Particle Dark Matter from Physics Beyond the Standard Model

Konstantin Matchev\textsuperscript{a,*}

\textsuperscript{a}Physics Department, University of Florida, Gainesville FL 32611, USA

In this talk I contrast three different particle dark matter candidates, all motivated by new physics beyond the Standard Model: supersymmetric dark matter, Kaluza-Klein dark matter, and scalar dark matter. I then discuss the prospects for their discovery and identification in both direct detection as well as collider experiments.

1. DARK MATTER AND PHYSICS BEYOND THE STANDARD MODEL

So far the existence of the dark matter (DM) is our best experimental evidence for new physics beyond the Standard Model. The most recent WMAP data\textsuperscript{1} confirm the standard cosmological model and precisely pin down the amount of cold dark matter as $0.094 < \Omega_{\text{CDM}} h^2 < 0.129$, in accord with earlier indications. Nevertheless, the exact nature of the dark matter still remains a mystery, as all known particles are excluded as DM candidates. This makes the dark matter problem the most pressing phenomenological motivation for particles and interactions beyond the Standard Model (BSM).

The weakly interacting massive particles (WIMPs) represent a whole class of particle dark matter candidates which are well motivated by both particle physics and astrophysics. On the particle physics side, many BSM theories predict stable WIMPs. On the astrophysics side, the result from the calculation of the WIMP thermal relic density falls in the right ballpark. WIMPs also offer excellent opportunities for detection: since they must have been able to annihilate sufficiently fast in the Early Universe, they should also produce observable signals in direct and indirect dark matter detection experiments.

Generally speaking, it is rather easy to cook up BSM dark matter. The main steps in model-building are the following:

1. enlarging the particle content of the SM;

2. introducing a symmetry which guarantees that one of the newly introduced particles is stable;

3. fudging the model parameters until the lightest new stable particle is neutral and has the proper thermal relic density.

In the next three sections I will illustrate this model-building recipe with three generic examples of BSM theories with good DM candidates. Section 2 is devoted to supersymmetry\textsuperscript{2} in its most popular version (minimal supergravity), where the DM candidate is the lightest superpartner. In Section 3 I consider the model of universal extra dimensions\textsuperscript{3} where the lightest Kaluza-Klein mode is the DM particle. Then in Section 4 I discuss DM in Little Higgs theories\textsuperscript{4}. In each case, after a brief introduction to the theory I will discuss why the DM particle is stable, what is its preferred mass range and what are the discovery prospects for its direct detection. The potential discovery and discrimination of these alternatives at high energy colliders is the subject of Section 5 while Section 6 contains a comparative summary and conclusions. The subject of distinguishing these scenarios in astroparticle physics experiments in space is covered in J. Feng’s contribution to these proceedings.
2. SUSY DARK MATTER

Supersymmetry (SUSY) is a theory with extra dimensions described by new *anticommuting* coordinates $\theta_\alpha$. The theory is defined in terms of superfields living in *superspace* $\{x^\mu, \theta\}$:
\[ \Phi(x^\mu, \theta) = \phi(x^\mu) + \psi^\alpha(x^\mu)\theta_\alpha + F(x^\mu)\theta^\alpha\theta_\alpha, \]
where the pair $\{\phi, \psi\}$ is a SM particle and its superpartner. Supersymmetry thus predicts a host of new particles, offering a potential solution to the DM problem. A robust prediction of SUSY is that each superpartner has couplings identical to and spin differing by 1/2 from the corresponding SM particle. Unfortunately, the superpartner mass spectrum is very model dependent as it is related to the details of SUSY breaking.

All superpartners are charged under a discrete symmetry called $R$-parity, which is a remnant of translational invariance along the $\theta$ coordinates. The $R$-parity assignments are +1 for SM particles and −1 for their superpartners. In many models one requires that $R$-parity is conserved, which provides a simultaneous solution to the proton decay problem. As a bonus, $R$-parity conservation guarantees that virtual supersymmetric contributions only arise at the loop level, thus avoiding constraints from precision electroweak data. As a result of $R$-parity conservation, the lightest superpartner (LSP), being odd under $R$-parity, is absolutely stable and becomes a DM candidate. In the remainder of this Section, we shall restrict ourselves to the case of minimal supergravity (mSUGRA) and describe the cosmologically preferred parameter space with a WIMP LSP.

2.1. The LSP as a SUSY WIMP

The desired WIMP in supersymmetry is the lightest neutralino $\tilde{\chi}_1^0$, which is a mixture of the superpartners of the hypercharge gauge boson ($\tilde{b}^0$), the neutral $SU(2)_W$ gauge boson ($\tilde{W}^0$), and the two neutral Higgs bosons ($\tilde{h}_u^0, \tilde{h}_d^0$):
\[ \tilde{\chi}_1^0 = a_1 \tilde{b}^0 + a_2 \tilde{W}^0 + a_3 \tilde{h}_u^0 + a_4 \tilde{h}_d^0. \]

In large regions of the mSUGRA parameter space, $\tilde{\chi}_1^0$ indeed turns out to be the LSP. Its gaugino fraction $R_\chi$
\[ R_\chi \equiv |a_1|^2 + |a_2|^2 \approx |a_1|^2 \]
is shown in Fig. 1 in the $m_0 - M_{1/2}$ slice of the mSUGRA parameter space. The pre-WMAP (post-WMAP) preferred parameter space is also shown in yellow (red). We easily see two regions where $\tilde{\chi}_1^0$ is a good DM candidate. The “coannihilation” region at low $m_0$ exhibits a gaugino-like LSP, whose relic density is diluted due to coannihilation processes involving $\tau$ sleptons. Alternatively, at large $m_0$ one finds the so called “focus point region” where the LSP has a non-negligible higgsino component, and annihilation is enhanced due to a complementary set of diagrams proportional to gaugino-higgsino mixing. Unlike the coannihilation region, the focus point region is characterized by heavy scalar superpartners, and as a result all virtual supersymmetric effects are suppressed. In the absence of any significant discrepancies from the SM, the focus point region tends to be preferred in global fits to the data.

Figure 1. Contours of constant gaugino fraction $R_\chi$ in percent, for $\tan \beta = 10, A_0 = 0, \mu > 0$ and $m_t = 174$ GeV. The (green) shaded regions are excluded from the requirement that the LSP be neutral (left) and the chargino mass bound from LEP (bottom and right). The light (yellow) shaded region in between corresponds to the pre-WMAP preferred range of $0.1 \leq \Omega h^2 \leq 0.3$. The red (dark) shaded region is the remaining parameter space after WMAP. From Ref. [8].
2.2. Direct detection of SUSY dark matter

The prospects for direct detection of SUSY WIMPs in experiments sensitive to spin-independent (spin-dependent) WIMP-nucleon interactions are depicted in Fig. 2 (Fig. 3) [11], for the set of 13 SUSY benchmark points from [12]. We see that spin-independent scattering offers the best possibilities for detection – about half of the benchmark points fall within the sensitivity range of the upcoming experiments. Unfortunately, we also see that due to accidental cancellations, one cannot place a firm lower bound on the predicted signal (see, e.g. points D and K).

Regarding spin-dependent scattering, the prospects are less optimistic, as all 13 benchmark points fall far below the experimental sensitivity. A likely signal in the spin-independent channel will still leave open the question of the exact nature of the DM particle, and its spin, in particular. In the next two Sections, we shall describe alternative DM candidates whose main difference from SUSY WIMPs is their spin.

3. UNIVERSAL EXTRA DIMENSIONS

Universal Extra Dimensions [3] is an extra dimension theory with new bosonic coordinates $y$ (in the simplest case of only one extra dimension, $y$ spans a circle of radius $R$):

$$
\Phi(x^\mu, y) = \phi(x^\mu) + \sum_{i=1}^{\infty} \phi^n(x^\mu) \cos(ny/R) + \sum_{i=1}^{\infty} \chi^n(x^\mu) \sin(ny/R)
$$

Each SM field $\phi$ ($n = 0$) has an infinite tower of Kaluza-Klein (KK) partners $\phi^n$ and $\chi^n$ with identical spins and couplings and masses of order $n/R$. In order to obtain chiral fermions, the extra dimension is compactified on an $S_1/Z_2$ orbifold. Fields which are odd under the $Z_2$ orbifold symmetry do not have zero modes ($\phi = \phi^n = 0$), which allows us to project out the zero modes of the fermions with the wrong chiralities and the 5th component of the gauge fields. The remaining zero modes are just the Standard Model particles in 3+1 dimensions.

A peculiar feature of UED is the conservation of KK number at tree level, a simple consequence of
momentum conservation along the extra dimension. However, bulk and brane radiative effects \[16,17\] break KK number down to a discrete conserved quantity, the so-called KK parity: \((-1)^n\), where \(n\) is the KK level. KK parity ensures that the lightest KK partner (LKP) at level one, being odd under KK parity, is stable and can be a DM candidate. Similar to the SUSY case, new physics contributions to various precisely measured low-energy observables only arise at the loop level and are small.

### 3.1. The LKP as a UED WIMP

Including the one-loop radiative corrections, the mass spectrum of the level 1 KK-partners (see Fig. 4) exhibits striking similarities to supersymmetry \[18\]. The LKP is a neutral WIMP which is a linear combination of the first KK mode \(B_1\) of the hypercharge gauge boson and the first KK mode \(W^0_1\) of the neutral \(SU(2)_W\) gauge boson. The mass matrix for the neutral gauge bosons at level \(n\) has the form

\[
\begin{pmatrix}
\frac{n^2}{R^2} + \frac{1}{2} g_1^2 v^2 + \delta m_{\tilde{B}_n}^2 \\
\frac{1}{2} g_1 g_2 v^2 + \frac{1}{4} g_2^2 v^2 + \delta m_{\tilde{W}_n}^2
\end{pmatrix}.
\]

Upon diagonalization, we find the Weinberg angle \(\theta_n\) at KK level \(n\) shown in Fig. 5. We see that while at tree level \(\theta_n\) is identical to the SM value, at one loop it is rather small. As a result, the LKP is predominantly \(B_1\), in analogy to the case of \(\tilde{b}_0\) in SUSY.

### 3.2. Relic density of KK dark matter

The relic density of Kaluza-Klein dark matter can be readily computed \[19\]. Unlike the case of supersymmetry, where the LSP is a Majorana fermion, here the LKP is a vector particle and the helicity suppression is absent. The LKP relic density

\[
\Omega h^2 = \frac{1.04 \times 10^9 \text{ GeV}^{-1}}{M_\sqrt{g_0}} \frac{x_F}{a + 3b/x_F} \tag{5}
\]

is mostly determined by the \(a\)-term in the velocity expansion of the annihilation cross-section, where \[19\]

\[
a = \frac{\alpha_1^2}{M_{KK}^2} \frac{380\pi}{81} ; \quad b = -\frac{\alpha_1^2}{M_{KK}^2} \frac{95\pi}{162} \tag{6}
\]

Here \(M_{KK} \sim R^{-1}\) is the LKP mass, \(x_F^{-1} = T_F/M_{KK}\) is the dimensionless freeze-out temperature and \(\alpha_1\) is the hypercharge gauge coupling constant. Unlike supersymmetry, coannihilation processes in UED lower the preferred LKP mass range (see Fig. 6).
3.3. Detection of KK dark matter

The prospects for direct detection of KK dark matter are summarized in Fig. 7 [20]. As in the case of SUSY, only spin-independent probes appear promising, since precision data has ruled out $R^{-1} < 250$ GeV [23]. The predictions are for $m_h = 120$ GeV and $0.01 \leq r = (M_Q - M_B)/M_B \leq 0.5$, with contours for specific intermediate $r$ labeled. A nice feature of UED is the constructive interference of the relevant diagrams, guaranteeing a lower bound on the detection rate, which is evident in Fig. 7.

4. LITTLE HIGGS THEORIES

Little Higgs theories alleviate the Higgs hierarchy problem by eliminating the quadratic divergence in the Higgs mass correction at one-loop (Fig. 8). New particles are introduced around the TeV scale and their couplings are such that the quadratic divergence cancels for each vertical pair of diagrams in Fig. 8. The special values of the couplings are guaranteed by a symmetry, as the Higgs boson is a pseudo-Goldstone boson.

However, generic Little Higgs models give tree-level contributions to precision data and are severely constrained [24]. One possible solution is to postulate a conserved $T$-parity [25], which may have a geometrical origin in theory space. The SM particles are chosen to be even under $T$-parity while all new particles are odd. This ensures that the lightest $T$-odd particle (LTP) is stable and again may serve as a DM candidate.

4.1. Dark matter in Little Higgs models

The relic density of little Higgs dark matter was studied in [20] for a specific model with a scalar LTP $N_1$, which is a mixture of an SU(2)-triplet
The absence of a helicity suppression requires relatively large masses $m_{N_1}$ for the LTP WIMP case. However, for $150 \text{ GeV} < m_{N_1} < 350 \text{ GeV}$, annihilation into $t\bar{t}$ and $hh$ is very efficient (even if $N_1$ is a pure singlet) and there is no preferred region for any value of the mixing angle $\theta_{\eta\varphi}$.

5. SUSY-UED DISCRIMINATION

We saw that the superpartners and level 1 KK partners in UED may have a very similar spectrum. In addition, both models have a DM candidate which could give a signal in upcoming dark matter detection experiments. The natural question then is, how can one distinguish the two scenarios? The two basic methods are: producing and studying the dark matter at a high energy collider; or looking for certain indirect DM signals.

Recall that the mass spectrum at each KK level in UED is rather degenerate (Fig. 4). The typical UED collider signatures therefore include soft leptons, soft jets and a modest amount of $E_T$.

5.1. Hadron colliders

At hadron colliders one would like to use the strong production of KK-quarks and KK-gluons, followed by a decay chain through $W_i^\pm$ and $W_i^0$, whose decays always yield leptons and/or neutrinos (see Fig. 4). Inclusive pair production of $SU(2)_W$ doublet quarks $Q_i$ results in a clean $4\ell E_T$ inclusive signature with a reasonable rate. This channel was studied in [19] for both the Tevatron and the LHC and the resulting reach is shown in Fig. 14. We see that for nominal integrated luminosities the LHC will see a UED signal throughout all of the cosmologically preferred range (see Fig. 4). However, UED and supersymmetry can be easily confused at hadron colliders, where spin determinations are rather challenging because of the unknown parton-level center-of-mass energy in the event.

5.2. Linear colliders

In contrast, at linear colliders the information about the spin of the produced particle is encoded in the angular distributions of its decay products. Consider, for example the two similar scenarios of

\[ \varphi_3^0 \text{ and an SU}(2)\text{-singlet } \eta_1^0 \text{ (see Fig. 9)} \]

\[ N_1 = \cos \theta_{\eta\varphi} \eta_1^0 + \sin \theta_{\eta\varphi} \varphi_3^0 \tag{7} \]

Figure 8. Top: SM diagrams leading to a quadratic divergence in the one-loop Higgs mass correction. Bottom: New physics contributions from Little Higgs theories which cancel the quadratic divergence.

Figure 9. Preferred relic density regions (green, light shaded) as a function of $\cos \theta_{\eta\varphi}$ and $m_{N_1}$. From Ref. [20].
Figure 10. UED discovery reach at the Tevatron (blue) and the LHC (red) in the $4\ell/E_T$ channel. We require a $5\sigma$ excess or the observation of 5 signal events, and show the required total integrated luminosity per experiment (in fb$^{-1}$) as a function of $R^{-1}$. From Ref. [18].

KK-muon production in UED

\[ e^+e^- \rightarrow \mu_1^+\mu_1^- \rightarrow \mu^+\mu^-\gamma_1\gamma_1 \]  
\[ e^+e^- \rightarrow \bar{\mu}_1^+\bar{\mu}_1^- \rightarrow \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0. \]

The angular distribution of the KK-muon $\mu_1$ (with respect to the beam axis) is given by

\[ \frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta, \]  
while for the smuon $\bar{\mu}$ we have

\[ \frac{d\sigma}{d\cos\theta} \sim 1 - \cos^2\theta. \]

In practice one measures the muon scattering angle $\theta_\mu$, which is significantly different for the two cases at hand (Fig. 11). In addition, the spin difference is reflected in the total cross-section, which can be measured very well, as well as in the energy dependence of the total cross-section at threshold.

6. CONCLUSIONS

Table 1 summarizes the main features of the models discussed in Sections 2-4. By now there are several well-motivated alternatives for BSM WIMPs and discriminating among them will be a challenge for the upcoming direct detection and hadron collider experiments. In this sense, astroparticle physics experiments in space may play an important role as discriminators among various DM alternatives and thus provide important clues to the identity of the dark matter.

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Table 1
Summary of the models discussed in the text.

| Model                  | SUSY | UED | Little Higgs |
|------------------------|------|-----|--------------|
| DM particle            | LSP  | LKP | LTP          |
| Spin                   | 1/2  | 1   | 0            |
| Symmetry               | R-parity | KK-parity | T-parity |
| DM mass range          | 50-200 GeV | 600-800 GeV | 400-800 GeV |

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