Soft terms from theories with a gauged R-symmetry in $\mathcal{N} = 1$ supergravity.

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- No dark matter
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An attempt to solve the first one is Supersymmetry (SUSY)

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What are the ingredients of a supersymmetric theory?[1]

- a Käler potential $K(\Phi, \bar{\Phi})$: (roughly) Information for kinetic terms.
- a superpotential $W(\Phi)$: (roughly) Information for interaction terms.
- a gauge kinetic function $f(\Phi)$

These three ingredients together with the particle content result in a (globally) supersymmetric Lagrangian

$$\mathcal{L}_{SUSY}$$

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Say one has a (globally) supersymmetric Lagrangian $\mathcal{L}_{SUSY}$ containing the Standard Model fields

- Every Standard Model field has a superpartner (that has not yet been detected)
- Global supersymmetry $\longrightarrow$ mass Standard Model field $=$ mass of its superpartner.
- Impossible, otherwise they'd already been detected.

Conclusion: Supersymmetry should be *broken*.

Add mass terms (and others) for superpartners by hand:

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- called 'Soft Supersymmetry Breaking Terms'
- These terms break supersymmetry explicitly.
- Where could they come from?

Summary of talk:

- Assume Supersymmetry is a *local* symmetry.
- gauged supersymmetry = *Supergravity*
- Supersymmetry is then broken spontaneously
- After supersymmetry breaking one hopes to retrieve some $\mathcal{L}_{SOFT}$

Before we start, there are two more things:

1. Hidden sector

- For reasons that I omit, the Standard Model fields cannot be the cause of supersymmetry breaking.
- We need to define a *hidden sector* of fields.
- These fields are usually very heavy and singlets under Standard Model gauge groups.
- The hidden sector scalars acquire a VEV and break supersymmetry spontaneously.
- Supersymmetry breaking is then communicated to the visible (Standard Model) due to gravity effects in the Lagrangian.

Footnote: There are a lot of ways to break supersymmetry, this is just one of them.

2. Cosmological constant

- In a QFT (quantum field theory) the value of minimum of the potential doesn't matter: A constant can always be added to the potential without changing the theory
- SUGRA contains gravity
- Gravity does feel such a 'vacuum energy' in the form of a cosmological constant.
- The cosmological constant $V_{\text{min}} = \Lambda \approx (10^{-3}\ \text{eV})^4$ is very small.

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We want the minimum of our potential to be very small and positive (like the cosmological constant).

Ingredients of a $\mathcal{N} = 1$ supergravity theory (up to Chern-Simons terms) are

- a Käler potential $K(\Phi, \bar{\Phi})$
- a superpotential $W(\Phi)$
- a gauge kinetic function $f(\Phi)$

The plan:

(a) Define particle content of hidden sector.
(b) Choose K, W, f based on symmetry principles.
(c) Fine-tune parameters such that the potential allows for small and positive minimum.
(d) Calculate soft breaking terms.
(e) (look at particle phenomenology)

(a) Particle content of hidden sector

- One chiral multiplet S (scalar and fermion) and one gauge multiplet (gauge boson and fermion).
- The gauge boson belongs to a $U(1)$ different from the Standard Model $U(1)_Y$
- the scalar s of the chiral multiplet has a *shift symmetry* under the extra $U(1)$
- $s \longrightarrow s - ic\theta$, where c is constant and θ is gauge parameter.

(b) Specify K, W, f

- $K(s, \bar{s})$ is function of both s and $\bar{s}$.
- A gauge invariant Kähler potential is a function of $s + \bar{s}$.
- (string inspired) choice: $K(s, \bar{s}) = -p \log(s + \bar{s})$ (p is a constant).

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A few remarks:

- under the shift symmetry $W \longrightarrow We^{-ibc\theta}$
- This is an R-symmetry $\longrightarrow$ Fayet-Iliopolous D-term.

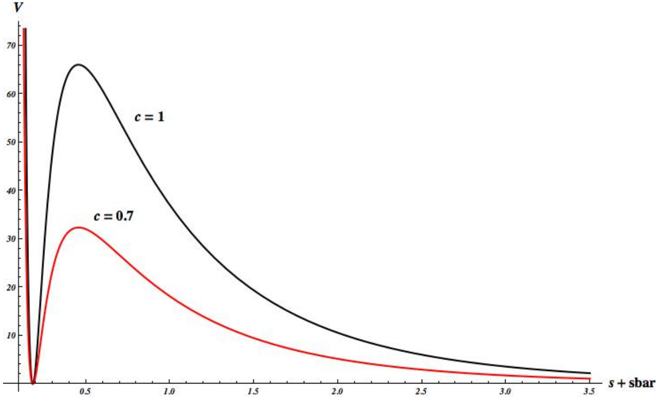
We have:

$$K = -p \log(s + \bar{s})$$
$$W = ae^{bs},$$

One still has to specify the gauge kinetic function $f(s)$:

- most general possible: $f(s) = \gamma + \beta s$.
- $\beta \neq 0$ implies existence of Green-Schwarz term.
- take $\beta = 0, \gamma = 1$.
- Tunability of the potential requires then $p = 1$

(c) Tune parameters to obtain small and positive minimum of the potential for $s + \bar{s}$



$$\mathcal{V} = \mathcal{V}_F + \mathcal{V}_D$$

- Negative F-term (from superpotential)
- Positive D-term (from shift symmetry)
- Tune parameters to obtain small cosmological constant

(d) Calculate soft terms

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Problem: The predicted universal soft masses squared m_0^2 for the sparticles are negative.

Possible solutions:

- Include extra (Polonyi-like) field z.

$$W = a(1 + \gamma z) + W_{MSSM}$$

  Not all γ are possible

$$\gamma \in [0.5, 1.707] \,.$$

- Give MSSM fields non-canonical Kähler potential

$$K = \cdots + (s + \bar{s})^{-\nu} \sum \varphi\bar{\varphi}$$

  Constraint on ν:

$$\nu > 2.6.$$

- Scalar sparticle masses (for $\gamma = 1$):

$$
\begin{aligned}
&m^2_{\tilde{Q}} = m^2_{\tilde{\bar{u}}} = m^2_{\tilde{\bar{d}}} = m^2_{\tilde{Q}} = m^2_{\tilde{\bar{Q}}} = m^2_0 \, \mathbb{I}, \\
&m^2_0 \approx 0.72 \, m_{3/2}.
\end{aligned} \tag{1}
$$

$\mathbb{I}$ is the unit matrix in family space

- trilinear couplings:

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\end{aligned} \tag{2}
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- We also have $B_0 = A_0 - m_{3/2}$, where B_0 generates a term proportional to $-\hat{\mu} B_0 H_u \cdot H_d +$ h.c.
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However, something strange is happening with the gaugino masses

$$K = -p\log(s+\bar{s}),$$
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Kahler Transformation

$$K \longrightarrow K + J + \bar{J}$$
$$W \longrightarrow We^{-J}$$

with $J = bS$ gives an classically equivalent theory

$$K = -p \log(s + \bar{s}) + b(s + \bar{s}),$$
$$W = a,$$

The answer is that gaugino masses are *always* generated at one-loop in a gravity mediated scenario (like ours)

Effect called *Anomaly mediation*

$$m_{1/2} = -\frac{g^2}{16\pi^2}\Big[(3T_G - T_R)m_{3/2} + (T_G - T_R)\mathcal{K}_\alpha F^\alpha + 2\frac{T_R}{d_R}(\log\det\mathcal{K}|_R{}'')_{,\alpha}F^\alpha\Big], \tag{3}$$

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T_R Dynkin index representation R (normalized to 1/2 for SU(N) fundamental), T_G Dynkin index adjoint representation.

We summarize the soft terms for $\gamma = 1$

$$
\begin{aligned}
m_0 &\approx 0.72\ m_{3/2}, \\
A_0 &\approx 1.72\ m_{3/2}, \\
B_0 &\approx 0.72\ m_{3/2}, \\
m_Y &\approx 0.0153\ m_{3/2}, \\
m_2 &\approx 0.0245\ m_{3/2}, \\
m_3 &\approx 0.0265\ m_{3/2}.
\end{aligned}
$$

Discussion on phenomenology:

- Specific relation between B_0 and A_0: $B_0 = A_0 - m_{3/2}$.
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- Specific relation between B_0 and A_0: $B_0 = A_0 - m_{3/2}$.
- Therefore tanβ is not an independent parameter!
- $m_Y < m_2 \longrightarrow$ dark matter candidate LSP is most likely the lightest neutralino, which is mostly Bino-like. (In constrast with mAMSB)
- Lower (LEP) bound on lightest chargino drive gravitino mass up to $m_{3/2} \gtrsim O(10\ \text{TeV})$. (In constrast with mSUGRA)
- Forces us to negotiably drop naturalness.

Conclusions:

- Model based on a gauged R-symmetry.
- Breaks supersymmmetry spontaneously.
- Minimum of the potential positive and tunably small
- Gravitino mass also tunable
- Soft masses realistic upon inclusion of one extra hidden sector field or noncanonical Kahler potentials.
- Phenomenology distinguishable from mSUGRA and mAMSB

(bonus slide) Outline:

- Make theory based on gauged R-symmetry
- Minimum of the potential has to be positive and small (tunable) *[I. Antoniadis and R. Knoops, arXiv:1403.1534 [hep-th]]*
- Cancel quantum anomalies *[I. Antoniadis, D. M. Ghilencea and R. Knoops, arXiv:1412.4807 [hep-th]]*
- Use this as 'hidden sector' and communicate SUSY breaking to MSSM *[I. Antoniadis and R. Knoops, to be published]*
- See if phenomenology is viable

(bonus slide) Difference with mSUGRA:

- No gaugino masses at tree level $\longrightarrow$ big mass differences (compared with mSUGRA)

Differences with mAMSB

- Spectrum resembles much the mAMSB spectrum
- Important difference: mAMSB LSP is mostly Wino-like neutralino, ours is mostly Bino-like.
- second term in $m_{1/2}$ is missing in mAMSB, our gaugino masses are slightly larger.
- We have no possible issues with tachyonic scalar masses.
- We have big tree-level A_0, compared with small A_0 generated at one-loop for mAMSB.

(bonus slide)

The real part of the scalar *s* acquires a vev, breaking the shift symmetry and supersymmetry by a combination of F-term and D-term breaking.

The gauge boson A_μ *eats* the imaginary part of the scalar *a* by a Stückelberg mechanism and becomes massive.

A linear combination of the two fermions, χ and the gaugino λ, is the Goldstino. This Goldstino is eaten by the gravitino by a super-BEH mechanism, and the gravitino becomes massive.