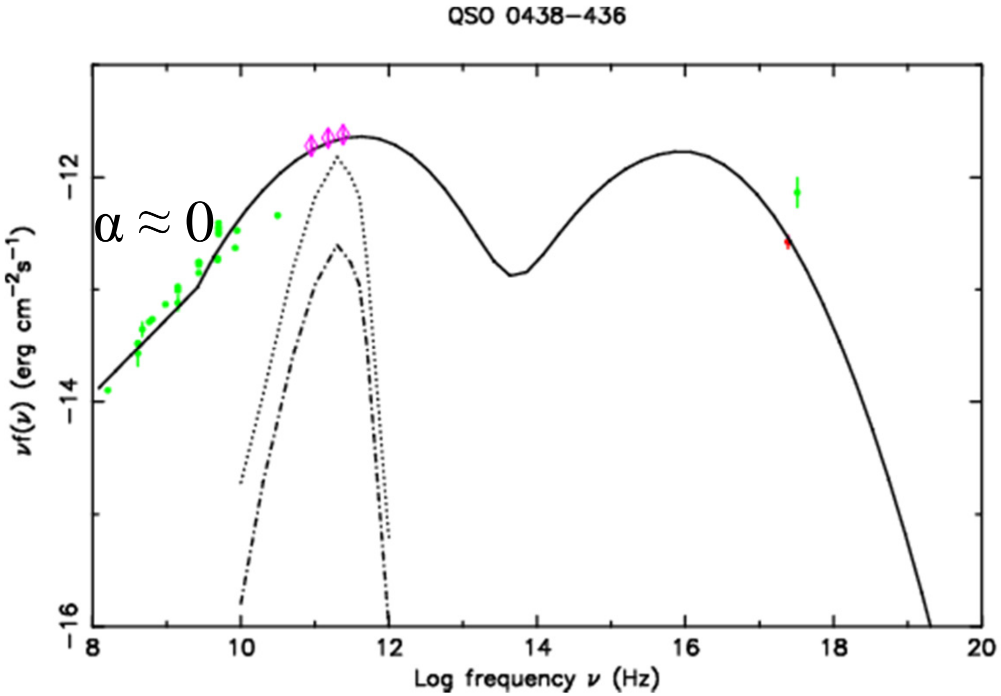
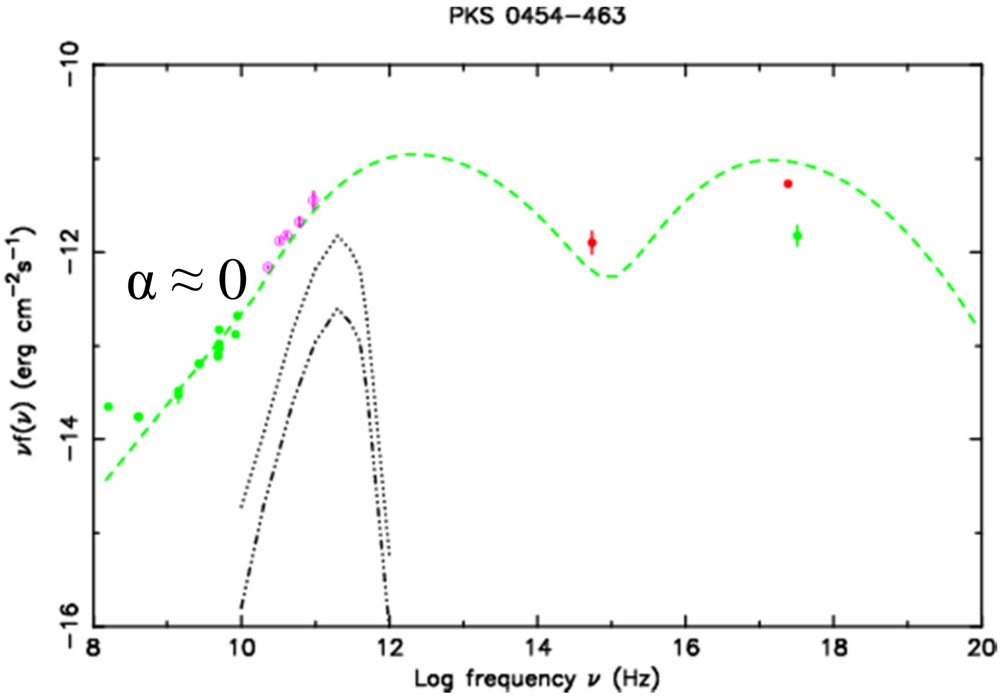
Extended jet models of black-hole binaries and AGNs

Andrzej A. Zdziarski
Centrum Astronomiczne im. M. Kopernika
Warszawa, Poland

With Marek Sikora, Patryk Pjanka, Łukasz Stawarz,
Denis Malyshev, Masha Chernyakova

Motivation: study broad-band spectra while accounting for approximately flat ($\alpha \approx 0$) radio spectra (of blazars in their low states and black-hole binaries in the hard state)



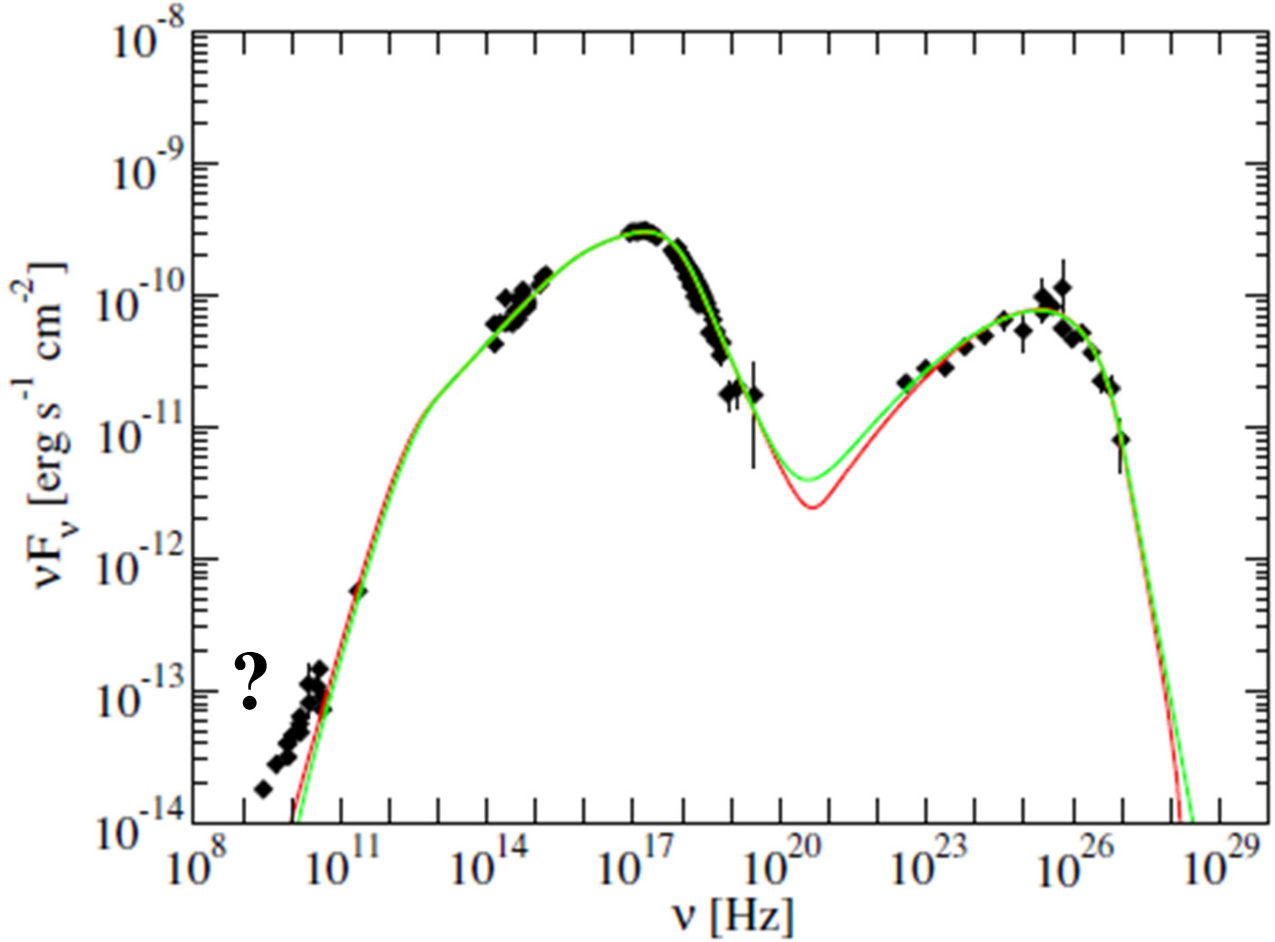


The traditional model: Blandford & Königl (1979), Königl (1981), ...

- This model assumes the power-law electron distribution maintained along the jet, $r^2\,N(\gamma)$ = constant, and the conserved magnetic energy flux (in toroidal field), r^2B^2 = constant, where r is the jet radius.
- For a conical jet, this leads to the synchrotron flux in the partially self-absorbed part of the spectrum with $\alpha = 0$ (as observed), independent of the electron power-law index.
- However, energy losses, in particular adiabatic, would unavoidably deplete the electron distribution.
- This then requires electron acceleration along the jet, to compensate for the losses.

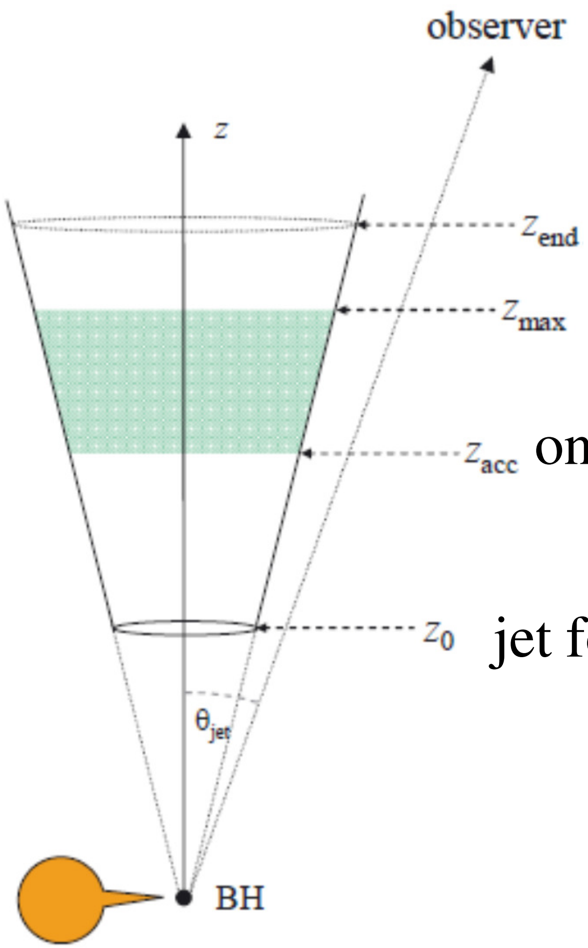
One-zone models

- Usually, they ignore the extended jet contribution:



Mrk 421, Abdo et al. 2011

A continuous jet model with acceleration



end of the jet

end of the acceleration

onset of acceleration

jet formation

Previous work: Khangulyan+, Reynoso +, ...

- A continuous conical jet model with electron acceleration, advection and energy losses.
- Acceleration along the jet $\propto \ln z$, e.g. due to shocks from colliding shells (e.g., Malzac 2013). This yields $\alpha = 0$.

AAZ, Stawarz, Pjanka & Sikora 2014a,
AAZ, Pjanka, Sikora & Stawarz 2014b

- The electron distribution along z is solved partly analytically from the continuity equation in both space, z, and Lorentz factor, γ, with adiabatic and radiative losses (synchrotron, irradiation by the donor star and accretion source, the Klein-Nishina cross section):

$$\frac{c}{z^2}\frac{\partial}{\partial z}\left[\Gamma_{\rm j}\beta_{\rm j}z^2 N(\gamma,z)\right]+\frac{\partial}{\partial\gamma}\left[\dot{\gamma}(\gamma,z)N(\gamma,z)\right]=Q(\gamma,z)$$

- The radiative transfer equation with the nonthermal source function is solved at all z, and the solution is integrated over z. This yields partially self-absorbed and optically-thin synchrotron spectra and Compton spectra.
- From the flux and $\tau = 1$ at the break frequency, $B_0 \propto z_{\rm acc}{}^{1/4}$ ($z_{\rm acc}$= the onset of acceleration).
- Relativistic electrons in the jet Compton upscatter the stellar (in HMXBs) and synchrotron radiation, which implies lower limits on B_0, $z_{\rm acc}$ (from flux upper limits), or determines them (from the Compton spectrum = data).

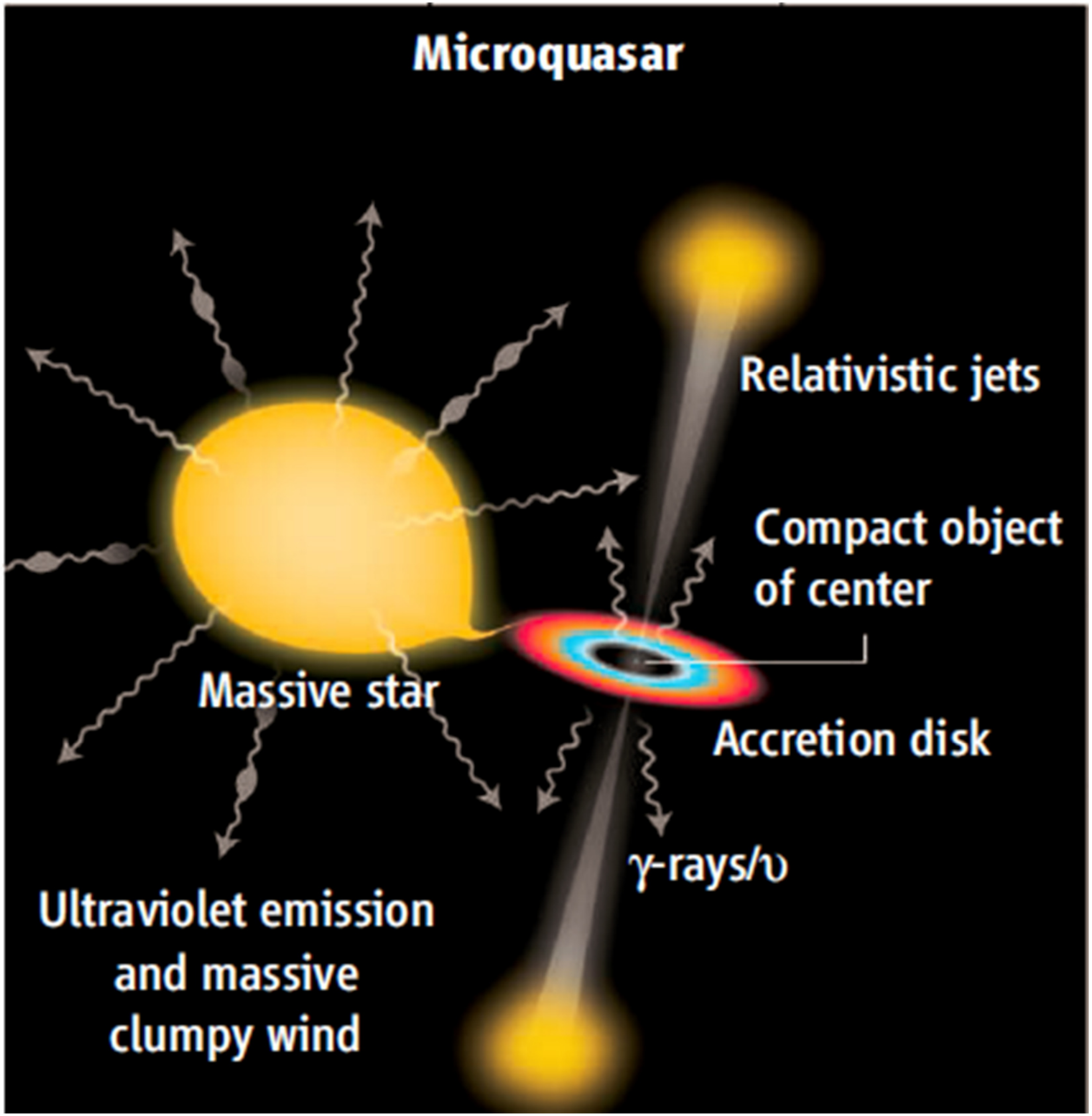
An analytical solution in the case of advection and synchrotron/Thomson losses:

- $$\tilde{N}(\gamma,\xi) = \frac{3\tilde{Q}_0\gamma^{-p}}{2(p-1)} \times \frac{(\xi'/\xi)^{\frac{2}{3}(p-1)}}{\left(1+\frac{2\gamma}{5\gamma_{\mathrm{b}}(\xi)}\right)^{2-p}} \, {}_2F_1\left[2-p, \frac{2-2p}{5}, \frac{7-2p}{5}; \frac{(\xi'/\xi)^{-5/3}}{1+\frac{5\gamma_{\mathrm{b}}(\xi)}{2\gamma}}\right]\Bigg|_{\xi'=\xi_{\mathrm{m}}}^{\xi'=\xi}$$

  with a hypergeometric function.
- An analytical formula for *N*(γ) taking into the energy loss rate dependent itself on *N*(γ) via the synchrotron self-absorption optical depth.

Applications

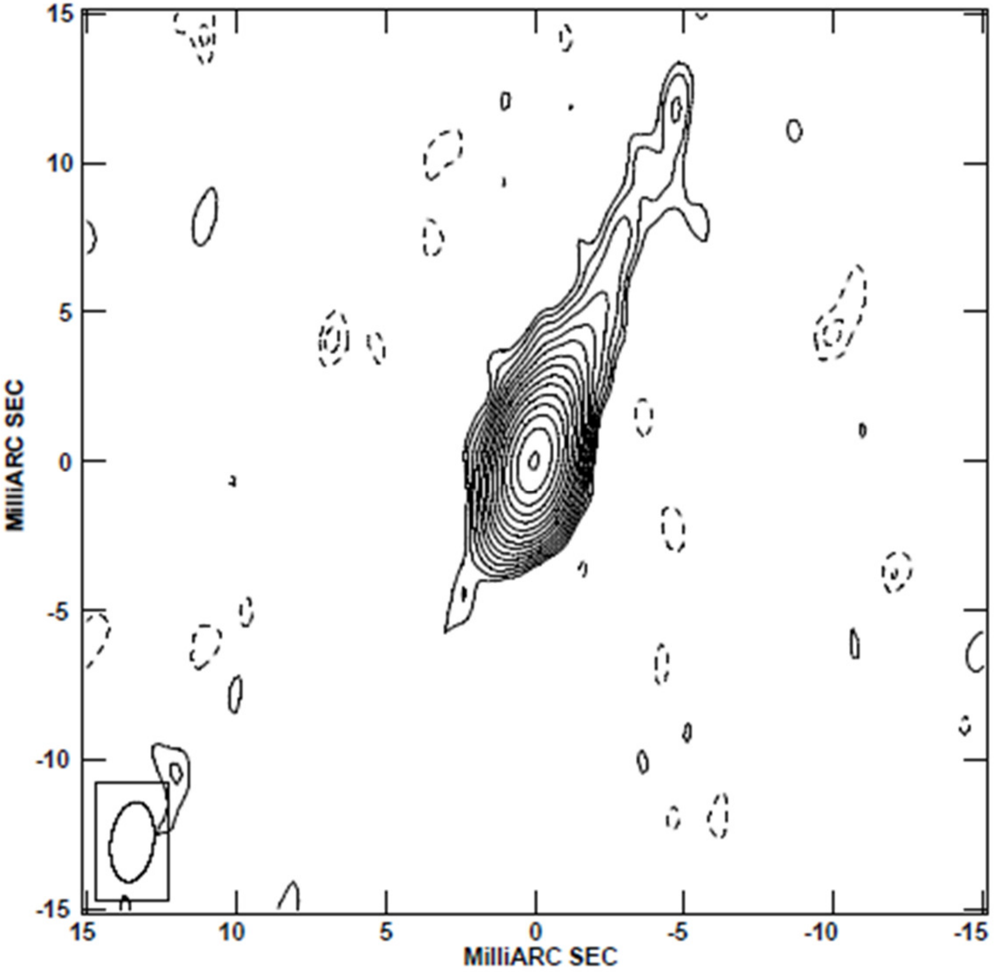
- Cyg X-1 in the hard state;
- Mrk 421



Mirabel 2012

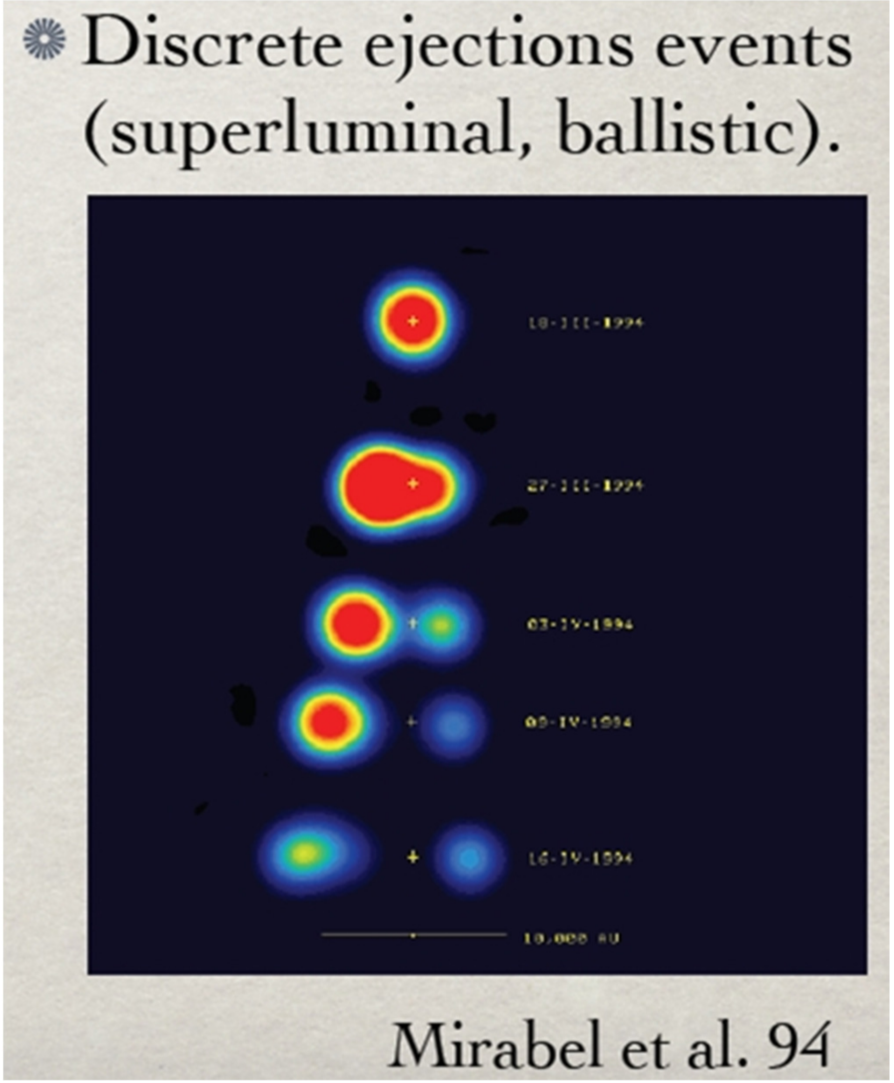
Two kinds of jets in black-hole binaries

steady and compact at low *L*, hard states



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

at highest *L,* soft states

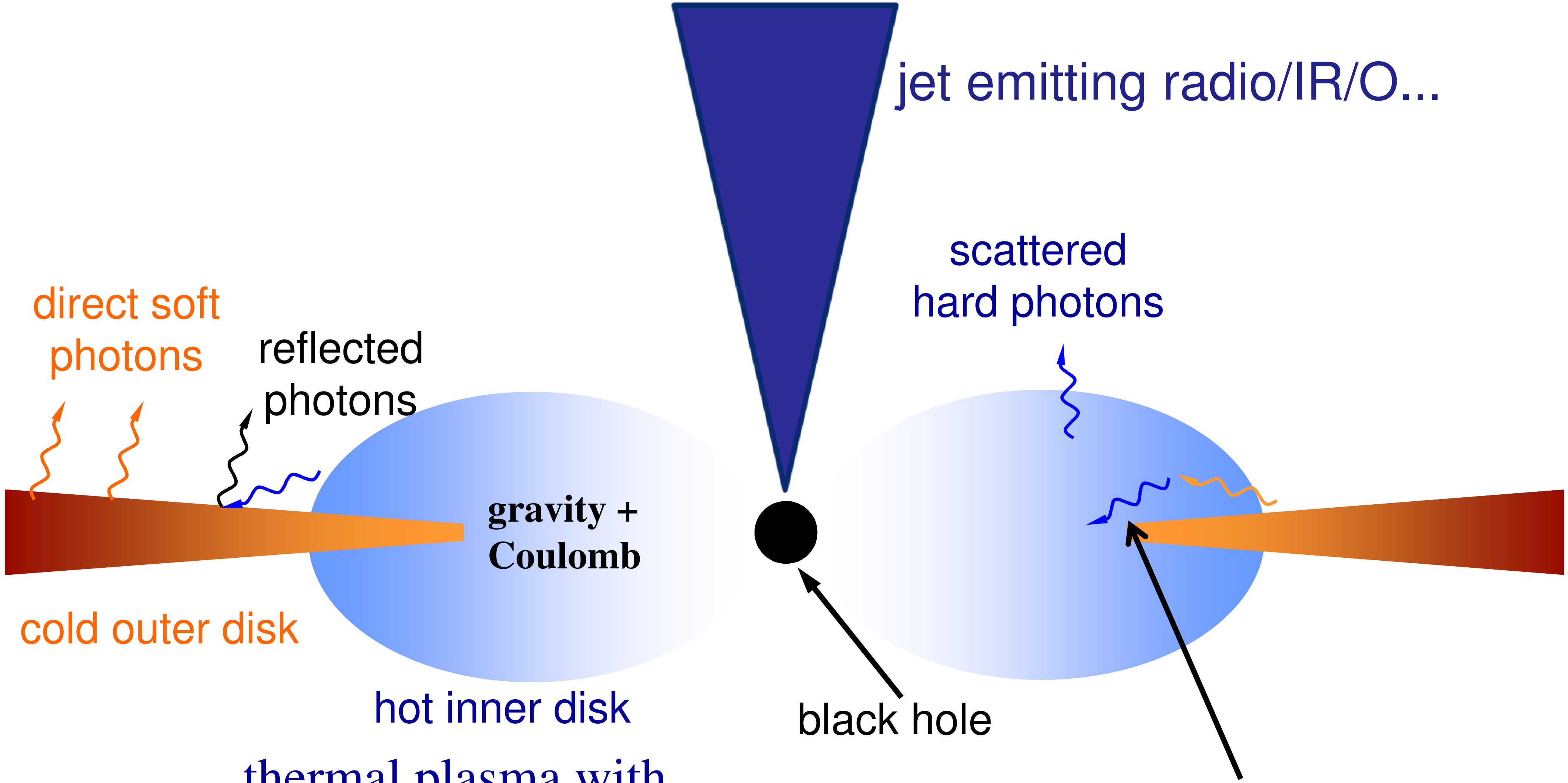


- Discrete ejections events (superluminal, ballistic).

Mirabel et al. 94

GRS 1915+105

A likely geometry of the hard state:



jet emitting radio/IR/O...

direct soft photons

reflected photons

scattered hard photons

gravity + Coulomb

cold outer disk

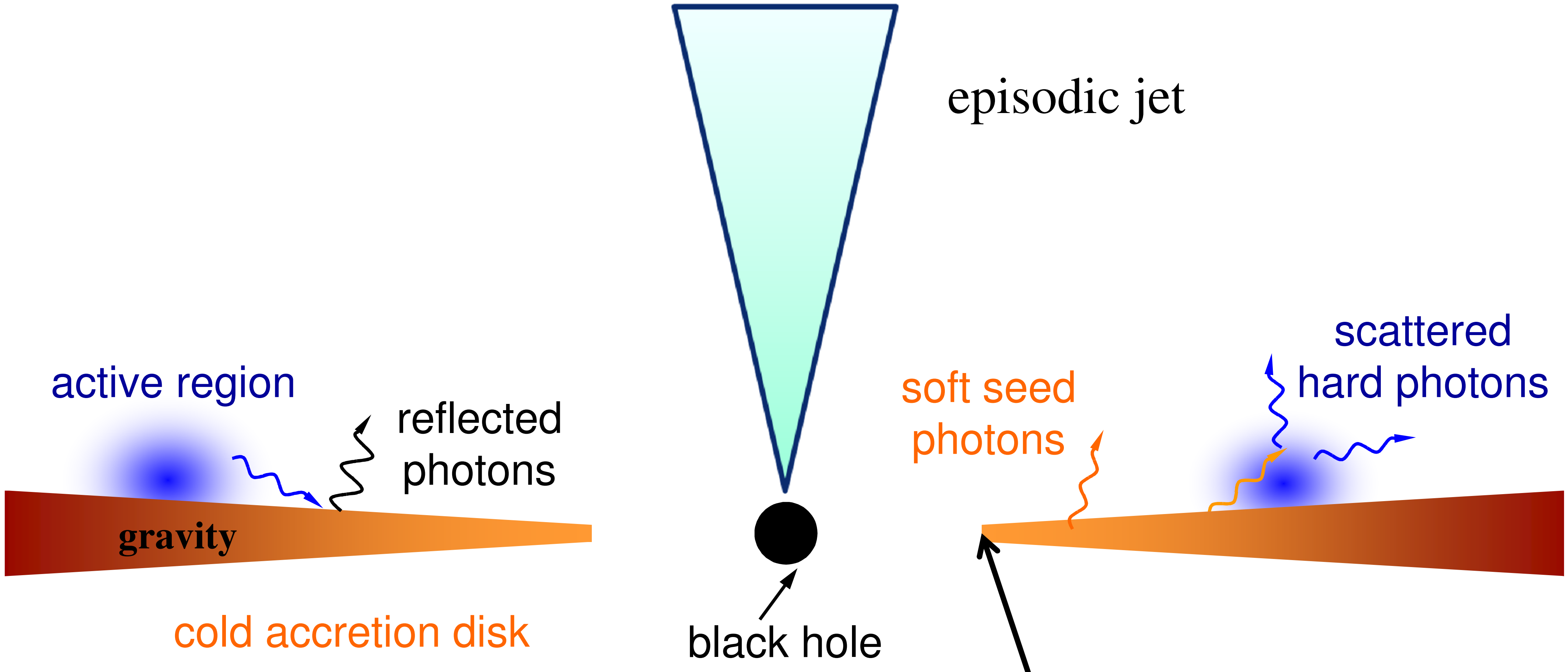
hot inner disk

black hole

thermal plasma with $kT_e \sim 50\text{–}150$ keV

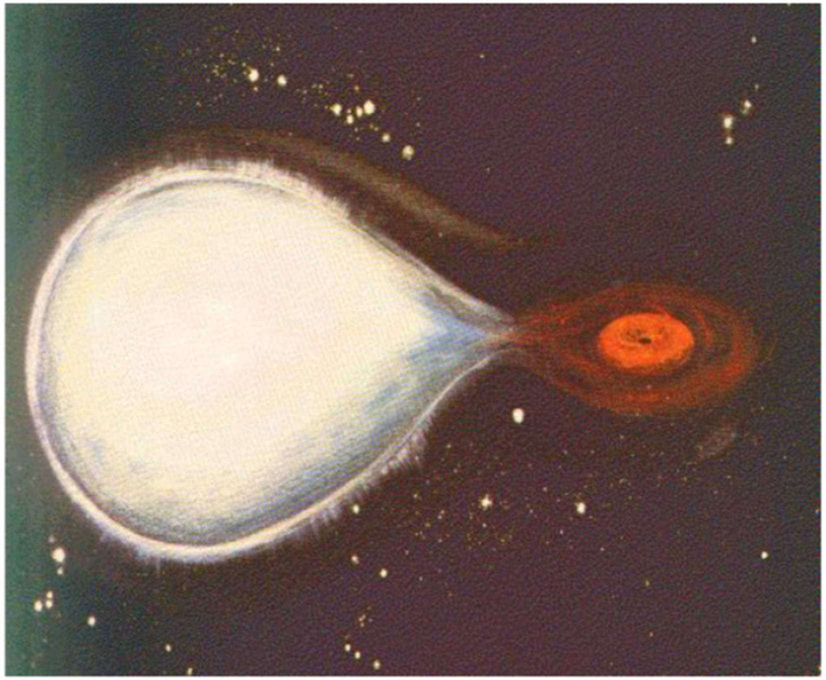
The inner disc radius poorly determined, ~10–200GM/c^2, L/L_E dependent

A likely geometry of the soft state:



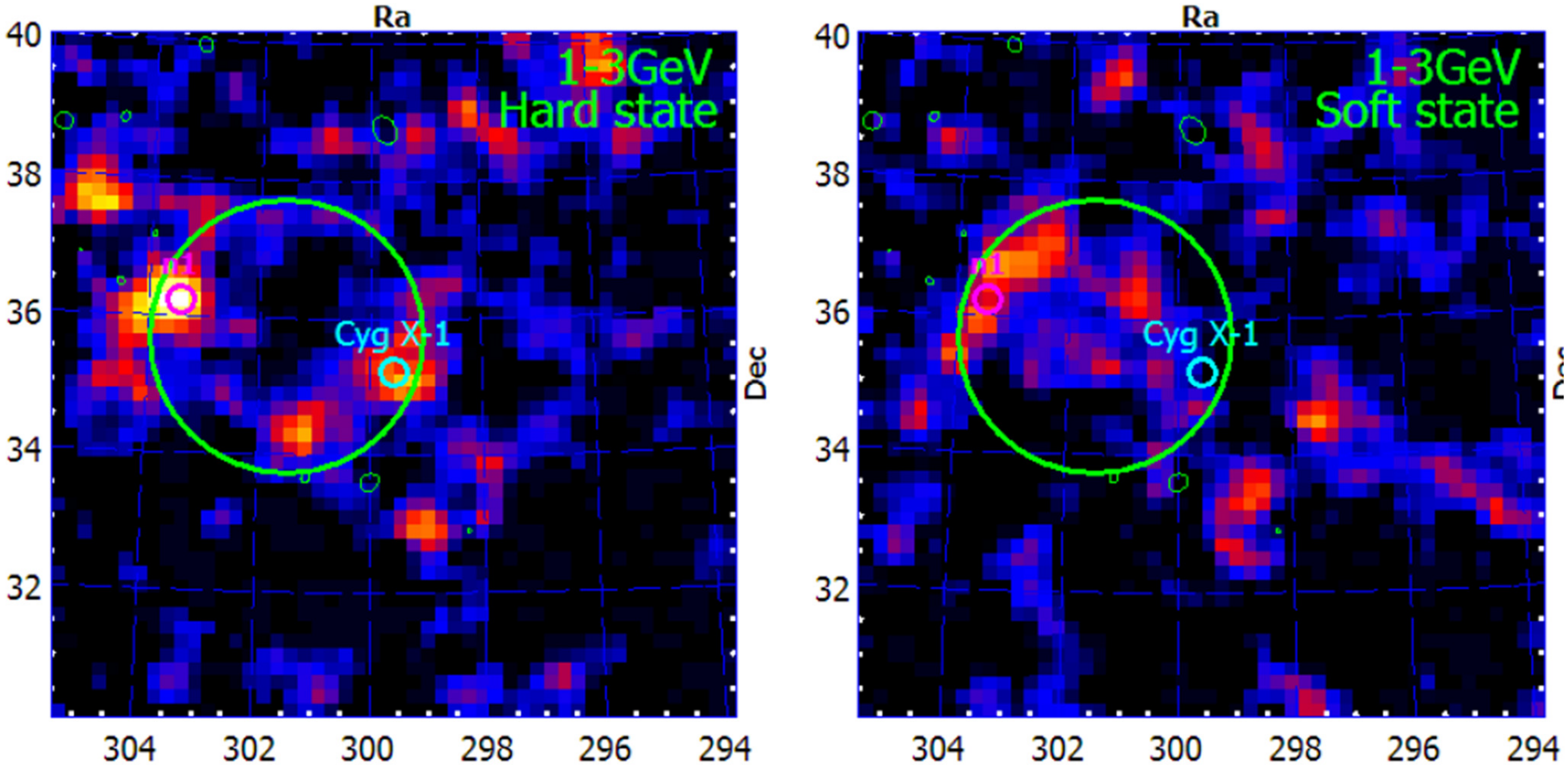
The inner disc radius probably at the innermost stable orbit, $6GM/c^2$ or less for a rotating black hole

Cyg X-1



- An accreting black-hole binary. Donor: OB supergiant. $P = 5.6$ d, $d \approx 1.9$ kpc, $M_{\mathrm{BH}} \approx 15\ \mathrm{M}_{\odot}$.
- Wind accretion, the donor nearly fills its Roche lobe.
- Emission from radio (resolved by VLBA) to MeV.

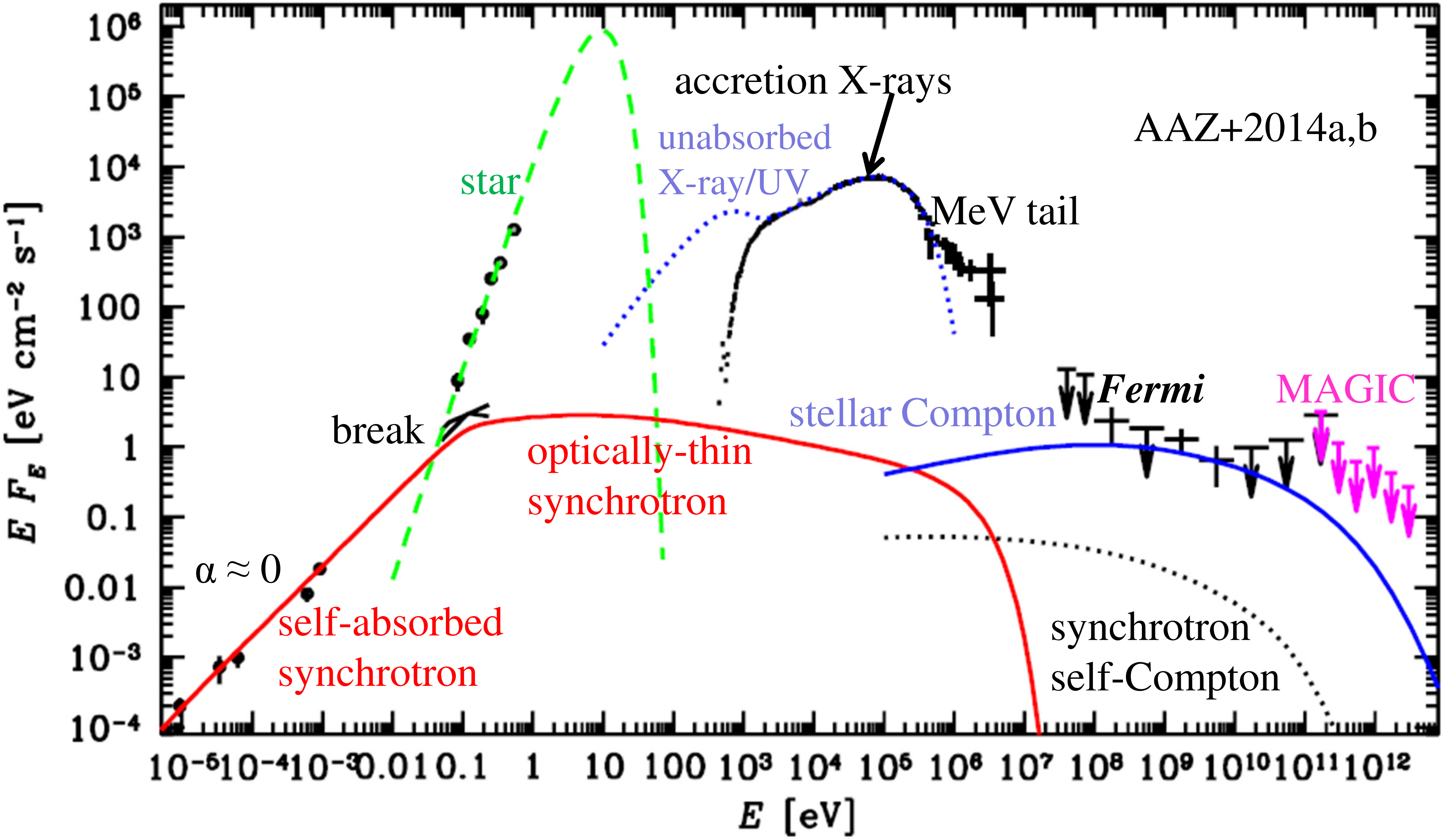
A detection of Cyg X-1 in the hard state by *Fermi*. Upper limit in the soft state.



Although the statistical significance is limited, it was later confirmed by Bodaghee et al. 2013, who found 21 days with detectable γ-ray emission from Cyg X-1, of which 20 were in the hard/intermediate state, and only 1 in the soft state.

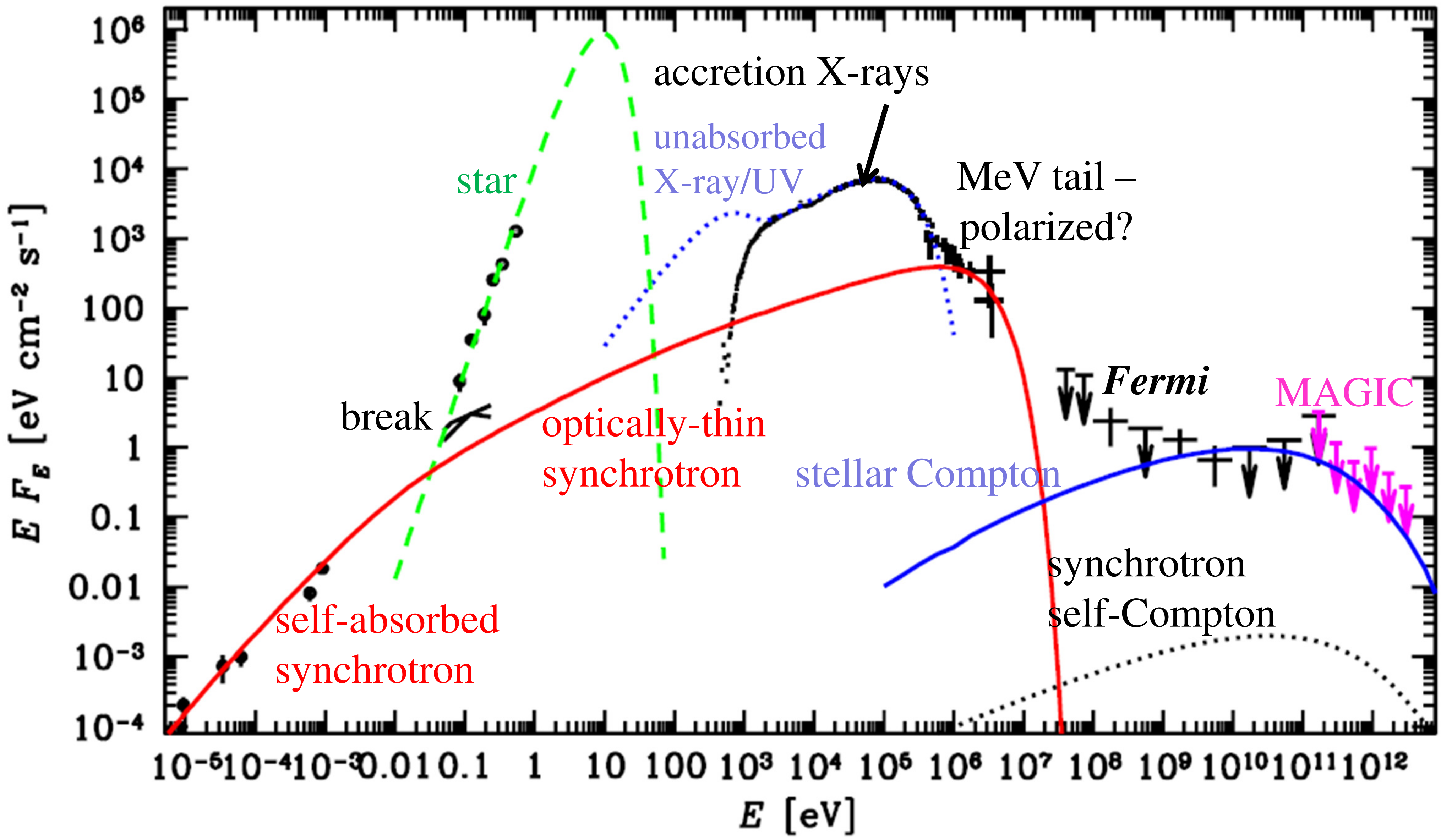
Malyshev, AAZ & Chernyakova 2013

Jet contributions to the hard-state spectrum of Cyg X-1



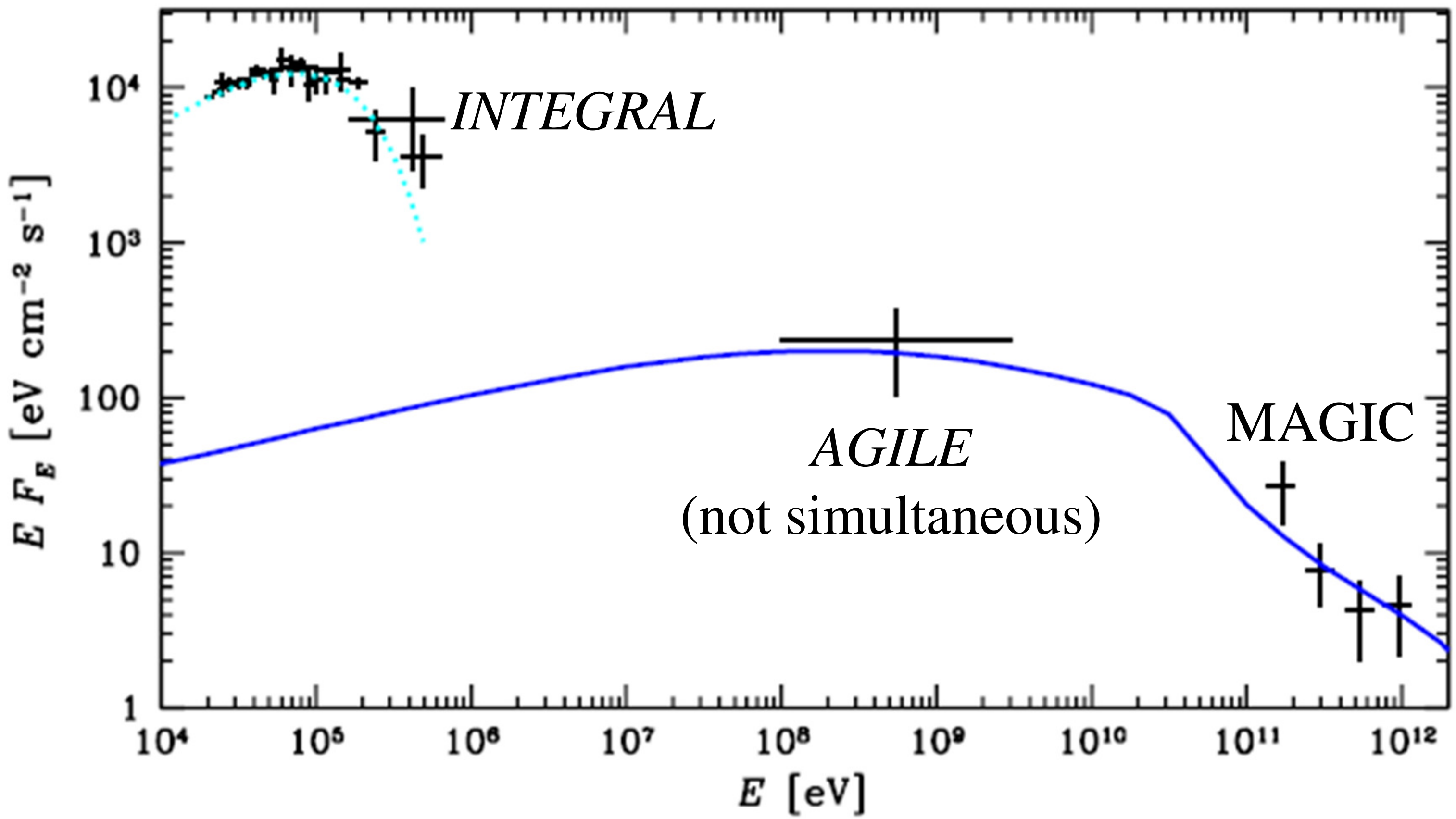
An inhomogeneous jet model with acceleration and losses. The acceleration index $p \approx 2.5$, $B_0 = 10^4$ G at $z_{\rm acc} \approx 800R_{\rm g}$, close to equipartition of $(B^2/8\pi)/u_{\rm gas} \sim 0.1$.

Model II. Reproducing the MeV tail, claimed to be polarized



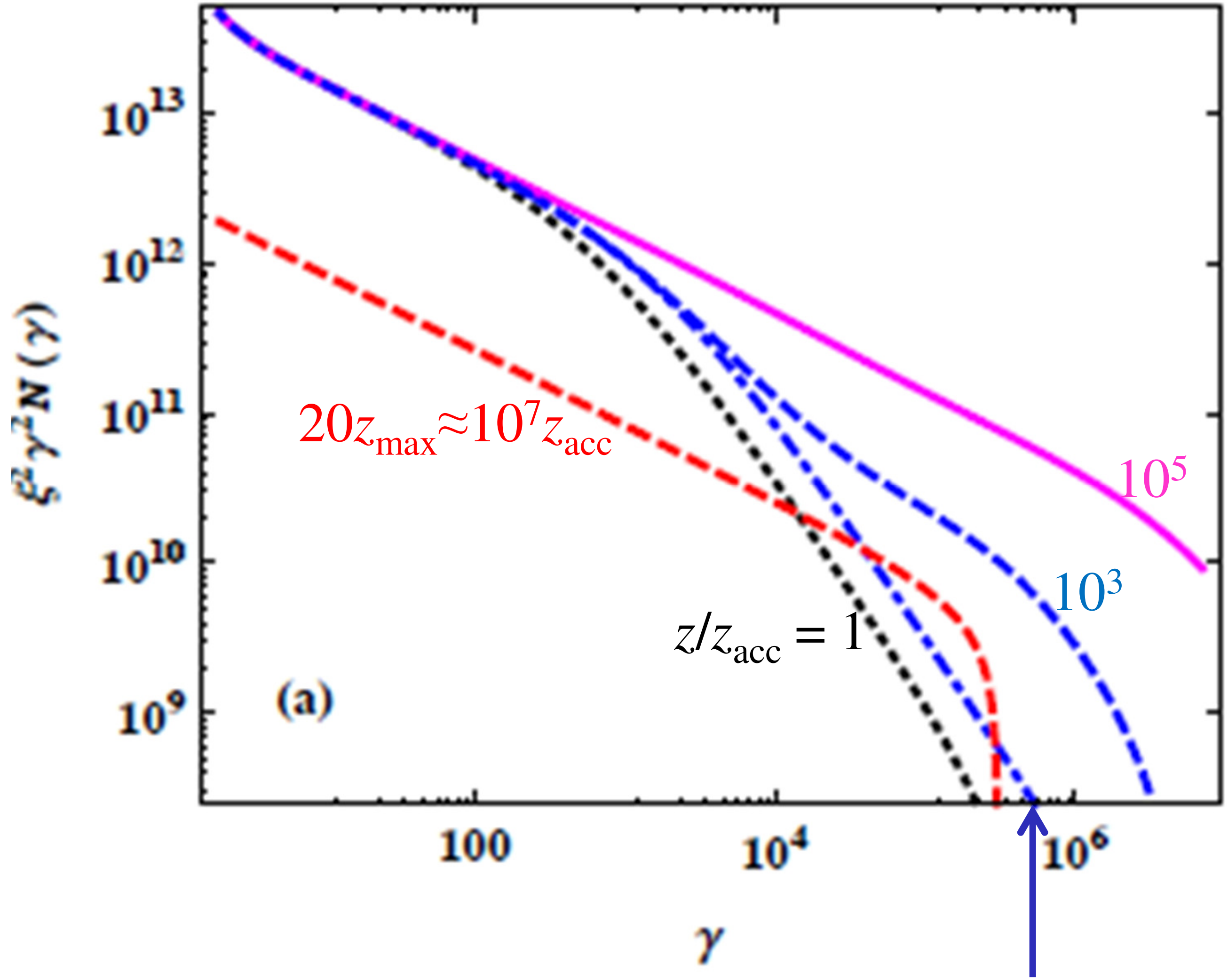
The model with the maximum possible jet contribution. The acceleration index p = 1.4, $B_0 = 5\times10^5$ G at the $z_{\rm acc} = 280R_{\rm g}$, $(B^2/8\pi)/u_{\rm gas} \sim 40$, magnetization parameter of $\sigma \approx 250$.

A transient TeV emission detected once by MAGIC



We model the MAGIC flare as a brief increase of the jet acceleration rate related by the X-ray flare detected simultaneously by *INTEGRAL*. The jet spectrum taking into account cooling is dominated by a region around $z \sim a$. The model can also explain the flare observed by *AGILE* at a different time.

The steady-state electron distribution for the $p = 2.5$ model: cooling effects



$20 z_{\mathrm{max}} \approx 10^7 z_{\mathrm{acc}}$

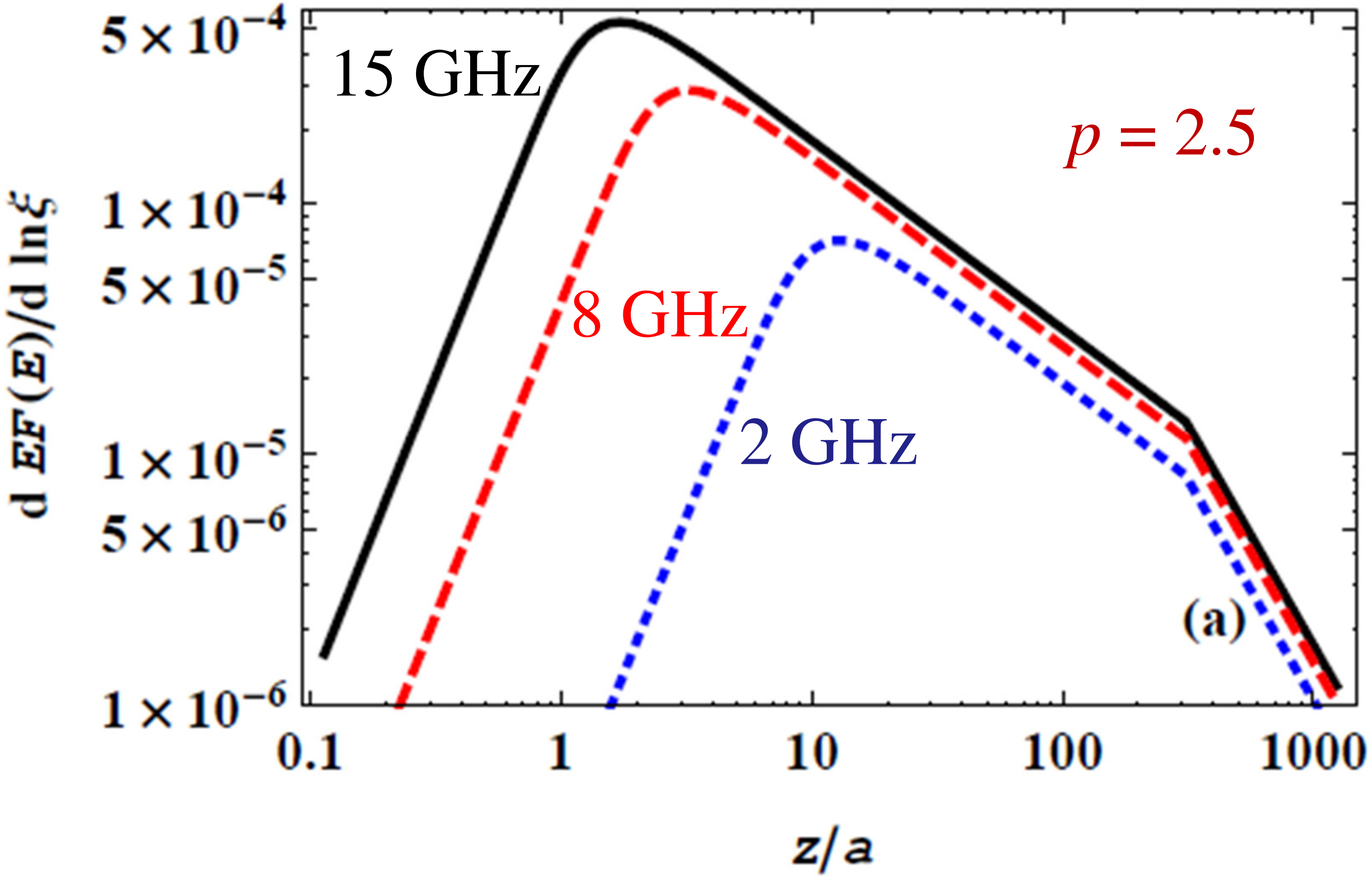
10^5

10^3

$z/z_{\mathrm{acc}} = 1$

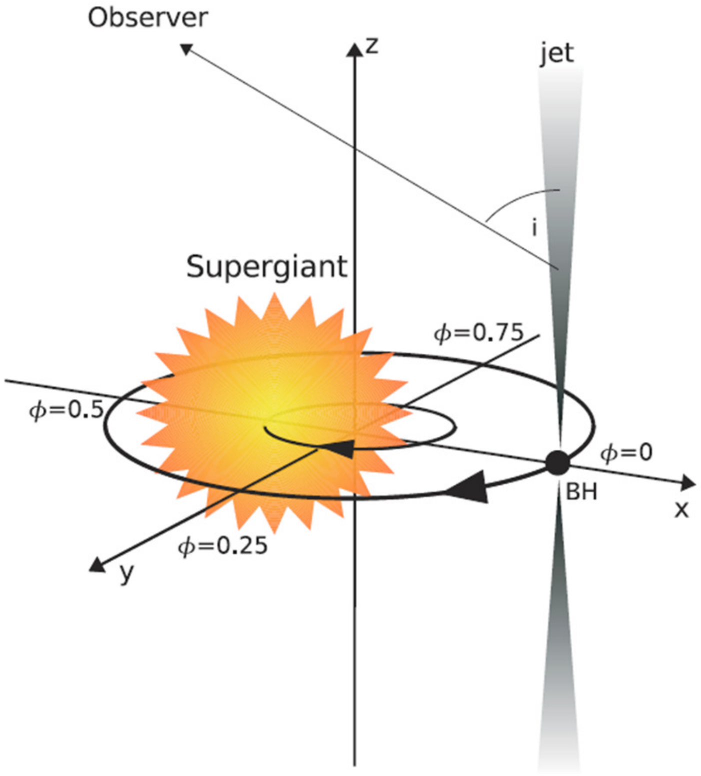
neglecting Klein-Nishina

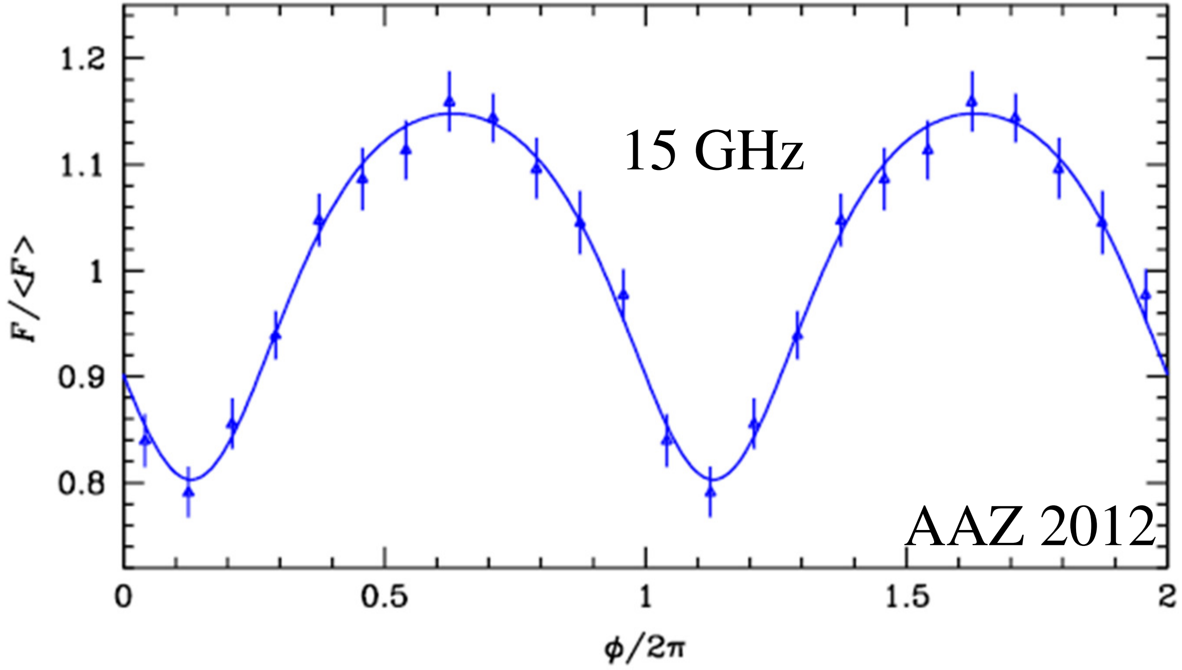
Vertical profile of the radio emissivity (= core shift):



15 GHz predicted to originate from $z \sim 2\times10^6 R_g \sim 1.5a$ (a = the stellar separation).

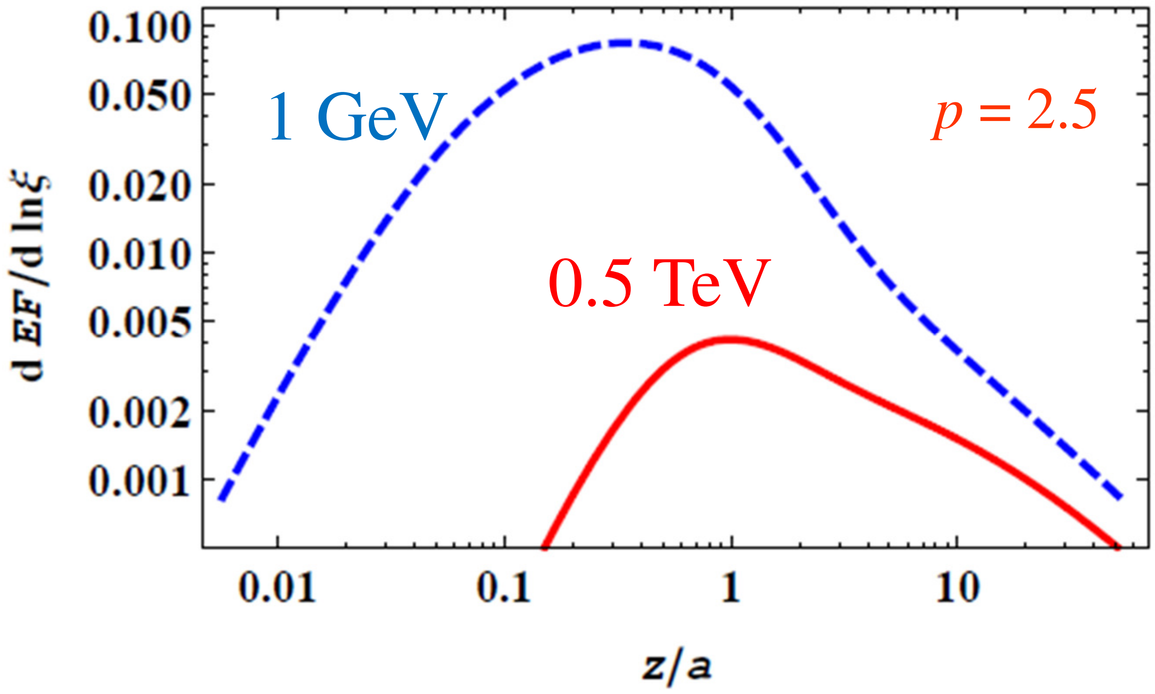
Independent determination of the location of the 15 GHz radio emission





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 $z/a \sim 1$, i.e., $z \sim 10^6 R_g \sim 10^3 z_{acc}$, providing an independent confirmation of the jet model.

Vertical profile of the γ-ray emissivity from blackbody upscattering



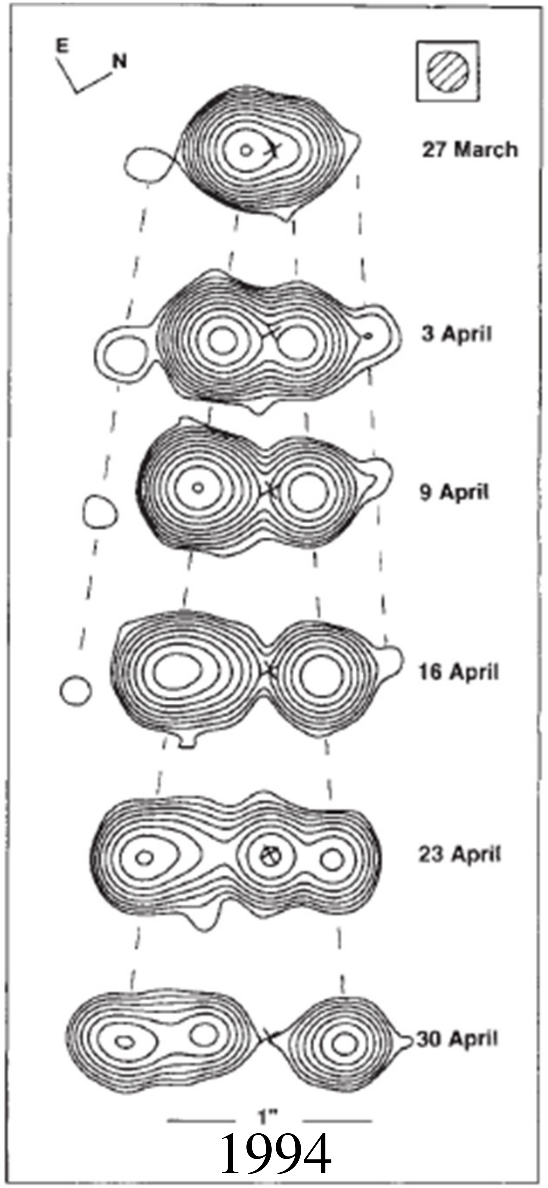
The maximum of the Compton-scattered blackbody emission is at $z \sim 10^3 z_{\rm acc} \sim 10^6 R_{\rm g} \sim a$. This is because the number of scattering electrons increases linearly with height but the seed stellar radiation is diluted at $z > a$.

Can the jet in Cyg X-1 be produced by a MAD accretion flow?

- **Yes.** The magnetic field implied by this scenario is ~10^5 G at ~$1000 r_g$, which agrees with our jet models with $p \approx 2$.
- If this is correct, the accretion models of Cyg X-1 need to be modified, to take into account the strong magnetic field present in the accretion flow.

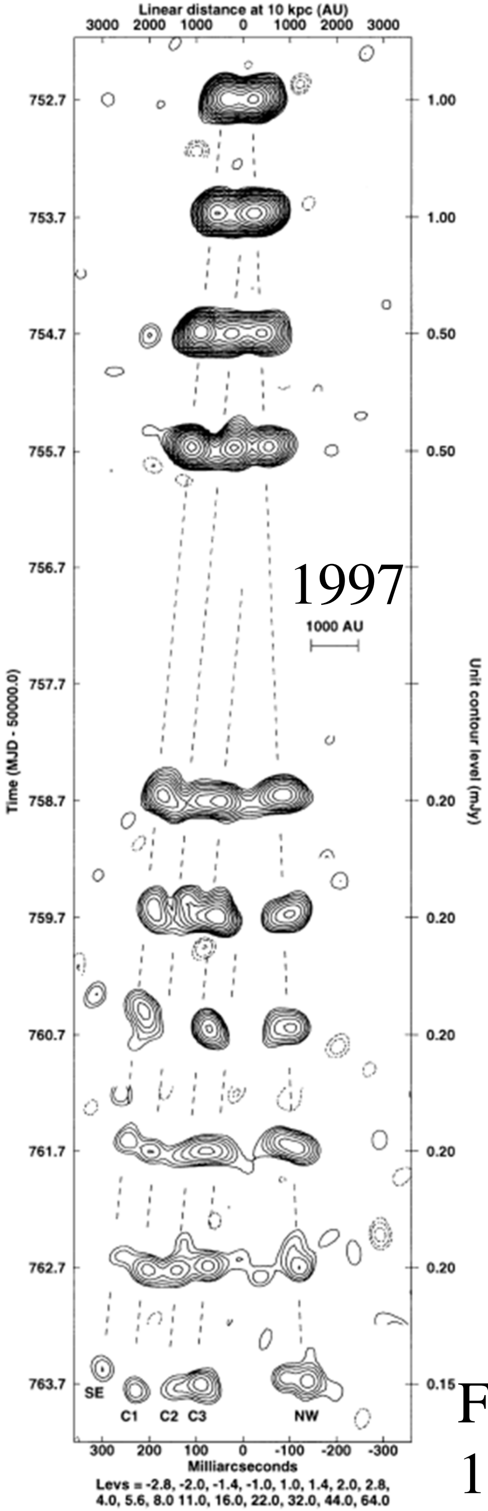
GRS 1915+105

Two major
mass
ejections



1994

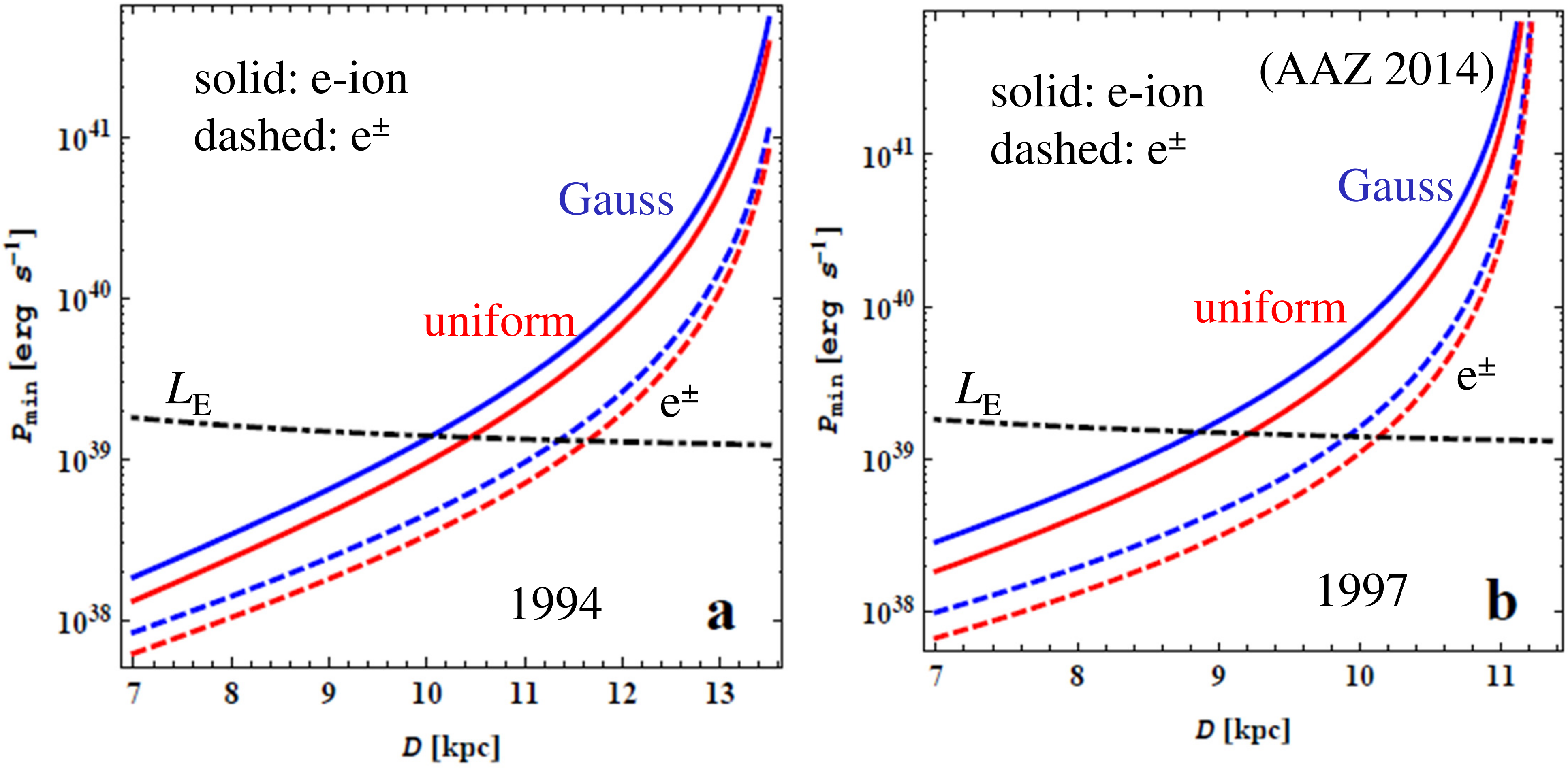
Mirabel &
Rodriguez
1994



1997

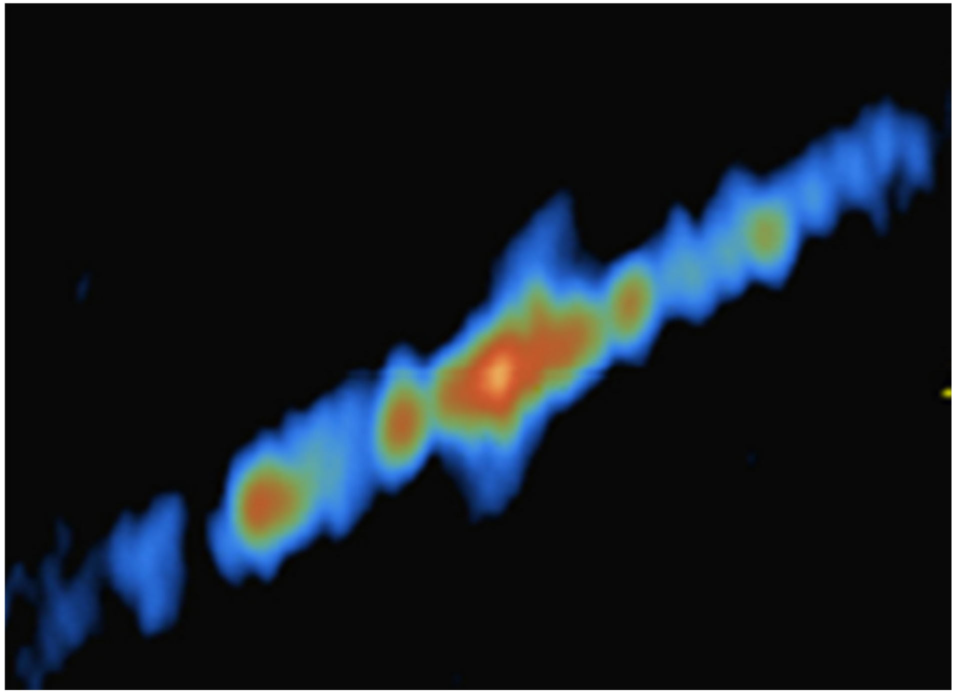
Fender+
1999

The *minimum* jet power of GRS 1915+105 as a function of the distance for the two major mass ejections:



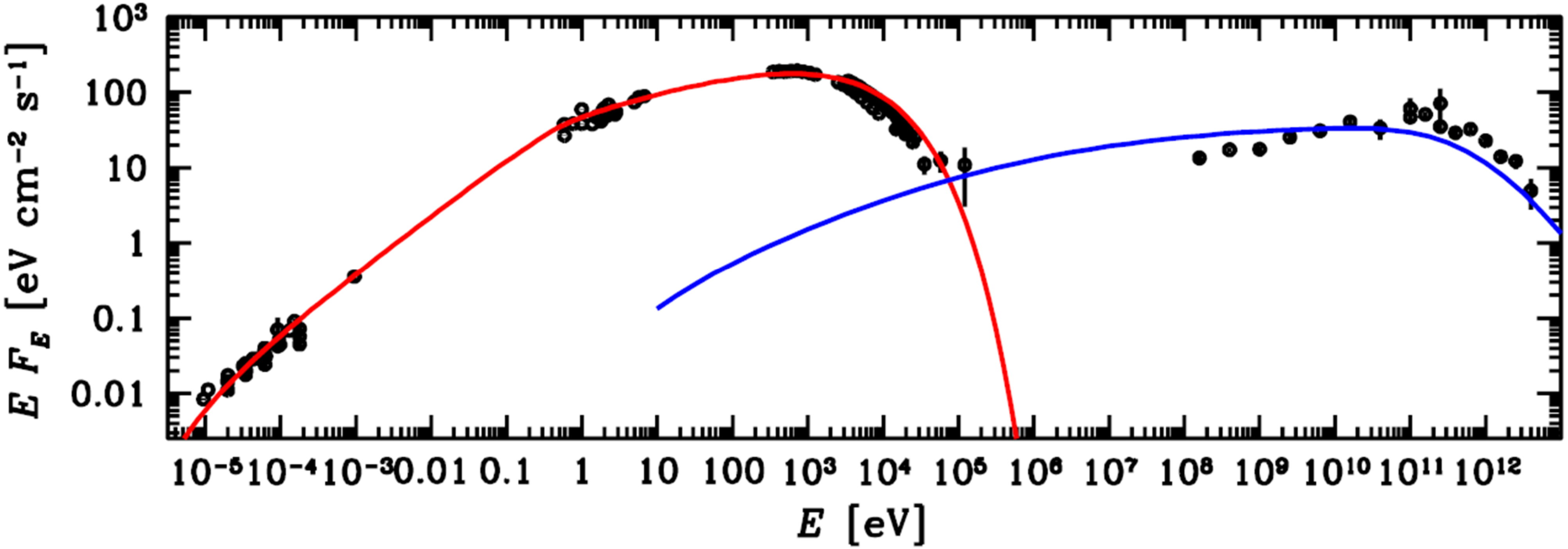
The distance measurement is $8.6^{+2.0}_{-1.6}$ kpc (Reid et al. 2014). The bolometric L during the ejections was ~L_E, implying Mdot c^2 ~ 5L_E or so. $L_{jet} \approx M$dot c^2 is fully compatible with the above constraints. **Thus, spin-extraction jet formation in a MAD accretion flow is *possible*.**

SS 433



- This X-ray binary jet system is precessing, which is not predicted if the jet is generated by the black-hole spin extraction. In this case the jet should be aligned with the black-hole spin axis, which cannot precess on the observed period of 162.5 d.
- Thus, the jet in this system is probably launched from the accretion flow (Blandford & Payne 1982; Sądowski + 2014; Sądowski & Narayan 2015), and ***not*** directly related to the spin of the compact object.

An extended jet model for Mrk 421: the maximum possible contribution



The γ-ray spectrum not well fitted. It most likely originates from a separate process (one-zone acceleration site).

The current development of the model

- A problem with this model for Mrk 421: the implied distance at which the acceleration begins is ~$1r_g$. This requires taking into account the jet acceleration and its paraboloidal shape.
- The updated model includes magnetic acceleration of the jet, the poloidal magnetic field component, and formation of the toroidal field.
- The corresponding radiation is calculated taking into account the variable Doppler factor.

Conclusions

- A jet model with distributed electron acceleration, energy losses and advection along the jet, accounting for flat radio spectra.
- The broad-band spectrum of Cyg X-1 in the hard state: the radio jet can also reproduce the observed GeV spectrum via Compton scattering of the blackbody emission from the donor.
- The electron acceleration starts at several hundred r_g.
- Only a weak jet contribution to X-rays is possible.
- The bulk of the 15 GHz emission originates at $\sim 10^6 r_g$, compatible with the observed strong orbital modulation.
- The jet in Cyg X-1 can be due to the extraction of the black-hole spin energy via a MAD accretion flow.
- The model applied to Mrk 421 requires that the acceleration zone is taken into account – work in progress.