A Lepto-Hadronic Model of γ-ray Signal From Extreme Blazars

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Obscured AGN

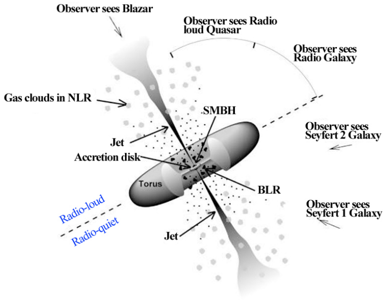
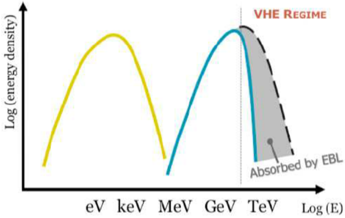


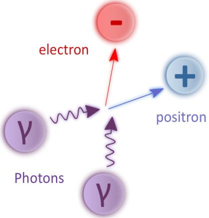
Figure: Schematic representation of the AGN physical model, illustrating the broad scales of the key regions. (Image: Urry and Padovani, PASP 107 (1995) 803)



1. LE peak: Synchrotron emission of relativistic electrons

2. HE peak: Inverse-Compton (IC) scattering of synch photons, or external photons (AD, DT, BLR)

Leptonic model



$\boxed{\gamma + \gamma_{\rm bg} \rightarrow {\rm e}^{+} + {\rm e}^{-}}$ *Breit-Wheeler Process*

γ-rays collides with EBL photons

Annihilated by $\rm e^{+}e^{-}$ pair production

$$\boxed{\epsilon_\gamma \epsilon_{\rm bg} \geqslant = \frac{2 m_e^2 c^4}{\epsilon_\gamma (1 - \cos\theta)}}$$

Prominent for very-high-energy γ-rays
VHE; $E > 30$ GeV (eg., blazars)

Probability of absorption, $\exp(-\tau) \propto \begin{cases} \epsilon_\gamma \\ z \end{cases}$

UHECR interactions

AGNs are also a potential candidate class of
ultrahigh-energy cosmic-ray ($E \gtrsim 10^{17}$ eV) acceleration

Initial state	**Target field**	**Process**	**Secondaries**
Nuclei	CBR	Pair-production (Bethe-Heiler)	$\mathrm{e}^{\pm}$
Nuclei	CBR	Photopion production	$p, n, \nu, \mathrm{e}^{\pm}, \gamma$
Nuclei	CBR	Photodisintegration	$p, n,^{3} He, \alpha, \gamma$
Nuclei	–	Nuclear decay	$p, n, \nu, e^{\pm}, \gamma$

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Photons	CBR	Pair-production (Breit-Wheeler)	$\mathrm{e}^{\pm}$
Photons	CBR	Double pair-production	$\mathrm{e}^{\pm}$
Electrons	CBR	Triplet pair-production	$\mathrm{e}^{\pm}$
Electrons	CBR	Inverse Compton scattering	γ
Electrons	B-field	Synchrotron radiation	γ

Lepto-hadronic model

1. EM cascade initiated by secondary $\mathrm{e}^{\pm}$ can produce secondary γ-ray spectrum that peaks at ~ 1 TeV energies, and extends down to GeV energies.

2. UHECR horizon is limited by interactions with CMB and EBL, to $\sim$1 Gpc at $E \approx 10^{19}$ eV, dropping to ~ 100 Mpc at $E > 5 \times 10^{19}$ eV.

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1. EM cascade initiated by secondary $\mathrm{e}^{\pm}$ can produce secondary γ-ray spectrum that peaks at ~ 1 TeV energies, and extends down to GeV energies.

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3. Deflections in Galactic & extragalactic magnetic fields must be such that, a substantial fraction of UHECRs survive along the line-of-sight.

4. The interaction timescale of UHECRs must be longer than escape timescales inside the acceleration region. Also, $L_{\mathrm{e}} + L_B + LCR < L_{\mathrm{Edd}}$ of the SMBH.

Deflections in EGMF

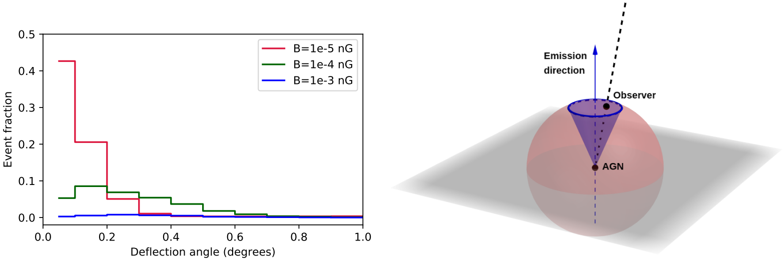


Figure: *Left*: Survival rate of UHECRs as a function of the angle from line-of-sight. *Right:* Schematic diagram of blazar emission geometry. (Image: S. Das, N. Gupta, S. Razzaque; *Astrophys. J.* **884** (2020) 149)

$$\Phi_{\mathrm{rms}} \approx 4^\circ \frac{60\ \mathrm{EeV}}{E/Z} \frac{B_{\mathrm{rms}}}{10^{-9}\ \mathrm{G}} \sqrt{\frac{D}{100\ \mathrm{Mpc}}} \sqrt{\frac{l_c}{1\ \mathrm{Mpc}}} \tag{1}$$

A 60 EeV proton traveling a distance of 50 Mpc undergoes a deflection of few degrees in an EGMF of rms value 1 nG.

Interaction timescales

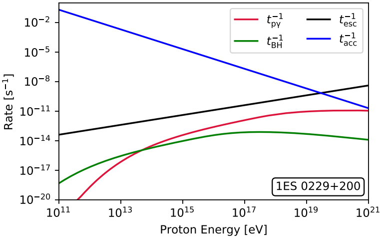


Figure: Timescale of photohadronic interactions inside the jet, with target photons from synchrotron and IC emission. (Image: S. Das, N. Gupta, S. Razzaque; *Astrophys. J.* **884** (2020) 149)

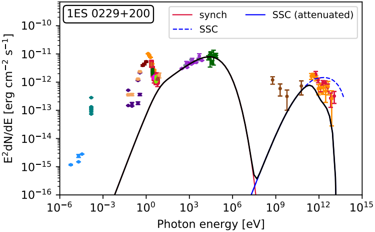
$$\frac{1}{t_{\mathrm{p}\gamma}} = \frac{c}{2\gamma_p^2} \int_{\epsilon_{th}/2\gamma_p}^{\infty} d\epsilon'_\gamma \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma} \times \int_{\epsilon_{th}}^{2\epsilon\gamma_p} d\epsilon_r \sigma(\epsilon_r) K(\epsilon_r) \epsilon_r \qquad (2)$$

$$t^p_{\mathrm{esc}} = \frac{R^2}{4D}; \quad D = D_0(E/E_0)^{2-q} \qquad (3)$$

$$t^p_{\mathrm{acc}} \simeq \frac{20\eta}{3}\frac{r_L}{c} \simeq \frac{20\eta}{3}\frac{\gamma_p m_p c}{eB} \qquad (4)$$

Under Bohm diffusion consition, $D = \eta r_L c/3$. Particles can be more diffusive than this, and we consider the Kraichnan model of diffusion ($q = 3/2$).

Multiwavelength SEDs



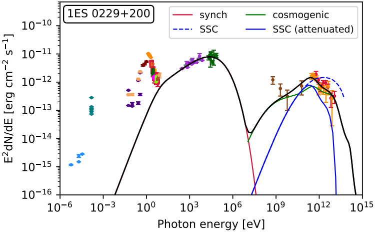


Figure: Multiwavelength spectrum of the HBLs, modeled using a pure leptonic model (*left*) and a leptonic + hadronic model (*right*). The attenuation due to EBL absorption is also shown. (Image: S. Das, N. Gupta, S. Razzaque; *Astrophys. J.* **884** (2020) 149)

$$L_{\mathrm{UHECR}} = \frac{2\pi d_L^2(1-\cos\theta_{\mathrm{jet}})}{\xi_B f_{\mathrm{CR}}} \int_{\epsilon_{\gamma,\mathrm{min}}}^{\epsilon_{\gamma,\mathrm{max}}} \epsilon_\gamma \frac{dN}{d\epsilon_\gamma dA dt} d\epsilon_\gamma \tag{5}$$

ξ_B → Survival rate of UHECRs within $0^\circ.1$ of the direction of propagation

f_{CR} → Ratio of the power in secondary photons to injected UHECR power

Deflections in GMF

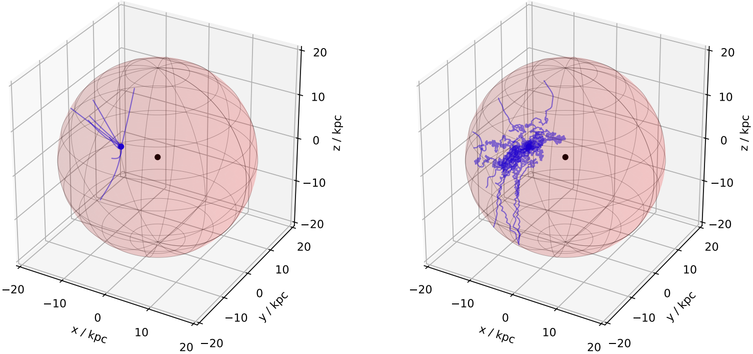


Figure: Backtracking simulations of 10 UHECR protons in the Jansson and Farrar magnetic field for E =10 EeV (left) and $E = 0.1$ EeV (right). Image: S. Das, N. Gupta, S. Razzaque; Astrophys. J. 2020

UHECRs & Secondary Neutrinos

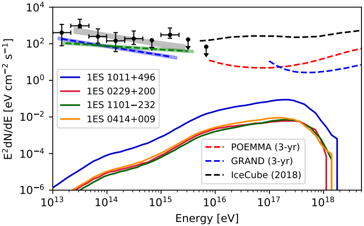


Figure: All-flavor neutrino flux at Earth produced in the same UHECR interactions as producing EM particles. (Image: S. Das, N. Gupta, S. Razzaque; *Astrophys. J.* **884** (2020) 149)

Number of UHECR events arriving at Earth

$$N_{\mathrm{evt,p}} = \frac{1}{\xi_B}\frac{\Xi\omega(\delta)}{\Omega}\int_{E_{\mathrm{th}}^{\mathrm{obs}}}^{E_{\mathrm{max}}^{\mathrm{obs}}} \frac{dN}{dE}dE \qquad (6)$$

Luminosity in neutrinos is constrained by the luminosity in UHECRs

$$L_\nu = L_{\mathrm{UHECR}} \times f_{\mathrm{CR}\to\nu} \times \xi_B \qquad (7)$$

$f_{\mathrm{CR}\to\nu}$ is the ratio of the power in secondary neutrinos to injected UHECR power

Summary

1. $\gamma-$rays produced in hadronic channels can explain the observed VHE spectrum from high frequency peaked BL Lacertae objects.
2. The distance of the sources must be such that a significant fraction of secondary particles reach Earth before they are scattered.

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1. $\gamma-$rays produced in hadronic channels can explain the observed VHE spectrum from high frequency peaked BL Lacertae objects.
2. The distance of the sources must be such that a significant fraction of secondary particles reach Earth before they are scattered.
3. The magnetic field plays an important role in the secondary flux from line-of-sight UHECR interactions – upper limits can be deduced.
4. Detection of UHECRs and neutrinos, from such point sources, by current and upcoming detectors is insignificant.