Big-bang nucleosyntheis and a hint to solve problems in astrophysics, cosmology and particle physics

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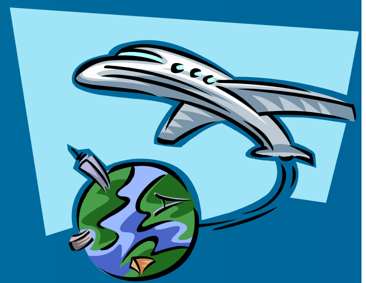


Contents

- Brief review of Big-bang Nucleosynthesis (BBN)
- Brief review of Supersymmetry (SUSY) and Supergravity (SUGRA)
- Cosmological and astrophysical constraints on Lightest SUSY Particle (LSP) and Next LSP (NLSP)
- Solving lithium problem

Brief review of
Big-bang nucleosynthesis (BBN)

Thermal history of the Universe

Big bang

cf) 1 GeV ~ 10^{13}K

time	"temperature"		
10^{-114} sec	10^{18} GeV	Planck scale	Inflation and Reheating (Planck scale – GUT phase transition?)
10^{-38} sec	10^{16} GeV	GUT phase transition?	Baryogenesis? (GUT phase transition? – Electroweak phase transition)
10^{-11} sec	10^{2} GeV	Electroweak phase transition	
10^{-5} sec	200 MeV	QCD phase transition	
0.1 sec	3 MeV	Neutrino decoupling	Big-Bang Nucleosynthesis (BBN) (Neutrino decoupling – Electron-positron annihilation)
1 sec	0.5 MeV	Electron-positron annihilation	
10^{10} sec	1 eV	Matter-radiation equality	
10^{12} sec	0.1 eV	Photon decoupling (CMB)	
≈			
13.7 Gyr ($\sim 10^{17}$ sec)	10^{-4} eV	Present	

Thermal history around BBN Epoch

cf) 100 MeV ~ 10^{12}K

Time	Temperature	Event	Reaction
10^{-4} sec	100 MeV	Muon annihilation	$(\mu^+ + \mu^- \rightarrow 2\gamma)$
≈			
0.1 sec	2 -- 3 MeV	Neutrino decoupling	$(\nu_e + e^- \not\rightleftarrows \nu_e + e^-)$
1 sec	1 MeV	n/p freezeout	$(n + \nu_e \not\rightleftarrows p + e^-)$
	0.5 MeV	Electron-positron annihilation	$(e^+ + e^- \rightarrow 2\gamma)$
10^2 sec	0.1 MeV	Beginning of BBN	
10^3 sec	0.07 MeV	End of (Standard) BBN	

Scenario of BBN

cf) 1 MeV ~ 10^{10}K

1) $T > 1\ \mathrm{MeV}\ (t < 1\mathrm{sec})$

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

Weak interaction is in equilibrium

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

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

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

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

Feezeout of weak interaction

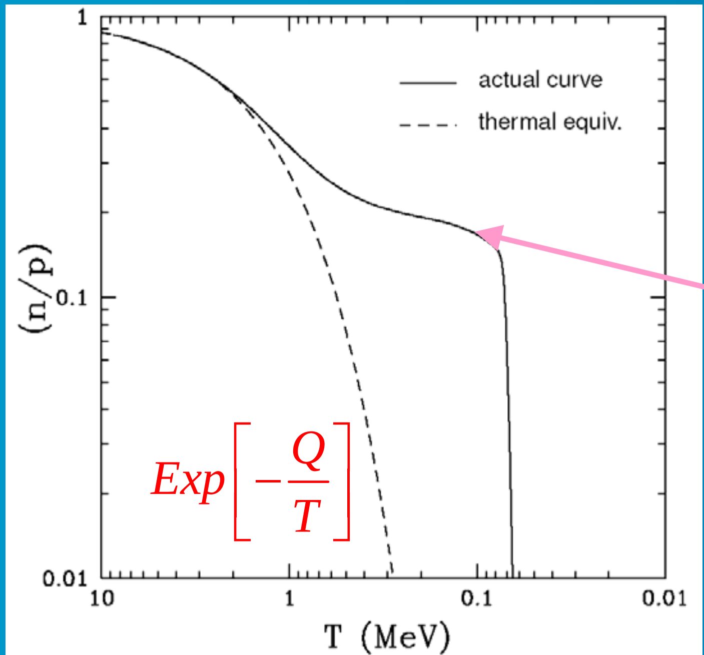
- Weak interaction rate $\Gamma_{n\leftrightarrow p} \sim \sigma_{n\leftrightarrow p} n_e \sim G_F^2 T^5$
- Hubble expansion rate $H = \dfrac{\dot{a}(t)}{a(t)} \sim T^2 / M_{pl}$

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

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

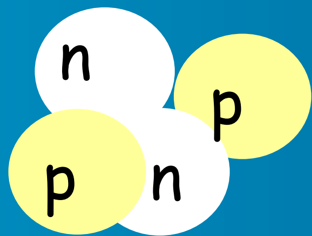
$$\left(\frac{n_n}{n_p} \right)_{\mathrm{freezeout}} \approx Exp\left[-\frac{Q}{T_f} \right]$$

He4 mass fraction



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

^4He



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

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

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.

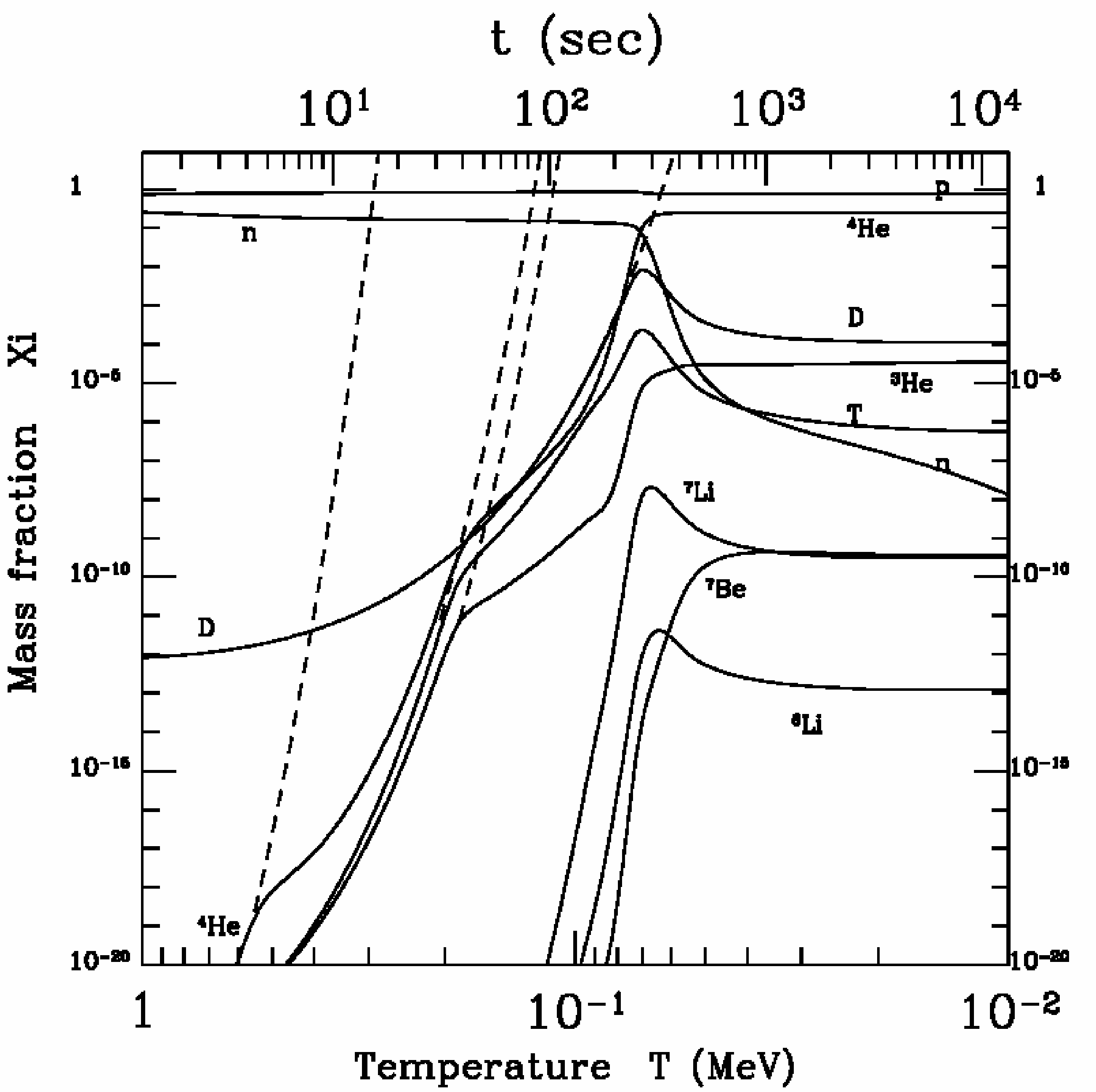
$${}^4\mathrm{He} + T \rightarrow {}^7\mathrm{Li}+\gamma$$

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

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

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

Time evolution of light elements

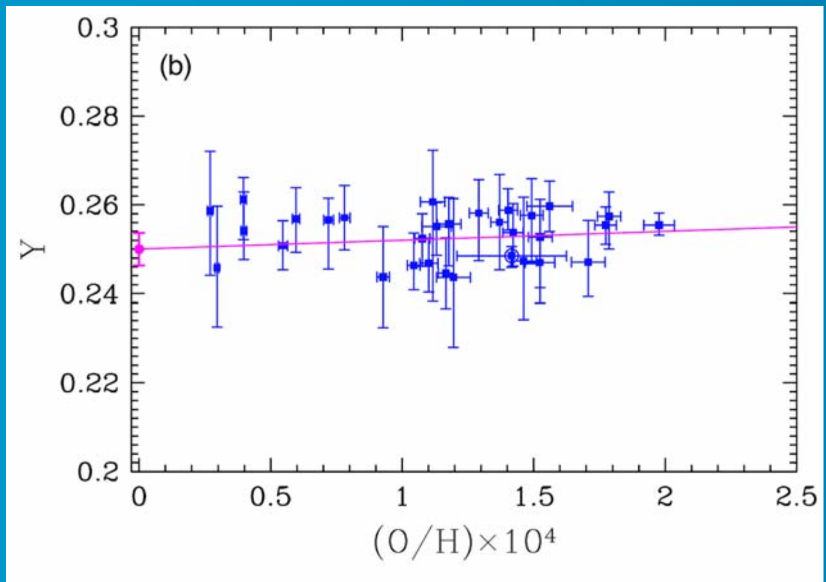


Observational light element abundances

1) ^{4}He

●Observing the recombination line in Metal poor extragalactic H II region, or blue compact galaxy

●Extrapolating them into zero metalicity



Fukugita, Kawasaki (06)

$$Y_p = 0.250 \pm 0.004$$

Fukugita, Kawasaki (06)

$$Y_p = 0.2474 \pm 0.0028$$

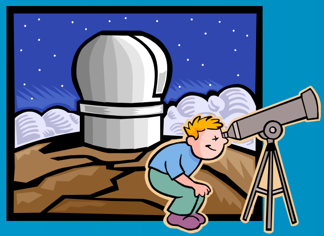
Peimbert, Luridiana, Peimbert (07)

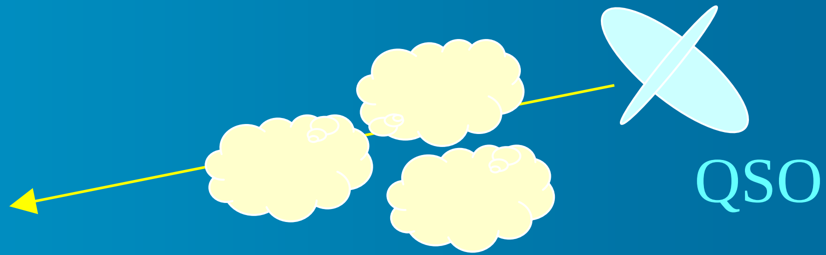
$$Y_p = 0.2516 \pm 0.0011$$

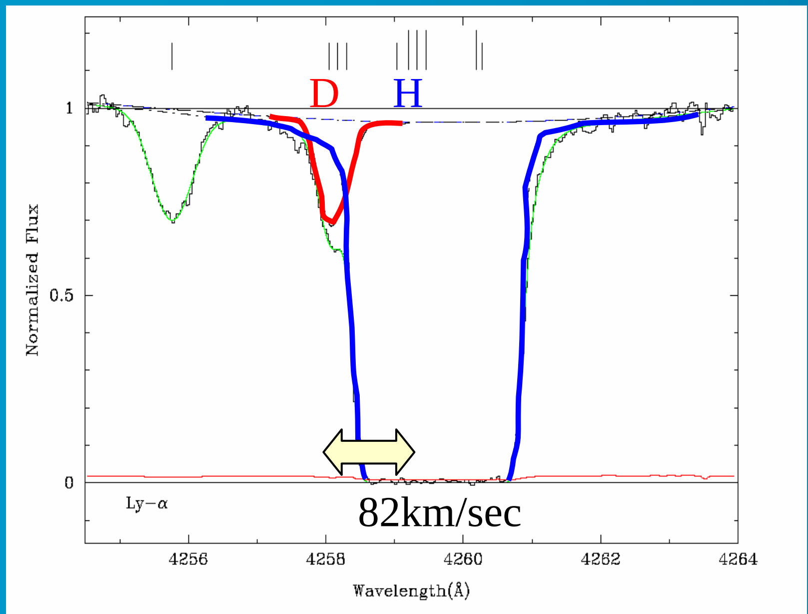
Izotov, Thuan, Stasinska (07)

2) Deuterium

Observed in high redshift QSO absorption system





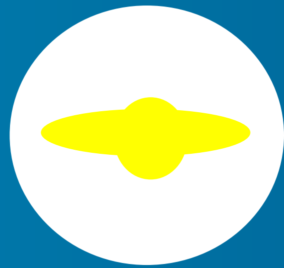


Burles and Tytler (1997)

$$D/H = (2.82 \pm 0.26) \times 10^{-5}$$

O’Meara et al.(2006)

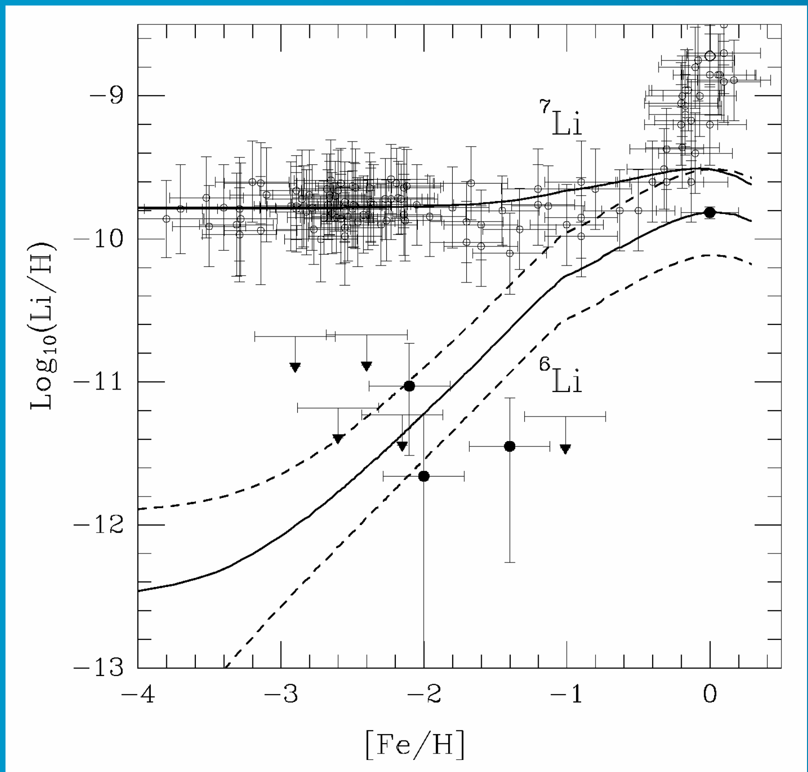
2) Lithium 7



- Observing metal poor halo stars in Pop II
- Abundance does not depend on metalicity so much for

$$T_{\mathrm{eff}} > 5700^{\circ}\mathrm{K}\ (\propto M),\quad [\mathrm{Fe}/H] < \text{-}2$$

"Spite's plateau"



Lemoine et al., 1997

$$\mathrm{Log}_{10}\left({}^{7}\mathrm{Li}/\mathrm{H}\right) = -9.63 \pm 0.06$$

Melendez and Ramirez(2004)

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 $\log_{10}\left({}^7Li/H\right) = -9.63 \pm 0.06\ (\pm 0.3)_{syst.}$

Melendez,Ramirez(2004)

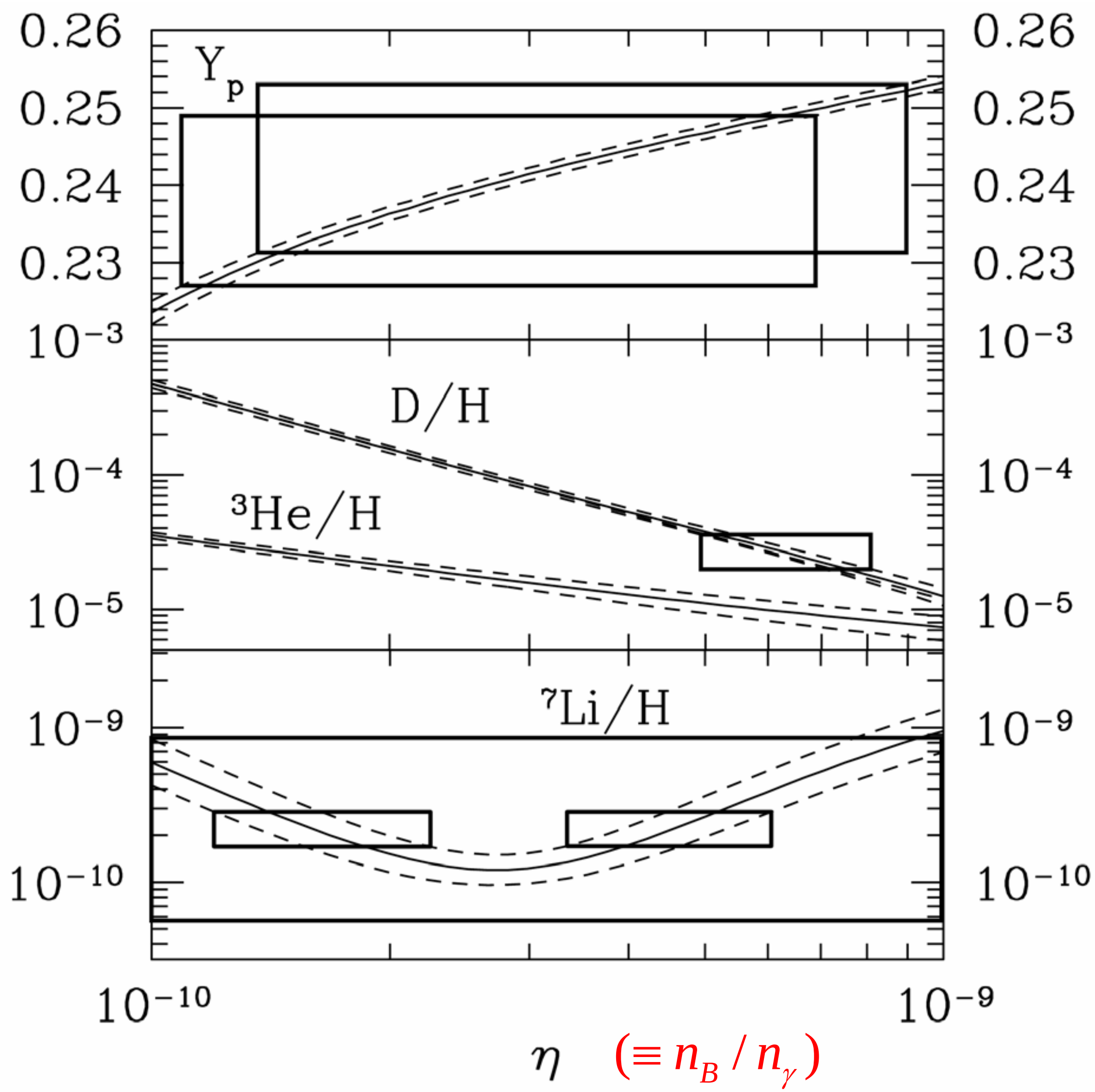
- Li6 ${}^6Li/{}^7Li < 0.046 \pm 0.022\ (\pm 0.084)_{sys}$

Asplund et al(2006)

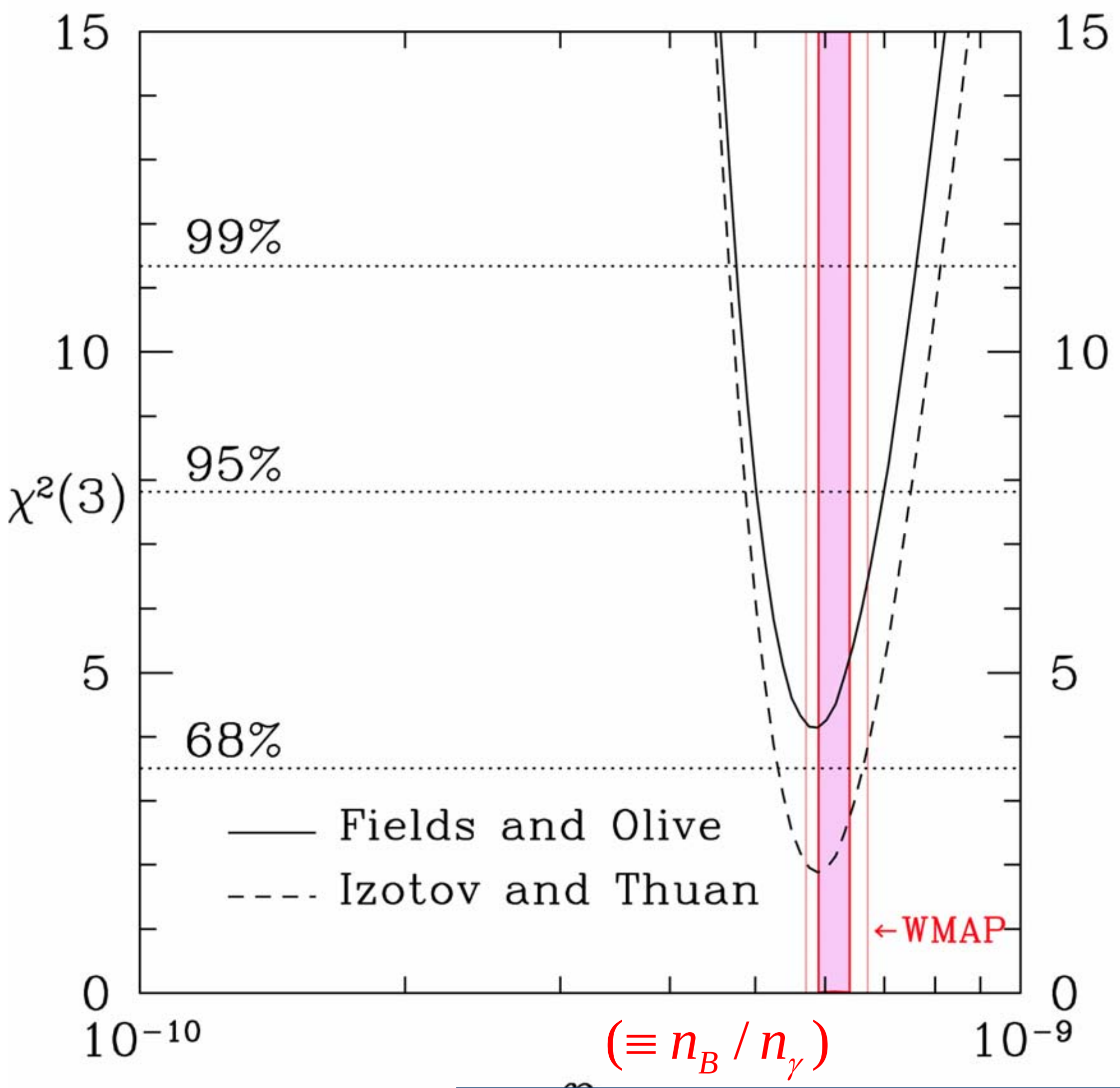
- He3 ${}^3He/D < 0.83 + 0.27$

Geiss and Gloeckler (2003)

SBBN



0.26
0.25
0.24
0.23
Y_p
10^{-3}
10^{-4}
10^{-5}
D/H
^{3}He/H
10^{-9}
10^{-10}
^{7}Li/H
10^{-10}
10^{-9}
$\eta \quad (\equiv n_B / n_\gamma)$



$$\eta_{\mathrm{WMAP}} = (6.225 \pm 0.160) \times 10^{-10}$$

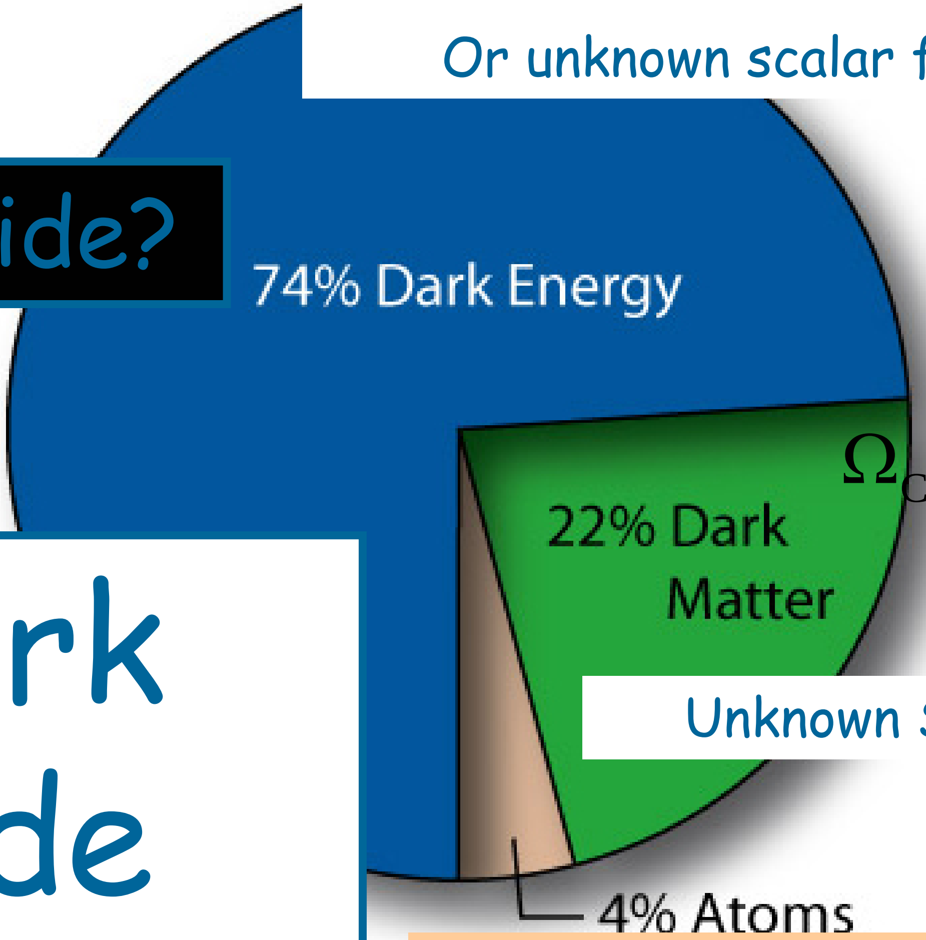
Brief review of Dark Matter (DM) in Supersymmetry (SUSY)

Dark Matter?

Einstein's Cosmological Constant

Or unknown scalar field?

Dark side?



$\Omega_{\mathrm{CDM}} h^2 \sim 0.1$

Dark side?

Unknown SUSY particles?

Dark Side 96%

Light side (Baryon) 4%

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

Realistic candidates of particle dark matter in SUSY/SUGRA

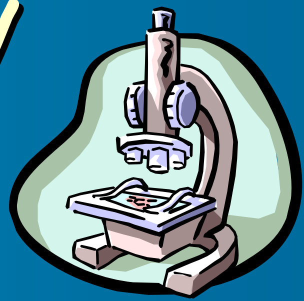
- Neutralino χ (Bino, wino, or higgsinos)

  Most famous Lightest Supersymmetric Particle (LSP) with m_χ ~100GeV (appears even in global SUSY)

- Gravitino ψ_μ

  super partner of graviton with spin 3/2 and $m_{3/2} \lesssim$ 100GeV (massive only in SUGRA (local SUSY))

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

Depending on SUGRA models

Hierarchy Problems

- GUT-scale

$$M_X \approx 10^{14} - 10^{15} GeV$$

- Weak-scale

$$M_W \approx 10^2 - 10^3 GeV$$

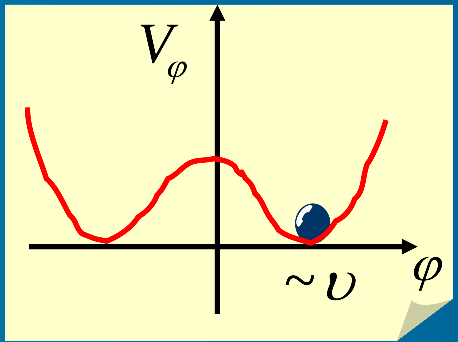
12-13 orders of magnitude !!!

Higgs mass

$$m^2_{\varphi 0} = \frac{d^2 V_\varphi}{d\varphi^2} \approx \lambda \upsilon^2 \approx O(M_W^2)$$

where Higgs's potential

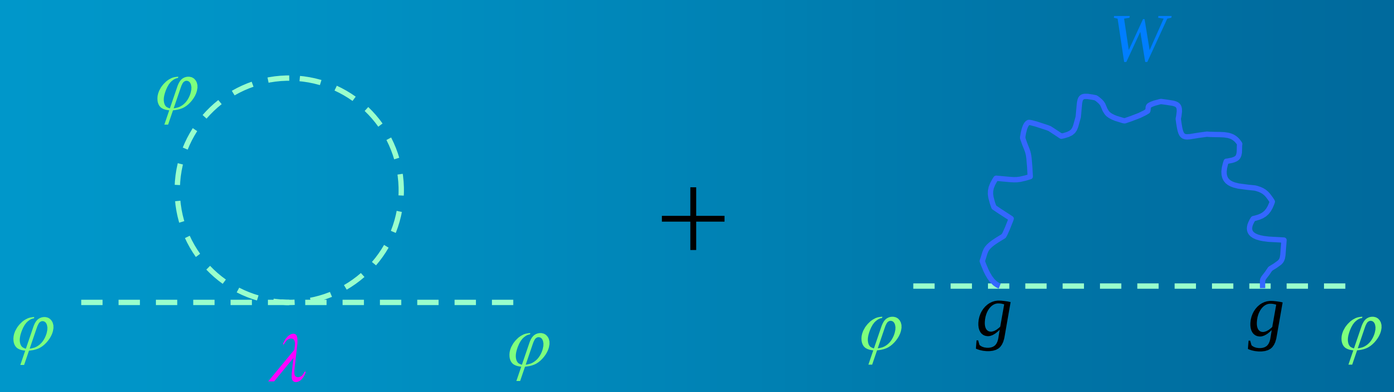
$$V_\varphi = \lambda\left(\varphi^\dagger \varphi - \upsilon^2/2\right)^2$$



c.f) Masses of fermions and vector bosons

$$m_\psi \sim h_\psi \langle\varphi\rangle,\ m_Z \sim g\langle\varphi\rangle$$

Radiative correction to Higgs mass in Quantum Field Theory



$$\delta m_\varphi^2 \sim \lambda\Lambda^2 + g^2\Lambda^2$$ ⬅ Quadratic divergence

Cut off scale $\Lambda \sim M_X \sim 10^{15}$ GeV

$$\delta m_\varphi^2 \sim \left(10^{15}\ \text{GeV}\right)^2 \ ?$$

How can we resolve the problem?

Weak scale in the tree level, $m_{\varphi 0}^2 \sim \left(10^2 GeV\right)^2$

In total, $\delta m_{\varphi}^2 \sim \left(10^{15} GeV\right)^2$

$$m_{\varphi}^2 \sim m_{\varphi\,0}^2 + \delta m_{\varphi}^2 \sim \left(10^{15} GeV\right)^2 \,?$$

To retain the hierarchy, we require an accidental cancellation,

$$m_{\varphi\,0}^2 + \delta m_{\varphi\,1}^2 + \delta m_{\varphi\,2}^2 + \delta m_{\varphi 3}^2 + \ldots \sim \left(10^2 GeV\right)^2 \,?$$

$$\left[O(10^{15} GeV)\right]^2$$

GDP in USA (2002)?

$ 10,110,087,734,958.95

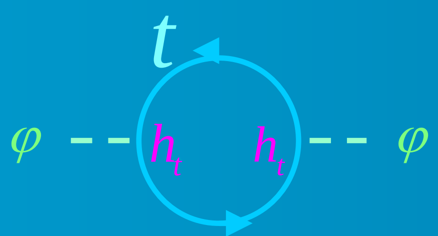
-) $ 10,110,087,734,957.70

$ 1.25

Fine tuning!

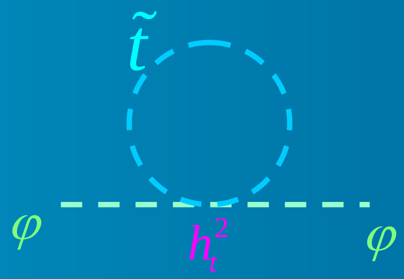
Solution in SUSY

In exact SUSY, the quadratic divergence is canceled by both boson and fermion loops.



$$-\frac{1}{(4\pi)^2} h_t^2 \Lambda^2$$

+



$$\frac{1}{(4\pi)^2} h_t^2 \Lambda^2$$

$= 0$

Exact SUSY

Even if ~~SUSY~~,

$$\delta m_\varphi^2 \sim \frac{1}{(4\pi)^2} h_t^2 m_{\tilde{t}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right)$$

We don't need a fine tuning when

$$m_{\tilde{t}}^2 \sim m_{\tilde{b}}^2 \sim \ldots \sim O(M_W^2)$$

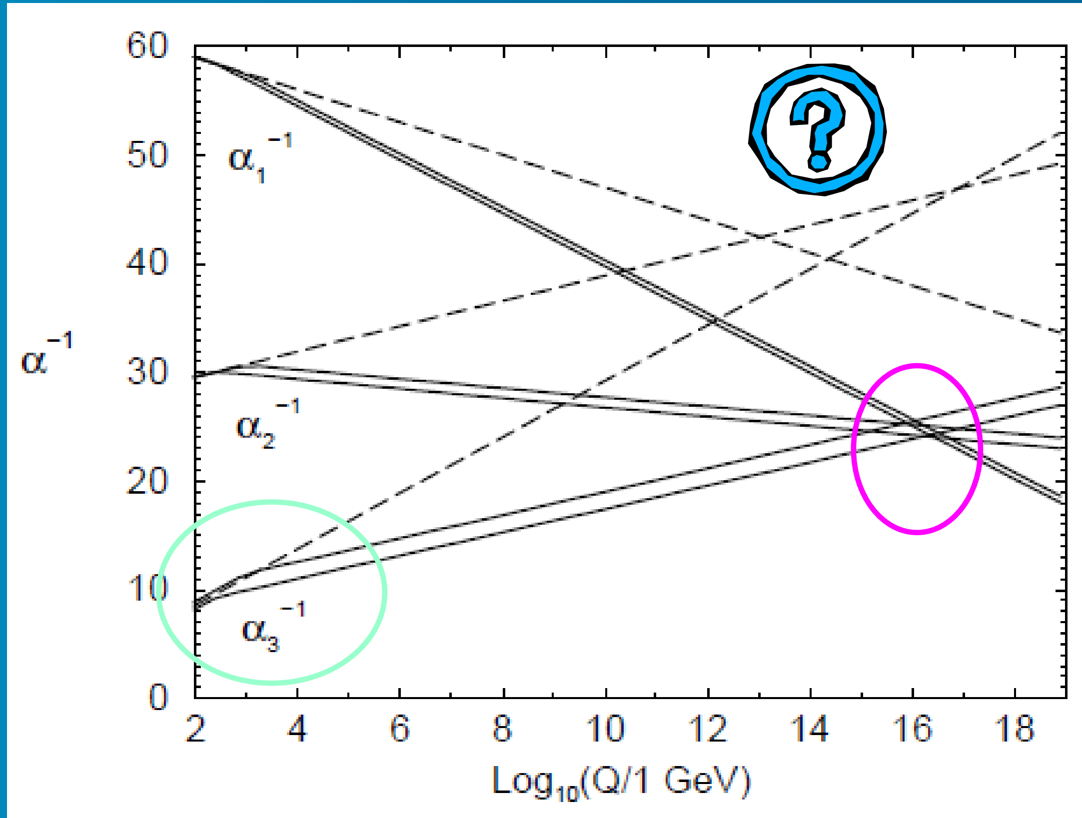
SUSY GUT

The coupling constants are unified at

$$M_X \approx 10^{16} GeV$$

A lot of new particles ,which do not obey the asymptotic free, appear at

$$\mu \geq 10^2 GeV$$



Martin, "A Supersymmetry Primer"

MSSM

- Minimal extension of Standard Model to supersymmetry including two Higgs doublets

$$W_{MSSM} = -\bar{u} y_u Q H_u + \bar{d} y_d Q H_d + \bar{e} y_e L H_d$$

~~$\bar{d} y_d Q H_u^*$~~ because of holomorphism in super pot.

$$H_u = \begin{pmatrix} h_u^+ \\ h_u^0 \end{pmatrix} \qquad H_d = \begin{pmatrix} h_d^0 \\ h_d^- \end{pmatrix}$$

- 105 masses, phases and mixing angles!!!

CMSSM

Constrained MSSM

Simplified into only five parameters from 105

① Common scalar mass at GUT scale: m_0

② Unified gaugino (fermion) mass at GUT scale: $m_{1/2}$

③ Ratio of Higgs vacuum expectation values: $\tan\beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$

④ Higgs/higgsino mass parameter (or its signature): μ

⑤ tri-linear coupling A_0

Super particles in CMSSM

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0 \ H_d^0 \ H_u^+ \ H_d^-$	$h^0 \ H^0 \ A^0 \ H^\pm$
squarks	0	−1	$\widetilde{u}_L \ \widetilde{u}_R \ \widetilde{d}_L \ \widetilde{d}_R$	(same)
			$\widetilde{s}_L \ \widetilde{s}_R \ \widetilde{c}_L \ \widetilde{c}_R$	(same)
			$\widetilde{t}_L \ \widetilde{t}_R \ \widetilde{b}_L \ \widetilde{b}_R$	$\widetilde{t}_1 \ \widetilde{t}_2 \ \widetilde{b}_1 \ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L \ \widetilde{e}_R \ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L \ \widetilde{\mu}_R \ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L \ \widetilde{\tau}_R \ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1 \ \widetilde{\tau}_2 \ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0 \ \widetilde{W}^0 \ \widetilde{H}_u^0 \ \widetilde{H}_d^0$	$\widetilde{N}_1 \ \widetilde{N}_2 \ \widetilde{N}_3 \ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm \ \widetilde{H}_u^+ \ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm \ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

stop

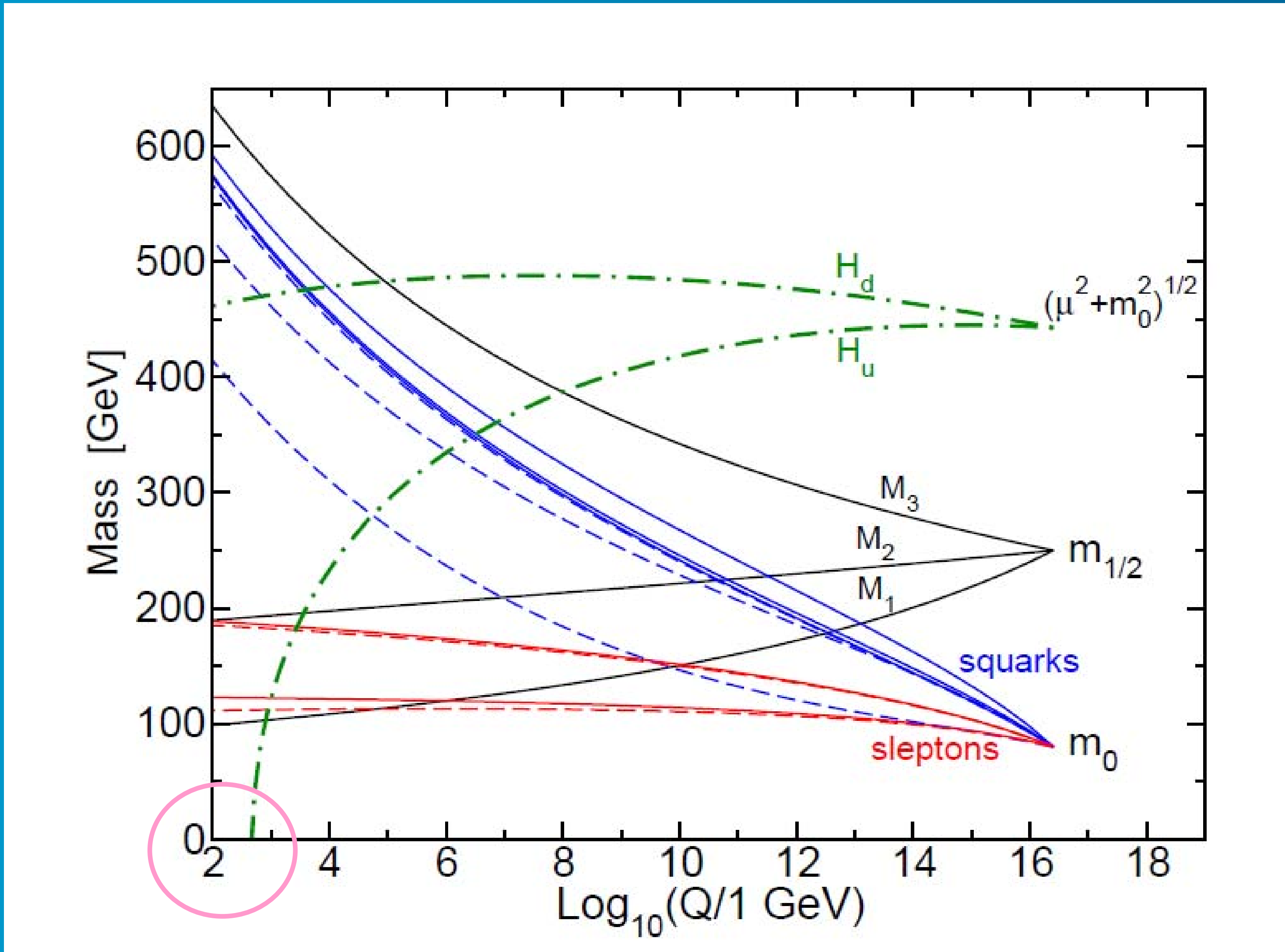
stau

sneutrino

bino, wino, higgsinos

Martin, "A Supersymmetry Primer"

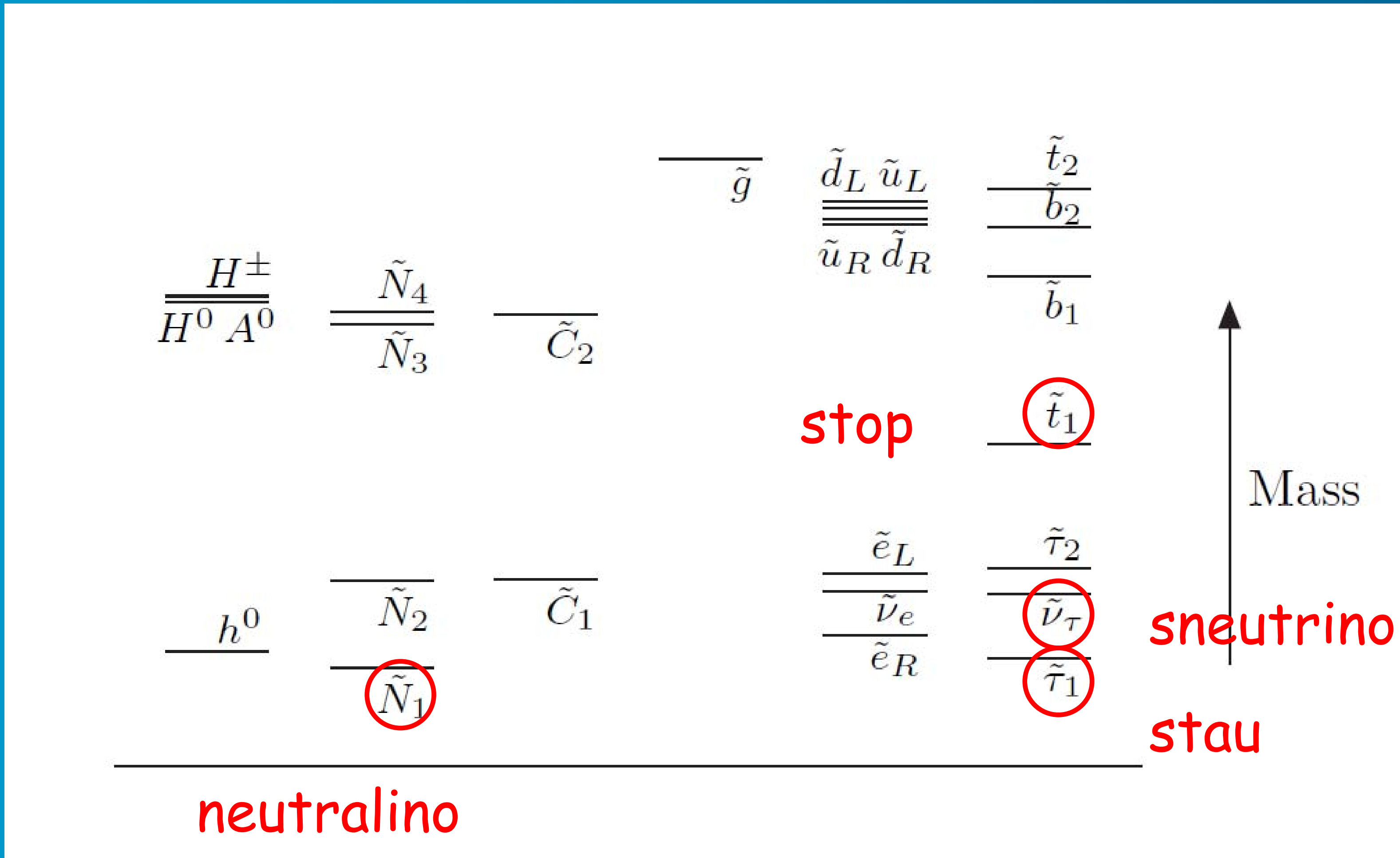
Running of Renormalization Group (RG) Equation in CMSSM



Negative Higgs mass term

Martin, "A Supersymmetry Primer"

Mass spectrum in CMSSM



Martin, "A Supersymmetry Primer"

Lightest SUSY particle (LSP)

- R-parity conservation

i)Decay

$$\tilde{\tau} \rightarrow \chi + \tau$$

(-1) (-1) × (+1)

ii) Pair annihilation/production

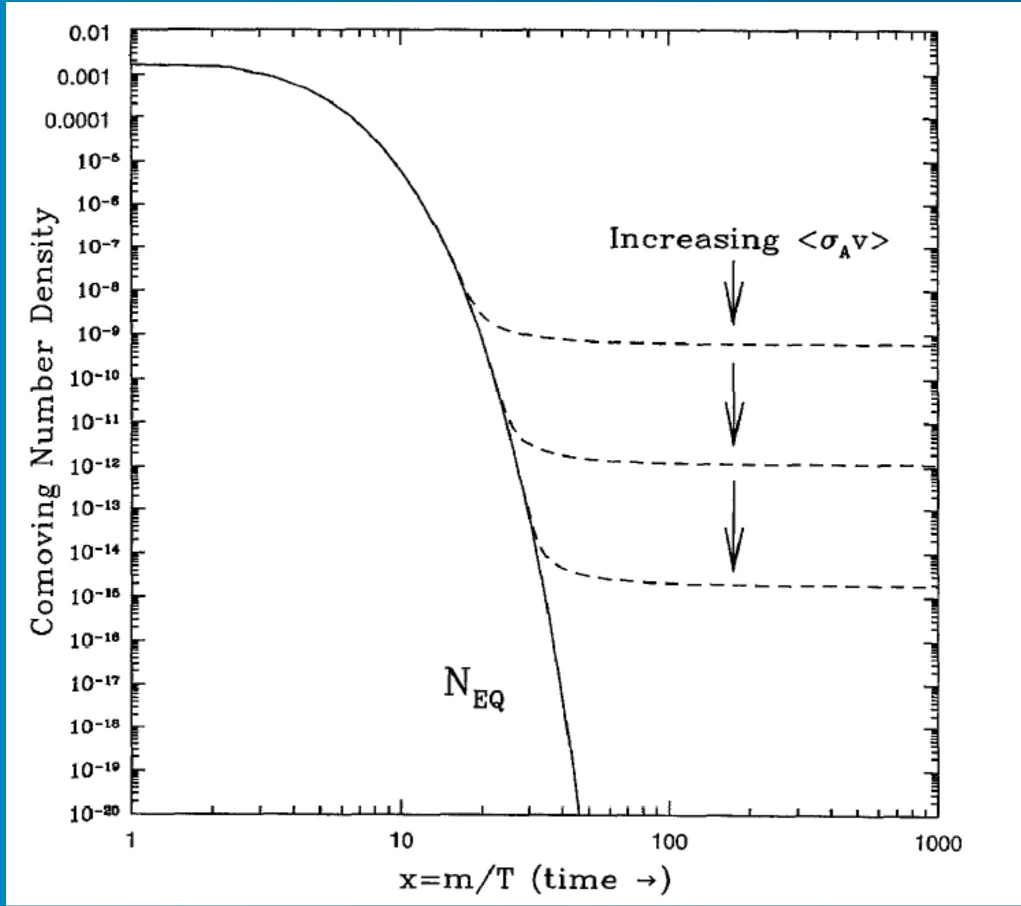
$$f + \overline{f} \leftrightarrow \chi + \chi$$

(+1) × (+1) (-1) × (-1)

Thermal freezeout

Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle [(n_\chi)^2 - (n_\chi^{eq})^2]$$



Kolb & Turner

$$n_\chi \sim \left. \frac{3H}{\langle \sigma v \rangle} \right|_{\text{frezeout}}$$

$$T_{\text{Freezeout}} \sim m_\chi / 30$$

$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\langle \sigma v \rangle}{\left(0.1/\text{TeV} \right)^2} \right)$$

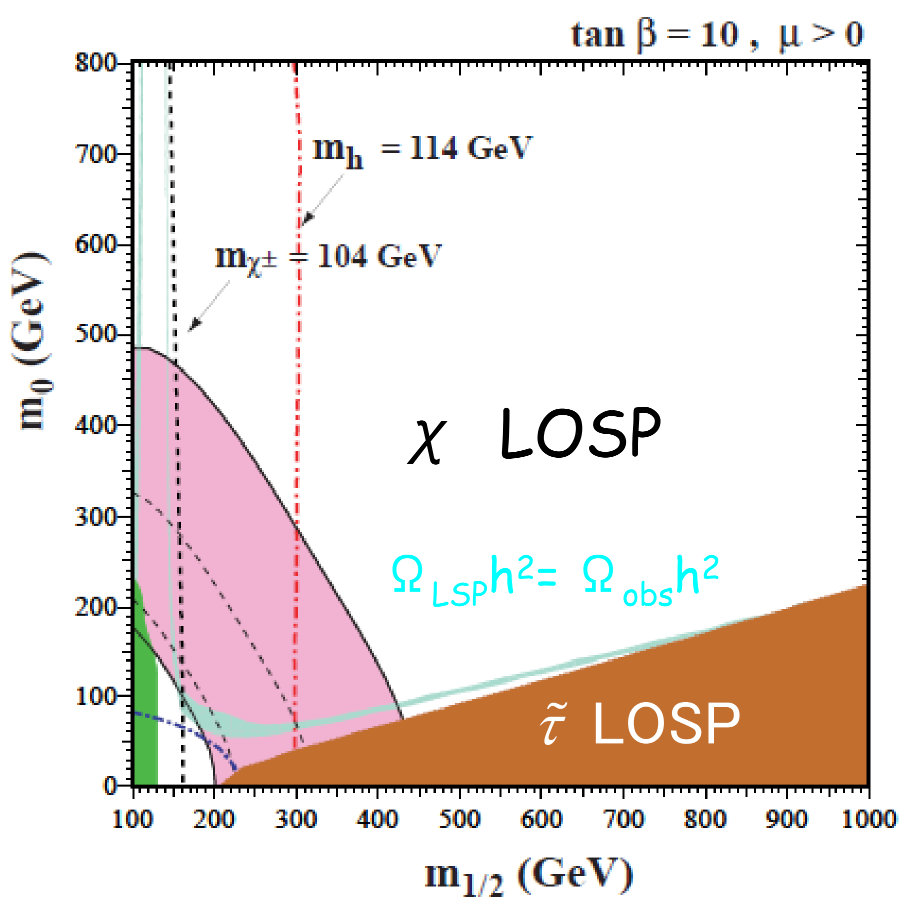
Ω does not depend on m_χ so much

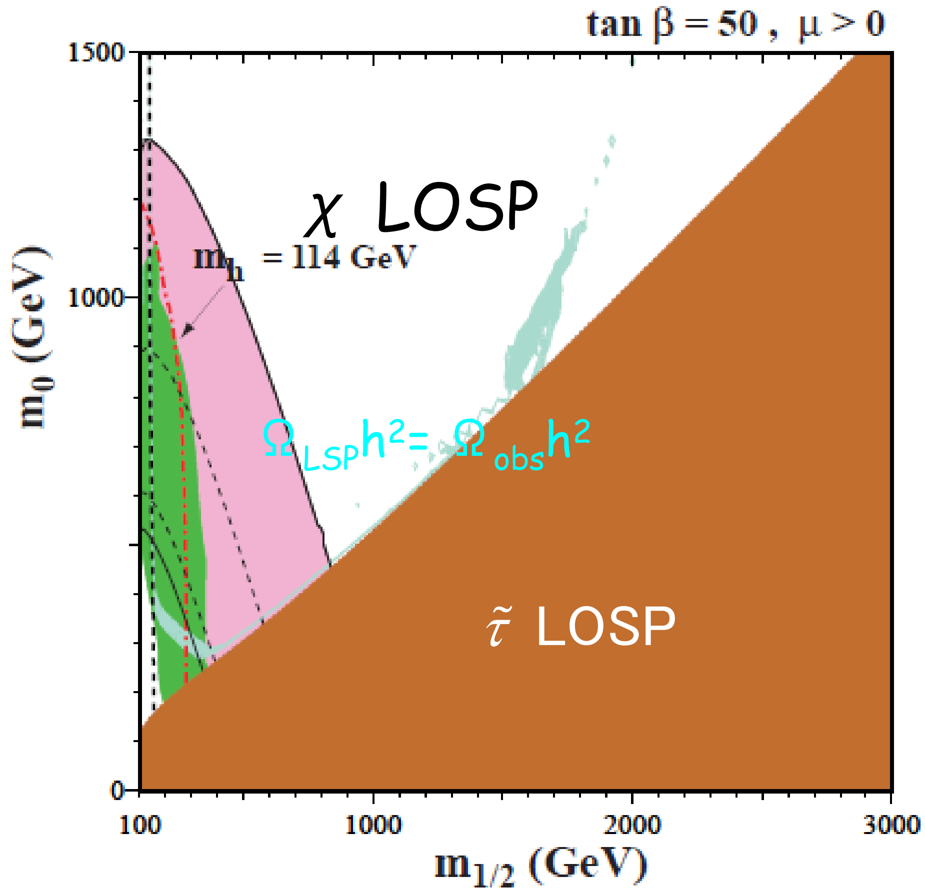
Predicting TeV Physics!!!

$$\langle \sigma v \rangle = 3 \times 10^{-26} cm^3 / s$$

LSP (LOSP) in CMSSM

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





Ellis,Olive,Santoso,Spanos(03)

Supergravitiy (SUGRA)

- Local theory of SUSY
  (predicting gravitino)

- Models of supersymmetry breaking
  (gravitino mass production by eating goldstino which appears in spontaneous symmetry breaking)

- Including general relativity
  (Unifying space-time symmetry with local SUSY transformation)

SUSY Breaking Models

- Gravity mediated SUSY breaking model

Observable sector

quark, squark, …

Only through gravity

Hidden sector

~~SUSY~~

$F \sim 10^{20-21} GeV^2$

- Masses of squarks and sleptons

$$m_{\tilde{q}}, m_{\tilde{\ell}} = F / M_{pl} = 10^2 - 10^3\ GeV$$

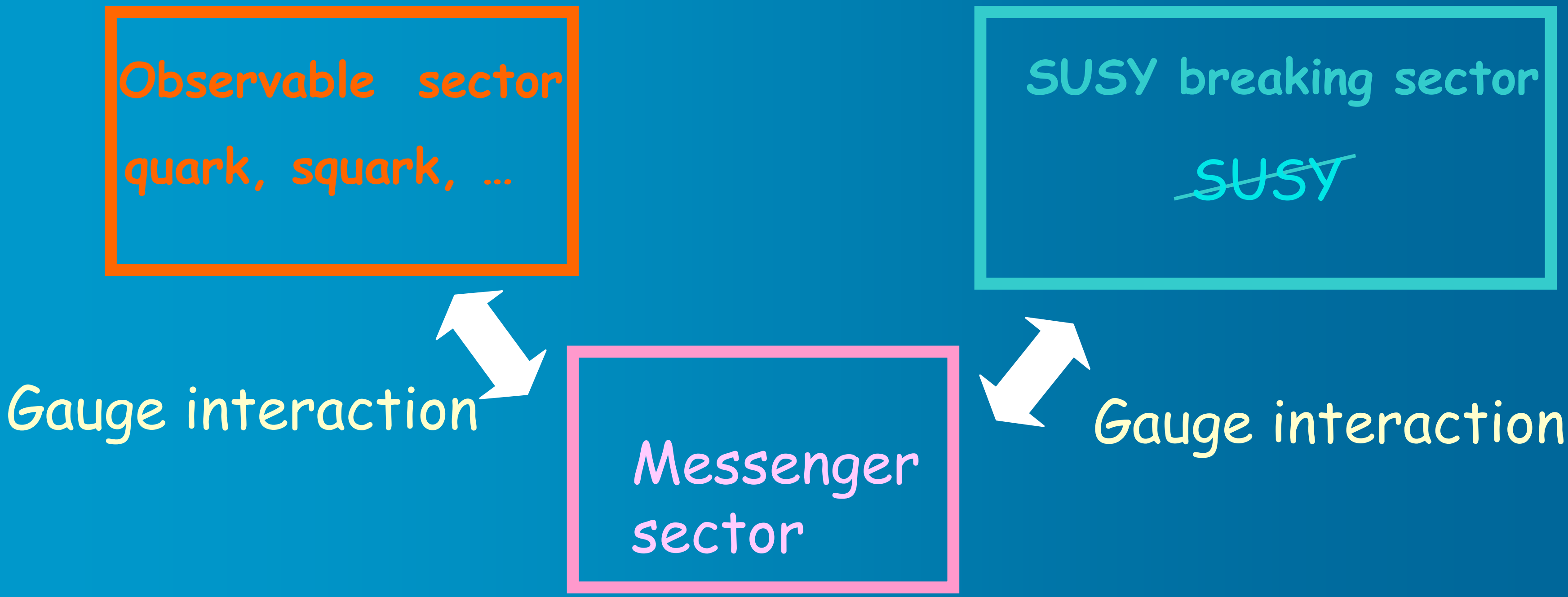
$$(F = 10^{20} - 10^{21}\ GeV)$$

- Gravitino mass

$$m_{3/2} = F / M_{pl} = 10^2 - 10^3\ GeV$$

SUSY Breaking Models II

- Gauge-mediated SUSY breaking model



$$m_{3/2} \sim F / M_p < 10\text{GeV}$$

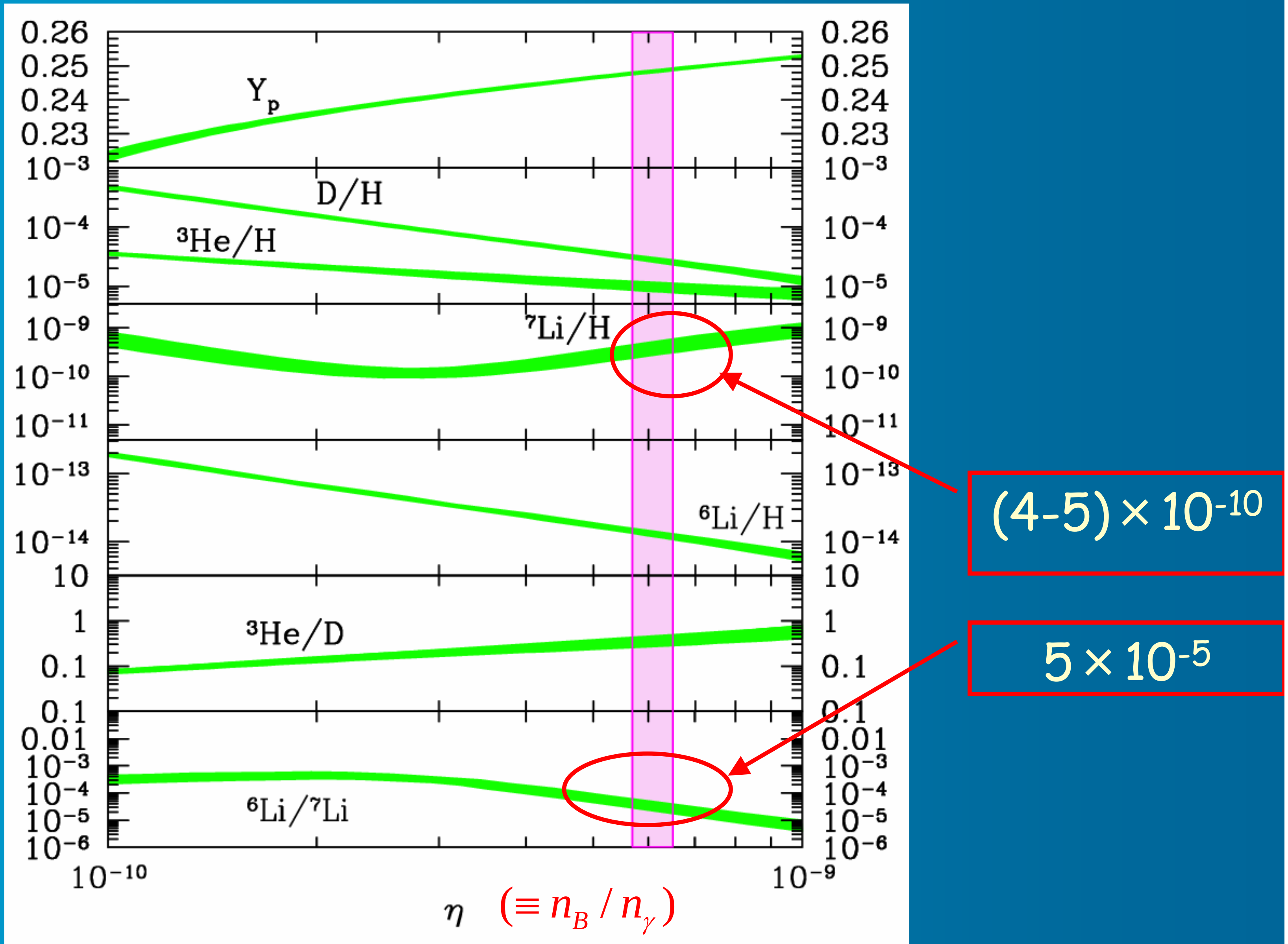
Lightest SUSY particle (LSP) may be necessarily the gravitino

Advanced topics

Lithium Problem

If we adopted no systematic errors for observational data of 6Li and 7Li , the BBN theory does not agree with observation of Li abundances.

SBBN

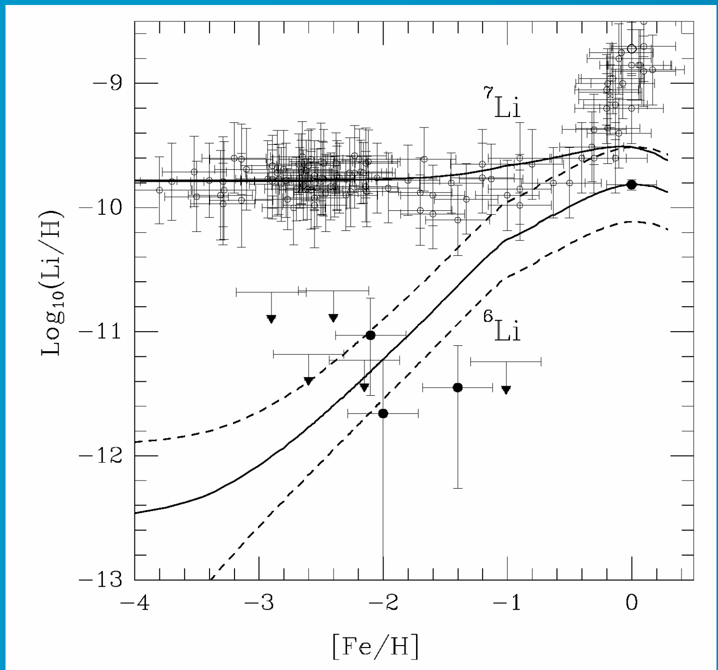


0.26
0.25
0.24
0.23
Yp
10⁻³
D/H
10⁻⁴
³He/H
10⁻⁵
⁷Li/H
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹³
⁶Li/H
10⁻¹⁴
10
³He/D
1
0.1
0.01
⁶Li/⁷Li
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻¹⁰
10⁻⁹
η (≡ n_B / n_γ)
(4-5) × 10⁻¹⁰
5 × 10⁻⁵

Lithium 7

a factor of two or three smaller !!!

- Expected that there is little depletion in stars.



Lemoine et al., 1997

$$^{7}\mathrm{Li/H} = 2.19^{+2.2}_{-1.1} \times 10^{-10} \quad (1\sigma)$$

$$\log\left(^{7}\mathrm{Li/H}\right) = -9.63 \pm 0.06 \ (1\sigma)$$

Bonifacio et al.(2002)

Melendez,Ramirez(2004)

$$^{7}\mathrm{Li/H} = 1.23^{+0.68}_{-0.32} \times 10^{-10} \quad (1\sigma)$$

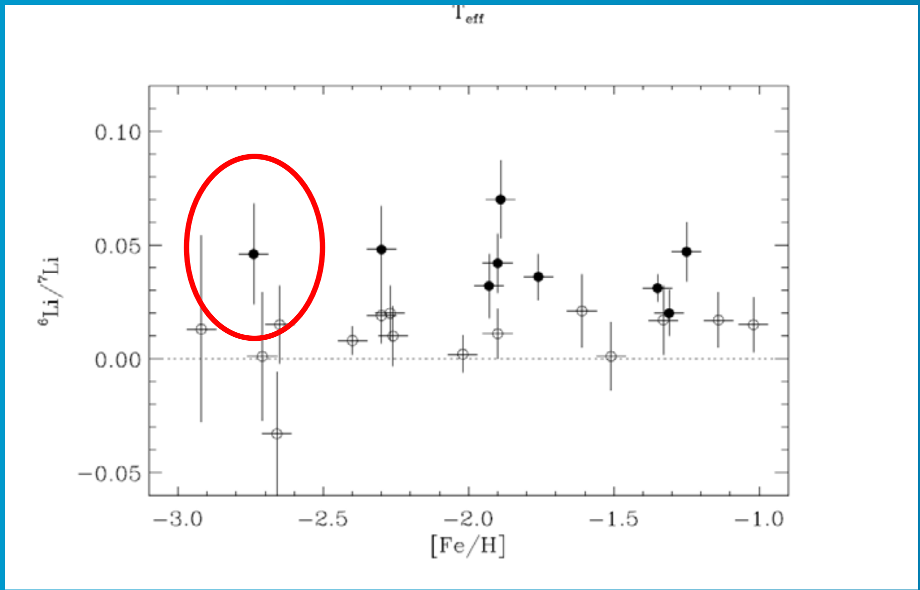
$$\log\left(^{7}\mathrm{Li/H}\right) = -9.90 \pm 0.09 \ (1\sigma)$$

Ryan et al.(2000)

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

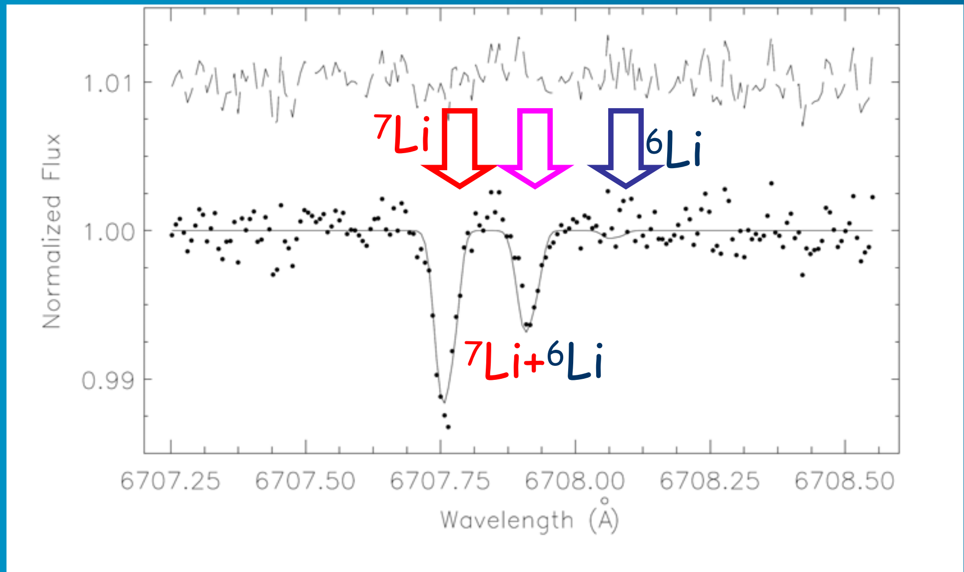
Astrophysically, factor-of-two depletion of Li7 needs a factor of O(10) Li6 depletion (Pinsonneault et al '02)

We need more primordial Li6?

Doppler broadening

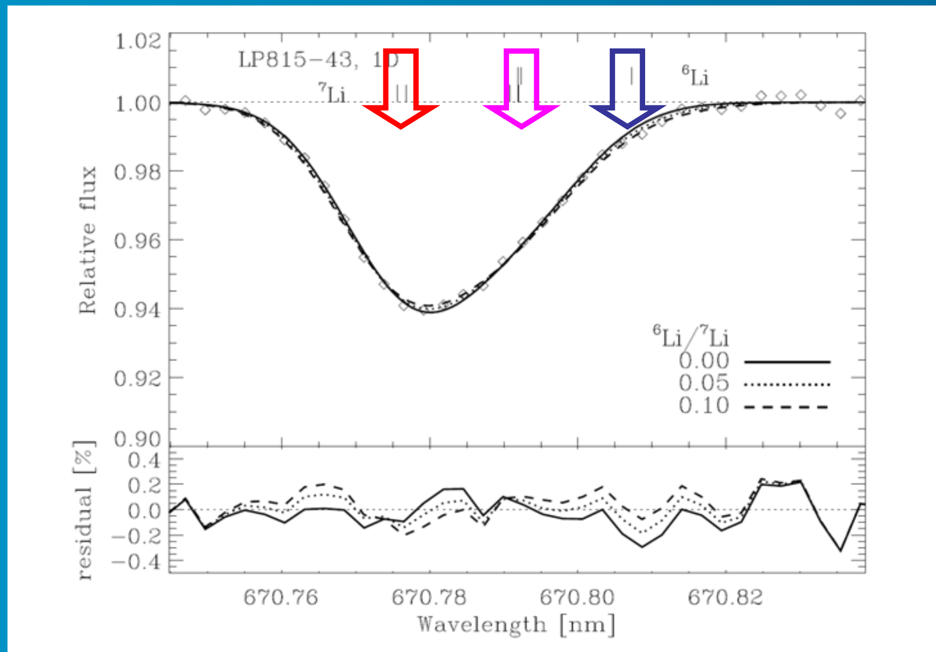
Cold ISM

Knauth,Federman,Lambert (2006)



LP815-43

Asplund et al.(2006)



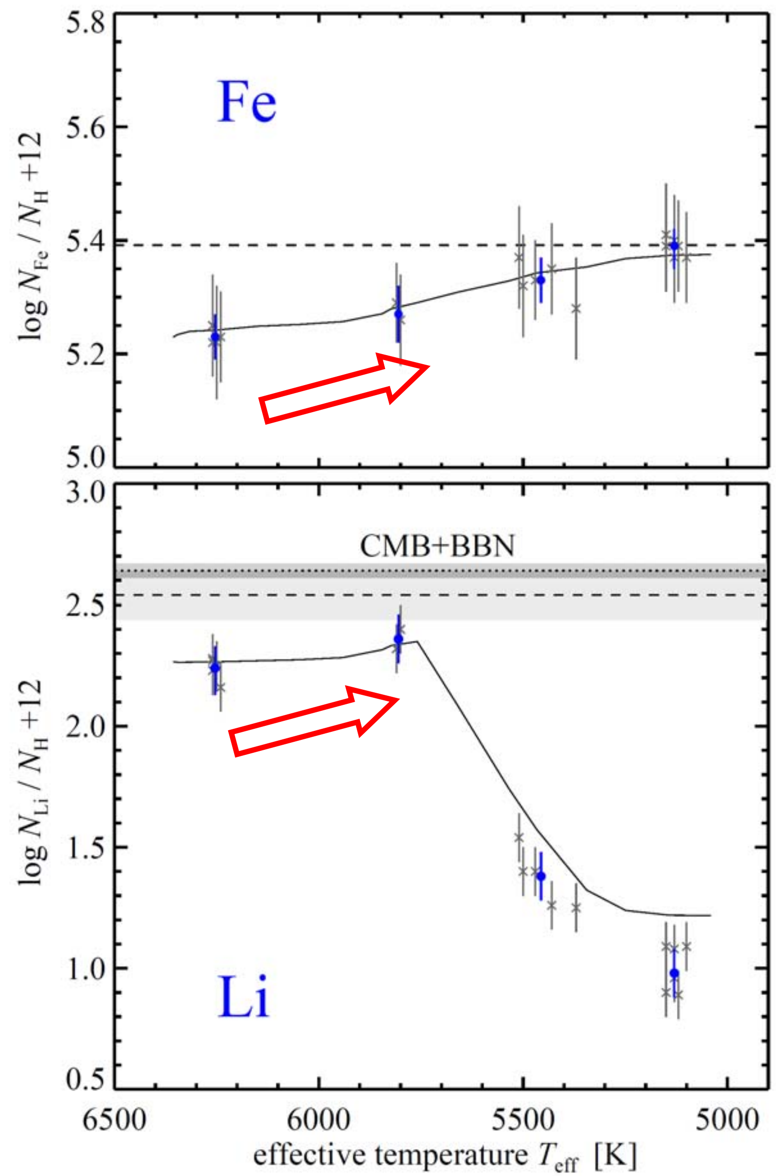
Astrophysical uncertainties in Li7

- Diffusion and convection

Korn et al (2006)

Destruction of Li7 in inner zone of stars

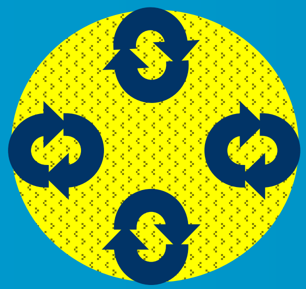
There is a trend of Iron and Li7 as a function of T_{eff}

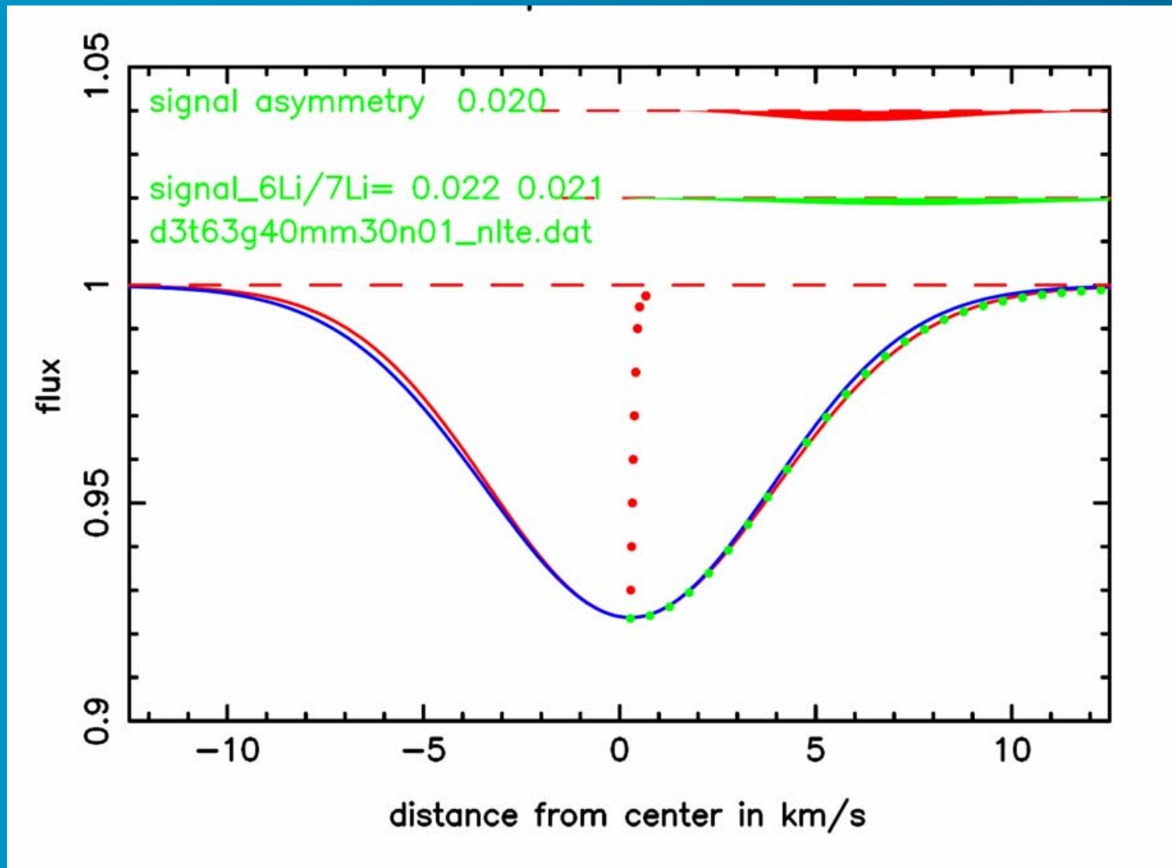


Astrophysical uncertainties in Li6

Cayrel, Steffen, Bonifacio, Ludwig and Caffau (2008)

- Asymmetries of the absorption line mimicked by convective motion





My attitude towards Li problem

It might be premature to accept that these observational values are purely primordial

- Adding large systematic errors by hand and constraining (non-)standard cosmological scenarios

- Inventing a new cosmological/particle-physics model to solve Li problem

Constraints on long-lived SUSY particles from BBN

- We add large systematic errors into observational Li7 and Li6 abundacnes

$$\log_{10}\left({}^{7}\mathrm{Li}/\mathrm{H}\right) = -9.63 \pm 0.06\ (\pm 0.3)_{syst.}$$

Melendez,Ramirez(2004)

$${}^{6}\mathrm{Li}/{}^{7}\mathrm{Li} < 0.046 \pm 0.022\ (\pm 0.084)_{sys}$$

Asplund et al(2006)

Massive particle decaying during/after BBN epoch produces high energy photons, hadrons, and neutrinos

↓

Destruction/production/dilution of light elements

↓

Severer constraints on the number density

Sato and Kobayashi (1977), Lindley (1984,1985), Khlopov and Linde (1984)

Ellis, Kim, Nanopoulos, (1984); Ellis, Nanopoulos, Sarkar (1985)

Kawasaki and Sato (1987)

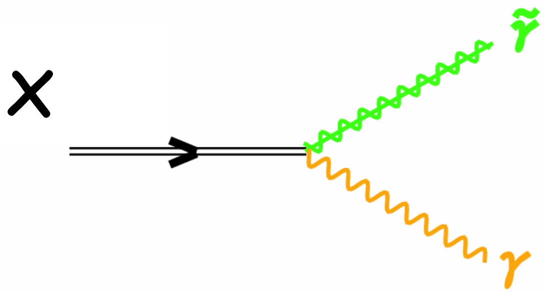
Reno and Seckel (1988), Dimopoulos, Esmailzadeh, Hall, Starkman (1988)

Kawasaki, Moroi (1994), Sigl et al (95), Holtmann et al (97)

Jedamzik (2000), Kawasaki, Kohri, Moroi (2001), Kohri(2001), Cyburt, Ellis, Fields, Olive (2003)

Kawasaki, Kohri, Moroi(04), Jedamzik (06)

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

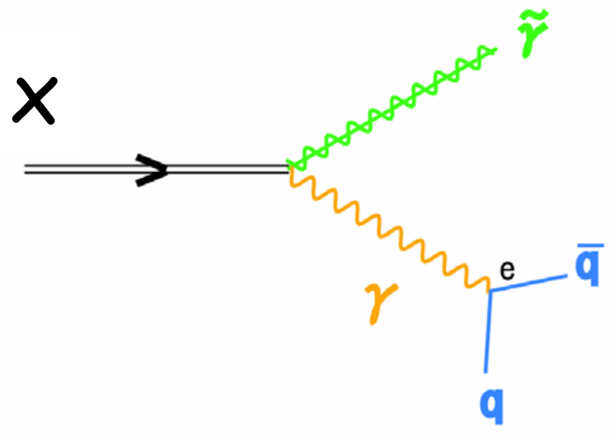
$$\mathrm{D} + \gamma \to p + n,$$
$$^4\mathrm{He} + \gamma \to {}^3\mathrm{He} + n, \quad \mathrm{T} + p, \quad D + p + n$$
$$^3\mathrm{He} + \gamma \to \mathrm{D} + p + n, \quad \mathrm{etc.}$$

He3/D >~ O(1)

Hadronic decay mode

Reno, Seckel (1988)

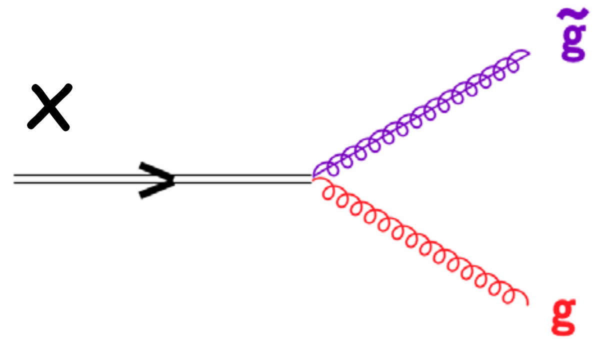
S. Dimopoulos et al.(1989)



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

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) $n + \pi^{+} \rightarrow p + \pi^{0}$ $\quad p + \pi^{-} \rightarrow n + \pi^{0}$

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

Hadron induced exchange

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

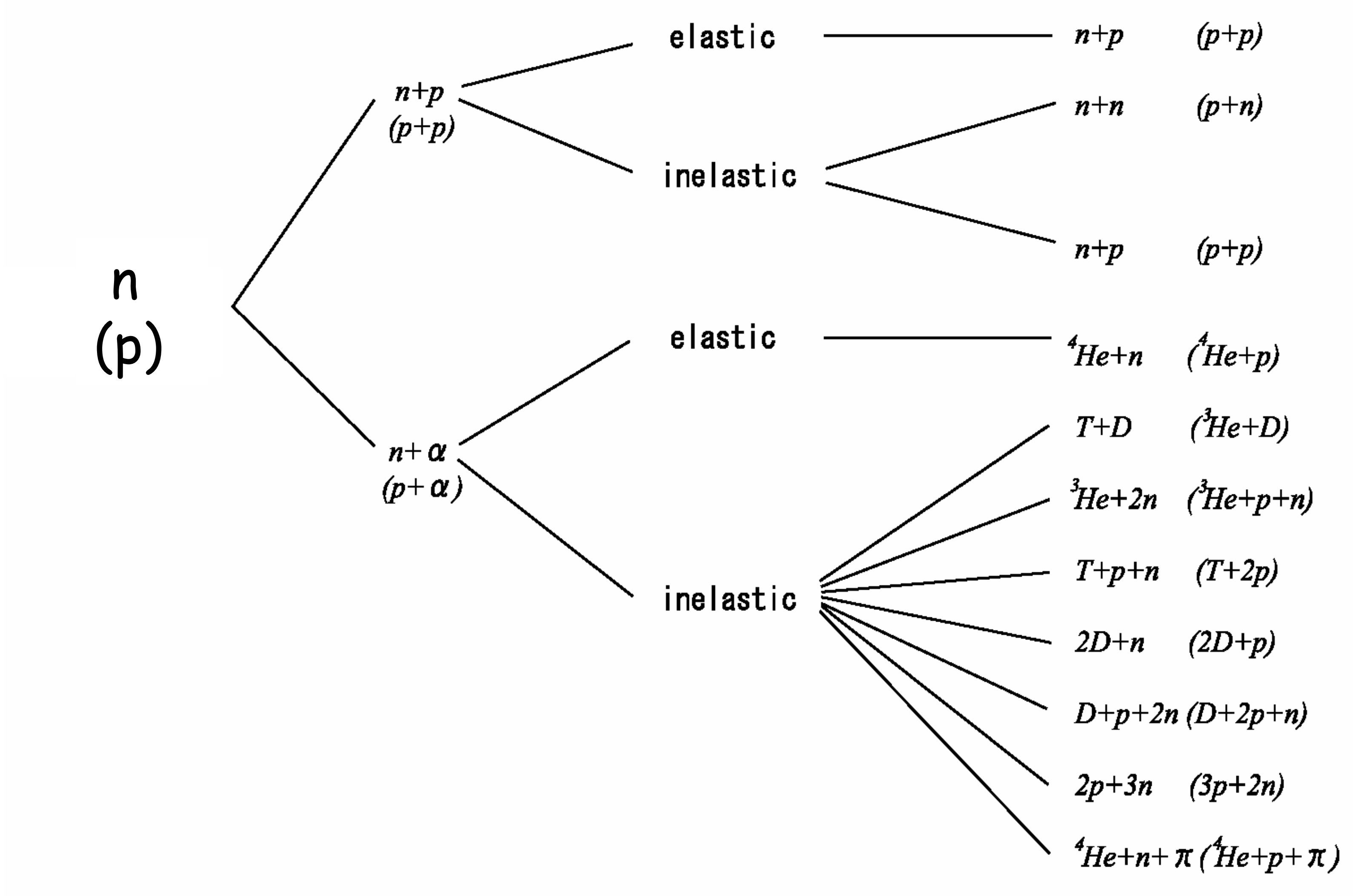
Even after freeze-out of n/p in SBBN

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)

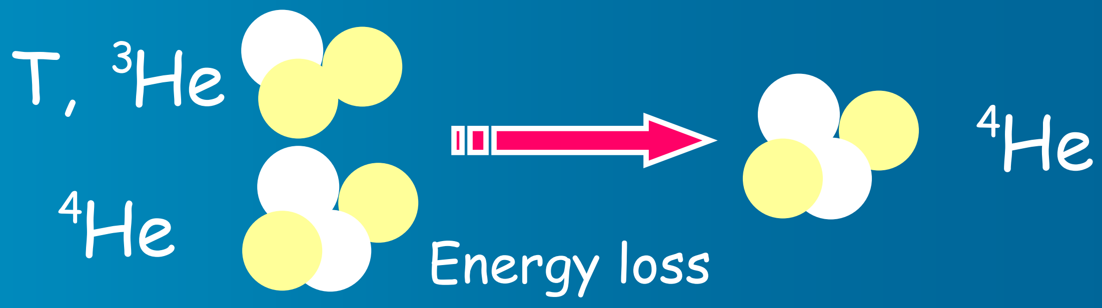


Non-thermal Li, Be Production by energetic nucleons or photons

dimopoulos et al (1989)
Jedamzik (2000)

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

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



① T(He3) – He4 collision

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

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

② He4 – He4 collision

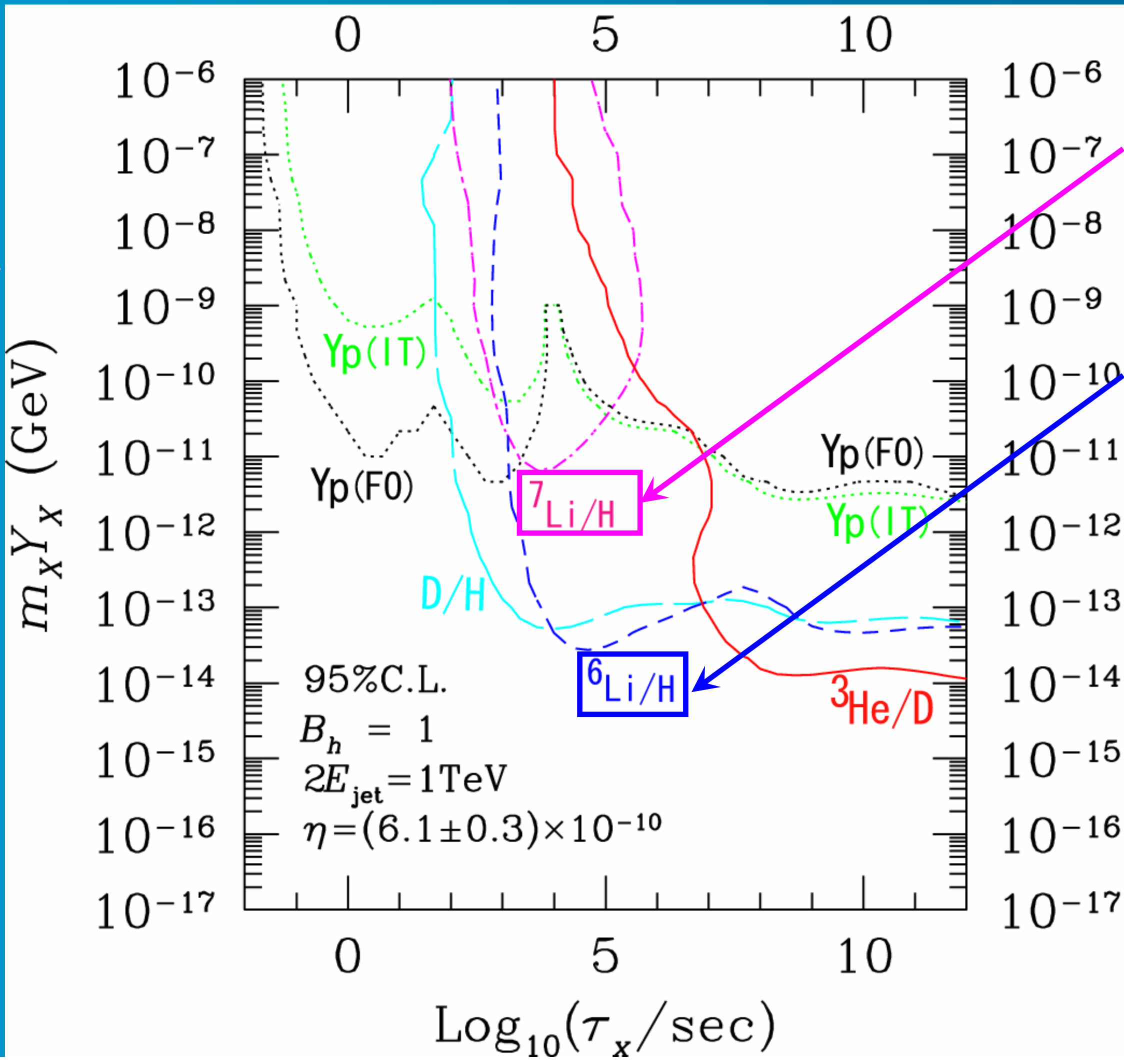
$${}^4He + {}^4He \rightarrow {}^6Li, {}^7Li, {}^7Be + \ldots$$

Massive particle X

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

Kawasaki, Kohri, Moroi (04)

$$Y_x \equiv n_x / s$$



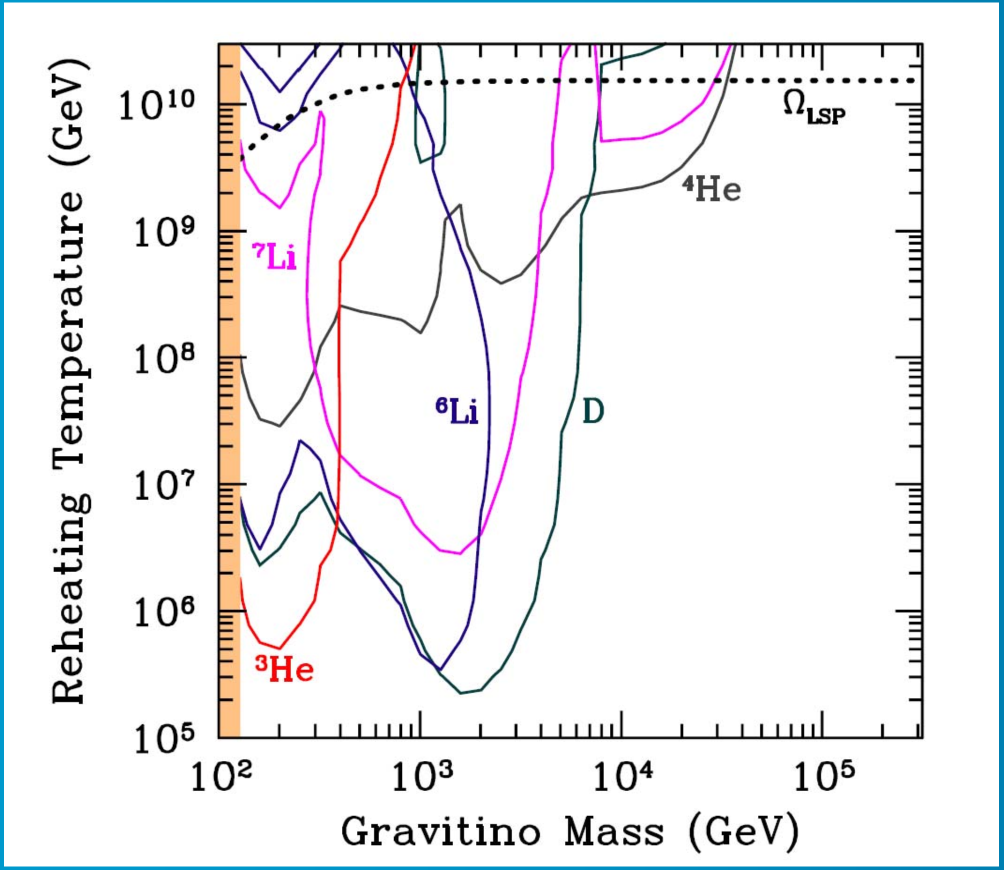
Mild observational upper bound

Mild observational upper bound

Neutralino (bino) LSP and gravitino "NLSP"

Upper bound on reheating temperature

Kawasaki, Kohri, Moroi, Yotusyanagi (08)



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

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

	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)

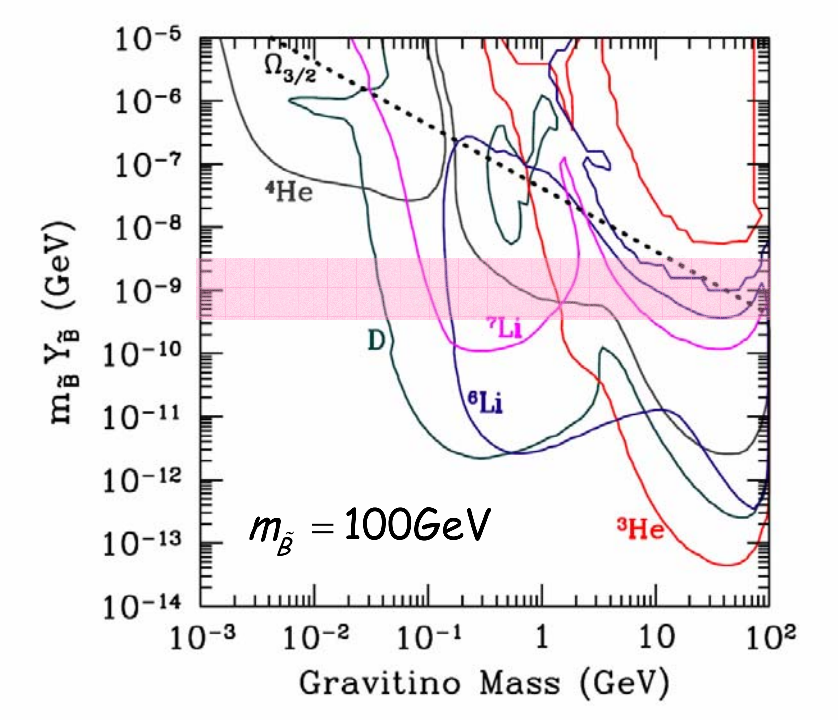
Lifetime

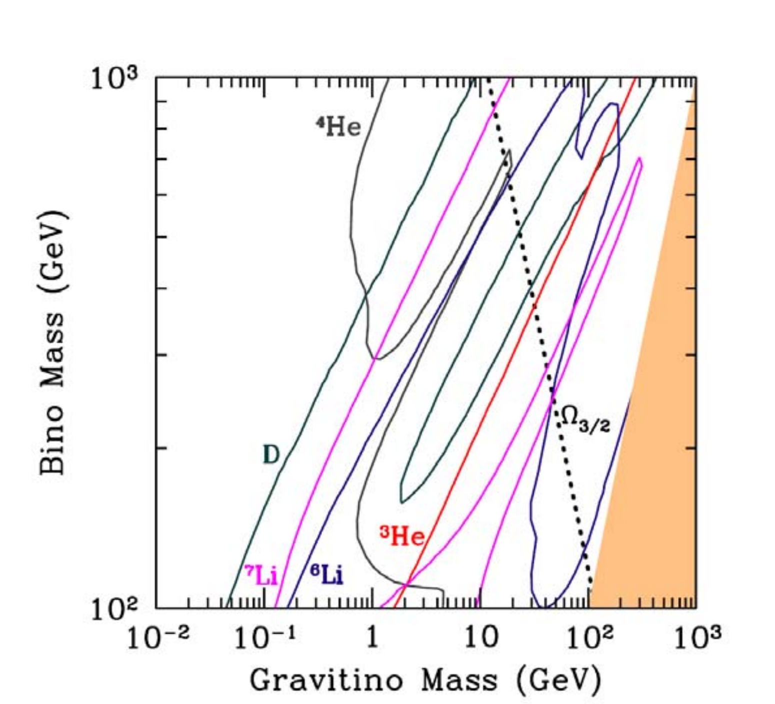
$$\tau \sim m_{3/2}^2 m_{pl}^2 / m_{NLSP}^5$$

Relic abundance

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

No allowed region for DM density





Sneutrino NLSP and gravitino LSP scenario

Stable (left-handed) sneutrino was excluded by the direct detection experiments because of its large cross section directly-coupled with W/Z bosons.

(left-handed) sneutrino should be unstable

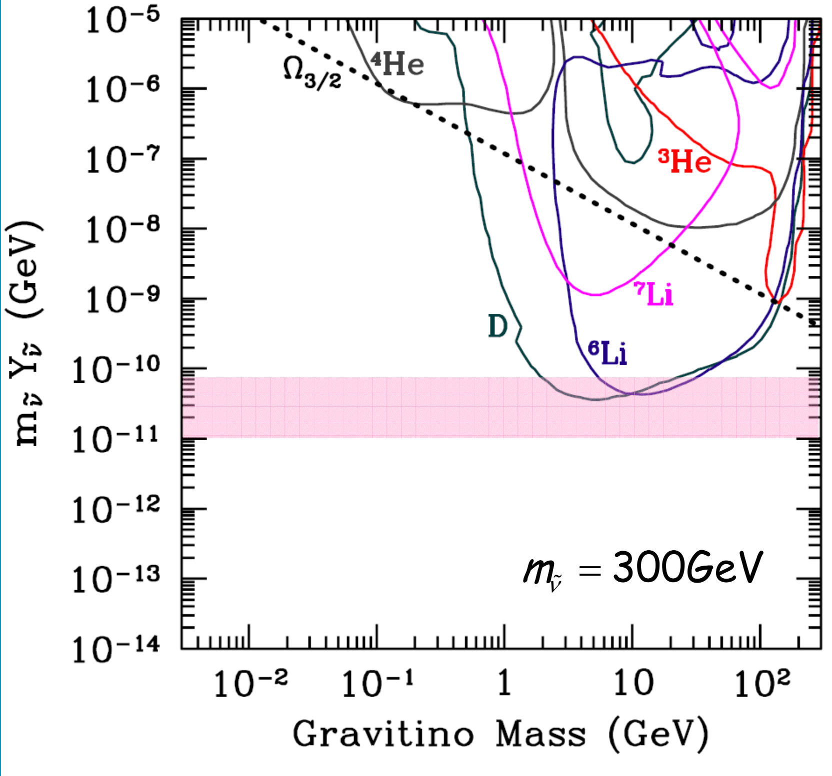
Gravitino LSP and thermally porduced sneutrino NLSP scenario

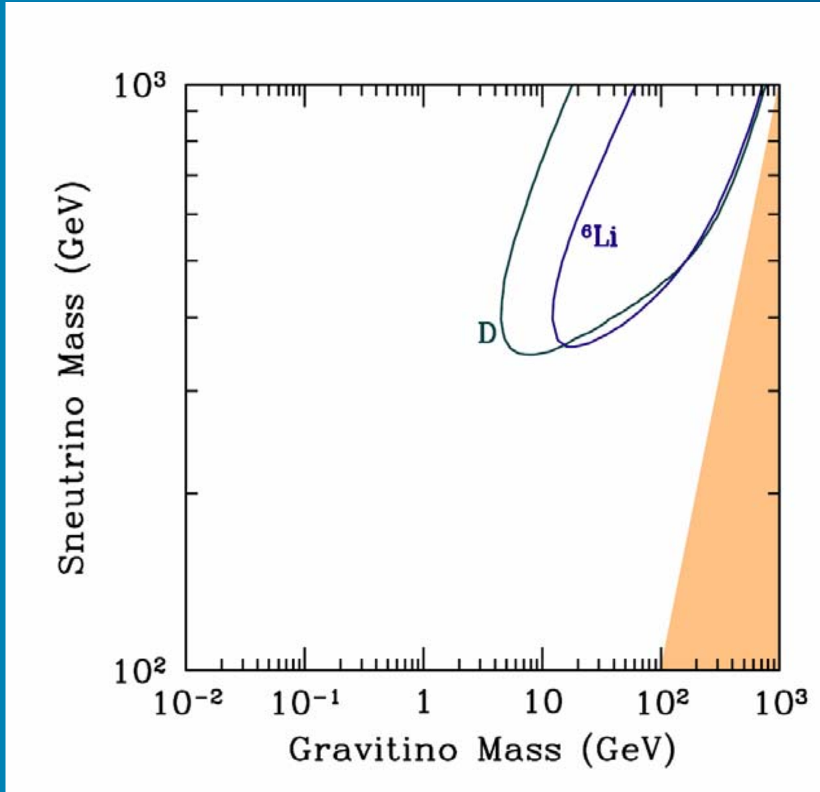
Kawasaki, Kohri, Moroi, Yotsuyanagi (08)

Ellis, Olive, Santoso (08)

Relic abundance

$$Y_{\tilde{\nu}} \simeq 2 \times 10^{-14} \times \left(\frac{m_{\tilde{\nu}}}{100\ \text{GeV}} \right)$$





No allowed region for DM density with 100GeV sneutrinos

Stau NLSP and gravitino LSP scenario

Stable stau with weak-scale mass (<100TeV) was excluded by the experiments of ocean water

NLSP stau should be unstable

Bound-state effect (see next)

CHArged Massive Particle (CHAMP)

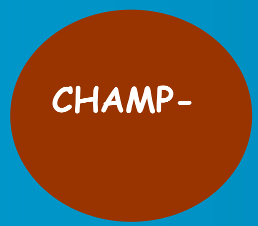
Kohri and Takayama, hep-ph/0605243
See also literature, Cahn-Glashow ('81)

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

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

- 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

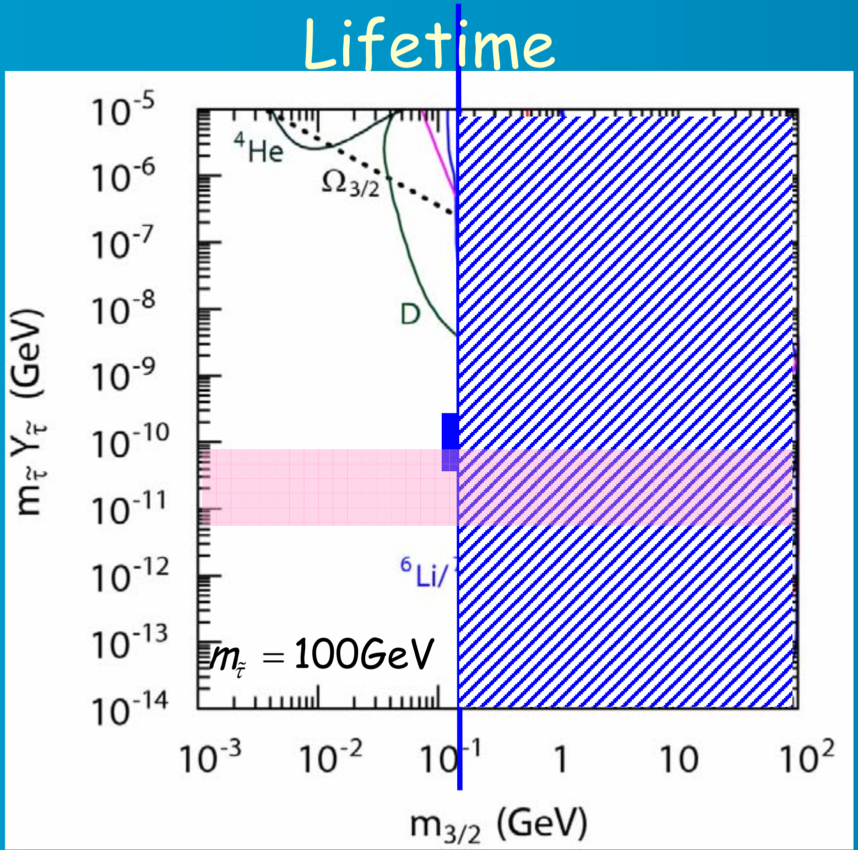
Stau NLSP and gravitino LSP Scenario in gauge mediation

Kawasaki, Kohri, Moroi PLB 649 (07) 436

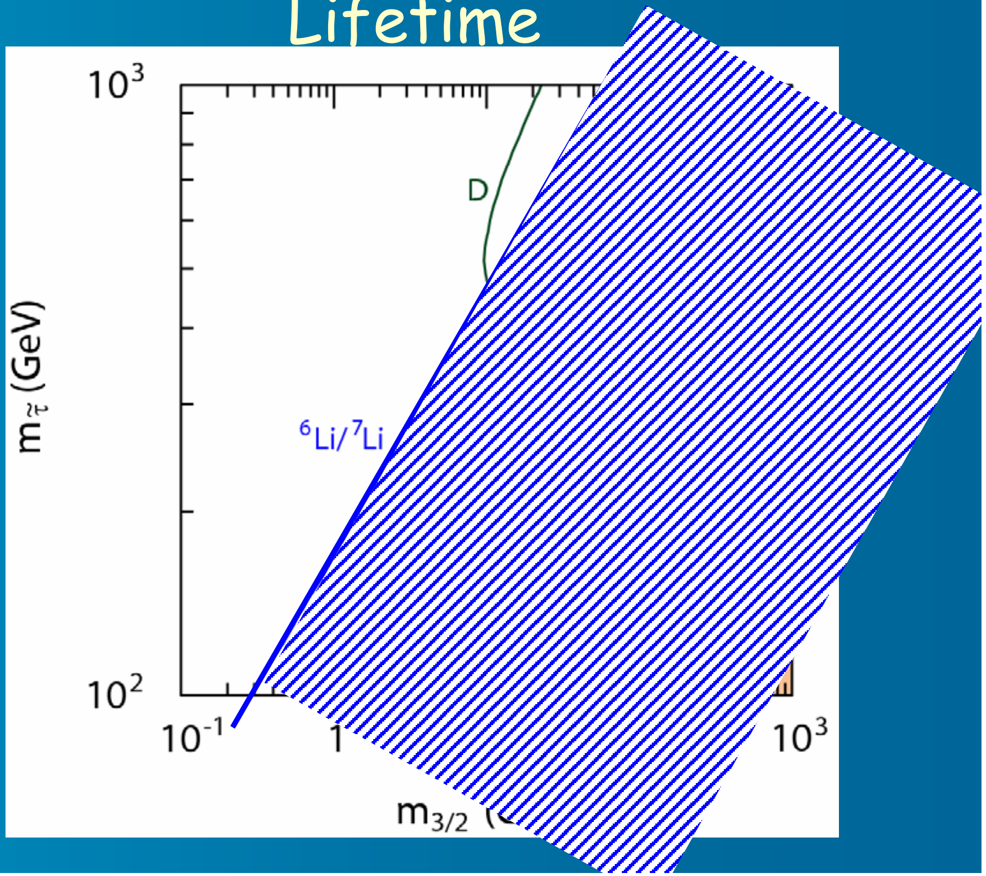
Relic abundance

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

Lifetime



Lifetime



Residual DM annihilation even at around BBN epoch

- To fit the PAMELA and ATIC2 positron signals and EGRET gamma-ray anomaly,

$$\langle \sigma v \rangle \sim 10^{-24} - 10^{-23} cm^3/s$$

- At least the annihilation must emit charged leptons

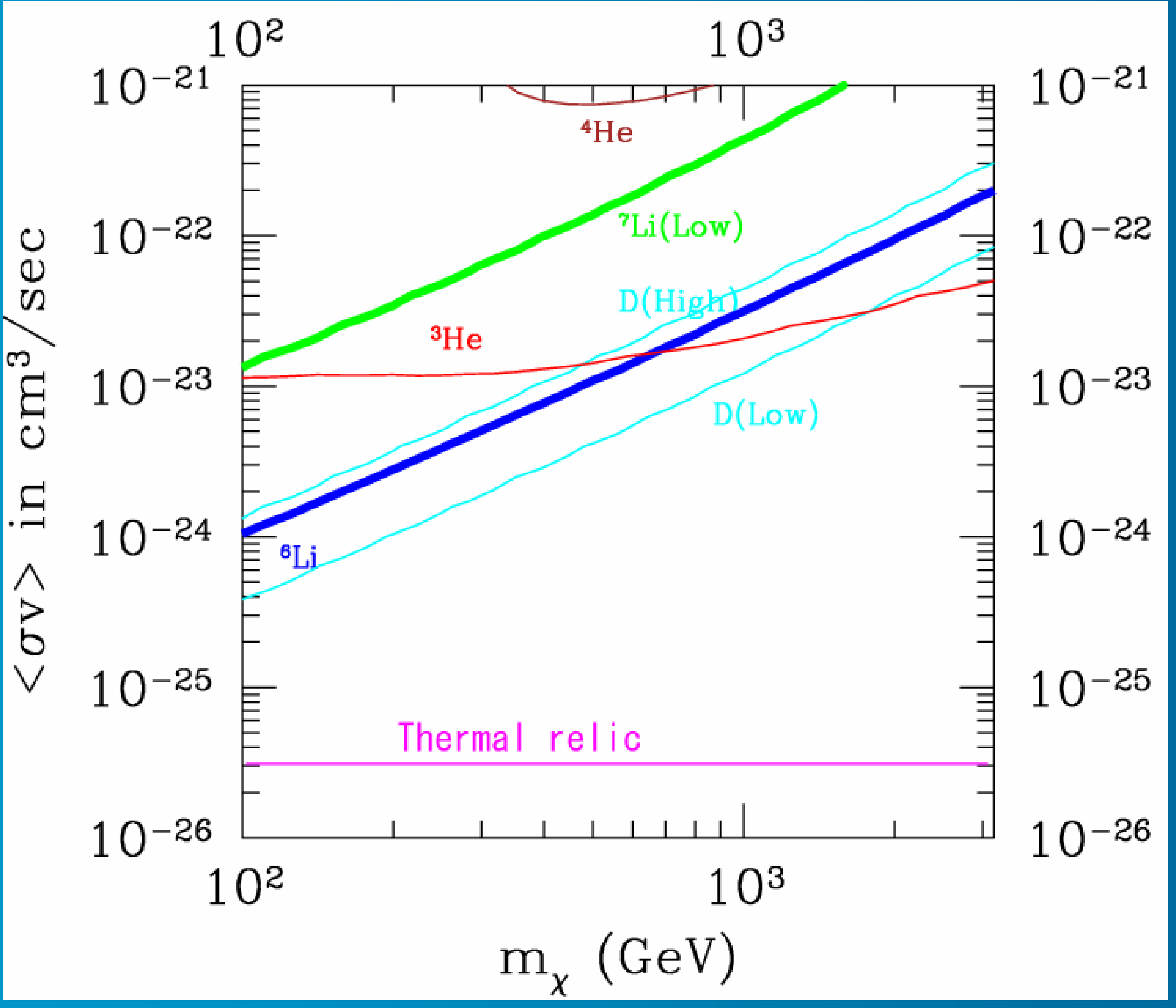
  Electromagnetic cascade shower is induced

- The annihilation might also emit hadrons

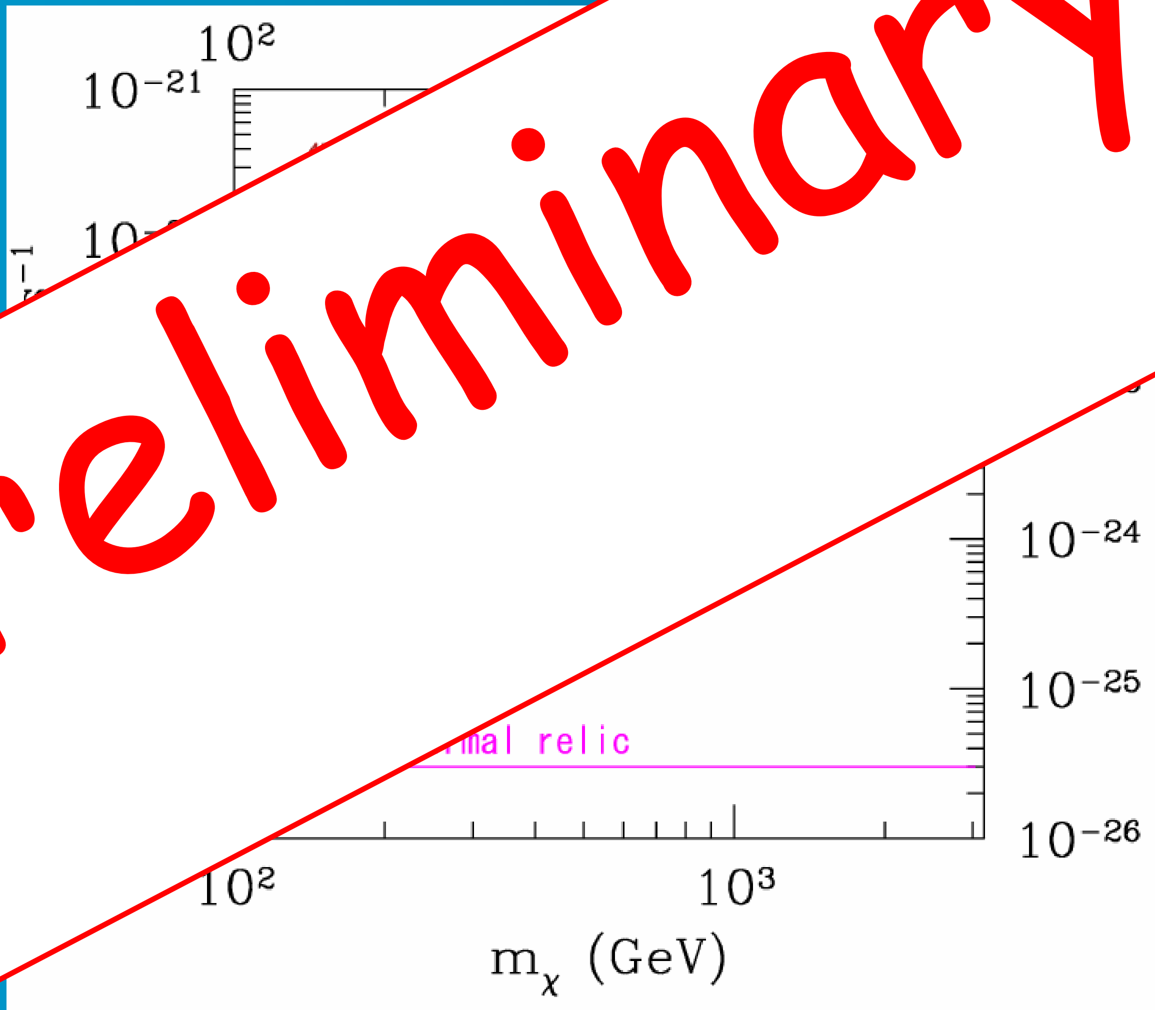
  Hadronic cascade shower is induced

Hadron emission by residual DM annihilation into WW in BBN epoch

Hisano et al in preparation



Charged-lepton (e^+e^-) emission by residual annihilation in BBN e



Preliminary

Solving Li problem in new particle physics models

- We do not adopt systematic uncertainties of observational Li7 and Li6 abundances

Reduction of ^{7}Li and production of ^{6}Li

Jedamzik (04) , Cumberbatch et al (08)

- Copious neutrons and tritiums are produced in hadronic shower process in decay/annihilation
- Reducing Be7 through

Jedazmik ('04)

$$^7Be(n,p)^7Li(p,^4He)^4He$$

(^{7}Li is produced later by $^7Be + e^- \to {}^7Li + \nu_e$)

- Tritium scatters off the background He4 and produces Li6

Dimopoulos et al ('89)
Kawasaki, Kohri, Moroi ('04)

$$T+4He \to {}^6Li+n$$

Stop NLSP and gravitino LSP

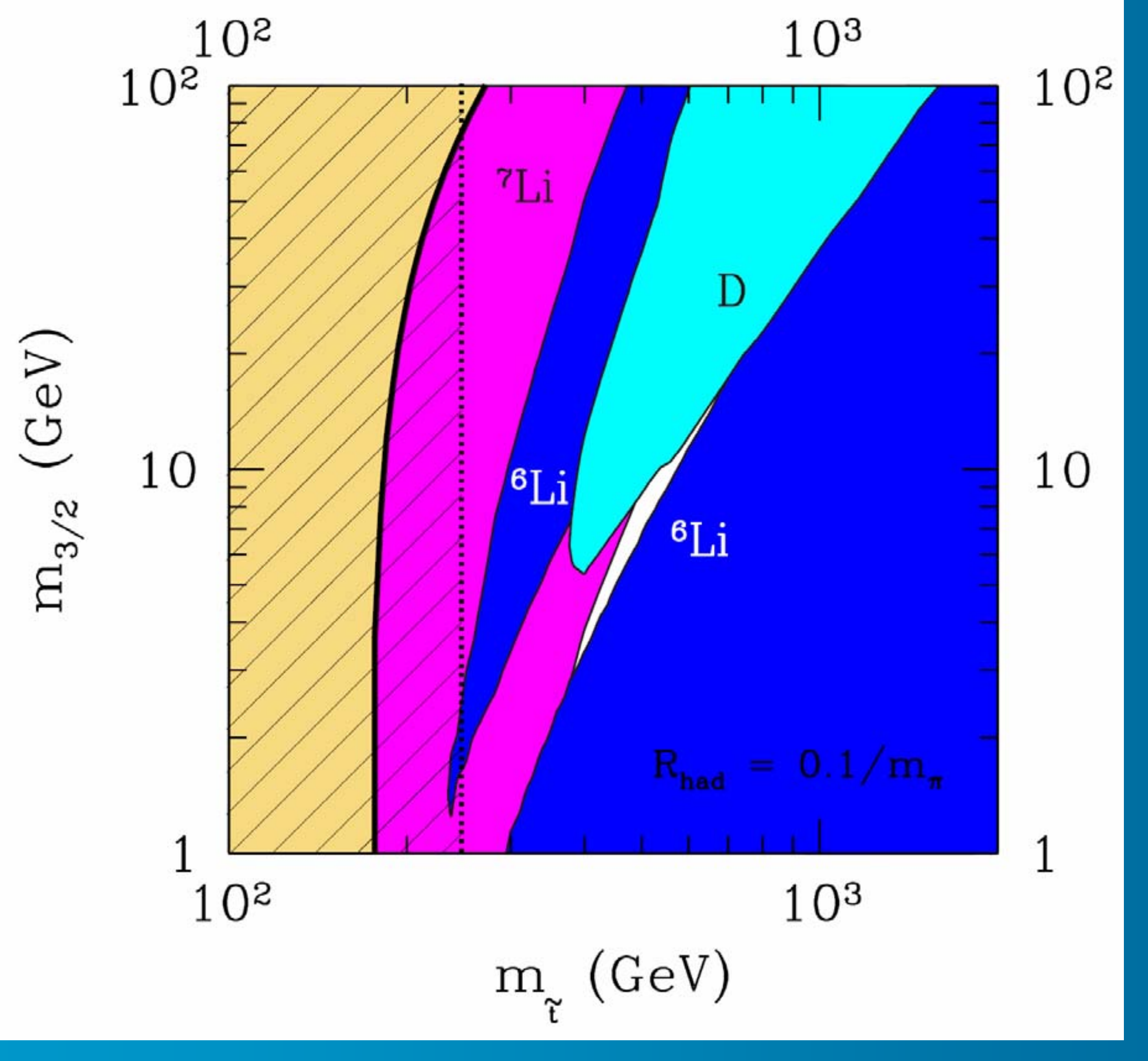
Kohri and Santoso (08)

- Stop can be NLSP in Non-universal Higgs masses (NUHM)
- Stop is confined into “messino” after QCD phase transition
- Second annihilation of stop occurs just after QCD phase transition through strong interaction
- Stop number density is highly suppressed, but it is appropriate to solve the Li problem

$$m_{\tilde{t}} n_{\tilde{t}} / s \sim 10^{-14} GeV - 10^{-13} GeV$$

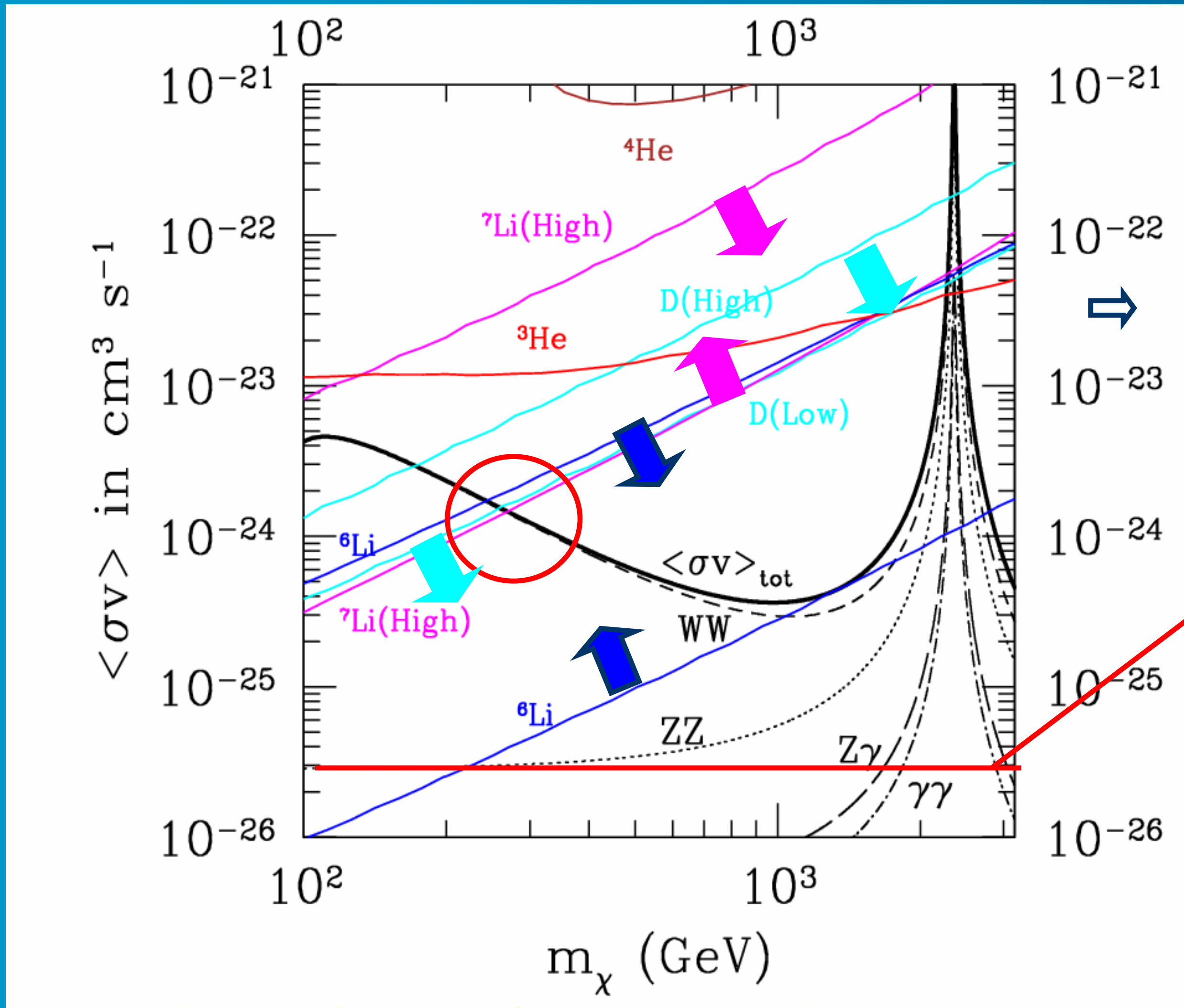
Stop NLSP and gravitino LSP

Kohri and Santoso arXiv:0811.1119v1 [hep-ph]



Residual annihilation of wino-like LSP

Hisano, Kawasaki, Kohri, Nakayama(08)



⇨

Thermal (bino) DM

We need nonthermal wino production by gravitino decay

Conclusion

- BBN is a strong tool to investigate decays or annihilations of long-lived SUSY particles.

- In neutralino LSP and unstable gravitino scenario, the constraint on reheating temperature after primordial inflation is

$$T_R \leq 3 \times 10^5 GeV - 10^7 \ GeV$$

$$(\text{for } m_{3/2} = 100 \ GeV \ - 1TeV)$$

- In the gravitino LSP scenario , thermal-relic NLSP fails to produce DM density for NLSP masses (100GeV – 1TeV) . We need thermal or nonthermal production of LSP gravitino through the decay of Inflaton, moduli, etc.

See Moroi, Murayama, Yamaguchi (93) for thermal production, and Endo, Takahashi, Yanagida (07) for non-thermal production of LSP gravitino