The origin of the powerful jets from Cyg X-3 in the soft spectral state

With Denys Malyshev, Guillaume Dubus, Xinwu Cao, Masha Chernyakova ...

Cyg X-3 – a puzzling microquasar

- A very luminous radio and X-ray source, Wolf-Rayet + either a low-mass BH or NS; a very short (for HMXBs) $P = 4.8$h, $L/L_{\rm Edd}$ up to ~1.
- A likely BH–BH or BH-NS progenitor and merger candidate.
- A hard state with a radio/X-ray correlation similar to BH binaries.
- Major radio flares ($\lesssim$20 Jy) and strong γ-ray emission in the soft, disc dominated state, unlike the jet quenching in BH LMXBs, but similar to luminous blazars.

High-energy γ-rays from Cyg X-3

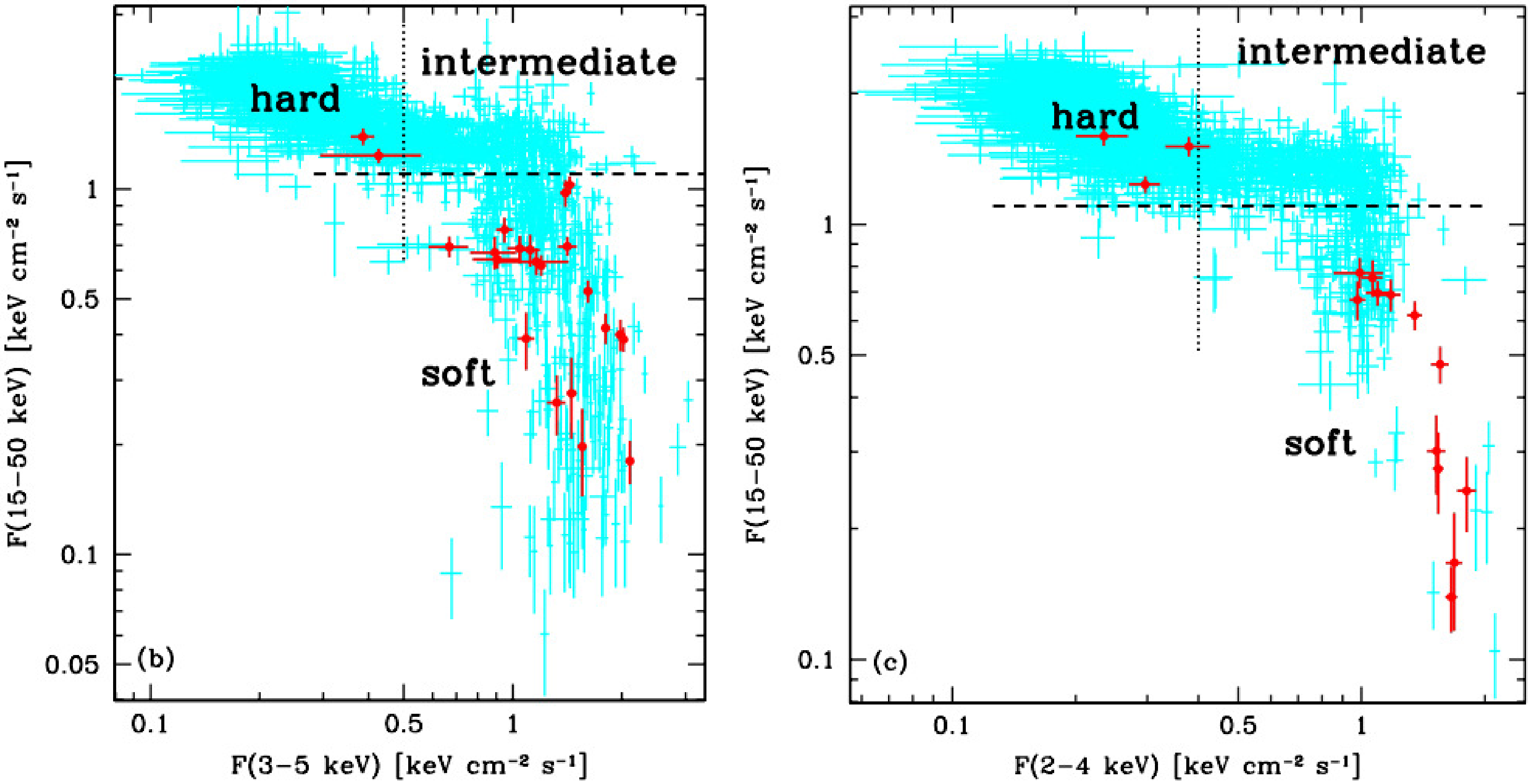
First detections by Abdo+09, Tavani+09.

AAZ+2018: a comprehensive study of γ-ray and radio emission during the lifetime of *Fermi*
Cao & AAZ 2020 – a magnetic advection model explaining the uniqueness of Cyg X-3

The high-energy γ-ray emission takes place mostly during the soft spectral state

The γ-ray flares shown in red

BAT



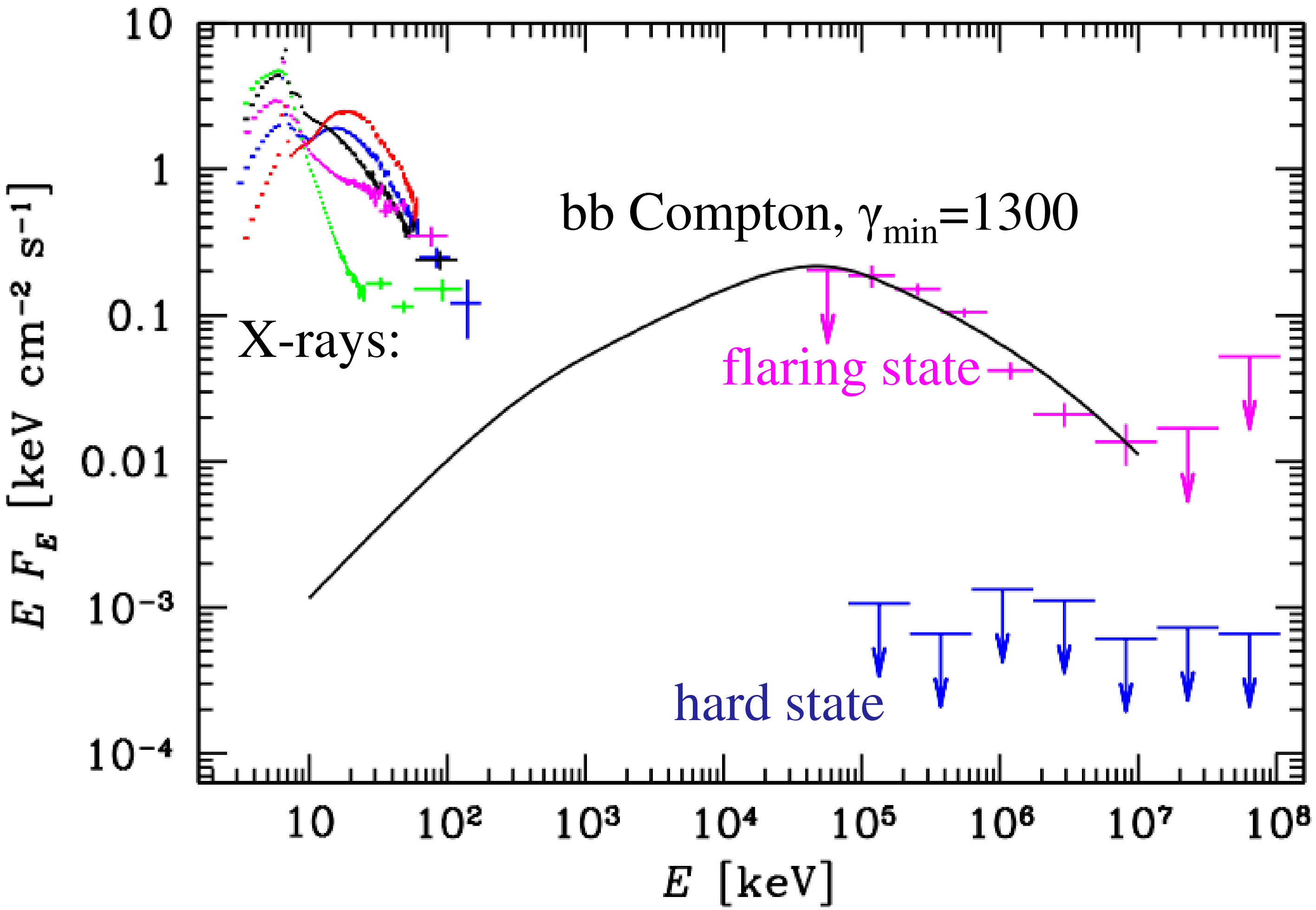
RXTE ASM

MAXI

The LAT γ-ray spectra and upper limits

Modelling the data: $N(\gamma) \propto \gamma^{-3.5}$, acceleration above $1500 \gtrsim \gamma_{min} \gtrsim 500$, electron acceleration with the index $\Gamma \approx 2.5$, Compton scattering of the donor blackbody photons.

Only upper limits in the intermediate and hard states.

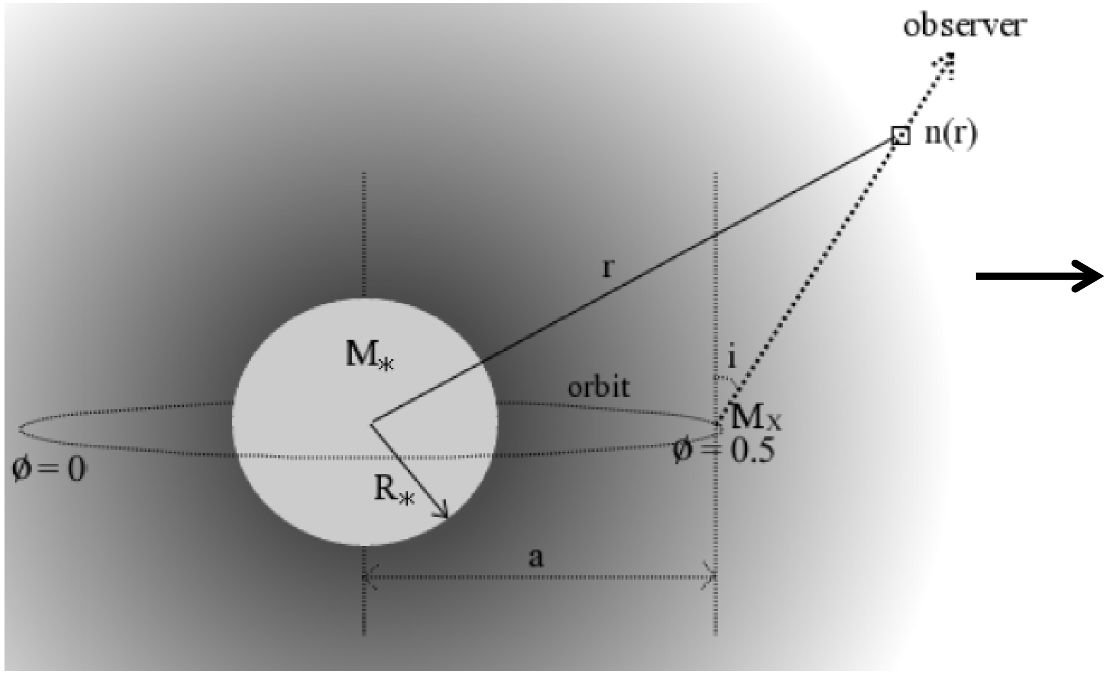


AAZ+ 2012, 2018

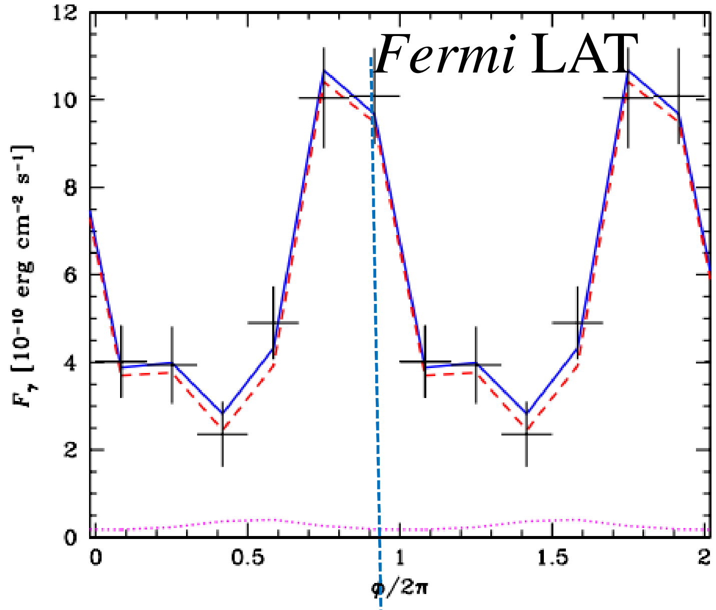
γ-ray modulation at the orbital period

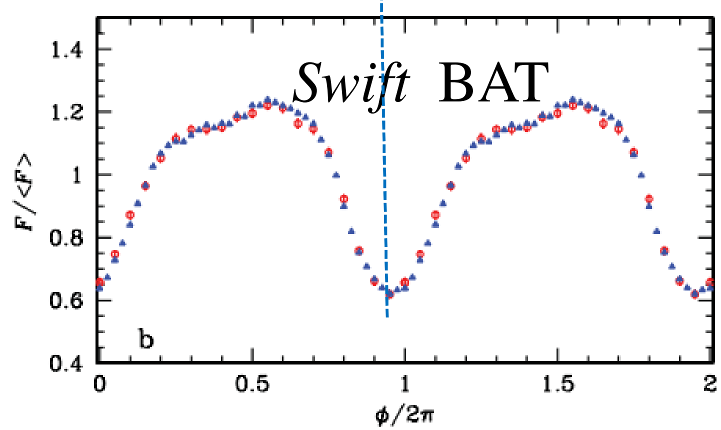
Orbital modulation of γ-rays during the flaring periods.
The γ-rays have the ***maximum*** close to the superior conjunction.

X-rays undergo wind absorption, thus their ***minimum*** *F* is at the superior conjunction (black hole behind the donor).



Folded lightcurves

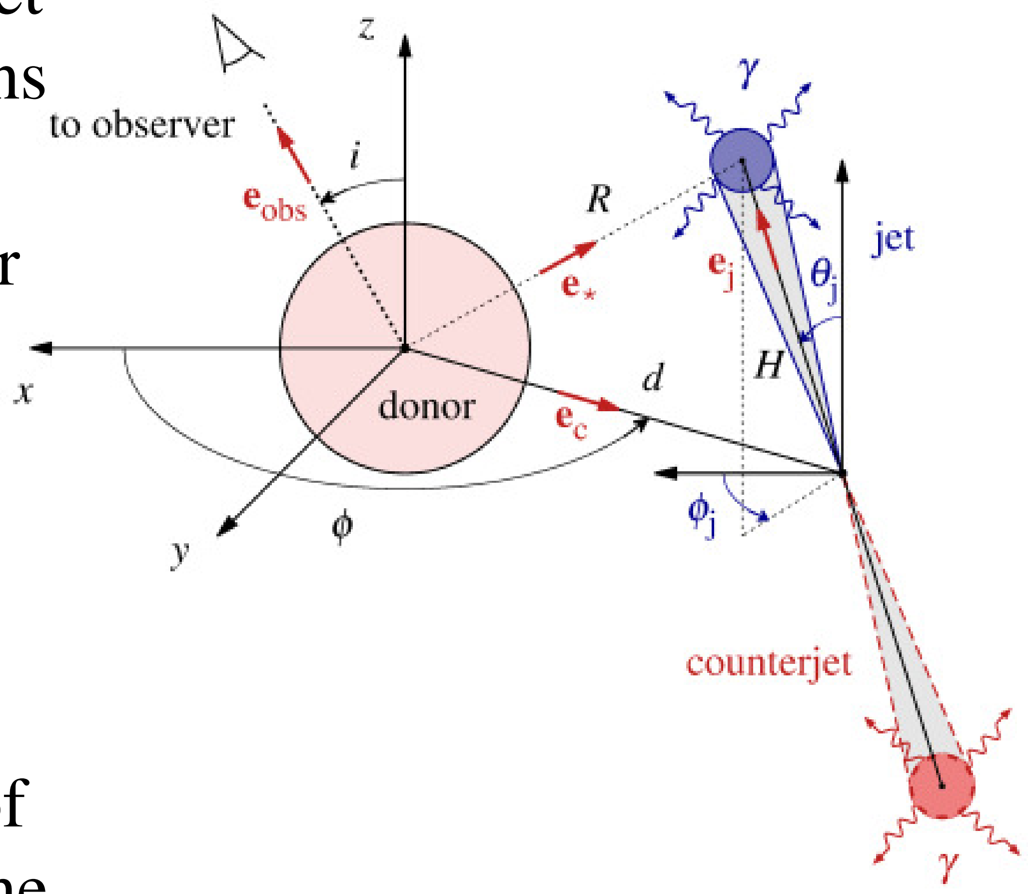




A model for the GeV emission

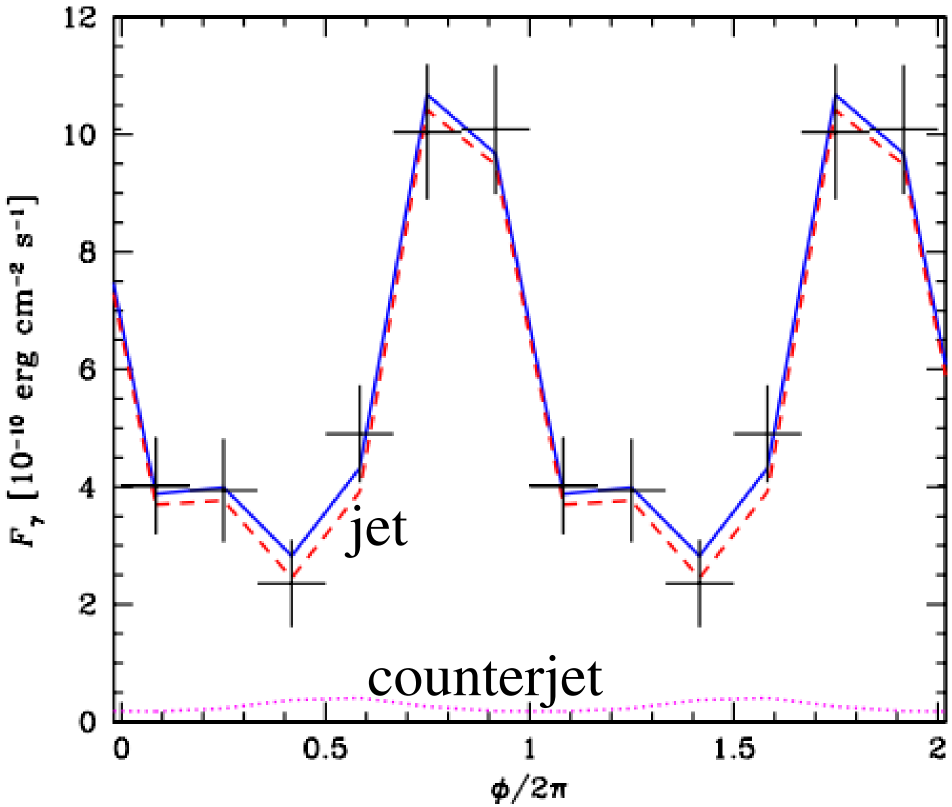
Compton scattering in the jet

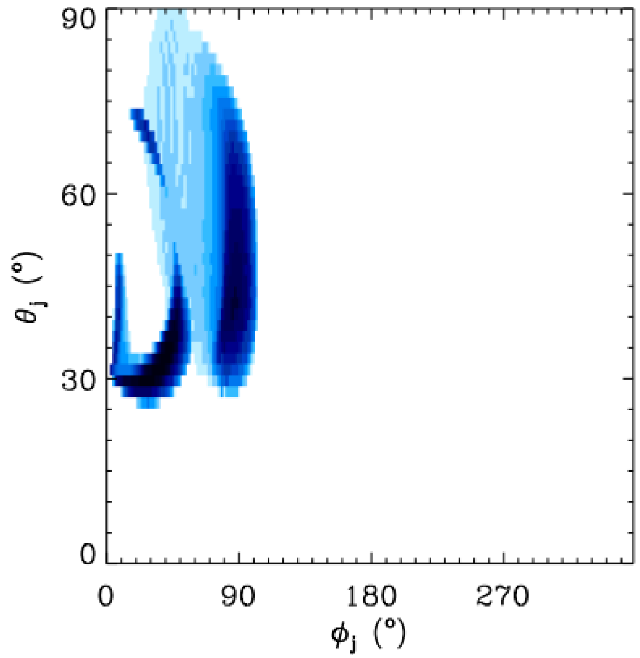
- The relativistic electrons in the jet Compton upscatter stellar photons to GeV energies.
- Highest scattering probability for electrons moving towards the stellar photons.
- Relativistic electrons emit along their direction of motion.
- Thus, most of the all emission is toward the star. The maximum of the observed emission is when the jet is behind the star.

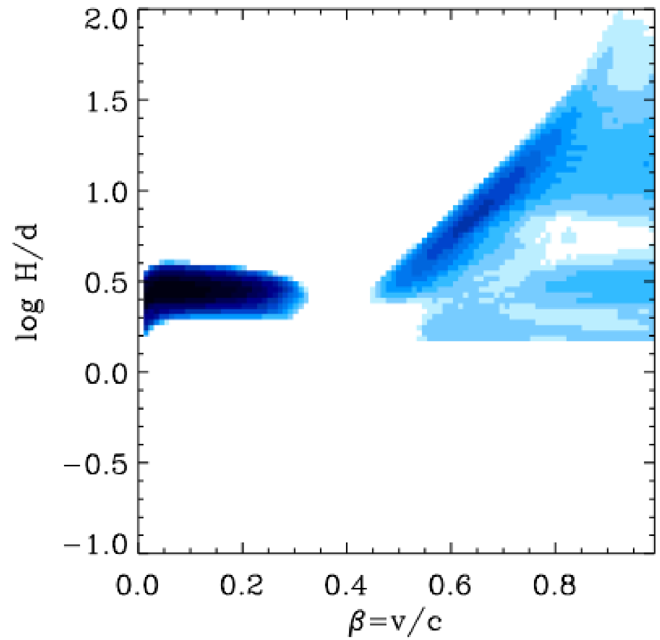


Dubus+10, AAZ+12, 18

Fit of this model to the folded γ-ray light curve





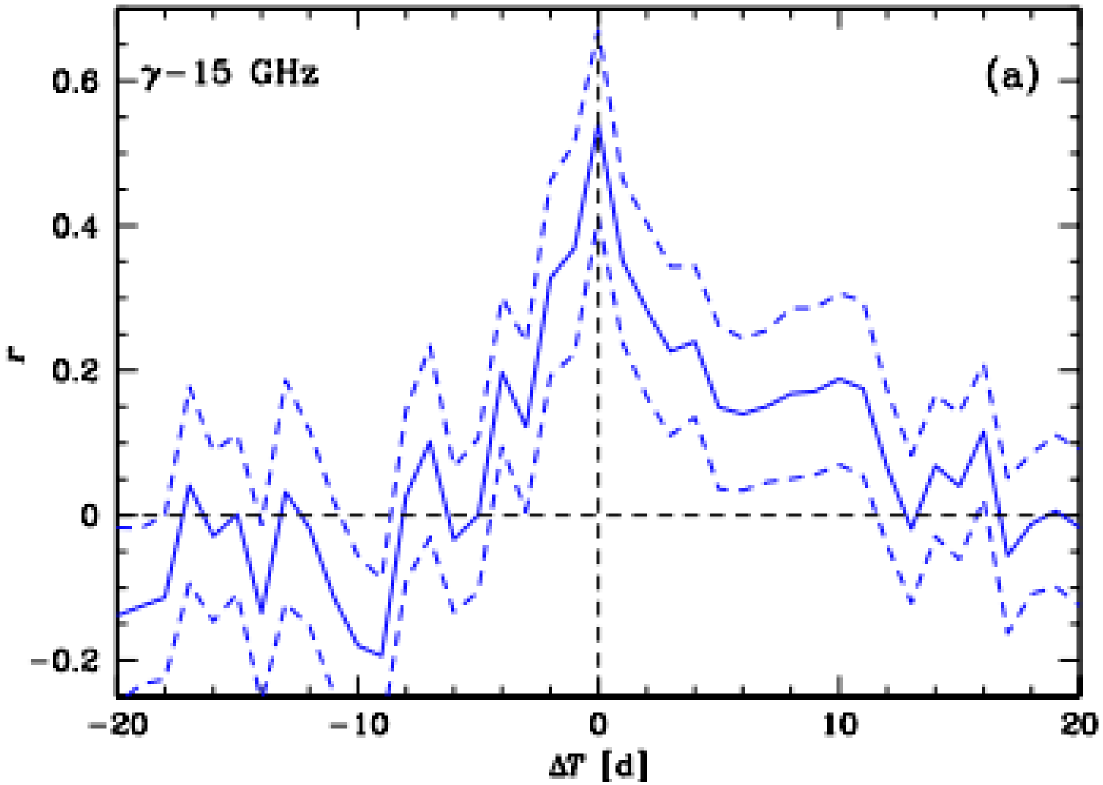


γ-ray emission region at ~(2–3)× stellar separation ~10^{12} cm~10^6 R_g. Jet inclined w/r the binary axis, θ≳30°, and relatively slow.

AAZ+18

Radio vs. γ-ray correlation

- A strong positive correlation at zero lag between GeV γ-rays and radio.

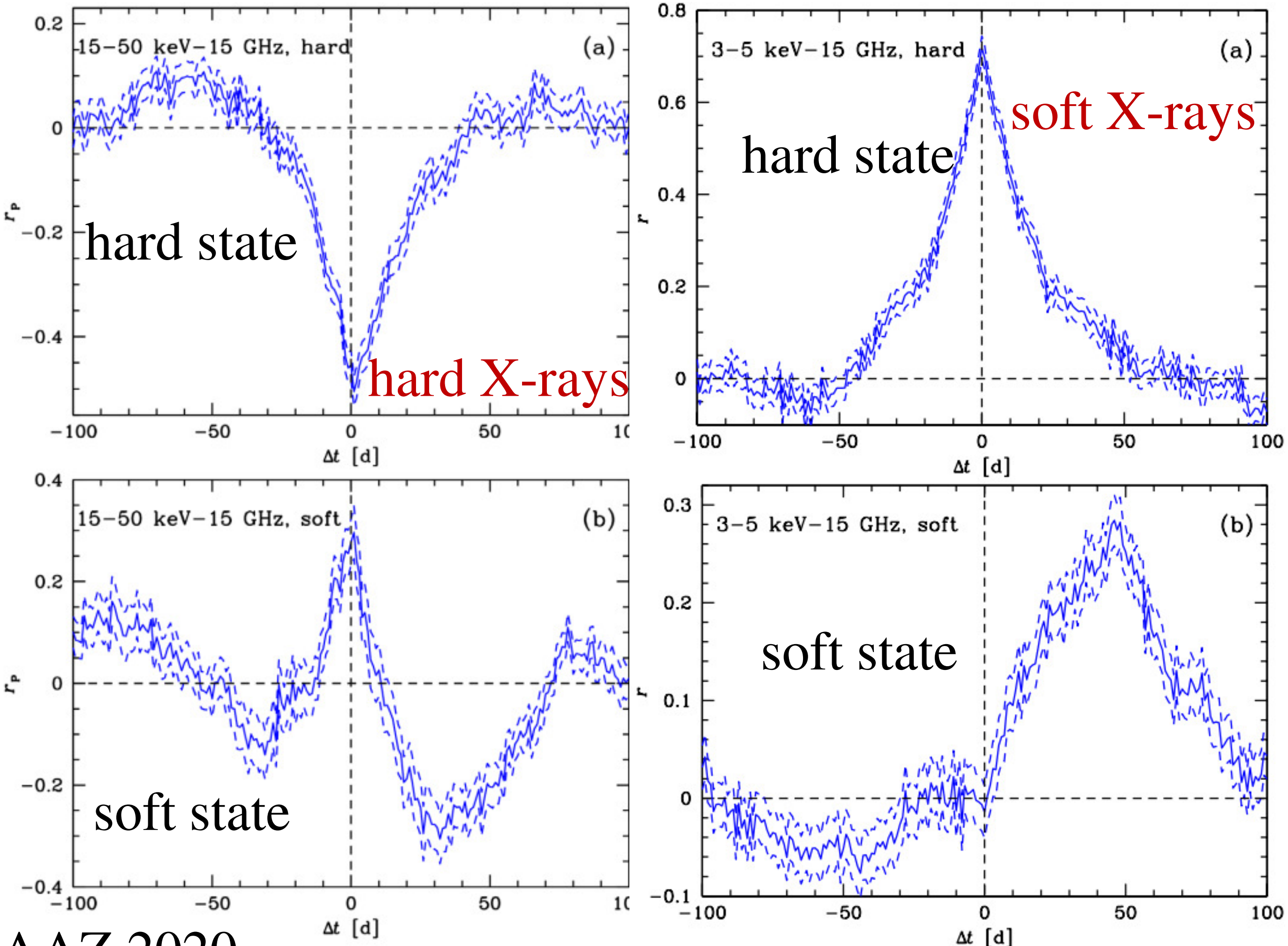


Radio/X-ray correlations and time lags

- 15 GHz radio: no lag w/r to soft X-rays in the hard spectral state, but a highly significant 45–50 d lag in the soft state.
- Hard X-rays: zero-lag positive/negative correlation in the soft/hard state.

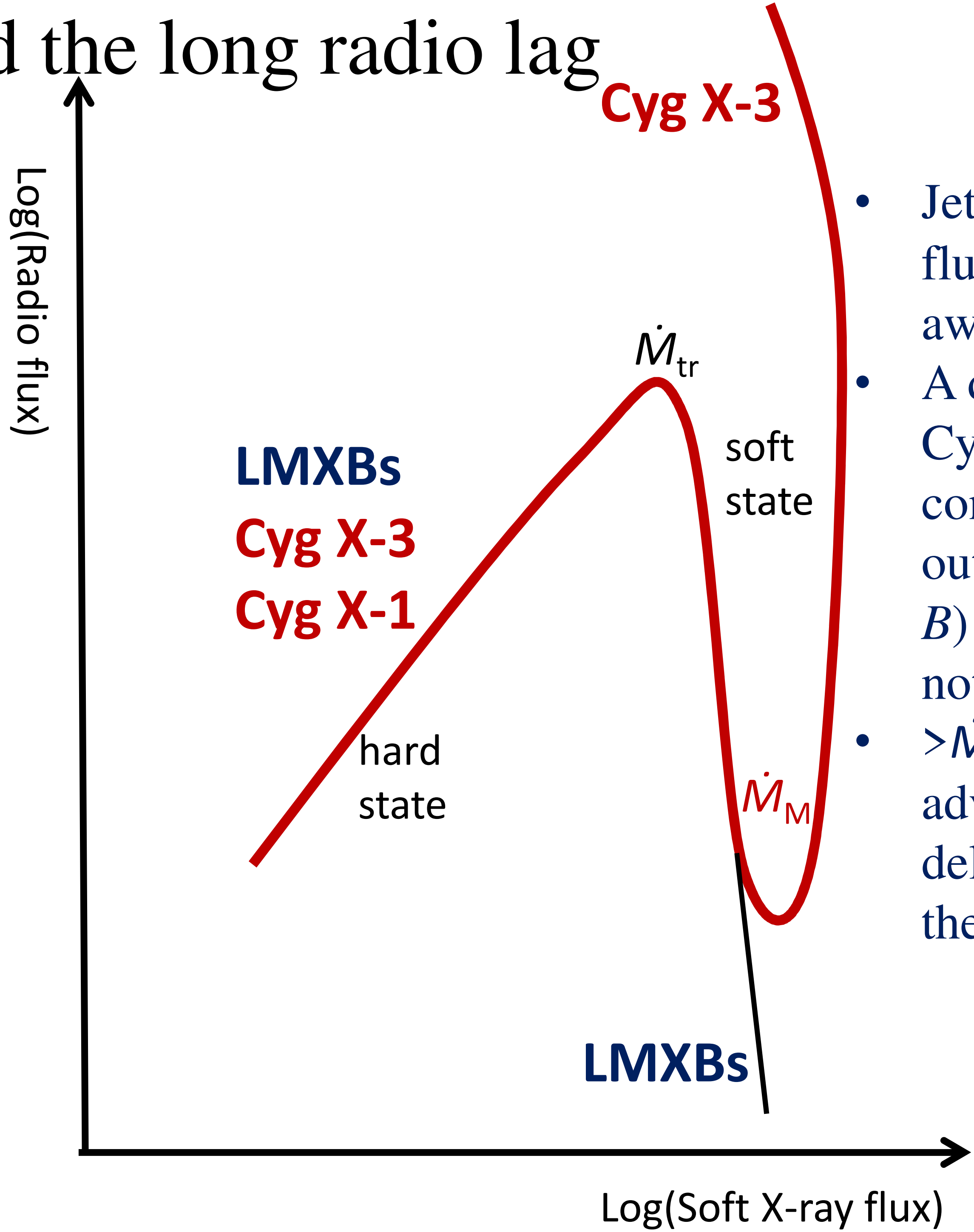
Hard state: pivot energy of a single spectrum at ~10 keV. The jet coupled to the hard X-ray emitting hot corona/flow in all states.

Soft state: different origins of the hard and soft X-rays.



AAZ+2018, Cao & AAZ 2020

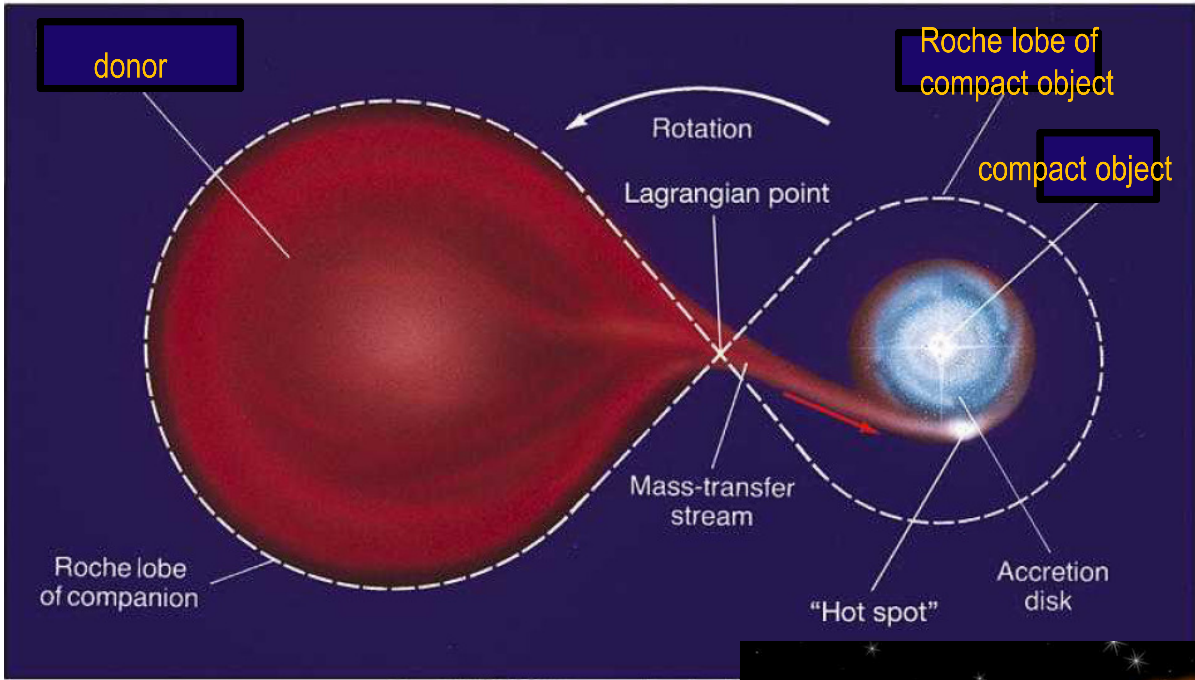
An explanation of the powerful soft-state emission and the long radio lag



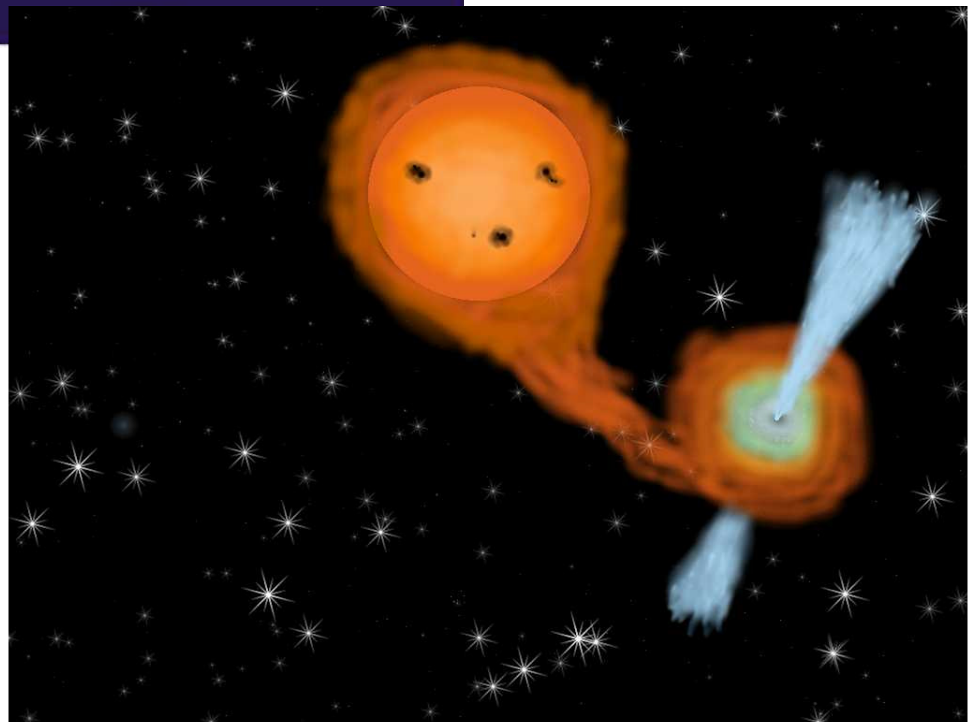
- Jet quenching at $\dot{M}_{tr}$: magnetic flux of the hard state diffusing away in a thin disc.
- A delayed powerful jet only in Cyg X-3 because a threshold condition (disk magnetic outflows above certain vertical *B*) being satisfied in Cyg X-3 but not in LMXBs:
- $>\dot{M}_M$: a large magnetic flux advected from the donor but delayed by the viscous time at the disk outer edge.

Cao & AAZ 20

- Magnetic flux, $B_{\perp}\times$area, advected only through the overflow region around the inner Lagrangian point, L_1, in LXMBs → weak advection of magnetic flux.



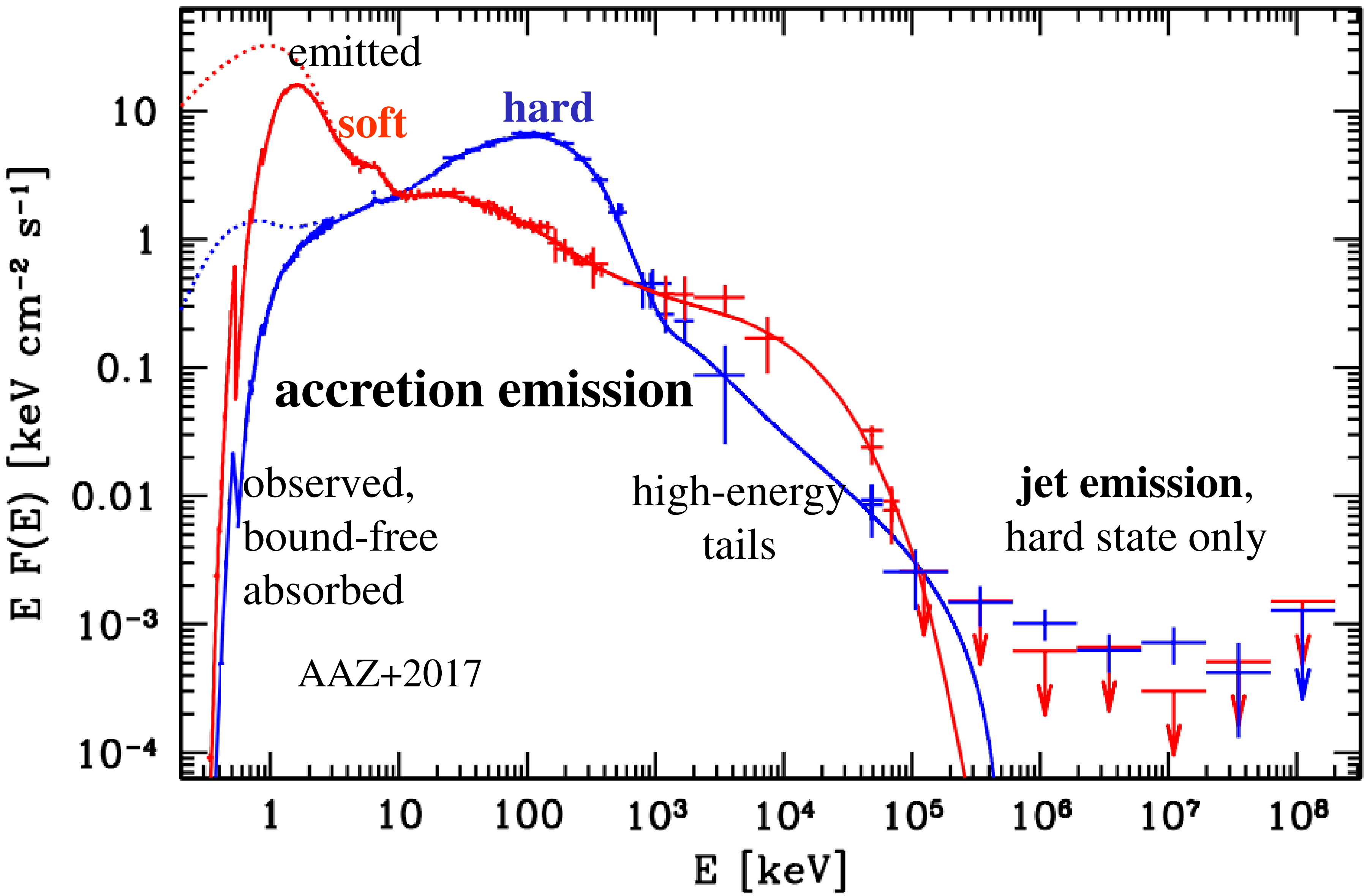
- A large fraction of the stellar surface can be tapped in wind-accretion binaries, like Cyg X-3.
- The flux-freezing condition: $B_{\perp}\Sigma =$ constant; Σ - the column density.
- A high $B_{\perp}$ can be thus achieved near the BH in HMXBs.



Conclusions

- Accurate *Fermi* LAT measurements of the spectra and orbital modulation of high-energy γ-rays.
- The jet is launched close to BH but it propagates without radiating up to R~10^6 R_g. Acceleration of power-law electrons above γ_{min}~10^3, which Compton-upscatter the stellar radiation, forming the orbitally-modulated γ-rays.
- The jet is inclined by $\theta \gtrsim 30°$ with respect to the binary axis.
- Discovery of a ~50 d lag of radio emission vs. soft X-rays.
- Interpreted as delayed appearance of magnetic flux advection from the donor above some threshold $\dot{M}$, above which magnetic outflows from the disk can take place.
- The lag time scale is the viscous time scale at the disc outer edge.

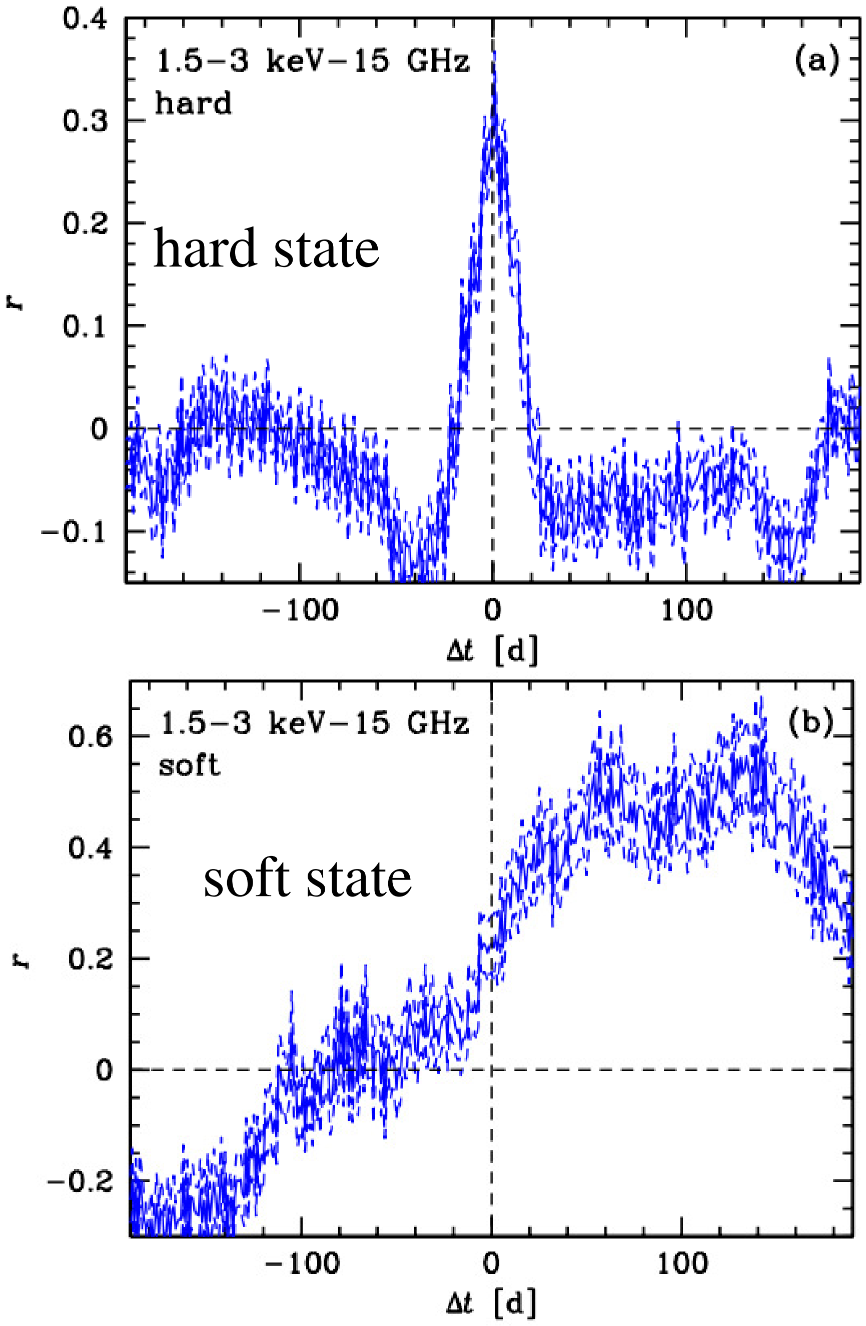
Comparison with the HMXB **Cyg X-1** – the γ-ray emission only in the hard state, weaker w/r to X-rays than in the soft state of Cyg X-3 by ~10^3



Cyg X-1

Correlations with soft X-rays: zero lag in the hard state, ~50–150 d lag in the soft state. Similar to Cyg X-3, but no strong radio flares and γ-ray emission in the soft state. Much lower L/L_{Edd}~0.03.

AAZ, Shapopi & Pooley 2020



Different origin of the soft and hard X-rays