Jets in accreting black-hole binaries

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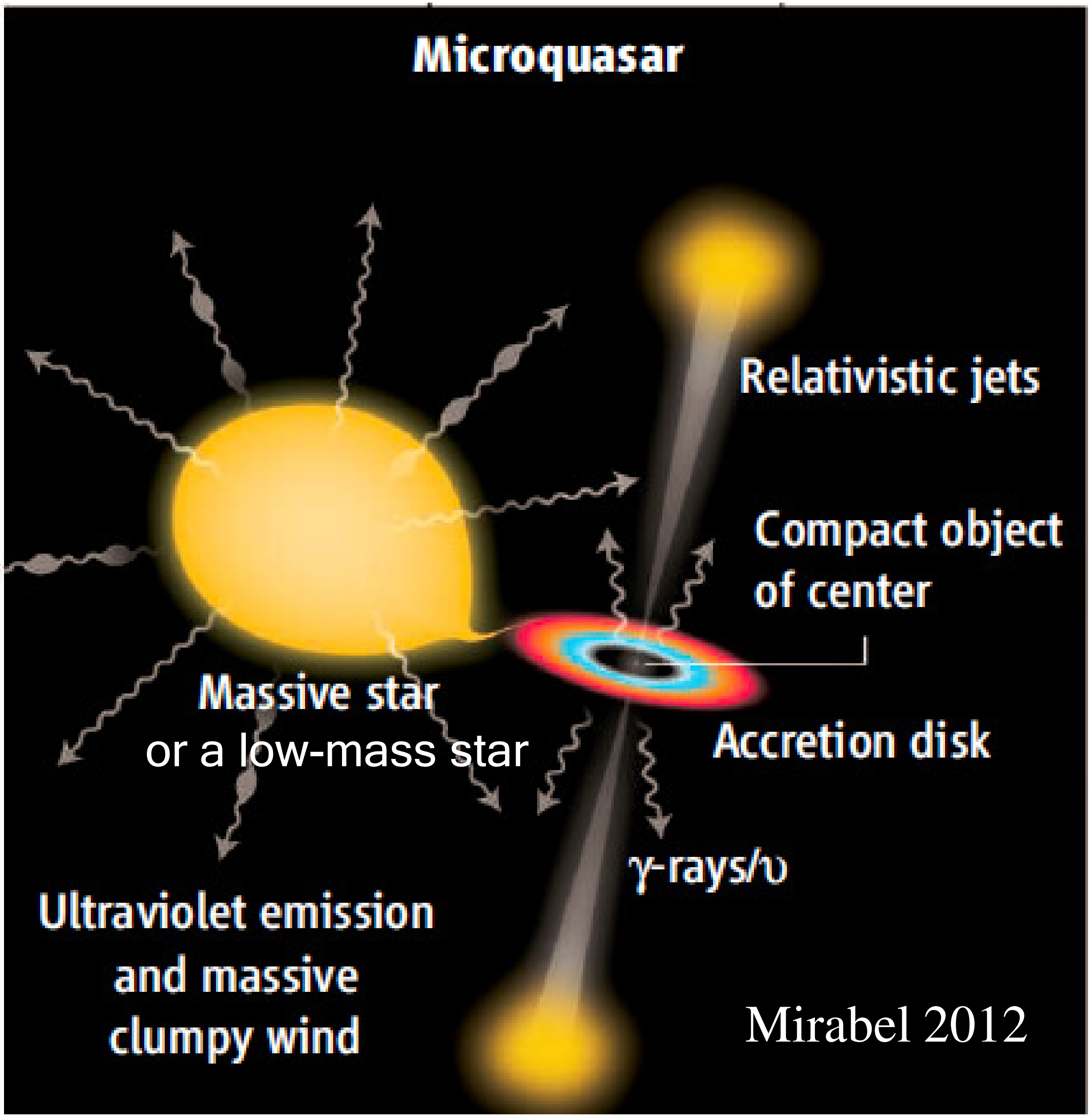
Accreting stellar binary systems with a compact object (black hole or neutron star)



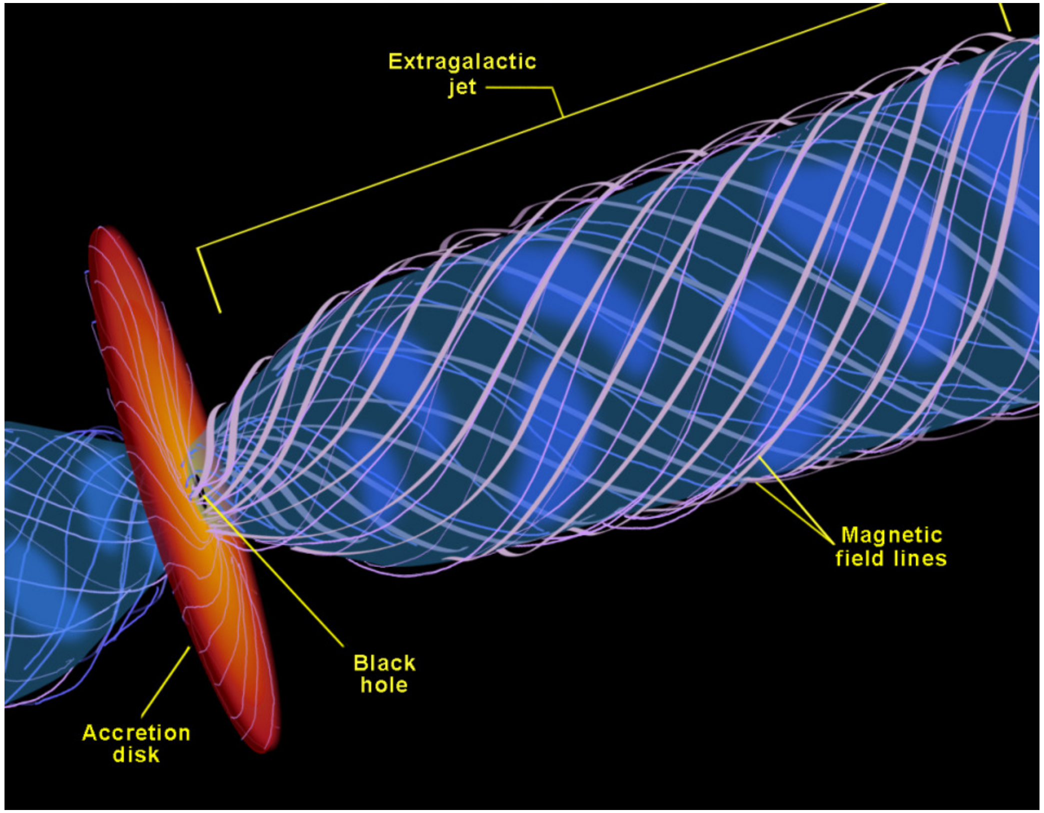
Mirabel 2012

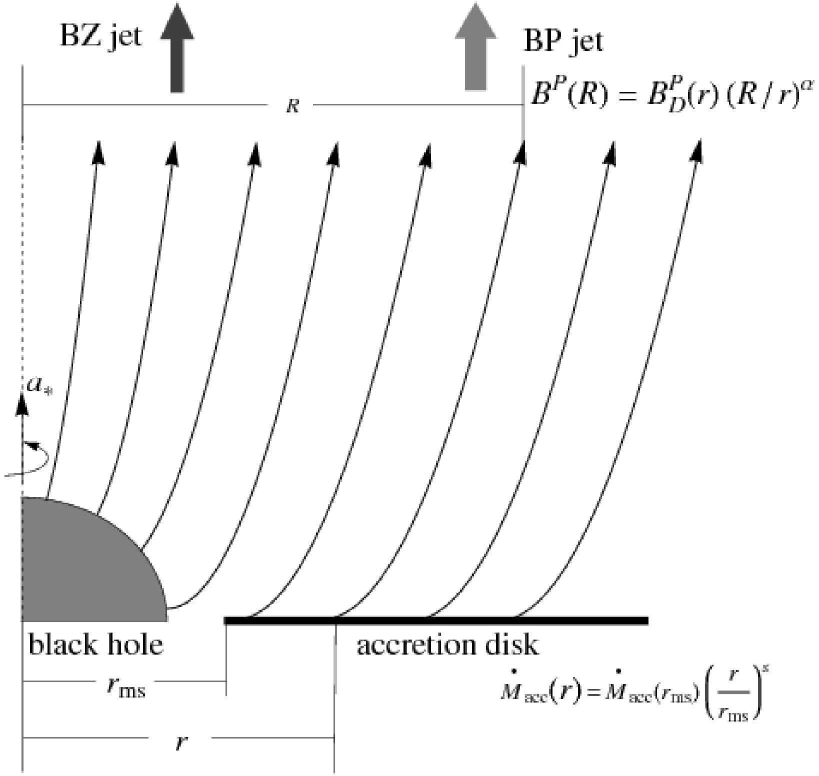
An accreting binary. The donor: either a high or a low-mass star.

Binaries containing a black hole (BH) and a massive donor (HMXB) are mostly persistent (high $\dot{M}$), and those with a low-mass donor (LMXB) are mostly transient (low $\dot{M}$; outbursts separated by years of quiescence).

Jet launching mechanisms

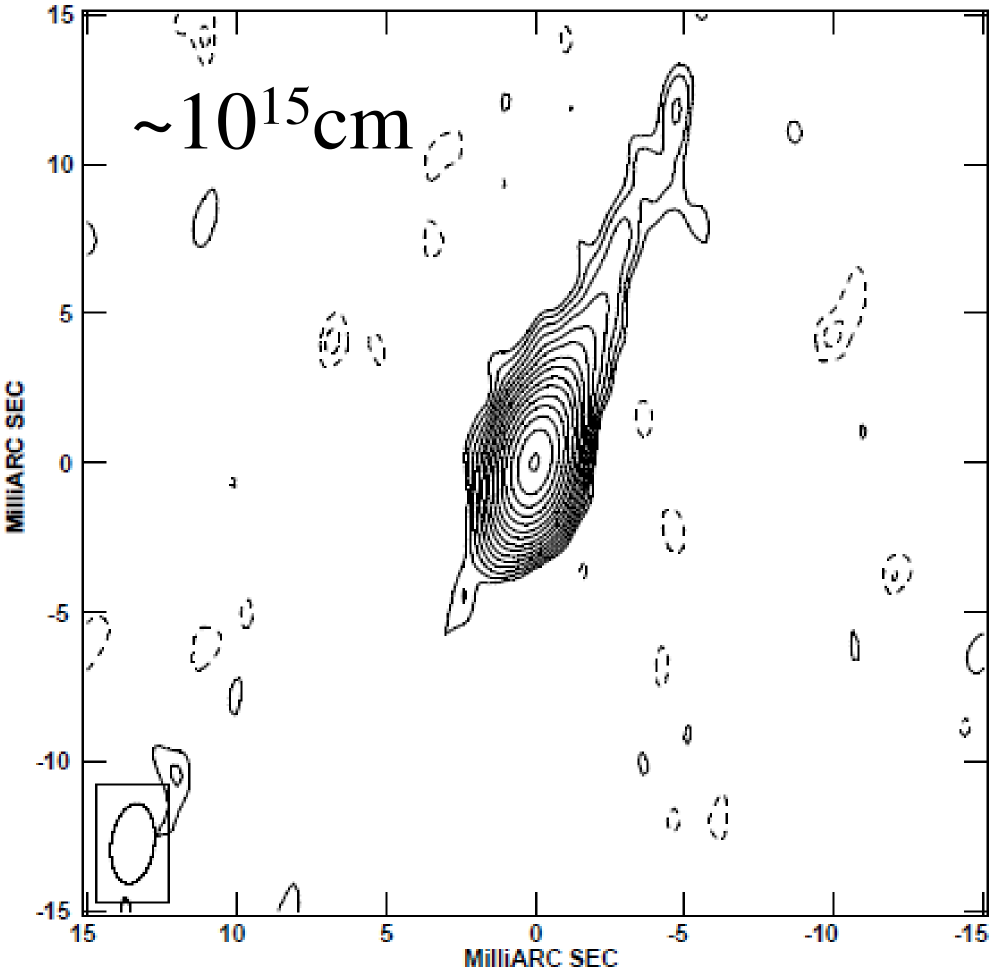
- Extraction of spin energy of a rotating BH (Blandford & Znajek 77; Tchekhovskoy+11; McKinney+12). $P_{\rm jet} \approx 96^{-1} a_*^2 B_{\parallel}^2 R_{\rm H}^2 c$.
- Collimation and acceleration by disc poloidal magnetic field (Blandford & Payne 1982). A lower jet power.
- Both mechanisms require the presence of a net vertical field.





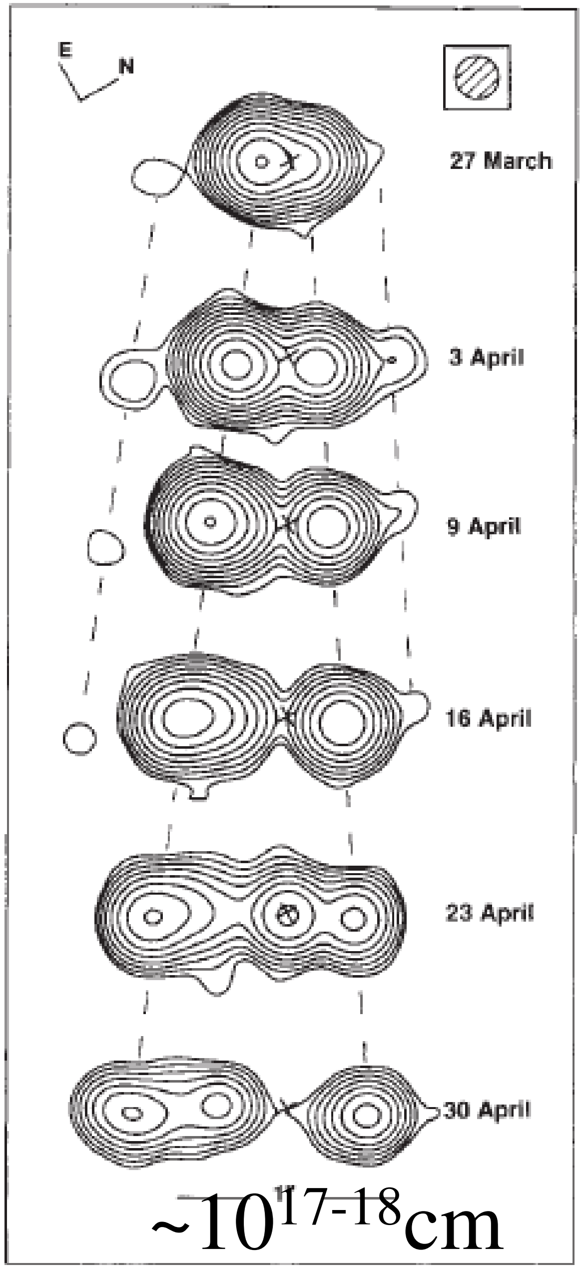
Two kinds of jets in BH binaries

steady and compact at low/medium *L*,
hard state



~10^{15}cm

Cyg X-1, Stirling+ 2001, Rushton+ 2010



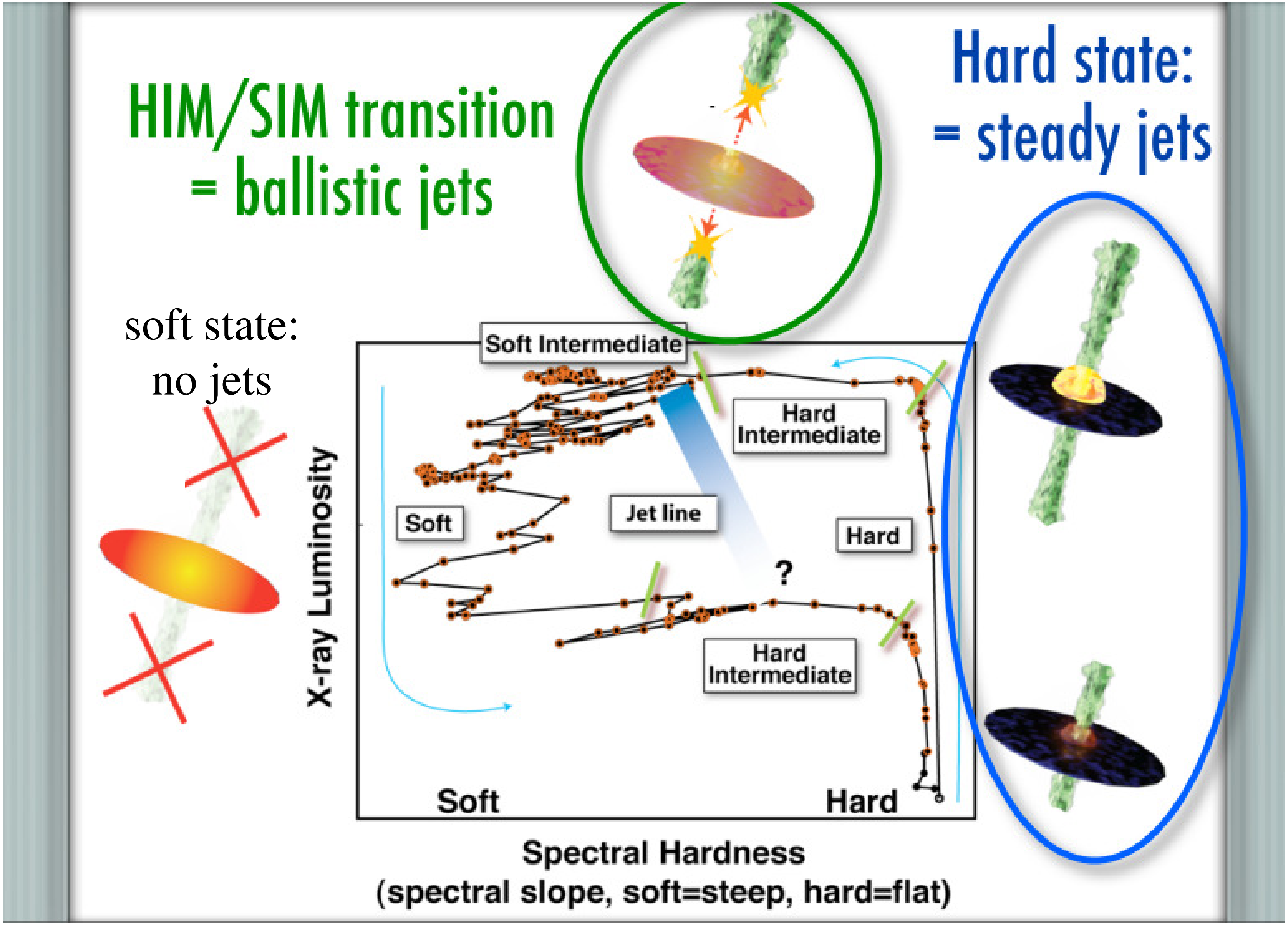
~$10^{17\text{-}18}$cm

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



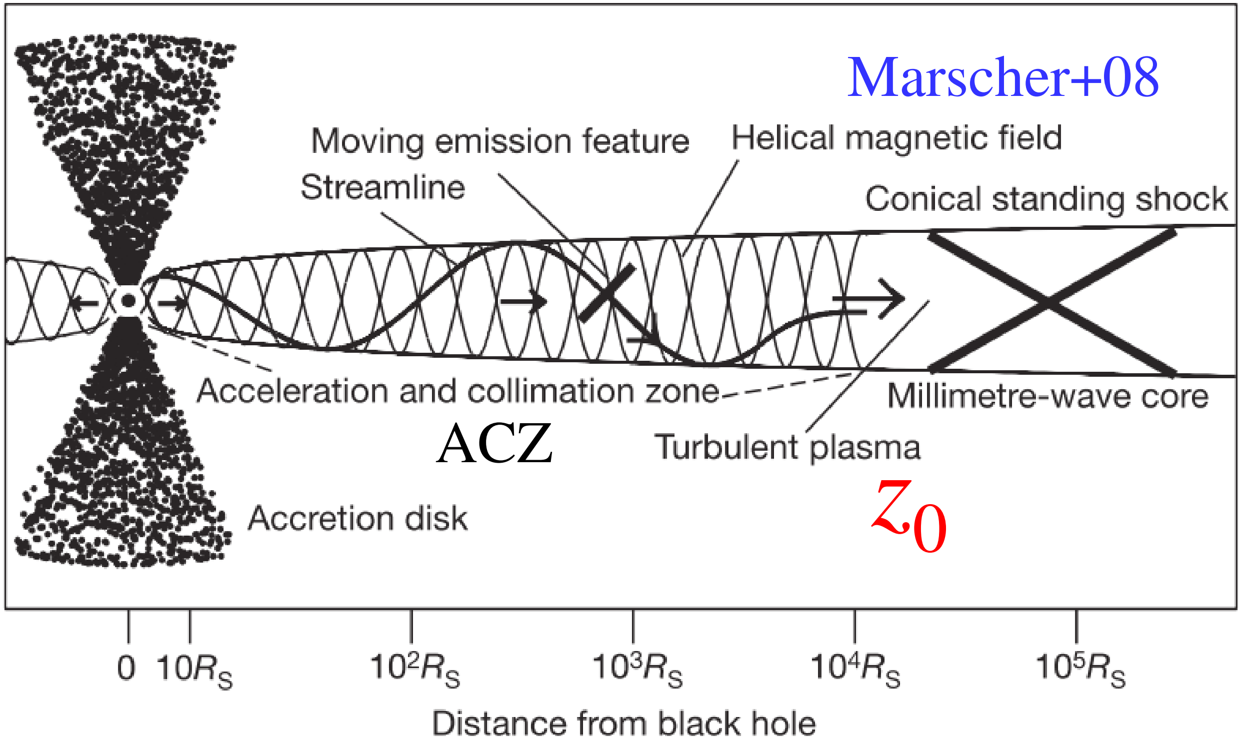
soft state:
no jets

Belloni
Fender

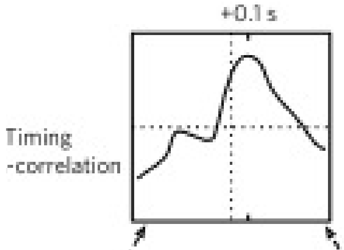
Compact jets: propagation

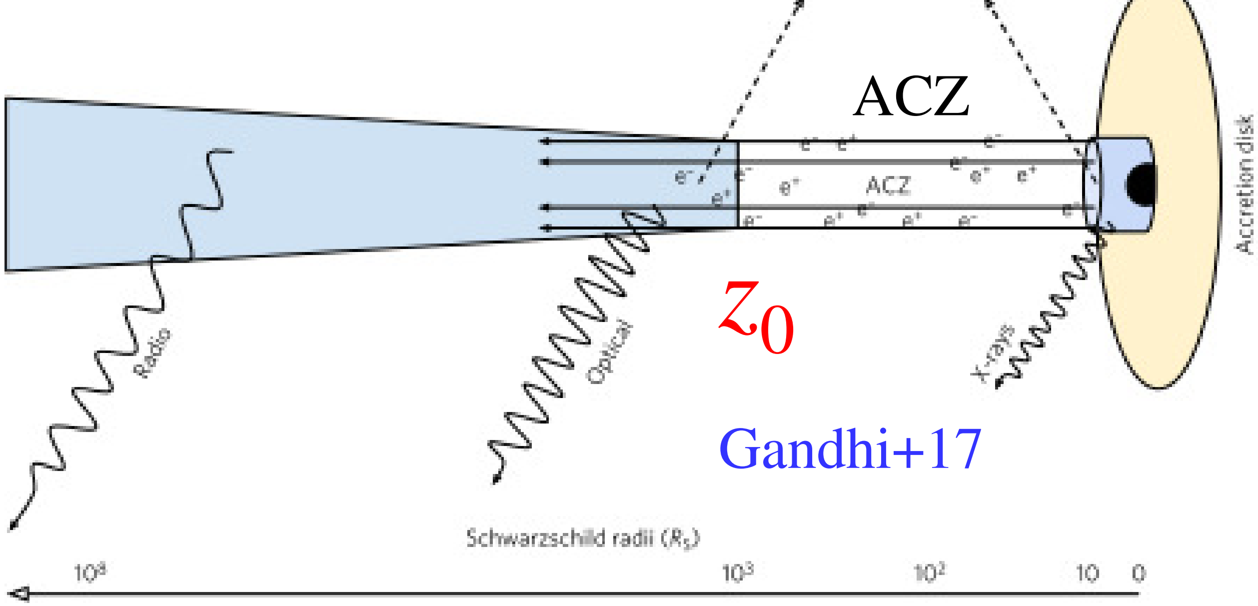
- The jet is initially magnetically-dominated and slow.
- The jet is accelerated at the expense of the toroidal magnetic energy flux.
- At some distance, z_0, along the jet a part of its power is dissipated and used to accelerate the electrons to relativistic energies.
- The nature of the dissipation process remains uncertain. It can be shocks or magnetic reconnection.

The jet structure



z_0 ~ 3000 R_g from a ~0.1 s time lag of the IR vs. X-rays (Gandhi=17)





Main models of jet radiation

1. A moving magnetized blob with relativistic electrons. This is a popular model for blazar emission. Can apply to ballistic blob ejection in transitional states of microquasars. Not for steady jets.
2. A conical jet with maintained power-law electron distribution and constant magnetic energy flux (Blandford & Königl 1979). Hard-state jets.

The main radiative processes are synchrotron emission and self-absorption, and Compton scattering of either synchrotron (SSC) or external photons.

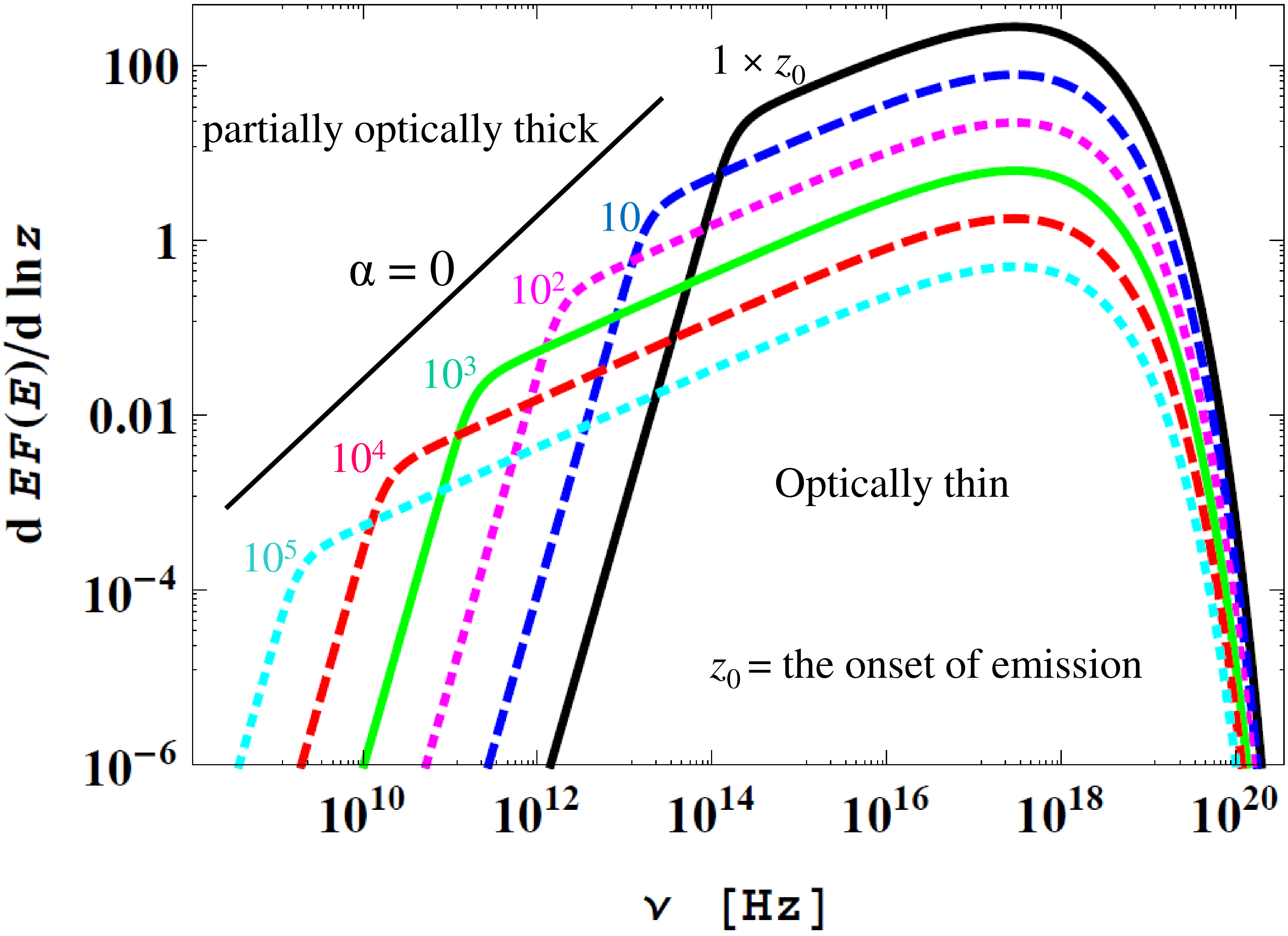
Main differences with respect to active galactic nuclei

- The radio vs. X-rays: BH binaries are much less radio loud than in AGNs (the `Fundamental Plane′; Merloni+03); caused by the scaling of the magnetic field strength with mass.
- Jets in black-hole binaries appear much slower than those in blazars; typical Lorentz factors $\Gamma \sim 2$ and $\Gamma \gtrsim 10$, respectively.
- But similar opening angles, $\Theta \sim 1^\circ$.

Compact hard-state jets:

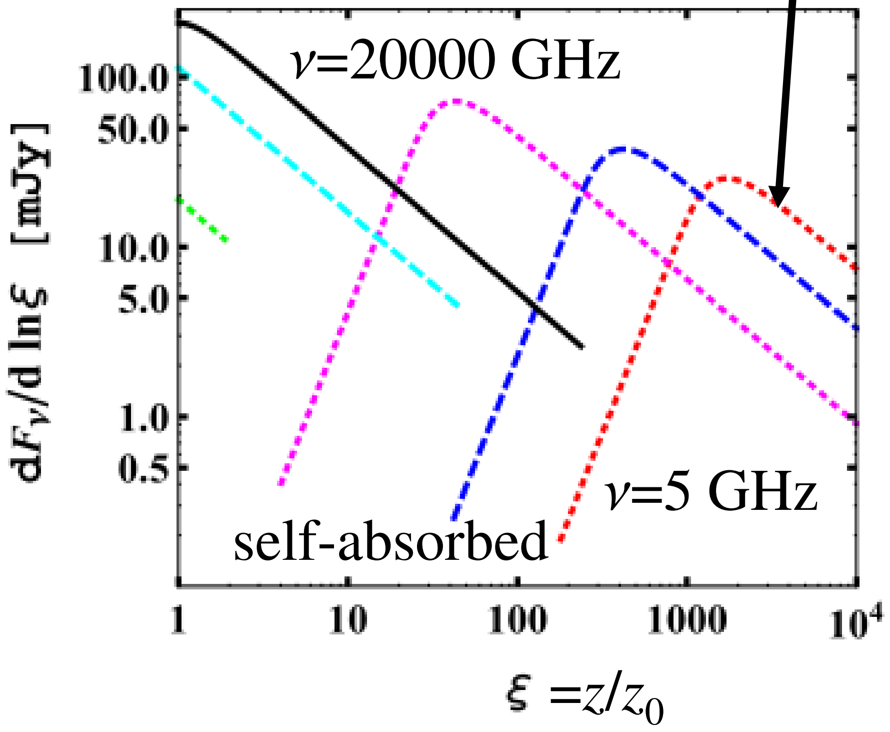
- The half-opening angle: usually of the order of $\Theta \sim 1^\circ$.
- The bulk Lorentz factor: $\Gamma \gtrsim 1.5$, poorly determined.
- The location of the onset of the emission: $z_0 \sim 10^{3-4} R_\mathrm{g}$.
- Approximately flat F_ν spectra ($\alpha \sim 0$), a break frequency in the IR, followed by an optically thin synchrotron spectrum.
- Usually explained by superposition of partially self-absorbed synchrotron spectra (Blandford & Königl 1979; Königl 1981).

Spectra from different parts of the jet

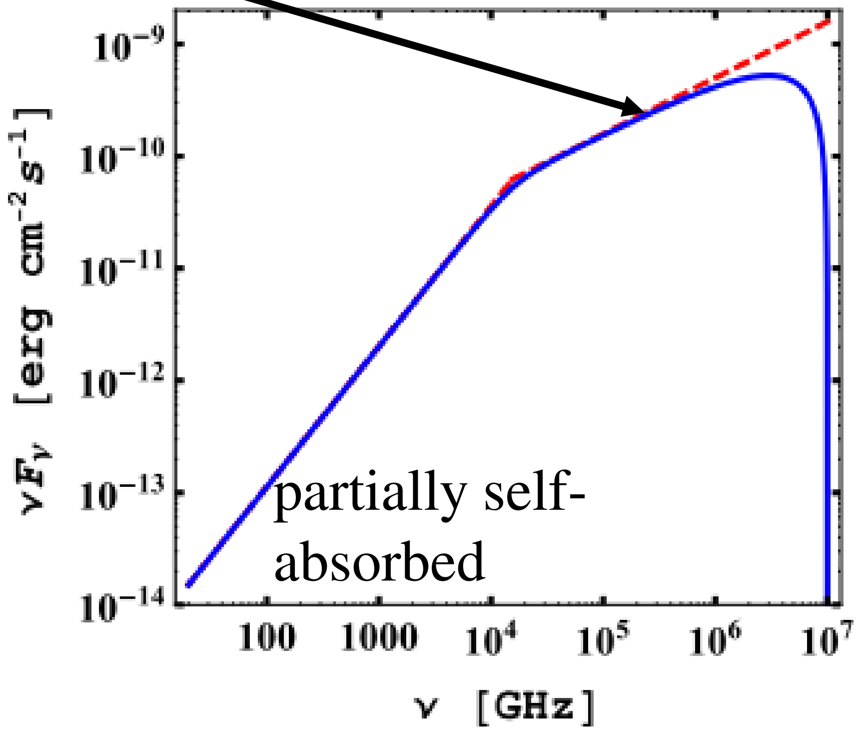


The structure of the emission

optically thin



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



An example of the total spectrum

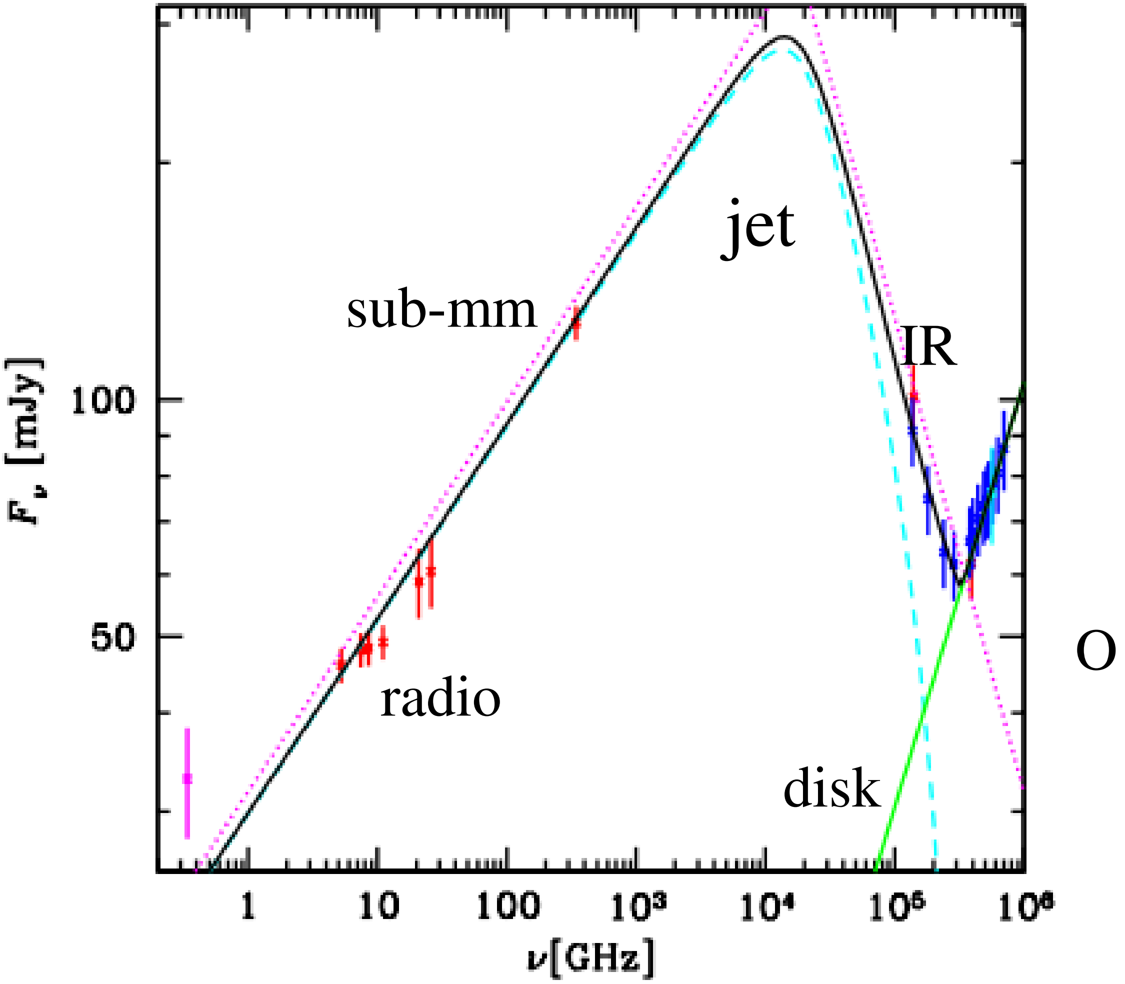
A well-studied LMXB: MAXI J1820+070

- A transient low-mass X-ray binary with a BH accretor, $P \approx 0.7$ d, $M_{\rm BH} \approx 6$–$7\,{\rm M}_\odot$ (Torres+20; Mikołajewska+22).
- A major outburst in 2018, the hard, intermediate, soft, intermediate, hard, quiescent states.
- 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 in the hard state on 2018 April 12;
- → an opportunity for accurate determination of the jet parameters.

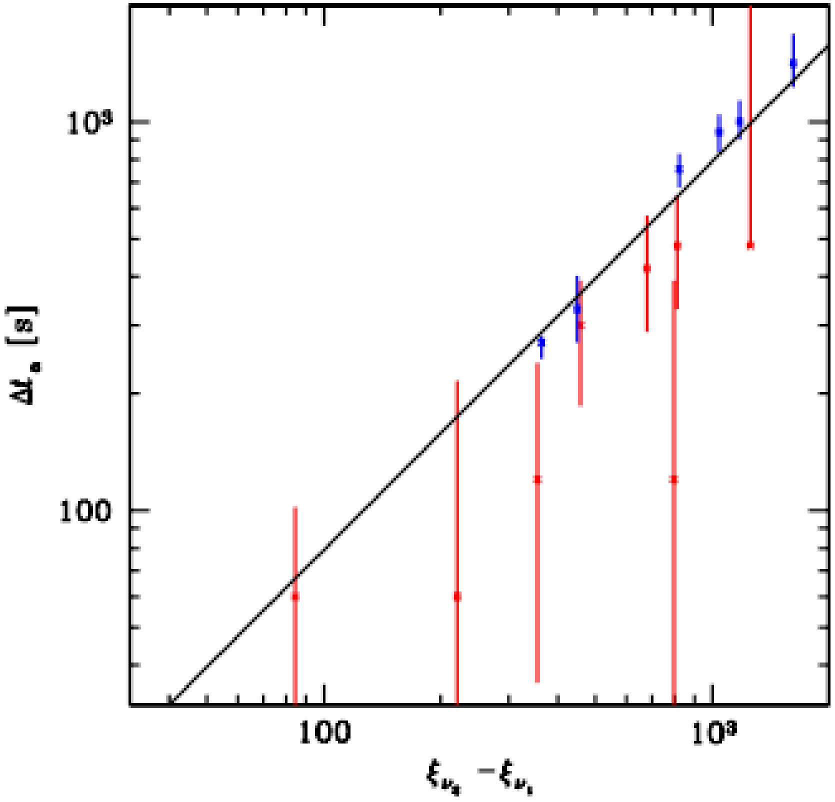
The hard-state jet in MAXI J1820+070

- The bright hard state on 2018 April 12: VLA, ALMA, VLT, NTT, NICER and INTEGRAL observations.
- Time lags including radio frequencies, power spectra, spectra.
- An analysis by AAZ, Tetarenko & Sikora 22.
- 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.

Fits to the spectrum and lags



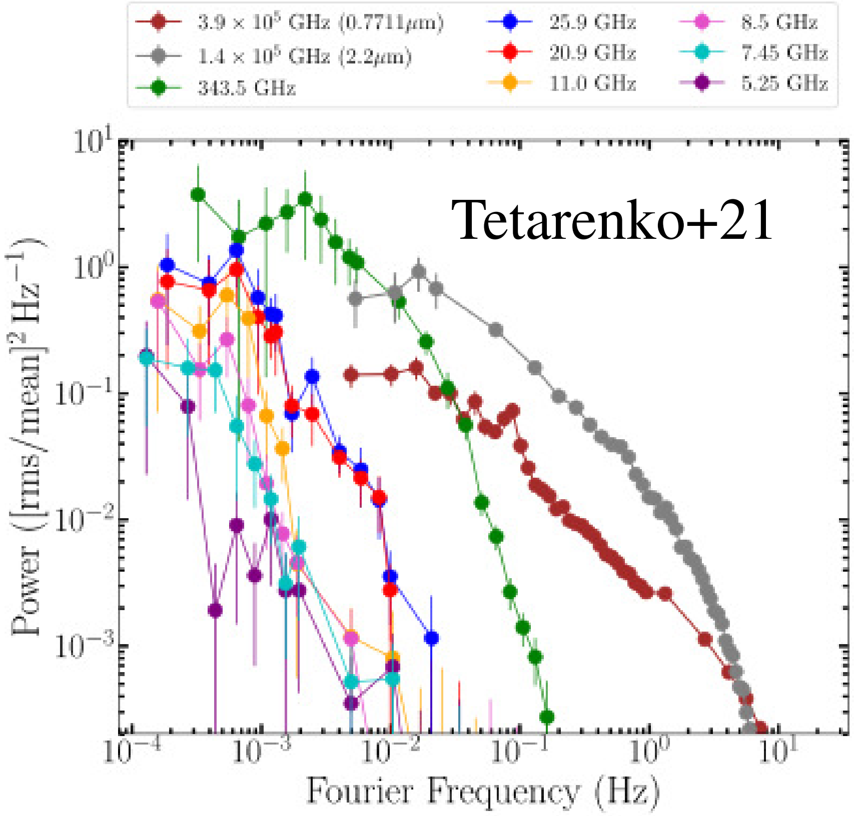
The observed spectrum
and our fit



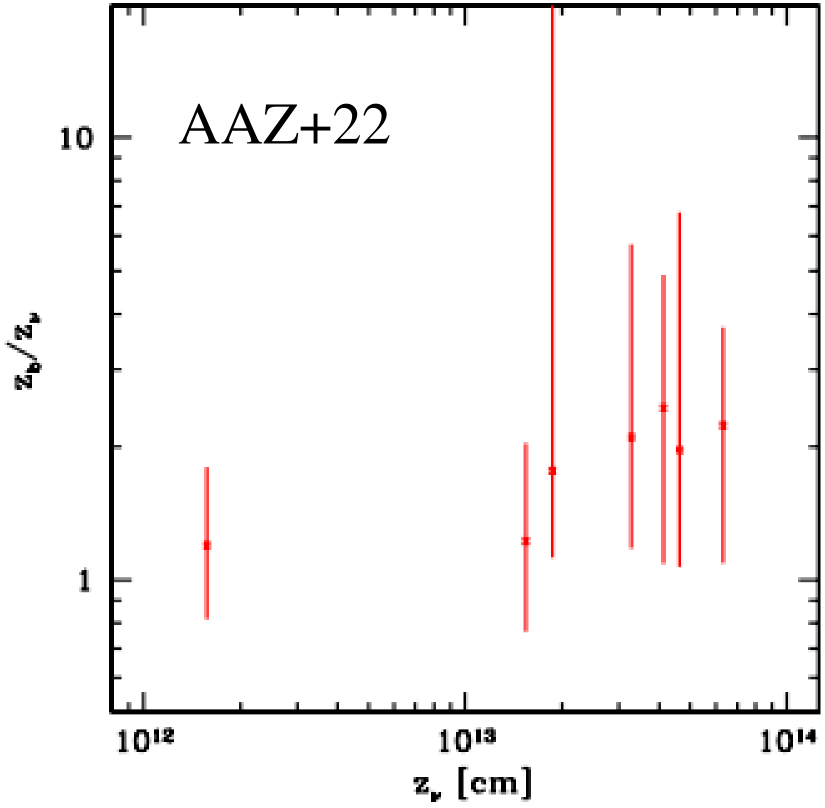
Time lags between various radio and sub-mm frequencies vs. the separation in units of z_0. Analogous to core shifts in blazars.

We obtain $z_0 \sim 10^4 R_g$, $B_0 \approx 10^4$ G.

Break frequencies of power spectra



Tetarenko+21



AAZ+22

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 $i = 64^\circ$, 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.

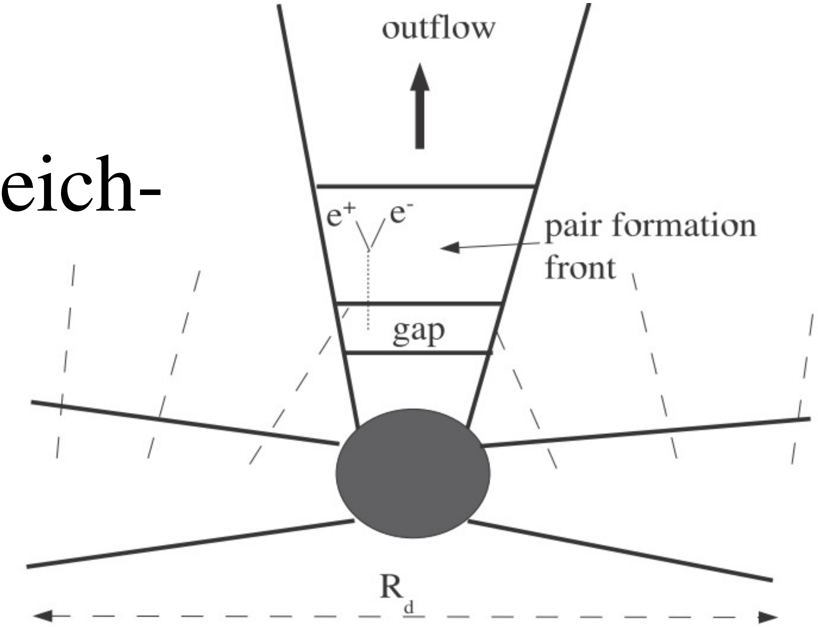
Are there e± pairs in jets?

- 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: $n_{GJ} = \dfrac{\Omega B}{2\pi e c} \propto P_j^{1/2}$

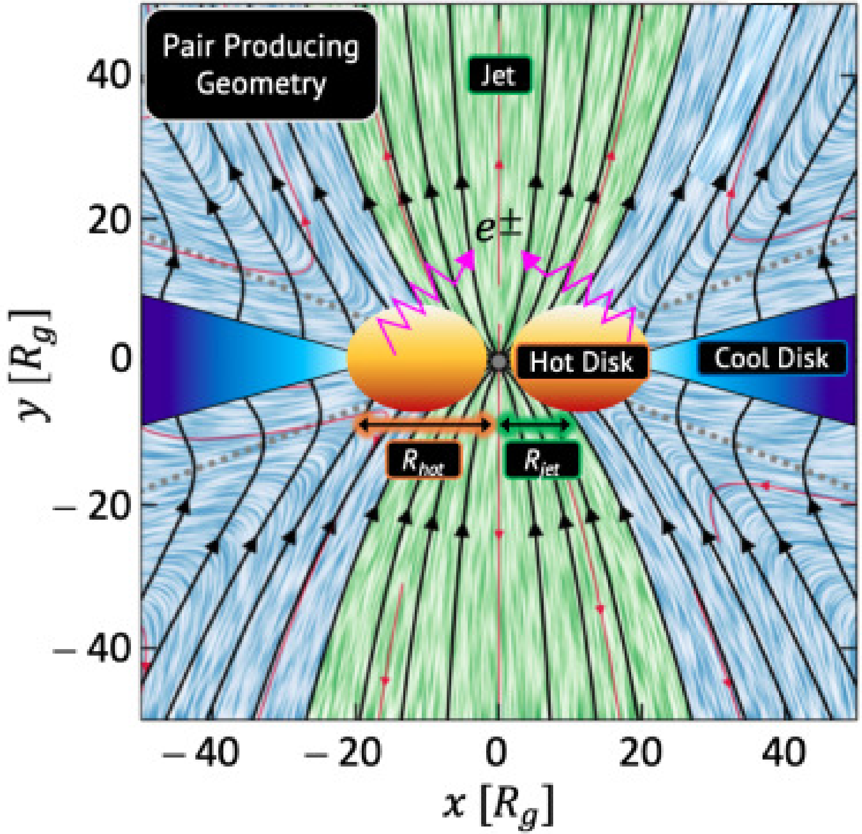
- Levinson & Rieger 07 give

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

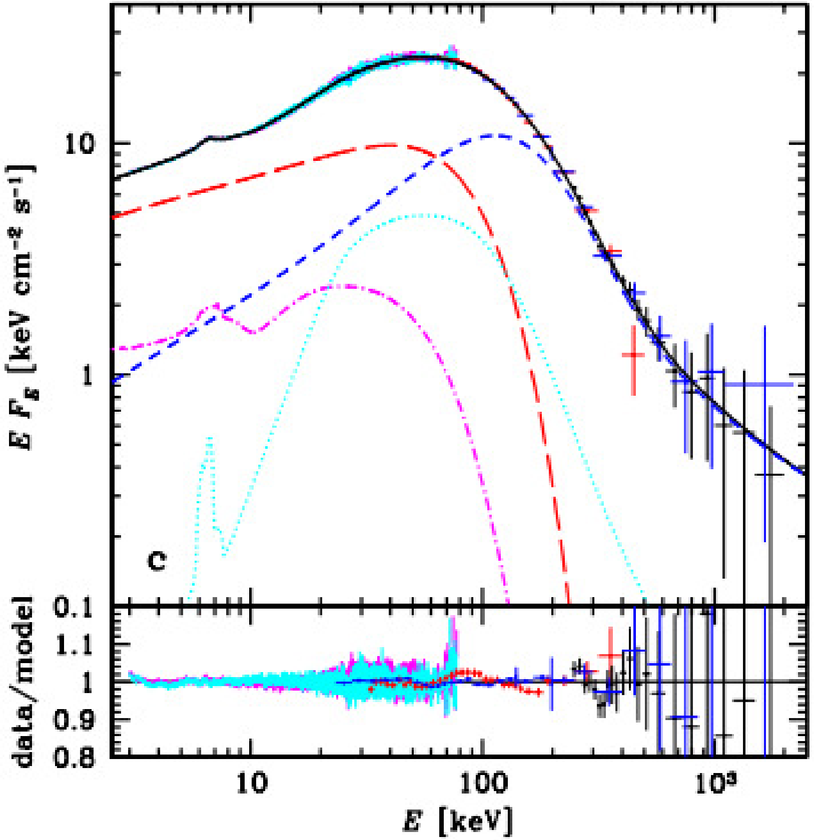


- Nokhrina+15 find $\sim 10^{12\text{-}15} n_{GJ}$ in blazars, and we find $> 10^7 n_{GJ}$ in MAXI J1820+070.
- This rules out this process as producing most of pairs.

An alternative: $\gamma\gamma$ e± pair production



The proposed geometry overplotted on the jet simulation from Tchekhovskoy 15.

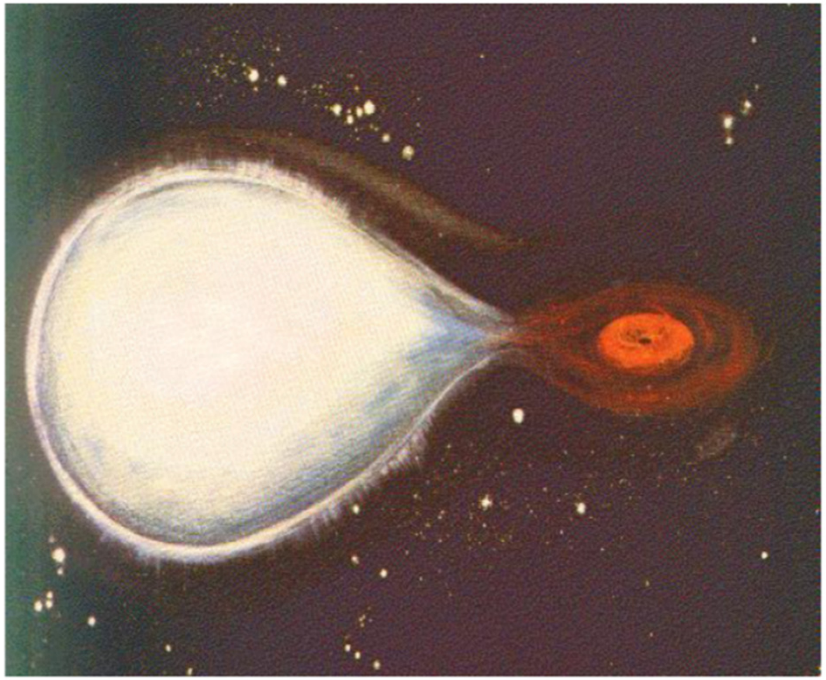


The spectrum of MAXI J1820+070 from NuSTAR and INTEGRAL

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

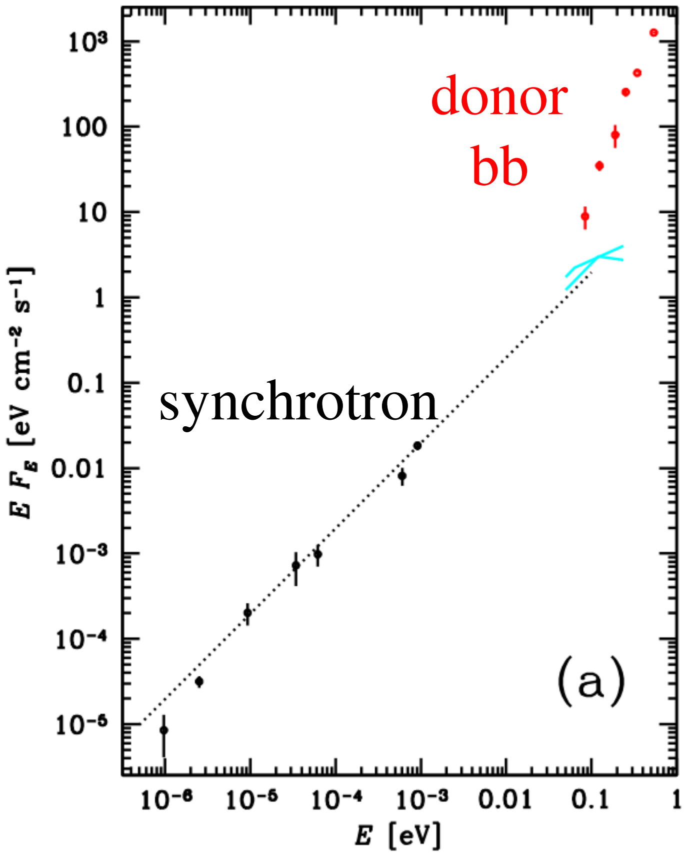
→ Pairs may dominate the jet by number.

Cyg X-1

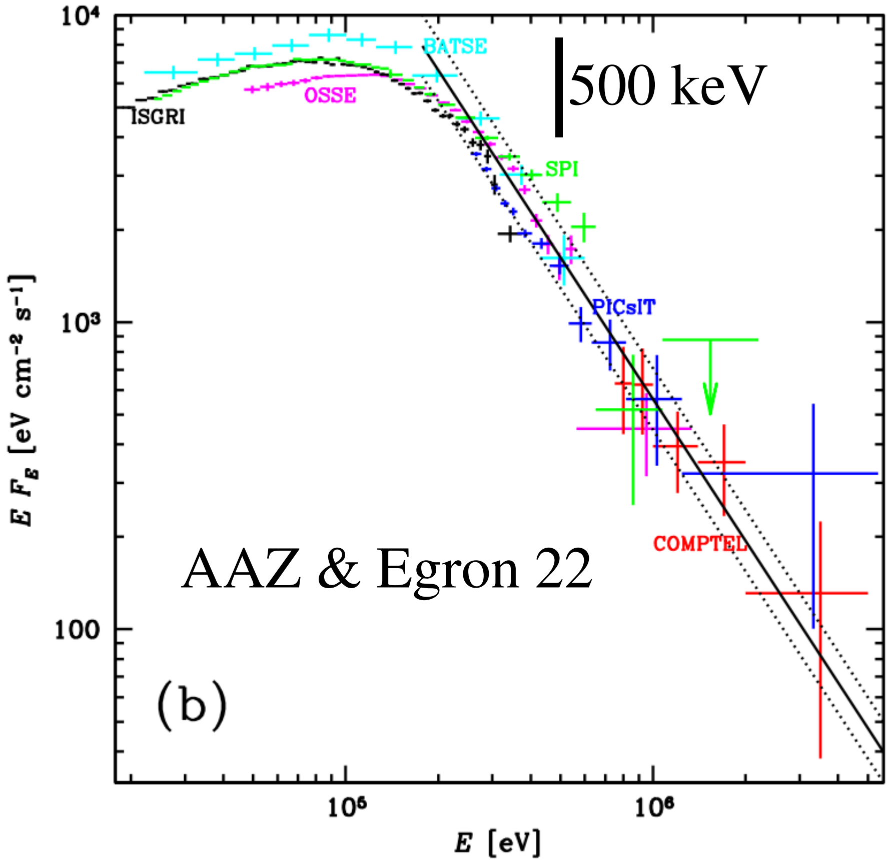


- An accreting black-hole binary. Donor: OB supergiant. $P = 5.6$ d, $D \approx 2$ kpc, $M_{\rm BH} \approx 20\ {\rm M}_\odot$ (Miller-Jones+21).
- Wind accretion, the donor nearly fills its Roche lobe.
- Emission from radio to GeV.

$\gamma\gamma$ $e^{\pm}$ pair production in Cyg X-1



The radio-to-IR spectrum
→ the electron flow rate

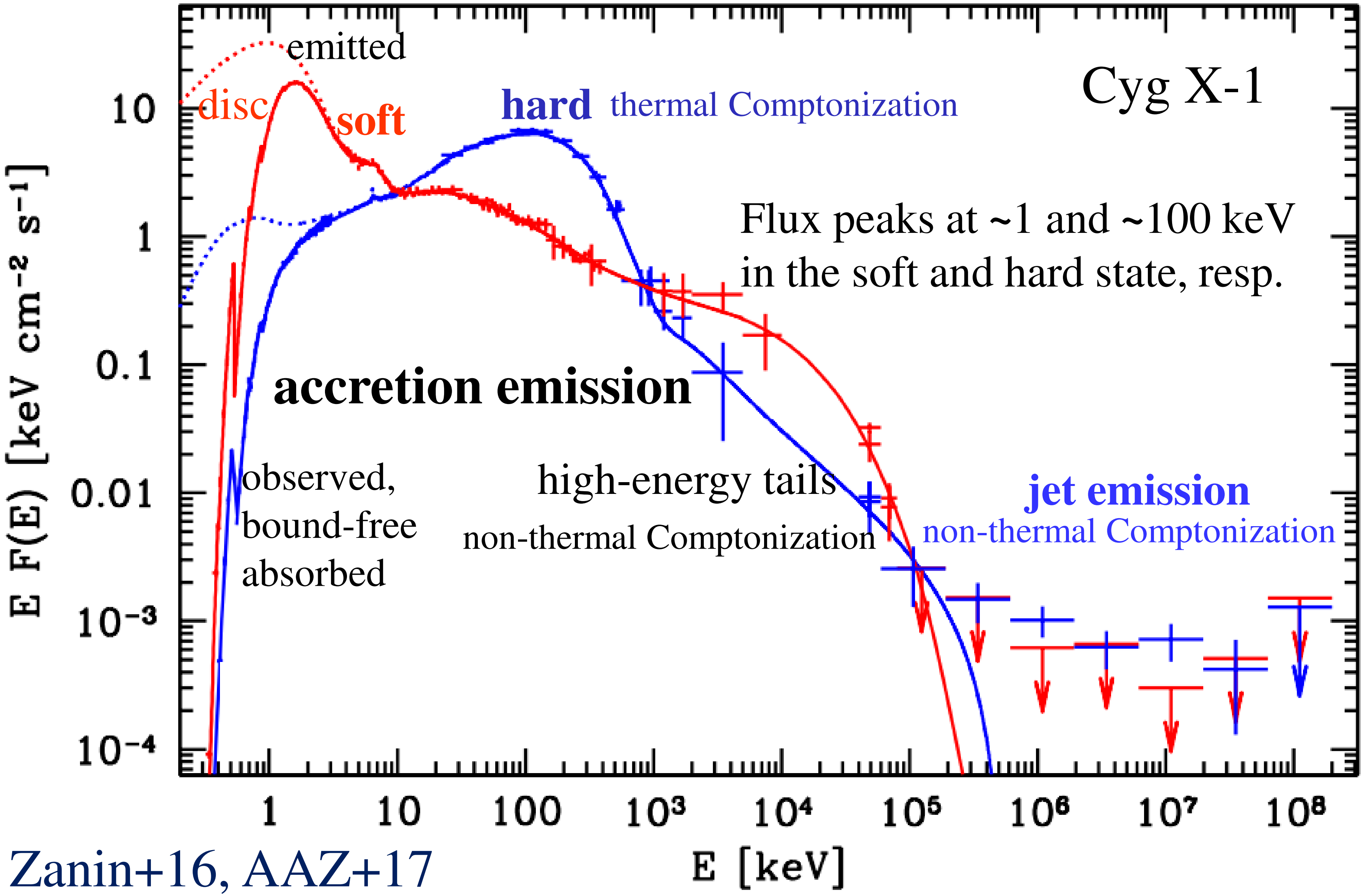


The Xγ spectrum of Cyg X-1
from CGRO and INTEGRAL →
the pair production rate

The pair production rate within the jet base: ~10^{40} s^{-1} ≈ the rate of the flow of $e^{\pm}$ calculated at ~$10^6 R_g$ from the observed synchrotron emission. The same coincidence as in MAXI J1820+070, also in the radio galaxy 3C 120.

→ Pairs may dominate the jet by number.

High-energy γ-rays in the hard and soft spectral states of Cyg X-1

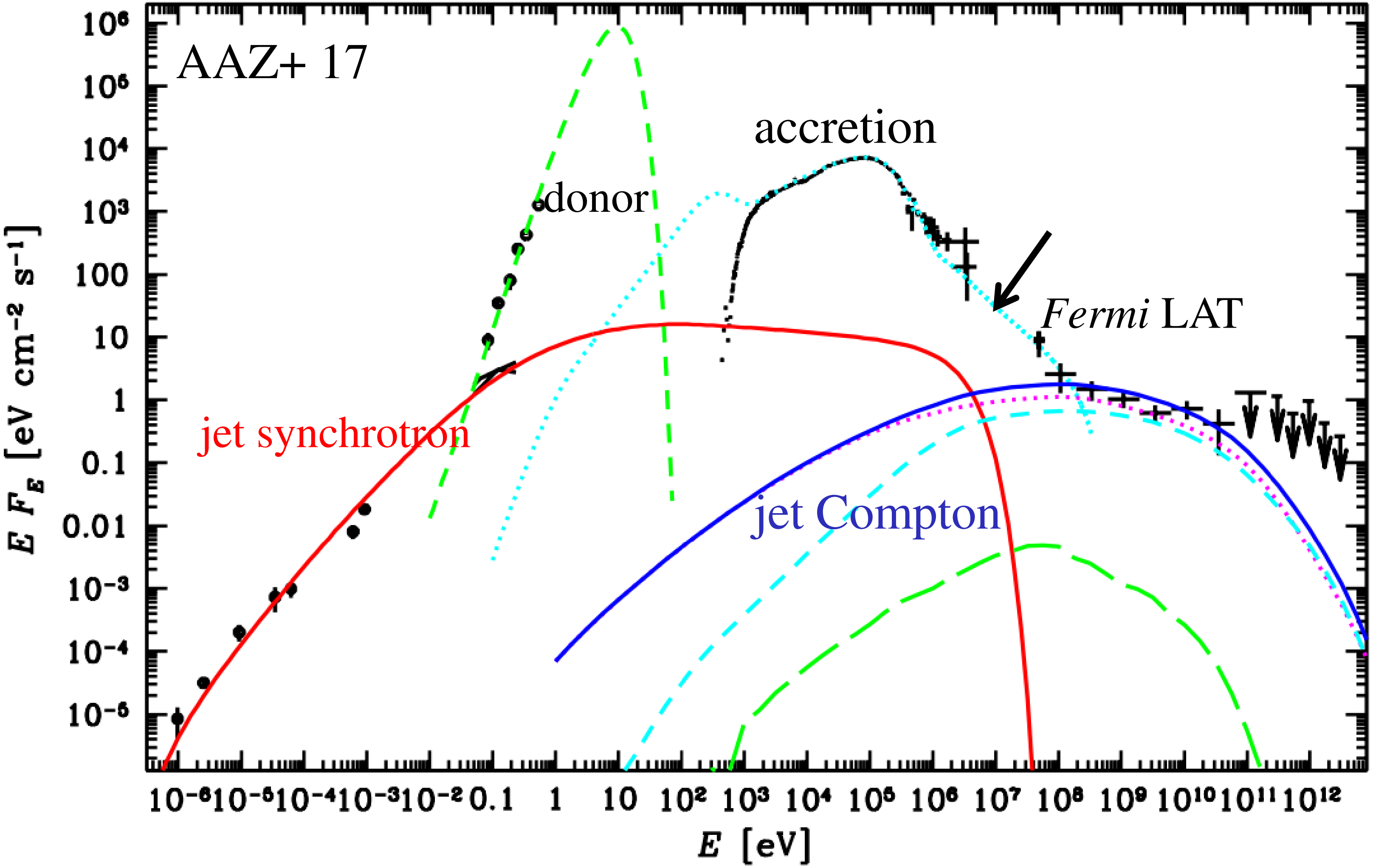


Flux peaks at ~1 and ~100 keV in the soft and hard state, resp.

Zanin+16, AAZ+17

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 jet power and the Blandford-Znajek mechanism

- We have $P_{\rm jet} \approx 96^{-1} a_*^2 B_{\parallel}^2 R_{\rm H}^2 c$, and $B_{\parallel} = B_{\perp}(c\beta\Gamma/\Omega_{\rm f} r)$ (B in the jet frame, ideal MHD; Blandford & Znajek 77).
- We can then compute the magnetic flux, $\Phi_{\rm j} = \int {\rm d}r B_{\parallel} r^2$, in the radio emission region (dominated by $B_{\perp}$) $\longrightarrow P_{\rm jet}$.
- The maximum Φ threading the BH, corresponding to magnetically arrested accretion (MAD), is $\Phi_{\rm BH} \approx 50(\dot{M}_{\rm accr} c r_{\rm g})^{1/2}$, and then $P_{\rm jet,max} \approx 1.5\dot{M}_{\rm accr} c^2$ (Tchekhovskoy+11).
- $\Phi_{\rm j}$ and $\Phi_{\rm BH}$ can be compared, and are found similar in luminous blazars (Zamaninasab+14, AAZ+15).

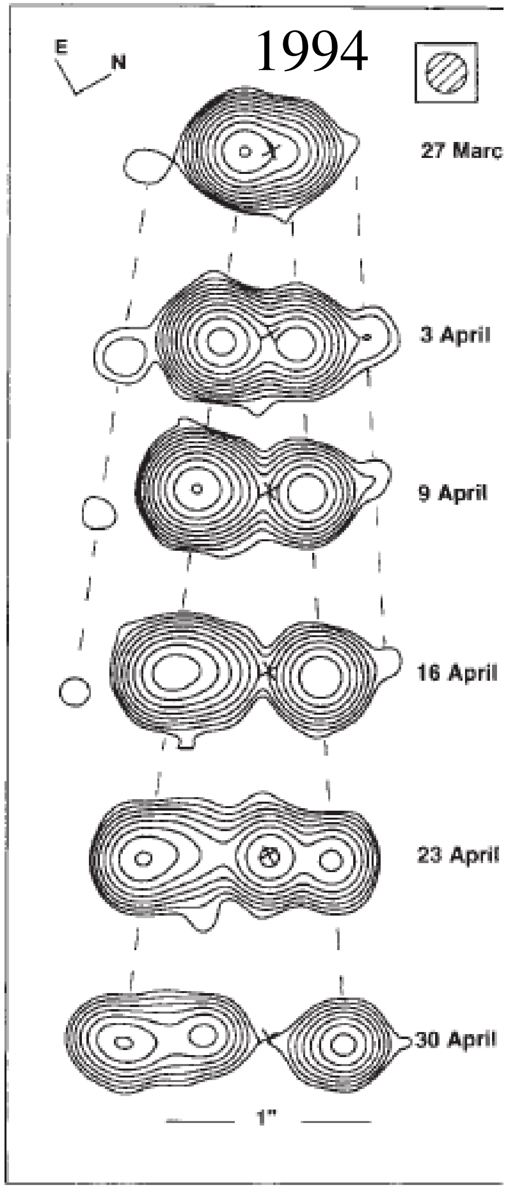
The jet power

- In MAXI J1820+070, $\Phi_{\mathrm{jet}} \sim 10^{22}\,\mathrm{G\,cm}^2 \sim \Phi_{\mathrm{BH}}$, which corresponds to the maximal jet power, $P_{\mathrm{j}} \approx \dot{M}_{\mathrm{accr}} c^2$, and magnetically arrested accretion – another coincidence.
- The jet power can be also calculated from the observed synchrotron emission.
- It consists of the components in (1) magnetic field and relativistic electrons and (2) the bulk motion of ions.
- The latter strongly depends on the abundance of pairs.
- In addition, we can consider the magnetization parameter, $\sigma_0 \equiv \frac{B_0^2/4\pi}{\eta u_{\mathrm{k},0} + \rho_0 c^2} \approx \frac{B_0^2/4\pi}{n_0 f_N \mu_{\mathrm{e}} m_{\mathrm{p}} c^2 (1 - 2n_+/n_{\mathrm{e}})}$, together with the causality constraint, $\sigma_0 \equiv (\Theta\Gamma/s)^2$, $s \lesssim 1$ (Tchekhovskoy+09).

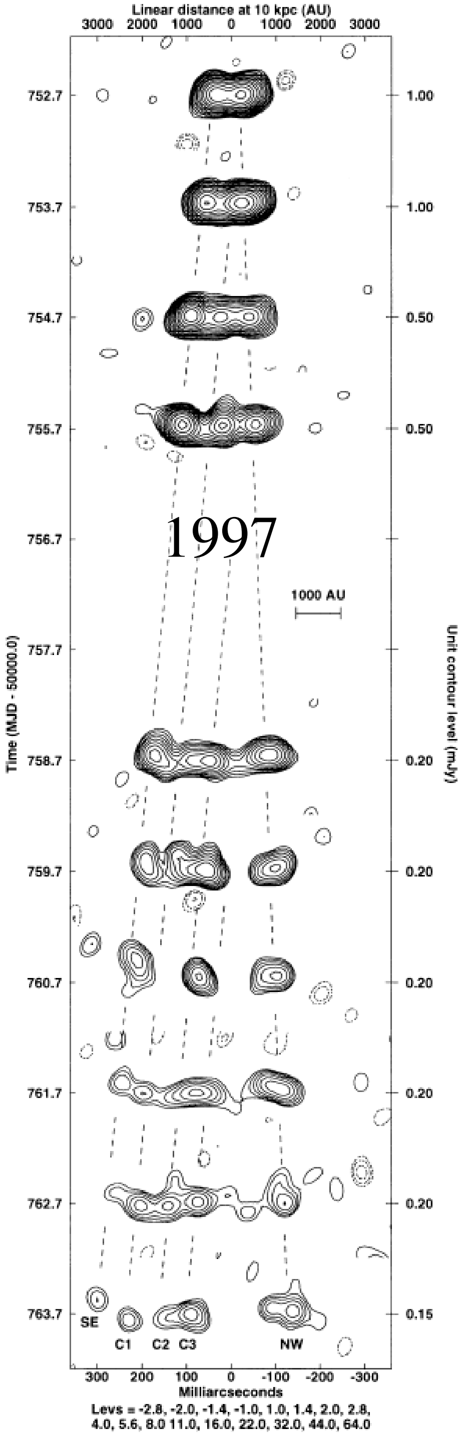
Ballistic jets in transitional states: the case of GRS 1915+105

GRS 1915+105

Two major mass ejections in 1994 and 97: the ejecta angular velocities allow us to calculate the bulk Lorentz factor as a function of the distance. Then the minimum (equipartition) jet power can be calculated based on the observed synchrotron spectrum.

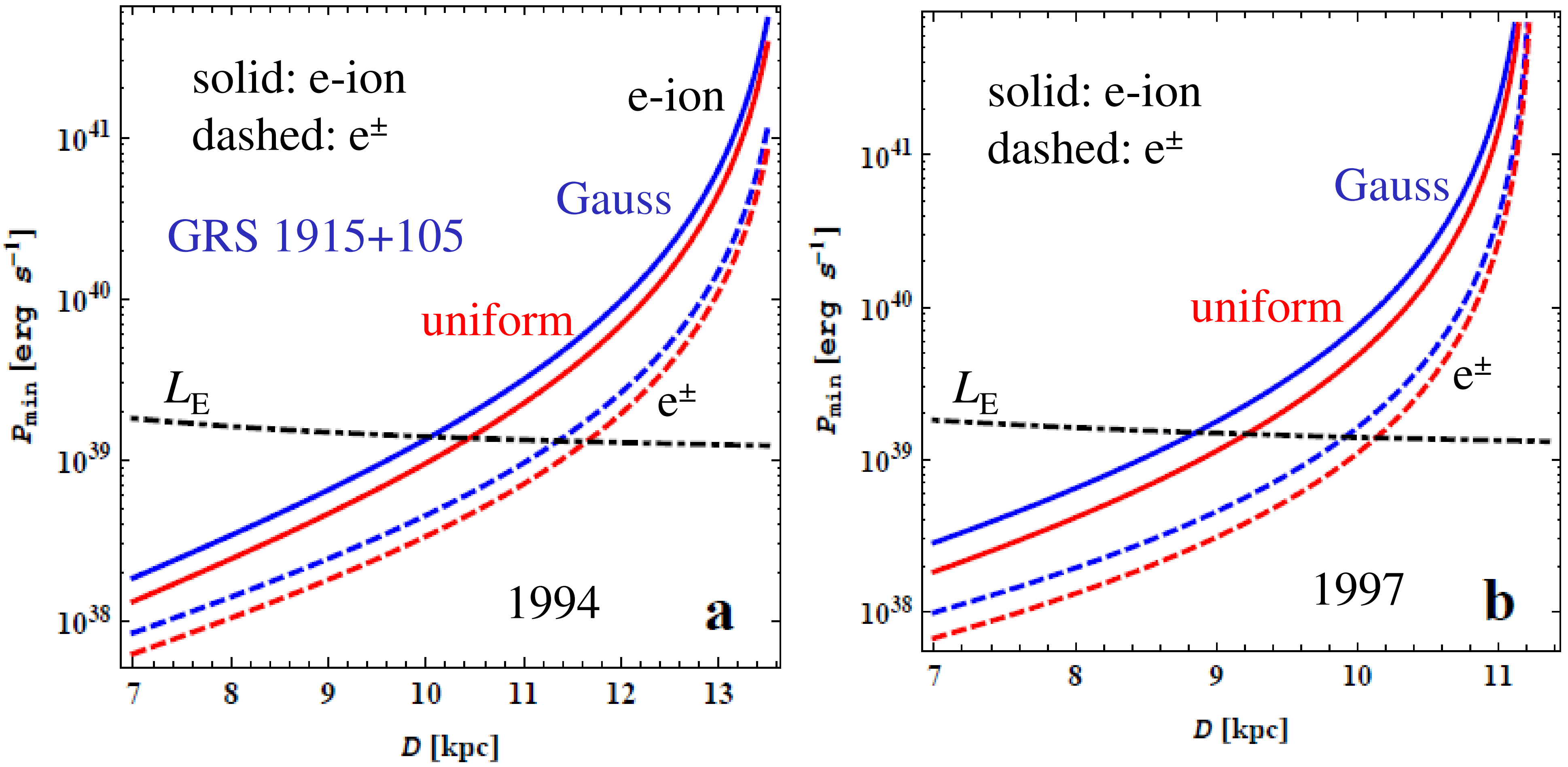


Mirabel & Rodriguez 1994



Fender+1999

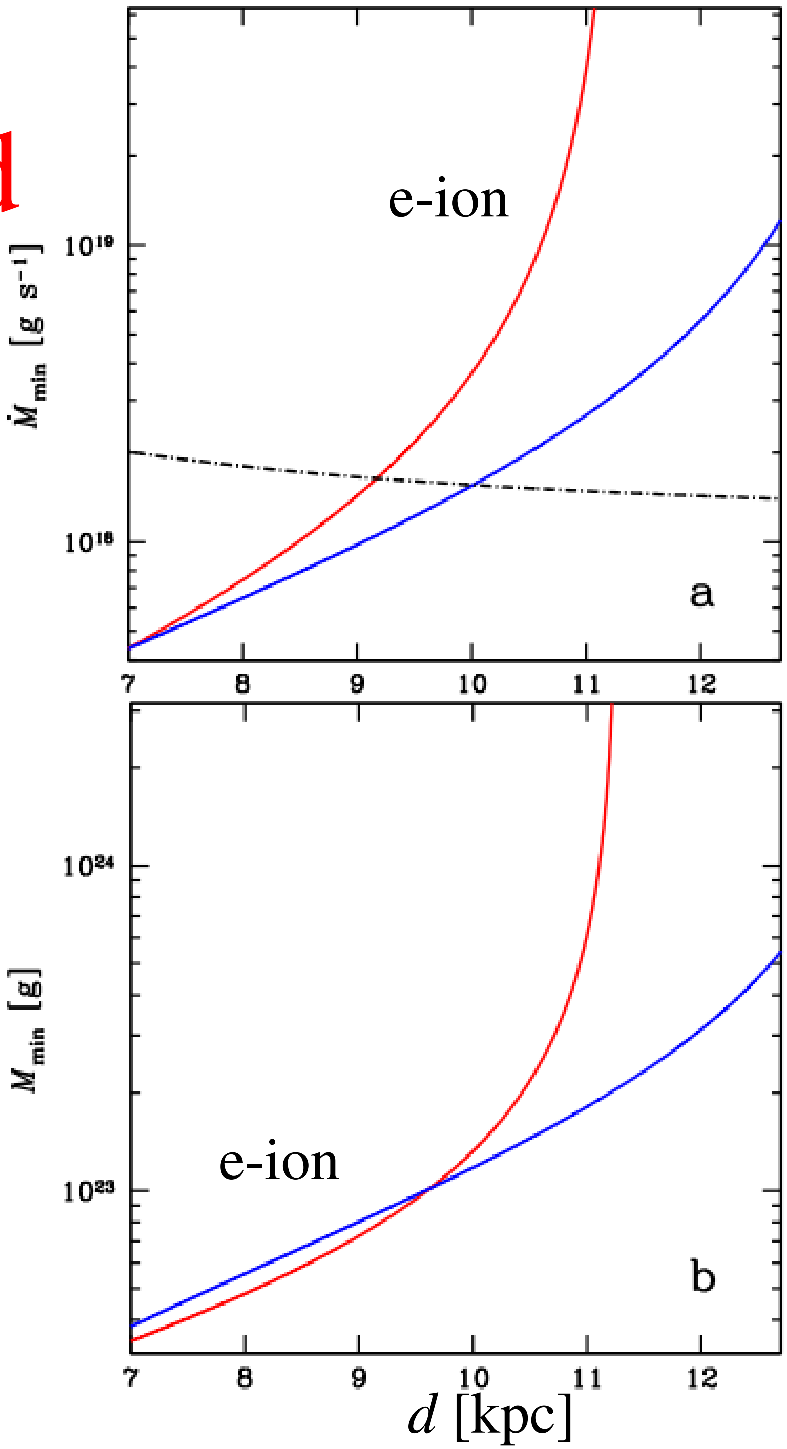
There have been previous claims of the jet power of **~10^{41} erg/s**. AAZ14 calculated the *minimum* jet power of as a function of the distance for the two major mass ejections:

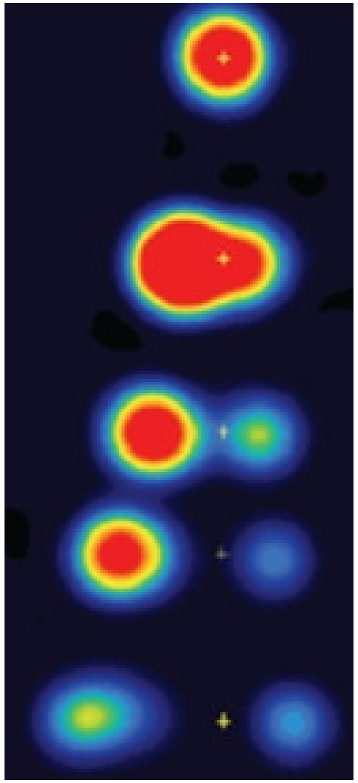


The present distance of $8.6^{+2.0}_{-1.6}$ kpc (Reid+14) implies a moderate, possibly sub-Eddington jet power and a slow jet, $\Gamma_j < 2$. The bolometric L during the ejections was $\sim L_E$, implying $\dot{M}_{accr}c^2 \sim 5L_E$, allowing $P_{jet} \lesssim \dot{M}_{accr}c^2$. Spin-extraction jet formation is possible but not proven.

The minimum jet mass flow rate and the ejecta mass

- We can also calculate the minimum $\dot{M}_{\rm j}$ through the jet and the minimum mass of the ejecta.
- Assuming no pairs, the minimum $\dot{M}_{\rm j} \approx 0.1\dot{M}_{\rm accr}c^2$.
- The minimum mass in the blob is accumulated during ~10^4 s.
- $\approx$ the accretion time from ~$10^3 R_{\rm g}$, which is the size of the radiation-pressure dominated disc region.





Summary

- Two types of jets in accreting BH binaries: compact steady jets and blob ejections.
- Pair production within the compact jet base by photons from the accretion flow can provide enough $e^{\pm}$ for the observed synchrotron emission.
- The magnetic flux measured in the emission region implies that accretion can be magnetically arrested.
- The estimated jet power $\lesssim \dot{M}_{\rm accr} c^2$ for both compact jets and ejecta.