General Semi-direct Gauge Mediation

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Based on work with

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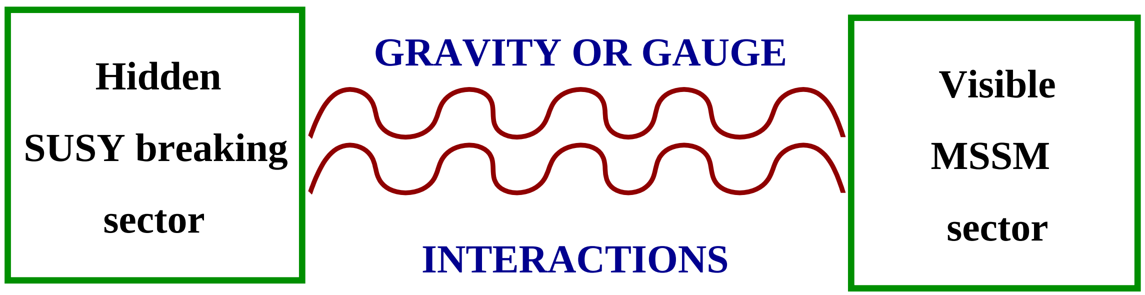
Supersymmetry is the most valuable candidate for physics beyond the Standard Model.

- **It addresses the hierarchy problem**
- **It provides exact gauge coupling unification at GUT scale**
- **It provides Dark Matter candidates**
- **... it is predicted by string theory**

However, it should be broken at low enough energy. This cannot be realized by a renormalizable theory at tree level (supertrace formula, gaugino Majorana masses).

Present paradigm: SUSY broken in a hidden sector and then communicated to the SM radiatively or by Planck-suppressed operators.

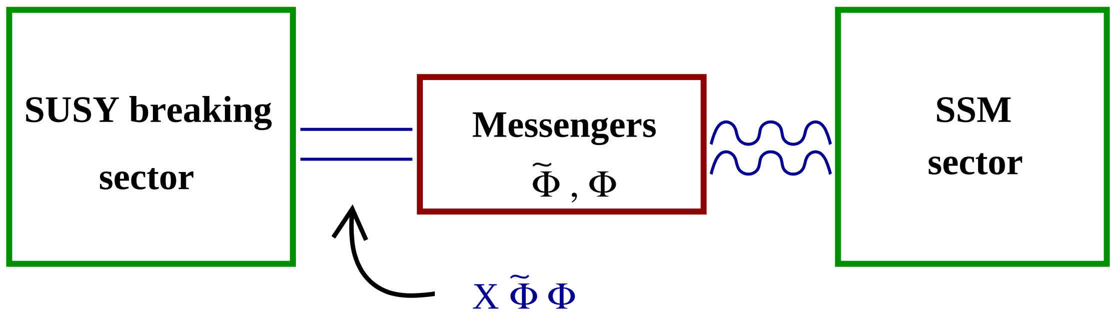
Supersymmetry breaking: gauge mediation vs gravity mediation.



Gauge dominated SUSY breaking scenarios more amenable to computations, and flavor blind (no additional source for FCNC). But they have a μ-problem and might have a Landau-pole problem.

Two popular frameworks of gauge mediation: minimal gauge mediation (MGM) and direct gauge mediation (DGM).

• **In MGM we have messenger fields which are charged under SM gauge interactions and couple to the hidden sector at tree-level as $\int d\theta^2 X\tilde{\Phi}\Phi$.**



The sparticle mass spectrum is rather simple $(X = x + \theta^2 F, \sqrt{F} < x)$

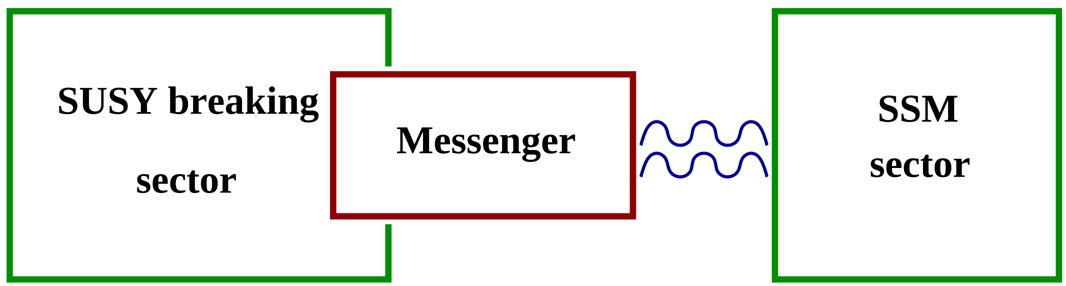
$$m_\lambda \sim \frac{\alpha_{SM}}{4\pi}\frac{F}{x}\left[1 + \mathcal{O}(\frac{F^2}{x^4})\right]$$

$$m_{sf}^2 \sim \left(\frac{\alpha_{SM}}{4\pi}\right)^2 \frac{F^2}{x^2}\left[1 + \mathcal{O}(\frac{F^2}{x^4})\right]$$

with $x \le 10^{15}\mathrm{GeV}$ for gauge mediation to dominate on gravity mediation.

Problems: the spurion coupling is put by hand; in concrete models difficult to generate both x and F of the right magnitude.

● In DGM the messengers belong to the hidden sector (no messengers, really) and the SM gauge group is part of the flavor group of the hidden sector.

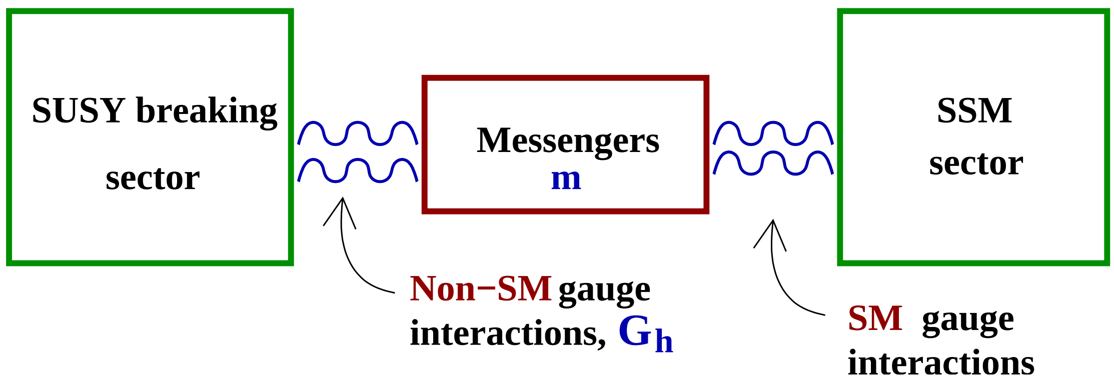


Problems: Landau pole due to large number of messengers; contribution to $\mathrm{Str} M^2_{\mathrm{mess}}$ which, if positive, may be a phenomenological disaster since it contributes scalar soft mass square with a minus sign

$$m^2_{sf} \sim -\mathrm{Str} M^2_{\mathrm{mess}} \log \frac{\Lambda_{UV}}{m^2} + \dots$$

where m is the messenger fermion mass and Λ_{UV} a ultraviolet cut-off. This would induce higgsing of $SU(3) \times U(1)$ interactions, if dominant!

• **Semi-direct gauge mediation** (SDGM): **messengers** couple to hidden sector through (non-SM) gauge interactions, but do not participate to DSB mechanism. [Randall; Seiberg,Volanski,Wecht]



Distinctive features: no spurion-like coupling (wrt MGM); softened Landau pole problem (wrt DGM) since the messenger group can be as small as U(1); need tree-level SUSY mass m for the messengers (typically put by hand).

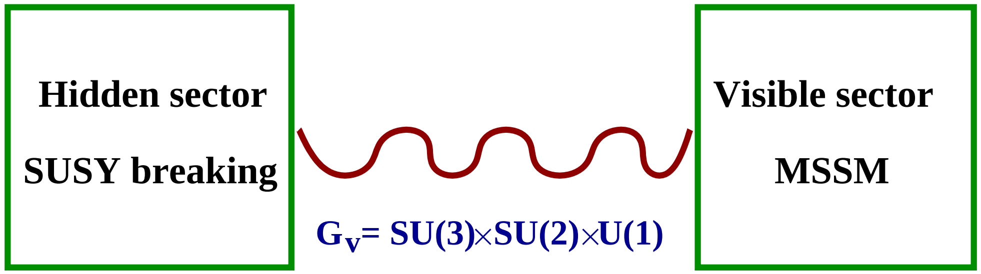
The **messenger group** G_h can be a (weakly gauged) **flavor** group of the hidden sector or a genuine **gauge** group; and can be either broken (higgsed) or unbroken by the DSB dynamics.

Naturalness and D-brane embedding 0906.0727

- SDGM arises generically in string/D-brane models: engineered different models of SDGM using D-branes at singularities.
- All parameters, including messenger SUSY mass, can be made natural (dynamically generated): strongly coupled messenger sector. Associated to geometry parameters.
- First steps towards holographic description of GM.

Question: does SDGM make generic (model-independent) predictions? Are there phenomenological signatures to single SDGM out?

General Gauge Mediation: efficient formalism to parametrize SUSY breaking sector effects in a model-independent way. [Meade,Seiberg,Shih]



In the limit $g_v \to 0$ the system separates into a SUSY breaking (hidden) sector and a supersymmetric one (SSM). The full Lagrangian, perturbative in g_v reads

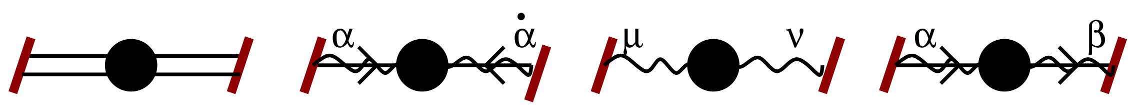
$$\mathcal{L} = \mathcal{L}_{SSM} + \int d^4\theta \, g_v V_v \mathcal{J}^v + \mathcal{O}(g_v^2)$$

where $\mathcal{J}^v$ is the hidden sector current superfield $(J^v, j^v_\alpha, j^v_\mu)$.

Philosophy: work exactly in the hidden sector but to leading order in g_v.

For computing soft masses, all we need to know about hidden sector is encoded in two point functions of the hidden sector current $\mathcal{J}^{\mathbf{v}}$

$$
\begin{aligned}
\langle \mathbf{J}(\mathbf{p})\mathbf{J}(-\mathbf{p})\rangle &= \mathbf{C}_0^{\mathbf{v}}(\mathbf{p}^2/\mathbf{M}^2) \\
\langle \mathbf{j}_\alpha(\mathbf{p})\bar{\mathbf{j}}_{\dot\alpha}(-\mathbf{p})\rangle &= \mathbf{p}_\mu \sigma^\mu_{\alpha\dot\alpha}\mathbf{C}_{1/2}^{\mathbf{v}}(\mathbf{p}^2/\mathbf{M}^2) \\
\langle \mathbf{j}_\alpha(\mathbf{p})\mathbf{j}_\beta(-\mathbf{p})\rangle &= \epsilon_{\alpha\beta}\,\mathbf{M}\,\mathbf{B}^{\mathbf{v}}(\mathbf{p}^2/\mathbf{M}^2) \\
\langle \mathbf{j}_\mu(\mathbf{p})\mathbf{j}_\nu(-\mathbf{p})\rangle &= (\mathbf{p}_\mu\mathbf{p}_\nu - \mathbf{p}^2\eta_{\mu\nu})\mathbf{C}_1^{\mathbf{v}}(\mathbf{p}^2/\mathbf{M}^2)
\end{aligned}
$$



$\mathbf{C}_0^{\mathbf{v}}$ $\mathbf{C}_{1/2}^{\mathbf{v}}$ $\mathbf{C}_1^{\mathbf{v}}$ $\mathbf{B}^{\mathbf{v}}$

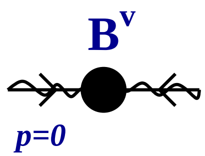
The blob encodes the exact hidden sector non-SUSY correction to the (SM) gauge field propagators.

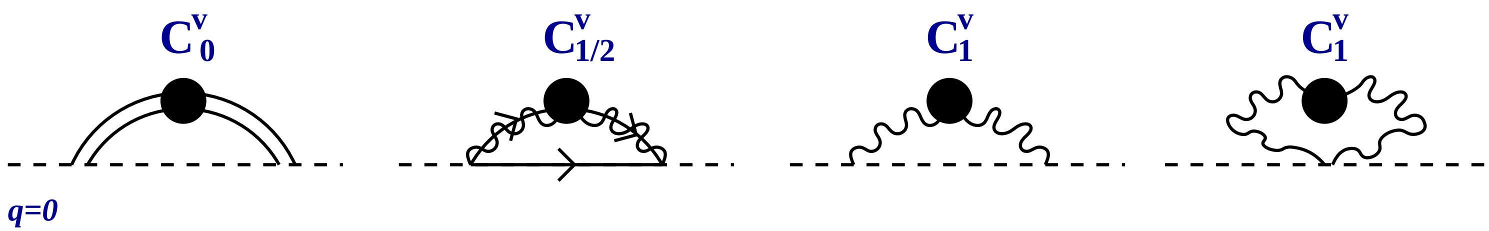
The $\mathbf{C}_\mathbf{s}$ are real while $\mathbf{B}$ is complex. In the SUSY limit

$$\mathbf{C}_0 = \mathbf{C}_{1/2} = \mathbf{C}_1 \;\;,\;\; \mathbf{B} = 0$$

(when SUSY broken, functions asymptote to these value in UV).

Soft mass spectrum is easily computed from above correlation functions

$\mathbf{m}_{\lambda} =$ 

$\mathbf{m}^2_{\mathbf{sf}} =$ 

The gaugino and sfermion masses read

$$
\begin{aligned}
\mathbf{m}_{\lambda} &= \mathbf{g}_{\mathbf{v}}^{\mathbf{2}}\,\mathbf{M}\,\mathbf{B}^{\mathbf{v}}(\mathbf{0}) \\
\mathbf{m}_{\mathbf{sf}}^{\mathbf{2}} &= -\frac{\mathbf{g}_{\mathbf{v}}^{\mathbf{4}}}{\mathbf{16}\pi^{\mathbf{2}}}\int \mathbf{dp}^{\mathbf{2}}\left(\mathbf{C}_{\mathbf{0}}^{\mathbf{v}}(\mathbf{p}^{\mathbf{2}}) - \mathbf{4C}_{\mathbf{1/2}}^{\mathbf{v}}(\mathbf{p}^{\mathbf{2}}) + \mathbf{3C}_{\mathbf{1}}^{\mathbf{v}}(\mathbf{p}^{\mathbf{2}})\right)
\end{aligned}
$$

Note: in the SUSY limit both vanish.

General Semi-Direct Gauge Mediation 0912.0743

In SDGM we can decouple the SUSY breaking sector as in GGM with $\mathbf{g_v} \leftrightarrow \mathbf{g_h}$ and define General SDGM re-writing the full Lagrangian as

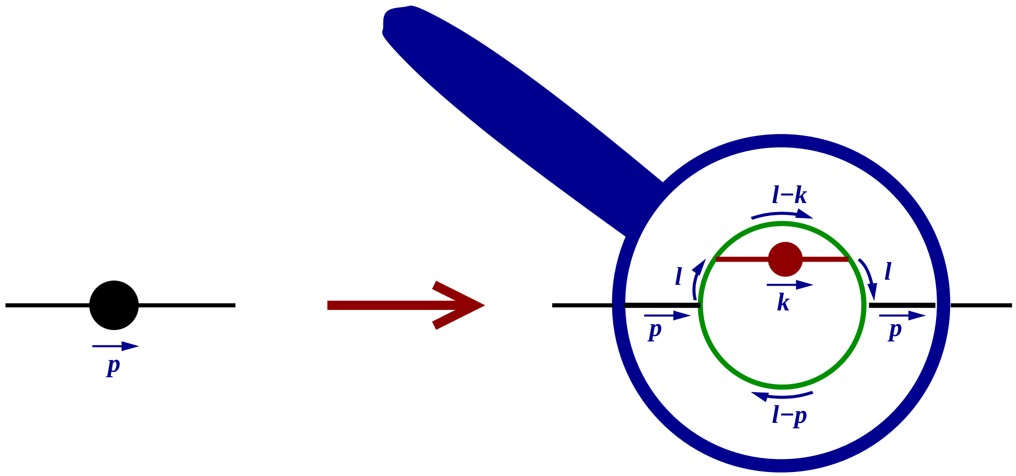
$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\mathbf{SSM}} + \int \mathbf{d}^4\theta \left(\mathbf{\Phi}^\dagger \mathbf{e}^{\mathbf{g_v V_v + g_h V_h}} \mathbf{\Phi} + \tilde{\mathbf{\Phi}} \mathbf{e}^{-\mathbf{g_v V_v - g_h V_h}} \tilde{\mathbf{\Phi}}^\dagger \right) \\ &+ \int \mathbf{d}^2\theta \, \mathbf{m} \mathbf{\Phi} \tilde{\mathbf{\Phi}} + \int \mathbf{d}^2\theta \, \mathrm{tr} \mathcal{W}_{\mathbf{h}}^{\mathbf{2}} + \mathbf{h.c.} + \int \mathbf{d}^4\theta \, \mathbf{g_h V_h} \mathcal{J}^{\mathbf{h}} + \mathcal{O}(g_h^2)\end{aligned}$$

where now $\mathcal{J}^{\mathbf{h}}$ is the hidden sector supercurrent associated to $\mathbf{G^h}$. The decoupling limit is now $\mathbf{g_h} \to \mathbf{0}$.

Note: can think of messengers as SSM matter in GGM, but messengers also have a SUSY mass $\mathbf{m}$ and $\mathbf{G^h}$ can be higgsed.

Comparing with GGM, we can express $\mathbf{B^v}, \mathbf{C_s^v}$ in terms of the hidden sector correlation functions $\mathbf{B^h}, \mathbf{C_s^h}$.

Tumbling: in SDGM we can **zoom-in** in the correlators of the global $\mathbf{G_v}$ currents and see how they depend on those of the global $\mathbf{G_h}$ currents.



Black= G_v −fields Red= G_h −fields Green = Messenger fields

$$\mathrm{B^v(p^2) = f\left(B^h(k^2), C^h_r(k^2)\right)} \quad \text{and} \quad \mathrm{C^v_s(p^2) = f\left(B^h(k^2), C^h_r(k^2)\right)}$$

- The above diagrams directly contribute to gaugino mass, and correct sfermions propagators, their mass squared getting then a further $\mathrm{g_v^2}$ $\longrightarrow$ in SDGM **gauginos** get a mass at $\mathrm{g_v^2 g_h^4}$, **sfermions** at $\mathrm{g_v^2 g_h^2}$, to leading order.

Soft mass spectrum

Doing explicit computations things simplify.

1. $\mathbf{B^v}$ is a function of $\mathbf{B^h}$ only, while $\mathbf{C^v_s}$ are functions of l.c. of $\mathbf{C^h_r}$ only!

$$\mathbf{B^v = f(B^h)} \quad \text{and} \quad \mathbf{C^v_s = f(C^h_r)}$$

2. Integration on internal momenta $\mathbf{l}$ (and also $\mathbf{p}$ for sfermions) gives back common $\mathbf{k}$-dependent kernels out of many different diagrams!

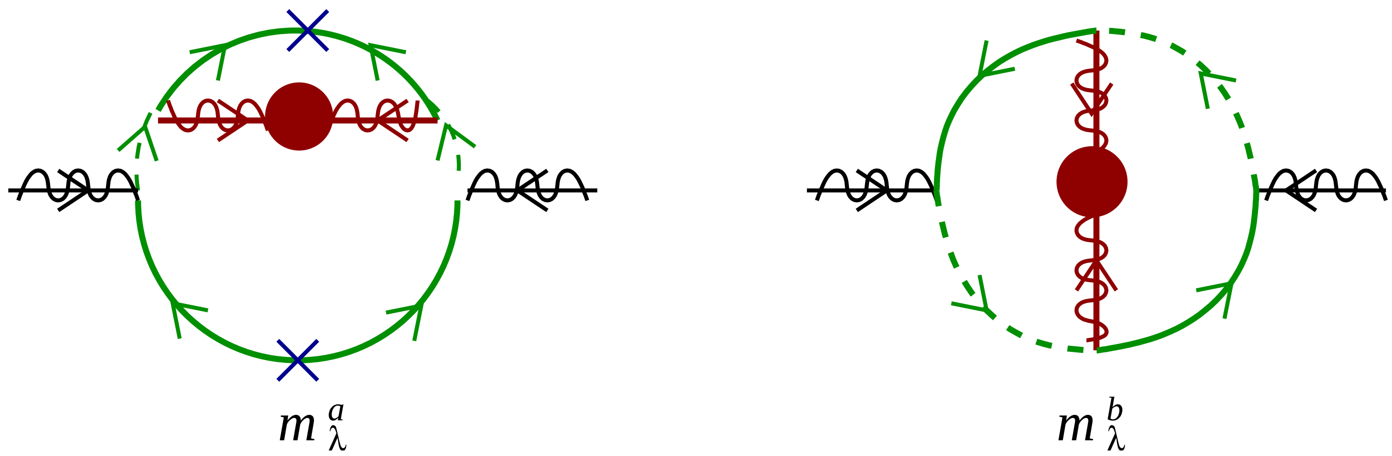
The final result is as follows

$$\mathbf{m_\lambda} = \frac{\mathbf{g_v^2 g_h^4}}{\mathbf{(4\pi)^2}}\mathbf{M}\int \mathbf{dk^2\, L(k^2/m^2)B^h(k^2)}$$

$$\mathbf{m^2_{sf}} = \frac{\mathbf{g_v^4 g_h^4}}{\mathbf{(4\pi)^6}}\int \mathbf{dk^2\, K(k^2/m^2)}\left(\mathbf{C^h_0(k^2) - 4C^h_{1/2}(k^2) + 3C^h_1(k^2)}\right)$$

where the (only) two **kernels** $\mathbf{L(k^2)}$ and $\mathbf{K(k^2)}$ are exactly computable in perturbation theory.

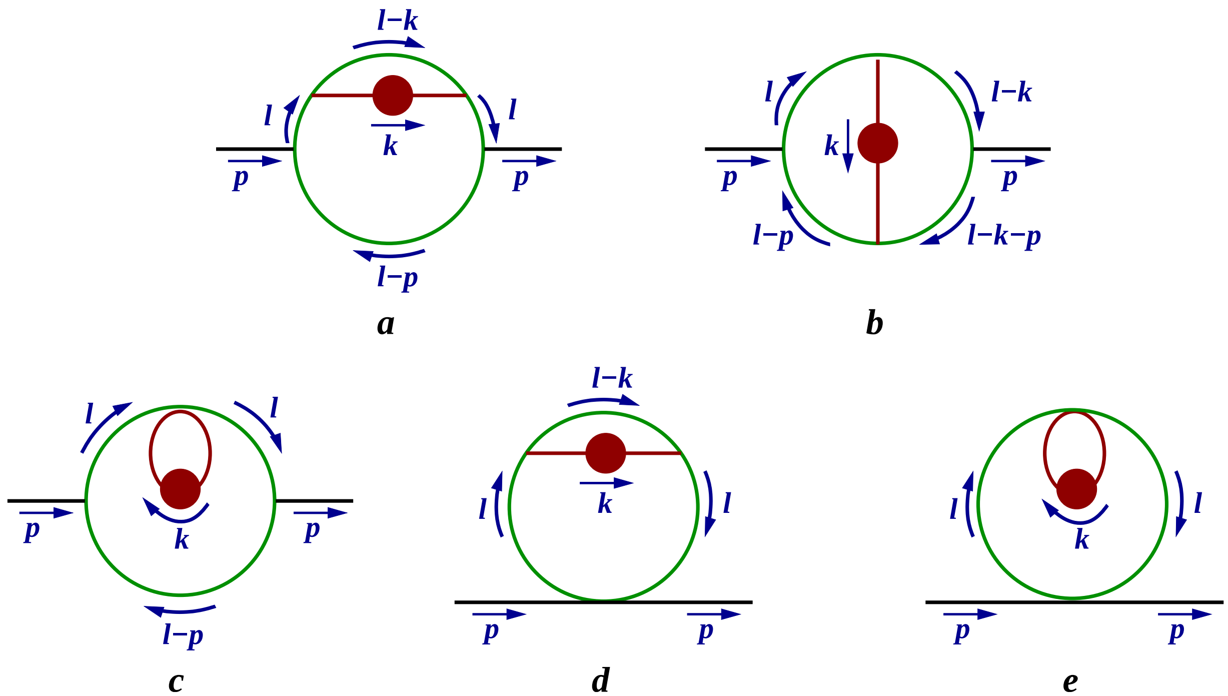
Gaugino screening: the kernel $\mathbf{L(k^2)}$ vanishes because of exact cancellation (at $\mathrm{p} = 0$) between the two diagrams contributing to it.



An explicit computation shows that $\mathbf{L(k^2) = L^a(k^2) + L^b(k^2) = 0}$. Next non-vanishing contribution expected at order $\mathbf{g_v^6 g_h^4}$!

Note: this is a model-independent feature. It holds regardless the details of hidden sector SUSY breaking dynamics.

Sfermion masses: get contribution from many graphs



The kernel $\mathbf{K(k^2/m^2)}$ is positive and has a soft behavior at large momenta

$$\mathbf{K(x)} = \begin{cases} \frac{\mathbf{5}}{\mathbf{18}}\mathbf{x^2} - \frac{\mathbf{137}}{\mathbf{1350}}\mathbf{x^3} + \frac{\mathbf{5437}}{\mathbf{176400}}\mathbf{x^4} + \mathcal{O}(\mathbf{x^5}) & \text{for } \mathbf{x} \to \mathbf{0} \\ \gamma \ \log \mathbf{x} \qquad (\gamma = \mathbf{14.4}) & \text{for } \mathbf{x} \to \infty \end{cases}$$

The gaugino/sfermion mass ratio goes as $\mathbf{m_\lambda / m_{sf}} \sim \mathbf{g_v^4 g_h^2}$!

- **The bad for the good: SDGM and Anomaly Mediation.**

AM is an always present gravitational contribution (relevant in sequestred case). [Giudice,Luty,Murayama,Rattazzi; Randall,Sundrum]

It predicts

$$\mathbf{m}_\lambda \sim \frac{\mathbf{g_v^2}}{\mathbf{16\pi^2}}\frac{\mathbf{M^2}}{\mathbf{M_{pl}^2}} \qquad \mathbf{m_{sq}^2} \sim \mathbf{m_\lambda^2} \qquad \mathbf{m_{sl}^2} \sim -\mathbf{m_\lambda^2}$$

SDGM can cure tachyonic slepton masses. Take same hidden sector.

- TeV **scale gaugino mass** $\longrightarrow \mathbf{M \sim 10^{12} GeV}$
- **Comparable** $\mathbf{m_{sf}^{SD} \sim m_{sf}^{AM}} \longrightarrow \mathbf{g_h \sim 10^{-2}}$
- **No tachyonic messengers** $\longrightarrow \mathbf{10^5 < m < 10^{10} GeV}$

Note: SDGM/AM conspiracy could arise quite naturally in string theory.

- **SDGM can also be used to cure tachyonic sfermion masses or invert hierarchy between gauginos and sfermions of DGM, but fine tuning needed.**

• Unscreening the gaugino. to appear soon

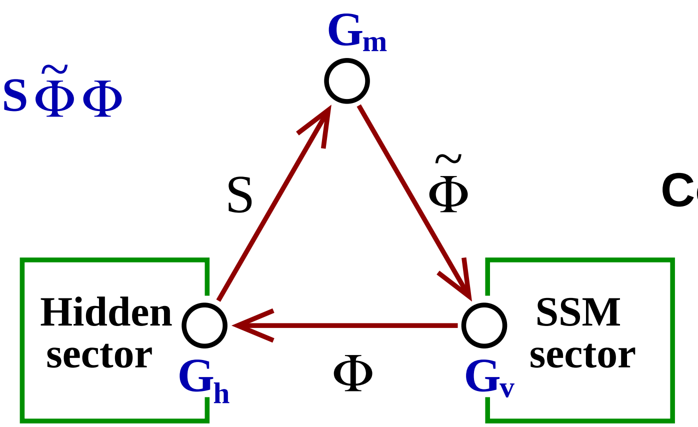
Allow for a chiral messenger sector: gauge symmetries prevent presence of tree level mass term. Gaugino unscreened since only one diagram contributes to its mass: no cancellation anymore!

At energies lower than M messengers get a SUSY mass, e.g. by higgsing.

If enough RG evolution between M and m gaugino mass is not heavily suppressed: sfermion/gaugino mass ratio can be of order 10.

Example:

$W = y\, S \tilde{\Phi} \Phi$



Higgsing: $\langle S \rangle = s \longrightarrow m = ys$

Confinement: $\tilde{\Phi}_{comp} = \frac{1}{\Lambda_m} S \tilde{\Phi} \longrightarrow m = y\Lambda_m$

Note: it comes from fractional D3-branes at a dP_3 Calabi-Yau singularity.

Conclusions...

- SDGM represents a large class of gauge mediation models.
- It can be quite naturally embedded in string theory (and retrofitted).
- We provided a current based descprition of SDGM. Some features:
  1. generically, the gaugino is screened
  2. sfermion squared mass sign is reversed w.r.t. gauge mediation
- SDGM can be used in combination with other mechanisms.
- Gaugino can be unscreened via a chiral messenger sector.

...and Outlook

- Finish the paper on unscreened gaugino!
- More phenomenolgy: other soft terms, e.g A-terms, $\mu/\mathrm{B}\mu$.
- More on AM(DGM)/SDGM conspiracy $\longrightarrow$ D-brane embedding?
- Look for a fully consistent AdS/CFT-like framework.

My own dream:

1. Embed a model of SUSY breaking in string theory and describe the strongly coupled part (the hidden, the messenger and possibly part of the visible sectors) via its gravity dual.

2. Engineer the rest (SSM) in terms of explicit D-branes sources.

3. Use AdS/CFT machinery to predict the sparticle mass spectrum and interactions.

A pictorial representation of this dream is as follows