# High energy processes in binary systems

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Binaries with high-energy EM emision

- **Systems powered by accretion onto a black hole or neutron star; emission of both the accretion flow and jet (covered in this talk).**

- So-called gamma-ray binaries, defined by the peak of their νF_ν spectrum at GeVs: pulsar wind colliding with stellar wind from a high-mass star (powered by pulsar rotation).

- γ-ray emitting pulsars in binaries, in particular recycled ms pulsars spun up by accretion, but no longer accreting (powered by pulsar rotation); in some cases pulsar wind ablating the low-mass companion $\rightarrow$ emission from the wind interacting with the companion; some sources switching between the pulsar and accretion modes.

- Colliding-wind binaries: collision of stellar winds from two massive stars;

- Novae: thermonuclear runaway on a white dwarf, high-energy emission due to particle acceleration in the ejecta.

- Coalescence of NS-NS and NS-BH binaries: jets and ejecta.

Accreting stellar binary systems with a compact object (black hole or neutron star)
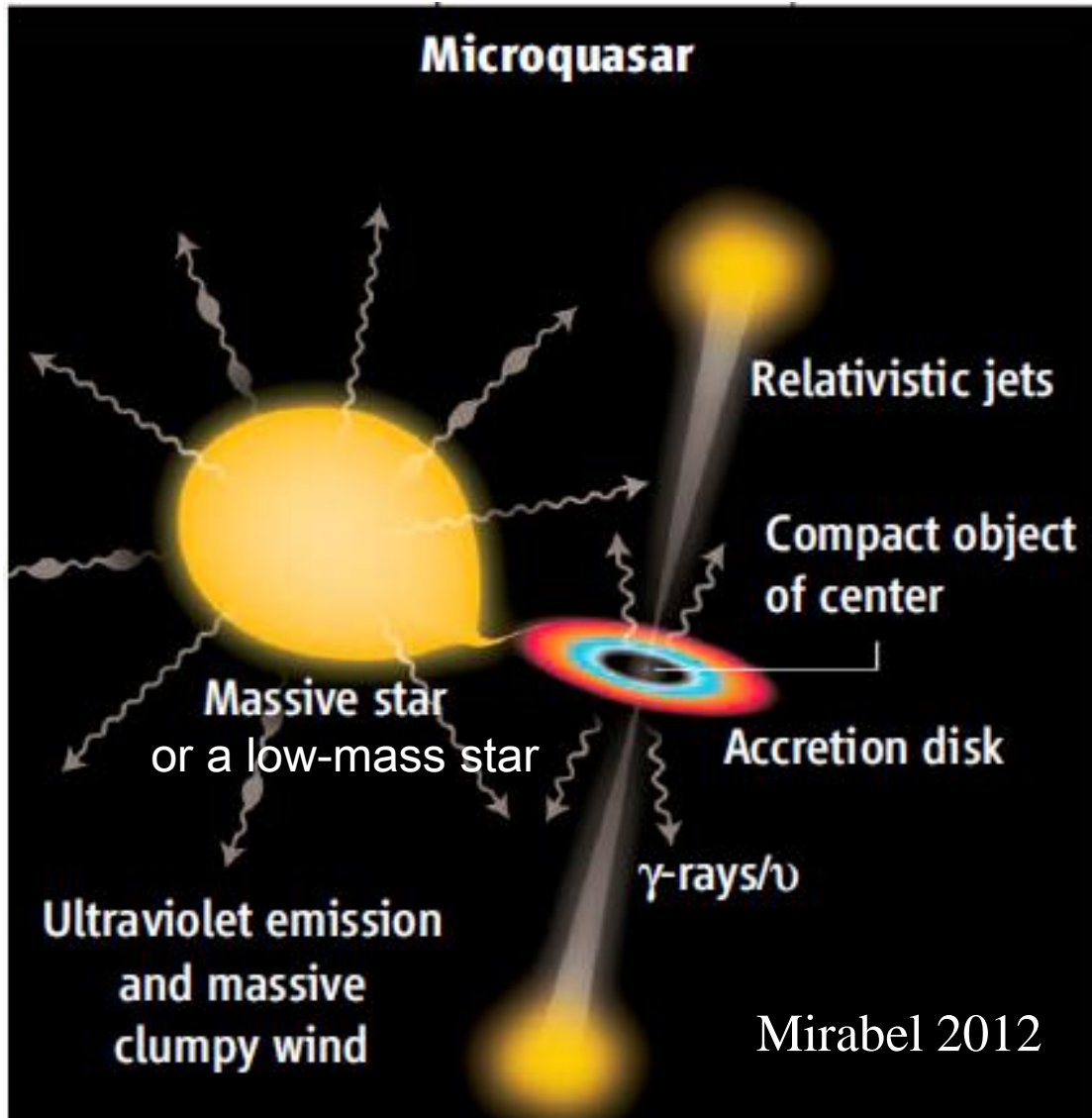
A sketch of an accreting binary. The donor: either a high or a low-mass star.

Binaries containing a BH and a massive donor are persistent, and those with a low-mass donor are mostly transient (outbursts separated by years of quiescence).

Cyg X-1, a black hole+OB supergiant binary
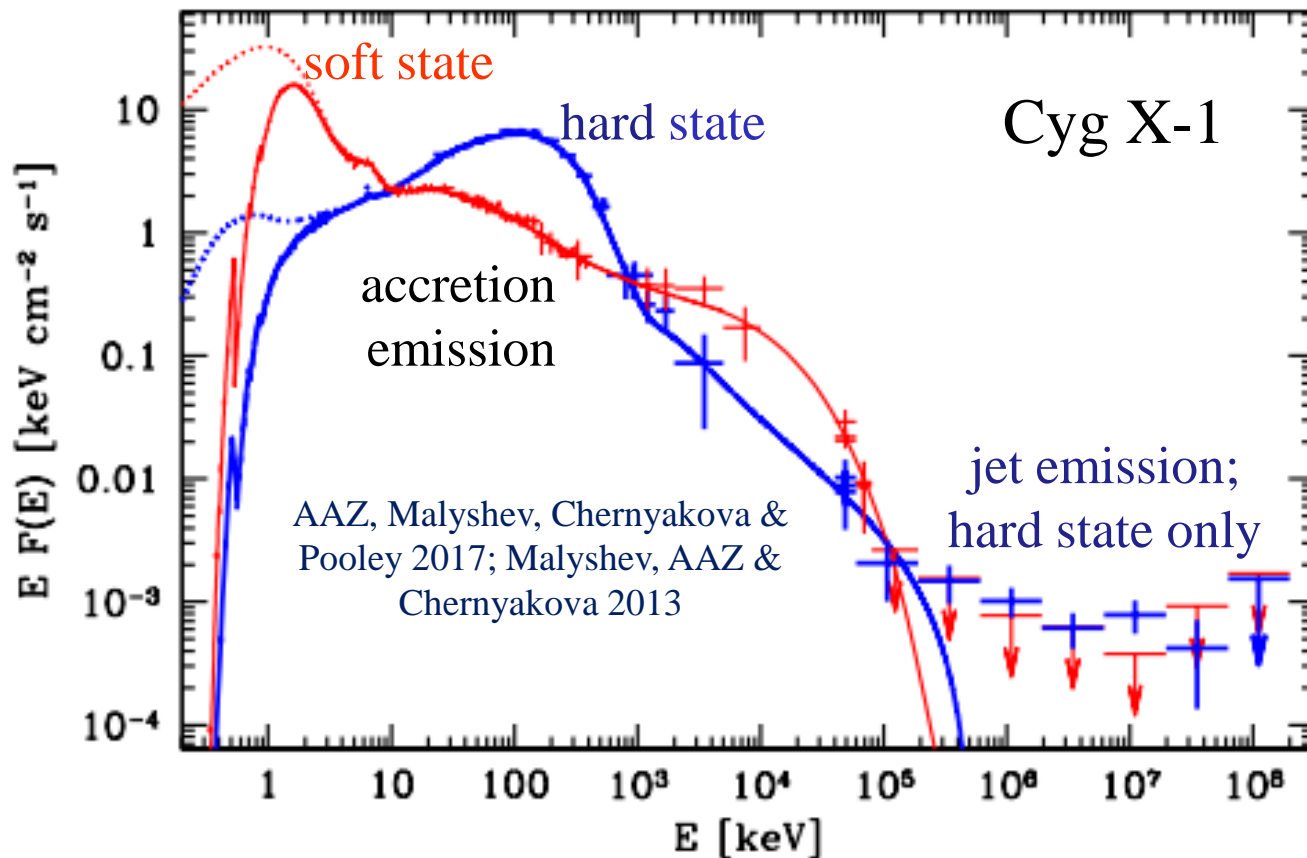
- High-energy γ-rays in the hard state only emitted by the jet seen in the radio to mm.
- The presence of a jet only in the hard state only is characteristic to most of known accreting BH binaries.

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

A jet model with electron acceleration, cooling, electron transport, all radiative processes. Compton scattering of stellar blackbody and SSC dominate the γ-ray emission.
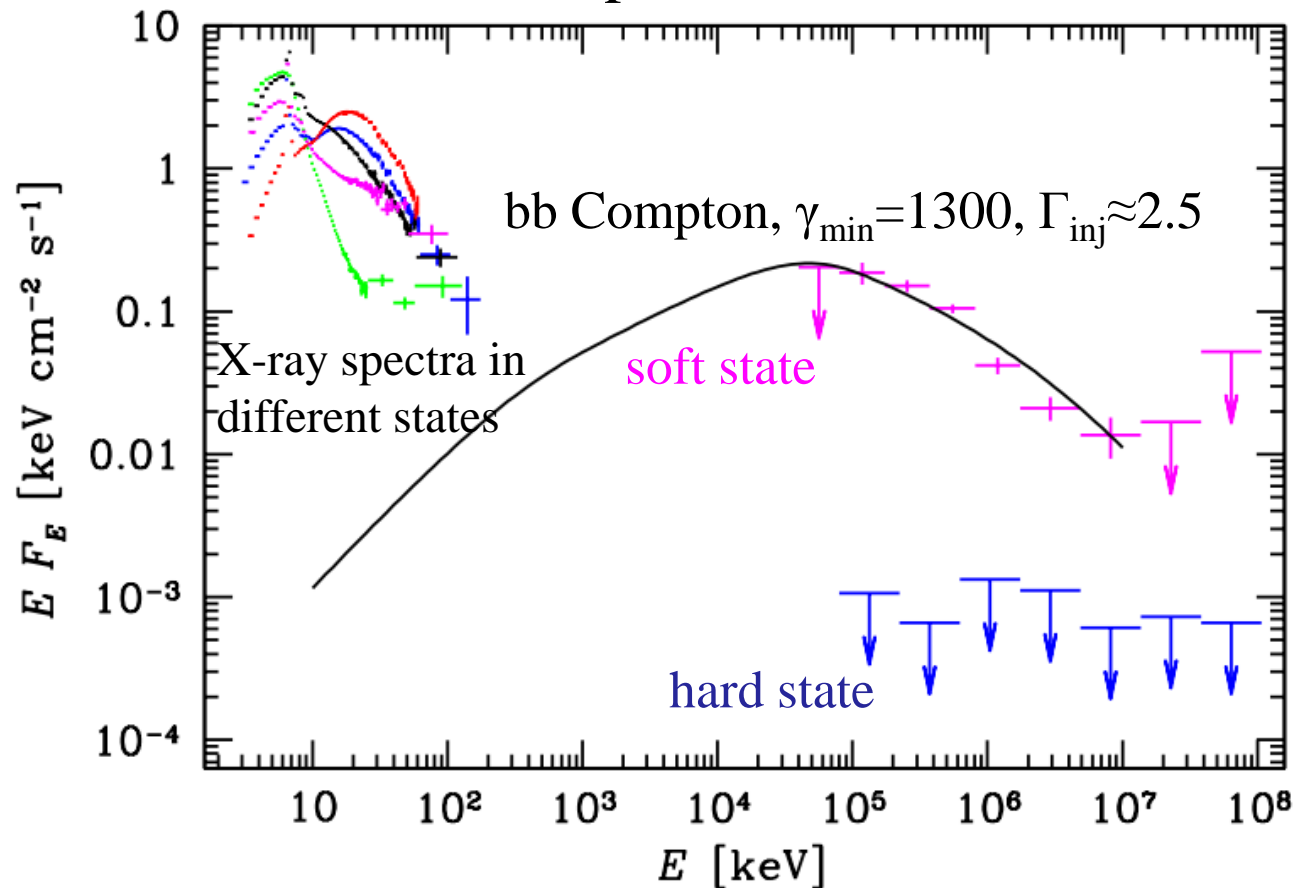
AAZ+ 2014a,b, 2017; Malyshev+ 2013
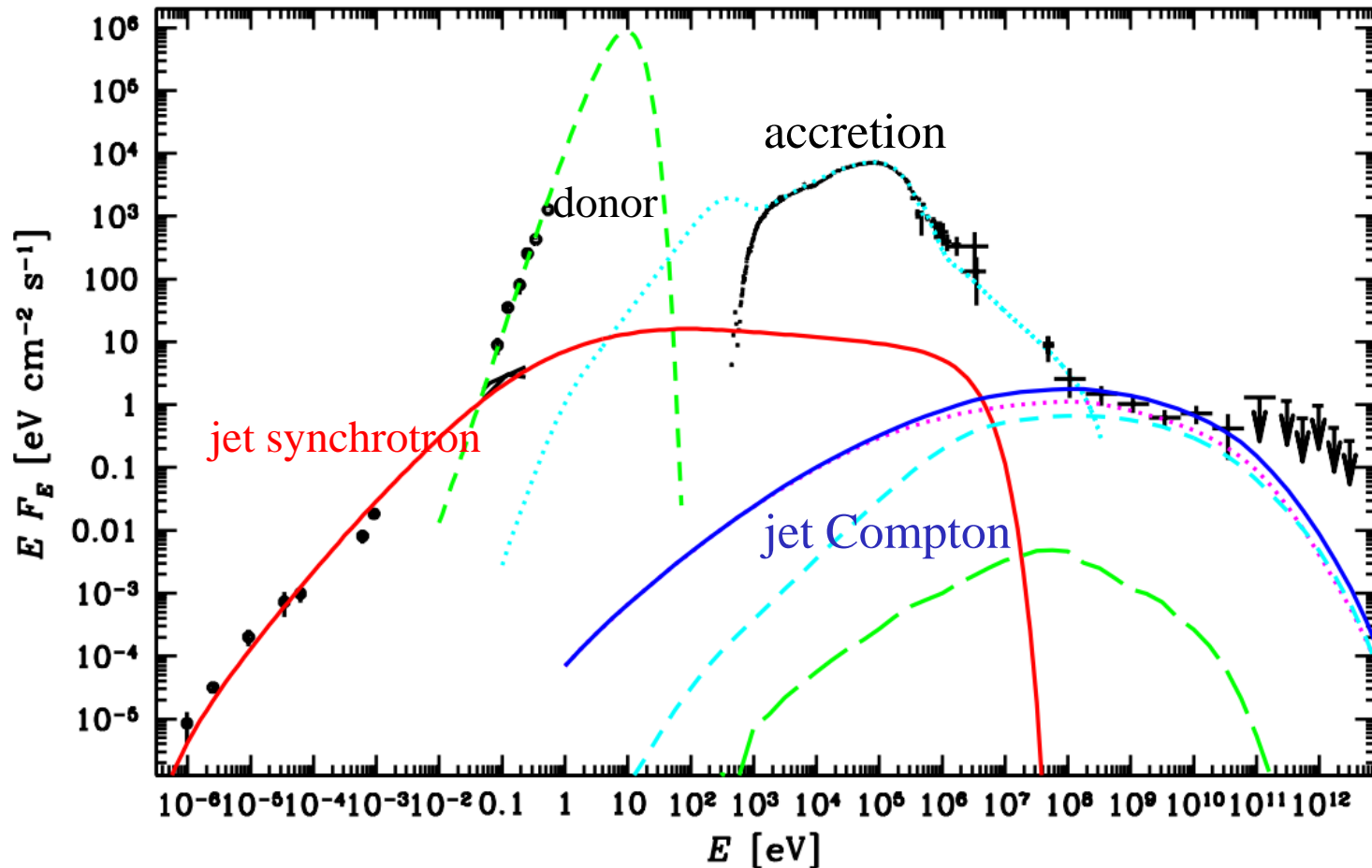
Electron acceleration from $z_{acc} \approx 100\,R_g$, at which distance $B \approx 8 \times 10^4$ G.

Cyg X-3: a compact object and a WR donor

High-energy emission detected in the soft state only. Electron acceleration above $\gamma_{min} \sim 10^3$ with an index $\Gamma \approx 2.5$, Compton scattering of the donor blackbody photons. The GeV emission strongly modulated on the orbital period.


bb Compton, $\gamma_{min}=1300$, $\Gamma_{inj} \approx 2.5$

X-ray spectra in different states

soft state

hard state

AAZ+ 2012, 2018

A model for the modulation of jet γ-ray 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.

Dubus+10, AAZ+18
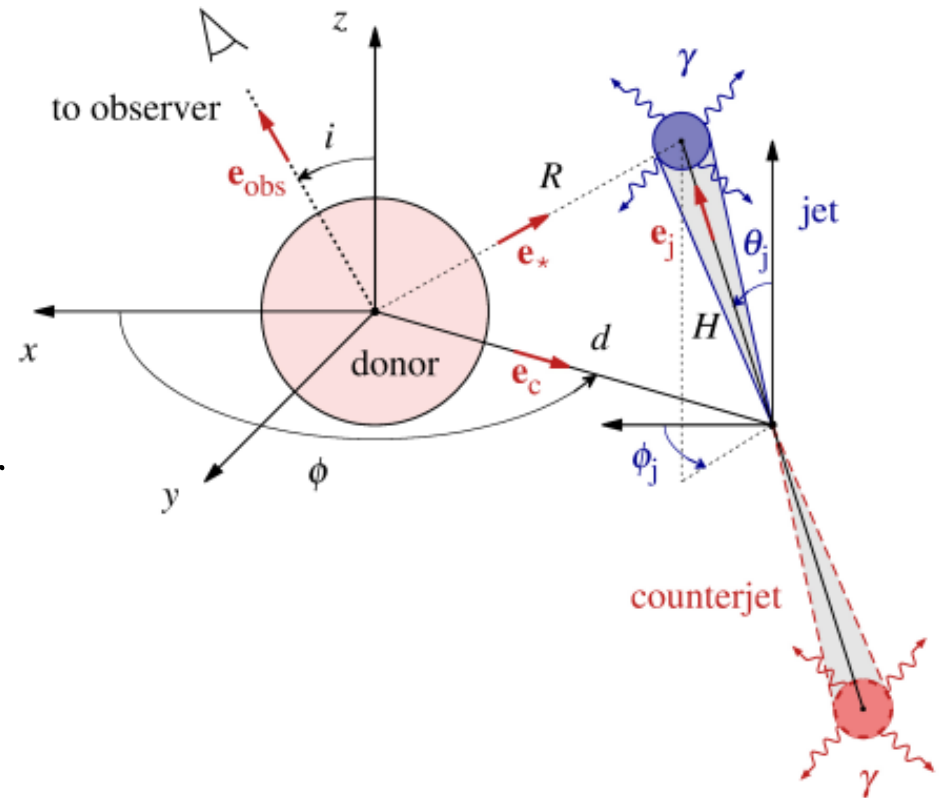
Fits of this model to the folded γ-ray light curve
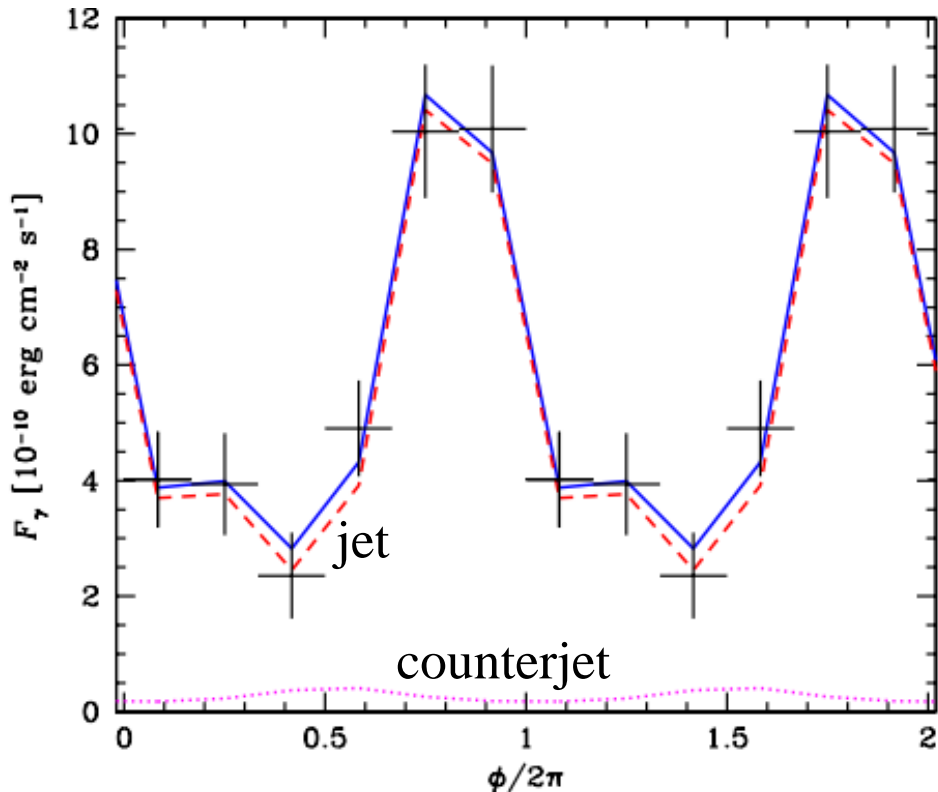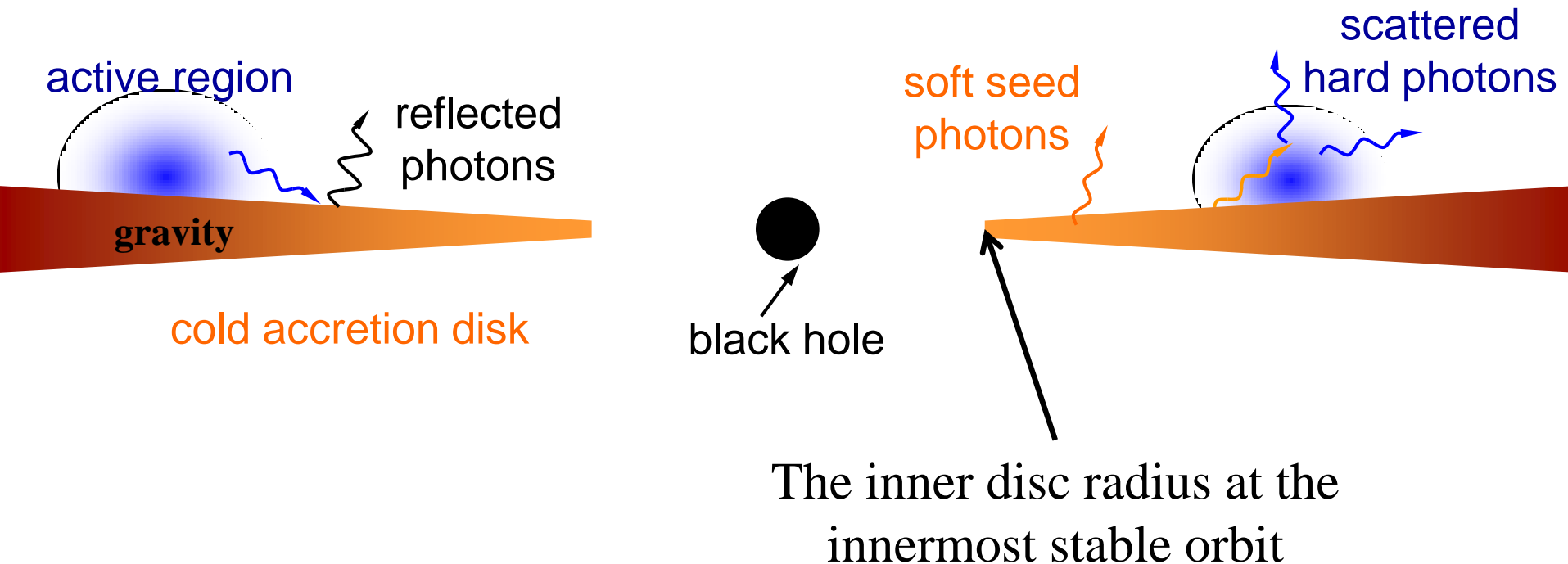

The distance along the jet from the compact object to the γ-ray emission region ≈3×the stellar separation, ~10^{12} cm~$10^6 R_g$. The jet is inclined w/r the binary axis, θ≳30°, and its velocity is ≳0.3c.

AAZ+18

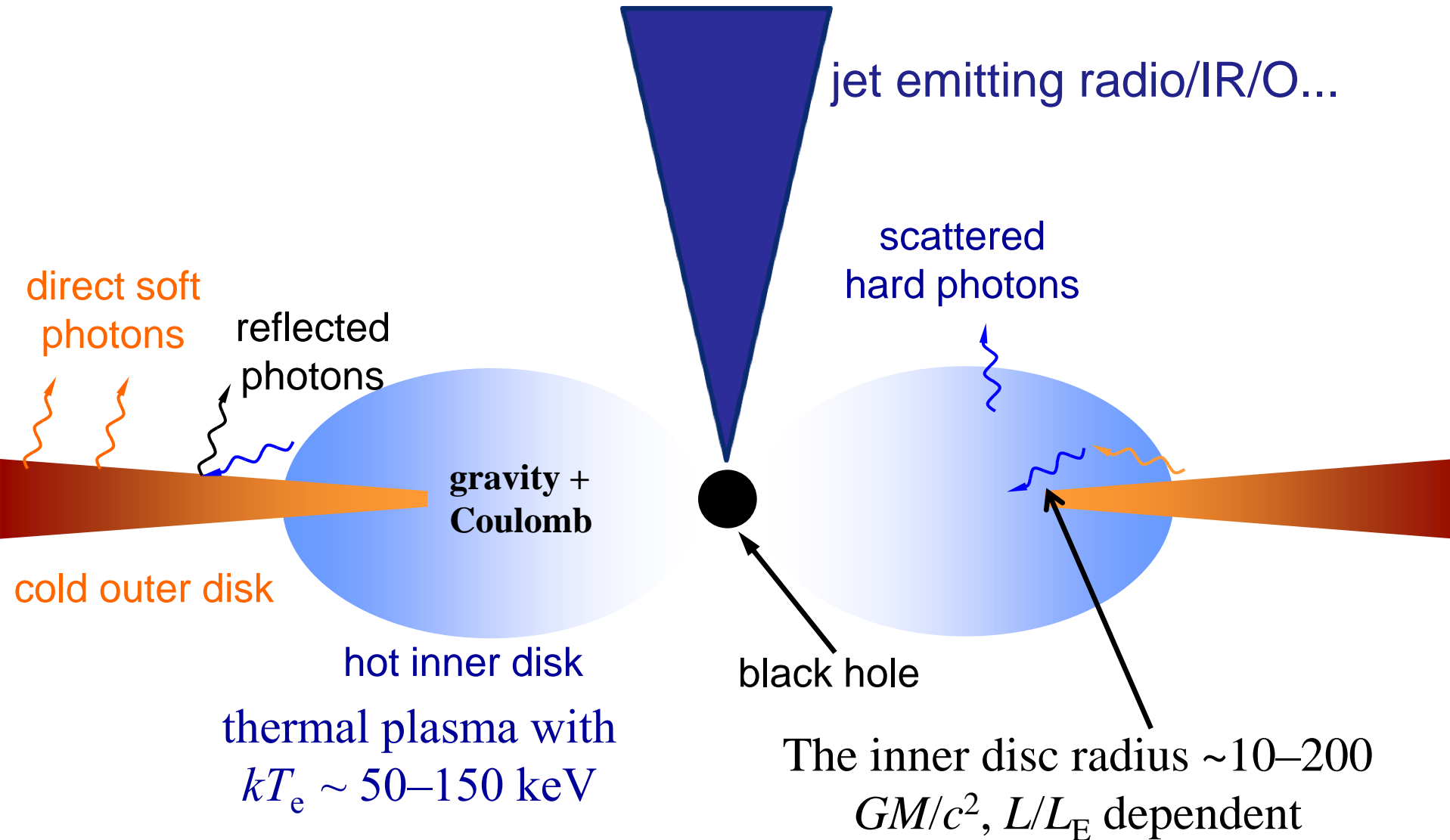# High-energy processes in the jets of accreting binaries

- Jet launching and bulk acceleration close to the BH without dissipation.

- Acceleration of electrons to relativistic energies at large distances, up to millions of gravitational radii.

- Synchrotron and Compton emission; γ-rays from Compton scattering of blackbody photons and synchrotron self-Compton.

- Hadronic processes, e.g., pion production, do not contribute to the observed spectra, as shown, e.g., by the strong orbital modulation of the GeV emission in Cyg X-3 (modelled by Compton scattering of the donor blackbody).

- γ-rays observed so far up to some tens of GeV (except for one transient TeV emission event at a low sigficificance). But TeV emission should be detected by CTA.

Disc/corona geometry of the soft state:

no jet
(except for Cyg X-3)

active region

reflected
photons

gravity

cold accretion disk

black hole

soft seed
photons

scattered
hard photons

The inner disc radius at the
innermost stable orbit

The truncated disc model for the hard state:

jet emitting radio/IR/O...

scattered
hard photons

direct soft
photons

reflected
photons

**gravity +
Coulomb**

cold outer disk

black hole

hot inner disk

thermal plasma with
$kT_e \sim 50$–150 keV

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

What we know:

- Matter accretes through the disc due to the magnetorotational instability (MRI; Balbus & Hawley 1991), which transfers the angular momentum outward. Initially, only some small residual magnetic field is required.

- It works for both hot and cold discs.

- The magnitude of the MRI viscosity depends on the presence of large-scale vertical magnetic field. It its absence, the viscosity parameter is α ≈ 0.01, but with a net field it can increase to α ~ 1 (Bai & Stone 2013).

- Jet formation appears to require the presence of a net vertical field.
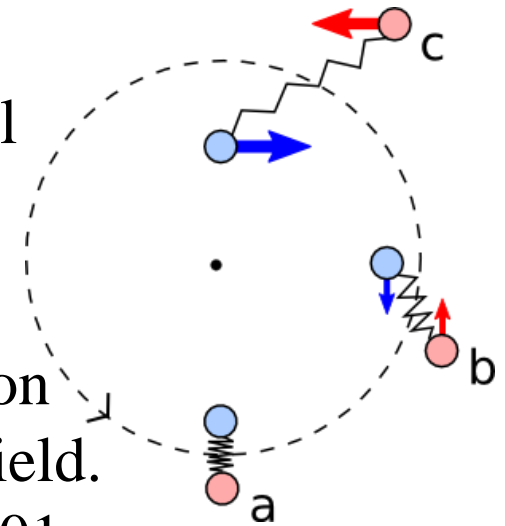
Two possible jet launching mechanisms

- A physically motivated and popular model (e.g., Tchekhovskoy+2011, McKinney+2012) is extraction of the spin energy of a rotating black hole (Blandford & Znajek 1977). $P_{jet} \sim (a/M)^2 B_\perp^2 r_g^2 c$.

- Another mechanism is collimation and acceleration by disc poloidal magnetic field (Blandford & Payne 1982). A lower jet power.
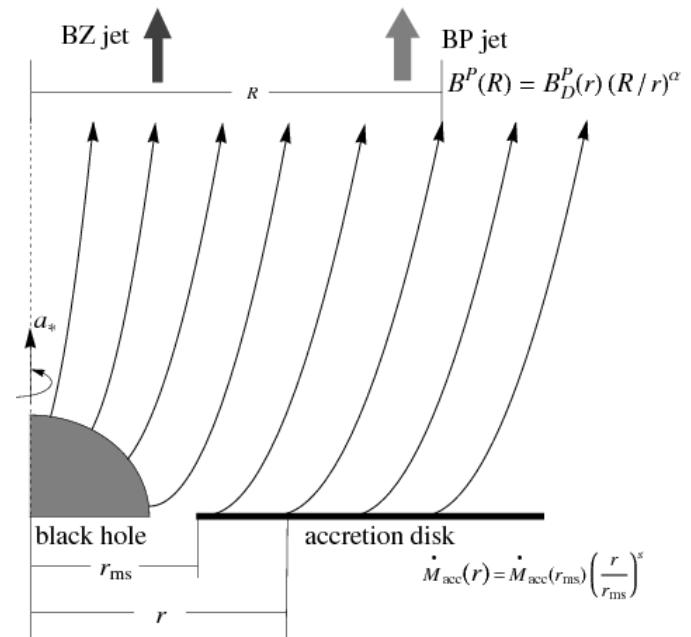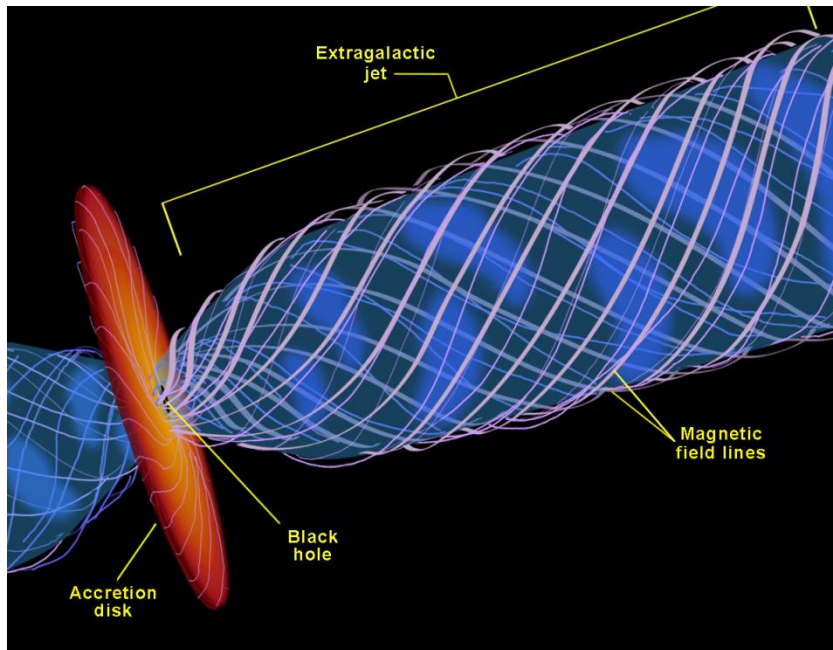
What is the origin of the large-scale field?

- In AGNs, large scale field can be advected from coherent patches of the interstellar medium (e.g., Cao & Lai 2019).

- However, field advection in accreting binaries faces two major problems:
  - jets are present in the hard state but absent in the soft state, while an extended outer cold disc is present in both states. Advection through that disc should be the same in both states.
  - magnetic fields of donors vary strongly while the jet radio emission in various systems is tightly connected to the accretion rate.

- Can a net field be generated locally?

Two proposals to generate net vertical field locally in the hot accretion flow.

- (1) Begelman & Armitage 2014:
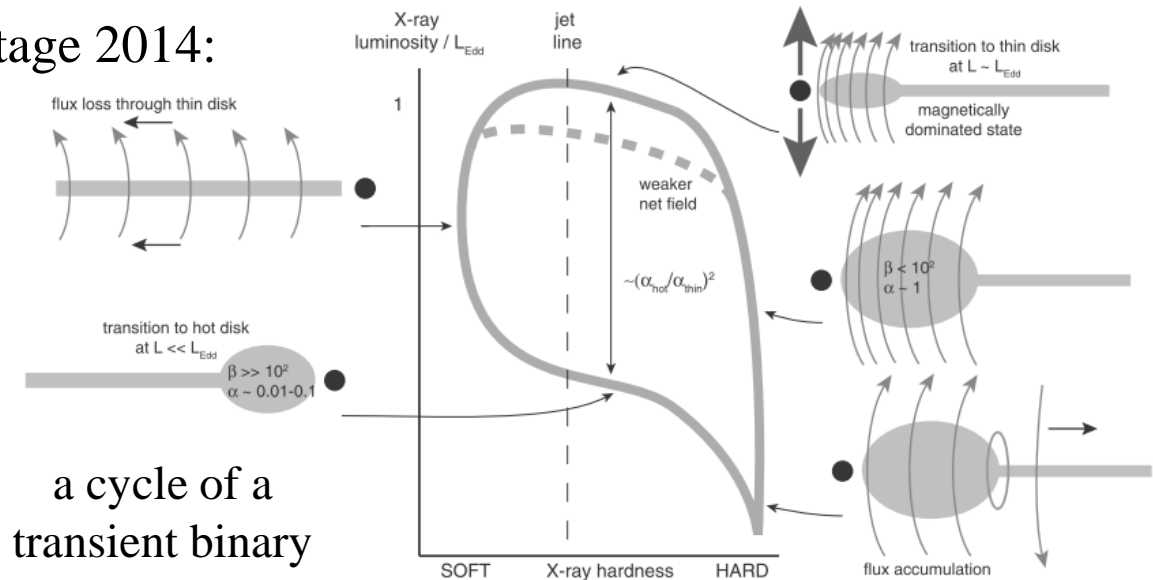
a cycle of a transient binary

- MRI generates closed field loops, also at the boundary of the hot (thick) and cold (thin) parts of the disc. The part of the loop in the cold disc diffuses away while the part in the hot disc is advected inward, which breaks the loop and creates a patch carrying vertical field with a random sign.

- Accumulation of those patches in a random-walk like process leads to a buid-up of some net flux with a given sign during a given occurrence of the hard state.

Generation of net vertical field locally in the hot accretion flow

- (2) Parfrey, Giannios & Beloborodov (2015):

- A somewhat similar process, but the closed magnetic loops open up at the boundary of the accretion flow and the BH horizon due to their different rotation velocity.

- This creates fluctuating vertical fields above and below the BH, which also reconnect, leading to cycles of the energy flux through the BH surface:
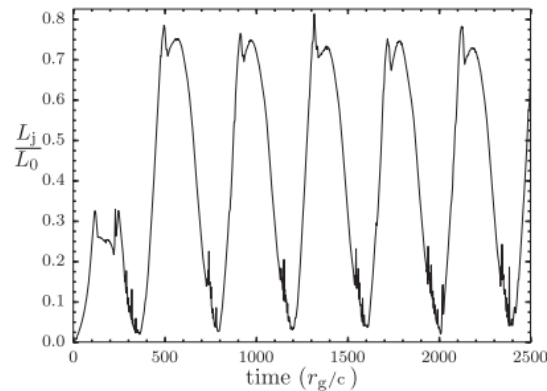
- However, the process is efficient only for retrograde accretion, unlikely for accreting binaries.

Summary

- Accreting BH binaries feature a disc and a jet, of which the jet is the main source of high-energy emission.

- The high-energy jet emission is dominated by Compton upscattering by relativistic electrons accelerated to high energies of some soft photons, either stellar blackbody (in the case of high-mass donors) or synchrotron or both.

- In most of the BH binaries, the jet is present only in the hard spectral state, in which also a hot plasma emitting hard X-rays is present.

- The jet can be formed by net vertical magnetic field connected to either a rotating BH or an inner part of the accretion disc.

- The origin of the net vertical field is unclear; its presence is simply assumed in most of papers.

- Advection from the donor unlikely; some proposals to generate it locally, to be verified.

- A lot of other unknowns not mentioned due to the lack of time; e.g., the jet composition (electron-ions vs. $e^{\pm}$ pairs).