Diffuse PeV neutrinos from hypernova remnants in star-forming galaxies

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We demonstrate that the excess of sub-PeV/PeV neutrinos recently discovered by IceCube could originate through hadronuclear processes from the same sources responsible for cosmic rays (CRs) with energy above the second knee at $\sim 5 \times 10^{17}$ eV. We furthermore propose that hypernova remnants with semi-relativistic ejecta in star-forming galaxies are these sources. By virtue of their fast ejecta, such objects can accelerate protons to $\gtrsim$ EeV energies, and the resulting CRs can interact with the dense surrounding medium during propagation in their host galaxies to produce high-energy neutrinos and gamma rays via proton–proton (pp) collisions. A scenario in which hypernova remnants account for the observed CR flux above the second knee can also account for the neutrino flux detected by IceCube. The accompanying gamma ray flux remains below the diffuse isotropic gamma ray background observed by the *Fermi* Large Area Telescope (LAT).

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Two PeV neutrinos were detected by the IceCube neutrino detector during the combined IC-79/IC-86 data period[1]. More recently, follow-up analysis by the IceCube collaboration uncovered 26 additional sub–PeV neutrinos [2]. If it is confirmed with adequate statistical significance, this result may have important implications, in particular for understanding the origin of PeV-EeV cosmic rays (CRs), because the collisions of hadronic CRs with background nuclei or photons produce, *inter alia*, charged mesons whose decay products include neutrinos: ($\pi^+ \rightarrow e^+\nu_\mu\bar{\nu}_\mu\nu_e$, $\pi^- \rightarrow e^-\nu_\mu\bar{\nu}_\mu\bar{\nu}_e$). A preliminary analysis shows that these 28 events, ranging from 60 TeV–2PeV, correspond to a 4.3 σ excess over the background of $10.6^{+4.5}_{-3.9}$ from atmospheric neutrinos and muons, and their sky distribution is consistent with isotropy [3], suggesting an extragalactic origin, although a part of them could come from Galactic sources [4]. Non-detection of higher energy events implies a cutoff above 2 PeV for a hard spectrum with power-law index of -2. Alternatively, it is also compatible with a slightly softer but unbroken spectrum with index $\sim -$(2.2-2.3) [2, 8, 9].

Several possible scenarios for the origin of these neutrinos have been discussed, including that they are 'cosmogenic', arising in $p\gamma$-collisions between CRs and cosmic background photons, or that they are generated within CR sources either in $p\gamma$- or pp-collisions between CRs and ambient radiation fields or gas respectively [5–9]. A cosmogenic origin for the IceCube events is excluded because the predicted PeV flux is well below the observed one [6]. $p\gamma$-collisions inside sources are not favored either because these would over–predict the flux above 1 PeV, unless strong magnetic fields are present inside the sources [9]. In the case of pp-collisions, each daughter neutrino typically takes 0.03– 0.04 of the parent proton's energy [10]. Thus, to produce a 1 PeV neutrino, we require a source located at redshift z to accelerate protons to $\gtrsim 60(\frac{1+z}{2})$ PeV. The transition from Galactic to extragalactic CRs is thought to be either at the second knee (4-8$\times 10^{17}$ eV, [11]) or at the ankle ($\lesssim 10^{19}$eV, [13]) in the CR spectrum. If the neutrinos are produced by the sources of extragalactic ultrahigh energy CRs (with energies above the second knee, hereafter simply UHECRs), the neutrino spectrum should extend to $\gtrsim 20/(1+z)$ PeV without any abrupt cutoff. This would not conflict with the current IceCube observations if the neutrino spectrum is softer than -2.2. Note that the source proton spectrum is not necessarily as soft as the neutrino spectrum, since in some specific scenarios, higher energy protons have lower production efficiencies of secondary pions. On the other hand, gamma rays will be simultaneously generated in the pion–production processes, and a source proton spectrum that is too soft (with power–law index $s < -2.2$) would over–predict [7] the 0.1-100 GeV diffuse isotropic gamma–ray background observed by Fermi/LAT [14]. We thus assume a harder proton spectrum here.

The single-flavor neutrino flux at PeV is $\Phi_\nu = (1.2 \pm 0.4) \times 10^{-8}\,{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$ [2]. This flux is approximately related to the flux of parent protons Φ_p by [7, 12, 20] $\varepsilon_\nu^2\Phi_\nu = \frac{1}{6}f_\pi(\varepsilon_p^2\Phi_p)$, where ε_ν and ε_p are the energies of the neutrino and proton respectively and f_π is the pion-production (via pp- or $p\gamma$-collisions) efficiency. Thus, UHECR sources that account for the sub–PeV/PeV neutrinos need to provide a proton flux of $\varepsilon_p^2\Phi_p = 6(\varepsilon_\nu^2\Phi_\nu)f_\pi^{-1} \simeq 7\times10^{-8}\,f_\pi^{-1}{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$ at 10–100 PeV energy. This flux corresponds to a local proton energy production rate of

$$\dot{W}_{p,0} \simeq \left(\frac{c\xi_z}{4\pi H_0}\right)^{-1}\alpha(\varepsilon_p^2\Phi_p) \simeq 10^{44.5}f_\pi^{-1}\,{\rm erg\,Mpc^{-3}yr^{-1}} \quad (1)$$

where c is the speed of light, H_0 is the Hubble constant, $\xi_z \simeq 3$ is a factor that accounts for the contribution from high-redshift sources [12], and $\alpha \simeq 10$ comes from normalization of the proton spectrum (e.g., for $s = -2$, $\alpha = \ln(\varepsilon_{p,{\rm max}}/\varepsilon_{p,{\rm min}})$). For comparison, the required local CR energy production rate is $\sim 10^{45.5}\,{\rm erg\,Mpc^{-3}yr^{-1}}$ if the transition from Galactic to extragalactic CRs occurs at the second knee and $\sim 10^{44.5}\,\mathrm{erg\,Mpc^{-3}yr^{-1}}$ if the transition occurs at the ankle for a $s=-2$ source spectrum[13]. Thus, if a certain type of source can only account for UHECRs above the ankle, an extremely high efficiency (i.e. $f_\pi \simeq 1$) is needed to produce a sufficient PeV neutrino flux. On the other hand, if the transition from Galactic to extragalactic CRs occurs at the second knee, we require $f_\pi \sim 0.1-0.3$ since the observed CR flux at the second knee is $\Phi_{CR} \approx (3-8)\times 10^{-7}\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$. This puts severe constraints on possible sources of UHECRs.

In short, the source population responsible for both PeV neutrinos and UHECRs should be able to produce $\gtrsim 1\,\mathrm{EeV}$ CR and have high pion conversion efficiency ($f_\pi \gtrsim 10\%$). Supernova remnants (SNRs) have been widely discussed as promising proton accelerators (see a recent review [15] and references therein). But normal SNRs with ejecta velocities $< 10^9\mathrm{cm\,s^{-1}}$ are not able to accelerate protons to $\sim 60\left(\frac{1+z}{2}\right)$ PeV [16], even considering a turbulently–amplified magnetic field (but see [17]). A subset of very energetic supernovae, called semi–relativistic hypernovae (hypernovae for short), has ejecta with much faster velocities, $\gtrsim 0.1c$, expanding into their progenitor stellar winds [18]. Assuming a CR-amplified magnetic field with a strength close to equipartition, hypernovae satisfy the Hillas condition [19] for acceleration of $\gtrsim 10^{18}$ eV protons and have thus been proposed as sources of UHECRs above the second knee [20], or even up to the highest CR energies when considering the fastest part of the ejecta and heavy nuclei acceleration [21]. In the following, we will investigate whether hypernovae could also be the origin of the recently discovered sub-PeV/PeV neutrinos provided that they are responsible for UHECRs above the second knee.

Neutrino emission from hypernova remnants — Accelerated protons will interact with the ISM before escaping from their host galaxies and produce neutrinos, gamma rays and electrons/positions. The energy loss time of CR protons in the ISM via pp-collisions is

$$\begin{aligned}\tau_{pp}(\varepsilon_p) &= [\kappa\sigma_{pp}(\varepsilon_p)nc]^{-1}\\ &= 6\times10^7\mathrm{yr}\left[\frac{\sigma_{pp}(\varepsilon_p=60\,\mathrm{PeV})}{100\,\mathrm{mb}}\right]^{-1}\left(\frac{n}{1\,\mathrm{cm^{-3}}}\right)^{-1}\end{aligned} \tag{2}$$

where $\kappa=0.17$ is the inelasticity, σ_{pp} is the cross section, and n is the number density of ISM protons. The pp-collision efficiency can be estimated by $f_\pi=\min(1,t_{\rm esc}/\tau_{pp})$ with $t_{\rm esc}$ as the escape timescale. Generally, there are two ways for CRs to escape from a galaxy. One, diffusive escape, is energy–dependent and the other, advective escape via a galactic wind, is energy–independent. The associated escape timescales can be estimated by $t_{\rm diff}=h^2/4D$ and $t_{\rm adv}=h/V_w$ respectively. Here $D=D_0(E/E_0)^\delta$ is the diffusion coefficient where D_0 and E_0 are normalization factors, and $\delta=0-1$ depending on the spectrum of interstellar magnetic turbulence. h is usually taken as the scale height of the galaxy's gaseous disk and V_w is the velocity of the galactic wind in which the CRs are advected. The diffuse gamma-ray emission from the Galactic plane implies $f_\pi \sim 1\%$ for TeV protons [22], so we may expect that f_π for >10PeV protons is $\ll 1\%$ in our Galaxy. However, since the hypernova rate should generally trace the cosmic star formation rate (SFR), which is known to increase dramatically with z from $z=0$ up to at least $z \sim$1–2, the properties of galaxies at $z \sim$1–2 (hereafter 'high-redshift' galaxies) are likely to be more important for determining the total diffuse neutrino flux. As our template systems, we consider such galaxies of two types, normal star-forming galaxies (NSG) and starburst galaxies (SBG).

High-redshift galaxies display different properties from nearby ones. High-redshift NSGs generally do not reveal well-developed disk structure and show more extended morphologies with typical scale height $h\sim 1$ kpc for massive systems [23, 24]. They also have much higher fractions of molecular gas [23] with typical column density $\Sigma \sim 0.1\,\mathrm{g\,cm^{-2}}$, implying volumetric average ISM densities of $n\sim \Sigma/2h \sim 10\,\mathrm{cm^{-3}}$. High-redshift SBGs typically have scale height $h\sim 500$ pc and average gas density $n\sim 200\,\mathrm{cm^{-3}}$ [25]. As for diffusion coefficients, recent studies on CR propagation and anisotropy in our Galaxy suggest $D_0 \sim 10^{28}\,\mathrm{cm^2s^{-1}}$ at 3 GeV and $\delta \simeq 0.3$ [26]. Since little is known about the diffusion coefficient in high-z galaxies, we adopt the same values of D_0 and δ as inferred in our Galaxy for high–redshift NSGs. We assume a lower diffusion coefficient $D_0 \sim 10^{27}\,\mathrm{cm^2s^{-1}}$ for high-redshift SBGs, because the magnetic fields in nearby SBGs such as M82 and NGC253 are observed to be ~ 100 times stronger than in our Galaxy and the diffusion coefficient is expected to scale with the CR's Larmor radius ($\propto \varepsilon_p/B$) [27]. Regarding advective escape, the velocity of the Galactic nuclear wind is $\sim 300\,\mathrm{kms^{-1}}$ [28, 29], while optical and X-ray observations show the velocity of the outflow in M82 are $\sim 500-600\,\mathrm{kms^{-1}}$ [30] and $1400-2200\,\mathrm{kms^{-1}}$ [31] respectively. Since galactic winds are probably driven by supernova explosions [32] whose rate is higher in high-redshift galaxies, we may expect their winds to be faster and take $V_w=500\,\mathrm{km\,s^{-1}}$ and $1500\,\mathrm{km\,s^{-1}}$ as the reference values for NSGs and SBGs respectively. Then we obtain

$$t^{\rm N}_{\rm diff}=5\times10^4\mathrm{yr}\,(\frac{h}{1\,\mathrm{kpc}})^2(\frac{D_0}{10^{28}\,\mathrm{cm^2\,s^{-1}}})^{-1}(\frac{\varepsilon_p}{60\,\mathrm{PeV}})^{-0.3} \tag{3}$$

$$t^{\rm N}_{\rm adv}=2\times10^6\mathrm{yr}\,(\frac{h}{1\,\mathrm{kpc}})(\frac{V_w}{500\,\mathrm{km\,s^{-1}}})^{-1} \tag{4}$$

for NSGs, and

$$t^{\rm B}_{\rm diff}=10^5\,\mathrm{yr}\,(\frac{h}{0.5\,\mathrm{kpc}})^2(\frac{D_0}{10^{27}\,\mathrm{cm^2\,s^{-1}}})^{-1}(\frac{\varepsilon_p}{60\,\mathrm{PeV}})^{-0.3} \tag{5}$$

$$t^{\rm B}_{\rm adv}=3\times10^5\mathrm{yr}\,(\frac{h}{0.5\,\mathrm{kpc}})(\frac{V_w}{1500\,\mathrm{km\,s^{-1}}})^{-1} \tag{6}$$

for SBGs. The escape timescale can be approximated by $t_{\rm esc} = \min(t_{\rm adv}, t_{\rm diff})$, and we may expect a break occurring in $t_{\rm esc}$ when $t_{\rm adv} = t_{\rm diff}$, i.e., $\varepsilon_{p,\rm b}^{\rm N} = 300\,{\rm GeV}\,(\frac{h}{1\,\rm kpc})^{3.3}(\frac{V_w}{500\,\rm km\,s^{-1}})^{3.3}(\frac{D_0}{10^{28}\,\rm cm^2\,s^{-1}})^{-3.3}$ and $\varepsilon_{p,\rm b}^{\rm B} = 1.6\,{\rm PeV}\,(\frac{h}{1\,\rm kpc})^{3.3}(\frac{V_w}{1500\,\rm km\,s^{-1}})^{3.3}(\frac{D_0}{10^{27}\,\rm cm^2\,s^{-1}})^{-3.3}$ for NSGs and SBGs respectively. We then find that the pp-collision efficiencies for production of 1 PeV neutrinos in NSGs and SBGs are respectively

$$f_\pi^{\rm N} = t_{\rm diff}^{\rm N}/\tau_{pp}^{\rm N} \simeq 0.01 \text{ and } f_\pi^{\rm B} = t_{\rm diff}^{\rm B}/\tau_{pp}^{\rm B} \simeq 0.4 \qquad (7)$$

The single-flavor neutrino flux at 1 PeV is then $\varepsilon_\nu^2\Phi_\nu = \frac{1}{6}[f_{\rm SB}f_\pi^{\rm B} + (1-f_{\rm SB})f_\pi^{\rm N}]\varepsilon_p^2\Phi_{\rm CR} \sim 10^{-8}\,{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$, which is comparable to the observed neutrino flux. Here $f_{\rm SB} \sim 10\% - 20\%$ [36] is the fraction of the SFR contributed by SBGs. If we assume that hypernovae account for CRs above $\sim 5\times10^{17}$eV, they should provide a CR flux of $\varepsilon_p^2\Phi_{\rm CR} \simeq 7\times10^{-7}\,{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$ at this energy [33] and the required local CR energy production rate $\dot{W}_0$ is then $\sim 10^{45.5}{\rm erg\,Mpc^{-3}yr^{-1}}$. Assuming that each hypernova releases $E_{k,\rm HN} = 5\times10^{52}$ erg of kinetic energy [18], a fraction η_p =10% of which goes into CRs, we find the required local event rate is about $600\,{\rm Gpc^{-3}yr^{-1}}$, consistent with the observed value [34].

The fluxes of secondary neutrinos and gamma rays produced by one hypernova ϕ_ν and ϕ_γ (in unit of eV^{-1}) are calculated with the following analytical approximation [10],

$$\phi_i(\varepsilon_i) \equiv \frac{dN_i}{d\varepsilon_i} \simeq \int_{\varepsilon_i}^{\infty} \frac{f_\pi}{\kappa} J_p(\varepsilon_p) F_i(\frac{\varepsilon_i}{\varepsilon_p}, \varepsilon_p)\frac{d\varepsilon_p}{\varepsilon_p} \qquad (8)$$

where i could be γ or ν. In the above equation, F_i is the spectrum of the secondary γ or ν in a single collision. We assume that the accelerated proton spectrum is $J_p = C_p\varepsilon_p^{-2}\exp(-\varepsilon_p/\varepsilon_{p,\rm max})$ where C_p is a normalization coefficient fixed by $\int\varepsilon_p J_p d\varepsilon_p = \eta_p E_{k,\rm HN}$. Here we neglect the contribution of secondary electrons/positrons and primary electrons via inverse Compton scattering and Bremsstrahlung radiation, because these are only important at $\lesssim 100\,{\rm MeV}$ [37]. To calculate the diffuse flux of neutrinos and gamma rays, we need to integrate the contribution from galaxies throughout the whole universe, i.e.

$$\Phi_i(\varepsilon_i^{\rm ob}) \equiv \frac{dN_i^{\rm ob}}{d\varepsilon_i^{\rm ob}} = \frac{1}{4\pi}\int_0^{z_{\rm max}} \rho(z)\Gamma_{\rm HN}^{\rm SFR}\phi_i[(1+z)\varepsilon_i^{\rm ob}]\frac{cdz}{H(z)} \qquad (9)$$

where $\rho(z) = \rho_0 S(z)$ represents the star-formation history with ρ_0 being the local SFR and $S(z)$ describing its evolution with redshift. The total SFR in the local universe is found to be $\rho_0 \sim 0.01\,M_\odot\,{\rm yr^{-1}Mpc^{-3}}$ and assumed to evolve as [39] $S(z) \propto (1+z)^{3.4}$ for $z<1$, $(1+z)^0$ for $1 \le z \le 4$ and $(1+z)^{-7}$ for $z>4$. Here we assume the fraction of SFR from SBGs is $f_{SB} = 20\%$ at any cosmic epoch. The factor $\Gamma_{\rm HN}^{\rm SFR}$ represents the ratio between the hypernova rate and SFR (in units of $M_\odot^{-1}$). Its value is normalized by requiring the local CR energy production rate of hypernovae to match the observed CR flux above the second knee. $H(z) = H_0\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}$ is the Hubble parameter and we adopt $H_0 = 71\,{\rm kms^{-1}Mpc^{-1}}$, $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$. While neutrinos can reach the Earth without interaction, very high energy (VHE, $\gtrsim 100\,$GeV) gamma rays can be absorbed by $e^\pm$ pair production on the intergalactic radiation field, initiating cascade processes and depositing energy into $<100\,$GeV photons. As long as the cascade is well developed, the VHE gamma rays injected at z will form a nearly universal spectrum which only depends on the total energy injected and the injection redshift z [40]. We integrate over redshift to sum up the contributions of cascades initiated at different z.

Panel (a) of Fig. 1 presents our calculated diffuse neutrino and gamma–ray fluxes. The red dashed and dash-dotted lines represent the neutrino flux from NSGs and SBGs respectively. At low energies, energy–independent advective escape dominates over energy-dependent diffusive escape, so the spectrum of neutrinos roughly follows the $s=-2$ accelerated proton spectrum. As the energy increases, the neutrino spectrum breaks because diffusive escape becomes faster than advective escape. Because $t_{\rm diff} \propto \varepsilon^{-0.3}$, the spectral index above the break increases by about 0.3. But the increase of the pp cross section at higher energies [10] compensates this somewhat, making the final spectral slope close to -2.2. Note that in this case the UHECRs are mostly produced by hypernovae in NSGs while the PeV neutrinos mainly arise from hypernovae in SBGs. This is because most hypernovae occur in NSGs while the pp-collision efficiency is much higher in SBGs.

Given the uncertainties in D at high redshift, we also consider an alternative case in which D_0 in high-redshift NSGs is 10 times smaller than in our Galaxy. There is observational evidence for stronger magnetic fields in such galaxies [41], so a smaller diffusion coefficient is plausible. With $D_0 = 10^{27}{\rm cm^2s^{-1}}$ and assuming $f_{SB} = 10\%$, we find that $f_\pi^N \simeq 0.1$ for production of PeV neutrinos, in which case both PeV neutrinos and UHECRs are produced predominantly by hypernovae in NSGs, as shown in panel (b) of Fig. 1.

In our model, there is no sharp cutoff in the neutrino spectrum above PeV, although the spectrum becomes softer at $\lesssim 10\,$PeV. This is because the energy of the corresponding parent proton is $\lesssim 0.6(\frac{1+z}{2})\,$EeV, approaching our assumed maximum energy of 1 EeV. Nevertheless, our model predicts a flux of a few times $10^{-9}\,{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$ around 10 PeV. This flux is consistent with the present non-detection of neutrinos above several PeV, but is likely to be detectable in the future. Given that the all–flavor exposure of IceCube is $\sim 10^{15}\,{\rm cm^2\,sr\,s}$ at 10 PeV [8] for 662 days, we may expect such a flux would lead to detection of $\sim 10\,$PeV neutrinos in $\lesssim 5-10\,$yrs operation.

Discussion — Including the cascade component, the total diffuse gamma ray flux at $<100\,$GeV is $\sim(7-8)\times10^{-8}\,{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$ in both cases, as shown with the solid blue lines in Fig. 1. Note that putative additional losses due to absorption of VHE photons by the radiation fields inside their host galaxies [42] and by synchrotron losses of the $e^\pm$ pairs in the host galaxy magnetic fields would lower the predicted cascade flux. The resulting flux is $\lesssim 50\%$ of the flux observed by LAT. Also note that although normal SNRs

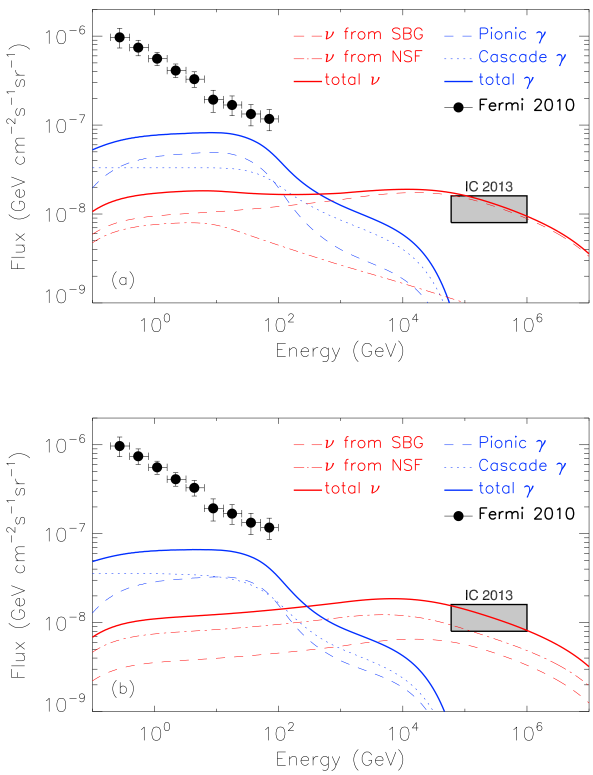

FIG. 1. Spectra of ν_μ and gamma rays produced by hypernova remnants in star-forming galaxies. Upper panel: the red dashed line and dash–dotted line represent the one–flavor neutrino flux from starburst galaxies and normal star-forming galaxies respectively, and the red solid line is their sum. Neutrino oscillations imply that $\nu_\mu : \nu_e : \nu_\tau = 1 : 1 : 1$ at the detector. The blue dashed and dotted lines represent the gamma ray fluxes from pion decay (accounting for intergalactic absorption) and the cascaded gamma ray flux, respectively, while the blue solid line is the sum of the two components. Data points are taken from [14]. The shaded rectangle shows the IceCube preliminary flux [2]. Lower panel: same as the upper one but with $D_0 = 10^{27}\,{\rm cm^2 s^{-1}}$ used for normal star-forming galaxies and $f_{SB} = 10\%$. See text for more discussion.

can not contribute to the $\gtrsim$100 TeV neutrino flux, they can accelerate protons to PeV and produce $< 100\,$TeV gamma rays, contributing to the diffuse gamma-ray background. Compared to normal supernovae, the local event rate of hypernovae is $\sim 1\%$ while their explosion energy is dozens of times larger, so the integral energy production rate of supernovae could be a few times larger than that of hypernovae. But the rate of hypernovae relative to supernovae can be higher at high redshifts, as semi-relativistic hypernovae may be engine-driven like long GRBs [43], which seem to occur preferentially in low-metallicity galaxies[44]. This would suggest a relatively smaller contribution of normal SNRs at higher z. Nevertheless, as a rough estimate, we predict that normal SNRs could produce a gamma-ray flux comparable to or even less than that of hypernova remnants, and in the former case the total gamma-ray flux at $10-100\,$GeV could reach the level of the observed one, providing a possible explanation for the apparent hardening in the spectrum of the diffuse isotropic gamma ray background at $> 10\,$GeV.

The local SFR density is estimated to be $\sim 0.01\,M_\odot\,{\rm Mpc^{-3}yr^{-1}}$, and employing the relation between SFR and infrared luminosity of a galaxy ${\rm SFR}\,[M_\odot\,{\rm yr}^{-1}] = 1.7\times10^{-10}L_{\rm IR}[L_\odot]$ [45], we find that a galaxy's CR luminosity, accommodated by hypernovae, is $L_{\rm CR} \sim 10^{40}{\rm erg\,s^{-1}}(\dot{W}_0/10^{45.5}{\rm erg\,Mpc^{-3}yr^{-1}})(L_{\rm IR}/10^{10}L_\odot)$. Given the infrared luminosity of our Galaxy is $\sim\ 10^{10}L_\odot$ and assuming a $pp-$collision efficiency of 10^{-3}, we estimate the total Galactic neutrino luminosity at $100\,$TeV-$1\,$PeV is $\lesssim\ 10^{36}{\rm erg\,s^{-1}}$. Note that our Galaxy might be too metal rich to host semi-relativistic hypernovae (or long GRBs) for the last several billion years [44], so this value could be smaller. Even if all these neutrinos are produced in the Galactic center and radiate isotropically, it would result in $\lesssim\ 1$ event detection during 662 days operation within a 8° circular region around the Galactic Center [46] and would not cause a strong anisotropy that violates the observations [2].

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