Big-bang nucleosynthesis and decaying- and/or annihilating (SUSY) dark matter

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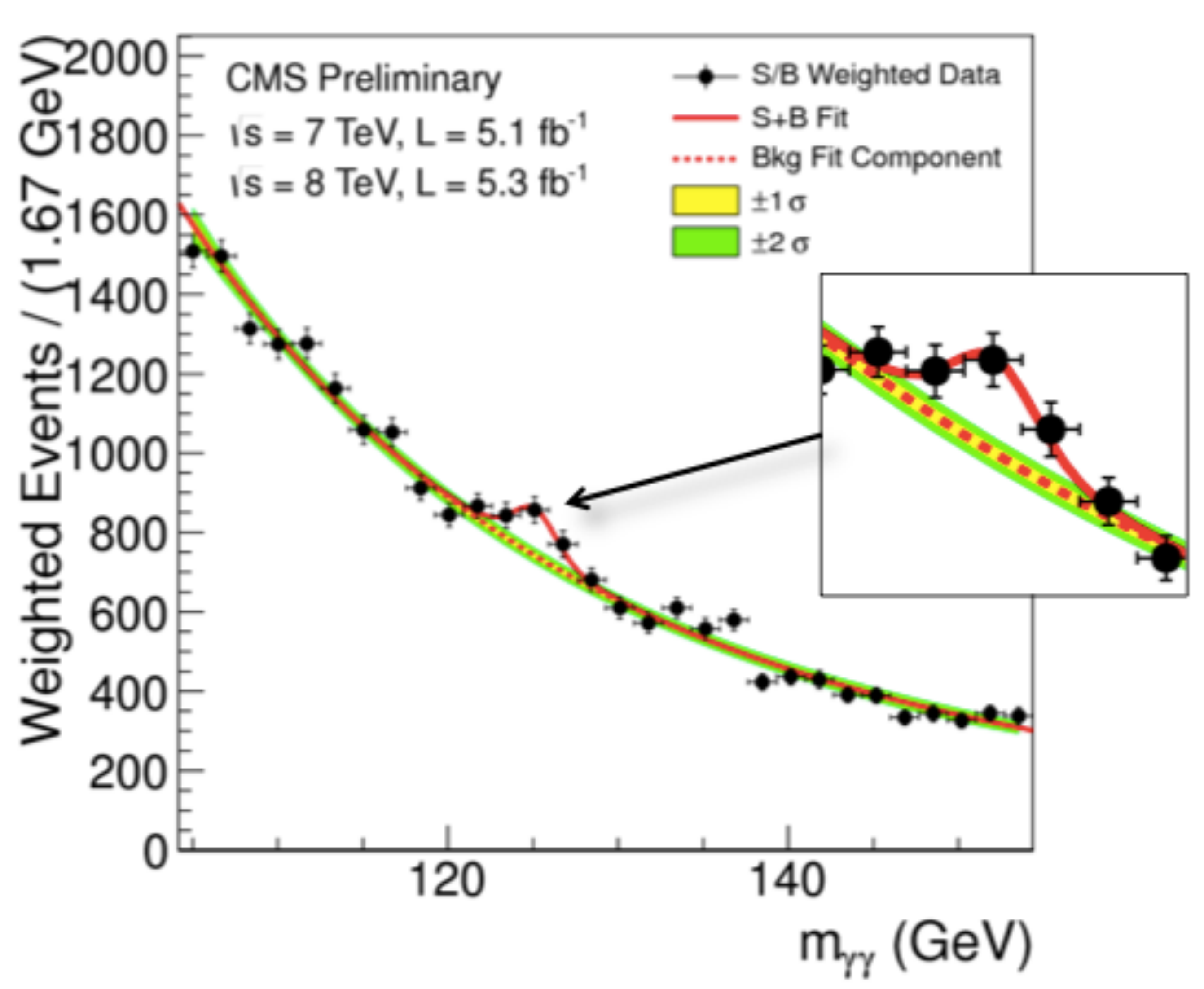
Abstract

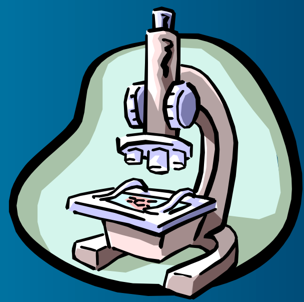
- BBN gives severe upper bounds on the amount of long-lived unstable particles such as gravitino (or reheating temperature after inflation)

- The discovered Higgs particle is relatively heavy, which may suggest a large SUSY-breaking scale. This would give us one of solutions to the gravitino problem with a shorter lifetime.

Discovery of a Higgs particle at LHC with m = 125.5 GeV



What is SUSY?

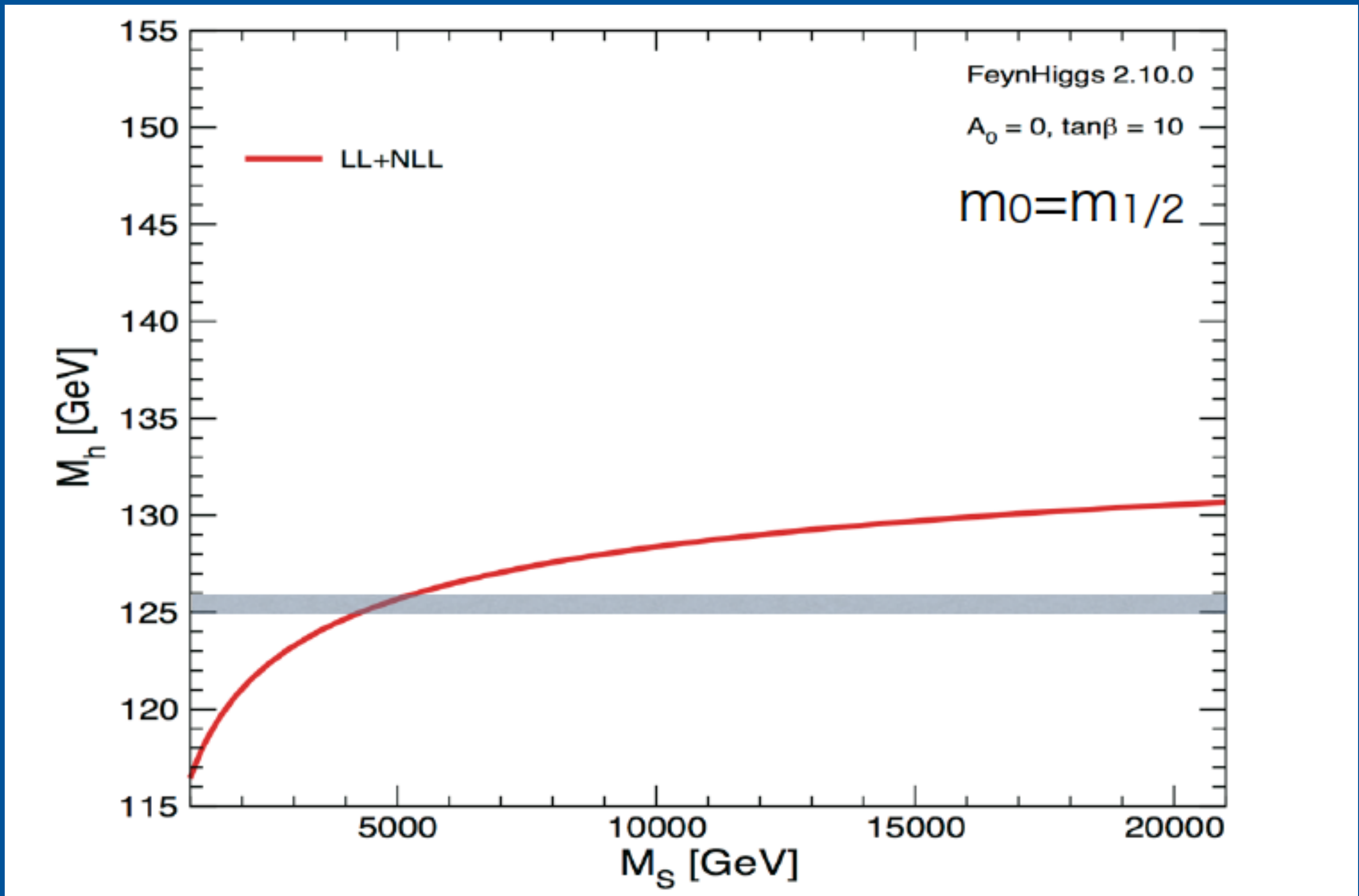


- Supersymmetry (SUSY)
  - Solving “Hierarchy Problem”
  - Realizing “Coupling constant unification in GUT”

Fermion		Boson
quark	$\longleftrightarrow$	squark
lepton	$\longleftrightarrow$	slepton
gaugino	$\longleftrightarrow$	photon (gauge boson)
gravitino	$\longleftrightarrow$	graviton

neutralino

We need heavy scalar top mass



Hahn et al, 2013

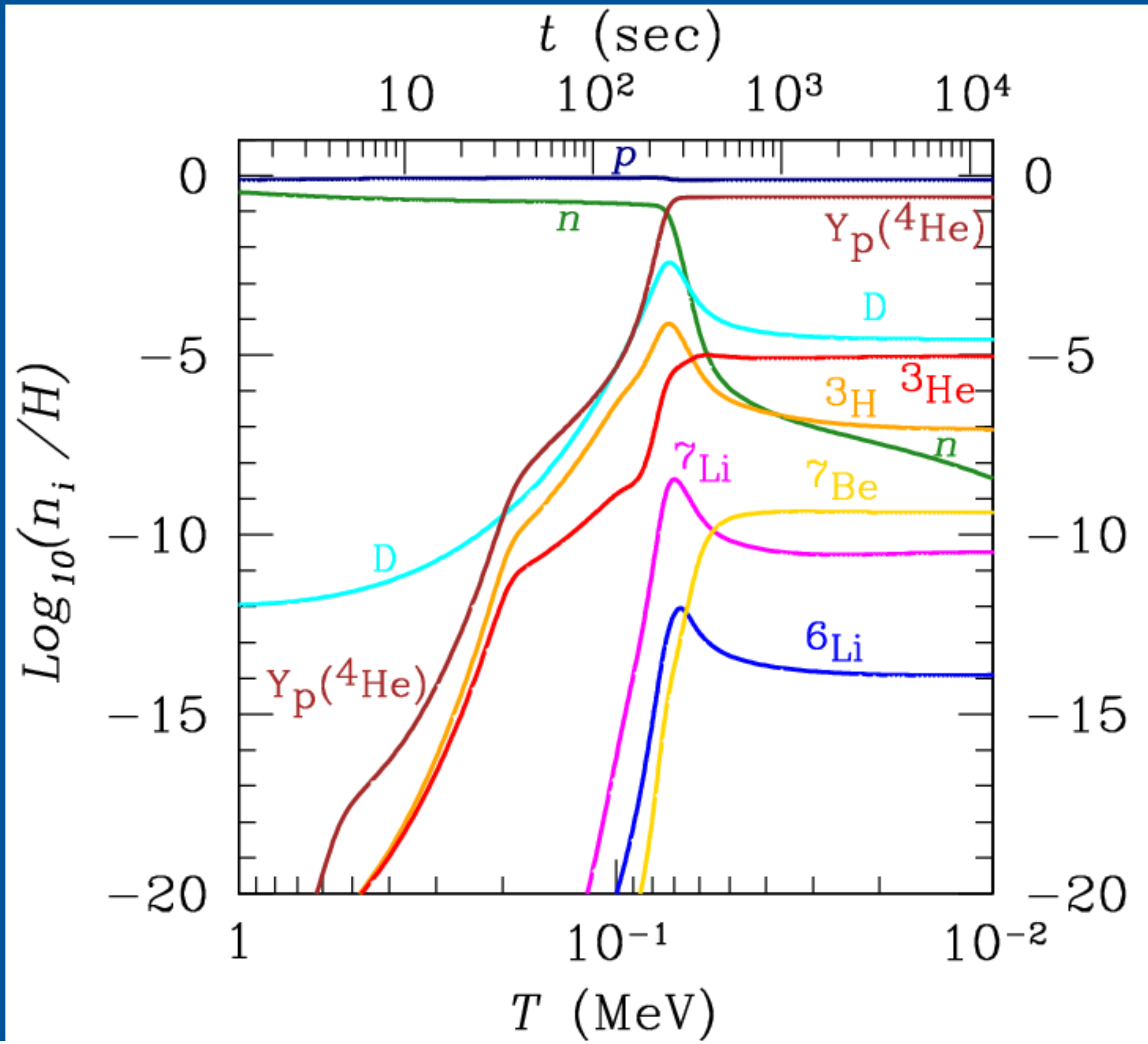
Realization, e.g., anomaly-mediated SUSY breaking

- moduli ~O(1000) TeV
- gravitino ~O(100) TeV
- squark, sleptons, gluinos ~ O(10)-O(100) TeV
- Gaugino (neutralino) ~O(1) – O(10) TeV

Big-bang Nucleosynthesis and unstable massive particles

Time evolution of light elements

$$\eta = 6 \times 10^{-10}$$



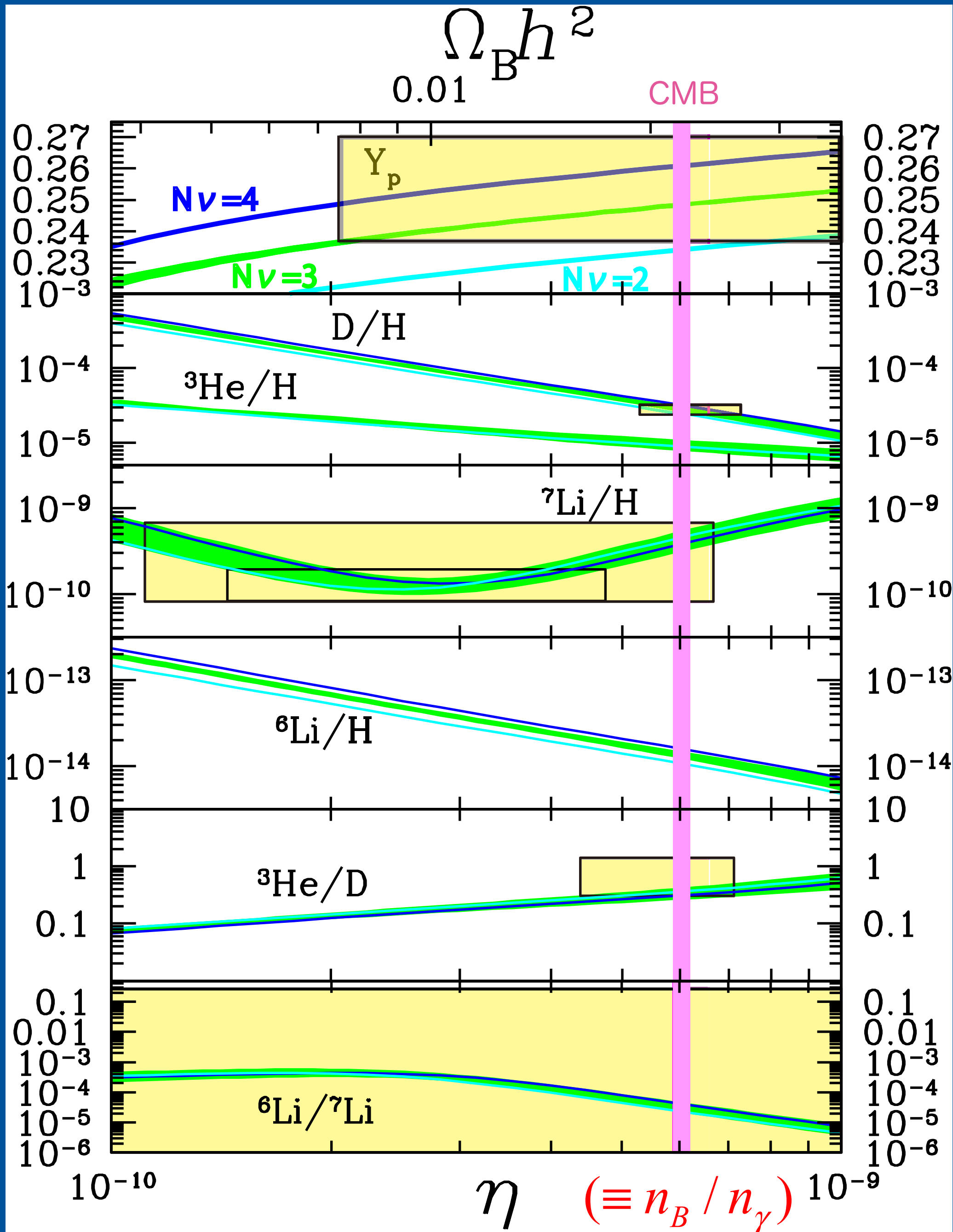
Observational Light Element Abundances

- He4 $Y_p = 0.2534 \pm 0.0083$ Aver, Olive, Skillman (2012)
- D $D/H = (2.82 \pm 0.20) \times 10^{-5}$ Pettini et al.(2008)
- Li7 $\log_{10}({}^7Li/H) = -9.90 \pm 0.09\ (\pm 0.35)_{syst.}$ Bonifacio et al (2006)

I will dicsuss this systematics later

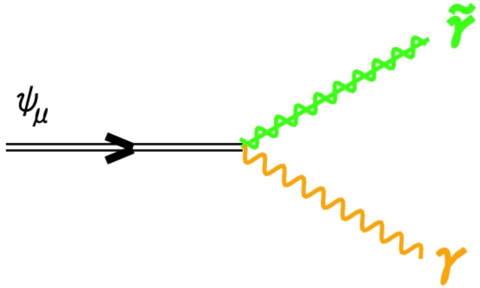
- Li6 ${}^6Li/{}^7Li < 0.046 \pm 0.022\ (\pm 0.106)_{sys}$ Asplund et al(2006)
- He3 ${}^3He/D < 0.83 + 0.27$ Geiss and Gloeckler (2003)

SBBN



$\Omega_B h^2$
0.01
CMB
Y_p
Nν=4
Nν=3
Nν=2
D/H
^{3}He/H
^{7}Li/H
^{6}Li/H
^{3}He/D
^{6}Li/^{7}Li
10^{-10}
10^{-9}
η $(\equiv n_B / n_\gamma)$

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

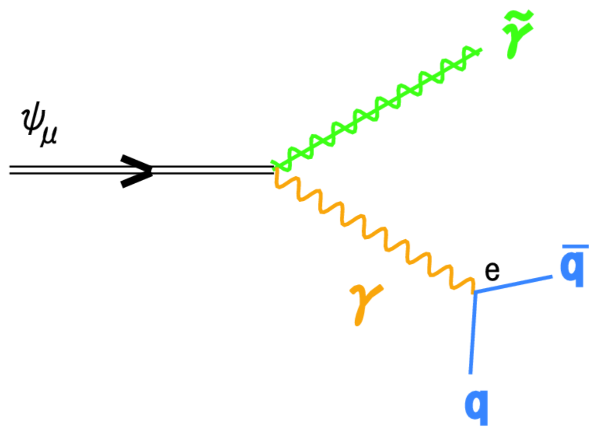
3) Photo-dissociation of light elements

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

He3/D >~ O(1)

Reno, Seckel (1988)
S. Dimopoulos et al.(1989)

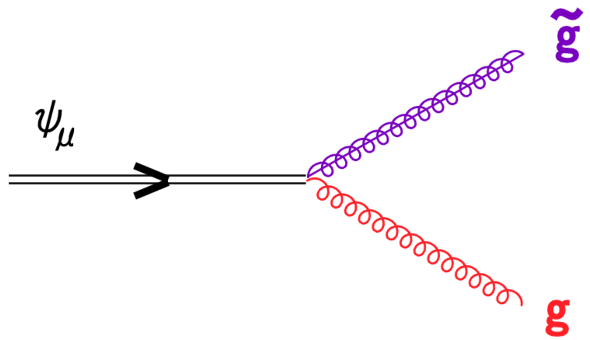
Hadronic decay mode



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

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

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

Hadron induced exchange

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

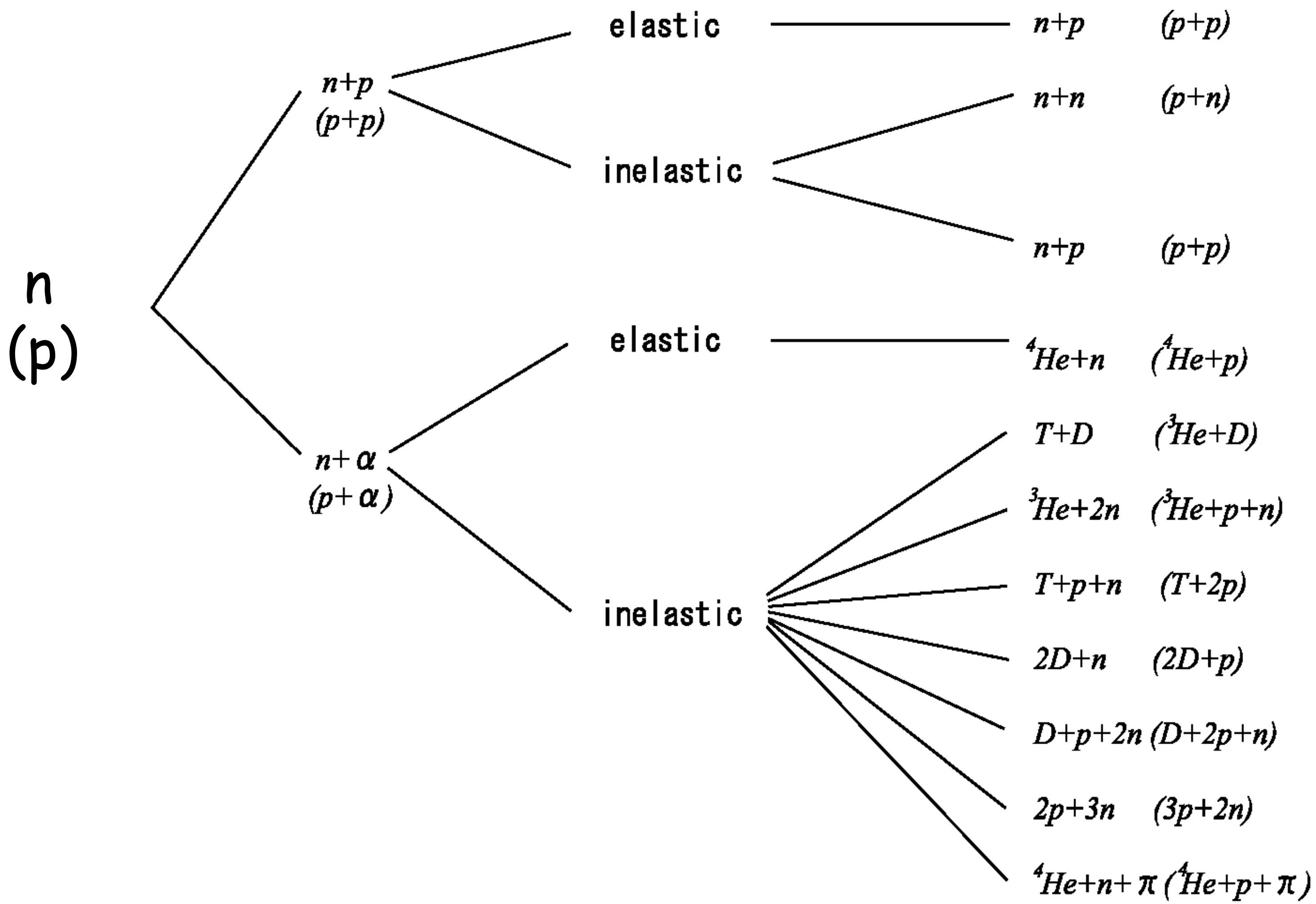
Even after freeze-out of n/p in SBBN

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)



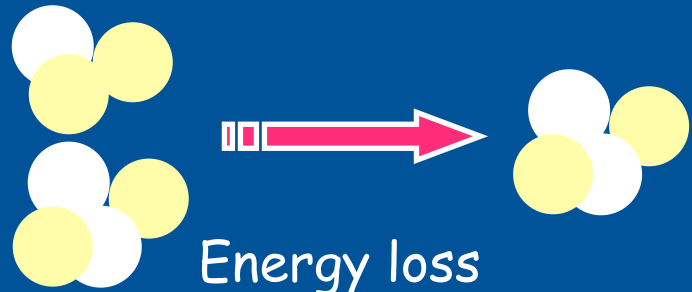
Non-thermal Li, Be Production by energetic nucleons or photons

S. 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

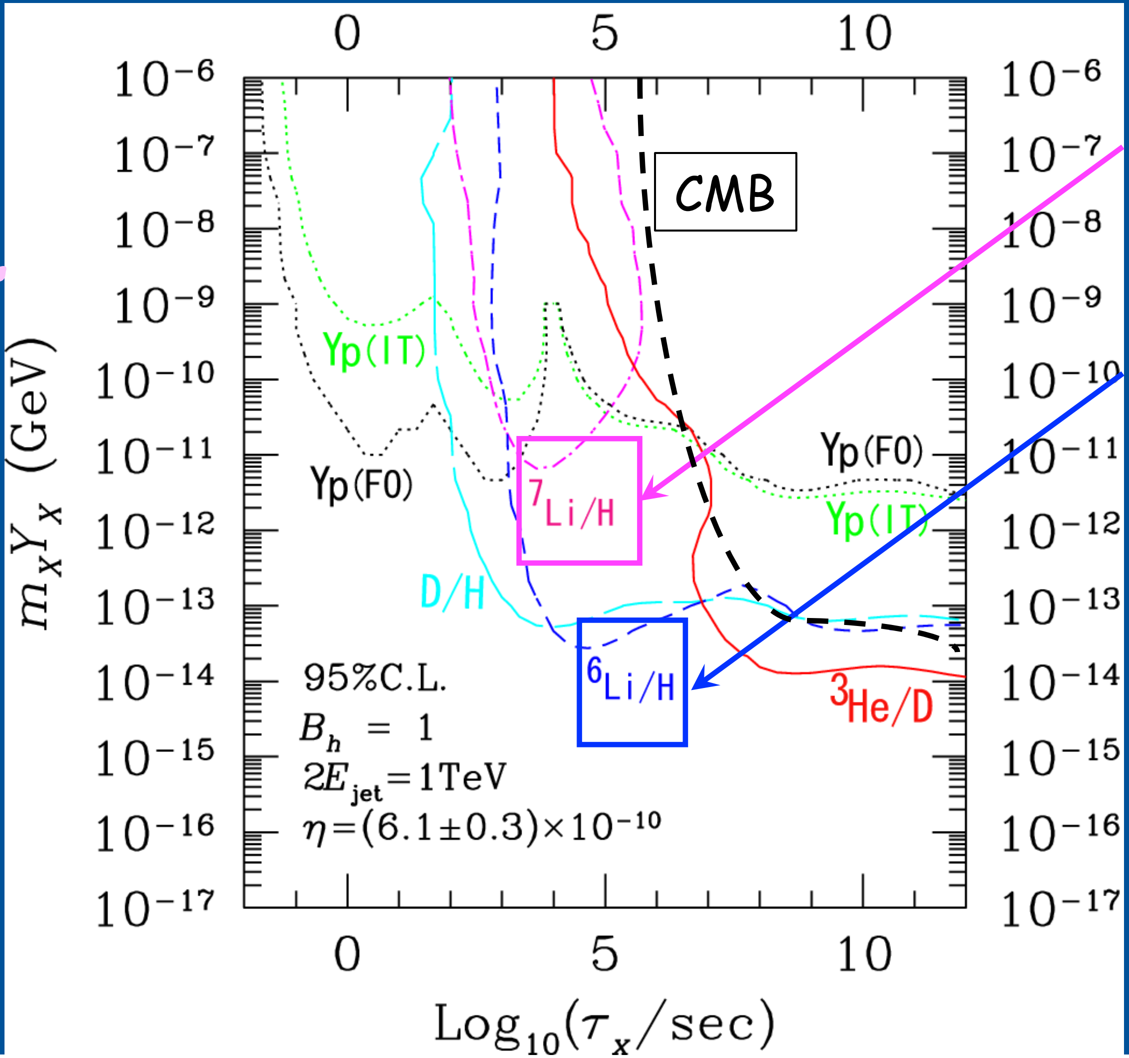
$$ {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{6}\mathrm{Li}, {}^{7}\mathrm{Li}, {}^{7}\mathrm{Be} + \ldots$$

Constraints on 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

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Gravitino production

- Thermal production

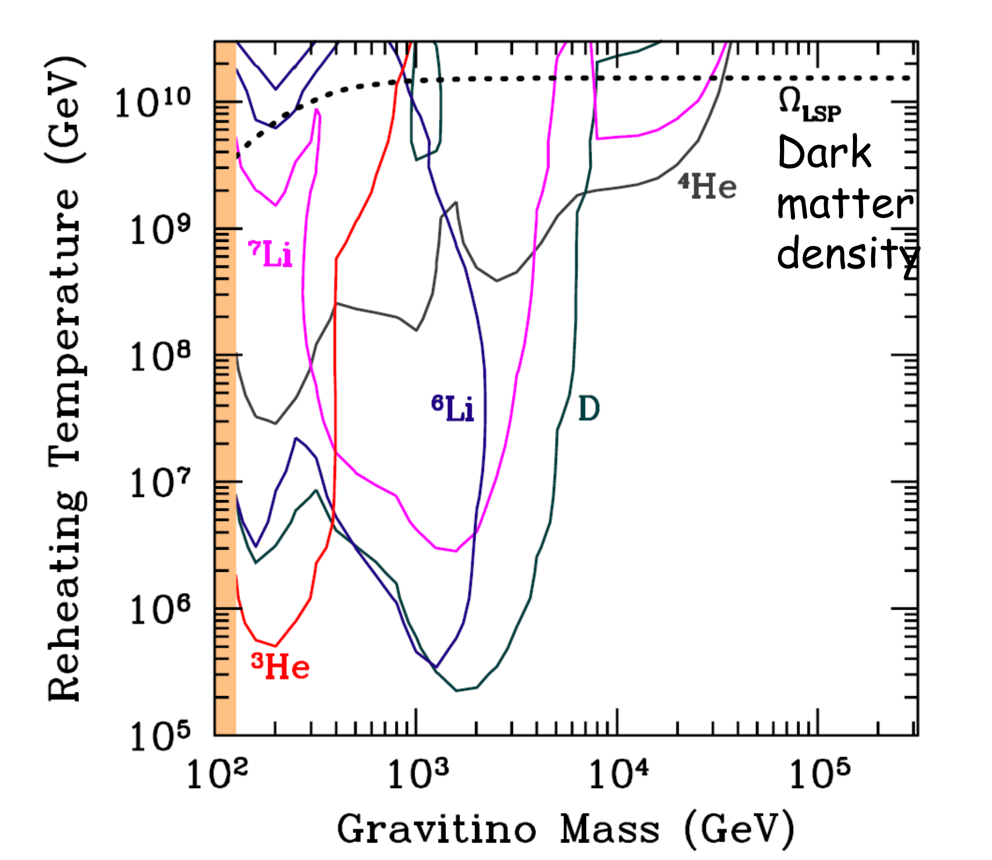
Bolz,Brandenburg,Buchmuller (01,08)
Kawasaki,Kohri,Moroi (05)
Pradler,Steffen (07)

$$Y_{3/2} \simeq 2 \times 10^{-14} \left(\frac{T_R}{10^8 \mathrm{GeV}} \right) \left(1 + \frac{m_{\tilde{g}}^2}{3 m_{3/2}^2} \right)$$

Neutralino (bino) LSP and gravitino "NLSP"

Upper bound on reheating temperature

Kawasaki, Kohri, Moroi, Yotusyanagi (08)



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

$$Y_{3/2} \equiv n_{3/2} / s$$

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

$$\sim 10^9\,\mathrm{s}\ \left(m_{3/2} / 10^2\mathrm{GeV}\right)^{-3}$$

In terms of BICEP2

- Tensor to scalar ratio

$$r = \frac{P_T}{P_S} = \frac{\dfrac{V}{3/2\pi\ M_G^4}}{\dfrac{V}{24\pi\ M_G^4 \varepsilon}} = 16\varepsilon = \frac{\dfrac{V}{3/2\pi^2 M_G^4}}{\left(5\times10^{-5}\right)^2}$$

- Potential

$$V^{1/4} \sim 2\times10^{16} GeV \left(\frac{r}{0.2}\right)^{1/4}$$

- Hubble parameter at inflation

$$H_{\inf} = \frac{\sqrt{V}}{3M_G} \sim 10^{14} GeV \left(\frac{V}{(2\times10^{16} GeV)^4}\right)^{1/2}$$

e.g., chaotic inflation with $V = \frac{1}{2} m_\phi^2 \phi^2$

- Mass

$$m_\phi \sim 2 \times 10^{13} GeV$$

- Decay rate through $L = y\phi\ \bar{\psi}\psi$ to be

$$\Gamma_{\phi \to \bar{\psi}\psi} \sim y^2 m_\phi$$

- Upper bounds on the coupling

$$y < 10^{-10} \frac{T_{R,upper}}{10^6 GeV}$$

Annihilating dark matter

Thermal freezeout

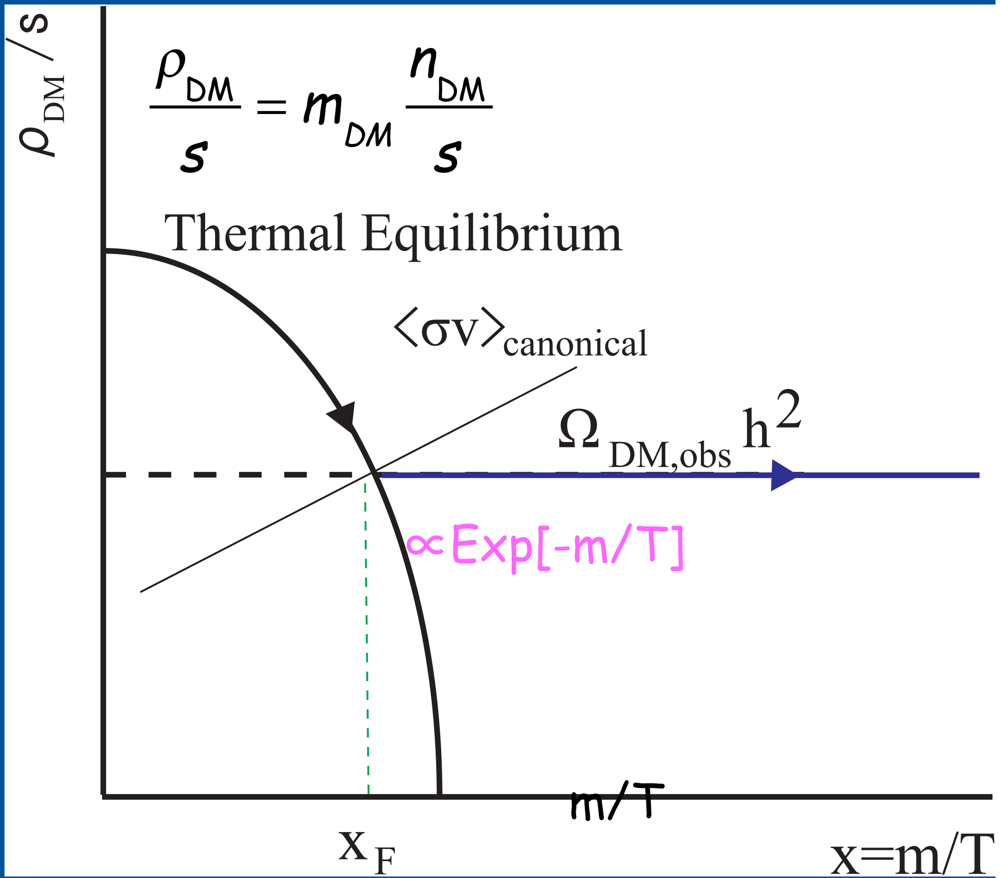
Boltzmann equation

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

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

$$T_{\text{Freezeout}} \sim m_\chi / 23$$

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



$\Omega_\chi\ h^2$ does not depend on m_χ

Predicting TeV Physics!!!

$$\langle\sigma v\rangle = 3\times10^{-26}\,cm^3/s$$

Residual annihilation of DM at BBN

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} \sim -\langle \sigma v \rangle_{ann} n_{DM}^2$$

$$\Delta \left(\frac{n_{DM}}{s} \right) \sim \frac{\langle \sigma v \rangle_{ann} n_{DM}}{H} \frac{n_{DM}}{s}$$

$\ll 1$ but non-zero!

- To fit the PAMELA, AMS-02 positron and electron signals,

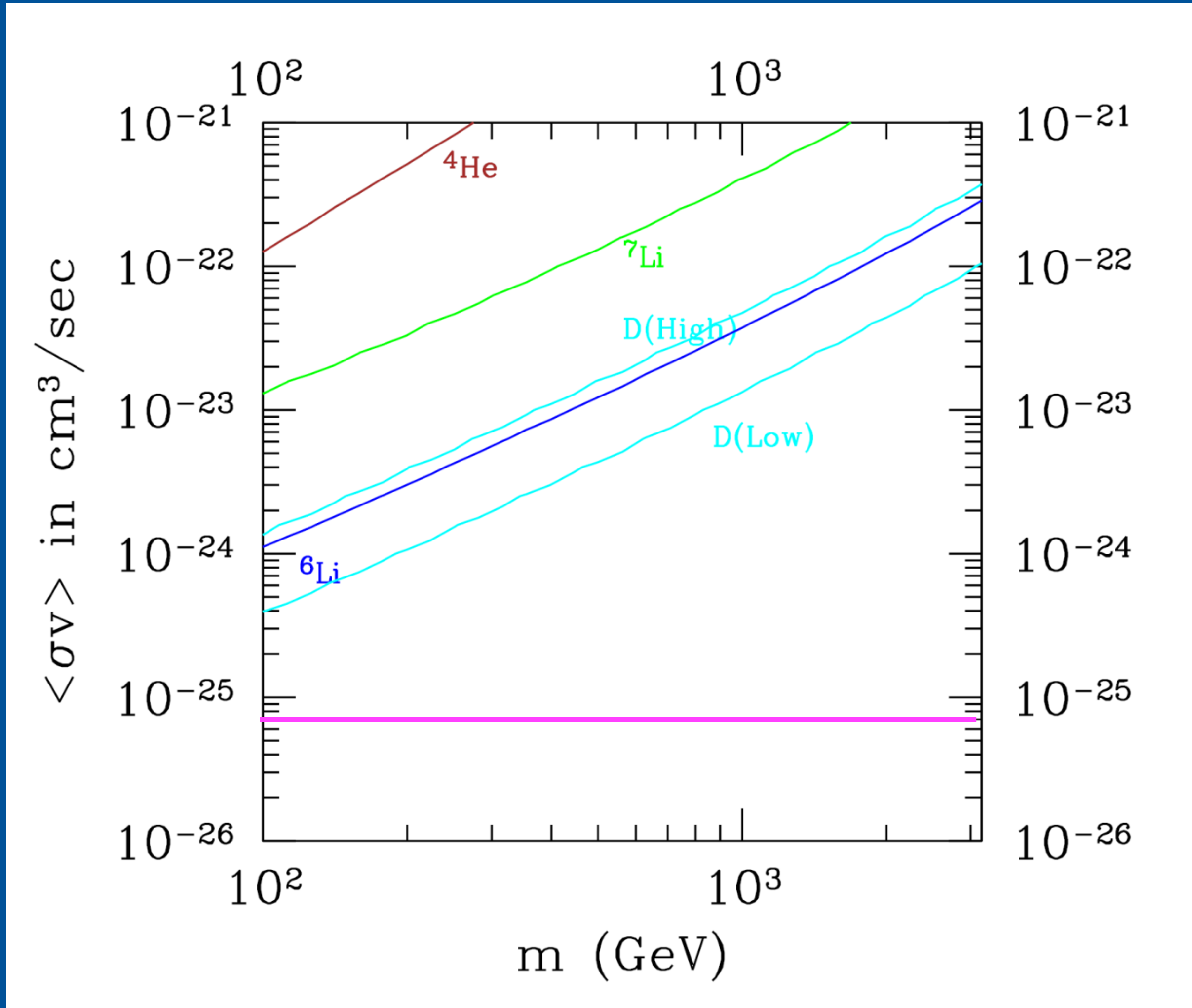
$$\langle \sigma v \rangle \sim 10^{-23} cm^3 / s$$

$O(10^3)$ times larger than canonical value,

$$\langle \sigma v \rangle_{canonical} \sim 3 \times 10^{-26} cm^3 / s$$

Hadron emission by residual annihilation at BBN epoch

Hisano et al (2009,2011)



Conclusion

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- A Higgs particle is relatively heavy, which may suggest a large SUSY-breaking scale. This would give us one of solutions to the gravitino problem with a shorter lifetime.