Supersymmetry, and its breaking

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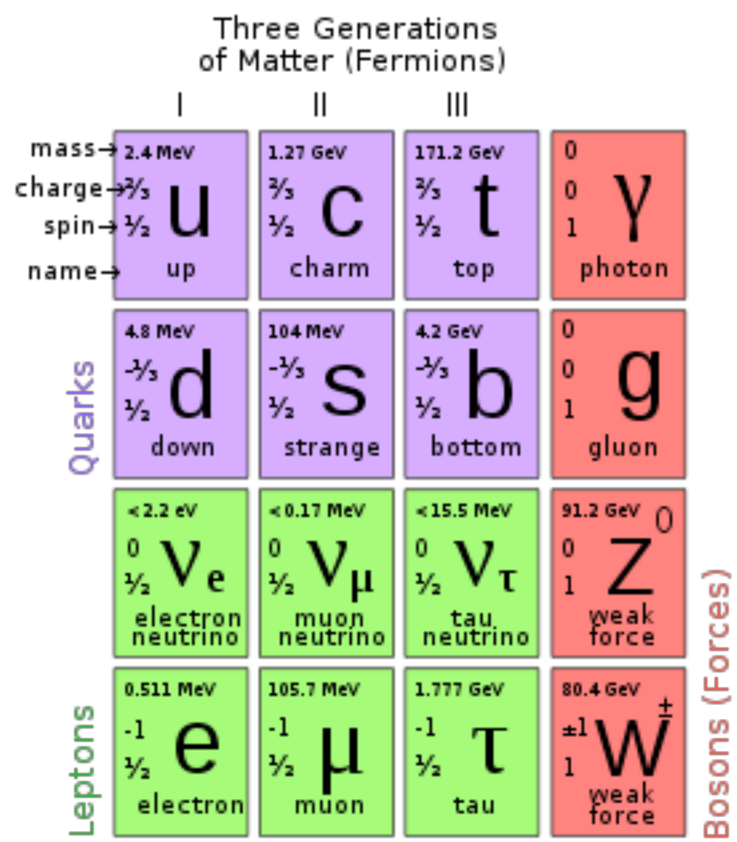
Outline

- General ideas and SUSY review
- Pheno summary, the MSSM, NMSSM
- The idea of mediation
- ISS metastable SUSY breaking (and Seiberg duality)
- Cosmological/thermal properties of ISS
- Phenomenological properties - two theorems and three models
- Phenomenological study of Gauge Mediation at LHC
- Deconstructed gauge mediation and Dirac gaugino models
- The Landau pole problem

General ideas: SUSY review

General ideas:



$$\mathcal{L} \supset \lambda_u q h u^c + \lambda_d q \tilde{h} d^c \ldots$$

$$m_u \sim \lambda_u \langle h \rangle$$

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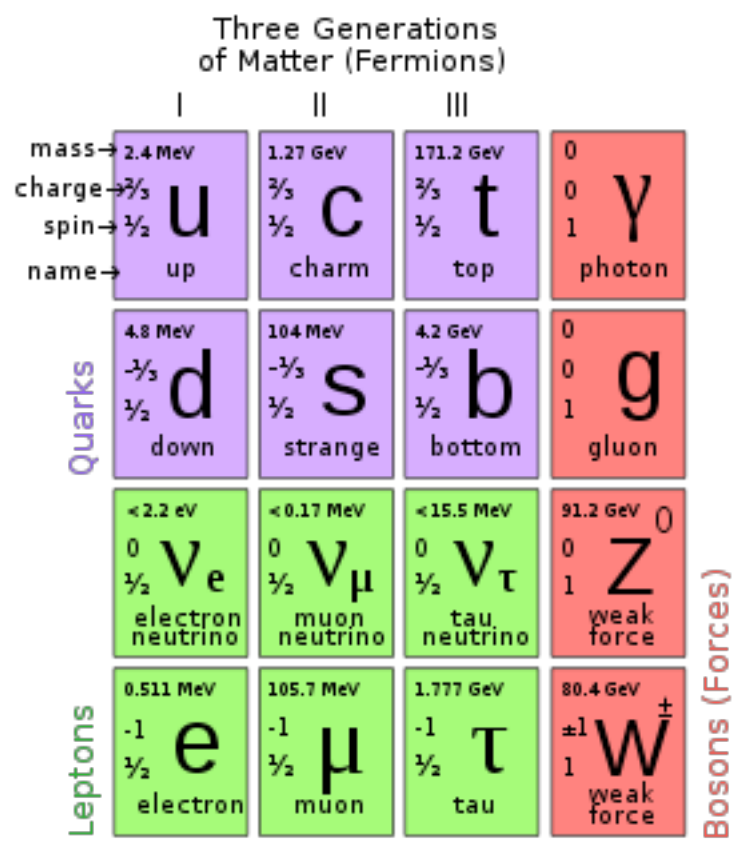

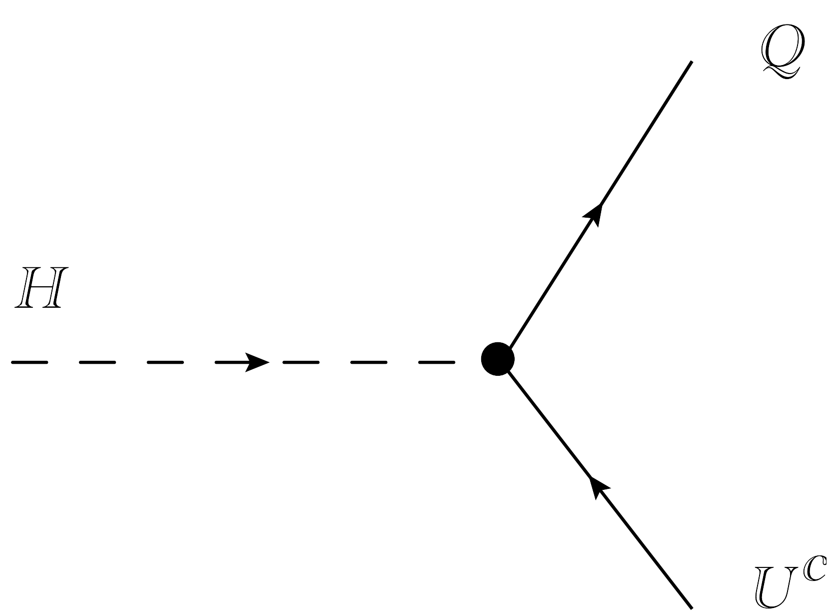

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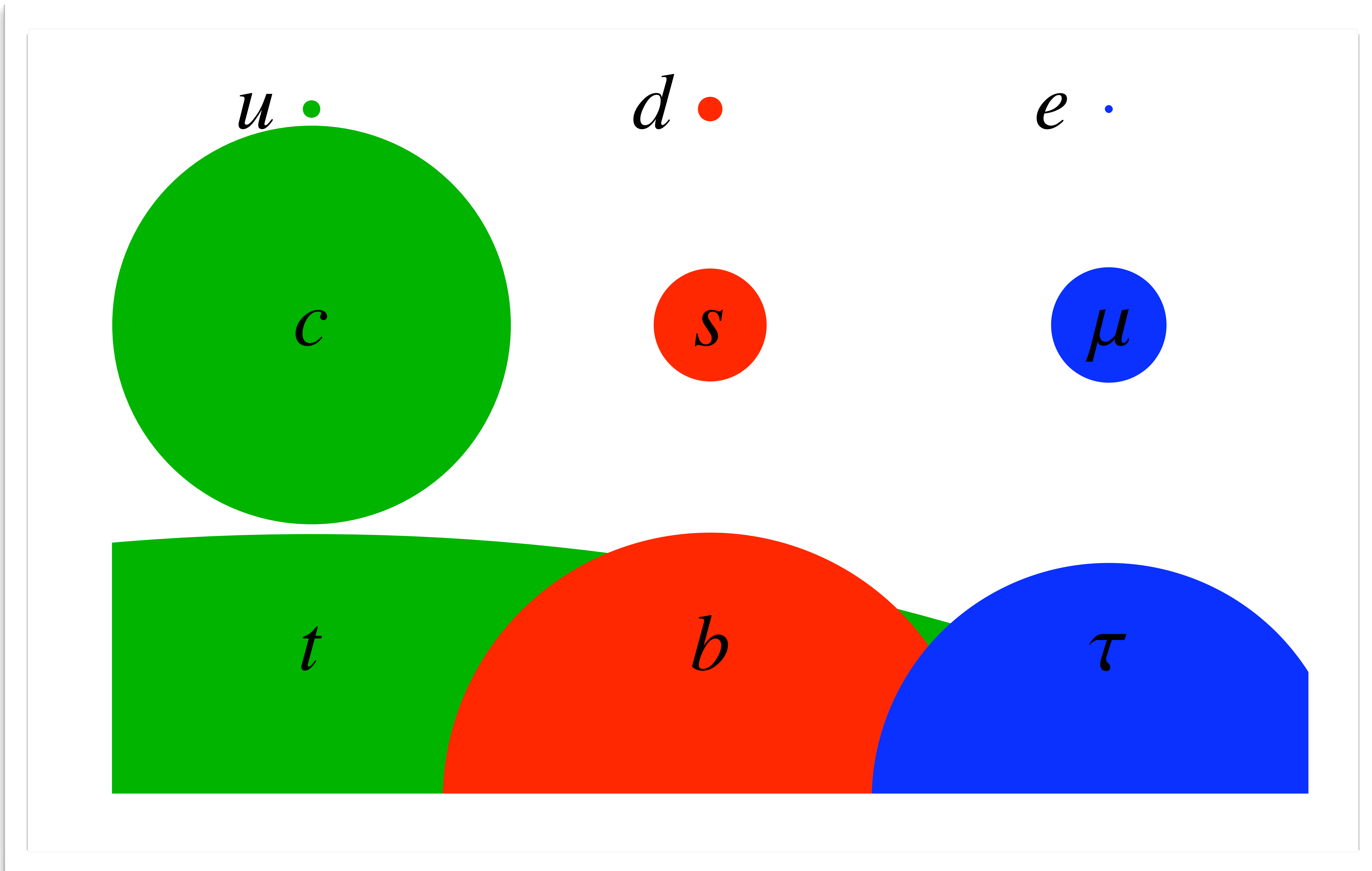

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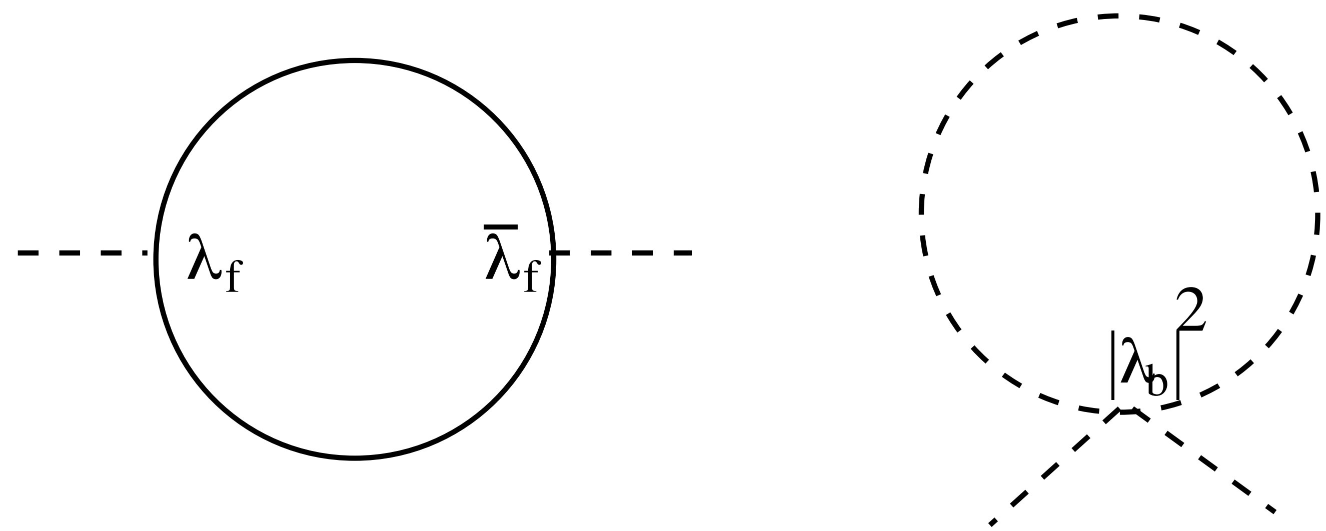
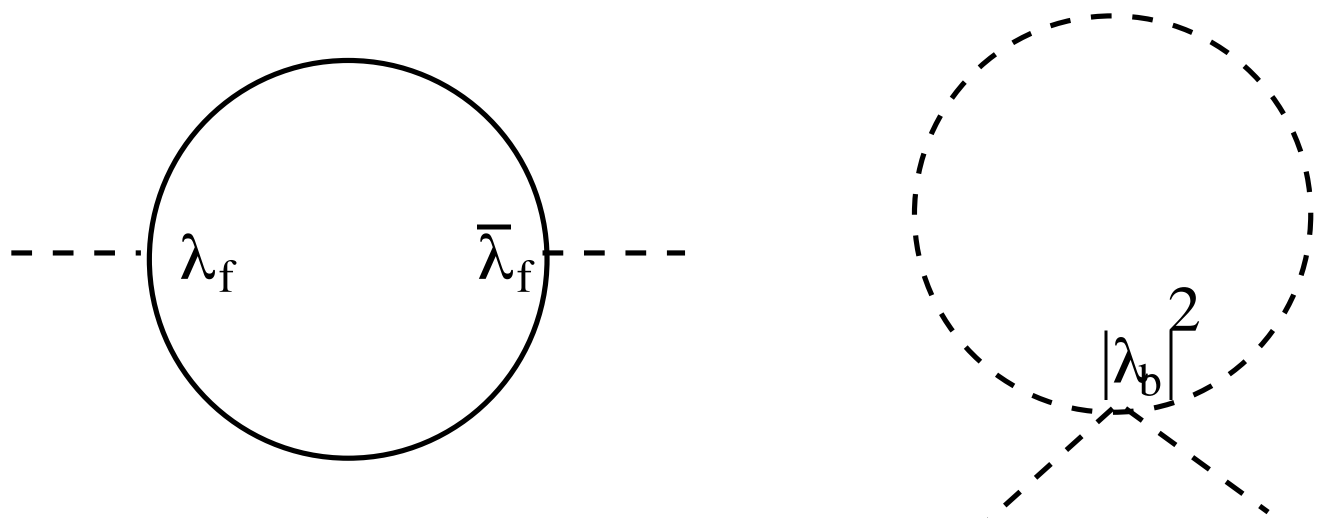


$$\delta V_{higgs} \sim (|\lambda_b|^2 - |\lambda_f|^2) H^2 \Lambda^2.$$

General ideas:

Hierarchy problem: higgs couples to scalars as well as quarks: then



$$\delta V_{higgs} \sim (|\lambda_b|^2 - |\lambda_f|^2)H^2\Lambda^2.$$

But Yukawas will run like logarithmically. Have to arrange precise cancellation around the weak scale - ***or a new symmetry thats sets the two couplings equal***.

General ideas:

$$\delta_\xi \phi = a\xi^\alpha \chi_\alpha.$$

$$\delta_\xi \chi^\alpha = b\sigma^\mu_{\alpha\dot{\alpha}}\overline{\xi}^{\dot{\alpha}}\partial_\mu \phi + c\xi^\alpha F.$$

$$\delta_\xi F = d\overline{\xi}_{\dot{\alpha}}\overline{\sigma}^{\mu\dot{\alpha}\alpha}\partial_\mu \chi_\alpha.$$

General ideas:

Require a transformation turning bosons into fermions

$$\delta_\xi \phi = a\xi^\alpha \chi_\alpha.$$

By spin and dimensions the fermion can only transform as

$$\delta_\xi \chi^\alpha = b\sigma^\mu_{\alpha\dot{\alpha}} \overline{\xi}^{\dot{\alpha}} \partial_\mu \phi + c\xi^\alpha F.$$

where F is some field of spin 0 and dimension 2 which can transform as

$$\delta_\xi F = d\overline{\xi}_{\dot{\alpha}} \overline{\sigma}^{\mu\dot{\alpha}\alpha} \partial_\mu \chi_\alpha.$$

General ideas:

$$[\delta_\xi, \delta_\eta]\varphi = ab(\eta\sigma^\mu\overline{\chi} - \chi\sigma^\mu\overline{\eta})\partial_\mu\varphi$$

$$[\delta_\xi, \delta_\eta]\chi = cd(\eta\sigma^\mu\overline{\chi} - \chi\sigma^\mu\overline{\eta})\partial_\mu\chi$$

So ab=cd.

Invariance of the Kinetic Lagrangian $L_{KE} = -i\chi\sigma^\mu\partial_\mu\overline{\chi} - \partial^\mu\varphi^*\partial_\mu\varphi + F^*F$
sets $b = ia;\ d = ic$

$$\left(\begin{array}{rcl} \sigma^\mu &=& (I, \sigma^i) \\ \overline{\sigma}^\mu &=& (I, -\sigma^i) \\ \sigma^{\mu\nu} &=& \frac{i}{4}(\sigma^\mu\overline{\sigma}^\nu - \sigma^\nu\overline{\sigma}^\mu) \end{array} \right)$$

General ideas:

Exercise - determine a,b,c,d:

$$[\delta_\xi, \delta_\eta]\varphi = ab(\eta\sigma^\mu\overline{\chi} - \chi\sigma^\mu\overline{\eta})\partial_\mu\varphi$$

$$[\delta_\xi, \delta_\eta]\chi = cd(\eta\sigma^\mu\overline{\chi} - \chi\sigma^\mu\overline{\eta})\partial_\mu\chi$$

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General ideas:

Chiral superfields:

to get *interactions* consider a large SUSY transformations of the boson: another exercise (introduces idea of superspace)

$$\begin{aligned}\Phi &= e^{\delta_\theta}\,\varphi \\ &= (1+\delta_\theta+\tfrac{1}{2!}\delta_\theta^2+\ldots)\varphi(x) \\ &= \varphi(y)+\sqrt{2}\theta\chi(y)+\theta\theta F(y)\end{aligned}$$

where $y^\mu = x^\mu + i\theta\sigma^\mu\overline{\theta}.$

Hence the components of any *function* of $\Phi(\theta, y)$ transform as the components of $\Phi(\theta, y)$ did themselves.

General ideas:

Superpotential:

Notice that the F-term transformed under SUSY as a total derivative. Hence take any function of chiral superfields W, and write

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

Example: top Yukawa

The desired effect

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

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

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

General ideas:

Kahler potential:

More generally can define Kinetic terms with 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 1: from now on often use same symbol for superfield and its scalar component!!!

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Alert 1: from now on often use same symbol for superfield and its scalar component!!!

Alert 2: Note that $\Big|_{\theta^2} = \int d^2\theta$

General ideas:

Vector superfields: $(A_\mu^a, \lambda_\alpha^a, D^a)$

in a similar fashion can gauge interactions - also get superpartner interactions

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{\text{chiral}} + \mathcal{L}_{\text{gauge}} \\
&\quad -\sqrt{2}g(\phi^* T^a \psi)\lambda^a - \sqrt{2}g\lambda^{\dagger a}(\psi^\dagger T^a \phi) + g(\phi^* T^a \phi)D^a.
\end{aligned}
$$

General ideas:

Field-strength superfield:

Like the chiral superfield but start by SUSY transformations on the gaugino ...

$$W_\alpha^a = -i\lambda_\alpha^a(y) + \theta_\alpha D^a(y) - (\sigma^{\mu\nu}\theta)_\alpha F_{\mu\nu}^a(y) - (\theta\theta)\sigma^\mu D_\mu \lambda^{a\dagger}(y)$$

Holomorphic gauge coupling ... $\tau \equiv \frac{\theta_{\rm YM}}{2\pi} + \frac{4\pi i}{g^2}$

$$S_{gauge} = \frac{1}{16\pi i}\int d^4x \int d^2\theta \, \tau \, W_\alpha^a W_\alpha^a + h.c.$$

$$= \int d^4x \left[-\frac{1}{4g^2} F^{a\mu\nu} F_{\mu\nu}^a - \frac{\theta_{\rm YM}}{32\pi^2} F^{a\mu\nu} \widetilde{F}_{\mu\nu}^a + \frac{i}{g^2} \lambda^{a\dagger} \overline{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2g^2} D^a D^a \right]$$

General ideas:

Renormalization-group running:

$$\mu \frac{dg}{d\mu} = -\frac{b}{16\pi^2} g^3 \quad \Rightarrow \quad \frac{1}{g^2(\mu)} = -\frac{b}{8\pi^2} \ln\left(\frac{|\Lambda|}{\mu}\right)$$

e.g. for SU(N) with F_Q flavours have $b = 3N - F_Q$

So that at one loop the holomorphic gauge coupling looks like

$$\tau_{1-\text{loop}} = \frac{b}{2\pi i} \ln\left(\frac{\Lambda}{\mu}\right)$$

where we define a holomorphic dimensional transmutation scale

$$\begin{aligned} \Lambda &\equiv |\Lambda| e^{i\theta_{\text{YM}}/b} \\ &= \mu e^{2\pi i \tau/b} \ , \end{aligned}$$

Lightning pheno summary

Lightning pheno summary

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 MSSM

For the SM Yukawa couplings need a second higgs and Superpotential

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

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The NMSSM

For the SM Yukawa couplings need a second higgs and Superpotential

$$W = \lambda_u Q H_u U^c + \lambda_d Q H_d D^c + \lambda_e L H_d E^c + \lambda S H_u H_d + \kappa S^3$$

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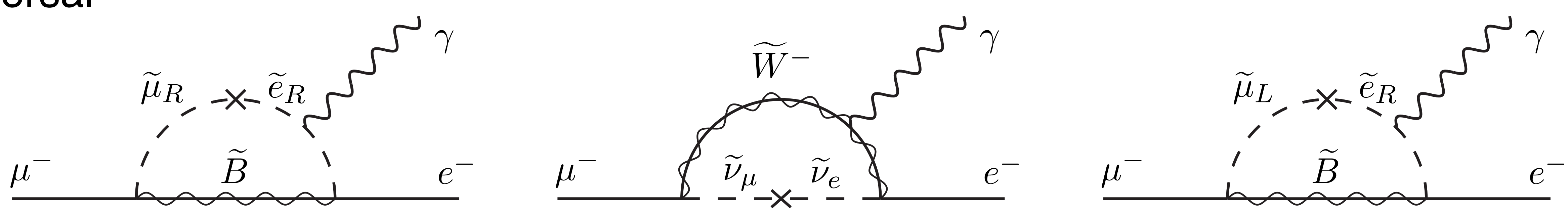
Soft supersymmetry breaking

How can we make sure we don't lose the cancellation of divergences?
Allow only dimensionful (soft) supersymmetry breaking (talk later about how this comes about)

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

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



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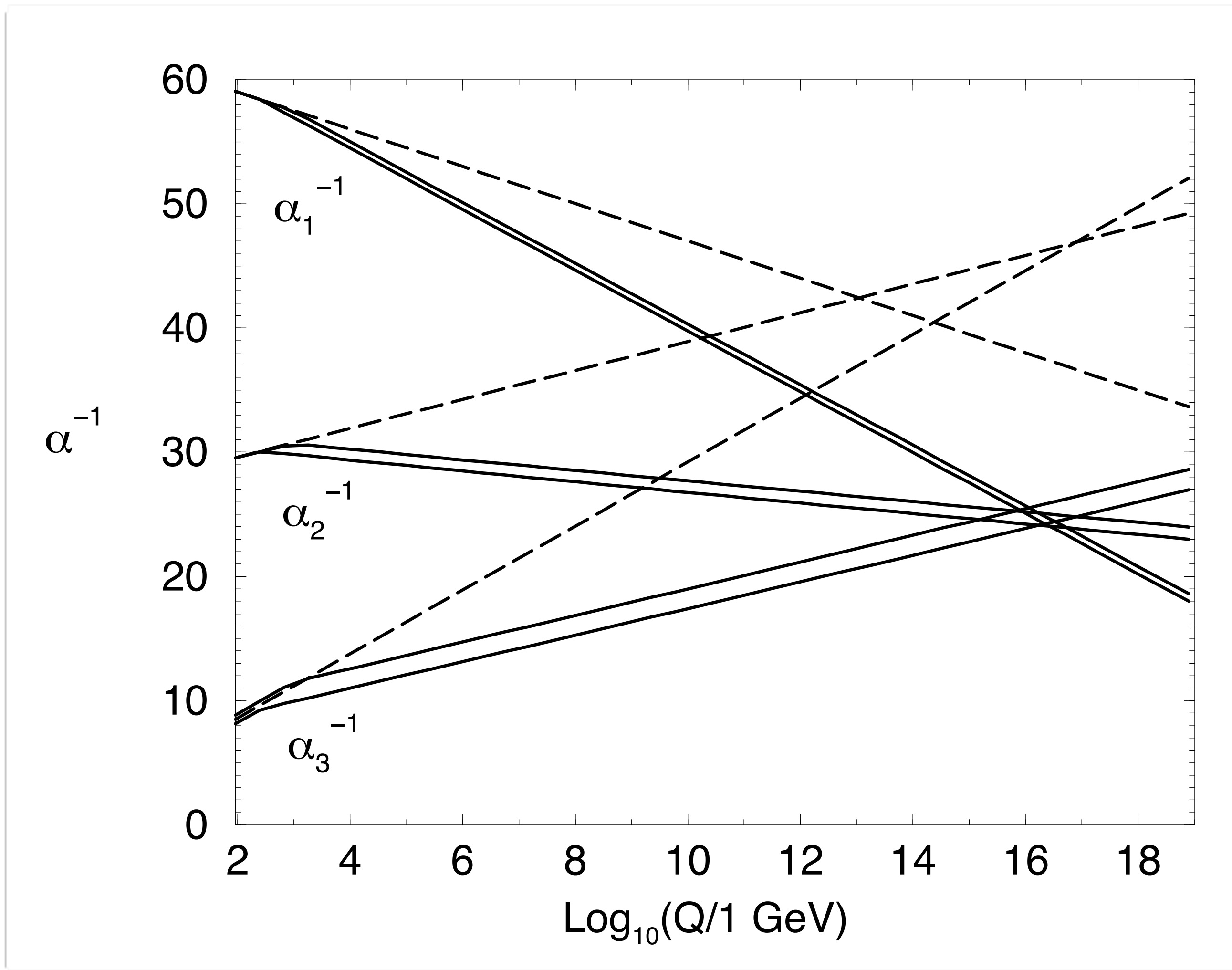
Soft supersymmetry breaking

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



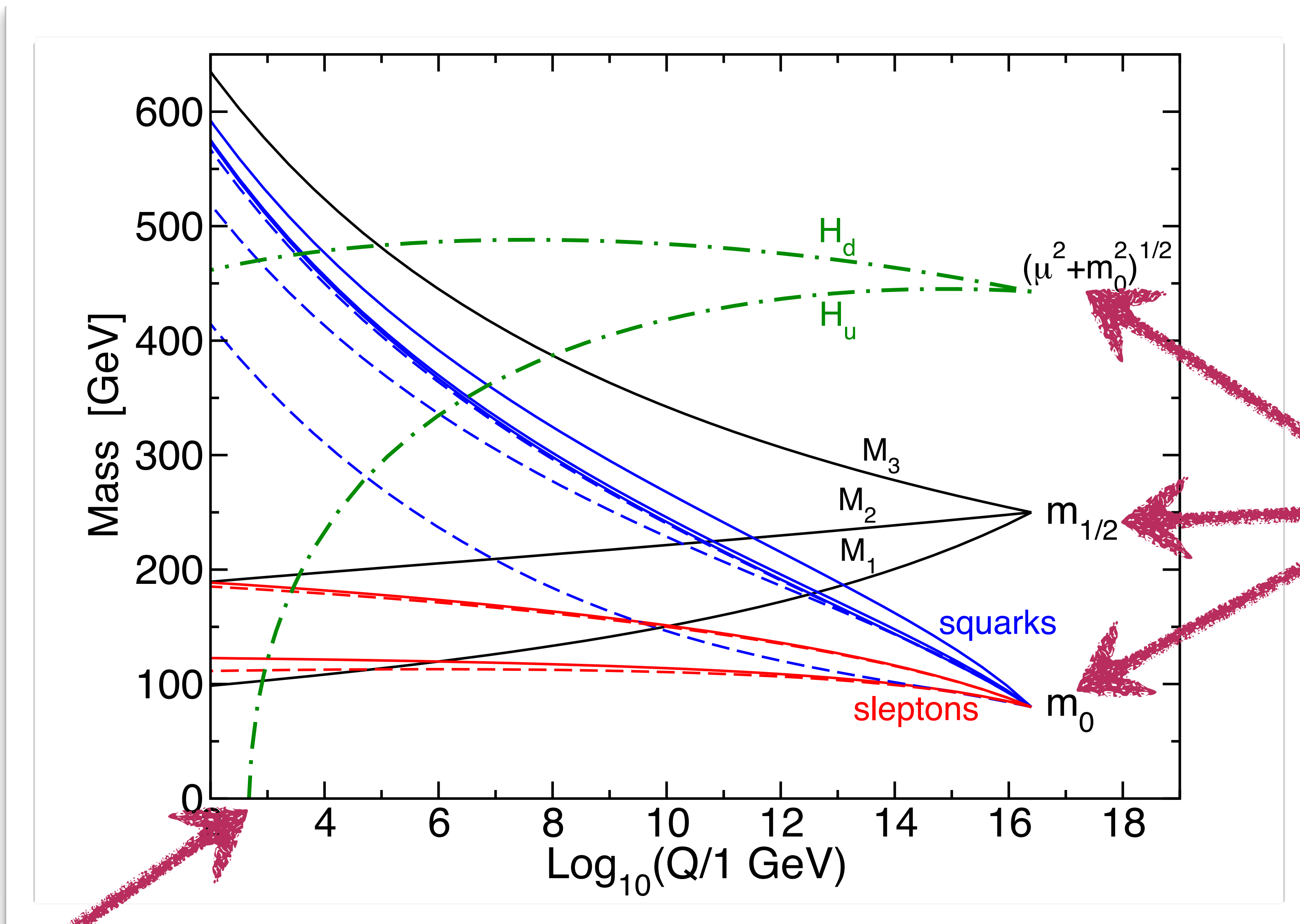
$$\frac{d}{dt}\alpha_a^{-1} = -\frac{b_a}{2\pi}$$

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

Lightning pheno summary

Soft supersymmetry breaking

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



This is the Constrained MSSM (CMSSM)

Ibanez+Ross

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Usually trade Higgs VEVs after EWSB to end up with 4 free parameters in CMSSM so we have $\tan\beta \equiv v_u/v_d$ where $v_u = \langle H_u^0 \rangle, v_d = \langle H_d^0 \rangle$ and free parameters

$$\tan\beta,\ A_0,\ m_0,\ m_{1/2}$$

$$v_u^2 + v_d^2 = v^2 = 2m_Z^2/(g^2 + g'^2) \approx (174\ \mathrm{GeV})^2$$

$$\begin{aligned} \sin(2\beta) &= \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2}, \\ m_Z^2 &= \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2 \end{aligned}$$

Lightning pheno summary

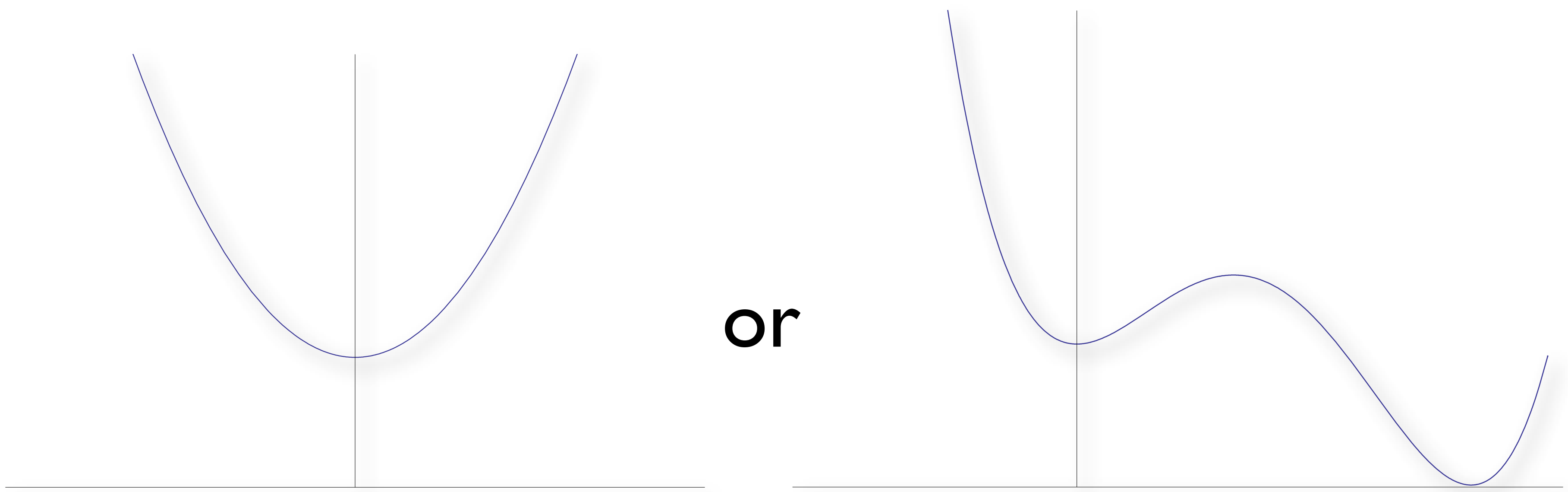
Physical spectrum (mass eigenstates) comes from a mixture of the gauge eigenstates:

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)

The idea of mediation

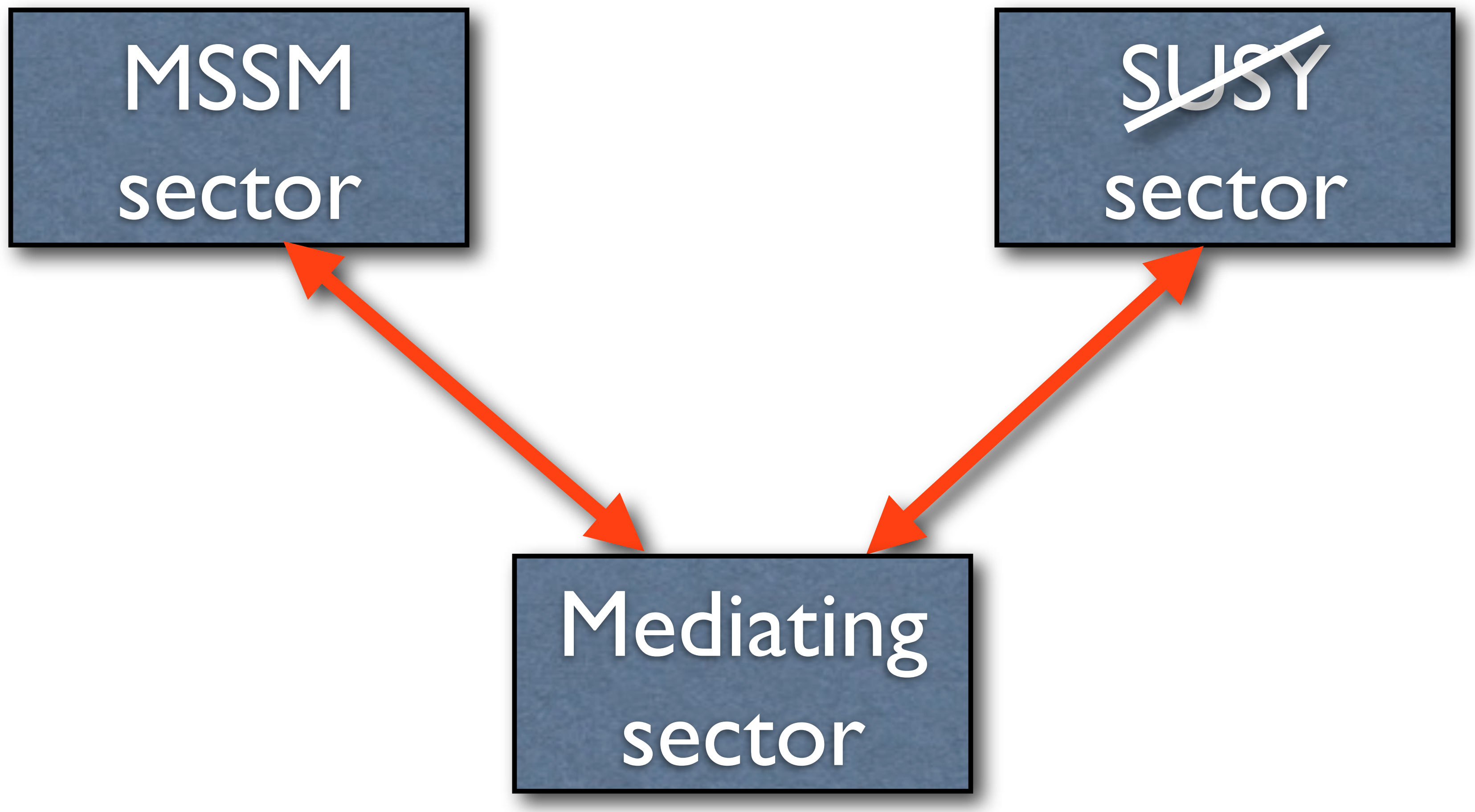
The idea of mediation:

Assume SUSY is broken in a non-MSSM sector:



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

The idea of mediation:

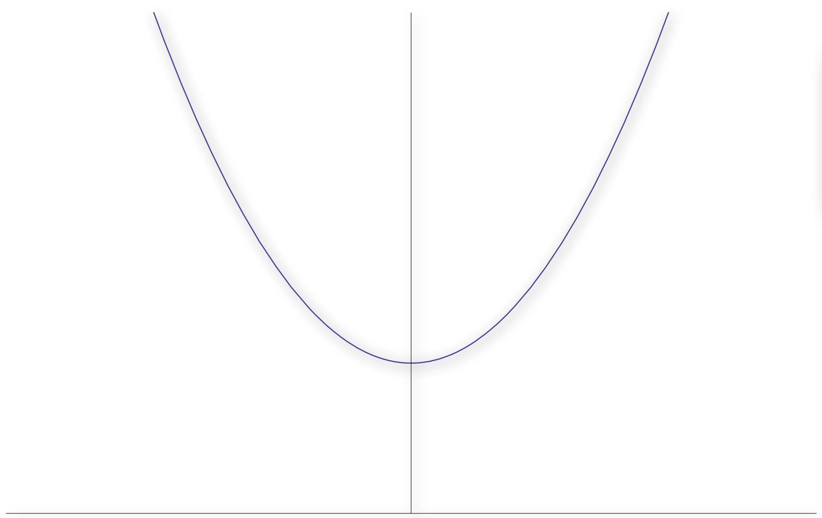


Supertrace sum rules (Dimopoulos Georgi) mean breaking in visible sector difficult
Mediating sector can be ***gauge, gravity***, anomaly etc

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

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 φ_2, φ 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:

Gravity mediation: suppose that the Kahler potential has Planck suppressed operators and that this is the only sort of coupling to a ***hidden*** SUSY breaking sector with non-zero F-terms:

$$K \supset \frac{\varphi\varphi^\dagger}{M_P^2}\varphi_{vis}\varphi_{vis}^\dagger$$

$$\mathcal{L}_{KE} = K(\Phi_i, \bar{\Phi}^j)|_{\theta^2\bar{\theta}^2} \supset \frac{|F_\varphi|^2}{M_P^2}\varphi_{vis}\varphi_{vis}^\dagger$$

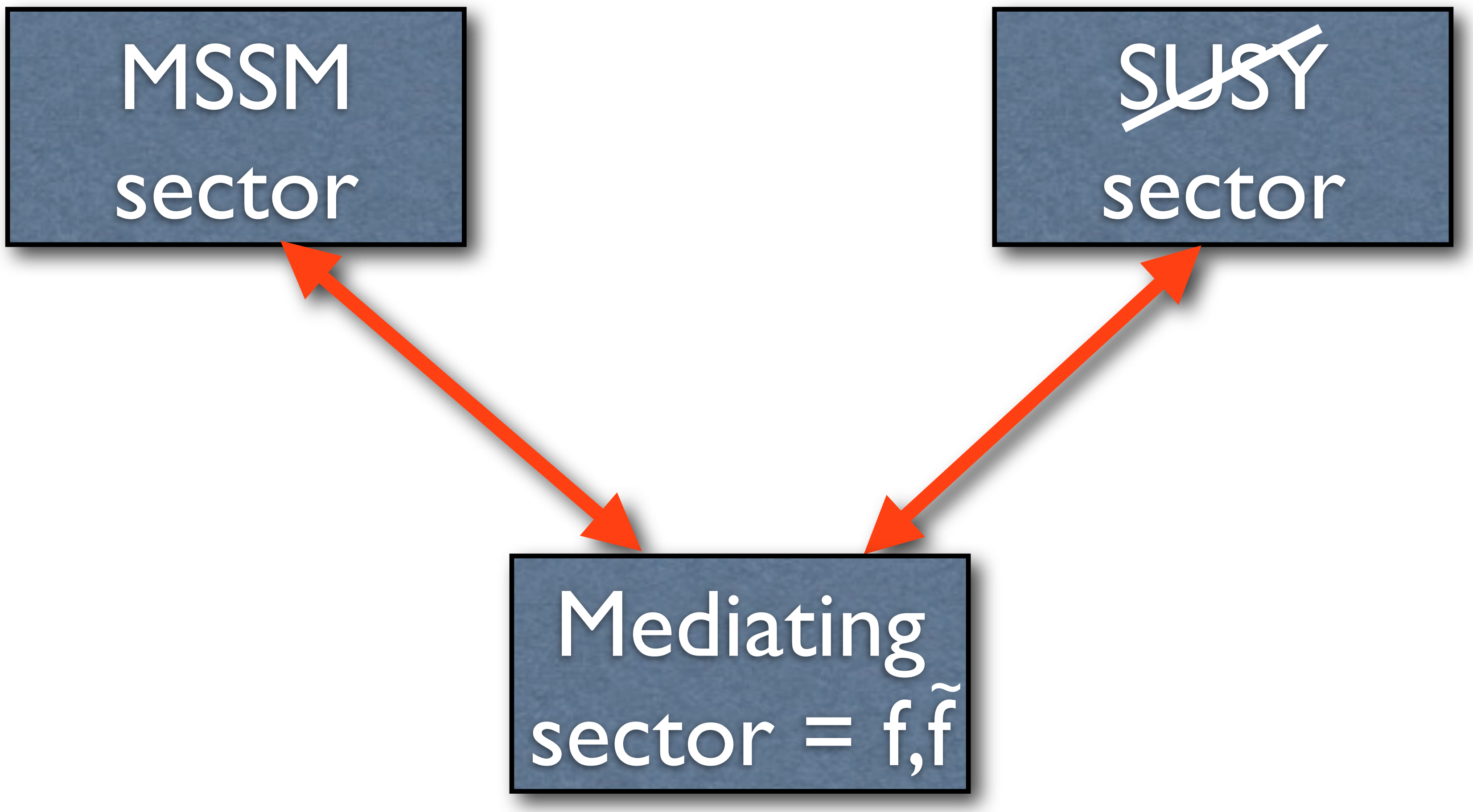
So if $F_\varphi \sim m_W M_P$ then have scalar masses of order m_W

Moreover $K \supset \frac{\varphi^\dagger}{M_P}H_u H_d + \frac{\varphi\varphi^\dagger}{M_P^2}H_u H_d + h.c.$

give mu and B terms of order m_W . (Giudice, Masiero mechanism)

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

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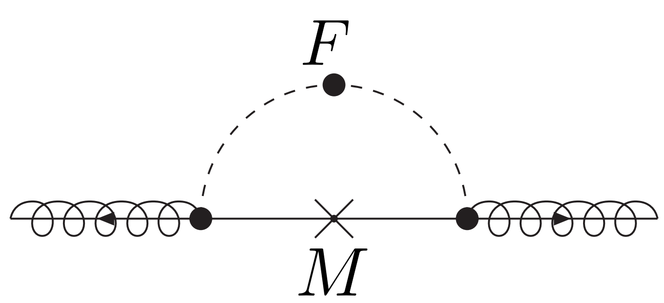
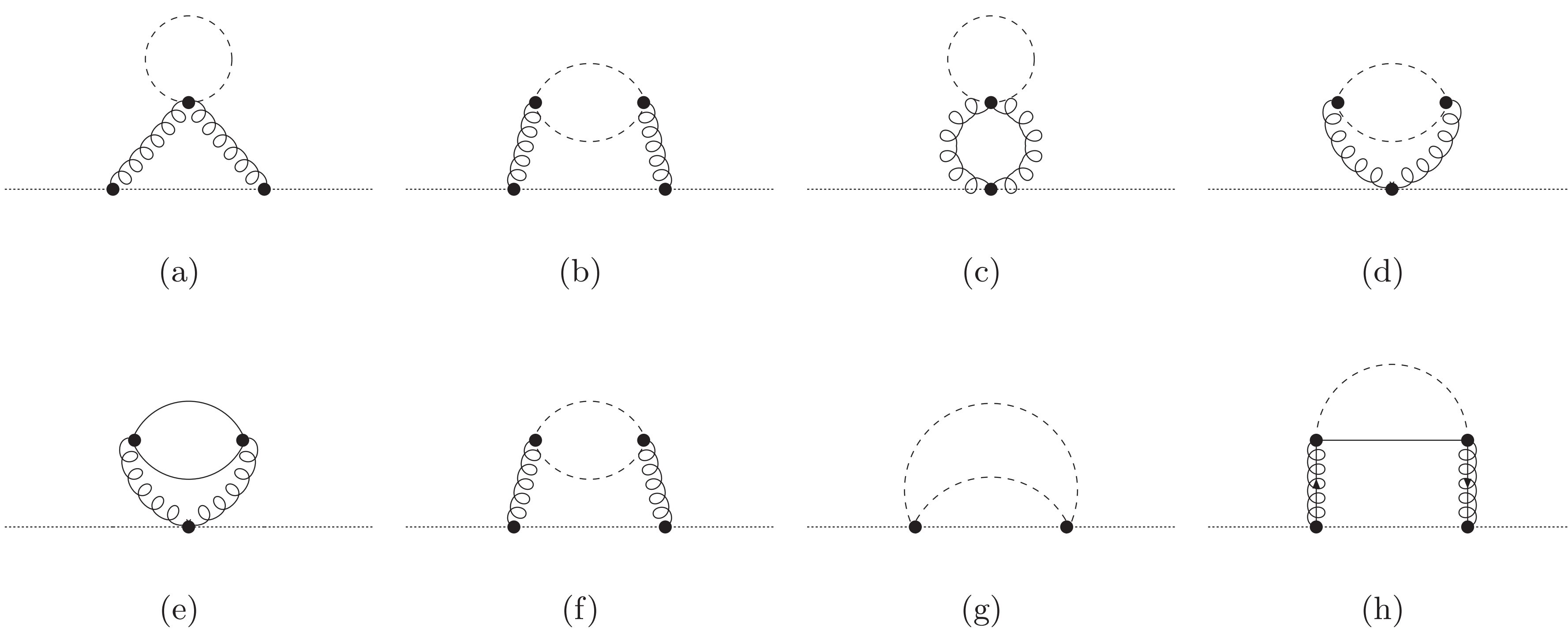


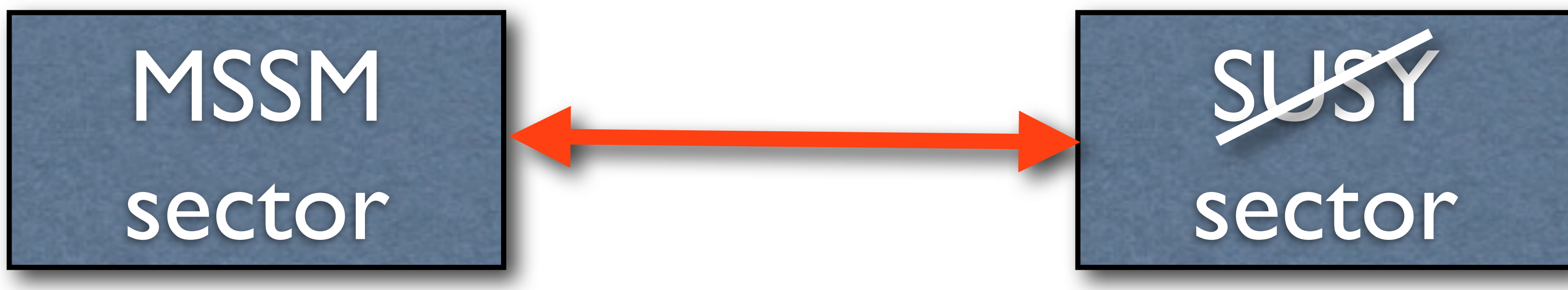
$$M_{\tilde{\lambda}_i} = k_i \frac{\alpha_i}{4\pi} \frac{F}{M}$$

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



The idea of mediation:

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)

The idea of mediation:

Maede, Seiberg, Shih, 2008

General Gauge mediation: suppose strong coupling enters the story. What can we say?

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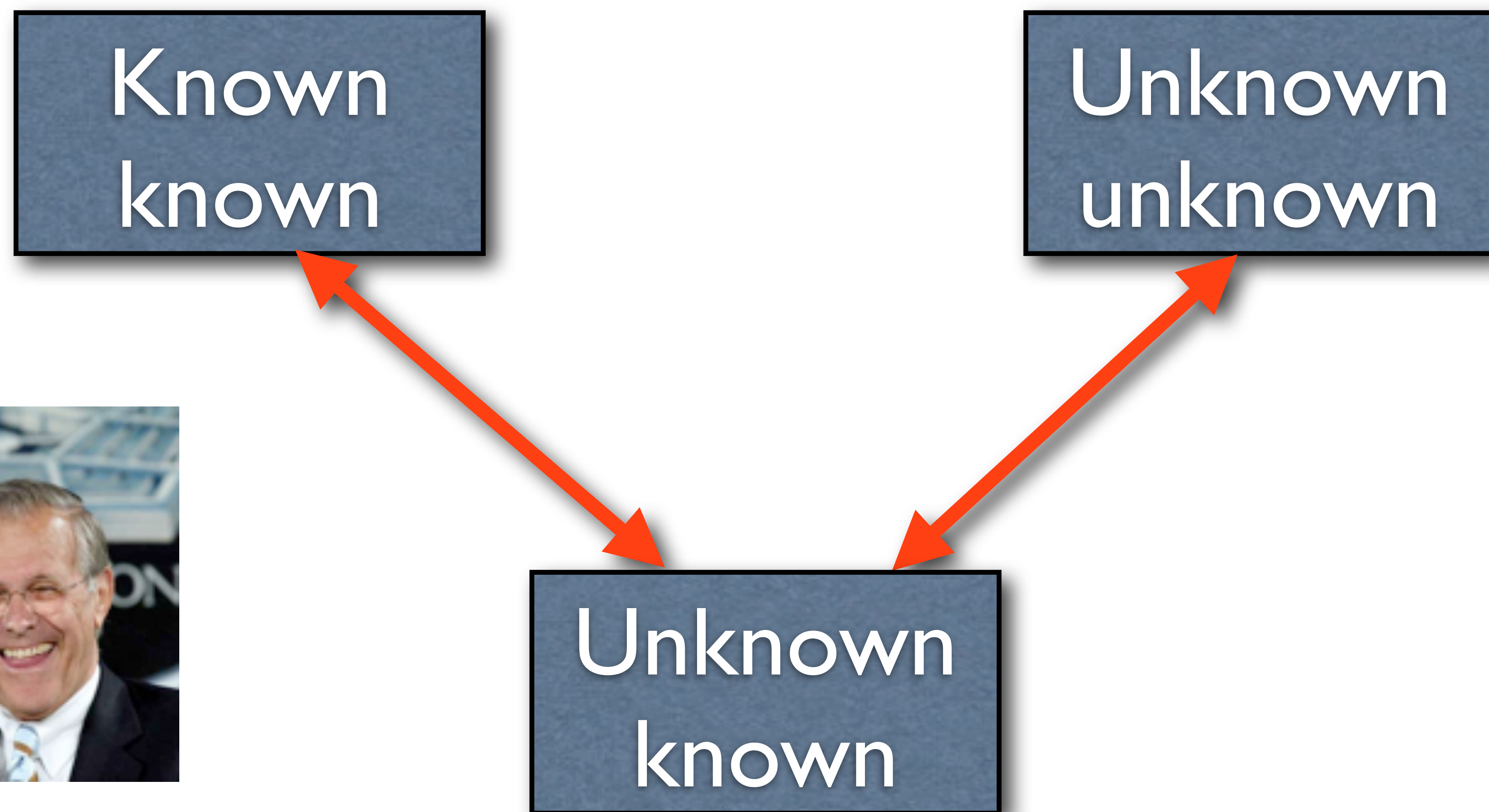


Only constrained by the requirement that the MSSM becomes decoupled from SUSY breaking sector when $\alpha_1 = \alpha_2 = \alpha_3 = 0$

The idea of mediation:

Maede, Seiberg, Shih, 2008

General Gauge mediation: suppose strong coupling enters the story. What can we say?

- The possible patterns of SUSY breaking (in the MSSM) can be completely determined by 6 combinations of gauge current correlators: sum rules

$$m_Q^2 - 2m_U^2 + m_D^2 - m_L^2 + m_E^2 = 0$$

$$2m_Q^2 - m_U^2 - m_D^2 - 2m_L^2 + m_E^2 = 0$$

- But what patterns are likely?
- What underlying physics is associated with each pattern?
- Clear objective: strategy for GMSB phenomenology at early LHC?

Summary of Questions:

- How hidden is hidden? Does SUSY breaking itself influence phenomenology?
- Direct mediation is clearly completely different for example - why?
- What underlying physics gives rise to what patterns?
- Clear objective: strategy for GMSB phenomenology at early LHC?

To help us answer these questions now turn to a simple dynamical model of (metastable) SUSY breaking (ISS)

ISS metastable SUSY breaking

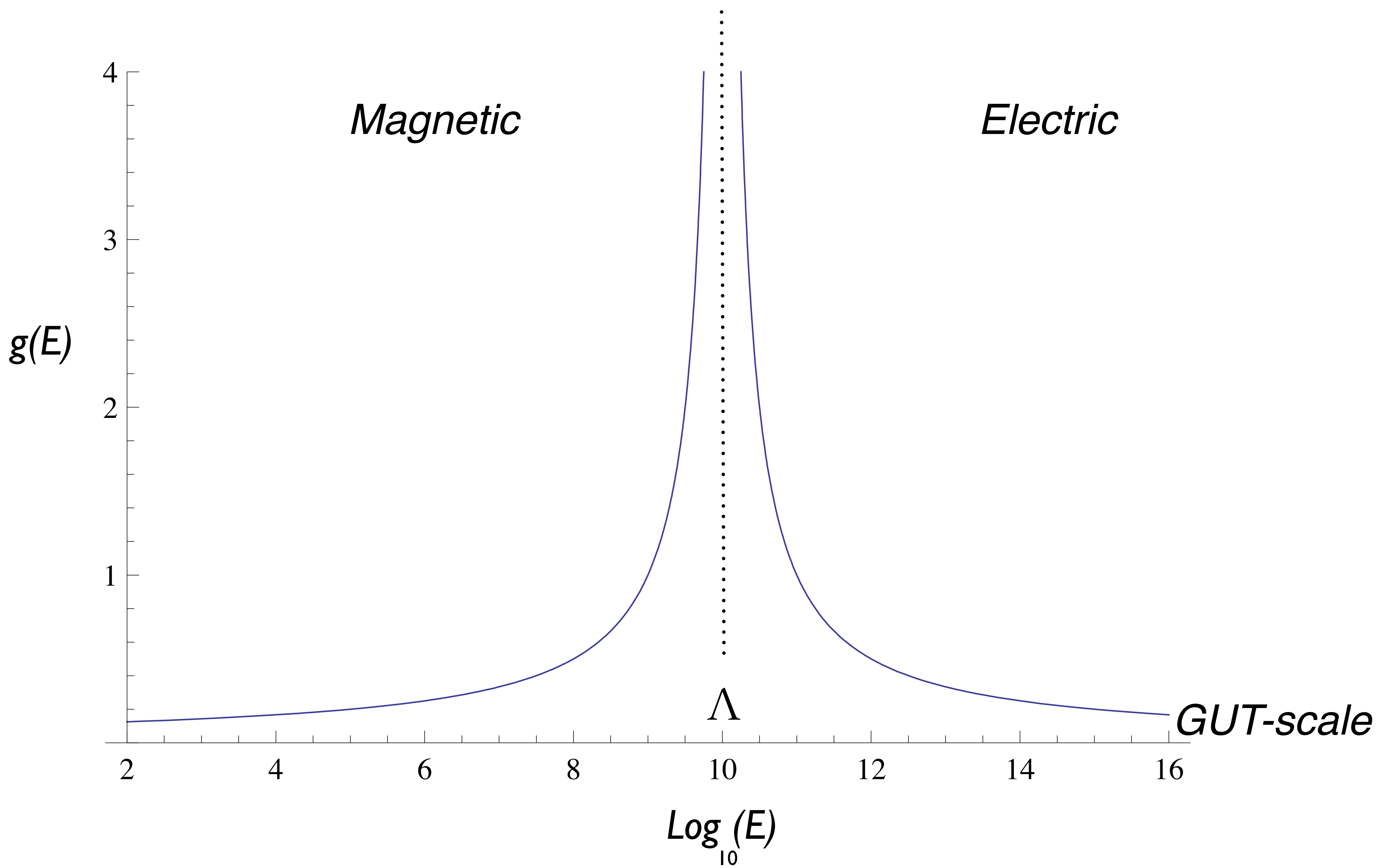
Based on ***Seiberg duality***: the electric model consists of ...

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

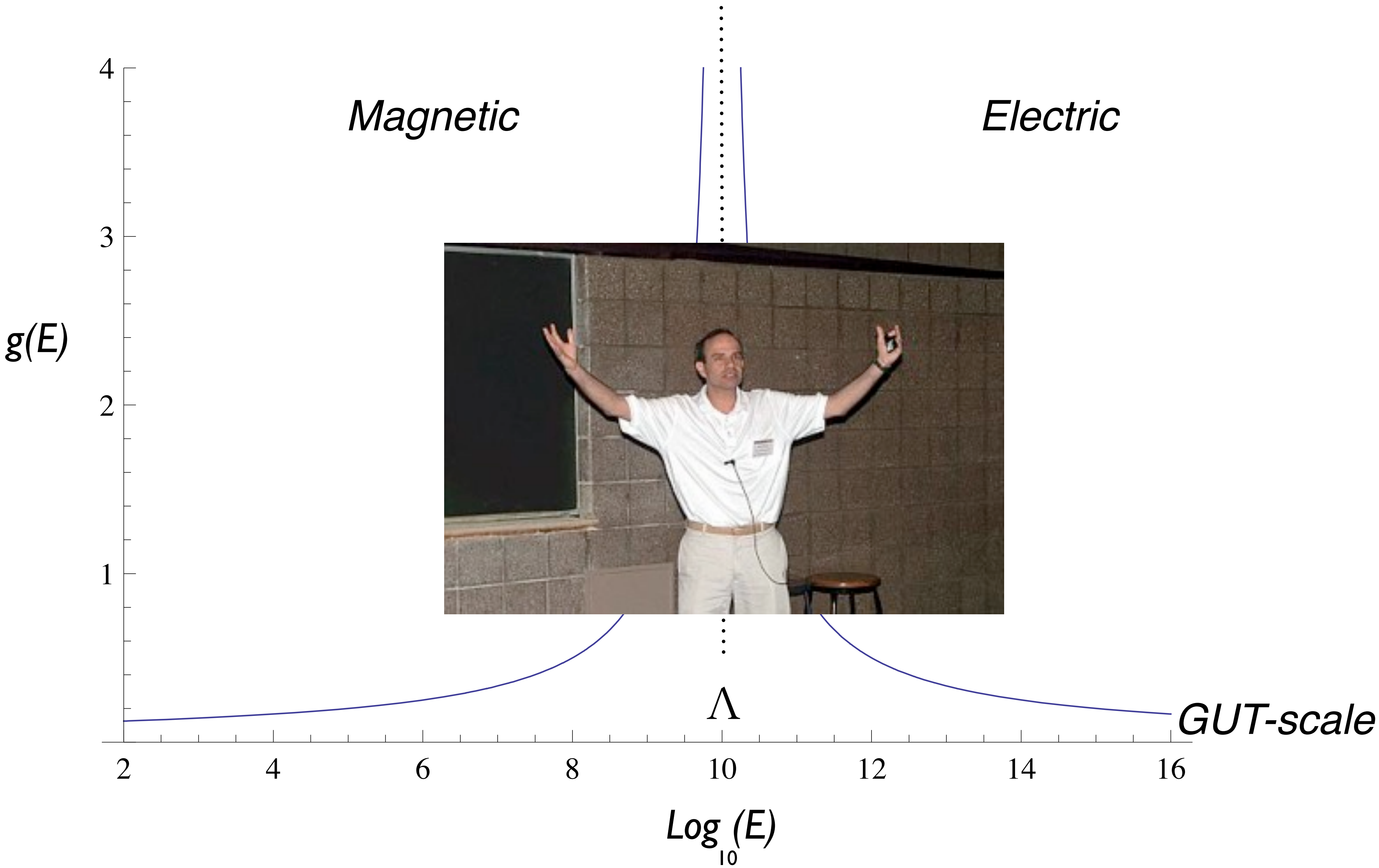
The gauge coupling runs as $e^{-8\pi^2/g^2(E)} = \left(\frac{E}{\Lambda}\right)^{-b_0}$

If the beta-function is negative $b_0 = 3N - F_Q > 0$ then hit Landau pole

ISS metastable SUSY breaking



ISS metastable SUSY breaking



ISS metastable SUSY breaking

The magnetic model found by matching moduli spaces (baryons) and global anomalies is

$\mathcal{N}=1$ gauge	$\mathrm{SU}(n)$	$n = F_Q - N$
singlet mesons	$\varphi = Q\tilde{Q}/\Lambda$	
F_Q quark and antiquarks	$q,\ \tilde{q}$	
Superpotential	$W_{cl} = q\varphi\tilde{q} - \mu_{ISS}^2\varphi$	$\mu_{ISS}^2 = -(m_Q\Lambda)$

Runs to weak coupling in IR if $\bar{b}_0 = 3n - F_Q < 0$, so strong->IR-free if

$$N + 1 \leq F_Q \leq \frac{3}{2}N$$

ISS metastable SUSY breaking

Can also see what's going on with quiver diagrams ...

	$SU(F_Q)$	$SU(F_Q)$	$U(1)_B$	$U(1)_R$
Q	$\square$	1	$\frac{1}{N}$	$1-\frac{N}{N_f}$
$\tilde{Q}$	1	$\tilde{\square}$	$-\frac{1}{N}$	$1-\frac{N}{N_f}$

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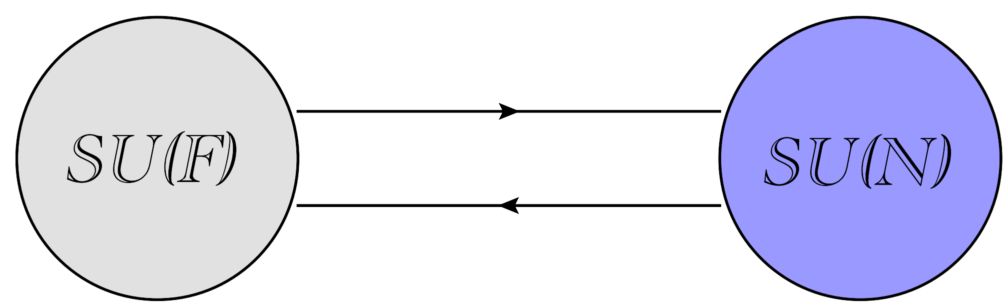
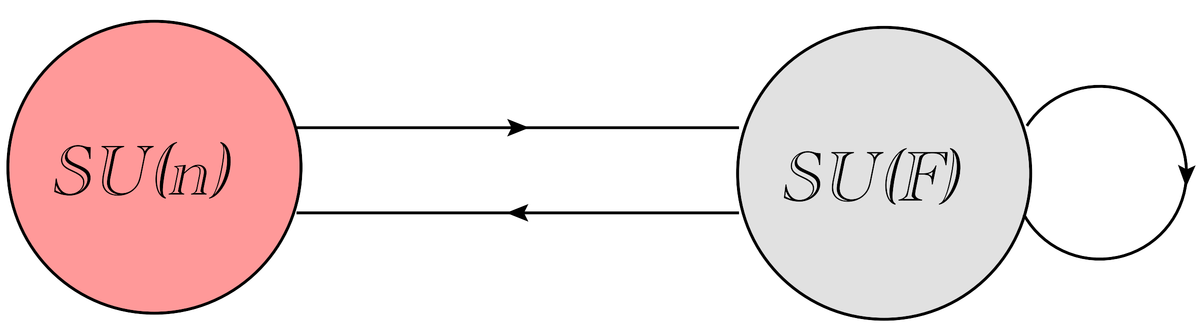
φ	$\square$	$\tilde{\square}$	0	$2\frac{n}{N_f}$

Table 2: *Spectrum and anomaly free charges in $SQCD_{\tilde{0}}$.*





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Other phases possible ...

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Free-electric phase:	$F_Q \quad \geq \quad 3N$
Interacting - IR fixed point:	$\frac{3N}{2} < \quad F_Q \quad < 3N$
Free-magnetic phase:	$N+1 \leq F_Q \leq \frac{3}{2}N$
s-confining:	$F_Q \quad = \quad N+1$
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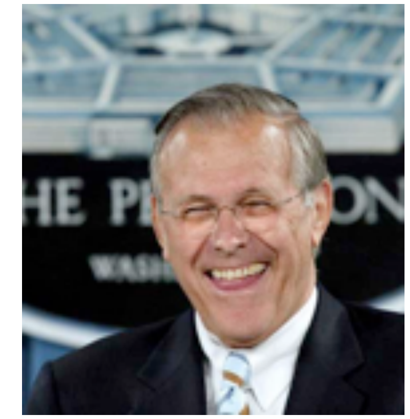
Interesting

Tests of Seiberg duality

Many tests e.g.1 : ‘t Hooft anomaly matching …

Tests of Seiberg duality



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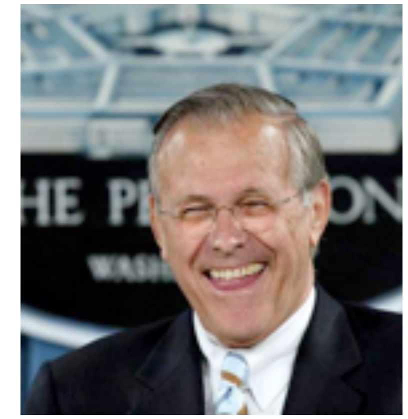

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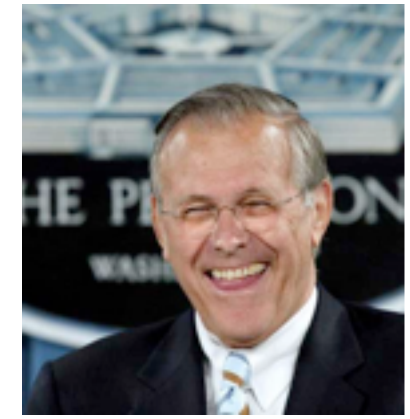

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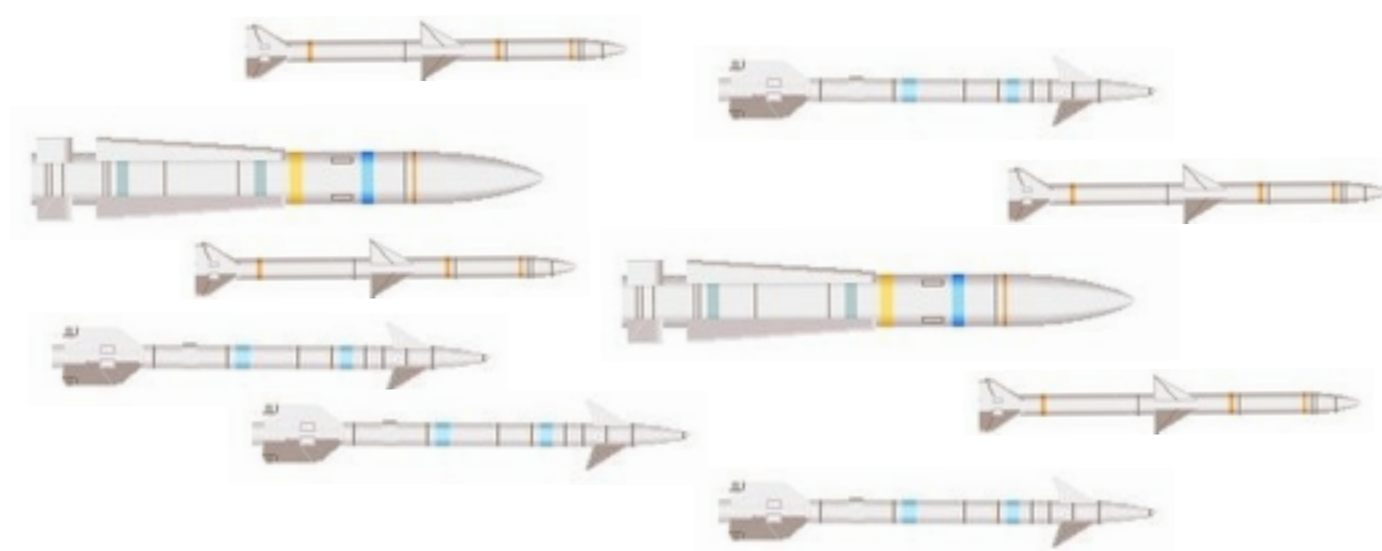
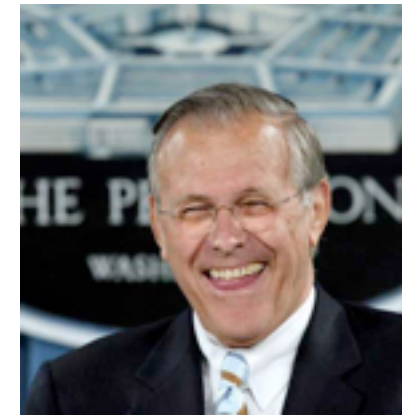


$SU(F_Q) \times SU(F_Q) \times U(1)_B \times U(1)_R$

global anomalies

Tests of Seiberg duality



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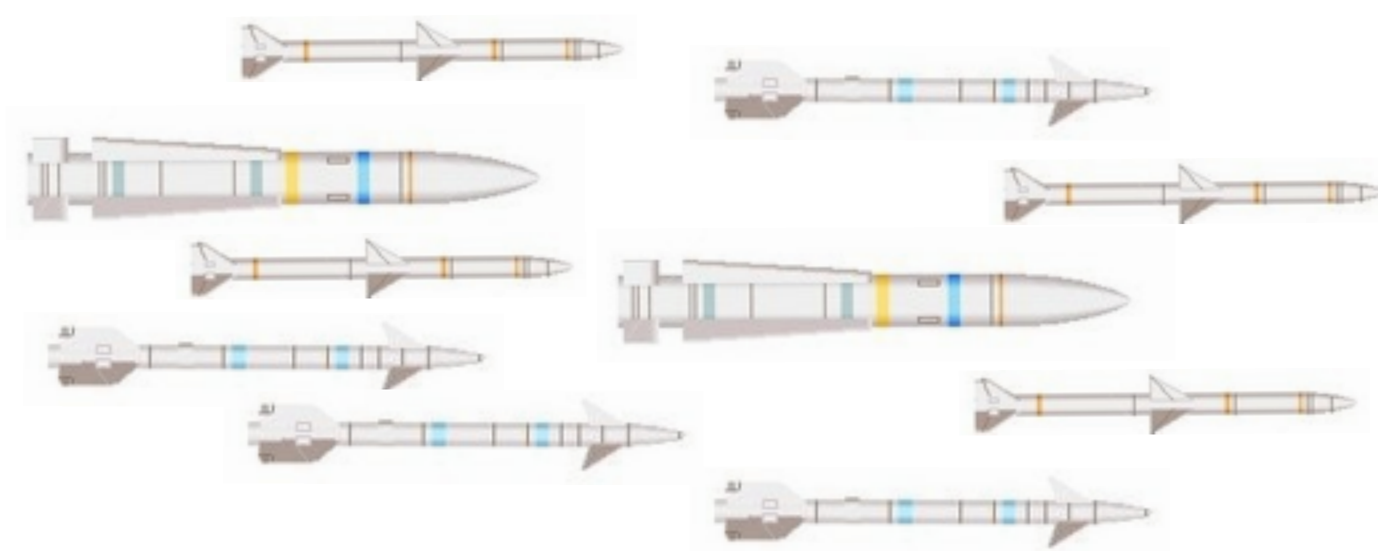

$SU(F_Q) \times SU(F_Q) \times U(1)_B \times U(1)_R$

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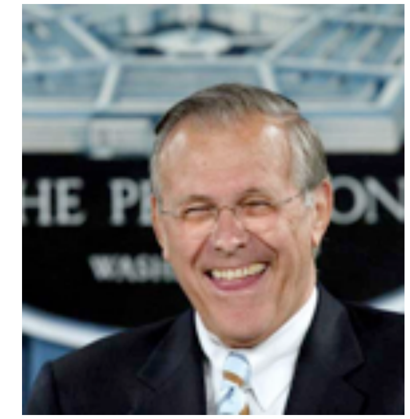
“unknown known”

Tests of Seiberg duality



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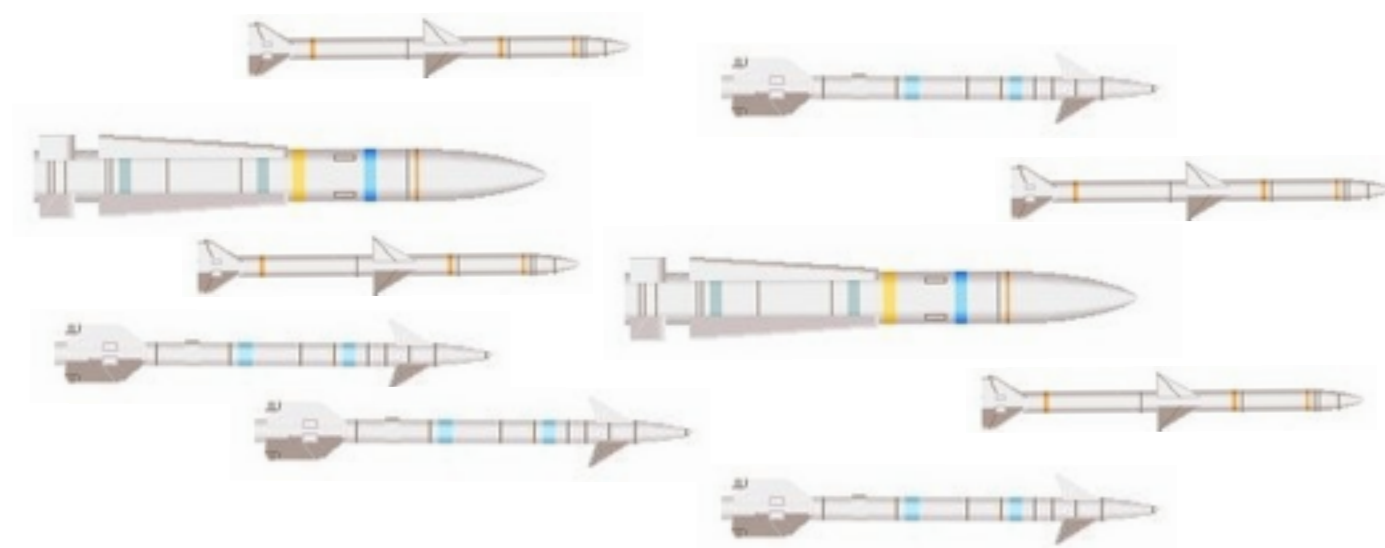
Magnetic



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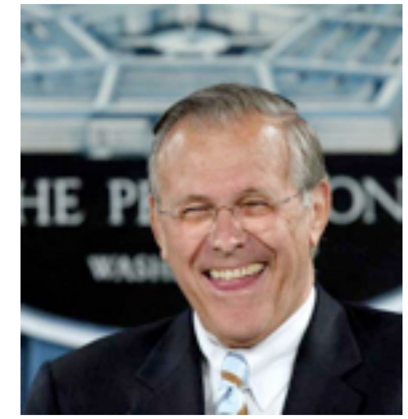

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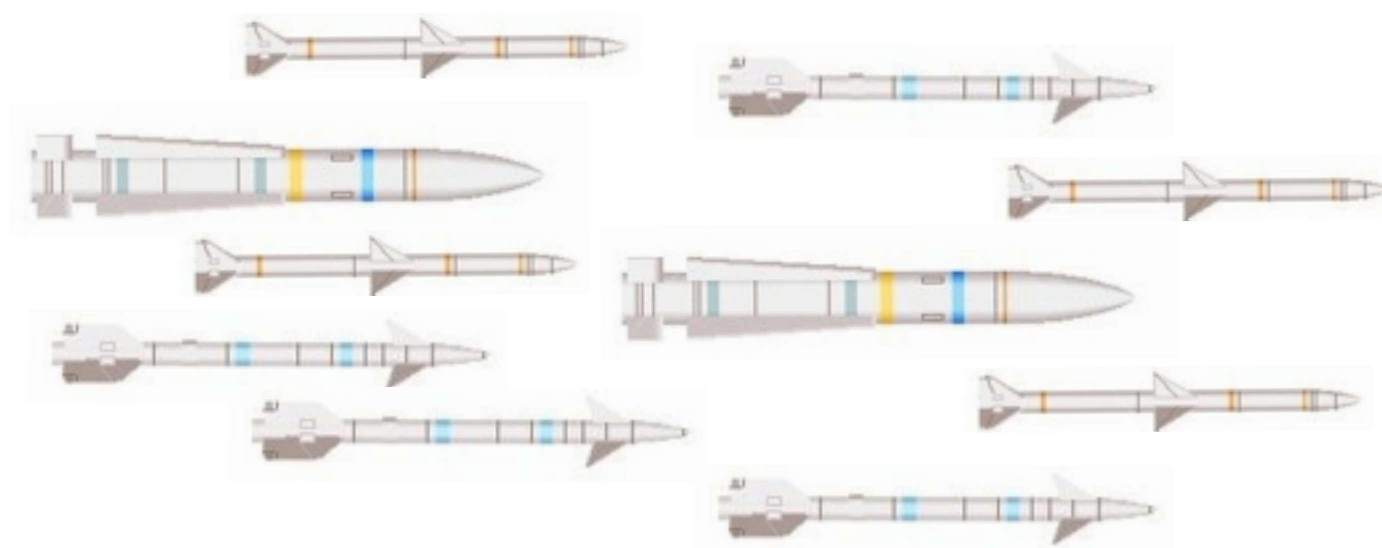

$SU(F_Q) \times SU(F_Q) \times U(1)_B \times U(1)_R$
global anomalies

“unknown known”

Hence all global anomalies should match!

Tests of Seiberg duality

Many tests e.g.1 : 't Hooft anomaly matching ...

Using an extremely important global U(1) symmetry of supersymmetric theories:

***R*-symmetry**

$$L_{\text{int}} = W|_{\theta\theta} + h.c.$$

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

Tests of Seiberg duality

Many tests e.g.1 : ‘t Hooft anomaly matching …

	$\mathrm{SU}(F_Q)$	$\mathrm{SU}(F_Q)$	$\mathrm{U}(1)_B$	$\mathrm{U}(1)_R$
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φ	$\square$	$\tilde{\square}$	0	$2\frac{\mathrm{n}}{\mathrm{N}_f}$

Table 2: *Spectrum and anomaly free charges in $SQCD_{\tilde{0}}$.*

Note that this U(1)_R is the "exact" R-symmetry related to the dimensions of operators at fixed points as R = 2/3 x Dimension

Tests of Seiberg duality

Many tests e.g.1 : ‘t Hooft anomaly matching ...

$$SU(F)^3 : -(F-N)+F=N$$

$$U(1)SU(F)^2 : \frac{N}{F-N}(F-N)\frac{1}{2}=\frac{N}{2}$$

$$U(1)_R SU(F)^2 : \frac{N-F}{F}(F-N)\frac{1}{2}+\frac{F-2N}{F}F\frac{1}{2}=-\frac{N^2}{2F}$$

$$U(1)^3 : 0$$

$$U(1) : 0$$

$$U(1)U(1)_R^2 : 0$$

$$U(1)_R : \left(\frac{N-F}{F}\right)2(F-N)F+\left(\frac{F-2N}{F}\right)F^2+(F-N)^2-1$$
$$=-N^2-1$$

$$U(1)_R^3 : \left(\frac{N-F}{F}\right)^3 2(F-N)F+\left(\frac{F-2N}{F}\right)^3 F^2+(F-N)^2-1$$
$$=-\frac{2N^4}{F^2}+N^2-1$$

Tests of Seiberg duality

Many tests e.g.2 : Dual-of-dual-of-theory = theory

Tests of Seiberg duality

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=

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Tests of Seiberg duality

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

$\mathcal{N}=1$ gauge	$\mathrm{SU}(n)$	$n = F_Q - N$
singlet mesons	$\varphi = Q\tilde{Q}/\Lambda$	
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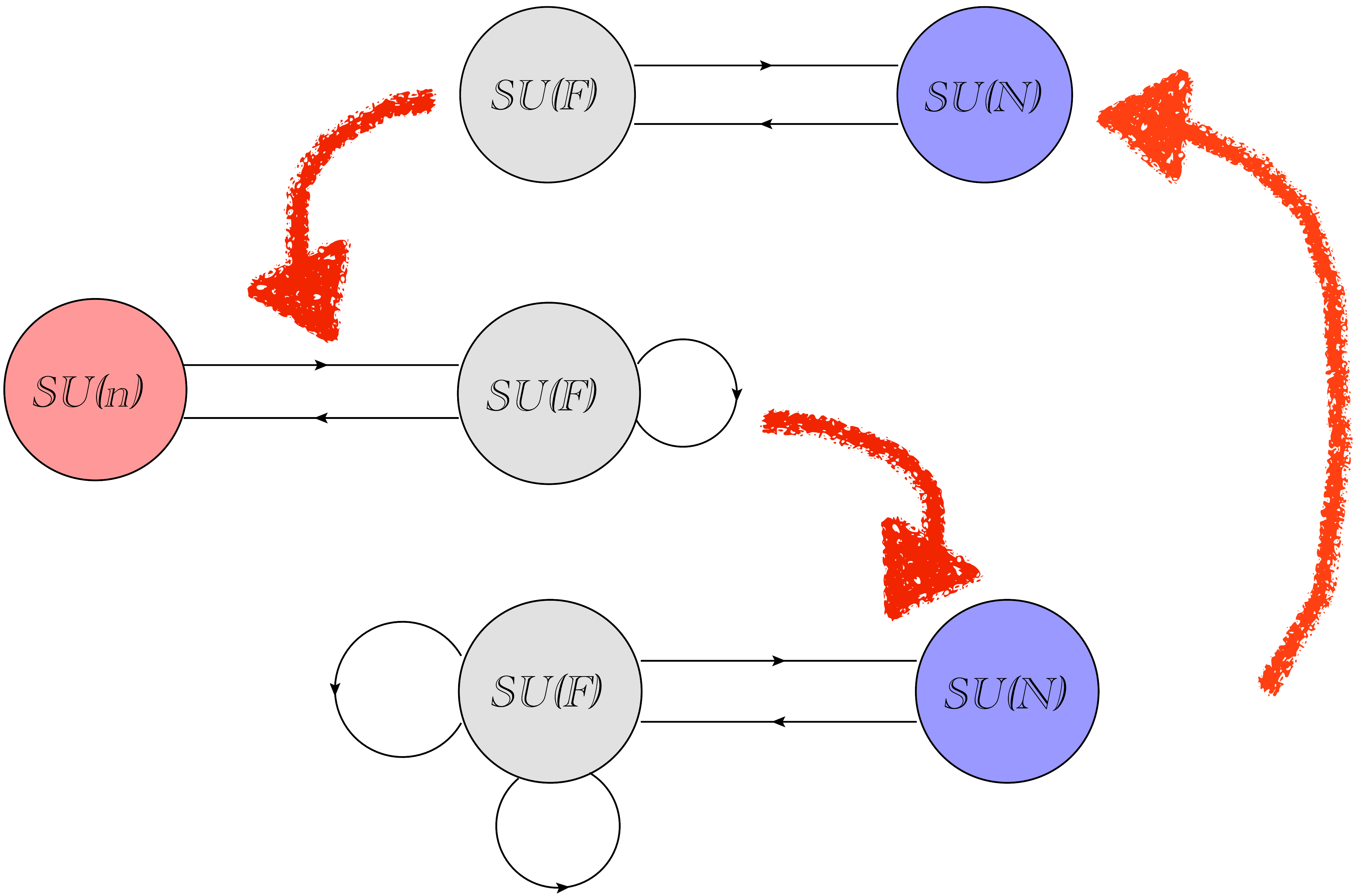
$\mathcal{N}=1$ gauge	$\mathrm{SU}(N)$	$N = F_Q - n$
singlet mesons	$\Phi = -q\tilde{q}/\Lambda\ ;\ \varphi$	
F_Q quark and antiquarks	$Q,\ \tilde{Q}$	
Superpotential	$W'_{elec} = \tilde{Q}\Phi Q - \Lambda\Phi\varphi + m_Q\Lambda\varphi$	$\equiv W_{elec}$

Tests of Seiberg duality

Many tests e.g.2 : Dual-of-dual-of-theory = theory



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ISS metastable SUSY breaking

The magnetic model found by matching moduli spaces (baryons) and global anomalies is

$\mathcal{N}=1$ gauge	$\mathrm{SU}(n)$	$n = F_Q - N$
singlet mesons	$\varphi = Q\tilde{Q}/\Lambda$	
F_Q quark and antiquarks	$q,\ \tilde{q}$	
Superpotential	$W_{cl} = q\varphi\tilde{q} - \mu^2_{ISS}\varphi$	$\mu^2_{ISS} = -(m_Q\Lambda)$

Runs to weak coupling in IR if $\bar{b}_0 = 3n - F_Q < 0$, so strong->IR-free if

$$N + 1 \leq F_Q \leq \frac{3}{2}N$$

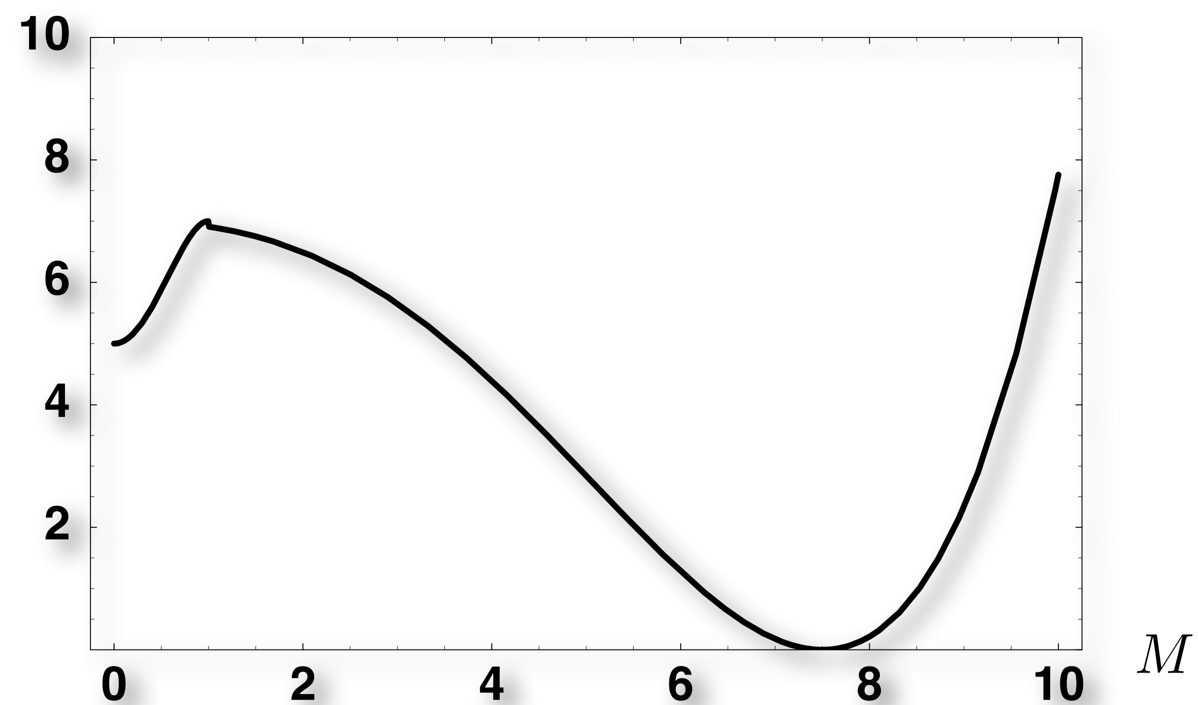
ISS metastable SUSY breaking

The magnetic model characteristics given by $W = W_{cl} + W_{dyn}$:

$$W_{cl} = \varphi q.\tilde{q} - \mu_{ISS}^2 \varphi$$

$$W_{dyn} = N \left(\frac{\det_{F_Q} \varphi}{\Lambda^{F_Q - 3n}} \right)^{1/n}$$

$\mu_{ISS}^2 \approx m_Q \Lambda$



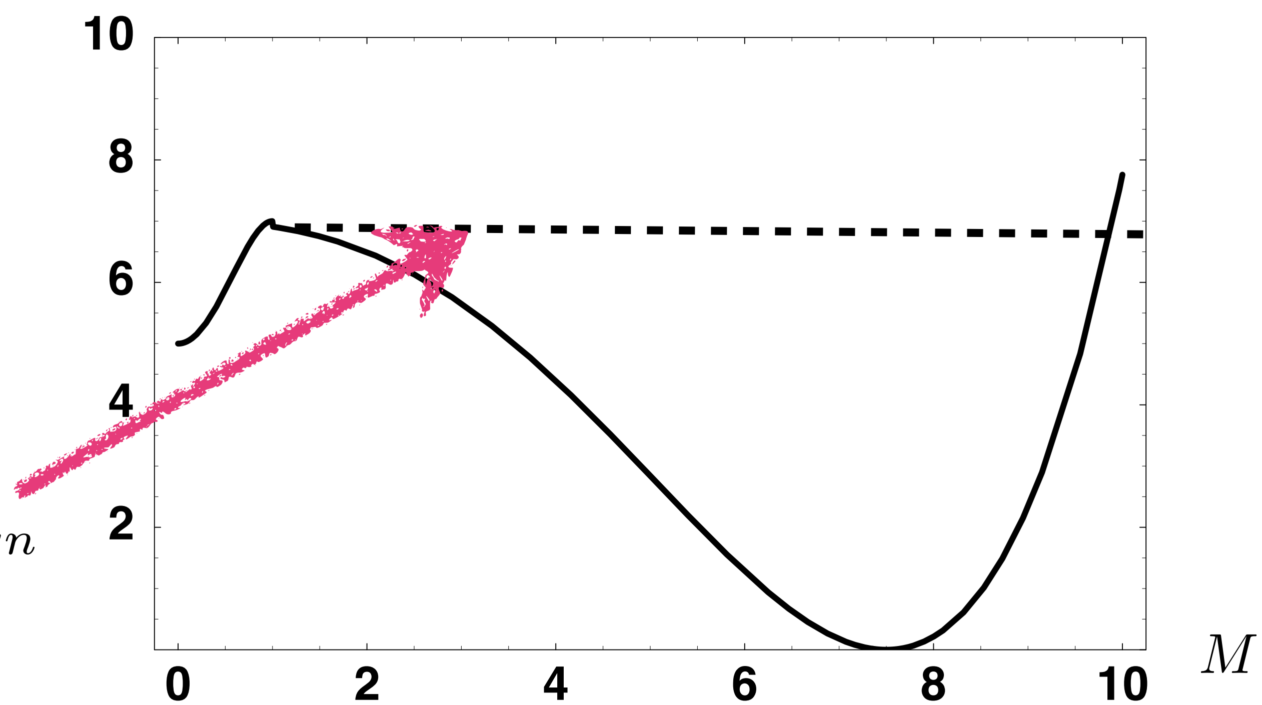
ISS metastable SUSY breaking

Let's understand the form of the potential ***a)***:

Near origin can ignore W_{dyn} so that $V \approx |\partial_\varphi W_{cl}|^2 = |q.\tilde{q} - \mu_{ISS}^2|^2$

Cannot solve V=0 because of Rank Condition: this is an O'R model!!

Potential without W_{dyn}



ISS metastable SUSY breaking

The metastable vacuum characterized by SU(n) being completely
Higgsed at the origin

$$\begin{aligned} \langle q \rangle &= \langle \tilde{q} \rangle = \mu \begin{pmatrix} \mathbf{1}_n \\ \mathbf{0}_{F_Q - n} \end{pmatrix} \ ; \ \langle \varphi \rangle = \mathbf{0} \\ V_+ &= (F_Q - n)\,|\mu^4| \end{aligned}$$

Can also be shown that there are no tachyons at one loop.

ISS metastable SUSY breaking

More on the dynamical term W_{dyn}

- Consider giving a VEV to
- then $m_q, m_{\tilde{q}} = \varphi$ and we can integrate out the quarks
- The beta function reverses sign since now no matter, and the theory confines with $W_{dyn} = \Lambda^3$
- Integrate out the heavy quarks and match the theories at their mass scale

ISS metastable SUSY breaking

SUSY preserving minima $|\text{vac}\rangle_0$ at

$$\begin{aligned}\langle q \rangle &= \langle \tilde{q} \rangle = 0 \ ; \ \langle \varphi \rangle = \varphi_0 \mathbf{1}_{F_Q} \\ \varphi_0 &= \mu \left(\epsilon^{\frac{F_Q - 3n}{F_Q - n}} \right)^{-1} \gg \mu \\ \epsilon &= \mu / \Lambda\end{aligned}$$

Have

$$\Lambda \gg \Phi_0 \gg \mu$$

so the minima are below Λ but the potential is very shallow

ISS metastable SUSY breaking

Let's understand the form of the potential ***b)***:

Actually we could have guessed that the theory would generate a W_{dyn} that restored supersymmetry!

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

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ISS metastable SUSY breaking

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

Want to ***not*** be able to solve: $$\frac{\partial W}{\partial X_i} = 0$$

If there are no symmetries and n fields then we have n equations and n unknowns

If there are k normal U(1) symmetries then the superpotential can be written as a function of the n-k invariants:

$$X_i / X_1^{\frac{q_i}{q_1}}$$

Thus n-k equations in n-k unknowns

ISS metastable SUSY breaking

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

But if we have a spontaneously broken R-symmetry then we must have at least one field with non-zero R-charge and we can write

$$W = X^{2/q} f(Y_i = X_i^q / X^{q_i})$$

For SUSY to be unbroken we now need to solve n equations for n-1 unknowns

$$\frac{\partial f}{\partial Y_i} = 0 \qquad f = 0$$

□

...)

ISS metastable SUSY breaking

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$$
\begin{aligned}
W_{cl} &= \varphi q.\tilde{q} - \mu_{ISS}^2\varphi \\
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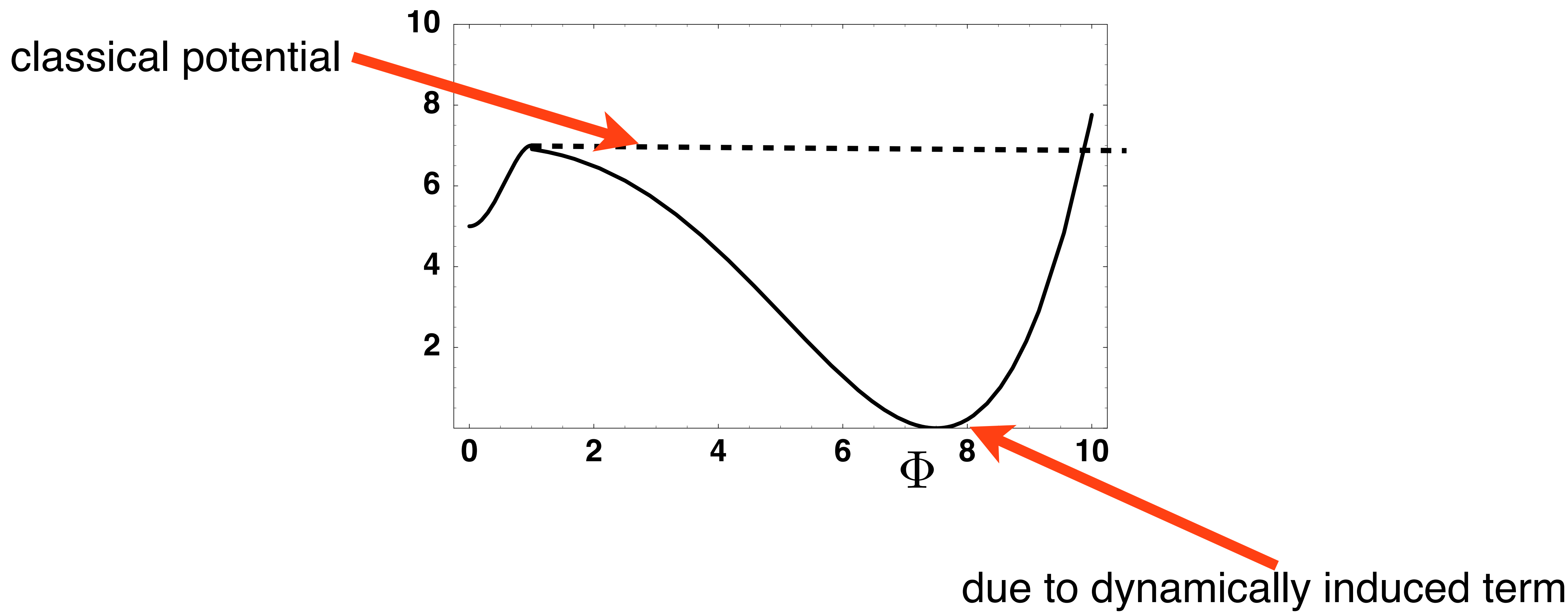
\end{aligned}
$$

Clearly R-symmetry broken by dynamical term

ISS metastable SUSY breaking

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



There are actually N SUSY preserving vacua differing by phase $e^{2\pi i/N}$ as required by Witten index of the microscopic theory

Some general cosmological observations

General cosmological observations

Rule of thumb: action for tunnelling

$$S_4 \sim 2\pi^2 \frac{\varphi_0^4}{V_+} = 2\pi^2 \frac{\varphi_0^4}{\mu^4}$$

$\Gamma_4/V_4 \sim e^{-S_4}$ can be made arbitrarily small by increasing φ_0.

General cosmological observations

Actually the bound on φ_0/μ is very weak...

$$\Gamma_4/V_4 \sim e^{-S_4}$$

Multiply by space-time volume of past light cone of Universe, i.e. $(10^{10}yr)^4$ gives $S_4 \gtrsim 400$ which gives

$$\frac{\varphi_0}{\mu} \gtrsim 3\left(\frac{F_Q}{n}\right)^{\frac{3}{4}}$$

General cosmological observations

Dynamical evolution at finite T ... (SAA, Jaeckel, Khoze hep-th/0610334)

Potential at finite temperature along direction φ is *(Dolan, Jackiw)*

$$V_T(\varphi) = V_{T=0}(\varphi) + \frac{T^4}{2\pi^2}\sum_i \pm n_i \int_0^\infty \mathrm{d}q\, q^2 \ln\left(1 \mp \exp(-\sqrt{q^2 + m_i^2(\varphi)/T^2})\right)$$

To first approximation only "light" ($m_i(\varphi)^2 \ll T^2$) states contribute

$$\begin{aligned} V_T - V_{T=0} &= -\frac{\pi^2 g_* T^4}{90} \\ g_* &= n_{B_{light}} + \frac{7}{8} n_{F_{light}} \end{aligned}$$

General cosmological observations

If $\mu \ll T \ll \varphi_0$ have

$$n_{B_{light}} = n_{F_{light}} = 4nF_Q \quad ; \ \varphi = 0$$
$$n_{B_{light}} = n_{F_{light}} = 0 \quad ; \ \varphi = \varphi_0$$

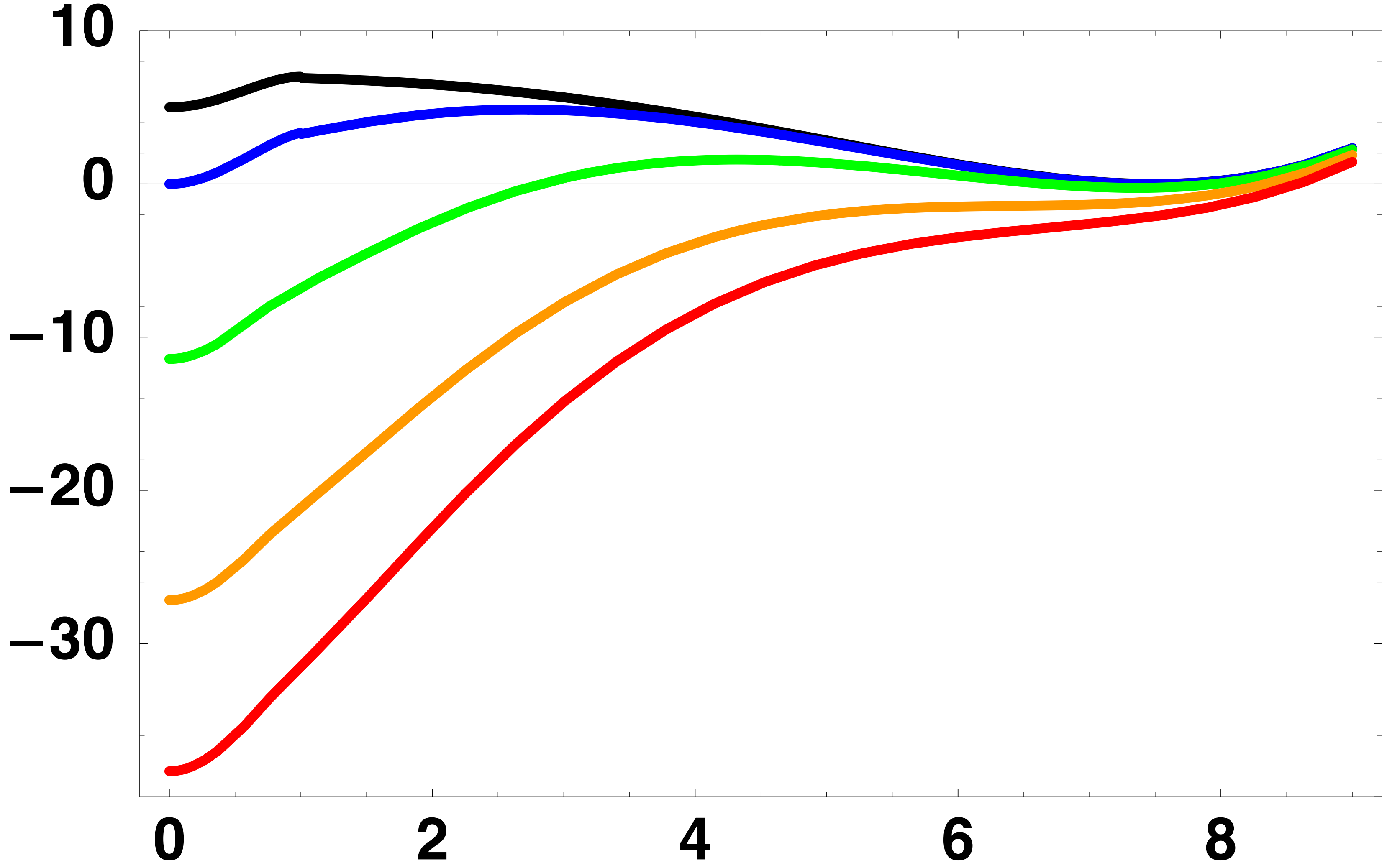
For now take all MSSM and gauge states as “light”.

Conclusion: for large enough T

$$V_+(T) < V_0(T)$$

This is a result of dynamical restoration of SUSY - have to integrate out flavours to reverse sign of β-function.

General cosmological observations



General cosmological observations

- The vacua become degenerate at $T_{degen} \sim h\mu$
- Bubble nucleation is never an important process in the transition $|vac_0\rangle \to |vac_+\rangle$
- The bump disappears at very low temperatures, $T_{crit} \sim \mu$, because of the shallowness and the confinement in $|vac_0\rangle$.

General cosmological observations

Does the phase transition complete?

- Time for φ to roll to origin much less than time to cool if $\varphi_0 \ll M_{Pl}$
- Damped to origin because of coupling $q\varphi\tilde{q}$ and couplings to messengers and/or MSSM.
- Remains trapped at origin at later times (Fischler, Kaplunovsky, Krishnan, Mannelli, Torres hep-th/0611018, Craig, Fox, Wacker, hep-th/0611006, SAA, Jaeckel, Khoze hep-th/0611030).

Some general phenomenological observations

General phenomenological observations

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

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But gaugino mass terms $M_\lambda \lambda^\alpha \lambda_\alpha$ break R-symmetry: conflict

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$$\mathcal{L}_{gauge} = \int d^2\theta W_\alpha W^\alpha$$

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

General phenomenological observations

Initially ISS looked promising and lots of excitement ...

1) Long lived vacuum because automatically very shallow

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

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

General phenomenological observations

Two possible options for doing phenomenology:

1) ***Explicit R-breaking***

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

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

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

2) ***Spontaneous R-breaking***

General phenomenological observations

Explicit Breaking example

Murayama and Nomura 2007

How to get an R-breaking gaugino mass without destabilising vacuum?
ISS is based on electric/magnetic Seiberg duals - suppose the messenger sector breaks R-symmetry maximally in the electric theory:

$$W_{elec} = m_Q Q\tilde{Q} + \frac{\lambda}{M_{Pl}} Q\tilde{Q} f\tilde{f} + M f\tilde{f}$$

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General phenomenological observations

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$$:= \varepsilon$$

Emergent R-symmetry

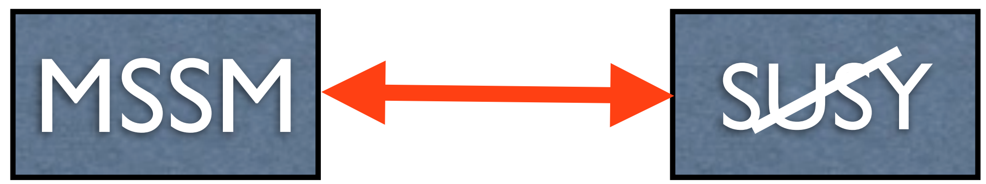
General phenomenological observations

Thanks to Nelson-Seiberg, a new lower vacuum appears but far away ...

The model generates gaugino and scalar masses as in ordinary GM - but you have to be reasonably careful to avoid vacuum decay

General phenomenological observations

Spontaneous R-Breaking example: has to be direct



Can simply "deform" ISS for *direct* gauge mediation (SAA, Durnford, Jaeckel, Khoze)

$$W_{cl} = W_{cl}^{ISS} + m\varepsilon_{ab}\varepsilon^{rs} q_r^a q_s^b$$

where $r, s = 1, 2$ are the 1st and 2 nd of 7 generations of "flavour".

and $a, b = 1, 2$ are gauge indices of the magnetic SU(n=2) theory.

Gauge the remaining 5 flavours: $SU(5)_f \supset G_{SM}$

Because of deformation Φ develops a VEV, and R-symmetry is broken.

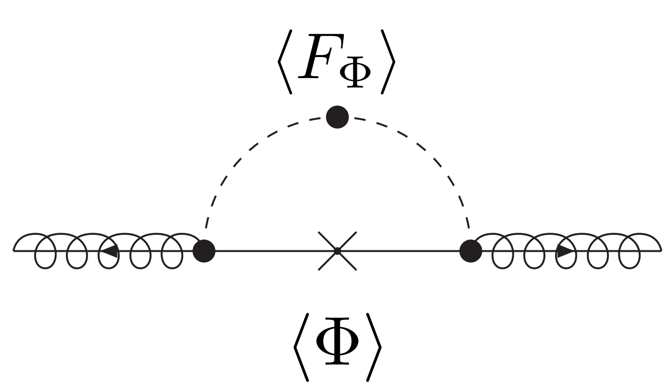
General phenomenological observations

Spontaneous R-Breaking example: has to be direct

The mediators are $q^a_{i=1..5}$ and $\tilde{q}^{i=1..5}_a$ and the typical scalar mass is

$$m_{scalar} \sim \frac{g_A^2}{16\pi^2}\mu_{ISS}$$

But ... this is a model of "slightly split SUSY" - gaugino masses are zero at tree-level. Typically suppressed by a factor of a few * 10



$$= 0$$

$$M_\lambda \sim \frac{g^2}{16\pi^2}\frac{F^3}{M^5}$$

General phenomenological observations

Komargodski-Shih theorem: *If there is a non-zero gaugino mass at leading order then there will be some value of pseudo-Goldstone mode (i.e.$\langle\Phi\rangle$) with tachyonic messengers.*

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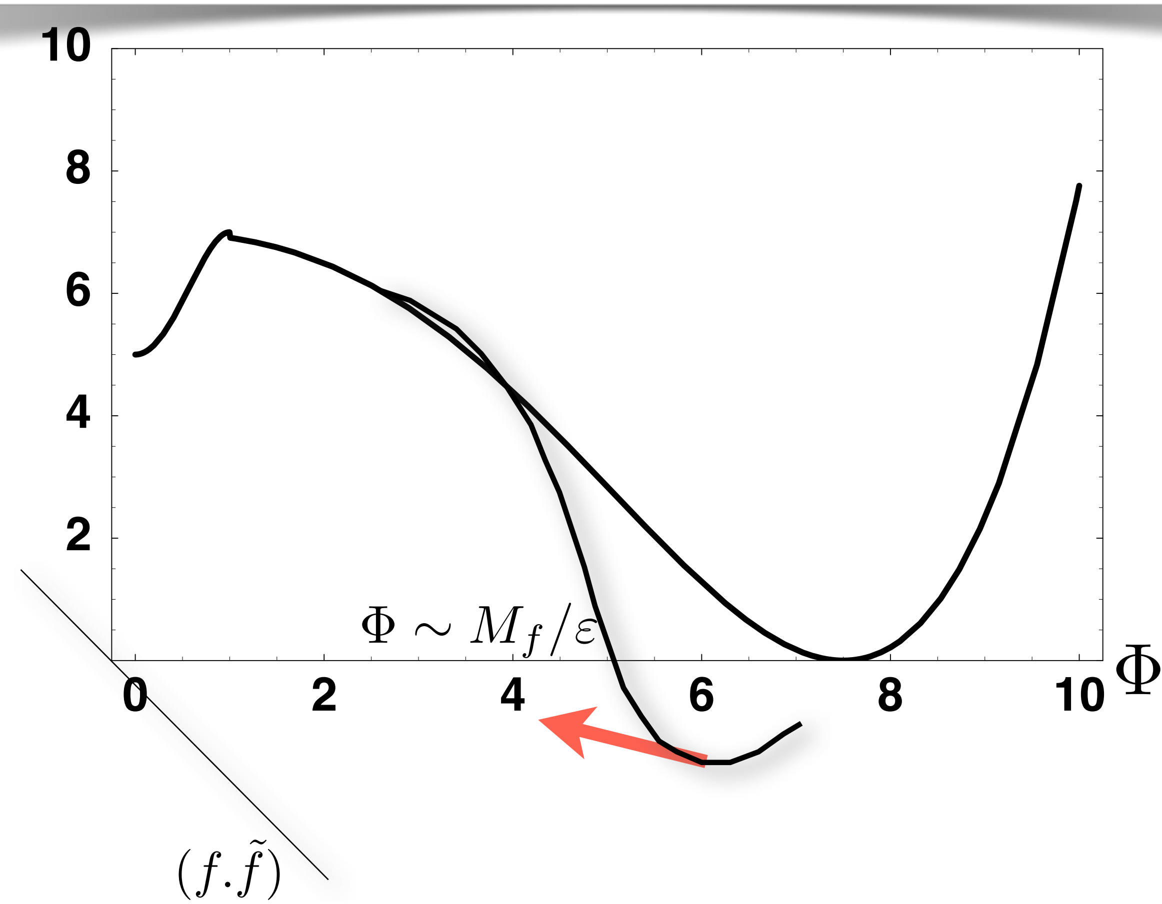
Non-zero gaugino masses at leading order require a lower lying vacuum at some point in moduli space, *at tree-level* (note that the basic ISS model does not have this). Because of these two theorems, metastability is doubly inevitable!!

General phenomenological observations

Hybrid model (SAA, Jaeckel, Khoze)

Simplest way to see this in action: bring in a lower lying vacuum from infinity by having explicit R-breaking messenger:

$$W_{cl} = W_{cl}^{ISS} + W^{deform} + W^{MN}$$



General phenomenological observations

Hybrid model (SAA, Jaeckel, Khoze)

At leading order gaugino masses from explicit f-messengers only, but scalars from both q and f-messengers.

$$\frac{M^2_{gaugino}}{m^2_{scalar}} \sim N_f.\frac{1}{1+\frac{N_q}{N_f}\left(\frac{M_f}{\varepsilon\mu_{ISS}}\right)^2}$$

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The distance away in field space of the lower vacuum is $\Phi \sim M_f/\varepsilon$

As this is brought in from infinity, the SUSY breaking goes from being infinitely split to standard ~ 1. Gaugino masses directly related to vacuum structure.

(...

Supersymmetry wants to preserve the SM gauge and matter structure as much as possible. Compositeness wants to break it up. But Seiberg duality can also help with the latter!

e.g. an s-confined trinification model (Kaplan Lepeintre Schmaltz)

preon	$Sp(6)_L$	$Sp(6)_H$	$Sp(6)_R$	$SU(3)_1$	$SU(3)_2$	$SU(3)_3$
a_1	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	1	1	1	1
p_1	$\square$	1	1	3	1	1
q_1	$\square$	1	1	1	$\bar{3}$	1
a_2	1	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	1	1	1
p_2	1	$\square$	1	1	3	1
q_2	1	$\square$	1	1	1	$\bar{3}$
a_3	1	1	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	1	1	1
p_3	1	1	$\square$	1	1	3
q_3	1	1	$\square$	$\bar{3}$	1	1

composite	$SU(3)_1$	$SU(3)_2$	$SU(3)_3$
$\Phi^{(1)} = p_1 q_1$	3	$\bar{3}$	1
$\Phi^{(2)} = p_2 q_2$	1	3	$\bar{3}$
$\Phi^{(3)} = p_3 q_3$	$\bar{3}$	1	3
$X = q_3 q_3$	3	1	1
$\overline{X} = p_1 p_1$	$\bar{3}$	1	1
$Y = q_1 q_1$	1	3	1
$\overline{Y} = p_2 p_2$	1	$\bar{3}$	1
$Z = q_2 q_2$	1	1	3
$\overline{Z} = p_3 p_3$	1	1	$\bar{3}$

...)

General phenomenological observations

What about $\Lambda_S < \Lambda_G$ ***?***

This would correspond to many messengers so *generally* associated with either extra-dimensions and/or strong coupling, e.g...

Pomarol Quiros
Antoniadis Dimpoulos Pomarol Quiros
Delgado Pomarol Quiros
Mirabelli Peskin
Kaplan Kribs Schmaltz
Csaki Erlich Grojean Kribs
Chacko Luty Nelson Ponton
Gherghetta Pomarol
Marti Pomarol
Gherghetta Pomarol (2003) ...
McGarrie Russo

e.g. *Gaugino mediation* - corresponds to SUSY breaking by twisted boundary conditions

Perturbatively or in 4D? See
Buican Meade Seiberg Shih
Green, Katz Komargodski
McGarrie

General phenomenological observations

What about $\Lambda_S < \Lambda_G$ ***?***

Strong coupling AdS/QCD picture

General phenomenological observations

What about $\Lambda_S < \Lambda_G$ ***?***

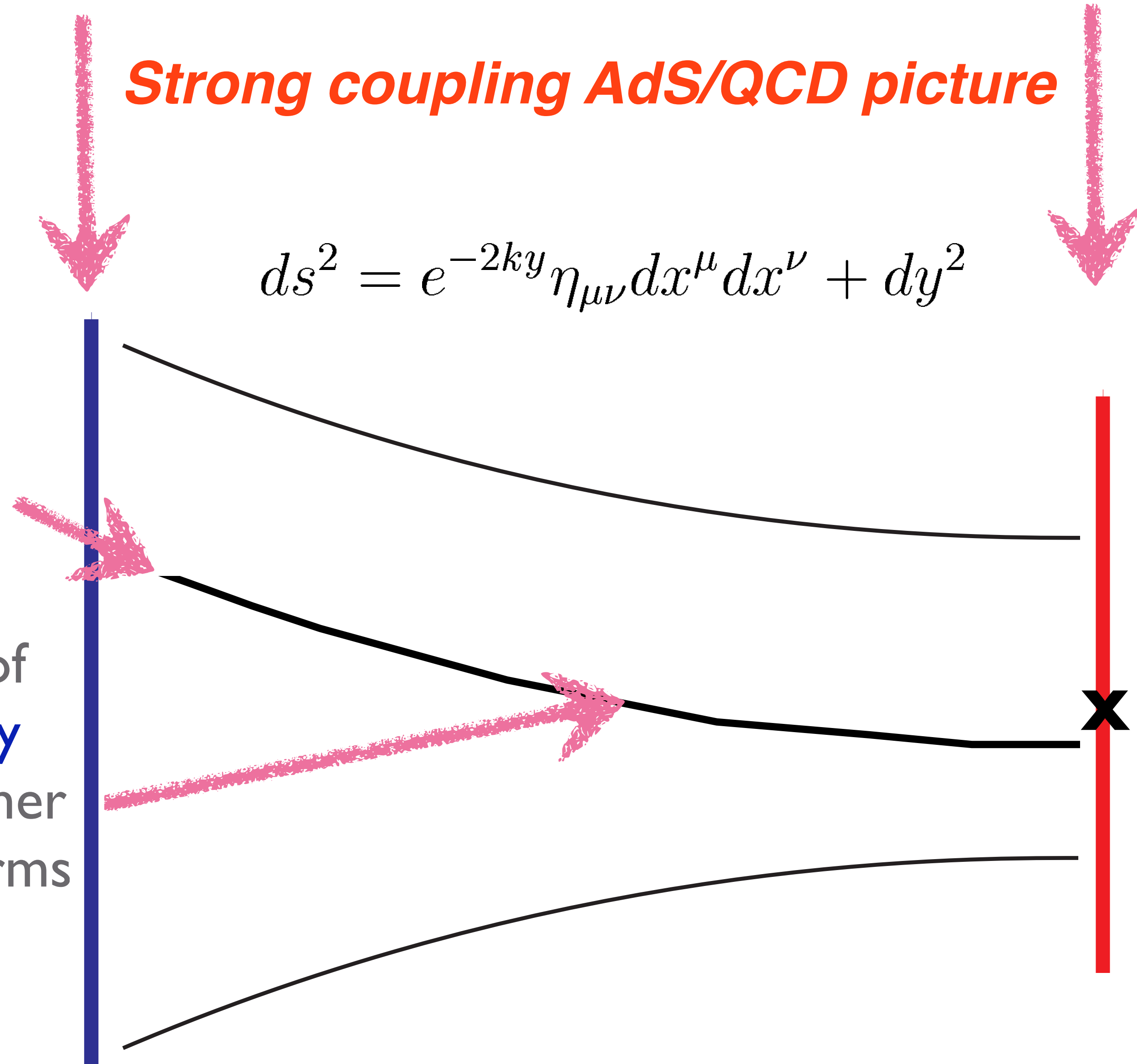
Elementary states go here

Purely composite states go here

Strong coupling AdS/QCD picture

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

UV values of bulk fields correspond to couplings in strongly coupled 4D CFT



5D bulk states are a mix of composite and elementary
They can be localized in either direction with bulk mass terms

Put SUSY breaking on the brane *by hand*

Conformal symmetry explicitly broken by UV brane

Conformal symmetry spontaneously broken by IR brane

General phenomenological observations

(SAA Gherghetta)

General phenomenological observations

Is there a 4D theory that exhibits this SUSY breaking dynamics? (SAA Gherghetta)

- Take the ISS model with Murayama-Nomura mediation
- Add extra quarks with mass Λ_{IR} until the electric phase enters the conformal window
- The running looks like ...

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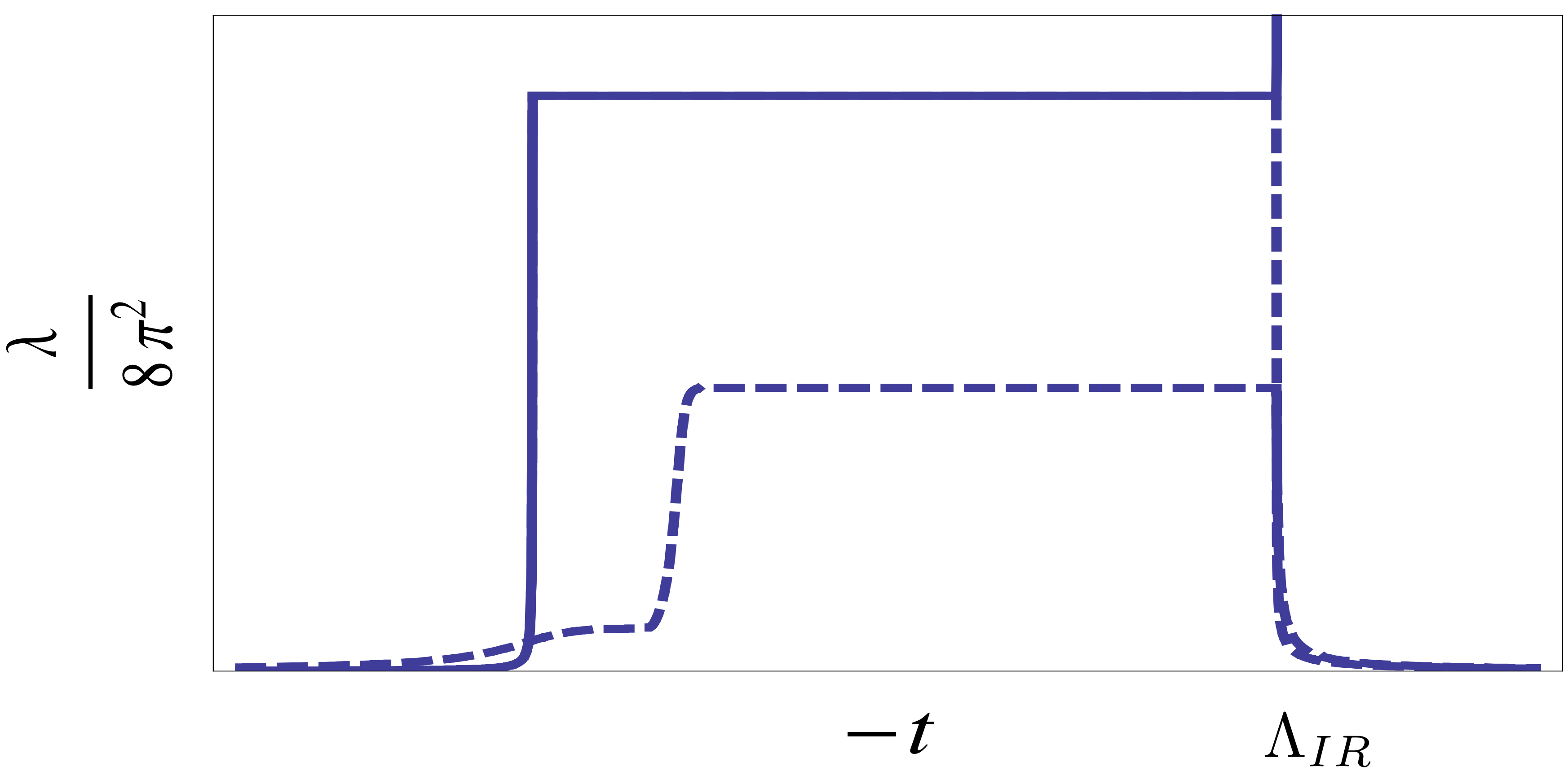

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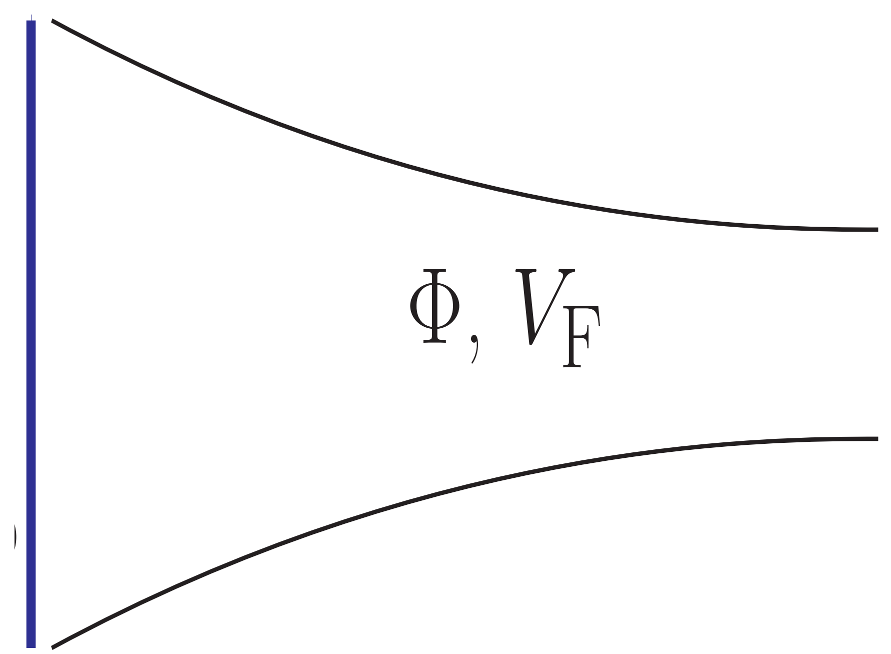

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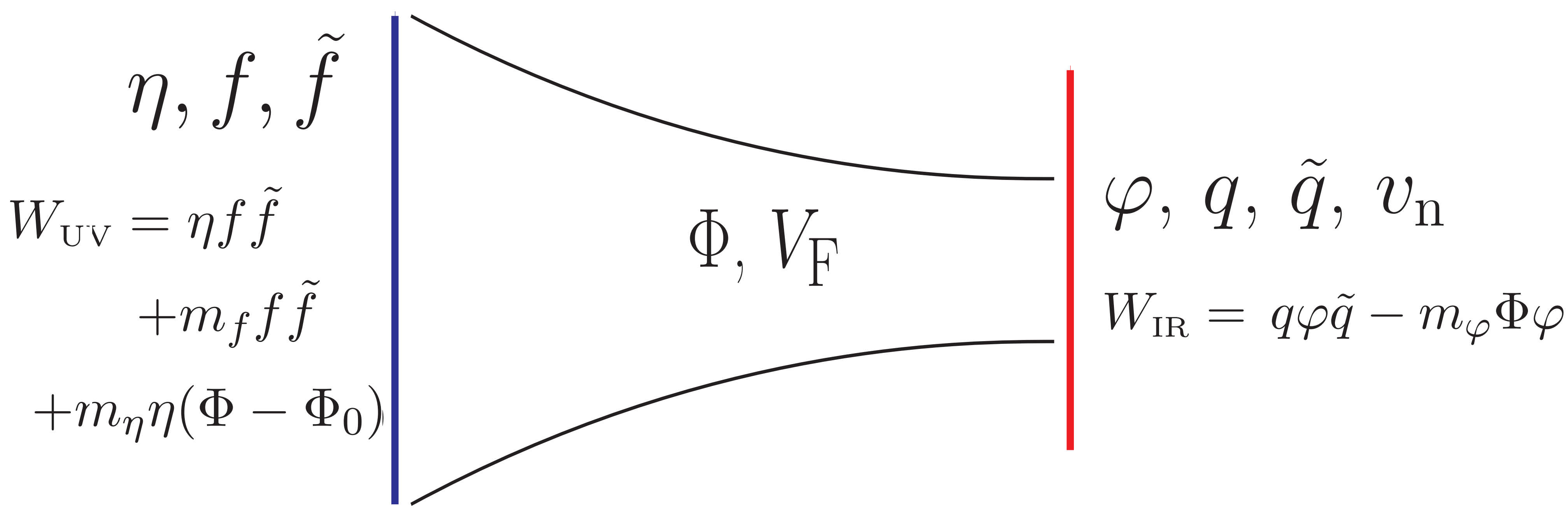

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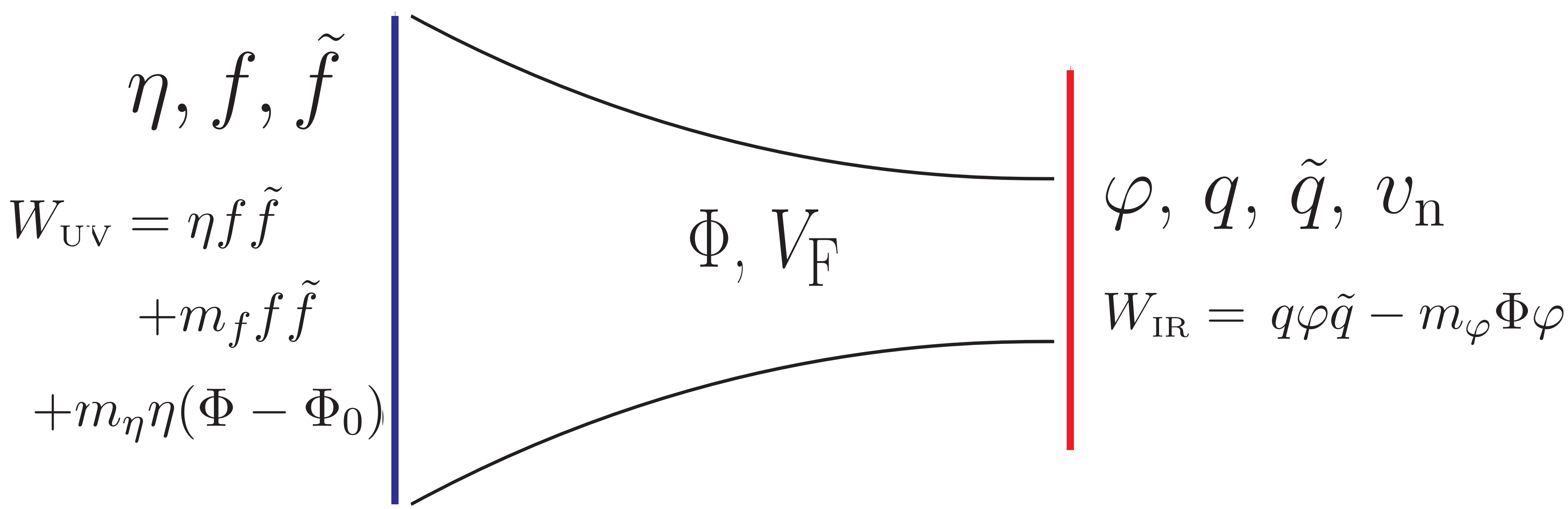

The bulk mesons mean this has to be like the dual-of-the-dual of ISS

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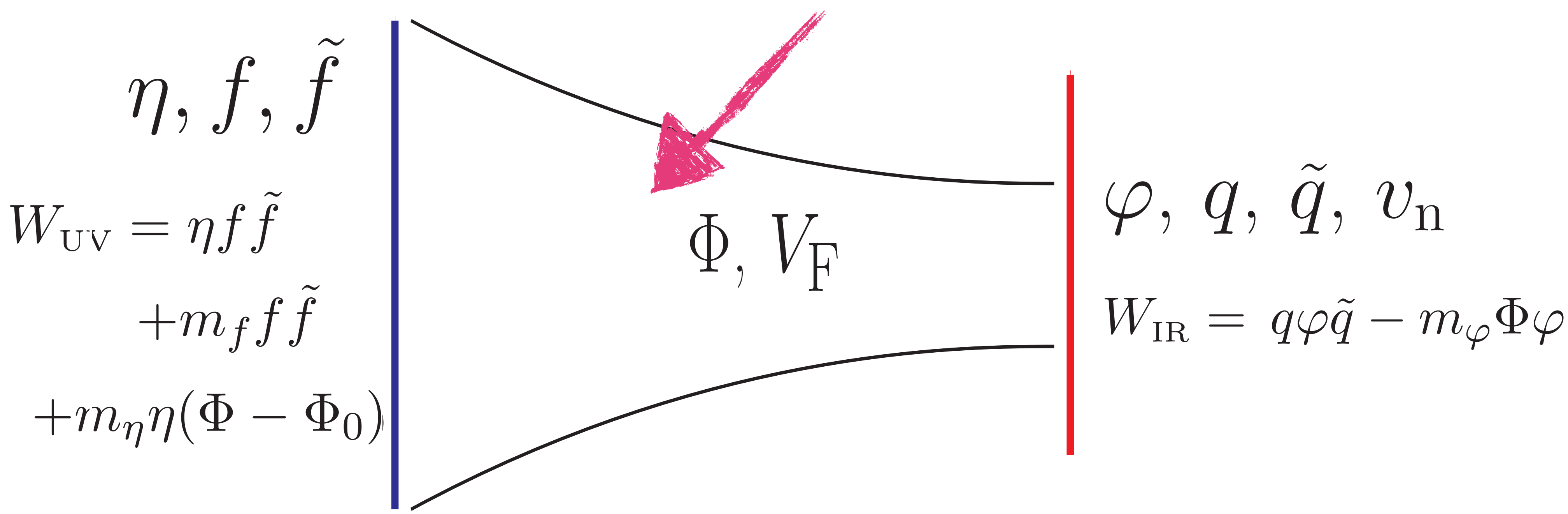
The bulk is a 6D theory (with constant S1)
because of R-symmetry: Klebanov + Maldacena



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General phenomenological observations

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\begin{aligned}
M_1 = \sqrt{\frac{\Pi_1}{\Pi_2}} M_2 &= \sqrt{\frac{\Pi_1}{\Pi_3}} M_3 \\
m^2_{\tilde{Q}} &= \frac{4}{3}\alpha_3\Pi_3 + \frac{3}{4}\alpha_2\Pi_2 + \frac{1}{60}\alpha_1\Pi_1 \\
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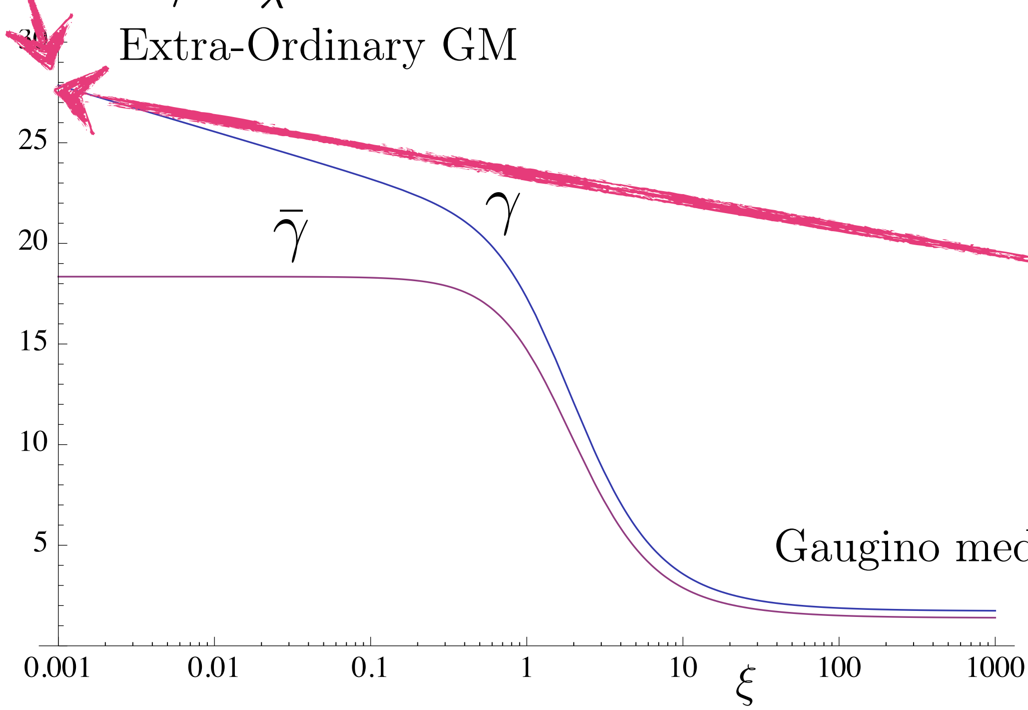
\end{aligned}
$$

$\gamma = 8\pi^2\Pi/M_\lambda^2$



$$m_i^2 = \sum_a \frac{2C_a}{b_{\rm CFT}} M^2_{\lambda_a}$$

General phenomenological observations

Find a 4 parameter GGM

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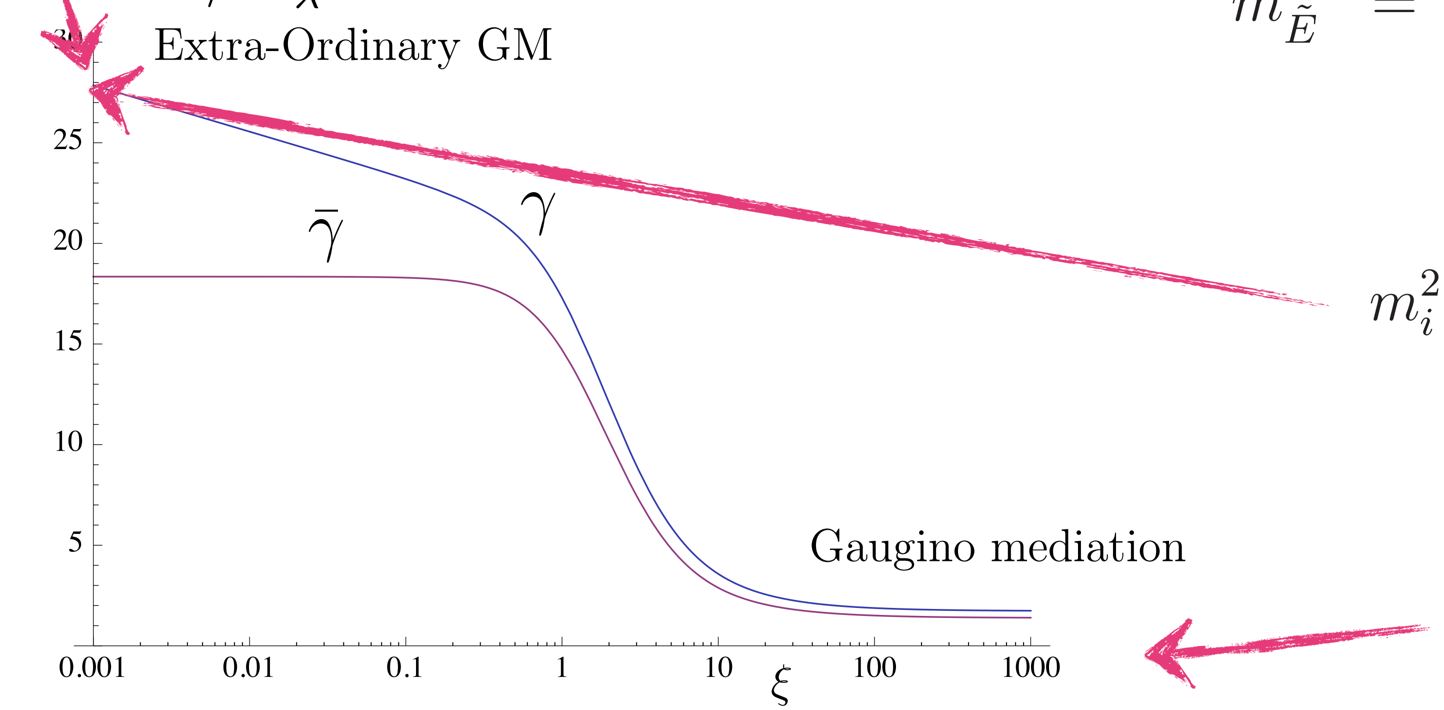

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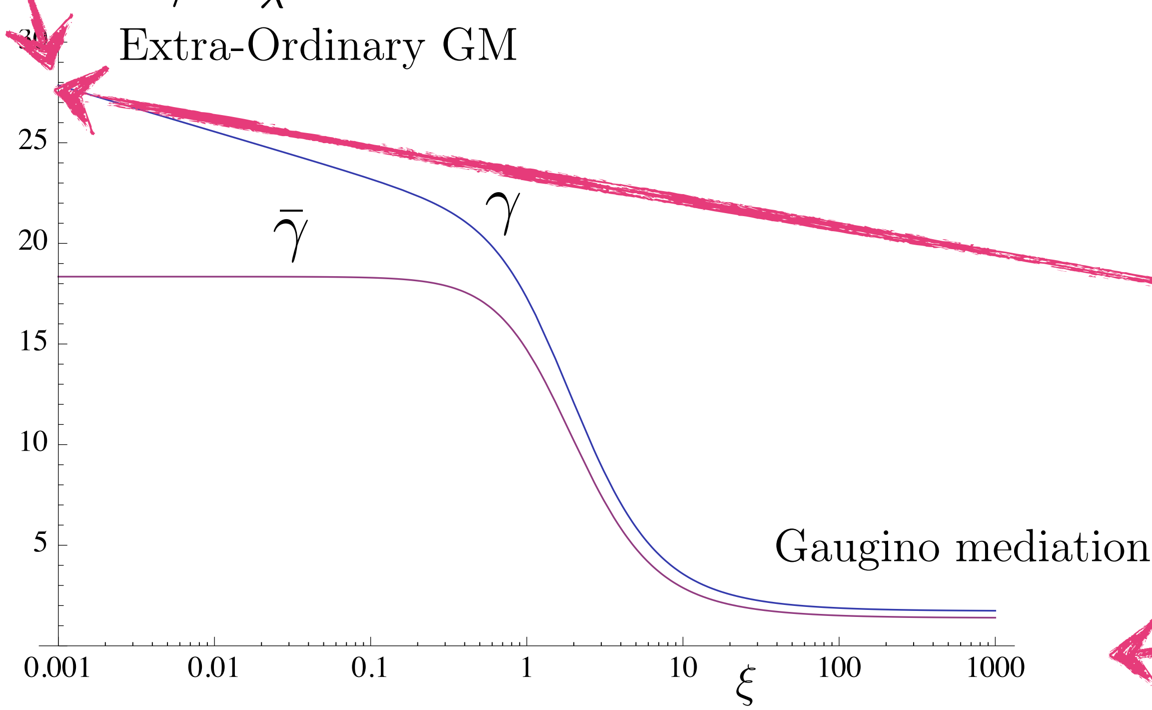

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gaugino is Dirac

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gaugino is Majorana

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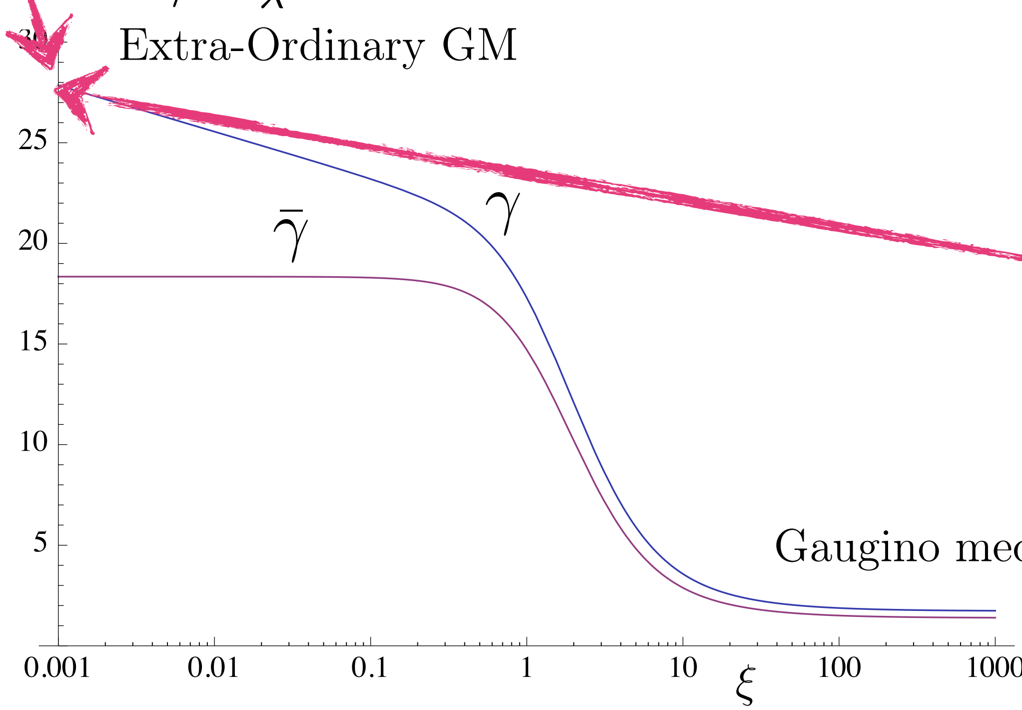

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gaugino is Dirac

Phenomenology of pure GGM for LHC

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"Pure" means no additional generation of Higgs "B term".
This must be generated radiatively -> large tan beta (Rattazzi, Sarid; Gabrielli Sarid)

General set-up for phenomenological study

Take Pure GGM parameter space and restrict to single effective scale for the gaugino masses and for the scalar masses

- includes any scenario with preserved GUT structure in mediation
- captures the main effects of R-symmetry and metastability
- is equivalent to $m_0,\ m_{1/2}$ in CMSSM
- in contrast with other pheno work (e.g. Carpenter; Rajaraman, Shirman, Smidt, Yu)

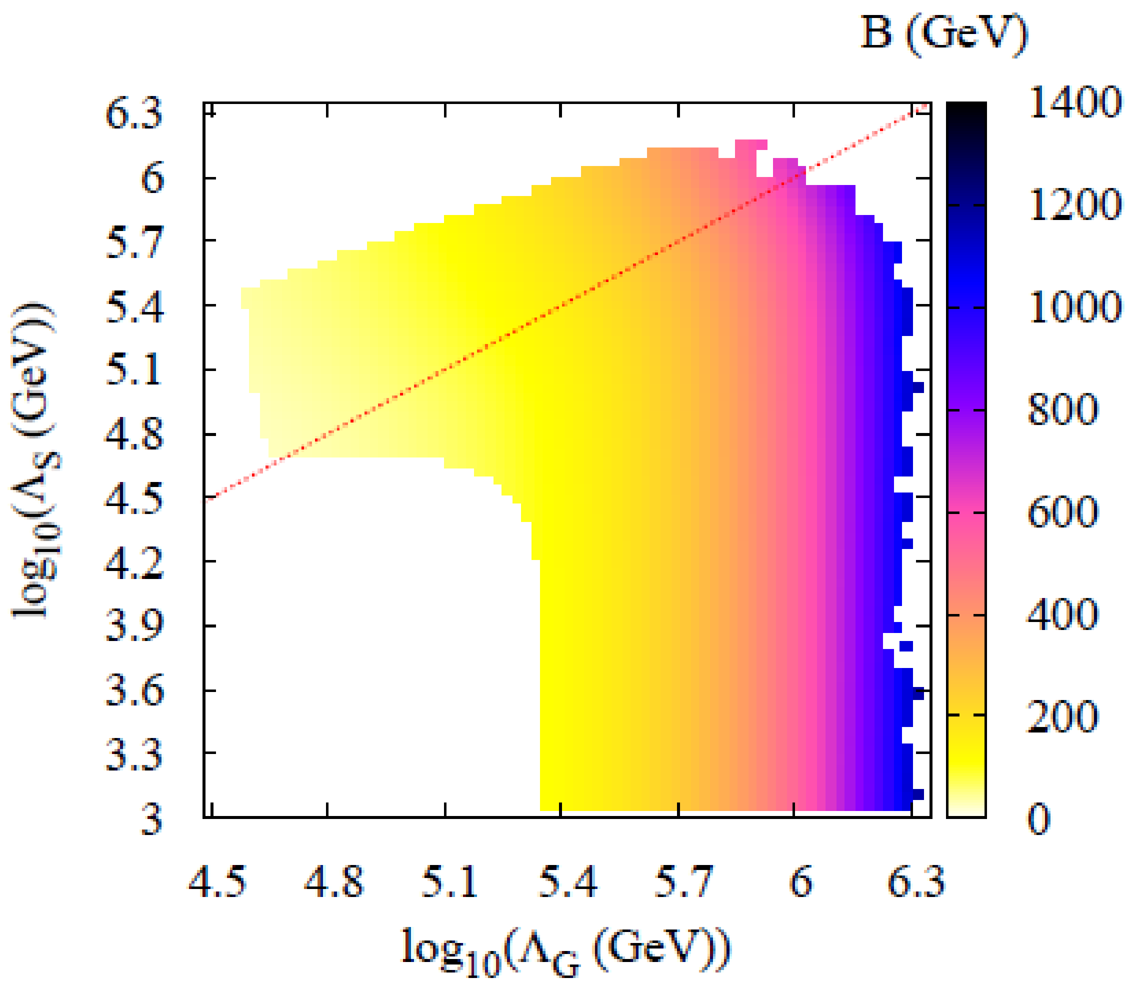
$$M_{\tilde{\lambda}_i}(M_{mess}) = k_i \frac{\alpha_i(M_{mess})}{4\pi} \Lambda_G$$

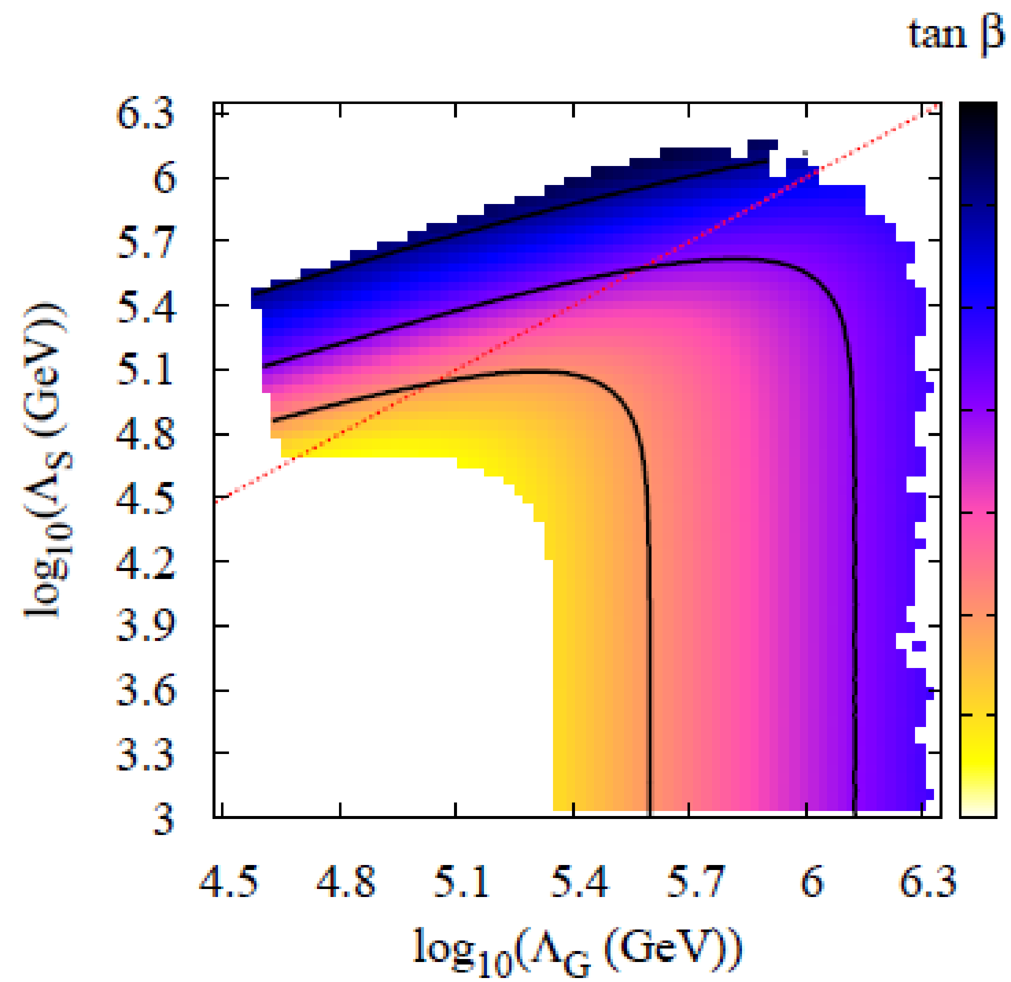
$$m^2_{\tilde{f}}(M_{mess}) = 2 \sum_{i=1}^{3} C_i k_i \frac{\alpha_i^2(M_{mess})}{(4\pi)^2} \Lambda_S^2$$

where C's are quadratic Casimir operators of gauge groups, $k_i = (5/3, 1, 1)$ and $k_i \alpha_i$ are equal at the GUT scale.

B and tan beta at low energy

e.g. take intermediate messenger scale: $M_{mess} = 10^{10}$ GeV ***(SoftSUSY***: Allanach)





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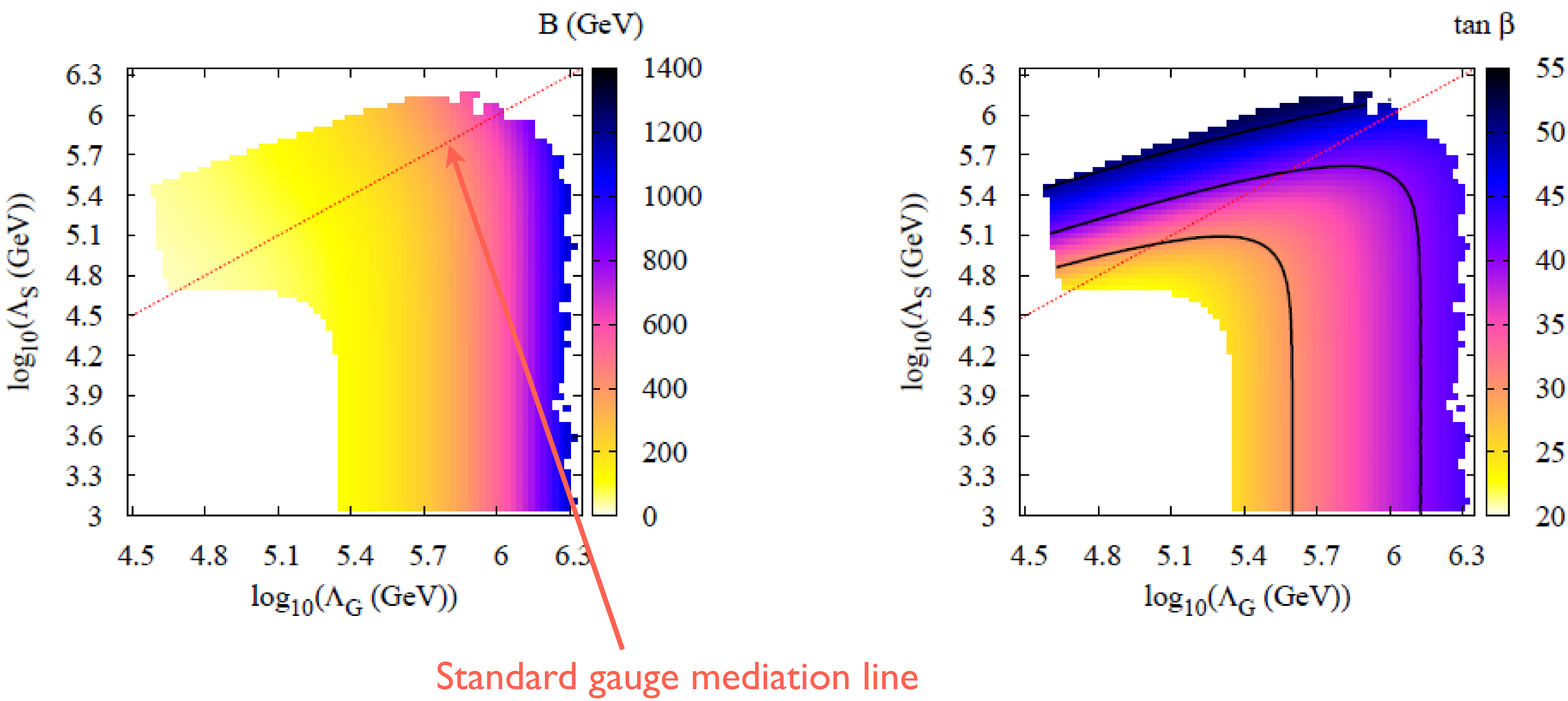

B and tan beta at low energy

Direct mediation with spontaneous R-breaking

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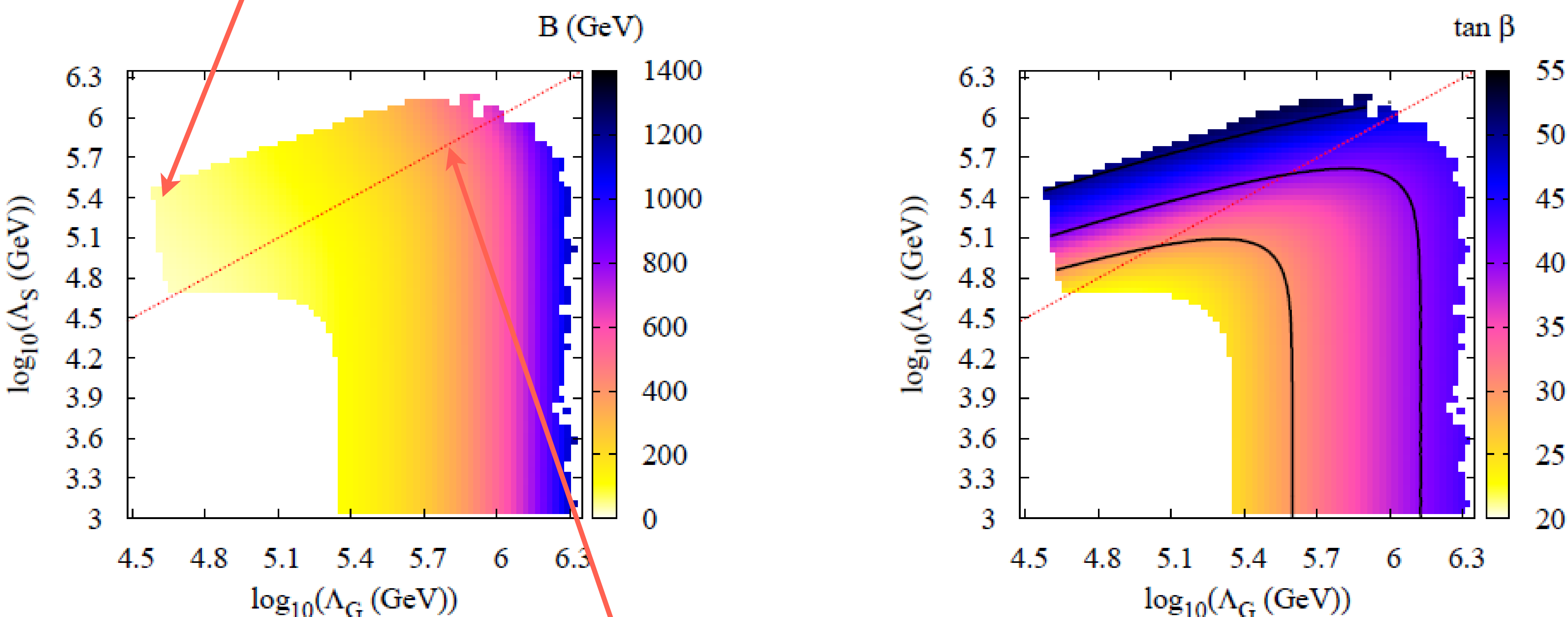

Standard gauge mediation line

B and tan beta at low energy

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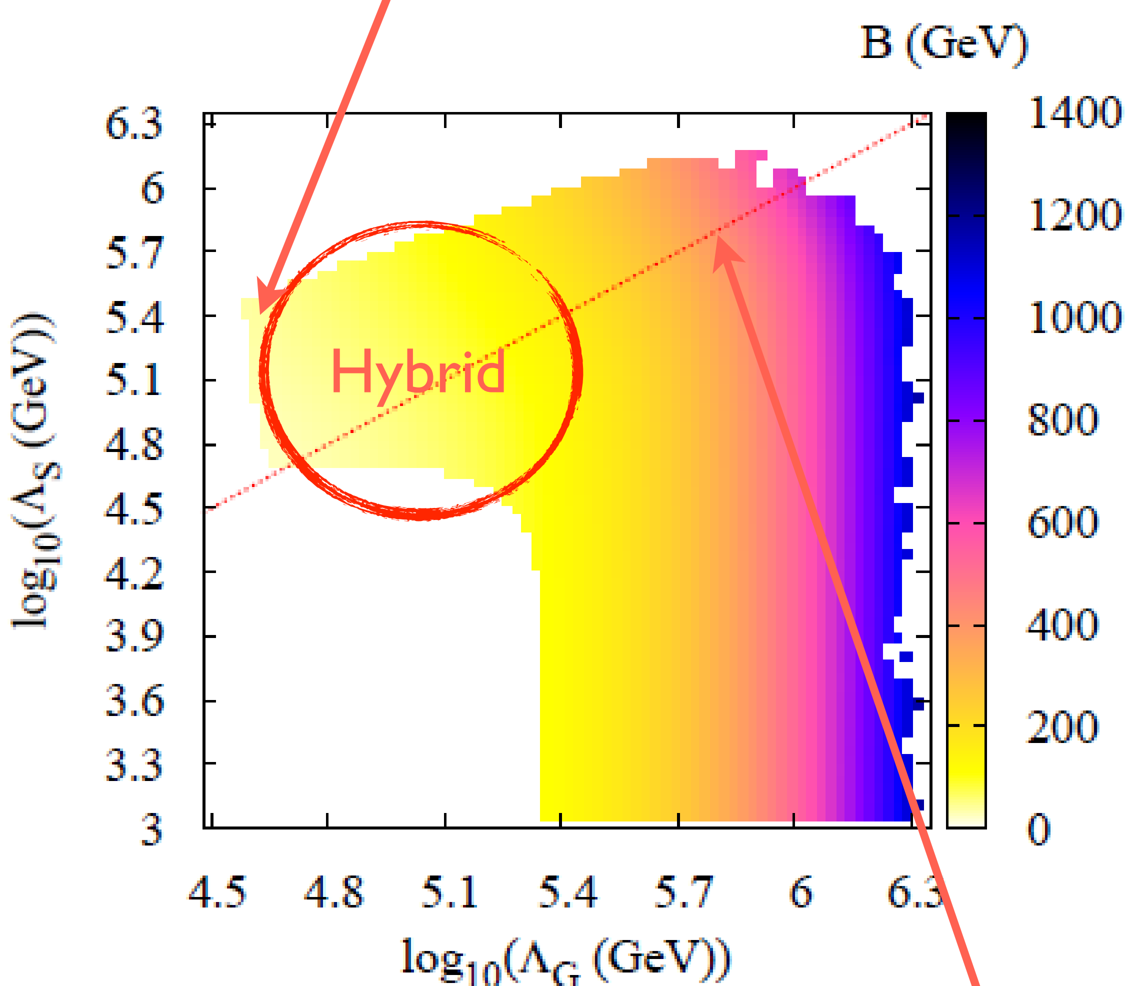

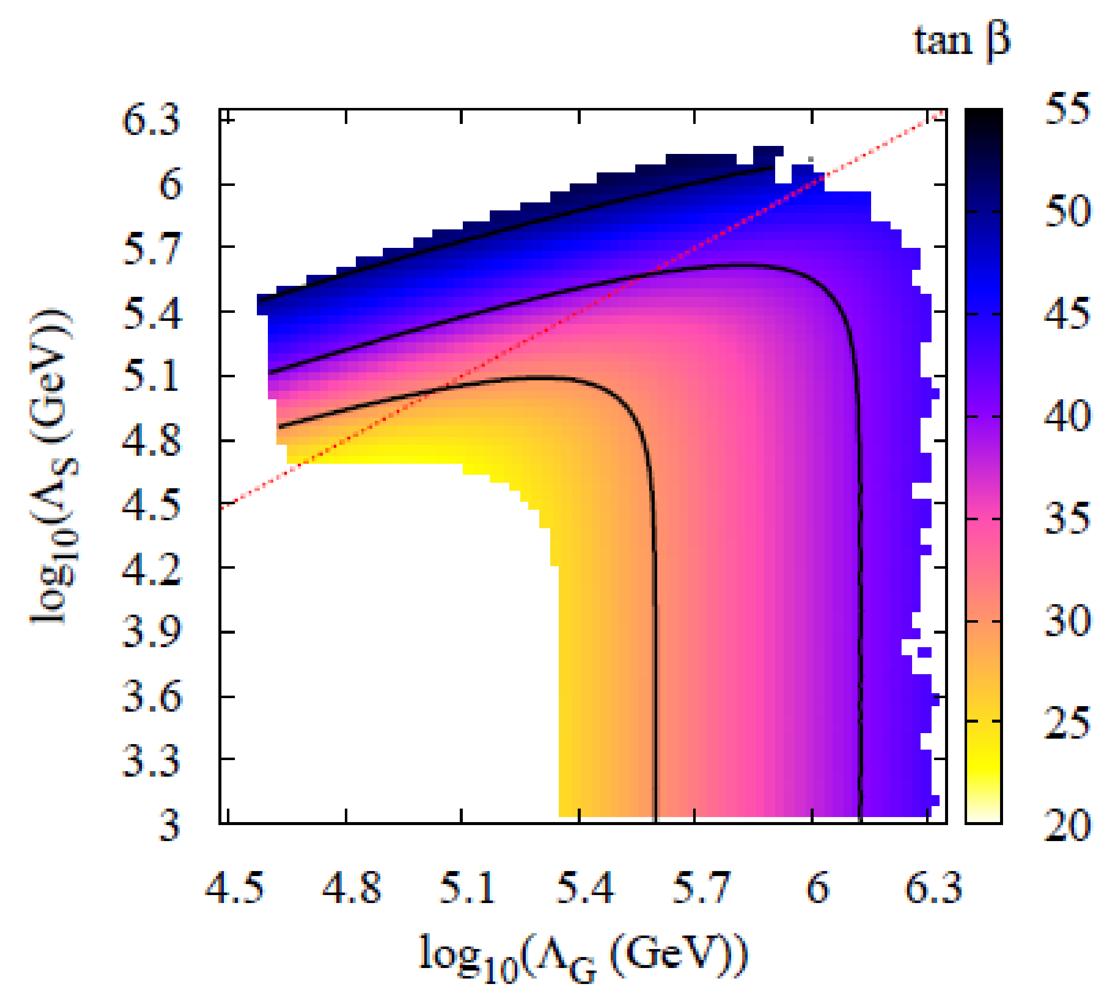

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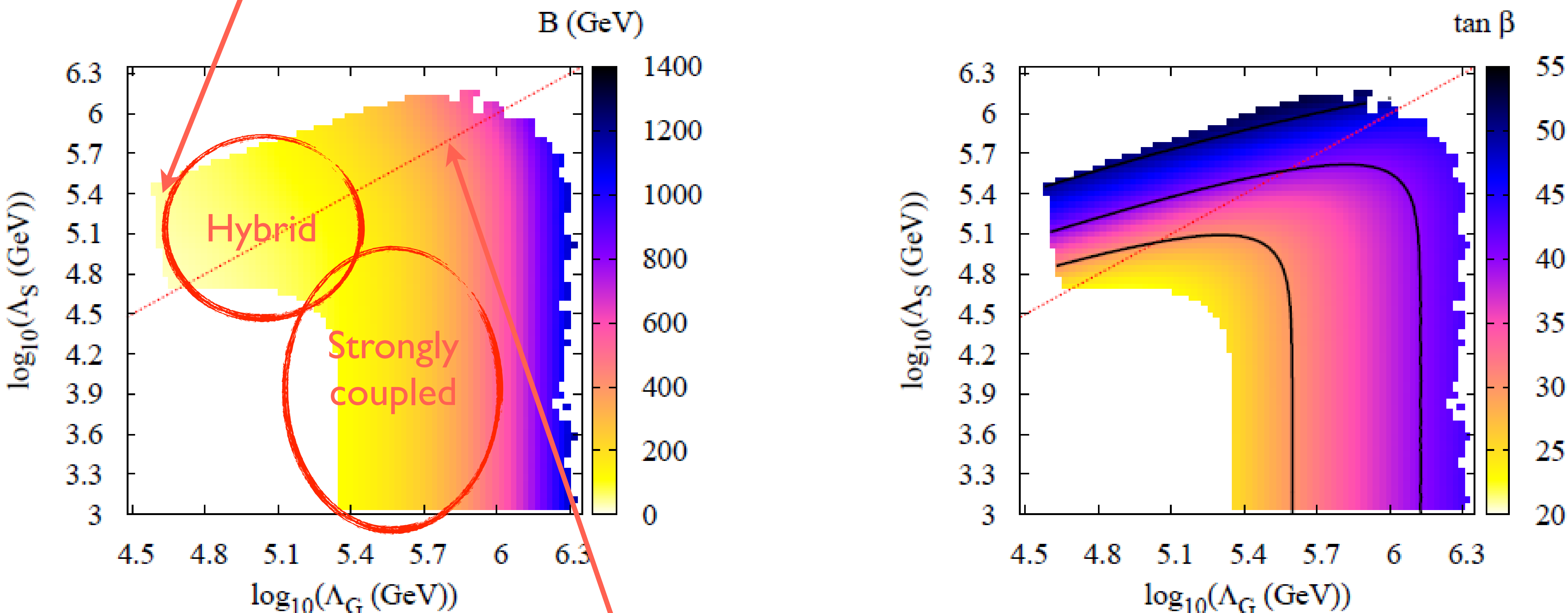


Standard gauge mediation line

Exclusions

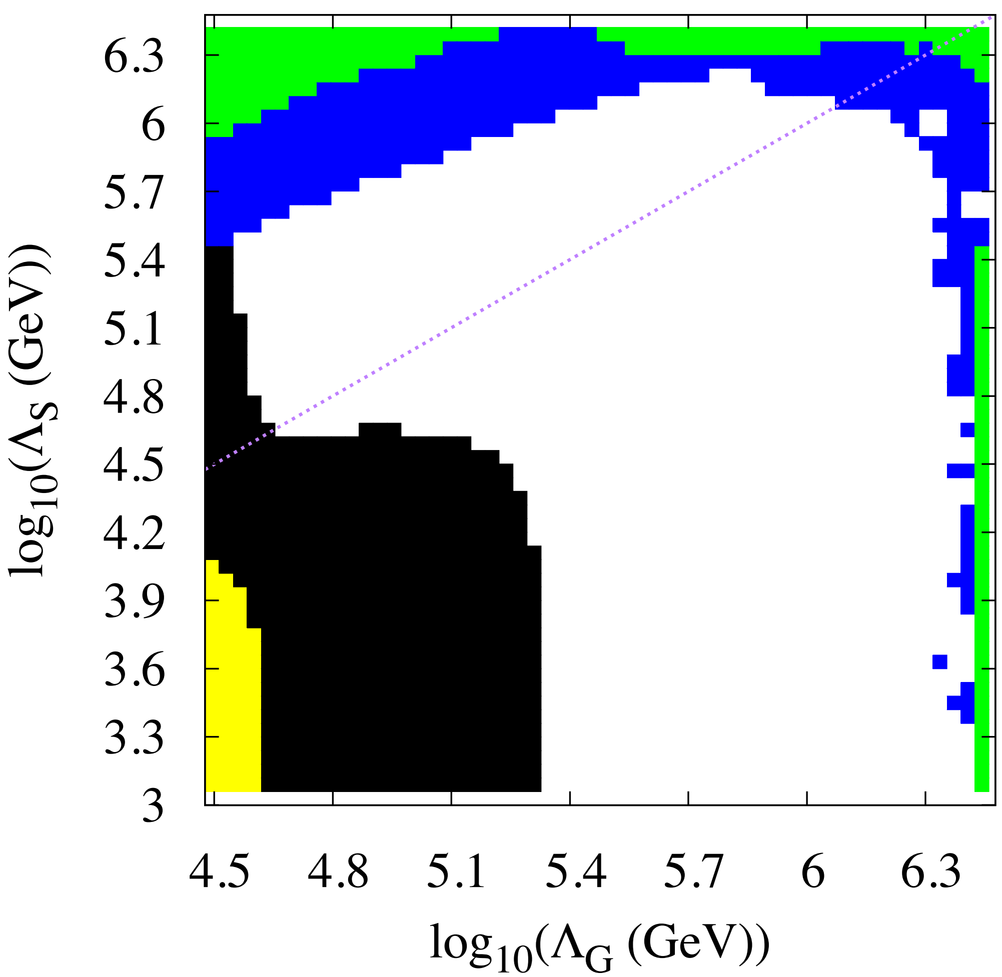


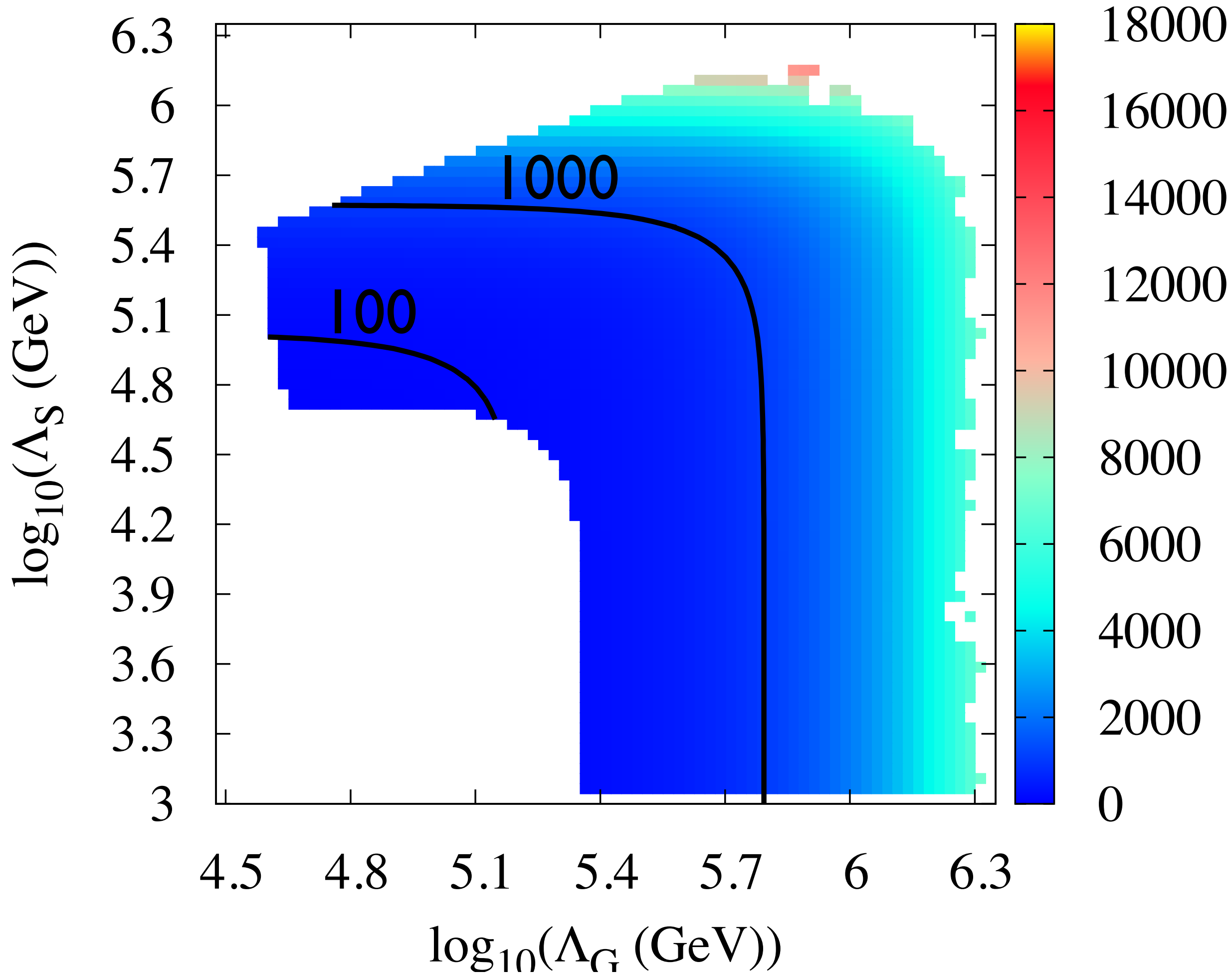
Figure 1: Pure GGM parameter space for intermediate messenger scales, $M_{\mathrm{mess}} = 10^{10}$ GeV. The dominant constraints excluding various areas around the allowed (white) region are indicated as follows: points in the black region violate the pre-LHC direct search limits, while yellow area is excluded by the presence of tachyons in the spectrum. In the blue region SoftSUSY has not converged and in the green region a coupling reaches a Landau pole during RG evolution. Ordinary gauge mediation lives on the dotted line.

Fine tuning

Dominated by scalar masses which decrease when either Λ_G or Λ_S decrease.
So starting at the line of standard gauge mediation and going to the split scenario by decreasing Λ_G does not increase tuning

$$c_a \equiv \left| \frac{\partial \ln M_Z^2}{\partial \ln a} \right|$$

(Barbieri, Strumia; de Carlos, Casas)



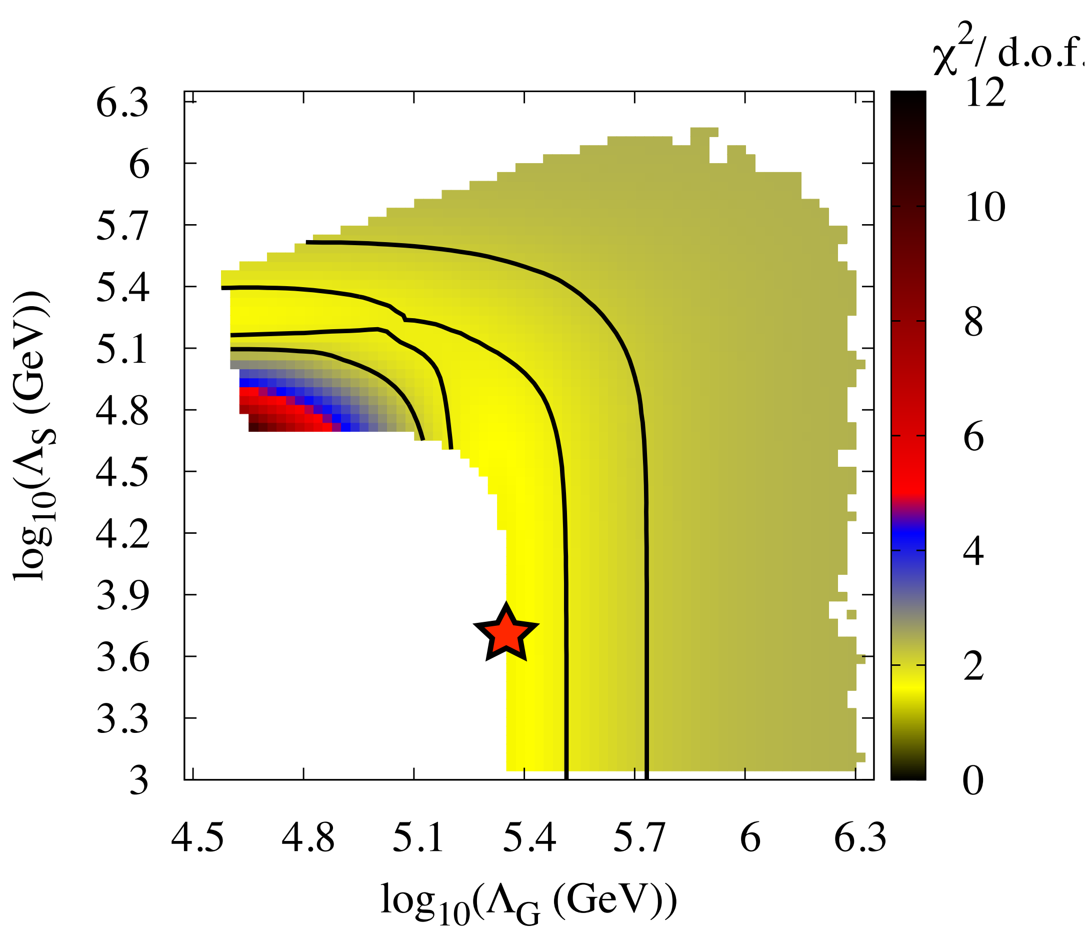
Experimental constraints

To compare with Normal Gauge mediation, look at general scalar and gaugino masses in gauge mediation and apply experimental bounds ...

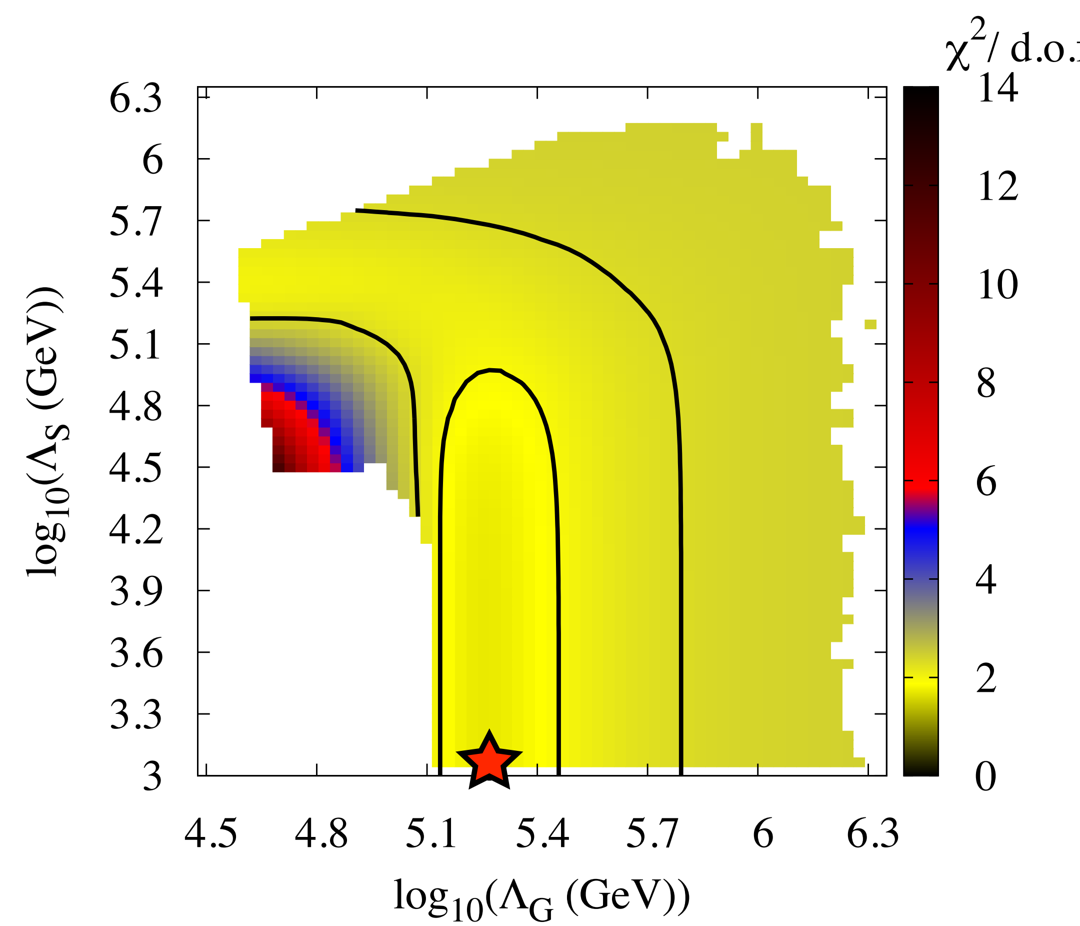
Observable	Constraint
$\delta a_\mu \times 10^{10}$	29.5 ± 8.8
$m_h[\mathrm{GeV}]$	> 114.4 GeV
$BR(B \to X_s \gamma) \times 10^4$	3.28 ± 0.29
$BR(B_s \to \mu^+ \mu^-)$	$< 5.8 \times 10^{-8}$
$BR(B \to D\tau\nu)$	0.416 ± 0.138
$BR(D_s \to \tau\nu)$	$5.7 \pm 0.5 \times 10^{-2}$
$BR(D_s \to \mu\nu)$	$5.7 \pm 0.5 \times 10^{-3}$
$R_{B\tau\nu}$	1.9 ± 0.60
Δ_{0-}	$0.031^{+0.03}_{-0.025}$
R_{l23}	1.004 ± 0.007

Experimental constraints

Fit doesn't favour degenerate SUSY breaking for scalars and gauginos



messenger scale = 10^{10}



messenger scale = 10^{14}

NLSP

The NLSP can eventually decay to the LSP (the gravitino)

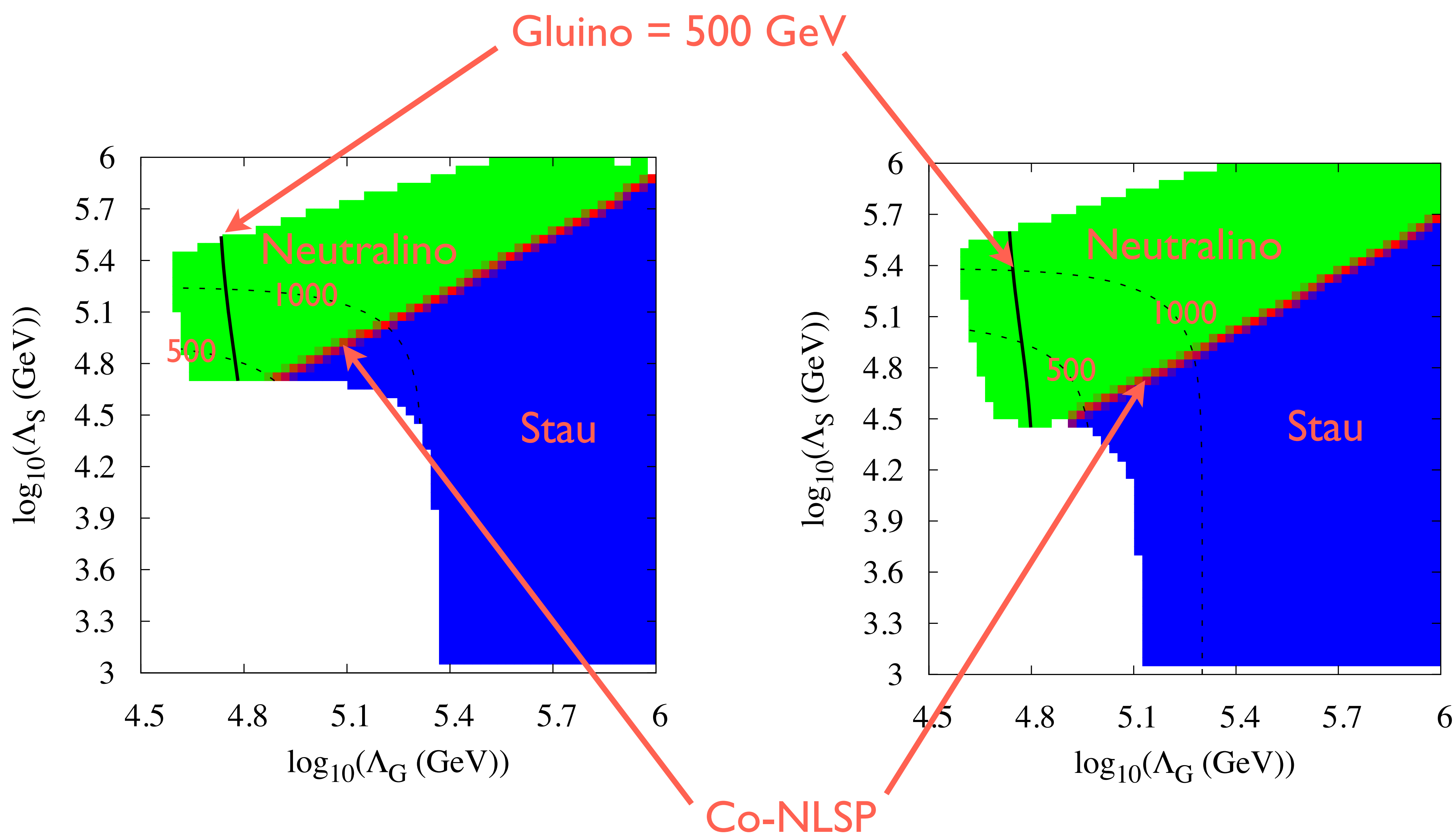
•Neutralino: displaced vertex with decay to photon $(\chi_1^0 \rightarrow \tilde{G}\gamma)$
or jet/lepton pairs $(\chi_1^0 \rightarrow \tilde{G}Z \rightarrow \tilde{G} + jets/l\bar{l})$

•Stau: displaced vertex with ionization track and decay
predominantly to jets $(\tilde{\tau}_R \rightarrow \tilde{G}\tau \rightarrow \tilde{G}\nu_\tau + jets/l'\bar{l})$

•Co-NLSP: neutralino/stau mass difference less than tau-mass - mix of two

NLSP

The NLSP is either neutralino or stau or co-NLSP



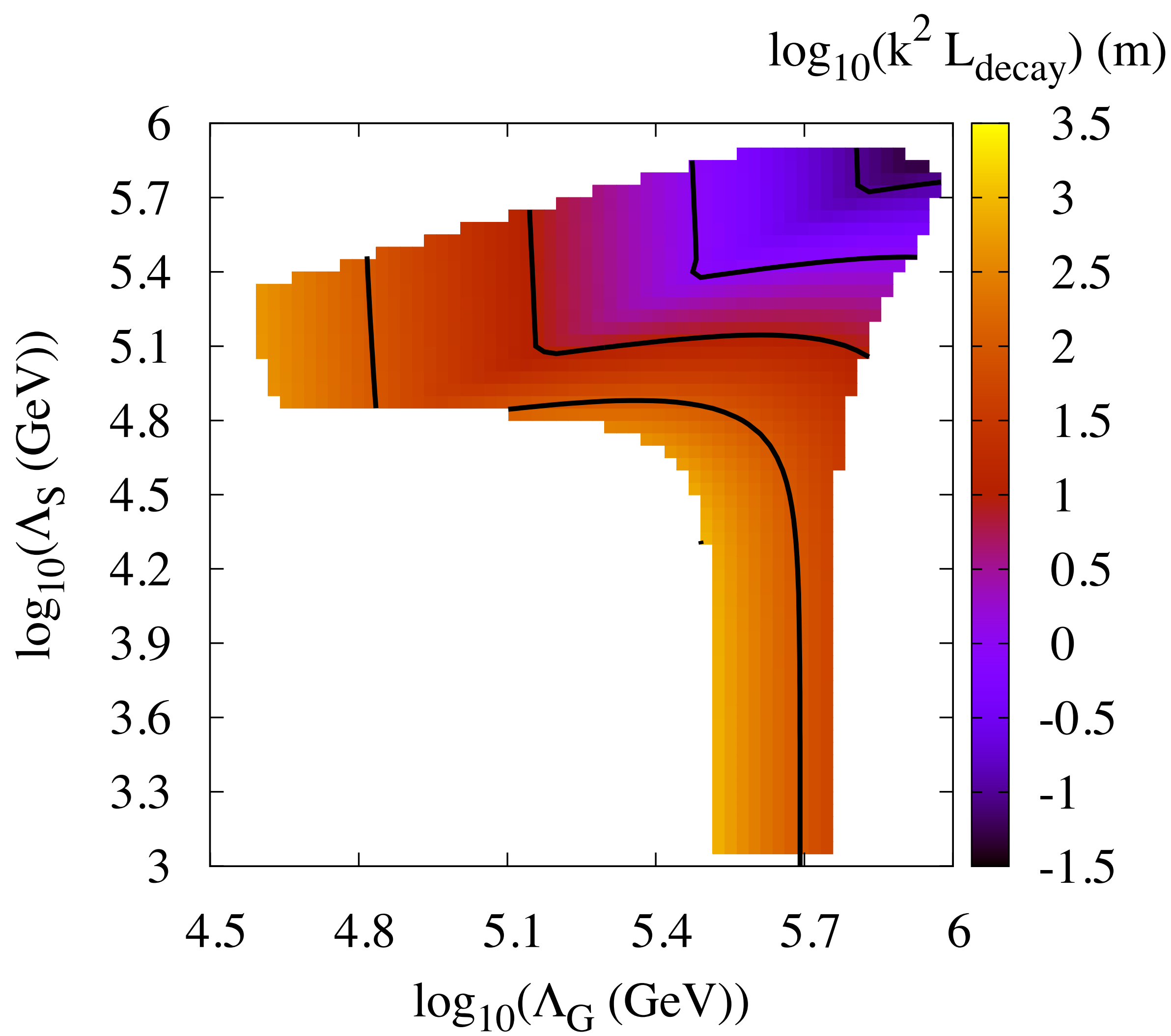
NLSP

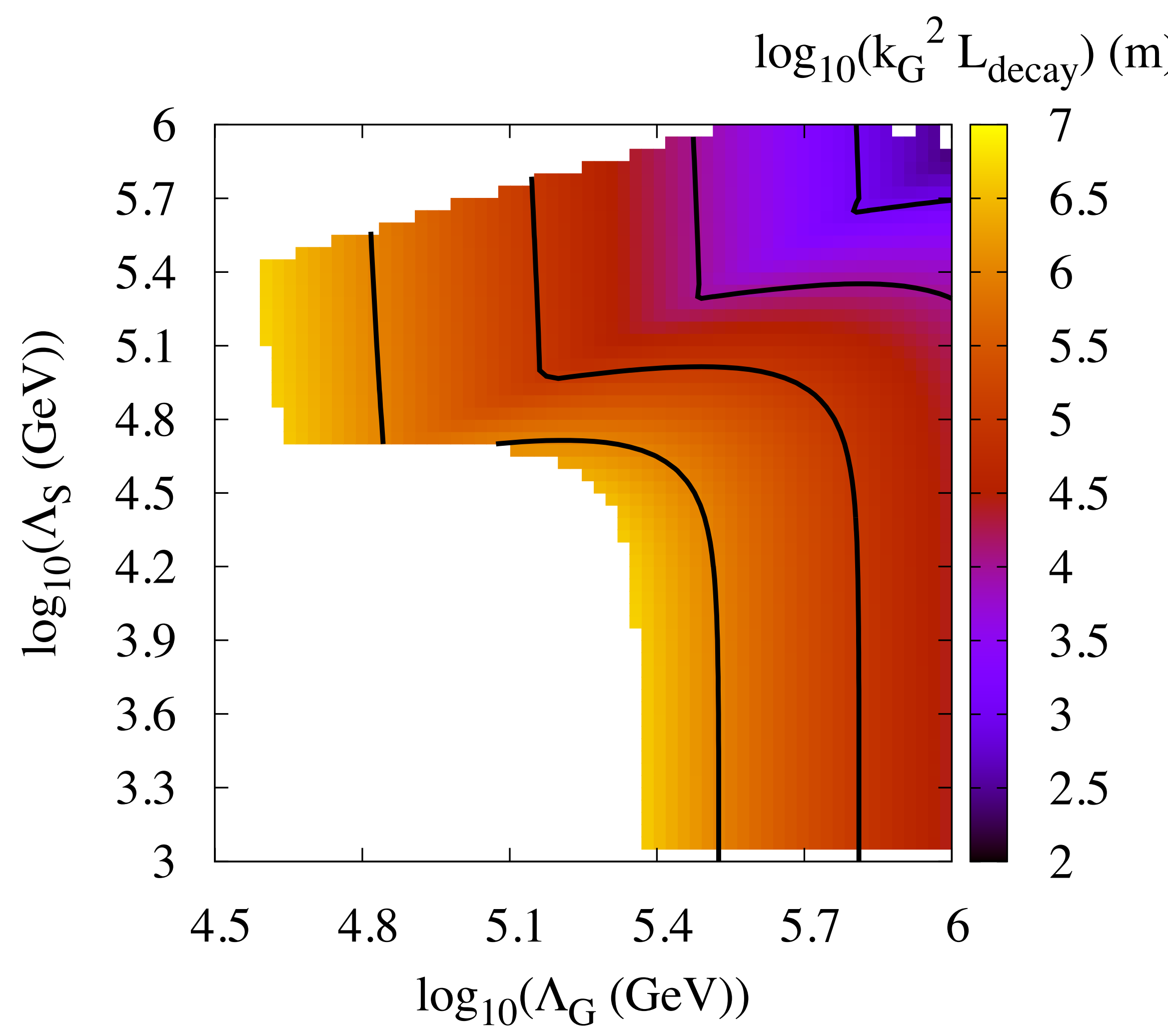
Decay inside detector?

(Bagger Matchev Pierce Zhang)

$$k_G^2 L_{decay} = \frac{1}{\kappa}\left(\frac{100\,\mathrm{GeV}}{m_{NLSP}}\right)^5 \left(\frac{\sqrt{\Lambda_G M_{mess}}}{100\,\mathrm{TeV}}\right)^4 0.1\,\mathrm{mm}$$

where κ is of order one (mixing in NLSP) and k_G is the effective number of messengers to the gaugino ($\Lambda_G = k_G F_0 / M_{mess}$)

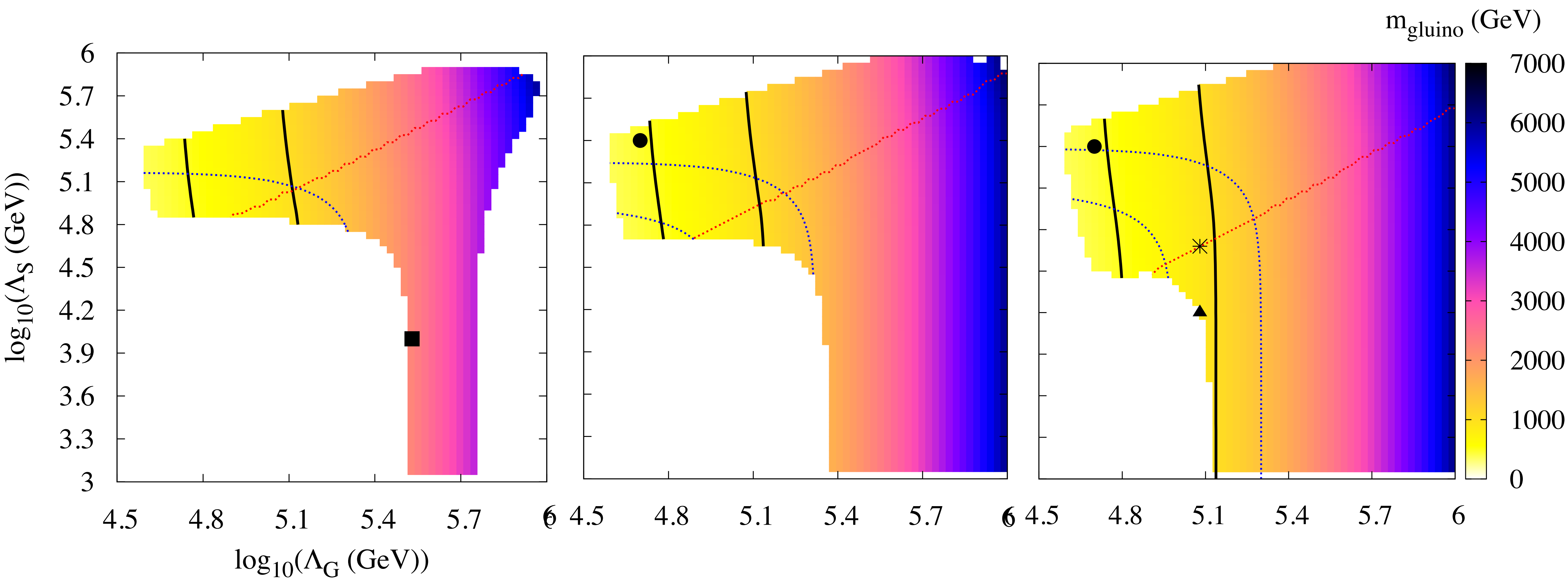




Benchmark points

http://www.ippp.dur.ac.uk/∼SUSY

Two light gluino points (direct mediation), a stau NLSP point (many messengers/ strong coupling) a co-NLSP point (close to ordinary GM) and a NLSP decay point



messenger scale = 10^8 10^{10} 10^{14}

Benchmark point	PGM1a	PGM1b
M_{mess} (GeV)	10^{10}	10^{14}
Λ_G (GeV)	5×10^4	5×10^4
Λ_S (GeV)	2.5×10^5	2.5×10^5
$\tan\beta$	46.6	41.2
χ_1^0	**67**	**67**
χ_2^0	136	133
χ_3^0	1038	936
χ_4^0	1039	938
$\chi_1^\pm$	136	134
$\chi_2^\pm$	1039	937
$\tilde{g}$	**458**	**453**
$\tilde{e}_L, \tilde{\mu}_L$	927	1013
$\tilde{e}_R, \tilde{\mu}_R$	540	712
$\tilde{\tau}_1$	392	544
$\tilde{\tau}_2$	898	964
$\tilde{\nu}_{1,2}$	925	1011
$\tilde{\nu}_3$	889	958

$\tilde{t}_1$	1418	1050
$\tilde{t}_2$	1729	1471
$\tilde{b}_1$	1578	1287
$\tilde{b}_2$	1731	1471
$\tilde{u}_L, \tilde{c}_L$	2011	1760
$\tilde{u}_R, \tilde{c}_R$	1803	1520
$\tilde{d}_L, \tilde{s}_L$	1983	1734
$\tilde{d}_R, \tilde{s}_R$	1774	1460
h_0	116.9	115.3
A_0, H_0	944	1032
$H^\pm$	947	1035

Benchmark points

http://www.ippp.dur.ac.uk/~SUSY

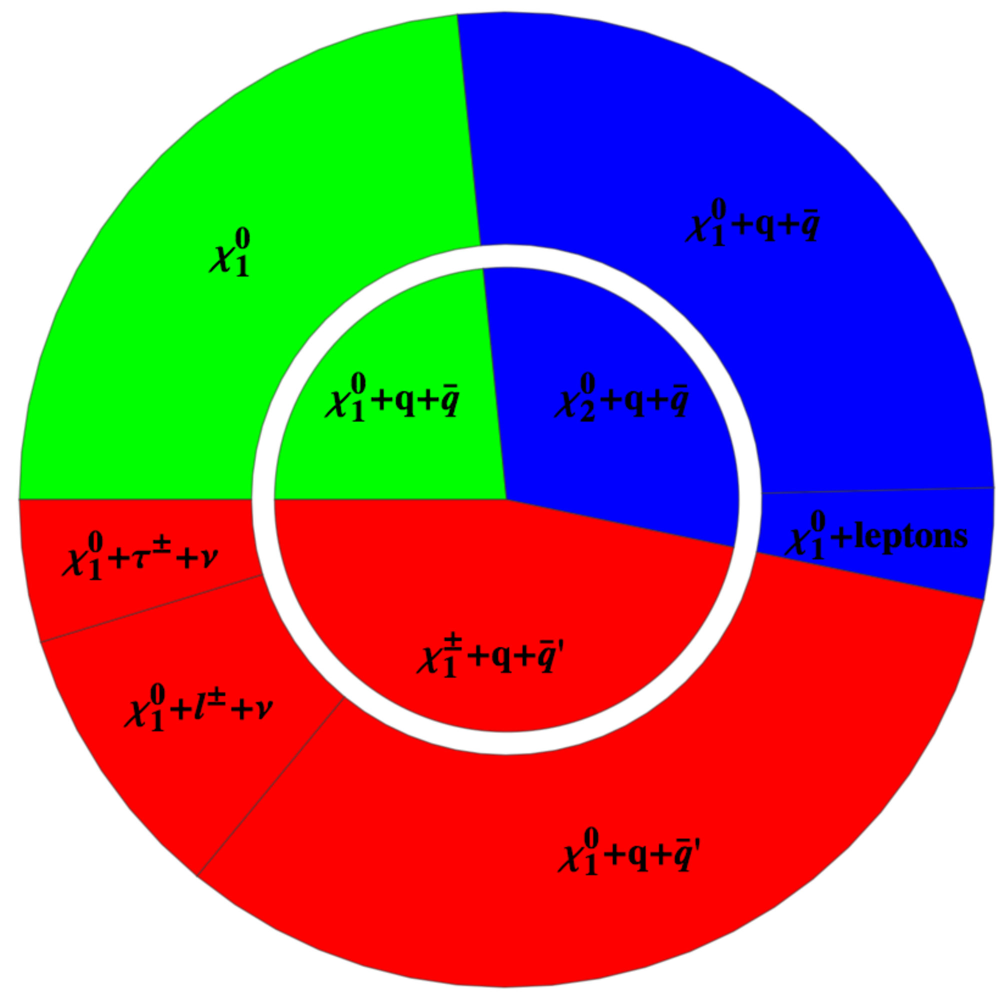
Production at 7TeV: most important processes (***Prospino2.1***:Beenakker, Hopker Spira Plehn)

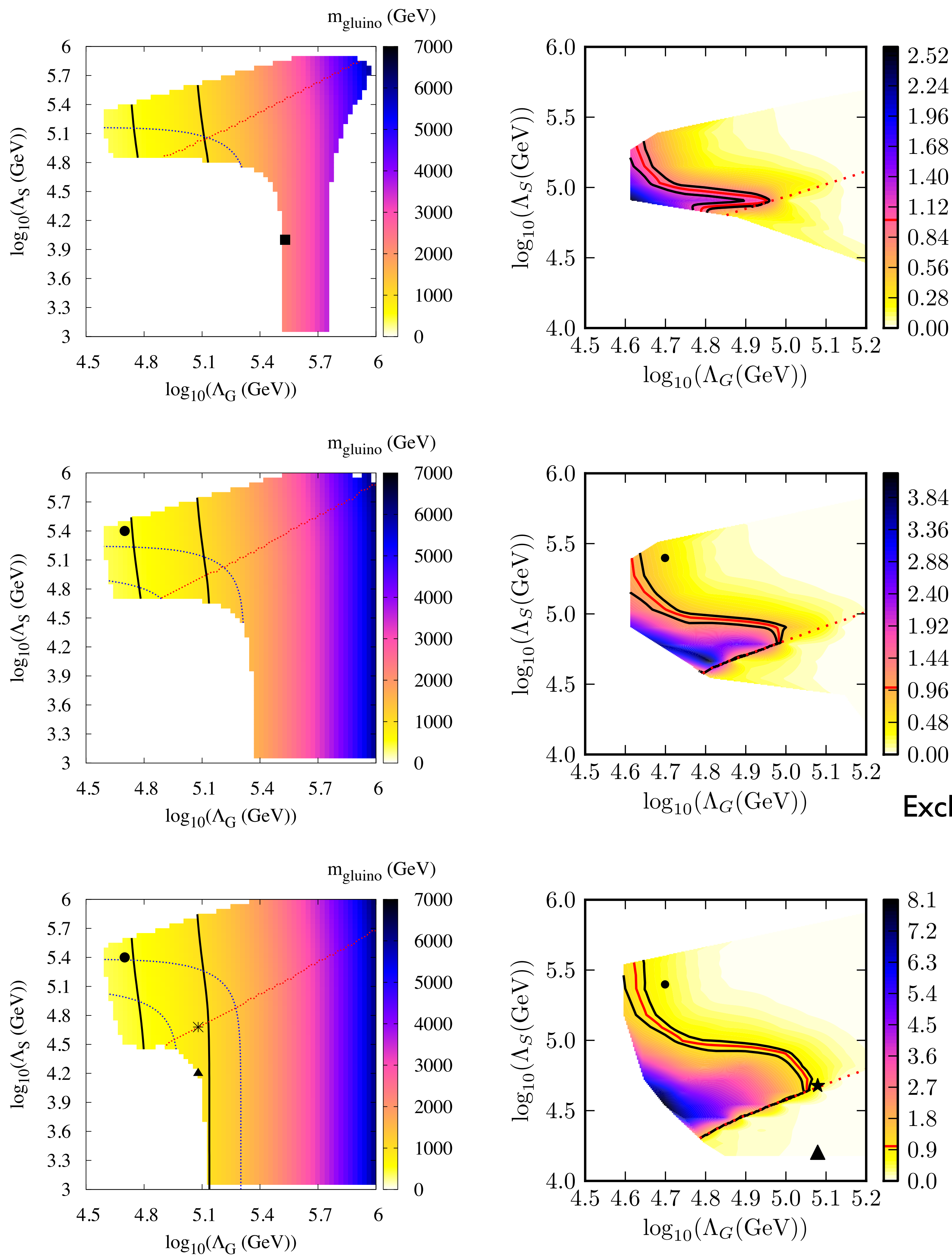
Benchmark Point	$\sigma_{pp\to\tilde{g}\tilde{g}}$	$\sigma_{pp\to\chi_2^0\chi_1^\pm}$	$\sigma_{pp\to\chi_1^+\chi_1^-}$	$\sigma_{pp\to\tilde{g}\tilde{q}}$
PGM1a	4090	2682	1320	18.9
PGM1a	4340	2835	1390	58.7

Benchmark Point	$\sigma_{pp\to\tilde{g}\tilde{g}}$	$\sigma_{pp\to\tilde{q}\tilde{q}}$	$\sigma_{pp\to\tilde{g}\tilde{q}}$	$\sigma_{pp\to\tilde{q}\bar{\tilde{q}}}$	$\sigma_{pp\to\tilde{\tau}_i\tilde{\tau}_j}$	$\sigma_{pp\to\chi_2^0\chi_1^\pm}$
Stau	17	190	164	54	91	49
Co-NLSP	16	133	128	34	17	50

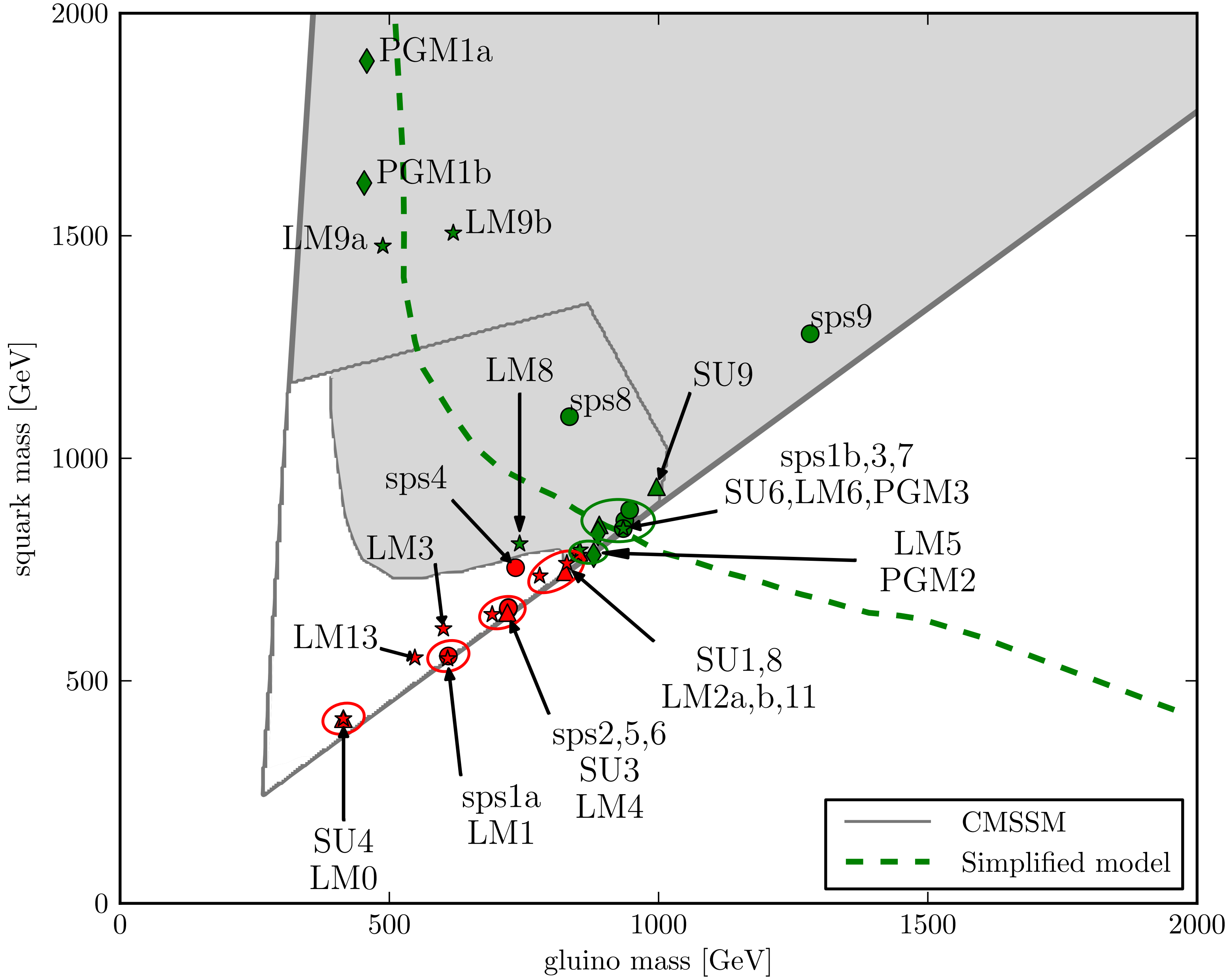
Decays of gluino:

(***SUSY-HIT***:Djouadi Muehlleitner Spira)





Exclusion plots at 35/pb: Dolan, Grellscheid, Jaeckel, Khoze, Richardson



(Dolan, Grellscheid, Jaeckel, Khoze, Richardson)

Figure 5: This plot shows constraints on the CMSSM for $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$ mapped into the plane of the physical squark (average of first generation) and gluino masses. The kite-shaped area shows the same region of parameter space as in Fig. 3. The grey area is still allowed, whereas the white region inside the kite is now excluded by the ATLAS measurements [3]. The region below the diagonal $m_{\tilde{g}} \lesssim m_{\tilde{q}}$ is not part of the CMSSM parameter space due to the influence of the gluino mass on the squark masses during the RG evolution. The dashed green line gives the constraints obtained from a simplified model (containing only squarks and gluinos and a massless neutralino) in [3]. The reduced sensitivity in the CMSSM is mainly due to the non-negligible neutralino mass. The labelled points are the benchmark points of Tab. 1. Red points are now excluded whereas green points are still viable.

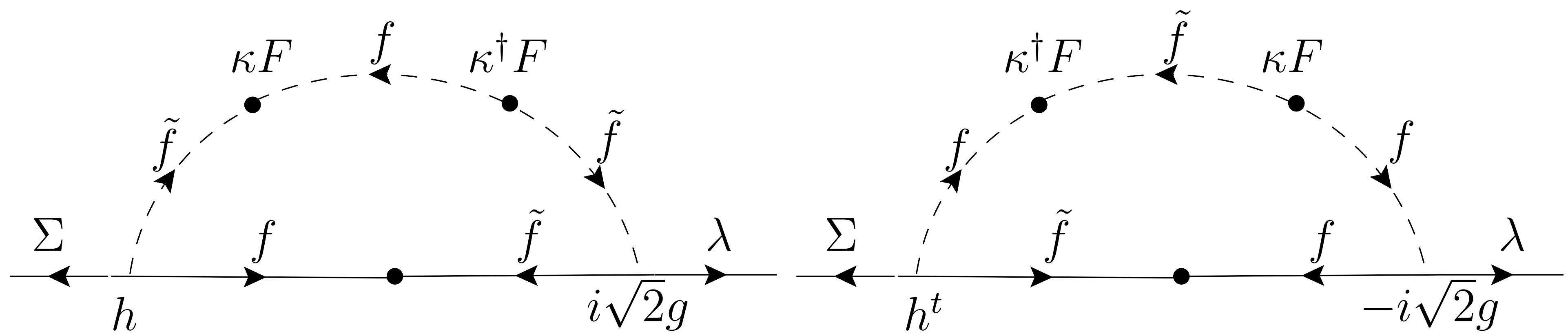
Deconstructed gaugino mediation and Dirac gauginos (w/ Mark Goodsell)

Dirac gauginos

- Majorana masses and SUSY breaking in conflict (R-symmetry/metastability)
- R-symmetry can protect the proton
- Find reduced FCNC's, eliminates EDM problem
- Different pheno. (Choi, Drees, Freitas, Zerwas ... Belanger, Benakli, Goodsell, Moura, Pukhov)

Dirac gauginos

- To get Dirac masses need to introduce chiral fields in adjoint for every gauge group
- The masses are of order $\mathcal{O}(F^2/M^3)$



- Note that this is *better than non-metastable Majorana models*
- *However still have a general problem with too light gauginos*

Dirac gauginos

- A second potential problem: for the scalars find

$$\begin{aligned}\mathcal{L} \supset & - m_\Sigma^2 \Sigma^a \overline{\Sigma}^a - \frac{B_\Sigma}{2}(\Sigma^a\Sigma^a + \overline{\Sigma}^a\overline{\Sigma}^a) \\ \supset & - \frac{1}{2}(m_\Sigma^2 + B_\Sigma)|\Sigma^a + \overline{\Sigma}^a|^2 - \frac{1}{2}(m_\Sigma^2 - B_\Sigma)|\Sigma^a - \overline{\Sigma}^a|^2\end{aligned}$$

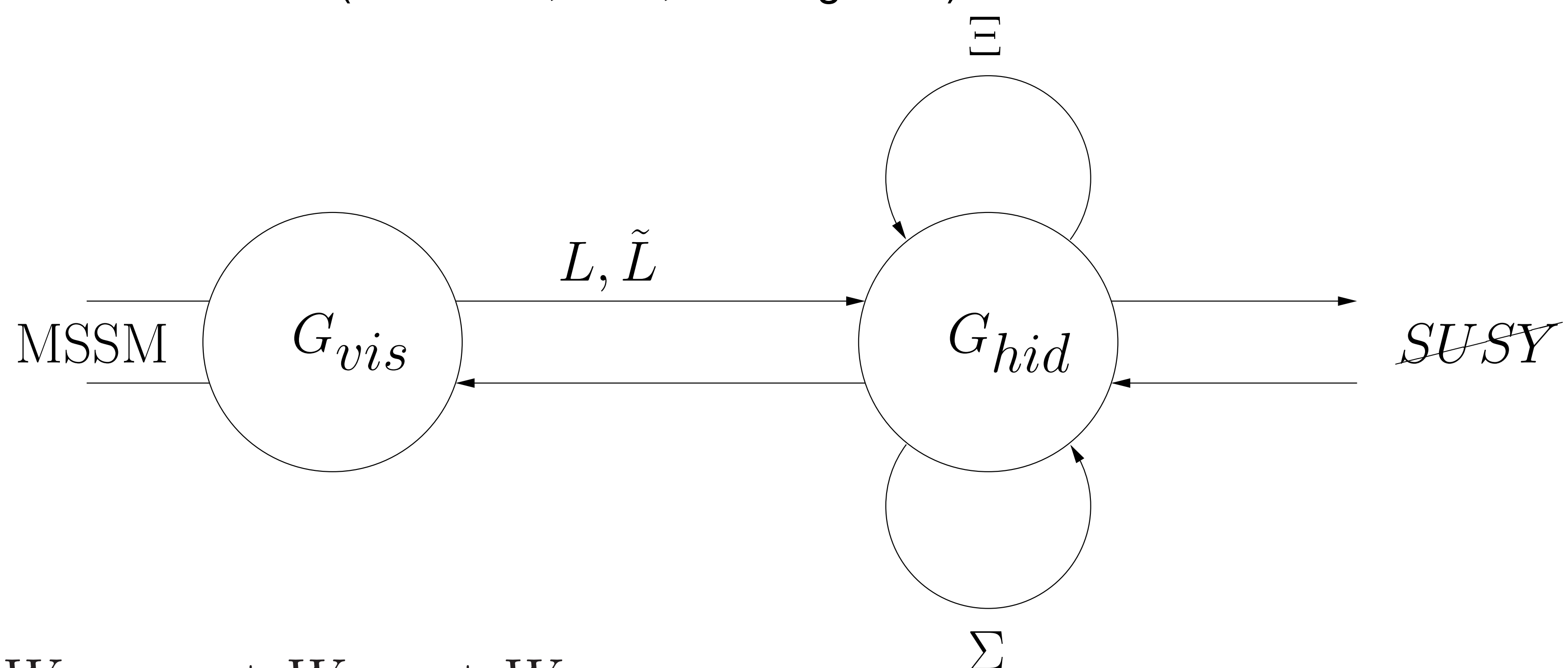
- and typically $B_\Sigma > m_\Sigma^2$
- *tachyons!!*

Dirac gauginos

- A third potential problem: the new adjoints change the beta functions and spoil unification
- Can solve this by adding bachelor fields to make everything SU(5), but need to beware of Landau poles

Dirac gauginos

- A toy model that solves many of these problems is based on deconstructed gaugino mediation (c.f. Green, Katz, Komargodski)



$$W = W_{\text{MSSM}} + W_{\text{higgsing}} + W_{\text{mess}} + W_{\not{SUSY}}$$

$$W_{\text{mess}} = S f_1 \tilde{f}_2 + M(f_1 \tilde{f}_1 + f_2 \tilde{f}_2) + h_1 f_1 \Sigma \tilde{f}_1 + h_2 f_2 \Sigma \tilde{f}_2.$$

$$W_{\text{higgsing}} = K(\frac{1}{5} L\tilde{L} - \mu_\ell^2) + L\Xi\tilde{L} + m\Xi\Sigma$$

- Preserves an R-symmetry $\left\{ \begin{array}{l} R_K = R_S = R_\Xi = R_{f_2} = R_{\tilde{f}_1} = 2 \\ R_\Sigma = R_L = R_{\tilde{L}} = R_{f_1} = R_{\tilde{f}_2} = 0 \end{array} \right.$

Dirac gauginos

- Link fields get VEVs $\langle L\rangle = \langle L\rangle = \mu_\ell,$ << M
- when momentum much larger SSM fields communicate to SUSY breaking at only 4 loops -> ***screening***
- Final light gauge group is diagonal combination of SM groups -> gaugino masses unscreened

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$$m_\lambda \simeq I_f \sqrt{2} h g_r \frac{1}{16\pi^2} \frac{|F|^2}{6M^3} \frac{\mu_\ell}{\sqrt{2(m^2+\mu_\ell^2)}} \,,$$

$$m_{\tilde{f}}^{2-loop} \approx \sum_f C_2(f,r) \frac{\sqrt{2} g_r^2}{16\pi^2} \frac{|F|}{M} \frac{\mu_\ell}{M}$$

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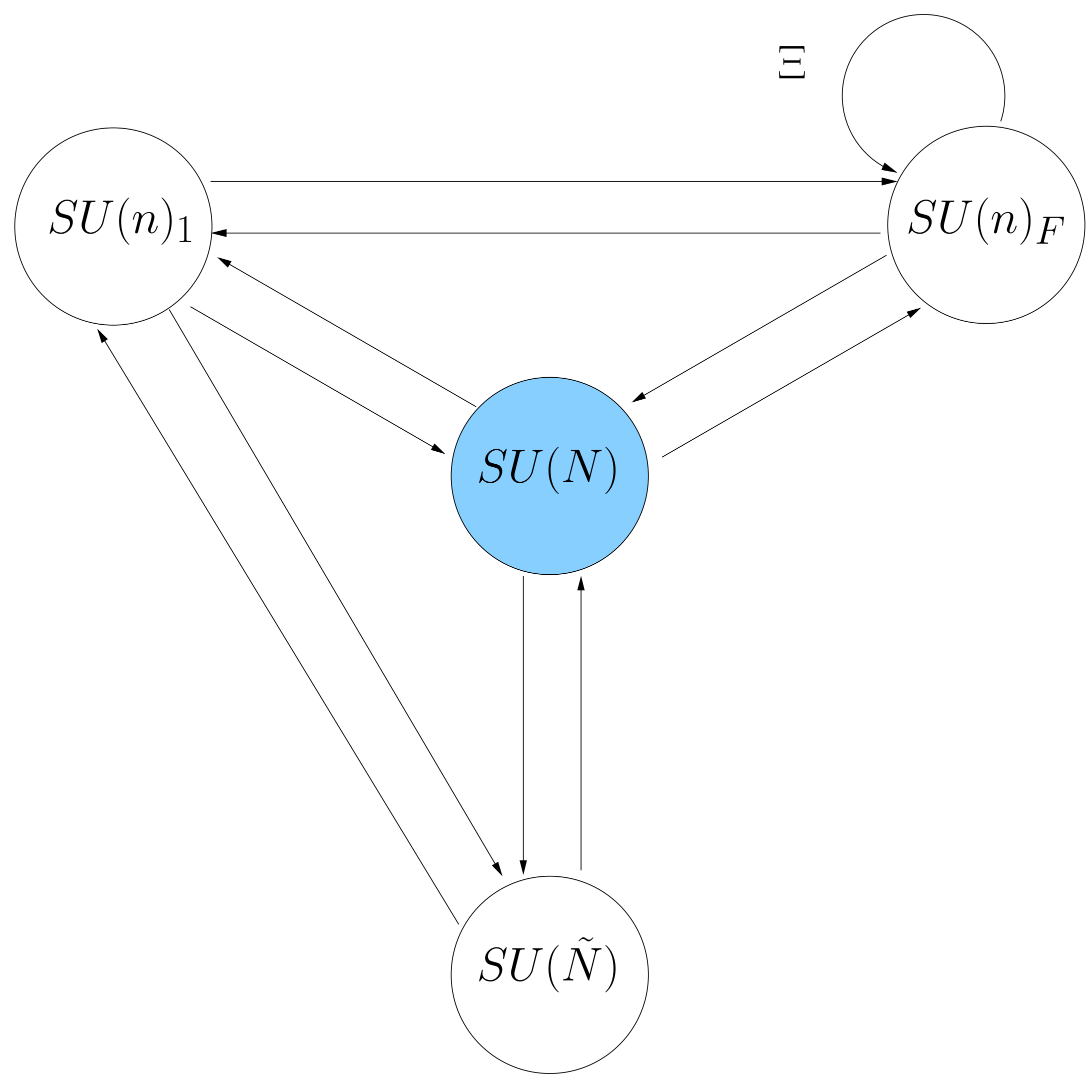
Screening factor

Dirac gauginos

- Full UV completion based in ISS model: May look complicated, but this contains the MSSM plus ***automatically the SUSY breaking, screening***, ***mediating sector, link field and mediation superpotentials!***



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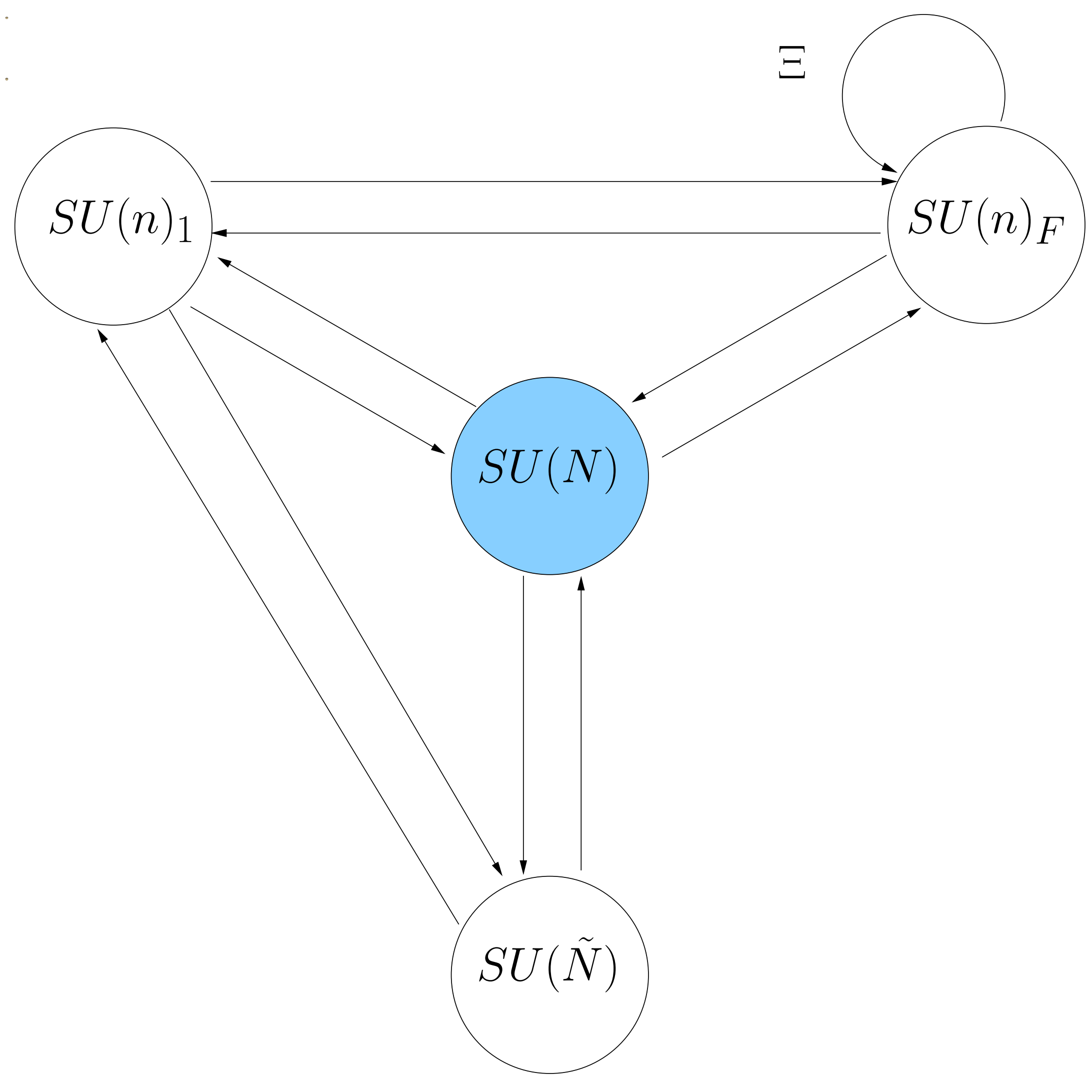

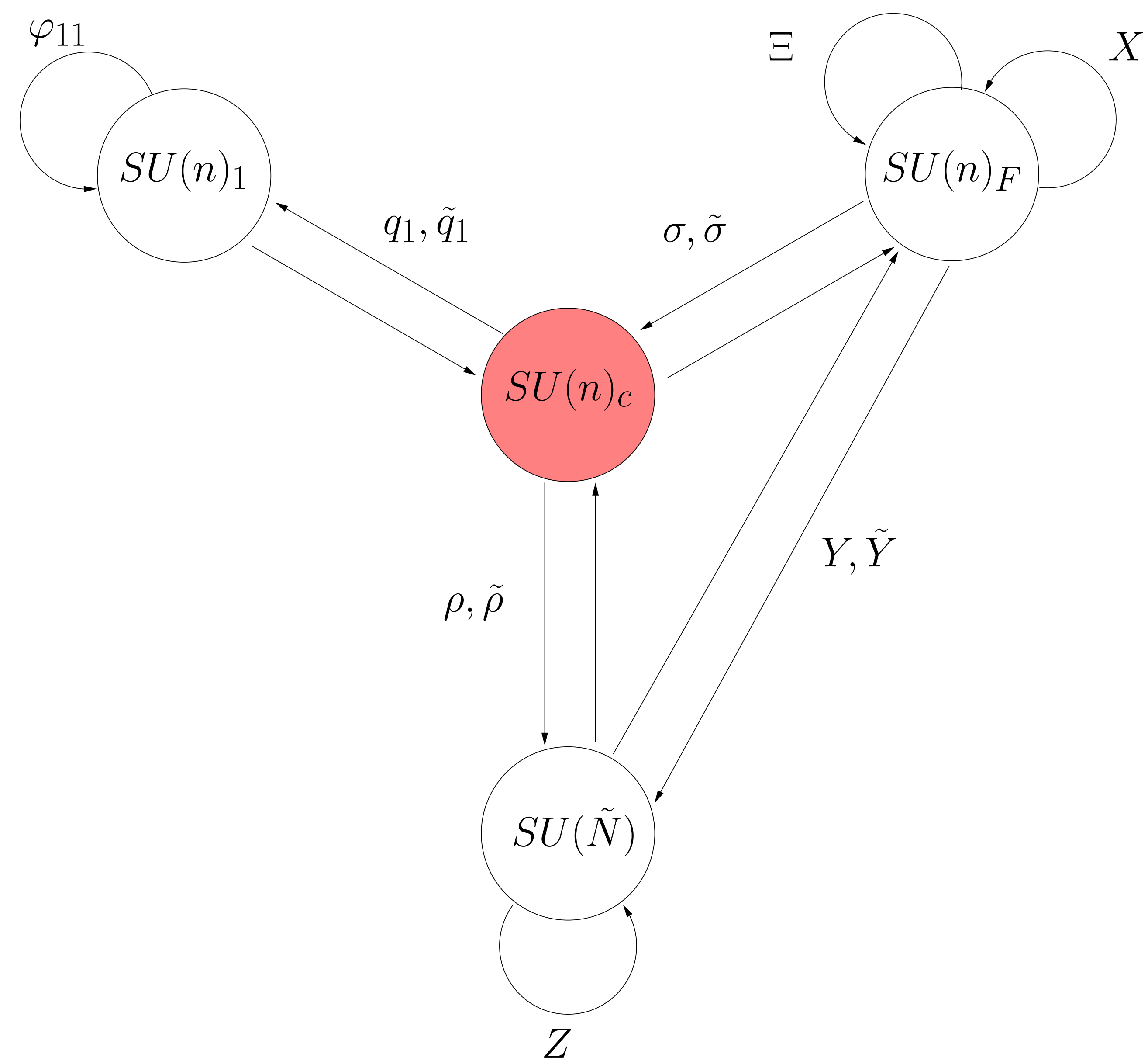

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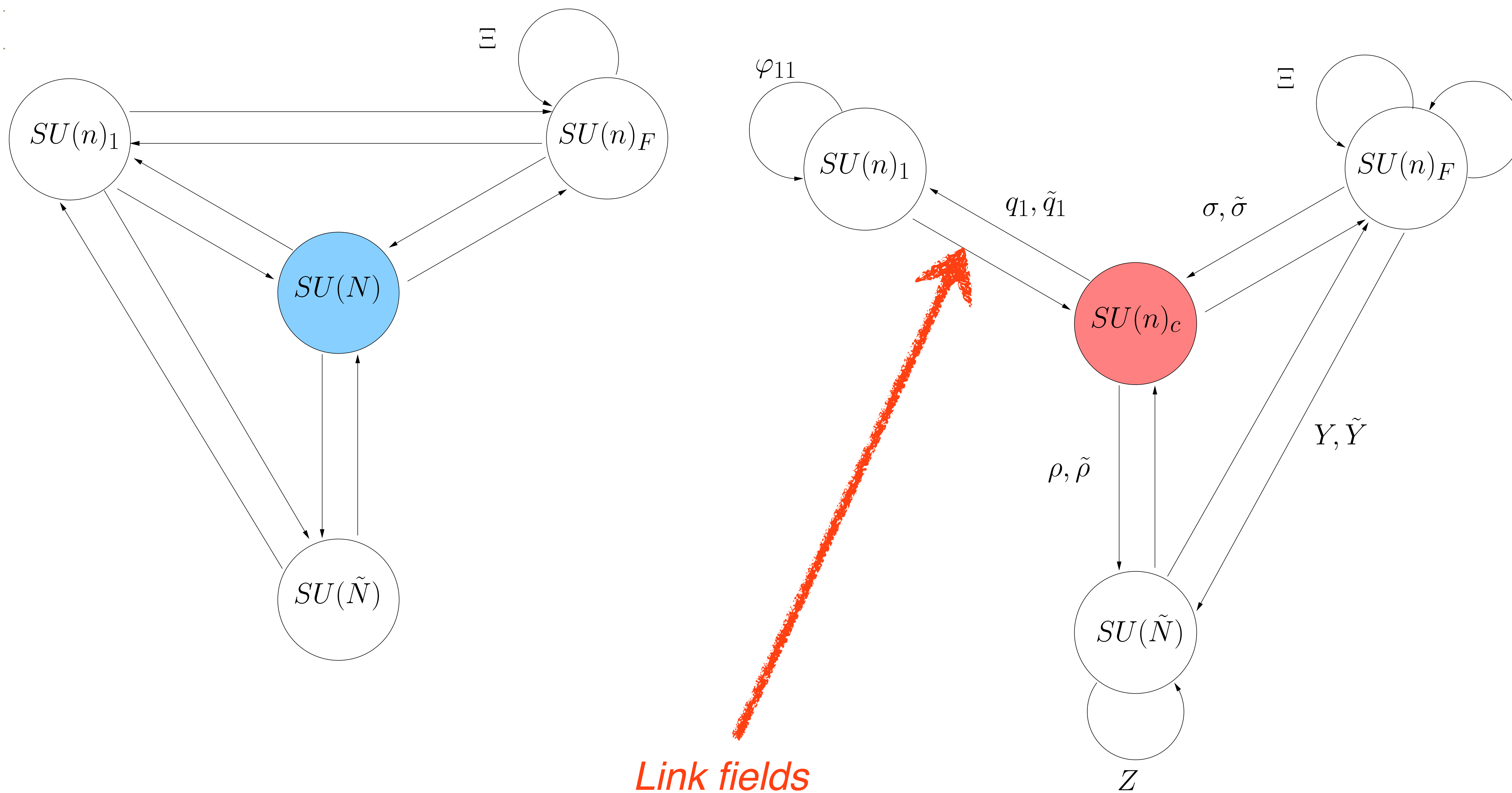

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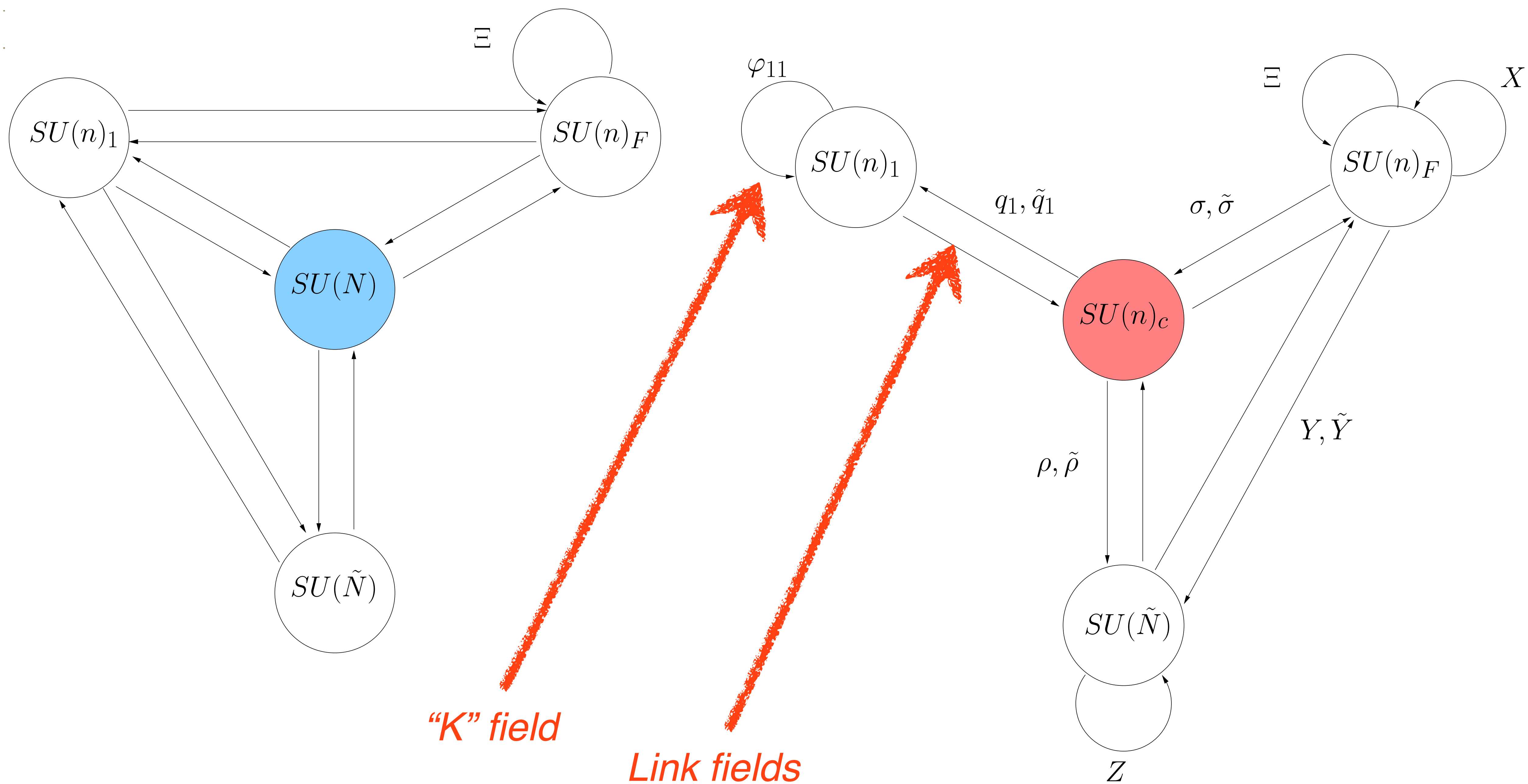

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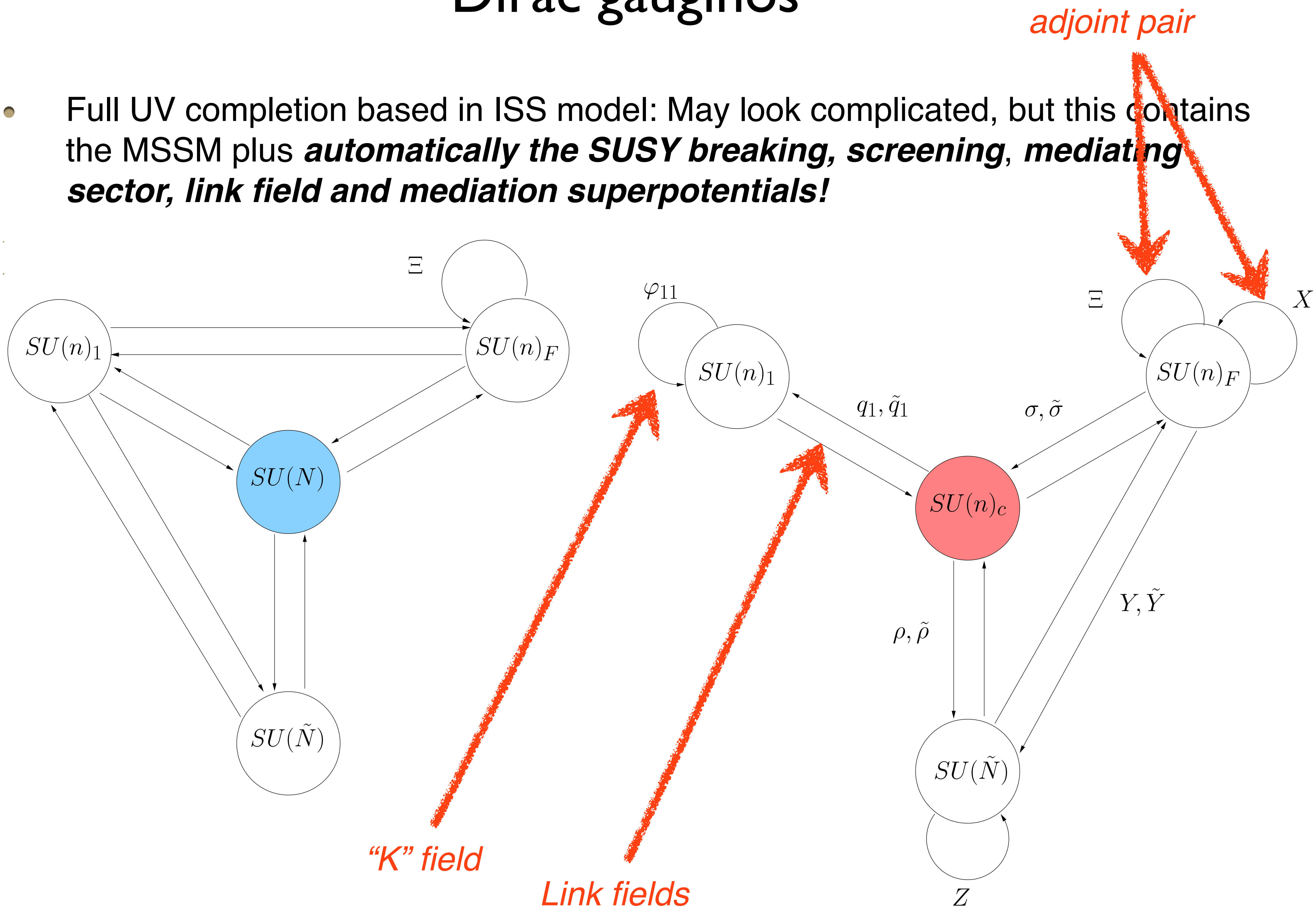

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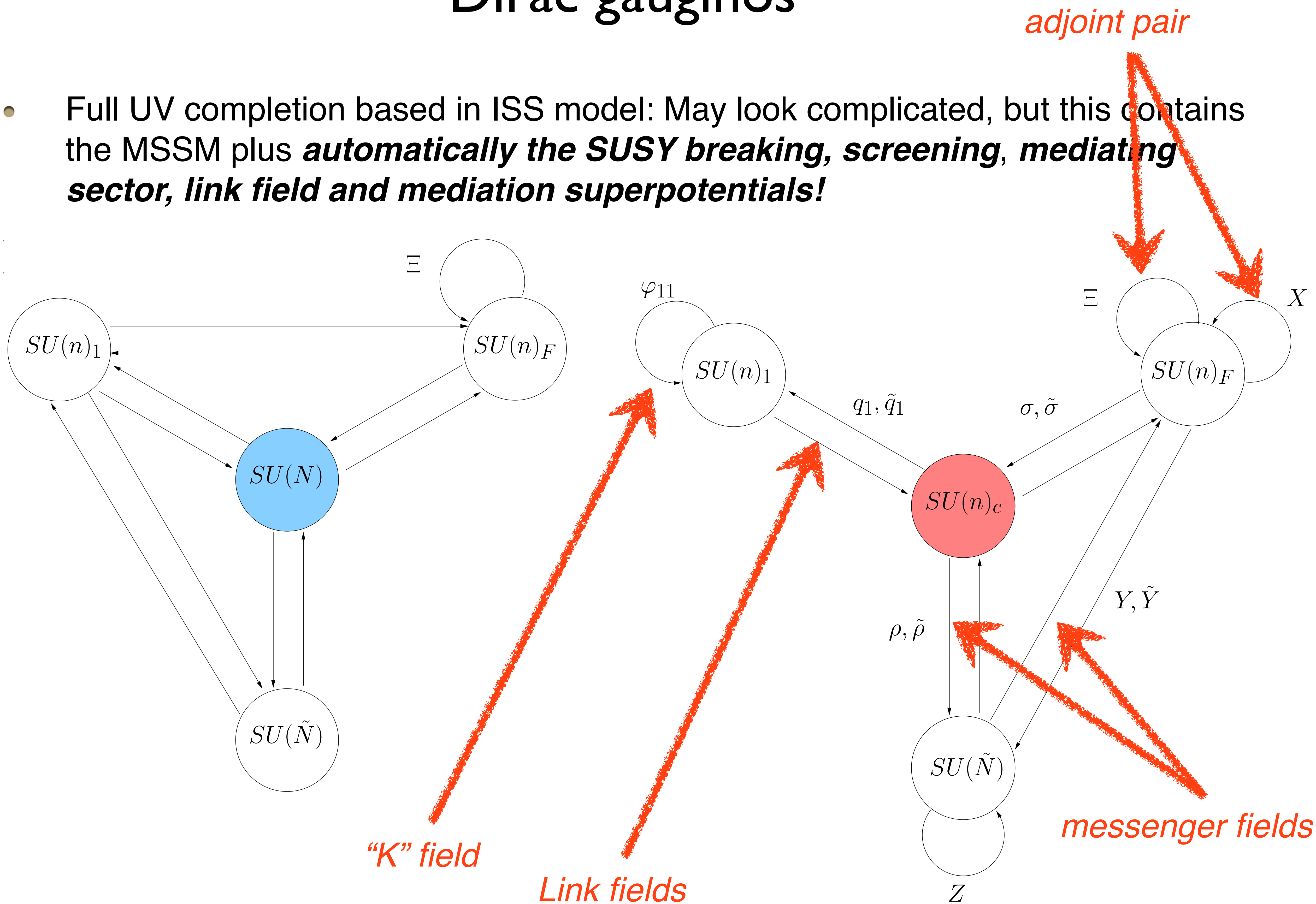

Dirac gauginos

- Find an interesting feature: the absolute scale of SUSY breaking decouples!

Dirac gauginos

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$$\mu^2_{ISS} \Rrightarrow \begin{pmatrix} \mu_1^2 & 0 & 0 \\ 0 & \mu_2^2 & 0 \\ 0 & 0 & \mu_3^2 \end{pmatrix} \begin{matrix} \} \; n \\ \} \; n \\ \} \, (N-n) \end{matrix}$$

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SUSY breaking scale a la ISS

Dirac gauginos

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Messenger scale

SUSY breaking scale a la ISS

Dirac gauginos

- Find an interesting feature: the absolute scale of SUSY breaking decouples!

Link field VEVs

Messenger scale

$$\mu^2_{ISS} \Rrightarrow \begin{pmatrix} \mu_1^2 & 0 & 0 \\ 0 & \mu_2^2 & 0 \\ 0 & 0 & \mu_3^2 \end{pmatrix} \begin{matrix} \} \; n \\ \} \; n \\ \} \, (N-n) \end{matrix}$$

SUSY breaking scale a la ISS

Dirac gauginos

- Find an interesting feature: the absolute scale of SUSY breaking decouples!

Link field VEVs

Messenger scale

$$\mu_{ISS}^2 \Rrightarrow \begin{pmatrix} \mu_1^2 & 0 & 0 \\ 0 & \mu_2^2 & 0 \\ 0 & 0 & \mu_3^2 \end{pmatrix} \begin{matrix} \}\ n \\ \}\ n \\ \}\,(N-n) \end{matrix}$$

SUSY breaking scale a la ISS

$$m_\lambda \sim \frac{g}{16\pi^2}\left(\frac{\mu_3}{\mu_2}\right)^4 m,$$

$$m_{\tilde{f}} \sim \frac{g^2}{16\pi^2}\left(\frac{\mu_3}{\mu_2}\right)^2 \mu_1$$

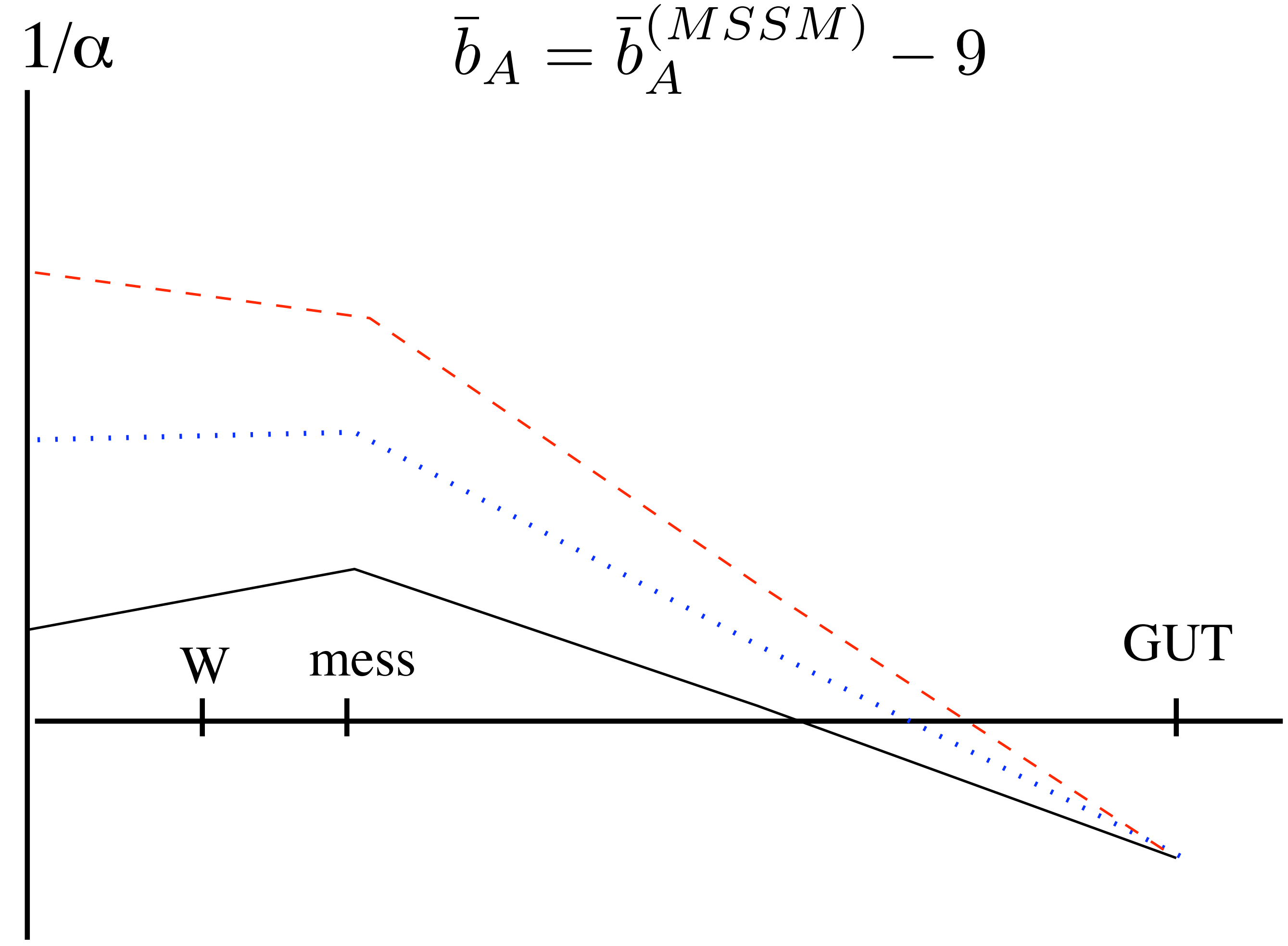
Observations on the Landau pole problem
(w/ V.V.Khoze)

Landau poles in direct gauge mediation:

Landau poles in direct gauge mediation:

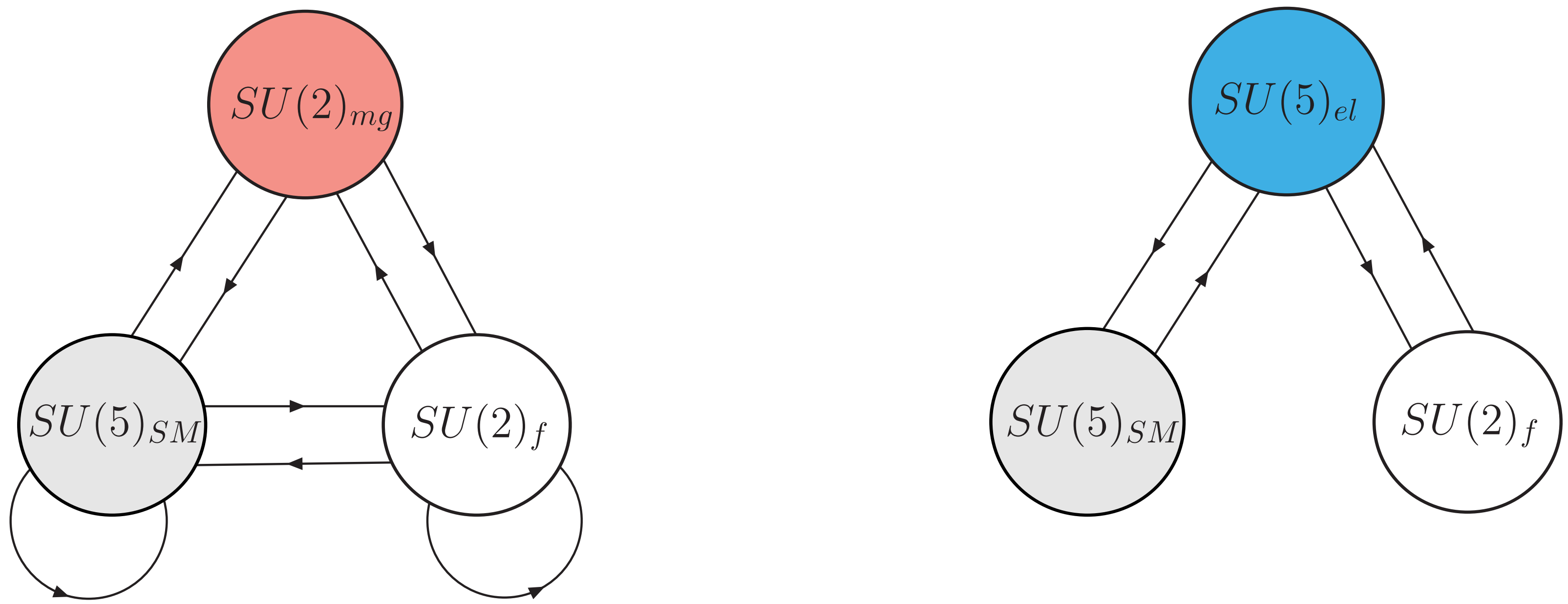
- Direct gauge mediation is attractive but typically a problem - a large contribution to the beta-functions...
- In this case (and typically) since the additional fields are in complete SU(5) multiplets there is a universal contribution above messenger scale

$$\bar{b}_A = \bar{b}_A^{(MSSM)} - 9$$



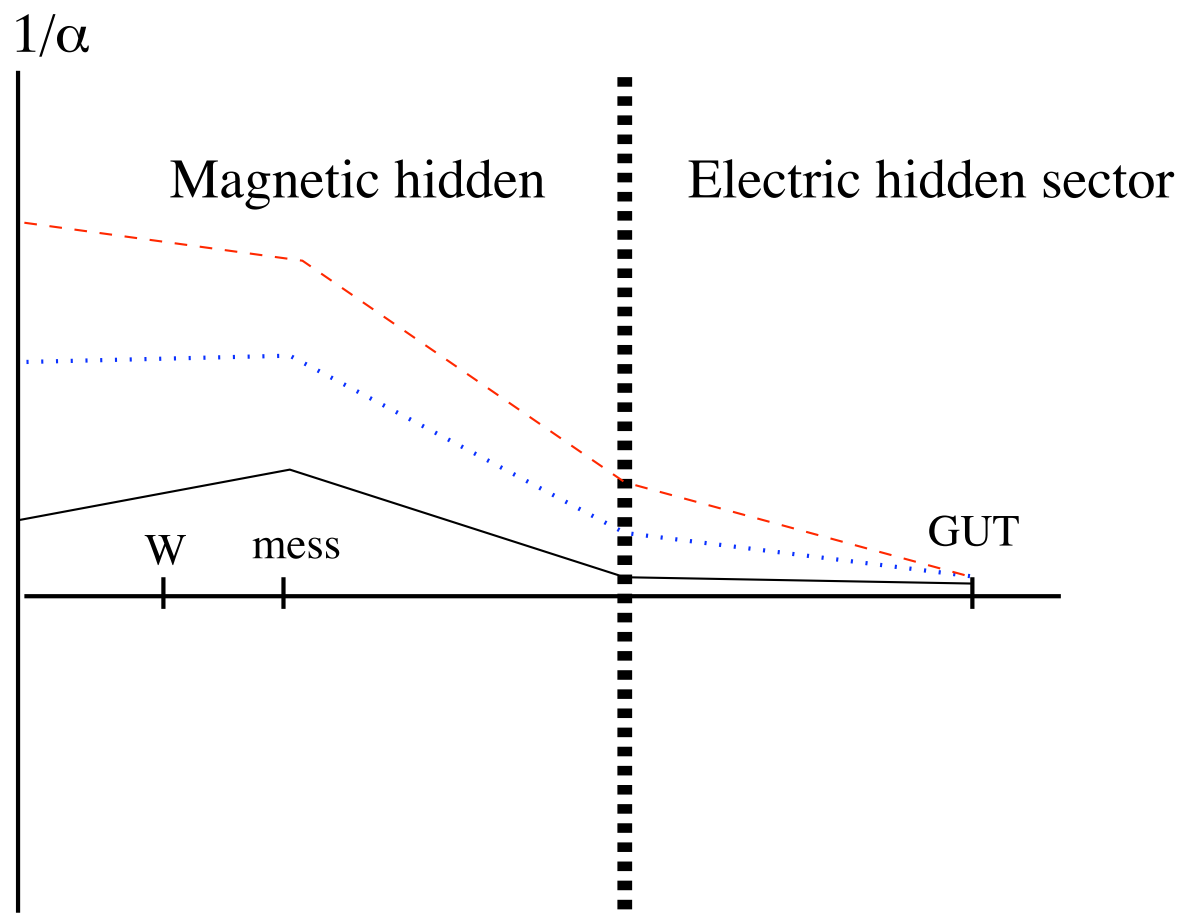
Solution 1: Deflected unification

The physics of the ISS sector changes at the strong coupling scale (i.e. the Landau pole scale of the ISS part of the theory) ...



Solution 1: Deflected unification

So the effective number of degrees of freedom decreases above the Landau pole scale of the SUSY-breaking ISS sector ...



Solution 1: Deflected unification

A Landau pole is avoided if this happens at a low enough scale ... e.g. $\Lambda_{ISS} \sim 10^{1-3}\mu_2$

$$(\alpha_{GUT}^{-1})^{(MSSM)} \lesssim 4\log(\Lambda_{ISS}/\mu_2) + 5\log(M_{GUT}/\mu_2)$$

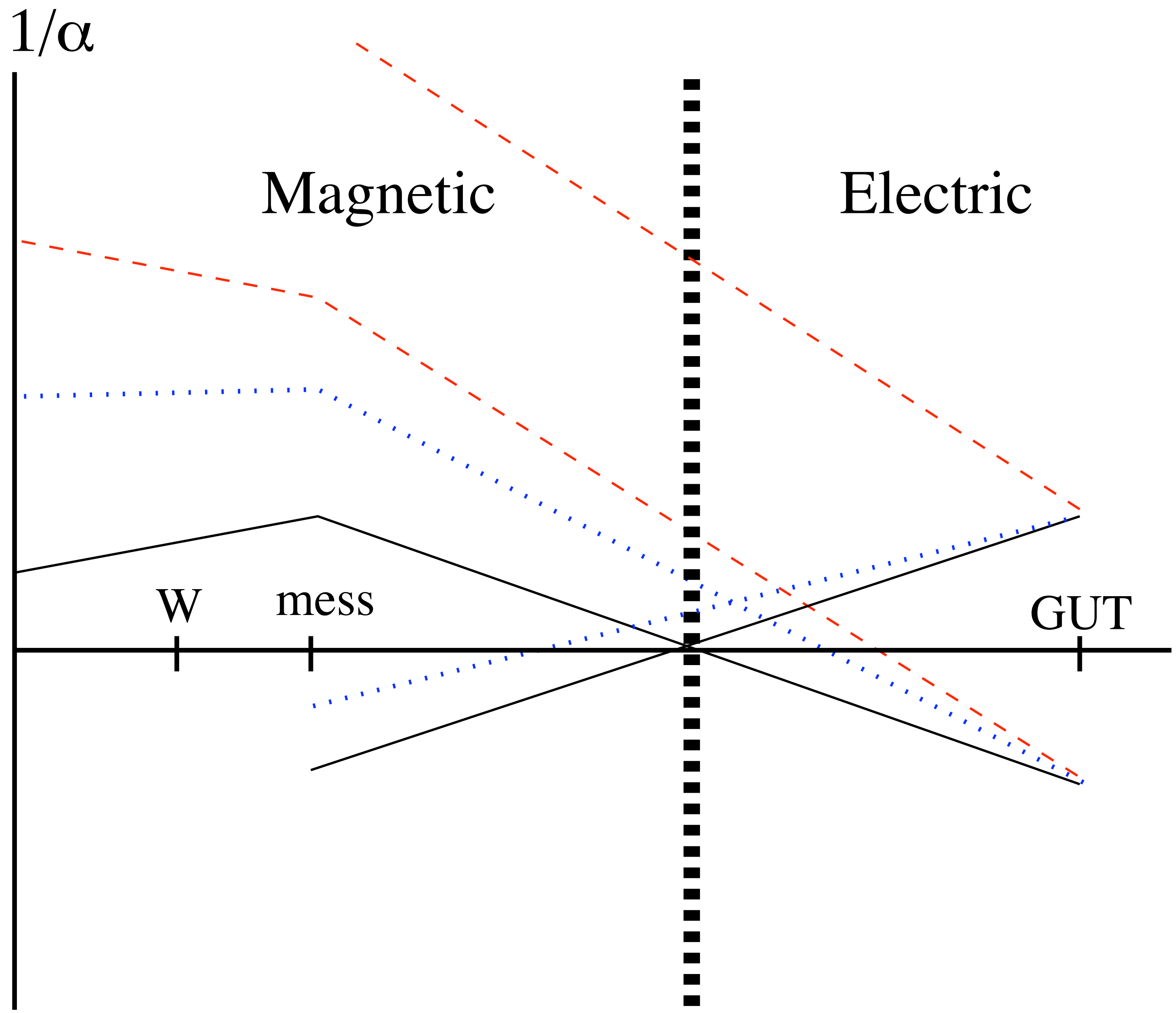
Landau pole avoided if ...

$$\mu_2 \geq 4 \times 10^5 \text{ GeV.}$$

Can be (just about) met by this model.

Solution 2: Dual unification

Could it be that the MSSM is itself a magnetic dual theory, with apparent GUTs in the magnetic theory mirroring unification in electric theory?



Solution 2: Dual unification

This picture is correct in known (Kutasov, Schwimmer, Seiberg) elec/mag duals to GUTs with adjoint X that breaks the GUT symmetry!

Works as follows: first need a superpotential for X ...

$$W_{\rm el} = \sum_{i=0}^{k-1} \frac{t_i}{k+1-i} \, {\rm Tr}\left[X^{k+1-i}\right]$$

When GUT symmetry unbroken then $SU(n) = SU(kF_Q - N)$

	$SU(F_Q)$	$SU(F_Q)$	$U(1)_B$	$U(1)_R$
Q	F_Q	1	$\frac{1}{N}$	$1 - \frac{2}{k+1}\frac{N}{F_Q}$
$\tilde{Q}$	1	$\overline{F_Q}$	$-\frac{1}{N}$	$1 - \frac{2}{k+1}\frac{N}{F_Q}$
X	1	1	0	$\frac{2}{k+1}$

Solution 2: Dual unification

Additional terms give the *same* GUT breaking in both theories:

$$SU(N) \to SU(r_1) \times SU(r_2) \ldots SU(r_k) \times U(1)^{k-1}$$

$$SU(n) = SU(kF_Q - N) \to SU(\bar{r}_1) \times SU(\bar{r}_2) \ldots SU(\bar{r}_k) \times U(1)^{k-1},$$

where $\bar{r}_i = F_Q - r_i$. Example ...

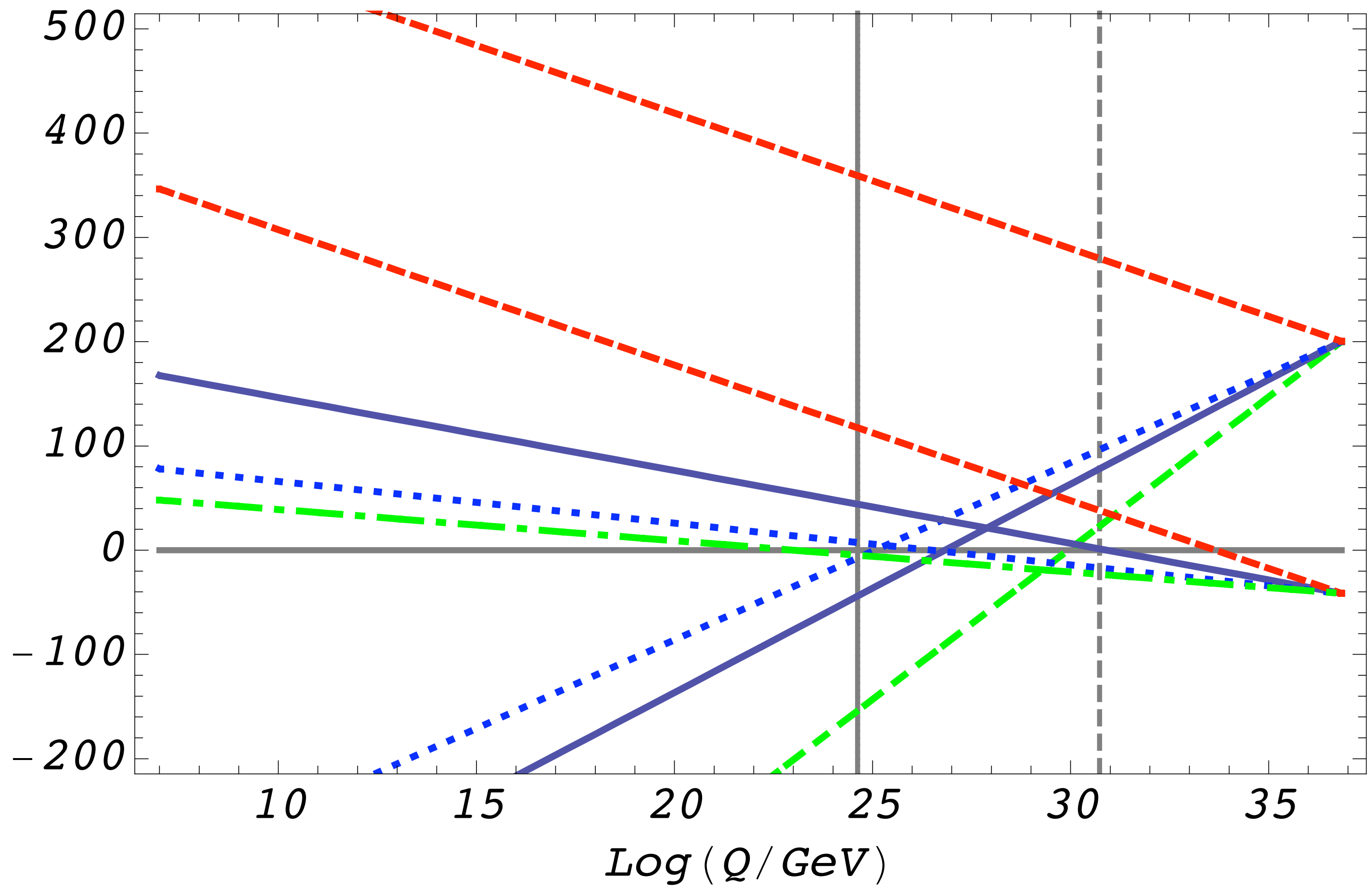
elec:	$SU(21) \to SU(11) \times SU(10) \times U(1),$
mag:	$SU(5) \to SU(2) \times SU(3) \times U(1),$

Solution 2: Dual unification

Moreover *unification in electric theory implies unification in magnetic theory.*

(SAA, Khoze)

$$\begin{array}{l} \text{elec: } SU(21) \to SU(11)\times SU(10)\times U(1), \\ \text{mag: } SU(5) \to SU(2)\times SU(3)\times U(1), \end{array}$$



Dual unified SU(5)

Electric theory: $\mathrm{SU}(11)\times\mathrm{Sp}(1)^3$

	$\mathrm{SU}(11)$	$\mathrm{Sp}(1)_a$	R_p
$Y_{a=1\ldots3}$	$\square$	$\square$	i
$\tilde{Q}_{\bar{J}=1\ldots3}$	$\tilde{\square}$	1	1
$\tilde{H}_{\bar{J}=1\ldots3}$	$\tilde{\square}$	1	-1
$\tilde{F}_{\bar{J}=1,2}$	$\tilde{\square}$	1	$-i$
$F_{J=1,2}$	$\square$	1	i
X	Adj	1	1
Z_a	1	$\square$	i

$$W = \frac{m_X}{2}X^2+\frac{s_0}{3}X^3+\kappa_i ZYX^i\tilde{H}$$
$$+\lambda_{ij}\tilde{Q}X^iYYX^j\tilde{H}+\lambda'_{ij}\tilde{F}X^iYYX^j\tilde{F}+\lambda''_{ij}\tilde{H}X^iF\tilde{Q}X^jF+\lambda'''_{ij}\tilde{F}X^iF\tilde{F}X^jF$$

Dual unified SU(5)

Chain of well understood dualities ..

Berkooz, Pouliot, Pouliot and Strassler

$SU(11) \times SU(2)^3$

↓ KSS duality

$SU(5) \times SU(2)^3$

↓ Sp(1) Confinement

similar to Leigh, Randall, Rattazzi

SU(5)

Dual unified SU(5)

Magnetic theory: $\mathrm{SU}(5)$

	$\mathrm{SU}(5)$	R_p
$\tilde{h}_{J=1\ldots3}$	$\tilde{\square}$	1
$\tilde{q}_{\bar{J}=1\ldots3}$	$\tilde{\square}$	-1
$\tilde{f}_{\bar{J}=1,2}$	$\tilde{\square}$	i
$f_{J=1,2}$	$\square$	$-i$
x	Adj	1
a_a	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	-1
h_a	$\square$	1

$$W = \frac{m_x}{2}x^2 - \frac{s_0}{3}x^3 + \tilde{\kappa}_i\, h x_s^i \tilde{h} + \tilde{\lambda}_{ij}\, \tilde{h} x_s^i a x_s^j \tilde{q} + \lambda_U aah + \tilde{\lambda}'_{ij}\, \tilde{f} x_s^i a x_s^j \tilde{f} + \text{quartic}$$

Dual unified SU(5)

Magnetic theory: $\mathrm{SU}(5)$

	$\mathrm{SU}(5)$	R_p
$\tilde{h}_{J=1\ldots 3}$	$\tilde{\Box}$	1
$\tilde{q}_{\bar{J}=1\ldots 3}$	$\tilde{\Box}$	-1
$\tilde{f}_{\bar{J}=1,2}$	$\tilde{\Box}$	i
$f_{J=1,2}$	$\Box$	$-i$
x	Adj	1
a_a	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	-1
h_a	$\Box$	1

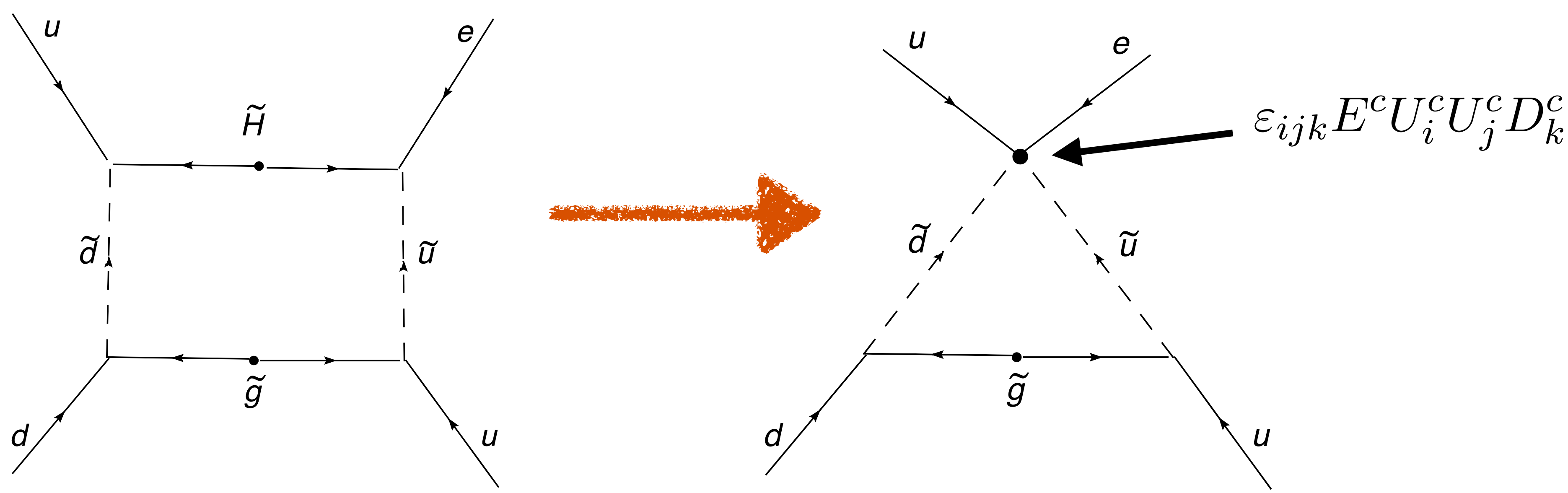
MSSM “mu-term”

$$W = \frac{m_x}{2}x^2 - \frac{s_0}{3}x^3 + \tilde{\kappa}_i\, h x_s^i \tilde{h} + \tilde{\lambda}_{ij}\, \tilde{h} x_s^i a x_s^j \tilde{q} + \lambda_U aah + \tilde{\lambda}'_{ij}\, \tilde{f} x_s^i a x_s^j \tilde{f} + \mathrm{quartic}$$

Up quark Yukawas generated by instantons (Intriligator, Pouliot)

Dual unified SU(5)

Application to proton decay - why does nature seem to unify but the proton not decay?



Note that the effective operator is a “baryon”: $\varepsilon AA(A\tilde{Q}) \supset \varepsilon EUUD$

Dual unified SU(5)

The baryon number violation proportional to a baryon operator in the magnetic theory *but this is generated in the electric theory: on dimensional grounds expect*

$$W_{el} \sim \frac{Q^d}{M_{GUT}^{d-3}}$$

where Q represents generic electric fields and d is *at least* N.

But we know how to map to the operator in the magnetic theory

$$\varepsilon_{ijk} E^c U_i^c U_j^c D_k^c \leftrightarrow \Lambda^{4-d} Q^d$$

hence

$$W_{eff} \supset \left(\frac{\Lambda}{M_{GUT}}\right)^{d-4} \frac{1}{M_{GUT}} \varepsilon_{ijk} E^c U_i^c U_j^c D_k^c$$

Dual unified SU(5)

In this case (X is dimensionless)...

$$W = \frac{(\tilde{F}X)^2\tilde{F}^2(XY)^7(YX\tilde{H})}{M_{GUT}^{10}} \leftrightarrow \left(\frac{\Lambda}{M_{GUT}}\right)^9 \frac{\varepsilon AA(A\tilde{Q})}{M_{GUT}}$$

Concussion

- SUSY is possible at the LHC
- Personally I think something like R-symmetric models may solve much of the fine-tuning of the MSSM
- Even if nature doesn't need SUSY, it can still teach us a lot about confinement, strong coupling etc thanks to fantastic properties such as holomorphy etc.