Extremely Long-Lived Charged Massive Particles
as A Probe for the Early Universe

Fumihiro Takayama (Cornell)

SUSY07 @Karlsruhe July 2007
WMAP DATA (First year)

$$\Omega_{DM} = 0.23 \pm 0.04$$
$$\Omega_{Total} = 1.02 \pm 0.02$$
$$\Omega_{baryon} = 0.044 \pm 0.004$$

More than 90% of total energy of the universe is unknown

- Dark matter $\sim$ 20%
- Dark energy $\sim$ 70%

What is the dark matter? Why is the relic $\Omega \sim O(0.1)$? How were they generated? When?…..
Extremely Long-Lived Charged Massive Particle

TeV scale new physics (SUSY, Extra Dimensions)
→ Copies of SM particles → Lightest one ~ stable
  Parity SM(even) Copies(odd)
Lightest one in SM sector: charged slepton, charged KK leptons etc

SuperWIMP dark matter scenario motivates Extremely Long-Lived CHAMPs.

e.g. Lightest one: Gravitino LSP,
Lightest one in SM: Stau NLSP (Selectron)
(Spanos talk)

Decay after BBN
NR decay: $m_{NLP} \sim m_{\text{superWIMP}}$

$\Omega_{\text{superWIMP}} \sim (m_{\text{superWIMP}}/m_{\text{CHAMP}})\Omega_{\text{CHAMP}}$

SuperWIMP dark matter → mass degeneracy
○ ○ ○ Late decay may not always provide the leading effects in the early Universe
Other phenomenon in early universe might happen without significant change from SBBN due to late decays.
Prospects of collider experiments for extremely long lived CHAMP search

Discovery (Heavily Ionizing Track, TOF etc) : **Stable inside detector**


Tevatron $m_C \sim 180\text{GeV}$ ($L=10\text{fb}^{-1}$, stable stau inside collider detector)
$LHC \quad m_C \sim 700\text{GeV}$

Mass, Couplings with SM particles, **Lifetime, Decay properties**

Trapping CHAMPs

Determination of lifetime, decay properties

Assuming model : SUGRA
non-trivial check of gravitino nature
→ mass, spin/coupling (measurement)


Other discovery possibility
.... Test standard Radiation Dominated cosmology scenario
and thermal freeze out of CHAMPs
The fate of the extremely long-lived CHAMPs

CHAMPs chemical decoupling

SBBN

CBBN

PDG2006

\[ T \sim 8\text{keV} \]

\[ \Omega_{\text{DM}} \sim \frac{m_{\text{DM}}}{m_{\text{CHAMP}}} \Omega_{\text{CHAMP}} \]

Low reheating temperature??
(Entropy production??)

hidden parameter for collider measurements

\[ T_r \sim m/25 \]

1MeV-50keV

T\sim\text{keV}
(Gravitino LSP)

0.1\text{eV}
Probe for the Early Universe

Find physical observable which does not significantly change from the primordial values set in the early stage of the history of the Universe.
Or Specify key initial conditions to describe the present universe which can be confirmed by astrophysical observations.

→ Light element abundances (He, D, Li…) $^6$Li as a function of CHAMP relic

Start from simple cosmological models
and get some inputs from collider experiments.

→ Low reheating temperature model

Compare the theoretical prediction with observed values
… Extract hidden parameters in collider experiment alone

→ Reheating temperature (Decay rate of key particle for reheating)
Bound state of a light element and a CHAMP during/after BBN

Kohri, F.T(2006)

Heavier elements may be captured in earlier time.

$T_c(^{7}{\text{Be}}) \sim 37\text{keV}, T_c(^7\text{Li}) \sim 25\text{keV}$

SBBN process completely decouple at $T \sim 50-20\text{keV}$

The abundance of heavier than Li may be changed from SBBN value.

$\tau_n = 885.7 \pm 0.8 \text{ s}$
The bound state can change nuclear reaction rates in BBN

\[ \sigma_{\text{fusion}}(v) = (\sigma_S + \sigma_P v^2 + \ldots) F_{ab}(v) - \sigma_0(v) \frac{2\pi Z_a Z_b \alpha}{v} e^{-\frac{2\pi Z_a Z_b \alpha}{v}} \]

Coulomb suppression weaken

Thermal average for momentum distribution of light elements
\[ \rightarrow \text{competition between Coulomb suppression and Boltzmann suppression} \]

Kinematics is also changed due to bound state
\[ \rightarrow \text{change of short distance reaction rate} \]

Virtual photon process (M.Pospelov(2006))
- SBBN: \( a+b \rightarrow c+\gamma \) (highly suppressed)
- CBBN: \( (a,\text{CHAMP})+b \rightarrow c+\text{CHAMP} \)
\[ \rightarrow \text{New } ^6\text{Li production process} \]

\[ \ldots \text{stable neutron like or more(?)} \]
\[ = \text{no coulomb suppression or enhancement/} \]
\[ (t > 10^6 \text{ sec}) \]
Virtual Photon processes (M.Pospelov(2006))

\[
\text{SBBN : } ^{4}\text{He} + D \rightarrow ^{6}\text{Li} + \gamma; \quad Q = 1.47\text{MeV} \\
\text{CBBN : } (^{4}\text{He}X^{-}) + D \rightarrow ^{6}\text{Li} + X^{-}; \quad Q \simeq 1.13\text{MeV}
\]

→ Significant \(^{6}\text{Li}\) production relative to the SBBN case \\
(Lifetime >> 10^4 sec) \\
: cross section ∼ O(10^6) enhancement

<table>
<thead>
<tr>
<th>(E [\text{keV}])</th>
<th>(\sigma_{1\rightarrow2} [\text{barn}])</th>
<th>(S [\text{MeV barn}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>(3.85 \times 10^{-6})</td>
<td>0.0426</td>
</tr>
<tr>
<td>20</td>
<td>(1.09 \times 10^{-4})</td>
<td>0.0410</td>
</tr>
<tr>
<td>36.4</td>
<td>(6.88 \times 10^{-4})</td>
<td>0.0380</td>
</tr>
<tr>
<td>50</td>
<td>(1.41 \times 10^{-3})</td>
<td>0.0357</td>
</tr>
<tr>
<td>100</td>
<td>(3.50 \times 10^{-3})</td>
<td>0.0286</td>
</tr>
</tbody>
</table>

CBBN and primordial $^6$Li abundance

$$\frac{dn_{^{4}\text{He}}}{dt} + 3Hn_{^{4}\text{He}} =$$
$$- \langle \sigma v \rangle_{\text{rec}} (n_{^{4}\text{He}} - n_{(C, ^{4}\text{He})} \bar{n}) + \frac{1}{\tau_C} n_{(C, ^{4}\text{He})}$$

$$\frac{dn_C}{dt} + 3Hn_C =$$
$$- \langle \sigma v \rangle_{\text{rec}} (n_{^{4}\text{He}} - n_{(C, ^{4}\text{He})} \bar{n}) + \langle \sigma_{\text{CBBN}}^{^6\text{Li}} v > n_{(C, ^{4}\text{He})}^{n_D} - \frac{1}{\tau_C} n_C$$

$$\frac{dn_{(C, ^{4}\text{He})}}{dt} + 3Hn_{(C, ^{4}\text{He})} =$$
$$- \langle \sigma v \rangle_{\text{rec}} (n_{^{4}\text{He}} - n_{(C, ^{4}\text{He})} \bar{n})$$
$$- \langle \sigma_{\text{CBBN}}^{^6\text{Li}} v > n_{(C, ^{4}\text{He})}^{n_D} - \frac{1}{\tau_C} n_{(C, ^{4}\text{He})}$$

Standard $m_C = 100\text{GeV}$

Proton bound state effect?

Li destruction

F.T(2007)
Connecting $^6$Li with the reheating temperature

Low reheating temperature models ($T_{RH} / m_{CHAMP} << O(10)$)

$$\frac{d\rho_{\phi}}{dt} + 3H\rho_{\phi} - \Gamma_{\phi}\rho_{\phi}$$

$$\frac{d\rho_{R}}{dt} + 4H\rho_{R} = \Gamma_{\phi}\rho_{\phi} + <\sigma v> [n_{C}^2 - n_{EQ}^2]$$

$$\frac{dn_{C}}{dt} + 3Hn_{C} = - <\sigma v> [n_{C}^2 - n_{EQ}^2] \quad (2)$$

Guidice, Kolb, Riotto(2000)

$$\Gamma_{\phi} = \sqrt{\frac{4\pi^3 g_*(T_{RH}) T_{RH}^2}{45 M_{pl}}},$$

$$\Omega_{C}^{TH(Low)} h^2 = 3.3 \times 10^{-8} \left[\frac{g_*(T_{RH})^{1/2}}{g_*(T_F)}\right] T_{RH}^3 GeV^{-2} \frac{T_{RH}^3 GeV^{-2}}{\gamma m_{C} x_F^{-4}}$$

$$\rho_R \sim 0, \rho_C \sim 0 \text{ at } t=t_I$$

(Other initial condition: Late time Entropy production
J.Pradler, F.Steffen(2006))

No direct decay to CHAMPs is assumed. (Inclusion of the decay $\rightarrow$ Kohri, Yamaguchi, Yokoyama(2005))
Implications of low reheating temperature of the Universe

Difficulties ??
Split hidden sector (Inflaton?) and visible sector (SM sector)
e.g SUGRA (assuming direct reheating from Inflaton)
Gravitino overproduction vs low reheating temperature

Interesting ??

Multi-step energy transfers
Inflaton $\rightarrow$ Gravitational particles $\rightarrow$ SM particles
$\rightarrow$ Stringly reheating ?? (in progress, H.Tye, X.Chen)

Multi-step reheating
Inflaton $\rightarrow$ Radiation Dominated $\rightarrow$ Matter Dominated $\rightarrow$ Radiation Dominated
(Late time Entropy production J.Pradler, F.Steffen(2006))
Summary

We discussed extremely long lived charged massive particles as a probe of the early Universe.

Primordial $^6$Li abundance may be sensitive to the number density of CHAMPs if the lifetime is longer than $10^4$ sec.

Discovery of CHAMPs and the measurement of lifetime may provide us some information about the reheating of the Universe for simple cosmological models.

To make my statement robust, we need further efforts to understand the relation between primordial and observed $^6$Li abundances and to fix uncertainties of CBBN prediction.