Decaying Dark Matter in Supersymmetric SU(5) Models

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Abstract
Motivated by recent observations from Pamela, Fermi and H.E.S.S., we consider dark matter decays in the framework of supersymmetric SU(5) grand unification theories. An SU(5) singlet $S$ is assumed to be the main component of dark matters, which decays into visible particles through dimension six operators suppressed by the grand unification scale. Under certain conditions, $S$ decays dominantly into a pair of sleptons with universal coupling for all generations. Subsequently, electrons and positrons are produced from cascade decays of these sleptons. These cascade decay chains smooth the $e^+ + e^-$ spectrum, which permit naturally a good fit to the Fermi LAT data. The observed positron fraction upturn by PAMELA can be reproduced simultaneously. We have also calculated diffuse gamma-ray spectra due to the $e^\pm$ excesses and compared them with the preliminary Fermi LAT data from 0.1 GeV to 10 GeV in the region $0^\circ \leq l \leq 360^\circ, 10^\circ \leq |b| \leq 20^\circ$. The photon spectrum of energy above 100 GeV, mainly from final state radiations, may be checked in the near future.

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I. INTRODUCTION

Electron, proton, photon, neutrino and their antiparticles are stable, at least on the cosmological time scale. Detection of these particles from cosmic rays provides an interesting window to look into the deep universe. Recently, the PAMELA experiment reported a significant excess in the positron fraction $e^+/ (e^+ + e^-)$ between 10 GeV and 100 GeV [1]. On the other hand, the measured antiproton to proton flux ratio appears to be consistent with predictions [2]. More recently, the Fermi LAT collaboration observed a smooth $e^+ + e^-$ spectrum with high accuracy. It is found to be falling as $E^{-3.0}$ from 20 GeV to 1 TeV [3], much harder than the predictions of conventional models. The H.E.S.S. collaboration measured the $e^+ + e^-$ spectrum from 600 GeV up to several TeV [4], which is consistent with the Fermi data in overlapping regions and steepens at about 1 TeV towards higher energy.

These excesses of electrons and positrons could be due to unidentified astrophysical sources, e.g., nearby pulsars or supernova remnants [5–7]. However, an explanation via dark matter (DM) annihilation or decay is, arguably, a much more interesting possibility, at least from the perspective of particle physics. The electron and positron spectra alone, even with higher precision and broader energy range, cannot decisively decide which explanation is more plausible [8]. Hopefully, the energy spectrum and the angular dependence of cosmic gamma rays [9–13], to be measured by the Fermi LAT in the near future, may provide a more definite answer. For the DM interpretation, the mass of the DM should be around several TeV, to provide the $e^\pm$ excesses from 20 GeV to 1 TeV and steepen sharply above 1 TeV. Furthermore, traditional WIMP DM candidates usually produce extra antiprotons. As Pamela does not observe any deviation on antiproton spectrum from the anticipation, WIMP DMs are now disfavored as potential sources of the observed cosmic-ray excesses. Still, there are plenty of freedoms for both DM annihilation and decay to reproduce the experimental $e^\pm$ spectra reasonably [14, 15]. For DM annihilation, a large boost factor in the order of $10^2$ to $10^3$ is needed for the theory to be consistent with the relic abundance measured by the WMAP [16]. As the clumpiness property of the DM distribution falls far short of such a large factor, one usually resorts to nonperturbative Sommerfeld [17–20] or Breit–Wigner [21–23] enhancement in model buildings. For DM decays, the lifetime should typically be around the order of $10^{26}$s to fit the $e^\pm$ data [14, 24, 25], which is much longer than the lifetime of the universe. Therefore the DM decay rates will not affect the relic
abundance appreciably.

The energetic $e^\pm$ flux produced from DM annihilations/decays would inevitably emit gamma rays. These gamma rays depend on the DM density as $\rho^2$ for annihilations and $\rho$ for decays. This will lead to different angular dependence of the gamma ray spectrum, which may be measurable in the near future to differentiate these two scenarios. The gamma ray spectrum can also be used to differentiate DM explanations from astrophysical ones.

In this paper, we will focused on DM decays. Notice that a lot of suppression will be needed for a TeV scale particle to have a lifetime $\sim 10^{26}$ s. If it decays via dimension four operators, tremendous fine tunings will be needed. If it decays via dimension six operators, it still needs to be suppressed by a scale $\sim 10^{16}$ GeV, which turns out to coincide with the grand unification theory (GUT) scale [26–28]. In the same spirit of Refs. [29, 30], we will take a singlet as the dark matter candidate and provide a detailed analysis in the frame of supersymmetric SU(5) GUT. To be consistent with the Pamela antiproton measurement, squark masses are assumed to be heavier than that of the SU(5) singlet $S$, so the $S$ decay would be quark phobic. The $S$ then decays dominantly into slepton pairs with a universal coupling for all generations. These sleptons decay quickly into leptons and lightest supersymmetric particles (LSPs), if R-parity is conserved. In this framework, we have obtained a reasonable fit to all $e^\pm$ data from Pamela, Fermi and H.E.S.S..

The $e^\pm$ fluxes from $S$ decays are inevitably accompanied by hard photons: coming from final state radiations (FSR) of cascade decays, including $S \rightarrow \tilde{\tau} \rightarrow \tau \rightarrow \pi^0 \rightarrow 2\gamma$ and the inverse Compton scattering (ICS) on the interstellar radiation field (ISRF). The gamma ray fluxes could have Galactic and extragalactic origins. We have calculated all these gamma ray spectra and compared them with the recent Fermi LAT measurement in the region $0^\circ \leq l \leq 360^\circ, 10^\circ \leq |b| \leq 20^\circ$ [31].

This paper is organized as follows. The supersymmetric SU(5) model plus a singlet $S$ is presented in Section II, where we have also discussed the possible decay channels of $S$ in some detail. In Section III, a reasonable fit is obtained to reproduce the observed $e^\pm$ fluxes, by tuning relevant parameters in the model. Section IV is devoted to the study of gamma-ray spectra from $e^\pm$ excesses. Finally we conclude with a summary in section V. The component field structure of the dimension six effective operators will be presented in the Appendix. In this paper, we have used the Navarro-Frenk-White (NFW) halo model [32] for DM distribution and the MED propagation model [33, 34]. For other halo and propagation
models, the conclusions are similar. In addition, all computations on astrophysical effects are performed semi-analytically instead of using the GALPROP program\(^1\).

II. A SUPERSYMMETRIC SU(5) MODEL

If the observed \( e^\pm \) excesses come from DM decays, the lifetime of a TeV scale DM should be \( \sim 10^{26} \) s. Such a long lifetime can be naturally realized through decays via GUT suppressed dimension six effective operators, similar to proton decays. This provides a strong motivation to study DM decays in the framework of grand unification theory [29, 30, 35–38].

In the minimal supersymmetric SU(5) model, the dark matter candidate would be the LSP, which is absolutely stable if R-parity is conserved. In addition, the mass of LSP is normally around several hundred GeV, which is too small to account for the Fermi and H.E.S.S. data even if it decays. To make a minimal extension, one can introduce an SU(5) singlet \( S \) as the dark matter candidate\(^2\) [29]. As \( S \) is neutral in the standard model (SM) gauge group, it does not disturb the gauge coupling unification. To eliminate lower dimensional operators which may lead \( S \) to decay too fast, we impose a \( Z_2 \) symmetry on the theory, under which \( S \) is odd while all other particles are even. Then \( S \) can decay into the MSSM particles only through dimension six operators, suppressed by \( M^2_{\text{GUT}} \). Assuming R-parity conservation and the \( Z_2 \) symmetry, all possible dimension six operators are [29]:

\[
\begin{align*}
&\frac{S^+ S 5^+ \overline{5}}{M^2_{\text{GUT}}} , \quad \frac{S^+ S T r(10^+10)}{M^2_{\text{GUT}}} , \quad \frac{S^+ S W^\alpha W^\alpha}{M^2_{\text{GUT}}} \quad \text{and} \quad \frac{S^+ S H^\pm_{u(d)} H_{u(d)}}{M^2_{\text{GUT}}} \\
&\quad \text{(1)}
\end{align*}
\]

Some or all of these operators may appear at the TeV scale when one integrates out heavy particles of the GUT scale. Here \( W^\alpha \) are the supersymmetric field strengths of SM gauge groups, \( H_u \) and \( H_d \) are the chiral superfields for Higgs, \( 5 \) and 10 are anti-fundamental and antisymmetric tensor representations of SU(5), respectively

\[
\bar{5}^T = (d^c, d^c, d^c, e, -\nu)_L
\]

\(^1\) Web page: http://galprop.stanford.edu/web_galprop/galprop_home.html

\(^2\) If R parity is conserved, the neutralino LSP would also be part of the DM. But for simplicity, we assume here that \( S \) is the dominant component of DM and the LSP contributes just a small portion to the relic density. We will show that such a scenario is feasible in the next section.
\[
10 = \frac{1}{\sqrt{2}} \begin{pmatrix}
0 & u^c & -u^c & u & d \\
-u^c & 0 & u^c & u & d \\
u^c & -u^c & 0 & u & d \\
u & -u & -u & 0 & e^c \\
d & -d & -d & -e^c & 0
\end{pmatrix}_L
\]  

(3)

Operators \( S^+ S H^+_{u(d)} H_{u(d)} \) and \( S^+ SW_a W^a \) in Eq.(1) may lead to final states containing significant number of quarks or mono-energetic gamma ray lines. To be consistent with experimental observations, these operators should be further suppressed, most likely due to unknown physics at the GUT scale. They will simply be neglected from now on. Operators \( S^+ S \tilde{5}^+_5 \) and \( S^+ STR(10^+10) \) in Eq.(1) may be rewritten in the form

\[
\sum_\Phi \frac{S^+ S \Phi^+ \Phi}{M^2_{GUT}}
\]  

(4)

Here the summation is over all lepton and quark chiral superfields. Assuming the singlet scalar develops a vacuum expectation value (VEV) \( \langle \tilde{s} \rangle \), the \( Z_2 \) symmetry is spontaneously broken and both components \((\tilde{s}, s)\) in \( S \) will decay.

Expanding Eq. (4) in terms of component fields, one has

\[
\sum_\Phi \frac{1}{M^2_{GUT}} \left( i \langle \tilde{s} \rangle \tilde{s}^* (\partial_\mu \bar{\psi} \sigma^\mu \psi) + i \langle s \rangle \tilde{\psi}^*(\partial_\mu \bar{\psi} \sigma^\mu \bar{s}) + \langle \tilde{s} \rangle \tilde{s}^* \tilde{\psi}^* \Box \tilde{\psi} \right) + h.c. + \ldots \]  

(5)

Here we have dropped total divergence terms. Operators from F-terms have also been neglected as they are suppressed by the leptonic Yukawa coupling constant. In addition, these operators will lead to many body decays which are further suppressed by phase spaces. Details of the expansion will be provided in Appendix A.

To fit the \( e^\pm \) fluxes data which steepens sharply above TeV, the mass of \( s \) and \( \tilde{s} \) will be assumed to be around several TeV. In addition, the squark masses are assumed to be heavier than the DM mass while the slepton masses to be about several hundred GeV. So, \( s \) and \( \tilde{s} \) can only decay into leptons, quarks and sleptons, and have no squarks in the final state. The assumptions on squark and slepton masses seems to be plausible, because squarks are much heavier than sleptons in general. This is due to the fact that squarks are color charged, which may affect drastically the renormalization group equations for the squark masses.

The decay width of \( s \) (\( \tilde{s} \)) due to the first two operators in Eq.(5) is proportional to the final state quark or lepton mass square. For the first operator \( \tilde{s}^* (\partial_\mu \bar{\psi} \sigma^\mu \tilde{\psi}) \), the dominant decay
channel is $\tilde{s} \to t\bar{t}$, which is suppressed by $M^2_t/M^2_s$ compared to the third operator $\tilde{s}^* \tilde{\psi}^* \Box \tilde{\psi}$ in Eq.(5). The main decay channel of $s$ through the second operator $\tilde{\psi}^* (\partial_\mu \psi^\mu s)$ is $s \to \tau \bar{\tau}$, which is again suppressed by $M^2_\tau/M^2_s$ compared to the third operator in Eq.(5). Thus the decays of $s$ will not be considered. The DM $\tilde{s}$ decays dominantly into a pair of sleptons, with universal coupling for all generations. For simplification, we will simply neglect the first two operators in Eq.(5) and only consider the operator $\tilde{s}^* \tilde{\psi}^* \Box \tilde{\psi}$ in the following. The remaining operator can be further rewritten as

$$\sum_{\tilde{l}} -\frac{1}{M^2_{\text{GUT}}} <\tilde{s}> <\tilde{s}> (\tilde{l}_L^* \Box \tilde{l}_L + \tilde{l}_R^* \Box \tilde{l}_R)$$

(6)

with $\tilde{l} = \tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$. The corresponding decay width reads

$$\Gamma_{\tilde{l}} = \frac{\sqrt{M^2_s - 4M^2_{\tilde{l}}} <\tilde{s}>^2 M^4_{\tilde{l}}}{16\pi M^2_s M^4_{\text{GUT}}}$$

(7)

Taking $M_{\text{GUT}} = 10^{16}$ GeV, $M_s \sim <\tilde{s}> \sim$ a few TeV and $M_{\tilde{l}} \sim$ several hundred GeV, the lifetime of $\tilde{s}$ would be around $10^{26}$ s, as one has hoped. Notice also that the decay width is proportional to $M^4_{\tilde{l}}$, so that even slightly different masses between $\tilde{e}$, $\tilde{\mu}$ and $\tilde{\tau}$ may lead to very different branching ratios.

With R-parity conservation, the slepton would decay to the LSP and lepton quickly.\(^3\) $e^\pm$ can be produced through the following cascade decay chains:

- selectron chain: $\tilde{s} \to \tilde{e} \to e$
- smuon chain: $\tilde{s} \to \tilde{\mu} \to \mu \to e$
- stau chain: $\tilde{s} \to \tilde{\tau} \to \tau \to e$

In total, the $e^\pm$ fluxes due to DM decays at the source are

$$Q^{DM}_e(\vec{r}, E) = \sum_{\tilde{l}} \frac{\Gamma^{DM}_{\tilde{l}} \rho^{DM}(\tilde{l})}{M^{DM}} dN^{DM}_{\tilde{l} \to e}$$

(8)

Here the summation is over all three cascade decay chains. $\Gamma^{DM}_{\tilde{l}}$ is the decay width of the $\tilde{l}$ cascade decay chain and $M^{DM}$ is the DM mass. Since the lifetimes of sleptons, muon

\(^3\) Here the LSP is assumed to be the neutralino. If the LSP is the gravitino and $\tilde{s}$ is heavier than $s$, $\tilde{s}$ would decay into $s$ predominately, instead of the sleptons.
and tau are extremely short compared with the DM decay, we can take the approximation \( \Gamma_\text{DM} = \Gamma_\tilde{\tau} \). And \( dN_\text{DM}/dE \) is the spectrum of electron or positron per DM decay via a particular \( \tilde{l} \) chain. For the stau chain, the \( e^\pm \) spectra are obtained by using PYTHIA package [39]. \( \rho_\text{DM}(r) \) is the DM mass density which is model-dependent. As an illustration we adopt the NFW halo model[32]

\[
\rho_\text{DM}(r) = \frac{\rho_\odot r_\odot}{r} \left(\frac{1 + r_\odot/r_s}{1 + r/r_s}\right)^2
\]

(9)

with solar system position \( r_\odot = 8.5 \) kpc, the DM density at earth \( \rho_\odot = 0.3 \) GeV/cm\(^3\) and \( r_s = 20 \) kpc.

III. ELECTRON AND POSITRON EXCESSES FROM DARK MATTER DECAY

A. Positron and Electron Propagation

Shown in Eq.(8) are the \( e^\pm \) fluxes due to DM decays at the source. However, only the \( e^\pm \) fluxes at the Earth are observable. It is thus necessary to consider the propagation of electrons and positrons in the Galaxy. The \( e^\pm \) flux per unit energy at an arbitrary space-time point is given by

\[
\Phi_\text{DM}^e(t, \vec{r}, E) = \frac{v_e}{4\pi} f_\text{DM}^e(t, \vec{r}, E).
\]

(10)

For energetic \( e^\pm \)'s that we consider, their velocity \( v_e \) is approximately equal to the light speed \( c \). The function \( f_\text{DM}^e(t, \vec{r}, E) \) satisfies the diffusion-loss equation

\[
\frac{\partial f_\text{DM}^e}{\partial t} = K(E) \cdot \nabla^2 f_\text{DM}^e + \frac{\partial}{\partial E} \left(B(E)f_\text{DM}^e\right) + Q_\text{DM}^e.
\]

(11)

Here the convection and advection terms have been neglected. \( Q_\text{DM}^e \) is due to the DM decays as given in Eq.(8). \( K(E) \) stands for the diffusion coefficient which is related to the rigidity of the particle. For \( e^\pm \), it can be parameterized as

\[
K(E) = K_0(E/\text{GeV})^\delta.
\]

(12)

\( B(E) = E^2/(\text{GeV} \cdot \tau_E) \) is the effective energy loss coefficient with \( \tau_E = 10^{16} \) s, which describes the energy loss of \( e^\pm \) due to ICS on the ISRF and synchrotron radiation. Eq. (11) can be solved in a solid flat cylinder parameterized by \( (r, z, \theta) \), with \( z \in [-L, L] \) in z direction and \( r \in [0, 20 \) kpc] in radius. The solar system corresponds to the position \( (r_\odot, z_\odot, \theta_\odot) =\)
Table I: Parameters in Eq.(15) in accord with the NFW halo model and MED propagation model.

| $a_0$ | $a_1$ | $a_2$ | $a_3$ | $b_1$ | $b_2$ | $c_1$ | $c_2$ |
|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.502 | 0.621 | 0.688 | 0.806 | 0.891 | 0.721 | 0.143 | 0.071 |

(8.5 kpc, 0, 0). $f_e^{DM}(t, \vec{x}, E)$ is assumed to vanish on the surface of the flat cylinder, which serves as the boundary condition for this equation. For the MED propagation model, $L$, $\delta$ and $K_0$ are chosen to be 4 kpc, 0.70 and 0.0112 kpc$^2$/Myr, respectively [40].

If $f_e^{DM}(t, \vec{x}, E)$ does not change with time, a steady state solution Eq. (11) can be obtained semi-analytically [34, 40–42]. The $e^\pm$ fluxes at the Earth are

$$
\Phi_e^{DM}(r_\odot, E) = \frac{c}{4\pi B(E)} \sum_l \rho_\odot \Gamma_i^{DM} \int_{E}^{M_{DM}/2} dE' I(\lambda_D(E, E')) \frac{dN_{i\rightarrow e}^{DM}}{dE'} .
$$

Here $\lambda_D(E, E')$ describes the diffusion length from energy $E'$ to $E$, which can be parameterized as

$$
\lambda_D^2 = 4K_0 \tau_E \left( \frac{(E/\text{GeV})^{\delta-1} - (E'/\text{GeV})^{\delta-1}}{1 - \delta} \right).
$$

The function $I(\lambda_D)$ is given by:

$$
I(\lambda_D) = a_0 + a_1 \tanh \left( \frac{b_1 - l}{c_1} \right) \left[ a_2 \exp \left( -\frac{(l - b_2)^2}{c_2} \right) + a_3 \right]
$$

with $l = \log_{10}(\lambda_D/\text{kpc})$. $I(\lambda_D)$ contains the whole information of the NFW halo model and MED propagation model. Parameters in Eq.(15) have been estimated numerically in Ref. [40] and listed in Table I.

B. Positron and Electron Backgrounds

For interstellar background fluxes of $e^\pm$, we use the “model 0” proposed by the Fermi LAT collaboration[7], which can be parameterized as [43].

$$
\Phi_{e^-}^{bkg}(E) = \frac{82.0 \epsilon^{-0.28}}{1 + 0.224 \epsilon^{2.93}} ,
$$

$$
\Phi_{e^+}^{bkg}(E) = \frac{38.4 \epsilon^{-4.78}}{1 + 0.0002 \epsilon^{5.63}} + 24.0 \epsilon^{-3.41}
$$

in units of GeV$^{-1}$m$^{-2}$s$^{-1}$sr$^{-1}$, where $\epsilon = E/1\text{GeV}$.
For electron/positron fluxes at the top of the Earth’s atmosphere $\Phi_{e^\pm}^{\oplus}$, solar modulation effects should be considered. Adopting the force field approximation, one has [44]

$$\Phi_{e^\pm}(E_{\oplus}) = \frac{E_{\oplus}^2}{E_{IS}^2} \Phi_{e^\pm}^{IS}(E_{IS}), \quad (18)$$

where $\Phi_{e^\pm}^{IS}$ stand for interstellar fluxes and $E_{\oplus} = E_{IS} + |Ze|\phi_F$, with $\phi_F = 0.55$GV as a typical value. It is clear that, at energies larger than $10$GeV, solar modulation effects could be neglected as $E_{\oplus} \approx E_{IS}$.

Finally, the $e^\pm$ fluxes and positron fraction at the top of the Earth’s atmosphere could be expressed as

$$E_{\oplus}^3 \times \Phi_{\oplus}(E_{\oplus}) = E_{IS}^3 \times \frac{E_{\oplus}^2}{E_{IS}^2} \left[ \Phi_{e^+}^{IS}(E_{IS}) + \Phi_{e^-}^{IS}(E_{IS}) + N \cdot \Phi_{e^+}^{BS}(E_{IS}) + \Phi_{e^-}^{BS}(E_{IS}) \right], \quad (19)$$

$$\frac{\Phi_{e^+}(E_{\oplus})}{\Phi_{e^+}(E_{\oplus}) + \Phi_{e^-}(E_{\oplus})} = \frac{\Phi_{e^+}^{IS}(E_{IS}) + \Phi_{e^-}^{IS}(E_{IS})}{\Phi_{e^+}^{BS}(E_{IS}) + \Phi_{e^-}^{BS}(E_{IS}) + N \cdot \Phi_{e^+}^{BS}(E_{IS}) + \Phi_{e^-}^{BS}(E_{IS})}. \quad (20)$$

Here $N$ is a normalization factor standing for the uncertainty of the electron flux. In this paper $N = 0.8$ is chosen to fit the experimental data.

### C. A Fit of PAMELA and Fermi LAT Data

For illustration, we choose DM mass $M_{\tilde{\chi}} = 6.5$ TeV, $M_{GUT} = 10^{16}$ GeV, $<\tilde{\chi}> = 20$ TeV, $M_{\tilde{\chi}} = 380$ GeV, $M_{\tilde{\chi}} = 370$ GeV, $M_{\tilde{\chi}} = 330$ GeV and $M_{LSP} = 300$ GeV.\(^4\) With this parameter set, the decaying DM produces extra $e^\pm$ fluxes from 10 GeV to 1 TeV, as shown in Fig.1a. The main contribution comes from the selectron chain. The cascade decay $\tilde{\chi} \to \tilde{\ell}^+ + \tilde{\ell}^- \to e^+ + e^-$ smooths the $e^+ + e^-$ spectrum and naturally allows for a good fit to the Fermi LAT measurement. The $e^\pm$ fluxes steepen above 1TeV sharply, which is consistent with the H.E.S.S. observation. The positron fraction are shown in Fig.1b, compared to the data of PAMELA, AMS-01, CAPRICE and HEAT.

\(^4\) We have checked explicitly that, for this set of slepton masses, the neutralino LSP could be only a minor part of the DM. For example, by using DarkSUSY package[45], we have obtained $\Omega_{LSP} h^2 = 0.009$, with the neutralino mass spectrum $M_{LSP} = M_{\chi_1} = 300$ GeV, $M_{\chi_2} = 315$ GeV, $M_{\chi_3} = 630$ GeV, $M_{\chi_4} = 690$ GeV and the gaugino fraction to be 0.03.
Figure 1: The SU(5) model gives a reasonable fit to the Fermi, H.E.S.S. and Pamela data with the example set of parameters given in the text. Left: Decaying DM produces extra $e^- + e^+$ fluxes above background via three different cascade decay chains. The green dot line, black dash dot line and pink dash dot dot line represent the selectron chain, the smuon chain and the stau chain, respectively. The red solid line includes all contributions from our fit. The black dash line shows the background as discussed in the text. Right: Including the $e^+$ background flux, decaying DM predicts a positron fraction which fits the experimental data. The red solid line shows the result of our fit, and the black dash line indicates the background.

IV. DIFFUSE GAMMA-RAYS FROM THE $e^\pm$ EXCESSES

The $e^\pm$ excesses are inevitably accompanied by photons coming from the FSR, ICS and synchrotron radiation stemming from them.

1) FSR: The bremsstrahlung of $e^\pm$ fluxes leads to the emission of energetic photon flux $\Phi_{FSR}$. Moreover, in our model the stau chain contains $\tau$ lepton which emits hard photons via the process $\tau \rightarrow \pi^0 \rightarrow \gamma + \gamma$. This mechanism is significant, especially at the high energy end of the spectrum. The largest energy of FSR photons could be around $M_{DM}/2$, which could be probed by the H.E.S.S. collaboration. Notice also that the spectrum of FSR is quite model-dependent. In addition, the FSR could come from within or without our Galaxy ($\Phi_{FSR}^{GAL}/\Phi_{FSR}^{EG}$).

2) ICS: The ICS radiation is produced when the $e^\pm$ excesses scatter on the ISRF. In our Galaxy the ISRF includes the cosmic microwave background (CMB), star light and the infrared light, while outside of our Galaxy the CMB component is dominant. The
corresponding ICS fluxes $\Phi_{\text{ICS}}^{\text{GAL}}$ and $\Phi_{\text{ICS}}^{\text{EG}}$, which should be observable by Fermi LAT, are closely related to the $e^\pm$ excesses. Therefore the ICS spectrum is, to some extent, model independent as long as the DM model can reproduce the Fermi and H.E.S.S. $e^\pm$ spectrum with reasonable accuracies.

(3) Synchrotron radiation: During propagation, the $e^\pm$ fluxes radiate photons in the Galactic magnetic fields. These photons should be very soft (around $10^{-6}$eV) and outside the energy range explored by Fermi LAT and H.E.S.S. experiments. They will not be considered in the following.

Notice that the extragalactic gamma rays are roughly of the same order as the Galactic ones. But the extragalactic component is isotropic while the Galactic one has angular dependence. The total gamma ray flux is obtained by summing all these contributions:

$$\Phi_\gamma = \Phi_{\text{FSR}}^{\text{GAL}} + \Phi_{\text{ICs}}^{\text{GAL}} + \Phi_{\text{FSR}}^{\text{EG}} + \Phi_{\text{ICs}}^{\text{EG}}$$ (21)

Specifically, we consider only photons in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$ in the following, as Fermi LAT has released the data in this region recently [31].

A. Galactic Gamma Rays from FSR

As photons propagate almost freely in the Galaxy, the differential flux of photons received at the Earth in a given solid angle $d\Omega$ is given by [40]

$$\frac{d\Phi_{\text{FSR}}^{\text{GAL}}}{dE_\gamma d\Omega} = 2\frac{r_\odot}{4\pi M_{\text{DM}}} \frac{\rho_\odot}{J} \sum_i \frac{dN_{\text{DM}}^{\Gamma_i}}{dE_\gamma}. $$ (22)

Here the factor of 2 takes into account the fact that both leptons and anti-leptons contribute equally to the FSR flux of gamma rays. $dN_{\text{DM}}^{\Gamma_i}/dE_\gamma$ is the photon spectrum per DM decay via a specific slepton chain. PYTHIA package [39] has been used here to obtain these spectra. $J$ encodes all the astrophysical information which is defined as

$$J = \Delta \Omega \int d\Omega \int_0^{\infty} ds \frac{\rho(r)}{r_\odot \rho_\odot}, $$ (23)

where the parameter $s$ is integrated along a line of sight. The parameter $s$ can be linked to parameters $r$, $l$ and $b$ by

$$r(s, l, b) = \sqrt{s^2 + r_\odot^2 - 2sr_\odot \cos l \cos b}. $$ (24)
Figure 2: Galactic gamma ray spectra from FSR (left) and ICS (right) via three different decay chains, plotted in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$.

From Eq. (23), one obtains $\mathcal{J} = 2.4$ in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$. The photon spectra from Galactic FSR are plotted in Fig. 2a, which peak around several hundred GeV. Notice that the stau chain gives a large contribution to the photon spectrum due to $\tau \rightarrow \pi^0 \rightarrow \gamma + \gamma$.

B. Galactic Gamma Rays from ICS

A pedagogical review about ICS was provided in [46]. We will calculate the ICS gamma rays semi-analytically, following Refs. [12, 43, 47, 48].

The differential flux of ICS photons received at the Earth in a given solid angle $d\Omega$ with energy between $E_\gamma$ and $E_\gamma + dE_\gamma$ can be expressed as:

$$
\frac{d\Phi_{ICSS}^{ICSS}}{dE_\gamma d\Omega} = \frac{2c}{4\pi \Delta \Omega} \int d\Omega \int_0^\infty ds \int_0^{\infty} d\epsilon \int_{M_e}^{M_{DM}/2} dE_e \frac{d\sigma^{ICS}(E_e, \epsilon)}{dE_\gamma} f_e^{DM}(\vec{r}, E_e) f_{ISRF}(\vec{r}, \epsilon),
$$

(25)

here $f_e(\vec{r}, E_e)$ denotes initial electron number density and $f_{ISRF}(\vec{r}, \epsilon)$ the ISRF photon number density. The factor of 2 reflects that both electrons and positrons contribute to the ICS gamma rays equally. The Compton cross section is given by the Klein-Nishina formula

$$
\frac{d\sigma^{ICS}(E_e, \epsilon)}{dE_\gamma} = \frac{3\sigma_T}{4\gamma_e^2 \epsilon} \left( 2q \ln q + 1 + q - 2q^2 + \frac{(q\Gamma)^2}{2(1 + q\Gamma)(1 - q)} \right),
$$

(26)

where

$$
q = \frac{E_\gamma}{\Gamma(E_e - E_\gamma)}, \quad \Gamma = \frac{4\gamma_e \epsilon}{m_e}, \quad \gamma_e = \frac{E_e}{m_e}.
$$

(27)
Here $\sigma_T = 0.67$ barn is the Compton scattering cross section in the Thomson limit and $m_e$ is the electron mass. Kinematics requires that $\epsilon \leq E_\gamma \leq (1/E_e + 1/4\gamma_e^2\epsilon)^{-1}$.

The initial electron or positron number density $f_e(\vec{r},E_e)$ can be obtained by solving Eq.(11) at each position. Notice that Eq.(11) is dominated by the energy loss term at high energy. That is to say, $e^\pm$ can not propagate far from the production position before losing most of their energy. Therefore, Eq.(11) may be solved point by point approximately

$$f_e^{DM}(\vec{r},E_e) = \frac{1}{B(E_e)} \frac{\rho(\vec{r})}{M^{DM}} \sum_l \Gamma_l Y_l(E_e)$$

with

$$Y_l(E_e) = \int_{E_e}^{M^{DM}/2} dE' \frac{dN^{DM}_{l\rightarrow e}}{dE'} .$$

To approximate further, we will assume that the ISRF photons have the same energy spectra at any point in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$. That is to say, the number density of ISRF $f_{ISRF}(\vec{r},\epsilon) = f_{ISRF}(\epsilon)$, which can be described by three blackbody-like spectra roughly [47]:

$$f_{ISRF}(\epsilon) = \sum_{i=1,2,3} N_i \epsilon^2 \pi^2 \frac{1}{e^{\epsilon/T_i} - 1}$$

with $T_1 = 2.753$ K, $N_1 = 1$ for the CMB, $T_2 = 3.5 \times 10^{-3}$ eV, $N_2 = 1.3 \times 10^{-5}$ for the infrared light and $T_3 = 0.3$ eV, $N_3 = 8.9 \times 10^{-13}$ for the star light.

In order to separate astrophysics and particle physics information, Eq.(25) can be rewritten as

$$\frac{d\Phi^{GAL\_ICS}}{dE_\gamma d\Omega} = 2c \frac{\rho_c}{4\pi M^{DM}} \sum_l \int_0^\infty \int_{E_e}^{M^{DM}/2} dE_e \frac{d\sigma^{ICS}(E_e,\epsilon)}{dE_\gamma} \frac{1}{B(E_e)} \Gamma_l Y_l(E_e) f_{ISRF}(\epsilon) .$$

Shown in Fig.2b is the ICS photon spectra in our model. One sees that the gamma ray fluxes come mostly from the electron chain and steepen sharply above 1 TeV.

C. Extragalactic Gamma Rays from FSR

To study gamma rays from the outside of our Galaxy, the effects due to the expansion of the Universe should be considered. By turning the line-of-sight integral into a redshift integral, the differential flux of isotropic photons of the extragalactic origin is given by [12, 49]

$$\frac{d\Phi^{EG\_FSR}}{dE_\gamma d\Omega} = \frac{2c}{4\pi M^{DM}} \frac{\rho_c}{\Omega} \sum_l \int_0^\infty dz \frac{e^{-\tau(E_\gamma,z)}}{H(z)} \frac{dN^{DM}_{l\rightarrow \gamma}}{dE_\gamma} \bigg|_{E'_\gamma = (1+z)E_\gamma} .$$
Figure 3: Extragalactic gamma ray spectra from FSR (left) and ICS (right) via three different decay chains, plotted in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$.

Here $z$ is the redshift, $H(z) = H_0 \sqrt{\Omega_\Lambda + \Omega_M(z + 1)^3}$ is the Hubble expansion rate, with $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$ and the present day normalized Hubble expansion rate $h = 0.72$[16]. $\rho_c = 5.5 \times 10^{-6}$GeV/cm$^3$ is the critical density of the Universe. We also take the dark matter density $\Omega_{DM} = 0.21$, the dark energy density $\Omega_\Lambda = 0.74$ and the matter density $\Omega_M = 0.26$[16]. The spectrum $dN_{\gamma}^{DM}/dE_{\gamma}$ is the same as that in Eq (22), except that the redshift effect has been included. The parametric form for the optical depth $\tau(E_{\gamma}, z)$ of the "fast evolution" model could be found in Refs. [50, 51]. Fig.3a shows those contributions of our model. Again the stau chain is important here because of the $\pi^0$ channel.

D. Extragalactic Gamma Rays from ICS

We adopt a semi-analytical calculation following Refs.[48, 49]. Concerning the dilution effect due to the expansion of the Universe, the diffusion-loss equation of electrons and positrons becomes

$$ \frac{\partial f_e^{DM}}{\partial t} = H(z)E_e \frac{\partial f_e^{DM}}{\partial E_e} + \frac{\partial}{\partial E_e} \left[ B^{EG}(z, E_e)f_e^{DM} \right] + Q_e^{DM} \, . $$

Here the extragalactic energy loss rate $B^{EG}(z, E)$ is given as

$$ B^{EG}(z, E_e) = \frac{4}{3} \sigma_T \gamma_e^2 \rho_{CMB}(1 + z)^4 $$(34)

with $\rho_{CMB} = \Omega_\gamma \rho_c = 0.26 \times 10^{-9}$GeV/cm$^3$ the present-day CMB energy density. For $e^\pm$ energy around several hundred GeV, the timescale of energy-loss is $E/B^{EG}(z, E) \sim 10^{14}$s,
which is much less than the Hubble time. That is to say, basically $e^\pm$ do not feel the redshift effect before losing most of their energy. So the Hubble term in Eq(33) can be safely neglected. The $e^\pm$ spectrum from DM decay can then be solved as

$$f_{eDM}(z, E_e) = \frac{(1 + z)^3}{BEG(z, E_e)} \frac{\Omega_{DM} \rho_c}{M_{DM}} \sum_i \Gamma_{e^\pm_i} Y(E_e).$$  \hspace{1cm} (35)$$

Finally, the differential flux of extragalactic ICS photons received at the Earth in an arbitrary solid angle $d\Omega$ with energy between $E_\gamma$ and $E_\gamma + dE_\gamma$ can be expressed as:

$$d\Phi_{ICS}^{EG} \frac{dE_\gamma}{d\Omega} = \frac{2c}{4\pi} \int_0^\infty \frac{dz dE_e}{(1 + z)^3 H(z)} f_\gamma(z, \epsilon) f_{eDM}(z, E_e) \frac{d\sigma_{ICS}(z, E_\gamma, \epsilon)}{dE_\gamma} \bigg|_{E_\gamma = (1 + z)E_\gamma}. \hspace{1cm} (36)$$

The spectrum $f_\gamma(z, \epsilon)$ of the background CMB radiation at redshift $z$ is given as

$$f_\gamma(z, \epsilon) = \frac{\epsilon^2}{\pi^2} \frac{1}{e^{\epsilon/[(1+z)T]} - 1} \hspace{1cm} (37)$$

with $T = 2.753$ K. The photon spectra from extragalactic ICS are plotted in Fig.3b, which are dominated by the selectron chain contribution. Because of the redshift, the spectrum drops rapidly at high energy.

Finally, Fig. 4 shows the total gamma ray spectra including all contributions. One can see that the FSR $\gamma$-rays dominate at higher energies while the ICS ones dominate at lower energies. Extragalactic gamma rays are not significant at high energy due to the redshift effect. The total gamma ray spectrum from $e^\pm$ excesses are consistent with the preliminary Fermi LAT data [31] from 0.1 GeV to 10 GeV, as shown in Fig. 4. The predicted gamma ray flux around several hundred GeV may be tested by the Fermi satellite in the near future.

V. SUMMARY

In this paper we have studied the DM decay in supersymmetric SU(5) models. An SU(5) singlet $S$, instead of LSP, is assumed to be the dominant component of DM. With R-parity conservation and a spontaneously broken $Z_2$ symmetry, the singlet $S$ can decay into visible particles through dimension six effective operators suppressed by the GUT scale. Assuming the squarks to be heavier than $S$, $S$ decays dominantly into a pair of sleptons through the effective operator $\tilde{s}^* (\tilde{l_L}^* \Box \tilde{l_L} + \tilde{l_R}^* \Box \tilde{l_R})$. Typically, the lifetime of $S$ is around $10^{26}$ s, much longer than the age of the Universe. Since the decay products of $S$ do not contain any quarks, our model is consistent with the Pamela antiproton measurement automatically. For
Figure 4: All gamma ray spectra in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$. Dots stand for the preliminary Fermi LAT data [31].

In illustration, we have chosen $M^{DM} = 6.5$ TeV, $M_{GUT} = 10^{16}$ GeV, $M_{\tilde{e}} = 380$ GeV, $M_{\tilde{\mu}} = 370$ GeV, $M_{\tilde{\tau}} = 330$ GeV and $M_{LSP} = 300$ GeV. With this parameter set, we have shown that the $S$ decays can account for the PAMELA, H.E.S.S. and Fermi LAT $e^\pm$ excesses. Numerically, we have adopted the NFW profile for the dark matter distribution and the MED propagation model for the cosmic ray propagation. To interpret these results, one should keep in mind that there exist substantial astrophysical uncertainties about $e^\pm$ background, $e^\pm$ propagation and the DM distribution.

When $e^\pm$ propagate from the decay position to the Earth, hard photons are emitted inevitable due to inverse Compton scattering and final state radiation. Future measurements of the diffuse gamma ray may distinguish DM explanations from astrophysical explanations by looking into the energy and angular distributions. We have calculated the gamma ray spectra in our model. The predicted photon spectrum are compared to the preliminary Fermi LAT measurement from 0.1 GeV to 10 GeV in the region $0^\circ \leq l \leq 360^\circ$, $10^\circ \leq |b| \leq 20^\circ$, which seems to be consistent with each other. The total gamma ray spectrum are dominated
by photons from Galactic final state radiation for the photon energy above 100 GeV, which may be tested by Fermi LAT in the near future.

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Appendix A: the component field structure of $S^+S\Phi^+\Phi$

We now provide the component field structure of the dimension six operator $S^+S\Phi^+\Phi$.

Define

\[
\Phi(y) = \tilde{\psi}(y) + \sqrt{2}\theta\psi(y) + \theta^2 F_{\psi}(y), \quad \Phi^+(y^+) = \tilde{\psi}^*(y^+) + \sqrt{2}\theta\tilde{\psi}(y^+) + \bar{\theta}^2 F^*_{\psi}(y^+) \tag{A1}
\]

\[
S(y) = \tilde{s}(y) + \sqrt{2}\theta s(y) + \theta^2 F_s(y), \quad S^+(y^+) = \tilde{s}^*(y^+) + \sqrt{2}\theta\tilde{s}(y^+) + \bar{\theta}^2 F^*_s(y^+) \tag{A2}
\]

with $y^m = x^m + i\theta\sigma^m\tilde{\theta}$ and $y^{+m} = x^m - i\theta\sigma^m\tilde{\theta}$.

Products of chiral superfields are again chiral superfields, and likewise for their conjugates. Define again

\[
A(y) = \Phi(y)S(y) = \tilde{a}(y) + \sqrt{2}\theta a(y) + \theta^2 F_a(y) \tag{A3}
\]

\[
A^+(y^+) = \Phi^+(y^+)S^+(y^+) = \tilde{a}^*(y^+) + \sqrt{2}\theta\tilde{a}(y^+) + \bar{\theta}^2 F^*_a(y^+) \tag{A4}
\]

The component fields of these composite superfields are

\[
\tilde{a} = \tilde{\psi}\tilde{s}, \quad a = \tilde{\psi}s + \tilde{s}\psi, \quad F_a = \tilde{\psi}F_s + \tilde{s}F_{\psi} - \psi s \tag{A5}
\]

\[
\tilde{a}^* = \tilde{\psi}^*\tilde{s}^*, \quad a^* = \tilde{\psi}^*\tilde{s} + \tilde{s}^*\tilde{\psi}, \quad F_a^* = \tilde{\psi}^*F_s^* + \tilde{s}^*F_{\psi}^* - \tilde{\psi}s \tag{A6}
\]

The $\theta\theta\tilde{\theta}\tilde{\theta}$ term of the dimension six operator

\[
\sum \frac{S^+S\Phi^+\Phi}{M^2_{\text{GUT}}} = \sum \frac{S^+\Phi^+\Phi S}{M^2_{\text{GUT}}} = \sum \frac{(\Phi S)^+ (\Phi S)}{M^2_{\text{GUT}}} = \sum \frac{A^+A}{M^2_{\text{GUT}}} \tag{A7}
\]
is given as [52]:

\[
F^*_a F_a + \frac{1}{4} \bar{a} \Box a + \frac{1}{4} \Box \bar{a}^* a - \frac{1}{2} \partial_m \bar{a}^* \partial^m \bar{a} + \frac{i}{2} \partial_m \bar{a} \sigma^m a - \frac{i}{2} \bar{a} \bar{\sigma}^m \partial_m a \tag{A8}
\]

Assuming the singlet scalar develops a vacuum expectation value (VEV) \( < \tilde{s} > \), the \( Z_2 \) symmetry is spontaneously broken and both components \( (\tilde{s}, s) \) in \( S \) will decay. Eq. (A8) can be reexpressed via Eq. (A5, A6).

\[
\sum_{\phi} \frac{1}{M_{GUT}^2} \left( i < \tilde{s} > \tilde{s}^*(\partial_\mu \psi \sigma^\mu \tilde{\psi}) + i < \tilde{s} > \tilde{\psi}^*(\partial_\mu \psi \sigma^\mu s) + < \tilde{s} > \tilde{\psi}^* \Box \tilde{\psi} \right) + h.c. + ... \tag{A9}
\]

Here we have dropped total divergence terms. Operators from F-terms have also been neglected as they are suppressed by the leptonic Yukawa coupling constant. In addition, these operators will lead to many body decays which are further suppressed by phase spaces.

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