SUSY from Cosmology Point of View

Takeo Moroi (Tohoku U)
1. Introduction
The standard model of particle physics is successful

- It well explains results of collider experiments
- Theoretically consistent (renormalizable)

The $\Lambda$CDM model (with inflation) is successful

- CMB anisotropy observed by the WMAP is well explained by (almost) scale-invariant primordial fluctuation
  \[ \Rightarrow \text{(Maybe) inflation} \]
- Sizable amount of dark matter
- Non-vanishing dark energy (cosmological constant?)
Current status of the observation of the universe

- Dark Energy (77%)
- Cold Dark Matter (19%)
- Atoms (4%)

Blue: mass density via gravitational lensing (by HST)
Pink: X-ray from baryons (by Chandra)

Supernova Cosmology Project
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)

No Big Bang: expands forever
Closed: recollapses eventually
Open: flat
The standard model is unsatisfactory for cosmology

- No candidate of inflaton
- No mechanism of generating baryon asymmetry
- No candidate of dark matter $\Leftrightarrow \Omega_{\text{CDM}} \simeq 0.2$
- ...

We need a candidate of dark matter

- Stable (or long-lived)
- Weakly coupled
- Massive (heavier than $\sim 1$ keV, if particle-like)

$\Rightarrow$ There is no such particle in the particle content of the standard model
We need new physics which contains dark-matter candidate

- SUSY
- UED
- Little Higgs (with $T$-parity)
- ...

What happens if dark-matter particle is produced in collider?

- Dark-matter particle is undetectable
- It becomes a source of missing $p_T$
- Missing $p_T$ signal is very important, although it is not always the case
2. SUSY
Important symmetry: $R$-parity

- $R = +/−$ for SM/SUSY particles
- $R$-parity is important to suppress nucleon decay

The LSP becomes stable if $R$-parity is conserved

⇒ Implications to cosmology
The LSP is a well-motivated candidate of dark matter

- If so, the LSP should be charge-neutral
- Otherwise, $R$-parity should be violated

Properties of dark matter depend what the LSP is

- LSP in the MSSM sector, or
- LSP as a superpartner of more exotic particles

Candidates of the LSP (with $R$-parity)

- The lightest neutralino
- Gravitino
- Exotic ones (axino, right-handed sneutrino, moduli, ...)
3. Case with Neutralino LSP
If the lightest neutralino $\chi_1^0$ is the LSP, …

- Relic abundance of the LSP is thermally determined (in the simplest case)
- $\Omega_{\text{LSP}} \propto (\text{annihilation cross section})^{-1}$

\[
\Rightarrow \quad \Omega_{\text{LSP}} \approx 0.2 \times \left( \frac{\langle \sigma v \rangle}{0.9 \text{ pb}} \right)^{-1}
\]
We should see if $\Omega_{\text{MSSM-LSP}} = \Omega_{\text{CDM}}$ holds using colliders

⇒ If $\Omega_{\text{MSSM-LSP}}^{(\text{rec})} = \Omega_{\text{CDM}}$, it supports the LSP-CDM scenario

⇒ If not, we need some exotic scenario

⇒ Test of the thermal history up to $T \sim O(10 \text{ GeV})$

For the reconstruction of $\Omega_{\text{MSSM-LSP}}$, we need to measure

- Masses of (MSSM) superparticles
- Mixing angles (of mass matrices of superparticles)
- Coupling parameters
- …

Accuracy of $\Omega_{\text{MSSM-LSP}}^{(\text{rec})}$ depends on underlying parameters
In some case, $\Omega_{\text{MSSM-LSP}}$ is determined only with the LHC

[Baltz, Battaglia, Peskin & Wizansky]
In other case, accuracy gets worse: focus-point case
Or we may need 1 TeV ILC: co-annihilation case

$\Rightarrow m_{\tilde{\tau}} - m_{\chi_1^0}$ is hard to measure
Another difficult case: Funnel region

⇒ $m_A$ and $\Gamma_A$ are hard to measure
In fact, $\chi_1^0$ may have non-thermal origin:

- Decay of other exotics (gravitino, moduli fields, ⋯)

Gravitino: superpartner of graviton

- Very weakly interacting: (interaction) $\propto M_{\text{Pl}}^{-1}$
- Very long-lived (if it’s unstable)

$$\tau_{3/2} \sim 10^4 \text{ sec} \times \left( \frac{m_{3/2}}{1 \text{ TeV}} \right)^{-3}$$

In SUSY cosmology, gravitino is important (and dangerous)

1. Gravitino is produced at the reheating era after inflation
2. Primordial gravitino decays at later epoch
3. The LSP (like $\chi_1^0$) is produced by the decay of gravitino
Standard BBN well explains abundances of light elements

⇒ Gravitino may spoil the success of standard BBN

- Hadro-dissociation
- Photo-dissociation
- $p \leftrightarrow n$ conversion

⇒ Too large gravitino abundance is dangerous

Gravitino production at the reheating era after inflation

$$n_{3/2} \sim 2 \times 10^{-14} \times \text{(entropy density)} \times \left(\frac{T_R}{10^8 \text{ TeV}}\right)$$
Upper bound on the reheat temperature

[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]
LSP is produced by the decay of gravitino

- \( T_R \gtrsim 10^{9-10} \text{ GeV} \) is necessary to produce sufficient LSP

\[
\Omega_{\text{LSP}} = \frac{m_{\text{LSP}}}{m_{3/2}} \left[ \Omega_{3/2} \right]_{\text{would-be}}
\]

- Stringent constraints from BBN

\[ \Rightarrow m_{3/2} \gtrsim 30 \text{ TeV} \]

In the anomaly-mediated model, this possibility is important

- In AMSB, Wino may be the LSP: \( \Omega_{\text{LSP}}^{(\text{thermal})} \ll 0.1 \)
- In AMSB, gravitino mass is \( O(10 - 100 \text{ TeV}) \)
LHC phenomenology in the AMSB case (with $\tilde{W}^0$ LSP)

- Masses of $\tilde{W}^\pm$ and $\tilde{W}^0$ are very close: $m_{\tilde{W}^\pm} - m_{\tilde{W}^0} \lesssim 200$ MeV
  $\Rightarrow \tilde{W}^\pm \rightarrow \tilde{W}^0 \pi^\pm$
  $\Rightarrow c\tau_{\tilde{W}^\pm} \sim 5$ cm

- It is non-trivial to detect $\tilde{W}^\pm$
  $\Rightarrow \tilde{W}^\pm$ may be observed as a short charged track

- In some class of anomaly-mediated model, squark and slepton masses are $O(10$ TeV)
  $\Rightarrow$ Hard to see signals from squark productions

Dominant production process of SUSY particles: $pp \rightarrow \tilde{g}\tilde{g}$

$\Rightarrow$ Gluon decays as $\tilde{g} \rightarrow \tilde{W}qq/\tilde{B}qq$
For discovery of “SUSY” signal, missing $E_T$ is useful as usual

[Asai, Moroi, Nishihara & Yanagida]
$m\tilde{g} - m\tilde{W}$ can be measured from dijet invariant mass

[Asai, Moroi, Nishihara & Yanagida]

For $\tilde{g} \rightarrow \tilde{W} q\bar{q}$: $M_{q\bar{q}} \leq m\tilde{g} - m\tilde{W} \Leftarrow$ parton-level relation

Dijet invariant mass: $Br(\tilde{g} \rightarrow \tilde{W} q\bar{q}) = 0.75$

- $(M_{13}, M_{24})$ or $(M_{14}, M_{23})$, whichever $|M_{ij} - M_{kl}|$ is smaller

$\Rightarrow \delta (m\tilde{g} - m\tilde{W}) \simeq 5\%$
Can we find charged Wino even if $c_{\tilde{T}_{W^\pm}} \sim 5 \text{ cm}$?

[For Tevatron, see Feng, Moroi, Randall, Strasslar & Su]

⇒ ATLAS has Transition Radiation Tracker (TRT)

- **TRT**: 54 – 106 cm from the beam pipe
- **TRT** continuously follows charged tracks
Searches for short-charged tracks is strongly recommended

⇒ Sizable number of charged Wino tracks

TRT has timing information: $\delta \beta \sim 0.1$ for $\beta < 0.85$

⇒ Wino mass may be determined: $\delta m_{\tilde{W}} \sim 10\%$
Measurement of Wino lifetime

[Asai, Moroi & Yanagida]

We may be able to use the distribution of travel length

\[ t_D = \frac{m_{\tilde{W}^\pm}}{|p_T|} (L_T - L_T^{(\text{min})}) \]

\[ \Rightarrow P(t_D) \propto e^{-t_D/\tau_{\tilde{W}^\pm}} \]

\[ L_T^{(\text{min})} = 60 \text{ cm} \]

\[ L_T^{(\text{max})} = 100 \text{ cm} \]

\[ \Rightarrow \tau_{\tilde{W}^\pm} \text{ may be determined with the accuracy of } 10 - 20 \% \]
Study of the Bino mass: \( \tilde{g} \rightarrow \tilde{B} q \bar{q} / \tilde{B} \rightarrow \tilde{W}^\pm W^\mp / W^\mp \rightarrow l\nu \)

[Asai, Jinnouchi, Moroi, Shirai & Yanagida, preliminary]

\[ \Rightarrow M^{(\text{max})}_{l\tilde{W}^\pm} \simeq m_{\tilde{B}} + \cdots \]

- \( L_T > 45 \text{ cm} \) is used
- \( M_2 = 200 \text{ GeV} \)
- \( M_1 = 400 \text{ GeV} \)
- \( M_3 = 1000 \text{ GeV} \)
- \( M^{(\text{max})}_{l\tilde{W}^\pm} \simeq 390 \text{ GeV} \)
3. Case with Gravitino LSP
Gravitino mass depends on the mechanism of SUSY breaking

- Anomaly mediation: \( m_{3/2} \sim \mathcal{O}(10 - 100 \ \text{TeV}) \)
  
  [Randall & Sundrum; Giudice, Luty, Murayama & Rattazzi]

- Gravity mediation: \( m_{3/2} \sim \mathcal{O}(10 \ \text{GeV} - 1 \ \text{TeV}) \)

- Gauge mediation: \( m_{3/2} \lesssim \mathcal{O}(10 \ \text{GeV}) \)
  
  [Dine & Nelson; Dine, Nelson, Nir & Shirman]

Gravitino is a well-motivated candidate of the LSP

- Missing \( p_T \) signal may not exist
  
  \[ \Rightarrow \] Heavy charged (or colored) particle (?)

- It may be the dark matter, although its confirmation is non-trivial
Gravitino may be dark matter, if it is the LSP

\[ \Omega_{3/2} = \Omega_{\text{CDM}}? \]

**Origins of gravitino**

- Decay of the MSSM-LSP
- Production at the very early universe (like reheating era)

**Check point: effects of the MSSM-LSP decay on BBN**

- The MSSM-LSP decays only into gravitino (+⋯)
- Lifetime of the MSSM-LSP becomes very long

\[
\tau_{\text{MSSM-LSP}} \sim 10^8 \text{ sec} \left( \frac{m_{\text{MSSM-LSP}}}{100 \text{ GeV}} \right)^{-5} \left( \frac{m_{3/2}}{100 \text{ GeV}} \right)^2
\]
BBN constraints: Bino as the MSSM-LSP

[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]

\[ \Omega_{\tilde{B}}^{(\text{Thermal})} \simeq 0.2 \times \left( \frac{m_{\tilde{B}}}{200 \text{ GeV}} \right)^2 \]
BBN constraints: Stau as the MSSM-LSP

[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]

\[ \Omega_{\tilde{\tau}}^{\text{(Thermal)}} \simeq 0.4 \times \left( \frac{m_{\tilde{\tau}}}{1 \text{ TeV}} \right)^2 \]
BBN constraints: Sneutrino as the MSSM-LSP

[Kawasaki, Kohri, Moroi & Yotsuyanagi, preliminary]

\[ \Omega_{\tilde{\nu}}^{(\text{Thermal})} \simeq 0.1 \times \left( \frac{m_{\tilde{\nu}}}{1 \text{ TeV}} \right)^2 \]
In order to realize gravitino-CDM scenario:

- Serious BBN constraints on the decay of MSSM-LSP
- Relic gravitino should be mainly from scattering processes

If gravitino is the LSP, gravitino may be produced at the LHC

⇒ Study of gravitino at the LHC (Hamaguchi-san's talk)

BBN constraints may be relaxed if $R$-parity is broken

[Buchmuller, Covi, Hamaguchi, Ibarra & Yanagida]

⇒ MSSM-LSP decays via $R$-violating interaction

⇒ $\tau_{3/2} \gg 10^{10}$ yr is possible to realize gravitino dark matter

⇒ Interesting signals in colliders and in astrophysics
Possible signals from the gravitino dark matter with RPV

- Gamma ray from the decay of gravitino CDM
  [Buchmuller, Covi, Hamaguchi, Ibarra & Yanagida]

- Positron from the decay of gravitino CDM

\[ m_{3/2} = 150 \text{ GeV} \quad \text{Lifetime} = 2.1 \times 10^{26} \text{(sec)} \]

[Data: EGRET, Data: HEAT]

[Data: Ishiwata, Matsumoto & Moroi, preliminary]
4. (No) Conclusion
We are all waiting for results from the LHC