Supersymmetry with an Inhomogeneous S

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A rough outline of the talk

- Why Supersymmetry?
- What is the *S*-term and why is it important?
- What do we need to turn the S-term inhomogeneous?
- Physics of the inhomogeneous S-term
- Application:
    - RH sleptons in scalar sequestering

Understanding Electroweak Scale

How do you generate this scale?

$$v_{\rm ew}^2 \sim \frac{m_w^2}{g^2}$$

Even after you generate this

—

how do you make it radiatively stable?

Understanding Electroweak Scale

mass scale we need to control

$$v_{\rm ew}^2 \sim \frac{m_w^2}{g^2} = \mathrm{fn}\left(g^2, y_t^2, \ldots, \tilde{m}_i^2, M_a^2, \ldots\right)$$

superpartner masses

In electroweak scale supersymmetry, you control electroweak scale by controlling superpartner masses

Understanding Electroweak Scale

Control superpartner masses

SUSY rotates chirality into scalar sector — gives full control of radiative corrections on superpartner masses

How do we generate small (electroweak scale) superpartner masses?

Understanding Electroweak Scale

parameter of mass dimension 2

parametrizes susy breaking scale

$$\tilde{m}^2 \sim \frac{F^2}{M^2}$$

mediation scale

For Planck mediation:

$$M = M_{\rm Pl}$$

$$F \sim 10^{10-11}\ {\rm GeV}$$

Understanding Electroweak Scale

$$\tilde{m}^2 \sim \frac{F^2}{M^2}$$

F^2: parameter of mass dimension 2

parametrizes susy breaking scale

M^2: mediation scale

Smallness of electroweak scale or smallness of superpartner masses raises the question

how do you generate

$$\sqrt{F} \ll M \quad \text{if} \quad M \sim M_{\rm Pl}$$

$$\sqrt{F}, M \ll M_{\rm Pl} \quad \text{if} \quad M \ll M_{\rm Pl}$$

Understanding Electroweak Scale

Smallness of electroweak scale or smallness of superpartner masses raises the question

how do you generate

•

$$\frac{\sqrt{F}}{M_{\rm Pl}} \ll 1$$

We know how nature does it with QCD

•

$$e^{-\frac{8\pi^2}{g^2}} \ll 1$$

SUSY model in a nut-shell

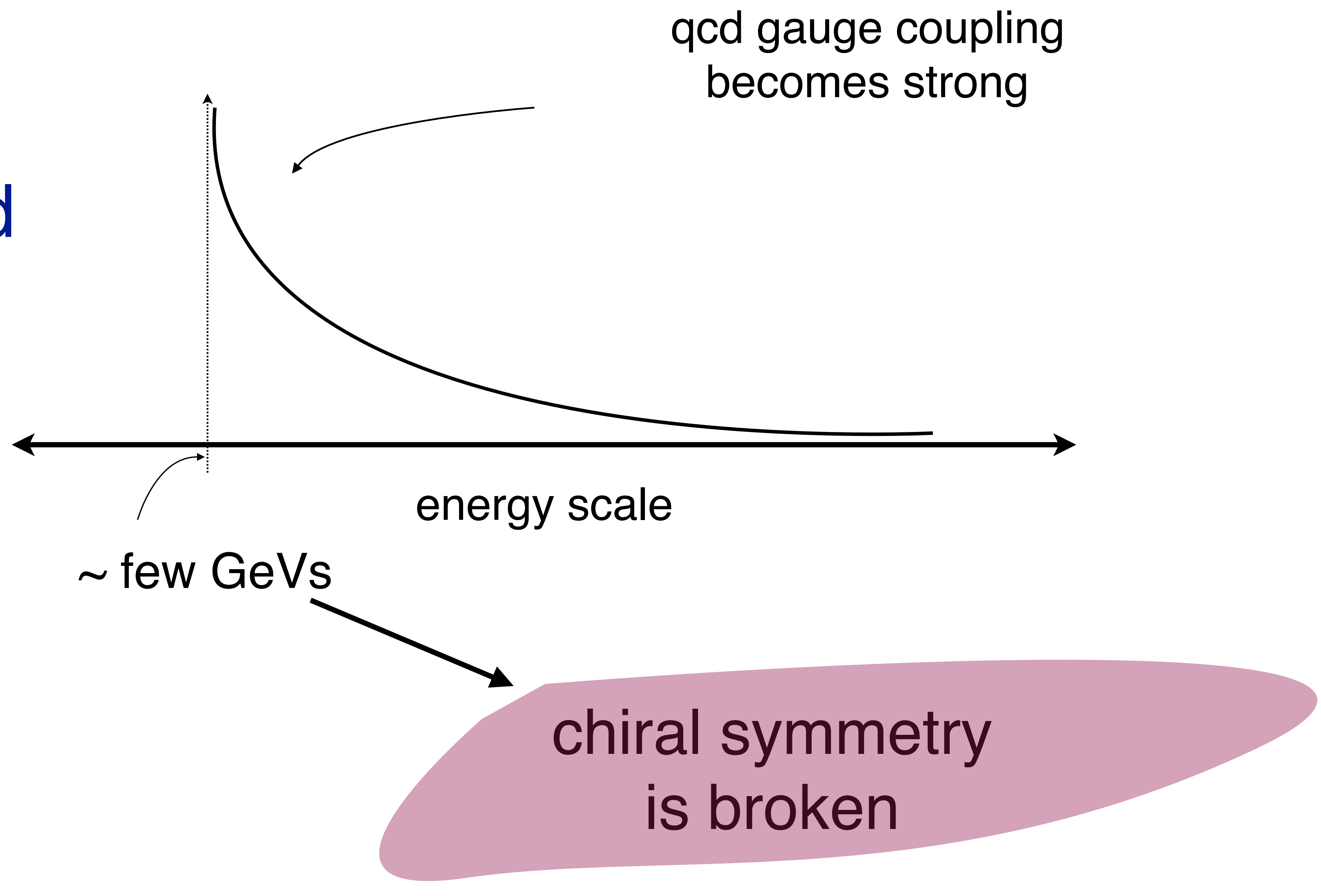
Skeleton of a complete SUSY model

Dynamical SUSY breaking
in a hidden sector

messenger mechanism
gravity, gauge, gaugino, anomaly etc etc

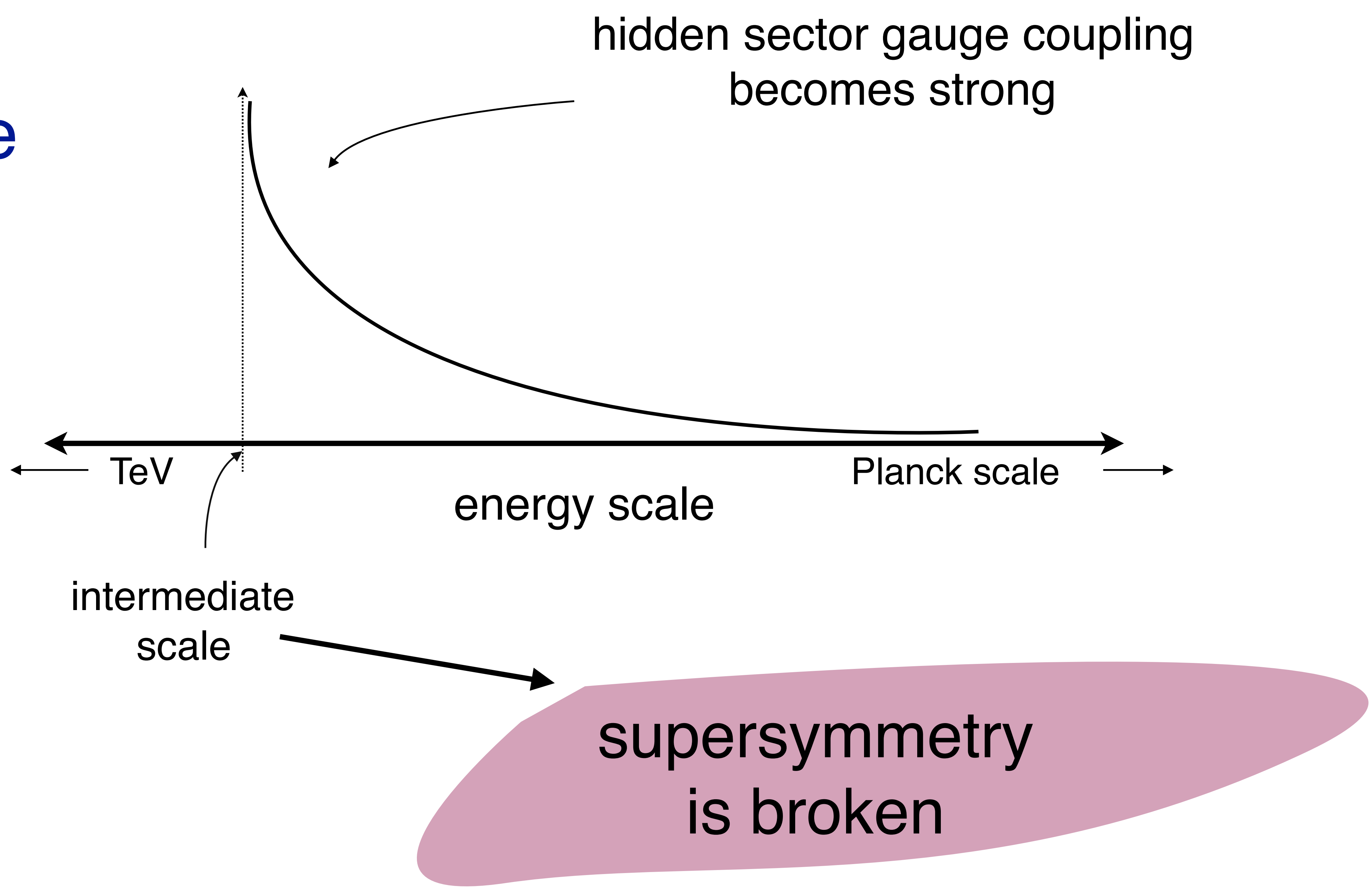
Understanding Electroweak Scale

take qcd



Understanding Electroweak Scale

just like
qcd



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What is the S-term and why is it important?

Before I understand this question let's visit the question of predictability in softly broken supersymmetric theories:

How much can you predict the IR if you have a model of UV

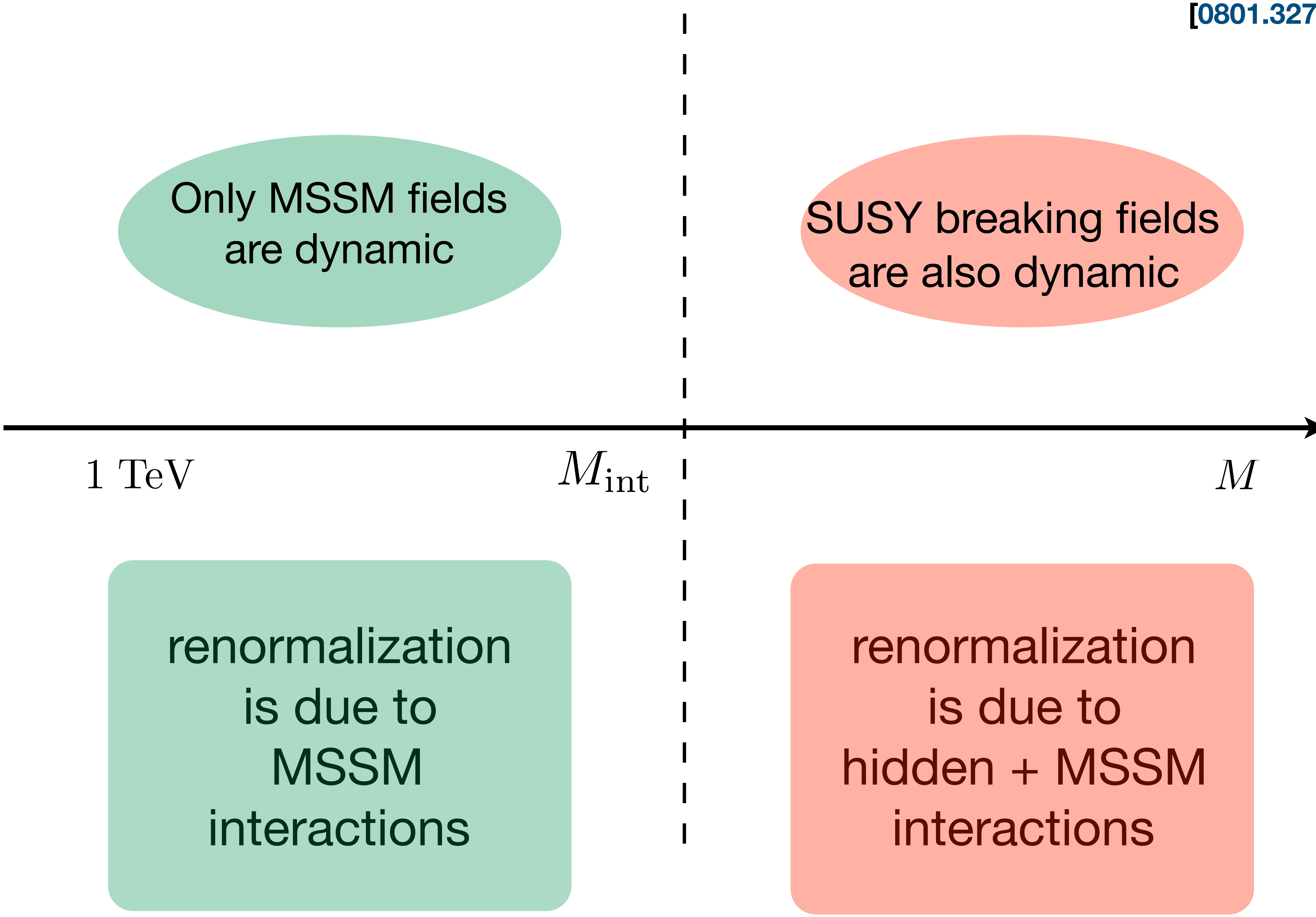
More importantly:

How well do you know UV if you know IR very well

Scales in renormalization

Cohen, Roy, Schmaltz
[hep-ph/0612100]

Meade, Seiberg, Shih
[0801.3278]



RGEs of SUSY breaking masses

Consider the first generation particles:
with MSSM interactions only

$$q_a \equiv \{\frac{32}{3}, 6, \frac{2}{5}\}$$

$$\frac{d}{dt}\widetilde{m}_Q^2 = \frac{1}{16\pi^2}\sum_{a=1}^{3} q_a\ g_a^2\ M_a^2$$

$$\widetilde{m}_Q^2 = \widetilde{m}_0^2\ +\ 4.5\ M_{1/2}^2$$

2
unknowns

RGEs of SUSY breaking masses

Consider the first generation particles:
with MSSM + hidden interactions

$$\frac{d}{dt}\widetilde{m}_Q^2 = \frac{1}{16\pi^2}\sum_{a=1}^{3} q_a\, g_a^2\, M_a^2\, G + \gamma\, \widetilde{m}_Q^2$$

$$\widetilde{m}_Q^2 = N_0 + \sum_{a=1}^{3} q_a\, N_a$$

4
unknowns

RGEs of SUSY breaking masses

$$\mathcal{S} \;=\; \mathrm{Tr}\left(\mathrm{Y}_{\phi}\mathrm{m}^2_{\phi}\right) \;=\; \tilde{\mathrm{m}}^2_{\mathrm{H_u}} - \tilde{\mathrm{m}}^2_{\mathrm{H_d}} + \mathrm{Tr}\left(\tilde{\mathrm{m}}^2_{\mathrm{q}} - \tilde{\mathrm{m}}^2_{\mathrm{l}} - 2\tilde{\mathrm{m}}^2_{\mathrm{u}} + \tilde{\mathrm{m}}^2_{\mathrm{d}} + \tilde{\mathrm{m}}^2_{\mathrm{e}}\right)$$

$$16\pi^2 \frac{d}{dt}\mathcal{S} \;=\; \left(\gamma + \frac{66}{5} g_1^2\right) \mathcal{S}$$

RGE for the *S*-term is homogeneous

with/without hidden sector dynamics

RGEs of SUSY breaking masses

$$\frac{d}{dt}\mathcal{S} \; = \; \left(\cdots\right) \times \mathcal{S}$$

You can show that

$$\mathcal{S}\Big|_{\mu=1\ \mathrm{TeV}} \neq 0 \quad \Longrightarrow \quad \mathcal{S}\Big|_{\mu=M_{\mathrm{int}}} \neq 0 \quad \Longrightarrow \quad \mathcal{S}\Big|_{\mu=M} \neq 0$$

Irrespective of any hidden sector dynamics

A way to make $\mathcal{S}$-term inhomogeneous

Consider a toy model with SQED and softly broken supersymmetry
and no hidden sector

A theory with a non zero *S*-term + no FI for Hypercharge **=** A theory with a zero *S*-term + FI for Hypercharge

$$V \to V + \#\mathcal{S}\ \theta^2\bar{\theta}^2$$

FI only runs because of gauge coupling running

$$\frac{d}{dt}\left(\frac{\mathcal{S}}{g^2}\right) = 0$$

A way to make $\mathcal{S}$-term inhomogeneous

Consider a toy model with SQED and softly broken supersymmetry
and no hidden sector

A theory with a non zero *S*-term + no FI for Hypercharge **=** A theory with a zero *S*-term + FI for Hypercharge

$$V \;\rightarrow\; V + \#\mathcal{S}\;\theta^2\bar{\theta}^2$$

This argument will break down if more operators exist that explicitly involve V

Can't probably be a superpotential operator

A way to make S-term inhomogeneous

Consider a toy model with SQED and softly broken supersymmetry
and no hidden sector

A theory with a non zero
S-term + no FI for Hypercharge

=

A theory with a zero
S-term + FI for Hypercharge

$$V \;\rightarrow\; V + \#\mathcal{S}\;\theta^2\bar{\theta}^2$$

C-terms

$$\int d^4\theta\, f_1\left(\phi\cdots\right)^\dagger\; e^{qV} f_2\left(\phi\cdots\right)$$

f_1, f_2 are chiral functions of fields ϕ with charge q

generates →

$$\int d^4\theta\;\times\left(\#\theta^2\bar{\theta}^2\;\mathcal{S}\right)\times f_1\left(\phi\cdots\right)^\dagger\; f_2\left(\phi\cdots\right)$$

You break the theorem above

A way to make S-term inhomogeneous

In the MSSM, the operator with lowest dimension would be, for example

$$\int d^4\theta \ \frac{k}{\Lambda} \ H_d^\dagger \ e^{V/2} \ \left(QU\right)$$

Equivalently, you can start with a soft operator (rotating k to superspace):

$$\mathscr{L}_{\rm soft} \supset C_u \ h_d^\dagger \ \tilde{q} \ Y_u \ \tilde{u}$$

You are guaranteed to get an Inhomogeneous S-term

MSSM with inhomogeneous S-term

Simplify:

- MSSM with only top Yukawa
- One extra soft operator

$$\mathscr{L}_{\rm soft} \supset C_t y_t \, h_d^\dagger \, \tilde{q}_3 \tilde{u}_3 \longrightarrow \text{C-terms}$$

Corrections at RGEs one loop order will be confined to soft masses for H_d, q_3, and u_3

First without the C-terms

RGEs for soft mass-squareds for *H_d*, *q_3*, *and u_3*

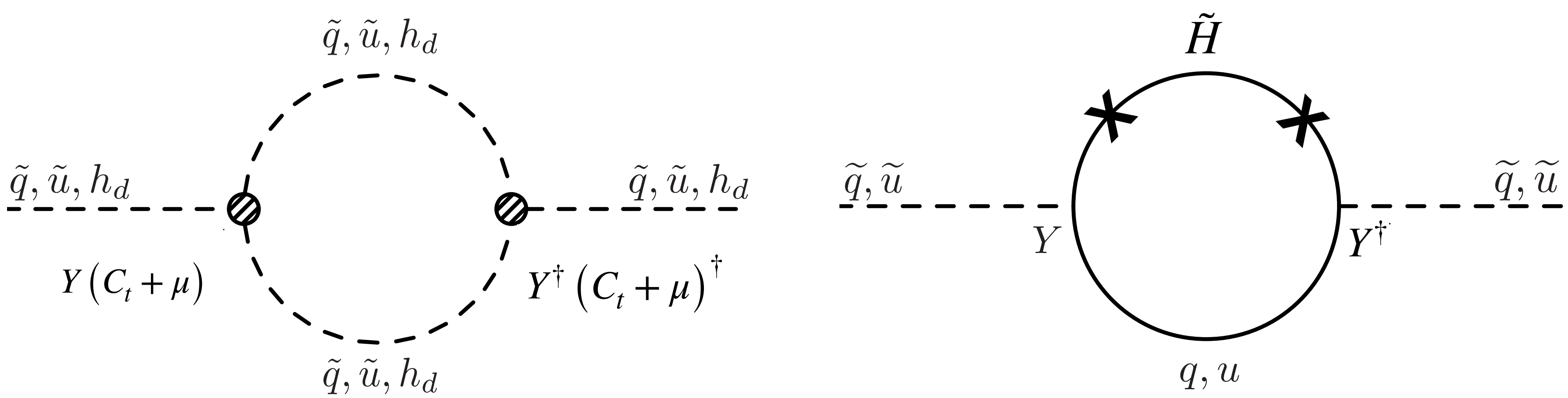
$$16\pi^2 \frac{d}{dt}\tilde{m}^2_{q_3} = 2X_t - \frac{32}{3}g_3^2 \left|M_3\right|^2 - 6g_2^2\left|M_2\right|^2 - \frac{2}{15}g_1^2\left|M_1\right|^2 + \frac{1}{5}g_1^2\mathcal{S}$$

$$16\pi^2 \frac{d}{dt}\tilde{m}^2_{u_3} = 4X_t - \frac{32}{3}g_3^2 \left|M_3\right|^2 - \frac{32}{15}g_1^2\left|M_1\right|^2 - \frac{4}{5}g_1^2\mathcal{S}$$

$$16\pi^2 \frac{d}{dt}\tilde{m}^2_{h_d} = -6g_2^2\left|M_2\right|^2 - \frac{6}{5}g_1^2\left|M_1\right|^2 - \frac{3}{5}g_1^2\mathcal{S}$$

$$X_t \equiv \left|y_t\right|^2\left(\tilde{m}^2_{q_3} + \tilde{m}^2_{u_3} + \tilde{m}^2_{h_u} + \left|A_t\right|^2\right)$$

Next: with the C-terms



You can guess that the effects of these diagram will be proportional to

$$|y_t|^2 \left(|C_t + \mu|^2 - |\mu|^2 \right)$$

Next: with the C-terms

$$16\pi^2 \frac{d}{dt}\tilde{m}^2_{q_3} \ = \ 2X_t - \frac{32}{3}g_3^2\left|M_3\right|^2 - 6g_2^2\left|M_2\right|^2 - \frac{2}{15}g_1^2\left|M_1\right|^2 + \frac{1}{5}g_1^2\mathcal{S} \quad + 2\xi_t$$

$$16\pi^2 \frac{d}{dt}\tilde{m}^2_{u_3} \ = \ 4X_t - \frac{32}{3}g_3^2\left|M_3\right|^2 - \frac{32}{15}g_1^2\left|M_1\right|^2 - \frac{4}{5}g_1^2\mathcal{S} \quad + 4\xi_t$$

$$16\pi^2 \frac{d}{dt}\tilde{m}^2_{h_d} \ = -6g_2^2\left|M_2\right|^2 - \frac{6}{5}g_1^2\left|M_1\right|^2 - \frac{3}{5}g_1^2\mathcal{S} \quad + 6\xi_t$$

$$X_t \ \equiv \ \left|y_t\right|^2\left(\tilde{m}^2_{q_3} + \tilde{m}^2_{u_3} + \tilde{m}^2_{h_u} + \left|A_t\right|^2\right)$$

$$\xi_t \ \equiv \ \left|y_t\right|^2\left(\left|C_t + \mu\right|^2 - \left|\mu\right|^2\right)$$

RGE for the $\mathcal{S}$-term

$$16\pi^2 \frac{d}{dt}\mathcal{S} \;=\; \frac{66}{5} g_1^2 \mathcal{S} - 12\ \xi_t$$

$$\mathcal{S}\Big|_{\mu=1\ \mathrm{TeV}} \neq 0 \quad \not\Longrightarrow \quad \mathcal{S}\Big|_{\mu=M_{\mathrm{int}}} \neq 0$$

Application

Perez, Roy, Schmaltz,

Phys.Rev. D79 (2009) 095016

scalar sequestering

is characterized by the spectrum at the intermediate scale

All scalars including scalar Higgses are massless

The spectrum is independent of details of messenger model and hidden sector model

only gauginos and Higgsinos are massive

Spectrum at the Intermediate Scale

Mediation scale

Dominated by (superconformal) dynamics in hidden sector

Intermediate scale

$$\begin{cases} \mu \sim M_a \\ B_\mu = 0 \\ \tilde{m}^2_\phi = 0 \\ \tilde{m}^2_{H_u} = \tilde{m}^2_{H_d} = - |\mu|^2 \end{cases}$$

Electroweak scale

A Sore point of scalar sequestering

Consider RH slepton mass at the EW scale

$$16\pi^2 \frac{d}{dt}\tilde{m}_e^2 = -\frac{24}{5} g_1^2 \left|M_1\right|^2$$

$$\tilde{m}_e^2(\mu) = \frac{6M_1^2(\mu)}{5b_1}\left[1 - \left\{1 - \frac{b_1 g_1^2(\mu)}{8\pi^2}\log\left(\frac{M_{\rm int}}{\mu}\right)\right\}^2\right]$$

Initial condition: $\tilde{m}_\phi^2 = 0$

Same as in gaugino mediation

$$\tilde{m}_e^2(\mu) \gtrsim M_1^2(\mu)$$

Implies:

$$M_{\rm int} \gtrsim \mu \times \exp\left[\frac{8\pi^2}{b_1 g_1(\mu)^2}\left(1 - \sqrt{\frac{6}{6+5b_1}}\right)\right]$$

$$\gtrsim 3.9 \times 10^{18}\ \text{GeV}\left(\frac{\mu}{1\ \text{TeV}}\right)$$

Scalar sequestering with C-terms

Consider RH slepton mass at the EW scale

$$16\pi^2 \frac{d}{dt}\tilde{m}_e^2 = -\frac{24}{5} g_1^2 \left|M_1\right|^2 + \frac{6}{5} g^2 \mathcal{S}$$

$$16\pi^2 \frac{d}{dt}\mathcal{S} = \frac{66}{5} g_1^2 \mathcal{S} - 12 \left|y_t\right|^2 \left(\left|C_t + \mu\right|^2 - \left|\mu\right|^2 \right)$$

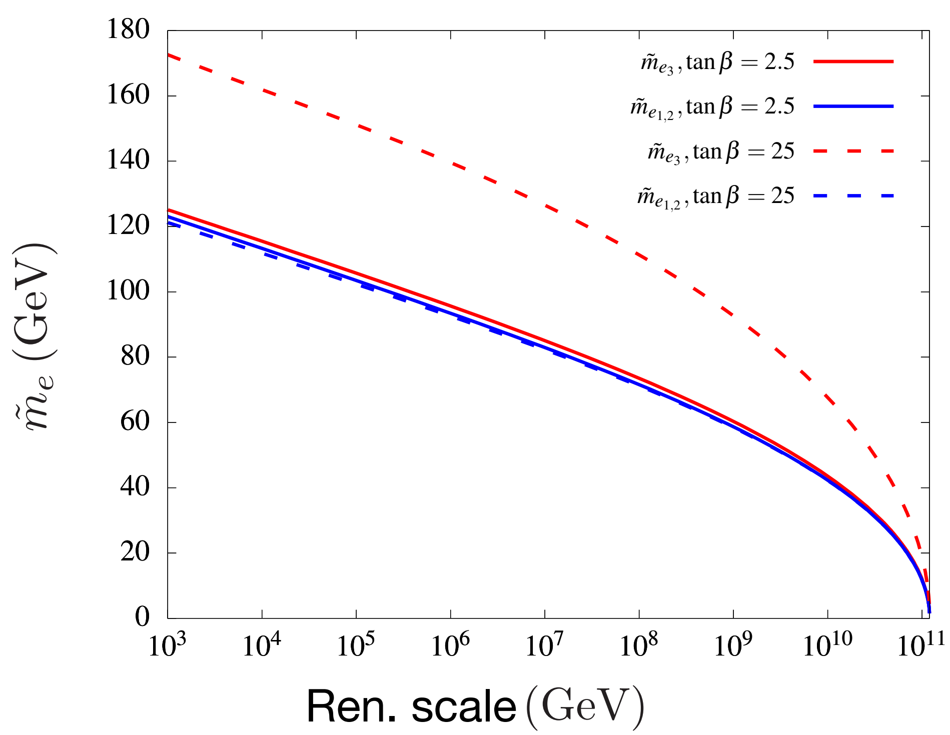
Take: $C_t = -\mu = 1 \text{ TeV}$

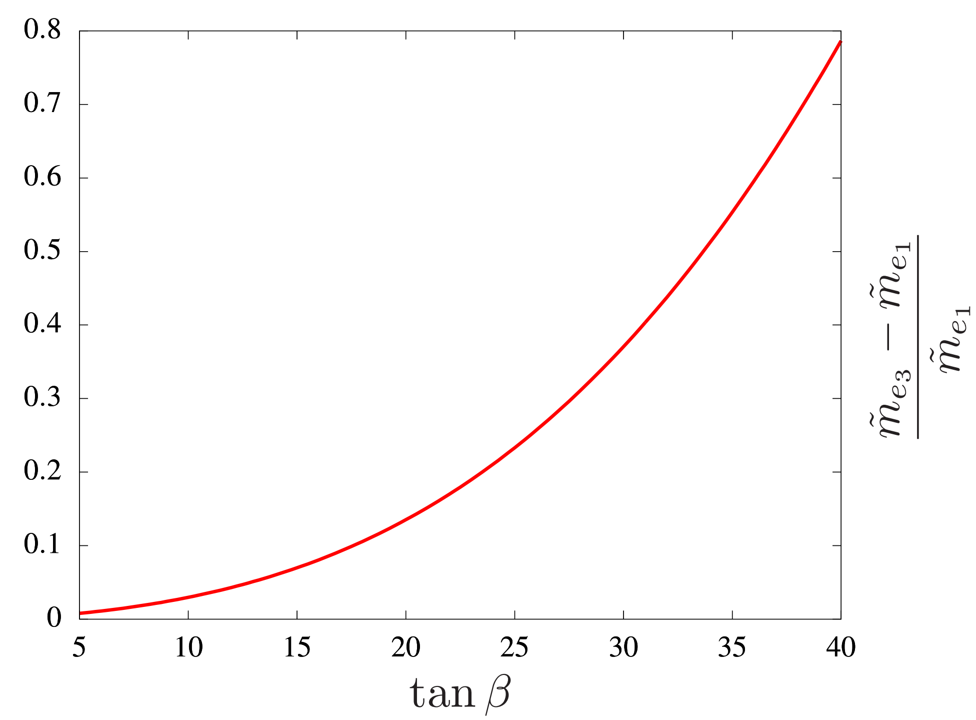
$M_1 = 100 \text{ GeV}$

Scalar sequestering with C-terms

Consider RH slepton mass at the EW scale

1. RH slepton masses are primarily given in terms of C_t and μ





2. Third generation RH sleptons are heavier

$$\tilde{m}^2_{e_3} > \tilde{m}^2_{e_{1,2}}$$

because of the initial condition

$$\tilde{m}^2_H = -|\mu|^2$$

Scalar sequestering with C-terms

Detailed phenomenological questions:

- Do you get EWSB?
- Do you get thermal relic?
- Do you avoid LHC bounds for light sleptons?
- Do you get the right Higgs mass?
- How big are the flavor changing effects, or (g-2)?
  - Can you still accommodate gauge coupling unification?
  - What is the fine tuning in this model?

For answers to some of these questions look for the forthcoming Chakraborty, Roy (Feb, 2019)

Done