Cosmology with long-lived charged particle

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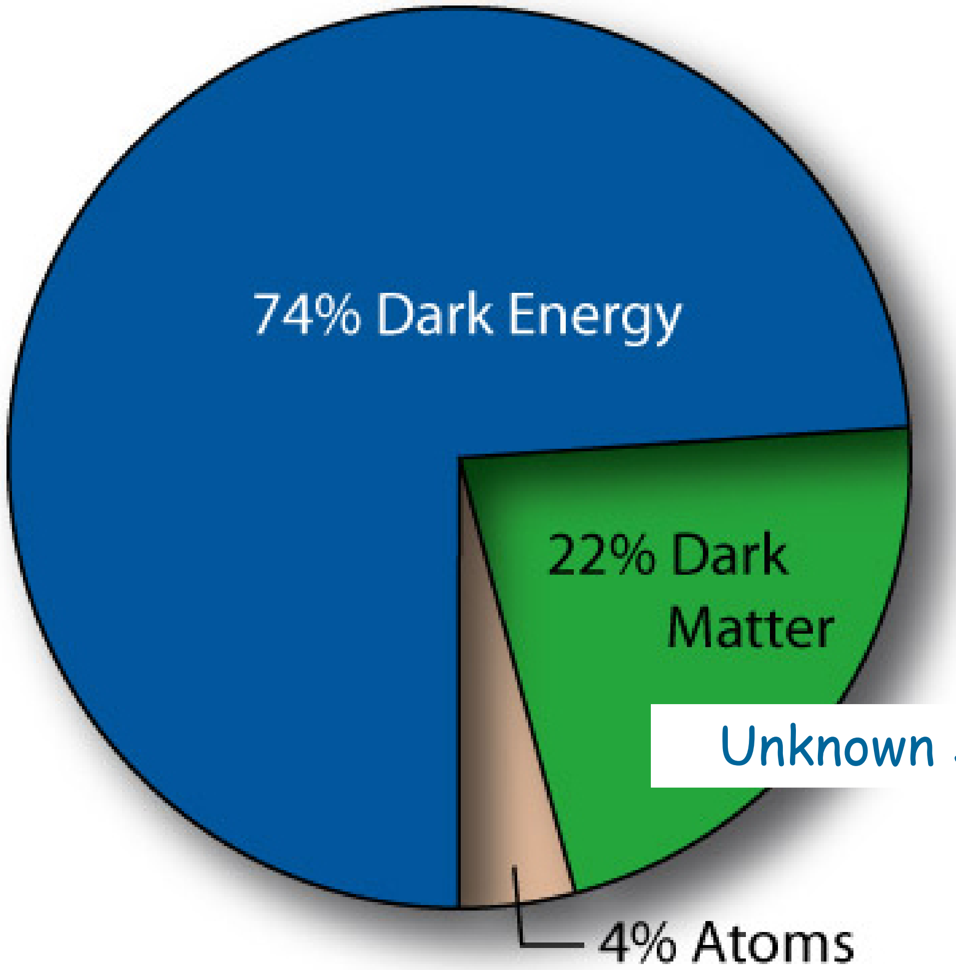
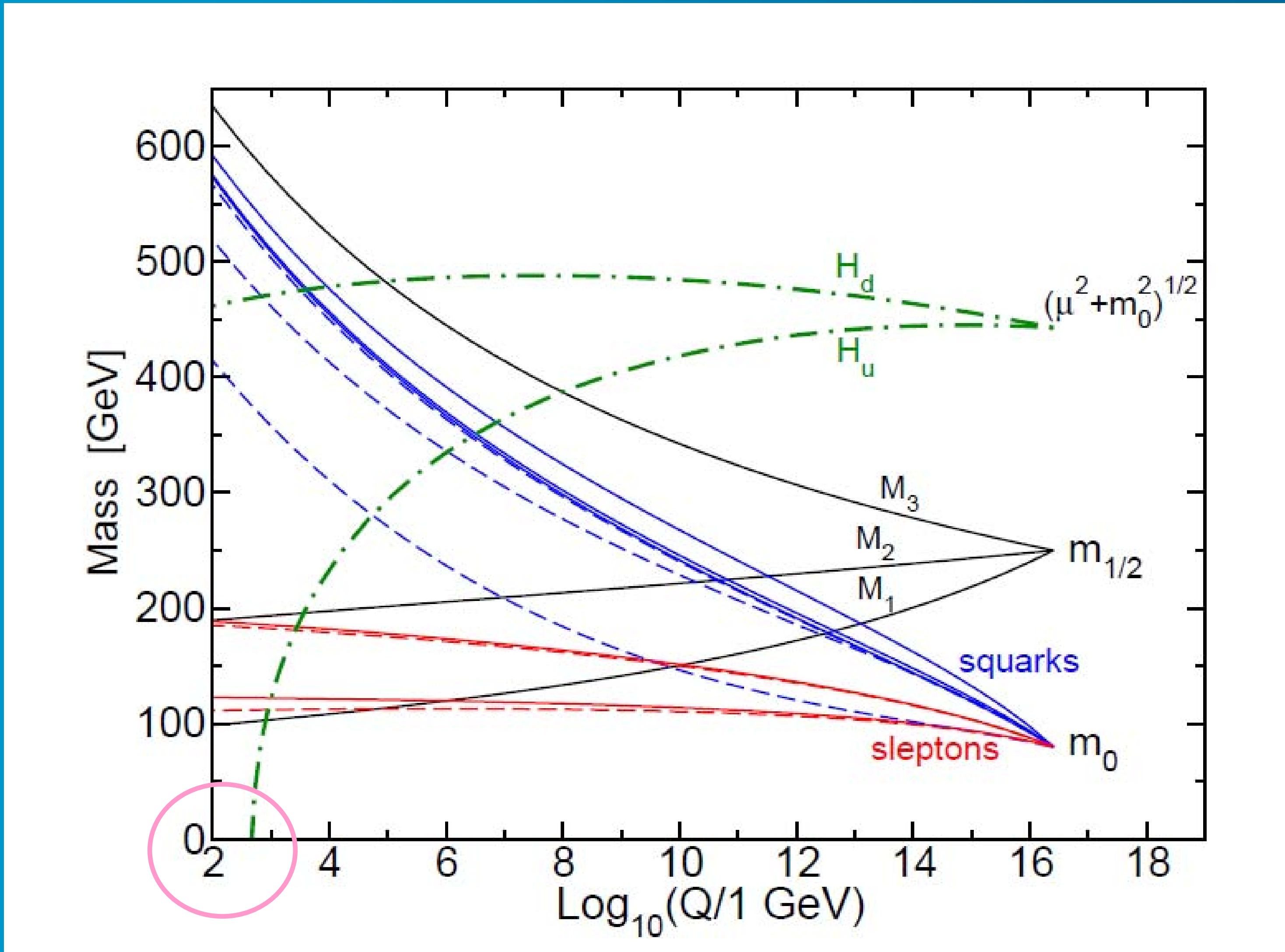
Dark Matter



Unknown SUSY particles?

http://map.gsfc.nasa.gov/media/060916

Running of Renormalization Group (RG) Equation in CMSSM

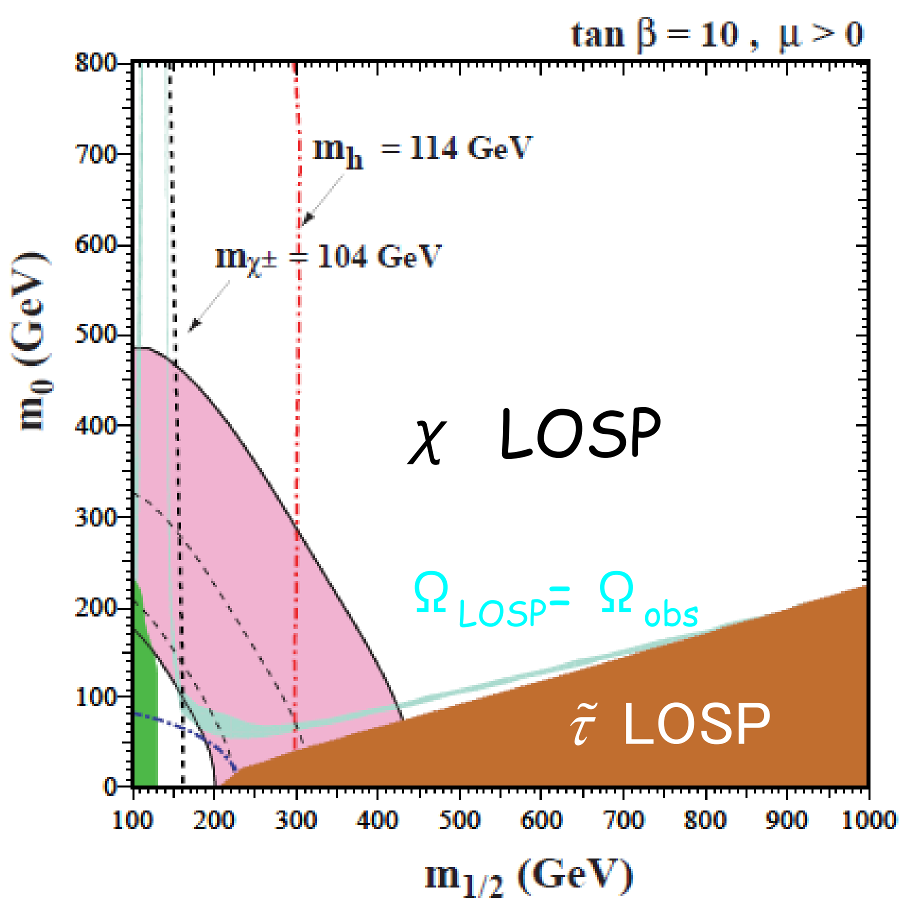


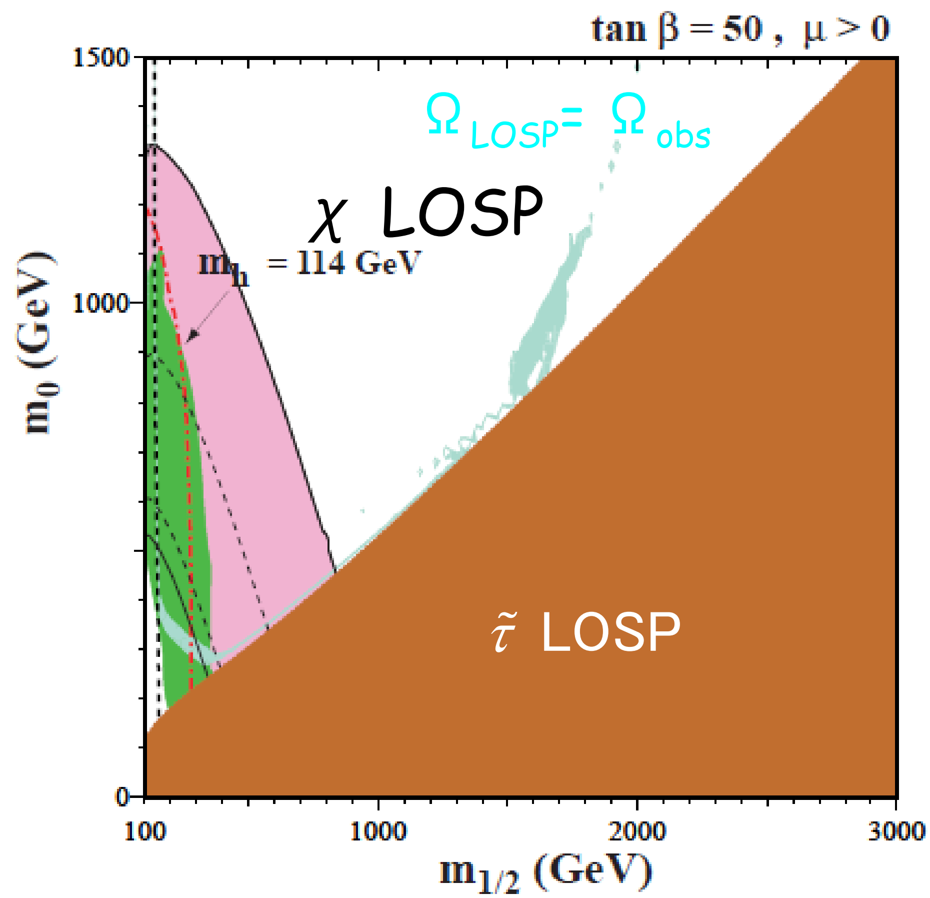
Negative Higgs mass term

Martin, "A Supersymmetry Primer"

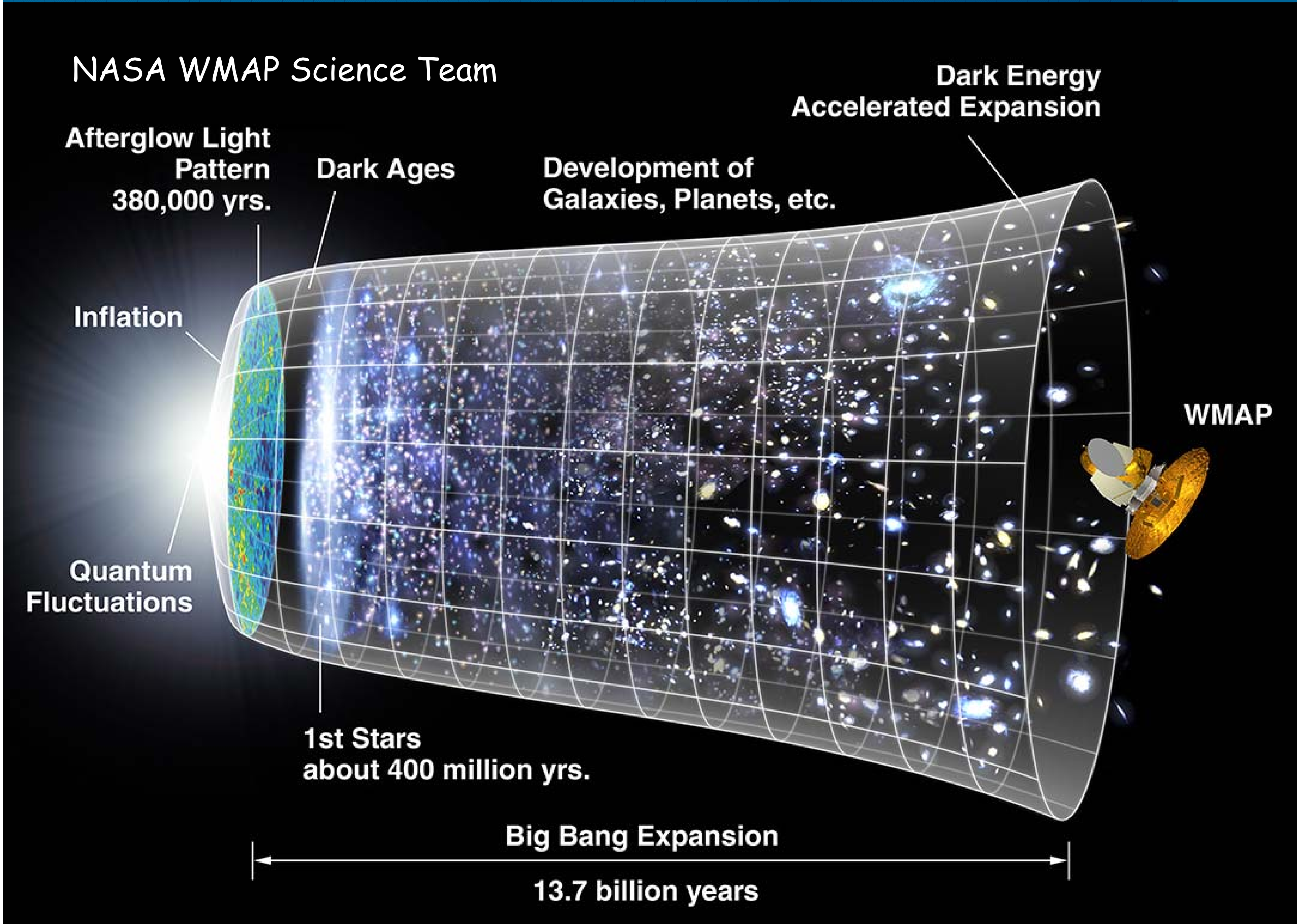
LSP (LOSP) in CMSSM

Neutralino or Scalar tau lepton (Stau) is the Lightest Ordinary SUSY Particle (LOSP)





Ellis,Olive,Santoso,Spanos(03)


NASA WMAP Science Team
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

Thermal history of the Universe

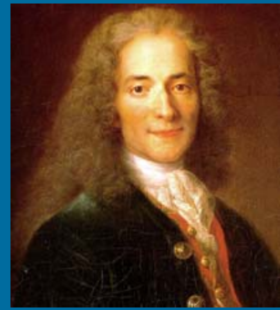
Big bang

cf) 1 GeV ~ 10^{13}K

1 eV ~ 10^{4}K

time	"temperature"		
10^{-44} sec	10^{18} GeV	Planck scale	Inflation and Reheating
10^{-38} sec	10^{16} GeV	GUT phase transition?	Baryogenesis?
10^{-11} sec	10^{2} GeV	Electroweak phase transition	
1 sec	1 MeV	Neutron decoupling	Big-Bang Nucleosynthesis (BBN)
10^{6} sec	1 keV	Galaxy-size perturbation reenters the horizon (LSS)	
10^{12} sec	0.3 eV	Matter-Radiation equality and Photon decoupling (CMB)	
≈			
13.7 Gyr (~10^{17} sec)	10^{-4} eV~2.7°K	Present	

宇宙の外には何がある？



Voltaire
(1694-1778)

- 神の存在を信じたデカルトに対してヴォルテールは「この世の無という隙間がなく、物質だけで全て満たされているのだとすると、物質とは違うはずの神は一体どこに存在しているのか？」とデカルトに反論した。物質世界の内と外という概念を導入せざるを得ない。

- To a question, "What exists outside the horizon?", we can say, quantum fluctuation exists outside the horizon in modern picture of Inflationary cosmology

Stau NLSP and gravitino LSP scenario

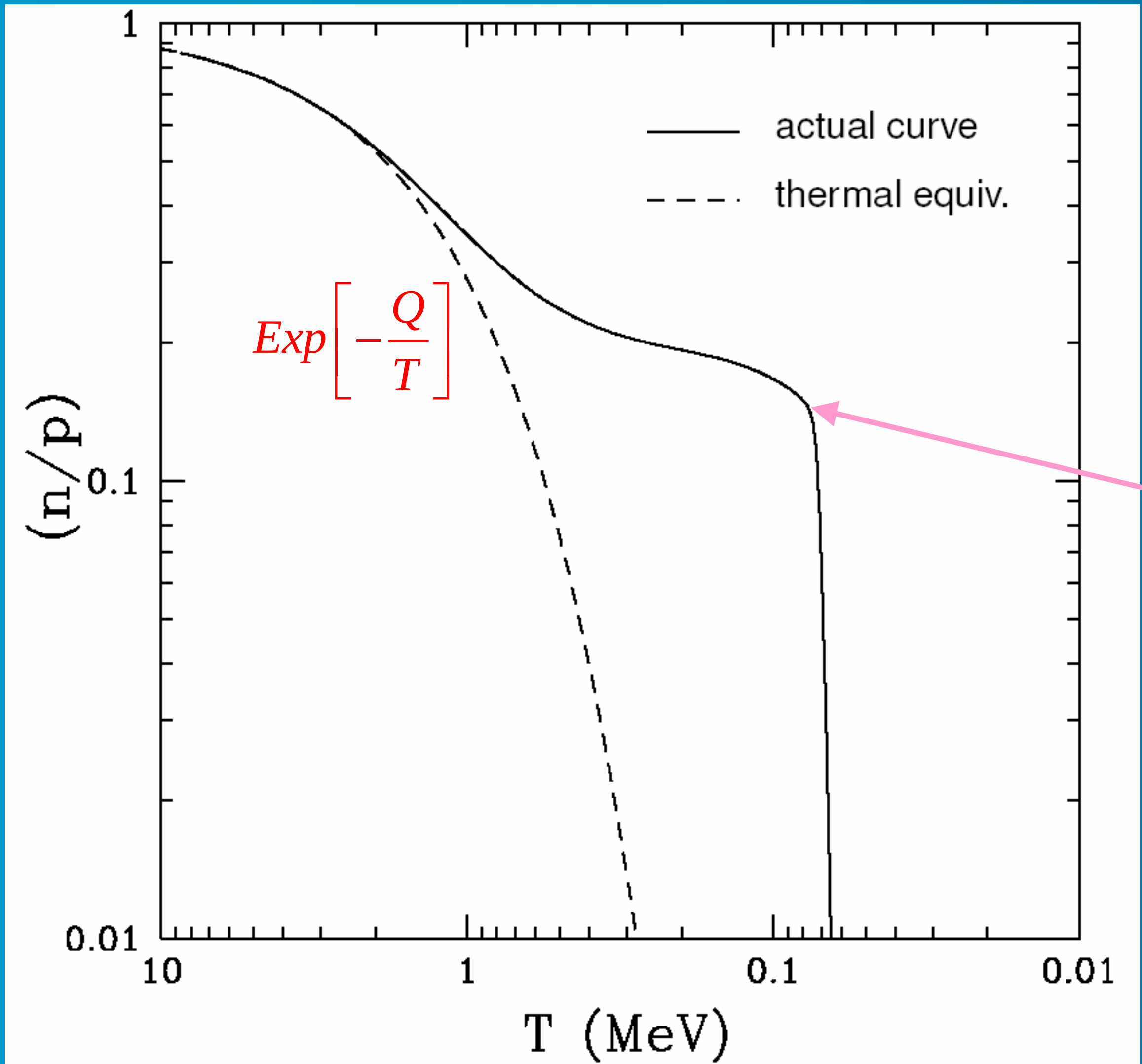
Stable stau with weak-scale mass (<10^2 TeV-10^5 TeV) was excluded by the experiments of ocean water

NLSP stau should be unstable

Bound states of stau and light elements should have been formed

Big-bang nucleosythesis (BBN)

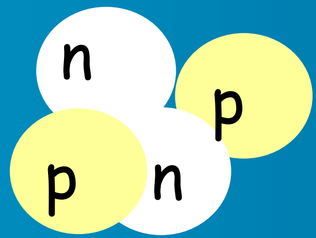
Freezeout of neutron to proton ratio



$$\left(\frac{n_n}{n_p}\right)_{\text{freezeout}} \approx \frac{1}{7}$$

He4 mass fraction

$^{4}\mathrm{He}$



$$n_{^4\mathrm{He}} = n_n / 2$$

$$Y_p \equiv \frac{\rho_{^4\mathrm{He}}}{\rho_B} \approx \frac{4 \times \cancel{m_N} \times n_{^4\mathrm{He}}}{\cancel{m_N} \times (n_n + n_p)} \approx \frac{2(n_n / n_p)_{\mathrm{freezeout}}}{(n_n / n_p)_{\mathrm{freezeout}} + 1} \approx 0.25$$

3) $T \sim 0.1$ MeV ($t \sim 100$ sec)

cf) 0.1 MeV ~ 10^9K

$$p + n \rightarrow D + \gamma$$

$T \ll B_D = 2.2$ MeV

4) $T < 0.1$ MeV ($t > 100$ sec)

$$n_D / n_H \sim 16.3 (T / m_N)^{3/2} \eta \ \exp[B_D / T] > 0.01$$

$$D + D \rightarrow T + p, \ {}^3\mathrm{He} + \mathrm{n}$$

$$T + D \ ({}^3\mathrm{He} + D) \rightarrow {}^4\mathrm{He} + \mathrm{n} \ ({}^4\mathrm{He} + \mathrm{p})$$

A little D and ^{3}He are left as cold ashes

There is no stable nuclei for A=5,8. Mass 7 nuclei are produced a little.

$${}^4\mathrm{He} + T \rightarrow {}^7\mathrm{Li} + \gamma$$

$${}^4\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$$

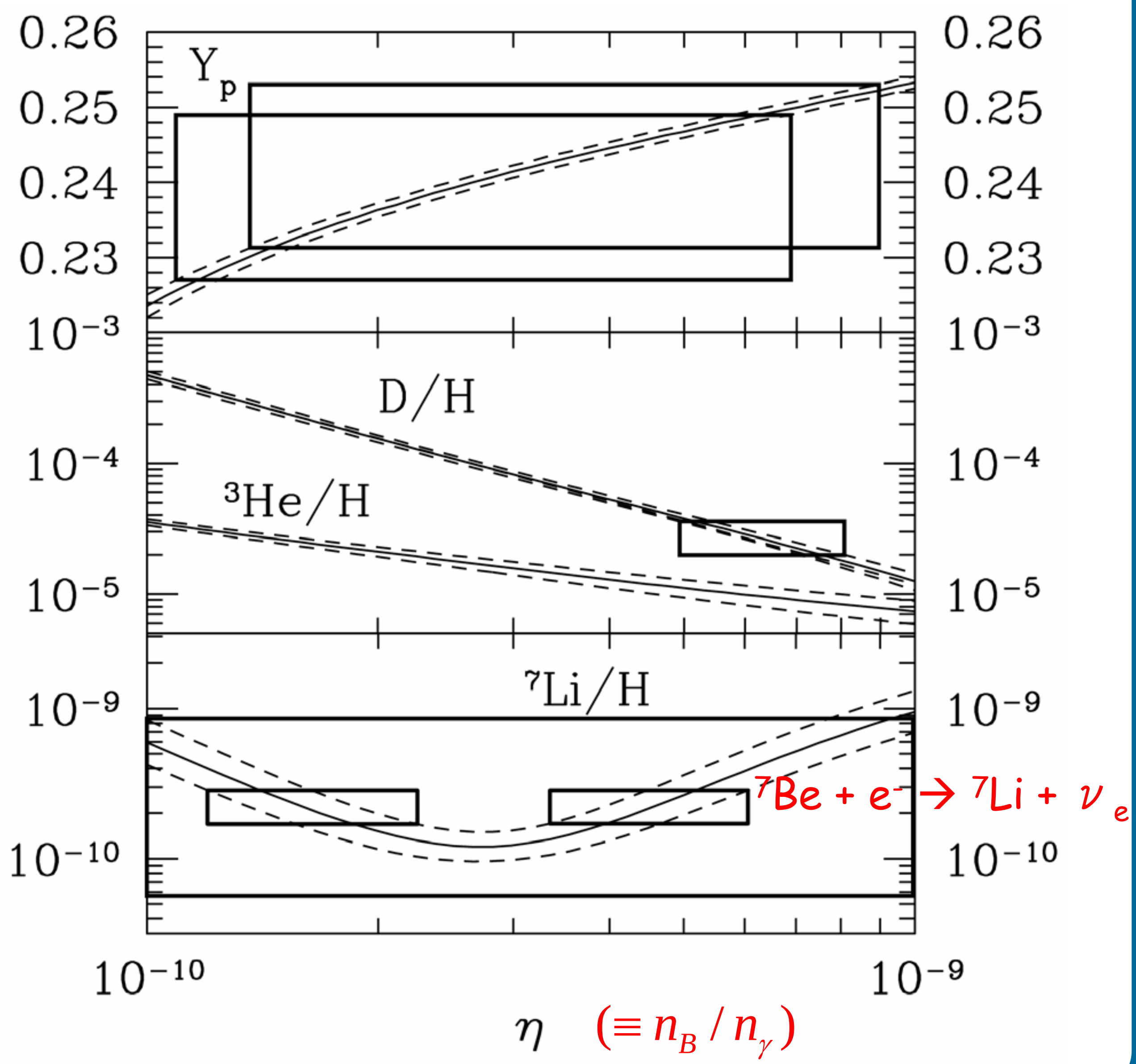
$$\hookrightarrow {}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$$

$${}^4\mathrm{He} + D \rightarrow {}^6\mathrm{Li} + \gamma$$

Observational Light Element Abundances

- He4 $Y_p = 0.2516 \pm 0.004$
  - Fukugita, Kawasaki (2006)
  - Peimbert,Lridiana, Peimbert(2007)
  - Izotov,Thuan, Stasinska (2007)
- D $D/H = (2.82 \pm 0.26) \times 10^{-5}$
  - O'Meara et al. (2006)
- Li7 $\log_{10}(^7Li/H) = -9.90 \pm 0.09\ (+0.35)_{syst.}$
  - Melendez,Ramirez(2004)
- Li6 $^6Li/^7Li < 0.046 \pm 0.022\ (+0.106)_{sys}$
  - Asplund et al(2006)
- He3 $^3He/D < 0.83 + 0.27$
  - Geiss and Gloeckler (2003)

SBBN


0.26
0.25
0.24
0.23
Y p
10−3
10−4
10−5
D/H
³He/H
10−9
10−10
⁷Li/H
⁷Be + e⁻ → ⁷Li + ν e
10−10
10−9
η (≡ n B / n γ)

CHArged Massive Particle (CHAMP)

Kohri and Takayama, hep-ph/0605243

See also literature, Cahn-Glashow ('81)

Candidates of long-lived CHAMP in modern cosmology

stau, stop …

"CHAMP recombination" with light elemcts

$T_c \sim E_{bin}/40 \sim 10\text{keV}$

$(E_{bin} \sim \alpha^2 m_i \sim 100\text{keV})$

See also the standard recombination between electron and proton, $(T_c \sim E_{bin}/40 \sim 0.1\text{eV}, E_{bin} \sim \alpha^2 m_e \sim 13.6\text{eV}))$

CHAMP captured-nuclei, e.g., $(C, {}^4He)$ changes the nuclear reaction rates dramatically in BBN

Pospelov's effect

Pospelov (2006),**hep-ph/0605215**

- CHAMP bound state with ^{4}He enhances the rate $D + {}^4He \to {}^6Li + \gamma$

$$D + ({}^4He, C^-) \to {}^6Li + C^-$$

- Enhancement of cross section

$$\sim (\lambda_\gamma / a_{Bohr})^5 \sim (30)^5 \sim 10^{7-8}$$

Confirmed by Hamaguchi etal (07), hep-ph/0702274

Stau NLSP and gravitino LSP Scenario

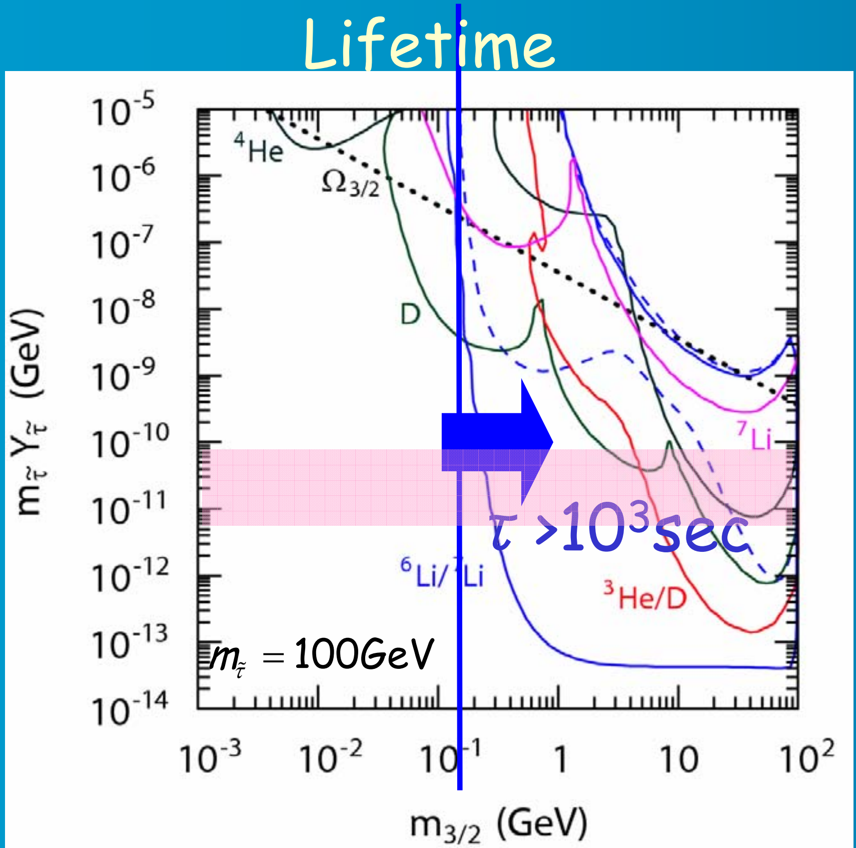
Kawasaki, Kohri, Moroi, Yotsuyanagi (08)

Relic abundance

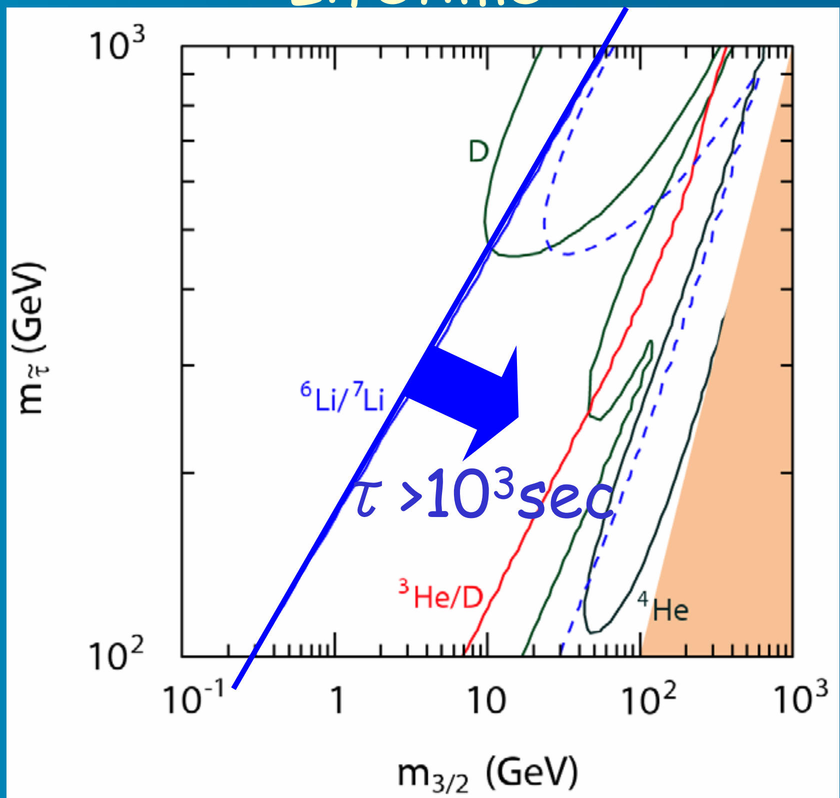
$$Y_{\tilde{\tau}} \simeq 7 \times 10^{-14} \times \left(\frac{m_{\tilde{\tau}}}{100\ \mathrm{GeV}}\right)$$

$$\tau \sim m_{3/2}^2 m_{pl}^2 / m_{NLSP}^5 \sim 10^3\, s \left(m_{NLSP}/10^2\mathrm{GeV}\right)^{-5} \left(m_{3/2}/10^{-1}\mathrm{GeV}\right)^2$$

Lifetime



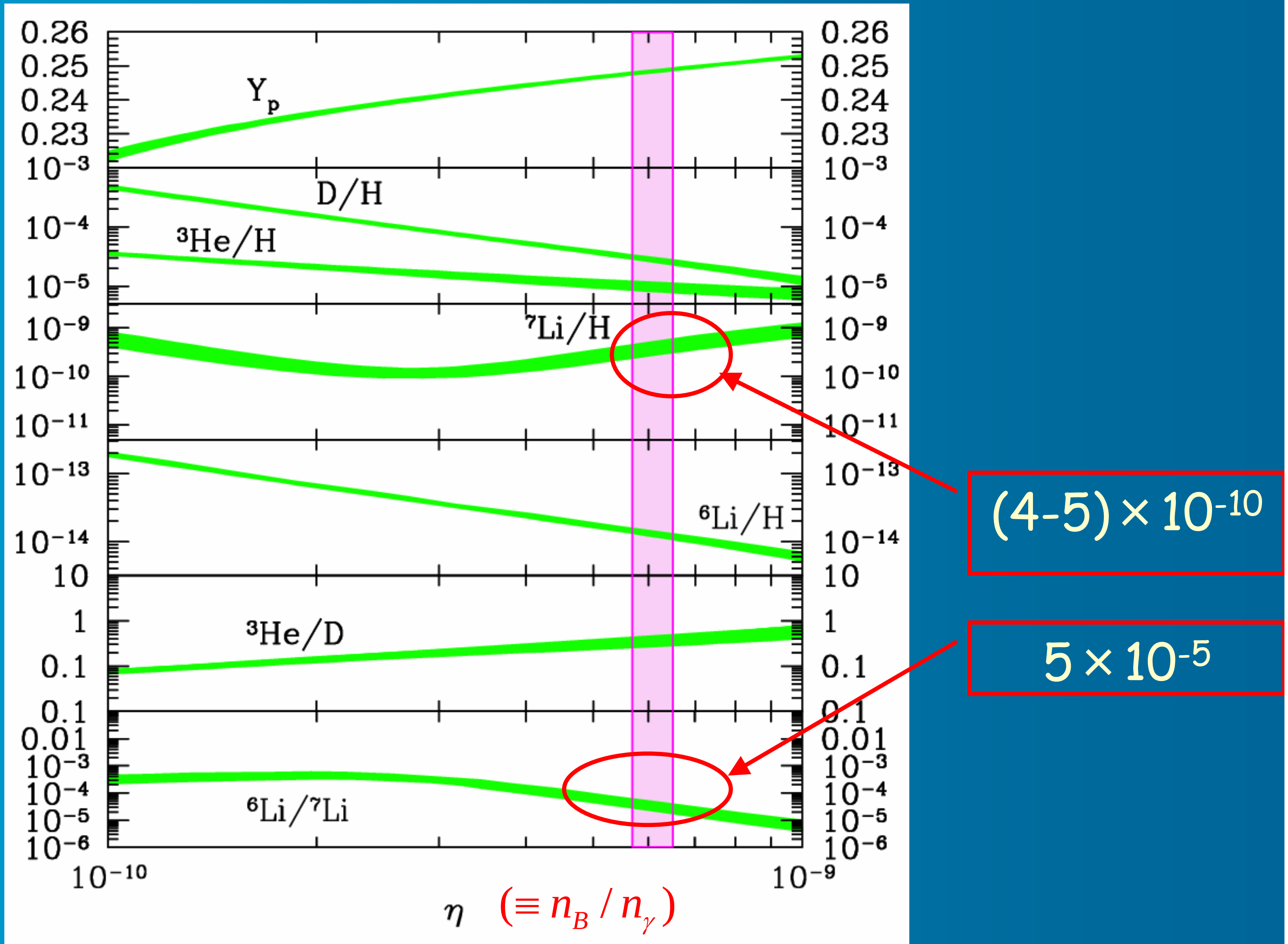
Lifetime



Lithium Problem

If we adopted smaller systematic errors for observational data of 6Li and 7Li , the BBN theory does not agree with observation of Li abundances.

SBBN

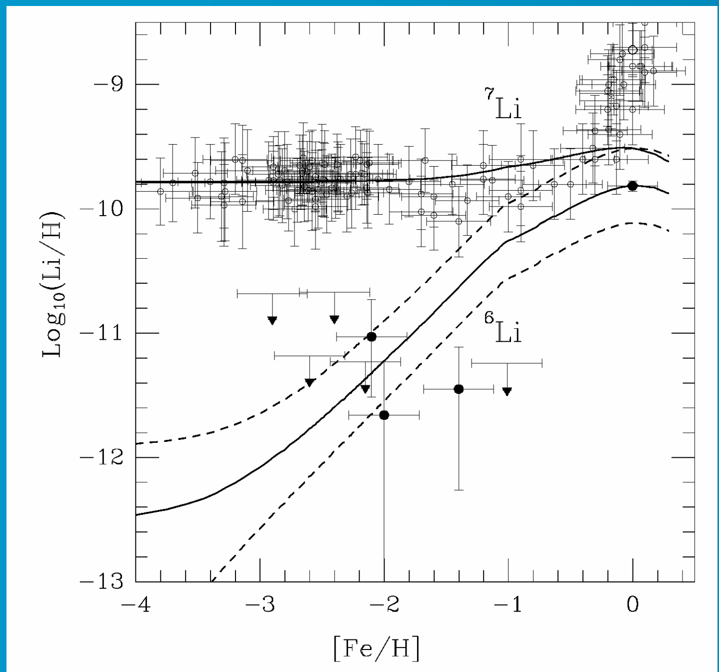


0.26
0.25
0.24
0.23
Y_p
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-11}
10^{-13}
^{6}Li/H
10^{-14}
10
1
^{3}He/D
0.1
0.01
10^{-6}
^{6}Li/^{7}Li
10^{-10}
10^{-9}
$\eta \quad (\equiv n_B / n_\gamma)$
$(4\text{-}5)\times 10^{-10}$
5×10^{-5}

Lithium 7

a factor of two or three smaller !!!

- Expected that there is little depletion in stars.



Lemoine et al., 1997

$$^7Li/H = 1.26^{+0.32}_{-0.21} \times 10^{-10} \quad (1\sigma)$$

$$\log\left(^7Li/H\right) = -9.90 \pm 0.09 \ (1\sigma)$$

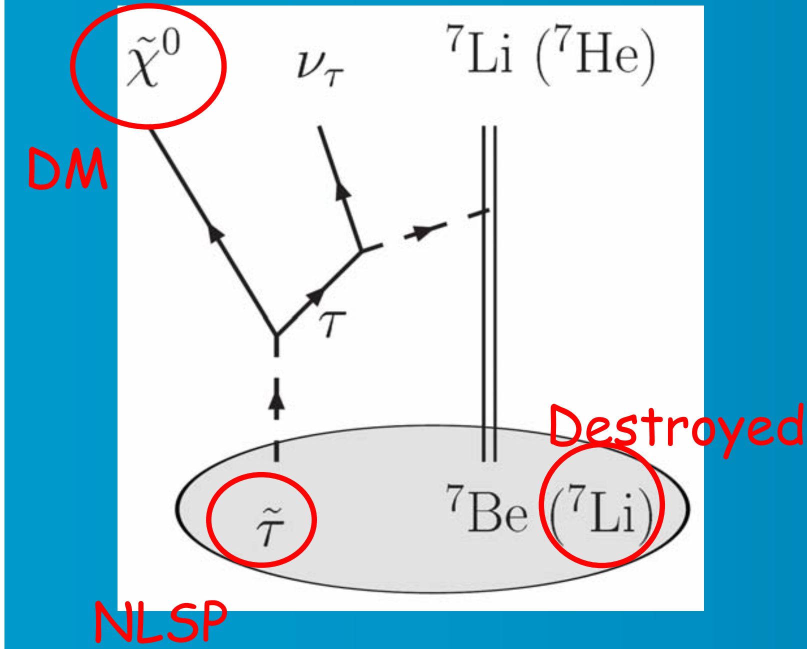
Ryan et al.(2000)

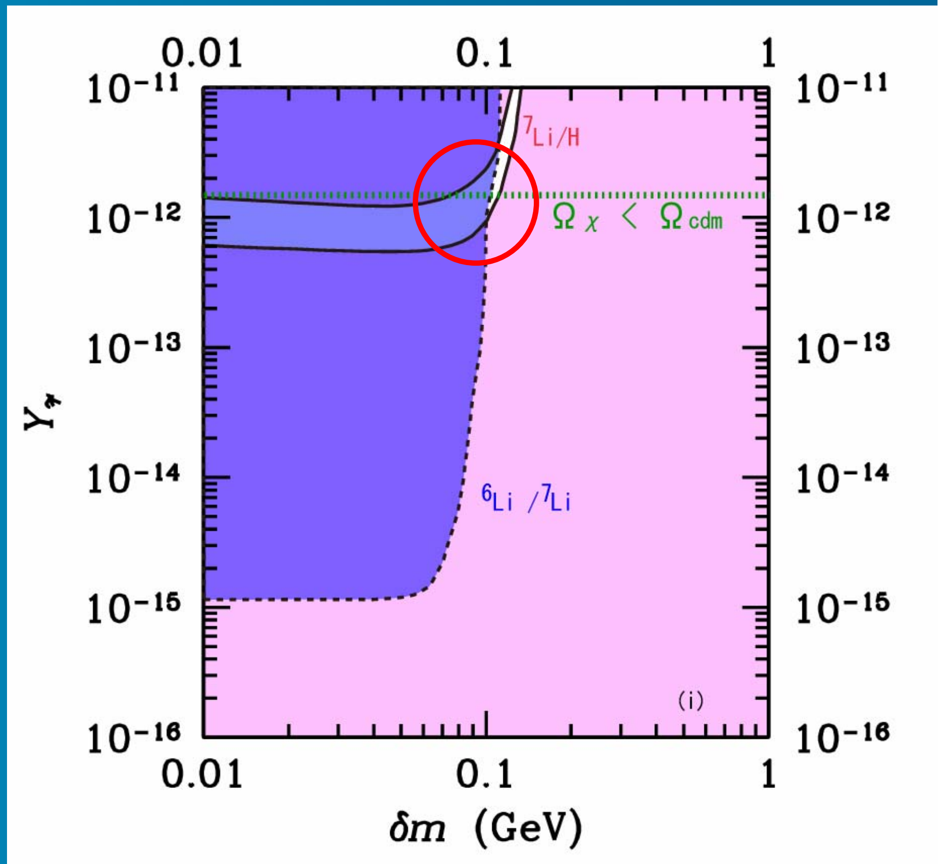
Bonifacio et al.(2006)

Degenerate stau NLSP and neutralino LSP Scenario

Jittoh, Kohri, Koike, Sato, Shimomura, Yamanaka, 2010

$\delta m = m_{\tilde{\tau}} - m_{\chi_0} < 0.1\mathrm{GeV}$ Long-lived and Charged current in BS



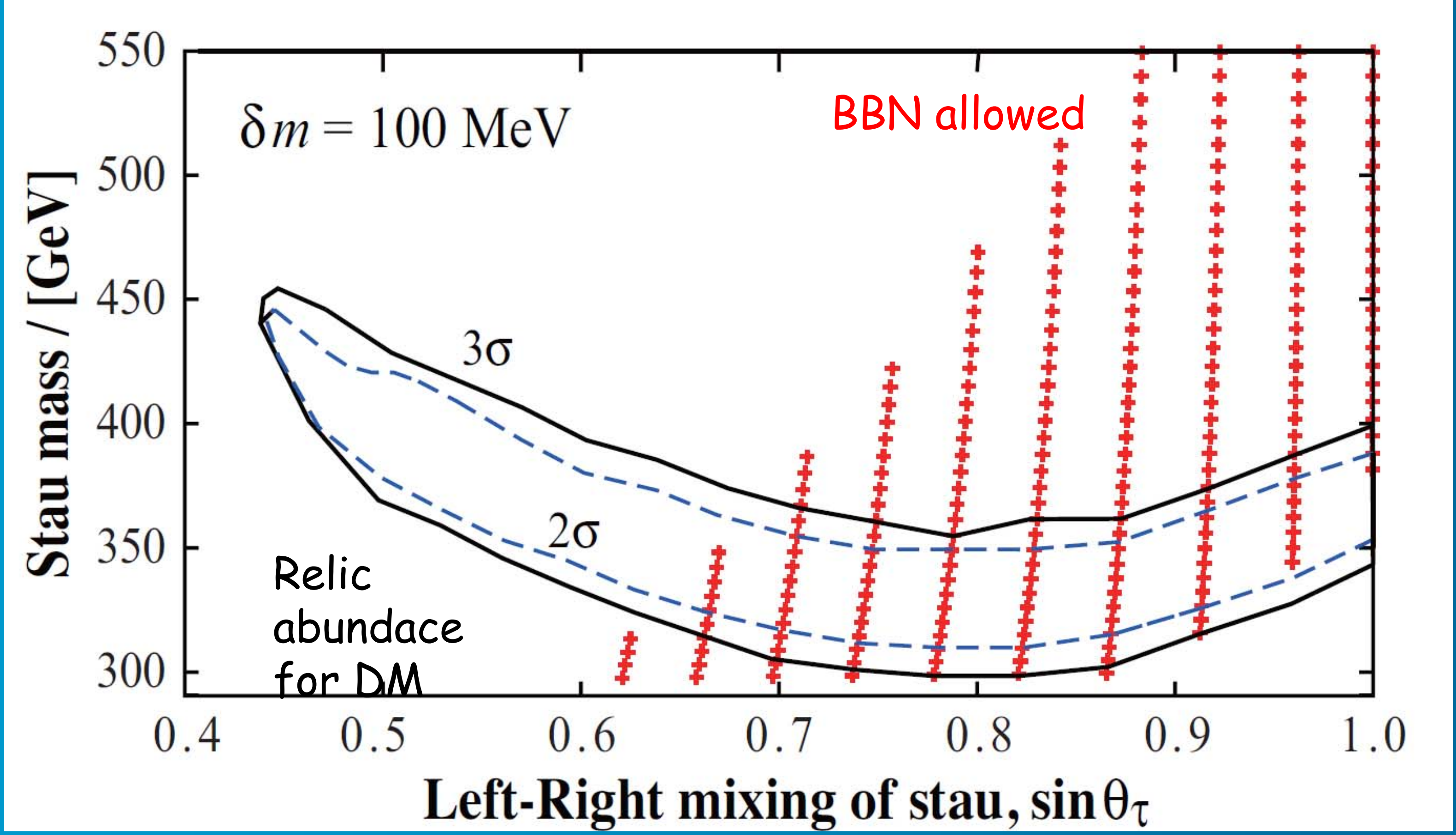


Effectively Be7, Li7 are destroyed!!!

See also Bird, Koopman and Pospelov (07)

Relic abundance and BBN constraint in degenerate-mass scenario

Jittoh, Kohri, Koike, Sato, Shimomura, Yamanaka, 2010



Large-scale structure (LSS)

- Primordial density perturbation created in inflation is a seed of galaxy

- The perturbation of Cold Dark Matter (CDM) could evolve without interacting background plasma of photon, proton and electron

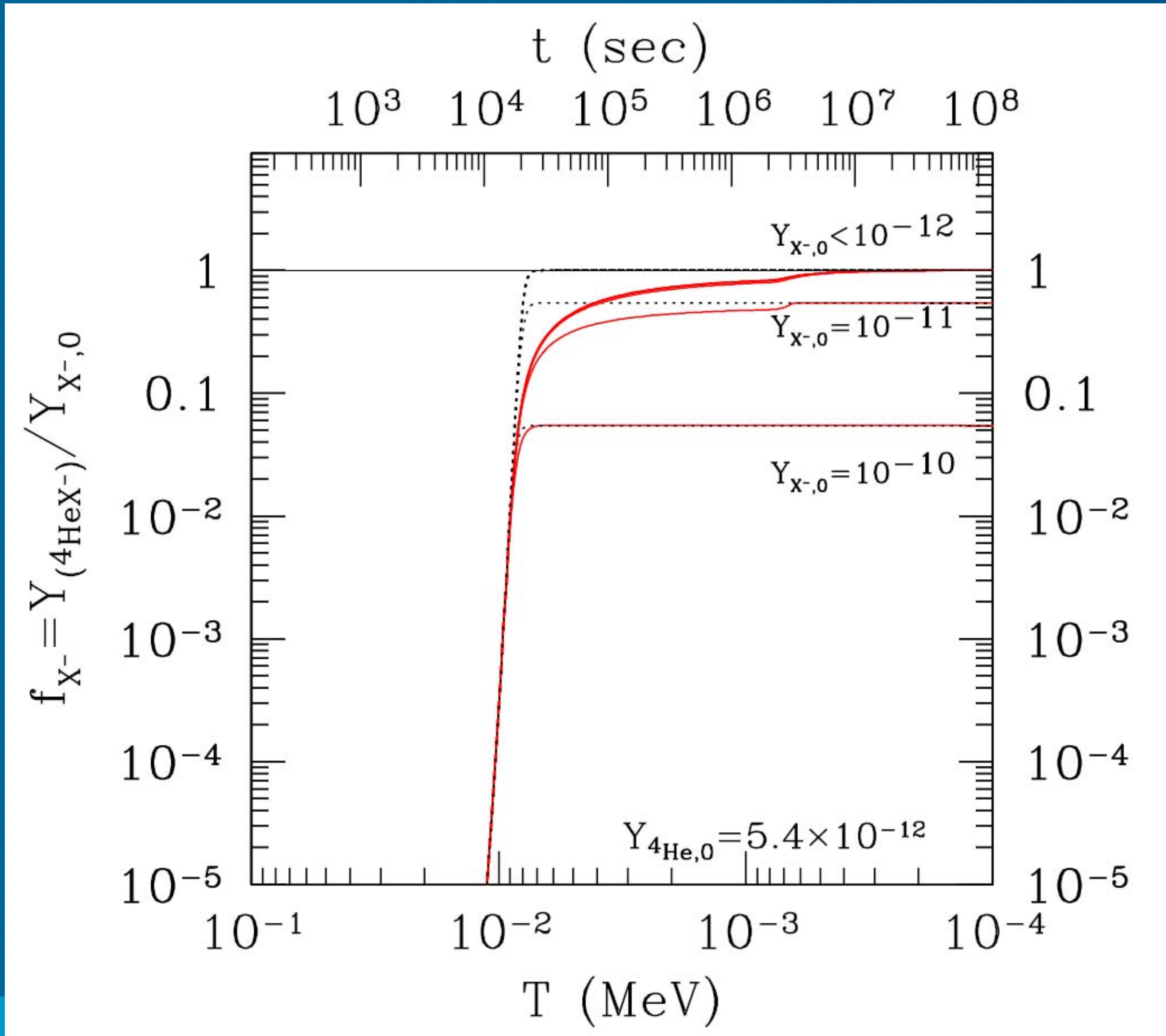
- Acoustic oscillation of CHAMP-radiation fluid could have erased the density perturbation of galaxy scale

$$k^{-1} \sim 0.1\,\mathrm{Mpc}\left(\tau/10^{6}s\right)^{1/2}$$

Shigurdson and Kamionkowski (04)

Kohri and Takahashi (09)

Fraction of bound state



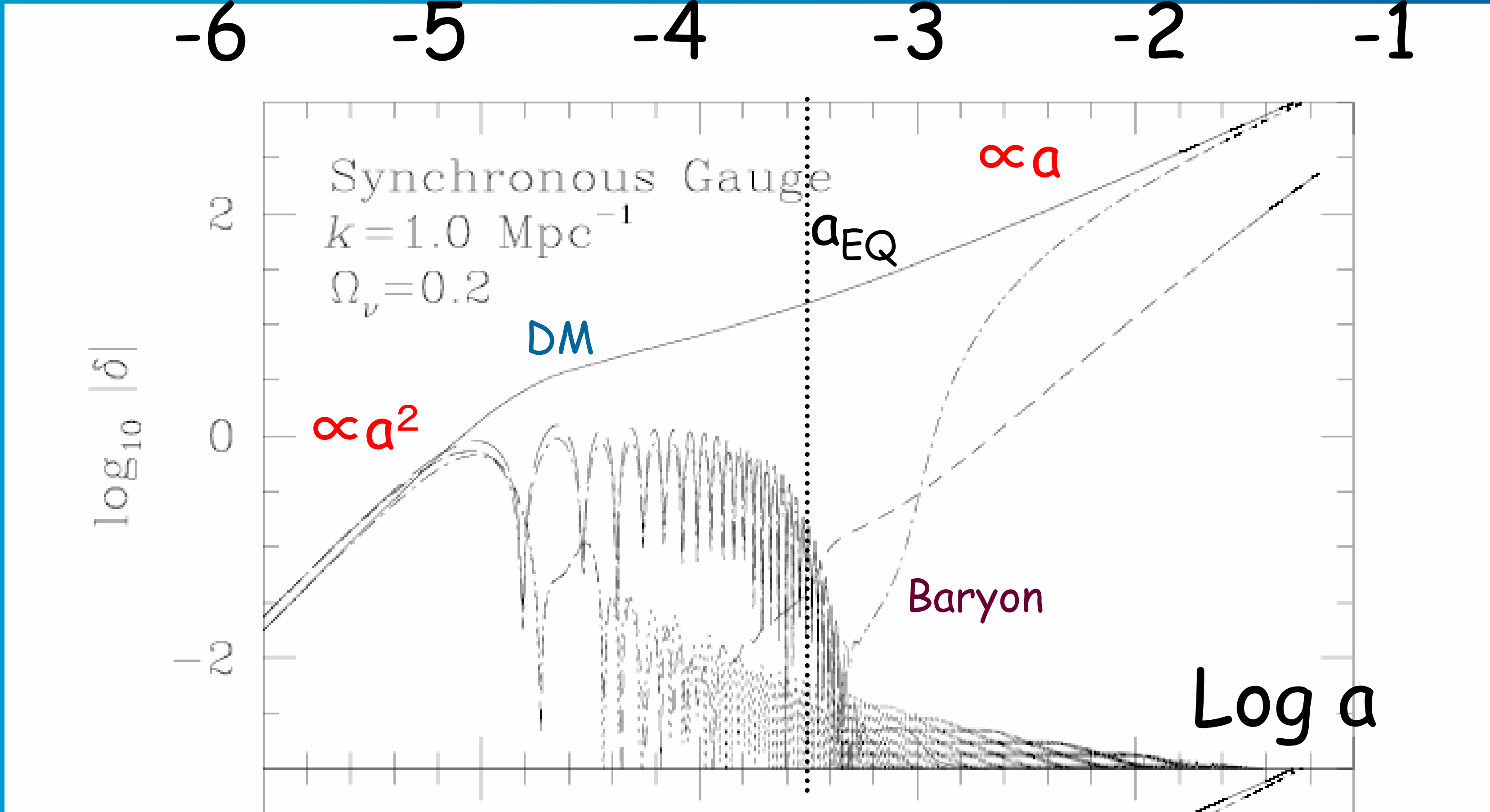
Most of CHAMPs are included into He4 for

Y < 10[12]

They are still positively-charged!

Time-evolution of fluctuation

Horizon reentry before matter-radiation equality epoch

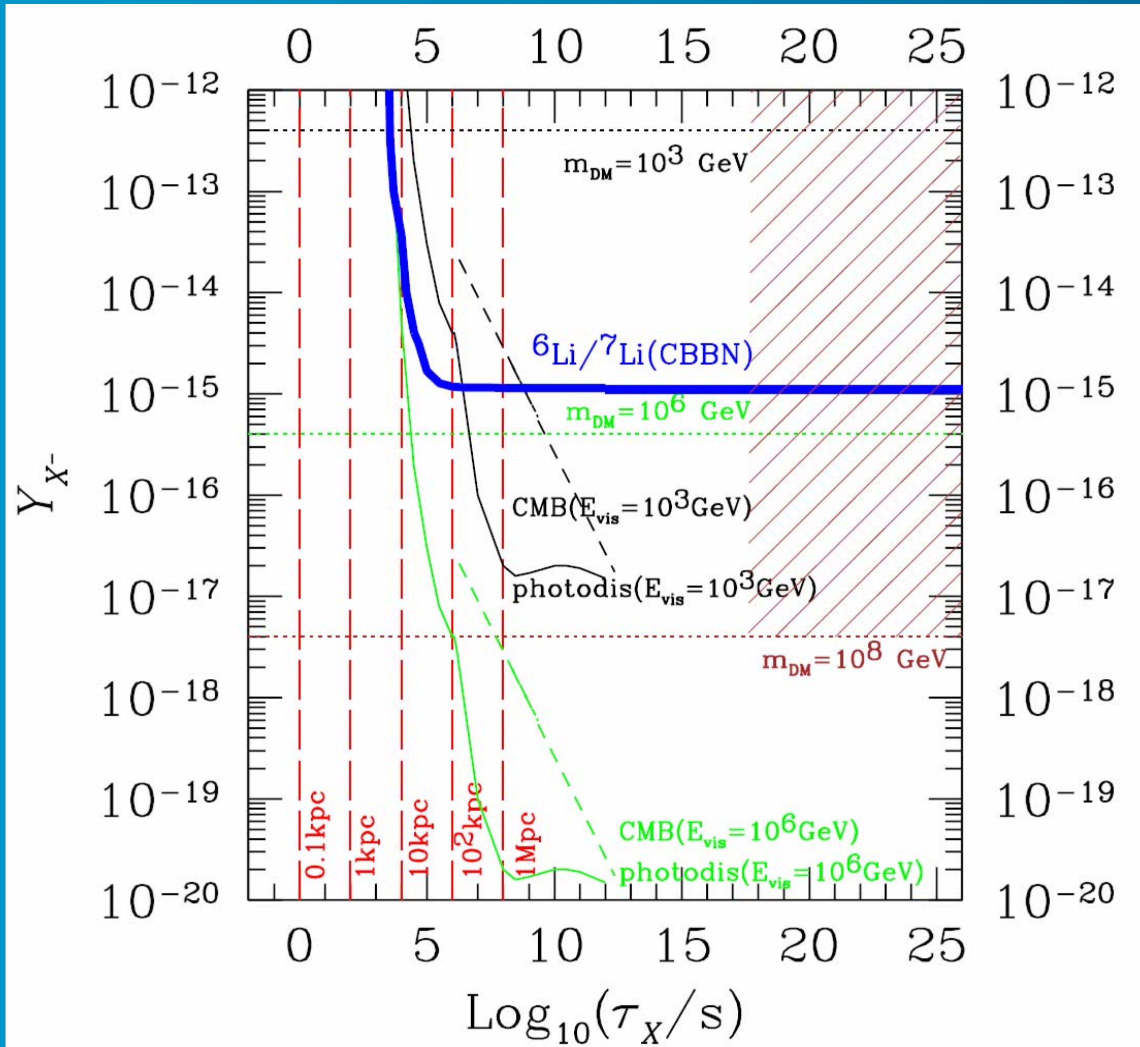


Ma and Bertschinger (95)

See also 松原隆彦「シリーズ 現代の天文学3 宇宙論 II 宇宙の進化」

Constraint from Large-Scale Structure

Kohri and Takahashi (09)



Detectability of long-lived stau in LHC

See also Takumi Ito's talk

Place additional stoppers near ATLAS or CMS to stop long-lived charged SUSY particles (even for $c\tau > 10$ m)

- 5 m Iron wall Hamaguchi, Kuno, Nakaya, and Nojiri (04)
- Water tank Feng and Smith (04)
- Surrounded rock

De Roek, Ellis, Gianotti, Mootgat, Olive and Pape (05)

See also Asai-Hamaguchi-Shirai (09) for a possibility of the detection without those additional stoppers

Summary

- The gravitino LSP with thermally produced stau NLSP scenario is severely constrained
- Long-lived CHAMPs should be also constrained by structure formation of galaxy
- Stau NLSP can be detected by LHC (See also Takumi Ito's talk)

Introduction to SUSY

- Supersymmetry (SUSY)

  - Solving "Hierarchy Problem"
  - Realizing "Coupling constant unification in GUT"

Fermion	⟷	Boson
quark	⟷	squark
lepton	⟷	slepton
photino	⟷	photon
gravitino	⟷	graviton

neutralino ← photino

Lightest SUSY particle (LSP) is a good candidate for dark matter

Supergravity

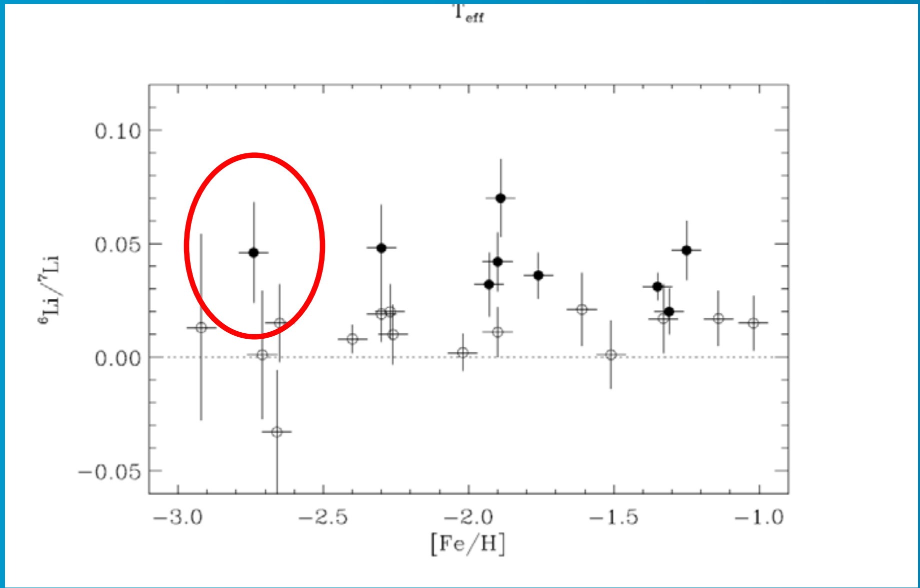
- Local theory of Supersymmetry and a good candidate for quantum gravity
- Predicting a massive super partner of graviton, gravititno
- Predicting a long-lived particle, e.g., decaying NLSP gravitino into LSP neutralino, or decaying NLSP neutralino or stau into gravitino LSP
- Typically the lifetime can be longer than one second! This is dangerous for cosmology.

$$\tau \sim m_{pl}^2 / m_{3/2}^3 \sim 10^6 \sec (m_{3/2} / 10^2 \mathrm{GeV})^{-3}$$

Lithium 6

Asplund et al.(2006)

- Observed in metal poor halo stars in Pop II
- ^{6}Li plateau?



$$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 0.022 - 0.090$$

$$^{7}\mathrm{Li}/\mathrm{H} \approx (1.1 - 1.5)\times 10^{-10}$$

still disagrees with SBBN

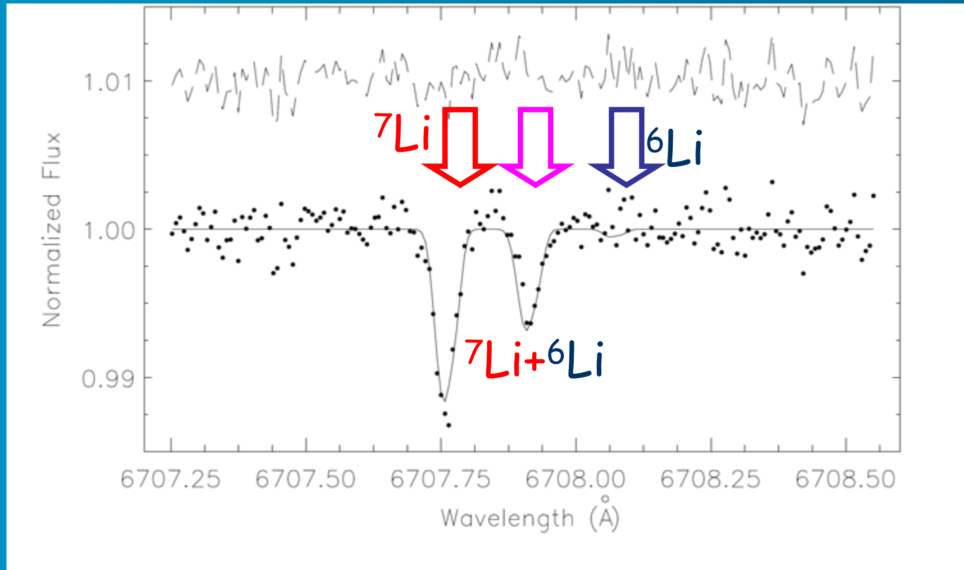
Astrophysically, factor-of-two depletion of Li7 needs a factor of O(10) Li6 depletion (Pinsonneault et al '02)

We need more primordial Li6?

Doppler broadening

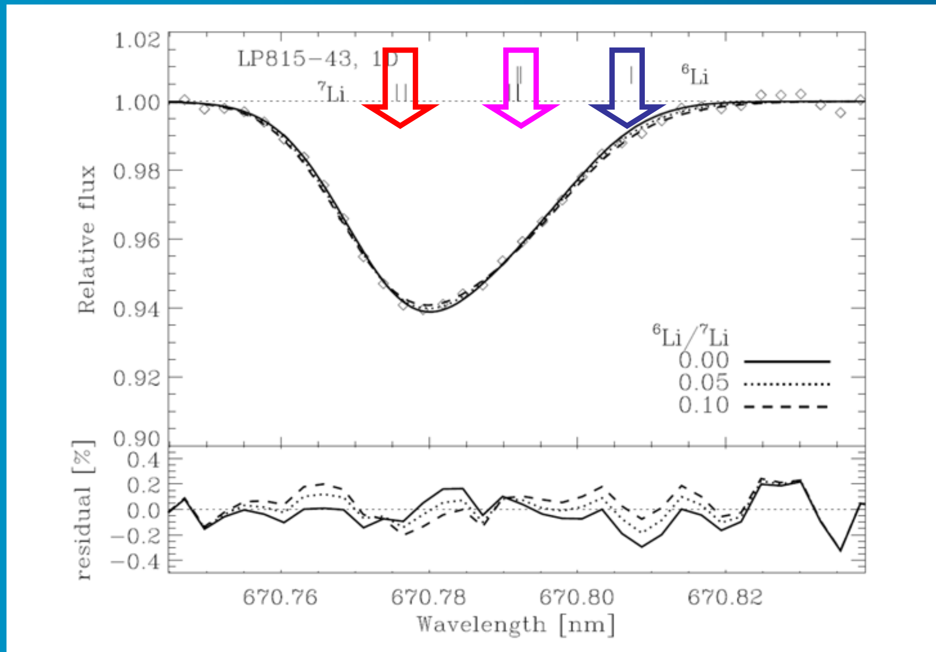
Cold ISM

Knauth, Federman, Lambert (2006)



LP815-43

Asplund et al.(2006)



Scenario of BBN

cf) 1 MeV ~ 10^{10}K

1) $T > 1$ MeV ($t < 1$sec)

- Radiation: $\gamma, e^{\pm}, \nu$
- Matter: n, p

Weak interaction is in equilibrium

$$n + e^{+} \leftrightarrow p + \overline{\nu_e}$$

$$\frac{n_n}{n_p} = Exp\left[-\frac{Q}{T}\right]$$

($Q \equiv m_n - m_p \sim 1.29$ MeV)

2) $T \sim 1$ MeV ($t \sim 1$ sec) cf) 1 MeV ~ 10^{10}K

Feezeout of weak interaction

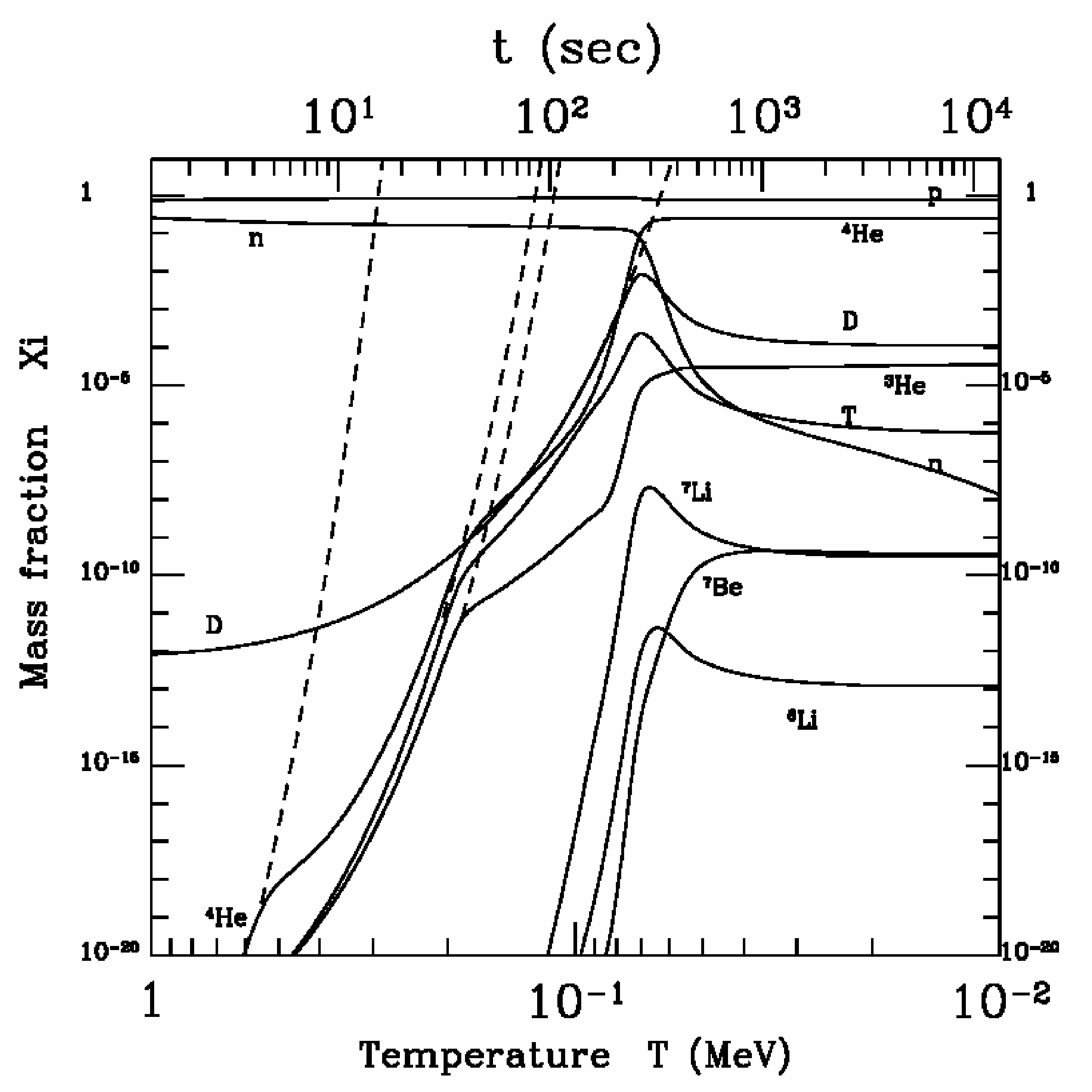
- Weak interaction rate $\Gamma_{n\leftrightarrow p} \sim \sigma_{n\leftrightarrow p} n_e \sim G_F^2 T^5$
- Hubble expansion rate $H = \frac{\dot{a}(t)}{a(t)} \sim T^2 / M_{pl}$

$$\frac{\Gamma}{H} \approx \left(\frac{T}{0.8\ \text{MeV}} \right)^3$$

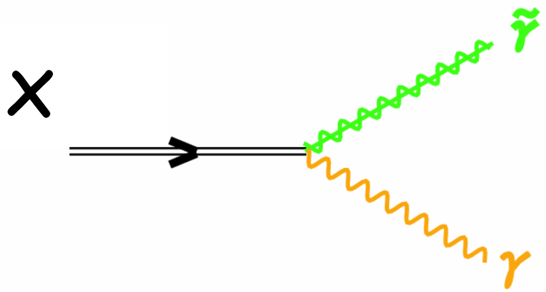
$\Gamma < H \quad (T < 0.8\ \text{MeV} \equiv T_f)$ ⇒ (n_n/n_p) is fixed

$$\left(\frac{n_n}{n_p} \right)_{\text{freezeout}} \approx Exp\left[-\frac{Q}{T_f} \right]$$

Time evolution of light elements



Radiative decay mode



1) Electro-magnetic cascade

$$\gamma + \gamma_{\rm BG} \to e^+ + e^-$$
$$\gamma + e^-_{\rm BG} \to \gamma + e^-, \quad e^- + \gamma_{\rm BG} \to e^- + \gamma$$
$$\gamma + \gamma_{\rm BG} \to \gamma + \gamma$$

2) many soft photons are produced

3) Photo-dissociation of light elements

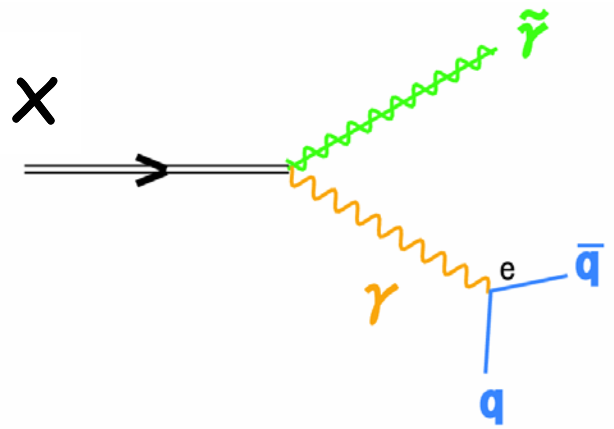
$$\mathrm{D} + \gamma \to p + n,$$
$$^4\mathrm{He} + \gamma \to {}^3\mathrm{He} + n, \quad \mathrm{T} + p, \quad D + p + n$$
$$^3\mathrm{He} + \gamma \to \mathrm{D} + p + n, \quad \mathrm{etc.}$$

He3/D >~ O(1)

Hadronic decay mode

Reno, Seckel (1988)

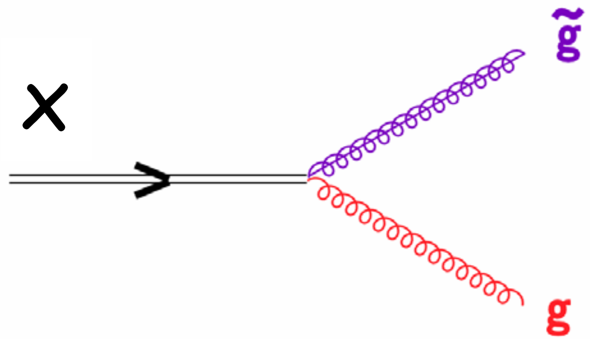
S. Dimopoulos et al.(1989)



$$B_h \approx \alpha / 4\pi \approx 10^{-3}$$

Two hadron jets with

$$E_{jet} = m_X / 3$$



$$B_h = 1$$

One hadron jet with

$$E_{jet} = m_X / 2$$

(I) Early stage of BBN (T > 0.1MeV)

Reno and Seckel (1988) Kohri (2001)

Extraordinary inter-conversion reactions between n and p

cf) $n + \pi^+ \rightarrow p + \pi^0$ $p + \pi^- \rightarrow n + \pi^0$

$$\Gamma_{n \leftrightarrow p} = \Gamma^{weak}_{n \leftrightarrow p} + \Gamma^{strong}_{n \leftrightarrow p}$$

Hadron induced exchange

$$\Gamma_{n \leftrightarrow p} \uparrow \quad \Rightarrow \quad n/p \uparrow$$

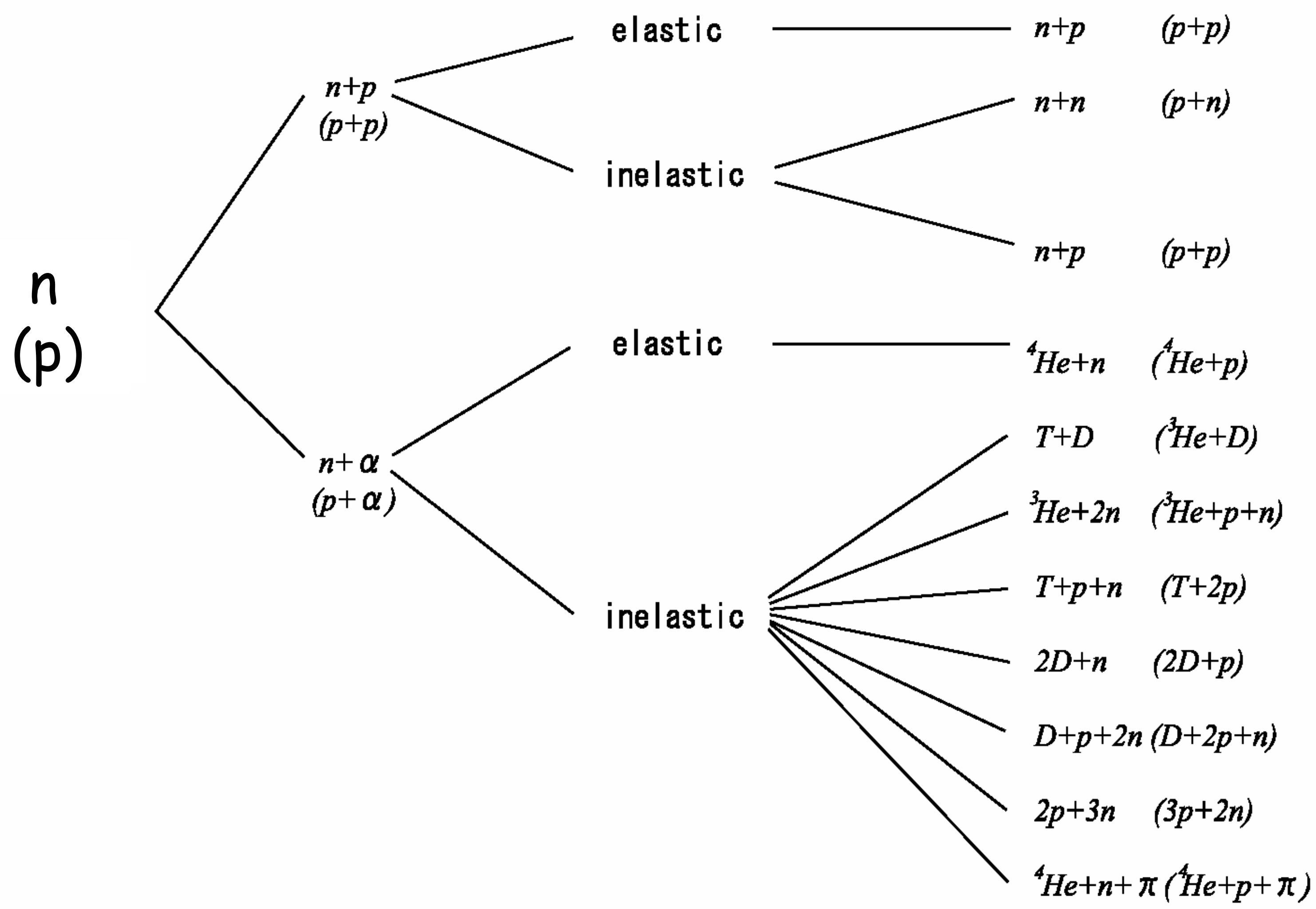
Even after freeze-out of n/p in SBBN

More He4, D, Li7 …

(II) Late stage of BBN (T < 0.1MeV)

Hadronic showers and "Hadro-dissociation"

S. Dimopoulos et al. (1988)
Kawasaki, Kohri, Moroi (2004)

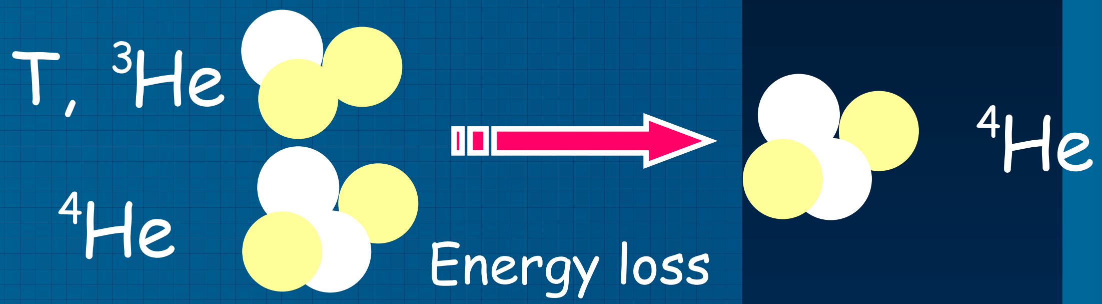


Non-thermal Li, Be Production by energetic nucleons or photons

Dimopoulos et al (1989)
Jedamzik (2000)

$$\mathrm{N}\ (\text{or}\ \gamma) + {}^4\mathrm{He} \rightarrow \begin{cases} {}^3\mathrm{He} + \mathrm{X} \\ \mathrm{T} + \mathrm{X} \end{cases}$$

$$\mathrm{N}\ (\text{or}\ \gamma) + {}^4\mathrm{He} \rightarrow {}^4\mathrm{He}^* + \mathrm{X}$$



① T(He3) – He4 collision

$$\mathrm{T} + {}^4\mathrm{He} \rightarrow {}^6\mathrm{Li} + n \quad [8.4\ \mathrm{MeV}]$$

$${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^6\mathrm{Li} + p \quad [7.0\ \mathrm{MeV}]$$

② He4 – He4 collision

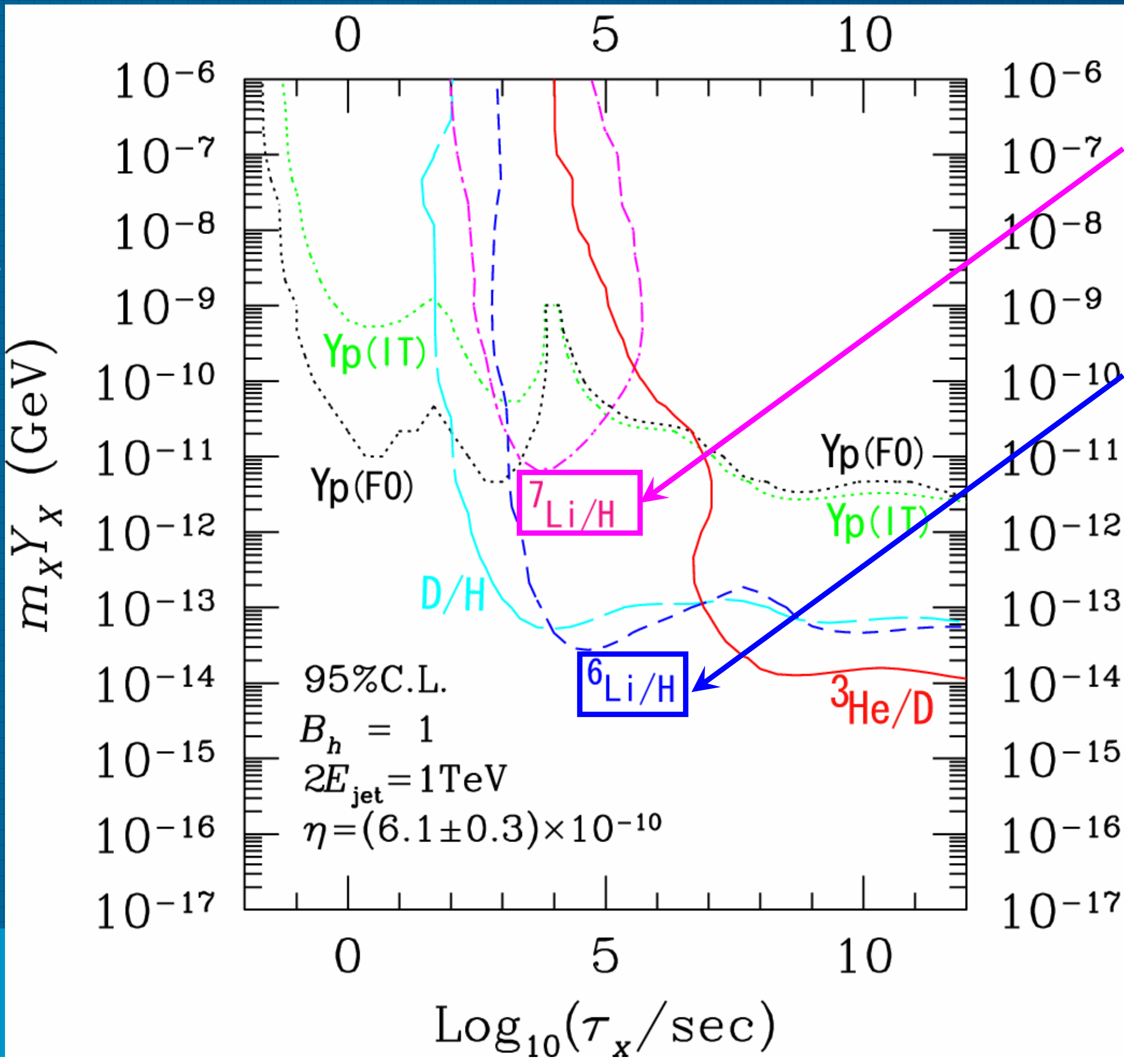
$${}^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^6\mathrm{Li}, {}^7\mathrm{Li}, {}^7\mathrm{Be} + \ldots$$

Massive particle X

Upper bounds on $m_x Y_x$ in both photodissociation and "hadrodissociation" scenario

Kawasaki, Kohri, Moroi (04)

$$Y_x \equiv n_x / s$$



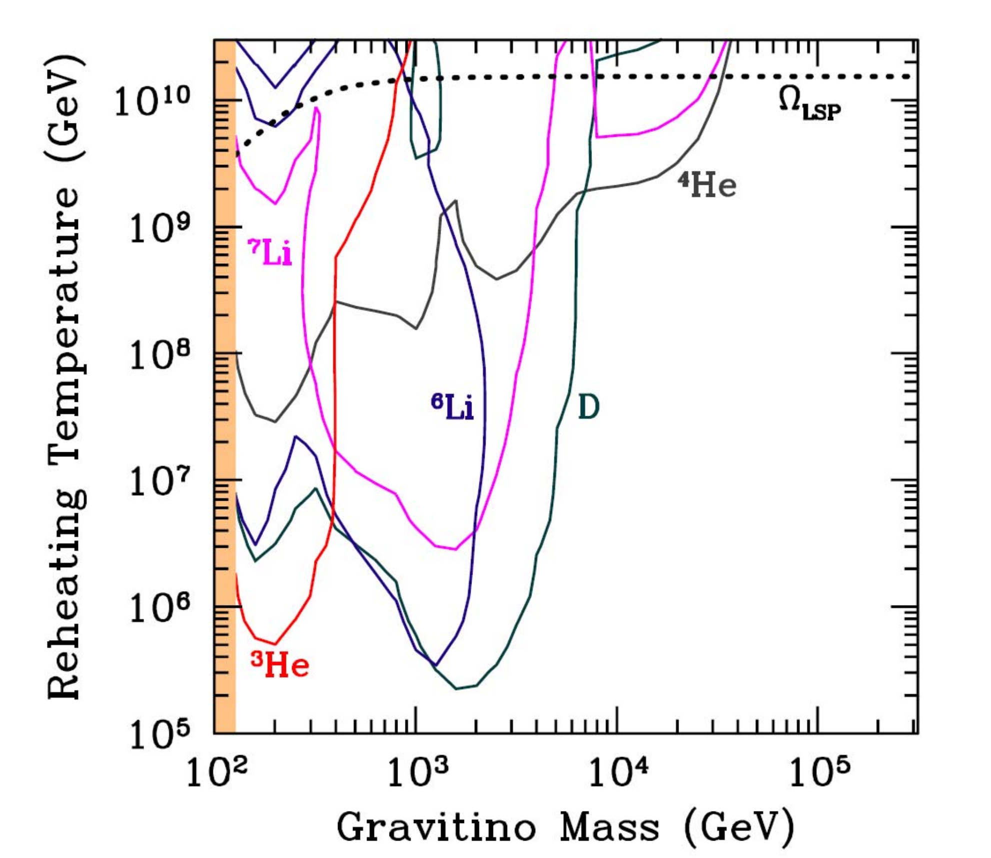
Mild observational upper bound

Mild observational upper bound

Neutralino (bino) LSP and gravitino "NLSP"

Upper bound on reheating temperature in case of gravitino NLSP and neutralino LSP scenario

Kawasaki, Kohri, Moroi, Yotsuyanagi (08)



$$T_R \approx 10^9 \, GeV \left(Y_{3/2} / 10^{-12} \right)$$

$$\tau \sim 10^6 \sec (m_{3/2} / 10^2 \mathrm{GeV})^{-3}$$

	Case 1
$m_{1/2}$	300 GeV
m_0	141 GeV
A_0	0
$\tan\beta$	30
μ_H	389 GeV
$m_{\chi_1^0}$	117 GeV
$\Omega_{\rm LSP}^{\rm (thermal)} h^2$	0.111

$$Y_x \equiv n_x / s$$

Neutralino (bino) NLSP and gravitino LSP

Gravitino LSP and thermally porduced neutralino (Bino) "NLSP" scenario

Feng, Su, and Takayama (03)

Steffen (06)

Kawasaki, Kohri, Moroi, Yotsuyanagi (08)

Lifetime

$$\tau \sim m_{3/2}^2 m_{pl}^2 / m_{NLSP}^5$$

Relic abundance

$$Y_{\tilde{B}} = 4 \times 10^{-12} \times \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right) \quad : \text{bulk}$$

No allowed region for DM density