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

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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 ～ 20 %

Dark energy ～ 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

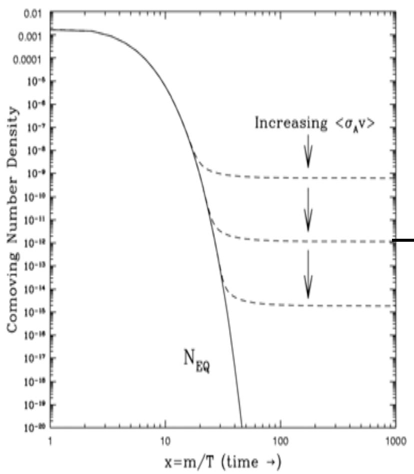
TeV scale new physics (SUSY, Extra Dimensions)

→ 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.



J.Feng, A.Rajaraman, F.T(2003), J.Feng,S.Su,F.T(2004)

e.g Lightest one : Gravitino LSP,

Lightest one in SM : Stau NLSP(Selectron)

(Spanos talk)

Decay after BBN

NR decay: $m_{NLP} \sim m_{superWIMP}$

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

SuperWIMP dark matter → mass degeneracy

。。。 Late decay may not always provide the leading effects in the early Univer

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

M.Drees, X.Tata(1990),J.Goity,W.Kossler,M.Sher(1993)J.Feng,T.Moroi(1998)

Tevatron m_C~ 180GeV (L=10fb^{-1}, stable stau inside collider detector)
→LHC m_C ~ 700GeV

Mass, Couplings with SM particles, Lifetime, Decay properties

Trapping CHAMPs

B.T.Smith, J.Feng(2004) K.Hamaguchi,Y.Kuno,T.Nakaya,M.Nojiri(2004)

Determination of lifetime, decay properties

Assuming model : SUGRA

non-trivial check of gravitino nature

→ mass, spin/coupling (measurment)

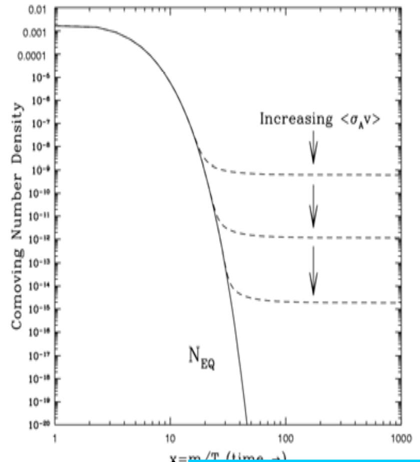
W.Buchmuller,K.Hamaguchi,M.Ratz,T.Yanagida(2004),J.Feng,A.Rajaraman,F.T(2004)

Other discovery possibility

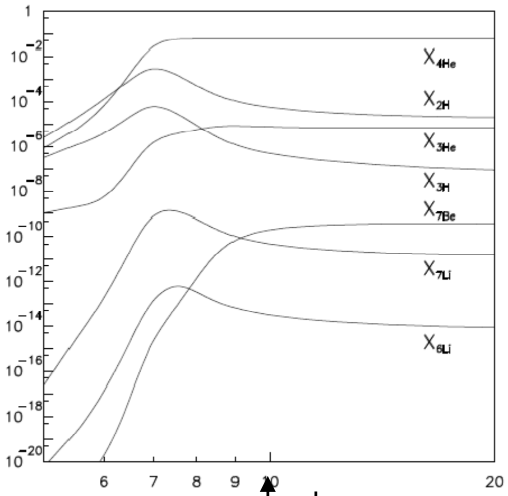
….Test standard Radiation Dominated cosmology scenario and thermal freeze out of CHAMPs

The fate of the extremely long-lived CHAMPs

CHAMPs chemical decoupling

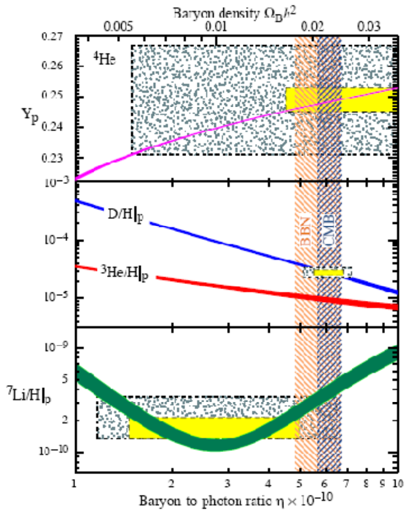


SBBN



50keV

CBBN



PDG2006

T ~ 8keV

CHAMPlate deacy : DM production?

$\Omega_{DM} \sim (m_{DM}/m_{CHAMP})\Omega_{CHAMP}$??

Low reheating temperature??
(Entropy production??)
→hidden parameter
for collider measurements

Matter-Radiation equality

T

$T_f \sim m/25$

1MeV-50keV

T~keV
(Gravitino LSP)

0.1eV

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)

CBBN

K.Kohri, F.T (2006), M.Pospelov (2006), M.Kaplinghat, A.Rajaraman(2006), R.Cyburt,J.Ellis,B.Field,K.Olive,V.Spanos(2006)

Bound state of a light element and a CHAMP during/after BBN

Kohri, F.T(2006)

Bound state formation → Photo destruction ←

$$[\frac{\partial}{\partial t}n_X]_{\rm capture} \simeq - <\sigma_r v> (n_C n_X - n_{(C,X)} n_\gamma(E > E_{\rm bin}))$$

$$n_\gamma(E > E_{\rm bin}) \equiv n_\gamma \frac{\pi^2}{2\zeta(3)} (\frac{m_X}{2\pi T})^{3/2} e^{-\frac{E_{\rm bin}}{T}}$$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3$$

→ $$T_c \simeq \frac{E_{\rm bin}}{40}$$

Nucleus(X)	binding energy (MeV)	atomic number
H	0.025	Z=1
D	0.050	Z=1
T	0.075	Z=1
^{3}He	0.270	Z=2
^{4}He	0.311	Z=2
^{5}He	0.431	Z=2
^{5}Li	0.842	Z=3
^{6}Li	0.914	Z=3
^{7}Li	0.952	Z=3
^{7}Be	1.490	Z=4
^{8}Be	1.550	Z=4
^{10}B	2.210	Z=5

R.N.Cahn,S.L.Glashow(1981)

Heavier elements may be captured in earlier time.

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

SBBN process completely decouple at T ~ 50-20keV

All exponential suppression is significant at below this T

Coulomb suppression (Low E)
Boltzmann suppression (low T)
β decay of neutron etc (small Hubble rate)

$\tau_n = 885.7 \pm 0.8$ s

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

CHAMP BBN (CBBN)

K.Kohri, F.T (2006), M.Pospelov (2006), M.Kaplinghat, A.Rajaraman(2006),
R.Cyburt,J.Ellis,B.Field,K.Olive,V.Spanos(2006)

The bound state can change nuclear reaction rates in BBN

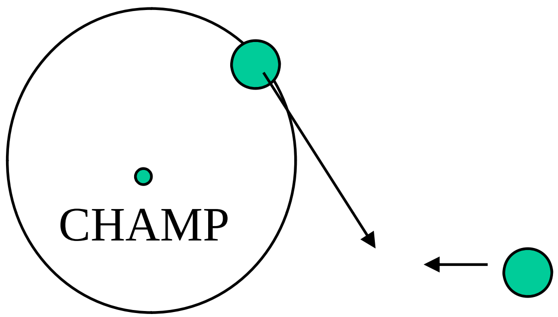
$$\sigma_{\rm fusion} v = (\sigma_S + \sigma_P v^2 + ...) F_{ab}(v)$$
$$= \sigma_0 v(v) \frac{2\pi Z_a Z_b \alpha}{v} e^{-\frac{2\pi Z_a Z_b \alpha}{v}}$$

→ Coulomb suppression weaken

Thermal average for momentum distribution of light elements
→ competition between Coulomb suppression and Boltzmann suppression

Kinematics is also changed due to bound state
→ change of short distance reaction rate

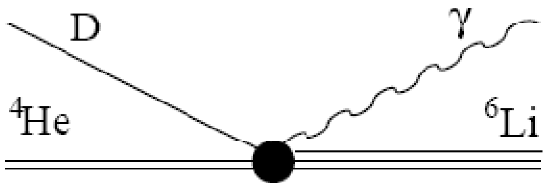
Virtual photon process (M.Pospelov(2006))
SBBN: a+b → c+γ (highly suppressed)
CBBN: (a,CHAMP)+b → c+CHAMP
→ New ^{6}Li production process

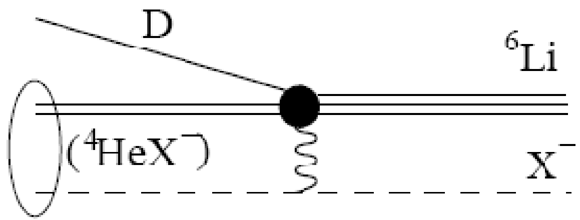


Proton capture(K.Kohri,F.T(2006), K.Jedamzik(2007))
… stable neturon like or more(?)
= no coulomb suppression or enhancement/
(t > 10^6 sec)

Virtual Photon processes (M.Pospelov(2006))

$$\mathrm{SBBN}: \ {}^4\mathrm{He} + \mathrm{D} \to {}^6\mathrm{Li} + \gamma; \quad Q = 1.47\mathrm{MeV}$$
$$\mathrm{CBBN}: \ ({}^4\mathrm{He}X^-) + \mathrm{D} \to {}^6\mathrm{Li} + X^-; \ Q \simeq 1.13\mathrm{MeV}.$$





→Significant ^{6}Li production relative to the SBBN case

(Lifetime >> 10^4 sec)

: cross section ~ O(10^6) enhancement

E [keV]	$\sigma_{1\to 2}$ [barn]	S [MeV barn]
10	3.85×10^{-6}	0.0426
20	1.09×10^{-4}	0.0410
36.4	6.88×10^{-4}	0.0380
50	1.41×10^{-3}	0.0357
100	3.50×10^{-3}	0.0286

K.Hamaguchi,T. Hatsuda, M.Kamimura, Y.Kino,T.Yanagida(2007)

CBBN and primordial ^{6}Li abundance

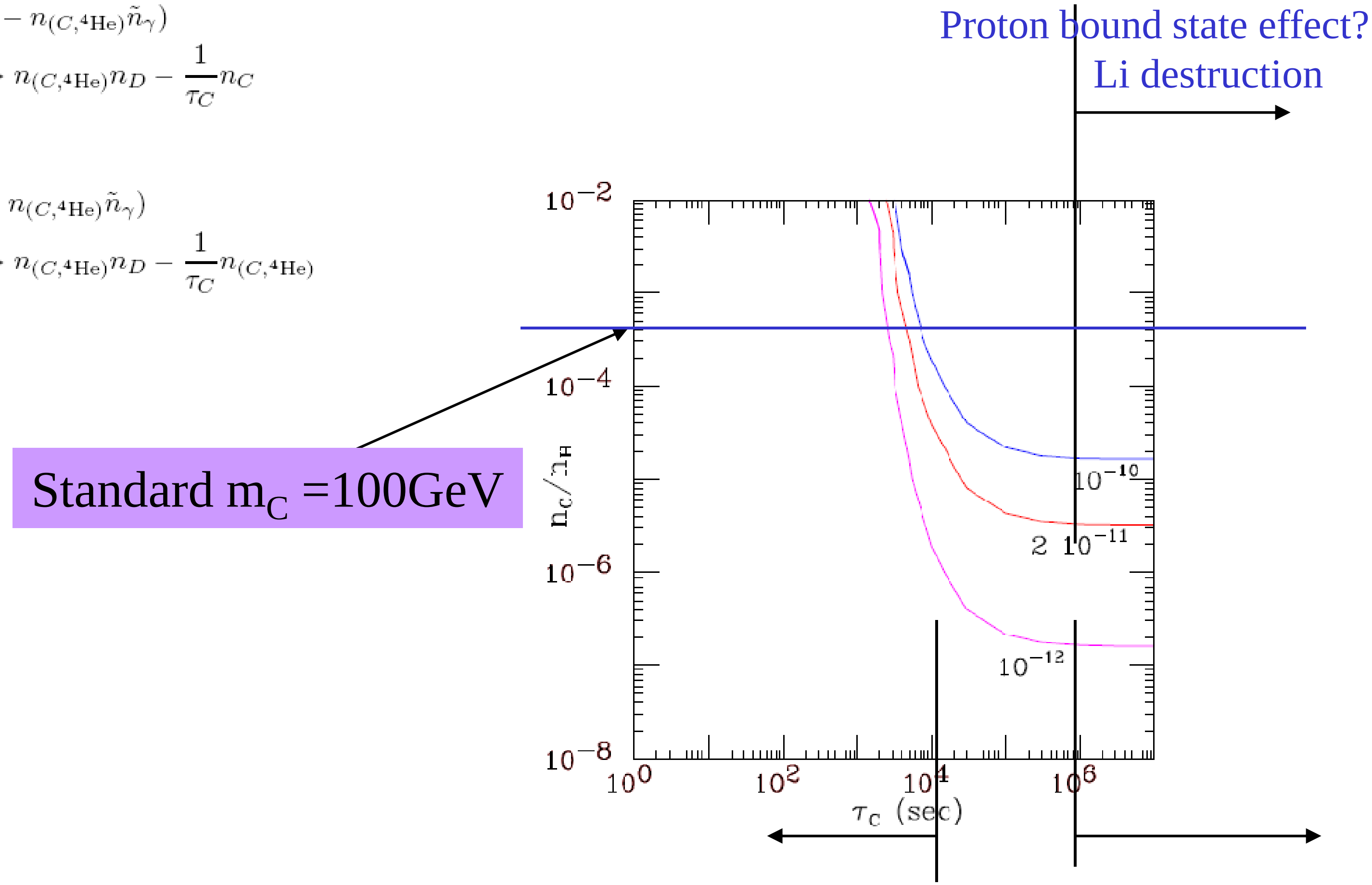
$$\frac{dn_{^4\mathrm{He}}}{dt} + 3Hn_{^4\mathrm{He}} = - < \sigma_{\mathrm{rec}} v > (n_C n_{^4\mathrm{He}} - n_{(C,^4\mathrm{He})} \tilde{n}_\gamma) + \frac{1}{\tau_C} n_{(C,^4\mathrm{He})}$$

$$\frac{dn_C}{dt} + 3Hn_C = - < \sigma_{\mathrm{rec}} v > (n_C n_{^4\mathrm{He}} - n_{(C,^4\mathrm{He})} \tilde{n}_\gamma) + < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_D - \frac{1}{\tau_C} n_C$$

$$\frac{dn_{(C,^4\mathrm{He})}}{dt} + 3Hn_{(C,^4\mathrm{He})} = < \sigma_{\mathrm{rec}} v > (n_C n_{^4\mathrm{He}} - n_{(C,^4\mathrm{He})} \tilde{n}_\gamma) - < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_D - \frac{1}{\tau_C} n_{(C,^4\mathrm{He})}$$

$$\frac{dn_{^6\mathrm{Li}}}{dt} + 3Hn_{^6\mathrm{Li}} = < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_{\mathrm{D}}$$

$$\frac{dn_{\mathrm{D}}}{dt} + 3Hn_{\mathrm{D}} = - < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_{\mathrm{D}}$$



F.T(2007)

Connecting ^{6}Li with the reheating temperature

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

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$
$$\frac{d\rho_R}{dt} + 4H\rho_R = \Gamma_\phi \rho_\phi + <\sigma v> 2 <E_C> [n_C^2 - n_{\rm EQ}^2]$$
$$\frac{dn_C}{dt} + 3Hn_C = - <\sigma v> [n_C^2 - n_{\rm EQ}^2] \qquad (2)$$

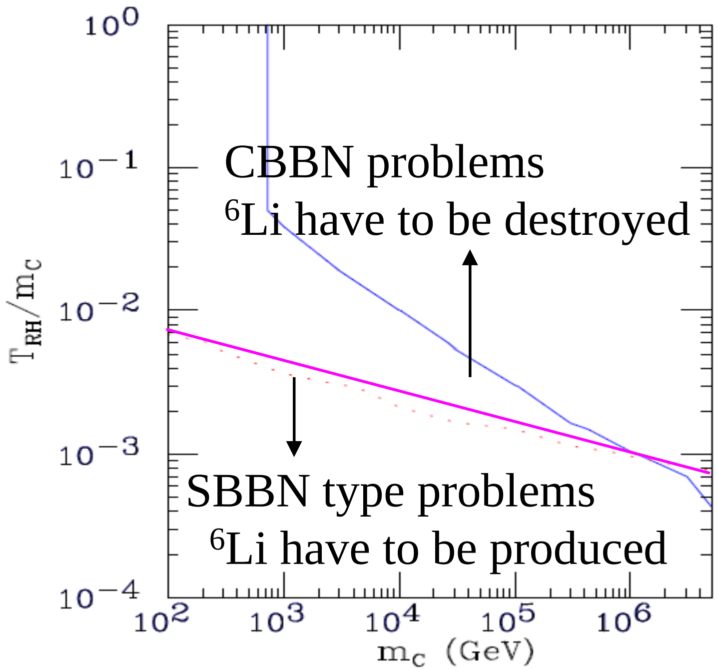
Guidice, Kolb, Riotto(2000)

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

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

$\rho_R \sim 0$, $\rho_C \sim 0$ at $t=t_I$

$\tau_c > 10^4$ sec



F.T(2007)

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

No direct decay to CHAMPs is assumed. (Inclusion of the decay → 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 → Gravitational particles → SM particles

→ Stringly reheating ?? (in progress, H.Tye, X.Chen)

Multi-step reheating

Inflaton→ Radiation Dominated→Matter Dominated→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.