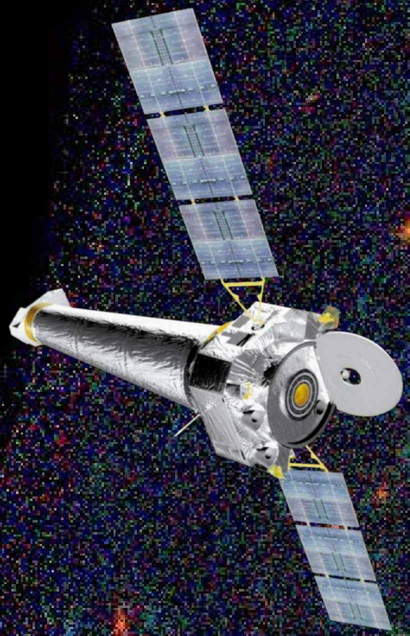
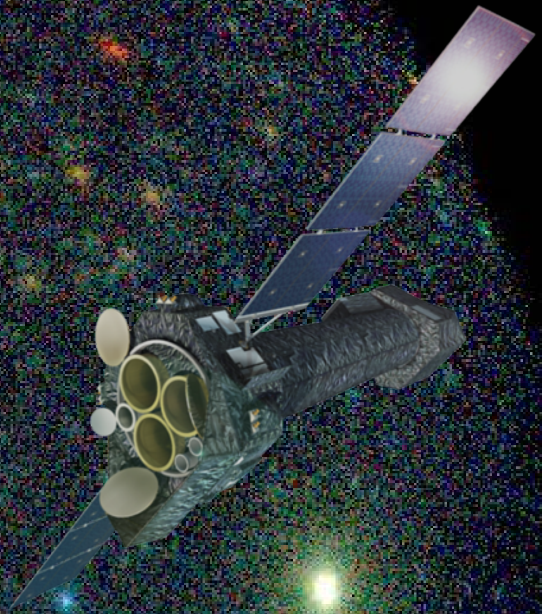
X-raying the wind interactions of massive binaries: what we have learned from 20 years of observations



Gregor Rauw



with contributions from Ronny Blomme, Enmanuelle Mossoux, Yaël Nazé, & Sophie Rosu

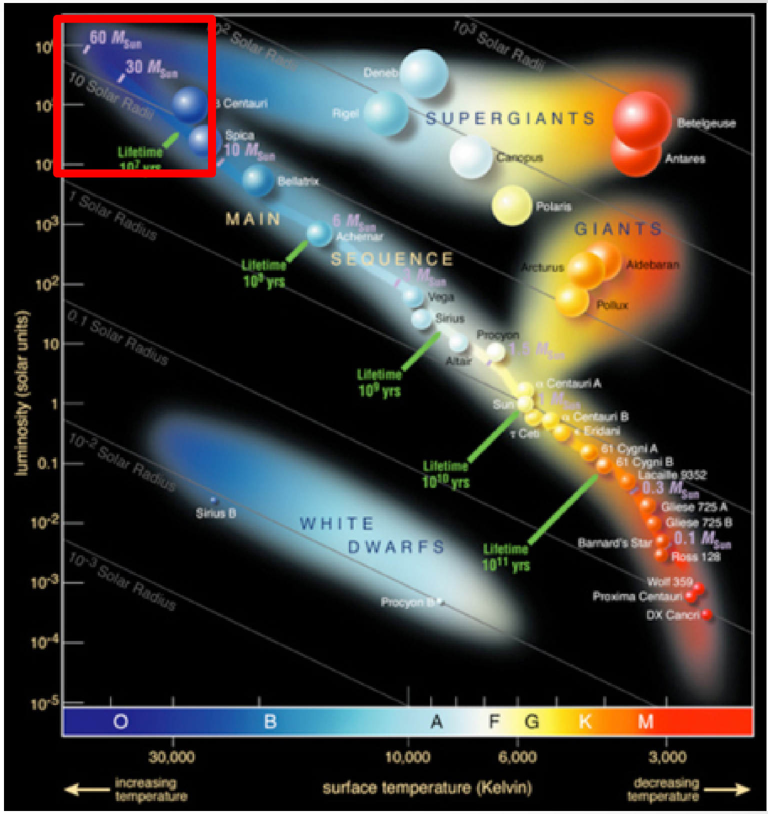
Massive stars

Hot ($T_{eff} \geq 30$ kK), massive (≥ 15 M_{Sun}) OB stars drive powerful stellar winds (e.g. Muijres+ 2012, A&A 537):

- Wind velocities ≥ 2000 km s^{-1}
- Mass-loss rates of ~ 10^{-6} M_{Sun} yr^{-1}

High fraction (> 50%) of binary or higher multiplicity systems (e.g. Sana+ 2012, Science 337).

- Winds are expected to interact in a wind-wind collision (e.g. Stevens+ 1992, ApJ 386).



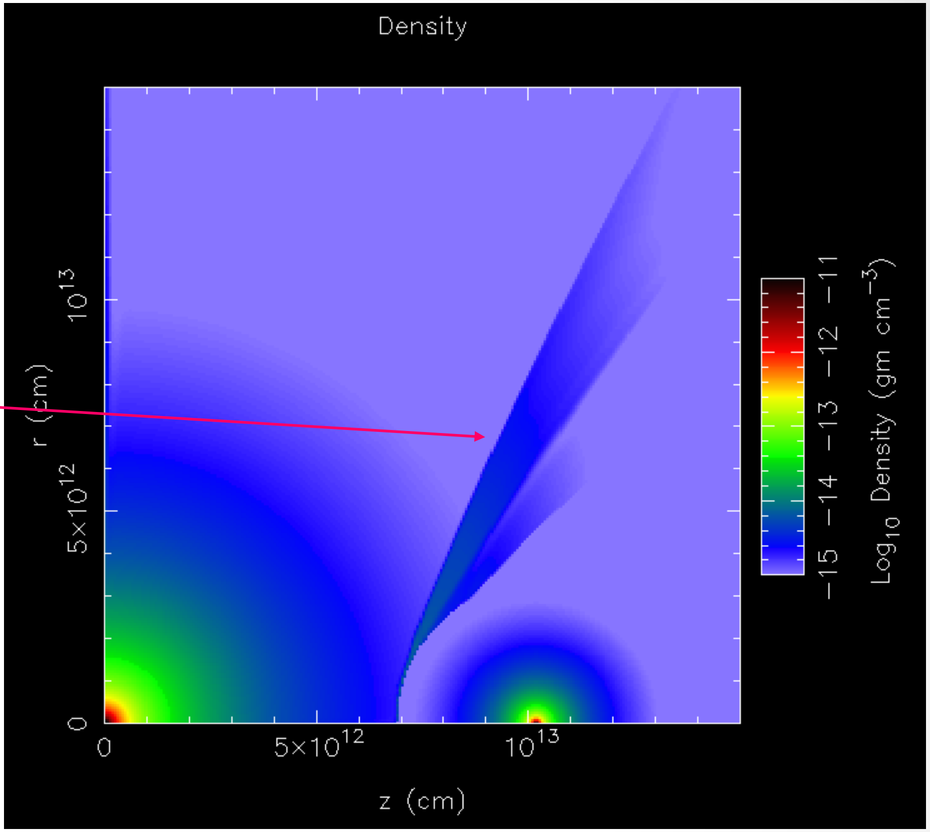
Wind interaction region with hot, X-ray emitting plasma (e.g. Stevens+ 1992, ApJ 386).

$$\rho_{s,j} = 4\,\rho_j,$$

$$v_{s,j} = v_j/4,$$

$$T_{s,j} = \frac{3\,\overline{m}_j\, v_j^2}{16\,k}$$

$$\eta = \frac{\dot{M}_1\, v_1}{\dot{M}_2\, v_2}$$

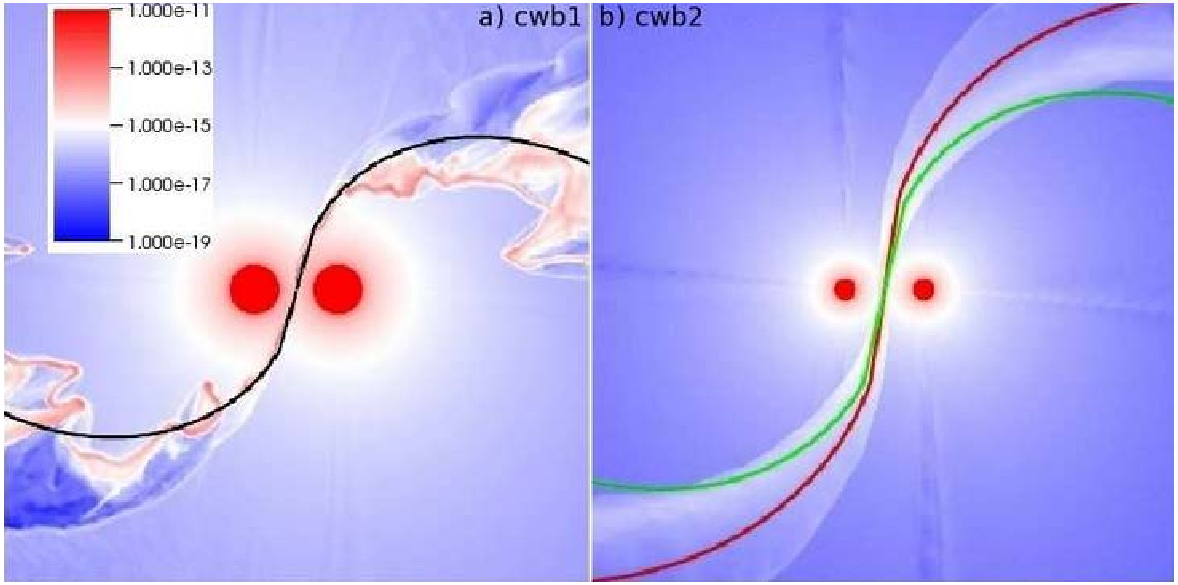


Massive binaries are expected to

- exhibit X-ray over-luminosities compared to single stars,
- display phase-locked variability of X-ray flux due to changing line-of-sight absorption and/or changing orbital separation.

Actual emission and its variability depend on efficiency of radiative and IC cooling (Stevens+ 1992, ApJ 386; Pittard 2009, MNRAS 396; Mackey+ 2023, MNRAS 526).

$$\chi = \frac{t_{\mathrm{cool}}}{t_{\mathrm{esc}}}$$



Efficient cooling ($\chi < 1$; close, short-period binaries): strong instabilities → reduced X-ray emission (Kee+ 2014, MNRAS 438).

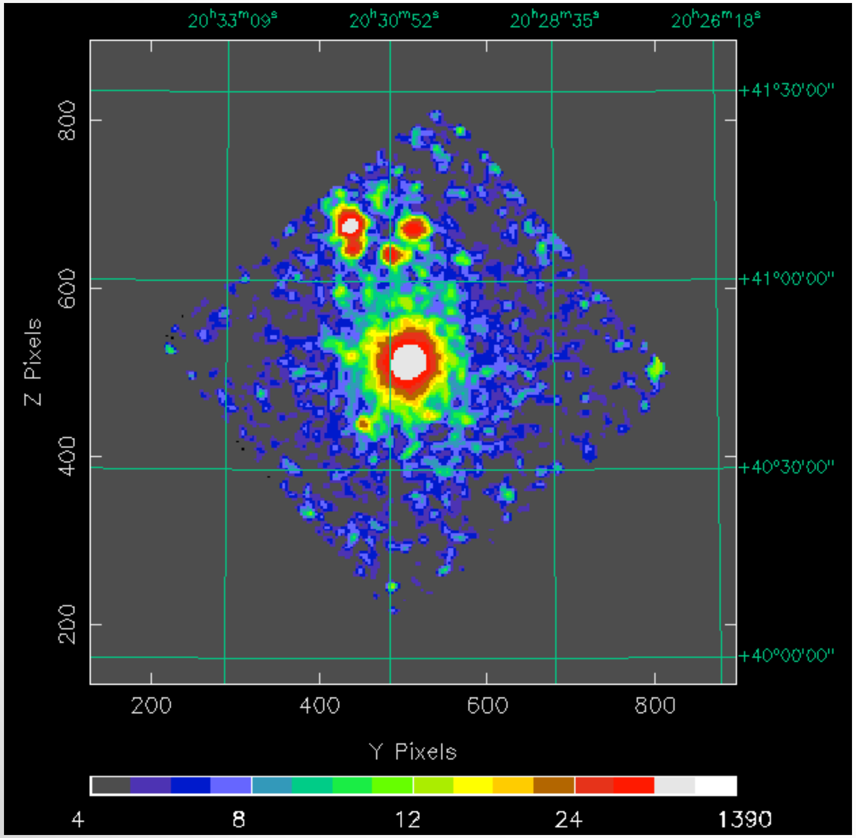
Adiabatic systems ($\chi >> 1$; wide, long-period binaries): stable wind-wind collision zone with X-ray emission expected to vary as $1/r$ (Stevens+ 1992, ApJ 386).

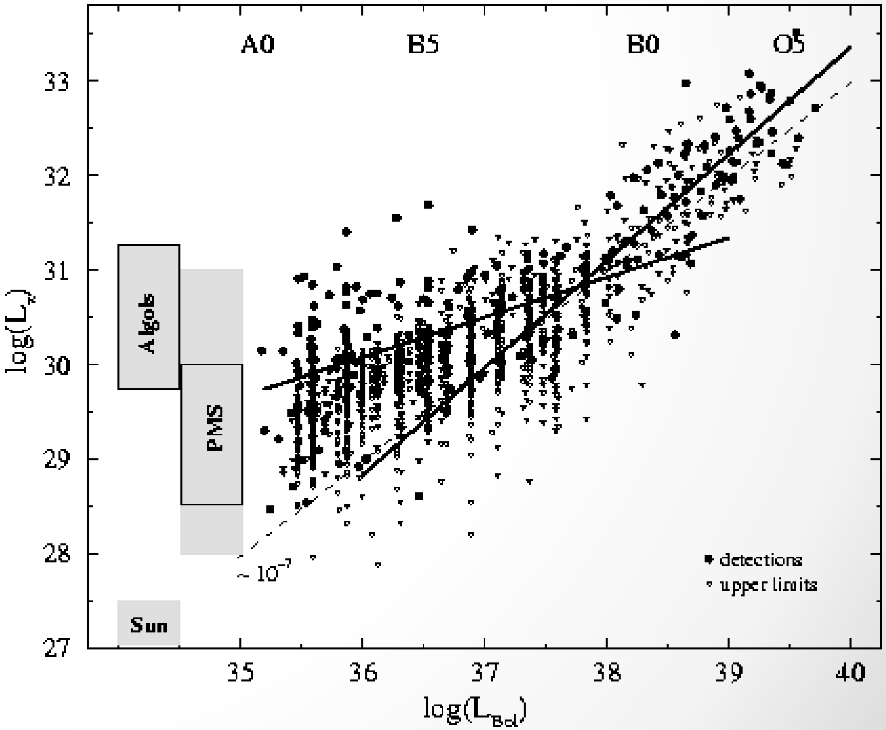
X-ray emission of massive stars

Serendipitously discovered with EINSTEIN satellite (Harnden+ 1979, ApJ 234, Seward+ 1979, ApJ 234).

Majority of bright sources are binaries (Chlebowski 1989, ApJ 342).

Simple scaling relation: $L_X/L_{bol} \sim 10^{-7}$ (Berghöfer+ 1997, A&A 322, Nazé 2009, A&A 506).

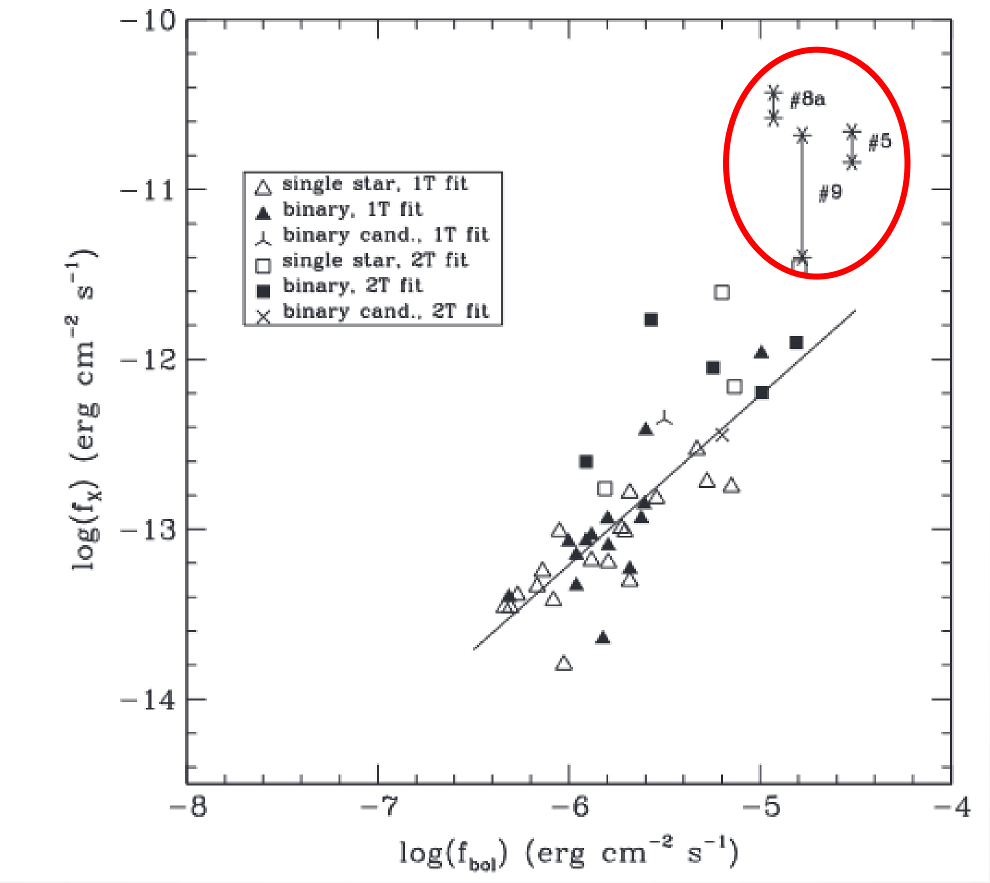




What we learned with XMM-Newton and Chandra

X-ray over-luminosity of massive binaries is the exception not the rule!

Large samples of massive stars show no strong difference in L_X/L_{bol} between binaries and single O-stars (e.g. Nazé 2009, A&A 506, Rauw+ 2015, ApJS 221):

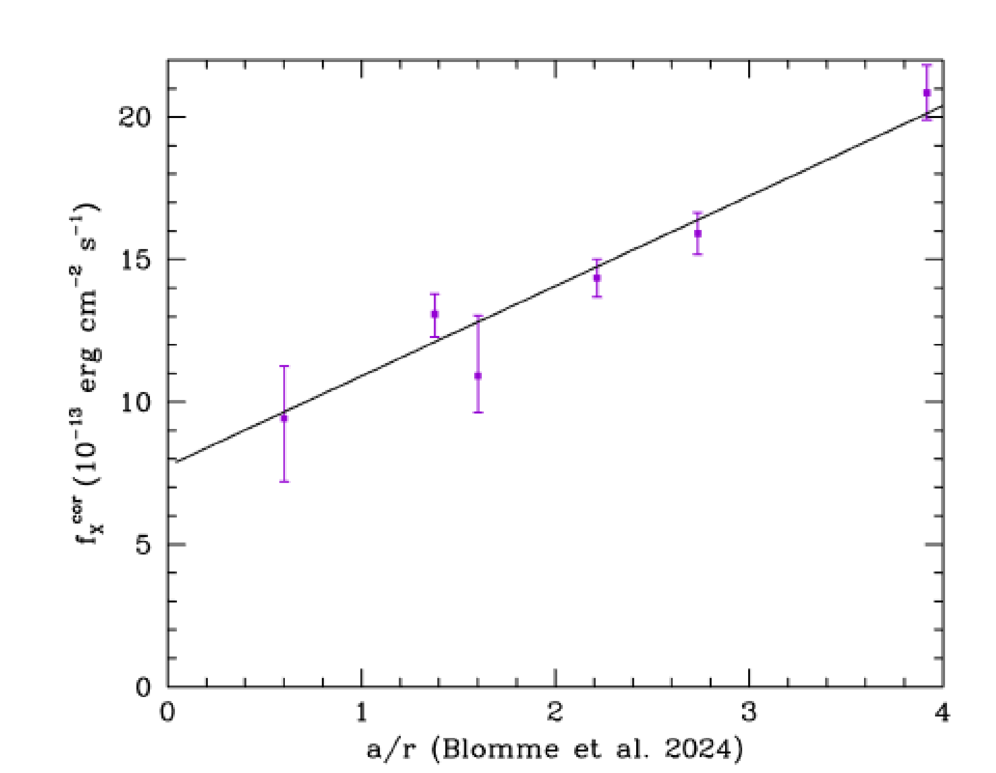


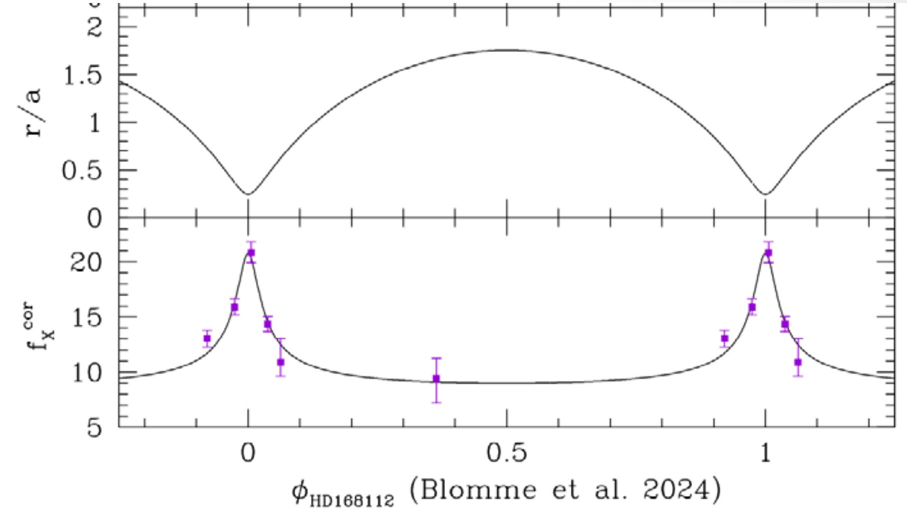
HD168112 (O4.5IV((f)) + O5.5V(n)((f)), P = 514 d, e=0.75, Blomme+ 2024, A&A 687) displays well defined 1/*r* variation as expected for adiabatic wind-wind collision (Rauw+ 2024, A&A 687).

Over-luminosity (by more than factor two) only seen during ~10% of orbit.

Intrinsic emission level fully consistent with $L_X/L_{bol} \sim 10^{-7}$.

HD168112

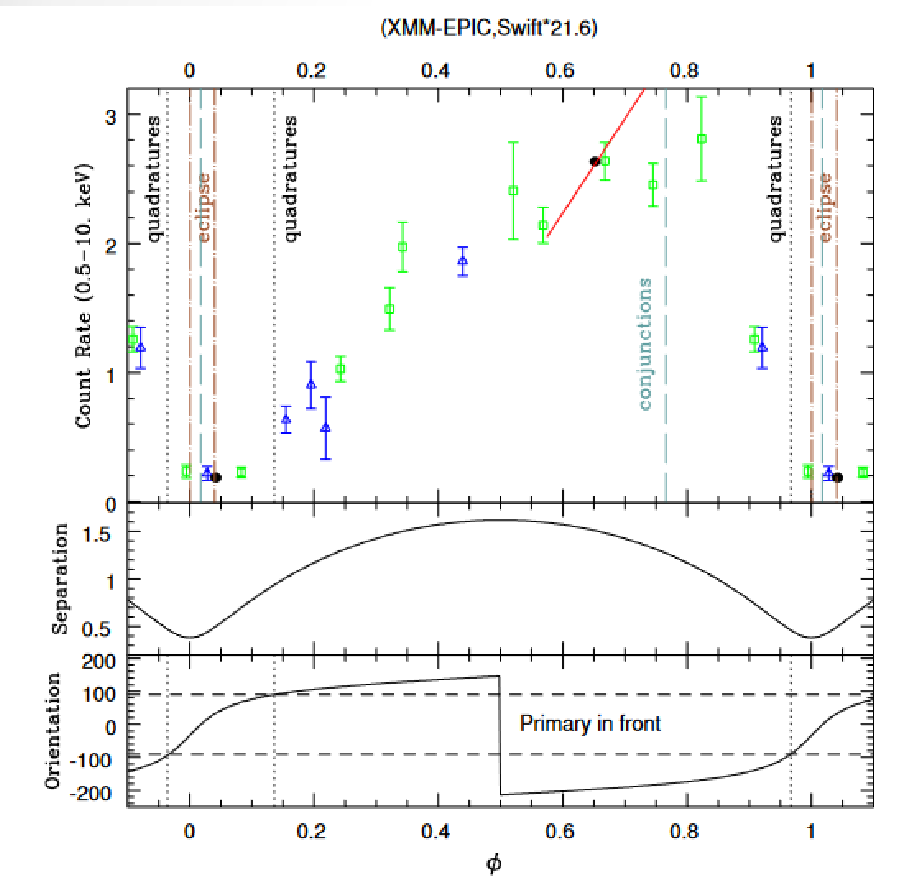




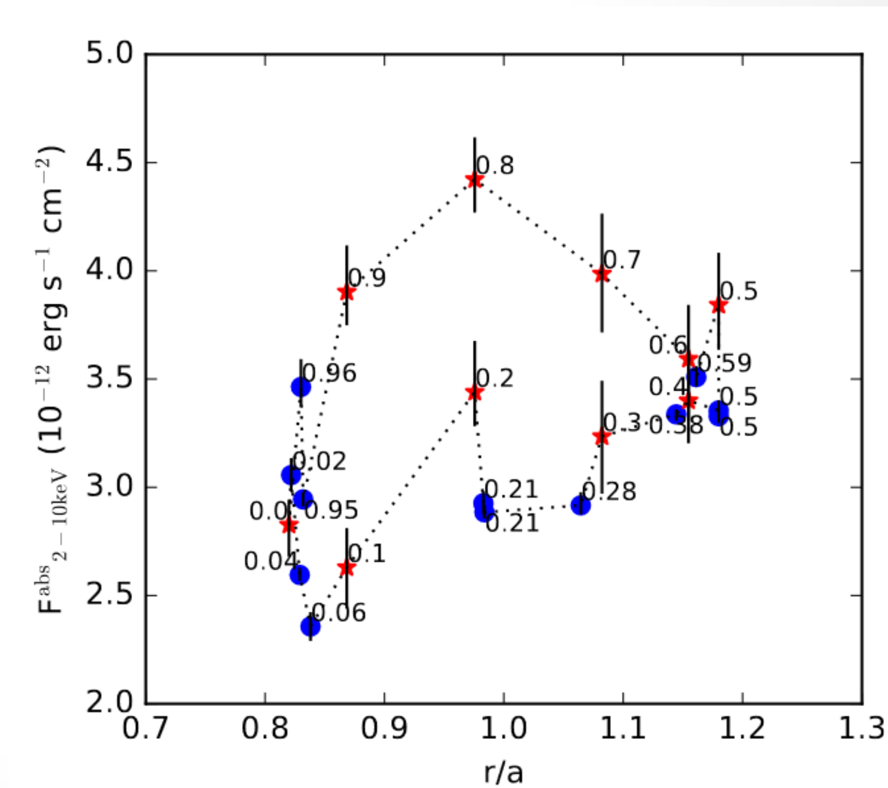
Some eccentric systems display hysteresis-like variations instead of the simple 1/*r* relation, e.g., HD166734 (O7.5If + O9I(f), P=34.5 d, e=0.62, Nazé+ 2017, A&A 607), Cyg OB2 #8a (O6 I + O5.5 III, P = 21.9 d, e=0.18, Mossoux+ 2020, A&A 636).

Collapse of the shock as it becomes radiative at periastron?

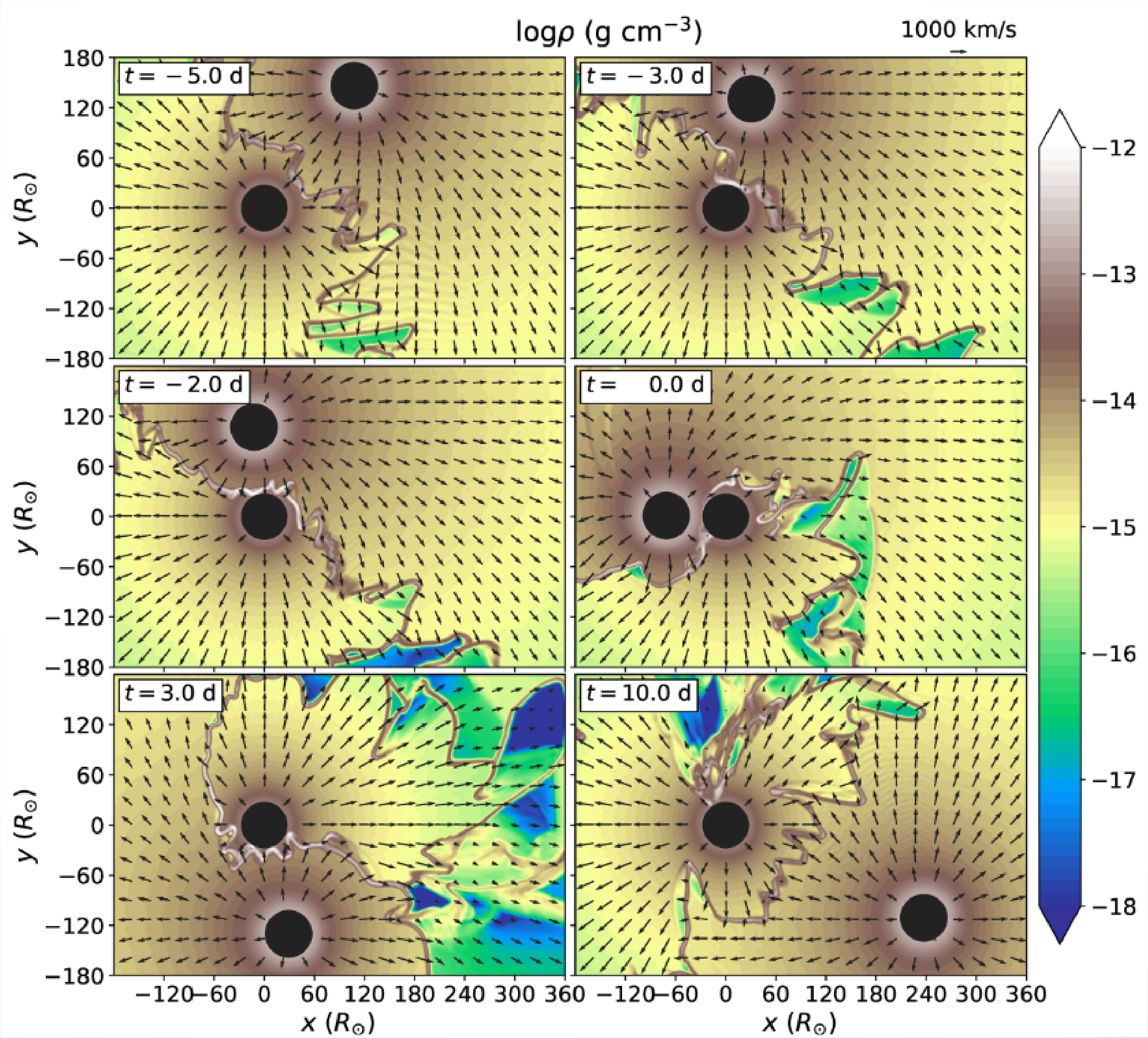
HD166734



Cyg OB2 #8a



Instabilities of radiative CW region can lead to accretion of clumps at periastron (Kashi 2020, MNRAS 492): 1.3 10^{-8} M_{Sun} per orbital cycle for HD166734.

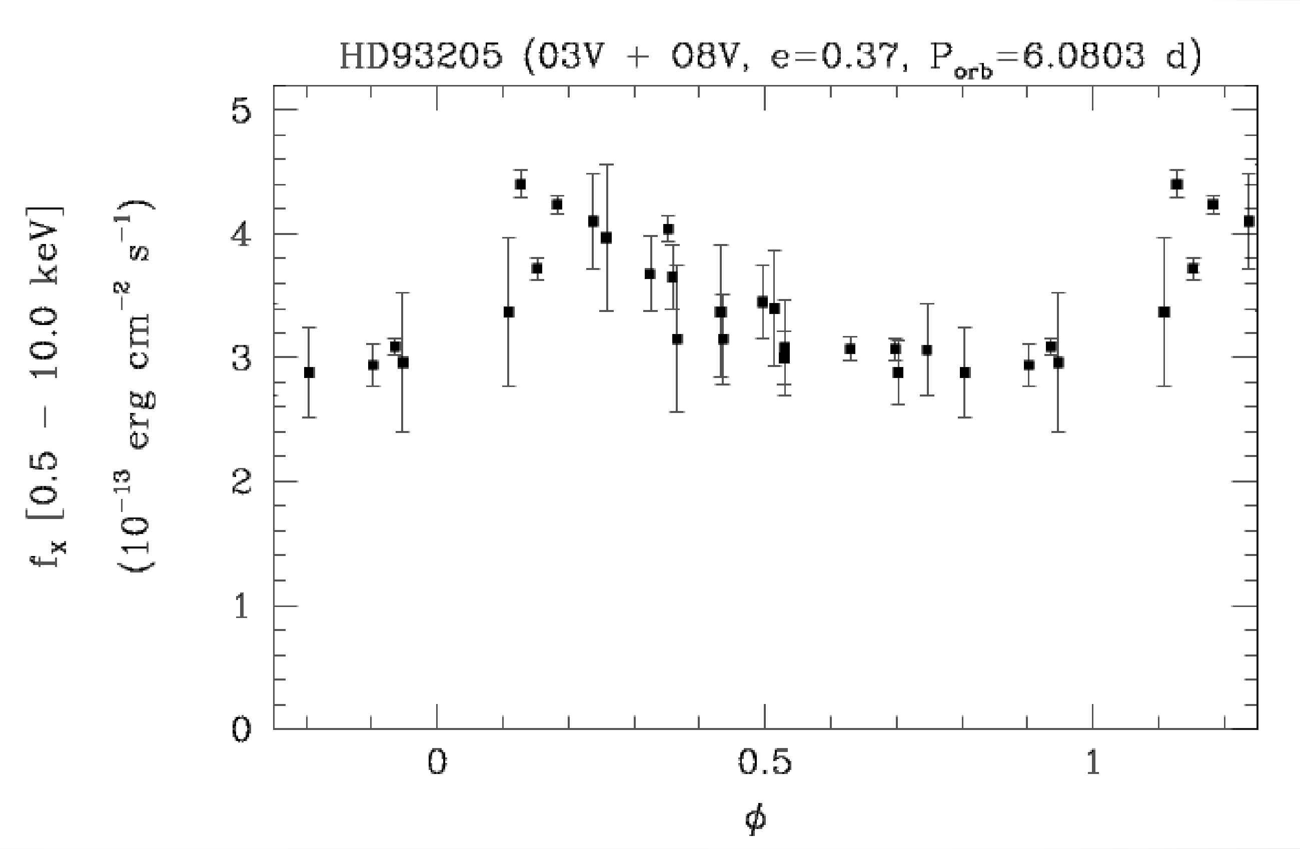


Not all short-period eccentric systems follow this description.

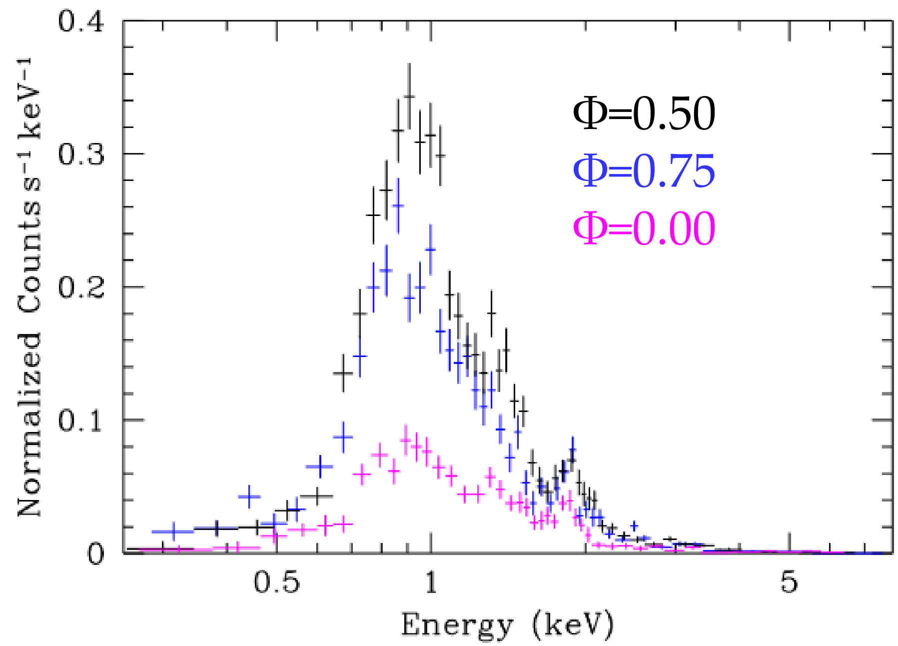
E.g., HD93205 (O3 V + O8 V, P = 6.08 d, e=0.37).

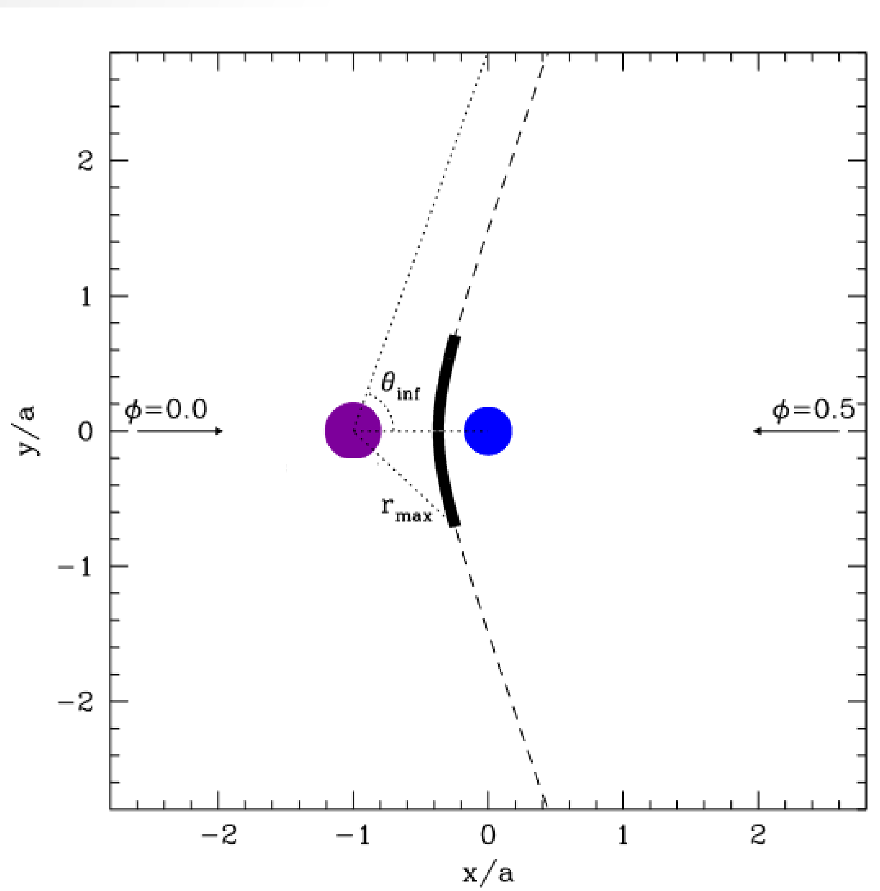
20 years of XMM-Newton data folded with ephemeris from Morrell+ (2001, MNRAS 326): maximum after periastron!

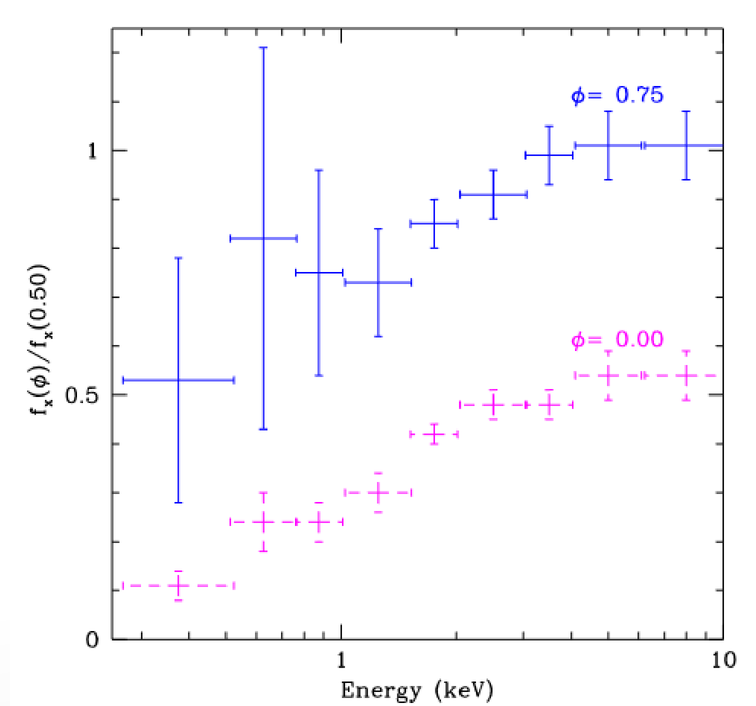
Still need to account for apsidal motion (1.95°/yr)… (see also talk by Sophie Rosu, later today).



X-ray spectral variations can be used to probe the properties of stellar winds, e.g., HDE228766 (Of+/WN8ha + O7 III-I, P=10.7 d, Rauw+ 2014, A&A 566).



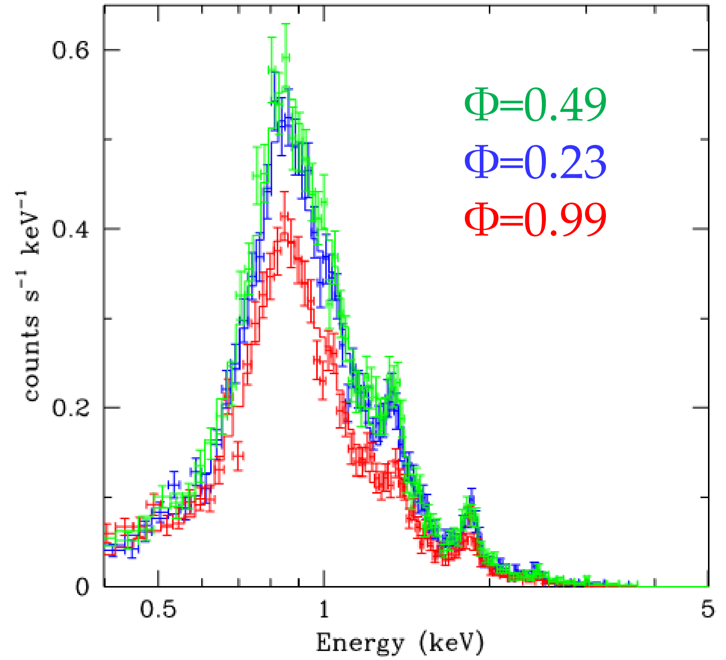


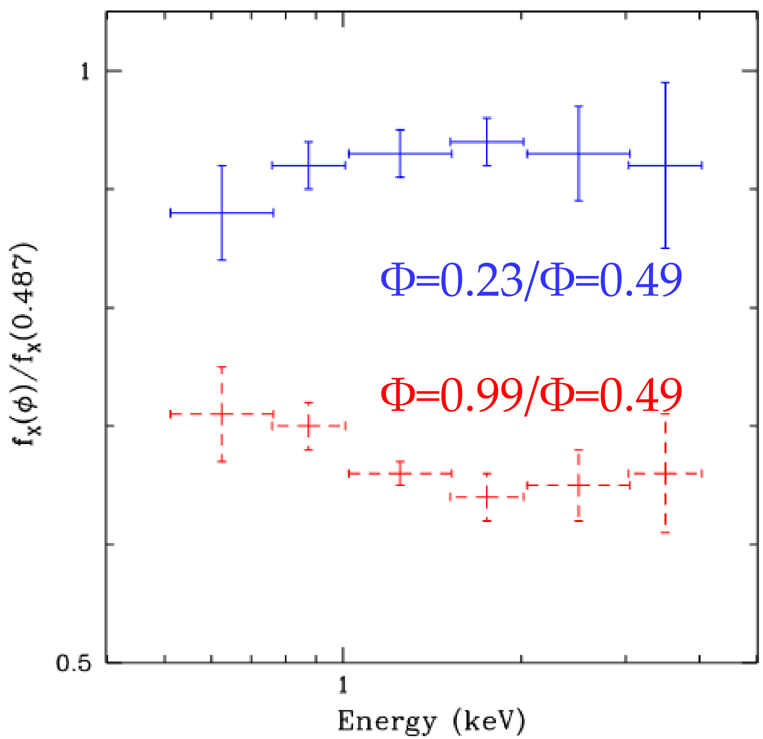


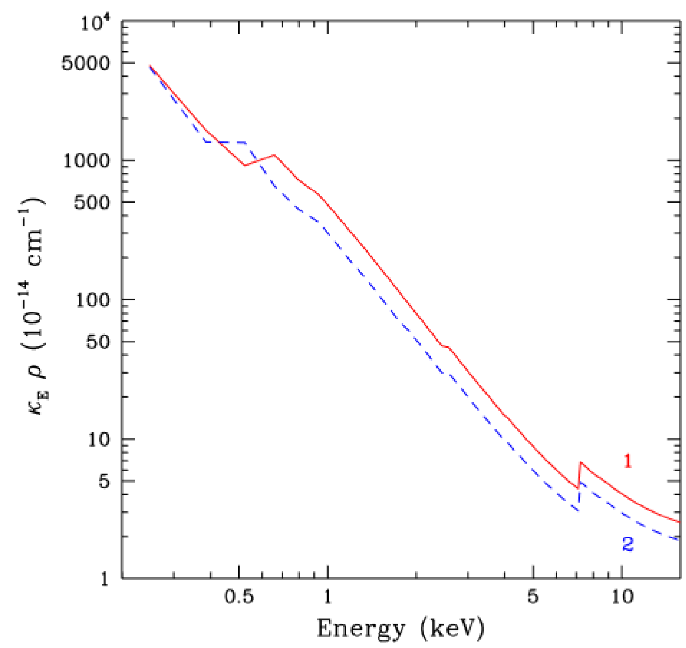
More complicated situation found for HD149404 (O7.5 I(f) + ON9.7, P=9.8 d, Rauw+ 2024, A&A 686):

lower amplitude variations without clear energy-dependence.

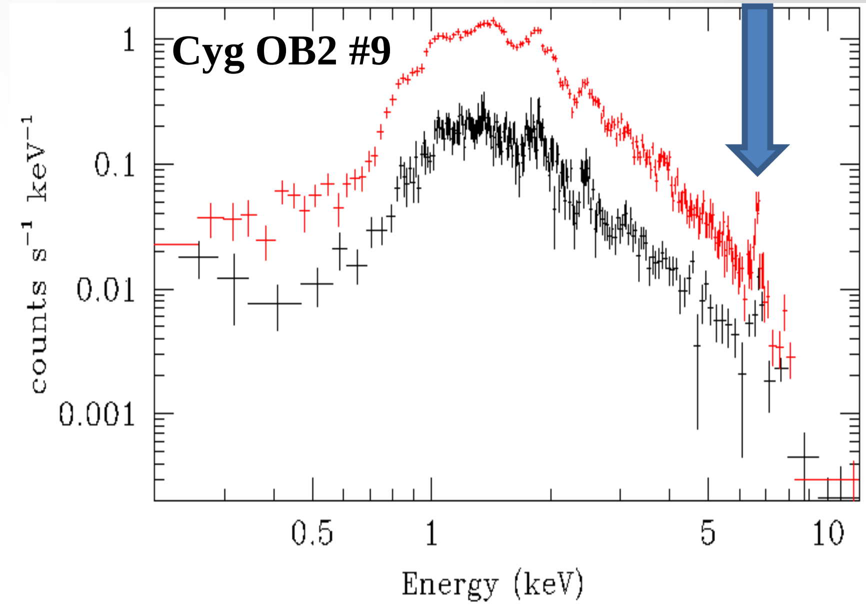
Evidence for optically thick clumps?

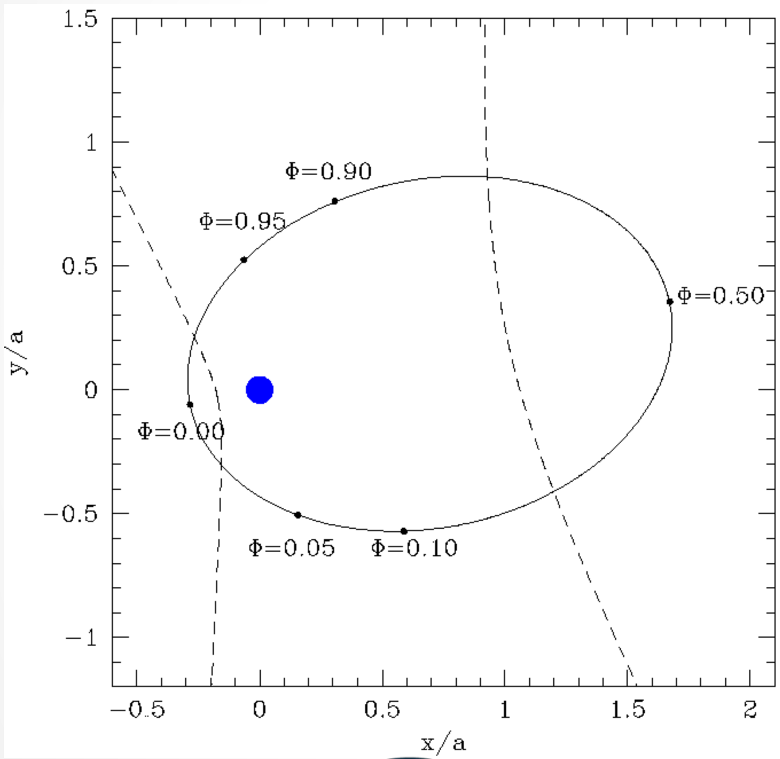


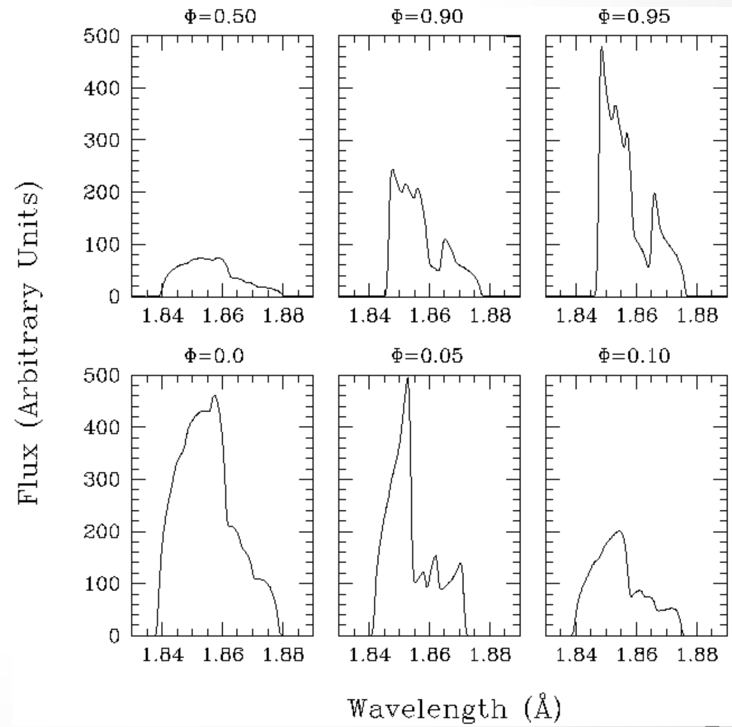




Some CWBs exhibit a strong Fe xxv line @ 6.7 keV formed in the wind interaction zone → ideal targets for high-res spectroscopy with X-IFU on Athena (Rauw + 2016, New Astronomy 43).







Conclusions

The wealth of XMM-Newton and Chandra observations of massive binaries has considerably changed our understanding of wind-wind collisions:

- the majority of CWBs are not X-ray overluminous,
- wide eccentric systems with adiabatic wind interactions follow a 1/r dependence as expected,
- shorter period eccentric systems switch between adiabatic and radiative regimes, possibly with accretion at periastron,
- hints of optically-thick clumps found in some systems, whilst others show no evidence of this kind.

More detailed studies will become possible with ESA's next X-ray observatory Athena.