Supersymmetry Breaking and Gauge Mediation

Zohar Komargodski

Institute for Advanced Study, Princeton

ZK, D. Shih arXiv:0902.0030

T. Dumitrescu, ZK, N. Seiberg, D. Shih arXiv:1003.2661

D. Green, A. Katz, ZK arXiv:1008.2215

Introduction

The Lagrangian of the MSSM is simple, and fixed uniquely once an R-parity is imposed.

However, SUSY has to be broken. We introduce by hand soft breaking terms, but we should later explain them as coming from spontaneous SUSY breaking.

$$\mathcal{L}_{soft} = \left(m_Q^2 Q^\dagger Q + m_U^2 U^\dagger U + ...\right) + m_3 \lambda^{(3)} \lambda^{(3)} + m_2 \lambda^{(2)} \lambda^{(2)} + m_1 \lambda^{(1)} \lambda^{(1)}$$

$$+ \text{Higgs} + \text{trilinear}$$

The mass terms $m_Q^2, m_U^2 ...$ are matrices in flavor space.

Introduction

They soft terms are not completely random.

- To address the hierarchy problem the sparticles the soft terms have to be around $\sim$100GeV or $\sim$1TeV.
- The sparticle's mass matrices have to be almost diagonal in flavor space to avoid constraints from flavor physics.
- The phases of the gaugino masses have to be aligned to avoid EDMs.

Gauge Mediation

Gauge Mediation is a way to transfer SUSY breaking from the hidden sector to the soft parameters.

It is defined by letting the SM gauge group act on the hidden sector. As shown by [Meade et al.], this definition implies two sum rules. But the remaining parameter space is still vast and mostly unexplored.

This idea solves automatically the flavor puzzle of the SSM. It can also explain why all the soft masses are at a TeV. We need to assume that the vacuum preserves CP in order for the gauginos' phases to be aligned. This is not automatic.

Minimal Gauge Mediation

As a simple example, we can start from a toy ansatz, not a real model [Dine, Fischler, Nelson, Shirman...].

SUSY breaking is implemented with a spurion $X = \theta^2 F$ and we have one superfield ψ in the fundamental of $SU(5)$ and $\tilde{\psi}$ is in the anti-fundamental of $SU(5)$. The coupling is

$$\int d^2\theta \left(X\psi\tilde{\psi} + M\psi\tilde{\psi} \right)$$

The $\psi, \tilde{\psi}$ fields are called messengers. Their spectrum is not supersymmetric because of the coupling to the spurion X.

Minimal Gauge Mediation

The non-supersymmetric spectrum of the messengers is transmitted radiatively at one and two loops to the gaugino masses and sparticle masses.

$$m_{\tilde{g}} \sim \frac{\alpha}{4\pi} \frac{F}{M} , \qquad m^2_{\tilde{f}} \sim \frac{\alpha^2}{16\pi^2} \frac{F^2}{M^2}$$

Thus, we get $m_{\tilde{g}} \sim m_{\tilde{f}}$, which is phenomenologically desirable.

SUSY Breaking Models

PROBLEM: come up with renormalizable SUSY QFTs that break SUSY spontaneously and see if they can be useful for gauge mediation.

SUSY can be broken in only two ways [Witten]

- At tree level
- Non-perturbatively

Obviously, it is simpler to study models of the first kind. Moreover, in many models based on non-perturbative effects the low energy description is in terms of tree-level SUSY breaking.

Tree Level SUSY Breaking

The most general theory of chiral superfields with canonical kinetic terms and arbitrary superpotential is

$$L = \int d^4\theta \sum_i \Phi_i \Phi_i^\dagger + \left(\int d^2\theta W(\Phi_i) + c.c. \right) \ .$$

We are looking for critical points of the potential $V = \sum_i \left| \frac{\partial W}{\partial \Phi_i} \right|^2$ with nonzero energy (denoted $\sqrt{F}$). However, such points with $m^2_{boson} > 0$ do not exist [Ray]. There are always tachyons or massless bosons. The former case is uninteresting.

Tree Level SUSY Breaking

Thus, every critical point with nonzero energy has massless bosons. In fact, if W is renormalizable, the massless boson corresponds to at least one complex pseudo-flat direction. We denote this direction by $X \in \mathbb{C}$.

This flat direction is noncompact and can be lifted by radiative corrections. We need to calculate the one-loop potential $V_{CW} = V_{CW}(X)$ and see whether it has any minima.

The answer is model dependent.

Tree Level SUSY Breaking

We can write down the most general renormalizable terms coupling the messengers to the pseudo-flat direction X

$$W_{X-messengers} = \int d^2\theta \left(\lambda_{ij} X \psi^i \tilde{\psi}^j + m_{ij} \psi^i \tilde{\psi}^j \right)$$

Since it is a model dependent question where X is stabilized, we can try to analyze the theory as a function of X and in the end plug the actual value of the VEV, X_{VAC}.

Gaugino Mass

As a first question, we can try to evaluate the gaugino mass as a function of X. This is an easy one-loop diagram and we get

$$m_{\tilde{g}} \sim \frac{\alpha}{4\pi} F \partial_X \ln \det \left(X \lambda_{ij} + m_{ij} \right) + \text{unimportant}$$

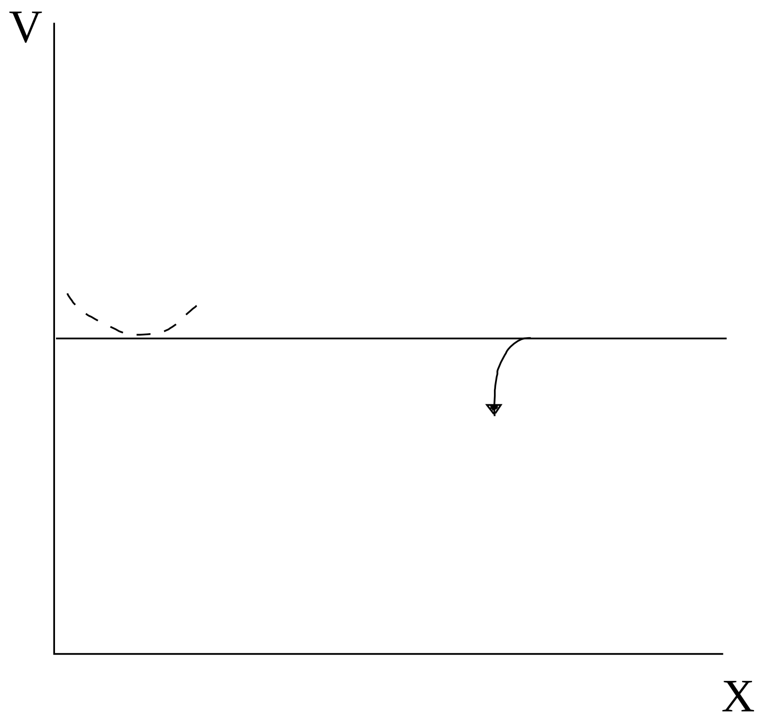
Suppose the leading term is nonzero at X_{VAC}, then $\det \left(X \lambda_{ij} + m_{ij} \right)$ depends on X nontrivially. But it is a (complex) polynomial, so if it depends on X, it has at least one zero at some X_{crit}.

At X_{crit} some of the ψ fermions are massless and it can also be shown that some boson becomes tachyonic.

Gaugino Mass

It is then possible to lower the energy of the pseudo-flat direction by rolling with these tachyons classically.

Therefore, any vacuum with nonzero gaugino masses (at leading order) must be meta-stable.



Gaugino Mass

This theorem guides us to look for better models. In particular, it has been hard to find phenomenologically compelling dynamical models of SUSY breaking. This is mostly because the search was for stable ground states.

This observation has been useful in model building attempts based on massive SQCD [Intriligator,Seiberg,Shih]. Once one gives up on the assumption of stability of the renormalizable effective description, it is possible to write down examples with comparable gaugino and scalar masses.

General Theories of Messengers

To summarize, theories of the form

$$W_{X-messengers} = \int d^2\theta \left(\lambda_{ij} X \psi^i \tilde{\psi}^j + m_{ij} \psi^i \tilde{\psi}^j \right)$$

have to be metastable in order to generate leading order gaugino masses. But even if so, what are the phenomenological possibilities? (This question was first raised by [Cheung, Fitzpatrick, Shih].)

One can study the ratio of the gaugino to scalar mass $\frac{m_{\tilde{g}}}{m_{\tilde{f}}}$. It can be shown that this is bounded from above in a simple way. The inequality is saturated for models in which m and λ commute (these are trivial generalizations of minimal gauge mediation).

General Theories of Messengers

Thus, this class of general theories of messengers is an interesting generalization of Minimal Gauge Mediation.

It arises as a low energy effective description of many dynamical models, and due to the inequality we proved, it is also clear that in these theories the Bino cannot be made heavier than it usually is in MGM.

An Extension

All the calculable dynamical theories known so far, reduce at low energies to one of the theories above (perhaps with corrections in the Kähler potential).

We will now briefly explain that there is a much more general class of theories, with qualitatively new, and largely unexplored, phenomenological predictions.

Gaugino Mediation

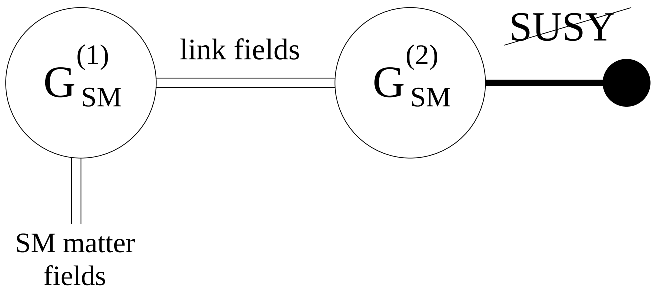
Are there theories with $m_{\tilde{g}} \gg m_{\tilde{f}}$? These cannot be the theories of messengers above.

Such a spectrum is claimed to be possible in 5D constructions [Kaplan et al., Chacko et al.] and some strongly coupled proposals in 4D [Roy, Schmaltz] (for which there is no existence proof yet).

One can also “deconstruct” the 5D theory [Arkani-Hamed et al., Hill et al.] into a 4D quiver gauge theory. In fact, two sites are enough to demonstrate the main point [Cheng et al., Csaki et al.].

Gaugino Mediation

The deconstruction ansatz looks as follows



The scale of the SUSY breaking sector is denoted M. The ansatz must satisfy some ad-hoc assumptions

- The link fields higgs the symmetry $G^{(1)}_{SM} \times G^{(2)}_{SM}$ to the diagonal G_{SM} at some scale v.
- The link fields should be supersymmetric at tree level, in other words, no charged fields under $G^{(1)}_{SM}$ can break SUSY at tree level.

Gaugino Mediation

- If $v \gg M$ the higgsing is much above the scale of SUSY breaking, so effectively the setup reduces to the old scenario. All the results discussed before are recovered.
- If $v \ll M$, then at scales below v the conventional picture emerges, but the two-loop integrals have, effectively, a cutoff v. So we can estimate $m^2_{\tilde{f}} \sim \frac{v^2}{M^2}\frac{\alpha^2}{16\pi^2}\frac{F^2}{M^2}$. But the visible gaugino is a mixture of the two gauginos of $G^{(1,2)}_{SM}$ and so it picks up the soft mass of $\tilde{g}^{(2)}$. Thus, $m_{\tilde{g}} \sim \frac{\alpha}{4\pi}\frac{F}{M}$. We see that the spectrum has suppressed scalar masses!
- For $v \sim M$ we obtain some mixed gauge-gaugino mediation.

Direct Gaugino Mediation

Are there simple single-sector theories that lead to this dynamics?

A-priori one would think this is unlikely, because if the model is indeed dynamical, it goes through strong coupling at some point. Therefore, if SUSY is broken it would be democratically distributed among all particles.

Direct Gaugino Mediation

Fortunately, this pessimistic intuition turns out to be wrong. We have considered $SU(N_c)$ gauge theory with N_f flavors Q^I ($I = 1...N_f$) and Yukawa couplings

$$W = m_I^J Q^I \tilde{Q}_J + S_i^a Q^i \tilde{Q}_a + \tilde{S}_a^i Q^a \tilde{Q}_i$$

where $S, \tilde{S}$ are gauge singlets and $i = 1...k$, $a = k+1...N_f$.

We can demonstrate via Seiberg duality that this simple theory flows in the IR to a variation of the deconstruction ansatz. (And the theory breaks SUSY at the same time!). The mass terms flow to v and M, and we can take the limit of small v.

The main ingredient that makes this model successful is that a mass term turns under duality to higgsing. This is very general and many other models exist.

Phenomenology

The phenomenology of even the simplest models of this form is unknown. It would be useful to consider the low energy effective theory in some generality and see what kinds of spectra it can predict. But we do know something:

- These theories interpolate between pure gauge and gaugino mediation. And the scale of mediation can be arbitrary. Low scale variations of gaugino mediation have been studied only recently by [De Simone et al., Abel et al.]. There are interesting experimental signatures.
- Such models formally belong to the class of [Meade et al.]. But their phenomenology would appear to be quite unconventional.

Phenomenology

Now that we know gaugino mediation can arise from simple single-sector four-dimensional theories, a thorough investigation of such models is warranted.

Conclusions and Open Questions

- We discussed some general results about gauge mediation, with an emphasis on theories which reduce to weakly coupled messengers.
- Such theories need to satisfy special constraints on their vacuum structure to generate leading order gaugino masses.
- There is a general inequality among the sparticles and gauginos in such models.
- We discussed a conceptually different set of theories, which can yield suppressed masses for the sparticles. We have found simple four-dimensional UV completions for such theories.
- It was emphasized that their phenomenology is largely unknown and is bound to be interesting.

Conclusions and Open Questions

- We close by remarking that the four-dimensional theory we presented here has, in the deep IR, some features in common with extra-dimensional models. It would be nice to investigate this possibility further.