TeV to PeV neutrinos from AGN coronae

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Introduction

High-energy astrophysical neutrinos are one of the important attributes of modern astrophysics because they can contain information about the structure and processes occurring in astrophysical sources. IceCube observes the astrophysical neutrino flux of $\sim 10^{-8}$ GeV cm^{-2}s^{-1}sr^{-1} in the energy range from $\sim$ 1 TeV to $\sim$ 10 PeV with high statistical significance.

The most promising "neutrino loud" sources are considered to be the central regions of active galactic nuclei (AGN), which are of increasing interest as an object of research in the field of high-energy astrophysics. In connection with the collection of statistics by the IceCube experiment, theoretical studies are becoming more and more relevant every year. For example, recent works [1, 3] are devoted to the study of neutrinos from AGN, which contribute to the IceCube spectrum. The calculation method in them is based on the construction of empirical models that borrow information about the radiation spectrum from the fitting of observations. At the same time, a more detailed Monte Carlo calculation of neutrinos from AGN [2] requires updating, since in addition to the accretion disk, the contribution from the hot component, the so-called "corona" of the disk, is important.

The purpose of this paper is to attempt to explain the IceCube spectrum within the framework of model [3] extended by the presence of the hot corona. To do this, we modify the spectrum of the target source photons and model the propagation of protons along a jet using the Monte Carlo approach. Then, using the numerical code based on the solution of the transport equations, we find the final neutrino spectrum from the AGN, taking into account their cosmological evolution.

Disk-Corona model

It is known from a number of observations that AGN are also bright in the X-ray range. One of the possible mechanisms of formation is the presence of the hot component (so-called corona) of electrons with energies $\sim$ 100 keV. Low-energy photons of the disk undergo inverse Compton scattering on the hot electrons, and as a result their frequency increases to X-ray range.

To find the spectrum of the two-component disk-corona system, it is necessary to solve the stationary Kompaneets equation, which describes the Comptonization of radiation on electrons. Assuming that the source of low-energy photons is located inside the electron plasma cloud with electron temperature T_e, the solution can be written as:

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

where $x = p/Te$, is dimensionless photon energy, $f(x)$ is the spectrum of low-frequency (radiation from accretion disc) photons, $G(x, x_0)$ is the Green function given in Appendix which contains information about Thomson optical depth τ_T and temperature T_e

Studying of particle acceleration is not the goal of this work, so we limit ourselves to a simple situation proposed in [2]. According to this assumption, protons are accelerated by an electric field near the vicinity of the SMBH and then released at some point z_0 from it. The proton spectrum at point z_0 is assumed to be proportional to E^{-2}, with a high-energy cut $E_{\max}$. As well as in [2] we assume $z_0 = 2r_g$.

Calculation and results

The spectrum calculation consists of two steps. In the first step, the propagation of protons along the jet axis in the disk-corona radiation field is modeled using the Monte Carlo approach. It is assumed that secondary leptons and photons freely escape from the interaction region, thereby giving an upper limit.

In the second step, we integrate over the AGN taking into account their cosmological evolution:

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

and also do not average on the disk-corona parameters.

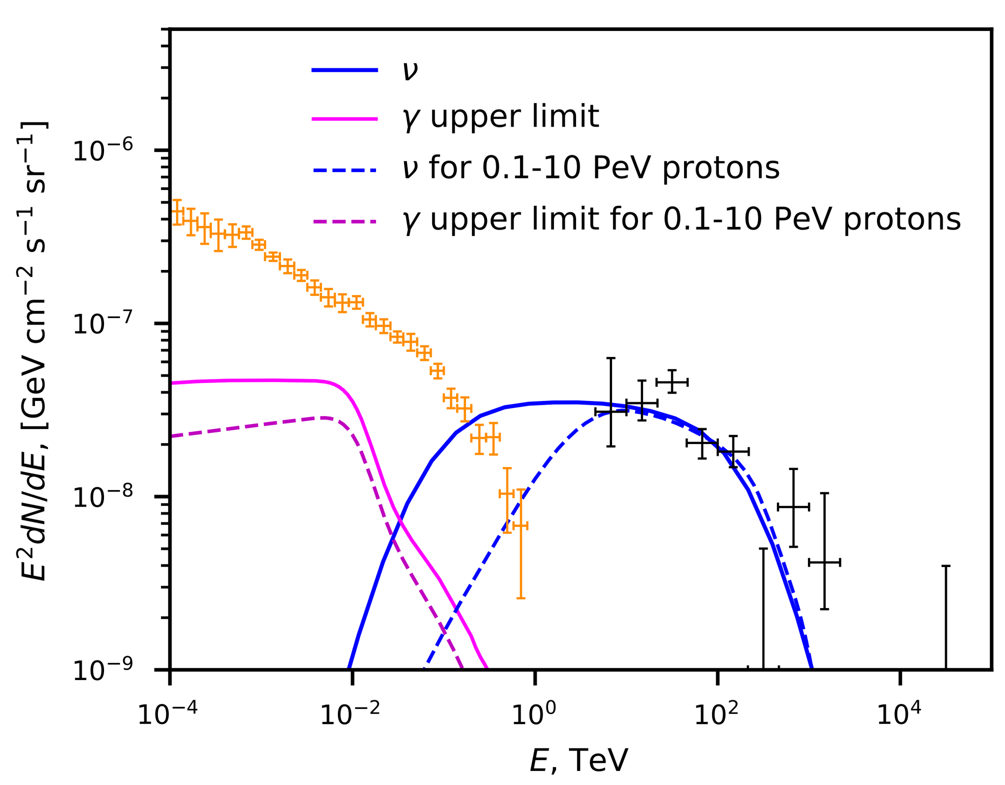

Figure 1. Resulting gamma (magenta) and neutrino (blue) fluxes from the AGN for $T_e = 100$ keV, $T_d = 10$ eV, $\tau_T = 1$ and $E_{\max} = 10$ PeV. The black data points is the IceCube spectrum and orange - cosmic γ ray background measured by the Fermi LAT.

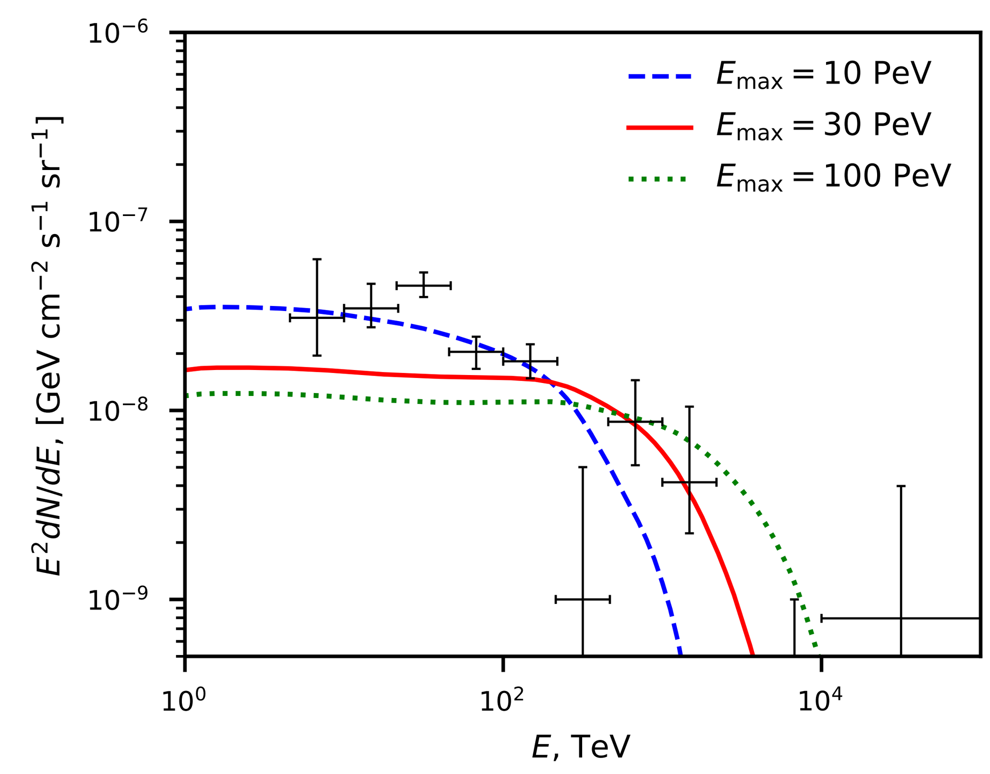

Figure 2. Dependence on $E_{\max}$, $T_e = 100$ keV, $T_d = 10$ eV, $\tau_T = 1$.

Comparisons

A similar calculation, but only for an anisotropic accretion disk with, was made by Kalashev et al. In [3] the spectrum is narrower because the accretion disk photons have an energy $\sim 10 - 100$ eV and therefore this model can explain narrow bumps in the observed spectrum. In [1] and [3] the phenomenological disk-corona models based on the observational spectra of AGN and empirical relations are presented. These papers take magnetic fields into account and consider specific acceleration models. We focus on the propagation of protons inside the jet using the Monte Carlo technique.

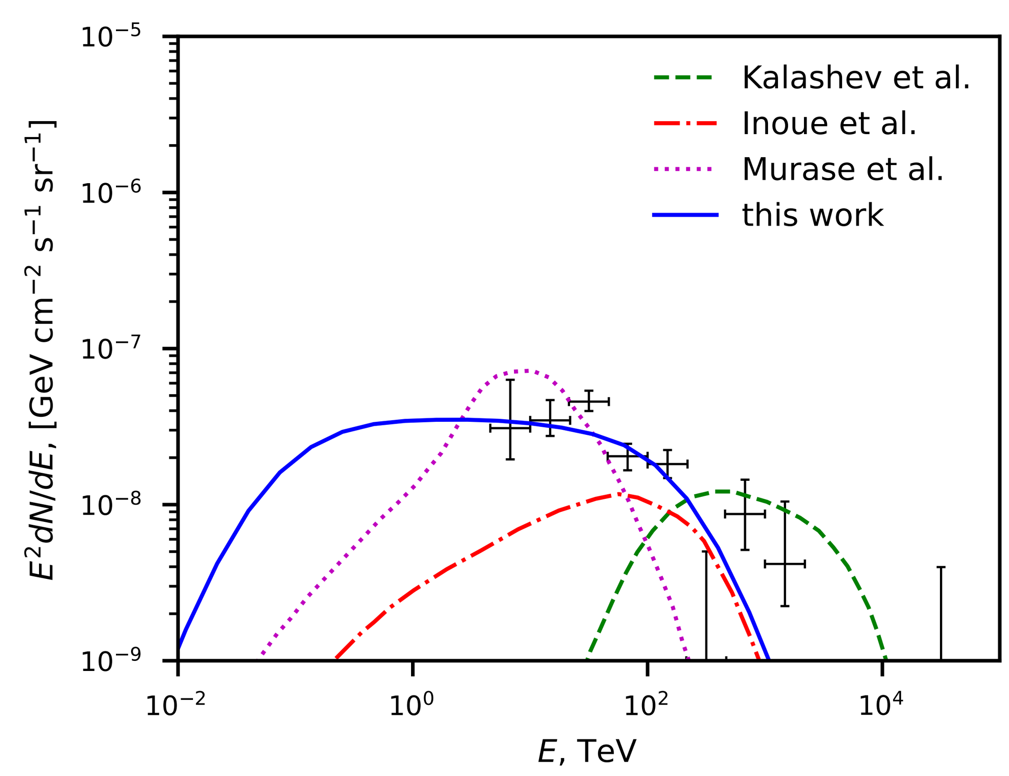

Figure 3. Resulting neutrino fluxes for AGN for various models. The dotted magenta line corresponds [3], green dashed line [2] for $E_{\max} = 100$ PeV and $T_d = 30$ eV, red dash-dotted line is model proposed in [1]. The black data points is the IceCube spectrum. The blue solid line - this work the parameters are the same as in Fig. 1

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Appendix: Corona spectrum

The solution to the problem of radiation Comptonization is described in the pioneering work of Sunyaev&Titarchuk 1980:

$$G(x, x_0) = \frac{\alpha(\alpha+3)}{2\alpha+3} \left(\frac{x}{x_0}\right)^{3+\alpha}, \quad 0 < x < x_0 \tag{2}$$

and for $x \geq x_0$

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

$$\alpha = \left(\frac{9}{4} + \frac{\pi^2 m_e}{3T_e(\tau_T + 2/3)^2}\right)^{1/2} - \frac{3}{2}, \tag{3}$$

m_e is the electron mass and $\Gamma(x)$ is the gamma function.

Note, that the spectral index α given in (3) is correct for $\tau_T \geq 3$ and $T_e \ll m_e$. For weakly relativistic plasma ($T_e \approx 50 - 100$ keV) and for $\tau_T \leq 1$ keV can be used good approximation:

$$\alpha = \frac{-\lg \tau_T + 2/(n+3)}{\lg(12n^2 + 25n)}, \text{where} \quad n = T_e/m_e. \tag{4}$$

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[2] O. Kalashev, D. Semikoz, and I. Tkachev. *J. Exp. Theor. Phys.*, 120(3):541–548, 2015.

[3] Kohta Murase, Shigeo S. Kimura, and Peter Meszaros. *Phys. Rev. Lett.*, 125(1):011101, 2020.