Supersymmetry

—

the high energy story

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Outline

- Understanding electroweak scale
- Models of Supersymmetry in a nut-shell
- Physics of soft masses:
    - mediation mechanisms
    - renormalization
    - Dynamical supersymmetry breaking
- D-type susy breaking
    - the μ-problem

Understanding Electroweak Scale

How do you generate this scale?

$$v_{\text{ew}}^2 \sim \frac{m_w^2}{g^2}$$

Even after you generate this

—

how do you make it radiatively stable?

Understanding Electroweak Scale

mass scale we need to control

$$v_{\rm ew}^2 \sim \frac{m_w^2}{g^2} = {\rm fn}\left(g^2, y_t^2, \ldots, \tilde{m}_i^2, M_a^2, \ldots\right)$$

superpartner masses

In electroweak scale supersymmetry, you control electroweak scale by controlling superpartner masses

Understanding Electroweak Scale

Control superpartner masses

SUSY rotates chirality into scalar sector — gives full control of radiative corrections on superpartner masses

How do we generate small (electroweak scale) superpartner masses?

Understanding Electroweak Scale

parameter of mass dimension 2

parametrizes susy breaking scale

$$\tilde{m}^2 \sim \frac{F^2}{M^2}$$

mediation scale

For Planck mediation:

$$M = M_{\mathrm{Pl}}$$

$$F \sim 10^{10-11}\ \mathrm{GeV}$$

Understanding Electroweak Scale

parameter of mass dimension 2

parametrizes susy breaking scale

$$\tilde{m}^2 \sim \frac{F^2}{M^2}$$

mediation scale

Smallness of electroweak scale or smallness of superpartner masses raises the question

how do you generate

$$\sqrt{F} \ll M \quad \text{if} \quad M \sim M_{\text{Pl}}$$

$$\sqrt{F}, M \ll M_{\text{Pl}} \quad \text{if} \quad M \ll M_{\text{Pl}}$$

Understanding Electroweak Scale

Smallness of electroweak scale or smallness of superpartner masses raises the question

how do you generate

$$\frac{\sqrt{F}}{M_{\rm Pl}} \ll 1$$

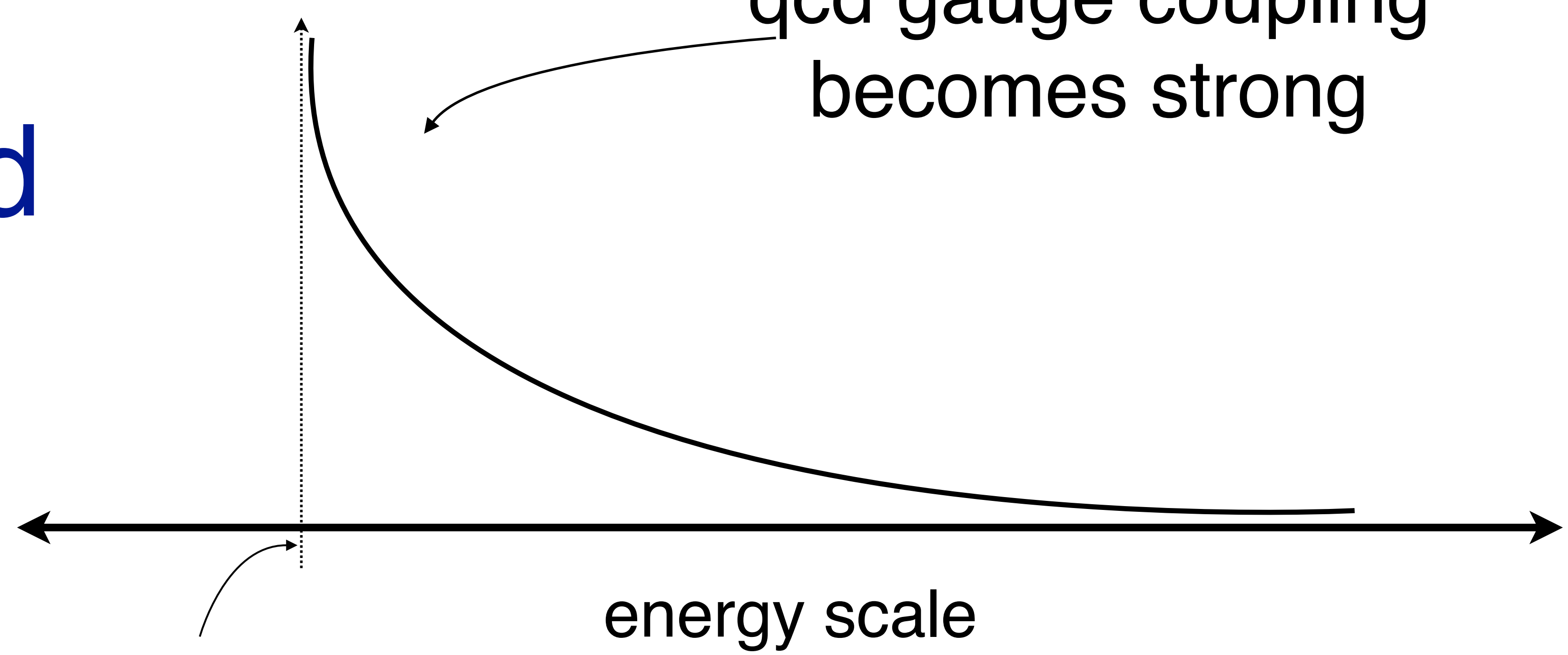
We know how nature does it with QCD

$$e^{-\frac{8\pi^2}{g^2}} \ll 1$$

Understanding Electroweak Scale

take qcd

qcd gauge coupling becomes strong



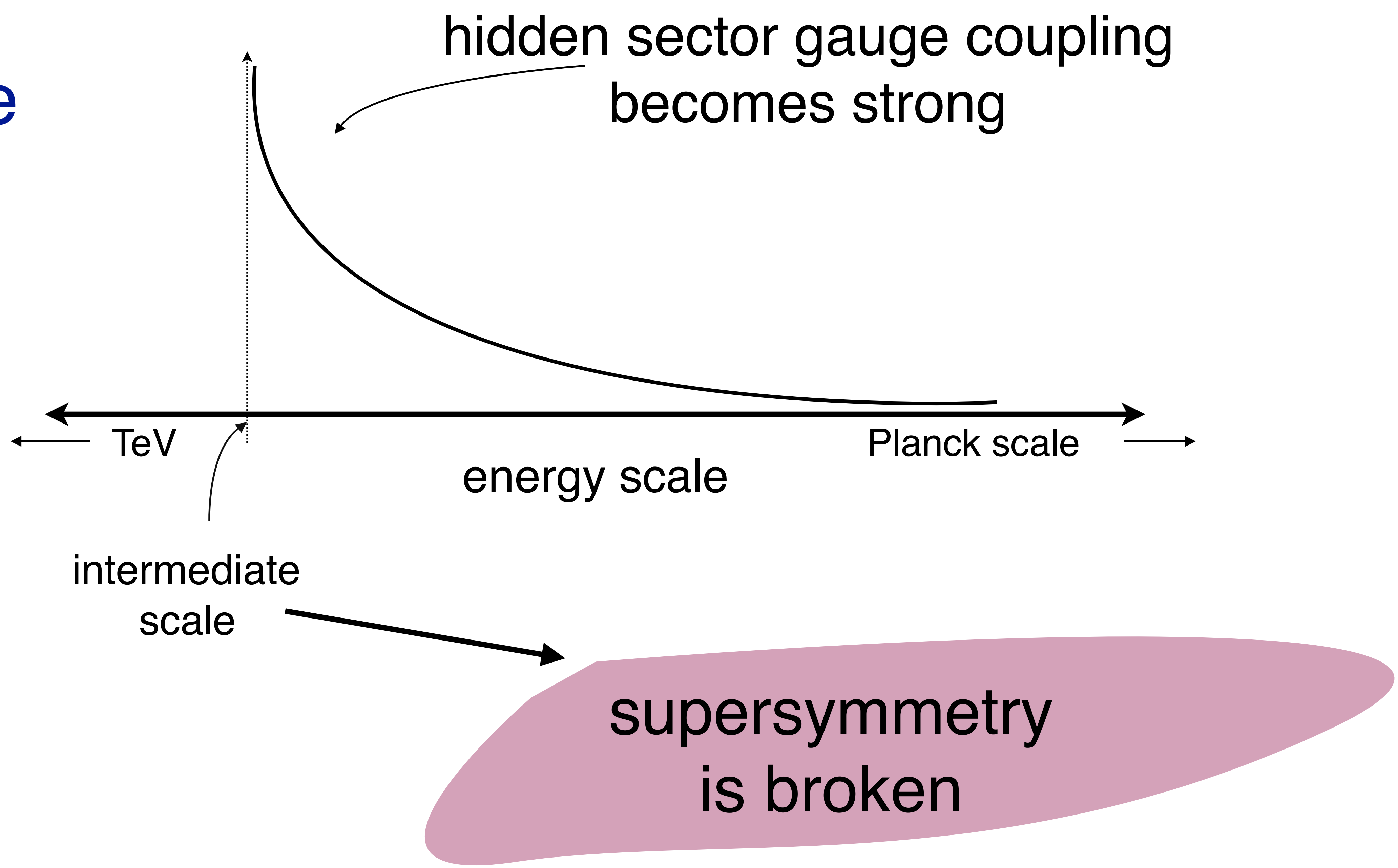
energy scale

~ few GeVs

chiral symmetry is broken

Understanding Electroweak Scale

just like
qcd



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SUSY model in a nut-shell

Skeleton of a complete SUSY model

Dynamical SUSY breaking
in a hidden sector

messenger mechanism
gravity, gauge, gaugino, anomaly etc etc

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flavor
problem

$\mu - B_\mu$
problem

tachyonic
sleptons

SUSY model in a nut-shell

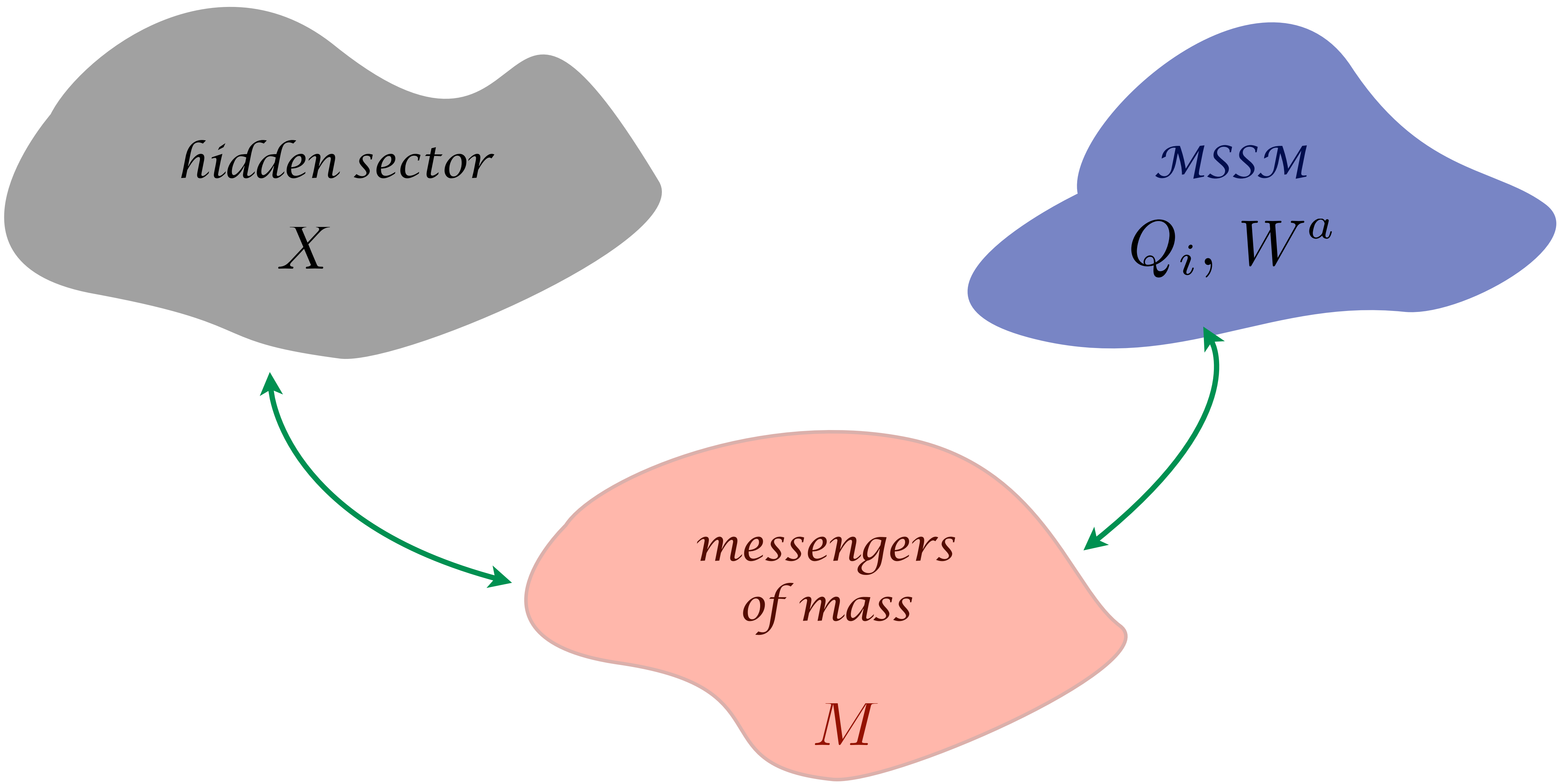
Skeleton of a complete SUSY model

Dynamical SUSY breaking
in a hidden sector

messenger mechanism
gravity, gauge, gaugino, anomaly etc etc

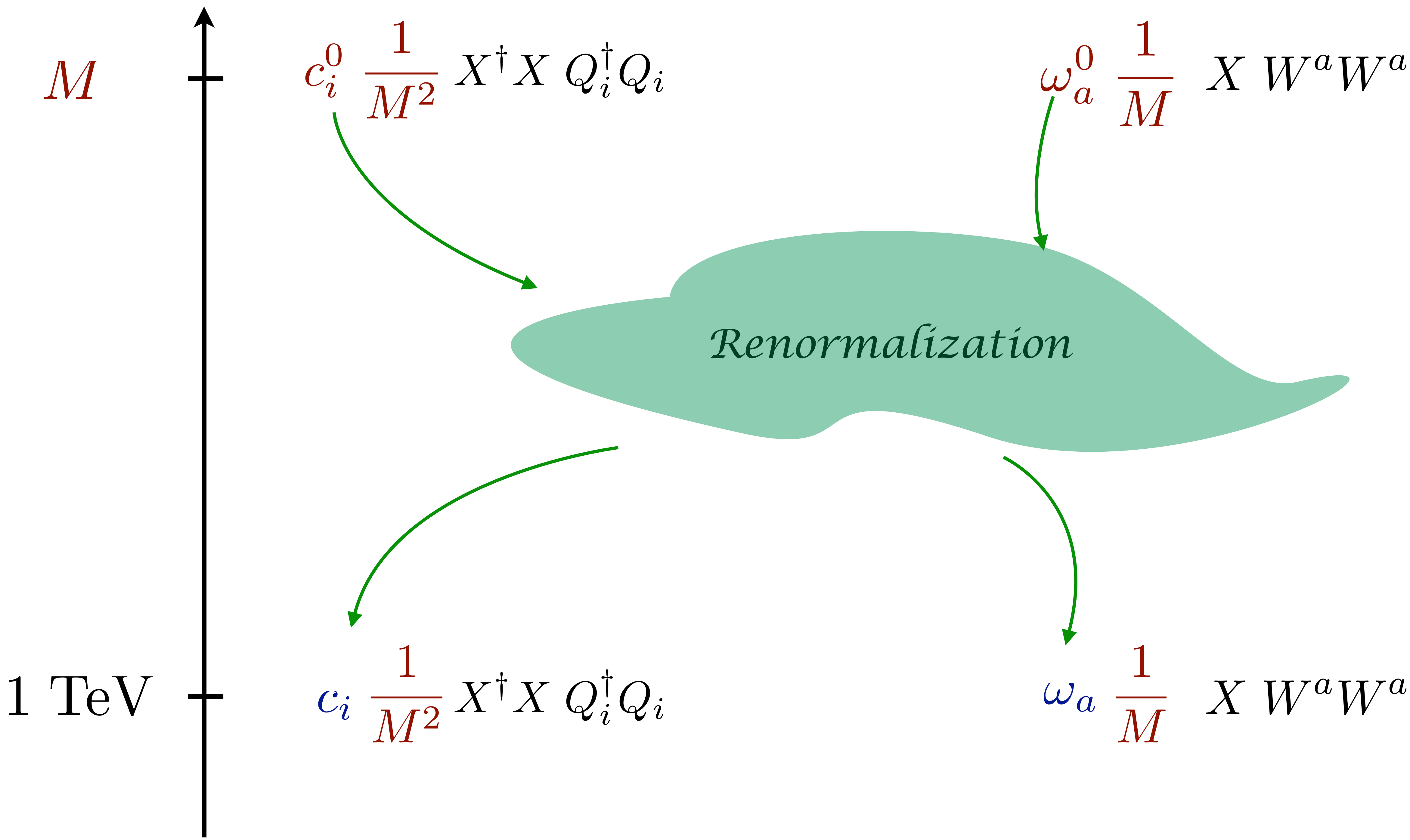
Exploring various susy models and their nuances is a semester long course — can't do justice in 45 minutes

Physics of soft masses

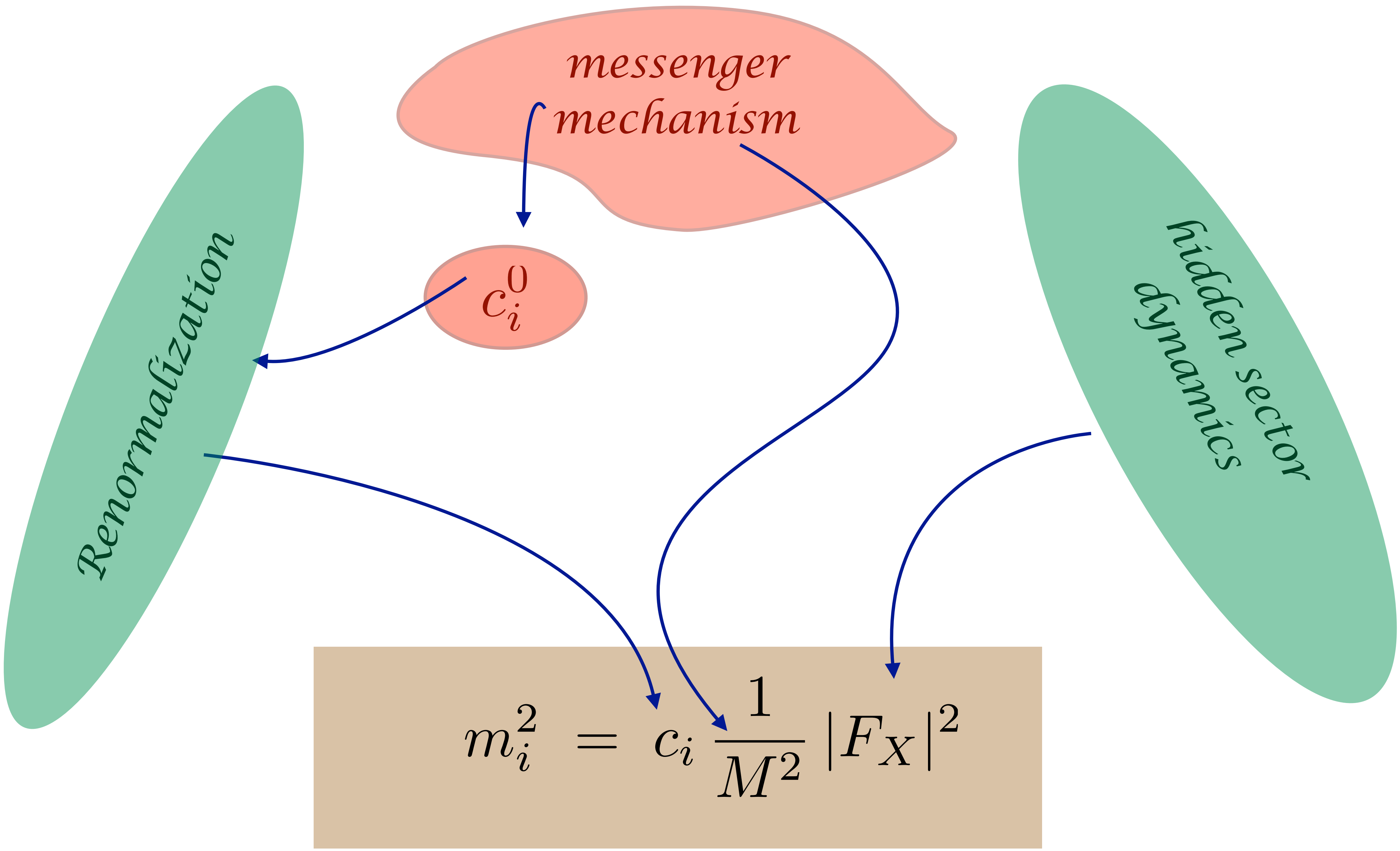


$$c_i^0 \, \frac{1}{M^2} \; X^\dagger X \, Q_i^\dagger Q_i \qquad\qquad \omega_a^0 \, \frac{1}{M} \, X \, W^a W^a$$

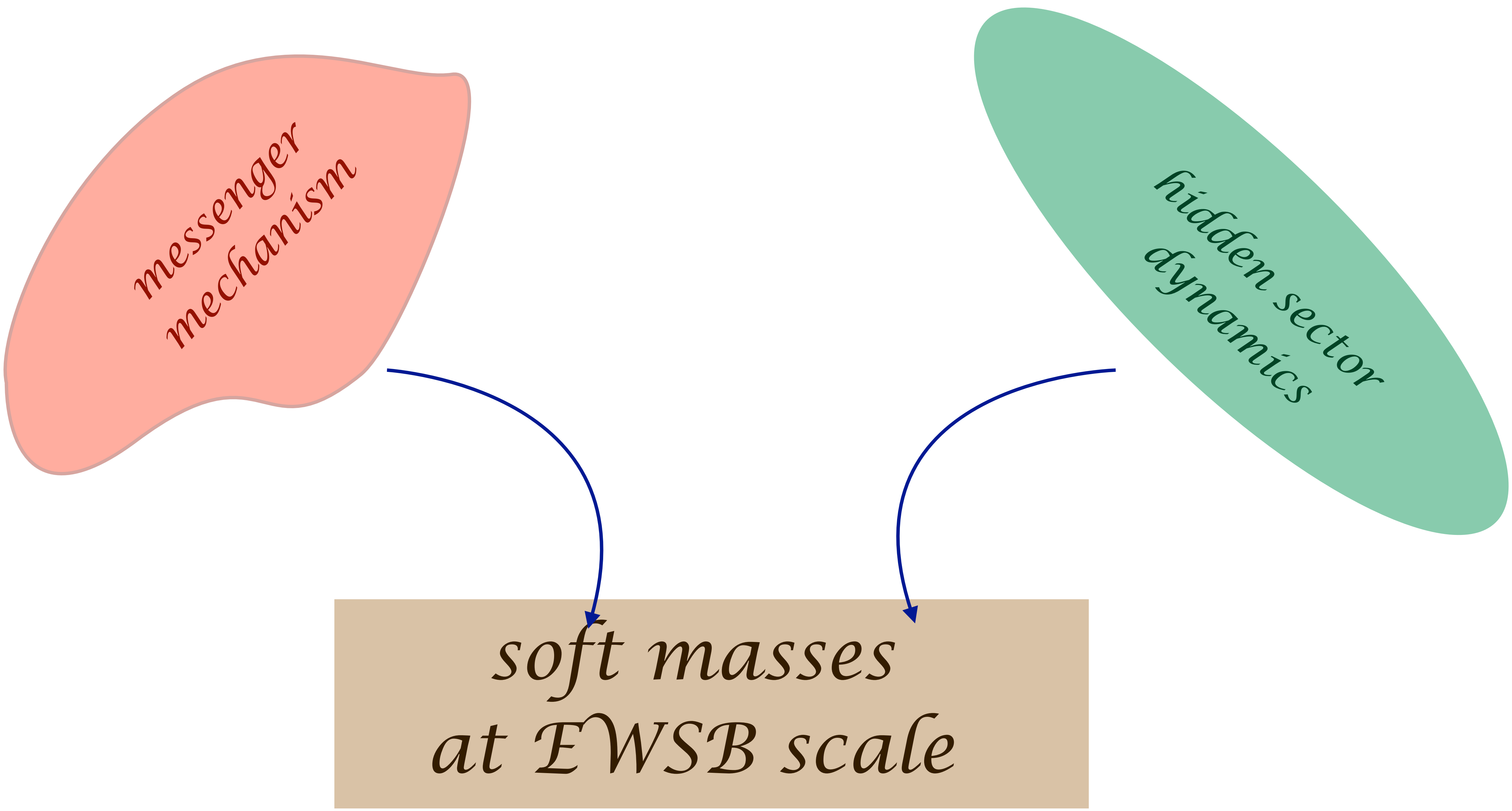
Physics of soft masses



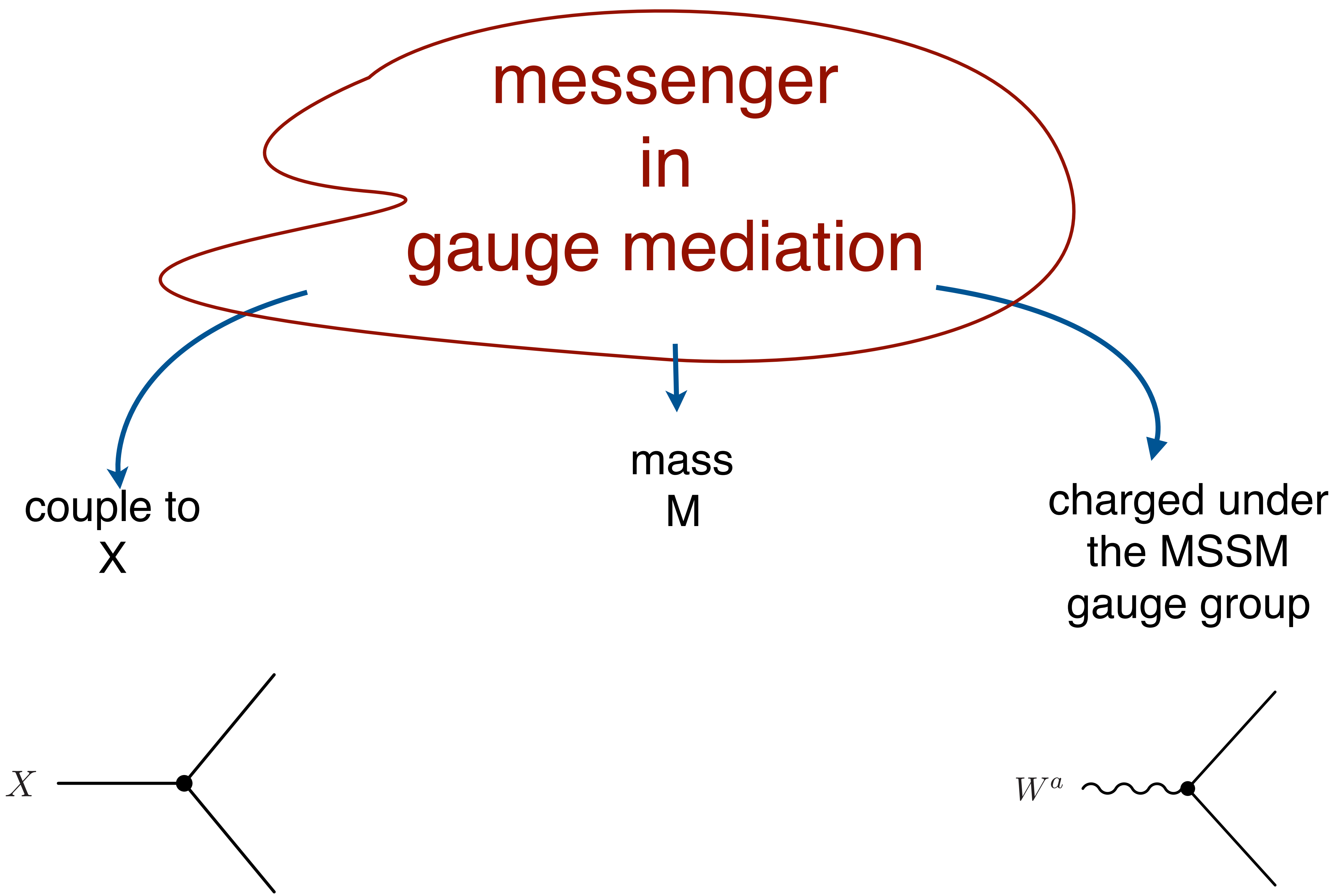
Physics of soft masses



Physics of soft masses



example: gauge mediation



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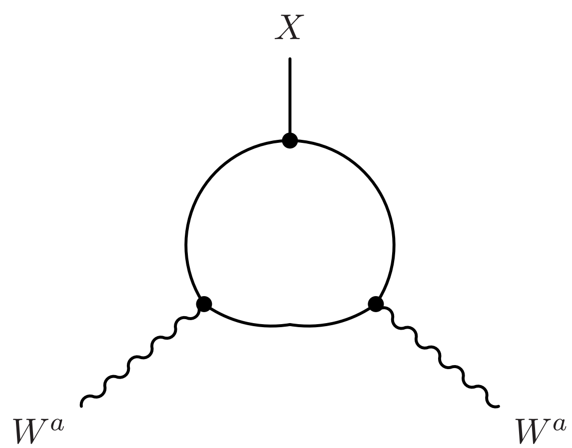
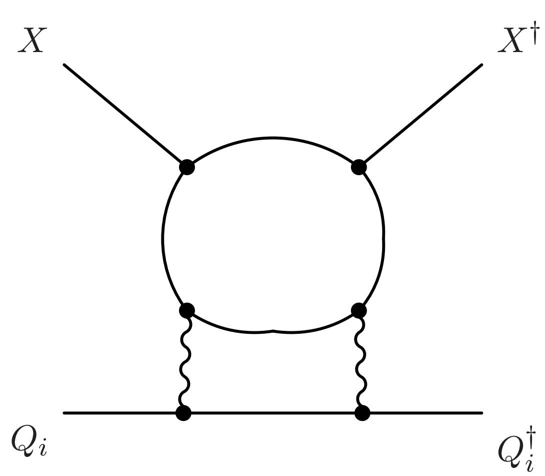


$$\sim \quad \frac{1}{16\pi^2} \quad \frac{X}{M} \, W^a W^a$$

ω_a^0



$$\sim \quad q_i \, \frac{g_i^4}{(16\pi^2)^2} \quad \frac{X^\dagger X}{M^2} \, Q_i^\dagger Q_i$$

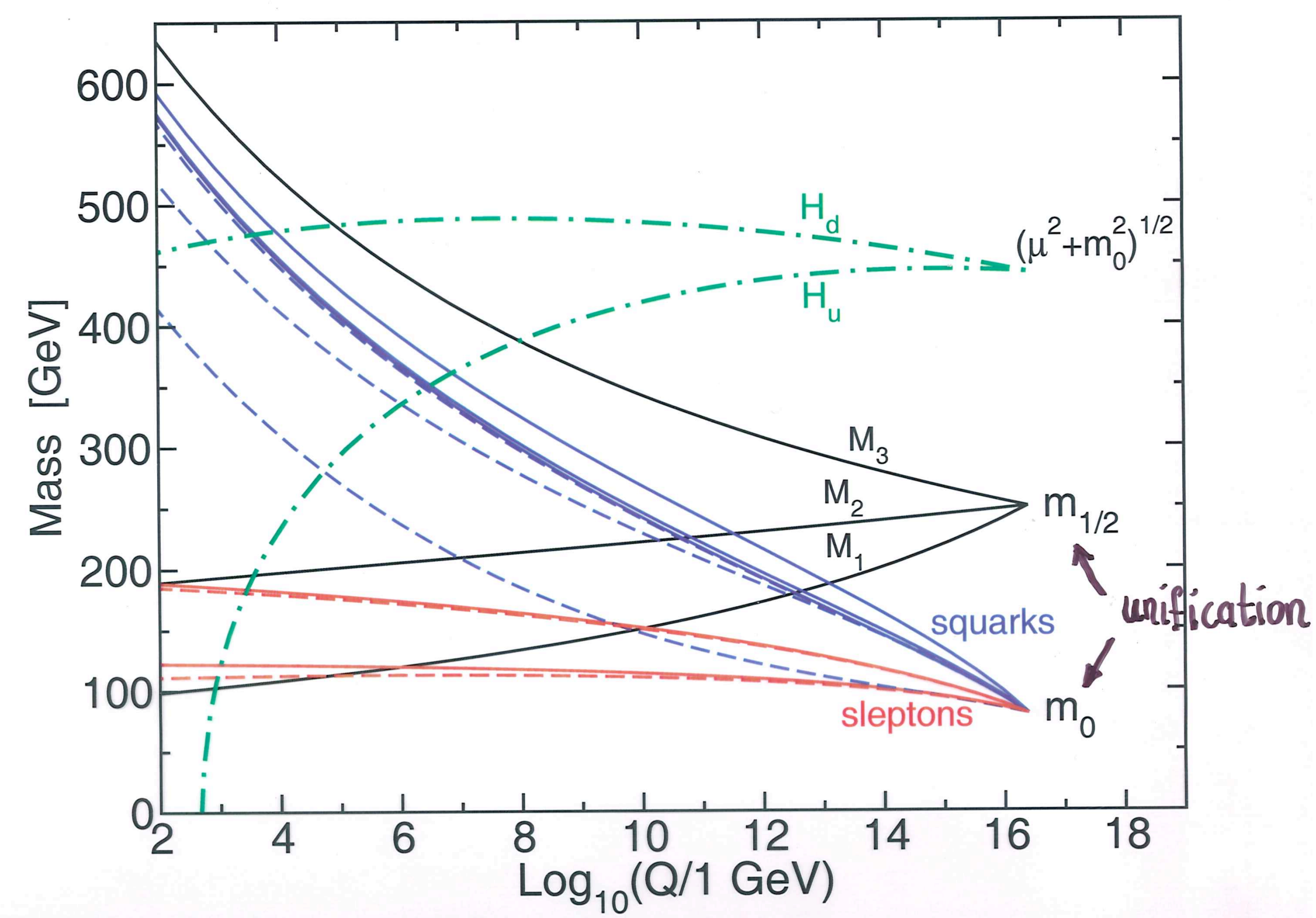
c_i^0

Renormalization

for example: take superpartner mass running in SO(10)

State of the art MSSM running

- *2 loop running*
- *1 loop matching at 1 TeV and at GUT*
- *automated*
    - *Isajet*
    - *Softsusy*
    - *Suspect*
    - -
    - -



Renormalization

for example: take superpartner mass running in
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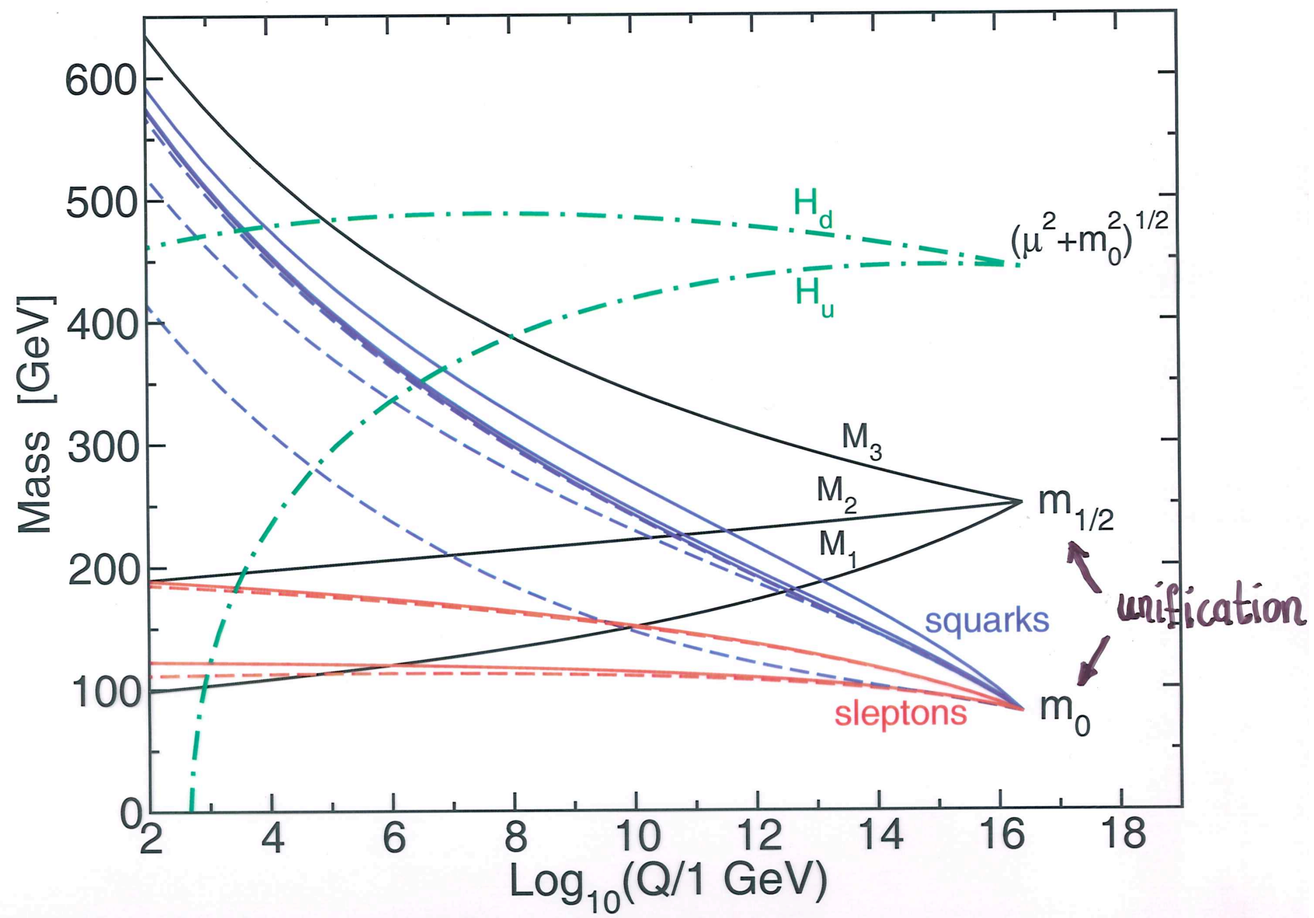
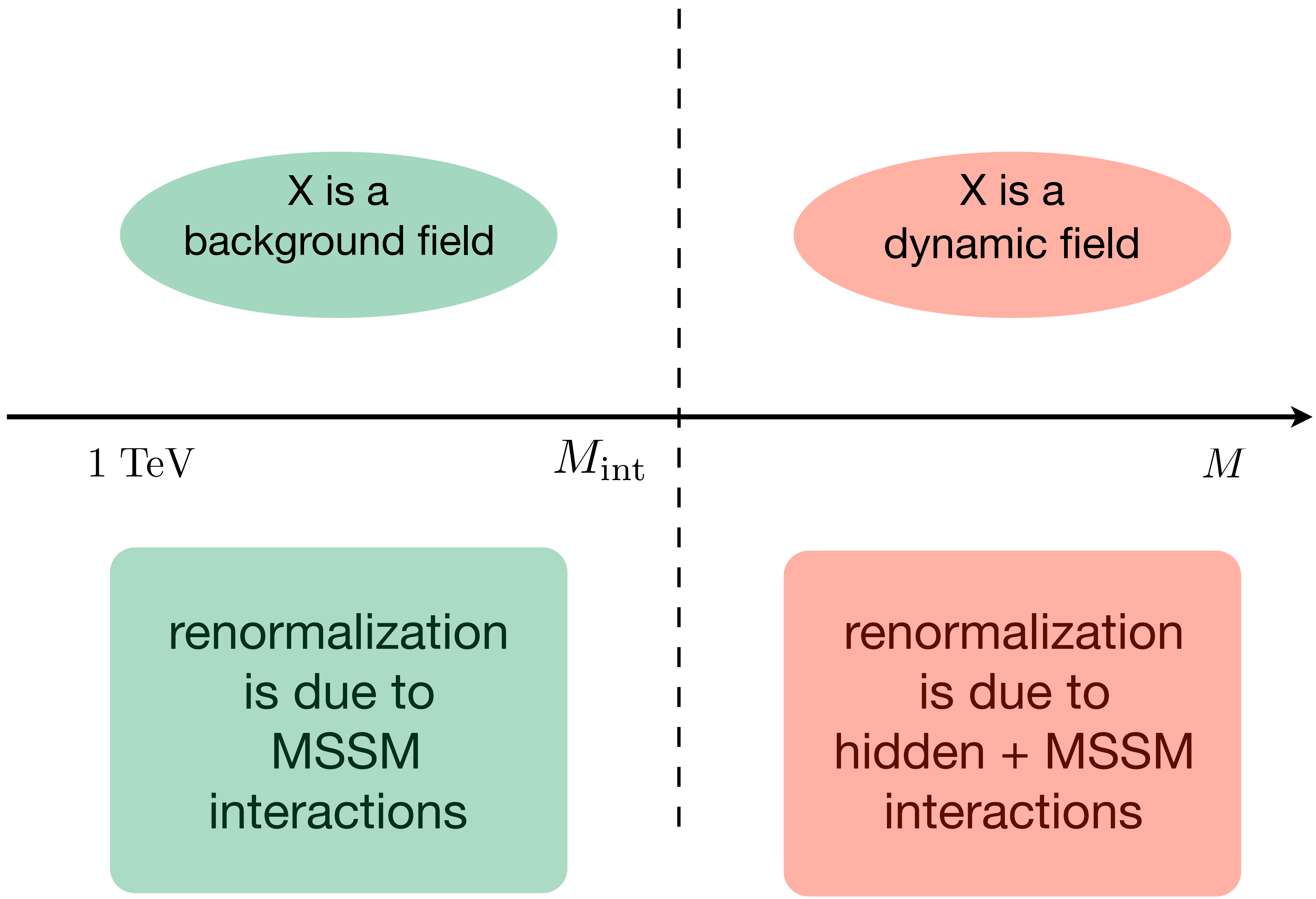


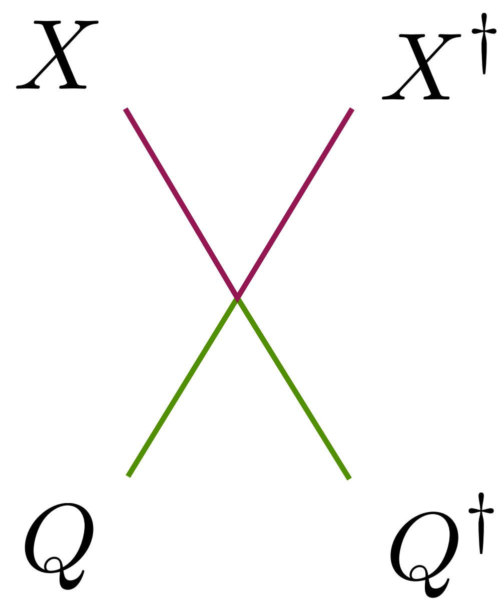
zillions of papers have used/still use this renormalization — all wrong!

Scales in renormalization



RGEs of SUSY breaking masses

RGE of the operator



RGEs of SUSY breaking masses

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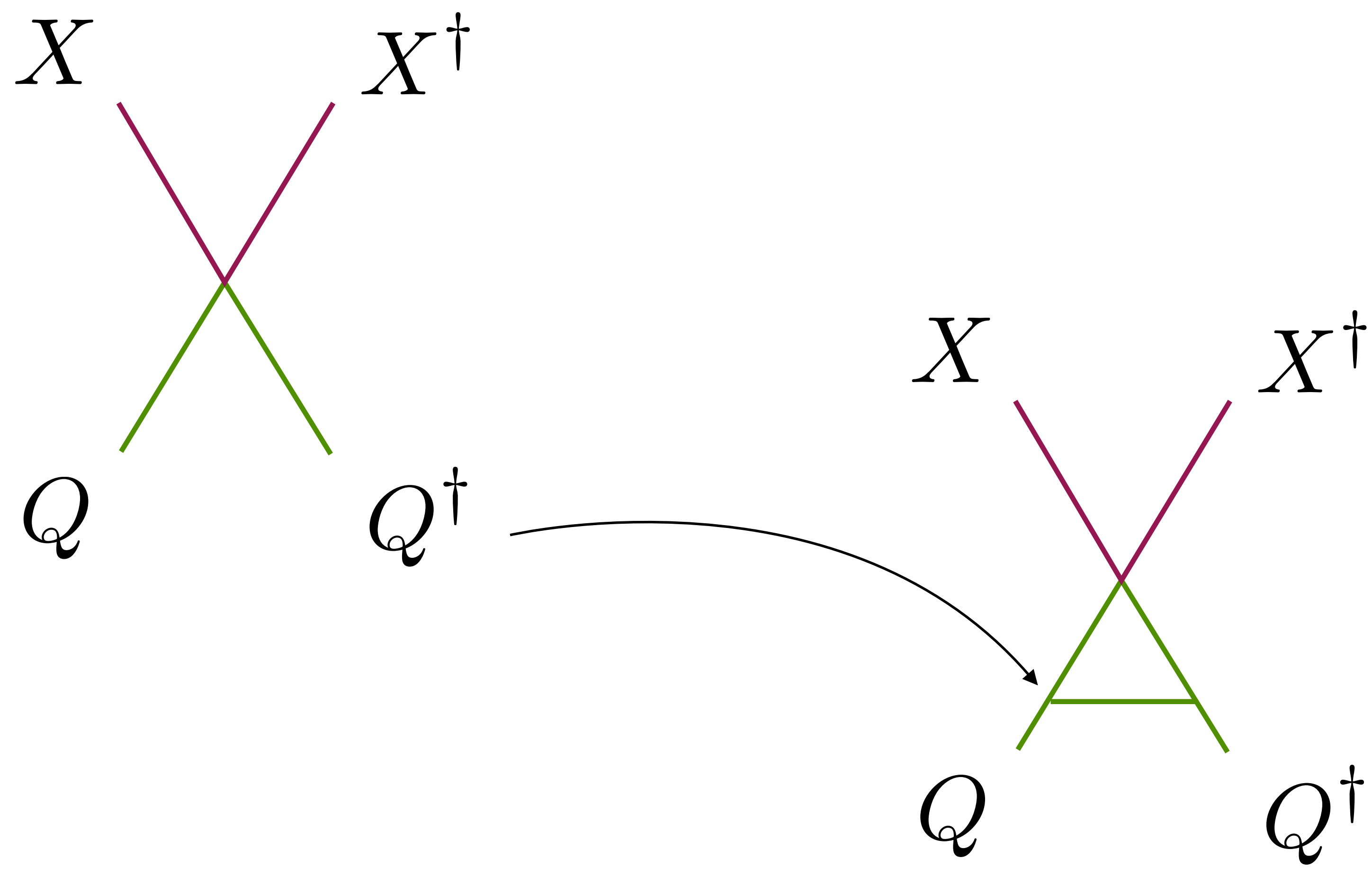
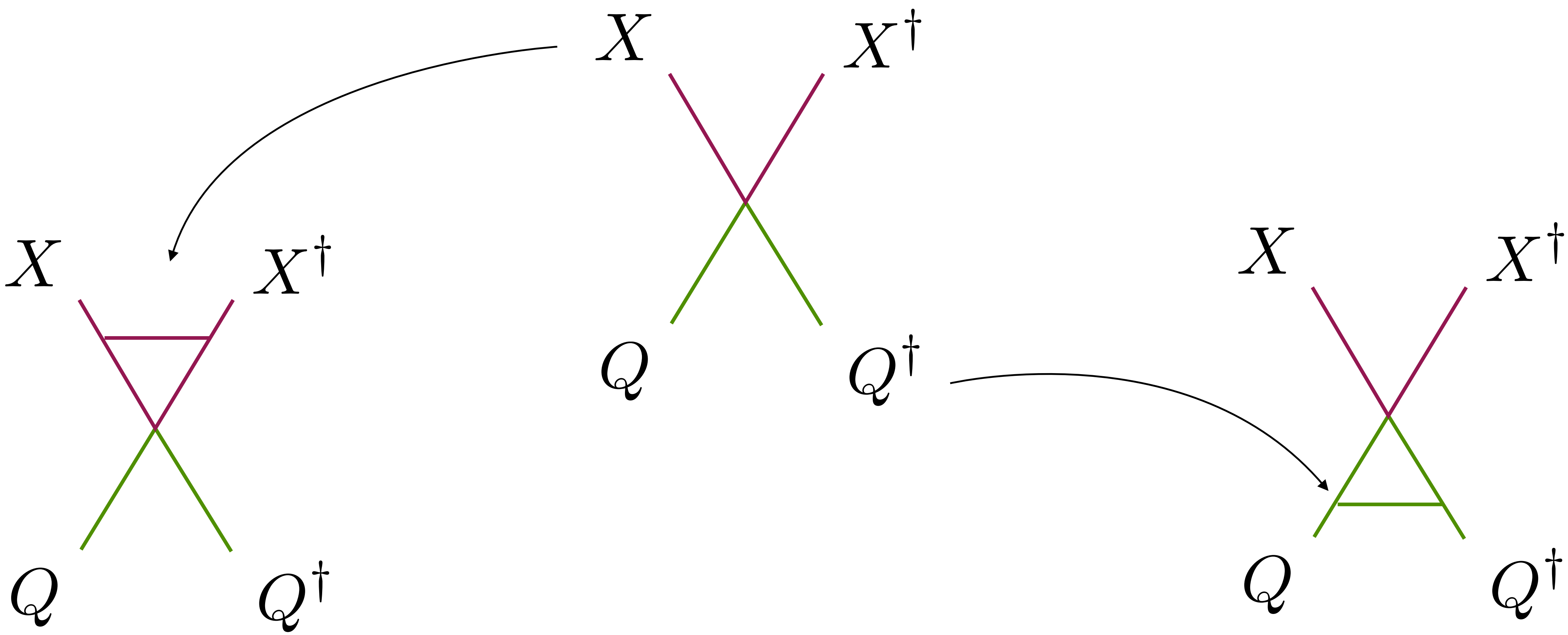


RGEs of SUSY breaking masses

RGE of the operator



RGEs of SUSY breaking masses

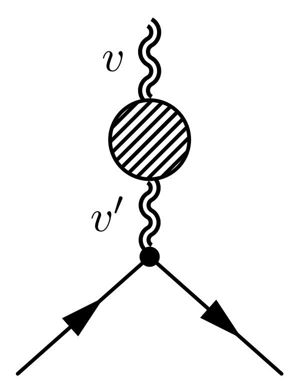
Cohen, Roy, Schmaltz

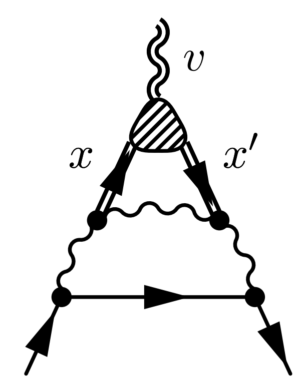
A general hidden sector

Operators:

$$\int d^4\theta\, k_{vi}\, \frac{V_v}{M^2} \Phi_i^\dagger \Phi_i + \int d^2\theta\, w_{xn} \frac{X_x}{M} W_n W_n$$

Diagrams:





RGEs

$$\frac{d}{dt} k_i = \gamma\, k_i - \frac{1}{16\pi^2} \sum_n 8\ \mathrm{C}_2^{\mathrm{n}}(R_i)\, g_n^6\ G_n$$

RGEs of SUSY breaking masses

with MSSM interactions only

$$\frac{d}{dt}\widetilde{m}_Q^2 = \frac{1}{16\pi^2}\sum_{a=1}^{3} q_a\ g_a^2\ M_a^2$$

$$q_a \equiv \{\frac{32}{3}, 6, \frac{2}{5}\}$$

$$\widetilde{m}_Q^2 = \widetilde{m}_0^2\ +\ 4.5\ M_{1/2}^2$$

2
unknowns

RGEs of SUSY breaking masses

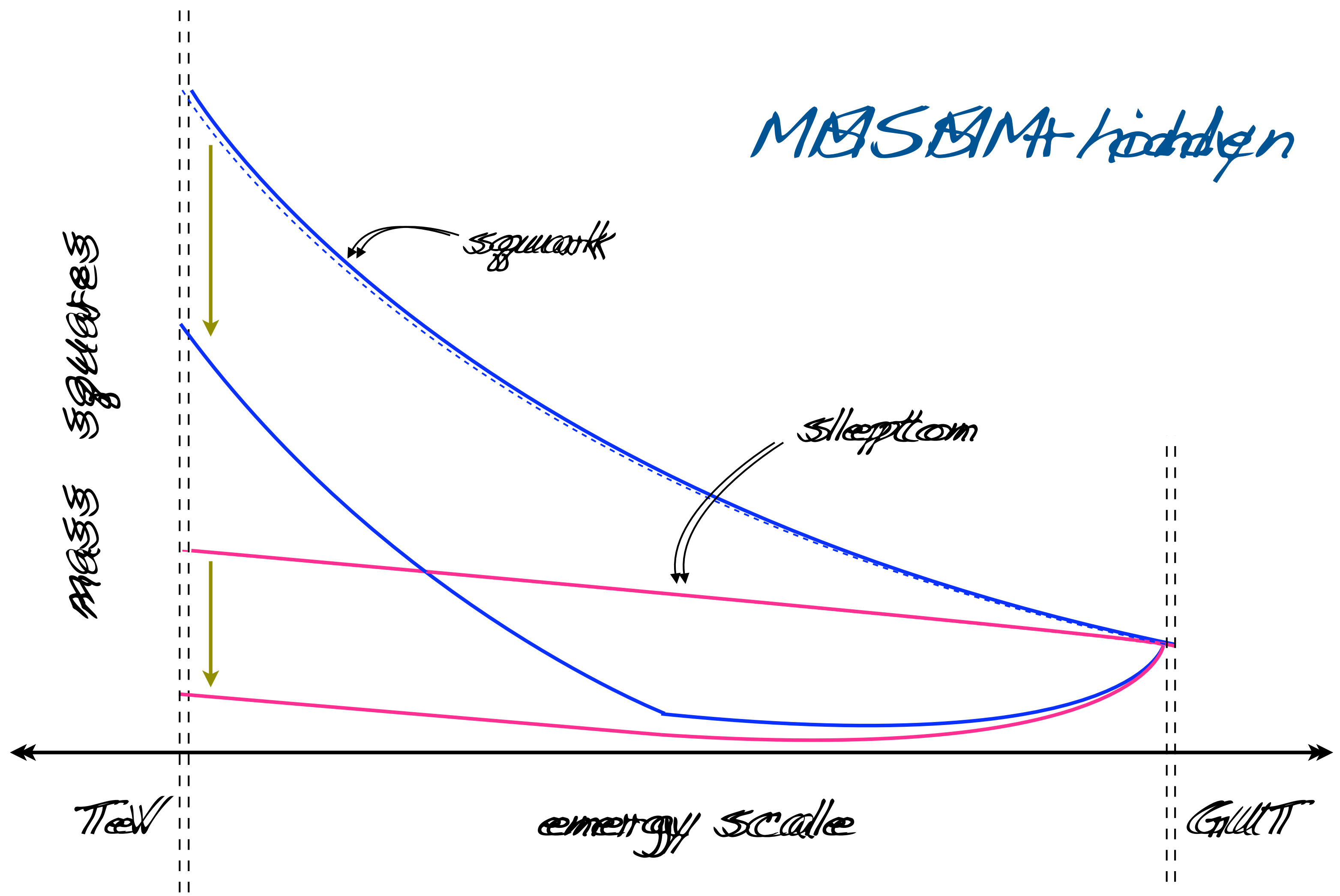
with MSSM + hidden interactions

$$\frac{d}{dt}\widetilde{m}_Q^2 = \frac{1}{16\pi^2}\sum_{a=1}^{3} q_a\, g_a^2\, M_a^2\, G + \gamma\, \widetilde{m}_Q^2$$

$$\widetilde{m}_Q^2 = N_0 + \sum_{a=1}^{3} q_a\, N_a$$

4 unknowns

RGEs of SUSY breaking masses



Hidden sector independent predictions

$$m^2_{\widetilde{Q}} - 2m^2_{\widetilde{U}} + m^2_{\widetilde{D}} - m^2_{\widetilde{L}} + m^2_{\widetilde{E}} = 0$$

holds for
unification, MSUGRA,
gauge mediation, gaugino mediation

Hidden sector independent predictions

$$3\left(\widetilde{m}_U^2 - \widetilde{m}_D^2\right) + \widetilde{m}_E^2 = 0$$

holds for
gauge mediation, gaugino mediation

Hidden sector independent predictions

all flavor universal models

e.g. MSUGRA, gauge/gaugino mediation

$$2\widetilde{m}^2_{Q_3} - \widetilde{m}^2_{U_3} - \widetilde{m}^2_{D_3} = 2\widetilde{m}^2_{Q_1} - \widetilde{m}^2_{U_1} - \widetilde{m}^2_{D_1}$$

Hidden sector independent predictions

all flavor universal models

e.g. MSUGRA, gauge/gaugino mediation

$$2\widetilde{m}^2_{L_3} - \widetilde{m}^2_{E_3} = 2\widetilde{m}^2_{L_1} - \widetilde{m}^2_{E_1}$$

Hidden sector independent predictions

all flavor universal models

e.g. MSUGRA, gauge/gaugino mediation

$$2\widetilde{m}^2_{L_3} - \widetilde{m}^2_{E_3} \neq 2\widetilde{m}^2_{L_1} - \widetilde{m}^2_{E_1}$$

right handed neutrinos
with large Yukawa coupling

Hidden sector independent predictions

all flavor universal models

e.g. MSUGRA, gauge/gaugino mediation

$$2\widetilde{m}^2_{Q_3} - \widetilde{m}^2_{U_3} = 2\widetilde{m}^2_{Q_1} - \widetilde{m}^2_{U_1}$$

$$\widetilde{m}^2_{E_3} = \widetilde{m}^2_{E_1}$$

Hidden sector independent predictions

all flavor universal models

e.g. MSUGRA, gauge/gaugino mediation

$$2\widetilde{m}^2_{Q_3} - \widetilde{m}^2_{U_3} \neq 2\widetilde{m}^2_{Q_1} - \widetilde{m}^2_{U_1}$$

$$\widetilde{m}^2_{E_3} \neq \widetilde{m}^2_{E_1}$$

large tan β

Hidden sector independent predictions

all flavor universal models

e.g. MSUGRA, gauge/gaugino mediation

$$3\widetilde{m}^2_{D_3} + \widetilde{m}^2_{E_3} - 2m^2_{\bar{H}} = 3\widetilde{m}^2_{D_1} + \widetilde{m}^2_{E_1} - 2\widetilde{m}^2_{L_1}$$

$$3\widetilde{m}^2_{U_3} - 3\widetilde{m}^2_{D_3} + 2\widetilde{m}^2_{L_3} - 2\widetilde{m}^2_{E_3} + 2m^2_{\bar{H}} = 3\widetilde{m}^2_{U_1} - 3\widetilde{m}^2_{D_1} + 2\widetilde{m}^2_{L_1} - 2\widetilde{m}^2_{E_1} + 2m^2_{H}$$

Hidden sector independent predictions

all flavor universal models

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$$3\widetilde{m}^2_{D_3} + \widetilde{m}^2_{E_3} - 2m^2_{\bar{H}} \neq 3\widetilde{m}^2_{D_1} + \widetilde{m}^2_{E_1} - 2\widetilde{m}^2_{L_1}$$

$$3\widetilde{m}^2_{U_3} - 3\widetilde{m}^2_{D_3} + 2\widetilde{m}^2_{L_3} - 2\widetilde{m}^2_{E_3} + 2m^2_{\bar{H}} \neq 3\widetilde{m}^2_{U_1} - 3\widetilde{m}^2_{D_1} + 2\widetilde{m}^2_{L_1} - 2\widetilde{m}^2_{E_1} + 2m^2_H$$

μ term is not fundamental

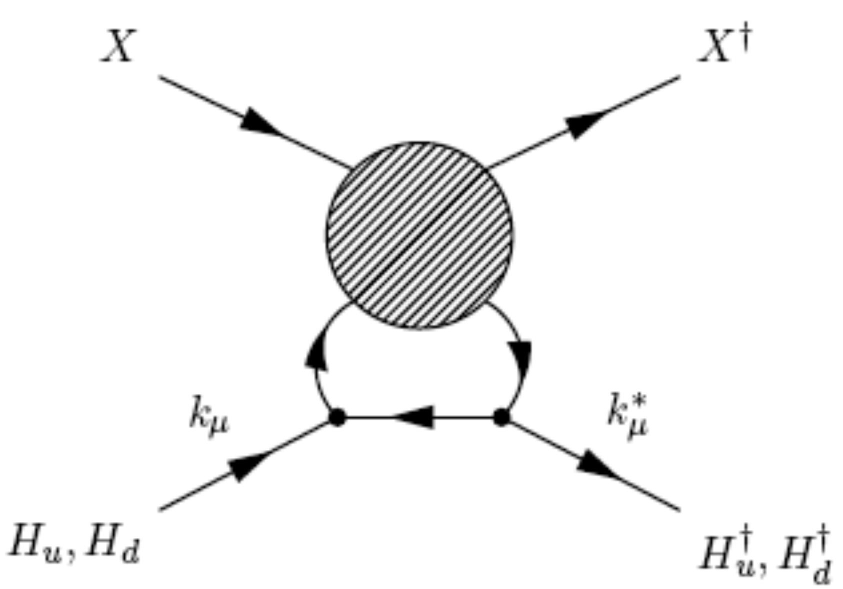
Hidden sector independent predictions

all flavor universal models

e.g. MSUGRA, gauge/gaugino mediation

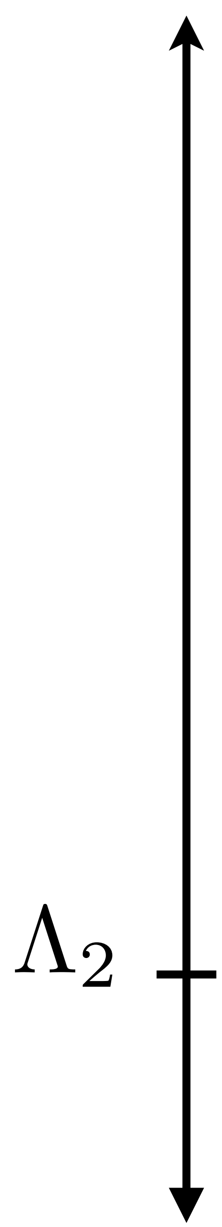
$$3\widetilde{m}^2_{D_3} + \widetilde{m}^2_{E_3} - 2m^2_{\bar{H}} \neq 3\widetilde{m}^2_{D_1} + \widetilde{m}^2_{E_1} - 2\widetilde{m}^2_{L_1}$$

$$3\widetilde{m}^2_{U_3} - 3\widetilde{m}^2_{D_3} + 2\widetilde{m}^2_{L_3} - 2\widetilde{m}^2_{E_3} + 2m^2_{\bar{H}} \neq 3\widetilde{m}^2_{U_1} -$$



μ term is not funda

Example of DSB



$$W = \lambda S^{ij} Q_i Q_j$$

$$\frac{\partial W}{\partial S^{ij}} = \lambda Q_i Q_j$$

$$\mathrm{Pf}(QQ) = \Lambda_2^4$$

	SU(2)	SU(4)
Q	$\square$	$\square$
S	1	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$

Take the limit of large field value (λS)

$$W_{\rm eff} = 2\,\Lambda_2^2\,\lambda S$$

Example of DSB

We can provide many more examples of DSB

all share the same feature

there is no elementary singlet field in the UV

gaugino masses are naturally suppressed wrt scalar masses

Example of DSB

SU(4) X U(1)

X_1	$\square$	-3
X_2	$\overline{\square}$	-1
X_3	$\begin{array}{c}\square\\[-3pt]\square\end{array}$	2
X_4	1	4

(Dine, Nelson, Nir, Shirman, '95)

$$g_4 \gg \lambda \gg g_1$$

$$W = \lambda X_1 X_2 X_4$$

$$W_{np} = \frac{\Lambda_4^5}{X_1 X_2 X_3^2}$$

susy breaking vev at

$$D_1 = 1.4\, F_{X_4} \neq 0$$

Superpartner masses from D-term

$$\mathbf{W}_{\text{eff}} \supset \; w_a \frac{X}{M_{\text{Pl}}} \, W_a W_a + \sqrt{2}\; \Omega_a \frac{W'}{M_{\text{Pl}}} W_a \Phi_a$$

Dirac
mass

majorana
mass

Superpartner masses from D-term

$$\mathbf{W}_{\text{eff}} \supset w_a \frac{X}{M_{\text{Pl}}} W_a W_a + \sqrt{2}\, \Omega_a \frac{W'}{M_{\text{Pl}}} W_a \Phi_a$$

Dirac mass

These interactions preserve an $\mathrm{U}(1)_R$

$$R[Q_i] = 1$$
$$R[W_a] = 1$$
$$R[\Phi_a] = 0$$

Dirac Gaugino Masses

gaugino contribution to scalar masses

$$\int d^4\theta \, \frac{1}{\Lambda^6} \, |W'W'|^2 Q^\dagger Q$$

gaugino mass

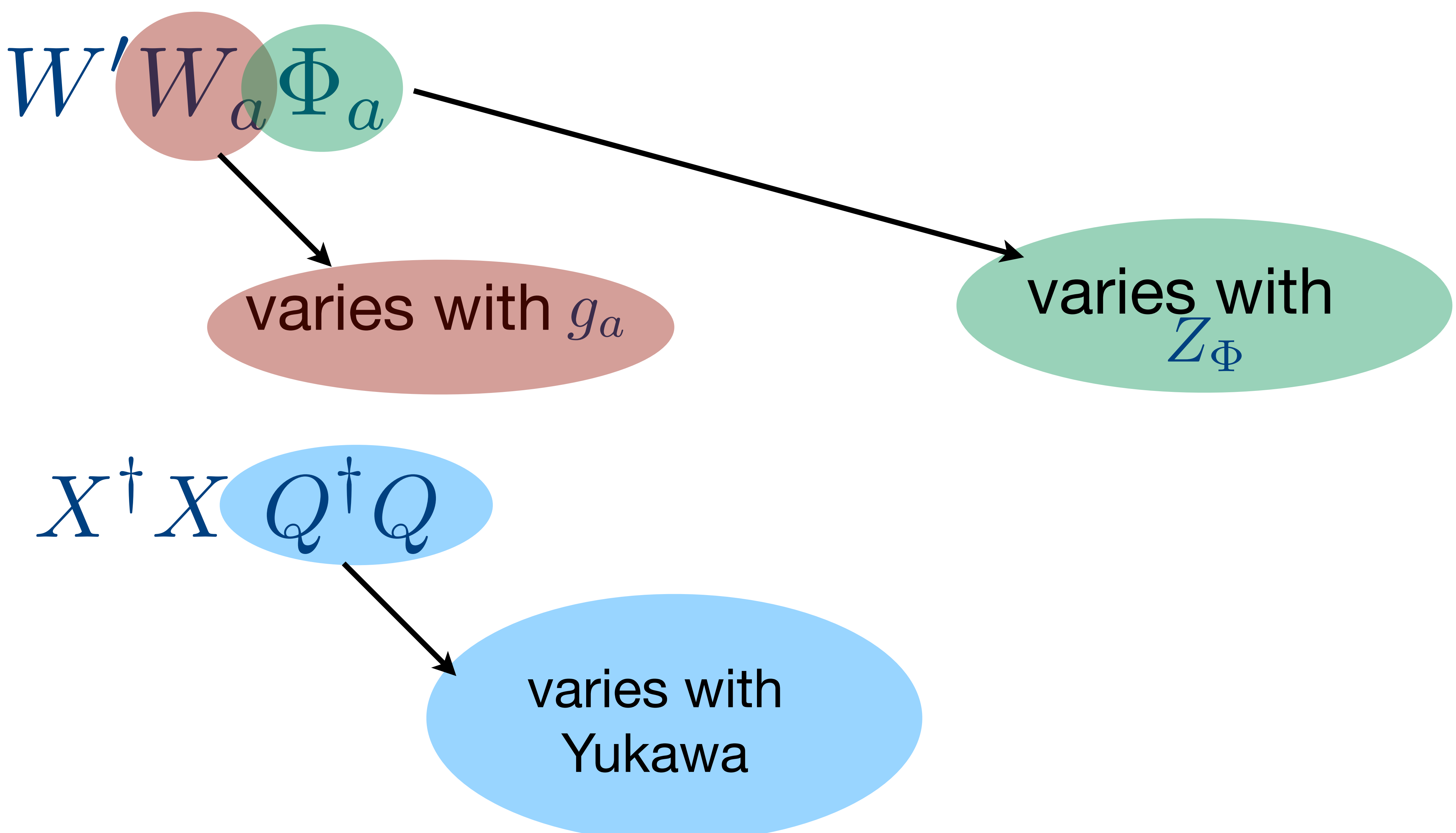
$$\frac{M^4}{\Lambda^2} \tilde{Q}^\dagger \tilde{Q}$$

extra suppression

no counterterm is needed and hence Dirac gauginos induce finite contributions to the scalars

A sample point

RGE evolution



A sample point

TeV scale outputs

$$M_a(M_{\rm Pl}) \;=\; 1\ {\rm TeV} \qquad \left\{ \begin{array}{lcl} M_3({\rm TeV}) & \sim & 5.4\ {\rm TeV} \\ M_2({\rm TeV}) & \sim & 1\ {\rm TeV} \\ M_1({\rm TeV}) & \sim & 600\ {\rm GeV} \end{array} \right.$$

A sample point

TeV scale outputs

$$M_a(M_{\rm Pl}) \; = \; 1 \; \text{TeV}$$

$$\left\{ \begin{array}{lcl} M_3(\text{TeV}) & \sim & 5.4 \; \text{TeV} \\ M_2(\text{TeV}) & \sim & 1 \; \text{TeV} \\ M_1(\text{TeV}) & \sim & 600 \; \text{GeV} \end{array} \right.$$

$$m_{\tilde{q}}^2(\text{TeV}) \; \sim \; (1.3 \; \text{TeV})^2 \times \; \text{flavor diagonal}$$

A deep problem in the Higgs sector

$$H_u \equiv H_u(h_u, \psi_{H_u}, F_{H_u})$$

$$H_d \equiv H_d(h_d, \psi_{H_d}, F_{H_d})$$

$\mu\, H_u\, H_d$ → supersymmetric mass

$B_\mu\, h_u\, h_d$ → supersymmetry breaking mass

A deep problem in the Higgs sector

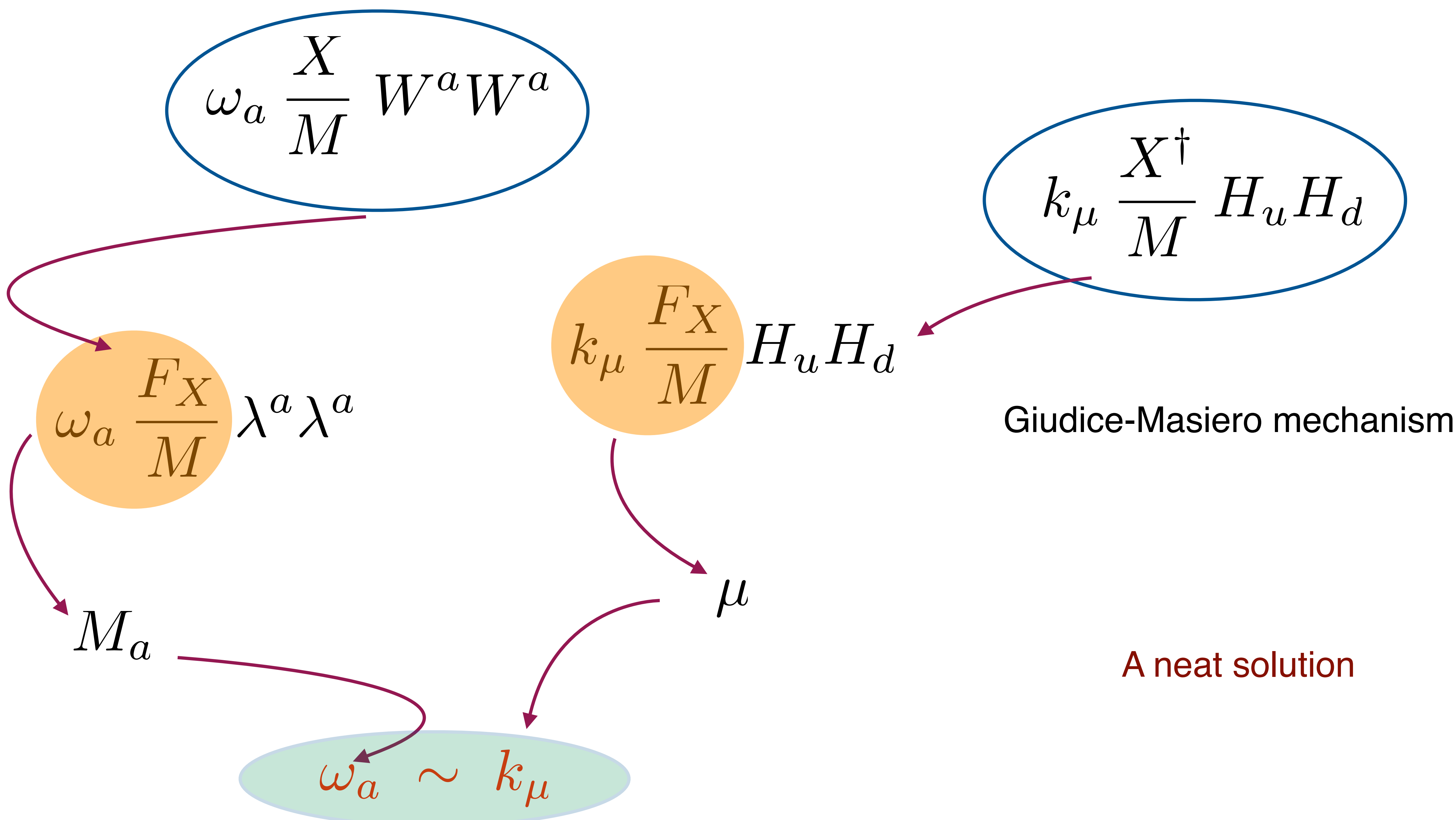
Natural electroweak symmetry breaking requires

$$\mu \sim M_a$$

$$B_\mu \sim |\mu|^2$$

μ problem

A deep problem in the Higgs sector



A deep problem in the Higgs sector

Nelson-Roy

We need a slightly more complicated operator
for D-term susy breaking

Operator:

$$\int d^2\theta \frac{1}{4} w_{2,\Phi_1,\Phi_2} \frac{\bar{D}^2(D^\alpha V' D_\alpha \Phi_1)}{M_m} \Phi_2.$$

$$\frac{\mu_{\Phi_2}}{2}(\widetilde{\phi}_1\widetilde{\phi}_2 - 2F_{\phi_1}\phi_2) \to \frac{\mu_{\phi_2}}{2}\widetilde{\phi}_1\widetilde{\phi}_2 + |\mu_{\phi_2}|^2|\phi_2|^2,$$

where

$$\mu_{\phi_2} = 2w_{2,\Phi_1,\Phi_2}\frac{\mathcal{D}}{M_m}.$$

\`

Let’s not conclude — since another SUSY talk is approaching