26 AUG 09

SELECTIONS FROM ISS

KEY PARTS OF : INTRILIGATOR, SEIBERG, SHIH : $\cancel{\text{SUSY}}$'ing, $\cancel{R}$'ing, METASTABLE VAC.
hep-th/0602239

THIS DRAWS HEAVILY FROM INTRILIGATOR & SEIBERG'S $\cancel{\text{SUSY}}$ LEC. SEE ALSO DINE'S CARGESE 08 LECTURES FOR A BRIEF SUMMARY.

THE MAIN IDEA IS EASY TO SUMMARIZE :

$\cancel{\text{SUSY}}$'ing VAC → NON GENERIC
METASTABLE $\cancel{\text{SUSY}}$'ing VAC → GENERIC

SINCE SQCD HAS N SUSY VACUA, IT WAS PREVIOUSLY NOT VIABLE FOR $\cancel{\text{SUSY}}$'ing, EVEN THOUGH IT HAS THE BENEFIT OF DSB SCALE GENERATION. BY COUPLING A SIMPLE $\cancel{\text{SUSY}}$'ING MODEL TO SQCD WE CAN HAVE DSB @ COST OF METASTABILITY.

ISS WORKS W/ A TREE-LEVEL $\cancel{\text{SUSY}}$'ING MODEL WHICH IS DUAL TO AN ELECTRIC SQCD THEORY.

PREVIOUS LIT OF METASTABLE $\cancel{\text{SUSY}}$: AFRAID OF METASTABILITY.
ISS EVEN ALLOWS METASTABILITY IN $\cancel{\text{SUSY}}$'ing SECTOR.

INTRODUCTORY REMARKS

- ACCEPT METASTABILITY FROM THE START.
- "NO SUSY VACUA" CONSTRAINTS THROWN OUT
  - ALLOW MODELS W/ NON-ZERO WITTEN INDEX, NO $U(1)_R$
- STILL REQ. GOLDSTINO (can be hidden in UV theory)

$\epsilon \equiv \frac{\mu}{\Lambda_m} \sim \sqrt{\frac{m}{\Lambda}}$

- VIABILITY DEPENDS ON PARAMETRICALLY LONG LIVED
- OLD MODELS OF $\cancel{\text{SUSY}}$: CALCULABLE WHEN VACUA @ LARGE FIELDS
- ISS MODEL : VACUA @ SMALL EXPECTATION VALUES
  FIX Λ, $\epsilon \to 0$: SUSY UNBROKEN & WE KNOW IR SPECTRUM
  KÄHLER POT OF LIGHT MODES SMOOTH, PARAM BY SMALL # OF $\mathcal{O}(1)$ COEF.
  → CANNOT COMPUTE COEF, BUT CAN STILL GET A LOT OF INFO

MAIN EXAMPLE (henceforth referred to as 'ISS MODEL')

$\mathcal{N}=1$ SQCD W/ $(N+1) \leq F < \frac{3}{2}N$ FREE MAG RANGE → CONTROLLED IN IR
IR THY WILL HAVE SP. $\cancel{\text{SUSY}}$ @ TREE LEVEL BY RANK CONDITION
(cf P. 36 & 56)

UV THY: CW POT IS NOT IR ANALYTIC → LOW E EFF POT IS ROBUST UPON INCLUDING UV EFFECTS.

2. THE MACRO MODEL, PART I

CHIRAL SF: Φ_{ij} , φ^i_c , $\tilde{\varphi}^{ic}$ $i = 1, \ldots, F$; $c = 1, \ldots, N$

$$\boxed{\begin{aligned} W &= h \,\mathrm{Tr}\, \varphi \Phi \tilde{\varphi} - h\mu^2 \,\mathrm{Tr}\, \Phi \\ &= h\, \varphi^i_c \Phi_{ij} \tilde{\varphi}^{jc} - h\mu^2 \Phi_{ij} \delta^{ij} \end{aligned}}$$

$$K = \mathrm{Tr}\, \varphi^\dagger \varphi + \mathrm{Tr}\, \tilde{\varphi}^\dagger \varphi + \mathrm{Tr}\, \Phi^\dagger \Phi$$
$$= K_{\text{can}}$$

GLOBAL ← for now

	$SU(N)$	$SU(F)$	$SU(F)$	$U(1)_B$	$U(1)'$	$U(1)_R$	
Φ	1	□	$\bar{□}$	0	-2	2	
φ	□	$\bar{□}$	1	1	1	0	
$\tilde{\varphi}$	$\bar{□}$	1	□	-1	1	0	
$h\delta^{ii}$	1	$\bar{□}$	□	0	2	0	SPURION

NOTE: $W = \underbrace{h \,\mathrm{Tr}\, \varphi \Phi \tilde{\varphi}}_{\text{MOST GENERAL } W \text{ CONSISTENT W/ SUPERPOT.}} - \underbrace{h\mu^2 \,\mathrm{Tr}\, \Phi}_{\text{BREAKS GLOBAL SYM} \to SU(N) \times \underbrace{SU(F)}_{\text{DIAG}} \times U(1)_B \times U(1)_R}$

$F > N \Rightarrow$ F-TERMS CANNOT ALL BE SET TO ZERO; $\cancel{\text{SUSY}}$ by rank condition.
see p. 36 for RANK CONDITION

CLASSICAL MODULI SPACE (UP TO GLOBAL SYM)

$$\Phi = \begin{pmatrix} 0 & 0 \\ 0 & \Phi_0 \end{pmatrix} \updownarrow (F-N) \qquad \underbrace{\varphi = \begin{pmatrix} \varphi_0 \\ 0 \end{pmatrix} \updownarrow F-N \; \updownarrow F \qquad \tilde{\varphi}^T = \begin{pmatrix} \tilde{\varphi}_0 \\ 0 \end{pmatrix}}_{\text{w/ } \tilde{\varphi}_0 \varphi_0 = \mu^2 \mathbb{1}_{N\times N}}$$

$\overleftrightarrow{(F-N)}$ $\overleftrightarrow{F}$ $\overleftrightarrow{N}$

$$V_{\text{min}} = (F-N) \left| h^2 \mu^4 \right|$$

VACUUM THAT PRESERVES UNBROKEN FLAVOR ROT (MAX UNBROKEN GLOBAL SYM)

$$\boxed{\Phi_0 = 0 \qquad \varphi_0 = \tilde{\varphi} = \mu \mathbb{1}_{N\times N}} \qquad (2.7)$$

EXPAND ABOUT THIS VACUUM TO IDENTIFY LIGHT FIELDS

$$\Phi = \begin{pmatrix} \delta Y & \delta Z^T \\ \delta \tilde{Z} & \delta \hat{\Phi} \end{pmatrix} \qquad \varphi = \begin{pmatrix} \mu + \frac{1}{\sqrt{2}}(\delta \chi_+ + \delta \chi_-) \\ \frac{1}{\sqrt{2}}(\delta \rho_+ + \delta \rho_-) \end{pmatrix} \qquad \tilde{\varphi}^T = \begin{pmatrix} \mu + \frac{1}{\sqrt{2}}(\delta \chi_+ - \delta \chi_-) \\ \frac{1}{\sqrt{2}}(\delta \rho_+ - \delta \rho_-) \end{pmatrix}$$

THIS JUST DEFINES A SET OF FIELDS w/ STUPID NAMES.

WE WANT TO SEE HOW W GIVES TREE-LEVEL MASSES TO THESE FIELDS.

<u>CLAIM</u>: ① MOST FIELDS GET MASSES $\sim |h\mu|$
② GOLDSTONE BOSONS OF BROKEN GLOBAL SYM: (MASSLESS)

$$\underset{SU(N)\times SU(F)\times U(1)_B / SU(N)_D}{\left(\frac{\mu^*}{\mu}\delta X_- - hc\right)} \; , \; \underset{SU(F)/SU(N)_F \times SU(F-N)\times U(1)_{B'}}{Re\left(\frac{\mu^*}{|\mu|}\delta\rho_+\right)} \; , \; Im\left(\frac{\mu^*}{|\mu|}\delta\rho_-\right) \quad \text{w/ } SU(N)_F \subset SU(F)$$

③ MASSLESS SCALARS ASSOC. W/ CLASSICAL FIELDS FLAT DIR:

$$\delta\hat{\Phi} \; , \; \delta\hat{X} \equiv \left(\frac{\mu^*}{\mu}\delta X_- + h.c\right)$$

<u>COMMENTS</u> (like a 'proof' but w/o proof)

WE CAN SHOW HEURISTICALLY THAT THE OTHER FIELDS GET TREE-LEVEL MASSES.

$$W = h\varphi^i_c \Phi_{ij}\tilde{\varphi}^{jc} - h\mu^2 \Phi_{ij}\delta^{ij}$$

$$\Rightarrow \begin{cases} \dfrac{\partial W}{\partial \varphi^i_c} = h\Phi_{ij}\tilde{\varphi}^{jc} & \dfrac{\partial W}{\partial \tilde{\varphi}^{jc}} = h\varphi^i_c\Phi_{ij} \\ \dfrac{\partial W}{\partial \Phi_{ij}} = h\left(\varphi^i_c\tilde{\varphi}^{jc} - \mu^2\delta^{ij}\right) & \end{cases}$$

$$V = |W_\varphi|^2 + |W_{\tilde{\varphi}}|^2 + |W_\Phi|^2$$

$\uparrow$ WHERE WE MEAN $|W_\phi|^2 = \sum_a \left(\frac{\partial W}{\partial \phi_a}\right)\left(\frac{\partial W}{\partial \phi_a}\right)^\dagger = Tr\left|\frac{\partial W}{\partial \phi}\right|^2$

THE FACTOR OF $|h|^2$ IS COMMON TO ALL TERMS, SET TO 1 FOR NOW.
WE CAN WRITE IN MATRIX NOTATION (implicit trace inside abs)

$$V = |\Phi\tilde{\varphi}|^2 + |\varphi\Phi|^2 + |\varphi\tilde{\varphi} - \mu^2\mathbb{1}|^2$$

$\uparrow$ IN MORE DETAIL:

$$\begin{aligned} \Phi\tilde{\varphi} &= \Phi_{ij}\tilde{\varphi}^{jc} = (\Phi\tilde{\varphi})_i{}^c \\ |\Phi\tilde{\varphi}|^2 &= (\Phi\tilde{\varphi})_{ic}\left[(\Phi\tilde{\varphi})^\dagger\right]^{ic} = (\Phi\tilde{\varphi})_{ic}(\tilde{\varphi}^\dagger\Phi^\dagger)^{ic} \\ &= \Phi_{ij}\tilde{\varphi}^i{}_c\,\tilde{\varphi}^\dagger{}_k{}^c\,\Phi^{\dagger ki} \\ &= Tr\,\Phi\tilde{\varphi}\tilde{\varphi}^\dagger\Phi^\dagger \end{aligned}$$

$$\Phi\tilde{\varphi} = \begin{pmatrix} \delta Y\left(\mu + \frac{1}{\sqrt{2}}(\delta X_+ - \delta X_-)\right) + \delta Z^T\frac{1}{\sqrt{2}}(\delta\rho_+ - \delta\rho_-) \\ \delta\tilde{Z}\left(\mu + \frac{1}{\sqrt{2}}(\delta X_- - \delta X_-)\right) + \delta\hat{\Phi}\frac{1}{\sqrt{2}}(\delta\rho_+ - \delta\rho_-) \end{pmatrix}$$

$$\begin{aligned} |\Phi\tilde{\varphi}|^2\Big|_{mass} &= |\mu|^2\delta Y\delta Y^\dagger + |\mu|^2\delta\tilde{Z}\delta\tilde{Z}^\dagger \quad \swarrow \text{implied trace} \\ &= |\mu\delta Y|^2 + |\mu\delta\tilde{Z}|^2 \end{aligned}$$

IN FACT, THE CALC IS MUCH SIMPLER IF WE ONLY LOOK AT MASS TERMS. IGNORE SUSY'ING CONSTANT, QUARTIC + TRILINEAR COUPLINGS.

NOW CONSIDER THE $(\varphi\tilde{\varphi} - \mu^2 \mathbb{1})$ TERM

$$\varphi\tilde{\varphi} - \mu^2\mathbb{1} = \begin{pmatrix} \frac{1}{2}(\delta\chi_+ + \delta\chi_-)(\delta\chi_+ - \delta\chi_-) & (\mu + \frac{1}{\sqrt{2}}(\delta\chi_+ + \delta\chi_-))\frac{1}{\sqrt{2}}(\delta\rho_+ - \delta\rho_-) \\ \frac{1}{\sqrt{2}}(\delta\rho_+ + \delta\rho_-)(\mu + \frac{1}{\sqrt{2}}(\delta\chi_+ - \delta\chi_-)) & \frac{1}{2}(\delta\rho_+ + \delta\rho_-)(\delta\rho_+ - \delta\rho_-) - \mu^2 \end{pmatrix}$$

THIS IS UGLY LOOKING. LET'S SIMPLIFY

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} A^\dagger & C^\dagger \\ B^\dagger & D^\dagger \end{pmatrix} = \begin{pmatrix} AA^\dagger + BB^\dagger & \\ & CC^\dagger + DD^\dagger \end{pmatrix}$$

we only care about diag terms for the trace (Tr implied)

$$\begin{aligned} \mathrm{Tr}\left|\varphi\tilde{\varphi} - \mu^2\right|^2_{\mathrm{MASS}} = {} & \frac{1}{2}\left|\mu(\delta\rho_+ - \delta\rho_-)\right|^2 + \frac{1}{2}\left|(\delta\rho_+ + \delta\rho_-)\mu\right|^2 \\ & - \frac{1}{2}(\mu^\dagger)^2(\delta\rho_+ + \delta\rho_-)(\delta\rho_+ - \delta\rho_-) \\ & - \frac{1}{2}\mu^2(\delta\rho_+ + \delta\rho_-)^\dagger(\delta\rho_+ - \delta\rho_-)^\dagger \end{aligned}
\;\Bigg|\; \begin{aligned} \rightarrow {} & \frac{1}{2}|\delta\rho_+ - \delta\rho_-|^2 + \frac{1}{2}|\delta\rho_+ + \delta\rho_-|^2 \\ & - \frac{1}{2}(\delta\rho_+ + \delta\rho_-)(\delta\rho_+ - \delta\rho_-) \\ & - \frac{1}{2}(\delta\rho_+ + \delta\rho_-)^\dagger(\delta\rho_+ - \delta\rho_-)^T \end{aligned}$$

STILL LOOKS UGLY, ESP SINCE μ COMES IN AS μ^2, $(\mu^\dagger)^2$, $|\mu|^2$. BUT THIS IS EASY TO FIX, AS HINTED BY THE PAPER. ABSORB μ INTO ρ:

$$\delta\rho_\pm \rightarrow \frac{\mu^*}{|\mu|}\delta\rho_\pm \qquad \frac{1}{|\mu|} \text{ TO PRESERVE NORMALIZATION}$$

NOW SPLIT $\delta\rho_\pm$ INTO Re & Im PARTS. (AS A MATRIX)

$$\delta\rho_\pm = a_\pm + ib_\pm \qquad \leftarrow \text{recall: } \begin{aligned} (a+ib)(c+id) &= ac + iad + ibc - bd \\ (a-ib)(c-id) &= ac - iad - ibc - bd \end{aligned}$$

$$\begin{aligned} 2\mathrm{Tr}\left|\varphi\tilde{\varphi} - \mu^2\right|^2_{\mathrm{mass}} = {} & + |\delta\rho_+|^2 \cancel{- \delta\rho_+\delta\rho_-^\dagger} \cancel{- \delta\rho_-\delta\rho_+^\dagger} + |\delta\rho_-|^2 \\ & + |\delta\rho_+|^2 \cancel{+ \delta\rho_+\delta\rho_-^\dagger} \cancel{+ \delta\rho_-\delta\rho_+^\dagger} + |\delta\rho_-|^2 \\ & - \delta\rho_+^2 \cancel{- \delta\rho_-\delta\rho_+} \cancel{+ \delta\rho_+\delta\rho_-} + \delta\rho_-^2 \\ & - (\delta\rho_+^\dagger)^2 \cancel{+ \delta\rho_-^\dagger\delta\rho_+^\dagger} \cancel{- \delta\rho_+^\dagger\delta\rho_-^\dagger} + (\delta\rho_-^\dagger)^2 \end{aligned}$$

THESE CANCEL b/c OF IMPLIED TRACE

$$\Rightarrow (a+ib)^2 + (a-ib)^2 = 2(a^2 - b^2)$$

$$\begin{aligned} &= 2(a_+^2 + b_+^2) + 2(a_-^2 + b_-^2) \\ &\quad - 2(a_+^2 - b_+^2) + 2(a_-^2 - b_-^2) \\ &= 4b_+^2 + 4a_-^2 \\ &= \boxed{4\left[\mathrm{Im}(\delta\rho_+)\right]^2 + 4\left[\mathrm{Re}(\delta\rho_-)\right]^2} \end{aligned}$$

w/ $\delta\rho_\pm = \frac{\mu^*}{|\mu|}\delta\rho_\pm$

$$|\Phi\tilde{\varphi}|^2 + |\varphi\Phi|^2\Big|_M = \boxed{|Y\mu|^2 + |\tilde{Z}\mu|^2 + |\mu Y|^2 + |\mu Z^T|^2}$$

SO WE SEE: Y, $\tilde{Z}$, Z^T, $\mathrm{Im}(\delta\rho_+)$, $\mathrm{Re}(\delta\rho_-)$ ALL GET TREE LEVEL MASSES.
SO WE'VE SEEN THAT THE FIELDS THAT ARE MASSIVE ARE INDEED THOSE THAT ISS CLAIM AREN'T MODULI

WHAT REMAINS TO FIGURE OUT: IDENTIFY FIELDS ASSOC. W/ GOLDSTONES & FLAT DIRECTIONS

NOW CONSIDER 1-LOOP EFF POTENTIAL IN BG OF VEVS $(\Phi_0 = 0,\ \varphi_0 = \tilde\varphi_0 = \mu 1\!\!1_N)$

$$V^{(1)} = \underset{\text{DIM-ANALYSIS}}{|h^4\mu^2|}\left(\frac{1}{2}\underset{\uparrow}{a}\,\mathrm{Tr}\,\delta\hat{\chi}^2 + \underset{\uparrow}{b}\,\mathrm{Tr}\,\delta\hat{\Phi}^\dagger\delta\hat{\Phi}\right) + \cdots$$

NUMERICAL COEFFICIENTS

↑ THIS FORM COMES FROM GLOBAL SYMMETRIES & SINGLE TRACES IN THE CW POTENTIAL.
(I DON'T QUITE UNDERSTAND. ISS SAYS THIS IS EQUIVALENT TO SAYING THAT ONLY PLANAR DIAGRAMS CONTRIBUTE @ 1-LOOP) } see below

PUTTING IN CLASSICAL MASSES (THIS IS DONE IN APP B OF ISS)

$$\rightarrow a = \frac{\log 4 - 1}{8\pi^2}(F-N) \qquad b = \frac{\log 4 - 1}{8\pi^2}N$$

LET'S TRY TO SKETCH WHAT'S GOING ON:

$$V^{(1)} = \frac{1}{64\pi^2}\left(\mathrm{Tr}\,M_B^4\log\frac{M_B^2}{\Lambda^2} - \mathrm{Tr}\,M_F^4\log\frac{M_F^2}{\Lambda^2}\right)$$

$\sim\langle\delta\hat{\chi}\rangle$ $\sim\langle\hat{\Phi}\rangle$

small (assume)

TREAT PSEUDOMODULI AS CLASSICAL BG (2-PARAM SPACE LABELED BY X_0, θ)

$$\Phi = \begin{pmatrix} \delta Y & \delta Z^T \\ \delta\tilde{Z} & X_0 1\!\!1_{(F-N)} + \delta\hat{\Phi}\end{pmatrix} \qquad \varphi = \begin{pmatrix} \mu e^{i\theta}1\!\!1_N + \delta\chi \\ \delta\rho \end{pmatrix} \quad \tilde\varphi^T = \begin{pmatrix} \mu e^{-i\theta}1\!\!1_N + \delta\tilde\chi \\ \delta\tilde\rho\end{pmatrix}$$

THIS APPARENTLY YIELDS

$$\langle V^{(1)}\rangle = \text{const} + h^4\mu^2\left(\frac{1}{2}aN\mu^2(\theta+\theta^*)^2 + b(F-N)|X_0|^2\right) + \cdots$$

CLASSICAL MASSES: PLUG $\Phi, \varphi, \tilde\varphi$ INTO CLASSICAL SUPERPOTENTIAL

$$\begin{aligned} W &= h\,\mathrm{Tr}\,\varphi\Phi\tilde\varphi - h\mu^2\,\mathrm{Tr}\,\Phi \\ &= h\,\mathrm{Tr}\big[\mu e^{\theta}\delta Z^T\delta\tilde\rho + \mu e^{-\theta}\delta\tilde{Z}^T\delta\rho + \delta\rho^T(X_0 + \delta\hat\Phi)\delta\tilde\rho - \mu^2(X_0 + \delta\hat\Phi) \\ &\qquad + \mu e^{\theta}\delta Y\delta\tilde\chi + \mu e^{-\theta}\delta Y^T\delta\chi\big] + \cdots \end{aligned}$$

OBSERVE:

- OFF-DIAGONAL COMPONENTS OF $\delta\hat\Phi$ DO NOT CONTRIBUTE
- $\delta\chi$, $\delta\tilde\chi$, δY ONLY COUPLE TO SUSY FIELDS $\delta\rho$, $\delta\tilde\rho$ THROUGH CUBIC OR HIGHER INTS.
  - ⇒ MASS MATRIX FOR THESE FIELDS WILL BE SUSY'IC
  - ⇒ THUS THESE DO NOT CONTRIBUTE TO SUPERTRACE

REMAINING TERMS:

$$W \supset h\sum_{f=1}^{F-N}\left[(X_0 + \delta\hat\Phi_{ff})(\delta\rho\,\delta\tilde\rho^T)_{ff} + \mu e^{\theta}(\delta\tilde\rho\,\delta Z^T)_{ff} + \mu e^{-\theta}(\delta\rho\,\delta\tilde{Z}^T)_{ff} - \mu^2(X_0 + \delta\hat\Phi_{ff})\right]$$

THIS IS JUST (F−N) COPIES OF THE FORM

$$W_{OR} = h\left(X\vec\Phi_1\cdot\vec\Phi_2 + \mu e^{-\theta}\vec\Phi_1\cdot\vec\Phi_3 + \mu e^{\theta}\vec\Phi_2\cdot\vec\Phi_4 - \mu^2 X\right)$$

THIS CALCULATION HAS BEEN DONE. (see App A of ISS) IT GIVES A CALCULATION FOR $\langle V^{(1)}\rangle$. THIS GIVES VALUES FOR a, b ABOVE.

THE SUPERPOTENTIAL ABOVE SHOULD GIVE $V^{(1)}$ @ THE TOP OF THE PAGE BUT I'M TOO DAMN TIRED TO CHECK.

THE POINT IS THIS: $a, b > 0$.
$\Rightarrow$ THE VACUA ARE <u>STABLE</u>, NO TACHYONIC DIRECTIONS.

SPECTRUM HAS HIERARCHY DICTATED BY MARGINALLY IRRELEVANT COUPLING h

- FIELDS w/ tree MASSES $\sim |h\mu|$
- PSEUDO MODULI $\sim |h^2\mu|$ from: $V^{(1)}_{\text{eff}}$
- GOLDSTONES OF BROKEN GLOBAL SYM REMAIN MASSLESS
- GOLDSTINO IS MASSLESS

<u>MACRO MODEL II: DYNAMICAL SUSY RESTORATION</u>

GAUGE $SU(N)$; FOCUS ON $F > 3N$ (IR FREE) ← PERTURBATIVE
SCALE Λ_m (↑ macro) s.t. STRONGLY COUPLED FOR $E > \Lambda_m$

$$e^{-\frac{8\pi^2}{g^2(E)} + i\theta} = \left(\frac{E}{\Lambda_m}\right)^{F-3N}$$

← LANDAU POLE @ $E = \Lambda_m$)

POTENTIAL NOW ALSO HAS D TERMS, $V = V_F + V_D$

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

THIS VANISHES IN $\Phi_0 = 0$, $\{\varphi_0 = \tilde{\varphi}_0 = \mu \mathbb{1}_N\}$ VACUUM (2.7)
$\Rightarrow$ THAT VAC REMAINS A MIN OF THE TREE-LEVEL POT.

$SU(N)$ IS COMPLETELY <u>HIGGSED</u> IN THIS VAC.

<u>SUPERHIGGS MECHANISM</u>:
- $SU(N)$ GAUGE FIELDS GET MASS $g\mu$
- GOLDSTONES $(\mathrm{Im}(\mu^* \delta\chi_- / |\mu|))$ EATEN
- PSEUDOMODULI $(\delta\hat{\chi}' = \mathrm{Re}(\mu^* \delta\chi_- / |\mu|)')$ GET MASS $g\mu$

PRIME MEANS really just traceless part

NON TACHYONIC

$\longrightarrow \delta\hat{\Phi}, \mathrm{Tr}\,\delta\hat{\chi}$ REMAIN AS CLASSICAL PSEUDOMODULI

<u>NEXT STEP</u>: COMPUTE $V^{(1)}$ FOR PSEUDOMODULI, DETERMINE IF THE PS/MOD ARE STABILIZED
<u>BUT</u>: NO ADDITIONAL WORK NEEDED! EFFECTS OF $SU(N)$ GAUGE FIELDS <u>DROPS OUT</u> TO LEADING $\mathcal{O}$ IN EFF POT FOR PSEUDOMODULI.

"PSEUDOFLAT"

WHY? TREE LEVEL SPECTRUM OF MASSIVE $SU(N)$ GAUGE FIELDS DO <u>NOT</u> DIRECTLY COUPLE TO ~~SUSY~~'ING! D-TERMS VANISH ON PSEUDOMOD SPACE VEVS $\langle\varphi\rangle$ & $\langle\tilde{\varphi}\rangle$ GIVE $SU(N)$ GAUGE FIELDS MASSES, BUT DO <u>NOT</u> COUPLE DIRECTLY TO ANY NON-ZERO F-TERMS.

THE NET EFFECT OF GAUGING $SU(N)$: RESTORES SUSY VACUA.
WE ALREADY EXPECT THIS (SQCD HAS N SUSY VACUA), BUT TO SEE IT:
$W = h\,\mathrm{Tr}\,\varphi\Phi\tilde{\varphi} - h\mu^2\,\mathrm{Tr}\,\Phi \Rightarrow \varphi$ & $\tilde{\varphi}$ GET MASS $\langle h\Phi\rangle$, CAN INT. OUT
LOW-E THY IS $SU(N)$ PURE SYM w/

USING SCALE MATCHING

$$e^{-\frac{8\pi^2}{g^2} + i\theta} = \left(\frac{\Lambda_L}{E}\right)^{3N} = \frac{h^F \det\Phi}{(\Lambda_m)^{F-3N}\, E^{3N}} \Rightarrow W_{\text{low}} = \underbrace{N\left(\frac{h^F \det\Phi}{(\Lambda_m)^{F-3N}}\right)^{1/N}}_{\text{GAUGINO COND!}} - h\mu^2\,\mathrm{Tr}\,\Phi$$

note: we are not including phys from UV cutoff Λ_m, this scale appears from expressing g in the holomorphic coupling

CONT'D

NOTE BOOK

(CONTINUING: SEE THE SUSY VACUA)

(F-N) SUSY VACUA FROM EXTREMIZING W:

PARAMETRICALLY SMALL ↓

$$\langle h\Phi \rangle = \Lambda_m \varepsilon^{\frac{2N}{F-N}} \mathbb{1}_{F\times F} = \mu \frac{1}{\epsilon^{(F-3N)/(F-N)}} \mathbb{1}_{F\times F} \quad ; \quad \epsilon \equiv \frac{\mu}{\Lambda_m}$$

FOR $|\epsilon| \ll 1$, $|\mu| \ll |\langle h\Phi \rangle| \ll |\Lambda_m|$.

↑ well below LANDAU POLE ⇒ LOW-E MACRO THY IS JUSTIFIED & RELIABLE

↑ GUARANTEES LONGEVITY OF METASTABLE NON SUSY VACUA (will see in §7)

SO WE SEE "<u>DYNAMICAL SUSY RESTORATION</u>" IN A TREE-LEVEL $\cancel{\text{SUSY}}$ MODEL

- for $\Lambda_m \to \infty$ w/ μ FIXED, THY BREAKS $\cancel{\text{SUSY}}$
- for Λ_m LARGE BUT FINITE (SMALL, NONZERO ε)
  - → SUSY VAC COMES IN FROM ∞
  - IN SEC 5 WE'LL REALIZE METASTABLE $\cancel{\text{SUSY}}$'ing DYNAMICALLY

<u>CONNECTION BTWN $\cancel{\text{SUSY}}$ & R SYM</u>

MACRO THY I HAD $U(1)_R$ & $\cancel{\text{SUSY}}$

MACRO THY II BREAKS $U(1)_R$ (ANOMALOUS UNDER SU(N) GAUGE GROUP)

⇒ ∃ SUSY VACUA.

FOR $\langle \Phi \rangle$ near origin, SU(N) IS IR FREE

⇒ $U(1)_R$ RETURNS AS <u>ACCIDENTAL SYM</u> OF IR THEORY

ie $\cancel{\text{SUSY}}$ NEAR ORIGIN ⟷ ACCIDENTAL R-SYM.

<u>EFFECTS FROM THE UNDERLYING MICRO THY</u>

Q: DO ABOVE RESULTS DEPEND ON PHYSICS @ UV CUTOFF SCALE $|\Lambda_m|$?

WE DON'T HAVE ANY CONTROL OF THAT PHYSICS.

OUR ONLY DIM-FUL PARAM IS μ, CAN ASSUME

$$|\varepsilon| = \left|\frac{\mu}{\Lambda_m}\right| \ll 1$$

<u>CLAIM</u>: THIS GUARANTEES THAT OUR CALC ABOVE GIVE DOMINANT EFFECT TO LOW ENERGY EFF THY.

LOOPS FROM HI-ENERGY UV

THESE SHOW UP AS CORRECTIONS TO EFFECTIVE KAHLER POT:

$$\delta K = \frac{c}{|\Lambda_m|^2} \mathrm{Tr}\left(\Phi^\dagger \Phi\right)^2 + \cdots$$

$\uparrow$ c IS DIMLESS $\mathcal{O}(1)$

USUAL ARGUMENT: DECOUPLING; HI-DIM OPS SUPPRESSED BY POWERS OF $|\Lambda_m|$ & HENCE DO NOT AFFECT LOW-E.

WHAT WE DID: WE LOOKED AT LOW E EFF POT $V^{(1)}$ OF PSEUDOFLAT DIR.
WE FOCUSED ON LIGHT FIELDS W/ MASS ~ μ (set $h=1$)
WE NEGLECTED MODES W/ MASS ~ Λ_m

THESE HEAVY MODES HAVE MASSES ALSO SPLIT BY ~~SUSY~~'ING
COULD THIS CHANGE OUR CONCLUSION ABOUT DECOUPLING OF EFF POT?

$\mathbb{R}$ ANALYTIC AS OPPOSED TO $\mathbb{C}$ ANALYTIC (HOLOMORPHIC)
NOT DIFFERENTIABLE @ ZERO

$V^{(1)}$ FROM P.64 IS PROPORTIONAL TO $|\mu^2|$
$\Rightarrow$ NOT REAL ANALYTIC IN μ^2 PARAMETER OF SUPERPOTENTIAL
(MAGIC WORD FOR SEIBERG

OOP! WILSONIAN VS 1PI ...

WHY? THE MODES WE INTEGRATED OUT BECOME MASSLESS AS $\mu \to 0$, SO CONTRIBUTION TO EFF POT. IS SINGULAR THERE.

ON THE OTHER HAND: CORRECTIONS FROM HEAVIER MODES ($\sim \Lambda_m$) ARE NECESSARILY REAL ANALYTIC IN μ^2.

$\Rightarrow$ LEADING CORRECTION FROM MICRO THY TO PSEUDOMODULUS MASS MUST HAVE COEFFICIENT

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

$\uparrow$ THIS IS $\mathbb{R}$ ANALYTIC SINCE IT IS DIFFERENTIABLE @ 0!

THIS IS SMALLER THAN LOW-E MACRO THY CONTRIBUTIONS.
WHY? INT OUT MASSIVE MODES FOR $\mu = 0$ & SUMMARIZE AS δK
USE THIS CORRECTED K W/ tree-level W TO FIND EFF ON PSEUDO-FLAT DIRECTIONS. THESE CORRECTIONS ARE ~ $|\mu^2 \epsilon^2|$ AND ARE NEGLIGIBLE.

THIS MATTERS: W/O DETAILS OF MICRO THY, CANNOT DETERMINE LOOP EFFECTS FOR $\sim\Lambda_m$ MODES. CANNOT EVEN DETERMINE SIGN OF COEF LIKE c IN δK $\Rightarrow$ CANNOT DETERMINE IF THEY STABILIZE/DESTABILIZE PSEUDOFLAT DIRECTIONS.
THUS IT'S GOOD THAT THEY CANNOT SPOIL THE STABILIZATION OF THE MACRO THY 1-LOOP EFFECTS

THIS BOILS DOWN TO AN 'OBVIOUS' DISCUSSION OF THE "IRRELEVANCE OF IRRELEVANT OPERATORS"

NOW SOMETHING NONTRIVIAL: IN GAUGED MACRO MODEL WE TOOK INTO ACCOUNT NONPERTURBATIVE EFFECTS IN W_{low}. THESE EFFECTS ARE <u>ALSO</u> SUPPRESSED BY $|\Lambda_m|$.

1. WHY IS THIS NON-RENORMALIZABLE INTERACTION RELIABLY COMPUTED EVEN THOUGH IT DEPENDS ON Λ_m?
2. WHY IS IT JUSTIFIED TO NEGLECT OTHER TERMS IN δK WHICH ARE ALSO SUPPRESSED BY POWERS OF Λ_m?

$\boxed{1}$ Λ_m APPEARED IN W_{low} AS A WAY TO PARAMETERIZE THE IR FREE GAUGE COUPLING g & E SCALES BELOW $|\Lambda_m|$.

THIS IS CONCEPTUALLY DIFFERENT FROM $|\Lambda_m|$ IN δK WHICH MANIFESTLY HAS TO DO WITH EFFECTS FROM THE MICROSCOPIC THY, IE PHYSICS ABOVE LANDAU POLE SCALE.

IN OTHER WORDS, W_{low} IS GENERATED BY LOW-E PHYSICS.
SANITY CHECK: $\langle\Phi\rangle$ @ SUSY VACUA $\ll |\Lambda_m| \Rightarrow$ READILY CALCULATED.

$\boxed{2}$ LEADING CONTRIBUTION TO $\delta K \sim |\Phi|^4/|\Lambda_m|^2$, CORRESPONDING TO

$$\Delta_K V_{eff} \sim \left|\frac{\mu^2\Phi}{\Lambda_m}\right|^2 \sim |\mu^2\epsilon^2|\,|\Phi|^2$$

FOR $|\epsilon| \ll 1$, $\Delta_K V_{EFF} \ll V^{(1)}$ FROM MACRO THY.
HIGHER CORRECTIONS TO K HAVE MORE (Φ/Λ_m) SUPPRESSION
$\rightarrow$ NEGLIGIBLE FOR $|\Phi| \ll |\Lambda_m|$
RECALL $|\epsilon| \ll 1 \leftrightarrow |\mu| \ll |\langle h\Phi\rangle| \ll |\Lambda_m|$ (P-66)

COMPARE $\Delta_K V_{eff}$ TO $\Delta_W V_{eff}$, CORRECTION FROM W_{low} IN MACRO II

$$\Delta_W V_{eff} \sim \left|\frac{\mu^2\,\Phi^{\frac{F-N}{F}}}{\Lambda_m^{\frac{F-3N}{N}}}\right|$$

FOR $|\Phi| \gg \left|\Lambda_m \epsilon^{\frac{3N}{F-3N}}\right|$, $\Delta_W V_{eff}$ IS MORE IMPORTANT.
FOR SMALLER VALUES OF Φ, BOTH ARE NEGLIGIBLE.

<u>CONCLUSION</u>: CORRECTIONS FROM UV THY & MACRO MODES @ Λ_m DO <u>NOT</u> INVALIDATE OUR CONCLUSIONS!

MACRO MODELS ARE "UNDER CONTROL"
& GIVE DOMINANT CONTRIBUTIONS TO LOW-E DYNAMICS.

METASTABLE VACUA IN SQCD

NOW WE ASSEMBLE ALL THESE TOOLS & PUT THEM TO USE.

MODEL: SU(N) SQCD w/ SCALE Λ, F QUARKS

$$W = \mathrm{Tr}\, mM \quad ; \quad m \text{ NON-DEGENERATE}$$

DIAGONALIZE w/ BIUNITARY TRANS.
DIAG ELEM CAN BE SET TO $m_i > 0, \in \mathbb{R}$

N SUSY GROUND STATES: $\langle M \rangle = \left(\Lambda^{3N-F} \det m\right)^{\frac{1}{N}} \frac{1}{m}$

PRESERVE ~~SUSY GROUND ST~~ BARYON #

$\Rightarrow \langle B \rangle = \langle \tilde{B} \rangle = 0$

CASE OF INTEREST: m_i SMALL, SAME ORDER OF MAGNITUDE

$$m_i \ll |\Lambda| \quad ; \quad \frac{m_i}{m_j} \sim 1$$

CAN BE STUDIED w/ SEIBERG DUALITY

CONSIDER: $F > N$; in $\lim m_i \to 0$, $m_i/m_j \sim 1$; $\boxed{\langle M \rangle \to 0.}$

CAN STUDY THIS MODEL IN THIS LIMIT w/ SEIBERG DUALITY:

MAGNETIC THY: SU(F−N) w/ SCALE $\tilde{\Lambda}$, F^2 SINGLETS M_m & F mag-quarks $q, \tilde{q}$

$M_m = M$

FREE MAGNETIC RANGE $F < \frac{3}{2}N$, MAG THY IR FREE
→ METRIC FOR MODULI SPACE SMOOTH AROUND ORIGIN

$$\Rightarrow K = \frac{1}{\beta}\mathrm{Tr}\left(q^\dagger q + \tilde{q}^\dagger \tilde{q}\right) + \frac{1}{\alpha|\Lambda|^2}\mathrm{Tr}\, M^\dagger M + \dots$$

$\alpha, \beta > 0, \mathbb{R}$
$\alpha, \beta \sim 1$

PRESICE VALUES CANNOT EASILY BE DETERMINED
(NOT ASSOCIATED w/ HOLOMORPHIC INFO)
BUT QUALITATIVE RESULTS WILL NOT DEPEND ON THIS.

Λ APPEARS B/C M IDENTIFIED w/ MICRO FIELD
$M = Q\tilde{Q}$ w/ $[M]_{\text{CLASSICAL}} = 2$

$$W_{\text{DUAL}} = \frac{1}{\hat{\Lambda}}\mathrm{Tr}\, Mq\tilde{q} + \mathrm{Tr}\, mM$$

$$\Lambda^{3N-F}\tilde{\Lambda}^{3(F-N)-F} \equiv (-)^{F-N}\hat{\Lambda}^{F}$$

THIS COMES FROM SCALE MATCHING of P.50, IS "EM DUALITY" eq. (5.6)
DEFINES $\hat{\Lambda}$

(5.6)

$\tilde{\Lambda}, \hat{\Lambda}$ NOT UNIQUELY DET BY ELECTRIC THEORY (JUST PARAMETERS IN MAG THY)
related to freedom to rescale $q, \tilde{q}$
(M HAS A FIXED NORMALIZATION FROM W, CAN IDENTIFY M w/ M IN ELEC THY.)

RESCALING $q, \tilde{q}$: ALSO AFFECTS β IN K, $\hat{\Lambda}$
CHANGES RELATIONS BTWN $B, \tilde{B} \longleftrightarrow q^{F-N}, \tilde{q}^{F-N}$
$\tilde{\Lambda}$ CHANGES TO PRESERVE (5.6)
reflects anomaly of $q\tilde{q}$ rescaling w/r t SU(F−N)

- USE FREEDOM TO RESCALE $q, \tilde{q}$ TO SET $\beta = 1$
BUT: CANNOT COMPUTE BOTH $\hat{\Lambda}, \tilde{\Lambda}$ IN TERMS OF ELECTRIC VARS } BECOMES MACRO I

- ALTERNATELY, RESCALE $q, \tilde{q}$ TO SET $B = Q^N = q^{F-N}$, $\tilde{B} = \tilde{Q}^N = \tilde{q}^{F-N}$ } BECOMES MACRO II

BUT: THEN CANNOT COMPUTE (DIMENSIONFUL) β.

we'll use both.

CASE: $m_i = m_0$
δK SUPPRESSED BY Λ, NOT IMPORTANT NEAR $M = q = \tilde{q} = 0$.
EVALUATE K @ $m_0 = 0$; CORRECTIONS ARE $\mathcal{O}(m_0^2/\Lambda^2) \rightarrow$ NEGLIGIBLE

$$\Rightarrow \begin{cases} K = \frac{1}{\beta} \mathrm{Tr}(q^\dagger q + \tilde{q}^\dagger \tilde{q}) + \frac{1}{\alpha|\Lambda|^2} \mathrm{Tr}\, M^\dagger M + \cdots \\ W_{\text{DUAL}} = \frac{1}{\hat{\Lambda}} \mathrm{Tr}\, M q\tilde{q} + \mathrm{Tr}\, mM \end{cases}$$

$\hookrightarrow$ THEN THIS THEORY MATCHES MACRO MODEL II, USING DICTIONARY

$$\begin{cases} \varphi = q, \quad \tilde{\varphi} = \tilde{q}, \quad \Phi = \frac{M}{\sqrt{\alpha}\Lambda}, \quad h = \frac{\sqrt{\alpha}\Lambda}{\hat{\Lambda}} \\ \mu^2 = -m_0 \hat{\Lambda}, \; \Lambda_m = \tilde{\Lambda}, \quad N = (F-N) \end{cases}$$

WHERE WE CHOSE $\beta = 1$, LEFT $\tilde{\Lambda}, \hat{\Lambda}$ AS PARAM..

CASE: $F = N + 1 \rightarrow$ MAGNETIC GAUGE GROUP IS TRIVIAL

SCALE $q, \tilde{q}$ AS IN SECOND CASE ABOVE ($B = q^{F-N}$, $\tilde{B} = \tilde{q}^{F-N}$)
THEN

$$K = \frac{1}{\beta} \mathrm{Tr}(q^\dagger q - \tilde{q}^\dagger \tilde{q}) + \cdots \longrightarrow K = \frac{1}{\underbrace{\beta|\Lambda|^{2N-2}}_{\text{for dims}}} (B^\dagger B + \tilde{B}^\dagger \tilde{B})$$

THE SUPERPOTENTIAL is DIFFERENT:

(PAGE 48)

$$W = \frac{1}{\Lambda^{2N-1}} (\tilde{B}^T M B - \underline{\det M}) + \mathrm{Tr}\, mM$$

$\uparrow$
FOR $N > 2$ THIS IS NEGLIGIBLE NEAR ORIGIN
$\Rightarrow$ THY BECOMES SAME AS $N=1$ THEORY FOR <u>MACRO I</u>

NOW WE JUST USE RESULTS OF §2 + §3

CONCLUSION: $N+1 \leq F < \frac{3}{2}N$ w/ SUITABLE TREE MASSES
$\Rightarrow$ SQCD HAS METASTABLE $\cancel{\text{SUSY}}$ GROUND STATE NEAR ORIGIN

IN FACT, COMPACT MODULI SPACE OF METASTABLE VACUA PARAMETERIZED BY GOLDSTONES.

<u>MIRACLE</u>: WE COULD ESTABLISH EXISTENCE OF METASTABLE STATE EVEN IN STRONGLY COUPLED REGIME. VAC PARAM BY JUST 2 DIMLESS #s, α, β. THIS RESULT EVEN INCLUDES NON-SUSY, NON-CHIRAL INFO.

COMMENTS ON GENERALIZATION

1. UNEQUAL TREE-LEVEL QUARK MASSES, $m_i \neq m_0$, $(m_i \ll |\Lambda|)$

FIRST CONSIDER $|m_i - m_0| \ll m_0 \ll |\Lambda|$ LIMIT

- EFFECT OF NONDEGENERACY IS SMALL POTENTIAL ON MOD SPACE OF METASTABLE VAC
- BUT VAC MANIFOLD FOR METASTABLE STATES IS COMPACT SO THY W/ UNEQUAL MASSES ALSO HAS METASTABLE VAC.

MORE GENERALLY, CONSIDER ARBITRARY $m_i \ll |\Lambda|$

- LOW-E EFT STILL IMPLIES METASTABLE STATE NEAR ORIGIN
- THE MACRO MODEL I SUPERPOTENTIAL IS MODIFIED $\quad \overset{\checkmark}{\mu_i^2} = -m_i \hat{\Lambda}$

$$W_{tree} = h \operatorname{Tr} \varphi \Phi \tilde{\varphi} - h\mu^2 \operatorname{Tr} \Phi \longrightarrow W_{tree} = h \operatorname{Tr} \varphi \Phi \tilde{\varphi} - h \sum_{i=1}^{F} \mu_i^2 \Phi^i_i$$

- WRITE m_i s.t. $m_1 \geq m_2 \geq \cdots \geq m_F > 0$.
- METASTABLE STATE IS

$$\Phi = 0 \qquad \varphi = \tilde{\varphi}^T = \begin{pmatrix} \varphi_0 \\ 0 \end{pmatrix}; \quad \varphi_0 = \operatorname{diag}(\mu_1, \ldots, \overset{F>N}{\downarrow}\mu_N)$$

- NONZERO F-TERMS: $F_{\Phi^i_i}$ for $i = (N+1), \ldots, F$

$$V_0 = \sum_{i=(N+1)}^{F} |h\mu_i^2|.$$

- METASTABLE VAC $\Rightarrow$ CRUCIAL THAT $\langle \varphi_0 \rangle$ SET BY N LARGEST MASSES OTHERWISE TREE-LEVEL SPECTRUM HAS UNSTABLE MODE THAT SLIDES HELPLESSLY TO VAC W/ $\langle \varphi_0 \rangle$ SET ON N LARGEST MASSES.

WHAT ABOUT $m_i \gg |\Lambda|$?

- IF ALL $m_i \gg |\Lambda|$, THEN NO REASON TO BELIEVE METASTABLE STATE $\exists$
- IF JUST ONE $m_F \gg |\Lambda|$ WHILE OTHER MASSES SMALL, WE CAN TREAT AS MASS PERTURBATION & INTEGRATE OUT, REDUCE TO THY W/ 1 LESS FLAVOR (AS LONG AS $F' \geq N+1$) & OUR LOW E ANALYSIS STILL IS VALID.

- WHAT IF WE TRIED TO PUSH OUR LUCK, $F = N+1 \to F' = N$

2. CHANGING # FLAVORS F

$F = N$ (ie $F = N+1 \to F' = N$)

IF $m_1, \ldots, m_N \ll m_{N+1} \ll |\Lambda|$, WE HAVE METASTABLE STATE
W/ $B_i = \bar{B}_i = 0 \quad \forall\, i = 1, \ldots, N$
$B_{N+1} = \bar{B}_{N+1} \neq 0$

NOW SUPPOSE WE CAN TRUST THIS FOR $m_{N+1} \gg |\Lambda|$

IF WE CAN TRUST $m_{N+1} \ll |\Lambda|$ RESULT FOR $m_{N+1} \gg |\Lambda|$, (IF!)
THEN WE CAN UNDERSTAND $F=N$.

$m=0 \rightarrow$ QUANT MOD CONSTRAINT : $\det M - B\tilde{B} = \Lambda^{2N}$
W SMOOTH K ON THIS SPACE

CONSIDER THY AROUND $M=0$, $B=\tilde{B}=i\Lambda^N$
K DEP ON FIELDS TANGENT TO Q.MOD C. @ THAT POINT:

$$K = \frac{1}{\alpha|\Lambda|^2}\mathrm{Tr}M^\dagger M + \frac{|\Lambda|^2}{\beta} b^\dagger b + \cdots$$

α, β DIMLESS, +'ive, R, incalc.

$$B = i\Lambda^N e^{b}$$
$$\tilde{B} = i\Lambda^N e^{-b}$$

TURN ON $\Delta W = m_0 \mathrm{Tr} M$ LEAVES $M \,\&\, b$ AS LEAD-O UNLIFTED FLAT DIR.
(LIFTED @ higher O by incalculable higher terms in K)
UNLIKE CASE W MORE FLAVORS (LOOPS OF MASSIVE-BUT-LIGHT FIELDS GIVE DOM CONTRIB.)
NO SUCH LIGHT FIELDS IN THIS CASE TO GIVE RELIABLE CALC.

motivated by flow from $F=N+1$ they, WE SUSPECT THERE ARE METASTABLE

SO FAR WE'VE FOCUSED ON $F < \frac{3}{2}N$ WINDOW WHERE MAG DOF ARE IR FREE
LET'S THINK ABOUT LARGER VALUES OF F.

$F \geq 3N$: ELEC THY NOT STRONGLY COUPLED IN IR $\rightarrow$ TRIVIAL DYNAMICS
METASTABLE STATES NOT PRESENT

$\frac{3}{2}N < F < 3N$: E & MAG FLOW TO SAME NONTRIVIAL FIXED POINT.
USE, AGAIN, MAGNETIC DESCRIPTION ... BUT NEED TO MODIFY :

DUALITY STILL VALID BELOW Λ ONLY
BUT NOW MAGNETIC THEORY IS INTERACTING (NOT FREE)

$\leftrightarrow$ for nonzero M,

just ADS

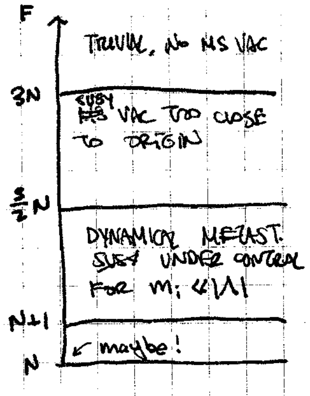
$$W_{dyn} = (N-F)\left(\frac{\det M}{\Lambda^{3N-F}}\right)^{\frac{1}{F-N}} = (N-F)\left(\frac{\Lambda^{3N-F}}{\det M}\right)^{\frac{1}{N-F}}$$

NEAR THE ORIGIN, SCALES LIKE $M^{\frac{F}{F-N}} > M^3$
$\rightarrow$ CANNOT BE NEGLECTED

$\Leftrightarrow \langle M \rangle = (\Lambda^{3N-F} \det m)^{\frac{1}{N}} \frac{1}{m}$ (from p.69)
is TOO CLOSE TO THE ORIGIN FOR METASTABLE STATE

$F = \frac{3}{2}N$: SUBTLE : IR FREE ONLY B/C OF 2-LOOP β-FUNC
W_{dyn} SCALES LIKE M^3, AGAIN CANNOT BE NEGLECTED NEAR ORIGIN
IN THIS CASE W_{dyn} INDEP OF Λ & W_{dyn}^{mag} IND OF Λ_m.

SUMMARY.



IF MASSES DEGENERATE → $U(F) \simeq SU(F) \times U(1)_B$ GLOBAL SYMMETRY. SUSY VACUA BREAK THIS (CONSISTENT W/ MASS GAP)

METASTABLE VAC: $U(F) \rightarrow SU(F-N) \times SU(N)$ + ACCIDENTAL R
so ∃ COMPACT MODULI SPACE OF VACUA

$$\mathcal{M}_c \cong \frac{U(F)}{SU(F-N) \times SU(N)}$$

THIS HAS A BIGGER CONFIG SPACE THAN ISOLATED SUSY VAC.
⇒ COSMOLOGY MAY FAVOR METASTABLE VAC

MASS SPECTRUM SUMMARY

- HEAVY MICROSCOPIC STATES w/ MASS $\sim \Lambda$
- LOW E MAGNETIC STATES
  - w/ TREE-LEVEL MASSES $\sim \sqrt{m\Lambda} \ll \Lambda$ (gauge fields, gauginos)
  - massive pseudomoduli ~ SUPPRESSED BY LOOP FACTOR OF IR FREE magnetic YUKAWA
- MASSLESS SCALARS
  - GOLDSTONE of $\mathcal{M}_c$
  - ~~MASSIF~~
- MASSLESS FERMIONS (inc GOLDSTINO) fermions
  - N^2 FERMIONIC PARTNERS OF Φ_0 PSEUDOMODULI
    (fermions ψ_M in nullspace of $\langle q \rangle$ & $\langle \tilde{q} \rangle$)

COOL FEATURE: $\mathcal{M}_c$ HAS NONTRIVIAL TOPOLOGY.
EXPECT SOLITONS w/ LIFETIME ~ metastable VAC

COMMENT ON LIFETIME of MS VAC (see § 7 for more details)

METASTABLE VAC:

$$\Phi = 0 \qquad \varphi = \tilde{\varphi}^T = \begin{pmatrix} \mu \mathbb{1}_N \\ 0 \end{pmatrix} \qquad w/ \quad V_+ = (F-N)|h^2\mu^4|$$

SUSY VAC:

$$\Phi = \frac{\mu}{h} \frac{1}{\epsilon^{(F-3N)/(F-N)}} \mathbb{1}_F \; ; \quad \varphi = \tilde{\varphi} = 0 \; , \quad V_0 = 0$$

F > 3N (MACRO THY IS IR FREE)

AS $\epsilon \to 0$, SUSY MIN IS PARAMETRICALLY FAR AWAY.
SEE COLEMAN'S "FATE OF FALSE VAC" FOR CALCULATION.

THE POINT IS THAT WE CAN GET $\tau \sim$ Age of Universe.

THOUGHTS ON MODEL BUILDING

1. NATURALNESS

$\epsilon \sim \sqrt{m/\Lambda}$, $V \sim |m^2 \Lambda^2|$ ⇝ NONPERT (power of Λ)

↑ DEPENDS ON TREE PARAMETER m
⇒ DOES NOT SATISFY PURIST'S REQUIREMENT THAT ALL LOW E SCALES ARE GENERATED DYNAMICALLY

IDEAL: FIND THIS W/ SAME IDEAS BUT m PLAYED BY SOME MARGINAL OR IRRELEVANT COUPLINGS.
eg. M'SUPR THY W/ OP SUPPRESSED BY PLANCK: $\frac{\lambda}{M_p^{\Delta}}\mathcal{O}$ w/ $\lambda \sim 1$

OP GETS DYNAMICAL F-TERM. $F_{\mathcal{O}} \sim \Lambda^{2+\Delta} \rightarrow V \sim \frac{\lambda^2 \Lambda^{4+2\Delta}}{M_p^{2\Delta}}$

2. DIRECT MEDIATION (simpler models)

$\cancel{SUSY}$ sector HAS LARGE GLOBAL SYM G W/ $H \subset G$ GAUGED & IDENTIFIED W/ (PART) OF SM GAUGE GROUP.

eg. GAUGE $SU(F)$ IN MACRO MODEL !!
BELOW Λ GAUGE GROUP IS $\underbrace{SU(F-N)}_{\text{DUAL TO } SU(N)} \times SU(F)$

THEN METAST. VAC: $SU(F-N) \times SU(F) \longrightarrow \underbrace{SU(F-N)}_{\text{EMBEDDED DIAGONALLY INTO } SU(F-N)\times SU(F)} \times \overbrace{SU(N)}^{\text{SUBGR OF } SU(F)}$

SOME OF LOW E GAUGE FIELDS ARE PART ELEC, PART MAG.
THINK OF THIS LOW E GAUGE GROUP AS $\subseteq$ SM.
↑ OR PART OF IT

BUT: IF WE IDENTIFY, eg., $SU(3)_c$ W/ $H \subset G$ (flavor sym) ? ↓
THEN THE COLORS OF THIS SECTOR → ADDITIONAL $SU(3)$ FLAVORS
TOO MANY FLAVORS → CAN HAVE DANGEROUSLY LOW LANDAU POLES

3. R SYMMETRY PROBLEM (lots of lit on this)

- NONZERO MAJORANA GLUINO MASS ⇒ R SYM MUST BE BROKEN
  THIS WOULD RESTORE SUSY (GENERICALLY)
- CAN SOLVE W/ GRAVITY
- OUR THEORIES (ISS): NO EXACT R-SYM → METAST. SUSY
  ACCIDENTAL R-SYM NEAR ORIGIN
- SMALL EFFECT OF EXPLICIT $\cancel{R}$ IN US STATE MAY BE ENOUGH TO AVOID R SYM PROBLEM.
- AS IT STANDS, TOY MODEL HERE HAS DISCRETE (Z_{2N}?) R SYM WHICH PROTECTS US GLUINO MASS, BUT THESE CAN BE EXPLICITLY BROKEN IN MICRO THY.