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An Effective Theory of Dirac Dark Matter

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A stable Dirac fermion with four-fermion interactions to leptons suppressed by a scale $\Lambda \sim 1$ TeV is shown to provide a viable candidate for dark matter. The thermal relic abundance matches cosmology, while nuclear recoil direct detection bounds are automatically avoided in the absence of (large) couplings to quarks. The annihilation cross section in the early Universe is the same as the annihilation in our galactic neighborhood. This allows Dirac fermion dark matter to naturally explain the positron ratio excess observed by PAMELA with a minimal boost factor, given present astrophysical uncertainties. We use the Galprop program for propagation of signal and background; we discuss in detail the uncertainties resulting from the propagation parameters and, more importantly, the injected spectra. Fermi/GLAST has an opportunity to see a feature in the gamma-ray spectrum at the mass of the Dirac fermion. The excess observed by ATIC/PPB-BETS may also be explained with Dirac dark matter that is heavy. A supersymmetric model with a Dirac bino provides a viable UV model of the effective theory. The dominance of the leptonic operators, and thus the observation of an excess in positrons and not in anti-protons, is naturally explained by the large hypercharge and low mass of sleptons as compared with squarks. Minimizing the boost factor implies the right-handed selectron is the lightest slepton, which is characteristic of our model. Selectrons (or sleptons) with mass less than a few hundred GeV are an inescapable consequence awaiting discovery at the LHC.

I. INTRODUCTION

We propose a new dark matter candidate that is a stable Dirac fermion with four-fermion couplings to leptons. This candidate automatically avoids the direct detection bounds from nuclear recoil direct detection experiments in the absence of couplings to quarks. The annihilation rate through a four-fermion leptonic operator yields a thermal relic abundance consistent with cosmological data for an electroweak scale mass and TeV scale suppressed operator. In this paper we present the effective theory, the application to the recent PAMELA positron ratio observations [1] and present a supersymmetric realization.

The annihilation rate of Dirac dark matter into leptons is not velocity suppressed, similar to KK dark matter [2, 3, 4], allowing for an unsuppressed annihilation rate in our local galactic neighborhood. This provides a compelling explanation of the up-turn in the ratio of positron flux to electron plus positron flux observed by the PAMELA collaboration for positron energies above about 10 GeV [1]. Several groups have already considered various implications of this result using pre-publication [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21] and post-publication [22, 23, 24, 25] PAMELA data. In our effective theory, we find that minimal enhancement in the local annihilation rate (a minimal boost factor) is required given the uncertainties in the local dark matter density as well as the present uncertainties in the background flux of electrons and positrons.

We first present our effective theory of Dirac dark matter. Our discussion is general; we consider all operators consistent with the symmetries. We focus on the four-fermion leptonic dimension-6 operator that gives the largest annihilation rate into positrons. We then proceed to calculate the thermal relic density resulting from these operators, determining the relative ranges of parameters that are consistent with the cosmological abundance $\Omega h^2 \simeq 0.1143 \pm 0.0034$ [26]. Since the thermally-averaged annihilation rate is not velocity suppressed, the same cross section that determines the thermal relic abundance also determines the local annihilation rate in the galaxy. This lack of velocity dependence also eliminates the uncertainty associated with the local WIMP velocity distribution.

We then discuss the indirect detection signal of Dirac dark matter through annihilation into leptons and anti-leptons. Understanding the size and uncertainties of background sources of electrons and positrons from non-dark matter sources is discussed in detail. We do not consider point astrophysical sources (such as pulsars [16, 18]), and instead concentrate on secondary production [27] from protons scattering off other protons, using the Galprop code [28]. Since the PAMELA collaboration has not provided the absolute flux of electrons or positrons, we must use other experimental results to determine the background spectra. We have analyzed the electron spectra of several recent experiments, including AMS-01 [29], ATIC [30], BETS [31, 32], CAPRICE [33], HEAT [34], and MASS [35], and thus determined the best-fit per experiment and range of experimentally measured background electron flux. The positron injection spectrum and its spatial distribution is determined from Galprop as secondary production of positrons from pri-

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mary cosmic rays (mostly protons) that scatter off other protons or nuclei. This spectrum is normalized by matching the well-measured proton flux, which we have cross-checked against the preliminary proton spectra results of PAMELA [36], and by the spatial distribution of interstellar gas.

The propagation and energy loss of the positrons is folded in consistently using Galprop to determine the positron spectrum and positron flux ratio that would be expected at PAMELA or AMS-02. We find the flux ratio spectrum matches the PAMELA data [1] with either a light Dirac fermion that annihilates into e^+e^-, or democratically into all charged leptons $\ell^+\ell^-$, $\ell = e, \mu, \tau$. Interpolations between these cases are also consistent with the data. The boost factor is minimized for the lightest mass dark matter particle and with annihilation purely into e^+e^-. We find it can be as small as 1, for the case of a 100 GeV Dirac fermion annihilating only into e^+e^-, assuming the local *average* relic density $\rho_{8.5} = 0.7$ GeV/cm^3 and an e^- cosmic spectrum $\Phi_{e^-}(E)$ that falls as $E^{-3.15}$, *or* for $\rho_{8.5} = 0.3$ GeV/cm^3 and an e^- spectrum that falls as $E^{-3.5}$. For canonical values we use in this paper, $\rho_{8.5} = 0.3$ GeV/cm^3 and $\Phi_{e^-}(E) \propto E^{-3.15}$, the boost factor is 5. Larger masses are permitted to the extent that a larger boost factor B is plausible, scaling approximately as $B \propto M^2$.

Dirac dark matter with a minimal boost factor immediately implies that PAMELA should see a sharp drop in their positron spectrum above the mass of the Dirac fermion. At exactly what mass we expect this drop to occur is nontrivially convoluted with the astrophysical uncertainties of the background flux and the local dark matter density. We will illustrate these uncertainties and their impact on a Dirac fermion dark matter interpretation. Other experiments, particularly Fermi/GLAST, should see a photon feature at the mass of the Dirac fermion, which results from final-state radiation off the charged lepton [37]. This observation may occur before, simultaneous with, or after PAMELA provides their spectral data up to their experimental limit.

There have also been hints of an excess in the flux of electrons *plus* positrons, reported by ATIC [30] for energies between about 300-500 GeV and PPB-BETS [32] for energies between about 200-500 GeV. An earlier study of the electron flux with an emulsion chamber balloon experiment [38] in the same energy range, however, did not observe an excess (see also [32]). Nevertheless, this hint has been recently investigated and interpreted in [10, 12, 22]. If this hint persists and is confirmed by future data, it is straightforward to explain with Dirac dark matter so long as the mass of the Dirac fermion is large. Within the uncertainties in the electron spectra, the boost factor needed to explain the PAMELA excess as well as a feature in the spectra observed by ATIC/PPB-BETS can be as small as 16 for $M = 400$ GeV.

Dirac fermion dark matter may interact in other ways, in particular with quarks. However, vector interactions between a Dirac fermion and quarks are highly constrained by the absence of direct detection through nuclear recoil, a fact well-known from neutrino dark matter (for example, see [39]). Other implications, such as indirect detection through accumulation and annihilation in the Sun are certainly possible if the dark matter scattering off protons in the Sun is efficient enough to bring capture and annihilation into equilibrium. For example, if the dominant annihilation mode were into *left-handed* leptons, then a neutrino signal becomes a distinct possibility.

Finally, we show that a viable ultraviolet (UV) completion for a Dirac fermion that automatically has the desired properties to explain the PAMELA positron excess is a Dirac bino in supersymmetry. Dirac gauginos occur automatically in supersymmetric models with an exact R-symmetry [40]. Model-building the lightest supersymmetric particle to be a Dirac bino is a fairly straightforward variation of the model proposed in [40] (albeit with some supergravity subtleties that we outline below). Four-fermion operators arise from the exchange of sfermions, and thus the relative strength of different operators can be directly interpreted in terms of the strength of couplings and the relative hierarchy of sfermion masses. Since a Dirac bino couples through hypercharge, the largest four-fermion couplings are to the right-handed sleptons. Moreover, models of supersymmetry run from higher scales often give the smallest masses to the right-handed sleptons. This provides a compelling explanation of the dominance of right-handed leptonic operators for annihilation. Minimizing the boost factor implies the right-handed selectron is the lightest slepton, which is characteristic of our model. We can use the annihilation rate to predict the range of slepton masses, less than a few hundred GeV, which provides fantastic opportunities for discovery and further study at the LHC.

II. DIRAC DARK MATTER

An effective field theory of Dirac dark matter is extremely simple. The purported dark matter particle is a Dirac fermion D that transforms under an exact continuous global symmetry $U(1)_D$, $D \to De^{i\theta_D}$. For the purposes of this discussion, we assume the full $U(1)_D$ global fermion number to be conserved, but a discrete subgroup may also suffice to ensure the particle is stable. The global $U(1)_D$ allows a vector-like mass term for D. The Lagrangian for this electroweak- and color-neutral particle is

$$\mathcal{L} \; = \; i\bar{D}\partial\!\!\!/ D - M\bar{D}D \qquad (1)$$

A general effective field theory for D interacting with the SM can be written as

$$\mathcal{L} = \sum_{n,i} \frac{\mathcal{O}_i^{(n)}}{\Lambda^{n-4}} \; , \qquad (2)$$

where the leading interactions are through n-dimensional operators labeled by i. The only operator at dimension-5,

$$\mathcal{O}^{(5)} \; = \; \frac{\bar{D}DH^\dagger H}{\Lambda} \tag{3}$$

while there are many operators at dimension-6, including

$$\mathcal{O}^{(6)}_{f_L} \; = \; c_f^L \frac{\bar{D}\gamma^\mu D \bar{f}\gamma_\mu P_L f}{\Lambda^2} \tag{4}$$

$$\mathcal{O}^{(6)}_{f_R} \; = \; c_f^R \frac{\bar{D}\gamma^\mu D \bar{f}\gamma_\mu P_R f}{\Lambda^2} \tag{5}$$

We did not write interactions involving $\bar{D}\gamma^\mu\gamma^5 D$ because they lead to either velocity-suppressed or mass-suppressed interactions. Since left-handed SM fields transform as doublets under $SU(2)_L$, for leptons c_ℓ^L automatically leads to equal interaction strength to charged left-handed leptons and their neutrino partners. Similarly, c_ℓ^R leads to an interaction with just right-handed charged leptons. The right-handed four-fermion leptonic operator will be the main focus of this paper.

Before proceeding, it is worthwhile to examine effects of the other operators. The leading dimension-5 operator, after electroweak symmetry breaking, leads to three effects: a coupling to a pair of Higgses, a coupling to just one Higgs, and a shift in the Dirac mass. The coupling $\bar{D}Dh^2$ allows dark matter to annihilate into a pair of Higgses. The single Higgs coupling, $(v/\Lambda) \times \bar{D}Dh$ has two interesting effects: If $M < m_h/2$, the Higgs could decay into a pair of dark matter fermions, with a branching ratio proportional to $(v/\Lambda)^2$ that could compete with $h \to \bar{b}b$ if $m_h \lesssim 2M_W$. If $M > m_h/2$, Higgs decays are essentially unaffected by the presence of Dirac dark matter. Nevertheless, this effective interaction can lead to dark matter annihilation through an s-channel Higgs. It is a model-dependent question whether the dimension-5 Higgs interaction is important or relevant. (For a Dirac bino, it is irrelevant, as we will see below.)

The dimension-6 operators include interactions between Dirac dark matter with both quarks and leptons, left-handed and right-handed. Vector-like interactions between dark matter and quarks leads to a spin-independent scattering cross section that is strongly constrained by direct dark matter searches such as CDMS [41] and Xenon [42]. Since no direct detection signal has been (unambiguously) observed, and PAMELA has not found an excess in anti-protons [43], we will not consider the four-fermion quark operators.

This leaves the four-fermion lepton operators. These operators are unconstrained by direct detection experiments because cross sections of dark matter with atomic electrons are suppressed by a tiny form factor [44]. The PAMELA positron ratio excess suggests maximizing the annihilation rate into positrons through the single operator $O^{(6)}_{e_R}$. We will also consider what happens in the right-handed flavor-democratic case with all three operators $O^{(6)}_{\ell_R}$ are present with equal strength, as well as mention what happens when both left-handed and right-handed flavor-democratic operators $O^{(6)}_{\ell_L}, O^{(6)}_{\ell_R}$, are present.

Dirac dark matter coupling to left-handed leptons provides an interesting possibility, since annihilation necessarily also yields neutrinos. A combination of small interactions with quarks as well as left-handed leptons may yield an interesting indirect signal resulting from the annihilation of Dirac dark matter in Sun. We leave this interesting calculation for future work.

III. RELIC ABUNDANCE

The relic abundance of a Dirac fermion has been calculated in [45, 46]. Unlike Majorana particles [47], the leading order contribution to the annihilation directly into leptons is *not* velocity-suppressed. This proves extremely convenient in providing a model-independent relationship between the thermal relic density at freeze-out in the early universe and the galactic annihilation rate occurring today. This relationship provides a tight constraint on the size and shape of the expected positron flux, making Dirac dark matter highly predictive.

In the presence of $O^{(6)}$, the thermally-averaged annihilation cross section can be written quite generally as

$$\langle \sigma_{\bar{D}D} v \rangle \; = \; \frac{M^2}{2\pi} \sum_f \frac{|c_f^{L(R)}|^2}{\Lambda^4} \tag{6}$$

where the sum is over all dimension-6 four-fermion operators. We have neglected the higher order temperature-dependent corrections proportional to $1/x_F \equiv T/M$, which shift the cross section by less than 10%. We have also ignored the masses of the final state fermions, which is of course an excellent approximation for leptons. All of the model-dependence is buried in the couplings c_f. Let's focus first on the case where the only open annihilation channel is to right-handed leptons, i.e., $c_e^R = 1$ and all other c's vanish.

The thermal relic abundance for Dirac fermions results in an equal abundance of particle D and anti-particle $\bar{D}$ (since we are assuming no pre-existing asymmetry in D number). Consequently, the relevant cross section that enters both the thermal relic abundance as well as the annihilation rate in the galaxy is [45]

$$\sigma_{\rm eff} \; = \; \sum_{ij} \frac{n_i n_j}{n_{\rm tot}^2} \langle \sigma_{ij} v \rangle \tag{7}$$

$$= \; \frac{1}{2} \langle \sigma_{\bar{D}D} v \rangle \; . \tag{8}$$

The factor of 1/2 accounts for only two of four annihilation rates ($D\bar{D}$ and $\bar{D}D$ but not DD or $\bar{D}\bar{D}$) being nonzero. The thermal relic abundance is then

$$\Omega h^2 = x_F \frac{8.54 \times 10^{-11} \text{ GeV}^{-2}}{\sqrt{g_\star} \langle \sigma_{\bar{D}D} v \rangle / 2} \; , \tag{9}$$

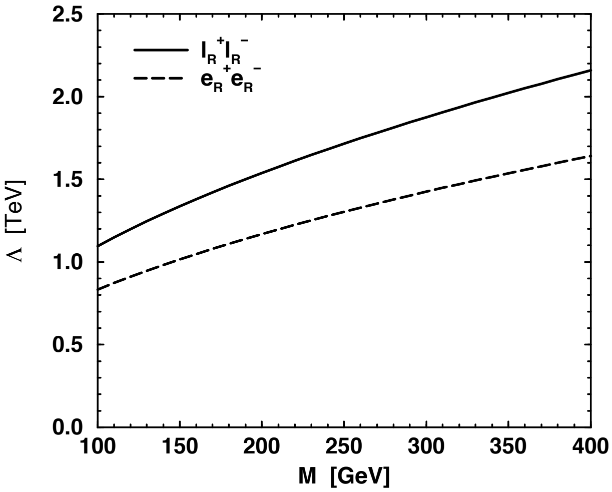

FIG. 1: Cutoff scale Λ as a function of the Dirac dark matter fermion mass M that gives the thermal relic abundance $\Omega h^2 = 0.114$, consistent with cosmological data. The top curve corresponds to the flavor-democratic scenario, $c_{e_R} = c_{\mu_R} = c_{\tau_R} = 1$, while the lower curve corresponds to electrons only $c_{e_R} = 1$. In both cases we took only right-handed leptons for simplicity; adding left-handed leptons is trivial.

where $g_\star \simeq 96$ is the number of relativistic degrees of freedom at freeze-out.

Using cosmological data to fix the thermal relic abundance to be $\Omega h^2 = 0.114$, we can determine the leading order (velocity-independent part) annihilation cross section,

$$\langle \sigma_{\bar{D}D} v \rangle \;=\; (1.25\ \mathrm{pb}) \frac{x_F}{21} \sqrt{\frac{96}{g_\star}} \qquad (10)$$

In Fig. 1 we show the relationship between Λ and M to obtain the thermal relic abundance consistent with cosmological data. The range of masses shown is illustrative. A lower bound on M can be established from the absence of a single photon plus missing energy signal at LEPI that would occur with the dimension-6 operator combined with an initial state photon. By contrast, LEPII does not place strong bounds on this process (for example, see [48]), essentially because the cross section is suppressed by $\alpha_{\rm em}$ and phase space that causes the signal to be too small to be seen above background. This suggests M could be as low as about 50 GeV. But as we will see, to explain the PAMELA positron ratio excess we need $M \lesssim 100$ GeV, and thus there is no direct limit from LEPII.

IV. POSITRONS FROM ANNIHILATION OF DIRAC DARK MATTER

A. Backgrounds and Galactic Propagation

Determining the background electron and positron flux is of utmost importance to establish that the positron ratio excess does, in fact, exist. The most complete calculation of the background fluxes of cosmic rays comes from the Galprop code [28], where antimatter is generated as secondary production from protons scattering off other protons and lighter nuclei. We will briefly explain the inputs to the code, the various propagation model and parameter dependencies, and thus our estimates of the uncertainties in the background. We use Galprop to propagate both signal and background. This is the only consistent way to treat propagation uncertainties. We have, nevertheless, cross-checked our signal using semi-analytic treatments of propagation [49].

Galprop is, for cosmic rays, similar in spirit to Pythia for collider experiments. Just as Pythia incorporates theoretical calculations, such as cross sections, as well as semi-analytic techniques, such parton showering, Galprop also incorporates both theoretical and experimentally-driven models and assumptions to predict cosmic ray spectra. There are three inputs to the code important for our analysis:

1. The electron source spectrum.
2. The nuclei source spectrum.
3. The propagation model and associated parameters.

Other important inputs include nuclear cross sections, interstellar gas distribution, etc [28].

The origin of the high-energy background spectrum of nuclei and electrons in the galaxy is presumed to come from supernovae, though it is at present not well understood. Galprop does not attempt to determine these spectra from first principles. Instead, the spectra are assumed to arise from an "injected" power-law input flux with coefficients, breaks, spatial distribution, and normalization determined by fitting to astrophysical data. Galprop self-consistently "propagates" all of the cosmic rays within galactic magnetic fields, allowing for particle collisions that result in secondary production of antiprotons, positrons, as well as secondary production of electrons, protons, etc.

The spectra in interstellar space differs from observations near Earth due to the solar modulation effect arising from the solar wind. This is expected to shift the observed energy by of order 0.6 GeV [50]. We focus only on the data above 5 GeV, thereby minimizing this systematic error.

Since PAMELA has not yet provided the absolute fluxes of electrons or positrons, we are forced to use data from other experiments to determine the absolute background flux. AMS-01 [29], ATIC [30], BETS [31, 32],

Experiment	power law index α
AMS-01 [29]	3.15 ± 0.04
ATIC [30]	3.14 ± 0.08
BETS [31, 32]	3.05 ± 0.05
CAPRICE [33]	3.47 ± 0.34
HEAT [34]	2.82 ± 0.16
MASS [35]	2.89 ± 0.10

TABLE I: Our weighted least-squares best fit to the electron flux, $\Phi_{e^-}(E) \propto E^{-\alpha}$, measured by the various experiments. The BETS best fit was taken from [32]; their best fit to just the lower energy data between 10 to 100 GeV is 3.00 ± 0.09 [31]; the error is assumed to be 1σ. The MASS best fit taken from [35]; the error is assumed to be 1σ. We emphasize that our reported errors for the other experiments are purely statistical (95% CL) with regard to fitting data (with errors) to a power law, and do not necessarily reflect the individual experiments' precision.

CAPRICE [33], HEAT [34], and MASS [35], have measured the electron flux, with or without charge identification. We have performed a weighted least-squares fit to their data for energies larger than 5 GeV. For BETS and MASS we used their reported their best fit, since their energy range began above 5 GeV. Our results are given in Table I. A very conservative interpretation of the data is that the observed electron flux is falling as $E^{-3.15\pm0.35}$ for $E > 5$ GeV, which spans all of the central best-fit values of the experiments. Another approach to the uncertainties in the electron spectra can be found in [51]. Their result for the electron flux is that it falls as $E^{-3.44\pm0.03}$, which is within our range, though with what seems to us to be an unrealistically small error.

The spectra of positrons is determined from secondary production, after protons (or heavier nuclei) inelastically collide into other protons or nuclei, emitting charged pions that decay into positrons. This requires simulating networks of hadron interactions and decays, using nuclear and particle physics data. The positron flux is thus ultimately determined by the injected nucleon spectrum, nuclear cross sections and the propagation model and parameters.

By fitting the resulting nucleon spectra to data, the injected nucleon spectrum and propagation parameters can be well constrained. A recent study by [52] used Galprop to fit to the proton spectra, the B/C ratio, and other data to determine the best-fit and a range of propagation parameters. We use their results in determining the propagation model and parameters that best reproduce the nucleon spectra. Their study [52] considered propagation with convection ("DC" model), with reacceleration ("DR" model), and reacceleration with a break in the spectra ("DRB" model). They also considered a "min", "max", and "best" set of propagation parameters for each model. We found that using the default proton injection spectrum in Galprop, combined with either the "min" or "max" sets of propagation parameters, generally gave a considerably worse fit to the experimentally observed proton spectrum [36, 53]. Since positrons derive from protons, we opted to consider only their "best" fits. We should emphasize that these three models do not represent the full uncertainty in propagation, but are rather meant to gain a quantitative understanding of the different spectra possible with qualitatively different models of propagation. Further studies of propagation effects can be found in [54]. In the end, the propagation parameter dependence is considerably milder than the present uncertainty arising from the background electron spectrum.

We therefore determined the background spectrum in the following way. Given a propagation model, the absolute positron spectrum is determined. Using the published PAMELA flux ratio data point at 4.5 GeV [1], we inverted the positron flux to obtain the absolute electron flux $\Phi_{e^-}(4.5\ \text{GeV} = 2.5 \times 10^{-4}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{GeV}^{-1}$, which is our normalization for the background. We then used our power-law best fit range to the electron data given in Table I as the background electron flux. This procedure assumes that any new physics contribution to the positron (or electron) flux at 4.5 GeV is negligible (which we verify, *ex post facto*, below). The resulting background positron fraction is shown in Figure 2 for the three propagation models we have chosen (Thick lines). The uncertainties due to the variations in the electron spectral slope are also shown (thin lines and blue band for the DC model). As advertised earlier, the uncertainty in the electron spectrum currently dominates, and will hopefully lessen as the absolute electron flux from PAMELA, Fermi/GLAST, and other instruments are released. However, despite the large uncertainty in background, the PAMELA shape and size, particularly at the highest energies, lies well outside our generous range of the predicted background from secondary production. We will now explore the possibility that this excess can be explained by annihilation of Dirac dark matter particles.

B. Positron Signal

The same processes that freeze out a thermal relic abundance of Dirac dark matter also leads to an annihilation rate in our galactic neighborhood. Since the thermally-averaged annihilation rate was dominated by the zero temperature limit, the same annihilation rate, Eq. (6), also applies to the annihilation happening in the galaxy today. This provides a model-independent relationship between annihilation rates, and provides one of the strongest constraints on a Dirac dark matter interpretation of the PAMELA excess.

The abundance in the local galactic neighborhood is typically taken to be $\rho_{8.5} = 0.3\ \text{GeV/cm}^3$ [53]. We assume an isothermal halo profile, where

$$\rho(r) = \rho_{8.5} \frac{r_{8.5}^2 + a^2}{r^2 + a^2} \tag{11}$$

with $a = 5$ kpc. Our results are not strongly sensitive to

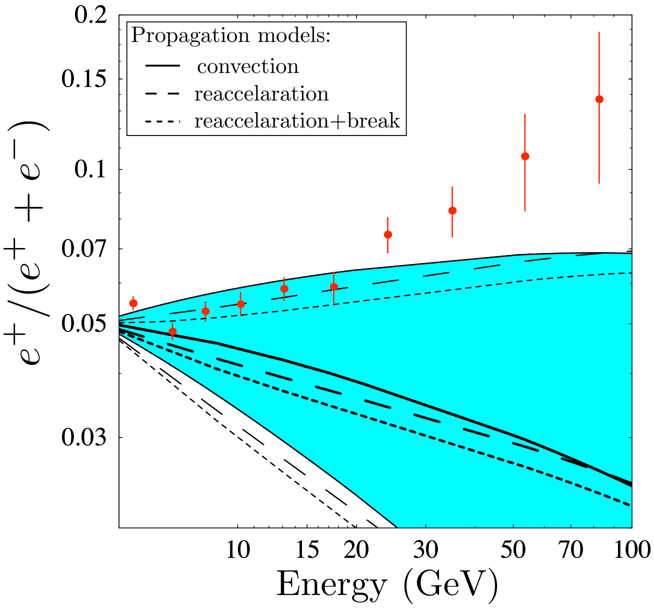

FIG. 2: The positron ratio assuming background only as calculated by Galprop for the 3 propagation models described in the text, DC (solid), DR (long dashed) and DRB(short dashed). The central thick lines assume an electron spectral spectrum $\Phi_{e^-}(E) \propto E^{-3.15}$ whereas the thinner lines above and below show the affect of varying the electron spectrum by $\Phi_{e^-}(E) \propto E^{-3.5}$ and $E^{-2.8}$, respectively, within the range as determined by Table I. The data is taken from the recent PAMELA observations [1].

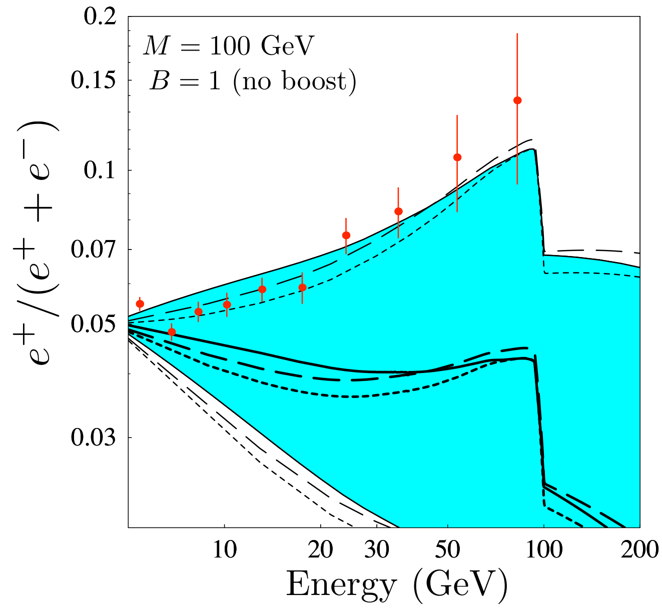

FIG. 3: The positron fraction from a 100 GeV Dirac dark matter particle that annihilates to right handed electrons. Three propagation models are plotted: DC (solid), DR (long dash), and DRB (short dash), as well as the uncertainty due to variation of the electron spectral slope. No boost factor was employed for this figure. Within the present astrophysical uncertainties, the PAMELA data can be explained so long as the electron spectrum is quite steep, $\Phi_{e^-} \propto E^{-3.5}$, corresponding to the top of the shaded blue band.

the choice of profile, since most energetic positrons arrive from our galactic neighborhood, of order 1 kpc, where the dark matter density is not nearly as uncertain as it is in the galactic center. The precise local *average* dark matter density is itself subject to uncertainties. Since this is a simple scaling of the signal, we will fold this uncertainty into the boost factor. But of course it should be remembered that, for example, a boost factor of 4 could be equivalently obtained by scaling $\rho_{8.5}$ up by a factor of 2, which is within the uncertainties [53, 55].

In addition to annihilation within the smooth dark matter halo, it has been suggested that indirect signals of dark matter annihilation could be boosted due to a large degree of clumpiness in our halo. Such clumps of dark matter may be a remnant of the hierarchical build-up of galactic halos from small to large (e.g. [56]). In particular, if the Earth happens to be near a dense dark matter clump, annihilation signals may be enhanced, though this does seem to be a probable scenario. Recent many body simulations show that though a boost factor of order a few is possible, while a boost exceeding of order 20 in the positron signal appears unlikely [57].

The basic physics that leads to a positron flux from dark matter annihilation is twofold: First, dark matter annihilates into SM matter. The annihilation could proceed directly into e^+e^-, or into for example $\mu^+\mu^-$, which then decays into electrons and positrons. Earlier analyses with pre-publication PAMELA data (e.g. [9]) suggest that the annihilation channels W^+W^-, $b\bar{b}$, $q\bar{q}$ are not nearly as favorable as directly into e^+e^- or $\ell^+\ell^-$, given a velocity-independent annihilation cross section and minimizing boost factors. We used DarkSUSY [58] to obtain the (at-source) energy distributions of positrons from annihilation into muons and taus.

The second component of a positron signal is the propagation of a positron with a given energy from where it was created to Earth. We propagate the signal positrons using Galprop for the three propagation models described above in the previous subsection.

Our results are shown in a series of figures. We begin with a Dirac dark matter candidate that couples only to right-handed electrons. This benchmark model maximizes the signal. Indeed, as can be seen in Figure 3, the PAMELA data lie within the uncertainty band of the expected signal, though fitting the data would require a rather steep electron spectrum, a hypothesis that will be surely be tested by PAMELA itself as well as Fermi/GLAST. It should be stressed that in Figure 3 we use an annihilation cross section given by Eq. (10) which matches the relic abundance calculation. Within the present astrophysical uncertainties, we find no boost factor is required to explain the preliminary data. The case where Dirac dark matter annihilates to left-handed electrons is a simple halving of this signal since half of the annihilations are to neutrinos.

In Figs. 4 and 5 we show the predicted positron ratio spectra for $M = 150$ GeV and boost factors of 5 and 15 respectively, again showing the astrophysical uncertainty from the propagation parameters as well as the electron flux. In Fig. 6 we show a comparison between annihilation to e^+e^- final state only versus democratic to $\ell^+\ell^-$. The boost factors were set to 10 and 30 respectively. In Fig. 7 we show the predicted positron ratio spectra for a range of masses $M = 100, 200, 400$ GeV. The corresponding boost factors are 5, 20, and 80. Notice that the scaling of the boost factor with mass is simply $B \propto M^2$. The boost factor required for $M = 400$ GeV seems probably beyond anything plausible from clumping. Nevertheless, if the ATIC/PPB-BETS hint persists, it is at least possible to simultaneously explain both excesses.

One observational prediction is clear. If a sharp drop in the positron spectrum is observed by PAMELA, this would provide strong evidence in favor of Dirac dark matter with a small to modest boost factor. It would suggest the ATIC/PPB-BETS excess is either an observational anomaly or unrelated to the PAMELA observations. On the other hand, if PAMELA were to observe a continuous rise in the positron fraction, this would provide evidence that a more massive particle annihilating to e^+e^- is simultaneously explaining both excesses. This would seem to require a larger boost factor. Exactly how large is dependent on the background flux of electrons. For a spectrum falling as $E^{-3.5}$ ($E^{-3.15}$), the boost factor needs to be of order 16 (80). Our estimates suggest the best fit to the present data in somewhat in between this range. If future evidence is further strengthened for the ATIC/PPB-BETS excess, we will be able to make more precise statements about the parameters and boost factors that best fit the data.

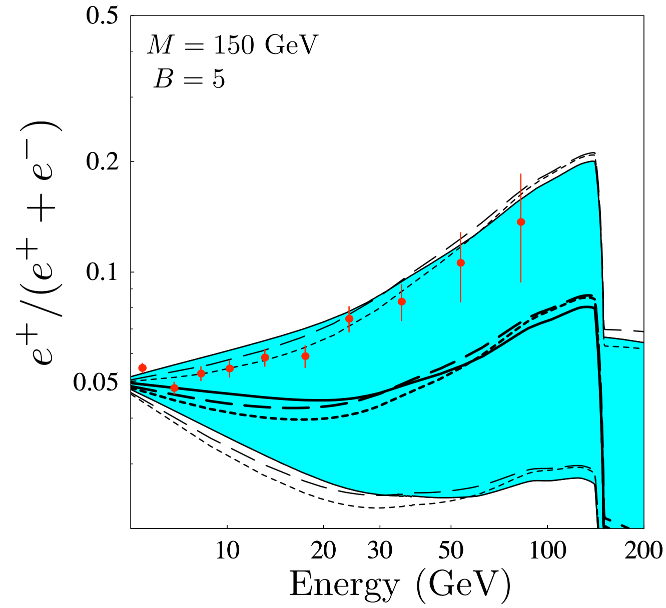

FIG. 4: Same as Fig. 3, except for $M = 150$ GeV and a boost factor of 5.

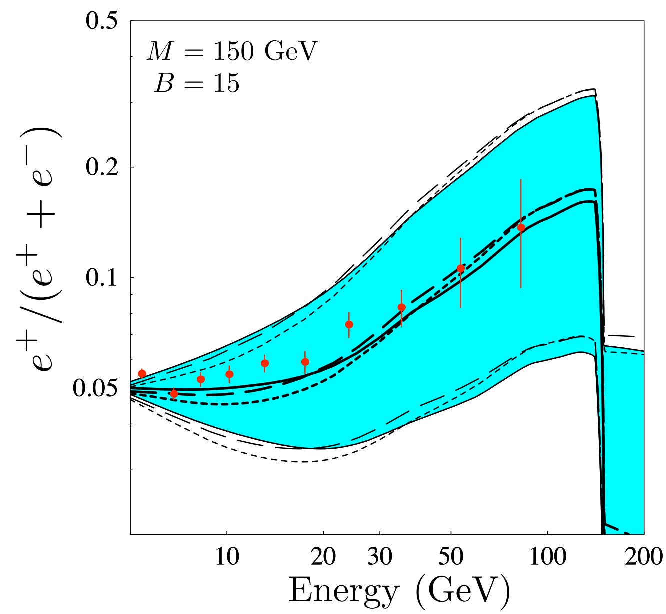

FIG. 5: Same as Fig. 4, except with a boost factor of 15.

V. THE DIRAC BINO AS DIRAC DARK MATTER

Our discussion up to now has been completely general with respect to an effective theory of Dirac dark matter. One candidate for Dirac dark matter seems particularly compelling: a Dirac bino in a low energy supersymmetric model. A Dirac bino arises in supersymmetry when the bino – the fermionic superpartner contained in the hypercharge superfield strength W_Y^α – acquires a Dirac mass with a gauge singlet S. This occurs when supersymmetry breaking arises from D-terms [59, 60, 61, 62]. For the Dirac bino, the operator is

$$\sqrt{2} \int d^2\theta \frac{W'_\alpha W_Y^\alpha S}{M_\star} \tag{12}$$

which gives rise to a Dirac mass term

$$\frac{D'}{M_\star}(\lambda\psi + h.c.) \tag{13}$$

where λ and ψ are the 2-component bino and singlet fermions, respectively. If no Majorana mass is generated by supersymmetry breaking, this mass term implies the Dirac bino is a pure Dirac fermion. This could be accomplished by accident (tuning all contributions to the Majorana mass to conspire to vanish) or by symmetries (supersymmetry breaking that respects a $U(1)_R$ symmetry, for example). In this section, we will first assume a

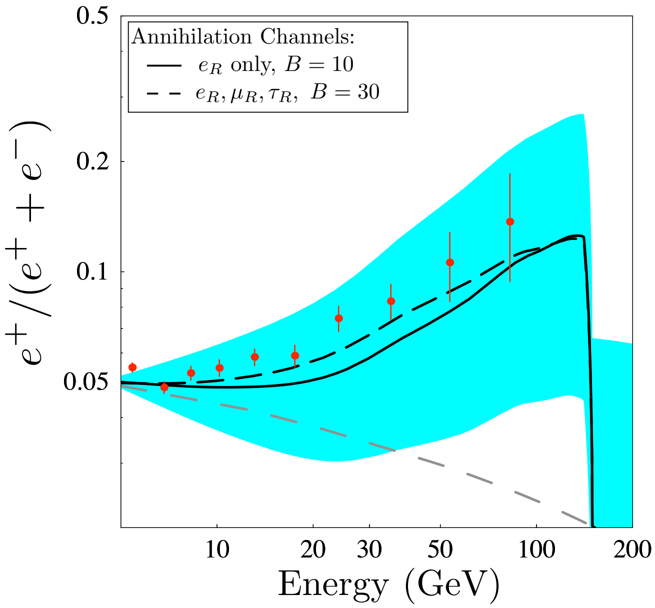

FIG. 6: The positron fraction from a 150 GeV Dirac dark matter particle that annihilates to leptons assuming the DC propagation model. The solid line corresponds to annihilations to just right-handed electrons with boost factor of 10, while the dashed line corresponds to annihilations to all right-handed leptons with boost factor of 30. The shaded blue band is the same as previous figures.

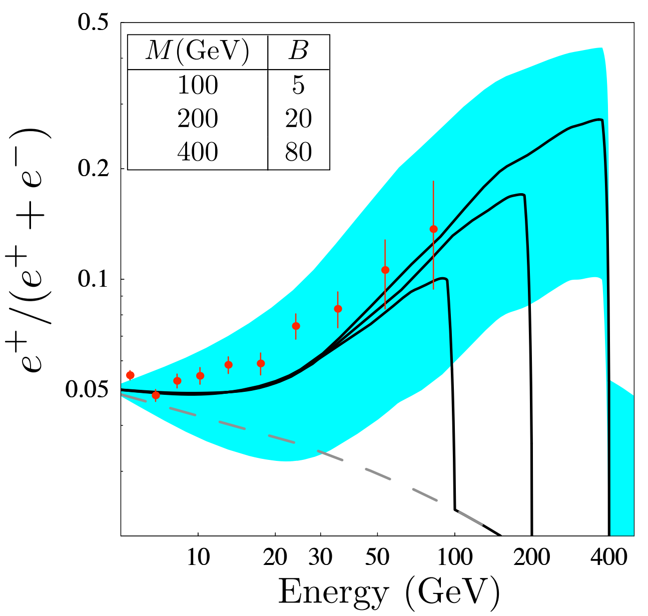

FIG. 7: Same Fig. 6, for $M = 100, 200, 400$ GeV. The DC model was used for propagation, and annihilation was assumed only into e^+e^-.

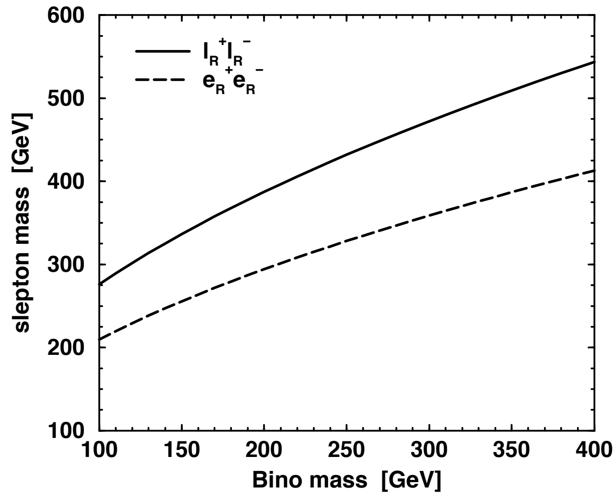

FIG. 8: Masses of the right-handed scalars such that the Dirac bino has a thermal relic abundance, $\Omega h^2 = 0.114$, consistent with cosmological data. The top curve corresponds to the flavor-democratic scenario, $m_{\tilde{e}_R} = m_{\tilde{\mu}_R} = m_{\tilde{\tau}_R}$, while the lower curve corresponds to electrons only $m_{\tilde{e}_R} = 1$. In both cases we took only right-handed leptons for simplicity; adding left-handed leptons is trivial.

Dirac bino exists, and consider the implications. At the end we will consider a model in which a Dirac bino may be automatic.

The relic abundance of an exact Dirac bino has been calculated before in Ref. [46] using t-channel (and u-channel) scalar exchange. Left-handed [right-handed] scalars give rise to a four-fermion interaction that can be Fierz transformed into our effective operators Eq. (4)-(5) with $c_L = (Y_L g')^2/2$ and $c_R = (Y_R g')^2/2$. Here Y_f is the hypercharge of the Standard Model fermions and g' is the hypercharge coupling. The cutoff scale is the mass of the exchanged scalar $\Lambda = m_{\tilde{f}}$. This allows us to immediately re-evaluate Fig. 1 in terms of the masses of the physical scalar states that resolve the four-fermion operators. This is shown in Fig. 8.

The dominance of the leptonic operators becomes clear for two reasons. First, the four-fermion operators to any Standard Model fermion are proportional to Y_f^4 (very much like KK dark matter [2, 3]), which is largest for the right-handed leptons. Second, since the operators scale as $1/m_{\tilde{f}}^4$, even a modest hierarchy in which sleptons are lighter than squarks will overwhelmingly cause the dominant annihilation channel to proceed through right-handed leptons. Hence, a Dirac bino naturally explains annihilation to charged leptons. The collider implication is clear: relatively light sleptons, in a mass range between about 200-400 GeV, are an inescapable consequence to obtain a thermal relic abundance consistent with cosmology and a positron signal consistent with PAMELA.

A pure Dirac bino-eigenstate has no coupling to the Z. This eliminates one source of vector interactions to quarks that would be devastating given the current nuclear recoil direct detection bounds. In the presence of Dirac Higgsinos, however, a residual coupling to the Z is generated. We can estimate the size of the D-D-Z coupling using the mass-insertion approximation, and we obtain $(g'v)^2/\mu^2$ where $v = 174$ GeV and μ is a Dirac Higgsino mass. This coupling needs to be smaller than about 0.01 to be safe against direct detection bounds [39], and thus we obtain $\mu > 600$ GeV.

A Dirac bino could also be seen in direct detection experiments through the exchange of squarks. The largest contribution arises from the exchange of first-generation right-handed up-type squarks. A preliminary estimate of the size of this contribution is that we need $m_{\tilde{u}_R} \gtrsim 1.5$ TeV. The other first generation squarks can be proportionally lighter, the bounds scaling roughly with hypercharge per exchange sfermion.

As we have seen from our model-independent analysis above, the boost factor is minimized when the annihilation proceeds only into electrons. Again, a mild hierarchy between $m_{\tilde{e}_R} < m_{\tilde{\mu}_R}, m_{\tilde{\tau}_R}$ would suffice to explain this. However, this is atypical of flavor-blind mediation mechanisms.

An intriguing possibility is that all gauginos are Dirac fermions, due to an exact R-symmetry that is preserved by supersymmetry breaking. This has been considered recently in [40], where it was shown that the squark and slepton masses could be nearly flavor-arbitrary without violating the constraints from flavor-violation in the Standard Model. This is suggestive as an explanation of why the sleptons could have a modest mass hierarchy while satisfying bounds from lepton flavor violation. However, the scenario we envision here is slightly different than was originally proposed in [40]. Here, the Dirac bino must be the lightest supersymmetric particle, and the sleptons must be heavier than the bino by roughly a factor of 2-3. This is the opposite mass hierarchy from what was considered in [40], and while the parametric scaling of the operators leading to lepton flavor violation is not expected to change, the full extent of the allowed flavor mixings in the slepton masses requires a re-evaluation of lepton flavor violation. This is in progress and will be presented elsewhere.

In an R-symmetric model, the dimension-5 operator Eq. (3) is absent since it is forbidden by the R-symmetry. There are, however, new dimension-5 operators that are allowed by the R-symmetry, such as $\overline{D}D\tilde{H}^\dagger\tilde{R}^\dagger$, which are suppressed by the Dirac Higgsino mixing mass μ. Since μ gives rise to both a Dirac Higgsino mixing mass as well as an $\tilde{R}$ scalar mass, and it must be larger than 600 GeV to keep the D-D-Z coupling in line, this operator is not kinematically relevant for the Dirac masses we considered here.

Another important issue is to understand how well the R-symmetry may be preserved. Supersymmetry breaking without R-symmetry breaking is commonplace, but R-violation creeps back in, due to the constant that is added to the superpotential of supergravity to cancel off the cosmological constant [63]. It is generally expected that this violation of R-symmetry in the hidden sector would feed into the visible sector through anomaly mediation. This would lead to Majorana masses for the gauginos, which would split the Dirac bino state into a two Majorana fermions. The heavier state would then decay into the lighter state on a timescale rapid compared to the age of the Universe, unless the mass splitting is very small. The resulting dark matter present in our galaxy today would be made of Majorana binos, which would not efficiently annihilate to leptons and thus would not be expected to explain the PAMELA excess. Dialing down the mass splitting is possible by lowering the gravitino mass, but then this allows the bino to decay into a light gravitino. There may be possible escapes with supergravity [63] or otherwise postulating supersymmetry without supergravity [64, 65], though our UV theory becomes an effective theory that will break down at an intermediate scale.

VI. DISCUSSION

We have presented an effective theory of a stable Dirac fermion dark matter candidate that couples to the Standard Model through dimension-6 four-fermion interactions. The annihilation rate is not velocity-suppressed, and thus the freeze-out thermally-averaged annihilation cross section is the same as the annihilation cross section that occurs in our galactic neighborhood. We have shown that if the annihilation proceeds into right-handed electrons, the PAMELA positron ratio excess can be explained with a minimal boost factor. Given present astrophysical uncertainties, the boost factor could be as small as 1 for $M = 100$ GeV if either $\rho_{8.5} = 0.7$ GeV/cm^3 and $\Phi_{e^-} \propto E^{-3.15}$ or $\rho_{8.5} = 0.3$ GeV/cm^3 and $\Phi_{e^-} \propto E^{-3.5}$. Larger Dirac fermion masses are possible to the extent that larger boost factors are plausible, scaling as $B \propto M^2$.

If the mass of the Dirac fermion is within the energy range that PAMELA can explore, they should see a striking feature in the positron fraction at the mass of the Dirac fermion. Fermi/GLAST could also see a feature in their photon spectrum resulting from final state radiation off one of the charged leptons. If the mass is large, this could simultaneously explain the hint of an excess at ATIC and PPB-BETS with a boost factor as small as 16 given the present uncertainty in the electron spectra.

Finally, we showed that a natural candidate for a Dirac fermion dark matter particle is a Dirac bino in supersymmetry. This can automatically explain the dominance of the right-handed leptonic operators. The reminder of the spectrum is somewhat restricted by the constraints from nuclear recoil direct detection. A detailed analysis of the model and spectrum is in progress. The inevitable consequence of this interpretation is the presence of relatively light sleptons, with masses 200-400 GeV, the range depending on the precise mass of the Dirac bino and the number of flavors of sleptons that are light. Minimizing the boost factor implies the right-handed selectron is the lightest slepton, which is characteristic of our model. This provides an exciting opportunities for LHC.

As a final concluding thought, is it possible to reconcile the PAMELA excess with the observation by DAMA/LIBRA of an annual modulation in nuclear recoil [66]? In an effective theory, it is straightforward to implement the inelastic mechanism [67, 68, 69] to explain the annual modulation. A second Dirac fermion D' is added to the effective theory, with D and D' permitted to mix with each other under a global $U(1)_D$ conservation. The heavier mass eigenstate is taken to be about 100 keV heavier than the actual Dirac dark matter particle. Then, one can simply add a four-fermion dimension-6 quark operator to the effective theory, $\bar{D}'\gamma^\mu D\bar{q}\gamma_\mu q/\Lambda^2$. The key is to ensure that a $\bar{D}'D$ or $\bar{D}D'$ operator is generated while a $\bar{D}D$ operator to quarks is not. This means a vector interaction exists between the light state D to the excited state D' with quarks of a scattered nucleus. Realizing this pattern of operators in a model is an interesting (and challenging) model-building problem we leave for future study. Interestingly, the range of dark matter masses that most easily permit an inelastic explanation of the annual modulation is about $70 - 250$ GeV. This exactly coincides with the range that is most favorable towards an explanation of the PAMELA positron ratio excess.

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