Composition of the jet in the microquasar Cygnus X-1

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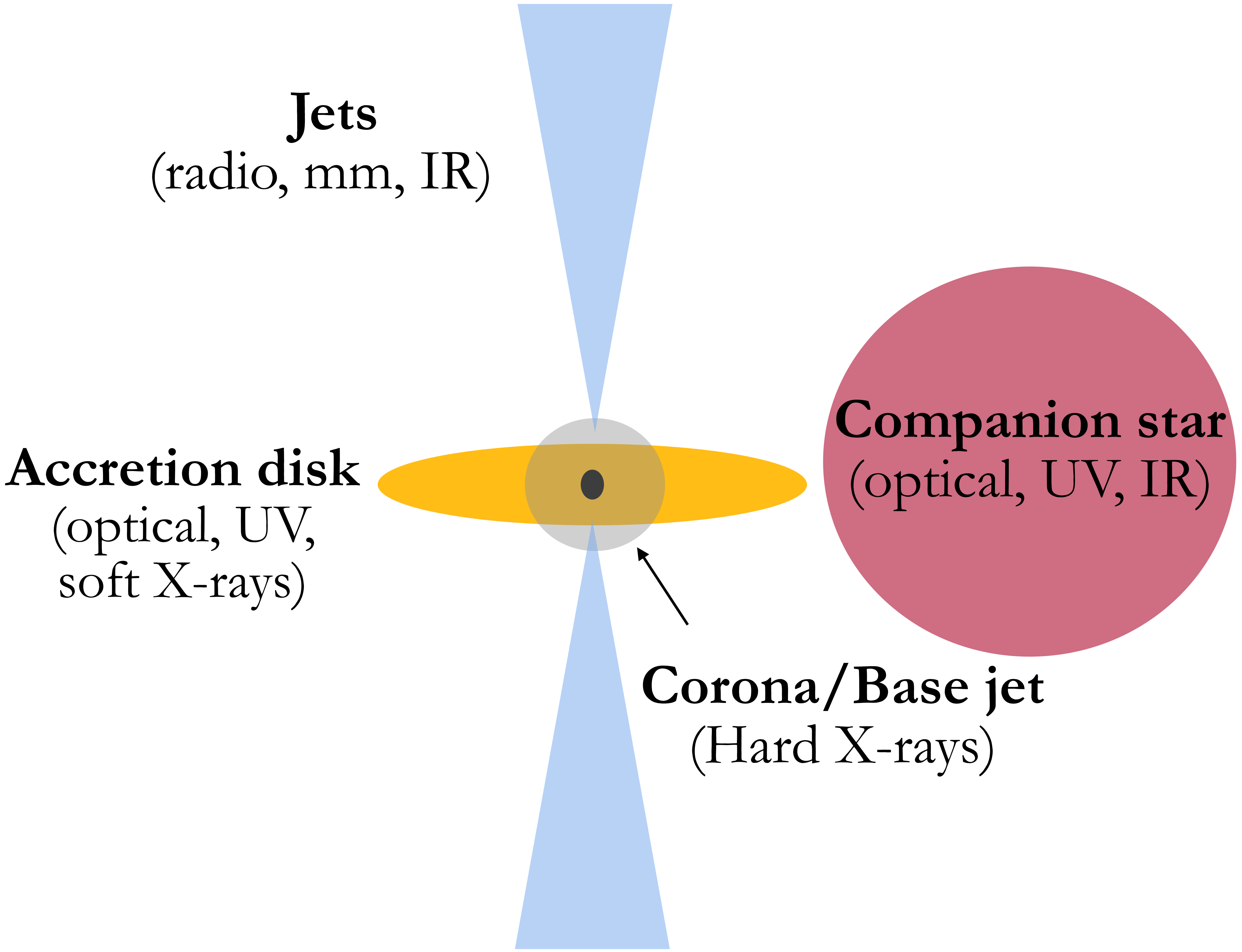
Main open questions about jets

- Astrophysical jets: relativistic and collimated outflows observed on various scales in several types of sources (AGNs, young stellar objects, GRBs and microquasars).
- How the jets are launched ?
- How do they interact with the environment ?
- **What is their composition ?**
- The jet composition should be affected by the physical mechanism responsible for launching the jets (independent constraints on the jet launching mechanism).

=> Focus on the jet composition of Cyg X-1

A simple illustration of a microquasar



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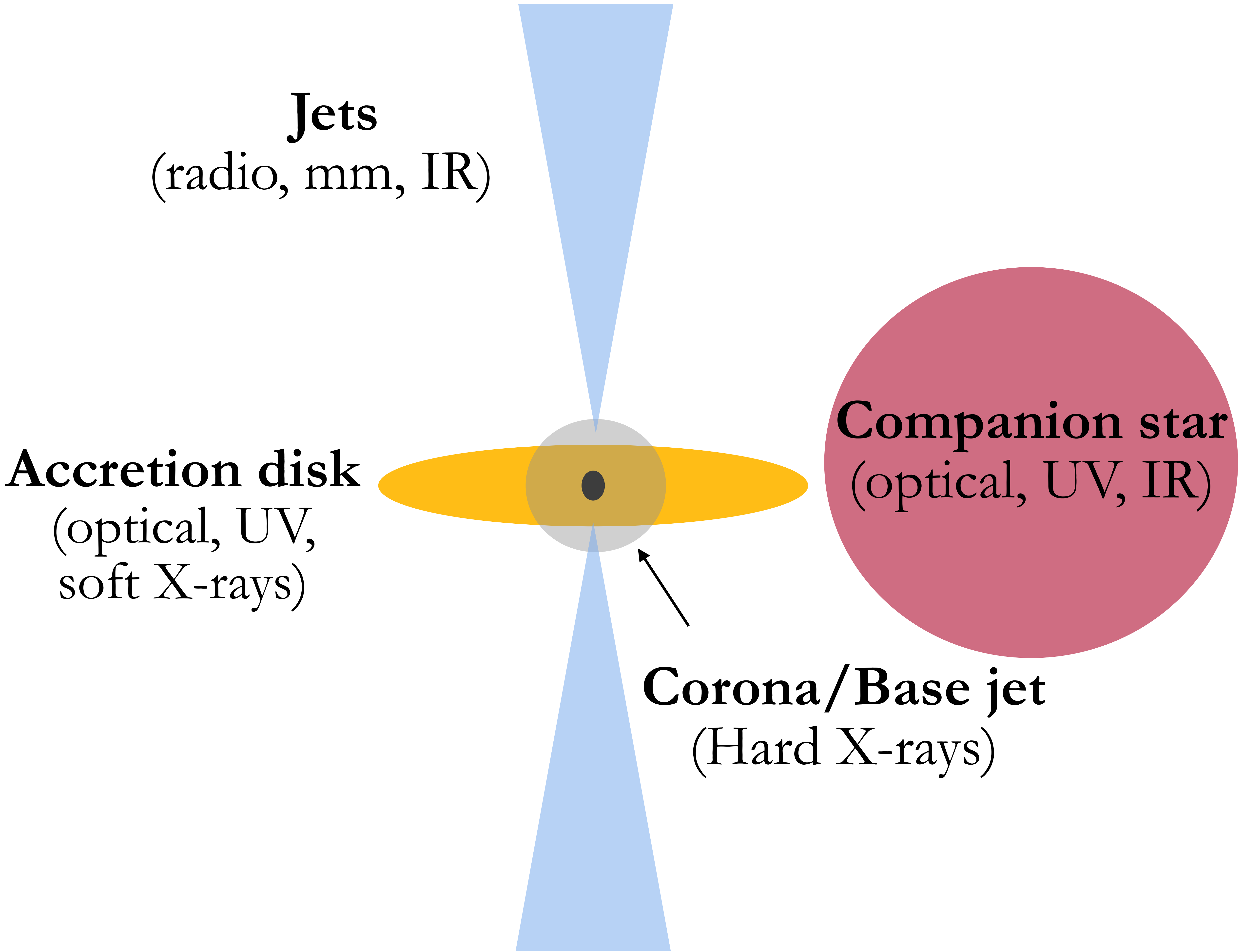

From radio to hard X-ray emission:
Relativistic leptons

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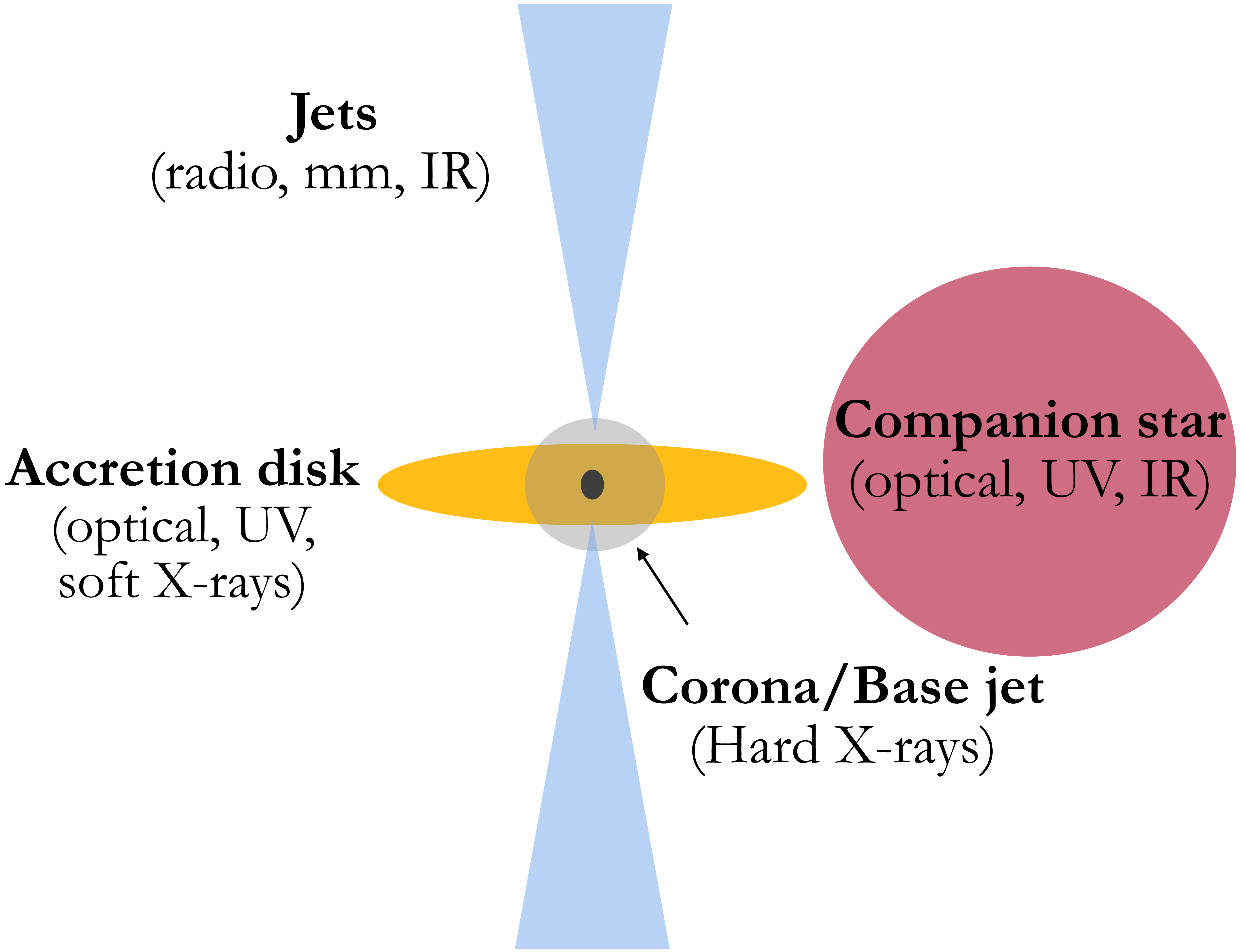


From radio to hard X-ray emission:
Relativistic leptons

What about the gamma-ray emission?
leptonic or hadronic processes?

Jet composition in microquasars

- Emission from radio to GeV γ-rays
- Nature of the matter outflowing in the jet: a long debate.
- **Baryonic plasma** (protons/ions and electrons): emission lines in the jet of HMXB: **SS433** (Fabrika +04) and LMXB: **4U1630-47** (Diaz Trigo +13).
- **Leptonic plasma** (electrons/positrons): responsible for the overall spectrum from radio to γ-rays (Bosch-Ramon +06).
- Both hadronic and leptonic scenarios can explain the **γ-ray emission** in microquasars.

Baryonic plasma

- If microquasar jets can efficiently accelerate hadrons to high energy, they could also be potential Galactic CRs sources (Cooper +20).
- A strong magnetic field is necessary to confines the particles in the acceleration region and provides enough power for particle acceleration.
- Inelastic collisions between relativistic jet protons and cold protons from the stellar wind of the companion star or thermal protons from the jet => produce neutral pions, which decay into **γ-rays and neutrinos** (Romero +03).
- Detection of neutrinos should be the unambiguous confirmation of the hadronic interactions (Aharonian + 06).

Leptonic plasma

- Relativistic e- in the jet lose E due to **synchrotron** (with some loss due to self-absorption) and **Inverse Compton** (low-energy photons from the accretion disk or from the stellar companion) => **from radio to γ-rays**
- Strong hints that extragalactic jets contain substantial numbers of e± pairs (Ghisellini +12; Pjanka +17; Snios +18; Sikora +20; Liodakis +22), but less clear for jets in microquasars.
- Mechanisms producing the e± pairs remain uncertain.
- A viable mechanism is e± pair production within the jet base by **collisions of photons emitted by the hot accretion flow** (e.g., Henri & Pelletier 1991; Beloborodov 1999; Levinson & Rieger 2011; Sikora +20).

Cygnus X-1

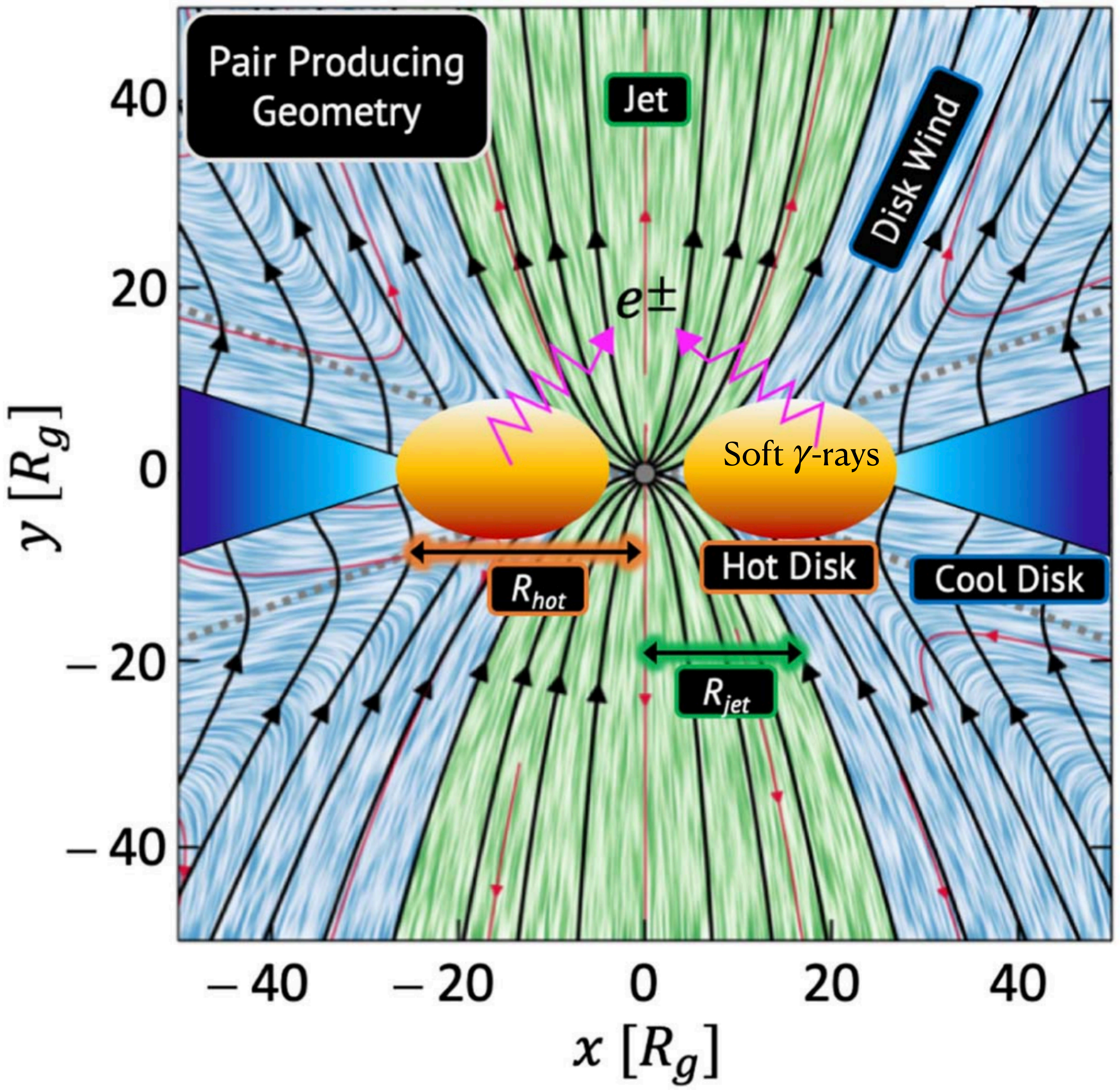
- The most studied microquasar (discovered in 1964).
- $M_{\mathrm{BH}} \approx 21 \pm 2\, M_\odot$ + supergiant donor $M_1 \approx 41 \pm 7\, M_\odot$ (Miller-Jones +21)
- Clumpy stellar wind (see Lai's talk!)
- Distance: $D \approx 2.2 \pm 0.2\,\mathrm{kpc}$
- Inclination: $i \approx 27.5^{\circ}{}^{+0.8}_{-0.6}$ or $\gtrsim 45°$ (IXPE: Krawczynski +22)
- Radio to GeV emission (Albert +07, Sabatini +10, Zanin +16)
- The origin of the γ-ray emission is still debated.

Jet composition in Cygnus X-1: leptonic ?

Based on the paper: Zdziarski & Egron, ApJ, 2022

- Hard X-ray spectral state: persistent, mildly relativistic radio-emitting jet
- Study of the abundance of $e^{\pm}$ pairs at the jet base (based on the average soft γ-ray spectrum)
- Estimate of the flow rate of leptons emitting the observed synchrotron radio-to-IR spectrum of the jet
- Comparison of the flow rate of leptons through the jet with the pair production rate

Pair-production at the base of the jet



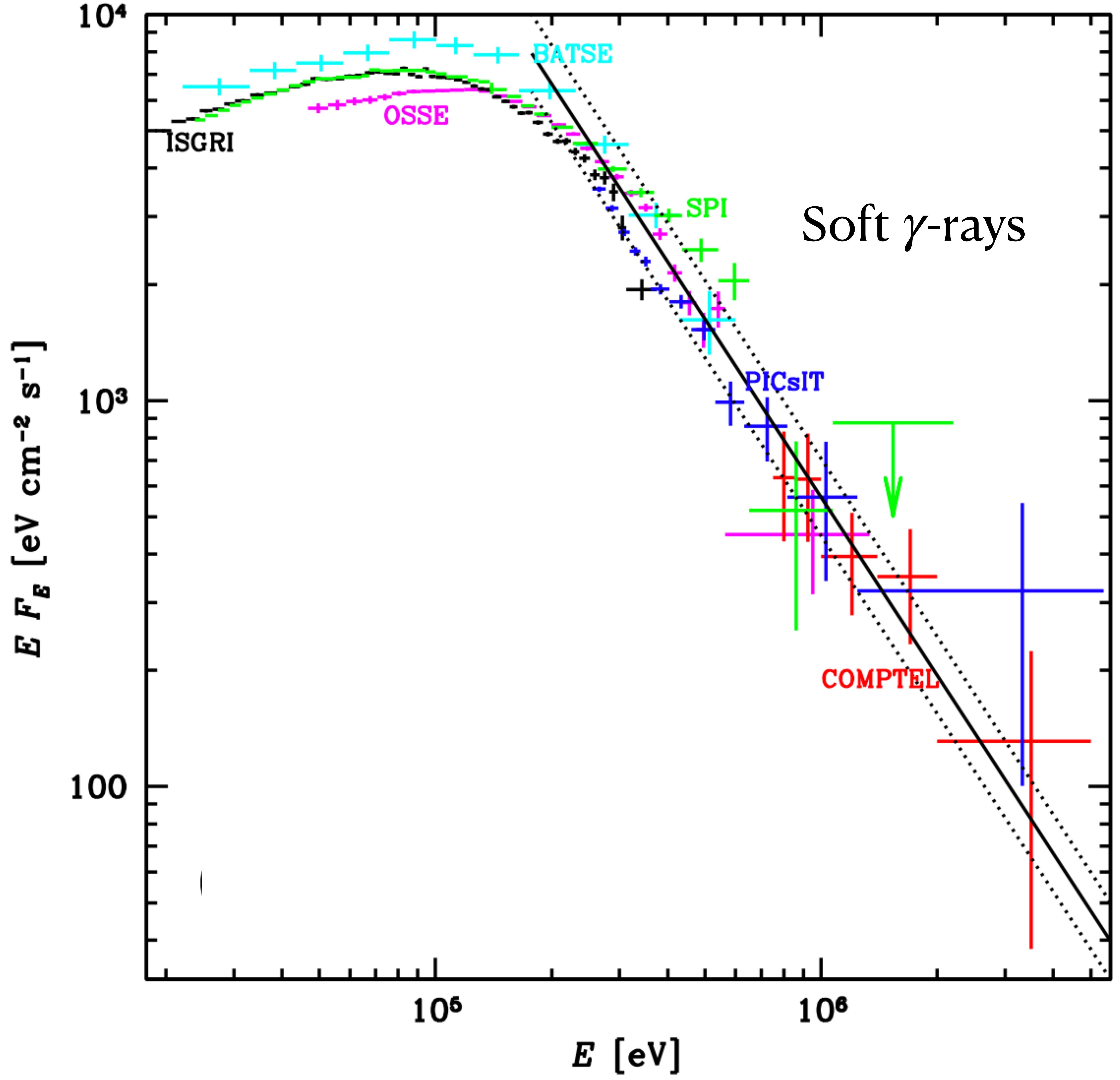
A possible mechanism is pair production at the jet base by **photon–photon collisions from its hot accretion flow:**

$$\gamma + \gamma \rightarrow e^+ + e^-$$

=> estimate the photon density within the jet base

Figure based on Tchekhovskoy (2015)

Pair-production at the base of the jet



Hard X-ray to soft γ-ray average spectra measured by Compton Gamma Ray Observatory and INTEGRAL.

Above 200 keV: power law approximation with a spectral index α_X and normalization at 511 keV of EF_E

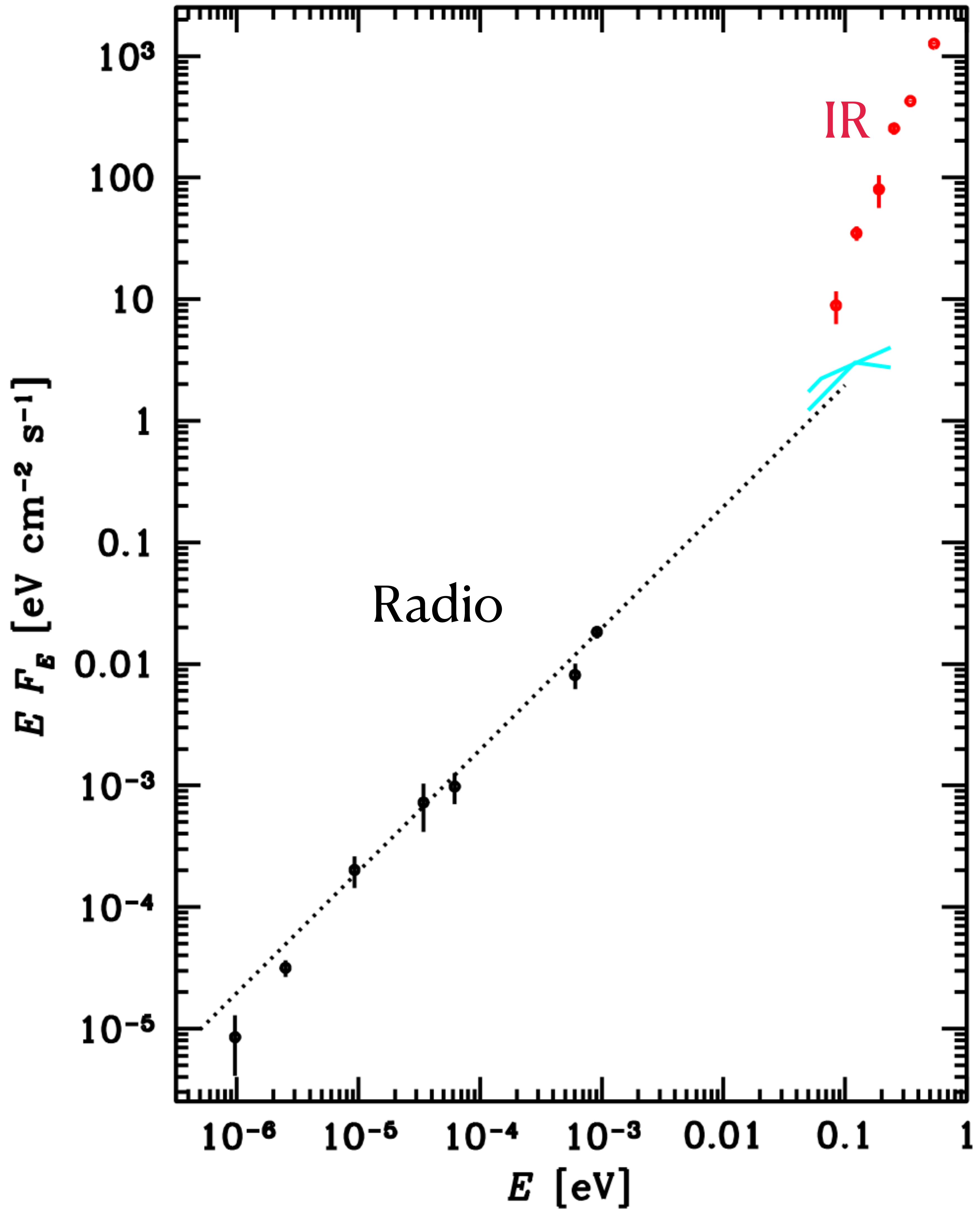
Rate of pair production by photons with such power law:

$$2\dot{N}_{+} \approx 3^{+2}_{-1} \times 10^{40} \left(\frac{R_{\rm hot}}{10R_{\rm g}}\right)^{-3} \left(\frac{R_{\rm jet}}{10R_{\rm g}}\right)^{2} {\rm s}^{-1}$$

with $R_{\rm hot}$ and $R_{\rm jet}$: radii of the hot accretion flow and the jet

(Svensson 1987 and Zdziarski +22)

Lepton rate emitting the synchrotron emission



Flat radio-to-IR spectrum in the hard state:

Radio 2–221 GHz : power-law fit with α = 0 with $F_\nu \propto \nu^\alpha$ and Fν = 13 mJy (Fender et al. 2000).

=> Jet emission: partially synchrotron self-absorbed.

=> Flow rate of non-thermal relativistic electrons emitting the synchrotron emission (Blandford & Königl 1979):

$$\dot{N}_e \approx 6.4 \times 10^{39} \beta_{eq}^{0.47} \left(\frac{\Gamma}{2.6}\right)^{2.7} \left(\frac{\Theta}{1^\circ}\right)^{0.74} \left(\frac{\gamma_{min}}{3}\right)^{-1.5} s^{-1}$$

with Beta eq: energy density of the relativistic e- equal to that of the magnetic field; Γ: jet bulk Lorentz factor; Θ: opening angle (Tetarenko et al. 2019)

Conclusions

- We calculated the e± pair production rate at the base of the jet of Cyg X-1 by collisions of photons from its hot accretion flow.
- The rate approximately equals the flow rate of the leptons emitting the observed synchrotron radio-to-IR spectrum of the jet
- Pair production in the jet base appears to be capable of providing enough leptons responsible for the jet synchrotron emission far away from the BH.
- This coincidence indicates the **jet composition can be e± pair dominated** (as in the microquasar MAXI J1820+070 and the radio galaxy 3C 120 - Zdziarski +22).
- The detection of Cyg X–1 from HAWC, and especially from **CTA** or LHAASO would exclude the possibility of purely leptonic jets since only the hadronic model is capable of producing significant TeV emission