Lecture III

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Sofly broken MSSM

Soft SUSY breaking terms in the MSSM

- For each term in the superpotential

$$W_{MSSM} = Y_u^{ij} Q_i u_j^c H_u + Y_d^{ij} Q_i d_j^c H_d + Y_l^{ij} L_i e_j^c H_d + \mu H_u H_d$$

- we can have the "A-terms" and "B-term"

$$A_u^{ij} Y_u^{ij} Q_i u_j^c H_u + A_d^{ij} Y_d^{ij} Q_i d_j^c H_d + A_l^{ij} Y_l^{ij} L_i e_j^c H_d + B\mu H_u H_d$$

- scalar masses for all scalars

$$m_{Qij}^2 \tilde{Q}_i^* \tilde{Q}_j + m_{uij}^2 \tilde{u}_i^* \tilde{u}_j + m_{dij}^2 \tilde{d}_i^* \tilde{d}_j + m_{Lij}^2 \tilde{L}_i^* \tilde{L}_j + m_{eij}^2 \tilde{e}_i^* \tilde{e}_j + m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2$$

- gaugino mass for all three gauge factors

$$M_1 \tilde{B} \tilde{B} + M_2 \tilde{W}^a \tilde{W}^a + M_3 \tilde{g}^a \tilde{g}^a$$

- A(18x3)+B(2)+m(9x5+2)+M(2x3)+μ(2)=111

  $U(1)_R \times U(1)_{PQ}$ removes only two phases

  cf. SM has two params in the Higgs sector

  107 more parameters than the SM!

Higgs potential

The Higgs potential in the MSSM is

$$V = m_1^2 H_d^\dagger H_d + m_2^2 H_u^\dagger H_u - m_3^2 (H_u H_d + c.c.) + \frac{g^2}{8}(H_d^\dagger \vec{\tau} H_d + H_u^\dagger \vec{\tau} H_u)^2 + \frac{g'^2}{8}(H_d^\dagger H_d - H_u^\dagger H_u)^2$$

where

$$m_1^2 = m_{H_d}^2 + \mu^2, \quad m_2^2 = m_{H_u}^2 + \mu^2, \quad m_3^2 = B\mu$$

Leaving on the neutral components

$$V = (H_d^{0*}\ H_u^{0*}) \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix} \begin{pmatrix} H_d^0 \\ H_u^0 \end{pmatrix} + \frac{g^2 + g'^2}{8}(|H_d^0|^2 - |H_u^0|^2)^2$$

breaks SU(2)xU(1) if $m_1^2 m_2^2 < m_3^4$

stable along the D-flat direction $H_d^0 = H_u^0$ if $m_1^2 + m_2^2 > 2m_3^2$

i.e., $m_1^2 m_2^2 < m_3^4 < (m_1^2 + m_2^2)/2$ which is possible

Higgs particles

$$V = (H_d^{0*}\ H_u^{0*}) \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix} \begin{pmatrix} H_d^0 \\ H_u^0 \end{pmatrix} + \frac{g^2 + g'^2}{8} (|H_d^0|^2 - |H_u^0|^2)^2$$

- Two Higgs doublets = 8 Klein-Gordon fields
- 3 of them eaten by the Higgs mechanism
- 8-3=5 physical degrees of freedom

  h^0, H^0, A^0, H^+, H^-
- 3 parameters m_1^2, m_2^2, m_3^2
- one of them fixed by $\langle H_d \rangle^2 + \langle H_u \rangle^2 = (174\text{GeV})^2$
- two remaining parameters

  $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$ and m_A

Higgs particles

$$V = (H_d^{0*}\ H_u^{0*}) \begin{pmatrix} m_1^2 & m_3^2 \\ m_3^2 & m_2^2 \end{pmatrix} \begin{pmatrix} H_d^0 \\ H_u^0 \end{pmatrix} + \frac{g^2 + g'^2}{8}(|H_d^0|^2 - |H_u^0|^2)^2$$

- Solve for mass eigenvalues of physical states

$$m_{A^0}^2 = 2m_3^2/\sin 2\beta, \qquad m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{h^0,H^0}^2 = \frac{1}{2}\left(m_{A^0}^2 + m_Z^2 \pm \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4m_{A^0}^2 m_Z^2 \cos^2 2\beta}\right), \qquad m_h \le m_Z!$$

- Lightest Higgs below m_Z: excluded!
- However, the quartic coupling evolves differently from the gauge coupling below the scalar top threshold

$$\Delta m_{h^0}^2 \simeq \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\ln\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

- Need stop > 500GeV to evade limits

gauginos, higgsinos

- charged ones "charginos"

$$(\tilde{W}^- \; \tilde{H}_d^-) \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

- neutral ones "neutralinos"

$$(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0) \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$$

Sfermions

- e.g., stop

$$(\tilde{t}_L^* \ \tilde{t}_R^*) \begin{pmatrix} m_{\tilde{Q}_3}^2 + m_t^2 & (A_t - \mu^* \cot\beta) m_t \\ (A_t^* - \mu \cot\beta) m_t & m_{\tilde{t}}^2 + m_t^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

one-loop RGE

- GUT prediction of gaugino masses

$$\frac{d}{dt}\frac{M_i}{g_i^2} = 0$$

$$M_1 : M_2 : M_3 \approx 1 : 2 : 7 \text{ at } m_Z$$

- gauge interaction boosts scalar masses

$$\frac{d}{dt}m^2 = -\frac{1}{16\pi^2}8C_F g^2 M^2$$

- Yukawa interaction suppresses scalar masses

$$16\pi^2\frac{d}{dt}m_{H_u}^2 = 3X_t - 6g_2^2M_2^2 - \frac{6}{5}g_1^2M_1^2$$

$$16\pi^2\frac{d}{dt}m_{\tilde{t}_R}^2 = 2X_t - \frac{32}{3}g_3^2M_3^2 - \frac{32}{15}g_1^2M_1^2$$

$$16\pi^2\frac{d}{dt}m_{\tilde{t}_L}^2 = X_t - \frac{32}{3}g_3^2M_3^2 - 6g_2^2M_2^2 - \frac{2}{15}g_1^2M_1^2$$

$$X_t = 2Y_t^2(m_{H_u}^2 + m_{\tilde{t}_R}^2 + m_{\tilde{t}_L}^2 + A_t^2)$$

- H_u mass-squared most likely to get negative!

RGE

- running of soft SUSY breaking parameters can be inferred from the RGE of coupling constants

$$Z_i \to \mathcal{Z}_i = Z_i(1-\theta^2 A_i)(1-\bar{\theta}^2 A_i^*)(1-\theta^2\bar{\theta}^2 m_i^2)$$

$$\frac{1}{g^2} \to \mathcal{S} = \frac{1}{g^2}\left(1-\theta^2 m_\lambda\right)$$

$$Z_i(t) = Z_i(0) - \frac{g^2 C_F^i}{4\pi^2} t + \sum_{j,k} \frac{\lambda_{ijk}^* \lambda_{ijk}}{16\pi^2} t$$

$$\mathcal{Z}_i(t) = \mathcal{Z}_i(0) - \frac{C_F^i}{4\pi^2}\frac{2}{\mathcal{S}+\bar{\mathcal{S}}} t + \sum_{j,k} \frac{\lambda_{ijk}^{0\,*} \lambda_{ijk}^0}{16\pi^2} \mathcal{Z}_i^{-1}\mathcal{Z}_j^{-1}\mathcal{Z}_k^{-1} t$$

Breaking SUSY

Auxiliary fields

- SUSY is broken if the auxiliary component of a superfield has an expectation value
- F-term breaking: $\langle z \rangle = \theta^2 f$, $f \neq 0$
- D-term breaking: $\langle W_\alpha \rangle = \theta_\alpha d$, $d \neq 0$
- Irrespective of dynamics that breaks supersymmetry, its effect can be parameterized in terms of these order parameters ("spurion")
- assume f and d dimension 1 for this purpose
- A spurion does not change the UV behavior of the theory, i.e. reintroduce quadratic divergences

Soft SUSY breaking

- Take $W = \lambda\phi^3 + \mu\phi^2 + m^2\phi$
- Using the spurion <z>=θ^2f, we can write the most general SUSY breaking terms in Kähler

$$\int d^4\theta\,(\alpha\langle z\rangle\phi^*\phi + h.c. + \beta\langle z^*z\rangle\phi^*\phi) = (\alpha f\phi^* F + \alpha^* f^*\phi F^*) + \beta f^* f\phi^*\phi$$

- Solving for the auxiliary component

$$F^*F + (W'F + \alpha f\phi^* F + h.c.) = -|W' + \alpha f\phi^*|^2$$
$$= -|W'|^2 - (\alpha f\phi W' + h.c.) - |\alpha f|^2\phi^*\phi$$
$$= -|W'|^2 - \alpha f(3\lambda\phi^2 + 2\mu\phi^2 + m^2\phi + h.c.) - |\alpha f|^2\phi^*\phi$$

- From the superpotential

$$\int d^2\theta\langle z\rangle(a\lambda\phi^3 + b\mu\phi^2 + cm^2\phi) = af\lambda\phi^3 + bf\mu\phi^2 + cfm^2\phi$$

- bottomline: any terms of type

$$-(A\lambda\phi^3 + B\mu\phi^2 + Cm^2\phi + h.c.) - m_\phi^2\phi^*\phi$$

Soft SUSY breaking

- Similarly for the gauge multiplet,

$$\int d^2\theta \langle z \rangle W_\alpha W^\alpha = f\lambda\lambda$$

namely gaugino masses

- If there is a chiral superfield in the adjoint rept, another possible term with D-term spurion is $$\int d^2\theta \phi W_\alpha \langle W^\alpha \rangle = d\psi\lambda$$

- Now the complete set of soft SUSY breaking

$$A\lambda\phi^3,\ B\mu\phi^2,\ Cm^2\phi,\ m_\phi^2\phi^*\phi,\ m_\lambda\lambda\lambda,\ m_d\lambda\psi$$

Tree-level SUSY breaking

- O'Raifeartaigh model $W = \lambda X(Z^2 - v^2) + mYZ$

$$F_X^* = \frac{\partial W}{\partial X} = \lambda(Z^2 - v^2) = 0$$

$$F_Y^* = \frac{\partial W}{\partial Y} = mZ = 0$$

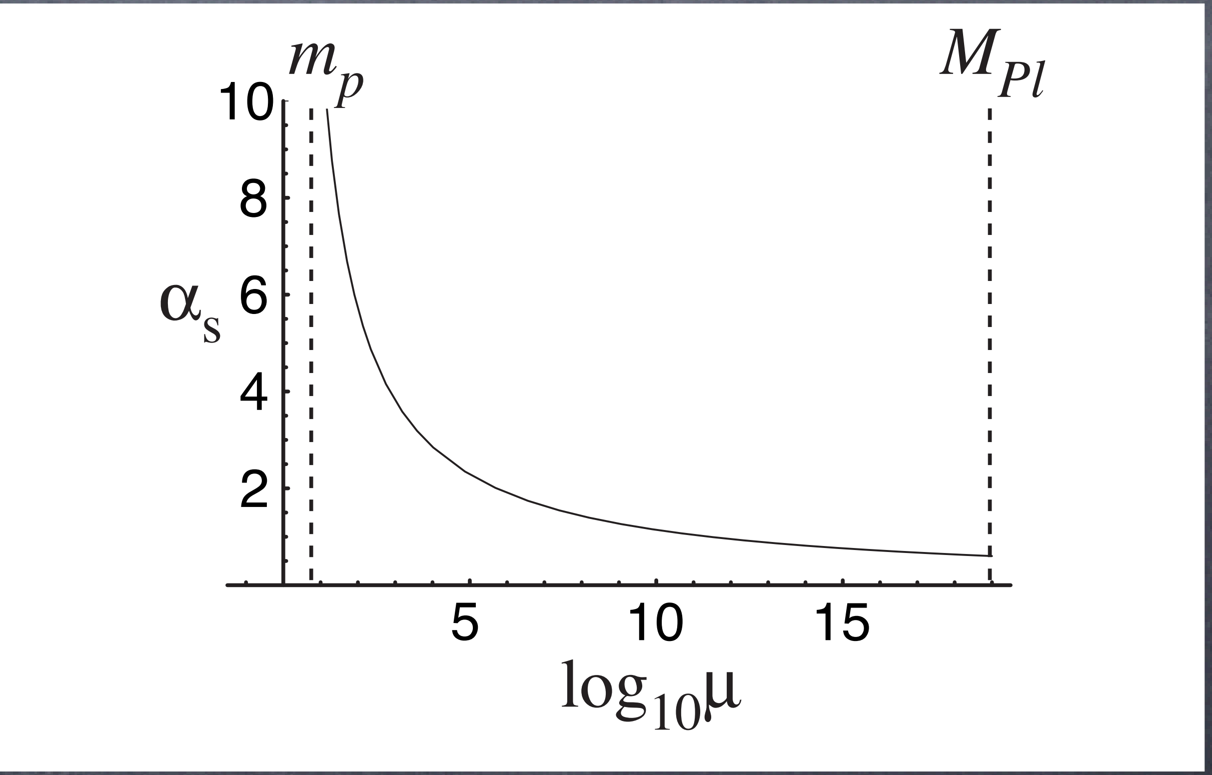
- Cannot be satisfied simultaneously
- Ground state at X=Y=Z=0
- $V=|F_X|^2=\lambda^2 v^4 \neq 0$
- ψ_Z: m^2
- A_Z: $m^2 \pm \lambda v^2$
- SUSY indeed broken
- However, the hierarchy $v \ll M_{Pl}$ put in by hand

Dynamical SUSY Breaking

- Nobody is worried why $m_p \ll M_{Pl}$
- If SUSY is broken also by strong gauge dynamics, hierarchy naturally understood
- If not broken at the tree-level, not broken at all orders in perturbation theory

broken non-perturbatively

$$m_p \approx M_{Pl} e^{-8\pi^2/g_s^2(M_{Pl})b_0}$$



Dynamical SUSY Breaking

- There are models known to break SUSY dynamically
  - SO(10) with single 16
  - SU(5) with 10+5*
  - SU(3)xSU(2) with Q, u, d, L and W=QdL
  - SU(2) with 4 Q's and 6 singlets $W=S_{ij}Q_iQ_j$
- SUSY is broken with $V \approx \Lambda^4$

Cosmological constant?

- Once SUSY is broken, there is a large vacuum energy $V \approx \Lambda^4$
- supergravity allows fine-tuning of the cosmological constant
- massless goldstino eaten by gravitino
- Global SUSY: $V = \Sigma_i |\partial_i W|^2 \approx \Lambda^4$
- supergravity: $V = e^K(|D_i W|^2 - 3|W|^2/M_{Pl}^2)$
- can choose a constant term in the superpotential to cancel the vacuum energy
- gravitino mass $m_{3/2} = e^{K/2}|W| \approx \Lambda^2/M_{Pl}$

N=1 Supergravity on a slide

- start with conformal supergravity ($g_{\mu\nu}$, ψ^μ, b_μ, A_μ)
- remove unwanted components by integrating out Weyl compensator chiral superfield S

$$\int d^4\theta S\bar{S}(-3M_{Pl}^2+\phi^*\phi+\cdots)+\int d^2\theta\left(S^3W+f(\phi)W_\alpha W^\alpha\right)$$

- Weyl scale $S\to S/W^{1/3}$

$$\int d^4\theta S\bar{S}\frac{-e^{-K/3}}{|W|^{2/3}}+\int d^2\theta\left(S^3+f(\phi)W_\alpha W^\alpha\right)$$

- depends only on $G=K+\ln|W|^2$ $\quad K=-\frac{1}{3}\ln(3M_{Pl}^2-\phi^*\phi-\cdots)$

$$V=e^G(G_i(G^i_j)^{-1}G^j-3)=e^K\left(F_i^*(K^i_j)^{-1}F^j-3|W|^2\right)$$

$$F_i=W_i+K_iW$$

- $\langle S\rangle=1+\theta^2\langle W\rangle$, $m_{3/2}=e^{K/2}|W|$

Soft SUSY breaking terms in the MSSM

- For each term in the superpotential

$$W_{MSSM} = Y_u^{ij} Q_i u_j^c H_u + Y_d^{ij} Q_i d_j^c H_d + Y_l^{ij} L_i e_j^c H_d + \mu H_u H_d$$

- we can have the "A-terms" and "B-term"

$$A_u^{ij} Y_u^{ij} Q_i u_j^c H_u + A_d^{ij} Y_d^{ij} Q_i d_j^c H_d + A_l^{ij} Y_l^{ij} L_i e_j^c H_d + B\mu H_u H_d$$

- scalar masses for all scalars

$$m_{Qij}^2 \tilde{Q}_i^* \tilde{Q}_j + m_{uij}^2 \tilde{u}_i^* \tilde{u}_j + m_{dij}^2 \tilde{d}_i^* \tilde{d}_j + m_{Lij}^2 \tilde{L}_i^* \tilde{L}_j + m_{eij}^2 \tilde{e}_i^* \tilde{e}_j + m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2$$

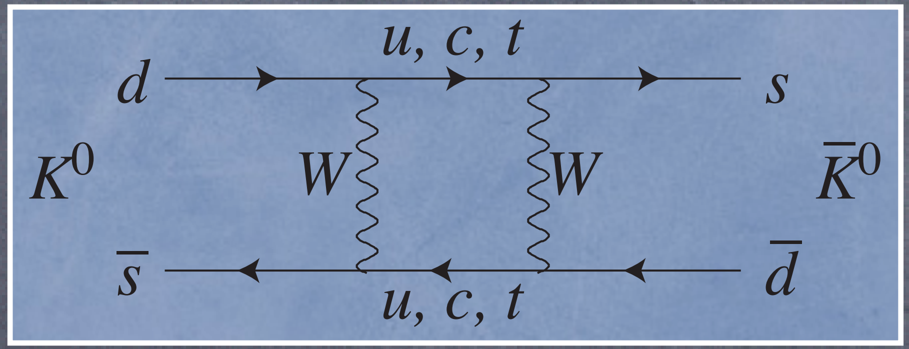
- gaugino mass for all three gauge factors

$$M_1 \tilde{B} \tilde{B} + M_2 \tilde{W}^a \tilde{W}^a + M_3 \tilde{g}^a \tilde{g}^a$$

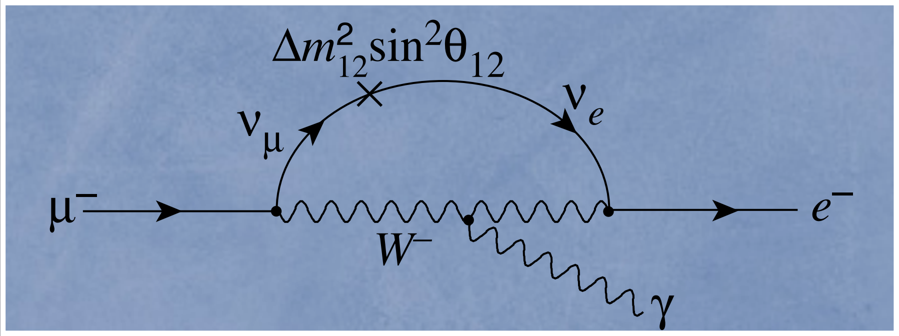
- A(18x3)+B(2)+m(9x5+2)+M(2x3)+μ(2)=111
  $U(1)_R \times U(1)_{PQ}$ removes only two phases
  cf. SM has two params in the Higgs sector
  107 more parameters than the SM!

Flavor-Changing Neutral Current

- There is no tree-level vertex such as $\bar{s}\gamma^{\mu} d Z_{\mu}$
- In the Standard Model, FCNC is highly suppressed
- e.g.,



$$\sim \frac{1}{16\pi^2} G_F^2 m_c^2 (V_{cd}^* V_{cs})^2$$



$$\sim \frac{e}{16\pi^2} G_F^2 m_\mu \Delta m_{12}^2 \sin^2\theta_{12}$$

SUSY flavor violation

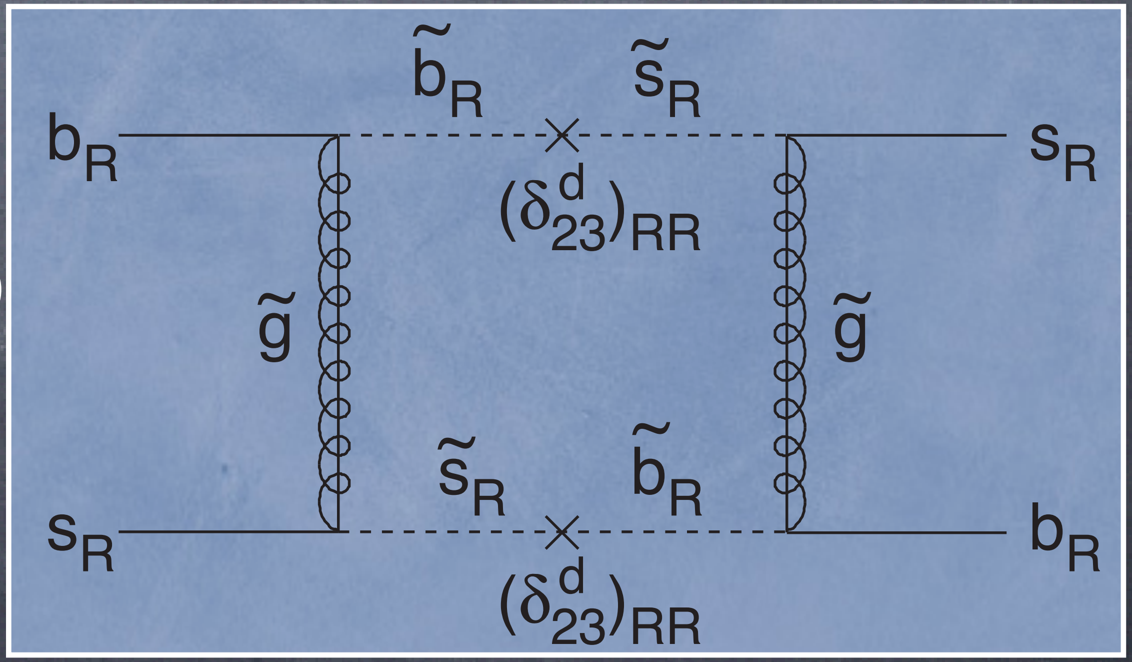
- soft SUSY breaking parameters can violate flavor

$$(\tilde{d},\, \tilde{s},\, \tilde{b}) \begin{pmatrix} m^2_{11} m^2_{12} m^2_{13} \\ m^2_{21} m^2_{22} m^2_{23} \\ m^2_{31} m^2_{32} m^2_{33} \end{pmatrix} \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}$$

$$(\delta^d_{12})_{RR} \equiv \frac{m^2_{12}}{m_{11} m_{22}} < 0.04 \frac{m_{SUSY}}{500\text{GeV}}$$

$$\sqrt{(\delta^d_{12})_{RR} (\delta^d_{12})_{LL}} < 0.001 \frac{m_{SUSY}}{500\text{GeV}}$$

K^0



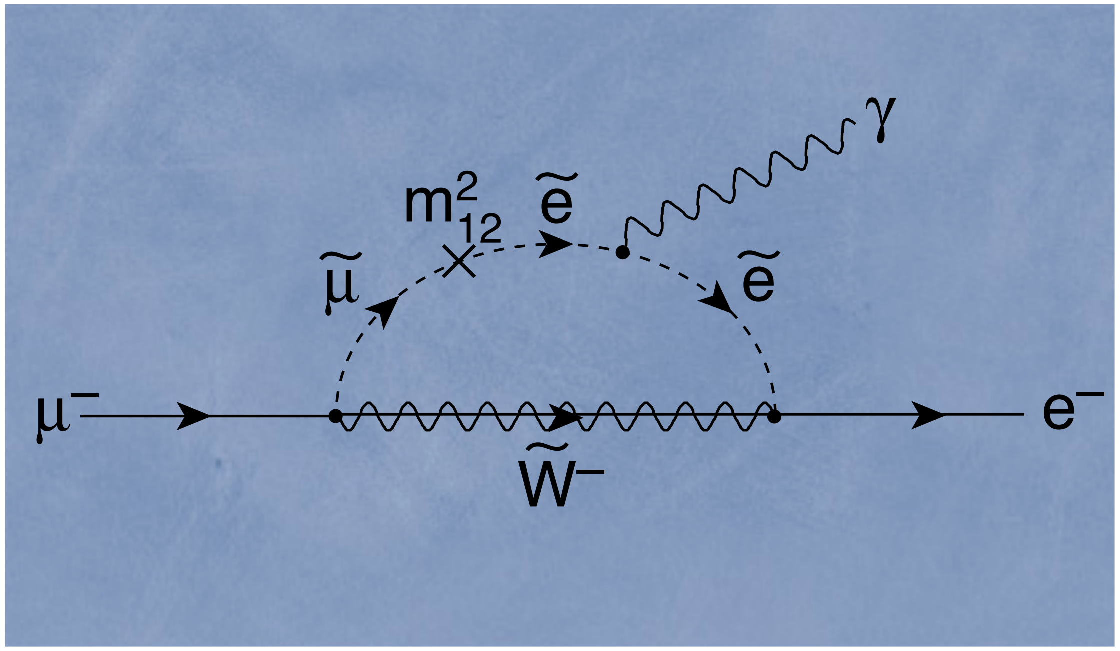
$\overline{K^0}$

SUSY flavor violation

- soft SUSY breaking parameters can violate flavor

$$(\tilde{e}, \tilde{\mu}, \tilde{\tau}) \begin{pmatrix} m_{11}^2 m_{12}^2 m_{13}^2 \\ m_{21}^2 m_{22}^2 m_{23}^2 \\ m_{31}^2 m_{32}^2 m_{33}^2 \end{pmatrix} \begin{pmatrix} \tilde{e} \\ \tilde{\mu} \\ \tilde{\tau} \end{pmatrix}$$

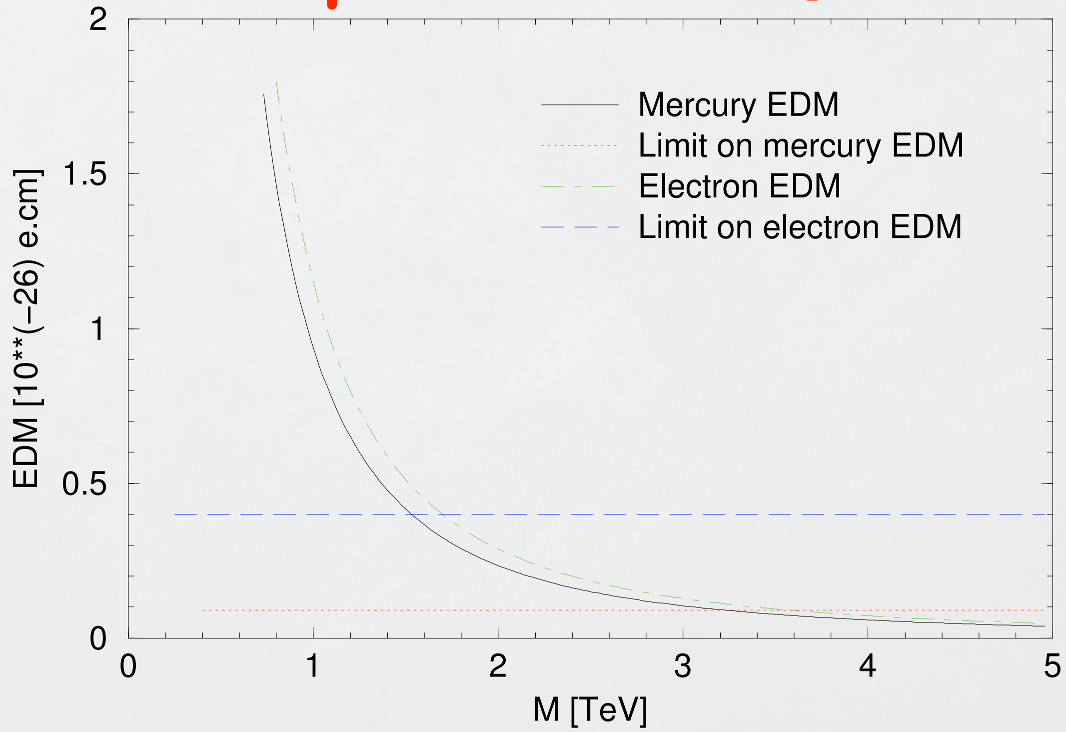
$$(\delta_{12}^{l})_{RR} < 3.9 \times 10^{-3}$$



Supersymmetric CP problem

- The relative phases of μ and $M_{1,2,3}$ are physical
- induces electric dipole moments $H \propto \vec{s} \cdot \vec{E}$
- stringent limits on electron, neutron, and Hg atom
- either m_{SUSY}>TeV or phase~10^{-2}

phase of μ



Falk, Olive, Pospelov, Roiban

Common simplifying assumptions

- soft SUSY breaking parameters all real
- "flavor-blind", namely, 3x3 sclar mass-squared matrices: $m_f^2 \propto I$
- gaugino masses unify: $M_1 = M_2 = M_3$ at M_{GUT}

Minimal SUGRA

(Hall, Lykken, Weinberg)

- Often, this problem is "solved" by assuming a very special Lagrangian called "minimal supergravity" $\int d^4\theta(-3M_{Pl}^2)\exp\left(\frac{-1}{3M_{Pl}^2}(\phi_i^*\phi^i + z_i^* z^i)\right)$
- Gives universal scalar mass: flavor-blind
- No theoretical justification for this very particular choice
- Just a convenient choice to obtain the minimal kinetic term with no Planck-suppressed corrections
- Not stable under renormalization

“minimal supergravity”

- At the GUT-scale 2×10^{16} GeV
- assume all scalar masses are equal $m_0{}^2$
- assume all gaugino massses are equal $M_{1/2}$
- assume all trilinear couplings are equal A_0
- in addition, B, Bμ
- calculate all SUSY breaking terms via RGE down from the GUT-scale
- fix m_Z: leaves four parameters (and sign(μ))

one-loop RGE

- GUT prediction of gaugino masses

$$\frac{d}{dt}\frac{M_i}{g_i^2} = 0$$

$$M_1 : M_2 : M_3 \approx 1 : 2 : 7 \text{ at } m_Z$$

- gauge interaction boosts scalar masses

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$$16\pi^2\frac{d}{dt}m_{\tilde{t}_R}^2 = 2X_t - \frac{32}{3}g_3^2M_3^2 - \frac{32}{15}g_1^2M_1^2$$

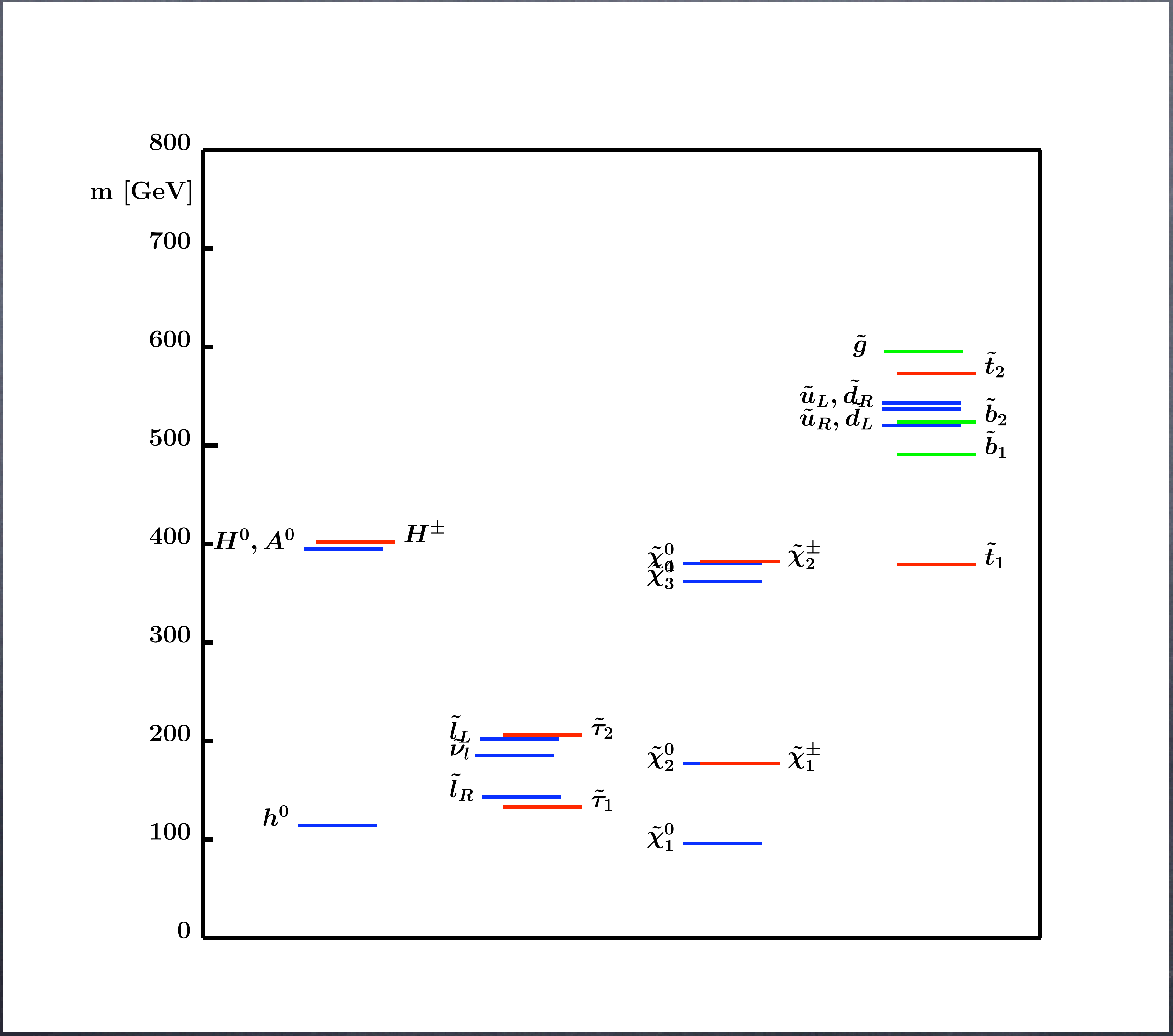
$$16\pi^2\frac{d}{dt}m_{\tilde{t}_L}^2 = X_t - \frac{32}{3}g_3^2M_3^2 - 6g_2^2M_2^2 - \frac{2}{15}g_1^2M_1^2$$

$$X_t = 2Y_t^2(m_{H_u}^2 + m_{\tilde{t}_R}^2 + m_{\tilde{t}_L}^2 + A_t^2)$$

- H_u mass-squared most likely to get negative!

sample spectrum

$m_0 = 100,\ m_{1/2} = 250,\ A_0 = -100,\ \tan\beta = 10,\ \mu > 0$

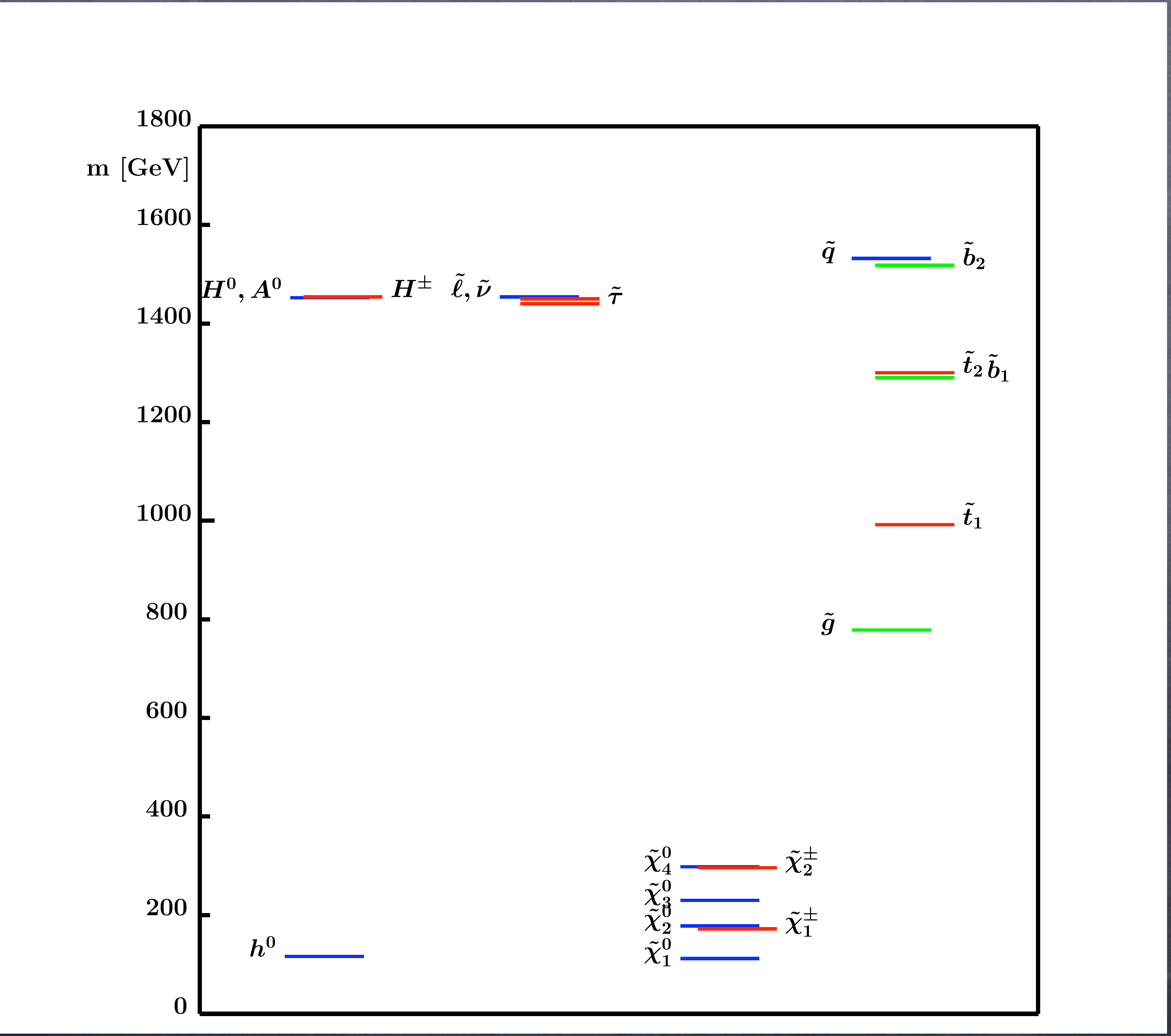


bulk region

SPS1a

sample spectrum

$m_0 = 1450,\ m_{1/2} = 300,\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$

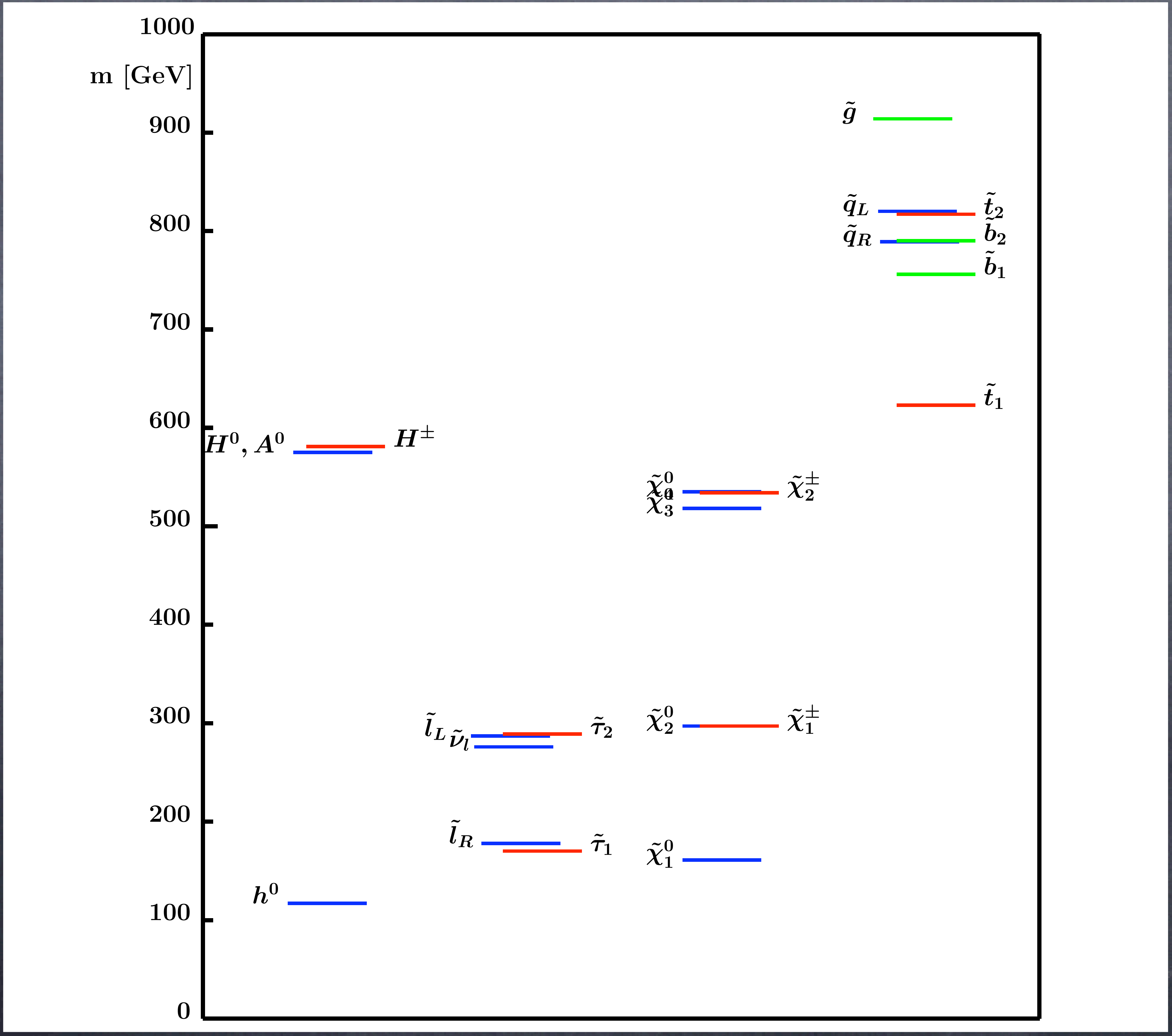


focus point region

SPS2

sample spectrum

$m_0 = 90,\ m_{1/2} = 400,\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$



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region

SPS3

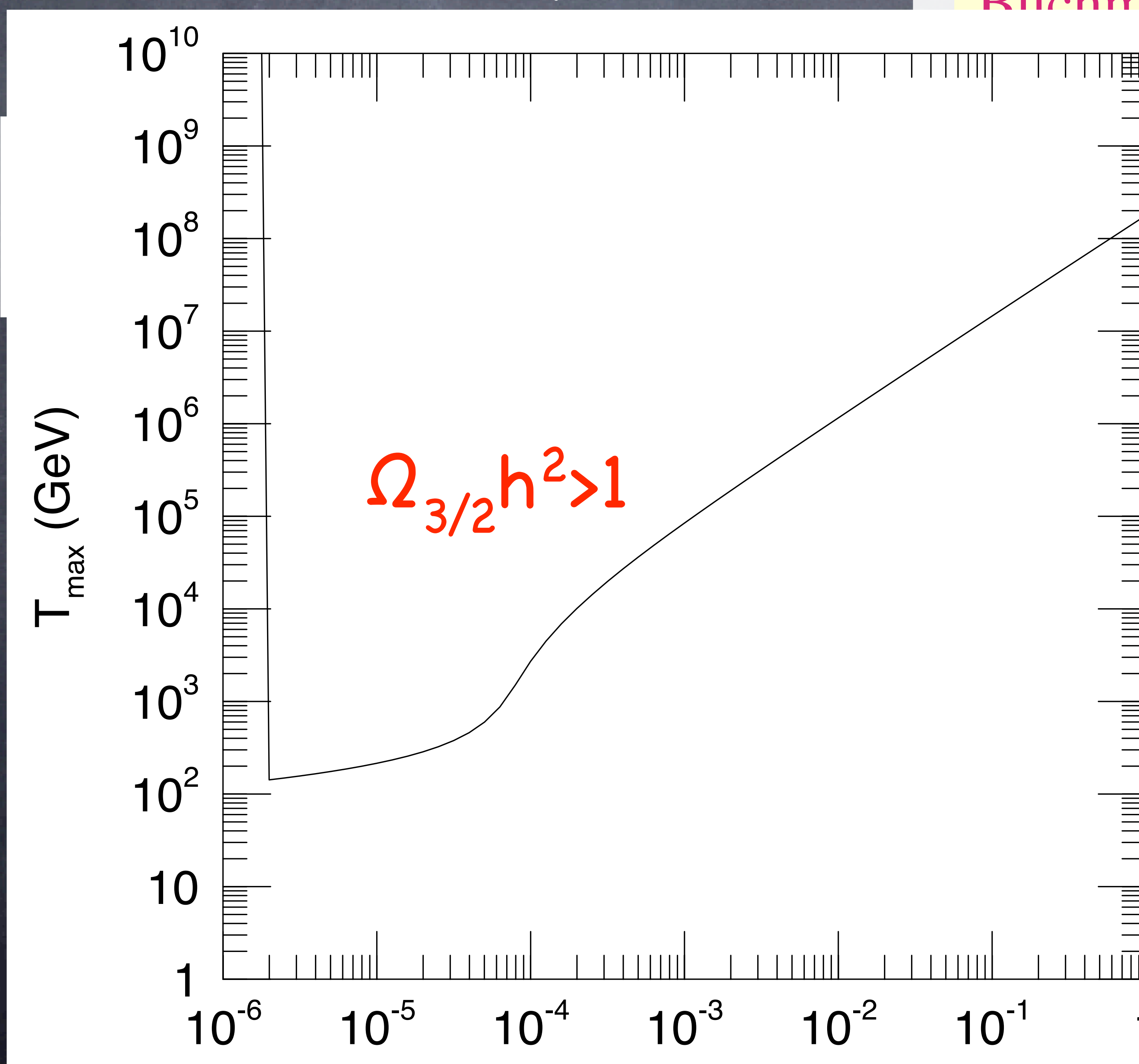
“Gravity” Mediation

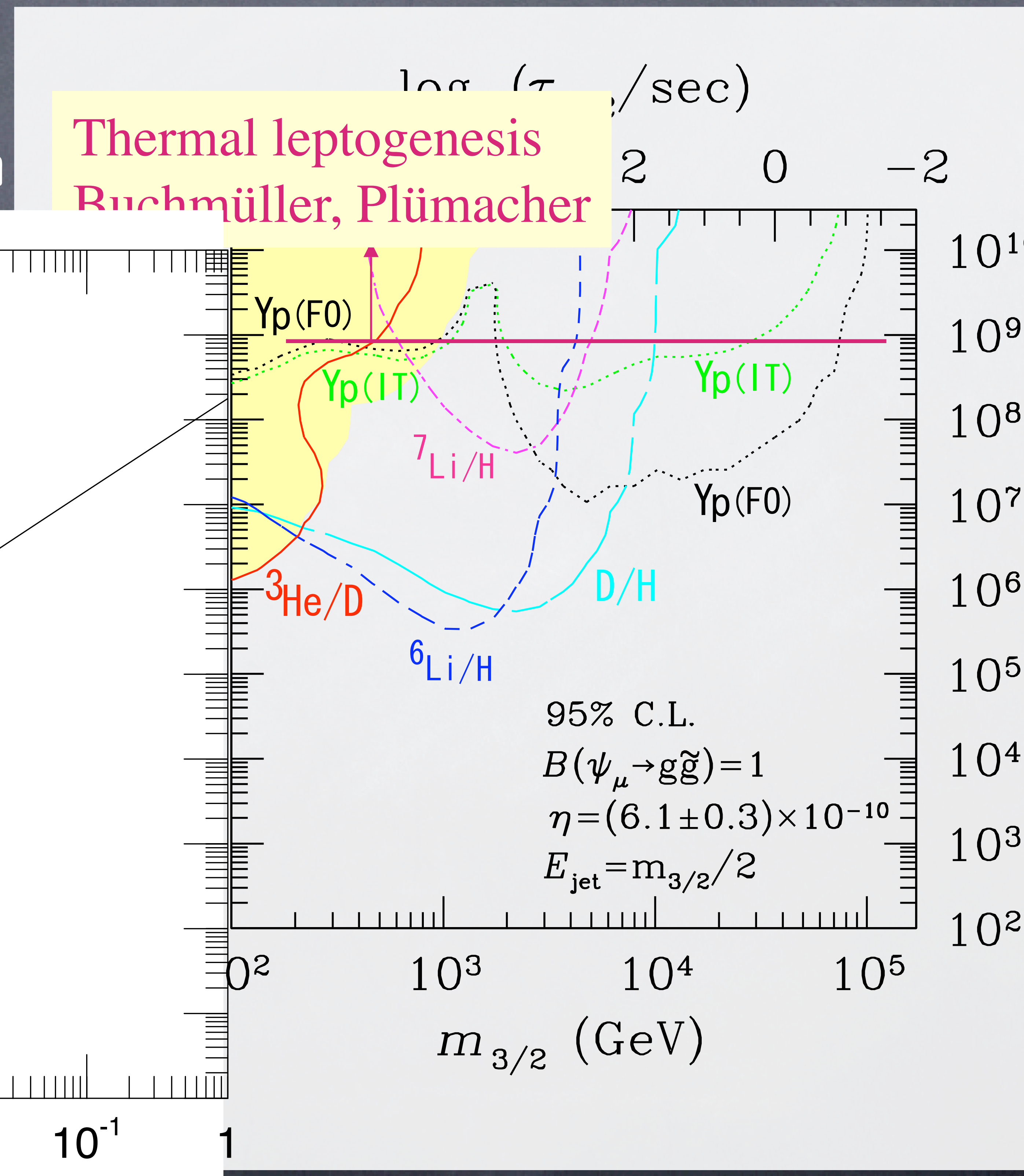
- People argued that the mediation of SUSY breaking by gravity is universal because the gravity couples universally
- But it is easy to see this is a big lie
- The minute you talk about gravity, we have a theory cutoff at the Planck-scale, and we can write arbitrary operators suppressed by the Planck scale w/o the knowledge of the fully consistent theory of quantum gravity

$$\int d^4\theta \lambda_{ij} \frac{z^* z}{M_{Pl}^2} \phi_i^* \phi_j \to m_{ij}^2 = \lambda_{ij} \left| \frac{F_z}{M_{Pl}} \right|^2 \qquad \int d^2\theta \lambda_i \frac{z}{M_{Pl}} W_\alpha^i W^{\alpha i} \to M_i = \lambda_i \frac{F_z}{M_{Pl}}$$

Gravitino Problem

- Gravitinos produced in





Moduli problem

- In string theory, we need to compactify 6 (or 7) extra dimensions into a small size
- moduli fields parameterize the size and shape of the compactified space (⇒flux)
- they do not have any potential in the supersymmetric limit
- their mass is $O(m_{3/2})$, very flat potential
- in early universe, they had $O(M_{Pl})$ amplitudes
- oscillate around the minimum, dominate
- when it decays, dilutes entropy by $\sim m_{3/2}/M_{Pl}$

Issue of mediation

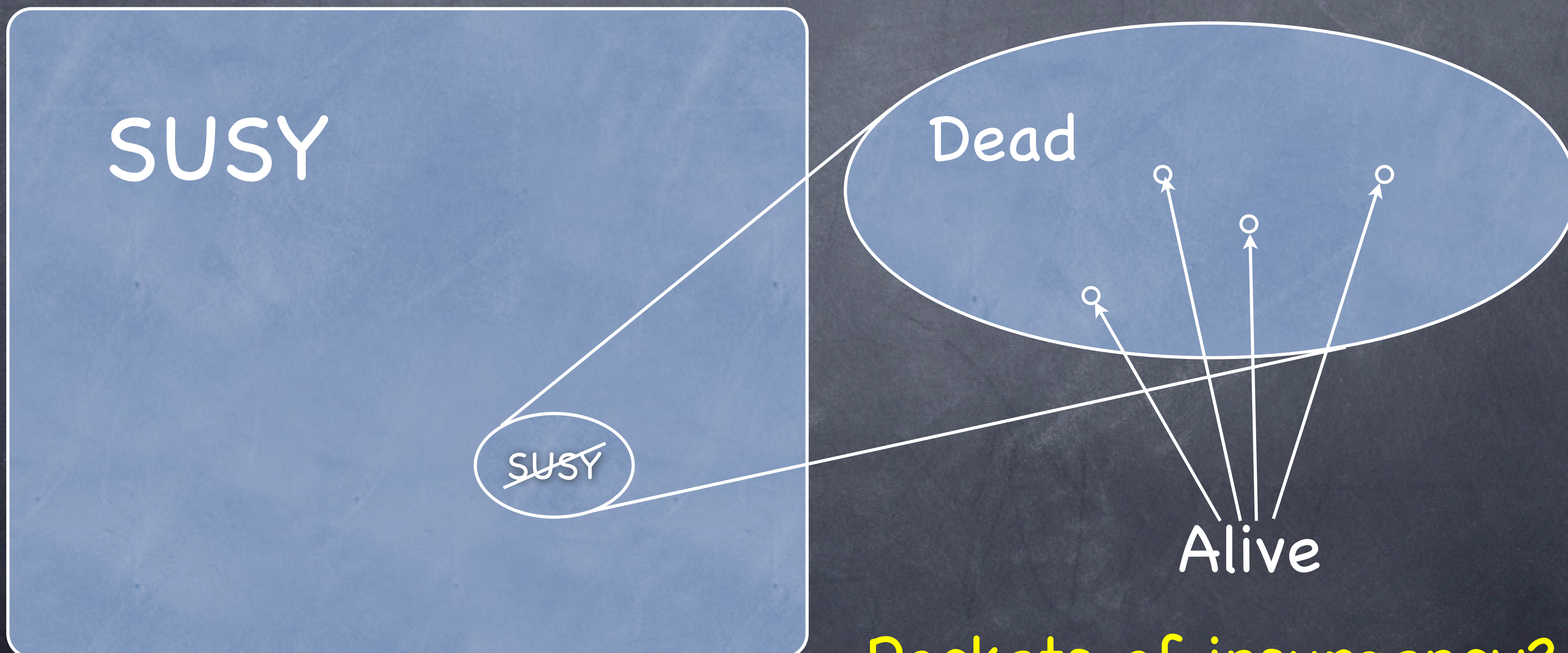
- Many gauge theories that break SUSY dynamically known
- The main issue: how do we communicate the SUSY breaking effects to the MSSM? "mediation"
- If the mediation mechanism is *flavor-blind*, there is no problem with FCNC
  - Gauge mediation (direct & indirect & NEW)
  - Gaugino mediation
  - Anomaly mediation

Big Change in Perception

- LHC is coming! Reaching the important energy scale $G_F^{-1/2}$=300 GeV known since 1933 paper by Fermi. Historic moment!
- Growing concern in the community
  - If there is new physics below TeV, we should have seen its hints by now. Most likely we don't find anything at the LHC.
- Now I think
  - It is quite likely to find new physics, especially supersymmetry, at the LHC!

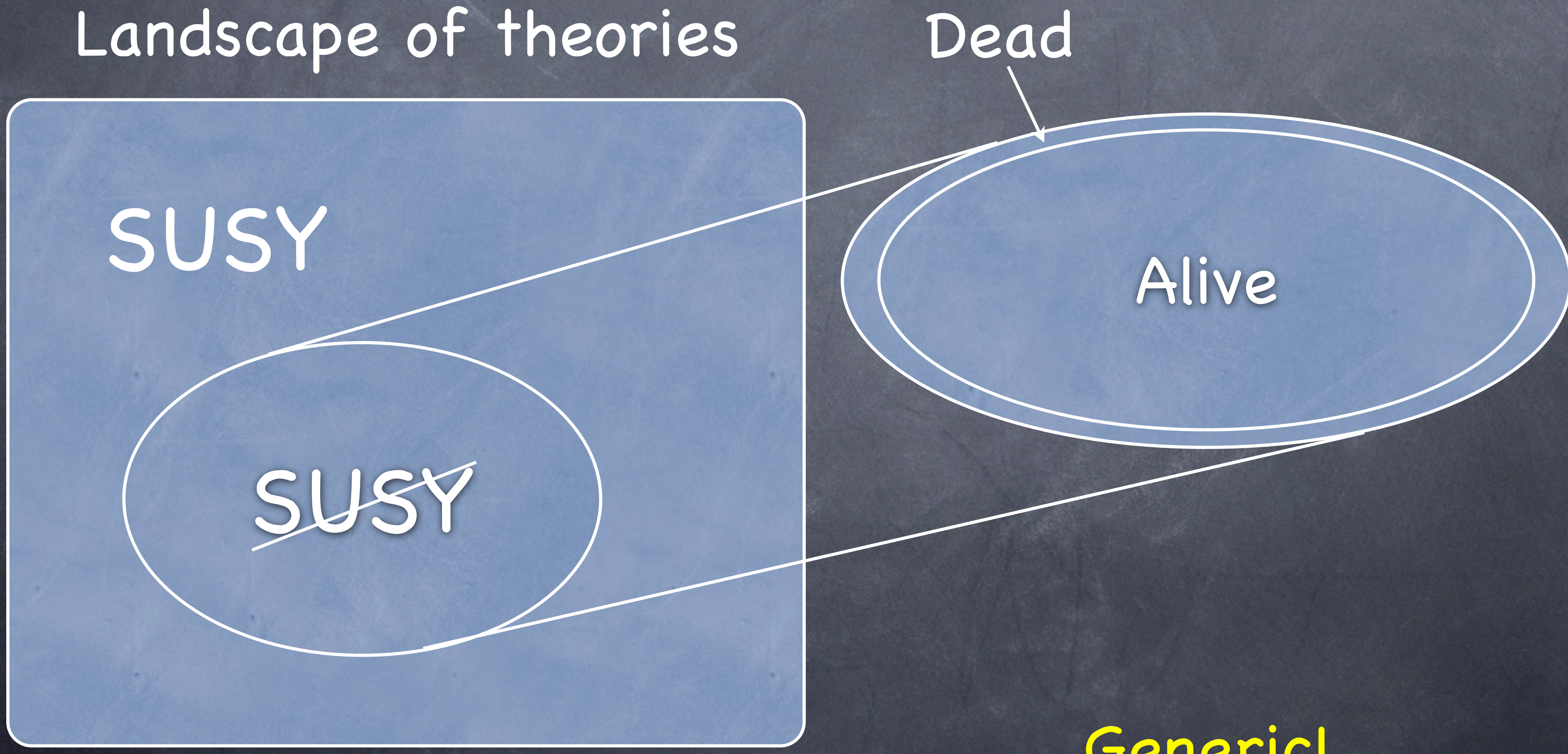
Likelihood of viable SUSY

Landscape of theories



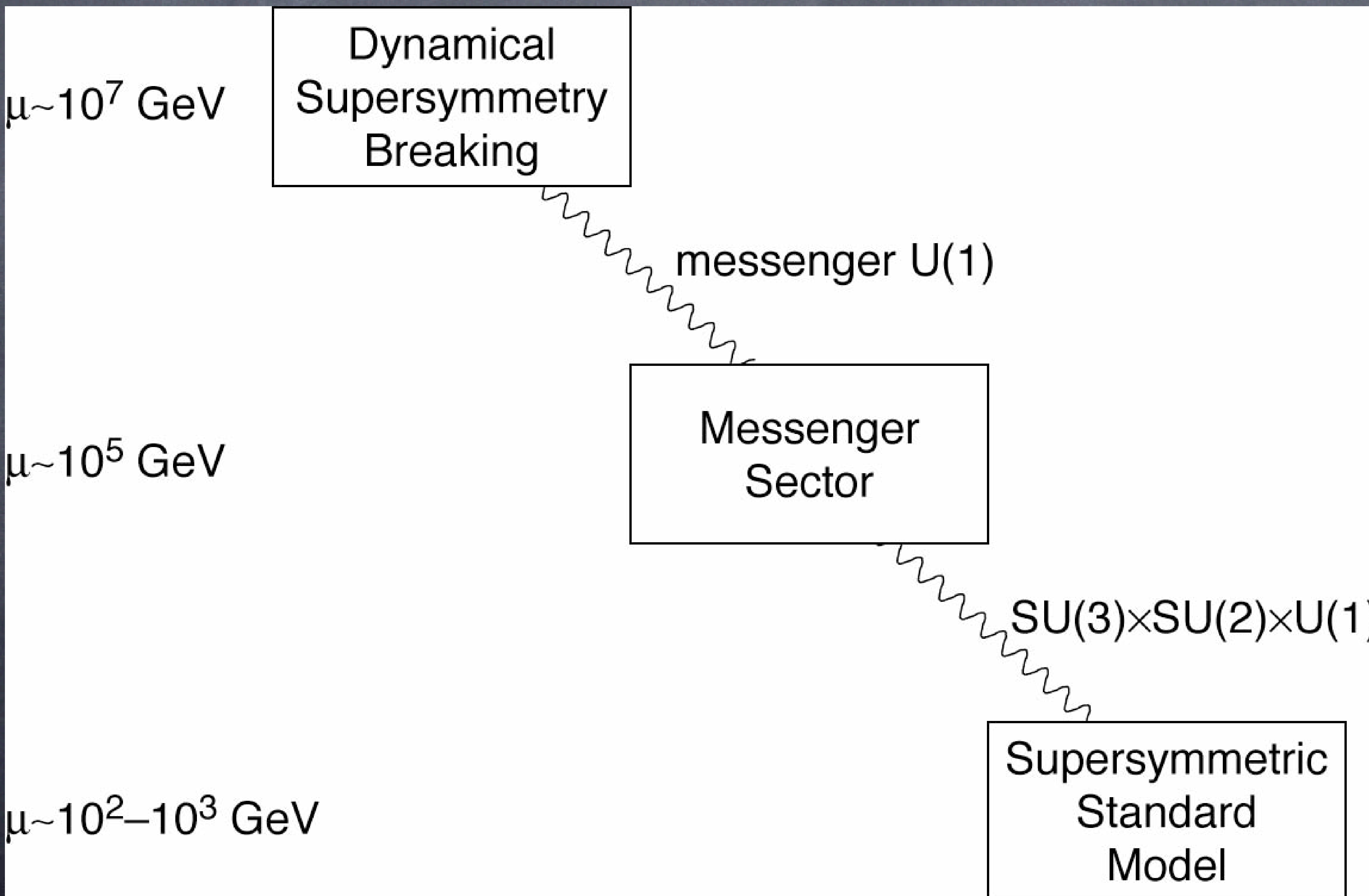
Pockets of insurgency?

Likelihood of viable SUSY



Generic!

Gauge Mediation (GMSB)



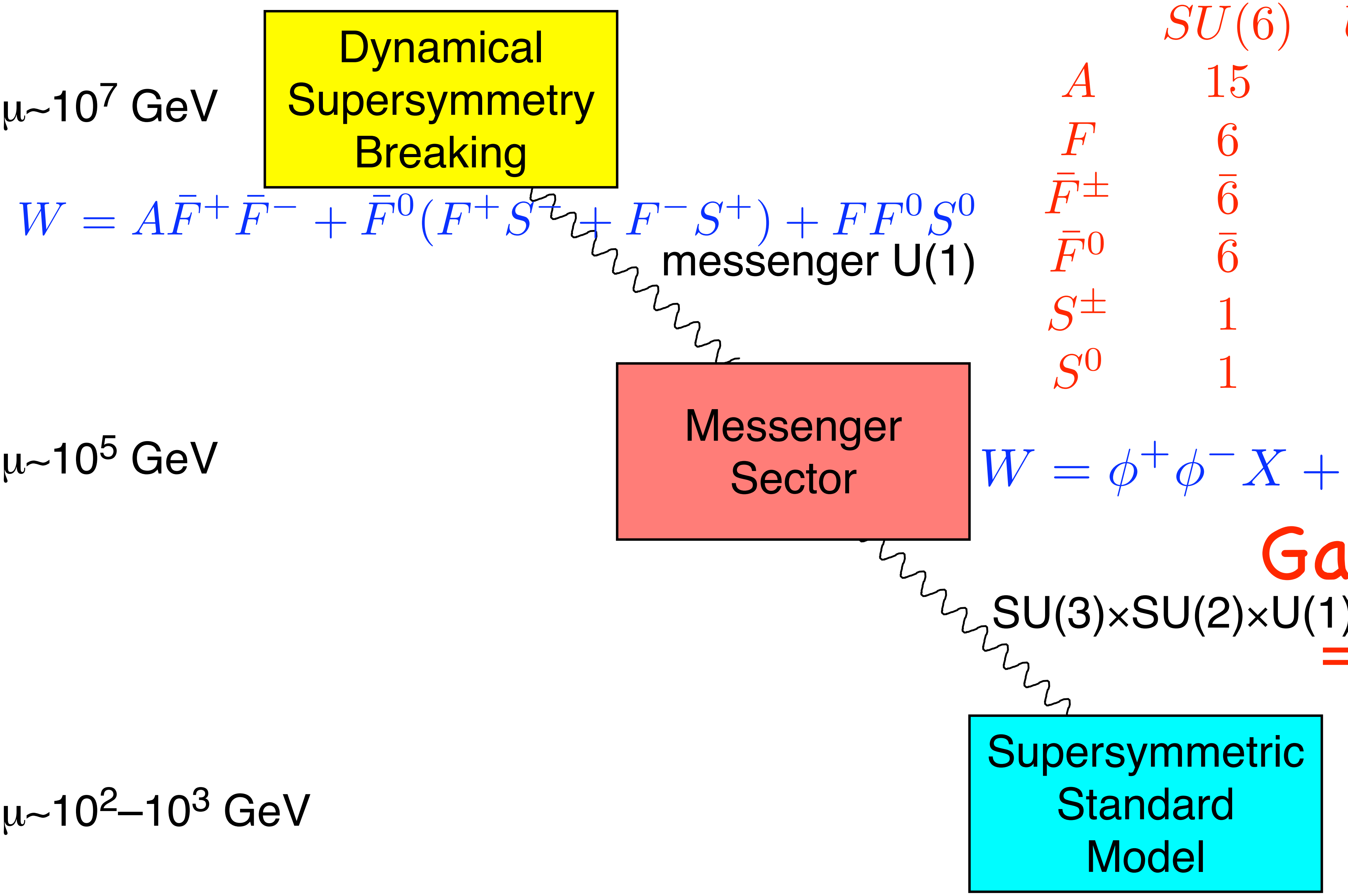
Special Model I SUSY Breaking

- Breaking SUSY has been difficult
- Nelson-Seiberg: you need either
  - non-generic superpotential
  - need exact $U(1)_R$ spontaneously broken
- Either way, theory needs to be rather spcial, not a whole lot of models known

	$SU(6)$	$U(1)$	$U(1)_m$	$U(1)_R$
A	15	$+2$	0	$-\frac{18}{7}$
F	6	-5	0	$-\frac{18}{7}$
$\bar{F}^{\pm}$	$\bar{6}$	-1	± 1	$\frac{16}{7}$
$\bar{F}^{0}$	$\bar{6}$	-1	0	$\frac{16}{7}$
$S^{\pm}$	1	$+6$	± 1	$\frac{16}{7}$
S^{0}	1	$+6$	0	$\frac{16}{7}$

$$W = A\bar{F}^{+}\bar{F}^{-} + \bar{F}^{0}(F^{+}S^{-} + F^{-}S^{+}) + FF^{0}S^{0}$$

Special Model II
Mediation Mechanism



$$W = A\bar{F}^+\bar{F}^- + \bar{F}^0(F^+S^- + F^-S^+) + FF^0S^0$$

	$SU(6)$	$U(1)$	$U(1)_m$	$U(1)_R$
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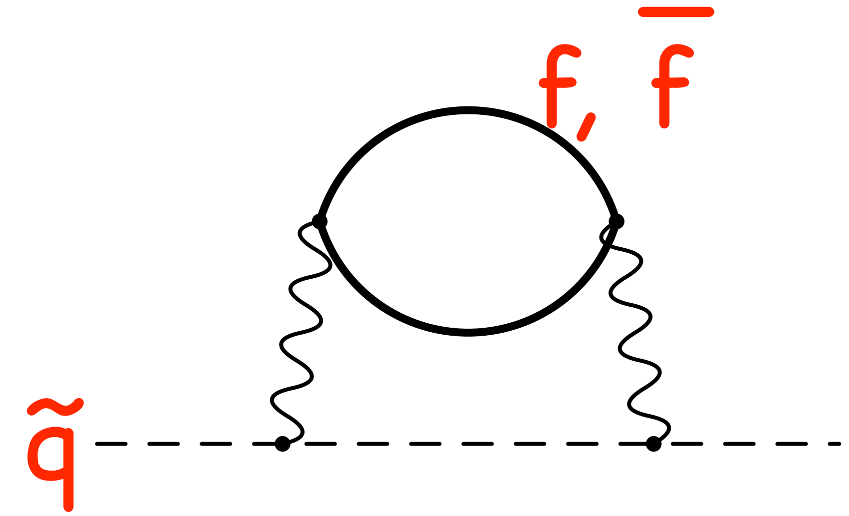
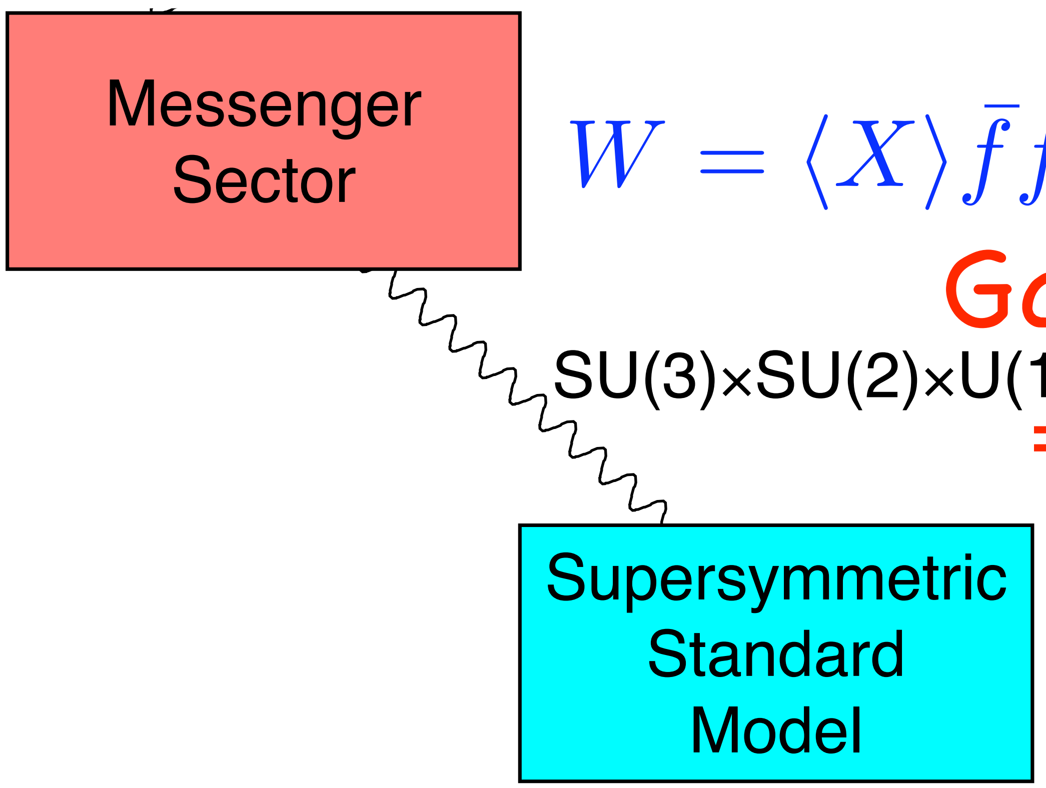
$$W = \phi^+\phi^- X + X^3 + X\bar{f}f$$

Gauge Mediation
⇒flavor blind

Dine–Nelson–Nir–Shirman

Special Model II
Mediation Mechanism





$$W = \langle X \rangle \bar{f} f$$

Gauge Mediation
$\Rightarrow$ flavor blind

Dine-Nelson-Nir-Shirman

Gauge Mediation (GMSB)

- Integrate out "messenger fields" $W = S f \bar{f}$
  N(5+5*) (i.e, d^c+L) $\langle S \rangle = \langle A_S + \theta^2 F_S \rangle \neq 0$
- integrate them out: changes the running of gauge coupling, wave function renormalizations

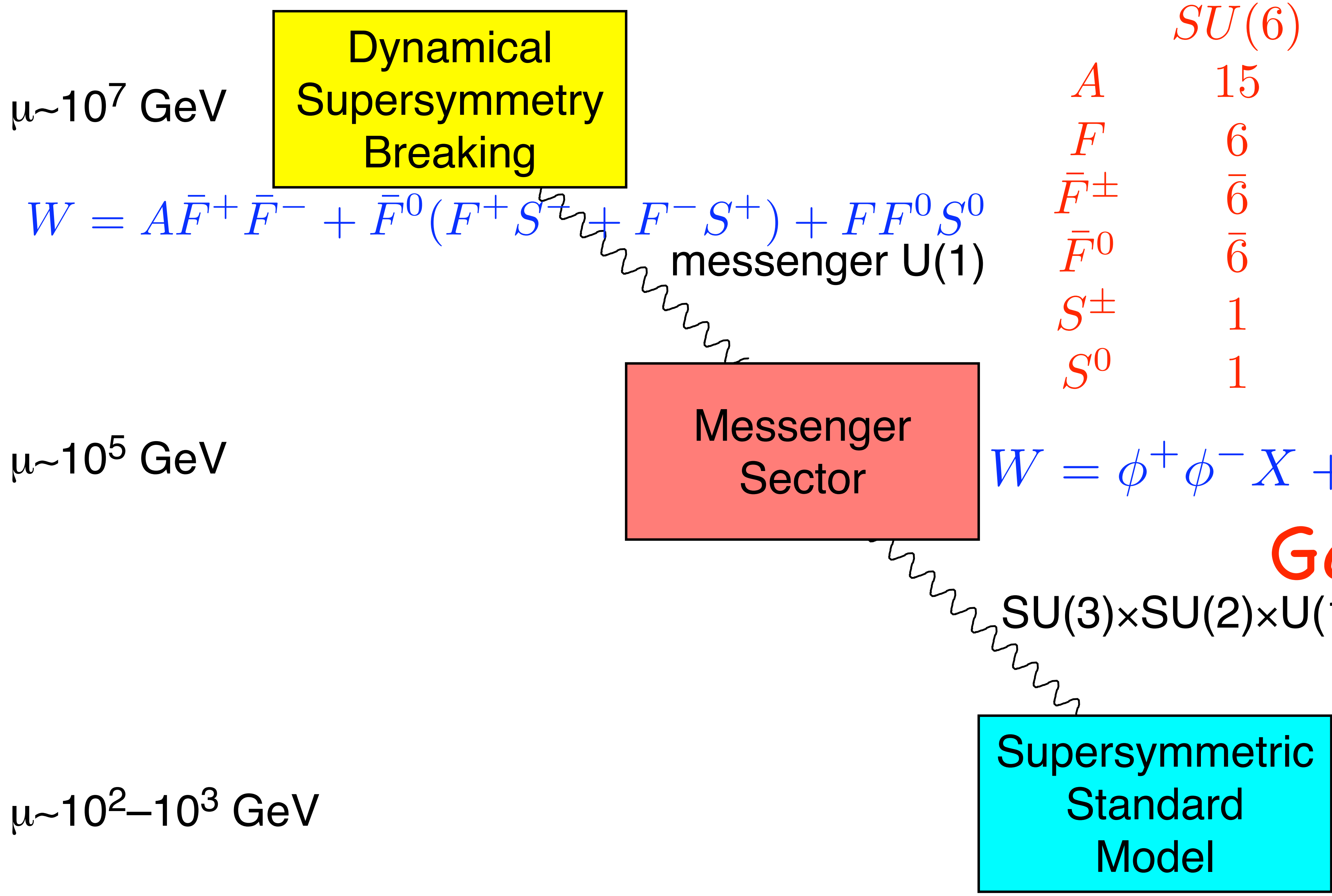
$$\frac{1}{g^2(\mu)} = \frac{1}{g_0^2} + \frac{b_0 + N}{8\pi^2} \ln \frac{\Lambda_{UV}}{S} + \frac{b_0}{8\pi^2} \ln \frac{S}{\mu}$$

$$\frac{M}{g^2} = \left. \frac{1}{g^2(\mu)} \right|_{\theta^2} = \frac{1}{8\pi^2} N \frac{F_S}{A_S}$$

$$Z_i(\mu) = Z_i(\Lambda_{UV}) \left(\frac{g^2(\Lambda_{UV})}{g^2(\sqrt{S^\dagger S})} \right)^{2C_F/b'} \left(\frac{g^2(\sqrt{S^\dagger S})}{g^2(\mu)} \right)^{2C_F/b}$$

$$m_i^2(\mu) = -\ln Z_i(\mu)|_{\theta^2\bar{\theta}^2} = 2C_F \frac{g^4}{(4\pi)^4} N \left(\frac{F_S}{A_S} \right)^2$$

Special Model II
Mediation Mechanism



$$W = A\bar{F}^{+}\bar{F}^{-} + \bar{F}^{0}(F^{+}S^{-} + F^{-}S^{+}) + FF^{0}S^{0}$$

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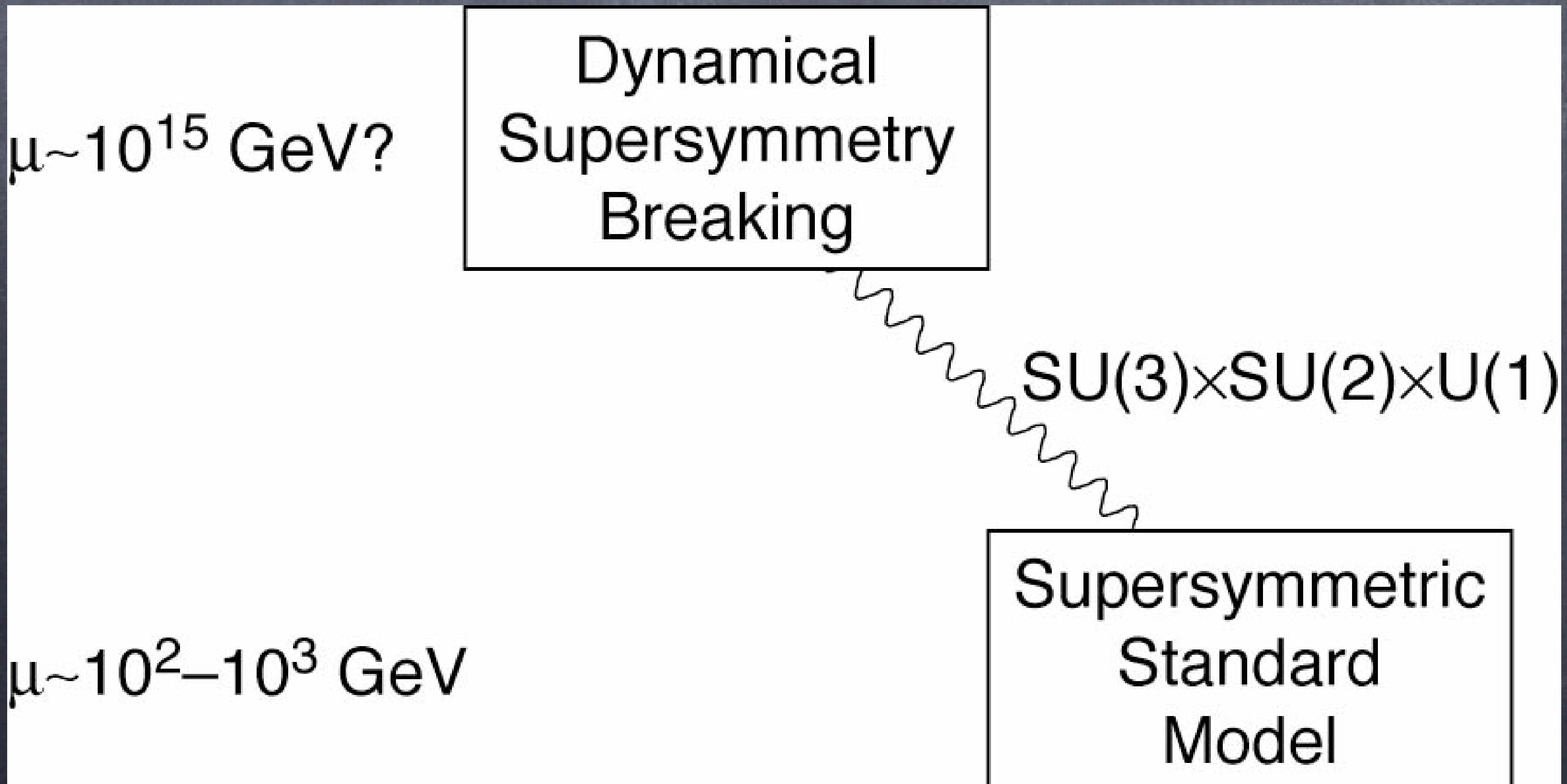
$$W = \phi^{+}\phi^{-}X + X^{3} + X\bar{f}f$$

Gauge Mediation
⇒flavor blind

Dine–Nelson–Nir–Shirman

Direct Gauge Mediation

- Too many sectors to worry about!
- e.g., SU(2)xSU(2) with Σ(2,2), Q(2,1)x6, Q'(1,2)x6, embed 3x2x1 into 6 (Agashe)
- Actually much harder to build a model, partly because of the Landau pole



New Generic Scheme

$$\frac{1}{M_{Pl}}\bar{Q}Q\bar{f}f$$

HM, Nomura

SUSY QCD
SU(Nc), SO(Nc), Sp(Nc)

$m_Q\bar{Q}Q$

$M\bar{f}f$

SUSY SM

no $U(1)_R$ symmetry imposed

most general superpotential

wide choice of gauge groups, matter content

$$N_c < N_f < \frac{3}{2}N_c$$

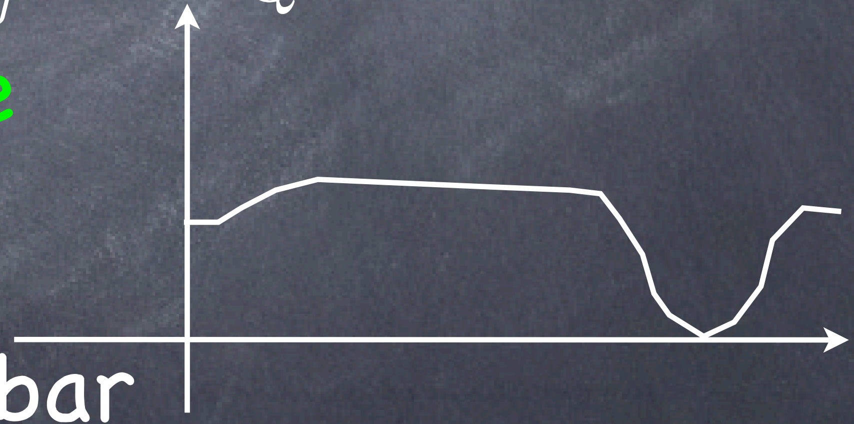
How it works

- SUSY SU(N_c) QCD $N_c<N_f<3N_c/2$ $W = m_Q^{ij}\bar{Q}_i Q_j$
- low-energy free magnetic theory ($m_Q<\Lambda$)

$$W = m_Q^{ij}\Lambda M_{ij} + M_{ij}\bar{q}^i q^j$$

- SUSY breaking @ $M_{ij}=0$, $\frac{\partial W}{\partial M_{ij}} = m_Q^{ij} \neq 0$
- Local minimum with long lifetime

$$W = \frac{1}{M_{Pl}}\bar{Q}Q\bar{f}f$$



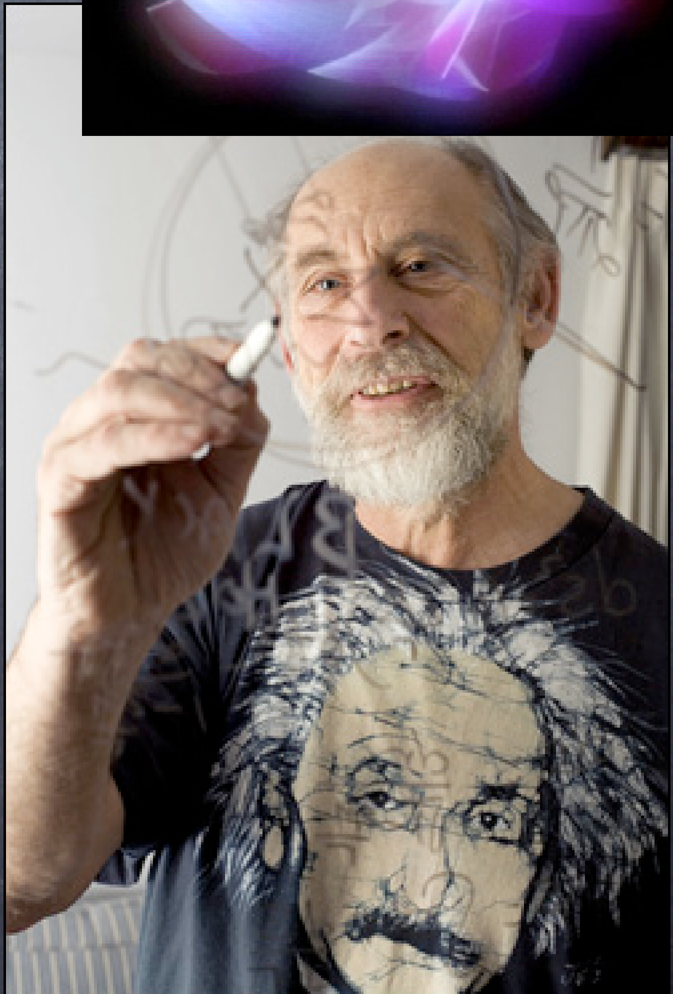
- Generates SUSY breaking in f, fbar
- their loops⇒gauge mediation

Intriligator, Seiberg, Shih

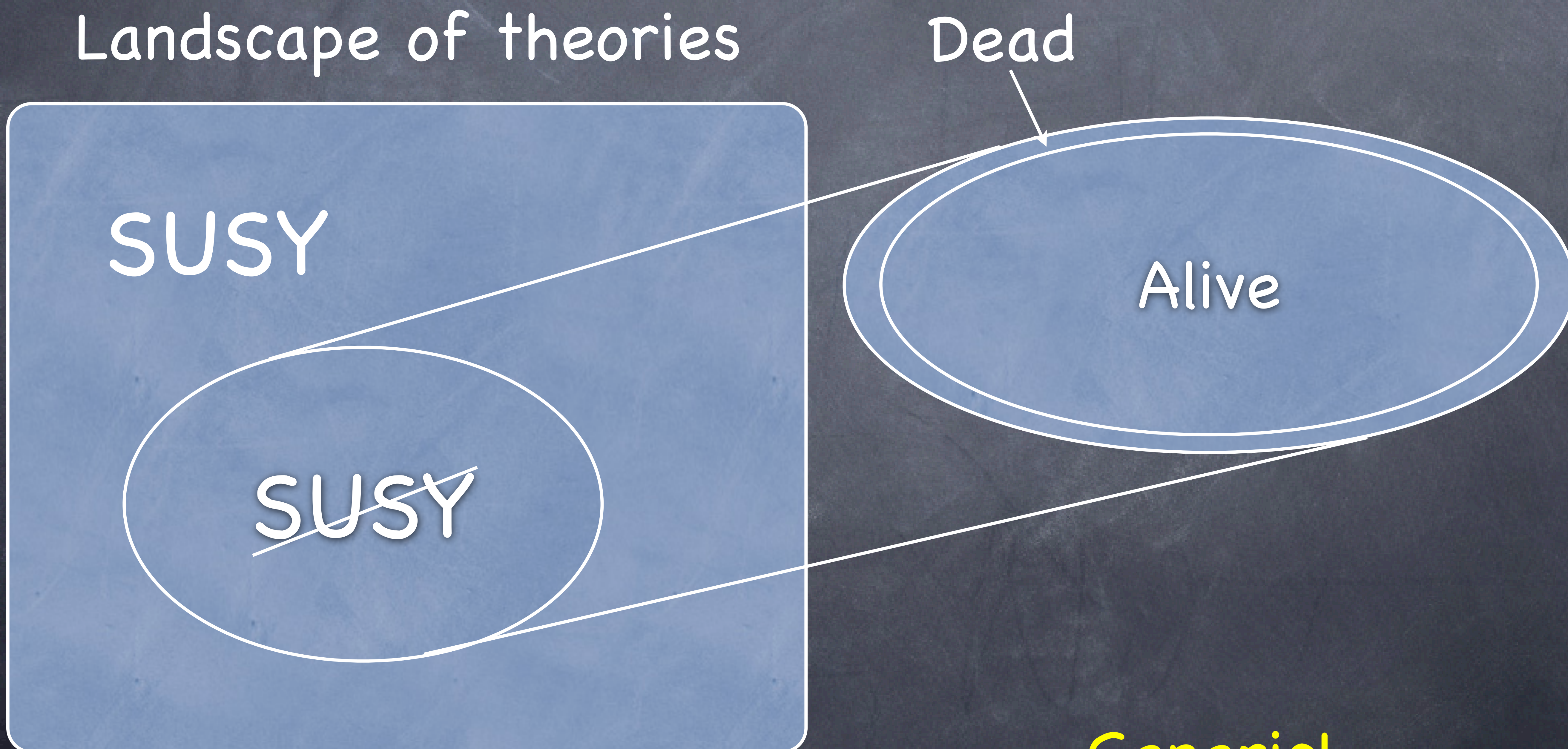
Good news for string theory

- String theory does not predict unique solution
- "Landscape" of possibilities for gauge groups, matter content, number of SUSY
- We at least need SM
- We tend to get extra "junks", i.e. extra gauge groups, extra vector-like matter
- the "junks" are precisely what we need to break SUSY via gauge mediation

Easy, Viable, Generic!



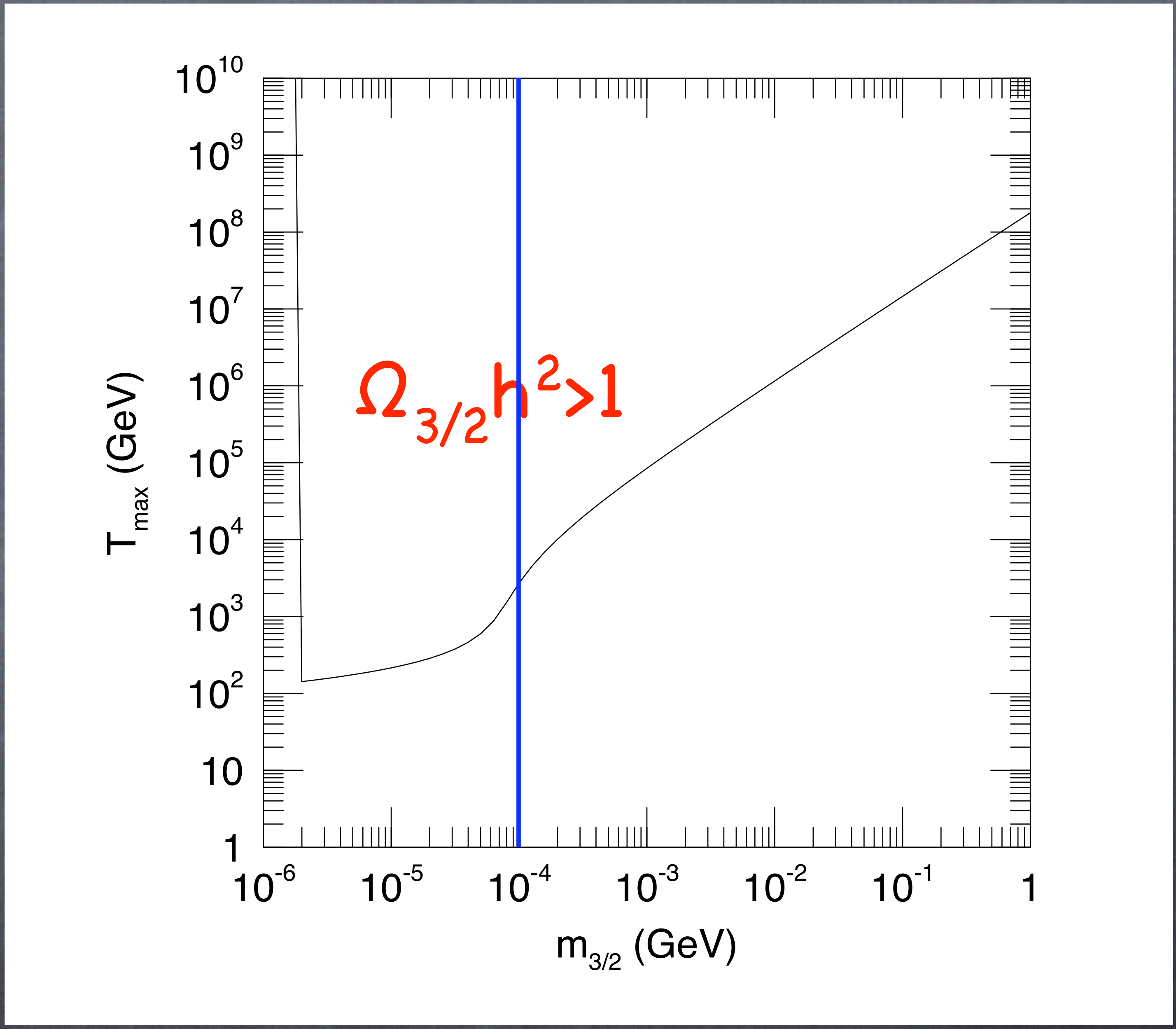
Likelihood of viable SUSY



Generic!

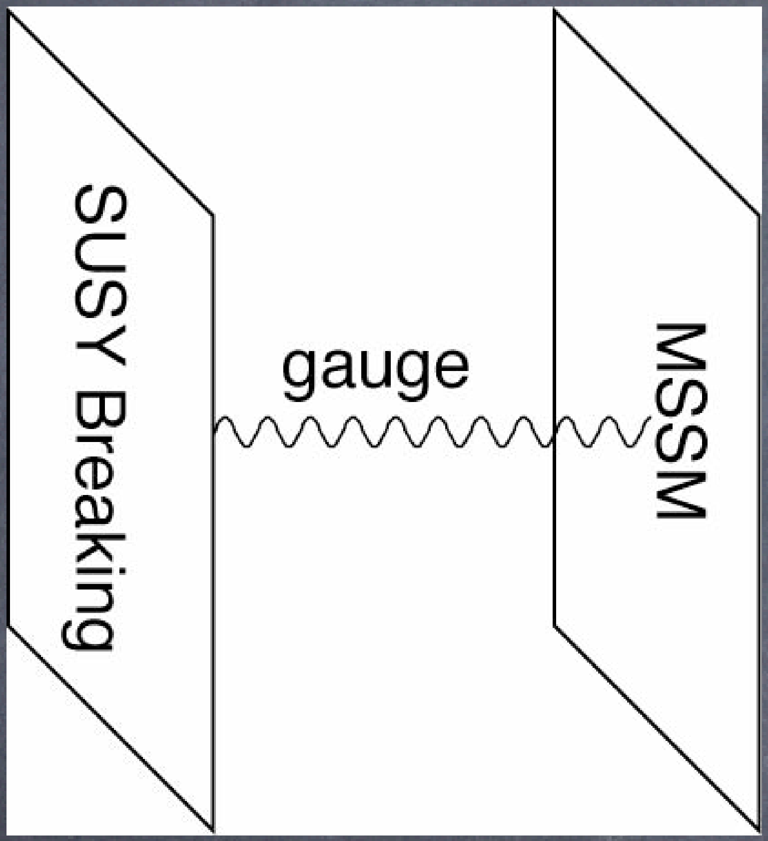
Gauge Mediation

- Assuming that the messenger scale is higher than ANY flavor physics, no FCNC
- $m_{3/2} \sim (10^7 \text{ GeV})^2/M_{Pl} \sim 100$ keV: the worst mass range
- there are models with $m_{3/2}<$keV
- "LSP" (e.g., neutralino, stau) may decay inside detectors



de Gouvêa, Moroi, HM

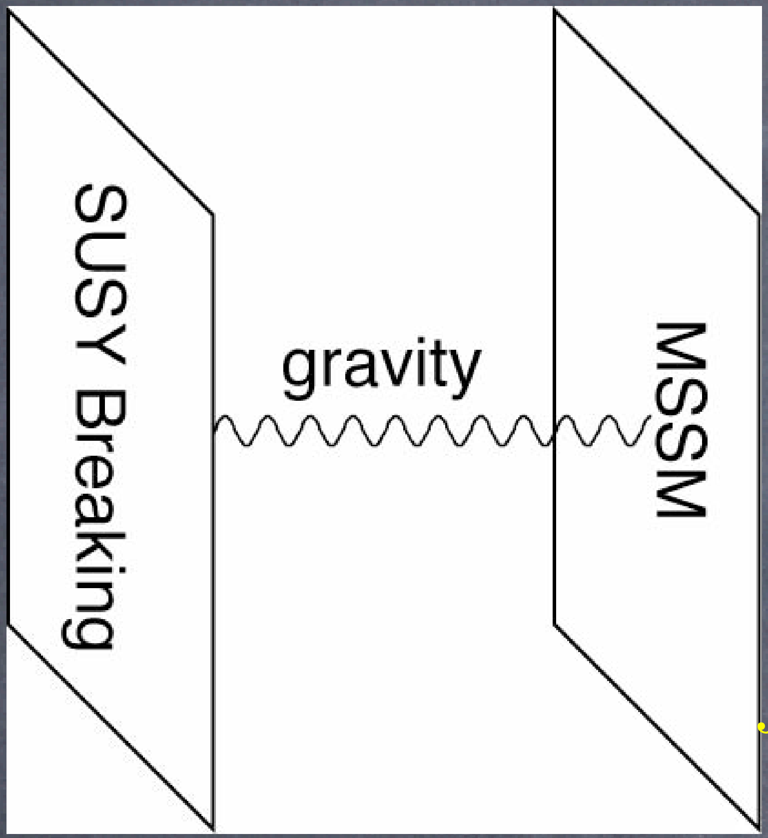
Gaugino Mediation (χMSB)



- DSB in another brane
- Gauge multiplet in the bulk
- Gauge multiplet learns SUSY breaking first, obtains gaugino mass
- MSSM at the compactification scale with gaugino mass only
- Scalar masses generated by RGE

Kaplan, Kribs, Schmaltz
Chacko, Luty, Nelson, Ponton

Anomaly Mediation (AMSB)



- no direct coupling between two sectors
- Supersymmetry breaking in the chiral compensator $\langle S \rangle = 1 + \theta^2 m_{3/2}$

$$\int d^4\theta S\bar{S}\phi^*\phi + \int d^2 \left(S^3 \lambda_{ijk}\phi_i\phi_j\phi_k + \frac{1}{g^2} W_\alpha W^\alpha \right)$$

- can be scaled away $\phi \to \phi/S$
- but the UV cutoff acquires S: $\Lambda_{UV} \to \Lambda_{UV} S$
- SUSY breaking through cutoff dependence: superconformal anomaly

Randall, Sundrum
Giudice, Luty, HM, Rattazzi

UV insensitivity

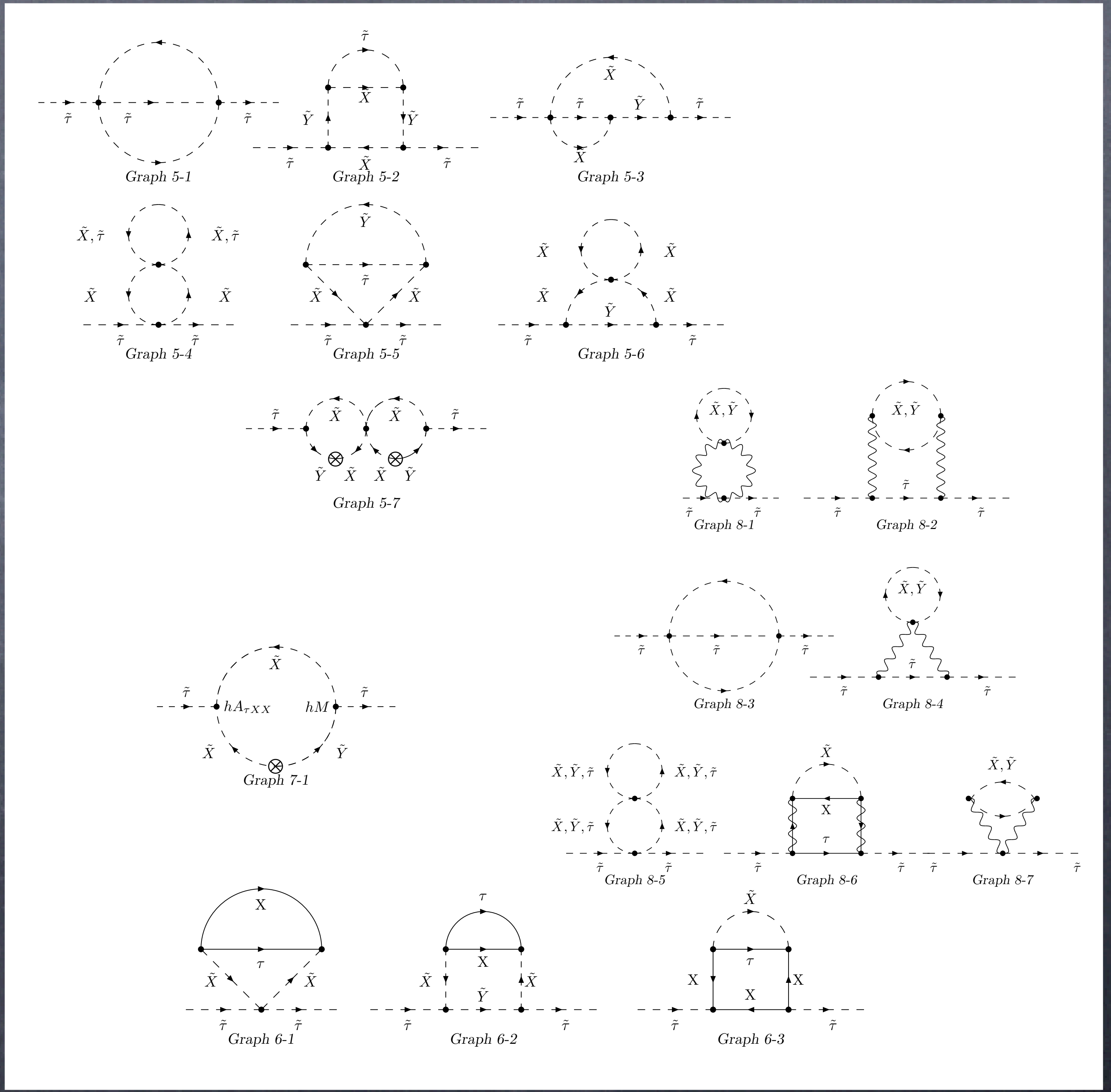
$$M_i = -\frac{\beta_i(g^2)}{2g_i^2} m_{3/2}, \quad m_i^2 = -\frac{\dot{\gamma}_i}{4} m_{3/2}^2, \quad A_{ijk} = -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k) m_{3/2}$$

- Surprising result: depends only on physics at the energy scale of interest
- No matter how complicated the UV physics is, including flavor physics with O(1) generation-dependent couplings, they all disappear from low-energy soft SUSY breaking
- e.g., decouple a massive matter field:
  - Changes the beta function
  - one-loop threshold correction precisely account for the change in gaugino mass

UV insensitivity cont.

- decouple a massive matter field
- two-loop threshold correction precisely account for the change in the anomalous dimension and hence the scalar mass

$$
\begin{aligned}
m_i^2 &= -\frac{\dot{\gamma}_i}{4} m_{3/2}^2, \\
A_{ijk} &= -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k) m_{3/2}
\end{aligned}
$$

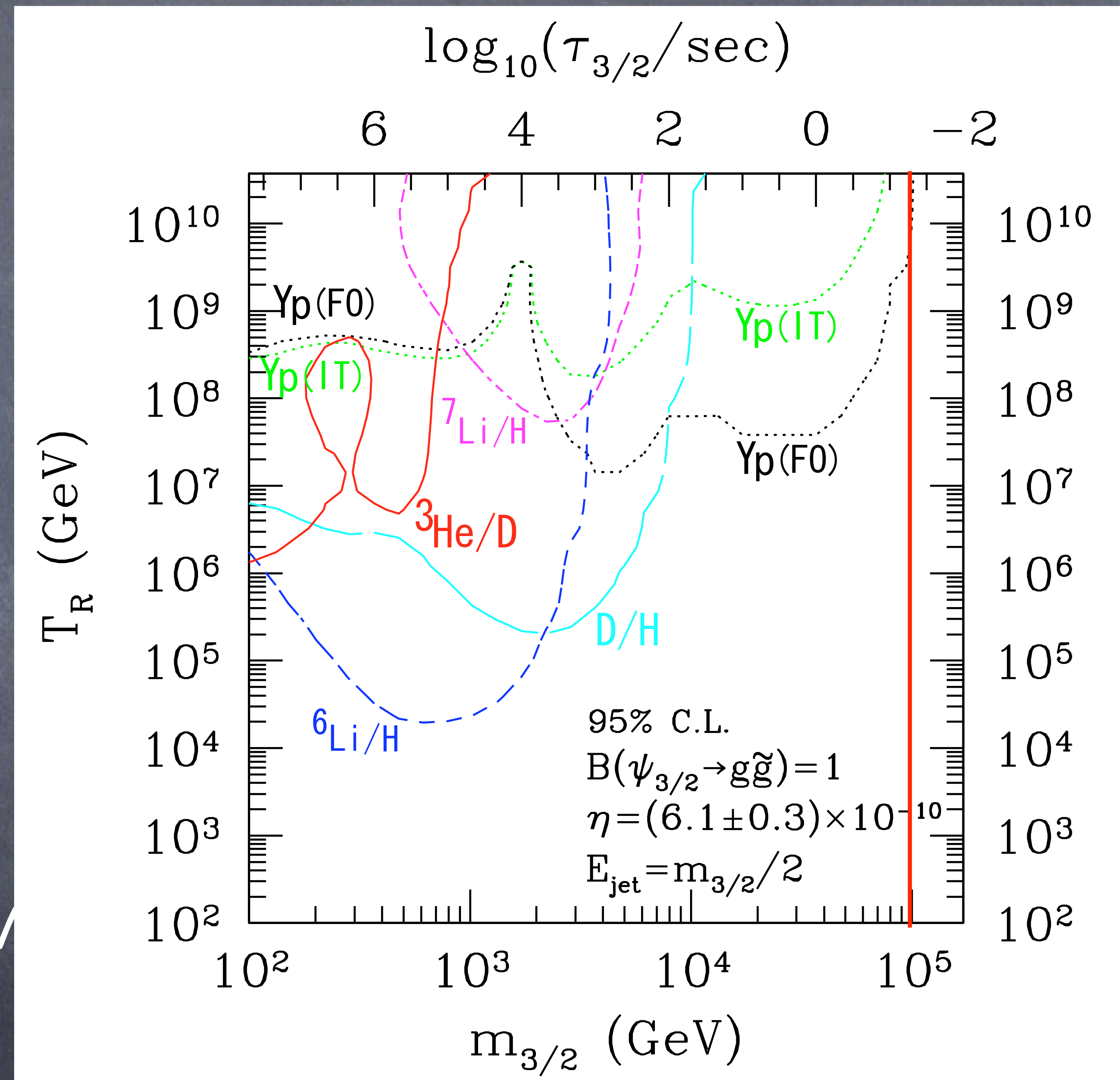


Gravitino OK

- Anomaly mediation with D-terms
- UV insensitive: solves flavor and CP problems no matter how complicated the UV physics is
- solves gravitino problem because

$m_{3/2} \sim (4\pi)^2 m_{SUSY} \sim 50\text{TeV}$

- moduli absent by



Kohri, Kawasaki, Moroi

What's the catch?

- Two problems
- negative slepton mass-squared
- can't have a light bulk moduli of $m \sim O(m_{3/2})$

cause additional terms of $O(m_{3/2}^2/m) \sim O(m_{3/2})$

- common fixes:
  - add m_0^2
  - add D_Y and D_{B-L}

$$
\begin{aligned}
m^2_{\tilde{l}} &= -0.344 M^2, \\
m^2_{\tilde{e}^c} &= -0.367 M^2, \\
m^2_{\tilde{q}} &= 11.6 M^2, \\
m^2_{\tilde{u}^c} &= 11.7 M^2, \\
m^2_{\tilde{d}^c} &= 11.8 M^2, \\
M &= \frac{m_{3/2}}{(4\pi)^2}
\end{aligned}
$$

fixing moduli

(Kachru, Kallosh, Linde, Trivedi)

- Use RR and NSNS anti-symmetric tensor fluxes on compactified space
- Fix complex structure moduli by fluxes
- Long throat in AdS (i.e. warped)
- Break SUSY with anti-D3 down the throat
- Kähler modulus with gaugino condensate?
- No SUSY breaking@tree-level (Camara, Ibañez, Uranga) in the "bulk"
- often Kähler moduli and anomaly mediated contribution comparable (Choi et al)
- can fix negative slepton mass-squared

Purely 4D "Conformal sequestering"

- You can replace the bulk (AdS) by a conformal field theory (CFT) in 4D
- Theory flows to an infrared fixed point where unwanted scalar mass operator vanishes (Luty, Sundrum)
- Effectively realizes physical separation with a bulk
- Again use SUSY QCD with a sufficiently large number of flavors $\frac{3}{2}N_c < N_f < 3N_c$ with gauged $SU(N_f)$ symmetry (Schmaltz, Sundrum)

SUSY spectra