Phenomenology of Mixed Modulus-Anomaly Mediated SUSY Breaking Models

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Based on work with Howard Baer, Eun-Kyung Park and Ting Wang

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Motivation and Framework

Phenomenology depends on how SUSY breaking effects are communicated to MSSM fields

- ⋆ Modulus (Gravity)-mediation+ assumptions mSUGRA Model $\Longrightarrow$ Universality
- ⋆ Gauge-mediation GMSB Models $\Longrightarrow m_i \propto g_i^2$
- ⋆ Anomaly-mediation AMSB Models $\Longrightarrow m_i \propto \beta_i$

Modulus + Anomaly Mediation

Mixed Modulus-Anomaly Mediated Supersymmetry Breaking (MM-AMSB)

WHY MM-AMSB?

MM-AMSB structure of MSSM soft SUSY breaking terms arises when extra dimensions of type IIB superstring curl up with fluxes (non-zero field strengths) along these extra dimensions.

Kachru, Kallosh, Trivedi and Linde Toy scenario

- ⋆ Stable ground state in controlled approximation (fluxes + gaugino condensation on $D7$ brane)
- ⋆ de Sitter universe (anti $D3$ brane)
- ⋆ Small SUSY breaking due to $\overline{D3}$ brane.

No concrete realization of KKLT idea with an explicit C-Y space and choice of fluxes that leads to ground state with required properties!

Phenomenological approach.

MSSM Soft terms analysed and some implications explored by,

Choi, Falkowski, Nilles, Olechowski, Pokorski
Choi, Jeong, Okumura; Falkowski, Lebedev, Mambrini; Kitano, Nomura.

Parameter Space

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 α

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.

Matter modular weights n_i= 0 (1)
Gauge kinetic function indices l_a= 1 (0) on $D7$ ($D3$) branes.

Model completely specified by

$$m_{3/2},\ \alpha,\ \tan\beta,\ sign(\mu),\ n_i,\ l_a$$

Radiative EWSB determines μ^2 as usual.

Soft SUSY Breaking Terms

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

$$\begin{aligned} M_a &= M_s\left(\ell_a\alpha + b_a g_a^2\right), \\ A_{ijk} &= M_s\left(-a_{ijk}\alpha + \gamma_i + \gamma_j + \gamma_k\right), \\ m_i^2 &= M_s^2\left(c_i\alpha^2 + 4\alpha\xi_i - \dot{\gamma}_i\right), \end{aligned}$$

with

$$c_i = 1 - n_i,$$

$$a_{ijk} = 3 - n_i - n_j - n_k,$$

$$\xi_i = \sum_{j,k} a_{ijk}\frac{y_{ijk}^2}{4} - \sum_a l_a g_a^2 C_2^a(f_i), \text{and } \dot{\gamma}_i = 8\pi^2\frac{\partial\gamma_i}{\partial\log\mu}$$

Note that if $n_i = 0$, $A_{ijk}^2 \sim 9m_i^2$ for the modulus-mediated contribution. Large A-parameters!

$\alpha = 0$ gives us the AMSB Model.

For large $|\alpha|$, AMSB terms subdominant. With universal l_a (n_i) we will have common gaugino (scalar) masses.

Generation-independent modular weights for MSSM multiplets ensures FCNC OK.

Models potentially have smaller fine tuning: even for heavy stop, $m^2_{H_u}$ can be modest at weak scale. (Lebedev,Nilles, Ratz; Choi et al; Kitano, Nomura).

In general, we lose the scale independence of the AMSB model. However, for $l_a = 1$, and

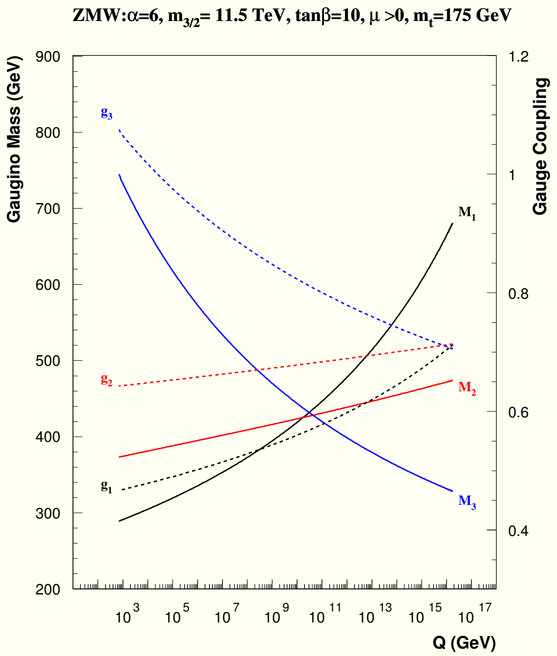
$n_{\rm matter} = \frac{1}{2}$, $n_{\rm Higgs} = 1$ (or $n_{\rm matter} = 1$, $n_{\rm Higgs} = 0$), this scale-independence is re-obtained! (Kitano-Nomura)

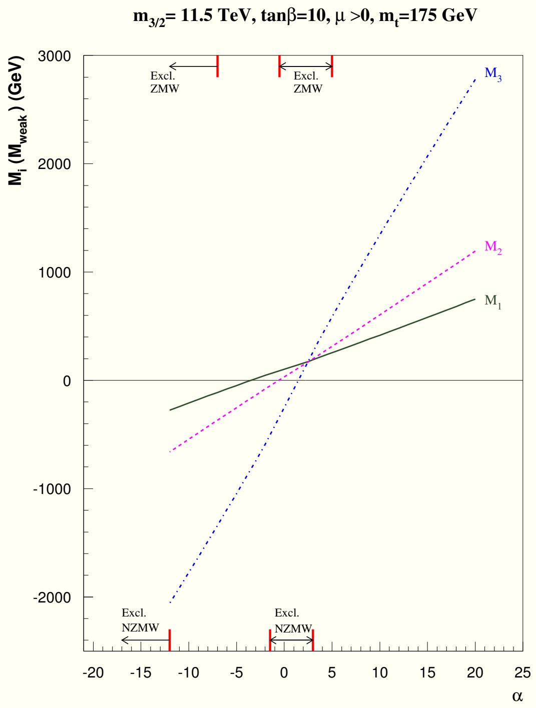
We will always fix $l_a = 1$ and examine two cases:

★ $n_i = 0$; Zero Modular Weight (ZMW).

★ $n_{\rm matter} = 1/2$, $n_{\rm Higgs} = 1$, Non-Zero Modular Weight (NZMW).

True Unification and Mirage Unification

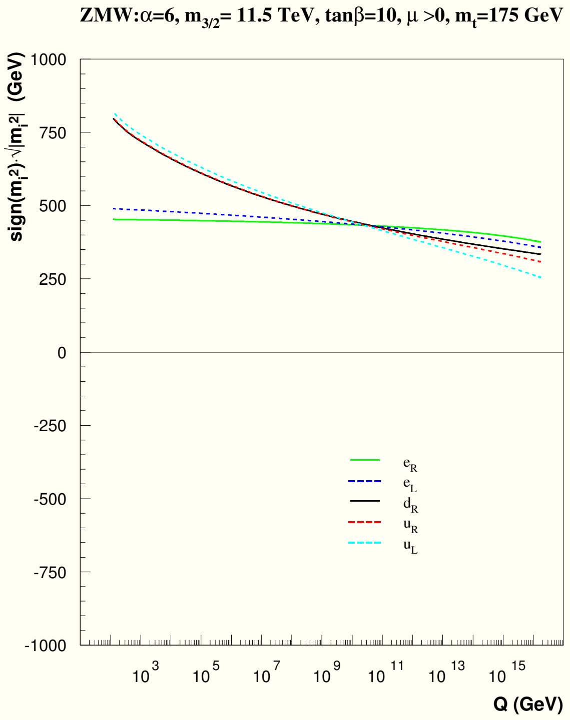


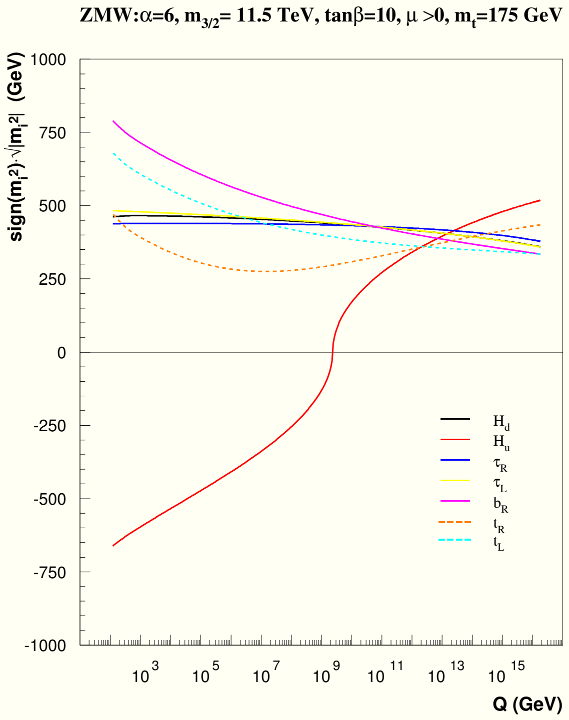


Low mirage unification scale

If $M_1\mathrm{weak} = \pm M_2\mathrm{weak}$, potential for agreement with relic density via Mixed Wino DM (MWDM) / Bino-Wino Coannihilation (BWCA).

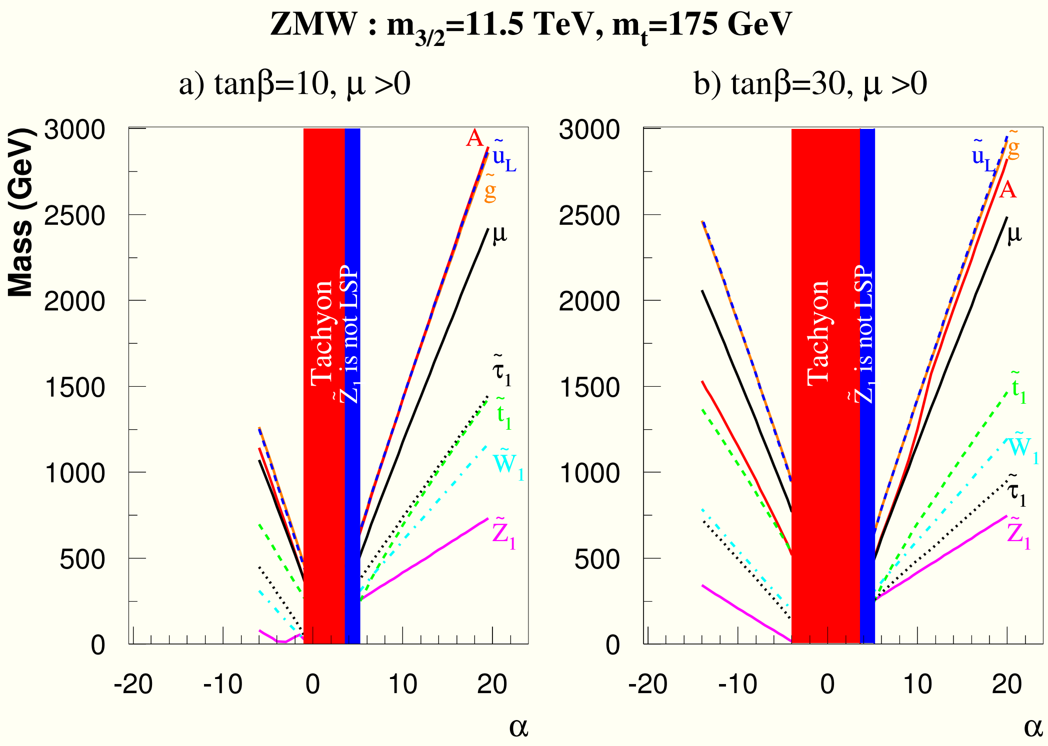
ZMW Model





Mirage unification for scalar masses also, but spoiled by Yukawa couplings (NZMW model is an exception). Note low value of $m_{\tilde{t}_R}$. Anticipate light $\tilde{t}_1$.

ZMW Model Mass Spectrum

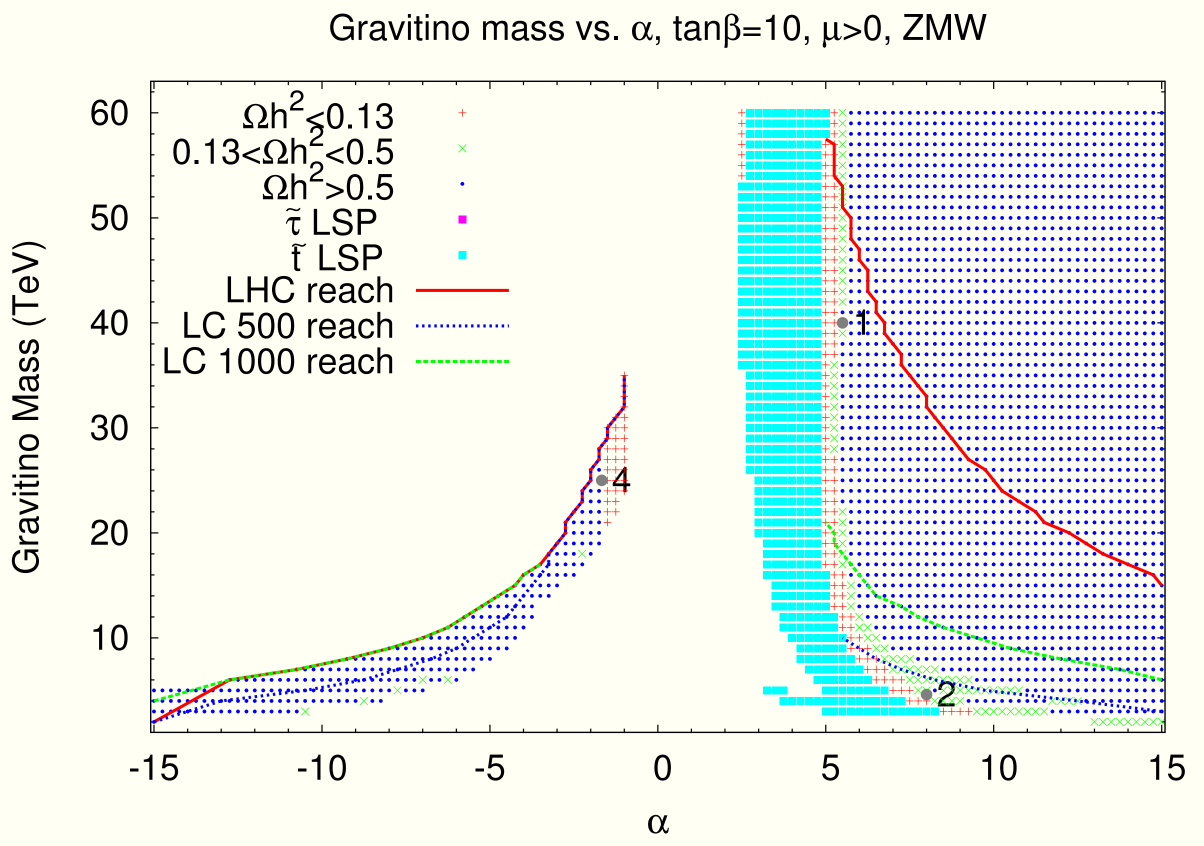


ZMW : $m_{3/2}$=11.5 TeV, m_t=175 GeV

a) tanβ=10, μ >0

b) tanβ=30, μ >0

For low positive α, $m_{\tilde{t}_1} \sim m_{\widetilde{Z}_1}$, and for large $\tan\beta$ $m_{\tilde{\tau}_1} \sim m_{\widetilde{Z}_1}$ also. Stop and stau co-annihilation mechanisms operative. For negative α in first frame, we have BWCA. No MWDM possible as for the required α, $\tilde{t}_1 =$ LSP.



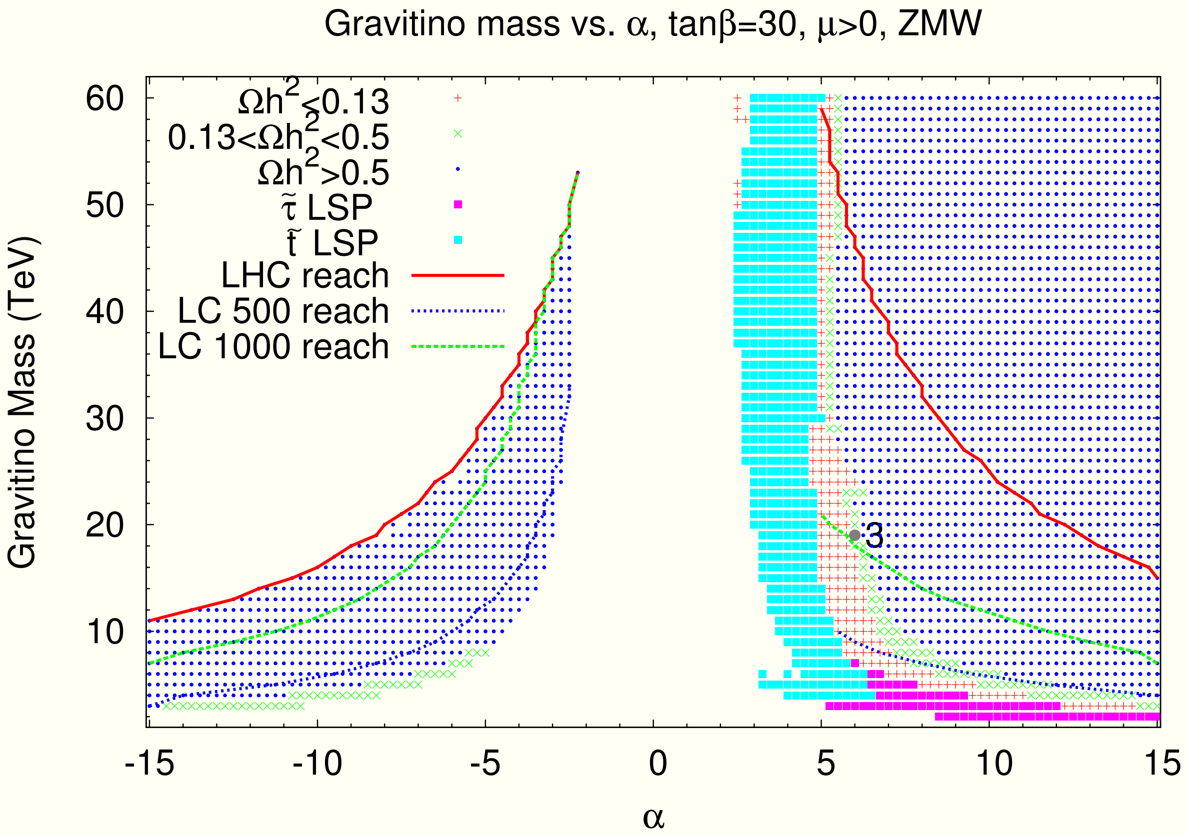
Stop coannihilation region.

Mixed higgsino region at low positive alpha.

BWCA for $\alpha < 0$. No MWDM region.

In the neighbourhood of Point 2, $m_{\tilde{t}_1} < m_t$, $m_h \lesssim 120$ GeV

⇒ Electroweak baryogenesis? (Carena, Quiros, Wagner; Balázs, Carena, Wagner)



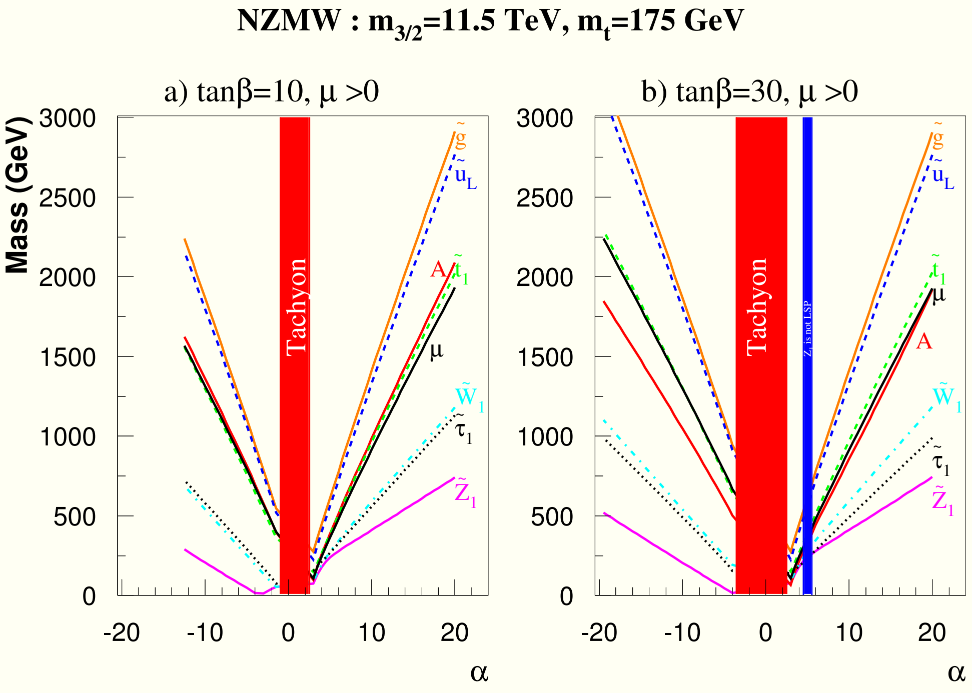
Stop and stau coannihilation regions.

BWCA region disappears.

LHC Covers most of the WMAP allowed planes except for large $m_{3/2}$ near $\alpha \sim 5-6$.

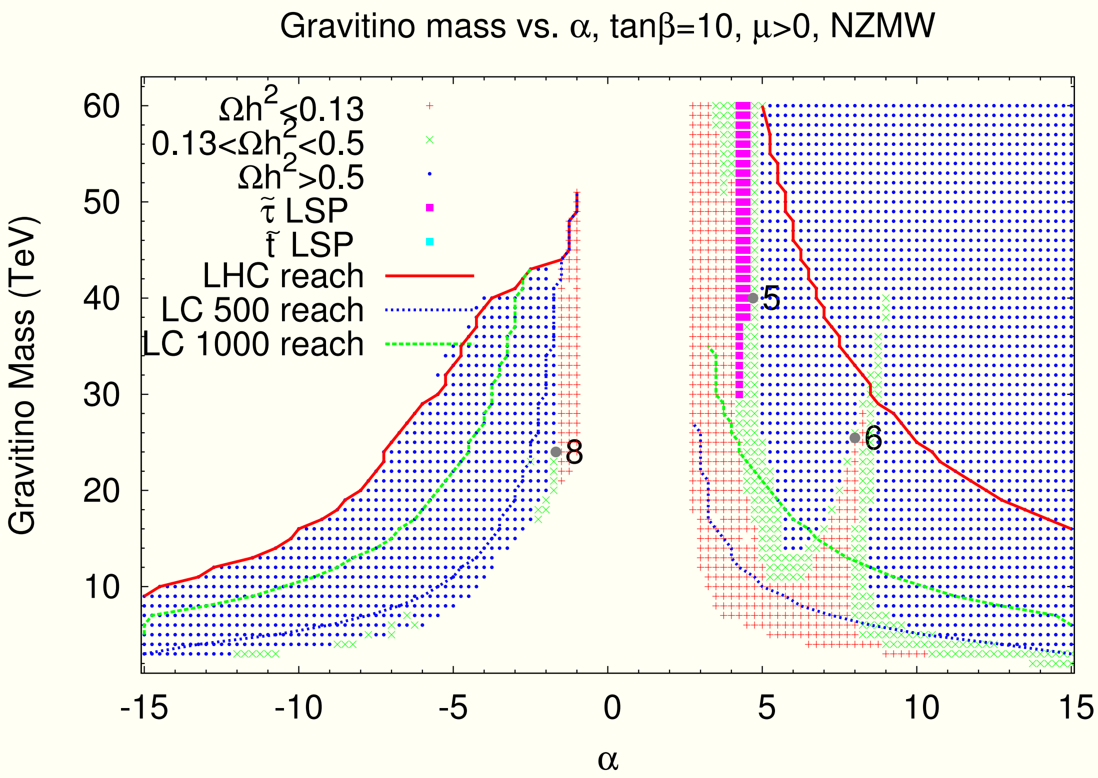
NZMW Model

Now the modulus-mediated contribution to A(GUT) $\sim M_s$, so stop is not as light as in ZMW case.



Stau NLSP $\Longrightarrow$ Stau co-annihilation; Higgs funnel annihilation

Also, BWCA for $\alpha < 0$, $\tan\beta \sim 10$.



Stau coannihilation, Higgs funnel and BWCA regions clearly seen.

Also, mixed bino-wino-higgsino region (via low $|M_3|$).

Bulk region at low $m_{3/2}$.

LHC reach qualitatively similar to ZMW case.

Direct and Indirect DM detection

Many experiments for direct and indirect WIMP detection.

Direct Detection

Stage 2 (CDMS2): SI $\sigma(\widetilde{Z}_1 p) > 3 \times 10^{-8}$ pb
Stage 3 (CDMS3, XENON): 10^{-9} pb

Indirect Detection

IceCube: 40 events/km^2/yr with $E_\mu > 50$ GeV,
GLAST: 10^{-10} events/cm^2/s with $E_\gamma > 1$ GeV,
Pamela: 2×10^{-9} events/GeV/cm^2/s/sr for positrons,
Pamela: 3×10^{-9} events/GeV/cm^2/s/sr for antiprotons,
GAPS: 3×10^{-13} events/GeV/cm^2/s/sr for antideuterons, $0.1 < T_{\overline{D}} < 0.25$ GeV.

Use Isatools for evaluating direct detection rates; DarkSUSY for indirect detection rates.

Eight Case studies (4 ZMW, / 4 NZMW)

Direct detection (Stage 2): No observable signals anticipated.
Direct detection (Stage 3): Observable signals if LSP has significant higgsino components or is close to Higgs funnel (2, 5, 7)
IceCube: No observable signals anticipated
GLAST: Observable signals in many cases (2-8)
e^+, $\bar{p}$: Observable signals near Higgs funnel(6, 7)
GAPS: Observable signal near Higgs funnel region/bulk region (2, 6, 7)
γ and antiparticle signals sensitive to halo profile. Our projections are on the optimistic side.

Generally, no DM signals in stau, stop co-annihilation regions or BWCA region anticipated as LSP is a bino.

Conclusions

- ⋆ MM-AMSB new, consistent, theoretically-motivated and phenomenologically viable framework. Fewer parameters than mSUGRA if the (discrete) modular weights are fixed. NZMW choice of modular weights appears to have an RG invariant spectrum, just as in the AMSB model.
- ⋆ Novel mass patterns possible; Unconventional $M_1 : M_2 : M_3$; $\tilde{t}_1$ very light, especially for ZMW model (possibly even accessible at the Tevatron).
- ⋆ Top-down framework that can give $M_1(\mathrm{weak}) \sim -M_2(\mathrm{weak})$ that was phenomenologically identified as a possibility for obtaining the right CDM relic density; also potentially gives reduced $|\mu|$ via relative reduction of M_3. Correct relic density possible via a variety of mechanisms including, bulk annihilation, Higgs funnel, stop or stau coannihilation, low $|\mu|$ via reduced M_3 and BWCA. MWDM and low $|\mu|$ via non-universal Higgs mass parameters was not possible for cases that we investigated. Collider and DM searches will discriminate between these various possibilities.

- ⋆ Heavy gravitino $\Longrightarrow$ Good for cosmology.
- ⋆ Large part of parameter space consistent with measured CDM relic density will be probed at LHC; over part of this space, precision measurements will be possible at a 1 TeV e^+e^- LC. Importantly, LC experiments will explore charginos and neutralinos in the BWCA region; these may be difficult to explore at the LHC on account of the small mass gap.
- ⋆ Mirage unification of soft SUSY breaking parameters (readily testable for gaugino masses if sparticles are accessible).
- ⋆ Possibility of direct determination of modular weights under investigation.