The origin of optical emission lines in the soft state of X-ray binary outbursts

The case of MAXI J1820+070

(2023MNRAS.521.4190K)

In collaboration with:

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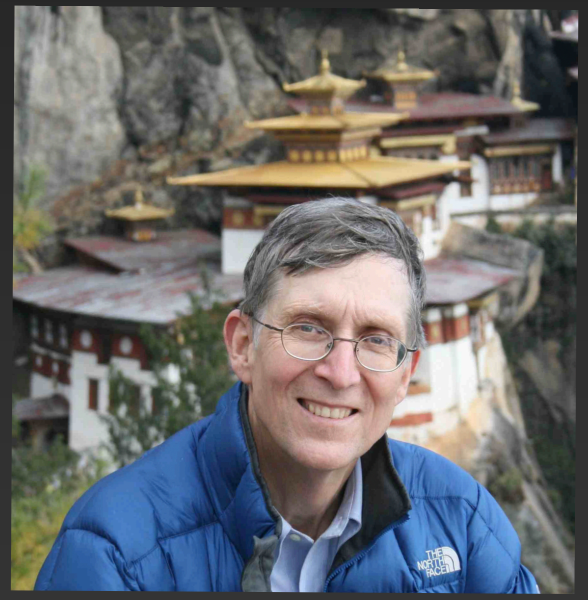

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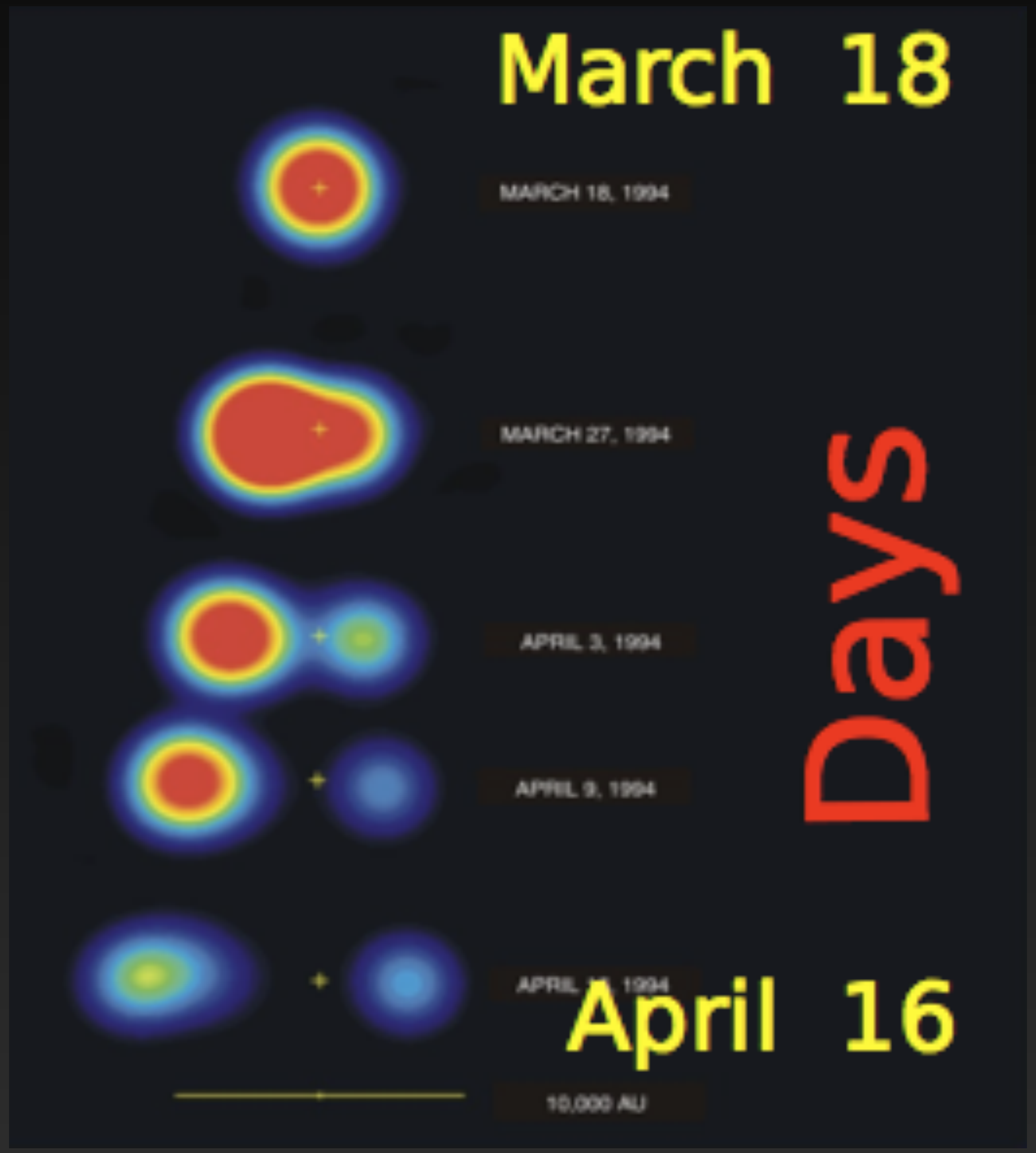
Karri Koljonen - Astro and Theory Seminar - NTNU -14.6.2023

Outline of the talk

- X-ray binaries
- Outflows in X-ray binaries
  - Accretion disk winds
- VLT/X-Shooter campaign on MAXI J1820+070
- Modeling the accretion disk wind

X-ray binaries
Astrophysics for the impatient



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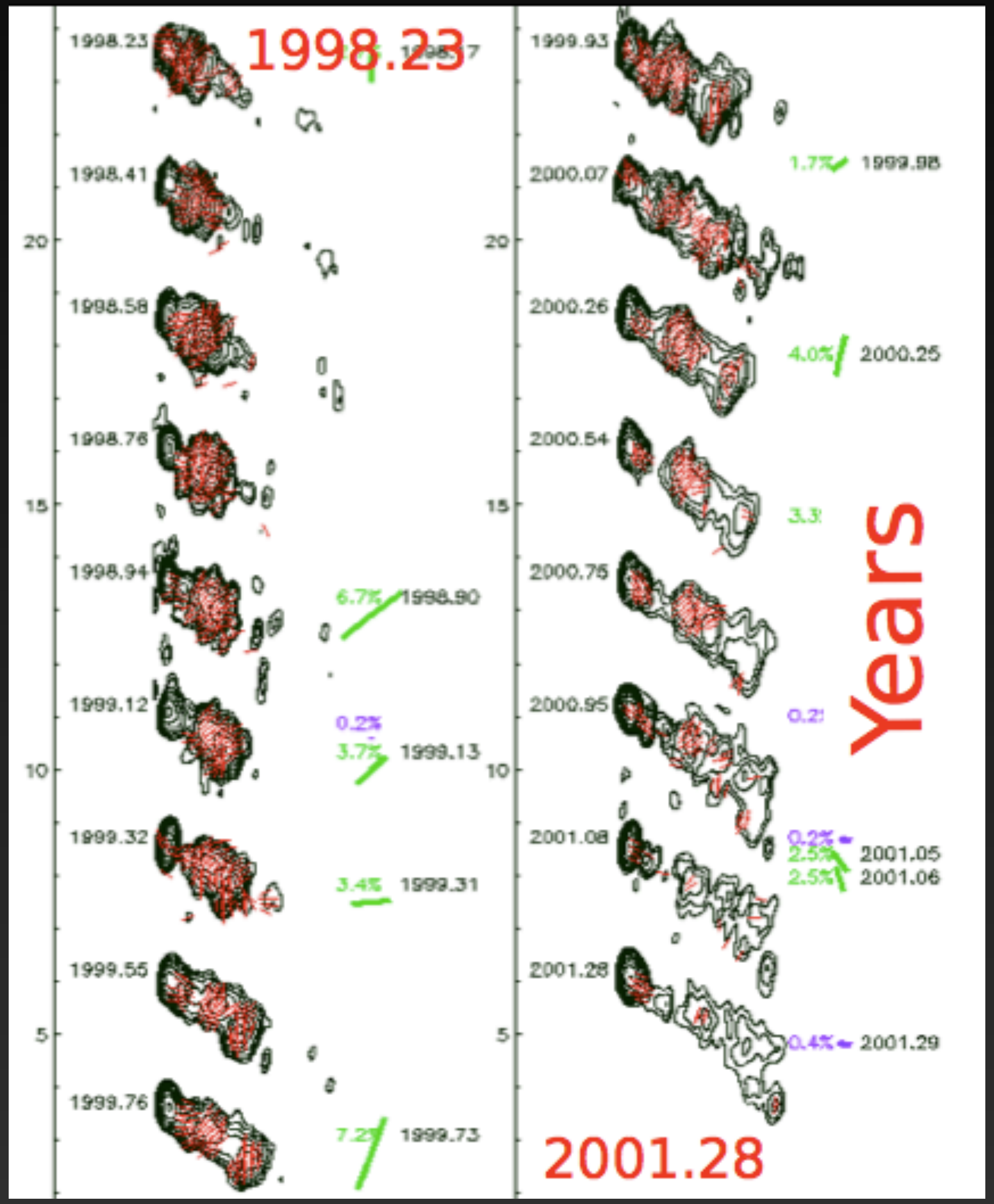
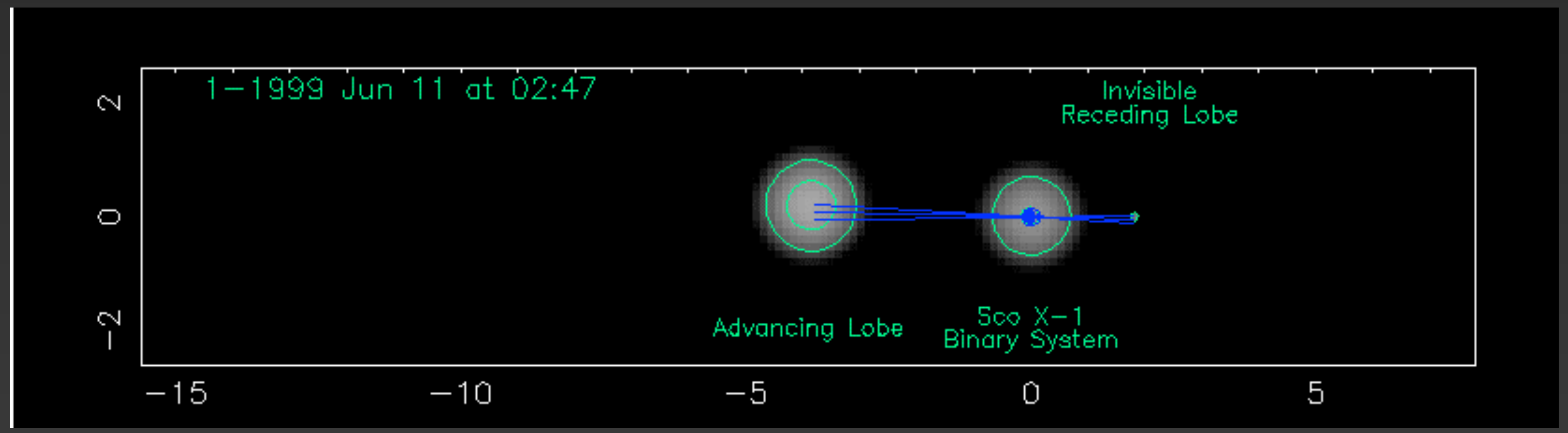
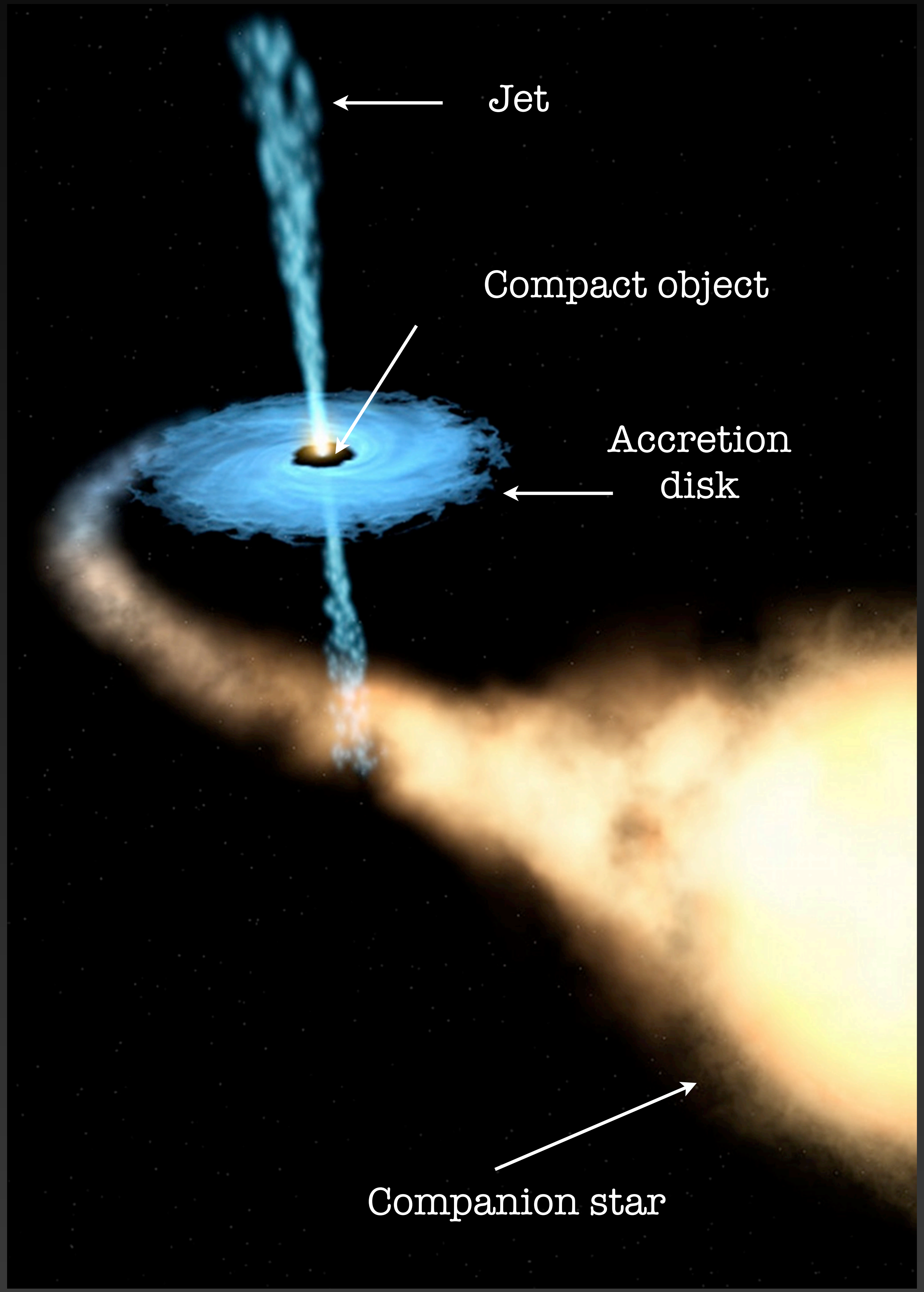


Jorstad+ 2005



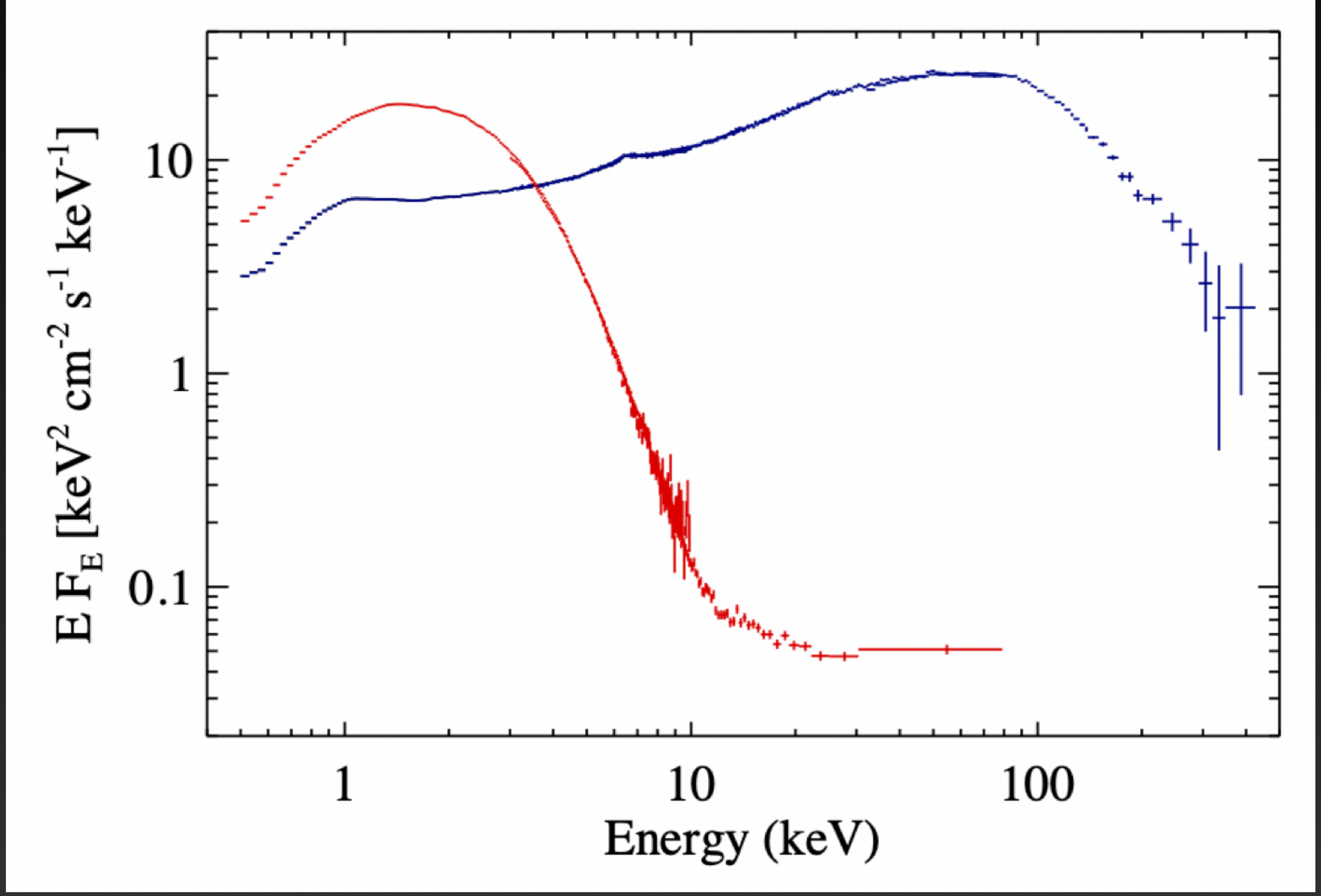
$$\tau \sim \frac{R_S}{c} = \frac{2GM}{c^3} \sim M$$



X-ray binaries

X-ray spectral states and outburst evolution

- Two "main states" (Tananbaum+72):
  - "Soft state": dominated by thermal emission peaking at ~ 1 keV + power law tail > 10 keV.
  - "Hard state": dominated by a power law component with a cutoff.

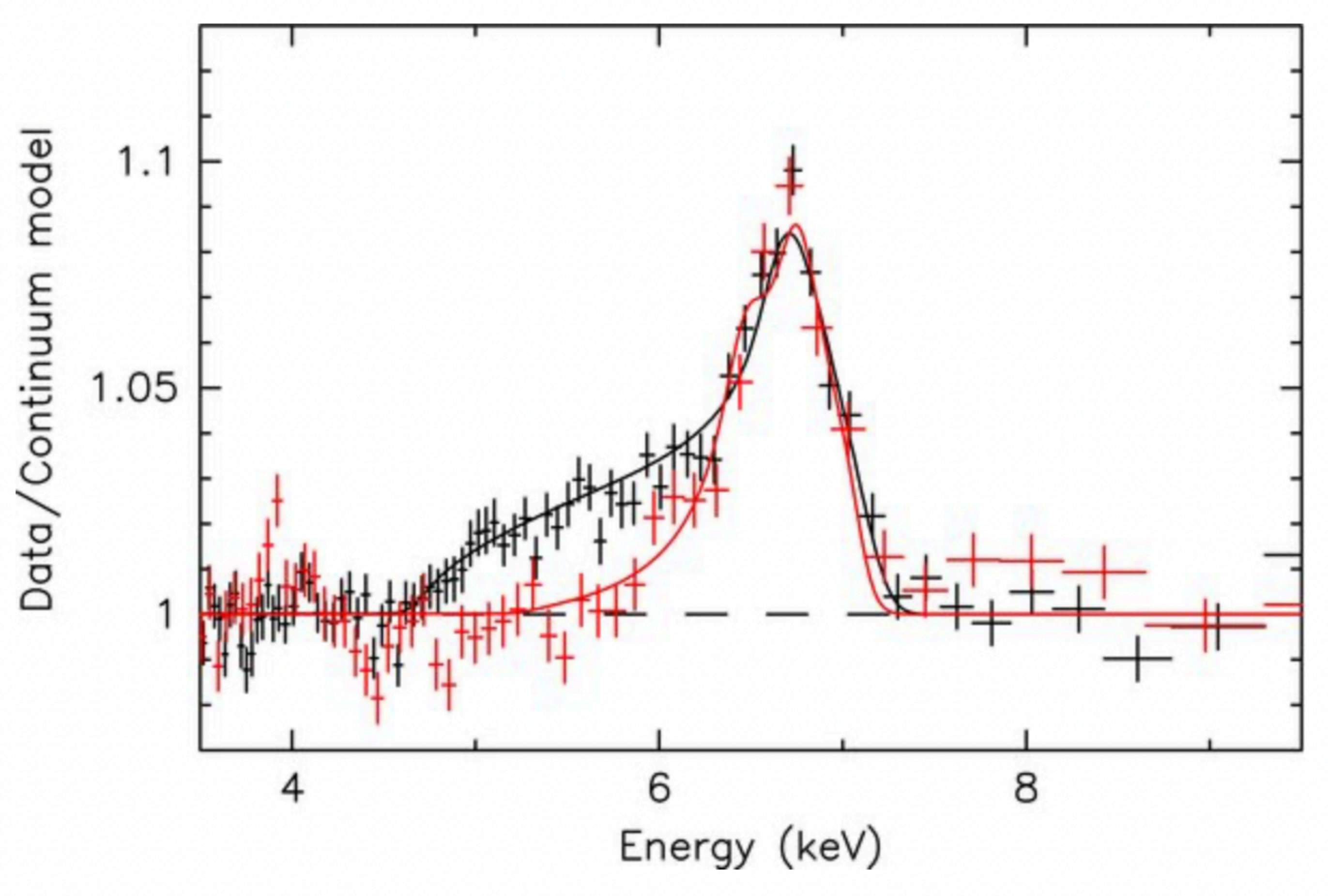


Kalemci+22

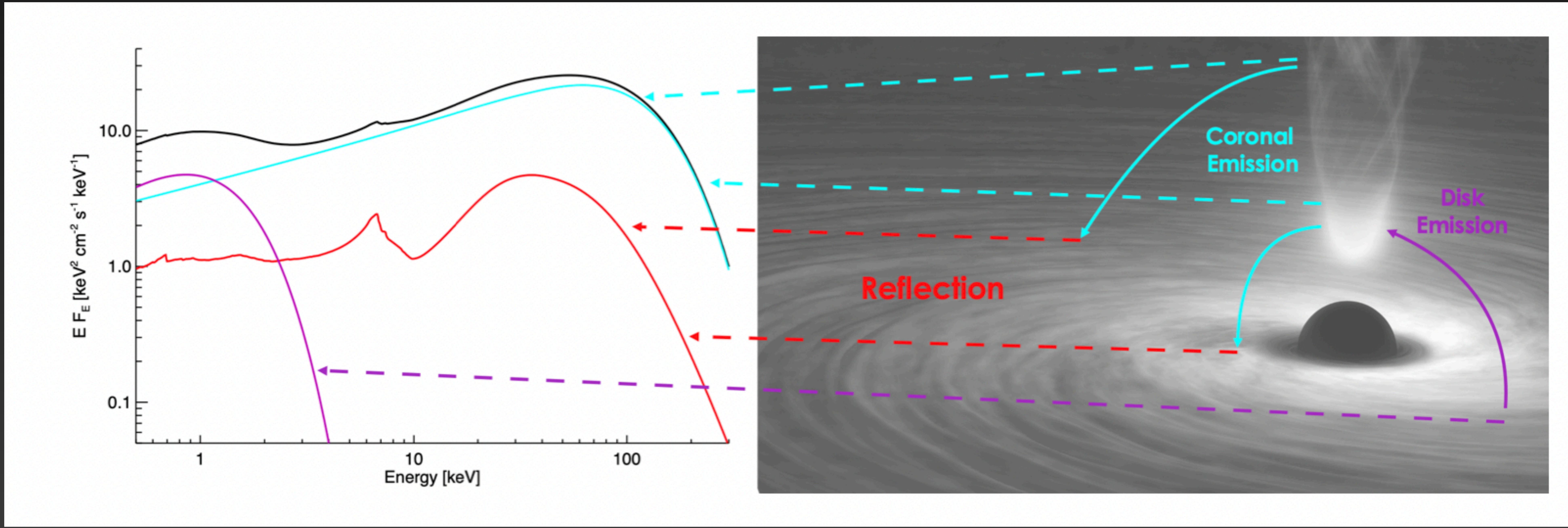
X-ray binaries

X-ray spectral states and outburst evolution

- Geometrically thin, optically thick accretion disk (Shakura & Sunyaev +73).
- Population of hot electrons: "the corona".
- X-rays from corona reflecting off the accretion disk.
  - Most prominent feature: broad Fe-K emission line.



Miller+10



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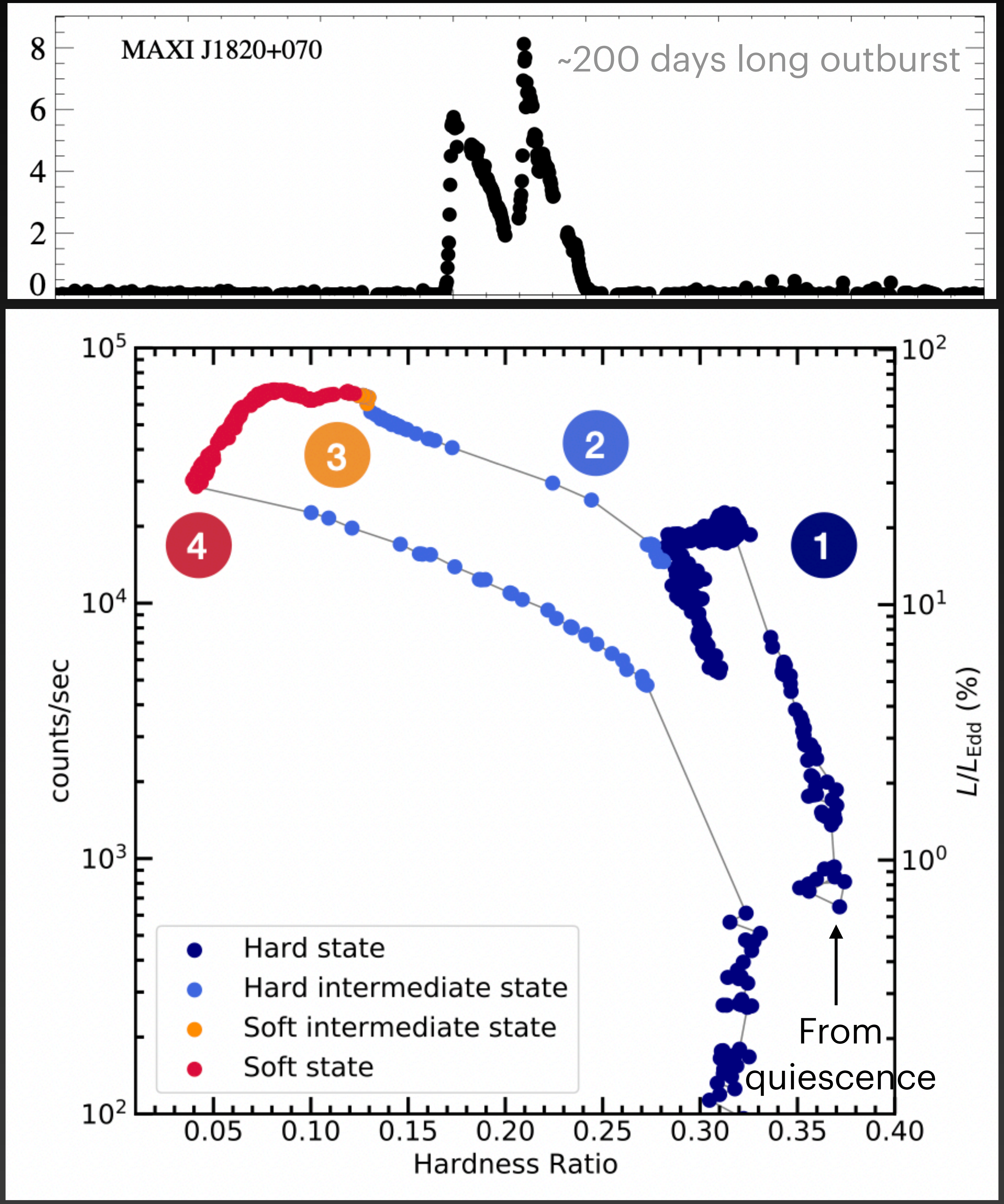
X-ray binaries

X-ray spectral states and outburst evolution

- Outburst evolution in the hardness-intensity diagram.
  - 1: Hard state
  - (2 & 3): Intermediate states
  - 4: Soft state



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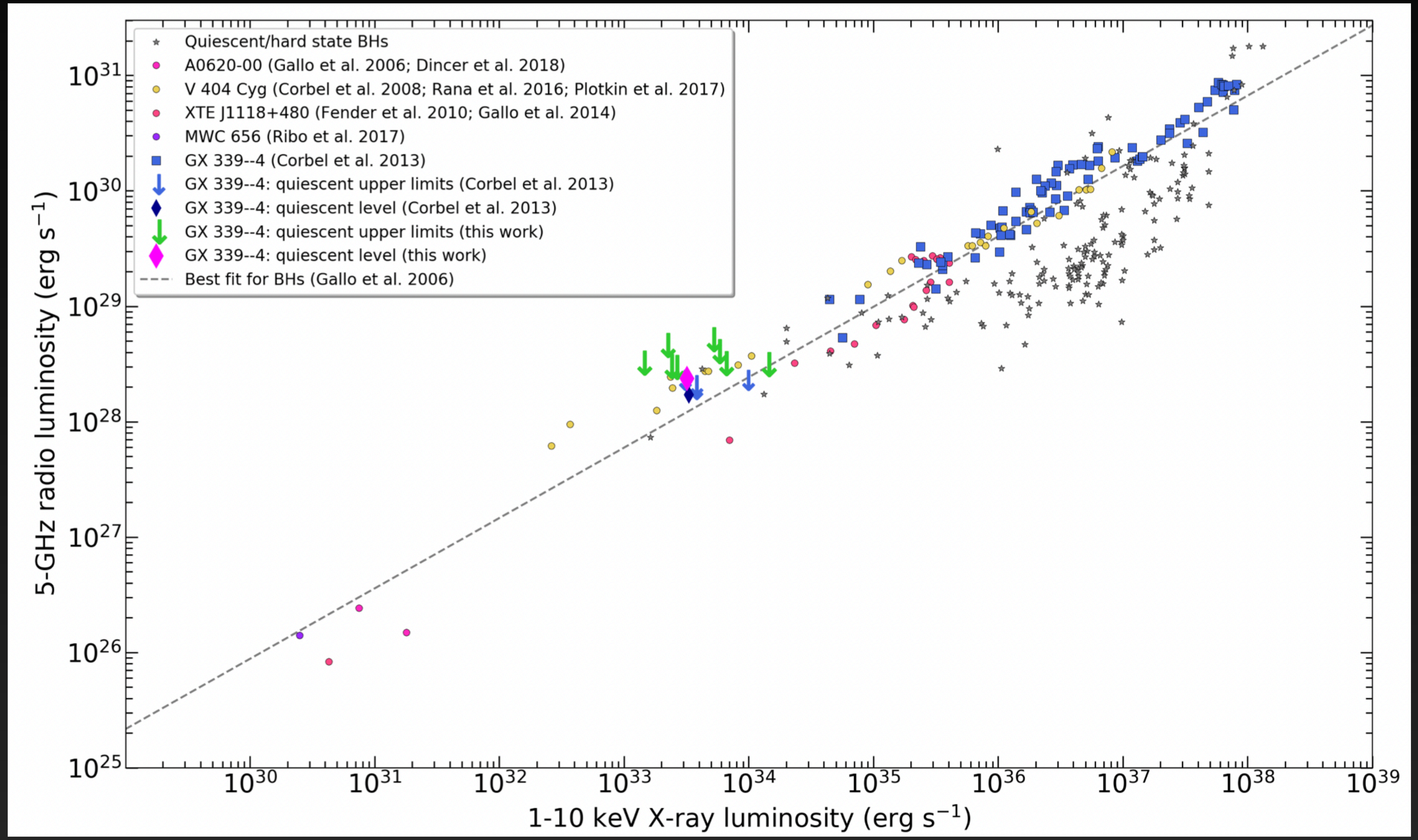
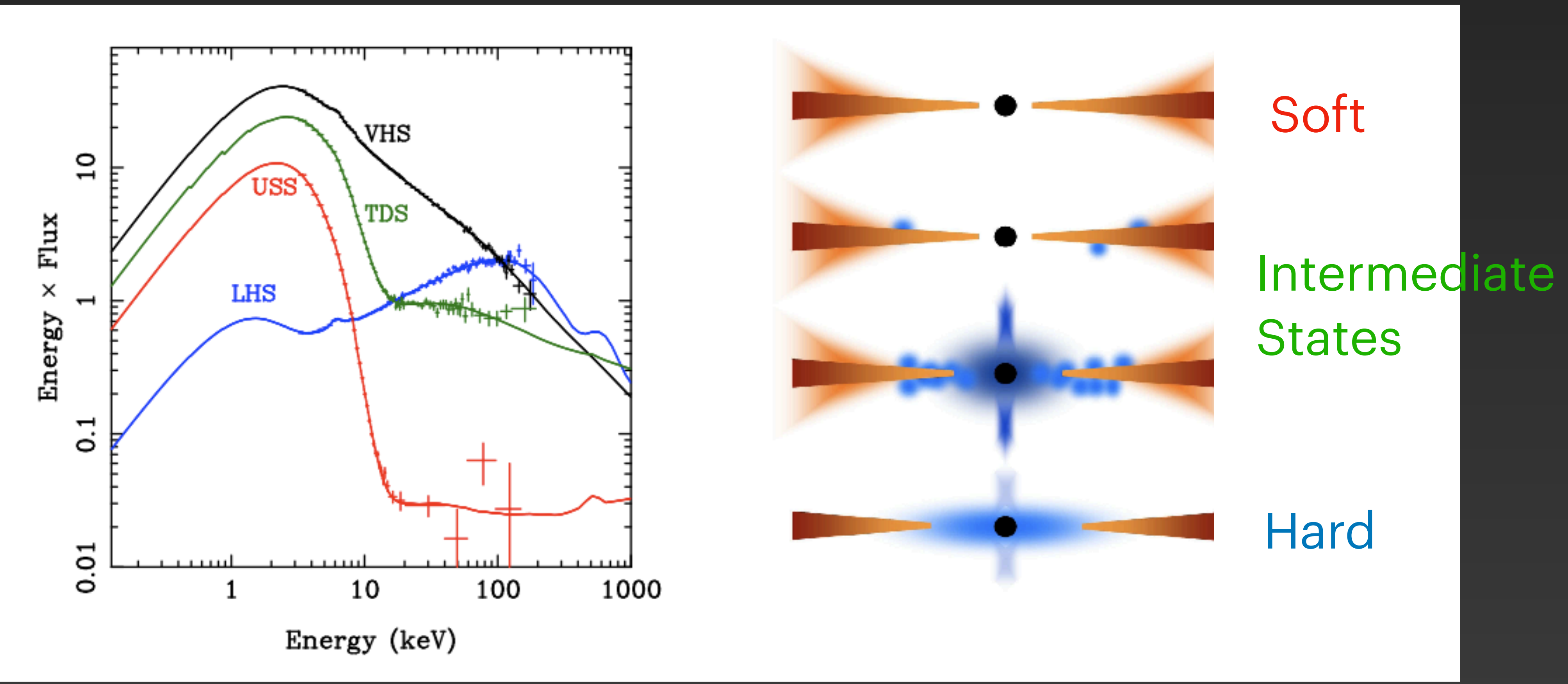
Outflows in XRBs

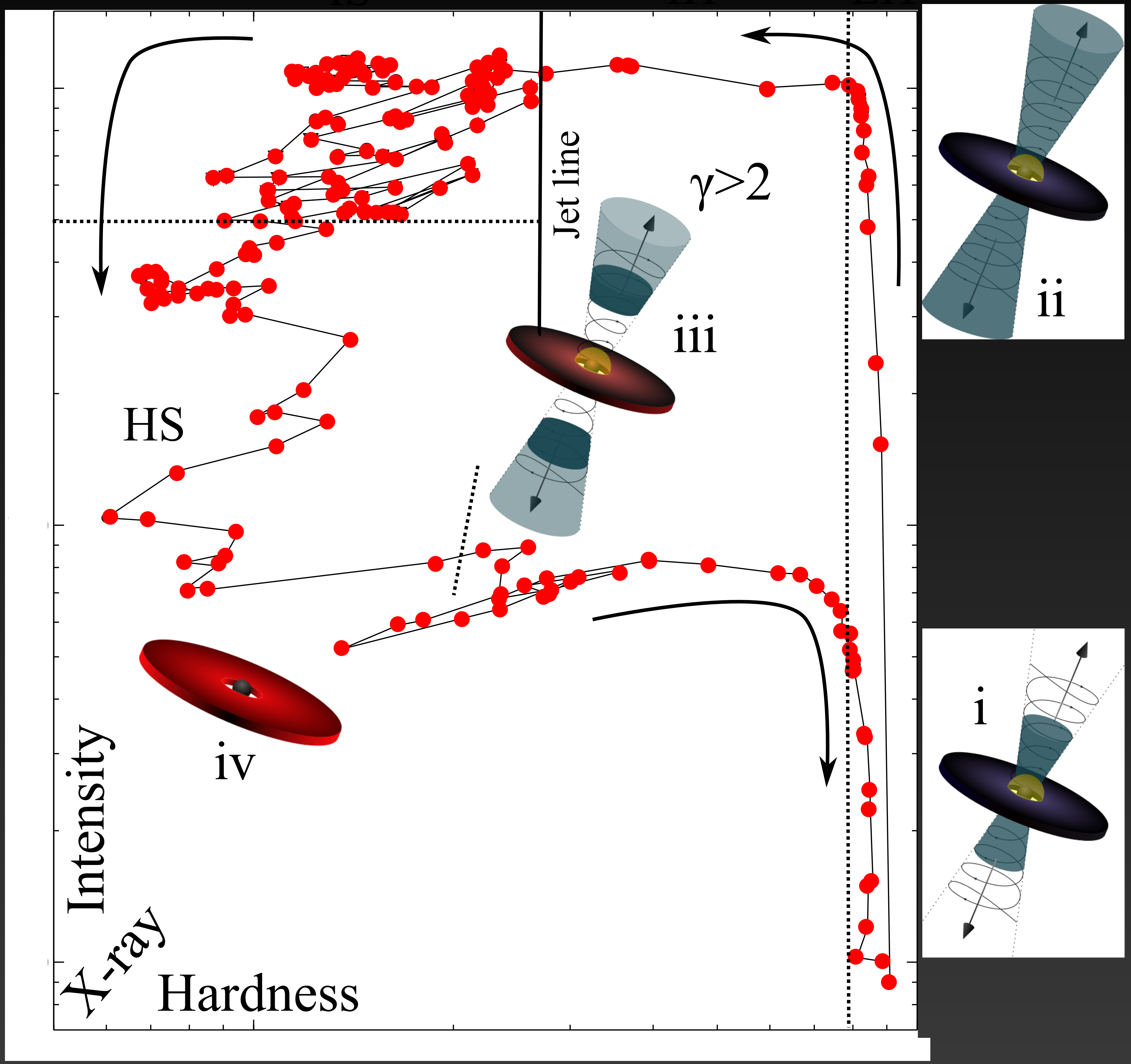
Jets



Radio/X-ray correlation - Hannikainen+98, Corbel+13, Tremou+20

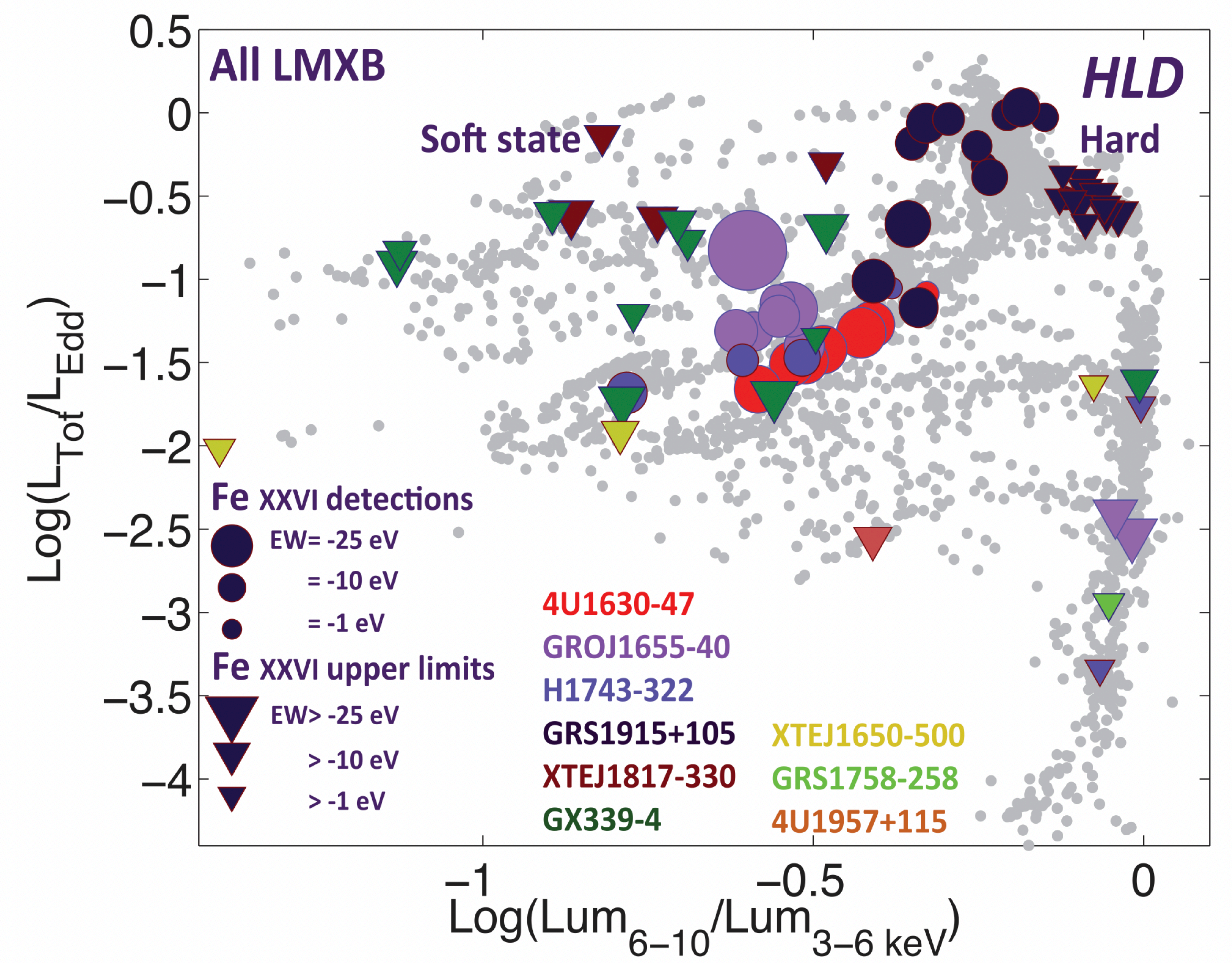


Zdziarski+02, Zdziarski & Gierlinski 04, Done+06

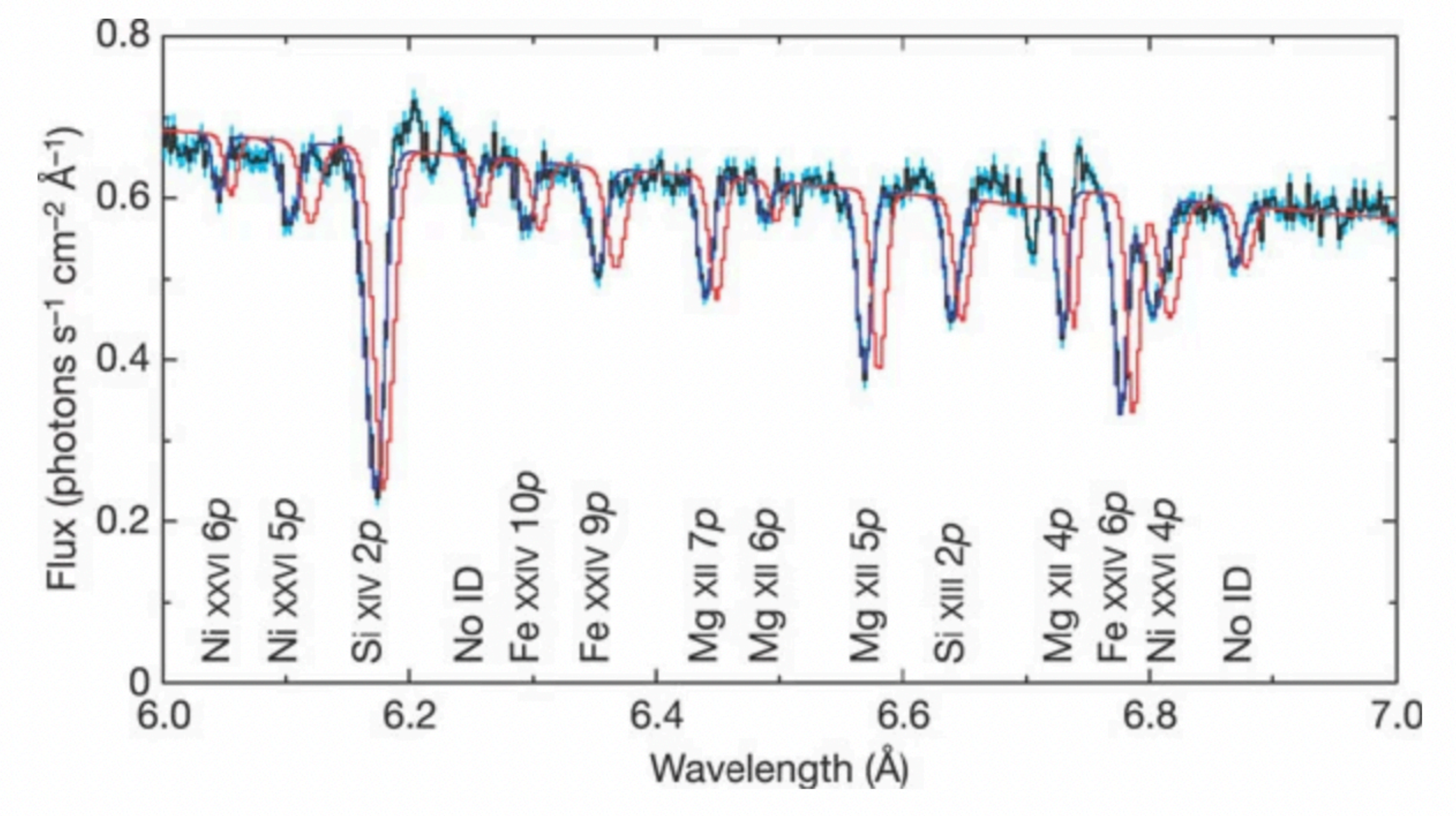


Belloni+05, Fender+04, Koljonen+13

Outflows in XRBs
Accretion disk winds



Ponti+12

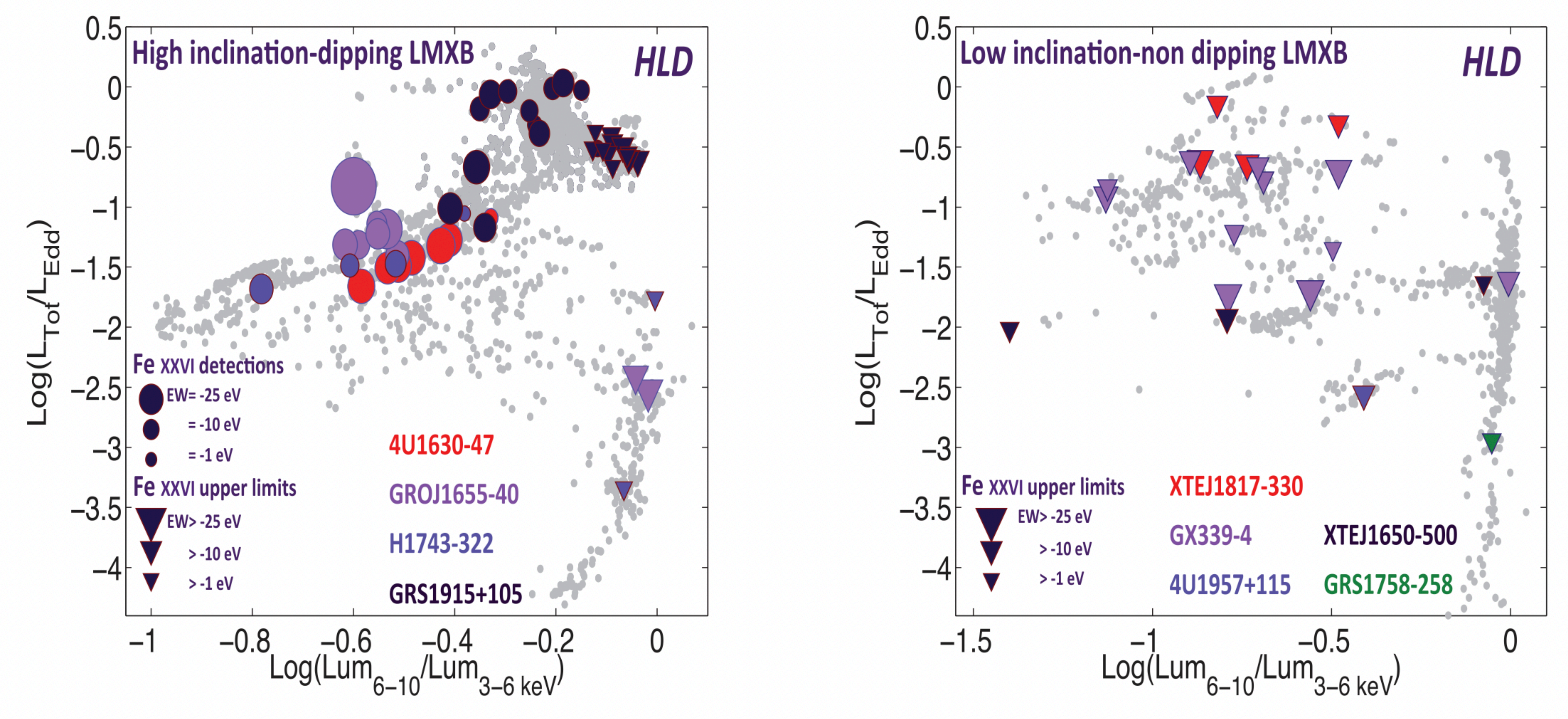


Chandra/GRO J1655-40/Miller+06

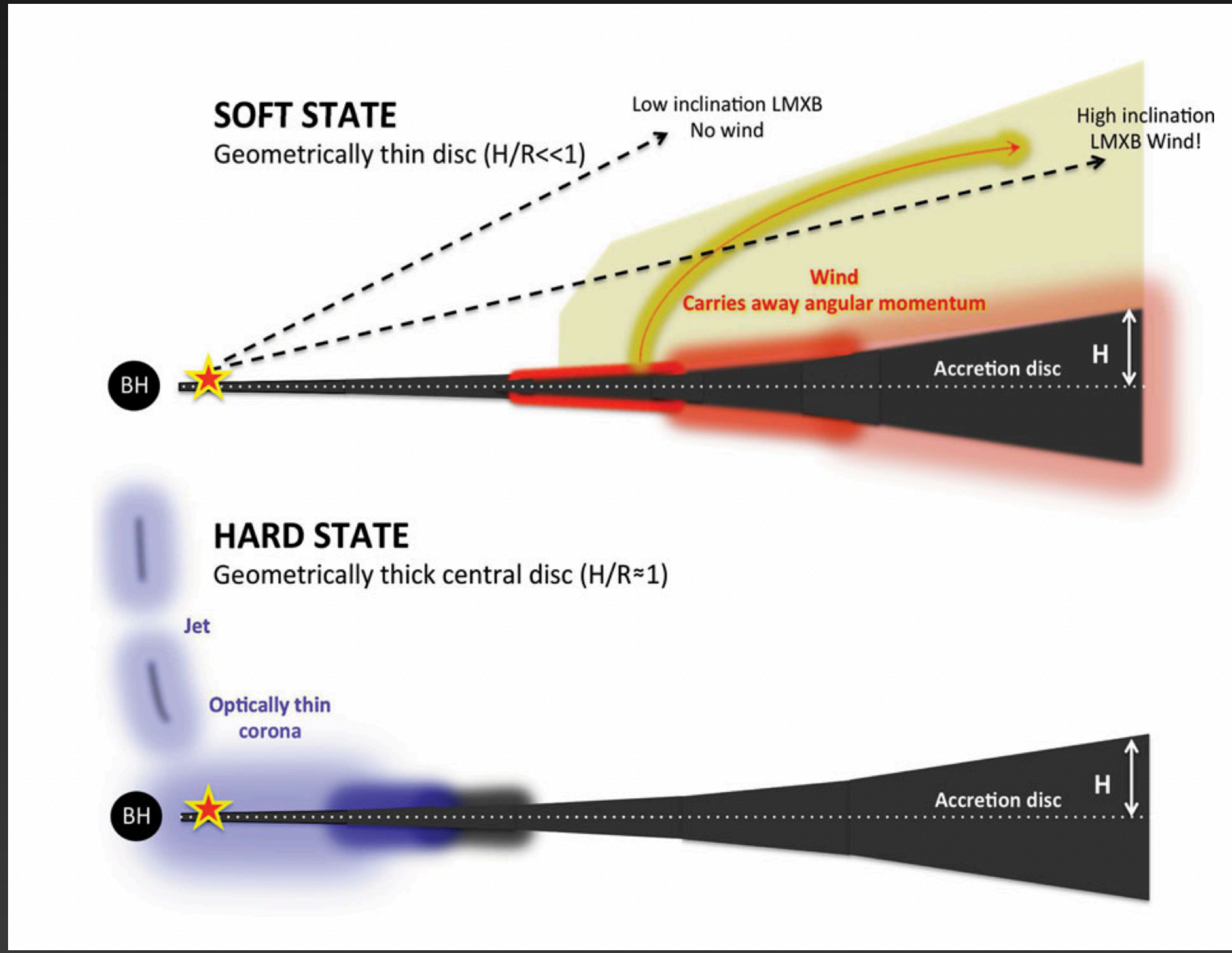
- High-resolution X-ray spectra revealed blue-shifted (~2000 km/s) X-ray absorption lines (Diaz Trigo & Boirin 16, Ponti+16).
- Typically strongest lines from H- and He-like Fe.

Outflows in XRBs
Accretion disk winds

- Equatorial disk winds driven by X-ray irradiation.
- Thermally-driven accretion disk wind is theoretically expected given sufficiently large disk subject to strong irradiation (e.g. Begelman+83, Woods+96, Proga & Kallman 2002, Higginbottom+19).
- Predominantly observed in the soft state and high-inclination sources (Ponti+12).
- X-ray absorption not seen in hard states. Why? Over-ionization (Jimenez-Garate+01, Ueda+10, Diaz-Trigo+12/14/16, Chakravorty+13, Higginbottom & Proga 15, Bianchi+17)? Obscuration (Ueda+10, Miller+12, Ponti+12)? Driving mechanism (Neilsen & Lee 09)?



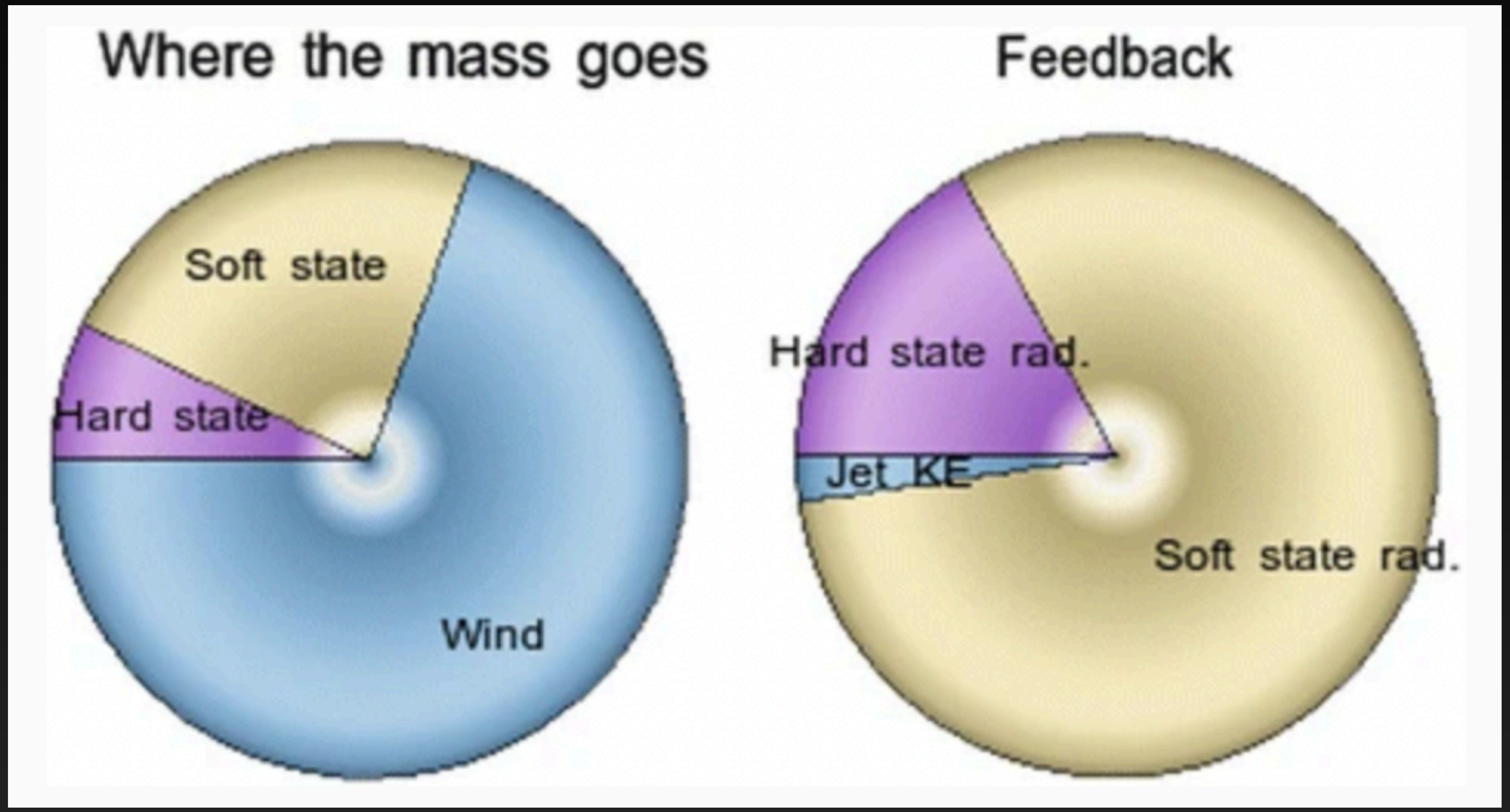
Ponti+12



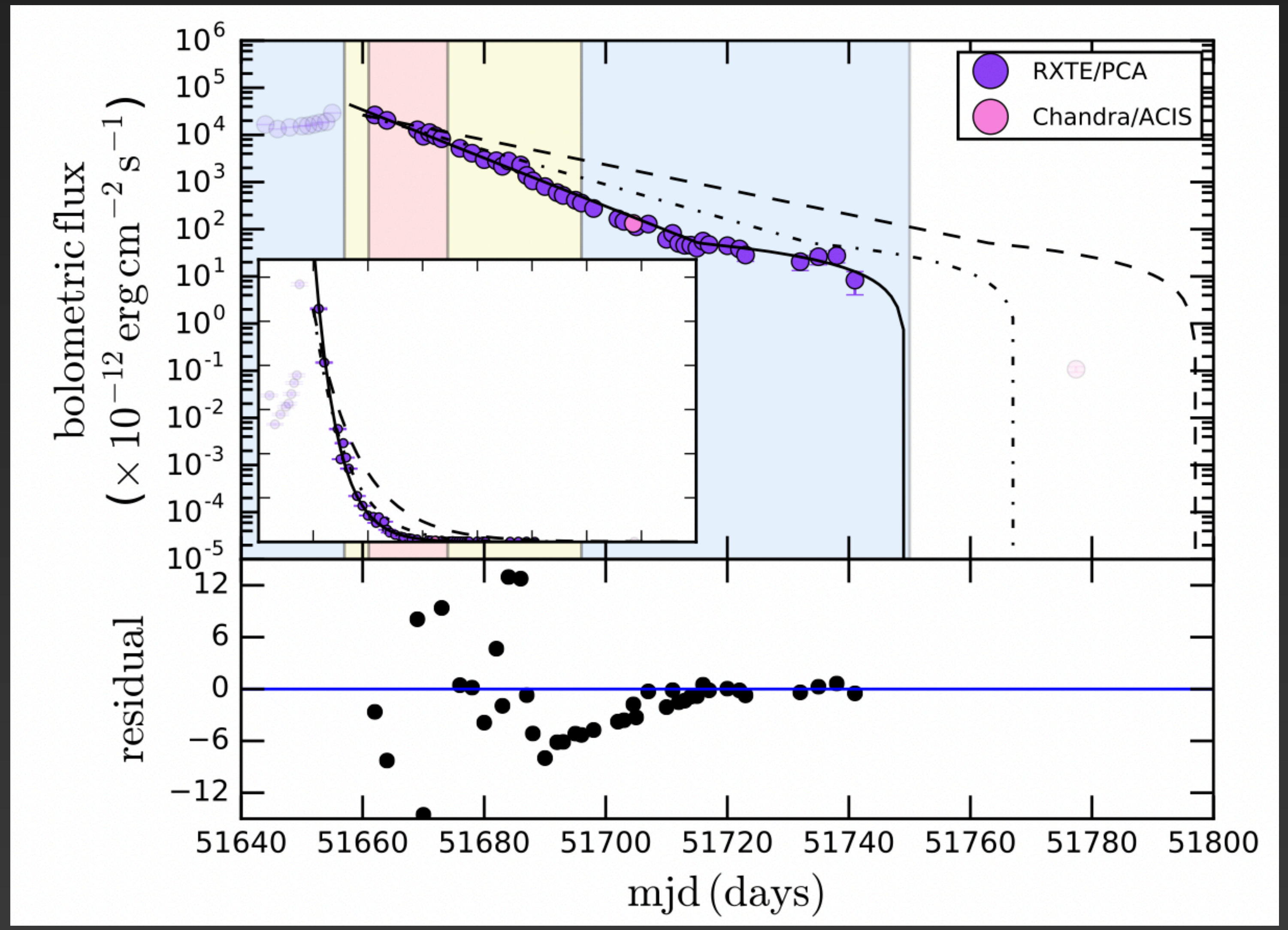
Ponti+12

Outflows in XRBs
Accretion disk winds

- Why winds are important?
- Ubiquitous in accreting systems: XRBs, CVs (e.g. Matthews+15), AGN (e.g. Tombesi 16), TDEs (Parkinson+20), YSOs (Ray & Ferreira 21)
- Kinetic luminosities are low, few orders of magnitude lower than anything else.
- Winds can carry as much mass as accreted or even more in certain cases.
- Impacts outburst evolution (V404 Cyg, Munoz-Darias+16), and angular momentum removal (Tetarenko+18).



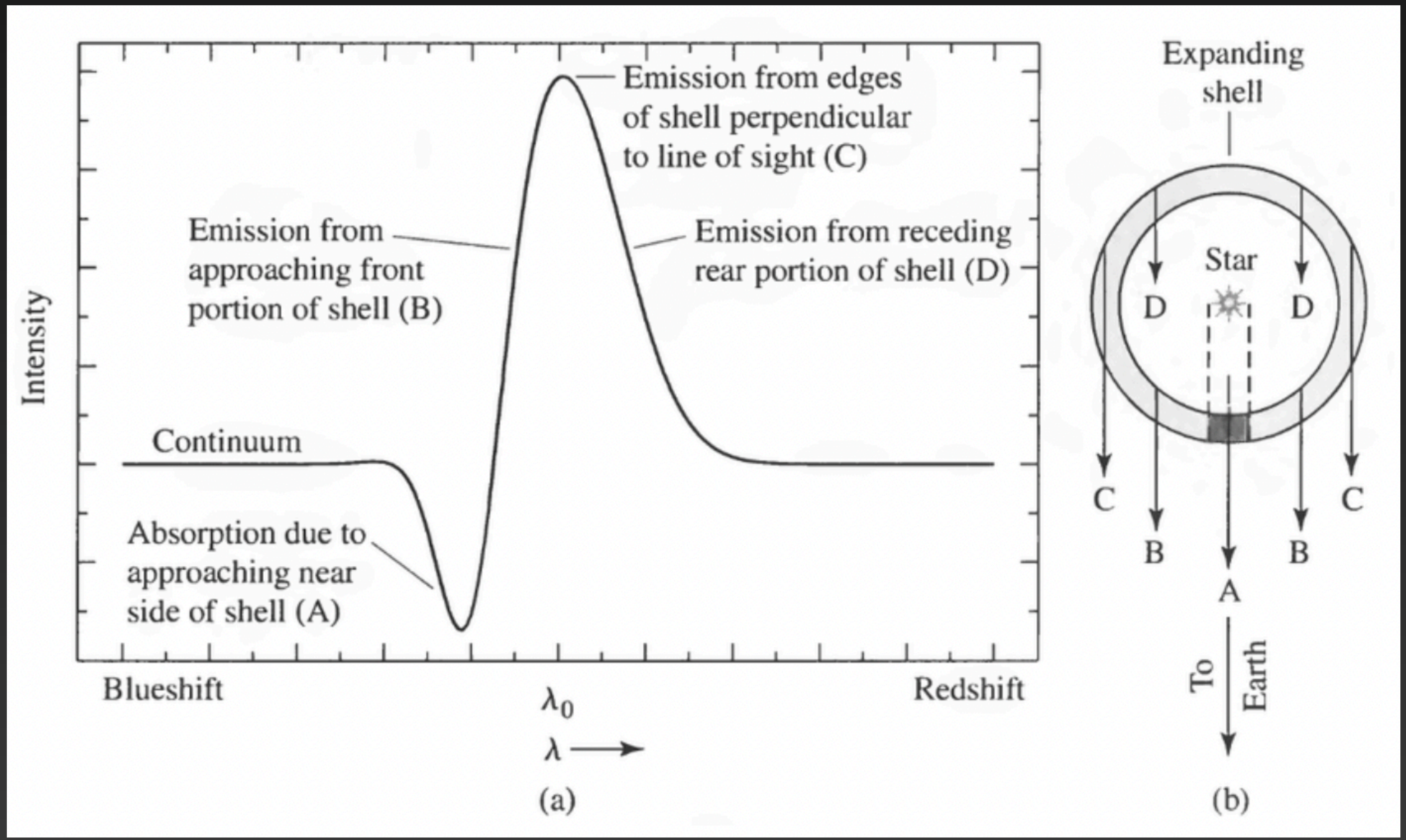
Fender, Munoz-Darias 16

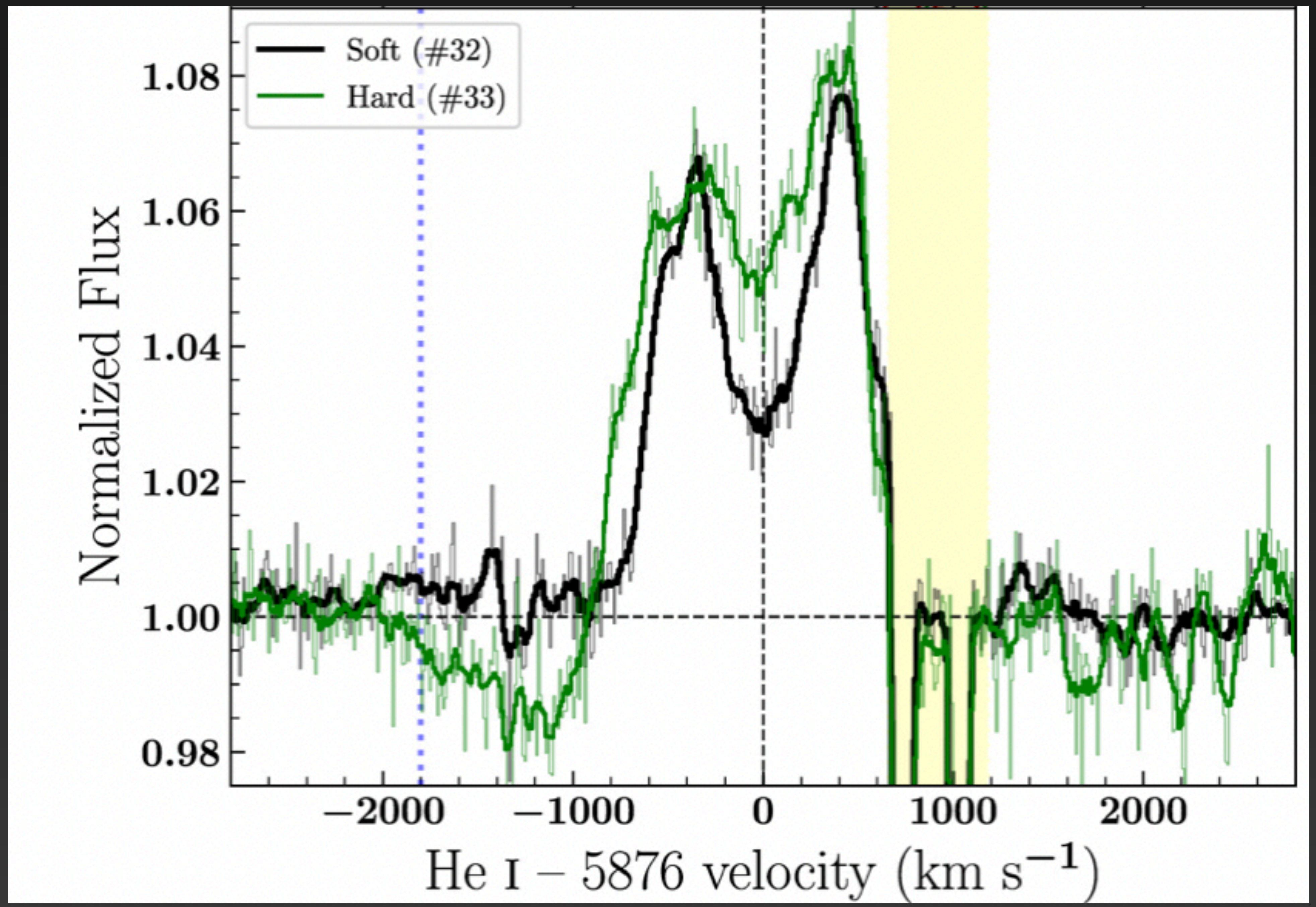


XTE J1550-564 - Tetarenko, B.+18

Outflows in XRBs
Hot and cold disk winds

- UV, optical, and NIR P-Cygni profiles in the hard state for H, He, and Fe II emission lines with velocities ~2000 km/s (Munoz-Darias+16, Munoz-Darias+18, Charles+19, Jimenez-Ibarra+19, Munoz-Darias+19).



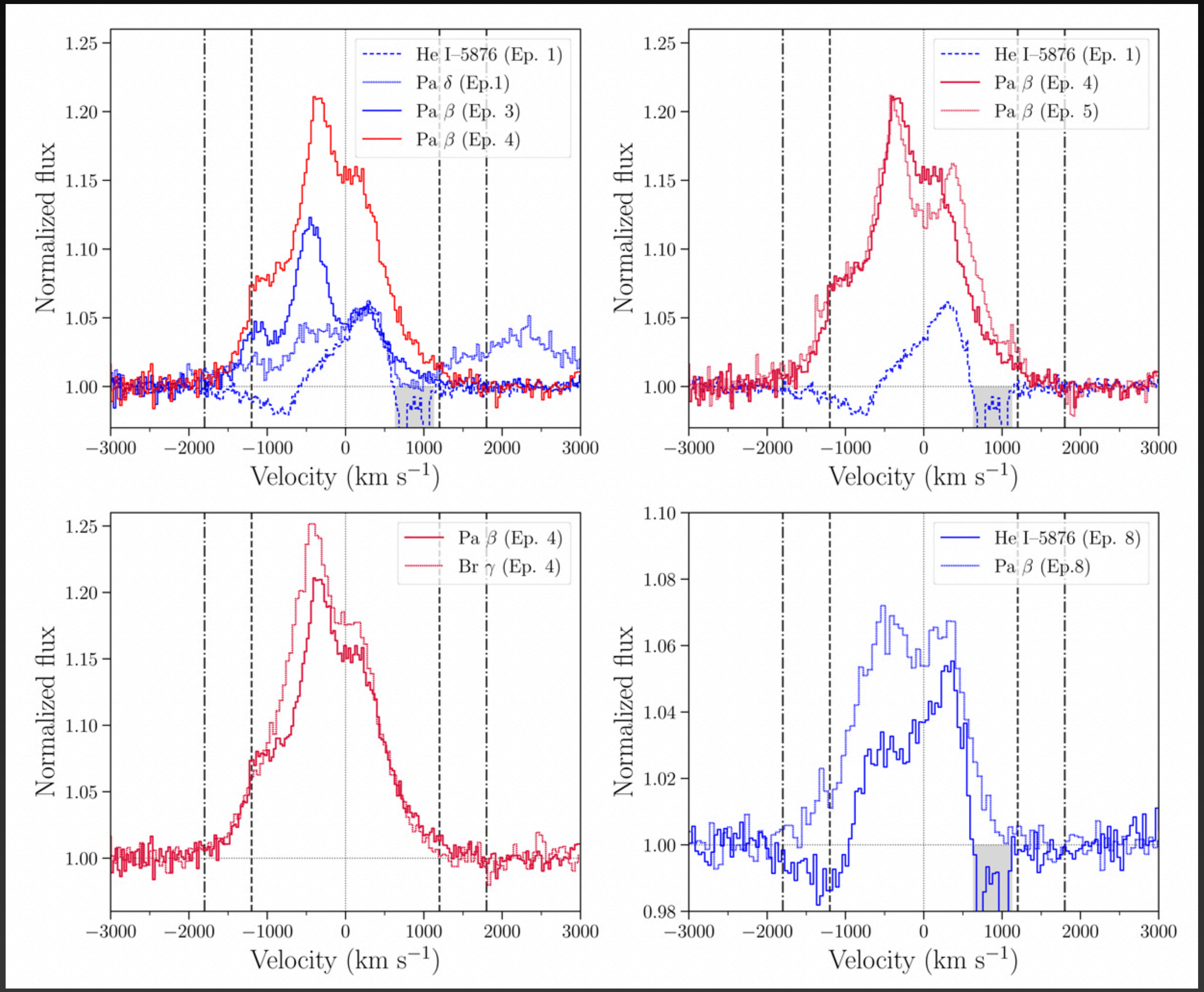


MAXI J1820+070/Munoz-Darias+19

Outflows in XRBs

Hot and cold disk winds

- Other evidence of cold winds?
- Similar kinetic properties as P-Cygni profiles superimposed on double-peaked emission lines (Sanchez-Sierras+20):
  - Broad emission line wings at ~2000 km/s.
  - Blue-side absorption.
- Part of the same outflow as disk wind?
- Same or different driving mechanisms?



MAXI J1820+070 / Sanchez-Sierras+20

Outflows in XRBs
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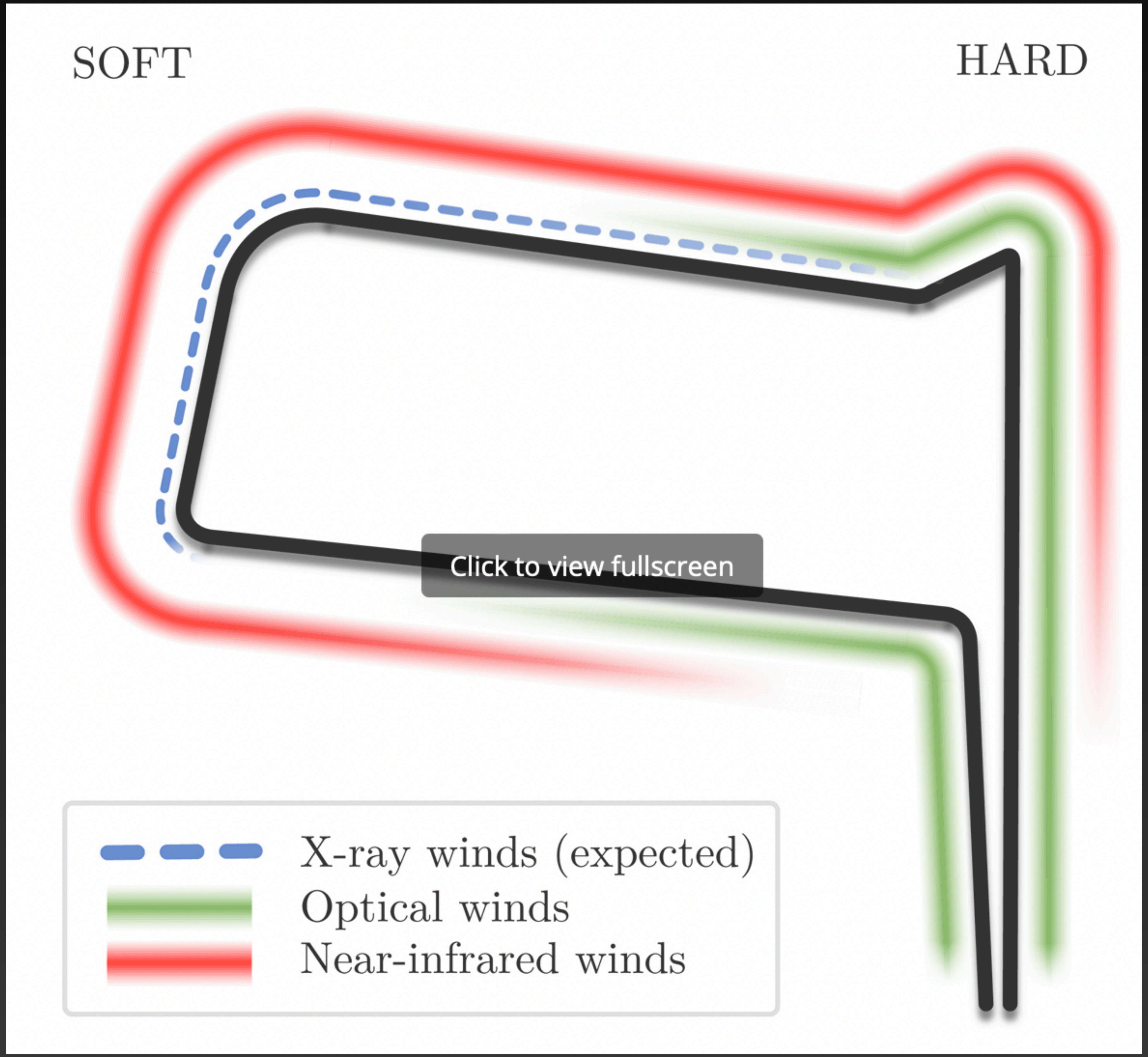
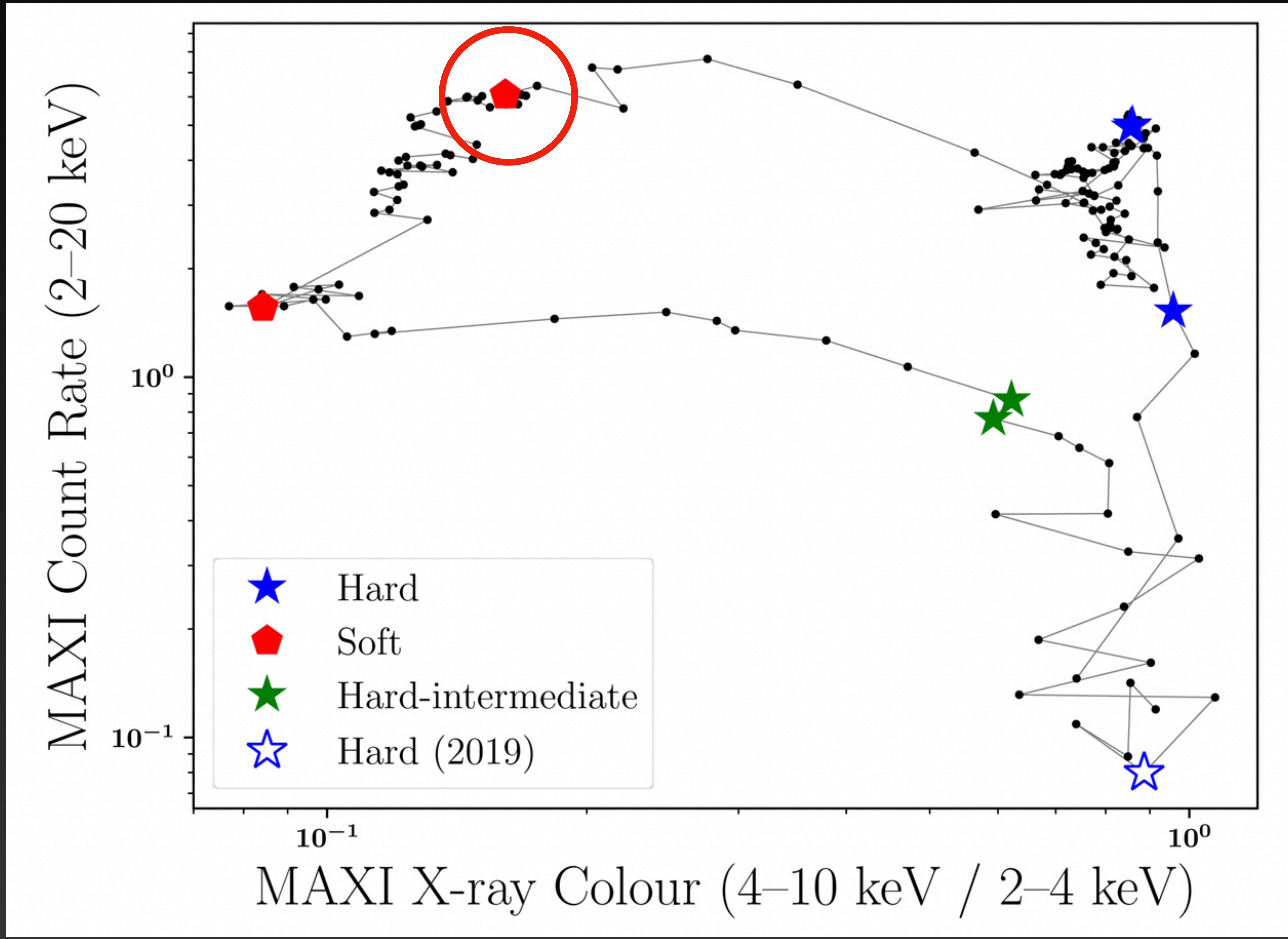


Sanchez-Sierras+20

X-Shooter campaign on MAXI J1820+070

What can we explain with a wind model?

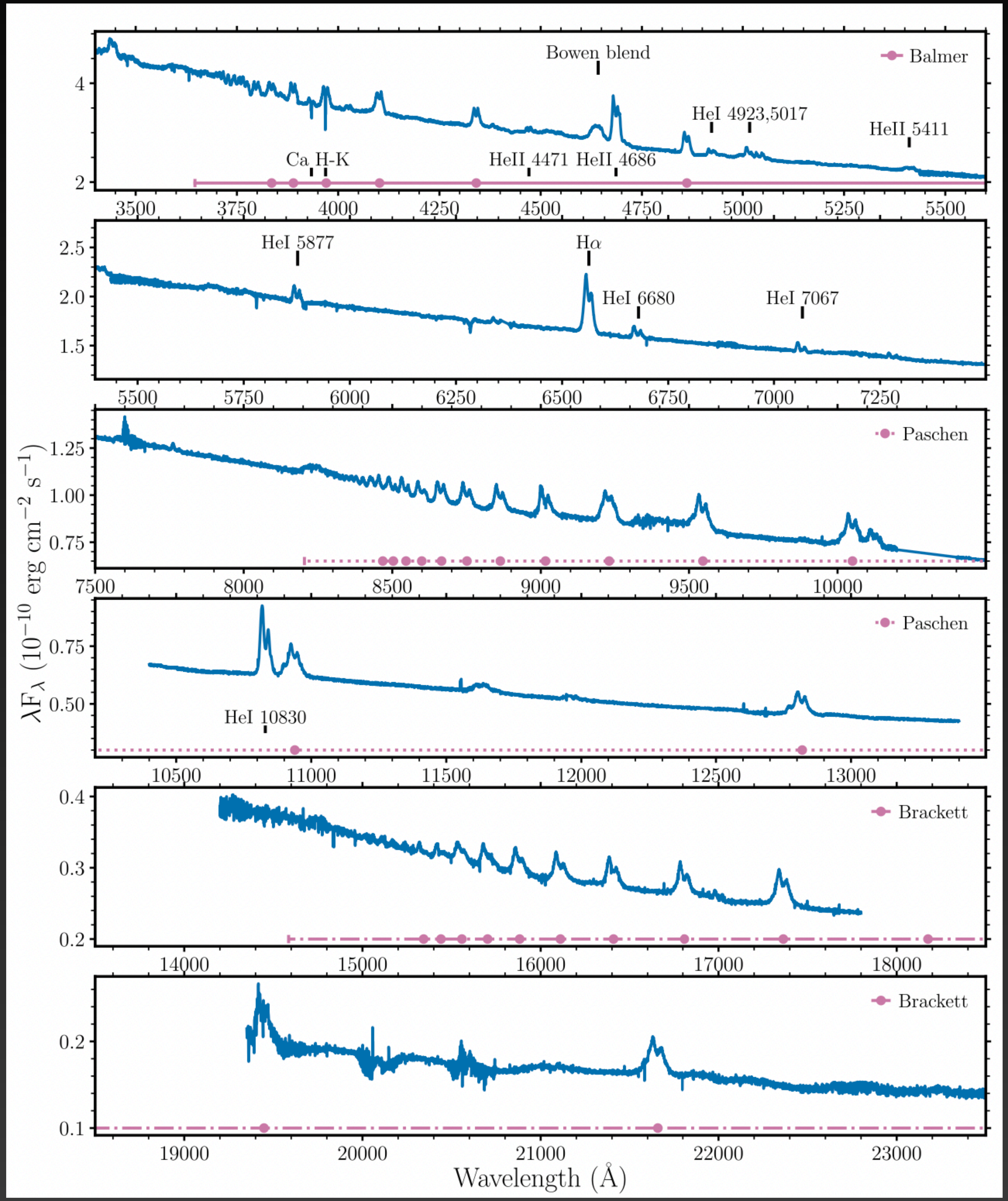
- We picked a soft state observation at a high luminosity/mass accretion rate.
- Typical location for strongly irradiated accretion disk, X-ray wind features (although no evidence as MAXI J1820 was too bright for Chandra/XMM).



X-Shooter campaign on MAXI J1820+070

Line spectrum

- Main features:
  - Rich emission line spectrum (Hydrogen series, He I, He II, Ca II, Bowen blend).
  - Flat Balmer decrement (~1.3).
  - No obvious wind absorption features (consistent with Munoz-Darias+19).



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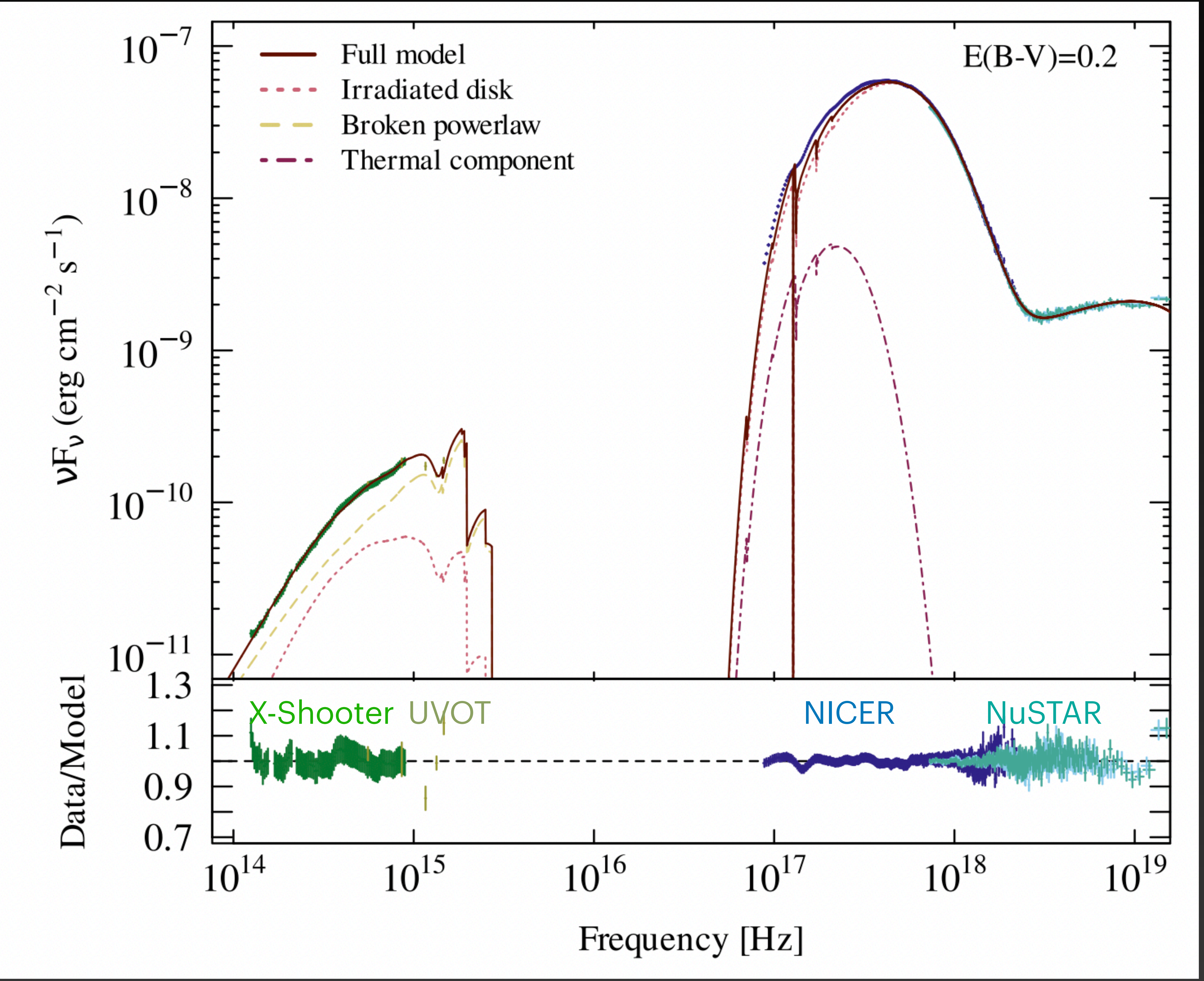
X-Shooter campaign on MAXI J1820+070

Modeling the spectral energy distribution

- SED fit (X-Shooter, NuSTAR, Swift/UVOT, NICER) with irradiated disk model + hard tail (OPTXRPLIR; Shidatsu+16, Kimura & Done 19).
  - Additional components:
    - Thermal: Plunge region (Fabian+20), inner disk irradiation (Done+12).
    - Power law: Wind reprocessing?
- Used as input continuum radiation for modelling the wind response.



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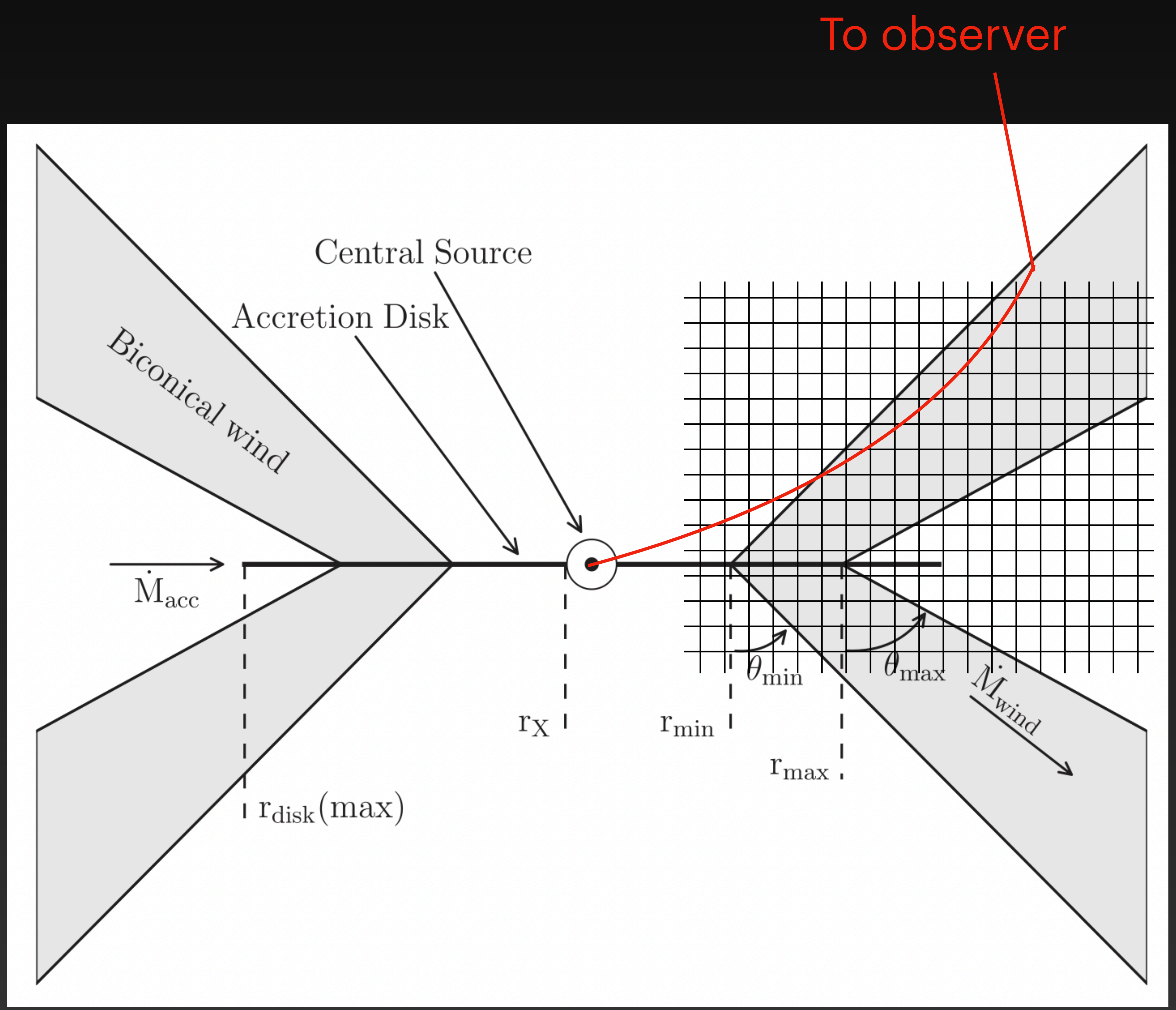
Modeling the wind response

Monte Carlo radiative transfer and photoionisation code "Python"

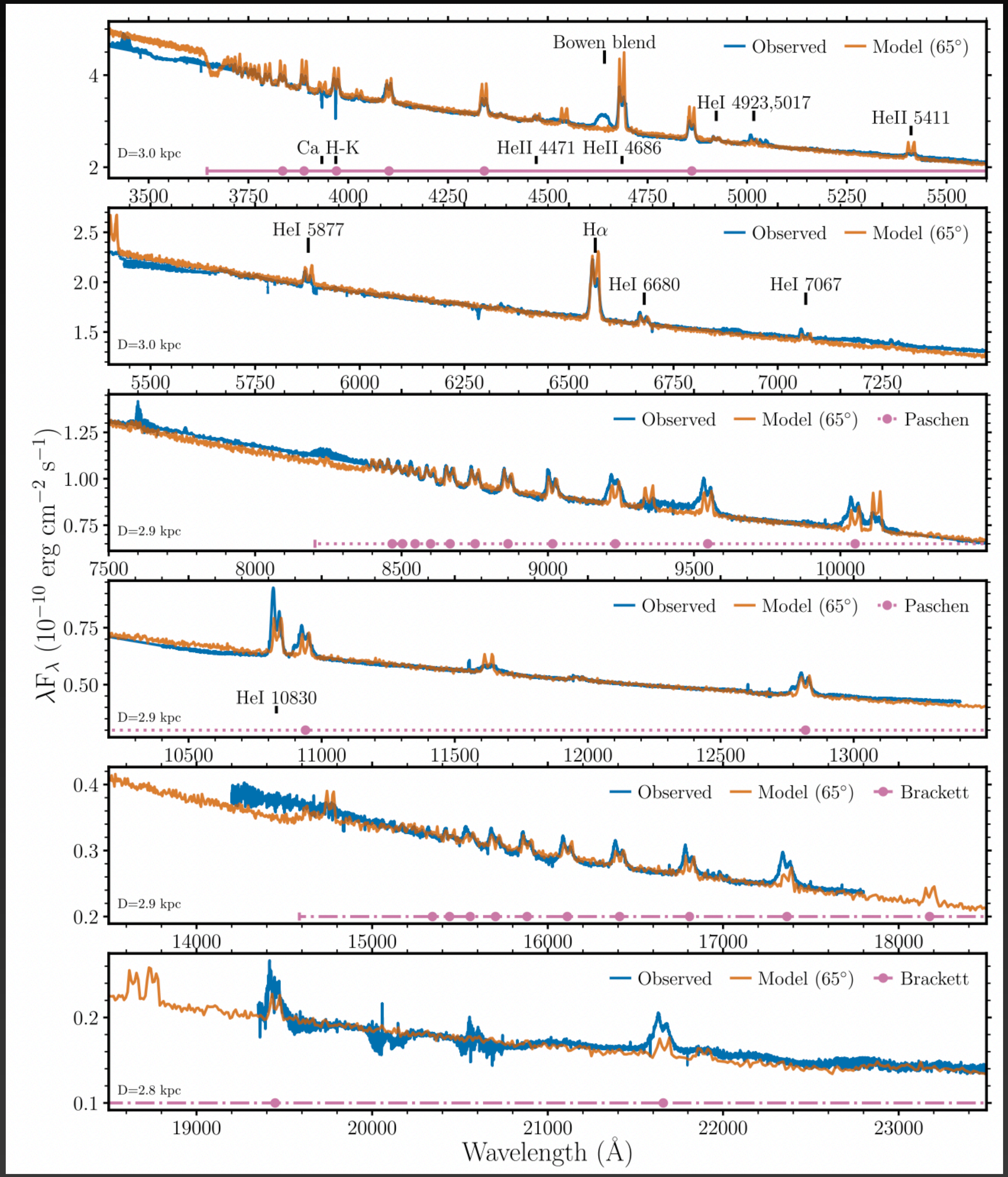
- "Python" is a very confusingly named code designed to model the spectra of objects with disc winds (Long & Knigge 02; Higginbottom+13; Matthews+15).
- Flexible, powerful code with a range of applications: AGN, XRBs, YSOs, WDs, stars, TDEs.
  - Photon packets (~10^7) fly through the wind grid.
  - Converge on ionisation state and temperature.
  - Mean intensity is calculated as a sum over photon trajectories (MC equivalent of an integral over "rays").



Modeling the wind response

Line spectrum

- MCRT computationally expensive, thus we did not perform grid-like searches. Instead, we iterated from physically plausible parameters adjusting a few parameters at a time until we achieve qualitatively similar line spectrum at a proper distance and inclination.
- The model can produce the observed line emission qualitatively.
  - Line strengths and widths are accurately produced.
  - Model lines fairly symmetric or stronger red peaks, while data show brighter blue peaks.
    - Deviations from non-axisymmetry, wind velocity, variability.
- Nevertheless, surprisingly good agreement, and it is the first time that full SED + ALL lines are modelled.



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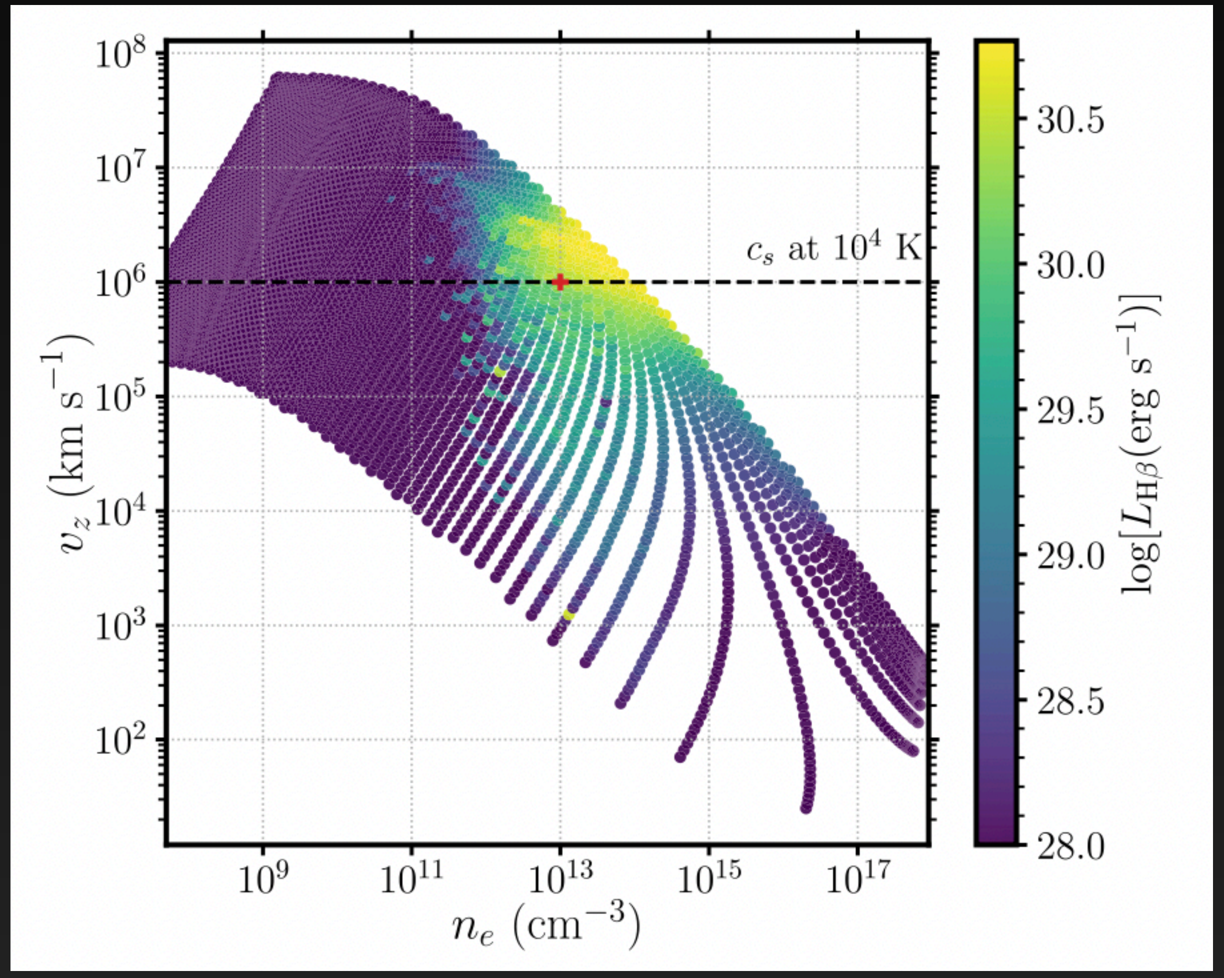
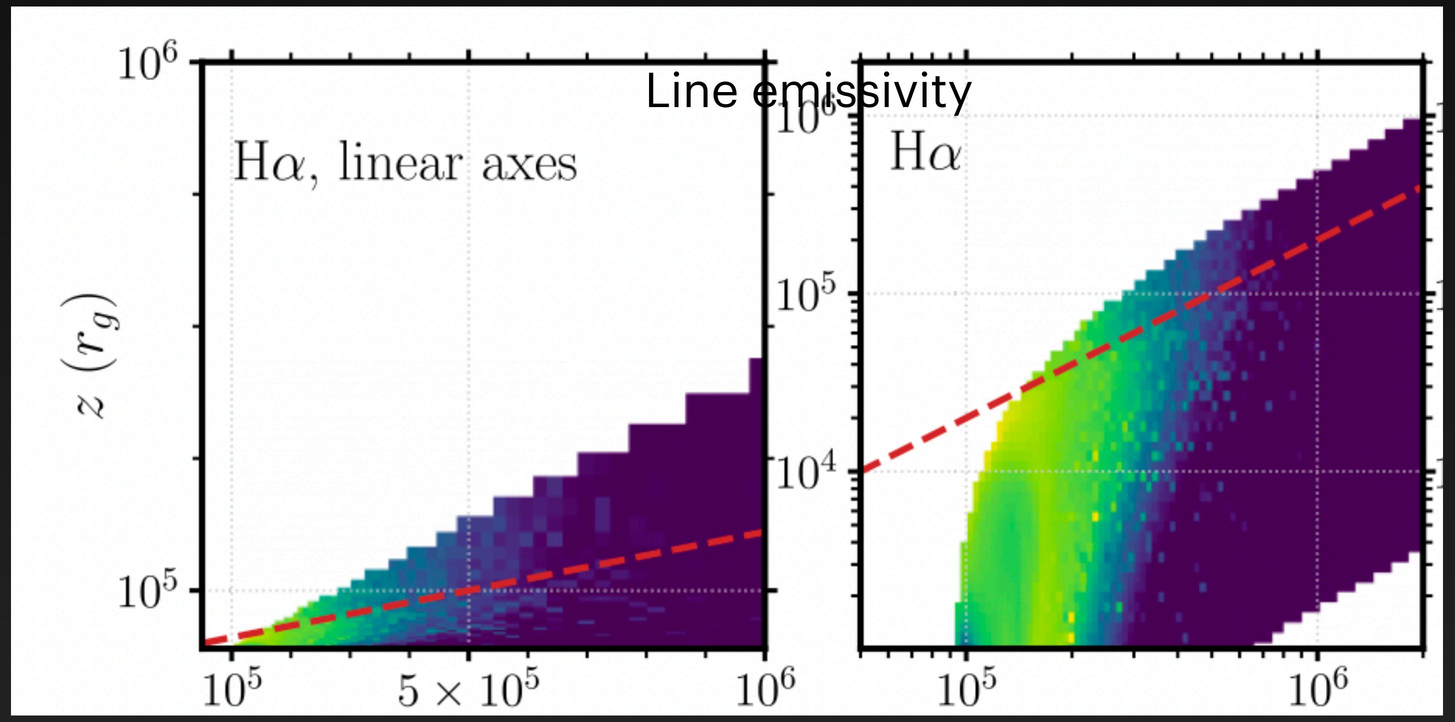
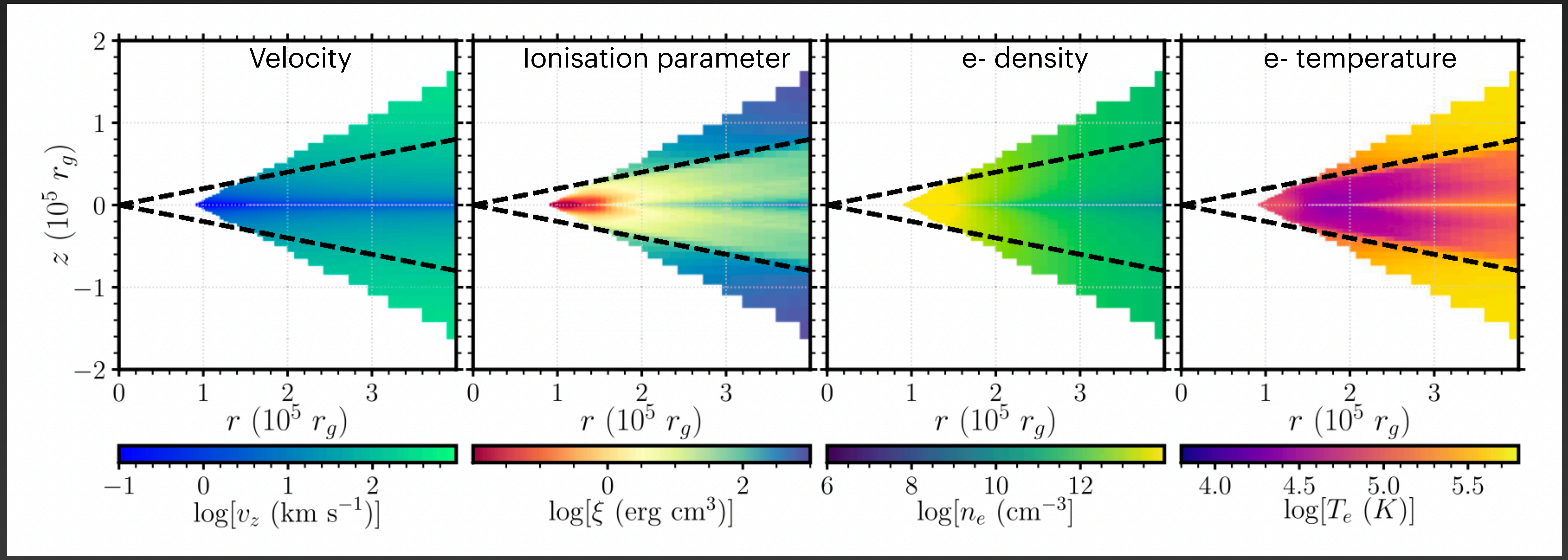
Modeling the wind response
Line-forming region

- 90% of the line-forming region is inside a wedge of z/r, moderate ionisation, moderately clumpy (f = 0.02) and T=2—4 10^4 K.
- Subsonic wind base with higher velocity, hotter, and less dense material further out.
- Characteristic conditions for line emission:
  - ne ~ 10^{13} cm^{-3},
  - Te ~ 40 000 K
  - vz ~ 10 km s^{-1}
- Fairly thin wedge of dense, warm gas moving at sub- to transonic velocities.
  - "Chromosphere" or wind base.







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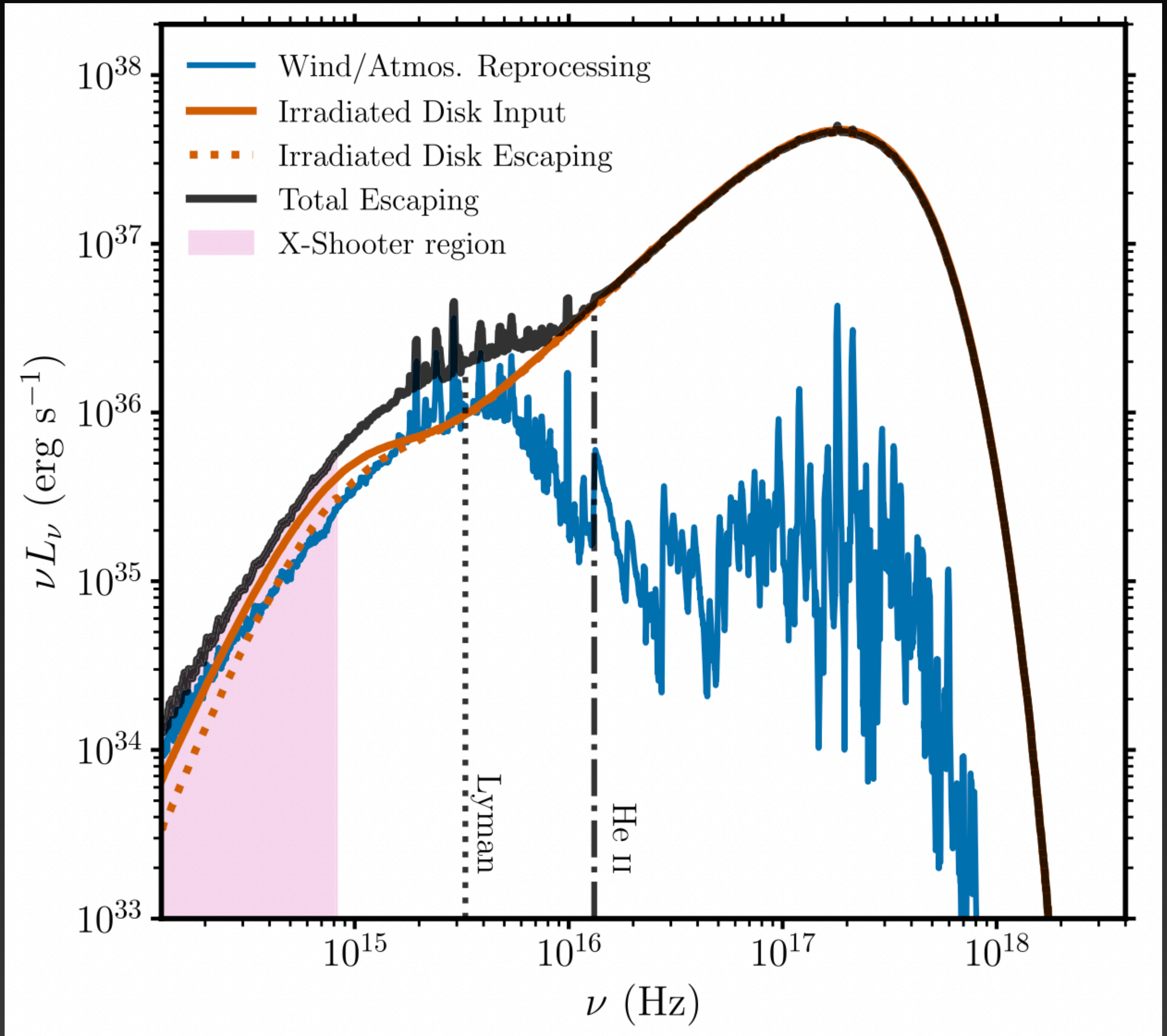
Modeling the wind response
Reprocessing in a wind base?

- Escaping spectrum is largely unmodified in EUV and X-rays.
- Redward of He II and Lyman edges the wind processes the disk radiation in a quasi-thermal optical-to-NIR bump.
- Wind absorbs ~ $3*10^{36}$ erg s^{-1} of the total luminosity close to peak and reradiates through a series of strong emission lines and recombination continua.
  - Noticeably changes the spectral slope at several wavebands.



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Conclusions
Wind bases or atmospheres?

- Emission lines consistent with coming from a transition region between the hydrostatic disk atmosphere and a thermally driven wind. The rapidly outflowing material is unlikely to be the source of significant optical emission (unless it is exceptionally clumpy and/or multiple phases co-exist in the outflow).
  - Likely not a unique model: any disk atmosphere likely produces similar results (e.g., temperature-inversion layer above an irradiated disk (Wu et al. 2001).
  - But the X-ray/hot wind is there! It has to start somewhere.
  - Clumpy winds (suitable for our conditions of line-forming region) suggested to explain fast optical dips accompanied by blue-shifted absorption (Charles+19, Jimenez-Ibarra+19).
- Disk winds can be significant "continuum reprocessors" and change the slope of the continuum SED: consistent with work on TDEs, AGN, CVs (Matthews+15,16; Parkinson+22).

Conclusions

The challenge of cold winds

- Fast material is hot ($T = 10^6$ K), so how do you get “cold” 10^4—10^5 K winds?
- Clumping/condensation due to thermal instability doesn’t work once thermal wind is developed.
- MHD wind might work, but needs high mass loss rates and/or clumping mechanisms.
- Clumping near the wind base (Waters+21)?
- More work needed! Wishlist: Complete physical picture of the irradiated disk atmosphere including its full radial and vertical structure.

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Thank you!