Coupling accretion flow and jets in black hole X-ray binaries: Insights from the multi-wavelength emission of Cygnus X-1

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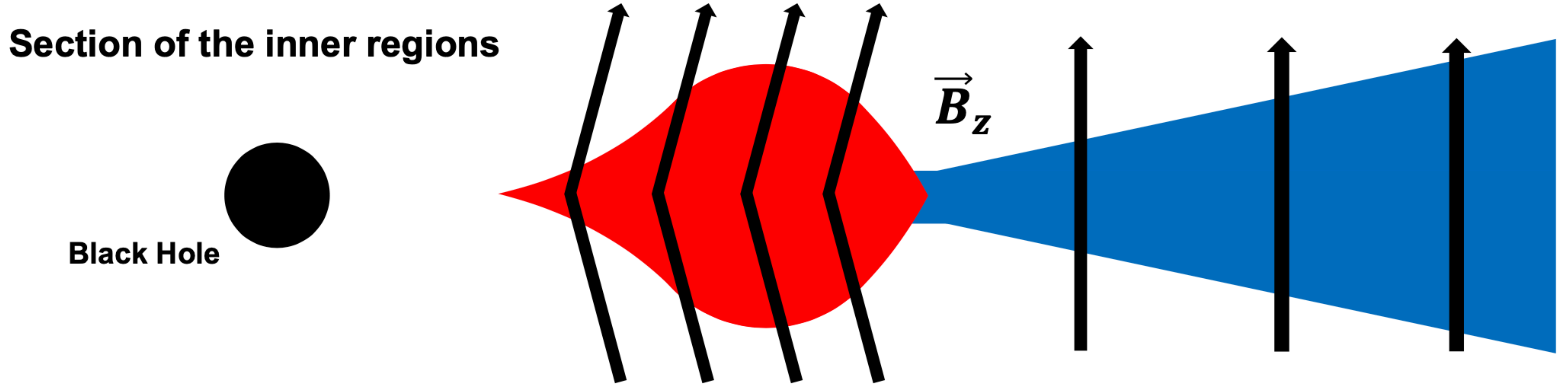
JED+SAD model :
a magnetised accretion-ejection structure

Jet Emitting Disc / Standard Accretion Disc



Jet Emitting Disk

- Self similar MHD solutions **(Ferreira 1997)**
- **Supersonic accretion speed**
- Optically thin
- Hot

} **Even at high $\dot{m}$**

—> hot comptonizing medium

Standard Accretion Disc

- From **(Shakura & Sunyaev, 1973)**
- Optically thick
- Geometrically thin
- Cold ~1 keV

—> soft thermal emission

Ferreira+ 06,22
Petrucci+ 08, 13
Marcel+18ab,19,20,21
Marino+21
Barnier+22

- **Calculation of steady state thermal structure and spectral energy distribution**
- **Comparison to spectral data (XRBs, AGN)**

JED-SAD parameters

JED-SAD dynamics parameters:

r_j : JED-SAD transition radius

$\dot{m}_0$: mass accretion rate at r_j

fixed parameters:

p : ejection index $\dot{m}(r) = \dot{m}_0 \left(r/r_\mathrm{j}\right)^p$

b: fraction of JED accretion power channelled to jet

m_s: JED mach number

α : SAD viscosity

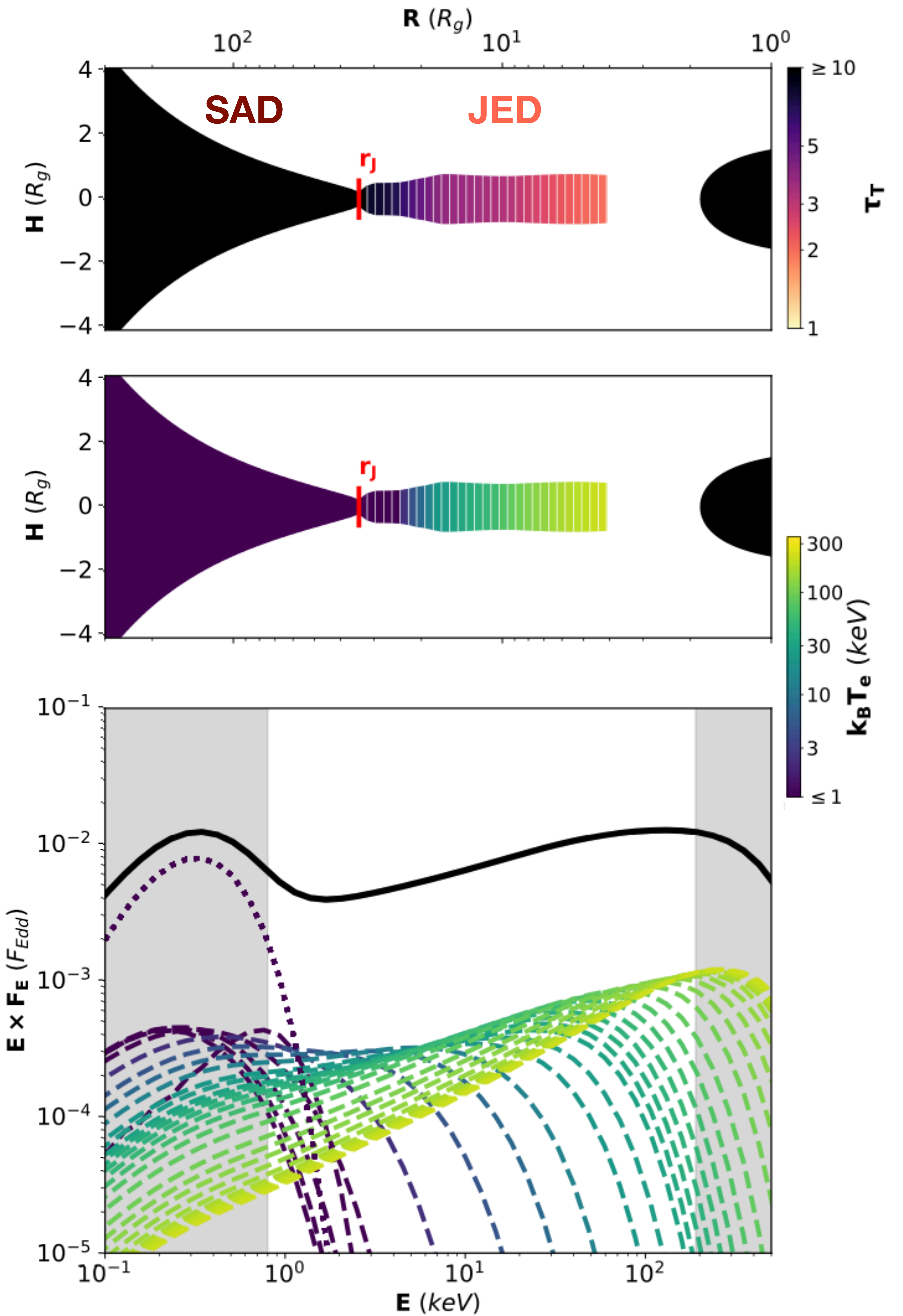
r_{ISCO} : inner JED radius

+reflection component parameters

Observer parameters:

θ : angle between JED-SAD plane and line of sight

D : distance



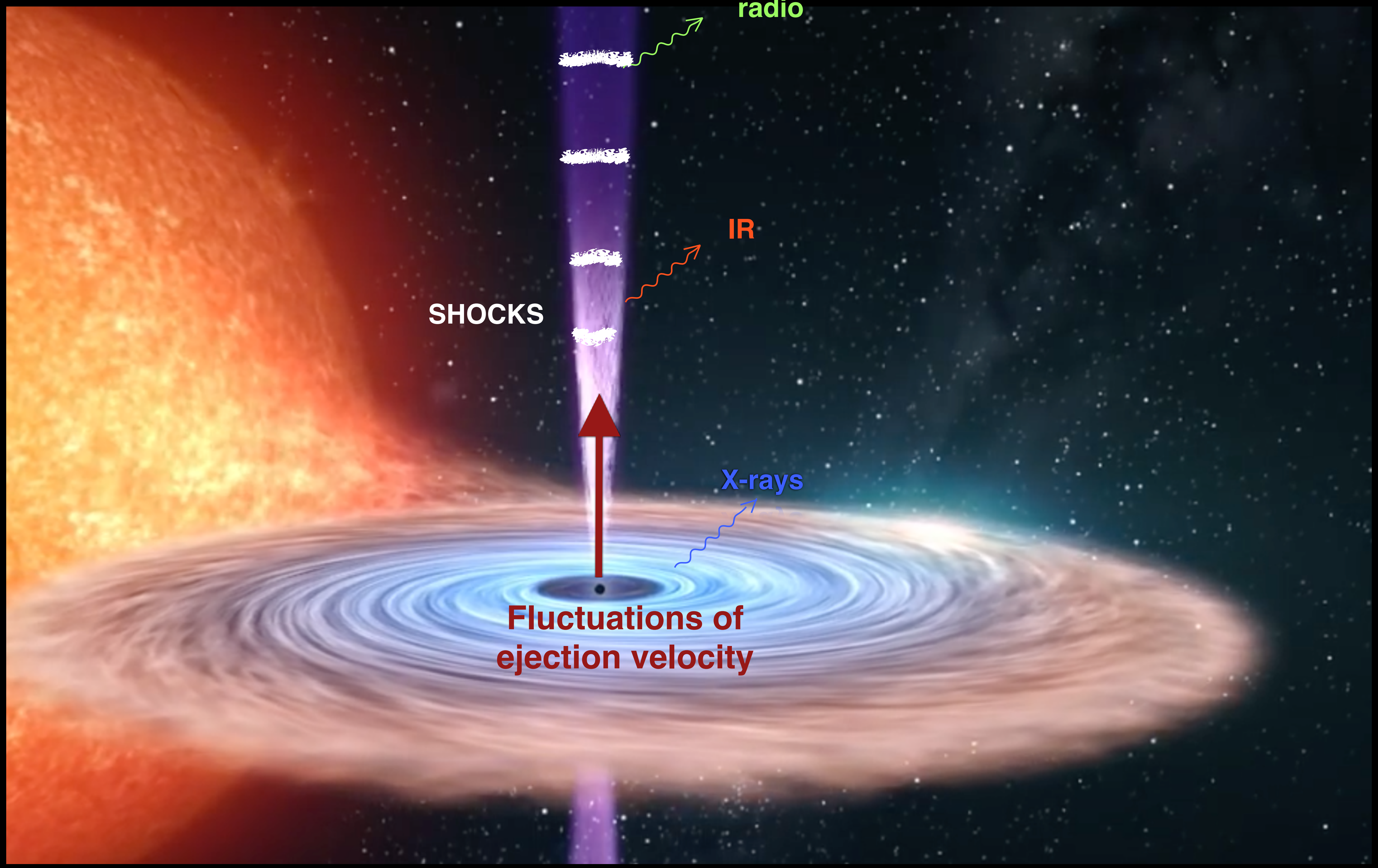
ISHEM: an internal shock model

- 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

Iamil 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

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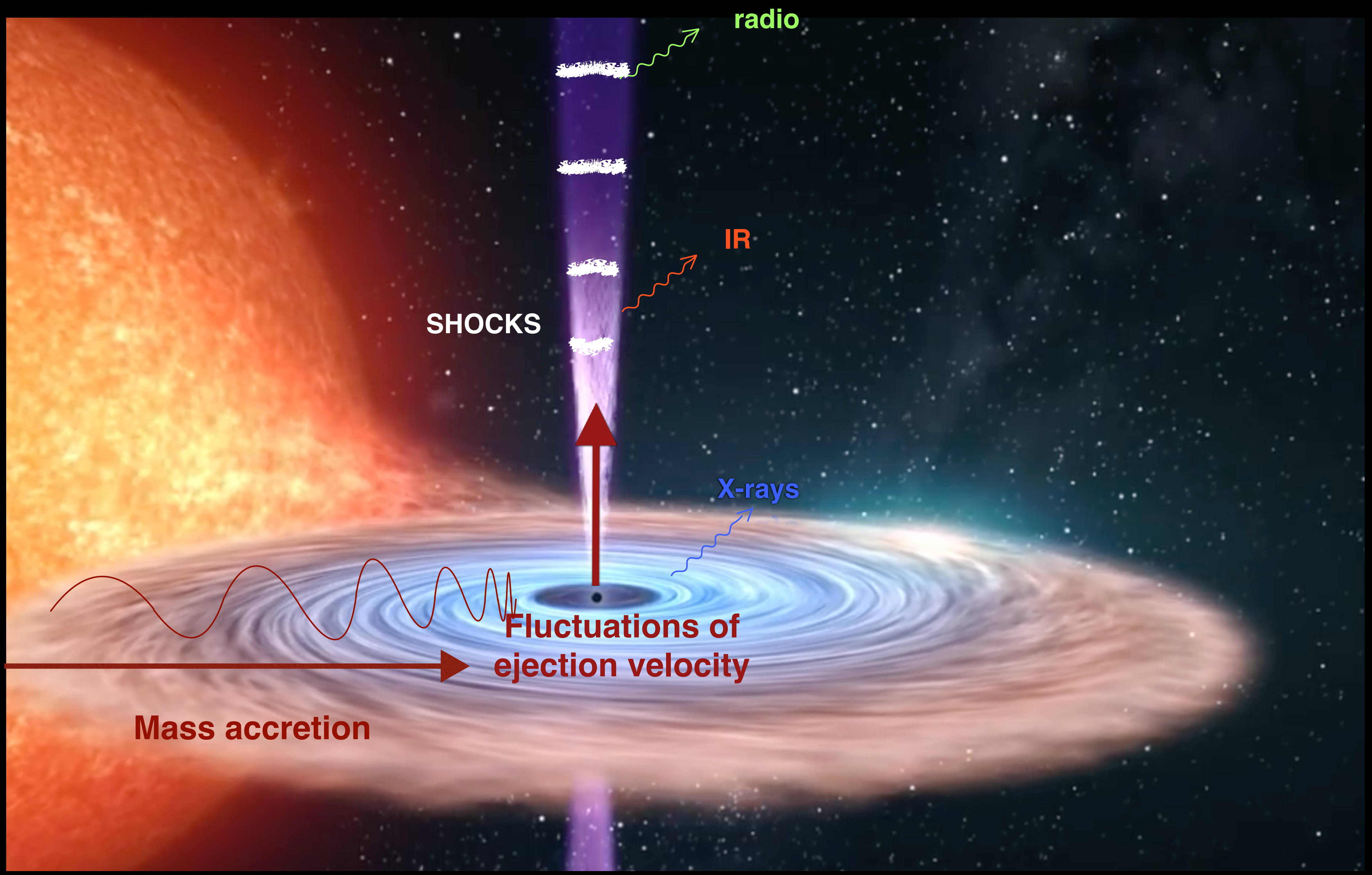


Malzac 2013,2014

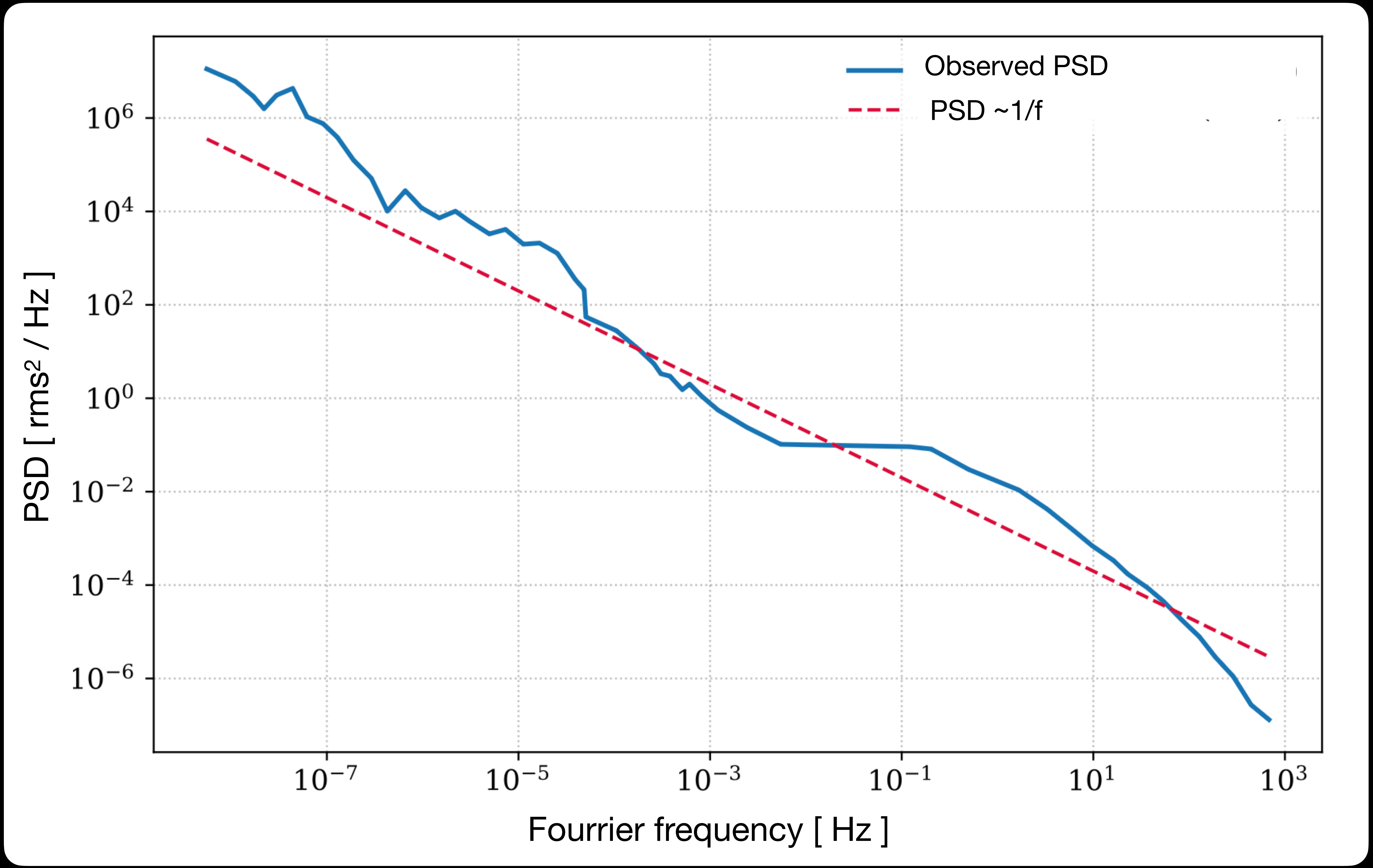
- Fluctuations of jet velocities driven by the accretion flow variability ?

Jet Lorentz factor fluctuations

- If jet velocity fluctuation are driven by accretion flow variability they should have a similar power spectra

- The accretion flow variability can be traced by the X-ray light curve

➡ inject jet Lorentz factor fluctuations with same power spectrum as the X-ray light curve.



Observed broad frequency X-ray PSD of Cyg X1, extracted from Gilfanov 2010 , used as input of the ISHEM simulations

ISHEM parameters

- Jet dynamics

  P_J : jet kinetic power

  Γ_J : time averaged bulk Lorentz factor

- Microphysics:

  χ_B : fraction of shock power into magnetic field

  s : slope of accelerated leptons energy distribution

  η_{acc} : efficiency of acceleration process

- Geometry:

  r_b : jet radius at base

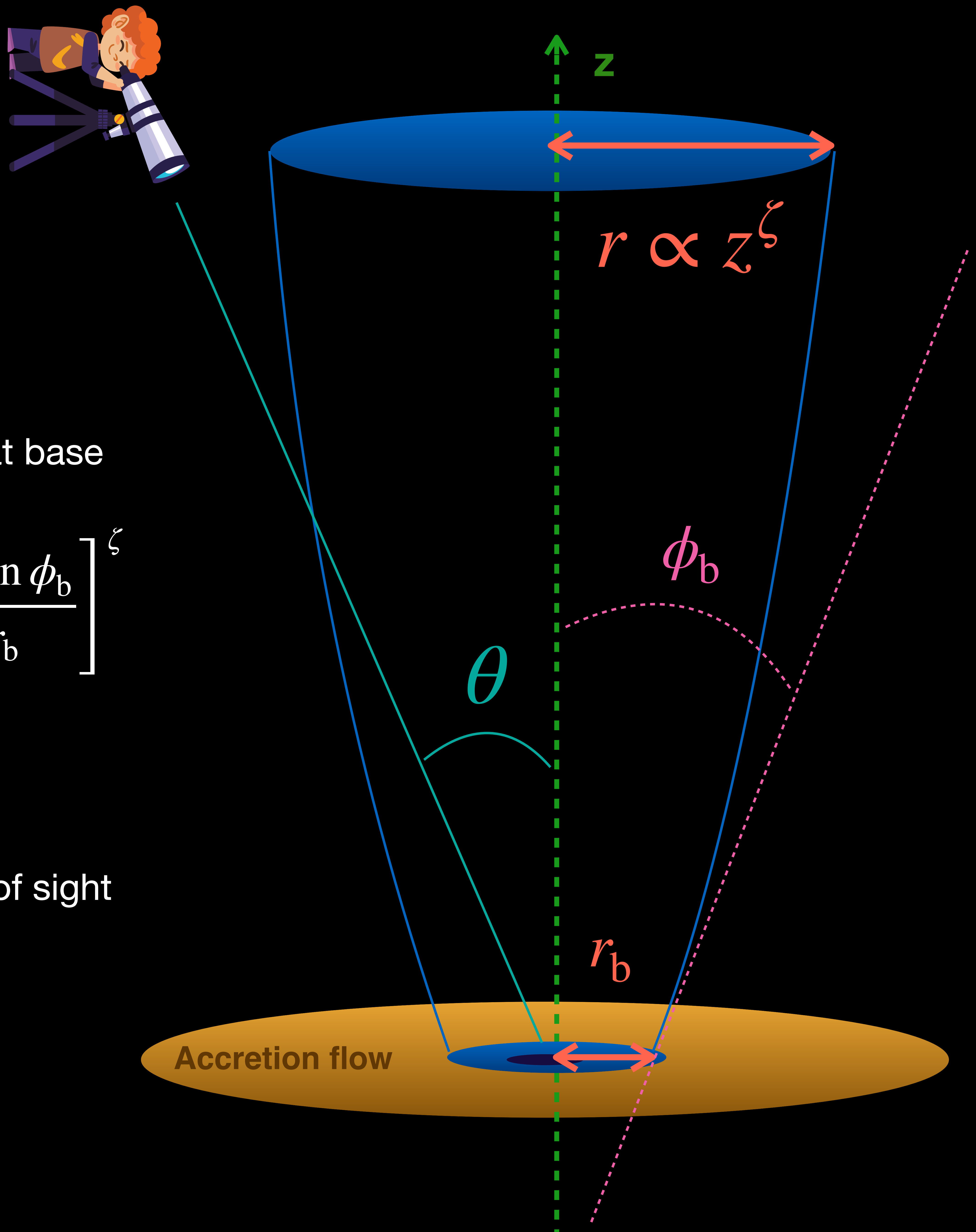
  ϕ_b : jet half-opening angle at base

  ζ : jet 'shape' $r = r_b \left[\frac{z \tan \phi_b}{r_b} \right]^\zeta$

- Observer:

  θ : angle between jet and line of sight

  D : distance



Joint JED-SAD-ISHEM fit to cygnus X-1

- Model normalisation defined by source distance D assumed in the range 2.05— 2.40 kpc (Miller-Jones et al. 2021)
- Inclination in the range 26.3-27.9 (Orosz et al. 2011)

- ISHEM parameters depend on the JED SAD structure:

  We assume the radial extension of the jet at the base corresponds to that of the JED

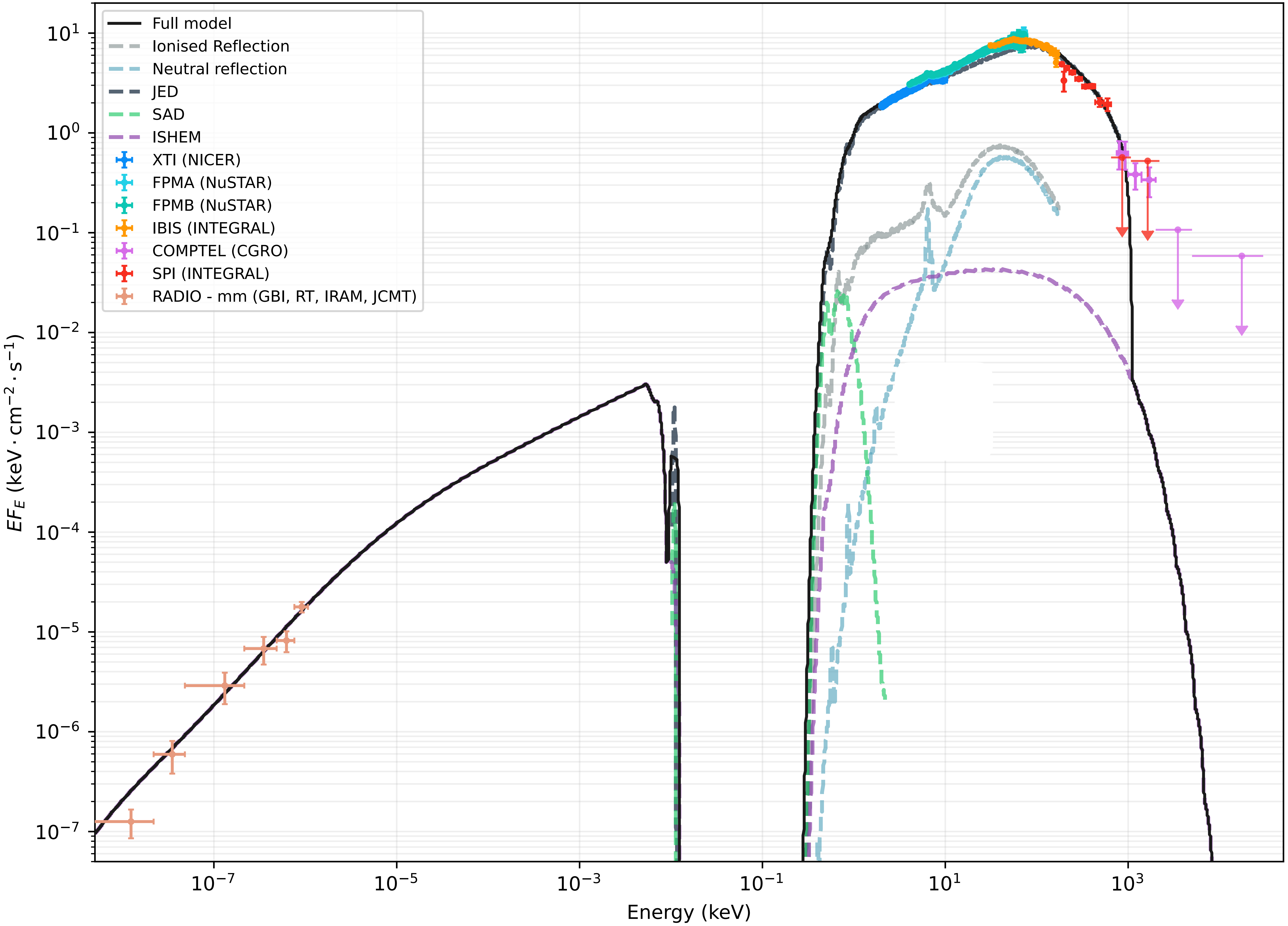
  The JED-SAD model 'predicts' the Blandford & Payne jet power and jet Lorentz factor

  Note: Blandford Znajek component ignored !

$$\begin{cases} r_{base} & = r_J \\ P_{\mathrm{J}} & = \frac{b\dot{m}}{2r_{isco}}\left(1 - \frac{r_{isco}}{r_J}\right) \\ \Gamma_{\mathrm{J}} & = 1 + \frac{b}{2r_{isco}}\left(1 - \frac{r_{isco}}{r_J}\right)\left(p \times \ln\left(\frac{r_J}{r_{isco}}\right)\right)^{-1} \end{cases}$$

- Joint fitting in XSPEC

Coupled JED-SAD+ISHEM fit of Cyg X-1



Data from :

Fender et al. 2000,
Krawczynski et al. 2022,
Jourdain et al. 2012,
McConnel et al. 2002

r_J	$24.81^{+1.18}_{-2.21}$	r_g
$\dot{m}$	$0.206^{+0.0016}_{-0.0011}$	$\dot{M}_{Edd}$
ϕ_b	5.09	deg
P_J	1.46×10^{-2}	P_{Edd}
Γ_J	3.68	-
ζ	$0.73^{+0.092}_{-0.098}$	-
s	$1.91^{+0.39}_{-0.23}$	-
$norm_{JED-SAD}$	$23.34^{+0.43}_{-0.42}$	kpc^{-2}
χ^2	1581.55	
ν	1350	
χ^2_ν	1.17	

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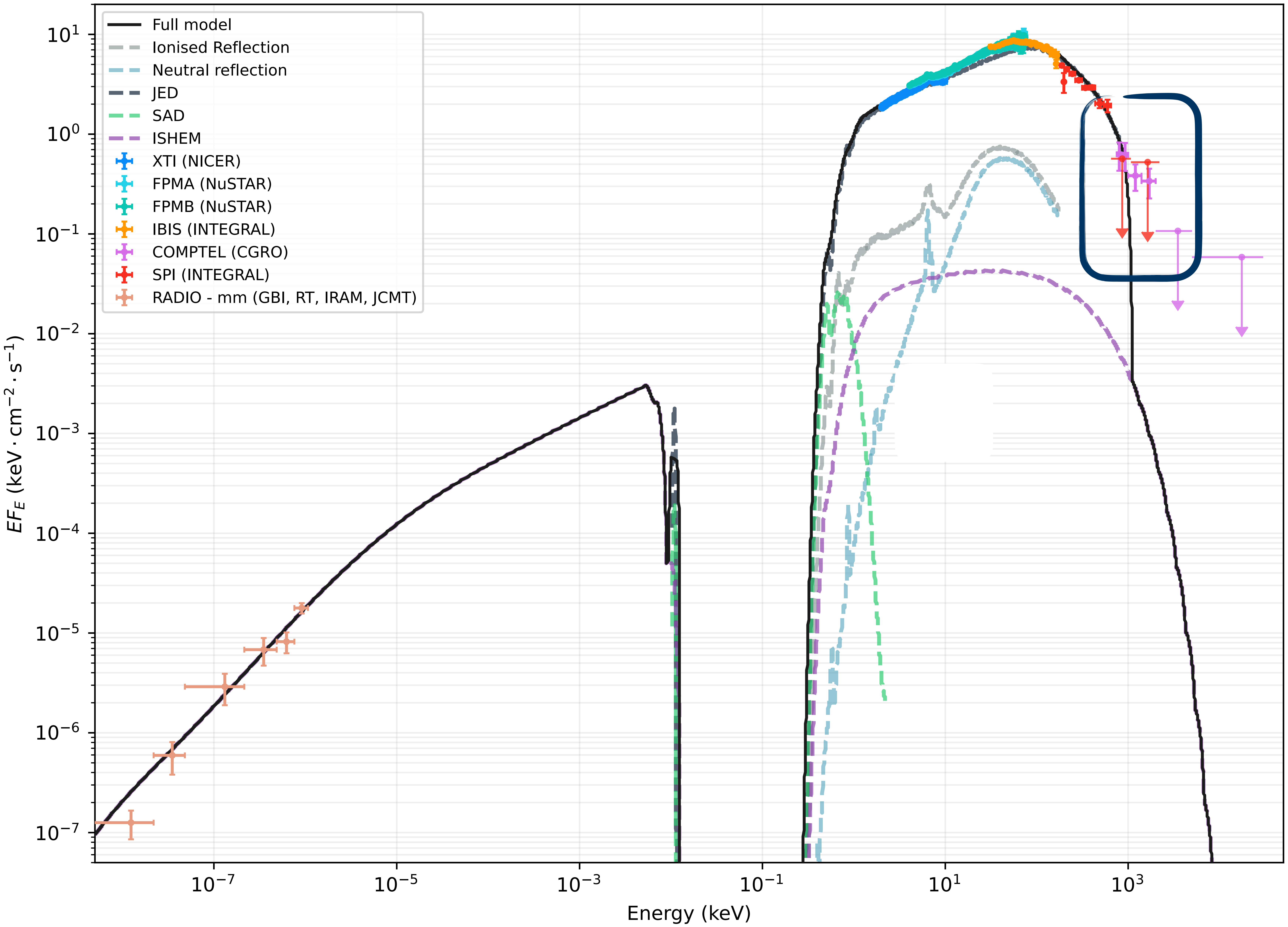

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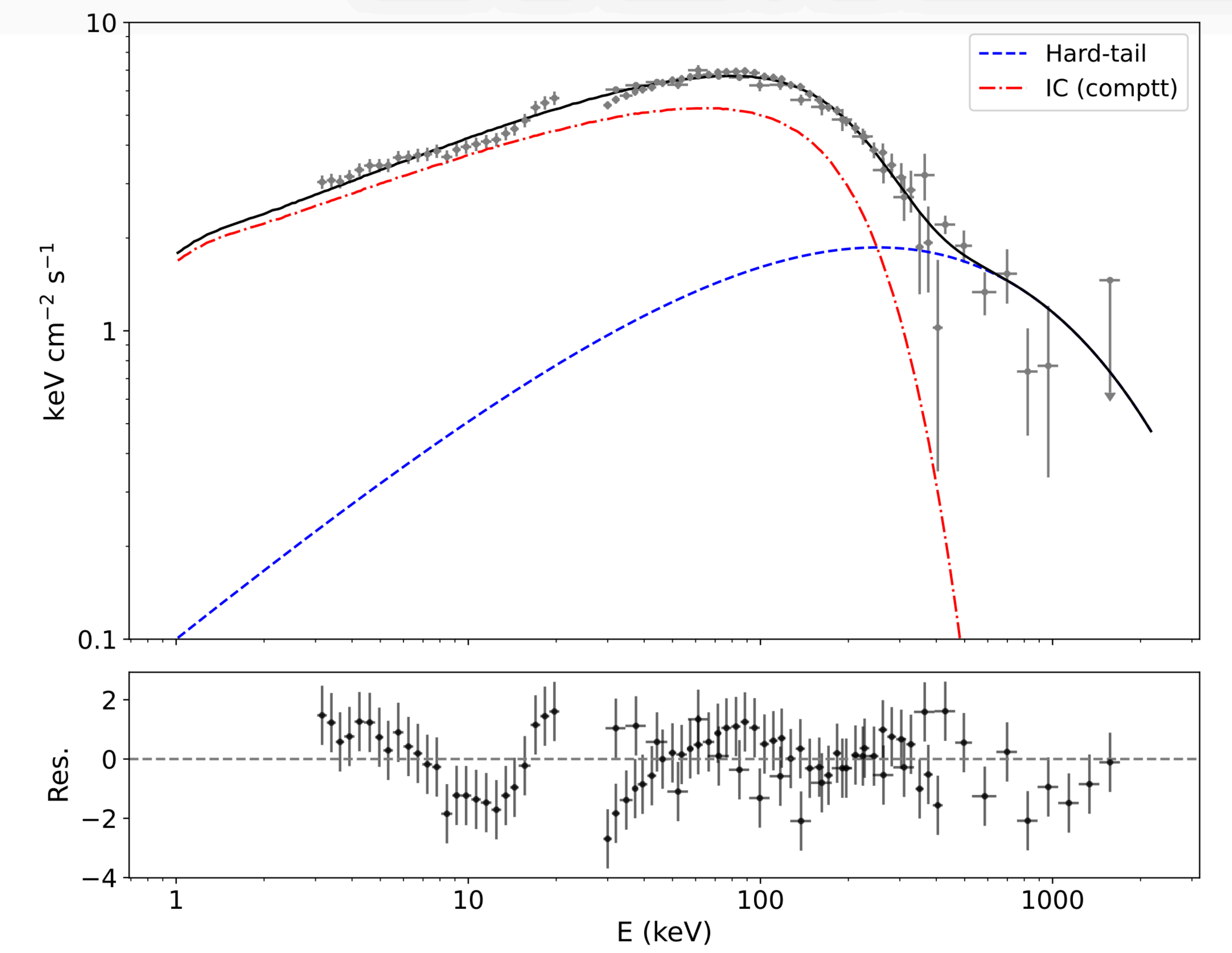
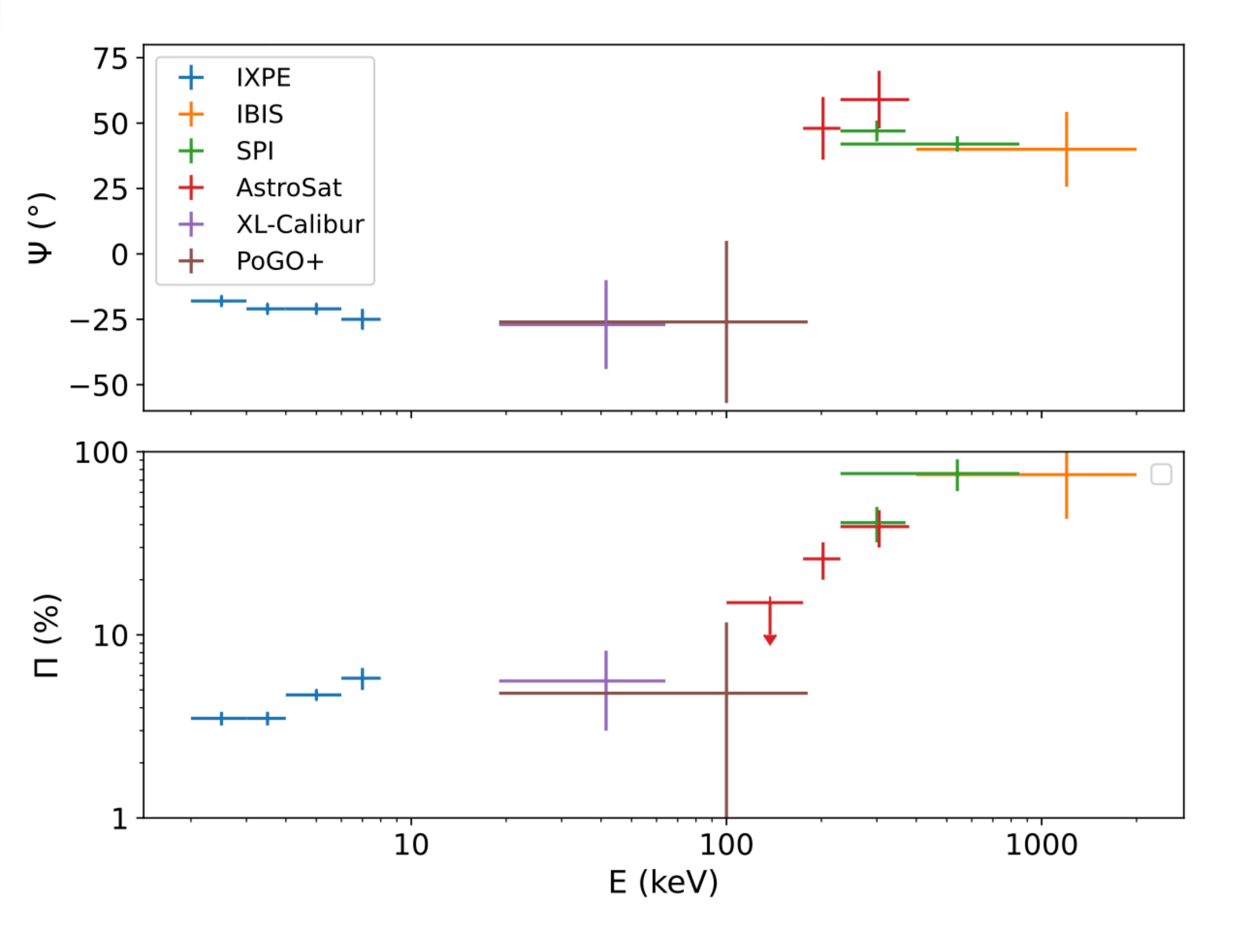
High energy emission of Cygnus X-1 in hard state

spectrum



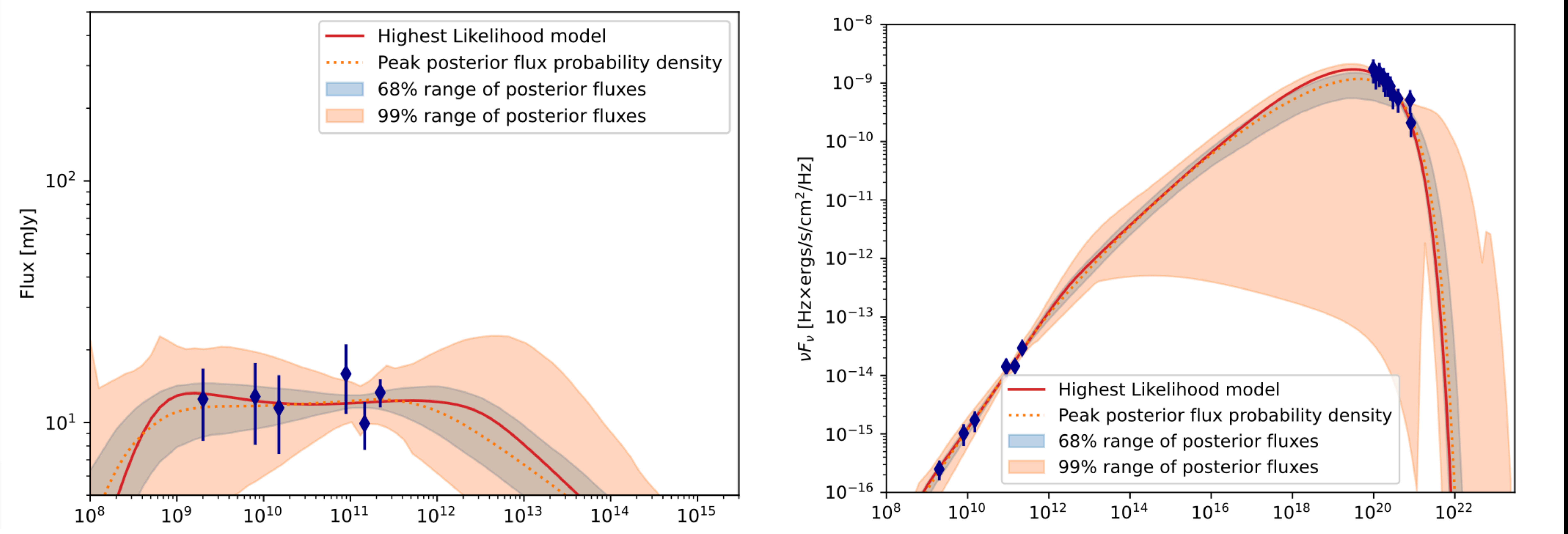
polarization



Bouchet et al. 2026

MeV excess as jet emission

ISHEM only fit focussing on radio-mm and MeV



	P_J	Γ_J	ϕ_b	χ_B	s	ζ	η_{acc}	D [kpc]	θ [deg]	χ^2
Best Fit	0.138	2.23	0.936	1.21×10^{-5}	1.41	0.711	4.26×10^{-2}	2	37.2	5.07
Peak MC	$0.28^{+0.02}_{-0.19}$	$2.2^{+1.4}_{-1.1}$	$0.87^{+4.4}_{-0.79}$	$2.1^{+28}_{-2.1}\times10^{-4}$	$1.1^{+0.34}_{-0.05}$	$0.70^{+0.06}_{-0.10}$	$4.4^{+2.6}_{-3.0}\times10^{-2}$	$2.0^{+0.30}_{-0.00}$	$26^{+14}_{-0.04}$	$6.8^{+4.0}_{-1.7}$
Median	$0.14^{+1.0}_{-0.08}$	$2.8^{+1.8}_{-1.0}$	$3.3^{+5.5}_{-3.0}$	$5.5^{+5.2}_{-5.2}\times10^{-4}$	$1.3^{+0.23}_{-0.20}$	$0.72^{+0.07}_{-0.07}$	$5.5^{+4.6}_{-2.0}\times10^{-2}$	$2.1^{+0.02}_{-0.77}$	$34^{+17}_{-6.7}$	$8.6^{+5.9}_{-2.2}$

- Requires very hard electron acceleration s=1.05–1.6)
- Not compatible with standard diffusive shock acceleration theory
- Similar to Zdziarski et al. 2012

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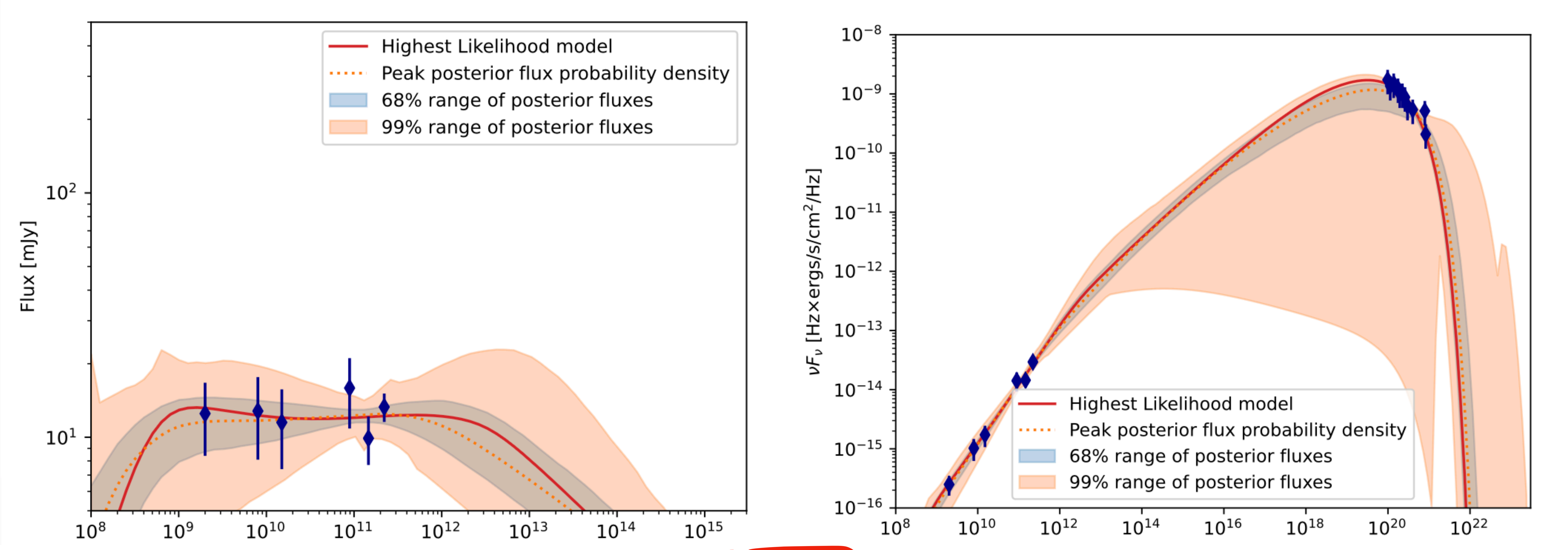

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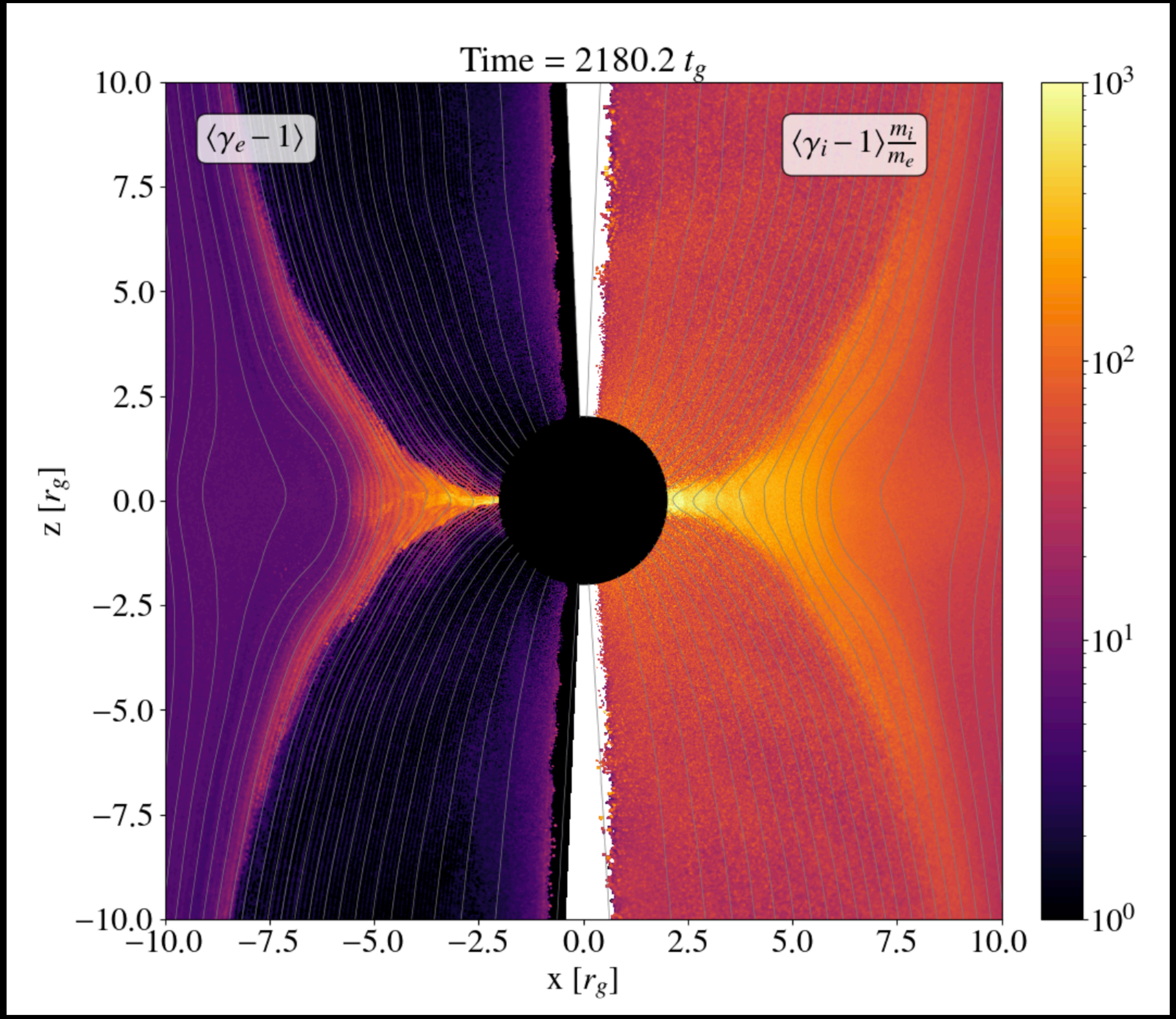
MeV excess as magnetospheric synchrotron emission ?

- Global GRPIC simulations indicate efficient particle acceleration in the black hole magnetosphere (e.g. Parfrey+2019, Crinquand+ 2020,2021)



Figueiredo et al. 2026

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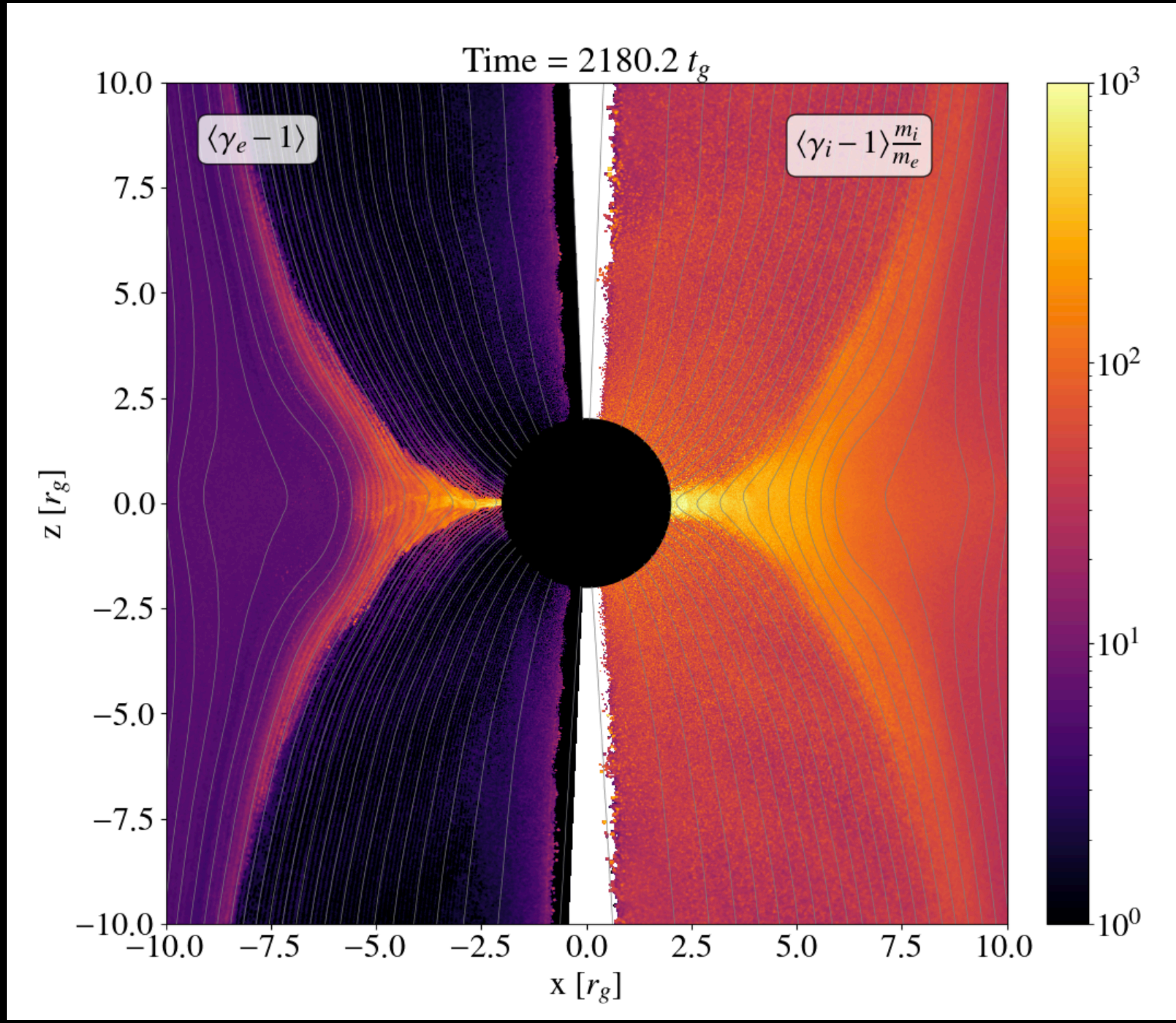
- MAD GRMHD simulations have shown the magnetic flux threading the horizon $\Phi_{\rm BH} \sim \pi r_g^2 B^2$ saturates around $\Phi_{\rm BH} \sim 50\dot{M}c^2$ (Tchekhovskoy + 2011, Narayan 2022)

- In the case of Cyg X-1, the JED-SAD model fitting provides $\dot{M}c^2 \simeq 0.2 L_{\rm Edd}$ which leads to $B \sim 10^8$ G.



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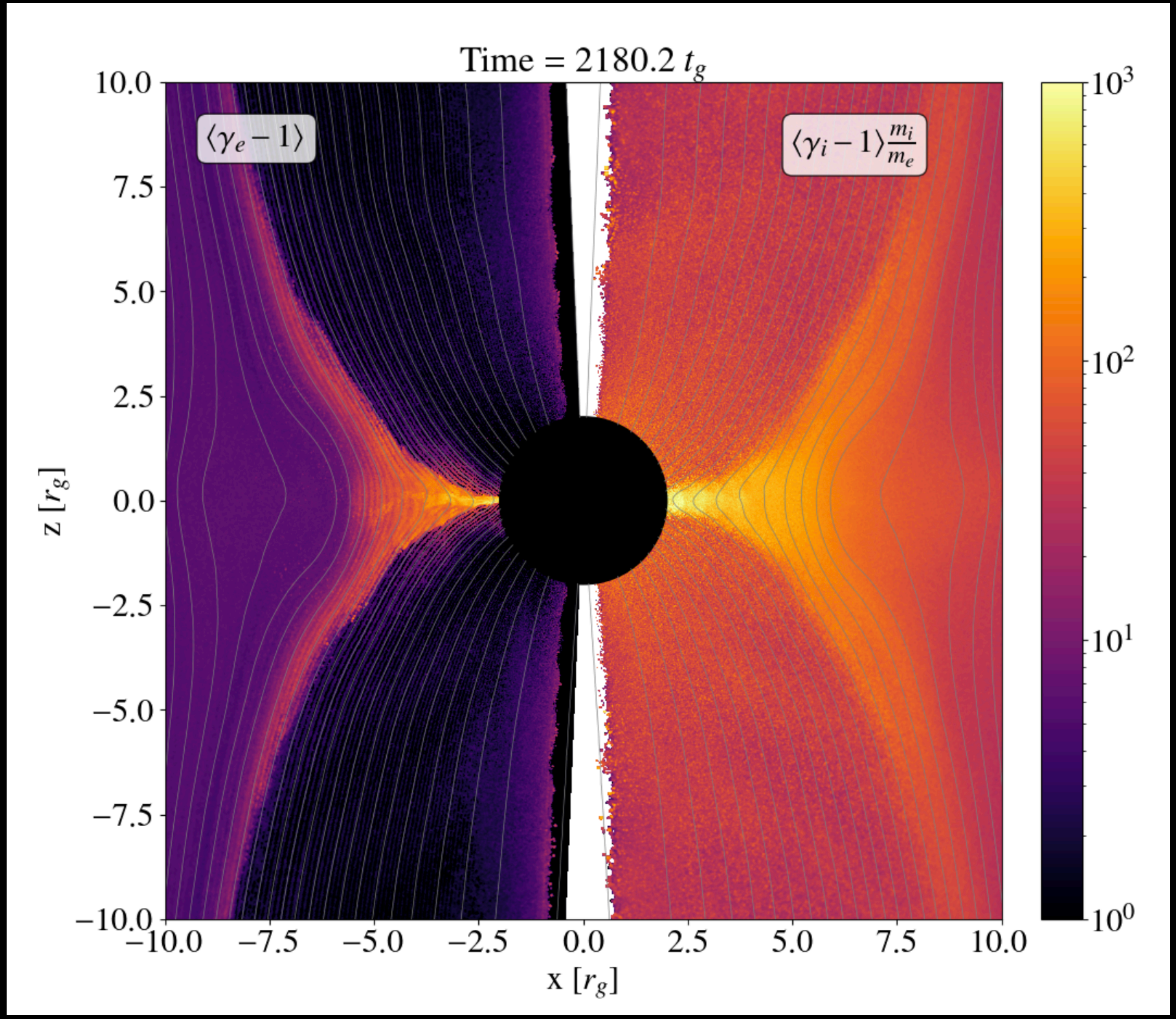
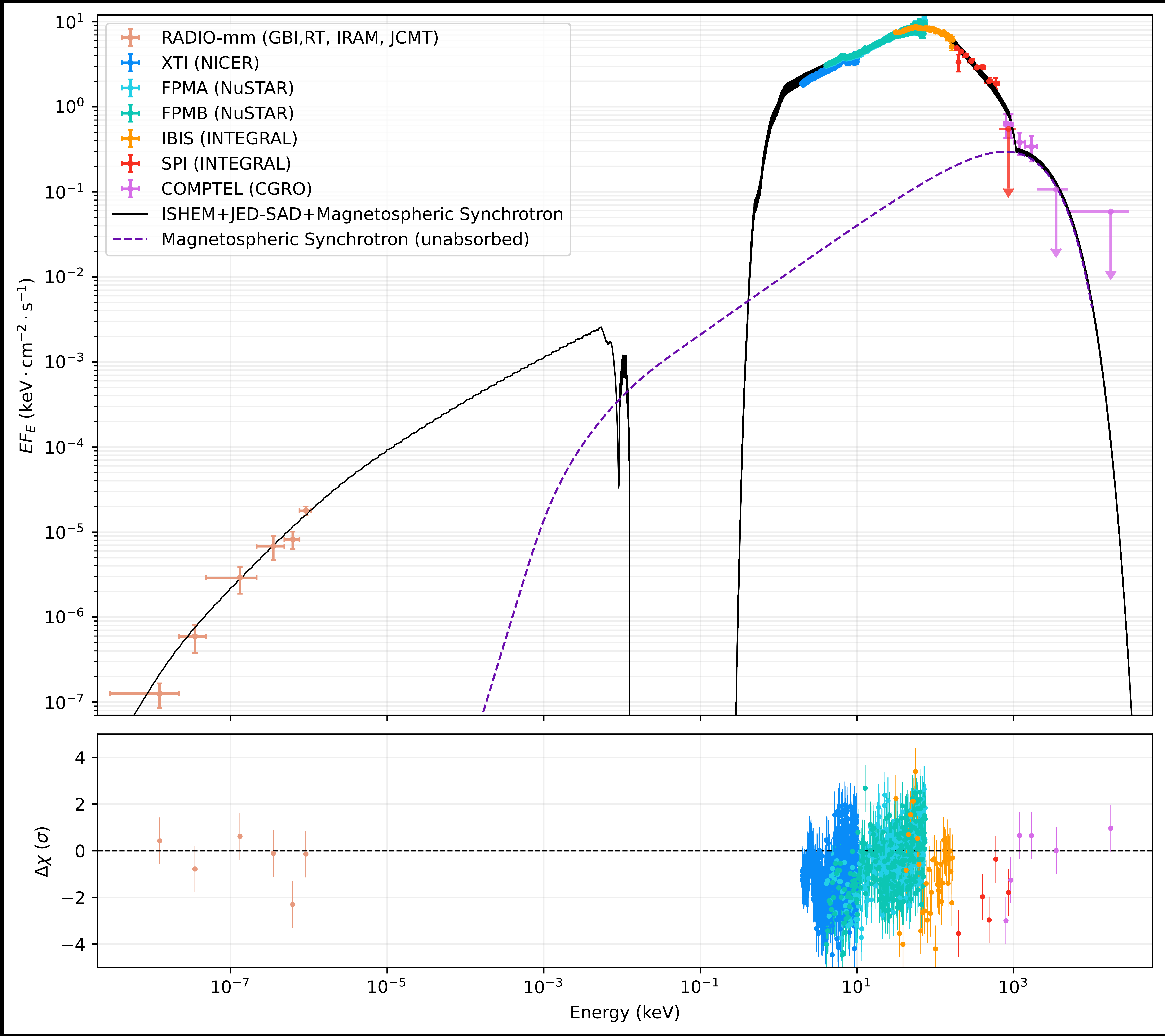


Figueiredo et al. 2026

➡Toy model of magnetospheric synchrotron emission:

- A sphere of radius $R \sim r_g$, filled with magnetic field $B \sim 10^8$ G, a Thomson thin plasma of relativistic leptons with a powerlaw energy distribution extending up to Lorentz factors $\gamma \sim 1000$

Magnetospheric Sychrotron emission



s	1.70	-
B	5.18×10^8	G
η_{acc}	5×10^{-2}	-
n_e	6.40×10^9	cm^{-3}
R	1.58	r_g
norm$_{synch}$	0.208	-
χ^2	1859.49	
ν	1352	
χ^2_ν	1.37	

Conclusions

- We fitted the SED of Cyg X-1 with a coupled JED SAD / ISHEM model, and find overal good agrreement :
- X-rays/hard X-rays are dominated by the accretion flow and well modeled by JED SAD model with $r_{\rm j} \simeq 25 r_g$, $\dot{m} \sim 0.2 L_{\rm Edd}/c^2$
- The flat radio-mm spectrum of Cyg X-1 is well represented by ISHEM, non-conical jet geometry appears to be required, our results suggest $\Gamma_{\rm J} \sim 3.6$, $P_{\rm j} \sim 10^{-2} L_{\rm Edd}$
- BZ jet component is not required
- Interpreting the MeV excess as jet emission requires a very hard acceleration which is not compatible with standard diffusive shock acceleration theory
- As an alternative we suggest that the MeV emission could be caused by relativistic particles accelerated in the black hole magnetosphere/plunging region.
- Polarization not modeled (yet), more MeV polarization data coming with COSI launch next year …

Thanks!