SUSY Dark Matter Models

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- mSUGRA model
- Normal scalar mass hierarchy
- NUHM1
- NUHM2
- MWDM
- BWCA
- LM3DM (compressed SUSY)
- mixed moduli-AMSB (KKLT)
Some successes of SUSY GUT theories

★ SUSY divergence cancellation maintains hierarchy between GUT scale \( Q = 10^{16} \) GeV and weak scale \( Q = 100 \) GeV

★ gauge coupling unification!

★ Lightest Higgs mass \( m_h \sim 130 \) GeV as indicated by radiative corrections!

★ radiative breaking of EW symmetry if \( m_t \sim 100 - 200 \) GeV!

★ dark matter candidate: lightest neutralino \( \tilde{Z}_1 \)

★ stable see-saw mechanism for neutrino mass

★ \( SO(10) \) SUSY GUT: baryogenesis via leptogenesis
Our strategy:

★ Assume MSSM is valid effective theory between $M_{\text{weak}}$ and $M_{\text{GUT}}$
  • LSP is stable: good candidate for CDM
★ Stipulate SSB terms at $Q = M_{\text{GUT}}$ and evaluate SSB at $M_{\text{weak}}$ via RG evolution
  • EW symmetry broken radiatively by large $m_t$
★ Invoke
  • minimal flavor violation
  • ignore $CP$-viol. phases
★ Spectra generated with Isajet/Isasugra
★ We will use the measured value $\Omega_{\text{CDM}} h^2 = 0.105 \pm 0.01$ as a guide to allowed phenomenology!
Case 1: paradigm mSUGRA model (thanks to Arnowitt, Nanopoulos, Weinberg, other pioneers···)

- $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$

![Diagrams showing allowed parameter space for mSUGRA model](image-url)
Main mSUGRA regions consistent with WMAP

★ most of parameter space excluded: $\Omega_{CDM}h^2$ too big!

★ Exceptions:
  - bulk region (low $m_0$, low $m_{1/2}$)
  - stau co-annihilation region ($m_{\tilde{\tau}_1} \simeq m_{\tilde{Z}_1}$)
  - HB/FP region (large $m_0$ where $|\mu| \to small$)
  - $A$-funnel ($2m_{\tilde{Z}_1} \simeq m_A, m_H$)
  - $h$ corridor ($2m_{\tilde{Z}_1} \simeq m_h$)
  - stop co-annihilation region (particular $A_0$ values $m_{\tilde{t}_1} \simeq m_{\tilde{Z}_1}$)
Constraints as $\chi^2$ on mSUGRA model

mSUGRA, $\tan\beta=10$, $\mu>0$, $A_0=0$, $m_{\text{top}}=175$ GeV
$e^+e^-$ input for $\delta a_\mu$  LEP2 excluded

mSUGRA, $\tan\beta=55$, $\mu>0$, $A_0=0$, $m_{\text{top}}=175$ GeV
$e^+e^-$ input for $\delta a_\mu$  LEP2 excluded
Sparticle reach of all colliders and relic density

$m_{\text{Sugra}}$ with $\tan\beta = 10, A_0 = 0, \mu > 0$

$m_{\text{Sugra}}$ with $\tan\beta = 45, A_0 = 0, \mu < 0$

HB, Belyaev, Krupovnickas, Tata
HB/FP region: absolute measure of $m_{\tilde{g}}$ at LHC!

- LHC events characterized by high jet, $b$-jet, isol. lepton multiplicity

![Graphs showing the distribution of jets and $b$-jets with different cuts.](image)

Barger, Shaughnessy, Summy, Wang
Measure $m_\tilde{g}$ in HB/FP region via total rate to $\sim 8\%$

- require cuts C1 plus $n(j) \geq 7$, $n(b-j) \geq 2$, $M_{\text{eff}} \geq 1400$ GeV

Augmented Effective Mass

Cuts C1, $n_{b\text{-jets}} \geq 2$ (60% eff.)

Barger, Shaugnessy, Summy, Wang
Direct detection of SUSY DM

scan over mSUGRA space ($\Omega_{CDM} h^2 \sim 0.11$):

★ Stage 1:
  - CDMS1, Edelweiss, Zeplin1

★ Stage 2:
  - CDMS2, CRESST2, Edelweiss2
  - Zeplin2, Xenon-10

★ Stage 3:
  - SuperCDMS, LUX, (mini)CLEAN
  - WARP, ArDM
Indirect detection (ID) of SUSY DM: $\nu$-telescopes

- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow b\bar{b}$, etc. in core of sun (or earth): $\Rightarrow \nu_\mu \rightarrow \mu$ in $\nu$ telescopes
- Amanda, Icecube, Antares

Diagram:

$\tilde{Z}_1 \rightarrow b\bar{b}$

$A \rightarrow \mu^+$

$\bar{c} \rightarrow \nu_\mu$
ID of SUSY DM: $\gamma$ and anti-matter searches

- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, \text{etc.} \rightarrow \gamma$ in galactic core or halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, \text{etc.} \rightarrow e^+$ in galactic halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, \text{etc.} \rightarrow \bar{p}$ in galactic halo
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow q\bar{q}, \text{etc.} \rightarrow \bar{D}$ in galactic halo
Direct and indirect detection of neutralino DM

mSUGRA, $A_0=0$, $\tan\beta=10$, $\mu>0$

mSUGRA, $A_0=0$, $\tan\beta=50$, $\mu<0$

HB, Belyaev, Krupovnickas, O’Farrill
SUGRA models with non-universal scalars

- Normal scalar mass hierarchy (NMH):
  - $BF(b \rightarrow s\gamma)$ prefers heavy 3rd gen. squarks
  - $(g - 2)_\mu$ prefers light 2nd gen. sleptons
  - $m_0(1) \simeq m_0(2) \ll m_0(3)$
    - (preserve FCNC bounds)
  - motivation: reconcile $BF(b \rightarrow s\gamma)$ with $(g - 2)_\mu$
    - HB, Belyaev, Krupovnickas, Mustafayev
Normal scalar mass hierarchy: parameter space

- $m_0(1) \simeq m_0(2) \ll m_0(3)$
- LHC: light sleptons, enhanced leptonic cascade decays
- ILC: first two gen. sleptons likely accessible; squarks/staus heavy
SUGRA models with non-universal Higgs mass (NUHM1)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_\phi^2 \neq m_0$: Drees; HB, Belyaev, Mustafayev, Profumo, Tata

- motivation: $SO(10)$ SUSYGUTs where $\hat{H}_{u,d} \in \phi(10)$ while matter $\in \psi(16)$

- $m_\phi^2 \gg m_0 \Rightarrow$ higgsino DM for any $m_0$, $m_{1/2}$

- $m_\phi^2 < 0 \Rightarrow$ can have $A$-funnel for any $\tan \beta$

$m_0=300\text{GeV}$, $m_{1/2}=300\text{GeV}$, $\tan \beta=10$, $A_0=0$, $\mu>0$, $m_t=178\text{GeV}$

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NUHM2 (2-parameter case)

- \( m_{H_u}^2 \neq m_{H_d}^2 \neq m_0 \): HB, Belyaev, Mustafayev, Profumo, Tata
- motivation: \( SU(5) \) SUSYGUTs where \( \hat{H}_u \in \phi(5) \), \( \hat{H}_d \in \phi(\bar{5}) \)
- can re-parametrize \( m_{H_u}^2, m_{H_d}^2 \leftrightarrow \mu, m_A \) (Ellis, Olive, Santoso)
- large \( S \) term in RGEs \( \Rightarrow \) light \( \tilde{u}_R, \tilde{c}_R \) squarks, \( m_{\tilde{e}_L} < m_{\tilde{e}_R} \)

LEP2

\( \sqrt{\chi^2} \)

\( \mu \) (GeV)

\( m_A \) (GeV)

\( m_{1/2} = 300 \text{ GeV}, \tan\beta = 10, A_0 = 0, m_t = 178 \text{ GeV} \)
Non-universal gaugino masses

- SUGRA models where GKF transforms non-trivially (Snowmass ’96)
- Heterotic superstring models with orbifold compactification: SUSY breaking dominated by the moduli field
- KKLTT model of type IIB string compactification with fluxes
- Extra-dimensional SUSY GUT models where SUSY breaking is communicated from the SUSY breaking brane to the visible brane via gaugino mediation (e.g. Dermisek-Mafi model)
- ...

- Here we adopt a phenomenological approach of independent $M_1, M_2, M_3$ but require consistency with WMAP

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Related work: Corsetti and Nath; Birkedal-Hansen and Nelson; Bertin, Nezri and Orloff; Bottino, Donato, Fornengo, Scopel; Belanger, Boudjema, Cottrant, Pukhov, Semenov; Mambrini, Munoz and Cerdeno; Auto, HB, Belyaev, Krupovnickas; Masiero, Profumo, Ullio
\( \Omega \bar{Z}_1 h^2 \) vs. \( M_1 \)

\( m_0 = 300 \text{ GeV}, m_{1/2} = 300 \text{ GeV}, \tan \beta = 10, A_0 = 0, \mu > 0, m_t = 178 \text{ GeV} \)
Sparticle mass spectra vs $M_1$

$m_0 = 300$ GeV, $m_{1/2} = 300$ GeV, $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$, $m_t = 178$ GeV
MWDM: plot \( r_1 \equiv M_1/M_2 \) (at \( M_{GUT} \) which gives \( \Omega_{CDM}h^2 \simeq 0.11 \))
MWDM: small $\tilde{Z}_2 - \tilde{Z}_1$ mass gap

$mSUGRA: \tan\beta=10, A_0=0, \mu>0, m_t=178$ GeV

$\text{NUGM: } M_1 \neq m_{1/2}, \tan\beta=10, A_0=0, \mu>0, m_t=178$ GeV

LEP 2
$m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM

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Bino-wino co-annihilation (BWCA) scenario

- If $M_1/M_2 < 0$, then no mixing between bino-wino
- Can only reduce relic density via bino-wino co-annihilation
  $(m_{\tilde{Z}_1} \sim m_{\tilde{W}_1} \sim m_{\tilde{Z}_2})$ when $M_1 \sim -M_2$ at $Q = M_{weak}$
- plot $r_1 = -M_1/M_2$ (at $M_{GUT}$)
BWCA: $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$, $m_t = 178$ GeV, $\Omega h^2 = 0.1126 \pm 0.001126$
In BWCA at $m_0 \lesssim 500$ GeV, $BF(\tilde{Z}_2 \rightarrow \tilde{Z}_1 \gamma)$ enhanced!

Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)
Mixed higgsino DM from a low $M_3$ (LM3DM)

$m_0=300$ GeV, $m_{1/2}=300$ GeV, $\tan\beta=10$, $A_0=0$, $\mu>0$, $m_t=175$ GeV

- low $M_3 \Rightarrow$ low $m_{\tilde{g}}$, $m_{\tilde{q}}$, $\mu$
- called “compressd SUSY” in related scenario by S. P. Martin

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Sparticle mass spectra for LM3DM

MHDM: $m_0 = 300\text{GeV}$, $m_{1/2} = 300\text{GeV}$, $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$, $m_t = 175\text{GeV}$

- low $m_{\tilde{g}}$, $m_{\tilde{q}}$, $\mu \Rightarrow$ huge DM detection rates!
Direct/indirect DM rates greatly enhanced for LM3DM

$m_0=300$ GeV, $m_{1/2}=300$ GeV, $\tan\beta=10$, $A_0=0$, $\mu>0$, $m_t=175$ GeV

**Graphs:**

- $\sigma_{p, p}(pb)$ vs. $M_3$ (GeV)
  - MHDM2
  - MHDM1 mSUGRA
- $\phi_{\mu}$ (km$^2$ yr$^{-1}$) vs. $M_3$ (GeV)
  - IceCube
  - LEP2
- $R_{\gamma}$ vs. $M_3$ (GeV)
  - GLAST
  - LEP2
- $R_{\mu}$ vs. $M_3$ (GeV)
  - Pamela
  - LEP2
- $R_{p}$ vs. $M_3$ (GeV)
  - Pamela
  - LEP2
- $R_{\gamma}$ vs. $M_3$ (GeV)
  - GAPS
  - LEP2
In LM3DM, $BF(\tilde{g} \rightarrow \tilde{Z}_i)$ loop decay enhanced!

MHDM: $-M_3 \leq m_{1/2}$, $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$, $m_t = 175$ GeV

In LM3DM, ratio \( m_{\tilde{g}} : m_{\tilde{W}_1} : m_{\tilde{Z}_1} \sim 2.5 : 1.5 : 1 \)

- Can search for \( p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow \text{jets} + \not{E}_T \) at Tevatron;
- Search is not pre-empted by LEP2 bounds on \( m_{\tilde{W}_1} \);
- Can see \( m_{\tilde{g}} \) from \( 200 - 340 \) GeV: HB, Mustafayev, Tata PRD75,035004 (2007)
Mixed modulus-AMSB models

★ KKL T model: type IIB superstring compactification with fluxes
  • stabilize moduli/dilaton via fluxes and e.g. gaugino condensation on $D7$ brane
  • introduce anti-$D3$ brane (uplifting potential; de Sitter universe with $\Lambda > 0$
  • small SUSY breaking due to $\overline{D3}$ brane
  • mass hierarchy: $m_{\text{moduli}} \gg m_{3/2} \gg m_{\text{SUSY}}$

★ MSSM soft terms calculated by Choi, Falkowski, Nilles, Olechowski, Pokorski

★ phenomenology: Choi, Jeong, Okumura, Falkowski, Lebedev, Mambrini, Kitano, Nomura

Parameter space of MM-AMSB (mirage unification) model

- MSSM sparticle mass scale $\sim \frac{m_3/2}{16\pi^2} \equiv M_s$

- Ratio of modulus-mediated and anomaly-mediated contributions set by a phenomenological parameter $\alpha$

- Modulus-mediated contributions depend on location of fields in extra dimensions. These contributions depend on “modular weights” of the fields, determined by where these fields are located.
  - modular weights $n_i = 0 \ (1) \ (\frac{1}{2})$ for D7 (D3) ((intersection))
  - Gauge kinetic function indices $l_a = 1 \ (0)$ on $D7 \ (D3)$ branes.

  Model completely specified by $m_3/2, \alpha, \tan\beta, \text{sign}(\mu), n_i, l_a$

- Radiative EWSB determines $\mu^2$ as usual; model into Isajet 7.75
**Soft SUSY Breaking Terms**

The soft terms renormalized at $Q \sim M_{\text{GUT}}$ are given by,

\[ M_a = M_s \left( \ell_a \alpha + b_a g_a^2 \right), \]
\[ A_{ijk} = M_s \left( -(3 - n_i - n_j - n_k) \alpha + \gamma_i + \gamma_j + \gamma_k \right), \]
\[ m_i^2 = M_s^2 \left( (1 - n_i) \alpha^2 + 4\alpha \xi_i - \dot{\gamma}_i \right), \]

with

\[ \xi_i = \sum_{j,k} (3 - n_i - n_j - n_k) \frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_a^2(f_i), \text{ and } \dot{\gamma}_i = 8\pi^2 \frac{\partial \gamma_i}{\partial \log \mu} \]
Measuring modular weights at LHC and ILC

A plot of the mirage unification scale versus modulus-AMSB mixing parameter $\alpha$, assuming $l = 1$.

At $Q = \mu_{\text{mir.}} = M_{\text{GUT}} e^{-8\pi^2/(l\alpha)}$, can determine soft terms via RG running up, if weak scale parameters are known.
At $Q = \mu_{\text{mir.}}$, ratio of scalar to gaugino masses is given by

$$\frac{m_i}{M_a} \bigg|_{\mu_{\text{mir.}}} = \sqrt{1 - n_i} \cdot \frac{l_a}{l_{\text{mir.}}}.$$ 

For $l_a = 1$, this measures the matter modular weight!
Gaugino masses at weak scale in MM-AMSB:

$m_{3/2} = 11.5$ TeV, $\tan\beta = 10$, $\mu > 0$, $m_t = 175$ GeV

Low mirage unification scale

If $M_1(\text{weak}) = \pm M_2(\text{weak})$, potential for agreement with relic density via MWDM or BWCA!
\( \alpha \ vs. \ m_{3/2} \) space for \( n_m = n_H = 0 \):

Gravitino mass vs. \( \alpha \), \( \tan \beta = 10, \, \mu > 0 \), ZMW

Stop coannihilation region.

Mixed higgsino region at low positive alpha.

BWCA for \( \alpha < 0 \). No MWDM region.
$\alpha$ vs. $m_{3/2}$ space for $n_m = \frac{1}{2}$, $n_H = 1$:

Stau coannihilation, Higgs funnel, MWDM and BWCA regions clearly seen.
Also, mixed bino-wino-higgsino region (via low $|M_3|$).
Bulk region at low $m_{3/2}$. 
Conclusions: SUSY dark matter models

- We use the measured relic density of CDM as a guide to SUSY phenomenology in the MSSM
  - mSUGRA models: allowed regions
    - HB/FP region: measure $m_{\tilde{g}}$ to $\sim 8\%$
  - NMH
  - NUHM1
  - NUHM2
  - MWDM
  - BWCA DM
  - LM3DM
  - mixed moduli-AMSB (KKLT, mirage unification)

- data coming soon from LHC will be final arbiter!