Low scale direct gauge mediation

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Outline

SUSY breaking and gauge mediation

TeV scale SUSY is provides an attractive solution of the hierarchy problems.
Specific models and mechanisms need to address several crucial issues

- Origin of the hierarchy, *i.e.* $M_{\text{SUSY}} \ll M_{\text{Pl}}$ (DSB + GMSB)
- SUSY breaking mechanism (GMSB)
- Absence of new FCNC (GMSB)
- Origin of μ term
- Little hierarchy problem

DSB and the gauge hierarchy

If SUSY unbroken at tree level

- Unbroken to all orders in perturbation theory
- Can be broken by non-perturbative effects
- SUSY breaking condensate $\Lambda = M_{\text{Pl}} \text{exp}(-8\pi^2 b/g^2) \ll M_{\text{Pl}}$
- Dynamical SUSY breaking can naturally explain origin of the hierarchy

But:

- DSB models are hard to find
- Strict conditions:
  - Non-zero Witten index
  - Need chiral models (some exceptions: ITIY models)
  - Need $U(1)_R$ symmetry or non-generic potential
- Many potentially interesting DSB models are non-calculable
- Calculable models typically have several scales and introduce scale hierarchies.

$$100\text{TeV} \ll M_{\text{SUSY}} \ll M_{\text{Pl}}$$

GMSB models

DSB is parameterized by spurion $S =< S > +\Theta^2 F$
Vector-like 4th generation interacts with the spurion and learns about SUSY breaking at tree level.

$$W = SQ\bar{Q}$$

Messenger fermion mass $< S >$
Messenger scalar masses $< S >^2 \pm F$
For $F \ll 10^{11} GeV$, Planck suppressed interactions are negligible and SM fields learn about SUSY breaking only through gauge interactions with massengers.
Superpartner masses

$$m_{\lambda_i} \sim \frac{\alpha_i}{4\pi} \frac{F}{M} \qquad m^2 \sim \sum_i \left(\frac{\alpha_i}{4\pi}\right)^2 \frac{F^2}{M^2}$$

Summary of GMSB

Advantages

- Automatic suppression of FCNC
- Do not need to invoke quantum gravity effects
- Low scale of SUSY breaking and messenger masses
- SUSY breaking sector can be potentially observable

Difficulties

- Complicated multi-sector models
- Low SUSY breaking scale hard to achieve
- μ-problem is more serious than in SUGRA
- Little hierarchy problem

Goal: Calculable model of very direct gauge mediation with low SUSY breaking scale, $F \sim 100$ TeV

ISS models

- Generically coupling between DSB sector and messengers

$$W = SQ\bar{Q}$$

  restores SUSY
- Some direct mediation models give up global SUSY breaking
  - allow runaway direction
  - calculable local minimum at large fields in orthogonal direction
- Acceptable if tunneling rate is small enough

Intriligator-Seiberg-Shih proposal:

- Give up on requirement of global SUSY breaking minimum
- Local SUSY breaking minima are generic
- Calculable SUSY breaking minima without scale hierarchies are generic

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Strategy to obtain calculable models:

- Use exact results in SUSY QCD: duality between different SUSY QCD theories with the same global symmetries
- IR free theory can be dual to asymptotically free one
- Start with O'Rafeartaigh model – calculable but not asymptotically free
- Find UV description of the O'Rafeartaigh model
  - SUSY restored by non-perturbative effects at large field values
- Verify that tunneling rate is small

O'Rafeartaigh model with $SU(N) \times SU(F)$ global symmetry

	$SU(N)$	$SU(F)$	$U(1)_R$
$\tilde{\phi}$	$\overline{\square}$	$\square$	0
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$\widetilde{M}$	1	$\mathbf{Ad} + \mathbf{1}$	2

,

$$W = \widetilde{M}_{ij} \tilde{\phi}^{ia} \tilde{\tilde{\phi}}^{j}_{a} + h f^2 Tr \widetilde{M}$$

F-term conditions for $\widetilde{M}$:

$$h f^2 \delta_{ij} + \tilde{\phi}^a_i \tilde{\tilde{\phi}}_{aj} = 0$$

$(\tilde{\phi}\tilde{\tilde{\phi}})_{ij}$ matrix has maximal rank $min(N, F)$.
SUSY is broken for $N < F$.

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Features of the model

- O'Rafeartaigh model – requires explicit mass scales etc.
- Massless fields at the minimum: Goldstones and pseudo-flat directions. E.g. $Tr\widetilde{M}$.
- Massless fields stabilized near the origin due to CW potential

$$V_{eff}^{(1)} \sim \frac{\log 4 - 1}{8\pi^2}(F - N)|Tr\widetilde{M}|^2 + \dots$$

- Accidental R-symmetry at the minimum of the potential
- Symmetry broken to $SU(N) \times SU(F - N) \times U(1)_R$
- Weakly gauging $SU(N)$ preserves SUSY breaking

- Tree level superpotential corresponds to magnetic description of $SU(N+F)$ SUSY QCD with F flavors and masses

$$hf^2 = m\Lambda_e$$

ϕ & $\bar{\phi}$ — dual quarks, $\widetilde{M}$ — mesons of electric description

- For $F > 3N$, magnetic description is weakly coupled in IR. Preceding analysis of metastable vacuum remains reliable.
- Global SUSY preserving vacuum exists
  - For large $\widetilde{M}$, low energy theory is pure SYM with the superpotential

$$W = N(\Lambda_m^{-(F-3N)} \det \widetilde{M})^{1/N}$$

- For $N = 1$ the electric dual is an s-confining SQCD
- Dual quarks ϕ, $\bar{\phi}$ are baryons of electric theory
- Non-perturbative superpotential

$$W = \frac{\tilde{\phi}\widetilde{M}\tilde{\bar{\phi}} - \det \widetilde{M}}{\Lambda^{2N-3}}$$

restores supersymmetry

Aside:
For $N = 0$ theory (quantum modified moduli space in electric description) ISS conjectured existence of local SUSY breaking minimum. While some evidence for such a minimum exists, dynamics is non-calculable.

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The Model

Embed SM into unbroken subgroup of the flavor symmetry of DSB sector. Need $F \geq 6$.
Electric theory: $SU(5) \times SU(6)_F$, $SU(5)_{SM} \subset SU(6)_F$.
Magnetic theory

	$SU(6)$	$U(1)$	$U(1)_R$
$\tilde{\phi}$	$\square$	1	0
$\tilde{\bar{\phi}}$	$\bar{\square}$	1	0
$\widetilde{M}$	$\mathbf{Ad}+\mathbf{1}$	0	2

$\tilde{\phi}, \tilde{\bar{\phi}}$ are baryons
M is usual meson

Under $SU(5)_{\rm SM}$:

$$\widetilde{M} = \begin{pmatrix} M_i^j & N^j \\ \bar{N}_i & X \end{pmatrix}, \quad \tilde{\phi} = (\phi, \psi), \quad \tilde{\bar{\phi}} = (\bar{\phi}, \bar{\psi})$$

$$M = \mathbf{Ad}+\mathbf{1},\ \phi = \square,\ \bar{\phi} = \bar{\square},\ N = \square,\ \bar{N} = \bar{\square},$$

$$X = 1,\ \psi = 1,\ \bar{\psi} = 1\ .$$

$$W = \bar{\phi} M \phi + \bar{\psi} X \psi + \bar{\phi} N \psi + \bar{\psi} \bar{N} \phi - h f^2 \left(\mathrm{Tr} \tilde{M} + X \right) \ .$$

At the minimum: $F_{\mathrm{Tr}M} \neq \sqrt{5} h f^2, \quad \langle \psi \rangle \neq 0$

Both M and $\bar{\phi},\ \phi$ (with $N, \bar{N}$) are potential messengers

Messenger spectrum:

- $\psi,\ N$ fermions have mass f
- $\psi,\ N$ scalars have masses squareds 0 and f^2 ($F_{\mathrm{Tr}M} = 0$)
- Scalars and fermions in M massless at tree level
- M scalars obtain mass at one loop from CW potential
- M fermions remain massless as long as R symmetry unbroken at the minimum

Gauginos massless if R-symmetry unbroken

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Solution: Need vev for M

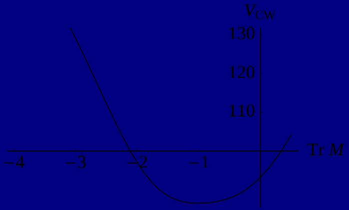
- From singlet dynamics

$$W_2 = m'(S\bar{Z} + Z\bar{S}) + (d\mathrm{Tr}M + m)S\bar{S}$$

  - $S,\ \bar{S}$ and $Z,\ \bar{Z}$ at the origin due to mass term
  - $\mathrm{Tr}MS\bar{S}$ coupling generates CW potential for $S,\ \bar{S}$

$$\frac{1}{64\pi^2} STr\mathcal{M}^4 \log\frac{\mathcal{M}^2}{\Lambda^2}$$

  - For small d: $\langle M\rangle \sim dm$



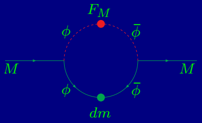
- From gauge dynamics (like Dine, Mason)

Fermion masses

Fermion messenger matrix

$$m_f = \begin{pmatrix} < M > & < \psi > \\ < \psi > & 0 \end{pmatrix}$$

Diagram for gaugino and M-fermion masses



- Leading order gaugino mass $m_\lambda \sim \text{Tr}(m_f^{-1}\mathcal{F}) = 0$
- Gaugino masses starts at order $\mathcal{O}(F^3/m_f^5)$
- Scalar masses $\mathcal{O}(F^2/m_f^2)$
- NEED $F \sim m_f^2$

Origin of scales

Electric theory determines natural values of couplings:

$$h \sim \frac{\Lambda}{\Lambda_{UV}}, \quad d \sim \frac{\Lambda}{\Lambda_{UV}} .$$

Generate SUSY breaking scale dynamically through supercolor sector: $SU(2)$ with 2 flavors, $p, \bar{p}$.

$$f^2(\mathrm{Tr}M + X) \;\to\; \frac{\det(p\bar{p})}{\Lambda'^2_{UV}}(TrM + X) \;\to\; \frac{1}{\Lambda^4_{UV}} \det(p\bar{p})(q_e \bar{q}_e)$$

Force $\det(p\bar{p}) = \Lambda^4_{sc}$

$$hf^2 = h\frac{\Lambda^4_{sc}}{\Lambda^2_{UV}} = \frac{\Lambda^4_{sc}\Lambda}{\Lambda^3_{UV}}$$

Need $m < \Lambda$ and $hf^2 \sim 100\text{TeV}$
Example:

$$\Lambda \sim \Lambda_{sc} \sim 10^{11} - 10^{12}, \quad m \sim 0.1\Lambda, \quad \Lambda_{UV} \sim 10^{16}$$

While all scales large, SUSY breaking scale f can be small with mass splittings in messenger multiplet of order 1.

Sparticle spectrum

- Leading contribution to spartner masses comes from $\phi, \bar{\phi}$ messengers
- Splittings in the supermultiplet are large; mixing with $N, \bar{N}$ modifies the usual result; calculation is needed.
- Component fields in M obtain masses at one loop and from gauge mediation. Contributions to spartner masses subleading.
- Additional fermion scalars at the scale of SM superpartners

Sparticle spectrum

Higgs sector

$$W_\mu = \beta \frac{p^2 \bar{p}^2}{\Lambda_{UV}^3} H_u H_d \,, \quad \mu \sim \beta f$$

After confinement of supercolor

$$\mu \sim \beta f \left(\frac{\Lambda_{sc}}{\Lambda_{\rm UV}} \right)^2 \sim \beta h^{1/2} f \frac{\Lambda_{sc}^2}{\Lambda_{\rm UV}^{3/2} \Lambda^{1/2}}$$

No B-term at tree level.
Small B-term is generated at two loop order

$$B_\mu \sim \frac{3\alpha_2}{2\pi} M_2 \mu \ln \frac{h f^2}{M_2 \mu} \sim \beta(100\text{TeV}) \left(\frac{\Lambda_{sc}}{\Lambda_{\rm UV}} \right)^{3/2}$$

Large $\tan\beta \sim 10 - 50$

Recent work on ISS models

- Kitano, Ooguri, Ookuchi
  - Close to us in spirit: very direct gauge mediation
  - Different mechanism for generation of fermion masses
  - Possibility to avoid Landau pole
  - Low SUSY breaking scale more difficult to achieve
- Dine, Feng, Silverstein and Dine, Mason
  - Tools to construct natural gauge mediation models in metastable vacua
  - Most general superpotential, all scales dynamical
  - Phenomenologically: more conventional GMSB
- Murayama, Nomura (twice)
  - Use ISS for DSB, but messengers not part of DSB sector
- Aharony, Seiberg
  - ISS type model in DSB sector and dynamics like Dine, Mason to break R-symmetry, generate gaugino masses.

Conclusions

- Combination of DSB and GM is very attractive
  - Explains $M_{\mathsf{SUSY}} \ll M_{\mathsf{Pl}}$
  - Suppresses FCNC
  - Possibility of observable SUSY breaking sector
- Metastable DSB (ISS) opens new possiblilities
  - Calculable low scale direct gauge mediation
  - Messengers directly participate in DSB dynamics ("no messenger models")
  - Messengers composites of DSB
  - Many new light particles, potential for interesting signatures
  - Improved situation with μ-term, further improvements possible
- Many other ISS inspired models proposed recently
- Further work on spartcile spectrum and phenomenological signatures/implications in progress