The jet emission in Cyg X-3

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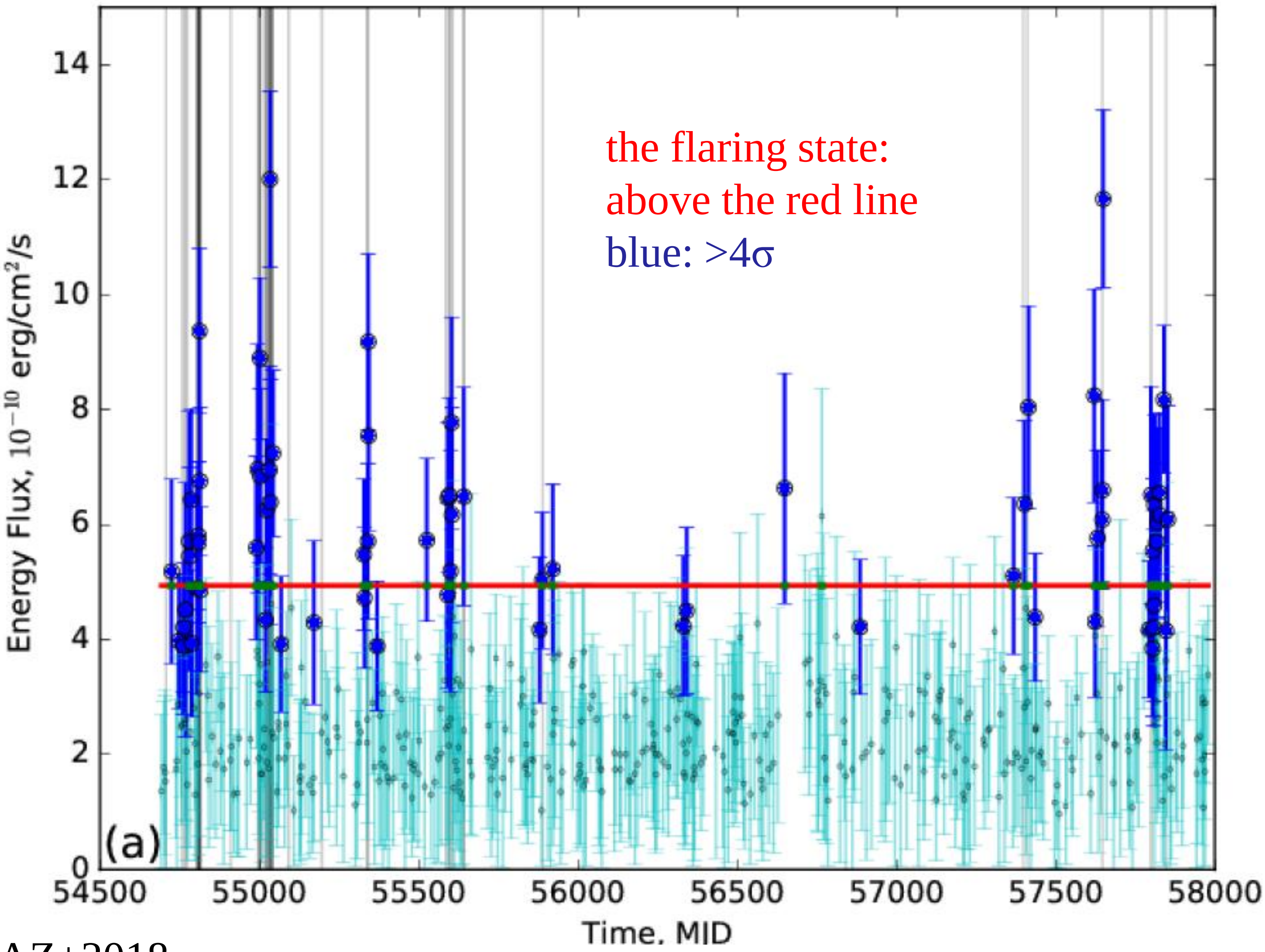
Cyg X-3 – a puzzling microquasar

- A very luminous radio and X-ray source, Wolf-Rayet + a compact object; a very short (for HMXBs) period of 4.8h.
- Compact object: either a low-mass BH (more likely) or NS.
- A likely BH–BH or BH-NS progenitor and merger candidate.
- X-ray spectral states similar to those of BH binaries.
- Major radio flares ($\lesssim$20 Jy) and strong γ-ray emission in the soft state, unlike the jet quenching in the soft state of BH binaries but similar to luminous blazars.
- One of two accreting X-ray binaries with emission at >0.1 GeV detected at high significance (by *Fermi*; Abdo+09, and *AGILE*, Tavani+09).

The γ-ray 0.1–100 GeV light curve

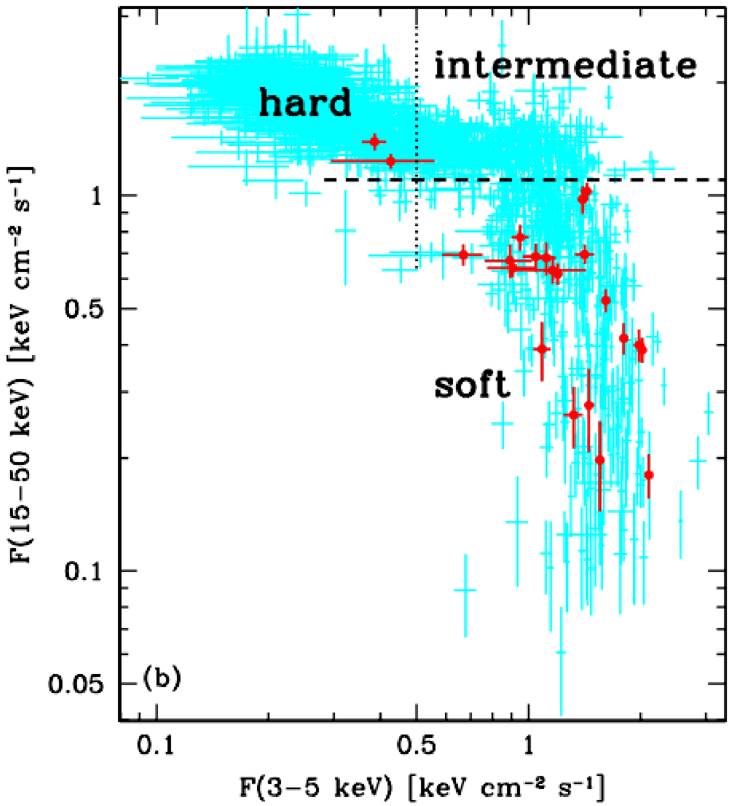


AAZ+2018

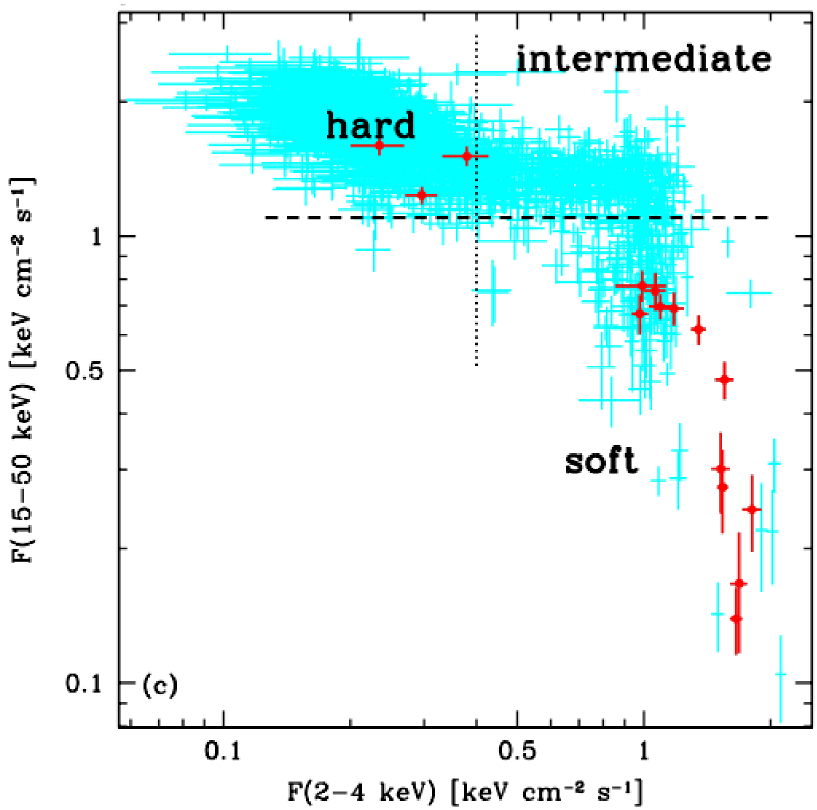
The high-energy γ-ray emission takes place mostly during the soft spectral state

The γ-ray flares shown in red

BAT



RXTE ASM

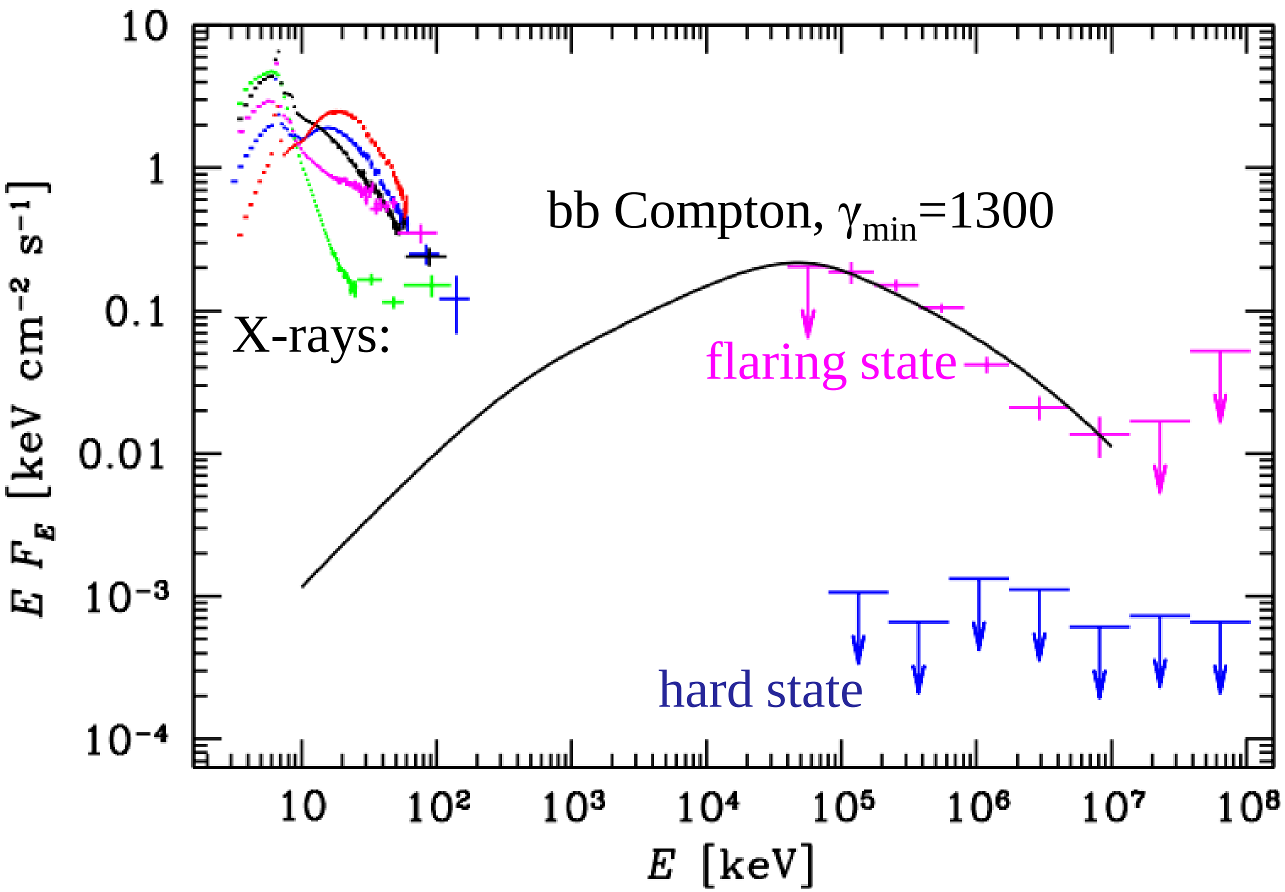


MAXI

The LAT γ-ray spectra and upper limits

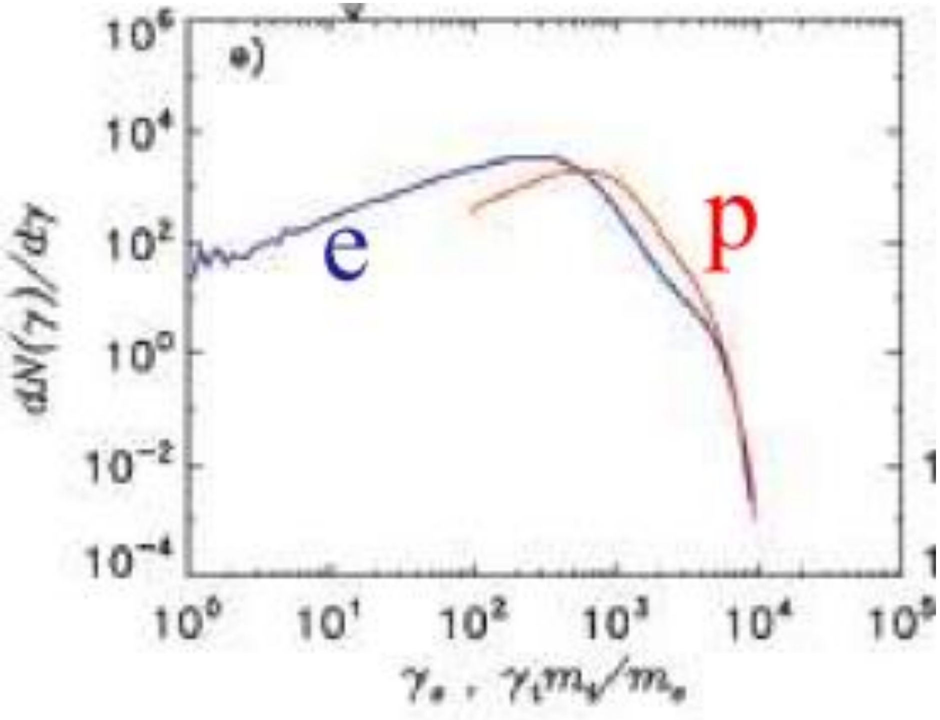
Modelling the data: $N(\gamma) \propto \gamma^{-3.5}$, acceleration above $1500 \gtrsim \gamma_{\rm min} \gtrsim 500$, electron acceleration with the index $\Gamma \approx 2.5$, Compton scattering of the donor blackbody photons.

Only upper limits in the intermediate and hard states.



AAZ+ 2012, 2018

Why a large γ_{min}?



Related to m_p/m_e: A quasi-Maxwellian electron distribution forms with the average energy of the order of the proton rest mass; acceleration only out of this distribution.

Spitkovsky 2008; Riquelme & Spitkovsky 2011; Sironi & Spitkovsky 2011

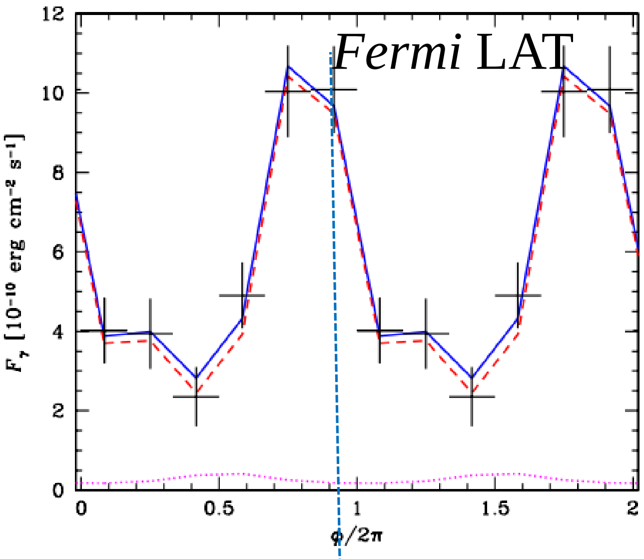
$$\gamma_{min} \sim m_p/m_e$$

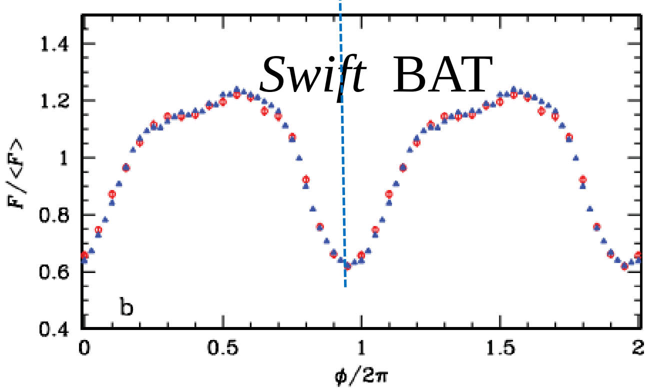
γ-ray modulation at the orbital period

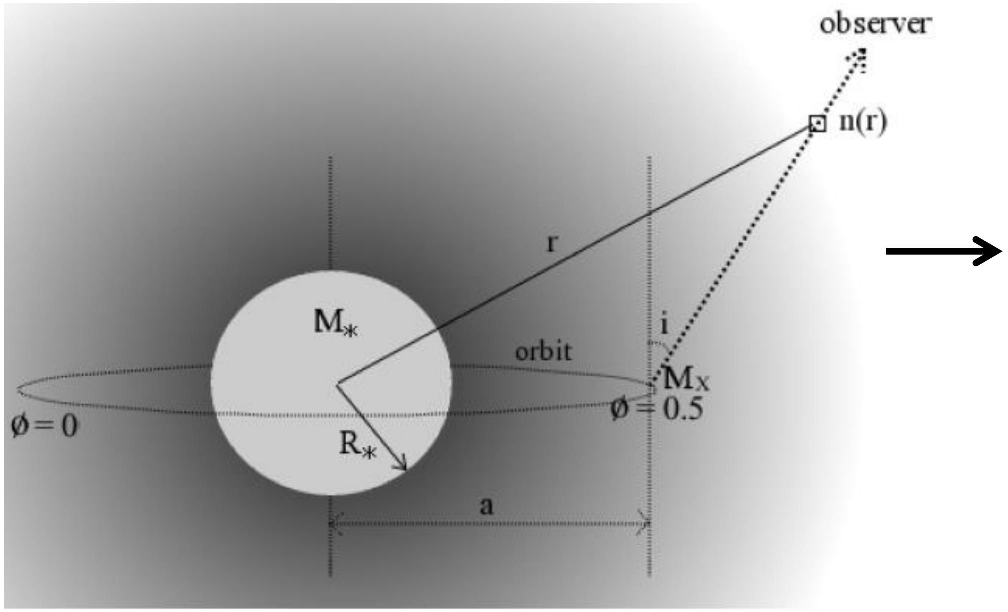
Orbital modulation of γ-rays during the flaring periods.
The γ-rays have the ***maximum*** close to the superior conjunction.

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

Folded lightcurves



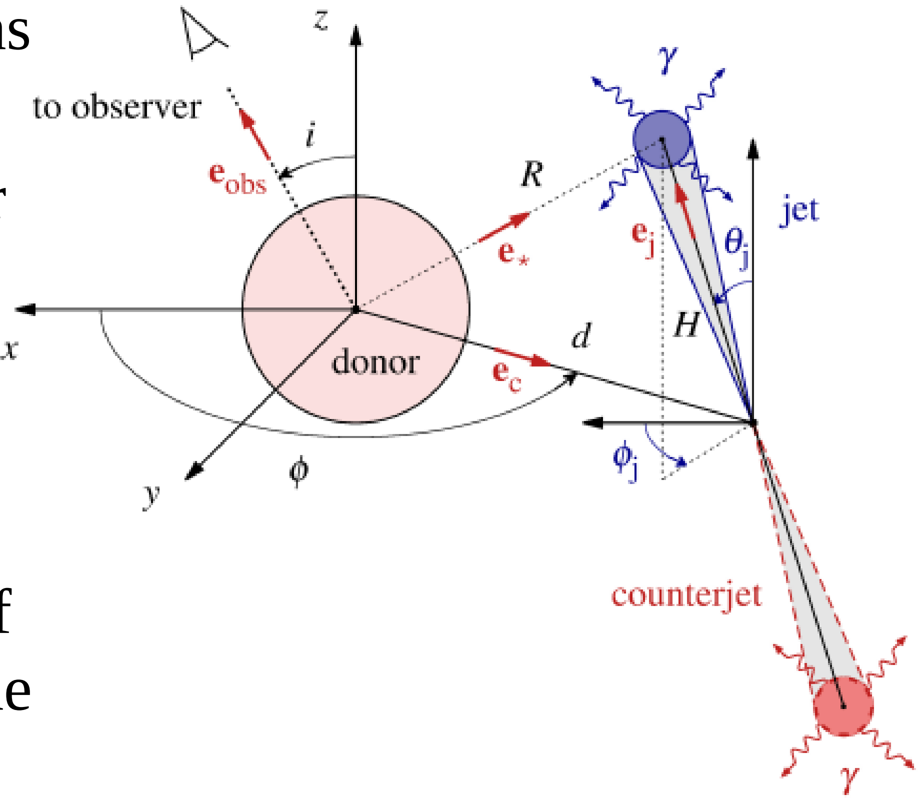




A model for the GeV emission

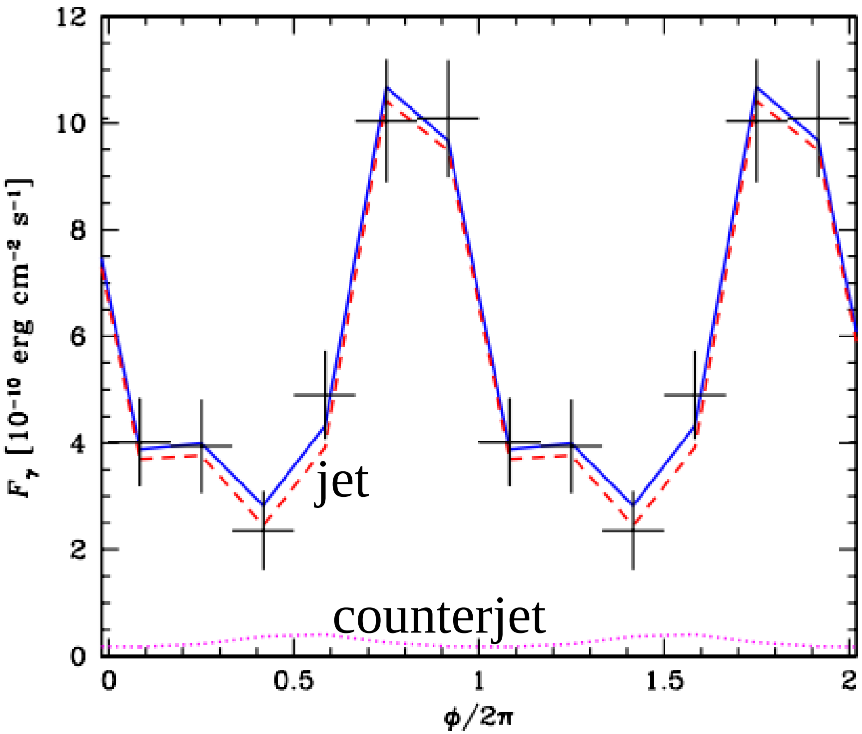
Compton scattering in the jet

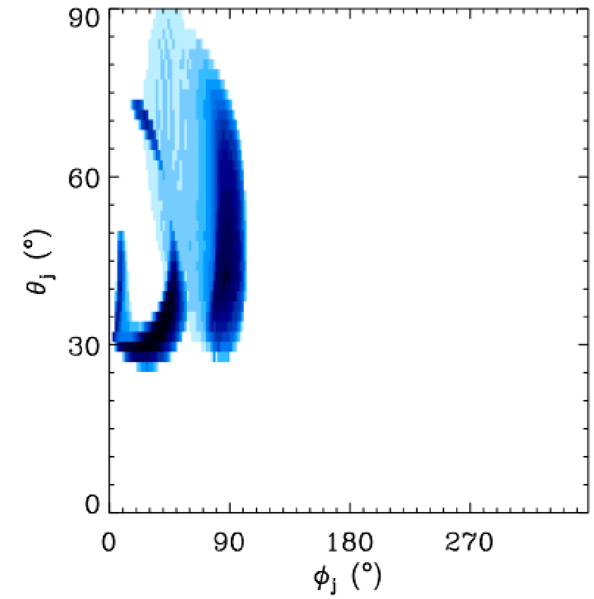
- The relativistic electrons jet Compton upscatter stellar photons to GeV energies.
- Highest scattering probability for head-on collisions with photons.
- Relativistic electrons emit along their direction of motion.
- Thus, most of the all emission is toward the star. The maximum of the observed emission is when the jet is behind the star.
- Hadronic models ruled out.

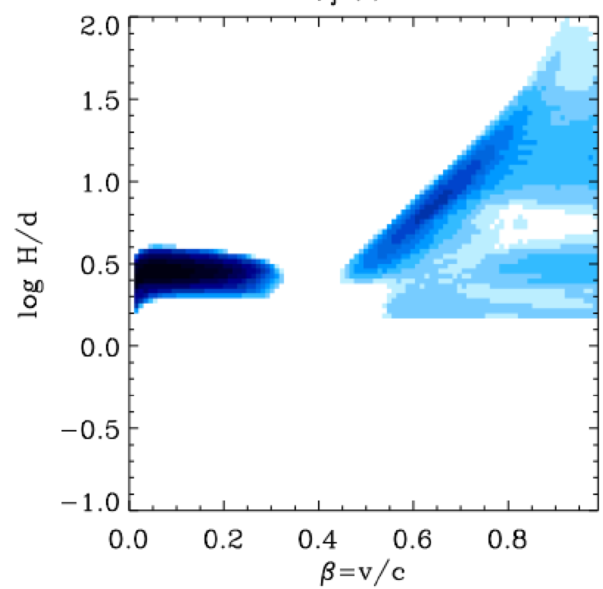


Dubus+10, AAZ+12, AAZ+18, 18

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.

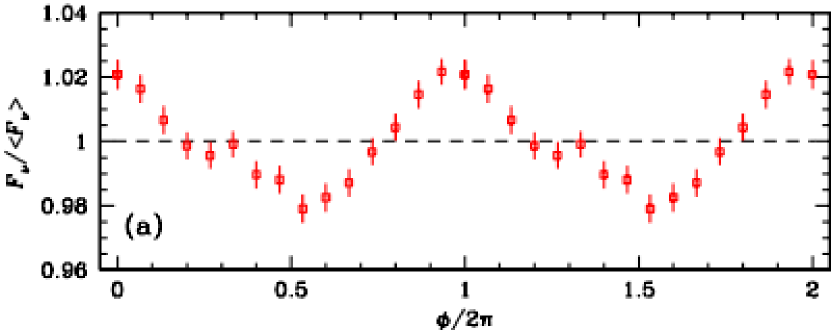
AAZ+18

Constraints on the γ-ray emitting region

- The dissipation region located at $\sim 10^{12}$ cm, as determined from the orbital modulation.
- The initial bulk Lorentz factor of $\Gamma \sim 2.5$ (from the γ-ray power) is reduced to $\Gamma \sim 1.2$ (from radio data).
- The jet kinetic power before deceleration is $\sim 10^{38}$ erg/s.
- The jet mass flow rate is several % of the accretion rate.
- The magnetic field $\ll$ equipartition, $B \lesssim 10^2$ G, implied by the maximum possible synchrotron contribution to the observed broad-band spectrum.

Orbital modulation of the radio emission in Cyg X-3

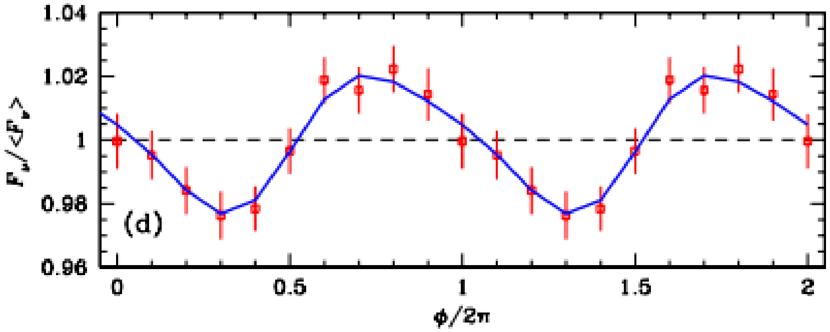
- We have discovered pronounced orbital modulation at 15 GHz.
- Due to free-free absorption in the wind of the donor, analogous to the X-ray modulation (due to bound-free absorption and Compton scattering).
- The observed strength and shape of the modulation strongly depend on the flux and spectral state. It is the strongest at the lowest radio fluxes.



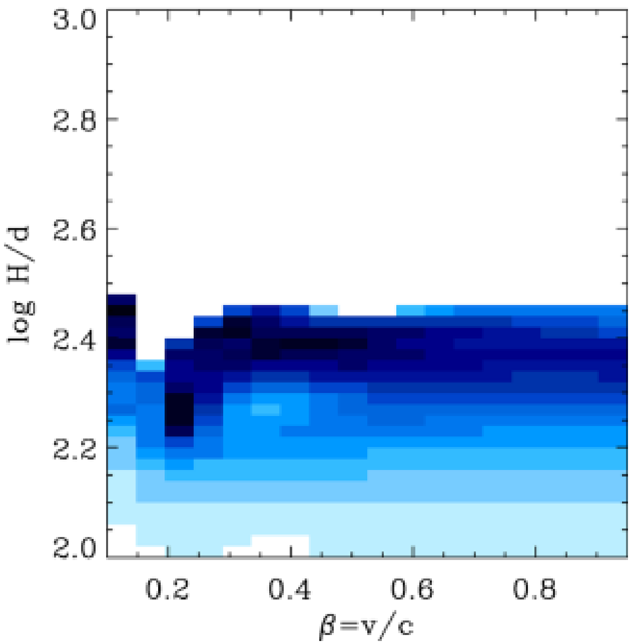
The entire data, 20 yr, 80000 measurements

AAZ+2018

Orbital modulation of the radio emission in Cyg X-3



The brightest part of the soft state, with a fit of the jet/wind model.

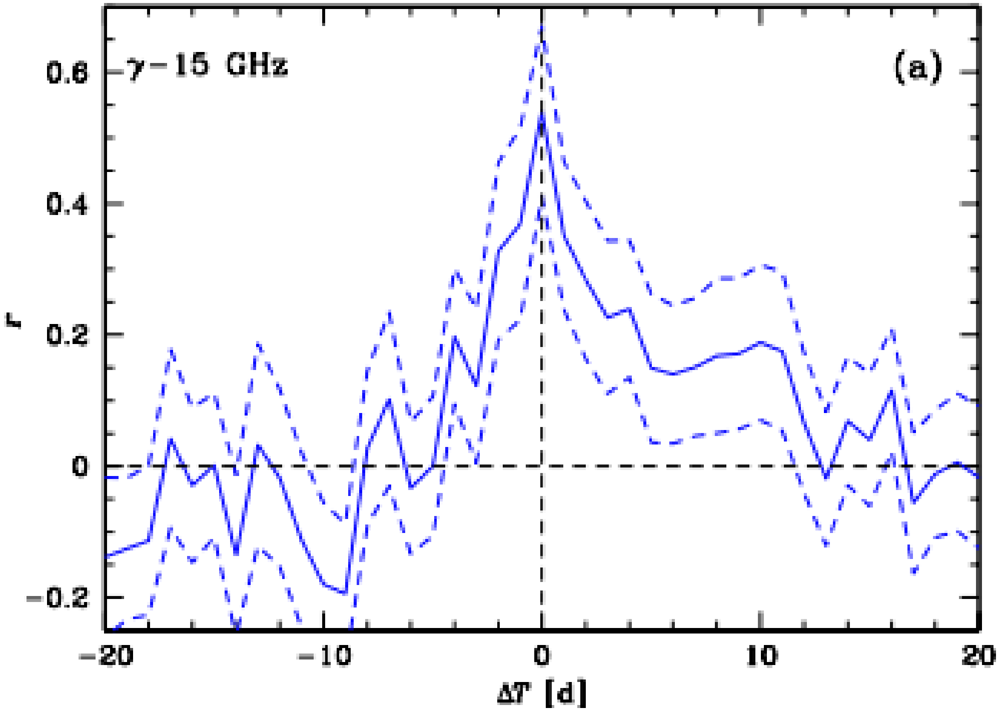


Modelling: the radio emitted at ~200 orbital separations.

AAZ+2018

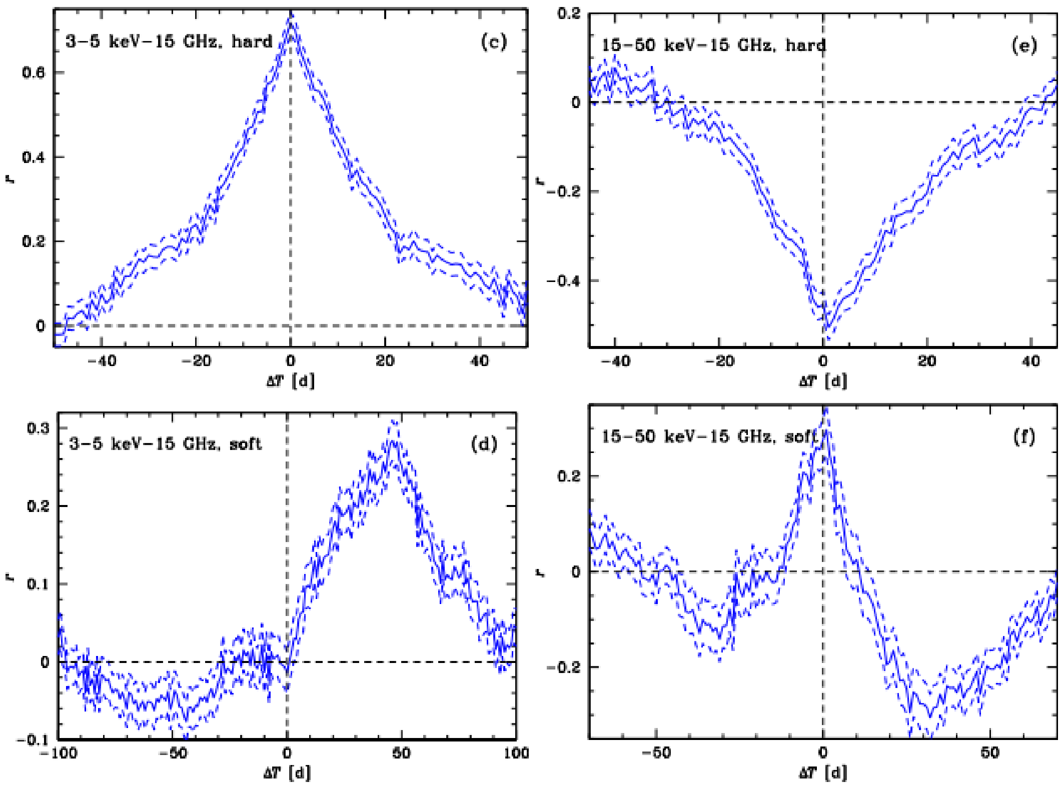
Correlations and time lags

- A strong positive correlation at a lag ≪1 d between GeV γ-rays and radio, but the asymmetry implies some radio lag.



Correlations and time lags

- 15 GHz radio: no lag w/r to soft X-rays in the hard spectral state, but a 45–50 d lag in the soft state.
- Corresponding anticorrelations with hard X-rays.
- The origin of the lags: probably the time needed for magnetic field accumulation in the disc.

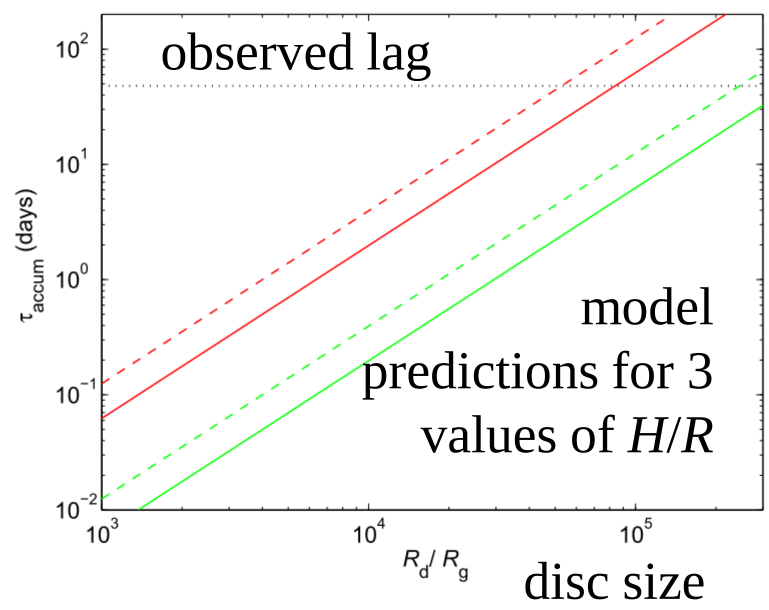


A model for the ~40–50-d lag of radio w/r to X-rays

- Advection of magnetic field from the companion in a disc: $\tau_{\rm adv} = \tau_{\rm dif}$ yields

$$\tau_{\rm accum} \approx 61\,{\rm d}\left(\frac{T_{\rm d}}{10^4\,{\rm K}}\right)^{1/2}\left(\frac{\mu}{4}\right)^{-1/2}\left(\frac{M_{\rm CO}}{10{\rm M}_\odot}\right)^{1/3}\left(\frac{\alpha}{0.1}\right)^{-1}\frac{P_{\rm m}}{2}\,\frac{\kappa_0}{\sqrt{3}}$$

Cao & AAZ 2019



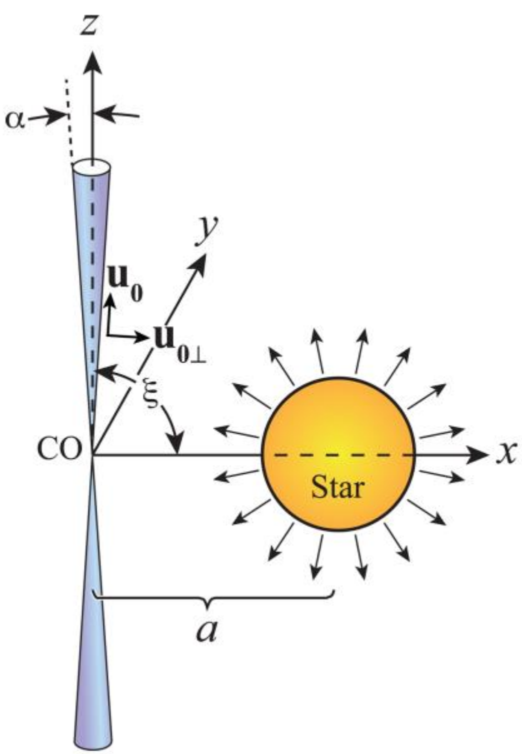
Is interaction of jets with stellar wind important?

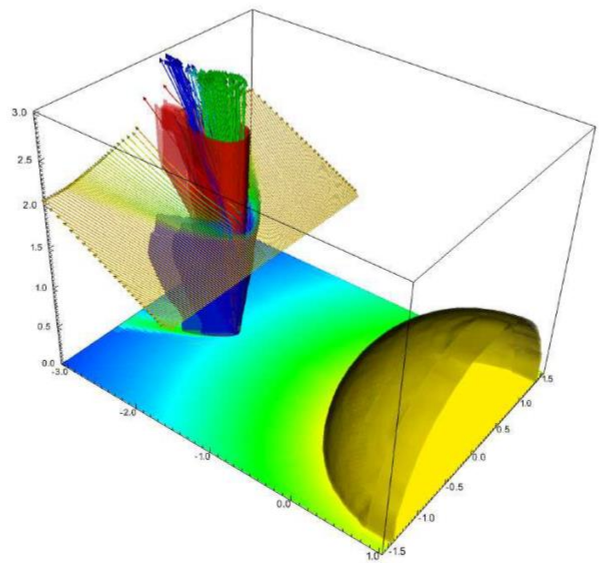
- Jets in binaries with massive donors move through a dense stellar wind; those with low-mass donors move in a low-density ISM.
- So far, the only two accreting binaries with discovered γ-ray emission are the HMXBs Cyg X-1 and Cyg X-3. The γ-ray emission appears to be dominated by jets.
- This points to the importance of either interaction with the stellar wind or Compton scattering of stellar blackbody photons or both.
- Models of jet-wind interaction: e.g., Perucho+2010, Yoon & Heinz 2015, Yoon, AAZ & Heinz 2016, Pjanka & Stone 2018.

Interaction of jets with stellar winds in high-mass X-ray binaries (Yoon, AAZ & Heinz 2016)

- Jets propagating in an external medium (ISM or stellar winds) form shocks, in particular recollimation shocks.
- In the case of a jet interacting with the stellar wind, we have found the existence of a critical jet power a recollimation shock is ***not formed***:

$$P_{\rm cr} \equiv \frac{1}{16}\dot{M}_{\rm w} v_{\rm w} v_{\rm j}.$$





Main conclusions

- Detailed *Fermi* LAT measurements of the spectra and orbital modulation of high-energy γ-rays.
- The jet launched close to BH, but it propagates not (or weakly) radiating up to R~10^6 R_g. Acceleration of power-law relativistic electrons above γ_{min}~10^3.
- The electrons Compton-upscatter the stellar radiation, forming the observed (orbitally modulated) γ-rays.
- The γ-ray emission is not hadronic.
- The jet kinetic power ~10^{38} erg/s ~L_X. The mass flow rate is several % of the accretion rate.
- Discovery of orbital modulation at 15 GHz, caused by free-free absorption in the wind.
- Discovery of a ~50 d lag of radio emission vs. soft X-rays in the soft state – advection of magnetic field.

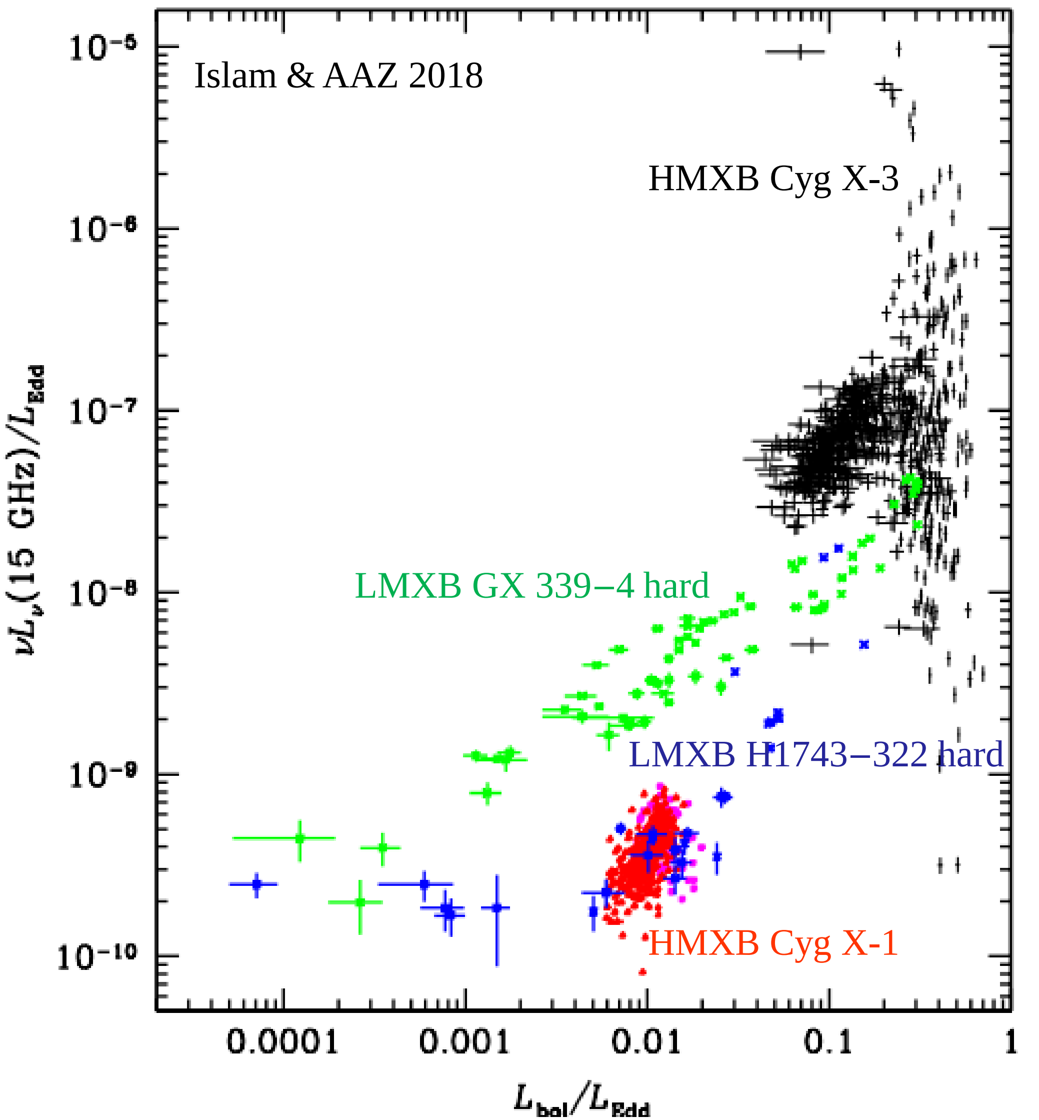
The discovered effect may explain the large difference in the radio loudness between Cyg X-1 and Cyg X-3:

GX 339−4: a LMXB on the radio-loud branch.

H1743−322: a LMXB on the radio-quiet branch.

A strong recollimation shock appears to be formed in Cyg X-3 due to the jet power being below critical.

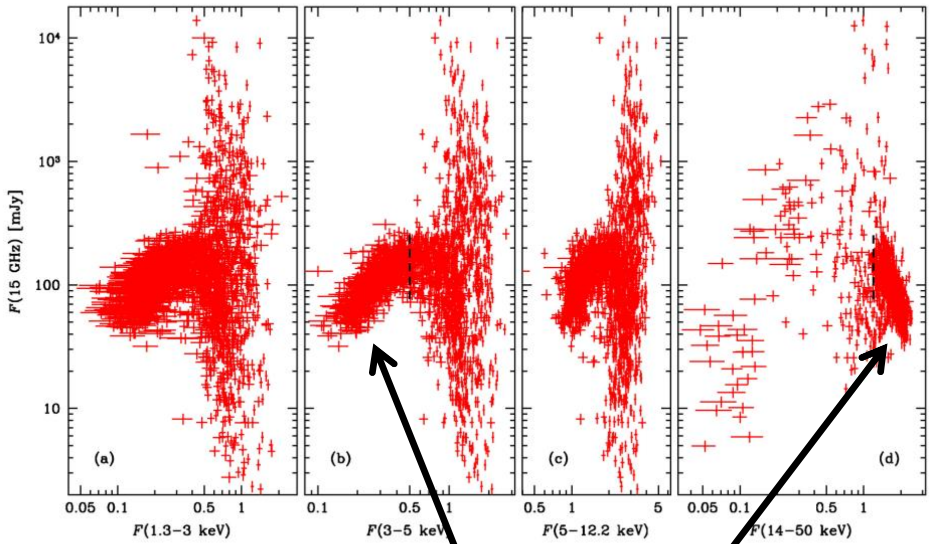
The jet power in Cyg X-1 can be above critical, no shock formed, similar to LMXBs on the radio-quiet branch.

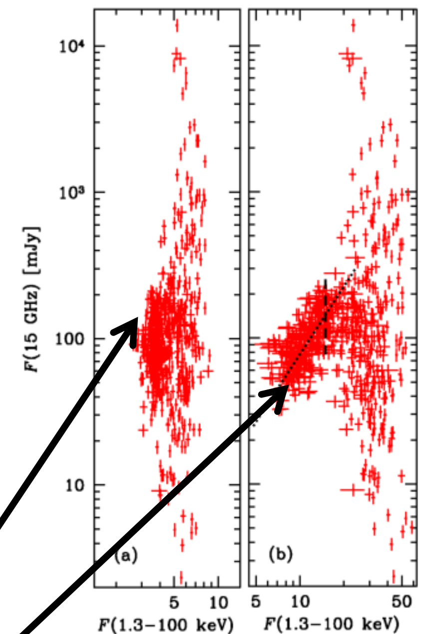


Why is Cyg X-3 unique in its bright γ-ray emission?

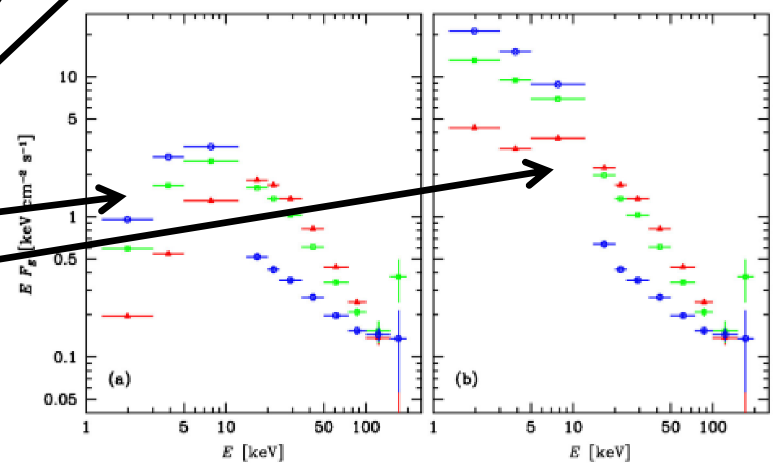
- **1.** A very compact binary with a very bright donor, $L_* \sim 10^{39}$ erg/s $\sim 10^6 L_\odot$.
- The stellar flux at the γ-ray emitting region is e.g. $\sim 10^2\times$ that in Cyg X-1, which has a 10× higher separation and a similar L_*. In LMXBs, L_* is $\ll$ that in Cyg X-3.
- Thus, synchrotron losses dominate in the jet acceleration region in LMXBs, and therefore there is no observable γ-ray emission.
- **2.** Cyg X-3 has an extremely strong wind, ~10× that in Cyg X-1. This may cause the presence of a reconfinement shock in this system, but not in others.
- However, neither explains the presence of a strong jet in most states of Cyg X-3 including the soft state, unlike LMXBs.
- The donor may have a strong *B* field, which is advected by the wind.

An implication of the radio/X-ray correlations

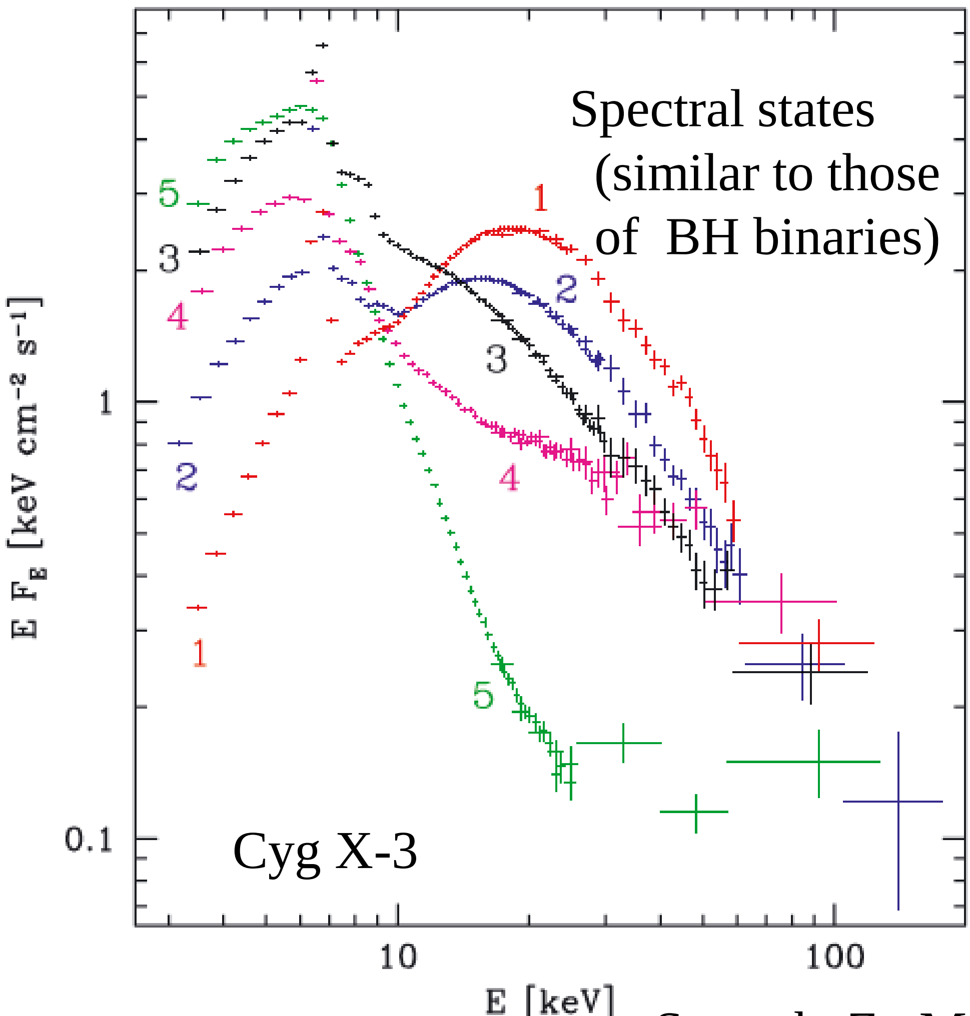


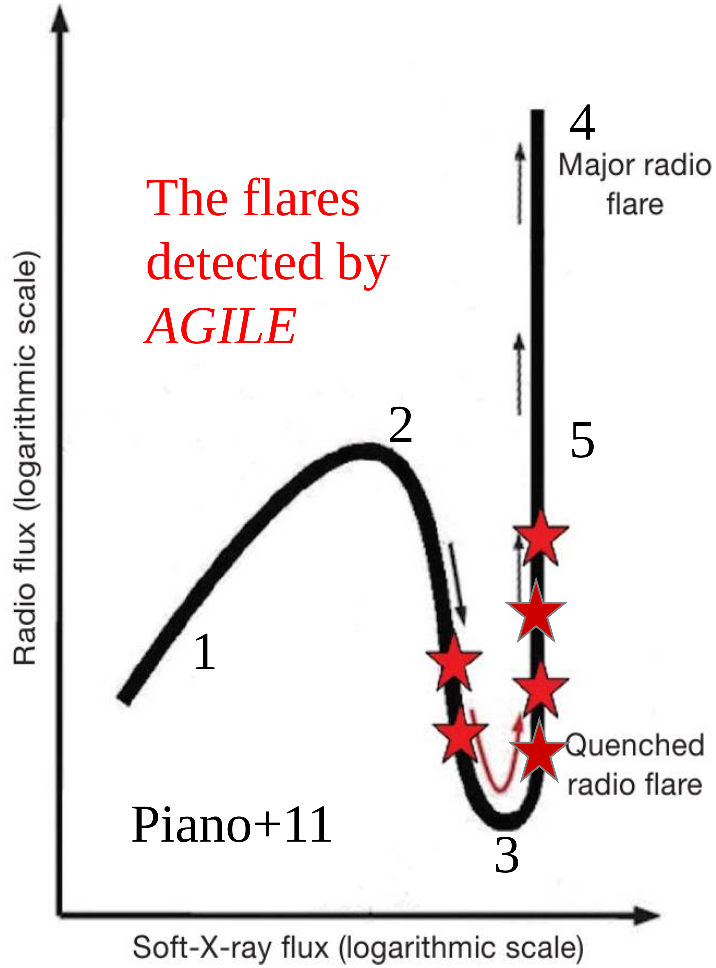


Radio in the hard state: correlated with soft X-rays, anticorrelated with hard X-rays. The bolometric flux has no correlation with radio unless strongly corrected for soft X-ray absorption ⟹ the intrinsic X-ray spectra in all states are much softer than they appear.



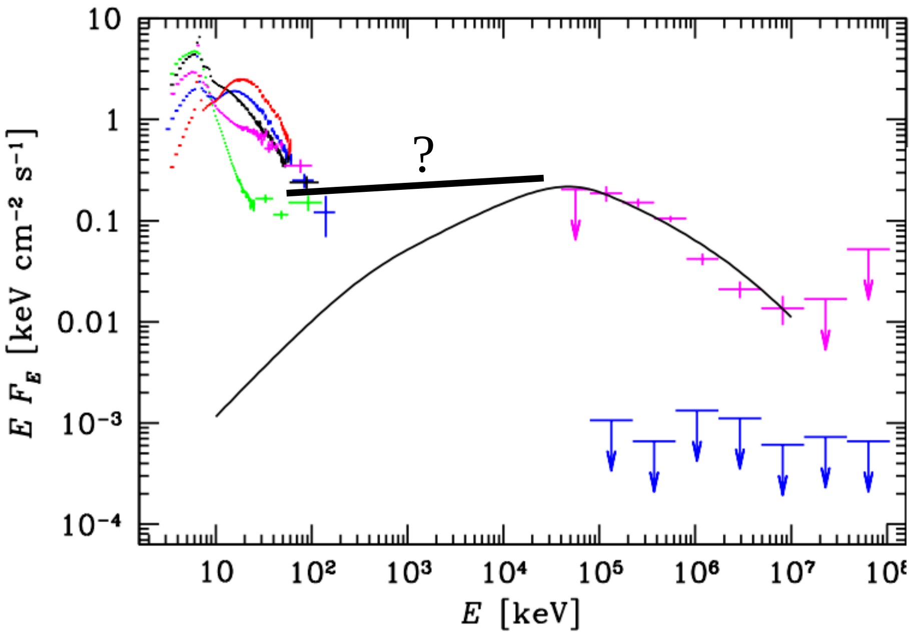
The high-energy γ-ray emission takes place mostly during soft X-ray states



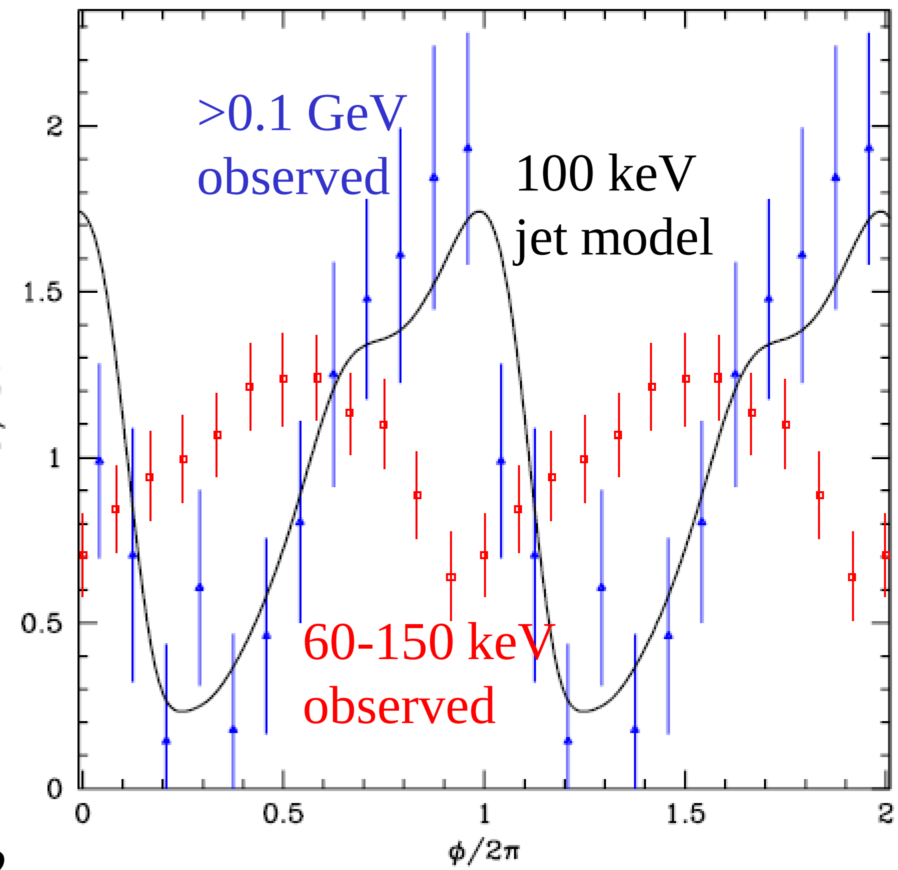


Szostek, Z., McCollough 2007

Can the high-energy tail of the X-ray emission be a low-energy tail of the γ-ray emission?



Orbital modulation during the periods of emission at >0.1 GeV:



No. The ~100-keV minima still correspond to the γ-ray maxima.

AAZ+ 2012