Low scale direct gauge mediation

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work in progress with C. Csaki and J. Terning

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Metastable SUSY breaking

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GMSB models

SUSY breaking is comminicated to SM through vector-like messengers

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

Spurion S has SUSY breaking vev, $S = M + F\theta^2$

Superpartner masses

$$m_a \sim \frac{\alpha_a}{4\pi}\frac{F}{M} \qquad m^2 \sim \left(\frac{\alpha_a}{4\pi}\right)^2 \frac{F^2}{M^2}$$

Problems

- μ-problems
- Little hierarchy problem
- Several sectors required to generate messenger spectrum, μ-term etc.

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- Direct mediation: messengers part of SUSY breaking sector
- Low energy SUSY breaking: $F/M^2 \sim 1$, $F/M \sim 80$ TeV
- SUSY breaking scale below 80 TeV requires large number of messengers

Generic *calculable* models of DSB have large hierarchies of vevs and relatively high SUSY breaking scale

ISS models

- Metastable SUSY breaking vacuum states are generic
- In many simple models metastable SUSY breaking minima exist near the origin of the moduli space

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

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

,

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

F-term conditions for $\widetilde{M}$: $\quad h f^2 \delta_{ij} + \phi^a_i \bar{\phi}_{aj} = 0$
$(\phi\bar{\phi})_{ij}$ matrix has maximal rank $min(N, F)$.
SUSY is broken for $N < F$.

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- O'Rafeartaigh model
- Symmetry broken to $SU(N) \times SU(F-N) \times U(1)_R$
- 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

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

- Accidental R-symmetry at the minimum of the potential
- 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

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

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: $SU(5) \times SU(6)_F$, $SU(5)_{SM} \subset SU(6)_F$.

$$\widetilde{M} \sim q\bar{q}, \quad \phi \sim q^5, \quad \bar{\phi} \sim \bar{q}^5$$

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

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

where

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

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

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

At the minimum: $F_{\text{Tr}M} \neq 0$, $\langle \psi \rangle \neq 0$
Both M and $\bar{\phi}$, ϕ (with $N, \bar{N}$) are potential messengers

Messenger spectrum:

- ψ, N fermions have mass f
- ψ, N scalars have masses squareds 0 and f^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
- M fermions remain massless when R symmetry unbroken at the minimum

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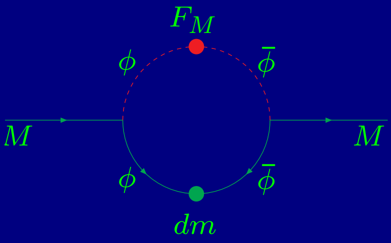
Solution:

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

- $S,\ \bar{S}$ and $Z,\ \bar{Z}$ at the origin due to mass term
- $\mathrm{Tr}MS\bar{S}$ coupling generates CW potential for $S,\ \bar{S}$
- For small d: $\langle M \rangle \sim dm$

Diagram for gaugino and M-fermion masses



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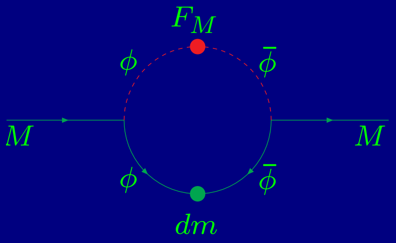

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Origin of scales

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, $p, \bar{p}$.

$$f^2(\mathrm{Tr}M + X) \quad \rightarrow \quad \frac{\det(p\bar{p})}{\Lambda_{UV}'^2}(TrM + X) \quad \rightarrow \quad \frac{1}{\Lambda_{UV}^4}\det(p\bar{p})(q_e\bar{q}_e)$$

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

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

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. Contributions to spartner masses subleading but may be non-negligible since super

S[article 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

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

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

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

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

Little Hierarchy

- Large ratio between squark and slepton/Higgs soft masses
- LEP bound on slepton masses implies $F/M \geq 80$ TeV and squarks with mass at least ~ 700GeV
- Contributions to up-type Higgs mass

$$m_{H_u}^2(M_{weak}) \sim m_{H_u}^2(M_{mess}) - \frac{3\lambda_t^2}{4\pi^2} m_{\tilde{Q}_L}^2 (\log \frac{M_{mess}}{m_{\tilde{t}}} + \frac{3}{2}),$$

  This is at least $-(500\ \text{GeV})^2$ and implies fine-tuning of about 3%.

Reducing fine-tuning:

- Lower scale of SUSY breaking
- Reduce hierarchy between sleptons and squarks

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Decrease hierarchy with more doublet than triplet messengers

Agashe and Graesser

Enlarge flavor symmetry of the DSB sector:
$SU(3) \times SU(2) \times U(1) \subset SU(5) \times SU(2)$

$$M, \phi, \bar{\phi}, N, \bar{N} \to (M_5, M_2), (\phi_5, \phi_2), (\bar{\phi}_5, \bar{\phi}_2)(N_5, N_2), (\bar{N}_5, \bar{N}_2)$$

- Can choose $SU(2)_W$ as a diagonal subgroup of $SU(2)$ in $SU(5)$ and extra $SU(2)$.
- $U(1)_Y$ charges of messengers are arbitrary
- Can arrange for large messenger hypercharge.
- Abandoning simple unification can allow $F/M \sim 50$ TeV and lower fine-tuning.

Flipped $SU(5)$

- Extend GUT to $SU(5) \times U(1)$
- Hypercharge $Y = T_{24} + X$ where
  $T_{24} = diag(1, 1, 1, -2/3, -2/3)$
  X charges are $10_{1,5}, \ \bar{5}_{-1/3}, \ 1_{-1}$
- Masses (squared) of right-handed sleptons increases approximately by a factor $11/5$.
- Low $F/M \sim 37\text{TeV}$ with right-handed sleptons at 100GeV and left-handed squarks at 400GeV
- $SU(5) \times U(1)_X$ can be embedded in the original $SU(6)$.
- However, large number of messengers leads to Landau pole below M_{GUT}.

Conclusions

- Calculable low scale direct gauge mediation
- Mechanisms for softening little hierarchy problems
- Improved situation with μ-term, further improvements possible
- Further work on spartcile spectrum and phenomenological signatures/implications in progress