

# EeV neutrinos associated with UHECR sources

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Electromagnetic energy losses of charged pions and muons suppress the expected high energy,  $\gtrsim 10^{18}$  eV, neutrino emission from sources of ultrahigh energy,  $\gtrsim 10^{19}$  eV, cosmic-rays. We show here that  $\gtrsim 10^{19}$  eV photons produced in such sources by neutral pion decay may escape the sources, thanks to the Klein-Nishina suppression of the pair production cross section, and produce  $\mu^\pm$  pairs in interactions with the cosmic microwave background. The flux of muon decay neutrinos, which are expected to be associated in time and direction with the electromagnetic emission from the sources, may reach a few percent of the Waxman-Bahcall bound. Their detection may allow one to directly identify the sources of  $\gtrsim 10^{19}$  eV cosmic-rays, and will provide the most stringent constraints on quantum-gravity-induced Lorentz violation.

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## I. INTRODUCTION

The observed characteristics of cosmic rays with energies exceeding  $10^{19}$  eV [1, 2, 3] suggest that there are cosmologically distributed astrophysical sources that accelerate protons to this high energy [4]. The main candidate sources are gamma-ray bursts (GRBs) and active galactic nuclei (AGN) [4]. The sources of the ultra-high energy cosmic rays (UHECRs) are expected to emit also high energy neutrinos, through the decay of charged pions produced in interactions of high energy protons with the intense radiation fields within the prospective sources [5]. Large neutrino telescopes, both operating and under construction, are expected to reach in the coming few years the sensitivity required for the detection of the predicted high energy neutrino signal [6].

The detection of high energy neutrinos associated spatially and/or temporally with electromagnetic emission from some sources will provide evidence for cosmic ray production in these sources. However, electromagnetic and adiabatic energy losses of charged pions and muons are expected to suppress the neutrino emission at high energy, where the charged particle life time exceeds its energy loss time [7, 8]. For example, in the case of GRBs the neutrino flux is expected to be suppressed above a few PeV [8, 9] to a level which would make it difficult to detect. This would make it difficult to obtain direct evidence for acceleration of protons to energy  $> 10^{19}$  eV.

We discuss here a new type of high energy,  $\gtrsim 10^{18}$  eV, neutrino signal, which is expected to be associated with UHECR sources, and which is not suppressed by the energy losses of charged pions and muons. Neutral pions produced in  $p\gamma$  interactions decay to photons before undergoing significant adiabatic and/or electromagnetic energy loss, since their life time is much shorter than that of charged pions and since they are not trapped by magnetic fields and hardly interact with the plasma and with the radiation field. The resulting high energy,  $\sim 10^{19}$  eV, photons are likely to escape the source, due to the Klein-Nishina suppression of the pair production cross section (see e.g. [10] for a discussion of the GRB case), and may

then produce muon pairs in interactions with cosmic microwave background (CMB) photons. Muon decay leads to the production of high energy,  $\gtrsim 10^{18}$  eV, neutrinos, which are associated, both in direction and in time, with the electromagnetic emission from the sources. High energy neutrino telescopes like ARIANNA [11] may allow one to detect these  $\gtrsim 10^{18}$  eV neutrinos.

In what follows we first discuss  $\mu^\pm$  pair production in interactions of  $\gtrsim 10^{19}$  eV photons with CMB photons, and show that  $\sim 5\%$  of the photon energy is expected to be converted to (prompt) high energy muons. We then discuss the production and escape of  $\gtrsim 10^{19}$  eV photons from GRB sources, as an example of likely sources of UHECRs which despite being optically thick to pair production for 1 GeV to 1 PeV photons, are likely to be optically thin for  $> 10^{19}$  eV photons. Finally, we discuss the expected neutrino flux and spectrum for UHECR sources which, like GRBs, deposit via pion production a significant fraction of the energy of UHECR protons in high energy photons, and which are optically thin for  $> 10^{19}$  eV photons.

## II. $\mu^\pm$ PAIR PRODUCTION IN INTERACTIONS WITH CMB PHOTONS

Consider a photon of energy  $\epsilon$  propagating through an isotropic radiation field with photon number density per unit energy  $dn/d\epsilon$ . The (inverse) mean free path (mfp) for  $e^\pm$  or  $\mu^\pm$  pair production is [8]

$$l^{-1} = \frac{1}{4\epsilon^2} \int_{2mc^2}^{\infty} dE E^3 \sigma(E) \int_{E^2/4\epsilon}^{\infty} dx x^{-2} \frac{dn}{d\epsilon}(\epsilon = x). \quad (1)$$

Here  $\sigma(E)$  is the cross section for interaction with energy  $E$  in the center of momentum frame, and  $m = m_e$  ( $m_\mu$ ) for  $e^\pm$  ( $\mu^\pm$ ) production. For a thermal radiation of temperature  $T$ ,  $dn/d\epsilon = \pi^{-2}(\hbar c)^{-3} \epsilon^2 / [\exp(\epsilon/T) - 1]$ , we

have, using  $u = E^2/4T\varepsilon$ ,

$$l^{-1} = \frac{2T^3}{\pi^2(\hbar c)^3} \int_{(mc^2)^2/4T\varepsilon}^{\infty} du u \sigma(\sqrt{4u\varepsilon T}) \ln \left[ (1 - e^{-u})^{-1} \right]. \quad (2)$$

At low energy,  $\varepsilon < (mc^2)^2/3T_{\text{CMB}} \approx 10^{19}$  eV, muon pair production is possible only in interaction with photons from the high energy tail of the CMB photon distribution, and the  $e^\pm$  pair production mfp,  $l_e$ , is much shorter than the  $\mu^\pm$  pair production mfp,  $l_\mu$ . The two mfp's become comparable at higher energy (note that the cross sections for  $\mu^\pm$  and  $e^\pm$  production are similar for  $E > 2m_\mu c^2$ ). Using eq. (2) we find  $R \equiv l_\mu/l_e = 36, 12, 8.6$  for  $T\varepsilon/(m_\mu c^2)^2 = 1, 3, 5$  respectively, corresponding to  $\varepsilon = (0.4, 1, 2) \times 10^{20}(1+z)^{-1}$  eV (Using  $T = T_{\text{CMB}}(z) = 2.3 \times 10^{-4}(1+z)$  eV). For photons in the energy range of  $\varepsilon \approx 10^{19}(1+z)^{-1}$  eV to  $\varepsilon \approx 10^{20}(1+z)^{-1}$  eV, the fraction of high energy photons converted to  $\mu^\pm$  pairs is thus  $f_\mu = 1/(1+R) \approx 0.03$  to 0.1, and the mfp is  $l_\mu \approx 10^{27}(1+z)^{-3}$  cm.

The fraction of photon energy converted to muons is higher than  $f_\mu$ , due to the following reason. The center of momentum energy of the pair production interaction is well above the electron rest mass. This implies that the  $e^\pm$  produced are relativistic in the center of momentum frame, and that most of the initial photon energy is carried (in the CMB frame) by one of particles produced. The resulting high energy electron (or positron) would lose most of its energy in a single inverse-Compton scattering of a CMB photon (which is deep in the Klein-Nishina regime), leading to the production of a secondary high energy photon, with energy which is not much smaller than that of the original photon. This process increases the effective mfp for photon energy loss to  $e^\pm$  to  $\simeq 10l_e$  (e.g. fig. 4 of [12]). Since the electron and photon mfp's are similar, this implies that muon pair production by secondary photons would increase the fraction of energy loss to muons by a factor of a few beyond  $f_\mu$  (The further small additional contribution to muon production via  $e\gamma \rightarrow e\mu^\pm$  may be neglected [13]). As we show below, while the prompt neutrinos (from the decay of prompt muons produced in an interaction of the original high energy photons with a CMB photon) are expected to arrive nearly simultaneously with the photons emitted by the source, neutrinos produced by interactions of secondary photons may suffer very long time delays due to deflection of the secondary high energy electrons by inter-Galactic magnetic fields. Since we are interested in neutrinos which may be associated directly with their sources, we restrict our discussion to neutrinos produced by the decay of prompt muons.

For the thermal CMB spectrum,  $e^\pm$  pair production in interactions with high energy,  $\varepsilon \sim 10^{19}$  eV, photons is dominated by photons of energy  $\sim T_{\text{CMB}} \sim 10^{-3}$  eV, well above the threshold energy,  $\sim (m_e c^2)^2/\varepsilon \sim 10^{-7}$  eV. However, the number density of  $\sim 10^{-7}$  eV background photons may be dominated by radio emission from objects like galaxies and AGN, rather than by the CMB.

The presence of such additional "radio background" photons may increase the  $e^\pm$  pair production rate, and thus reduce the value of  $f_\mu$ . Assuming that the  $\sim 10^{-7}$  eV ( $\sim 10$  MHz) radio background observed at Earth is of extra-Galactic origin,  $l_e$  is reduced, with respect to its value in the presence of CMB photons only, by a factor of  $\simeq 2$  for  $\varepsilon \sim 10^{19}$  eV, and by a factor of  $\simeq 10$  for  $\varepsilon \sim 10^{20}$  eV (see, e.g., fig. 1 of [14]). The actual reduction in  $l_e$  is expected to be much smaller, since the  $\sim 10$  MHz radio background is dominated by Galactic emission. The extra-Galactic contribution to the radio background is probably lower than 10% of the observed background (see discussion in sec. 4 of [15]), which implies that  $l_e$  is not much affected for  $\varepsilon < 10^{20}$  eV. Moreover, the contribution of radio background photons to  $e^\pm$  pair production interactions becomes smaller with increasing redshift: At higher redshift the energy density of the CMB is higher, while the energy density of the radio background is expected to be lower, since this background is produced by sources like galaxies and AGN and is therefore accumulating on a time scale comparable to the age of the universe. Thus, for cosmic-ray sources lying at  $z = 1$  to  $z = 2$ , which are expected to dominate neutrino production (e.g. [9]), we expect the effect of radio background photons to be small.

### III. HIGH ENERGY PHOTON EMISSION: THE GRB CASE

Both GRBs and AGN may be capable of accelerating protons to ultra-high energy. The fact that out to  $\sim 100$  Mpc, the propagation distance of  $10^{20}$  eV protons, there is no AGN luminous enough to meet the energy output constraint,  $L \gtrsim 10^{48}$  erg/s for proton acceleration to  $10^{20}$  eV [4], suggests that AGN are not the sources of UHECRs observed at Earth. We therefore focus below on high energy photon production in GRBs.

Observed GRB properties suggest that they may accelerate protons to  $\gtrsim 10^{20}$  eV and that they may produce the UHECR flux observed at Earth [16, 17]. In [8] it was shown that  $> 10^{16}$  eV protons, which are accelerated within the gamma-ray emitting region of the GRB source, lose a significant fraction,  $\sim 20\%$ , of their energy to pion production before escaping the source (on average, a proton undergoes a single pion production interaction before escaping). In fact, for protons accelerated to  $\gtrsim 10^{19}$  eV within the gamma-ray emitting region, the fraction of energy lost to pion production may be somewhat higher than 20%. In [8], only the  $\Delta$ -resonance contribution to the  $p\gamma$  interaction rate was considered. This is an excellent approximation for  $\sim 10^{16}$  eV protons, for which the interaction with the dominant  $\epsilon \sim 1$  MeV GRB photons is at the  $\Delta$ -resonance. Since the spectrum of higher energy photons, for which the interaction is at an energy higher than the resonance, is steep,  $dn/d\epsilon \propto \epsilon^{-2}$ , the contribution of interactions with these photons to the  $p\gamma$  interaction rate is small (see discussion follow-

ing eq. 1 of [8]). For protons of much higher energy,  $\varepsilon \gg 10^{16}$  eV, the energy  $\varepsilon_\Delta$  of photons for which the interaction is at the  $\Delta$ -resonance is lower than 1 MeV,  $\varepsilon_\Delta \sim 1(10^{16}\text{eV}/\varepsilon)$  MeV. Since the GRB spectrum is harder below 1 MeV,  $dn/d\varepsilon \propto \varepsilon^{-1}$ , the relative contribution of non-resonant interactions (compared to the resonant ones) is  $\approx (1/5) \times \ln(\varepsilon/10^{16}\text{eV})$  (the 1/5 factor is due to the non-resonant cross section being  $\sim 5$  times smaller; see eqs. 1 & 2 of [8]). This holds for protons of energy  $\varepsilon < 10^{19}$  eV, for which  $\varepsilon_\Delta > 1$  keV. The GRB spectrum is expected to become self absorbed,  $dn/d\varepsilon \propto \varepsilon$ , at  $\varepsilon < 1$  keV (see below), and  $p\gamma$  interactions of  $\varepsilon > 10^{19}$  eV protons are dominated by the non-resonant interactions with  $> 1$  keV photons. The  $p\gamma$  interaction rate for these protons is thus similar to the interaction rate of  $\sim 10^{16}$  eV protons,  $(1/5) \times \ln(10^{19}/10^{16}) \sim 1$ . However, since the fraction of energy loss per interaction is higher for interactions well above the resonance, the fraction of energy loss to pion production may be  $\sim 50\%$  for  $\varepsilon > 10^{19}$  eV protons.

Let us consider next the question of whether or not  $\gtrsim 10^{19}$  eV photons can escape the GRB source (see also [10]). The escape of high energy photons is limited by pair production interactions. The optical depth to pair production within the GRB source may be estimated as follows. It is widely accepted that GRB gamma-rays are produced by the dissipation of the kinetic energy of a highly relativistic outflow, usually referred to as a "fireball", driven by accretion onto a compact object (presumably  $\sim 1$  solar mass black hole) [18]. Let us denote the radius at which gamma-ray emission arises by  $R$ , and the outflow Lorentz factor by  $\Gamma$ . The pair production optical depth for a photon of high energy  $\varepsilon$  is given by the product of the pair production rate,  $1/t'_{\gamma\gamma}(\varepsilon)$ , and the dynamical time, the time required for significant expansion of the plasma,  $t'_d \simeq R/\Gamma c$  (primes denote quantities measured in the outflow rest frame),  $\tau_{\gamma\gamma}(\varepsilon) \simeq R/\Gamma c t'_{\gamma\gamma}(\varepsilon)$ .  $t'_{\gamma\gamma}(\varepsilon)$  depends on the energy density and on the spectrum of the radiation. The (outflow rest frame) radiation energy density is approximately given by  $U'_\gamma = L/4\pi R^2 c \Gamma^2$ , where  $L$  is the GRB luminosity. The GRB spectrum can typically be described as a broken power law,  $dn/d\varepsilon \propto \varepsilon^{-\beta}$ , with  $\beta \approx -1$  at low energy,  $\varepsilon < \varepsilon_b \sim 1$  MeV, and  $\beta \approx -2$  at  $\varepsilon > \varepsilon_b \sim 1$  MeV. High energy photons with energy  $\varepsilon'$  exceeding  $\varepsilon'_b \equiv 2(m_e c^2)^2/\varepsilon'_b$ , may produce pairs in interactions with photons of energy exceeding  $\varepsilon' = 2(m_e c^2)^2/\varepsilon' < \varepsilon'_b$  (the rest frame photon energy  $\varepsilon'$  is related to the observed energy by  $\varepsilon = \Gamma\varepsilon'$ ). For  $\varepsilon' < \varepsilon'_b$  we have  $dn/d\varepsilon' \propto \varepsilon'^{-1}$ , which implies that the number density of photons with energy exceeding  $\varepsilon'$  depends only weakly on energy. Thus,  $t_{\gamma\gamma}$  is nearly independent of energy for  $\varepsilon' > \varepsilon'_b$ ,  $t_{\gamma\gamma}^{-1} \approx (\sigma_T/16)cU'_\gamma/\varepsilon'_b$ , which gives

$$\tau_{\gamma\gamma}(\varepsilon > \varepsilon_b) \simeq 10^2 \frac{L_{52}}{\Delta t_{-2} \Gamma_{2.5}^4}. \quad (3)$$

Here  $L = 10^{52} L_{52} \text{erg s}^{-1}$ ,  $\Gamma = 10^{2.5} \Gamma_{2.5}$ , and the emission radius  $R$  is related to the observed variability time  $\Delta t = 10^{-2} \Delta t_{-2}$  s by  $\Delta t \approx R/2\Gamma^2 c$ . Photons of lower

energy,  $\varepsilon < \varepsilon_b$ , interact to produce pairs only with photons of energy  $\varepsilon' > 2(m_e c^2)^2/\varepsilon' > \varepsilon'_b$ . Since the number density of these photons drops like  $1/\varepsilon'$ , we have  $\tau_{\gamma\gamma}(\varepsilon < \varepsilon_b) \approx (\varepsilon/\varepsilon_b)\tau_{\gamma\gamma}(\varepsilon > \varepsilon_b)$ , i.e.

$$\tau_{\gamma\gamma}(\varepsilon < \varepsilon_b) \simeq 10^{-3} \frac{L_{52}}{\Delta t_{-2} \Gamma_{2.5}^6} \frac{\varepsilon}{1 \text{ MeV}}. \quad (4)$$

The extension of GRB spectra to  $\sim 100$  MeV and the characteristic variability time,  $\Delta t_{-2} \sim 1$ , imply  $\Gamma_{2.5} \gtrsim 1$ . Since thermal pressure acceleration can not lead to much larger Lorentz factors,  $\Gamma_{2.5} \approx 1$  is typically adopted (e.g. [18]).

Eq. (3) implies that the pair production optical depth is large,  $\sim 10^2$ , for high energy,  $\varepsilon > \varepsilon_b \approx 10^{11} \Gamma_{2.5}^2$  eV, photons. However, at very high energy the source might become optically thin again. This is due to the fact that the spectra do not extend as  $dn/d\varepsilon' \propto \varepsilon'^{-1}$  to arbitrarily low energy. Synchrotron self-absorption is expected to "cutoff" the spectrum at some energy  $\varepsilon'_L \ll \varepsilon'_b$ , below which the spectrum is expected to follow  $dn/d\varepsilon' \propto \varepsilon'$ . For high energy photons with energy  $\varepsilon'$  exceeding  $\varepsilon'_L \equiv 2(m_e c^2)^2/\varepsilon'_L$ , pair production would be dominated by interactions with photons of energy  $\sim \varepsilon'_L$ , and the Klein-Nishina suppression of the pair production cross section would imply  $\tau_{\gamma\gamma} \propto 1/\varepsilon'$ . For typical GRB parameters we expect  $\varepsilon_L \sim 1$  keV [19, 20], consistent with BeppoSAX GRB spectra [21]. Using eq. (3) we thus have

$$\tau_{\gamma\gamma}(\varepsilon > \varepsilon_L) \simeq 10^{-3} \frac{L_{52}}{\Delta t_{-2} \Gamma_{2.5}^2} \left( \frac{\varepsilon_L}{1 \text{ keV}} \frac{\varepsilon}{10^{19} \text{ eV}} \right)^{-1}. \quad (5)$$

We note here that the recent detection of (apparently) simultaneous optical/UV and gamma-ray emission appears to be inconsistent with the standard fireball model, since the optical/UV flux is much higher than expected in a model where synchrotron self-absorption is important below  $\sim 1$  keV. We have shown, however, that the optical/UV emission may in fact be naturally produced in this model by "residual" dissipation of kinetic energy at radii larger than that of the gamma-ray emission region [20].

#### IV. THE EXPECTED NEUTRINO SIGNAL

Let us assume that the sources of UHECRs deposit a significant fraction of the UHECR energy output into pion production, and that they are optically thin for  $> 10^{19}$  eV photons. The fraction of UHECR energy that would be converted to high energy neutrinos, via the escape of high energy photons and their interaction with CMB photons, is  $\approx (1/2) \times 0.05 \times 2/3 \sim 2\%$ . The first factor accounts for the fraction of energy deposited in neutral (as opposed to charged pions), the second accounts for the fraction of photon energy deposited in (prompt) muon pairs in interaction with CMB photons, and the last term accounts for the fraction of energy deposited into neutrinos by the muon decay. This implies that the

expected neutrino flux may reach a few percent of the Waxman-Bahcall bound [9], which is the neutrino flux that would be obtained if all the energy produced by the sources of UHECRs were deposited into pions.

At redshift  $z$ , the energy of photons capable of producing muon pairs in interactions with CMB photons of energy  $\sim 3T_{\text{CMB}}$  is  $\sim 10^{19}(1+z)^{-1}$  eV. The characteristic energy of neutrinos arising from such interactions is  $\sim 3 \times 10^{18}(1+z)^{-1}$  eV, and the energy with which they will be observed at Earth is  $\sim 3 \times 10^{17}[(1+z)/3]^{-2}$  eV. The neutrino flux from muon production on the CMB is expected to be strongly suppressed below this energy. The muon decay neutrino flavor ratio,  $\Phi_{\nu_e}^0 : \Phi_{\nu_\mu}^0 : \Phi_{\nu_\tau}^0 = 1 : 1 : 0$ , is expected to be modified by neutrino oscillations [22] to  $\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} = 0.4 : 0.3 : 0.3$  at Earth, slightly different from the  $1 : 1 : 1$  flavor ratio for neutrinos produced by charged pion decay. The predicted neutrino flux may be detectable by the suggested AR-IANNA neutrino telescopes [11], which is designed for detection of neutrinos of energy  $\gtrsim 10^{17.5}$  eV.

It is important to emphasize here that the (prompt) neutrino signal is expected to be associated in both time and direction with the electromagnetic emission of the source, and that this association can not be affected by the presence of inter-galactic magnetic fields, which may deflect the charged muons. The amplitude of a large scale inter-galactic magnetic field is limited by Faraday rotation measures to less than 1 nG [23]. Given the muon rest-frame lifetime,  $t_\mu = 2 \times 10^{-6}$  s, the angle by which the muon may be deflected before decaying is only  $\theta \approx t_\mu eB/m_\mu c \sim 10^{-10}(B/1\text{nG})$ , and the related time delay is  $\Delta t_B \approx \theta^2 l_\mu/c \sim 1(B/1\text{nG})(l_\mu/10^{27}\text{cm})$  ms. On the other hand, neutrinos produced by the decay of secondary muons (muons produced by high energy photons

generated by inverse-Compton scattering of CMB photons by  $e^\pm$  pairs produced by the original high energy photon), may suffer strong delays since the mean free path of secondary electrons is large,  $\sim 10^{26}$  cm, and they may therefore be significantly deflected by inter-Galactic fields.

The comparison of arrival times of GRB-induced neutrinos and GRB photons may allow one to test for Lorentz invariance violation (LIV) as expected due to quantum gravity effects [8, 24]. Since the time delay is expected to be an increasing function of neutrino energy,  $\Delta t_{\text{LIV}} \approx (d/c)(\epsilon_\nu/\xi E_{\text{planck}})^n$ , the  $10^{18}$  eV neutrinos discussed in this paper would provide much more stringent tests than the pion decay  $\sim 10^{15}$  eV neutrinos expected to be produced within the GRB source. The accuracy with which the time delay could be measured is limited by the duration of the burst photons, which ranges from few ms's for short bursts to tens of seconds for long ones. A possible complication in this context is the possible emission of  $\sim 10^{17}$  eV neutrinos during the GRB "afterglow" phase, which may take place on time scale of hours [25]. For  $10^{18}$  eV neutrinos originating from  $z = 1$  ( $d \sim 10^{28}$  cm), a time delay of hours would probe  $\xi_1 \gtrsim 10^4$  for  $n = 1$  or  $\xi_2 \gtrsim 10^{-3}$  for  $n = 2$ . It is important to note here that since the background level of neutrino telescopes is very low, especially at high neutrino energy, the detection of a single EeV neutrino from the direction of a GRB on a time scale of even years after the burst would imply an association of the neutrino with the burst and will therefore establish a time delay measurement.

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