STAR-FORMING GALAXIES AS THE ORIGIN OF THE ICECUBE PeV NEUTRINOS

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ABSTRACT

Star-forming galaxies, due to their high star formation rates, and hence large number of supernova remnants (SNRs) therein, are huge reservoirs of cosmic rays (CRs). These CRs collide with gases in galaxies and produce high-energy neutrinos through proton–proton collisions. In this paper, we calculate the neutrino production efficiency in star-forming galaxies by considering realistic galaxy properties, such as the gas density and galactic wind in star-forming galaxies. To calculate the accumulated neutrino flux, we use the infrared luminosity function of star-forming galaxies recently obtained by the Herschel PEP/HerMES survey. The intensity of CRs producing PeV neutrinos in star-forming galaxies is normalized with the observed CR flux at EeV (1 EeV = 10^18 eV), assuming that SNR or hypernova remnants in star-forming galaxies can accelerate protons to EeV energies. Our calculations show that the accumulated neutrino emission produced by CRs in star-forming galaxies can account for the flux and spectrum of the sub-PeV/PeV neutrinos under reasonable assumptions on the CR confinement time in these galaxies.

Key words: cosmic rays – neutrinos

1. INTRODUCTION

The IceCube Collaboration recently announced the discovery of extraterrestrial neutrinos. With 37 events ranging from 60 TeV to 3 PeV within three years of operation, the excess over the background atmospheric neutrinos and muons reaches 60 TeV to 3 PeV within three years of operation, the excess of extraterrestrial neutrinos. With 37 events ranging from 3 PeV suggests that the neutrino source is either a hard power-law spectrum with a break above 3 PeV, or an unbroken power-law spectrum with a softer index of \( \Gamma \approx 2.2–2.3 \) (Aartsen et al. 2014; Anchordoqui et al. 2014a; Winter 2014). The sky distribution of these events is consistent with isotropy (Aartsen et al. 2014), implying that an extragalactic origin is dominant, although a fraction of them could come from Galactic sources (Fox et al. 2013; Razzana 2013; Ahlers & Murase 2014; Lunardini et al. 2014; Neronov et al. 2014).

The source of the IceCube neutrinos is still controversial. The proposed astrophysical sources include starburst and star-forming galaxies (Loeb & Waxman 2006; He et al. 2013; Murase et al. 2013; Anchordoqui et al. 2014b; Liu et al. 2014; Tamborra et al. 2014; Wang et al. 2014), gamma-ray bursts (Waxman & Bahcall 1997; Cholis & Hooper 2013; Liu & Wang 2013; Murase & Ioka 2013), and the jets and/or cores of active galactic nuclei (AGNs; Anchordoqui et al. 2008; Kalashev et al. 2013; Stecker 2013; Dermer et al. 2014), newborn pulsars (Fang et al. 2014), etc. In this paper, we focus on the scenario of starburst/star-forming galaxies where cosmic rays (CRs) collide with dense gases in the interstellar medium and produce neutrinos. The gamma-ray observations of nearby star-forming galaxies by the Fermi Large Area Telescope (LAT), including M31, LMC, SMC, M82, NGC 253, and NGC 2146 (Ackermann et al. 2012; Tang et al. 2014), have proven that proton–proton (pp) collisions occur in such star-forming galaxies, and so they are guaranteed factories of high-energy neutrinos.

In their pioneering work on the starburst galaxy scenario, Loeb & Waxman (2006) assume that CRs in the starburst galaxies lose almost all of their energy into pions and calibrate the GeV neutrino emissivity with the synchrotron radio emissivity. A simple power-law extrapolation is then used to estimate the neutrino flux at PeV energies. On the other hand, the non-detection of events beyond 60 TeV within three years of operation, the excess over the background atmospheric neutrinos and muons reaches 5.7σ (Aartsen et al. 2014). The non-detection of events beyond 3 PeV suggests that the neutrino flux follows either a hard power-law spectrum with a break above 3 PeV, or an unbroken power-law spectrum with a softer index of \( \Gamma \approx 2.2–2.3 \) (Aartsen et al. 2014; Anchordoqui et al. 2014a; Winter 2014). The sky distribution of these events is consistent with isotropy (Aartsen et al. 2014), implying that an extragalactic origin is dominant, although a fraction of them could come from Galactic sources (Fox et al. 2013; Razzana 2013; Ahlers & Murase 2014; Lunardini et al. 2014; Neronov et al. 2014).

1 In another model, the transition occurs at the “ankle” (\( \leq 10^{19} \) eV) (Katz et al. 2009), where the spectral index flattens from \(-3.3\) to \(-2.7\).
obscured or low-luminosity AGNs, all of which contribute to the star formation rate (SFR) in the universe (Gruppioni et al. 2013). The gas density in a galaxy is expected to relate to its SFR, and hence to the IR luminosity of the galaxy. Then, with these galaxy properties known, we are able to calculate the neutrino fluxes produced in star-forming galaxies of different luminosities and populations.

In Section 2, we first outline the neutrino production process in star-forming galaxies. In Section 3, we describe the galaxy parameters that are needed to calculate the accumulated neutrino flux from star-forming galaxies. In Section 4, we invoke the luminosity function to calculate the accumulated neutrino flux produced by all of the star-forming galaxies in the universe. Finally, we provide our conclusions and discussions in Section 5.

2. NEUTRINO PRODUCTION PROCESS IN STAR-FORMING GALAXIES

Supernova remnants (SNRs) are widely discussed as accelerators of CRs. Due to the high SFRs in star-forming galaxies, a large number of SNRs reside in these galaxies, and hence these galaxies are huge reservoirs of CRs. The total energy of CRs injected into a galaxy per unit time is proportional to the total SFR of the galaxy, i.e., \( L_p \propto \text{SFR} \), where \( L_p \) represents the luminosity in CR protons. The total infrared luminosity of a galaxy is a good tracer for its SFR, and hence to the IR luminosity of the galaxy. Then, we invoke the luminosity function to calculate the accumulated fluxes produced in star-forming galaxies of different luminosities and populations.

Since galaxies with higher IR luminosities are observed to have stronger magnetic fields (Thompson et al. 2006), and the diffusion coefficient is expected to scale with the CR Larmor radius, these high-luminosity galaxies could have a smaller diffusion coefficient. Thus, we allow lower values of the diffusion coefficient for galaxies with IR luminosity \( L_{\text{TIR}} > 10^{11} L_\odot \) in the calculation, while the diffusion coefficient for galaxies with IR luminosity \( L_{\text{TIR}} < 10^{11} L_\odot \) is fixed to \( D_{\text{diff}} \approx 10^{28} \text{cm}^2 \text{s}^{-1} \), that is, the same value as that of our Galaxy. The energy dependence of the diffusion coefficient is also unknown. We assume two cases, one is the commonly used value \( \delta = 0.5 \), based on the measurements of the CR confinement time in our Galaxy (Engelmann et al. 1990; Webber et al. 2003), which is also consistent with Kraichnan-type turbulence. Another choice is \( \delta = 1/3 \), assuming the Kolmogorov-type turbulence.

In the advection escape case, CRs are confined in the galactic wind and transported outward with the wind on a characteristic timescale

\[
\tau_{\text{adv}} = \frac{H}{v_w} = 1.8 \times 10^6 \frac{H}{1 \text{kpc}} \left( \frac{v_w}{500 \text{km s}^{-1}} \right)^{-1} \text{yr},
\]

where \( v_w \) is the speed of the galactic wind. The real escape time should involve both effects, and we parameterize it as \( \tau_{\text{esc}} = \tau_{\text{diff}} + \tau_{\text{adv}} \).

The flux of the neutrinos produced in one galaxy is then calculated by the following analytical formula

\[
L_\nu(E_\nu) \approx \int_{E_*}^{\infty} \frac{dE_\nu}{E_\nu} \int \frac{dE_p}{E_p} \int_{E_\nu}^{E_p} \frac{E_\nu}{E_p} E_\nu f_s(E_p) L_p f_{\text{ii}}(E_\nu/E_p, E_p) dE_p.
\]

3. GALAXY PARAMETERS

We have seen that the pion-production efficiency depends on galaxy parameters, such as the gas surface density \( \Sigma_g \), galactic wind velocity \( v_w \), scale height of the galaxy \( H \), etc. In this section, we try to provide a description of these parameters, which are needed to calculate the accumulated neutrino flux in Section 4. Since the infrared luminosity function is used to characterize the population of galaxies, we try to build relations
between these parameters and the total infrared luminosity of the
galaxy.

To determine the gas surface density $\Sigma_g$, we employ the
widely used Kennicutt–Schmidt law, which relates the SFR surface
density $\Sigma_{\text{SFR}}$ to the gas surface density, i.e.,
$\Sigma_{\text{SFR}} \propto \Sigma_g^{1.4}$ (Kennicutt 1998). The Kennicutt–Schmidt law,
although discovered for galaxies in the local universe, is also
proven to be valid at high redshift (Genzel et al. 2010). In
this paper, we use the classic form given by Kennicutt
(1998), i.e.,
$$\Sigma_{\text{SFR}} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_g}{1 M_\odot \text{pc}^{-2}}\right)^{1.4 \pm 0.15} M_\odot \text{yr}^{-1}\text{kpc}^{-2}. \quad (6)$$

If the radius of each galaxy is known, then we can derive the
SFR surface density $\Sigma_{\text{SFR}} = \text{SFR}/\pi R^2$. Assuming the Chabrier
initial mass function (IMF; Chabrier 2003), we have
$$\text{SFR} = \frac{L_{\text{TIR}}}{10^{10} L_\odot} M_\odot \text{yr}^{-1}. \quad (7)$$

Substituting this relation into the Kennicutt–Schmidt Law, we obtain
$$\Sigma_g = (7.07 \pm 1.63) \times 10^{-5} \left(\frac{L_{\text{TIR}}}{L_\odot}\right)^{1.4 \pm 0.15} \left(\frac{R}{\text{pc}}\right)^{2} \left(\frac{\text{g cm}^{-2}}{1.5 \pm 0.15}\right). \quad (8)$$

There is a correlation between the SFR and the total stellar mass for
the majority of star-forming galaxies, which are known as the main-sequence (MS) galaxies. The relation is quite
tight in the local universe (Peng et al. 2010, 2012) and
also works well at higher redshift (Daddi et al. 2007; Elbaz et al.
2007; Rodighiero et al. 2010). In this paper, we use the SFR–stellar mass relation provided by Bouchè et al. (2010) and
Genzel et al. (2010), i.e.,
$$\text{SFR}(M_\odot \text{yr}^{-1}) = 150 \left(M_\odot / 10^{11} M_\odot\right)^{0.8} \left((1 + z)/3.2\right)^{2.7} \text{for} \quad z < 2.3 \quad \text{and} \quad \text{SFR}(M_\odot \text{yr}^{-1}) = 163 \left(M_\odot / 10^{11} M_\odot\right)^{0.8} \text{for} \quad z > 2.3 \quad \text{up to} \quad z = 4, \quad \text{since the redshift evolution flattens above} \quad z \sim 2.5.$$  

While the MS galaxies follow the SFR-stellar mass relation above,
some galaxies have much higher efficiencies when transforming
gas to stars, and so they have higher SFRs given the same
stellar mass. These outliers generally follow another linear relation between SFRs and stellar masses with an offset
of a factor of a few from that of the MS. The offset can be
measured by, namely, the specific star formation rate (sSFR),
which is defined as SFR/$M_\ast$. Galaxies with higher sSFR are thought to be off-MS galaxies and in a merger mode.
According to Gruppioni et al. (2013), normal spiral galaxies,
starburst galaxies, and SF-AGNs (spiral) are thought to be
mostly on-MS galaxies, while SF-AGNs (SB) are thought to be
off-MS galaxies. In our calculation, the SFR-stellar mass relation is increased by 0.6 dex for off-MS galaxies. For the
Chabrier IMF, the relation between the total stellar mass and
the total infrared luminosity can be summarized as
$$M_\ast = \begin{cases} 
10^{11} \left(\frac{L_{\text{TIR}}}{1.5 \alpha / 10^{12} L_\odot}\right)^{1.25} \left(\frac{1 + z}{3.2}\right)^{-3.38} \quad (z < 2.3), \\
9 \times 10^{10} \left(\frac{L_{\text{TIR}}}{1.5 \alpha / 10^{12} L_\odot}\right)^{1.25} \quad (z > 2.3), 
\end{cases} \quad (9)$$

where $\alpha$ is equal to 1 and 4 for on-MS galaxies and off-MS
galaxies, respectively.

The relation between stellar mass and galaxy radius has been studied by different authors (Shen et al. 2003; Dutton
et al. 2011; Mosleh et al. 2011; Law et al. 2012; Cebrián & Trujillo 2014). For local late-type galaxies, Shen et al. (2003)
found a relation based on the Sloan Digital Sky Survey:
$$R_{\text{SDSS}} = 0.1 \left(\frac{M_\ast}{M_\odot}\right)^{0.14} \left[1 + \frac{M_\ast}{3.98 \times 10^{10} M_\odot}\right]^{0.25} \text{kpc}. \quad (10)$$

At high redshift, galaxies tend to be more compact, but the
scaling still functions (Dutton et al. 2011; Mosleh et al. 2011;
Law et al. 2012). Law et al. (2012) found a redshift-dependent relation,
$$\frac{R}{R_{\text{SDSS}}} \approx \begin{cases} 
1 \quad (z < 1), \\
2/(1 + z)^{-1.07} \quad (z > 1). 
\end{cases} \quad (11)$$

Combining the SFR-stellar mass relation and the radius-stellar mass relation above, we can now derive the galaxy radius $R$
from its SFR. As the star-forming galaxies at high redshift are
more consistent with triaxial ellipsoids with minor/major axis
ratio $\sim 0.3$ (Law et al. 2012), we assume $H = 0.3 \, R$.

Galactic-scale gaseous outflows or winds in star-forming
galaxies are ubiquitous at all cosmic epochs (Heckman et al.
1990; Pettini et al. 2001; Shapley et al. 2003). Such outflows are powered by supernova explosions or other
processes. The dependence of the galactic wind speed on the
galaxy’s SFR has been studied. For ultraluminous infrared
galaxies at low redshifts, winds from more luminous starbursts
have higher speeds roughly as $v_w \propto \text{SFR}^{0.35}$ (Martin 2005). A similar relation is found in star-forming galaxies at $z \approx 1.4, \quad$ showing $v_w \propto \text{SFR}^{0.3}$ with an error in $v_w$ of 34% (Weiner et al. 2009). Combining with Equation (1), we get
$$v_w \approx 175 \left(\frac{\text{SFR}}{M_\odot \text{yr}^{-1}}\right)^{0.3} \approx 400 \left(\frac{L_{\text{TIR}}}{10^{11} L_\odot}\right)^{0.3} \text{km s}^{-1}. \quad (12)$$

Once the galaxy parameters are known, we can calculate the
pion-production efficiency $f_{\pi}$ of CRs in galaxies with different
luminosities. Figure 1 shows the efficiency $f_{\pi}$ for CRs producing 1 PeV neutrinos in a galaxy at $z = 1$. One can see
that the $pp$ interaction is quite inefficient in low IR luminosity
galaxies, due to the low gas densities in these galaxies. As the
IR luminosity increases, the pion-production efficiency
increases. It also shows that the pion-production efficiencies
are higher in off-MS galaxies, which is due to the denser ISM
in them. We also give the uncertainty of $f_{\pi}$ in Figure 1 (the shaded region), taking into account the uncertainties in the
Kennicutt–Schmidt Law (including the uncertainty in slope)
and in the galactic wind velocity. We find the uncertainty of $f_{\pi}$
is about 50% which mainly results from the uncertainty in the slope of the Kennicutt–Schmidt Law.

In our calculation, we assumed that the column density of gas in a galaxy is uniform out to a limiting radius in a galaxy. The realistic gas density distribution in a galaxy may have a smooth gradient outward. Correspondingly, the CR injection rate, which traces the SFR, may follow the same distribution. We employ an exponential density profile found by Kravtsov (2013) to recalculate the pion-production efficiency and find that the overall efficiency is decreased by a factor of about 30%.

The pion-production efficiency also depends on the energy of CRs. As the diffusion escape is faster at higher energies while the advection and pp interaction timescales are energy-independent, the pion-production efficiency would break at some energy and then decrease as the energy of the CRs increases. As a result, the escape efficiency for CRs, $f_{\text{esc}} = 1 - f_{\pi}$, increases with energy. That means that CRs above 1 EeV are able to escape almost freely from their host galaxies and contribute to the observed flux of extragalactic CRs.

4. ACCUMULATED NEUTRINO FLUX WITH NORMALIZATION TO EeV CRs

In this section, we compute the accumulated neutrino flux by adopting the Herschel PEP/HerMES luminosity function (Gruppioni et al. 2013). Herschel is the first telescope that allows us to detect the far-IR population up to $z \approx 4$. Gruppioni et al. (2013) estimate the luminosity functions of different galaxy populations including normal spiral galaxies, starbursts, and star-forming galaxies containing obscured or low-luminosity AGNs. The galaxy classification is based on IR spectra where those that have far-IR excess with significant ultraviolet extinction are classified as starbursts and those that have mid-IR excess are classified as galaxies with obscured or low-luminosity AGNs (SF-AGN). The SF-AGN family includes Seyferts, LINERs, and ULIRGs containing AGNs. SF-AGNs are further divided into two subclasses: SF-AGNs (SB) which resemble starburst galaxies and SF-AGNs (spiral) which resemble normal spiral galaxies. This family, although containing AGNs, is dominated by star formation but not by AGN processes. The accumulated neutrino flux is the sum of the contribution from all of the galaxies throughout the whole universe, i.e.,

$$E_p^2 \Phi_{\nu}^{\text{accu}} = \frac{E_p^2 c}{4\pi} \int_0^{E_{\text{max}}} \int_{L_{\text{TIR,min}}}^{L_{\text{TIR,max}}} \sum_i f_i(L_{\text{TIR}, i}, z) L_{\text{IR}, i} (1 + z) E_p L_{\text{TIR}} H_{\nu} (1 + z) \delta \Omega_M + \Omega_L \times dL_{\text{TIR}} dz,$$

(13)

where $f_i(L_{\text{TIR}, i}, z)$ is the luminosity function for each galaxy family $i$, $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_L = 0.73$.

The luminosity function of a certain class of galaxies (denoted by the subscript $i$) can generally be described as

$$f_i(L_{\text{TIR}, i}, z) = \delta^\alpha \left( \frac{L_{\text{TIR}}}{L^\ast} \right)^{1-\alpha} \times \exp \left[ -\frac{1}{2\sigma^2} \log^{2} \left( \frac{1}{\frac{L_{\text{TIR}}}{L^\ast}} \right) \right],$$

(14)

where $L^\ast$ evolves as $(1 + z)^{\delta L_1}$ at $z < z_{b, L}$, and as $(1 + z)^{\delta L_2}$ at $z > z_{b, L}$, while $\delta^\ast$ evolves as $\alpha(1 + z)^{\delta^\ast}$ at $z < z_{b, \rho}$, and as $(1 + z)^{\delta^\ast}$ at $z > z_{b, \rho}$. For each population of galaxies, the parameters of the luminosity functions, such as $L^\ast$, $\alpha$, $\delta L_1$, $\delta L_2$, $z_{b, L}$, $z_{b, \rho}$, $k_{L, 2}$, and $k_{\rho, 1}$, are provided in Table 8 in Gruppioni et al. (2013). The number ratio between the two subclasses of SF-AGNs (i.e., SF-AGNs (spiral) and SF-AGNs (SB)) evolves with redshift, as given in Table 9 of Gruppioni et al. (2013).

To compute the accumulated neutrino flux from all star-forming galaxies, we need to determine the normalization of the CR intensity at EeV energies in each galaxy, i.e., the factor $C$ in Equation (1). We assume that the CRs which escape from these galaxies are responsible for the extragalactic CR flux at EeV. As EeV CRs do not suffer significant attenuation during their propagations to the earth, the expected CR flux at $E_p$ is

$$E_p^2 \Phi_p \mid_{E_p = 1 \text{ EeV}} \approx 2 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},$$

(15)

The observed flux at 1 EeV is about $E_p^2 \Phi_p \mid_{E_p = 1 \text{ EeV}} \approx 2 \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, according to several CR experiments such as HiRes (High Resolution Fly’s Eye Collaboration et al. 2009), Auger (Pesce 2012), KASCADE-Grande (Chiavassa et al. 2014), and TA (Abu-Zayyad et al. 2015). Then, we obtain the normalization factor $C \approx 2 \times 10^{22} \text{ eV}^{-1} \text{ s}^{-1}$.

The accumulated neutrino flux can then be obtained using Equation (13). Since the galaxy parameters are all determined, there are only two free parameters, i.e., the diffusion coefficients $D_0$ and $\delta$, which are not well-understood. We
study whether the theoretical flux agrees with observations under reasonable values of these two parameters. We find that for $\delta = 1/3$, $D_{0,H} \approx 10^{27.2} \text{ cm}^2 \text{s}^{-1}$ (the diffusion coefficient for galaxies with high IR luminosity $L_{\text{IR}} > 10^{11}L_\odot$) leads to the total neutrino flux that can fit the IceCube data, as shown in Figure 2. Note that the diffusion coefficient for galaxies with low IR luminosity $L_{\text{IR}} < 10^{11}L_\odot$ is fixed to $D_{0,L} = 10^{28} \text{ cm}^2 \text{s}^{-1}$. The figure shows contributions from various types of galaxies. We find that star-forming galaxies and starburst galaxies contribute significant fractions of the neutrino flux, while the spiral galaxies contribute the least. As expected, the neutrino spectrum becomes softer at high energies where the diffusion time is shorter than the advection time. The slope becomes steeper than $\Phi(E_\nu) \propto E_\nu^{-2.1}$ above PeV energy.

For $\delta = 0.5$, smaller values of $D_{0,H} \approx 10^{26} \text{ cm}^2 \text{s}^{-1}$ are needed to fit the IceCube data, as shown in Figure 3. With a large $\delta$, the neutrino spectrum becomes softer than $\Phi(E_\nu) \propto E_\nu^{-2.3}$ above PeV energy, which could explain the non-detection of neutrinos above 3 PeV (Anchordoqui et al. 2014a; Winter 2014). The lower value of $D_{0,H}$ leads to a diffusion coefficient of $D = 5.7 \times 10^{25} \text{ cm}^2 \text{s}^{-1}$ at $E_\nu = 100 \text{ PeV}$. The confinement of 100 PeV protons requires $E = cB_l > 100 \text{ PeV}$, which leads to a coherence length $l_c > 0.1 \text{ pc}B_{-2.5}(E/100 \text{ PeV})$. Thus, the minimum required diffusion coefficient is $D(100 \text{ PeV}) = (1/3)l_c = 3 \times 10^{27} \text{ cm}^2 \text{s}^{-1}$ (Tamborra et al. 2014). The diffusion coefficient obtained above in explaining the IceCube data satisfies this condition.

We calculate the diffuse gamma-ray flux accompanying the neutrino emission, following the approach of Chang & Wang (2014). The results are also shown in Figures 2 and 3 for the cases of $\delta = 1/3$, $D_{0,H} \approx 10^{27.2} \text{ cm}^2 \text{s}^{-1}$, and $\delta = 0.5$, $D_{0,H} \approx 10^{26} \text{ cm}^2 \text{s}^{-1}$, respectively. In the calculation, we considered the synchrotron loss effect of electron–positron pairs produced by the absorbed gamma-rays in the galaxies. The strengths of the magnetic fields in the galaxies are assumed to be $B = 400 \mu G$ ($\Sigma_e/\text{ g cm}^{-2} B^{-0.7}$) (Thompson et al. 2006; Lacki & Thompson 2010). We find that the accompanying gamma-ray flux is below the diffuse isotropic gamma-ray background observed by the Fermi/LAT (The Fermi LAT collaboration et al. 2014).

We also study the neutrino flux from star-forming galaxies in different luminosity ranges. Figure 4 presents the result for $\delta = 0.5$ and $D_{0,H} \approx 10^{26} \text{ cm}^2 \text{s}^{-1}$, which are the same parameters as those in Figure 3. We can see that most of the neutrino flux is contributed by the galaxies with total IR luminosities in the range $10^{11} - 10^{13}L_\odot$. This indicates that the accumulated neutrino flux is dominated by high-luminosity starburst and SF-AGN galaxies.

Figure 5 shows the flux contributed by on-MS galaxies and off-MS ones separately. According to their locations on the SFR-stellar mass plane, normal spiral galaxies, starburst galaxies, and SF-AGNs (spiral) are thought to be mostly on-MS galaxies, while SF-AGNs (SB) are thought to be off-MS galaxies (Gruppioni et al. 2013). Figure 5 suggests that on-MS...
galaxies dominate the contribution to the total neutrino flux over off-MS galaxies.

In the above calculations, we have assumed that the CR diffusion coefficient in galaxies with IR luminosity $L_{\text{IR}} < 10^{11} L_\odot$ is fixed to $D_{\text{IR}} = 10^{28} \text{ cm}^2 \text{ s}^{-1}$, i.e., the same value as that of our Galaxy. However, there is observational evidence for a smaller diffusion coefficient in high-redshift star-forming galaxies (Bernet et al. 2013). Thus, we recalculate the neutrino flux by taking $D_{\text{IR}} = 10^{27} \text{ cm}^2 \text{ s}^{-1}$ for galaxies with total IR luminosity $L_{\text{IR}} < 10^{11} L_\odot$, while keeping the other parameters unchanged. The comparison between these two cases is shown in Figure 6. As is shown, the total neutrino flux changes only a little. This is mainly because low IR luminosity galaxies contribute sub-dominantly to the total neutrino flux due to lower pion-production efficiencies.

5. DISCUSSIONS AND CONCLUSIONS

The proposed scenario above is based on the assumption that CR protons in star-forming galaxies are accelerated to energies above 1 EeV. Though we suggest that remnants of hypernovae or other peculiar types of supernova in these galaxies are possible accelerators of these CRs, the estimate of the neutrino flux presented in this paper does not depend on any specific accelerator sources. If remnants of normal supernovae in star-forming galaxies are able to accelerate protons to energies above 100 PeV due to higher magnetic fields in these galaxies, then our calculations also apply. Nevertheless, the fact that normalizing the CR intensity in star-forming galaxies at EeV with the observed CR flux results in a neutrino flux comparable to that observed by IceCube implies that star-forming galaxies are potential origins of both IceCube PeV neutrinos and extragalactic EeV CRs.

We note that Tamborra et al. (2014) have discussed the possibility that star-forming galaxies are the main sources of IceCube PeV neutrinos by adopting the IR luminosity function of Gruppioni et al. (2013). They first calculated the diffuse gamma-ray background produced by star-forming galaxies using the correlation between the gamma-ray intensity and infrared luminosity reported by Fermi observations. They then obtained the PeV neutrino flux assuming that all the gamma-rays are produced by hadronic $pp$ collisions and used power-law extrapolation to PeV energy. However, the correlation between gamma-ray luminosities and infrared luminosities is based on observations of nearby galaxies and it is unclear whether this correlation applies to high-redshift star-forming galaxies. Instead, we do not rely on this correlation, but calculate the pion-production efficiencies (and hence the neutrino flux) in these galaxies using the available knowledge about high-redshift star-forming galaxies.

To summarize, we have calculated the neutrino flux produced by CRs in different populations of star-forming galaxies considering realistic galaxy properties and the latest IR luminosity functions. By normalizing the CR intensity from the galaxies with the observed flux of EeV CRs, we have found that the accumulated neutrino flux from star-forming galaxies can explain the IceCube observations of sub-PeV/PeV neutrinos.

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![Figure 5](image5.png)

Figure 5. Same as Figure 3, but the contribution of the galaxies is divided into two subclasses, on-MS galaxies and off-MS galaxies. The black line shows the total flux, while the red and blue lines show the flux contributed by off-MS and on-MS galaxies, respectively.

![Figure 6](image6.png)

Figure 6. Accumulated neutrino flux of star-forming galaxies with different values of $D_{\text{IR}}$, while the other parameters remain unchanged. The black and red lines shows the cases with $D_{\text{IR}} = 10^{28} \text{ cm}^2 \text{ s}^{-1}$ and $D_{\text{IR}} = 10^{27} \text{ cm}^2 \text{ s}^{-1}$, respectively.

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