Jets in accreting X-ray binaries: MAXI J1820+070, Cyg X-1, Cyg X-3

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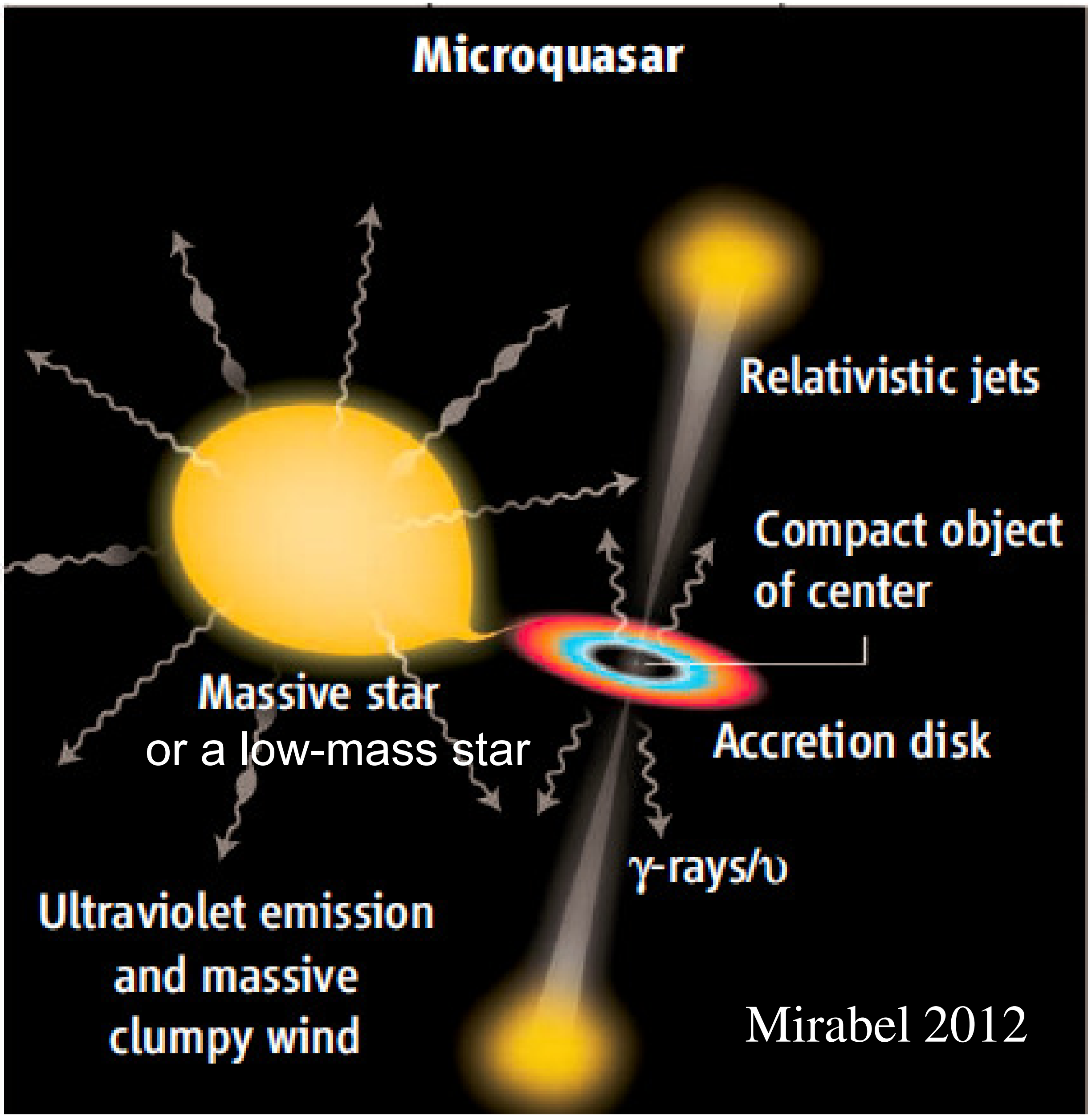
Accreting stellar binary systems with a compact object (black hole or neutron star)

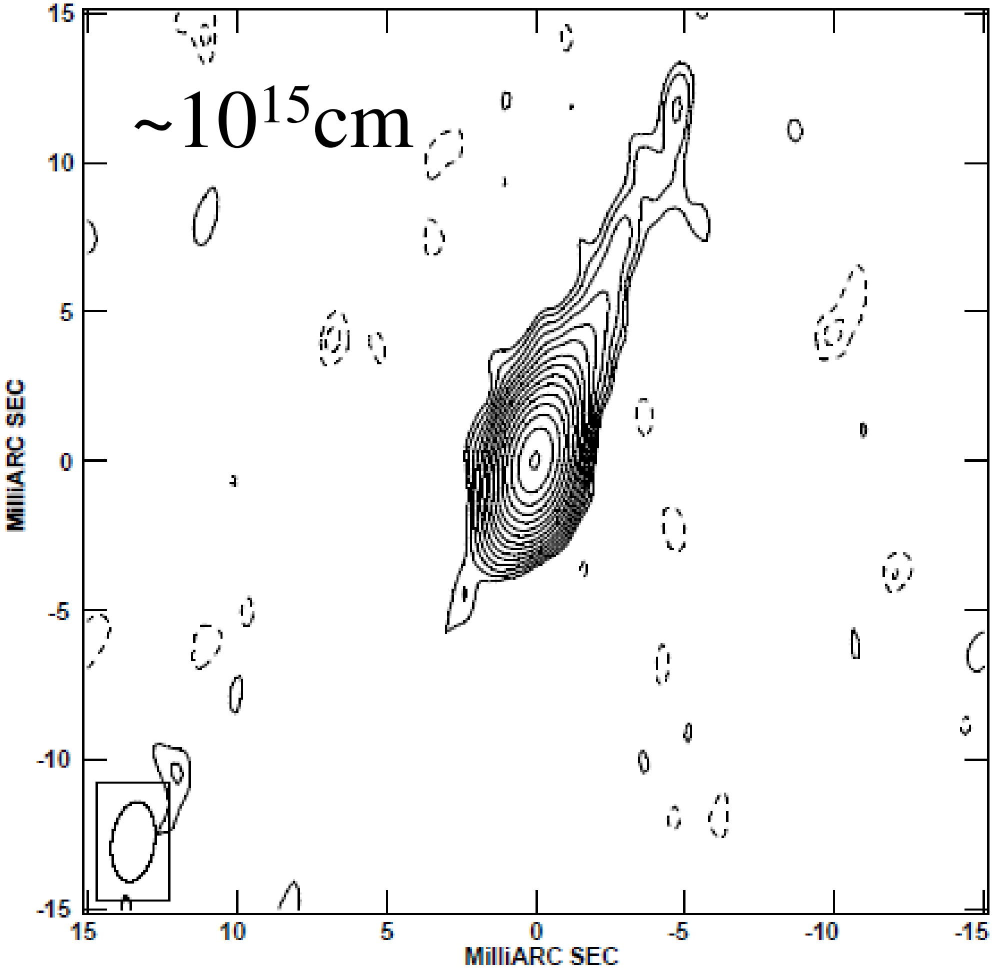


An accreting binary. The donor: either a high or a low-mass star.

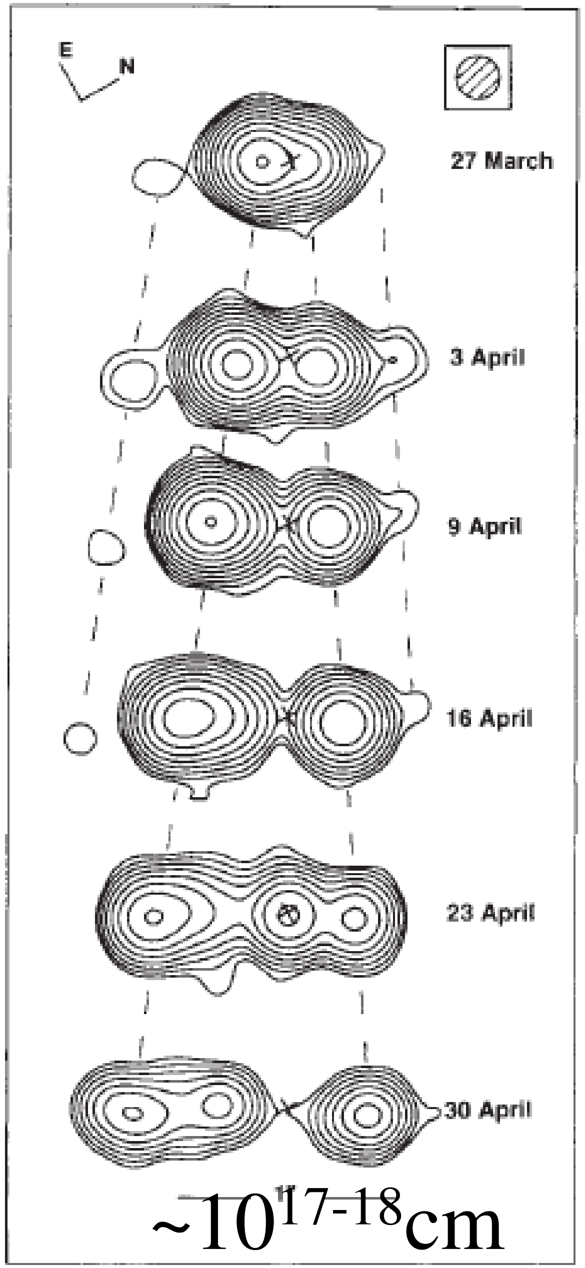
Binaries containing a black hole (BH) and a massive donor (HMXB) are mostly persistent, and those with a low-mass donor (LMXB) are mostly transient (outbursts separated by years of quiescence).

Two kinds of jets in BH binaries

steady and compact at low/medium L,
hard state



Cyg X-1, Stirling+ 2001, Rushton+ 2011

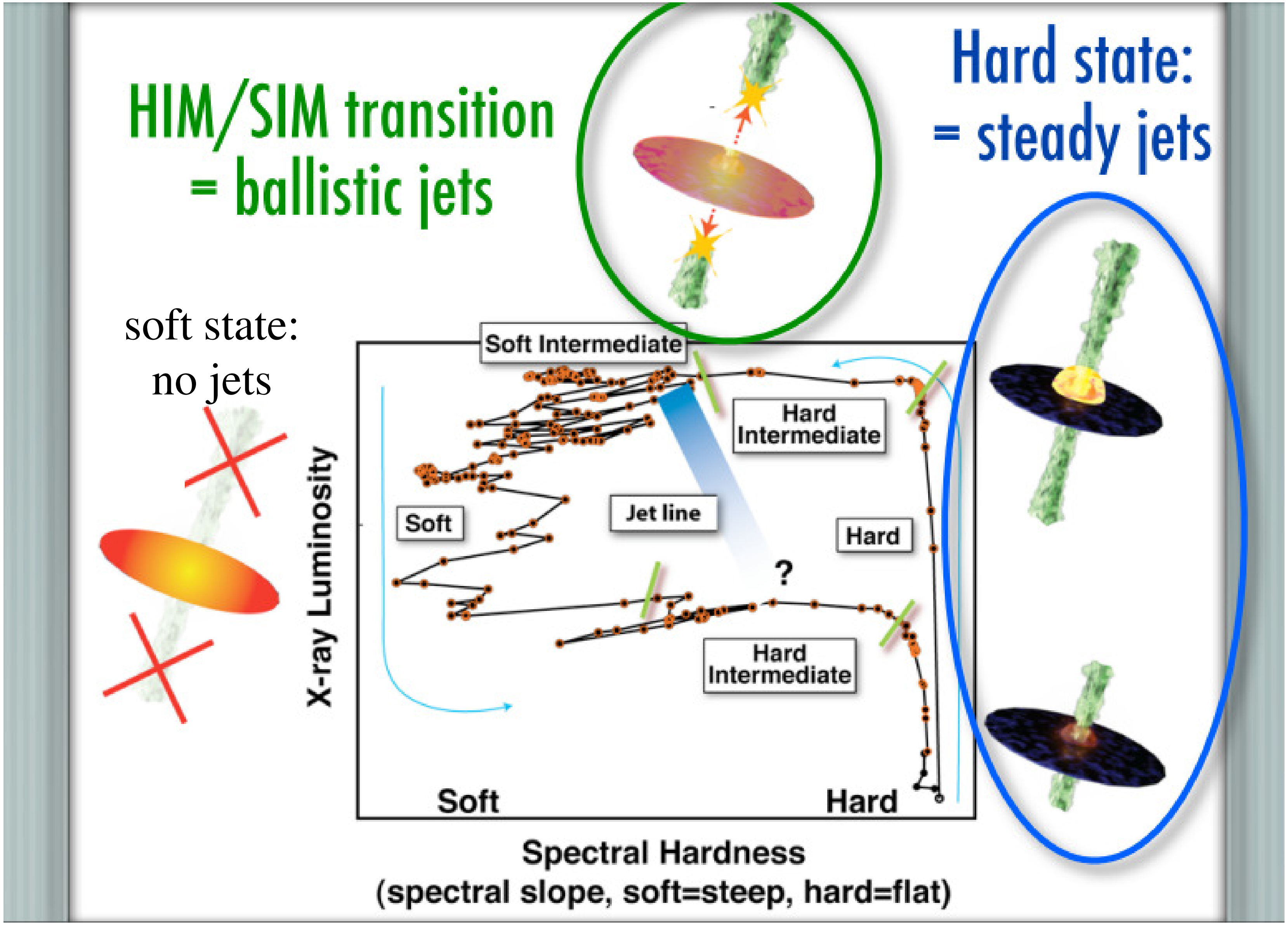


high L at
hard-to-soft
transitions

Mirabel+94

GRS 1915+105

Jet appearance on the hardness-luminosity diagram: either in hard state or at hard-to-soft transitions



Belloni
Fender

Compact hard-state jets:

- The half-opening angle: usually of the order of $\Theta \sim 1^{\circ}$.
- The bulk Lorentz factor: $\Gamma > 1.5$, poorly determined.
- The location of the onset of the emission: $z_0 \sim 10^3 R_g$ (gravitational radii) or more.
- Approximately flat F_ν spectra ($\alpha \sim 0$), a break frequency in the IR, followed by an optically thin synchrotron spectrum.
- Usually explained by superposition of partially self-absorbed synchrotron spectra (Blandford & Königl 1979; Königl 1981).
- Our work on MAXI J1820+070: determine the spatial structure and the parameters of jets in accreting BH binaries better.

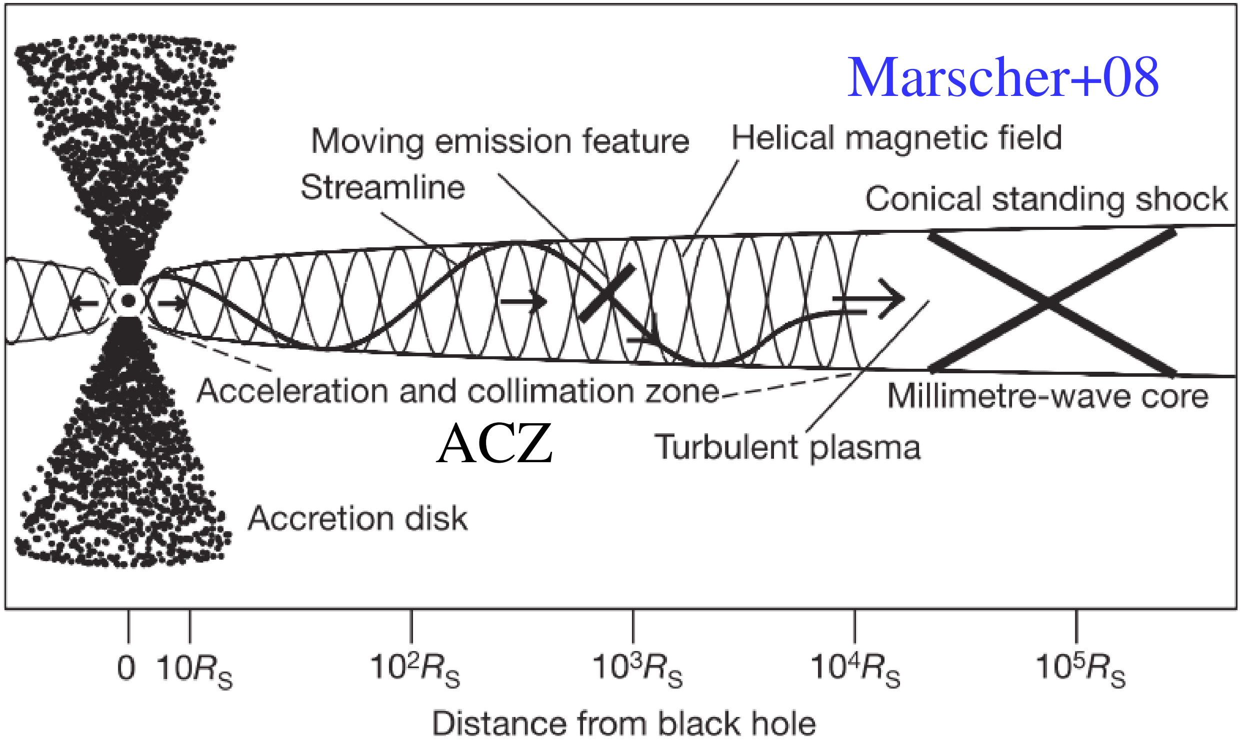
MAXI J1820+070

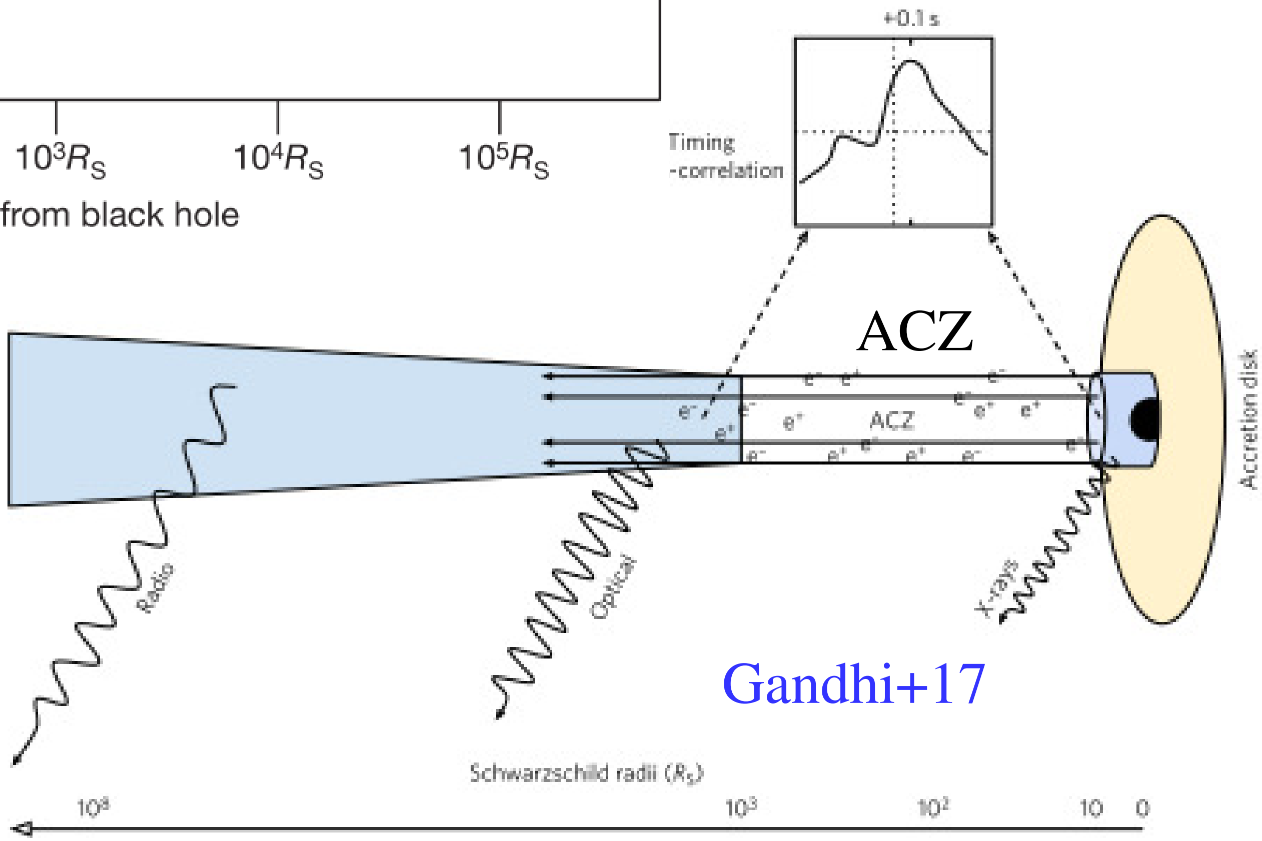
- A transient low-mass X-ray binary with a black-hole accretor, $P \approx 0.7$ d, $M_{\rm BH} \approx 6$–$8\ M_\odot$ (Torres+20).
- A major outburst in 2018, the hard, intermediate, soft, intermediate and hard states and quiescence.
- The jet inclination 64±5° (Wood+21), the binary one 66–81° (Torres+20), $D \approx 3 \pm 0.3$ kpc (Atri+20).
- A lot of observations by various instruments; a large multiwavelength campaign on 2018 April 12;
- → an opportunity for accurate determination of the jet parameters.

The hard-state jet in MAXI J1820+070

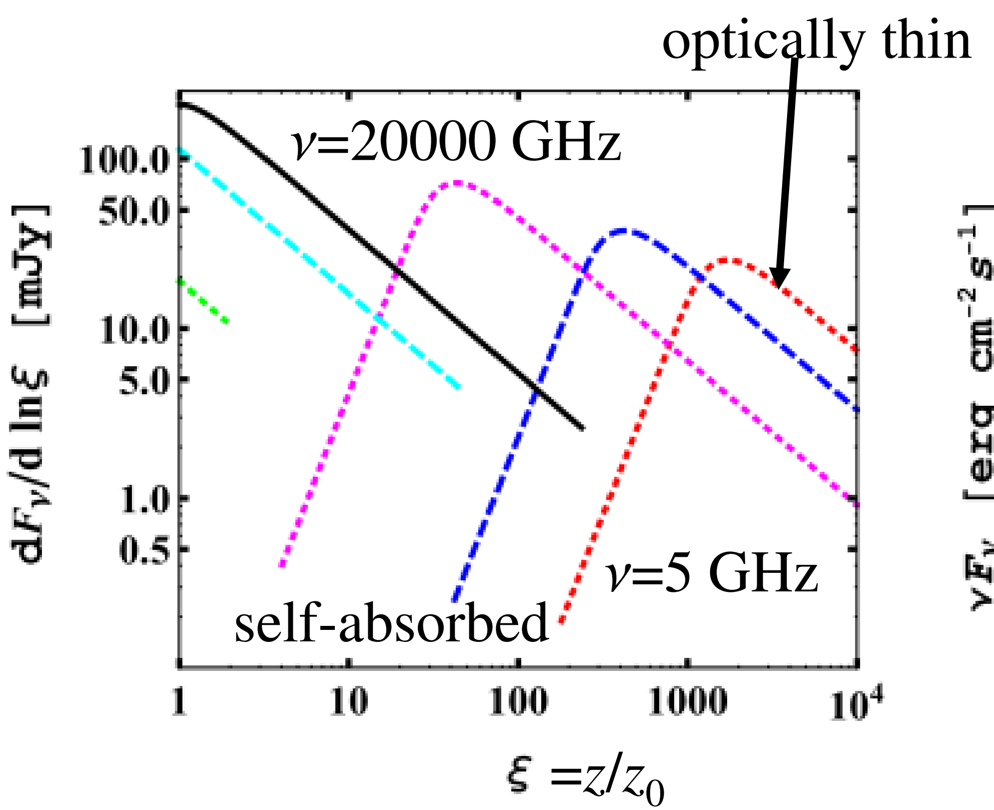
- A unique data set acquired during a bright hard state on 2018 April 12: VLA, ALMA, VLT, NTT, NICER and INTEGRAL; spectral and timing data.
- An analysis by AAZ, Tetarenko & Sikora 21.
- We find $\Theta \approx 1$–$1.5°$, $\Gamma \approx 1.8$–4.
- Model: a conical jet with a constant velocity and partially self-absorbed synchrotron emission from power-law electrons, *B* parametrized by equipartition, power-law dependencies on the distance.

The jet structure and time lags

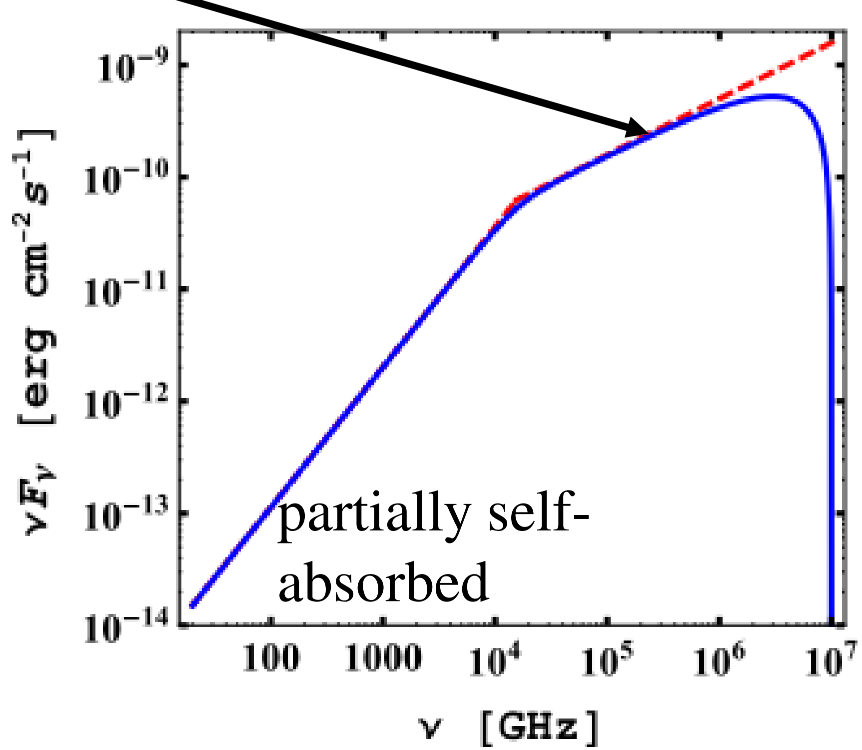




The structure of the emission

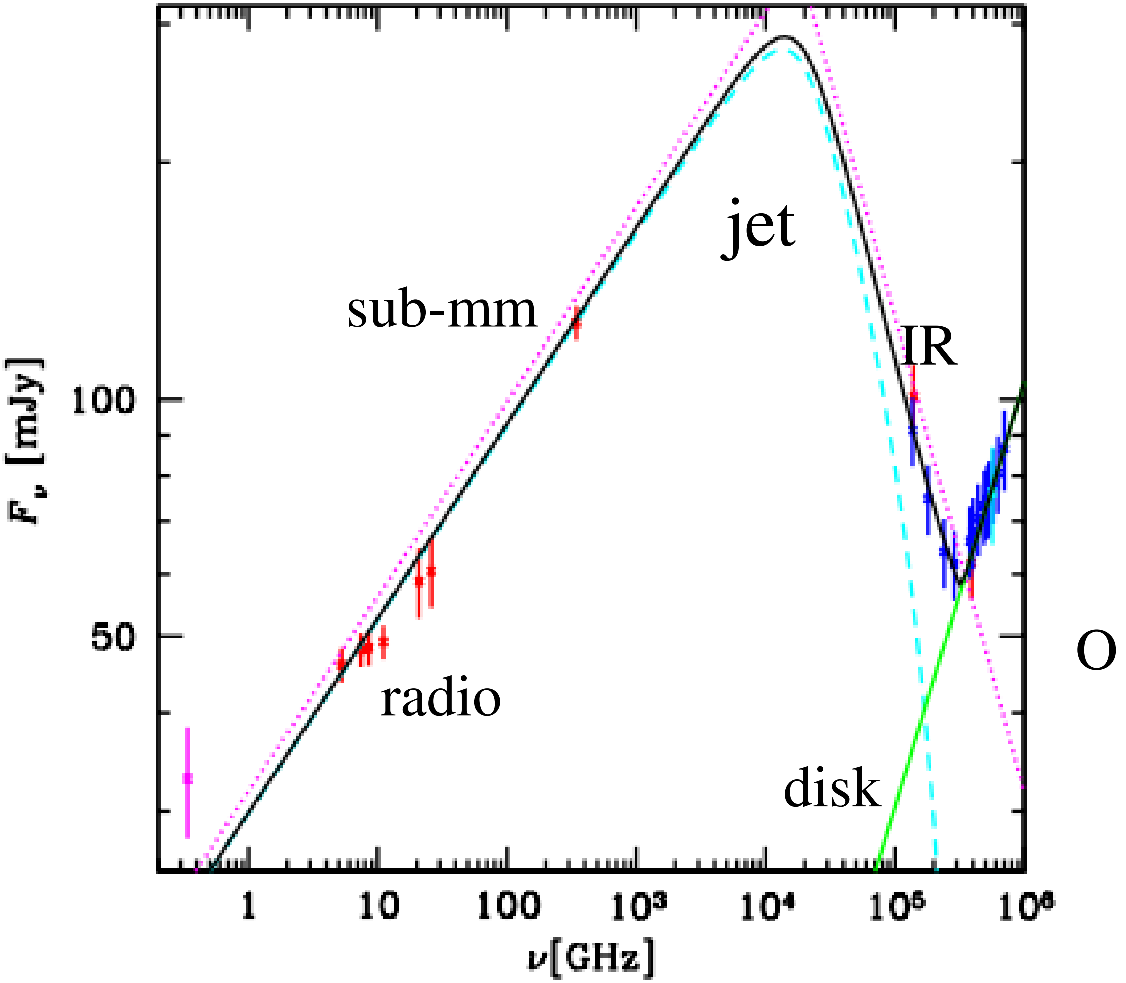


An example of the spatial structure of the synchrotron emission at various frequencies. Peak of local emission roughly $\propto z^{-1}$.

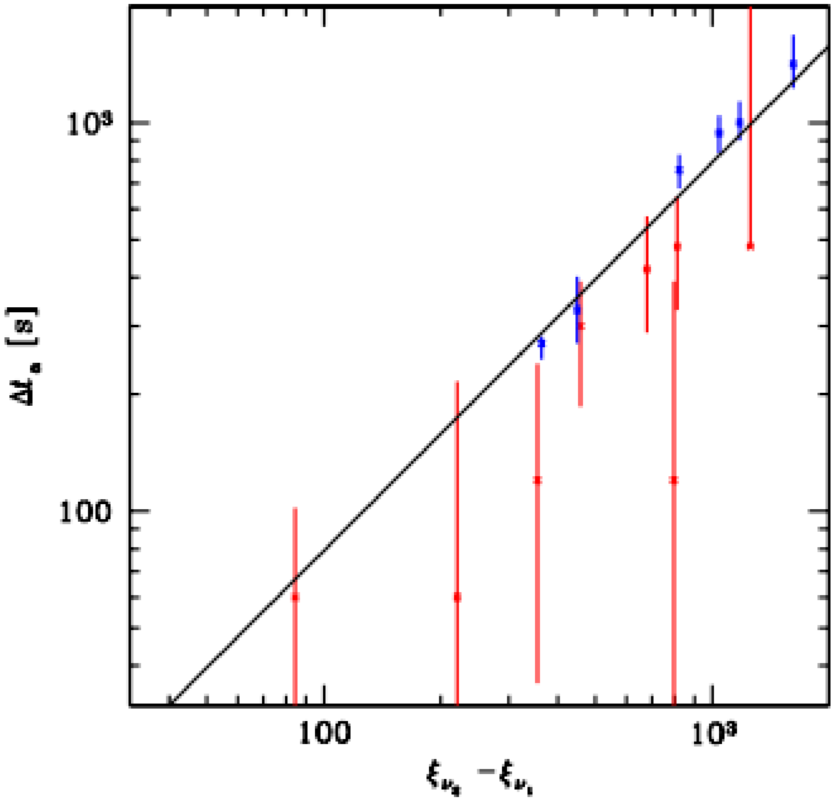


An example of the model spectrum

Fits to the spectrum and lags

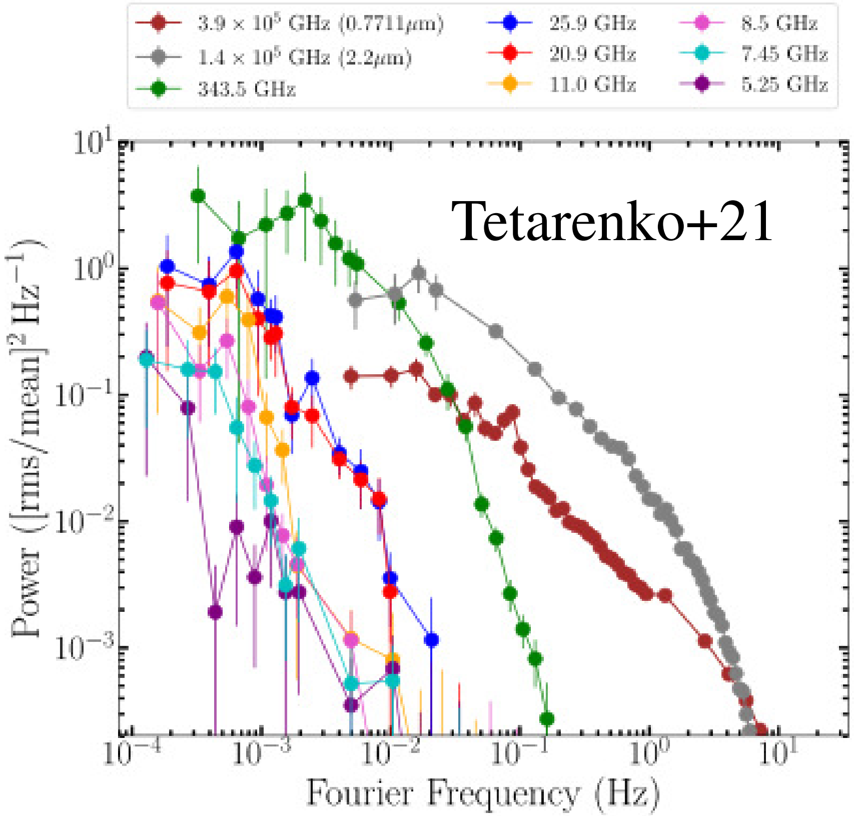


The observed spectrum and our fit



Time lags between various radio and sub-mm frequencies vs. the separation in units of z_0. Analogous to core shifts in blazars.

Break frequencies of power spectra



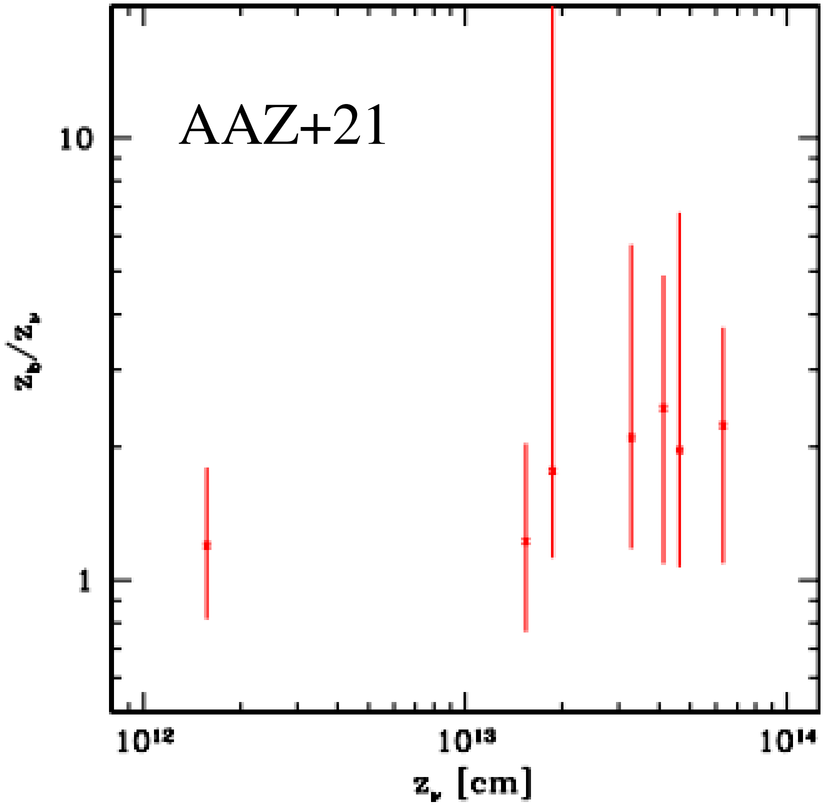


Figure 7. The locations of the emission at the observed frequencies based on the break in the power spectra as $z_{\rm b} = \beta c/f_{\rm break}$ for $\Gamma = 3$ and $i = 64°$, shown as their ratio to the locations based on time lags and the slope of the partially self-absorbed spectrum, $z_\nu \approx z_0(\nu/\nu_0)^{-0.88}$.

The distances corresponding to the jet propagation during the break time scales, $z_{\rm b}$, found to be roughly equal to the distances of the maximum emission at a given frequency, z_ν. It may be due to viscous damping during perturbation propagation.

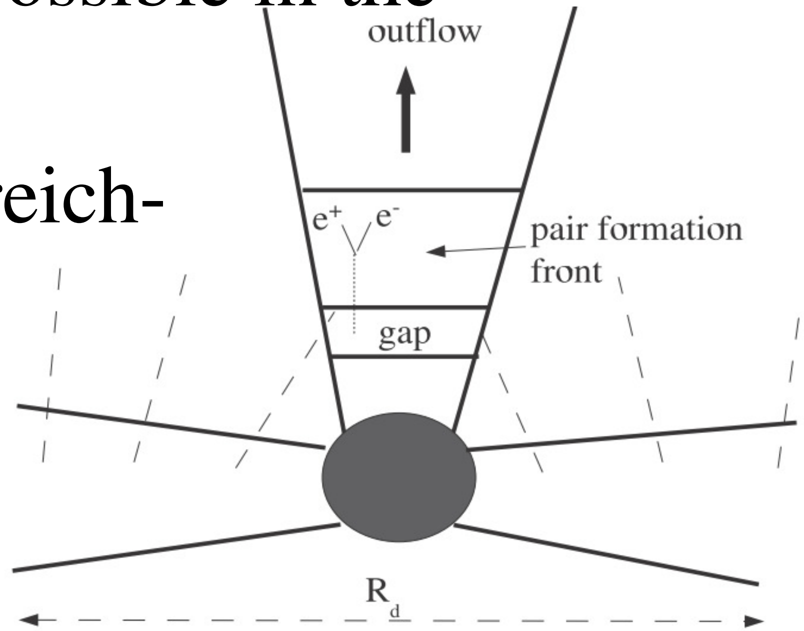
Are there e$^{\pm}$ pairs in jets, and if yes, how are they produced?

- Arguments for $n_e \gg n_p$ in blazars and radio galaxies (e.g. Sikora+20).
- Pair production in spark gaps possible in the Blandford-Znajek mechanism.
- But this is limited by the Goldreich-

Julian density: $n_{GJ} = \dfrac{\Omega B}{2\pi ec}$

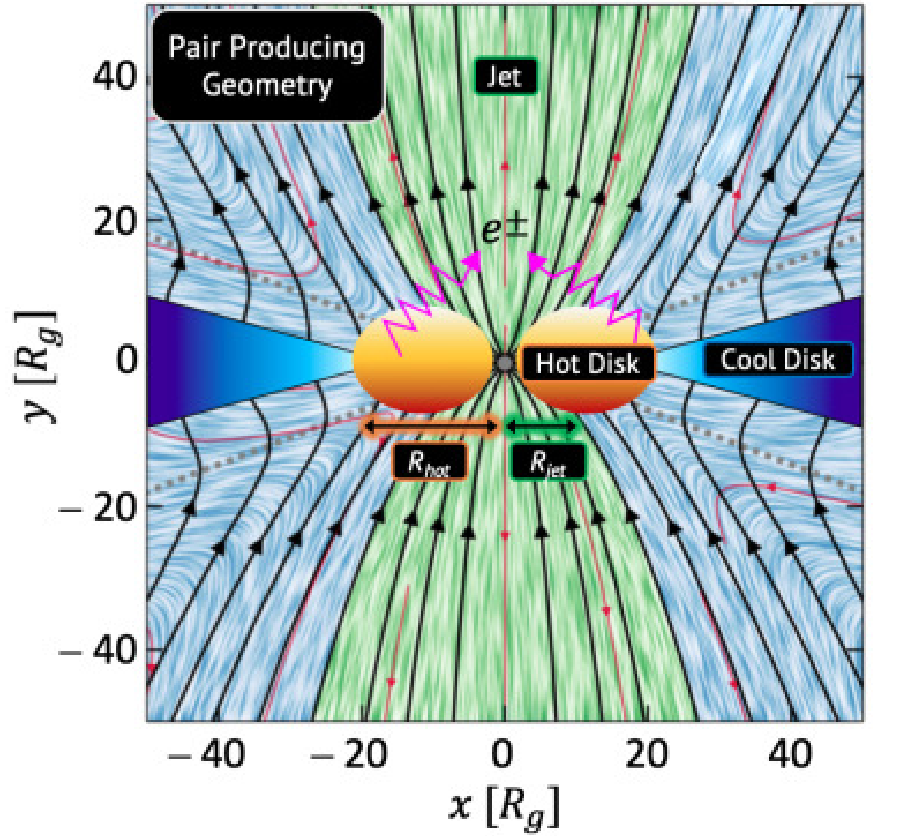
- Levinson & Rieger 2007 give

a limit of $n < 10^3 n_{GJ}$.

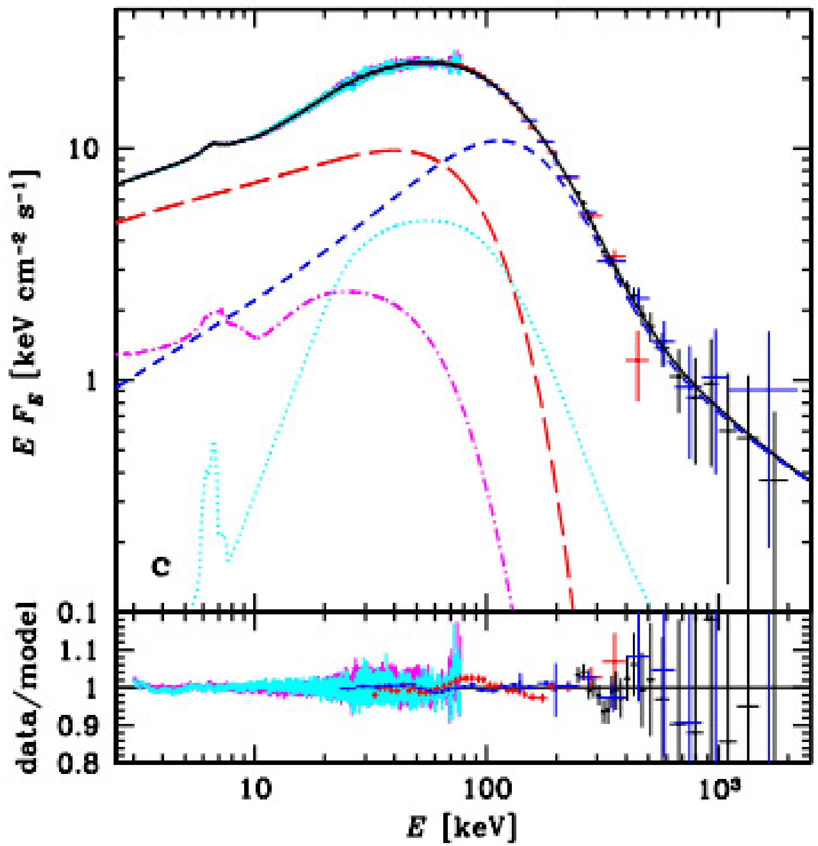


- Nokhrina+15 find $\sim 10^{12\text{-}15} n_{GJ}$ in blazars, and we find $> 10^7 n_{GJ}$ in MAXI J1820+070.

An alternative: $\gamma\gamma$ $e^{\pm}$ pair production



The assumed geometry shown on the jet simulation plot from Tchekhovskoy 2015.



The spectrum of the source from NuSTAR and INTEGRAL

The pair production rate within the (empty) jet base: $10^{40-41}\mathrm{s}^{-1} \approx$ the rate of the flow of $e^{\pm}$ calculated from the observed synchrotron emission. A remarkable coincidence, since both numbers are based on very different information.

$\rightarrow$ Pairs may dominate the jet by number.

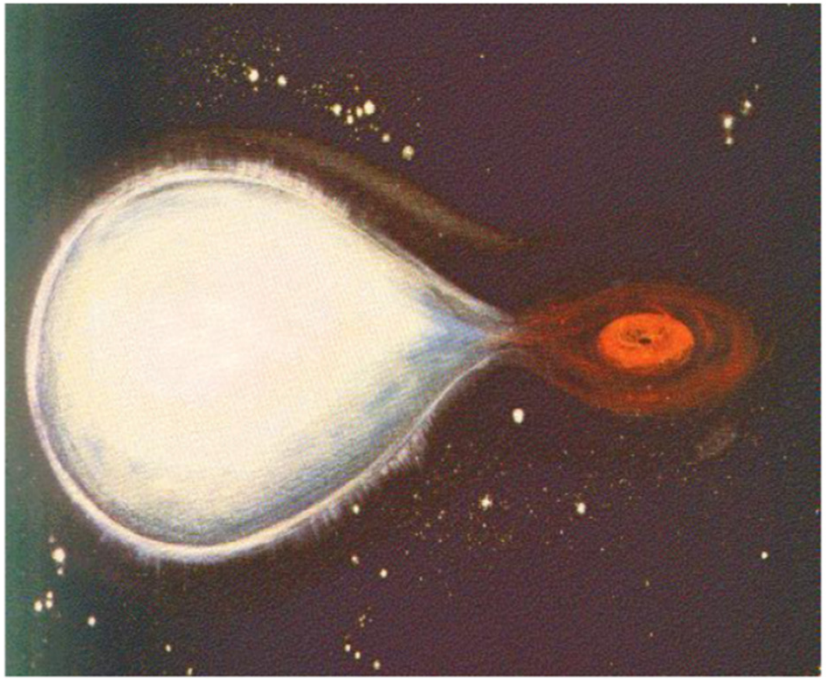
The jet power and the Blandford-Znajek mechanism

- We compute the magnetic flux, $\Phi_{\rm j}=\int {\rm d}r B_\perp r^2$, in the emission region (assuming ideal MHD), which is equal that threading the BH.
- We find $\Phi_{\rm j} \sim 10^{22}$G cm^2, which corresponds to the maximal jet power, $P_{\rm j} \approx \dot{M}c^2$, and a magnetically arrested accretion (MAD) – another coincidence.
- But the jet power in the emission region is dominated by the bulk motion of ions, which number strongly depends on the abundance of pairs.
- $P_{\rm j} \approx \dot{M}c^2$ *only* for low pair abundance.
- Thus, if pairs dominate, $P_{\rm j} \ll \dot{M}c^2$ and some assumptions above (e.g. ideal MHD) are not satisfied.

Conclusions for MAXI J1820+070

- MAXI J1820+070 in the hard state from the spectrum and time lags: Partially self-absorbed synchrotron, the jet opening angle $\Theta \approx 1$–$1.5°$, the bulk Lorentz factor $\Gamma \approx 1.8$–4.
- Pair production within the jet base by photons from the accretion flow able to provide enough $e^{\pm}$ for the observed synchrotron emission.
- The magnetic flux measured in the emission region implies the accretion can be magnetically arrested if pairs do not dominate.

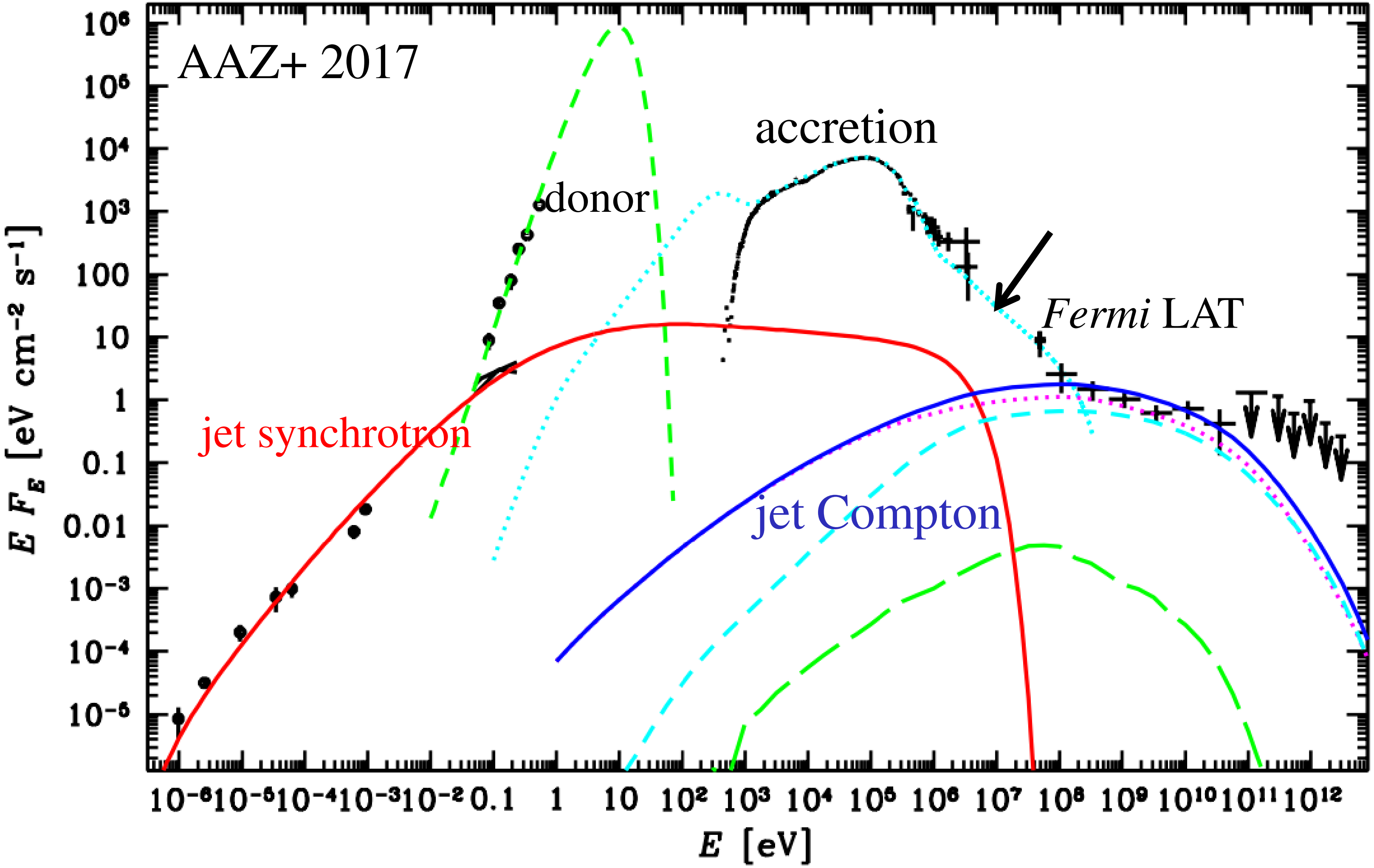
Cyg X-1



- An accreting black-hole binary. Donor: OB supergiant. $P = 5.6$ d, $D \approx 2$ kpc, $M_{BH} \approx 20\ M_{\odot}$ (Miller-Jones+21).
- Wind accretion, the donor nearly fills its Roche lobe.
- Emission from radio to GeV.

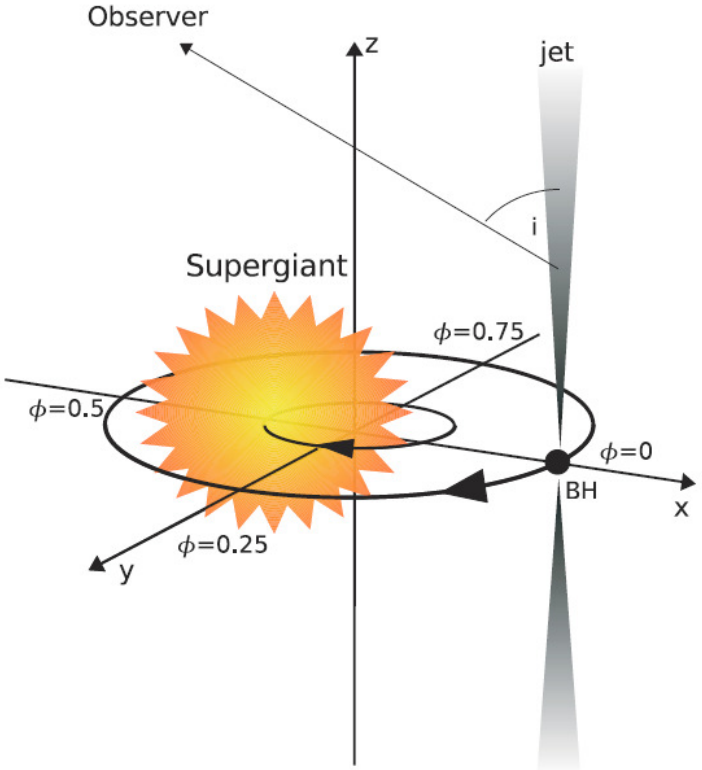
The broad-band spectrum in the hard state of Cyg X-1

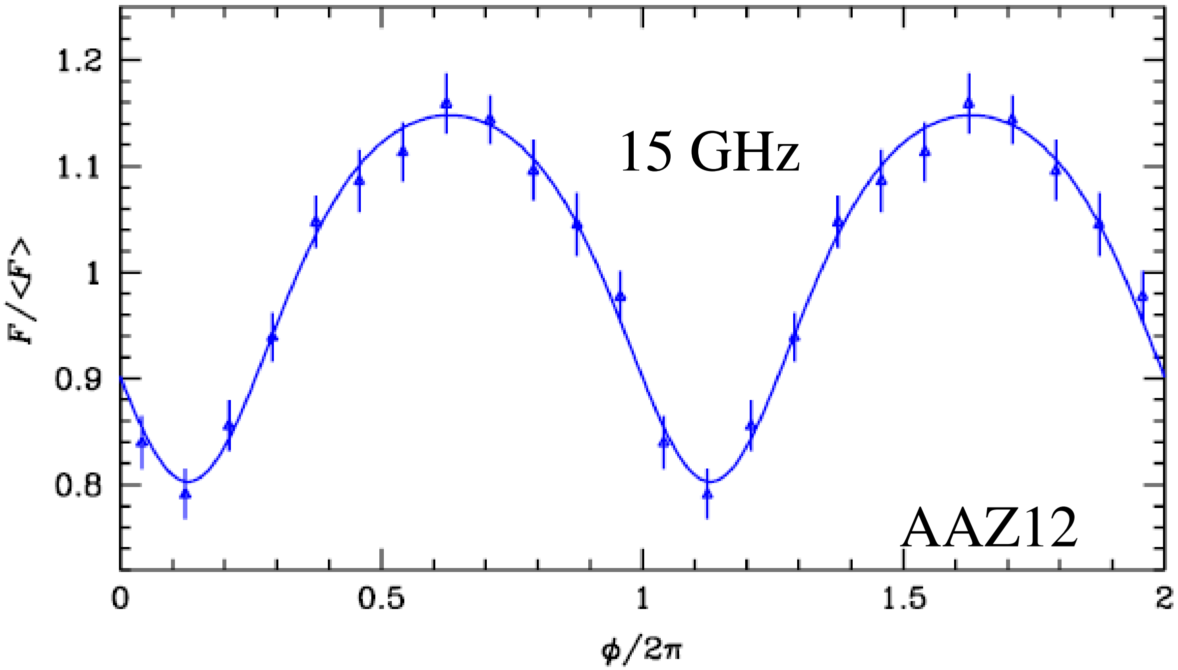
The spectrum modelled including all radiative processes. Compton scattering of stellar blackbody and SSC dominate the γ-ray emission.



The acceleration index $p \approx 2.5$, $B_0 = 10^4$ G at $z_0 \approx 10^3 R_g$

The location of the 15 GHz radio emission

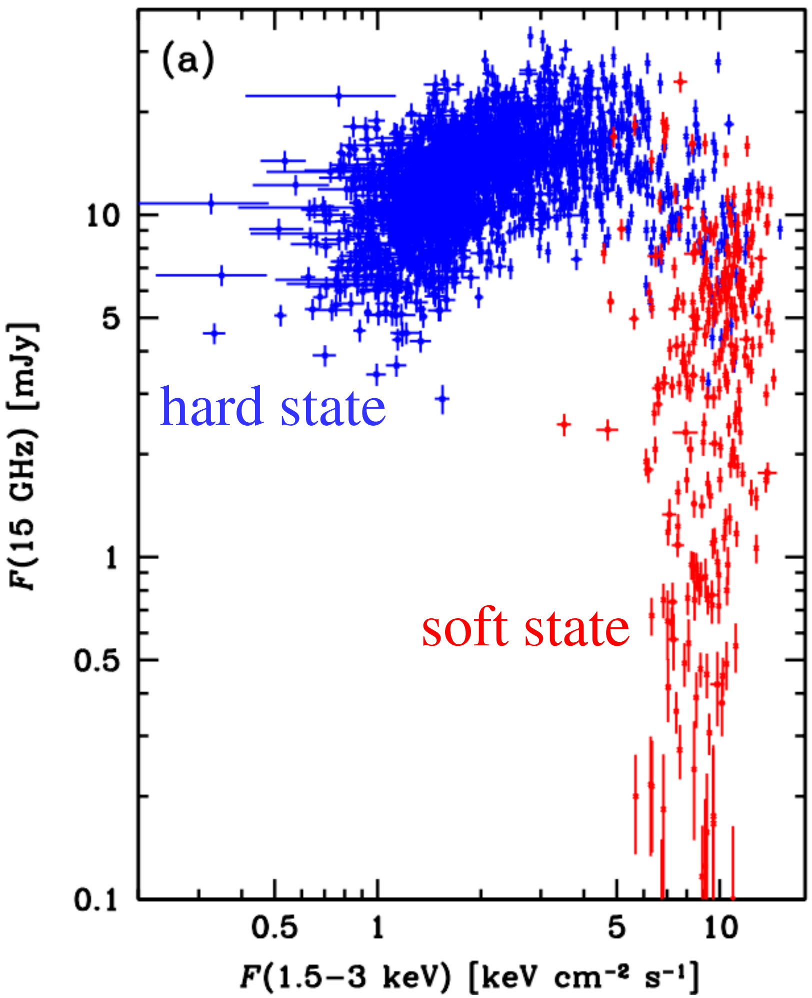


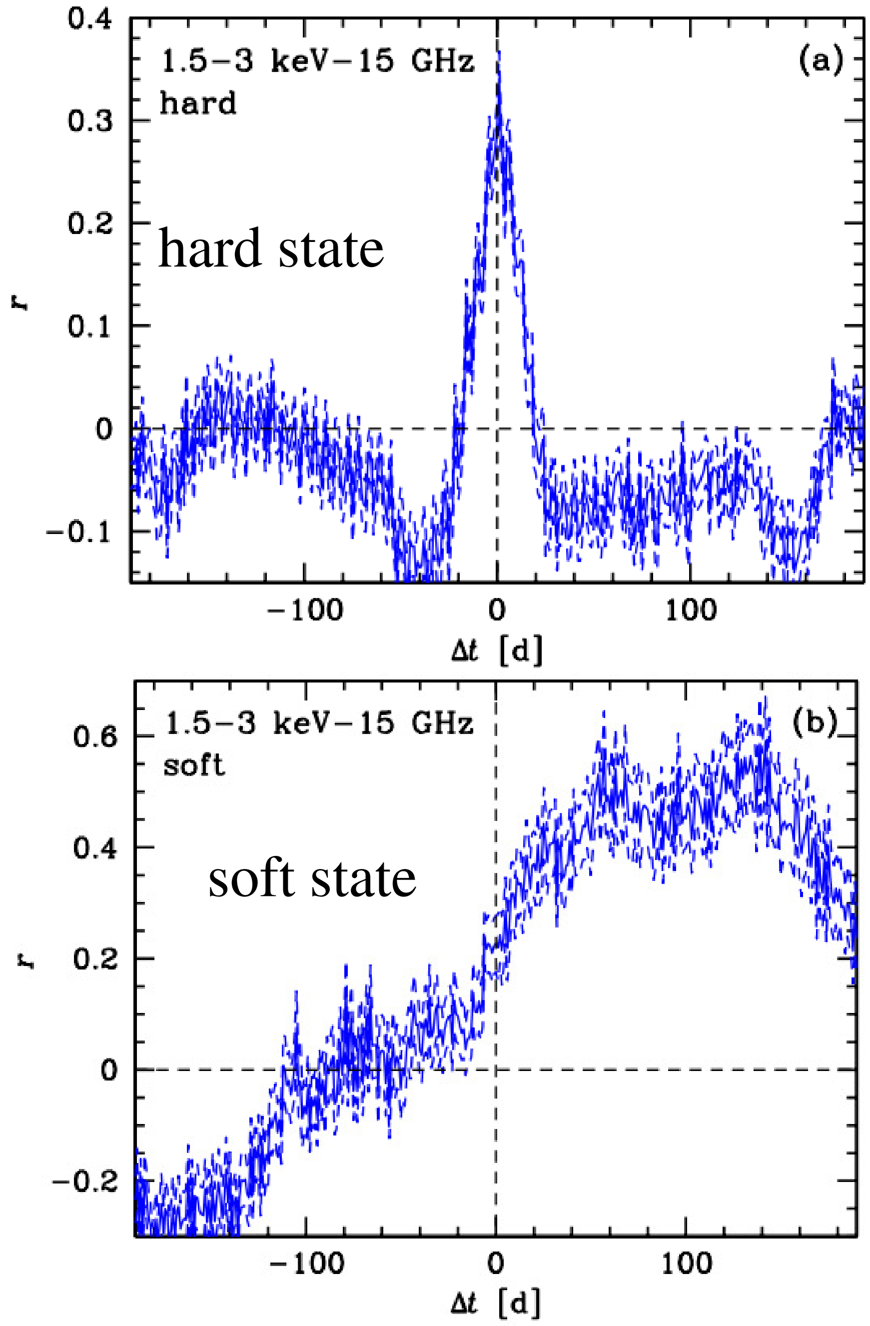


Free-free absorption of the jet radio emission in the wind of the donor causes orbital modulation, fitted by an irradiated stellar-wind model. This yields z/a ~ 1, i.e., z ~ $10^6 R_g$.

The emission is partially self-absorbed synchrotron. This roughly agrees with the location of the radio emission in MAXI J1820+070.

Radio correlations with soft X-rays: zero lag in the hard state, ~50–150 d lag in the soft state





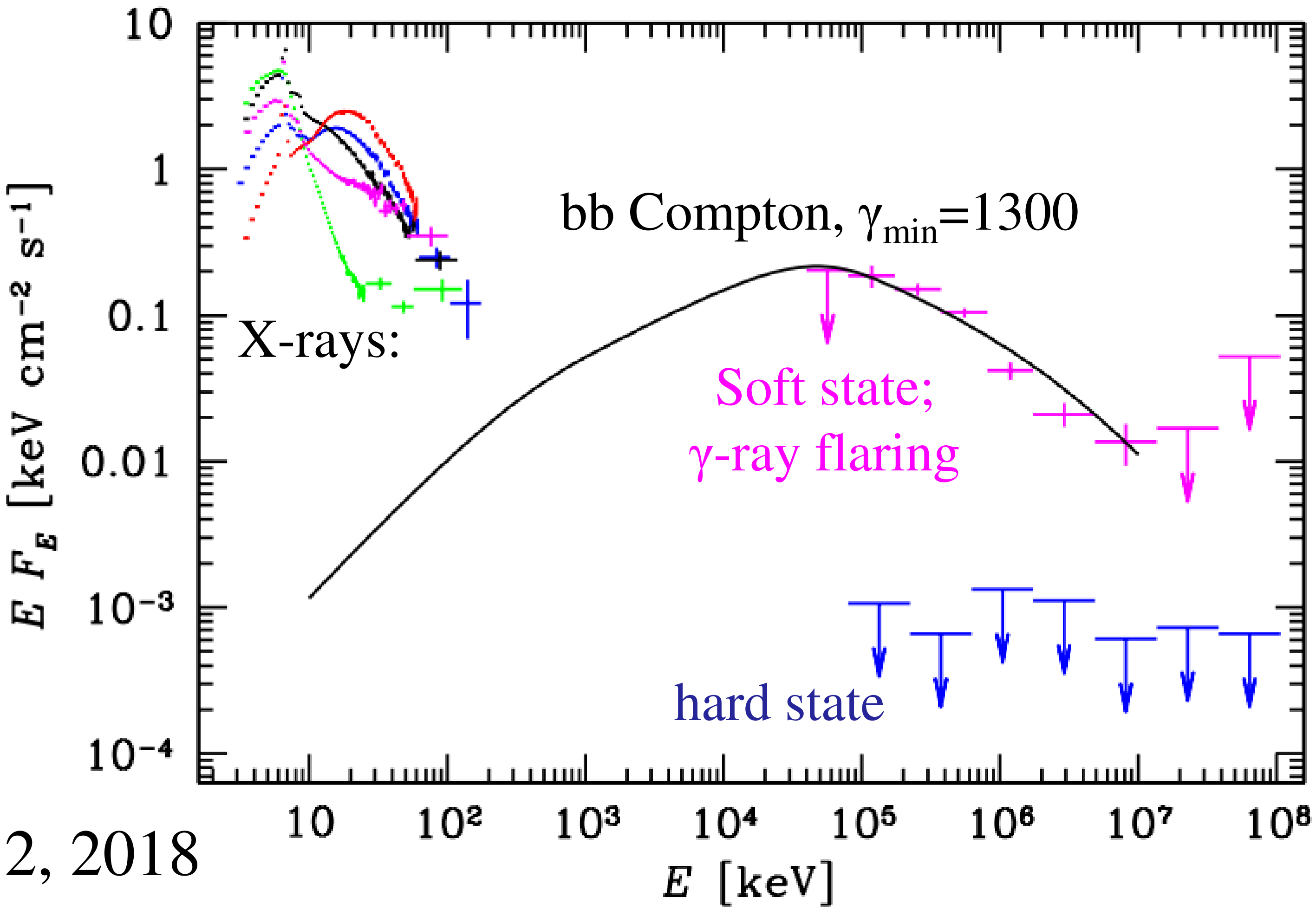
Different origin of the soft and hard X-rays

Cyg X-3 – a puzzling microquasar

- A very luminous radio and X-ray source, Wolf-Rayet + a compact object; a very short period (for a HMXB) of $P \approx 4.8$h.
- Compact object: either a low-M BH (more likely) or a NS (AAZ, Mikołajewska & Belczyński 2013).
- X-ray spectral states similar to those of BH binaries.
- Major radio flares ($\lesssim$20 Jy) and strong γ-rays in the *soft* state, unlike the jet quenching in the soft state of BH binaries but similar to luminous blazars.

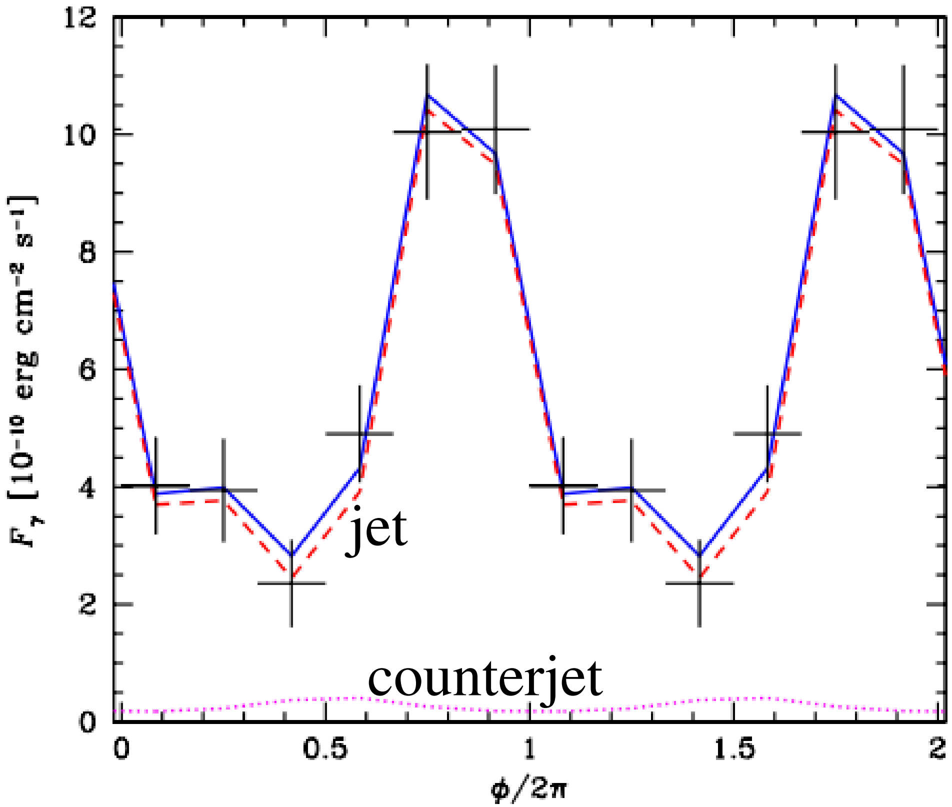
The LAT γ-ray spectra and upper limits

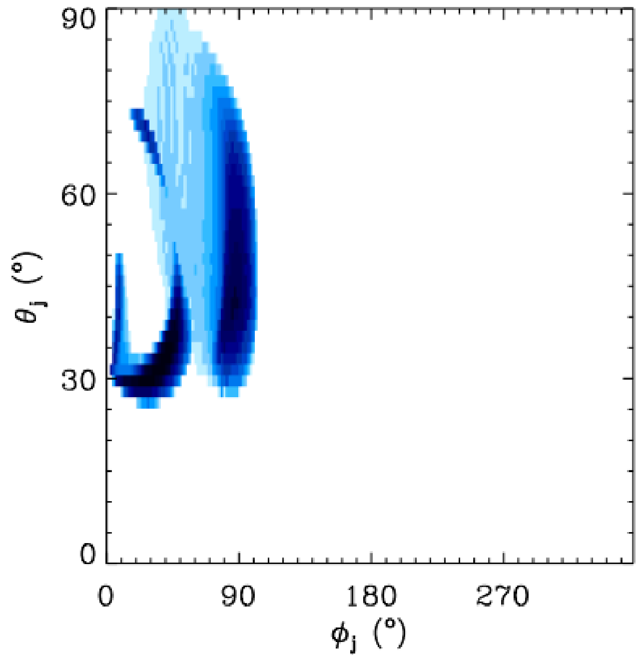
The soft spectral state: $N(\gamma) \propto \gamma^{-3.5}$, acceleration above $1500 \gtrsim \gamma_{min} \gtrsim 500$, Compton scattering of the donor bb photons.

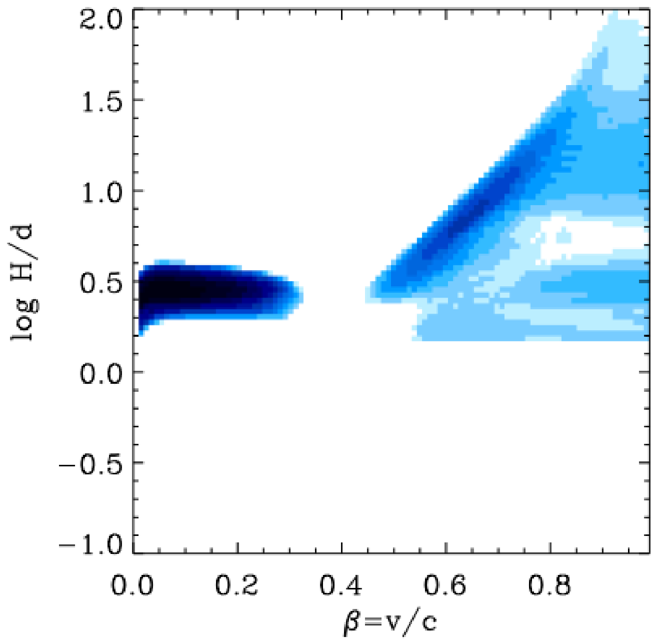


AAZ, Sikora+ 2012, 2018

Fit of a Compton anisotropy model to the folded γ-ray light curve





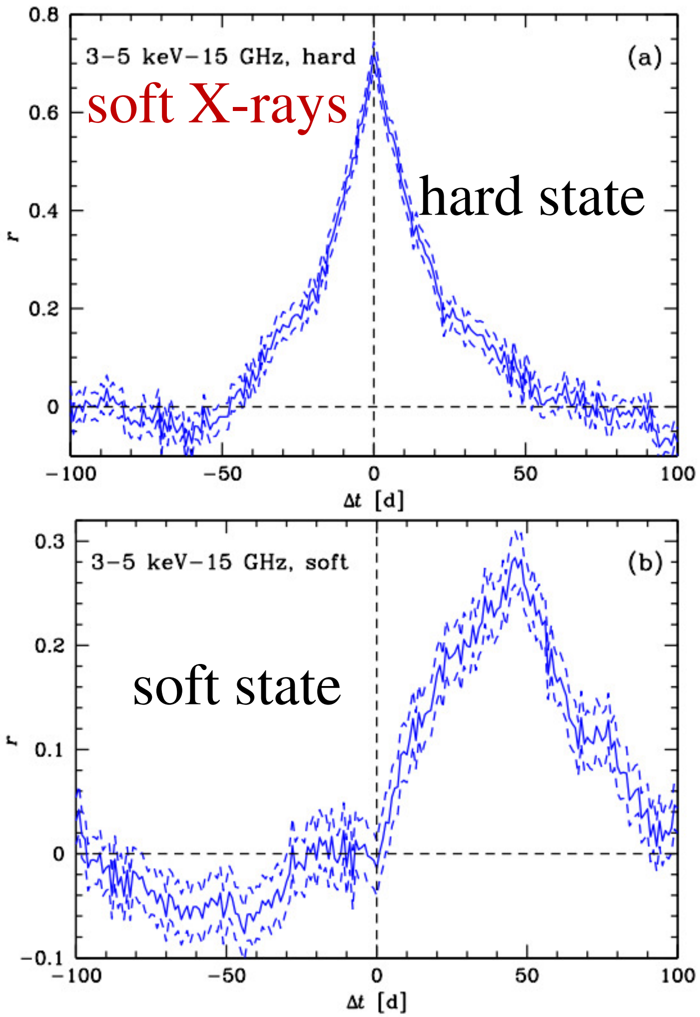


γ-ray emission at ~(2–3)× stellar separation ~10^{12} cm~10^6 R_g. Jet inclined w/r the binary axis at θ≳30°, and relatively slow.

AAZ+18

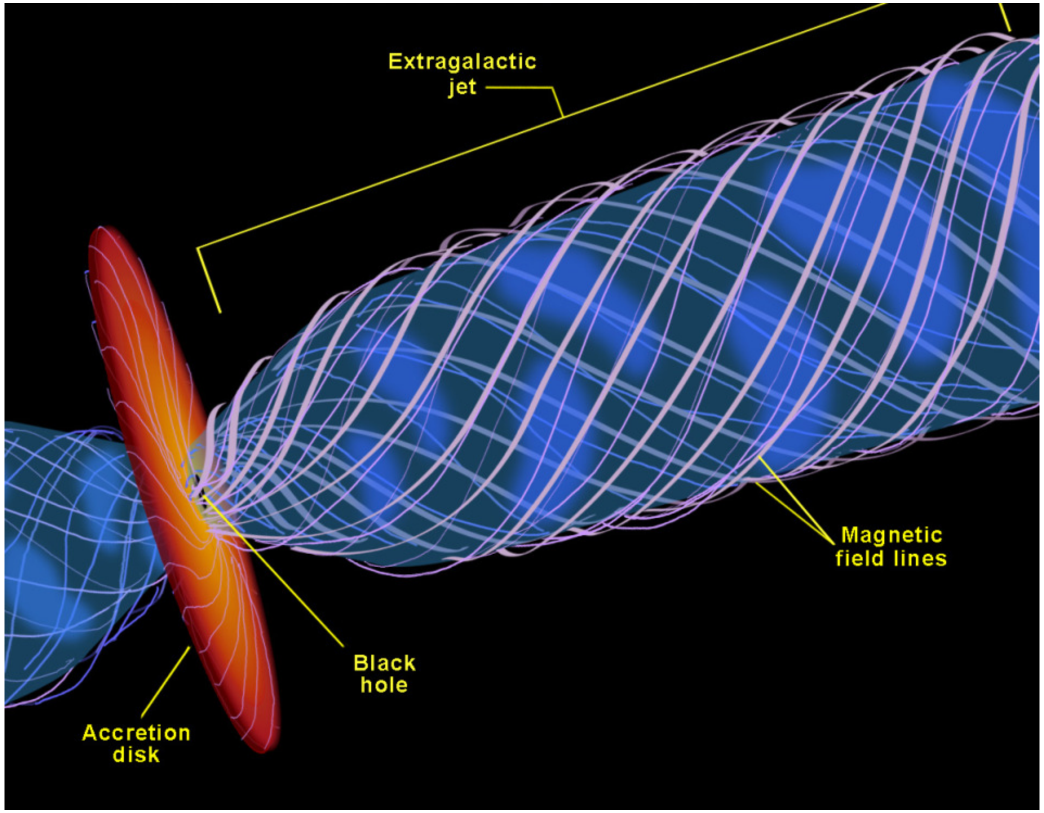
Radio/X-ray correlations and time lags

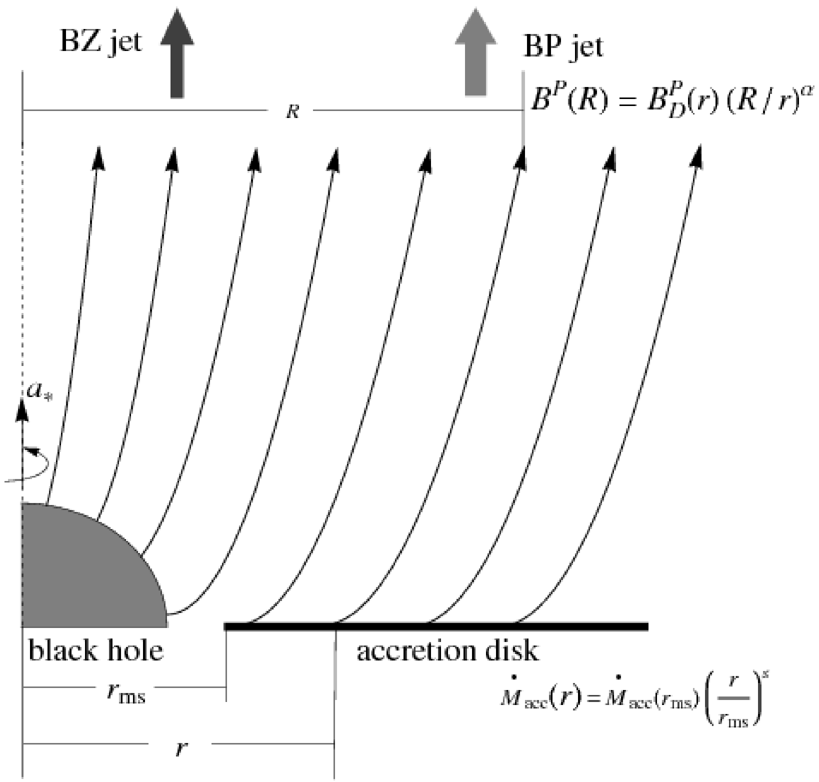
- 15 GHz radio: no lag w/r to soft X-rays in the hard spectral state, but a highly significant ~50 d lag in the soft state (as in Cyg X-1).



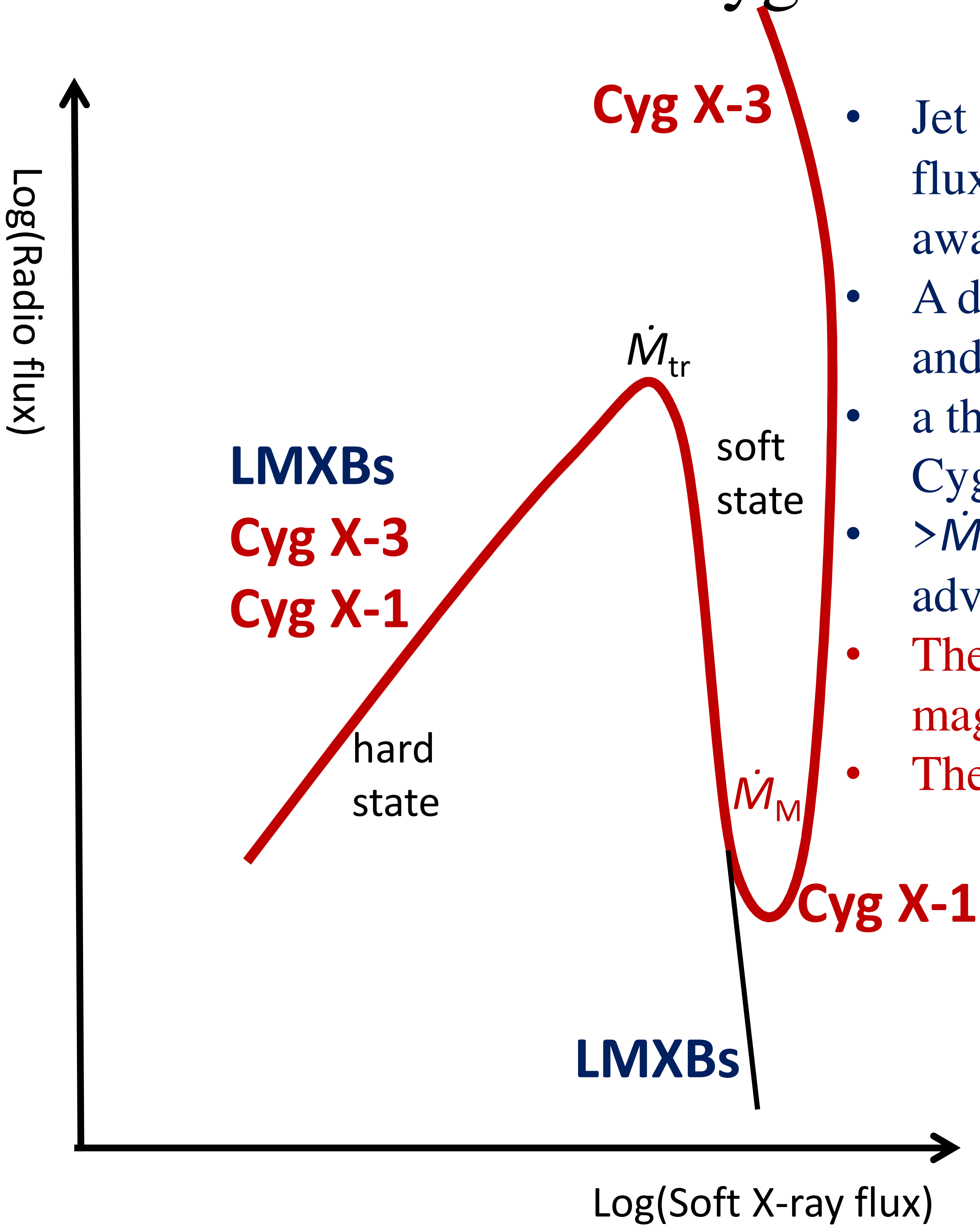
Jet launching mechanisms

- Extraction of spin energy of a rotating BH (Blandford & Znajek 77; Tchekhovskoy+11; McKinney+12). $P_{\rm jet} \sim a_*^2 B_\perp^2 R_g^2 c$.
- Collimation and acceleration by disc poloidal magnetic field (Blandford & Payne 1982). A lower jet power.
- Both mechanisms require the presence of a net vertical field.





BH LMXBs vs. Cyg X-3 & Cyg X-1



- Jet quenching at $\dot{M}_{tr}$: magnetic flux of the hard state diffusing away in a thin disc.
- A delayed jet only in Cyg X-3 and Cyg X-1 →
- a threshold condition satisfied in Cyg X-3,1 but not in LMXBs:
- $>\dot{M}_{tr}$: a large magnetic flux advected from the donor.
- The threshold condition: onset of magnetic outflows.
- The lag time scale: viscous.

Cao & AAZ 20

Conclusions for Cyg X-1 and X-3

- Cyg X-1 hard state: Synchrotron emission above $z_0 \approx 10^3 R_g$, 15GHz emission from $\sim 10^6 R_g$.
- Cyg X-3 soft state: γ-ray emission from $R \sim 10^6\ R_g$. Acceleration of power-law electrons above $\gamma_{\rm min} \sim 10^3$. Orbitally-modulated γ-rays imply the jet inclined by $\theta \gtrsim 30°$ w/r the binary axis.
- Scattering of the blackbody donor emission dominate γ-rays in both sources.
- Long lags of ~100 d of radio w/r to soft X-rays in the soft states: delayed magnetic ouflows removing the disc angular momentum→magnetic flux advection from the donor.
- The lag ≈ the viscous time scale at the disc outer edge.