INTRODUCTION

We will discuss here three topics. These are: (1) Neutralino dark matter from the perspective of a sparticle landscape[1], and sparticle mass hierarchies; (2) The dual probe of supersymmetry with dark matter detection, and with leptonic and jet signatures and missing energy from sparticle production at the LHC[2]; (3) An out of the box possibility of extra weakly interacting dark matter (a Stino XWIMP), or milli-charged dark matter arising from the Stueckelberg extensions of the MSSM or the SM.

We begin with supersymmetry which is an attractive symmetry for the construction of fundamental interactions in four dimensions[9]. For a variety of reasons supersymmetry must be made local[10,11] which leads to what one calls supergravity. Further support for supergravity comes from the fact that it is the field point limit of string theory which is a candidate theory of quantum gravity. The above provides the rationale for utilizing $N = 1$ supergravity as a natural framework for model building. In this class fall the sugra, string and D brane models. These are all high scale models which differ among other things, by the nature of soft SUSY breaking. Soft breaking can be classified broadly as arising from gravity mediation[12,13,14,15], from gauge mediation[16], as well as other possibilities such as from anomaly mediation etc. In this analysis we will focus on the gravity mediation of soft breaking. The minimal supergravity models are characterized by the parameter space in the soft sector at the GUT scale consisting of the four parameters ($m_0$, $m_{1/2}$, $A_0$, $B_0$) where ($m_0$, $m_{1/2}$) are the universal (scalar, gaugino) masses, $A_0$ is the universal trilinear coupling, and $B_0$ is the parameter which appears as $B_{H_0}H_1H_2$, where $\mu$ is the co-efficient of the bilinear Higgs term in the superpotential which appears in the form $\mu H_1H_2$. After radiative electroweak symmetry breaking (REWSB) one determines $\mu$ except for its sign, and the masses $B_0$ for $\tan \beta$ which is defined to be the ratio of two Higgs VEVs, i.e., $\tan \beta = \langle H_2 \rangle / \langle H_1 \rangle$, where ($H_2$, $H_1$) are responsible for mass generation of (u quarks, d quarks and leptons). Thus the parameter space of the model after REWSB is spanned by ($m_0, m_{1/2}, A_0, \tan \beta, \text{sign} (\mu)$) (see, e.g., [17]). The mSUGRA model is precisely defined to be a model with the parameter space specified above.

We note that supergravity models provide a broad framework for model building. Thus one can both reduce the parameter space of the model by additional constraints such as in no-scale models or by putting further constraints on the mSUGRA parameter space, or enlarge the parameter space by inclusion of non-universalities. Models with enlarged parameter space include sugra models with non-universalities, heterotic string and D brane models with large volume compactifications, and many other scenarios[18,19]. We note that irrespective of the details of the models, all models of this sort fall in
the general class where SUSY is broken by gravity mediation. Some generic non-universalities in supergravity models (one can label such models as SUSY-NUGRA) can be discussed by the inclusion of non-universalities in the Higgs sector (NUH), in the third generation sector (NUq3), and in the gaugino sector (NUG). Thus, for example, in the NUH case one can include nonuniversalities at the GUT scale so that (i) NUH: $M_{H_u} = m_0 (1 + \delta_{H_u})$, $M_{H_d} = m_0 (1 + \delta_{H_d})$. Similarly for the third generation one can include nonuniversalities such that (ii) NUq3: $M_{3} = m_0 (1 + \delta_{3})$, $M_{a3, d3} = m_0 (1 + \delta_{d3})$, and finally for the gaugino sector one may include nonuniversalities such that (iii) NUG: $M_{1} = m_{1/2}, M_{2} = m_{1/2} (1 + \delta_{M_2}), M_{3} = m_{1/2} (1 + \delta_{M_3})$. In all cases the $\delta$‘s parameterize the nonuniversalities and one may take their ranges to lie in some reasonable interval such as $-0.9 < \delta < 1$.

In supergravity models the lightest neutralino turns out to be the lightest supersymmetric particle (LSP) over a large region of the parameter space, and is thus a candidate for dark matter with R parity. For neutralino dark matter the satisfaction of the WMAP constraints \textsuperscript{20} \(0.855 < \Omega_{cdm} h^2 < 0.1189\) (2$\sigma$) is achieved typically in three broad regions. These include the co-annihilation regions, the Hyperbolic Branch/Focus Point (HB/FP) region, and pol regions. The co-annihilation regions contain stau co-annihilation, stop co-annihilations etc. The relic density analysis allows a region of the parameter space where the CP odd Higgs is light and where WMAP constraints are also satisfied. Recently light Higgses in the sector of neutralino dark matter have been discussed in \textsuperscript{21} \textsuperscript{23}. Based on restricted analyses it is often stated that only small slivers of the mSUGRA parameter space remain consistent with WMAP. However, this conclusion is erroneous since a large part of the parameter space opens up when $A_0$ and $\tan \beta$ are fully explored.\textsuperscript{31} \textsuperscript{32} \textsuperscript{31}. There is an enormous literature on the analyses of SUSY dark matter. A small sample can be found in \textsuperscript{33} \textsuperscript{34} \textsuperscript{35} \textsuperscript{36}.

**HIERARCHICAL MASS PATTERNS**

An approach which has proved useful in the analysis of dark matter and in correlating it with the LHC physics is in terms of particle mass patterns \textsuperscript{1} \textsuperscript{27} \textsuperscript{2}. As there are 32 particle masses in MSSM (including Higgses in this definition), then using sum rules one has upwards of $10^{32}$ mass hierarchies. If one focusses on the first four lightest sparticles this number reduces to about $10^4$. It reduces further, and quite drastically, in well motivated models such as mSUGRA, NUSUGRA, and in string and D brane models when one imposes the accelerator and WMAP constraints, and the constraints of REWSB. For the case of mSUGRA, with $\mu > 0$ one finds that 16 patterns survive (labeled mSP1-mSP16 and can be decomposed more simply in terms of the NLSP):

- **Chargino Patterns** ($\mu > 0$)
  - mSP1: $\tilde{X}_1^0 < \tilde{X}_1^- < \tilde{X}_2^- < \tilde{X}_1^+$, mSP2: $\tilde{X}_1^0 < \tilde{X}_1^- < \tilde{X}_2^- < A/H$,
  - mSP3: $\tilde{X}_1^0 < \tilde{X}_1^- < \tilde{X}_2^- < \tilde{t}_1$, mSP4: $\tilde{X}_1^0 < \tilde{X}_1^- < \tilde{X}_2^- < \tilde{g}$.

- **Stau Patterns** ($\mu > 0$)
  - mSP5: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{l}_R < \tilde{\nu}_R$, mSP6: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{X}_1^< < \tilde{X}_2^>$,
  - mSP7: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{l}_R < \tilde{\tau}_1^+$, mSP8: $\tilde{X}_1^0 < \tilde{\tau}_1 < A \sim H$,
  - mSP9: $\tilde{X}_1^0 < \tilde{t}_1 < \tilde{l}_R < \tilde{A}/H$, mSP10: $\tilde{X}_1^0 < \tilde{t}_1 < \tilde{l}_R$.

- **Stop Patterns** ($\mu > 0$)
  - mSP11: $\tilde{X}_1^0 < \tilde{t}_1 < \tilde{X}_1^< < \tilde{X}_2^>$, mSP12: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{X}_1^+$,
  - mSP13: $\tilde{X}_1^0 < \tilde{t}_1 < \tilde{l}_R < \tilde{\nu}_R$.

- **Higgs Patterns** ($\mu > 0$)
  - mSP14: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{X}_1^+$, mSP15: $\tilde{X}_1^0 < \tilde{A} \sim H < \tilde{X}_1^+$,
  - mSP16: $\tilde{X}_1^0 < \tilde{A} \sim H < \tilde{\tau}_1$.

The notation mSP stands for minimal SUSY Pattern. For the case $\mu < 0$ one finds more Stau and Stop Patterns and additionally a new type appears which is the neutralino pattern

- **Stau Patterns** ($\mu < 0$)
  - mSP17: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{X}_1^< < \tilde{X}_1^+$, mSP18: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{l}_R < \tilde{t}_1$,
  - mSP19: $\tilde{X}_1^0 < \tilde{t}_1 < \tilde{l}_R < \tilde{X}_1^+$.

- **Stop Patterns** ($\mu < 0$)
  - mSP20: $\tilde{X}_1^0 < \tilde{t}_1 < \tilde{X}_2^- < \tilde{X}_1^+$, mSP21: $\tilde{X}_1^0 < \tilde{\tau}_1 < \tilde{TA} < \tilde{X}_2^>$,

- **Neutralino Pattern** ($\mu = 0$)
  - mSP22: $\tilde{X}_1^0 < \tilde{X}_2^- < \tilde{X}_1^+ < \tilde{g}$.

We note that only 6 of the 22 patterns listed above are sampled in the Snowmass,\textsuperscript{37} in the PostWMAP3,\textsuperscript{38} and in the CMS LM and HM benchmarks. Since it is imperative that one sample all the patterns, benchmarks for the 22 patterns have been given recently in \textsuperscript{2}. As an example, an application using mSP4 is given in \textsuperscript{39}. With the inclusion of nonuniversalities in the soft breaking sector for the cases of NUH, NUq3, and NUG 15 more mass patterns emerge which may be labeled NUSP1-NUSP15 (see \textsuperscript{2}).

It turns out that the direct detection of dark matter (for early works see e.g. \textsuperscript{40} \textsuperscript{41} \textsuperscript{42} \textsuperscript{43}) produces a strong dispersion between the Chargino Patterns and the Stop Patterns (more examples of model discrimination with dark matter connected to LHC signatures may be found in \textsuperscript{27} and also in \textsuperscript{44}). Another interesting phenomenon is the appearance of the Chargino Wall in mSP1 which runs horizontally up to ~650 GeV in the neutralino mass for mSUGRA and up to ~850 GeV in the neutralino mass for the NUG model under naturalness assumptions. Here one finds that the spin independent cross section is maintained at ~$(2 - 5) \times 10^{-8}$ pb level over the entire range of neutralino mass enhancing the prospects for the discovery of dark matter on the Wall in upgraded dark mat-
ter experiments. We add that while a larger Higgsino content is known to give rise to strong SI cross sections [45] the finding that the Wall is composed essentially entirely of mSP1 points in sugra models [27] is an entirely new result which also has important implications for LHC studies. In addition to the neutralino, there are other alternatives dark matter candidates such as the gravitino in sugra models, the least massive KK particle (LKP) as, e.g. inUED models; a massive spin 1 in Little Higgs Models, Dirac neutrinos, dark matter from the hidden sector, and several other interesting possibilities. A recent work has observed [46] that a comparison of spin dependent vs spin independent scattering cross sections can be used to distinguish some of the models listed above.

Dual probes of SUSY with dark matter detection and + leptons and jets + $\vec{E}_T$

It is important to pursue correlated studies of experimentally constrained dark matter [47] (see also [48]) with signatures at the Large Hadron Collider. Some recent analyses of LHC signature spaces have been studied in [1,27] with signatures at the Large Hadron Collider. Some recent analyses of LHC signature spaces have been studied in [1,27,2,49,50,51,52,53,54,55,56]. One finds that dark matter detection is in some ways complementary to LHC in its probe of the SUSY parameter space. That is, dark matter direct detection can probe some parts of the parameter space which may be hard to reach with low luminosity at the LHC. One such example is given in Fig.[2] where one finds that a much larger part of the parameter space of chargino patterns can be explored with Super CDMS (which covers the whole Wall) than with 10 fb$^{-1}$ of integrated LHC luminosity in the OS 2$t$ channel. The plot shows remarkable separation between the stau co-annihilation region and the hyperbolic branch.

HIDDEN SECTOR DARK MATTER

We discuss now an out of the box possibility for dark matter. An interesting possibility arises in that dark matter can originate from a hidden sector. In sugra unified models and in string and in brane models a hidden sector exists which contains fields which are sin-
glets of the Standard Model gauge group. Thus it is interesting to investigate if the hidden sector can provide us with the relevant candidate for dark matter which produces relic density within the WMAP bounds. Suppose there is dark matter whose interactions with quarks and leptons are weaker than weak, or extra-weak. How can such dark matter arise? Such extra-weak dark matter can arise when one has two sectors: a physical sector where MSSM fields reside and a hidden sector. The hidden sector fields do not carry MSSM quantum numbers and the physical sector fields do not carry the quantum numbers of fields in the hidden sector. Thus the sectors do not have a direct communication.

If, however, one introduces a connector sector which carries dual quantum numbers and interacts with the physical sector fields as well as with the hidden sector fields then the sectors can communicate [4]. Further, spontaneous breaking in the connector sector would produce mixing effects in the mass matrices in the visible sector which can lead to detectable signals. We give now an explicit demonstrations of the above. We begin by considering for the hidden sector just a $U(1)$ gauge multiplet. For the Connector Sector we consider the chiral fields $\phi^\pm$ with charges $\pm Q_\chi$ under $U(1)_\chi$ and charges $\pm Y_\theta$ under $U(1)_Y$. For technical reasons one needs to add a Fayet-Iliopoulos term $\mathcal{L}_{FI} = \xi_\chi D\chi + \xi_Y D_Y$. Vacuum solutions for this model give $\langle \phi^+ \rangle = 0$, and $\langle \phi^- \rangle \neq 0$ and one has mixings involving the visible sector, the hidden sector and the connector sector. We discuss the implication of this mixing for dark matter.

After spontaneous breaking there are now six Majorana spinors $(\chi_\theta^-, \lambda_\chi^-, \lambda_3, h_1, h_2)$ where $\chi_\theta^-$ is the spinor that arises from $\phi^-$. This leads to mass diagonal states $(\xi_1^0, \xi_2^0, \xi_1^1, \xi_2^1, \tilde{\chi}_1^\mu, \tilde{\chi}_2^\mu)$. The above scenario is actually realized in the Stueckelberg $U(1)_\chi$ extension of the MSSM [5][6]. In the St extensions there is a mixing between the two $U(1)$ factors in the theory, i.e., $U(1)_\chi$ and $U(1)_Y$ which arises from the following Lagrangian:

$$\mathcal{L}_{St}(V, S, \tilde{S}) = (M_1 C + M_2 B + S + \tilde{S})^2|_{\theta \theta \theta \theta},$$

where $V = (C, B)$ are vector superfields and $S$ is a chiral superfield. In the vector field sector this leads to in particular the combination $\frac{1}{2}(\partial_{\mu} \phi + M_2 B_{\mu} + M_1 C_{\mu})^2$ where $B_{\mu}$ is the gauge field of $U(1)_Y$ and $C_{\mu}$ is the gauge field of $U(1)_{\chi}$, and $\phi$ is the axion which gets absorbed in the unitary gauge. The parameter that produces mixings between the visible sector and the hidden sector is $\varepsilon = M_2/M_1$, and an analysis based on precision electroweak data gives the constraint $\varepsilon \lesssim .06$. Because of the smallness of $\varepsilon$ the interactions of $\xi_1^0$ and $\xi_2^0$ with the visible sector quarks and leptons are extra weak. Using the index 1 to denote the lighter of each type of Majorana we now have the following situation: either one has $m_{\chi_1^0} > m_{\chi_1^\mu}$ or one has $m_{\chi_1^0} < m_{\chi_1^\mu}$. For the case when $m_{\chi_1^0} > m_{\chi_1^\mu}$, $\chi_1^0$ will still be the LSP and not much will change. However, for the case when $m_{\chi_1^0} < m_{\chi_1^\mu}$ it is $\xi_1^0 \equiv \tilde{\chi}_1^{0\prime}$ which is the LSP, and the LSP in this case will be extra weakly interacting. We will call this particle an XWIMP or Stino for obvious reasons. XWIMPS cannot annihilate in sufficient amounts by themselves to satisfy the relic density constraints as mentioned already. However they can do so via co-annihilation, i.e., via the processes $\xi_1^0 + \xi_2^0 \rightarrow X$, $\xi_1^0 + \chi_1^0 \rightarrow X'$, and $\chi_1^0 + \chi_1^0 \rightarrow X''$ where each $X$ are (pairs of) Standard Model particle. The effective cross section for the annihilation of the extra-weakly interacting Stinos is then

$$\sigma_{eff} \sim \varepsilon \chi^0 \chi^0 \left( \frac{Q^2}{1 + Q^2} \right)^2, \quad Q \sim (1 + \Delta)^{3/2} e^{-x_\chi^0 \Delta},$$

where $\Delta = (m_{\chi_1^0} - m_{\chi_1^\mu})/m_{\chi_1^0}$, $x_f = m_{\chi_1^0}/T_f$ and $T_f$ is the freeze out temperature. For $x_f \Delta \ll 1$, $Q \sim 1$ and one can produce enough co-annihilation to efficiently annihilate the XWIMPS, and find their relic density within the WMAP range. The above can be generalized to include other MSSM channels.

The second case of dark matter from the hidden sector that we consider is the case of milli-charged dark matter. It has been known for some time [5] that milli-charged matter arises from the kinetic mixing with two $U(1)$s through a mixing term (defined here by $\delta$) generated by exchange of heavy fields. Such mixings can survive at low energy. In the diagonal basis one gets two massless gauge bosons, one of which is the ordinary photon ($A_\mu$) and the other a (massless) paraphoton ($A'_\mu$). In an appropriate basis the interactions can be written in the form $A \cdot (J + \delta^{\text{hid}}) + A' \cdot J^{\text{hid}}$. Here the photon couples to the hidden sector matter fields with a coupling proportional to the small mixing $\delta$ which is generated by the exchange of heavy fields, while the paraphoton does not couple with the visible sector and only couples to the hidden sector. Dark matter in this model has been analyzed in [62]. Milli-charged matter also arises in Stueckelberg extensions of the Standard Model [63][64] where two $U(1)$ gauge fields mix via mass mixing. Such models can arise from string constructions [63][64]. Some recent works involving St mass generation can be found in [65][66][67].

The St models can also sustain milli-charged dark matter [7][8]. The St models we will discuss here includes both mass and kinetic mixing via a Lagrangian of the form $\mathcal{L}_{SKM}$

$$\mathcal{L}_{SKM} \supset -\frac{1}{4} \left( C_{\mu} C^{\mu\nu} + 2\delta C_{\mu} B^{\mu\nu} + B_{\mu \nu} B^{\mu\nu} \right) \right) - \frac{1}{2} \left( \partial_{\mu} \phi + B_{\mu} \right)^2 J, \quad B_{\mu} = B_{\mu}^{\text{hid}} C_{\mu}.$$
mode (normal photon) and the other vector boson modes are all massive. For $Z'$, $A_T$ there are interactions of the generic form

$$\mathcal{L}_{\text{SKM}} \sim f_1((\varepsilon - \delta) J_\mu + f_2 J^{\text{had}}_\mu) Z'^\mu + f_3 (J^{\text{vis}}_\mu - \varepsilon J^{\text{had}}_\mu) A_T^\mu,$$

where $f_{1,2,3} = f_{1,2,3}(\varepsilon, \delta)$ (see [8] for the complete form). The constraints on $\varepsilon$ and $\delta$ are gotten by fits to the precision electroweak data, where one finds for example $(\varepsilon, \delta) = (-0.06, 0.03)$ can fit the data with the same precision as does the SM. If there is hidden sector matter it would carry milli-charge. An interesting possibility is that such matter could be candidate for dark matter [7, 8].

Consider for specificity that the hidden sector contains Dirac fermions. Such fermions ($\chi_n$) will couple to a $Z'$ with normal electroweak strength and thus can produce a significant size decay width for $Z'$ into ordinary quarks and leptons when $M_{\chi_n}$ is below $M_{Z'}/2$ and dark matter constraints can be easily satisfied [7]. However, one consequence of this phenomenon is that the dilepton signal associated with the decay of the $Z'$ into ordinary leptons will be highly suppressed because of the significantly larger decay of the $Z'$ into the hidden sector fermions. Further, it would at first appear that the mechanism above for the satisfaction of relic density constraints may not work when the Dirac fermion mass in above $M_{Z'}/2$. However, it is well known that the thermal averaging over the poles for annihilations in the early universe can allow one to satisfy the relic density constraints. The mechanism comes into play when the Dirac fermion mass $M_{\chi_n}$ is larger than $M_{Z'}$ and indeed in this case it is possible to satisfy the WMAP constraints over a significant part of the parameter space. Further, in this case one also has a strong dileptonic signal for the $Z'$ which is accessible at the Tevatron and at the LHC [8-68].

**Concluding Remarks:** We summarize now our results. We have shown that in a broad class of models one finds the existence of a Wall consisting of a copious number of parameter points in the Chargino Patterns. The chances of discovery of dark matter on the Wall are enhanced due to clustering. The neutralino-proton scalar cross sections at the Wall is $\sigma_{SI}(\chi p) \sim 10^{-44.5}\pm 5\text{cm}^2$ well within the reach of the next generation of dark matter experiments. We have also argued that the direct detection of dark matter along with the LHC signatures provide a dual probe of SUSY. Thus in some cases dark matter detection can probe the parameter space of supergravity models which may not be easily accessible at the LHC at least with low luminosity in multilepton modes. Thus the direct detection of dark matter and LHC signatures are complementary in their probe of SUSY.

Finally, we have argued that the hidden sector is a viable source of dark matter. Specifically we have discussed two cases regarding dark matter from the hidden sector. These include an extra weakly interacting Majorana dark matter candidate which is a linear combination of fields in the hidden sector and the connector sector, and a milli-charged dark matter matter candidate which arises from matter Dirac fermions in the hidden sector.

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