Anomaly mediated supersymmetry breaking and the ancillary *U*(1) symmetry

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AMSB soft masses

- The Weyl compensator formulism of supergravity:

$$L = \sqrt{-g}\left\{ \int d^4\theta f\left(Q^+, e^{-V} Q\right)\phi^+\phi + \int d^2\theta \left[W(Q)\phi\phi\phi + \tau(Q) ww + \text{h.c.} \right] \right\}$$
$$+ \left(\text{graviton supermultiplet stuff}\right)$$

…where $\phi = 1 + F\theta\theta$.

- Scalar (and trilinear) soft masses are revealed by
  1. making the field strength renormalization explicit,
  2. expanding superfield notation,
  3. and Taylor expanding.
- For gaugino soft masses
  1. perform one loop correction to gauge kinetic function,
  2. expand superfield notation,
  3. and Taylor expand.
- AMSB soft masses can dominate
  – if the visible and hidden sectors only communicate through gravity.

Virtues of AMSB

- Very natural, not optional
- Only 2 parameters and 1 binary choice
- RG invariant soft mass expressions
- UV insensitive
- Solves the supersymmetry flavor problem
- Gauge coupling unification
- Distinct and predictive spectrum
- Modest model building
- Good μ term solutions
- Strong CP problem naturally solved

AMSB soft masses (I)

- The MSSM with AMSB has parameters:

$$\langle F \rangle, \ \tan\beta, \text{ and } \mathrm{sgn}(\mu)$$

- The AMSB spectrum is RG invariant.

$$m_{\Phi}^2 = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right)\langle F \rangle^2$$

$$M_i = \frac{\beta_g}{g}\langle F \rangle$$

$$A_y = -\frac{\beta_y}{y}\langle F \rangle$$

- For example:

$$m_{Q_3}^2(g,y) = \left(-\frac{11}{50}g_1^4 - \frac{3}{2}g_2^4 + 8g_3^4 + y_t\hat{\beta}_{y_t} + y_b\hat{\beta}_{y_b}\right)\tilde{m}^2$$

$$\left(\tilde{m} = \frac{\langle F \rangle}{16\pi^2}\right)$$

- 2 parameters, 1 binary choice.
- Valid at any scale the MSSM is valid.
- Predictive spectrum.
- Flavor diagonal soft masses.

AMSB and thresholds

- Two distinct classes of AMSB threshold corrections:
  - Scalar in X defines a threshold.
  - "Aligned" thresholds: $X = M\square\ [= M(1+F\square\square)]$.
  - Not aligned thresholds: $X \neq M\square$.
- Aligned thresholds:
  - Threshold corrections to soft masses are zero (at one loop).
  - Threshold corrections to soft masses arise at order:

$$\frac{\langle F \rangle^4}{\square^2}$$

    - UV insensitivity
    - Flavor problem solution
  - Two understandings:
    - Pauli-Villars regularization
    - Dimensional reduction (DRED) regularization
- Not aligned thresholds:
  - May arise when a light scalar singlet is responsible for spontaneously generating the masses of the threshold.
  - Large model-dependent threshold corrections.

1. Murayama, Pierce
2. Katz, Shadmi, Shirman
3. Pomarol, Rattazzi
4. Randall, Sundrum

AMSB is testable

- Gauginos
  - The AMSB gaugino spectrum is distinct:

    $$M_1 : M_2 : M_3 \approx 3 : 1 : 7$$

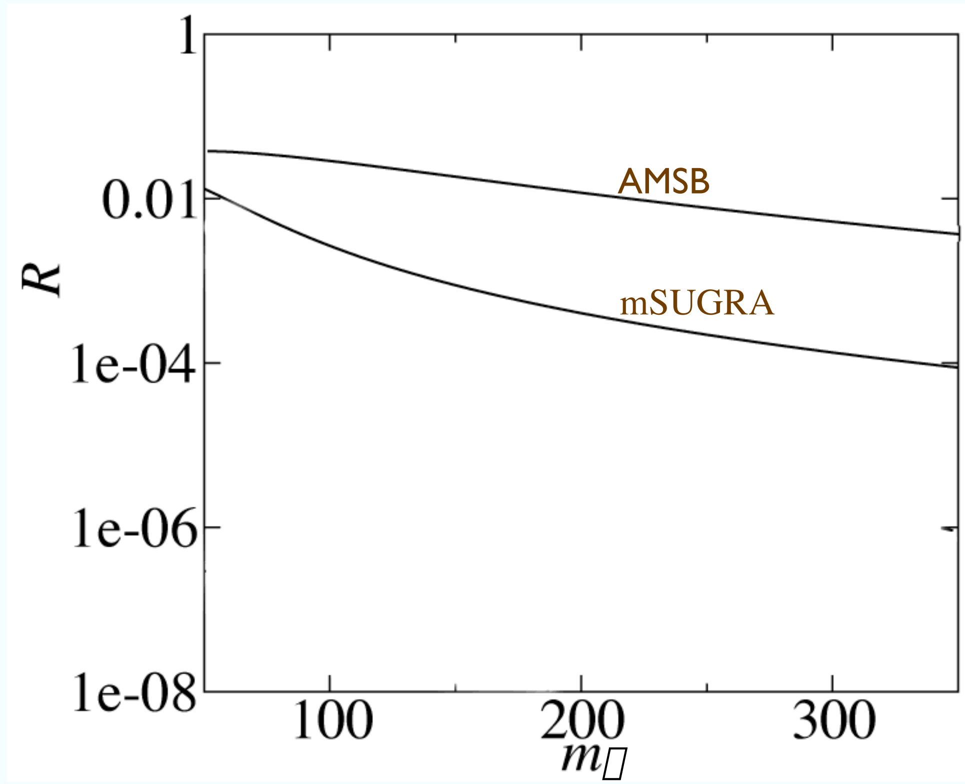
  - …as opposed to mSUGRA:

    $$M_1 : M_2 : M_3 \approx 1 : 2 : 7$$

  - Wino (Higgsino) LSP has great detection prospects as CDM.
  - The lightest chargino and neutralino are nearly degenerate.
- Scalars
  - The scalar spectrum of pure AMSB is very predictive, but unacceptable.
  - Fixes to the scalar spectrum may retain distinction in some models.

AMSB cold dark matter

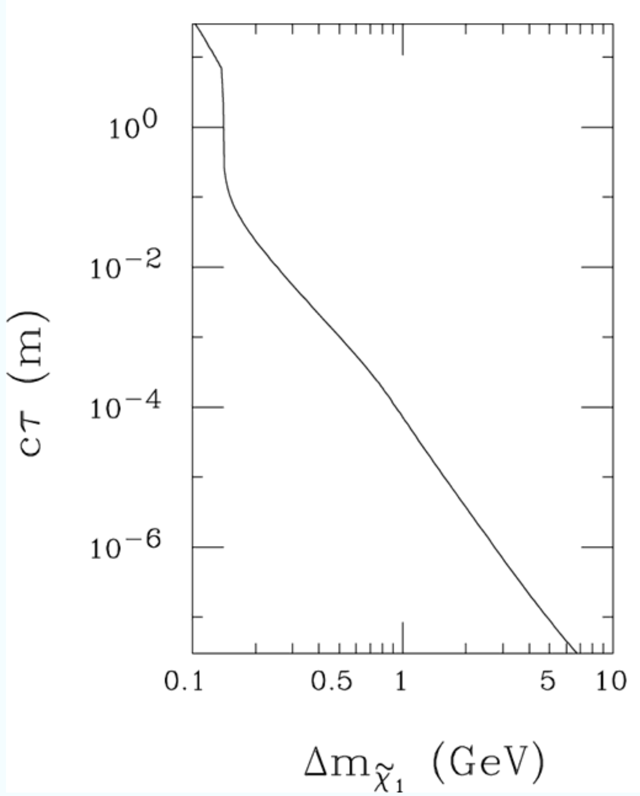
Elastic scattering of neutralinos on ^{73}Ge



- *R* is in events/day/kg.
- For mSUGRA: $M_1 = \square/3$, $M_2 = 2\square/3$, $\tan\square = 4$.
- For AMSB: $M_1 = 3\square/2$, $M_2 = \square/2$.
- In common: $\tan\square = 4$, $m_{\text{squark}} = 2$ TeV, $m_A = 500$ GeV, $A = 0$.

1.BM, Wells

AMSB gauginos at colliders



- The lightest chargino mass is ~M_2, nearly degenerate with the lightest neutralino mass.
- Chargino decays may have observable vertex displacements.

1. Gunion, Mrenna
2. Cheng, Dobrescu, Matchev

The MSSM with AMSB is sick

- All slepton soft masses are negative m^2 at low scales:

$$m^2_{\tilde{\ell}} \propto \mp[\text{gauge}] + [\text{Yukawa}]$$

$$m^2_{\tilde{L}} = \left(-\frac{99}{50} g_1^4 - \frac{3}{2} g_2^4 + y_e \hat{\beta}_e \right) \tilde{m}^2$$

$$m^2_{\tilde{e}} = \left(-\frac{198}{25} g_1^4 + 2 y_e \hat{\beta}_e \right) \tilde{m}^2$$

- Electromagnetism is broken.
- UV insensitivity makes slepton solutions tricky.
- If not for this, AMSB would be an ideal standard.

AMSB is curable

- Help comes in two forms:
  - Change the low energy theory (the MSSM)
  - Faint echos from exotics in a high energy theory
- Ways to change the MSSM:

change the sign

$$m_{\tilde{L}}^2 = \left(-\frac{99}{50} g_1^4 - \frac{3}{2} g_2^4 + y_e \hat{\beta}_e \right) \tilde{m}^2$$

change the group

add new Yukawas

Existing slepton solutions

Bulk scalars (aka mAMSB). Sleptons get a boost m_0^2. — Randall, Sundrum; Gherghetta, Giudice, Wells; Feng, Moroi

"Deflected AMSB" (aka anti-GMSB). The AMSB RG trajectory is derailed by intermediate scale vector pair multiplets. — Pomarol, Rattazzi

"Gaugino assisted AMSB." MSSM gauge multiplets in the bulk; no scalars in the bulk or hidden sector. — Kaplan, Kribs

Exotic Yukawa couplings for sleptons. New couplings boost AMSB slepton mass. — Chacko, Luty, Maksymyk, Ponton

Asymptotically free gauge groups. i.e., $SU(3)$ electroweak at 10 TeV. — Nelson, Weiner

***R*-parity violation.** New Yukawa contributions through *LLe* in superpotential. No modifications to the MSSM. — Allanach, Dedes

Exotic *D*-terms. Scalar soft masses shifted up or down according to exotic $U(1)$ charges. — Katz, Shadmi, Shirman; Arkani-Hamed, Kaplan, Murayama, Nomura; Jack, Jones; Carena, Huitu, Kobayashi; BM, Wells

Exotic $U(1)$ concerns

1. Origin of the *D*-term vev
2. The crossing of thresholds
3. The charge assignments of the Q, u, d, L, e, H_u, H_d and exotic multiplets.
4. Proper electroweak symmetry breaking.
5. *Z*-*Z*' kinetic mixing
6. *Z*-*Z*' mass mixing

Some of these can only be addressed with explicit model building.

Our $U(1)$ selection

Motivation
AMSB is testable
AMSB is sick
AMSB is curable
Existing solutions
D-term solutions
Ancillary $U(1)$
Reconciliation with prior efforts
Conclusions

- What motivated $U(1)$'s are on the market?
  - B-L, $U(1)_{□}$ from E_6, hypercharge, …?
  - All have opposite signs for the L and e multiplets.
- Our focus, only consider the class of $U(1)$'s that:
  1. Preserve gauge unification.
  2. (Chiral) anomaly free.
- …also:
  - (MS)SM matter charged under the $U(1)$.
  - Generation independent charges.
  - The $U(1)$ is broken by exotic scalars that don't derail RG invariance.
- May create a light or heavy Z'.
- We are not model building.

Charge assignments of the ancillary *U*(1)

- We require the absence of chiral anomalies.
  - i.e., eliminate *YYX*, *YXX*, *XXX*, *SU*(2)*SU*(2)*X*, *SU*(3)*SU*(3)*X*, and gravitational anomalies.
- Along with charge conservation for $U(1)_a$:

$$Q_L = 3q$$
$$Q_e = r$$
$$Q_Q = -q$$
$$Q_u = -(2q + r)$$
$$Q_d = 4q + r$$
$$Q_{H_u} = 3q + r$$
$$Q_{H_d} = -(3q + r)$$

- Two parameters.
- Same signs for the *L* and *e* multiplets are possible!
- Singlets are required to break the *U*(1). Assume irrelevant low-scale phenomenology.

I.Chamseddine, Dreiner

The ancillary $U(1)$ assisted spectrum

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- Positive slepton masses require $r > 0$ and $q > 0$.
- Normalize $r = 1$.
- Total parameters: F, $\tan\square$, $\mathrm{sgn}\square$, q, $\square$, and g_a. (6)
- The soft masses get shifted by *D*-term contributions:

$$\left(m_L^D\right)^2 = 3q\square\tilde{m}^2$$

$$\left(m_e^D\right)^2 = \square\tilde{m}^2$$

$$\left(m_Q^D\right)^2 = \square q\square\tilde{m}^2$$

$$\left(m_u^D\right)^2 = \square(2q+1)\square\tilde{m}^2$$

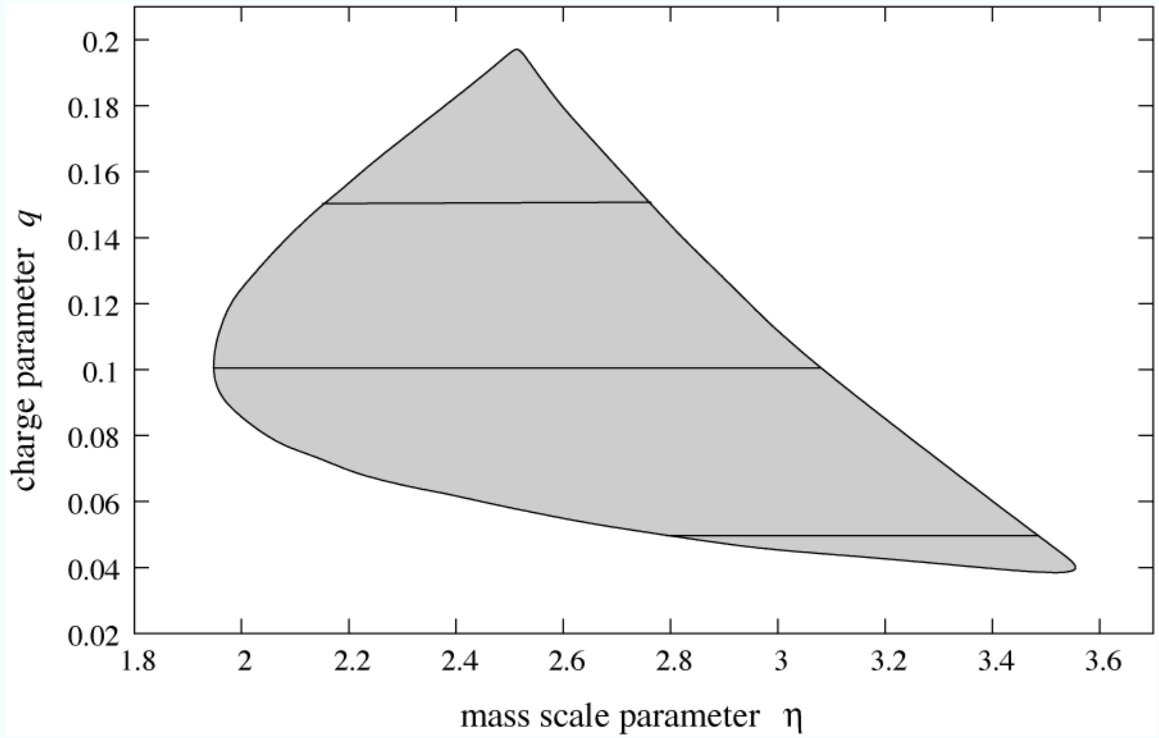
$$\left(m_d^D\right)^2 = (4q+1)\square\tilde{m}^2$$

$$\square\tilde{m} = \frac{\langle F\rangle}{16\square^2}\square$$

Achievements of the ancillary *U*(1)

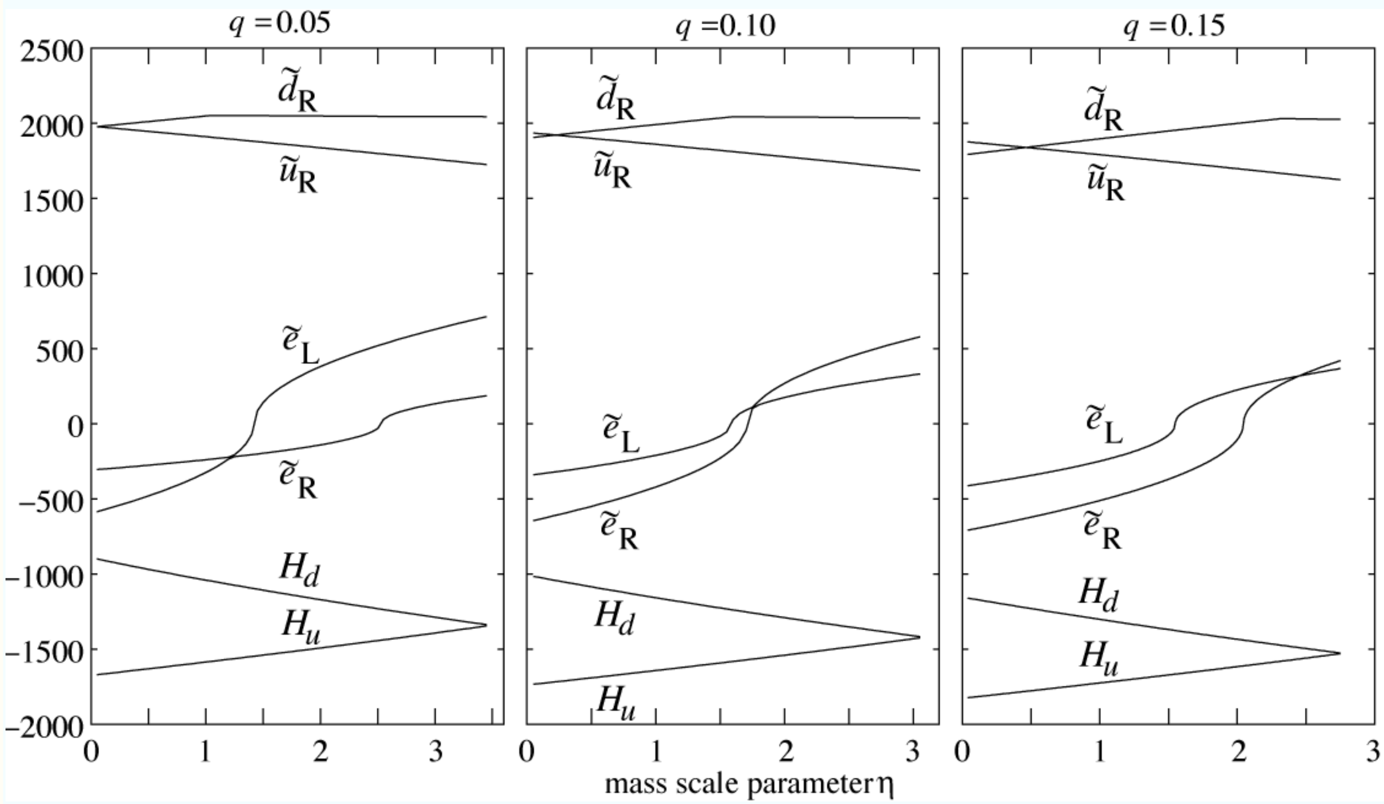
- We learn, this slepton solution necessitates:
  - *Q* soft mass must decrease.
  - *u* soft mass must decrease.
  - *d* soft mass must increase.
- Measuring a few soft masses, reveals the entire scalar spectrum (for the 1st and 2nd generations).
  - Say we know the soft scale from gauginos.
  - Measuring the selectron mass reveals the *D*-term vev.
  - Measuring any other scalar, reveals parameter q.
  - All 1st and 2nd generation scalars masses are then revealed.
- The heaviest scalar partner cannot be heavier than $\sim 6\tilde{m}^2$.
  - Due to the requirement that 1st generation sleptons have positive mass.

The ancillary $U(1)$ assisted spectrum



- Parameters: $\tilde{m}^2 = 500$ GeV, $\tan\beta = 10$, $g_a(m_Z) = g_Y(m_Z)$
- Shape dictated by acceptable slepton masses and proper electroweak breaking.

The ancillary *U*(1) assisted spectrum



- Parameters: $\tilde{m}^2 = 500\ \mathrm{GeV},\ \tan\beta = 10,\ g_a(m_Z) = g_Y(m_Z)$
- Right hand sides are cut off by improper electroweak symmetry breaking.

Reconciliation with prior efforts (1)

- *B*-*L* and exotic hypercharge *D*-terms. (Arkani-Hamed, et al.)
  - Two *D*-terms necessary due to opposite charge assignments for *L* and *e*.
  - Exotic hypercharge *D*-term vev established through kinetic mixing with *B*-*L*.
  - No kinetic term for *B*-*L*.
- Kinetic mixing free *U*(1) and exotic *D*-terms. (Jack, Jones)
  - Kinetic mixing arises through loops.
  - Exotic charges set by $\mathrm{Tr}(YQ) = 0$ to eliminate kinetic mixing.
  - *D*-term vevs established through Fayet-Iliopolous terms.

$$L \quad \square\square D \quad \square \quad \langle D \rangle = \square$$

- Both yield viable sparticle spectrums.

1. Arkani-Hamed, Kaplan, Murayama, Nomura
2. Jack, Jones

Reconciliation with prior efforts (2)

- All (chiral) anomaly free *U*(1)'s that preserve gauge unification are specific manifestations of the ancillary *U*(1).
  - For *Y*, $q = -1/6$ and $r = 1$.
  - For *B-L*, $q = -1/3$ and $r = 1$.
  - For J&J, $q = -7/3$ and $r = 3$.
- Furthermore, the existing solutions with two *D*-terms can be mapped to a single ancillary *U*(1).
  - Take *B-L* and *Y*, for example:

$$Q_i^{a} D_{a} = Y_i D_Y + Q_i^{B-L} D_{B-L}\ ? \qquad \left(D_{a} \equiv -\tilde{m}^2\right)$$

  - We recast:

$$D_{a} = r_Y D_Y + r_{B-L} D_{B-L} \text{ and } q = \frac{q_Y D_Y + q_{B-L} D_{B-L}}{r_Y D_Y + r_{B-L} D_{B-L}} \quad (r = 1)$$

  - Try H_u:

$$\begin{aligned} Q_{H_u}^{a} D_{a} &= (3q + r) D_{a} \\ &= \left[3\left(\frac{\left(-\frac{1}{6}\right) D_Y + \left(-\frac{1}{3}\right) D_{B-L}}{(1) D_Y + (1) D_{B-L}}\right) + (1)\right]\left\{(1) D_Y + (1) D_{B-L}\right\} \\ &= \tfrac{1}{2} D_Y + 0 D_{B-L} \end{aligned}$$

Summary

- AMSB is fascinating:
  - Anomaly mediated supersymmetry breaking is present in all broken supergravity theories.
  - The pure AMSB spectrum is very immune from high scale physics.
  - Pure AMSB does not have flavor problems.
  - Pure AMSB has other desirable theoretical properties.
- AMSB has distinct experimental signatures:
  - Detectable rates for cold dark matter.
  - Detectable displaced vertex in chargino to neutralino decays.
- AMSB is sick:
  - Pure AMSB has broken electromagnetism.
- AMSB is curable:
  - Many slepton solutions exist. None are sufficiently compelling.
  - *D*-term slepton solutions are motivated and viable.
  - The ancillary $U(1)$ formalism:
    1. Retains gauge coupling unification.
    2. Is chiral anomaly free.
    3. Allows model independent predictions about the sparticle spectrum.
    4. Reconciles past efforts employing 2 D-terms into a single D-term solution.
    5. Retains the unique gaugino spectrum of AMSB.
    6. Retains predictive (RG invariant) scalar masses.