

Modeling the multiwavelength emission from blazar TXS 0506+056

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Obscured AGN

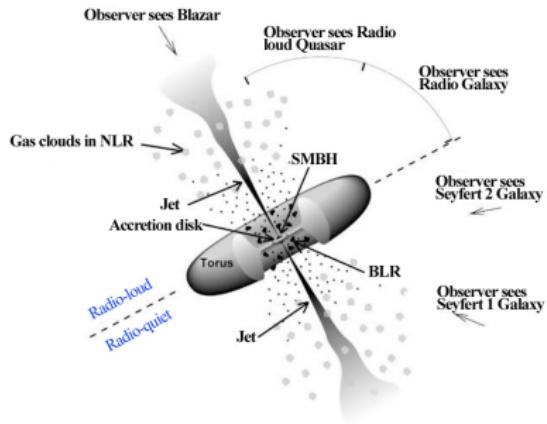
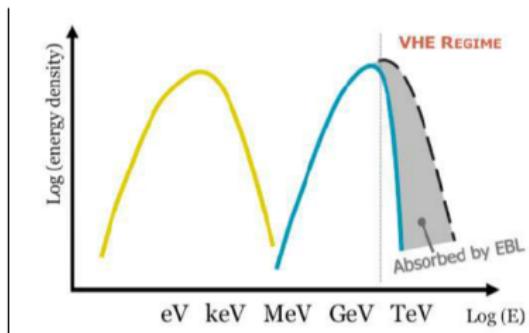
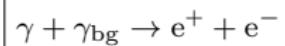
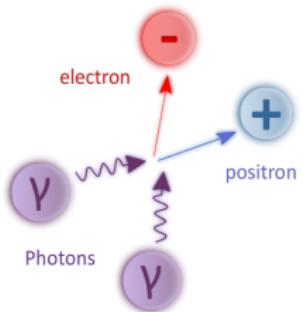


Figure: Schematic representation of the AGN physical model, illustrating the broad scales of the key regions.
(Image: Urry and Padovani, PASP 107 (1995) 803)



- 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



Breit-Wheeler Process

γ -rays collides with EBL photons

Annihilated by e^+e^- pair production

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

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

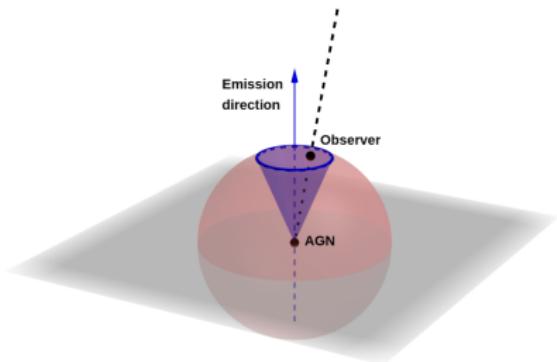
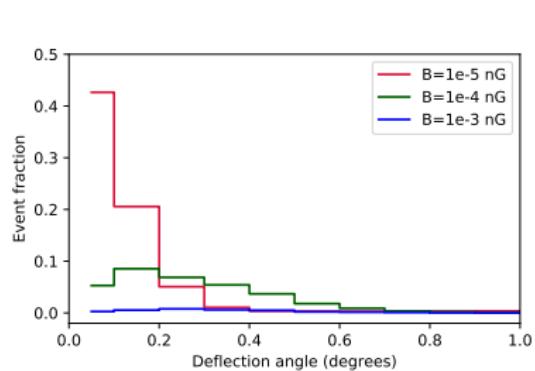
AGNs are also a potential candidate class of
ultrahigh-energy cosmic-ray ($E \gtrsim 10^{17}$ eV) acceleration

Initial state	Target field	Process	Secondaries
Nuclei	CBR	Pair-production (Bethe-Heiler)	e^\pm
Nuclei	CBR	Photopion production	p, n, ν, e^\pm, γ
Nuclei	CBR	Photodisintegration	$p, n, {}^3He, \alpha, \gamma$
Nuclei	-	Nuclear decay	p, n, ν, e^\pm, γ
Photons	CBR	Pair-production (Breit-Wheeler)	e^\pm
Photons	CBR	Double pair-production	e^\pm
Electrons	CBR	Triplet pair-production	e^\pm
Electrons	CBR	Inverse Compton scattering	γ
Electrons	B-field	Synchrotron radiation	γ

Lepto-hadronic model

- ① EM cascade initiated by secondary 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 ~ 1 Gpc at $E \approx 10^{19}$ eV, dropping to ~ 100 Mpc at $E > 5 \times 10^{19}$ eV.
- 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, $L_e + L_B + L_p < L_{\text{Edd}}$ of the SMBH.

Deflections in EGMF



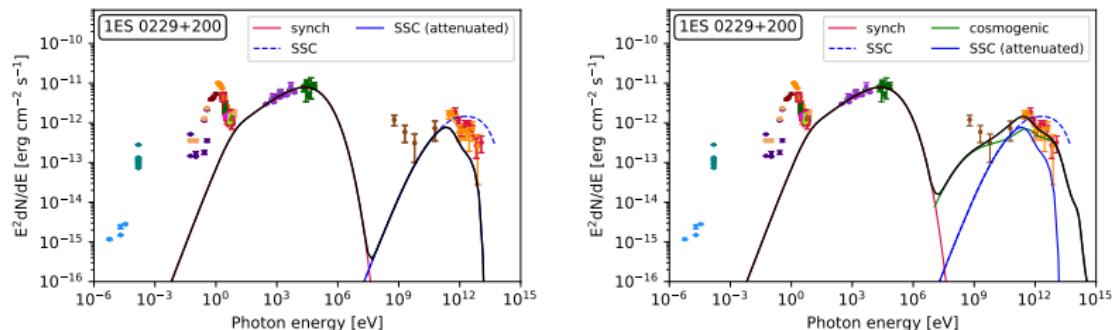
[Das, Gupta, Razzaque; ApJ 2020]

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

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

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

Multiwavelength SEDs



[Das, Gupta, Razzaque; ApJ 2020]

Figure: Multiwavelength SED of the HBLs; pure leptonic model (*left*) and a leptonic + hadronic model (*right*).

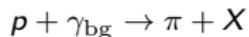
$$L_{\text{UHECR}} = \frac{2\pi d_L^2(1 - \cos \theta_{\text{jet}})}{\xi_B f_{\text{CR}}} \int_{\epsilon_{\gamma,\min}}^{\epsilon_{\gamma,\max}} \epsilon_{\gamma} \frac{dN}{d\epsilon_{\gamma} dA dt} d\epsilon_{\gamma} \quad (2)$$

$\xi_B \rightarrow$ Survival rate of UHECRs within $0^\circ.1$ of the direction of propagation

$f_{\text{CR}} \rightarrow$ Ratio of the power in secondary photons to injected UHECR power

Neutrinos from blazar jet

Photopion production



π^0 and π^+ are produced

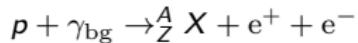
Hadronuclear interaction



π^0, π^+, π^- are produced

$$\begin{aligned}\pi^0 &\rightarrow 2\gamma, & \pi^+ &\rightarrow \mu^+ + \nu_\mu, & \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ \mu^+ &\rightarrow e^+ + \bar{\nu}_\mu + \nu_e, & \mu^- &\rightarrow e^- + \nu_\mu + \bar{\nu}_e\end{aligned}$$

Pair-production



- π^0 -decay γ -rays undergo $\gamma\gamma$ pair production with soft photons from leptonic emission and external photons ($\gamma\gamma \rightarrow e^+ e^-$)

- γ -ray attenuation at TeV energies $Q'_{\gamma, \text{esc}}(\epsilon'_\gamma) = Q'_{\gamma, \pi}(\epsilon'_\gamma)(1 - \exp(-\tau_{\gamma\gamma})) / \tau_{\gamma\gamma}$
- Secondary cascade radiation contributes to the SED, constraining neutrino flux

TXS 0506+056

- Recently, the MAGIC collaboration has analyzed data from a long-term (Nov 2017 – Feb 2019) multi-wavelength campaign of the γ -ray blazar TXS 0506+056.
- A γ -ray flaring activity was observed by MAGIC during December 2018 in the VHE band ($E \gtrsim 100$ GeV). No neutrino event was detected.
- We model the observed SED using one-zone leptohadronic emission considering $p\gamma$ interaction of shock-accelerated protons with the leptonic emission
- **We check the plausibility of cosmogenic γ -ray contribution at multi-TeV energies**

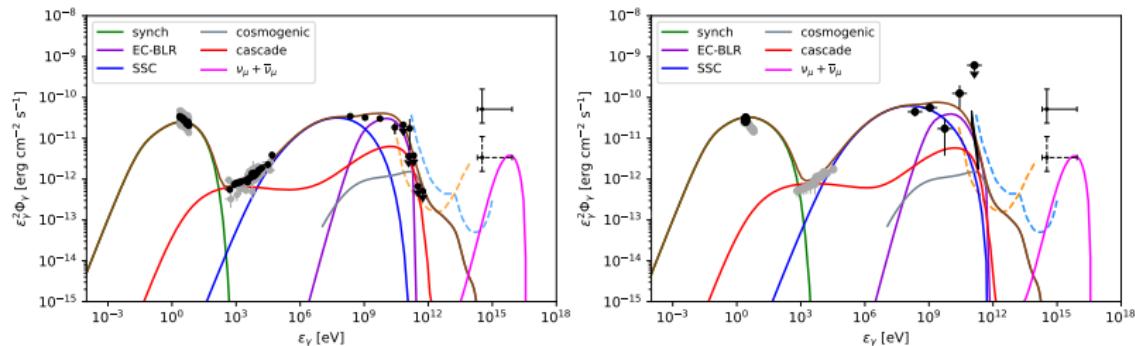
Model considerations

- Log-parabola electron injection – undergoes SYN and SSC/ IC emission
- The relativistic protons interact inside the jet → spectrum cut off at certain energy

An external blackbody photon field of peak energy $\epsilon \simeq m_\pi m_p c^4 / 20E_\nu \simeq 440$ eV, i.e., in the UV to soft X-ray energy band, is required, to maximize the neutrino production

- Kinetic power in protons interacting inside the jet, L_p gives the normalization, used to calculate the luminosity in UHE protons
- We assume the protons escape efficiently beyond this energy up to $\sim 10^{20}$ eV – quasi-ballistic propagation \implies faster escape at higher rigidities

Multiwavelength SED



[Das, Gupta, Razzaque; A&A 2022 (under review)]

Figure: MWL SED of TXS 0506+056, in the low state and high state including (i) leptonic emission (ii) $p\gamma$ processes inside the jet (iii) line-of-sight UHECR interactions

Parameters	Low State	High State	Parameters	Low State	High State
δ_D	28	"	$E'_{e,\min}$ [GeV]	0.20	0.25
B' [G]	0.28	"	$E'_{e,\max}$ [GeV]	10	25
R' [cm]	10^{16}	"	L_e [erg/s]	5.8×10^{44}	7.6×10^{44}
u'_{ext} [erg/cm³]	0.01	"	$E'_{p,\min}$ [GeV]	10	"
T' [K]	2×10^5	"	$E'_{p,\max}$ [PeV]	6.3	"
α (e/p spectral index)	2.0	"	L_p [erg/s]	1.6×10^{48}	"

Cosmogenic neutrinos

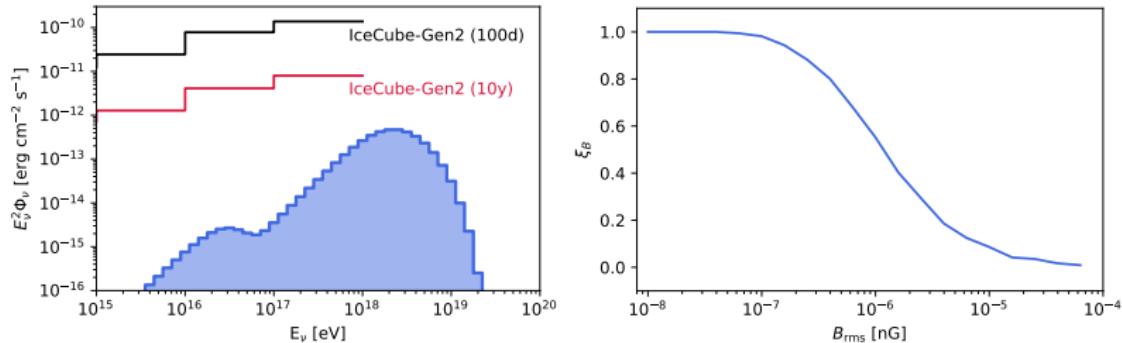


Figure: Cosmogenic neutrino spectrum using the same normalization as obtained for the γ -rays

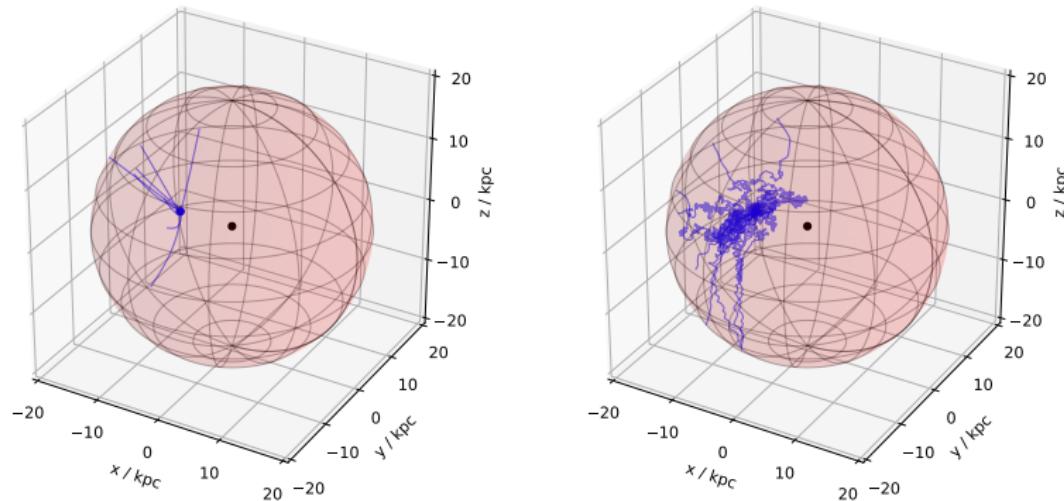
[Das, Gupta, Razzaque; A&A 2022 (under review)]

- The maximum flux of cosmogenic γ -rays allowed by the SED for fixed value of L_{uhep} and f_{CR} gives the value of ξ_B , which constrains B_{rms}

$$\frac{L_{\text{UHE}p}}{4\pi d_L^2} = \frac{1}{\xi_B f_{\gamma,p}} \int_{\epsilon_{\gamma,\min}}^{\epsilon_{\gamma,\max}} \epsilon_{\gamma} \frac{dn}{d\epsilon_{\gamma} dAdt} d\epsilon_{\gamma} \quad (3)$$

- The resulting cosmogenic ν spectrum is below the 10-yr sensitivity of IceCube-Gen2 for this source at EeV energies

Deflections in GMF



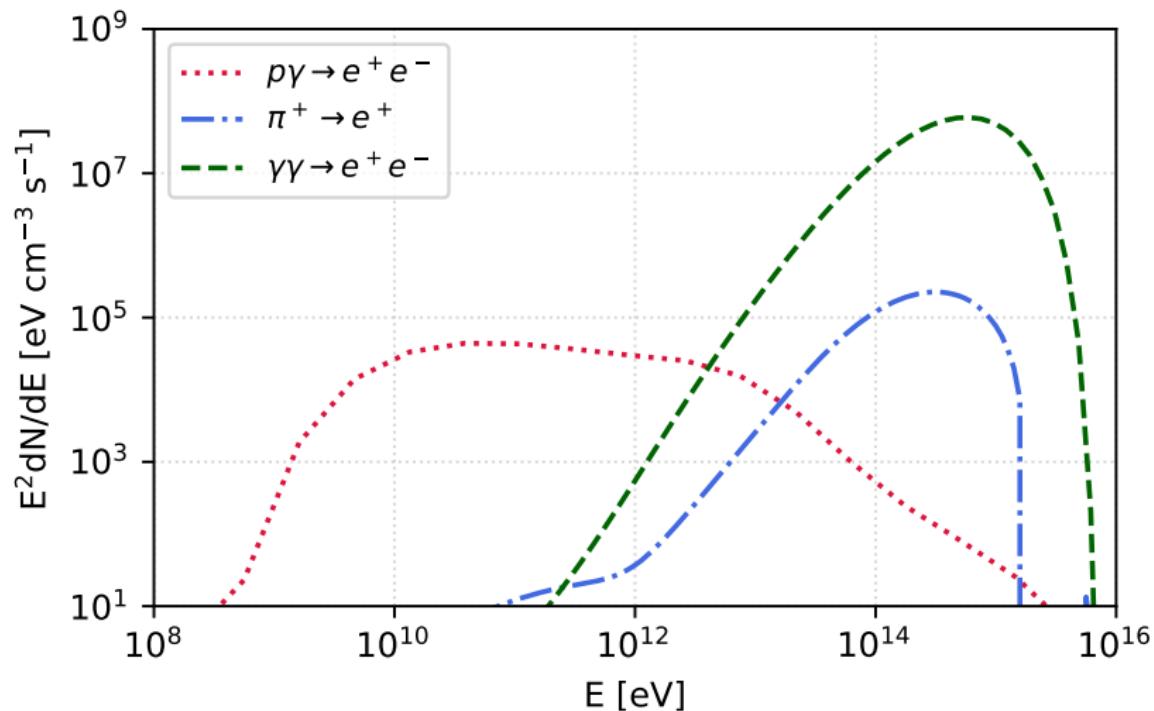
[Das, Gupta, Razzaque; ApJ 2020]

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).

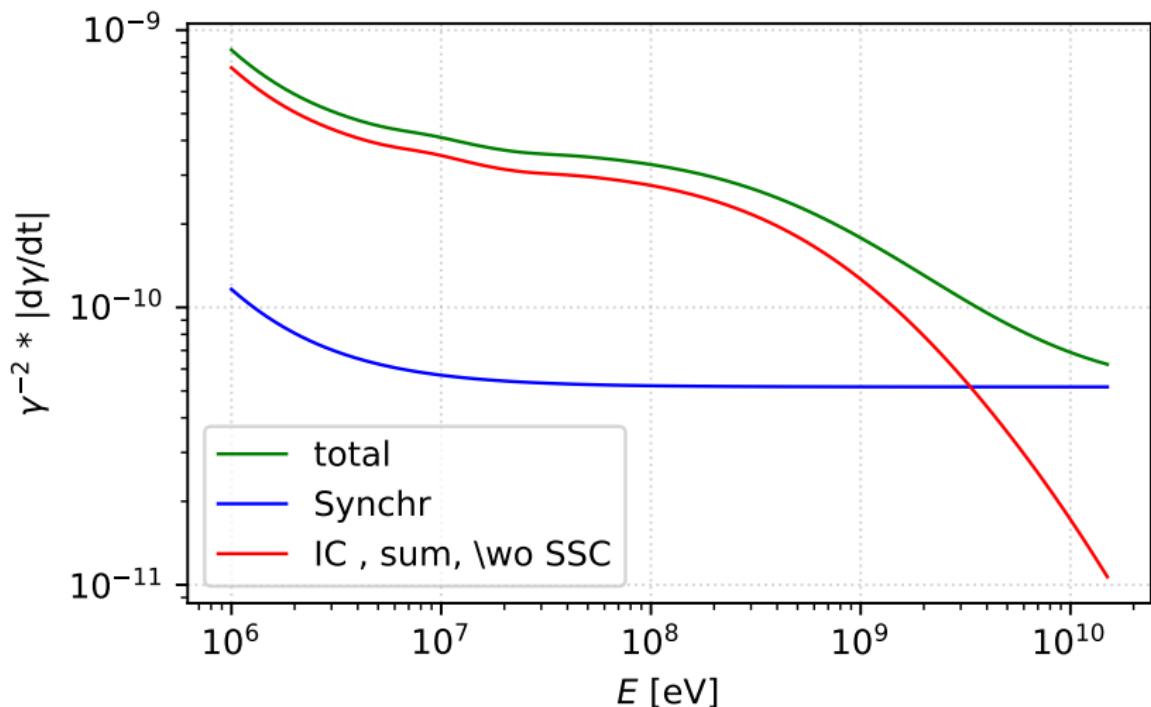
Concluding Remarks

- The neutrino event rate is $\mathcal{N}_{\nu_\mu + \bar{\nu}_\mu} = 1 \times (\Delta T / 7.5 \text{ yrs})$ and increased γ -ray activity does not yield an increased neutrino flux
- Leptonic emission from the jet dominates the GeV range – cascade emission from CR interactions in the jet contributes to the X-ray and VHE range.
- The line-of-sight cosmogenic γ rays from UHECRs produce a hardening in the VHE spectrum – CTA should be able to constrain such a scenario
- Cosmogenic γ -ray flux bounds the RMS value of the EGMF to $\gtrsim 10^{-5}$ nG. The cosmogenic ν flux is < IceCube-Gen2 detection potential for 10 yrs of obs.

Secondary electrons



Cascade loss rate



Interaction timescales

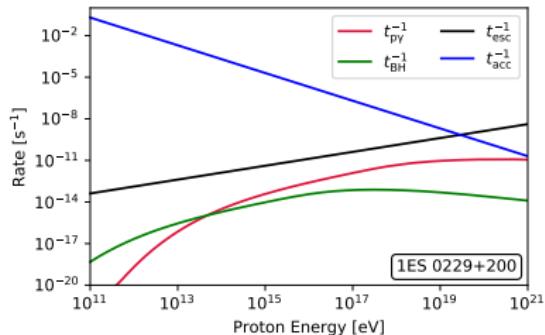


Figure: Timescale of photohadronic interactions inside the jet, with target photons from synchrotron and IC emission. (Image: S. Das, N. Gupta, S. Razzaque; *Astrophys. J.* **884** (2020) 149)

$$\frac{1}{t_{p\gamma}} = \frac{c}{2\gamma_p^2} \int_{\epsilon_{th}/2\gamma_p}^{\infty} d\epsilon'_\gamma \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma} \times \int_{\epsilon_{th}}^{2\epsilon\gamma_p} d\epsilon_r \sigma(\epsilon_r) K(\epsilon_r) \epsilon_r \quad (4)$$

$$t_{esc}^p = \frac{R^2}{4D}; \quad D = D_0(E/E_0)^{2-q} \quad (5)$$

$$t_{acc}^p \simeq \frac{20\eta}{3} \frac{r_L}{c} \simeq \frac{20\eta}{3} \frac{\gamma_p m_p c}{eB} \quad (6)$$

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

UHECRs & Secondary Neutrinos

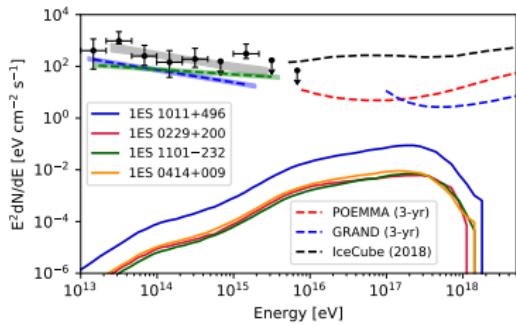


Figure: All-flavor neutrino flux at Earth produced in the same UHECR interactions as producing EM particles.
(Image: S. Das, N. Gupta, S. Razzaque; *Astrophys. J.* **884** (2020) 149)

Number of UHECR events arriving at Earth

$$N_{\text{evt,p}} = \frac{1}{\xi_B} \frac{\Xi \omega(\delta)}{\Omega} \int_{E_{\text{th}}^{\text{obs}}}^{E_{\text{max}}^{\text{obs}}} \frac{dN}{dE} dE \quad (7)$$

Luminosity in neutrinos is constrained by the luminosity in UHECRs

$$L_\nu = L_{\text{UHECR}} \times f_{\text{CR} \rightarrow \nu} \times \xi_B \quad (8)$$

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