Probing TR at the LHC with long-lived staus.

Koichi Hamaguchi (Tokyo U. + IPMU)

based on, M.Endo, KH, K.Nakaji, [arXiv:1008.2307]
+ M.Endo, KH, K.Nakaji, in preparation

Non-Thermal Cosmological Histories of Universe
at Michigan Center for Theoretical Physics, October, 2010
(Non-) Thermal History of the Universe

- Inflation
- Reheating $T_R$
- BBN (1 sec)
- Last scattering surface
- Today ($10^{10}$ yr)

Time
(Non-) Thermal History of the Universe

..... How far can we go back in time?
(Non-) Thermal History of the Universe

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- inflation
- reheating $T_R$
- $T_{\text{decouple}}$
- BBN (1 sec)
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- CMBR
- today ($10^{10}$ yr)

If Dark Matter = WIMP

He4, D, ....

$T_{\text{decouple}}$
(Non-) Thermal History of the Universe

..... How far can we go back in time?

If Dark Matter = Gravitino

This talk

If Dark Matter = WIMP

He4, D, ....

CMBR

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reheating \( T_R \)

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today \((10^{10}\text{yr})\)
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today ($10^{10}$yr)

inflation

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Note: another possibility = Gravitational Wave

[cf. K.Nakayama’s talk on Monday]
(Non-) Thermal History of the Universe

..... How far can we go back in time?

If Dark Matter = Gravitino

If Dark Matter = WIMP

Entropy production \( \Delta \) ?

Note: another possibility = Gravitational Wave
[cf. K.Nakayama's talk on Monday]
before the main part,... a comment on moduli problem

\[ \Gamma_X = \frac{c}{4\pi} \frac{m_X^3}{M_P^2} \]
\[ T_X = (\pi^2 g_* / 90)^{-1/4} \sqrt{M_P \Gamma_X} \]
\[ \approx 5.5 \times 10^{-3} \text{ MeV} \cdot c^{1/2} \left( \frac{m_X}{1 \text{ TeV}} \right)^{3/2} \]

\[ m_X \gtrsim 100 \text{ TeV} \quad \Rightarrow \quad T_X \gtrsim \mathcal{O}(\text{MeV}) \]

.......But this is not sufficient !!
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Moduli-Induced Gravitino Problem

Endo, KH, Takahashi, 0602061
Nakamura, Yamaguchi, 0602081
Asaka, Nakamura, Yamaguchi, 0604132
Dine, Kitano, Morisse, Shirman, 0604140
Endo, KH, Takahashi, 0605091

\[ \Gamma(X_R, I \rightarrow 2\psi_{3/2}) \approx \frac{1}{288\pi} \frac{|G_X|^2 m_X^5}{g_{XX} m_{3/2}^2}, \]

Generically, \(|G_X| > m_{3/2}/m_X \)

\[ \rightarrow \quad \text{Br}(X \rightarrow 2 \text{ gravitinos}) \approx O(1) !!! \]

\[ \text{---\rightarrow Serious problems,} \]

\[ \text{even if } T_X > 1 \text{ MeV}. \]

\[ m_{\text{NLSP}} = 100 \text{ GeV}. \text{ We have chosen } m_X = 10^3 \text{ TeV and } c = 1 \text{ as representative values. The bounds become severer for larger } m_X. \]
before the main part, ... a comment on moduli problem

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Main messages of this talk:

In SUSY models with gravitino LSP + stau NLSP,

1. $T_R > \text{a few } 10^8 \text{ GeV}$
   → tested at 7 TeV 1fb\(^{-1}\) ($\approx$ within 1.5 years !)

2. Stau lifetime can be measured at the LHC.
   ($\rightarrow T_R$ may be determined,
   assuming $\Omega_G^{\text{thermal}} h^2 \approx \Omega_{DM} h^2$. If not, $\rightarrow$ upper bound on $T_R$. )

* with entropy production $\Delta$, replace $T_R \rightarrow T_R \times \Delta^{-1}$
Main messages of this talk:

1. Introduction
   In SUSY models with gravitino LSP + stau NLSP,

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Introduction
We assume: SUSY + gravitino LSP + stau NLSP
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why SUSY?

- naturalness, coupling unification, DM, ….
- many non-SUSY scenarios for BSM $\rightarrow$ low E cut-off
  $\rightarrow$ difficult to discuss $T \gtrsim$ cut-off (inflation/reheating/baryogenesis…)


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LSP = stable (assuming R-parity)
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In SUSY Standard Model in SUGRA,.....

squarks: \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}_i \quad \tilde{u}_{Ri} \quad \tilde{d}_{Ri}

sleptons: \begin{pmatrix} \tilde{\nu}_L \\ \tilde{\nu}_R \end{pmatrix}_i \quad \tilde{e}_L \quad \tilde{e}_{Ri}

gauginos and higgssinos: \tilde{\chi}_i^0, \tilde{\chi}_i^\pm, \tilde{g}

gravitino: \tilde{G}
We assume: SUSY + gravitino LSP + stau NLSP

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- sleptons: $\tilde{e}_L, \tilde{e}_R$
- gauginos and higgsinos: $\tilde{\chi}^0, \tilde{\chi}^\pm, \tilde{g}$
- gravitino: $\tilde{G}$

neutral and color singlet

excluded by direct detection experiments  
(cf. Falk, Olive, Srednicki’94)
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why gravitino LSP?

LSP = stable (assuming R-parity) 
$\rightarrow$ only gravitino or neutralino are allowed.

$\rightarrow$ NLSP becomes long-lived. We assume stau NLSP. 
  (e.g., for $m_{\text{NLSP}} = 200$ GeV, lifetime $= O(10\text{sec - day})$ for $m_{\text{gravitino}} = O(0.1 - 10$ GeV)

..... realized in many attractive models ..... 
- GMSB (in particular, with messenger # > 1) 
- Sweet Spot SUSY [Ibe, Kitano ’07] (cf. R.Kitano’s talk) 
- F-theory GUT [Marsano, Saulina, Schafer-Nameki ’08 / Heckman, Shao, Vafa ’10]
Probing $T_R$ at the LHC with long-lived staus ??

..... in gravitino DM scenario with stau NLSP.
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(thermally produced)
POINT: gravitino abundance is determined by $T_R$.

time | temperature

??     | inflation
?? $T_R$ Reheating $\rightarrow$ gravitino

$10^{10}$ yr $\rightarrow$ 3 K $\rightarrow$ today

DM
Probing $T_R$ at the LHC with long-lived staus ??

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$$\Omega^{\text{thermal}}_{\tilde{G}} h^2 \approx 0.1 \left( \frac{3 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\text{gluino}}}{1 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^8 \text{ GeV}} \right)$$

$$\leq \Omega_{DM} h^2 = 0.11$$
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Key eq.

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comments
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comments

(1) bino and wino contributions are usually small, becomes comparable if $m_{\text{wino/bino}} \simeq m_{\text{gluino}}$.

$$\Omega_{3/2} h^2 \simeq \left( \frac{1 \text{ GeV}}{m_{3/2}} \right) \left( \frac{T_R}{10^8 \text{ GeV}} \right) \times \left[ 0.14 \left( \frac{m_{\tilde{B}}}{1 \text{ TeV}} \right)^2 + 0.38 \left( \frac{m_{\tilde{W}}}{1 \text{ TeV}} \right)^2 + 0.34 \left( \frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^2 \right],$$
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(2) “no entropy production” is assumed.
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\[ \rightarrow \text{ replace } T_R \rightarrow T_R \times \Delta^{-1} \text{ in the following discussion.} \]
Key eq. 

\[
\Omega_{\tilde{G}}^{\text{thermal}} h^2 \approx 0.1 \left( \frac{3 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\text{gluino}}}{1 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^8 \text{ GeV}} \right)
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comments

(3) other contributions to DM.

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\Omega_{\tilde{G}}^{\text{thermal}} h^2 + \Omega_{\tilde{G}}^{\text{Non-thermal}} h^2 + \Omega_{\text{other DMs}} h^2 = \Omega_{\text{DM}} h^2 \approx 0.1
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- stau NLSP decay: small for \( m_{\text{stau}} < 1 \text{ TeV} \).
- inflaton decay: small for large \( T_R \) [cf. Endo, Kawasaki, Takahashi, Yanagida ’06–’07]
- decay of SUSY field [cf. R. Kitano’s talk]: can be large depending on SUSY sector
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→ in the simplest case, \( \Omega^\text{thermal}_{\tilde{G}} h^2 = \Omega_{\text{DM}} h^2 \simeq 0.1 \)

..... if not, \( \Omega^\text{thermal}_{\tilde{G}} h^2 \leq \Omega_{\text{DM}} h^2 \) (→ upper bound on T_R)
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- 2. Use upper bound from BBN
- 3. Stau lifetime $\rightarrow$ gravitino mass
Probing high $T_R$ scenario at the LHC with long lived stau.

M. Endo, KH, K. Nakaji, arXiv:1008.2307
Probing high $T_R$ scenario at the LHC with long lived stau.

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thermal leptogenesis: $T_R > O(10^9)$ GeV
non-thermal leptogenesis: $T_R > O(10^6)$ GeV
some typical inflation models: $T_R = O(10^4-10^{13})$ GeV

$\rightarrow$ any signal at the LHC ??
Probing **high $T_R$ scenario** at the LHC with long lived stau.

Logic [Fujii, Ibe, Yanagida,'04]
Probing \textbf{high $T_R$ scenario} at the LHC with long lived stau.

\textbf{Logic} \hspace{1cm} [Fujii, Ibe, Yanagida,'04]

(1) For a given \textbf{stau mass} $\rightarrow$ upper bound on \textbf{gravitino mass}

$$m_{\tilde{G}} \leq m_{\tilde{G}}^{\text{max}} (m_{\tilde{\tau}})$$

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BBN: constraint on $(Y_{\tilde{\tau}}, \tau_{\tilde{\tau}})$

$$Y_{\tilde{\tau}} = Y_{\tilde{\tau}} (m_{\tilde{\tau}})$$

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→ constraint on $(m_{\tilde{\tau}}, m_{\tilde{G}})$

Assuming:  
thermal relic abundance of stau  
If not: the bound is relaxed.
Probing high $T_R$ scenario at the LHC with long lived stau.

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BBN: constraint on $(Y_{\tilde{\nu}}, \tau_{\tilde{\nu}})$

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2. For a given $T_R$
   - upper bound on gluino mass
Probing high $T_R$ scenario at the LHC with long lived stau.

Result

upper bound on the gluino mass for given $T_R$

Note: taken $m(\text{bino})=m(\text{wino})=1.1m(\text{stau})$ to have conservative bound on $T_R$. M. Endo, KH, K. Nakaji, arXiv:1008.2307
Probing high $T_R$ scenario at the LHC with long lived stau.

Result

- # of produced staus at 14 TeV $10 \text{fb}^{-1}$
- # of produced staus at 7 TeV $1 \text{fb}^{-1}$

upper bound on the gluino mass for given $T_R$
Probing high $T_R$ scenario at the LHC with long lived stau.

M. Endo, K. H, K. Nakaji, arXiv:1008.2307

Result

# of produced staus at 14 TeV $10\text{fb}^{-1}$
# of produced staus at 7 TeV $1\text{fb}^{-1}$

Checked: after triggers and cuts, 20-50% events remain.

trigger assumption:

- $\geq 1$ isolated $e$ ($p_T > 20$ GeV), or
- $\geq 1$ isolated $\mu$ ($p_T > 40$ GeV), or
- $\geq 1$ isolated $\tau$ ($p_T > 100$ GeV), or
- $\geq 1$ isolated stau ($p_T > 40$ GeV and $\beta > 0.7$, $\eta < 1.0$ or $\beta > 0.8$, $\eta < 2.8$), or
- $\geq 2$ staus ($p_T > 40$ GeV and $\beta > 0.7$, $\eta < 1.0$ or $\beta > 0.8$, $\eta < 2.8$)

stau cuts assumptions:

$p_T > 20$ GeV & $\eta < 2.5$ & $0.5 < \beta < 0.9$ $\rightarrow$ almost background free!
Probing high $T_R$ scenario at the LHC with long lived stau.

Result

upper bound on the gluino mass for given $T_R$

# of produced staus at 14 TeV $10\text{fb}^{-1}$

# of produced staus at 7 TeV $1\text{fb}^{-1}$

$T_R > a \text{ few } 10^8 \text{ GeV}$ can be probed at 7 TeV $1\text{fb}^{-1}$ !!!

M.Endo, KH, K.Nakaji, arXiv:1008.2307
Probing high $T_R$ scenario at the LHC with long lived stau.

**COMMENT**
- So far we’ve assumed that the stau annihilation is dominated by EW process (which is usually the case).
- but if the stau-higgs coupling is extremely enhanced, stau abundance can be reduced (BBN bound is relaxed).

[Ratz, Schmidt-Hoberg, Winkler,’08, Pradler, Steffen,’08]
3 stau lifetime measurement (and $T_R$)

+ M. Endo, KH, K. Nakaji, in progress

see also earlier work on “stopping gluinos” [hep-ph/0506242]
Arvanitaki, Dimopoulos, Pierce, Rajendran, Wacker

Many independent motivations to measure
the lifetime of long-lived charged massive particles.....

● Planck scale measurement, if $m_G$ is determined by kinematics
  [Buchmuller, KH, Ratz, Yanagida,’08]
● Test of FIMP mechanism [cf. talks by T. Moroi and L. Hall]
● Li problem/solution [cf. talk by K. Olive]
● etc etc
stau lifetime measurement (and $T_R$)

+ M. Endo, KH, K. Nakaji, in progress

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Arvanitaki, Dimopoulos, Pierce, Rajendran, Wacker
So far we’ve used only the upper bound: \( m_{\tilde{G}} \leq m_{\tilde{G}}^{\text{max}}(m_{\tilde{\tau}}) \)

.... Can we determine gravitino mass more directly??

---
stau lifetime measurement!!

---

3 stau lifetime measurement (and \( T_R \))

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\[ \Omega_{\text{DM}} h^2 = 0.11 \]

Assumption

(if not, \( T_R \rightarrow T_R^{\text{max}} \))
\[
\Omega^\text{thermal}_{\tilde{G}} h^2 \approx 0.1 \left( \frac{3 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\text{gluino}}}{1 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^8 \text{ GeV}} \right)
\]

= \Omega_{\text{DM}} h^2 = 0.11

by invariant mass method
[cf. Ito, Kitano, Moroi,'09]

assumption
(if not, \( T_R \to T_R^{\text{max}} \))

Gluino mass is more difficult but should be possible at high luminosity

\text{squark mass} @100 \text{fb}^{-1}
\[ \Omega_{\tilde{G}}^{\text{thermal}} h^2 \simeq 0.1 \left( \frac{3 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\text{gluino}}}{1 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^8 \text{ GeV}} \right) \]

\[ = \Omega_{\text{DM}} h^2 = 0.11 \]

(If not, \( T_R \to T_R^{\text{max}} \))
\[ \Omega_{\widetilde{G}}^{\text{thermal}} h^2 \simeq 0.1 \left( \frac{3 \text{ GeV}}{m_{\widetilde{G}}} \right) \left( \frac{m_{\text{gluino}}}{1 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^8 \text{ GeV}} \right) \]

\[ = \Omega_{\text{DM}} h^2 = 0.11 \]

Assumption

(if not, \( T_R \rightarrow T_R^{\text{max}} \) )
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\[ = \Omega_{\text{DM}} h^2 = 0.11 \]

Assumption
(if not, \( T_R \rightarrow T_R^{\text{max}} \))

by velocity measurement
(+ momentum measurement)

mass = \( p / (\beta \gamma) \)

Figure 18: \( \beta \) resolution and reconstructed mass for sleptons from the GMSB5 sample.

ATLAS, 0901.0512
\[ \Omega_{\tilde{G}}^{\text{thermal}} h^2 \approx 0.1 \left( \frac{3 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\text{gluino}}}{1 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^8 \text{ GeV}} \right) \]

\[= \Omega_{\text{DM}} h^2 = 0.11 \]

**Assumption** (if not, \( T_R \rightarrow T_R^{\text{max}} \))

*by velocity measurement* (+ momentum measurement) \[ \text{mass} = \frac{p}{(\beta \gamma)} \]

*Figure 18: \( \beta \) resolution and reconstructed mass for sleptons from the GMSB5 sample.*

ATLAS, 0901.0512
stau lifetime measurement [Asai, KH, Shirai, '09]

- at the LHC,.....
stau lifetime measurement [Asai, KH, Shirai,’09]

- typically most of staus have large velocity and escape from detector.
• typically most of staus have large velocity and escape from detector.

but we can't see its decay in these events.....

cf. proposals to stop them outside detector:

KH, Kuno, Nakaya, Nojiri,’04
Feng, Smith,’04
de Roeck, KH, Nojiri, ’06

But not realistic now....
• typically most of staus have large velocity and escape from detector.
• but some of them have sufficiently small velocity and stop at calorimeters.
• typically most of staus have large velocity and escape from detector.
• but some of them have sufficiently small velocity and stop at calorimeters.
• but their late-time decay has **wrong timing** and **wrong direction**;
• difficult to reject backgrounds
• difficult to trigger.

..... **during pp collision.**
Idea:

use periods of no pp collision !!

possible strategies:

• for short lifetime: use beam-dump signal.
  (or use empty bunch [CMS study, ’09])

• for long lifetime: use shutdown time.

stau lifetime measurement [Asai, KH, Shirai,’09]
• for short lifetime: use **beam-dump signal**.

(I) select the stopping event by **online Event Filter**.
• for short lifetime: use **beam-dump signal.**

(I) select the stopping event by **online Event Filter.**

- (1) missing ET > 100 GeV
- (2) 1 jet PT > 100 GeV + 2 jets PT > 50 GeV
- (3) isolated track with PT > 0.1 m(stau).
- (4) extrapolate the track to calorimeter and energy deposit < 0.2 p(stau).
- (5) extrapolate the track to muon system and no muon track.

---

**SUSY events stopped!!**
• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.
• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

(II) send a beam-dump signal, which immediately stops the pp collision.
• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

(II) send a beam-dump signal, which immediately stops the pp collision.

(III) change the trigger menu to the one optimized for stau decay.
• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

(II) send a beam-dump signal, which immediately stops the pp collision.

(III) change the trigger menu to the one optimized for stau decay.

(IV) wait for stau decay.
• for short lifetime: use beam-dump signal.

(I) select the stopping event by online Event Filter.

(II) send a beam-dump signal, which immediately stops the pp collision.

(III) change the trigger menu to the one optimized for stau decay.

(IV) wait for stau decay.
- for short lifetime: use **beam-dump signal**.

(I) select the stopping event by **online Event Filter**.

(II) send a **beam-dump signal**, which immediately stops the pp collision.

(III) **change the trigger menu** to the one optimized for stau decay.

(IV) **wait** for stau decay.

```
Δt
```

SUSY events  →  **beam-dump**  →  SUSY stopped!!  →  change trigger menu  →  decay!!  →  SUSY events

restart pp collision

```
time
```
• for long lifetime: use shutdown time

running (pp collision)  

stopped  

winter shutdown

time
• for long lifetime: use shutdown time

- running (pp collision)
- stopped

- winter shutdown

change trigger menu
• for long lifetime: use shutdown time

running (pp collision)  

stopped  

change trigger menu  

decay!!

winter shutdown  

time
TABLE I: Expected statistical errors for each lifetime. $\langle N_D \rangle$ is the expected number of staus' decays in the corresponding period. For 100 fb$^{-1}$ and $\tau_X \approx O(1)$ sec, the empty-bunch method will be useful. (See discussion below.) [SPS7 point, 1 year data]

<table>
<thead>
<tr>
<th>lifetime</th>
<th>10 fb$^{-1}$</th>
<th>100 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\langle N_D \rangle$</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>0.1 sec</td>
<td>0.008 ± 0.1 sec</td>
<td>-</td>
</tr>
<tr>
<td>0.2 sec</td>
<td>1.2 ± 0.15 sec</td>
<td>-</td>
</tr>
<tr>
<td>0.5 sec</td>
<td>23 ± 0.1 sec</td>
<td>-</td>
</tr>
<tr>
<td>1 sec</td>
<td>64 ± 0.1 sec</td>
<td>-</td>
</tr>
<tr>
<td>10 sec</td>
<td>156 ± 0.9 sec</td>
<td>-</td>
</tr>
<tr>
<td>100 sec</td>
<td>171 ± 9 sec</td>
<td>-</td>
</tr>
<tr>
<td>1000 sec</td>
<td>144 $^{+230}_{-170}$ sec</td>
<td>-</td>
</tr>
<tr>
<td>10 day</td>
<td>26 ± 2.2 day</td>
<td>262 ± 0.7 day</td>
</tr>
<tr>
<td>100 day</td>
<td>143 $^{+49}_{-25}$ day</td>
<td>1430 $^{+20}_{-13}$ day</td>
</tr>
<tr>
<td>10 year</td>
<td>14 $^{+7}_{-3}$ year</td>
<td>138 $^{+1.6}_{-1.2}$ year</td>
</tr>
<tr>
<td>50 year</td>
<td>2.8 $^{+110}_{-21}$ year</td>
<td>28 $^{+21}_{-12}$ year</td>
</tr>
<tr>
<td>300 year</td>
<td>0.5  -</td>
<td>5 $^{+224}_{-88}$ year</td>
</tr>
</tbody>
</table>

O(0.1 sec .... 100 years) can be probed!!
\[ \Omega_{\tilde{G}}^{\text{thermal}} h^2 \simeq 0.1 \left( \frac{3 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\text{gluino}}}{1 \text{ TeV}} \right)^2 \left( \frac{T_R}{10^8 \text{ GeV}} \right) \]

\[ = \Omega_{\text{DM}} h^2 = 0.11 \]

\[ \uparrow \text{assumption} \]

\[ \text{(if not, } T_R \rightarrow T_R^{\text{max}} \text{) } \]

\[ \tau_{\tilde{\tau}} = \frac{48\pi M_{\text{pl}}^2 m_{\tilde{\tau}}^2}{m_{\tilde{\tau}}^5} \]

\[ \text{can be determined} \]

\[ \text{at the LHC !!!} \]
In SUSY models with gravitino LSP + stau NLSP,

\[ T_R > a \text{ few } 10^8 \text{ GeV} \]
\[ \rightarrow \text{ tested at } 7 \text{ TeV } 1\text{fb}^{-1} \ (\approx \text{ within } 1.5 \text{ years} !) \]

Stau lifetime can be measured at the LHC.

\[ \rightarrow T_R \ \text{may be determined,} \]
\[ \text{assuming } \Omega_G^{\text{thermal}} h^2 \approx \Omega_{\text{DM}} h^2 \ \text{If not, } \rightarrow \text{ upper bound on } T_R. \]

* with entropy production \( \Delta \), replace \( T_R \rightarrow T_R \times \Delta^{-1} \)
DISCUSSION

gravitational wave may probe TR (and dilution).

[cf. talk on Monday]

Figure 3. Primordial gravitational wave spectrum for $T_R = 10^9$ GeV and $T_R = 10^5$ GeV are shown by thin and thick lines for $r = 0.1$ and 0.001. Also shown are expected sensitivity of DECIGO (green dashed), correlated analysis of DECIGO (blue dot-dashed), ultimate-DECIGO (purple dashed) and correlated analysis of ultimate-DECIGO (red dotted), from upper to lower.

Figure 6. Gravitational wave spectrum for the dilution factor $F = 10^2$ and $10^4$. Here we have fixed $r = 0.1$, $T_R = 10^9$ GeV and $T_x = 1$ GeV.
additional slides
• typically most of staus have large velocity and escape from detector.
• but some of them have sufficiently small velocity and stop at calorimeters.

Example of SUSY model point SPS7 (\( \sigma_{\text{SUSY}} = 3.5 \text{ pb} \))

From Asai, KH, Shirai '09 (See related work “stopping gluino”, Arvanitaki et.al.)
lifetime measurement: "empty bunch" method (cf. CMS study, CMS PAS EXO-09-001)

compared to "beam-dump" method,.....

advantages:
• pp collision can continue
• sensitive to (much) shorter lifetime

disadvantages:
• difficult to correspond the stop and decay, if lifetime is longer than the empty bunch period.
• # of decay observed is reduced.