(Extra)Ordinary Gauge Mediation

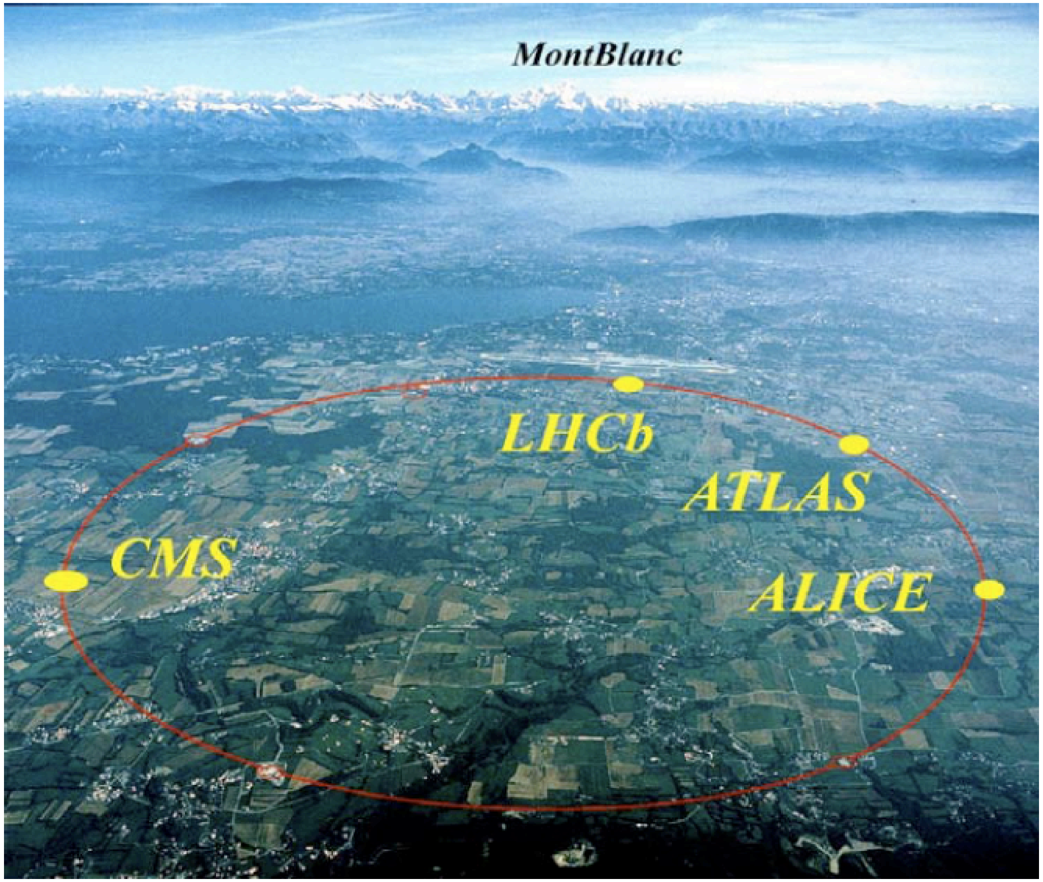
David Shih
IAS

Based on:

Clifford Cheung, Liam Fitzpatrick, DS, hep-ph/0710.3585

DS, hep-th/0703196

The LHC is coming...



What will we see?

The MSSM

- The MSSM is still the most well-motivated possibility.

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\ \mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$
($\times$3 families)	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\ \overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$
($\times$3 families)	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\ \mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\ \mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$

Table 1.1: Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\ \mathbf{8},\ \mathbf{1}\ ,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\ \mathbf{1},\ \mathbf{3}\ ,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\ \mathbf{1},\ \mathbf{1}\ ,\ 0)$

Table 1.2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

MSSM, cont'd

- But even if we are fortunate enough to discover the MSSM at the LHC, the main theoretical challenge will still be ahead of us: explaining the origin of the 100+ soft SUSY breaking parameters.

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

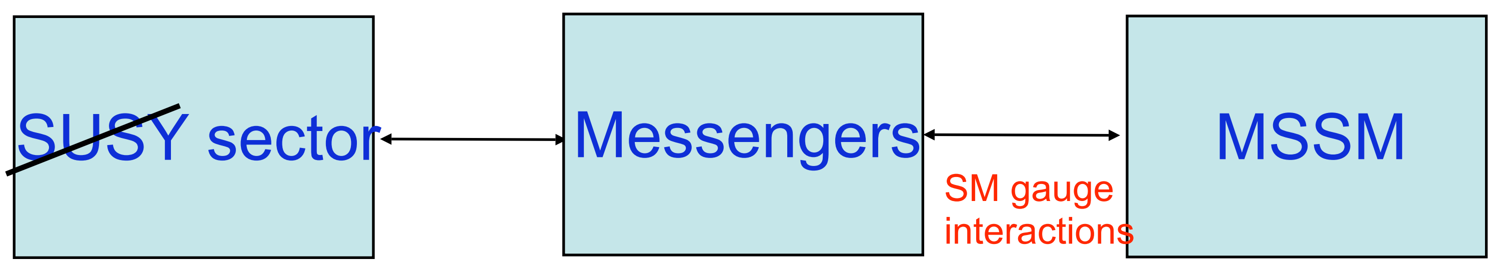
- Any explanation will have to address various problems, including:
  - SUSY flavor problem
  - SUSY CP problem
  - "little hierarchy" problem

Gauge Mediation

Alvarez-Gaume, Claudson, Dimopoulos, Dine, Fischler, Nappi, Ovrut, Raby, Srednicki, Wise; Dine, Nelson, Nir, Shirman

Gauge mediation is a successful theory of the soft masses. It has many attractive features, including:

- flavor blindness
- calculability
- predictivity
- distinctive phenomenology



“Ordinary” Gauge Mediation

“Ordinary” Gauge Mediation

The details of the hidden sector are generally irrelevant for determining the low-energy MSSM spectrum.

Thus, it is useful to parametrize the SUSY-breaking sector in a model independent way, through a singlet spurion field X:

$$\langle X \rangle = M + \theta^2 F$$

“Ordinary” Gauge Mediation

The details of the hidden sector are generally irrelevant for determining the low-energy MSSM spectrum.

Thus, it is useful to parametrize the SUSY-breaking sector in a model independent way, through a singlet spurion field X:

$$\langle X \rangle = M + \theta^2 F$$

By coupling X directly to messenger fields $\phi_i, \tilde{\phi}_i$ transforming in vector-like representations of the SM gauge group, we obtain a simple family of gauge mediation models known as “ordinary” or “minimal” gauge mediation.

$$W = \sum_{i=1}^{N} \lambda_i X \phi_i \tilde{\phi}_i$$

“Ordinary” Gauge Mediation

The details of the hidden sector are generally irrelevant for determining the low-energy MSSM spectrum.

Thus, it is useful to parametrize the SUSY-breaking sector in a model independent way, through a singlet spurion field X:

$$\langle X \rangle = M + \theta^2 F$$

By coupling X directly to messenger fields $\phi_i,\ \tilde{\phi}_i$ transforming in vector-like representations of the SM gauge group, we obtain a simple family of gauge mediation models known as “ordinary” or “minimal” gauge mediation.

$$W = \sum_{i=1}^{N} \lambda_i X \phi_i \tilde{\phi}_i$$

Simplest choice consistent with unification:

$$\phi_i \in \mathbf{5} \quad \tilde{\phi}_i \in \bar{\mathbf{5}} \quad \text{of} \quad SU(5)$$

OGM Spectrum

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

where $C_{\tilde{f}}^r \neq 0$ only if f is charged under the gauge group r.

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

where $C_{\tilde{f}}^r \neq 0$ only if f is charged under the gauge group r.

Only a few parameters determine the entire MSSM spectrum!

- Messenger scale: M
- SUSY breaking scale: $\sqrt{F}$
- Messenger number: N

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100\ \mathrm{TeV}$$ (leading order in F/M)

where $C_{\tilde{f}}^r \neq 0$ only if f is charged under the gauge group r.

Only a few parameters determine the entire MSSM spectrum!

- Messenger scale: M
- SUSY breaking scale: $\sqrt{F}$
- Messenger number: N

In particular, spectrum is independent of the messenger couplings λ_i .
So doublet/triplet splitting has no effect on the spectrum,

$$W = \lambda_3 X q\tilde{q} + \lambda_2 X \ell\tilde{\ell}$$

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$

(leading order in F/M)

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

Some features of the OGM spectrum:

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

Some features of the OGM spectrum:

- Gravitino LSP: m(gravitino) ~ F/Mpl ~ eV

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m^2_{\tilde{f}} = 2\sum_{r=1}^{3} C^r_{\tilde{f}} \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

Some features of the OGM spectrum:

- Gravitino LSP: m(gravitino) ~ F/Mpl ~ eV
- m(colored) >> m(uncolored), or more precisely,

$$M_3 : M_2 : M_1 \sim m_{\tilde{q}} : m_{\tilde{\ell}_L} : m_{\tilde{\ell}_R} \sim \alpha_3 : \alpha_2 : \alpha_1$$

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

Some features of the OGM spectrum:

- Gravitino LSP: m(gravitino) ~ F/Mpl ~ eV
- m(colored) >> m(uncolored), or more precisely,

$$M_3 : M_2 : M_1 \sim m_{\tilde{q}} : m_{\tilde{\ell}_L} : m_{\tilde{\ell}_R} \sim \alpha_3 : \alpha_2 : \alpha_1$$

- m(gaugino)/m(sfermion) increases with N

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

Some features of the OGM spectrum:

- Gravitino LSP: m(gravitino) ~ F/Mpl ~ eV
- m(colored) >> m(uncolored), or more precisely,

$$M_3 : M_2 : M_1 \sim m_{\tilde{q}} : m_{\tilde{\ell}_L} : m_{\tilde{\ell}_R} \sim \alpha_3 : \alpha_2 : \alpha_1$$

- m(gaugino)/m(sfermion) increases with N
- heavy higgsinos: $\mu \sim m_{\tilde{t}}$

OGM Spectrum

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde f}^2 = 2\sum_{r=1}^{3} C_{\tilde f}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

$$\Lambda_G = \sqrt{N}\Lambda_S = NF/M \sim 100 \text{ TeV}$$ (leading order in F/M)

Some features of the OGM spectrum:

- Gravitino LSP: m(gravitino) ~ F/Mpl ~ eV
- m(colored) >> m(uncolored), or more precisely,

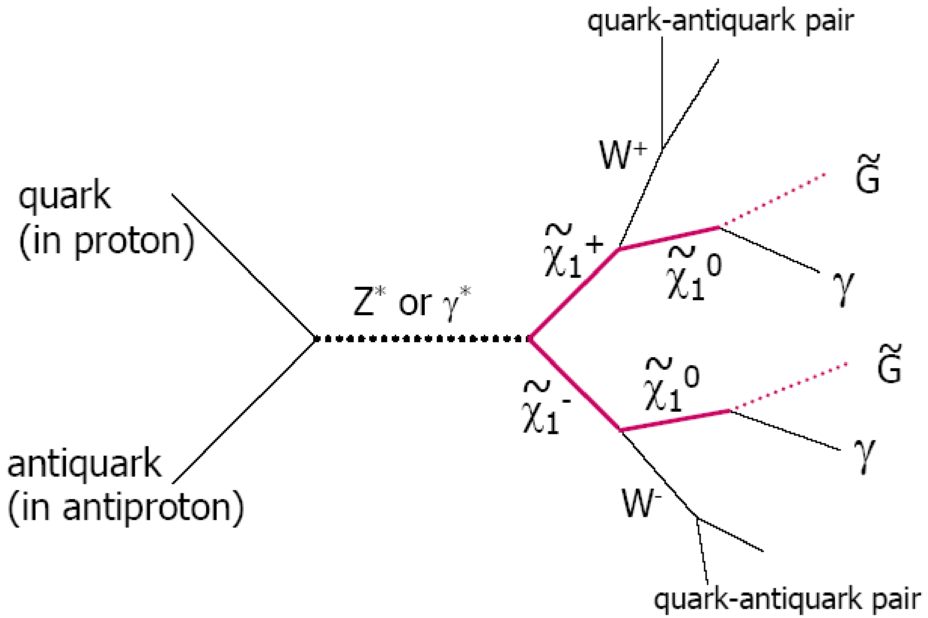
$$M_3 : M_2 : M_1 \sim m_{\tilde q} : m_{\tilde \ell_L} : m_{\tilde \ell_R} \sim \alpha_3 : \alpha_2 : \alpha_1$$

- m(gaugino)/m(sfermion) increases with N
- heavy higgsinos: $\mu \sim m_{\tilde t}$

$\Longrightarrow$ Bino or right-handed slepton NLSP!

More on the NLSP

- The nature of the NLSP determines much of the collider phenomenology, since every sparticle decay chain passes through it
- In particular, promptly decaying bino NLSP have a very clean and distinctive collider signature: diphoton+MET:



$\mathcal{O}(10^3 - 10^4)\ \mathrm{fb}^{-1}$ cross section at the LHC

SM background virtually non-existent

Gauge mediation = OGM?

It is crucial to fully map out the phenomenology of gauge mediation, if we are to discover or rule it out at the LHC.

Motivated by this, we studied the phenomenology of a large family of simple extensions of OGM, obtained by deforming the OGM superpotential by messenger mass terms

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

In fact, this corresponds to the most general messenger superpotential allowed by gauge symmetry and renormalizability.

"(Extra)ordinary gauge mediation"

EOGM – why not?

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

EOGM – why not?

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

Surprisingly, these models have not been much explored. Why not?

EOGM – why not?

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

Surprisingly, these models have not been much explored. Why not?

- "They have explicit mass parameters. This seems unnatural."

  These mass parameters are analogous to the mu term of the MSSM. If we allow for the latter, then there is no reason not to allow for former.
  Also, there are now many examples of strongly-coupled SUSY gauge theories where EOGM-type superpotentials are dynamically generated.

EOGM – why not?

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

Surprisingly, these models have not been much explored. Why not?

– “They have explicit mass parameters. This seems unnatural.”

  These mass parameters are analogous to the mu term of the MSSM. If we allow for the latter, then there is no reason not to allow for former.
  Also, there are now many examples of strongly-coupled SUSY gauge theories where EOGM-type superpotentials are dynamically generated.

– “They have dangerous contributions to sfermion masses from hypercharge D-terms.”

  These can be forbidden by global symmetries (e.g. generalized messenger parity). We will assume this is the case for the rest of today’s talk.

EOGM – why not?

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

Surprisingly, these models have not been much explored. Why not?

- "They have explicit mass parameters. This seems unnatural."

  These mass parameters are analogous to the mu term of the MSSM. If we allow for the latter, then there is no reason not to allow for former.
  Also, there are now many examples of strongly-coupled SUSY gauge theories where EOGM-type superpotentials are dynamically generated.

- "They have dangerous contributions to sfermion masses from hypercharge D-terms."

  These can be forbidden by global symmetries (e.g. generalized messenger parity). We will assume this is the case for the rest of today's talk.

- "They can't possibly give rise to phenomenology that is qualitatively different than OGM."

  Actually...

EOGM - why not?

In today's talk, we will see that many of the classic features of OGM can be modified in this more general (but just as "ordinary"!) class of models.

Thus, there is more to gauge mediation than just OGM!

R-symmetry

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

R-symmetry

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

- We will limit our study to models with a continuous $U(1)_R$ symmetry

R-symmetry

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

- We will limit our study to models with a continuous $U(1)_R$ symmetry

Motivations:

- Imposing an R-symmetry cuts down the parameter space, simplifies analysis, and has interesting consequences.
- Need an R-symmetry for SUSY breaking (Nelson & Seiberg)

R-symmetry

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j$$

- We will limit our study to models with a continuous $U(1)_R$ symmetry

Motivations:

- Imposing an R-symmetry cuts down the parameter space, simplifies analysis, and has interesting consequences.
- Need an R-symmetry for SUSY breaking (Nelson & Seiberg)

Example:

$$R(X) = 2, \quad R(\phi_i) = -2i, \quad R(\tilde{\phi}_i) = 2i$$

$$W = \mathcal{M}_{ij}(X) \phi_i \tilde{\phi}_j = \lambda_i X \phi_i \tilde{\phi}_i + m_i \phi_i \tilde{\phi}_{i+1}$$

$$\mathcal{M} = \begin{pmatrix} \lambda X & m \\ 0 & \lambda X \end{pmatrix}, \qquad \mathcal{M} = \begin{pmatrix} \lambda X & m & 0 \\ 0 & \lambda X & m \\ 0 & 0 & \lambda X \end{pmatrix}, \qquad etc.$$

Determinant Identity

Because of the R-symmetry, the messenger mass matrix $\mathcal{M} \equiv \lambda X + m$ satisfies an important identity:

$$\det \mathcal{M} = X^n G(m, \lambda)$$

This determinant identity, which follows directly from the R-symmetry, has a number of important consequences.

E.g. in the previous example $\det \mathcal{M} = \lambda^N X^N$ (note: independent of m!)

Classifying models using the determinant identity

$$\det(m + \lambda X) = X^n G(m, \lambda)$$

Classifying models using the determinant identity

$$\det(m + \lambda X) = X^n G(m, \lambda)$$

- $n = 0: \quad \det(m + \lambda X) = \det m \qquad (\Rightarrow \det \lambda = 0)$

Classifying models using the determinant identity

$$\det(m + \lambda X) = X^n G(m, \lambda)$$

- $n = 0 :\quad \det(m + \lambda X) = \det m \qquad (\Rightarrow \det \lambda = 0)$

- $n = N :\quad \det(m + \lambda X) = X^N \det \lambda \qquad (\Rightarrow \det m = 0)$

Classifying models using the determinant identity

$$\det(m + \lambda X) = X^n G(m, \lambda)$$

- $n = 0 : \quad \det(m + \lambda X) = \det m \qquad (\Rightarrow \det \lambda = 0)$
- $n = N : \quad \det(m + \lambda X) = X^N \det \lambda \qquad (\Rightarrow \det m = 0)$
- $0 < n < N : \quad \det(m + \lambda X) = X^n G(m, \lambda) \qquad (\det m,\ \det \lambda \neq 0)$

Classifying models using the determinant identity

$$\det(m + \lambda X) = X^n G(m, \lambda)$$

- $n = 0: \quad \det(m + \lambda X) = \det m \qquad (\Rightarrow \det \lambda = 0)$
- $n = N: \quad \det(m + \lambda X) = X^N \det \lambda \qquad (\Rightarrow \det m = 0)$
- $0 < n < N: \quad \det(m + \lambda X) = X^n G(m, \lambda) \qquad (\det m,\ \det \lambda \neq 0)$

These three categories of models have very different properties. Since OGM belongs to the second category, we will focus on this category in today's talk.

Phenomenology of (Extra)Ordinary Gauge Mediation

Soft masses

Soft masses

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

- Straightforward to compute soft masses, using technique of "analytic continuation in superspace" (Giudice & Rattazzi).

Soft masses

$$M_r = \frac{\alpha_r}{4\pi}\Lambda_G, \qquad m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \Lambda_S^2$$

- Straightforward to compute soft masses, using technique of "analytic continuation in superspace" (Giudice & Rattazzi).
- Same general structure as OGM, but now scales Λ_G, Λ_S are given by different expressions:

$$\Lambda_G = F\partial_X \log\det\mathcal{M} = \frac{nF}{X}$$

Using determinant identity
$\det\mathcal{M} \propto X^n$

$$\Lambda_S^2 = \frac{1}{2}|F|^2\partial^2_{XX^*}\sum_{i=1}^{N}(\log|\mathcal{M}_i|^2)^2$$

Soft masses, cont'd

$$\Lambda_G = F \partial_X \log \det \mathcal{M} = \frac{nF}{X}$$

$$\Lambda_S^2 = \frac{1}{2} |F|^2 \partial^2_{X X^*} \sum_{i=1}^{N} (\log |\mathcal{M}_i|^2)^2$$

Soft masses, cont'd

$$\Lambda_G = F\partial_X \log\det\mathcal{M} = \frac{nF}{X}$$

$$\Lambda_S^2 = \frac{1}{2}|F|^2\partial^2_{XX^*}\sum_{i=1}^{N}(\log|\mathcal{M}_i|^2)^2$$

- Λ_G is always independent of the couplings! Consequence: gauginos always obey the GUT relations in these models.

Soft masses, cont'd

$$\Lambda_G = F\partial_X \log\det\mathcal{M} = \frac{nF}{X}$$

$$\Lambda_S^2 = \frac{1}{2}|F|^2\partial^2_{XX^*}\sum_{i=1}^{N}(\log|\mathcal{M}_i|^2)^2$$

- Λ_G is always independent of the couplings! Consequence: gauginos always obey the GUT relations in these models.

A direct consequence of R-symmetry!

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3 \approx 1 : 2 : 7$$

Soft masses, cont'd

$$\Lambda_G = F\partial_X \log\det\mathcal{M} = \frac{nF}{X}$$

$$\Lambda_S^2 = \frac{1}{2}|F|^2\partial^2_{XX^*}\sum_{i=1}^{N}(\log|\mathcal{M}_i|^2)^2$$

- Λ_G is always independent of the couplings! Consequence: gauginos always obey the GUT relations in these models.

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3 \approx 1 : 2 : 7$$

A direct consequence of R-symmetry!

- Λ_S in general depends on the messenger superpotential couplings. So, let us define the "effective messenger number"

$$N_{eff}(X, m, \lambda) = \frac{\Lambda_G^2}{\Lambda_S^2} = \left[\frac{1}{2n^2}|X|^2\partial^2_{XX^*}\sum_{i=1}^{N}\left(\log|M_i|^2\right)^2\right]^{-1}$$

Soft masses, cont'd

$$\Lambda_G = F\partial_X \log\det\mathcal{M} = \frac{nF}{X}$$

$$\Lambda_S^2 = \frac{1}{2}|F|^2\partial^2_{XX^*}\sum_{i=1}^{N}(\log|\mathcal{M}_i|^2)^2$$

- Λ_G is always independent of the couplings! Consequence: gauginos always obey the GUT relations in these models.

$$M_1 : M_2 : M_3 = \alpha_1 : \alpha_2 : \alpha_3 \approx 1 : 2 : 7$$

A direct consequence of R-symmetry!

- Λ_S in general depends on the messenger superpotential couplings. So, let us define the "effective messenger number"

$$N_{eff}(X,m,\lambda) = \frac{\Lambda_G^2}{\Lambda_S^2} = \left[\frac{1}{2n^2}|X|^2\partial^2_{XX^*}\sum_{i=1}^{N}\left(\log|M_i|^2\right)^2\right]^{-1}$$

Remember, in OGM one has $\Lambda_G = NF/X, \quad \Lambda_S = \sqrt{N}F/X, \quad N_{eff} = N$

Doublet/Triplet Splitting

$$\mathbf{5} \rightarrow (\mathbf{3},\ \mathbf{1},\ -\frac{1}{3}) \oplus (\mathbf{1},\ \mathbf{2},\ \frac{1}{2})$$

$$W = (\lambda_{3ij} X + m_{3ij}) q_i \tilde{q}_j + (\lambda_{2ij} X + m_{2ij}) \ell_i \tilde{\ell}_j$$

Doublet/Triplet Splitting

$$\mathbf{5} \rightarrow (\mathbf{3},\ \mathbf{1},\ -\frac{1}{3}) \oplus (\mathbf{1},\ \mathbf{2},\ \frac{1}{2})$$

$$W = (\lambda_{3ij} X + m_{3ij}) q_i \tilde{q}_j + (\lambda_{2ij} X + m_{2ij}) \ell_i \tilde{\ell}_j$$

In OGM, the spectrum does not depend on the superpotential couplings, so doublet/triplet splitting has no effect.

Doublet/Triplet Splitting

$$\mathbf{5} \to (\mathbf{3},\ \mathbf{1},\ -\frac{1}{3}) \oplus (\mathbf{1},\ \mathbf{2},\ \frac{1}{2})$$

$$W = (\lambda_{3ij} X + m_{3ij}) q_i \tilde{q}_j + (\lambda_{2ij} X + m_{2ij}) \ell_i \tilde{\ell}_j$$

In OGM, the spectrum does not depend on the superpotential couplings, so doublet/triplet splitting has no effect.

However, in EOGM, the sfermion masses do depend on the superpotential couplings, so now doublet/triplet splitting can have a big effect.

Doublet/Triplet Splitting

$$\mathbf{5} \rightarrow (\mathbf{3},\ \mathbf{1},\ -\frac{1}{3}) \oplus (\mathbf{1},\ \mathbf{2},\ \frac{1}{2})$$

$$W = (\lambda_{3ij} X + m_{3ij}) q_i \tilde{q}_j + (\lambda_{2ij} X + m_{2ij}) \ell_i \tilde{\ell}_j$$

In OGM, the spectrum does not depend on the superpotential couplings, so doublet/triplet splitting has no effect.

However, in EOGM, the sfermion masses do depend on the superpotential couplings, so now doublet/triplet splitting can have a big effect.

This sensitivity to doublet/triplet splitting is the main source of differences between OGM and EOGM.

Doublet/Triplet Splitting (cont'd)

- Doublet/triplet splitting means there can be different numbers of effective doublet and triplet messengers:

$$N_{eff,2} = N_{eff}(X, m_2, \lambda_2), \qquad N_{eff,3} = N_{eff}(X, m_3, \lambda_3)$$

$$m_{\tilde{f}}^2 = 2\sum_{r=1}^{3} C_{\tilde{f}}^r \left(\frac{\alpha_r}{4\pi}\right)^2 \frac{\Lambda_G^2}{N_{eff,r}} \quad \Rightarrow \quad m_{\tilde{q}} : m_{\tilde{\ell}} \sim \frac{\alpha_3}{\sqrt{N_{eff,3}}} : \frac{\alpha_2}{\sqrt{N_{eff,2}}}$$

- This can alter the spectrum in various ways. For instance, it can change the relations between slepton and squark masses -- one no longer necessarily has $m_{\tilde{q}} : m_{\tilde{\ell}} \sim \alpha_3 : \alpha_2$

- A less obvious, but also important consequence is a "focussing" effect in the running of the Higgs soft masses...

D/T Splitting and "Focussing"

$$m_{H_u}^2 \sim m_{H_u}^2(M_{mess}) - \frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \log \frac{M_{mess}}{m_{\tilde{t}}}$$

$\alpha_2^2 \Lambda_G^2 / N_{eff,2}$ $\alpha_3^2 \Lambda_G^2 / N_{eff,3}$

- In OGM, the first term is always smaller than the second, leading to

$$m_{H_u}^2 \sim -\frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \log \frac{M_{mess}}{m_{\tilde{t}}} \lesssim -(\mathrm{TeV})^2$$

- This implies that there must be at least 0.1-1% fine tuning in the mu parameter in order to achieve the observed EWSB:

$$\mu^2 + m_{H_u}^2 \approx -\frac{m_Z^2}{2}$$

"Little hierarchy problem"

D/T Splitting and "Focussing"

$$m_{H_u}^2 \sim m_{H_u}^2(M_{mess}) - \frac{3}{4\pi^2} y_t^2 m_{\tilde{t}}^2 \log \frac{M_{mess}}{m_{\tilde{t}}}$$

$\alpha_2^2 \Lambda_G^2 / N_{eff,2}$ $\alpha_3^2 \Lambda_G^2 / N_{eff,3}$

- Agashe & Graesser pointed out that with different numbers of doublets and triplets, one can make the first and second terms comparable, leading to a smaller Higgs mass parameter and hence smaller mu.

- Thus with doublet/triplet splitting, one can get much smaller mu in EOGM than OGM!

$$\mu \gtrsim 1 \text{ TeV normally} \rightarrow \mu \ll 1 \text{ TeV with “focussing”}$$

Higgsino NLSPs

- Small mu in turn implies that the lightest neutralino is Higgsino like:

$$m_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

(Bino, wino)

Higgsinos

- So the NLSP can be the Higgsino, not the bino or the stau!!

- Because of the bias from OGM, this is not a well-studied scenario. It could have interesting implications at the LHC, e.g.

$$ZZ,\ Zh,\ hh + MET \text{ instead of } \gamma\gamma + MET$$

- Could the LHC be a Higgs factory??

Unification?

Doublet/triplet splitting can potentially spoil gauge coupling unification. However the R-symmetry improves the situation.

To see this, let us begin by ordering the eigenvalues of the doublet and triplet messenger mass matrices.

$$\mathcal{M}_{r;0} \equiv m_Z < \mathcal{M}_{r;1} < \mathcal{M}_{r;2} < \cdots < \mathcal{M}_{r;N} < \mathcal{M}_{r;N+1} \equiv m_{GUT}, \quad (r = 2, 3)$$

Running the gauge couplings up gives

$$\begin{aligned} \alpha_r(M_{GUT}) &= \alpha_r(m_Z) + \sum_{i=0}^{N} \frac{b_r - i}{2\pi} \log \frac{\mathcal{M}_{a,i+1}}{\mathcal{M}_{a,i}} \\ &= \alpha_{GUT;MSSM} - \frac{1}{2\pi}(N \log M_{GUT} - \log \det \mathcal{M}_r) \end{aligned}$$

Unification?

Doublet/triplet splitting can potentially spoil gauge coupling unification. However the R-symmetry improves the situation.

To see this, let us begin by ordering the eigenvalues of the doublet and triplet messenger mass matrices.

$$\mathcal{M}_{r;0} \equiv m_Z < \mathcal{M}_{r;1} < \mathcal{M}_{r;2} < \cdots < \mathcal{M}_{r;N} < \mathcal{M}_{r;N+1} \equiv m_{GUT}, \quad (r = 2, 3)$$

Running the gauge couplings up gives

$$\begin{aligned} \alpha_r(M_{GUT}) &= \alpha_r(m_Z) + \sum_{i=0}^{N} \frac{b_r - i}{2\pi} \log \frac{\mathcal{M}_{a,i+1}}{\mathcal{M}_{a,i}} \\ &= \alpha_{GUT;MSSM} - \frac{1}{2\pi}(N \log M_{GUT} - \log \det\ \mathcal{M}_r) \end{aligned}$$

Only depends on the determinant!

Unification (cont'd)

$$\alpha_r(M_{GUT}) = \alpha_{GUT;MSSM} - \frac{1}{2\pi}(N \log M_{GUT} - \log \det \mathcal{M}_r)$$

According to the determinant identity,

$$\det \mathcal{M}_r = X^n G(m_r, \lambda_r)$$

In general, $G(m, \lambda)$ is independent of some of the couplings. Then these couplings can be split arbitrarily without spoiling unification.

E.g., $G(m, \lambda) = \det \lambda$ independent of m. Then as long as $G(\lambda_2) = G(\lambda_3)$ gauge coupling unification can be preserved.

An example

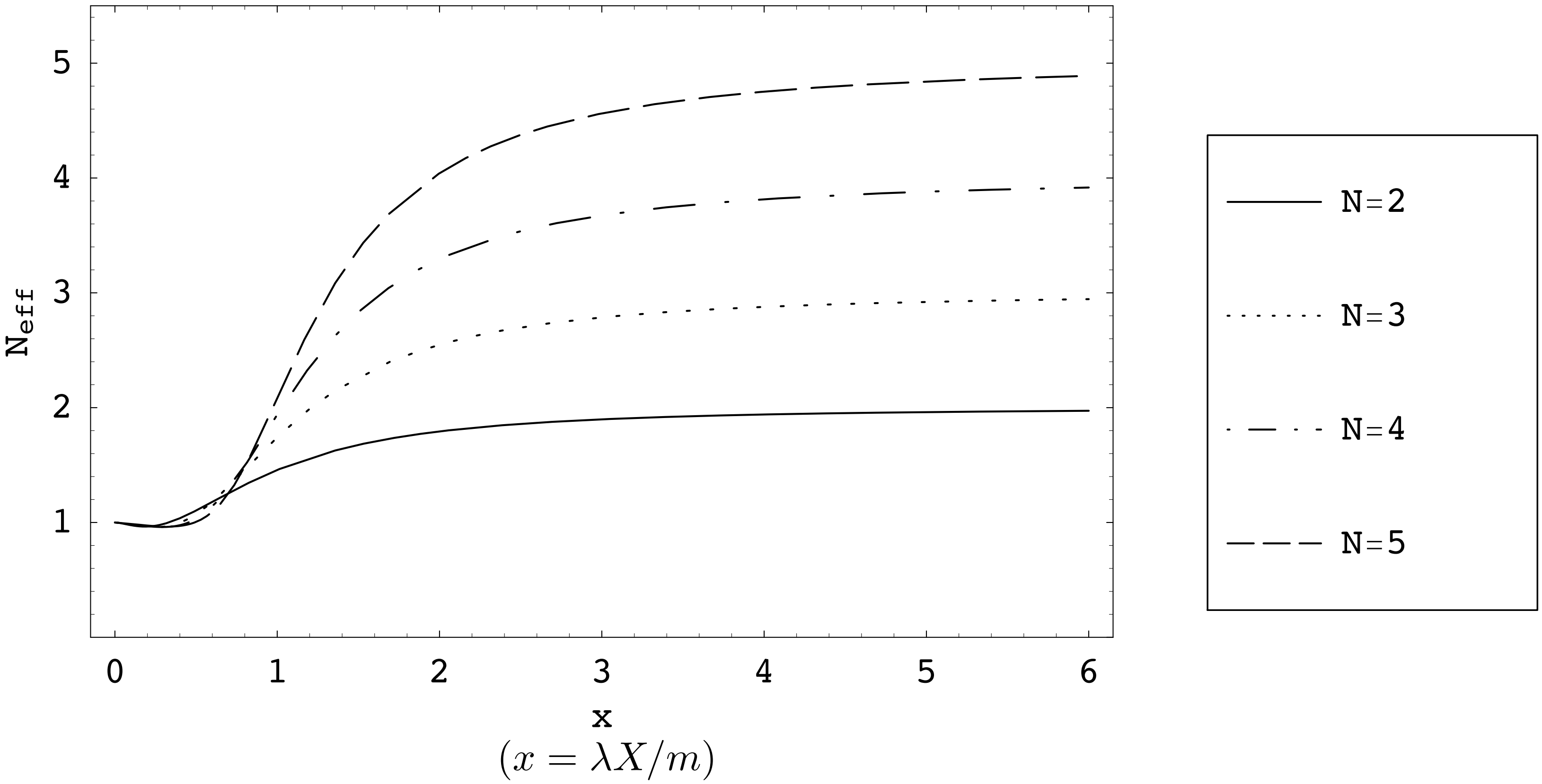
- Consider again the model

$$W = \mathcal{M}_{ij}(X)\phi_i\tilde{\phi}_j = \lambda_i X \phi_i \tilde{\phi}_i + m_i \phi_i \tilde{\phi}_{i+1}$$

$$\mathcal{M} = \begin{pmatrix} \lambda X & m \\ 0 & \lambda X \end{pmatrix}, \qquad \mathcal{M} = \begin{pmatrix} \lambda X & m & 0 \\ 0 & \lambda X & m \\ 0 & 0 & \lambda X \end{pmatrix}, \qquad etc.$$

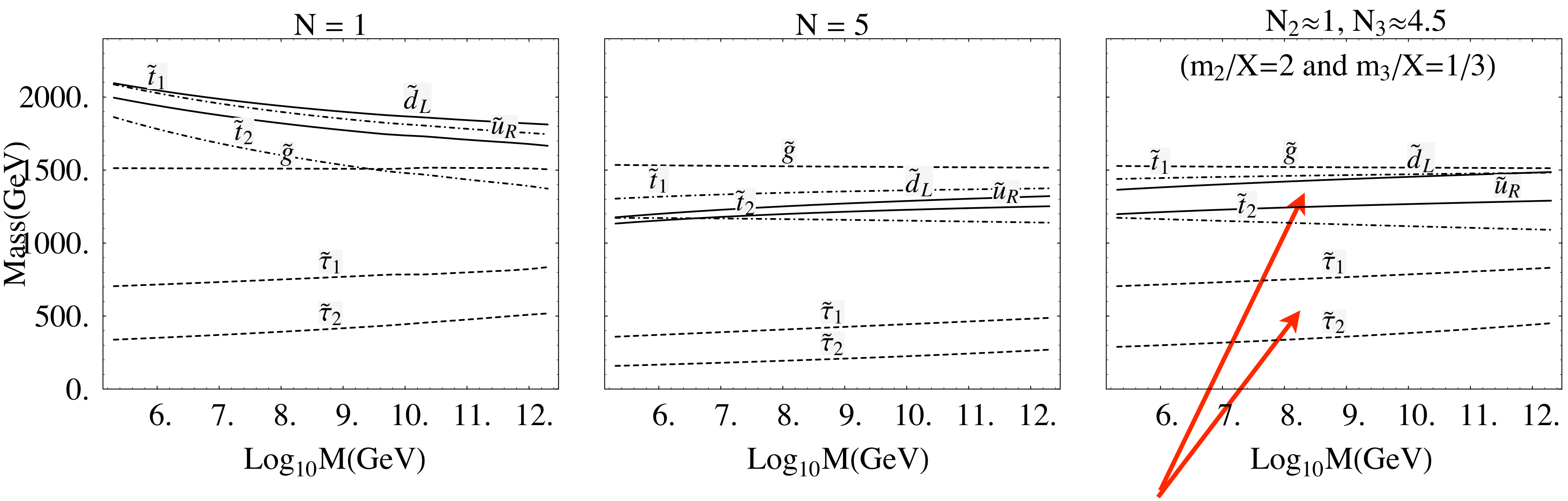
- At large X, the model is equivalent to N messenger OGM. At small X, there is only one light messenger. Thus Neff interpolates between 1 and N.

Example: Neff



Example: spectra

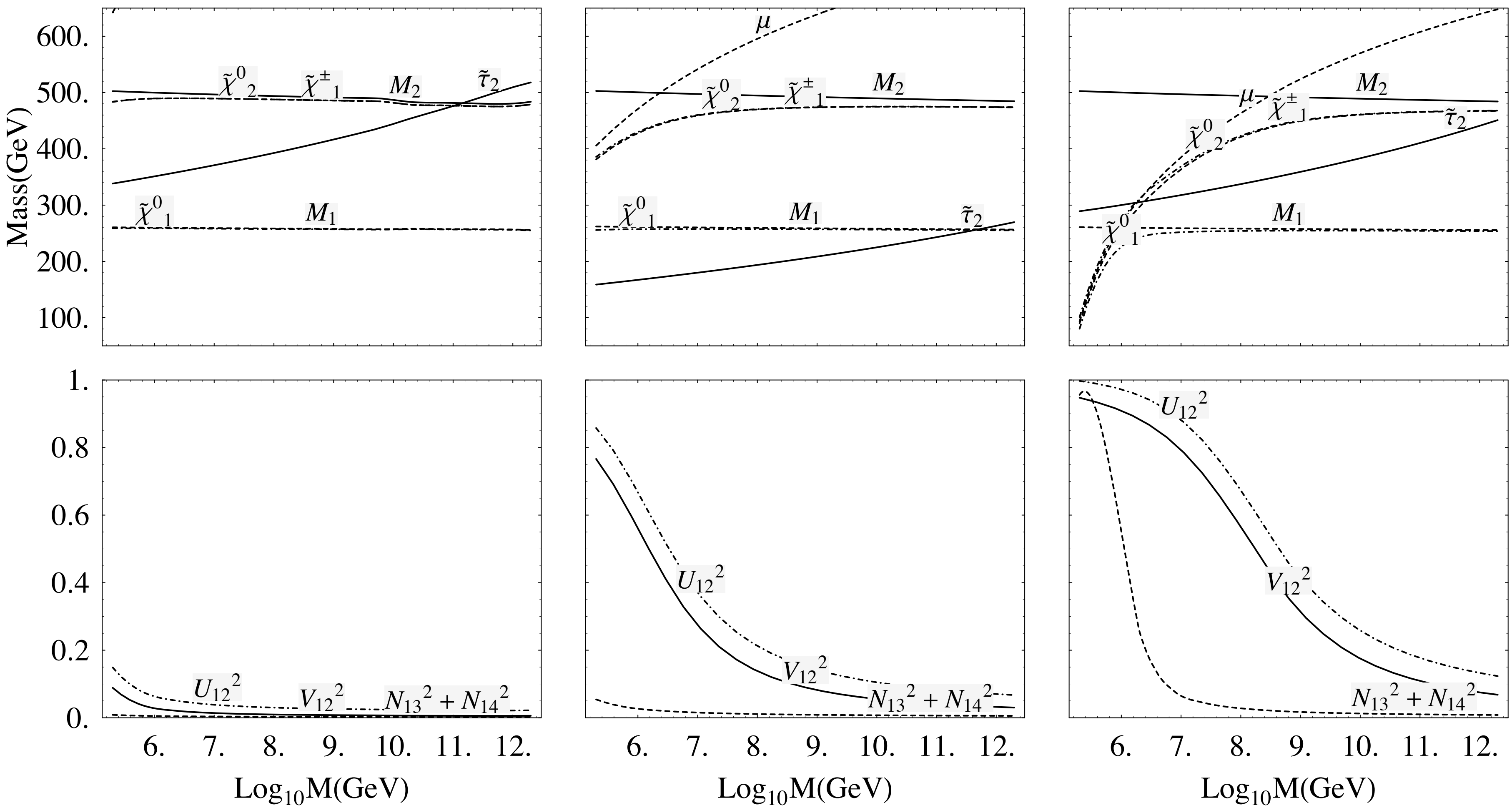
$(\Lambda_G = 200 \text{ TeV}, \ \tan\beta = 20)$



Squark and
slepton masses
squashed

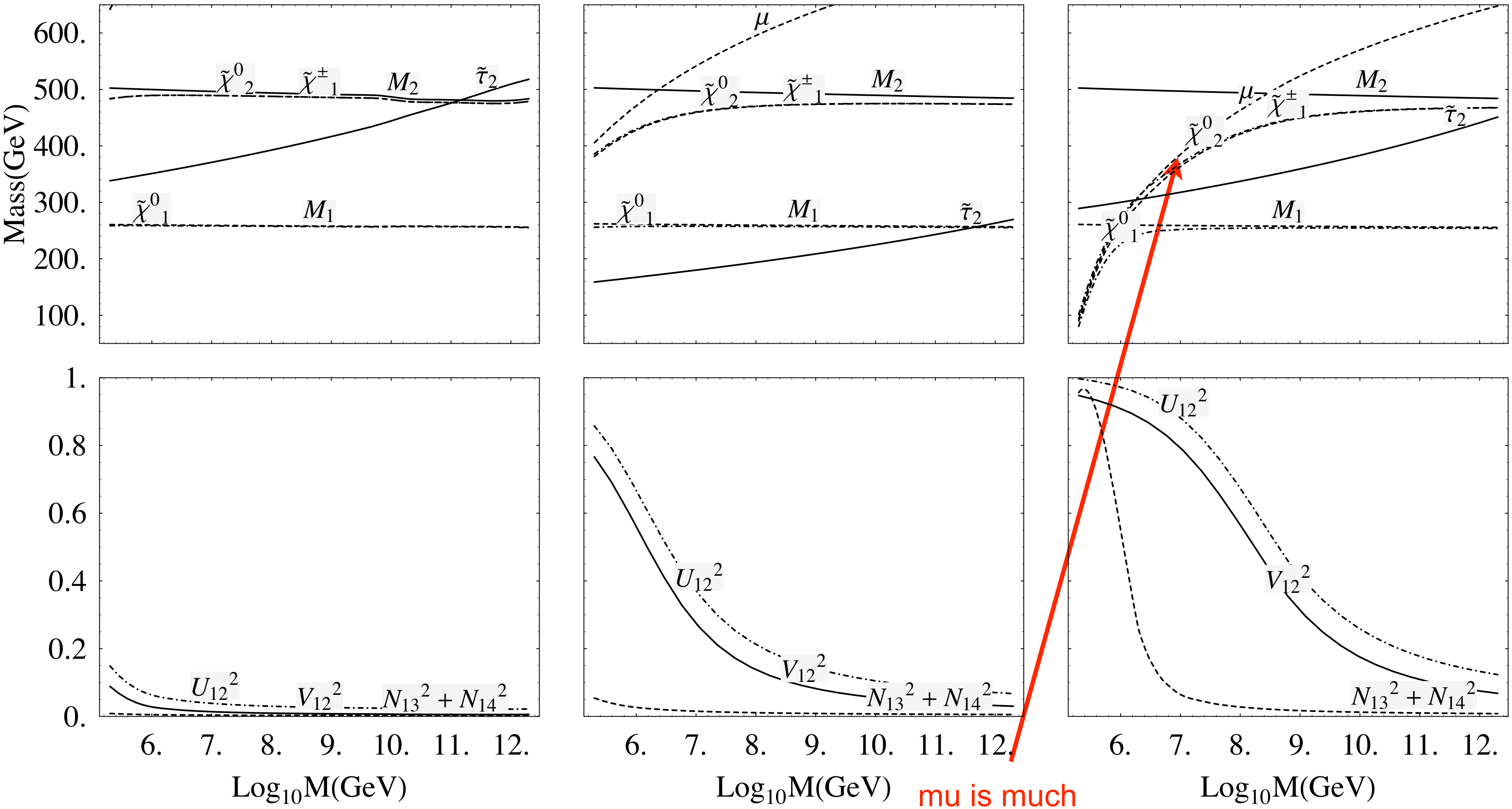
Example: spectra

$(\Lambda_G = 200\ \mathrm{TeV},\ \tan\beta = 20)$



Example: spectra

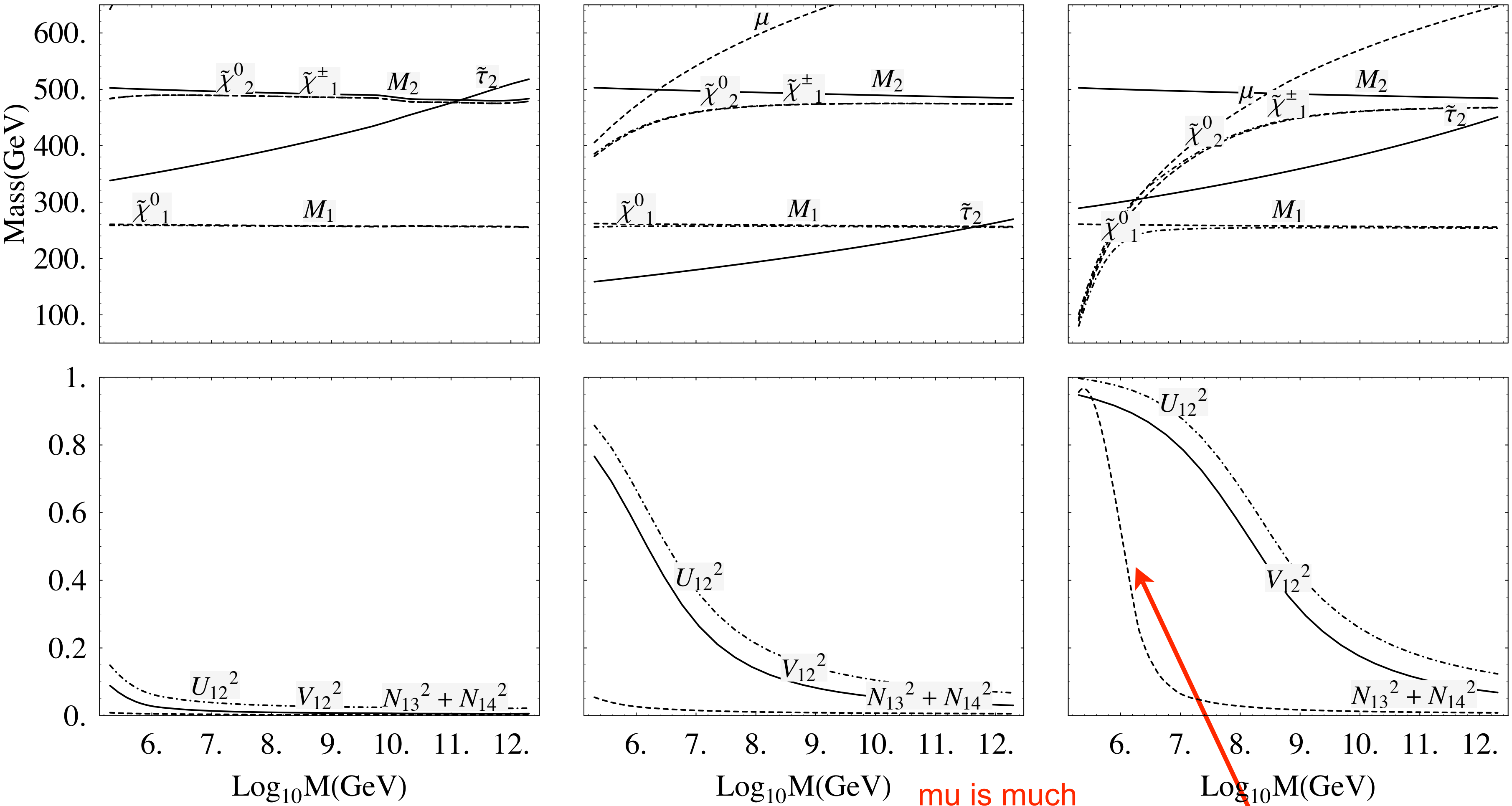
$(\Lambda_G = 200\ \text{TeV},\ \tan\beta = 20)$



mu is much smaller than in OGM...

Example: spectra

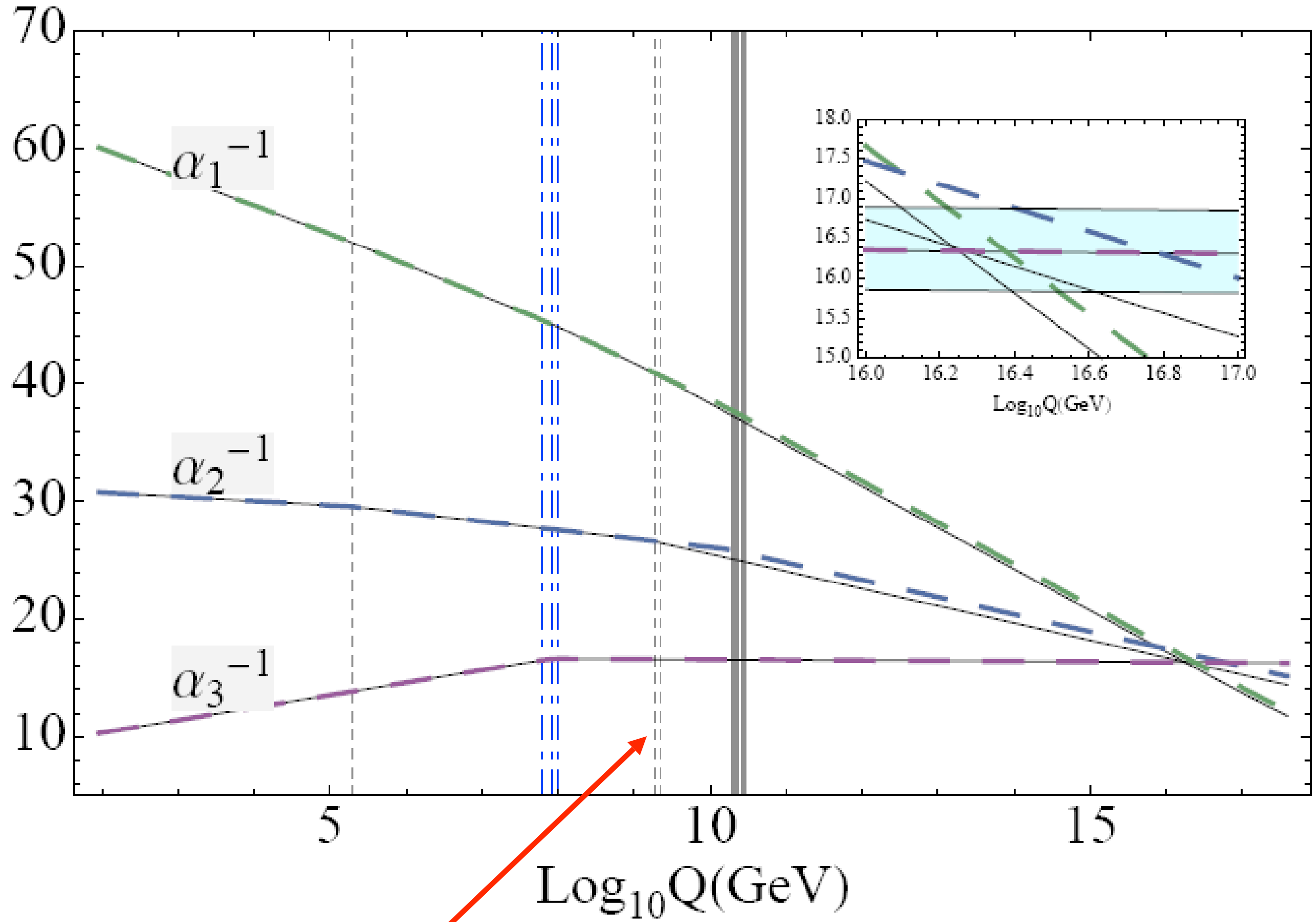
$(\Lambda_G = 200\ \text{TeV},\ \tan\beta = 20)$



mu is much smaller than in OGM...

... so the Higgsino can be the NLSP

Example: unification



R-symmetry guarantees that the heavy doublet messengers come in just right to fix up the running!

Minimal Completions

Minimal Completions = O'R models

Minimal Completions = O'R models

- So far we have treated the SUSY-breaking field X in these models as a spurion for the unspecified hidden sector.

Minimal Completions = O'R models

- So far we have treated the SUSY-breaking field X in these models as a spurion for the unspecified hidden sector.

- Now let us go one step further and attempt to specify the hidden sector in this framework.

Minimal Completions = O'R models

- So far we have treated the SUSY-breaking field X in these models as a spurion for the unspecified hidden sector.

- Now let us go one step further and attempt to specify the hidden sector in this framework.

- Many choices for the hidden sector are possible, but one is especially minimal. Because of the R-symmetry, these EOGM models are one step away from being generalized O'Raifeartaigh models.

$$\delta W = f X$$

Pseudo-moduli space

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j + f X$$

$$-F_X^* = \phi^T \lambda \tilde{\phi} + f, \quad -F_\phi^* = (\lambda X + m)\tilde{\phi}, \quad -F_{\tilde{\phi}}^* = \phi^T (\lambda X + m$$

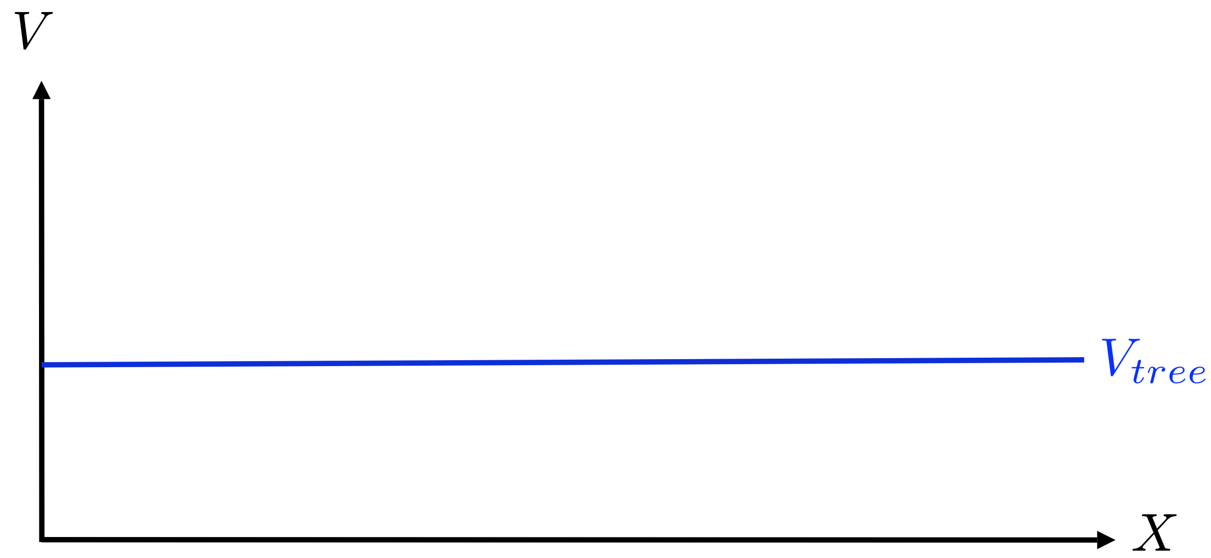
Pseudo-moduli space

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j + f X$$

$$-F_X^* = \phi^T \lambda \tilde{\phi} + f, \quad -F_\phi^* = (\lambda X + m)\tilde{\phi}, \quad -F_{\tilde{\phi}}^* = \phi^T (\lambda X + m$$

- SUSY is broken along a pseudo-moduli space

$$\phi = \tilde{\phi} = 0, \quad X_{min} < |X| < X_{max}, \quad V_{tree} = |f|^2$$



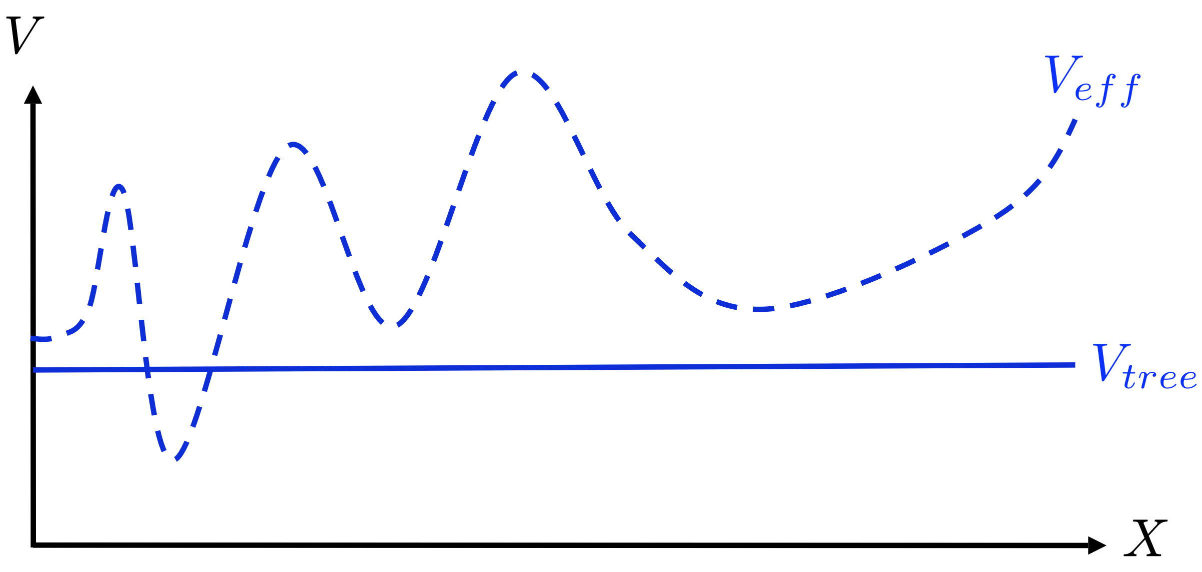
Pseudo-moduli space

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j + f X$$

$$-F_X^* = \phi^T \lambda \tilde{\phi} + f, \quad -F_\phi^* = (\lambda X + m)\tilde{\phi}, \quad -F_{\tilde{\phi}}^* = \phi^T (\lambda X + m$$

- SUSY is broken along a pseudo-moduli space

$$\phi = \tilde{\phi} = 0, \quad X_{min} < |X| < X_{max}, \quad V_{tree} = |f|^2$$



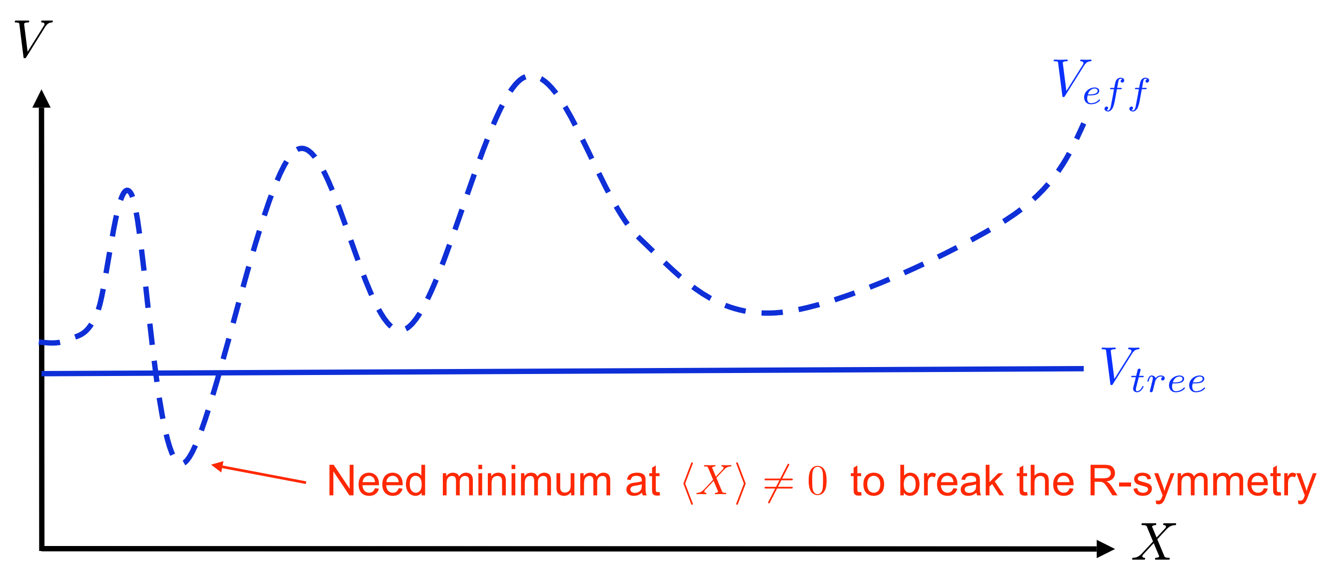
Pseudo-moduli space

$$W = \lambda_{ij} X \phi_i \tilde{\phi}_j + m_{ij} \phi_i \tilde{\phi}_j + f X$$

$$-F_X^* = \phi^T \lambda \tilde{\phi} + f, \quad -F_\phi^* = (\lambda X + m)\tilde{\phi}, \quad -F_{\tilde{\phi}}^* = \phi^T (\lambda X + m$$

- SUSY is broken along a pseudo-moduli space

$$\phi = \tilde{\phi} = 0, \quad X_{min} < |X| < X_{max}, \quad V_{tree} = |f|^2$$



R-charge Condition

R-charge Condition

- The simplest O’R models do not have an R-breaking vacuum.

R-charge Condition

- The simplest O'R models do not have an R-breaking vacuum.
- The existence of such a vacuum requires a field with $R \neq 0, 2$. (DS)

R-charge Condition

- The simplest O'R models do not have an R-breaking vacuum.
- The existence of such a vacuum requires a field with $R \neq 0, 2$. (DS)
- Interestingly, all R-symmetric deformations of OGM have this property:

$$\det \lambda \neq 0 \qquad \Rightarrow R(\tilde{\phi}_i) = -R(\phi_i)$$
$$\text{If } \; m_{ij} \neq 0 \Rightarrow R(\phi_i) + R(\tilde{\phi}_j) = 2$$

So either $R(\phi_i)$, $R(\tilde{\phi}_i)$, $R(\phi_j)$, or $R(\tilde{\phi}_j)$ must be different from 0, 2.

Thus, any R-symmetric deformation of OGM leads to a viable model of SUSY and R-symmetry breaking!

These are possibly the simplest known models of "direct gauge mediation."

Simplest example with spontaneous $\cancel{R}$

Simplest example with spontaneous $\cancel{R}$

- Perturb N=2 OGM with the only renormalizable interactions allowed by an R-symmetry:

$$W = \lambda X(\phi_1\tilde{\phi}_1 + \phi_2\tilde{\phi}_2) + m\phi_1\tilde{\phi}_2 + fX$$

Simplest example with spontaneous $\cancel{R}$

- Perturb N=2 OGM with the only renormalizable interactions allowed by an R-symmetry:

$$W = \lambda X(\phi_1\tilde{\phi}_1 + \phi_2\tilde{\phi}_2) + m\phi_1\tilde{\phi}_2 + fX$$

Straightforward to find messenger masses, compute Coleman-Weinberg potential:

$$V_{CW} = \mathrm{Tr}\, M_B^4 \log\frac{M_B^2}{\mu^2} - \mathrm{Tr}\, M_F^4 \log\frac{M_F^2}{\mu^2}$$

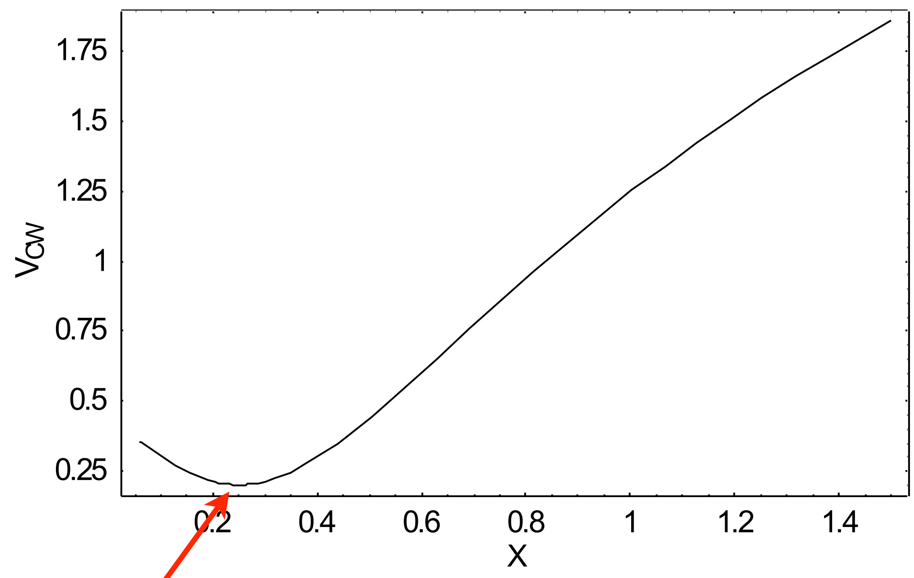
Simplest example with spontaneous $\cancel{R}$

- Perturb N=2 OGM with the only renormalizable interactions allowed by an R-symmetry:

$$W = \lambda X(\phi_1\tilde{\phi}_1 + \phi_2\tilde{\phi}_2) + m\phi_1\tilde{\phi}_2 + fX$$

Straightforward to find messenger masses, compute Coleman-Weinberg potential:

$$V_{CW} = \mathrm{Tr}\, M_B^4 \log \frac{M_B^2}{\mu^2} - \mathrm{Tr}\, M_F^4 \log \frac{M_F^2}{\mu^2}$$



An R-symmetry breaking minimum is generated at one-loop!

Conclusions, future directions

- We have argued that OGM is part of a much wider model space which is not forbidden by any symmetries.
- By exploring this model space, we have seen that many of the classic features of OGM can qualitatively change.
  - higgsino-like neutralino NLSP
  - small mu
  - squashed slepton/squark spectrum
- Thus, gauge mediation, even in its simplest form, allows for richer phenomenological possibilities than previously thought.

Conclusions, cont'd

- Some future directions/open questions are:
  - Collider phenomenology of these models, esp. higgsino NLSP (work in progress)
  - What happens if we give up R-symmetry altogether?
  - Can these types of models be generated dynamically?
  - Cosmological implications – R-axion, (nearly) stable messengers?
  - What do known solutions to the mu problem look like in this framework?