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Fermi / PAMELA / ATIC anomaly from decaying leptonic Dark Matter

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Abstract

- We demonstrate that an economical two Higgs doublet model can explain the electron and positron excesses in the recent Fermi, PAMELA and ATIC experiments by the three body decays of the dark matter (DM) fermions without requiring the fine turning of the couplings and degeneracy of masses. We also show that the mass and lifetime of the decaying DM particle may not be fixed to be around 1 TeV and 10^26 sec, respectively.

Outline

- Fermi / PAMELA / ATIC cosmic rays excesses
- FPA anomaly from three-body decays
- FPA anomaly, neutrino masses and LG
- Conclusion

Fermi / PAMELA / ATIC cosmic rays excesses

- Fermi: arXiv:0905.0025 [astro-ph.HE]
- PAMELA: *Nature* **458** (2009) 607
- ATIC: *Nature* **456** (2008) 362

FPA data

NATURE | Vol 458 | 2 April 2009

arXiv:0905.0025v1 [astro-ph.HE] 30 Apr 2009

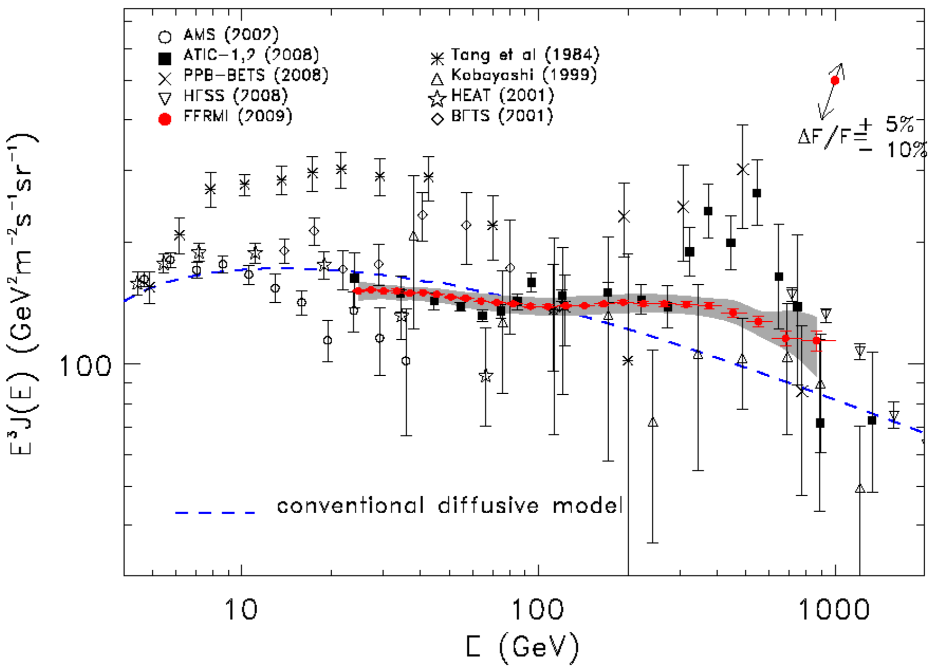

FIG. 3: (color) The Fermi LAT CR electron spectrum (red filled circles). Systematic errors are shown by the gray band. The two-headed arrow in the top-right corner of the figure gives size and direction of the rigid shift of the spectrum implied by a shift of $^{+5\%}_{-10\%}$ of the absolute energy, corresponding to the present estimate of the uncertainty of the LAT energy

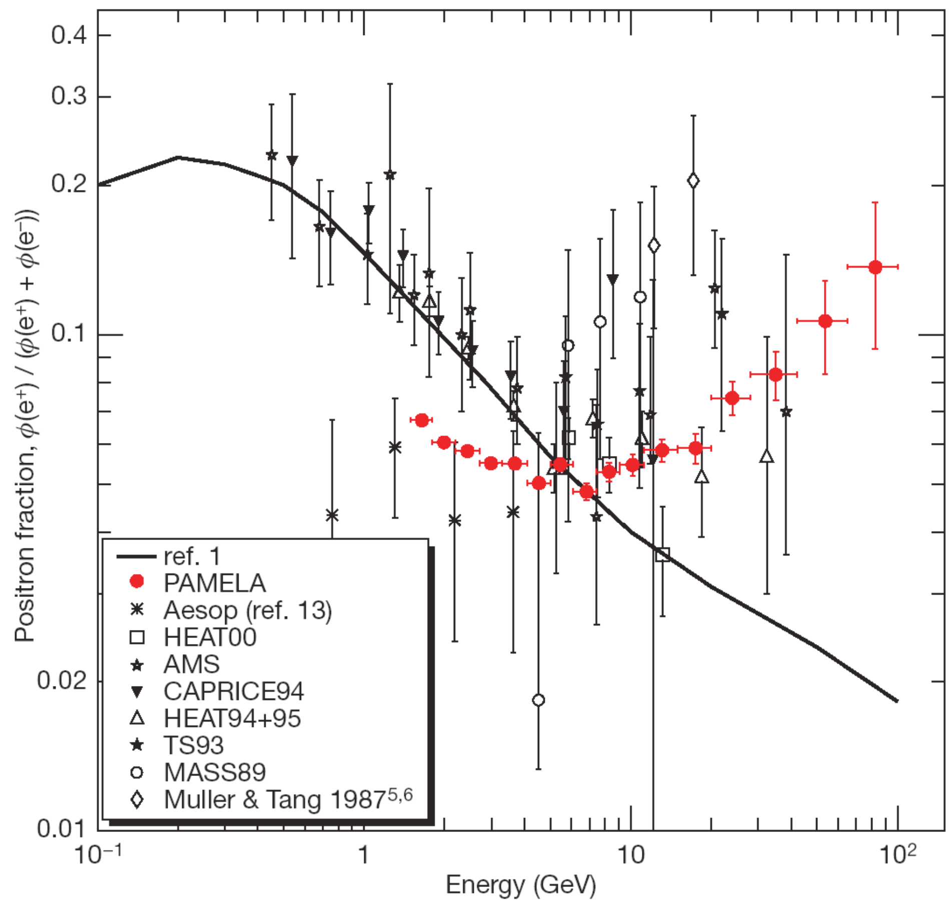

Figure 2 | PAMELA positron fraction with other experimental data and with secondary production model. The positron fraction measured by the PAMELA experiment compared with other recent experimental data (see refs 5–7, 11–13, 30, and references within). The solid line shows a calculation[1] for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without reacceleration processes. Error bars show 1 s.d.; if not visible, they lie inside the data points.

Possible explanations of FPA anomaly

Astrophysics: nearby pulsars or microquasars etc.

Particle physics:

DM decay

- $M \gtrsim 1$ TeV
- $\tau \lesssim 10^{26}$ s

DM annihilation

- 0.5 TeV < M < 1 TeV
- $<\sigma v> \sim 10^{-26}\ \mathrm{cm^3 s^{-1}} \sim 10^{-9}\ \mathrm{GeV^{-2}}$
- $BF \sim 10^2 - 10^4$

$$\text{high mass} \sim (\text{small coupling})^{-1}$$

Propagation of electrons/positrons in the galaxy

The transport equation for electrons/positrons in a stationary two-zone diffusion model with cylindrical boundary conditions can be written as

$$0 = \frac{\partial f}{\partial t} = \nabla \left[K(T, \mathbf{r}), \nabla f \right] + \frac{\partial}{\partial t} \left[b(T, \mathbf{r}) f \right] + Q(T, \mathbf{r}),$$

where $f(T, \mathbf{r}, t)$ is the number density of particles per unit kinetic energy, $K(T, \mathbf{r})$ is the diffusion coefficient, b is the energy loss rate function and Q is the source term:

$$Q_{dec} = \frac{1}{\tau} \frac{\rho}{M} \frac{dN_e}{dE_e}, \qquad Q_{ann} = \eta \left(\frac{\rho}{M} \right)^2 \sum \langle \sigma v \rangle \frac{dN_e}{dE_e}, \quad \eta = \frac{1}{2}, \frac{1}{4}.$$

The electron/positron flux from DM decay Φ_e^{DM} can be written as

$$\Phi_e^{DM}(E) \frac{4\pi}{v} = f_e(E) = \frac{[BF]}{b(E)} \int_E^{E_{max}} dE' I(\lambda_D(E, E')) Q(E'),$$

where BF is the boost factor, $I(\lambda_D)$ is the halo function, λ_D is the diffusion length.

The boundary conditions require the solution $f(T, \vec{r}, t)$ to vanish at the boundary of the diffusion zone, which is approximated by a cylinder with half-height $L = 1$–15 kpc and radius $R = 20$ kpc.

Spherically symmetric DM density profile

$$\rho(r) = \frac{\rho_0}{(r/r_c)^{\gamma}[1 + (r/r_c)^{\alpha}]^{(\beta-\gamma)/\alpha}}, \tag{6}$$

where $r = |\vec{r}|$ and the parameters α, β, γ and r_c are listed in table 1 for some commonly used halo models. Finally, ρ_0 is a parameter that is adjusted to yield a local halo density of $\rho(r_\odot) = 0.30$ GeV cm^{-3} [19], with $r_\odot = 8.5$ kpc being the distance of the Sun to the Galactic center.

Table 1. Parameters characterizing some commonly used halo models.

Halo model	α	β	γ	r_c (kpc)
Navarro, Frenk, White [30]	1	3	1	20
Isothermal	2	2	0	3.5
Moore [31]	1.5	3	1.5	28

FPA anomaly from three-body decays

- **Toy model: 0901.2681 [hep-ph]**
- **Split SUSY realization: 0905.0652 [hep-ph]**

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PHYSICS LETTERS B

ATIC/PAMELA anomaly from fermionic decaying dark matter

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Toy model

Two scalar doublets model: ***φ***, η + 2 neutral leptons N_k.

Non-SM particles are odd under Z_2 symmetry.

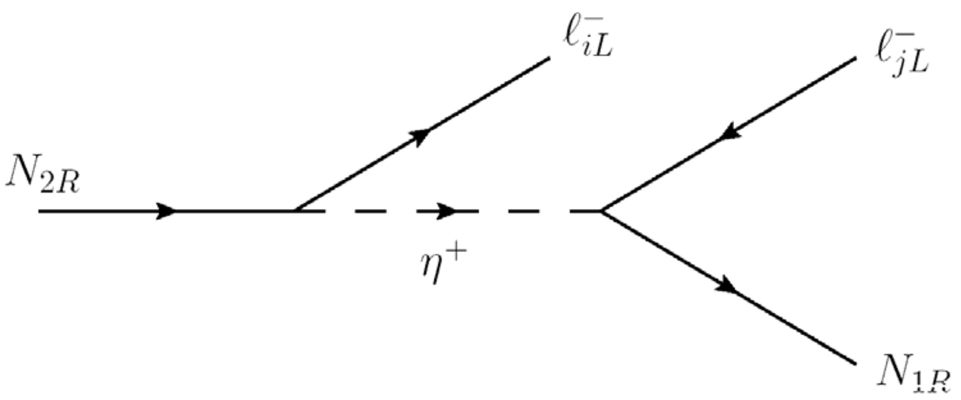
The new Majorana mass term and Yukawa couplings can be written as

$$M_k N_k N_k + y_{ik} \bar{L}_i \eta N_k + \text{H.c.},$$

where L is the lepton doublet and i, k are the flavor indexes. We consider the mass spectrum $M_1 < M_2 < M_\eta$.

Integration over η gives dim6 operator $\sim y^2 M_\eta^{-2} N_1 N_2 \bar{\ell}_{iL} \ell_{jL}$.

DM decay



The liftime of N_2 is given by

$$\tau_{N_2} \simeq \frac{1}{\Gamma(N_2 \to N_1 \ell_i^{\pm} \ell_j^{\mp})} = \frac{128(2\pi)^3}{3} \frac{M^4 M_2^3}{(M_{21}^2)^4},$$

where $M_{21}^2 = M_2^2 - M_1^2$ is the squared-mass splitting of DM and $M \equiv M_\eta / y$ with $y \equiv |y_{ik}|$. The energy distribution of electrons/positrons produced in a single three body decay of N_2 can be written as

$$\frac{dN_e}{dE} = \frac{72 M_2^3}{(M_{21}^2)^4} \left(M_{21}^2 - \frac{16}{9} M_2 E \right) E^2.$$

Electron/positron fluxes

The DM component of the primary electron/positron flux is given by

$$\Phi_e^{DM}(E) = \frac{c}{4\pi M_2 \tau_{N_2}} \int_0^{M_{21}^2/(2M_2)} dE' G(E, E') \frac{dN_e}{dE'},$$

where E is in units of GeV and c is the speed of light. All the information about astrophysics is encoded in the Green function $G(E, E')$, approximately given by

$$G(E, E') \simeq \frac{10^{16}}{E^2} \exp[a + b(E^{\delta-1} - E'^{\delta-1})]\theta(E' - E) \quad [\mathrm{cm}^{-3}\mathrm{s}].$$

The coefficients a, b for the spherically symmetric Navarro, Frenk and White density profile of DM in our Galaxy and the diffusion parameter δ are listed in Table II.

TABLE II: Astrophysical coefficients for the propagation models M1, MED and M2.

Model	δ	a	b
M1	0.46	−0.9809	−1.1456
MED	0.70	−1.0203	−1.4493
M2	0.55	−0.9716	−10.012

The total electron and positron fluxes are

$$\Phi_{e^-} = \xi\Phi_{e^-}^{prim} + \Phi_{e^-}^{DM} + \Phi_{e^-}^{sec}$$
$$\Phi_{e^+} = \Phi_{e^+}^{DM} + \Phi_{e^+}^{sec},$$

respectively, where $\Phi_{e^-}^{prim}$ is a primary astrophysical component, presumably from supernova remnants, $\Phi_{e^-(+)}^{DM}$ is an exotic primary component from DM decays, $\Phi_{e^-(+)}^{sec}$ is a secondary component from the spallation of cosmic rays on the interstellar medium, and ξ is a free parameter to fit the data when no DM source exists. We take $\xi = 0.7$ to fit the ATIC data. For the background fluxes we use the parametrizations

$$\Phi_{e^-}^{prim}(E) = \frac{0.16E^{-1.1}}{1 + 11E^{0.9} + 3.2E^{2.15}} \quad [\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}],$$
$$\Phi_{e^-}^{sec}(E) = \frac{0.7E^{0.7}}{1 + 110E^{1.5} + 600E^{2.9} + 580E^{4.2}} \quad [\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}],$$
$$\Phi_{e^+}^{sec}(E) = \frac{4.5E^{0.7}}{1 + 650E^{2.3} + 1500E^{4.2}} \quad [\mathrm{GeV^{-1}cm^{-2}s^{-1}sr^{-1}}].$$

Results

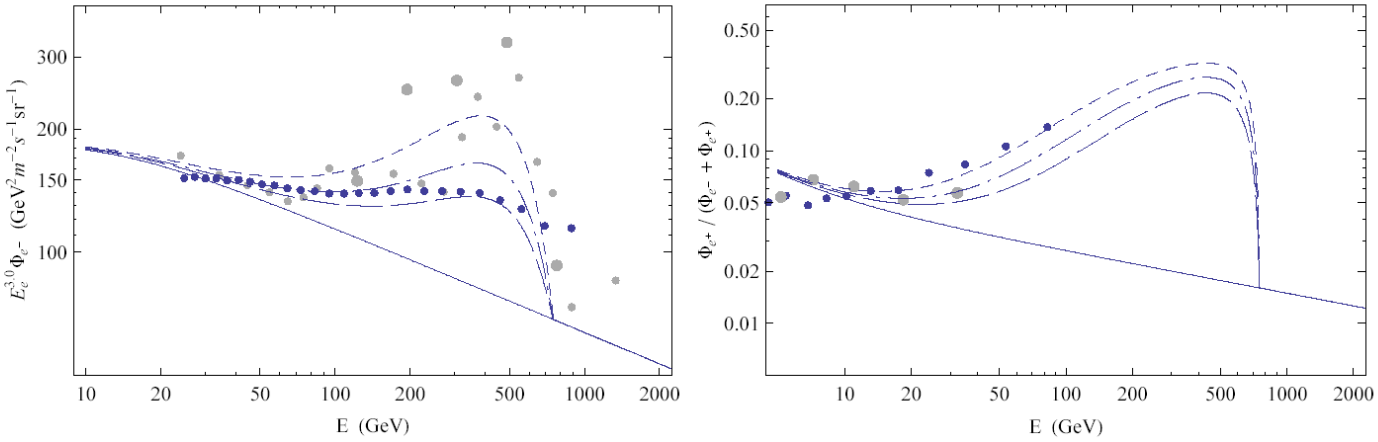


FIG. 2: Electron energy spectra (left) and positron fractions (right) of the DM decays, where $M_1 = 10$ GeV, $M_2 = 1.5$ TeV, $\tau_2 \sim 10^{26}$ s, short-dashed, dot-dashed and long-dashed lines represent $M = 4 \times 10^{15}$, 4.5×10^{15} and 5×10^{15} GeV, small-black and large-gray dots stand for the observations of Fermi and PPB-BETS (left) and PAMELA and HEAT (right), small-gray dots stand for ATIC, and solid lines correspond to the backgrounds calculated from Eqs. (8)-(10), respectively.

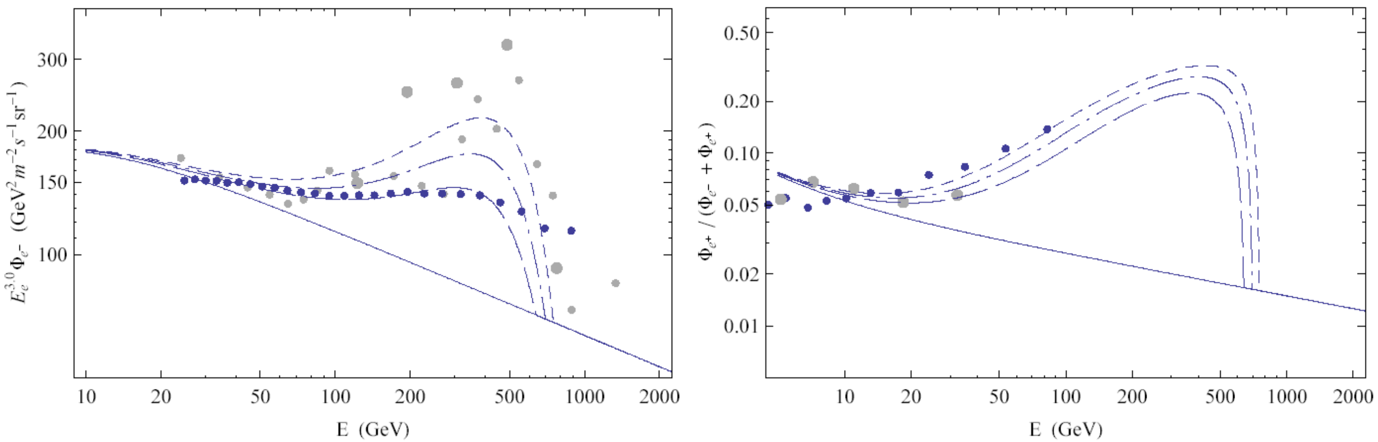


FIG. 3: Legend is the same as Fig. 2 but $M = 4 \times 10^{15}$ GeV, $M_2 = 2$ TeV and short-dashed, dot-dashed and long-dashed lines represent $M_1 = 1$, 1.1 TeV and 1.2 TeV, respectively.

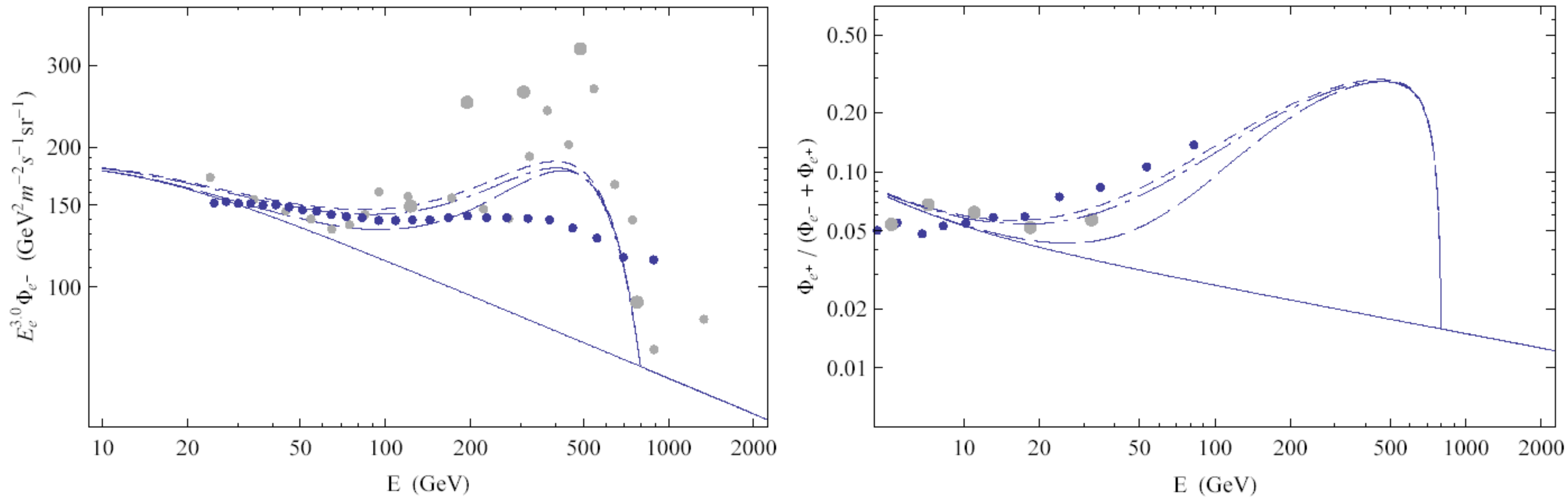


FIG. 4: Electron energy spectra (left) and positron fractions (right) for the decays of DM particles with $M_2 = 100$ TeV, $\tau_2 = 5\times10^{24}$ s and $M_1 = (100-0.8)$ TeV (dashed lines) where small-black and large-gray dots stand for the observations of Fermi and PPB-BETS (left) and PAMELA and HEAT (right), small-gray dots stand for ATIC, and solid, short-dashed, dot-dashed and long-dashed lines correspond to the backgrounds, M1, MED and M2, respectively.

Production of the DM leptons

N are produced copiously after the big bang. N is typical *unwanted relic.* Inflation dilutes N away, since its number density reduces exponentially.

Present abundance of N may be generated at the end of reheating in the lepton scattering.

How to verify the model?

The model can be verified by precise measurements of the electron spectrum and positron fraction, since the shapes of the corresponding curves are not very flexible.

In particular, further measurements of the positron fraction at energies higher than 100 GeV are crucial in testing the same origin of the FPA electron/positron excesses.

Finally, the gamma-ray observations may help us to verify the model.

Split SUSY realization

We focus on the lepton trilinear couplings

$$\mathcal{L}_{\not R} = \lambda_{[ij]k} \Big(\bar{\ell}_k P_L \ell_j \tilde{\nu}_{iL} + \bar{\ell}_k P_L \nu_{iL} \tilde{\ell}_{jL} + \bar{\ell}_j P_R \nu^c_{iL} \tilde{\ell}_{kR} - \bar{\ell}_k P_L \ell_i \tilde{\nu}_{jL} - \bar{\ell}_k P_L \nu_j \tilde{\ell}_{iL} - \bar{\ell}_i P_R \nu^c_{jL} \tilde{\ell}_{kR} \Big) + \mathrm{H.c.}$$

for simplicity, we take the bino as the neutralino denoted by $\tilde{\chi}^0_1$ and the couplings to leptons are given by [22]

$$\mathcal{L}_{\tilde{\chi}^0_1 \ell \tilde{\ell}} = \frac{g}{\sqrt{2}} \tan\theta_W \bar{\ell} \left(c^\ell_L P_R \tilde{\ell}_L + c^\ell_R P_L \tilde{\ell}_R \right) \tilde{\chi}^0_1,$$

$$\mathcal{L}_{\tilde{\chi}^0_1 \nu \tilde{\nu}} = \frac{g}{\sqrt{2}} \tan\theta_W c^\nu_L \left(\bar{\nu} P_R \tilde{\chi}^0_1 \right) \tilde{\ell}_L \qquad (3)$$

with θ_W being Weinberg angle, $c^\ell_R = -2$, $c^\ell_L = 1$ and $c^\nu_L = 1$.

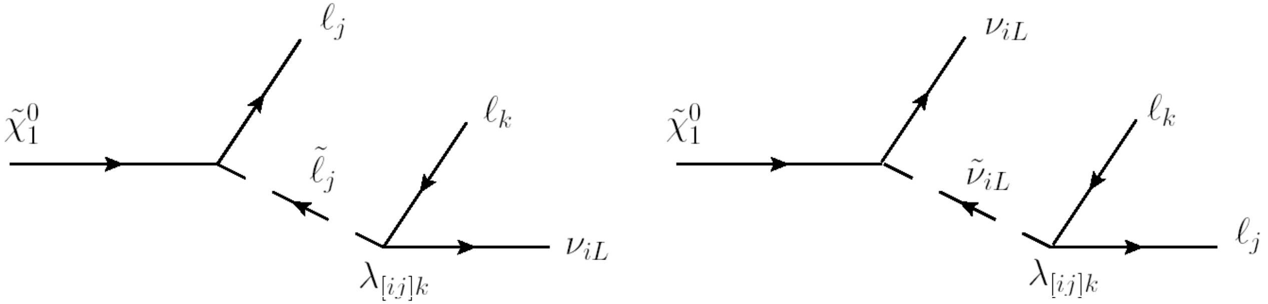


FIG. 1: The Feynman diagram for LSP decay in split SUSY.

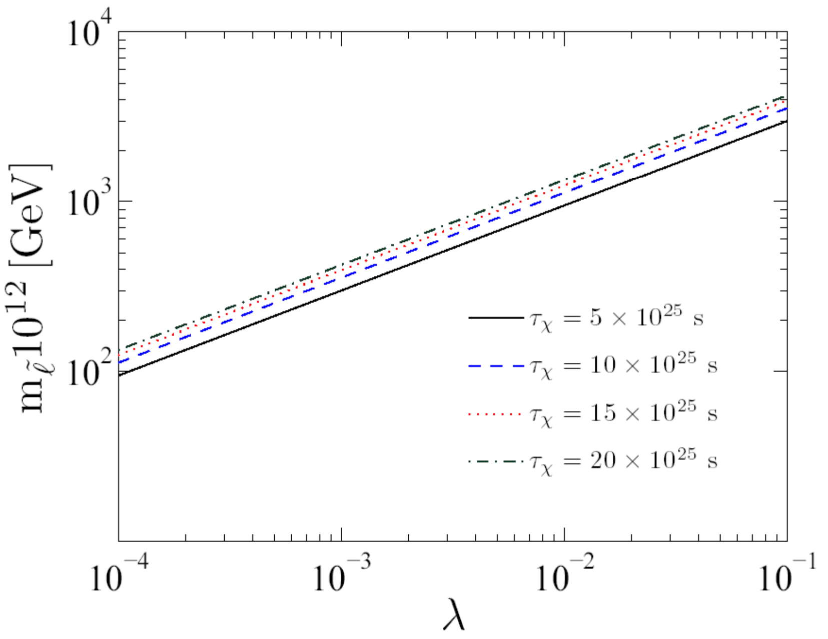


FIG. 2: Typical lifetime for PAMELA/ATIC anomalies as a function of the slepton mass and the unspecified parameter $\lambda = \lambda_{[ij]k}$ in log scale.

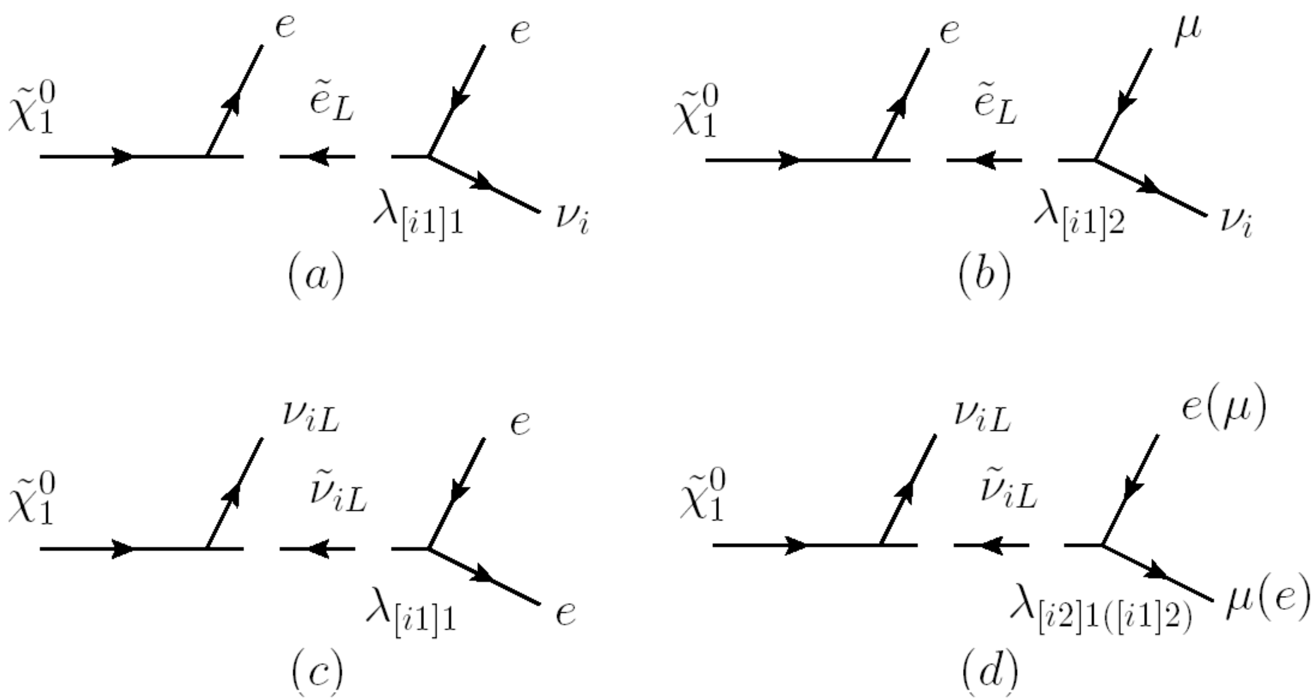


FIG. 3: Feynman diagrams for the neutralino decays in split SUSY.

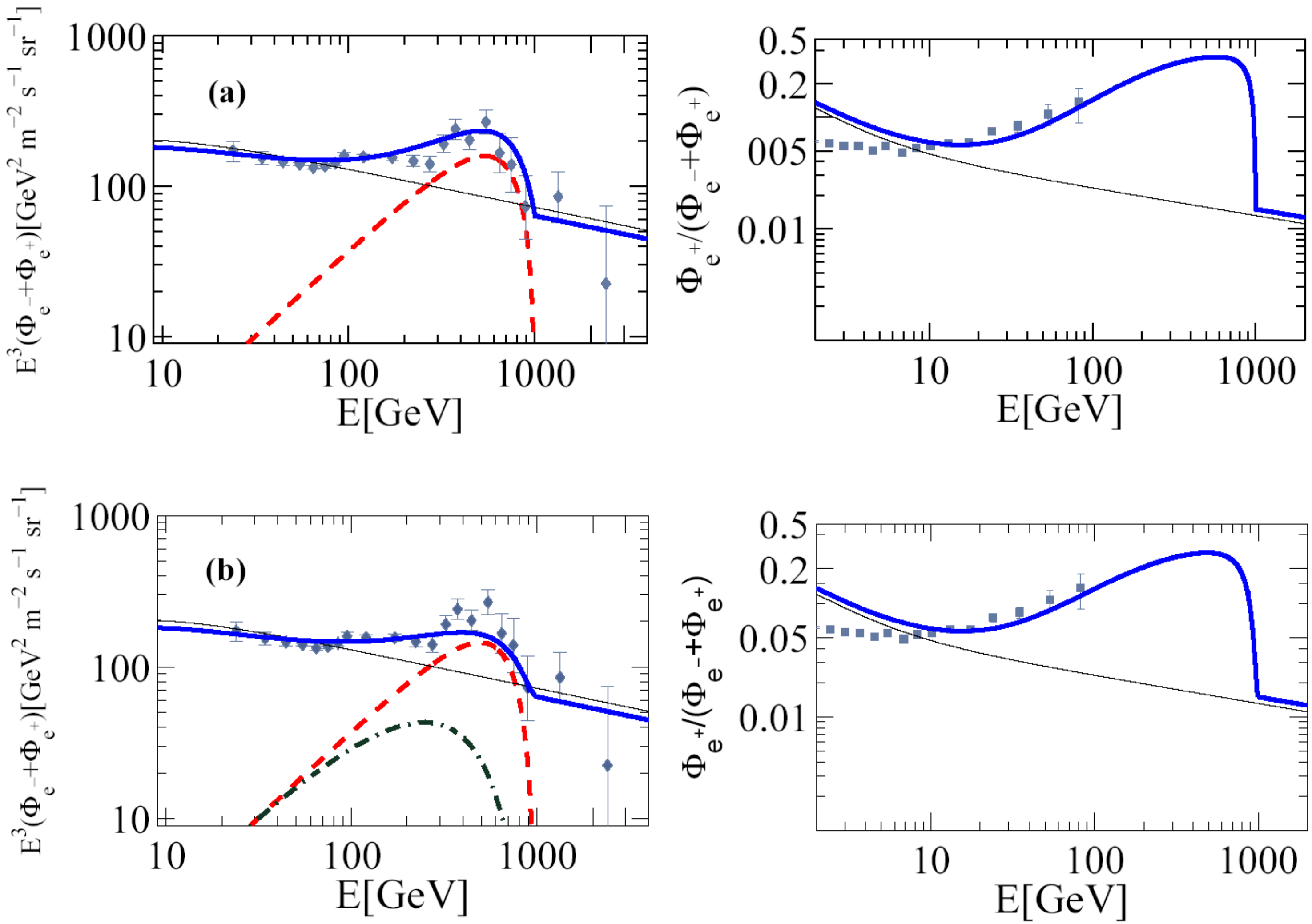


FIG. 5: (a) [(b)] The effects of Fig. 3(a) [(b)] on the ATIC and PAMELA anomalies, where the thin solid line is the background with $\kappa = 0.8$, the thick solid (dashed, dash-dotted) line for ATIC denotes the effect with (without) the background, and the dashed and dash-dotted lines in (b) represent the contribution of $d\Gamma_{b1}/dE$ and $d\Gamma_{b2}/dE$, respectively.

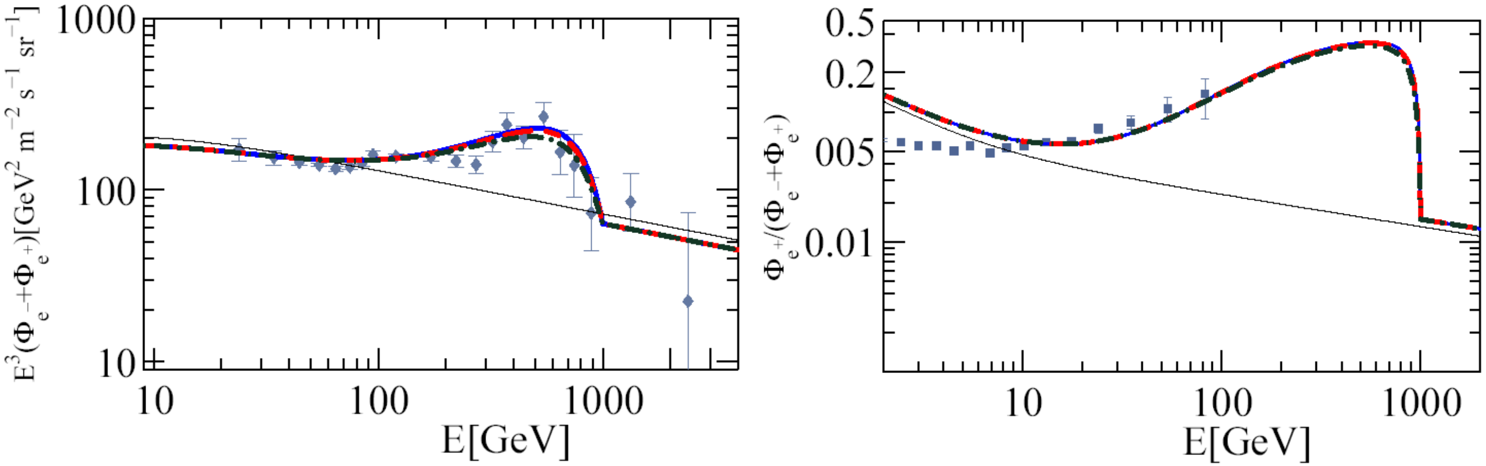


FIG. 6: The results by combining Fig. 3(a) and (b) with different partitions described by (c_ζ^2, s_ζ^2), where the solid, dashed and dash-dotted lines stand for (0.8, 0.2), (0.6, 0.4) and (0.3, , 0.7), respectively.

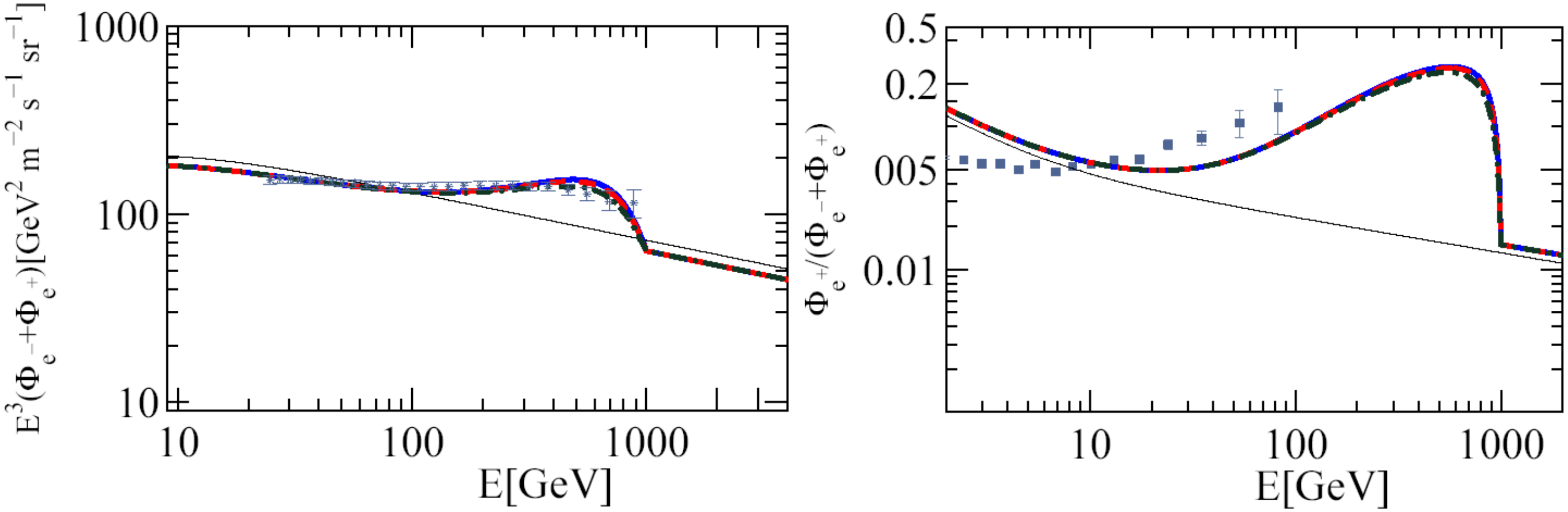


FIG. 7: The legend is the same as Fig. 6 but with $\tau_\chi = 4 \times 10^{26}$ s.

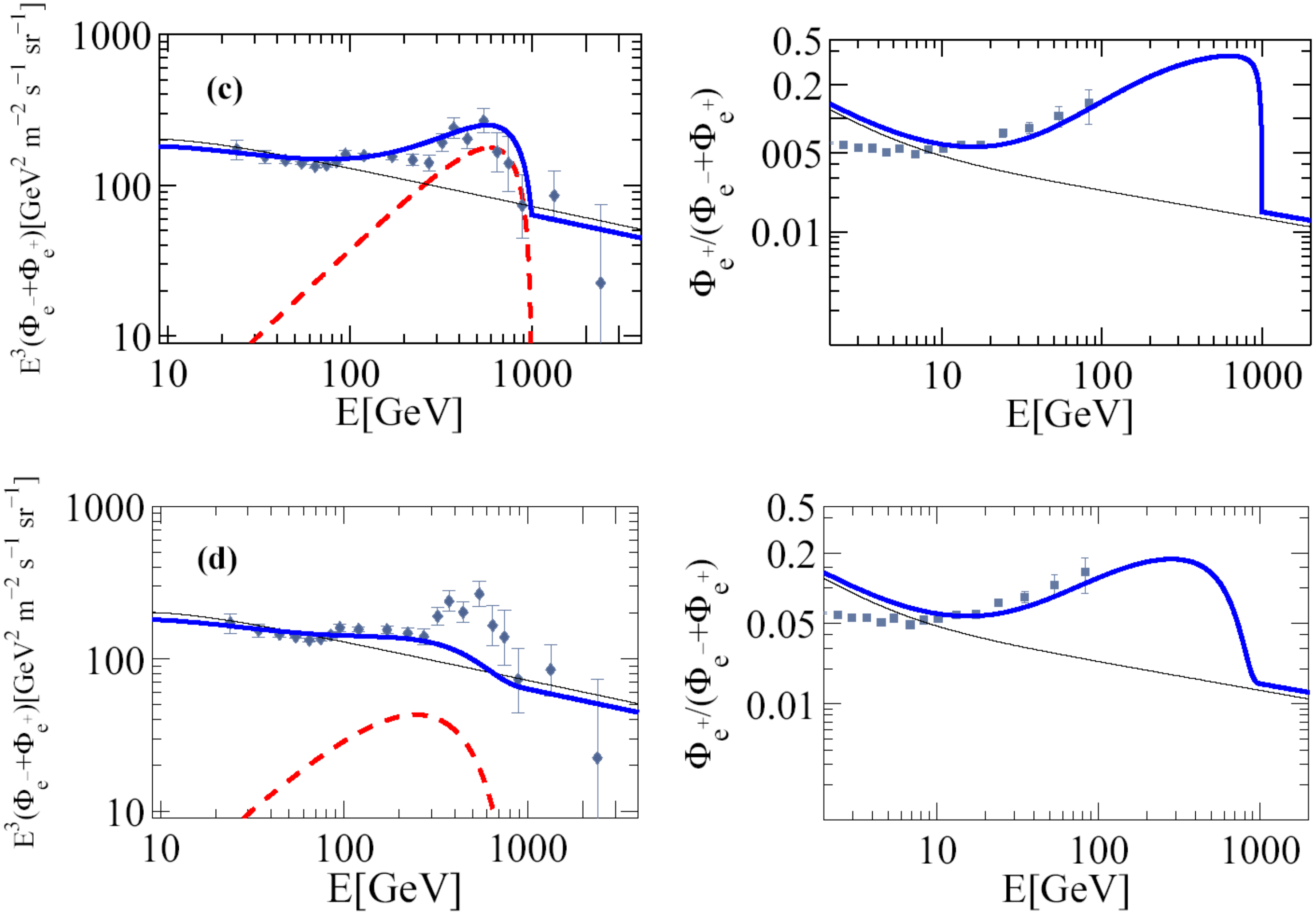


FIG. 8: (c) [(d)] Results explain the ATIC and PAMELA anomalies by Fig. 3(c) [(d)], where the solid (dashed) line for ATIC denotes the effect with (without) the background.

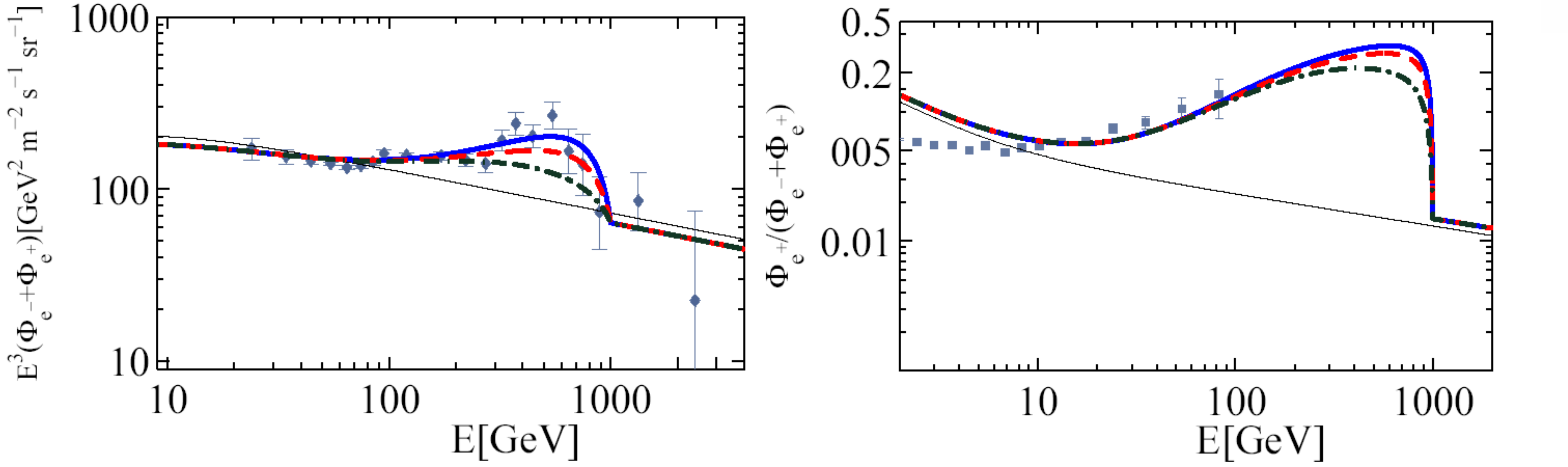


FIG. 9: Legend is the same as Fig. 6, but for Fig. 3(c) and (d).

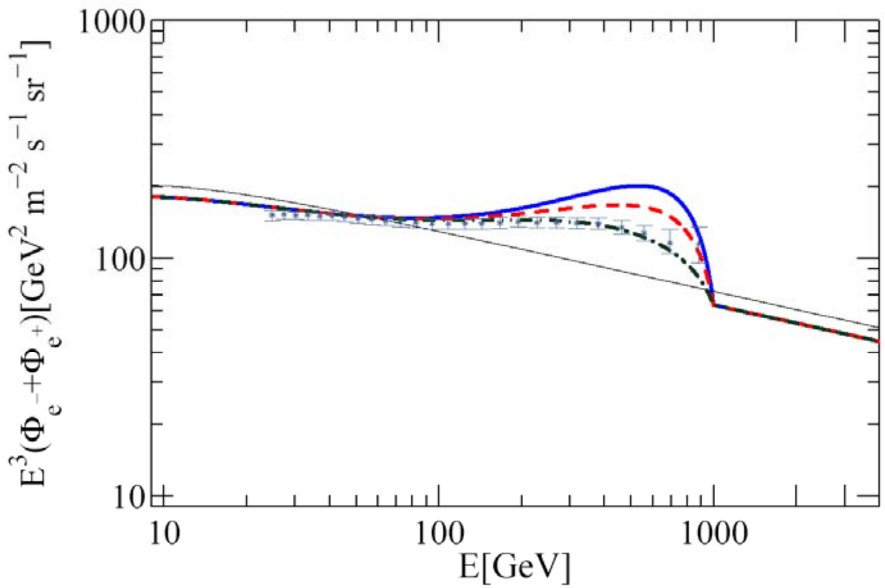


FIG. 10: The positron+elcetron flux from Figs. 3 (c) and (d) due to the sneutrino.

FPA anomaly, neutrino masses and LG

We introduce four new neutral leptons N_i ($i = 1, 2, 3$) and N with the masses of M_i and M, and two new doublet scalars ζ and η with the masses of M_ζ and M_η, respectively, in the SM. These new particles have non-trivial transformation properties under the two discrete symmetries Z_2 and Z_2' as listed in Table I, whereas the SM particles are trivial under these symmetries.

TABLE I: Transformations of the new particles under the discrete symmetries of Z_2 and Z_2'.

Particle	ζ	η	N_i	N
Z_2	$-$	$+$	$-$	$+$
Z_2'	$+$	$-$	$+$	$-$

The relevant Majorana mass terms and Yukawa couplings as well as the soft breaking term involving the new particles can be written as

$$\frac{M_{ij}}{2} N_i^T C N_j + \frac{M}{2} N^T C N + y_{ij} \bar{L}_i \zeta N_j + y_i' \bar{L}_i \eta N + \mu^2 \eta^\dagger \zeta + \text{H.c.}, \qquad (1)$$

Neutrino masses

$$\frac{\lambda}{2}(\phi^\dagger \zeta)^2 + \text{H.c.}\,, \tag{2}$$

where ϕ is the Higgs boson in the SM. As in Ref. [19], N_i ($i = 1, 2, 3$) are needed to achieve

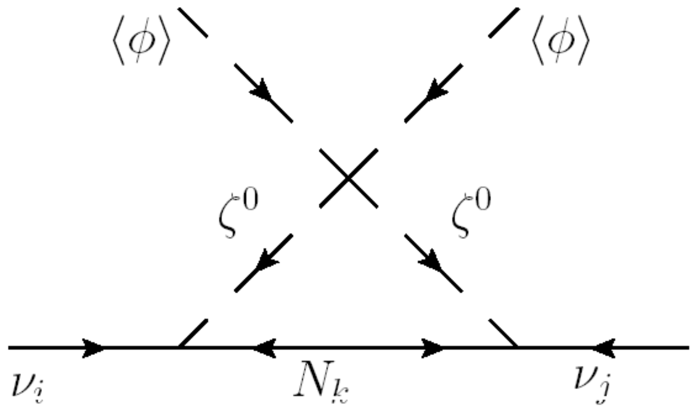


FIG. 1: One-loop generation of neutrino masses; $i, j, k = 1, 2, 3$.

the realistic neutrino masses and mixings. The simplified formula for the neutrino masses

$$(m_\nu)_{ij} = \frac{\mathcal{O}(\lambda)}{16\pi^2} \sum_{k=1}^{3} \frac{y_{ik} y_{jk}}{M_k} v^2 \tag{3}$$

leads to the natural values of $m_\nu = \mathcal{O}(0.01 - 0.1 \text{ eV})$ if $\lambda = \mathcal{O}(10^{-4})$, $y_{ij} = \mathcal{O}(10^{-3})$ and $M_i = \mathcal{O}(100 \text{ GeV} - 10 \text{ TeV})$.

Leptogenesis

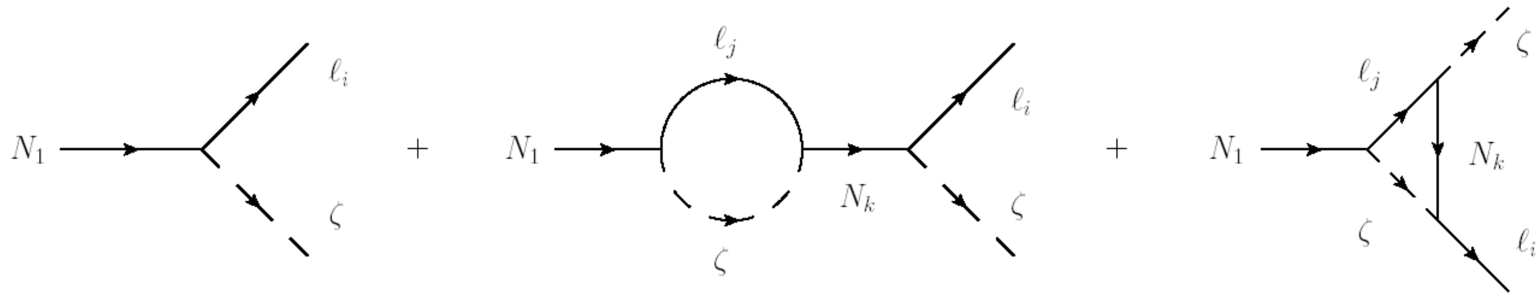
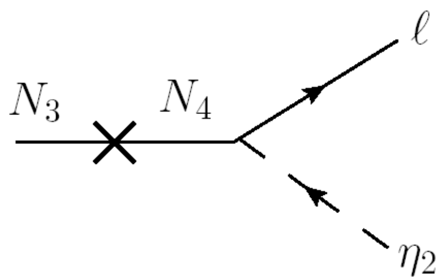


FIG. 2: The $N_1 \to \ell_i \zeta$ decay: tree level diagram (left) and one-loop diagrams which are relevant to the leptogenesis, where $i, j, k = 1, 2, 3$.

$$\Gamma(N_1 \to e^{\mp}\zeta^{\pm}) = \frac{|y_{11}|^2}{16\pi} M_1 r^2$$

with $r = 1 - M_\zeta^2/M_1^2$. The out-of-equilibrium condition requires $r \sim 10^{-4}$.

This mass degeneracy could be avoided in the extended model, e.g., by using the mechanism, proposed by Chuan-Hung Chen in 0905.3425 [hep-ph].



Decaying Dark Matter

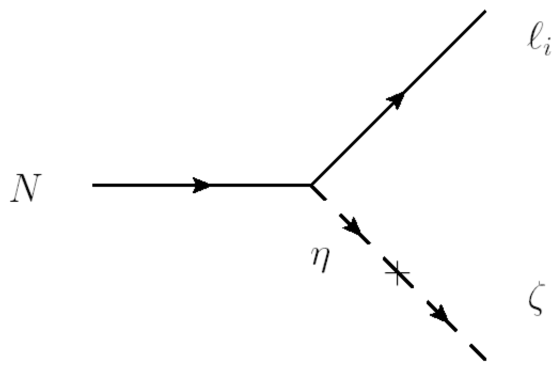
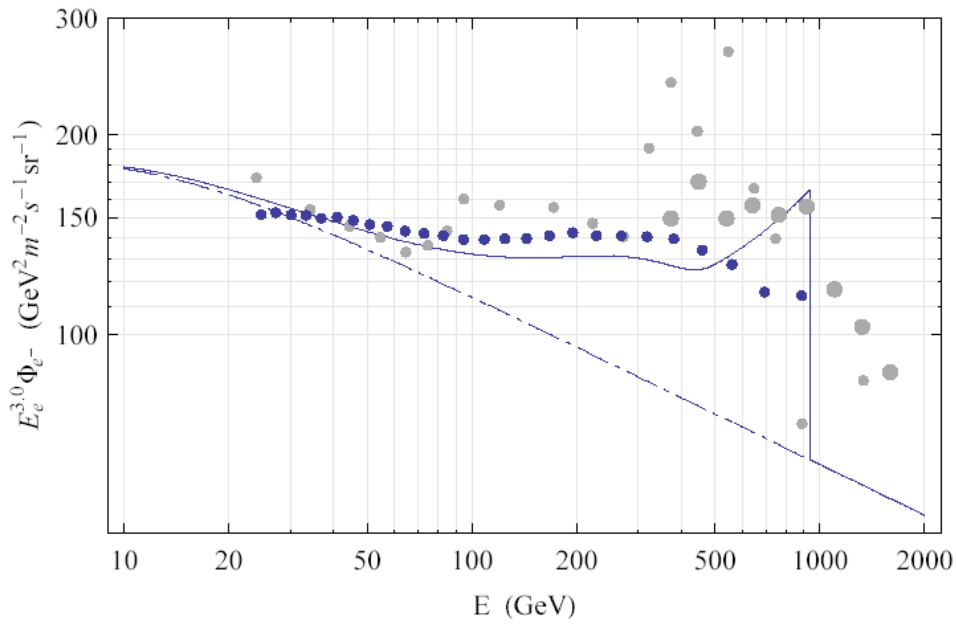
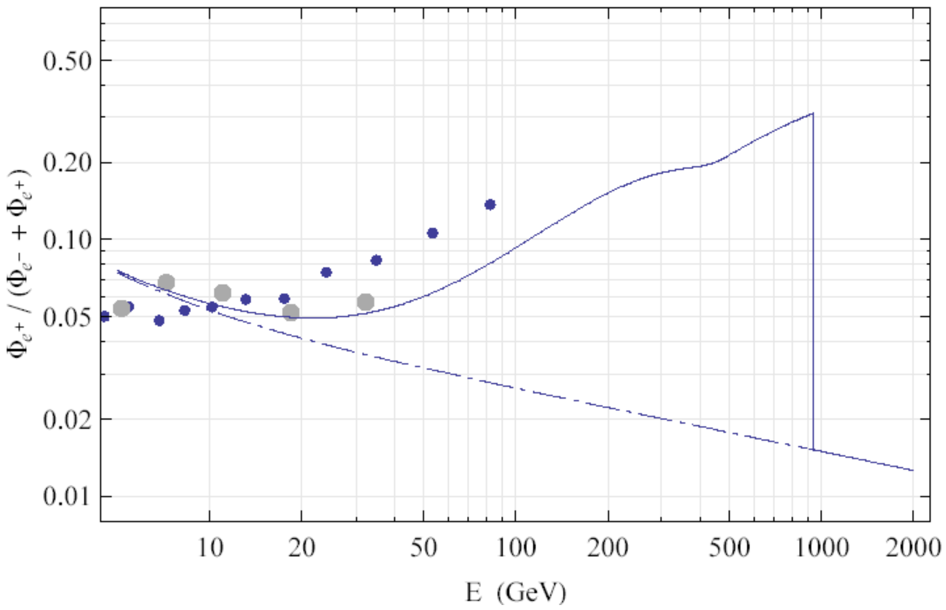


FIG. 3: Diagram for the DM decay; $i = 1, 2, 3$.





Conclusion

- We have investigated a new mechanisms to generate the electron/positron excess from the decays of DM leptons.
- We have shown that the observed FPA anomaly can be explained by the decay of the neutral lepton N_2 with the mass $M_2 \geqslant 1.5$ TeV and the lifetime $\tau_2 \leqslant 10^{26}$ s.
- We have shown that the FPA anomaly can be naturally explained in split SUSY model by the neutralino decays with including the muon effects.
- We have found the economy generalization of the SM to explain the neutrino masses, LG and FPA anomaly.