Neutrinos from charm production: atmospheric and astrophysical applications

Mary Hall Reno
Department of Physics and Astronomy
University of Iowa
Iowa City, Iowa, 52242, USA

1 Introduction

High energy neutrino production occurs in a variety of contexts. Accelerator physics experiments have used neutrino beams with average energies ranging up to ~ 350 GeV incident neutrino energy [1]. Neutrino fluxes produced as secondary particles from cosmic ray interactions in the atmosphere have been observed in a variety of underground experiments, including Super Kamiokande [2], MINOS [3] and IceCube [4, 5]. Indeed, the mismatch between the theoretically predicted flux of muon neutrinos which travel through the diameter of the Earth and the actual measured flux led to the discovery of neutrino oscillations and the mass-squared difference of muon and tau neutrinos [2].

The neutrino production process is essentially the same for neutrino beams whether in accelerator laboratories or astrophysical and cosmic sources. Accelerated protons or ions interact with nucleon or nuclear targets. Pions, kaons and other mesons are produced. Some of these mesons decay to neutrinos. In astrophysical sources, the targets may also be photons. The highest energy neutrino fluxes are predicted theoretically from cosmic ray interactions with the cosmic microwave background. With such low energy photon targets, the neutrinos come mainly from Δ^+ production near threshold and subsequent decay, strongly boosted because the the ultrahigh cosmic ray energies required to produce the Δ's. These neutrinos are sometimes called GZK (Greisen, Zatsepin, Kuzmin) or cosmogenic neutrinos [6].

With the exception of the GZK neutrinos, important ingredients in the theoretical predictions of the neutrino flux are the hadronic cross sections for meson production and the longitudinal energy distributions of those mesons. A review of the inputs and uncertainties in the evaluation of the atmospheric lepton flux, primarily from pion and kaon decay at low energies, appears in Ref. [7]. A nice description of semi-analytic evaluations of the contributions of pion and kaon decay to the atmospheric lepton fluxes is given in Ref. [8]. At higher energies, charm production and decay can make significant contributions to the lepton fluxes in both the atmospheric neutrino flux and the flux of neutrinos from astrophysical sources. The key element is the short charmed meson lifetime. Despite the low cross section for $c\bar{c}$ production relative to pion and kaon production, the fact that there is an energy range where all the charmed mesons decay while few of the pions and kaons decay permits the neutrino flux from charm to dominate at those energies (see, e.g., Ref. [9]).

As the underground neutrino telescope IceCube has progressed to include a substantial fraction of its design volume of one kilometer-cubed, the collaboration has presented their results for the atmospheric flux in the range of $10^5 - 10^6$ GeV [4, 5]. This is precisely the energy range where neutrinos from atmospheric charm may begin to dominate over neutrinos from pions and kaons. The Large Hadron Collider (LHC), currently with $\sqrt{s} = 7$ TeV, probes an equivalent cosmic ray energy on a stationary target of $E = 2.6 \times 10^7$ GeV. The ALICE Collaboration has reported the cross section for $\sigma_{c\bar{c}}$ for $\sqrt{s} = 2.76$ TeV and 7 TeV [10] that can constrain models of charm production used in evaluations of the atmospheric neutrino flux at high energies. It makes a reevaluation of the atmospheric neutrino flux from charm a useful activity.

In this paper, a sketch of the atmospheric neutrino flux evaluation is presented. Our results rely on a dipole model evaluation of the hadronic charm pair cross section [11]. In the next section, we sketch the ingredients in the evaluation of the atmospheric lepton fluxes. The details of the calculation of the charm cross section and energy distribution in proton-air collisions was discussed by R. Enberg in this conference. In the third section, a brief discussion of charm production and decay to neutrinos in the context of astrophysical sources is presented [12]. We conclude with a summary in Section 4.

2 Atmospheric lepton fluxes

As noted above, the atmospheric lepton flux arises from the decays of particles produced by cosmic ray interactions in the Earth's atmosphere. We briefly review here the semi-analytic approach [8, 13]. To first approximation, the incident flux can be characterized by a broken power law, with spectral index α and normalization A, as [8, 13]

$$\phi_p \simeq \frac{\mathcal{A}}{(E/\mathrm{GeV})^{\alpha}}\ (\mathrm{cm}^2 \mathrm{s}\,\mathrm{sr}\,\mathrm{GeV})^{-1}\ . \tag{1}$$

For $E < 5 \times 10^6$ GeV, $\mathcal{A} = 1.7$ and $\alpha \simeq 2.7$, while for $E > 5 \times 10^6$ GeV, $\mathcal{A} = 174$ and $\alpha \simeq 3$. The incident protons interact with air nuclei to produce mesons: pions, kaon, charmed mesons, etc. As we will sketch below, depending on the characteristic scales at a given energy, the atmospheric lepton flux scales approximately as $E^{-\alpha}$ or as $E^{-(\alpha+1)}$. This scaling behavior is slightly modified by energy dependence in hadronic cross sections and by the feed down of the break in the cosmic ray spectrum.

The energy scaling is best understood by considering column depths and interaction lengths. We define the column depth by

$$X = \int_{\infty}^{\ell} d\ell' \rho(h(\ell', \theta)) \tag{2}$$

for the atmospheric density $\rho(h)$ which depends on altitude h. To first approximation, the atmospheric density can be described by an exponential: $\rho \simeq \rho_0 \exp(-h/h_0)$ for scale height $h_0 = 6.4$ km and $\rho_0 = 2 \times 10^{-3}$ g/cm^3. For an exponential atmosphere, the column depth and density are related by

$$h_0 \rho(h)/\cos\theta = X(h, \theta)\,.$$

Cosmic ray protons incident on the atmosphere have a cross section with air nuclei ($\langle A \rangle = 14.5$) of $\sigma_{pA} \simeq 300$ mb, so they have an interaction length of $\lambda \simeq 80$ g/cm^2. For vertically incident cosmic rays, this corresponds to a height of interaction of $h \simeq 15$ km.

The probability for a meson M to decay depends on its energy. For low energy mesons, all the mesons will decay so $P_{\rm dec}^{\rm lowE} \simeq 1$, while for high energy mesons where $E_M c\tau_M/m_M > h \simeq 15$ km or h_0, $P_{\rm dec}^{\rm highE} \simeq h_0 m_M/(E_M c\tau_M) \equiv E_c^M/E_M$. High energy meson also interact with air nuclei in transit.

The energy in the denominator of $P_{\rm dec}^{\rm highE}$ is the origin of the flux scaling as $\phi_\nu \sim E^{-(\alpha+1)}$ for leptons from high energy mesons, while for neutrinos from low energy mesons, the energy scaling is $\phi_\nu \sim E^{-\alpha}$. In Table 1, we show the critical energies E_c^M for vertical mesons. For $E_\nu \ll E_c^M$ for a given meson, the low energy flux behavior is appropriate. An extra power of energy suppresses the neutrino flux for $E_\nu \gg E_c^M$.

As Table 1 shows, the critical energy for charmed mesons is quite large. While the charm production cross section is low relative to, for example, pion production, the extra power of energy in the flux allows the charm contribution to "catch up" to the other meson contributions. The neutrino flux from pion and kaon decay is called the "conventional flux," while the neutrino flux from charmed meson decay is called the "prompt flux."

More quantitatively, we reproduce the general approximate formulas for the atmospheric neutrino fluxes [8, 13]. They depend on the meson production cross section via

$$\begin{aligned} S(N \to M) &= \int_E^\infty dE' \frac{\phi_N(E')}{\lambda_N(E')} \frac{dn(N \to M; E', E)}{dE} \\ &\equiv Z_{NM}(E) \frac{\phi_N(E)}{\lambda_N(E)} \end{aligned} \tag{3}$$

where

$$\frac{dn(N \to M; E', E)}{dE} = \frac{1}{\sigma_{NM}(E')} \frac{d\sigma_{NM}(E', E)}{dE}\;, \tag{4}$$

and $\lambda_N = (N_A \sigma_N / A)^{-1}$ is the cosmic ray interaction length for protons in air. The low and high energy fluxes, from cosmic rays N which produce meson M, followed by $M \to \nu X$ decays, are

$$\phi_\nu^{\rm low} = \frac{Z_{NM} Z_{M\nu}}{1 - Z_{NN}} \phi_N \ , \quad (5)$$

$$\phi_\nu^{\rm high} = \frac{Z_{NM} Z_{M\nu}}{1 - Z_{NN}} \phi_N \frac{\ln(\Lambda_M / \Lambda_N)}{1 - \Lambda_N / \Lambda_M} \frac{E_c^M}{E} \phi_N \ , \quad (6)$$

where $\Lambda_N = \lambda_N / (1 - Z_{NN})$. The Z-moments $Z_{M\nu}$ are defined with respect to the energy distribution of the neutrino from the meson decay, rather than with differential cross sections.

A key feature in these expressions is that the charm pair production cross section is dominated by energies near threshold. At high energies, this means that one needs parton distribution functions at small Bjorken x in the parton model approach. Prompt fluxes based on next-to-leading order QCD calculations with small x parton distribution function extrapolations appear in, for example, Refs. [14, 15, 16]. Further discussions of small x contributions also appear in Ref. [17]. The dipole approximation is another approach that models the low x behavior. Guided by a QCD motivated form [18] that accounts for gluon fluctuations to heavy quarks [19] and based on a parameterization from Ref. [20], we have evaluated the prompt flux of neutrinos from charm in Ref. [11]. The prompt flux based on this dipole model (DM) approach to charm production is shown in Fig. 1 by the solid lines. There is a range of predictions due to uncertainties in the value of the charm quark mass, the dipole parameters and scales, and the gluon parton distribution function. For comparison, the vertical conventional muon neutrino plus antineutrino flux from Ref. [7] is shown in Fig. 1 by the dashed line. More details of the dipole model evaluation were discussed in the talk by R. Enberg in this conference.

The IceCube Collaboration has published limits on a diffuse flux of astrophysical muon neutrinos [5] which requires an understanding of the atmospheric neutrino flux. In Ref. [5], IceCube shows limits on the prompt flux, and they are able to exclude

Meson (M)	Critical Energy E_c^M
Charged Pion $\pi^\pm$	115 GeV
Charged Kaon $K^\pm$	850 GeV
Charged Charmed Meson $D^\pm$	3.8×10^7 GeV
Neutral Charmed Meson $D^0, \overline{D}^0$	9.6×10^7 GeV
Strange Charged Charmed Meson $D_s^\pm$	8.5×10^7 GeV

Table 1: Critical energies for vertical atmospheric neutrino flux contributions from meson decays. See, for example, Ref. [9].

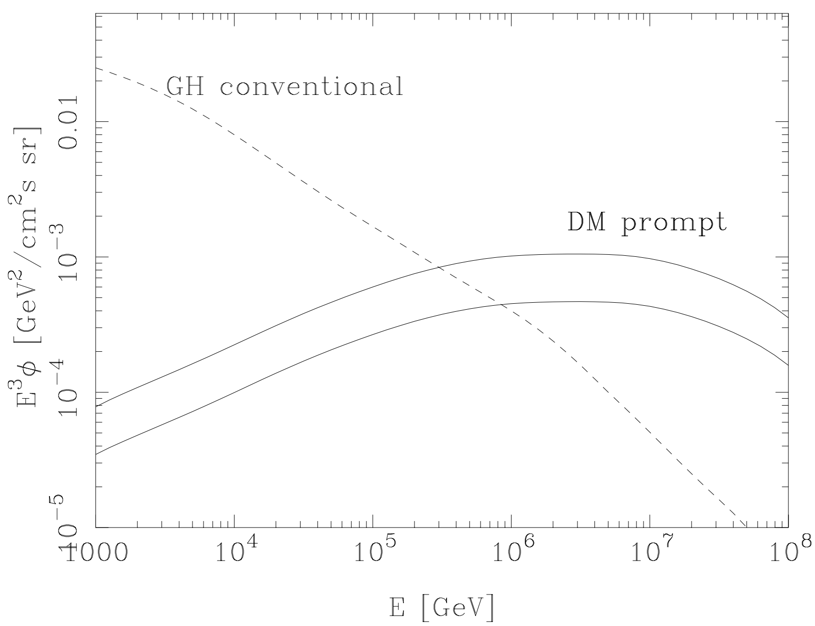

Figure 1: Vertical muon neutrino plus antineutrino flux from Ref. [11]. The solid lines show the range of predictions of neutrinos from charm evaluated using the dipole model (DM). The dashed line shows the vertical flux from Gaisser and Honda (GH) in Ref. [7].

some of the the prompt flux predictions. Their analysis used an extrapolation the conventional neutrino spectrum of Honda et al. from Ref. [21]. As noted in Ref. [5], one expects that the steepening of the incident cosmic ray spectrum and changes in the cosmic ray composition will modify the extrapolation, so one should not regard the limits on the prompt flux in Ref. [5] as the final word.

In addition to the neutrino flux, there has been recent interest in prompt contributions to the atmospheric muon flux. With the muon lifetime equal to 2.2×10^{-6} s, the decay length including time dilation is longer than 15 km (altitude of production) for $E_\mu > 2.4$ GeV, so muons can be treated as essentially stable particles at higher energies. In the three-body decays of charmed mesons, the muon energy distribution is essential the same as the muon neutrino and electron neutrino energy distributions. To a good approximation, the charm contribution to the atmospheric muon flux at high energies is thus equal to its contribution to the muon neutrino flux. Illana, Lipari Masip and Meloni noted in Ref. [22] that unflavored mesons with prompt electromagnetic decays could provide a significant portion of the prompt muon flux. Their evaluation of $\eta,\ \eta',\rho^0$ and ω production and decay to $\mu^+\mu^-$ lead to the prompt electromagnetic component dominating the conventional muon flux for $E \simeq 1.5\times 10^6$ GeV. High energy comparisons of the prompt muon and prompt neutrino fluxes will ultimately test this prediction, since in the absence of the prompt electromagnetic decays, the prompt muon and muon neutrino fluxes are equal.

3 Astrophysical neutrino fluxes

The eventual dominance of charm contribution to neutrino fluxes can also occur in astrophysical sources. Any site where pions are produced is also potentially a site where charmed particles can also be produced. The typical astrophysical source has an astrophysical accelerator which accelerates cosmic rays with a spectrum scaling as E^{-2} for Fermi shock acceleration [13]. There are generally nucleon targets and often photon targets, where

$$\begin{aligned} pp &\to \pi^0,\pi^\pm,K^\pm,D^\pm,\ \text{etc} \\ p\gamma &\to \Delta^+\to n\pi^+,\ \text{etc} \end{aligned}$$

followed by decays. With astrophysical sources, the cosmic rays may be screened (hidden sources), or they may escape along with photons (transparent sources), or it may be an intermediate situation. Generally, however, neutrinos do escape the source.

In Ref. [12], we have looked at two types of sources: a slow jet supernova (SJS) [23], in which a mildly relativistic jet does not emerge from the source, and a gamma ray burst (GRB) with a highly relativistic jet and escaping photons [24]. Neutrinos may be the only signals of slow jet supernovae.

The energy behavior of the neutrino flux has similar qualitative features to the atmospheric neutrino flux, with some additional corrections due to hadronic cooling (and $p\gamma$ interactions) and radiative cooling due to the large magnetic fields. As discussed in Ref. [25], for sources where the neutrinos come from pp interactions, the scaling is approximately

$$\begin{aligned} \phi_\nu &\sim E^{-2} && \text{decay dominated} \\ &\sim E^{-3} && t_{hadronic}/t_{decay}<1 \\ &\sim E^{-4} && t_{radiative}/t_{decay}<t_{hadronic}/t_{decay}<1\ . \end{aligned}$$

The shortest characteristic time gives the most important process, eventually leading to a steep flux that cuts off at an energy that is also governed by the maximum

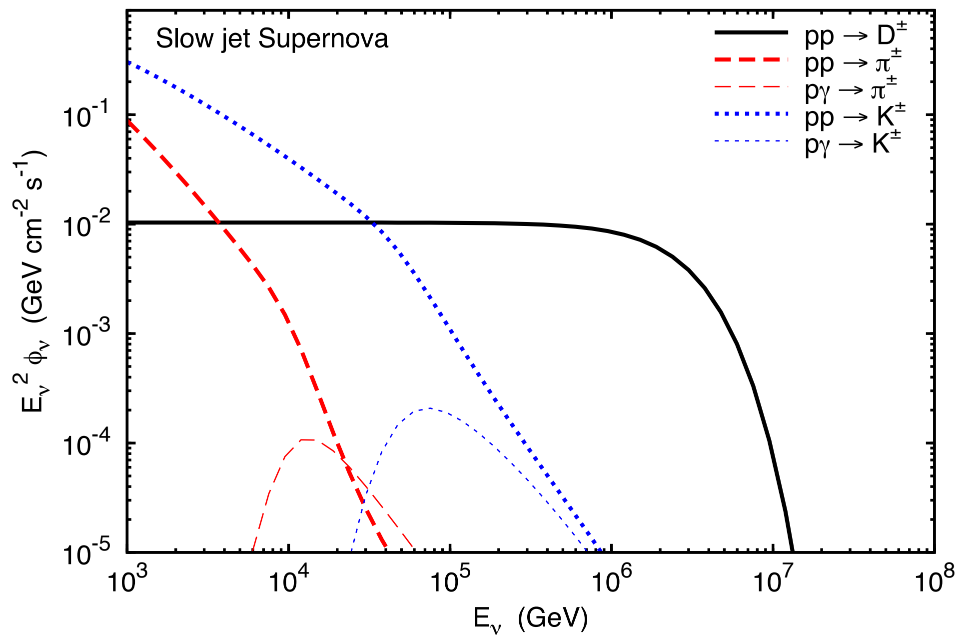

Figure 2: Flux of neutrinos from production and decay of mesons in a slow jet supernova model, from Ref. [12].

proton energy. Neutrino flux calculations from astrophysical sources have an extensive literature, including Ref. [25, 26, 27] and [28].

We have used the Z-moment method to evaluate the contributions from a number of meson decays to the neutrino flux. We used the dipole model evaluation of Z_{pD} from Ref. [11] with a further approximation that it is constant in energy. Our evaluation of the neutrino flux, including charm meson contributions, from an astrophysical source was normalized to a source distance of 20 Mpc and jet luminosity of 3×10^{50} erg/s. The SJS has a magnetic field $B' = 1.2 \times 10^9$ G in the frame co-moving with the jet with bulk Lorentz factor of the jet $\Gamma_j = 3$. The GRB model for this calculation has $B' = 1.1 \times 10^7$ G and $\Gamma_j = 100$. Another distinction is the photon distribution, which is thermal for the SJS, but non-thermal for the GRB. Further details of the parameters appear in Ref. [12].

The SJS model has a prominent contribution from charm decay at high energy, while at low energies, pion and kaon contributions dominate, as shown in Fig. 2 which also appears in Ref. [12]. The $p\gamma$ contributions are small, because the photons are thermalized. Ultimately, the turn over in the flux comes from the fact that the proton energy is cut off because of proton cooling. In Ref. [29], the diffuse flux of neutrinos from SJS sources is discussed.

In the GRB model considered here, $p\gamma$ contributions are comparable to pp contributions to pion and kaon production. Charm production and decay have a small contribution beyond the "conventional" contributions.

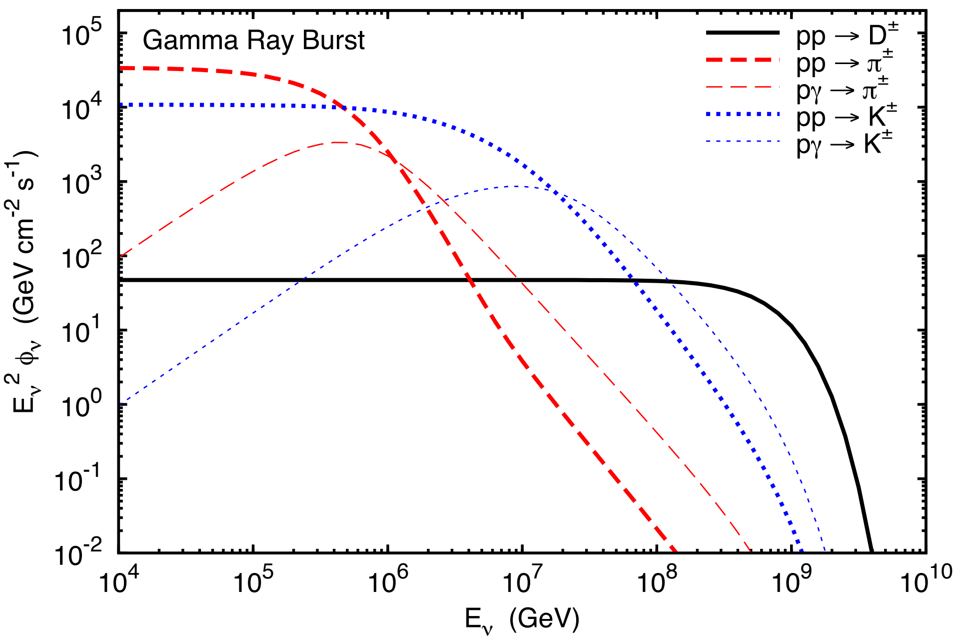

Figure 3: Flux of neutrinos from production and decay of mesons in a gamma ray burst model, from Ref. [12].

In the figures, we show the sum of muon neutrino plus antineutrino fluxes without including oscillation effects. Interesting oscillation phenomena both within the source and in transit to Earth have been studied, for example in Ref. [30].

4 Discussion

While the atmospheric neutrino flux is a background to searches for a diffuse astrophysical neutrino fluxes or fluxes from point sources, atmospheric leptons are intrinsically interesting probes of hadron physics at high energies. As the LHC experiments probe new regions in kinematic variables, the cross sections and energy distributions used to evaluate the atmospheric lepton fluxes will be reexamined. The detailed calculation of neutrino fluxes from astrophysical sources is more speculative, however, given that cosmic rays are accelerated to high energies, one expects accompanying neutrinos. We may be able to learn more about cosmic ray sources from their accompanying neutrinos, including the prompt contributions.

I am grateful to Rikard Enberg and Ina Sarcevic for their continued collaboration with me on this topic. This work is supported in part by DOE contract DE-FG02-91ER40664.

References

[1] K. Nakamura et al. (Particle Data Group), J. Phys. G **37**, 075021 (2010) .

[2] Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **81**, 1562-1567 (1998).

[3] P. Adamson *et al.* [MINOS Collaboration], Phys. Rev. **D73**, 072002 (2006).

[4] R. Abbasi *et al.* [IceCube Collaboration], Phys. Rev. **D83**, 012001 (2011).

[5] R. Abbasi *et al.* [IceCube Collaboration], Phys. Rev. **D84**, 082001 (2011).

[6] G. T. Zatsepin, V. A. Kuzmin, JETP Lett. **4**, 78-80 (1966); K. Greisen, Phys. Rev. Lett. **16**, 748-750 (1966).

[7] T. K. Gaisser and M. Honda, Ann. Rev. Nucl. Part. Sci. **52**, 153 (2002).

[8] P. Lipari, Astropart. Phys. **1**, 195-227 (1993).

[9] C. G. S. Costa, Astropart. Phys. **16**, 193 (2001).

[10] Christine Nattrass, at the Workshop on Non-Perturbative QCD, Paris, June, 2011.

[11] R. Enberg, M. H. Reno and I. Sarcevic, Phys. Rev. D **78**, 043005 (2008).

[12] R. Enberg, M. H. Reno and I. Sarcevic, Phys. Rev. D **79**, 053006 (2009).

[13] T. K. Gaisser, Cosmic Rays and Particle Physics (Cambridge University Press, Cambridge, 1990).

[14] L. Pasquali, M. H. Reno, I. Sarcevic, Phys. Rev. **D59**, 034020 (1999).

[15] L. Pasquali, M. H. Reno, Phys. Rev. **D59**, 093003 (1999).

[16] G. Gelmini, P. Gondolo, G. Varieschi, Phys. Rev. **D61**, 036005 (2000); Phys. Rev. **D61**, 056011 (2000).

[17] P. Gondolo, G. Ingelman, M. Thunman, Astropart. Phys. **5**, 309-332 (1996).

[18] E. Iancu, K. Itakura and S. Munier, Phys. Lett. B **590**, 199 (2004).

[19] N. N. Nikolaev, G. Piller and B. G. Zakharov, Z. Phys. A **354**, 99 (1996).

[20] G. Soyez, Phys. Lett. **B655**, 32-38 (2007).

[21] M. Honda et al., Phys. Rev. D **75**, 043006 (2007), See also, G. Barr et al., Phys. Rev. D **70**, 023006 (2004).

[22] J. I. Illana, P. Lipari, M. Masip and D. Meloni, Astropart. Phys. **34** 663 (2011).

[23] S. Razzaque, P. Meszaros and E. Waxman, Mod. Phys. Lett. A **20**, 2351 (2005).

[24] P. Meszaros, Rept. Prog. Phys. **69**, 2259 (2006).

[25] S. Ando and J. F. Beacom, Phys. Rev. Lett. **95**, 061103 (2005).

[26] S. Horiuchi and S. Ando, Phys. Rev. D **77**, 063007 (2008).

[27] M. Kachelriess and R. Tomas, Phys. Rev. D **74**, 063009 (2006).

[28] X. Y. Wang and Z. G. Dai, arXiv:0807.0290 [astro-ph].

[29] R. Gandhi, A. Samanta and A. Watanabe, JCAP **0909**, 015 (2009).

[30] S. Razzaque and A. Y. Smirnov, JHEP **1003**, 031 (2010).