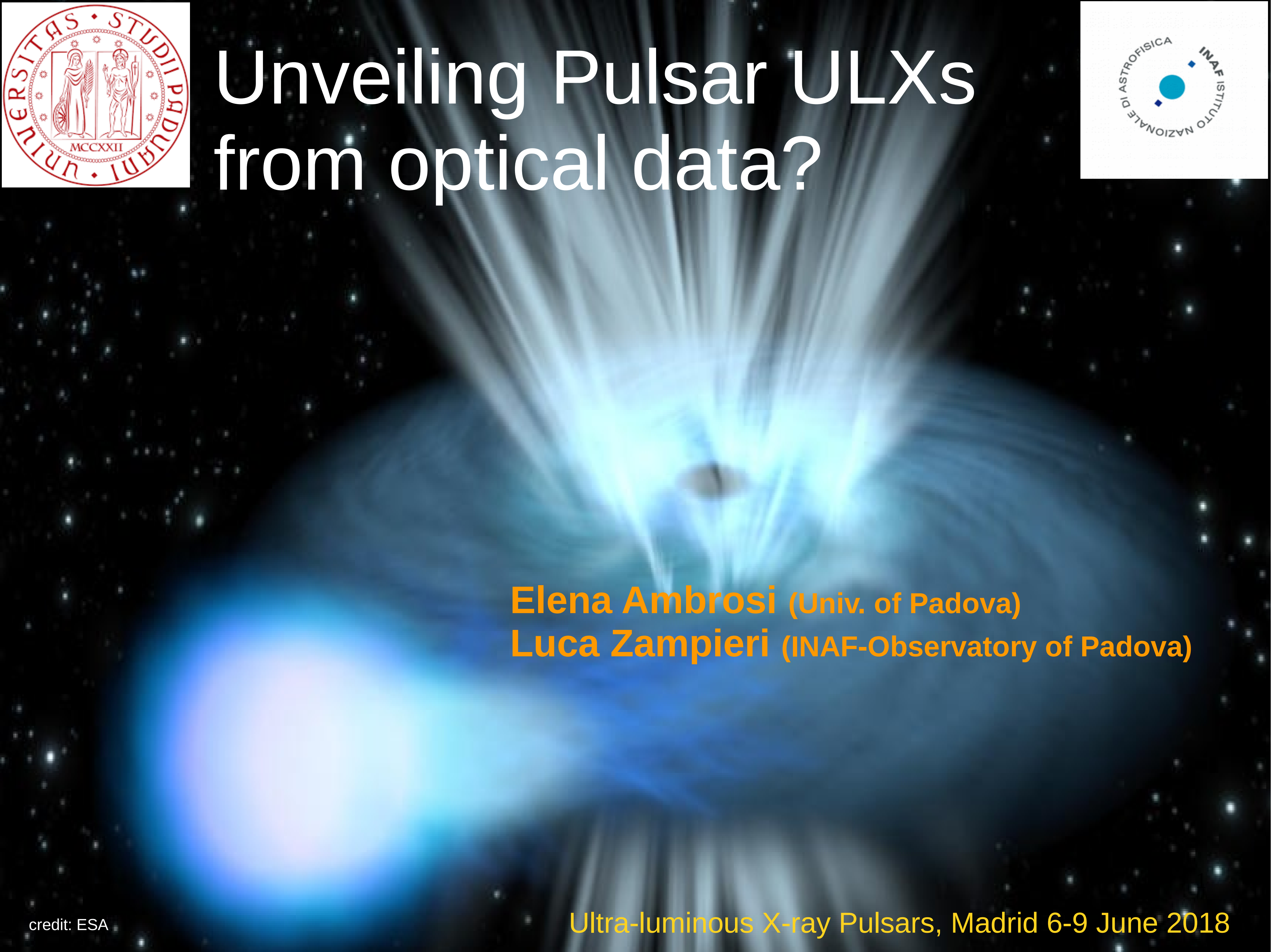
Unveiling Pulsar ULXs from optical data?



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credit: ESA

Ultra-luminous X-ray Pulsars, Madrid 6-9 June 2018

Outline

- Introduction Motivation and aim of this study
- Part 1 Description of the model, results for ULXs with black holes (BHs)
- Part 2 Extension of the model to ULXs with neutron stars, preliminary results, differences with BH ULXs
- Conclusions and future developments

Optical Emission in X-ray Binaries arises from the outer regions of the accretion disc and the donor star. Effects of X-ray illumination need to be included

Modelling the optical emission of ULXs (Patruno & Zampieri 2008, 2010) allows us to:

Compare theoretical Colour-Magnitude Diagrams (CMDs) in different bands and Spectral Energy Distributions (SEDs) with photometry of ULX optical counterparts

IN ORDER TO:

Constrain donor masses
Constrain accretion mechanism and disc geometry (standard accretion, super-Eddington accretion, super-Eddington accretion with ouflows)
Determine effects of disc geometry on emission properties
Constrain the nature of the compact object

Starting Point: Model for sub-Eddington accretion

(Patruno & Zampieri 2008, 2010 - PZ)

Calculation of the evolutionary tracks of binary systems provide donor mass, orbital period, T_{eff}, mass transfer and donor radius as a function of time
Initial parameters: M_{BH}, M_{donor}, orbital separation

- A **standard irradiated accretion disc** and irradiated donor are considered → irradiating flux produced by ALL the inner region of the disc
- Each anulus of the disc emits as a black body with a temperature

  $T^4_{tot} = T^4_{visc} + T^4_{self\text{-}irr}$ (Copperwheat et al. 2005)

- Star surface temperature: $T^4_{*} = T^4_{eff} + T^4_{irr}$

Present Model: super-Eddington accretion

(Ambrosi & Zampieri 2018, sub. to MNRAS)

$\dot{M} \geq \dot{M}_{crit}$ → Bimodal disc structure:

Inner advection dominated slim disc + outer standard disc with outflow

Once the outflow sets in, it is divided into three regions depending on its optical depth and on the mechanism of transfer of energy

$R_{ph} = R_{ph}(\dot{m}, \varepsilon_{\omega})$, where ε_{ω} is the fraction of the gravitational potential energy which is spent to accelerate the outflow (**Poutanen et al. 2007**)

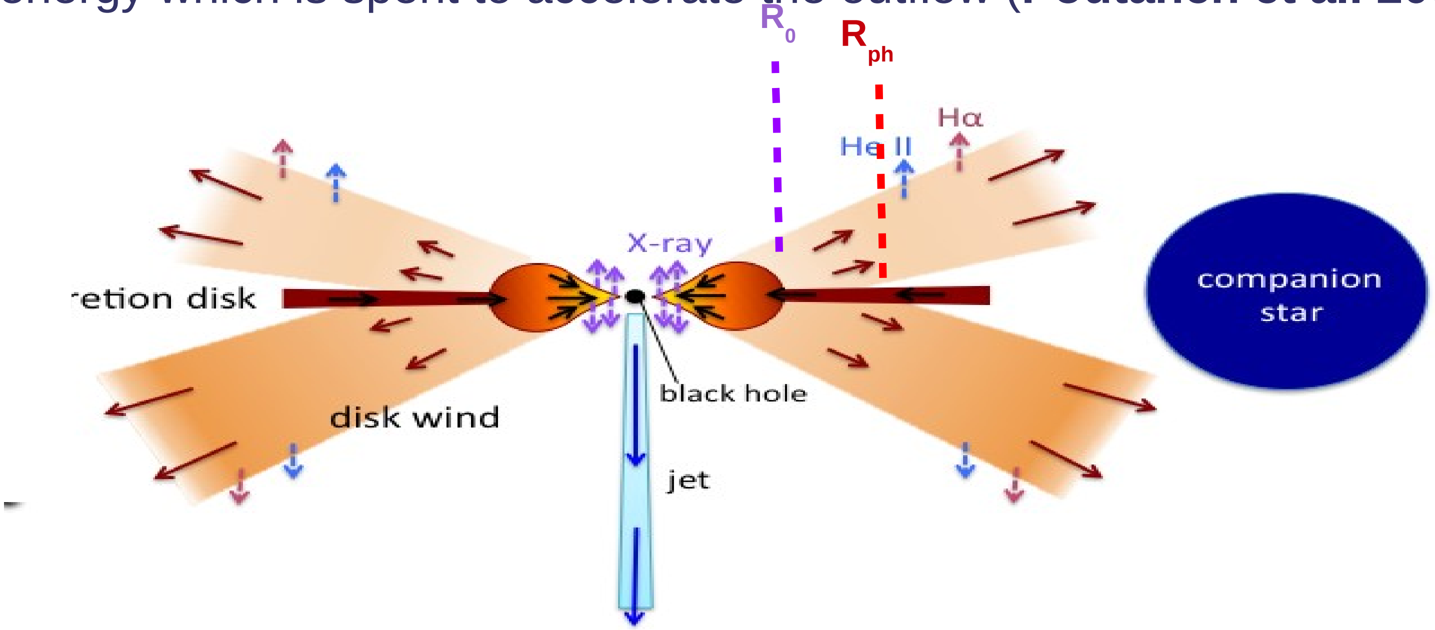
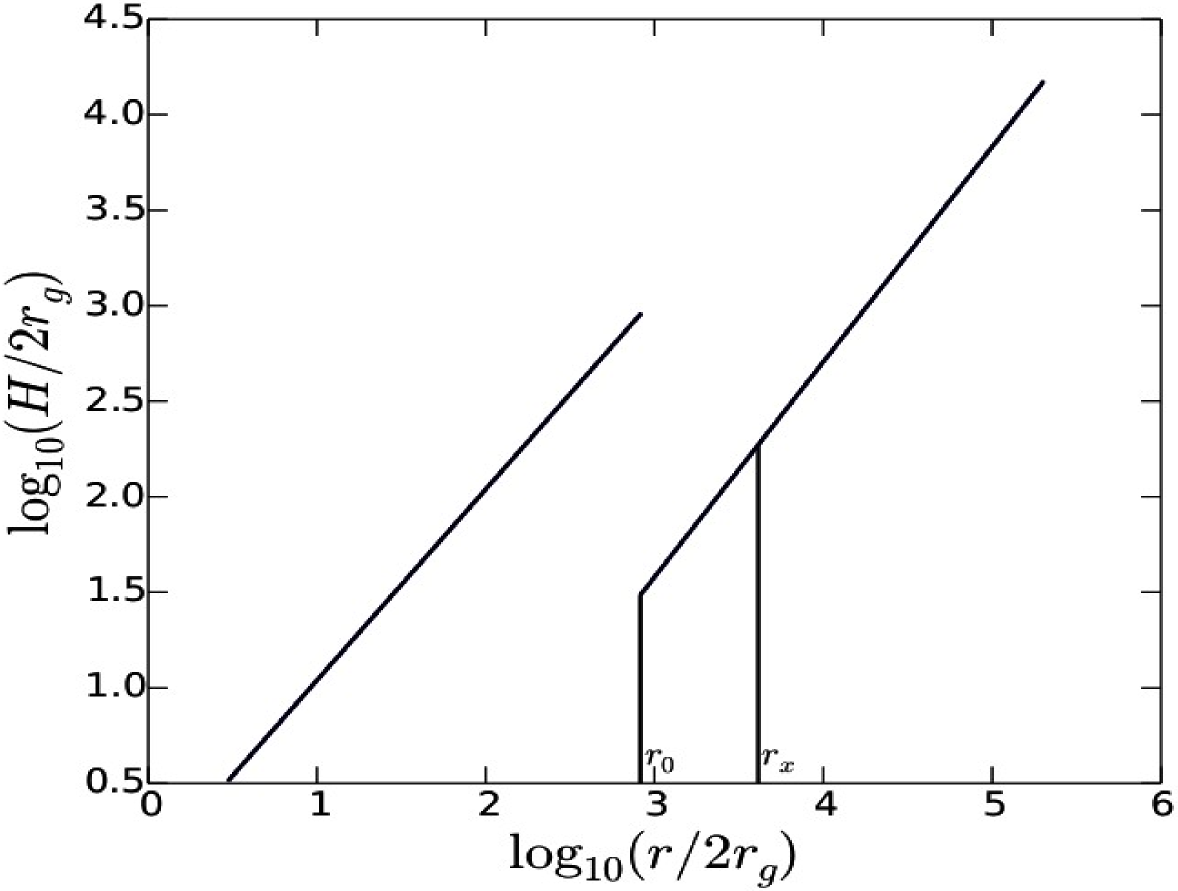


Image credit: Kyoto Univ.

Disc Self-Irradiation

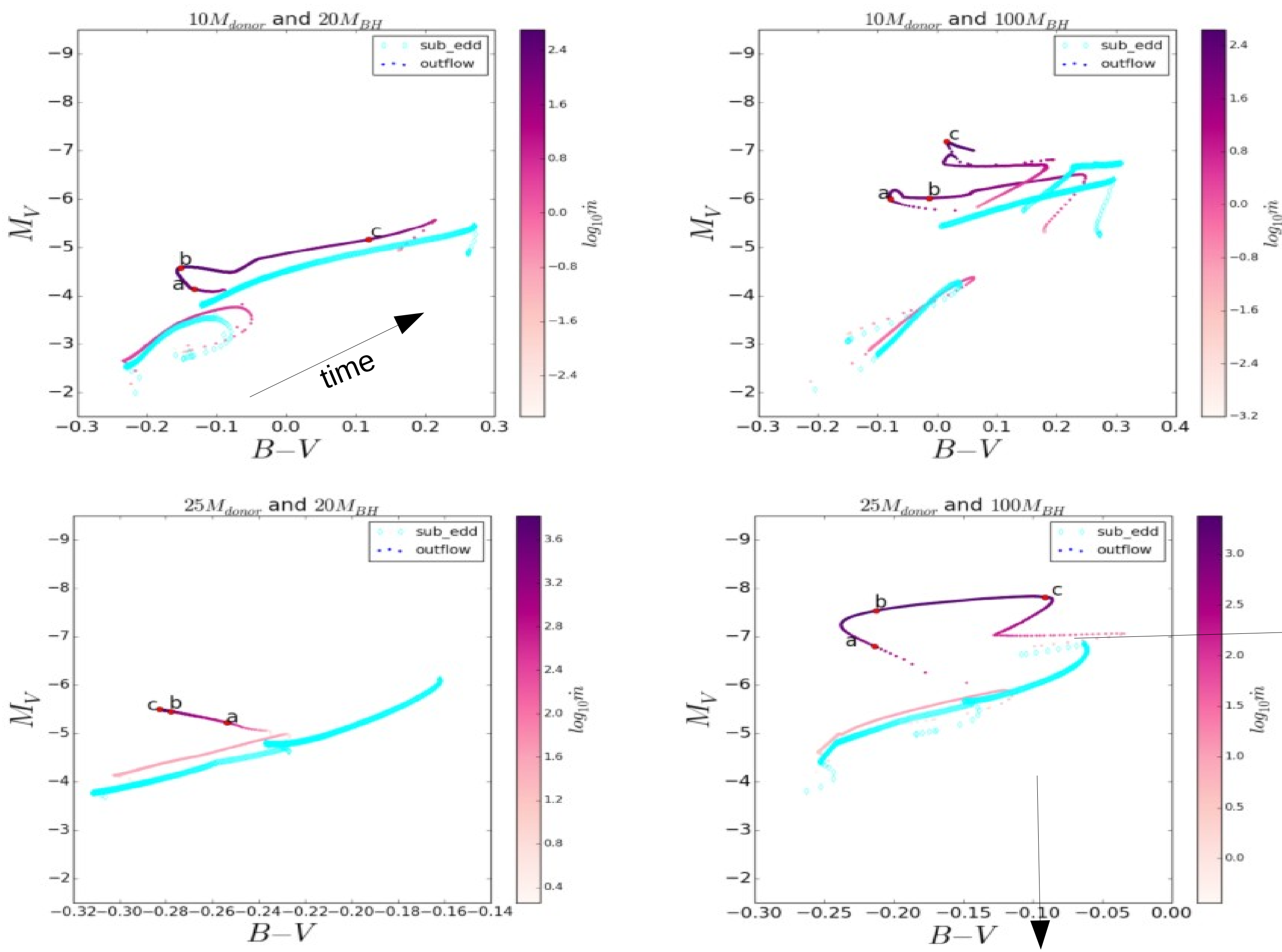


The outflow is so extended that its emission in the optical-through soft X-rays can be dominant

Self-irradiation is due to the UV-Xray flux produced in the region between r_{ph} and r_x, where r_x is the radius of the last annulus emitting in the UV-Xray band

If $R_{ph} > R_x$ there is no self-irradiation

Evolutionary tracks on the CMDs: comparison between PZ and the model with **super-Eddington accretion** (Ambrosi & Zampieri 2018)



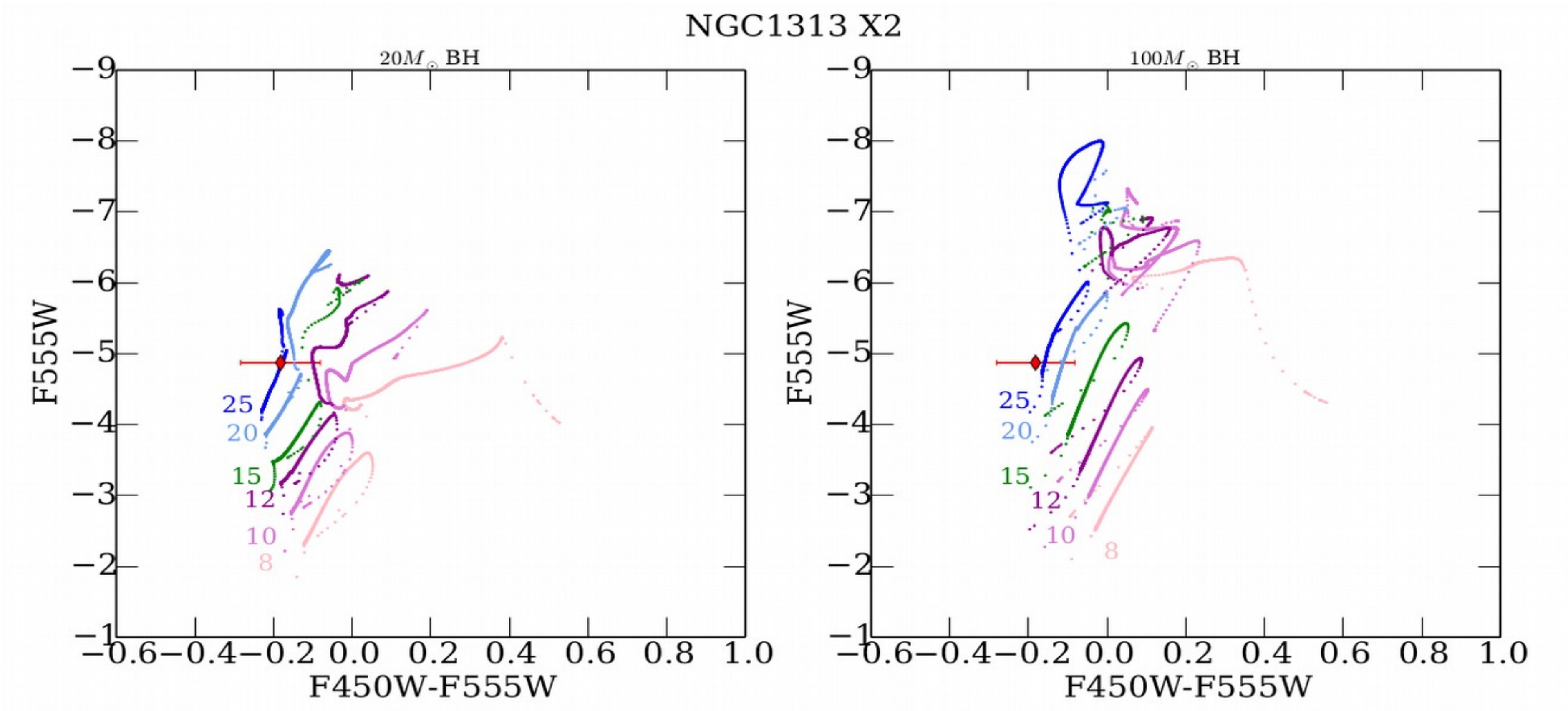
After MS: Luminosity is larger than that in PZ
Colours are initially bluer and then become comparatively redder

Donor ascending along the giant branch is highly super-Eddington

The two models tracks overlap when the donor is on the MS

Sub-Eddington accretion
During MS mass transfer is mildly super-Eddington

NGC 1313 X-2 (Ambrosi & Zampieri 2018)



Combining HST data (Tao et al. 2011) and information on the environment:
- Distance 4.07 Mpc
- Belongs to a young population
aged ~ 20 Myrs (Grisè et al.(2008))
- P~ 6.12 days (Liu et al., 2009; Zampieri et al. 2012)
- Lx= ~ 1.0e39 – 3.0e40 erg/s

NGC 1313 X-2 is well represented by a system with a ~ 20M black hole accreting above Eddington from a massive evolved donor
The period of the synthethic system is ~ 5 days, in fair agreement with the observed one.

What about Pulsar ULXs?

Is it possible to constrain the mass of the donor and the evolutionary stage of a Pulsar ULX from the optical emission?

We used the MESA code (Paxton et al. 2013, 2105) to evolve ULX binaries with a Neutron Star and donors of different masses, assuming:

- Non-magnetized NS of 1.4 M_{sol}

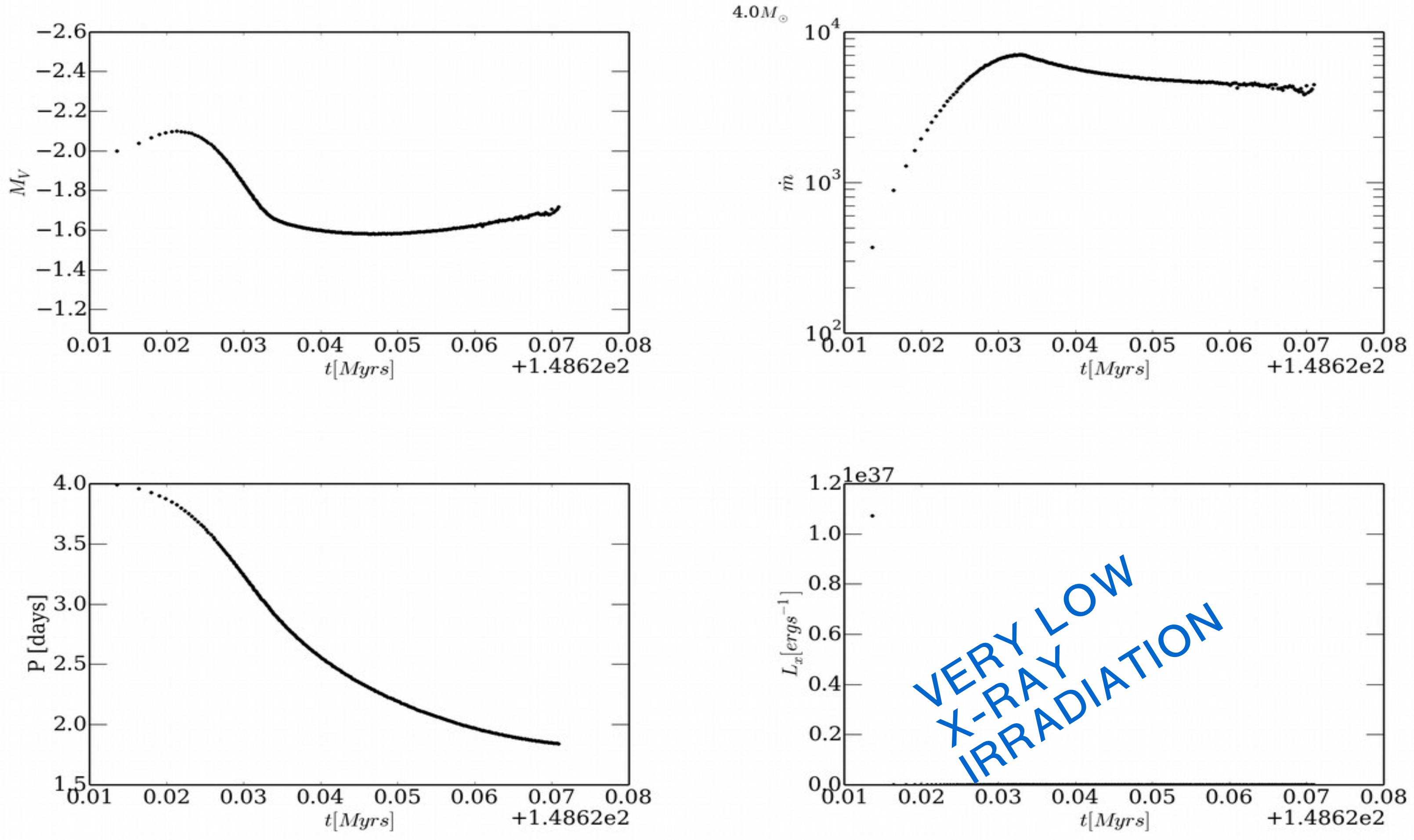
- Conservative mass transfer (all the mass lost by the donor accretes onto the NS, no mass and angolar momentum losses from the system)

- Case A mass transfer evolved until the NS becomes very massive (~2.5 M_{sol}) or mass transfer becomes unstable

- Initial conditions: binary separation is chosen so that accretion starts at around terminal-age main sequence

- Donor mass: an intermediate mass (2-4 Msun) donor is considered, broadly consistent with estimates of binary properties based on X-ray data and modelling of M82 X-2 (Bachetti et al. 2014) and NGC 5907 ULX-1 (Israel et al. 2017; see also Tauris et al. 2000)

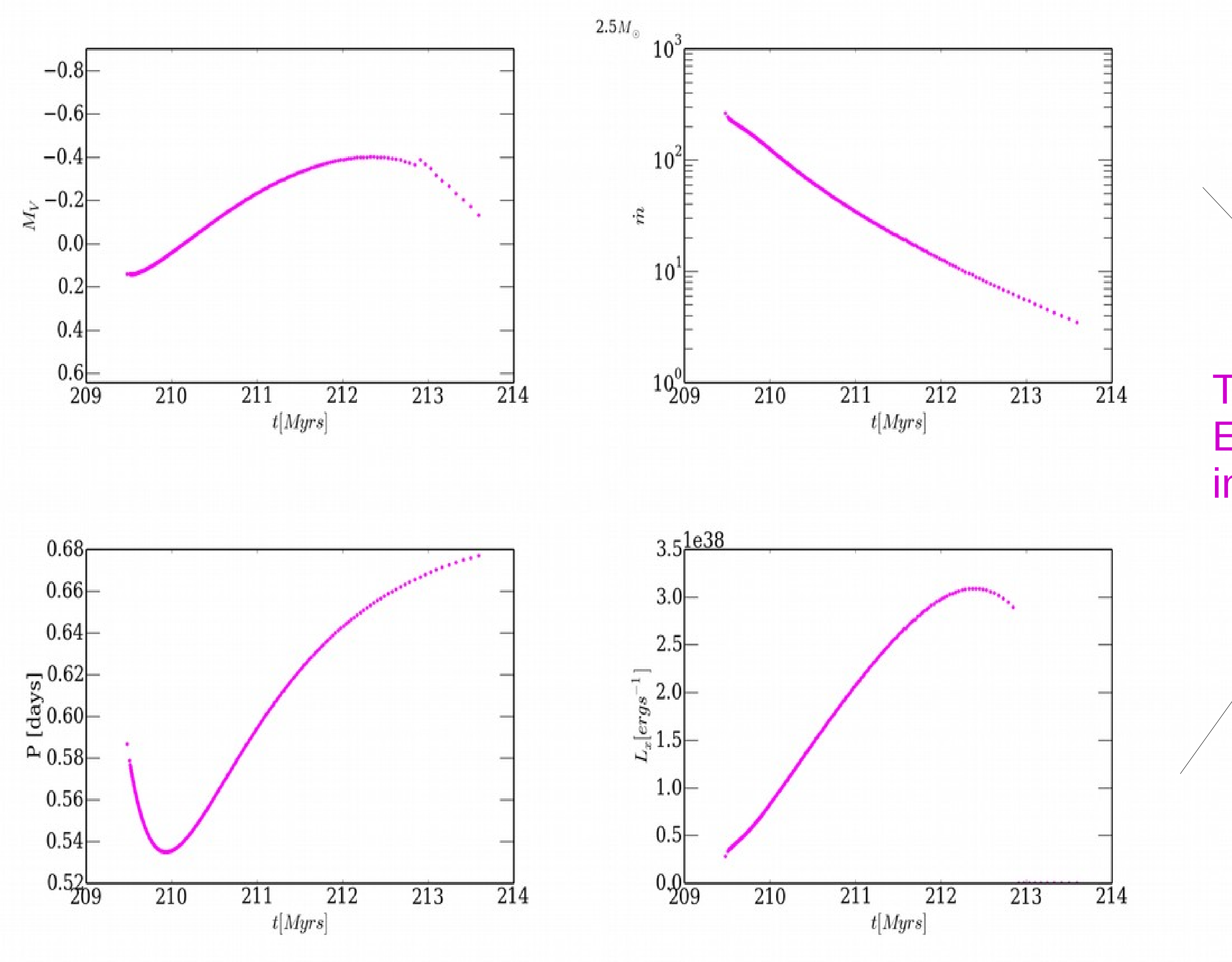
EVOLUTION DURING THE ACCRETION PHASE OF A NS ULX BINARY WITH A 4 Msun DONOR



Accretion rate is largely super-Eddington – In these conditions:

- Very low self-irradiation because extended outflow covers the inner irradiating region
- Intrinsic emission of the outer disc dominates the optical flux
- Evolution of V mag depends on the evolution of the mass transfer and on the fraction of visible outer standard disc (also dependent on Mdot)

EVOLUTION DURING THE ACCRETION PHASE OF A NS ULX BINARY WITH A 2.5 Msun DONOR

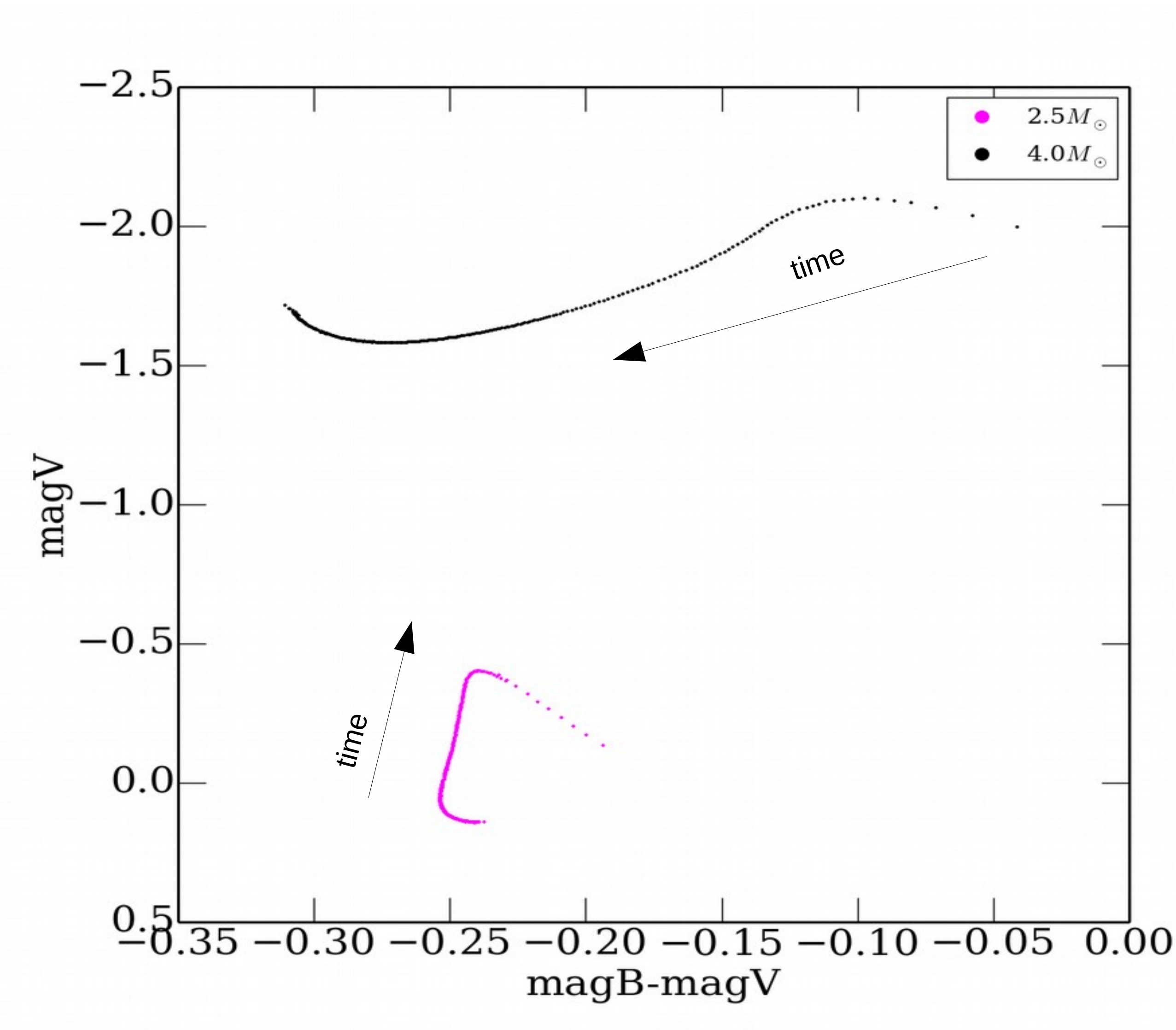


The accretion rate is super Eddington and irradiation is important

Accretion rate is super-Eddington – In these conditions:

- Intrinsic emission of the **irradiated** outer disc dominates the optical flux
- Evolution of V magnitude follows that of X-ray irradiation, that increases with decreasing mass transfer

Evolutionary tracks of NS ULX binaries on the color-magnitude diagram



Ambrosi & Zampieri (2018b, in preparation)

Tracks of NS ULX binaries with intermediate mass donors have blue colours, but very faint V magnitudes

They are much weaker than BH ULXs with more massive donors

Essentially undetectable with HST

For NS ULXs with more massive donors (e.g. NGC 7793 P13), the disc is more extended and the optical emission from the irradiated companion is expected to be important

We could not steadily evolve such systems with MESA (mass transfer is highly unstable from the very beginning of the contact phase)

SUMMARY AND CONCLUSIONS

- We implement a model of an accretion disc with a bimodal structure for ULXs accreting above Eddington

- Super-critical accretion has considerable effects on the optical emission

- The irradiating flux in presence of an outflow remains considerably stronger than that produced by a standard disc. However, at very high accretion rates the contribution of X-ray irradiation becomes progressively less important in comparison with the intrinsic flux emitted from the disc

- For BH ULXs: After Main Sequence the evolutionary tracks of the optical counterpart on the colour-magnitude diagram are markely different from those computed for Eddington-limited accretion

- NGC 1313 X-2: well represented by a system with a $\sim$ 20M black hole accreting above Eddington from a massive evolved donor

SUMMARY AND CONCLUSIONS

- We used the MESA code to evolve ULX binaries with a NS and donors of 2-4 Msun

- In this preliminary calculation we assumed:
  - a non magnetized neutron star
  - conservative mass transfer (therefore the effects of the mass and angular momentum loss of the donor are underestimated)

- Tracks of NS ULX binaries with intermediate mass donors have blue colours, but very faint V magnitudes

- They are much weaker than those of BH ULXs with more massive donors and are essentially undetectable with HST (consistent with non-detection of the counterpart of NGC 5907 ULX-1, Sutton et al. 2013)

- We could not steadily evolve systems with more massive donors (mass transfer is highly unstable from the very beginning of the contact phase)