Soft terms from theories with a gauged R-symmetry in supergravity.

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Outline:

- Specify a simple model based on gauged shift symmetry
- A combination of D-term and F-term SUSY breaking will allow for small and positive cosmological constant
- SUSY breaking scale is tunable
- Then, we use this as 'hidden sector' in gravity mediated scenario and look for its low energy spectrum

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Ingredients of $\mathcal{N} = 1$ SUSY (or SUGRA) theory:

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

Kähler transformations: A supergravity theory (with $W(z) \neq 0$) can be written in terms of

$$\mathcal{G} = K + \log(W\bar{W}). \tag{1}$$

- $\mathcal{G}$ should be gauge invariant.
- $\mathcal{G}$ is invariant under Kähler transformations:

$$K(z,\bar{z}) \longrightarrow K(z,\bar{z}) + J(z) + \bar{J}(\bar{z})$$
$$W(z) \longrightarrow We^{-J(z)}$$

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Conclusion: K and W do not need to be gauge invariant. A gauge transformation can leave a Kähler transformation.

R-symmetry

- Gauge transformation α

$$K(z,\bar{z}) \longrightarrow K(z,\bar{z}) + \alpha r(z) + \alpha \bar{r}(\bar{z})$$
$$W(z) \longrightarrow W e^{-r(z)\alpha}$$

  - if $r(z)$ is some imaginary constant $r(z) = i\xi$, then the gauge symmetry is then said to be an 'R-symmetry'
  - In Supergravity this implies the presence of a constant *Fayet-Iliopoulos (FI) D-term* in the scalar potential.
  - FI terms can be very useful in breaking supersymmetry.

If $W \longrightarrow We^{-i\xi\alpha}$ in (abuse of notation)

$$\mathcal{L} \ni \int d^2\theta W + \text{h.c.} \tag{2}$$

Then invariance of $\mathcal{L}$ implies

$$d\theta \longrightarrow d\theta e^{i\xi\alpha/2}$$
$$\theta \longrightarrow \theta e^{-i\xi\alpha/2}$$
$$\chi \longrightarrow \chi e^{i\xi\alpha/2}$$

because

$$\Phi = \phi + \theta\chi + \theta^2 F \tag{3}$$

Important:

- In general superpartners ϕ and χ have same quantum numbers.
- But for R-symmetries, the charge of ϕ and χ differs by $\xi/2$.

our goals (for now):

Take a model with

- one chiral multiplet S invariant under shift symmetry (gauge parameter α, 'charge' c)

$$s \longrightarrow s - i\alpha c \tag{4}$$

- one gauge multiplet (of shift symmetry)

- Obtain tunable minimum of scalar potential ($\sim$ cosmological constant) by cancellation between
  - **F-term**: From whatever superpotential we can write down for S.
  - **D-term**: From gauge contributions (including FI-terms)

- **Kähler potential**:

  Gauge invariance $\to K(s + \bar{s})$
  Take for some number p

$$K(s, \bar{s}) = -p \log(s + \bar{s}) \tag{5}$$

  - S can be heterotic string dilaton or compactification modulus.

- **Superpotential**: Most general possibility (some constants a, b)

$$W = ae^{bs} \tag{6}$$

- **Gauge kinetic function**: Most general possibility (some constants γ, β)

$$f(s) = \gamma + \beta s \tag{7}$$

Cosmological constant: Let's look in which parameter region we have a tunable (positive) minimum of the scalar potential.

- For $p \geq 3$: V is monotonically decreasing.
- If $p = 2 \rightarrow$ 'tunability requires' $f(s) = s$. The Lagrangian then includes a (non-gauge invariant) term

$$\mathcal{L}_{GS} = \frac{1}{8}\text{Im}(f(s))\epsilon^{\mu\nu\rho\sigma}F^{A}_{\mu\nu}F^{A}_{\rho\sigma} \tag{8}$$

- Leaves us with $p = 1$, where tunability demands $f(s) = 1$. (Constant γ can be absorbed in other constants)

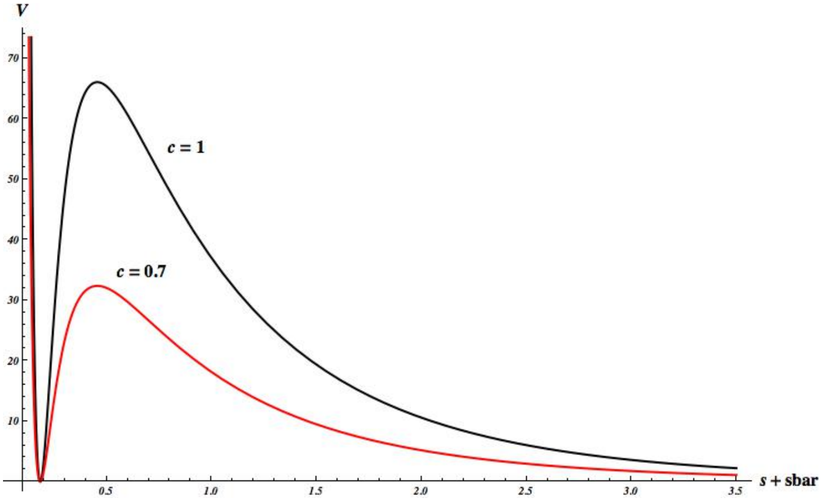
Kähler transformation: The model

$$K = -\log(s + \bar{s}),$$
$$W = ae^{bs} \tag{9}$$

is classically equivalent to

$$K = -\log(s + \bar{s}) + b(s + \bar{s}),$$
$$W = a \tag{10}$$

Avoid R-charges and anomalies $\longrightarrow$ take second representation.


V
70
60
50
40
30
20
10
c = 1
c = 0.7
0.5
1.0
1.5
2.0
2.5
3.0
3.5
s + sbar

In this model:

- Real part of s gets VEV and breaks SUSY
- Im(s) is eaten (Stuckelberg) by gauge boson, which becomes massive.
- Linear combination of chiral fermion and gaugino is eaten (SuperHiggs) by gravitino, other one acquires a mass by SUSY breaking.
- Important: All surviving particles have masses of supersymmetry breaking scale

We have:

- A toy model of supersymmetry breaking based on a gauged shift symmetry that
  - Breaks supersymmetry
  - Leaves us in a (meta-)stable deSitter vacuum, and tunable cosmological constant.
  - Separately tunable supersymmetry breaking scale.
  - All fields have masses of $m_{3/2}$

Question: Is the phenomenology realistic?

If we add some MSSM superfields

$$K = -\log(s + \bar{s}) + b(s + \bar{s}) + \sum \varphi\bar{\varphi}$$
$$W = a + W_{\mathrm{MSSM}}(\varphi) \quad (11)$$

It turns out that $m_\varphi^2 < 0$.
The minimal model does not work.

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:

$$\nu > 2.6.$$

Up next: Calculate the soft SUSY breaking terms in $\mathcal{L}_{soft}$

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Like in mSUGRA:

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- A-terms
- $B\mu$-term with $B = A - m_{3/2}$
- All about of the same order, slight γ-dependence

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However, gauginos are still massless at tree-level: m_A are proportional to derivatives of the gauge kinetic functions f_A, which is constant in our model.

But we had another 'representation' of this theory by a Kahler transformation, the model

$$K = -\log(s + \bar{s}), \\ W = ae^{bs} \tag{12}$$

is classically equivalent to

$$K = -\log(s + \bar{s}) + b(s + \bar{s}), \\ W = a \tag{13}$$

Let's redo our analysis in the first 'representation'.

R-charges

- same scalar potential $\rightarrow A, B, m_0$ stay the same
- In this frame, the shift symmetry acts partly as an R-symmetry
- All previous uncharged (MSSM and hidden) fermionic fields acquire an R-charge
- This gives anomalies, that need to be canceled

- We have however, an axion at our disposal with a Green-Schwarz counter term if the gauge kinetic functions are linear
- $f_A(s) = 1/g_A^2 + \beta_A s$
- Choose β_A such that it cancels the corresponding mixed anomaly $U(1)_R \times G_A$

$$\mathcal{L}_{GS} = \frac{1}{8}\mathrm{Im}(f_A(s))\epsilon^{\mu\nu\rho\sigma}F^A_{\mu\nu}F^A_{\rho\sigma}$$
$$\delta\mathcal{L}_{GS} = -\frac{\alpha\beta_A c}{8}\epsilon^{\mu\nu\rho\sigma}F^A_{\mu\nu}F^A_{\rho\sigma}$$

- Cubic $U(1)_R^3$ anomaly canceled similarly
- Gaugino mass can now be calculated and is proportional to β_A

$$m_A = -\frac{1}{2}\beta_A e^{\mathcal{K}/2} g^{s\bar{s}} \bar{\nabla}_{\bar{s}} \bar{W}. \quad (14)$$

This is strange

- The answer to the puzzle is that gaugino masses are *always* generated at one-loop in a gravity mediated scenario (like ours)
- Effect called **Anomaly mediation**

$$m_{1/2} = -\frac{g^2}{16\pi^2}\Big[(3T_G - T_R)m_{3/2} + (T_G - T_R)\mathcal{K}_\alpha F^\alpha + 2\frac{T_R}{d_R}(\log\det\mathcal{K}|_R{}'')_{,\alpha}F^\alpha\Big], \tag{15}$$

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

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$$\left. +2\frac{T_R}{d_R}(\log\det\mathcal{K}|_R{}'')_{,\alpha}F^\alpha\right], \qquad (15)$$

- First term:
  - Proportional to beta-function.
  - Always present and main ingredient for so-called 'Anomaly Mediated' theories (like mAMSB)
- Second term:
  - Only present when there are fields with Planck-scale vevs (like *s* and *z*).
  - Is absent in mAMSB, but present in our model.
- Third term: Vanishes in our model.

Question: If we would have worked with the theory before the Kähler transformation. Are the gaugino masses the same?

- Difference in Kähler potentials $\delta\mathcal{K} = b(s + \bar{s})$
- Second term in $\delta m_{1/2}$ is proportional to $\partial_s \delta K$
- This contribution also differs for both 'representations'

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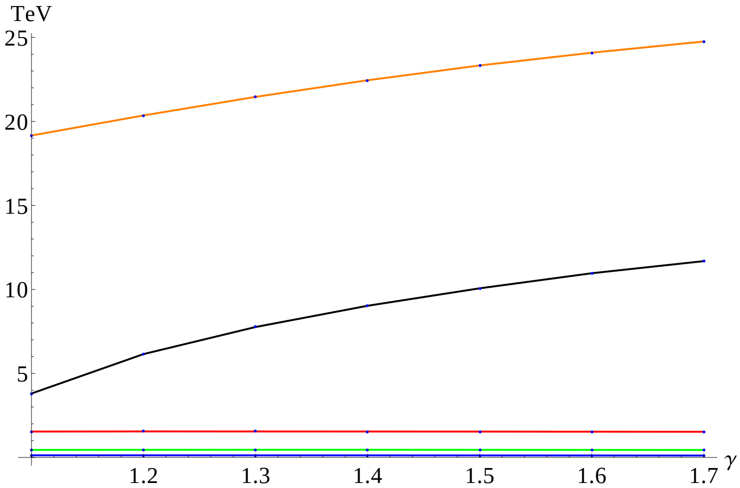
- Difference in Kähler potentials $\delta\mathcal{K} = b(s + \bar{s})$
- Second term in $\delta m_{1/2}$ is proportional to $\partial_s \delta K$
- This contribution also differs for both 'representations'
- We showed that both 'representations' match when all contributions are added (Green-Schwarz contribution + Anomaly mediated)

Phenomenology:

- Two 'input' parameters that determine soft terms: $m_{3/2}$ and γ
- A, B, m_0 proportional to $m_{3/2}$ (slight dependence on *gamma*)
- gaugino masses also proportional to $m_{3/2}$, but $m_Y < m_2$ and about 20-30 orders of magnitude lower than A, B, m_0
- Since parameter B is fixed, tanβ is also fixed (in contrast with mSUGRA)

Mass spectrum:



sbottom squark (yellow), stop squark (black), gluino (red), lightest chargino (green) lightest (Bino-like) neutralino (blue) for $m_{3/2} = 25\text{TeV}$

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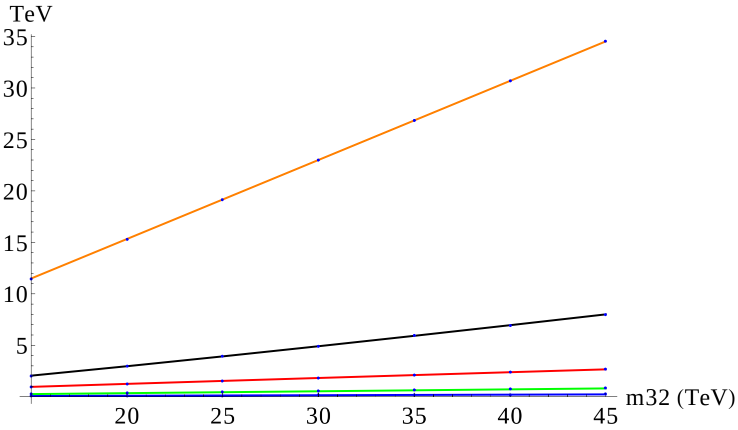

sbottom squark (yellow), stop squark (black), gluino (red), lightest chargino (green) lightest neutralino (blue) for $\gamma = 1.1$

Conclusions:

- Model based on a gauged shift symmetry.
- Breaks supersymmmetry
- Minimum of the potential positive and tunably small
- Gravitino mass also tunable
- Some nice results for the gaugino masses
- Soft masses realistic upon inclusion of one extra hidden sector field
- Phenomenology distinguishable from mSUGRA and mAMSB