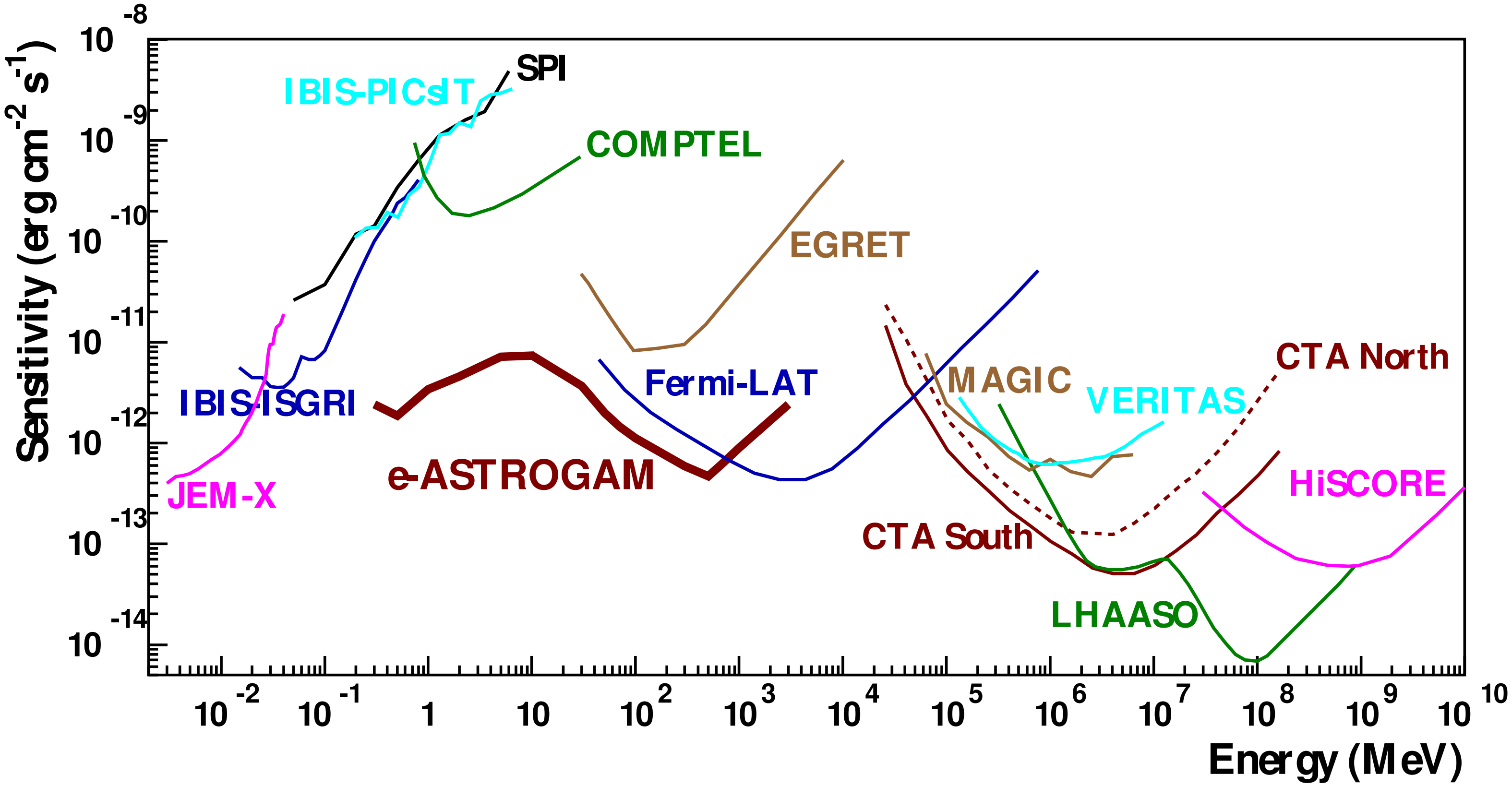
γ-rays from binaries
and prospects with
e-Astrogam

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

e-ASTROGAM scientific requirements

1. Achieve a sensitivity better than INTEGRAL/CGRO/COMPTEL by a factor of 20–100 in the range 0.2–30 MeV
2. Fully exploit gamma-ray polarization for both transient and steady sources
3. Improve significantly the angular resolution (to reach, e.g., ~ 10′ at 1 GeV)
4. Achieve a very large field of view (~ 2.5 sr) ⇒ efficient monitoring of γ-ray sky

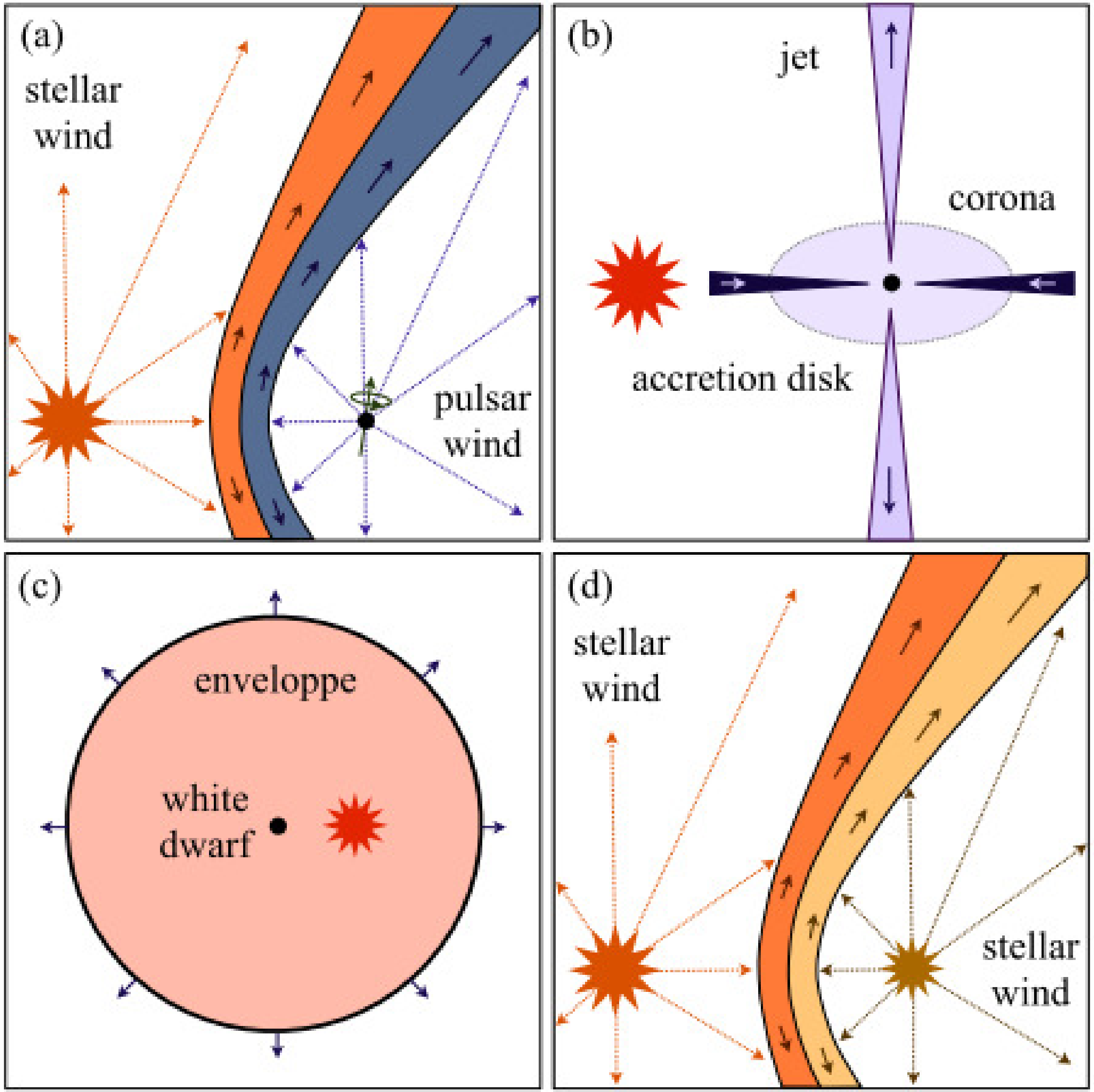
Submitted to ESA M-5



Types of γ-ray emitting binaries

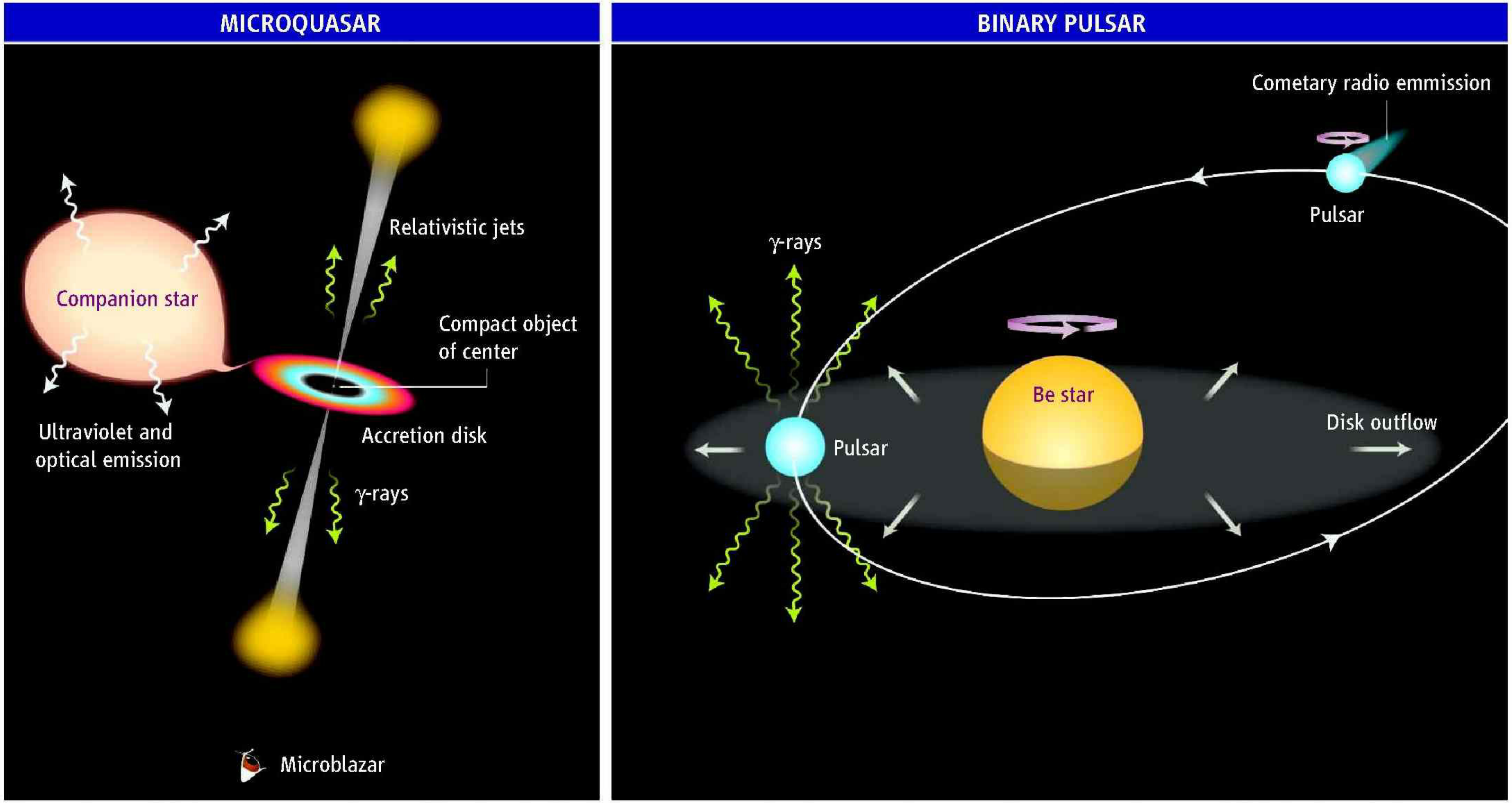
- The so-called gamma-ray binaries, defined by the peak of their νF_ν spectrum at a GeV: most likely pulsar wind colliding with stellar wind from a high-mass star, powered by pulsar rotation;
- Microquasars: powered by accretion onto a black hole or neutron star, γ-ray emission of either the accretion flow or a jet;
- γ-ray emitting pulsars in binaries, in particular recycled ms pulsars spun up by accretion, but no longer accreting (powered by pulsar rotation);
  - As above, but pulsar wind ablating the low-mass companion: black widows, redbacks; some γ-ray emission from pulsar wind interacting with the companion (as in gamma-ray binaries);
- Transitional sources switching between pulsar and accretion; strong γ-ray emission during accretion stages, possibly from a jet;
- Colliding-wind binaries: collision of stellar winds from two massive stars;
- Novae: thermonuclear runaway on a white dwarf, γ-ray emission from the ejecta.

Types of γ-ray emitting binaries



Dubus 2015

A past controversy on the nature of **gamma-ray binaries**: Microquasars vs. pulsar/stellar wind collisions

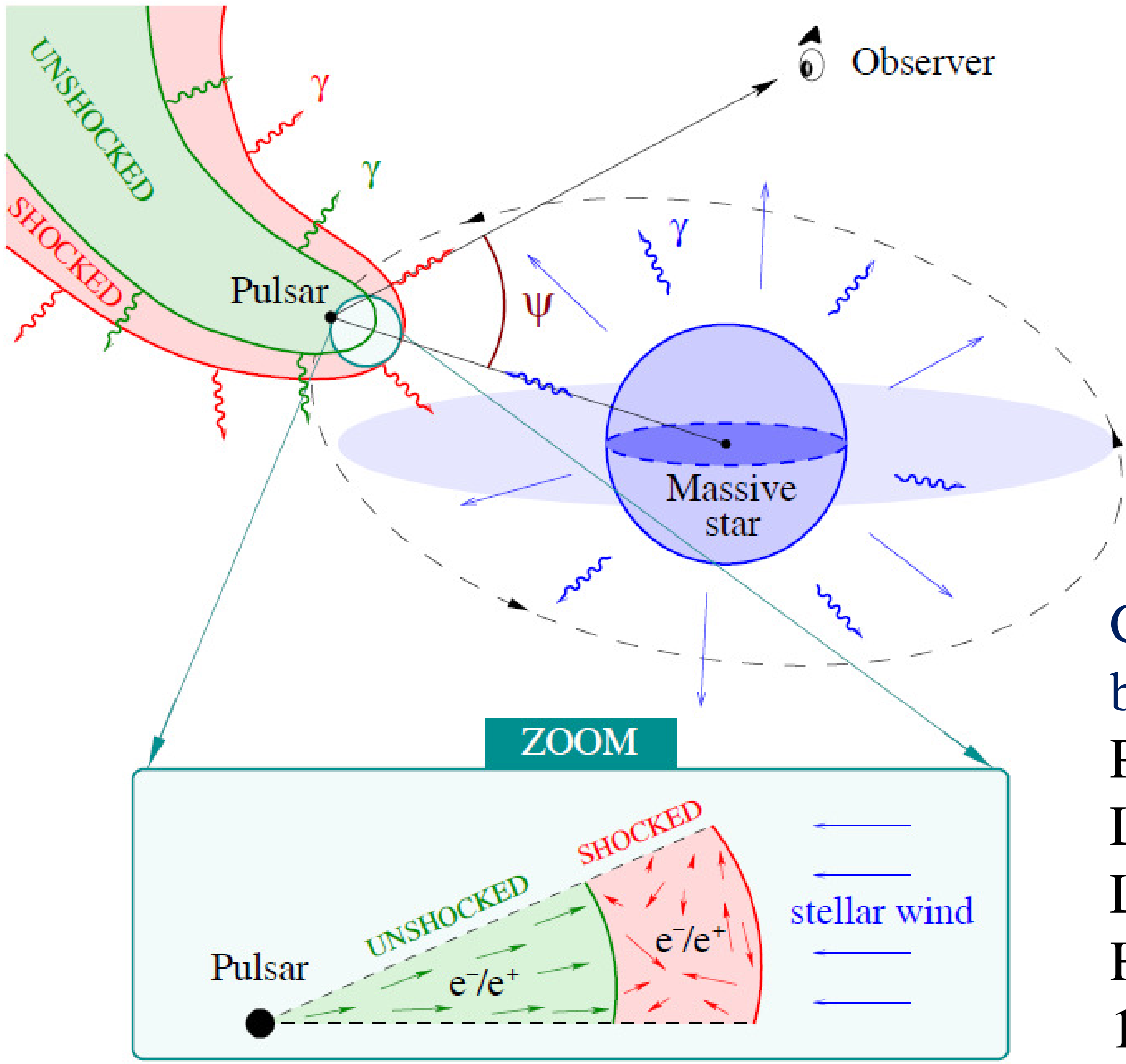


Alternative models for very energetic γ-ray binaries. **(Left)** Microquasars are powered by compact objects (neutron stars or stellar-mass black holes) via mass accretion from a companion star. This produces collimated jets that, if aligned with our line of sight, appear as microblazars. The jets boost the energy of stellar photons to the range of very energetic γ-rays. **(Right)** Pulsar winds are powered by the rotation of neutron stars; the wind flows away to large distances in a comet-shaped tail. Interaction of this wind with the companion-star outflow may produce very energetic γ-rays.

Mirabel 2006

Currently, most people agree on the pulsar+stellar wind collision model.

The pulsar + massive star model; a pulsar wind nebula in a binary



Cerutti, Dubus & Henri 2009

Currently known gamma-ray binaries:

PSR B1259−63

LS I +61°303

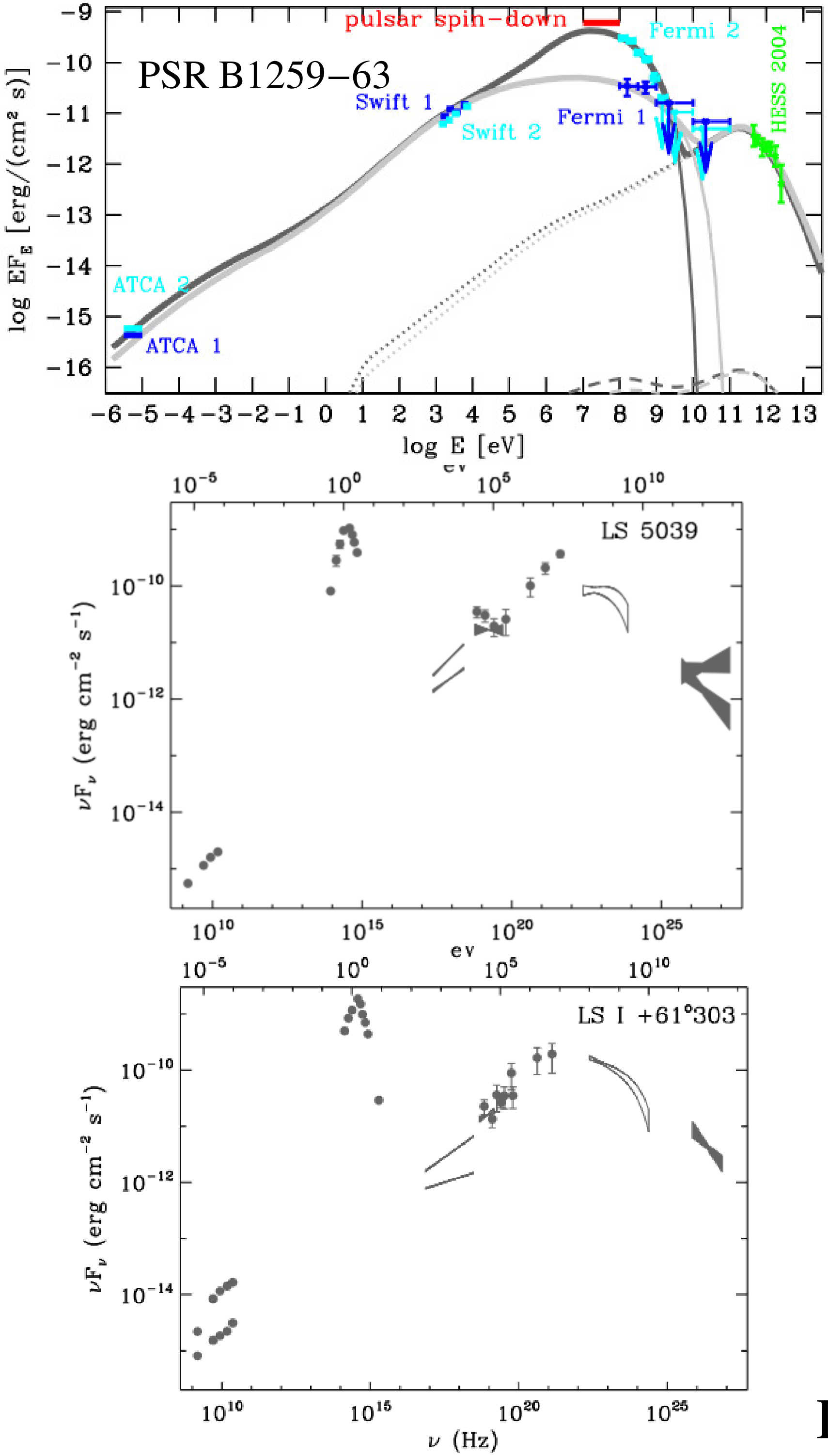
LS 5039

HESS J0632+057

1FGL J1018.6−5856

CXOU J053600.0−673507 (LMC)

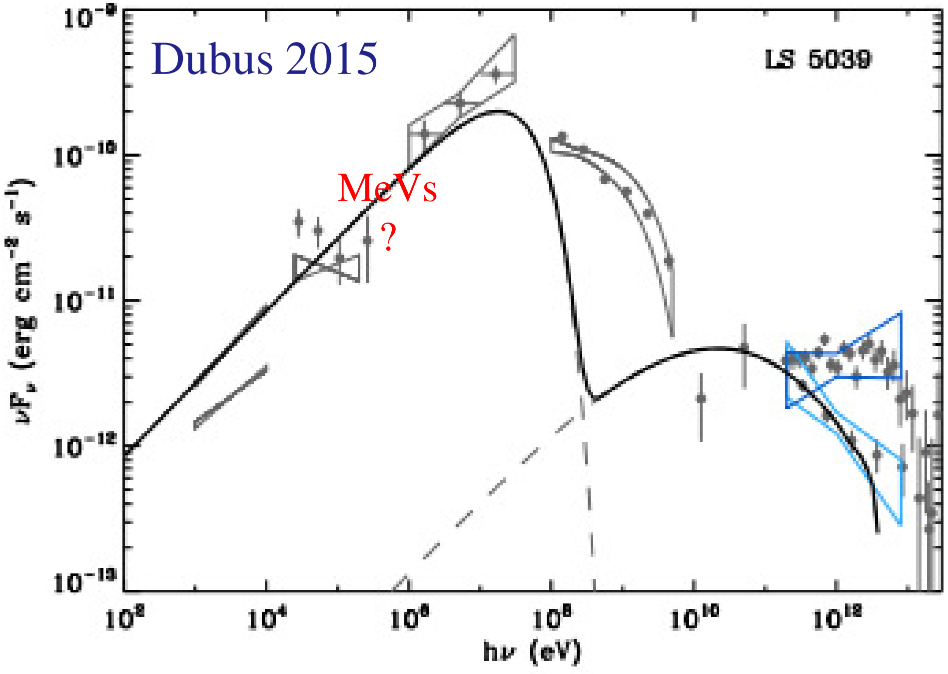
A comparison of three gamma-ray binaries:

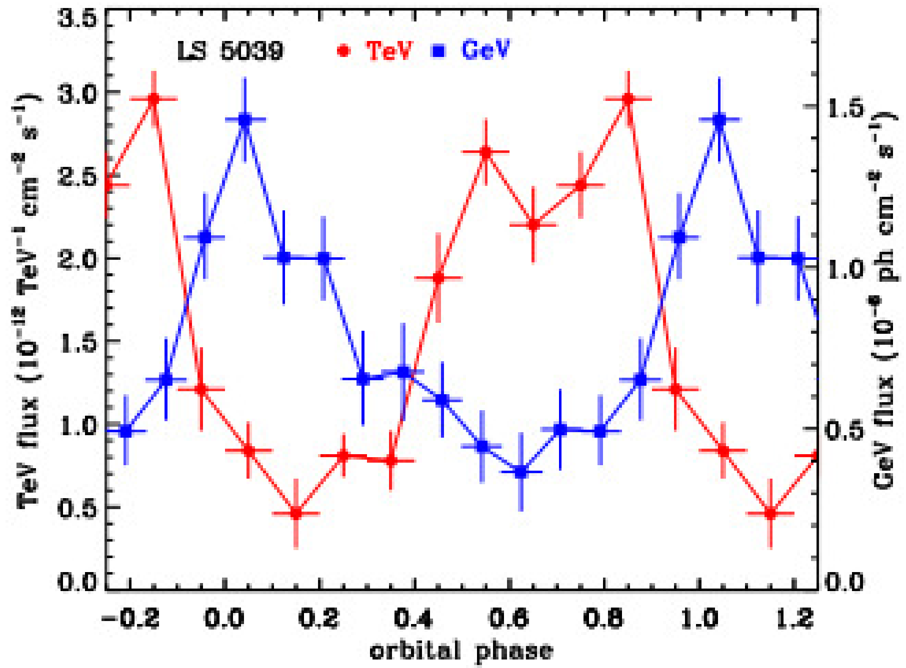


Their spectra look very similar to each other: **peak in the MeV-GeV range**, and PSR B1259–63 is a 48-ms radio pulsar with a Be companion (3.4 yr orbit), in which the wind of the pulsar interacts with the wind of the Be star around periastron, giving rise to the broad-band emission. The radio pulsation disappear at the periastron passage.

Dubus 2013

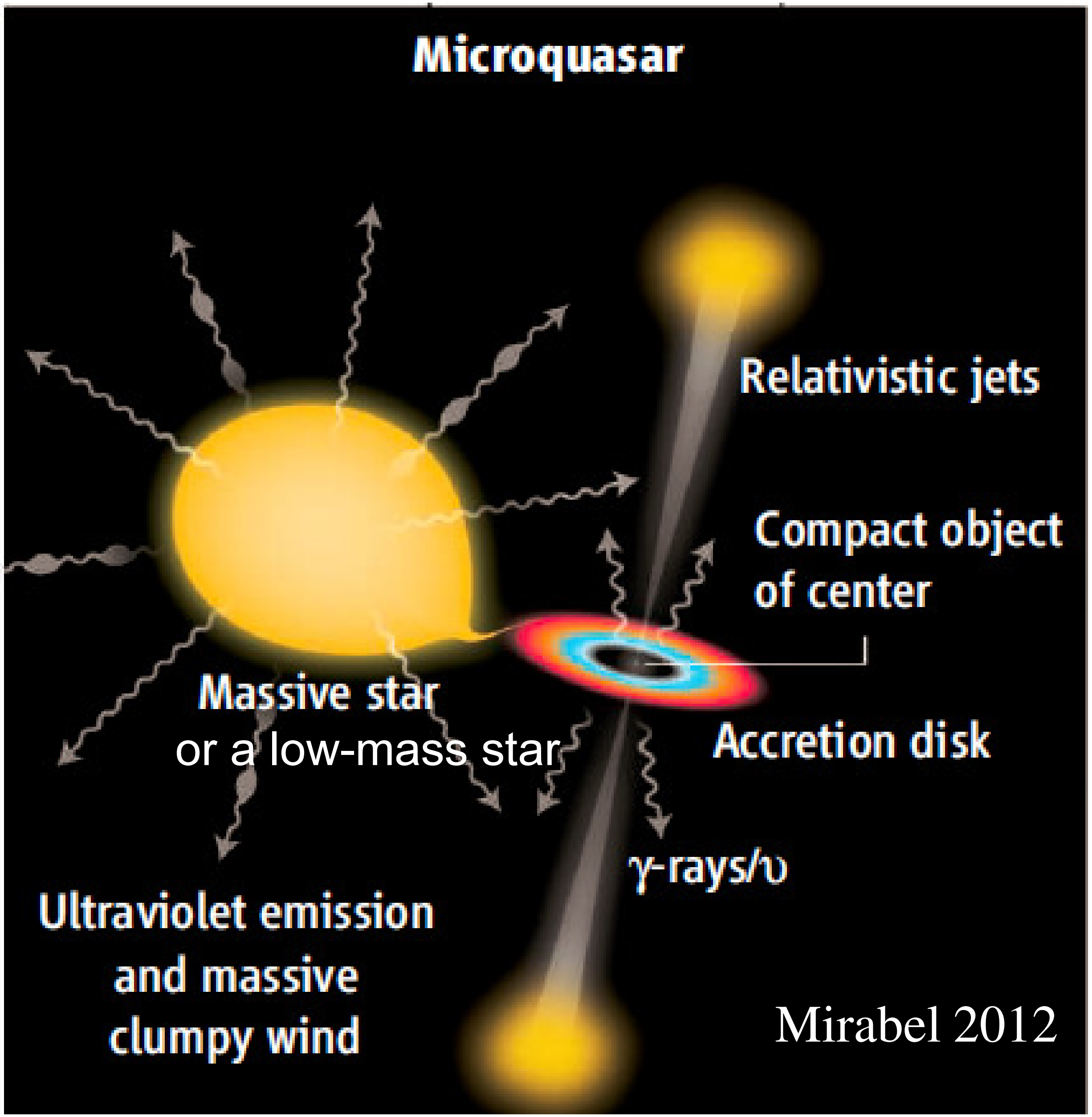
Some outstanding issues for gamma-ray binaries





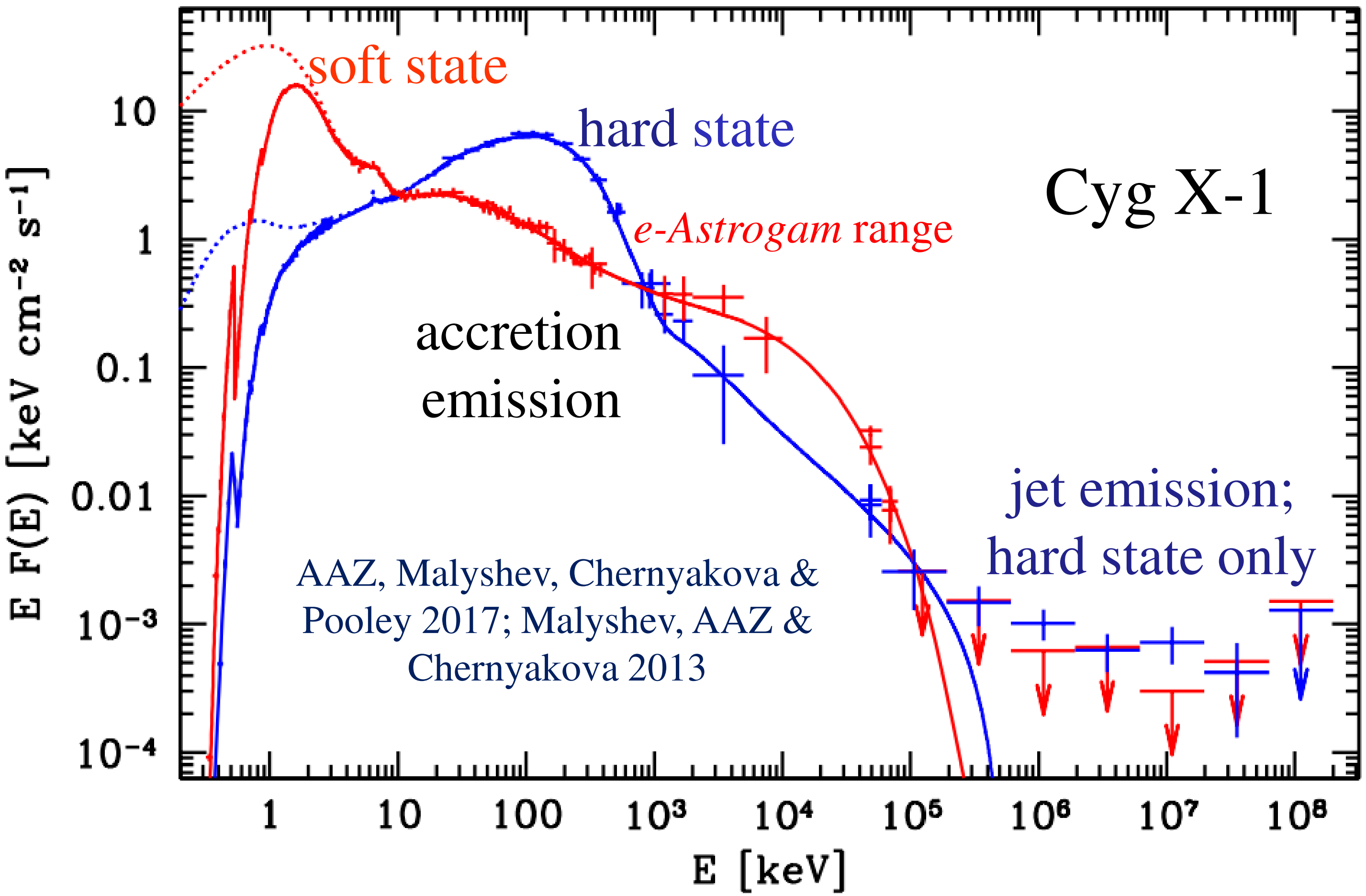
- Complex phenomenology requiring complex, multi-component models.
- Different electron populations for GeVs and TeVs; location?
- The peak in GeVs in PSR B1259–63 a month *after* the periastron passage.
- MeV spectra known only from COMPTEL; e.g., a mismatch with the *Fermi* spectrum in LS 5039.
- The virtually unknown MeV range: to be studied by *e-Astrogam*.

Microquasars



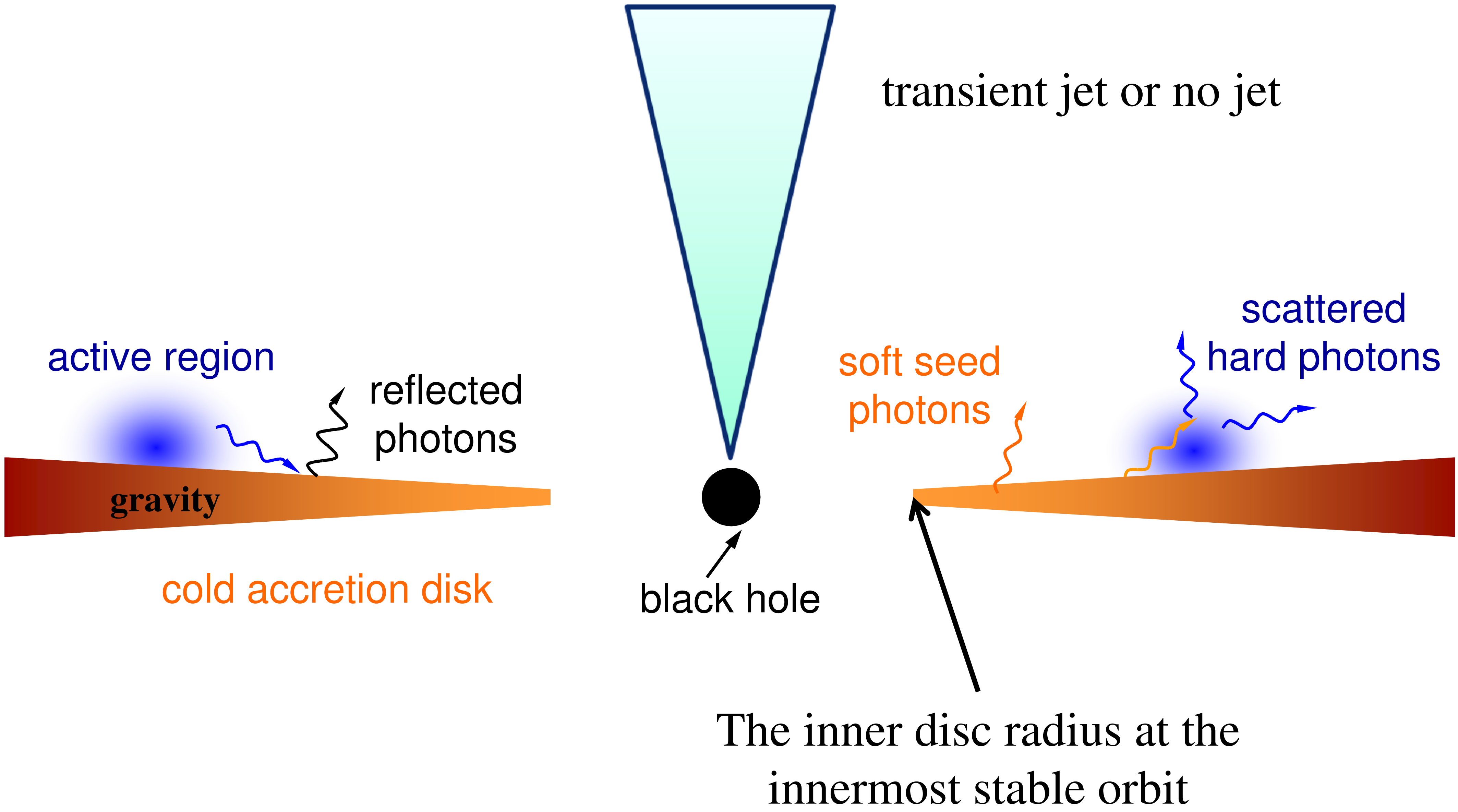
The accretion flow can emit soft γ-rays, and the jet, high and very high energy γ-rays. So far, unambiguous high-energy γ-ray detections of only Cyg X-3 and Cyg X-1 (high-mass donors).

Cyg X-1, a black hole+OB supergiant binary

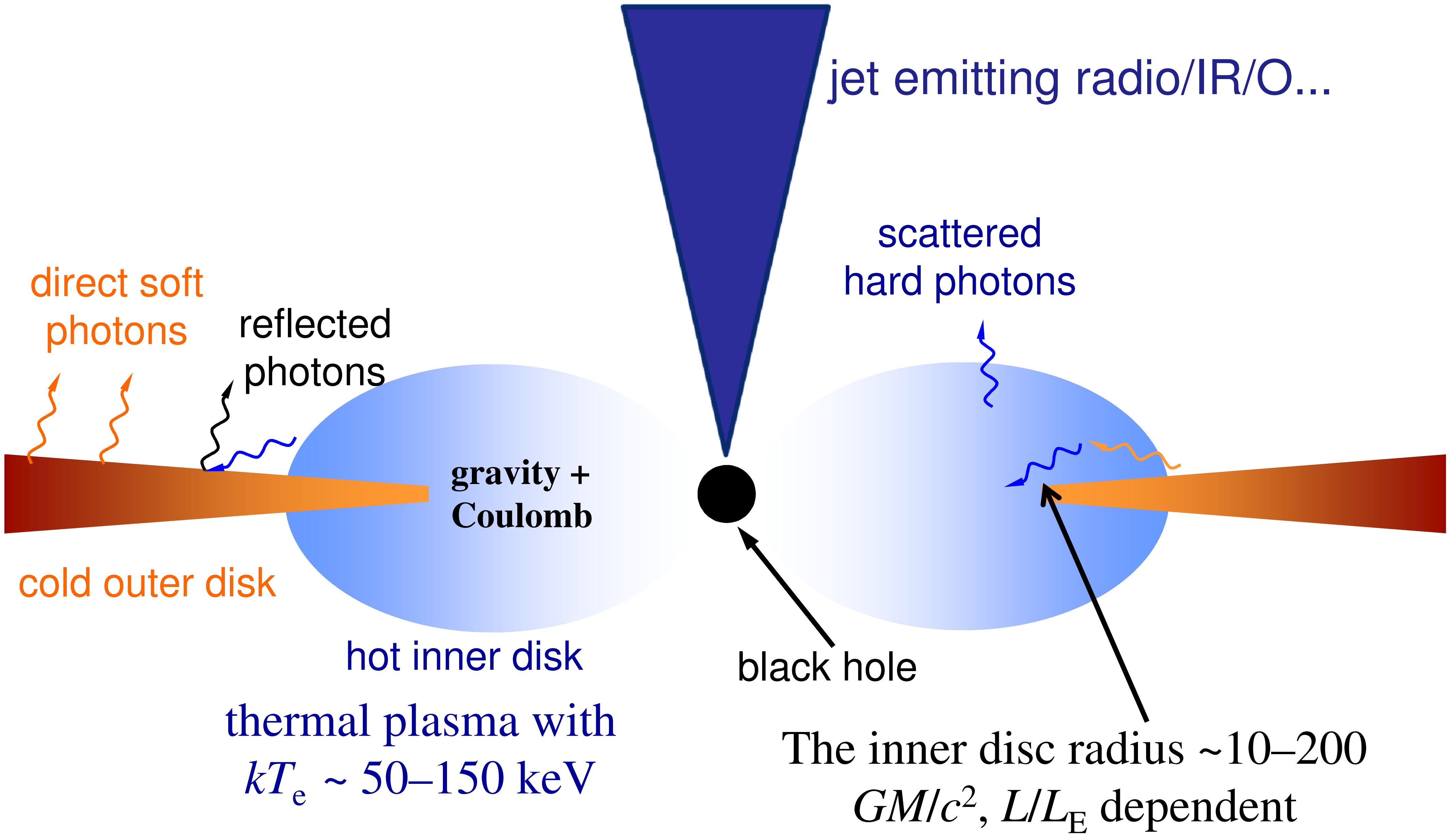


- High-energy tails extending to several MeVs in both the hard and soft states.
- High-energy γ-rays in the hard state only (Malyshev+2013, Zanin+2016, AAZ+2017); emitted by the jet seen in the radio to mm.
- AAZ+2017 found soft spectral components at <100 MeV, with the flux in the soft state being higher than that in the hard state. They match well the extrapolations of the accretion models. To be tested by *e-Astrogam*.

Disc/corona geometry of the soft state:

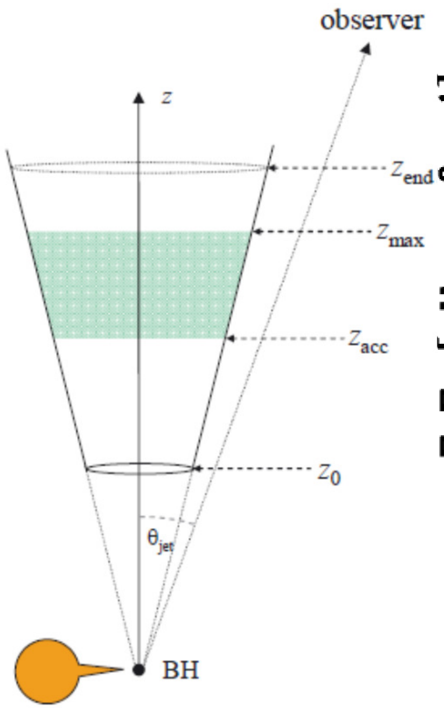


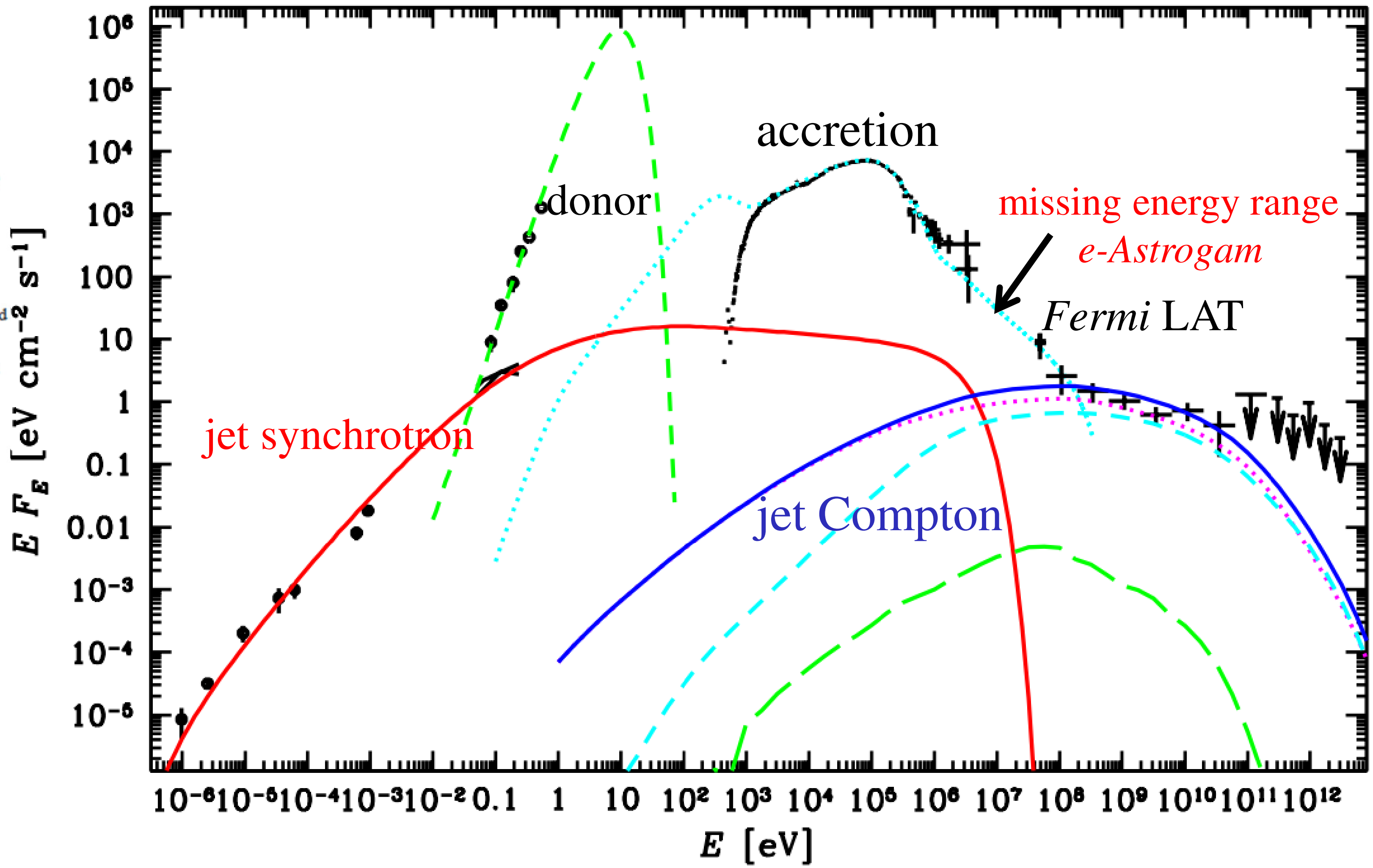
The truncated disc model for the hard state:



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

The shown broad-band spectrum is reproduced by a model with electron acceleration, cooling, electron transport, all radiative processes. Compton scattering of stellar blackbody and SSC dominate the γ-ray emission.



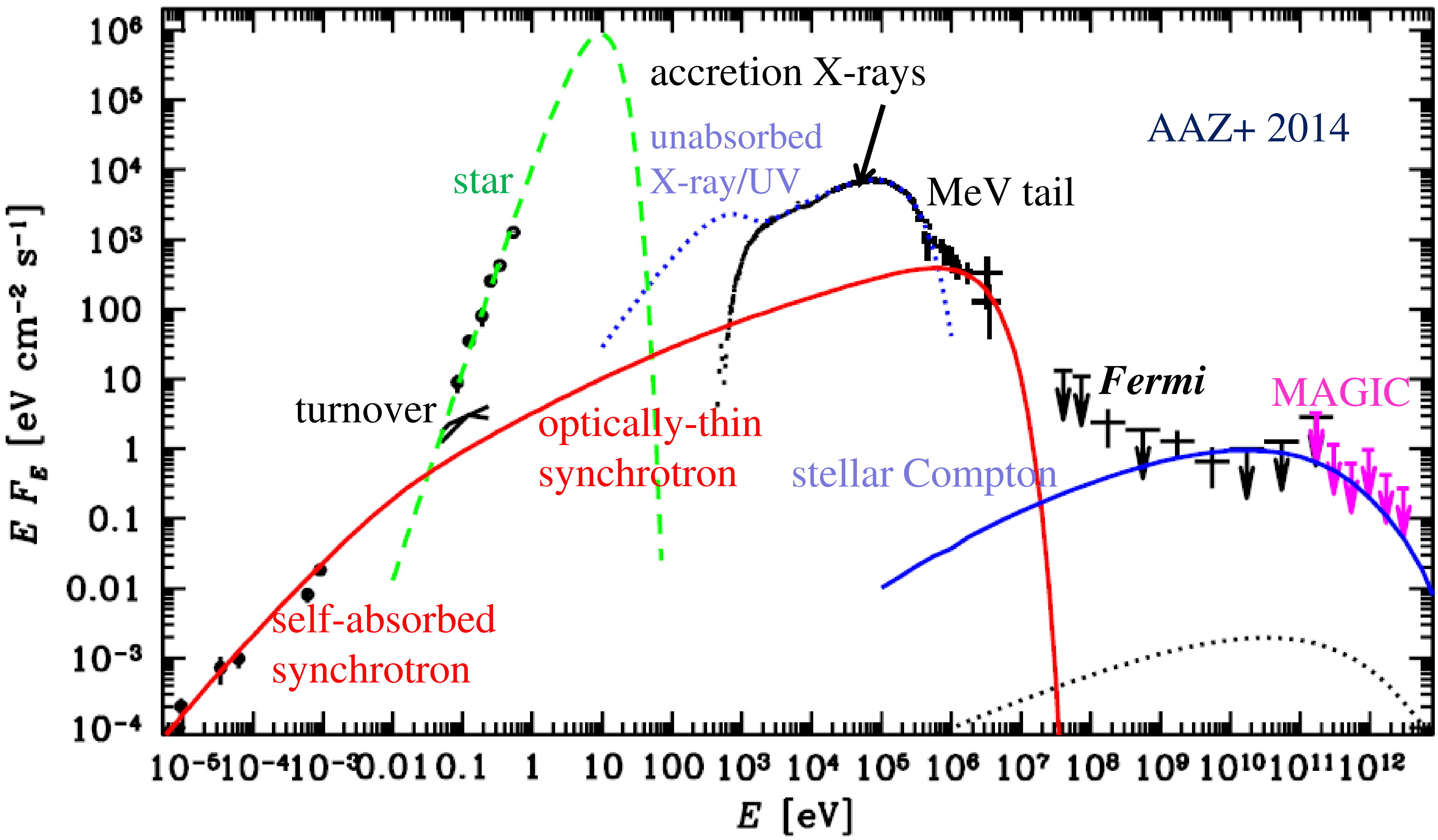


AAZ+ 2014a,b, 2017

Very strong 0.2–2 MeV polarization claimed from *INTEGRAL* Compton-mode data in the hard state of Cyg X-1

- Laurent+ 2011 (*Science*) and Rodriguez+ 2015 (*ApJ*) claim linear polarization of ~70% above 400 keV. Substantial doubts about the reality of that effect.
- If it is real, it is likely to be synchrotron jet emission.
- A revision of the results of Laurent+ 2011 given by Laurent (2016, *INTEGRAL* conference presentation), no publication as yet. In particular, the strong high-energy tails claimed before appear to be spurious.
- The presence of the polarization was to be tested by the SGR detector onboard *Hitomi*.
- Will be studied by *e-Astrogam*, also *Astrosat*.

A jet model reproducing the MeV tail.

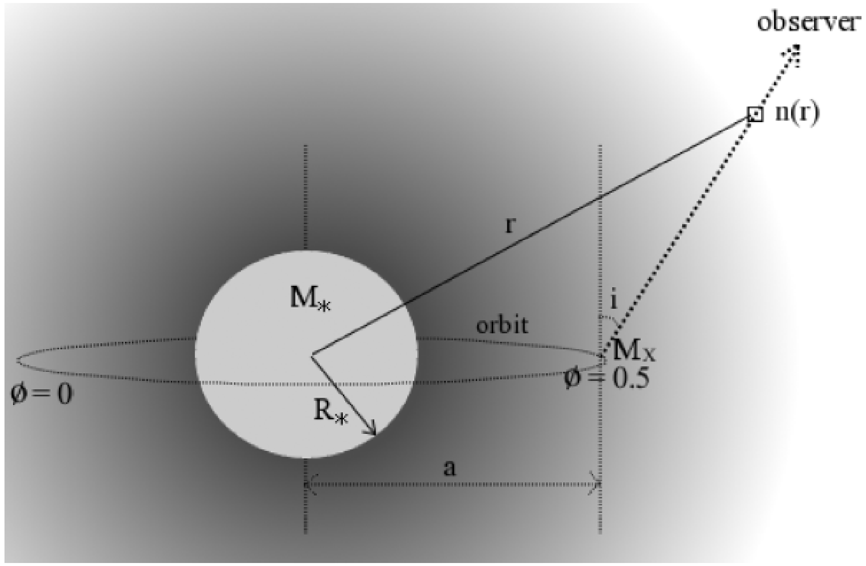


The acceleration index $p = 1.5$ (very hard), $B_0 = 5\times10^5$ G at the jet base of $z_0 = 240R_g$, extreme $(B^2/8\pi)/u_{gas} \sim 10^5$. Given the substantial variability of both the accretion flow and the jet, strong fine-tuning is required. ***e-Astrogam* observations crucial.**

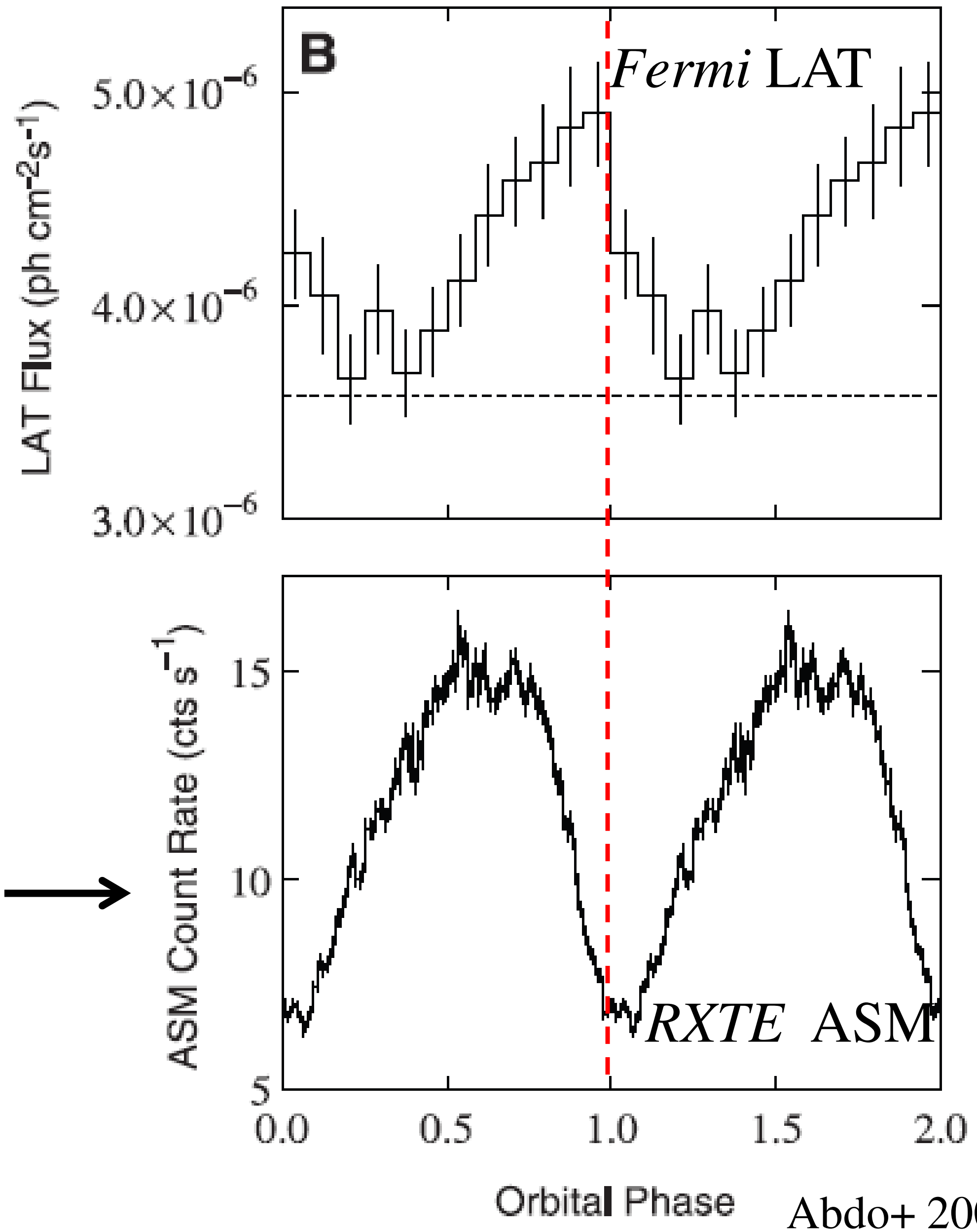
Cyg X-3: γ-ray detection by *Fermi* in the soft state

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

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



Folded lightcurves



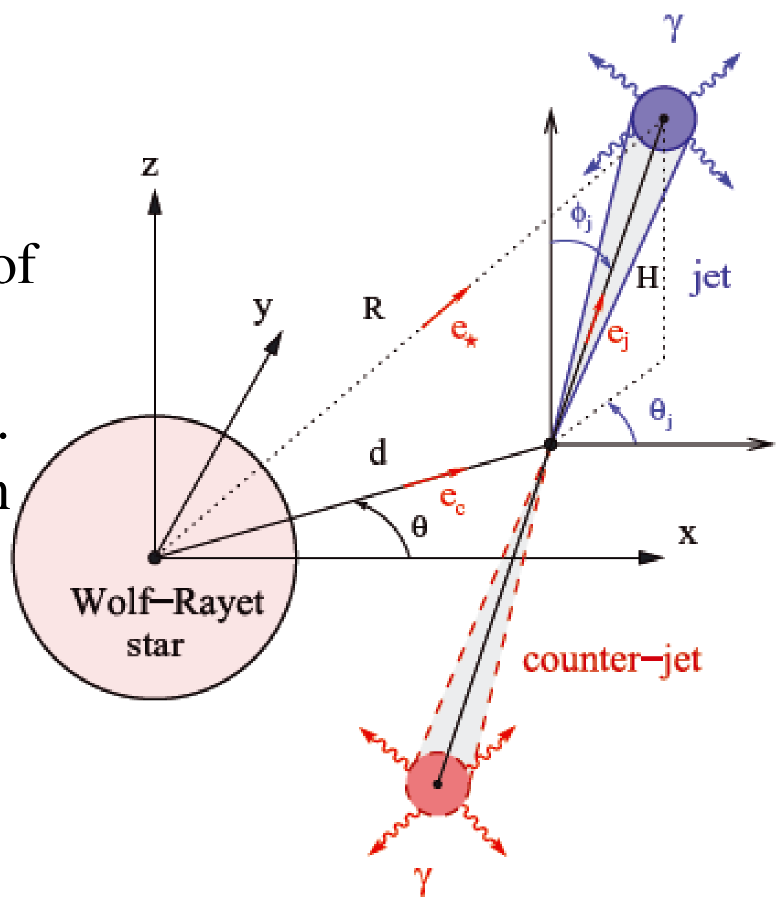
Abdo+ 2009

Also detections by *AGILE*

A model for the modulated GeV emission

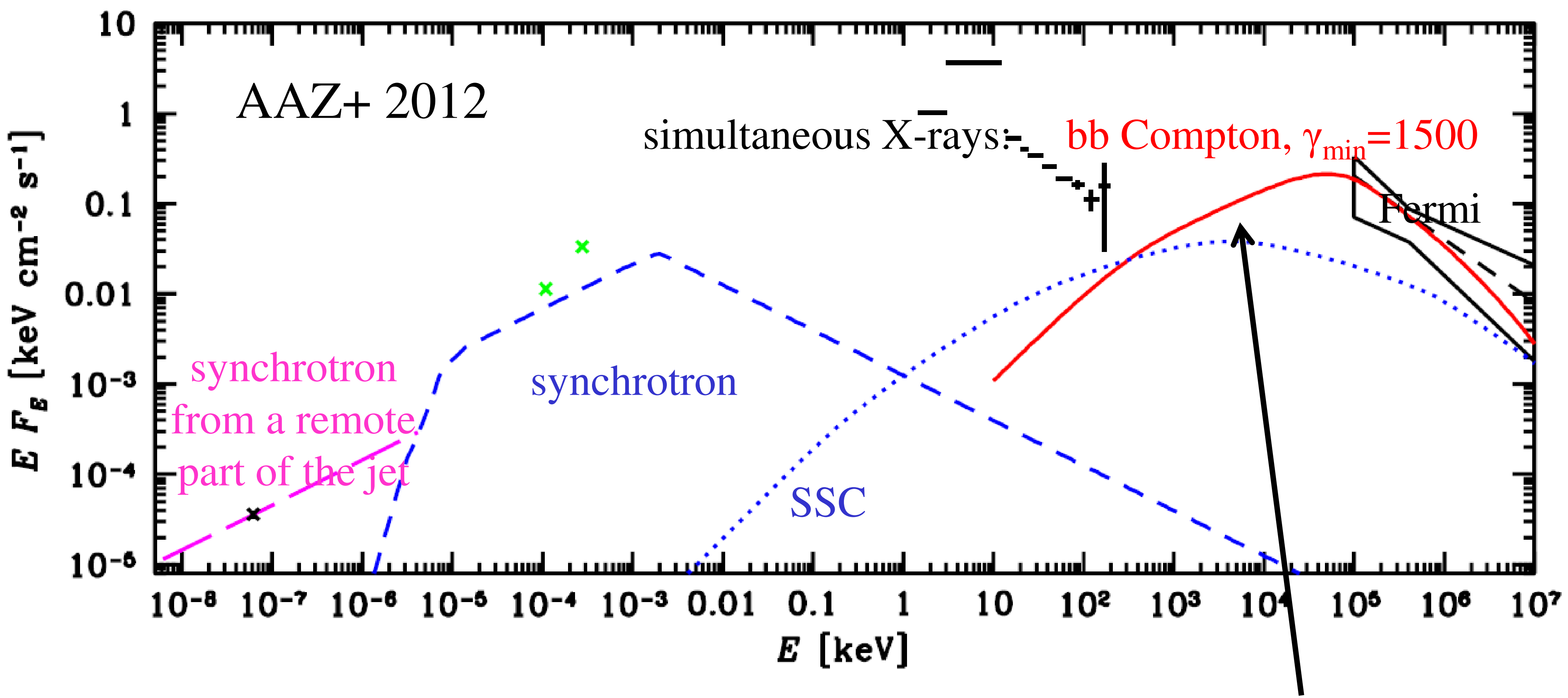
Compton anisotropy:

- The relativistic electrons in the jet Compton upscatter stellar photons to GeV energies.
- Highest scattering probability for electrons moving towards the stellar photons.
- 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.
- Fits of the model determine the γ-ray source location, ~the binary separation.



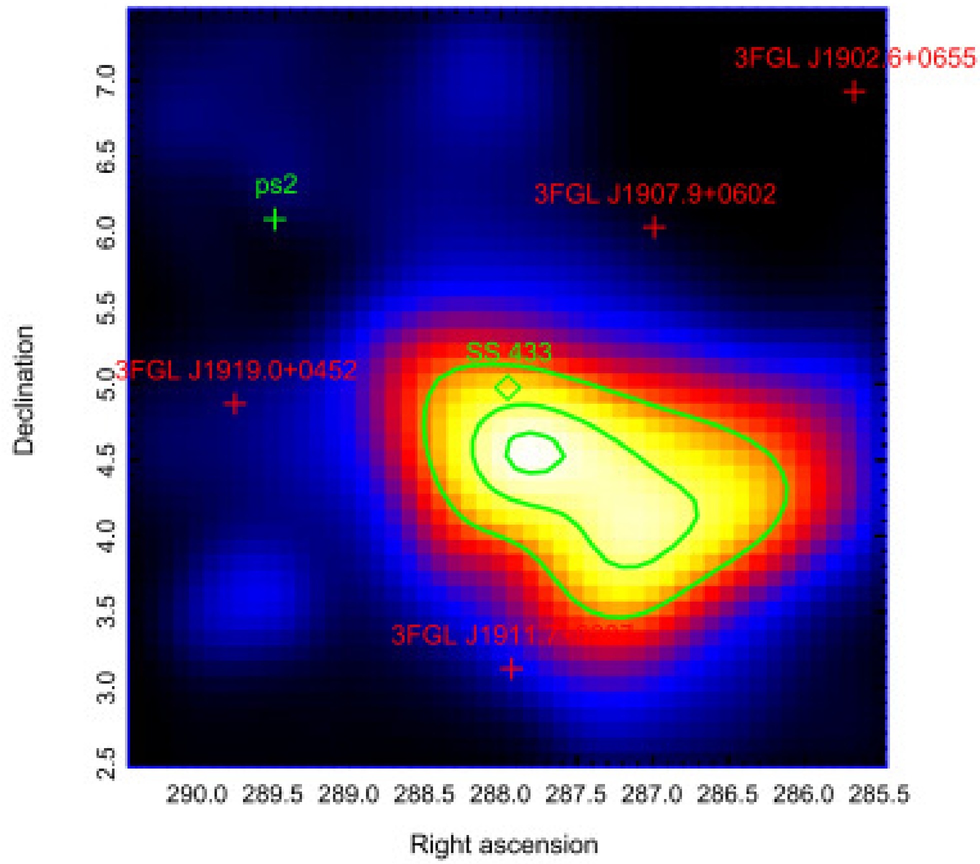
Dubus+ 2010

A spectral model of the broad-band spectrum:



The MeV-range spectrum: transition from the spectrum dominated by accretion to that jet-dominated; to be investigated by *e-Astrogam*

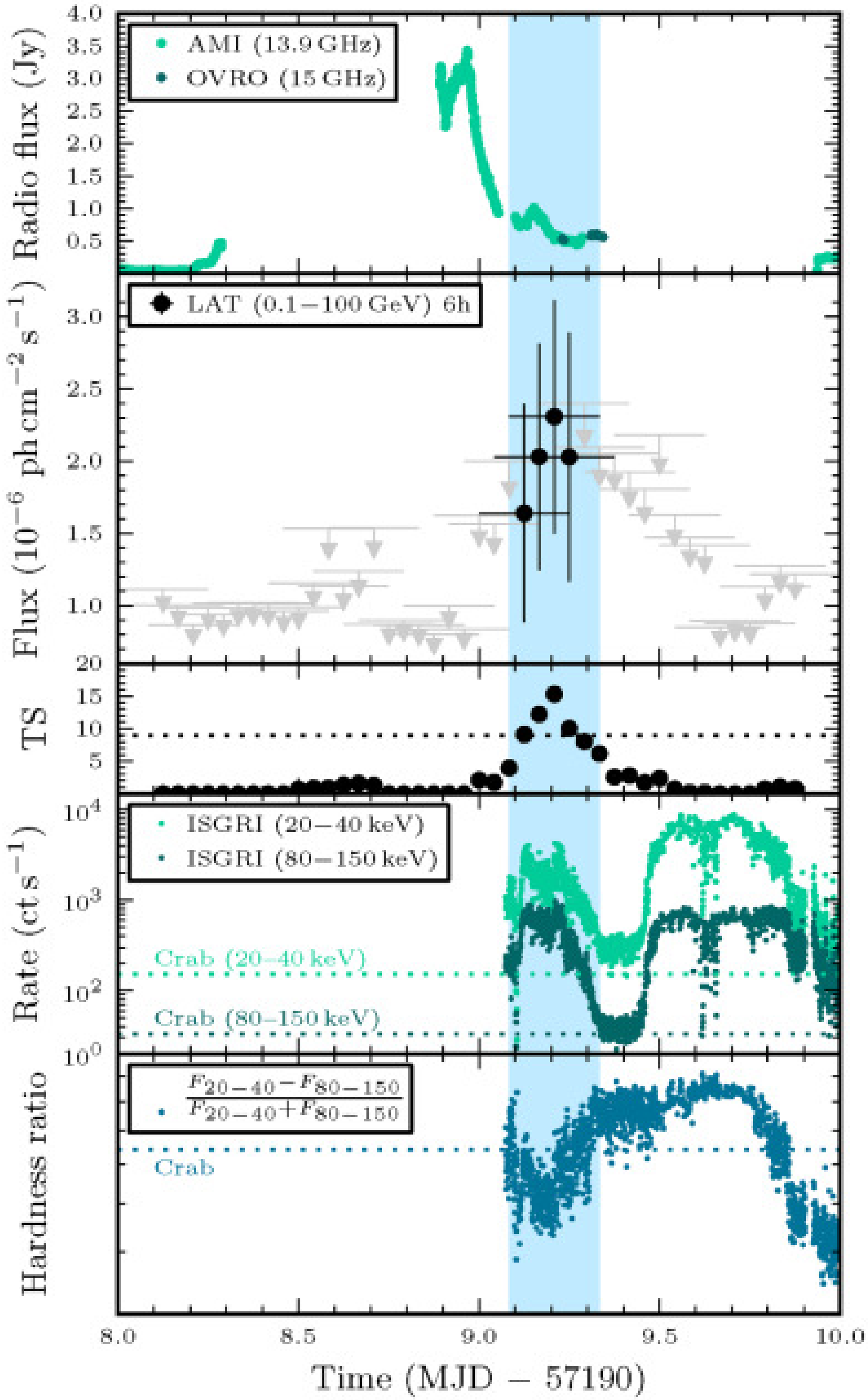
γ-rays from SS 433?



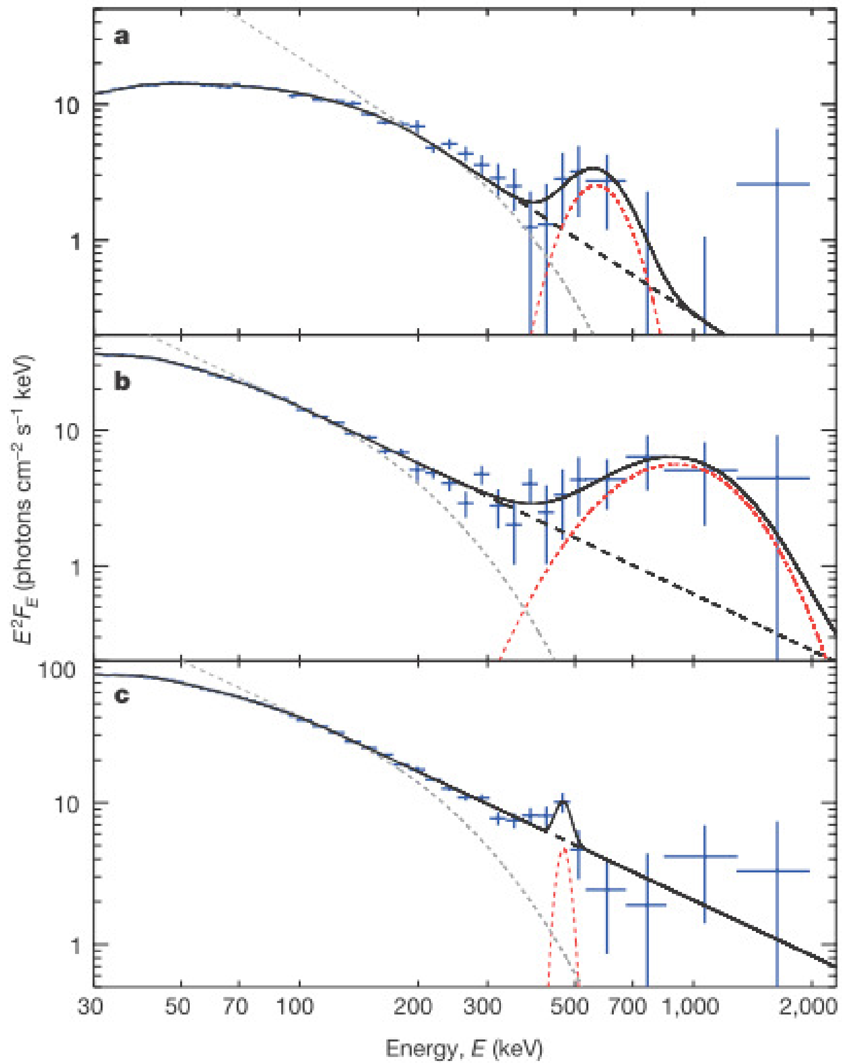
Fermi LAT;
Bordas+2015

- High-energy γ-rays are emitted from the direction of the microquasar SS 433, but it is difficult to distinguish them from those from the SNR W49.

V404 Cyg: the marginal *Fermi*-LAT detection of HE γ-rays by Loh+2016:



Strong e± pair annihilation spectra claimed from V404 Cyg



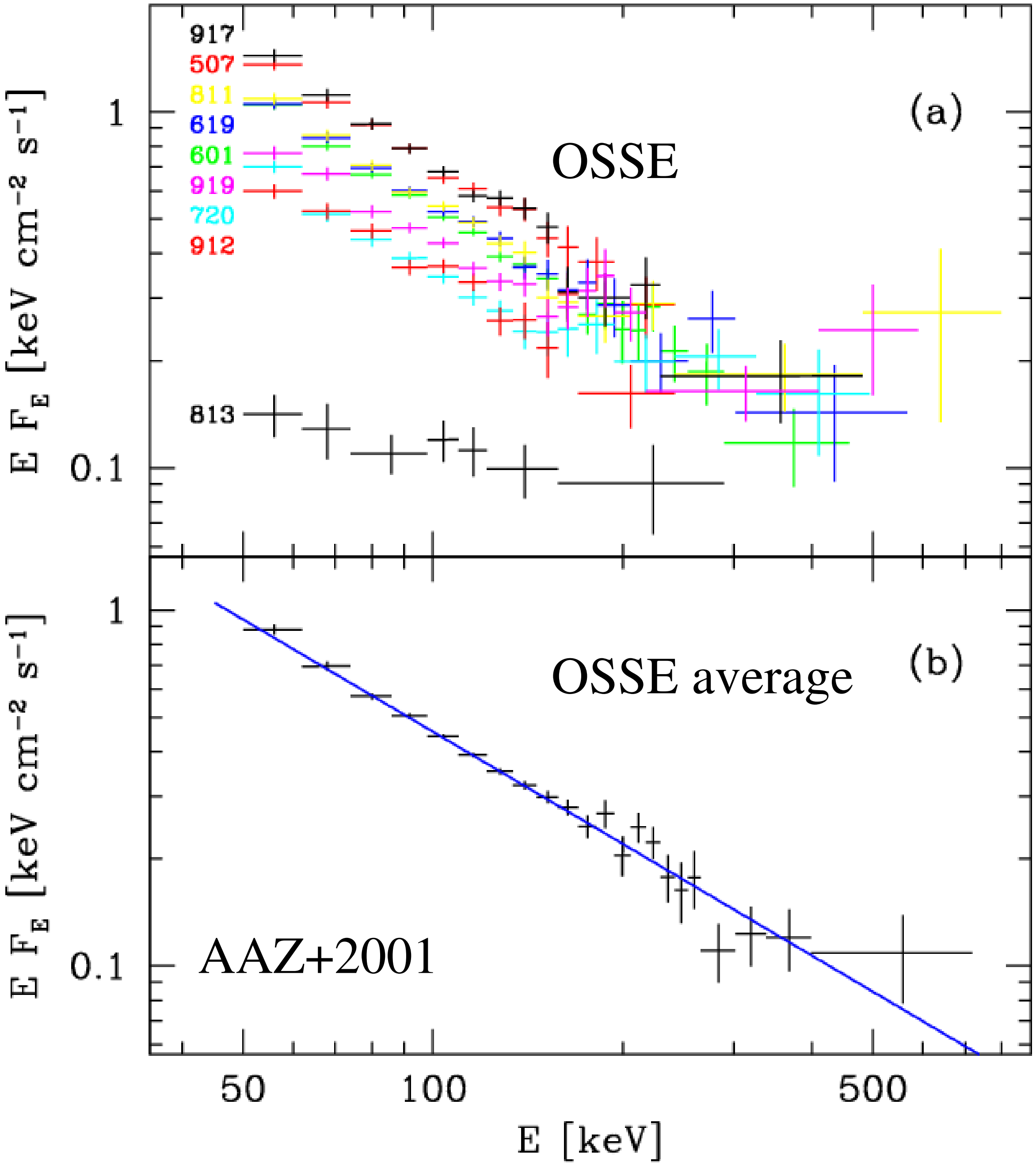
Siebert, Diehl+ 2016, *Nature*

No detailed theoretical model as yet.

e-Astrogam will measure e± pair annihilation features in microquasars in much more detail.

Luminous BH LMXBs, e.g., GRS 1915+105

- No high-energy cutoff seen in observations by the *CGRO* OSSE; the spectrum at higher energies to be measured by *e-Astrogam*.

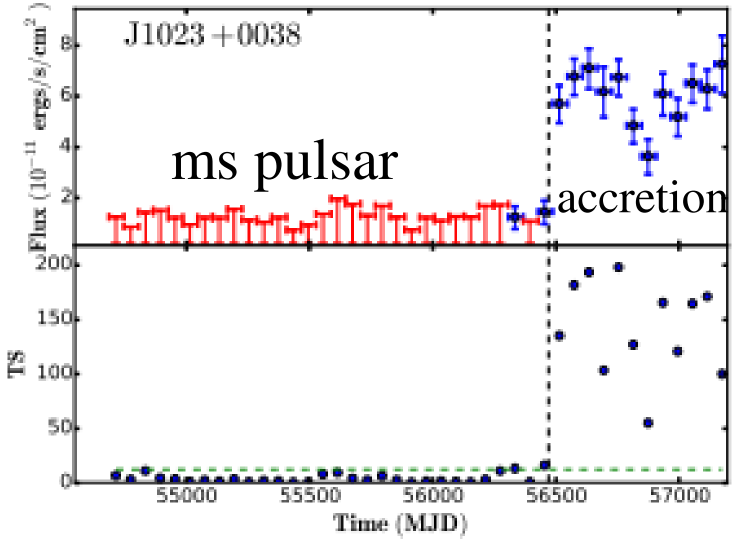


Transitional ms pulsars during accretion states

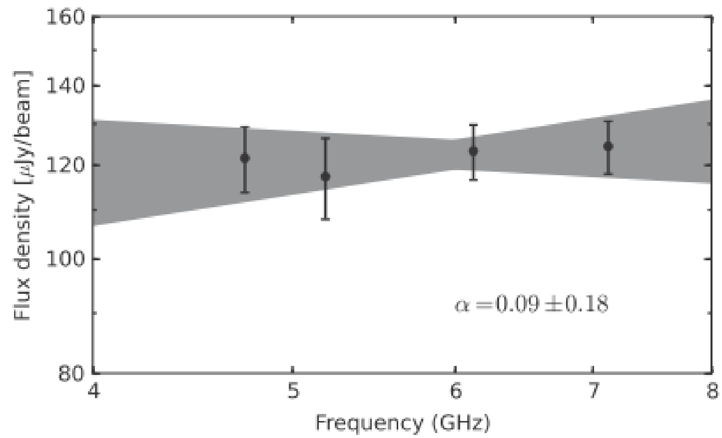
- A few ms pulsars have recently been discovered to change between rotation-powered pulsar states and accretion-powered X-ray pulsar states (e.g., Archibald+2009; Papitto+2013; De Martino+2010,2013,2015; Bassa+2014).
- During their rotation-powered states, they show the usual pulsed magnetospheric emission from radio to high-energy γ-rays.
- Two cases of transitions into sub-luminous states with accretion discs, with $L_X \sim 10^{33}$ erg/s: PSR J1023+0038 (Stappers+2014) and PSR J1227−4853 (De Martino+2010,2013).
- Unexpectedly, these sources during the weak accretion states show large increases of the high-energy γ-ray luminosity, up to a factor of several.
- Initially, the enhanced γ-ray emission was attributed to the pulsar wind interacting with the accretion disc or a propellering magnetosphere.
- However, a strong radio emission with the spectral index of $\alpha \approx 0$ was then found in PSR J1023+0038 (Deller+2015). Such emission is characteristic to radio jets in accreting systems.
- This makes likely that the γ-ray emission is from the jet, thus being the first such case in an LMXB.

The ms pulsar transitions in γ-rays

Torres+ 2017

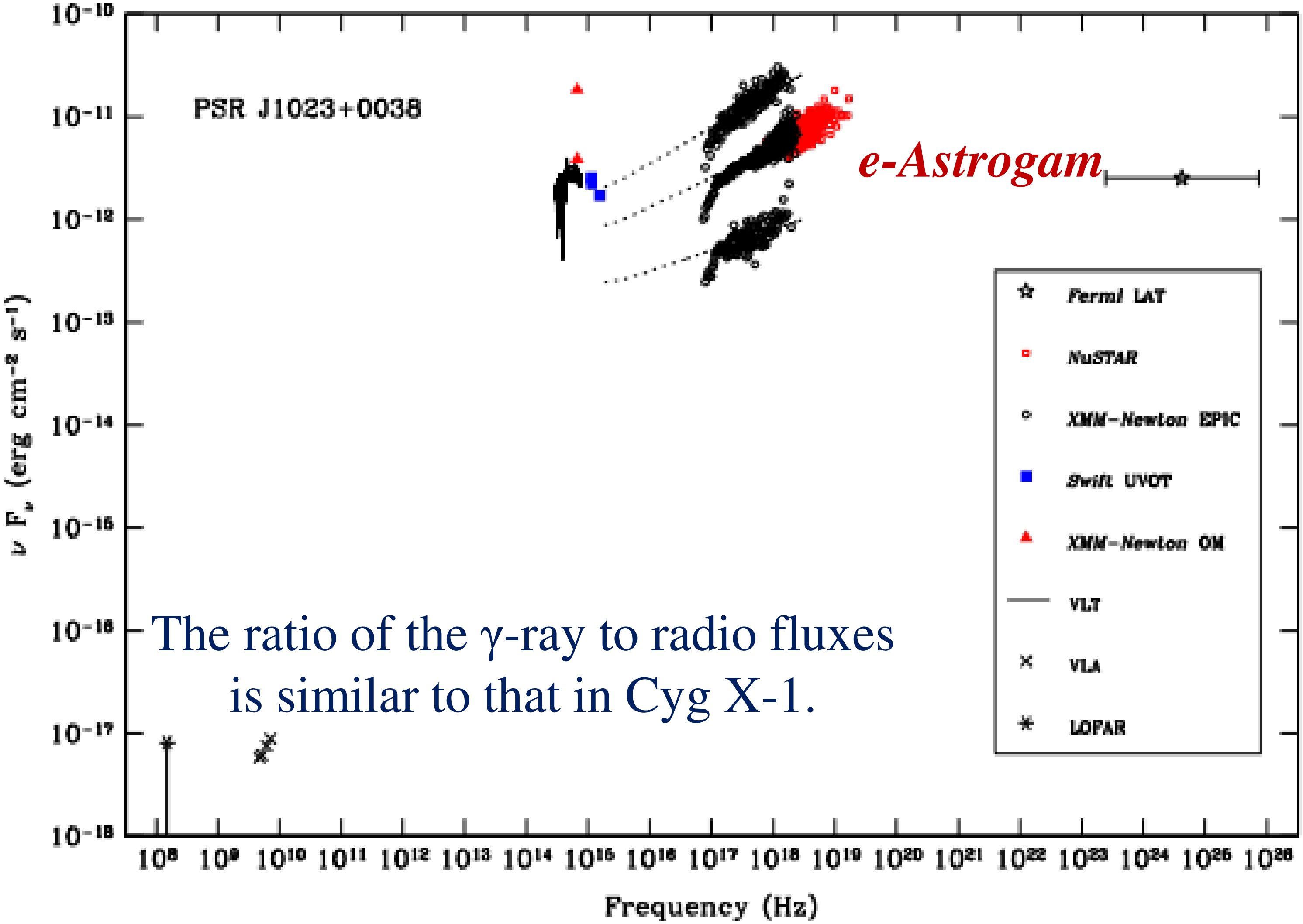


An example of the radio spectrum, $\alpha \approx 0$.



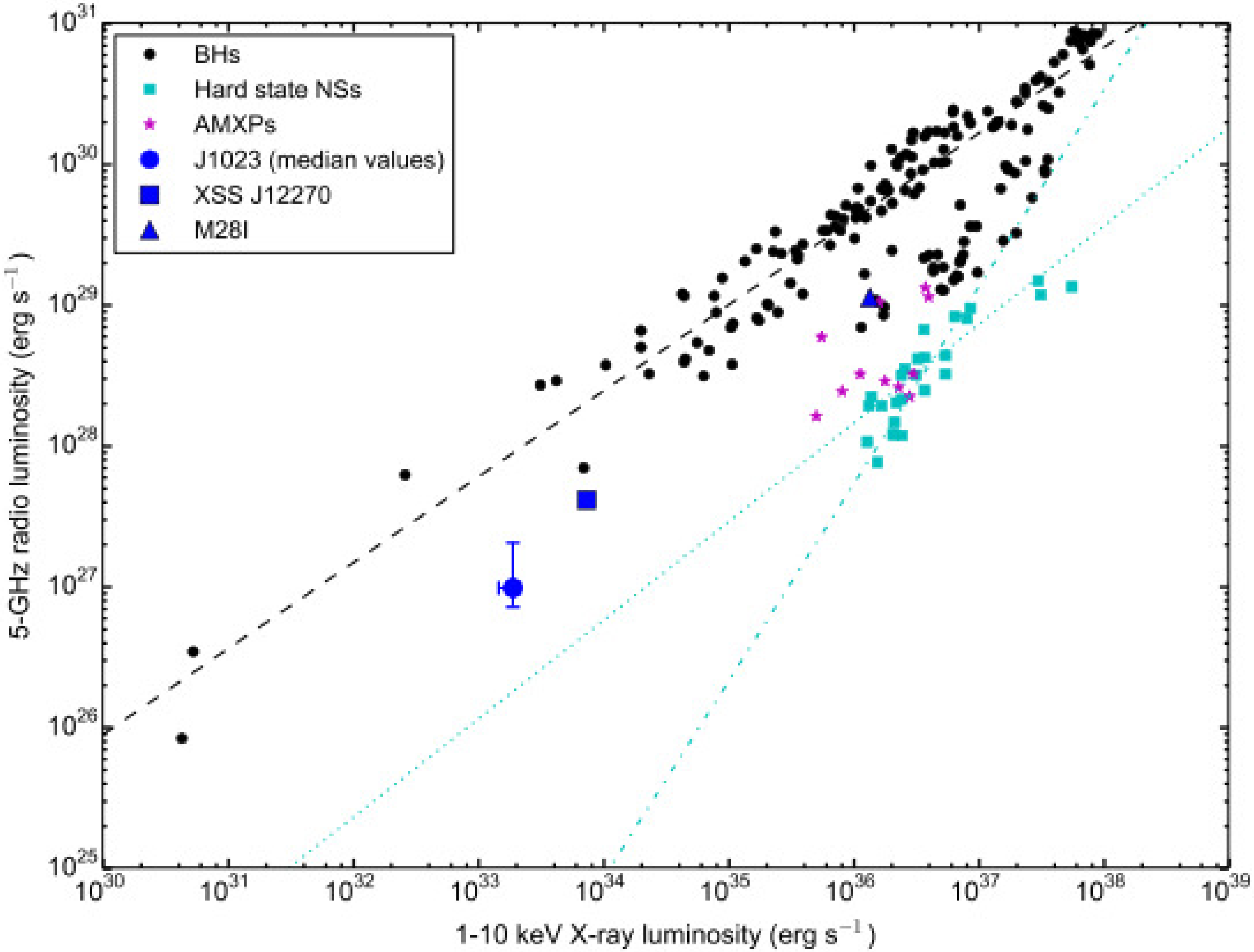
Is this a manifestation of the low-luminosity accretion states being dominated by jet emission?

The broad-band spectrum of PSR J1023+0038



e-Astrogam will be able to study the transitionary region from X-rays to the MeV range, and unambiguously determine the nature of the γ-rays.

The radio flux in the LMXB states of transitional pulsars is much stronger than that implied by the radio/X-ray correlation for accreting NS sources



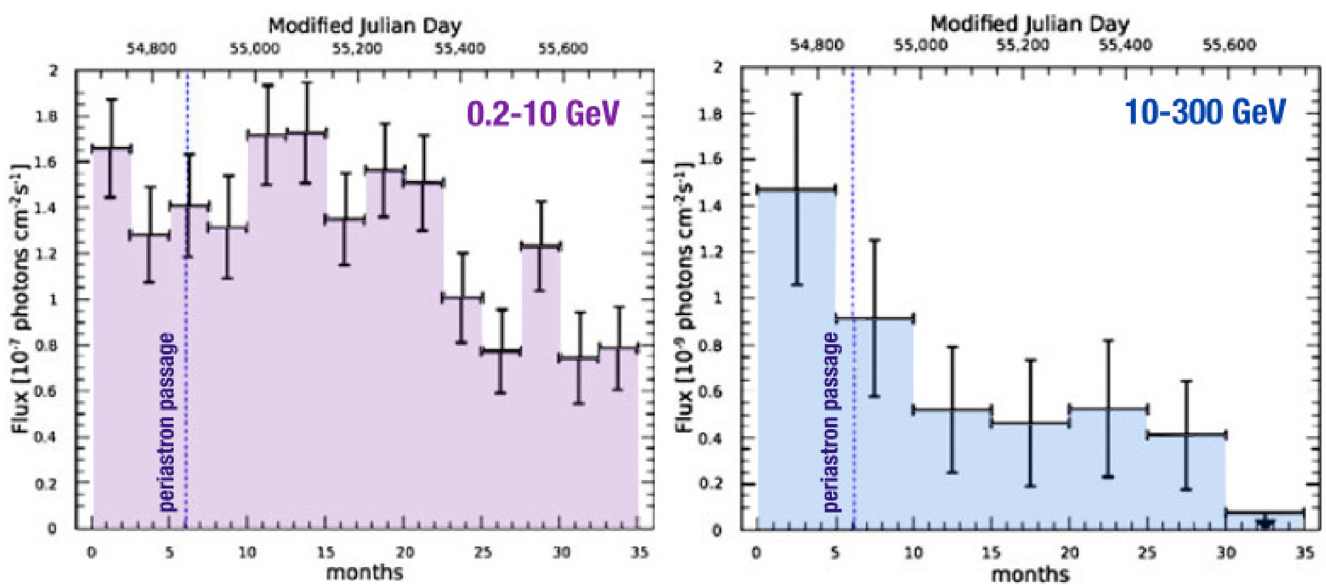
Deller+2015

γ-ray emission of low-mass vs. high-mass X-ray binaries

- Cyg X-1 and Cyg X-3 are high-mass X-ray binaries, and their γ-ray emission appears to be dominated by Compton up-scattering of stellar blackbody by relativistic electrons.
- Also, interaction of the stellar wind with the jet can enhance the γ-ray emission (Yoon, AAZ, Heinz 2016).
- LMXBs lack these factors.
- Still, relativistic electrons in the jets of LMXBs will emit SSC and up-scattering of disc photons.
- Low accretion-rate states may be jet-dominated and can have substantial γ-ray emission (see PSR J1023+0038).
- ***ASTROGAM*** will, most likely, detect many LMXBs in γ-rays.

Colliding-wind high-mass binaries

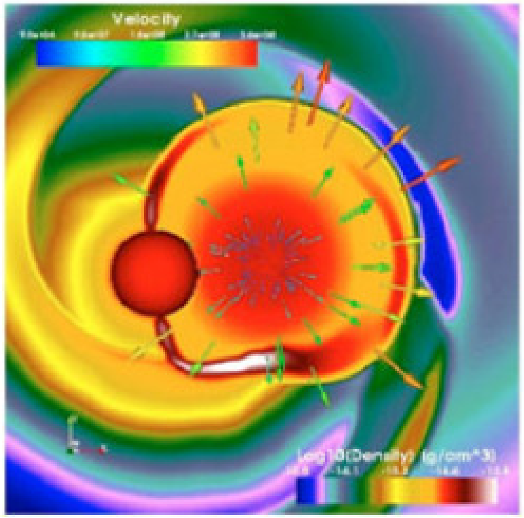
- Only one colliding-wind binary has been detected in high-energy γ-rays (by *AGILE* and *Fermi*), Eta Car, a binary with a ~$100M_\odot$ LBV and an O or WR star in a 5.5 year orbit. The γ-ray luminosity ≈ 0.2% of the available wind kinetic power.
- Why so few? Why is acceleration so inefficient?
- *e-Astrogam* will be able to detect more sources in the range <100 MeV.

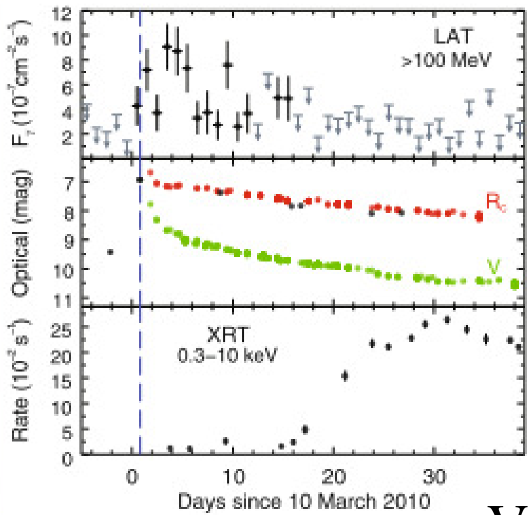


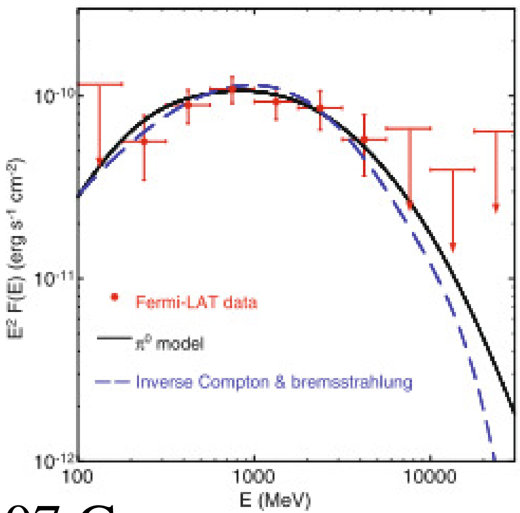
Reitberger+2012

Novae

- MeV-range emission in lines predicted theoretically but not detected yet.
- The first nova detected in high-energy γ-rays was V407 Cyg, which is in a symbiotic system with a red giant in a long orbit. This prompted models of the emission in collision of the ejecta with the stellar wind.
- However, all the subsequent 8 detections were from novae in close low-mass binaries. The acceleration mechanism is probably internal shocks in the ejecta.







V407 Cyg

Final remarks

- Intersection of the accretion and jet components in the MeV region in microquasars. *e-ASTROGAM* will disentangle those contributions in particular in Cyg X-1, Cyg X-3 and PSR J1023+0038, already detected in γ-rays.
- It will resolve the issue of the origin of MeV tails, either from non-thermal Comptonization or jet synchrotron emission.
- It will measure the MeV polarization in Cyg X-1.
- It will measure orbital modulation in γ-rays in both microquasars and gamma-ray binaries.
- It will likely detect many LMXBs and colliding-wind binaries in γ-rays.