Single Sector SUSY Breaking in Field Theory and Gravity

Sebastián Franco

KITP Santa Barbara

SUSY Breaking '11 - CERN

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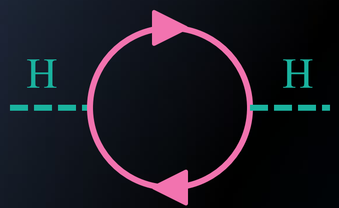
Based on work with: Benini, Craig, Dymarsky, Essig, Kachru, Simic, Torroba and Verlinde

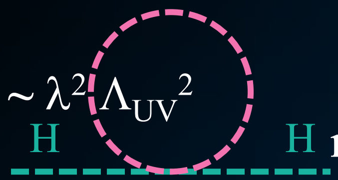
Motivation

Electroweak symmetry breaking → condensation of a scalar field (Higgs) with appropriate charges

- Hierarchy problem: stability of a light Higgs



$+m_H^2 \sim \lambda^2 \Lambda_{UV}^2$



$m_H^2 \sim \lambda^2 \log(\Lambda_{UV}/m_S)$

In the absence of fine-tuning, it must be cut-off around the TeV scale

Supersymmetry provides a nice way to stabilize the small mass of the Higgs

- Flavor physics: structure of couplings of the Higgs to other fields

$$\mathcal{L}_{\rm int} = \lambda_{\rm top}\Psi^{(3)} H \Psi^{(3)} + \lambda_{\rm charm}\Psi^{(2)} H \Psi^{(2)} + \lambda_{\rm up}\Psi^{(1)} H \Psi^{(1)}$$

$$\lambda_{top} : \lambda_{charm} : \lambda_{up} \sim 1 : 10^{-3} : 10^{-5}$$

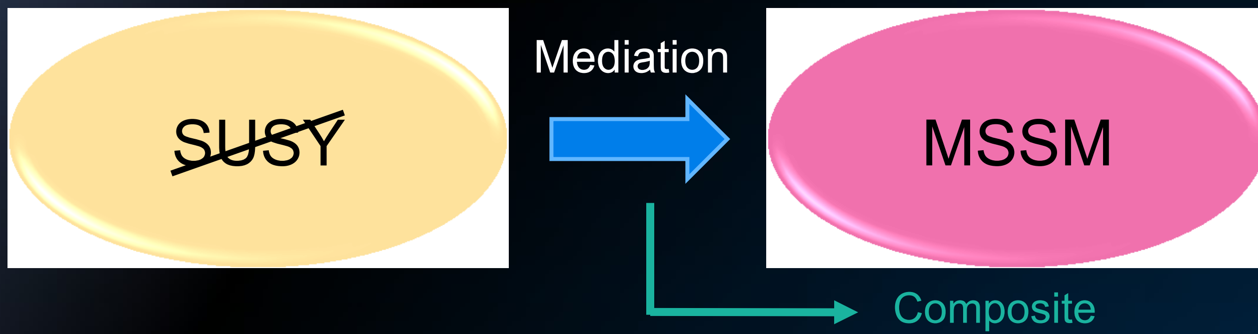
span 5 orders of magnitude!

Is it possible to construct models that simultaneously explain both features?

Alternative motivation

- Theorem: under certain assumptions, SUSY breaking in the MSSM would lead to a colored scalar (squark) lighter than the down quark

Dimopoulos, Georgi



Gravity mediation → heavy, Planck scale, fields (higher dim. ops.)

Gauge mediation → massive fields with SM charges (loops)

- Are there models with a less modular structure? Arkani-Hamed, Luty, Terning

> **Single-sector SUSY breaking**
>
> Strongly coupled sector which both breaks SUSY and produces (some of) the quarks and leptons of the Standard Model as composites of the same dynamics

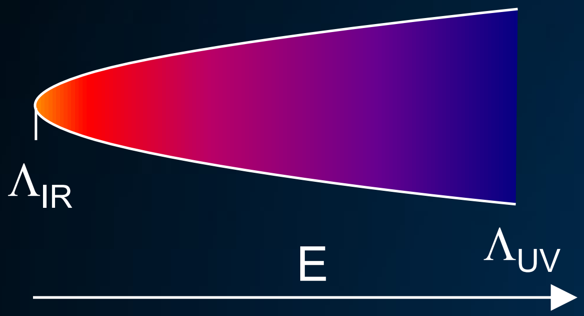
- So far, all available realizations of this idea were non-calculable

Taming strong coupling

- Dynamical SUSY breaking in general, and single-sector models in particular, involve strong coupling

- Two useful tools to deal with strongly coupled quantum field theories:
    - Duality
    - Holography (calculating, modeling and motivating)

- Holography provides an intuitive visualization of dynamics through the geometrization of the energy scale as a 5th dimension



- Today: exploit these tools to build calculable single-sector models

Single-sector SUSY breaking

- It correlates in a predictive way SUSY-breaking soft terms with a possible model of flavor physics

- Composites generations:
  - Products of basic fields
  - Coupling to Higgs comes from higher dimension operator suppressed by a flavor scale M_{flavor}

$$\mathcal{W}_{\text{Yuk}} \sim \frac{1}{M_{\text{flavor}}^2}(Q\tilde{Q})H(Q\tilde{Q}) + \frac{1}{M_{\text{flavor}}}(Q\tilde{Q})H\Psi^{(3)} + \Psi^{(3)}H\Psi^{(3)}$$

Composites

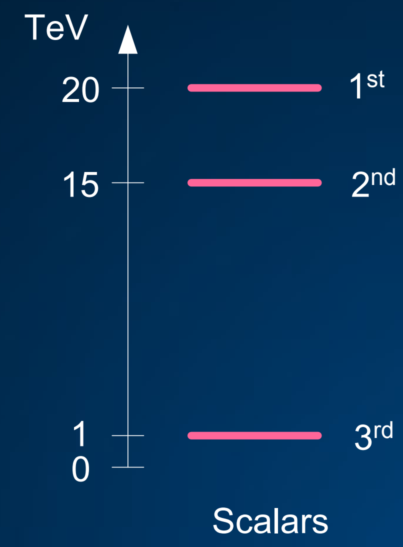
large soft masses

suppressed Yukawas

e.g. two composite generations (1^{st} and 2^{nd})

Similar to: Dimopoulos, Giudice

Cohen, Kaplan, Nelson



Calculable single-sector models from SQCD

Franco, Kachru

Supersymmetric QCD: $SU(N_c)$ super Yang-Mills with N_f flavors Q and $\tilde{Q}$

(A) SQCD with massive flavors

Seiberg duality:

theories A and B are equivalent in the IR

(B) IR-free dual with calculable ~~SUSY~~

Intriligator, Seiberg, Shih

Gauge group	Matter content
$SU(N)$ with $N = N_f - N_c$	➢ N_f dual quarks: q $\tilde{q}$
	➢ Mesons: $\Phi = Q\tilde{Q}$

- Full models: we realize two full composite generations via the mesons $\Phi = Q\tilde{Q}$

- As is standard, we embed the SM gauge group as a weakly gauged subgroup of the global symmetry group of the SUSY breaking (SQCD) dynamics

Toy example: one composite $\bar{5}$

- Consider SU(6) SQCD with $N_F = 7$ massive flavors

$$SU(7)_{\text{Flavor}} \xrightarrow[\text{ISS vacuum}]{} SU(6) \supset SU(5)_{SM} \qquad \begin{cases} Q = (5+1)+1 \\ \tilde{Q} = (\bar{5}+1)+1 \end{cases}$$

- Composites from dual mesons:

$$\Phi = \begin{pmatrix} Y_{1\times 1} & Z^T_{1\times 6} \\ \tilde{Z}_{6\times 1} & \Phi_{0,6\times 6} \end{pmatrix}$$

composites (pseudomoduli)

$$\begin{array}{ccc} SU(6) & & SU(5)_{SM} \\ \text{Adj}+1 & \longrightarrow & \bar{5} + [24+5+1+1] \end{array}$$

- Extra mesons charged under the MSSM get massive by coupling to spectators:

$$W_3 = \lambda \left[(Q\tilde{Q})_{\mathbf{5}} X_{\bar{\mathbf{5}}} + (Q\tilde{Q})_{\mathbf{24}} X_{\mathbf{24}} \right] \longrightarrow \boxed{m \sim \Lambda}$$

Dimensional hierarchy

- In models where the first two generations come from composite, dimension 2 operators in the UV theory, assuming elementary Higgs:

$$Y \sim \begin{pmatrix} \varepsilon^2 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon^2 & \varepsilon \\ \varepsilon & \varepsilon & 1 \end{pmatrix} \qquad \varepsilon = \frac{\Lambda}{M_{\text{flavor}}}$$

Reasonable starting point for $\varepsilon \sim 10^{-2}$

- We can improve the flavor structure by engineering:

$$Y \sim \begin{pmatrix} \varepsilon^4 & \varepsilon^3 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & \varepsilon & 1 \end{pmatrix} \qquad \varepsilon \sim 10^{-1}$$

  - 3^{rd} generation: elementary
  - 2^{nd} generation: dimension 2
  - 1^{st} generation: dimension 3

- Implementation: field theories that break SUSY and have dual descriptions with mesons of various dimensionalities

- We constructed explicit models using SQCD with an adjoint X

Kutasov, Schwimmer, Seiberg

Craig, Essig, Franco, Kachru, Torroba

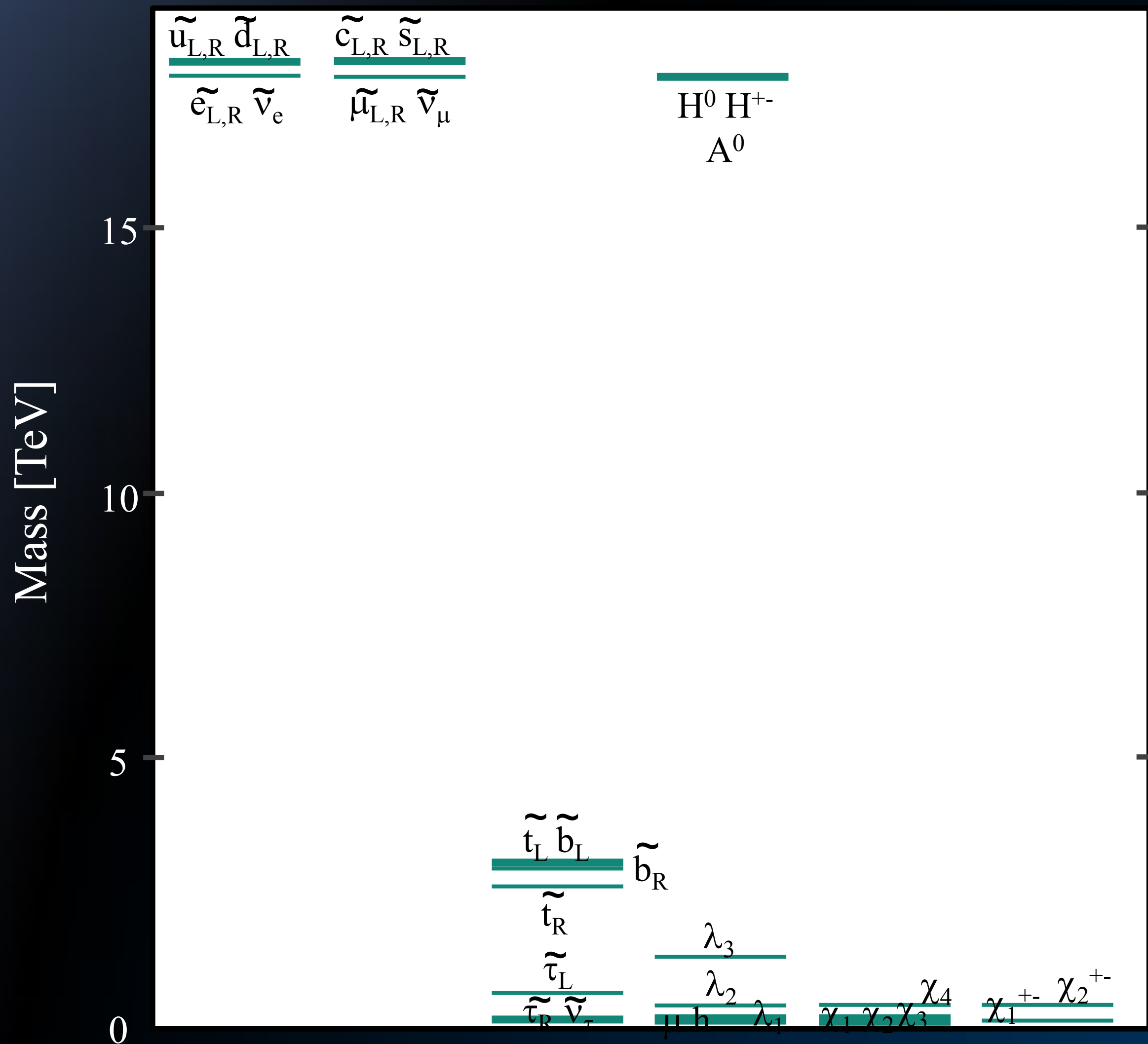
$$M_1 = Q\,\tilde{Q} \qquad M_2 = Q\,X\,\tilde{Q}$$

Summary of scales

Parameters		Particle masses
Yukawa couplings with dimensional hierarchy $\varepsilon = \Lambda/M_{flavor} \sim 0.1$	$M_{flavor} \sim 10^{17}$ GeV	
	$\Lambda \sim 10^{16}$ GeV	heavy composites $\Lambda \sim 10^{16}$ GeV
SUSY breaking	$\mu \sim 200$ TeV	$(5+\bar{5})$ messengers $h\mu \sim 200$ TeV
		1st and 2nd gen. scalars $h^2\mu/(4\pi) \sim 20$ TeV
R-symmetry breaking W_{mag} [illegible]$^2\mu_\phi \mathrm{tr}(\Phi^2)$	$\mu_\phi \sim 1$ TeV	3rd gen. scalars $g^2\mu/(4\pi)^2 \sim$ TeV; gauginos $g\mu_\phi \sim$ TeV

- Interestingly, it is also possible to construct models based on SQCD with an adjoint in which all soft masses are generated by gauge mediation and are thus universal

A fully calculable spectrum



tan β ~ 10

Schafer-Nameki, Tamarit, Torroba

- Extremely economical, even in comparison to other “minimal” models!

Composite models from Gauge/Gravity duality

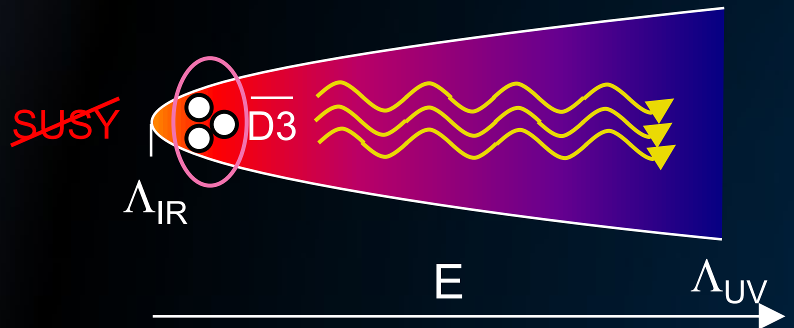
- Gauge/Gravity duality provides another avenue for producing similar calculable single-sector SUSY breaking models

- If the SUSY breaking sector has sufficiently large t' Hooft coupling and rank, we can trade the field theory for a classical supergravity theory

Constructing a model

Benini, Dymarsky, Franco, Kachru, Simic, Verlinde
Gabella, Gherghetta, Giedt

1) Gravity dual of a strongly coupled sector with a SUSY breaking metastable state at an exponentially small scale



Similar to a slice of AdS_5:

$$\boxed{ds^2 = (r/L)^2(\eta_{\mu\nu}dx^\mu dx^\nu) + (L/r)^2 dr^2}$$

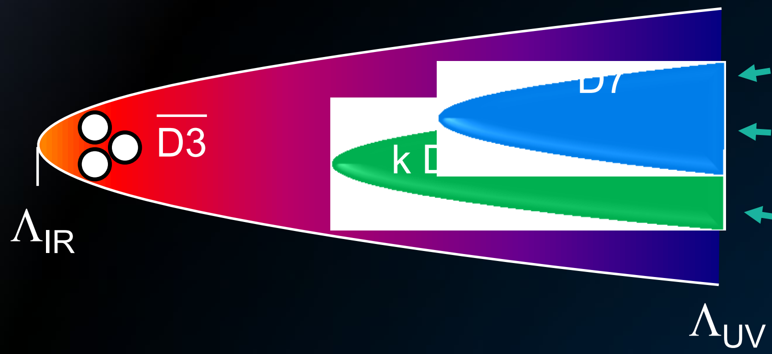
$r > r_{min}$

Probe anti D3-branes in the dual of a confining theory (e.g. warped deformed conifold)

2) Embed SM gauge group into global symmetry group of the strong sector

global symmetry → gauge symmetry in the bulk

In type IIB, this is achieved by a stack of D7-branes extending radially



- “flavor brane”
- chiral matter
- SU(k) G_{SM} “color branes”

3) We obtain chiral composites at intersections with other D7-brane stacks

- The supergravity dual of the anti D3-brane state is known
- Using this dual, the program described above can be carried out explicitly

Benini, Dymarsky, Franco, Kachru, Simic, Verlinde

Conclusions

Gauge theory

- Single sector models are and interesting and relatively unexplored class of SUSY models. We have provided calculable realizations of this scenario based on simple variations of SQCD
- The models are calculable in a weakly coupled Seiberg dual description
- Realistic Yukawa textures can be obtained via dimensional hierarchy

Holography

- It is possible to geometrize models with strongly coupled gauge mediation and compositeness using confining examples of AdS/CFT with massive flavors
- It is possible to interpolate between different phenomenological scenarios by tuning the positions of D-brane intersections

Conclusions

- It is possible to construct models with less extra matter (e.g. based on SQCD with Sp gauge group)

  Franco, Kachru

  Behbahani, Craig, Torroba

- There are various model building directions, such as 10-centered models, which have a particularly minimal matter content

  Behbahani, Craig, Torroba

- There are straightforward modifications with elementary H_u, and composite H_d that solve the μ/B_μ problem and explain why $m_b, m_\tau \ll m_t$

  Csaki, Falkowski, Nomura, Volansky

  Schafer-Nameki, Tamarit, Torroba

- Models with "more minimal SSM" spectrum (i.e. inverted hierarchy of scalar masses) can naturally give rise to new physics in some sectors without it showing up in others

Thank you!

Additional slides

Gauge Theory

Calculable single-sector models from SQCD

Franco, Kachru

Supersymmetric QCD: $SU(N_c)$ super Yang-Mills with N_f flavors Q and $\tilde{Q}$

(A) SQCD with massive flavors

Seiberg duality $\longleftrightarrow$ full IR equivalence

(B) IR-free dual with calculable ~~SUSY~~

Intriligator, Seiberg, Shih

Theory B:

Gauge group

$SU(N)$ with $N = N_f - N_c$

Matter content

- N_f dual quarks: $q \quad \tilde{q}$
- Mesons: $\boxed{\Phi = Q\tilde{Q}}$

$$W = h\,\mathrm{Tr}\, q\,\Phi\,\tilde{q} - h\mu^2 \mathrm{Tr}\;\Phi$$

μ [illegible] 0^{16} GeV

- As is standard, we embed the SM gauge group as a weakly gauged subgroup of the global symmetry group of the SUSY breaking (SQCD) dynamics
- We realize two full composite generations via the mesons $\Phi = Q\tilde{Q}$

The metastable ISS vacuum

$$q^T = \begin{pmatrix} \chi_{N\times N} \\ \rho_{N_c\times N} \end{pmatrix} \qquad \tilde{q} = \begin{pmatrix} \tilde{\chi}_{N\times N} \\ \tilde{\rho}_{N_c\times N} \end{pmatrix} \qquad \Phi = \begin{pmatrix} Y_{N\times N} & Z^T_{N\times N_c} \\ \tilde{Z}_{N_c\times N} & \Phi_{0,N_c\times N_c} \end{pmatrix}$$

- Tree-level minimum: $\langle \chi\tilde{\chi}\rangle = \mu^2$ Φ_0 arbitrary
- There are pseudomoduli. They are lifted by a 1-loop Coleman-Weinberg potential, resulting in a vacuum at:

$$\Phi_0 = 0 \qquad \chi = \tilde{\chi} = \mu\,\mathbf{1}_N$$

Symmetries

□ G_{SM}

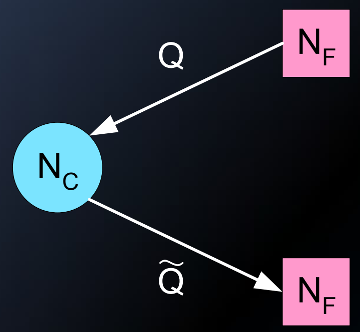
$SU(N) \times SU(N)_D \times SU(N_F) \times U(1)_B \times U(1)_R' \times U(1)_R$

- Non-vanishing μ
- χ and $\tilde{\chi}$ vevs

More details about embedding the MSSM

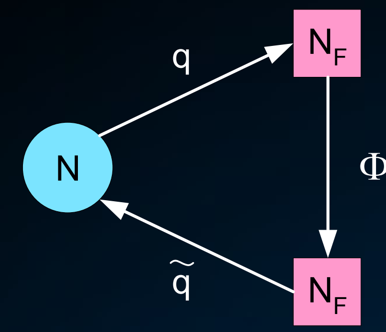
Franco, Kachru

(1)



Seiberg dual

(2)



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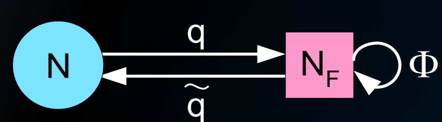

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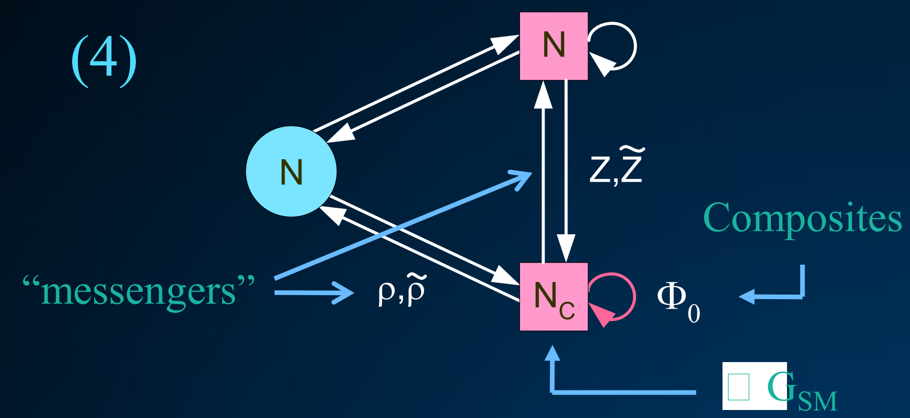


3) Non-vanishing μ $\quad SU(N_F) \times SU(N_F) \rightarrow SU(N_F)$

4) χ and $\tilde{\chi}$ vevs $\quad SU(N_F) \rightarrow SU(N) \times SU(N_C)$

- In order to circumvent the Dimopoulos-Georgi theorem, composites (i.e. mesons) must be massless at tree-level (i.e. pseudomoduli)

More realistic models

- Given the large top quark Yukawa coupling, it is natural to make the first two generations composite and keep the third one elementary

Two composite $(10+\bar{5})$ generations

- Take SU(16) SQCD with $N_F = 17$ massive flavors

$$SU(17)_{\text{Flavor}} \longrightarrow SU(16) \supset SU(5)_{SM}$$

$$Q = (5 + 5 + \bar{5} + 1) + 1$$

$$\tilde{Q} = (\bar{5} + \bar{5} + 5 + 1) + 1$$

$$\Phi_0 = 2\times(10 + \bar{5}) + [5\times 24 + 2\times 15 + 2\times\overline{15} + 2\times\overline{10} + 3\times 5 + \bar{5} + 6\times 1]$$

- Compare it to the non-calculable $SU(13) \times SU(15) \times [SU(15) \times SU(3)]$ model

A Calculable Spectrum

- The main virtue of this class of models is their calculability
- Spectrum of matter charged under G_{SM} in the $g_{SM} \to 0$ limit

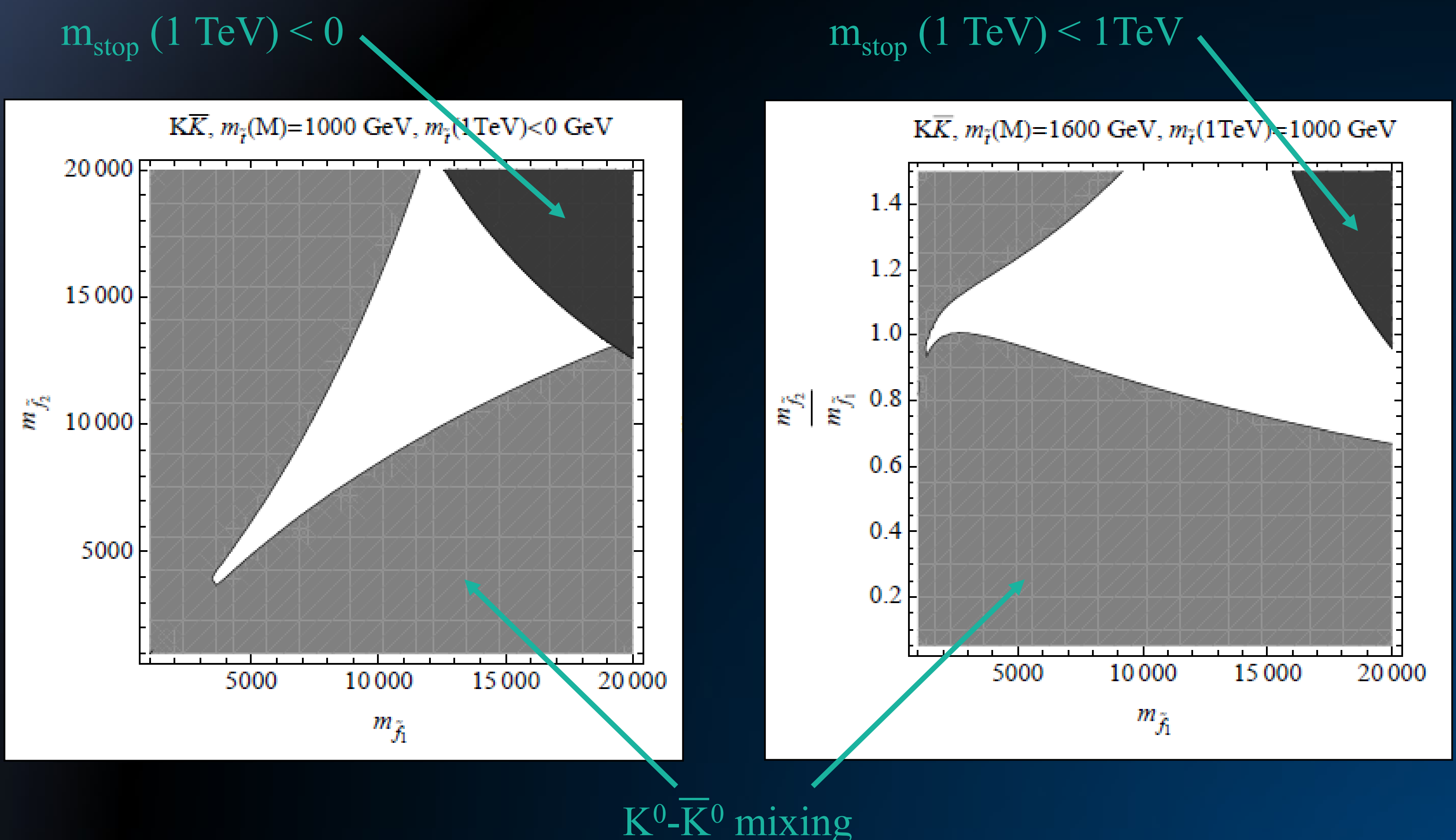
			Fermions	Bosons
MSSM	*elementary*	$\Psi^{(3)}$	0	0
	composite	$\Psi^{(1,2)}$	0	$h^2\mu$
Messengers	*composite*	*heavy*	Λ	Λ
		light	$h\,\mu$	$h\,\mu$
			$h\,\mu$	0

NG bosons from $SU(N_F) \to SU(N) \times SU(N_C)$ breaking. They get a mass $\sim g_{SM}\,\mu$

- MSSM gauginos get a mass $m_\lambda \sim g_{SM}{}^2\,\mu_\phi$ (R-symmetry breaking W_{mag} [illegible]$^2\mu_\phi \mathrm{tr}(\Phi^2)$)

Constraints on sfermion masses

- Contraints on 1st and 2nd generation sfermion masses from K^0-$\overline{K}^0$ mixing and the stop mass



Craig, Essig, Franco, Kachru, Torroba

Earlier single-sector models

Generalities

Arkani-Hamed, Luty, Terning

- Previous constructions were based on appropriate dynamical SUSY breaking models that generalize the 3-2 model
- Gauge group: $G_{lift} \times G_{comp}$ Λ_{lift} Λ_{comp}
- G_{lift} generates a dynamical superpotential that breaks SUSY

	G_{lift}	G_{comp}	G_{global} G_{MSSM}
Q	$\square$	$\square$	1
L	$\overline{\square}$	1	$\overline{\square}$
$\bar{U}$	1	$\overline{\square}$	$\square$
"preon" fields → P	1	R	1

$$W = \lambda Q L \bar{U}$$

- There is a metastable vacuum with 0
- Composites ~ $P\,\bar{U}$

- Some general properties of the spectrum:
    - Scalar masses of composite generations unify at Λ_{comp}
    - Gauginos and elementary sfermions get masses from gauge mediation
- The scalar mass^2 of preons is non-calculable in these models (not even the sign). Dynamical assumptions are necessary for the models to work.

An example: two composite $(10+\overline{5})$ generations

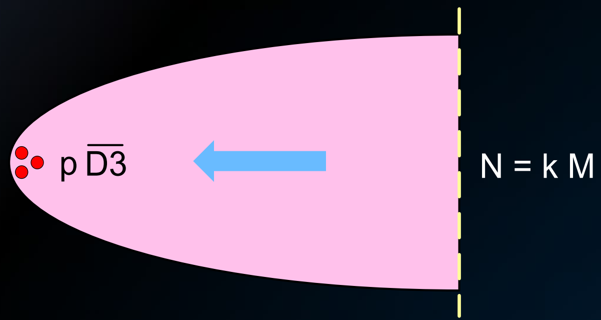
		SU(13)	SU(15)	SU(15)	SU(3)
	Q	$\square$	$\square$	1	1
	L	$\overline{\square}$	1	$\overline{\square}$	1
	$\overline{U}$	1	$\overline{\square}$	$\square$	1
P	$\overline{D}$	1	$\overline{\square}$	1	1
P	S	1	$\square$	1	$\square$

- In what follows, we will build calculable models using our current understanding of dynamical SUSY breaking models

Holography

SUSY breaking state

- Exponentially small SUSY-breaking in KS throat $\longrightarrow$ add $\overline{\text{D3}}$-branes



Kachru, Pearson, Verlinde

Argurio, Bertolini, Kachru, Franco

$$g_s V_{\text{eff}}(\Phi) \simeq \sqrt{\det(G_{\|})}\left(p - i\frac{4\pi^2}{3}F_{kjl}\text{Tr}\Big([\Phi^k,\Phi^j]\Phi^l\Big) - \frac{\pi^2}{g_s^2}\text{Tr}\Big([\Phi^i,\Phi^j]^2\Big) + \ldots\right)$$

$$[[\Phi^i,\Phi^j],\Phi^j] - i g_s^2 f \epsilon_{ijk}[\Phi^j,\Phi^k] = 0$$ $\longrightarrow$ p-dimensional SU(2) representation

- The $\overline{\text{D3}}$-branes expand to a radius: $$R^2 \sim 4\pi^2 \frac{p^2}{M^2} R_{S^3}^2$$

- Vacuum energy: $$V_0 \sim p\, T_{\overline{\text{D3}}}\, e^{-\frac{8\pi k}{3 g_s M}}$$

Supergravity dual of the anti D-brane state

DeWolfe, Kachru, Mulligan

$$ds^2 = r^2 e^{2a(r)} \eta_{\mu\nu} dx^\mu dx^\nu + e^{-2a(r)} \left(\frac{dr^2}{r} + \sum_{i=1}^{2} (e_{\theta_i}^2 + e_{\phi_i}^2) + e^{2b(r)} e_\psi^2 \right)$$

$$\begin{aligned}
e^{-4a} &= \boxed{\frac{1}{4} g_s \bar{N} + \frac{1}{8}(g_s \bar{M})^2 + \frac{1}{2}(g_s \bar{M})^2 \log r} \\
&\quad + \frac{1}{r^4}\left[\left(\frac{1}{32} g_s \bar{N} + \frac{13}{64}(g_s \bar{M})^2 + \frac{1}{4}(g_s \bar{M})^2 \log r\right)\mathcal{S} - \frac{1}{16}(g_s \bar{M})^2 \phi\right] \\
e^{2b} &= \boxed{1} + \frac{1}{r^4}\mathcal{S} \\
k &= \boxed{g_s \bar{M} \log r} + \frac{1}{r^4}\left[\left(\frac{3}{8}\frac{\bar{N}}{\bar{M}} + \frac{11}{16} g_s \bar{M} + \frac{3}{2} g_s \bar{M} \log r\right)\mathcal{S} - \frac{1}{4} g_s \bar{M} \phi\right] \\
\Phi &= \boxed{\log g_s} + \frac{1}{r^4}[\phi - 3\mathcal{S} \log r]
\end{aligned}$$

$$\mathcal{S} \sim \frac{p}{N} e^{\left(-\frac{8\pi N}{3 g_s M^2}\right)}$$

Vacuum Energy

- Normalizable perturbation $\longrightarrow$ spontaneous SUSY breaking

Composites from String Theory

Benini, Dymarsky, Franco, Kachru, Simic, Verlinde

- Two intersecting Ouyang D7-branes:

$$w_1 = \mu \qquad\qquad w_4 = \nu \qquad\qquad w_1 w_2 - w_3 w_4 = 0$$

- SUSY flux:

$$F = iC\left(\frac{3}{2}|\mu|^2 + |w|^2\right)\frac{dw \wedge d\bar{w}}{\left(|w|^2 + |\mu|^2\right)^2}$$

Marchesano, McGuirk, Shiu

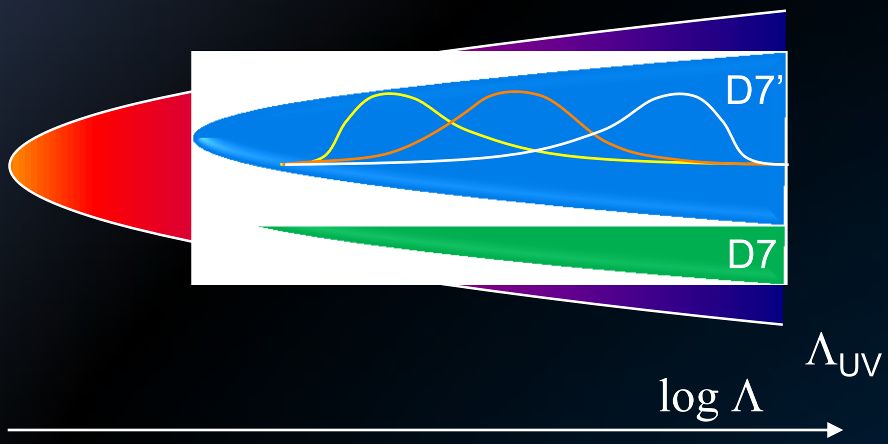
$$\int F = 2\pi p$$

- Zero modes:

$$\left.\begin{array}{lr} \psi_- \sim w^j \left|\frac{w}{\mu}\right|^{-\frac{C}{2} - C\log\left|\frac{w}{\mu}\right|} dw^{1/2} & NN \\ \psi_+ \sim \bar{w}^{-j-1}\left|\frac{w}{\mu}\right|^{\frac{C}{2} + C\log\left|\frac{w}{\mu}\right|} d\bar{w}^{1/2} & N \end{array}\right\} \qquad \begin{array}{l} \Delta = \frac{3}{2}(j-p) + \frac{9}{4} \\ R = j + \frac{3}{2} \end{array}$$

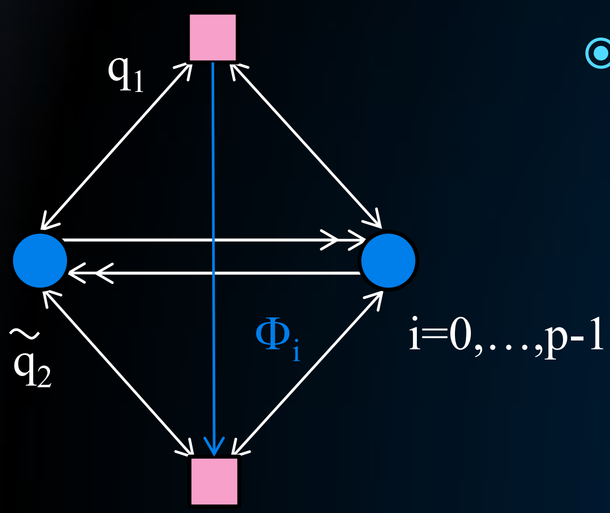
$$\left.\begin{array}{lr} \psi_+^\dagger \sim w^k \left|\frac{w}{\mu}\right|^{\frac{C}{2} + C\log\left|\frac{w}{\mu}\right|} dw^{1/2} & NN \\ \psi_-^\dagger \sim \bar{w}^{-k-1}\left|\frac{w}{\mu}\right|^{-\frac{C}{2} - C\log\left|\frac{w}{\mu}\right|} d\bar{w}^{1/2} & N \end{array}\right\} \qquad \begin{array}{l} \Delta = \frac{3}{2}(k+p) + \frac{9}{4} \\ R = k + \frac{3}{2} \end{array}$$

Wave functions



- Peaks at regular intervals in log Λ

Gauge theory interpretation



- Couplings in the UV:

$$W \supset \sum_{r=0}^{p-1} \Phi_r \tilde{\mathcal{O}}_r$$

$$\tilde{\mathcal{O}}_j = \tilde{q}_2 (A_1 B_2)^j q_1$$