REALISTIC GRAVITY MEDIATION OF SUPERSYMMETRY BREAKING

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- SUSY breaking.

  Standard problems and scenarios.

- SUGRA models.

  Soft masses and flavor structure.

- Weakly coupled models.

  Superselection rules.

- Sequestered models.

  Dynamics of extra dimensions.

SUSY BREAKING

Direct spontaneous SUSY breaking at the tree-level implies, in a renormalizable and anomaly-free theory, a sum rule that is in contradiction with experimental observation:

$$\mathrm{STr}\,[\mathcal{M}^2] = \sum_J (-1)^{2J}(2J+1)\, m_J^2 = 0$$

It is thus assumed that SUSY breaking occurs at M in a hidden sector and is transmitted to the visible sector only by interactions becoming relevant at M_{I}, with $M \ll M_{\mathrm{I}}$. The effective breaking scale for the visible sector is then M^2/M_{I}.

The generic effective Lagrangian for the visible sector consists of a SUSY-preserving part, of the form

$$\mathcal{L}_{\mathrm{susy}} = \left[\Phi_i^\dagger e^{g_a V_a} \Phi_i\right]_D + \mathrm{Re}\left[\mathcal{W}_a^2\right]_F + \mathrm{Re}\left[\frac{1}{2}\mu_{ij}\,\Phi_i\Phi_j + \frac{1}{3}y_{ijk}\,\Phi_i\Phi_j\Phi_k\right]_F$$

plus a SUSY-breaking part containing the effects mediated by interactions from the hidden sector, which can be parametrized by soft breaking terms:

$$\mathcal{L}_{\mathrm{soft}} = -\,m_{0\,ij}^2\,\phi_i^*\phi_j - m_{1/2\,a}\,\bar{\lambda}_a\lambda_a - \mathrm{Re}\left[\frac{1}{2}B_{ij}\,\mu_{ij}\,\phi_i\phi_j + \frac{1}{3}A_{ijk}\,y_{ijk}\,\phi_i\phi_j\phi_k\right]$$

This general situation is not yet acceptable. There are two delicate points concerning the structure of soft terms:

- Flavor: m_0^2 must be positive and also approximately flavor universal in order to preserve the standard GIM mechanism.
- Hierarchy: μ, $\sqrt{B\mu}$, m_0 and $m_{1/2}$ must all be close to the electroweak scale $M_{\rm EW}$, in order to naturally explain EWSB.

The main issue is then to find a microscopic setup providing these needed peculiarities in a natural and robust way. This has led to two main classes of models.

Gauge mediation

The mediating interactions can be some new charged states with large mass $M_{\rm M}$. In this case, $m_{1/2}$ and m_0^2 are generated by gauge loops:

$$m_{1/2} \sim \frac{g^2}{16\pi^2}\frac{M^2}{M_{\rm M}}\,, \quad m_0^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2\left(\frac{M^2}{M_{\rm M}}\right)^2$$

The soft masses have a common scale given by

$$m_{\rm soft} \sim \frac{g^2}{16\pi^2}\frac{M^2}{M_{\rm M}}$$

This scenario does well for the flavor structure of soft terms and bad for their hierarchy.

Dine, Nelson, Shirman

Gravity mediation

The mediating interactions can be gravitational, with couplings suppressed by M_P. In this case, $m_{1/2}$ and m_0^2 are generated by gravity tree-level effects:

$$m_{1/2} \sim \frac{M^2}{M_\mathrm{P}}\,,\ \ m_0^2 \sim \left(\frac{M^2}{M_\mathrm{P}}\right)^2$$

The soft masses have a common scale given by

$$m_\mathrm{soft} \sim \frac{M^2}{M_\mathrm{P}}$$

This scenario does bad for the flavor structure of soft terms and well for their hierarchy.

Chamseddine, Arnowitt, Nath
Barbieri, Ferrara, Savoy
Hall, Lykken, Weinberg

SUGRA MODELS

Consider a generic SUGRA theory with chiral and vector multiplets Φ_v and V_v in the visible sector, and similarly Φ_h and V_h in the hidden sector.

The gravitational interactions can be described by a conformal and a chiral compensator multiplets C and S, and possibly also chiral moduli multiplets T.

The basic scales characterizing the effective theory are $M_{\rm P}$ and $m_{3/2} = M^2/M_{\rm P}$, which are very well separated.

First, we assume that SUSY breaking originates from Φ_h, V_h, with non-vanishing values for the corresponding auxiliary fields:

$$\frac{|F_h|}{M_{\rm P}}, \frac{|D_h|}{M_{\rm P}} \sim m_{3/2}$$

Next, we assume that the CC is tuned to zero; this implies a correlated value for the gravitational auxiliary field in S:

$$|F_S| \sim m_{3/2}$$

Finally, we assume that the moduli T have a gravitational nature and thus also get a non-vanishing auxiliary field; typically:

$$\frac{|F_T|}{|T|} \sim m_{3/2}$$

Soft terms come from higher-dimensional operators mixing the fields of the visible sector to those of the hidden or the interactions sectors.

Brane mediation

A first effect comes from the fields Φ_h and V_h. It is induced by gravity effects, in general both at the tree and loop levels:

$$m_{1/2} \sim \left(1+0\right)\frac{|F_h|}{M_\mathrm{P}} \sim m_{3/2}$$

$$m_0^2 \sim \left(1+\frac{\Lambda^2}{16\pi^2 M_\mathrm{P}^2}\right)\frac{|F_h|^2 - D_h^2}{M_\mathrm{P}^2} \sim \left(1+\frac{\Lambda^2}{16\pi^2 M_\mathrm{P}^2}\right) m_{3/2}^2$$

The coefficients are uncalculable, if nothing special is assumed and the effective theory is valid up to $\Lambda \sim 4\pi M_\mathrm{P}$.

Anomaly mediation

A second effect comes from the field S. It is induced by gauge loop corrections breaking scale invariance:

$$m_{1/2} \sim \frac{g^2}{16\pi^2}\,|F_S| \sim \frac{g^2}{16\pi^2}\, m_{3/2}$$

$$m_0^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2 |F_S|^2 \sim \left(\frac{g^2}{16\pi^2}\right)^2 m_{3/2}^2$$

The coefficients are calculable. They are universal and have a definite sign: positive for squarks and negative for sleptons.

Randall, Sundrum

Giudice, Luty, Murayama, Rattazzi

Moduli mediation

A third effect comes from the fields T. It is induced by gravity effects at the tree and/or loop levels, depending on the situation:

$$m_{1/2} \sim \Big(1 + 0\Big)\frac{|F_T|}{|T|} \sim m_{3/2}$$

$$m_0^2 \sim \left(1 + \frac{\Lambda^2}{16\pi^2 M_{\rm P}^2}\right)\frac{|F_T|^2}{|T|^2} \sim \left(1 + \frac{\Lambda^2}{16\pi^2 M_{\rm P}^2}\right) m_{3/2}^2$$

Again, the coefficients are in general uncalculable, unless specific assumptions are made.

In this general setup, m_0^2 is therefore naturally expected to be a generic matrix in flavor space. This is incompatible with experimental constraints. Indeed, the present bounds on non-universalities of scalar soft masses are:

$$\left(\frac{\delta m^2_{\rm u\not{n}iv}}{m^2_{\rm univ}}\right)_{\rm squarks} \lesssim 3 \times 10^{-4} \left(\frac{m_{\rm univ}}{M_{\rm EW}}\right)$$

$$\left(\frac{\delta m^2_{\rm u\not{n}iv}}{m^2_{\rm univ}}\right)_{\rm sleptons} \lesssim 3 \times 10^{-3} \left(\frac{m_{\rm univ}}{M_{\rm EW}}\right)^2$$

It is clear that some more specific assumptions about the fundamental theory are needed, in order to explain in a robust way these suppressions.

WEAKLY COUPLED MODELS

A first possibility is to assume weak coupling. Loops are then cut off at $\Lambda \sim M_{\rm S} \ll 4\pi M_{\rm P}$ and suppressed by the factor

$$\frac{M_{\rm S}^2}{16\pi^2 M_{\rm P}^2} \ll 1$$

In this situation, it is technically possible to assume that classical effects are for some reason universal and that non-universal loop corrections are small.

The requirement that the underlying theory should provide a unified description of interactions however naturally suggests that (gravity loop) $\sim$ (gauge loop) at the scale $M_{\rm S}$, that is:

$$\frac{M_{\rm S}^2}{16\pi^2 M_{\rm P}^2} \sim \frac{g^2}{16\pi^2} \;\Rightarrow\; \frac{M_{\rm S}}{M_{\rm P}} \sim g \sim 7 \times 10^{-1}$$

This applies, for instance, to standard superstring models.

In this setup, the leading contributions to $m_{1/2}$ and m_0^2 come thus from tree-level gravitational effects that are assumed to be universal and have the standard scale:

$$m_{\rm univ} \sim m_{3/2}$$

The leading non-universal corrections come from gravity loops and have a relative suppression factor given by:

$$\frac{\delta m^2_{\not{u}\mathrm{niv}}}{m^2_{\mathrm{univ}}} \sim \frac{g^2}{16\pi^2} \sim 3 \times 10^{-3}$$

Louis, Nir

Brignole, Ibañez, Muñoz

The main issue in this scenario is the possibility of achieving at the same time non-universal Yukawa couplings and universal scalar soft masses at the classical level.

The most promising attempts in finding concrete examples of this type in string theory are based on the idea that flavor may arise from geography in the internal dimensions.

Lebedev

A general study of the viability of this option in string theory, taking into account low-energy dynamical effects, would be extremely interesting.

SEQUESTERED MODELS

A second possibility is to assume the existence of an extra dimension, along which the visible and hidden sectors are separated and interact only gravitationally. The relevant loops are then cut off at $\Lambda \sim M_{\rm C} \ll 4\pi M_{\rm P}$ and suppressed by

$$\frac{M_{\rm C}^2}{16\pi^2 M_{\rm P}^2} \ll 1$$

In this situation, any local classical effect is forbidden and only non-local quantum effects can occur. These are universal and reliably computable within a SUGRA description.

To get a satisfactory situation, with large enough $m_{1/2}$ and positive m_0^2, the gravity and anomaly loop effects must be of comparable size, with (gravity loop) $\sim$ (gauge loop)^2 at $M_{\rm C}$, that is:

$$\frac{M_{\rm C}^2}{16\pi^2 M_{\rm P}^2} \sim \left(\frac{g^2}{16\pi^2}\right)^2 \;\Rightarrow\; \frac{M_{\rm C}}{M_{\rm P}} \sim \frac{g^2}{4\pi} \sim 4 \times 10^{-2}$$

Interestingly enough, this situation can be naturally realized in a dynamical way through non-perturbative effects, thanks to the numerical accident $\ln(M_{\rm P}/m_{3/2}) \sim (g^2/4\pi)^{-1}$.

Randall, Sundrum

In this setup, the leading contributions to $m_{1/2}$ and m_0^2 come thus from 1-loop gauge effects and 1-loop gravity effects that are automatically universal, with a common scale:

$$m_{\rm univ} \sim \frac{g^2}{16\pi^2} m_{3/2}$$

A generic source of non-universal corrections arises from gravity loops involving couplings with two extra derivatives and inverse-powers of the bulk gravity scale. By power counting, their relative size is expected to be

$$\frac{\delta m^2_{\rm u\!\!/niv}}{m^2_{\rm univ}} \sim \left(\frac{g^2}{16\pi^2}\right)^{4/3} \sim 5 \times 10^{-4}$$

Rattazzi, Scrucca, Strumia

The main issue in this scenario is the possibility of making extra model-dependent non-universal effects related to radius stabilization small enough.

Concrete examples of viable models have be constructed, with anomaly mediation for $m_{1/2}$ and F-type moduli mediation or D-type brane mediation for m_0^2, although with slightly larger non-universal corrections.

Gregoire, Rattazzi, Scrucca

CONCLUSIONS

- A robust explanation of the structure of soft masses is linked to the structure of the high-energy theory.
- The presence of extra dimensions could potentially play a central role in this context.
- Weakly coupled and sequestered models have complementary advantages and disadvantages.