# *Vanilla Supersymmetry and Beyond*

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# Overview

# Overview

*Background/motivation*

*Vanilla MSSM and beyond*

*The importance of mediation*

*Scherk-Schwarz: What a top-down theory of broken SUSY looks like*

# *The hierarchy problem*

# The hierarchy problem

Higgs-like particle discovered in 2012:

Hierarchy problem - why is the Weak Scale so much lower than the Planck Scale - and how is it protected?

More precisely perturbation theory with a higgs scalar is suspect: very "massive states" dominate any calculation to do with higgs physics.

In fact we don't even need a heavy resonance: this is true for any change (in e.g. beta functions) at a high scale.

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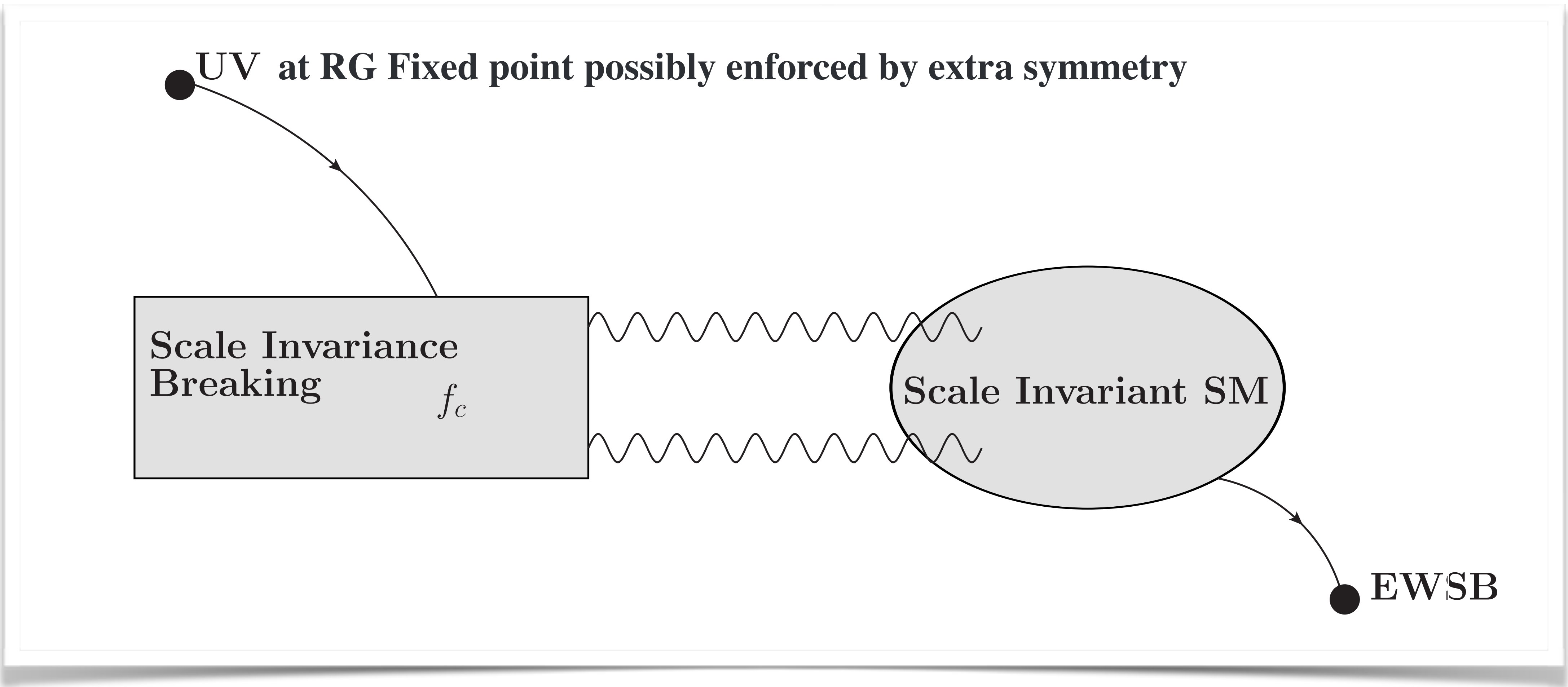
4. ***Misaligned Supersymmetry*** - the "magic symmetry" that makes even non-supersymmetric non-tachyonic string theory finite. Dimensional supersymmetry breaking in the effective theory, but not soft(!)

# *What is really going on ...*



# *SUSY in 2 slides*

***Superpotential***:

- The "F-term" (highest dimension component) of a chiral superfield transforms under SUSY as a total derivative.
- Any function of chiral superfields is also a chiral superfield.
- Ergo for invariant interactions, take any function of chiral superfields W …

$$L_{int} = W|_{\theta\theta} + h.c. \qquad \left( \text{gives} \quad V = \left|\frac{\partial W}{\partial \Phi_i}\right|^2 \right)$$

The effect

***Example: top Yukawa***

| | | | |
|---|---|---|---|
| $H_u =$ | $h_u$ | $\tilde{h}_u$ | $F_{h_u}$ |
| $Q =$ | $\tilde{q}$ | $q$ | $F_Q$ |
| $t_c =$ | $\tilde{t}_c$ | $t_c$ | $F_{t_c}$ |

$$W_{top-Yukawa} = \lambda_t Q H_u t_c$$

$$L_{top-Yukawa} = -\lambda_t q h_u t_c - \lambda_t \tilde{q}(\tilde{h}_u t_c) - \lambda_t (q\tilde{h}_u)\tilde{t}_c + \lambda_t^2 |h_u \tilde{t}|^2 + \lambda_t^2 |h_u \tilde{q}|^2 + \ldots.$$

# SUSY in 2 slides

***Kahler potential***:

Generally can define the Kinetic terms as the “D-term” of a real function K,

$$L_{KE} = K(\Phi_i, \bar{\Phi}^j)|_{\theta^2\bar{\theta}^2} = \frac{\partial K}{\partial\Phi_i \partial\bar{\Phi}^j} \partial_\mu \varphi_i \partial^\mu \varphi^{j*} + \ldots$$

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*Alert: often use same symbol for superfield and its scalar component!!!*

# *The MSSM*

For the SM Yukawa couplings need a second higgs and Superpotential

$$W = \lambda_u Q H_u U^c + \lambda_d Q H_d D^c + \lambda_e L H_d E^c$$

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# *The NMSSM*

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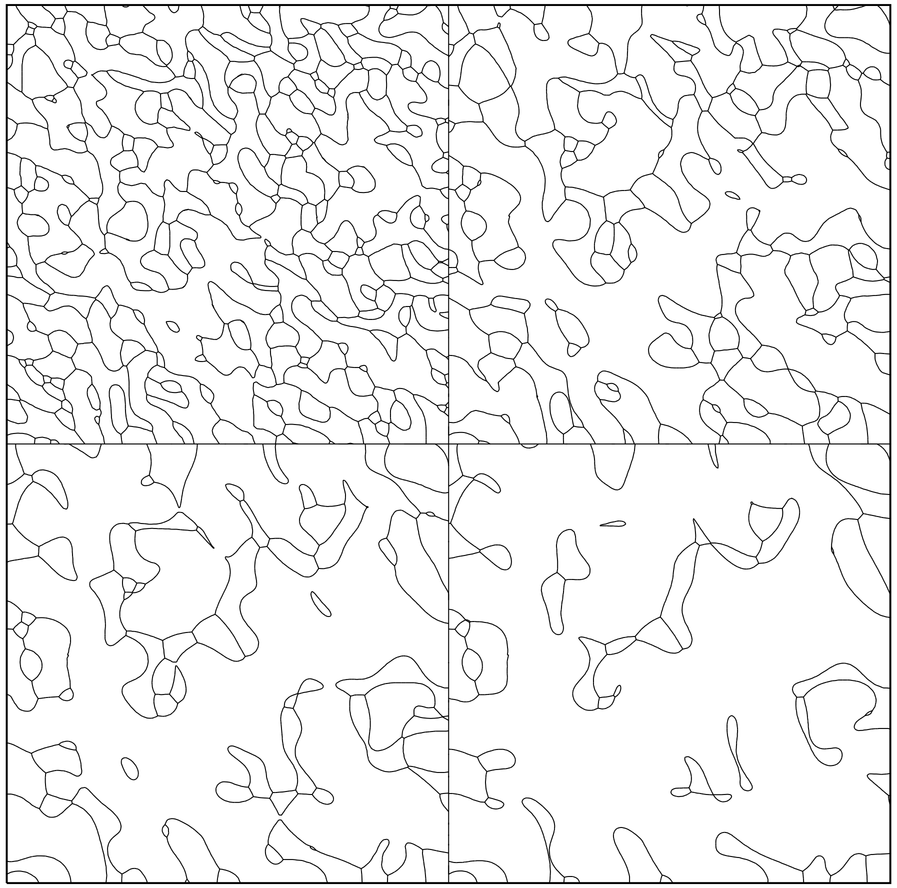
# *Domain wall problem for NMSSM*

The good and bad thing about the NMSSM is its Z3 symmetry: after EWSB the Universe looks like …



(from SAA, Sarkar, White)

# The Generalised NMSSM

If you want to avoid domain wall problems sadly you have to break Z3 but the breaking can be small (SAA, Sarkar, White):

$$W = \lambda_u Q H_u U^c + \lambda_d Q H_d D^c + \lambda_e L H_d E^c + \lambda S H_u H_d + \lambda S^3 + S^4/M_{Pl}$$

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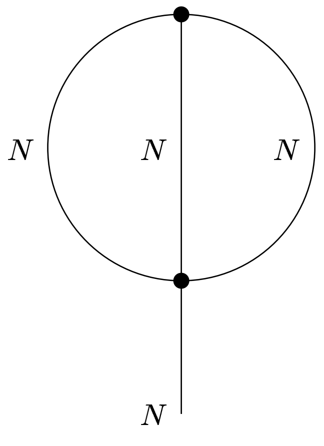

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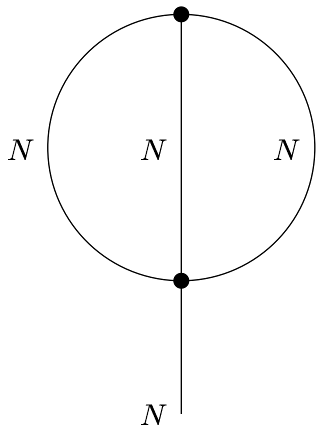


There is a solution: a symmetry that imposes only even terms in K and odd terms in W (SAA):
Such symmetries are typically either R-symmetries or modular symmetries.

# *The Generalised NMSSM*

Several examples in literature (e.g. in SAA and Pangiotakopoulos, Pilaftsis)
The upshot is there is no large naturalness benefit from the accidental Z3
although the singlet may be good for other things (alleviating fine-tuning):

$$W = \lambda_u Q H_u U^c + \lambda_d Q H_d D^c + \lambda_e L H_d E^c$$
$$+\lambda S H_u H_d + \lambda S^3 + S^4/M_{Pl} + \mu H_u H_d + \mu' S^2$$

It raises Higgs mass (e.g. Ghilencea, Ross, Schmidt-Hoberg) and also gives
portal couplings

- The last term comes about from the Giudice Masierio mechanism: e.g. For a heterotic string theory with a T2 torus factor: the torus metric is

$$G_{ij} = \frac{T_2}{U_2}\begin{pmatrix} 1 & U_1 \\ U_1 & |U|^2 \end{pmatrix}$$

where

$$\begin{aligned} iU &= U_1 + iU_2 \\ iT &= T_1 + iT_2, \end{aligned}$$

we then find

$$K/M_{Pl}^2 = -\log(S+\bar{S}) - \log\left((T+\bar{T})(U+\bar{U}) - (H_U+\bar{H}_D)(H_D+\bar{H}_U)\right)$$

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- Stringy bonus: $H_U \to H_U + C,\ H_D \to H_D - C^*$ shift symmetry implies that the light higgs is

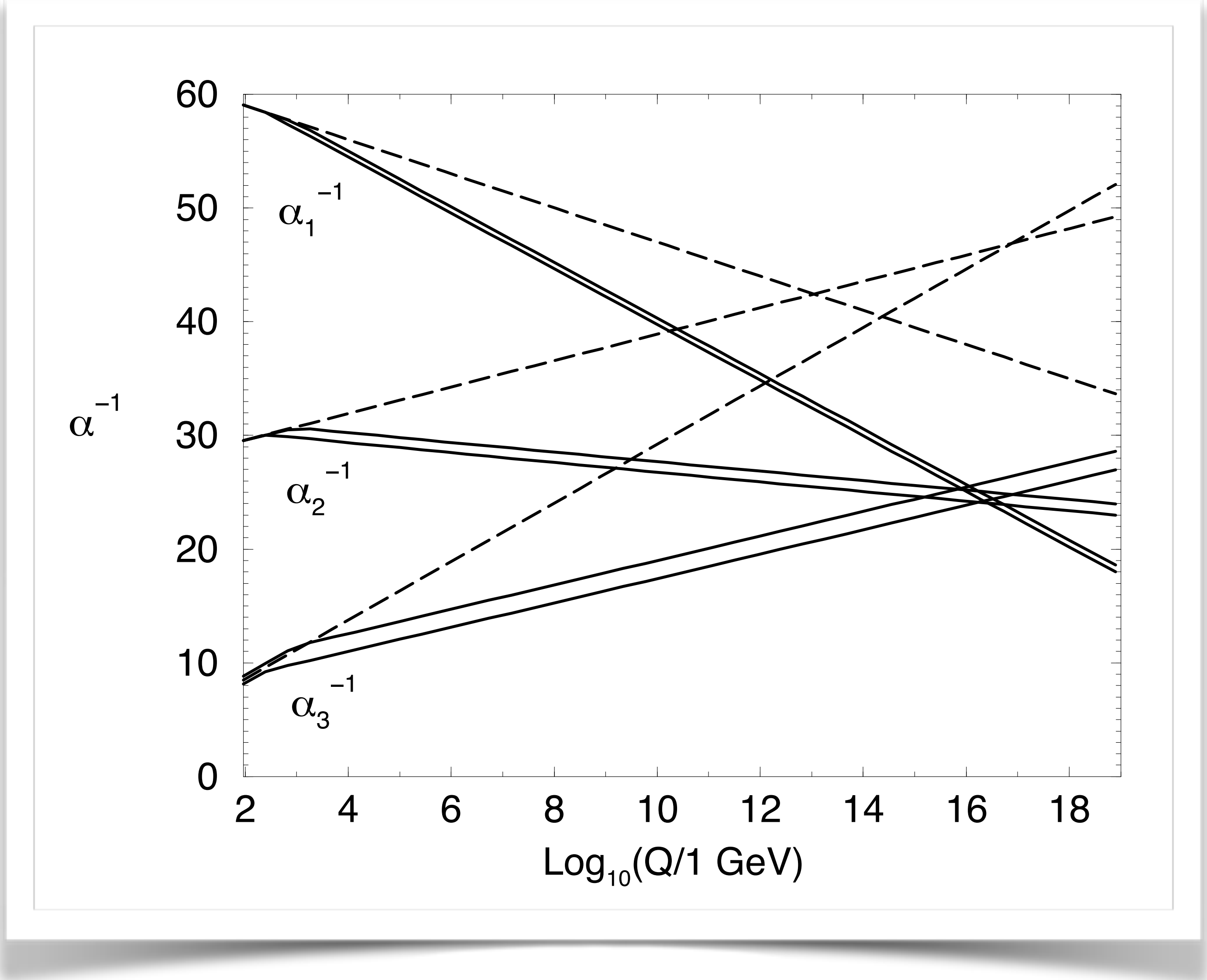
(Hebecker, Knochel, Weigand; Luo, Zwirner)

$$h = \frac{1}{\sqrt{2}}(H_U - \bar{H}_D)$$

# *Lightning Pheno summary*

## Successes ...

Major success! Unification of gauge couplings looks better (see Martin review 9709356)



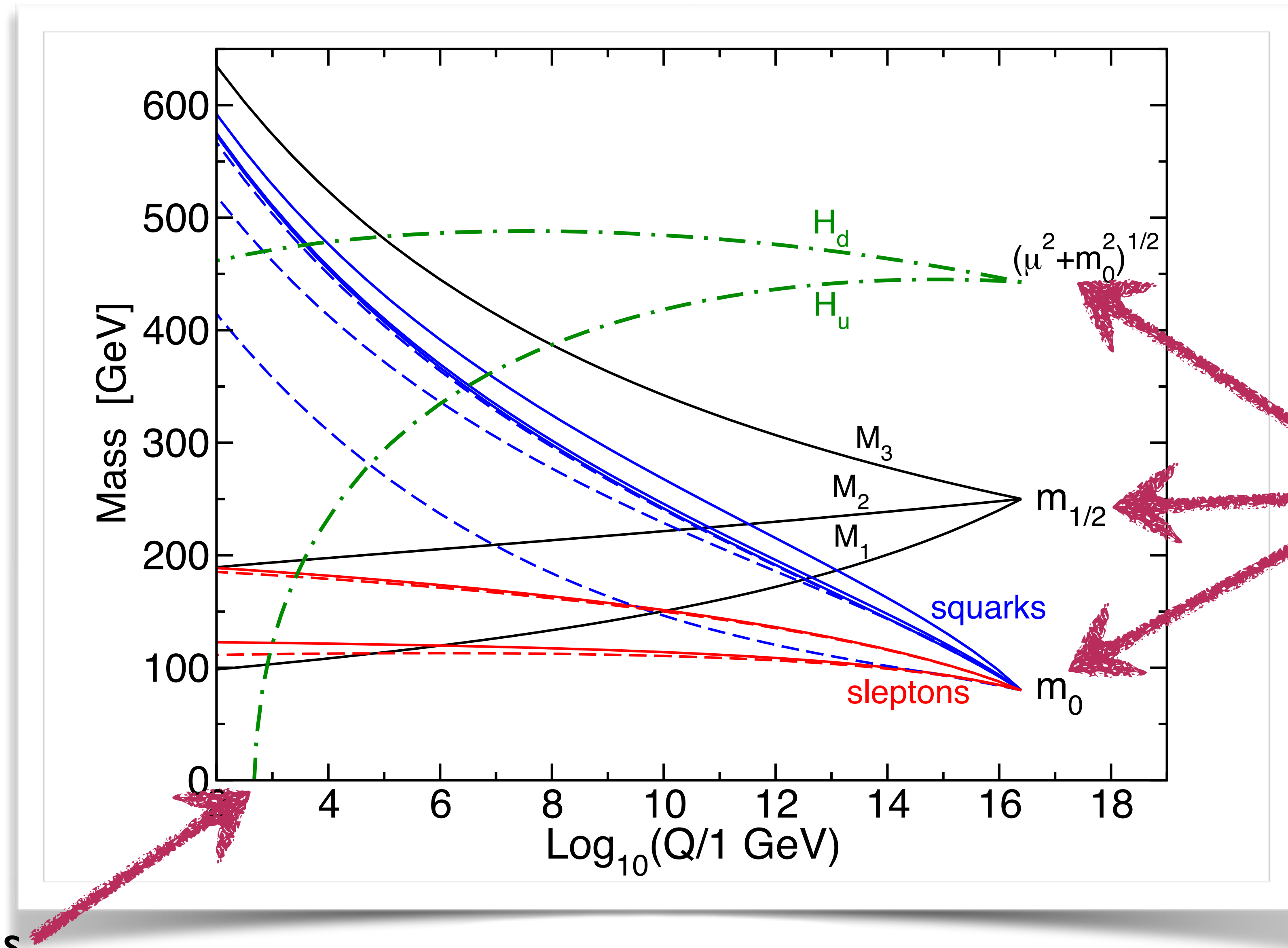

$$\frac{d}{dt}\alpha_a^{-1} = \frac{b_a}{2\pi}$$

$$-(b_1, b_2, b_3) = \begin{cases} (41/10,\ -19/6,\ -7) & \text{Standard Model} \\ (33/5,\ 1,\ -3) & \text{MSSM} \end{cases}$$

# Lightning Pheno summary

## Successes ...

Another major success! EWSB is driven by the large top Yukawa via RG effects -




This is the Constrained MSSM (CMSSM)

Ibanez+Ross

# *Lightning Pheno summary*

Physical spectrum (mass eigenstates) comes from a mixture of the gauge eigenstates:

| Names | Spin | $P_R$ | Gauge Eigenstates | Mass Eigenstates |
|---|---|---|---|---|
| Higgs bosons | 0 | $+1$ | $H_u^0\ H_d^0\ H_u^+\ H_d^-$ | $h^0\ H^0\ A^0\ H^\pm$ |
| squarks | 0 | $-1$ | $\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$ | (same) |
| | | | $\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$ | (same) |
| | | | $\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$ | $\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$ |
| sleptons | 0 | $-1$ | $\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$ | (same) |
| | | | $\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$ | (same) |
| | | | $\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$ | $\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$ |
| neutralinos | $1/2$ | $-1$ | $\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$ | $\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$ |
| charginos | $1/2$ | $-1$ | $\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$ | $\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$ |
| gluino | $1/2$ | $-1$ | $\widetilde{g}$ | (same) |
| goldstino (gravitino) | $1/2$ $(3/2)$ | $-1$ | $\widetilde{G}$ | (same) |

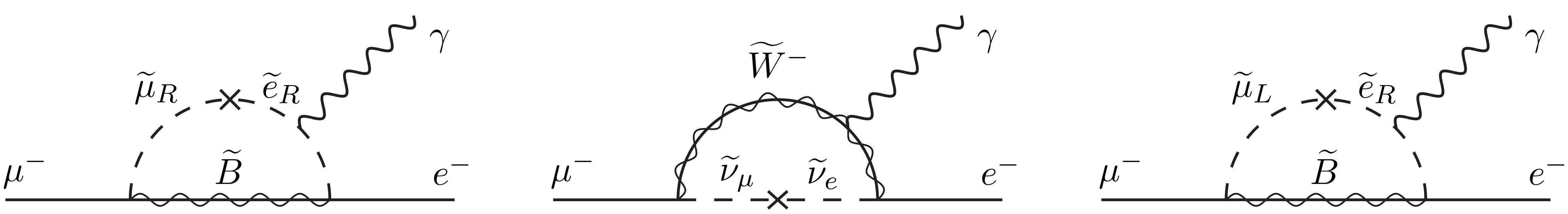
# *Lightning Pheno summary*

## *Failure ...*

SUSY-breaking soft so we don't lose the famous cancellation of divergences
But no explanation of form of soft-supersymmetry breaking

$$\begin{aligned}\mathcal{L}_{\rm soft}^{\rm MSSM} &= -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\ &\quad -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\ &\quad -\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\ &\quad - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.\end{aligned}$$

Many constraints on the form of the SUSY breaking: e.g. $\mu \longrightarrow e\gamma$ - often assumed universal



# *The idea of mediation*

*Or in DESY …*

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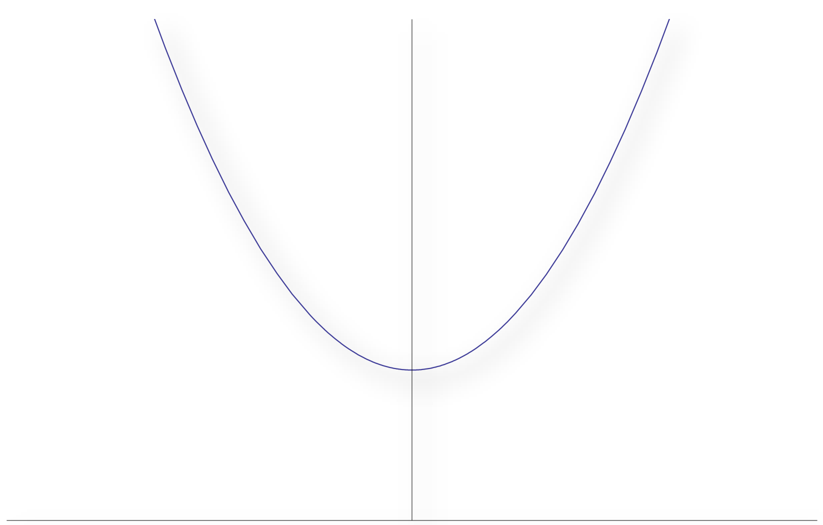
*www.thefreedictionary.com …*

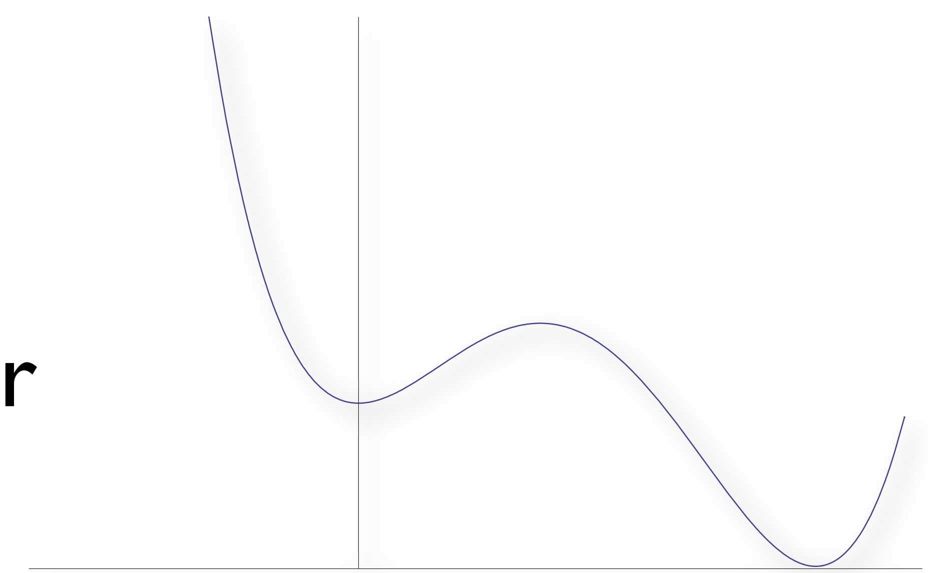
*(I) “A contemplative discourse, usually on a religious or philosophical subject.”*
*(II) “A form of religion practiced by Eastern mystics who stare fixedly at their own navels to induce a mystical trance. Also known as omphalism.”*

# *The idea of mediation*

Assume SUSY is broken in a non-MSSM sector:



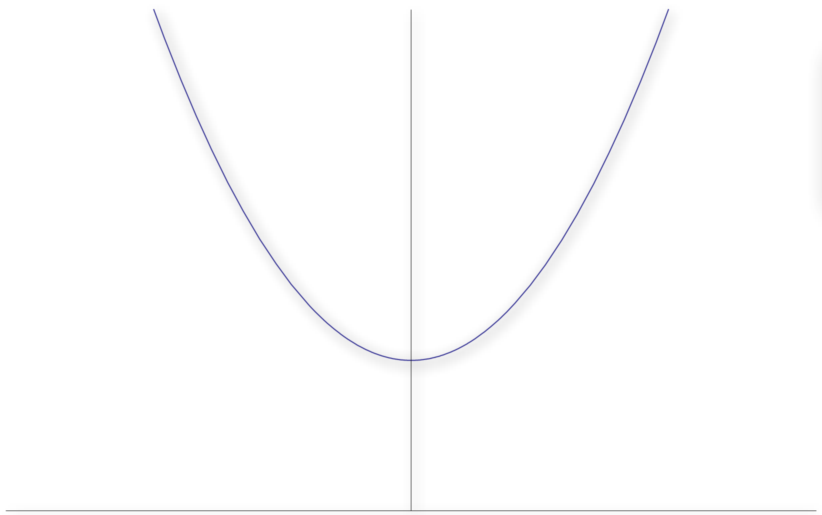
or



$$V = \left| \frac{\partial W}{\partial \Phi_i} \right|^2$$

# *The idea of mediation*

Simple example of SUSY breaking model: O'Raighfeartaigh



$$W_{susy-break} = h\varphi\varphi_1^2 + m\varphi_1\varphi_2 - \mu^2\varphi$$

$$\begin{aligned} F_\varphi &= (\frac{\partial W}{\partial \varphi})^* = h\varphi_1^2 - \mu^2 \\ F_{\varphi_1} &= 2h\varphi\varphi_1 + m\varphi_2 \\ F_{\varphi_2} &= m\varphi_1 \end{aligned}$$

Clearly no solution that has all F-terms zero hence $V = \left|\frac{\partial W}{\partial \Phi_i}\right|^2 > 0$

In this model a linear combination of $\varphi_2, \varphi$ is a Goldstino (pseudo-flat scalar direction and massless fermion)

In supergravity (when we gauge the whole superspace) the Goldstino is eaten by the gravitino

# *The idea of mediation*

***Visible sector breaking (no mediation):*** Very low scale breaking with generally SUSY breaking masses …

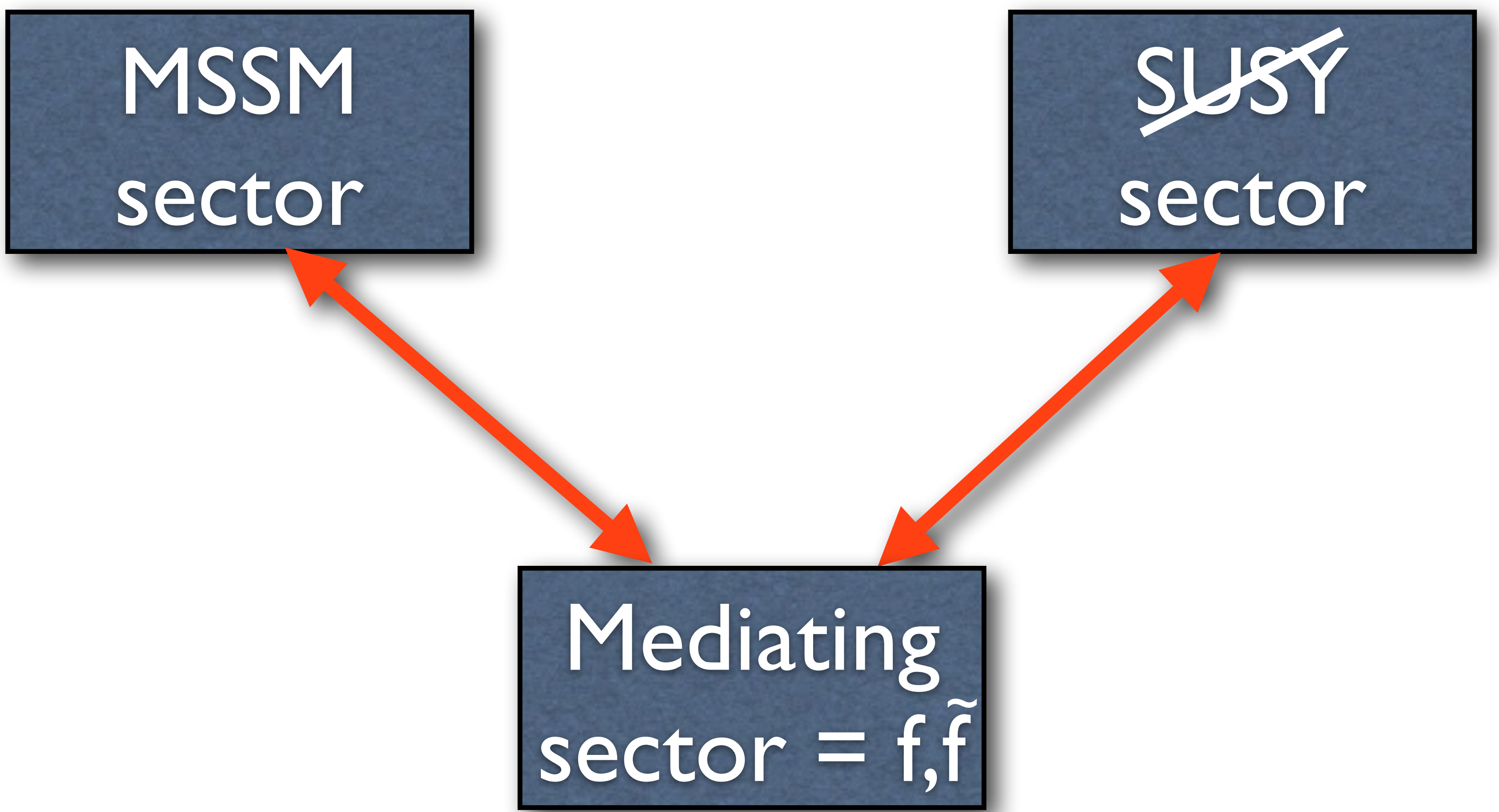
$$M^2 \sim F$$

Supertrace sum rules (Dimopoulos Georgi) mean breaking directly in the visible sector is phenomenologically difficult:

$$STr(M^2) = 0 \longrightarrow m^2_{\tilde{d}} + m^2_{\tilde{s}} + m^2_{\tilde{b}} \sim (5\text{GeV})^2$$

# *The idea of mediation*

***Gauge mediation:*** Low scale mediation. If SUSY is not hidden then this will be the dominant effect. Giudice Rattazzi Phys Rep 1999




$$(f.\tilde{f})\varphi \quad = \quad (f.\tilde{f})(\varphi + \theta^2 F)$$

Universal form for gaugino and sfermion masses - of same order $M \sim F/M_f$

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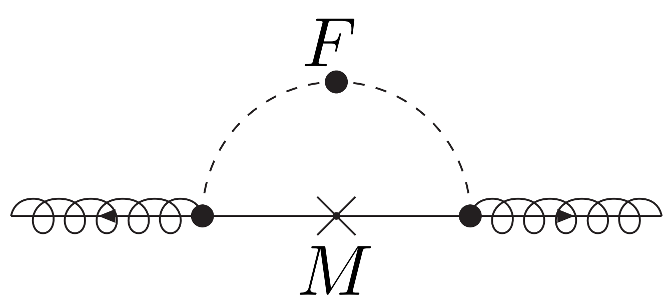
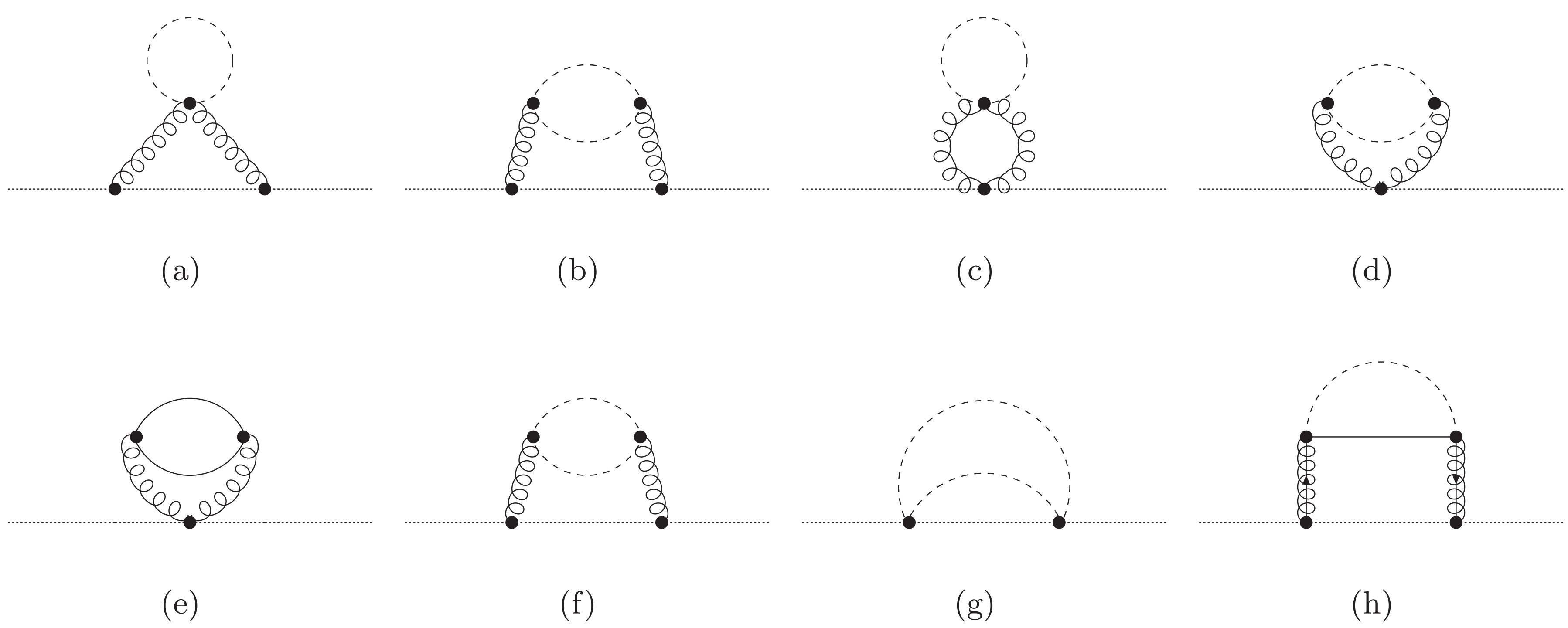


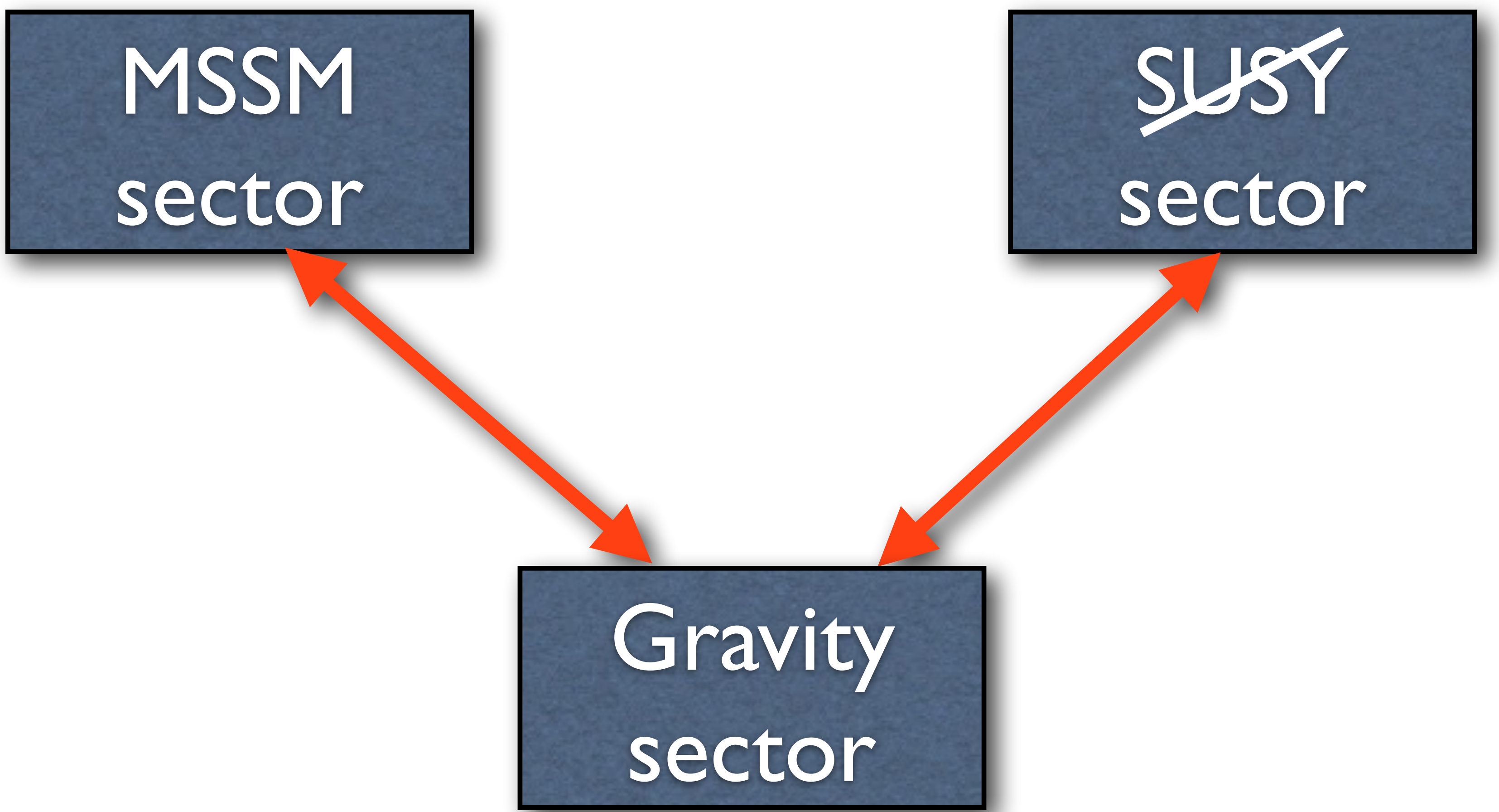

$$M_{\tilde{\lambda}_i} = k_i \frac{\alpha_i}{4\pi} \frac{F}{M}$$

$$m^2_{\tilde{f}} = 2 \sum_{i=1}^{3} C_i k_i \left( \frac{\alpha_i}{4\pi} \frac{F}{M} \right)^2$$



# *The idea of mediation*

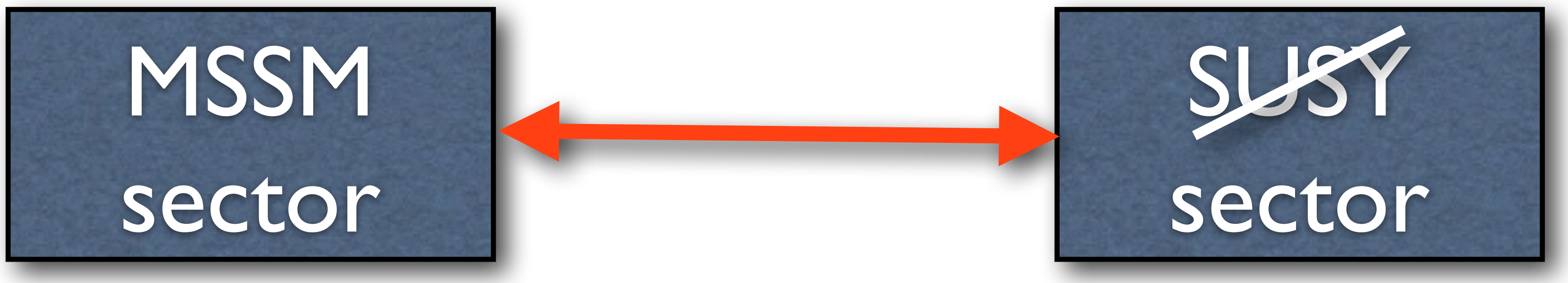
***Gravity mediation:*** High scale mediation. If SUSY is “hidden” (typical string theory assumption and easiest to achieve).




SUSY breaking masses of order $M \sim F/M_{Pl}$

# *The idea of mediation*

***Direct Gauge mediation:*** Try to embed the messengers in the SUSY breaking dynamics.




SUSY breaking dynamics now important; can have much smaller gaugino masses

Poppitz Trivedi (1996) ....
Izawa, Momura, Tobe, Yanagida (1997)
Csaki, Shirman, Terning (2006)
Kitano Ooguri Ookouchi (2006)
SAA, Durnford, Jaeckel, Khoze (2007)
SAA, Jaeckel, Khoze, Matos (2008)

# *Not-cheating: Dynamical SUSY Breaking and the importance of R-symmetry*

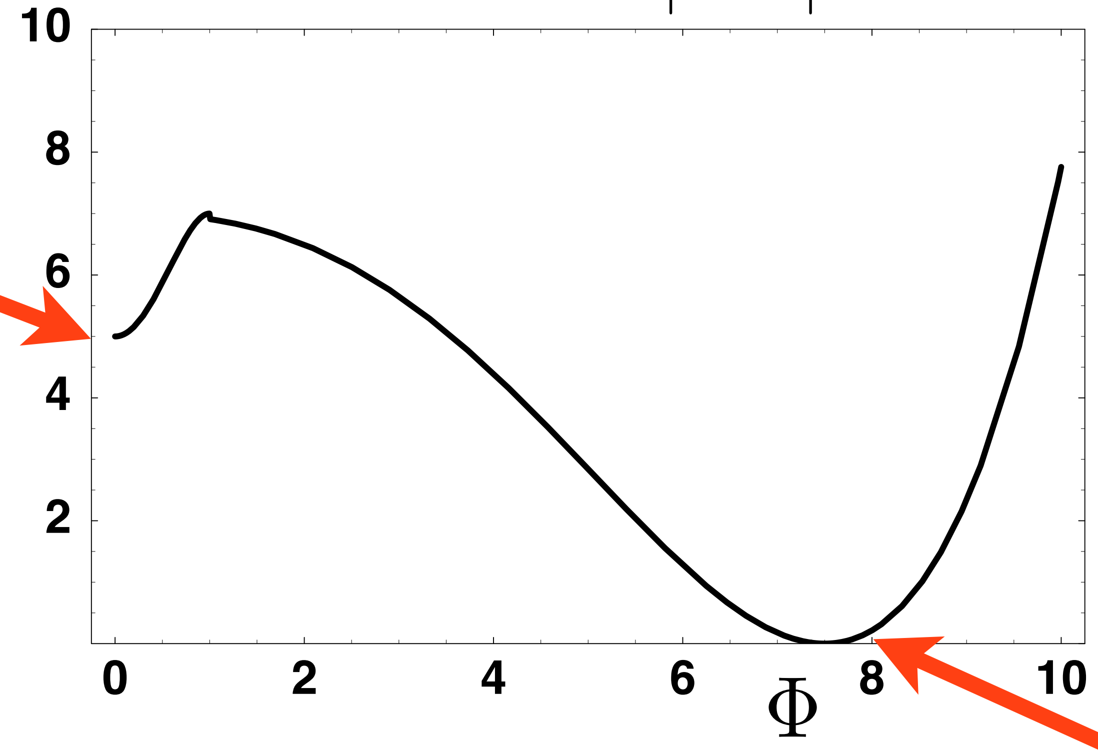
# Dynamical SUSY breaking

ISS (2006) renewed interest in DSB (Intriligator Seiberg Shih)

| | |
|---|---|
| $\mathcal{N} = 1$ gauge | SU($N$) |
| $F_Q$ quark and antiquarks | $Q,\, \tilde{Q}$ |
| Superpotential | $W_{elec} = m_Q Q\tilde{Q}$ |

# *Dynamical SUSY breaking*

$$V = \left|\frac{\partial W}{\partial \Phi}\right|^2$$




Universe sits here

vacuum is supersymmetric

# Th'm: Nelson-Seiberg

*In a generic theory dynamical SUSY breaking requires an R-symmetry:*

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

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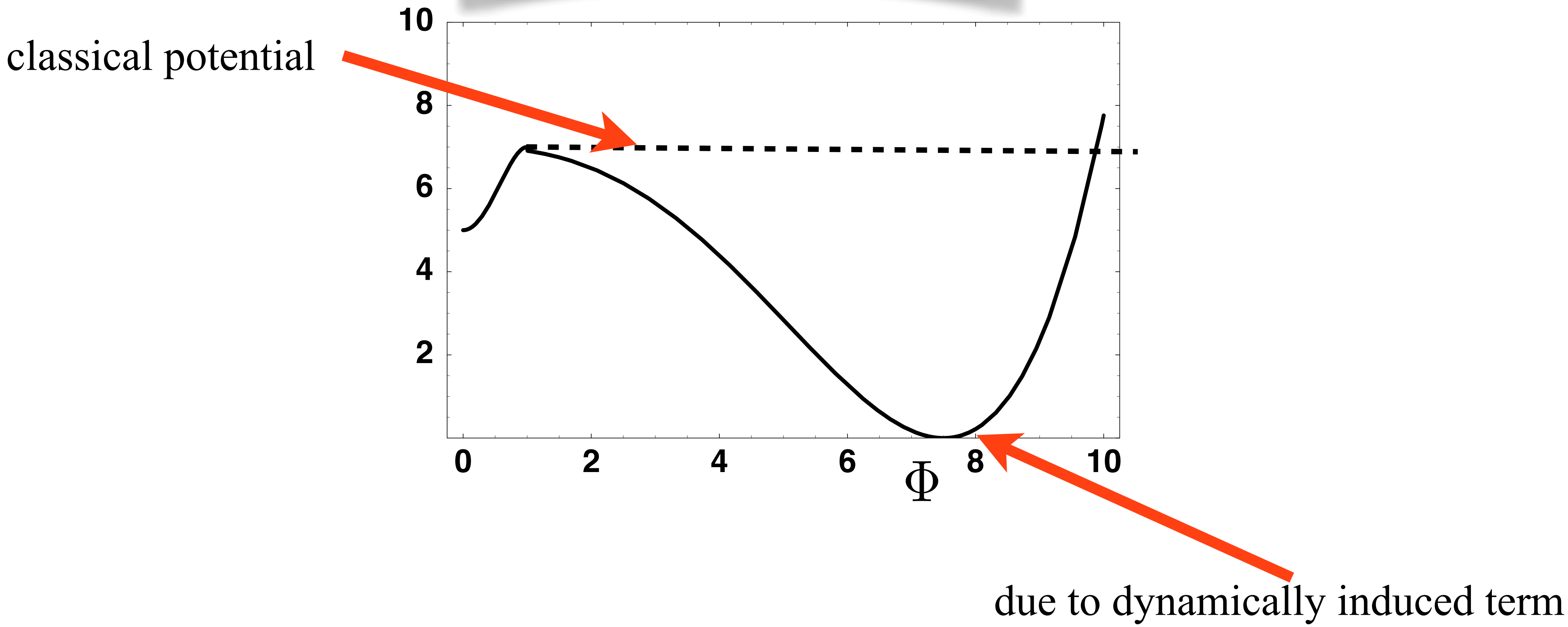
The Ordinary GM paradigm ***cheats*** by writing $(f.\tilde{f})\Phi = (f.\tilde{f})(M + \theta^2 F)$

# Th'm: Nelson-Seiberg

The origin of ISS is metastable because of an *anomalous* R-symmetry

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



# Th'm: Nelson-Seiberg

Looked promising and lots of excitement ...

1) Long lived vacuum because automatically very shallow

2) R-symmetry breaking as well albeit anomalous, but ...

... sadly gaugino masses still zero. So require extra R-symmetry breaking, but then still need to worry about stability of SUSY breaking minimum.

# Th'm: Nelson-Seiberg

Two possible options for doing phenomenology:

1) Explicit R-breaking

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

a global SUSY minimum develops $\mathcal{O}(1/\varepsilon^{\rm power})$y in field space

$$M_\lambda \propto \varepsilon^{\rm power'}$$

2) Spontaneous R-breaking

# Explicit Breaking example

Murayama and Nomura 2007

How to get an R-breaking gaugino mass without destabilising vacuum?
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***Emergent R-symmetry***

# *Clues from String Theory?*
# *String models with SUSY breaking and Scherk-Schwarz*

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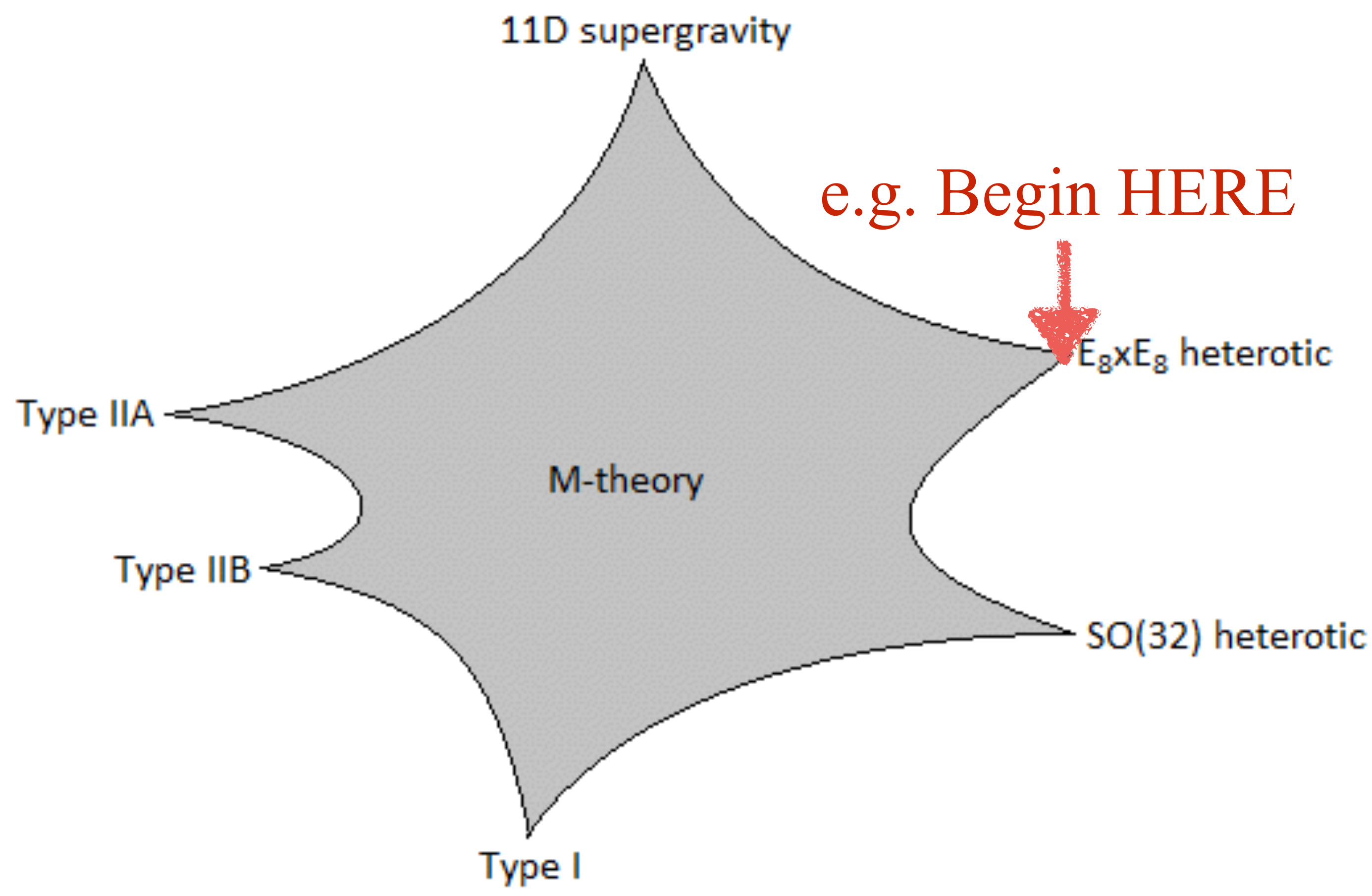

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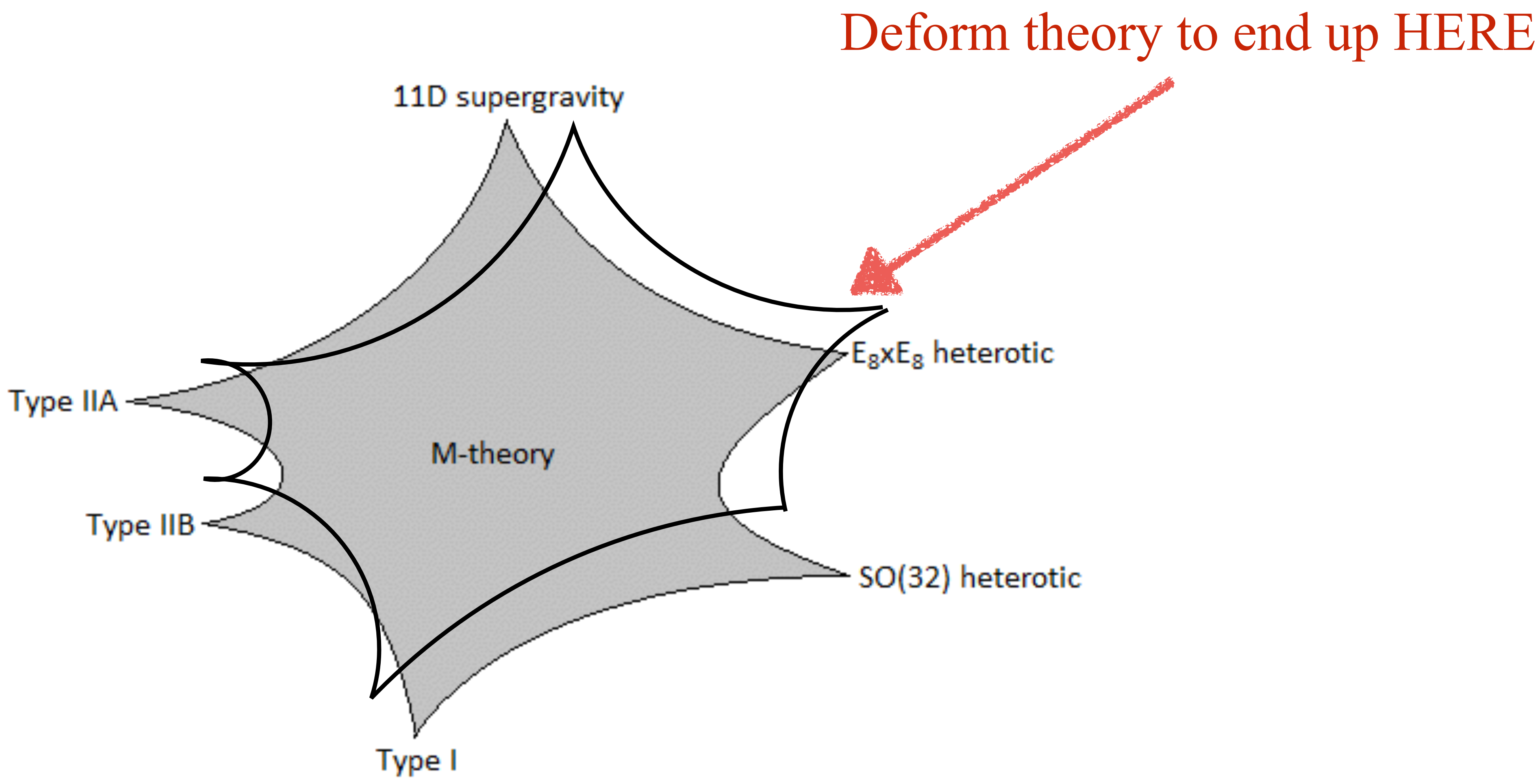

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- ***The order parameter is 1/Radius.***
- For SUSY breaking to be spontaneous, the world-sheet supercurrent must be preserved under the discrete transformations but not commute with the local generator $\mathbf{Q_e}$

$$[T_F(z), \mathbf{Q}_e(z)] \neq 0$$

e.g. in Heterotic string define everything in terms of internal charge lattice:

***Let*** $\mathbf{Q}_e = \mathbf{e}\cdot\mathbf{Q}$

***Partition function deformed according to*** (Rohm, Kounnas, Rostand, Ferrara, Porratti, Zwirner)

$$Z_{\text{model}} = \sum_{\alpha,\beta,n,m} Tr\,\mathbf{g}\,q^{[\mathbf{L}'_0]}\overline{q}^{[\overline{\mathbf{L}}'_0]}$$

$$\mathbf{L}'_0 = \frac{1}{2}\left[\mathbf{Q}_L - \mathbf{e}_L(n_1+n_2)\right]^2 + \frac{1}{4}\left[\frac{m_1 + \mathbf{e}\cdot\mathbf{Q} - \frac{1}{2}(n_1+n_2)\mathbf{e}^2}{r_1} + n_1 r_1\right]^2$$
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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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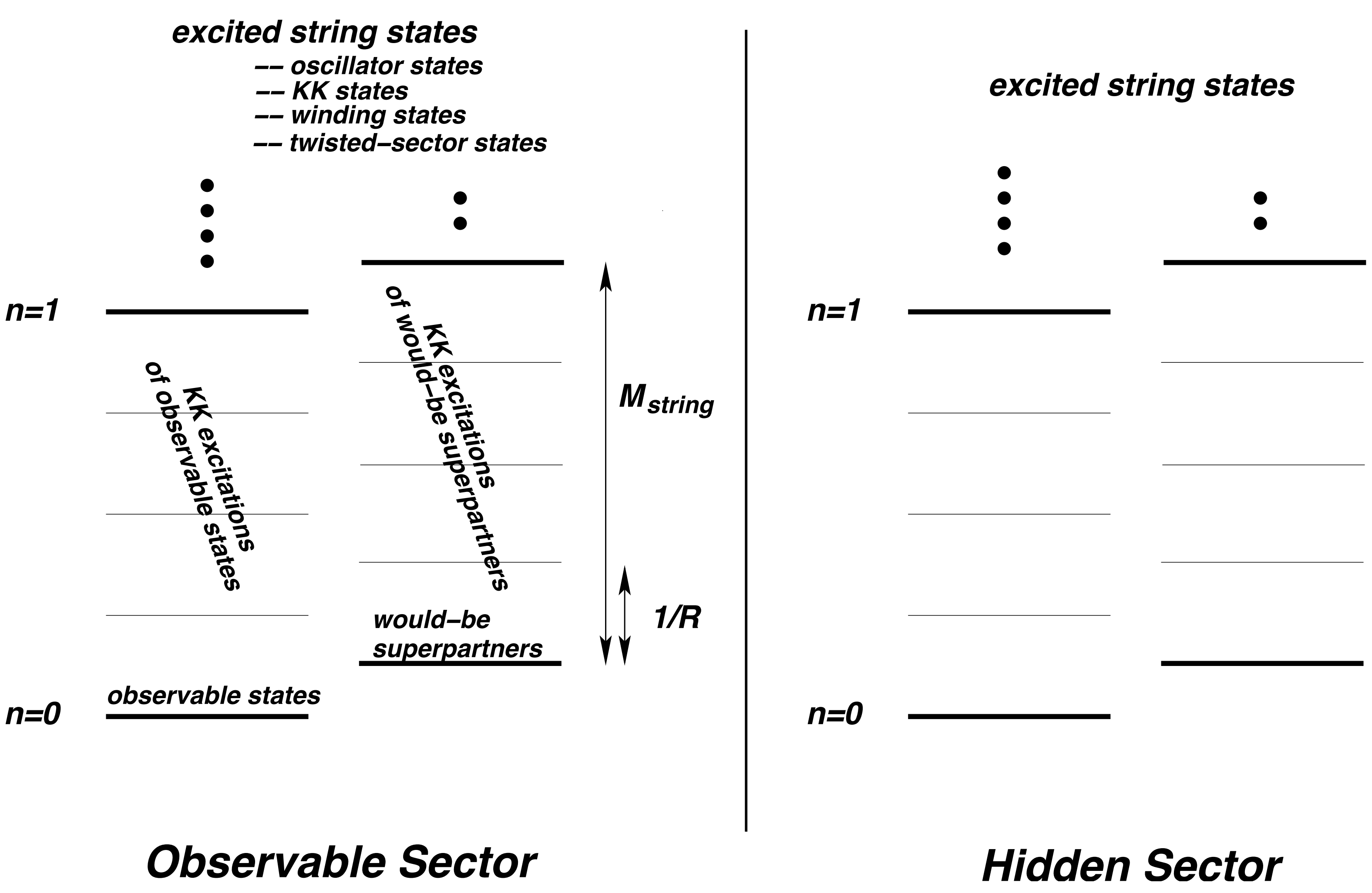
Different charges!! c.f. folded SUSY with a twist (Craig et al)

# Phenomenology

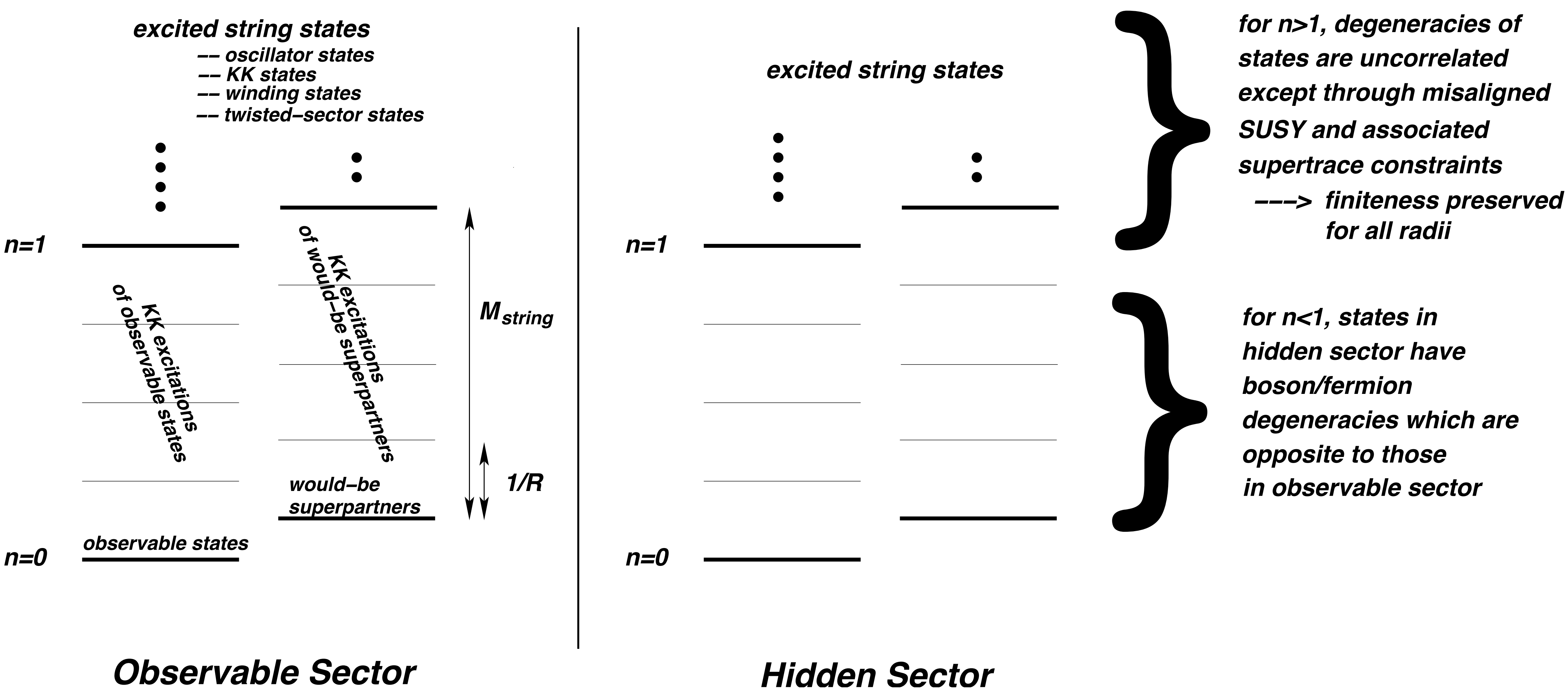



for n>1, degeneracies of states are uncorrelated except through misaligned SUSY and associated supertrace constraints
---> finiteness preserved for all radii

for n<1, states in hidden sector have boson/fermion degeneracies which are opposite to those in observable sector

# Phenomenology

***A phenomenological model would look generically like ...***



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$$
\begin{aligned}
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