Effects of radiation cooling in the internal shock model for the multi-wavelength emission of jets from X-ray binaries

Julien Malzac

With help from Alessio Marino, Carlotta Miceli, Renaud Belmont, Alexandre Marcowith, Pierre-Olivier Petrucci,
Poshak Gandhi, Federico Vincentelli, Melania del Santo, Dave &Tom Russell…

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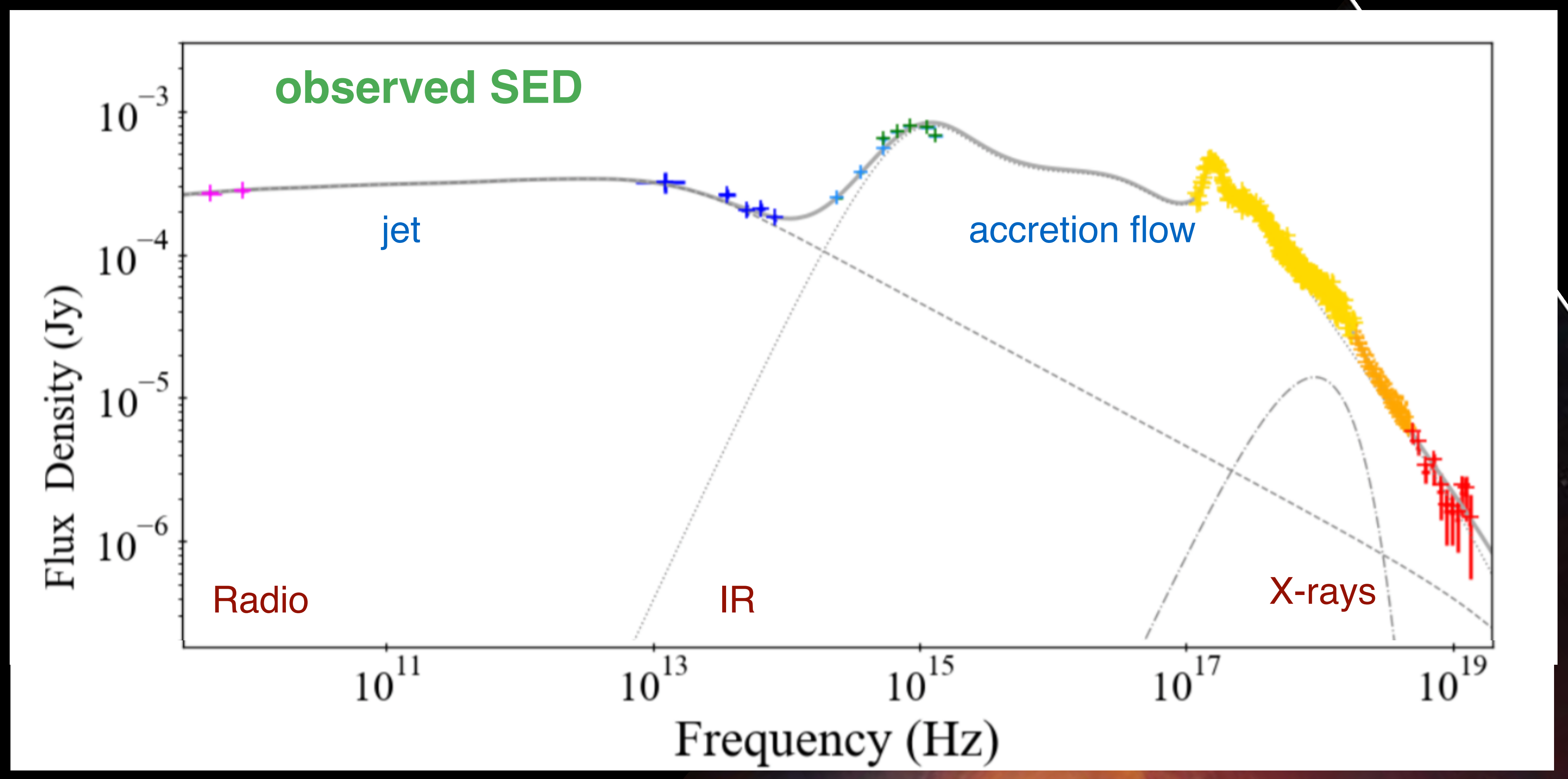
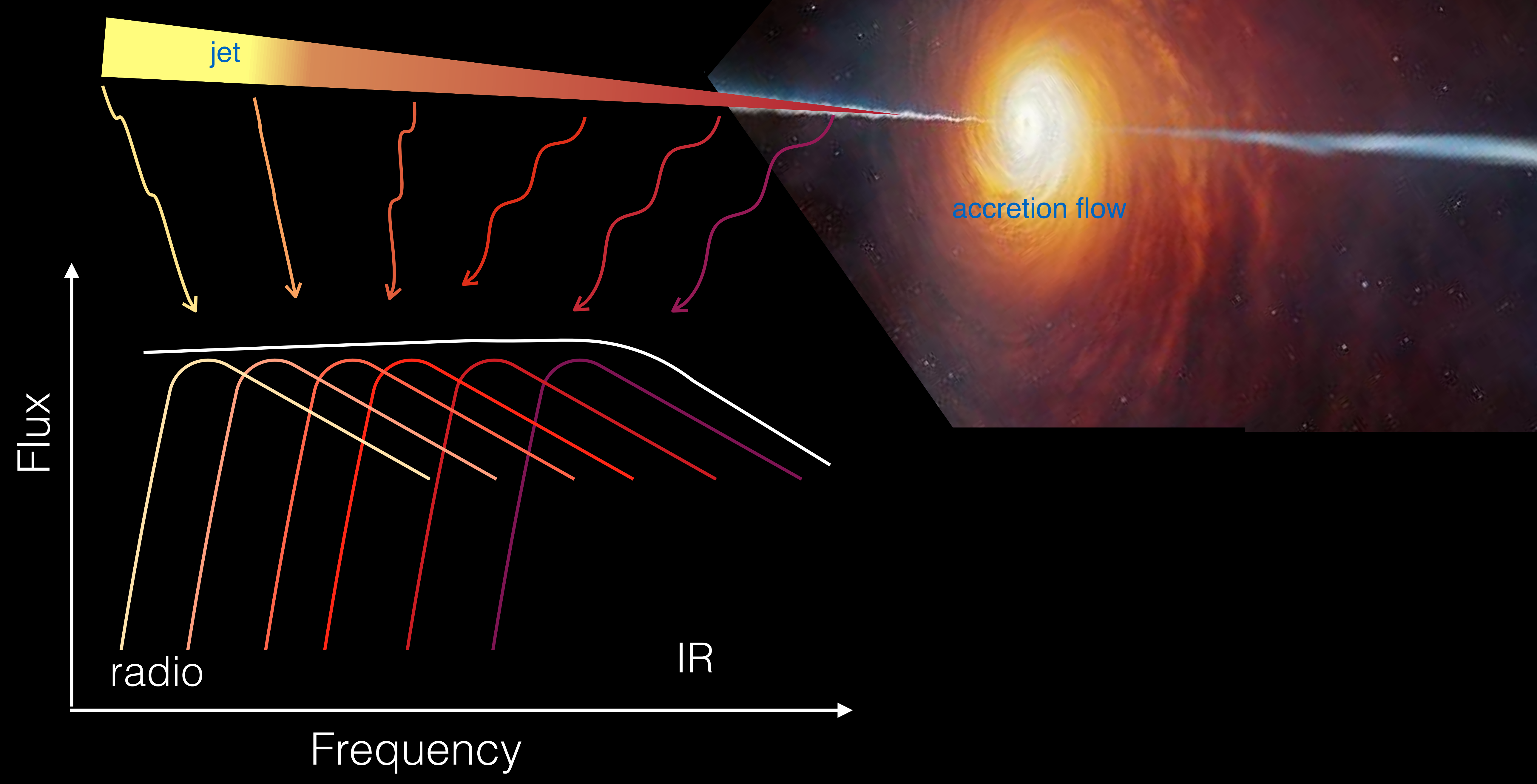
The problem of dissipation in compact jets of X-ray binaries

- Standard conical jet model

synchrotron from populations of relativitic leptons distributed along the jets (Blandford & Koenigl 1979)





The problem of dissipation in compact jets of X-ray binaries

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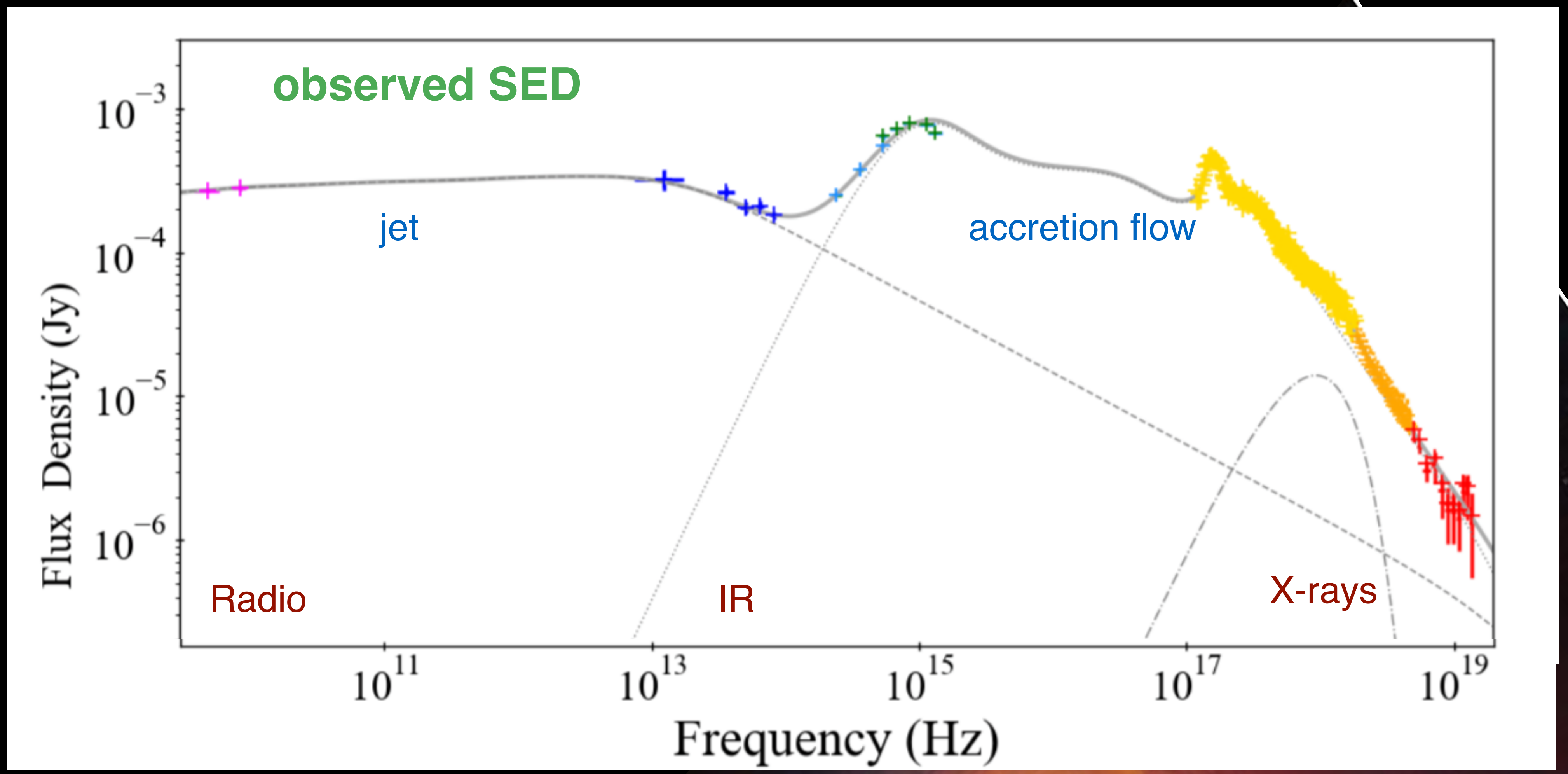
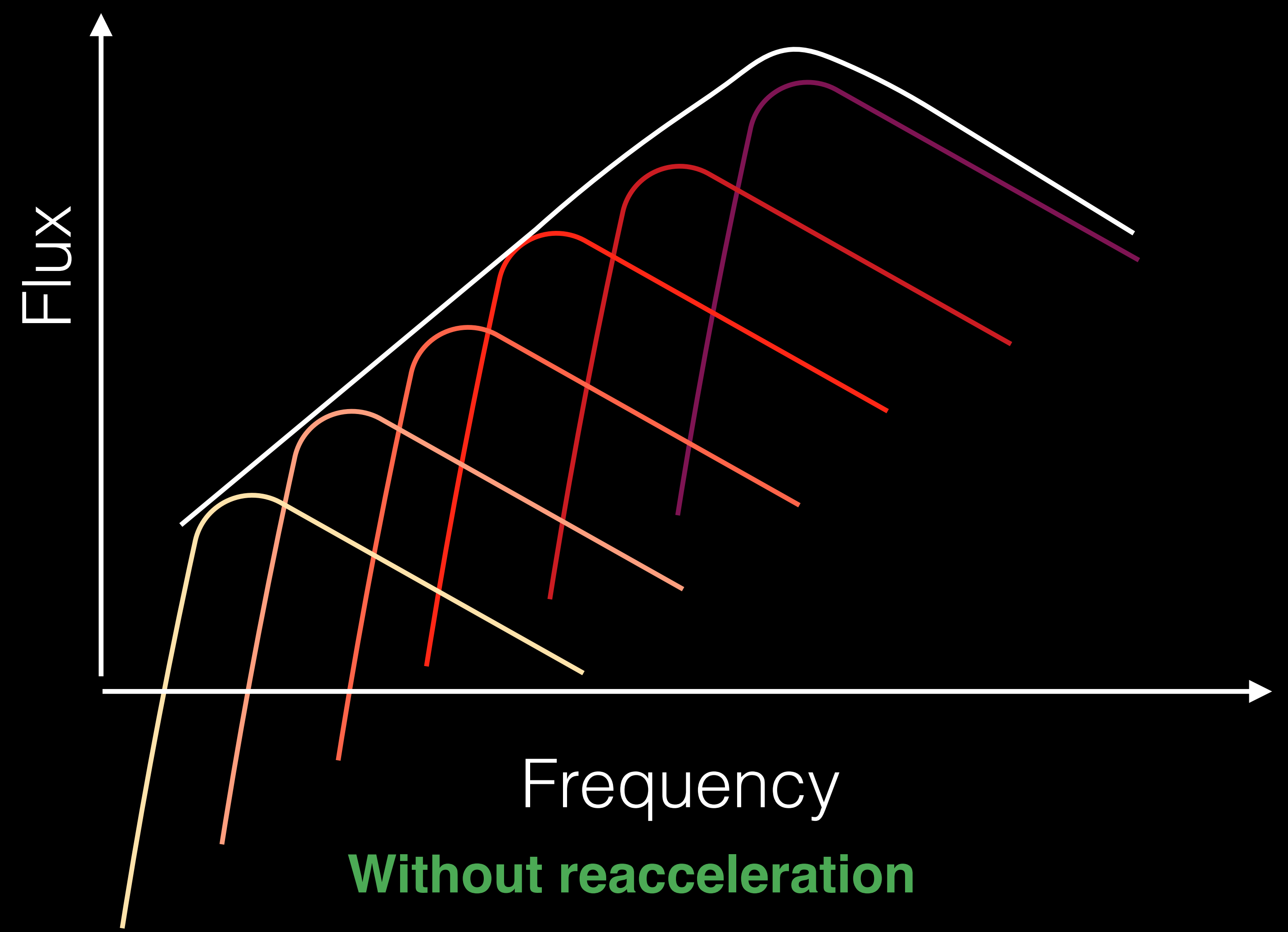
  synchrotron from populations of relativitic leptons distributed along the jets (Blandford & Koenigl 1979)

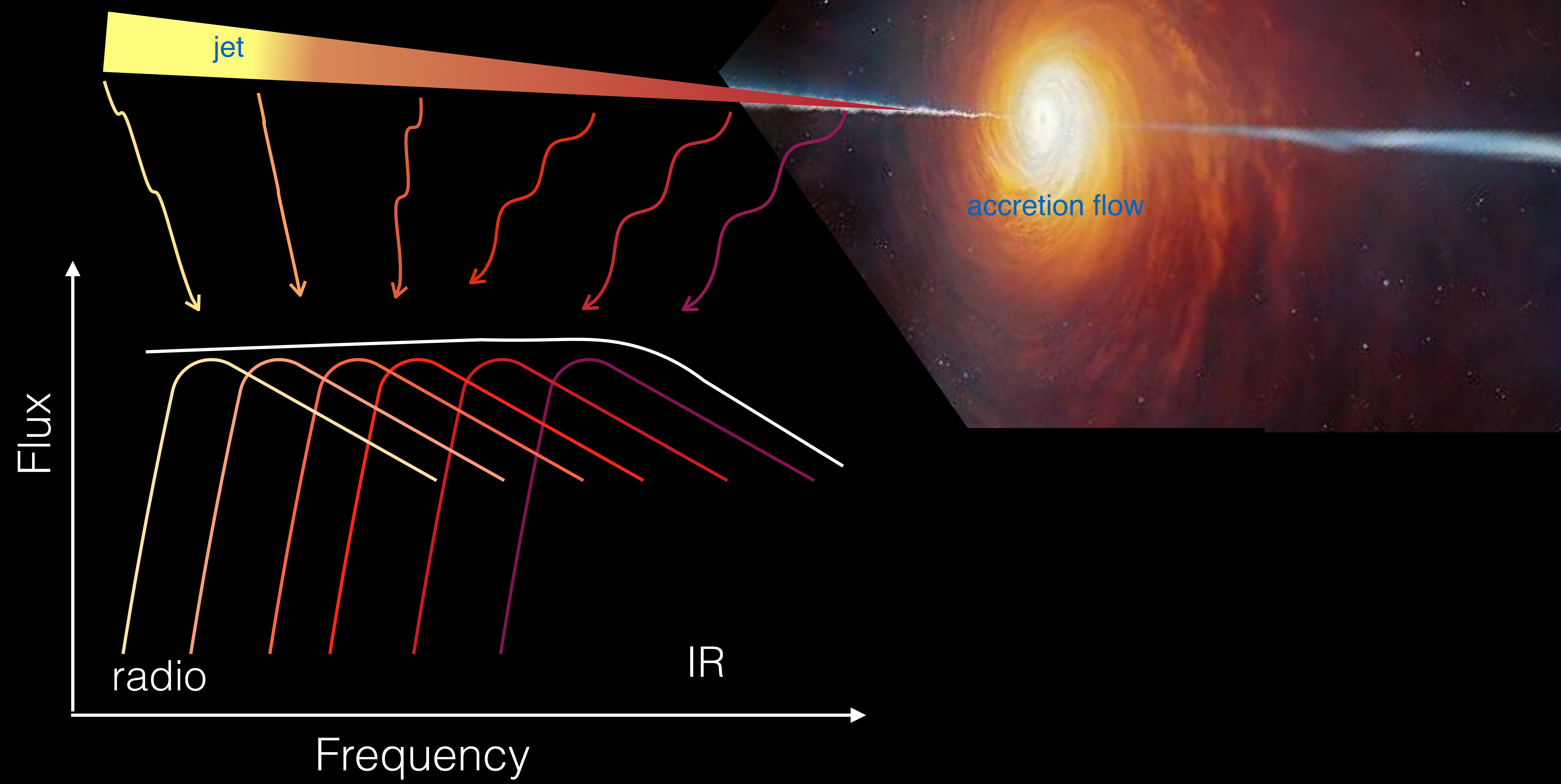
- Rapid cooling of leptons by expansion

  ⇒ resulting spectra are too inverted





Without reacceleration



➡ Reacceleration of leptons along the jet

➡ Dissipation/re-acceleration mechanism required

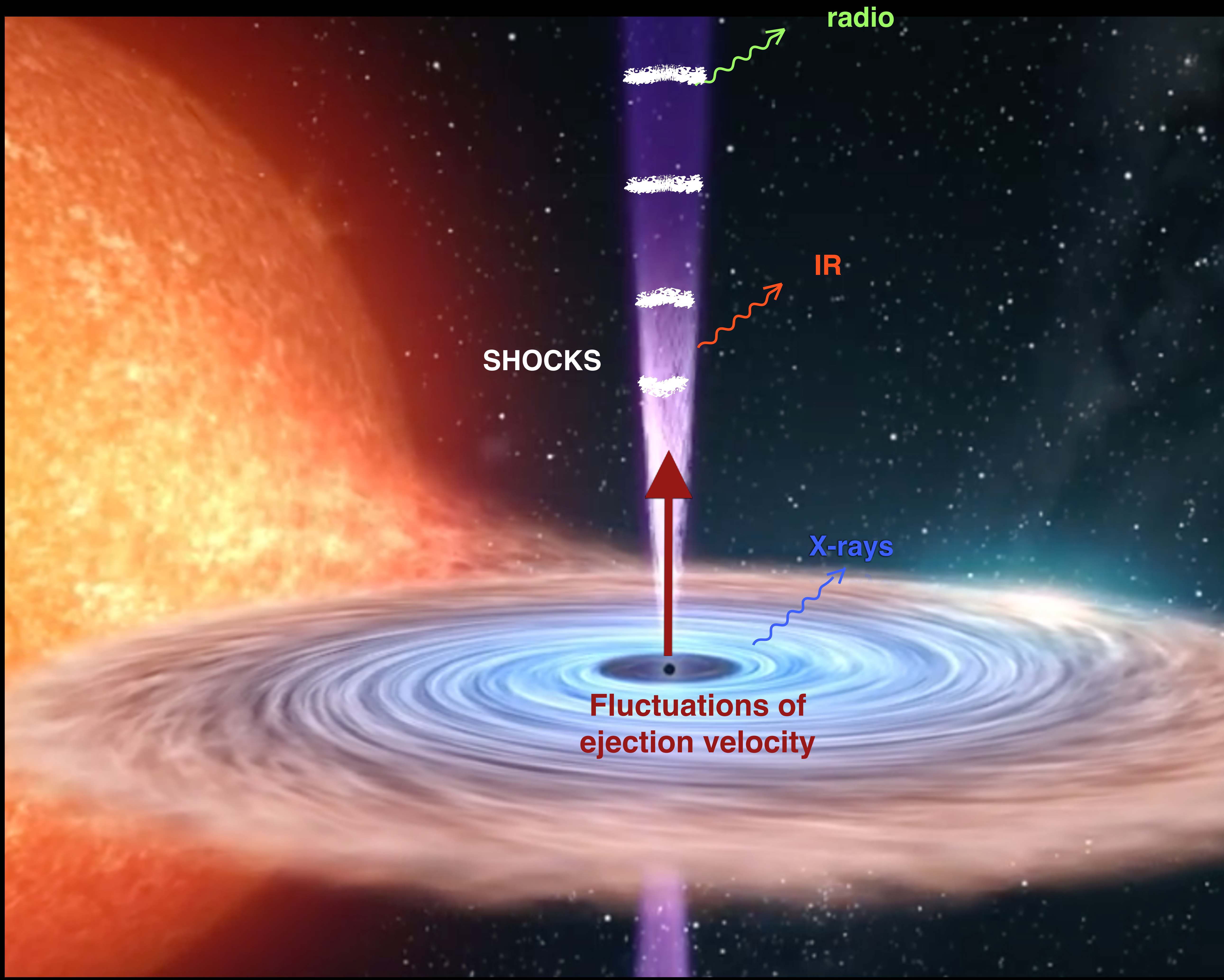
ISHEM: an internal shock model

- Jet= ‘shells‘ ejected a time intervals ~ tdyn with randomly variable Lorentz factors
- Faster shells catch up will slower shells and collide
- Shocks, particle acceleration, and emission of synchrotron radiation
- Hierarchical merging process

Jamil et al. 2010; Malzac 2013

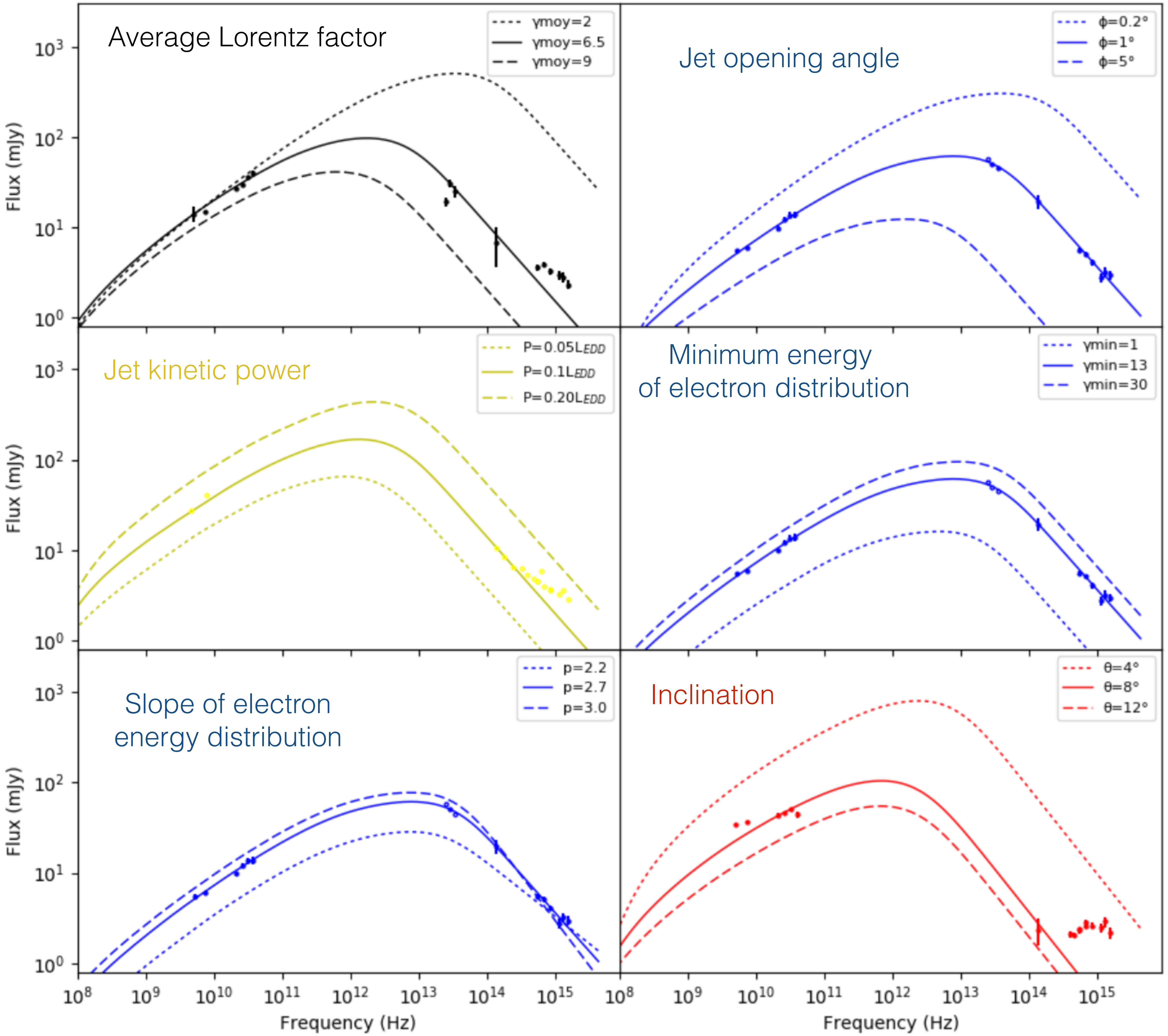
➡ ISHEM code: simulate SEDs and light curves

➡ Results depend mostly on Fourrier power spectrum of velocity fluctuations.



Malzac 2013,2014

Effects of parameters on SED



➡SED shape depends only on PSD of fluctuations

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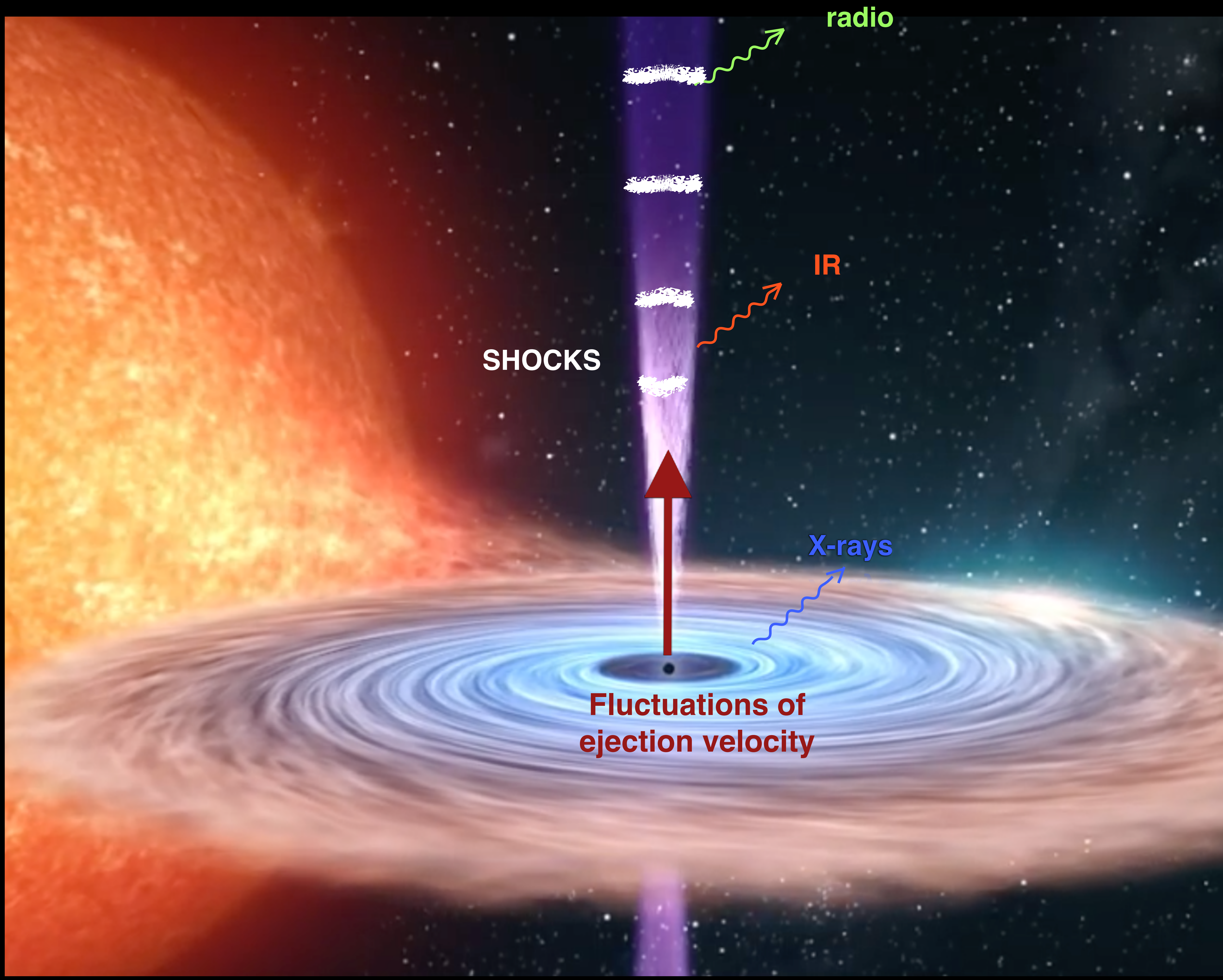

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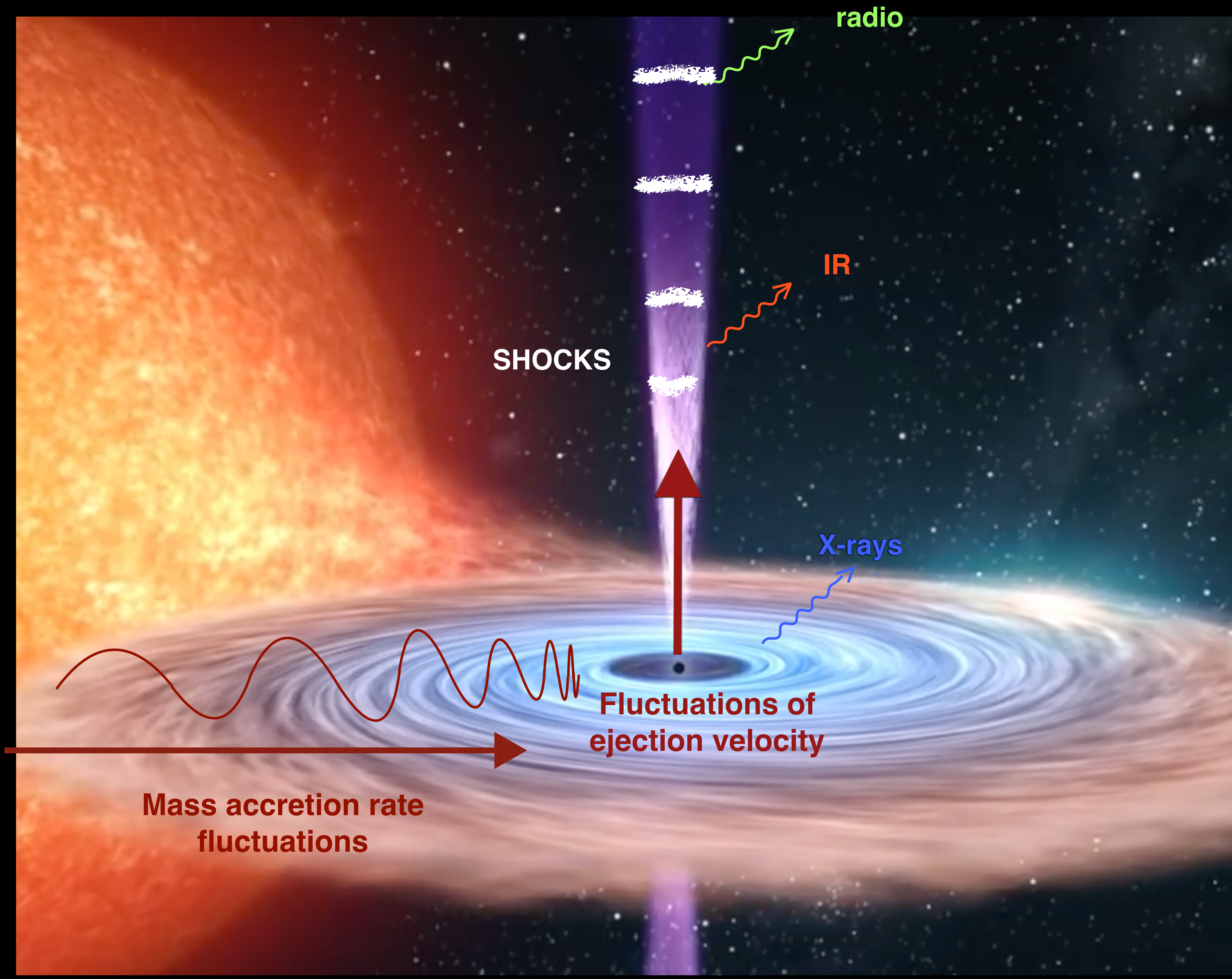
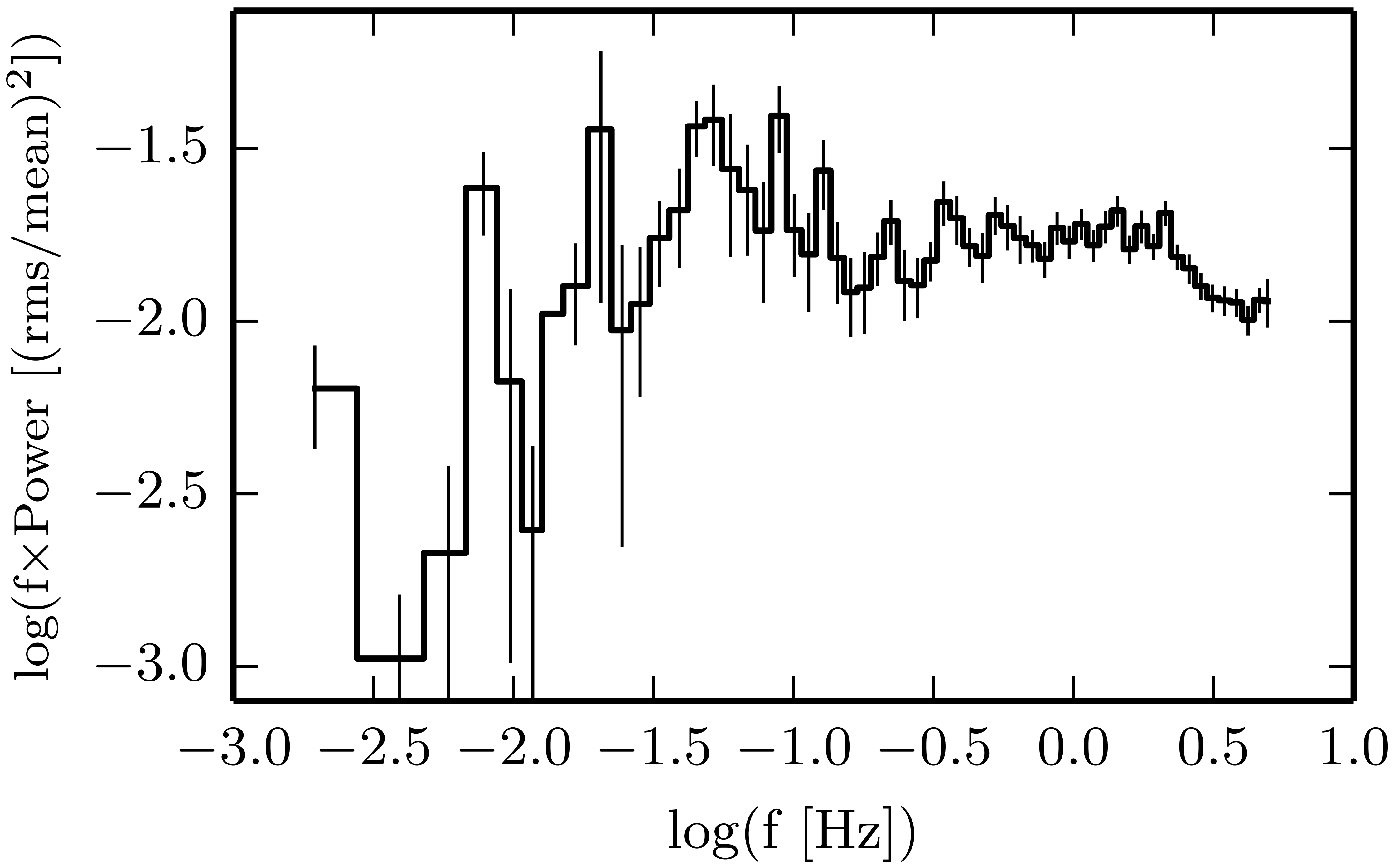


Malzac 2013,2014

- Fluctuations of jet velocities driven by the accretion flow variability ?

- Jet Lorentz factor fluctuations driven by accretion flow variability (traced by X-ray light curves)

Fourier PDS of X-ray light curve
=
Power spectrum of Lorentz factor fluctuations



Drappeau, et al. MNRAS, 2015;
Data from Gandhi et al. 2011

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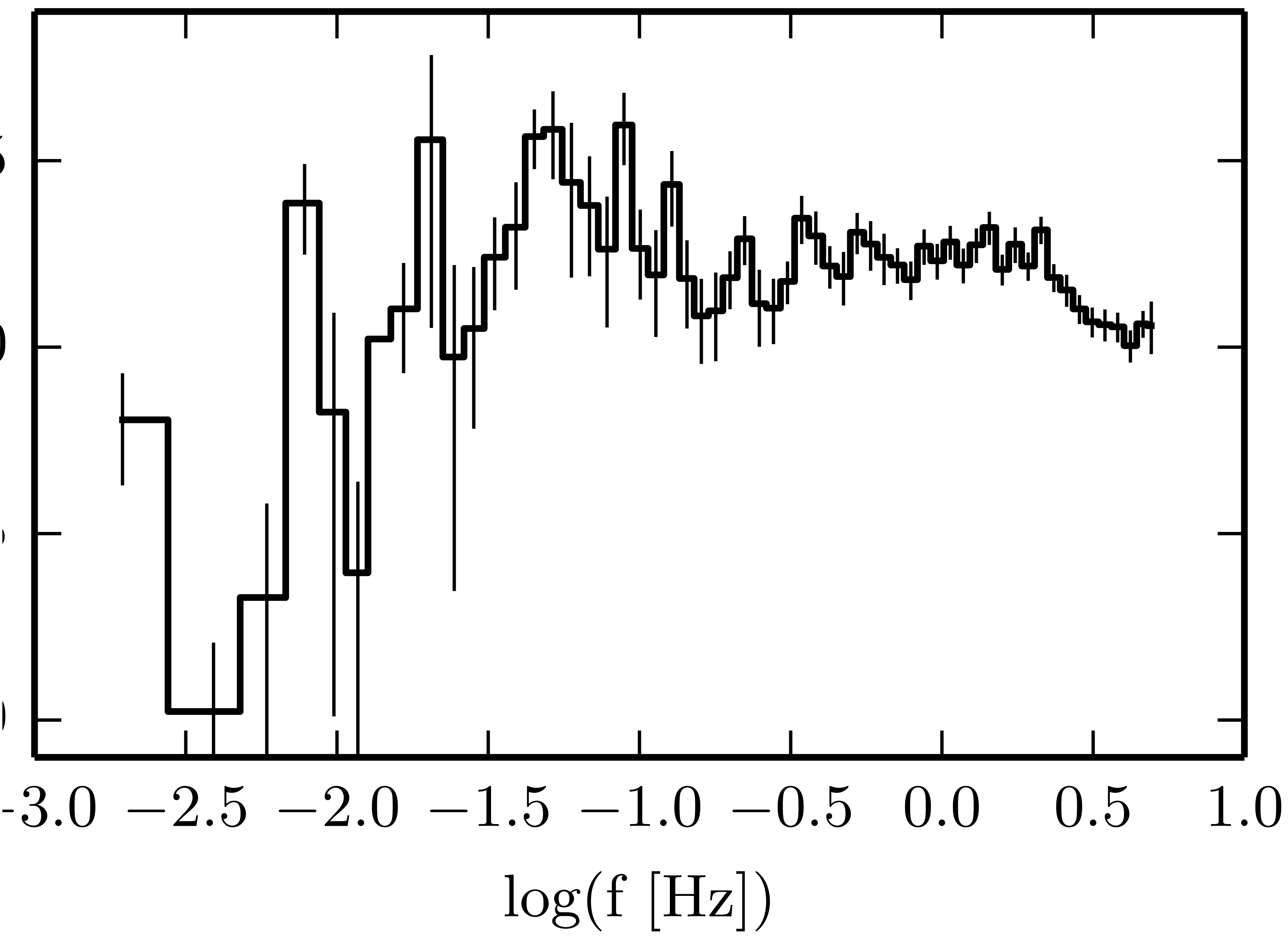
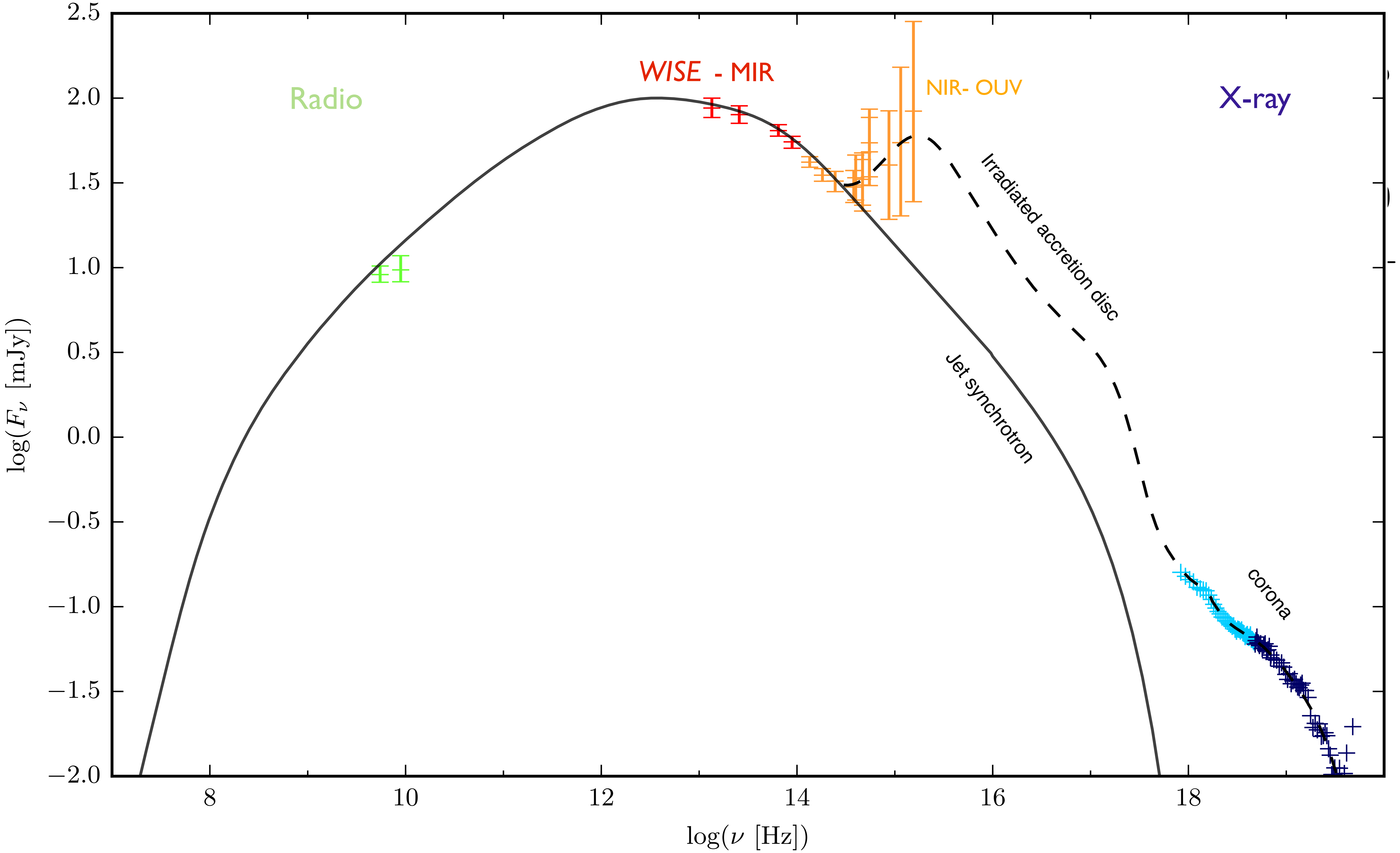




Jet SED

Drappeau, et al. MNRAS, 2015;
Data from Gandhi et al. 2011

Limitations of ISHEM

- Radiation losses neglected (no particle cooling due to emission of radiation)
- No inverse Compton emission
- Lepton energy distribution is fixed (power-law), no emission from thermal particles

➡ **CoolShem: resolution of kinetic equations**

- Assume shock acceleration injects a power-law energy distribution of leptons
- Determine evolution of particle energy distribution in shocked shells under effects of
    - injection of accelerated particles
    - adiabatic expansion cooling
    - Synchrotron Self Compton cooling (and heating through absorption)

Shell geometry

Homogeneous expanding cylinder

$$z = z_0 + \Gamma\beta ct,$$

$$R = R_0 + \Gamma\beta ct\tan\phi,$$

$$\tilde{H} = \tilde{H}_0 + 2\tilde{\beta}ct, \quad V = \pi R^2\tilde{H}$$

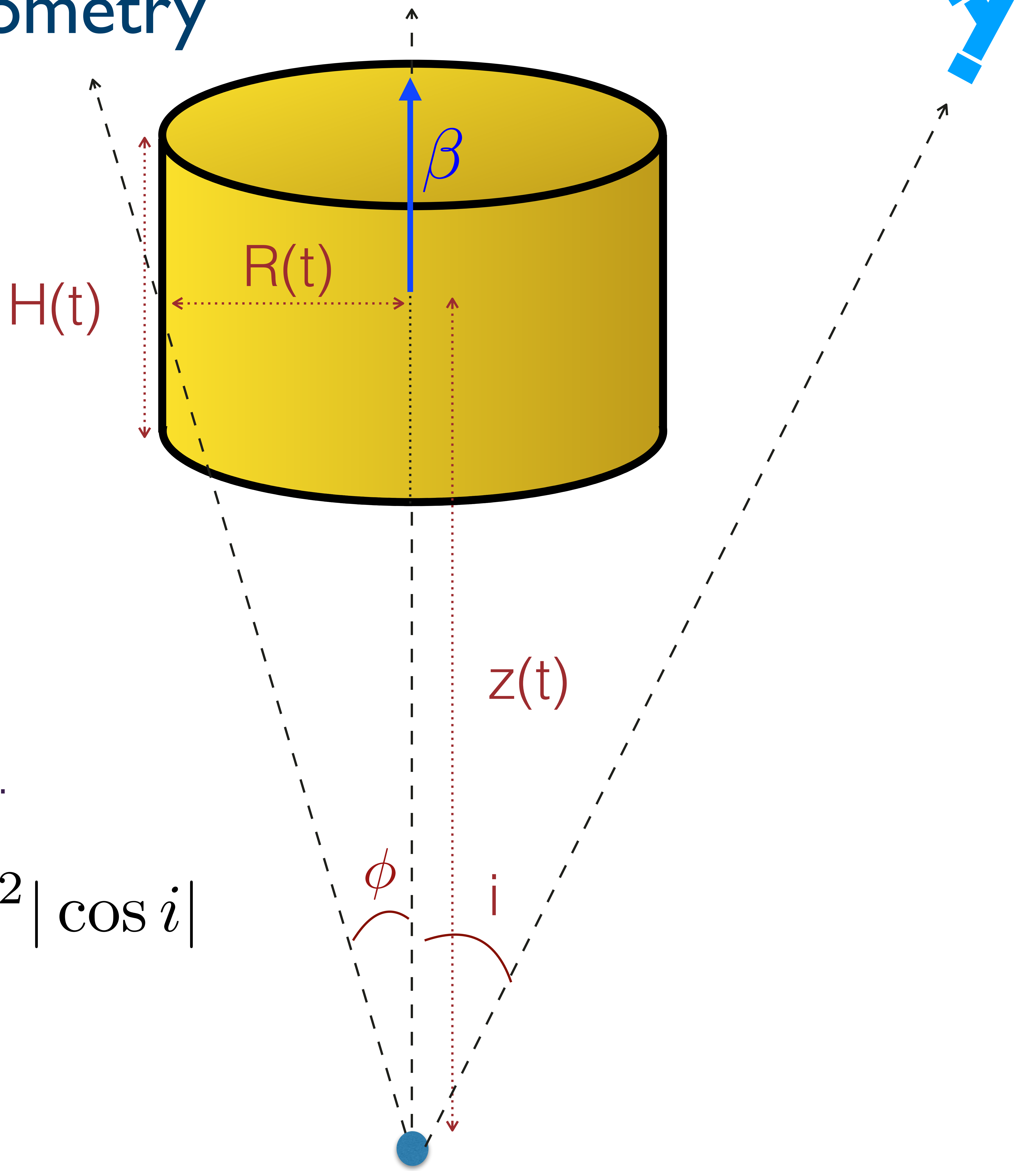
↑

Longitudinal expansion/compression velocity

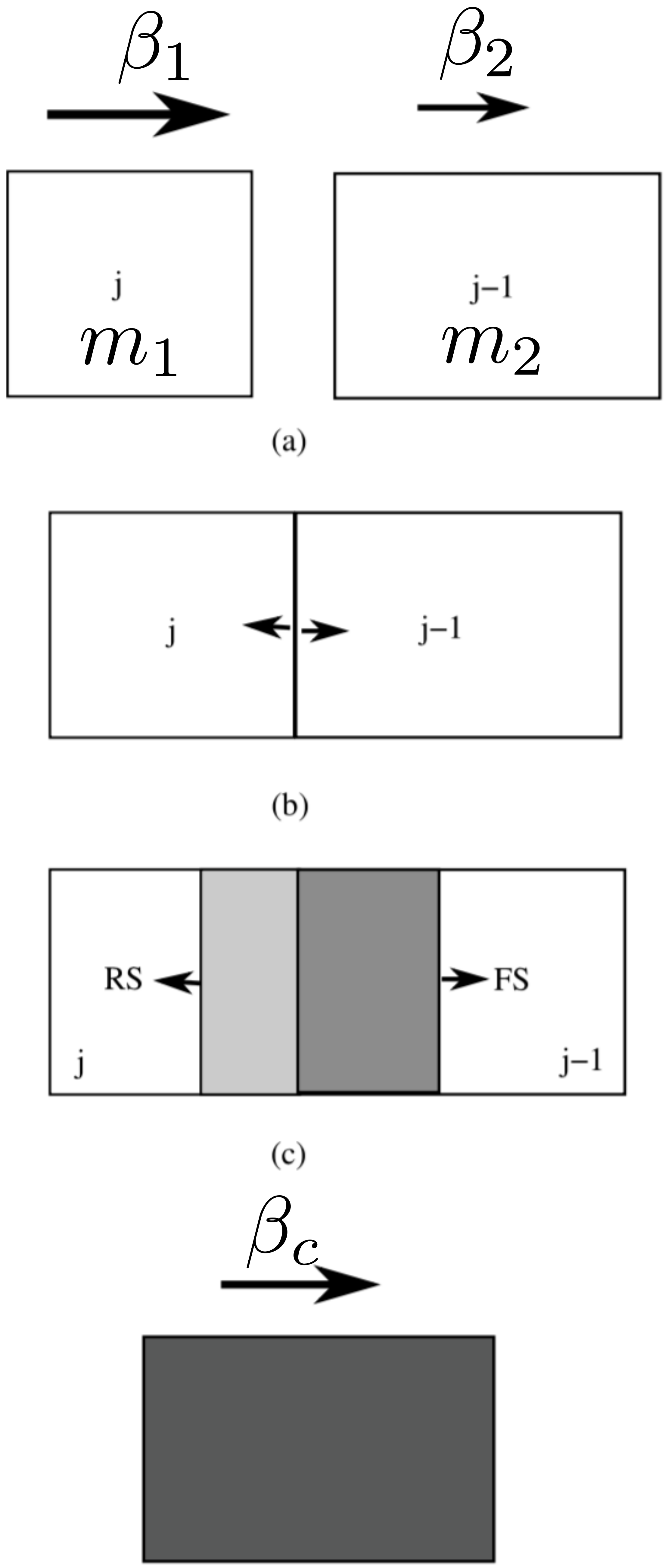
Observed with an inclination i in comoving frame.

Projected area: $$A_\perp = 2R\tilde{H}\sin i + \pi R^2|\cos i|$$

Mean geometrical 'depth' : $$\langle l\rangle = \frac{V}{A_\perp}$$



Shell collisions



(a)

(b)

(c)

(d)

Energy dissipated during collision:

$$E_{s,i} = (\gamma_1 m_1 + \gamma_2 m_2)c^2 - \gamma_c (m_1 + m_2)c^2.$$

$$\gamma_c = \frac{m_1\gamma_1 + m_2\gamma_2}{\sqrt{m_1^2 + m_2^2 + 2m_1m_2\gamma_1\gamma_2\,(1-\beta_1\beta_2)}}$$

Reverse and forward shock front velocities
estimated from jump conditions
of Blandford & Mc Kee (1978)

Shock crossing times —> dissipation time t_{dis}

During this duration, we assume dissipation occurs at a constant rate: $P_T = E_{s,i}/t_{dis}$

After t_{dis} , dissipation stops.

In practice, other collisions with other shells may happen during t_{dis}

Evolution of magnetic field energy in shocked shell

A fraction χ of the shock power is used to grow magnetic energy ϵ at a rate $\dot{\epsilon} = \chi P_{\rm T}$

$$\frac{d\epsilon}{dt} = \dot{\epsilon} - \underbrace{\frac{2}{3}\frac{\epsilon}{R}\frac{dR}{dt}}$$

Magnetic pressure work against external medium as shell expands

$$dW = PdV = \frac{\epsilon}{3}\frac{dV}{V} \simeq \frac{2\epsilon}{3}\frac{dR}{R}$$

(longitudinal expansion losses neglected)

Solution for conical expansion:

$$\epsilon = \left[\frac{3}{5}\dot{\epsilon}\tau_d(x^{5/3} - 1) + \epsilon_0\right] x^{-2/3}$$

$$\tau_d = \frac{z_0}{\Gamma\beta c}$$

$$x = \frac{R}{R_0} = \frac{z}{z_0} = 1 + \frac{t}{\tau_d}$$

$$B = \sqrt{8\pi\epsilon/V}$$

Evolution of lepton energy distribution in a shocked shell

Solving the kinetic equation for $N(\gamma, t)$ in the one zone approximation

$$\partial_t N = \partial_\gamma \left[\dot{\gamma}_c N + H(\gamma, t) \gamma p \, \partial_\gamma \frac{N}{\gamma p} \right] + S(\gamma, t),$$

Cooling rate
(adiabatic expansion +
Synchrotron
self-Compton emission)

$$\dot{\gamma}_c \simeq \frac{\gamma}{\tau_a(t)} + \frac{\gamma^2}{\tau_r(t)}$$

Synchrotron
self-absorption

$$H = \frac{4\pi}{2me^2c^2} \int_0^{+\infty} d\nu \frac{J_\nu(\nu, t)}{\nu^2} j_s(\gamma)$$

Acceleration
(power-law prescription
consistent with available
acceleration power)

$$S = K_0(t) \gamma^{-s}$$

for

$$\gamma_{\max}(t) > \gamma > \gamma_{\min}(t)$$

Using numerical scheme by Chang & Cooper 1970 (fully implicit)

Evolution of radiation field

Solving the kinetic equation for radiative energy in the one zone approximation

$$\partial_t U(\nu, \mu, t) = J_{\rm ssc}(\nu, t) - A(\nu, \mu, t) U(\nu, \mu, t),$$

Radiation energy at photon frequency ν travelling in direction

$\mu = \cos i$

Synchrotron $[B(t), N(\gamma, t)]$
+Compton $[U, N(\gamma, t)\ ]$
emissivities

$$A = \alpha_\nu c + c/\langle l \rangle$$

Synchrotron absorption
$B(t), N(\gamma, t)$

Photon escape
μ, t

For a 'small' time step evaluate : $U(t+\Delta) = \frac{J_{\rm ssc}}{A}\left[1 - e^{-A\Delta}\right] + U(t) e^{-A\Delta}$

Use this to solve lepton kinetic equation for $N(t+\Delta)$, re-evaluate $U(t+\Delta)$ …

…iterate until convergence

Observable radiation

Flux received at a large distance D:

$$F(\mu_\mathrm{o}, \nu_o, t_\mathrm{o}) = \frac{\delta^3}{D^2}\frac{c}{\langle l\rangle}U(\nu, \mu, t)$$

$$\delta = [\Gamma(1-\mu_o\beta)]^{-1}, \quad \nu = \nu_o/\delta, \quad t = \delta t_o, \quad \mu = \frac{\mu_o - \beta}{1-\mu_o\beta}$$

Convolution with green function accounting for light crossing time delays:

$$F_{s\nu}(t_r) = \int_{t_0}^{t_1} F(t')g_l(t', t_r)dt'.$$

The code provides an average of the flux over specified exposure times $\Delta_r = t_f - t_i$

$$\bar{F}_\nu = \int_{t_i}^{t_f} \frac{F_{s\nu}}{\Delta_r}dt_r$$

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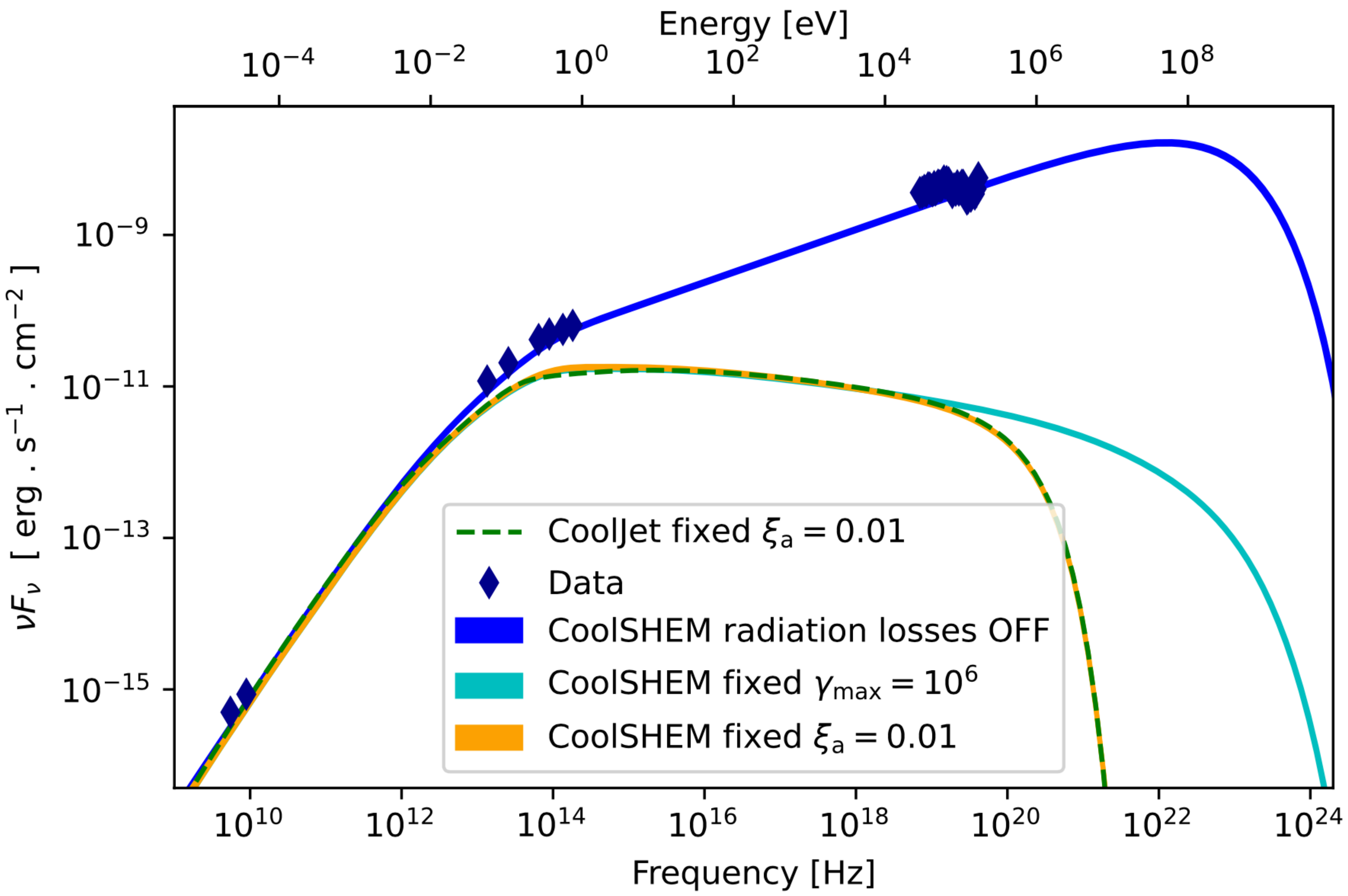
➡ Time consuming calculations

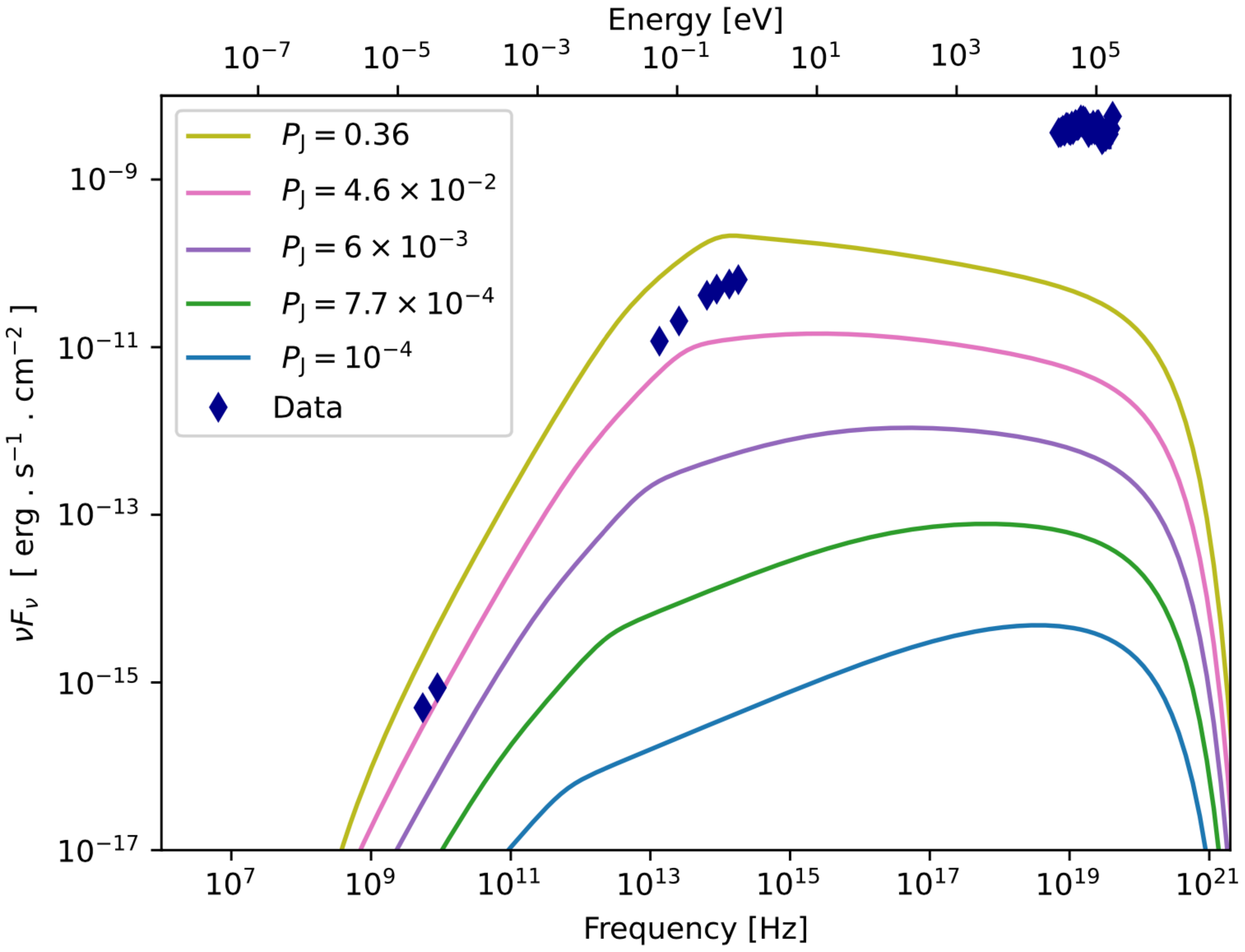
➡ CoolJet: uses time averaged dissipation along jet to calculate SEDs

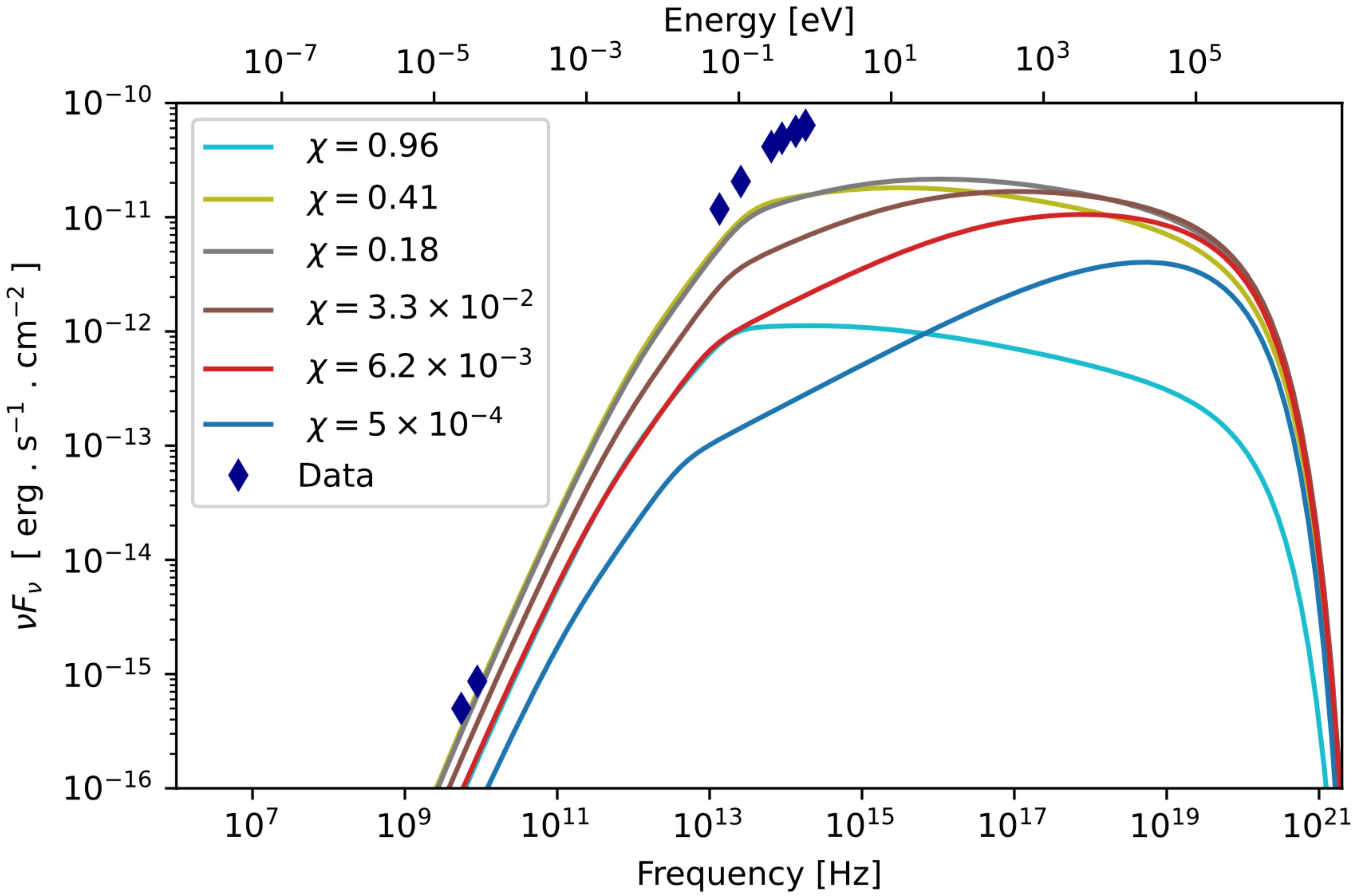
➡ much faster, modest loss of accuracy

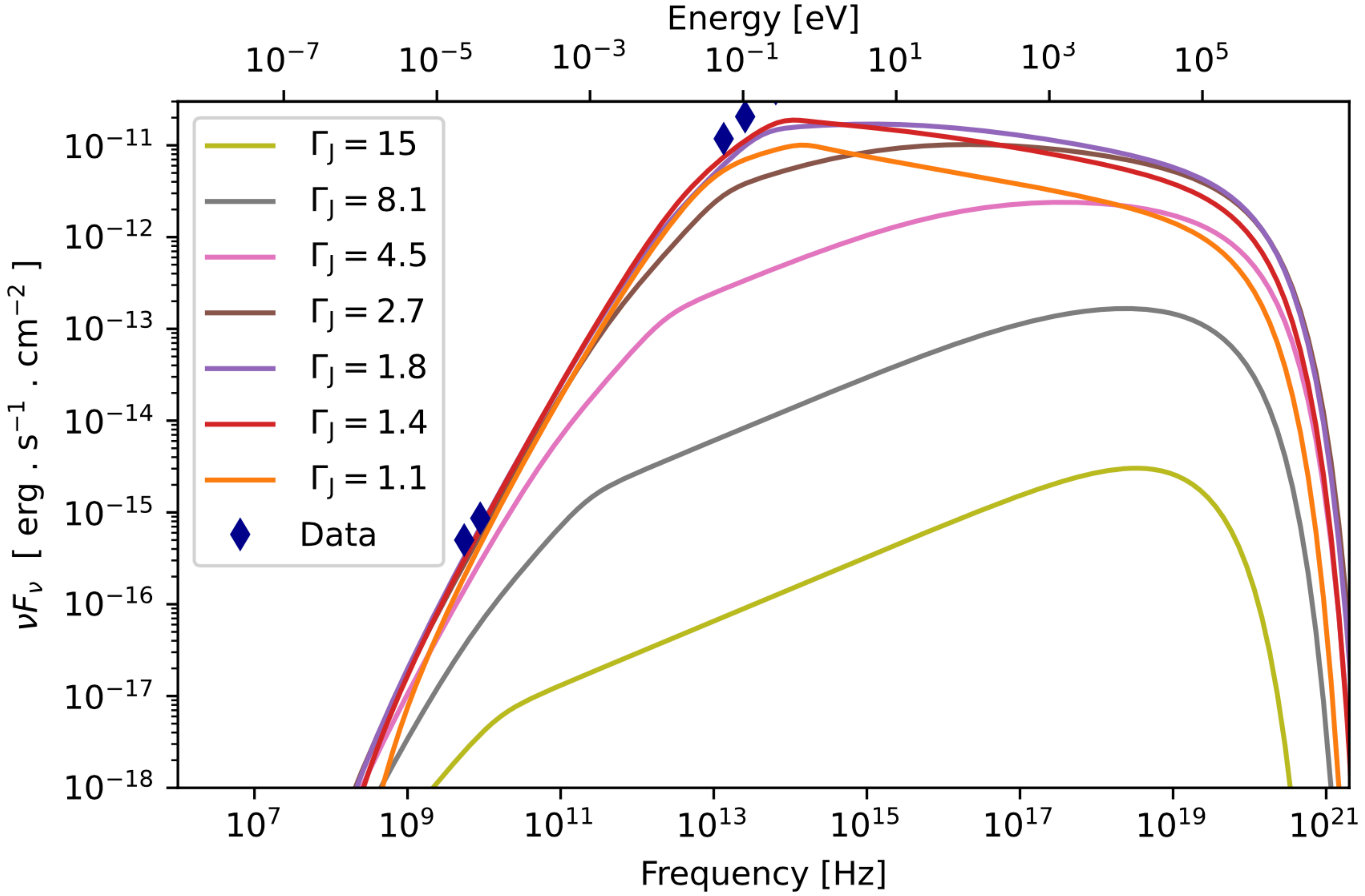
➡ parameter space exploration, spectral fits (coupled with mcmc package eemc)

Effects of radiation losses






Energy [eV]
10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5}
νF_ν [erg . s^{-1} . cm^{-2}]
10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}
$\chi = 0.96$
$\chi = 0.41$
$\chi = 0.18$
$\chi = 3.3 \times 10^{-2}$
$\chi = 6.2 \times 10^{-3}$
$\chi = 5 \times 10^{-4}$
Data
10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21}
Frequency [Hz]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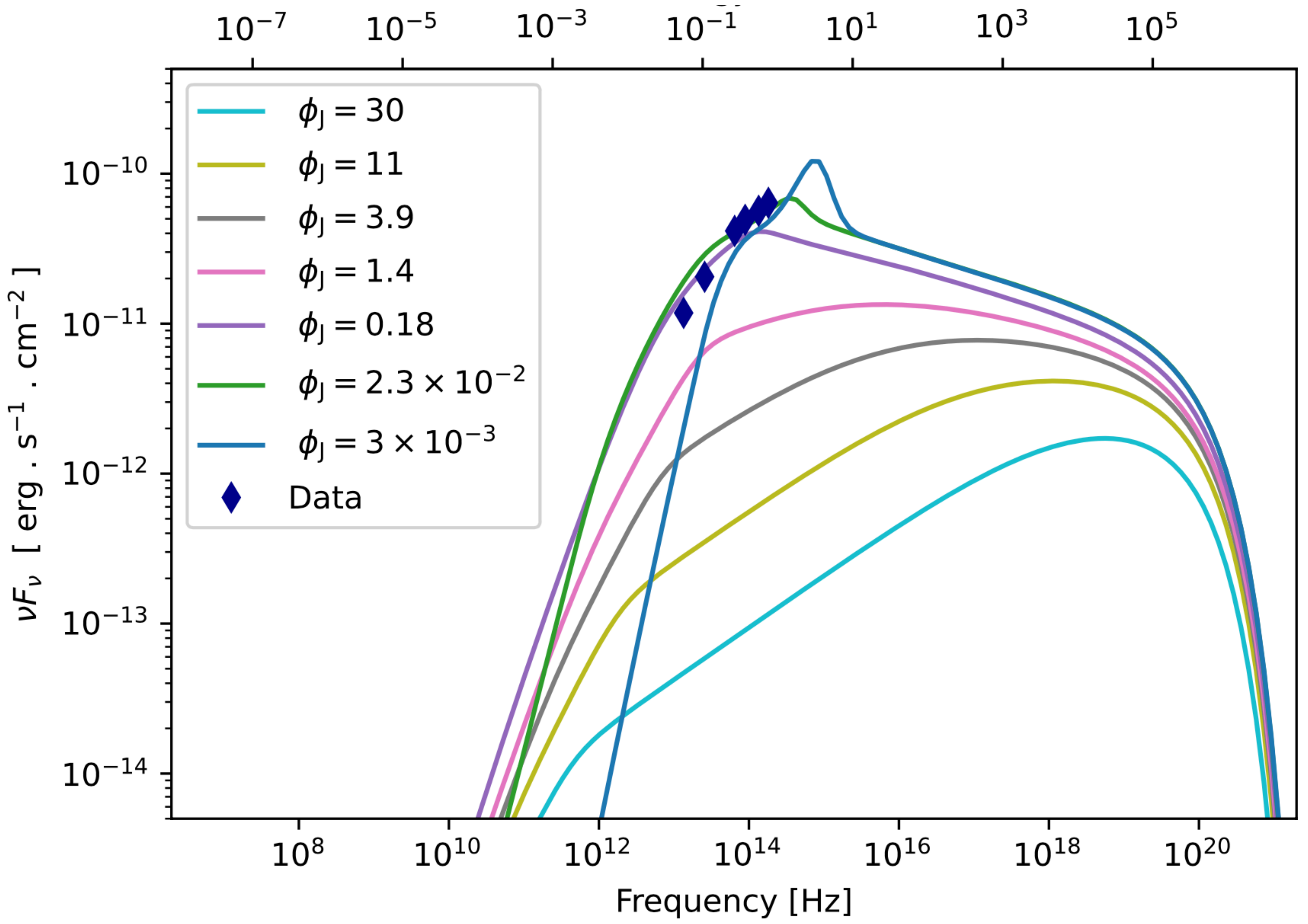
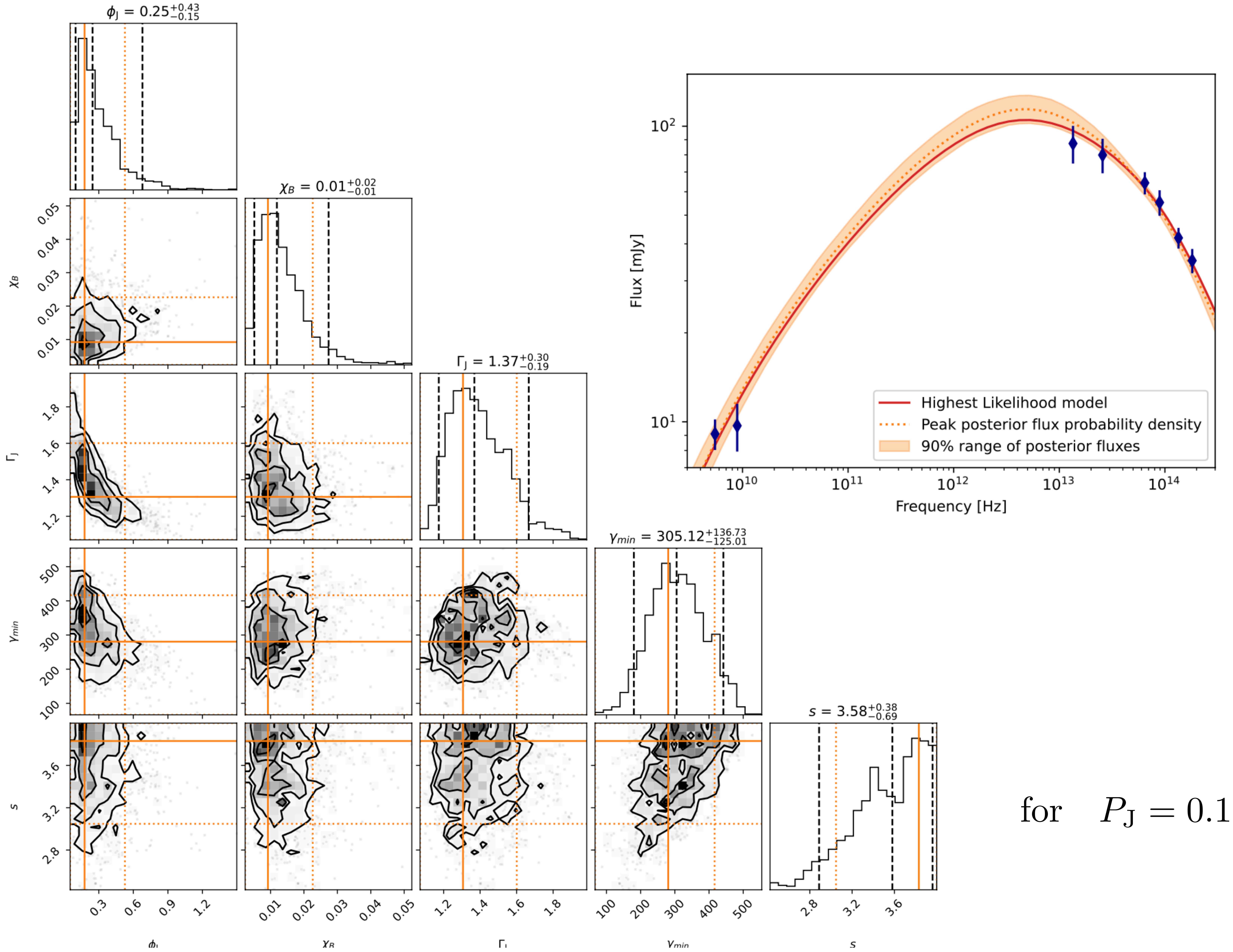
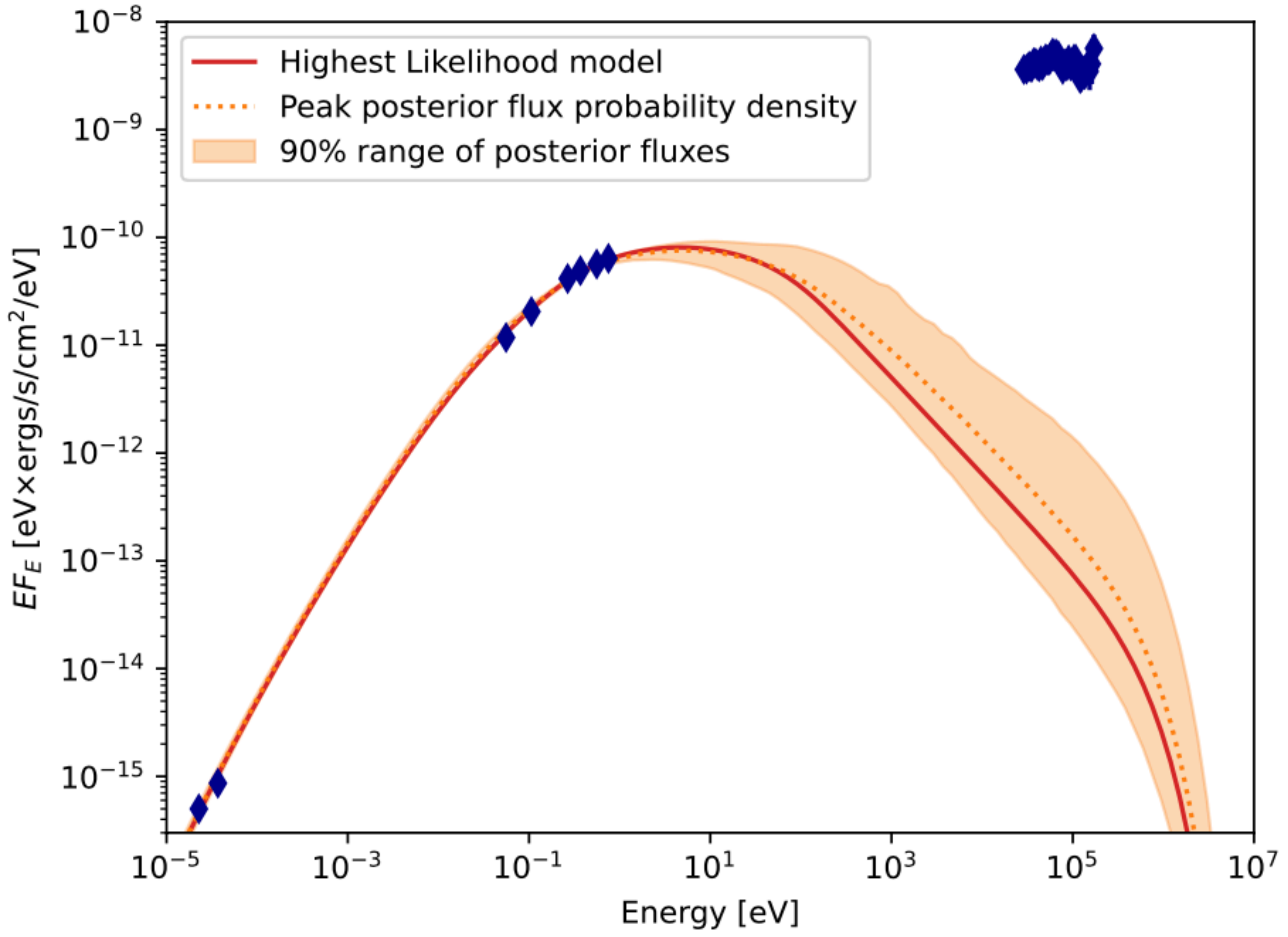
νF_ν [erg . s^{-1} . cm^{-2}]
10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16} 10^{-17} 10^{-18}
$\Gamma_{\rm J} = 15$
$\Gamma_{\rm J} = 8.1$
$\Gamma_{\rm J} = 4.5$
$\Gamma_{\rm J} = 2.7$
$\Gamma_{\rm J} = 1.8$
$\Gamma_{\rm J} = 1.4$
$\Gamma_{\rm J} = 1.1$
Data
10^{7} 10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21}
Frequency [Hz]


10^{-7} 10^{-5} 10^{-3} 10^{-1} 10^{1} 10^{3} 10^{5}
νF_ν [erg . s^{-1} . cm^{-2}]
10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14}
$\phi_{\rm J} = 30$
$\phi_{\rm J} = 11$
$\phi_{\rm J} = 3.9$
$\phi_{\rm J} = 1.4$
$\phi_{\rm J} = 0.18$
$\phi_{\rm J} = 2.3 \times 10^{-2}$
$\phi_{\rm J} = 3 \times 10^{-3}$
Data
10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}
Frequency [Hz]

Comparison to data: GX 339-4





for $\quad P_\mathrm{J} = 0.1\,L_E, \quad i = 40^\circ, \quad D = 8\,\mathrm{kpc}.$

Conclusions

➡ New version of ISHEM (CoolSHEM/CoolJET) is available

- includes more physics: radiation losses and detailled treatment of particle cooling
- easier to use and fit observed spectral energy distributions

➡ Qualitative effects of radiation cooling:

- In bright hard states and HIMs, radiation cooling is strong in the IS scenario:
  suppress synchrotron emission at and above OIR frequencies
- SED shape does not depend only on the power spectrum of the jet Lorentz factor fluctuations (not anymore).

➡ Comparisons to data:

- Results obtained from ‘fits’ with the classic version of ISHEM are quantitatively different but qualitatively similar
- Due to radiative cooling, the jet contribution to (hard) X-ray band expected to be negligible with the internal shock model