Progress in SUSY breaking

SAA, C-S Chu, J.Jaeckel, V.V.Khoze, hep-th/0610334;

SAA, J.Jaeckel, V.V.Khoze, hep-th/0611130;

SAA, V.V.Khoze, hep-th/0701069;

SAA, C.Durnford, J.Jaeckel, V.V.Khoze, arXiv/0707.2958

Outline

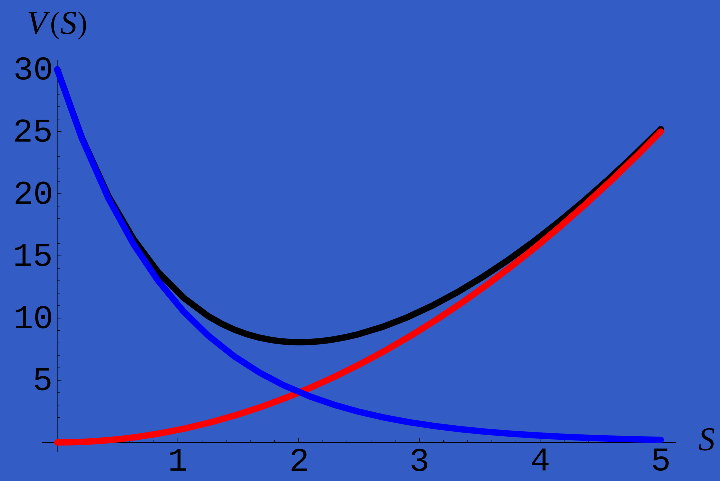
1. Inevitability of Metastability: the Nelson-Seiberg theorem
2. ISS metastable SUSY breaking
3. Cosmological properties: why the early Universe prefers them
4. More minimal mediation: SUSY breaking with spontaneous R-symmetry breaking

Inevitability of metastability

Prehistory ($\lesssim 2006$)

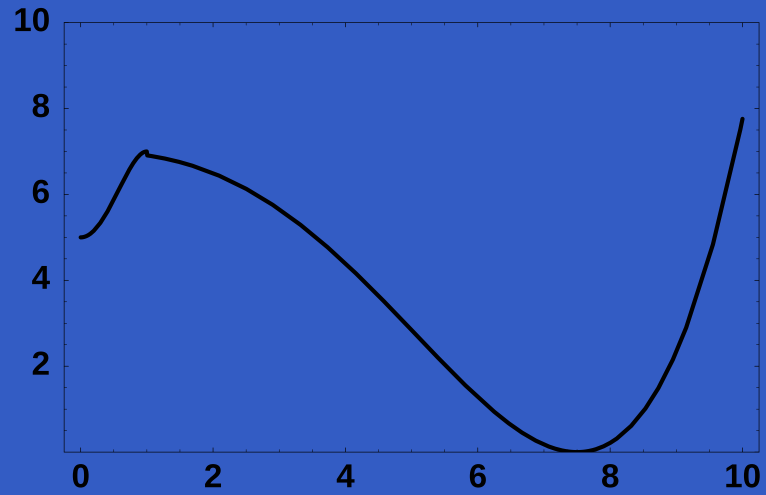
Dynamical SUSY Breaking (DSB). N=1 superpotentials augmented by dynamically generated term from strongly coupled gauge theory:

$$W = W_{cl} + W_{dyn}$$



Maybe the picture is more like

(Intriligator, Seiberg, Shih hep-th/0602239)



Metastability and Nelson-Seiberg

- Consider low-energy, calculable models of SUSY breaking
- The potential is $V = |F_i|^2 = |\frac{\partial W}{\partial \Phi_i}|^2$
- Q: When is SUSY broken? i.e. when does $F_i = 0$ not have solutions for all i?
- A: (Nelson-Seiberg) In a *generic theory,* when there is an R-symmetry.

$$\begin{aligned} \Phi_i &\longrightarrow e^{iR_i\alpha}\Phi_i \\ \theta &\longrightarrow e^{i\alpha}\theta \\ W &\longrightarrow e^{-2i\alpha}W \end{aligned}$$

Metastability and Nelson-Seiberg

But gaugino mass terms $M_\lambda \lambda^\alpha \lambda_\alpha$ have non-zero R-charge (since $W_\alpha = \lambda_\alpha + \ldots$, and $\mathcal{L}_{gauge} = \int d^2\theta W_\alpha W^\alpha$)

Non-zero gaugino masses require both R-symmetry and SUSY breaking but these are mutually exclusive!

Metastability and Nelson-Seiberg

Option 1: explicit R breaking

$$W = W_{R-sym} + \varepsilon W_{R-breaking}$$

A global SUSY minimum develops $\mathcal{O}(1/\varepsilon)$ away in field space, with $M_\lambda \propto \varepsilon$

Metastability and Nelson-Seiberg

Option 2: spontaneous R breaking

- How to do it?
- The massless R-axion?

To give the axion a mass need additional R-symmetry breaking $\varepsilon W_{R-breaking}$, but now M_λ is independent of ε

Metastability and Nelson-Seiberg

Corollary: the Universe is metastable!

ISS metastable models

ISS meta-stable models

Content of the microscopic “electric model” *(Intriligator, Seiberg, Shih hep-th/0602239)*

$N=1$ gauge	$SU(N_c)$	
mesons	$Q^j\tilde{Q}_j$	$;\ i,j=1\dots N_f$
fundamental electric quarks	Q_i^a	$;\ a=1\dots N_c$
antifundamentals (Dirac mass m_Q)	$\tilde{Q}_a^i$	

If the beta function is negative $\hat{b}_0 = 3N_c - N_f > 0$ then the Wilsonian gauge coupling

$$e^{-8\pi^2/\hat{g}^2(E)} = \left(\frac{E}{\hat{\Lambda}}\right)^{-\hat{b}_0}$$

is strongly coupled in the IR ($\hat{\Lambda}$ is the Landau pole).

ISS meta-stable models

For certain values of parameters a Seiberg dual exists in the IR

Content of the macroscopic "magnetic model"

$N=1$ gauge	$SU(N)$	$N = N_f - N_c$
mesons	Φ_i^j	$;\ i,j = 1 \dots N_f$
fundamental magnetic quarks	φ_i^a	$;\ a = 1 \dots N$
antifundamentals	$\tilde{\varphi}_a^i$	

Exists if $b_0 = 3N - N_f < 0$ so the Wilsonian coupling is runs to weak coupling in the IR.

ISS meta-stable models

Thus we require

$$N_c + 1 \leq N_f < \frac{3}{2} N_c$$

Lowest values are $N_c = 5$, $N_f = 7$.

Assume minimal Kahler potential $K = \varphi\bar{\varphi} + \tilde{\varphi}\bar{\tilde{\varphi}} + \Phi\bar{\Phi}$

Characteristics of the IR theory

The tree level superpotential of the theory is an O'Raifeartaigh model and breaks SUSY!

$$W_{cl} = h\, \mathrm{Tr}_{N_f}(\varphi \Phi \tilde{\varphi}) - h\mu^2 \mathrm{Tr}_{N_f} \Phi$$

where $\mu^2 \approx m_Q \Lambda$. The rank condition gives $|\mathrm{vac}\rangle_+$:

$$F_{\Phi^i_j} = h\, (\varphi_i . \tilde{\varphi}^j - \mu^2 \delta^j_i) \neq 0$$

cannot be satisfied since $\varphi_i . \tilde{\varphi}^j$ has rank $N = N_f - N_c < N_f$.

Characteristics of the IR theory

Metastable vacuum characterized by

$$\begin{aligned} \langle \varphi \rangle &= \langle \tilde{\varphi} \rangle = \mu \begin{pmatrix} \mathbf{1}_N \\ \mathbf{0}_{N_f - N} \end{pmatrix} \; ; \; \langle \Phi \rangle = \mathbf{0} \\ V_+ &= (N_f - N) \left| h^2 \mu^4 \right| \end{aligned}$$

Can also be shown (ISS) that there are no tachyons at one loop

Note that the $SU(N)$ theory is completely Higgsed near the origin

And the SUSY preserving minima?

Consider giving a VEV to Φ...

- The non-perturbative contribution to superpotential is determined by *integrating out heavy* φ *and* $\tilde{\varphi}$ *modes;*

$$W = W_{cl} + W_{dyn}$$

$$W_{dyn} = N \left(\frac{h^{N_f} \mathrm{det}_{N_f} \Phi}{\Lambda^{N_f - 3N}} \right)^{\frac{1}{N}}$$

And the SUSY preserving minima?

SUSY preserving minima $|\text{vac}\rangle_0$ at

$$\begin{aligned} \langle\varphi\rangle &= \langle\tilde{\varphi}\rangle = 0 \ ; \ \langle\Phi\rangle = \Phi_0 \mathbf{1}_{N_f} \\ \Phi_0 &= \mu \left(h \epsilon^{\frac{N_f - 3N}{N_f - N}} \right)^{-1} \gg \mu \\ \epsilon &= \mu/\Lambda \end{aligned}$$

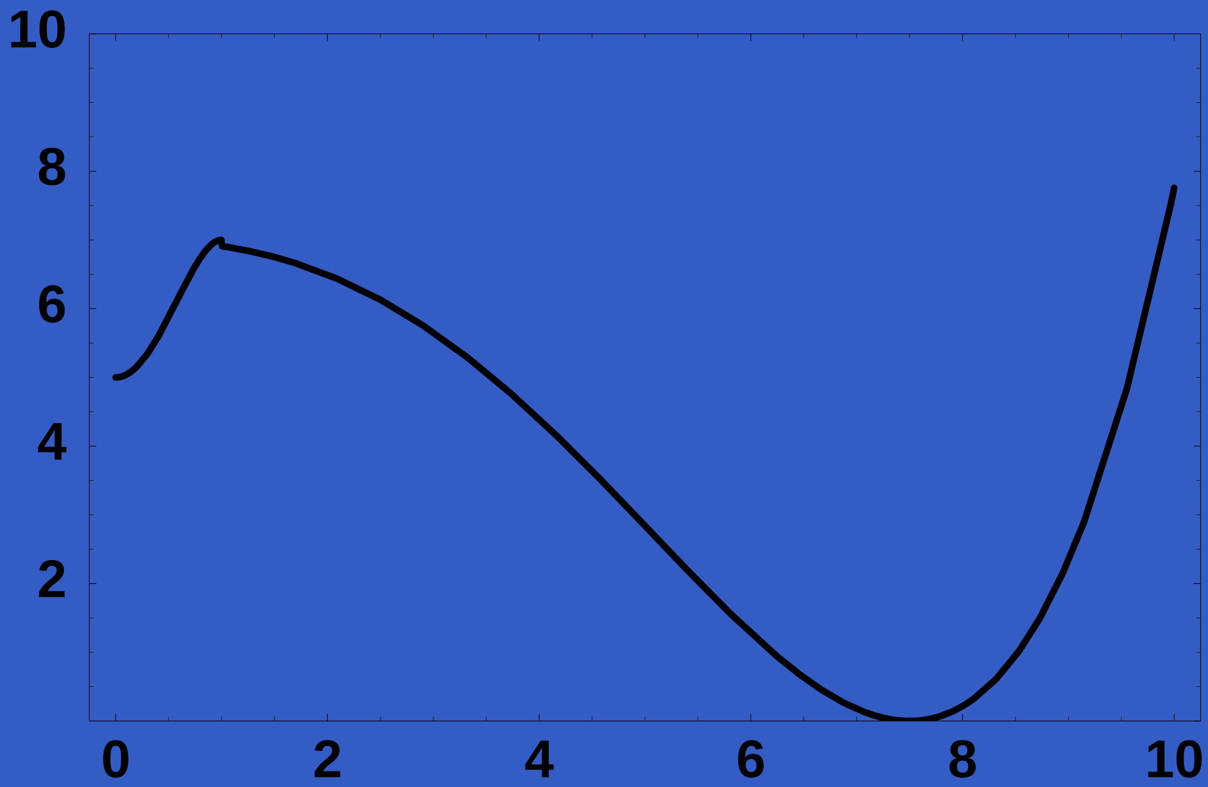
Have

$$\Lambda \gg \Phi_0 \gg \mu$$

so the minima are below Λ but the potential is very shallow

And the SUSY preserving minima?

- There are actually N_c SUSY preserving vacua differing by phase $e^{2\pi i/N_c}$ as required by Witten index of the microscopic theory



Why is this interesting?!

- The metastable potential long lived: $S_4 \sim 2\pi^2 \frac{\Phi_0^4}{V_+} = 2\pi^2 \frac{\Phi_0^4}{h^2 \mu^4}$
- The form of the O'Raifeartaigh IR superpotential is explained
- Theorem (Nelson-Seiberg): Breaking SUSY $\rightarrow$ R-symmetry $\rightarrow$massless gauginos or R-axion. These models evade it by having SUSY preserving vacua.

Cosmological properties

Dynamical Evolution at finite T

(SAA, Jaeckel, Khoze hep-th/0610334)

Potential at finite temperature along direction Φ is *(Dolan, Jackiw)*

$$V_T(\Phi) = V_{T=0}(\Phi) + \frac{T^4}{2\pi^2}\sum_i \pm n_i \int_0^\infty \mathrm{d}q\, q^2 \ln\left(1 \mp \exp(-\sqrt{q^2 + m_i^2(\Phi)/T^2})\right)$$

To first approximation only "light" ($m_i(\Phi)^2 \ll T^2$) states contribute

$$\begin{aligned} V_T - V_{T=0} &= -\frac{\pi^2 g_* T^4}{90} \\ g_* &= n_{B_{light}} + \frac{7}{8} n_{F_{light}} \end{aligned}$$

Dynamical Evolution at finite T

If $\mu \ll T \ll \Phi_0$ have

$$\begin{aligned} n_{B_{light}} &= n_{F_{light}} = 4NN_F \quad ; \ \Phi = 0 \\ n_{B_{light}} &= n_{F_{light}} = 0 \quad ; \ \Phi = \Phi_0 \end{aligned}$$

For now take all MSSM and gauge states as “light”.

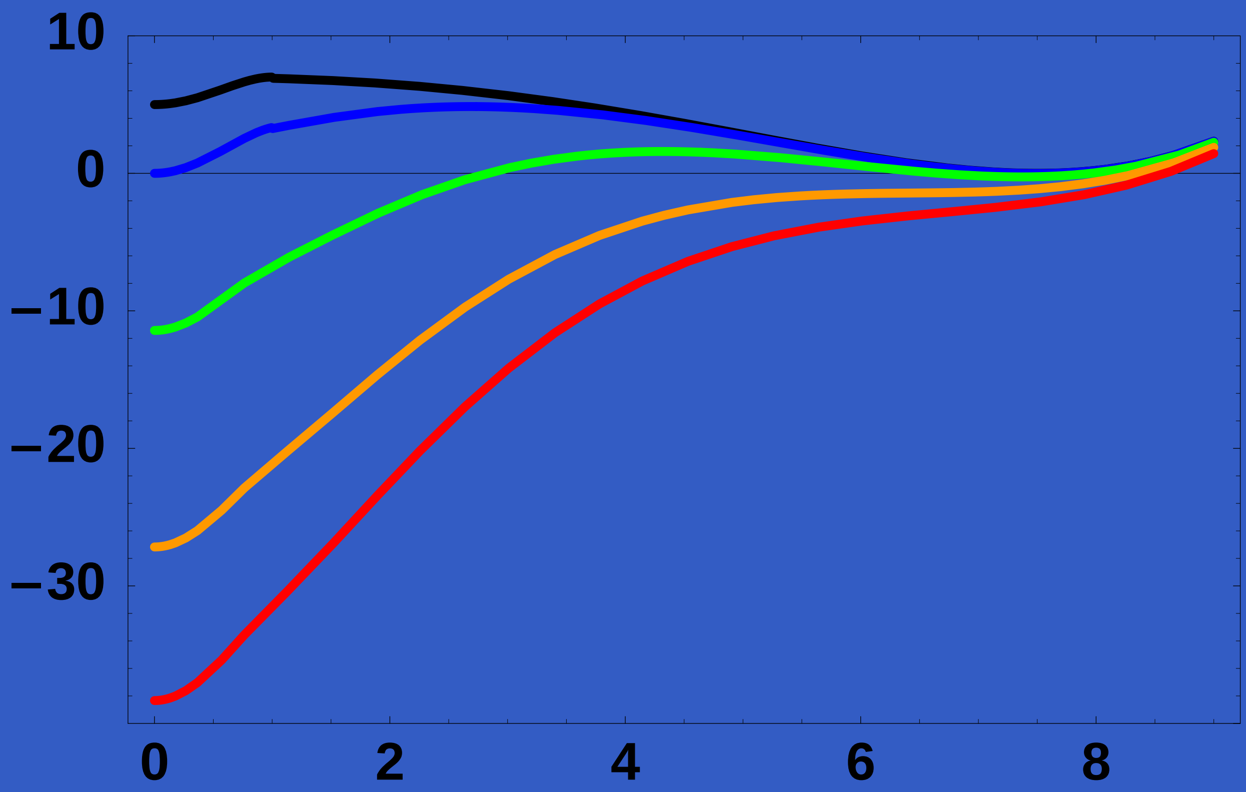
Dynamical Evolution at finite T

Conclusion: for large enough T

$$V_+(T) < V_0(T)$$

This is a result of dynamical restoration of SUSY - have to integrate out flavours to reverse sign of β-function.

Dynamical Evolution at finite T



The various temperatures

- The vacua become degenerate at $T_{degen} \sim h\mu$
- Bubble nucleation is never an important process in the transition $|vac_0\rangle \rightarrow |vac_+\rangle$
- The bump disappears at very low temperatures, $T_{crit} \sim \mu$, because of the shallowness and the confinement in $|vac_0\rangle$.
- Rolls to origin and is damped there because of coupling $h\varphi\Phi\tilde{\varphi}$ and couplings to messengers and/or MSSM.
- Remains trapped at origin at later times (Fischler, Kaplunovsky, Krishnan, Mannelli, Torres hep-th/0611018, Craig, Fox, Wacker, hep-th/0611006, SAA, Jaeckel, Khoze hep-th/0611030).

A sufficient bound on T_R

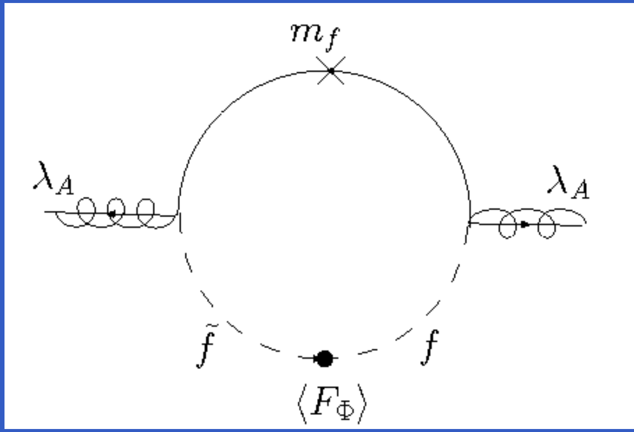
The Universe always ends up in the metastable minimum, if ISS sector is in thermal equilibrium and

$$T_{crit} \sim \mu \lesssim T_R \lesssim \Lambda$$

More minimal mediation

Spontaneous R-symmetry breaking

- First - note that even though R-symmetry is explicitly broken, $M_\lambda = 0$ in metastable minimum.
- How to generate an R-breaking M_λ without destabilizing? For example, consider adding explicit R-symmetry breaking: R-messengers called f. These would generate gaugino masses, if $W \supset Tr(\Phi) f.\tilde{f} - m_R f.\tilde{f}$



Spontaneous R-symmetry breaking

- But global SUSY now restored at

$$\langle f.\tilde{f}\rangle = h\mu^2 \;;\;\; Tr(\langle\Phi\rangle) = m_R$$

- This is the approach of most, e.g. Aharony, Seiberg and Murayama, Nomura

Spontaneous R-symmetry breaking

- Consider "baryon-deformed" ISS:

$$W = \Phi_{ij}\varphi_i.\tilde{\varphi}_j - Tr(\mu^2\Phi) + m\varepsilon_{ab}\varepsilon_{rs}\varphi^a_r\varphi^b_s$$

  where $r, s = 1, 2$ are the 1st and second generation numbers only. The last term can also be written as $m \det \varphi$.

- We will use φ and $\tilde{\varphi}$ to mediate to gauginos so let $N_f = 7$ and gauge $SU(5)_f \supset G_{SM}$ factor
- take $\mu^2_{ij} = diag\{\mu_2^2\mathbf{I_2},\ \mu_5^2\mathbf{I_5}\}$

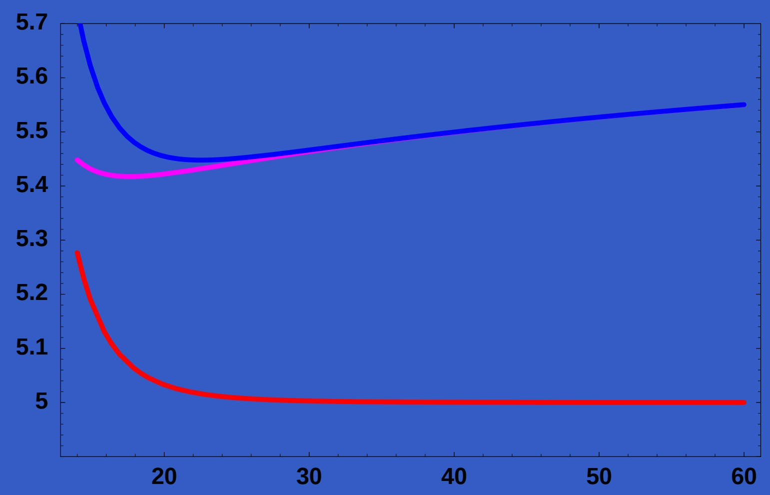
Spontaneous R-symmetry breaking

As prescribed by Shih (hep-th/0703196) the model has an R-symmetry with $R \neq 0, 2...$

	$SU(5)$	$SU(2)$	$U(1)_R$
$\Phi_{ij} \equiv \begin{pmatrix} Y & Z \\ \tilde{Z} & X \end{pmatrix}$	$\begin{pmatrix} 4\times 1 & \square \\ \bar{\square} & Adj+1 \end{pmatrix}$	$\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$	2
$\varphi \equiv \begin{pmatrix} \phi \\ \rho \end{pmatrix}$	$\begin{pmatrix} 1 \\ \bar{\square} \end{pmatrix}$	$\square$	1
$\tilde{\varphi} \equiv \begin{pmatrix} \tilde{\phi} \\ \tilde{\rho} \end{pmatrix}$	$\begin{pmatrix} 1 \\ \square \end{pmatrix}$	$\bar{\square}$	-1

Spontaneous R-symmetry breaking

- Note: runaway to broken SUSY with $\tilde{\phi} \to \infty$ and $\phi.\tilde{\phi} = \mu_2^2$
- The Coleman-Weinberg potential stabilizes the "runaway" $\tilde{\phi}$ direction:



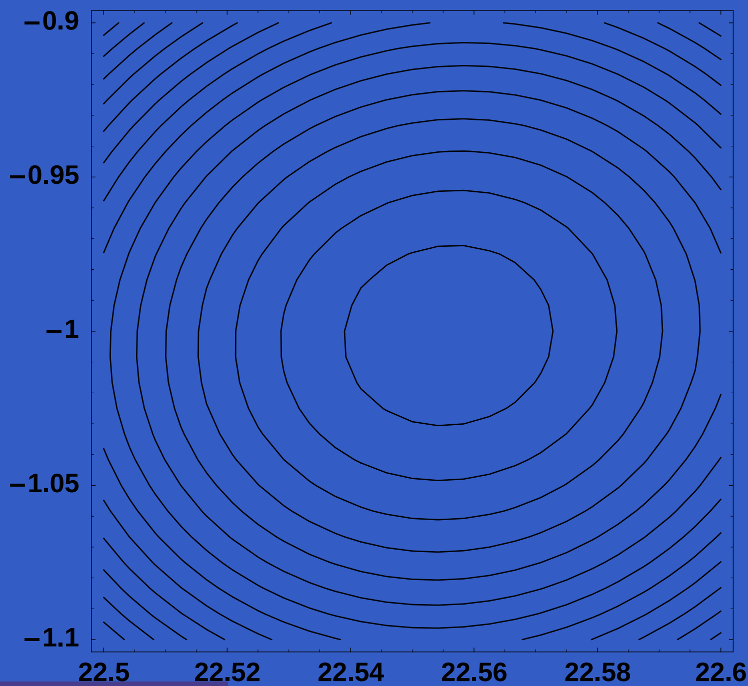
Spontaneous R-symmetry breaking

Note that m can be linked to irrelevant operators in electric theory, (but we will treat it as a free parameter)

$$
\begin{aligned}
B_{Mag}\Lambda^{-N} &= B_{Elec}\Lambda^{-N_c} \rightarrow \\
m &\sim \frac{\Lambda^3}{M_X^2}
\end{aligned}
$$

Spontaneous R-symmetry breaking

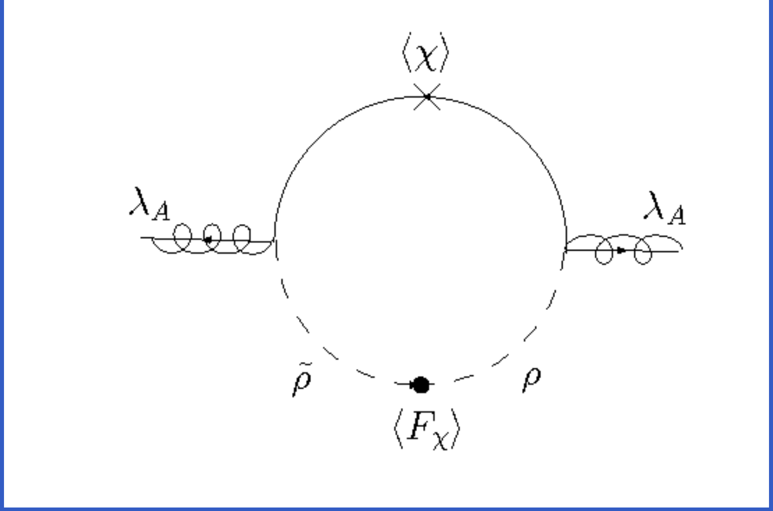
- Define $X = \chi \mathbf{I_5}$ and $Y = \eta \mathbf{I_2}$ and $\tilde{\phi} = \xi \mathbf{I_2}$
- Taking $m \sim \mu_2 \sim \mu_5$, the Coleman-Weinberg potential gives $\langle \chi \rangle, \sqrt{F_\chi} \sim \mu_2$: Contours of $V(\chi, \xi)$;



Spontaneous R-symmetry breaking

- Gaugino mass is now

$$M_\lambda \approx \frac{g_A^2}{16\pi^2}\chi\frac{\hat{\mu}^2}{\mu^2}$$



Spontaneous R-symmetry breaking

- Scalar masses can be much larger (don't depend on R-symmetry breaking:

$$M_{scalar} \sim \frac{g_A^2}{16\pi^2}\hat{\mu}$$

The deformation m takes phenomenology continuously from gauge-mediation-like to "split-SUSY-like"

Two issues: the R-axion

- Can be solved because W_{np} is an explicit breaking $\rightarrow$ mass.
- The R-axion is the phase of the field that spontaneously breaks the symmetry; i.e. $\eta = |\eta| e^{2i\frac{a_R}{f_R}}$; $\chi = |\chi| e^{2i\frac{a_R}{f_R}}$
- In our case $f_R \sim \mu_{2,5}$
- Axion mass arises from cross term in

$$
\begin{aligned}
V &\supset 25 \left| \langle\eta\rangle\langle\chi\rangle^{\frac{3}{2}} \exp\left(5\mathrm{i}\frac{a_R}{\langle\eta\rangle}\right) \Lambda^{-\frac{1}{2}} - \mu_5^2 \right|^2 \\
&= 25 \left[\langle\eta\rangle^2 \langle\chi\rangle^3 + \mu_5^4 + 2\mu_5^2 \langle\eta\rangle\langle\chi\rangle^{\frac{3}{2}} \Lambda^{-\frac{1}{2}} \cos\left(5\mathrm{i}\frac{a_R}{\langle\eta\rangle}\right)\right], \\
m_{a_R} &\sim 25\mu(\mu/\Lambda)^{\frac{1}{4}} \gtrsim 100 MeV
\end{aligned}
$$

$$
\mu/\Lambda \gtrsim 10^{-24}
$$

Two issues: Landau poles

Since the additional fields are in $SU(5)$ multiplets, the beta functions of the MSSM gauge couplings are modified universally as

$$b_A = b_A^{(MSSM)} - 9$$

The SM gauge couplings at a scale $Q > \mu$ in our model are therefore related to the traditional MSSM ones as

$$\alpha_A^{-1} = (\alpha_A^{-1})^{(MSSM)} - \frac{9}{2\pi} \log(Q/\mu)$$

$$\frac{\Lambda^{(MSSM)}}{\mu} \sim 10^5$$

Our solution: Both the MSSM and the ISS sector are magnetic duals!

Summary

- Metastability inevitable for low energy SUSY breaking
- Metastable SUSY breaking vacua are preferred in early Universe by thermal effects
- Both are a feature of dynamical restoration of SUSY - generic
- Required temperatures are only $T_R \sim \mu$
- Extremely simple model of direct mediation from baryon-deformed ISS
- Phenomenology is anywhere between gauge-mediation and split-SUSY
- Landau pole in MSSM $\longrightarrow$ electric dual of MSSM?