UHECR Interactions As The Origin of VHE γ-Rays From BL Lacs

Saikat Das[1] · Nayantara Gupta[1] · Soebur Razzaque[2]

[1]Astronomy & Astrophysics Group, Raman Research Institute, India
[2]Centre for Astro-Particle Physics, University of Johannesburg, South Africa

Motivation

Unattenuated TeV γ-ray spectrum observed in some high-synchrotron peaked (HSP) blazars is unexpected due to intrinsic/extrinsic $\gamma\gamma$ absorption in EBL and/or Klein Nishina effect.

One-zone Leptonic Model

The high-energy peak in blazar SED is most efficiently modeled using a one-zone leptonic emission, where the synchrotron/external photons are upscattered by relativistic electrons.

SSC & Line-of-Sight γ-Rays

Ultrahigh-energy cosmic rays can interact with cosmic background photons to produce the observed γ-ray signal along the line of sight, provided they are not deflected significantly.

(A) Emission From The Relativistic Jet

Emission region inside the jet contains a relativistic plasma of electrons & protons moving through a magnetic field B in a spherical blob of radius R.

- The total kinetic power in the jet must be lower than the Eddington luminosity of the SMBH, i.e., $L_{\rm Edd} > L_{\rm jet} = L_e + L_B + L_p$

Leptons

- The constant injection in the comoving frame of the jet is given by

$$Q_e(E_e) = A_e\left(\frac{E_e}{E_0}\right)^{-\alpha} \exp\left(-\frac{E_e}{E_{e,\rm cut}}\right) \qquad (1)$$

- Electrons and positrons are radiatively cooled by synchrotron and synchrotron self-Compton (SSC) process
- We solve the transport equation to calculate the spectrum at a time t

$$\frac{\partial N_e}{\partial t} = Q_e(E_e, t) - \frac{\partial}{\partial E_e}(bN_e) - \frac{N_e}{t_{\rm esc}} \qquad (2)$$

- $b(E_e, t)$ is the energy-loss rate and $t_{\rm esc} = R/c$ is the escape timescale

Hadrons

- Protons are accelerated up to an energy given by the Hillas condition

$$E_{p,\rm max} \sim 2\beta cZeBR \qquad (3)$$

- Being heavier than electrons, they are not cooled sufficiently inside the jet

$$N_p(E_p) = t_{\rm dyn}Q_p(E_p) = \frac{dN}{dE_p} = A_pE_p^{-\alpha} \qquad (4)$$

- Extragalactic propagation of protons produce ν_e, ν_μ, γ, e^+, e^- by virtue of photo-pion and pair-production interactions on CMB and EBL
- $e^\pm$, γ can induce electromagnetic cascade down to GeV energies.

Step 1: Source parameters
- Fit Synch spectrum & calculate SSC spectrum
- B, R, $E_{e,\rm max}$, $E_{e,\rm min}$, δ, Γ

Step 2: UHECR acceleration
- UHECR interaction and escape timescale inside jet
- Calculate $E_{p,\rm max}$

Step 3: Magnetic fields
- UHECR survival along the direction of propagation
- $B_{\rm rms}$ of the turbulent field

Step 4: Blazar SED

EM cascade contribution – SED from SSC+ line-of-sight UHECR interactions on CMB/EBL

(B) Timescales calculation

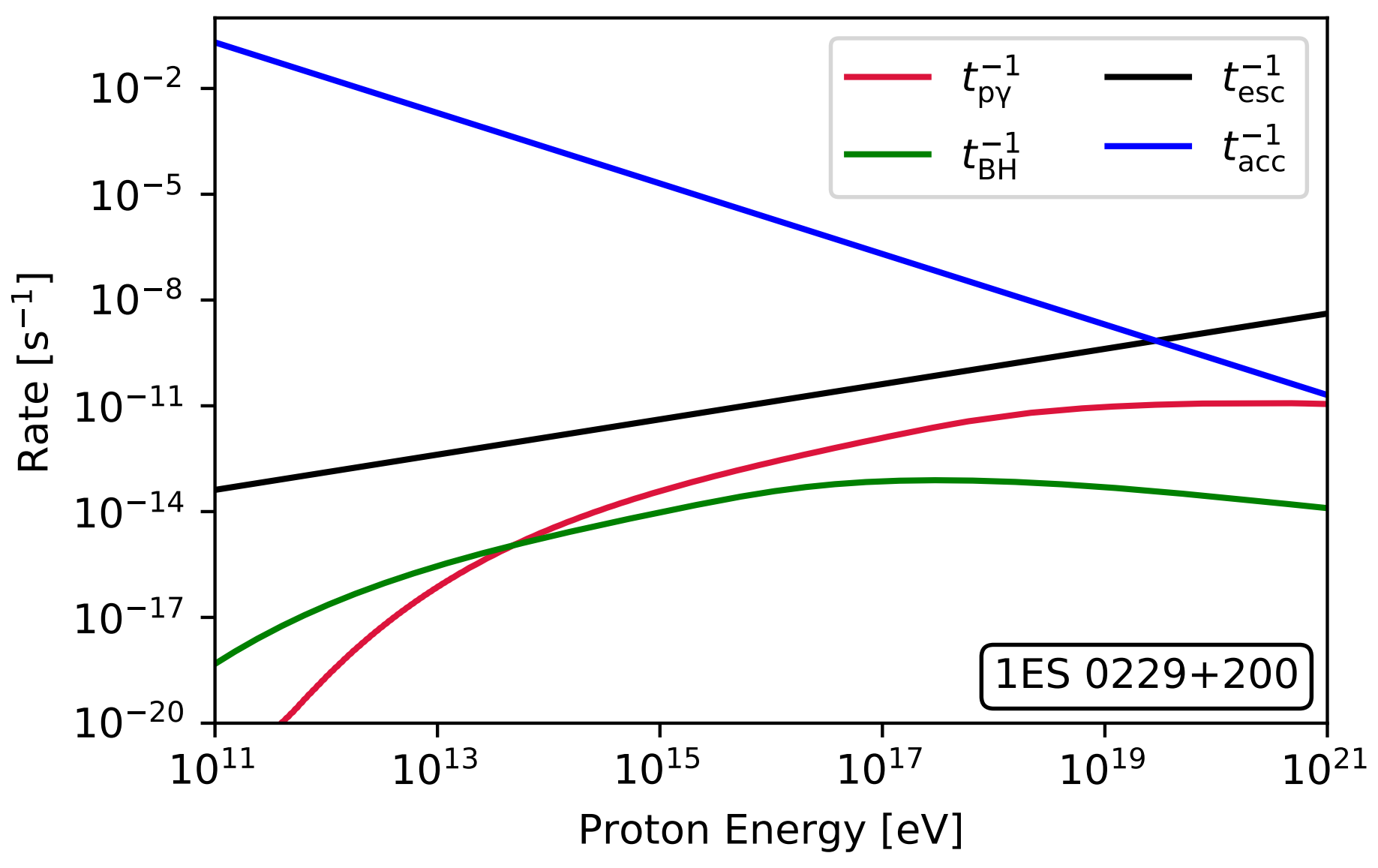


Figure 1. Timescale of photohadronic interactions inside the jet, with target photons from synchrotron and IC emission.

$$\frac{1}{t_{p\gamma}} = \frac{c}{2\gamma_p^2}\int_{\epsilon_{th}/2\gamma_p}^{\infty} d\epsilon'_\gamma \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma} \times \int_{\epsilon_{th}}^{2\epsilon\gamma_p} d\epsilon_r \sigma(\epsilon_r)K(\epsilon_r)\epsilon_r$$

$$t^p_{\rm esc} = \frac{R^2}{4D}; \quad D \propto E^{1/2}$$

$$t^p_{\rm acc} \simeq \frac{20\eta}{3}\frac{r_L}{c} \simeq \frac{20\eta}{3}\frac{\gamma_p m_p c}{eB}$$

1. UHECRs interactions with synch & SSC photons inside the jet is low.
2. Acceleration dominates over escape at least up to 10^{19} eV

(C) Deflections In Magnetic Field

RMS deflection in CR trajectory over a distance D

$$\Phi_{\rm rms} \approx 4^\circ\left(\frac{60\ \text{EeV}}{E/Z}\right)\left(\frac{B_{\rm rms}}{10^{-9}\ \text{G}}\right)\sqrt{\frac{D}{100\ \text{Mpc}}}\sqrt{\frac{l_c}{1\ \text{Mpc}}} \qquad (5)$$

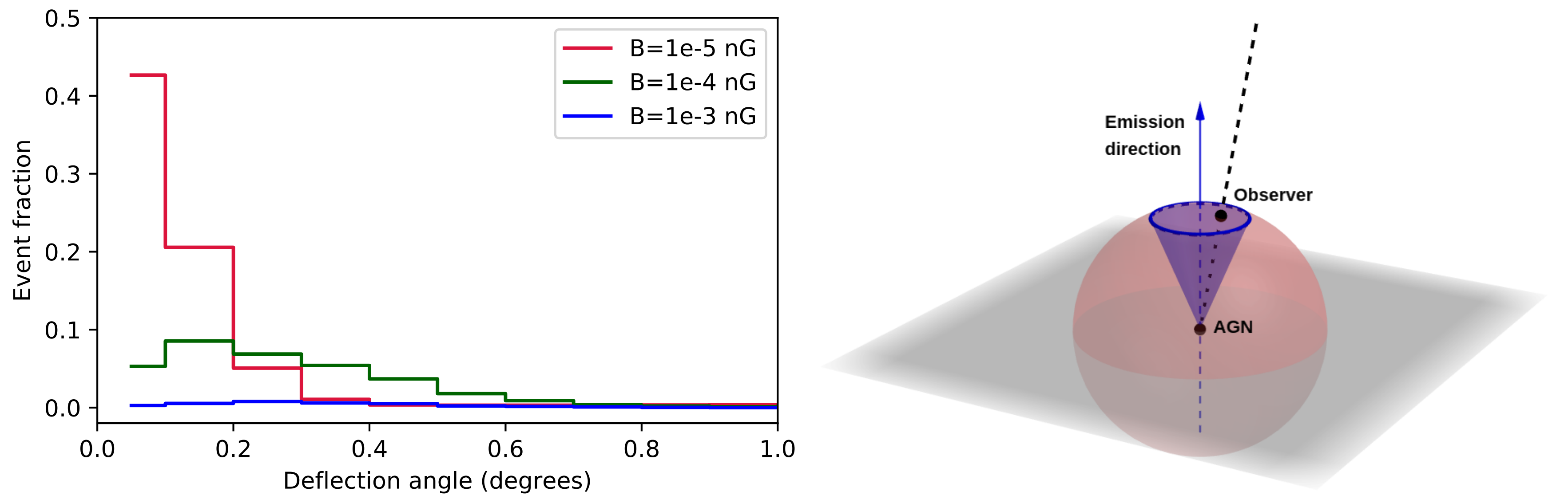


Figure 2. *Left*: Survival rate of UHECRs as a function of the angle from line-of-sight. *Right:* Schematic diagram of blazar emission geometry.

1. Survival rate increases with decreasing $B_{\rm rms}$ and higher θ bin width.
2. Survival rate $\xi_B \approx 0.45$ ($< 0.1^\circ$) for $B_{\rm rms} = 10^{-5}$ nG, D $= 1$ Gpc

(D) Blazar SED

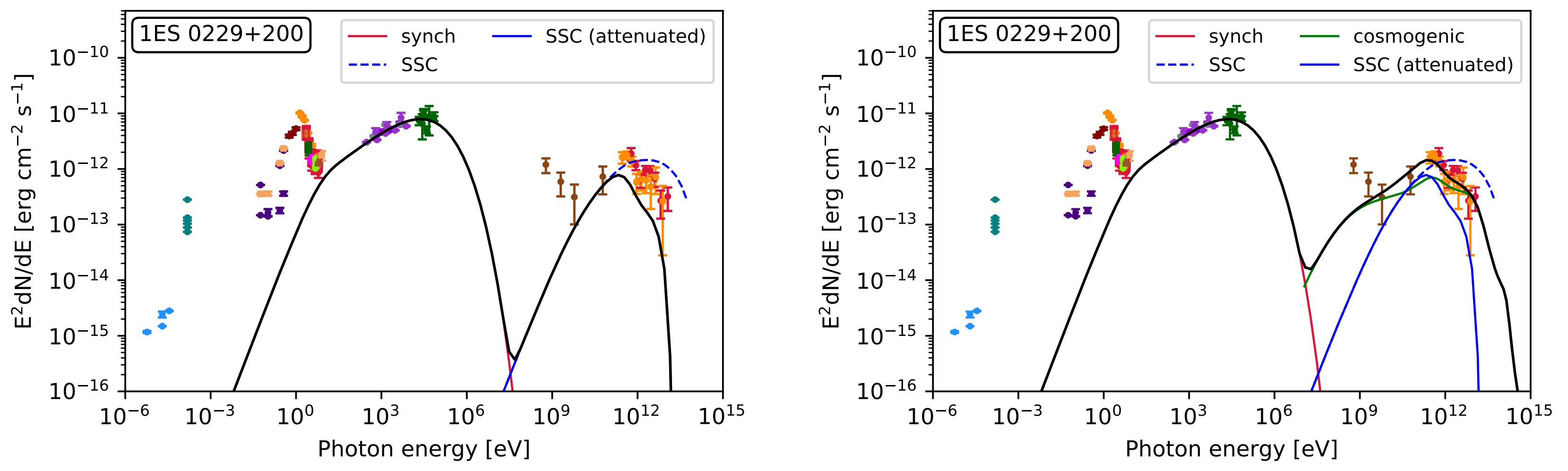
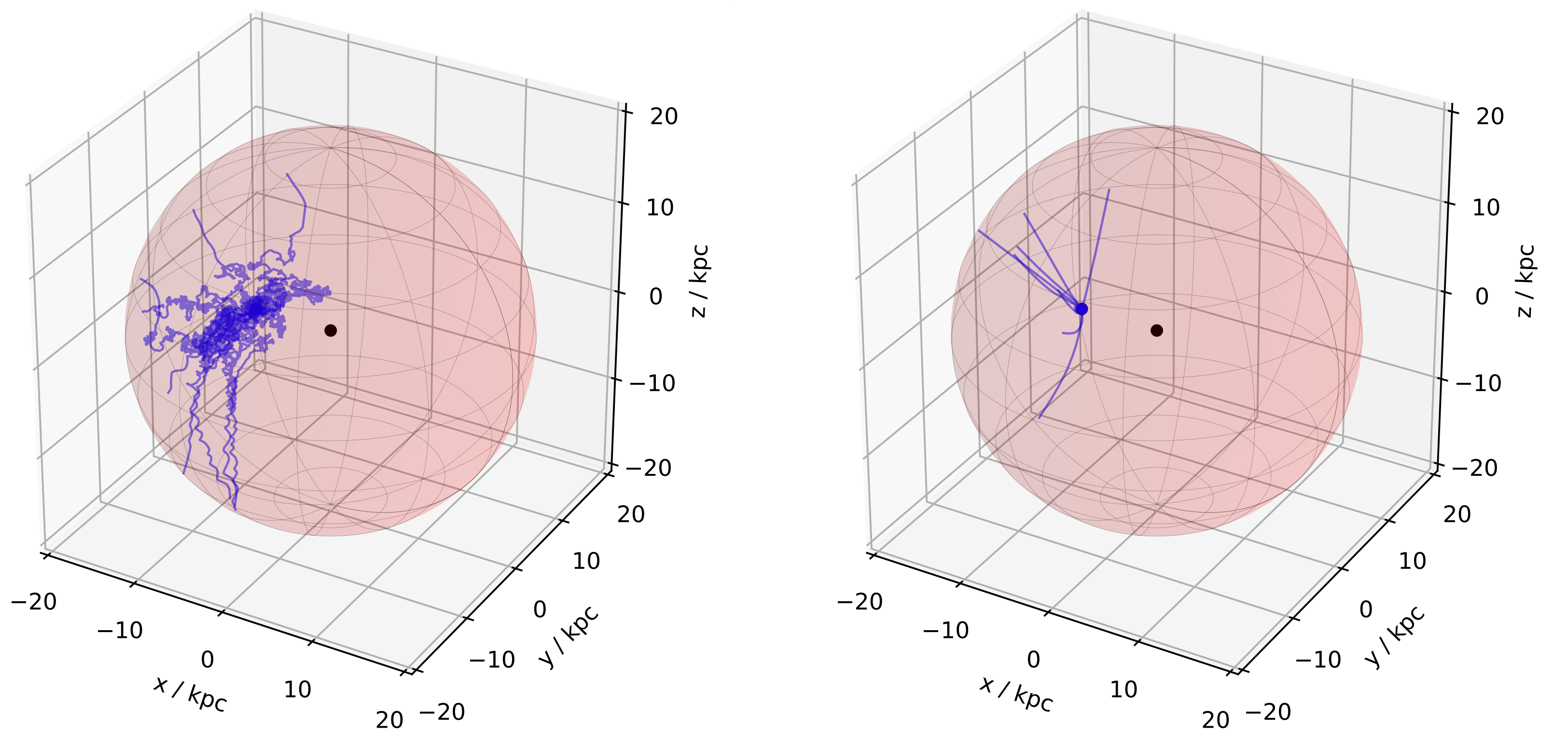


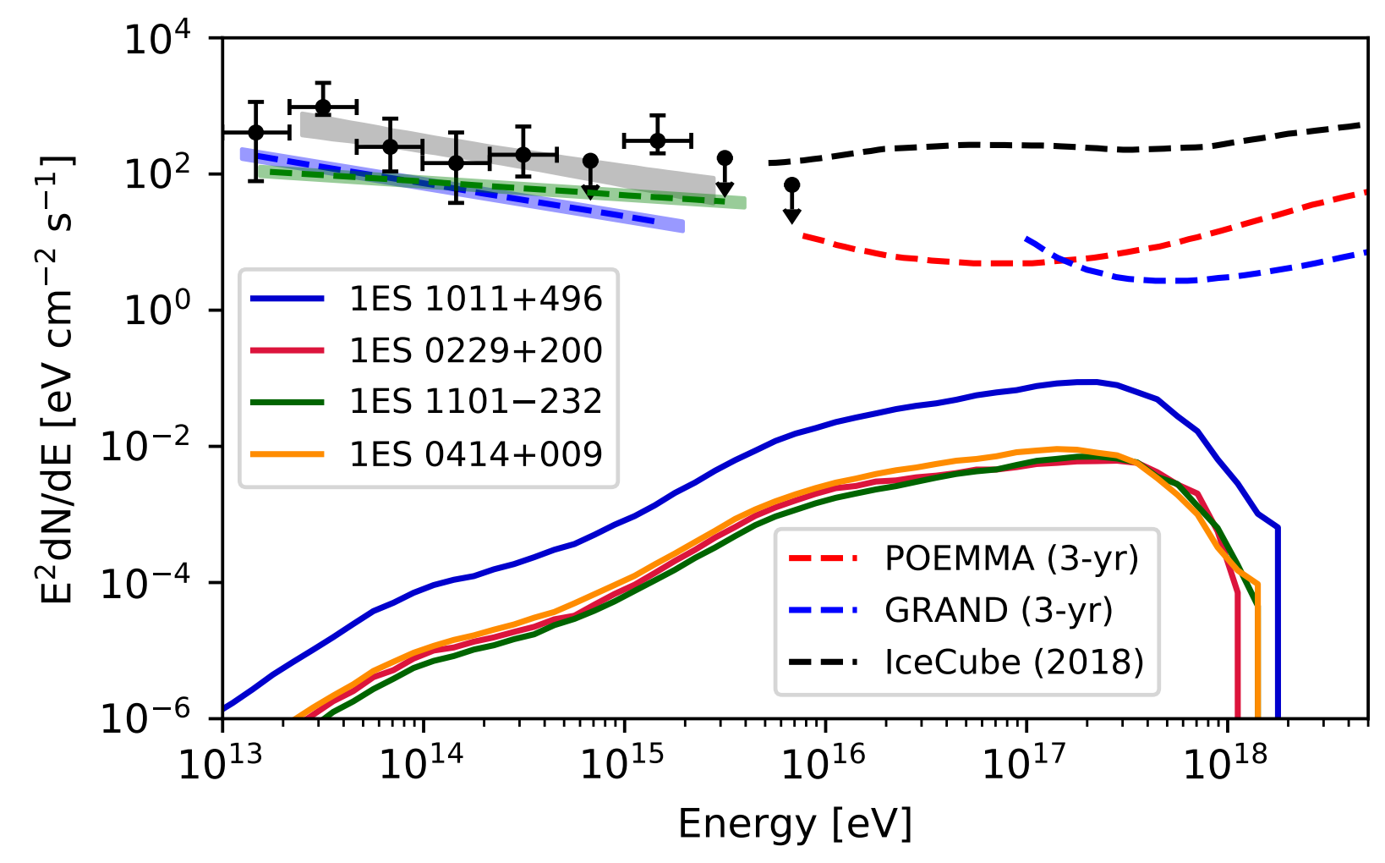
Figure 3. Multiwavelength SED of the HBLs, modeled using a pure leptonic model (*left*) and a leptonic + hadronic model (*right*). The attenuation due to EBL absorption is also shown.

The luminosity requirement in UHECRs is given as

$$L_{\rm UHECR} = \frac{2\pi d_L^2(1-\cos\theta_{\rm jet})}{\xi_B f_{\rm CR}}\int_{\epsilon_{\gamma,\rm min}}^{\epsilon_{\gamma,\rm max}} \epsilon_\gamma \frac{dN}{d\epsilon_\gamma dAdt} d\epsilon_\gamma \qquad (6)$$

(E) UHECRs and secondary neutrinos





Top: UHECR trajectory in GMF for $E_{p,\rm max} = 0.1$ (left) & 10 EeV (right)

- Neutrino flux is too low for detection by current instruments.
- A simultaneous observation of p, γ, and ν is difficult.

References

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