Jets in black-hole binaries. Some aspects related to polarization

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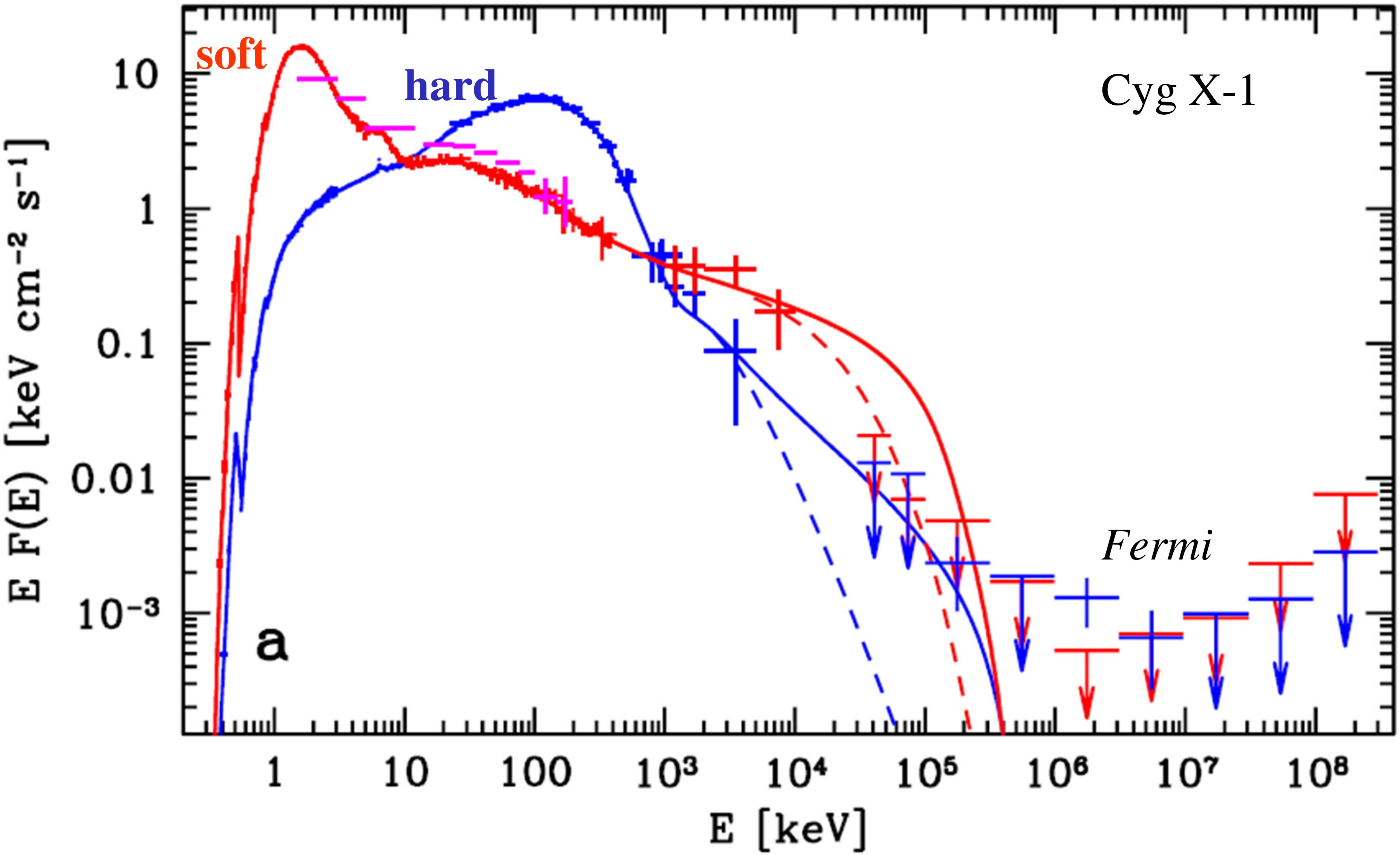
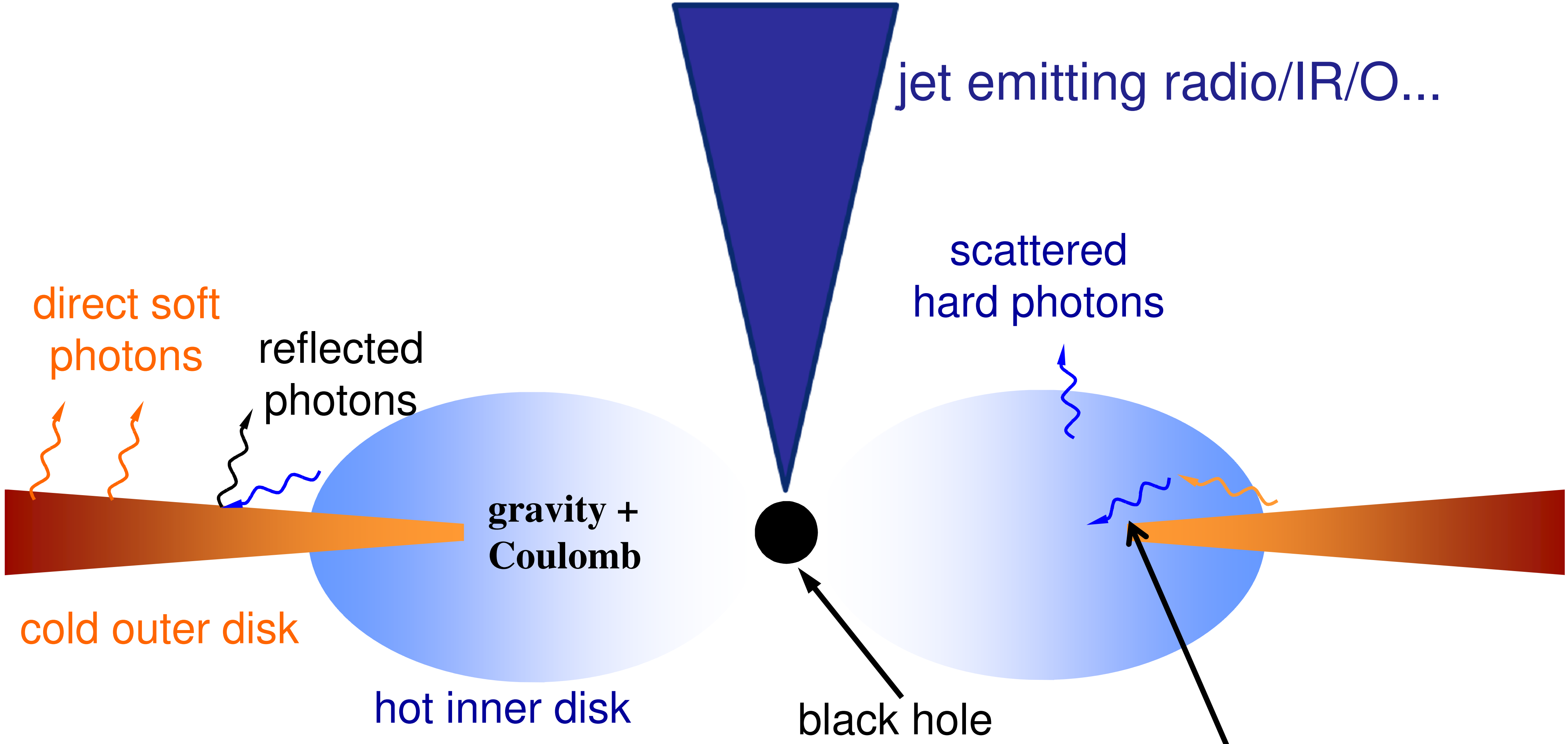
Two main spectral states of black-hole binaries, hard and soft



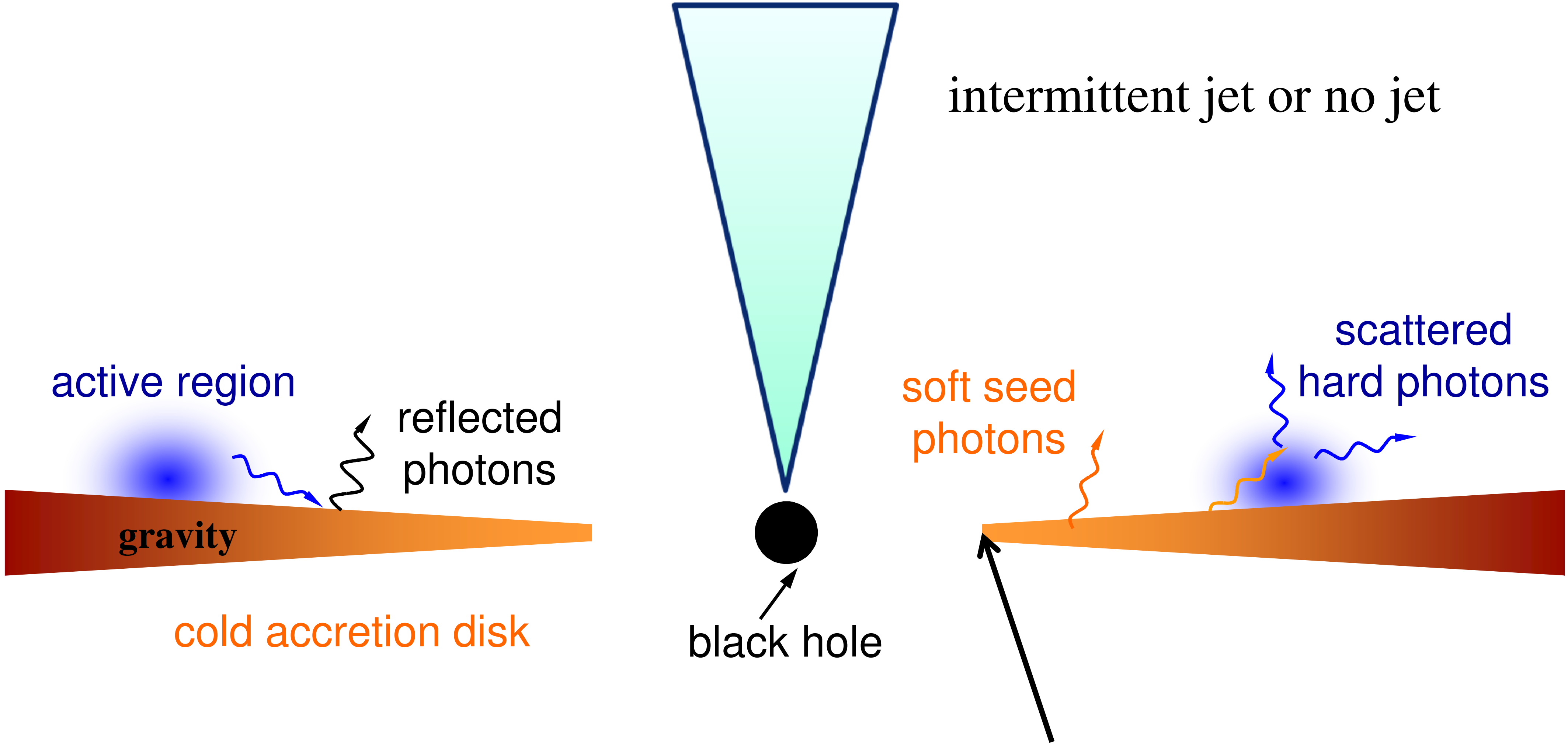
A likely geometry of the hard state:



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:

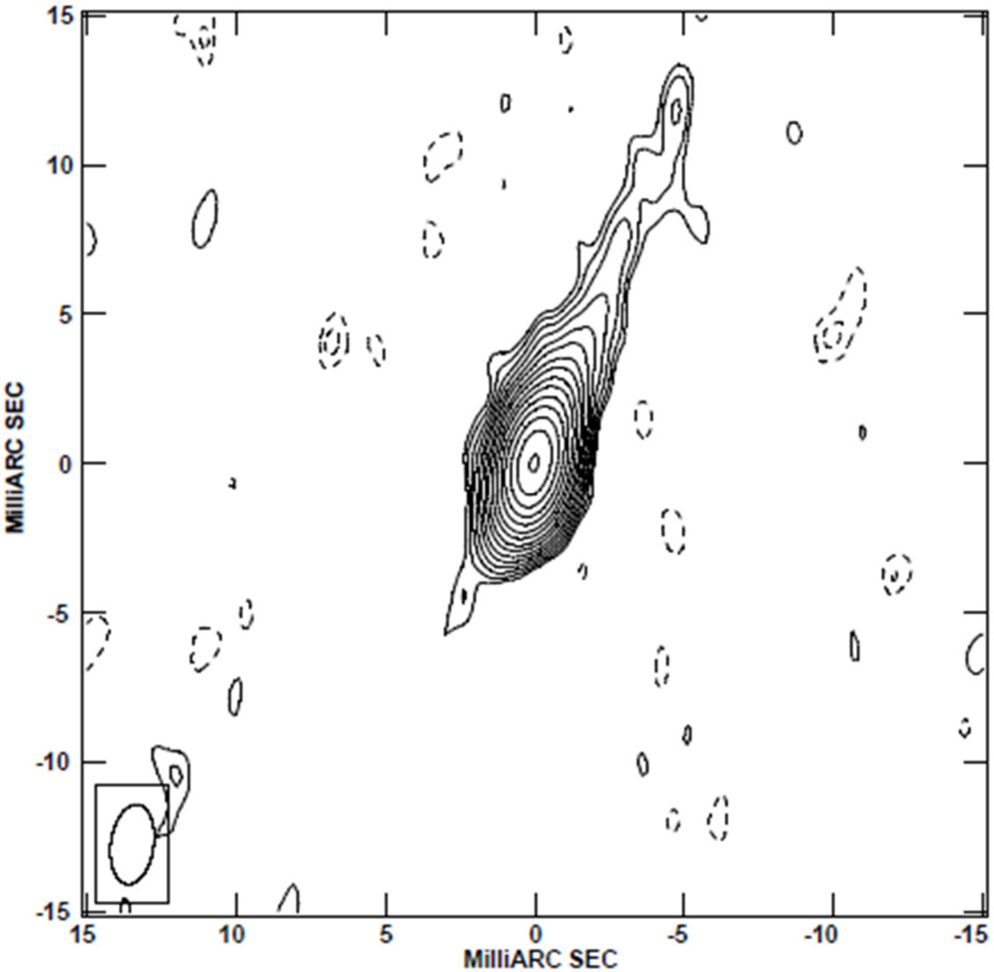


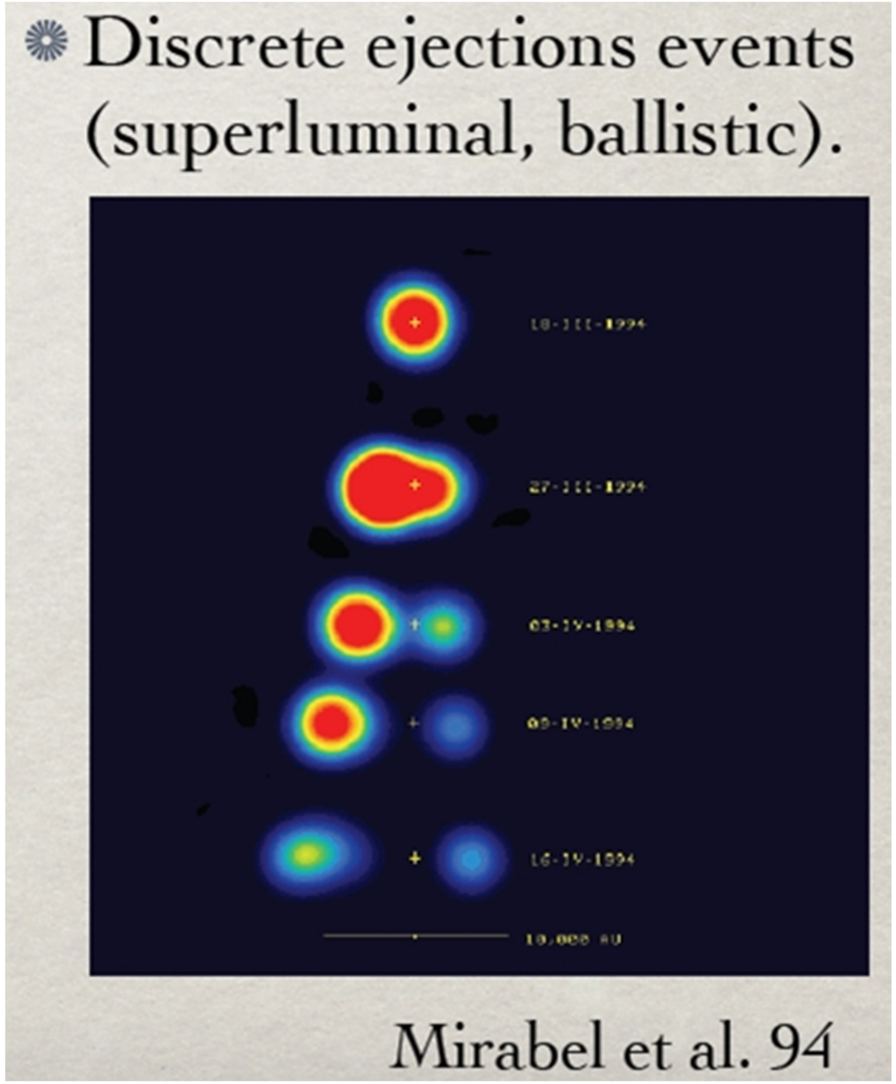
The inner disc radius probably at the innermost stable orbit, $6GM/c^2$ or less for a rotating black hole

Two kinds of jets in black-hole binaries

at highest L, soft states

steady and compact at low L, hard states





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

GRS 1915+105

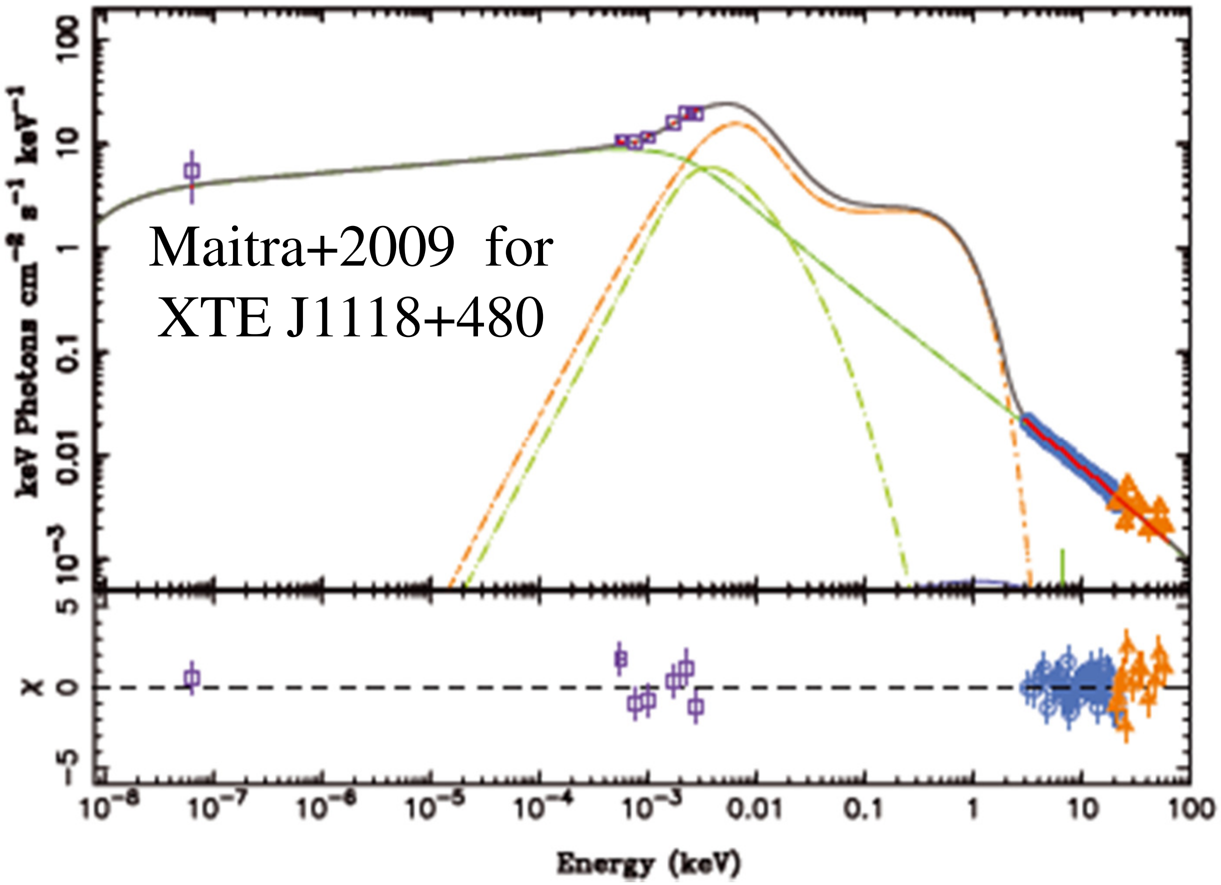
I. What is the contribution of jets to X-rays in black-hole binaries?

The hard state

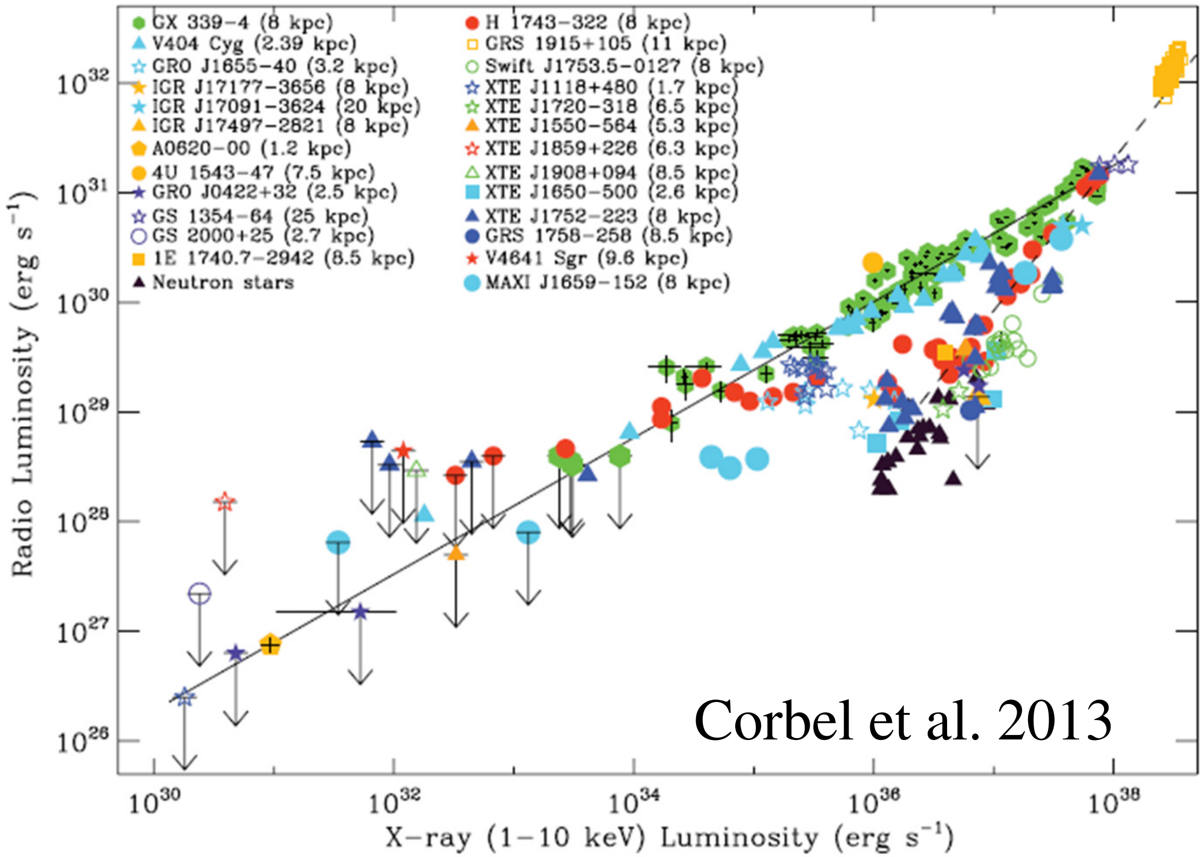
- Disputed geometry and components, either:
  - a hot inner flow overlapping with an outer disc;
  - the same with some blobs of cold matter;
  - a disc extending to ISCO with a corona;
  - the X-ray emission from a jet, synchrotron and/or Compton.
- The main physical process, either:
  - Compton upscattering by thermal electrons;
  - Compton upscattering by hybrid, thermal and non-thermal, electrons;
  - synchrotron emission.
- The main seed photons for Compton scattering, either:
  - disc blackbody photons;
  - synchrotron photons.

X-ray jet synchrotron models:

The X-rays in the hard state supposed to be optically thin non-thermal synchrotron emission of the jet. The model still popular, e.g., ***`such*** (hard-state X-ray) ***emission can be readily associated with the cooling of highly relativistic electrons'*** in a recent work.

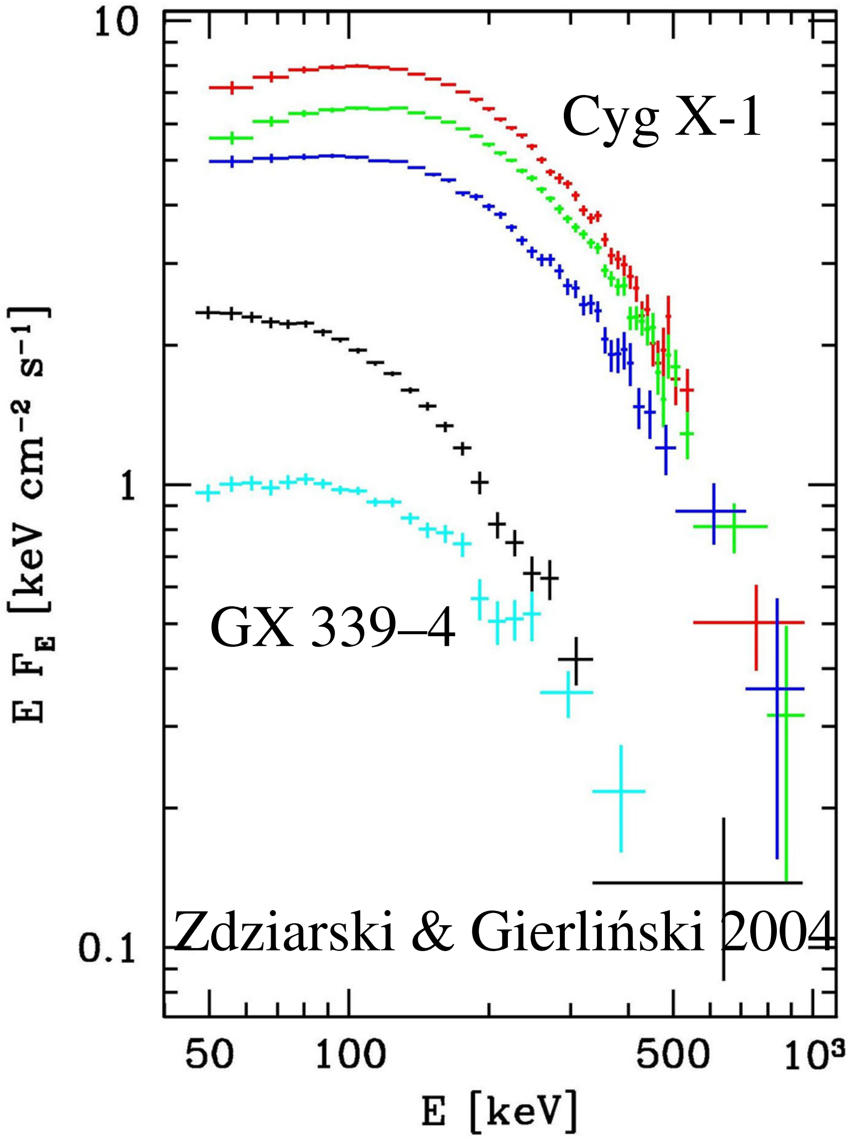


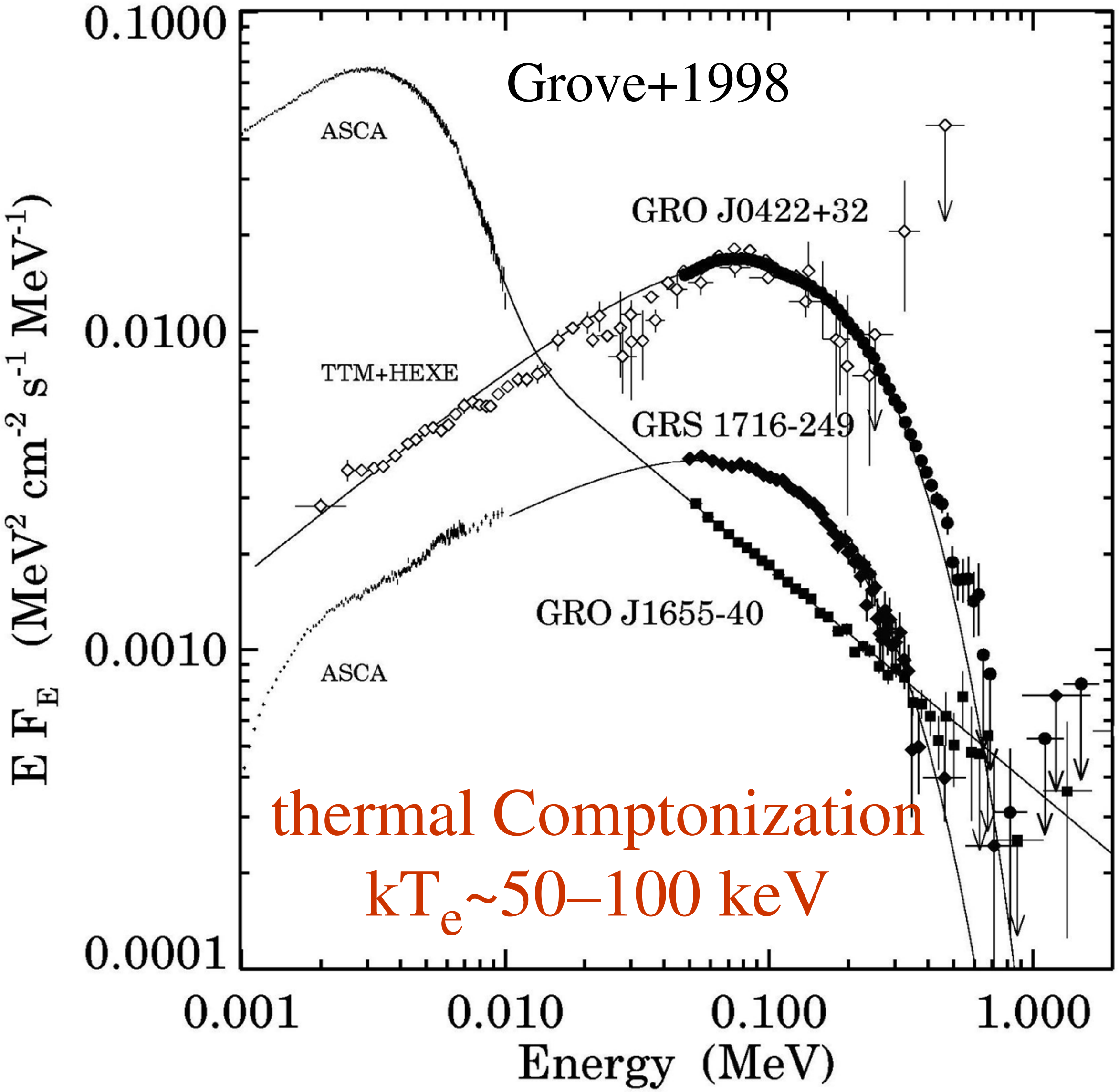
Radio/X-ray correlation in black-hole X-ray binaries in the hard state



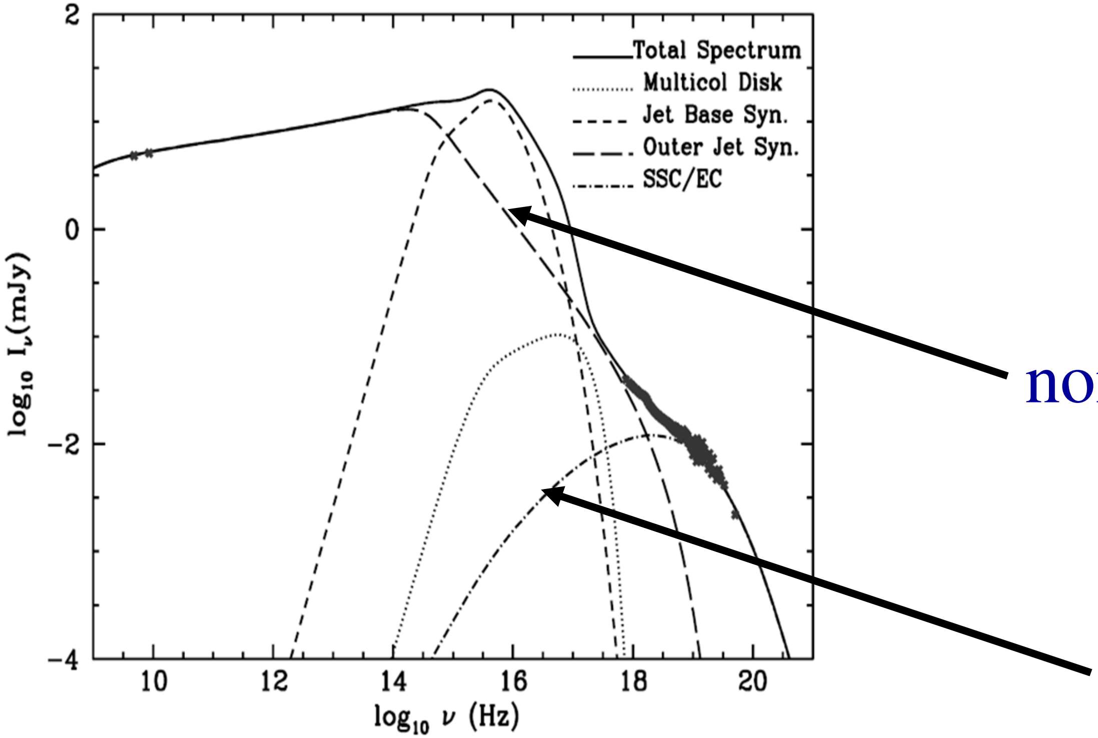
Taken as an argument for the synchrotron jet origin of X-rays (Falcke, Körding & Markoff 2004). However, it can be interpreted as due to a common dependence on the accretion rate, e.g., Merloni, Heinz & di Matteo 2003. Gardner & Done 2013 argue that since it is a single correlation from high to very low *L*, and the high-*L* states are not jet-dominated, the low-*L* states are also not jet-dominated.

A problem for this model: a common high-energy cutoff in the bright hard state of black-hole binaries, well-fitted by thermal Compton (cf. no universal high-energy synchrotron cutoff in blazars)





To address the cutoff problem, a thermal Compton jet model was proposed:



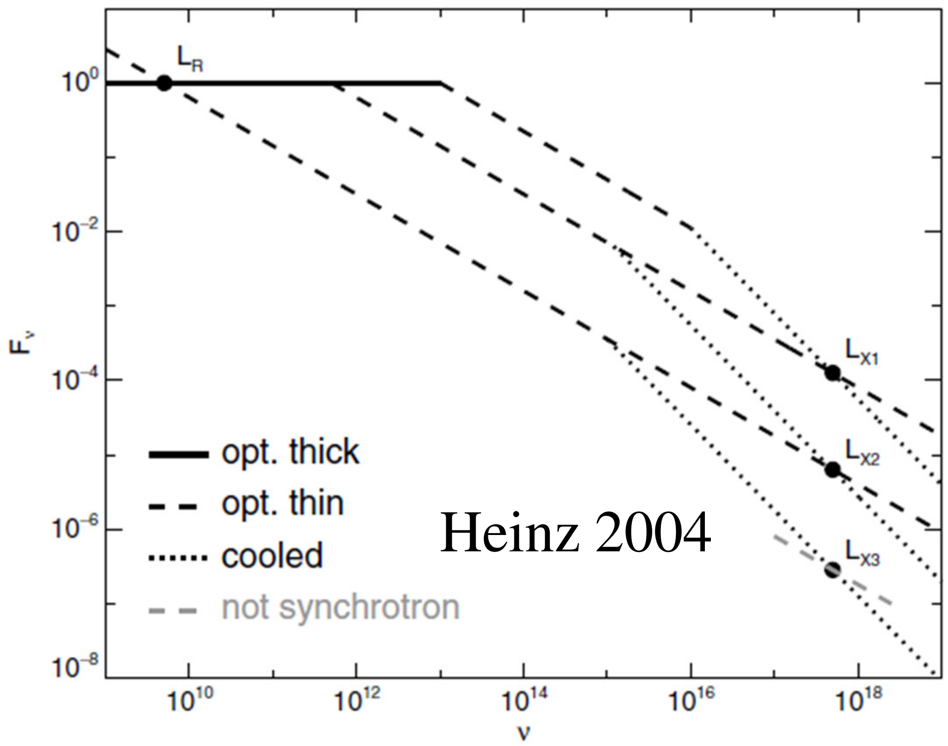
Markoff+2005

Thermal Compton at kT_e ~ **3–5 MeV**; the observed cutoff at ~100 keV from the 1st-order scattering; strong fine-tuning required. The physics of this component unclear, no analogous component seen in blazar jets.

The hard X-rays produced first in a single scattering, later soft X-rays from synchrotron higher up in the jet. This disagrees with the observed hard lags.

Also, copious $e^{\pm}$ pairs will be produced; the model is out of equilibrium by a factor of ~100 (Malzac+09).

Further issue: cooling

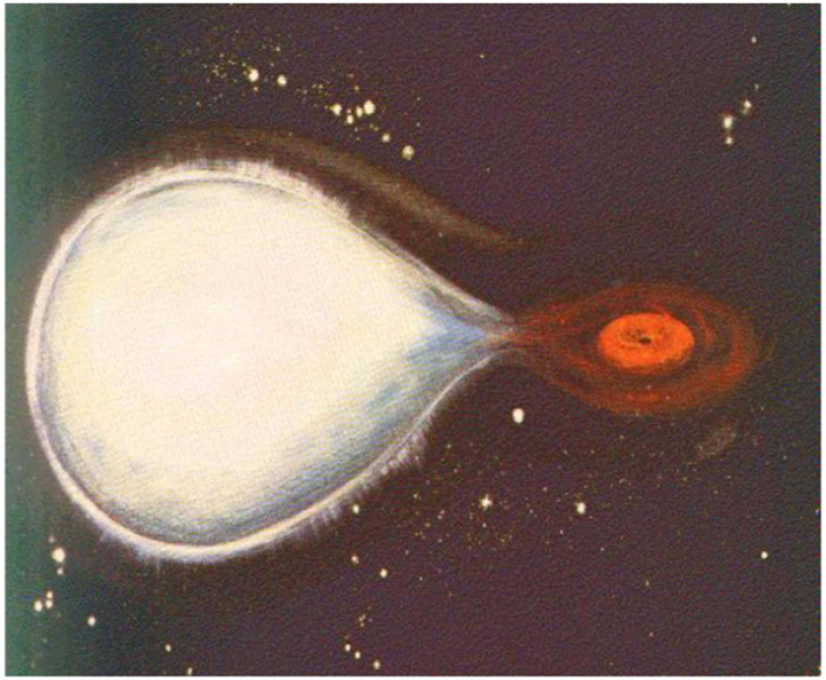


Modelling is with a single optically thin non-thermal power law from the turnover frequency to X-rays. But a break with $\Delta\alpha = 0.5$ is expected due to cooling. This would further reduce the contribution of non-thermal synchrotron to X-rays.

Thus, the jet dominant origin of X-rays in the hard state ruled out. But it remains possible, and likely, in quiescent states, $L < 10^{-5}\ L_E$ (e.g., Xie+2014)

II. The jet contribution to broad-band spectrum of Cyg X-1 in the hard state

Cyg X-1

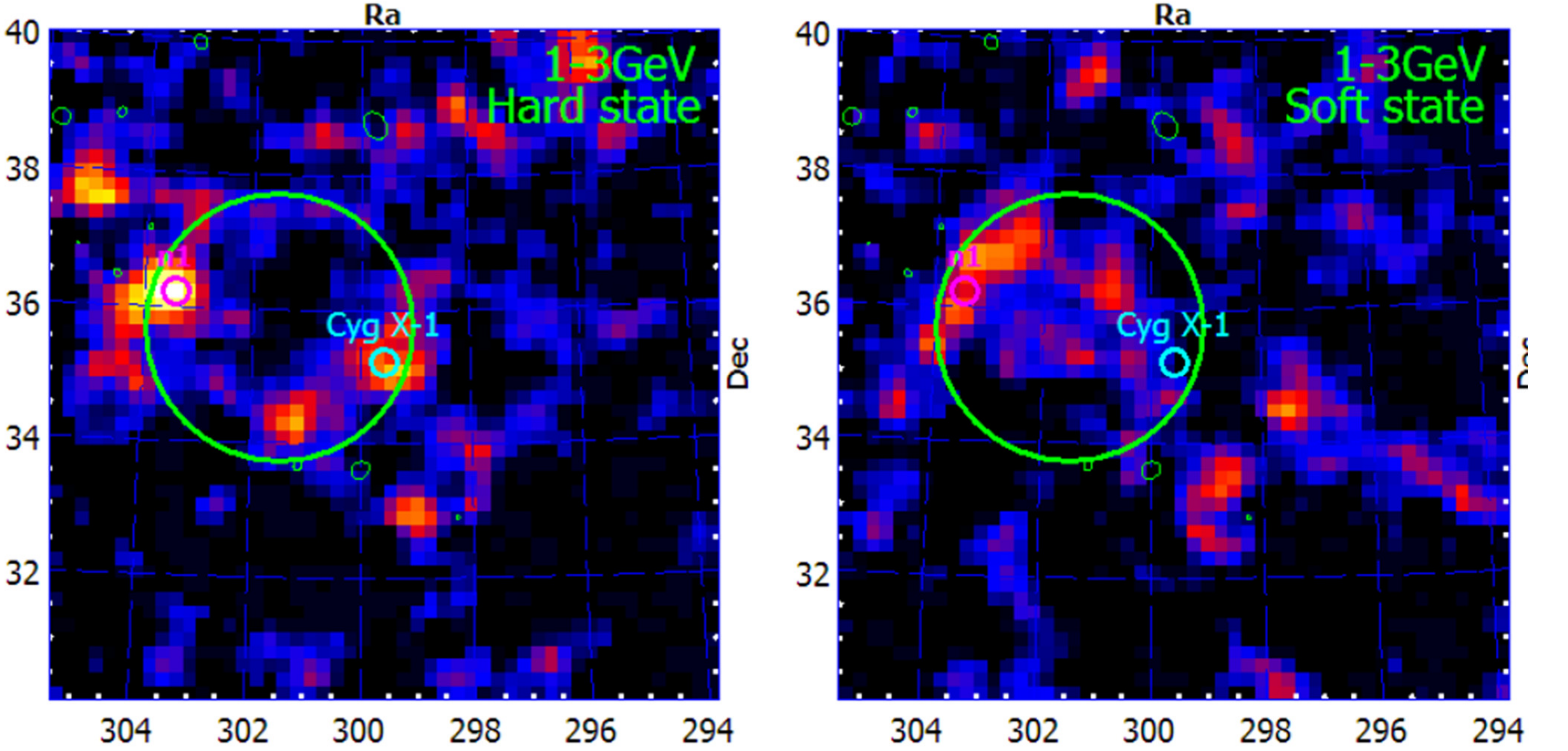


- An accreting black-hole binary. Donor: OB supergiant. $P = 5.6$ d, $d \approx 1.9$ kpc, $M_{\rm BH} \approx 15\ M_\odot$.
- Wind accretion, the donor nearly fills its Roche lobe.
- Emission from radio (resolved by VLBA) to MeV.

A detection of Cyg X-1 in the hard state

Malyshev, Z., Chernyakova 2013

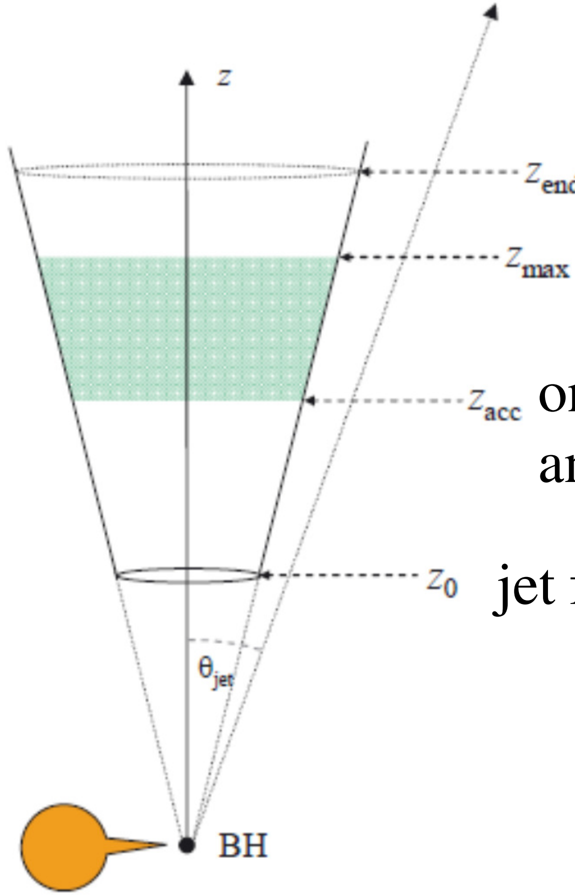
Upper limits in the soft state



Although the statistical significance is 4σ, 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.

New analysis of the Fermi LAT data by de Oña Wilhelmi: ~5σ

A jet model for the hard state of black-hole binaries



Previous work:
Reynoso +, Vila +, ...

- A continuous jet needed to account for the radio spectrum with the spectral index of $\alpha \approx 0$.
- Dissipation distributed along the jet $\propto \ln z$, e.g. due to shocks from colliding shells (Malzac 2013) and conserved magnetic flux ($B \propto z^{-1}$), accounting for $\alpha \approx 0$ (Blandford & Königl 1979).

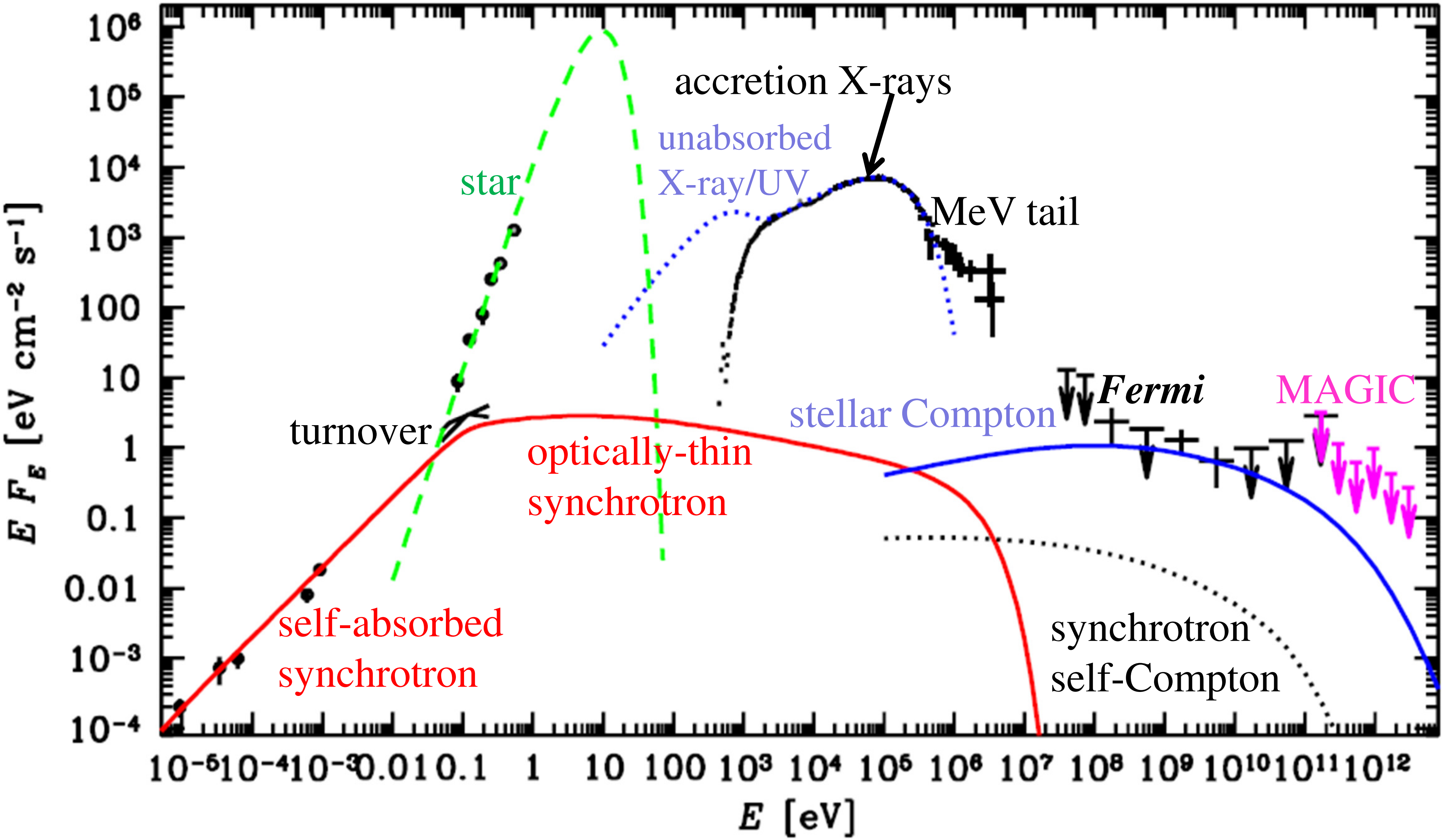
Zdziarski, Pjanka, Sikora, Stawarz 2014a, b

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

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

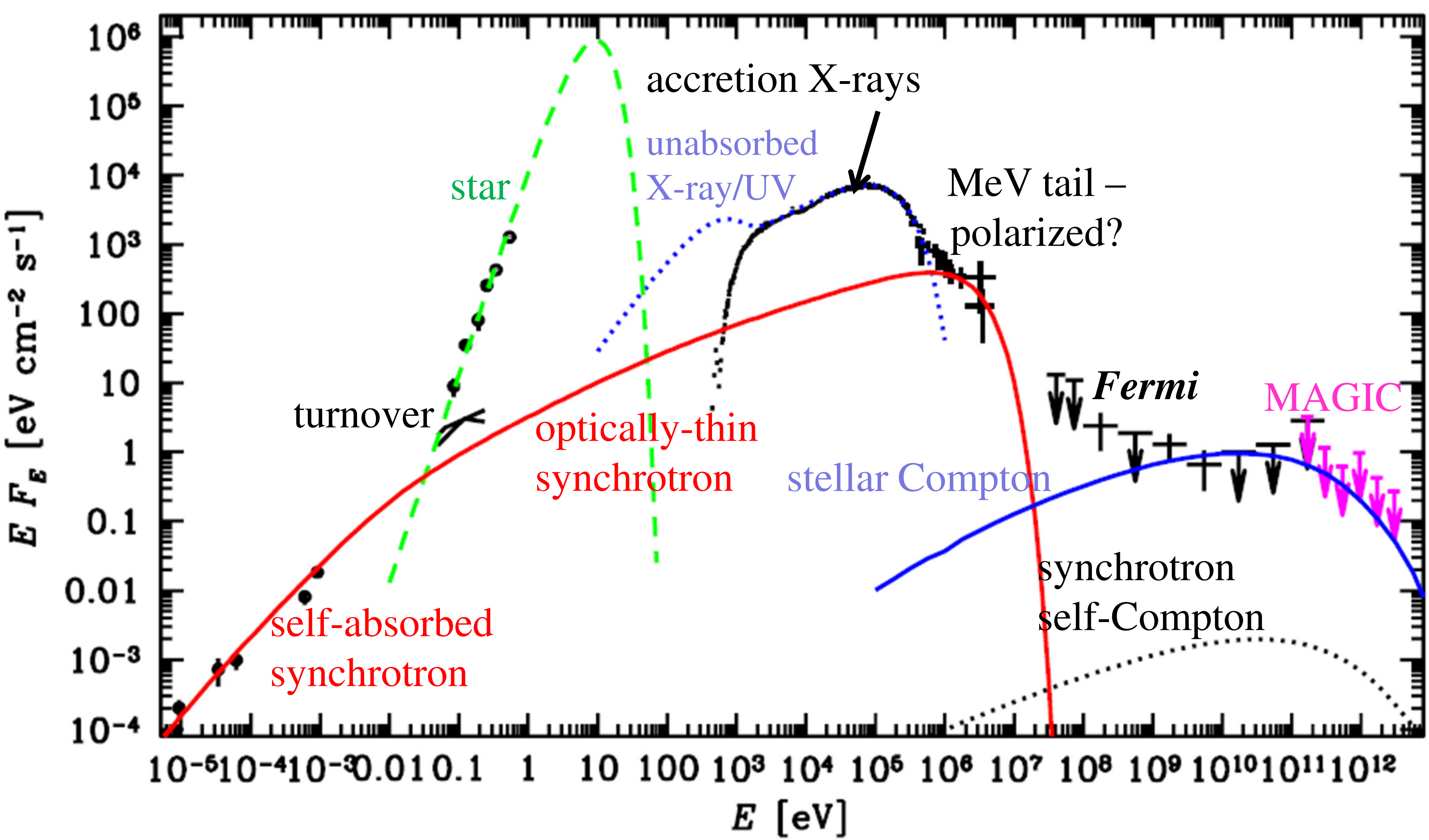
- The radiative transfer equation with the nonthermal source function is solved at any z, and the solution is integrated over z. This yields partially self-absorbed and optically-thin synchrotron spectra and Compton spectra.
- From the flux and $\tau = 1$ at the turnover frequency, $B_0 \propto z_{\rm acc}{}^{1/4}$ ($z_{\rm acc}$= the onset of dissipation).
- 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).

Model I. Typical electron acceleration.



The MeV tail in the hard state from hybrid Comptonization in the accretion flow. The acceleration index $p \approx 2.5$ (typical), $B_0 = 10^4$ G at $z_{acc} \approx 800R_g$, close to equipartition of $(B^2/8\pi)/u_{gas} \sim 0.1$, but with $\sigma \approx 10^{-4}$. The *Fermi* spectrum fitted.

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



The acceleration index $p = 1.4$ (very hard), $B_0 = 5\times10^5$ G at the $z_{acc} = 250R_g$, $(B^2/8\pi)/u_{gas} \sim 10^2$, magnetization parameter of $\sigma \approx 10^2$.

Is the MeV tail polarized?

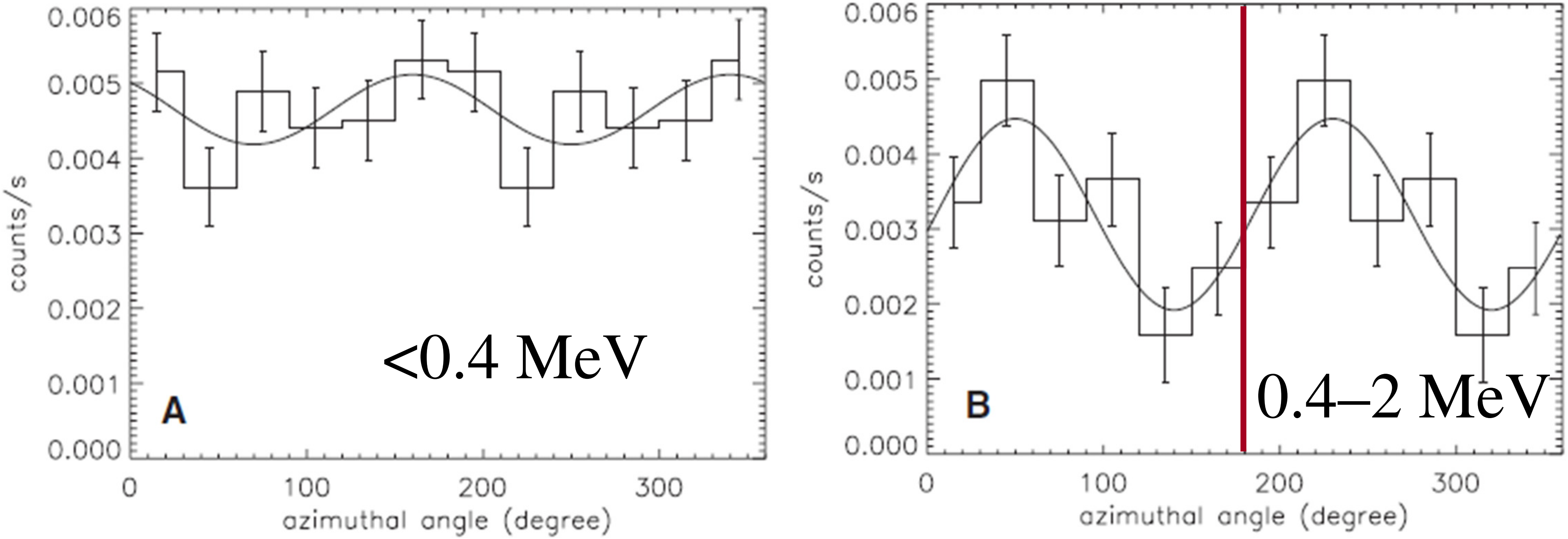
- Laurent et al. 2011 (*Science*) and Jourdain et a. 2012 (*ApJ*) claim linear polarization of 76±15% above 400 keV based on averaging several years of *INTEGRAL* data.
- If it is real, it is most likely synchrotron jet emission.

Very strong polarization in the hard-state MeV tail claimed by Laurent+ 2011.

Based on the Compton mode of the *INTEGRAL* IBIS detector

Polarization fraction <20%

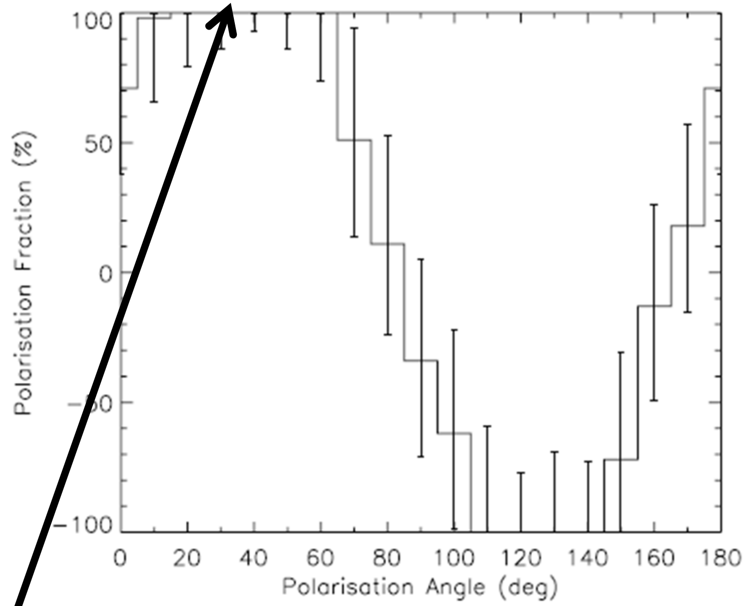
Polarization fraction of 67±30%; note that only the 0°–180° bins are independent.

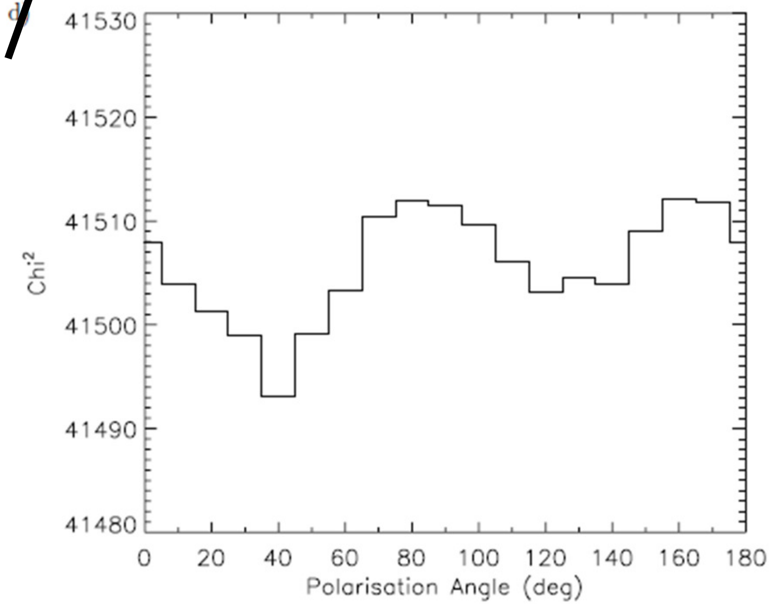


The statistical significance of this result is small. Furthermore, a number of problems with the paper (wrong spectrum, wrong polarization angle etc).

Strong polarization in the hard state at $E \geq$ 230 keV claimed by Jourdain+ 2012

- From the *INTEGRAL* SPI data.
- 230–850 keV: linear polarization fraction 76±15%, position angle 42±3°.
- No polarization at $E < 230$ keV.
- This roughly agrees with the result of Laurent + 2011 at >400 keV but there is a disagreement below 400 keV.
- The 370–850 keV data best-fitted with the polarization fraction >100% - ?
- $\Delta\chi^2 \approx 15$ at $\chi^2 \approx 41500$. But PF>100% is unphysical, $\Delta\chi^2$ at PF $\approx$ 70% is ~ 0.
- Is it real?

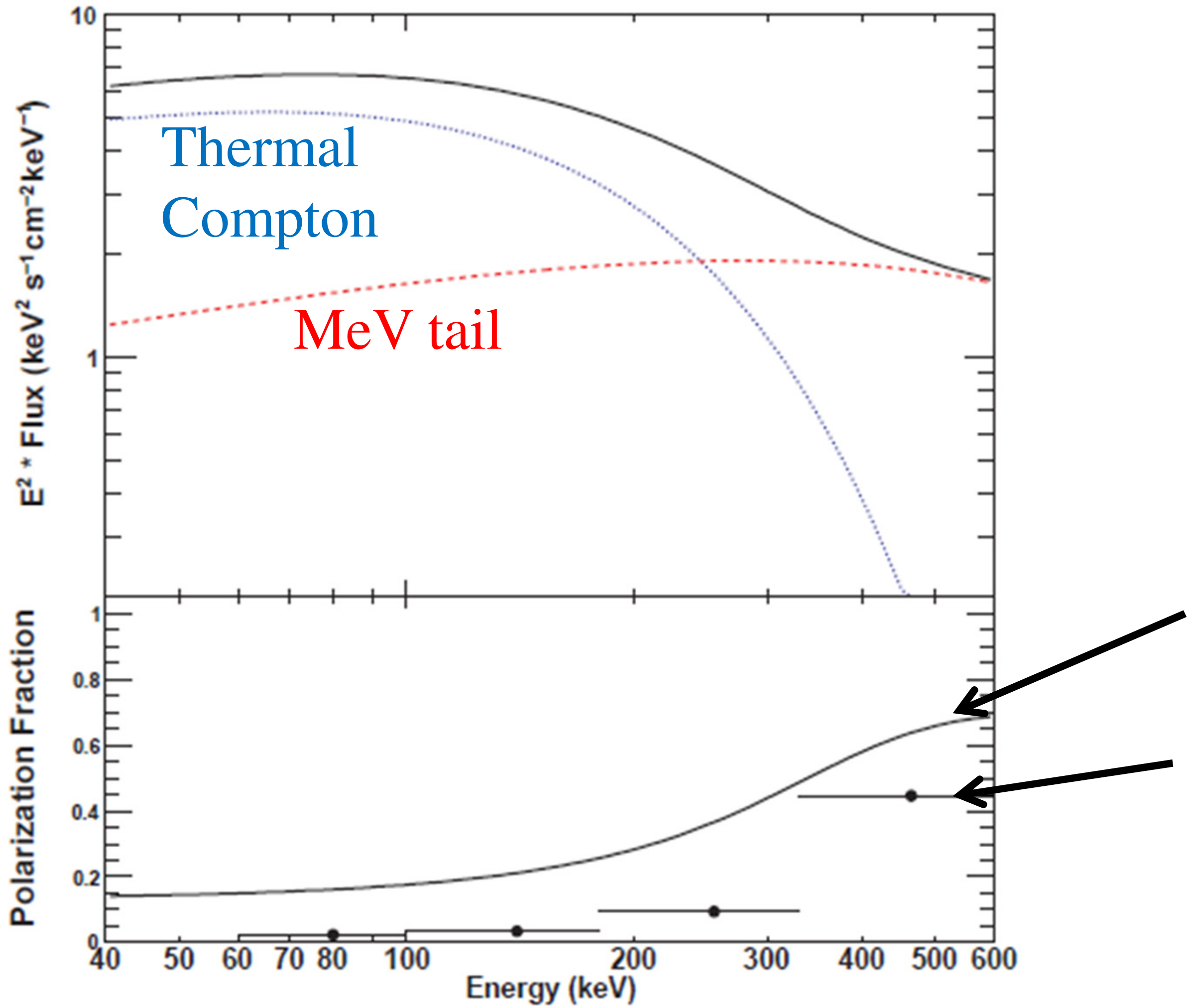




Other problems

- The maximum linear polarization degree: $\Pi \leq (p+1)/(p+7/3) = 0.71$ for $p = 2.3$.
- The claimed extremely strong polarization requires highly ordered magnetic field at an oblique angle with no variability.
- In blazars, Π always < 50%, usually ~10%.
- Similar MeV tails occur also in other BH binaries, e.g., GX 339–4. Usually fitted by hybrid Comptonization; jet origin would require strong fine-tuning.
- Correlated short-time scale variability may test the origin of the MeV tail.

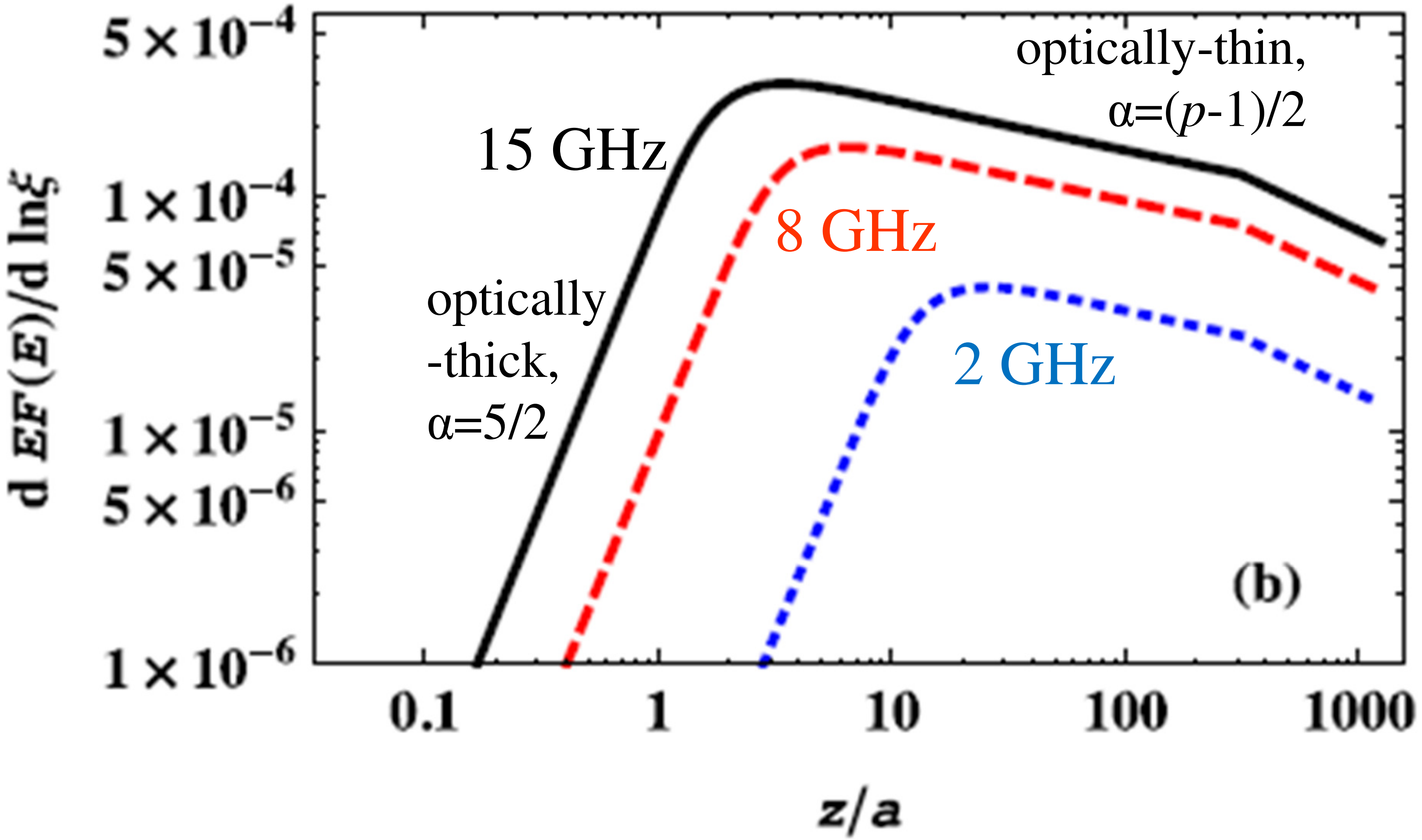
The Soft Gamma-ray Detector on board *Astro-H*, to be launched in 2015, can measure hard X-ray polarization



Polarization of jet self-absorbed emission in the radio-IR range

- The polarization of a synchrotron self-absorbed source is given by $\Pi \leq 3/(6p+13)$, i.e., it is much lower than that of the optically-thin medium.
- This lead Russell & Shahbaz (2014) to propose that the upper limit to polarization of the radio spectrum of Cyg X-1 in the hard state of $<8\%$ in the model with the MeV tail dominated by a polarized jet is due to the above.
- However, partially self-absorbed emission of jets is actually dominated by optically-thin contribution.

Spatial contributions to the radio emission of Cyg X-1 in the partially self-absorbed region:



We see that emission at a given frequency is dominated by the optically-thin part.

Can the strong MeV polarization be from the accretion flow?

- Romero+2014 proposed a model with ordered, predominantly poloidal, magnetic field in the accretion flow.
- They used results of Korchakov & Syrovatskii 1962 but confused the intrinsic field with that projected on the plane of the sky. Since the disc in Cyg X-1 is viewed at a low angle with respect to the normal, this mistake leads to a strong overestimate of the theoretical polarization.
- The jet is launched perpendicularly to the inner accretion flow, and thus the polarization should be perpendicular to the jet, while it is at an oblique angle.
- Thus, the model is highly unlikely.

III. Jet contribution to the broad-band spectrum of Cyg X-3 in the soft state

Zdziarski, Sikora, Dubus, Yuan, Ogorzałek 2012;
Zdziarski, Maitra, Frankowski, Skinner, Misra, 2012

The soft state

- Blackbody (with a colour correction) emission of an optically thick disc extending to the innermost stable orbit (stability of r_{in}).
- The blackbody emission is stable, almost no variability. This disagrees with the basic accretion disc theory, but it agrees with some simulations.
- The emission follows $L \propto T^4$ in most cases.
- The blackbody is often followed by a variable high-energy tail, most likely from Compton upscattering of the blackbody photons by relativistic electrons with a non-thermal distribution, with the spectrum measured up to ~10 MeV.

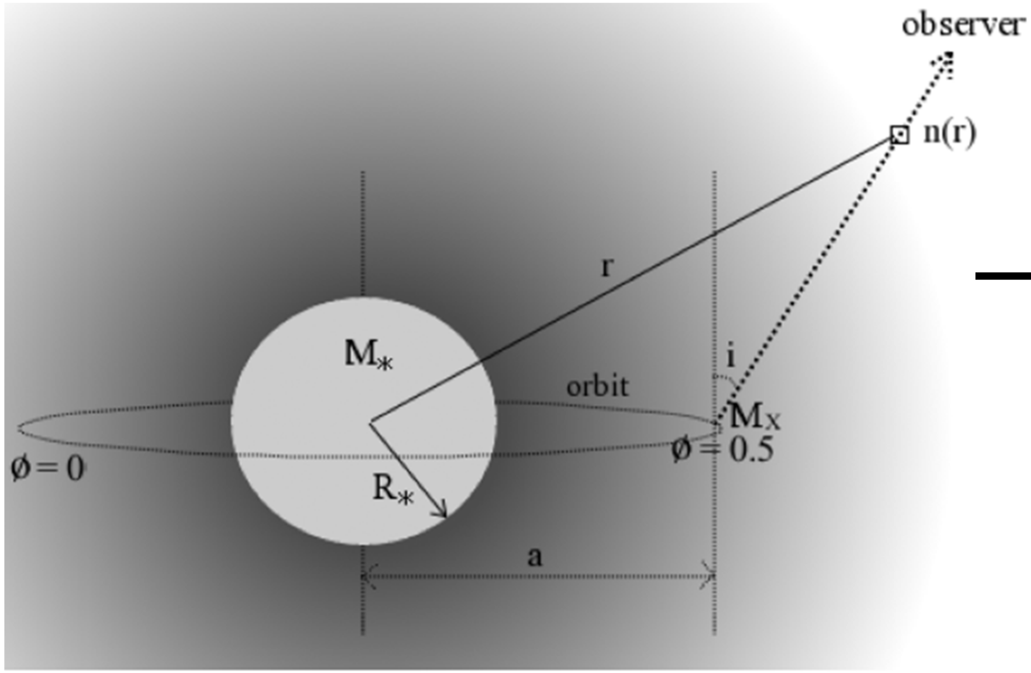
Cyg X-3

- A very luminous radio and X-ray source, WR donor + a compact object, a very short (for HMXBs) period of 4.8h.
- Z., Mikołajewska & Belczyński (2013) found the mass of the compact object of (1.3–4.5) $M_{\odot}$, i.e., a low-mass black hole or a neutron star is possible.
- But the X-ray spectra generally similar to those of spectral states of black-hole binaries.
- Cyg X-3 is the only certainly accreting X-ray binary with high-significance emission at >0.1 GeV, detected by *Fermi* and *AGILE*.

Observations by *Fermi*, 0.1–100 GeV

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

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



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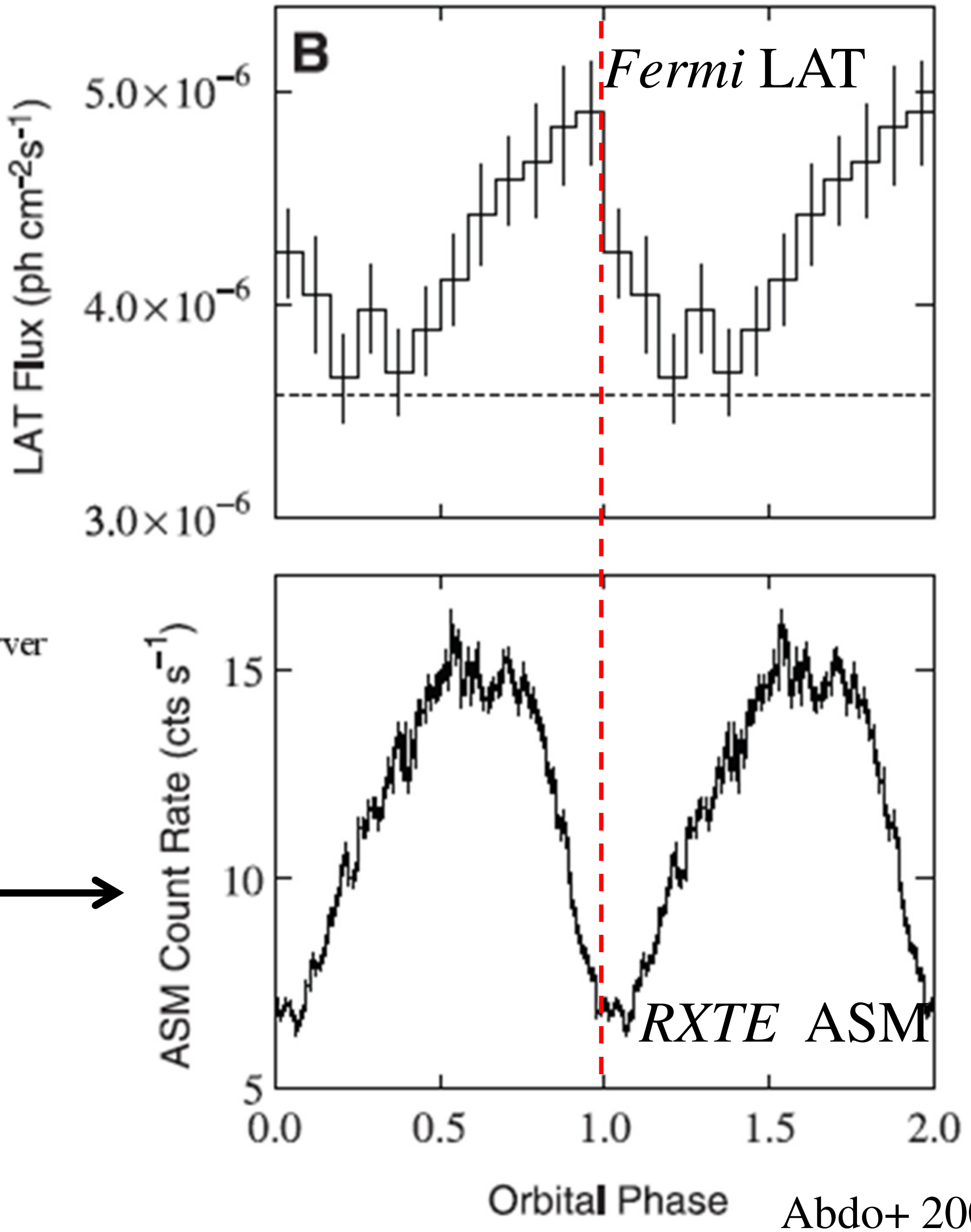
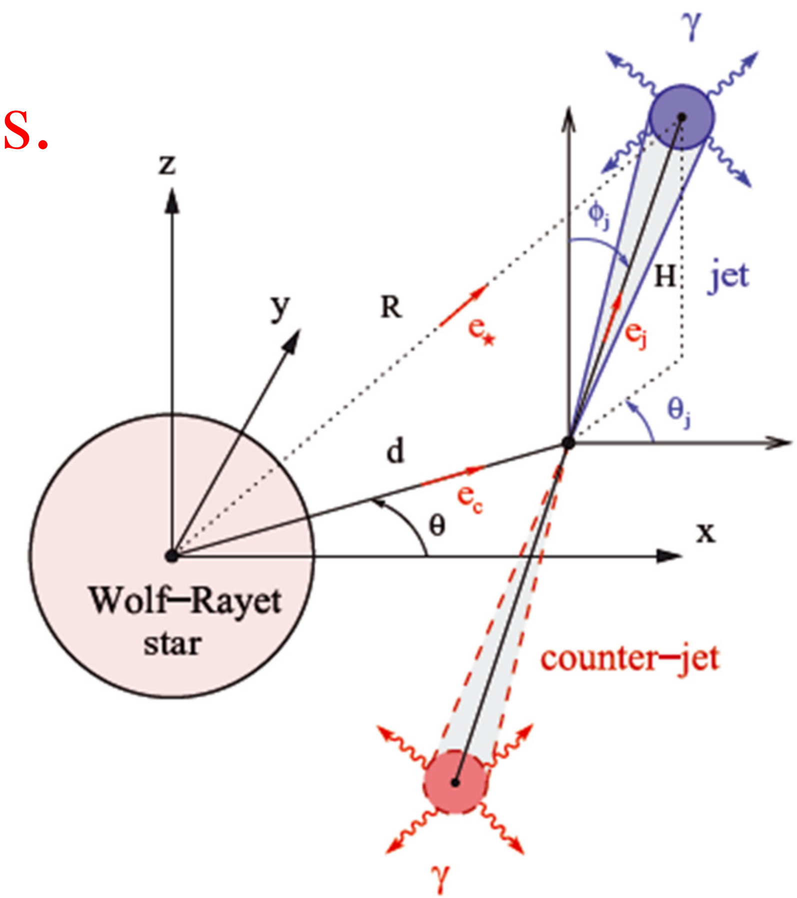
Folded lightcurves



Abdo+ 2009

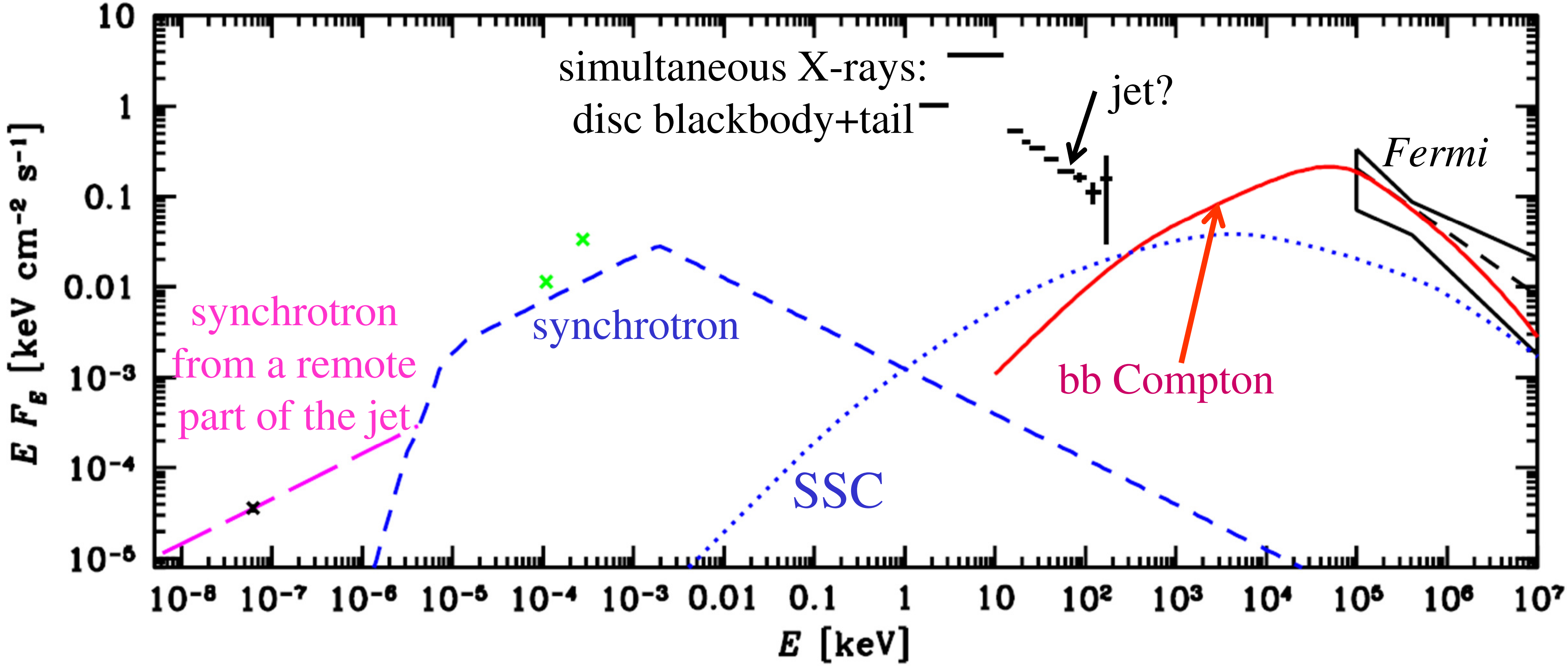
The modulated GeV emission from Compton anisotropy

- Jet relativistic electrons Compton upscatter stellar photons to GeVs.
- Highest scattering probability for head-on electron-photon collisions.
- Relativistic electrons emit along their direction of motion.
- Thus, maximum of the emission toward the star. The observed maximum when the jet is behind the star.



Dubus, Cerutti & Henri 2010

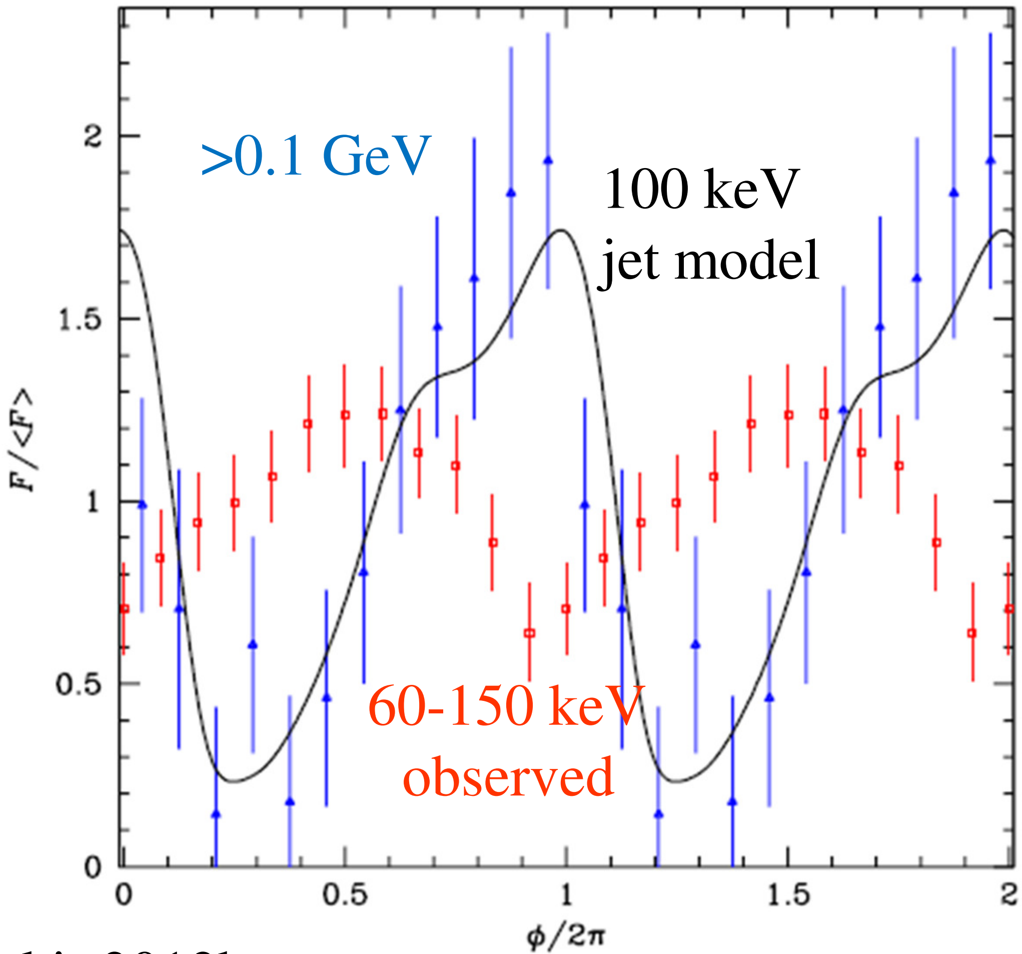
The broad-band soft-state spectrum compared to a jet model



Zdziarski+2012a

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

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



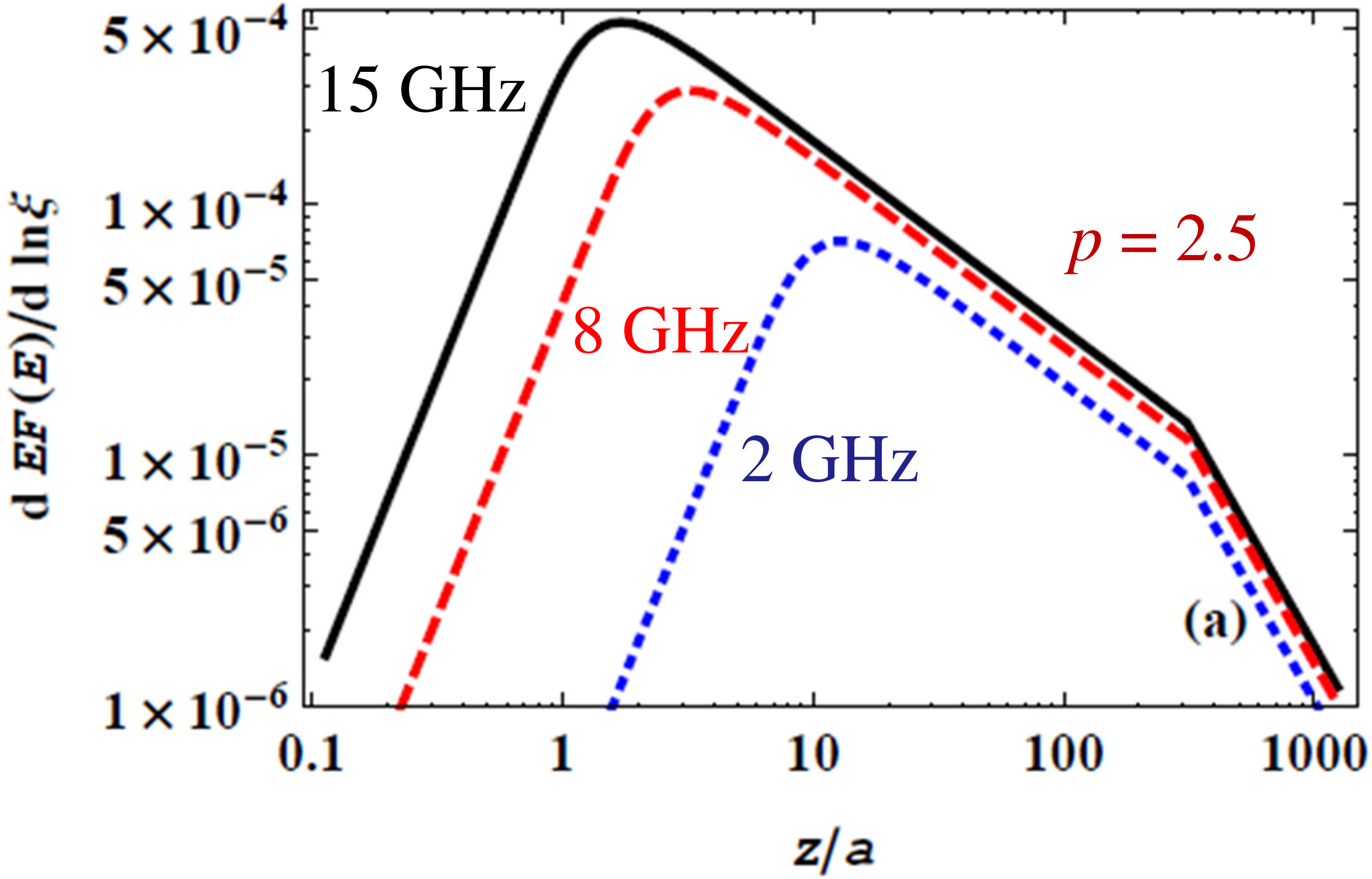
Zdziarski+2012b

IV. Are jets from powerful radio sources dominated by magnetic field?

Zamaninasab+2014, Nature

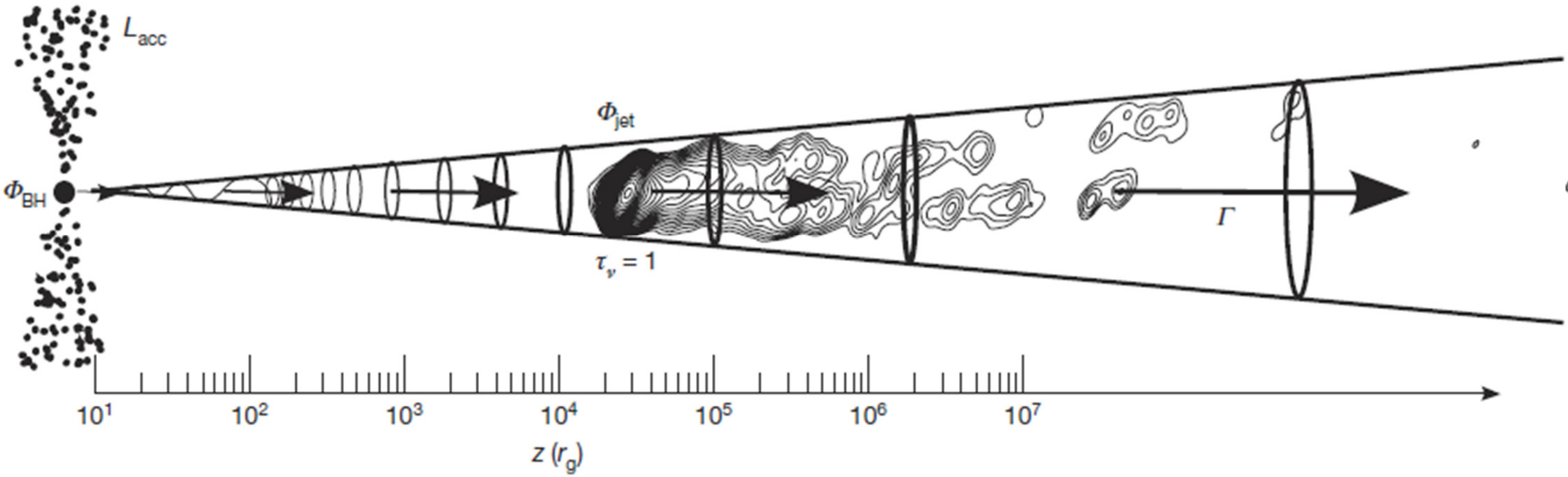
- If the accretion disc is threaded with poloidal magnetic flux, it is transported inwards and accumulate in the central region until the gas ram pressure is balanced by the magnetic pressure (magnetically arrested disc, MAD).
- The saturation occurs at the magnetic flux of $\sim 50 r_g (M\text{dot}\ c)^{1/2}$.
- If the black-hole spin is >0.5 or so, the Blandford-Znajek mechanism forms a jet with the magnetic power of $P_B \approx M\text{dot}\ c^2$.
- The magnetic field of that jet cannot be measured close to the black hole, but it can on parsec scale in strong extragalactic radio sources via the radio core shift.

An example of core shift



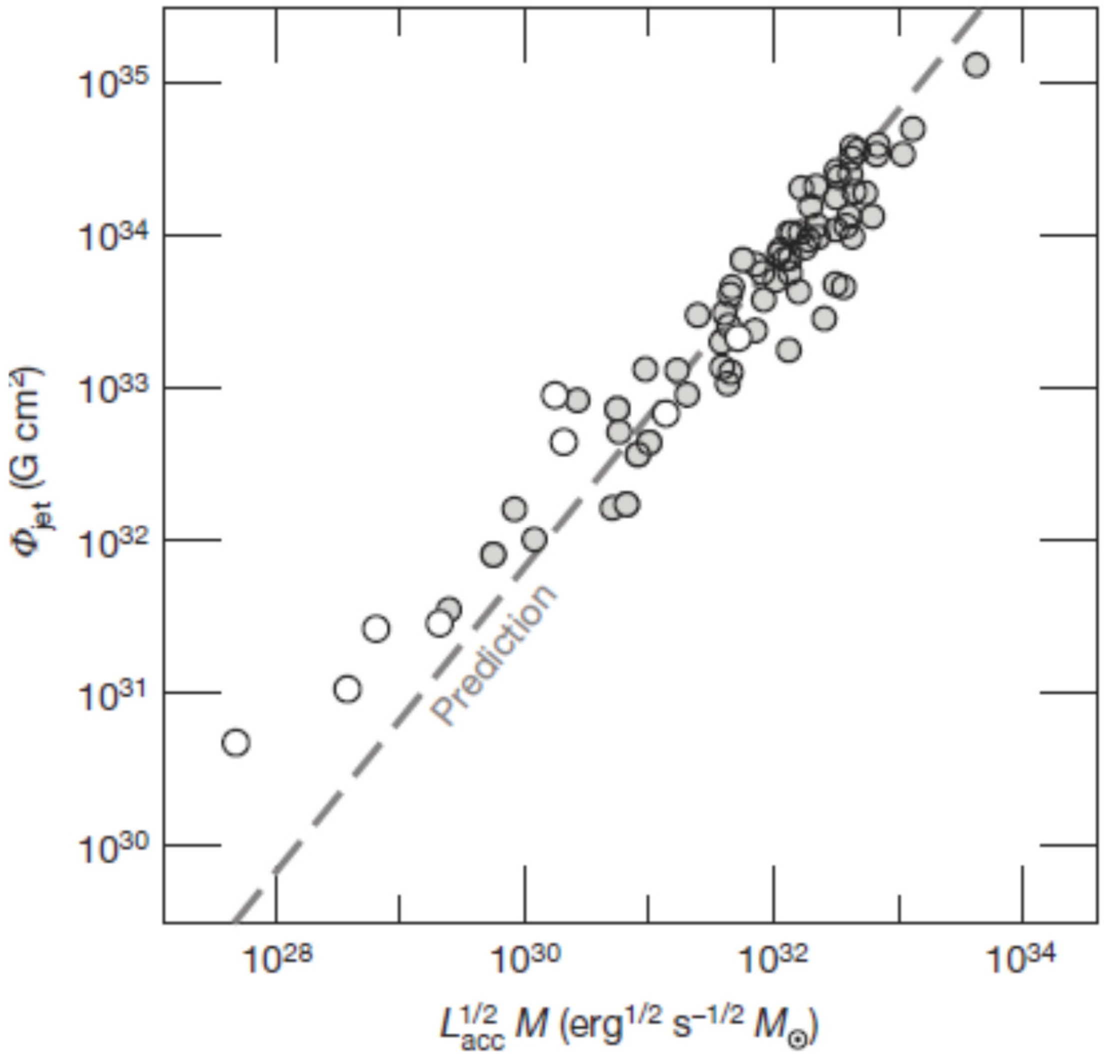
The emission at a given frequency is synchrotron self-absorbed up to some height, z, and then it becomes optically thin. In the standard model, $z(\nu) \propto \nu^{-1}$. In this way we can measure the jet magnetic field at a given height and thus the jet magnetic power.

The core at a given ν is observed at $\tau \approx 1$.



Very good agreement with observations:

jet B estimate



accretion rate estimate

Zamaninasab+2014

Can the jet in Cyg X-1 be maximal BZ?

- No. The magnetic field implied by this scenario is $>10^7$ G at $\sim 100 r_g$, which is ~10 times higher than even that in the strongly magnetized model reproducing the MeV tail.
- Such a field would be in conflict with the observed GeV emission.
- Also the jet power is $\sim 10^{38}$ erg/s, which is more than the estimate of the jet power from a ring nebula (Gallo et al. 2005).
- But Cyg X-1 in the hard state emits at ~1% L_E, while the sample of Zamaninasab+2014 consists of objects with $L \sim L_E$.
- The magnetically-arrested disc/BZ model is not universal and Cyg X-1 does not seem to have a magnetically arrested disc.

Conclusions

- A weak jet contribution to X-rays in majority of black-hole binaries, with possible exception of quiescence.
- The jet in the hard state of Cyg X-1 dominates radio/mm and GeV bands, weak contribution to X-rays.
- The detection of MeV polarization appears controversial, to be settled by ***Astro-H***.
- The flat radio/mm partially self-absorbed emission dominated by optically-thin jet regions; thus a weakness of polarization not due to self-absorption.
- The hard tail in the soft state of Cyg X-3 not due to jet.
- A very interesting new finding of jets in luminous objects being dominated by magnetic field (MAD+BZ).

The method of Jourdain+

- Using photon interactions with more than one of the 19 SPI detectors and measuring the angular distribution of the scatter directions.
- Comparing that to simulations using a GEANT4 model of the instrument.
- Another paper giving details mentioned as in preparation, but not available so far.