A Definitive Signal of Multiple SUSY breaking

Cliff Cheung, JM, Yasunori Nomura and Jesse Thaler
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Following on from
Goldstini (1002.1967) – C.Cheung, Y.Nomura and J.Thaler
Outline

- Motivation
- Review of the Goldstini framework
- An simple setup
- A smoking-gun collider signature
- Cosmology with goldstini
- Cosmology and Colliders collide
- Conclusions
Motivation

An old philosophy: simplicity

- Believe new physics should be as simple as possible to explain data

  ⇒ expect $\text{SM sector} + (\text{e.g.}) \text{ SUSY sector} + \text{ desert}$?
An old philosophy: simplicity

- Believe new physics should be as simple as possible to explain data
- $\Rightarrow$ expect **SM sector** + (e.g.) **SUSY sector** + **desert**?

(Of course, Standard Model doesn’t look especially simple...)}
Motivation

Another philosophy: many many sectors

- Complexity of string compactifications
  - → many sequestered hidden sectors?
    - (e.g. Giddings et.al. hep-th/0105097
      Dimopoulos et.al. hep-th/0104239
      …)

- Is it testable?
- Fantastical astrophysical/collider consequences
  - “axiverse”
  - “photini”
  - Arvanitaki et.al. 0905.4720
  - Arvanitaki et.al. 0909.5440
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Goldstini

- $N$ sequestered SUSY sectors

$\Rightarrow N$ copies of global SUSY

$\Rightarrow N$ massless goldstini-fermions ??
Goldstini

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Goldstini: A Quick Review
A Smoking Gun Signature
Gravitino Cosmology

Include gravity: **only one true SUSY**

\[ \text{SUSY}^N \rightarrow \text{SUGRA} \times (\text{SUSY}_{\text{approx}})^{N-1} \]

- \( \text{SUGRA} \Rightarrow \text{massive gravitino} \)
- \( (\text{SUSY}_{\text{approx}})^{N-1} \Rightarrow N-1 \text{massive "goldstini" } \zeta_1, \zeta_2 \ldots \zeta_{N-1} \)

Jeremy Mardon – UC Berkeley

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Gravitino has:
- Standard mass and couplings set by SUGRA

Goldstini have:
- mass = $2m_{3/2}$ (universal!)
- interactions with SM sector similar to gravitino’s
- ...but with coupling strength a free parameter

*conditions apply
The Factor of Two
a quick treatment

Consider the field $X_i$ that breaks SUSY in sector $i$:

$$\mathcal{L} = \int d^4 \theta \left( X_i^\dagger X_i + \ldots \right) + \int d^2 \theta \mu_i^2 X_i + \text{h.c.}$$

A non-linear parametrization is appropriate:

$$X_i = e^{Q \eta_i / \sqrt{2} F_i} (x_i + \theta^2 F_i) = x_i + \eta_i^2 / 2 F_i + \sqrt{2} \theta \eta_i + \theta^2 F_i$$

Low-energy effects of supergravity found by reinstating the conformal compensator:

$$\mathcal{L} = \int d^4 \theta \ C^\dagger C (X_i^\dagger X_i + \ldots) + \int d^2 \theta \ C^3 \mu_i^2 X_i + \text{h.c.}$$

with: $C = 1 + \theta^2 m_3 / 2$

Rescale $CX_i \rightarrow X_i$ to canonically normalize:
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$$\mathcal{L} \supset \int d^2 \theta \ C^2 \mu_i^2 X_i \supset (2m_{3/2}) \mu_i^2 (\eta_i^2/2F_i)$$
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$$\mathcal{L} \supset \int d^2\theta \ C^2 \mu_i^2 X_i \supset (2m_{3/2})\mu_i^2(\eta_i^2/2F_i) = -\frac{1}{2}(2m_{3/2})\eta_i^2$$
The Factor of Two
a quick treatment

Goldstini get a mass $2m_{3/2}$

- The gravitino eats one linear combination:

$$\tilde{G} \supset \eta_{\text{long}} = \left( F_1 \eta_1 + F_2 \eta_2 + \ldots \right) / \sqrt{F_1^2 + F_2^2 + \ldots}$$

... and gets standard mass $m_{3/2} = \frac{F_{\text{tot}}}{\sqrt{3}M_{\text{Pl}}}$

- other linear combinations are physical goldstini $\zeta_a$, with mass $m_\zeta = 2m_{3/2}$
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Aside: How exact is the 2

- Assumes F-term breaking (for simplicity)
- Valid at tree level for sequestered sectors
  - Anomaly mediation
    \[ \delta m_\zeta \sim (\text{loop suppression}) \times m_{3/2} \]
  - Multiple sectors mediating SUSY to SM sector
    \[ \delta m_\zeta \sim (\text{loop suppression}) \times \tilde{m} \]
standard goldstone-fermion couplings:

\[ \mathcal{L} \supset \frac{\tilde{m}^2}{F_i} \eta_i \ell \ell^\dagger - \frac{i}{\sqrt{2}} \frac{M[\eta]}{F_i} \eta_i \sigma^{\mu\nu} \tilde{g} G_{\mu\nu} \]

(\tilde{m}^2[i] and \(M[i]\) are the contributions to soft masses from sector \(i\))

- gravitino has couplings \(\sim \frac{\tilde{m}^2}{F_{tot}}, \frac{M_{1/2}}{F_{tot}}\)
- goldstini can have much larger/smaller couplings
Goldstini and Gravitino Couplings

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Goldstini

Gravitino has:
- Standard mass and couplings set by SUGRA
  \[ m_{3/2} = \frac{F_{\text{tot}}}{\sqrt{3}M_{Pl}}; \quad \text{coupling} \sim \frac{m^2_{\text{soft}} \text{or} M_1/2}{F_{\text{tot}}} \]

Goldstini have:
- mass = 2m_{3/2} \quad \text{(universal!)*)
- interactions with SM sector similar to gravitino’s*
- ...but with coupling strength \( \tilde{m}^2_i / F_i \) \quad \text{(free parameter)}

*conditions apply
A New BSM Playground

Interesting Possibilities:

- Colliders?
  
  ...

- Cosmology?
  
  ...

But could we ever see unambiguous evidence for a Goldstini setup?
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An Simple Setup
Part 1: SUSY-breaking

- Just 2 SUSY sectors $\rightarrow$ gravitino $\tilde{G}$ + goldstino $\zeta$
- SUSY is dominantly broken in sector 1
  $$F_1 \gg F_2$$
- The 2 sectors mediate similar SUSY masses to SM sector
  $\Rightarrow$ goldstino couples much more strongly than gravitino
- LOSP heavier than goldstino or gravitino
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Part 1: SUSY-breaking

\[ \tilde{G} \]

\[ \zeta \]

\[ m_{\text{LOSP}} \]

\[ m_{\zeta} = 2m_{3/2} \]

\[ m_{3/2} \]

\[ \sqrt{F_1} \]

\[ \sqrt{F_2} \]
Imagine LOSP is a charged slepton

- LOSP can decay to $\zeta$ or $\tilde{G}$

**$F_2$ controls**

- coupling to $\zeta$: $\sim 1/F_2$

**$F_1$ controls**

- masses: $m_{3/2} \approx \frac{1}{2} m_{\zeta} \approx \frac{F_1}{\sqrt{3} M_{Pl}}$
- coupling to $\tilde{G}$: $\sim 1/F_1$

$$\tau_{\ell} \sim 20 s \times \left(\frac{300 \text{GeV}}{m_{\ell}}\right)^5 \left(\frac{\sqrt{F_2}}{10^9 \text{GeV}}\right)^4$$

$$\text{Br}_{\ell \rightarrow \tilde{G}} \sim \left(\frac{F_2}{F_1}\right)^2$$
A Smoking Gun Signature

- long-lived charged sleptons at LHC

\[ \tilde{\ell} \rightarrow \ell \]

\[ \zeta \text{ or } \tilde{G} \]

- Fraction stopped in detector or in stopper → decays studies

- Expect decay to gravitino → measurement of mass and decay rate allows reconstruction of \( M_{Pl} \) (Buchmuller et al ’04)
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  → measurement of mass and decay rate allows reconstruction of \( M_{Pl} \) (Buchmuller et al ’04)
But decay is primarily to \textit{goldstino}

\[ \rightarrow \text{mismeasurement of } M_{Pl} \]
\[ \rightarrow \text{alarm bells} \]
\[ \rightarrow \text{search for rare decays to } \tilde{G} \]
\[ \rightarrow \text{predict both } m_{3/2} \text{ and } \text{Br}(\text{LOSP} \rightarrow \tilde{G}) \]

- Observing rare decays to gravitinos confirms the setup.
Is this generic?

- \( m_{3/2, \zeta} \) reconstructed from \( m_\tilde{\ell} \) and \( E_\ell \) (from \( \tilde{\ell} \) decay)
  - limited by \( m_\tilde{\ell} \) and \( E_\ell \) resolution
  - better for larger \( m_{3/2, \zeta} \)
  - need \( m_{3/2} \gtrsim (0.05 - 0.2)m_\ell \) for mass measurement
    (Corollary: don’t worry about deviations from factor 2)

- Need to see some gravitinos
  - need \( \text{Br}(\tilde{\ell} \rightarrow \tilde{G}) \gtrsim 10^{-4} - 10^{-3} \)
    (assuming 100-1000 fb\(^{-1}\) and \( m_\tilde{\ell} \sim 150\text{GeV} \))

\( i.e. \) We need to be in the right part of parameter space.

But what we learn:

- Discovery of gravitino and goldstino
- Demonstration of SUGRA
- Existence of sequestered sectors with SUSY
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(Hamaguchi et.al. hep-ph/0612060)

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Goldstino Cosmology
1: Overabundance problem

Abundance

- Gravitinos with $\sim$GeV mass very weakly coupled → never in thermal equilibrium
- Rare scattering and decay processes produce small abundance
- Solve Boltzmann equations to find yield $Y$
Goldstino Cosmology

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**Coupling to scalar–fermion is dim. 4**

$$\frac{dY}{d\ln T} \sim M_{Pl} \left( T \sigma v + \Gamma / T^2 \right) \sim \frac{M_{Pl} m^4_f}{F^2 T} + \frac{M_{Pl} m^6_f}{F^2 T^3}$$

$\rightarrow$ **dominated by low-$T$** (cuts off around $m_f$)
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Coupling to gaugino–gauge-boson is dim. 5

$$\frac{dY}{d\ln T} \sim M_{Pl} T \sigma v \sim \frac{M_{Pl} M_{1/2}^2}{F^2} T$$

→ high-$T$ dominated → sets a bound on $T_{\text{Reheat}}$
Gravitino Cosmology

1: Overabundance problem

Overabundance bound

(de Gouvea et al '97)
Gravitino Cosmology

1: BBN problem

- Slepton LOSP freezes out and then decays later
- decay products can change primordial element abundances
- $\rightarrow$ bound on LOSP lifetime
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$\tilde{G}$ heavy enough for LHC mass measurement $\Leftrightarrow$ BBN problem
Goldstino is like a gravitino with extra large coupling to SSM

overabundance bound becomes stronger (unless...)

BBN bound becomes weaker (faster LOSP decay)
Goldstino Cosmology: Alleviating the gravitino problem

Goldstino is like a gravitino with extra large coupling to SSM

- bound set by $F_2$ not $F_{tot}$
- $m_{3/2}$ bound weakened by factor $F_2/F_1$

BBN bound becomes weaker (faster LOSP decay)
Goldstino Cosmology: Alleviating the gravitino problem

Goldstino is like a gravitino with extra large coupling to SSM

- **high T production:**
  \[ T_R \text{ bound lower by factor} \quad \left(\frac{F_2}{F_1}\right)^2 \]

- **low T production:**
  \[ m_\zeta / \tau_{LOSP} \sim \frac{F_1}{F_2^2} \text{ bounded from below} \]

overabundance bound becomes stronger (*unless...*)
$m_{\tilde{\ell}} = 100 \text{GeV}$

**Goldstini: a Quick Review**

**A Smoking Gun Signature**

**Gravitino Cosmology**

Smoking gun signature + Cosmology = Success

Jeremy Mardon – UC Berkeley

A Definitive Signal of Multiple SUSY breaking
Smoking gun signature + Cosmology = Success

\[ m_\tilde{\ell} = 100 \text{GeV} \]

**Results:**

- Smoking-gun signature possible, consistent with cosmological bounds.
- Saturating \( T_R \) bound → goldstino DM

Need \( T_R \lesssim 10^5 - 10^7 \text{ GeV} \)?

(big improvement on standard gravitino

...but no thermal leptogenesis?)

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R symmetry in 2nd SUSY sector?
- Goldstino does not couple to gauginos
- Only gravitinos produced at high $T_R$
  
  Allow $T_R$ up to $\sim 10^{10} \text{ GeV}$
  $\rightarrow$ Thermal leptogenesis + gravitino DM
Smoking gun signature + Cosmology = Success

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Conclusions

- A striking signature of the Goldstini framework exists
- May be seen at the LHC *consistently with cosmology*

Would provide evidence for:
- SUGRA
- SUSY at scales $\sim 10^8 - 10^{10}$ GeV
- Multiple sequestered sectors
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