The Applicability of High-Redshift SFGs as Hidden Neutrino Sources

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Abstract

Two years' detection of astrophysical neutrinos from 2010 to 2012 obtained 28 events beyond 30 TeV and 2 events of them reach the PeV scope. The discovery of ultra-high-energy neutrinos promotes new techniques to study the acceleration mechanism of cosmic rays. On the other hand, *Fermi* LAT extended the energy range of isotropic gamma-ray background (IGRB) and extragalactic gamma-ray background (EGB) to 100 MeV-820 GeV utilizing 50 months' observation. In our work, we employ the fluxes of IGRB and non-blazar EGB to constrain the neutrino injecta due to pp collisions and we study the star-forming galaxies (SFG) and star-burst galaxies (SBG) as neutrino sources. Under non-blazar constraints, we find that the neutrino contribution from SFG and SBG located at lower redshift (< 5) are not sufficient to explain the IceCube flux ($\approx 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}). Motived by this, we consider the neutrino injecta of possible high-redshift neutrino sources (HRNS). Our calculations lead to an interesting conclusion that there exists a redshift z_a such that the gamma-ray radiation (> 100GeV) from the sources beyond z_a will sufficiently interact with EBL-CMB photons and finally reach an equilibrium state. In other words, if we fix the fraction of neutrino flux ξ_ν contributed from sources $z_s > z_a$, the accompanying gamma-ray flux is almost unchanged. Therefore, we can move HRNS to a lower redshift (higher than z_a) avoiding the uncertainties of high-redshift EBL and star-formation rate. Using the simplified method, we find that the high-redshift sources cannot dominate the IceCube neutrinos. We also find HRNS will contribute EBG flux above 100 GeV, which challenges the applicability of HRNS as ideal hidden neutrino sources. Thus, efforts on other alternative hidden scenarios such as opaque SFG/SBG in the sense of gamma-ray observation and GRBs with chocked jets may be able to interpret the absent neutrino flux and satisfy the non-blazar EBL simultaneously.

I. $z < 5$ SFG/SBG contributions and non-blazar constraints

One paper by Bechtol et al. (2015) suggests that blazars constitute $86^{+16}_{-14}\%$ of total EBG intensity and the non-blazar EGB component is allowed in the range $< 28\%$ with 14% as the best-fit value, which exerts a strong constraint to the neutrino sources. Here, we assume the non-blazar component is dominated by HNe and SNe in star-forming galaxies and star-burst galaxies in a redshift range $z < 5$ and perform a combined fit of neutrino flux and gamma-ray flux. In this work, we use the HNe/SNe scenario discussed in Senno et al. (2015) and generalize the scenario to a non-blazar case by violating the relation $\xi_{sbg}+\xi_{sfg} = 1$, where ξ_{sbg} and ξ_{sfg} represent the fraction of neutrinos contributed by SBG and SFG respectively. The results calculated by adaptive Monte Carlo method are demonstrated in Fig 1. The green dashed line is the expected neutrino flux and green solid line represents the gamma-ray flux. In the left figure, we use 14% EGB (thick black line) to constrain the neutrino flux and in the right figure we use the upper limit (28% EGB, the upper edge of the pink area). We can find, under both situations, the neutrino fluxes are not sufficient to explain the IceCube data. Therefore, many papers are published to discuss the hidden neutrino sources recently.

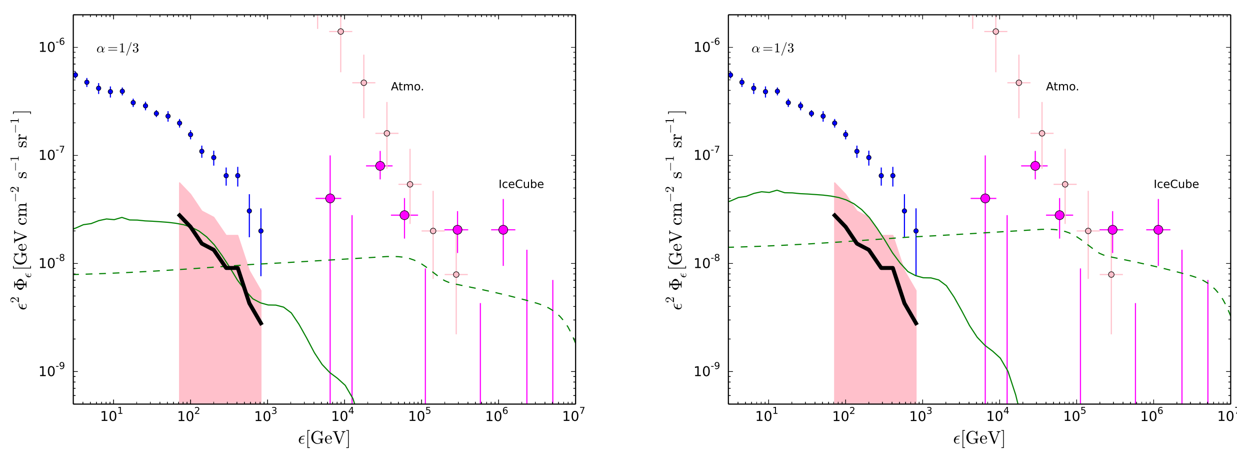

Figure 1: Combined constraints of gamma-ray flux and IceCube neutrino flux per flavour. (The α in these figures can be ignored since it represents the power-law index in the diffusion coefficient.)

II. The applicability of high-redshift sources

One of the hidden scenarios is the distant (high-redshift) neutrino sources. For example, Chang et al. (2016) find that a large fraction of neutrino sources should locate at high redshift and less than 20% of the neutrinos are allowed to be generated from distances at $z < 5$. In addition, Xiao et al. (2016) show that Pop-III HNRs up to $4 < z < 10$ could contribute to the diffuse high-energy backgrounds without violating the residual diffuse gamma-ray background constraint. However, in this paper, we will test the applicability of high-redshift sources as hidden neutrino sources through a different method.

At first, we consider the influence of redshift distributions of neutrino injection. We fix the local neutrino flux $\epsilon^2\Phi(\epsilon, z = 0)$ and assume the neutrino injection per redshift interval has the form

$$\epsilon^2 s(\epsilon, z) = \epsilon^2 \Phi(\epsilon, z = 0) \times \omega(z), \tag{1}$$

where $\omega(z)$ is a normalized function interpreted as the redshift distribution. Since $\omega(z)$ is an arbitrary normalized function, we can choose a point source $\delta(z - z_s)$ or other normalized functions in an given interval. To find the dependence of $\omega(z)$, we use the Gaussian function normalized in the interval $0 < z < 5$

$$\omega(z; \sigma, \mu) = \frac{\frac{1}{\sqrt{2\pi}\sigma} e^{-(z-\mu)^2/2\sigma^2}}{\int_0^5 \frac{1}{\sqrt{2\pi}\sigma} e^{-(z-\mu)^2/2\sigma^2} dz}, \quad z \in (0, 5], \tag{2}$$

where the position and the concentration of $\omega(z)$ are controlled by μ and σ. Here, $\epsilon^2\Phi(\epsilon, z = 0)$ is taken from Fig 1 (right) and we calculate the corresponding gamma-ray fluxes (as shown in Fig 2 - right) from various redshift distributions (as shown in Fig 2 - left) : $\omega(z; 0.5, 2.5)$-blue, $\omega(z; 1.0, 1.0)$-red, $\omega(z; 2.0, 2.5)$-green, $\omega(z; 0.5, 4.5)$-cyan and the reconstructed $\omega(z)$ (black dashed) from previous calculations where the star-formation rate from Hopkins & Beacom (2006), Yuksel et al. (2008) is used.

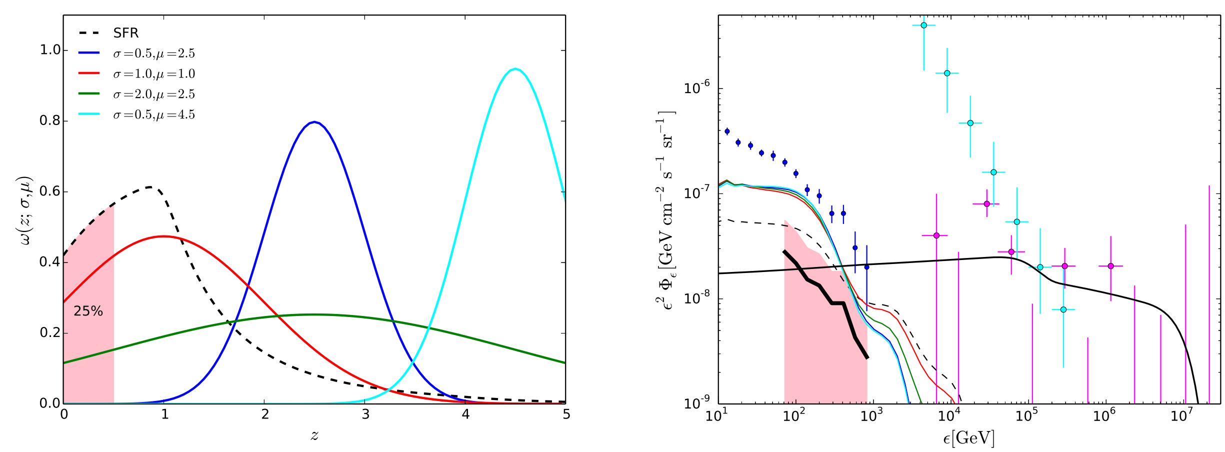

Figure 2: Different normalized functions used in this calculation (left) and the corresponding gamma-ray fluxes (left). In the right figure, the local neutrino flux is fixed (black line).

In the left figure, the pink area represent the fraction of neutrinos from the sources at redshifts $z_s < 5$. These sources contribute $\approx 25\%$ of the cumulative neutrinos which is consistent with the prediction (20%) from Chang et al. (2016). In order to interpret the resultant gamma-ray flux, we put forward a hypothesis that there exists a redshift z_a such that the gamma-ray radiation (> 100GeV) from the sources beyond z_a will sufficiently interact with EBL-CMB photons and finally reach an equilibrium state. In other words, if we fix the fraction of neutrino flux ξ_ν contributed from sources $z_s >$

z_a, the accompanying gamma-ray flux is almost unchanged and we cannot distinguish the redshift distribution from the gamma-ray flux when $z_s > z_a$. Meanwhile, the discrepancies in the right figure come from the sources $z_s < z_a$. Because the gamma-ray injections cannot sufficiently interact with EBL, we get a higher flux at TeV and lower flux at low energy (< 500 GeV). So we conclude, if the local neutrino flux is fixed and $\xi_{\nu,1} > \xi_{\nu,2}$, we can predict the relation of gamma-flux as $\epsilon^2\Phi_\gamma(1\ \mathrm{TeV}, z=0)_1 < \epsilon^2\Phi_\gamma(1\ \mathrm{TeV}, z=0)_2$ and $\epsilon^2\Phi_\gamma(100\ \mathrm{GeV}, z=0)_1 > \epsilon^2\Phi_\gamma(100\ \mathrm{GeV}, z=0)_2$. Thus, the gamma-ray fluxes in the right figure can be directly interpreted under such assumption.

To test the assumption and estimate the value of z_a, we calculate the gamma-ray fluxes from a single source with the neutrino injection 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} located at redshift $z_s = 0.5,\ 1.0,\ 1.5,\ 2.0,\ 2.5,\ 10.0$ respectively. We use the EBL models from Finke et al. (2010) and Inoue et al. (2013) for low-redshift ($z < 5$) and high-redshift ($z > 5$) calculations. Figure 3 illustrates the gamma-ray fluxes. From this figure, we

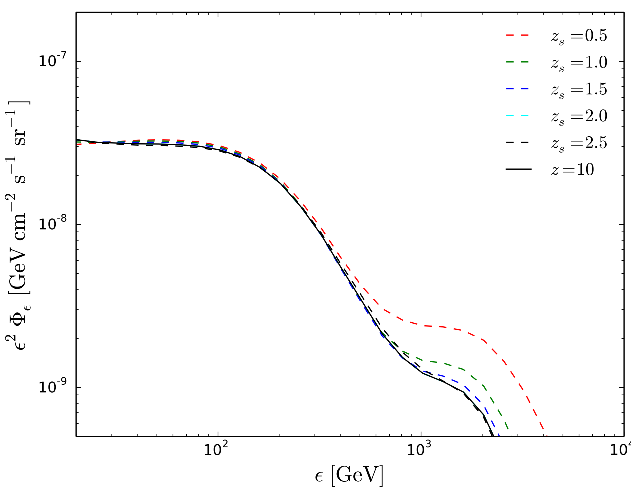

Figure 3: The gamma-ray fluxes of single neutrino sources located at $z_s = 0.5,\ 1.0,\ 1.5,\ 2.0,\ 2.5,\ 10.0$

find the locations no longer influence the gamma-ray fluxes when the redshifts are higher than 2. The result is enough to certify the hypothesis and we conclude $1.5 < z_a \leq 2$.

Therefore, we can move HRNS to a lower redshift ($> z_a$) avoiding the uncertainties of high-redshift EBL and star-formation rate. Now, we are ready to examine the applicability of high-redshift neutrino sources. As a supplementary neutrino injection, the overall high-redshift neutrino flux is assumed to be 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} and is equivalent to a single source whose redshift is higher than z_a. For example, if we add such a single source to the calculation in the Fig 1 (left), the total neutrino flux and gamma-ray flux are shown in Fig 4. The dashed lines are fluxes for the SBG/SFG ($z_s < 5$) contribution. After adding a single source (e.g. at $z = 3$) to the calculation, we get the solid lines. From this figure we find that the total neutrino flux is still lower

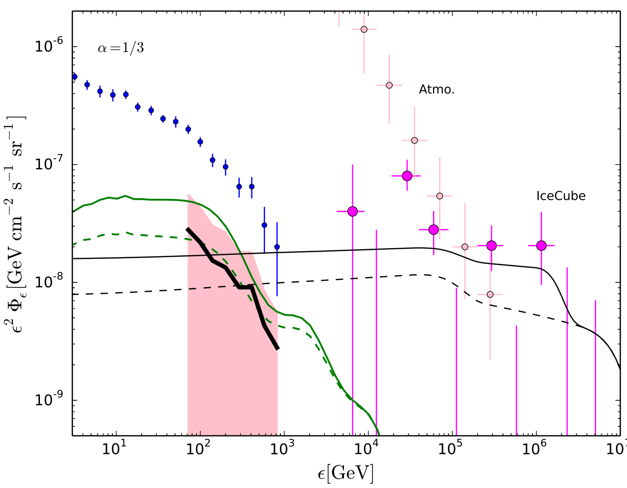

Figure 4: Total neutrino flux (black line) and gamma-ray flux (green line).

than the detected flux under the 28% EGB constraint. Moreover, HRNS will contribute EBG flux above 100 GeV which shows the HRNS dominated by *pp* mechanism cannot be regarded as ideal hidden sources without violating the non-blazar gamma-ray flux and the IceCube neutrinos are dominated by neither low-redshift SBG/SFG nor high-redshift sources.

Under the 28% EGB constraint, the overall neutrino flux considering a high-redshift injection are not sufficient to fit the IceCube flux very well. If we improve the high-redshift contribution to fit the IceCube data, the accompanying gamma-ray flux will exceed the non-blazar upper-limit. Thus, the applicability of high-redshift neutrino sources as "hidden" neutrino sources is determined by the uncertainty range of non-blazar EGB.