DISCRIMINATING LOCAL SOURCES OF HIGH-ENERGY COSMIC-RAY ELECTRONS AND POSITRONS BY ENERGY SPECTRUM AND ANISOTROPY MEASUREMENTS

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ABSTRACT

Recently, the Fermi-LAT collaboration published the result of the cosmic-ray (CR) positron-electron ($e^+ + e^-$) anisotropy measurement with seven years of data, which provides the strongest restriction of the $e^+ + e^-$ anisotropy up to now. In this paper, we combine all the leptonic data of AMS-02 and the anisotropy upper limits of Fermi-LAT to test the models which explain the AMS-02 data by contributions of local CR sources. We calculate the total $e^+ + e^-$ anisotropy from all the CR sources in each model, including the contribution from background supernova remnants (SNRs). Our results indicate that the anisotropy upper limits given by Fermi-LAT disfavor a dominant contribution from Vela SNR in the sub-TeV region, while the models in which Monogem Ring or Loop I acts as the dominant source remain safe under the restriction of Fermi-LAT. Then we discuss several possible features of the prominent $e^+ + e^-$ spectra above TeV, along with their anisotropy spectrum. These anisotropies are large enough to be detected by future CR instruments like HERD, which may provide important evidences for the origin of high-energy $e^+ + e^-$. The study combining the anisotropy and energy spectrum can also be crucial to discriminate the astrophysical and dark matter origins of high-energy $e^+ + e^-$. 

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1. INTRODUCTION

The measurement of cosmic-ray (CR) leptonic spectra has entered into a new stage after the launch of the Alpha Magnetic Spectrometer (AMS-02) in May 2011 (Aguilar et al. 2013). The AMS-02 collaboration has obtained the exclusive positron/electron ($e^\pm$) spectrum (Aguilar et al. 2014), owing to the strong capability of the sign-of-charge discrimination. This measurement provides stronger constraints on theoretical models of the cosmic lepton origin, compared with merely the measurement of the positron plus electron ($e^+ + e^-$) spectrum. The high-precision results of AMS-02 not only confirm the existence of the electron-positron excess detected by previous experiments (Chang et al. 2008; Adriani et al. 2009), but also indicate that the electron spectrum has a larger excess than that of the positron (Feng et al. 2014; Li et al. 2015; Lin et al. 2015). This extra excess of electrons can be interpreted as the spectral fluctuation brought by discrete local supernova remnants (SNRs) (Lin et al. 2015).

After the work of Shen (1970), many astrophysical models have been proposed, in which nearby SNRs are calculated separately from background SNRs (Atoyan et al. 1995; Kobayashi et al. 2004; Di Mauro et al. 2014), in order to explain the CR observations. Along this approach, we have carefully investigated local CR sources and discussed their parameters of electron injection, to fit all the leptonic data of AMS-02 and give predictions to $e^+ + e^-$ spectrum beyond 1 TeV (Fang et al. 2017, hereafter Paper I). Vela SNR is traditionally believed to the most important local source around TeV, while other candidates have also been utilized to explain the extra electron excess when Vela lose its dominance. Although we argue that the possible sub-TeV scenarios may be few, the current leptonic data of AMS-02 cannot provide discrimination to them.

However, things are different when the anisotropy in the arrival direction of cosmic electrons is taken into account. Even two sources produce similar leptonic spectra, the angular distributions would be different due to their different positions. Also, the degree of anisotropy of these sources may also not be the same, or even have difference in magnitude. Therefore the anisotropy measurement can provide an unprecedentedly strong constraint on theoretical models. Linden & Profumo (2013) depicted the prospective of ascertaining the origin of the pulsar account for the positron excess, by the anisotropy measurement of atmospheric Cherenkov telescopes. More recently, Manconi et al. (2017) performed a detailed analysis of local CR $e^\pm$ sources, and presented the corresponding anisotropies.
In March 2017, the Fermi-LAT collaboration published the result of anisotropy measurement with seven years of data (Abdollahi et al. 2017). As no significant anisotropy has been detected in any angular scale, Fermi-LAT provided the strongest upper limit of anisotropy so far. Basing on the models in Paper I, we combine the total anisotropy of those models to give further discussion on the origin of high energy $e^\pm$. Our work has several differences with previous works, such as Manconi et al. (2017). First, we adopt the seven years data of $e^+ + e^-$ anisotropy given by Fermi-LAT to test our models. Second, we emphasize the importance of calculating the total anisotropy of all the sources in each model, including the SNR background which also has a considerable anisotropy. We also show the predicted $e^+ + e^-$ spectra in the TeV region together with their anisotropies.

Besides, the capability of the High Energy cosmic-Radiation Detection (HERD, Zhang et al. 2014), which is planned for about a 10-year operation starting around 2020, is considered in our present discussions. The core of HERD is a 3-d cubic calorimeter, which is surrounded by four micro-strip silicon trackers from the side and one from the top. This design makes a large geometrical acceptance of $> 3 \text{ m}^2 \text{ sr}$ for electrons. One of the main scientific objectives of HERD is to measure the energy spectrum and anisotropy of $e^+ + e^-$ up to 10 TeV, while sources contribute in TeV region may have anisotropies large enough to be detected. So we give an estimation on the detection capability of $e^+ + e^-$ anisotropy for HERD, and compare it with the theoretical anisotropy of each model.

This paper is organized as follows. In Section 2, we introduce our method of calculating the CR leptonic spectra, including the injection and propagation of CR leptons; the calculation of the anisotropy is also described. In Section 3, we present our leptonic spectra in sub-TeV and extra models in TeV separately, together with all their anisotropies. Some complementary content is shown in Section 4, which is followed by the conclusion in the last section.

2. METHOD

In Paper I, we have already described our calculation of $e^\pm$ spectra in detail, so in the following we do not give elaborate explanation on the content overlapping with the previous work.

2.1. Propagation of Galactic Electrons and Positrons

The trajectories of Galactic $e^\pm$ are tangled by the random magnetic field in the Galaxy, so their propagation can be described by the diffusion process. The number density of $e^\pm$, marked with $N$ here, is given by the diffusion equation with consider-
ation of energy loss during their propagation, which has the form of

\[
\frac{dN}{dt} - \nabla(D \nabla N) - \frac{\partial}{\partial E}(bE) = Q, \tag{1}
\]

where \(D\) denotes the diffusion coefficient, \(b\) denotes the energy-loss rate and \(Q\) is the CR source function. Since convection and reacceleration have little effect in the energy range above 10 GeV where we are interested (Delahaye et al. 2010), the relevant terms are not included in Equation (1).

The propagation zone of CRs is set as a cylindrical slab, with radius of 20 kpc (Delahaye et al. 2010) and a half thickness \(z_h\). The diffusion coefficient \(D\) has the form of \(D(E) = \beta D_0 (R/1 \text{ GV})^\delta\), where \(D_0\) and \(\delta\) are both constants, \(\beta\) is the velocity of particles in the unit of light speed and \(R\) is the rigidity of CRs. In this work, the propagation parameters—\(D_0\), \(\delta\), \(z_h\)—refer to Yuan et al. (2017), which can be called the finished version of the propagation parameters used in Paper I. We assume an linear correlation between the solar modulation parameter and solar activities (specifically, the sunspot numbers) to give a time-varying constrain to the former. We choose the best performing model in Yuan et al. (2017), that is, the revised diffusion reacceleration model, in which the propagation parameters are: \(D_0 = (2.08 \pm 0.28) \times 10^{28} \text{ cm}^2 \text{ s}^{-1}\), \(\delta = 0.500 \pm 0.012\), and \(z_h = 5.02 \pm 0.86 \text{ kpc}\).

The energy-loss rate is given by \(b(E) = -b_0(E) E^2\), where \(b_0(E)\) is decided by synchrotron and inverse Compton radiation of CR \(e^\pm\). We set the interstellar magnetic field in the Galaxy to be 1 \(\mu\)G to get the synchrotron term (Han & Qiao 1994; Delahaye et al. 2010). The seed photon field of inverse Compton process consists of stellar radiation, reemitted infrared radiation from dust, and cosmic microwave background (CMB). We adopt the description of Schlickeiser & Ruppel (2010) to calculate the inverse Compton term, in which a relativistic correction to the cross-section is considered.

For a point source with burst-like injection, the source function can be written as

\[
Q(E, \mathbf{x}) = Q(E) \delta(t - t_s) \delta(\mathbf{x} - \mathbf{x}_s), \tag{2}
\]

where \(Q(E)\) represents the energy distribution of injection, \(t_s\) is the time of CR injection, and \(\mathbf{x}_s\) is the location of the source. The coordinate origin is set to be the location of the solar system. Although we have assumed a disk-like propagation zone, if the propagation scale of \(e^\pm\) is much smaller compared with \(z_h\), we may adopt a spherically symmetric time-dependent solution to Equation (1). This is safe for high energy \(e^\pm\), as we discussed in Paper I (see also Kobayashi et al. 2004). Thus
the number density of observed $e^\pm$ contributed by a source with distance $r$ and age $t$ can be expressed as

$$N(E, t, r) = \frac{1}{(\pi\lambda^2)^{3/2}} \frac{b(E_0)}{b(E)} \exp \left( -\frac{r^2}{\lambda^2} \right) Q(E_0),$$

where $E_0 = E/(1 - b_0 Et)$ is the initial energy of arrival $e^\pm$ with energy $E$, and

$$\lambda \equiv 2 \left( \int_E^{E_0} \frac{D(E')dE'}{b(E')} \right)^{1/2}$$

describes the propagation distance of $e^\pm$ with arrival energy $E$. Consequently, the average intensity of $e^\pm$ born in a burst-like point source is given by

$$\bar{I}(E) = \frac{c}{4\pi} N(E, t, r).$$

We separate local discrete sources from distant sources when dealing with SNRs. The average intensity of local SNRs can be simply calculated by Equation (5). For distant SNRs, we assume a smooth spatial distribution derived by Lorimer (2004), and the SN explosion rate is set to be $f = 4$ century$^{-1}$ galaxy$^{-1}$ (Delahaye et al. 2010). The critical distance and age between local and distant SNRs are still set to be $r_m = 1$ kpc and $t_m = 3 \times 10^5$ years as what we do in Paper I. So the spectrum of the distant component is written as

$$\bar{I}(E) = \frac{c}{4\pi} \left( \int_0^{t_m} dt \int_0^\infty dr \int_0^{2\pi} d\varphi - \int_0^{t_m} dt \int_0^{r_m} dr \int_0^{2\pi} d\varphi \right) \times f \rho(r, \varphi) N(E, t, r) r,$$

where $\rho(r, \varphi)$ describes the spatial distribution given by Lorimer (2004) but centered on the solar system.

### 2.2. Galactic Sources of Electrons and Positrons

SNRs have long been believed to be the main astrophysical sources of Galactic electrons. Particles can be boosted to very high energy in shock waves of SNRs. In this process, the energy spectrum of the accelerated particles turns out to be a power-law form. A cut-off energy in TeV is also suggested to the energy spectrum by $\gamma$-ray observations to SNRs. So the spectrum of electrons injected into ISM can be expressed as

$$Q(E) = Q_0 (E/1 \text{ GeV})^{-\gamma} \exp(-E/E_c),$$
Table 1. The name, location, distance, and age of SNRs within 1 kpc. One can refer to Di Mauro et al. (2014) and references therein for parameters of these sources; while for Monogem Ring and Loop I, their distance and age listed here are taken from Plucinsky (2009) and Egger & Aschenbach (1995) respectively.

| Name                | l(°) | b(°) | r(kpc) | t(kyr) |
|---------------------|------|------|--------|--------|
| G65.3+5.7           | 65.3 | +5.7 | 0.8    | 28     |
| Cygnus Loop         | 74.0 | −8.5 | 0.54   | 10     |
| G114.3+0.3          | 114.3| +0.3 | 0.7    | 7.7    |
| R5                  | 127.1| +0.5 | 1.00   | 25     |
| G156.2+5.7          | 156.2| +5.7 | 1.00   | 20.5   |
| HB9                 | 160.9| +2.6 | 0.8    | 5.5    |
| Vela Jr.            | 266.2| −1.2 | 0.75   | 3      |
| RX J1713.7-3946     | 347.3| −0.5 | 1.00   | 1.6    |
| Vela YZ             | 263.9| −3.3 | 0.29   | 11.3   |
| Monogem Ring        | 203.0| +12.0| 0.3    | 86     |
| Loop I (NPS)        | 328.3| +17.6| 0.1    | 200    |

where $Q_0$ is the normalization of the injection spectrum. Background SNRs share a common injection spectrum. Their $Q_0$ and $\gamma$ are determined in the following fittings and $E_c$ is set to be 20 TeV, as what we do in Paper I. For local SNRs, we estimate their parameters individually. Our sample of local SNRs is shown in Table 1.

Multi-wavelength observations of electromagnetic radiation of SNRs are very useful tools to constrain their electron injection spectra. Four sources in our sample, HB9, Vela Jr., RXJ1713.7-3496, and Cygnus loop, have not only observations in radio band, but also measurements in X-ray or (and) $\gamma$-ray. we constrain injection parameters of these sources by fitting to multi-wavelength data. Radio and X-ray emission are assumed to be produced by synchrotron radiation of electrons. As to $\gamma$-ray, we give priority to a leptonic origin, that is, $\gamma$-ray is generated by inverse Compton scattering of background photon field by electrons in SNRs. If leptonic model cannot fit well to the multi-wavelength data of a source, we will turn to a hybrid model in which both leptonic and hadronic origin of $\gamma$-ray are taken into account. One may refer to Paper I for detailed process and fitting results for those four sources.
For other local SNRs, G65.3+5.7, G114.3+0.3, R5, G156.2+5.7, we estimate their parameters simply by radio observations. Assuming the radio emission of SNRs are entirely produced by synchrotron radiation of SNRs, we get an expression for $Q_0$ which is given by Di Mauro et al. (2014), as

$$Q_0 = 1.2 \times 10^{47} \text{ GeV}^{-1} (0.79)^\gamma \left(\frac{r}{\text{kpc}}\right)^2 \left(\frac{B}{100 \mu \text{G}}\right)^{-(\gamma+1)/2} \left(\frac{B_{r}^{1 \text{GHz}}}{\text{Jy}}\right), \quad (8)$$

where $B$ is the magnetic field of SNR, $B_{r}^{1 \text{GHz}}$ marks the radio flux at 1 GHz which can be found in the Green catalog (Green 2014). The electron spectra index $\gamma$ is simply related to the radio spectra index $\alpha_r$ by $\gamma = 2\alpha_r + 1$. We calculate $B$ applying the method of Arbutina et al. (2011) based on minimum-energy assumption:

$$B[\text{G}] \approx \left[6.286 \times 10^{(9\gamma-79)/2} \frac{\Gamma(\frac{3-\gamma}{2})\Gamma(\frac{3-2}{2})\Gamma(\frac{\gamma+7}{4})}{\Gamma(\frac{\gamma+5}{2})}(m_e c^2)^{2-\gamma} \right.$$

$$\left.\times \frac{(2c_1)^{1-\gamma/2}}{c_5} (1+\kappa) \frac{B_{r}^{1 \text{GHz}}[\text{Jy}]}{f r[\text{kpc}] \theta[\text{arcmin}^3]} \right]^{2/(\gamma+5)},$$

where $m_e c^2$ is rest energy of electron, $c_1$ and $c_5 = c_3 \Gamma(\frac{3-\gamma}{12})\Gamma(\frac{3+19}{12})/(\gamma + 1)$ are defined in Pacholczyk (1970), $f=0.25$ is the volume filling factor of radio emission, $\theta$ is the angular radius of SNR which can be found in the Green catalog. We quote the expression of Yamazaki et al. (2006) to estimate the cut-off energy $E_c$:

$$E_c = 14 \text{ TeV} v_{s,8} (B/10 \mu \text{G})^{-1/2}, \quad (10)$$

where $v_{s,8}$ is the shock velocity in unit of $10^8 \text{ cm s}^{-1}$ which depends on evolution of SNR. As can be see in Paper I, Vela YZ, Monogem Ring, and Loop I are the most important candidate SNRs in sub-TeV region, so we leave the discussion of them in the following fittings.

Pulsars are generally assumed to be the most important astrophysical $e^\pm$ sources accounting for the observed positron excess. They convert their spin-down energy partially to relativistic winds of charged particles, including $e^\pm$ pairs. For young and middle aged pulsars, they may be surrounded by an observable pulsar wind nebula (PWN, see Gaensler & Slane 2006, and references therein). Particles injected into a PWN are constrained for a period of time until the crush of the PWN, after which particles escape into the ISM (van der Swaluw et al. 2004). Thus we emphasize the injection spectrum for pulsar should be the spectrum of PWN, rather than that of pulsar itself (Malyshev et al. 2009). If one attempt to estimate the injection...
parameters of a pulsar with multi-band observations, the spectral energy distribution of its PWN is what should be studied, no that of the pulsar.

The injection spectra of PWNe are assumed to be the same form as Equation (7). As in Paper I, their spectral index are set to be free parameters in the following fittings and cut-off energies are fixed at 2 TeV, if not specifically stated. We mark the total spin-down energy released by pulsar with $W_p$ and the efficiency of energy conversion to injected electrons or positrons with $\eta$, then we have a relation

$$\int_{E_{\text{min}}}^{\infty} Q(E) E \, dE = \eta W_p, \quad (11)$$

where $E_{\text{min}} = 0.1$ GeV and $\eta$ is treated as a fitting parameter since it can hardly be pinpointed. The spin-down luminosity $\dot{E}$ evolves with the age of pulsar $t$ (Pacini & Salvati 1973), and we integrate it with time to get the spin-down energy

$$W_p = \dot{E} t \left( 1 + \frac{t}{\tau_0} \right), \quad (12)$$

where $\dot{E}$ and $t$ can be obtained from the ATNF catalog (Manchester et al. 2005). After all these parameters settled, the normalization $Q_0$ are determined subsequently.

In fact, not all the pulsars in the ATNF catalog can be dealt with in this way. For millisecond pulsars, they have acquired angular momentum from their companion stars. We give an age cut to ATNF pulsars above $10^4$ kyr—on the one hand, pulsars older than this age contribute little to the energies we are interested in; on the other hand, millisecond pulsars are eliminated from our sample since their 'character age' given by the ATNF catalog are very large.

Secondary positrons produced by inelastic collision between CR nuclei and ISM are considered to be full responsible for measured positron spectrum in early researches, and now they are treated as the background of positron spectrum. We cite the calculation given by Delahaye et al. (2009) to obtain the secondary component of positrons. The source function is assumed to be steady and homogeneous in a slab geometry, as

$$Q_{\text{sec}}(E) = 4\pi \sum_{i,j} n_j \int dE' \Phi_i(E') \frac{d\sigma_{ij}(E', E)}{dE}, \quad (13)$$

where $i$ and $j$ mark the species of CR nuclei and ISM gas respectively. The number density of ISM is assumed to be constant as $n_H = 0.9$ cm$^{-3}$ and $n_{He} = 0.1$ cm$^{-3}$. Di Mauro et al. (2014) fit the AMS-02 data to get the intensities of incident H and He, and we adopt their result here. We select the scattering cross-section $d\sigma/dE$
of p-p collision given by Kamae et al. (2006), and empirical rescaling to collisions between other species can be found in Norbury & Townsend (2007). In the fitting process of the next section, a free rescaling parameter \( c_{e^+} \) is needed to accommodate the estimated positron intensity to the data. This difference may be attributed to the uncertainty in the calculation above, or come from the propagation parameters.

In summary, SNR background is the dominant electron source below hundreds of GeV, above which local SNRs and pulsars make significant contribution to the electron spectrum. For positron spectrum, secondary component is important below tens of GeV, and the contribution of pulsars becomes absolutely predominant in higher energies.

### 2.3. Anisotropy of Electrons and Positrons

Presupposing the dipolar distribution of the intensity of CRs, the anisotropy of CRs is generally defined as

\[
\Delta = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}},
\]

where \( I_{\text{max}} \) and \( I_{\text{min}} \) are the maximum and minimum values of the CR intensity, respectively. If we take a specific form of the angular distribution of the CR intensity from a source as

\[
I_i(n) = \bar{I}_i(1 + \Delta_i n_i \cdot n),
\]

where \( \bar{I}_i = (I_{\text{max},i} + I_{\text{min},i})/2, n_i \) is the direction of the source, and \( \Delta_i \) denotes the anisotropy of that source, then under the diffusion model, Equation (14) can be rewritten as

\[
\Delta_i = \frac{3D}{c} \cdot \frac{\left| \nabla N_i \right|}{N_i},
\]

which is derived by Ginzburg & Syrovatskii (1964). Combining Equation (16) and Equation (3), we get the explicit expression of the \( e^\pm \) anisotropy of a single source:

\[
\Delta_i = \frac{3D}{c} \cdot \frac{2r_i}{\lambda_i^2},
\]

Let us review the definition of \( \lambda_i \) in Equation (4): if \( E \) is close enough to \( E_0 \), the diffusion scale can be then approximated by \( \lambda_i = 2\sqrt{D\bar{t}_i} \). For a source with age of 10 kyr, this approximation only brings a relative error of several percent to the anisotropy even in TeV range. Under this approximation, Equation (17) has a form of

\[
\Delta_i = \frac{3r_i}{2c\bar{t}_i},
\]
in which the anisotropy is simply decided by the age and distance of the source. We still adopt Equation (17) to calculate the anisotropy in the following, but we should keep in mind the anisotropy of a single source only has a weak dependence on the diffusion coefficient $D$.

In order to comparing theoretical models with experimental data, it is essential to calculate the total anisotropy contributed by all the sources in each model. The total intensity is given by summation of Equation (15):

$$I(n) = \sum_i \bar{I}_i (1 + \Delta_i n_i \cdot n).$$  \hspace{1cm} (19)

Then the total anisotropy can be obtained from the definition of Equation (14):

$$\Delta = \frac{\sum \bar{I}_i \Delta_i n_i \cdot n_{\text{max}}}{\sum \bar{I}_i},$$ \hspace{1cm} (20)

where $n_{\text{max}}$ is the direction of the maximum intensity. For local SNRs, their location can be found in the Green catalog. As to pulsars, their Galactic longitude $l$ and latitude $b$ are given in the ATNF catalog. Equation (20) indicates that the contribution of an individual source to the total anisotropy is related to its relative intensity compared with the total average intensity, rather than its absolute intensity. Note the quantity $\bar{I}_i \Delta_i / \sum \bar{I}_i$, which often appears in the graphs of previous works, does not describe the anisotropy of a source; it has the connotation of the anisotropy produced by a source embedded in an isotropic background.

Since the distribution of distant SNRs is symmetric around the Galactic center but not the solar system, and they also have significant contribution to the electron spectrum, we emphasize that the SNR background should be a considerable component in the calculation of anisotropy. We treat the SNR background component as a whole, so its anisotropy may also be calculated by Equation (16). If we take a difference step $\Delta r$ of 0.1 kpc, the $e^-$ anisotropy of SNR background can be estimated by

$$\Delta_{bkg} = \frac{3D}{c} \cdot \frac{1}{N_{bkg}} \cdot \left| \frac{N_{bkg}^+ - N_{bkg}^-}{2\Delta r} \right|,$$ \hspace{1cm} (21)

where $N_{bkg}$ is obtained by Equation (6), $N_{bkg}^+$ and $N_{bkg}^-$ are the number densities at 8.6 kpc and 8.4 kpc from the Galactic center respectively, and of course, both with $l = 0, b = 0$. The direction vector of the background component is $n_{bkg} = \{1, 0, 0\}$ in rectangular coordinate.
For each model in the following, we need to find \( n_{\text{max}} \) in different energy bands. We calculate \( I(l, b) \) for every \( 1^\circ \times 1^\circ \) grid to find the maximum \( I(l, b) \) and thus obtain \( n_{\text{max}} \). The positions of all our local SNRs are listed in Table 1, while the location of PWNe discussed in the following sections can be found in Table 3.

3. RESULTS

In paper I, we first propose several theoretical models and test them by fitting to all the leptonic data of AMS-02. Then we give some expectations of the \( e^+ + e^- \) spectrum above 1 TeV and focus on the possibilities of bump spectral features in TeV region. In this work, we still perform analyses on sub-TeV and TeV energies separately. We combine leptonic data of AMS-02 and the latest anisotropy data of \( e^+ + e^- \) given by the Fermi-LAT collaboration to test our models in sub-TeV region. The anisotropies corresponding to our TeV expectations will also be shown below.

Several experiments of \( e^+ + e^- \) spectrum have already covered energies from sub-TeV to TeV, such as the Fermi-LAT (Fermi-LAT Collaboration et al. 2017) and ground-based Cherenkov telescopes like HESS (Aharonian et al. 2008, 2009), MAGIC (Borla Tridon 2011) and VERITAS (Staszak & for the VERITAS Collaboration 2015). However, we still choose the data of AMS-02 to test our sub-TeV astrophysical sources, since AMS-02 provides so far the most precise measurement to all four groups of leptonic spectra simultaneously and thus can put strongest restrictions to theoretical models. Due to the differences between the \( e^+ + e^- \) spectrum of AMS-02 and other experiments above, we adopt the \( e^+ + e^- \) measurement of AMS-02 alone in our fittings. The global fitting to the AMS-02 data leads to a self-consistent picture.

The Fermi-LAT collaboration has published the dipole anisotropy of \( e^+ + e^- \) using almost seven years of data (Abdollahi et al. 2017). They get an unprecedented sensitivity to dipole anisotropy down to a level of \( 10^{-3} \) thanks to their largest sample collection to date. Also, space telescopes like Fermi-LAT should be ideal instruments to detect anisotropy, due to the consistent survey of the entire sky. To search for the anisotropy, the Fermi-LAT collaboration applies four different methods to create the reference sky map. In the present work, we choose the result in which the reference map is constructed by the ’shuffling technique’ while the upper limits are calculated by the frequentist method.

As we mentioned in Section 1, we give a simple calculation of the expected anisotropy detection capability of HERD here. We briefly summarize the baseline performance of HERD first; one can refer to Zhang et al. (2014) for details. The energy range of HERD for electrons is from 100 MeV to 10 TeV, with energy reso-
### Table 2. Fitting results of sub-TeV models. Loop I is abbreviated to Lp1, and Vela YZ is abbreviated to Vela in this table.

| Model     | $\gamma$ | $Q_0[10^{50}\text{GeV}^{-1}]$ | $c_{e^+}$ | $\gamma_{\text{PWN}}$ | $\eta$ | $\phi[\text{GV}]$ | $\alpha_{\text{vela}}$ | $\chi^2$/d.o.f |
|-----------|----------|--------------------------------|-----------|------------------------|-------|-----------------|------------------|----------------|
| Vela      | 2.42     | 2.48                           | 0.857     | 1.82                   | 0.90  | 0               | 0.56             | 0.43           |
| Vela+Lp1  | 2.50     | 3.11                           | 0.95      | 1.79                   | 0.86  | 0.10            | 0.433            | 6.29           |
| Vela+MR   | 2.51     | 3.35                           | 0.98      | 1.79                   | 0.85  | 0.14            | 0.465            | 2.24           |

The Sub-TeV Region

We consider three different models to explain the AMS-02 leptonic data. In the first model, Vela YZ is set to be the predominant SNR in sub-TeV, which is a common picture among previous works. If we investigate further on the parameters of Vela YZ with present observations, it may contribute little to the electron spectrum. Then we need to find proper candidate to explain the electron excess, which leads to the other two models: Loop I as predominant local SNR or Monogem Ring as predominant SNR.

For PWNe, we take a unified picture for all the models. We do not intend to sum all the pulsars in our sample to fit the data, as $\eta$ may have a vast variety for different pulsars, and it is also unpractical to set $\eta$ of all the pulsars as free parameters. In Paper I, we select the PWN of pulsar B0656+14, dubbed Monogem, as the single PWN to fit the AMS-02 data; in this work, Geminga is chosen as the single PWN, which can be ascribed to several reasons. First, Geminga is one of the most well studied pulsars. $\gamma$-ray measurements of its PWN given by Milagro...
Abdo et al. (2009) and recent HAWC (Baughman et al. 2015) imply the probability of significant positron contribution from Geminga (Hooper et al. 2017). Second, Geminga have a small anisotropy due to its close distance and relatively old age, which may help to keep the total $e^+ + e^-$ anisotropy under the limits given by Fermi-LAT. Besides, our new diffusion coefficient is about two times larger than the previous one; to get a reasonable $\eta$, Geminga may be a better choice than Monogem, since the former has a much larger spin-down energy.

So far, we have introduced five free parameters shared by all the three models, they are: $Q_0$ and $\gamma$ for SNR background, $\eta$ and $\gamma_{\text{PWN}}$ for Geminga, and $c_{e^+}$ for secondary positrons. Besides, a solar modulation potential $\phi$ (Gleeson & Axford 1968) is also needed to accommodate data below tens of GeV.

3.1.1. Vela YZ

Vela SNR is widely believed to be the most important local electron source since its appropriate age and distance and its strong radio flux may lead to significant contribution to electron spectrum. Vela SNR mainly consists of a PWN—Vela X, and two shell structure—Vela Y and Vela Z (Rishbeth 1958). We do not include Vela X here since it cannot help to explain the extra excess of electrons compared with positrons, due to its PWN nature (Weiler & Panagia 1980). In this model, we take $B = 30 \mu G$, $E_c = 2$ TeV and $B_1\text{GHz} = 1000$ Jy as in Paper I. The radio spectral index is left to be free as it is a crucial parameter to the dominance of Vela YZ but still with large uncertainty in observation. We seek the best-fit model by minimizing chi-squared statics between model and AMS-02 leptonic data\footnote{Steven G. Johnson, The NLopt nonlinear-optimization package, http://ab-initio.mit.edu/nlopt}. The best-fit parameters of this subsection are all listed in Table 2. Figure 1 shows the best-fit leptonic spectra and the anisotropy corresponding to the $e^+ + e^-$ spectrum.

The best-fit $\alpha_{\text{vela}}$ is 0.56, larger than the 0.519 in Paper I, which indicates the demand for the contribution of Vela YZ is less. Our new diffusion coefficient is larger than that adopted in Paper I, so the electrons from distant SNRs have more chance to reach the earth. This leads to the increase of the background component in higher energies and at the same time, the lower demand for Vela YZ. Even so, Vela YZ still produce such a remarkable anisotropy that the total theoretical anisotropy almost coincides with the upper limits calculated by Fermi-LAT, as shown in Figure 1. In this model, Vela YZ begins to lead the anisotropy from around 100 GeV to 1 TeV, above which its anisotropy is somehow offset by that of G65.3+5.7 whose position is opposite to Vela YZ. Vela YZ dominates the anisotropy not only because
Figure 1. The results of global fitting to AMS-02 data for Vela YZ model and the corresponding anisotropy of $e^+ + e^-$. Top left: electron flux; top right: positron flux; middle left: positron plus electron flux; middle right: positron fraction; bottom: anisotropy of positron plus electron. The legend explains different components in each sub-graph. In the legends, 'TOT' stands for total value, 'BKG' stands for SNR background, 'Other SNRs' refers to the summation of our local SNRs, except for Vela YZ, Monogem Ring, and Loop I. In the bottom graph, the dash and dotted lines represent for the quantity $\bar{I}_i \Delta_i / \sum \bar{I}_i$. Note $\bar{I}_i \Delta_i / \sum \bar{I}_i$ of 'Other SNRs' are not shown in the bottom graph, although they are included in the calculation of the total anisotropy.
its considerable flux of electrons, but also its relatively large $r/t$ ratio, as explained by Equation (18). The result indicates that the upper limits given by Fermi-LAT disfavors a relatively young SNR like Vela to dominate in sub-TeV region. We can also see the expected sensitivity of three years of HERD data is obviously lower than the theoretical anisotropies of this model, which may give a more convincing judgement to this scenario.

For fitting results of Geminga, $\gamma_{\text{PWN}} = 1.82$ is a reasonable spectral index for PWN, and $\eta = 0.90$ is still an acceptable value. Since Geminga is a nearby source with a relatively old age, its anisotropy contribution is not outstanding as shown in Figure 1. This also implies the anisotropy data of Fermi-LAT rejects Vela X as the single PWN, because the anisotropy of Vela X is 30 times larger than that of Geminga.

### 3.1.2. Loop I (NPS)

We investigate a little more for parameters of Vela YZ in this model. Sushch & Hnatyk (2014) derive a magnetic field of 46 $\mu$G in the region where Vela YZ is located. A shock velocity of $6 \times 10^7$ cm s$^{-1}$ is suggested by Sushch et al. (2011), which leads to $E_c = 4$ TeV if we adopt Equation (10). The latest result of the radio spectrum of Vela Y and Vela Z can be found in Alvarez et al. (2001). Sushch & Hnatyk (2014) merge the radio spectrum of Vela Y and Vela Z and obtain a spectral index of 0.735. If we take parameters above, Vela YZ contribute little to the electron spectrum as shown in Paper I. This is mainly because of the much larger radio spectra index compared with that of Vela YZ model. To explain the extra excess of electrons, Loop I is one of the only two candidate local SNRs.

Although Loop I is believed to be an old structure ($\sim 10^6$ years) due to the low velocity of neutral gas surrounding it (Sofue et al. 1974), the soft X-ray emission from the interior of Loop I indicates that there may be one or more subsequent SN events in the Sco-Cen association (Borken & Iwan 1977; Egger & Aschenbach 1995), which is located in the center of Loop I. The North Polar Spur is the most prominent structure of Loop I, both in radio and X-ray maps, which can be interpreted by the reheating of a recent SN (Egger & Aschenbach 1995). What is more, Fermi-LAT collaboration also detect high energy $\gamma$-ray emission in NPS region and the shape of this excess is similar to those seen in synchrotron emission (Casandjian et al. 2009). This may buttress the reheating picture of Loop I. We set $2 \times 10^5$ years as the age of NPS which is suggested by Egger & Aschenbach (1995), and the distance to NPS is 100 pc. As in Paper I, we let the spectral index, total energy, and cut-off energy free in the fitting, and mark them with $\alpha_{\text{loop}}, W_{\text{loop}},$ and $E_{c,\text{loop}}$. 
Figure 2. Same as Figure 1, but for the Loop I (NPS) scenario.

The fitting result and $e^+ + e^-$ spectrum are shown in Figure 2. The best-fit parameters of NPS have little difference from those of the same model in Paper I. The anisotropy spectrum is much smaller than the upper limits of Fermi-LAT; in
the region of hundreds of GeV, the anisotropies are even smaller than the expected sensitivity of HERD. However, the anisotropies below 100 GeV may be detected by HERD, where the anisotropy is dominated by the SNR background. The bump above 1 TeV is mainly produced by G65.3+5.7, which has a relatively large anisotropy. This indicates a source that has no obvious feature in $e^+ + e^-$ spectrum may shape an eminent structure in the anisotropy spectrum.

### 3.1.3. Monogem Ring

In addition to Loop I, Monogem Ring (MR) is the other potential contributor in sub-TeV, when Vela YZ contribute little to electron flux. MR is long considered as the counterpart of pulsar B0656+14 which is located 288 pc away. A distance of $\sim 300$ pc corresponds to an age of $8.6 \times 10^4$ years and an initial explosion energy of $0.19 \times 10^{51}$ erg, under the Sedov-Taylor model (Plucinsky et al. 1996). Like the previous model, we set $\alpha_{mr}$, $W_{mr}$, and $E_{c, mr}$ as free parameters. As can be seen in Table 2, the best-fit electron energy is $2.24 \times 10^{48}$ erg. Relating this $W_{mr}$ and the initial explosion energy of $0.19 \times 10^{51}$ erg, a large conversion efficiency of $10^{-2}$ is required.

Figure 3 shows the fitting results with $e^+ + e^-$ anisotropies. The anisotropy spectrum is also under the limits of Fermi-LAT. Although the $\Delta_i$ of MR is larger than the case of Loop I (NPS) and its anisotropy is superposed on that of Geminga due to their similar galactic longitude, its anisotropy contribution is somehow counteracted by the background component of SNR. From this two models, namely Loop I (NPS) model and Monogem Ring model, we can see that a nearby and relatively old SNR can not only explain the extra electron excess, but also keep the anisotropy spectrum of $e^+ + e^-$ in a safe zone under the constraint of Fermi-LAT. Also, the anisotropy of this model seems possible to be detected by HERD under 200 GeV. In this range, MR has a significant contribution to the anisotropy. So this model may be distinguished from the last one by the future anisotropy detection, since the direction of MR is almost contrary to the SNR background or Loop I.

### 3.2. The TeV Region

In the $e^+ + e^-$ spectrum above TeV, the contribution from old and distant sources decreases significantly, thus distinct spectral features produced by local sources are expected in TeV region. New generation of instruments like DAMPE (Chang 2014) and CALET (Torii 2014) have already been in orbit today. Their scientific objectives include the high precision measurement of $e^+ + e^-$ spectrum above 1 TeV, and their preliminary results may be coming soon. In fact, our sub-TeV models in the previous
subsection have already given $e^+ + e^-$ spectra beyond TeV, although they predict no prominent feature in TeV region. We draw the anisotropies of Loop I (NPS) model in Figure 4 as an example to show the anisotropy spectrum up to tens of TeV. Although
Figure 4. Anisotropy spectrum of $e^+ + e^-$ of Loop I (NPS) model up to tens of TeV. The thick black line represents the total anisotropy, while $\bar{I}_i \Delta_i / \sum \bar{I}_i$ of local SNRs are drawn with thin lines with different colours. The detection capability of HERD is calculated with the fluxes of $e^+ + e^-$ of Loop I (NPS) model.

The anisotropy increases to tens of percent in 10 TeV, it seems not to be detected by HERD. This should be attributed to the low TeV flux of $e^+ + e^-$ of the Loop I (NPS) model, which constrains the minimum detectable anisotropy of HERD. The Monogem Ring model is in a similar case.

In this subsection, we give several extra models to discuss the possibilities of remarkable spectral features of $e^+ + e^-$ in TeV region, and we also check their anisotropy spectra. In each model, a prominent TeV source is added on the Loop I (NPS) model introduced in Section 3.1.2, to give a complete spectrum. Of course, for the model that Vela YZ acts as the dominant source in TeV, the Vela YZ component in the Loop I (NPS) model should be subtracted. HESS has detected a spectra cut-off in 1 TeV (Aharonian et al. 2009), which is confirmed by the preliminary result of VERITAS (Staszak & for the VERITAS Collaboration 2015). However, the MAGIC collaboration claims that their preliminary data can be fitted by a single power law (Borla Tridon 2011). The latest result of Fermi-LAT shows a single power law $e^+ + e^-$ spectrum from 50 GeV to 2 TeV, and an exponential cut-off below 2 TeV is disfavored (Fermi-LAT Collaboration et al. 2017). Due to the inconsistency
Figure 5. The scenario of Vela YZ dominating in TeV region, with consideration of a release time for Vela YZ. The flux of Vela YZ is overlaid on that of Loop I (NPS) model in sub-TeV to get a complete picture, and the Vela YZ component in Loop I (NPS) model is subtracted. Top graphs: the $e^+ + e^-$ spectrum and anisotropy spectrum in the case of an injection age of 1 kyr for Vela YZ, dashed line in the right graph represent the quantity of $\bar{I}_i \Delta_i / \sum \bar{I}_i$ of Vela YZ; bottom graphs: the same with the top ones but with an injection age of 5 kyr for Vela YZ.

among this TeV measurements, we do not conform our TeV models to these data intentionally, but draw them in the following figures for comparison.

3.2.1. Vela YZ

Kobayashi et al. (2004) have shown the scenario that if we take into account the release time, that is, the time delay of electron injection, Vela YZ may distance itself from the background and produce a distinctive spectral feature in TeV region. However, to pinpoint the release time may be hard since it is related to the evolution of SNR and the process of CR escape. Dorfi (2000) points out that particles begin to escape from the shock front when the velocity of the shock has dropped to the order
of the Alfvén velocity of ISM. The mean Alfvén velocity of ISM can be calculated by
\[ v_A = 2.18 \times 10^6 \, \text{cm s}^{-1} \left( \frac{m_i}{m_p} \right)^{-1/2} (n_{\text{ISM}}/\text{cm}^{-3})^{-1/2} \left( B/\mu \text{G} \right), \]
where \( m_i \) is the ion mass, \( m_p \) is the mass of proton, \( n_{\text{ISM}} \) and \( B_{\text{ISM}} \) are number density and magnetic field of ISM respectively. The dynamics of expansion of Vela SNR suggests \( n_{\text{ISM}} \leq 0.01 \, \text{cm}^{-3} \) \( \text{(Sushch \\& Hnatyk (2014))} \), and if we assume \( B_{\text{ISM}} \) to be 10 \( \mu \text{G} \), the Alfvén velocity of the surrounding ISM should be \( \approx 1 \times 10^7 \, \text{cm s}^{-1} \). As we mentioned in the previous subsection, the shock velocity of Vela YZ region is observed to be \( 6 \times 10^7 \, \text{cm s}^{-1} \), and the shock velocity evolves with \( t^{-3/5} \) in Sedov phase. So the initial velocity should be larger than \( 10^8 \, \text{cm s}^{-1} \), which is much faster than the Alfvén velocity of ISM. This indicates that a considerable release time for Vela YZ may be reasonable.

In this model, we try two different injection age: \( t = 1 \, \text{kyr} \) and \( t = 5 \, \text{kyr} \), which correspond to a long release time and a time delay of half age of Vela, respectively. In our sub-TeV models, the total injection energy of electrons is at the magnitude of \( 10^{47} \) erg. We fix the injection energy at \( 2 \times 10^{47} \) erg, which is also suggested by Sushch \\& Hnatyk (2014). For spectral index, we assume a typical value of 2.0, since a larger spectral index prevents Vela YZ from dominating in TeV region, as we have shown in Paper I. Equation (10) implies \( E_c \) depends on time with \( t^{-3/10} \), thus there is little difference between cut-off energy for injection age of 1 kyr and 5 kyr. We set \( E_c = 4 \, \text{TeV} \) for both case.

Figure 5 presents the result of this model. The two top graphs show the \( e^+ + e^- \) spectrum and the anisotropy spectrum in the case of \( t = 1 \, \text{kyr} \). Vela YZ can indeed produce a prominent feature of \( e^+ + e^- \) spectrum in TeV region and maintain the spectral break just below 1 TeV. However, its anisotropy spectrum seems conflict with the last data point of Fermi-LAT. This is because the injection age of 1 kyr correspond to a much larger anisotropy of Vela YZ itself. The high energy \( e^+ + e^- \) spectrum of Fermi-LAT can be described by a single power law up to 2 TeV. Meanwhile, there seems a slight break in about 800 GeV. As can be seen in the bottom left graph of Figure 5, the case of \( t = 5 \, \text{kyr} \) may be similar to the spectral shape of the Fermi-LAT data; in fact, if we set the injection energy larger, the model could have a better consistency with the Fermi-LAT data. However, Vela YZ have an non-negligible electron contribution extending to sub-TeV region for the \( t = 5 \, \text{kyr} \) case, thus the anisotropy spectrum of this case cannot side-step the constraint of the anisotropy data of Fermi-LAT, as shown in the bottom right graph of Figure 5. Besides, for both cases, the anisotropy spectra are within the expected detection ability of HERD.

3.2.2. Vela X
As in paper I, we cite the model of Hinton et al. (2011) for Vela X. Vela X consists of two components: a halo and a ‘cocoon’. However, the 100 GeV cut-off energy of the derived electron spectrum for the former and the total leptonic energy of $10^{46}$ erg for the latter prevent Vela X to create a distinctive spectral feature in TeV region. Hinton et al. (2011) point out that the low cut-off energy for the halo component may be attributed to an energy dependent escape which happens at the time of the crush of the original PWN. They assume a spectral index of 1.8, a cut-off energy of 6 TeV, and a total leptonic energy of $6.8 \times 10^{48}$ erg in their model. After considering the liberation time of electrons, their result shows that Vela X can produce a prominent TeV spectrum of $e^+ + e^-$. Nevertheless, another precondition of their spectral shape is the small diffusion coefficient they choose, which is an order of magnitude smaller...
than ours. We have explained in Paper I that if we use our diffusion coefficient with their injection spectral parameters, the predicted $e^+ + e^-$ flux of Vela X is too large even in sub-TeV region, and has a serious contradiction with the AMS-02 data. We should also point out that the total leptonic energy of $6.8 \times 10^{48}$ erg may be a too large value, since the spin-down luminosity of Vela X given by the ATNF catalog is $6.92 \times 10^{36}$ erg, corresponding to a spin-down energy of merely $5 \times 10^{48}$ erg. Besides, the four years observation of Fermi-LAT combining with the radio data of Vela X derives a total energy converted to leptons of $9 \times 10^{47}$ erg (Grondin et al. 2013). This may be regarded as the upper limit of the leptonic injection energy.

Here we present two scenarios based on different treatments to Vela X: the one is the model given by Hinton et al. (2011) with an injection age of 3 kyr; in the other one, we adopt the diffusion coefficient of our own. For the later, a small leptonic injection energy is indispensable to avoid the conflict with the $e^+ + e^-$ data of AMS-02 or the anisotropy constraint of Fermi-LAT. We set an injection energy of $10^{47}$ erg and a smaller injection age of 1 kyr for the second model. The predicted $e^+ + e^-$ spectra and anisotropies are shown in Figure 6. For the first model, the TeV cut-off of the $e^+ + e^-$ spectrum is still kept, and the predicted anisotropies are below the upper limits of Fermi-LAT. However, the anisotropies cannot be detected by HERD until 4 TeV due to the low $e^+ + e^-$ fluxes in several TeV. The second case is similar with the previous model of Vela YZ because of the similarity of their parameters. The anisotropy spectrum of this case is expected to be detected by HERD in TeV range.

3.2.3. Cygnus Loop

Another famous nearby SNR—Cygnus Loop—does not appear in the graphs above due to its very low cut-off energy (72 GeV) given by multi-band fitting in Paper I. However, there is no available X-ray spectrum of the whole region of Cygnus Loop, so the fitted cut-off energy may not be so compelling. If we calculate with Equation (10), the cut-off energy of Cygnus Loop should be in TeV range. Then Cygnus Loop may become a prominent TeV electron generator. In this model, we keep the parameters of Cygnus Loop fitted in Paper I, except for the cut-off energy. The size of Cygnus Loop is approximately 200 arcmin, then a distance of 540 pc corresponds to a radius of 15 pc. The velocity of shock wave can be estimated by $0.4 R/t$ (Sushch et al. 2011), where $R$ is the radius of the shell and $t$ is the age the SNR. We derive a shock velocity of $6 \times 10^7$ cm s$^{-1}$, and the magnetic field given by multi-band fitting is $9.7 \, \mu$G, so the cut-off energy is estimated to be approximately 8 TeV. Since Cygnus Loop also has a large anisotropy, a considerable release time is necessary to avoid serious conflict with
Figure 7. Cygnus Loop overlays on Loop I (NPS) model. The cut-off energy of Cygnus Loop is 8 TeV, other injection parameters are kept as the fitted value in Paper I: $\gamma = 1.99$, $Q_0 = 10^{50}$ GeV$^{-1}$. Left: the $e^+ + e^-$ spectrum compared with experimental data; right: the corresponding anisotropy, upper limits of Fermi-LAT, and expected detection ability of HERD.

Figure 8. Same as Figure 7, but replace Cygnus Loop with Vela Jr. the anisotropy limits of Fermi-LAT. We set an injection age of 3 kyr, corresponding to a release time of 7 kyr. The $e^+ + e^-$ spectrum and corresponding anisotropy are presented in Figure 7. In $e^+ + e^-$ spectrum, Cygnus Loop seems to have relatively small contribution to the sub-TeV region; however, the total anisotropy spectrum still cross the highest energy data of Fermi-LAT. Obviously, this is due to the large anisotropy of Cygnus Loop itself, as the case of Vela YZ or Vela X.

3.2.4. Vela Jr.
Table 3. Members of the Multi-PWN model in Section 4.1. Their position, distance, and age are referred to the ATNF catalog. The total spin-down energy $W_p$ is calculated by Equation (11). The last two columns are given by the fitting described in Section 4.1 (the upper and lower bounds of $\gamma_{PWN}$ are set to be 2.0 and 1.5 in the fitting process).

| Name  | $l(\degree)$ | $b(\degree)$ | $r$(kpc) | $t$(kyr) | $W_p$ $(10^{49}$ erg) | $\gamma_{PWN}$ | $\eta$ |
|-------|--------------|--------------|-----------|----------|----------------------|---------------|-------|
| J0940-5428 | 277.5        | -1.3         | 0.38      | 42       | 1.34                 | 1.5           | 0.018 |
| Geminga | 195.1        | +4.3         | 0.25      | 342      | 1.23                 | 2.0           | 0.44  |
| B1001-47  | 276.0        | +6.1         | 0.37      | 220      | 0.480                | 2.0           | 0.39  |
| J2043+2740 | 70.6         | -9.2         | 1.48      | 1200     | 25.8                 | 2.0           | 0.19  |

In the former TeV models, the predicted anisotropy spectrum always cross the upper limits given by Fermi-LAT (cross the last upper limit band for most cases), except for the case taking a much smaller diffusion coefficient of Hinton et al. (2011). If we intend to obtain a remarkable $e^+ + e^−$ spectral feature above TeV and completely avoid the anisotropy constraint of Fermi at same time, the dominant local source should appear in energy range higher than several TeV. Thus a young and relatively distant source may meet the condition. In Paper I, we have discussed the possibility of Vela Jr. as the dominant source in TeV region. Since the real total leptonic injection energy may be hard to be ascertained, we assume an injection energy of $3 \times 10^{48}$ erg which is five times larger than the default value, to ensure a protruding spectral feature. Other parameters remain as fitted values. The result is shown in Figure 8. The $e^+ + e^−$ spectral bump is in tens of TeV, which may be beyond the detection range of DAMPE and CALET. Meanwhile, the predicted anisotropy spectrum is indeed entirely under the upper limits of Fermi-LAT. Above 5 TeV, the anisotropy can be expectedly detected by the HERD, so this should be a relatively optimistic case than the Loop I (NPS) model, as shown in Figure 4.

4. DISCUSSION
4.1. Multi-PWN Model

Although our Loop I (NPS) model and Monogem Ring model fit well to the AMS-02 data and their anisotropy spectra are entirely under the upper limits of Fermi-LAT, they predicted fewer $e^+ + e^−$ flux in $\sim 1$ TeV compared with all those TeV measurements (this can be seen in Figure 5–8). The reason is that all the local sources in sub-TeV—Loop I, MR, and Geminga—begin to descend just below 1 TeV in the spectrum. Geminga has the sharpest decline due to its relatively old age. Here
we would like to test a model that consists of a group of PWNe, instead of the case of a single PWN applied above. Young member(s) in the PWN group may help to make up the flux around 1 TeV.

We use the method of Di Mauro et al. (2014) to select powerful PWNe. We divide the energy range from 10 GeV to 1 TeV into four bins with equal length in logarithmic scale. For each bin, we calculate the integrated positron flux for all the PWNe in our sample, with a uniform spectral index of 1.8 and conversion efficiency of 0.05. Then all the PWNe are ranked by their integrated flux in each bin. We sum their rank of the four bins for each PWN individually, and the ten with the smallest summed rank are selected as our candidates. They are: J0940-5428, B1055-52, J0633+1746 (Geminga), B0355+54, B1001-47, B0656+14 (Monogem), J0538+2817, J1732-3131, J2043+2740, B1742-30. As we have discussed above, the anisotropy limits of Fermi-LAT disfavor significant contribution from Vela X in sub-TeV, so we do not include it here.

We still choose the Loop I (NPS) model, and replace Geminga with the ten PWNe, to fit the AMS-02 data. Spectral index and conversion efficiency of each PWN are set to be free, and the cut-off energy is fixed at 2 TeV for all the PWN members. Other parameters in the model remain unchanged as given in Table 2. In the new fitting, the $\eta$ of six PWNe converge to zero, which indicates the other four sources are enough to explain the AMS-02 data. We present the fitting result along with the information of these four PWNe in Table 3. The leptonic spectra of the multi-PWN model and the anisotropy of $e^+ + e^-$ are shown in Figure 9. We also draw the preliminary data of VERITAS in the $e^+ + e^-$ spectrum for comparison. The multi-PWN model indeed rise the $e^+ + e^-$ around 1 TeV compared with the original Loop I (NPS) model, and a congruity between VERITAS data and this model can be seen. Like the Loop I (NPS) model, the $e^+ + e^-$ anisotropy of this multi-PWN model is also under all the upper limits of Fermi-LAT. The difference is, the predicted anisotropy spectrum of the later is high enough to be detected by HERD, which can be seen in Figure 9.

The flux increase in $\sim$ 1 TeV owes much to the source J0940-5428 which has a significant contribution up to several TeV. J0940-5428 is a Vela-like pulsar due to its fast spinning, relatively young age, and large spin-down luminosity (Crawford & Tiffany 2007). The ATNF catalog now adopts the newest electron-density model provided by Yao et al. (2017) to measure distances of pulsars, which derives a much closer location of J0940-5428 of 0.38 kpc, compared with the old estimation of $\sim$ 4 kpc. This is crucial to update the status of J0940-5428 in the $e^+/e^-$ spectrum. However, we should note that we still have much less knowledge of J0940-5428 at present than
Figure 9. Same as Figure 2, but replace single PWN case with multi-PWN model. 'J0940', 'B1001', and 'J2043' are abbreviate to J0940-5428, B1001-47, and J2043+2740, respectively.

well-studied sources like Geminga. Researches have shown that J0940-5428 may not
be surrounded by an observable synchrotron nebula as the case of Vela X or Geminga (Wang et al. 2014).

4.2. Prospect to Possible Improvements

As mentioned above, the best way to investigate $e^+/e^-$ injection is to analyze the multi-wavelength data of $e^+/e^-$ sources. Although observations of electromagnetic emission only reflect the source parameters at present age, we may apply theoretical models of evolution of the source to constrain the injection parameters. This should be prior to simply ‘adjust’ the parameters of sources. Among our local SNR sample, Vela Jr. and RX J1713-3946 are covered best by multi-band observations. For traditionally important sources like Vela and Cygnus Loop, there may still be room for improvement.

The decision of spectral index of Vela YZ is crucial to its contribution. The radio spectral index of 0.735 is given by observation from 85.7 MHz to 2700 MHz. However, we should point out that in an environment of 30 $\mu$G, the synchrotron peak frequency corresponding to 10 GeV electron is $\sim$ 10 GHz, which is out of the range of radio observations above. Thus data of WMAP and Planck, which work in frequencies larger than 10 GHz, may help to give further estimation. In fact, Abdo et al. (2010) have already adopted the data of WMAP in their analyses of spectral energy distribution of Vela X. However, there is an obvious offset between the radio spectrum given by Alvarez et al. (2001) and WMAP measurement shown in Abdo et al. (2010). This difference need to be carefully studied, and the data of Plank may help to resolve this problem. Besides, the ROSAT all-sky survey provides a spatially resolved picture for the whole region of Vela in soft-Xray (Lu & Aschenbach 2000), which may further restrict the parameters of Vela YZ. For Cygnus Loop, it has been carefully studied by XMM-Newton and Suzaku (Uchida et al. 2009, and references therein), although for its sub-regions at present. A global spectrum in X-ray will give a clearer picture of the cut-off energy of electrons.

4.3. Dark Matter Origin of High-Energy $e^\pm$

Another promising explanation for the CR $e^\pm$ excess is the annihilation/decay of dark matter (DM) particles (Bergström et al. 2008; Yin et al. 2009; Zhang et al. 2009). Note that since the detectable CR positrons and electrons from DM are usually expected to be smoothly contributed from a small region within a few kpc around the Solar system, DM particles would not produce significant anisotropies. Moreover, the contributions of electrons and positrons are equal in usual DM models, while they may be quite different in astrophysical models. Therefore, the study
combining the anisotropy and spectrum results can be crucial to discriminate the different origins of high-energy electrons and positrons.

5. CONCLUSION

In this paper, we use the latest anisotropy result of Fermi-LAT to test local source models aimed to explain the leptonic data of AMS-02. Our results show that the anisotropy spectrum of Vela YZ model almost coincides with the upper limits given by Fermi-LAT. This means the result of Fermi-LAT disfavors Vela YZ as the dominant local SNR in sub-TeV region to some extent. The other two models, where Loop I (NPS) or Monogem Ring plays the role of the dominant local SNR, remain safe under the restriction of the Fermi-LAT data. Next generation instruments like HERD can provide cogent judgment to the Vela YZ model, or even distinguish the other two cases. It is should be pointed out that the SNR background has a considerable contribution to the anisotropy which is even larger than that of some discrete local sources like Geminga, so this component should not be neglected in the calculation.

The origin of CR electrons in the TeV region may become unambiguous compared with that in the sub-TeV region, since sources that provide significant contributions to the TeV scale are fewer. Combining with the energy spectra, and anisotropies measured by future facilities, we can get a clear picture of the origin of high energy electrons. We find that our models can produce large enough anisotropies to be detected by HERD. Meanwhile, some of these models are slightly disfavored by the anisotropy limit in the highest energy bin of Fermi-LAT. A smaller diffusion coefficient or a young and relatively distant source like Vela Jr. can relax such tension. Cancelation of anisotropies among several sources may also be a solution to avoid the constraint. Therefore, if the electron source can be ascertained in future, the diffusion coefficient of CR electrons and the electron injection age of the source may be determined subsequently, the later of which can hardly be determined by observations of electromagnetic radiations.

In summary, our study shows that combining the CR leptonic spectra and the $e^+ + e^-$ anisotropy is very powerful to probe the origin of high energy CR electrons. With large data accumulation in future instruments like HERD, the CR electron emission spectrum and even emission time can be well constrained. The study of high energy electrons may lead a profound influence on astrophysical researches like SNR theory, more than the origin of themselves.
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