Anomaly mediated supersymmetry breaking and the ancillary $U(1)$ formalism

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with James Wells

Motivation:
Why theorists deserve to do physics

- The necessity for a Higgs mechanism:
  - Higgs mechanism ≠ Higgs scalar boson.
  - We know:
    - The photon exists. $M_\gamma < 0.000\,000\,000\,000\,000\,000\,000\,2$ GeV
    - The *Z* boson exists. $M_Z = 91.1876 \pm 0.0021$ GeV
    - The *W* bosons exist. $M_W = 80.423 \pm 0.039$ GeV
    - Electroweak precision data…
    - …namely, $M_W = M_Z \cos\theta_W$.
  - The standard model unifies these as *SU*(2)x*U*(1).
- The simplest solution mandates a fundamental scalar Higgs.
- A scalar Higgs must be protected or banished.
  - QFT is unkind to scalars.
  - Strong dynamics banishes the scalar.
  - Extra dimensions protects the scalar.
  - Little Higgs protects the scalar.
  - Supersymmetry relegates (banishes) the scalar.
  - Occam's razor mandates supersymmetry studies.
- The Higgs sector is the gateway to all future understanding.

Why Supersymmetry?

- Supersymmetry is the only non-trivial extension of the Poincare group.
- Although not engineered for, we get gifts:
  - A hierarchy solution
  - An explanation for electroweak symmetry breaking
  - GUT evidence and motivation
  - A natural cold dark matter candidate
  - …and more.

Supersymmetry must be broken

- Supersymmetry is spontaneously broken if:

$$e^{i\left(\xi Q+\bar{\xi}\bar{Q}\right)}\left|0\right\rangle \neq \left|0\right\rangle \Leftrightarrow \left\langle 0\right|H\left|0\right\rangle \neq 0$$

  - Need either a fermion condensate, *F* vev, or *D* vev.
- For EWSB, we know the breaking pattern because of measurements.
- Gravity mediated supersymmetry breaking problems
  - Flavor problems
  - CP problems
  - No predictable spectrum
  - Structure model building
- Gauge mediated supersymmetry breaking problems
  - Gaugino masses
  - CP problems
  - The μ problem
  - Loss of CDM candidate
  - Structured model building
- Anomaly mediate supersymmetry breaking problems
  - The μ problem
  - Spectrum problem

AMSB is fascinating

- 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

Origin of AMSB

- AMSB soft mass contributions are always present.
- How can AMSB be the dominant source for soft masses?
  - Our sector and the hidden sector must have no direct (Yukawa, gauge, etc.) interactions.
  - A general supergravity theory has the form:

$$L = \sqrt{-g}\left\{ \int d^4\theta\, f\left(Q^{+}, e^{-V} Q\right)\phi^{+}\phi + \int d^2\theta \left[W(Q)\phi^3 + \tau(Q)ww + \text{h.c.}\right] \right\}$$

$$+ \left(\text{graviton supermultiplet stuff}\right)$$

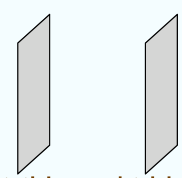
  - To dominate, AMSB requires:

$$f = -3m_{\mathrm{P}}^2 + f_{\text{visible}} + f_{\text{hidden}}$$

$$W = W_{\text{visible}} + W_{\text{hidden}}$$

$$\tau ww = \tau_{\text{visible}} w_{\text{visible}}^2 + \tau_{\text{hidden}} w_{\text{hidden}}^2$$

- This is realizable two ways:
  - Geometric separation
  - A conformal hidden sector



1. Randall, Sundrum
2. Giudice, Luty, Ratazzi, Murayama
3. Luty, Sundrum

What is the super-Weyl anomaly? (1)

- "What is the Weyl anomaly?" (aka conformal anomaly)
  - The Weyl transformation: $g_{\mu\nu}(x) \to \Omega(x) g_{\mu\nu}(x)$.
  - This rescaling can be understood in terms of the (modified) stress-energy tensor $\Theta^{\mu\nu}$.
  - For *classical* scale invariant theories, $\Theta^{\mu}_{\mu} = 0$.
  - Quantization generates an anomaly.
- "What is the super-Weyl anomaly?"
  - Just the Weyl anomaly in a supersymmetric theory.

What is the super-Weyl anomaly? (2)

- "What's supergravity got to do with Weyl transformations?"
  - The Weyl compesator formalism of supergravity:

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

  - …by using the Weyl compensator $\phi = 1 + F_\phi\theta^2$.
  - …by a Weyl transformation and substituting out auxiliary fields, canonical supergravity (i.e. Wess and Bagger) is recovered.
  - A specific Weyl transformation is required:

$$g_{\mu\nu}(x) \to -\frac{3m_{\mathrm{P}}^2}{f} g_{\mu\nu}(x)\ .$$

- "But the Weyl compensator ϕ seems to have nothing to do with the Weyl transformation."
  - The Weyl compensator ϕ makes each term Weyl invariant.

1. Randall, Sundrum

What is the super-Weyl anomaly? (3)

- The Weyl compensator □ accompanies all mass scales in the lagrangian.
  - A general scale invariant superpotential is 100% Yukawa.

$$W = y_{ijk} Q_i Q_j Q_k$$

  - Redefine: $Q \Box \; Q\Box$
  - If any $<Q> \neq 0$, □ would be attached to it after the redefinition.
  - Even the cut off scale □ (i.e., Pauli-Villars regulators) get □ attached to it.
  - How? Through positing the PV mass to originate from a Higgs mechanism.
- From this, we can now see how to get soft masses.
  - For example, to generate gaugino masses:
  - Through 1-loop renormalization:

$$\Box(Q) ww \; \Box \; \left[\Box(Q) + 2b \ln(\Box\Box)\right] ww$$

  - Expanding superfield notation and Taylor expanding yields,

$$M_{\Box} = \frac{\Box_g}{g} \langle F \rangle \; .$$

- The scalar and trilinear soft masses are also produced by the same superfield and Taylor expansions.

1. Katz, Shadmi, Shirman
2. Randall, Sundrum

The pure AMSB spectrum (I)

- The MSSM with AMSB has parameters:

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

- The AMSB spectrum is RG invariant.

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

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

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

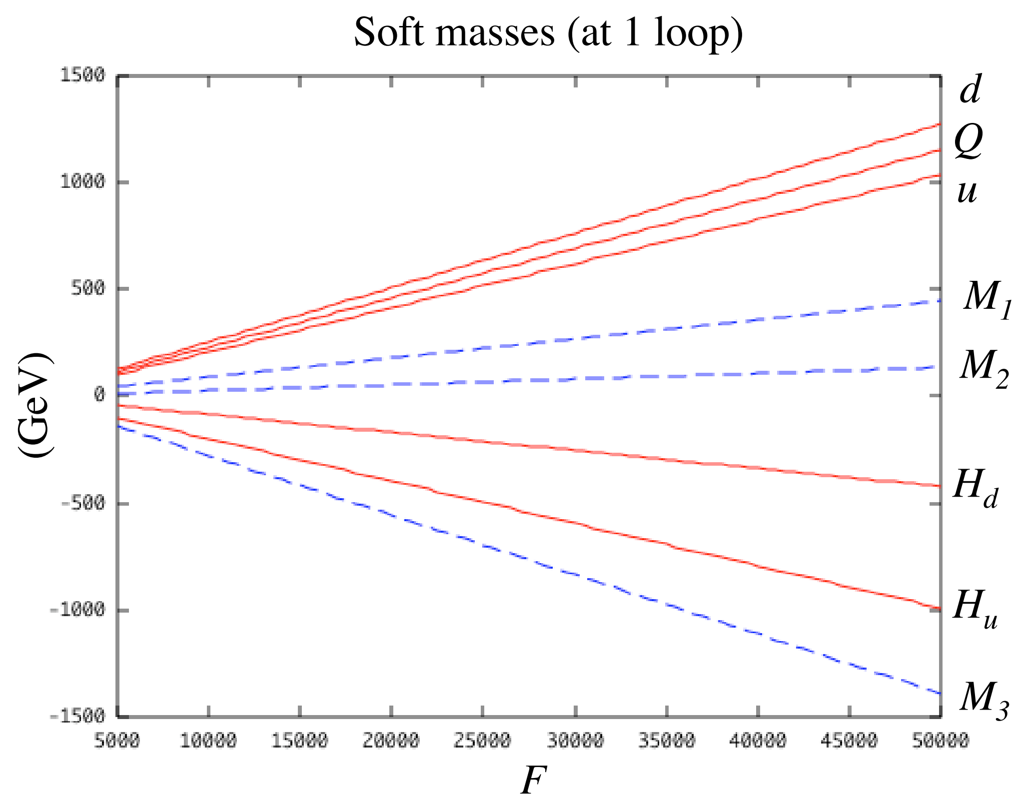
$$\left[\tilde{m} = \frac{\langle F \rangle}{16\pi^2}\right]$$

- For example:

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

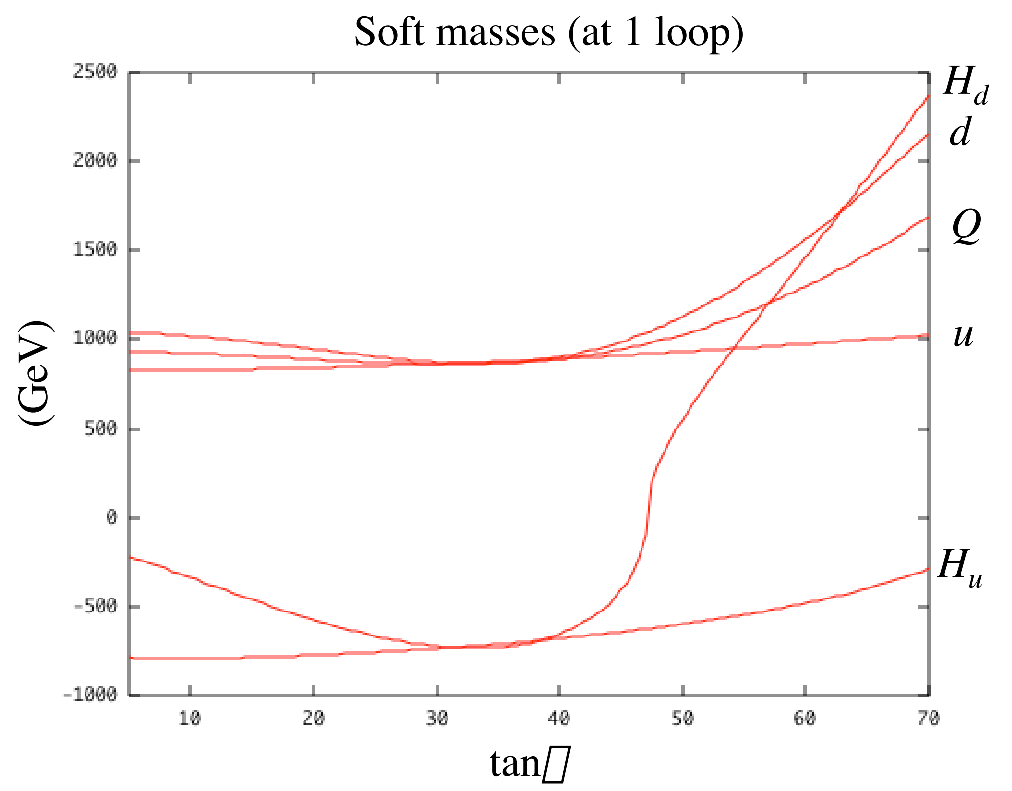
- 2 parameters.
- Valid at any scale the MSSM is valid.
- Predictive spectrum.
- Flavor diagonal soft masses.
- No explicit model building thus far.

The pure AMSB spectrum (2)



- Here, $\tan\beta = 10$ and $\mu < 0$.
- F controls the scale of the spectrum.
- F should be on the order 10 TeV.

The pure AMSB spectrum (3)



- Here, F = 40 TeV and $\mu < 0$.
- tanβ controls the qualitative features of the spectrum.
- M_1 = 358 GeV, M_2 = 108 GeV, and M_3 = -1,110 GeV

AMSB and thresholds

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

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

• 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 detectable

- The AMSB gaugino spectrum is distinct:

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

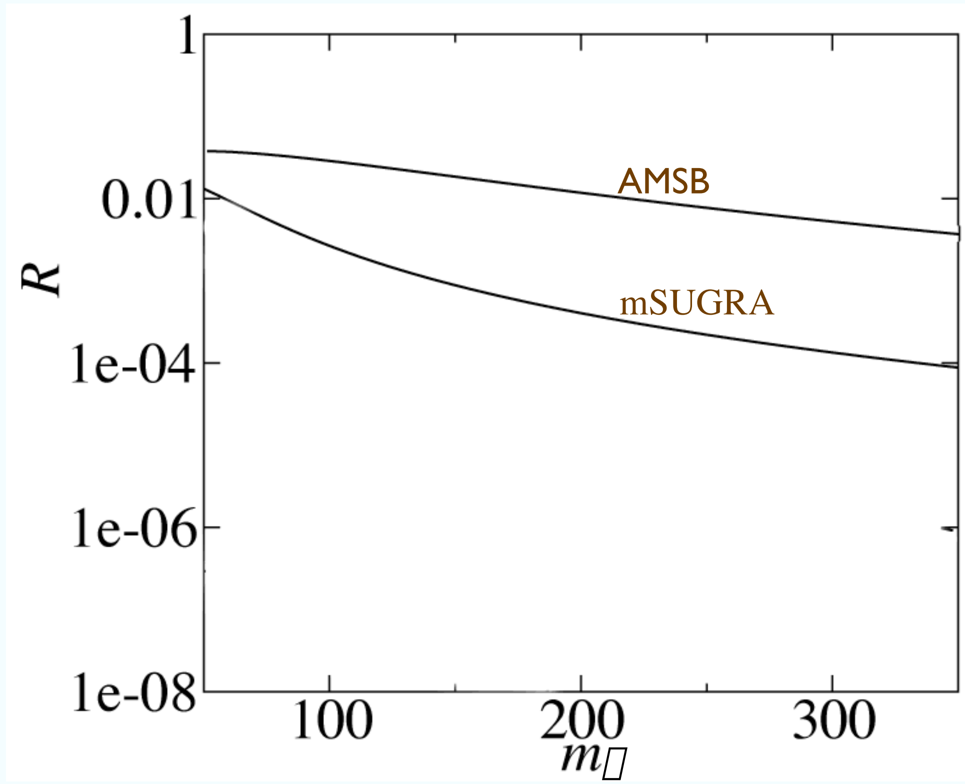
- …as opposed to mSUGRA:

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

- Wino LSP has great detection prospects as CDM
- The lightest chargino and neutralino are nearly degenerate.
- 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

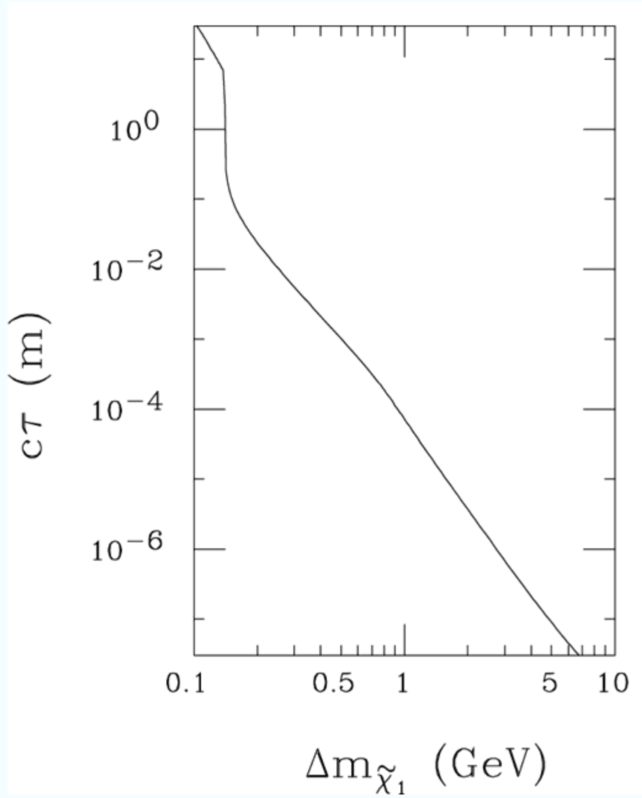
Elastic scattering of neutralinos on ^{73}Ge



- *R* is in events/day/kg.
- For mSUGRA: $M_1 = □/3$, $M_2 = 2□/3$, $\tan□ = 4$.
- For AMSB: $M_1 = 3□/2$, $M_2 = □/2$.
- In common: $\tan□ = 4$, $m_{squark} = 2$ 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 displacement at colliders.

I.Gunion, Mrenna

AMSB is sick

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

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

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

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

- Electromagnetism is broken.
- UV insensitivity makes slepton solutions tricky.
- If not for this, AMSB would probably the standard paradigm.

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

D-terms in supersymmetry

- The vector superfield consists of
  - a vector field,
  - a fermion (gaugino) field,
  - and a non-propagating auxiliary (scalar) field, called "*D*".
- By its e.o.m., $D = -g(\phi^* Q \phi)$.
- *D*-terms exist in all supersymmetric gauge theories. For *U*(1)'s,

$$L \supset -\frac{1}{2} g^2 \left(\sum_i q_i \phi_i^* \phi_i \right)^2 .$$

- If any of these scalars have a vev, mass is generated for all scalars. Typically,

$$m_\phi^2 = -q_i g \langle D \rangle \quad \to \quad \text{typically, } m_\phi^2 = q_i m_{\text{soft}}^2$$

- …simultaneously, the *U*(1) becomes a massive *Z*':

$$L \supset \left(D^\mu \phi \right)^+ \left(D_\mu \phi \right) \text{ where } D_\mu \phi = \left(\partial_\mu - i g q_i A_\mu \right) \phi$$

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

- 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 $U(1)$'s that:
  1. Preserve gauge unification.
  2. (Chiral) anomaly free.
- …also:
  - (MS)SM matter charged under the $U(1)$.
  - Generation independent charges.
  - Not broken by exotic scalars that alter the pure AMSB spectrum.
    - No Yukawa interactions with (MS)SM matter.
    - No communication with heavy friends.
- 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 $U(1)_a$:

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

- 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

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

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

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

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

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

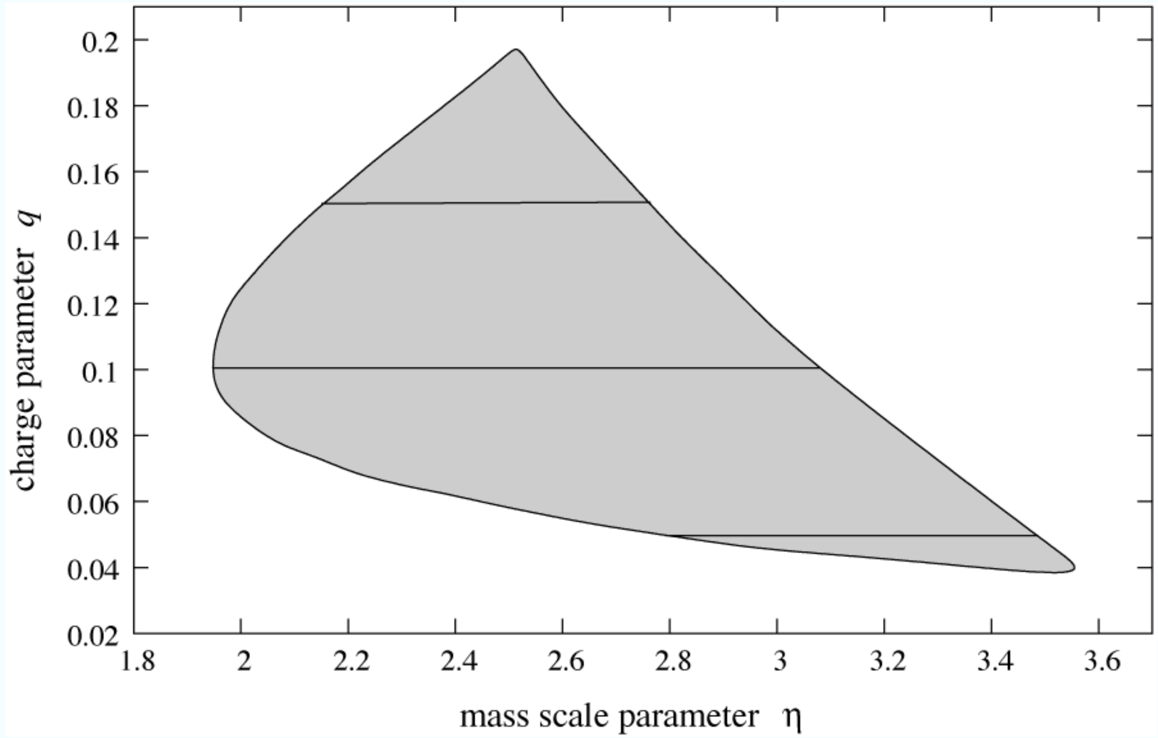
$$\left(m_d^D\right)^2 = (4q+1)\,\xi\,\tilde{m}^2$$

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

Achievements of the ancillary $U(1)$

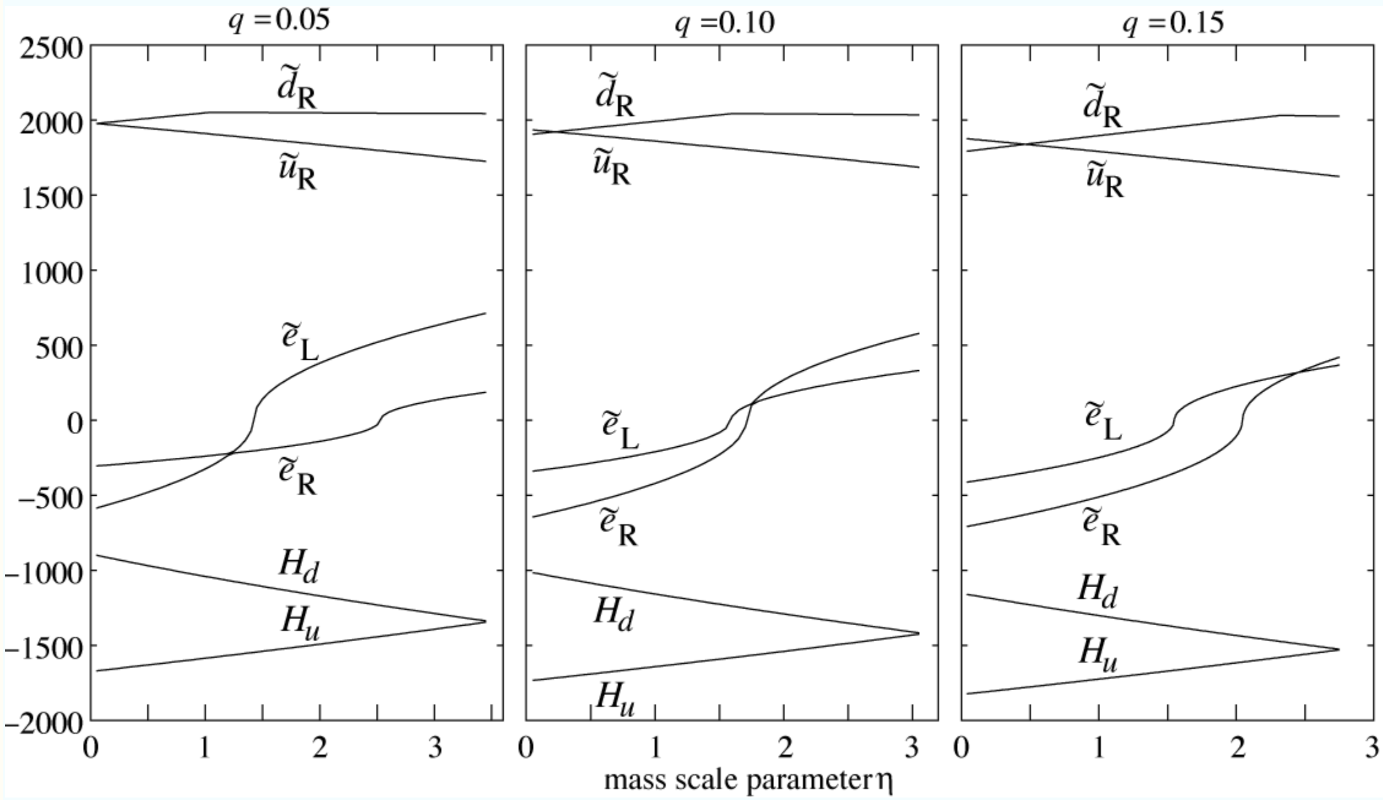
- We learn, this slepton solution necessitates:
  - *Q* soft mass must decrease.
  - *u* soft mass must decrease.
  - *d* soft mass must increase.
- Measuring a few soft masses, reveals the entire scalar spectrum (for the 1st and 2nd generations).
  - Say we know the soft scale from gauginos.
  - Measuring 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 $\mathrm{Tr}(YQ) = 0$.
  - *D*-term vevs established through Fayet-Iliopolous terms.

$$L \supset \xi D \Rightarrow \langle D \rangle = \xi$$

- Both yield viable sparticle spectrums.

1. Arkani-Hamed, Kaplan, Murayama, Nomura Harnik, Murayama, Pierce.
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:

$$Q_{H_u}^{a} D_{a} = (3q + r) D_{a}$$

$$= \left[3\left(\frac{\left(-\frac{1}{6}\right) D_Y + \left(-\frac{1}{3}\right) D_{B-L}}{(1) D_Y + (1) D_{B-L}}\right) + (1)\right]\left\{(1) D_Y + (1) D_{B-L}\right\}$$

$$= \tfrac{1}{2} D_Y + 0 D_{B-L}$$

Experimentally distinguishing scenarios

- No reasonable way to distinguish the *U*(1) choices via sparticle measurements alone.
  - The ancillary *U*(1) should have rational charges.
  - The *B*-*L* and J&J scenarios have irrational ancillary *U*(1) charges.
  - (Furthermore, kinetic mixing of the ancillary and hypercharge *U*(1)s yield irrational effective charges.)

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 the unique scalar spectrum of AMSB.

μ term concerns

Motivation
AMSB is fascinating
Origin
Soft masses
Thresholds
μ term
CP violation
AMSB is detectable
AMSB is sick
AMSB is curable
Conclusions

- All supersymmetric standard models must address the origin of the μ term.
- AMSB has relatively simple μ term solutions.
- For example, consider the effective operator

$$\mathcal{L} \supset \int d^4\theta \; c \, \frac{S + S^{+}}{m_{\mathrm{P}}} H_u H_d \Phi^{+}\Phi \; + \text{h.c.} \; .$$

- Also, the resulting bilinear soft term is

$$B = \frac{1}{2}\left(\gamma_{H_u} + \gamma_{H_d}\right)\langle F \rangle \; .$$

1.Randall, Sundrum

CP violation concerns

- Strong CP conerns:
  - CP violation constraints require that the trilinear and bilinear soft terms, A_i and B, be on order 1/100.
  - At the high scale, rotate away any phases for A_i and B.
  - The trilinear couplings then have no problem.
  - The phase of B is model-dependent, but the example μ term solution has no problem.
- ϵ_K concerns:
  - Also model dependent.
  - Possibly, there's nothing in the bulk to communicate CP violation from the hidden to visible sector.

1.Randall, Sundrum