Models of SUSY Dark Matter with a well-tempered neutralino

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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

★ quadratic divergence cancellation allows widely disparate scales to co-exist:
  e.g. 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 (Paige, Protop., HB, Tata)
★ We will use the measured value $\Omega_{\text{CDM}} h^2 = 0.105 \pm 0.01$ as a guide to allowed phenomenology! (Isatools:IsaReD)
Case 1: mSUGRA (CMSSM) model

- allowed parameter space: mSUGRA model
  - $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$

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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 $m_{\tilde{t}_1} \simeq m_{\tilde{Z}_1}$)
\[ \chi^2 \text{ from } \Omega_{\tilde{Z}_1} h^2, (g - 2)_\mu, \ BF(b \rightarrow s\gamma) \]
Direct, indirect, collider 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

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Case 2: non-universal generations

- Normal scalar mass hierarchy (NMH):
  - $BF(b \to s\gamma)$ prefers heavy 3rd gen. squarks
  - $(g - 2)_\mu$ prefers light 2nd gen. sleptons
  - $m_0(1) \approx m_0(2) \ll m_0(3)$
    - (preserve FCNC bounds)
  - motivation: reconcile $BF(b \to s\gamma)$ 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
Case 3: NUHM1 (non-universal Higgs mass: 1 param.)

- $m_{H_u}^2 = m_{H_d}^2 \equiv m_{\phi}^2 \neq m_0$: 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 $\tan \beta$
Case 4: NUHM2 (2-parameter case)

- $m^2_{H_u} \neq m^2_{H_d} \neq m_0$: 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 $m^2_{H_u}$, $m^2_{H_d} \leftrightarrow \mu$, $m_A$ (Ellis, Olive, Santoso)
- large $S$ term in RGEs $\Rightarrow$ light $\tilde{u}_R$, $\tilde{c}_R$ squarks, $m_{\tilde{e}_L} < m_{\tilde{e}_R}$

![Graph showing NUHM2: $m_0=300\text{GeV}$, $m_{1/2}=300\text{GeV}$, $\tan\beta=10$, $A_\mu=0$, $m_t=178\text{GeV}$]
Non-universal gaugino masses: case 5-7

☆ Motivation:
  • SUGRA models where GKF transforms non-trivially (Snowmass ’96)
  • Heterotic superstring models with orbifold compactification: SUSY breaking dominated by the moduli field
  • KKLT model of type IIB string compactification with fluxes
  • Extra-dimensionaSusy 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:
  • independent $M_1, M_2, M_3$, but require consistency with WMAP
    * MWDM: HB, Mustafayev, Park, Profumo, JHEP0507, 046 (2005)

- 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
$\Omega h^2$ vs. $M_1$

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

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

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Case 5: MWDM (mixed wino DM)

- plot \( r_1 \equiv \frac{M_1}{M_2}(M_{GUT}) \) s.t. \( \Omega_{CDM} h^2 \simeq 0.11 \)

![Graph showing r1 vs. m0 and m1/2](image)
MWDM: small $\tilde{Z}_2 - \tilde{Z}_1$ mass gap

- mSUGRA: $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \sim \frac{m_\tilde{g}}{7}$
- MWDM: $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} \sim 20 - 60$ GeV: two body $\tilde{Z}_2$ decays closed!

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

NUGM: $M_1 \neq m_{1/2}$, $\tan\beta=10$, $A_0=0$, $\mu>0$, $m_t=178$ GeV
$m(\ell^+\ell^-)$: mass gap observable at LHC for MWDM
Case 6: Bino-wino co-annihilation (BWCA)

- 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 $M_1 \simeq -M_2$ at $Q = M_{\text{weak}}$
- plot $r_1 = -M_1/M_2(M_{\text{GUT}})$

Diagram:

BWCA: $\tan\beta = 10$, $A_0 = 0$, $m_{\tilde{t}} = 178$ GeV, $\Omega h^2 = 0.1126 \pm 0.001126$

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In BWCA at $m_0 \lesssim 500$ GeV, $BF(\tilde{Z}_2 \rightarrow \tilde{Z}_1 \gamma)$ enhanced!

MWDM: $M_2 \neq m_{1/2}$, $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$, $m_t = 178$ GeV

BWCA: $M_2 \neq m_{1/2}$, $\tan \beta = 10$, $A_0 = 0$, $\mu > 0$, $m_t = 178$ GeV

Haber+Wyler; Ambrosanio+Mele; Baer+Krupovnickas: JHEP 0209, 038 (2002)
Case 7: LM3DM (mixed higgsino DM from a low $M_3$)

$m_0=300$ 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
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

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In LM3DM, $BF(\tilde{g} \rightarrow \tilde{Z}_i g)$ loop decay enhanced!

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

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

- Can search for $p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow jets + E_T$ 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)
Case 8: Compressed SUSY (Steve Martin)

- in models with low $M_3$ and $A_0 \sim -M_1$, the $\tilde{t}_1$ becomes quite light
- Martin finds that if
  - $m_t < m_{\tilde{Z}_1} \lesssim m_t + 100$ GeV and
  - $m_{\tilde{Z}_1} + 25$ GeV $\lesssim m_{\tilde{t}_1} \lesssim m_{\tilde{Z}_1} + 100$ GeV, then
- $\tilde{Z}_1 \tilde{Z}_1 \rightarrow t\bar{t}$ is dominant dark matter annihilation mechanism in early Universe!
- implications for LHC, DD, IDD: (HB, Box, Park, Tata: arXiv:0707.0618)
  - light $m_{\tilde{g}}$ with $\tilde{t}_1 = NLSP$
  - collider signatures depend on whether $\tilde{t}_1 \rightarrow c\tilde{Z}_1$ or $bW\tilde{Z}_1$
  - if $\tilde{t}_1 \rightarrow c\tilde{Z}_1$, then large $E_T + jets$, but very low isolated lepton rates
  - IDD halo annihilation signals enhanced since $\tilde{Z}_1 \tilde{Z}_1 \rightarrow t\bar{t} \rightarrow \gamma$s, anti-matter
Case 9: Mixed higgsino DM from high $M_2$ (HM2DM)

- high $M_2 \Rightarrow$ low $|\mu|$, so MHDM but high $m_{\tilde{q}_L}$
- HB, Mustafayev, Summy, Tata
high $M_2$ pushes $SU(2)$ scalar masses up: then enhance top-Yukawa push down! $\mu^2 \sim -m_{H_u}^2$ lowered
Sparticle mass spectra for HM2DM

$m_0 = 300 \text{GeV}, m_{1/2} = 300 \text{GeV}, \tan\beta = 10, A_0 = 0, \mu > 0, m_t = 171.4 \text{GeV}$

- low $|\mu| \Rightarrow$ MHDM: large DM detection rates!
• well-tempered $\tilde{Z}_1$ models asymptote at $\sigma(\tilde{Z}_1 p) \sim 10^{-8}$ pb!
Case 10: Mixed modulus-AMSB (mirage unification)

- KKLT 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,

\[
M_a = M_s (\ell_a \alpha + b_a g_a^2),
\]

\[
A_{ijk} = M_s (- (3 - n_i - n_j - n_k) \alpha + \gamma_i + \gamma_j + \gamma_k),
\]

\[
m_i^2 = M_s^2 ((1 - n_i) \alpha^2 + 4 \alpha \xi_i - \dot{\gamma}_i),
\]

with

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

At $Q = \mu_{\text{mir.}}$, ratio of scalar to gaugino masses is given by

\[
\left. \frac{m_i}{M_a} \right|_{\mu_{\text{mir}}} = \sqrt{1 - n_i} / l_a.
\]

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

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

Low mirage unification scale

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

Stop coannihilation region.

Mixed higgsino region at low positive alpha.

BWCA for $α < 0$. No MWDM region.
Stau coannihilation, Higgs funnel, MWDM and BWCA regions clearly seen. Also, mixed bino-wino-higgsino region (via low $|M_3|$). Bulk region at low $m_{3/2}$. 
We use the measured relic density of CDM as a guide to SUSY phenomenology in the MSSM

- mSUGRA models: allowed regions
- NMH
- NUHM1, NUHM2
- MWDM
- BWCA DM
- LM3DM, compressed SUSY
- HM2DM
- well-tempered neutralino models: $\sigma(\tilde{Z}_1p) \sim 10^{-8}$ pb!
- mixed moduli-AMSB (KKLT, mirage unification)

Data coming soon from LHC will be final arbiter!