High-energy gamma-ray and neutrino production in star-forming galaxies across cosmic time: Difficulties in explaining the IceCube data

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Abstract

We present a new theoretical modeling to predict luminosity and spectrum of gamma-ray and neutrino emission of a star-forming galaxy, from star formation rate ($\psi$), gas mass ($M_{\text{gas}}$), stellar mass, and disk size, taking into account production, propagation and interactions of cosmic rays. The model reproduces the observed gamma-ray luminosities of nearby galaxies detected by Fermi better than the simple power-law models as a function of $\psi$ or $\psi M_{\text{gas}}$. Then this model is used to predict the cosmic background flux of gamma-ray and neutrinos from star-forming galaxies, by using a semi-analytical model of cosmological galaxy formation that reproduces many observed quantities of local and high-redshift galaxies. Calibration of the model using gamma-ray luminosities of nearby galaxies allows us to make a more reliable prediction than previous studies. In our baseline model star-forming galaxies produce about 20% of isotropic gamma-ray background unresolved by Fermi, and only 0.5% of IceCube neutrinos. Even with an extreme model assuming a hard injection cosmic-ray spectral index of 2.0 for all galaxies, at most 22% of IceCube neutrinos can be accounted for. These results indicate that it is difficult to explain most of IceCube neutrinos by star-forming galaxies, without violating the gamma-ray constraints from nearby galaxies.

Key words: Neutrinos — Gamma rays: galaxies — Gamma rays: diffuse background

1 Introduction

The IceCube Collaboration has revealed the existence of extraterrestrial high energy neutrinos, though their origin still remains a mystery (Aartsen et al. 2013). The arrival distribution is consistent with being isotropic and the flavor ratio is consistent with $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, suggesting an extragalactic, astrophysical origin. A variety of source models has been proposed so far, such as gamma-ray bursts, active galactic nuclei, star-forming galaxies, and galaxy clusters, though no individual source has been identified yet (for recent reviews, see, e.g., Mészáros 2017, Halzen 2017).

Star-forming galaxies are one possible origin of the IceCube neutrinos, in which cosmic rays (CRs) are produced by supernovae and they produce pion-decay neutrinos via inelas-
tic collisions with the interstellar medium (ISM) (Loeb & Waxman 2006; Thompson et al. 2006; Stecker 2007; Lacki et al. 2011; Murase et al. 2013; He et al. 2013; Tamborra et al. 2014; Anchordoqui et al. 2014; Liu et al. 2014; Emig et al. 2015; Chang et al. 2015; Giacinti et al. 2015; Senno et al. 2015; Chakraborty & Izaguirre 2016; Xiao et al. 2016; Bechtol et al. 2017). Starburst galaxies are especially important in this context, because CRs are expected to efficiently produce pions due to their high gas densities and confinement by strong magnetic fields. However, a definite conclusion has not yet been reached about whether star forming galaxies are the dominant source of IceCube neutrinos. Tamborra et al. (2014) concluded that starburst sources have a possibility to explain a significant fraction of the IceCube flux based on an empirical relation between gamma-ray and infrared luminosities, while Bechtol et al. (2017) argued that galaxies cannot produce more than 30% of the IceCube data if the upper limit on non-blazar fraction of the extragalactic gamma-ray background is considered. Xiao et al. (2016) found that star-forming galaxies might explain about 50% of the IceCube flux, but assuming a dominant contribution from hypernovae, which is rather uncertain. In these studies, however, little attention was paid to the consistency of the model with observed gamma-ray fluxes from nearby star-forming galaxies (Ackermann et al. 2012a; Tang et al. 2014; Peng et al. 2016), which should provide a useful constraint because gamma-rays are inevitably emitted if neutrinos are produced in a star-forming galaxy.

In this work, we present a new calculation of the contribution from star-forming galaxies to the diffuse gamma-ray and neutrino background, which takes into account cosmic-ray physical processes in galaxies and is consistent with the gamma-ray observations of nearby galaxies. For this purpose, we construct a new theoretical framework to predict both flux and spectrum of gamma-ray and neutrino emissions from a galaxy based on star formation rate (SFR), stellar mass, gas mass, and effective radius.

Gamma-ray flux from a galaxy has been modeled in a number of studies to predict the cosmic gamma-ray background from star forming galaxies (Strong et al. 1976; Lichti et al. 1978; Dar & Shaviv 1995; Pavlidou & Fields 2002; Thompson et al. 2007; Ando & Pavlidou 2009; Fields et al. 2010; Makiya et al. 2011; Stecker & Venters 2011; Ackermann et al. 2012a; Chakraborty & Fields 2013; Lacki et al. 2014; Komis et al. 2017; Lamastra et al. 2017), and most studies estimated gamma-ray luminosity only from one or two physical quantities (e.g. SFR, gas mass, or infrared luminosity) assuming empirical relations. However, such an approach may induce some bias in predictions of the cosmic background (Komis et al. 2017). Gamma-ray spectrum was also often treated in a simple way, using the Milky Way and M82 spectra as templates for normal and starburst galaxies. Our model includes a larger number of physical quantities of a galaxy to take into account the production, propagation and interactions of cosmic rays, and hence flux and spectrum can be calculated for diverse individual galaxies across cosmic time.

This modeling is compared with the observed gamma-ray luminosities of six nearby galaxies, and we will show that our modeling reproduces the observed gamma-ray luminosities better than the simple scaling relations with SFR and gas mass. Then the cosmic background flux and spectrum of gamma-rays and neutrinos are calculated by using a semi-analytical model of cosmological galaxy formation (the Mitaka model, Nagashima & Yoshii 2004), which reproduces many observational data of local and high-\(z\) galaxies. The Mitaka model provides us with the physical quantities of galaxies to predict gamma-ray and neutrino emissions, based on a self-consistent calculation of formation and evolution of galaxies in a cosmological framework, taking into account key baryonic processes such as gas cooling, star-formation, galaxy merger and subsequent starbursts.

We organize this paper as follows. The new model of gamma-ray and neutrino emission from a star-forming galaxy is described in section 2. The model prediction is compared with the gamma-ray observations of nearby galaxies in section 3. Before discussing the cosmic neutrino background, we examine the expected contribution to IceCube neutrinos from the Galactic disk in section 4. Then the results on the cosmic gamma-ray and neutrino background will be presented in section 5. Discussions on model dependence and uncertainties are given in section 6, followed by summary in section 7. We adopt a flat \(\Lambda\)CDM cosmology with \(\Omega_M = 0.3\), \(\Omega_B = 0.05\) and \(h = 0.7\) throughout this work.

2 Methods

2.1 Production, Propagation and Interaction of Cosmic Rays

Suppose that the four quantities of SFR (denoted as \(\psi\)), stellar mass \(M_*\), gas mass \(M_{\text{gas}}\), and the effective disk radius \(R_{\text{eff}}\) (the radius including a half of the total galactic light, related to the exponential scale \(R_d\) as \(R_{\text{eff}} = 1.68 R_d\)) are given for a galaxy. We first need to determine the production rate of pions by CR interactions as a function of the CR proton energy \(E_p\).

We assume that the production rate of CRs is proportional to SFR, and the CR spectrum at the time of injection into the ISM is described by a single power-law. Then the number of CRs produced in a galaxy per unit time and CR energy is expressed as

\[
\frac{dN_p}{dtdE_p} = C \left( \frac{\psi}{M_\odot \text{yr}^{-1}} \right) \left( \frac{E_p}{\text{GeV}} \right)^{-\Gamma_{\text{inj}}},
\]  

(1)

where the normalization factor \(C\) will be fixed by fitting to the observed gamma-ray luminosities of nearby galaxies later. Observations of the cosmic-ray spectrum on Earth, gamma-
ray spectrum of supernova remnants and the Galactic diffuse gamma-ray emission favor the injection spectral index in a range of $\Gamma_{\text{inj}} = 2.2 - 2.4$ (see Ackermann et al. 2012b; Caprioli 2012 and references therein). In this work we adopt $\Gamma_{\text{inj}} = 2.3$ as the baseline value, but we will also test the case of the strong shock limit, $\Gamma_{\text{inj}} = 2$.

A fraction $f_\pi(E_p)$ of CRs interact with the ISM before they escape into the intergalactic space, and it can be expressed as $f_\pi(E_p) = 1 - \exp(-t_{\text{esc}}/t_{\text{pp}})$, where $t_{\text{esc}}(E_p)$ is the escape time of a CR particle from the galaxy and $t_{\text{pp}}(E_p)$ is the mean time to interact with the ISM by the proton-proton ($pp$) collisions. This can be written as $t_{\text{pp}} = (n_{\text{gas}}\sigma_{pp}c)^{-1}$, where $n_{\text{gas}}$ is the number density of ISM and $\sigma_{pp}(E_p)$ is the inelastic part of the $pp$ cross section, for which we use the formula given in Kelner et al. (2006). We calculate $n_{\text{gas}}$ as $n_{\text{gas}} = M_{\text{gas}}/(2\pi R_{\text{cl}}^2 H_g m_p)$, where $m_p$ is the proton mass and $H_g$ is the scale height of the gas disk.

Our galaxy formation model does not compute the scale height $H_g$. The mechanism to determine disk heights of galaxies is complex depending on many physical processes including magnetic field and cosmic rays, gas pressure, and turbulent motion. In this work, we take a simple empirical approach to estimate $H_g$ by assuming $H_g \propto R_{\text{eff}}$, and the coefficient is determined by the observations for our Galaxy: $H_g = 150$ pc (Mo et al. 2010) and $R_{\text{eff}} = 6.0$ kpc (Sofue et al. 2009). Observations of nearby galaxies show that the stellar scale height of disks ($H_*$) is roughly proportional to $R_{\text{eff}}$, and the above $H_g/R_{\text{eff}}$ ratio is consistent with observations if the difference between stellar and gas scale heights is taken into account ($H_* \sim 2H_g$ in our Galaxy). In section 6 we will also examine other modelings of $H_g$ and effects on our results. In the Mitaka galaxy formation model, starbursts occur at the time of major merger of two disk galaxies, resulting in a formation of spheroidal galaxy. We assume that such star-bursting galaxies are nearly spherical and hence $H_g = R_{\text{cl}}$.

The escape time $t_{\text{esc}}$ is determined by the shorter one of the CR diffusion time $t_{\text{diff}}$ and the advection time by galactic outflow $t_{\text{adv}}$, i.e., $t_{\text{esc}} = \min(t_{\text{diff}}, t_{\text{adv}})$. These are estimated from galactic properties as $t_{\text{diff}} = R_{\text{cl}}^2/[2D(E_p)]$ and $t_{\text{adv}} = H_g/\sigma$, where $D(E_p)$ is the diffusion coefficient of CRs and $\sigma$ is the escape velocity from the gravitational potential of the galactic disk. We estimate $\sigma$ from $H_g$ and the column density of total mass $\Sigma = (M_\star + M_{\text{gas}})/(\pi R_{\text{cl}}^2)$ assuming the relation for the isothermal sheet: $G\Sigma = \sigma^2/(2\pi H_g)$ (Mo et al. 2010).

The diffusion coefficient $D$ is not well constrained by observations. Theoretically, $D$ is expected to depend on the CR energy $E_p$ and magnetic field strength $B$. Furthermore, fluctuation pattern of magnetic fields is important for CR diffusion. We consider two regimes regarding the proton Larmor radius $R_L = 2.0 \times 10^{-7}(E_p/\text{GeV})(B/6 \mu\text{G})^{-1}$ pc following Aloisio & Berezhinsky (2004). Suppose that there is a coherent length of turbulence $l_0$ and magnetic fields are random and uncorrelated beyond $l_0$. This length should be smaller than the region size, i.e., $l_0 \leq H_g$. Then the diffusion of high energy CRs with $l_0 < R_L < (H_g l_0)^{1/2}$ is described by the small-angle random scattering approximation with a mean free path $l_{\text{diff}} \sim (R_L^2/l_0)$, and hence $D \sim c l_{\text{diff}}/(3 \sim c R_L^2/l_0)$. It should be noted that when $R_L > (H_g l_0)^{1/2}$ the mean free path becomes larger than $H_g$, and hence in this regime we set $l_{\text{diff}} \sim H_g$, and hence $D \sim c H_g/3$ and $t_{\text{diff}} = 3H_g/(2c)$. Diffusion of lower energy CRs with $R_L < l_0$ is determined by resonant scattering in the turbulent magnetic field fluctuations, resulting in $D \sim c l_0(R_L/l_0)^{3/2}$, where $\delta$ depends on the spectrum of interstellar turbulence and we adopt $\delta = 1/3$ for the Kolmogorov-type turbulence. Then the diffusion coefficient can be described as follows:

$$D(E_p) = \begin{cases} \frac{4}{3} \left( \frac{R_L}{l_0} \right)^{3/2} + (\frac{R_L}{l_0})^2 \frac{R_L}{H_g} & (R_L \leq \sqrt{H_g l_0}) \\ (R_L > \sqrt{H_g l_0}) \end{cases}$$

(see also Parizot 2004).

The coherent length of turbulence $l_0$ is poorly understood theoretically, but $l_{\text{outer}} \sim 100–200$ pc has been suggested for turbulence generated by supernova remnants in the Milky Way (Haverkorn et al. 2008; Chepurnov & Lazarian 2010; Iacobelli et al. 2013), where $l_{\text{outer}}$ is the outer scale of turbulence and related as $l_0 = l_{\text{outer}}/5$ for the Kolmogorov-type turbulence. If this is a result of physics of supernova remnants interacting with the ISM, it may not strongly depend on the global properties of galaxies. Therefore, as a baseline model we use a common value of $l_{0,\text{max}} = 30$ pc for all galaxies whose $H_g$ is larger than $l_0$, but $l_0 = H_g$ for smaller galaxies, i.e., $l_0 = \min(l_{0,\text{max}}, H_g)$. Uncertainties and other possible modelings about $l_0$ will be discussed section 6. The Larmor radius becomes larger than $l_0$ for a very high energy of $E_p > 1.5 \times 10^{17}(l_0/30 \text{pc})(B/6 \mu\text{G})$ eV, and hence the regime of $R_L < l_0$ is relevant for GeV gamma-rays and PeV neutrinos in most galaxies.

In order to estimate magnetic field strength, we assume that energy density of magnetic field is close to that of supernova explosions injected into ISM on the advection time scale, $t_{\text{adv}} = H_g/\sigma$. Then using a dimensionless parameter $\eta$, magnetic field is given as $B^2/(8\pi) = \eta E_{\text{SN}} v_{\text{SN}} t_{\text{adv}}/V$, where $E_{\text{SN}}$ is the kinetic energy of a supernova, $v_{\text{SN}}$ the supernova rate in a galaxy, and $V = 2\pi R_{\text{cl}}^2 H_g$ the volume of gas disk. We set $\eta = 0.03$ because it reproduces the observed magnetic field strength of our Galaxy ($6 \mu\text{G}$, Beck 2008; Haverkorn 2015), using $\psi$, $R_{\text{eff}}$, $M_{\text{gas}}$ and $M_\star$ in table 1. Here we made standard assumptions that stars heavier than $8M_\odot$ end their life by supernovae, $E_{\text{SN}} = 10^{51}$ erg and the Salpeter IMF (Woosley & Weaver 1995; Salpeter 1955) for all galaxies.

Now we can calculate the CR production rate $dN_p/dtdE_p$ and the fraction $f_\pi$ of these interacting with the ISM as a func-
tion of $E_p$, if $M_*$, $M_{gas}$, $\psi$, and $R_{eff}$ of a galaxy are given.

### 2.2 Neutrinos and Gamma-rays from Galaxies

Then the number luminosity of neutrinos or gamma-rays, i.e., number of particles produced per unit time and particle energy in a galaxy is calculated as

$$\frac{dL_{N,i}}{dE_i} = \frac{\int_{E_i}^{\infty} f_i \frac{dN_0}{dE_0} \frac{dn_i}{dE_i} dE_i}{\int_{E_i}^{\infty} f_i dE_i}$$  \hspace{1cm} (3)

where the index $i$ denotes neutrino or gamma-ray ($i = \nu, \gamma$), $dn_i/dE_i$ is the number of neutrinos or gamma-ray photons per unit particle energy $E_i$ generated from one $pp$ interaction, which is a function of $E_i$ and $E_p$, and calculated by using the formulae in Kelner et al. (2006). It should be noted that in eq. (3) we only consider the initial $pp$ collision of each cosmic ray with the ISM, because a CR particle loses a significant fraction of its energy in the first collision and subsequent interactions have minor energetical contribution to the gamma-ray or neutrino spectrum. Furthermore, the contribution from the second and later interactions is effectively taken into account because we fix the normalization factor $C$ to fit the observed gamma-ray luminosity of nearby galaxies.

The cosmic background radiation flux of gamma-rays or neutrinos per steradian and per unit $E_l$ is then calculated as

$$\Phi_i(E_l) = \frac{c}{4\pi} \int dz \frac{dt}{dz} (1 + z) \frac{dL_{N,i}[1 + z; E_i; z]}{dE_i^{\text{rest}}},$$  \hspace{1cm} (4)

where $E_i^{\text{rest}} = (1 + z)E_i$ is the rest-frame particle energy and $dL_{N,i}[E_i^{\text{rest}}; z]/dE_i^{\text{rest}}$ is the neutrino/gamma-ray number luminosity density at redshift $z$ per unit comoving volume. Our galaxy formation model generates mock galaxy catalogues at various redshifts, in which the $j$-th galaxy is given a weight $n_j^{\text{gal}}$ (comoving number density of such a galaxy). We use morphology, $\psi$, $M_{gas}$, $M_*$ and $R_{eff}$ of these catalog galaxies to calculate the number luminosity density by summing up the catalog galaxies as:

$$\frac{dL_{N,i}[E_i; z]}{dE_i} = \sum_j n_j^{\text{gal}} \left[ \frac{dL_{N,i}(E_i)}{dE_i} \right]_j.$$  \hspace{1cm} (5)

For the gamma-ray background, additional corrections are necessary to eq. (4) to take into account the attenuation of gamma-ray flux due to $e^\pm$ creation by interaction with background optical and infrared photons, and the subsequent cascade emission produced by $e^\pm$. We use the baseline model calculation of $\tau_{\gamma\gamma}[E_i; z]$ in Inoue et al. (2013) for the absorption optical depth, and calculate the cascade emissivity following the treatment of Inoue & Ioka (2012).

### 2.3 Semi-Analytical Modelling of Galaxy Formation

In this work we use a semi-analytical model of cosmological galaxy formation model presented by Nagashima & Yoshiii (2004), which is called the Mitaka model. This model first computes merger history of dark matter haloes based on the extended Press-Schechter theory. Then baryonic processes in these haloes, such as gas cooling, star formation, supernova feedback and galaxy mergers, are calculated with phenomenological prescriptions. Free parameters included in describing baryons are determined to match several observations of local galaxies. This model reproduces various observed properties of local and high-$z$ galaxies such as luminosity functions, size-luminosity relation, luminosity densities, and stellar mass densities (Nagashima & Yoshii 2004; Kashikawa et al. 2006; Kobayashi et al. 2007,2010).

This model includes two modes of star formation: starburst and quiescent. Starburst is assumed to occur after major mergers of galaxies leading to spheroidal galaxies, and otherwise stars are formed in a disk (the quiescent mode). Contributions of starbursts to the total cosmic SFR in this model is about 5% at $z \sim 0$, which increases to 15% at $z \sim 1$ and 30% at $z \sim 2$.

### 3 Comparison with Nearby Galaxies

To fix the value of the normalization factor $C$ in the equation (1), we use the data of six galaxies detected by the Fermi-LAT, including three normal galaxies (SMC, LMC, MW) and three starbursts (NGC253, M82, NGC2146). It should be noted that the latter three galaxies are generally called “starbursts” by their intensive star formation activity, but their morphology is disk-like without evidence of major mergers in recent past. Therefore we treat these as disk galaxies in theoretical modeling, and hence the definition of “starburst” is different from that (major merger) used in the galaxy formation model. Their physical quantities are shown in table 1.

There are several notes for this sample. A different photon energy range of gamma-ray luminosity $L_\gamma$ is used for NGC 2146 in the literature, and hence we also change the range in theoretical calculation accordingly. Stellar mass $M_*$ for M82 is not yet observationally well constrained, and we used a dynamical mass $M_{dyn} \sim 10^{10} M_\odot$ (Sofue et al. 1992) and estimated $M_*$ from $M_* = M_{dyn} - M_{gas}$. However, even if we set $M_*=0$ for M82, our results are hardly changed. In addition to the galaxies shown in table 1, M31, NGC4945, NGC1068 and Arp220 are also detected in gamma-rays. However, we do not use NGC4945, NGC1068 and Arp220 in our calculation because gamma-ray emissions from these galaxies are likely affected by AGN activities (Ackermann et al. 2012a, Yoast-Hull et al. 2017). M31 is also removed from the sample, because a recent analysis of gamma-rays from M31 has shown that the emission is not correlated with regions where most of the atomic and molecular gas reside, suggesting that they are not originated from the CR-ISM interactions (Ackermann et al. 2017).

Then the parameter $C$ is determined by the standard $\chi^2$ fit-
energy neutrinos. It is important to check the predicted neutrino decay, and hence the Milky Way could also be a source of high-energy Galactic emission (DGE), which is mostly from the pion interaction. This is comparable to the standard assumption that CRs carry 10% of supernova explosion energy. This slightly larger value may be rather surprising that this simple model predicts correct luminosities for various types of galaxies, widely ranging from dwarf galaxies like LMC and SMC to intense starburst galaxies. Note that C can be converted to the energy injected into CRs from a supernova, as can be seen from equation 1. Setting the energy range of CRs to be $10^{15} - 10^{17}$ eV, the best-fit C corresponds to CR energy of $0.24 E_{SN}$ with the same $E_{SN}$, IMF, and the threshold stellar mass for supernovae assumed in the model. This is comparable to the standard assumption that CRs carry $\sim 10\%$ of supernova explosion energy. This slightly larger value is partly a result of considering only the first time $pp$ interaction to produce gamma-rays, as mentioned above.

## 4 Gamma-rays and Neutrinos from the Galactic Disc

The gamma-ray sky measured by Fermi is dominated by the diffuse Galactic emission (DGE), which is mostly from the pion decay, and hence the Milky Way could also be a source of high-energy neutrinos. It is important to check the predicted neutrino flux from the Milky Way does not contradict with the IceCube data. In figure 2 we show our model prediction of the Galactic diffuse gamma-ray and neutrino emission with our baseline model parameters but changing $\Gamma_{M82}$. For comparison, we also show the pion-decay component of the $^{8}$Be decay 150 GeV model of DGE in Ackermann et al. (2012b) (A12 model, hereafter) within the low latitude regions of $|b| < 8^\circ$, which was calculated by the more detailed GALPROP code and is in good agreement with the observed data. The flux of our model is normalized so that it matches the A12 model at GeV. We also show the IceCube neutrino flux data, which is scaled into the region from the whole IceCube data assuming isotropy.

### Table 1. Properties of gamma-ray galaxies

| Objects | $L_{\gamma}$ \[$10^{39}$ erg s$^{-1}$]\* | ref. | $\psi$ \[M$_{\odot}$ yr$^{-1}$\] | ref. | $M_{\text{gas}}$ \[10^7 M_{\odot}\] | ref. | $M_{\text{e}}$ \[10^{20} M_{\odot}\] | ref. | $R_{\text{eff}}$ \[kpc]\* | ref. |
|---------|--------------------------------|-----|-----------------|-----|-----------------|-----|-----------------|-----|-----------------|-----|
| MW      | 0.82±0.24                      | (1) | 2.6             | (3),(4) | 4.9             | (8) | 50              | (14) | 6.0            | (19) |
| LMC     | 0.047±0.005                    | (1) | 0.24            | (4),(5) | 0.53            | (9) | 1.5             | (15) | 2.2            | (20) |
| SMC     | 0.011±0.003                    | (1) | 0.037           | (4),(5) | 0.45            | (10) | 0.46            | (15) | 0.7            | (21) |
| NGC253  | 6±2                            | (1) | 7.9             | (4),(6) | 4.3             | (11) | 21              | (16) | 3.7            | (22) |
| M82     | 15±3                           | (1) | 16.3            | (4),(6) | 1.3             | (12) | 8.7$^\dagger$    | (17) | 1.2            | (22) |
| NGC2146 | 40±2                           | (2) | 17.5$^\dagger$  | (7) | 4.1             | (13) | 20              | (18) | 1.8            | (23) |

*The photon energy range is 0.1–100 GeV except for NGC 2146, for which 0.2-100 GeV is adopted according to ref. (2).

†Estimated from the radio continuum luminosity at 1.4 GHz and eq. (13) of ref. (7).

References: (1) Ackermann et al. (2012a) (2) Tang et al. (2014) (3) Diehl et al. (2006) (4) Makiya et al. (2011) (5) Kennicutt et al. (2008) (6) Sanders et al. (2003) (7) Yun et al. (2001) (8) Paladini et al. (2007) (9) Staveley-Smith et al. (2003) and Fukui et al. (2008) (10) Stanimirović et al. (1999) and Leroy et al. (2007) (11) Knudsen et al. (2007) and Springob et al. (2005) (12) Chynoweth et al. (2008) and Mao et al. (2000) (13) Tsai et al. (2009) (14) Bland-Hawthorn & Gerhard (2016) (15) McConnell et al. (2012) (16) Lucero et al. (2015) (17) Sofue et al. (1992) (18) Skibba et al. (2011) (19) Sofue et al. (2009) (20) van der Marel (2006) (21) Gonidakis et al. (2009) (22) J-band half-light radius in Jarrett et al. (2003), converted into kiloparsec using distances taken from the NASA/IPAC Extragalactic Database (23) H$\alpha$ half-light radius in Marcum et al. (2001)
Figure 2 indicates that our model matches the A12 model for $\Gamma_{\text{inj}} = 2.3$, in which case the contribution from the Milky Way can possibly explain 13% of the IceCube energy flux. It should be noted here that we do not introduce any cut off in the accelerated cosmic ray spectrum (equation 1), which may be rather unrealistic. Indeed, if we introduce a cutoff at PeV, for example, the contribution decreases to 3%. Interestingly, some previous studies have also suggested a considerable contribution to IceCube neutrinos from the Milky Way (Gaggero et al. 2015; Neronov & Semikoz 2015; Palladino & Vissani 2016). Increased statistics of the IceCube neutrino events in the future may reveal an excess from the Galactic disk region compared with the isotropic component, which would give important information about the maximum cut-off energy of proton acceleration in the Milky Way. On the other hand, a hard injection spectrum of $\Gamma_{\text{inj}} \lesssim 2.1$ is disfavored because the Galactic disk component of neutrinos would be too strong, unless there is a cut-off below $E_p \sim 10^{14}$ eV.

5 Cosmic Gamma-Ray and Neutrino Background

Figure 3 presents the cosmic gamma-ray and neutrino background spectra predicted by our baseline model, in comparison with the Fermi and IceCube data. Our calculations show that the gamma-ray energy flux from star-forming galaxies is $(5.1 - 7.0) \times 10^{-4}$ MeV cm$^{-2}$ s$^{-1}$ str$^{-1}$ above 100 MeV, which is 18 – 25% of the IGRB flux observed by Fermi, in reasonable agreement with previous studies (Fields et al. 2010; Makiya et al. 2011; Stecker & Venters 2011; Ackermann et al. 2012a; Lacki et al. 2014).

The neutrino flux predicted by our baseline model ($\Gamma_{\text{inj}} = 2.3$) is only 0.5% contribution to the IceCube data. If we assume a harder spectrum at injection $\Gamma_{\text{inj}} = 2.1$ and 2.2, the contributions increase to 8.4% and 2.1% respectively. Even in the most optimistic (and extreme) case of $\Gamma_{\text{inj}} = 2$ in all galaxies, star-forming galaxies can account for only 22% of the IceCube data. It should be noted that such a hard injection spectrum in our Galaxy is in contradiction with the Galactic diffuse gamma-ray spectrum and the isotropy of the IceCube data. Therefore, we conclude that star-forming galaxies cannot be the major source of the IceCube neutrinos, and a reasonable estimate of their contribution is about 1-8% or less.

6 Dependence on model parameters

Dependence of our results on different modelings of $l_{0,\text{max}}$ and $H_g$ is shown as the change of the gamma-ray luminosities of nearby galaxies (figure 4) and the cosmic gamma-ray/neutrino background flux (figure 5) from our baseline model. For $l_{0,\text{max}}$ we test different values of 10 and 100 pc from the baseline model (30 pc), and also test a model with $l_{0,\text{max}} = H_g$, as the case where the coherent scale of turbulence is determined by the system size. The model with $l_{0,\text{max}} = 10$ pc also agrees reasonably well with the $L_\gamma$ data of nearby galaxies, and the models with $l_{0,\text{max}} = 100$ pc and $l_{0,\text{max}} = H_g$ show larger deviation, especially MW and NGC 253 up to a factor of 3. The changes of background fluxes are small (less than 20%) for $l_{0,\text{max}} = 10$ or 100 pc, but the neutrino flux is reduced by a factor of 2–3 in
the model of $l_{0,\text{max}} = H_g$. This is because $l_0$ becomes larger in galaxies of $H_g > 30 \, \text{pc}$, and the diffusion coefficient becomes larger with larger $l_0$ if $R_L < l_0$ which is valid in most galaxies.

To check the dependence on the modelling of $H_g$, we test the following two cases for disk galaxies: (1) assuming that the height of gas disk in all disk galaxies are similar to that of the Milky Way, i.e., $H_g = 150 \, \text{pc}$, and (2) assuming energy equipartition between gas motion and energy produced by supernovae, as $\rho_{\text{gas}} \sigma^2 = \alpha E_{\text{SN}} \rho_{\text{SN}} \tau_{\text{div}} / V$, where $\rho_{\text{gas}} = M_{\text{gas}} / V$ is ISM gas density. In the latter case both $\sigma$ and $H_g$ are determined by this relation combined with $G \Sigma = \sigma^2 / (2 \pi H_g)$, without using $H_g \propto R_{\text{eff}}$. The dimensionless factor $\alpha = 4$ is determined to reproduce $H_g = 150 \, \text{pc}$ for physical quantities of the Milky Way.

The lower panel of figure 4 shows that different modelling of $H_g$ results in clear discrepancies between predicted and observed $L_\gamma$ for local galaxies. As shown in the lower panels of figure 5, the gamma-ray and neutrino background flux is reduced in the constant $H_g$ model by a factor of about 2. This is likely because the gas density is underestimated in small galaxies whose density is higher if we assume $H_g \propto R_{\text{eff}}$. The background fluxes are reduced even by a larger factor of about 3–4, for the model assuming equipartition between gas and supernovae. This implies that gas density is higher than that expected from equipartition. Such a situation may be expected, especially in starburst galaxies, if gas density becomes high enough before star formation starts and supernova energy is injected to the ISM. Figure 4 indeed indicates that the discrepancy in the gas-SN equipartition model is larger for starburst galaxies. In any case, different modelings of $l_{0,\text{max}}$ and $H_g$ lead to lower neutrino background flux, and hence it does not affect our conclusions that the majority of IceCube neutrinos cannot be explained by star-forming galaxies.

### 7 Summary

In this work we constructed a new theoretical model to predict flux and spectrum of gamma-rays and neutrinos by interactions of cosmic-rays produced by supernovae in a star-forming galaxy, and applied it to predict the flux and spectrum of the cosmic gamma-ray and neutrino background radiation.

Our model calculates gamma-ray and neutrino spectra of a star-forming galaxy from four physical quantities, i.e. SFR, size, gas mass, and stellar mass, taking into account the production, propagation and interactions of cosmic rays in the ISM. This model is tested against the gamma-ray luminosities measured by Fermi of the six nearby galaxies listed in table 1. In spite that this sample includes a wide variety of star-forming galaxies, from dwarf galaxies like LMC and SMC to starburst galaxies such as M82, our model reproduces the observed gamma-ray luminosities fairly well, within a factor of $\sim 2$. The agreement is significantly better than the simple phenomenological modelings assuming a power-law relation between $L_\gamma$ and SFR or SFR $\times M_{\text{gas}}$. This model can be tested with a larger sample of nearby galaxies by high-sensitivity gamma-ray observations of future projects such as Cherenkov Telescope Array (CTA).

We have examined the neutrino emission from the disk of our Galaxy predicted by our model, and found that the observed isotropic distribution of IceCube neutrinos constrains the injection cosmic-ray energy spectrum to be softer than $\Gamma_{\text{inj}} \sim 2.2$, unless there is a cut-off at $\lesssim 10^{14} \, \text{eV}$ in the CR energy spectrum.

The contribution from star-forming galaxies to the extragalactic gamma-ray and neutrino background is calculated by using a semi-analytical cosmological galaxy formation model. This model is quantitatively in agreement with many observations of galaxies at local and high redshifts. We have found that
star-forming galaxies make about 20% of the isotropic gamma-ray background flux unresolved by Fermi, and only 1-8% or less of the IceCube flux, with reasonable values of $\Gamma_{\text{inj}} = 2.1 - 2.3$. Even with the most optimistic case where $\Gamma_{\text{inj}} = 2.0$ in all galaxies, the contributions is no more than 22%. Therefore, we conclude that the majority of IceCube neutrinos cannot be explained by star-forming galaxies. We also examined dependence of these results on modelings about $f_{\text{inj},\text{max}}$ (the maximum length of coherence in ISM turbulence) and $H_g$ (gas scale height of a galactic disk), and found that alternate prescriptions give even lower neutrino flux.

Our results demonstrate that star-forming galaxies make only a minor contribution to the IceCube flux, implying that other sources are required to explain most of the observed data. Since correlation analyses have shown that gamma-ray blazars and gamma-ray bursts are not the dominant source (Aartsen et al. 2015b, 2017), there is no strong candidate for the origin of IceCube neutrinos. Future detectors such as the IceCube-Gen2, as well as multi-messenger approaches with next-generation telescopes like CTA, will be the key to understand the nature of high-energy neutrinos.

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