View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Texas A&M Repository

# ATIC and PAMELA Results on Cosmic $e^{\pm}$ Excesses and Neutrino Masses

Xiao-Jun Bi[1],* Pei-Hong Gu[2],† Tianjun Li[3],‡ and Xinmin Zhang[4]§

[1] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 10049, China & Center for High Energy Physics, Peking University, Beijing 100871, P.R. China*

[2] *The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34014 Trieste, Italy*

[3] *Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, P. R. China, and George P. and Cynthia W. Mitchell Institute for Fundamental Physics, Texas A&M University, College Station, TX 77843, USA*

[4] *Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, P.R. China*

arXiv:0901.0176v2 [hep-ph] 2 Jun 2009

Recently the ATIC and PAMELA collaborations released their results which show the abundant $e^{\pm}$ excess in cosmic rays well above the background, but not for the $\bar{p}$. Their data if interpreted as the dark matter particles' annihilation imply that the new physics with the dark matter is closely related to the lepton sector. In this paper we study the possible connection of the new physics responsible for the cosmic $e^{\pm}$ excesses to the neutrino mass generation. We consider a class of models and do the detailed numerical calculations. We find that some models can account for the ATIC and PAMELA $e^{\pm}$ and $\bar{p}$ data and at the same time generate the small neutrino masses.

PACS numbers: 14.60.Pq, 95.35.+d [MIFP-08-35]

## A. Introduction

Recently the ATIC [1] and PPB-BETS [2] collaborations have reported the electron/positron spectrum measurement up to $\sim 1$ TeV, with an obvious bump above the background at $\sim 300-800\,\text{GeV}$ and $\sim 500-800\,\text{GeV}$, respectively. At the same time, the PAMELA collaboration also released their first cosmic-ray measurements on the positron fraction [3] and the $\bar{p}/p$ ratio [4]. The positron fraction shows the significant excesses above $10\,\text{GeV}$ up to $\sim 100\,\text{GeV}$, compared with the background predicted by the conventional cosmic-rays propagation model. This result is consistent with the previous measurements by HEAT [5] and AMS [6]. Clearly, the ATIC, PPB-BETS and PAMELA results indicate the existence of a new source of primary electrons and positrons while the hadronic processes are suppressed. It is well known that the annihilation of the dark matter (DM) can be a possible origin for the primary cosmic rays, which can account for the ATIC/PPB-BETS and PAMELA data simultaneously [7]. However, the $\bar{p}/p$ ratio gives strong constraint on the nature of dark matter particles. The widely discussed lightest neutralino in supersymmetric models as dark matter candidate may be difficult to explain the PAMELA data due to the constraints [7, 9]. These constraints may imply some special relations between the DM sector and leptons.

Another interesting topic related to the leptons is the neutrino mass-generation. In order to understand the small but nonzero neutrino masses, required by various neutrino oscillation experiments, we can consider the elegant seesaw [10] extension of the standard model (SM). The original seesaw scenario is realized by integrating out the heavy particles at tree level [10, 11]. As an alternative, one may consider the radiative seesaw models [12, 13, 14, 15] where the small neutrino masses are generated at loop level.

In this paper we connect the leptonic annihilation of the DM to the mass generation of the neutrinos. We find that in some radiative seesaw models the neutral Majorana or Dirac fermions as the DM can dominantly annihilate into the charged leptons and neutrinos. For proper choice of model parameters and boost factor, the leptonic annihilations of the DM can explain the electron/positron excesses observed by the ATIC/PPB-BETS and PAMELA cosmic-ray experiments. With small modifications, we might explain the INTEGRAL [16] experiment via the exciting DM [17]. In addition, we propose one kind of models with traditional seesaw mechanism [10]. These models can explain the ATIC/PPB-BETS and PAMELA cosmic-ray experiments similarly, and explain the INTEGRAL experiment as well.

## B. Effective Lagrangian

We start with our discussions with an effective Lagrangian

$$\mathcal{L} \supset -y_\ell \overline{\ell^-_{L,R}} \eta^- \chi + \text{H.c.}\,, \tag{1}$$

where $\ell = e, \mu, \tau$ are the charged leptons, $\eta^{\pm}$ is a scalar carrying the same charge as $\ell^{\pm}$, $\chi$ denotes a neutral fermion. We further assume $\eta^{\pm}$ and $\chi$ to have no other Yukawa couplings with the SM particles. Therefore, in case of $m_\chi < m_{\eta^\pm}$, $\chi$ can dominantly annihilate into the

*Electronic address: bixj@ihep.ac.cn
†Electronic address: pgu@ictp.it
‡Electronic address: tli@itp.ac.cn
§Electronic address: xmzhang@ihep.ac.cn

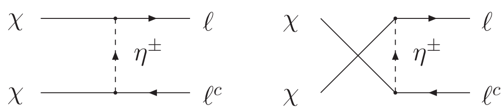


FIG. 1: The annihilations of the Majorana $\chi$ into the charged leptons through the exchange of $\eta^{\pm}$.

charged leptons since the loop-order annihilations of $\chi$ into quarks and/or photon are highly suppressed. Fig. 1 shows the annihilations of the Majorana $\chi$ into the charged leptons while Fig. 2 is for the Dirac $\chi$.

The cross sections of $\chi$ annihilating into the charged leptons are given by

$$
\begin{aligned}
\sigma_{\alpha\beta} v &\equiv \sigma_{\chi\chi\rightarrow \ell_\alpha \ell_\beta^c} v \\
&= \frac{1}{32\pi}|y_\alpha|^2|y_\beta|^2 \frac{1}{s\sqrt{s\left(s-4m_\chi^2\right)}}\left\{\sqrt{s\left(s-4m_\chi^2\right)}\right. \\
&\quad + \left[2\left(m_{\eta^\pm}^2 - m_\chi^2\right) + \frac{2m_\chi^2 s}{s+2m_{\eta^\pm}^2-2m_\chi^2}\right]\ln\left|\frac{s+2m_{\eta^\pm}^2-2m_\chi^2-\sqrt{s\left(s-4m_\chi^2\right)}}{s+2m_{\eta^\pm}^2-2m_\chi^2+\sqrt{s\left(s-4m_\chi^2\right)}}\right| \\
&\quad \left. +2\left(m_{\eta^\pm}^2 - m_\chi^2\right)^2\left[\frac{1}{s+2m_{\eta^\pm}^2-2m_\chi^2-\sqrt{s\left(s-4m_\chi^2\right)}} - \frac{1}{s+2m_{\eta^\pm}^2-2m_\chi^2+\sqrt{s\left(s-4m_\chi^2\right)}}\right]\right\},
\end{aligned}
\tag{2a}
$$

$$
\begin{aligned}
\sigma_{\alpha\beta} v &\equiv \sigma_{\chi\chi^c\rightarrow \ell_\alpha \ell_\beta^c} v \\
&= \frac{1}{32\pi}|y_\alpha|^2|y_\beta|^2 \frac{1}{s\sqrt{s\left(s-4m_\chi^2\right)}}\left\{\sqrt{s\left(s-4m_\chi^2\right)}\right. \\
&\quad +2\left(m_{\eta^\pm}^2 - m_\chi^2\right)\ln\left|\frac{s+2m_{\eta^\pm}^2-2m_\chi^2-\sqrt{s\left(s-4m_\chi^2\right)}}{s+2m_{\eta^\pm}^2-2m_\chi^2+\sqrt{s\left(s-4m_\chi^2\right)}}\right| \\
&\quad \left. +2\left(m_{\eta^\pm}^2 - m_\chi^2\right)^2\left[\frac{1}{s+2m_{\eta^\pm}^2-2m_\chi^2-\sqrt{s\left(s-4m_\chi^2\right)}} - \frac{1}{s+2m_{\eta^\pm}^2-2m_\chi^2+\sqrt{s\left(s-4m_\chi^2\right)}}\right]\right\},
\end{aligned}
\tag{2b}
$$

where $\chi$ is a Majorana or Dirac particle, respectively. Here $v$ is the relative velocity between the two annihilating particles in their cms system. Up to $\mathcal{O}(v^2)$, the cross sections (2a) and (2b) can be respectively simplified as

$$
\sigma_{\alpha\beta} v \simeq \frac{1}{128\pi}|y_\alpha|^2|y_\beta|^2\frac{1}{(2+r)^2}v^2\frac{1}{m_\chi^2} \quad \text{in Majorana case}\,, \tag{3a}
$$

$$
\sigma_{\alpha\beta} v \simeq \frac{1}{128\pi}|y_\alpha|^2|y_\beta|^2\left\{\frac{4}{(2+r)^2}+\left[\frac{1}{(2+r)^2}-\frac{4}{(2+r)^3}\right]v^2\right\}\frac{1}{m_\chi^2} \quad \text{in Dirac case}\,, \tag{3b}
$$

with the definition,

$$
r \equiv \frac{m_{\eta^\pm}^2 - m_\chi^2}{m_\chi^2} > 0\,. \tag{4}
$$

By inputting $v \sim 10^{-3}$ (the average velocity in our galaxy) and $r = 0$, we further derive

$$\langle\sigma_{\alpha\beta}v\rangle \lesssim 1.5\times10^{-32}\,\text{cm}^3\text{sec}^{-1}\left(\frac{700\,\text{GeV}}{m_\chi}\right)^2|y_\alpha|^2|y_\beta|^2 \quad \text{in Majorana case}\,, \tag{5a}$$

$$\langle\sigma_{\alpha\beta}v\rangle \lesssim 5.9\times10^{-26}\,\text{cm}^3\text{sec}^{-1}\left(\frac{700\,\text{GeV}}{m_\chi}\right)^2|y_\alpha|^2|y_\beta|^2 \quad \text{in Dirac case}\,, \tag{5b}$$

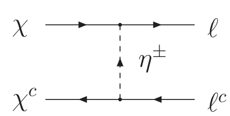


FIG. 2: The annihilations of the Dirac $\chi$ into the charged leptons through the exchange of $\eta^\pm$.

where $y_{e,\mu,\tau}$ should be smaller than $\sqrt{4\pi}$ for a perturbative theory.

In the following, we will embed the effective Lagrangian Eq. (1) into some radiative seesaw models where the tiny neutrino masses arise from loop contributions. And we can embed the effective Lagrangian Eq. (1) into the models with traditional seesaw mechanism as well. For our convention, we denote the SM lepton doublets, right-handed leptons and Higgs doublet as $\psi_{L_\alpha}(\mathbf{2},-\frac{1}{2}) = \left(\nu_{L_\alpha},\ell^-_{L_\alpha}\right)^T$, $e_{R_\alpha}(\mathbf{1},-1)$ and $\phi(\mathbf{2},-\frac{1}{2}) = (\phi^0,\phi^-)^T$, respectively, where their $SU(2)_L\times U(1)_Y$ quantum numbers are given as well.

### C. Model I with Majorana Neutrino Masses and Mixings from Radiative Corrections

We consider a Majorana radiative seesaw model [12, 13] where one introduces three right-handed neutrinos $\chi_{R_i}$ and a SM scalar doublet $\eta$ with $SU(2)_L\times U(1)_Y$ quantum numbers $(\mathbf{2},-\frac{1}{2})$. In this model, $\chi_{R_i}$ and $\eta$ are odd under a $\mathbf{Z}_2$ symmetry, while the SM fields carry even parity. Respect to this $\mathbf{Z}_2$, the scalar doublet $\eta$ will not develop nonzero vacuum expectation value (VEV). Therefore, as shown in Fig. 3, the neutrino masses can

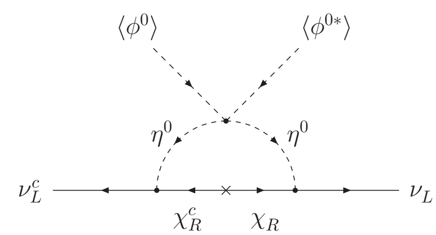


FIG. 3: The loop diagram for generating small masses of Majorana neutrinos.

be radiatively generated through the following Yukawa couplings, the Majorana mass term of the right-handed neutrinos, and the quartic interaction of scalars

$$-\mathcal{L} \supset \frac{1}{2}m_{\chi_i}\overline{\chi^c_{R_i}}\chi_{R_i} + y_{\alpha i}\overline{\psi_{L_\alpha}}\eta\chi_{R_i} + \lambda(\phi^\dagger\eta)^2 + \text{H.c.}\,. \tag{6}$$

Here we have conveniently chosen the base, in which the Majorana mass matrix of the right-handed neutrinos is diagonal and real, i.e. $m_\chi = \text{Diag}\{m_{\chi_1}, m_{\chi_2}, m_{\chi_3}\}$. Obviously, the above Lagrangian in Eq. (6) can induce the effective theory in Eq. (1). If the lightest $\chi$ is lighter than $\eta_R = \frac{1}{\sqrt{2}}\text{Re}(\eta^0)$, $\eta_I = \frac{1}{\sqrt{2}}\text{Im}(\eta^0)$ and $\eta^\pm$, it will have no decay modes and will dominantly annihilate into the charged leptons and the neutrinos. The total cross section of the lightest $\chi$ into the charged leptons and neutrinos is given by

$$\langle\sigma v\rangle \lesssim 3.0\times10^{-32}\,\text{cm}^3\text{sec}^{-1}\left(\frac{700\,\text{GeV}}{m_\chi}\right)^2\left[(y^\dagger y)_{ii}\right]^2\,. \tag{7}$$

Here $m^2_{\eta^0_R} \simeq m^2_{\eta^0_I} \simeq m^2_{\eta^\pm}$ has been adopted since we are interested in the case where the Yukawa couplings $y_{\alpha i}$ are large enough for a desired cross section and the quartic coupling $\lambda$ is small enough to guarantee the smallness of neutrino masses.

Because the two light right-handed neutrinos $\chi_1$ and $\chi_2$ can be degenerate, we might explain the INTEGRAL [16] experiment via the exciting DM [17]. To explain the INTEGRAL experiment by producing $\chi_2$ via the channel $\chi_1\chi_1 \to \chi_1\chi_2$ through the tree-level and ladder diagrams [17], we introduce a SM singlet $S$ that is $\mathbf{Z}_2$ even.

The discussions are similar to the following subsection **D** except that we will have additional terms in the Lagrangian in addition to that in Eq. (14)

$$-\mathcal{L} = \frac{1}{2}\mu^2 S^2 + \frac{1}{3!}A_1 S^3 + \frac{1}{4!}\lambda' S^4 + \frac{\lambda_9}{2}A_2 S(\eta^\dagger\eta) + \frac{\lambda_{10}}{2}A_3 S(\phi^\dagger\phi) + \text{H.c.} , \quad (8)$$

where $A_i$ are mass dimension-one parameters. In short, this approach needs some fine-tuning.

To avoid the fine-tuning, we can consider the large discrete symmetry $\Gamma$ in the dark matter sector, for example $Z_4$ in Ref. [17], or as discussed in subsection **D**. Note that the Majorana masses for the right-handed neutrinos are forbidden by $\Gamma$ since it is not $\mathbf{Z}_2$. We will need two SM singlet Higgs fields: one generates the large Majorana masses, while the other generates the small mass splitting around 1 MeV and has Yukawa coupling about 0.18 or larger to the DM and exciting DM fields so that we can produce $\chi_2$ [17]. Because this kind of model is similar to the models in the following subsection **C**, we will not study it in detail here.

### D. Model II with Dirac Neutrino Masses and Mixings from Radiative Corrections

Let us consider a Dirac radiative seesaw model [14] by extending the SM with a SM scalar doublet $\eta(\mathbf{2}, -\frac{1}{2})$, a complex scalar $\xi(\mathbf{1}, 0)$, a real scalar $\sigma(\mathbf{1}, 0)$, three right-handed neutrinos $\nu_{R_\alpha}(\mathbf{1}, 0)$ and three Dirac fermions $\chi_{L_i,R_i}(\mathbf{1}, 0)$. In this model, there is a $U(1)_D$ gauge symmetry under which $\xi$, $\nu^c_{R_\alpha}$ and $\chi_{R_i}$ carry the quantum number $\mathbf{1}$. In addition, $\eta$, $\sigma$ and $\chi_{L_i,R_i}$ are odd while all of other fields are even under a $Z_2$ symmetry. Moreover, $\nu_{R_\alpha}$ and $\chi^c_{L_i,R_i}$ are arranged for the same lepton number with the SM leptons. Conserving the $U(1)_D$, $Z_2$ and lepton number, we can write down the following interactions

$$-\mathcal{L} \supset y_{\alpha i}\overline{\psi_{L_\alpha}}\eta\chi^c_{L_i} + h_{\alpha i}\sigma\overline{\nu_{R_\alpha}}\chi^c_{R_i} + f_{ij}\xi\overline{\chi_{R_i}}\chi_{L_j} + \mu\sigma\eta^\dagger\phi + \text{H.c.} . \quad (9)$$

Since $\eta^0$ and $\sigma$ are forbidden to develop the nonzero VEVs as a result of the $\mathbf{Z}_2$ protection, the neutrinos can only obtain their small Dirac masses via the one-loop diagram, as shown in Fig. 4. It is straightforward to see the effective Lagrangian in Eq. (1) can be embedded into this Dirac radiative seesaw model. Note there exists a mixing between $\xi$ and $\phi^0$, which will lead to the co-annihilation of the dark matter into the quarks. But $\langle\xi\rangle$ should be about one order larger than $\langle\phi^0\rangle$ for giving the dark matter a mass close to the TeV scale. So, the $\xi - \phi^0$ mixing, of the order of $O(\langle\phi^0\rangle/\langle\xi\rangle) \sim 0.1$, could have no significant implications. For convenience and without loss of generality, we, in the following, shall choose the basis in which the Dirac mass matrix of the singlet fermions is diagonal and real, i.e. $m_\chi = f\langle\xi\rangle = \text{Diag}\{m_{\chi_1}, m_{\chi_2}, m_{\chi_3}\}$. Similar to that in the Majorana radiative seesaw model, here the lightest $\chi$ can also dominantly annihilate into the charged leptons and the neutrinos if it is lighter than $\eta_I = \frac{1}{\sqrt{2}}\text{Im}(\eta^0)$, $\eta^\pm$ and the other two physical states $\rho_{1,2}$ (combinations of $\eta_R = \frac{1}{\sqrt{2}}\text{Re}(\eta^0)$ and $\sigma$). The total cross section of this lightest $\chi$ into the charged leptons and neutrinos is given by

$$\langle\sigma v\rangle \lesssim 5.9\times 10^{-26}\,\text{cm}^3\text{sec}^{-1}\left(\frac{700\,\text{GeV}}{m_\chi}\right)^2 \times\left\{\left[\text{Tr}(h^\dagger h)_{ii}\right]^2 + 2\left[\text{Tr}(y^\dagger y)_{ii}\right]^2\right\} . \quad (10)$$

Here $m^2_{\rho_1} \simeq m^2_{\rho_2} \simeq m^2_{\eta^0_I} \simeq m^2_{\eta^\pm}$ has been adopted by taking small trilinear coupling $\mu$. This is consistent with our scope for large Yukawa couplings $y_{\alpha i}$ and $h_{\alpha i}$ and then a desired cross section.

Naively, we may guess that we do not need to introduce another SM singlet Higgs field $\xi'$ to explain the INTEGRAL experiment. However, the Dirac masses for $\chi^i_{LR}$ are generated from the terms $f_{ij}\xi\overline{\chi^i_R}\chi^j_L$, and we need two degenerate Dirac fermions $\chi'^i_{LR}$ in the mass basis. Because the masses for dark matter fields is about 600-800 GeV and the mass splitting for the two light Dirac fermions is about a few MeVs, we obtain that the Yukawa coupling constants for $\xi\chi'^1_L\chi'^2_R$ and $\xi\chi'^2_L\chi'^1_R$ are about $10^{-5}$ unless we fine-tune the coefficients $f_{ij}$. Thus, it is difficult to generate $\chi'^2_{LR}$ through the tree-level and ladder diagrams, and then explain the INTEGRAL experiment [17]. Therefore, we introduce another SM singlet Higgs field $\xi'$ with VEV about 10 MeV. $\xi'$ has $U(1)_D$ charge $+\mathbf{1}$ and is $\mathbf{Z}_2$ even. The additional Lagrangian is

$$\begin{aligned}-\mathcal{L} = {} & \frac{1}{2}m^2_{\xi'}\xi'^\dagger\xi' + \frac{\lambda'_1}{4}(\xi'^\dagger\xi')^2 + \frac{\lambda'_2}{2}(\xi'^\dagger\xi')(\eta^\dagger\eta) \\ & + \frac{\lambda'_3}{4}\sigma^2(\xi'^\dagger\xi') + \frac{\lambda'_4}{2}(\xi'^\dagger\xi')(\xi^\dagger\xi) + \frac{\lambda'_5}{2}(\xi'^\dagger\xi')(\phi^\dagger\phi) \\ & + \Big( f'_{ij}\xi'\overline{\chi^i_R}\chi^j_L + \tilde{m}^2\xi^\dagger\xi' + \frac{\lambda'_6}{2}(\xi^\dagger\xi')^2 \\ & + \frac{\lambda'_7}{2}(\xi^\dagger\xi')(\xi'^\dagger\xi') + \frac{\lambda'_8}{2}(\xi^\dagger\xi')(\xi^\dagger\xi) \\ & + \frac{\lambda'_9}{2}(\xi^\dagger\xi')(\eta^\dagger\eta) + \frac{\lambda'_{10}}{4}\sigma^2(\xi^\dagger\xi') \\ & + \frac{\lambda'_{11}}{2}(\xi^\dagger\xi')(\phi^\dagger\phi) + \text{H.c.}\Big) . \quad (11)\end{aligned}$$

To explain the INTEGRAL experiment, we need $f'_{ij}$ to be about 0.18 or larger [17].

### E. Model III with Neutrino Masses and Mixings from Traditional Seesaw Mechanism

We consider the generalized Standard Model with two or three heavy right-handed neutrinos. The neutrino masses and mixings are generated via the traditional seesaw mechanism, and the observed baryon asymmetry is explained via leptogensis.

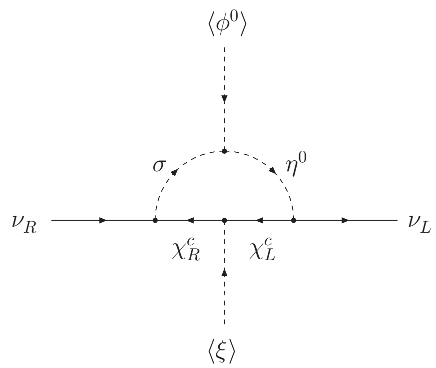


FIG. 4: The loop diagram for generating small masses of Dirac neutrinos.

First, we consider the model that can only explain the ATIC and PAMELA experiments. We introduce dark matter sector that has a SM singlet scalar field $\widetilde{E}$ with $SU(2)_L \times U(1)_Y$ quantum numbers $(\mathbf{1}, -\mathbf{1})$ and a Majorana fermion $\chi$. To have a stable dark matter candidate $\chi$, we consider the $\mathbf{Z}_2$ symmetry under which only $\widetilde{E}$ and $\chi$ are odd. The renormalizable Lagrangian for the dark sector and its interaction with the SM is

$$-\mathcal{L} = \frac{1}{2}m_\chi \overline{\chi^c}\chi + \frac{1}{2}m_E^2 \widetilde{E}^\dagger \widetilde{E} + \frac{\lambda_1}{4}(\widetilde{E}^\dagger \widetilde{E})^2 + \frac{\lambda_2}{2}(\widetilde{E}^\dagger \widetilde{E})(\phi^\dagger \phi) + \left(y_e^i \overline{e_R^i}\widetilde{E}\chi + \text{H.c.}\right) , \quad (12)$$

where $m_\chi$ and $m_E$ are mass terms, and $\lambda_i$ and $y_e^i$ are Yukawa couplings. Also, $\lambda_1$ and $\lambda_2$ are real, while $y_e^i$ can be complex and then violate CP symmetry. To have $\chi$ as a dark matter, we require that $m_\chi < m_E$.

Second, we can generalize the dark matter sector in the above model to explain the INTEGRAL experiment. In the dark matter sector, in addition to $\widetilde{E}$ as above, we introduce a SM singlet scalar field $S$, and two Majorana particles $\chi_1$ and $\chi_2$ respectively with left and right chiralities [17]. And the discrere symmetry in the dark matter sector is $\mathbf{Z}_4$. Under $\mathbf{Z}_4$, the fields in the dark matter sector transform as follows

$$\chi_{1,2} \to e^{\pm i\pi/2}\chi_{1,2} \ , \ \widetilde{E} \to e^{-i\pi/2}\widetilde{E} \ , \ S \to -S \ . \quad (13)$$

The renormalizable Lagrangian is

$$\begin{aligned} -\mathcal{L} = {} & m_D \overline{\chi_1^c}\chi_2 + \frac{1}{2}m_E^2 \widetilde{E}^\dagger \widetilde{E} + \frac{1}{2}m_S^2 S^\dagger S + \frac{\lambda_1}{4}(\widetilde{E}^\dagger \widetilde{E})^2 \\ & + \frac{\lambda_2}{4}(S^\dagger S)^2 + \frac{\lambda_3}{2}(S^\dagger S)(\widetilde{E}^\dagger \widetilde{E}) \\ & + \frac{\lambda_4}{2}(\widetilde{E}^\dagger \widetilde{E})(\phi^\dagger \phi) + \frac{\lambda_5}{2}(S^\dagger S)(\phi^\dagger \phi) \\ & + \Big( y_e^i \overline{e_R^i}\widetilde{E}^\dagger \chi_1 + y_1 S \overline{\chi_1^c}\chi_1 + y_2 S \overline{\chi_2^c}\chi_2 \\ & + \frac{\lambda_6}{2}S^2(\widetilde{E}^\dagger \widetilde{E}) + \frac{\lambda_7}{2}S^2(\phi^\dagger \phi) + \text{H.c.}\Big) \ . \end{aligned} \quad (14)$$

In the basis $\chi, \chi_* = 1/\sqrt{2}(\chi_1 \mp \chi_2)$, the mass matrix for $\chi$'s is

$$M = \begin{pmatrix} y_+ S - m_D & y_- S \\ y_- S & y_+ S + m_D \end{pmatrix} \ , \quad (15)$$

where $y_\pm = \frac{1}{2}(y_1 \pm y_2)$. Thus, at the leading order, the Dirac fermion can be decomposed as two degenerate Majorana fermions $\chi$ and $\chi^*$. If the $\mathbf{Z}_4$ symmetry is broken weakly to $\mathbf{Z}_2$ by giving $S$ a VEV, we expect these states to be split by a small amount $\delta = 2y_+\langle S\rangle$. Suppose $m_S^2 < 0$, we obtain that $\langle S^2\rangle = -m_S^2/\lambda_2$, and the mass splitting is then just $\delta = y_+|m_S|/\sqrt{\lambda_2}$ [17]. To explain the INTEGRAL experiment, the mass splitting is about a few MEV. Note that the couplings $y_\pm$ can be as small as around 0.18, and then the VEV of $S$ should be around 10 MeV. Thus, the mixing between the Higgs field $\phi^0$ and $S$ is very small from $\lambda_5$ term, and then the anti-protons from the $\chi\chi$ annihilation are highly suppressed.

Interestingly, this kind of models can be naturally embedded into the supersymmetric flipped $SU(5) \times U(1)_X$ models [18] and the string or F-theory derived flipped $SU(5) \times U(1)_X$ models [19]. An important difference of this kind of models from the other two models is that it predicts no neutrino signals from DM annihilation. The models I and II give large neutrino fluxes as well as the positron flux. Detecting neutrino fluxes from the Galactic Center may discriminate these models.

### F. Phenomenology

In this part we study the dark matter models given above in detail to explain the ATIC and PAMELA data. The propagation of charged particles in the Galaxy is calculated numerically in order to compare with data measured at the Earth. The charged particles propagate diffusively in the Galaxy due to the scattering with random magnetic field [20]. The interactions with interstellar medium will lead to energy losses of the primary electrons and positrons. In addition, the overall convection driven by the Galactic wind and reacceleration due to the interstellar shock will also affect the distribution and spectrum of electrons. The propagation equation can be written as [21]

$$\frac{\partial \psi}{\partial t} = Q(\mathbf{r}, p) \ + \ \nabla \cdot (D_{xx}\nabla\psi - \mathbf{V_c}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \ \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla \cdot \mathbf{V_c}\psi)\right] \ , \quad (16)$$

where $\psi$ is the number density of cosmic ray particles per unit momentum interval, $Q(\mathbf{r}, p)$ is the source term, discribing the primary particles injected into the interstellar meadium, $D_{xx}$ is the spatial diffusion coefficient, $\mathbf{V_c}$ is the convection velocity, $D_{pp}$ is the diffusion coefficient in momentum space used to describe the reacceleration process, $\dot{p} \equiv \mathrm{d}p/\mathrm{d}t$ is the momentum loss rate, mainly induced by synchrotron radiation and inverse Compon scattering. In the work we solve Eq. (16) numerically adopting the GALPROP package [22].

For DM annihilation, the source term of electrons and positrons have the form

$$Q_A(\mathbf{r}, E) = BF \frac{< \sigma v >_A \rho^2(r)}{2\, m_{DM}^2} \frac{dN(E)}{dE} \quad , \tag{17}$$

where, BF is the boost factor, $< \sigma v >_A$ is the DM annihilation cross section, $m_{DM}$ is the mass of DM particle, and $\frac{dN(E)}{dE}$ is the electron/positron spectrum from one pair of DM annihilation, $\rho(r)$ is DM density distribution in the Galaxy. In this work, we adopt the NFW profile [23] for DM distribution with the local DM density $\rho_\odot = 0.3\,\text{GeV/cm}^3$.

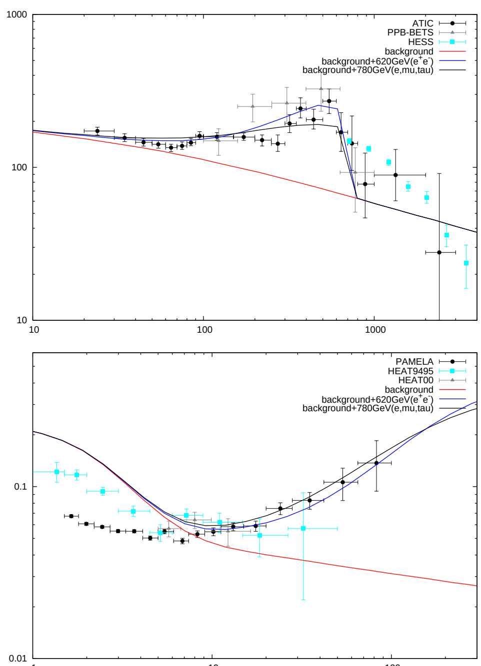


FIG. 5: Top: Electron/positron spectrum including contribution from DM annihilation compared with the ATIC/PPB-BETS data; Bottom: $e^+/(e^- + e^+)$ including contribution from DM annihilation as function of energy compared with the PAMELA and HEAT data. Two models are considered: in one model DM mass is 620 GeV with $e^+e^-$ being the main annihilation channel, while in the other model DM mass is 780 GeV with equal branching ratio into $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$.

In Fig. 5 we show our results compared with the ATIC/PPB-BETS and PAMELA/HEAT data. Two models are adopted to account for the data. In one model we assume the dark matter mass 620 GeV and dark matter annihilates into electron/positron pairs dominantly. In the other model we take the DM mass as 780 GeV and assume DM annihilates into $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ with equal branching ratios. We can see that both models can give good fit to the data. The value $BF < \sigma v >$ is taken as $7.2 \times 10^{-24}\,\text{cm}^3\text{s}^{-1}$ and $1.8 \times 10^{-23}\,\text{cm}^3\text{s}^{-1}$ respectively for the two models, corresponding to the boost factor 240 and 600 respectively if we assume DM produced thermally with natural value $< \sigma v >= 3 \times 10^{-26}\,\text{cm}^3\text{s}^{-1}$. In order to explain the ATIC/PPB-BETS and PAMELA/HEAT data we consider the scenario where the DM is produced by some nonthermal mechanism [24]. According to Eqs. (5a) and (5b) with the Yukawa couplings $y_{\alpha,\beta} < \sqrt{4\pi}$, we can see that: (i) for the Majorana fermion as dark matter, the required boost factor should be larger than $\mathcal{O}(10^7)$, which is in lack of reasonable explanation; (ii) for the Dirac fermion as dark matter, the boost factor can be absent or can be as small as $\mathcal{O}(10)$, which may be due to the clumps of DM distribution [25].

## G. Summary

The recent observations by ATIC/PPB-BETS and PAMELA imply that DM should dominantly annihilate into the leptons. This phenomenon inspires us to connect the leptonic annihilation of the DM with other leptonic processes, such as the neutrino mass-generation. In some radiative seesaw models, where the neutrinos obtain their small Majorana or Dirac masses at one-loop order, DM can naturally have dominant channel annihilating into the leptons. We show that the Dirac radiative seesaw model can account for the observed electron/positron excesses even if we don't introduce large boost factor. However, the Majorana case is strongly disfavored due to a unreasonably large boost factor to account for the PAMELA/ATIC data. With small modifications, we might explain the INTEGRAL experiment via the exciting DM. Furthermore, we constructed one kind of models with traditional seesaw mechanism. These models can not only explain the ATIC/PPB-BETS and PAMELA cosmic-ray experiments similarly, but also explain the INTEGRAL experiment.

## Acknowledgments

This work was supported in part by the Natural Sciences Foundation of China (Nos. 10575111, 10773011, 10821504, 90303004, 10533010, 10675136), by the Chinese Academy of Sciences under the grant No. KJCX3-SYW-N2, and by the Cambridge-Mitchell Collaboration in Theoretical Cosmology.

[1] J. Chang *et al.*, Nature **456**, 362 (2008).

[2] S. Torii, *et al.*, arXiv:0809.0760 [astro-ph].

[3] O. Adriani *et al.*, arXiv:0810.4995 [astro-ph].

[4] O. Adriani *et al.*, arXiv:0810.4994 [astro-ph].

[5] S.W. Barwick *et al.* [HEAT Collaboration], Astrophys. J. **482**, L191 (1997).

[6] M. Aguilar *et al.* [AMS-01 Collaboration], Phys. Lett. B **646**, 145 (2007).

[7] M. Cirelli, M. Kadastik, M. Raidal and A. Strumia, arXiv:0809.2409 [hep-ph]; N. Arkani-Hamed, D. P. Finkbeiner, T. Slatyer and N. Weiner, arXiv:0810.0713 [hep-ph]; I. Cholis, D. P. Finkbeiner, L. Goodenough and N. Weiner, arXiv:0810.5344 [astro-ph]. P.F. Yin, Q. Yuan, J. Liu, J. Zhang, X.J. Bi, S.H. Zhu, X.M. Zhang, arXiv:0811.0176;

[8] S. Baek and P. Ko, arXiv:0811.1646 [hep-ph]; K. Ishiwata, S. Matsumoto and T. Moroi, arXiv:0811.0250 [hep-ph]; P. J. Fox and E. Poppitz, arXiv:0811.0399 [hep-ph]; C. R. Chen, F. Takahashi and T. T. Yanagida, arXiv:0811.0477 [hep-ph]; K. Hamaguchi, E. Nakamura, S. Shirai and T. T. Yanagida, arXiv:0811.0737 [hep-ph]; A. Ibarra and D. Tran, arXiv:0811.1555 [hep-ph]; J. Zhang , X.J. Bi, J. Liu, S.M. Liu, P.F. Yin, Q. Yuan, S.H. Zhu, arXiv:0812.0522.

[9] F. Donato, D. Maurin, P. Brun, T. Delahaye, P. Salati, e-Print: arXiv:0810.5292 [astro-ph].

[10] P. Minkowski, Phys. Lett. **67B**, 421 (1977); T. Yanagida, in *Proc. of the Workshop on Unified Theory and the Baryon Number of the Universe*, ed. O. Sawada and A. Sugamoto (KEK, Tsukuba, 1979), p. 95; M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, ed. F. van Nieuwenhuizen and D. Freedman (North Holland, Amsterdam, 1979), p. 315; S.L. Glashow, in *Quarks and Leptons*, ed. M. Lévy *et al.* (Plenum, New York, 1980), p. 707; R.N. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980).

[11] M. Magg and C. Wetterich, Phys. Lett. B **94**, 61 (1980); J. Schechter and J.W.F. Valle, Phys. Rev. D **22**, 2227 (1980); T.P. Cheng and L.F. Li, Phys. Rev. D **22**, 2860 (1980); G. Lazarides, Q. Shafi, and C. Wetterich, Nucl. Phys. B **181**, 287 (1981); R.N. Mohapatra and G. Senjanović, Phys. Rev. D **23**, 165 (1981).

[12] E. Ma, Phys. Rev. Lett. **81**, 1171 (1998); and references therein.

[13] E. Ma, Phys. Rev. D 73, 077301 (2006); J. Kubo, E. Ma, D. Suematsu, Phys. Lett. B **642**, 18 (2006).

[14] P.H. Gu and U. Sarkar, Phys. Rev. D **77**, 105031 (2008).

[15] P.H. Gu and U. Sarkar, Phys. Rev. D **78**, 073012 (2008).

[16] E. Churazov, R. Sunyaev, S. Sazonov, M. Revnivtsev and D. Varshalovich, Mon. Not. Roy. Astron. Soc. **357**, 1377 (2005); G. Weidenspointner *et al.*, arXiv:astro-ph/0601673; G. Weidenspointner *et al.*, arXiv:astro-ph/0702621.

[17] D. P. Finkbeiner and N. Weiner, Phys. Rev. D **76**, 083519 (2007).

[18] K. J. Bae, J. H. Huh, J. E. Kim, B. Kyae and R. D. Viollier, arXiv:0812.3511 [hep-ph].

[19] J. Jiang, T. Li, D. V. Nanopoulos and D. Xie, arXiv:0811.2807 [hep-th].

[20] T.K. Gaisser, *Cambridge, UK: Univ. Pr. (1990) 279 p*

[21] A.W. Strong and I. V. Moskalenko, Astrophys. J. **509**, 212 (1998). [arXiv:astro-ph/9807150].

[22] http://galprop.stanford.edu/

[23] J.F. Navarro, C.S. Frenk, S.D.M. White, Astrophys. J. **490**, 493 (1997).

[24] W.B. Lin, D.H. Huang, X. Zhang, R.H. Brandenberger, Phys. Rev. Lett. **86**, 954 (2001); R. Jeannerot, X. Zhang and R. Brandenberger, JHEP 9912, 003 (1999).

[25] Q. Yuan, X.J. Bi, JCAP 0705, 001 (2007); J. Lavalle, Q. Yuan, D. Maurin, X.-J. Bi A&A **479**, 427 (2008).