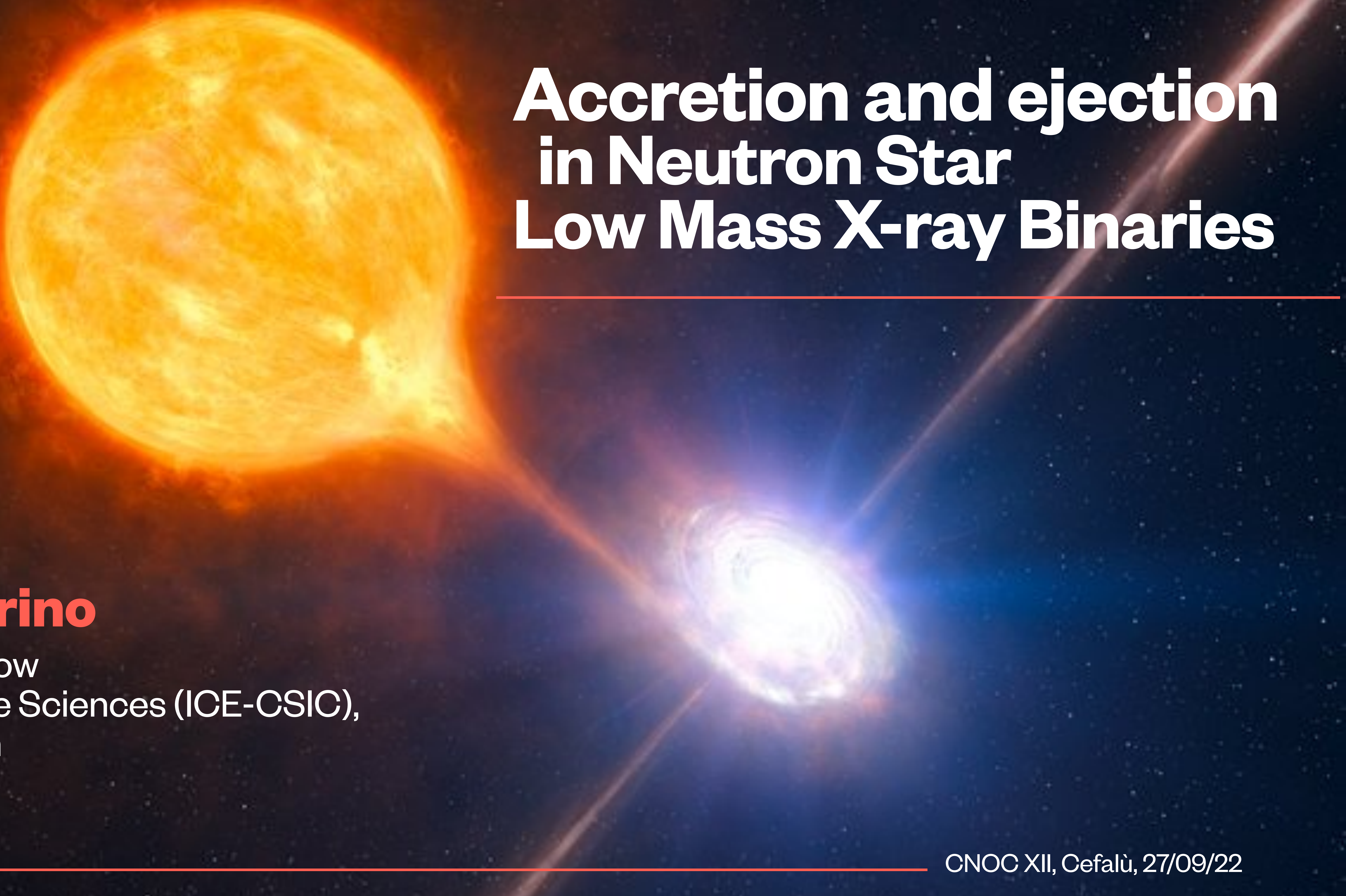
Accretion and ejection in Neutron Star Low Mass X-ray Binaries



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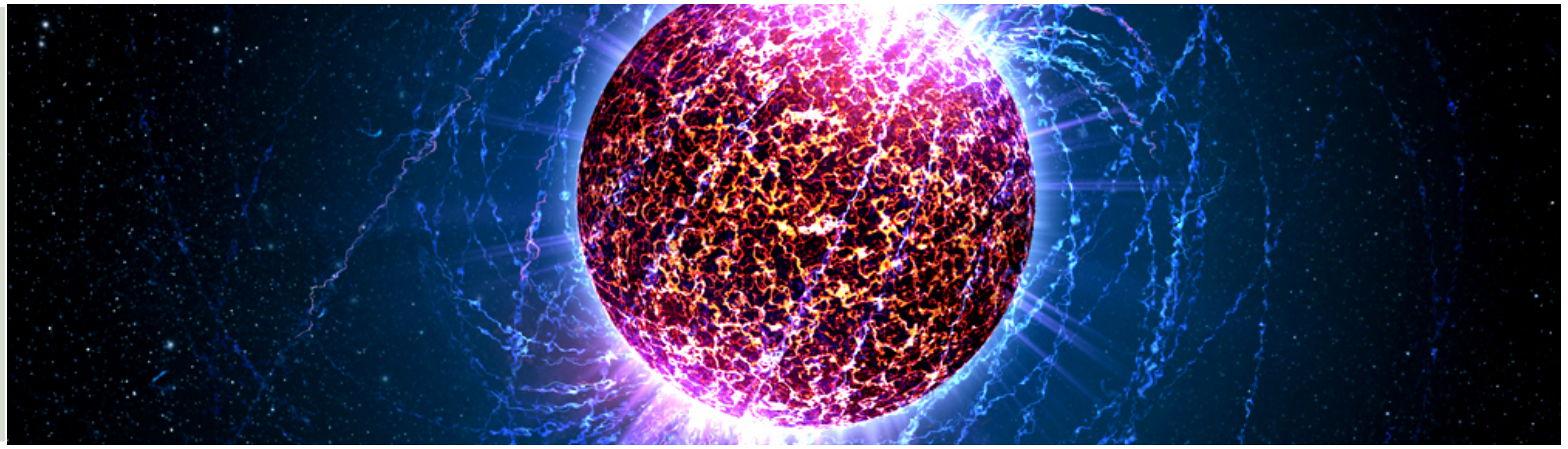
Outline

1

A walk through the zoo of Neutron Star Low Mass X-ray Binaries

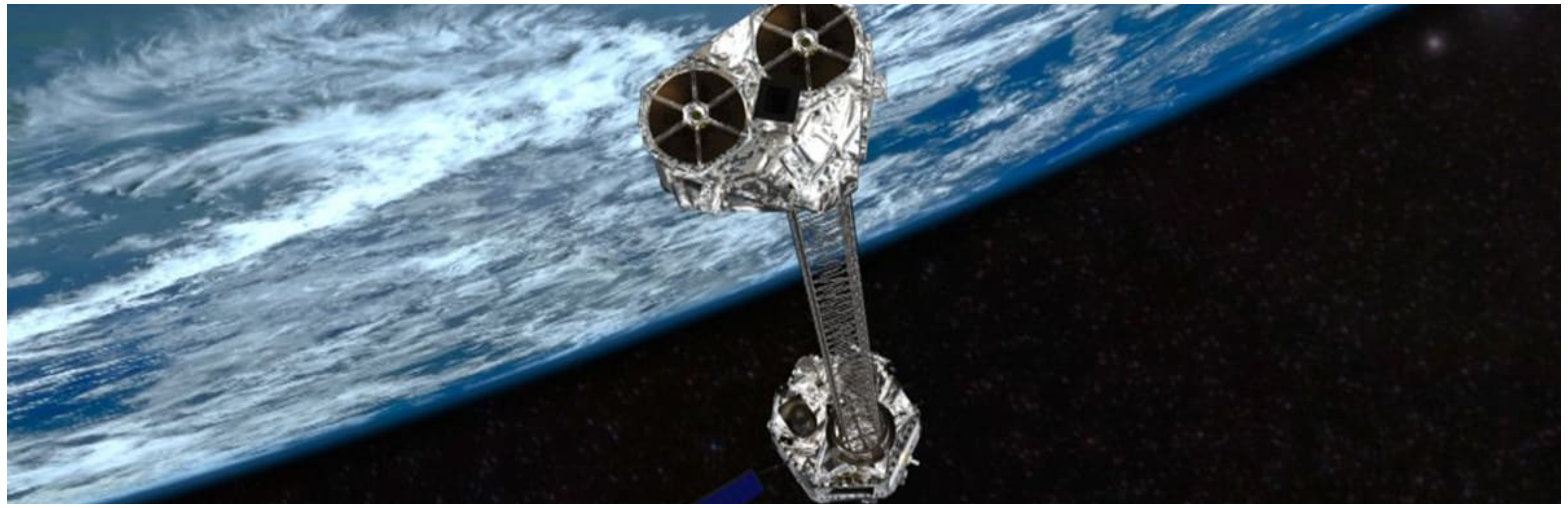
+ AMXPs, tMSPs and a lot of other acronyms..



2

How to investigate accretion physics using X-ray spectroscopy

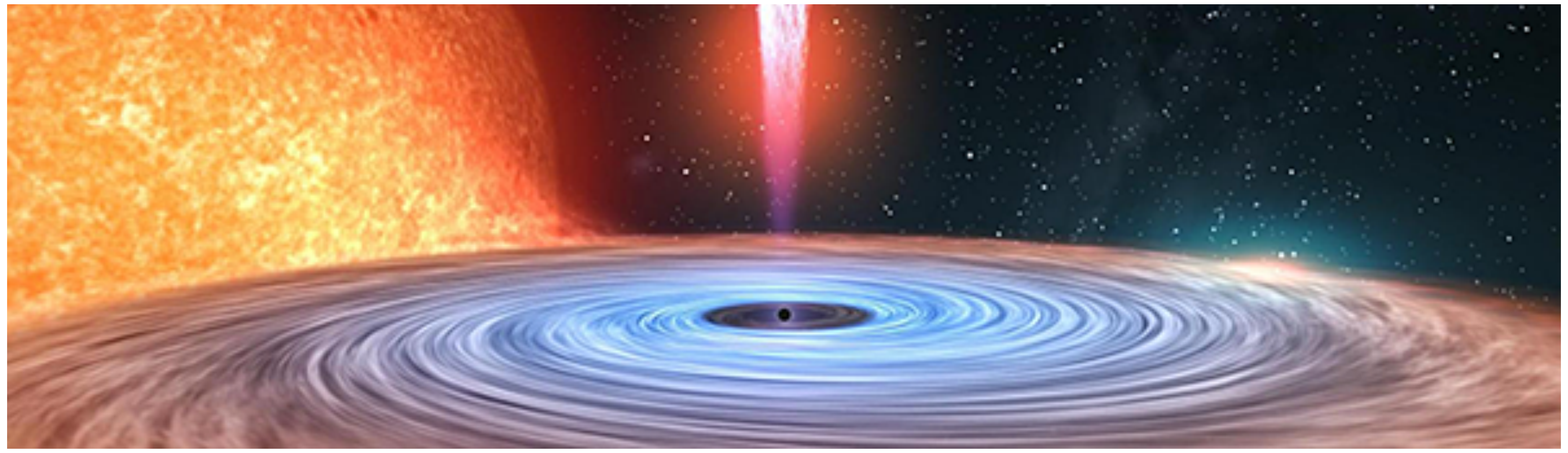
+ Type-I X-ray bursts and why we should care about them..



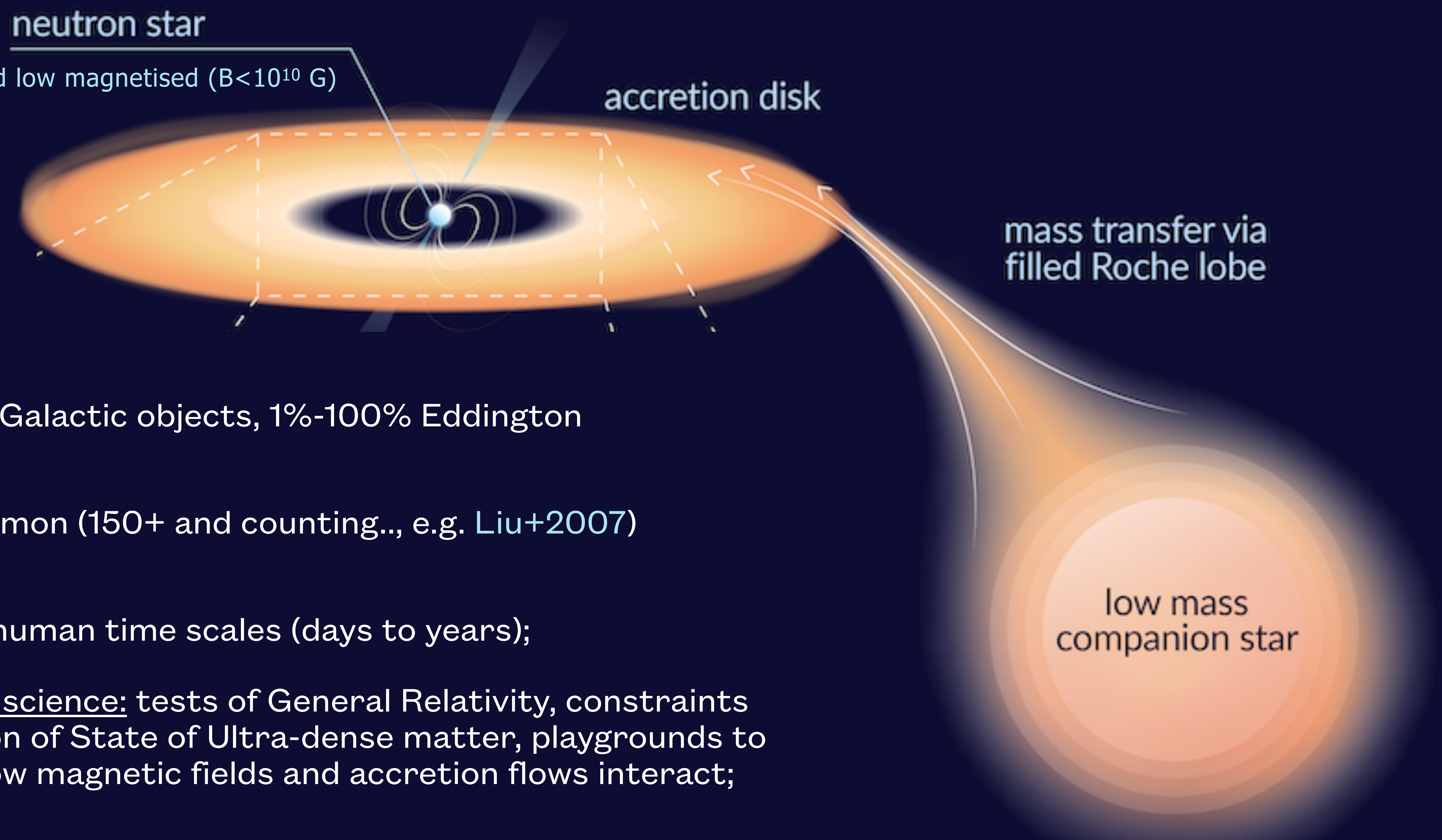
3

Beyond accretion: jets and winds

+ how NS LMXBs stand out with respect to BH systems..



Neutron Star Low Mass X-ray Binaries



- X-rays bright (Galactic objects, 1%-100% Eddington luminosity);
- Relatively common (150+ and counting.., e.g. Liu+2007) objects;
- Evolving over human time scales (days to years);
- <u>Goldmines for science:</u> tests of General Relativity, constraints on the Equation of State of Ultra-dense matter, playgrounds to understand how magnetic fields and accretion flows interact;

Image credit: Shanika Galaudage

The NS LMXBs zoo: transients vs. persistent systems

The NS LMXBs zoo: transients vs. persistent systems

The NS LMXBs zoo: transients vs. persistent systems

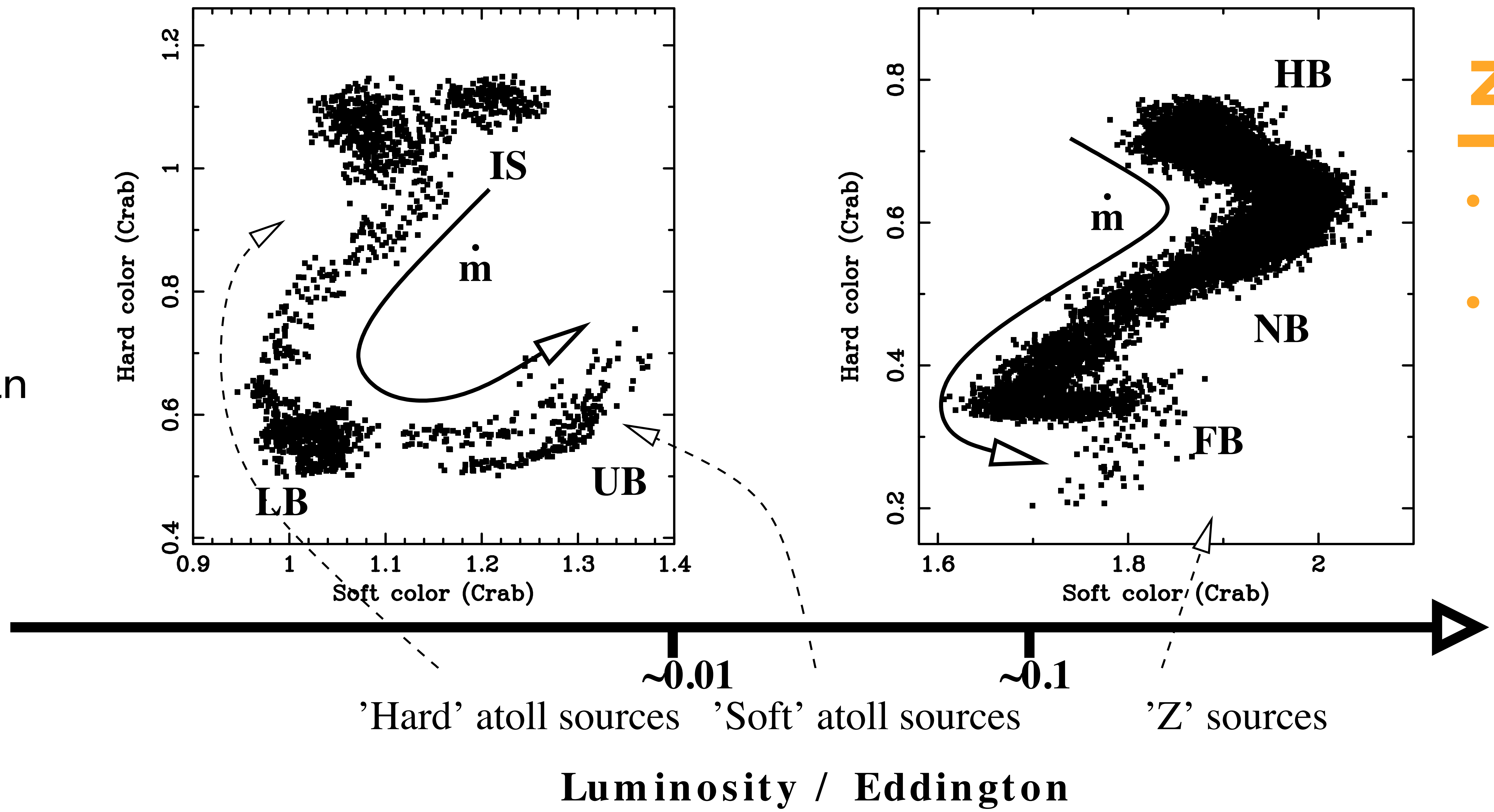
The NS LMXBs zoo: Z sources and atolls

- NS LMXBs can be classified according to the tracks they “draw” on a color-color diagram (Hasinger & Van der Klis89):

from Migliari+06

Atolls

- Persistent or transient sources;
- In outburst, are normally fainter than Z-sources (but can sporadically reach Eddington);



Z sources

- Mostly persistent;
- Always within 10% Eddington;

- An exception to such a dichotomy: the existence of hybrid atoll/Z-sources, e.g. the transient source XTE J1701-462 (Homan+10) -> now in outburst after 16 years!

see talks by Ambrosino, Papitto, Miraval Zanon, Baglio and Illiano for more details!

The NS LMXBs zoo: pulsating and non-pulsating sources

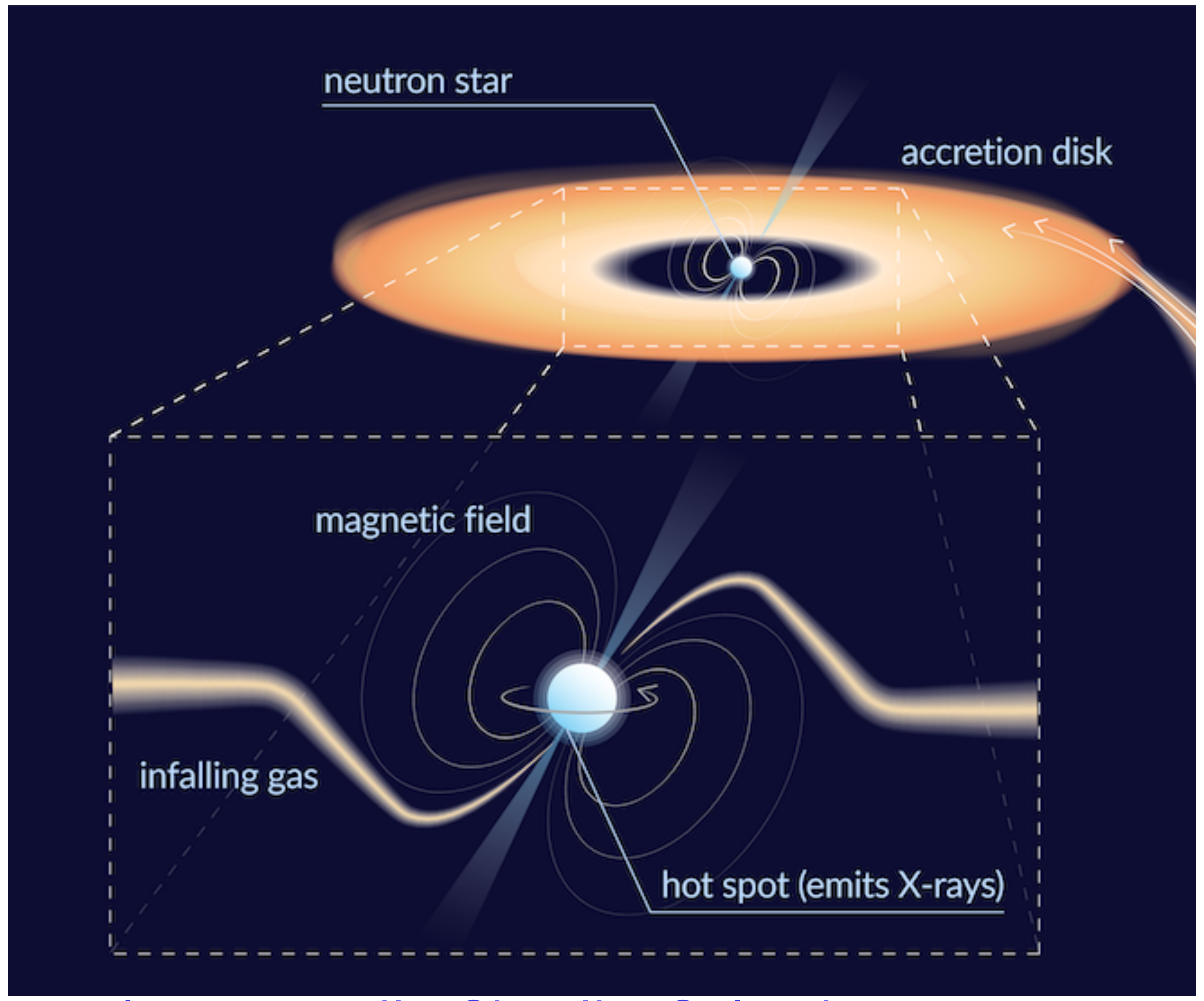
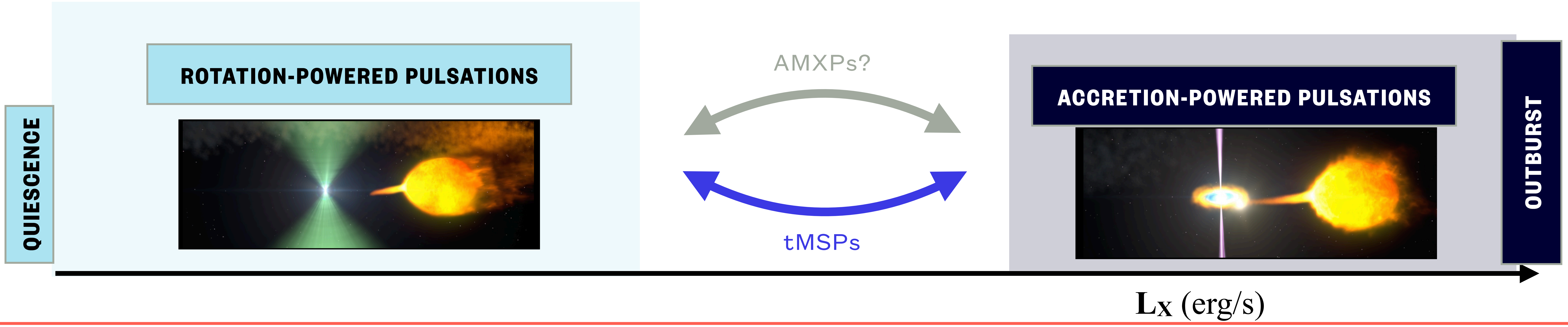
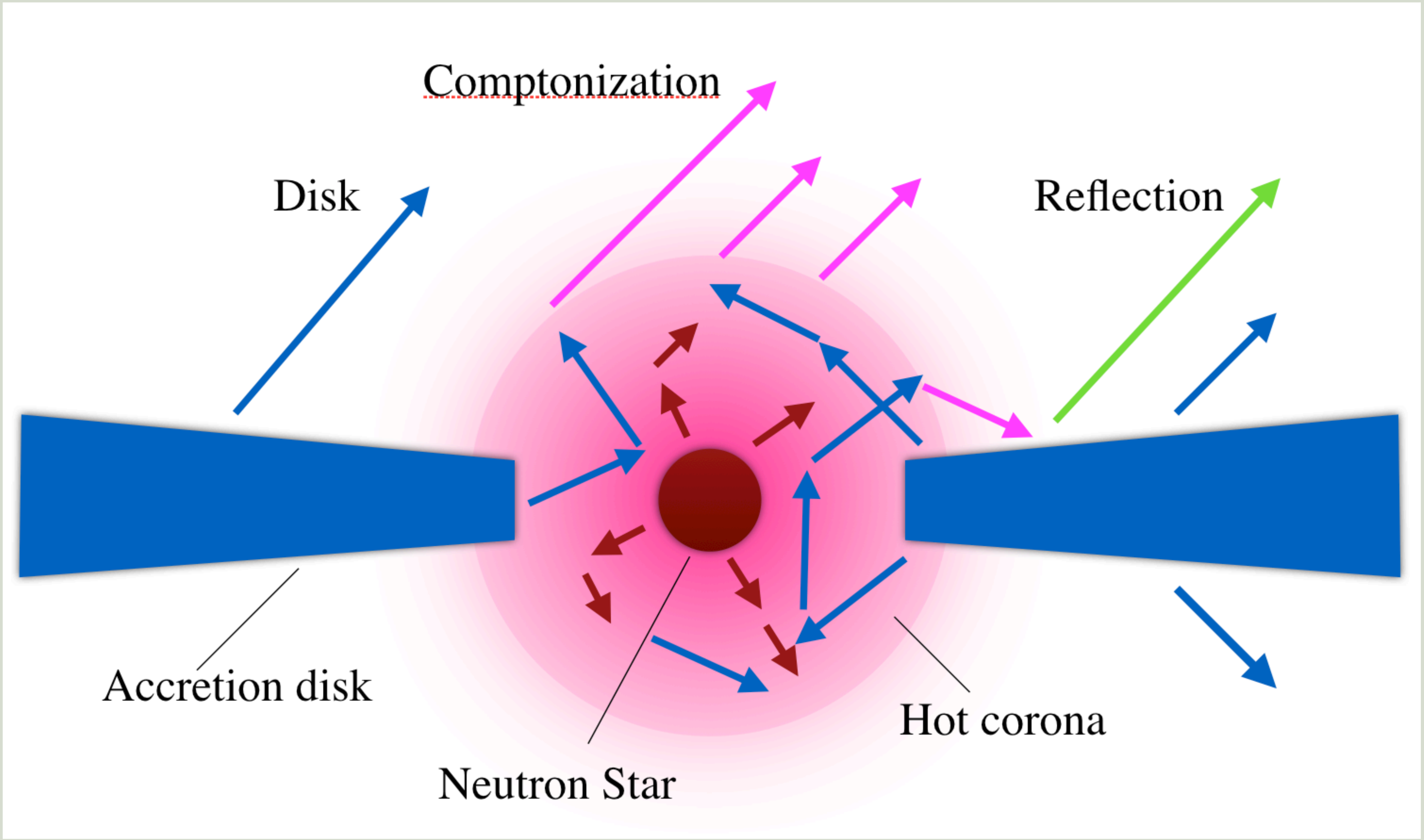


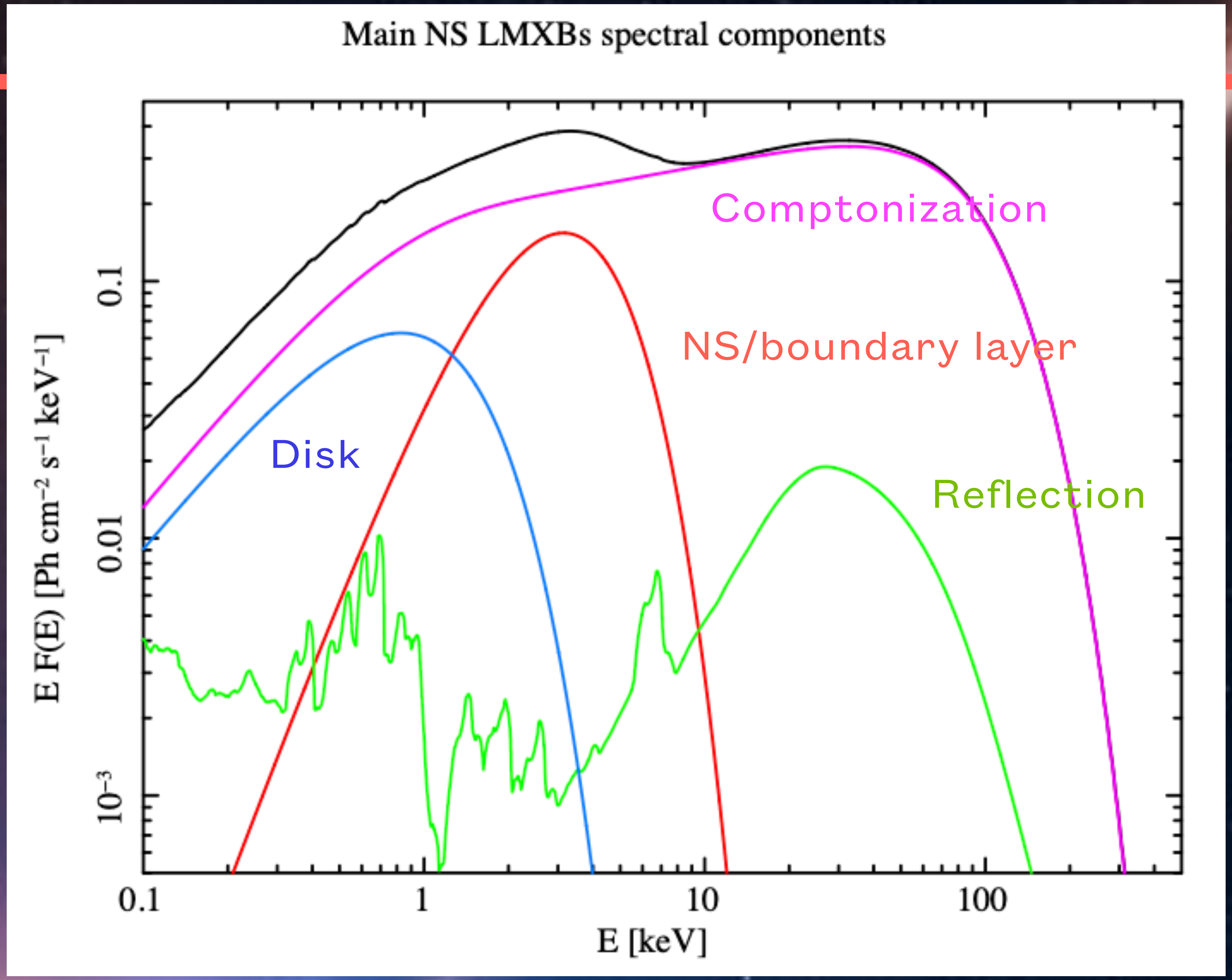
Image credit: Shanika Galaudage

- NS LMXBs in outburst are **never** visible as radio pulsars;
- Most NS LMXBs in outburst are **not** visible as X-ray pulsars either;
- Most of the pulsating NS LMXBs are identified as Accreting Millisecond X-ray Pulsars (AMXPs, Di Salvo & Sanna 22, Patruno & Watts 21) and Transitional Millisecond X-ray Pulsars (tMSPs, Papitto & Di Martino 21);
- tMSPs in quiescence become visible as radio pulsars (e.g. Papitto+13, Bassa+14), AMXPs (as far as we know) not (e.g. Iacolina+09,10, Patruno+17)



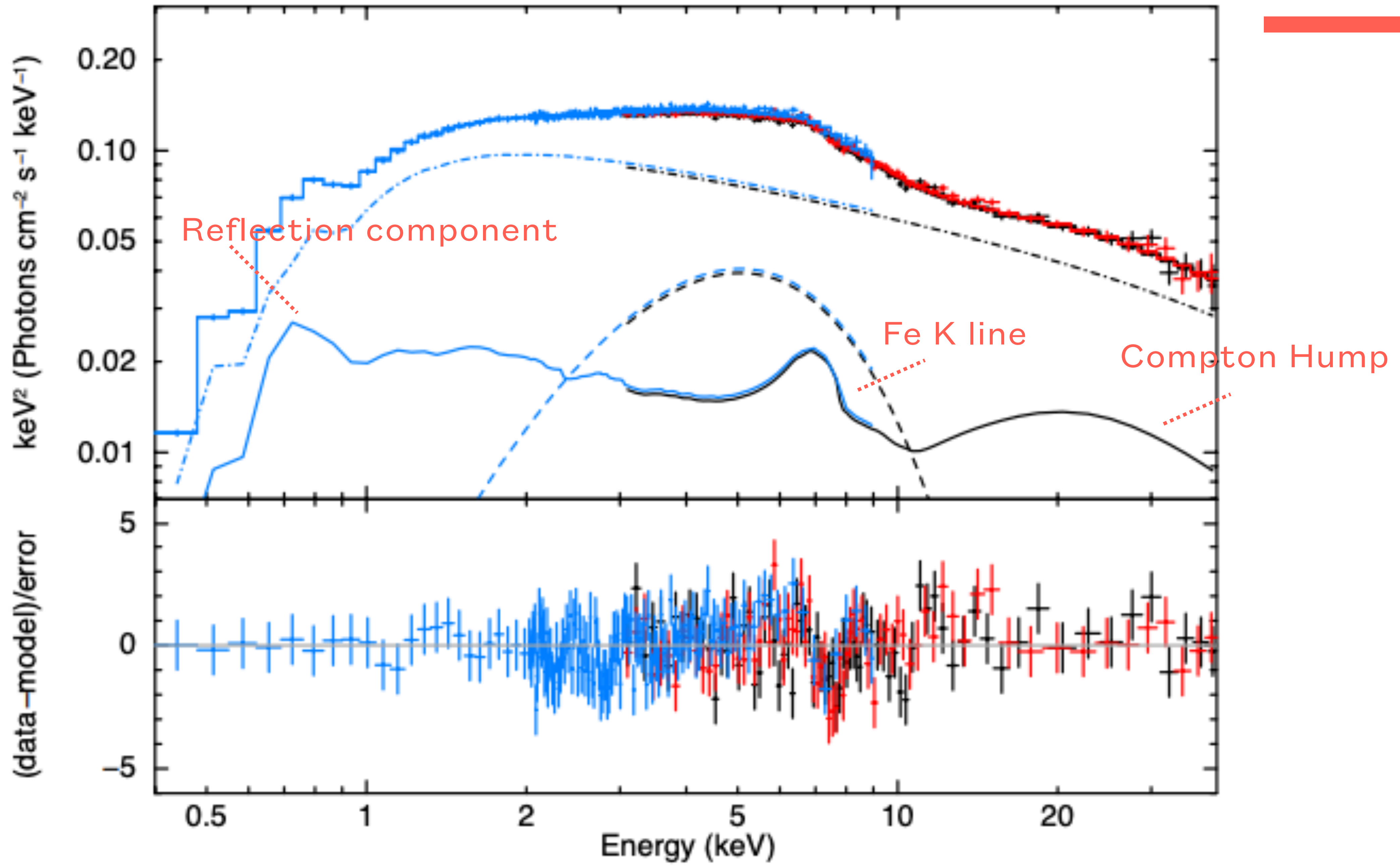


- A schematic view of the inner region of the accretion flow..

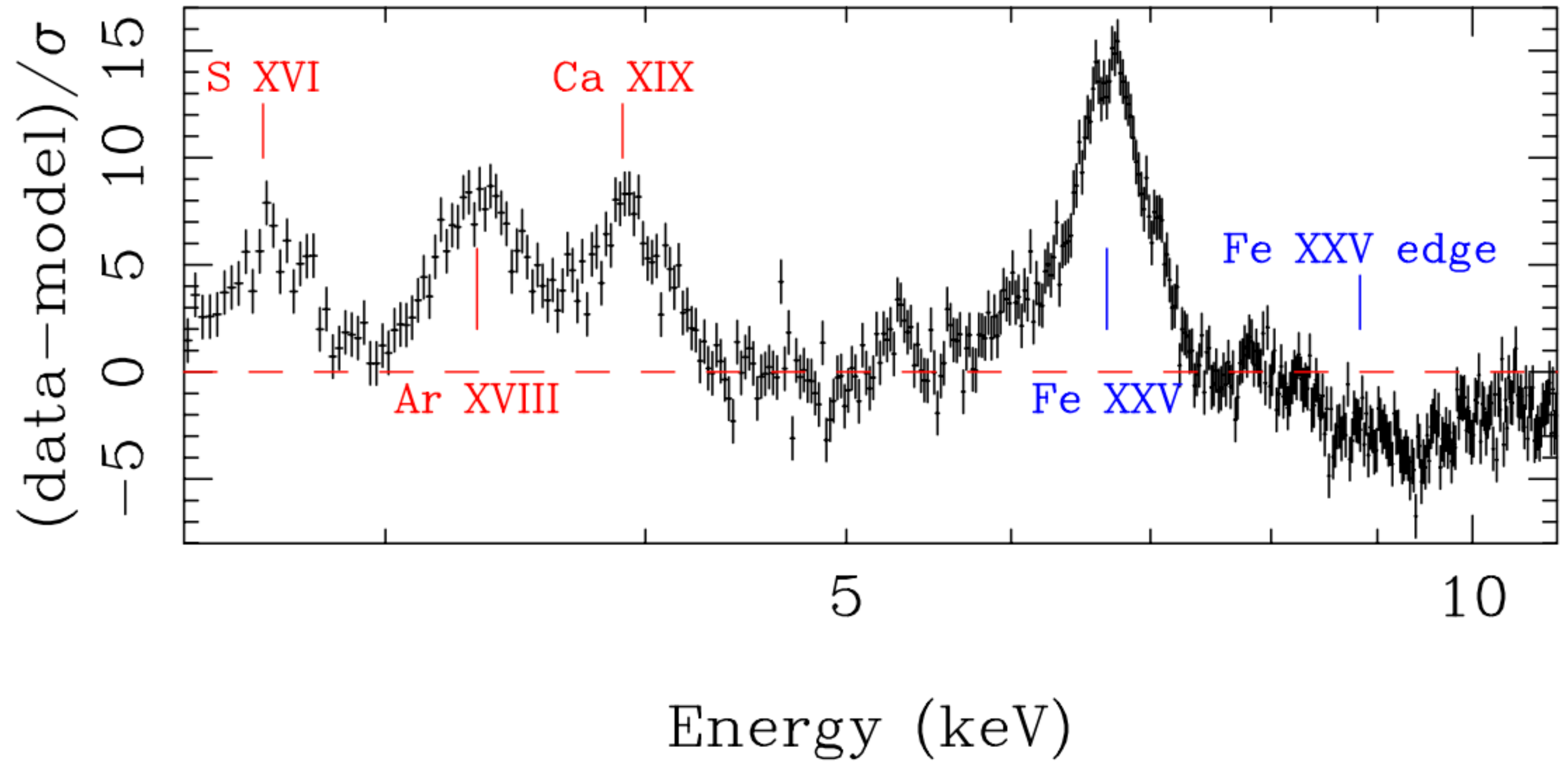


- .. and their main spectral components

X-rays spectra (in outburst): main ingredients



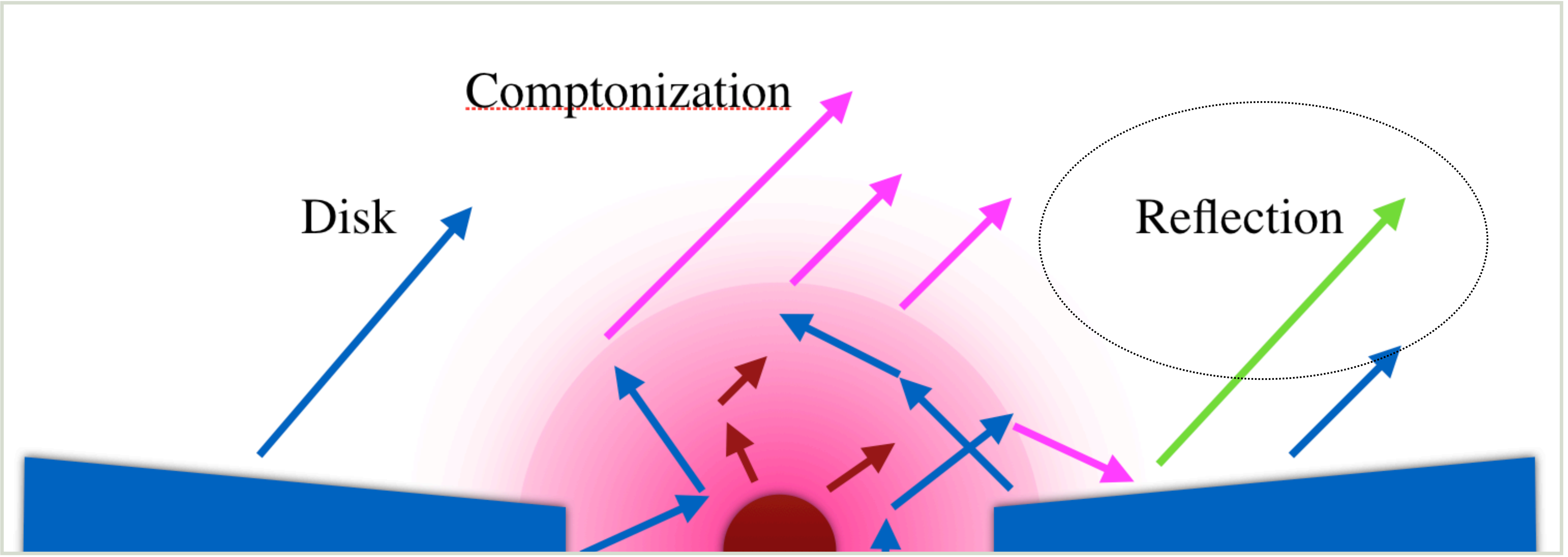
NICER-NuSTAR best-fit model of 4U 1534-624, Ludlam+21



XMM-Newton residuals of 4U 1705-44 showing discrete reflection features, Di Salvo+09

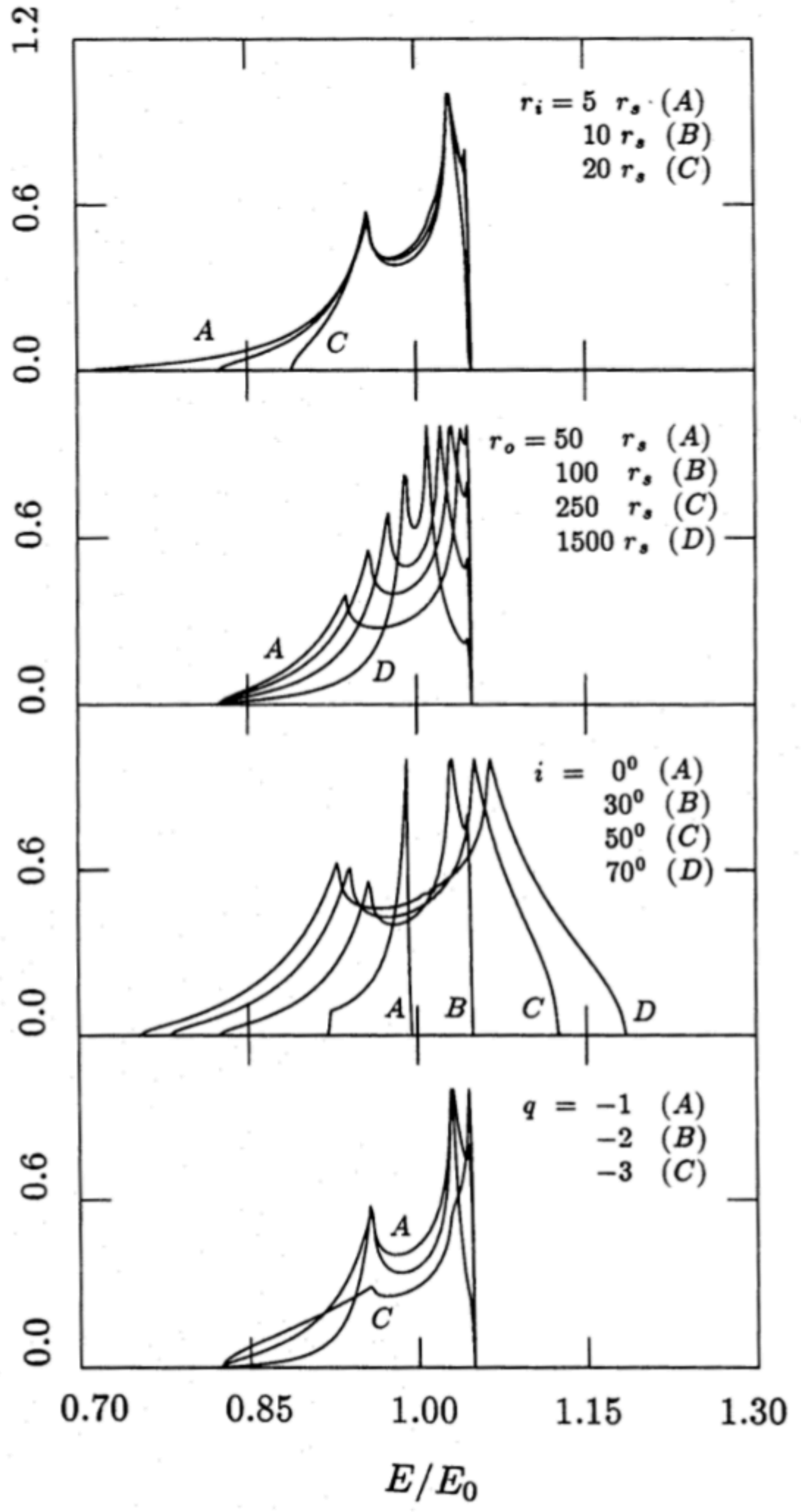
Reflection spectra

- A fraction of the Comptonisation spectrum hitting the disc undergoes a reprocessing and arises a **reflection component**;
- Most prominent features: a Compton hump (at about 10-30 keV), a fluorescence Fe K line at about 6-7 keV and several other discrete features and absorption edges;
- The shape of the overall reflection spectrum is influenced by **the inclination of the system, the ionisation of the disc, the amount of radiation intercepted by the disc**..



see Anitra's talk!

The Fe K line as a diagnostics for the NS radius



How the iron line profile changes with the binary parameters, Fabian+89

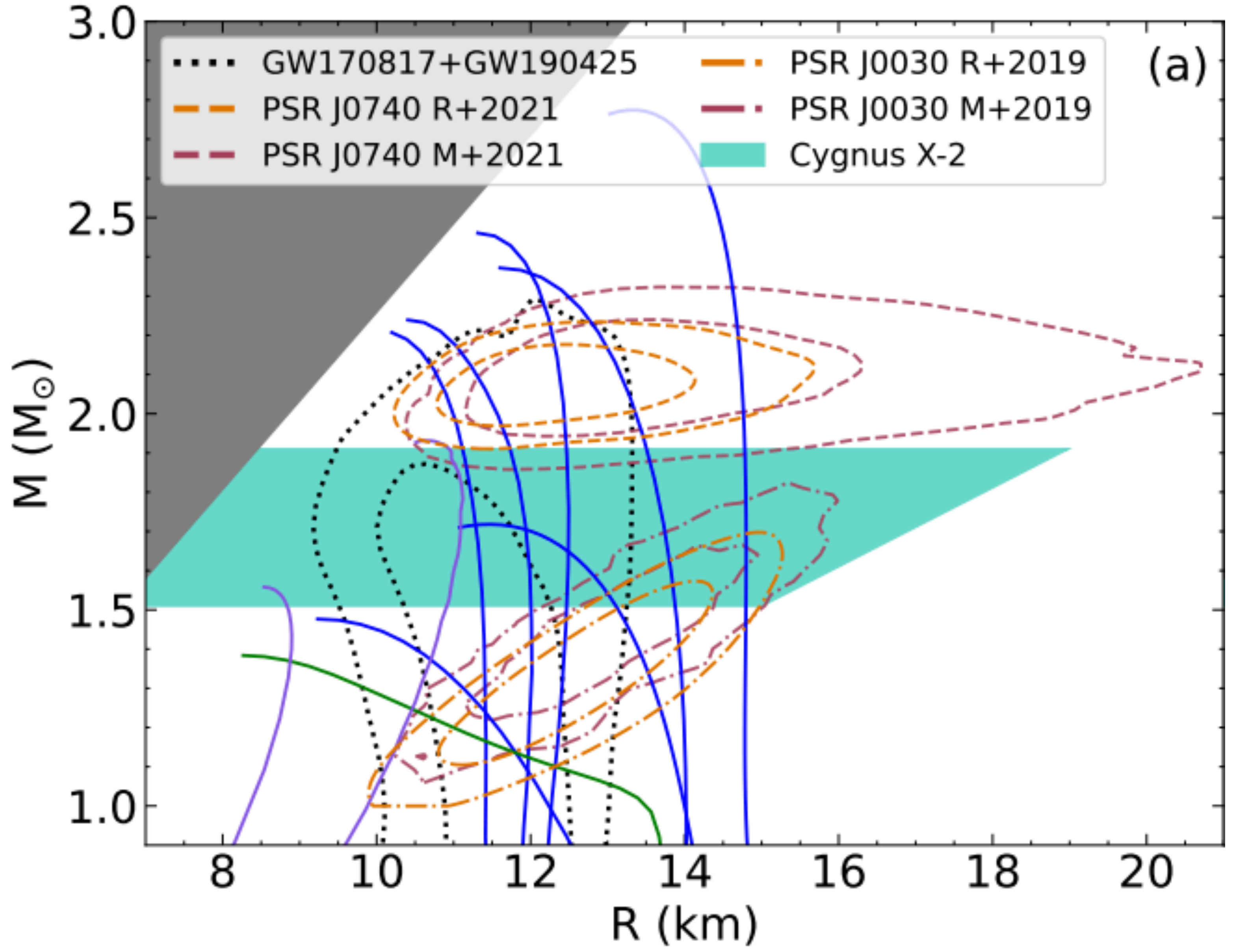
- The Fe K line profile is shaped by the inclination of the system, the emissivity, the outer radius and most importantly the inner radius of the disk;

- With enough statistics and spectral resolution, fitting the iron line profile can provide an accurate estimate of the inner radius of the disk (see e.g. Cackett+10, Egron+11, Matranga+17, Di Salvo+19);

- The inner radius of the disk is an upper limit on the NS radius!

- Spectral analysis of the reflection component and in particular of the Fe K line can be used as a tool to constrain the Equation of State of the Ultra-dense matter (e.g. Ozel & Freire 16);

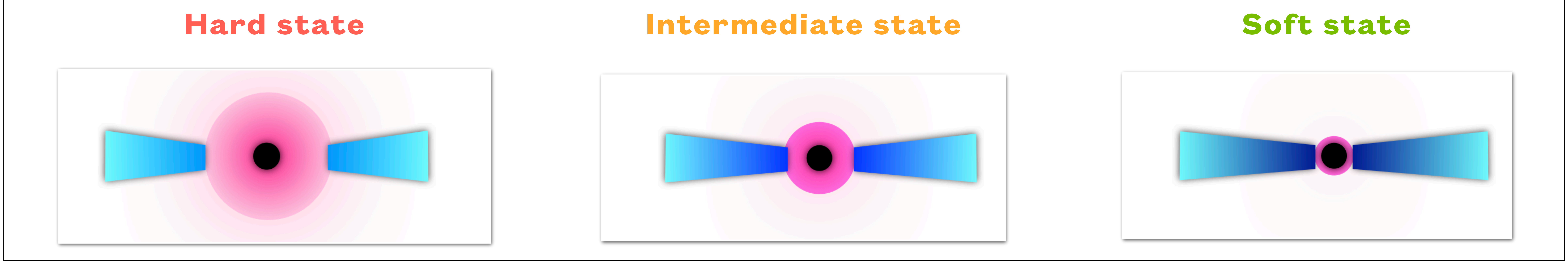
Constraints on the NS radius of Cyg X-2 from the spectral analysis by Ludlam+22

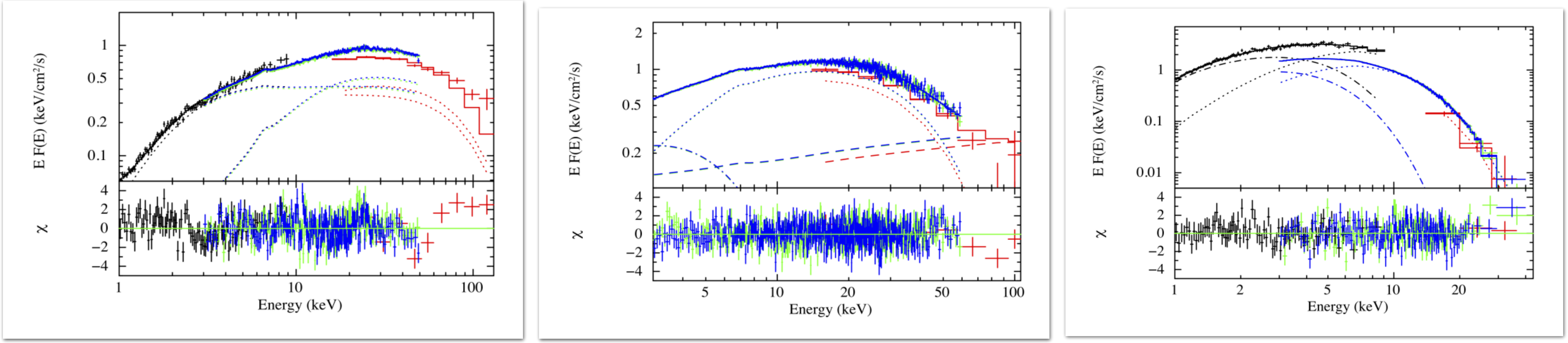


Spectral states

- According to the way those building blocks assemble, we identify three main spectral states, most likely connected to changes in the **geometry of the accretion flow**.

THE EXACT GEOMETRY IS STILL MATTER OF DEBATE

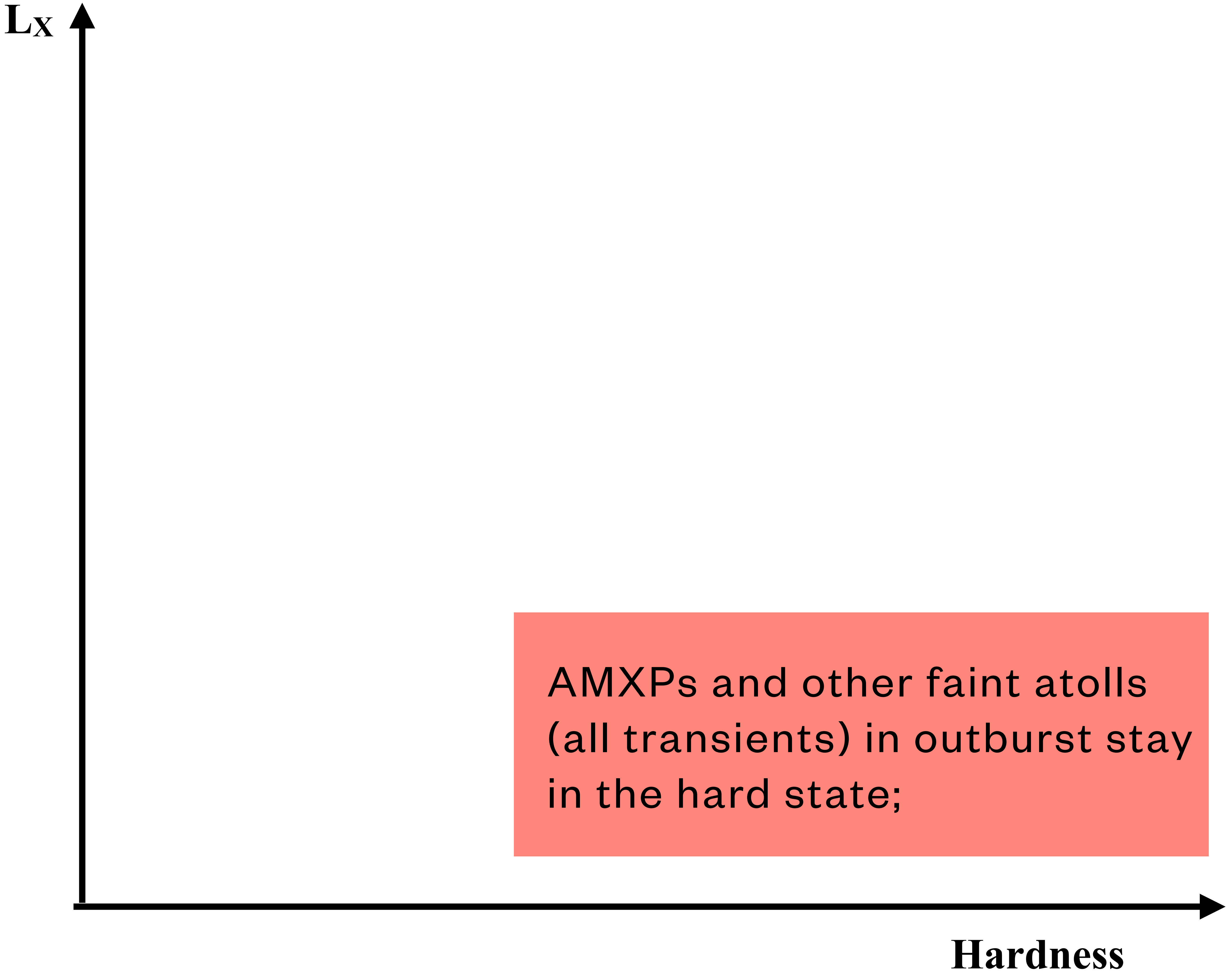




Examples of NS LMXBs spectral states, Marino+2019b

Spectral variability in NS LMXBs

- NS LMXBs display different behaviours regarding the variety of exhibited spectral states:



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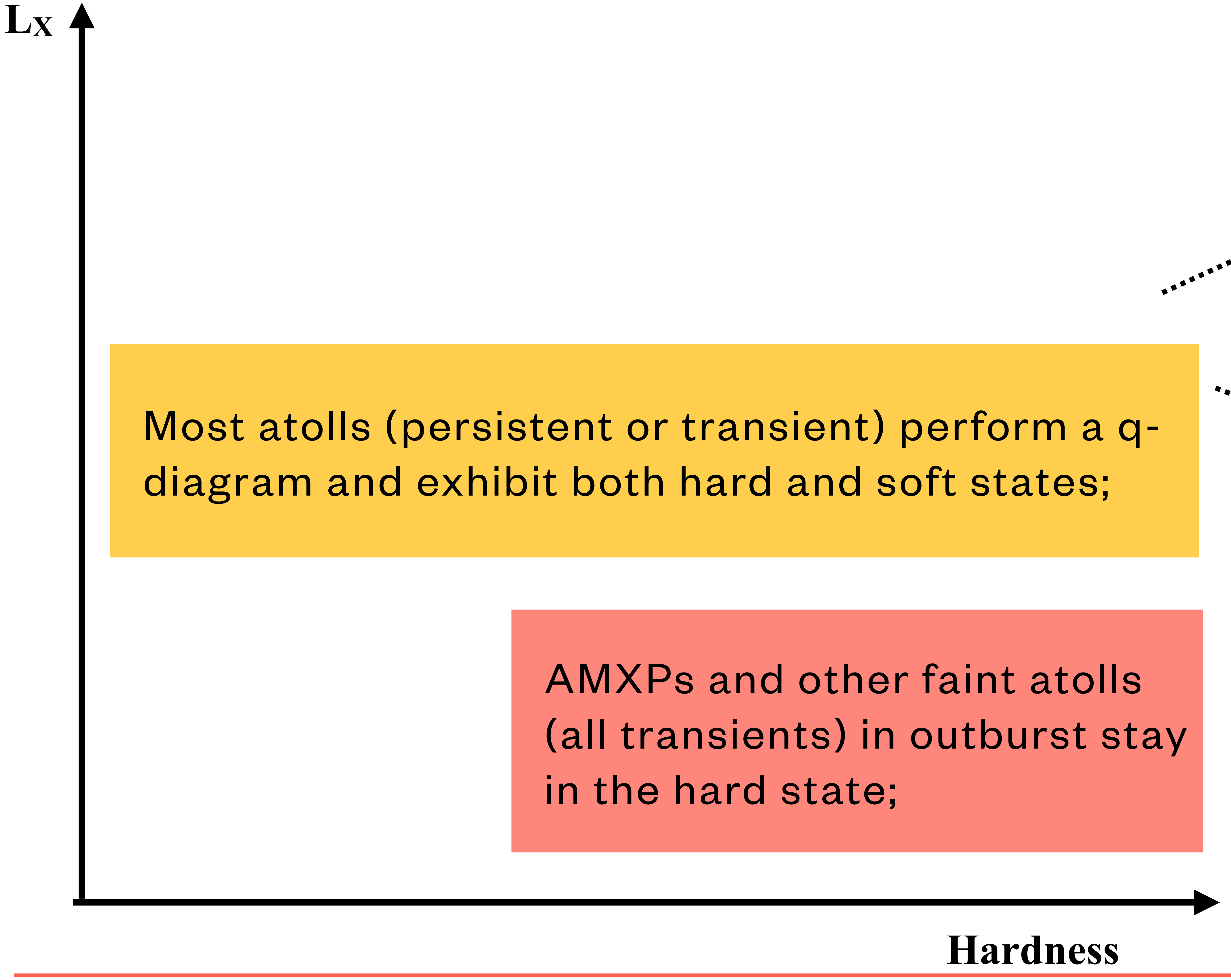
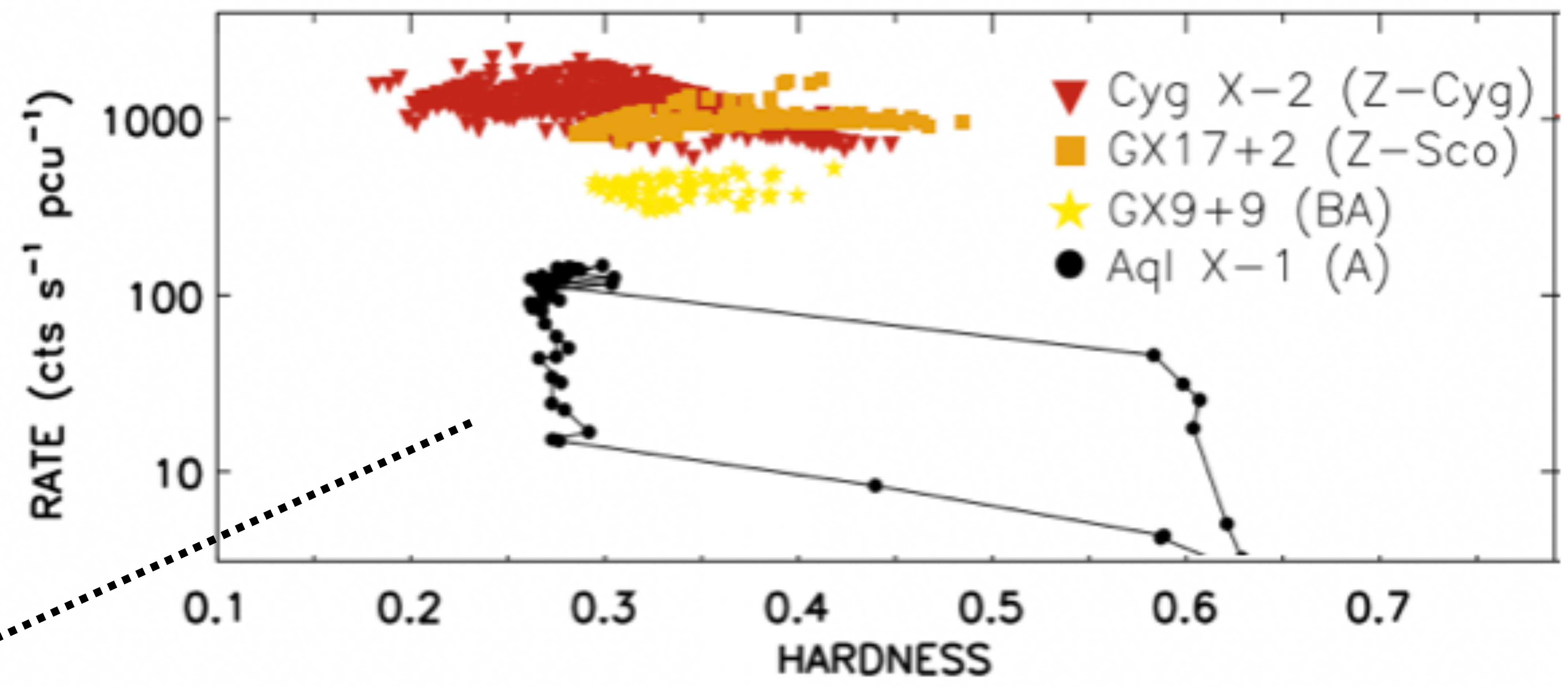
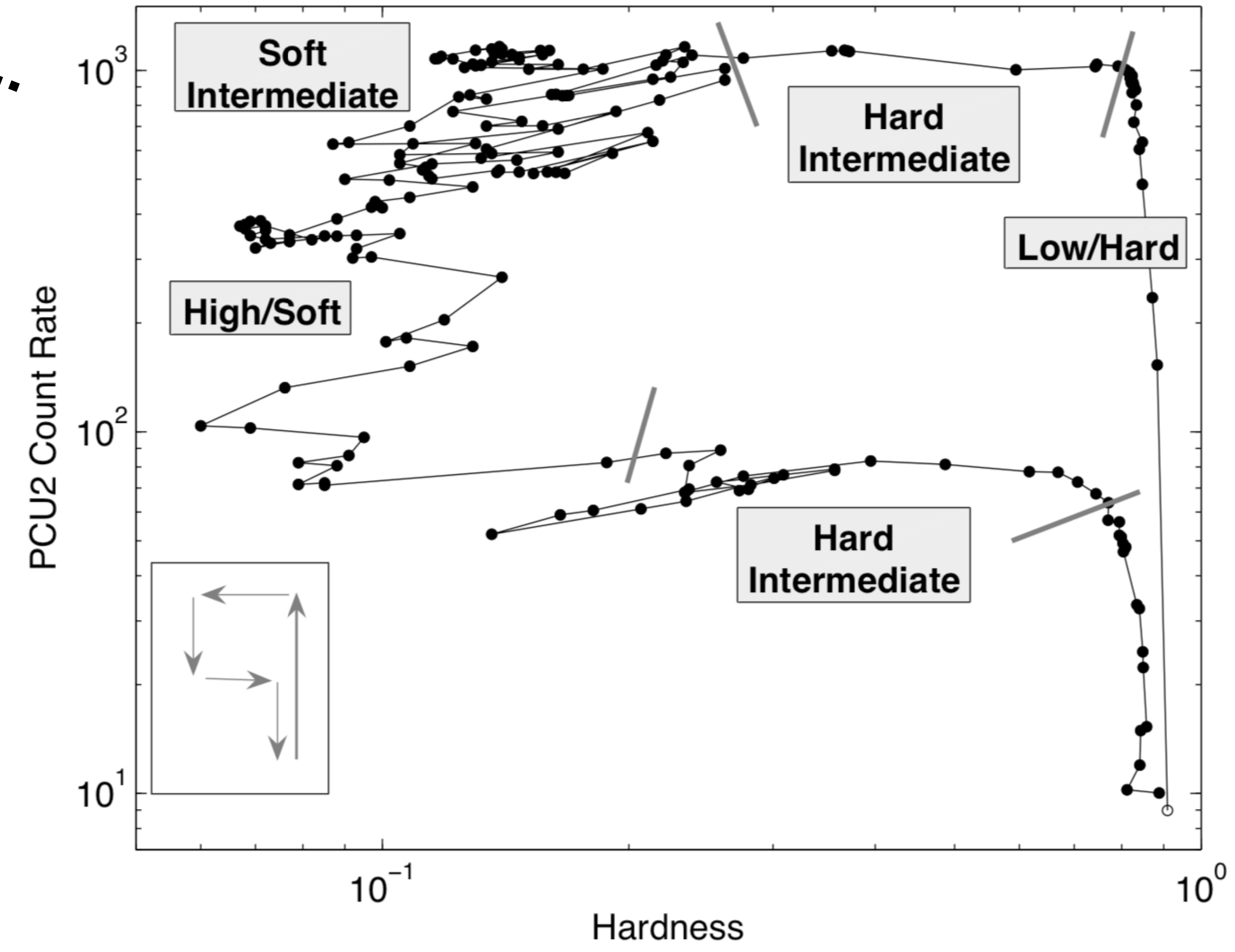




Observed behaviours for different classes of NS LMXB, Munoz Darias+14



A behaviour similar to BH transients, see Malzac's talk

Schematic q-diagram for the BH LMXB GX 339-4, Belloni+04

Spectral variability in NS LMXBs

- NS LMXBs display different behaviours regarding the variety of exhibited spectral states:

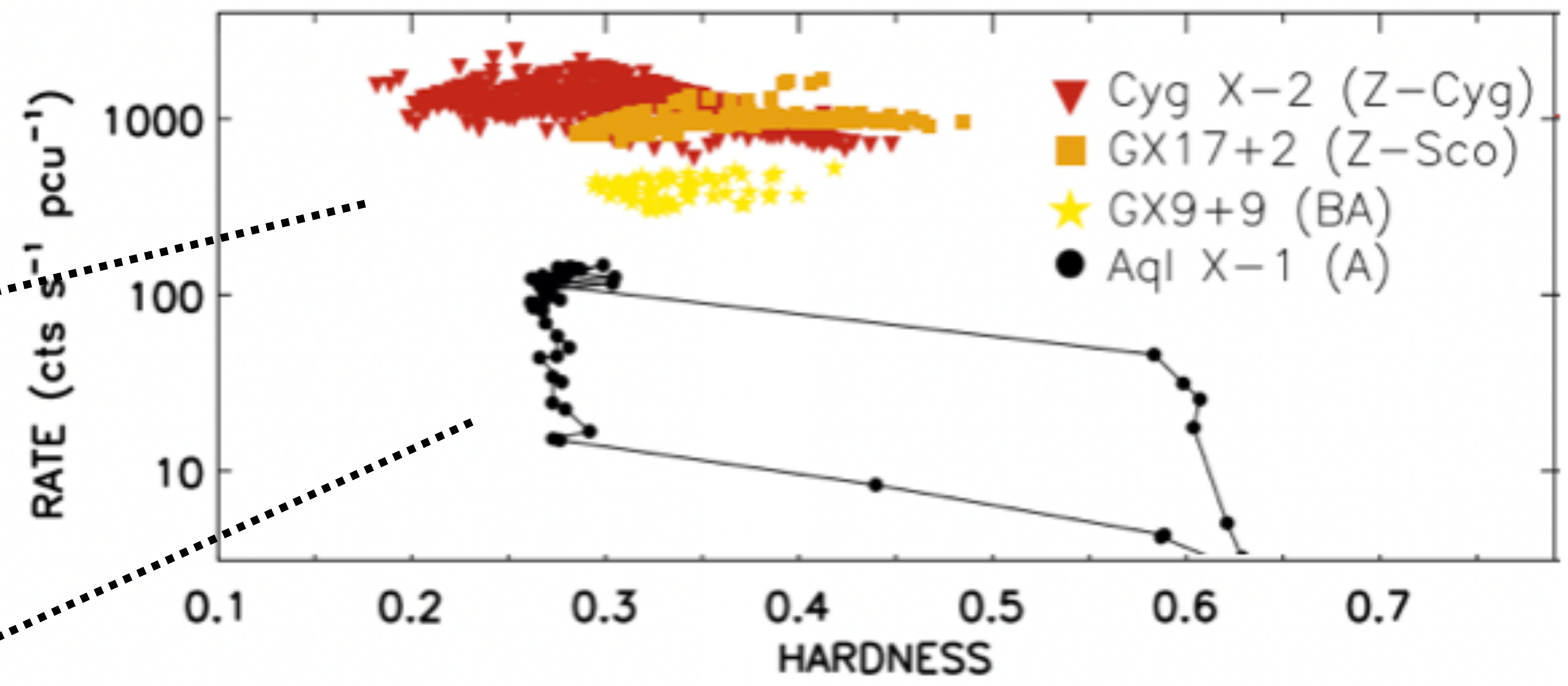
L_X

Bright atolls and Z-sources (almost all persistent) are found typically in the soft state;

Most atolls (persistent or transient) perform a q-diagram and exhibit both hard and soft states;

AMXPs and other faint atolls (all transients) in outburst stay in the hard state;

Hardness



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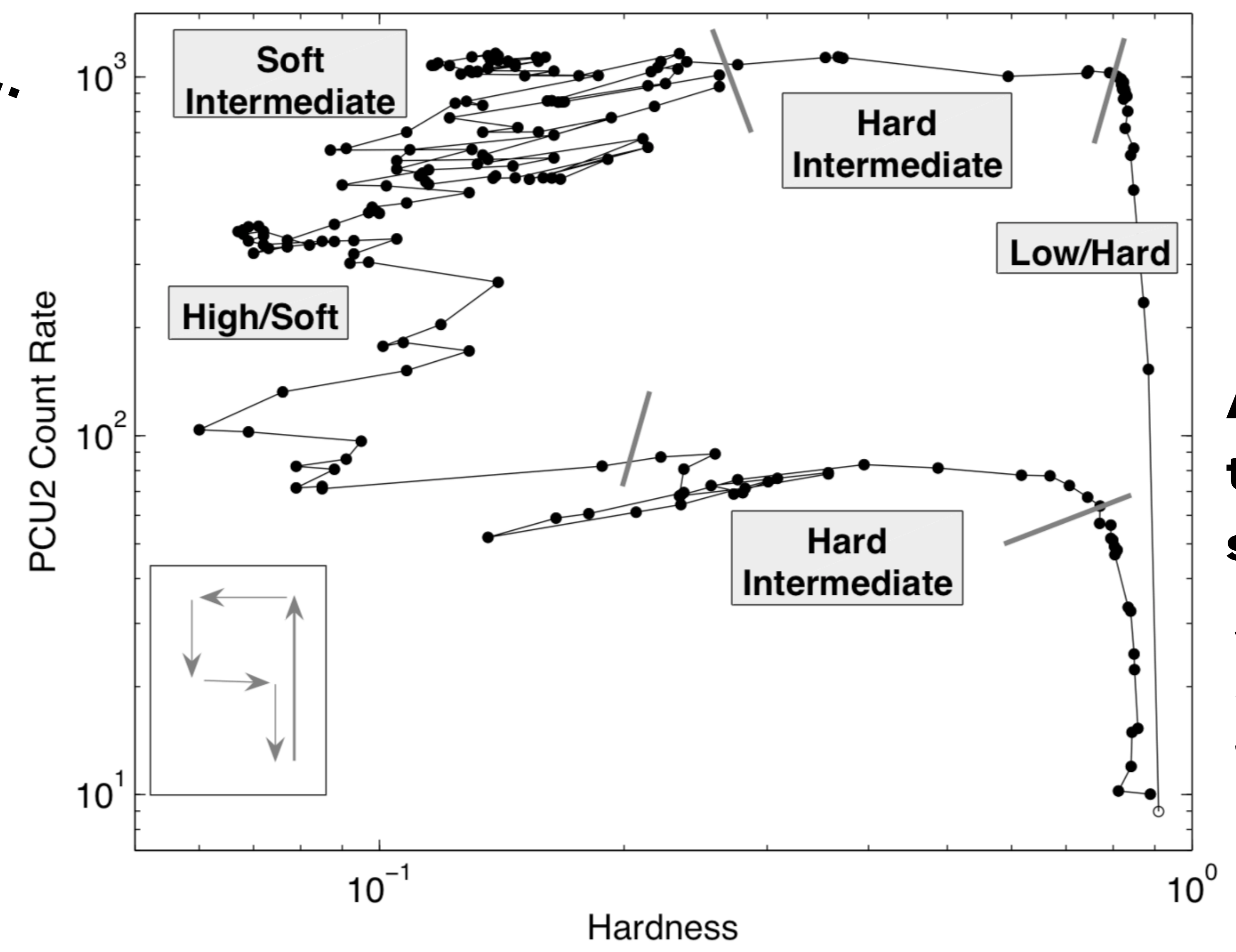

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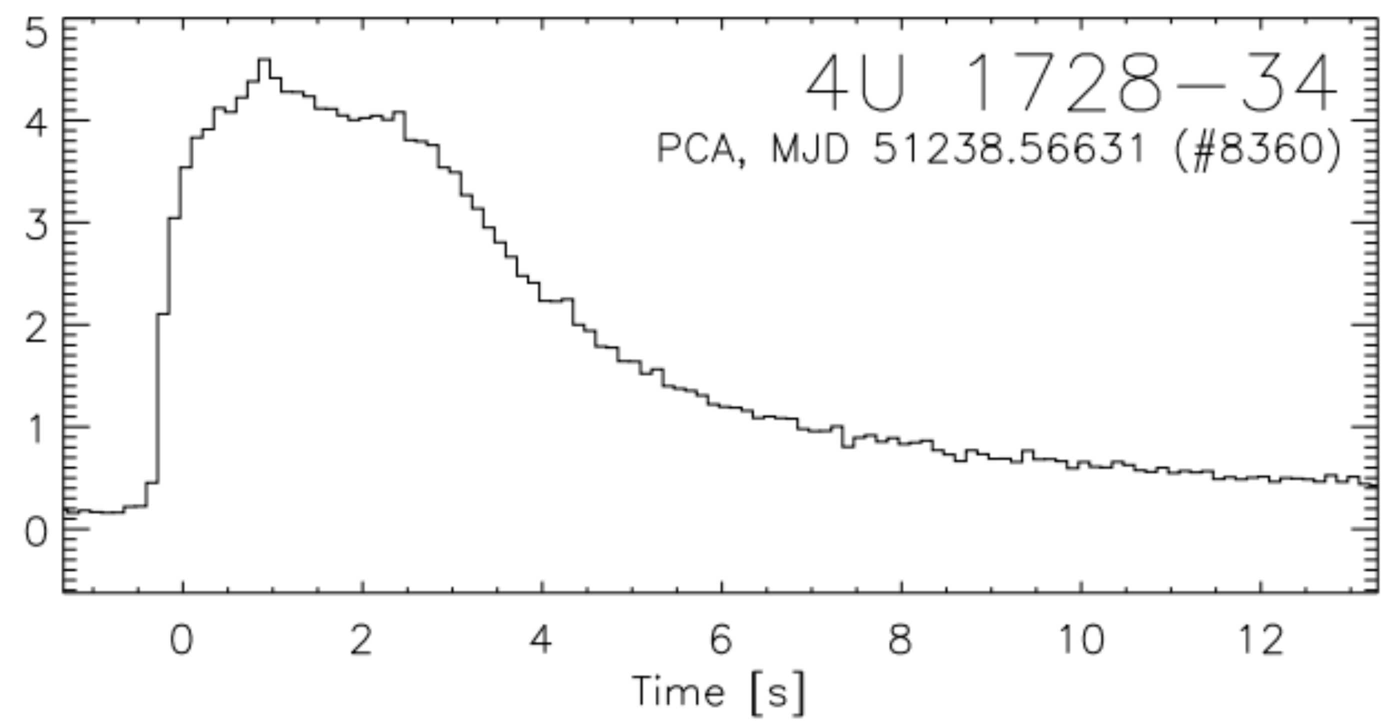
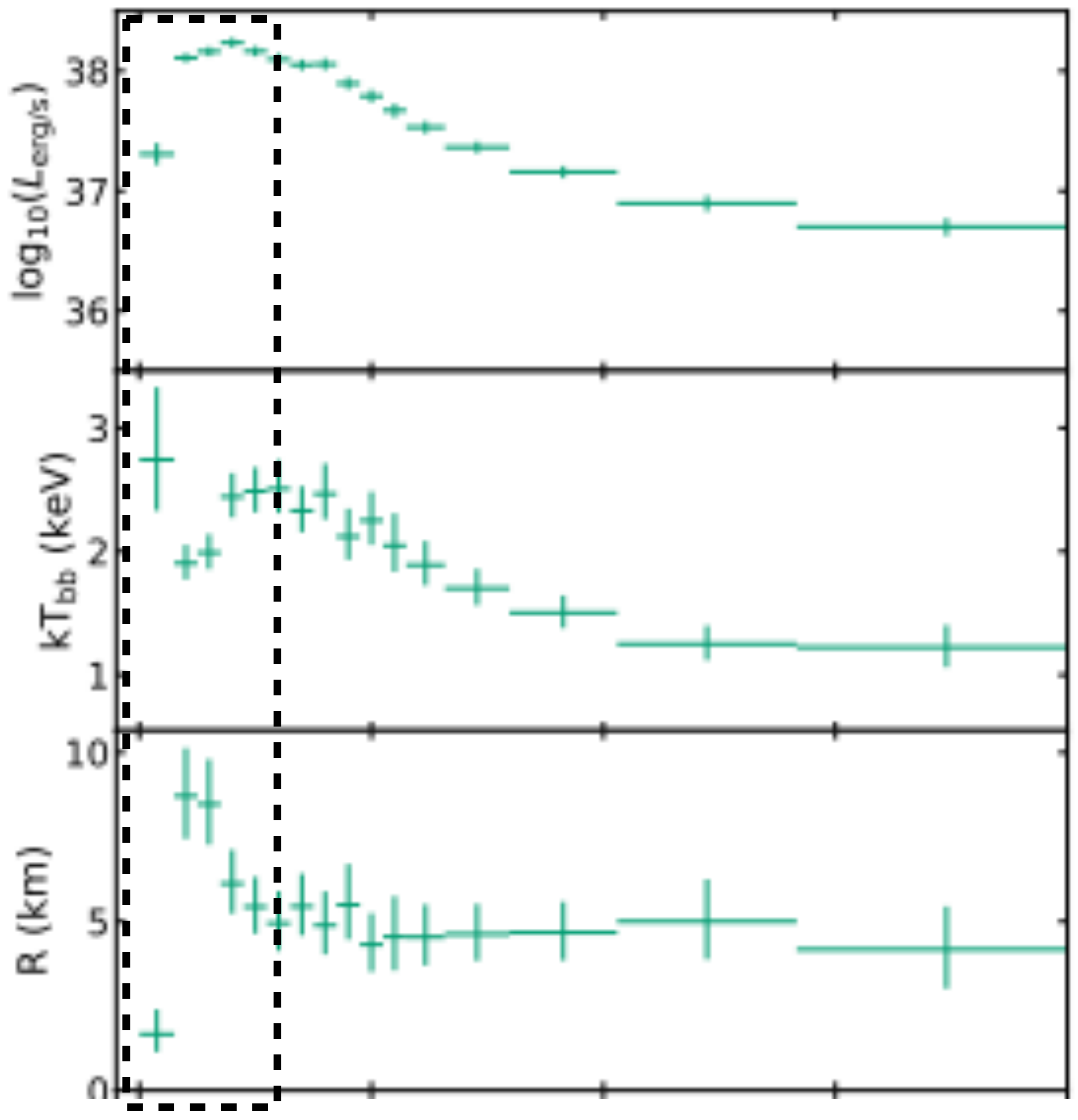
Schematic q-diagram for the BH LMXB GX 339-4, Belloni+04

Type-I X-ray bursts

- Thermonuclear explosions occurring due to the piling up of the accreted material on top of the NS surface (Galloway21 for a review);
- Duration connected to the chemical composition of the accreted material;
- Dominant blackbody spectra from the NS surface (kT about 2-3 keV at the peak);
- Certain bursts reach the Eddington Limit at the peak -> Photospheric Radius Expansion (PRE);
- Proof of PRE bursts from Time Resolved Spectroscopy (increase in radius corresponding to a decrease in temperature);
- **Diagnostics for the distance** (most NS LMXBs distances are known thanks to them, e.g. Galloway+08) **and the radius** (Ozel+15);

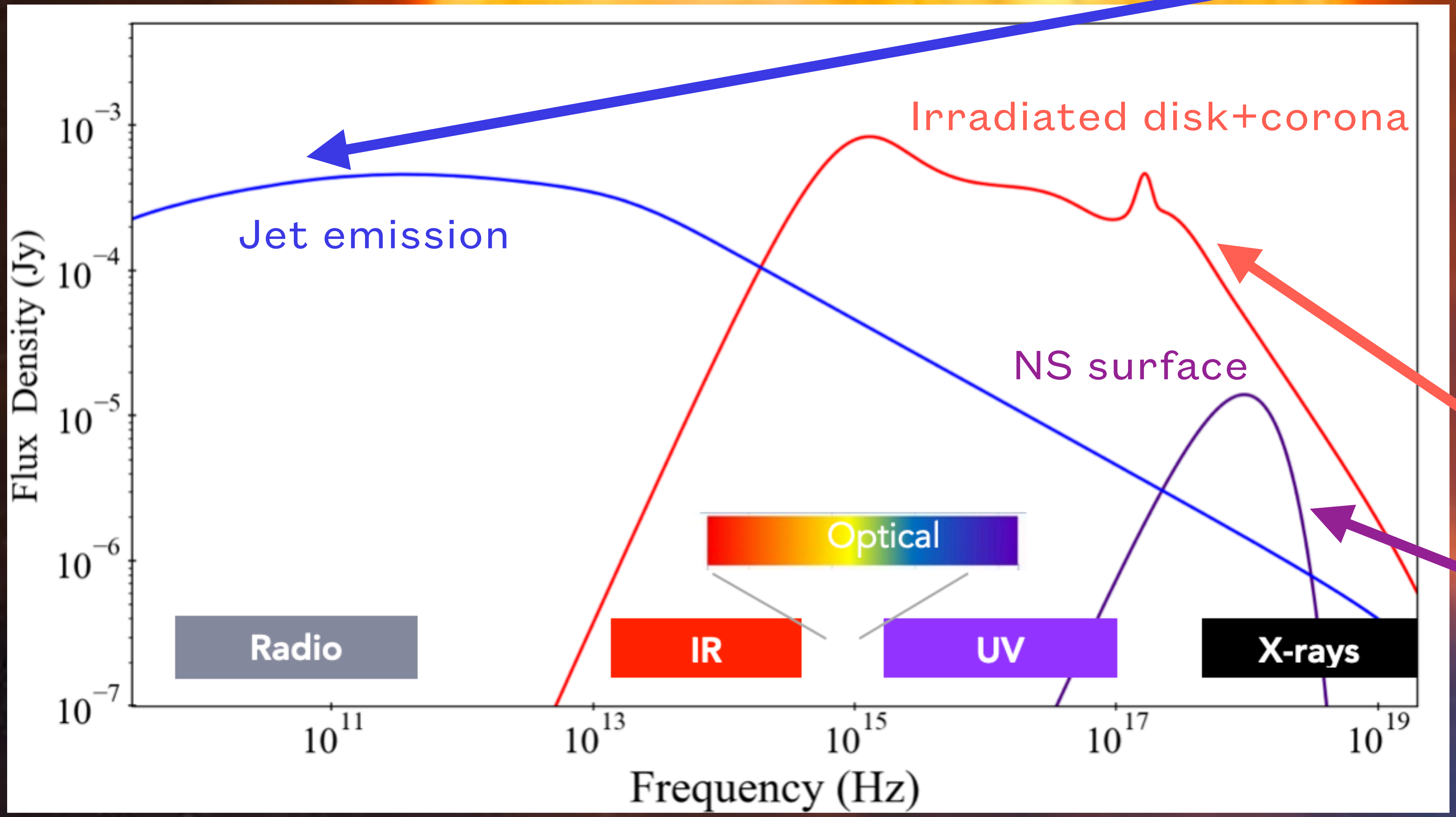


Examples of type-I X-ray burst, Galloway+20



Temperature and radius evolution of a PRE burst ,Pike+21

DISCLAIMER: here emission from the donor is negligible



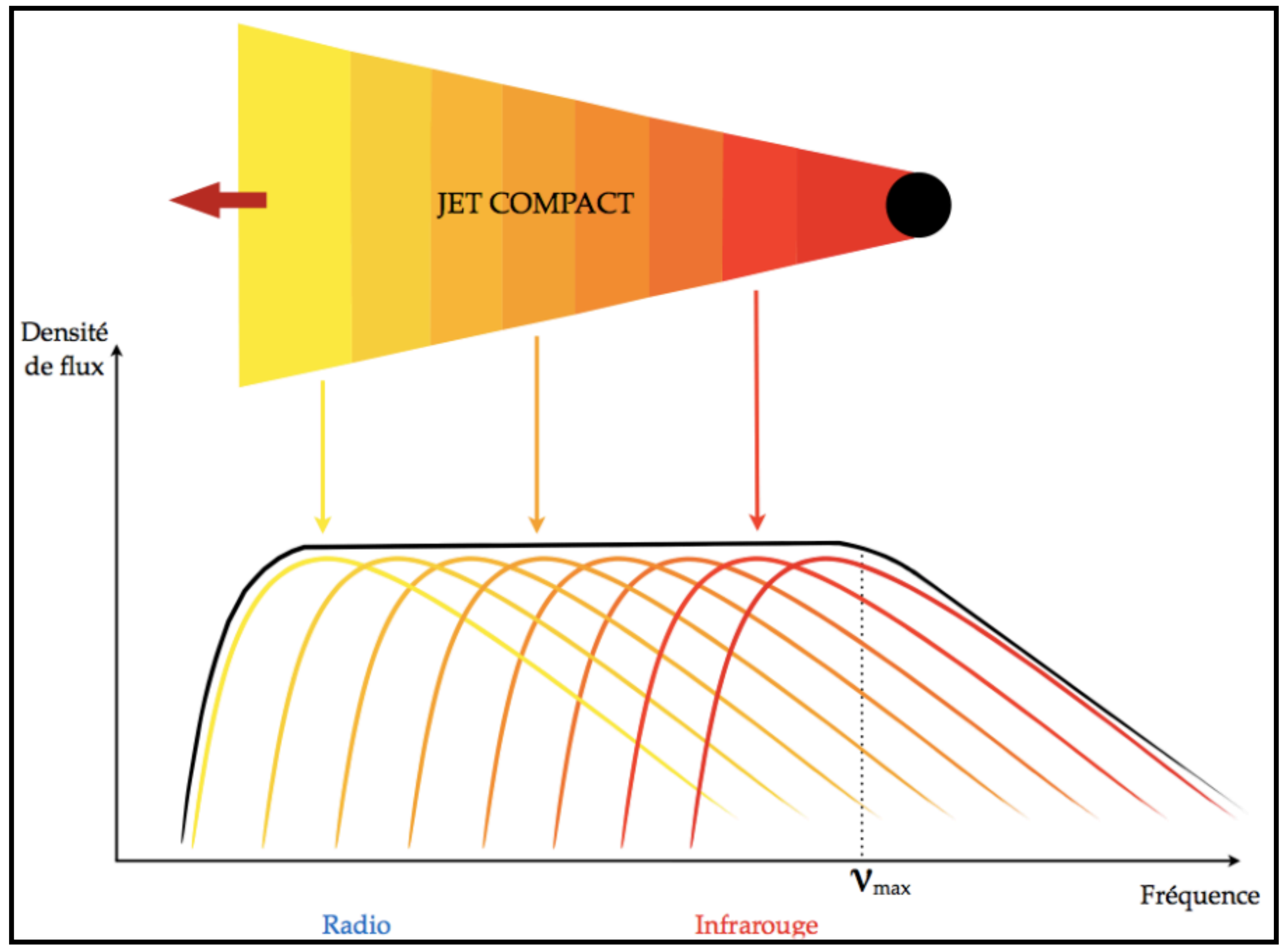
Spectral Energy Distribution of a NS LMXB, Marino+20

Beyond X-rays: emission across the whole electromagnetic spectrum

Ejection: the other face of the medal

- **Jets:** collimated outflows of ionised particles;
- In binaries they are typically not resolved (with a few exceptions, e.g. Fomalont+01) -> compact jets;
- Radio-to-IR emission, due to self-absorbed synchrotron spectra emitted by the various shells;

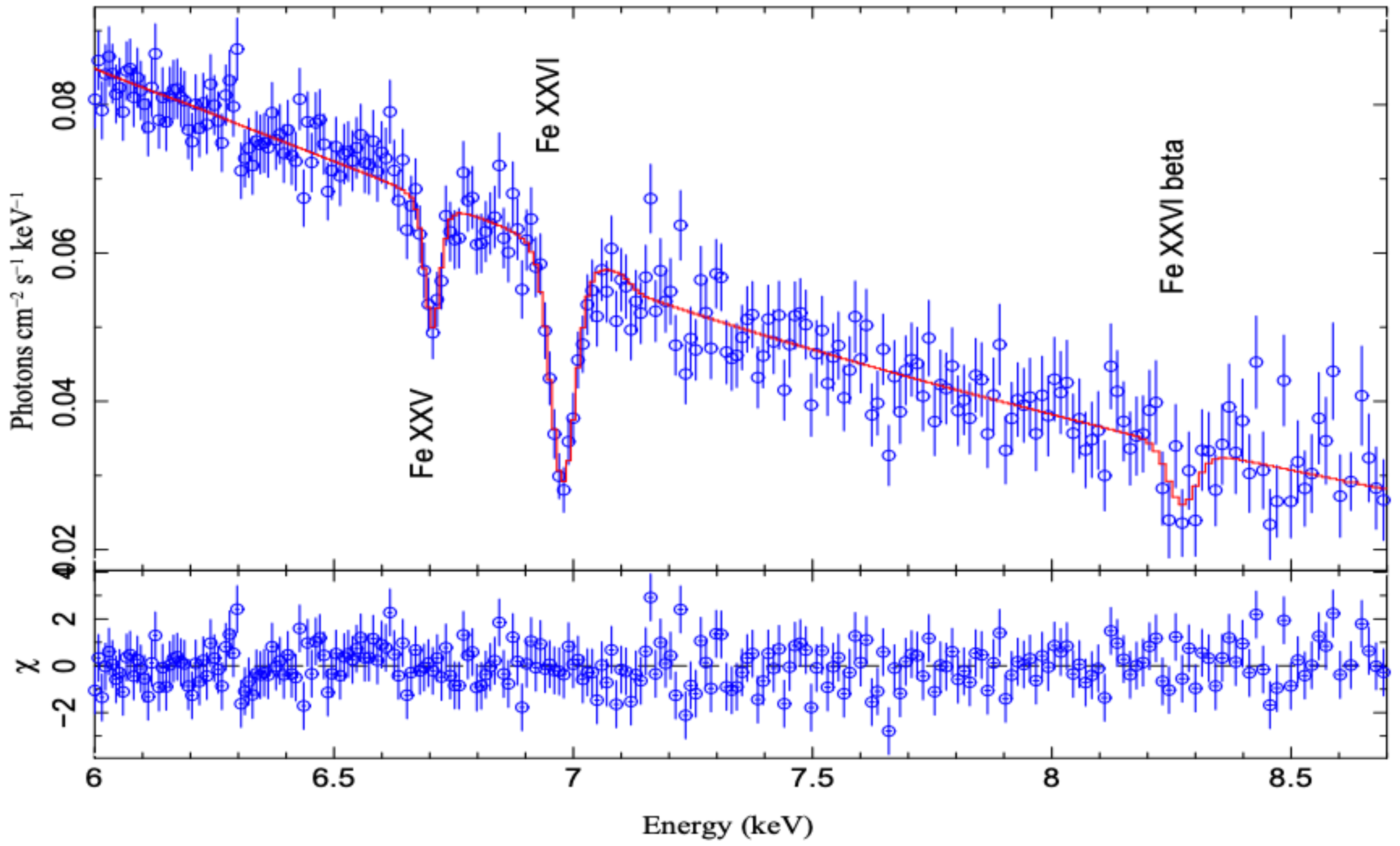
see Carotenuto, Egron, Casella talks



Origin of the flat radio-to-IR jet spectrum, Coriat11

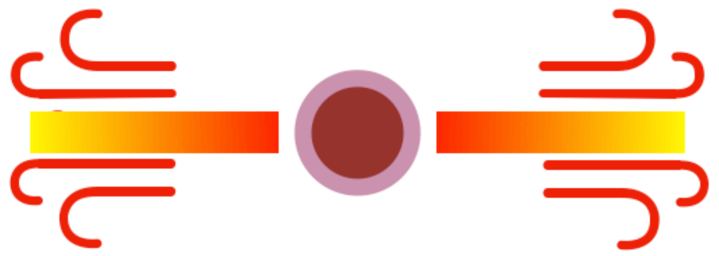
- **Winds:** Equatorial outflows, originating from the disc;
- Found through the detection of blue-shifted alsorption lines in X-rays / UV / optical spectra in high inclination XRBs.
- They can be multi-layered (Castro Segura+22);

see Parra, Munoz-Darias talks



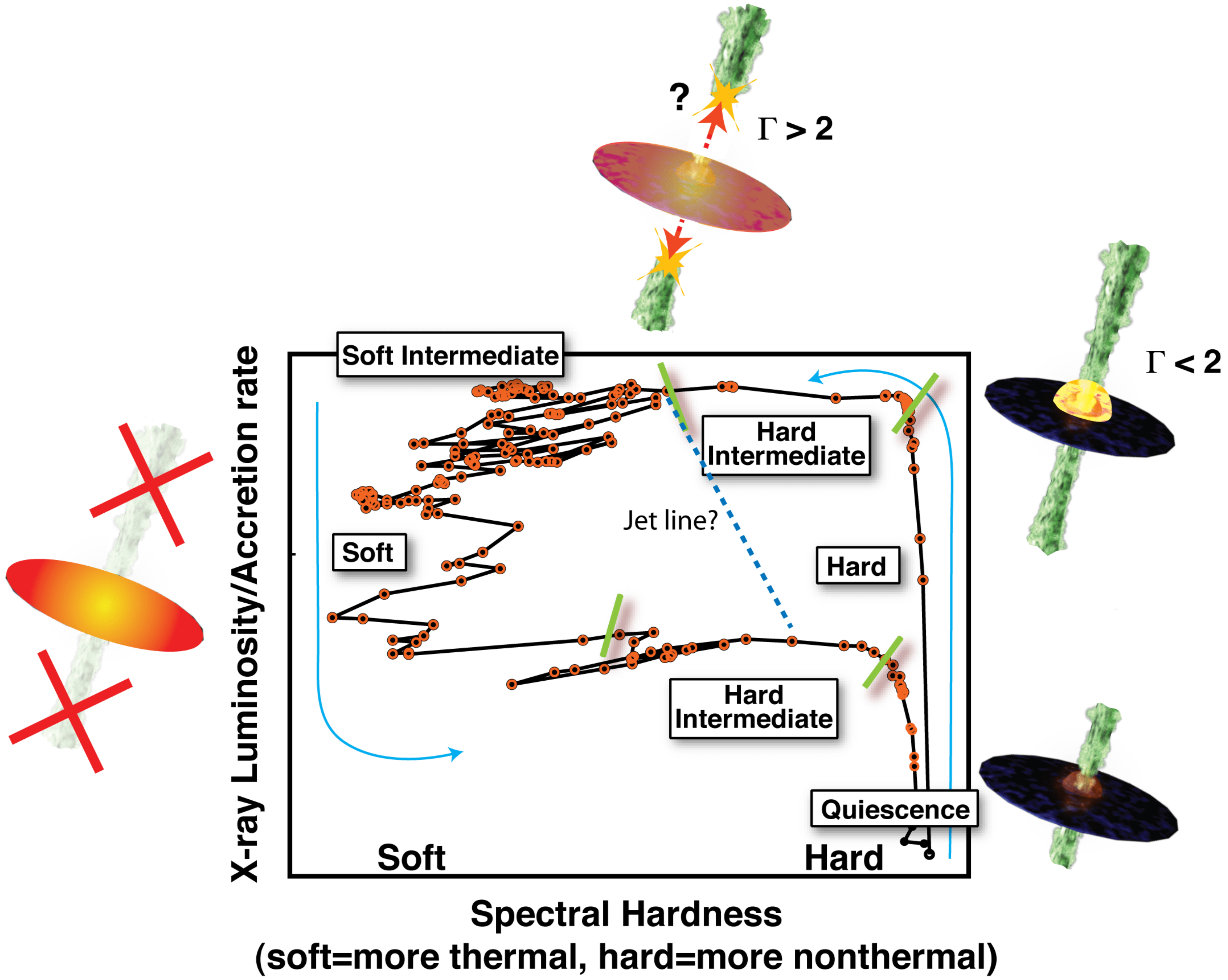
Blueshifted absorption lines, D'Aì+14

Back to the q-diagram: the accretion-ejection interconnection

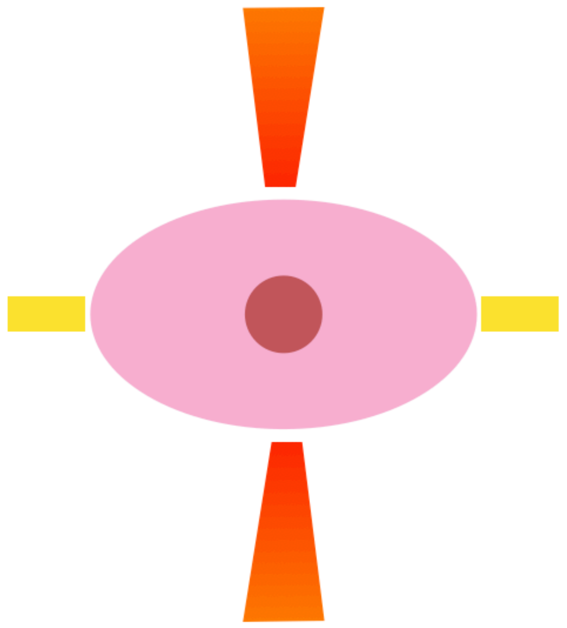


Soft state

- Disk-dominated or BB-dominated;
- Disk close to the NS surface;
- **No jets (jet quenching);**
- **Disk winds;**



Plot by Sera Markoff

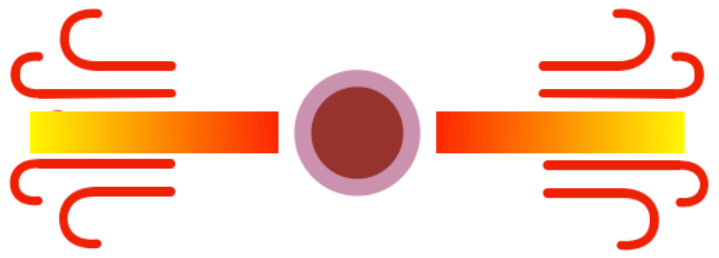


Hard state

- Comptonization-dominated;
- Disk (most likely) truncated;
- **Compact jets;**
- **No disk winds;**

see Vincentelli's talk

Back to the q-diagram: the accretion-ejection interconnection



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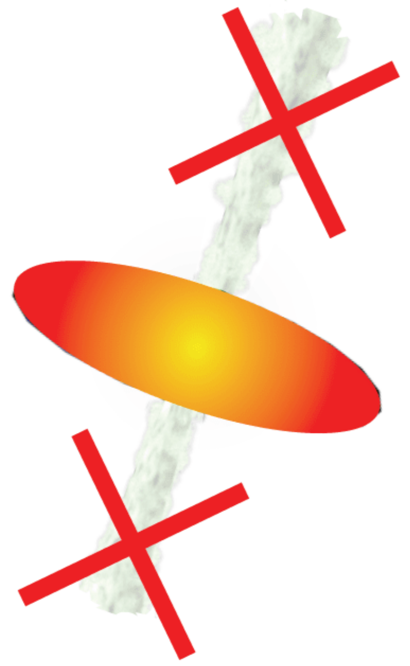

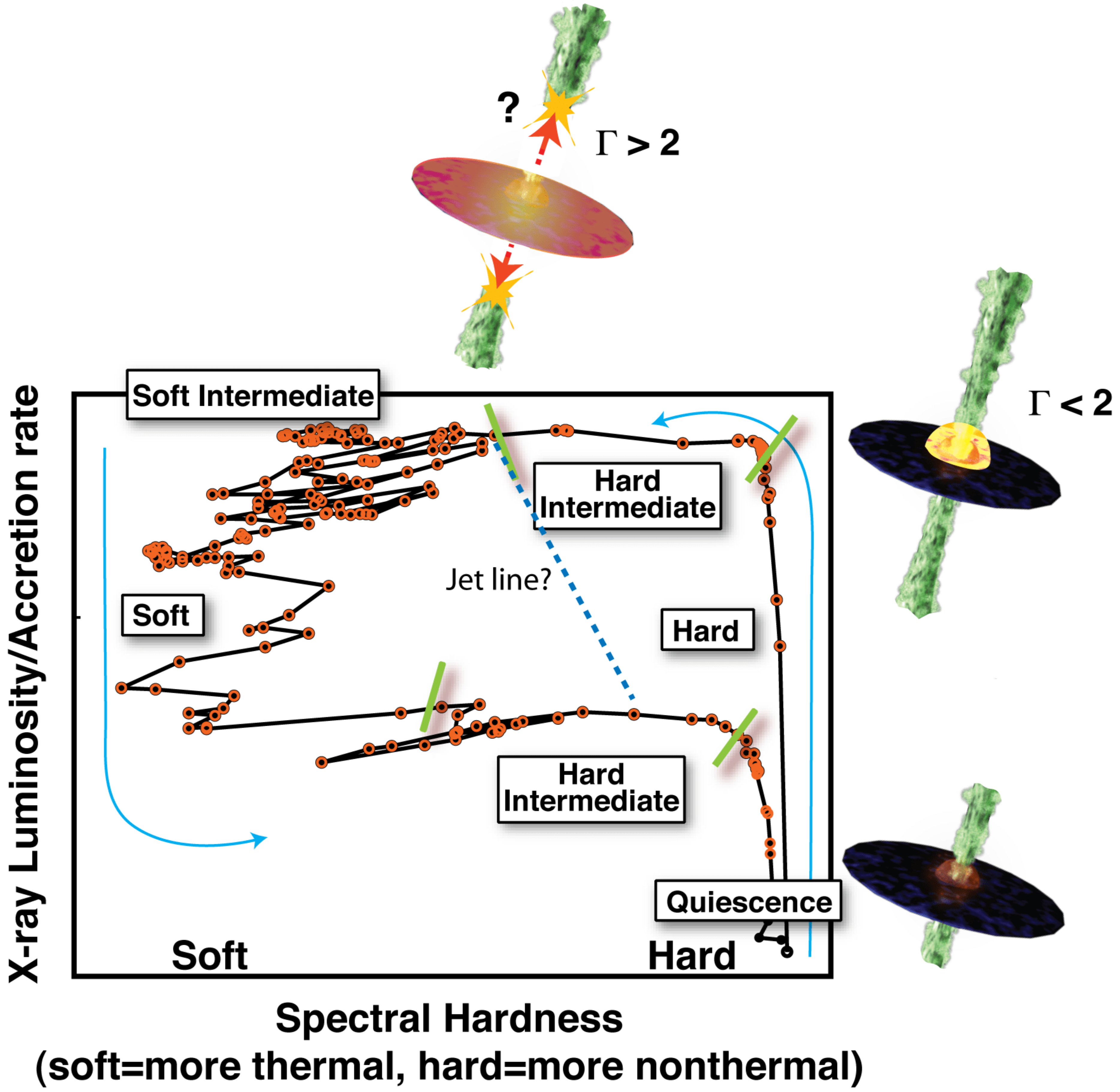

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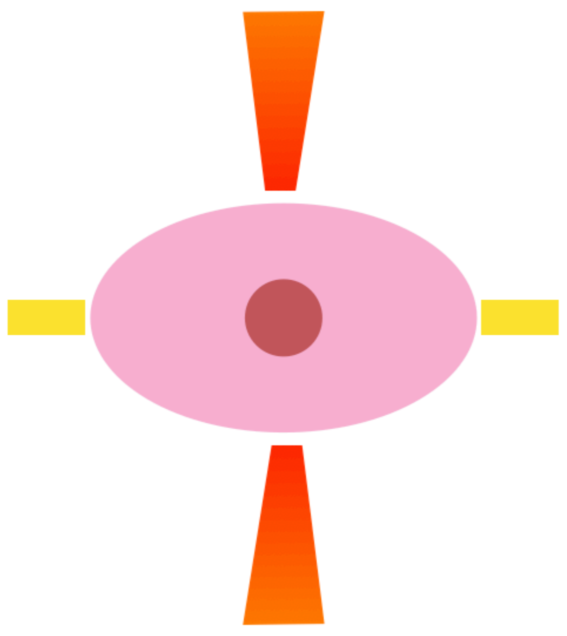


Hard state

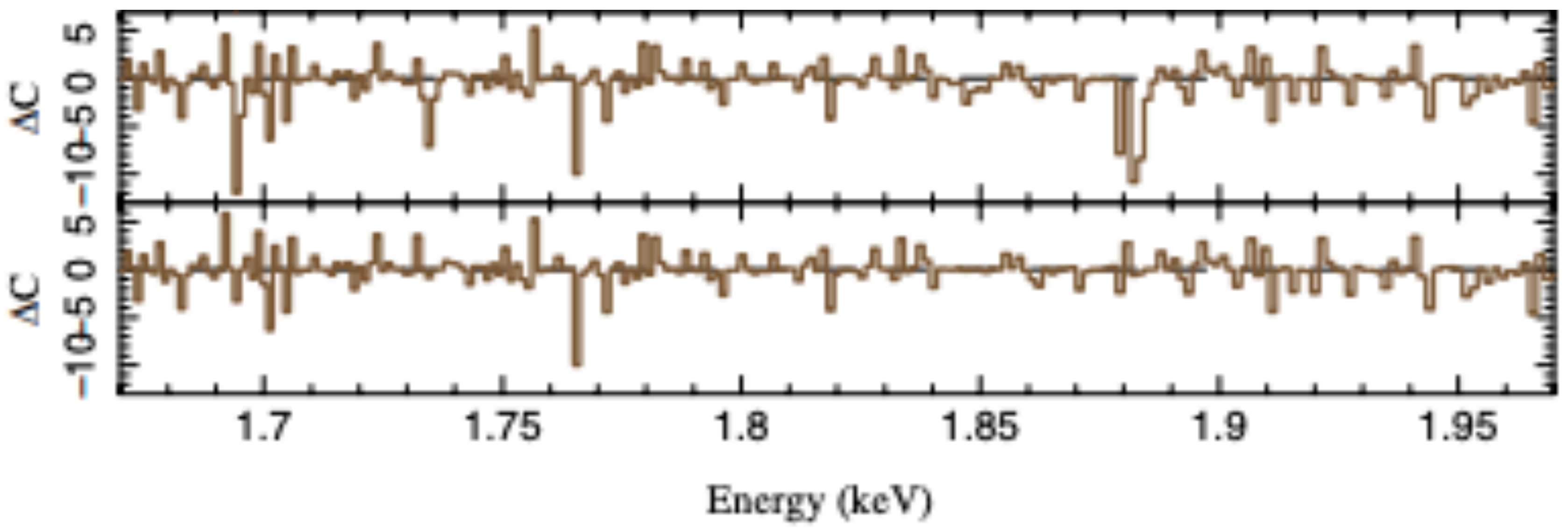
- Comptonization-dominated;
- Disk (most likely) truncated;
- **Compact jets;**
- **No disk winds;**

.. IS IT THOUGH?

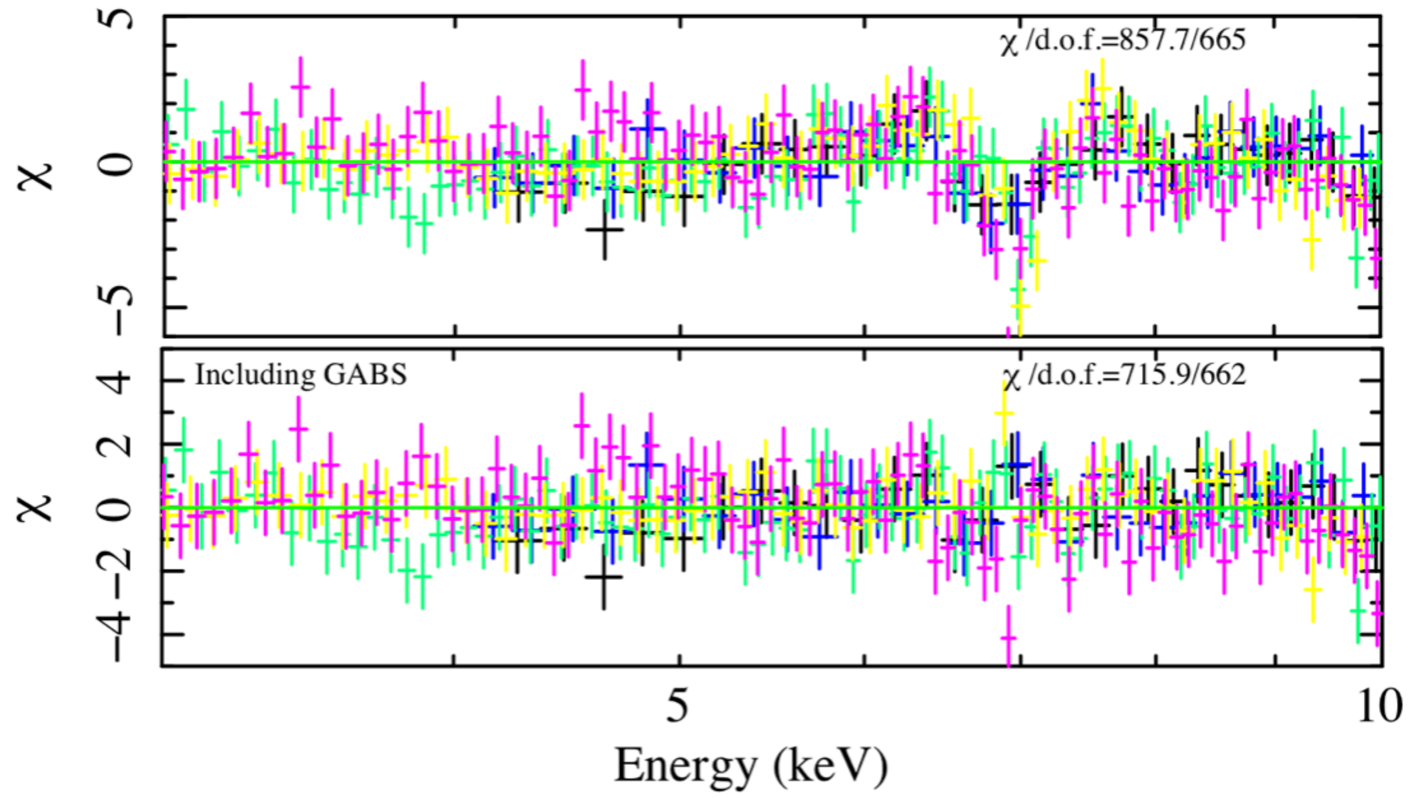
see Vincentelli's talk

Unexpected X-ray winds in "hard state" spectra in AMXPs

Residuals of Nowak+19 Chandra/HETG with and without absorption line



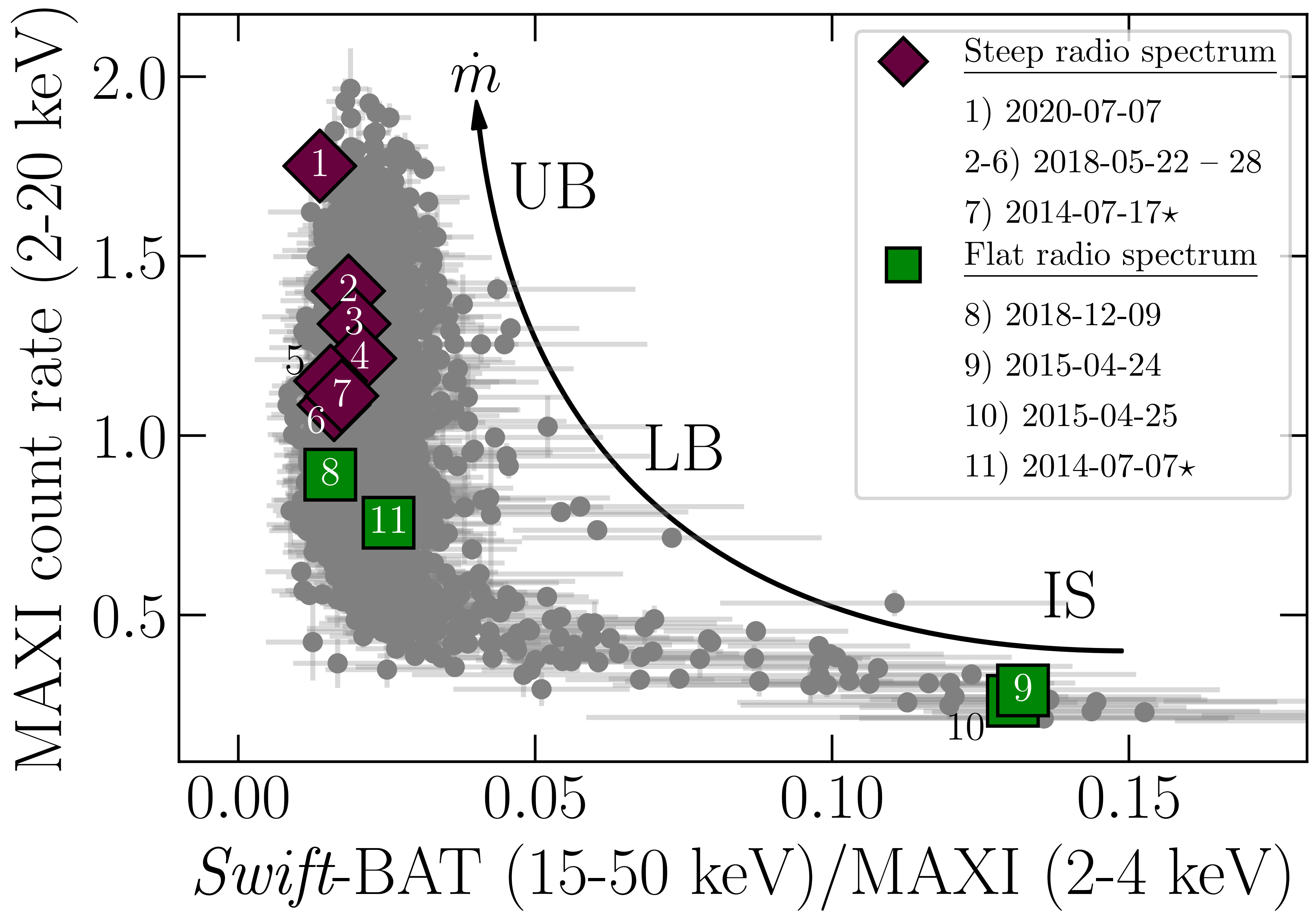
Residuals of Marino+22 NICER/XMM-Newton and NuSTAR spectra with and without absorption line



- **X-ray winds** in XRBs are typically detected in soft states (review: Diaz Trigo & Boirin 16);
- In recent years, a few cases of detections of blue-shifted absorption lines have been reported for AMXPs - which typically display **rather hard and faint outbursts**;
- Evidence for a disc wind (Si XIII) during the hard state of the AMXP IGR J17591 (Nowak+19);
- Evidence for a highly ionised disk wind from the detection of a blue shifted Fe XXVI line (7 keV) in Swift J1749.4-2807 (Marino+22), the spectrum was typical of a hard state;
- Weaker evidences in two other AMXPs (van den Eijnden+18, Di Salvo+19);

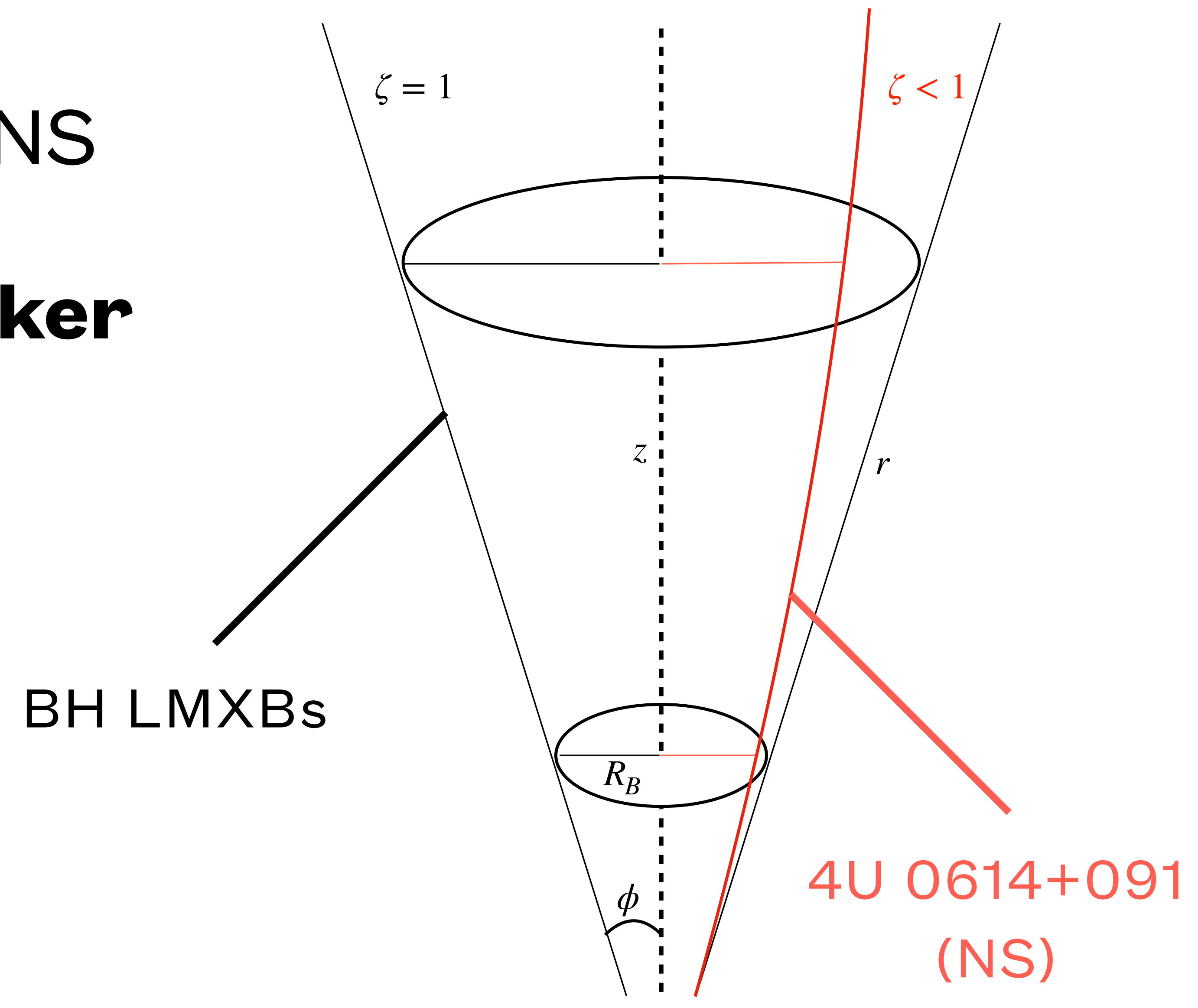
- Propeller-driven outflows?

Peculiarities about NS LMXBs jets (quenching, geometry and more)



Jet quenching (purple diamonds) occurring not at the state transition but rather at high luminosities; Russell+21

- **Jet quenching** seems **not to be the norm** for soft state of NS LMXBs (e.g. Migliari+04, Diaz Trigo+18);
- Jet quenching not at the spectral state transition but rather beyond a luminosity threshold in 4U 1820-30 (Russell+21);
- A 2022 dense radio-X-rays campaign (PIs: Russell; Marino) on 4U 1820-30 is ongoing (*coming soon..*)
- Applying ISHEM (Malzac13,14) to a NS LMXB results i**n different jet geometry** for NS LMXBs or a **weaker coupling** with the accretion flow (Marino+20);



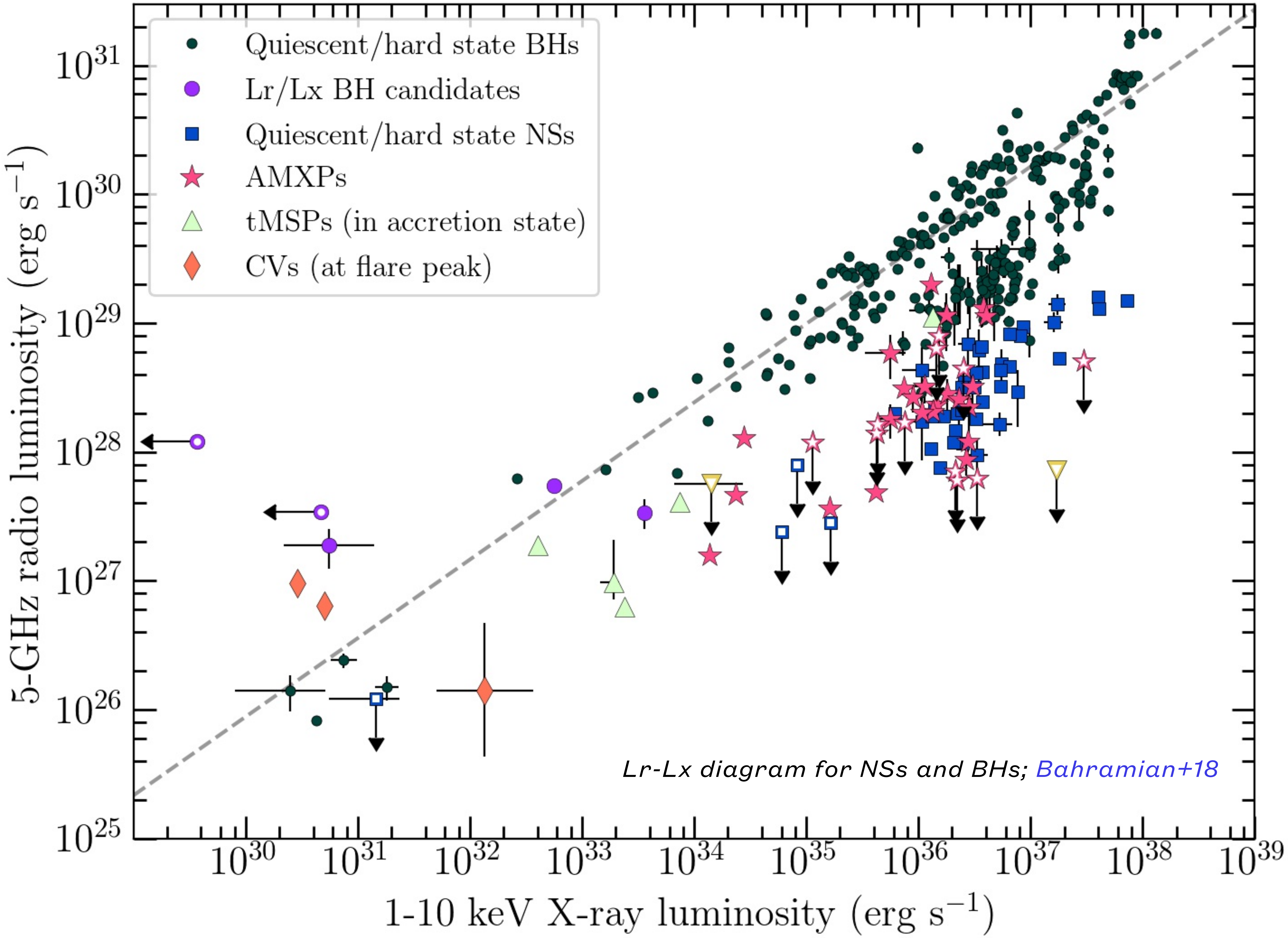
Conical geometry (BH LMXBs) and parabolic geometry (NS LMXBs?) for jets; Marino+20

- What's the role (if any) of the NS magnetic field, spin and emitting surface in affecting jet properties and its coupling with the accretion flow?

NS LMXBs in the radio:X-ray diagram

- NS LMXBs are typically radio fainter than BH systems (a factor around 20, e.g. Gallo+18);
- AMXPs and tMSPs can be significantly radio brighter than the other NS LMXBs (e.g. Russell+18, Coti Zelati+21);
- Evidences for non-conservative mass-transfer in AMXPs: Hernandez-Santisteban+18, Di Salvo+08, Sanna+17; Marino+19a

- A pattern of strong outflows in AMXPs?



Lr-Lx diagram for NSs and BHs; Bahramian+18

Summary

- NS LMXBs are natural laboratories that allow scientists to: (i) explore the physics of accretion in the strong gravitational field regime, (ii) investigate the behaviour of ultra-dense matter in the NS core and (iii) test our understanding of the accretion-ejection engine on magnetised objects;
- Many open issues: *how NSs unique features (magnetic field, solid surface, boundary layers) affect jet launching/coupling with the accretion flow? What does launch winds in AMXPs hard states? How do bursts affect the accretion environment? How does the accretion geometry change with respect to the spectral state? Why are pulsations so rare?*
- Future X-ray missions may open a golden era of X-ray spectroscopy of these objects (XRISM, Athena), with the help of polarimetry (IXPE now, eXTP later, see talks by Capitanio & Gnarini);
- However, multi-wavelength synergy is necessary to have a full picture of the ongoing physics.


That's all Folks!
Questions?