Exploring the formation of binary systems of Ultraluminous X-ray Sources

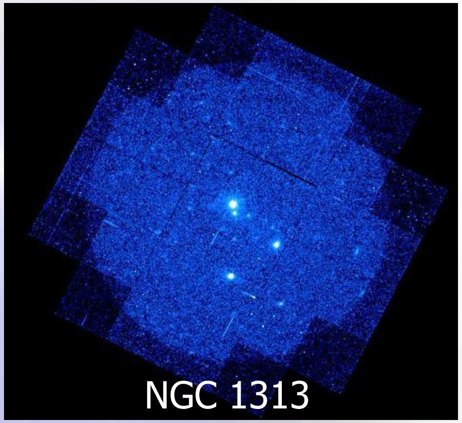
Luca Zampieri
Michela Mapelli
INAF-Astronomical Observatory of Padova

Outline

- Ultraluminous X-ray Sources (ULXs): questions and interpretations
- Stellar optical counterparts, bubble nebulae, metallicity of the environment
- Formation of ULX BHs and binaries
- Modelling optical emission (CM diagrams) including X-ray irradiation and binary formation

Ultraluminous X-ray Sources (ULXs)

- The most powerful (persistent) point-like, off-nuclear X-ray sources in nearby galaxies, with L >> Ledd for 1 Msun (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

- Statistics

  ~ 20% Background AGNs

  ~ 5% Supernovae interacting with the circumstellar medium

  Majority (~ 60-70%) are accreting BHs in binaries. What speaks for it?

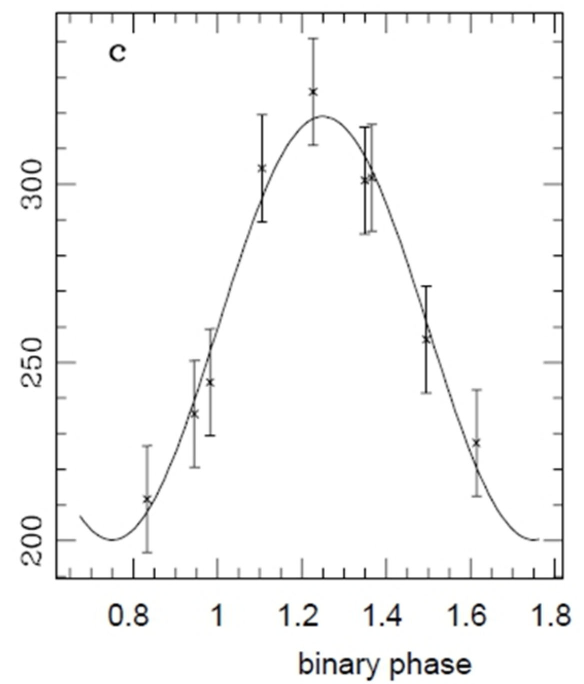
ULXs: BH binaries

- High X-ray luminosity, X-ray spectra, short term variability
- Often in young stellar environments, stellar optical counterparts
- (Orbital) modulation in the X-ray and (possibly) optical band (from ~6 hr to ~60 days)
- Timing properties (QPOs)
- Correlation with host galaxy SFR as for HMXBs, high luminosity end of the XLF of HMXRBs

Colbert & Mushotzky 1999; Roberts & Warwick 2000; La Parola et al. 2001; Strohmayer & Mushotzky 2003; Swart et al. 2004; Zampieri et al. 2004; Mucciarelli et al. 2005, 2006, 2007; Soria et al. 2005; Kaaret et al. 2004, 2006; Liu et al. 2002, 2004, 2007; Pakull et al. 2006; Grise' et al. 2008, 2011, 2013; Stobbart et al. 2006; Strohmayer et al. 2007; Gladstone et al. 2009; Zampieri & Roberts 2009; Feng & Soria 2011; Grimm et al. 2003; Mineo et al. 2012; Esposito et al. 2013; Wolter et al. 2006, 2011

→ **First measurement of a mass function in M 101 ULX-1 (Liu et al. 2013)**

Mbh>4.6+/- 0.3 Msun



Liu et al. 2013

ULXs: questions and interpretations

What are the masses of the BHs powering these sources?

What are the properties of their accretion flow?

What is the relation with their environment?

What may ULXs tell us about stellar or intermediate mass BH formation? And about extreme accretion environments?

Concerning the first question:

- **Stellar-mass BHs of ~10 Msun** (King et al. 2001, King 2008)
- **Massive stellar BHs of ~30-80 Msun** (Mapelli et al. 2009; Zampieri & Roberts 2009; Belczynski et al. 2010)
- **Intermediate-mass BHs of 10^2–10^4 Msun** (Colbert & Mushotzky 1999)

Concerning the second question:

- Ordinary sub-Eddington accretion
- Or a different accretion regime from Galactic BH binaries?

Cosmological implications for the seeding of the first super-massive objects and/or the rapid appearance of the first generation of AGNs at very high z

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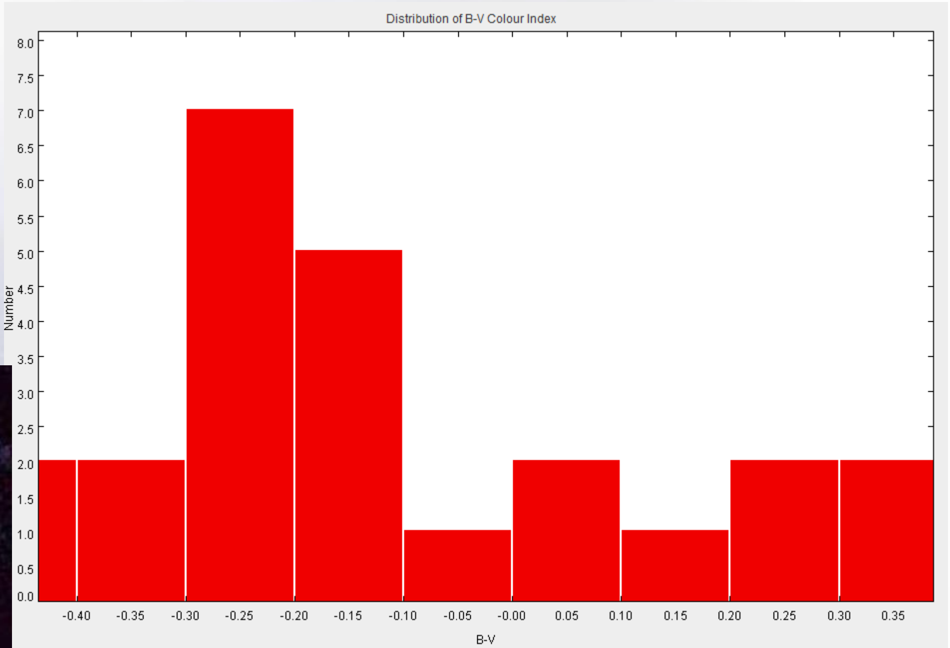
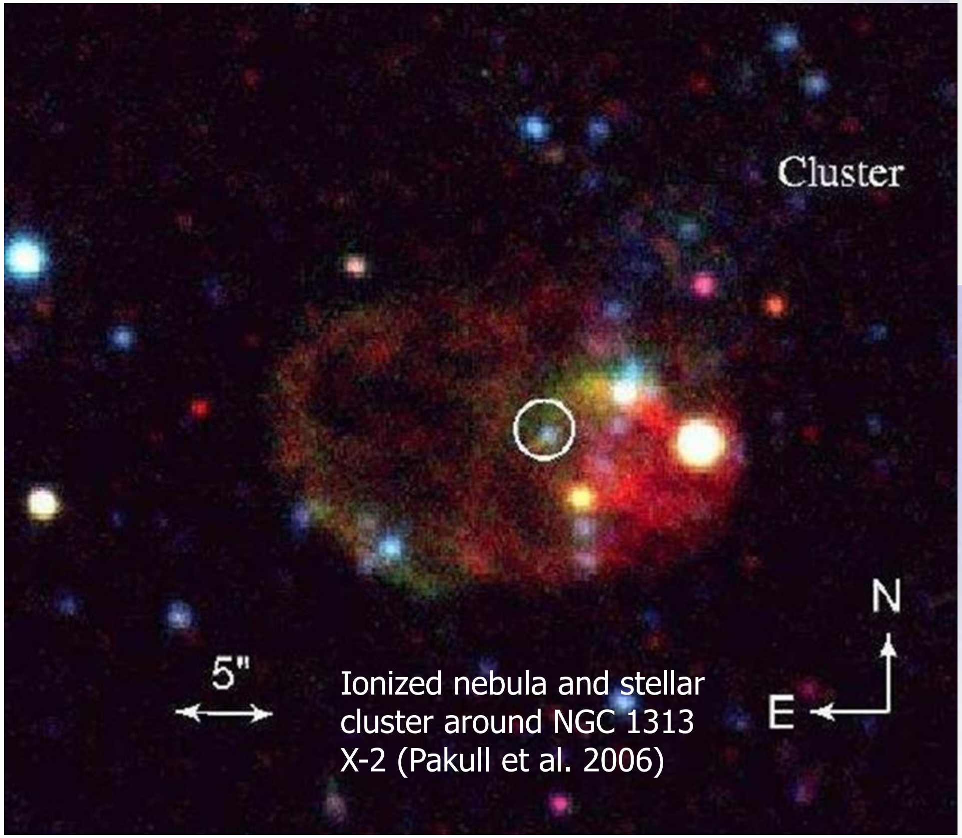
Stellar optical counterparts and bubble nebulae

- For a few tens of ULXs point-like HST optical counterparts have been detected
- More than 10 have unique optical counterparts (Tao et al. 2011; Gladstone et al. 2013)
  - mostly blue, with a red tail
  - giant and supergiant stars





Ionized nebula and stellar cluster around NGC 1313 X-2 (Pakull et al. 2006)

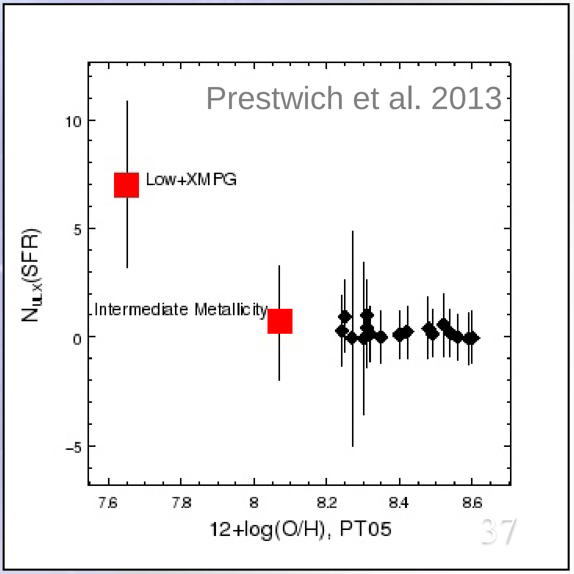
- Huge (hundreds of pc) ionized optical emission nebulae (Pakull & Mirioni 2002)
  - X-ray photoionized (e.g. Ho II X-1, Kaaret et al. 2004) and/or shock excited
  - Inferred energetics (~1.0e52 erg) and kinematic ages (~1 Myr) important to constrain binary evolution models
  - Cluster age ~ few tens of Myr (Grise' et al. 2008, 2011)

Environment: metallicity

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

- Line intensities of HII regions in ULX host galaxies → 0.1-0.5 Zsun for a sample of ~60 galaxies, marginal anticorrelation Nulxs/SFR vs Z (96% c.l.; Mapelli et al. 2010)

- 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)



ULXs preferentially associated to low Z environments

→ *At Z~0.1 Zsun RLO binaries with stellar-mass BHs produced more effectively thanks to the fact they undergo more easily a common envelope phase and have natal kicks (Linden et al. 2010), but …*

→ *it could be easier to make BHs of the right size to produce ULXs*

Massive BH formation through direct collapse of massive low-Z stars → Mbh~30-80 Msun (Mapelli et al. 2009; Zampieri & Roberts 2009; Belczynski et al. 2010)

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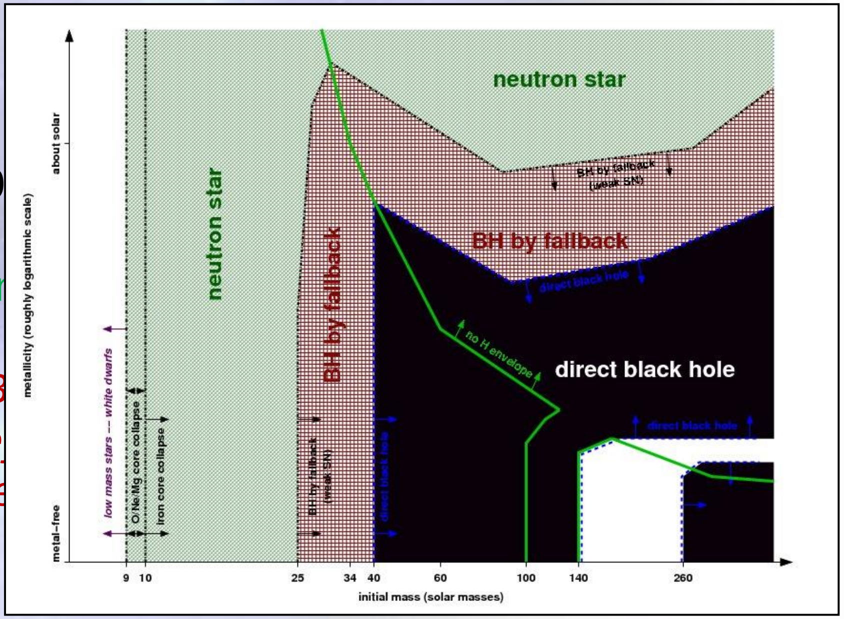

Heger et al. 2003

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Theoretical models of ULXs: formation of ULX binaries

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)

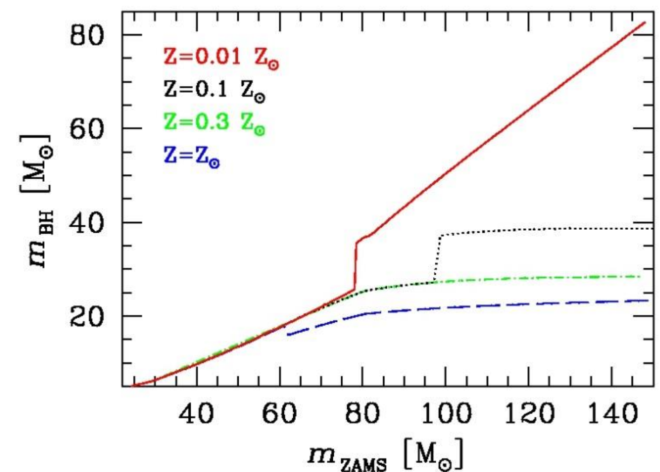
Metallicity dependence of mass loss (Vink et al. 2001) and massive BH formation (Belczynski et al. 2010) included

In isolation, easy to form ULX binaries with low mass BHs, but difficult with massive BHs

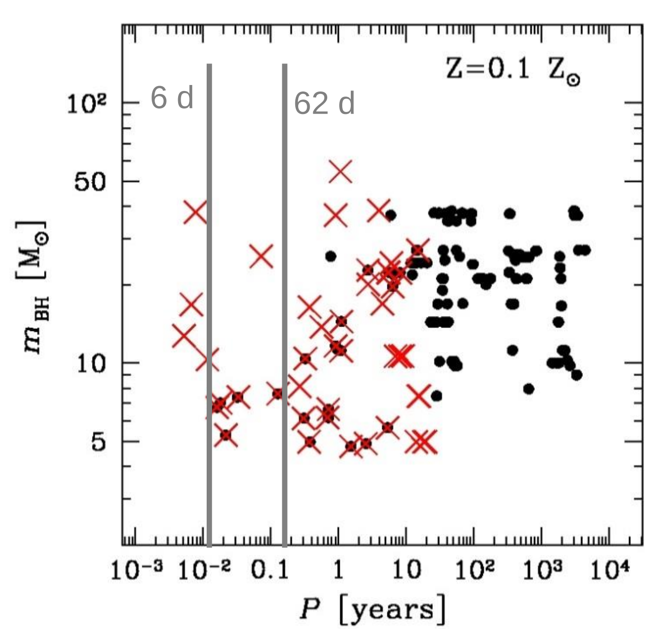
However, in young clusters with low-Z, 3-body encounters and dynamical exchanges change the evolution of massive BHs

Both BHs and massive BHs can power RLO ULXs

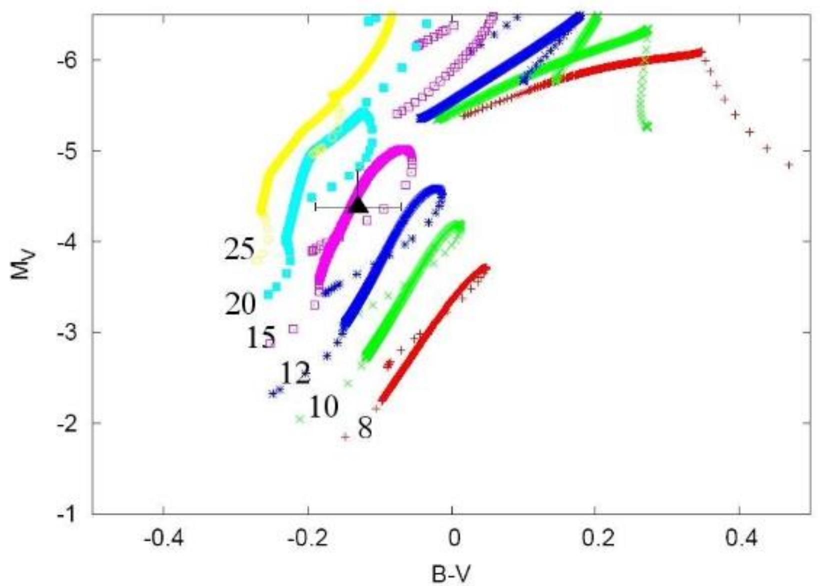
Agreement also with observed offset of ULXs from their parent clusters (Zezas et al. 2002; Kaaret et al. 2004; Poutanen et al. 2013; Berghea et al. 2013)



Mapelli et al. 2013



Theoretical models of ULXs: CM diagram and irradiation



Patruno and Zampieri 2010

ULX BH binary models compared with optical through X-ray spectra of ULXs and colour-magnitude diagrams of the counterparts

- Including stellar+binary evolution (Madhusudhan et al. 2008; Patruno & Zampieri 2008, 2010)
- Including cluster evolution and Z-dependent stellar evolution (Mapelli and Zampieri 2014)

Theoretical models of ULXs: CM diagram and irradiation

- Including X-ray irradiation of the outer accretion disc and donor surface, treated assuming a X-ray illuminated plane-parallel atmosphere in radiative equilibrium (e.g. Wu et al. 2001; Copperwheat et al. 2005, 2007; Mucciarelli et al. 2007; Grise' et al. 2012)

→ face-on and superior conjunction

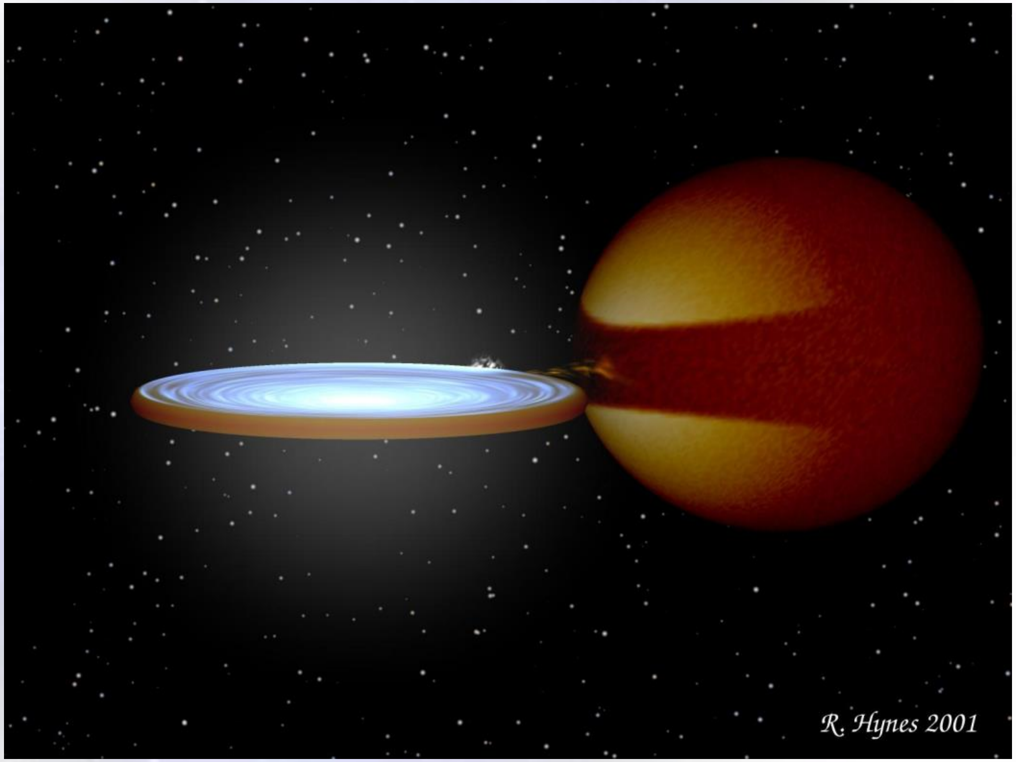
→ albedo=0.9

→ two bands (soft/hard) incident X-ray spectrum: Fsoft/Fhard = 0.1 - 0.2

→ bolometric correction and colours of the donor interpolated as a function of effective temperature

→ standard accretion disc Super-Eddington accretion not allowed (excess mass expelled)

→ at present, we are trying to model disc emission at super-Eddington rates approximating irradiation geometry with a slim disc (Ambrosi et al. 2014)



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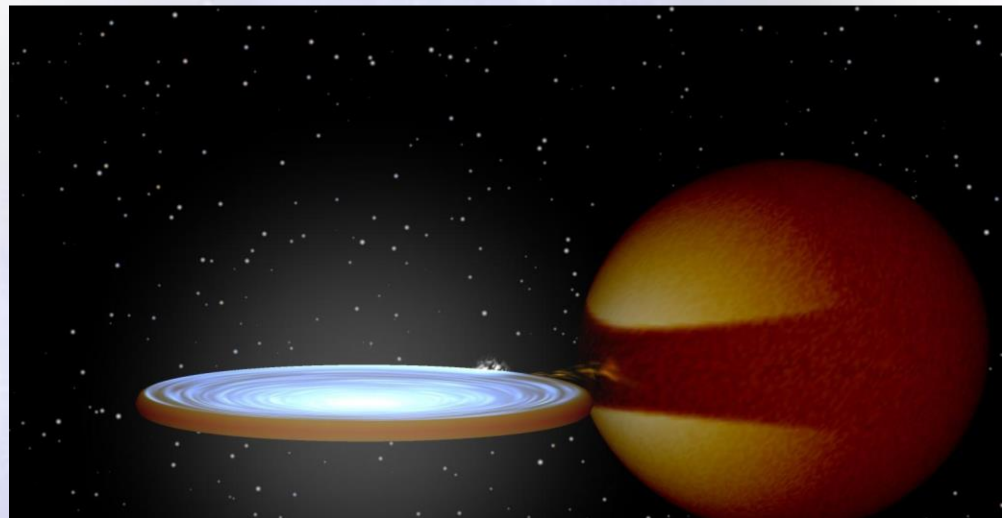
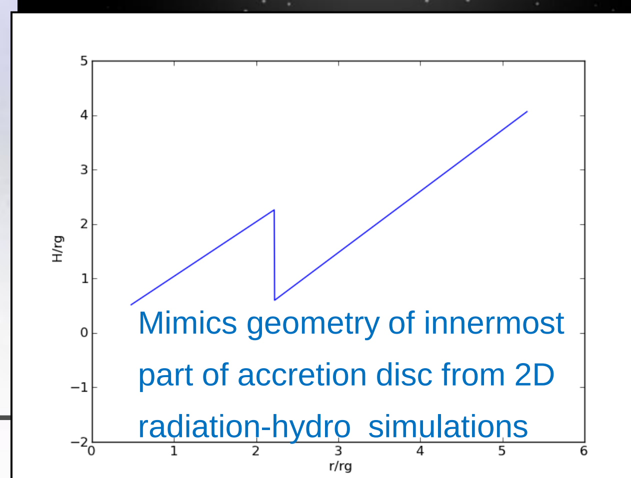
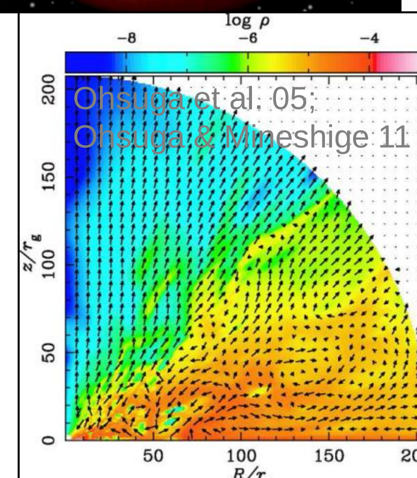


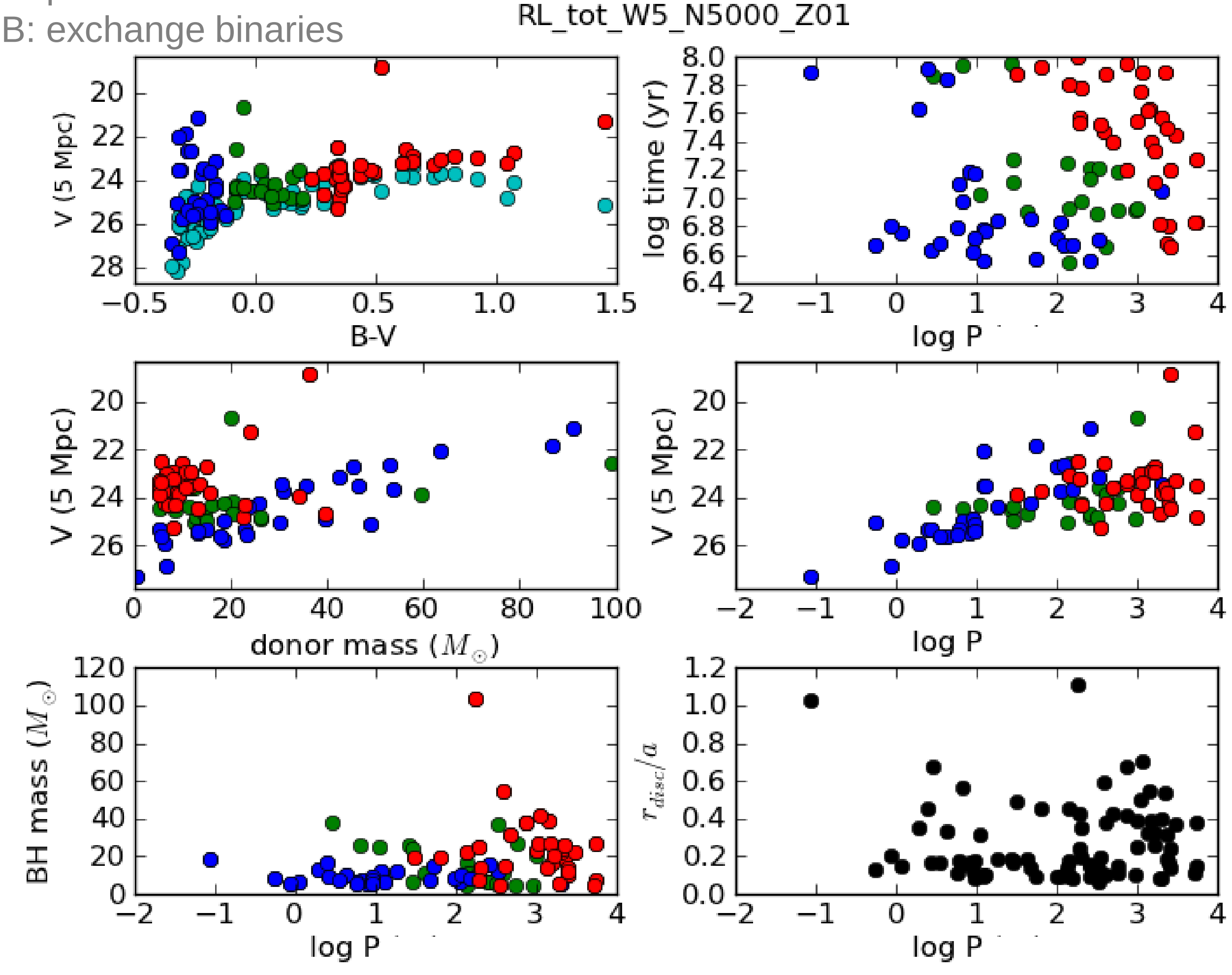




Modelling optical emission including binary formation

- Blue: mostly PBs containing MS companions, with masses >10 Msun
- Green: mostly EBs containing both BHs and MSBHs with 10-20 Msun evolved donors and large separations (10-1000 days). Disc is extended and optical spectrum appears redder
- Red: mostly EBs containing both BHs and MSBHs with 10-20 Msun evolved donors and very large separations (> 100 days)

PB: primordial binaries
EB: exchange binaries



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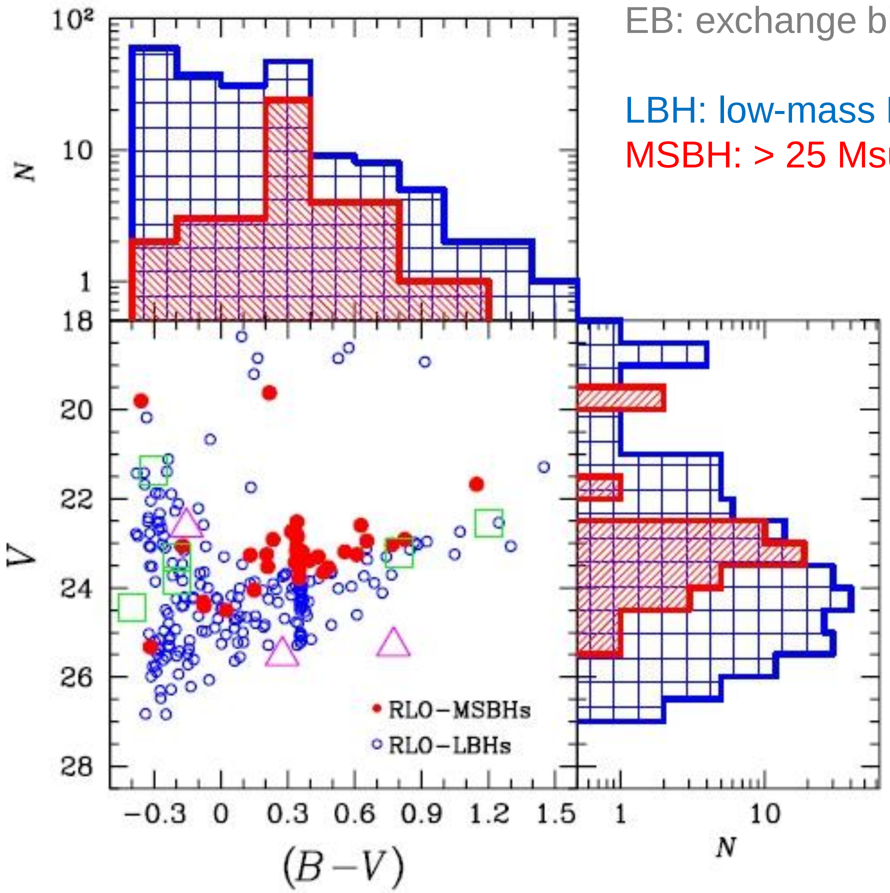

Mapelli et al. 2014

- Blue counterparts are mostly associated with PBs and LBHs
- EBs populate sequence on the right, with predominantly older and less-massive donors

  → MSBHs sub-class of EBs
- *MSBHs produced through dynamical interaction, the timescale of which is sufficiently long that massive donors are already evolved*
- HST photometry (Gladstone et al. 13): **9 ULXs** with F435W and F555W (or F606W) data

Modelling optical emission: preliminary results

Observed counterparts populate the same region in the CMD as the simulated ones

- M81 X-6, NGC 1313 X-1 matched only by PBs
- NGC 1313 X-2, NGC 2403 X-1, NGC 5204 X-1 matched by both PBs and EBs
- Ho IX X-1, IC 342 X-1, M 82 X-1 matched only by EBs
- M83 XMM1 does not match

- If emission is not significantly beamed or super-Eddington (Lx < 5 Ledd): NGC 1313 X-2, Ho IX X-1, IC 342 X-1, (marginally) NGC 5204 X-1 matched only by MSBH exchange binaries

Conclusions

ULXs reside in (confirmed also by tentative orbital period identifications):

→ *short-period PBs with massive (> 20 Msun) MS donors or strongly irradiated low-mass companions*

→ *long-period (> 10 days) PBs or EBs with less massive and more evolved donors*

In this case, (a) ULXs may contain MSBHs and (b) they likely underwent a previous contact phase to account for the inferred kinematic ages of the bubble nebulae (~1 Myr)