Dark Matter Searches: the Theoretical Scenario

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The zoo of dark matter candidates is HUGE:

SIMPs, gravitino, axion, LSP, Kaluza-Klein, String inspired candidates, CHAMPs, axino, WIMPzillas, SIDM, scalar DM, superWIMPs, LDM, ...

Since the LHC will start operations soon,

let us concentrate on SUSY candidates:

**neutralino, sneutrino, gravitino**
**Baryon and lepton number violation**

e.g. Operators like $d^c d^c u^c$, $QLd^c$, $LLe^c$, $LH_2$ are allowed in the superpotential.

Too fast proton decay

To preserve B and L conservation one can impose a discrete symmetry (R-parity).

![Diagram of particle interactions and superpartners]

In models with R parity the LSP is stable since e.g.: $(-1) \tilde{\gamma}$

Thus it is a candidate for dark matter.

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the Theoretical Scenario
A good dark matter candidate must fulfil $\Omega h^2 \approx 0.1$

Recalling that $\Omega \propto \frac{1}{\sigma_{\text{annihilation}}}$

It is easy to check that a particle with weak scale interactions has the appropriate value of the annihilation cross section to obtain $\Omega h^2 \approx 0.1$

THUS AN INTERESTING CANDIDATE FOR DARK MATTER IS:
- a Weakly Interacting Massive Particle with a mass $\sim 10^{2-3}$ GeV

AND, AN INTERESTING CANDIDATE FOR WIMP IS: a Neutralino
- It has weak interactions and a mass $\sim 10^{2-3}$ GeV
- It is stable, since it is the LSP
- It is a neutral particle

- We will analyze The Neutralino in the context of Supergravity (SUGRA), and Superstrings
DIRECT DETECTION in SUGRA

Working in the framework of SUGRA, the masses, $M_a$, $m_\alpha$, are generated at high energy once SUSY is broken through gravitational interactions.

✓ The simplest possibility is to assume universality: $M_a = M$, $m_\alpha = m$

The RGEs are used to derive the low-energy soft parameters

With $M_{GUT} \approx 2 \times 10^{16}$ GeV, in the MSSM $m^2_{H_u}$ evolves towards large and negative values

$\mu^2 \approx -m^2_{H_u} - (1/2)M^2_{Z}$ is large

$m^2_H \approx m_A \approx m^2_{H_d} - m^2_{H_u} - M^2_{Z}$ is large

Small cross section
More sensitive detectors producing further data are needed e.g. 1 tonne detectors where
\[ \sigma_{\chi_1^0-n} \sim 10^{-10} \text{ pb} \]

**Experimental constraints:**
-- masses of the Higgs and superpartners
-- low energy observables \( \text{BR}(b \rightarrow s\gamma), \text{BR}(B_s \rightarrow \mu^+ \mu^-) \), \( g-2 \)

**Astrophysical constraints:**
-- Relic density \( 0.1<\Omega_{DM} h^2<0.3 \), WMAP range: \( 0.094<\Omega_{DM} h^2<0.129 \)

In addition, the parameter space may be limited by Charge and Colour Breaking constraints
Departures from universality can lead to an increase of the predictions for $\sigma_{\chi_1^0-n}$

\[ e.g.: \quad m_{Hu}^2 = m^2 (1 + \delta_u) \quad \checkmark \delta_u > 0 \]

\[ \mu^2 \approx -m_{Hu}^2 - (1/2)M_Z^2 \]
\[ m_{H}^2 \approx m_{A}^2 \approx m_{Hd}^2 - m_{Hu}^2 - M^2 \]

are smaller

Thus $\sigma_{\chi_1^0-n}$ is increased

**Summary**

- Neutralinos with masses $\approx (10-400)$ GeV can be obtained within the reach of detectors

- Next experiments, $\sigma_{\chi_1^0-n} \approx 10^{-7,-8}$ pb, will cover a small part of the parameter space

Baek, Cerdeño, Y.G. Kim, Ko, C.M., 05
Since the low-energy limit of superstring theory is 4-dimensional SUGRA, the neutralino is also a candidate for dark matter in superstring constructions.

Taking into account that the soft terms can in principle be computed in these constructions, one can study the associated $\chi_1^0$-nucleon cross section.

Of course, the results in superstrings will be a subset of the ones studied in SUGRA, e.g. in the dilaton limit $M = \sqrt{3} m$, $A = -M$.

The previous general analysis of soft terms in SUGRA, and the strategy to obtain a large cross section, is very useful for the study of these more specific cases.
Can non-universal masses arise from a more fundamental theory?

After compactification of the Heterotic Superstring on a 6-dimensional orbifold, the resulting 4D SUGRA is described by:

$$ m^2_\alpha = m^2_{3/2} \left\{ 1 + n_\alpha \cos^2 \theta + \frac{q^A_\alpha}{q^-_C} \left[ (6 - n_C) \cos^2 \theta - 5 \right] \right\} $$

These soft terms are generically **non-universal**

Few free parameters: \( m_{3/2}, \theta \)

\[ \delta_{H_u} = 10 - 17 \cos^2 \theta, \quad \delta_{H_d} = -\frac{5}{2} + \cos^2 \theta, \]
In the MSSM there are only left-handed sneutrinos:

\[ W = \epsilon_{ab} \left( Y_u^{ij} \tilde{H}_2^b \tilde{\Phi}_i^a \tilde{u}_j^c + Y_d^{ij} \tilde{H}_1^b \tilde{\Phi}_i^a \tilde{d}_j^c + Y_e^{ij} \tilde{H}_1^a \tilde{\Phi}_i^b \tilde{e}_j^c \right) + \mu \ H_1 \ H_2 \]

There is an extra diagram due to the \( Z \) exchange in the \( t \)-channel

\[ \downarrow \]

Scattering cross section too large or relic density too small
The MSSM with a right-handed sneutrino

\[ W = \epsilon_{ab} \left( Y^u_{ij} \hat{H}_2^b \hat{Q}^a_i \hat{u}_j + Y^d_{ij} \hat{H}_1^b \hat{Q}^a_i \hat{d}_j + Y^e_{ij} \hat{H}_1^a \hat{L}^b_i \hat{e}_j + Y^{ij}_{\nu} \hat{H}_2^b \hat{\nu}_1 \right) + \mu H_1 H_2 \]

\[
\begin{pmatrix}
m^2_L & F \\
F & m^2_\nu
\end{pmatrix}
\]

\[ \nu_1 = -\sin \theta \nu_L + \cos \theta \nu_R \]

Sizeable mixings reduce the coupling to the Z-boson, which couples only to left-handed fields.

The problem with this mechanism it that \( F \sim A_\nu m_\nu \)

Thus the LSP is a purely right-handed sneutrino implying scattering cross section too small, relic density too large.
But the MSSM also has theoretical problems

- And, in particular, a very important one is the so-called $\mu$ problem

\[ V(H_u, H_d) = \frac{1}{8} (g^2 + g'^2) [(H_d^2 - H_u^2)]^2 + m_1^2 H_1^2 + m_2^2 H_2^2 + (\mu H_1 H_2 \phi + \text{c.c.}) \]

- **The $\mu$ problem**

  - The presence of the $\mu$ term is crucial
    - $\mu = 0 \Rightarrow \begin{cases} \text{the minimum of } V_{H_2} \text{ occurs for } <H_1> = 0 \\ \text{unacceptable axion} \end{cases}$

  - But in principle, the natural scale of $\mu$ is $M_P$!
    - Since $w = \mu H_1 H_2 \ldots$
\[ \mu \ H_1 \ H_2 \rightarrow \lambda S \ H_1 \ H_2 \rightarrow \mu_{\text{eff}} = \lambda \langle S \rangle \]

- **NMSSM** has a richer and more complex phenomenology:
  - 2 extra Higgses
  - 1 additional neutralino

A light Higgs is experimentally viable: Implications for \( \sigma_{\chi-n} \)

Large values of \( \sigma_{\chi_1-0-n} \), within the reach of detectors, can be obtained:
- Very light, singlet-like Higgses \( m_h \geq 15 \text{ GeV} \)
Right-handed sneutrino in extensions of the NMSSM

$$W = \epsilon_{ab} \left( Y_{u}^{ij} \hat{H}_{2}^{b} \hat{Q}_{i}^{a} \hat{u}_{j}^{c} + Y_{d}^{ij} \hat{H}_{1}^{a} \hat{Q}_{i}^{b} \hat{d}_{j}^{c} + Y_{e}^{ij} \hat{H}_{1}^{a} \hat{L}_{i}^{b} \hat{e}_{j}^{c} + Y_{\nu}^{ij} \hat{H}_{2}^{b} \hat{\bar{\nu}}_{j}^{c} \right)$$

$$+ \lambda \ S \ H_{1} \ H_{2} + k \ S \ S \ S + \lambda' \ S \ \nu^{c} \ \nu^{c}$$

Recall that in the MSSM we said:
The LSP is a purely right-handed sneutrino implying scattering cross section too small, relic density too large

Nevertheless, here the singlet introduced to solve the $\mu$ problem, provides efficient interactions of sneutrino too.

E.g. $\tilde{\nu}_{R} \tilde{\nu}_{R} \rightarrow \nu_{R} \nu_{R}$ through the t-channel where neutralinos are exchanged

Thus in principle one can obtain a correct relic density and reasonable detection cross section

Cerdeño, C.M., Seto, in preparation
• **Baryon and lepton number violation**

e.g. Operators like $d^c d^c u^c$, $QLd^c$, $LLe^c$, $LH_2$ are allowed in the superpotential.

Too fast proton decay

But let us suppose that one of them is allowed and the others are forbidden.

Then the proton is stable but the **LSP** is no longer stable.

Thus the LSP (neutralino, sneutrino) is **not a candidate for dark matter**.
**Gravitino as a DM candidate in models where R-parity is broken**

In this case the gravitino indeed also decays through:

$$L_{\text{int}} = -\frac{i}{8M_{\text{pl}}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda F_{\nu\rho},$$  \hspace{1cm} (4)

where $\psi_\mu$ is the gravitino field, $F_{\nu\rho}$ is the field strength for the photon, and $\lambda$ represents the superpartner of the photon, “photino”, which contains a neutrino component via neutralino-neutrino mixing after the sneutrino develops the vacuum expectation value. Thus we evaluate the lifetime of the gravitino as follows:

$$\Gamma(\tilde{G} \rightarrow \gamma\nu) = \frac{1}{32\pi} |U_{\gamma\nu}|^2 \frac{m_3^{3/2}}{M_{\text{pl}}^2} \left(1 - \frac{m_\nu^2}{\frac{2}{3} m_3^2}\right)^3 \left(1 + \frac{1}{3} \frac{m_\nu^2}{m_3^2}\right) \approx \frac{1}{32\pi} |U_{\gamma\nu}|^2 \frac{m_3^{3/2}}{M_{\text{pl}}^2},$$  \hspace{1cm} (5)

Thus the lifetime of the gravitino may be longer than the age of the Universe
INDIRECT DETECTION in the MSSM

- Decays of gravitinos in the galactic halo will produce gamma rays, and these can be measured, e.g., in space–based detectors.

An upcoming experiment such as GLAST might detect the gamma rays produced by the decay of gravitinos in the galactic halo.

Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, 2007
Bertone, Buchmuller, Covi, Ibarra, 2007
CONCLUSIONS

The neutralino in the MSSM, can be good candidate for dark matter

- $\sigma\chi_1^0$-nucleon in supergravity, with universal soft terms, is too small
- Larger $\sigma\chi_1^0$-nucleon can be obtained with non-universal masses
  Regions accesible for experiments are present

- Neutralinos with masses $\approx (10-500)$ GeV can be obtained within the reach of dark matter detectors in the MSSM

- Similarly in the NMSSM (50-100) GeV and orbifolds (200-400) GeV

The sneutrino in extensions of the NMSSM with a dynamical Majorana mass can also be a good candidate.

The gravitino in models where R parity is broken can in principle be a dark matter candidate, and might be detected

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