

Title: Supersymmetric $U(1)'$ Models

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Abstract: Extension of the minimal supersymmetric standard model (MSSM) that include a $U(1)'$ gauge symmetry are motivated by top-down constructions and offer an elegant solution to the MSSM μ problem. In this talk I will describe some of the opportunities that such models offer, such as a new mechanism for mediation of supersymmetry breaking, as well as some of the challenges in constructing viable supersymmetric $U(1)'$ models.

Supersymmetric $U(1)'$ Models

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PRL **100** 041802 (2008) [arXiv:0710.1632]

PRD **77** 085033 (2008) [arXiv:0801.3693]

arXiv:0811.1196 [to appear in PLB]

Motivation

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- Mediation mechanism of **SUSY breaking** determines the low energy phenomenology

Reminder

- MSSM superpotential

$$W = y_u H_u Q u^c + y_d H_d Q d^c + y_e H_d L e^c + \mu H_u H_d$$

- Soft susy breaking Lagrangian (schematically)

$$\begin{aligned} \mathcal{L}_{\text{soft}} \ni & -\frac{1}{2} m^2 \phi \phi^\dagger && \text{(scalar masses)} \\ & -\frac{1}{2} M \tilde{\lambda} \tilde{\lambda} && \text{(gaugino masses)} \\ & -\frac{1}{6} A \phi_i \phi_j \phi_k && \text{(A terms)} \\ & -\frac{1}{2} b \phi_i \phi_j \\ & + h.c. \end{aligned}$$

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- Why should SUSY-conserving μ be related to SUSY-breaking m^2 and b ?

$$\text{Large } \tan \beta \text{ limit: } M_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \dots$$

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- $U(1)'$ models offer a solution

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$$W = y_u H_u Q u^c + y_d H_d Q d^c + y_e H_d L e^c + \lambda S H_u H_d$$

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- $\mu_{\text{eff}} = \lambda \langle S \rangle$ can be related to SUSY-breaking m^2 and b

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Outline

- Z' mediation - A new mediation mechanism of SUSY breaking
 - General features
 - Specific implementation

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- General issues with SUSY $U(1)'$ models
 - Accidental symmetries
 - Vacuum structure

Paul Langacker, GP, Itay Yavin arXiv:0811.1196 [to appear in PLB]

Z' Mediation of SUSY Breaking

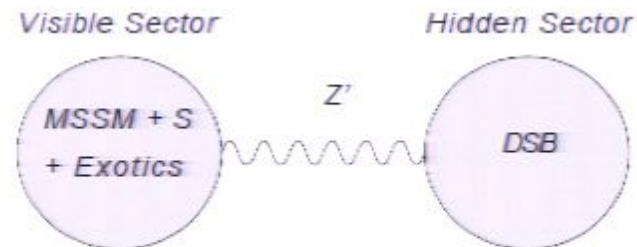
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Sectors

- No direct renormalizable interaction between visible and hidden sector fields
- **Both** are charged under $U(1)'$



- At Λ_S the Z' -ino becomes massive. For $X = M + \theta^2 F$

$$M_{\tilde{Z}'} \sim \frac{g_{z'}^2}{16\pi^2} \frac{F}{M}$$

- How are MSSM fields affected?

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Masses

- Gaugino $\tilde{\lambda}_i$ decouple when $g_i \rightarrow 0$

\Rightarrow To “feel” SUSY breaking all masses must be $\propto g_{z'}^2$

- Scalar masses

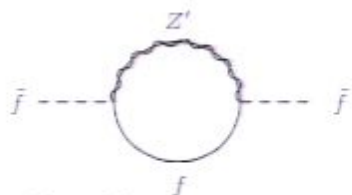
$$m_{\tilde{f}_i}^2 \propto g_{z'}^2$$

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos' masses must be also $\propto g_a^2$

$$M_a \propto g_{z'}^2 g_a^2$$

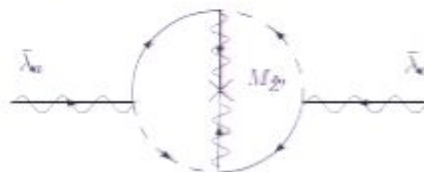
Masses

- Scalars get a mass at one loop



$$m_{\tilde{f}_i}^2 \sim \frac{g_{z'}^2 Q_{f_i}^2}{16\pi^2} M_{\tilde{Z}'}^2 \log \left(\frac{\Lambda_S}{M_{\tilde{Z}'}} \right)$$

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos get a mass at two loops



$$M_a \sim \frac{g_{z'}^2 g_a^2}{(16\pi^2)^2} M_{\tilde{Z}'} \log \left(\frac{\Lambda_S}{M_{\tilde{Z}'}} \right)$$

- Ratio of masses

$$\frac{m_{\tilde{f}_i}}{M_a} \sim \frac{M_{\tilde{Z}'}}{4\pi} \bigg/ \frac{M_{\tilde{Z}'}}{(4\pi)^4} = (4\pi)^3 \sim 1000$$

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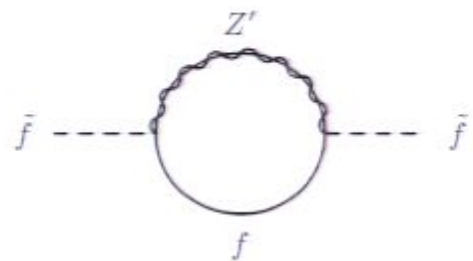
- LEP direct searches imply EW-ino mass > 100 GeV
 \Rightarrow heavy scalars ~ 100 TeV $\Rightarrow M_{\tilde{Z}'} \sim 1000$ TeV
- Mini version of split-susy (Arkani-Hamed & Dimopoulos 2004)
split susy scalar mass 10^9 GeV
- Like split-susy no flavor or CPV problems due to heavy scalars
- Like split-susy need one fine-tuning to set EW breaking scale
- Unlike split-susy μ parameter scale set by $U(1)'$ breaking

Elements of Z' mediation

- To break the $U(1)'$ symmetry introduce SM singlet field (charged under $U(1)'$)
- $\mu H_u H_d \rightarrow \lambda S H_u H_d \Rightarrow$ Large μ term
- Include exotic matter $\sum_i Y_i S X_i X_i^c$
 - Cancel anomalies associated with $U(1)'$
 - Drive S negative


Driving S negative

- Scalar mass RGE has contributions from various diagrams



A Feynman diagram representing a scalar mass correction. It consists of a central circle with a wavy top edge and a solid bottom edge. The top edge is labeled Z' and the bottom edge is labeled f . Two dashed lines, representing scalar fields, enter from the left and exit to the right, both labeled \bar{f} .

$$\Rightarrow \frac{dm_S^2}{dt} = -8g_{z'}^2 Q_S^2 M_{Z'}^2$$



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$$\Rightarrow \frac{dm_S^2}{dt} = 4\lambda^2 (m_S^2 + m_{H_u}^2 + m_{H_d}^2) + Y_i^2 (m_S^2 + m_{X_i}^2 + m_{X_i^c}^2)$$

- At $t = 0$ gauge term drives m_S positive

As t becomes more negative m_i grow and at some point m_S goes negative

Masses

- Ratio of masses

$$\frac{m_{\tilde{f}_i}}{M_a} \sim \frac{M_{\tilde{Z}'}}{4\pi} \bigg/ \frac{M_{\tilde{Z}'}}{(4\pi)^4} = (4\pi)^3 \sim 1000$$

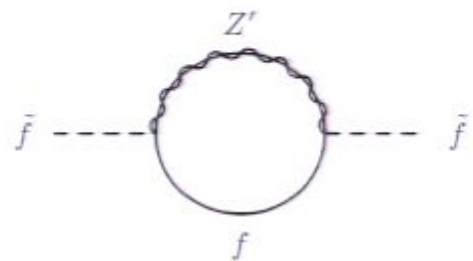
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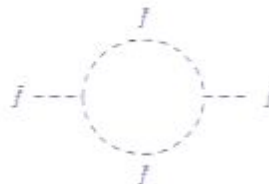
Driving S negative

- A term is also generated



$$\Rightarrow \frac{dA}{dt} = 4\lambda M_{\tilde{Z}'} g_{z'}^2 (Q_i^2 + Q_j^2 + Q_k^2)$$

- A term contribution to m_S RGE can be neglected



$$\Rightarrow \frac{dm_S^2}{dt} \propto A^2 \propto g_{z'}^4$$

- For $U(1)$ there is also



$$\Rightarrow \frac{dm_S^2}{dt} = 2g_{z'}^2 Q_S \text{Tr}(Q_j m_j^2)$$

Does not contribute

Higgs mass matrix

- Scalar S potential

$$V(S) = \underbrace{m_S^2 |S|^2}_{\text{Rad. Gen.}} + \underbrace{\frac{1}{2} g_{z'}^2 Q_S^2 |S|^4}_{D \text{ term}}$$

- VEV of S

$$\langle S \rangle = \left| \frac{m_S}{g_{z'} Q_S} \right|$$

- Higgs mass matrix

1) “ M ” terms: $m_{H_u}^2, m_{H_d}^2$ from RGEs

2) F terms: $\lambda^2 S^2 H_i^2 \Rightarrow \lambda^2 \langle S \rangle^2$

3) D terms: $\frac{1}{2} g_{z'}^2 (Q_2 H_u^2 + Q_1 H_d^2 + Q_S S^2)^2 \Rightarrow g_{z'}^2 \langle S \rangle^2 Q_S Q_i$

4) A terms: $A S H_u H_d \Rightarrow A \langle S \rangle H_u H_d$

Higgs mass matrix

- Higgs mass matrix

$$\mathcal{M}_H^2 = \begin{pmatrix} m_2^2 & -A_H \langle S \rangle \\ -A_H \langle S \rangle & m_1^2 \end{pmatrix}$$

$$m_2^2 = m_{H_u}^2 + g_z^2 Q_S Q_2 \langle S \rangle^2 + \lambda^2 \langle S \rangle^2$$

$$m_1^2 = m_{H_d}^2 + g_z^2 Q_S Q_1 \langle S \rangle^2 + \lambda^2 \langle S \rangle^2$$

- To generate Λ_{EW} must fine-tune linear combination of H_i to be much lighter than natural scale
- Typically find solutions by tuning $|m_2^2| \ll m_1^2 \sim g_z^2 M_{Z'}^2 / 16\pi^2$
- $\tan \beta \approx m_1^2 / A_H \langle S \rangle \sim 10 - 100$
- Get single SM-like Higgs scalar, with mass ~ 140 GeV.
- Remaining Higgs particles are at ~ 100 TeV

“Beyond MSSM” Masses

“Beyond MSSM” particles:

- Exotic superfield

$$W \ni \sum_i Y_i S X_i X_i^c$$

Exotic superfield mass: $Y_i \langle S \rangle \quad \checkmark$

- Z' superfield

- \tilde{Z}' gaugino: $M_{\tilde{Z}'} \quad \checkmark$
- Z' gauge boson $?$

- S superfield

- scalar $\langle S \rangle \quad \checkmark$
- fermion - Singlino - $\tilde{S} \quad ?$

Non-scalar masses

- As a result of S getting a VEV, Z' gauge boson gets a mass from $U(1)$ Higgs mechanism

$$M_{Z'} = \sqrt{2}g_{z'}|Q_S|\langle S \rangle$$

- The singlino \tilde{S} receives a mass via mixing with \tilde{Z}'

$$\mathcal{L} = -\sqrt{2}g_{z'}(S Q_S \tilde{S})\tilde{Z}'$$

Singlino Z' -ino mass matrix

$$\mathcal{M}_{SZ} = \begin{pmatrix} 0 & -\sqrt{2}g_{z'}Q_S\langle S \rangle \\ -\sqrt{2}g_{z'}Q_S\langle S \rangle & M_{\tilde{Z}'} \end{pmatrix}$$

Eigenvalues given by usual seesaw formula

$$\mathcal{M}_{SZ}^{(1)} = -\frac{M_{Z'}^2}{M_{\tilde{Z}'}} \quad \mathcal{M}_{SZ}^{(2)} = M_{\tilde{Z}'}$$

General features - Summary

- High energy spectrum $g_{z'} \sim \lambda \sim (0.1 - 1)$:

$$Z'\text{-ino mass } M_{\tilde{Z}'} \sim 1000 \text{ TeV}$$

$$\text{Typical scalar mass } m_{\tilde{f}_i} \sim 100 \text{ TeV}$$

$$\langle S \rangle \sim M_{\tilde{Z}'} / 4\pi \sim 100 \text{ TeV}$$

$$\mu = \lambda \langle S \rangle \sim 10 - 100 \text{ TeV}$$

$$\text{Exotic superfield mass } Y_i \langle S \rangle \sim 10 - 100 \text{ TeV}$$

$$M_{Z'} = \sqrt{2} g_{z'} Q_S \langle S \rangle \sim 10 - 100 \text{ TeV}$$

$$M_{\tilde{S}} = \frac{M_{Z'}}{M_{\tilde{Z}'}} M_{Z'} \sim 1 - 10 \text{ TeV}$$

- Low energy spectrum

$$\text{SM} + \text{Higgs} + SU(3)_C \times SU(2)_L \times U(1)_Y \text{ gauginos}$$

General features - Summary

- Interesting case for $g_{z'} \ll \lambda$

$$|M_{H_u}|^2 \sim \frac{g_{z'}^2 M_{\tilde{Z}'}^2}{16 \pi^2} \text{ tuned against } \lambda^2 \langle S \rangle^2$$

$$\Rightarrow \langle S \rangle \sim \frac{g_{z'}}{\lambda} \frac{M_{\tilde{Z}'}}{4\pi}$$

$$M_{\tilde{S}} \sim \frac{g_{z'}^2 Q_S^2 \langle S \rangle^2}{M_{\tilde{Z}'}} \sim g_{z'}^2 \frac{g_{z'}^2}{16 \pi^2} M_{\tilde{Z}'}$$

– Very light singlino $M_{\tilde{S}} \sim (10^{-3} - 10^{-5}) M_{\tilde{Z}'}$

– Z' gauge-boson, $M_{Z'} \sim g_{z'} Q_S \langle S \rangle$, in this case can be light enough to be produced @ LHC

- Low energy spectrum

SM + Higgs + $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauginos +

+ Singlino and even Z'

Specific Models

- The free parameters are: $g_{z'}$, λ , Y_i , $U(1)'$ charges, $M_{\tilde{Z}'}$, and SUSY breaking scale Λ_S
- Minimal choice (leads to a light wino, $M_2 < M_{1,3}$):
 - 3 families of colored exotics (D)
 - 2 families of uncolored $SU(2)_L$ singlet families (E)

both have $U(1)_Y$ charge

- Superpotential

$$W = \lambda S H_u H_d + y_D S D D^c + y_E S E E^c + \text{quark} + \text{lepton}$$

- Taking $Q_1 = 1$, Q_2 and Q_Q are free parameters
(other charges are determined by anomalies)
- Other constraints
 - $U(1)'$ spontaneously broken by radiative corrections
 - Allow appropriate fine tuning to break EW symmetry
 - Check for color or charge breaking minima

RGE running

- Very different scales

Ideal approach: integrate out different fields at each scale

Highly non trivial task

e.g integrate out heaviest particle \tilde{Z}'

\Rightarrow different RGEs for Yukawas and quartic couplings (“SUSY breaking”)

- Simplified treatment: integrate out heavy scalars and \tilde{Z}' at the same scale

disadvantage: multiple RGE threshold corrections

Two regions $M_{\tilde{Z}'} < \mu < \Lambda_S$ and $\mu < M_{\tilde{Z}'}$

RGE running

- $M_{\tilde{Z}'} < \mu < \Lambda_S$: use usual soft SUSY RGEs
one loop RGEs for: gauge and Yukawas, $M_{\tilde{Z}'}$, and $m_{\tilde{f}_i}$, and A terms
two loop RGEs for gaugino masses
- $\mu < M_{\tilde{Z}'}$: SM + Higgs + gauginos
one loop RGEs: SM Higgs and quartic, Yukawas, gauge and gaugino mass
+ Threshold corrections e.g.

$$m_H^2(\mu \approx m_{\tilde{f}_i}) = \min(\mathcal{M}_H^2) - \frac{3Y_t^2}{16\pi^2} m_{\tilde{f}_i}^2$$

Five Benchmark Models

All mass units are GeV $M_{\bar{Z}'}$ fixed at 1000 TeV

	1	2	3	4	5
Q_2	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	$-\frac{1}{2}$
Q_Q	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-2	-2
$g_{z'}$	0.45	0.23	0.23	0.06	0.04
λ	0.5	0.8	0.8	0.3	0.3
Y_D	0.6	0.7	0.8	0.4	0.6
Y_E	0.6	0.6	0.6	0.1	0.1
$\langle S \rangle$	2×10^5	7×10^4	6×10^4	2×10^5	8×10^4
$\tan \beta$	20	29	33	45	60
M_1	2700	735	650	760	270
M_2	710	195	180	340	123
M_3	4300	1200	1100	540	200
m_H	140	140	140	140	140
$m_{\bar{Q}_3}$	1×10^5	5×10^4	4×10^4	8×10^4	4×10^4
$m_{\bar{L}_3}$	3×10^5	10^5	10^5	2×10^4	10^5
$m_{3/2}$	890	3600	810	3	0.1
$m_{\bar{S}}$	4300	230	160	31	4
$m_{Z'}$	7×10^4	1.5×10^4	1.3×10^4	5600	2100

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Gauge Unification?

- $U(1)'$ symmetry \Rightarrow new anomaly cancellation condition

\Downarrow

Introduce new “exotic” matter

- X_i charged under SM and $U(1)'$
- SM singlet(s) S_i give mass to X_i : $SX_iX_i^c \in W$
- Problem: Typically exotics spoil MSSM unification
- Solutions:
 - Give up unification
 - Embed $G_{\text{SM}} \times U(1)'$ inside a larger group such as E_6
 \Rightarrow need extra “Higgses” that reintroduce μ problem
[Langacker and J. Wang '98]
 - Add complete $SU(5)$ multiplets of exotic matter

SM Singlets

- Adding complete $SU(5)$ multiplets of exotic matter



Must introduce more than one singlet field

[Erler '00, Morrissey and Welsh '05]

- Singlet fields should:
 1. Break $U(1)'$ symmetry
 2. Generate effective μ term for H_u and H_d
 3. Give mass to exotic matter

Generic Problems with Multiple Singlets

- $U(1)'$ + gauge unification \Rightarrow Multiple singlet fields
- Problem 1: Accidental global symmetries:
Once broken lead to axion-like bosons
- Problem 2: Generating required vacuum structure:
Exotics might remain massless

Accidental Global Symmetries

- Consider only D-terms and soft masses in scalar potential

$$V(S_1, \dots, S_N) = \sum_i m_i^2 |S_i|^2 + \frac{g_{z'}^2}{2} \left(\sum_i Q_i |S_i|^2 \right)^2.$$

- N scalar fields \Rightarrow N phases

one linear combination “eaten” by Z' gauge boson

$\Rightarrow N - 1$ “accidental” global symmetries

If all spontaneously broken, get $N - 1$ massless Nambu-Goldstone bosons

- Global symmetries anomalous under G_{SM}

\Rightarrow one linear combination is an axion with mass Λ_{QCD}^2/f

Other bosons are massless **excluded!**

- Even axion problematic: For $f \sim 100$ TeV, mass ~ 100 eV

Experimental constraint: Axion mass should be ≤ 10 meV

Breaking the Accidental Global Symmetries

- Only way out, explicitly break the $N - 1$ global symmetries
Need $N - 1$ linearly independent terms in the superpotential
- Ideally use only cubic terms: $S_i S_j S_k, S_i^2 S_j \in W$
unlike bilinear terms $\mu S_i S_j \in W$ do not require mass scale μ
- Can we use only cubic terms?

Interlude:

Linear Equations over Finite Algebraic Field

- Given k singlets with $U(1)'$ charges $Q_1 \dots Q_k$
 find l singlet fields with charges $Q_{k+1} \dots Q_{k+l}$ $N = k + l$
 such that $Q_1 \dots Q_{k+l}$ are the solution on $k + l - 1$ linear equations
 $S_i S_j S_m \Rightarrow Q_i + Q_j + Q_m = 0$ or $S_i^2 S_j \Rightarrow 2Q_i + Q_j = 0$

- In matrix form:

$$\begin{pmatrix} 1 & 1 & 1 & 0 & \dots & 0 \\ 2 & 1 & 0 & 0 & \dots & 0 \\ \cdot & & & & & \\ \cdot & & & & & \\ \cdot & & & & & \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} Q_1 \\ Q_2 \\ \cdot \\ \cdot \\ \cdot \\ Q_N \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \end{pmatrix}$$

- Consider equations over \mathbb{F}_3 , Algebraic field with 3 elements: $\{0, 1, 2\}$
 or $Q_i \rightarrow Q_i \bmod 3$

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Linear Equations over Finite Algebraic Field

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Linear Equations over Finite Algebraic Field

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NO!

- μ problem: have μ in $\mu H_u H_d \in W$ at the same scale
as the soft parameters $(b, m_{H_u}^2, m_{H_d}^2)$
- Here not using μ term to generate vacuum structure
Need μ to give mass larger than MeV
- Term can arise from Giudice-Masiero mechanism $\mu \sim F/M_P$

Example: Erler's Model

- MSSM + Exotics: two pairs of $\mathbf{5} + \mathbf{5}^*$: (D_i, L_i) and (D_i^c, L_i^c) , $i = 1, 2$
need two singlets: S, S_D with charges $Q_S = 1$ $Q_{S_D} = 3/2$

S generates μ term and give mass to L, L_c , S_D give mass to D, D^c

- Using only cubic terms requires 4 extra singlets

The superpotential terms are:

$$S_1 S_1 S_2, S_2 S_3 S_D, S_1 S_4 S_D, S S_3 S_3, S S S_4$$

- With bilinears can do with only 2 extra singlets

$$\mu S S_1 + y_1 S_1 S_2 S_D + y_2 S S_2 S_2 \in W$$

New singlets' charges $Q_{S_1} = -1$ $Q_{S_2} = -1/2$

Generating required vacuum structure

- Need to give vacuum expectation value (vev) to multiple scalars. How?
- No “rigorous” proofs but the big picture is:
- Easier to analyze by ignoring F terms for now

$$V(S_1, \dots, S_N) = \sum_i m_i^2 |S_i|^2 + \frac{g_{z'}^2}{2} \left(\sum_i Q_i |S_i|^2 \right)^2.$$

- Reasonable to assume some m_i^2 are driven negative by RGEs
- Consider two cases
 1. Only one fields develop a vev
 2. “Flat” direction
- First case:
 - If for only one field $m_i^2 < 0$, it will develop a vev
 - If multiple fields have $m_i^2 < 0$,
only the field with largest $|m_i^2/Q_i|$ develop a vev

“Flat” direction

- Assume that for two fields with opposite charges S_i and S_j
 $|Q_j|m_i^2 + |Q_i|m_j^2 < 0$
 \Rightarrow “runaway” direction: $V \rightarrow -\infty$, for $|Q_i||S_i|^2 = |Q_j||S_j|^2 \rightarrow \infty$
- Adding F terms stabilize the vevs at finite values
 \Rightarrow Generate vevs for S_i and S_j
- After “vacuum insertion” A terms can generate linear terms in the potential for other fields: $A |S_i| |S_j| S_m \in V$
 \Rightarrow generate vev for S_m
- This case is phenomenologically favorable

Example: Erler's Model

- Recall superpotential

$$\mu S S_1 + y_1 S_1 S_2 S_D + y_2 S S_2 S_2 \in W$$

and charges: $Q_{S_1} = -1$ $Q_{S_2} = -1/2$ $Q_S = 1$ $Q_{S_D} = 3/2$

- We need S and S_D to develop a vev

For simplicity ignore μ term and assume $y_1 \ll y_2, g_{z'}$

Scalar potential ("turning off" A terms)

$$V(S, S_D, S_1, S_2) = \sum_i m_i^2 |S_i|^2 + \frac{g_{z'}^2}{2} \left(\sum_i Q_i |S_i|^2 \right)^2 + |y_2|^2 |S_2|^4$$

- Flat direction for S_2 and S_D , assume

$$|Q_{S_1}| m_{S_D}^2 + |Q_{S_D}| m_{S_1}^2 > 0 \text{ and } |Q_{S_2}| m_{S_D}^2 + |Q_{S_D}| m_{S_2}^2 < 0$$

- The vevs are

$$|S_D|^2 = -\frac{4}{9} \frac{m_{S_D}^2}{g_{z'}^2} - \frac{1}{18y_2^2} (3m_{S_2}^2 + m_{S_D}^2) \quad |S_2|^2 = -\frac{1}{6y_2^2} (3m_{S_2}^2 + m_{S_D}^2)$$

Notice $|S_i| \propto 1/y_2^2$ remnant of the flat direction

Example: Erler's Model

- S_2 and S_D have vevs
- Recall superpotential

$$\mu S S_1 + y_1 S_1 S_2 S_D + y_2 S S_2 S_2 \in W$$

- “Turn on” A term for $S S_2 S_2$
linear term for S : $A S |S_2|^2 \in V$
 \Rightarrow generate vev for S
- Final result: both S and S_D have vevs \checkmark

Future Directions

- Other Z' mediation models
 - Models with gauge unification?
 - Implement Erler's model [In progress]
 - Models with wino/bino LSP?
- Combine with other mediation mechanisms
 - e.g. anomaly mediation [In progress]
- Incorporate in other top-down models
- Models of the hidden sector

Conclusions

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New mechanism for mediation of SUSY breaking
via a $U(1)'$ gauge interaction
- Specific implementation
 - heavy sfermions, Higgsinos, exotics $\sim 10 - 100$ TeV
 - Light gauginos $\sim 100 - 1000$ GeV, of which the lightest can be wino-like and a light Higgs ~ 140 GeV

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- $U(1)'$ + gauge unification \Rightarrow Multiple singlet fields
Generic problems:
- accidental symmetries \Rightarrow light bosons
 - Solution: explicitly breaking via SP terms
Cubic might not be feasible, bilinears ok
- Vacuum structure: multiple scalar vevs
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- More work to be done!