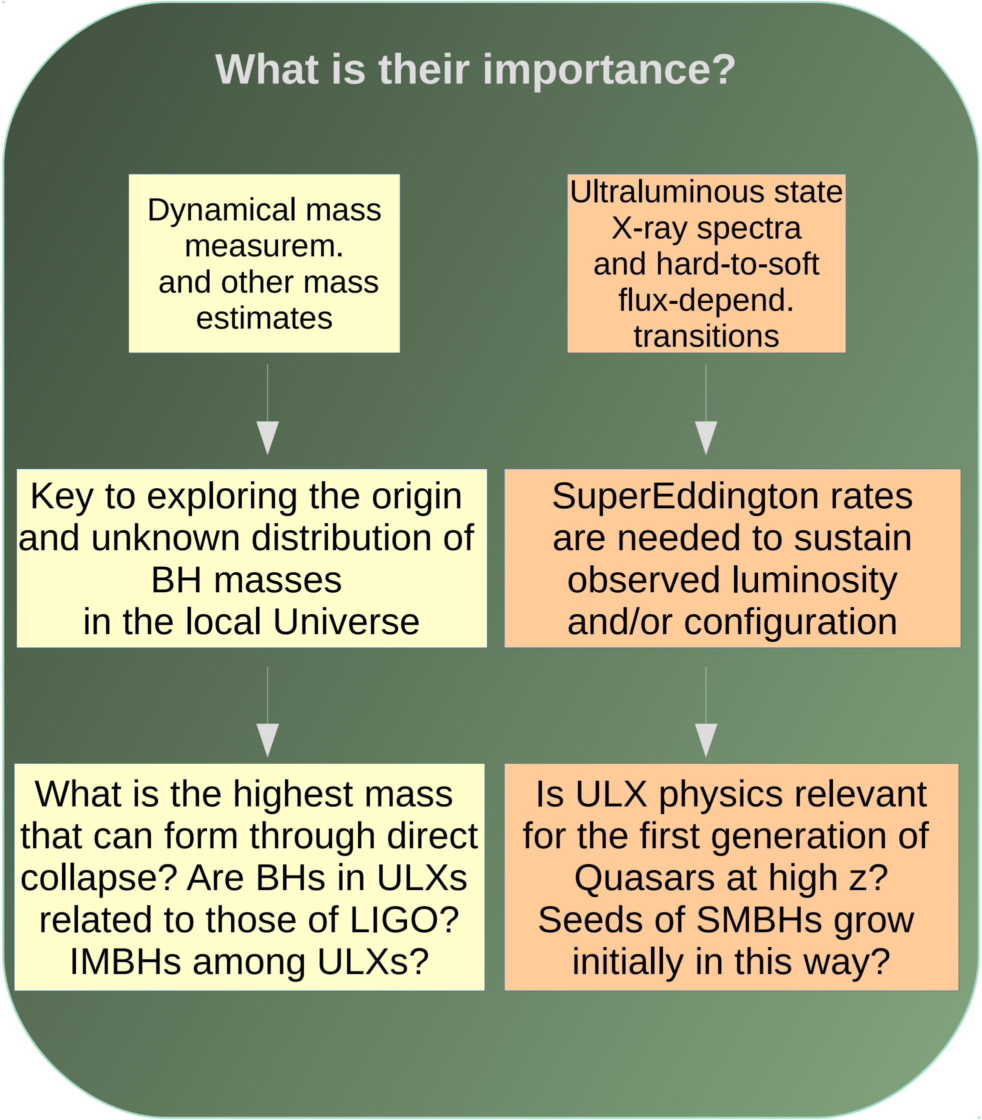
Chandra: Swartz et al. 2011
XMM-Newton: Walton et al. 2011

∼ 20% Background AGNs

∼ 5% Supernovae interacting with circumstellar medium

60-70% Accreting binaries

What is their importance?



Dynamical mass measurem. and other mass estimates

Key to exploring the origin and unknown distribution of BH masses in the local Universe

What is the highest mass that can form through direct collapse? Are BHs in ULXs related to those of LIGO? IMBHs among ULXs?

Ultraluminous state X-ray spectra and hard-to-soft flux-depend. transitions

SuperEddington rates are needed to sustain observed luminosity and/or configuration

Is ULX physics relevant for the first generation of Quasars at high z? Seeds of SMBHs grow initially in this way?

Accreting compact objects with significantly different masses

First measurements of a mass function in ULXs

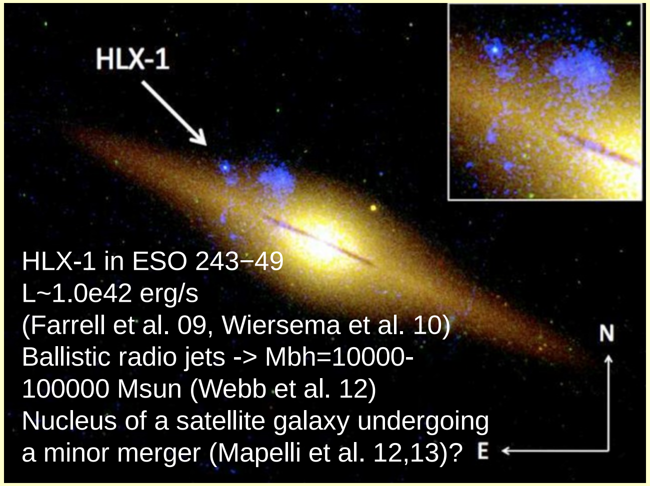
M 101 ULX-1 (Liu et al. 2013)**:**

Mbh > 5 Msun

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

Mbh < 15 Msun

Intermediate mass Black Holes?

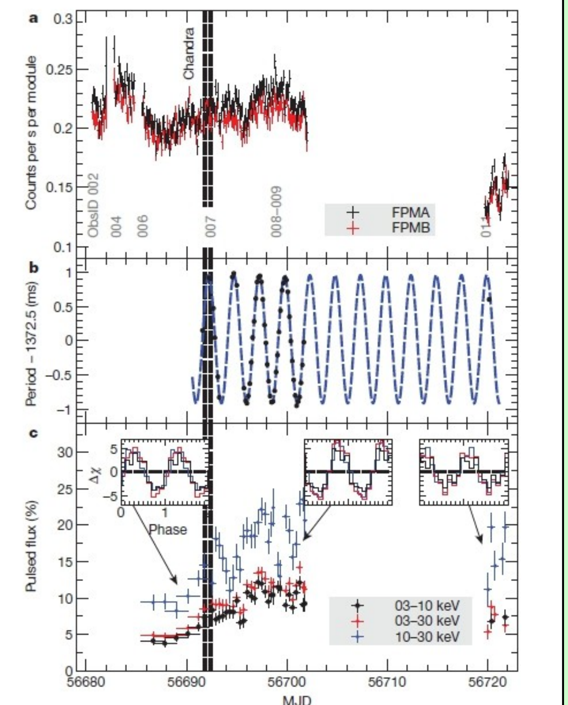


HLX-1 in ESO 243–49
L~1.0e42 erg/s
(Farrell et al. 09, Wiersema et al. 10)
Ballistic radio jets -> Mbh=10000-100000 Msun (Webb et al. 12)
Nucleus of a satellite galaxy undergoing a minor merger (Mapelli et al. 12,13)?

An ultraluminous accreting pulsar!

A modulated periodicity detcted in the background-subtracted 3–30 keV **NuSTAR** light curve of **M 82 X-2** (Bachetti et al. 2014)

Mean period: 1.37252266(12) s
Orbital modulation: 2.51784(6) d



Bachetti et al. 2014

Present census

- Compact objects with small mass:
1 BH with Mbh<15 Msun and 1 NS

- More massive BHs:
1 BH with MBH>5 Msun and 1 IMBH candidate

NGC 7793 P13
L/Ledd > 5-10 Ledd

M 101 ULX-1
L/Ledd < 5

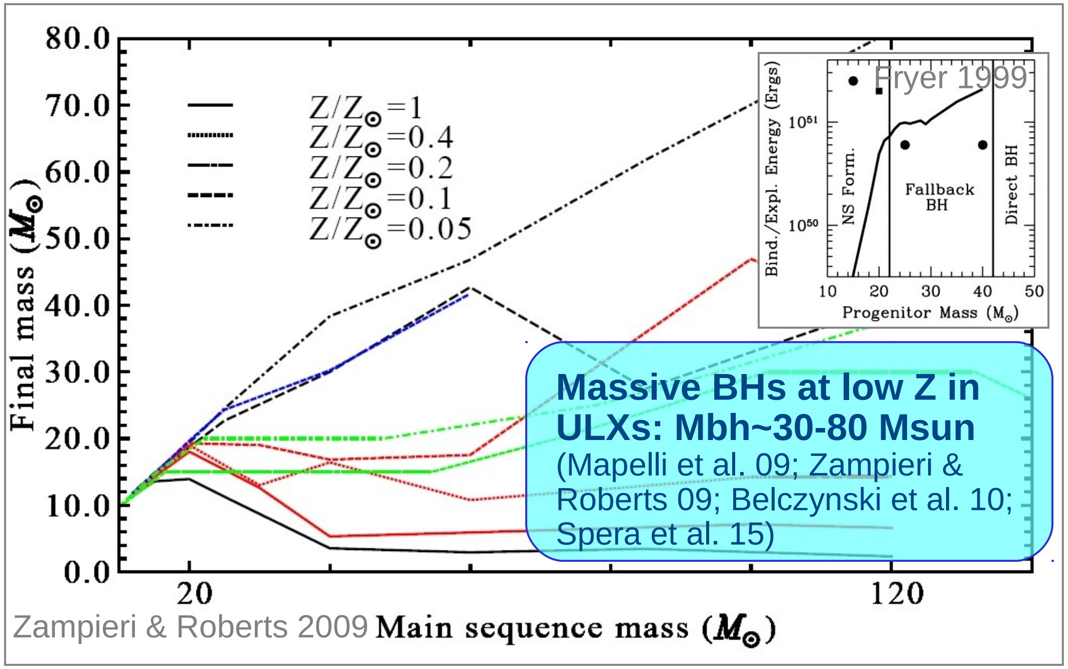
M82 X-2
L/Ledd = 100

ULXs: Masses and binary evolution

ULXs host accreting compact objects with significantly different masses

After the discovery of **GW150914**, we know that massive (30 Msun) BHs exist! Could BHs in the same mass range (20-100 Msun) be hosted also in ULXs?

Possible evidence comes from the association of ULXs with low metallicity environments (Swartz et al. 08; Mapelli et al. 2010; Walton et al. 2011; Prestwich et al. 2013), where it may be possible to form massive BHs through direct collapse

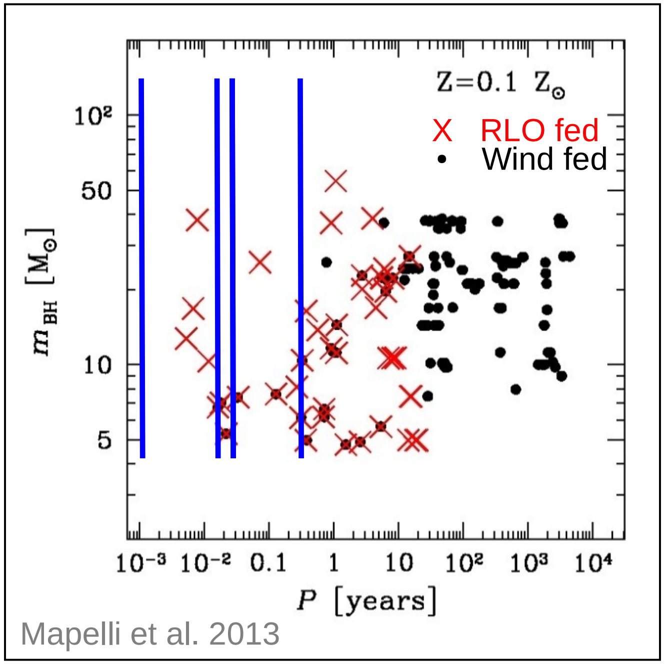


Fryer 1999

Massive BHs at low Z in ULXs: Mbh~30-80 Msun
(Mapelli et al. 09; Zampieri & Roberts 09; Belczynski et al. 10; Spera et al. 15)

Zampieri & Roberts 2009

Is it possible that massive (and also stellar-mass) BHs undergo a Roche-lobe-fed active ULX phase?



Mapelli et al. 2013

Binary evolution in a cluster with Z-dependent stellar evolution (Mapelli et al. 13; Mapelli & Zampieri 14)

Difficult to form ULX binaries with massive BHs in isolation (Linden et al. 2010), but not in young low-Z clusters

Dynamical interactions change their evolution

Both stellar-mass and massive BHs can power Roche-lobe-fed ULXs

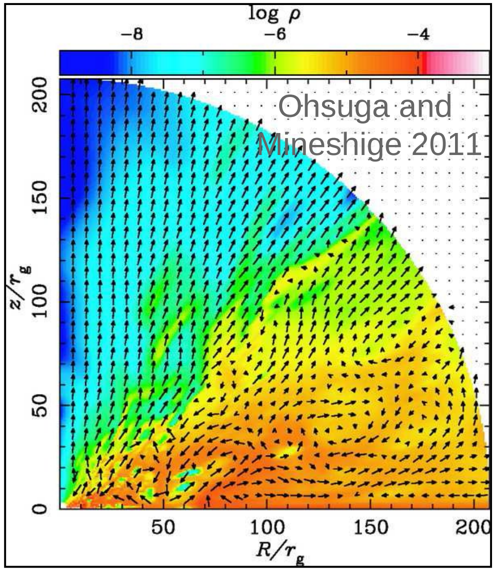
ULXs: Super-Eddington rates

Besides the nature of their compact objects, *the other challenge of ULXs is the character of their accretion flow*, able to deliver luminosities 10-100 times larger than Ledd

$$L_{max} \approx b \cdot 10^{40}\,\mathrm{erg/s}$$
$$\dot{M} = L_{max}/(\eta c^2) \approx 10^{20}\, b\,(0.1/\eta)\,\mathrm{g/s}$$

For reasonable beaming factors (b>0.1), Mdot is in excess of MdotEdd for a 10 Msun BH (1.0e19 g/s)

What is the accretion physics for stellar-mass BHs or NSs emitting at this pace?
Lab for extreme accretion environments (where photon trapping becomes important), relevant for first Quasars at very high z



Ohsuga and Mineshige 2011

Supercritical accretion onto BHs

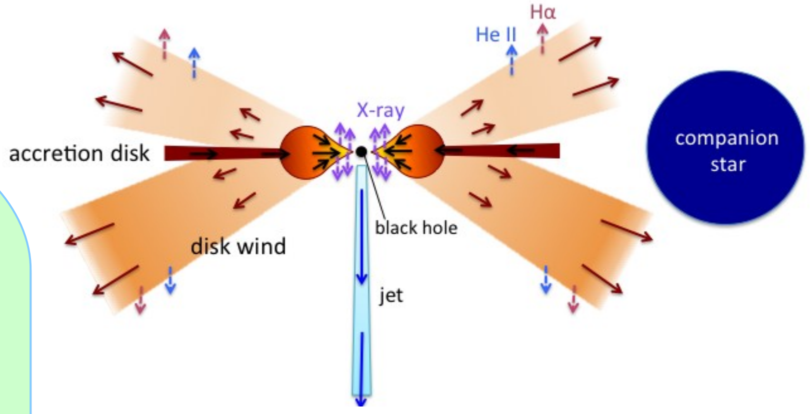
2D magneto-hydro simulations show an advection-dominated disc and an outflow region, with powerful clumpy winds driven by radiation pressure (e.g. Ohsuga and Mineshige 2011, Takeuchi et al. 2013, 2014)

It can explain some basic facts concerning the X-ray spectral components and the short-term variability at high energies observed in some ULXs (Sutton et al. 2013; Pintore et al. 2014, Middleton et al. 11, 15)

Supported also by the detection of *emission lines and blueshifted (0.2c) absorption lines from highly ionized Fe, O and Ne* in the high-resolution X-ray spectra of NGC 1313 X-1 and NGC 5408 X-1, although with cumulative significance only slightly above 5 sigma (Pinto et al. 2016)

A comprehensive multi-wavelength variability model

***Goal**: Investigate the complex emission expected at super-Eddington rates and constrain the physical properties of ULXs*



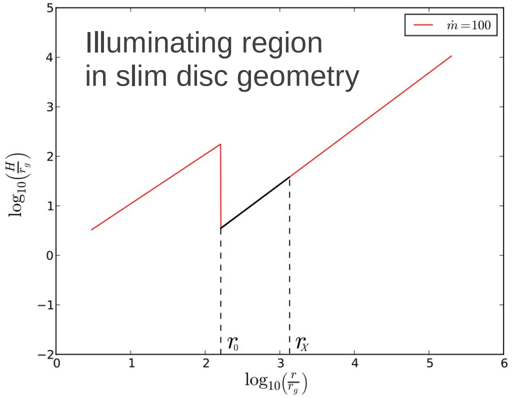
Calculation of the optical-through-X-ray emission of ULX binaries during their evolution, accounting for super-Eddington accretion (Ambrosi & Zampieri 2016)

Starting point: model of Patruno & Zampieri (2008, 2010)

Bimodal structure assumed if Mdot > MdotEdd:
Inner flow with non-standard (slim) disc geometry (H ~ r) and temperature profile (T proportional to $r^{-1/2}$)

Transition radius to standard disc (e.g. Watari et al. 2000):
r0/rg = Mdot/MdotEdd
where advected heat = viscously dissipated heat

Outflows included at Mdot > MdotEdd (Poutanen et al. 2007)



Ambrosi & Zampieri 2016

Calculation of the optical light curve assuming different irradiation geometries (Nayerhoda & Zampieri 2016)

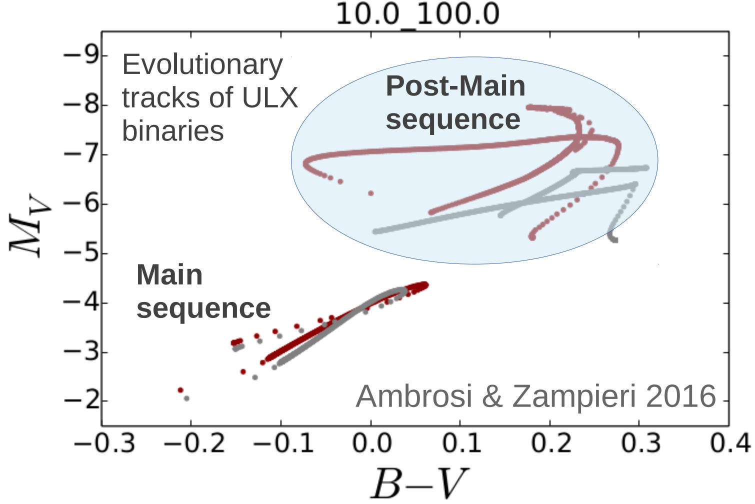
Filling/Underfilling Roche lobe donor (with gravity/limb darkening)

Emission comes from standard/slim disc+donor. X-ray illuminating region in slim disc geometry differs from standard

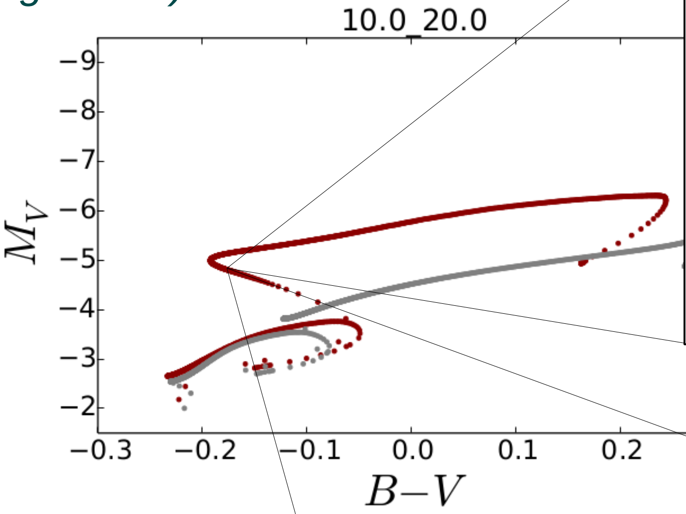
Irradiated surfaces treated as plane-parallel atmospheres in radiative equilibrium (Wu et al. 01; Copperwheat et al. 05, 07)

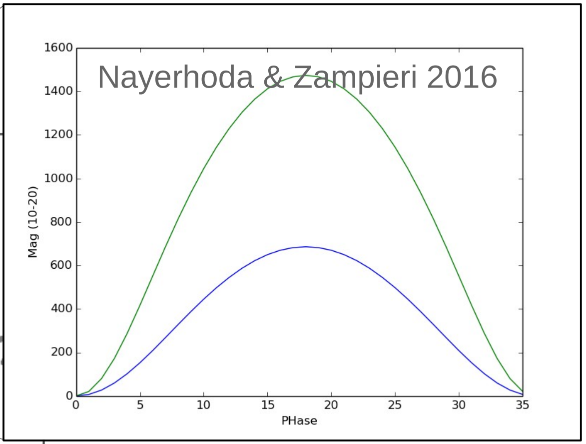
A comprehensive multi-wavelength variability model

A few preliminary results (work in progress ...)



Ambrosi & Zampieri 2016





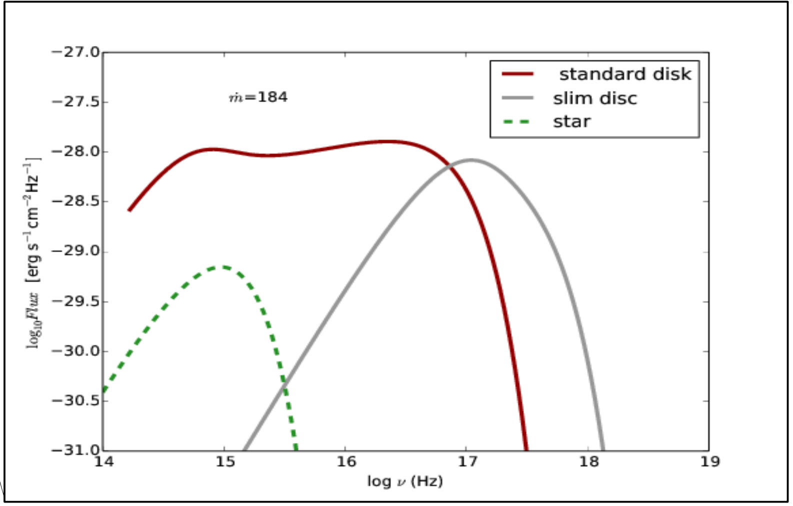
Nayerhoda & Zampieri 2016

Snaphots of the optical-through-X-ray spectrum and of the optical light curve (in millimag) during a super-Eddington phase

Broadband emission properties of ULXs accreting above Eddington

Owing to the larger Mdot, in the post-main sequence phase evolutionary tracks (in red) are brigther and bluer than those computed assuming Eddington-limited accretion (gray lines; Patruno & Zampieri 2008, 2010)

Next step: Test the model against NGC 7793 P13, that has a dynamically measured BH mass, is accreting above Eddington, and has optical light curve and broadband spectra available



Conclusions

2 ULXs have dynamical constraints on the mass of the compact object:

NGC 7793 P13	M 101 ULX-1
< 15 Msun	> 5 Msun
L/Ledd > 5-10	L/Ledd < 5

1 is an accreting pulsars and then a NS (M82 X-2)

1 is a (strong) candidate IMBH (ESO 243-49 HLX-1)

Good progress in understand the role of low metallicity in BH formation and
in modelling the evolution of ULX binary systems including dynamical effects in their natal clusters

Both stellar-mass and massive BHs can power ULXs

Present effort to model multiwavelength variability at non-standard super-Eddington rates in order to test the model of emission and to constrain the physical properties of ULXs

More constraining and accurate measurements of the ULX multiwavelength variability needed:

- X-ray broadband spectral measurements of ULX needed to investigate subtle spectral features and elusive lines (analysis in progress on a sample of bright ULXs; Pintore et al. 2016)
- Simultaneous optical-through-X-rays monitoring campaigns needed to identify orbital periods and constrain physical parameters (analysis in progress on Ho IX X-1; Fiori et al. 2016)