Stable SuperWeakly Interacting Massive Particles (SuperWIMPs)

~ Late decaying particles and the implications for
astrophysical observations and collider experiments ~

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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 %

Currently the gravitational property has been well-established.
The identification of microscopic properties of dark matter is on going projects.

What is the dark matter ? Why is the relic $\Omega \sim O(0.1)$?
How dark and How cold? ...no coupling with photons?
and when should it be dark?
Has the dominant matter of the universe been "dark" since big bang?

New Physics:

Dark Matter

Relic density → WIMP with O(1)TeV scale mass

Stability → Parity

Since the freeze out before BBN, the universe would be dominated by “dark” matter.

TeV scale New Physics

(Stabilization of EW scale,

hierarchy problems EW scale vs Planck or GUT scale)

Parity→ Suppress undesired tree level processes

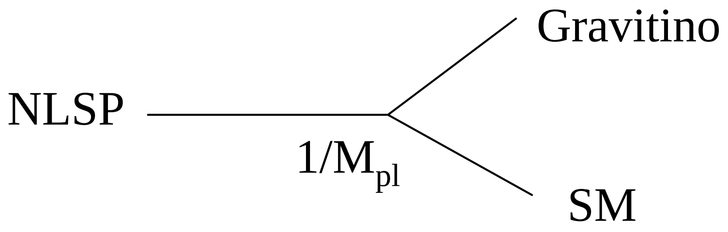
However, the other type of dark matter candidates may also be well-motivated.

Gravitino : a partner of graviton in supersymmetric theory

Gravitational coupling with Standard Model Particles

H.Pagel, J.Primack(1982),S.Weinberg(1982),L.Krauss(1983),
D.Nanopoulos,K.Olive,M.Sredincki(1983),M.Khlopov,A.Linde(1984),
J.Ellis,J.Kim,D.Nanopoulos(1984),R.Juszkiewicz,J.Silk,A.Stebbins(1985),
T.Moroi,H.Murayama,M.Yamaguchi(1992)

Not thermalized…..No hope for the direct detection



No phenomenological probe for these gravitational relics as dark matter candidates ??
What does the $\Omega \sim 0.1$ mean ?
…. NLSP is long-lived …

$\tau \sim 10^3 - 10^7$ sec for $m_G \sim (1\text{-}100)$GeV

Other superWIMP candidates

Strong CP problem in SUSY → PQ symmetry:
Axino LSP: L.Covi et al (1999)

Tiny neutrino mass from small yukawa in SUSY:
Right handed sneutrino: T.Moroi et al(2006)

Relation to dark energy in SUSY:
Quintesino :X.Bi, M.Li, X.Zhang(2003)

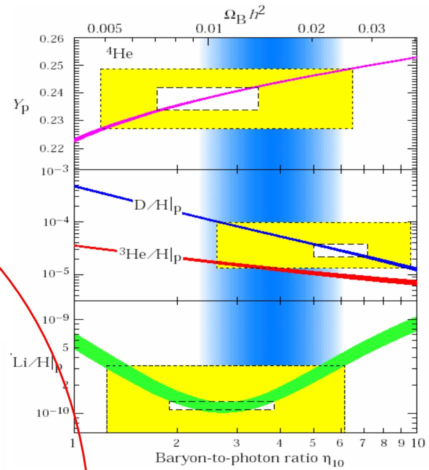
Extra dimensional model with low fundamental scale:
KK Graviton in UED: J.Feng et al (2003)

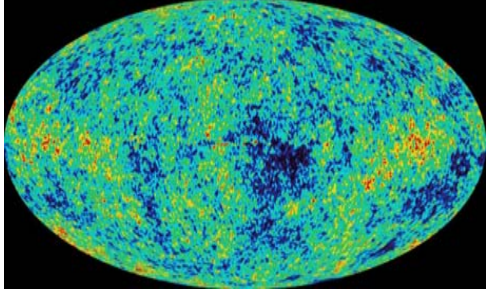
History of the Universe in superWIMP scenario

$\Gamma \sim \sigma v n_{SM} \ll H \sim T^2 / M_{pl}$

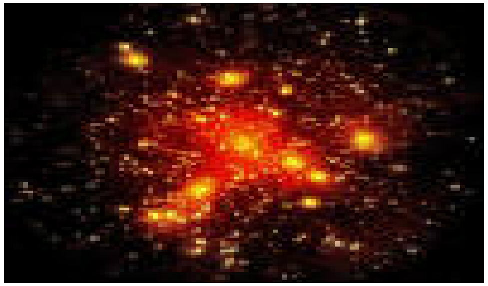
BBN

PDG2002



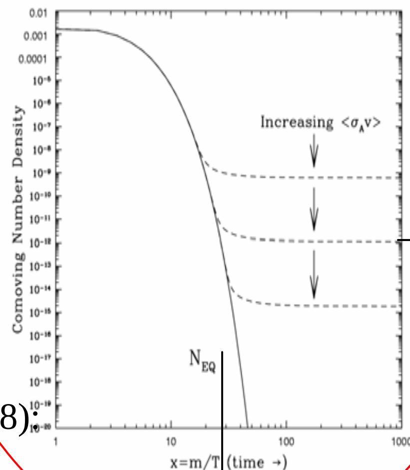


CMB



Large scale strucure

LLMP chemical decoupling



Ω_{Reheat}

Reheating

Buchmuller et al(1998):
gravitno/axino

J.Feng et al(2003)
(L.Covi et al(1999) axino)

LLMP late deacy : superWIMP production

LLMP decay: $m_{NLSP} \sim m_G$?

$\Omega_{DDM} \sim (m_G / m_{NLSP}) \Omega_{NLSP}$

Matter-Radiation equality

T

$T_f \sim m/25$

1MeV-50keV

T~keV
(Gravitino LSP)

0.1eV

Two important probes for the early Universe before SBBN era(1sec)
(in gravitino LSP scenario)

NLSP !! (not portion but a key probe for the early universe!!)

The dominant production of Gravitino LSP is :

Preheating production, Moduli decays ??
← highly depend on underling theory and hard to confirm the mechanism

Inevitable: Reheating production(hidden part)
→ probe the highest temperature of the universe
(GUT/Planck scale physics ?)

$\Omega_{reheat} \sim T_{RH} < \Omega_{DM} - \Omega_{DDM}$
connection to leptogenesis

Production from NLSP decays(visible part)
→probe the nature of the Universe
at the freeze out of NLSP

$\Omega_{DDM} = (m_{DDM} / m_{NLSP})\Omega_{DDM}$

Astrophysical observables may constrain
the number density of NLSPs

The kinds of NLSP

Neutral NLSPs (neutralino, sneutrino)

→Same collider signatures as the case of neutral NLSPs (Missing E_T)

The lifetime measurement will be hard…

WIMP DM direct/indirect detection will provide the key info.

Charged/colored NLSPs(charged sleptons, gluino, squarks)

Totally different collider signature from the case of WIMP DM scenario

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

Mass, Couplings with SM particles, Lifetime, Decay properties

Trapping CHAMPs = possibility to measure the lifetime of CHAMP

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

How do we lean the key quantities of superWIMP scenario ?

Relic density of NLSP,
Amount of the energy injection due to NLSP decay (hadronic or EM)
Lifetime of NLSP,
Mass of NLSP, Mass of superWIMP

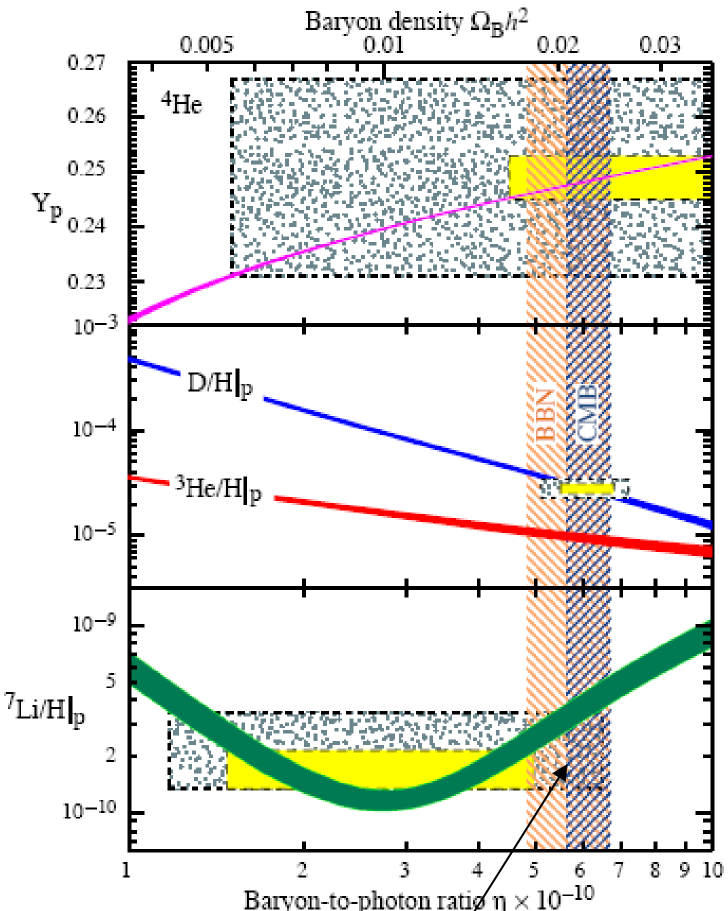
Astrophysical constraints(not measurments) on late decaying particles
Light element abundances(D,He,Li), Structure formation,
CMB black body spectrum….

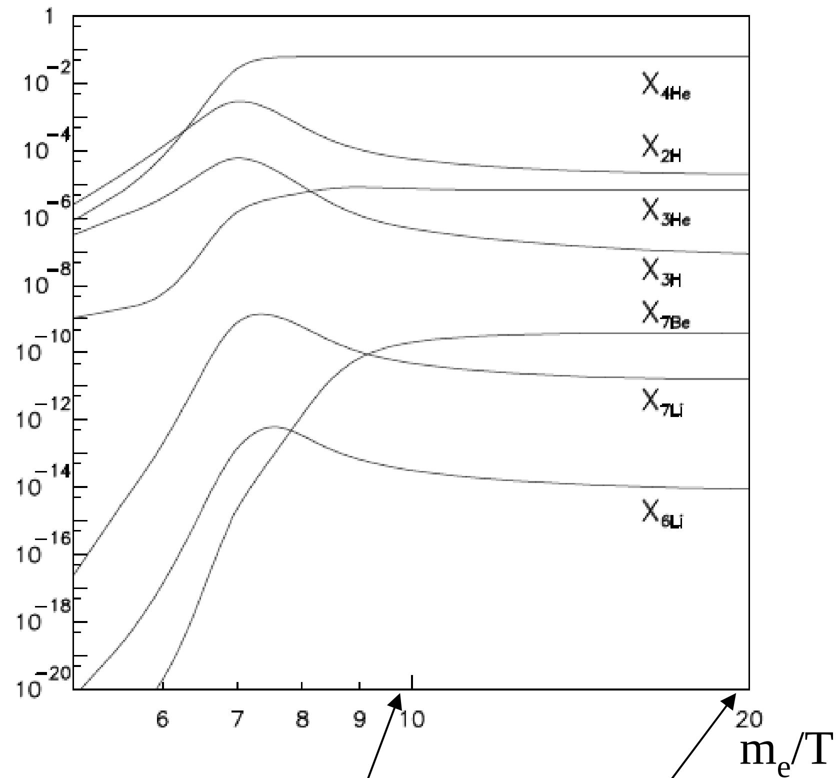
These carry several primordial information.

(As a reference for recent status of constraint on theoretical parameter space see M.Pospelov et al, arXiv:0807.4287 and the refs therein)

After WMAP, ……….

SBBN with CMB baryon-to-photon ratio and observed abundance of light elements





50keV

25keV

PDG(2006)

SBBN processes decouple until T=20keV

Low ^{7}Li
R.Cyburt,B.Field,K.Olive(2004)

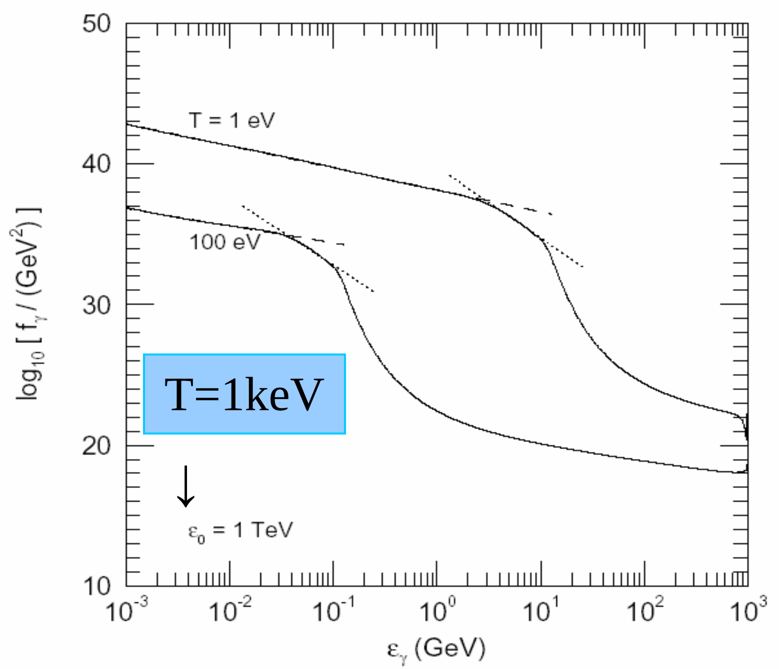
←Nuclear fix is unlikely !!
(100, 1000times larger cross section)

LLMP → superWIMP+SM….the SM particles contain/produce hard photons.

Thermalization

Soft photons from EM energy injection

- Photon-photon scattering $(\gamma + \gamma_{BG} \to \gamma + \gamma)$
- Pair creation in nuclei $(\gamma + N_{BG} \to e^+ + e^- + N)$
- Compton scattering $(\gamma + e^-_{BG} \to \gamma + e^-)$
- Inverse Compton scattering $(e^\pm + \gamma_{BG} \to e^\pm + \gamma)$



↑ ↑

D He

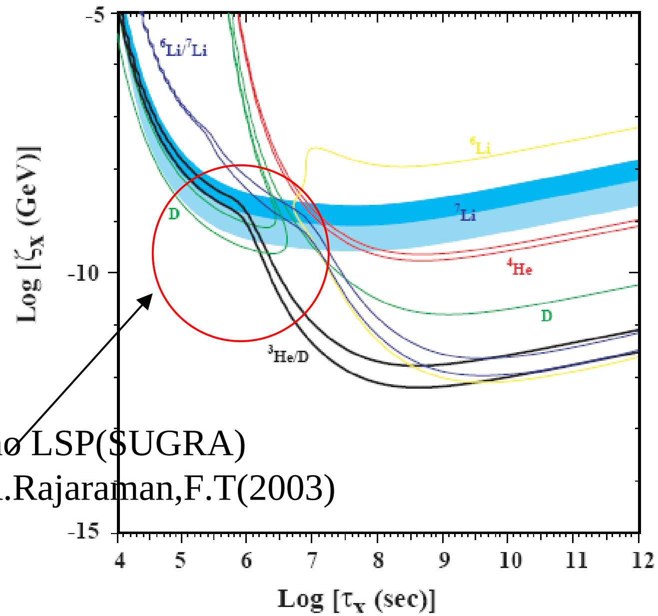
M.Kawasaki, T.Moroi (1995)

$\gamma + \gamma BG \to e^+ + e^-$

$:E > E_{th} = m_e^2/22T$

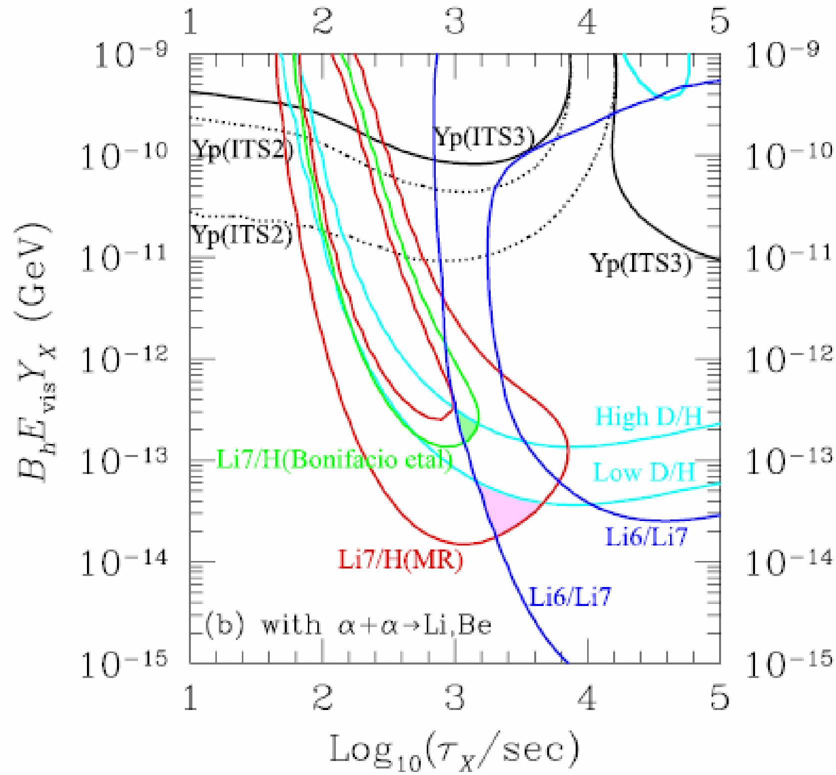
Late decay of NLPs and the change of light element abundances
(assuming freely propagating LLMPs)

EM solution for low ^{7}Li



Graivitino LSP(SUGRA)
J.Feng,A.Rajaraman,F.T(2003)

J.Ellis, K.Olive, E.Vangioni(2005)



Daniel Cumberbatch[1], Kazuhide Ichikawa[2], Masahiro Kawasaki[2], Kazunori Kohri[3,4], Joseph Silk[1] and Glenn D. Starkman[1,5] (2007)

Hadronic solution for low ^{7}Li

Neutron injection due to late decays

^{7}Be + n → p + ^{7}Li
^{7}Li + p → 2 ^{4}He

K.Jedamzik(2005)

Long-Lived Charged Massive Particles

→The lifetime and the other properties may be able to be examined at collider experiments.

Look at the role of the early universe in more detail

Several discussions on the astrophysical role of CHAMPS by focusing on the fate of CHAMP (considering where the CHAMP is inside the Earth).
Glashow et al(1990), S.Dimopoulos et al(1990)

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

Kohri, F.T(2006)

Bound state production — Photo destruction

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

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

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

$$\longrightarrow \quad T_c \simeq \frac{E_{\rm bin}}{40}$$

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

Heavier elements may be captured in earlier time.

$T_c(^7\mathrm{Be})$ ~ 37keV, $T_c(^7\mathrm{Li})$ ~ 25 keV

SBBN process completely decouple at T ~ 50-20keV

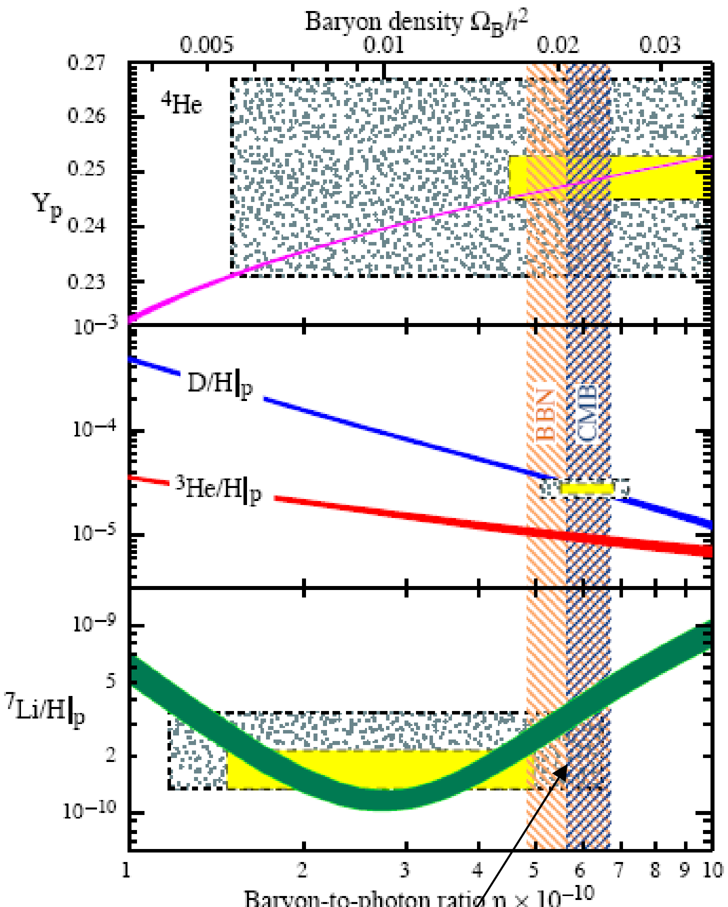
All exponential suppression is significant at below this T

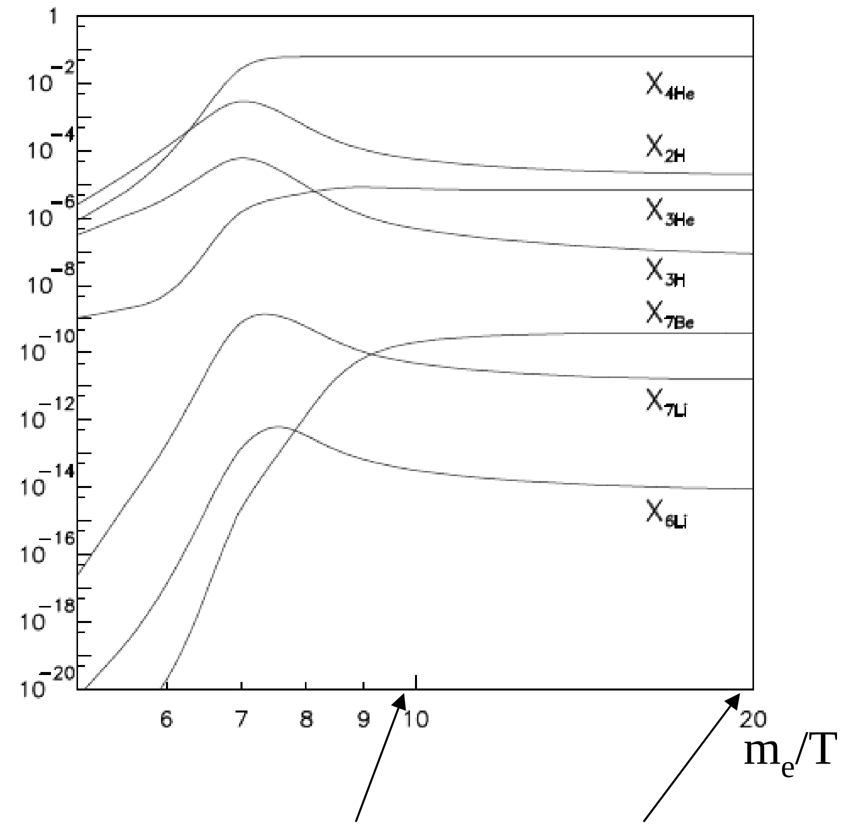
Coulomb suppression (Low T)
Boltzmann suppression (low T)
β decay of neutron etc (small Hubble rate)

$\tau_n = 885.7 \pm 0.8$ s

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

SBBN with CMB baryon-to-photon ratio
and observed abundance of light elements





50keV 25keV

PDG(2006)

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R.Cyburt,B.Field,K.Olive(2004)

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←Nuclear fix is unlikely !!

(100, 1000times larger cross section)

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

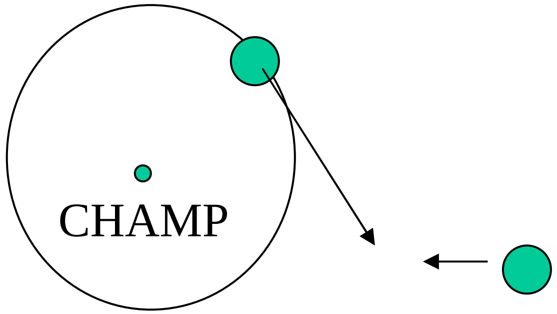
$$\sigma_{\text{fusion}} v = (\sigma_S + \sigma_P v^2 + ...) F_{ab}(v)$$
$$= \sigma_0 v(v) \frac{2\pi Z_a Z_b \alpha}{v} e^{-\frac{2\pi Z_a Z_b \alpha}{v}}$$

→ Coulomb suppression weaken

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

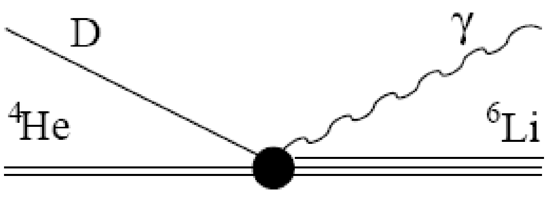
Kinematics is also changed due to bound state
→ change of short distance reaction rate

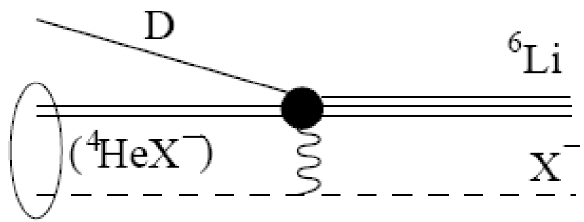
Virtual photon process (M.Pospelov(2006))
SBBN: a+b → c+γ (highly suppressed)
CBBN: (a,CHAMP)+b → c+CHAMP
→ New ^{6}Li production process



Virtual Photon processes (M.Pospelov(2006))

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





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

(Lifetime >> 10^3 sec)

: cross section ~ O(10^6) enhancement

Reaction	EM Transition	$A(B,\gamma)$ Q_{SBBN} (MeV)	$[X^-A](B,C)X^-$ Q_{CBBN} (MeV)	Enhancement $\sigma_{\mathrm{CBBN}}/\sigma_{\mathrm{SBBN}}$
$d(\alpha,\gamma)^6\mathrm{Li}$	E2	1.474	1.124	7.0×10^7
$^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$	E1	2.467	2.117	1.0×10^5
$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	E1	1.587	1.237	2.9×10^5
$^6\mathrm{Li}(p,\gamma)^7\mathrm{Be}$	E1	5.606	4.716	2.9×10^4
$^7\mathrm{Li}(p,\gamma)^8\mathrm{Be}$	E1	17.255	16.325	2.6×10^3
$^7\mathrm{Be}(p,\gamma)^8\mathrm{B}$	E1	0.137	-1.323	N/A

R.Cyburt, J.Ellis, B.Field, K.Olive,V.Spanos(2006)

Estimations beyond SBBN nuclear matrix elements

Born approximation focusing on EM coulomb interaction
K.Jedamzik(2007)

3-body quantum mechanical calculation with nuclear potentials

E [keV]	$\sigma_{1\to2}$ [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

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

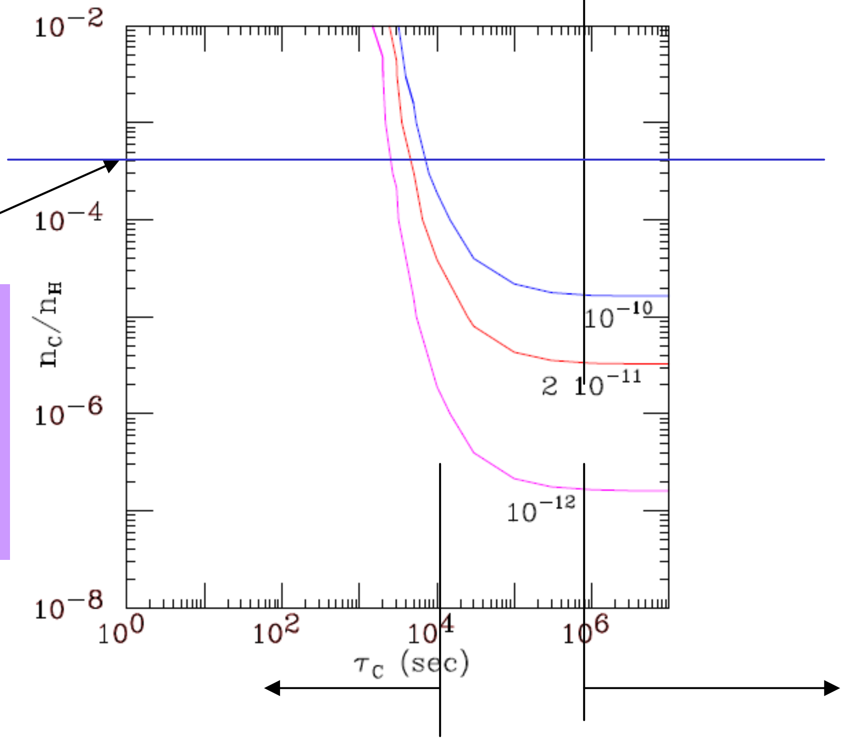
$$\frac{dn_C}{dt} + 3Hn_C = - < \sigma_{\mathrm{rec}} v > (n_C n_{^4\mathrm{He}} - n_{(C,^4\mathrm{He})}\tilde{n}_\gamma) + < \sigma^{CBBN}_{^6\mathrm{Li}} v > n_{(C,^4\mathrm{He})} n_D - \frac{1}{\tau_C} n_C$$

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

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

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

Proton bound state effect?
Li destruction



Standard m_C =100GeV
(only consider
2CHAMP→2photons
No charge asymmetry)

F.T(2007)

Beyond standard radiation dominated universe or not

$$\dot{n}_\chi = -3H n_\chi - \langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right) + \frac{b}{m_\phi}\Gamma_\phi \rho_\phi$$

$H \sim \rho$ or ρ^2

Addition of new particles
Stau NLSP: large tanβ, higgs final state
M.Ratz(2008),J.Pradler et al(2008)
Correction from slowly moving CHAMP
C.Berger et al(2008)

Non-thermal production

Phenomenological studies (assuming small non-thermal production):
Or Entropy production → dilute NLSP relics
J.Pradler, F.Steffen(2007)
A Low Reheating temperature model F.T(2007)

Further discussions on CBBN

^{7}Li CBBN production/destruction

Bird, Koopmans, Pospelov (2007)

^{9}Be CBBN production

Pospelov, Pradler, Steffen(2008)

Theoretical calculations on several CBBN processes

Kamimura, Kino, Hiyama(2008)

Phase space suppressed decay

stau→ neutralino+tau+pion, …

Jitoh, Kohri, Koike, Sato, Shimomura, Yamanaka(2007)

Structure formation of the universe

Collisionless → $n_{superWIMP}$; Collisional → n_{NLSP}

$$n_{DM} = n_{superWIMP} + n_{NLSP}$$

NLP kinetic decoupling due to the late decay

NLP = CHAMP : tight coupling with baryon-photon fluid

(K.Sigurdson, M.Kamionkowski (2003))

Collisional damping but different from Silk damping

Phase space volume can be Cold or Cool if the velocity of superWIMP is enough small.

Free streaming effect due to superWIMPs

Momentum distribution is not well known thermal distribution

→ Difference in the damping of the dark matter power spectrum

W.Lin, D.Huang, X.Zhang, R.Brandenberger (2000),M.Kaplinghat(2005)

Phase space volume v.s Free streaming scale (cusp v.s substructure)

NR late decay : the cut off scale controlled by two variables
lifetime of NLSP and the velocity of superWIMP in late decays

J.Cembranos, J.Feng, A.Rajaraman, F.T (2005)
M.Kaplinghat (2005)
X.Bi, M.Li, X.Zhang(2003)

Relativistic/early decay: the cut off scale does not depend on the decay time

Cosmic ray production of NLSPs

NLSP=stau,
Penetration of the earth
Simultaneous pair creation → detection at south pole
Z.Chacko et al(2003)…..from neutrino cosmic ray

(*) proton cosmic ray
….small rates if we assume collision of a point particle.
Any anomaly at high energy collision above TeV?
….LHC may tell us them.

Summary

There have been several discussions on superWIMP dark matter scenarios.

These dark matters can not be directly detected, but several projects on WIMP DM direct searches will have a strong implication for these scenarios.

LHC and further understanding to identify primordial light elements abundances will provide an answer for our question whether we need to modify some standard models(particle physics/astrophysics/cosmology) by additional new physics or not.