

Gauge Mediation as a Generic Phenomenon in the Supersymmetric Landscape

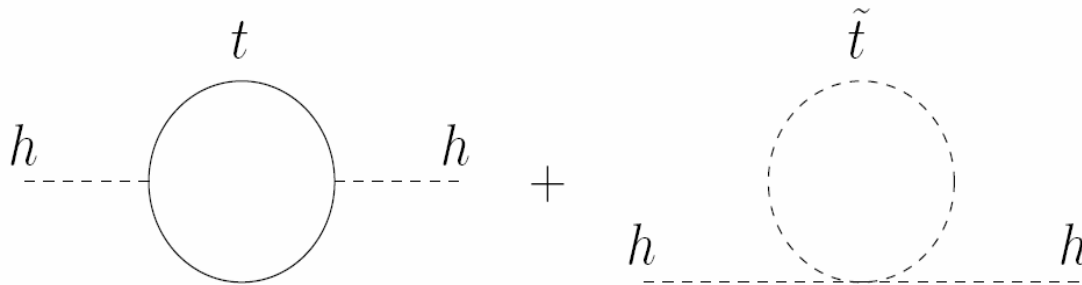
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with Hitoshi Murayama [hep-ph/0612186 \[PRL\]](#)
[hep-ph/0701231 \[PRD\]](#)

Weak scale supersymmetry

Stabilizes the EW scale against quantum corrections



Superparticles \sim TeV

... opposite statistics
same quantum #

Weakly coupled extension of the standard model

→ easy to evade constraints from precision EW data

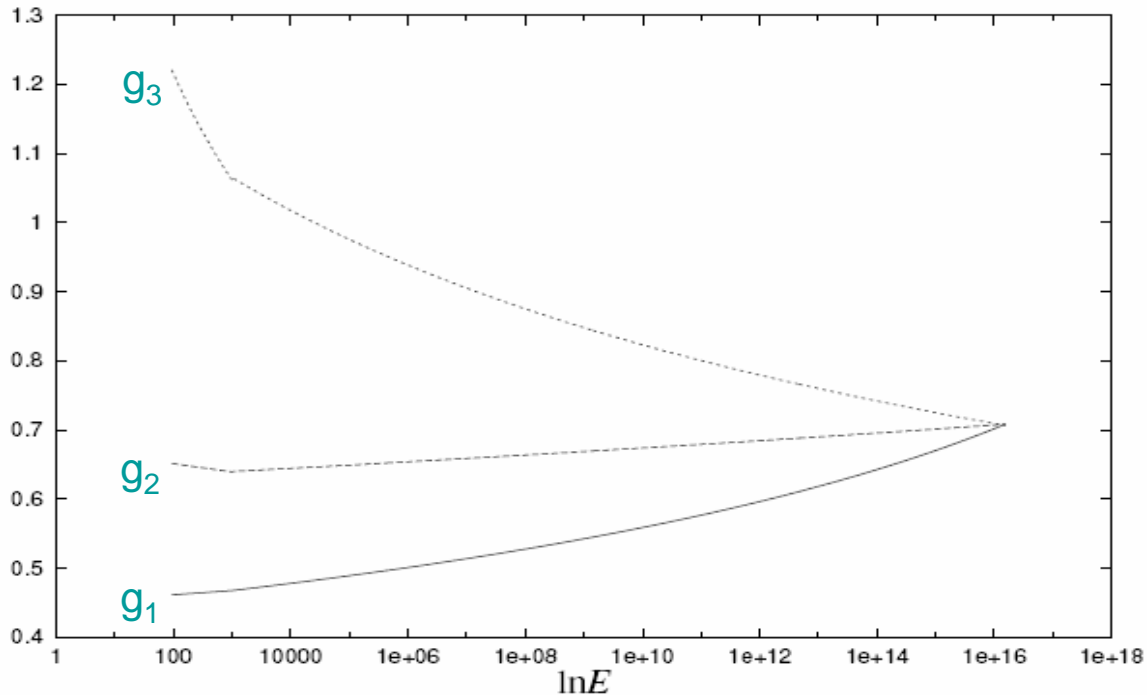
Alternative --- Higgs as a pseudo Nambu-Goldstone boson

e.g. little Higgs, holographic Higgs, twin Higgs, ...

R parity → candidate for the Dark Matter

An attraction

Elegant connection to UV



e.g.

string theory



supersymmetry



DSB

$$M_{\text{unif}} \sim 10^{16} \text{ GeV}$$

Electroweak scale as a result of “simple” dimensional transmutation ... dynamical SUSY breaking + radiative EWSB

Supersymmetric grand desert & rich TeV physics

... possibility of connecting low energy data to super-high energy physics

Is it really “simple”?

So many “need to do” ---

- Need to break supersymmetry
- Need to mediate the breaking effect to the SSM sector
- Need to preserve observed small rates of flavor changing and CP violating processes
- Need to produce the correct Higgs sector (μ term, ...)
- ...

... have been an arena of intensive model building

→ diminish the simplicity of the basic picture

Focus on the issue of SUSY breaking and mediation

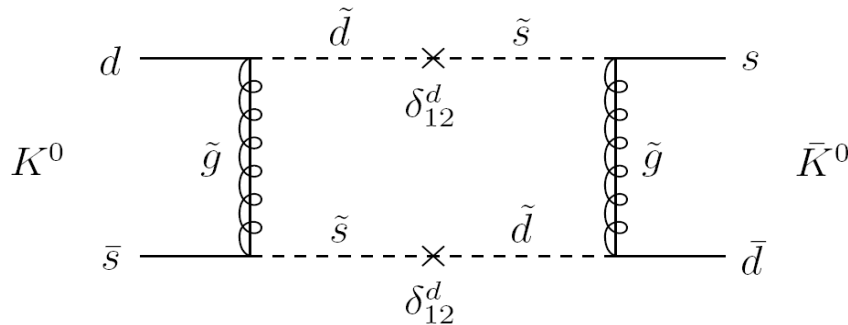
How generically does SUSY break?

How generically can consistent mediation occur?

Flavor and supersymmetry

Most of the MSSM parameter region is excluded

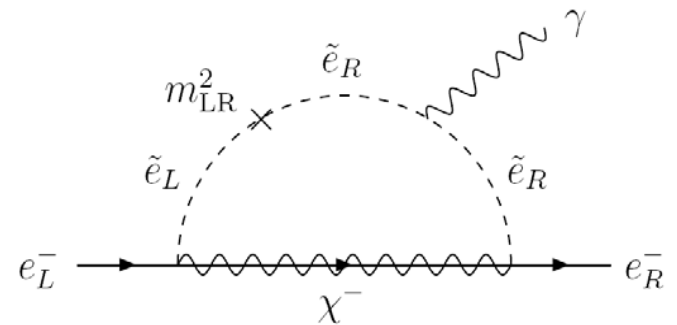
$$m_{\text{SUSY}}^2 (\tilde{d} \quad \tilde{s} \quad \tilde{b})^* \begin{pmatrix} 1 & \delta_{12}^d & \delta_{13}^d \\ \delta_{21}^d & 1 & \delta_{23}^d \\ \delta_{31}^d & \delta_{32}^d & 1 \end{pmatrix} \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}$$



$$\delta_{12}^d \lesssim 0.001 \frac{m_{\text{SUSY}}}{500 \text{ GeV}}$$

... made worse after B data

EDM for e^- , n , Hg, ...



$$m_{\text{SUSY}} \gtrsim 1 \text{ TeV or phase } \lesssim 10^{-2}$$

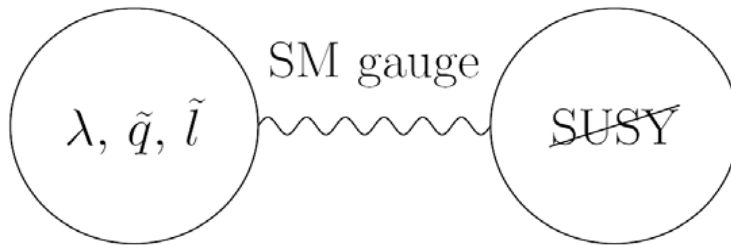
... have to be taken care as a zero-th order thing

Various mechanisms/models proposed

Elaborate model building = fragile artwork?

Gauge mediation scenario

“Automatic” flavor universality:



Mediation assumed to occur at low energies

... insensitive to structures at super-high energies

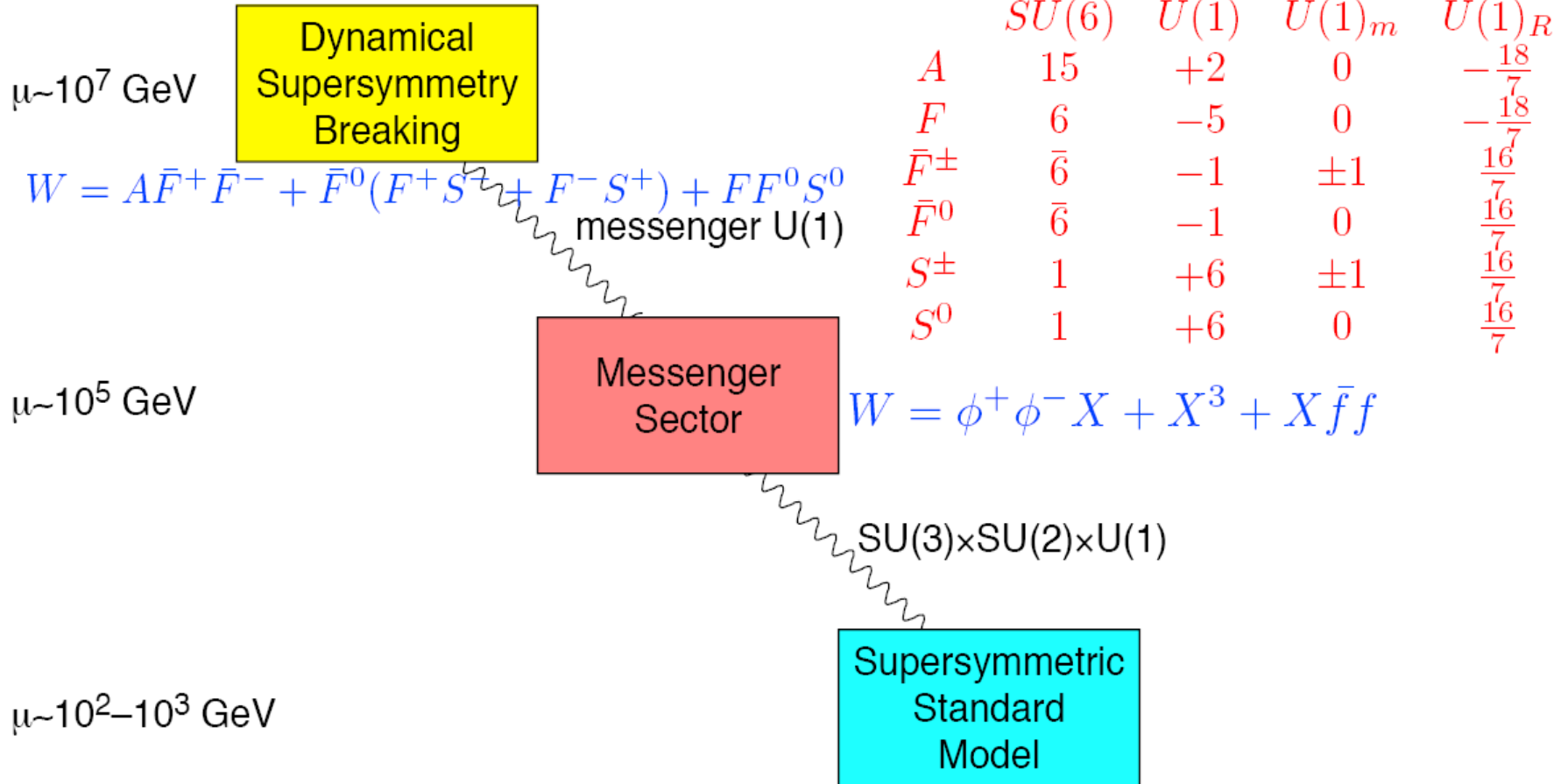
Beautiful idea --- Models?

- R symmetry needed for generic superpotentials Nelson, Seiberg
- Gaugino masses require R-symmetry breaking
- Potentially hazardous R axion
- Avoid Landau pole due to contribution from the ~~SUSY~~ sector
- ...

seem to require special structures

An early model

Dine, Nelson, Nir, Shirman ('95)

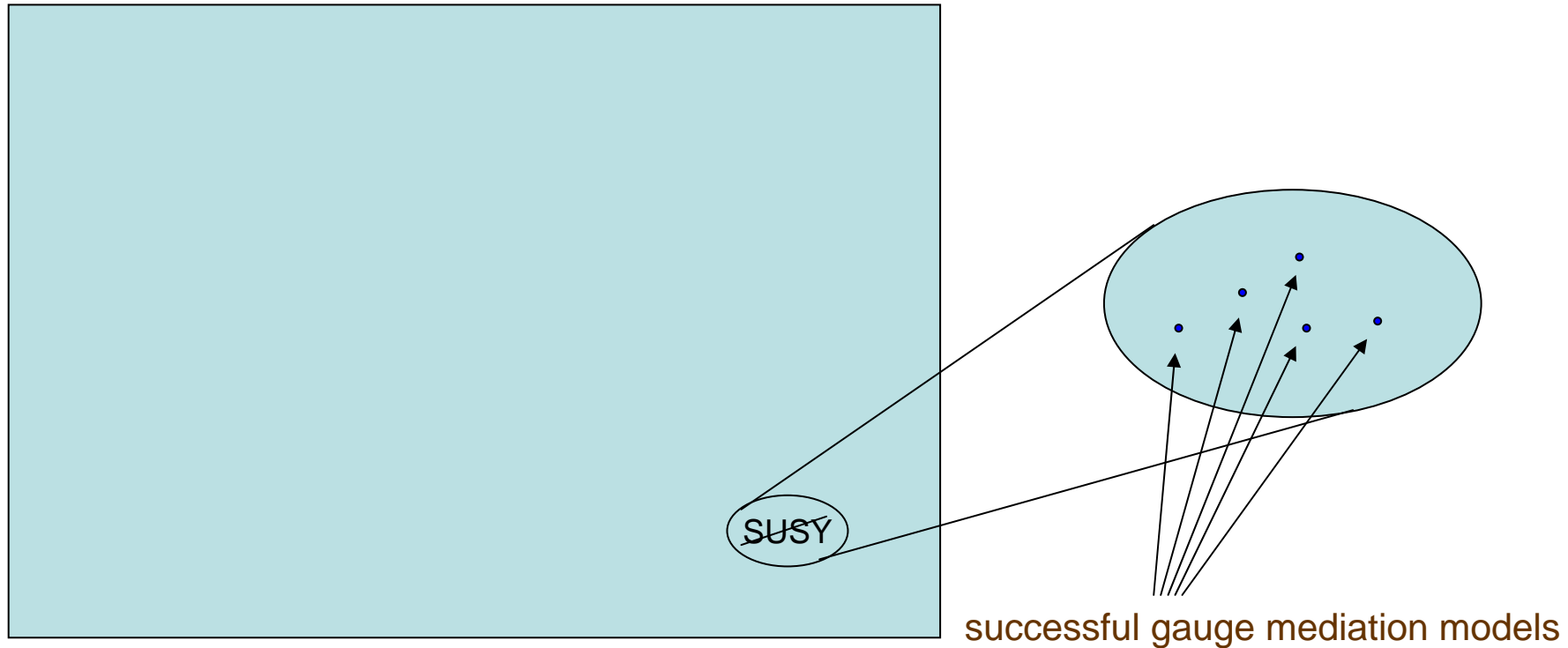


Some later improvements (e.g. ~~SUSY~~: chiral \rightarrow vectorlike)

\rightarrow situation not very much different

The basic picture

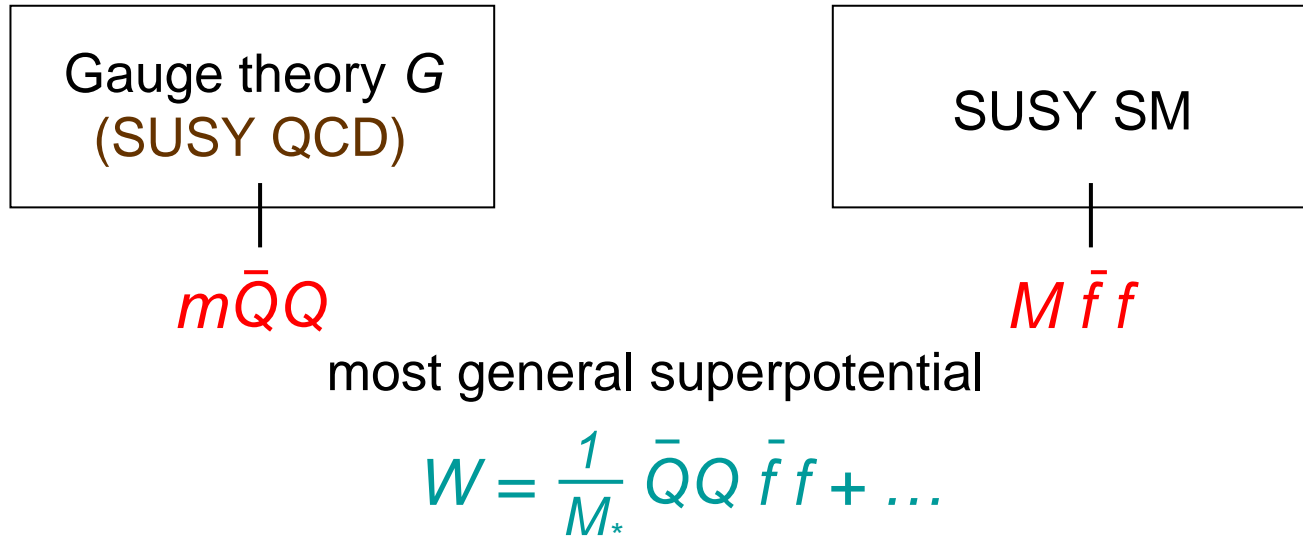
“Landscape” of supersymmetric theories



Do we believe?

→ Gauge mediation interesting only academically ...

Our scheme



- No R symmetry imposed
(most general superpotential consistent with gauge symm.)
- ~~SUSY~~ as well as successful gauge mediation occur
for wide choice of gauge groups, matter content

$$N_c < N_f < 3N_c/2 \\ \text{for } G = \text{SU}(N_c)$$

Gauge mediation simplified

Murayama, Y.N., PRL 98, 151803 ('07) [hep-ph/0612186]

$G = \text{SU}(N_c)$ as an example [SO(N_c), Sp(N_c) also OK]

Vectorlike “quarks” Q^i, \bar{Q}^i ($i=1, \dots, N_f$) and messengers f, \bar{f}

$$W = m_{ij} \bar{Q}^i Q^j + \frac{\lambda_{ij}}{M_*} \bar{Q}^i Q^j \bar{f} f + M \bar{f} f + \dots$$

M_* : fundamental scale (can be M_{Pl}).

We take

$$m_{ij} < \Lambda, \quad M \ll M_*$$

Λ : the dynamical scale of SU(N_c).

The theory works for $N_c < N_f < 3N_c/2$ → take $N_f = N_c + 1$ as an example

The low energy dynamics is described by

“mesons” $S^{ij} \sim \bar{Q}^i Q^j / \Lambda$, “baryons” $b_i \sim \epsilon_{ii_1 \dots i_{N_c}} Q^{i_1} \dots Q^{i_{N_c}} / \Lambda^{N_c-1}$, and antibaryons.

The superpotential is generated dynamically

$$W_{\text{dyn}} = \bar{b}_i S^{ij} b_j - \frac{\det S^{ij}}{\Lambda^{N_f-3}} \quad \text{Seiberg ('94)}$$

Take $m_{ij} = -m_i \delta_{ij}$, $m_1 > m_2 > \dots > m_{N_f} > 0$ without loss of generality

W_{dyn} + “quark” mass term then becomes

$$W = \bar{b}_i S^{ij} b_j - \frac{\det S^{ij}}{\Lambda^{N_f-3}} - m_i \Lambda S^{ii}$$

This leads to supersymmetry breaking
at a local minimum

Intriligator, Seiberg, Shih

$$b = \bar{b} = \begin{pmatrix} \sqrt{m_1 \Lambda} \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \quad S^{ij} = 0,$$

$$F_{S^{ij}} = m_i \Lambda \delta_{ij}$$

- The $\det S^{ij}$ term is irrelevant for $N_c > 3$
(leads to supersymmetric vacua far away)
- $\text{rank}(\bar{b}_i b_j) = 1$... $\langle \bar{b}_i b_j \rangle$ cannot absorb $F_{S^{ij}}$
- Classical flat direction S^{ij} lifted by 1-loop Coleman-Weinberg potential

can be viewed as a result of accidental $R(S^{ij}) = 2$, $R(b_i) = R(\bar{b}_i) = 0$

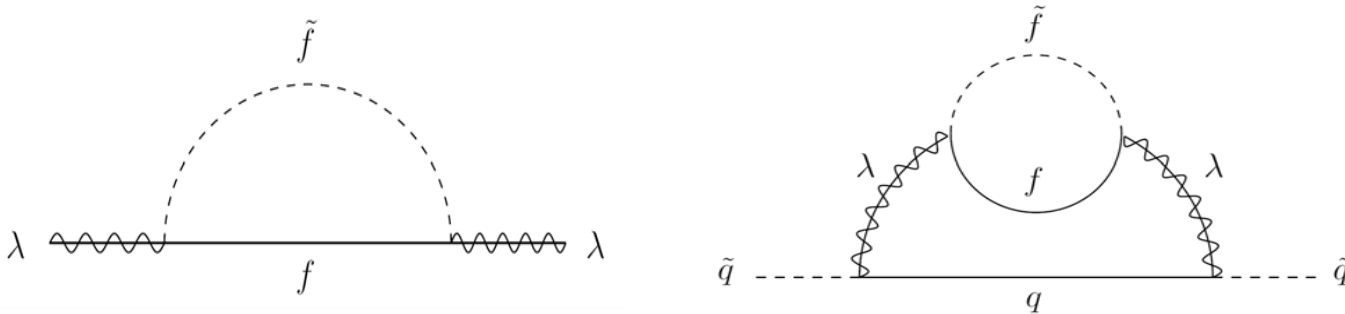
Successful gauge mediation achieved

SUSY and SUSY masses for f, \bar{f} generated:

$$W_{\text{mess}} = \frac{\lambda_{ij}\Lambda}{M_*} S^{ij} \bar{f} f + M \bar{f} f \quad \Longrightarrow \quad \begin{aligned} M_{\text{mess}} &\simeq M \\ F_{\text{mess}} &= \frac{\lambda_{ij}\Lambda}{M_*} F_{S^{ij}} = \frac{\bar{m}\Lambda^2}{M_*} \end{aligned}$$

where $\bar{m} \equiv \sum_{i \neq 1} \lambda_{ii} m_i$

The usual loop diagrams of messengers:



→ flavor universal superparticle masses: $m_{\text{SUSY}} \simeq \frac{g^2}{16\pi^2} \frac{\bar{m}\Lambda^2}{MM_{\text{Pl}}}$

... together with W_{MSSM} , leads to fully realistic phenomenology

- Conditions on parameters

- $m_{\text{SUSY}} = O(100 \text{ GeV} - 1 \text{ TeV})$

$$\frac{\bar{m}\Lambda^2}{MM_{\text{Pl}}} \approx 100 \text{ TeV}$$

- Gauge mediation dominance: $m_{3/2} \approx m\Lambda/M_{\text{Pl}} \lesssim 10^{-2}m_{\text{SUSY}}$

$$mM \lesssim 10^{-4}\bar{m}\Lambda$$

- Messenger non-tachyonic

$$M^2 > \frac{\bar{m}\Lambda^2}{M_{\text{Pl}}}$$

- Viability of the analysis

$$m \lesssim 0.1\Lambda$$

easily satisfied:

e.g. $\lambda_{ij} \sim \lambda_{ijkl} \sim 1, \Lambda \sim 10^{11} \text{ GeV}$
 $m \sim \bar{m} \sim 10^8 \text{ GeV}, M \sim 10^7 \text{ GeV}$

- $U(1)_R$ violating effects

- Higher dimension operators: $\Delta W = \frac{\lambda_{ijkl}}{M_{\text{Pl}}} \bar{Q}^i Q^j \bar{Q}^k Q^l = \frac{\lambda_{ijkl}\Lambda^2}{M_{\text{Pl}}} S^{ij} S^{kl}$

$$\frac{\lambda_{ijkl}\Lambda^2}{M_{\text{Pl}}} \lesssim \min \left\{ 0.1(m\Lambda)^{1/2}, 10^{-2} \frac{MM_{\text{Pl}}}{\lambda\Lambda} \right\}$$

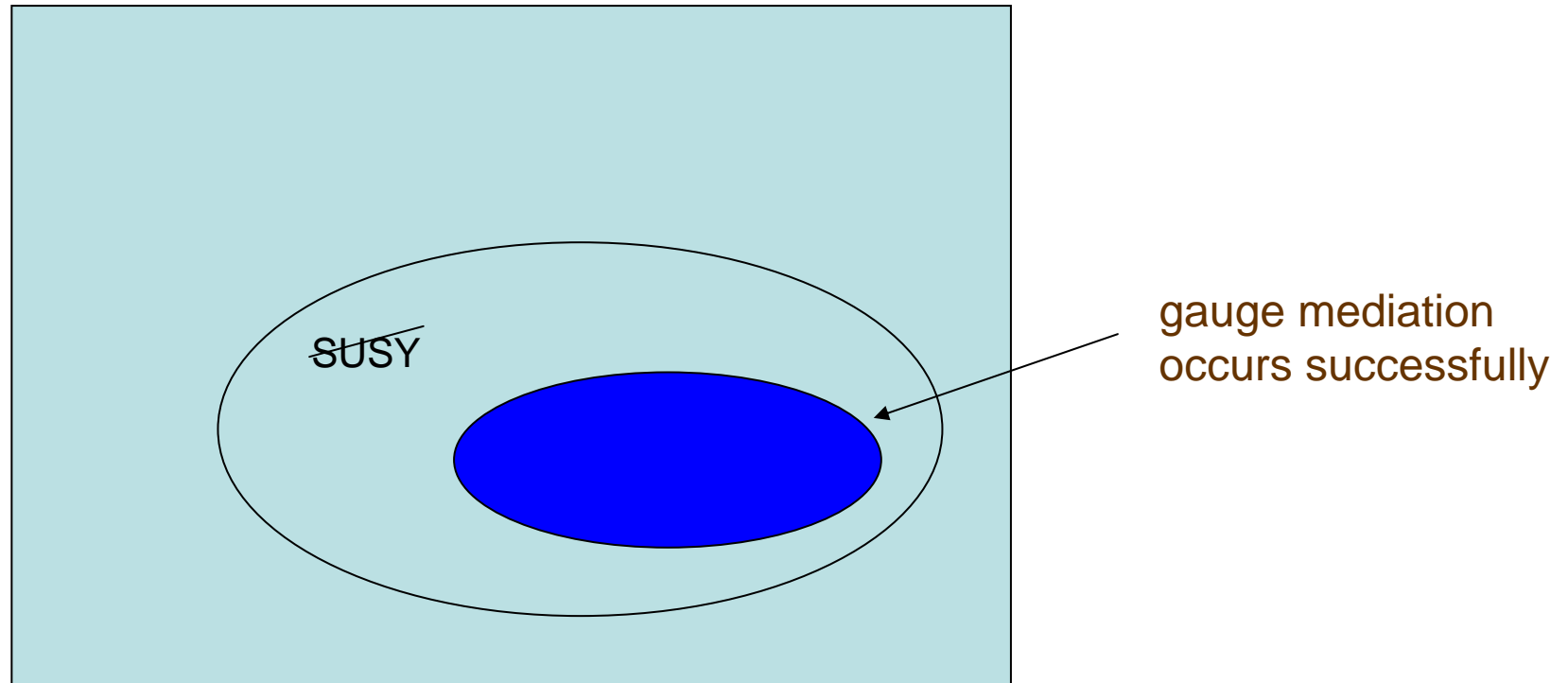
- Messenger loop: $\Delta V \approx \frac{\bar{m}^2\Lambda^4}{16\pi^2 M_{\text{Pl}}^2} \mathcal{F} \left(\frac{\lambda_{ij}\Lambda S^{ij}}{MM_{\text{Pl}}} \right)$

$$M \gtrsim \frac{\lambda^2 m^{1/2} \Lambda^{5/2}}{M_{\text{Pl}}^2}$$

(M_* is set to M_{Pl} for simplicity)

New picture

“Landscape” of supersymmetric theories



Gauge mediation may be a rather generic phenomenon
in the landscape of possible supersymmetric theories.

(string theory gives extra junk? – extra group, vectorlike matter)

The structure is more general

Murayama, Y.N., PR D75, 095011 ('07) [hep-ph/0701231]

The basic idea:

$$W = -\mu^2 S + \kappa S f \bar{f} + M f \bar{f}$$

$$K = |S|^2 - \frac{|S|^4}{4\mathcal{M}^2} + O\left(\frac{|S|^6}{\mathcal{M}^4}\right)$$

$$\left(\begin{array}{l} \text{previous example:} \\ \mu^2 \sim m\Lambda, \quad \kappa \sim \frac{\lambda\Lambda}{M_*}, \\ \mathcal{M} \sim 4\pi\sqrt{m\Lambda} \end{array} \right)$$

The scalar potential

$$V = |\mu^2 - \kappa f \bar{f}|^2 \left(1 + \frac{|S|^2}{\mathcal{M}^2} + O\left(\frac{|S|^4}{\mathcal{M}^4}\right) \right) + |\kappa S f + M f|^2 + |\kappa S \bar{f} + M \bar{f}|^2 \Rightarrow \text{global SUSY minimum at}$$

$$S = -\frac{M}{\kappa}, \quad f = \bar{f} = \frac{\mu}{\kappa^{1/2}}$$

has a local ~~SUSY~~ minimum at $S = f = \bar{f} = 0$, as long as $M^2 > \kappa\mu^2$

- Tunneling rate can be small

$$\Gamma/V \sim \mu^4 e^{-B} \quad B > O(100) \text{ for } M \gtrsim \kappa^{1/2} \mu$$

- Effect of messenger loop suppressed

$$\Delta V \approx \frac{\kappa^2 \mu^4}{16\pi^2} \mathcal{F}\left(\frac{\kappa S}{M}\right) \quad \text{small for } M \gtrsim \frac{\kappa^2}{4\pi} \mathcal{M}$$

Successful gauge mediation occurs

$$M_{\text{mess}} = M + \kappa \langle S \rangle \approx M$$

$$F_{\text{mess}} = \kappa \langle F_S \rangle = \kappa \mu^2$$

→ **superparticle masses:** $\simeq \frac{g^2}{16\pi^2} \frac{\kappa \mu^2}{M}$

“Model building” questions

- How to generate the $|S|^4$ term in K (cf. 1-loop CW)
- How to suppress S^2 and S^3 terms in W (cf. composite S)

Various examples can be considered

based on

- O’Raifeartaigh model
- Quantum modified constraints [Izawa-Yanagida-Intriligator-Thomas]
- Smooth confinement [Intriligator-Seiberg-Shenker]
- Various calculable/incalculable ~~SUSY~~ models [3-2 model, SU(5), ...]

SO(10) model with $\psi(\mathbf{16})$ and $H(\mathbf{10})$

SO(10) with $\psi(\mathbf{16})$ and $H(\mathbf{10})$ and

$$W = \lambda \psi \psi H - \frac{m}{2} H^2$$

The low energy dynamics is described by $X = \psi \psi H$ and $Y = H^2$.

The nonperturbative superpotential is

$$W_{\text{np}} = c \frac{\Lambda_s^{21/5}}{X^{2/5}}$$

Λ_s : dynamical scale of SO(10)

The model is calculable for $\lambda \ll 1$ and $m \ll \Lambda_s$.

moduli space of vacua:

$$\langle X \rangle = \left(\frac{2}{5\lambda} \right)^{5/7} \Lambda_s^3, \quad Y : \text{arbitrary}$$

At low energy,

$$W = -\frac{m}{2}Y$$
$$K = \frac{3}{2}|\langle X \rangle|^{2/3} + \frac{|Y|^2}{2|\langle X \rangle|^{2/3}} - \frac{|Y|^4}{6|\langle X \rangle|^2} + O(|Y|^6)$$

The quartic interaction in K generated (at tree level)

Introduction of the coupling of $Y = H^2$

to the messengers induces gauge mediation

total superpotential:

$$W = \lambda\psi\psi H - \frac{m}{2}H^2 + \frac{\eta}{2M_*}H^2 f \bar{f} + M f \bar{f}$$

... most general under the gauge symmetry

Successful region widely open

cf.

$$\mu^2 \simeq \frac{m\Lambda_s}{\lambda^{5/21}}, \quad \kappa \simeq \frac{\eta\Lambda_s}{\lambda^{5/21}M_*}, \quad \mathcal{M} \simeq \frac{\Lambda_s}{\lambda^{5/21}}$$

Hidden sector contribution

Murayama, Y.N., Poland

Take the 1st model with $G = SU(N_c)$, $N_c < N_f < 3N_c/2$

$$W_{\text{el}} = -m_i \delta_{ij} Q^i \bar{Q}^j + \frac{\lambda_{ij}}{M_*} Q^i \bar{Q}^j f \bar{f} + M f \bar{f}$$

Below Λ , the theory is described by

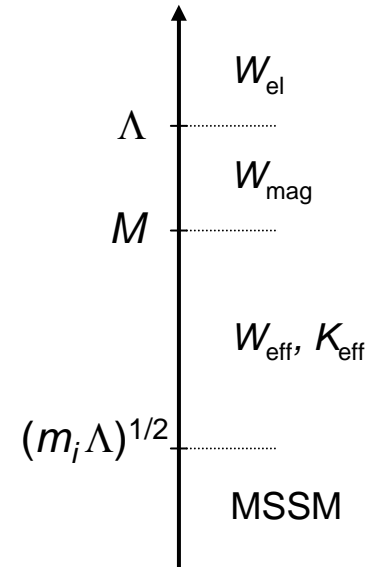
$$W_{\text{mag}} = -m_i \Lambda \delta_{ij} S^{ij} + q_i S^{ij} \bar{q}_j + \lambda_{ij} \frac{\Lambda}{M_*} S^{ij} f \bar{f} + M f \bar{f}$$

with $G_{\text{dual}} = SU(N_f - N_c)$, $S^{ij} \sim Q^i \bar{Q}^j$, & dual quarks q_i, \bar{q}_i

Below M , the messengers are integrated out

$$W_{\text{eff}} = -\mu_i^2 \delta_{ij} S^{ij} + a q_i S^{ij} \bar{q}_j + \frac{1}{2} \omega_{ij}^A S^{ij} \mathcal{W}^{A\alpha} \mathcal{W}_\alpha^A$$

$$K_{\text{eff}} = K_{\text{kin}} + k_{a\,kl}^{ij} S_{ij}^\dagger S^{kl} \phi_a^\dagger \phi_a + \eta_{ai}^j q^{\dagger i} q_j \phi_a^\dagger \phi_a + \bar{\eta}_{ai}^j \bar{q}^{\dagger i} \bar{q}_j \phi_a^\dagger \phi_a$$



W_α^A and ϕ_α :
MSSM fields

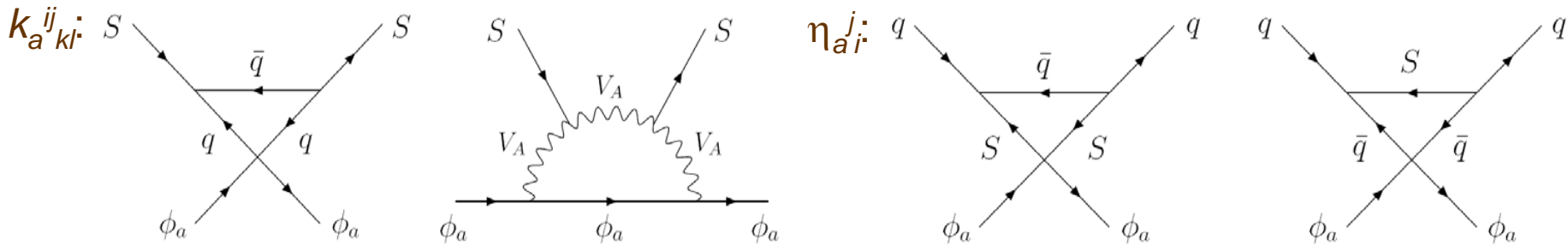
The hidden sector fields decouple only at $\mu_i \sim (m_i \Lambda)^{1/2}$

RGE contribution from the hidden sector

between M and μ_j affects the MSSM spectrum

Cohen, Roy, Schmaltz

Evolution of k_a^{ij} and η_a^{ji} ($=\bar{\eta}_a^{ji}$):



For $M_* \sim M_{\text{Pl}}$, $M < O(10^{-4}) \Lambda$, and we find

the hidden sector contribution is at most of $O(10\%)$

[Not strictly calculable; expected to be larger for small $(3N_c - 2N_f)/N_c$]

$$M_A = g_A^2 \mathcal{J}$$

$$m_\phi^2 = \sum_{A=1,2,3} C_\phi^A \mathcal{I}_A$$

The contribution of the hidden sector to \mathcal{I}_A are of $O(10\%)$ or smaller

... still allows to be extracted in simple cases, e.g., $N_{\text{mess}} = 1$

- For $M_* < M_{\text{Pl}}$, M can be larger
 - $M \sim \Lambda$... $O(100\%)$ effect
 - $M \gg \Lambda$... $m_\phi^2 \gg M_A^2$
- In the $SO(10)$ model (tree level origin of K), the effect is essentially absent

Summary

- Weak scale supersymmetry well motivated
- Gauge mediation
 - Simple solution to the SUSY flavor problem
 - Insensitive to high energies
- Tremendous simplification of models achieved
 - No $U(1)_R$, local minimum, ...
 - Gauge mediation may be generic in the landscape of possible supersymmetric theories
- The problem of flavor greatly ameliorated
- Hidden sector contribution (generically) expected to be small