Models of Supersymmetry for Dark Matter

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In SUSY, the spectrum of elementary particles is doubled with masses \( \approx 1 \text{ TeV} \)

Thus even the simplest SUSY model, the \textbf{Minimal Supersymmetric Standard Model (MSSM)}, predicts a rich phenomenology

But... is SUSY still alive?
SuSy searches: final comments

- With Run2 we are already surpassing Run1 limits:
  - gluino limits reached 1.8 TeV
  - Squark limits reached ~1 TeV (stop ~0.8 TeV)
- New strategies adopted to explores compresses spectrum regions (even though trigger is a problem)

CAVEAT: simplified models are good benchmarks but they don’t cover full SuSy phase space (BR variation, degenerate masses, etc.). We are not even close to declare SuSy dead.

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Nevertheless, from theoretical viewpoint, by construction, the MSSM produce too fast proton decay

Operators like \( \hat{d} \hat{c} \hat{u} \), \( \hat{Q} \hat{L} \hat{d} \), \( \hat{L} \hat{L} \hat{e} \), \( \hat{L} \hat{H} \) violating Baryon and Lepton number are allowed in the superpotential

To conserve B and L number, one can impose a discrete symmetry (\( R \) parity)

Notice that this (conservative) approach forbids all couplings

In models with RPC the LSP is stable since:
Thus it is a candidate for dark matter
So, once eliminated (ALL) B and L number violating operators, we are left with the superpotential of the MSSM:

$$W = Y_{ui}^i \hat{H}_2^b \hat{Q}_i^a \hat{u}_j^c + Y_{di}^i \hat{H}_1^a \hat{Q}_i^b \hat{d}_j^c + Y_{ei}^i \hat{H}_1^a \hat{L}_i^b \hat{e}_j^c + \mu \hat{H}_1^a \hat{H}_2^b$$

where the term $\mu \hat{H}_1 \hat{H}_2$ is necessary e.g. to generate Higgsino masses. Present experimental bounds imply: $\mu \geq 100 \text{ GeV}$

• Here we find another problem of SUSY models

The $\mu$ problem: What is the origin of $\mu$, and why is so small $\ll M_{\text{Planck}}$?

The MSSM does not solve the $\mu$ problem

one takes for granted that the $\mu$ term is there and $\sim M_w$, and that’s it

in this sense the MSSM is a kind of effective theory
In the MSSM, the lightest mass eigenstate (lightest neutralino) with a mass $\sim$ GeV-TeV is a good candidate for dark matter, because:

- It is a neutral particle, otherwise it would bind with nuclei and would be excluded from unsuccessful searches for exotic heavy isotopes.
- It is a stable particle, since can be the LSP.
- It is a WIMP (Weakly Interacting Massive Particle)

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and a WIMP has the appropriate value of the annihilation cross section to obtain:

$$\Omega_{\text{WIMP}} h^2 \sim \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\sigma_{\text{ann}} v} \sim 0.1$$

where $\sigma_{\text{ann}} = \sigma_{\text{weak}}$. The thermal cross section is $\sigma_{\text{ann}} v \sim 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$.
In view of the LHC1 constraints on SUSY, Higgs data, flavour physics observables, in the phenomenological MSSM (pMSSM) with 10 independent parameters, $M_a$, $m_\alpha$, $A_\alpha$, $\tan \beta$, $\mu$, one obtains for neutralino DM

Future experiments will explore larger regions of the parameter space

Bagnaschi et al., 2015
Are there other candidates for DM in SUSY models?
In the MSSM there are only left-handed sneutrinos:

\[ W = e_{ab} \left( Y_{u}^{ij} \hat{H}^{\bar{b}}_2 \hat{Q}^a_i \hat{d}^c_j + Y_{d}^{ij} \hat{H}^a_1 \hat{Q}^b_i \hat{d}^c_j + Y_{e}^{ij} \hat{H}^a_1 \hat{L}^b_i \hat{\bar{e}}^c_j - \right) + \mu \hat{H}^1 \hat{H}^2 \]

(left-handed) sneutrino couples with Z boson

- Too large annihilation cross section (implying too small relic density)

- Too large direct detection cross section (already disfavoured by current experiments)

(Ibáñez ’84; Hagelin, Kane, Rabi ’84)

(Falk, Olive, Srednicki ’94)
IS THERE LIFE BEYOND THE MSSM/NEUTRALINO DM?
The $\mu$-problem, $W = ... + \mu \hat{H}_u \hat{H}_d$, is solved in the Next-to-MSSM introducing an extra singlet superfield:

$$\mu \hat{H}_1 \hat{H}_2 \xrightarrow{\lambda \hat{N} \hat{H}_1 \hat{H}_2} \mu_{\text{eff}} = \lambda \langle N \rangle$$

- NMSSM has a richer and more complex phenomenology:

  additional Higgs, the singlet $N$
  additional neutralino, the singlino $\tilde{N}$

Neutralino DM is viable
Right-handed sneutrino DM in the (extended) NMSSM

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

\[ + \lambda \hat{N} \hat{H}_{1} \hat{H}_{2} + k \hat{N} \hat{N} \hat{N} + \lambda_{N} \hat{N} \hat{\nu}^{c} \hat{\nu}^{c} \]

Note that in the MSSM a purely right-handed sneutrino LSP implies a scattering cross section too small (suppressed by \( Y_{\nu} \)), and a relic density too large.

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

Cerdeño, C.M., Seto, 08
Neutralino and Right-handed sneutrino in the NMSSM

Extensions of the MSSM can be more flexible (new light mediators)

Low-mass SUSY WIMPs are still viable (1-100 GeV)

DGC, Peiró, Robles JCAP 08 (2014) 005
DGC, Peiró Robles, 2015
IS THERE LIFE
BEYOND R-PARITY CONSERVATION/NEUTRALINO-SNEUTRINO DM?
are allowed in the superpotential

TRPV

\[ \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{e}_k, \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}^c_k, \lambda''_{ijk} \hat{d}_i \hat{d}_j \hat{u}^c_k \]

BRPV

\[ \varepsilon_i \hat{H}_u \hat{L}_i \]

\[ \lambda_i \nu_{Ri} \hat{H}_u \hat{H}_d + \kappa_{ijk} \nu_{Ri} \nu_{Rj} \nu_{Rk} \]

are also allowed, break R parity
are harmless for proton decay

However, R-parity forbids all these terms
But the choice of R-parity is *ad hoc.*

There are other symmetries that forbid some of these terms, but others are allowed

*Also stringy selection rules:*
  - particles are attached to different sectors in the compact space
  - or they have extra $U(1)$ charges

\[ d^c (3, 1, 1/3, - , - , - , - , - , - , - , - , - , - , - ) \] e.g. the sum of $U(1)$ charges might imply \[ \hat{d}^c \hat{d}^c \hat{u}^c \]
\[ d^c (3, 1, 1/3, - , - , - , - , - , - , - , - , - , - , - ) \]
\[ u^c (3, 1, -2/3, - , - , - , - , - , - , - , - , - , - , - ) \] But e.g. \[ \lambda_i \nu_{Ri} \hat{H}_u \hat{H}_d \] might be allowed
So one can work with different combinations of RPV terms:

\[ W = W_{\text{MSSM}} + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{e}^c_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}^c_k + \lambda''_{ijk} \hat{d}^c_i \hat{d}^c_j \hat{d}^c_k \]

\[ W = W_{\text{MSSM}} + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{e}^c_k + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{d}^c_k + \lambda''_{ijk} \hat{d}^c_i \hat{d}^c_j \hat{u}^c_k \]

\[ W = W_{\text{MSSM}} + \varepsilon_i \hat{H}_u \hat{L}_i \]

When the RH sneutrinos \( \tilde{\nu}_R \) acquire VEVs of order the EW scale, an effective \( \mu \)-term from \( \nu \) is generated as well as effective Majorana masses for neutrinos: EW scale seesaw

\[ m_\nu \sim m_D^2/M_M = (Y_\nu \nu_u)^2/(\kappa \nu_R) \sim (10^{-6} 10^2)^2/10^3 = 10^{-11} \text{ GeV} = 10^{-2} \text{ eV} \]

\[ Y_\nu \hat{H}_u \hat{L}_R \]

\[ Y_\nu \sim \text{the electron Yukawa} \]
RPV couplings generate larger mass matrices than those of RPC models such as MSSM or NMSSM, since EWSB implies that the neutral scalars develop VEVs:

\[ \langle H_u^0 \rangle = v_u \quad \langle H_d^0 \rangle = v_d \]

\[ \langle \tilde{\nu}_i \rangle = \nu_i \quad \langle \tilde{\nu}_i^c \rangle = \nu_i^c \]

**“Neutralinos”**

\[ \chi^{0T} = (\tilde{B}^0, \tilde{W}^0, \tilde{H}_d, \tilde{H}_u, \nu_{R}, \nu_{L}) \]

\[ \tilde{\chi}^0_{4,5,6,7,8,9,10} \quad \tilde{\chi}^0_{1,2,3} \]

**“Charginos”**

\[ \Psi^{+T} = (-i\tilde{\chi}^+, \tilde{H}_u^+, e_R^+, \mu_R^+, \tau_R^+) \]

\[ \tilde{\chi}^+_{1,2} \]

**“Neutral Higgses”**

\[ S'_\alpha = (h_d, h_u, (\tilde{\nu}_i^c)^R, (\tilde{\nu}_i)^R) \]

\[ h_{4,5} \equiv h, H, h_{1,2,3}, h_{6,7,8} \]

\[ P'_\alpha = (P_d, P_u, (\tilde{\nu}_i^c)^I, (\tilde{\nu}_i)^I) \]

\[ P_4 \equiv A, P_{1,2,3}, P_{5,6,7} \]

**“Charged Higgses”**

\[ S'^{+\alpha} = (H_d^+, H_u^+, \tilde{e}_L^+, \tilde{\mu}_L^+, \tilde{\tau}_L^+, \tilde{e}_R^+, \tilde{\mu}_R^+, \tilde{\tau}_R^+) \]

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After several years of LHC running, direct searches of SUSY based mainly on the existence of missing energy in the final state have failed to find a signal that exceeds the SM background.

Time for experimentalists to look for RPV SUSY in detail?

★ RPV can hide SUSY by removing the usual missing energy signatures

★ RPV can produce displaced vertices, multilepton final states,...
Besides, all particles, not only the neutral ones, are potential LSP’s stau, squark, chargino,..., sneutrino

because the LSP is not stable, decaying into two SM particles

Thus the problem of stable charged particles as DM is not present:
e.g. in the $\mu\nu$SSM a left-handed sneutrino LSP with a mass $\sim 90$-$150$ GeV will produce for $\mathcal{L} = 300$ fb$^{-1}$ a detectable number of events with diphoton + leptons/missing energy.

Ghosh, Lara, Lopez-Fogliani, C. M., Ruiz de Austri, in preparation
Gravitino DM in models with RPV

- The **LSP** is no longer stable since it can decay into SM particles
  Thus the neutralino or the sneutrino cannot be used as candidates for DM
- **Nevertheless**, the gravitino can be a (decaying) DM candidate
The gravitino LSP in RPV decays due to the photino-neutrino mixing, opening the channel

In supergravity

\[ L_{\text{int}} = -\frac{i}{8M_{\text{pl}}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda F_{\nu\rho}, \]

\[ \Gamma(\tilde{\psi}_{3/2} \rightarrow \gamma \nu) = \frac{1}{32\pi} |U_{\tilde{\gamma} \nu}|^2 \frac{m_{3/2}^3}{M_p^2}. \]

The decay width is suppressed both by the Planck mass and the R-parity breaking, which is expected to be very small:

\[ |U_{\tilde{\gamma} \nu}|^2 \sim |g_1 \nu/M_1|^2 \sim 10^{-14} - 10^{-15} \]

Since \( \nu \sim 10^{-4} \text{ GeV} \) because its minimization equation contains the small Yukawa \( Y_\nu \sim 10^{-6} \) in order to reproduce neutrino data

Thus the lifetime can be longer than the age of the Universe (\( \sim 10^{17} \text{ s} \)), and the gravitino can be a good DM candidate

\[ \tau_{3/2} = \Gamma^{-1}(\tilde{\gamma} \rightarrow \gamma \nu) \approx 8.3 \times 10^{26} \text{ sec} \times \left( \frac{m_{3/2}}{1\text{ GeV}} \right)^{-3} \left( \frac{|U_{\tilde{\gamma} \nu}|^2}{7 \times 10^{-13}} \right)^{-1} \]

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Detection of gravitino DM

- Decays of gravitinos in the galactic halo, at a sufficiently high rate, would produce gamma rays that could be detectable in experiments.

**Fermi Large Area Telescope (LAT)**, might in principle detect this flux of gamma rays predicted in RPV models with gravitino DM.

Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida, 07; Bertone, Buchmuller, Covi, Ibarra, 07
Ibarra, Tran, 08; Ishiwata, Matsumoto, Moroi, 08
Choi, López-Fogliani, C.M., Ruiz de Austri, 09
Choi, Yaguna, 10; Choi, Restrepo, Yaguna, Zapata, 10; Diaz, García Saenz, Koch, 11
Restrepo, Taoso, Valle, Zapata, 11
Gómez-Vargas, Fornasa, Zandanel, Cuesta, C.M., Prada, Yepes, 11

\[
\left[ \frac{E^2 \, dJ}{dE} \right]_{\text{halo}} = \frac{2E^2}{m_{3/2}} \frac{dN_\gamma}{dE} \frac{1}{8\pi^2 \tau_{3/2}} \int_{\text{los}} \rho_{\text{halo}}(l) dl,
\]

Since a gravitino decays into a photon (and a neutrino), this produces a line at energies equal to \( m_{3/2}/2 \).
More recently, together with Fermi-LAT collaborators we performed the following:

**Search for 100 MeV to 10 GeV γ-ray lines in the Fermi-LAT data and implications for gravitino dark matter in the μνSSM**


Category II paper:

-Fermi-LAT Collaboration: Albert, Bloom, Charles, Gómez-Vargas, Mazziotta, Morselli

External authors: C. M., Grefe, Weniger

Constraining $m_{3/2}$ and gravitino lifetime

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If the gravitino is the DM: $m_{3/2} < 20$ GeV

Results updated with 5.8 years of data from Fermi LAT

Gómez-Vargas, López-Fogliani, C.M., Perez, Ruiz de Austri, in preparation
Conclusions

There are interesting models of SUSY for DM:

- **MSSM** introduces a bunch of new particles
- **NMSSM** solves the $\mu$ problem of the **MSSM** introducing an extra singlet

\[ \lambda \hat{N} \hat{H}_1 \hat{H}_2 + \lambda_N \hat{N} \hat{\nu}^c \hat{\nu}^c \]

The neutralino or RH sneutrino are candidates for DM

If RPV is allowed

very rich phenomenology: displaced vertices, multi-lepton/jet events

- **TRPV, BRPV**

**$\mu$νSSM** solves the $\mu$ problem and explains the origin of neutrino masses using right-handed neutrinos

\[ \hat{\nu}_i^c \hat{H}_1^a \hat{H}_2^b \]

The gravitino can be a candidate for DM with \[ m_{3/2} < 20 \text{ GeV} \]