A measurement of Neutralino Mass at the LHC in Light Gravitino Scenarios

Koichi Hamaguchi (Tokyo U. and IPMU)

at LHC focus week, IPMU, June ’08

with Eita Nakamura and Satoshi Shirai (Tokyo U.),
arXiv: 0805.2502
Summary:

- We considered SUSY models with
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- We considered SUSY models with a very light gravitino LSP
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- We considered SUSY models with a very light gravitino LSP and a neutralino NLSP.
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• and presented a neutralino mass measurement.
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Summary:

- We considered SUSY models with a very light gravitino LSP and a neutralino NLSP.
- and presented a neutralino mass measurement based on the $M_{T2}$ method.
- Independent of other masses / cascade patterns.
- Complementary to (better than) other methods.
$M_{T2}$ method

Lester, Summers, '99
Barr, Lester, Stephens, '03

$m_A = ?$
$M_{T2}$ method

Lester, Summers, '99
Barr, Lester, Stephens, '03

$m_A = ?$

$P_{T,miss}$

$X$ (missing)

$X$ (missing)
\( M_{T2} \) method

Lester, Summers, '99
Barr, Lester, Stephens, '03

\[
(M_{T2})^2 = p_{T\text{miss}}^{\text{miss},1} + p_{T\text{miss}}^{\text{miss},2} = p_{T\text{miss}}^{\text{miss}} \left[ \max \left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \right],
\]

\[
(M_T^{(i)})^2 = m_B^2 + m_X^2 + 2(E_T^{\text{miss},i} E_T^{B,i} - p_T^{\text{miss},i} \cdot p_T^{B,i}) \quad \text{for} \quad i = 1, 2
\]

\( m_A = ? \)
$$\left( M_{T2} \right)^2 = \min_p \left[ \max \left\{ (M^{(1)}_T)^2, (M^{(2)}_T)^2 \right\} \right],$$

$$\left( M^{(i)}_T \right)^2 = m^2_B + m^2_X + 2(E^{\text{miss},i}_T E^{B,i}_T - p^{\text{miss},i}_T \cdot p^{B,i}_T) \quad \text{for} \quad i = 1, 2$$

is designed to have the endpoint at $m_A$,
$\mathcal{M}_{T2}$ method

Lester, Summers,'99
Barr, Lester, Stephens,'03

\[
(M_{T2})^2 \equiv \min_{p_{T,1}^{\text{miss}}, p_{T,2}^{\text{miss}}} \left[ \max \left\{ (M_{T}^{(1)})^2, (M_{T}^{(2)})^2 \right\} \right],
\]

\[
(M_{T}^{(i)})^2 = m_B^2 + m_X^2 + 2(E_T^{\text{miss},i} E_T^{B,i} - p_{T}^{\text{miss},i} \cdot p_{T}^{B,i}) \quad \text{for} \quad i = 1, 2
\]

is designed to have the endpoint at $m_A$,

\[ \ldots \text{when we input the correct value of } m_X. \]
$M_{T2}$ method

Lester, Summers,'99
Barr, Lester, Stephens,'03

$$(M_{T2})^2 = \min(p_T^{\text{miss},1} + p_T^{\text{miss},2} = p_T^{\text{miss}} \left[ \max\left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \right) ,$$

$$(M_T^{(i)})^2 = m_B^2 + m_X^2 + 2(E_T^{\text{miss},i} E_T^{B,i} - p_T^{\text{miss},i} \cdot p_T^{B,i}) \quad \text{for} \quad i = 1, 2$$

is designed to have the endpoint at $m_A$, events

.....when we input the correct value of $m_X$.

But in general, we don’t know $m_X$. only a relation $m_A(m_X^{\text{trial}})$ obtained.
**$M_{T2}$ method**

Lester, Summers,’99
Barr, Lester, Stephens,’03

\[
(M_{T2})^2 = \min_{p_T^{\text{miss},1} + p_T^{\text{miss},2}} \left[ \max\left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \right],
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(M_T^{(i)})^2 = m_B^2 + m_X^2 + 2(E_T^{\text{miss},i} E_T^{B,i} - p_T^{\text{miss},i} \cdot p_T^{B,i}) \quad \text{for} \quad i = 1, 2
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is designed to have the endpoint at $m_A$,

...when we input the correct value of $m_X$.

But in general, we don’t know $m_X$.

only a relation $m_A(m_X^{\text{trial}})$ obtained.

**recent developments:**

“kink” in $m_A(m_X^{\text{trial}})$ may determine $m_A$ and $m_X$ simultaneously!

(Lester, Barr, 0708;
Cho, Choi, Kim, Park, 0709 + 0711;
Barr, Gripaios, Lester, 0711;
Nojiri, Shimizu, Okada, Kawagoe, 0802; 
.........)

☛ See Wednesday Talks by
Y.G.Kim, C.Lester, Y.Shimizu.
The $M_{T2}$ method, as described by Lester, Summers, '99 and Barr, Lester, Stephens, '03, is designed to have the endpoint at $m_A$, where:

\[
(M_{T2})^2 = \min_{p_T^{\text{miss},1}, p_T^{\text{miss},2}} \left[ \max \left\{ (M_T^{(1)})^2, (M_T^{(2)})^2 \right\} \right],
\]

\[
(M_T^{(i)})^2 = m_B^2 + m_X^2 + 2(E_T^{\text{miss},i} E_T^{B,i} - p_T^{\text{miss},i} \cdot p_T^{B,i}) \quad \text{for} \quad i = 1, 2
\]

is designed to have the endpoint at $m_A$, when we input the correct value of $m_X$. But in general, we don’t know $m_X$. Only a relation $m_A(m_X^{\text{trial}})$ obtained.

Here, we discuss an interesting case in that we will know $m_X = 0$. 

...when we input the correct value of $m_X$. 

But in general, we don’t know $m_X$. 

only a relation $m_A(m_X^{\text{trial}})$ obtained.
Suppose that large missing $P_T$ signals at the LHC will be accompanied by two high $P_T$ photons.
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→ a natural candidate for the underlying model is a SUSY model with gravitino LSP
Suppose that large missing $P_T$ signals at the LHC will be accompanied by two high $P_T$ photons.

→ a natural candidate for the underlying model is a SUSY model with gravitino LSP + neutralino NLSP.
We can assume $m_X = m_{\text{Gravitino}} \approx 0$ in $M_{T2}$ method.
We can assume $m_X = m_{\text{Gravitino}} \approx 0$ in $M_{T2}$ method and therefore directly measure $m_{\text{neutralino}}$ by the $M_{T2}$ method.
• $\geq 4$ jets with $p_T > 50$ GeV and $p_{T,1,2} > 100$ GeV.
• $\geq 2$ photons with $p_T > 20$ GeV.
• $M_{\text{eff}} > 500$ GeV ($M_{\text{eff}} = \sum_{\text{jets}} p_T + p_{\text{miss}}$).
• $p_{\text{miss}} > 0.2M_{\text{eff}}$.

**example 1:**

**SPS8**
example 2: SIGM

- $\geq 4$ jets with $p_T > 50$ GeV and $p_{T,1,2} > 100$ GeV.
- $\geq 2$ photons with $p_T > 20$ GeV.
- $M_{\text{eff}} > 500$ GeV ($M_{\text{eff}} = \sum_{\text{jets}} p_T + p_{\text{miss}}$).
- $p_T^{\text{miss}} > 0.2M_{\text{eff}}$.

Model from KH, Shirai, Nakamura, Yanagida, '08
Summary:

- We considered SUSY models with a very light gravitino LSP and a neutralino NLSP.
- and presented a neutralino mass measurement based on $M_{T2}$ method.
- independent of other masses / cascade patterns.
- complementary to other methods.
Motivation:

Why gravitino LSP ??
Why such a light gravitino ??
Gravitino Problems

| time   | temperature | state      |
|--------|-------------|------------|
| ??     | ~ 0         | inflation  |
| ??     | $T_R$       | reheating  |
| \approx|             |            |
| ~ 1 sec| ~ 1 MeV    | Big Bang Nucleosynthesis |
| \approx|             | \rightarrow D, $^4\text{He}$, \ldots |
| 14 Gyr| 2.7 K       | observed   |

thermal history

baryogenesis

\rightarrow n_B/s \approx 10^{-10}
Gravitino Problems

thermal history with gravitino $\psi_{3/2}$

unstable gravitino

$T_R$  reheating  $\psi_{3/2}$

$\approx 1$ sec BBN $\rightarrow D, ^4He, \cdots$

?? $\Rightarrow$ decay

today observed

stable gravitino

$T_R$  reheating  $\psi_{3/2}$

$\approx 1$ sec BBN $\rightarrow D, ^4He, \cdots$

?? $\Rightarrow$ decay

today observed

overclose??
dark matter??

NLSP
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

\[ \Omega_{3\sigma} h^2 = 0.105^{+0.021}_{-0.030} \]

\[ m_{1/2} = 500 \text{ GeV} \]

\[ m_{1/2} = 2 \text{ TeV} \]

Moroi, Murayama, Yamaguchi,’93

Bolz, Brandenburg, Buchmuller,’00

Fig. from Steffen and Pradler,’06

Pagels and Primack,’82,

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto,’05

Weinberg,’82 + many others

Fig. from Kawasaki, Kohri, Moroi, Yotsuyanagi,’08
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

$\Omega_{DM} h^2 = 0.105^{+0.021}_{-0.030}$

$\Gamma = 500 \text{ GeV}$

$\Gamma = 2 \text{ TeV}$

BBN

allowed

Moroi, Murayama, Yamaguchi,'93

Bolz, Brandenburg, Buchmuller,'00

Fig. from Steffen and Pradler,'06

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Gravitino Problems

stable (LSP) gravitino

\[ \Omega \tilde{G} < \Omega_{\text{CDM}} \]

unstable gravitino

\[ \Omega_{\text{LSP}} \]

---

Moroi, Murayama, Yamaguchi, ’93
Bolz, Brandenburg, Buchmuller, ’00
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Gravitino Problems

stable (LSP) gravitino

unstable gravitino

\[ \Omega \tilde{G} < \Omega_{\text{CDM}} \]

allowed

BBN (NLSP)

\[ \Omega_m h^2 = 0.105^{+0.021}_{-0.050} \]

Weinberg, '82 + many others

Fig. from Kawasaki, Kohri, Moroi, Yotsuyanagi, '08

Moroi, Murayama, Yamaguchi, '93

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Pagels and Primack, '82,

Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, '05

\[ \Omega \tilde{G} \]

allowed

BBN

Fig. from Steffen and Pradler, '06

Weinberg, '82 + many others

Fig. from Kawasaki, Kohri, Moroi, Yotsuyanagi, '08
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

BBN

Ω < Ω_{CDM}

allowed

hot DM

BN (NLSP)

allowed

16 eV

Moroi, Murayama, Yamaguchi, ’93
Bolz, Brandenburg, Buchmuller, ’00
Fig. from Steffen and Pradler, ’06

Pagels and Primack, ’82,
Viel, Lesgourgues, Haehnelt, Matarrese, Riotto, ’05

Weinberg, ’82 + many others
Fig. from Kawasaki, Kohri, Moroi, Yotsuyanagi, ’08
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

\[
\Omega_{\text{dm}}^2 h^2 = 0.105^{+0.021}_{-0.030}
\]

\[
\Omega_{\text{LSP}}^2 h^2
\]

16 eV
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

16 eV
Gravitino Problems

stable (LSP) gravitino
- $16\text{ eV}$

unstable gravitino
- allowed

thermal leptogenesis
- allowed

nonthermal leptogenesis
- allowed
Gravitino Problems

In addition, direct production of gravitinos from inflaton $\Rightarrow$ exclude most inflation models
Gravitino Problems

- Stable (LSP) gravitino
- Unstable gravitino

In addition, direct production of gravitinos from inflaton exclude most inflation models.

Note: low TR doesn't help.

**FIG. 3:** Constraints from the gravitino production by the inflaton decay, for \( m_{3/2} = 1 \text{ TeV} \) with \( B_h = 1 \) (case A), \( m_{3/2} = 1 \text{ TeV} \) with \( B_h = 10^{-3} \) (case B), \( m_{3/2} = 100 \text{ TeV} \) (case C), and \( m_{3/2} = 1 \text{ GeV} \) (case D). The region above the solid (gray) line is excluded for each case. For

Fig. from Endo, Takahashi, Yanagida, '07

[Image of diagram with various regions labeled and a graph showing constraints on \( \langle \phi \rangle \) vs. \( m_\phi \) in GeV]
Gravitino Problems

- Stable (LSP) gravitino
- Unstable gravitino (allowed)

- Thermal leptogenesis
- Nonthermal leptogenesis

In addition, direct production of gravitinos from inflaton→exclude most inflation models

Fig. from Endo, Takahashi, Yanagida, '07

Note: low TR doesn’t help.

In particular, gravity.mediation (incl. mSUGRA) has a difficulty...

Solutions:
- Inflation with zero VEV (Z_2)
- Gravitino LSP
- Very heavy gravitino

FIG. 3: Constraints from the gravitino production by the inflaton decay, for \( m_{3/2} = 1 \text{ TeV} \) with \( B_h = 1 \) (case A), \( m_{3/2} = 1 \text{ TeV} \) with \( B_h = 10^{-3} \) (case B), \( m_{3/2} = 100 \text{ TeV} \) (case C), and \( m_{3/2} = 1 \text{ GeV} \) (case D). The region above the solid (gray) line is excluded for each case. For
Gravitino Problems

stable (LSP) gravitino

unstable gravitino

allowed

16 eV

allowed
Gravitino Problems

stable (LSP) gravitino  
unstable gravitino

Ultralight gravitino is completely free from cosmological problems!!
Summary:

• We considered SUSY models with a very light gravitino LSP and a neutralino NLSP
• and presented a neutralino mass measurement

\[ m_{\text{neutralino}} \]

based on \( M_{T2} \) method

• independent of other masses / cascade patterns
• complementary to other methods
Gravitino and NLSP at the LHC

| Mass State | Signal | Comment |
|------------|--------|---------|
| \( \tilde{\tau} \) NLSP | “kink” in charged track | |
| \( \tilde{\chi}^0 \) NLSP | non-pointing photon | the same as LSP signal.... |
| Gravitino | ultralight gravitino | |

This work
| Gravitino and NLSP at the LHC | ultralight gravitino $\tilde{G}$ | charged track $\tilde{G}$ | charged track $\tilde{G}$ |
|-----------------------------|---------------------------------|------------------------|------------------------|
| $\tilde{\tau}$ NLSP | “kink” in charged track | | charged track |
| $\tilde{\chi}^0$ NLSP | $2\gamma + E_{T,miss}$ non-pointing photon | | the same as $\tilde{\chi}^0$ LSP signal.... |

KH, Shirai, Yanagida,’07 cf. talk at previous focus week (Dec.'07)

This work
| Gravitino and NLSP at the LHC | ultralight gravitino | \( \tilde{G} \) |
|--------------------------------|---------------------|------------------|

| Gravitino | NLSP |
|-----------|------|
| \( \tilde{\tau} \) | \( \tilde{\chi}^0 \) |

F determination

| 2γ + \( E_T, \text{miss} \) |
|-----------------------------|

This work

| "kink" in charged track |
|--------------------------|

| charged track |
|---------------|

| non-pointing photon |
|---------------------|

| the same as \( \tilde{\chi}^0 \) LSP signal.... |

KH, Shirai, Yanagida,'07 cf. talk at previous focus week (Dec.'07)
### Gravitino and NLSP at the LHC

| Gravitino and NLSP at the LHC | ultralight gravitino $\tilde{G}$ | charged track $\tilde{\tau}$ |
|-------------------------------|-----------------------------------|-------------------------------|
| $\tilde{\tau}$ NLSP           | $F$ determination                  | charged track                 |
| $\tilde{\chi}^0$ NLSP         | $2\gamma + E_T,\text{miss}$       | non-pointing photon $\tilde{\chi}^0$ |

- KH, Shirai, Yanagida, ’07
cf. talk at previous focus week (Dec.’07)

**This work**
Gravitino and NLSP at the LHC

\[ \tilde{G} \]

NLSP

\[ \tilde{\chi}_0 \]

Kawagoe, Kobayashi, Nojiri, Ochi, '03

non-pointing photon

F determination

This work

the same as LSP signal....

ultralight gravitino

\[ 2\gamma + E_{T,\text{miss}} \]
| Gravitino and NLSP at the LHC | ultralight gravitino $\tilde{G}$ | charged track | charged track |
|------------------------------|-------------------------------|---------------|---------------|
| $\tau$ NLSP                  | “kink” in charged track       |               |               |
| $\chi^0$ NLSP                | non-pointing photon           |               | the same as LSP signal.... |
| $2\gamma + E_T, \text{miss}$ |                               |               |               |

KH, Shirai, Yanagida,’07

cf. talk at previous focus week (Dec.’07)

This work
### Gravitino and NLSP at the LHC

| Gravitino \ NLSP at the LHC | ultralight gravitino $\tilde{G}$ |
|-----------------------------|----------------------------------|
| $\tilde{\tau}$ NLSP        | "kink" in charged track          |
| $\chi^0$ NLSP              | charged track                    |

- K.H, Shirai, Yanagida,'07 cf. talk at previous focus week (Dec.'07)
- "kink" in charged track
- charged track
- F determination
- non-pointing photon $2\gamma + E_T,\text{miss}$
- the same as LSP signal....

- talk by R. Kitano on Thursday!
Gravitino and NLSP at the LHC.

- Charged track: \( \tilde{G} \)
- NLSP: \( \tilde{\chi}_0 \)
- Charged track: \( \tilde{\chi}_0 \)
- CMS stopper-detector
- Non-pointing photon: \( 2\gamma + E_T,_{\text{miss}} \)
- This work
- Non-pointing photon: \( \tilde{\chi}_0 \)

Non-pointing photon: the same as LSP signal.

SUGRA test?! (Buchmuller, KH, Ratz, Yanagida, '04)

Talk by R. Kitano on Thursday!
### Gravitino and NLSP at the LHC

| Particle | Description |
|----------|-------------|
| \( \tilde{\tau} \) | NLSP |
| \( \tilde{G} \) | Ultralight gravitino |
| \( \tilde{\chi}^0 \) | NLSP |
| \( 2\gamma + E_{T,\text{miss}} \) | F determination |

**K.H. Shirai, Yanagida,’07**

CF. talk at previous focus week (Dec.’07)

"Kink" in charged track

| Charged track |
|---------------|
| \( \tilde{G} \) |
| \( \text{NLSP} \) |

\( \sim \)

**F determination**

**This work**

**Talk by R. Kitano on Thursday!**

| Charged track |
|---------------|
| The same as LSP signal.... |
**Gravitino and NLSP at the LHC**

| Gravitino and NLSP at the LHC | ultralight gravitino | charged track |
|-------------------------------|----------------------|---------------|
| $\tilde{G}$                   | $\tilde{\chi}^0$     | non-pointing photon |
| $\tilde{\tau}$ NLSP           |                       | $2\gamma + E_T,\text{miss}$ |
| $\tilde{\chi}^0$ NLSP        |                       | $F$ determination |

- K.H. Shirai, Yanagida, ’07 cf. talk at previous focus week (Dec.’07)
- “kink” in charged track
- non-pointing photon
- charged track
- talk by R. Kitano on Thursday!

**This work**

Let’s see what the LHC will find.....!
backup slides
Another Side Remark

- thermal leptogenesis \( TR > 10^9 \text{GeV} \) \( \rightarrow \) \( m_G > O(10) \text{ GeV} \)
- \( \Rightarrow T_{\text{stau}} \gg 1000 \text{ sec.} \) \( \rightarrow \) excluded by CBBN? (unless
Another Side Remark

- thermal leptogenesis $\ TR > 10^9\text{GeV} \rightarrow m_G > O(10)\ \text{GeV}$
- $\rightarrow T_{\tau\text{stau}} \gg 1000\ \text{sec.} \rightarrow$ excluded by CBBN?? (unless

A solution: a small R-parity violation can help it.

- $\lambda > 10^{-14}$ is large enough to make $T_{\tau\text{stau}} < 1000\ \text{sec},$
- $\lambda < 10^{-7}$ is small enough to satisfy the constraints including baryon washout,
- and to make the gravitino stable, i.e. $T_{\text{gravitino}} > T_{\text{universe}}.$
- (Buchmuller, Covi, KH, Ibarra, Yanagida,’07; cf. Takayama Yamaguchi,’00)
Another Side Remark

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(Buchmuller, Covi, KH, Ibarra, Yanagida,’07; cf. Takayama Yamaguchi,’00)

And the gravitino DM decay can be (or has already been?!) seen by CRs !!!

Ibarra, Tran,’08 ➔
(Ishikawa, Matsumoto, Moroi,’08 ➔

\[ \gamma \text{ (EGRET)} \]

\[ e^+ \text{ (HEAT)} \]
Gravitino Interaction: extremely weak

suppressed by $\sim \frac{1}{M_P}$ (or $\sim \frac{1}{F} \sim \frac{1}{M_P m_{\tilde{G}}}$)

Gravitino Mass: model dependent

eV  keV  MeV  GeV  TeV

GMSB

$\tilde{g}$MSB

gravity-MSB

AMSB, mMSB
SUSY models with an ultralight gravitino is

$\left( m_{\tilde{G}} \lesssim 10 \text{ eV} \right)$

No Cosmological Problem! at all!
SUSY models with an ultralight gravitino is

\[ m_{\tilde{G}} \lesssim 10 \text{ eV} \]

No Cosmological Problem! at all!

LSP (gravitino) ≠ CDM (too light \( \rightarrow \) hot DM), but....
SUSY models with an ultralight gravitino is

\( m_{\tilde{G}} \lesssim 10 \text{ eV} \)

No Cosmological Problem! at all!

LSP (gravitino) ≠ CDM (too light → hot DM), but....

\[ m_{\tilde{G}} \sim 10 \text{ eV} \implies F = \Lambda^2 \sim (100 \text{ TeV})^2 \]

100 TeV DM ➔ natural thermal relic DM if strongly interacting
In general, \( \Omega_{X}^{\text{thermal}} \sim 0.2 \left( \frac{\text{pb}}{\sigma_{\text{ann.}}(XX \rightarrow \text{all})} \right) \)

**No Cosmological Problem! at all!**

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- LSP (gravitino) $\neq$ CDM (too light $\rightarrow$ hot DM), but....

$$m_{\tilde{G}} \sim 10 \text{ eV} \quad \Longrightarrow \quad F = \Lambda^2 \sim (100 \text{ TeV})^2$$

100 TeV DM $\Rightarrow$ natural thermal relic DM if strongly interacting
In general, \( \Omega_X^{\text{thermal}} \sim 0.2 \left( \frac{\text{pb}}{\sigma_{\text{ann.}}(XX \to \text{all})} \right) \)

\[
\sigma_{\text{ann.}} \sim \mathcal{O}(\alpha) \quad \longrightarrow \quad m \sim \mathcal{O}(0.1 - 1) \text{ TeV}
\]

\[
\sigma_{\text{ann.}} \sim \mathcal{O}(4\pi) \quad \longrightarrow \quad m \sim \mathcal{O}(10 - 100) \text{ TeV}
\]

No Cosmological Problem! at all!

- LSP (gravitino) \( \neq \) CDM (too light \( \rightarrow \) hot DM), but....

\[ m_{\tilde{G}} \sim 10 \text{ eV} \implies F = \Lambda^2 \sim (100 \text{ TeV})^2 \]

100 TeV DM \( \Rightarrow \) natural thermal relic DM if strongly interacting
No Cosmological Problem! at all!

- LSP (gravitino) ≠ CDM (too light → hot DM), but....

  - $m_{\tilde{G}} \sim 10$ eV $\implies F = \Lambda^2 \sim (100$ TeV)$^2$
  - 100 TeV DM $\implies$ natural thermal relic DM if strongly interacting

DM may be 100 TeV composite “baryon” made from strongly self-interacting hidden-sector/messenger particles

Dimopoulos, Giudice, Pomarol '96 / KH, Shirai, Yanagida '07