Radio-to-gamma-ray emission from jets in Cyg X-1 and Cyg X-3

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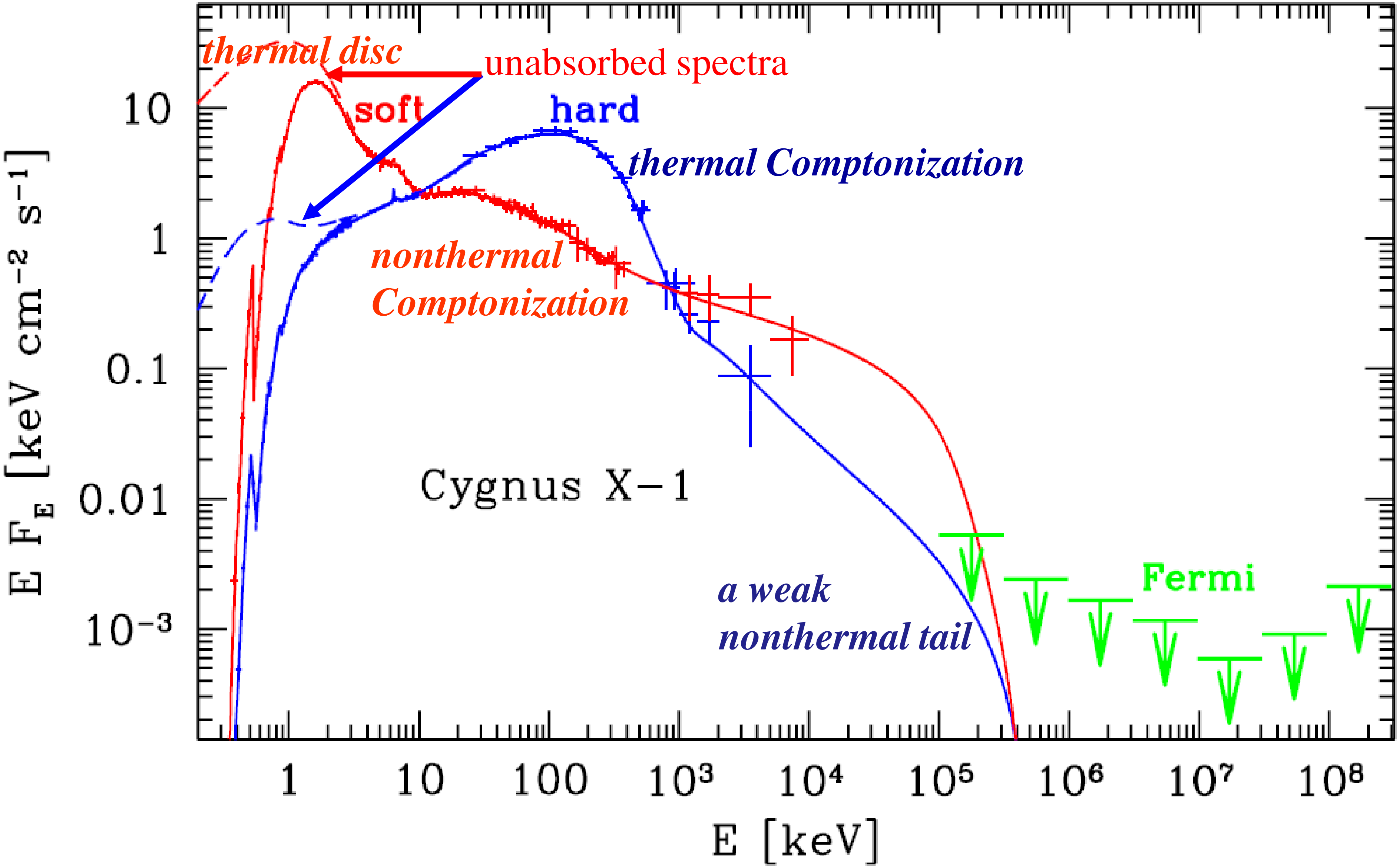
1. The jet of Cyg X-1 in the hard spectral state and MeV γ-rays

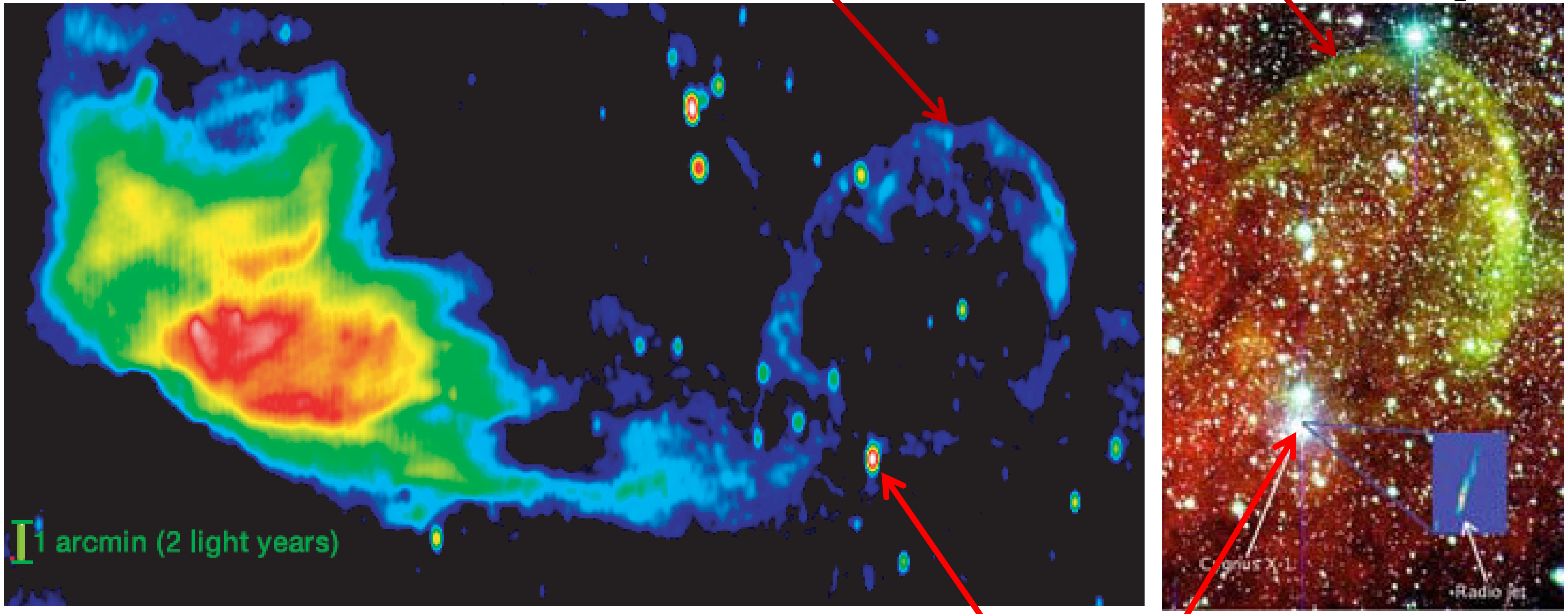
A jet model with emission from radio to high-energy γ-rays. How much does the jet contribute at various wavelengths?

Two main spectral states of Cyg X-1



Fermi upper limits obtained by Malishev & Chernyakova 2012.

The jet power of Cyg X-1



radio 1.4 GHz

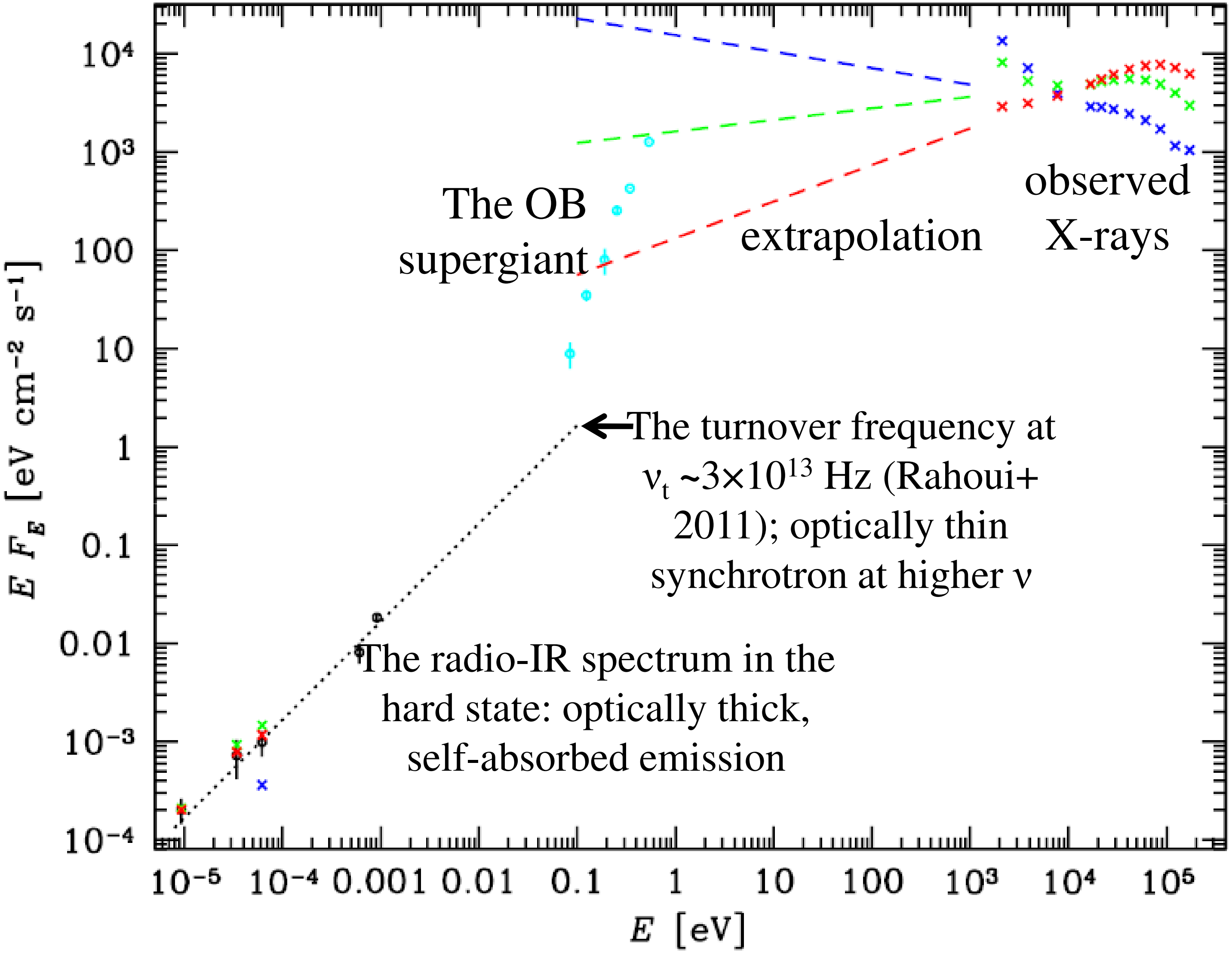
the jet-blown ring nebula

optical

radio jet of Cyg X-1

Interpreting the ring nebula as heated by the jet of Cyg X-1, Gallo et al. (2005) and Russell et al. (2007) obtained the jet kinetic power of ~10^{37} erg/s.

Can the X-rays be from optically-thin jet emission?



The OB supergiant

extrapolation

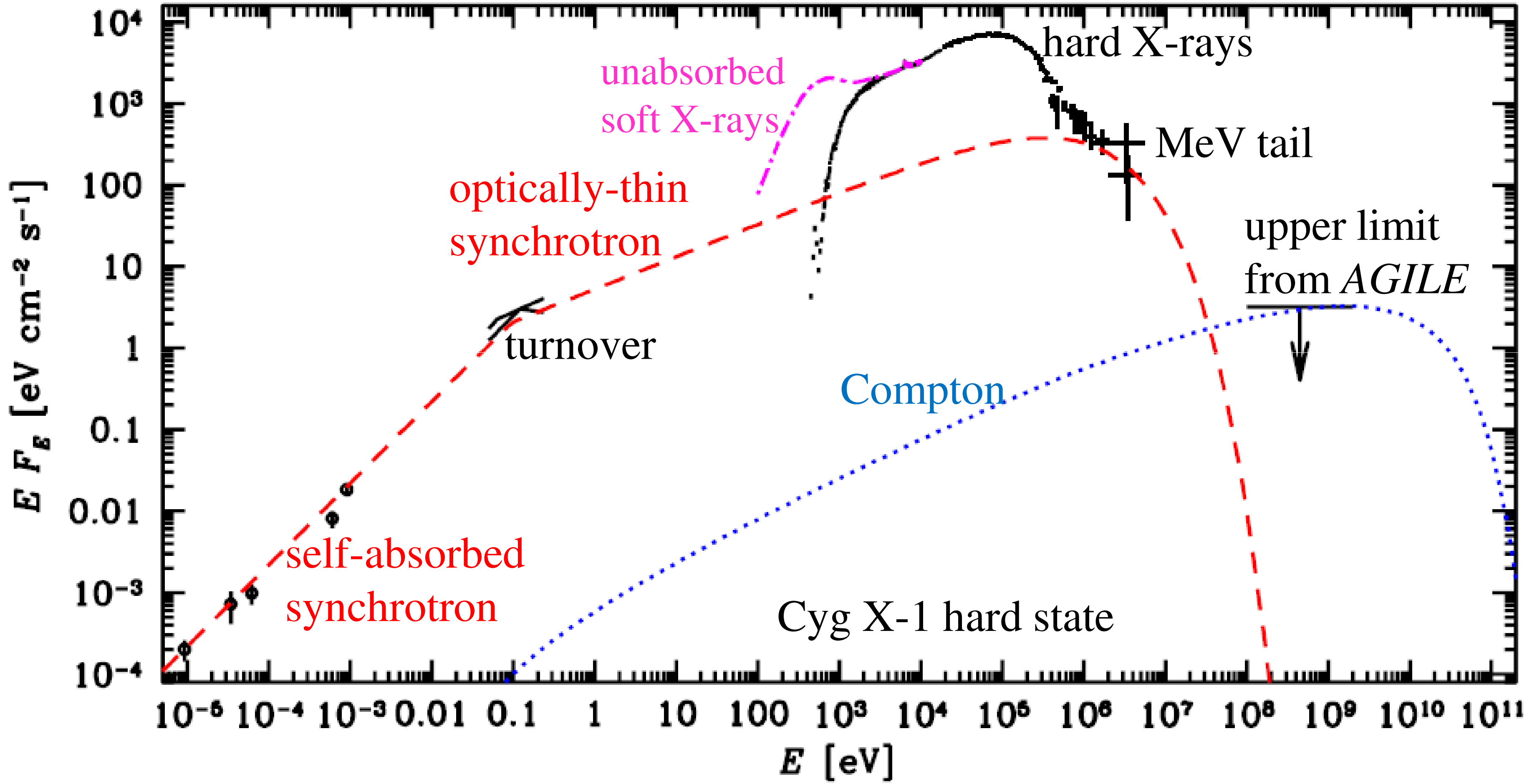
observed X-rays

The turnover frequency at ν_t ~3×10^{13} Hz (Rahoui+ 2011); optically thin synchrotron at higher ν

The radio-IR spectrum in the hard state: optically thick, self-absorbed emission

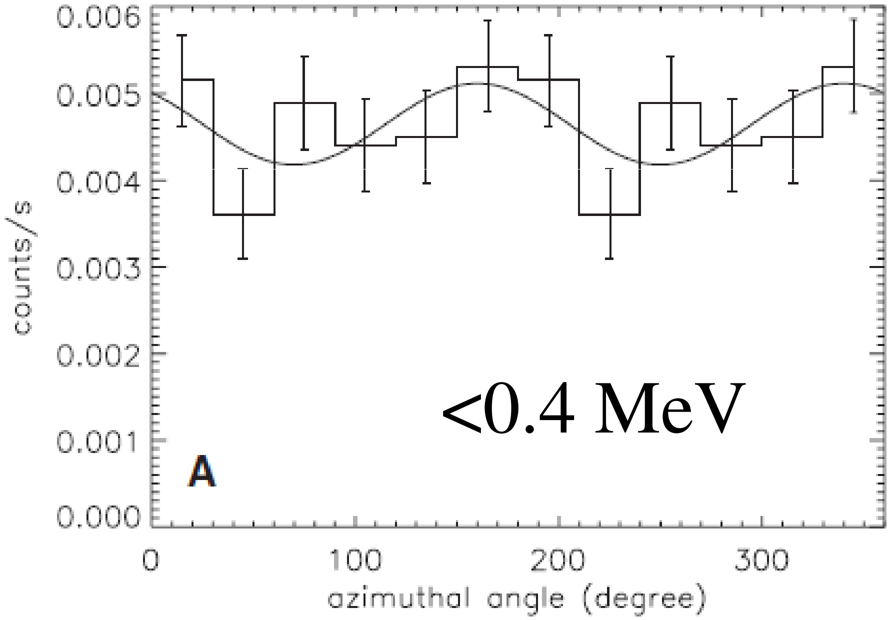
No. The X-ray spectra when extrapolated to lower energies are much above the extension of the radio spectra up to the turnover frequency.

Can the MeV tail in the hard state be from optically-thin jet emission?

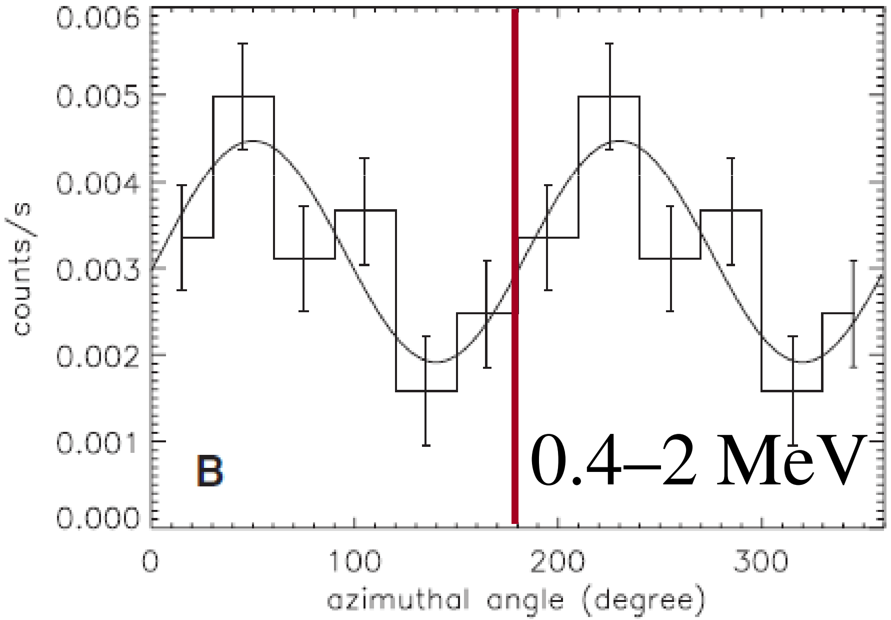


Yes, though it is not certain.

Polarization at the level of 67±30% in the hard state claimed in the 0.4–2 MeV band of Cyg X-1 by Laurent et al. (2011).



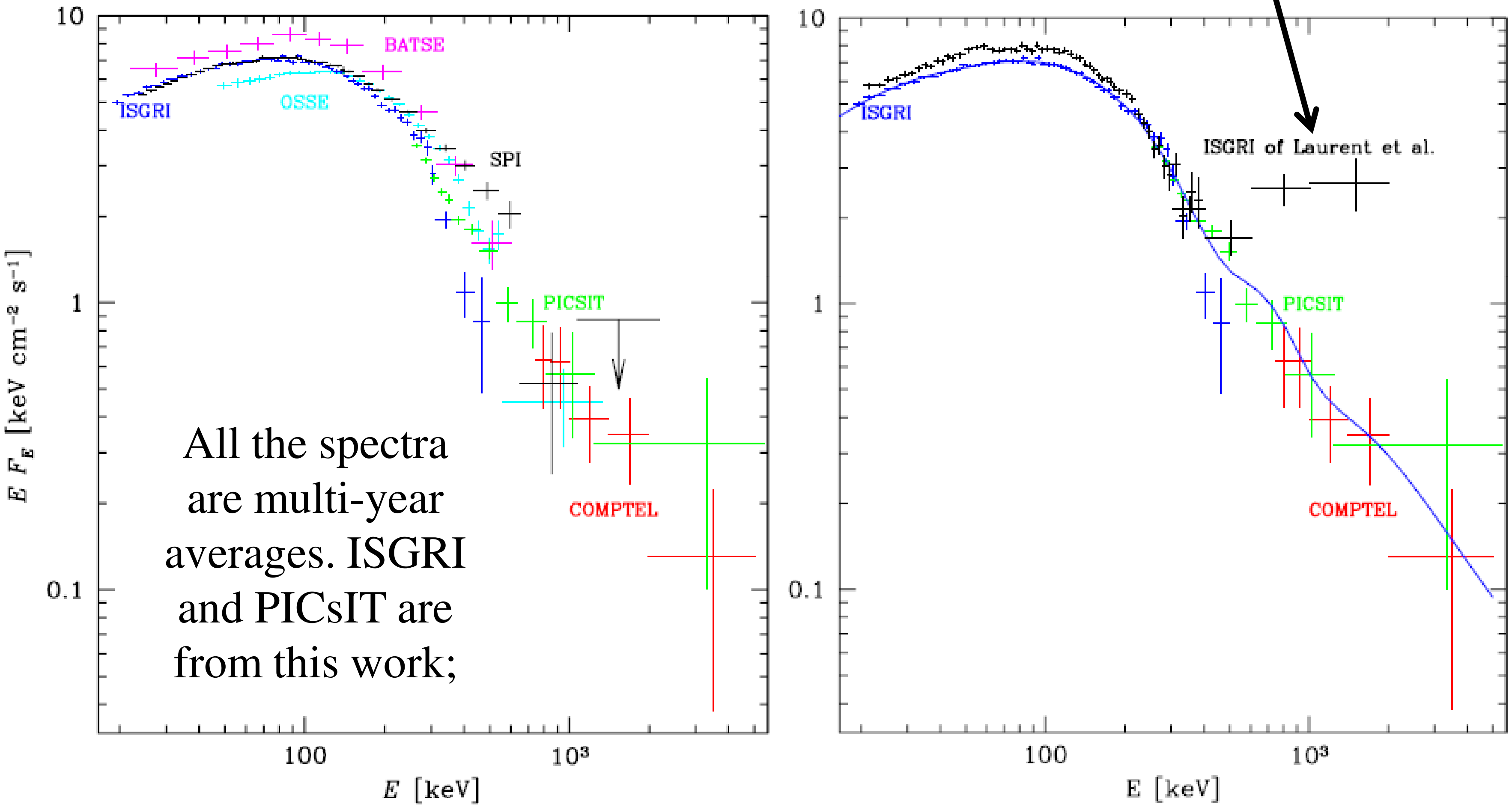
Polarization fraction <20%



Polarization fraction 67±30%

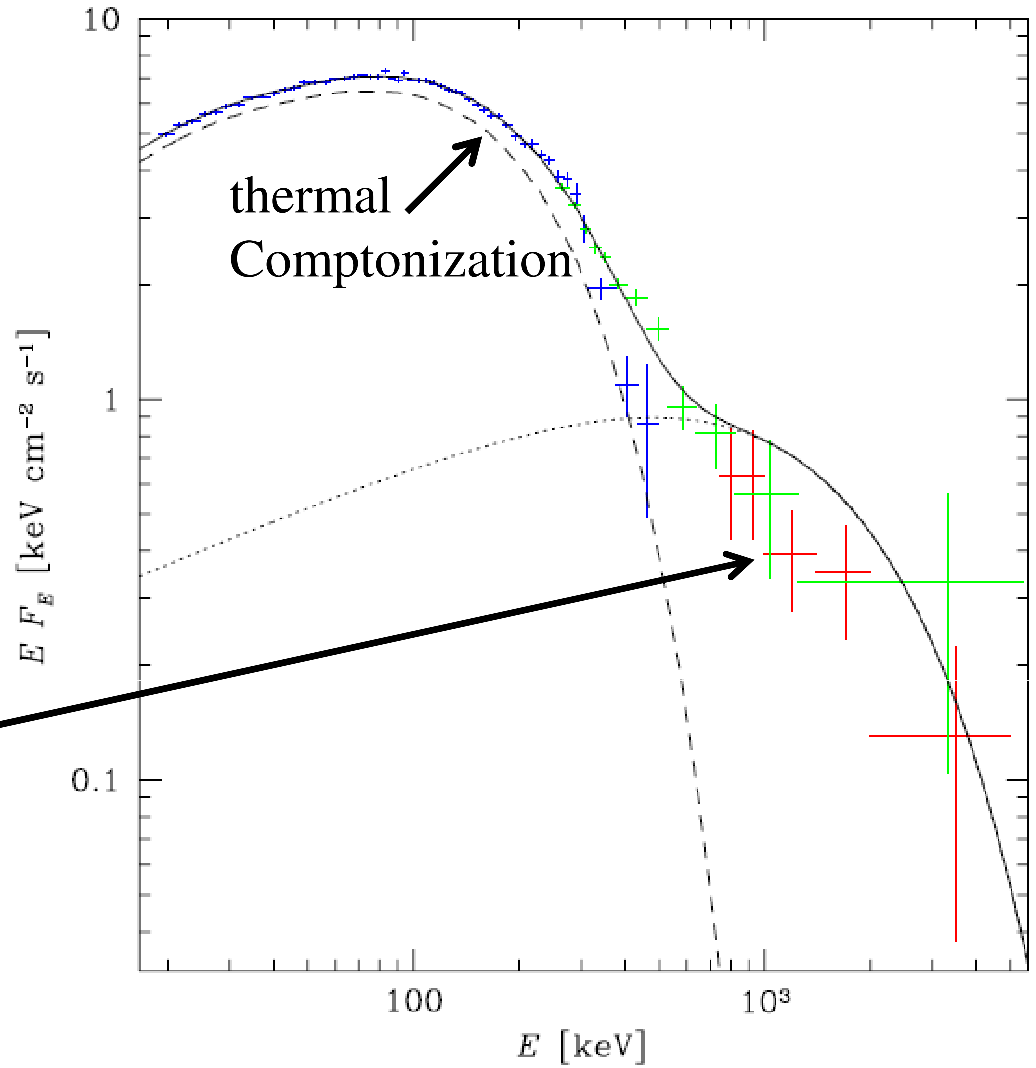
A problem with that measurement:

The fluxes at >400 keV of Laurent+ disagree with all other measurements.



All the spectra are multi-year averages. ISGRI and PICsIT are from this work;

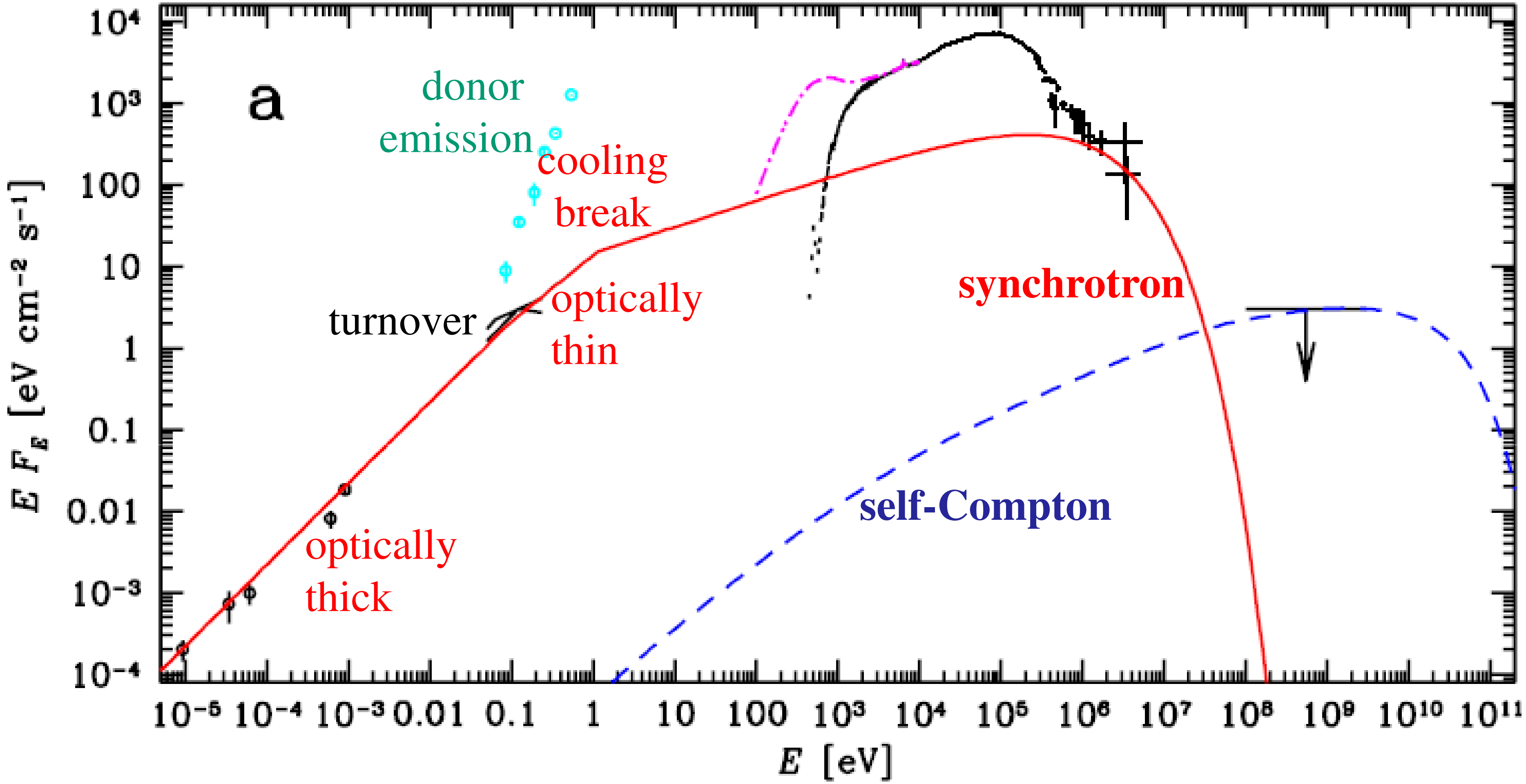
CGRO data from McConnell+ 2002; SPI data from Jourdain+ 2012



The observed high-energy tail:

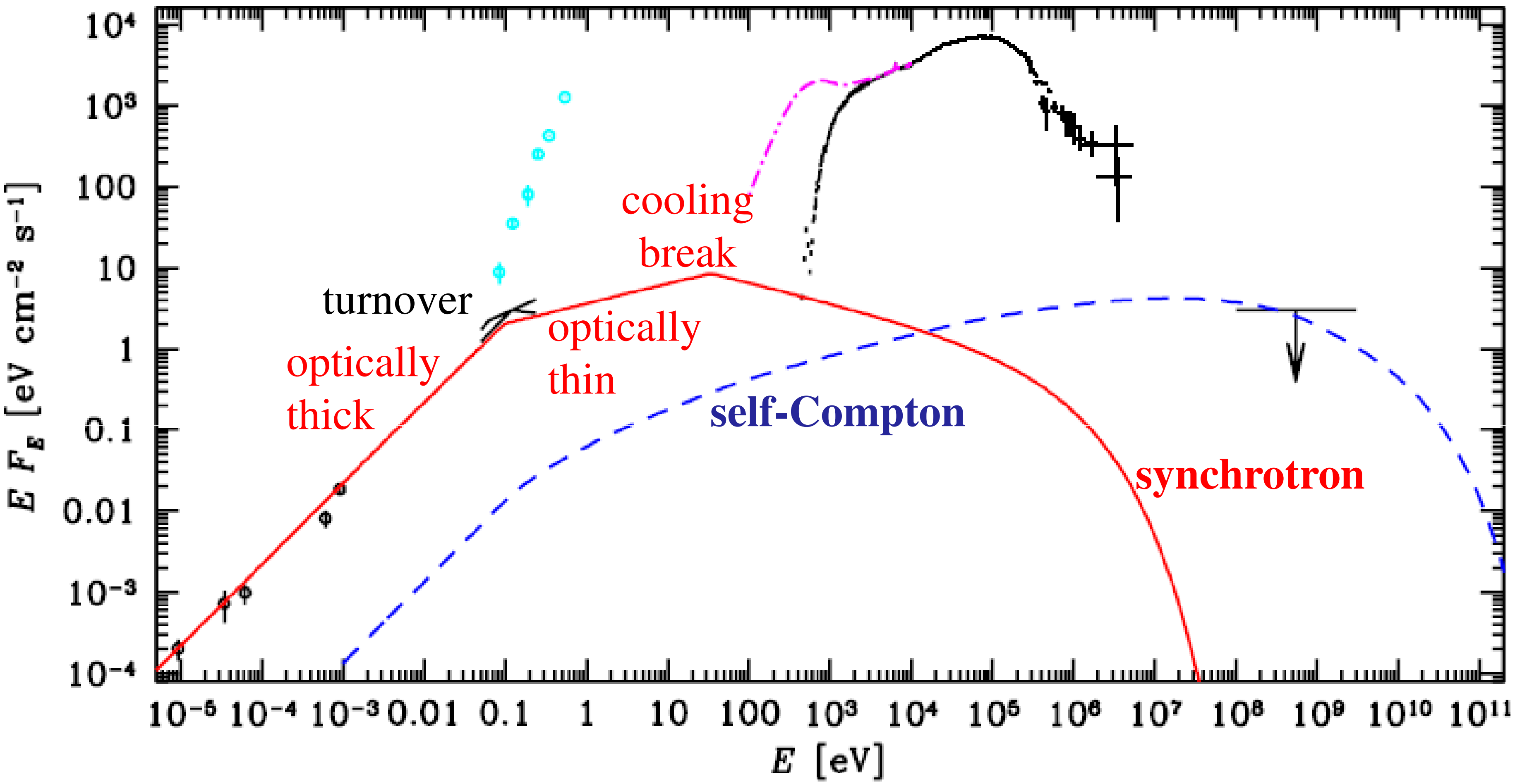
The tail can be due to synchrotron emission from the jet, provided it has a high-energy cutoff at ~1 MeV, or from non-thermal Comptonization in the hot accretion flow.

A jet model yielding the observed MeV tail:



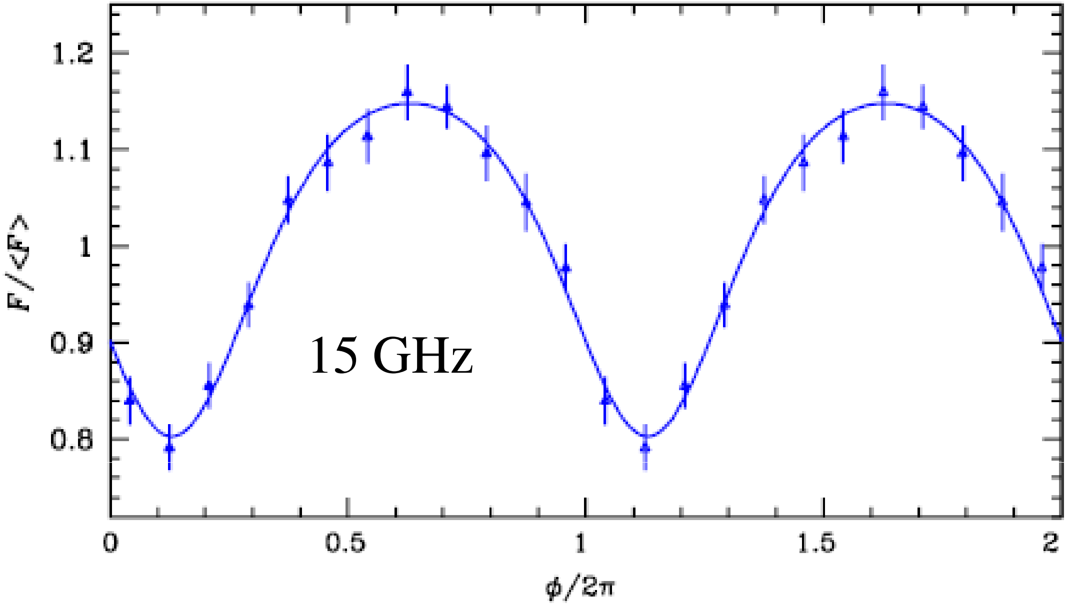
The acceleration index is $\Gamma = 1.3$ (rather hard), B(base) $\geq 10^4$G, $10^3 R_g < z(\text{base}) < 2\times10^3 R_g$ (from the Poynting flux). But there are no observational constraints on the actual synchrotron slope.

A jet model *not* yielding the observed MeV tail:



The acceleration index is $\Gamma = 2.5$ (usual), B(base)>10^3G, $10^3 R_g < z(\text{base}) < 3\times10^3 R_g$ (from the Poynting flux). The MeV tail is then from accretion-flow non-thermal Compton.

Free-free absorption of 15 GHz radio emission from the jet in the wind of the donor



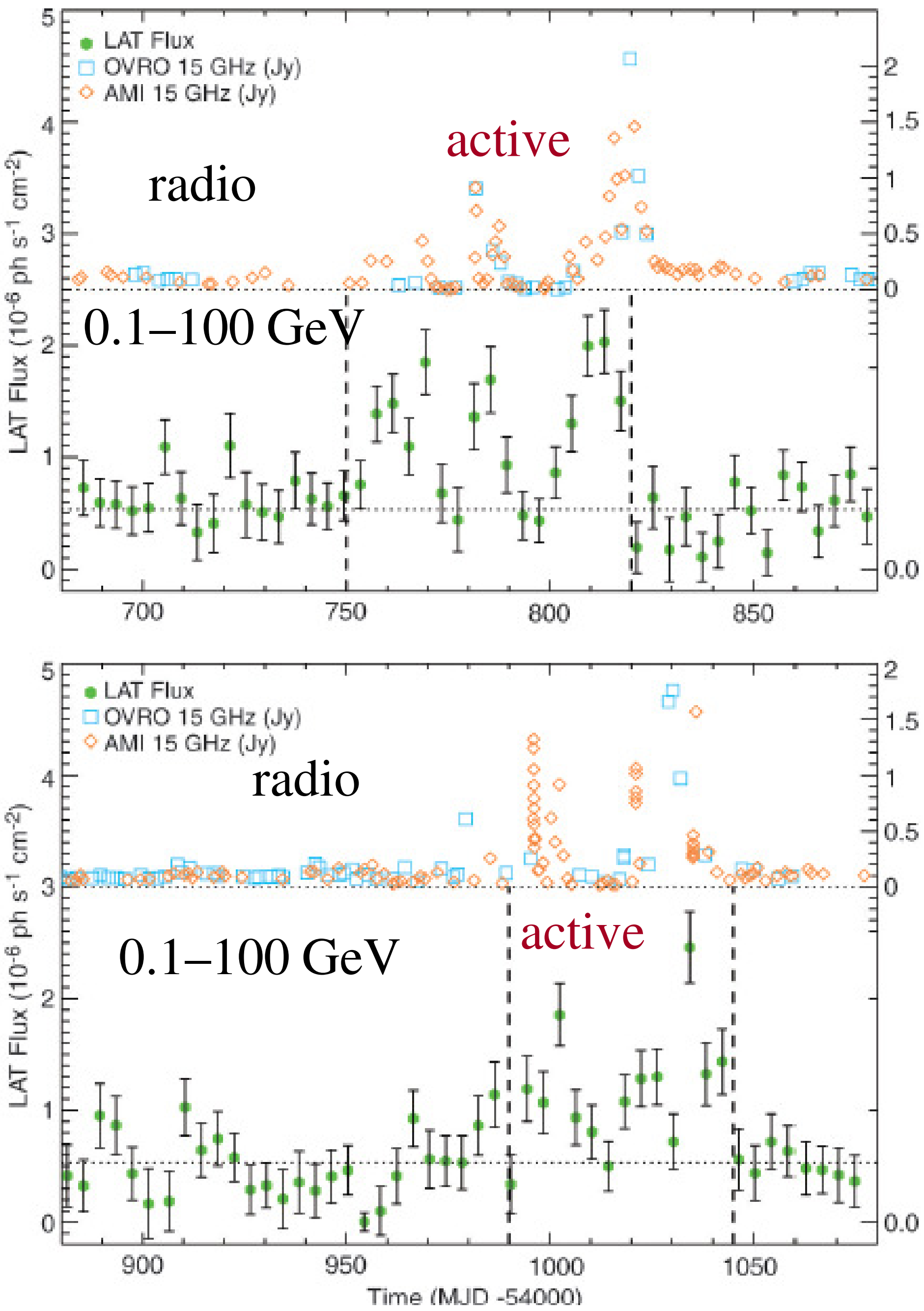
The observed orbital modulation (with the fractional depth of ≈ 0.3) is fitted by an irradiated stellar-wind model. This yields $z/a \sim 1$ (where a is the orbital separation), i.e., $z \sim 3\times10^{12}$ cm $\sim 10^6 r_g$. The standard jet model (Blandford & Königl 1979) predicts $z \propto \nu^{-1}$. Given that the turnover $\nu_t \sim 3\times10^{13}$ Hz, the jet base is predicted at $\sim 10^3\ r_g$, confirming the previous result.

2. GeV γ-rays from Cyg X-3 in the soft spectral state

The electron spectrum during GeV emission detected by *AGILE* and *Fermi*; the contribution of the jet to X-rays.

Observations by *Fermi*, 0.1–10 GeV

Abdo+ 2009



radio

active

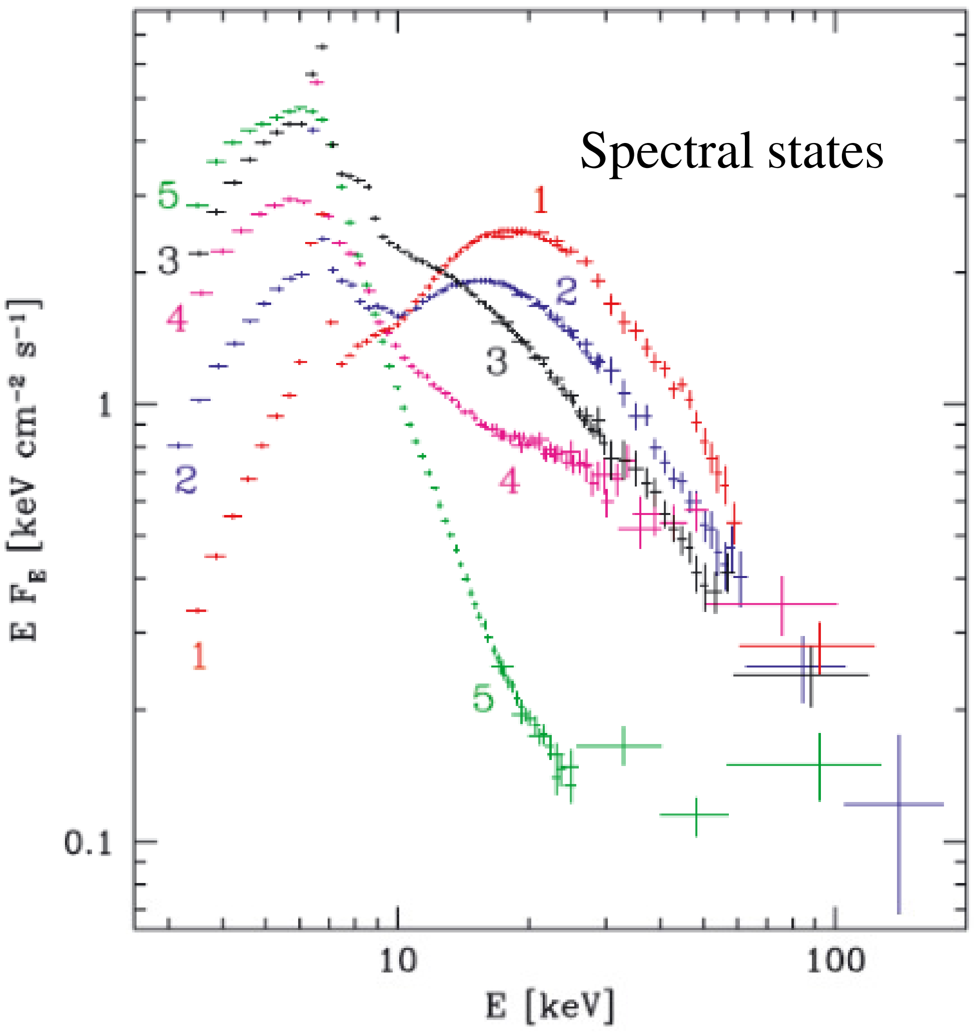
0.1–100 GeV

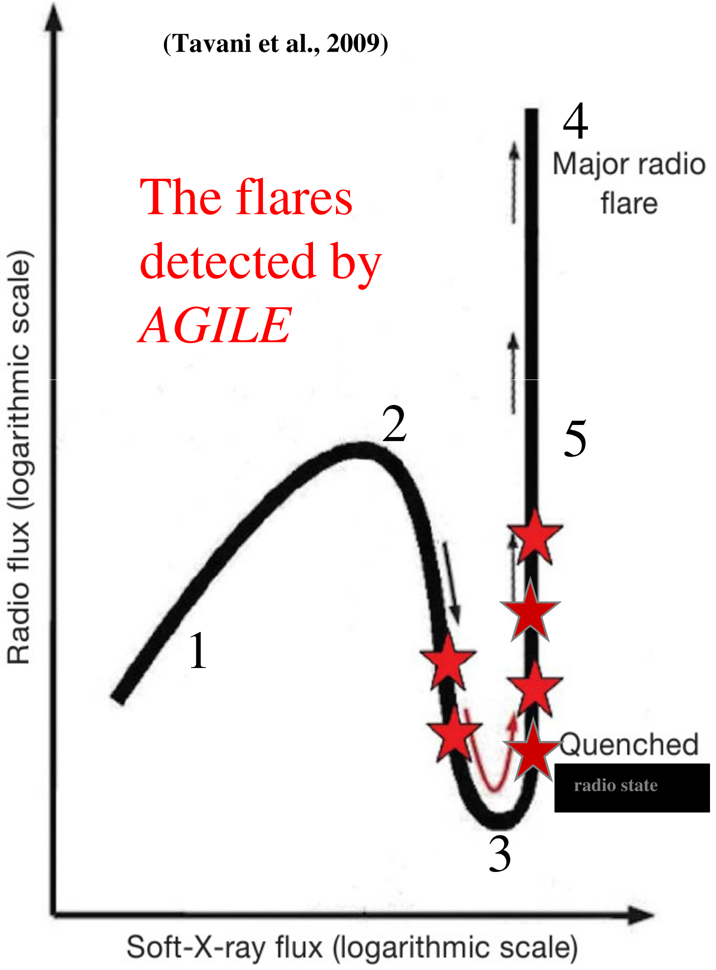
radio

active

0.1–100 GeV

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



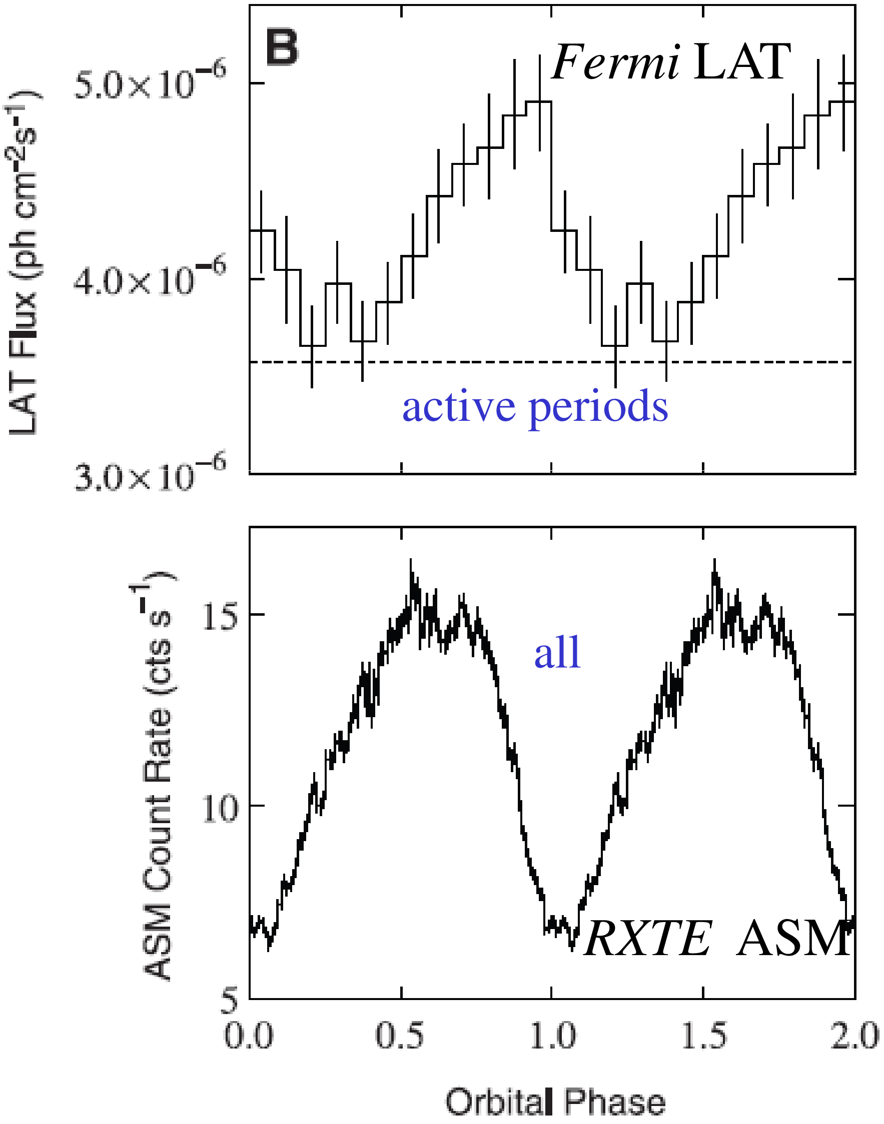

(Tavani et al., 2009)

The flares detected by *AGILE*

Observations by *Fermi*, 0.1–100 GeV

Orbital modulation of γ-rays during the active periods.

Folded lightcurves



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

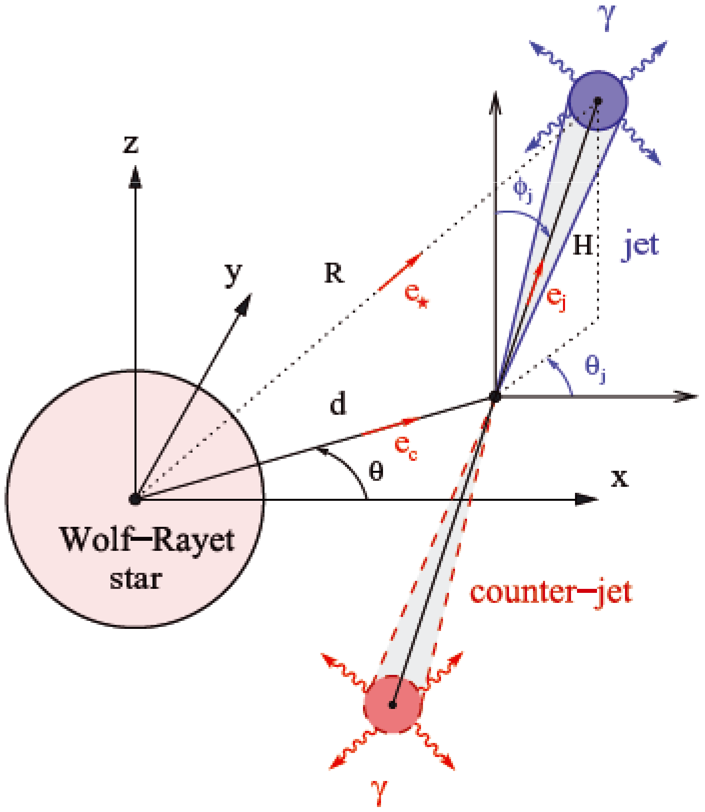
But the γ-rays have the ***maximum*** close to the superior conjunction.

Abdo+ 2009

A model for the GeV emission

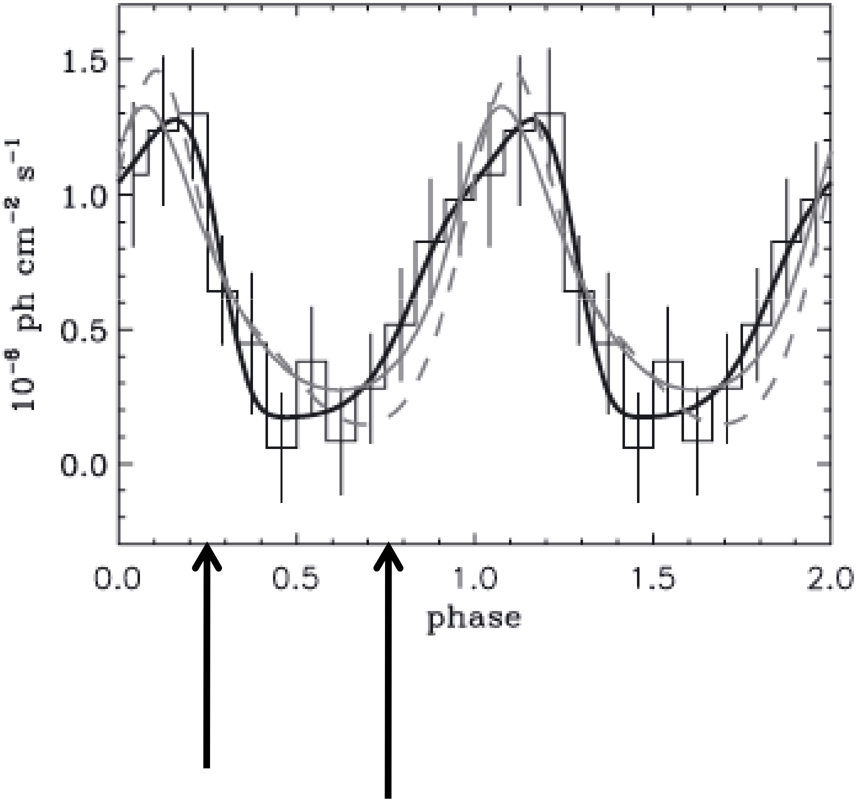
Compton anisotropy

- The relativistic electrons in the jet Compton upscatter stellar photons to GeV energies.
- Highest scattering probability for electrons moving towards the star.
- 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+ 2010

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



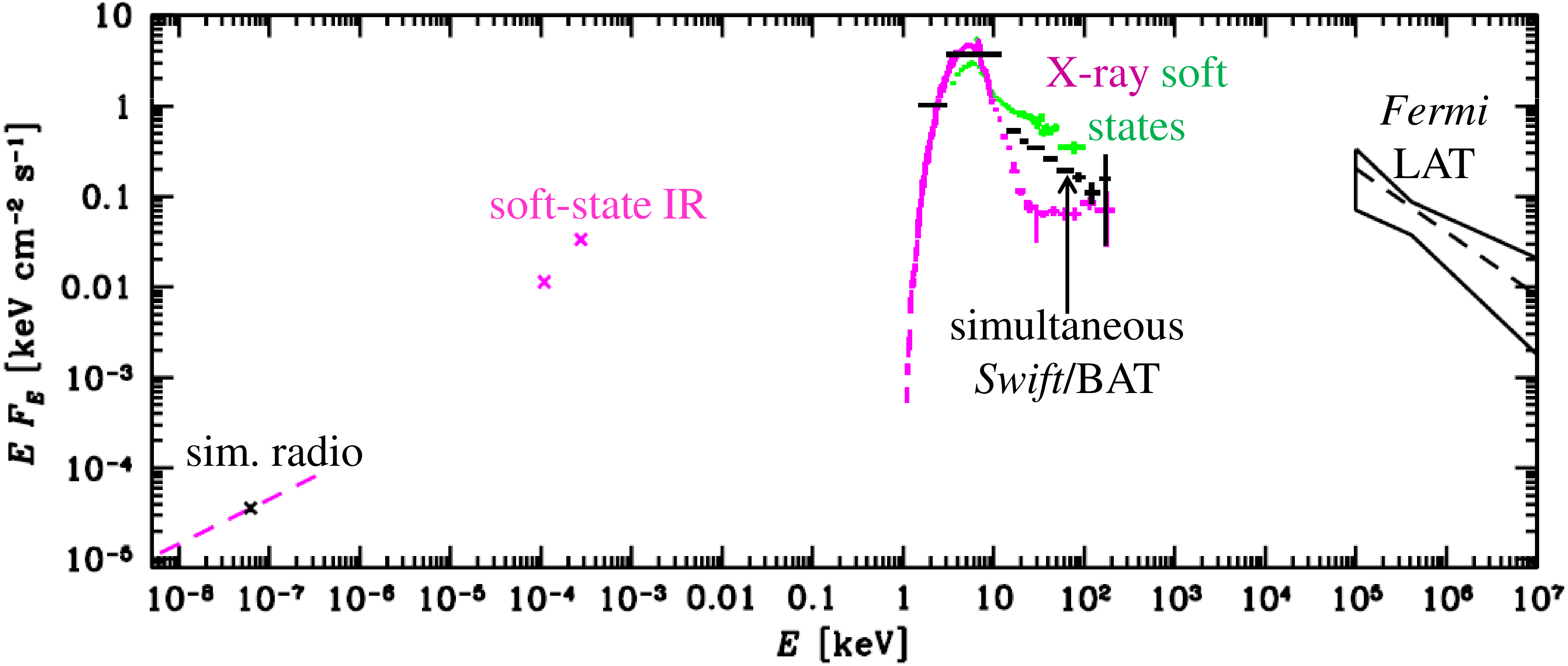
Sup.
conjunction

Inf.
conjunction

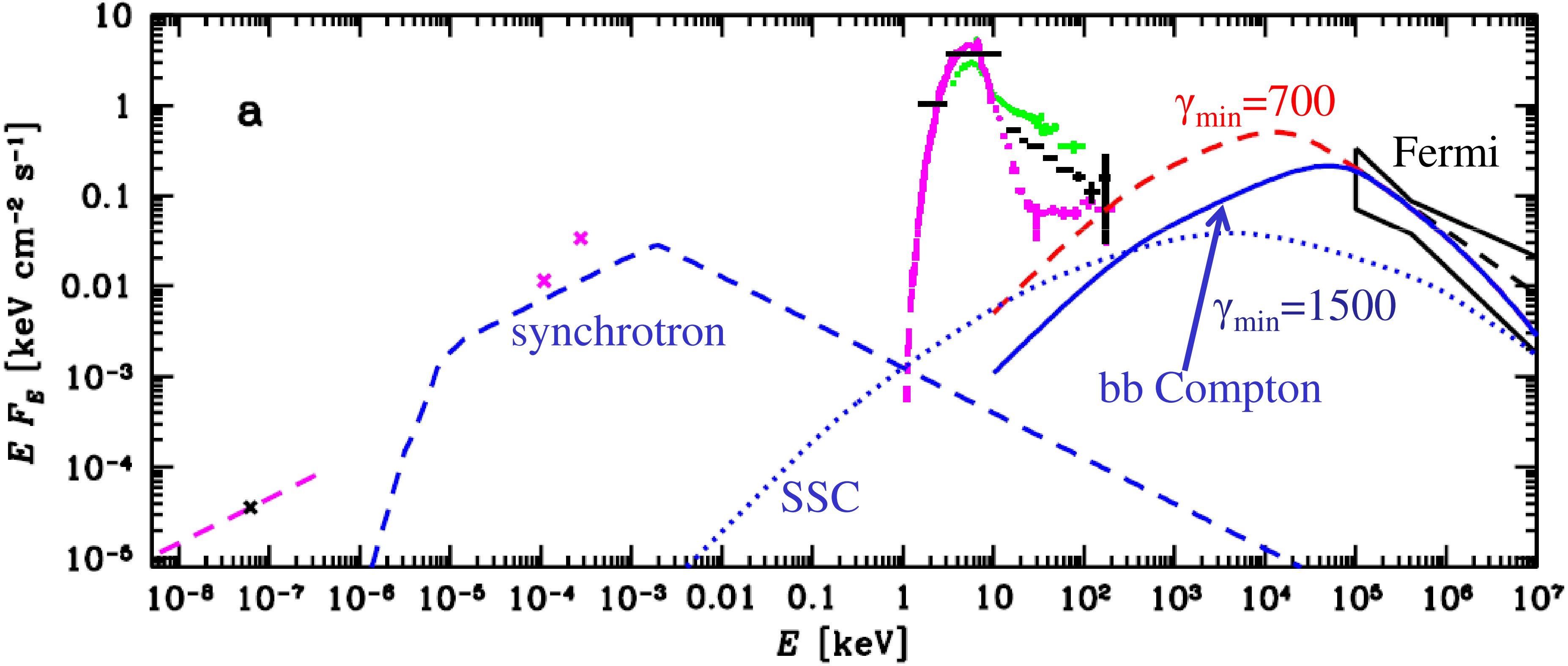
The distance along the jet from the compact object at which the γ-ray emission takes place is at ~2 of the stellar separation, ~10^{12} cm.

The broad-band spectrum in the soft state

A low-energy cutoff in the electron distribution is required, given an extrapolation of the *Fermi* spectrum would overproduce the X-rays by a large factor:

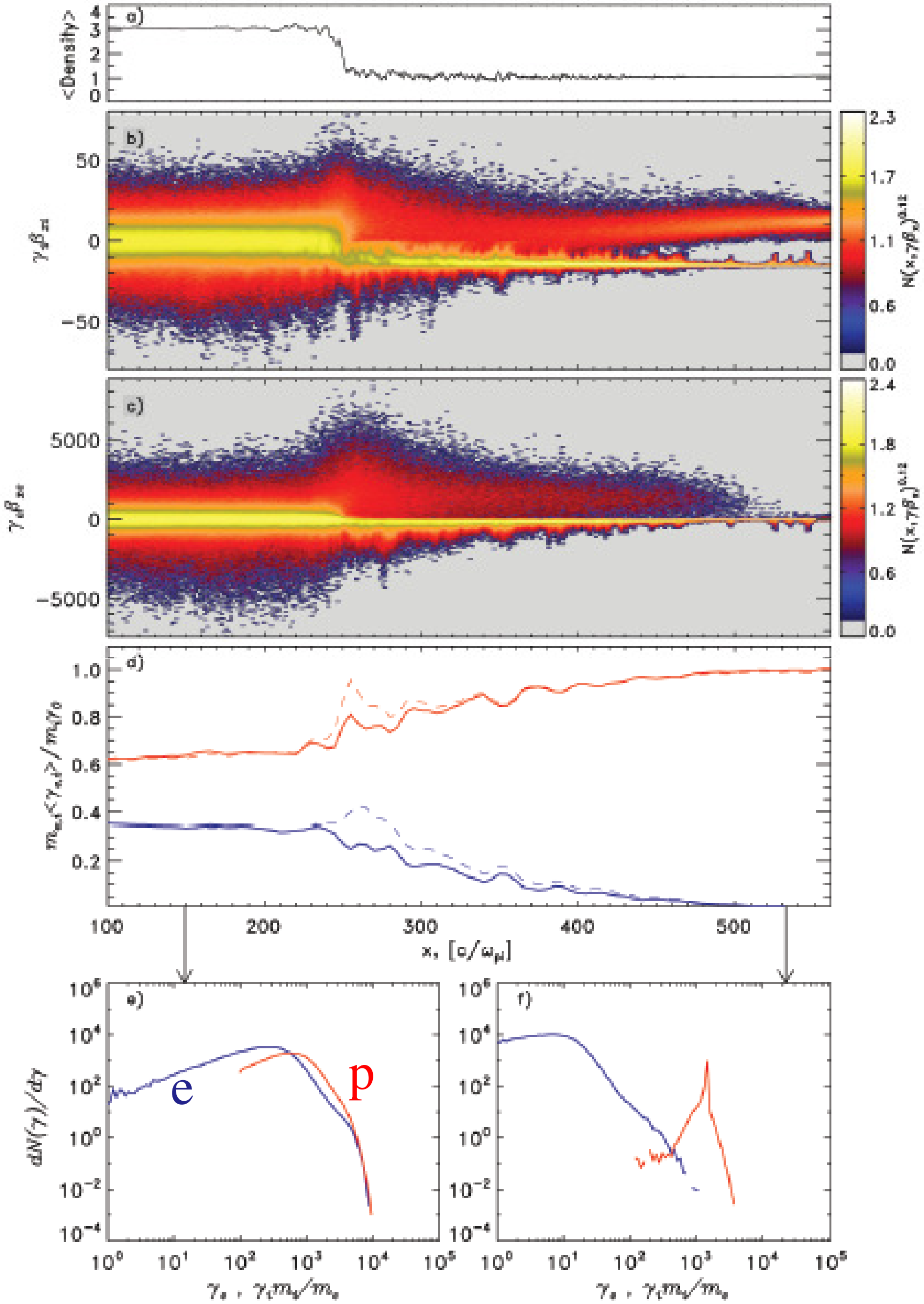


Constraints from the data: $N(\gamma) \propto \gamma^{-(3.5\text{-}4)}$, $1500>\gamma_{\mathrm{min}}>700$. The acceleration index is $\Gamma \geq 2.5$. The magnetic field is required to be $\ll$ equipartition, $B<10^2$ G or so.



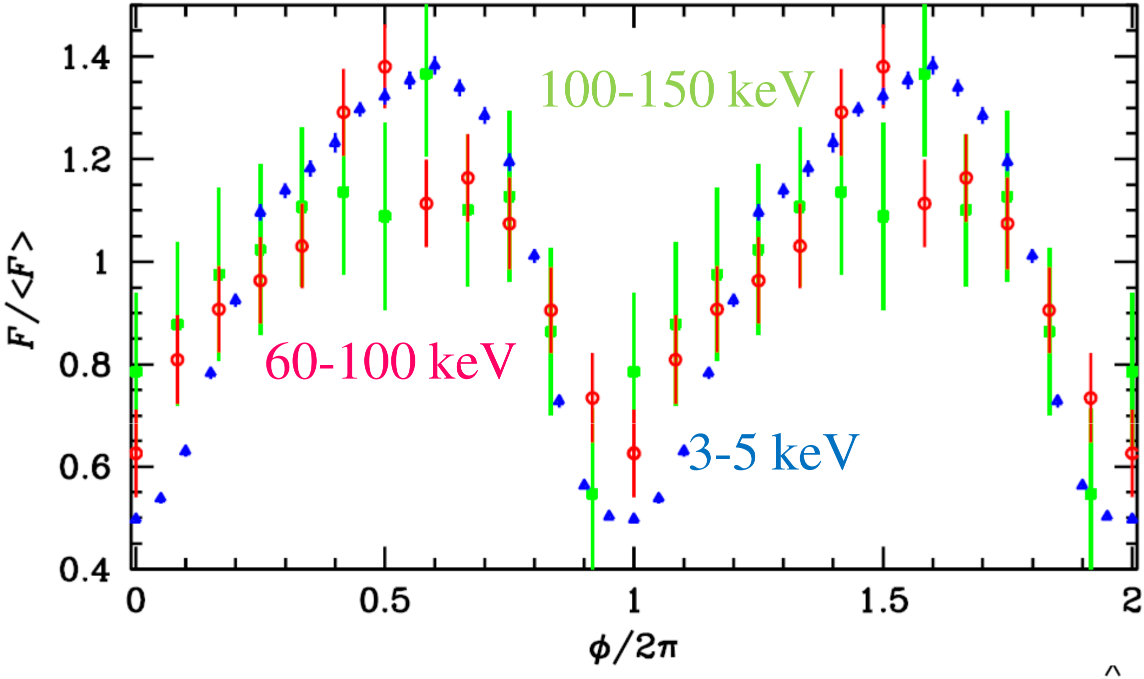
Confirmed by the hard spectrum observed by *AGILE* below 0.1 GeV.

Theoretical modelling: Spitkovsky 2008; Riquelme & Spitkovsky 2011; Sironi & Spitkovsky 2011



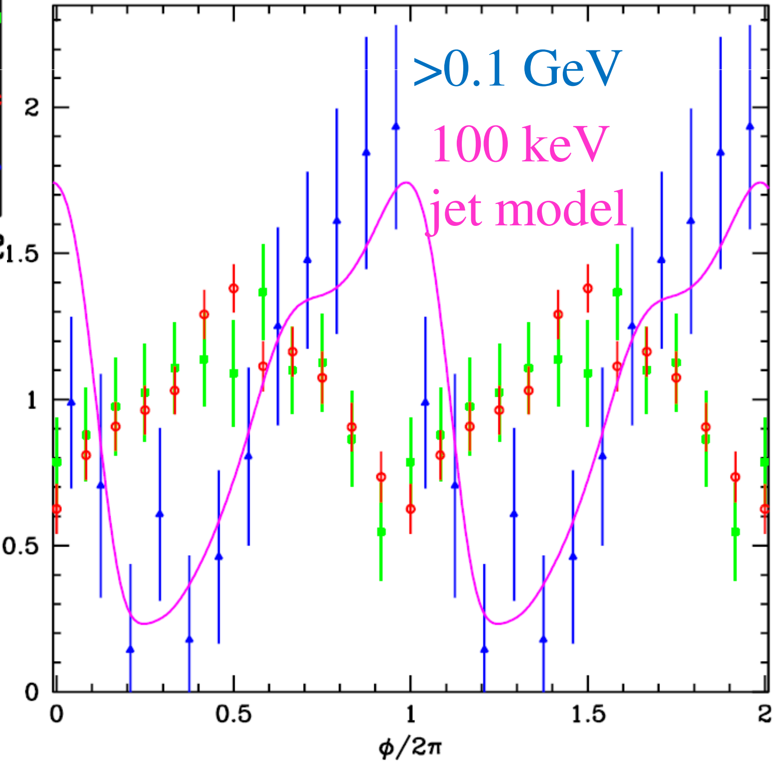
The down-stream electron spectrum: a sharp break above $\gamma > 300$, i.e, a fraction of the proton/electron mass ratio; steep slopes of accelerated electrons

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



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

Folded light curves during the periods of emission at >0.1 GeV



Resulting constraints on the jet in Cyg X-3

- The jet is launched close to black hole, but it propagates without radiating up to $R \sim 10^6\ R_g$. At this radius, a shock (possibly due to reconfinement by the stellar wind) forms, which accelerates relativistic electrons with a power-law distribution above $\gamma_{min} \sim 10^3$ or so.
- The electrons Compton-upscatter the stellar radiation, forming the observed γ-rays.
- To avoid strong synchrotron losses, the magnetic field in the γ-ray region has to be weak, $<10^2$ G or so.
- The jet mass flow rate is several % of the accretion rate.

Conclusions

- Cyg X-1 in the hard state: The average *INTEGRAL* ISGRI and PICsIT spectra disagree with the presence of a very strong high-energy tail claimed by Laurent et al. (Science, 2011). We still find an MeV tail, which may or may not be due to the jet emission.
- The structure of the jet: the jet base emitting at IR and above is at $\sim 10^3 R_g$ and its magnetic field is $B \sim 10^4$ G. The orbital modulation of the 15 GHz radio emission implies it is from $\sim 10^6 R_g$.
- Cyg X-3 in the soft state: the GeV emission is Compton upscattering of stellar blackbody at $\sim 10^6 R_g$. This implies the electron distribution in the jet has a low-energy cutoff at $\gamma_{min} >$ 300 or so. The magnetic field: $B < 10^2$ G.
- This cutoff agrees with particle-in cell simulations of collisionless shocks; the cutoff is related to the proton/electron mass ratio.
- No jet contribution at hard X-rays detected.

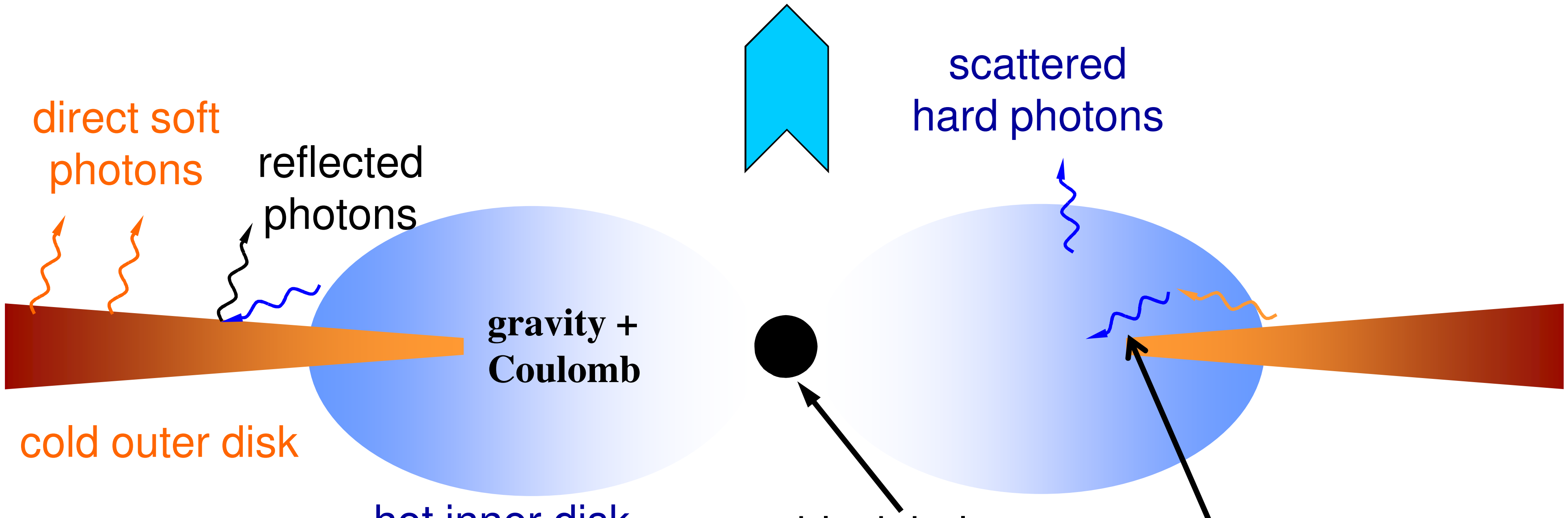
Why is Cyg X-3 unique in emitting γ-rays?

- It is a very compact, $P = 4.8$ hr, binary with a very bright companion, $L_* \sim 10^{39}$ erg/s $\sim 10^6 L_\odot$.
- The stellar flux at the γ-ray emitting region is then $\sim 10^2$ times higher than in Cyg X-1, which has a 10 times higher separation. Then, in low mass X-ray binaries, L_* is orders of magnitude lower than in Cyg X-3.
- Thus, synchrotron losses dominate in the jet acceleration region in other black-hole binaries, and therefore there is no observable γ-ray emission.
- Furthermore, Cyg X-3 has an extremely strong wind, ~10 times stronger than in Cyg X-1. This may cause the presence of a reconfinement shock in this system, but not in others. This requires a large initial jet opening angle, $>30^\circ$ or so (such a wide angle is seen in M87).

Cyg X-1

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

A likely geometry of the hard state:



jet emitting radio/IR/O...

scattered
hard photons

direct soft
photons

reflected
photons

**gravity +
Coulomb**

cold outer disk

hot inner disk

black hole

thermal plasma with
$kT_{\mathrm{e}} \sim 50$–150 keV

The inner disc radius poorly
determined, ~ 10–$200\,GM/c^2$, L/L_{E}
dependent

A jet model

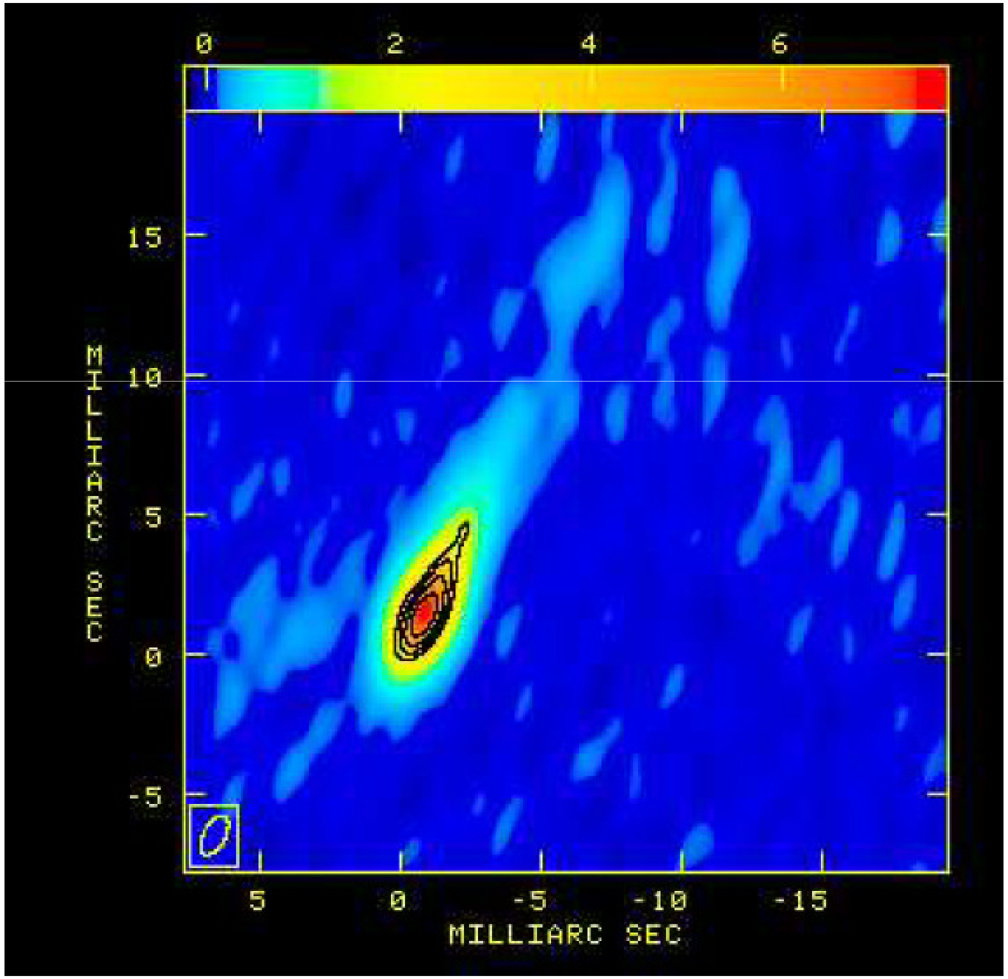
- We have developed an analytical jet model based on that of Blandford & Königl (1979), but reformulated in terms of observed quantities and including self-Compton component.
- The nonthermal synchrotron source function is integrated along the line of sight through a conical jet. This yields both the self-absorbed and optically-thin parts of the synchrotron spectra.
- From the requirement of the self-absorbed flux at the turnover frequency, we find a $z \propto B^4$ dependence for the jet base (defined as the onset of emission), where z is the base distance from the origin.
- The synchrotron self-Compton component is calculated.
- This yields a lower limit on B from the condition that the synchrotron process yields the observed flux but the Compton component is below the observational upper limit.
- An upper limit on B is from the Poynting flux being < the total kinetic jet power.

Implications of the jet model

- The MeV tail can be from jet synchrotron, in which case a very hard acceleration index, $\Gamma \approx 1.3$, is implied. Also, only ~1% of the electrons are accelerated, to account for the observed jet power of ~10^{37} erg/s.
- The MeV tail can also be due to non-thermal electrons forming a high-energy tail to the distribution of thermal electrons in the hot accretion flow. In that case $\Gamma > 2$, and all the electrons in the jet may be accelerated.
- The jet base emits the bulk of photons at the turnover energy of ~0.1 eV. The jet base is at ~$10^3 R_g$, which yields, via $z \propto \nu^{-1}$ (of the model), that 15 GHz photons are emitted at ~$10^6 R_g$, which approximately equals the orbital separation.
- This agrees with the observed strong orbital modulation of radio photons, ~30% at 15 GHz.

The problem of extended radio emission

Stirling+ 2001; Rushton 2009; Rushton+ 2011



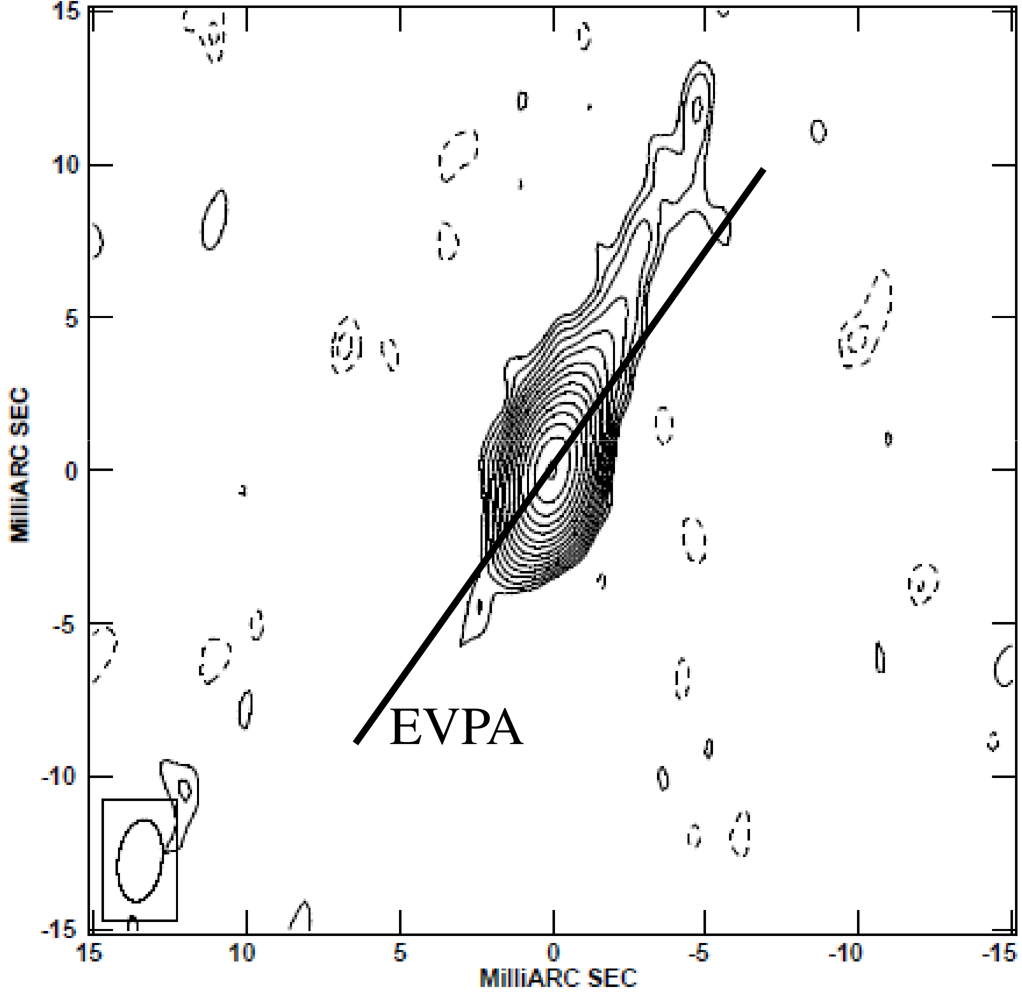
About 50% of the radio emission is resolved. At 15 GHz, this corresponds to $z \sim 2\times10^{14}$ cm, i.e., 70a (orbital separations). Then, we should expect virtually no orbital modulation due to the stellar wind whereas we observe 30%.

Also, Heinz (2006) used the resolved z to calculate the jet kinetic power. He obtained several orders of magnitude less than 10^{37} erg/s inferred from the ring nebula.

The observed modulation implies the resolved part of the jet is not a simple continuation of the inner jet. A secondary dissipation event most likely takes place at $z \sim 10^1 a$.

An issue of the jet position angle in Cyg X-1

Stirling+ 2001; Rushton 2009; Rushton+ 2011



Note that the position angle of the jet in Cyg X-1 given by the discovery paper (Stirling+ 2001) is incorrect, given there as +(17°−24°) whereas it is –(17°−24°). The incorrect angle is quoted in Laurent+ 2011, which led them to conclude that their polarization angle of EVPA = 140±15° (equivalent to –40°±15°) is close to being perpendicular whereas it is close to being parallel to the jet.

Radio polarization <10%

Main properties of Cyg X-3

- A very luminous radio and X-ray source.
- A very short 4.8 hr period.
- The donor is a WR star (the only WR X-ray binary in the Galaxy). The compact object is most likely (but not certainly) a black hole.
- Strong extinction makes the donor invisible in the optical radiation, strong stellar wind makes the X-rays strongly absorbed.
- The X-ray spectra generally similar to those of spectral states of black-hole binaries.

Some general questions:

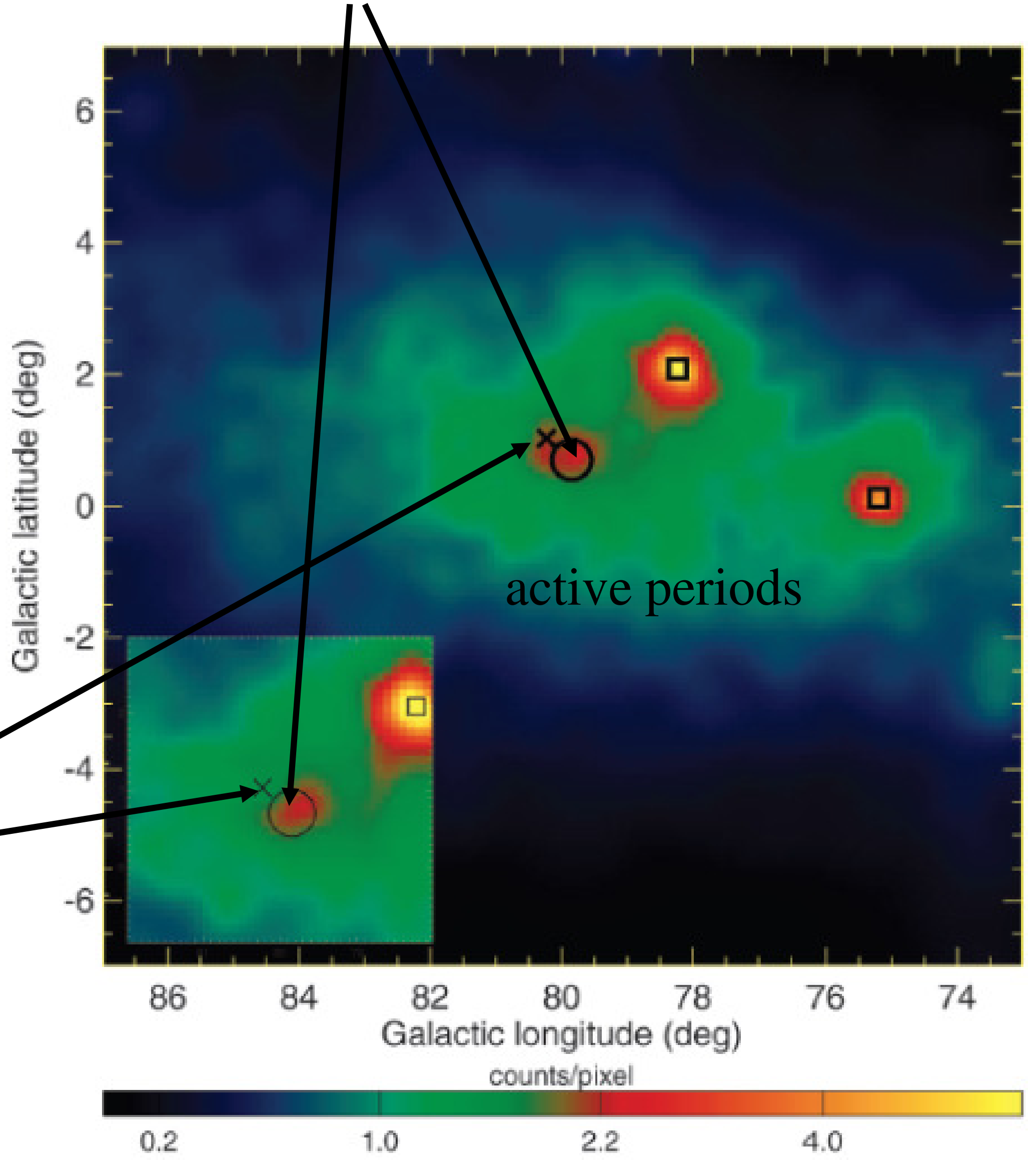
- Why do black-hole binaries have the X-ray and γ-ray from their jets relatively weaker than in AGNs with jets?
- Why is Cyg X-3 the only accreting X-ray binary for which GeV emission has been detected?

Many unconfirmed past claims of detections of high and very high energy γ-rays from binaries (and other sources).

- A large number of claims for Cyg X-3 in GeV, TeV, PeV, all unconfirmed or wrong.
- One detection by *CGRO*/EGRET of a transient, most likely a binary.
- A plausible detection by *CGRO*/EGRET of Cen X-3, but unconfirmed so far.

Observations by *Fermi*, 0.1–100 GeV

The emission from the pulsar PSR J2032+4127 has only narrow pulses, which intervals are removed from the data for Cyg X-3, which results in a loss of only 20% of the Large Area Telescope exposure.

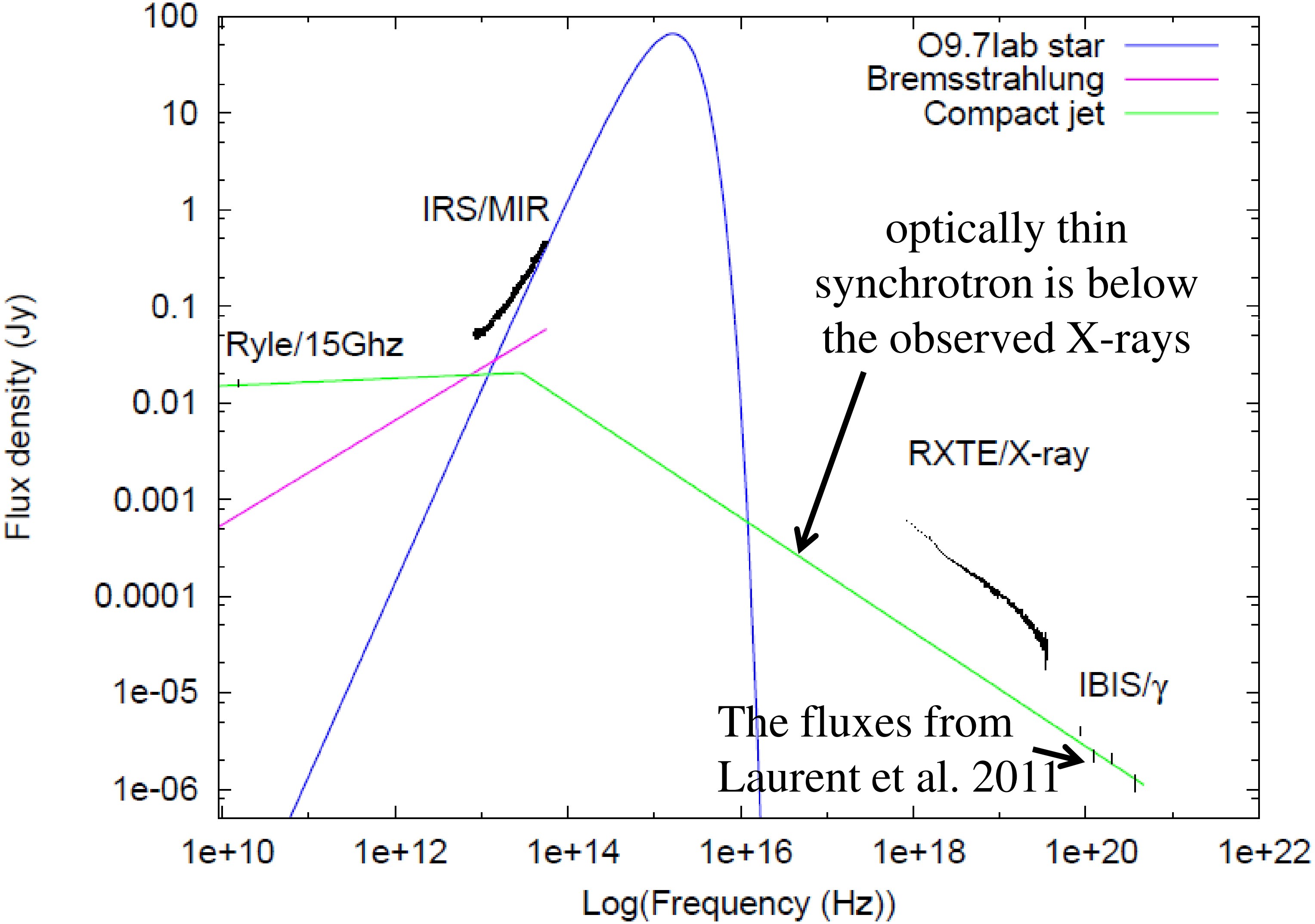


Cyg X-3, 29σ significance

active periods

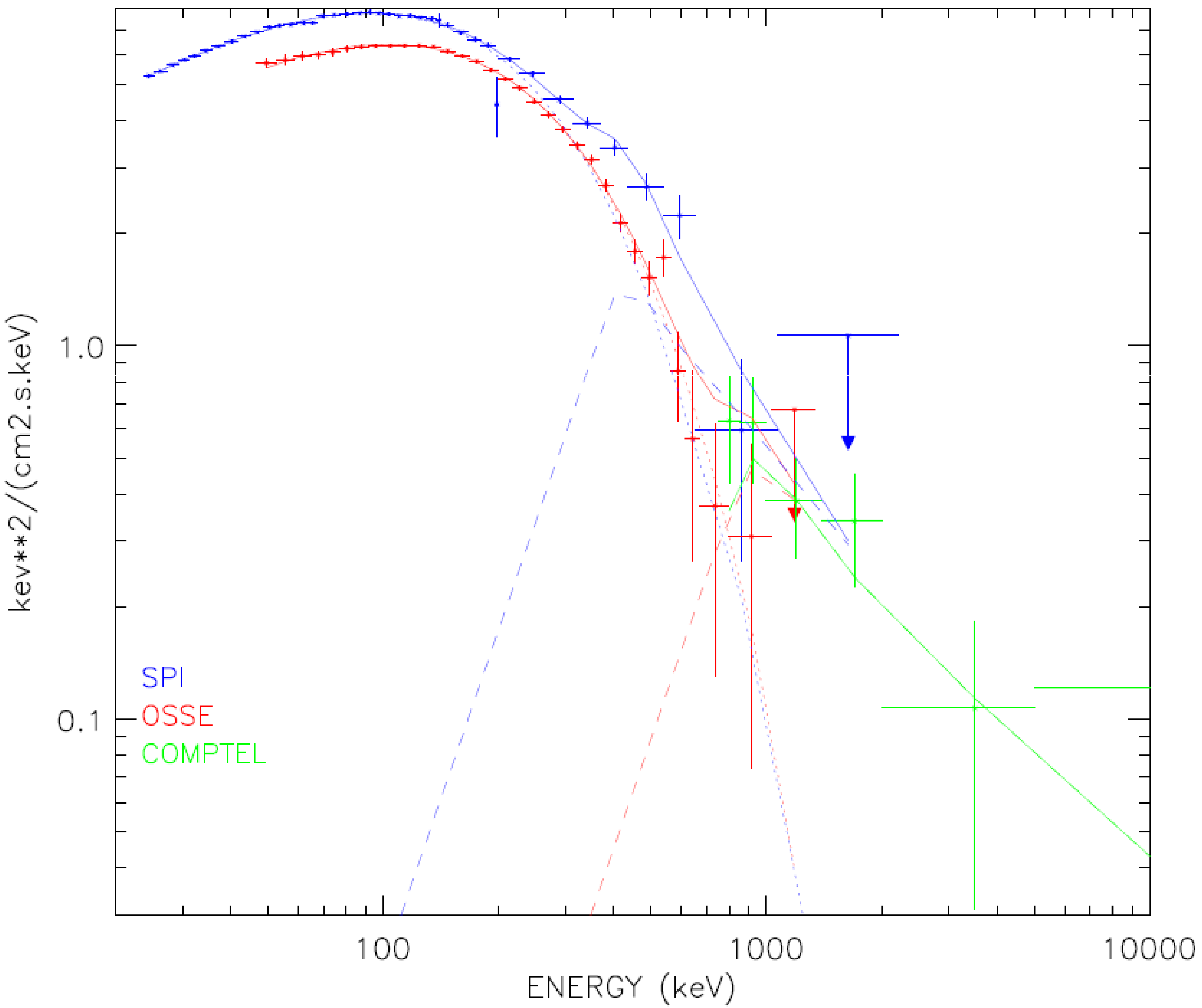
PSR J2032+4127
30′ away from Cyg X-3

Rahoui et al. 2011 determined the synchrotron turnover frequency in Cyg X-1and confirmed that X-rays are not synchrotron. But a jet contribution at MeV is possible.


optically thin synchrotron is below the observed X-rays

The fluxes from Laurent et al. 2011

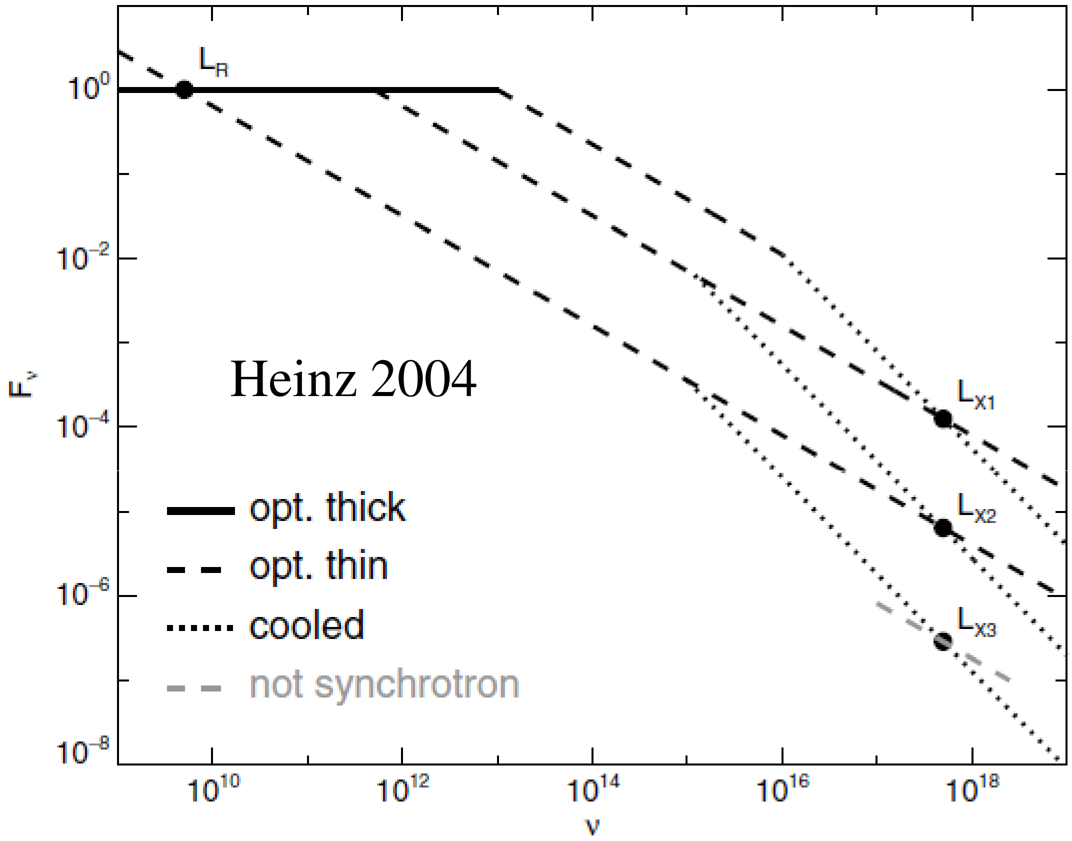
A new independent study of the hard-state spectrum of Cyg X-1



Jourdain,
Roques,
Malzac 2012

A confirmation of our results.

A further issue: electron cooling



Modelling is usually done with an optically thin non-thermal power law from the turnover frequency to X-rays. But a break with $\Delta\alpha = 0.5$ is expected in the UV due to cooling. This would strongly reduce the contribution of non-thermal synchrotron to X-rays and γ-rays.

To avoid this problem, Laurent et al. suggested $B \sim 0.01$ G. However, the bulk of the optically emission usually comes from the base of the jet, expected at $\sim 10^3 R_g$, at which a much stronger field is expected ($\sim 10^5$ G in the inner accretion flow, and $B \propto R^{-1/2}$).

Electron cooling

- The electron distribution steepens by $\Delta p = 1$above the energy at which synchrotron losses start to dominate over adiabatic losses:

$$\dot{\gamma}_{\rm s} = \frac{4}{3}\frac{\sigma_{\rm T}}{m_{\rm e}c}\frac{B^2}{8\pi}\gamma^2, \quad \dot{\gamma}_{\rm ad} \simeq \frac{2\beta_{\rm J}\gamma_{\rm J}c}{3z}\gamma$$

- Scaling the magnetic field at the base of the jet we find the synchrotron photon energy corresponding to the break as:

$$E_{\rm b} \simeq \frac{1.8\times10^{-10}\delta^3\xi}{q^{3/2}}\,{\rm keV}$$

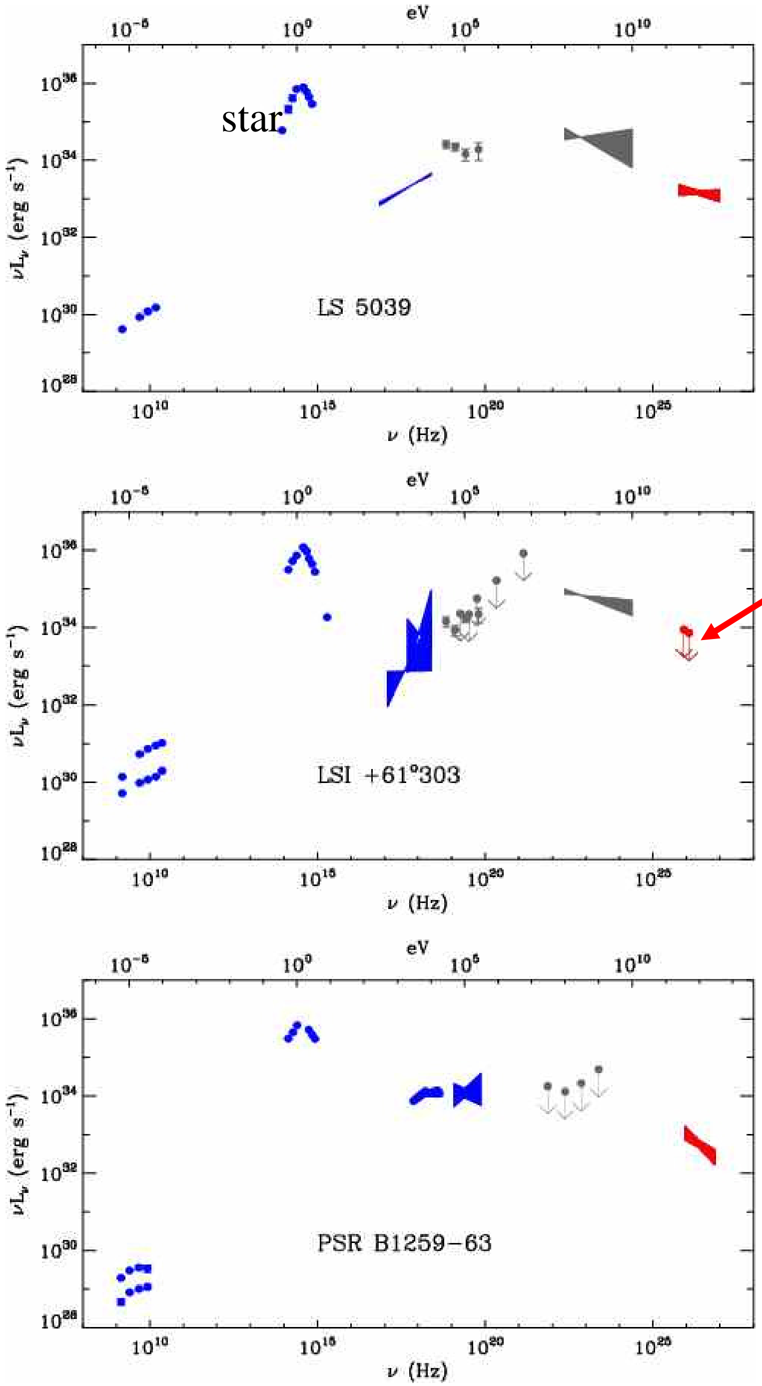
  where δ is the jet opening angle ($\ll$1), ξ is the emission radius in unit of GM/c^2, and q is the ratio of the magnetic energy flux to $\dot{M}c^2$.

- Then, the break energy is at $\ll$1MeV for any reasonable parameters.

Binaries emitting high-energy γ-rays

- PSR B1259–63, a young radio pulsar + Be star, emission from the pulsar wind colliding with the stellar wind;
- The persistent γ-ray sources LS I +61 303, LS 5039, HESS J0632+057; most likely also emission from the pulsar wind colliding with the stellar wind;
- Colliding stellar winds of massive binaries, e.g.,WR 20a, have been predicted to emit γ-rays. The emission found by HESS was extended, thus it was not clear if the binary itself is emitting γ-rays. Eta Carinae detection by *AGILE* and *Fermi*;
- Radio pulsars in binaries, in particular ms radio pulsars (spun up by accretion), which are usually in binaries. Several ms radio pulsars have been detected by *Fermi*.
- The accreting black-hole binary Cyg X-1 – a short transient TeV emission observed by MAGIC, but only a 4σ significance;
- The only unambiguous detection of an accreting binary in γ-rays is that of Cyg X-3 by *Fermi* and *AGILE*.

The γ-ray loud emitting binaries:

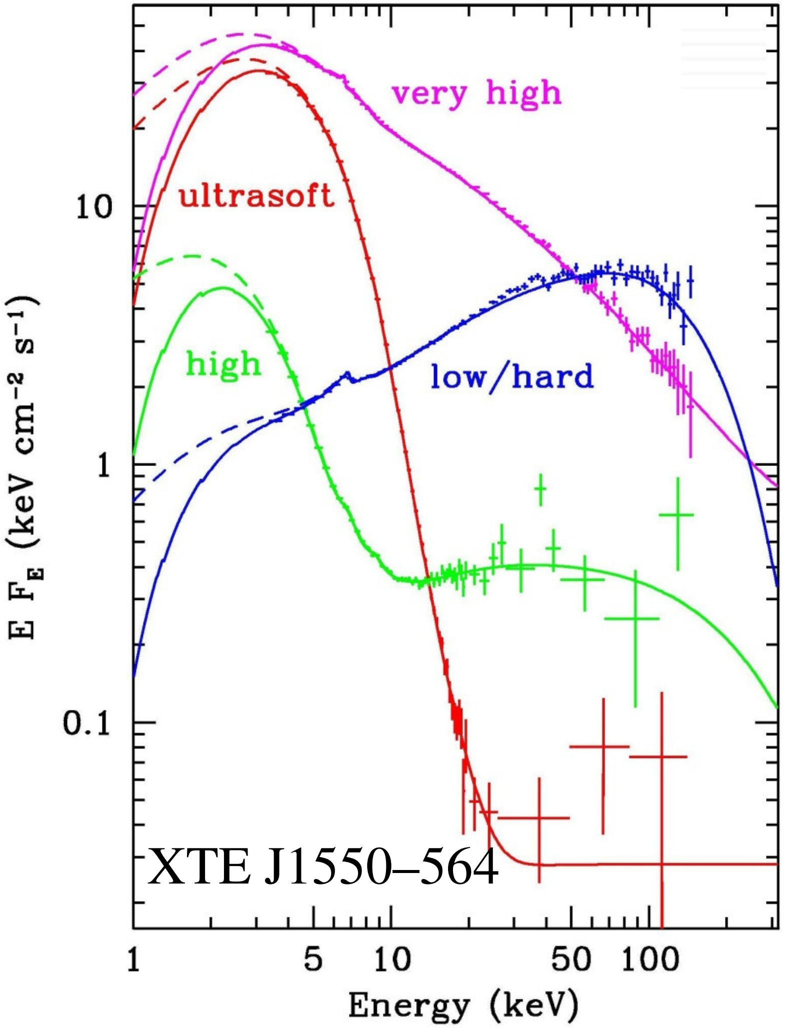


also detections by MAGIC and VERITAS

Dubus 2006 „Gamma-ray binaries: pulsars in disguise”; Z.+ 2010

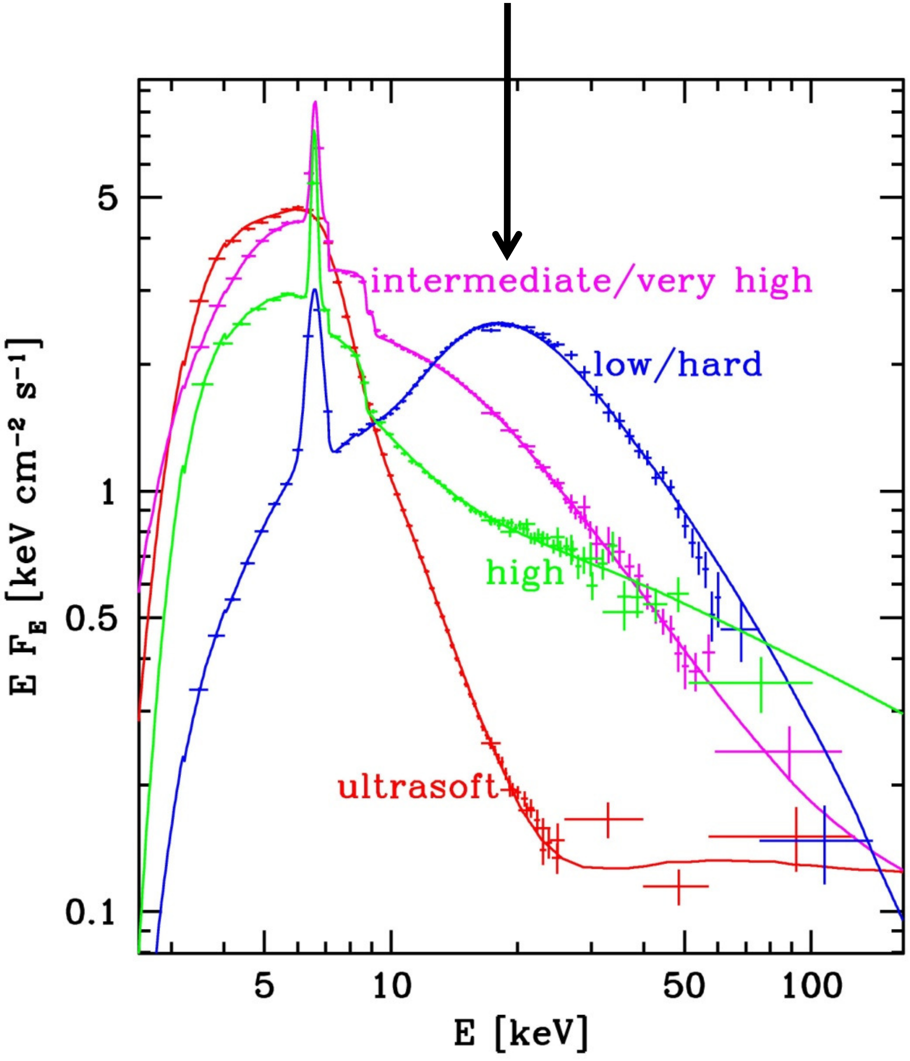
They are powered by relativistic pulsar wind colliding with a wind of the massive companion, *not accretion*. They are not microquasars.

XTE J1550–564 – a transient black-hole low-mass binary



Cygnus X-3: a black hole?

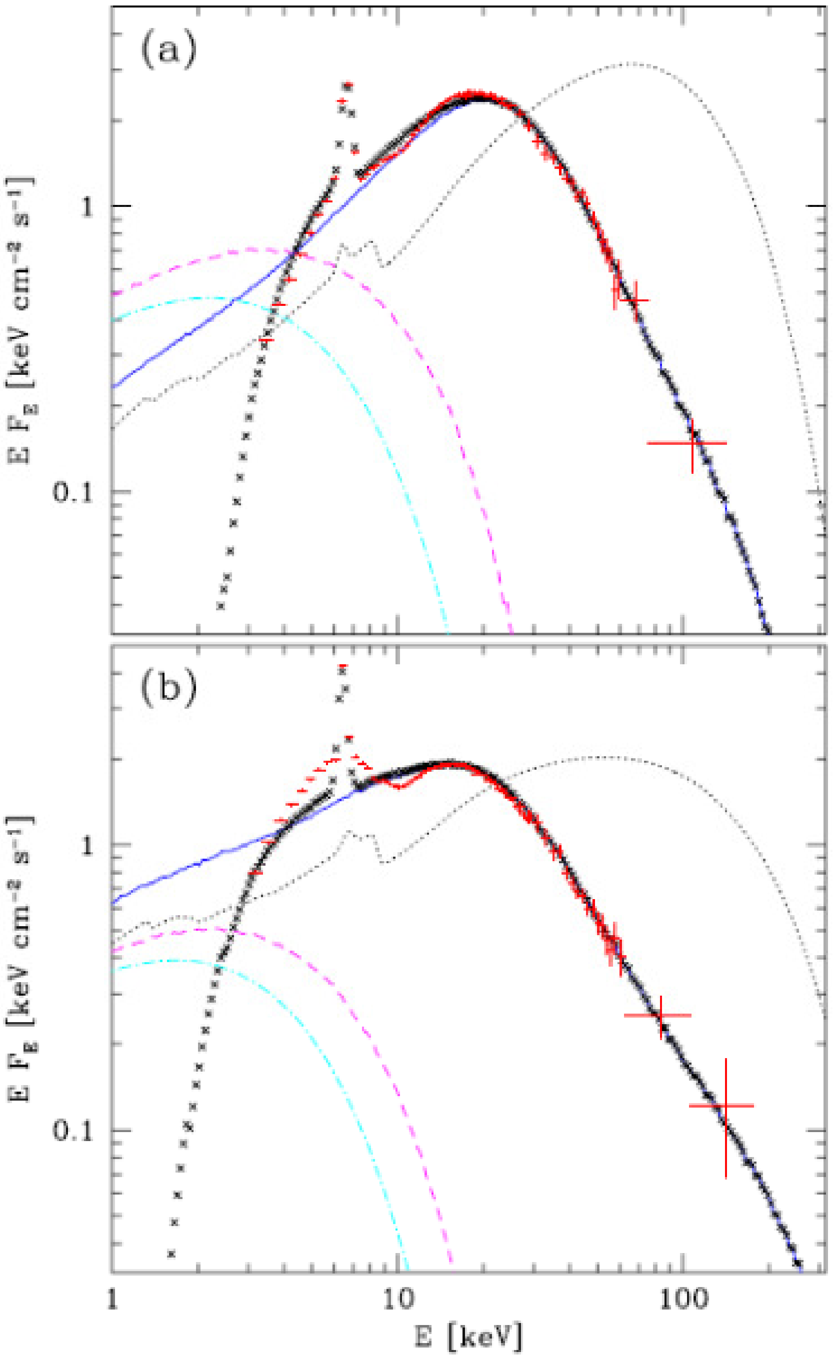
The peculiarly low value of the high-energy break in the hard state



Szostek, Z. & McCollough 2008

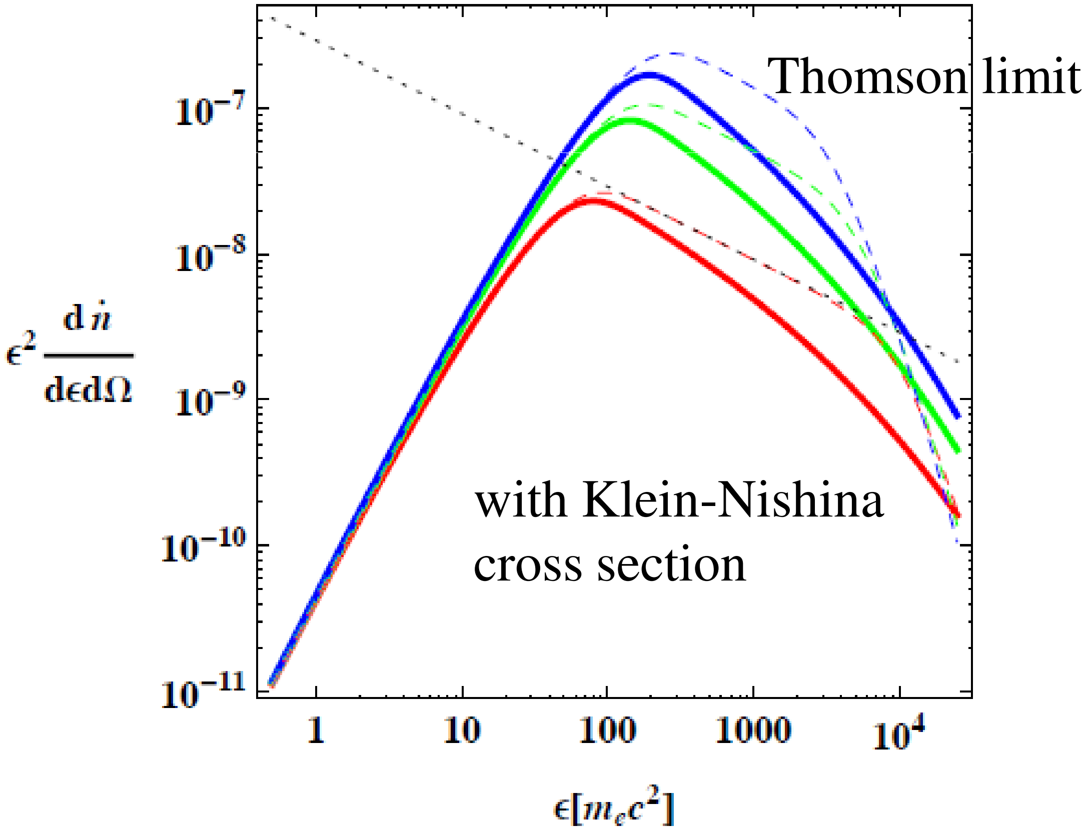
The peculiar form of the hard state spectra in Cyg X-3 can be explained by Compton down-scattering in the dense stellar wind from the companion WR star. The intrinsic spectra are from thermal Comptonization in a hot plasma typical for black hole binaries, *kT* ≈ 30–50 keV. Downscattering moves the break to ~20 keV.

Z., Misra & Gierliński 2010

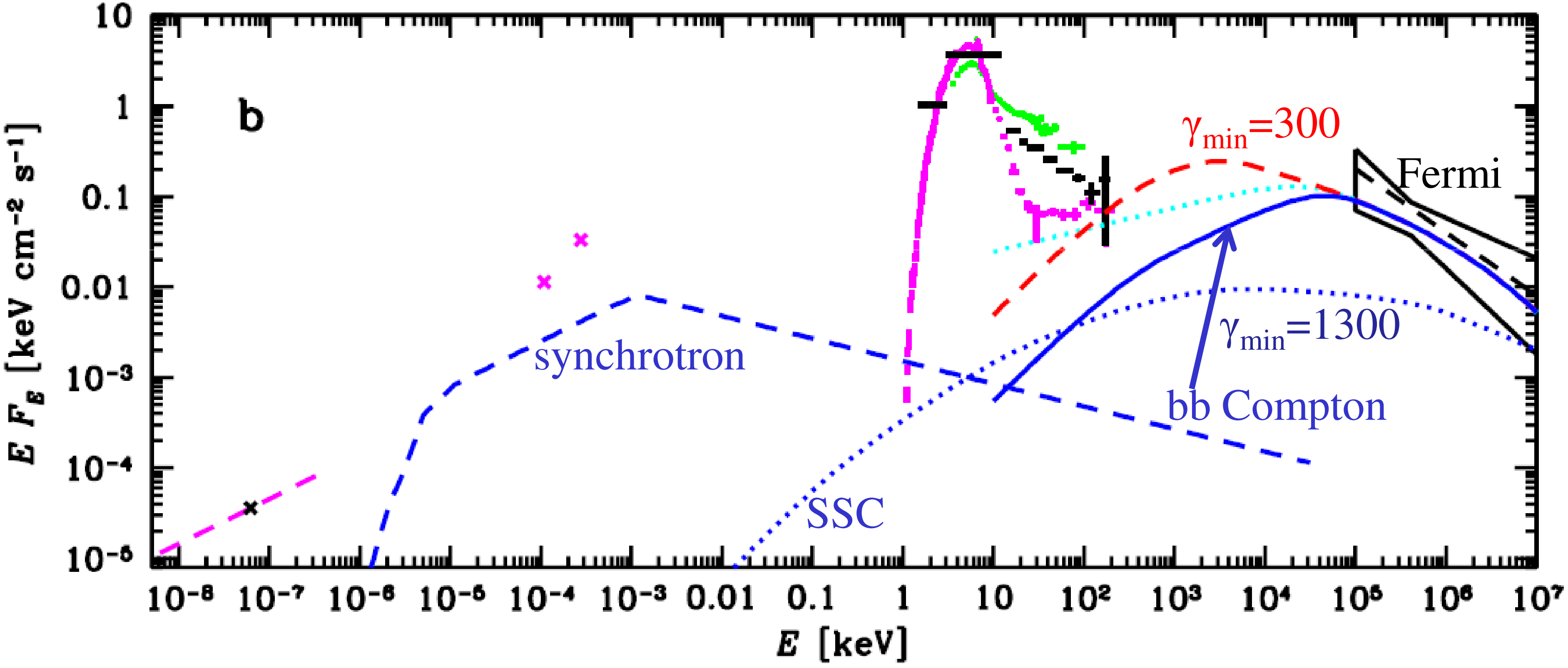


Calculations of Compton spectra from a mono-directional beam incident on a cloud of power-law electrons with a low-energy cutoff:

$N(\gamma) \propto \gamma^{-4}$;
$\gamma_{\min} = 1000$;
The scattering angle:
$\vartheta = 60^\circ, 90^\circ, 120^\circ$
from bottom to top.
The seed photons are
blackbody with
$T = 10^5$ K.

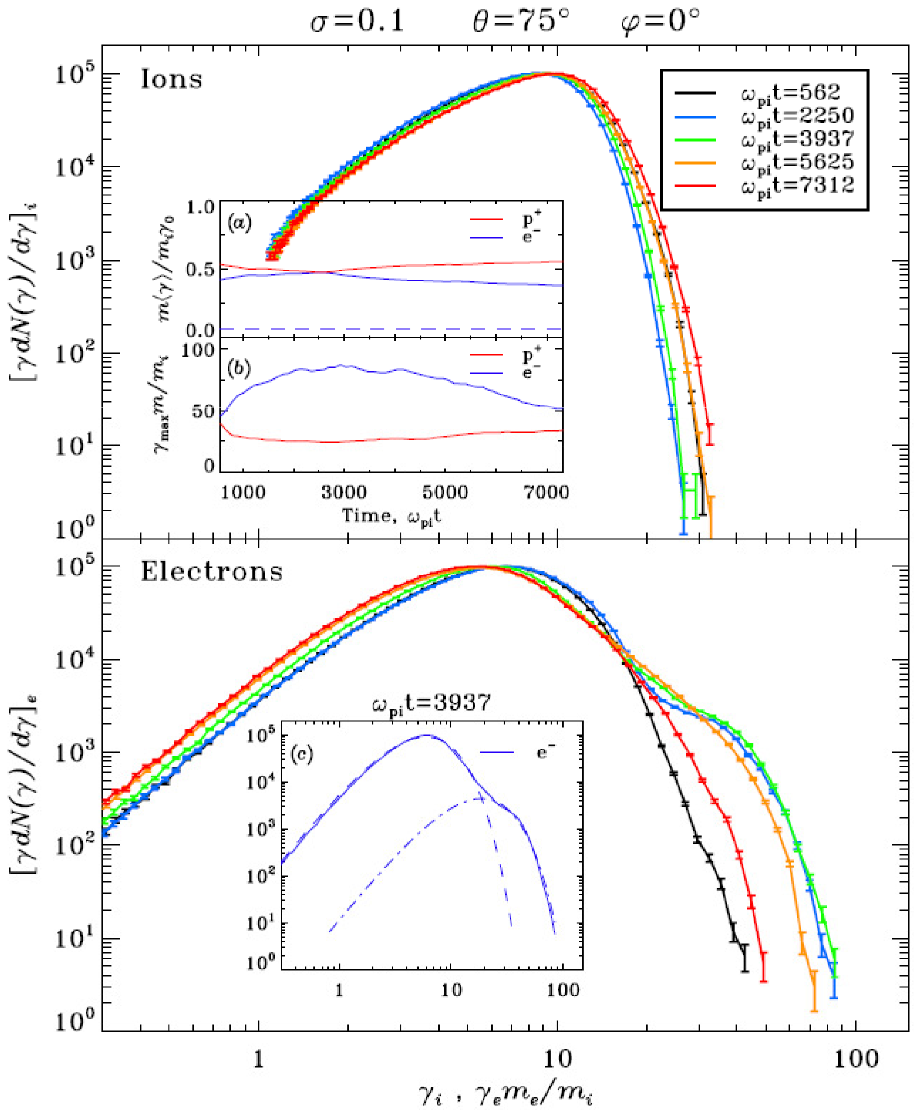


Constraints from the data for $N(\gamma) \propto \gamma^{-3.5}$: $1300 > \gamma_{\min} > 300$



Z. et al. 2012

A quasi-Maxwellian peaked at $\gamma \sim m_i/m_e$



Sironi &
Spitkovsky 2011