DARK MATTER IN VIEW OF RECENT EXPERIMENTS

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We discuss new models of dark matter (DM) developed recently in light of the anomalous signals from DAMA, INTEGRAL, AMS, PAMELA, ATIC and Fermi. If the results of any of the experiments are the result of DM interactions with ordinary matter, whether through scattering or annihilation, the DM must have properties atypical of an ordinary Weakly Interacting Massive Particle (WIMP) from the Minimal Supersymmetric Standard Model (MSSM). Many of these new models of DM developed to explain these signals involve low mass hidden sectors with complex dynamics. We outline features required by the new models to be phenomenologically viable.

1 Recent Experiments and Their Implication for Dark Matter

There have been a slew of results recently from the dark matter experiments. There are three avenues of exploration in the hunt for dark matter. The first is to produce the particle directly in the laboratory, one of the major goals of the Large Hadron Collider (LHC) at CERN. The second is to directly detect the particle in a (usually) underground laboratory: a DM particle bounces off a nucleus in a very sensitive detector, and the small recoil energy is observed. And the third is to see the products of the annihilations of such particles with detectors on the ground or in space. These last two methods have yielded some remarkable results recently, and we await the results to come from the LHC.

In the area of direct detection, DAMA for many years has been claiming an annual modulation in the rate of nuclear recoils in the sodium iodide detectors [1]. This experiment has by now collected a very large amount of data, 0.82 ton years. It had been thought that an elastically scattering WIMP interpretation was inconsistent with the constraints from other direct detection experiments. With the new experimental effect of channeling [2], however, their signal has been shown to be potentially consistent with an elastically scattering, though rather light, Weakly Interacting Massive Particle (WIMP), with mass in the several GeV range [3] (though it has been shown elsewhere [4] that the lowest nuclear recoil bin has an important effect on the fit to the DAMA data). It may also be explained by a non-standard WIMP which recoils inelastically from the nucleus [5].

In the area of indirect detection, the PAMELA [6] and ATIC [7] experiments have reported excesses in the fluxes of cosmic ray electrons and positrons over the expected background. The PAMELA experiment (carried on a European Space Administration satellite) has observed the electron and positron fluxes separately in 10-100 GeV range, while the ATIC balloon experiment (with two flights at the south pole) has observed the total flux of electrons plus positrons (not being able to determine charge) in the 50-700 GeV range. Considering electrons and positrons, from, e.g., interactions of cosmic rays in the interstellar medium, one expects a featureless distribution falling with energy. PAMELA, however, saw a rise in the ratio of positron to electron plus positron fluxes, and ATIC saw a feature in the total $e^+ + e^-$ flux consistent with a rise and sharp fall in the flux.

More recently NASA's Fermi Large Area Telescope [8] has reported results on the flux of electrons plus positrons (like ATIC unable to determine charge) in the same energy range as ATIC, but with much higher precision. The experiment does not see the large rise and steep drop of ATIC, but neither does it fall as steeply as is expected from the standard cosmic ray model. These results are inconclusive on the question of annihilating DM as the source of the excess, especially since no sharp feature was detected.

If the PAMELA, ATIC, or Fermi results are to be explained in terms of annihilating DM, its features, like the features of a DAMA DM particle, must be non-standard. The annihilating DM particle needs to satisfy non-trivial constraints on the size of the annihilation cross-section [9,10], on the measured $\bar{p}$ flux [11], and on limits on hard photons from HESS and EGRET [12], but these are better accommodated with the more mild excess observed by PAMELA than they were with the ATIC results. All of these features imply that an ordinary neutralino from Supersymmetry (SUSY) cannot explain the excess.

In addition, the INTEGRAL satellite has a long standing excess in the 511 keV line toward the galactic center [13]. It may be explained by exotic annihilating MeV DM which couples to the SM through 10^{-6} gauge couplings of a new MeV mass gauge boson [14].

Lastly, there is the mystery of the WMAP haze. It was shown in [15] that the excess synchrotron radiation in the WMAP 22-93 GHz bands can be explained by an ordinary several hundred GeV mass WIMP annihilating to W^+W^- with cross-section $\langle \sigma v \rangle \simeq 3 \times 10^{-26}$ cm^3/s, consistent with the relic abundance predicted by thermal freeze-out.

While the prospect of DM detection is exciting, many of these hints are likely to find a more pedestrian explanation. The DAMA result may simply be some systematic background which is up to now unknown and unaccounted for. The Fermi results, with its superior statistics, strongly suggest that the ATIC results are instrumental, rather than cosmic, in origin. And both the Fermi and PAMELA results may be explained by an astrophysical source, such as a pulsar [16], or by previously unaccounted for acceleration mechanisms in the supernova remnant source [17,18]. Recently, it was shown that the e^+e^- injection from pulsars may contribute significantly to the haze [19].

While the probability of any one of these signals being the result of DM rather than another source is rather low, the prospect of detecting the elusive dark matter through its particle interactions is a high risk, high reward game. Fortunately, there are other results on the horizon to settle these experimental questions with regard to DM. In the case of DAMA, a high voltage run of CDMS and a low threshold analysis of the CDMS-SUF data will shed some light on the elastic scattering window [20]. Other low threshold experiments to probe this low mass region, such as DAMIC, are being designed and built. XENON has recently carried out a high nuclear recoil analysis of their data. CRESST is sensitive to an inelastically scattering DM candidate which may explain DAMA. Fermi has recently given us more information with the cosmic ray electron spectrum in the ATIC energy range, and while it does not show the ATIC feature, neither does it fall as quickly as the expected background, leaving some uncertainty still as to whether a DM explanation is still feasible.

While each of these signals is an exciting possible hint for DM, most imply a non-standard DM candidate. In the case of DAMA, this is an unusually light or inelastic WIMP. In the case of the signal from INTEGRAL, this is an MeV mass dark state with anomalously small gauge couplings. In the case of the cosmic-ray electron and positron signals, this is a hadrophobic WIMP with a boosted annihilation cross-section. These non-standard DM signals have implications for DM detection at the LHC, the next important experiment on the near horizon with regards to DM.

And regardless of whether the signals survive further scrutiny as DM explanations, a very positive aspect of these hints from the theoretical point of view is that they have driven us to consider models of DM outside of the 0.1-1 TeV weakly interacting particle regime. These signals have caused the community to take a deeper look into dark sectors where the dynamics is complex in order to explain the non-standard WIMP signals from DAMA, PAMELA, ATIC, Fermi, and INTEGRAL. The dark sectors may have multiple forces to which it couples, including strong dynamics, and its mass may be much lower than the weak scale, while these states couple to the visible sector through weak scale suppressed operators. The spirit of these models follows the Hidden Valley (HV) [21].

These hidden sectors provide many remedies for the class of models relevant to the recent signals. The low mass hidden sectors naturally give rise to a light DM candidate for DAMA, and in some cases even INTEGRAL [22,23]. The low mass forces can generate a Sommerfeld enhancement [24] needed to boost the cross-section for the cosmic-ray electron-positron excesses [25]. And in many of these models, hadrophobic dark matter candidates can easily be generated, especially in the context of solutions to the baryon-dark matter coincidence that we discuss below.

These dark sectors in many cases have important implications for collider experiments, which is a key tool on the near horizon for determining the nature of the DM. In the context of supersymmetry, the presence of these low mass hidden sectors implies the decay of MSSM SUSY partners to the lower mass hidden particles. This means reduced missing energy, as first discussed in the context of HV [26], and more recently in the DM models [23,35]. We now turn to discussing concrete hidden sector dark matter models.

2 Hidden Sector Dark Matter

Each of the signals from the recent experiments can be connected to low mass hidden sectors. The INTEGRAL signal can be explained by MeV DM communicating to the SM through an MeV dark force which couples weakly to the SM with strength $\theta \sim 10^{-6}$ [14]. For the cosmic-ray positron excesses from AMS [27] and PAMELA, a GeV mass force may mediate an enhanced annihilation cross-section relative to the cross-section at freeze-out, as first pointed out in [12,25]. An elastically scattering GeV mass state can explain the DAMA signal. These low mass sectors have escaped detection at high energy hadron colliders and the precision e^+e^- machines, LEP, CLEO, DAΦNE, Belle and BaBar, provided that these hidden sectors couple only weakly to the SM sector either through small couplings or through higher dimension operators which suppress the interaction [28,29].

The connection of the *dark* hidden sector to the SM sector can be described in terms of higher dimension operators:

$$\mathcal{L} = \frac{\mathcal{O}_{SM}\mathcal{O}_{hid}}{M^{d-4}}, \tag{1}$$

where d is the dimension of the product of the operators in the numerator. The nature of the connector depends on the particular mediators which are being integrated out. There are two basic types of connectors that we consider here. First through kinetic mixing between a hidden sector force and hypercharge which gives rise to an operator

$$\mathcal{L} = \theta F_{\mu\nu} U^{\mu\nu} \tag{2}$$

where $U^{\mu\nu}$ is the field strength tensor of the dark hidden sector $U(1)_D$ and θ is the mixing angle (expected in many cases to be on the order of a loop factor, $10^{-2} - 10^{-3}$). Second through singlets which couple to both sectors, generating an operator

$$\mathcal{L} = \frac{\mathcal{O}_{SM}\mathcal{O}_{hid}}{M^2} \tag{3}$$

where $M = m_S/y$, y is the product of the couplings of the singlet to the hidden and visible sectors and m_S is the singlet mass. In the simple case of four fermion operators, the relevant operators generated by kinetic mixing (KM) and singlet (S) mediators are

$$\mathcal{L}_{KM} \sim g_D g_Y \theta \frac{\bar{X}X\bar{F}F}{m_{U_D}^2}, \qquad \mathcal{L}_S \sim \lambda_D \zeta \frac{\bar{X}X\bar{F}F}{m_S^2}, \tag{4}$$

where g_D and g_Y are the coupling constants of the dark $U(1)_D$ and hypercharge, respectively, X is the dark fermion in the hidden sector, m_{U_D} is the mass of the dark gauge boson, F is any SM fermion, and the couplings for the singlet case arise from the Lagrangian

$$\mathcal{L}_S = \lambda_D S\bar{X}X + \zeta S\bar{F}F. \tag{5}$$

Now in the context of SUSY, both of these operators will communicate SUSY breaking to the hidden sector [23,25,30,31,32]. Generically, the size of the SUSY breaking mass communicated to the hidden sector through these operators is set by the size of the effective coupling between the two sectors. For kinetic mixing mediated SUSY breaking, the SUSY breaking may be communicated through two-loop gauge mediation, where the gauge fields doing the mediating are mixed by kinetic terms (another interesting class of models discussed elsewhere [30] uses the D-terms to communicate the SUSY breaking). The mass scale in the hidden sector set in this way is parametrically given by

$$m_{hid} \sim \frac{g_D g_Y \theta m_{SUSY}}{16\pi^2} \log\left(\frac{\Lambda^2}{m_{hid}^2}\right), \tag{6}$$

where g_Y is the SM hypercharge coupling, while for singlet mediated SUSY breaking, the mass scale is set by one loop graphs and is

$$m_{hid} \sim -\frac{y m_{SUSY}}{4\pi} \log\left(\frac{\Lambda^2}{m_{hid}^2}\right), \tag{7}$$

where Λ is the scale of SUSY breaking. For a particular class of constructions discussed previously [32], these models can result in negative mass-squareds for the hidden scalars. When these hidden scalars get vevs, they break the $U(1)_D$ and give masses to the dark forces set by the same scale m_{hid}.

Now we can see how these hidden sectors connect to the phenomenological models of DM. The MeV DM model [14] has all the characteristics of a hidden DM model. In order to explain the 511 keV signal from INTEGRAL and obtain the correct relic abundance, the MeV DM must couple through an MeV mass gauge boson to electrons with coupling constant $\sim 10^{-6}$. These mass scales and couplings may be set by SUSY breaking [23], with MeV $\sim 10^{-6} m_{SUSY}$, as expected from Eq. (6), for $\theta \sim 10^{-6}$ and g_D and g_Y both $\mathcal{O}(1)$.

In hidden sector dark matter models where the mass scale in the hidden sector is set by SUSY breaking, even when the DM no have weak scale masses, the dark matter abundance naturally comes out to be in the right range. The theoretical bias towards weak scale dark matter is based on the idea that the annihilation cross-section needed to get the observed relic abundance is a weak scale cross-section, the so-called WIMP miracle,

$$\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \sim \frac{1}{m_{weak}^2}. \tag{8}$$

This can be generalized by simply taking the couplings smaller than one:

$$\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \sim \frac{g_D^2 g_Y^2 \theta^2}{m_{hid}^2}. \tag{9}$$

One can see that as long as $m_{hid} \sim g_D g_Y \theta m_{weak}$, as is the case for the class of models we have been considering here (Eq. (6)), and the gauge couplings are $\mathcal{O}(1)$, the WIMP miracle still holds, even though the dark matter can be much lighter than the weak scale. This observation was given the name "WIMPless miracle" [33].

Likewise, the GeV mass scalars in the hidden sector needed for the Sommerfeld enhanced annihilation cross-sections for the cosmic-ray positron excesses can be easily generated for a natural value of $\theta \sim 10^{-2-3}$ [25]. Singlet mediation also works well to generate the GeV scale, as discussed in [31,32]. The GeV mass sector, within the context of SUSY, contains an R-parity odd matter field which is stable. This state may be a DM candidate if its relic abundance agrees with cosmological constraints, and potentially a candidate for an elastically scattering WIMP explanation of the DAMA result [31]. In the context of GeV scale models, both the GeV scale dark force for the Sommerfeld enhancement and GeV mass DM for DAMA can result from the GeV mass hidden sectors. The DM is naturally multi-component, with the annihilation of heavier component explaining the cosmic-ray electron excess.

We now turn to a different class of hidden DM models where the DM is naturally in the GeV range and couples to the SM sector through higher dimension operators.

3 Dark Matter and the Baryon Coincidence Problem

We now consider a different type of hidden sector model where the dark matter number density is set not by thermal freeze-out, as in the standard case, but by the baryon asymmetry. The DM itself carries baryon or lepton number and its mass is related to the proton mass by

$$m_{DM} = c\frac{\Omega_{DM}}{\Omega_b} m_p, \tag{10}$$

where c is an $\mathcal{O}(1)$ number set by the baryon number of the DM. Since $\Omega_{DM}/\Omega_b \approx 5$, the DM is in the several GeV mass range, and resides in a low mass hidden sector.

There are a number of models that have been considered in the context of the baryon-DM coincidence problem [34]. Here we discuss only one which has appeared recently [35] since it is in the class of low mass sectors communicating through higher dimension operators in Eq. (1). It is unique in that it does not sequester baryon number between the dark and visible sectors while the net baryon number of the universe is zero, rather it starts with a net non-zero baryon or lepton number and distributes it evenly between the sectors through higher dimension operators. When the higher dimension operator drops out of thermal equilibrium, the baryon asymmetry freezes separately into the two sectors.

We consider in particular a leptonic DM model. There is a lepton asymmetry in the standard model (SM) sector which is transfered to the DM through an operator

$$W = \frac{\bar{X}^2 LH}{M}. \tag{11}$$

Here X is the DM which carries lepton number 1/2, L is a lepton doublet and H is the Higgs doublet. There is a Z_4 symmetry which keeps the DM stable. As long as this operator decouples before the temperature that X becomes non-relativistic, an asymmetry is frozen separately into the SM and DM sectors. A UV completion for this model involves, e.g. electroweak doublets D and $\bar{D}$:

$$W = M_D \bar{D} D + \lambda' \bar{X} D H_u + y' L \bar{D} \bar{X}, \tag{12}$$

with $M = M_D/(\lambda' y')$.

Now the baryon number density is about 10^{-10} of the thermal number density. This thermal abundance of the DM must be annihilated away to leave only the one part in 10^{10} asymmetric part. One possibility is annihilation to NMSSM axions, through a singlet which couples both to SM Higgs and to the DM X

$$\Delta W = \lambda_X S\bar{X}X + \zeta S H_u H_d. \tag{13}$$

Then we can have the annihilation $\bar{X}X \to aa$, where a is the lightest pseudoscalar in the Higgs sector. This gives an annihilation cross section

$$\langle \sigma v_{rel} \rangle = \frac{1}{16\pi}\frac{m_X^2}{s^4}, \tag{14}$$

which is large enough to annihilate away the thermal abundance for $s < 200$ GeV. Once this efficient annihilation of the symmetric part of the DM density has occurred, one is left only with the asymmetry between X and $\bar{X}$ in the dark sector, which is related to the baryon density through the relation Eq. (10).

There are other classes of models one can consider in the same spirit, for example where the DM carries baryon number and the superpotential is

$$W = \frac{\bar{X}^2 udd}{M^2}, \tag{15}$$

or an $L = 1$ leptonic DM candidate

$$\mathcal{L} = \frac{\bar{X}^2 LHLH}{M^4}, \tag{16}$$

where X is now a sterile neutrino, as is evident from the UV completion of this operator

$$\mathcal{L} = \bar{X}LH' - \frac{\lambda}{4}[(HH')^2 + \text{h.c.}], \tag{17}$$

where H' is an electroweak doublet which gets no vacuum expectation value.

3.1 Implications for Collider Searches of Dark Matter

Like the hidden sector models discussed in the previous section, the MSSM Lightest Supersymmetric Partner (LSP) is unstable to decay to the light hidden sector states. Because the DM carries lepton or baryon number, often these decay chains involve multiple leptons or jets.

In the case of the leptonic DM, decays typically involve the MSSM LSP going to an additional lepton plus the DM states. The lepton can be either charged or a neutrino. If the latter, the LSP decay is completely invisible, and one can mistake the MSSM LSP for a DM candidate. In addition, depending on the scale M, the lifetimes can be quite long, as in the decay

$$c\tau(\tilde{\tau}_R \to \tau\nu\bar{X}\bar{X}) \sim \text{mm}\left(\frac{M}{10^6\ \text{GeV}}\right)^2\left(\frac{m}{200\ \text{GeV}}\right)^6\left(\frac{m_{\tilde{\tau}}}{100\ \text{GeV}}\right)^{-7}, \tag{18}$$

where we have assumed a common mass scale $m \sim m_{\tilde{\nu}} \sim m_{\chi^0}$.

In the case of the baryonic decay, the decays are often even more exotic. The MSSM LSP decays to three jets plus the DM. In this case, since the operator is suppressed by higher powers of M than for the leptonic DM, even for a scale M at the TeV scale, these decays give rise to displaced vertices:

$$c\tau(\chi^0 \to XXqqq) \sim 100\ \text{m}\left(\frac{M}{\text{TeV}}\right)^4\left(\frac{m}{500\ \text{GeV}}\right)^6\left(\frac{m_{\chi^0}}{100\ \text{GeV}}\right)^{-11}. \tag{19}$$

If the scale is much higher, the MSSM LSP is stable on detector time scales

In these models, one must be on the look-out for exotic DM signals at the LHC, in particular long lived, but unstable, MSSM LSPs which give rise to a secondary vertex displaced from the interaction point in the detector.

4 Concluding Remarks

It's an exciting time for DM. There are many different detection prospects. Already there are puzzles and hints from DAMA, HEAT, AMS, PAMELA, Fermi, and INTEGRAL. In each of these areas there is more data to come. In direct detection, CDMS is planning low and high nuclear recoil threshold analyses to test the DAMA anomalies, new low nuclear recoil threshold experiments are being designed and carried out, XENON has a high threshold analysis looking for inelastic DM, and CRESST has a few anomalous events which may be a hint for inelastic DM. In the cosmic-ray electron and positron excesses, AMS has a new mission approved to test the PAMELA results, and Fermi gives a highly precise measurement of the cosmic ray electron spectrum out to a TeV. Fermi will have new photon data coming available in the coming months which may also test the WIMP dark matter hypothesis, if it has either standard annihilation modes or annihilation consistent with the cosmic-ray electron and positron excesses. All these astrophysical probes will be complementary to the direct production at the LHC.

If any of the early hints from these experiments are real signals from the dark sector, we will have to re-think our models of and search strategies for the DM. The dark sector, like the visible sector, may be complex, with multiple new light states and dark forces.

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