Neutrino emission of Fermi supernova remnants

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ABSTRACT

The Fermi γ-ray space telescope reported the observation of several Galactic supernova remnants recently, with the γ-ray spectra well described by hadronic *pp* collisions. The possible neutrino emissions from these Fermi detected supernova remnants are discussed in this work, assuming the hadronic origin of the γ-ray emission. The muon event rates induced by the neutrinos from these supernova remnants on typical km^3 neutrino telescopes, such as the IceCube and the KM3NET, are calculated. The results show that for most of these supernova remnants the neutrino signals are too weak to be detected by the on-going or upcoming neutrino experiment. Only for the TeV bright sources RX J1713.7-3946 and possibly W28 the neutrino signals can be comparable with the atmospheric background in the TeV region, if the protons can be accelerated to very high energies. The northern hemisphere based neutrino telescope might detect the neutrinos from these two sources.

Subject headings: radiation mechanism: non-thermal — supernava remnants — gamma rays: theory — neutrinos

1. Introduction

Supernova remnants (SNR) are usually thought the most possible candidate of the acceleration site of Galactic cosmic rays (CRs). However, there is no firm evidence to verify such a conjecture. Hign energy γ-ray observations of the sky, by e.g., the Cerenkov telescope High Energy Stereoscopic System (HESS) and the Fermi space telescope, can provide very useful information which enables us to approach the acceleration sources of CRs. One good example is the SNR RX J1713.7-3946. The early observation of the very high energy (VHE) γ-ray emission from RX J1713.7-3946 by CANGAROO indicated that there might be nuclei acceleration in this SNR (Enomoto et al. 2002). The following detailed observation made by

HESS favored a hadronic origin of the VHE γ-ray emission according to the spectral shape (Aharonian et al. 2006). Although there are claims against the hadronic scenario or favoring the leptonic scenario of the emission mechanism of SNR RX J1713.7-3946 (e.g., Liu et al. 2008; Fan et al. 2010a,b; Ellison et al. 2010), it is still one of the most interesting candidates of CR nuclei acceleration sources.

After about one year's operation, Fermi collaboration reported the observations of over 1400 sources, within which 41 are possible associations of SNRs (Abdo et al. 2010a). However, it is very likely that some of the 41 sources are actually associated with pulsars or pulsar wind nebulae (PWN) rather than the SNRs. According to the morphology analysis, Fermi collaboration identified three sources with firm association with SNRs: W44 (Abdo et al. 2010d), W51C (Abdo et al. 2009) and IC443 (Abdo et al. 2010e). Further studies revealed other candidate sources of SNRs, including Cassiopeia A (Abdo et al. 2010b), W28 (Abdo et al. 2010c), RX J1713.7-3946 (Funk 2009) and W49B (Abdo et al. 2010f). The spectral studies of most of these sources favor hadronic origin of the γ-ray emission (see also, Araya & Cui 2010; Ohira et al. 2010), although for several ones the leptonic scenario can also give an acceptable fit to the data.

It is difficult to identify the hadronic sources of CRs using γ-rays alone. Neutrinos, if detected, can be regarded as a definite diagnostic of the hadronic nature of the γ-ray sources. Actually after the great progress of the discoveries of many VHE γ-ray sources by e.g., HESS, MAGIC and Milagro, many works studied the possible perspective of detecting neutrinos from these sources with ongoing or upcoming neutrino detectors (e.g., Kistler & Beacom 2006; Beacom & Kistler 2007; Gabici et al. 2008; Bi et al. 2009). The general result is that given the γ-rays are produced through hadronic interactions of pp collisions, some bright γ-ray sources with hard spectra might be able to be detected with km^3 level neutrino telescope like IceCube. However, the signals are usually weak.

Since the Fermi observations of the several SNRs, especially for those associated with molecular clouds, show strong hints of nuclei acceleration in the SNRs, these SNRs should be prior targets for the neutrino detection. Furthermore, the combined fit of the Fermi data and VHE data (if available) can help to better determine the underlying CR spectra, and give more precise prediction of the neutrino spectra. In this work we try to explore the detectability of neutrinos from the Fermi detected SNRs, under the assumption that the γ-rays are produced through pp collision in the sources. The neutrino detector configuration adopts typical km^3 projects, such as IceCube and KM3NET. There are also other studies of the neutrino emission from Fermi sources such as the blazars (Neronov & Ribordy 2009) and the newly discovered nova (Razzaque et al. 2010).

This paper is organized as follows. In Sec. 2 we first derive the proton spectra in these

SNRs to reproduce the γ-ray data measured by Fermi and higher energy experiments. Then the neutrino emissions of these sources are discussed in Sec. 3. We draw the conclusion in Sec. 4.

2. Fitting the gamma-ray spectra with hadronic model

In this section we calculate the π^0-decay induced γ-rays due to pp collisions. We employ the parametrization given in Kamae et al. (2006) to calculate the differential production spectra of secondary particles, including γ-rays and neutrinos. The proton spectrum at the source is adjusted to reproduce the GeV-TeV data of the SNRs. Following the ways of Fermi collaboration, we generally adopt a broken power-law function to describe the proton spectrum. The high energy cutoff of the proton spectrum is not well constrained by the current TeV data. Therefore we adopt three cases for comparison: without cutoff, exponential cutoff with $E_c = 50$ TeV and $E_c = 10$ TeV respectively. However, there are two exceptions: RX J1713.7-3946 and W28.

- RX J1713.7-3946 — The HESS experiment gave very good measurements of the TeV γ-ray spectrum of this source up to energies exceeding 100 TeV (Aharonian et al. 2007). The measured spectrum shows an evident curvature which disfavors a single power-law with high significance (Aharonian et al. 2007). We find that a power-law distribution of protons with an exponential cutoff can well reproduce the observational GeV-TeV data (Fig. 1). By fitting data we find the power-law index and the cutoff energy are 1.7 and ~ 70 TeV respectively.
- W28 — In the vicinity of SNR W28, HESS observation revealed 4 sources: HESS J1801-233 (W28 North), HESS J1800-240B (W28 South), HESS J1800-240A and HESS J1800-240C (Aharonian et al. 2008). The Fermi observation discovered two sources coinciding with HESS J1801-233 and HESS J1800-240B. For other two sources the upper limits were given (Abdo et al. 2010c). For these four sources we adopt a single power-law function of the proton spectrum since it is not well constrained by the data. As for the cutoff of proton spectrum, we also assume the three cases described above.

The calculated energy spectra of γ-rays from the 10 sources[1] are shown in Figs. 1 and 2. The corresponding spectral parameters of these sources are compiled in Table 1. It is shown that generally a broken power-law spectrum of protons can give good description to

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[1] For W28 there are 4 sources.

the Fermi data. As discussed in Ohira et al. (2010), this can be explained as the escape effect of CRs from a finite-size region of the SNR. In GALPROP, a phenomenological model for Galactic CR propagation, the injection spectrum of CRs is also adopted as a broken power-law function with break energy at several GeV (Strong & Moskalenko 1998), which is very similar with the results indicated by the γ-rays. This is regarded as a support that SNRs are the sources of Galactic CRs (Ohira et al. 2010).

From the γ-ray intensity we can directly infer the neutrino flux of these sources. The details will be given in the next section. According to Figs. 1 and 2 we can get a rough idea that RX J1713.7-3946, Cassiopeia A and W28 should give larger neutrino signals than others.

Table 1: Coordinates and proton spectral parameters of the SNRs

	R.A.	Dec.	γ_1	γ_2	$E_{\rm br}$(GeV)	$E_{\rm cut}$(TeV)
RX J1713.7-3946 (G347.3-0.5)	17^h14^m	$-39°45'$	1.70	1.70	—	68
W49B (G43.3-0.2)	19^h11^m	$+09°06'$	2.45	2.55	5	—
IC443 (G189.1+3.0)	06^h17^m	$+22°34'$	2.09	2.87	69	—
W44 (G34.7-0.4)	18^h56^m	$+01°22'$	2.00	3.20	10	—
W51C (G49.2-0.7)	19^h24^m	$+14°06'$	2.00	2.65	15	—
Cassiopeia A (G111.7-2.1)	23^h23^m	$+58°48'$	1.90	2.30	30	—
W28 North (G6.4-0.1)	18^h00^m	$-23°26'$	2.70	2.70	—	—
W28 South (G6.4-0.1)	18^h00^m	$-23°26'$	2.38	2.38	—	—
HESS J1800-240A (G6.4-0.1)	18^h00^m	$-23°26'$	2.10	2.10	—	—
HESS J1800-240C (G6.4-0.1)	18^h00^m	$-23°26'$	2.40	2.40	—	—

3. Neutrino emissions and muon events

In this section, we discuss the capability of detecting neutrino signals from the SNRs discussed in the previous section. The SNRs can be treated as point sources at the neutrino telescope. The SNRs in the northern hemisphere are possibly detected by the km^3 volume detector IceCube located at the south pole. For the sources in the southern hemisphere we discuss detectability on an imaginary km^3 scale detector located in the northern hemisphere of the earth, such as the proposed KM3NET.

The initial neutrino flavor ratio is $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ from the decay of π^+ and π^- produced by high energy pp collisions. Such high energy neutrinos arrive at the neutrino telescope after oscillations. For the vacuum oscillation, we adopt neutrino mixing angles as

$\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{13} = 0.01$ (Schwetz et al. 2008), and the neutrino flavor conversion probabilities are $P_{\nu_e\leftrightarrow\nu_\mu} = 0.22$, $P_{\nu_\mu\leftrightarrow\nu_\mu} = P_{\nu_\mu\leftrightarrow\nu_\tau} = 0.39$ (Covi et al. 2010). Then the flux of muon-neutrinos arriving at the earth is $\Phi_{\nu_\mu} = \sum_i \Phi^{\rm ini}_{\nu_i} P_{\nu_i\leftrightarrow\nu_\mu} \sim \Phi^{\rm ini}_{\nu_\mu}/2$. We neglect the matter effect in the earth because we discuss the high energy neutrinos with $E > 1$ TeV here. In addition, if the neutrino energy is larger than 10 TeV, the absorption effects of the earth becomes important. Therefore, the detected neutrino flux should be multiplied by a factor $\exp[-\rho_N l \sigma_t(E_\nu)]$ to take into account such absorption effects, where ρ_N is the averaged nucleon numbers, l is the distance when neutrino travel through the earth, and $\sigma_t(E_\nu)$ is the total cross section of neutrino-nucleon scattering. The fluxes of muon neutrinos of these sources are shown in Figs. 1 and 2.

The charged-current interactions between muon-neutrinos and nucleons around/inside the detector will produce high energy muons, which can emit Cherenkov light and then be recorded by the detector. The conversion probability of a muon-neutrino into a muon is

$$P_{\rm CC} dr\, dE_{\nu_\mu} = \left[\frac{d\sigma^{\nu p}_{\rm CC}(E_{\nu_\mu}, E^0_\mu)}{dE^0_\mu}\,\rho_p + (p\to n)\right] dr\, dE_{\nu_\mu}, \tag{1}$$

where $\rho_p(\rho_n)$ is the number density of protons (neutrons) in the matter. The cross sections of deep inelastic neutrino-nucleon scattering processes are given by (Barger et al. 2007)

$$\frac{d\sigma^{\nu\,(p,n)}_{\rm CC}(E_\nu, y)}{dy} \simeq \frac{2\, m_{p,n}\, G_F^2}{\pi}\, E_\nu \left(a^{\nu\,(p,n)}_{\rm CC} + b^{\nu\,(p,n)}_{\rm CC}\,(1-y)^2\right), \tag{2}$$

where $y \equiv 1 - E_\ell/E_\nu$, $a^{\nu\,(p,n)}_{\rm CC} = 0.15, 0.25$, $b^{\nu\,(p,n)}_{\rm CC} = 0.04, 0.06$.

If the scattering between neutrino and nucleon occur inside the detector, then the muon tracks will also start inside the detector. This is the so-called contained event. The differential muon event rate of contained events is given by (Erkoca et al. 2009)

$$\left(\frac{d\Phi_\mu}{dE_\mu}\right)^{\rm con} = L_{\rm det}\int_{E_\mu}^{\infty} dE_{\nu_\mu}\frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} P_{CC} + (\nu\to\bar\nu), \tag{3}$$

where $L_{\rm det}$ is the length of the detector, which is adopted to be 1 km.

The neutrino induced muons could also be produced in the medium around the instrument volume. In such cases, some of the muons can propagate into the detector and leave the tails of tracks in the detector. These events are called through-going muons. For the high energy neutrinos, they could produce muons which can travel a long distance, and enhance the final muon event rate. The muons will lose energy due to ionization and radiation when they travel in the medium. To calculate the event rate of through-going muons, the energy losses of muons before they arrive at the detector need to be taken into account. If we consider the average rate of muon energy loss as $dE_\mu/dx = -\alpha - \beta E_\mu$, the distance that a muon with energy E_μ^0 can travel in matter when its energy drops to E_μ is given by

$$R(E_\mu^0, E_\mu) = \frac{1}{\rho\beta} \ln \frac{\alpha + \beta E_\mu^0}{\alpha + \beta E_\mu}. \tag{4}$$

On the other hand, if the detector observes a muon with energy of E_μ, the initial muon energy at the place with a distance r from the detector could be calculated as

$$E_\mu^0 = e^{\beta\rho r} E_\mu + (e^{\beta\rho r} - 1)\frac{\alpha}{\beta}. \tag{5}$$

Therefore, the event rate of through-going muons is given by (Erkoca et al. 2009; Covi et al. 2010)

$$\left(\frac{d\Phi_\mu}{dE_\mu}\right)^{\rm thr} = \int_{E_\mu}^{\infty} dE_{\nu_\mu} \int_0^{R(E_{\nu_\mu}, E_\mu)} dr\, e^{\beta\rho r} \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} P_{\rm CC} P_{\rm surv} + (\nu \to \bar{\nu}), \tag{6}$$

where the factor $dE_\mu^0/dE_\mu = e^{\beta\rho r}$ accounts for the energy shift when the muon travel in the medium before arriving at the detector, $P_{\rm surv}$ is the surviving probability of the muon before decay, which roughly equals to 1 for high energy neutrino interested here (Erkoca et al. 2009).

The total muon event number at the detector is

$$N = \int d\Omega \int dE_\mu \frac{d\Phi_\mu}{dE_\mu} A_{\rm det} T f(E_\mu), \tag{7}$$

where $f(E_\mu)$ is the energy response function with energy resolution width $\Delta \log_{10} E_\mu = 0.3$, T is the operation time, and $A_{\rm det}$ is the effective area of the detector. For the contained events, $A_{\rm det}$ is assumed to be 1 km^2, and for the through-going events, $A_{\rm det}$ is the effective muon detecting area which is a function of muon's energy and direction. We take the effective muon detecting area of the IceCube from Gonzalez-Garcia et al. (2009). To calculate the final muon event number, we add the contained and through-going muons together.

The main background for high energy neutrino detection is the atmospheric neutrinos. Here we use a parameterizations of atmospheric neutrino flux following Erkoca et al. (2009), which describes the calculated results of Honda et al. (2007). The high angular resolution of the detector can be used to suppress the atmospheric neutrino background. In this work we utilize an angle resolution of 1° (half angle of a cone).

Compared to the SNR neutrino signals, the atmospheric neutrino background is large but decrease quickly as E_ν^{-3}. Therefore we only pay attention to muon events with energy higher than TeV. In Fig. 3, we show the differential muon rates of the through-going (left) and contained (right) events respectively, induced by neutrino emission from Cassiopeia A.

According to the γ-ray emission, we know that Cassiopeia A has a larger initial neutrino flux with $E_\nu > 1$ TeV than other sources in the northern hemisphere. Furthermore, the atmospheric neutrino flux from the direction of Cassiopeia A is relatively small due to the large zenith angle. Therefore Cassiopeia A should be the most possible candidate of detecting neutrinos among these SNRs in the northern hemisphere, which can be probed with the on-going IceCube detector. However, we can see that the muon rate with energy of O(TeV) from Cassiopeia A is lower by about one order of magnitude compared with the atmospheric background, even for the case without energy cutoff of the proton spectrum. For $E \gtrsim 10$ TeV the signal will exceed the background. However, the absolute event rate is too low ($O(0.1)$) to be detected. If there is energy cutoff of the accelerated protons at the level of $10-100$ TeV like SNR RX J1713.7-3946, the detection perspective of neutrinos from Cassiopeia A by IceCube would be poorer.

The total muon event numbers of six of the SNRs compiled in Table 1 in one year exposure are shown in Fig. 4. Note that the four γ-ray sources in the vicinity of W28 are added together to be one neutrino source due to the relatively poor angular resolution of neutrino detector. The result of SNR W44 is not displayed either due to its extremely soft spectrum at high energy range. The contained and through-going muon events are added together. For the four SNRs located in the northern hemisphere, i.e., W49B, IC443, W51C and Cassiopeia A, the total muon event number with $E > 1$ TeV is only $O(0.1)$. Compared with the atmospheric background with the event rate of several, it seems to be very difficult for IceCube to discover the neutrinos from these SNRs.

For the two SNRs located in the southern hemisphere, RX J1713.7-3946 and W28, the situation are better. We study the detectability with an assumed km^3 level neutrino telescope in the northern hemisphere (for example, the KM3NET located at the Mediterranean Sea). The actual detectability needs full Monte Carlo simulation based on realistic detector configuratio, here we adopt the same instrumental parameters of this detector as IceCube. We neglect the angular information of the atmospheric neutrinos, but take a directional averaged background. We also assume the detector only has half of the time to observe the southern sky per year. This is a reasonable approximation if the detector does not locate at the north pole. It is shown that the muon event number with E> 1TeV can reach 3 for RX J1713.7-3946 at such a detector in one year. Compared with the background level of $1-2$, it would be hopeful to detect the SNR neutrinos. This result is easy to understand because RX J1713.7-3946 is the brightest source in the $1-10$ TeV range among these SNRs. For W28, the number of muon event might reach the order of 1 for the case without cutoff of the accelerated proton spectrum. For larger detectors and/or longer exposure time, we may still have chance to detect such neutrinos. If there is a cutoff of the proton spectrum at energy $\sim 10-100$ TeV the number of signal events would decrease significantly.

4. Conclusion

In this work we investigate the possible neutrino emissions of several Fermi detected SNRs. Seven SNRs are compiled in this work according to the Fermi observations, most of which are also detected by high energy observations such as HESS, MAGIC and VERITAS. The study of the γ-ray spectra of these sources tend to favor hadronic CRs acceleration at the sources. Therefore the accompanied neutrino emission will be a unique diagnostic of the nature of the radiation of these SNRs. Assuming the γ-rays are produced through pp collisions, we first determine the proton spectral parameters and intensity normalization using the GeV band data from Fermi and the available TeV band data from MAGIC, VERITAS or HESS. The proton spectra are generally adopted as a broken power-law. For RX J1713.7-3946 the TeV data measured by HESS are precise enough to determine the cutoff energy of protons. However, for other sources we cannot precisely determine the high energy behaviors using the present data. Therefore we assume $E_{\rm cut} = \infty$, 50 TeV and 10 TeV for the accelerated proton spectra for comparison. The neutrino signals are then calculated based on km^3 level experiments like IceCube in the south hemisphere and KM3NET in the north hemisphere.

The results show that for the four SNRs located in the northern sky, W49B, IC443, W51C and Cassiopeia A, the numbers of TeV muons induced by the muon-neutrinos are only of the order $O(0.1)$ with one year exposure of IceCube, whereas the atmospheric background is larger by one or two orders of magnitude. Compared with the large atmospheric background the detectability seems quite poor. The two sources located in the southern sky, RX J1713.7-3946 and W28, have larger neutrino signals than other sources. We assume an IceCube-like detector located in the northern hemisphere of the Earth to estimate the detectability of such northern sky sources. We find that the number of muon events from RX J1713.7-3946 can reach several for one year observation. The atmospheric background in 1° cone is of the same level as the signal. For W28 the signal will be slightly weaker than that of RX J1713.7-3946, if the cutoff energy of accelerated protons is high enough. We expect that for a long time exposure (e.g., ~ 10 yr) of a km^3 neutrino telescope located in the northern hemisphere, it would be possible to detect the neutrinos from the SNRs like RX J1713.7-3946. If these neutrinos are really detected, it would be the smoking gun of identifying the acceleration sources of the Galactic CRs.

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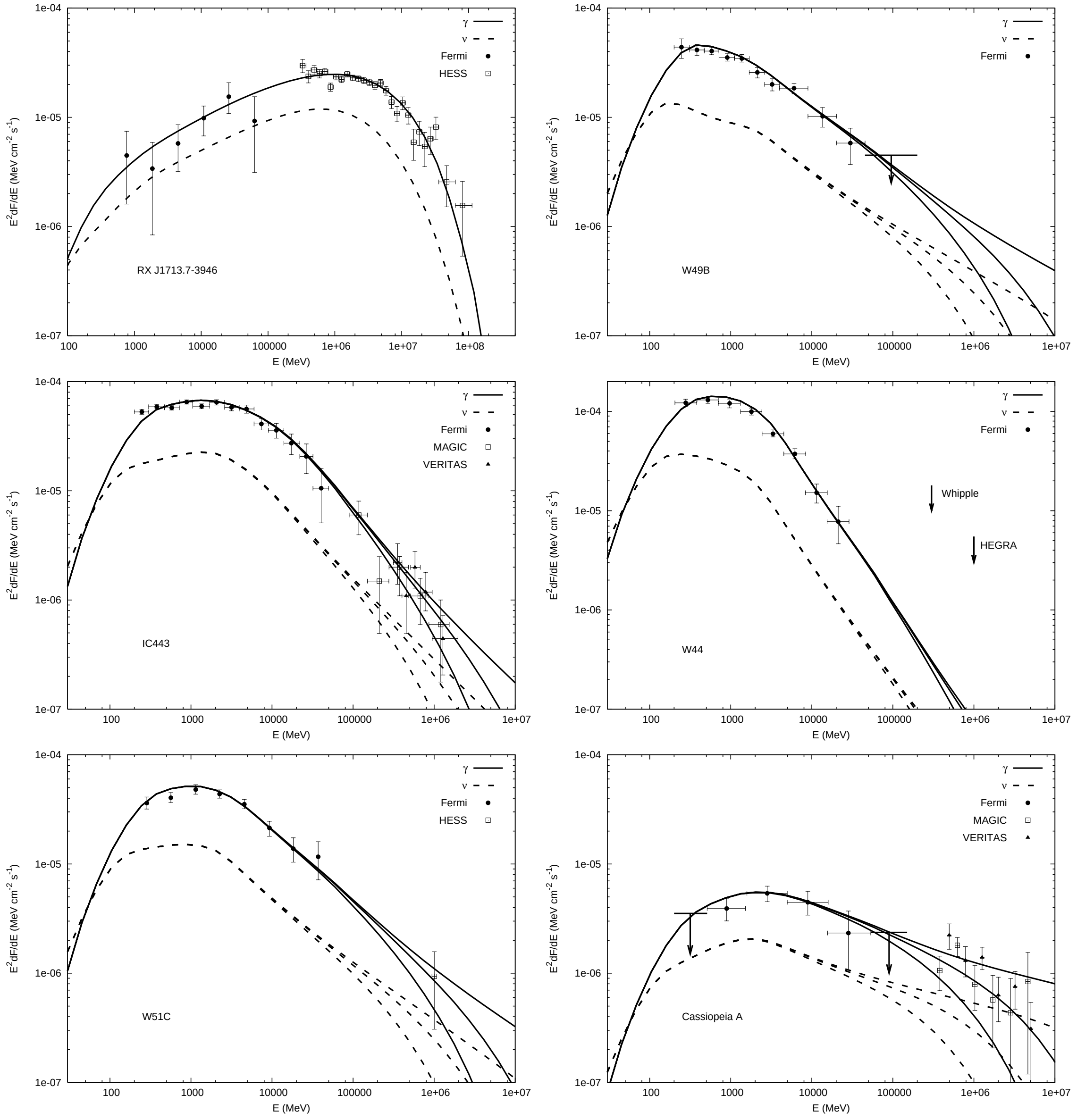

Fig. 1.— The γ-ray spectra of seven SNRs revealed by Fermi, together with available measurements at TeV energy range by Cerenkov telescope. As a comparison we also show the flux of muon neutrinos of each source (see Sec. 3). References of the γ-ray data are: RX J1713.7-3946, Fermi (Funk 2009), HESS (Aharonian et al. 2007); W49B, Fermi (Abdo et al. 2010f); IC 443, Fermi (Abdo et al. 2010e), MAGIC (Albert et al. 2007a), VERITAS (Acciari et al. 2009); W44, Fermi (Abdo et al. 2010d), Whipple (Buckley et al. 1998), HEGRA (Aharonian et al. 2002); W51C, Fermi (Abdo et al. 2009), HESS (Fiasson et al. 2009); Cassiopeia A, Fermi (Abdo et al. 2010b), MAGIC (Albert et al. 2007b), VERITAS (Humensky 2008).

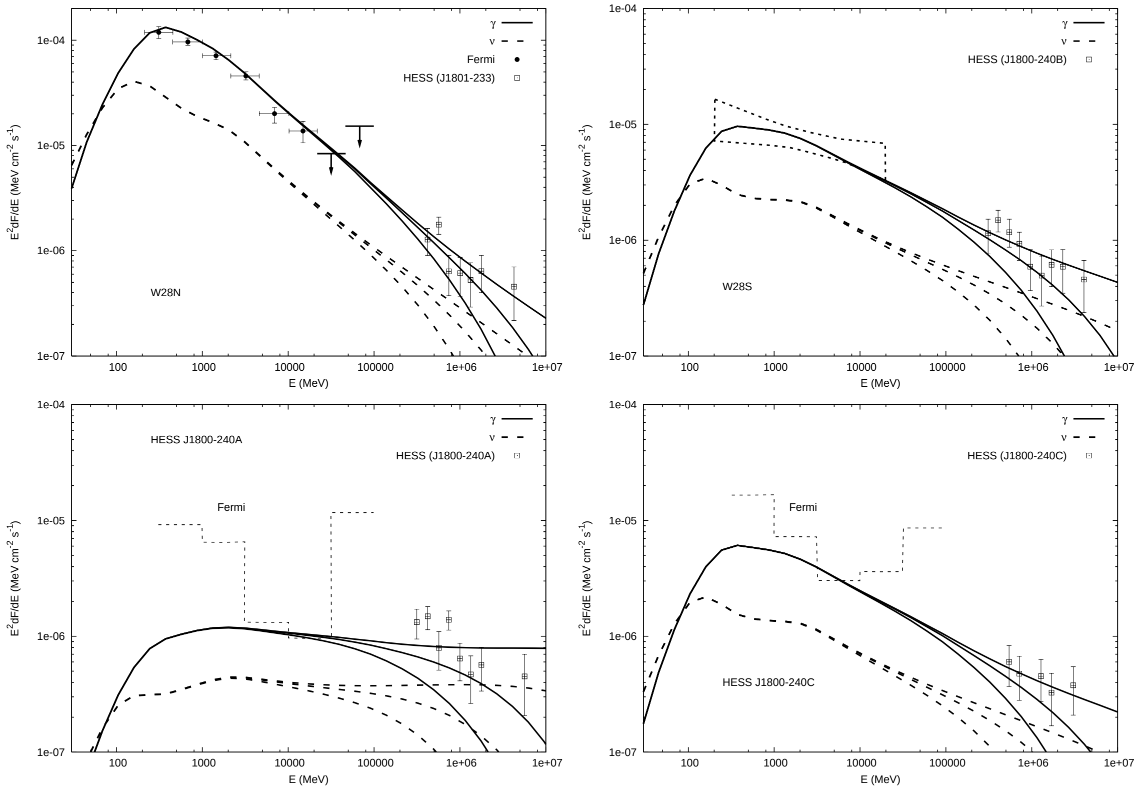

Fig. 2.— Continuance of Fig. 1. The Fermi data are adopted from Abdo et al. (2010c), and the HESS data are from Aharonian et al. (2008).

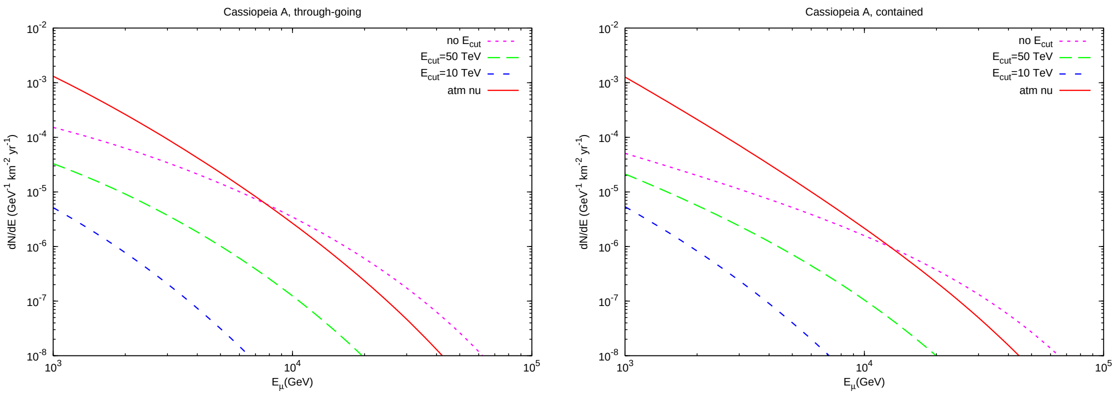

Fig. 3.— The differential through-going (left) and contained (right) muon rate of Cassiopeia A at IceCube. The four lines in each panel represent muon events induced by SNR neutrinos without $E_{\rm cut}$, with $E_{cut} = 50, 10$ TeV, and the atmospheric neutrinos respectively.

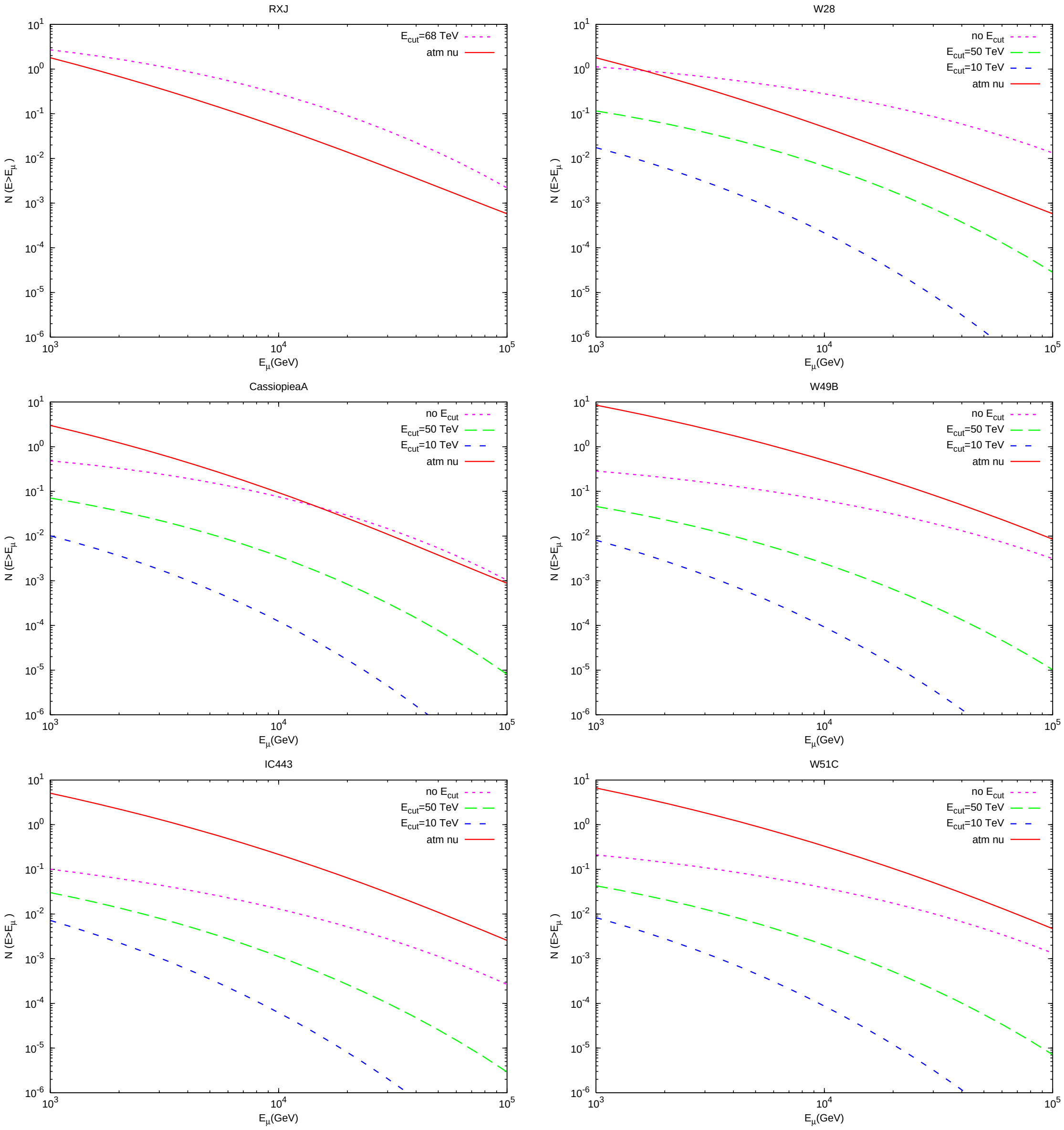

Fig. 4.— The total muon number in one year induced by neutrino emissions from the six Fermi SNRs. See the text for details.