METASTABLE SUSY BREAKING

- §1-5, 7 OF INTRILIGATOR, SEIBERG, SHIH   hep-th/0602239
- BG READING: INTRILIGATOR & SEIBERG   hep-th/0702069

THE BIG PICTURE

WE WANT TO WRITE DOWN MODELS OF REALISTIC ~~SUSY~~'ing. THE SUPERTRACE RULE ($\mathrm{STr}\, M^2 = 0$) FORCES A MODULAR STRUCTURE,

$$\boxed{\cancel{SUSY}} \text{ — messengers — } \boxed{MSSM}$$

↑ THE QUESTION IS HOW TO BUILD MODELS FOR THIS SECTOR.

↑ eg. gauge mediation ... } ALL KNOWN MODELS OF GAUGE MEDIATION RESTORE SUSY SOMEWHERE IN FIELD SPACE. (DINE, NELSON '94)

↓

NOT AS EASY AS YOU'D NAÏVELY THINK!
eg. 1st model of ~~SUSY~~'ing is often O'RAIFEARTAIGH
- 3 fields
- special superpotential

} have to work hard to kill SUSY vacua!

⇝ ~~SUSY~~'ing is non-generic (~~SUSY~~'ing VACUA)

- A NICE IDEA IS DYNAMICAL ~~SUSY~~'ing. $\boxed{DSB}$ — mess — $\boxed{MSSM}$
  - BREAK SUSY VIA STRONG DYNAMICS
    ↑ non Abelian, ASYMP FREE
  - ~~SUSY~~ SCALE GENERATED BY DIMENSIONAL TRANSMUTATION

$$\tau = \frac{b}{2\pi i}\log\frac{\Lambda}{\mu} \quad \Leftarrow \quad \Lambda = |\Lambda|\, e^{i\theta_{YM}/b}$$

$$= \frac{4\pi i}{g^2} + \frac{\theta_{YM}}{2\pi}$$

$$\Lambda \sim \Lambda_{UV}\, e^{-8\pi^2/bg_0}$$

⇝ this gives us natural TeV-scale ~~SUSY~~'ing.

BUT DYNAMICAL $\not{S}$USY'ING IS EVEN *MORE* 'NON-GENERIC' THAN OTHER WAYS OF BREAKING SUSY!

- MODELS END UP RATHER COMPLICATED, REQ. Xral GAUGE THY, SPECIAL STRUCTURE
- SQCD w/ SU(N) HAS ITS OWN PROBLEMS
  - Strong coupling — "calculability" ⟷ use <u>duality</u> (SEIBERG)
  - WITTEN INDEX = N

↳ in lim of large masses, THY IS SYM
$\Rightarrow \exists$ N <u>SUSY</u> VACUA.

HISTORICALLY: WITTEN'S CALCULATION OF HIS INDEX WAS THE "NAIL IN THE COFFIN" FOR DYNAMICAL SUSY BREAKING.

$\exists$ famous exceptional cases, eg (3-2), (4-1), ITIY MODELS
BUT IT SEEMED REALLY DIFFICULT TO CONSTRUCT A DSB SECTOR.

<u>WHAT MAKES $\not{S}$USY'ING GENERIC?</u>

no 'fine tuning' or 'special relations' among model parameters.

USEFUL NOTION OF 'GENERICITY':

'GENERIC' $\Rightarrow$ n EQUATIONS FOR n UNKNOWNS GENERICALLY HAVE A SOLUTION.

<u>NELSON-SEIBERG R-SYMMETRY THM</u> (hep-ph/9309299)

$\not{S}$USY $\Rightarrow \exists$ R SYMMETRY (R is necessary for $\not{S}$USY)
SSB $\not{R}$ $\Rightarrow$ $\not{S}$USY. (SSB $\not{R}$ is sufficient for $\not{S}$USY)

<u>ASSUMPTIONS</u>: GENERIC EFF $\mathcal{L}$, CALCULABLE (LOW E THY = WESS-ZUMINO, no gauge)

Pf/ $R[W] = 2$ (for non R-sym: $Q[W] = 0$)

$$W(\Phi_1, \dots, \Phi_n) = \Phi_1^{2/r_1}\, w(\Phi_2 \Phi_1^{-r_2/r_1}, \dots, \Phi_n \Phi_1^{-r_n/r_1})$$

$$V=0 \Rightarrow \partial_i W = 0 \Rightarrow \begin{cases} \frac{2}{r_1}\Phi_1\, w(\cdots) = 0 \Rightarrow w(\cdots) = 0 \\ \partial_{i\neq 1} w(\cdots) = 0 \end{cases}$$

$\Rightarrow$ n EQNS FOR $(n-1)$ UNKNOWNS
OVERCONSTRAINED: generically no solution $\Rightarrow$ $\not{S}$USY

PROBLEMS W/ R SYMMETRY

- SUSY-breaking ($\cancel{\text{SUSY}}$) $\Rightarrow$ need R SYM
- NONZERO GAUGINO MASS $\Rightarrow \cancel{R}$ (m_λ BREAKS R)
- IF SSB $\cancel{R} \to$ MASSLESS GOLDSTONE

$\Rightarrow$ R SYM EXPLICITLY BROKEN ... BUT THEN $\exists$ SUSY VACUA!

$\uparrow$

GRAVITY HATES CONTINUOUS SYM
& LIKES TO BREAK THEM EXPLICITLY
$\to$ MASS TO GOLDSTONE, MAY NOT BE ENOUGH

$\leadsto \exists$ SUSY VACUA IN A 'GENERIC' THEORY!

LEMONADE OUT OF LEMONS:

METASTABLE $\cancel{\text{SUSY}}$

- GENERIC - CAN USE FRAMEWORK OF SQCD
- EXPLICIT $\cancel{R}$, REALIZED AS ACCIDENTAL SYM IN LOW-E THY
- SMALL PARAMETER ϵ WHICH PARAMETERIZES
  - explicit R breaking
  - separation of SUSY & $\cancel{\text{SUSY}}$'ing vacua in field space

BUT WE STILL HAVE POTENTIAL PROBLEMS W/ CALCULABILITY

SQCD IN ASYMPTOTICALLY FREE REGIME
$\to$ IR CONFINING ... ? LOW E DOF.

TRICK: USE SEIBERG DUALITY!

ELECTRIC THY SU(N) w/ $Q, \bar{Q}$

$W = 0$
ASYMP. FREE ($F < 3N$)
IR FREE FOR ($F > 3N$)

	SU(N)	SU(F)	SU(F)
Q	$\square$	$\square$	
$\bar{Q}$	$\bar{\square}$		$\bar{\square}$

$\Updownarrow$ Seiberg

MAGNETIC THY SU(n) w/ $\underbrace{q, \tilde{q}}_{\text{mag. quarks}}, \Phi$ — meson of Electric

$n \equiv F - N$

$W_m = \tilde{q} \Phi q$

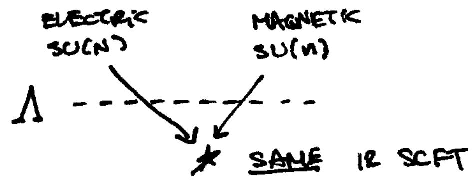
IR FREE ($F < \frac{3}{2}N$)

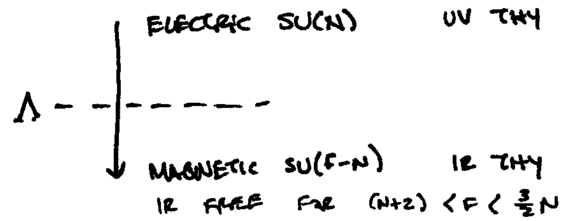
$N+2 < F < \frac{3}{2}N$

(ASYMP FREE for $F > \frac{3}{2}N$)

	SU(n)	SU(F)	SU(F)
q	$\square$	$\bar{\square}$	
$\tilde{q}$	$\bar{\square}$		$\square$
Φ		$\square$	$\bar{\square}$

SEIBERG DUALITY:





SO NOW WE HAVE A REGIME WHERE WE CAN USE SQCD TO FIND METASTABLE SUSY VACUA IN A WAY WHERE WE HAVE CONTROL OF THE UV & IR.

STRATEGY – ISS
1. write down IR model w/ tree-level ~~SUSY~~'ing
   this will be our SU(n) MAGNETIC thy, but not yet gauged.
2. gauge the theory – metastable vacuum
3. show results are insensitive to UV theory details.
3. WRITE DYNAMICAL THY

① "MACRO MODEL I" ← MAGNETIC SUPERPOTENTIAL

$$W = \underbrace{h \,\mathrm{Tr}\, \varphi \Phi \tilde{\varphi}}_{\text{most gen. } W \text{ cons. w/ sym.}} - h\mu^2\, \mathrm{Tr}\, \Phi \qquad K = \text{can.}$$

	SU(n)	SU(F)	SU(F)	U(1)$_B$	U(1)'	U(1)$_R$
$q = \varphi$	$\square$	$\bar{\square}$	1	1	1	0
$\bar{q} = \tilde{\varphi}$	$\bar{\square}$	1	$\square$	−1	1	0
Φ	1	$\square$	$\bar{\square}$	0	−2	2

$\Delta W = -h\mu^2\, \mathrm{Tr}\, \Phi$ BREAKS GLOBAL SYM $\to SU(n) \times SU(F)_{DIAG} \times U(1)_B \times U(1)_R$

this term is associated w/ mass of ELECTRIC QUARKS in the UV theory. (IS susy notes, p.31)

~~SUSY~~ BY THE RANK CONDITION

THIS IS JUST ONE OF MANY WAYS TO BREAK SUSY @ tree-level

F-term BREAKING: if $F \neq 0 \Rightarrow V \sim |F|^2 \neq 0 \Rightarrow$ ~~SUSY~~

$$\boxed{-F_{\Phi}^{\dagger} = \underbrace{h\varphi\tilde{\varphi}^T}_{\text{RANK } n} + \underbrace{h\mu^2}_{\text{RANK } F > n \;\; (\sim \mathbb{1}_{F\times F})}}$$ (matrix eqn)

THUS THE 1st & 2ND TERMS CANNOT CANCEL COMPLETELY

$$V \sim (F-n)\,|h\mu^2|^2 \quad \Rightarrow \quad \cancel{\text{SUSY}}$$

ISS: CONSIDER VACUUM THAT PRESERVES MAXIMUM UNBROKEN GLOBAL SYMMETRIES: (up to flavor rot)

$$\Phi_0 = 0 \qquad \varphi = \tilde{\varphi}^T = \begin{pmatrix} \mu\,\mathbb{1}_{n\times n} \\ 0 \end{pmatrix} \updownarrow F$$

(near origin)

CALCULATION: EXPAND ABOUT THIS VACUUM.

$$\begin{aligned} V &= |W_\varphi|^2 + |W_{\tilde{\varphi}}|^2 + |W_\Phi|^2 \\ &= |\Phi\tilde{\varphi}|^2 + |\varphi\Phi|^2 + |\varphi\tilde{\varphi}|^2 \end{aligned}$$

contains mass terms!

check for tadpoles, run-aways

$\exists$ CLASSICAL FLAT DIRECTIONS (pseudomoduli) WHICH ARE LIFTED BY 1-LOOP COLEMAN-WEINBERG POTENTIAL

SPECTRUM

E

$|h\mu|$ FIELDS w/ tree-level masses

$|h^2\mu|$ FIELDS w/ 1-loop MASSES

0 MASSLESS GOLDSTONES + GOLDSTINO

NO TACHYONIC DIRECTIONS; ~~SUSY~~'ing VACUA ARE STABLE. (1-loop)

aside: Komargodski-Shih thm

$\Rightarrow$ ANOMALOUSLY SMALL GAUGINO MASS

(thm relates gaugino mass to topology of low-E eff pseudomoduli space)

② MACRO MODEL II

NOW WE ACTUALLY GAUGE $SU(n)$

$F > 3n \longleftrightarrow F < \frac{3}{2}N$, (magnetic) IR FREE thy.

- FIRST THING TO CHECK: EFFECT OF D-TERMS ON SCALAR POTENTIAL

$$V_D = \frac{1}{2} g^2 \sum_A \left(\mathrm{Tr}\, \varphi^\dagger T_A \varphi - \mathrm{Tr}\, \tilde{\varphi} T_A \tilde{\varphi}^\dagger \right)^2$$

... BUT $V_D = 0$ ON VACUUM OF MACRO MODEL I.
$\Rightarrow$ PREVIOUS VACUUM REMAINS A MINIMUM OF TREE-LEVEL POT.

- SUPERHIGGS MECHANISM
  - $SU(N)$ GAUGE FIELDS GET MASS $g\mu$
  - GOLDSTONES EATEN
  - SOME PSEUDOMODULI GET MASS $g\mu$

- NEXT CALCULATE COLEMAN-WEINBERG POTENTIAL FOR PSEUDOMODULI TO CHECK STABILITY.

  BUT: EFFECT OF $SU(N)$ GAUGE FIELDS DROP OUT @ LEADING O
  - D-TERMS VANISH ON VACUUM MANIFOLD
  - MASSIVE GAUGE FIELDS DO NOT COUPLE TO NONZERO F-TERMS

- NET EFFECT OF GAUGED $SU(n)$: SUSY VACUA RESTORED! $W_{dyn} = (\det \Phi)^{\frac{1}{F-N}}$

~~why?~~ $\varphi, \tilde{\varphi}$ GET MASS $\langle h\Phi \rangle$
INTEGRATE OUT (SCALE MATCHING)
$\rightarrow$ LOW E THY IS PURE SYM

FOR $F < \frac{3}{2}N$
$W_{dyn} \sim \Phi^{>3}$
INSIGNIFICANT FOR SUSY VACUUM NEAR ORIGIN

introduce DYNAMICAL SCALE $\tilde{\Lambda}$

SUSY VAC: $$\langle h\Phi \rangle = \tilde{\Lambda} \left(\frac{\mu}{\Lambda} \right)^{\frac{2N}{F-n}} \mathbb{1}_{F\times F} = \mu \frac{1}{\epsilon^{(F-3n)/(F-n)}} \mathbb{1}_{F\times F}$$

$\epsilon \equiv \mu/\Lambda$, SMALL PARAMETER , $\ll 1$

$$\underbrace{|\mu| \ll}_{\text{STABILITY OF METASTABLE VACUA}} \underbrace{|\langle h\Phi \rangle| \ll |\Lambda|}_{\text{well below Landau pole, LOW-E EFT JUSTIFIED}}$$

DYNAMICAL SUSY RESTORATION

- $\Lambda \to \infty$ w/ μ fixed : THY BREAKS SUSY (SUSY VAC $\to \infty$)
- Λ large, finite : SUSY VACUA COMES IN FROM ∞

EFFECTS FROM UV THEORY

expect: DECOUPLING OF Λ-SCALE THY FROM $E \ll \Lambda$ EFT.

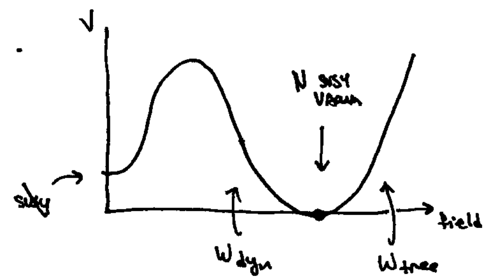
V_{cw} (for MACRO THY) $\sim |\mu^2|$
NOT IR ANALYTIC IN μ^2 PARAM OF W
<u>why</u>? MODES WE INTEGRATED OUT BECOME MASSLESS AS $\mu^2 \to 0$

ON THE OTHER HAND, CONTRIBUTION FROM <u>MICRO</u> THY MUST GO AS

$$|\mu^2| \frac{\mu^2}{|\Lambda_m|^2} = |\mu^2 \epsilon^2| \ll |\mu^2|$$

THIS <u>is</u> IR ANALYTIC ($|\mu|^2$ vs. $|\mu^2|$) IN μ^2. DIFFERENTIABLE @ 0.
COMES FROM INTEGRATING OUT HEAVY MODES ($\sim \Lambda_m$).

CORRECTIONS $\sim |\mu^2 \epsilon^2| \longrightarrow$ NEGLIGIBLE.
$\uparrow$ show up in δK



③ METASTABLE VAC IN SQCD – ISS

LAST INGREDIENT: MAKE ~~SUSY~~'ing DYNAMICAL

<u>ELECTRIC (UV) THEORY</u>: SU(N) SQCD w/ HOLOMORPHIC SCALE Λ, F QUARKS

$$W = \mathrm{Tr}\, m M$$

$\uparrow$ $\curvearrowleft$ $M = Q\bar{Q}$
m degenerate (nondeg. discussed as deformation)

$m_i \ll |\Lambda|$

<u>SEIBERG DUALITY</u> : $SU(N) = SU(F-N)$ magnetic thy w/ SCALE $\tilde{\Lambda}$
F MAG QUARKS q & $\tilde{q}$ } F^2 MESONS M

$F < \frac{3}{2}N \to$ IR FREE. SMOOTH K NEAR ORIGIN $\to$ $K = \frac{1}{\beta}\mathrm{Tr}(q^\dagger q + \tilde{q}^\dagger \tilde{q})$
$+ \frac{1}{\alpha|\Lambda|^2}\mathrm{Tr}\, M^\dagger M + \dots$

$$W_m = \frac{1}{\hat{\Lambda}}\mathrm{Tr}\, M q\tilde{q} + \mathrm{Tr}\, m M$$

α, β UNDETERMINED.

$\uparrow$
$\Lambda^{3N-F} \tilde{\Lambda}^{3(F-N)-F} = (-)^{F-N} \hat{\Lambda}^F$
from scale matching of UV + IR theories.

$\uparrow$ SUPPRESSED BY $\tilde{\Lambda}$
NOT IMPORTANT NEAR ORIGIN

THIS THY MATCHES OUR MACRO MODEL II w/

$$\varphi, \tilde{\varphi} = \tilde{q}, \tilde{q} \qquad h = \sqrt{\alpha}\,\frac{\Lambda}{\hat{\Lambda}} \qquad \tilde{\Lambda} = \tilde{\Lambda}$$

$$\Phi = \frac{M}{\sqrt{\alpha}\,\Lambda} \qquad \mu^2 = -M_0 \hat{\Lambda} \qquad n = F - N$$

<u>CONCLUSION</u>: $N+2 \le F < \frac{3}{2}N$ w/ SUITABLE TREE MASSES HAS METASTABLE SUSY GROUND STATE NEAR ORIGIN

- WE ESTABLISHED THIS IN STRONGLY COUPLED REGIME OF UV THY
- VAC PARAM BY 2 DIMLESS #'S α, β
- RESULT INCLUDES non-SUSY, non-CHIRAL INFO.

LIFETIME OF METASTABLE VACUUM:

plugging into "BOUNCE ACTION" of COLEMAN, $S \sim \frac{1}{|\epsilon|^{4(F-3n)/(F-n)}} \gg 1$

$$\langle \Phi_{ISS} \rangle = 0$$

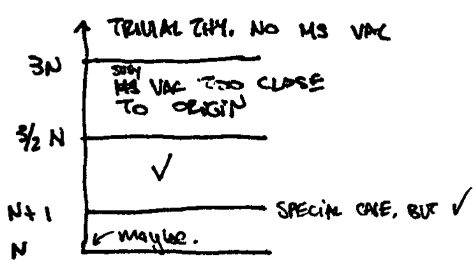
$$\langle \Phi_{SUSY} \rangle = \frac{\mu}{h} \frac{1}{\epsilon^{(F-3n)/(F-n)}} \mathbb{1}_F$$

SUSY & SUSY VACUA ARE <u>PARAMETRICALLY</u> FAR APART

PARAM is $\epsilon \ll 1$

<u>CLOSING REMARKS</u>

- CAN GENERALIZE TO NONDEGENERATE m
- CAN GENERALIZE TO DIFF RANGE OF F



- METASTABLE VAC HAS COMPACT, CONTINUOUS SPACE OF VACUA (MODULI SPACE) cf DISCRETE SPACE OF SUSY VACUA

→ EARLY UNIVERSE MAY PREFER TO POPULATE METASTABLE VAC