Perspectives on Ultraluminous X-ray sources after the discovery of Ultraluminous Pulsars

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and

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Outline

- Some basic facts on Ultra-Luminous X-ray sources (ULXs)
- Two new pulsar ULXs discovered within EXTraS
- Current evidences for BH and NS ULXs
- Perspectives studies on:

  Modelling the multiwavelength emission of ULXs

  Super-Eddington accretion in NS ULXs

Ultraluminous X-ray sources (ULXs)

What are they?

- *Point-like off-nuclear X-ray sources in other 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?

Detection of pulsations, dynamical mass measurements and other evidences

↓

ULXs are crucial to explore the origin, distribution and properties of NSs and BHs in the local Universe

↓

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

Large Eddington ratios, Ultraluminous state X-ray spectra and spin evolution

↓

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

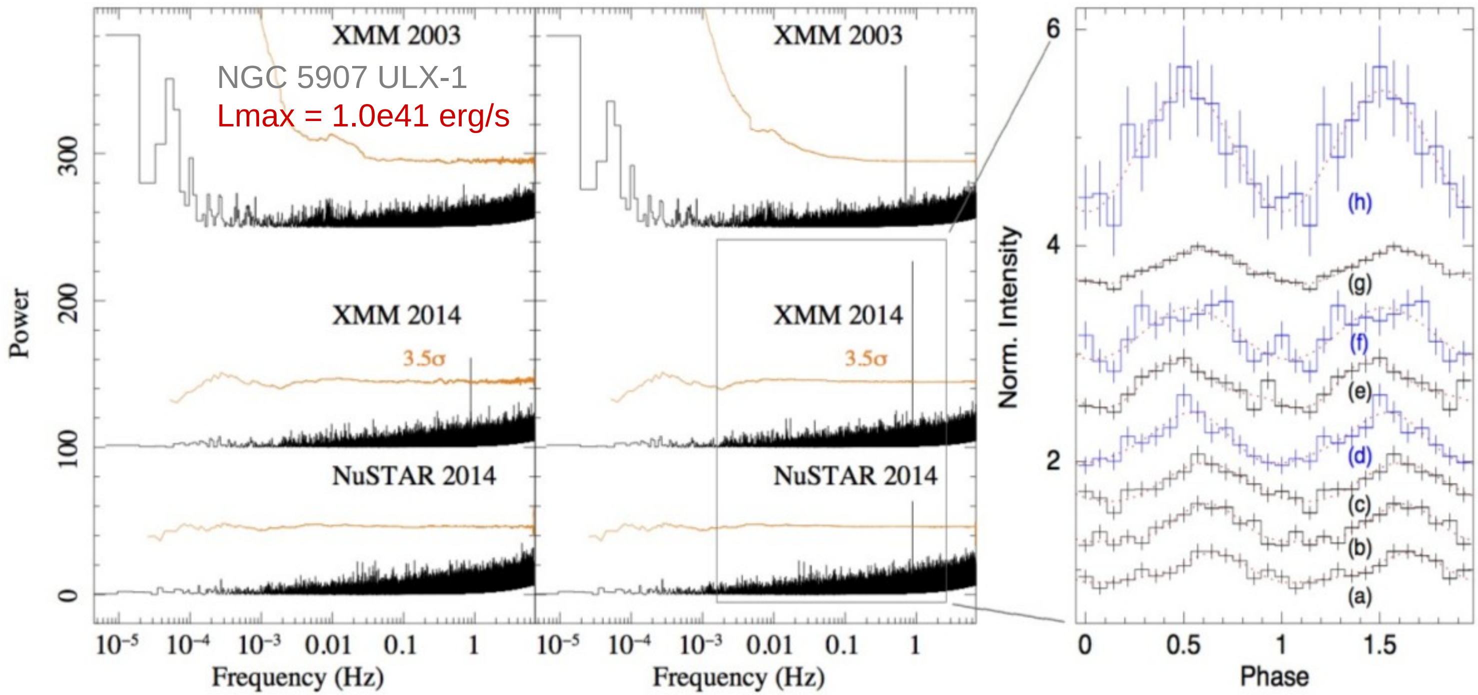
↓

What is the structure of B fields in these sources? Is ULX physics relevant for the first generation of Quasars at high z?

NGC 5907 ULX-1 and NGC 7793 P13: Two new pulsar ULXs discovered within EXTraS

Israel et al. 2017a

Yesterday's talk by G. L. Israel



Fourier power spectra for Feb 2003 and Jul 2014 EPIC observations (0.1–12 keV)

Central panels show the PSD after correcting the photon arrival times for Pdot

Pulsed fraction is increasing from 12% below 2.5 keV up to about 20% above 7 keV

NGC 5907 ULX-1 (Israel et al. 2017a)

Period ~ 1.43 s (2003)
~ 1.14 s (2014)

Secular period deriv.
~ -8.1e-10 s/s

Shortest ever spin-up rate and highest Lx among pulsar ULXs

NGC 7793 P13 (Israel et al. 2017b, Fuerst et al. 2016)

Period ~ 0.42 s

Secular period deriv.
~ -4.0e-11 s/s

Fastest spinning ULX

Discovered within the EXTraS project (Italy, UK, Germany; Funded within the EU/FP7 Cooperation Space framework), devoted to a systematic search for fast transients and both periodic and aperiodic variability in the XMM-Newton data archive - **PI: A. De Luca**

BH or NS ULXs?

NS ULXs

Direct evidence from detection of pulsations in 3 ULXs: **M 82 X-2** (Bachetti et al. 2014), **NGC 5907 ULX-1**, **NGC 7793 P13**

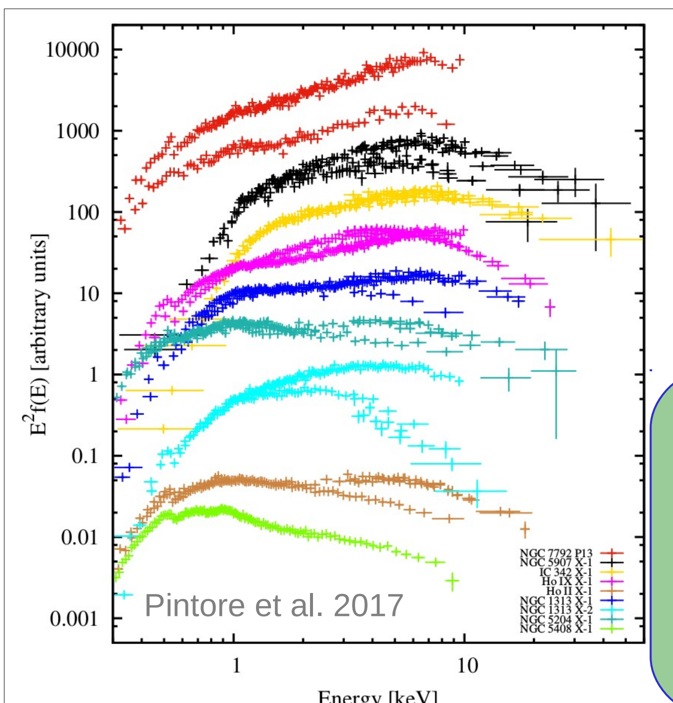
BH ULXs

Only dynamical mass measurements can directly prove the existence of BH ULXs but they are difficult to obtain

Actual direct evidence from one measurement (**M 101 ULX-1**, Liu et al. 2013): **Mbh > 5 Msun**

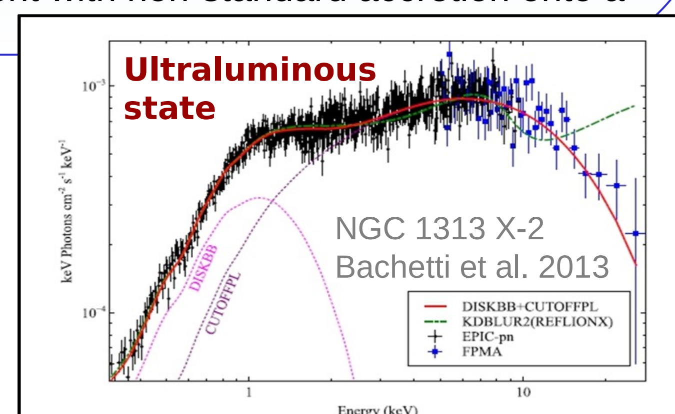
Indirect arguments for existence of BH ULXs, based on some a*nsatz*

- If Galactic BH states and transitions are identified (X-ray, radio), spectroscopic estimates/mass scaling can be used (→ **Mbh > 1.0e4 Msun** in the IMBH candidate **ESO 243-49 HLX-1,** Farrell et al. 2009)
- If emission not strongly beamed, **X-ray luminosity** of bright (~ 1.0e40 erg/s) ULXs consistent with an accreting BH of stellar origin (< 80 Msun). *After GW150914, we know that massive (> 30 Msun) BHs do exist!*
- Broadband XMM(+NuSTAR) spectra described in terms of two-thermal components spectral models (**ultraluminous state,** Gladstone et al. 2009) consistent with non-standard accretion onto a BH (e.g. Middleton et al. 2015)



However, ULX spectra can be well fit also with a **model for Galactic accreting magnetic NSs** (Pintore et al. 2017, *see poster #F03*)

A subsample has hardness comparable to that of NS ULXs



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- Possible evidence for massive (20-80 Msun) BHs comes from the association of ULXs with low metallicity environments (e.g. Mapelli et al. 2010; Prestwich et al. 2013), where it may be possible to form them through direct collapse (Zampieri & Roberts 2009; Mapelli et al. 2009; Belczynski et al. 2010)
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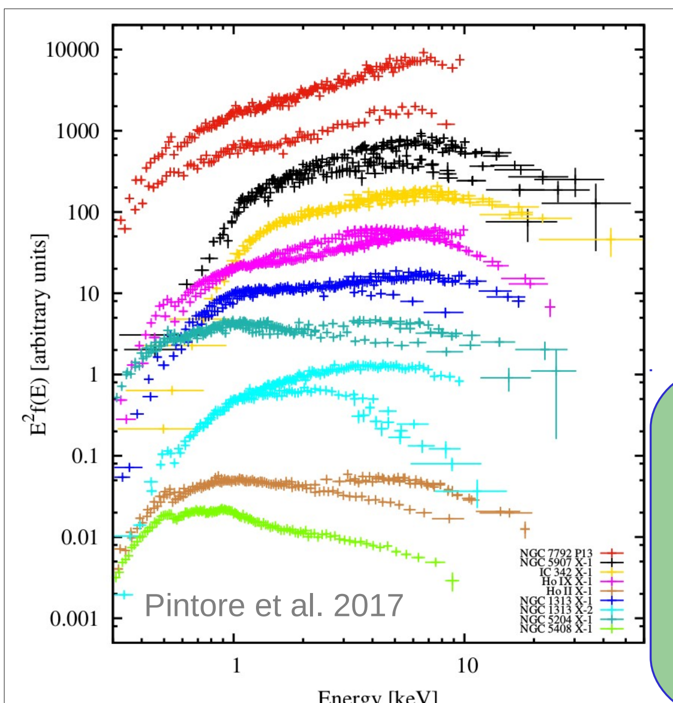

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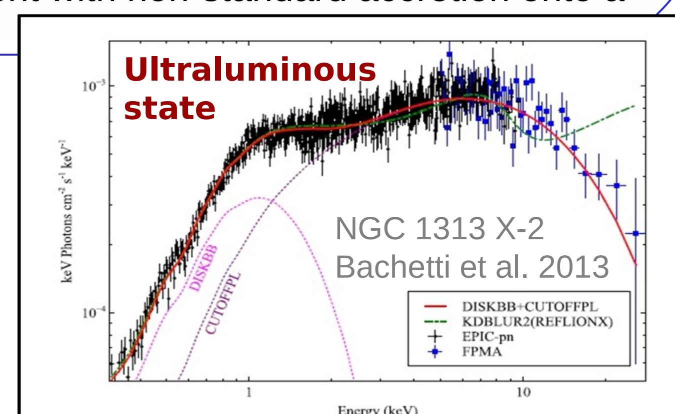


Super-Eddington accretion

For bright ULXs:

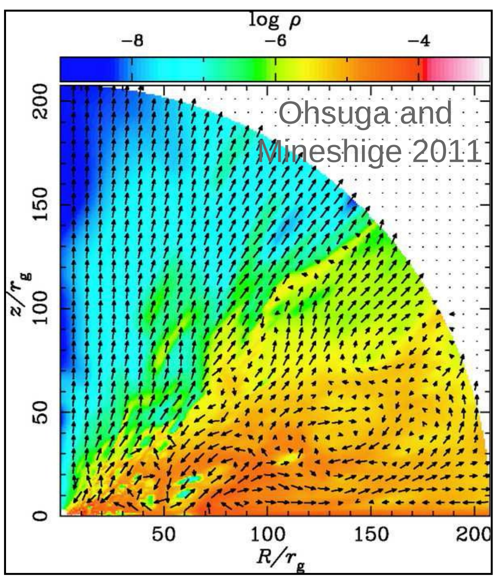
$$L_{max} \approx b \cdot 10^{40}\ \mathrm{erg/s}$$

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

Mdot is provided by Roche lobe overflow from massive stars (MS, giant) or low mass stars in the giant phase

Mass	Phase	Timescale	Transfer rate (g/s)	Mdot,edd BH (*)	Mdot,edd NS
10 Msun	MS	Nuclear	1.0e20	50	
10 Msun	MS	Unstable	2.0e22		200000
1 Msun	Giant	Thermal	2.0e21	1000	20000
10 Msun	Giant, He	Nuclear	1.0e21	500	
10 Msun	Giant	Thermal	2.0e22	10000	200000

(*) Mbh = 20 Msun

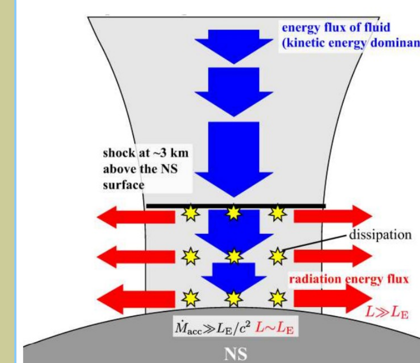


Supercritical accretion onto BHs

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)

Supercritical accretion onto magnetized NSs

If B field is sufficiently high, it plays an important dynamical role and has important effects on the emission properties (Bachetti et al. 2014, Dall'Osso et al 2015, Mushtukov et al. 2015a,b)



Accretion column
Kawashima et al. 2016

Variability at high energies when line of sight to inner disc crosses turbulent eddies (Middleton et al. 2011, 2015)
Emission lines and blueshifted absorption lines detected in 3 ULXs (Pinto et al. 2016, 2017)

Perspective studies: Modelling the multiwavelength emission of ULXs

Modelling the multiwavelength emission of ULXs is a potentially useful tool to discriminate between NS and BH systems, and accretion geometry

Model of optical-through-X-ray emission of ULX binaries (Patruno & Zampieri 2008) recently developed including super-Eddington accretion (*yesterday's talk by E. Ambrosi*)

Bimodal structure assumed in inner flow at Mdot > MdotEdd

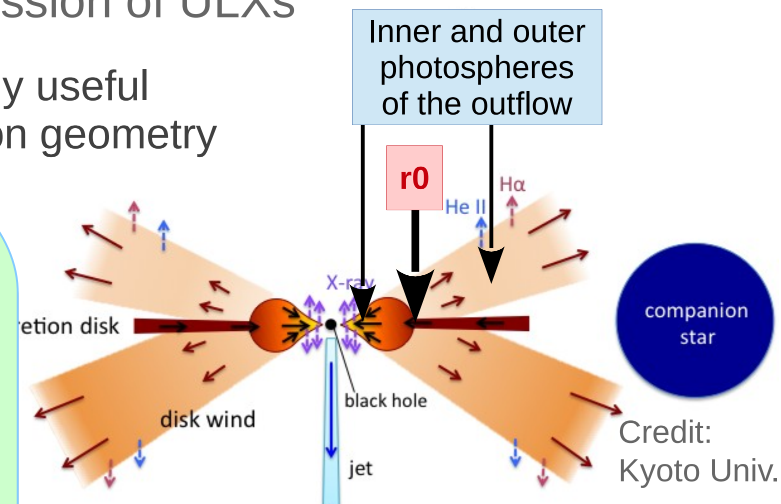
Non-standard (slim) disc geometry (e.g. Watari et al. 2000):

H ~ r and T prop. to r $^{-1/2}$

Transition radius to standard disc, where advected heat is equal to viscously dissipated heat: **r0**/rg = Mdot/MdotEdd

Optically thick outflow (Poutanen et al. 2007)

r0 marks also the boundary between the regions where outward advection of energy (r<r0) and radiative diffusion of energy (r>r0) dominates in the outflow



Credit: Kyoto Univ.

Evolving companion (8-25 Msun)

Properties self-consistently calculated during the evolution of the binary

Geometry-dependent self-irradiation

Depends on amount of shielding of the outer disc and donor induced by the changing structure of inner disc

Performed preliminary comparison between available photometry of some ULXs (Tao et al. 2011, Gladstone et al. 2013) and model predictions for BH binaries with Mbh = 20, 100 Msun (bracketing mass range of BHs of stellar origin)

Model calculations for NS binaries is in progress

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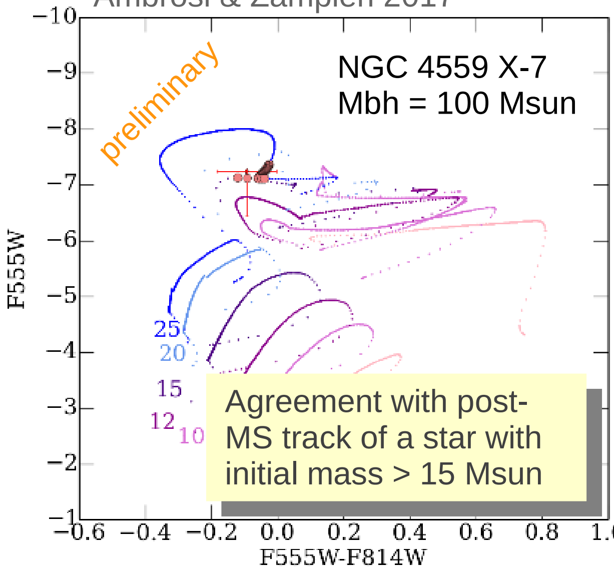
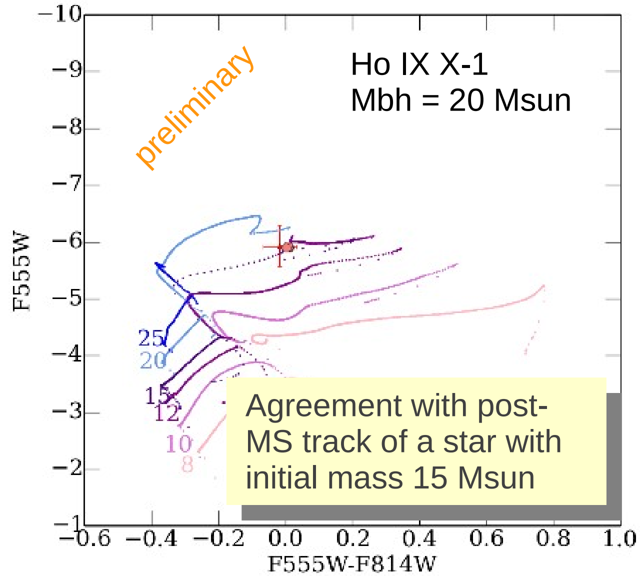
Perspective studies: Modelling the multiwavelength emission of ULXs

Ambrosi & Zampieri 2017



Agreement with post-MS track of a star with initial mass > 15 Msun



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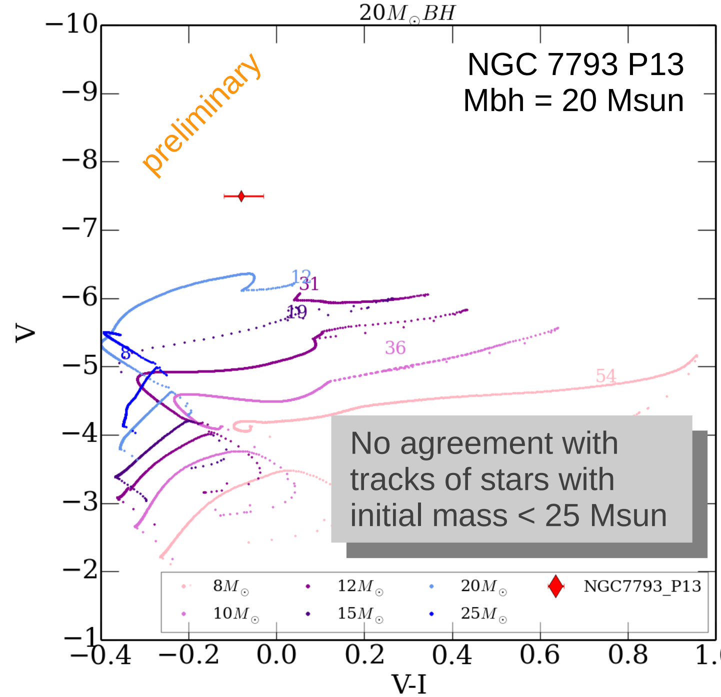
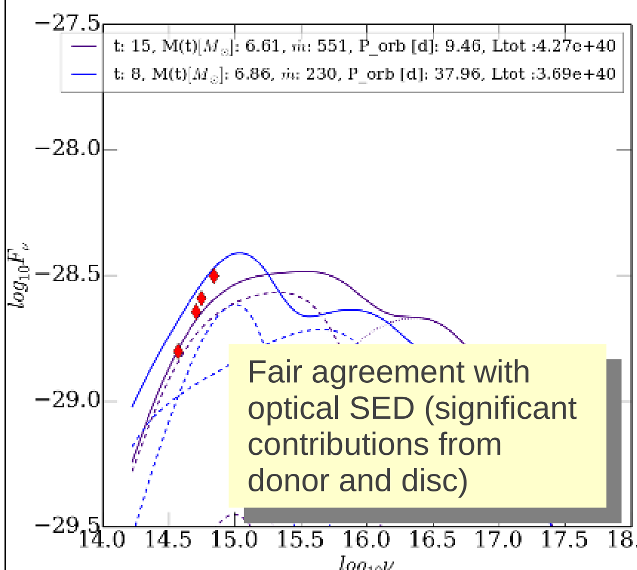
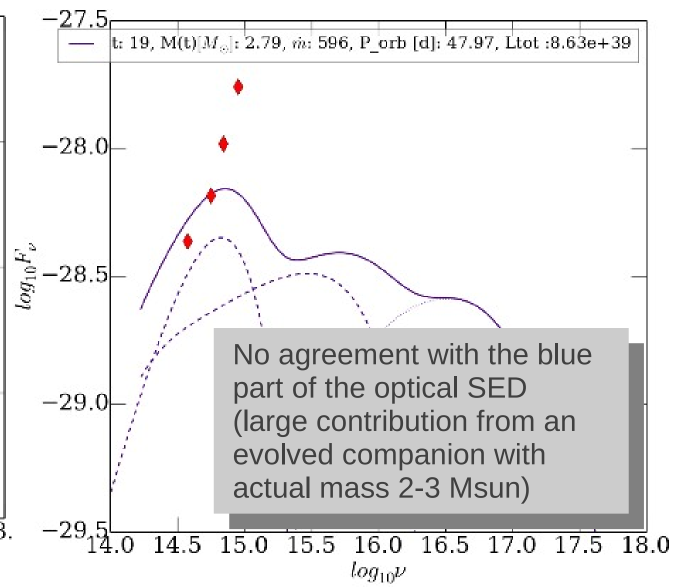


No agreement with tracks of stars with initial mass < 25 Msun



Fair agreement with optical SED (significant contributions from donor and disc)



No agreement with the blue part of the optical SED (large contribution from an evolved companion with actual mass 2-3 Msun)

Zamp

NGC 7793 P13

Accretion disc geometry in NS ULXs may be different from that of BHs

With a NS, will optical emission be dominated by the star and X-irradiation be more efficient?
Will both facts boost the optical luminosity at the observed level?

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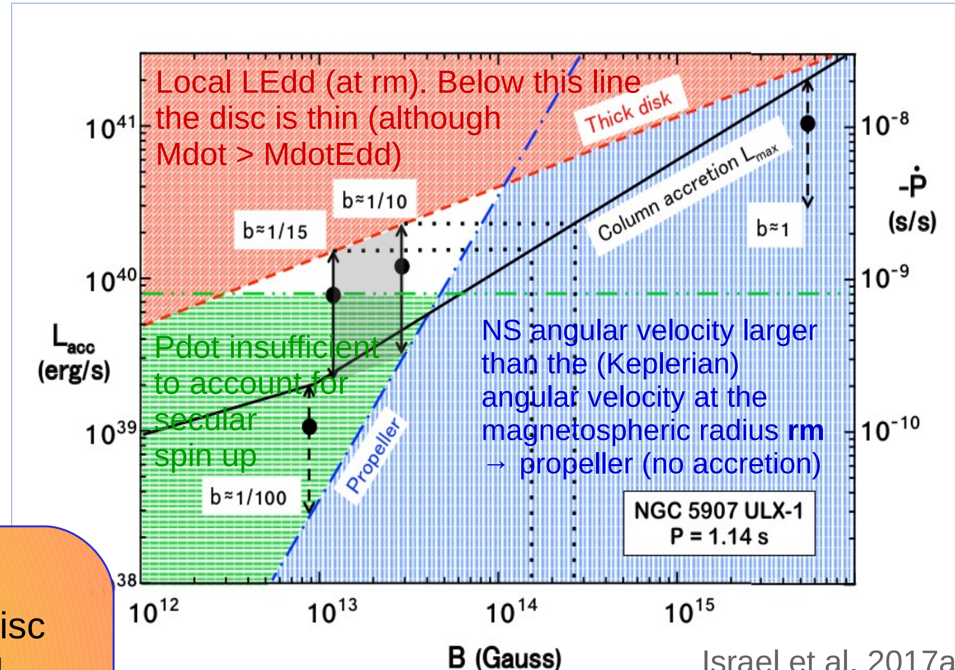
Perspective studies: Super-Eddington (column) accretion onto NSs in strong magnetic fields

- Maximum L of the accretion column (**black line**) depends on surface B field (Mushtukov et al. 2015a,b; *yesterday's talk by V. Suleimanov*)

  → If B > 3.0e12 G, electron scattering cross section for (extraordinary mode) photons below the cyclotron energy < Thomson cross-section
  → **Lacc > Ledd**

- Radiation escapes more easily along the sides of the accretion funnel than along it, leading to a *geometric beaming* **b (>1/10): Lacc = Lmax x b**

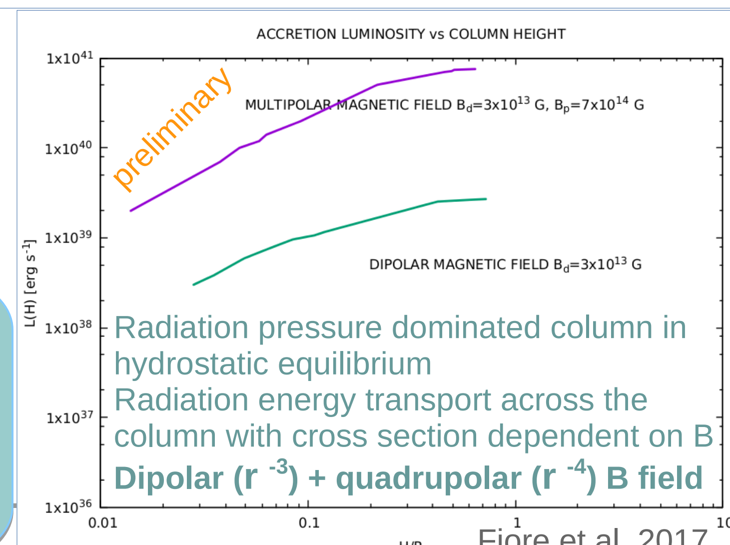


Israel et al. 2017a

Values of **B ~ 2.0e13 G (dipolar) and b ~ 1/10** allow for accretion to take place (avoiding the propeller) while the disc remaining thin at **rm** over the entire range of variability of L

Lacc = 2.0e41 x b erg/s ~ 2.0e40 erg/s

The accretion column can sustain this luminosity if there is **a surface field B ~ 3.0e14 G** → *Can this be an additional multipolar component at the base of the accretion column?*



Fiore et al. 2017

Calculation of the maximum luminosity adding a quadrupolar component (Bq prop. r^{-4}) at the base of the accretion column (Fiore, Zampieri, Turolla et al. 2017)

→ Model based on the formalism of Mushtukov et al. (2015a,b)

Conclusions

- Modelling the multiwavelength emission of ULXs accreting above Eddington:

  A potentially useful tool to discriminate between BH and NS ULXs and a powerful way to understand them

- Super-Eddington accretion in NS ULXs:

  An accreting magnetized NS can self-consistently emit an accretion luminosity above 1.0e40 erg/s (NGC 5907 ULX-1) if there is an additional multipolar component of the field with a value in excess 1.0e14 G at the base of the accretion column