# Mediation of Supersymmetry Breaking in String Compactifications

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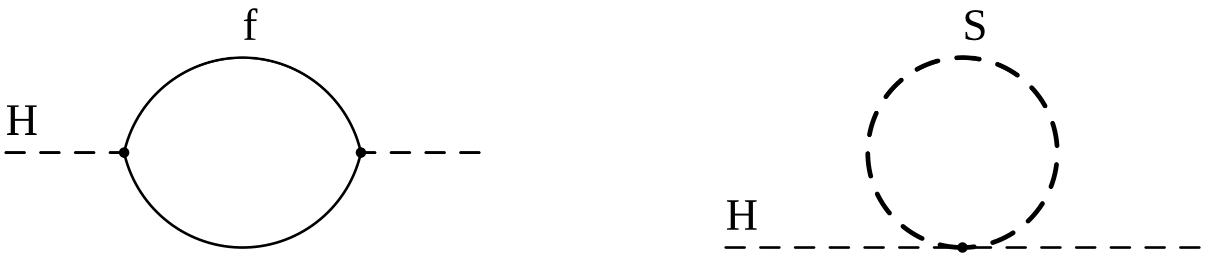
## The hierarchy problem

In Standard Model, the Higgs mass receives quadratically divergent contribution

$$m_h^2 \sim \Lambda^2$$




(a) (b)

Hence, if Standard Model were valid description of nature up to the Planck scale, one would expect Planck scale Higgs

$$m_h \sim M_P \gg M_w.$$

In 2007 LHC will turn on in Geneva.

It is widely hoped that LHC will discover mechanism of stabilization of the weak scale and of electro-weak symmetry breaking.

The leading candidate is the low-energy supersymmetry.

## MSSM

In MSSM one extends the spectrum of SM by adding a superpartner $\tilde{\phi}$ for each Standard Model particle.

The SM quadratically divergent contribution to Higgs mass gets canceled by opposite contribution from superpartner particles, hence

$$m_h^2 \sim m_{SUSY}^2,$$

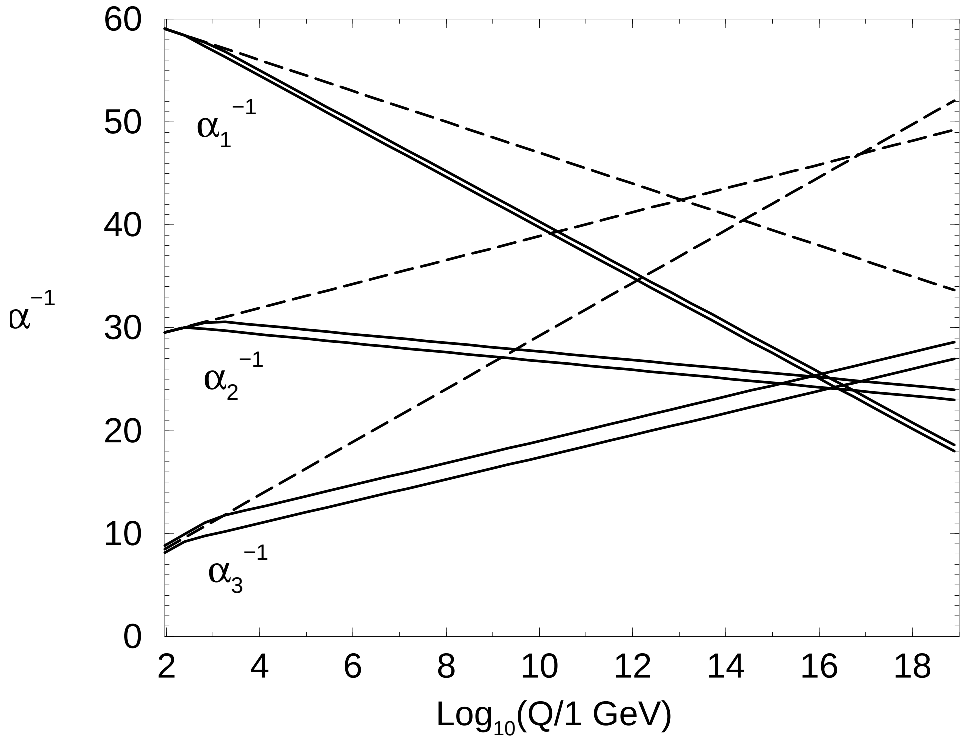
where $m_{SUSY}$ is the scale of supersymmetry breaking.

Hence, one expects SUSY to be just around the corner!

$$m_{SUSY} \sim M_{weak}.$$

MSSM predicts naturally light Higgs scalar. Some argue that Higgs should have been already observed...

However, one optimistic evidence: *gauge coupling unification.*



## SUSY breaking

To explain the weak scale, it is necessary to break SUSY around TeV.

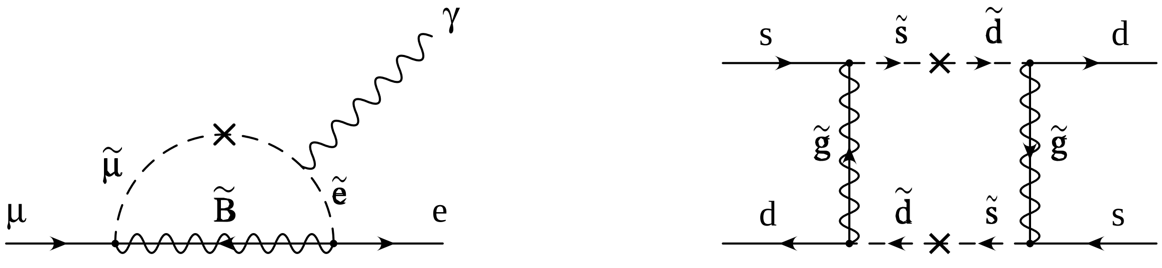
*Bottom-Up:* parametrize SUSY breaking using soft SUSY breaking terms (these do not reintroduce quadratic divergences)

$$\mathcal{L}_{soft} = m_\lambda \lambda\lambda + \tilde{q}^\dagger m_{\tilde{q}} \tilde{q} + \ldots$$

$\sim 100$ new parameters!

Hints of organizing principle: *flavor universality*

Flavor dependent squark masses induce large flavor changing neutral currents (FCNC's)



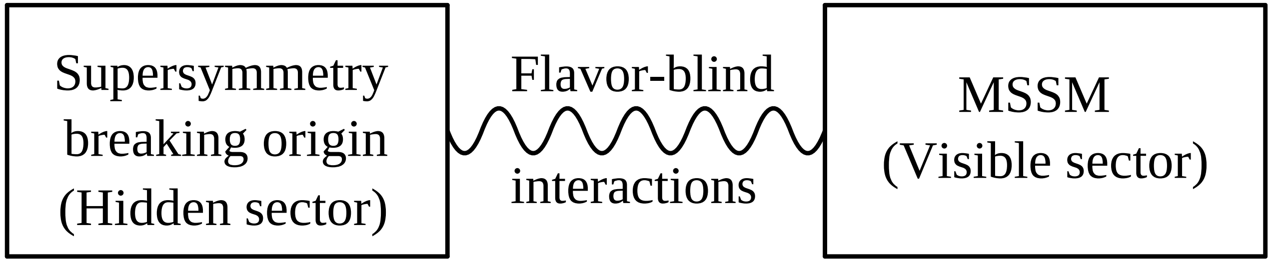

(a) (b)

Limits on $\mu \to e\gamma$ and $K^0 - \overline{K}^0$ mixing give

$$\frac{\Delta m^2_{\tilde{q}}}{m^2_{\tilde{q}}} \lesssim 10^{-3}$$

Flavor symmetry is broken by Yukawa's $\rightarrow$ it cannot explain flavor universality of sparticle masses.

One way to implement flavor universality is to assume existence of hidden sector which dynamically breaks SUSY. If the breaking is mediated to SM using flavor-blind interactions, the constraints on the sparticle mass degeneracies are automatically obeyed.



Possible flavor-blind mediation interactions:

gauge forces: gauge and gaugino mediation

coupling to conformal supermultiplet: anomaly mediation

coupling to dilaton: dilaton mediation

## *Gravity & Moduli mediation:*

Let $X$ be a 'spurion' field that parametrizes the supersymmetry breaking sector. SUSY breaking is described by spurion F-term

$$\langle X \rangle = X_0 + \theta^2 F_X .$$

Integrating out massive bulk fields leads to generic couplings

$$\int d^4\theta \frac{c_i}{M^2} X^\dagger X Q_i^\dagger Q_i .$$

It is expected that $c_i \sim \mathcal{O}(1)$ are flavor dependent, because the bulk fields have different couplings to different generations.

The couplings $\int d^4\theta \frac{c_i}{M} X^\dagger X Q_i^\dagger Q_i$ contain mass terms for SM sparticles

$$m_i^2 \sim c_i \frac{F_X^\dagger F_X}{M^2}$$

that are flavor non-universal. Since $M \leq M_P$ and $c_i = \mathcal{O}(1)$, this is comparable to universal gravity contribution

$$m^2 \sim \frac{F_X^\dagger F_X}{M_P^2}.$$

Hence gravity mediation is non-universal since such massive fields occur in any theory of quantum gravity (i.e. string theory).

## *Gauge Mediation*

SUSY breaking mediated by messenger fields charged under standard model gauge group that couple to the hidden sector.

$\phi_i + \tilde{\phi}_i, i = 1, \ldots N$ in $\mathbf{5} + \overline{\mathbf{5}}$ of $SU(5)$ (to preserve unification)

$$W = \tilde{\phi}_i X \phi_i + W_{MSSM}$$

The spurion field $\langle X \rangle = M + \theta^2 F$ parametrizes the SUSY breaking sector.

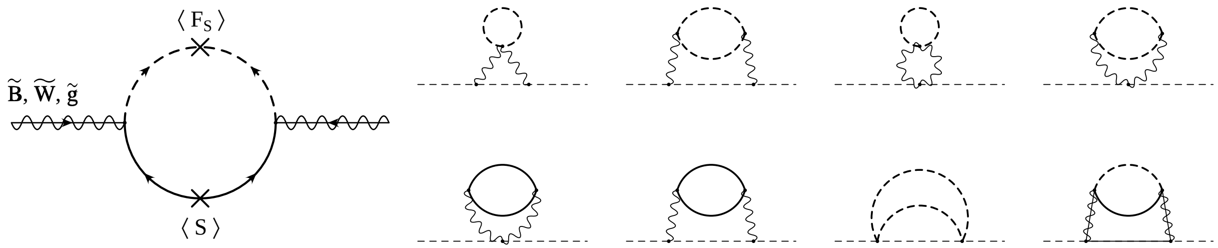
$M$ : mass of the messengers

$F$ : SUSY breaking F-term.

Scalar masses depend on gauge quantum number only$\longrightarrow$ flavor universal.

Gaugino masses are generated at one-loop and squark & slepton masses are generated at two loops, giving comparable answers

$$m_\lambda \sim N \frac{\alpha F}{M} \quad m_{\tilde{q}}^2 \sim N \left(\frac{\alpha F}{M}\right)^2 .$$



*Constrains on gauge mediation.*

Gauge mediation should dominate over moduli/GR medation

$$m_{scalar} \sim \frac{\alpha F}{M} \gg \frac{F}{M_P}.$$

This puts upper bound on the messenger masses

$$M \lesssim 10^{15}\mathrm{GeV}.$$

For TeV sparticle masses, this gives a bound on the strength of SUSY breaking

$$F \lesssim (10^{10}\mathrm{GeV})^2.$$

Gauge coupling running modified above the messenger mass scale $M$

$$\delta\alpha_{GUT}^{-1} = -\frac{2N}{2\pi}\ln\left(\frac{M_{GUT}}{M}\right).$$

For perturbative unification with $M \sim 10^{10}\mathrm{GeV}$ gives $N \lesssim 5$.

## *Constraints from Cosmology*

In gauge mediated SUSY breaking, gravitino is the LSP

$$m_{3/2} \sim \frac{F}{M_P}$$

In the early universe, it freezes out at $T \sim m_{3/2}$ with abundance

$$\Omega_{3/2} \sim \frac{\sqrt{F}}{10^6 \mathrm{GeV}}$$

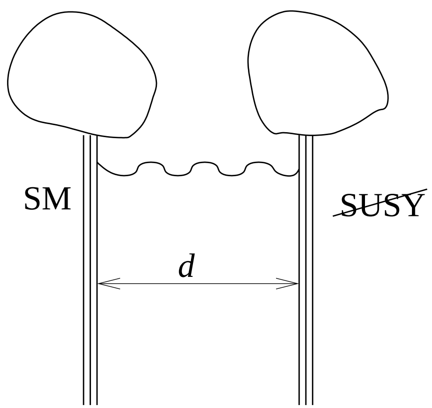
To avoid overclosing the universe, one needs

$$F \lesssim (10^6 \mathrm{GeV})^2.$$

## *String Theory Models*

For concreteness Type II string theory compactification with SM and hidden sector living on two stacks of D-branes.

SUSY is broken dynamically in the hidden sector gauge group at a dynamically induced scale $\Lambda_H$. We assume that all string moduli are stabilized *supersymmetrically* at scale $\gg \Lambda_H$ so they can be safely integrated out. [GKP, KKLT]



## *Mediation of SUSY breaking*

The mass of the open strings stretching between the D-brane stacks is

$$M = \frac{d}{\ell_s^2}.$$

If $M \ll M_s$ or equivalently $d \ll \ell_s$ then dominant interaction between the D-brane stacks is via the stretched open strings; they act as messengers of SUSY breaking.

The open strings are chiral fields $\phi_i + \tilde{\phi}_i$ in $\mathbf{5} + \overline{\mathbf{5}}$ of $SU(5)$ GUT. This gives exactly the minimal model of gauge mediation discussed above.

If $M = \frac{d}{\ell_s^2} \gg M_s$, or equivalently $d \gg \ell_s$ the dominant interaction is via closed strings $\rightarrow$ gravity and moduli mediation wins.

Hence, one suppresses moduli mediation and achieves flavor universality by bringing the D-brane stacks close together $d \ll \ell_s$ so that gauge mediation dominates.

## *Concrete Semi-realistic Example with D7-branes*

*Visible sector:* use F-theory heterotic string duality to make $SU(5)$ GUT with three generations via spectral cover construction: dual to heterotic $E_8$ boundary.

*Hidden sector:* use $SU(5)$ with one generation. At $\Lambda_H \sim M_{GUT} \exp\left(-2\pi/13\alpha_{GUT}\right)$ the theory confines and breaks SUSY with SUSY breaking F-term:

$$F \sim \left(\frac{\Lambda_H}{4\pi}\right)^2 \sim (10^{10}\text{GeV})^2.$$

This gives TeV sparticles, if $M \sim 10^{15}\text{GeV}$. Need brane separation $d \sim 10^{-2}\ell_s$.

## *Geometry*

*F-theory:* elliptic four-fold with base $B$ that is a $\mathbb{P}^1$ fibration over $dP_8$. Gauge symmetry comes from two stacks of D7-branes wrapping two sections of the $\mathbb{P}^1$ fibration.

*Het string:* elliptic fibration over $dP_8$ with two spectral covers giving visible and hidden sector. Note that on heterotic side, the two sectors communicate via gravity and moduli mediation...

## *Moduli Stabilization*

Complex structure moduli can be stabilized supersymmetrically at large scale $\gg \Lambda_h$ using NS-NS and RR fluxes

$$W_{GVW} = \int_X \Omega \wedge G.$$

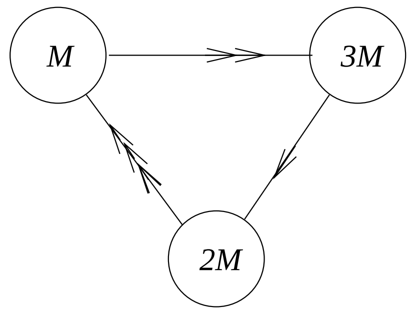
Kähler moduli can be stabilized using D3-brane instantons, i.e. D3-branes wrapping $\pi^*(E)$; the inverse images of exceptional divisors $E \subset dP_8$ under the $\mathbb{P}^1$ fibration of $X$.

The relative distance of the two D7-branes is a complex structure modulus, hence one can tune it to $d \ll \ell_s$ using fluxes to bring the D7's close together for gauge mediation to dominate.

# *D3-brane Models*

Get "quiver MSSM" from a D3-brane sitting at a partially resolved $dP_8$ singularity. [Verlinde & Wijnholt]

Hidden sector from fractional D-branes sitting at an obstructed singularity (i.e. $dP_1$) [Berenstein et al., Franco et al., Bertoliny et al.]




In this model, the SM + hidden sector could be separated by a large throat from the rest of the CY that would decouple the UV physics. [Verlinde, Wijnholt]

## *Higher Dimensional Sequestering*

Anomaly and gaugino mediation use physics of extra dimensions to achieve flavor universality. One assumes that the visible and hidden sectors are separated by a 'large distance' $L$ so that the dangerous flavor non-universal soft terms are Yukawa suppressed:

Integrating out bulk fields with mass $M$ generates flavor non-universal soft terms

$$\int d^4\theta \frac{c_i}{M^2} X^\dagger X Q_i^\dagger Q_i$$

If the bulk fields are sufficiently heavy $M > 1/L$, then $c_i$ are Yukawa suppressed

$$c_i \sim e^{-ML} \ll 1.$$

## *Anomaly Mediation*

In superconformal calculus, the SUGRA action is written as

$$\mathcal{L} = \int d^4\theta \phi^\dagger \phi f(q) + \int d^2\theta \left(\phi^3 W(q) + \tau(q) W_\alpha^2\right) + h.c.$$

where $f = -3M_P^2 \exp(-K/3M_P^2)$. The matter couplings of the conformal compensator $\phi$ are determined by mass dimension and $U(1)_R$ charge. To recover usual SUGRA, one sets $\langle\phi\rangle = 1$.

In anomaly mediation one uses the universal coupling of $\phi$ to mass dimension to impart universal sparticle masses [Randall & Sundrum]

$$m_\lambda = \frac{\beta(g)}{2g} F_\phi \qquad m_0^2 = -\frac{1}{4}\frac{d\gamma}{d\ln\mu}|F_\phi|^2$$

where $\langle\phi\rangle = 1 + F_\phi\theta^2$. This leads to tachyonic sleptons $\rightarrow$ one has to combine anomaly mediation with another mediation mechanism.

In anomaly mediation all superpartners get mass $m \sim F_\phi$.

To impart F-term from the conformal compensator, one assumes existence of a hidden sector that breaks SUSY with F-term $F_0$.

In generic situations

$$F_\phi \lesssim \frac{F_0}{M_P}$$

where $F_0$ Hence, moduli mediation generates non-universal masses $m \sim F_0/M_P$ that are larger than the anomaly mediated ones.

To achieve dominant F-term for the conformal compensator, one assumes that SUSY is broken in a distant sequestered sector so that moduli mediated soft-terms are Yukawa suppressed.

## *Gaugino Mediation*

In gaugino mediation, SUSY breaking sector is again sequestered. However, SM gauge fields and gauginos live in (part of) the bulk.

The gauginos couple directly to the hidden sector and get a large mass

$$\int d^2\theta \frac{X}{M} W^\alpha W_\alpha \supset \frac{F_X}{M} \lambda\lambda.$$

Flavor blind squark and slepton masses are radiatively induced by RG running from gaugino masses.

## *Sequestering in Gaugino Mediation*

The gaugino masses are suppressed by powers of $m_{KK} = 1/L$ because of the reduction from higher dimensional bulk gauge sector to four dimensions. Hence moduli mediated soft terms are comparable, unless they are Yukawa suppressed.

In summary, first step to embedding anomaly and gaugino mediation into string theory is to find compactifications in which bulk fields have masses larger than the KK mass $m_{KK} \sim 1/L$.

In hep-th/0601111 I argued with S. Kachru and J. McGreevy, that in most compactifications there are bulk moduli, whose masses are parametrically lighter than $1/L$.

Hence, in most compactifications one would expect gravity and gaugino mediation to dominate over anomaly and gaugino mediation.

## *Mass Scales in String Theory*

Consider compactification on an isotropic manifold with linear size $L$.

KK scale:

$$m_{KK} \sim \frac{1}{L}.$$

4D Planck mass comes from reducing the Einstein action:

$$\int_{\mathbb{R}^4 \times X} \sqrt{g} R \sim Vol(X) \int_{\mathbb{R}^4} \sqrt{g} R,$$

so

$$M_P \sim L^3.$$

## *Masses of Bulk Fields*

For illustration, consider shape moduli of the compactification manifold. Their kinetic energy is roughly

$$K \sim -M_P^2(\partial_\mu \phi)^2 \sim -L^6(\partial_\mu \phi)^2.$$

Hence a bulk field with potential energy near minimum

$$V \sim V_0 \phi^2,$$

has mass

$$m_\phi \sim \frac{\sqrt{V_0}}{L^3}.$$

Most local contributions to potential energy $V_0$ scale slower than the volume, because of *bulk locality*. Hence $m_\phi$ decreases parametrically faster than the KK-mass $1/L$.

*Example: Type IIB string.*

*Complex structure moduli:* have tree level potential energy from NS-NS and RR fluxes $G = F - \tau H$

$$V \sim \int_X \sqrt{g}\, g^{ii'} g^{jj'} g^{kk'} G_{ijk} G_{i'j'k'}.$$

The metric scales as $g_{ij} \sim L^2$ so the potential energy is scale independent

$$V \sim (L)^0.$$

So the moduli mass scales as

$$m_\phi \sim \frac{\sqrt{V}}{L^3} \sim \frac{1}{L^3}.$$

## *Type IIB contd.*

*Kahler moduli:* are usually stabilized by nonperturbative effects, i.e. D3-brane instantons, nonperturbative dynamics on D7-brane world-volume gauge theories.

These vanish exponentially at large volume

$$V \sim\sim \exp(-L^4).$$

Perturbative quantum corrections to Kahler potential give

$$V \sim \frac{c}{L^{18}} + \frac{c'}{L^{20}},$$

so the Kahler moduli masses scale faster than $1/L$. [Berg, Haack & Körs]

## *Anisotropic Compactifications: Heterotic M-theory*

One compactifies M-theory on a CY-manifold times an interval $X \times I$. The gauge symmetry lives on the $E_8$ boundaries. If the interval $I$ has length $L \gg R_X$, one could hope to sequester the two boundaries...relevant for anomaly mediation.

Indeed, the complex structure moduli get mass from $G$-flux potential

$$m_{cplx} \sim \frac{1}{L},$$

that is comparable to KK-scale. It is a detailed numerical question whether their couplings are Yukawa suppressed.

## *Heterotic M-theory contd*

However, the Kahler moduli do not get mass from the $G$-flux. They can get mass from membrane instantons stretched across the interval $I$ and wrapping a curve in $X$. The instantons lead to exponentially suppressed masses:

$$m_{Kahler} \sim \exp(-L)$$

which are much smaller than $m_{KK} \sim \frac{1}{L}$ in the region $L \gg \ell_{11}$ that is interesting for anomaly mediation.

In compactifications with gauge bundles that have $U(1)$ factors such that $c_1(E) \neq 0$, the Kahler moduli get large mass from gauge fluxes:

$$m \sim \sqrt{\frac{1}{L}}.$$

The gauge potential however does not fix the overall volume modulus $J$, because the potential just imposes the supersymmetry condition $c_1(E) \wedge J \wedge J = 0$ which is homogeneous is $J$.

Hence $J$ can generate unsuppressed non-universal couplings.

## *Possible Caveats*

Models with small # of moduli, whose couplings are highly constrained by symmetry arguments, i.e. the radion field. [Luty & Sundrum]

Highly anisotropic compactifications (relevant mainly for anomaly mediation).

Large numerical factors in front of the parametric scaling of bulk moduli masses, that enhance the bulk masses above $m_{KK}$.

## *Conclusions*

- in $\sim 2-3$ years we will know whether low-energy supersymmetry is realized in nature and should have hints about the mechanism of SUSY breaking
- absence of FCNC's indicates that SUSY mediation is flavor blind. This favors i.e. gauge, gaugino or anomaly mediation.
- gauge mediation can be naturally embedded into string theory by taking visible and hidden sectors at two nearby stacks of D-branes
- it would be interesting to build more realistic models of gauge mediation

## *Conclusions II*

- in most string compactifications gravity and moduli mediation dominate over anomaly and gaugino mediation because the bulk fields are too light so Yukawa suppression does not work

- there might be exceptions to this 'no-go theorem'...i.e. anisotropic compactifications.

- It would be interesting to find explicit compactifications where our no-go theorem is evaded!