TeV-PeV neutrinos from AGN coronae

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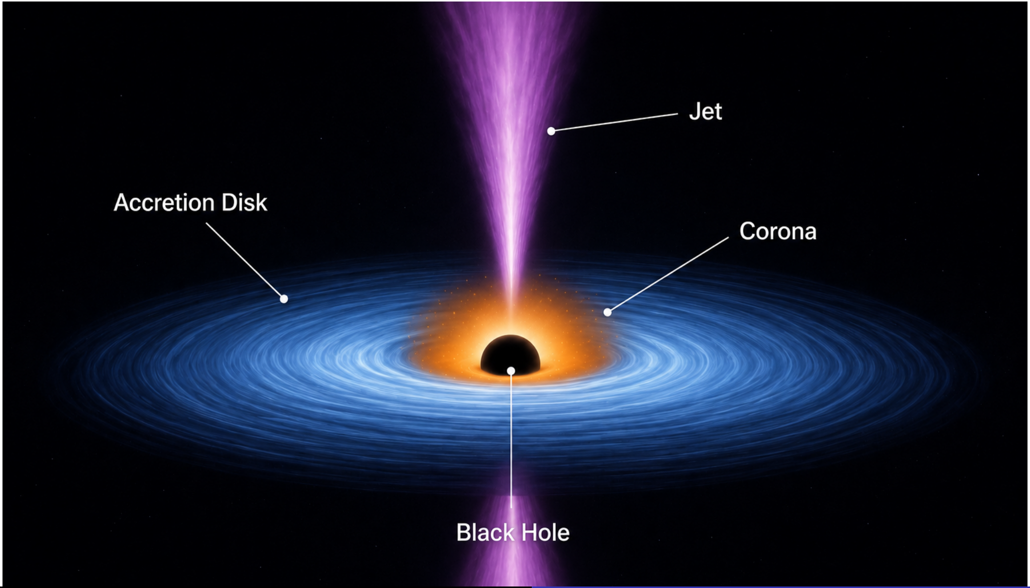
Questions

- Is it possible to explain TeV-PeV neutrinos in coronal scenario?
- Which classes of AGN are more neutrino-loud?
- For which parameters is it possible?
- Technical details
- Results

AGN



Coronal spectrum

$$F(x) = \int_0^\infty \frac{1}{x_0} G(x, x_0) f(x_0) dx_0, \quad (1)$$

$G(x, x_0)$ - Green function given in *Sunyaev, Titarchuk (1980)*

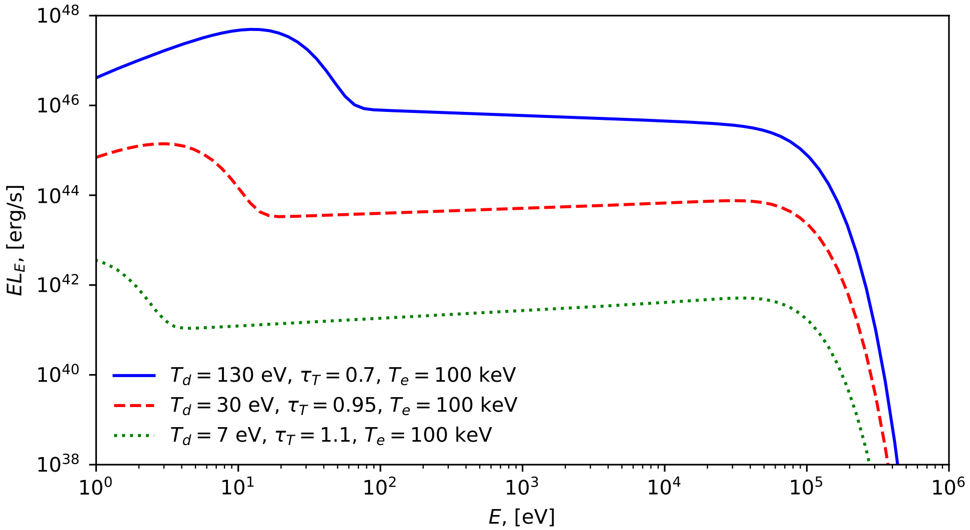
$$G(x, x_0) = \frac{\alpha(\alpha+3)}{\Gamma(2\alpha+4)} \left(\frac{x_0}{x}\right)^\alpha \exp(-x) \times \int_0^\infty t^{\alpha-1} \exp(-t)(x+t)^{\alpha+3} dt, \quad (2)$$

$f(x_0)$ - spectrum of soft photons (accretion disk in our case)

relativistic correction, *Pozdnyakov et al. (1983)*

$$\alpha = \frac{-\lg \tau_T + 2/(n+3)}{\lg(12n^2 + 25n)}, \qquad n = T_e/m_e \quad (3)$$

Model SED



10^{48}
10^{46}
10^{44}
10^{42}
10^{40}
10^{38}
EL_E, [erg/s]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
E, [eV]
$T_d = 130$ eV, $\tau_T = 0.7$, $T_e = 100$ keV
$T_d = 30$ eV, $\tau_T = 0.95$, $T_e = 100$ keV
$T_d = 7$ eV, $\tau_T = 1.1$, $T_e = 100$ keV

Acceleration

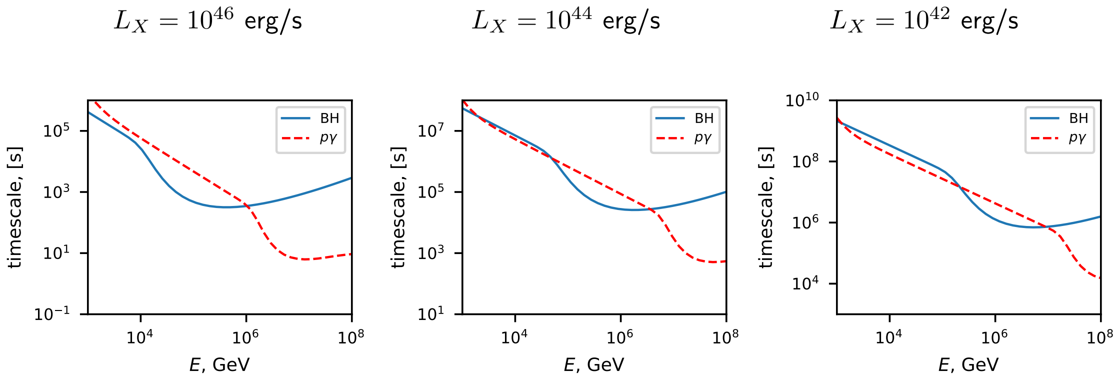
Proton injection spectrum

$$j \propto E^{-1}, \quad E < E_{\text{max}} \tag{4}$$

Proton spectral index is motivated by recent PIC simulations *Kisaka et al. (2020)*

We focus on accelerated protons with $E_{\text{max}} \sim$ 10-100 PeV, which corresponds to a threshold photon energy of 1-10 eV.

Timescales



energy-loss timescale

$$t^{-1} = \int d\Omega \int dE \, (1 - \cos\theta) n(\mathbf{p}, r, z) \sigma(\epsilon_r) K(\epsilon_r), \quad (5)$$

Monte-Carlo. Sampling

Method proposed in *Kalashev et al. (2015)* but for the accretion disk only. We extend this approach to incorporate the coronal component.

Proton path

$$\tau_j = \int_{z_{j-1}}^{z_j} R(E,z)dz, \quad \text{where } \tau_j = -\log \xi_1 \tag{6}$$

Angle of interaction

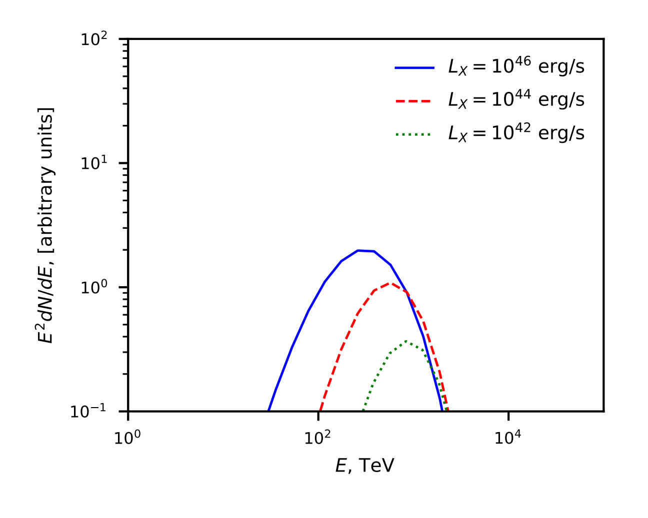
$$\xi_2 = \frac{1}{R(E,z_j)} \int_{r_g}^{r_j} r dr R(E,z_j,r), \quad \cos\theta_j = z_j/\sqrt{z_j^2 + r_j^2} \tag{7}$$

Photon energy

$$\xi_3 = \frac{1}{R(E,z_j,r_j)} \frac{1-\cos\theta_j}{z_j^2 + r_j^2} \int_0^{p_j} dp p^2 n(p,z_j,r_j)\sigma(\epsilon_r) \tag{8}$$

Neutrino spectrum in rest frame

$E_{\text{max}} = 10$ PeV



Diffuse neutrino flux

Integration over sources

$$\Phi_\nu(E) = \frac{c}{4\pi H_0} \int dz \frac{1}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}} \int d\log L_X \frac{d\rho(z, L_X)}{d\log L_X} \frac{L_\nu(E', L_X)}{E'}, \quad (9)$$

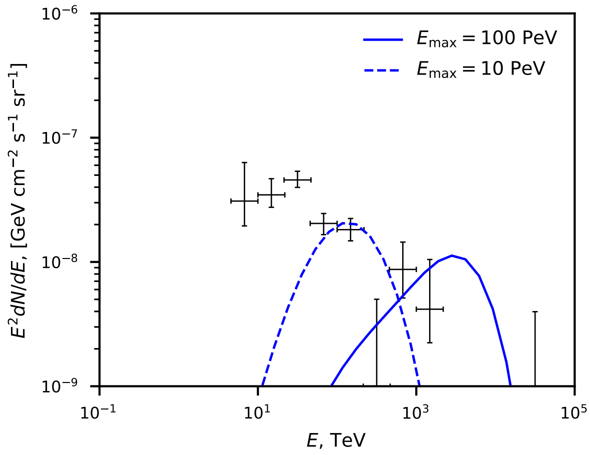
where $d\rho/d\log L_X$ is the X-ray luminosity function provided for example in *Ueda et al. (2014)*

Normalization

We assume a direct proportionality between neutrino luminosity and X-ray luminosity: $L_\nu \propto L_X$. The computed neutrino flux is then normalized to the IceCube diffuse flux. The resulting normalization factor implies $L_\nu \approx 0.1 L_X$ i.e., the neutrino luminosity is about 10% of the X-ray luminosity.

Diffuse neutrino spectrum

$L_\nu \approx 0.1 L_X$



Generalization of the scheme to an arbitrary proton propagation angle

non-zero χ

$$R(E,z,r,\varphi) = \frac{1-\cos\theta}{z^2+r^2-2zr\sin\chi\cos\varphi}\int dpp^2 n(p,z,r)\sigma(\epsilon_r), \tag{10}$$

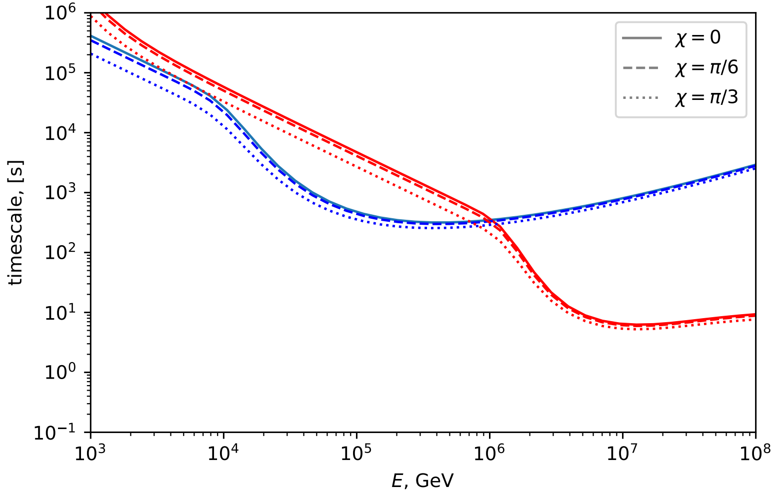
where $\cos\theta = z\cos\chi/\sqrt{z^2+r^2-2zr\sin\chi\cos\varphi}$.

Consequently, a dependence on the azimuthal angle φ emerges, which must also be accounted for in Monte Carlo simulations.

$$\xi = \frac{\int_0^{\varphi_j} d\varphi R(E,z_j,r_j,\varphi)}{\int_0^{2\pi} d\varphi R(E,z_j,r_j,\varphi)}, \tag{11}$$

Angular dependence

Timescales for various proton propagation angles



Conclusions

- The present work demonstrates that the account of the flat corona emission provides conditions for efficient neutrino production in a ~ 50 TeV - sub PeV energy band for reasonable values of the parameters for $p\gamma$ interactions only.

- In the flat corona scenario, the resulting neutrino spectrum is found to be independent of the proton propagation angle.

- The effect might become appreciable if the detailed internal structure of the corona were considered (in progress now)

Acknowledgments

Thank you for your attention!

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BACKUP

turbulence-related effects?

Spatial diffusion

Spatial diffusion mean free path λ (related to the diffusion coefficient by $D = \lambda c/3$) is given by $\lambda = \eta_g E/(eB)$

For our estimates, we adopt $B = 10^3$ G as a plausible value for this acceleration model. The gyrofactor can span a wide range of values; for example, in blazars η_g can be as high as $\sim 10^4$

λ in units of r_g can be in the range $1r_g - 10^2 r_g$ at a typical energy of 10 PeV, where $p\gamma$ interactions dominate over Bethe–Heitler processes.

Mean free path

The mean free path for $p\gamma$ interactions, $\lambda_{p\gamma}$, can be calculated using the relation

$$1 = \int_{z_0}^{\lambda_{p\gamma}} R(z, E) dz \ , \tag{12}$$

Within the framework of the model adopted in this work, $\lambda_{p\gamma} \sim 10^{-3} r_g$, $10^{-1} r_g$, and $10^2 r_g$ for luminosities $L_X = 10^{46}$, 10^{44}, and 10^{42} erg/s, respectively and $E = 10$ PeV.

Gamma rays?

To estimate the spectrum of secondary photons and electrons, one can solve the one-dimensional stationary transport equations. Transport equations incorporating inverse Compton scattering and photon-photon annihilation can be written in the following form for electrons (or positrons):

Transport equation for electrons (positrons)

$$c\frac{\partial n_e}{\partial z} = -n_e(p)\int n_{\mathsf{ph}}(\epsilon)(1-\mu)\frac{d\sigma_{\mathsf{ICS}}}{dp'}\,d\epsilon\,d\mu\,dp' + \int n_e(p')n_{\mathsf{ph}}(\epsilon)(1-\mu)\frac{d\sigma_{\mathsf{ICS}}}{dp}\,d\epsilon\,d\mu\,dp' + \frac{1}{2}\int n_\gamma(p')n_{\mathsf{ph}}(\epsilon)(1-\mu)\frac{d\sigma_{\gamma\gamma}}{dp}\,dp'\,d\mu\,d\epsilon \tag{13}$$

Gamma rays?

and for photons:

Transport eqution for photons

$$c\frac{\partial n_\gamma}{\partial z} = -n_\gamma(p)\int n_{\text{ph}}(\epsilon)(1-\mu)\frac{d\sigma_{\gamma\gamma}}{dp}\,d\epsilon\,d\mu\,dp_1 + \int n_e(p')n_{\text{ph}}(\epsilon)(1-\mu)\frac{d\sigma_{\text{ICS}}}{dp}\,d\epsilon\,d\mu\,dp'. \tag{14}$$