SUSY Dark Matter

Pearl Sandick
the University of Texas at Austin
Plan

• Why Supersymmetry?
• How-to Guide to SUSY Phenomenology
• WIMPs and WIMPier DM Candidates
Why SUSY?

- Aesthetically “neat” extension
- Stabilizes the Higgs vev (Hierarchy Problem)
- Gauge coupling unification
- Predicts a light Higgs boson
Extended the Poincare algebra:

\[ Q |\text{boson}\rangle = |\text{fermion}\rangle \quad \text{and} \quad Q |\text{fermion}\rangle = |\text{boson}\rangle \]

Find a consistent theory with *interplay* of Poincaré and internal symmetries.

Supersymmetry is the *only nontrivial extension* of the Poincaré algebra in a consistent 4-d QFT.
Why SUSY?

- Aesthetically “neat” extension
- Stabilizes the Higgs vev (Hierarchy Problem)

\[ V = m_H^2 |\mathcal{O}|^2 + \lambda |\mathcal{O}|^4 \]

From W and Z masses, know \( |\mathcal{O}| \geq 174 \text{ GeV} \), so expect \( |m_{h^2}| \sim (100 \text{ GeV})^2 \)

\[ \Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + \ldots \]

\[ \Delta m_H^2 \propto \log(\Lambda_{UV}) \ll m_H^2 \]

SUSY maintains hierarchy of mass scales.

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Why SUSY?

- Aesthetically “neat” extension
- Stabilizes the Higgs vev (Hierarchy Problem)
- Gauge coupling unification

Near miss!

Just right!

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Why SUSY?

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- Stabilizes the Higgs vev (Hierarchy Problem)
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- Predicts a light Higgs boson

\[ 105 \text{ GeV} \lesssim m_h \lesssim 135 \text{ GeV} \]

\[ 114.4 \text{ GeV} < m_h < 157 \text{ GeV} \]

LEP Collaborations and Electroweak Working Group, August 2009
MSSM: Minimal Supersymmetric Standard Model

Has the minimal particle content possible in a SUSY theory.
<table>
<thead>
<tr>
<th>particle</th>
<th>sparticle</th>
<th>$SU(3)_c$</th>
<th>$SU(2)_w$</th>
<th>$U(1)_Y$</th>
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<tbody>
<tr>
<td>$(u \ d)_i$</td>
<td>$(\bar{u} \ d)_i$</td>
<td>3</td>
<td>2</td>
<td>$\frac{1}{6}$</td>
</tr>
<tr>
<td>$u^c_i$</td>
<td>$\bar{u}^c_i$</td>
<td>$\bar{3}$</td>
<td>1</td>
<td>$-\frac{2}{3}$</td>
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<tr>
<td>$d^c_i$</td>
<td>$\bar{d}^c_i$</td>
<td>$\bar{3}$</td>
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<td>$\bar{e}^c_i$</td>
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<td>1</td>
<td>1</td>
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<tr>
<td>$W$</td>
<td>$\tilde{W}$</td>
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<td>3</td>
<td>0</td>
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<tr>
<td>$g$</td>
<td>$\tilde{g}$</td>
<td>8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$B$</td>
<td>$\tilde{B}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$(H_u^+ \ H_u^0)$</td>
<td>$(\tilde{H}_u^+ \ H_u^0)$</td>
<td>1</td>
<td>2</td>
<td>$\frac{1}{2}$</td>
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<td>1</td>
<td>2</td>
<td>$-\frac{1}{2}$</td>
</tr>
</tbody>
</table>

Also

axion: $a$, spin 0
saxion: $s$, spin 0
axino: $\tilde{a}$, spin $\frac{1}{2}$
graviton: $G$, spin 2
gavitino: $\tilde{G}$, spin $\frac{3}{2}$
Explicitly add [soft] SUSY-breaking terms to the theory:

- Masses for all gauginos and scalars
- Couplings for scalar-scalar and scalar-scalar-scalar-scalar interactions

Don’t observe boson-fermion degeneracy, so SUSY must be broken (How?)

Most general case (MSSM) has > 100 new parameters!
OR make some assumptions about SUSY breaking at a high scale, and evolve mass parameters down to low scale for observables

Explicitly add [soft] SUSY-breaking terms to the theory:
- Masses for all gauginos and scalars
- Couplings for scalar-scalar-scalar and scalar-scalar-scalar-scalar interactions

Example: CMSSM (similar to mSUGRA)
- Assume universality of soft SUSY-breaking parameters at $M_{\text{GUT}}$

Free Parameters: $m_0$, $m_{1/2}$, $A_0$, $\tan(\beta)$, sign($\mu$)
Apply constraints from *colliders and cosmology*:

- $m_h > 114 \text{ GeV}$
- $m_{\chi^\pm} > 104 \text{ GeV}$
- $\text{BR}(b \rightarrow s \gamma)$
- $\text{BR}(B_s \rightarrow \mu^+\mu^-)$
- $(g_\mu - 2)/2$

\[ 0.09 \lesssim \Omega \chi h^2 \lesssim 0.12 \]

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$\mu^2 < 0$ (no EWSB)

CMSSM

$\tan \beta = 10$, $\mu > 0$

LEP Higgs mass
Relaxed LEP Higgs
LEP chargino mass
g$_\mu$ -2 suggested region

stau LSP

Ellis, Olive, Sandick (2006)

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CMSSM

Ellis, Olive, Sandick (2006)

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• The LSP may be an excellent dark matter candidate
• The lightest one may be \( \text{stable} \) (WIMP?) with \( \Omega \chi h^2 \approx \Omega_{\text{DM}} h^2 \)

Caveat: The lightest SUSY particle (LSP) is stable if R-parity is conserved.

\[ R = (-1)^{3B+L+2S} = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for sparticles} \end{cases} \]

Why conserve R-parity?
• Stability of proton
• Neutron-antineutron oscillations
• Neutrino mass

Ad hoc?
• SO(10) GUTs
• B and L numbers become accidental symmetries of SUSY
SUSY DM Candidates

• A plethora of DM candidates:
  – neutralinos (our favorite WIMPs)
  – sneutrinos (also WIMPs)
  – gravitinos (SuperWIMPs)
  – axinos (SuperWIMPs)
Dark Matter Detection

• **Colliders**
  – Produce WIMPs directly (missing energy signature)
  – Observe decays of NLSPs (for WIMPs or SuperWIMPs)

• **Direct Detection**
  – Observe WIMPs through interactions with matter in terrestrial detectors

• **Indirect Detection**
  – Observe products of WIMP annihilation/decay in terrestrial or space-based detectors

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SuperWIMPs (E-WIMPs)

- Interaction scale with ordinary matter suppressed by large mass scale:
  - For gravitino, $m_P \approx 10^{19}$ GeV (gravitational interactions)
  - For axino, $f_a \approx 10^{11}$ GeV
    \[ \sigma \approx \left( \frac{m_W}{f_a} \right)^2 \sigma_{\text{weak}} \]
    \[ \approx 10^{-18} \sigma_{\text{weak}} \]
    \[ \approx 10^{20} \text{ pb} \]

Choi & Roszkowski (2005)
Axinos

- Axion is a solution to the strong CP problem, i.e. Why does QCD conserve CP when CP violating operators are allowed?
  - Peccei-Quinn Mechanism: Promote CP-violating operator to a field by requiring new global (P-Q) symmetry
  - P-Q symmetry is spontaneously broken $\rightarrow$ Axion is Goldstone Boson ("pseudo" due to small mass from QCD vacuum effects)
  - SUSY: axion is in a chiral multiplet with axion + saxion, axino:
    $$ \Phi_a = (s + ia)/\sqrt{2} + \vartheta \tilde{a} + (F \text{ term}) $$

- Axion gets its mass from QCD effects: $m_a \approx f_\pi m_\pi / f_{PQ}$

- SUSY breaking splits saxion/axino masses from tiny axion mass
  - $m_s \sim m_{\text{SUSY}}$ (not LSP)
  - $m_{\tilde{a}}$ unconstrained (could be LSP and DM)

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Axino Dark Matter

- If the axino is the LSP, expect
  
  \[ \Omega_{\tilde{a}} h^2 = \Omega_{\tilde{a}}^{NTP} h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{a} h^2 \]

- TP axinos are CDM for \( m_{\tilde{a}} \gtrsim 0.1 \text{ MeV} \)

- See Baer et al. (2010) and references therein
FIGURE 2. The plane \((m_{1/2}, m_0)\) for axino only slightly less massive than the NLSP and \(T_R = 50\,\text{GeV}\) (left window) and for \(m_3 = 1\,\text{TeV}\) and \(T_R = 200\,\text{GeV}\) (right window). We take \(\tan\beta = 10, A_0 = 0, \mu > 0\) and \(\tan\beta = 10, A_0 = 0, \mu > 0\). The regions excluded by LEP are shown in red. The dark green (orange, white) regions correspond to \(0.094 < \Omega_a h^2 < 0.129\) (\(\Omega_a h^2\) too large and excluded, too small but otherwise allowed). The red line divides the neutralino and stau NLSP regions.

Covi et al. (2004); Choi and Roszkowski (2005)
Axino Dark Matter

- Unfortunately, no direct or indirect WIMP detection signals are expected for stable axino dark matter.

- If R-parity is broken, decaying axinos may be responsible for anomalous CR positron excess measured by PAMELA.
  - Depending on R-parity breaking model, radiative or leptonic decay channels may be preferred. i.e. $\tilde{a} \rightarrow e^+ e^- \nu_i$

- Collider signatures are possible, but depend on NLSP:
  - Charged NLSP would be easy to see, but would need to carefully study its decays to determine what the LSP is. Decays would likely happen outside the detector (need to trap staus).
  - Neutral NLSP would be harder to see, and could itself be dark matter. Mass and couplings compatible with .

  see, for example, Covi & Kim (2009)
Gravitino Dark Matter

• Like axino, both thermal and non-thermal production mechanisms
  
  - NTP:
    \[ \Omega_NTP h^2 = \frac{m_G}{m_{NLSP}} \Omega_{NLSP} h^2 \]
    
    • Late decays of NLSP can lead to entropy overproduction and hot dark matter, so \( m_{NLSP} > 500 \text{ GeV} \)
    
    • \( \Omega_G h^2 \sim 0.1 \) for \( 1 \text{ GeV} < m_G < 700 \text{ GeV} \) (Steffen, 2006)
  
  - TP:
    \[ \Omega_{TP} h^2 \simeq 0.2 \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \left( \frac{100 \text{ GeV}}{m_G} \right) \left( \frac{m_\tilde{g}(\mu)}{1 \text{ TeV}} \right)^2 \]
    
    • \( T_R \ll T_f \) to avoid overproduction of gravitinos (“Gravitino Problem”)
    
    • For natural ranges of gluino and gravitino masses, one can have TP \( \Omega_G h^2 \sim 0.1 \) at \( T_R \) as high as \( 10^{9-10} \) GeV.

• NLSP decays produce energetic SM particles, could spoil BBN light element abundances
• Gravitino mass depends on how SUSY breaking is communicated to the observable sector (mediation):
  - Gravity (modulus) mediated SUSY:
    • $m_{3/2} \approx 100 \text{ GeV} – \text{few TeV}$
  - Anomaly mediated SUSY:
    • $m_{3/2} \approx 10 \text{ TeV} – 100 \text{ TeV}$
  - Gauge mediated SUSY:
    • $m_{3/2} \approx 10 \text{ eV} – 1 \text{ GeV}$
  - Gaugino mediated SUSY:
    • $m_{3/2} \approx 10 \text{ GeV} – \text{TeV}$

maybe LSP
not LSP
probably LSP
maybe LSP
Gravitino Dark Matter

• Neutrino signals? Only if gravitino is unstable... (RPV)
  – NLSP decays to SM particles quickly
  – Gravitinos TP at reheating
  – Long-lived, \(~150\) GeV gravitinos decay, contributing to the CR positron excess and the diffuse gamma-ray flux

\[ E^2 \times dJ/dE \text{ (GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}) \]

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Covi et al. (2009)

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Gravitino vs. Axino

- Can we tell them apart?
- Maybe! If long-lived staus are accumulated and observed (i.e. at the LHC), we might be able to determine if CDM is axino or gravitino based on stau decay event distributions.

Brandenburg et al. (2005)
"WIMP Miracle"

1. New (heavy) particle $\chi$ in thermal equilibrium:
   $$\chi \chi \leftrightarrow f \bar{f}$$

2. Universe expands and cools:
   $$\chi \chi \leftrightarrow f \bar{f}$$

3. $\chi$'s "freeze out"
   $$\chi \chi \leftrightarrow f \bar{f}$$

Jungman, Kamionkowski and Griest, PR 1996

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Expansion and annihilation compete to determine the number density:

\[
\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v_{rel} \rangle \left[ n_X^2 - (n_X^{eq})^2 \right]
\]

Stable matter with GeV-TeV mass and weak-scale interaction strength yield

\[\Omega h^2 \sim 0.1\]

Jungman, Kamionkowski and Griest, PR 1996

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Sneutrinos

• L-handed neutrinos have L-handed sneutrino superpartners in the MSSM
  – Large coupling to Z boson leads to low relic abundance and larger-than-observed scattering rates with nuclei. Falk, Olive & Srednicki (1994)
  – Low mass window closed by limits from invisible Z decay at LEP. LEPEWWG (2003)

• R-handed neutrinos can be added to the SM to explain the origin of neutrino masses, so expect R-handed sneutrino partners.
  – L-R mixed sneutrinos have reduced coupling to Z, but a significant L-R mixing is only possible in very particular SUSY-breaking scenarios.
  – Pure R-handed sneutrinos could be CDM, but can't be thermal relics because their coupling to ordinary matter is very small. These ARE viable DM candidates in SUSY models with extended gauge or Higgs sectors (and therefore additional matter interactions). Arina & Fornengo (2007), Asaka, Ishiwata & Moroi (2007), Cerdeno & Seto (2009), etc.
Sneutrino Dark Matter

- Example: MSSM + gauged $U(1)_{BL}$
  - DM could be $R$-sneutrino if $U(1)_{BL}$ is broken at $\sim$TeV scale.

- Example: MSSM + singlet superfield $S$ for $\mu$ problem + singlet superfield $N$ for $R$-($s$)neutrino states
  - DM is pure $R$-sneutrino with couplings to MSSM fields, so it has the properties of a thermally-produced WIMP.

- Example: MSSM + 6 complex sneutrino fields (12 mixed L/R sneutrino mass eigenstates)
  - DM could be lightest sneutrino, or combination of long-lived sneutrinos

Take-home message:

Sneutrino DM must be substantially $R$-handed to suppress coupling to $Z$, so generally arises in extended versions of the MSSM.

Properties of sneutrino depend on the MSSM extension – many possibilities.

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Neutralinos

• The LSP is a neutralino in much of parameter space of even most-constrained SUSY models.
• The lightest one may be a stable WIMP with $\Omega \chi h^2 \approx \Omega_{\text{DM}} h^2$

\[
(\tilde{W}^3, \tilde{B}, \tilde{H}^0_1, \tilde{H}^0_2)
\]

\[
\begin{pmatrix}
M_2 & 0 & -g_2 v_1 & g_2 v_2 \\
0 & M_1 & g_1 v_1 & -g_1 v_2 \\
-\frac{g_2 v_1}{\sqrt{2}} & g_1 v_1 & -\mu \\
\frac{g_2 v_2}{\sqrt{2}} & -\frac{g_1 v_2}{\sqrt{2}} & -\mu & 0
\end{pmatrix}
\begin{pmatrix}
\tilde{W}^3 \\
\tilde{B} \\
\tilde{H}^0_1 \\
\tilde{H}^0_2
\end{pmatrix}
\]

\[
\chi = \alpha \tilde{B} + \beta \tilde{W}^3 + \gamma \tilde{H}^0_1 + \delta \tilde{H}^0_2
\]

Properties of neutralino LSP depend on its composition.
CMSSM

Focus Point

\( \mu^2 < 0 \) (no EWSB)

LEP Higgs mass

Relaxed LEP Higgs

LEP chargino mass

\( g_\mu -2 \) suggested region

Coannihilation Strip

stau LSP

Ellis, Olive, Sandick (2006)
Rapid annihilation funnel $2m_\chi \approx m_A$

$\mu > 0$, $\tan \beta = 50$

Ellis, Olive, Sandick (2006)
If neutralinos are DM, they are present locally, so will occasionally bump into a nucleus.

Effective 4-fermion lagrangian for neutralino-nucleon scattering (velocity-independent pieces):

\[ L = \alpha_2 \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q}_i \gamma_\mu \gamma^5 q_i + \alpha_3 \bar{\chi} \chi \bar{q}_i q_i \]

**Spin dependent**
- Fraction of nucleus participates
- Important for capture & annihilation rates in the sun

**Spin independent**
- Whole nucleus participates
- Best prospects for direct detection

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CMSSM

Ellis, Olive, Sandick (2009)

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Departures from CMSSM

- More general patterns of SUSY breaking:
  - NU scalar masses $m_0$
  - NU Higgs masses?
  - NU gaugino masses $M_{1/2}$
  - NU trilinear couplings $A_0$
- Extended particle content
  - NMSSM
  - nMSSM
  - UMSSM
  - etc.

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Departures from CMSSM

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  - etc.

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CMSSM – Higgs masses determined by

\[ m_{1}(M_{GUT}) = m_{2}(M_{GUT}) = m_{0} \]

NUHM1 – One extra free parameter:

\[ m_{1} = m_{2} \]

NUHM2 – No constraint at GUT scale

CMSSM GUT-scale inputs:

- \( m_{0}, m_{1/2} \) and \( A_{0} \) and the sign of \( \mu \)

Use electroweak vacuum conditions:

\[
m^{2}_{A}(Q) = m^{2}_{1}(Q) + m^{2}_{2}(Q) + 2\mu^{2}(Q) + \Delta_{A}(Q)
\]

\[
\mu^{2} = \frac{m^{2}_{1} - m^{2}_{2} \tan^{2} \beta + \frac{1}{2}m^{2}_{Z}(1 - \tan^{2} \beta) + \Delta^{(1)}_{\mu}}{\tan^{2} \beta - 1 + \Delta^{(2)}_{\mu}},
\]

\[
Q = (m_{\tau R} m_{\tau L})^{1/2}
\]

\[
m_{A} \equiv m_{A}(Q)
\]

\[
\mu \equiv \mu(m_{Z})
\]

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• The identification of dark matter is a very interesting problem.

• Supersymmetry is an attractive theory in which there are several possible dark matter candidates.
  – SuperWIMPs: Axino and Gravitino
  – WIMPs: Sneutrino and Neutralino

• Dark matter phenomenology depends on many assumptions about SUSY breaking, but some general conclusions can be drawn (especially for MSSM neutralino dark matter).

• We hope for agreement among many experiments and techniques (direct detection, indirect detection, and collider experiments) to give us a consistent picture of dark matter and its properties.