Low scale direct gauge mediation

Yuri Shirman

with C. Csaki and J. Terning

Eötvös-Cornell Summer Workshop, 2007

SUSY breaking and gauge mediation

TeV scale SUSY is an attractive solution of the gauge hierarchy problem.

Specific models and mechanisms need to address several crucial issues

- Origin of the hierarchy, *i.e.* $M_{\not{\text{SUSY}}} \ll M_{\text{Pl}}$
- ~~SUSY~~ mechanism in MSSM sector
- Absence of new FCNC
- Origin of μ term
- Little hierarchy problem

Dynamical ~~SUSY~~ and gauge mediation successfully address several of these problems

GMSB models

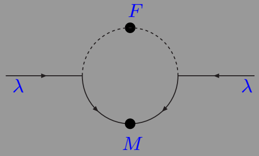
- ~~SUSY~~ is parameterized by spurion $S = M + \theta^2 F$
- Vector-like 4th generation interacts with the spurion and learns about ~~SUSY~~ at tree level.

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

- Messenger fermion mass M
  Messenger scalar masses $M^2 \pm F$
- For $\sqrt{F} \ll 10^{11} GeV$, Planck suppressed interactions are negligible and SM fields learn about ~~SUSY~~ only through gauge interactions with messengers.

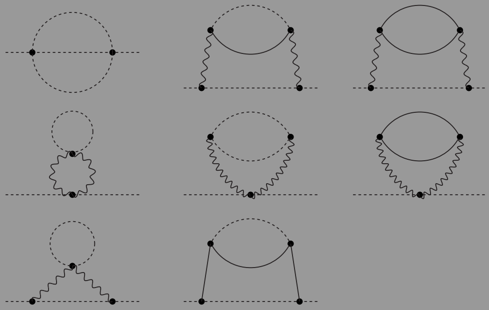
GMSB models

Gaugino masses



$$m_{\lambda_i} \sim \frac{\alpha_i}{4\pi} \frac{F}{M}$$

Scalar masses^2



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

Problems

- Gauge mediation:
  - Complicated multi-sector models
  - Low ~~SUSY~~ scale hard to achieve
- DSB
  - DSB models are hard to find
  - Strategy in the search for DSB models:
    - Need Witten index $(-1)^F = 0$ – chiral theories only
    - No classical flat directions
    - Spontaneously broken $U(1)_R$ symmetry
    - *Some exceptions – ITIY models*
  - Many potentially interesting DSB models are non-calculable
  - Calculable models typically have several scales relevant for low energy physics and introduce scale hierarchies.

ISS proposal

- Generically coupling between DSB sector and messengers

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

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

Intriligator-Seiberg-Shih proposal:

- Accept metastability from the start
- Calculable *metastable* ~~SUSY~~ minima without scale hierarchies are generic

ISS proposal

- Generically coupling between DSB sector and messengers

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

restores SUSY. ~~SUSY~~ vacuum is only metastable

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

Intriligator-Seiberg-Shih proposal:

- Accept metastability from the start
- Calculable *metastable* ~~SUSY~~ minima without scale hierarchies are generic

Duality in SUSY QCD

Consider $SU(N_c)$ gauge theory with F flavors

	$SU(N_c)$	$SU(F)_L$	$SU(F)_R$	$U(1)_R$
Q	$\square$	$\bar{\square}$	1	$\frac{F-N_c}{N_f}$
$\bar{Q}$	$\bar{\square}$	1	$\square$	$\frac{F-N_c}{F}$

Will choose $N_c+1 < F < \frac{3}{2}N_c$
Superpotential (breaks R-symmetry):

$$W = m \mathrm{Tr} Q\bar{Q}$$

Duality in SUSY QCD

Dual description in IR

- Dual gauge group $SU(N)$, $N = F - N_c$
- Quarks confine to form mesons, $\widetilde{M} \sim (Q\bar{Q})/\Lambda$
- F flavors of dual quarks

	$SU(N)$	$SU(F)_L$	$SU(F)_R$	$U(1)_R$
q	$\square$	$\overline{\square}$	1	$\frac{F-N}{N_f}$
$\bar{q}$	$\overline{\square}$	1	$\square$	$\frac{F-N}{F}$
$\widetilde{M}$	1	$\square$	$\overline{\square}$	$\frac{2N}{F}$

Superpotential:

$$W = \widetilde{M} q \bar{q} + \mu^2 \mathrm{Tr} \widetilde{M}, \quad \mu^2 = m\Lambda$$

Dual description is IR free.
Perturbative calculations reliable at $E \ll \Lambda$

Special case: s-confining QCD

When $F = N_c + 1$:

- No dual gauge group. Theory of mesons and baryons in IR
- Dual quarks are baryons of magnetic theory

$$B \sim \frac{(Q)^{N_c}}{\Lambda^{N_c-1}}, \quad \bar{B} \sim \frac{(\bar{Q})^{N_c}}{\Lambda^{N_c-1}}$$

- Instanton generated terms in the superpotential

$$W = \frac{1}{\Lambda^{2N_c-1}}((Q\bar{Q})(Q)^{N_c}(\bar{Q})^{N_c} - \det(Q\bar{Q})) + m\mathrm{Tr}(Q\bar{Q})$$
$$= (\widetilde{M}B\bar{B} - \frac{\det\widetilde{M}}{\Lambda^{N-2}}) + \mu^2\mathrm{Tr}\widetilde{M}$$

$\det\widetilde{M}$ is an irrelevant operator in IR.

SQCD as an O'Rafeartaigh model

	$SU(F)$	$U(1)_R$
B	$\square$	0
$\bar{B}$	$\bar{\square}$	0
$\widetilde{M}$	$\mathbf{Ad}+\mathbf{1}$	2

,

$$W = \widetilde{M}_{ij} B^i \bar{B}^j + h f^2 \mathrm{Tr} \widetilde{M} , \qquad h f^2 = \mu^2$$

Accidental R-symmetry in IR (broken by $\det \widetilde{M}$)
F-term conditions for $\widetilde{M}$:

$$h f^2 \delta_{ij} + B_i \bar{B}_j = 0$$

$F = N + 1$ equations but $(B\bar{B})_{ij}$ matrix has rank 1.
Tree level: SUSY broken

SQCD as an O'Rafeartaigh model

At the minimum:

- $B_F = \bar{B}_F = hf^2 \ll \Lambda$
- Several massless fields (Goldstones and pseudo-flat directions)
- $\mathrm{Tr}\widetilde{M}$ is a flat direction (lifted by quantum corrections)

Perturbative analysis

- IR description is weakly coupled.
- Perturbative corrections dominate over strong coupling effects for vevs small compared to Λ.
- Massless fields obtain positive masses at one loop (ISS)

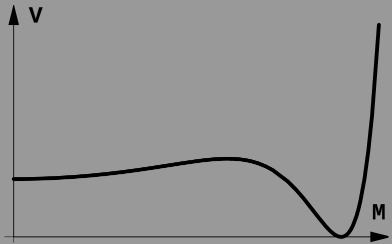
$$V_{eff}^{(1)} \sim \frac{\log 4 - 1}{8\pi^2}(F - N)|Tr\widetilde{M}|^2 + \dots$$

SQCD as an O'Rafeartaigh model

- ~~SUSY~~ minimum $B\bar{B} = hf^2$, M is arbitrary
- $\det M$ restores SUSY
- SUSY preserving minimum $B = \bar{B} = 0$,

$$M = m_{ij}^{-1} \left(\det m \, \Lambda^{F-2}\right)^{\frac{1}{F-1}}$$

- For small m potential is fully calculable



Tunneling probability $\sim \exp(-S_{bounce})$

$$S_{bounce} \sim \left(\frac{\Lambda}{\mu}\right)^{4(F-3)/(F-1)} \gg 1$$

GMSB

Great starting point for the model

- Embed SM into subgroup of the flavor symmetry.
- Flavor group is broken to $F-1$. Need $F \geq 6$
- $SU(5)_{SM} \subset SU(6)_F$

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

$$\widetilde{M} = \begin{pmatrix} M_i^j & N^j \\ \bar{N}_i & X \end{pmatrix} , \quad B = (\phi, \psi) \, , \quad \bar{B} = (\bar{\phi}, \bar{\psi})$$
$$M = \mathbf{Ad} + \mathbf{1}, \; \phi = \square, \; \bar{\phi} = \overline{\square}, \; N = \square, \; \bar{N} = \overline{\square},$$
$$X = 1, \; \psi = 1, \; \bar{\psi} = 1 \, .$$

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

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

In IR effectively added 7 SM flavors; In UV added 5. Landau pole at $\sim 10^{12}$.

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

Messenger spectrum:

- $\psi,\ N$ fermions have mass $\sqrt{h}f$
- $\psi,\ N$ scalars have masses^2 0 and $2hf^2$ ($F_{\mathrm{Tr}M} = 0$)
- Scalars and fermions in M massless at tree level
- M scalars obtain mass at one loop from CW potential

Phenomenological disaster:

- Massless messenger scalars are unacceptable
- Scalar superpartner mass^2 vanish for this messenger spectrum

Unbroken R-symmetry implies

- Massless fermions in M
- Massless gauginos

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

Messenger spectrum:

- $\psi, \ N$ fermions have mass $\sqrt{h} f$
- $\psi, \ N$ scalars have masses^2 0 and $2hf^2$ ($F_{\text{Tr}M} = 0$)
- Scalars and fermions in M massless at tree level
- M scalars obtain mass at one loop from CW potential

Phenomenological disaster:

- Massless messenger scalars are unacceptable
- Scalar superpartner mass^2 vanish for this messenger spectrum

Unbroken R-symmetry implies

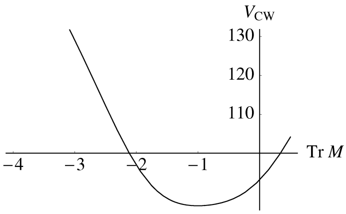
- Massless fermions in M
- Massless gauginos

Solution: Need vev for M

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

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

$$\frac{1}{64\pi^2} \mathrm{S}Tr\mathcal{M}^4 \log \frac{\mathcal{M}^2}{\Lambda^2}$$



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

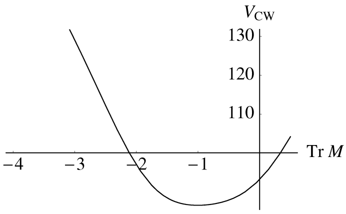
Solution: Need vev for M

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

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

$$\frac{1}{64\pi^2}\mathrm{S}Tr\mathcal{M}^4 \log\frac{\mathcal{M}^2}{\Lambda^2}$$

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

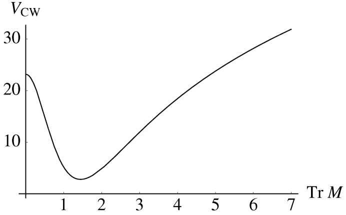


Solution: Need vev for M

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

From gauge dynamics (like Dine, Mason)

- Induce vev via $U(1)$ interaction
- $S,\ Z$ with charge $+1$, $\bar{S},\ \bar{Z}$ with charge -1
- Tree level: $S \neq 0$, $Z = -dMS/m'$
- CW potential: non-trivial vev
- ~~SUSY~~ partially from new sector: $F_Z \neq 0$.

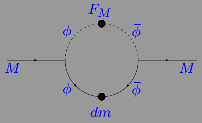


Fermion masses

Fermion messenger matrix

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

Diagram for gaugino and M-fermion masses



- Leading order gaugino mass $m_\lambda \sim \mathrm{Tr}(m_f^{-1}\mathcal{F}) = 0$
- 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

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

$$W = \frac{1}{\Lambda_{UV}^3} \det(p\bar{p})(Q\bar{Q})$$

Require $\det(p\bar{p}) = \Lambda_{sc}^4$

$$W = \frac{1}{\Lambda_{UV}^3} \det(p\bar{p})(Q\bar{Q}) \;\rightarrow\; \frac{\Lambda_{sc}^4}{\Lambda_{UV}^3}(Q\bar{Q}) \;\rightarrow\; \frac{\Lambda}{\Lambda_{UV}} \frac{\Lambda_{sc}^4}{\Lambda_{UV}^2} \mathrm{Tr}(M+X)$$

Electric theory determines natural values of couplings:

$$h \sim \frac{\Lambda}{\Lambda_{UV}}, \quad f^2 \sim \frac{\Lambda_{sc}^4}{\Lambda_{UV}^2}, \quad d \sim \frac{\Lambda}{\Lambda_{UV}}.$$

Origin of scales

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

$$W = \frac{1}{\Lambda_{UV}^3} \det(p\bar{p})(Q\bar{Q})$$

Require $\det(p\bar{p}) = \Lambda_{sc}^4$

$$W = \frac{1}{\Lambda_{UV}^3} \det(p\bar{p})(Q\bar{Q}) \;\rightarrow\; \frac{\Lambda_{sc}^4}{\Lambda_{UV}^3}(Q\bar{Q}) \;\rightarrow\; \frac{\Lambda}{\Lambda_{UV}} \frac{\Lambda_{sc}^4}{\Lambda_{UV}^2} \mathrm{Tr}(M+X)$$

Electric theory determines natural values of couplings:

$$h \sim \frac{\Lambda}{\Lambda_{UV}}, \quad f^2 \sim \frac{\Lambda_{sc}^4}{\Lambda_{UV}^2}, \quad d \sim \frac{\Lambda}{\Lambda_{UV}}.$$

Higgs sector

$$W_{\mu-term} = \beta \frac{p^2 \bar{p}^2}{\Lambda_{UV}^3} H_u H_d$$

After confinement of supercolor

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

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

$$B_\mu \sim \frac{3\alpha_2}{2\pi} M_2 \mu \ln \frac{h f^2}{M_2 \mu}$$

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

Estimate of scales

- Constraints

$$\frac{\Lambda\Lambda_{sc}^4}{\Lambda_{UV}^3} \sim F \sim (100\text{TeV})^2\,, \quad \frac{\Lambda_{sc}^4}{\Lambda_{UV}^3} \sim \mu \sim 100GeV\,, \quad \Lambda_{UV} \sim 10^{11}GeV$$

- Can be satisfied by

$$\Lambda \sim \Lambda_{sc} \sim 10^8\,, \quad m \sim 0.1\Lambda, \quad \Lambda_{UV} \sim 10^{10} \quad m' \sim 10^3 GeV$$

- Bounce action:

$$S_b \sim \frac{(\Delta M)^4}{F^2} \sim 5 \cdot 10^8$$

- Lifetime of the vacuum

$$\tau \sim \frac{1}{100\text{GeV}} \frac{1s}{10^{24}\text{GeV}^{-1}} \sqrt{\frac{2\pi}{S_b}} e^{S_b} \sim 10^{2\cdot 10^8}\, s$$

While all scales large, SUSY scale $\sqrt{hf^2}$ 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 (Nomura and Tobe)
- Component fields in M obtain masses at one loop and from gauge mediation. Their contributions to spartner masses subleading.
- Additional fermionic adjoints at the scale of SM superpartners

Related work on ISS inspired models

- Kitano, Ooguri, Ookuchi, hep-ph/0612139
- Dine, Feng, Silverstein, hep-th/0608159
- Dine, Mason, hep-ph/0611312
- Murayama, Nomura, hep-ph/0612186 and hep-ph/0701231
- Aharony, Seiberg, hep-ph/0612308

Conclusions

- Combination of DSB and GM is very attractive
  - Explains $M_{\cancel{\text{SUSY}}} \ll M_{\text{Pl}}$
  - Suppresses FCNC
  - Possibility of observable ~~SUSY~~ 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