元素合成と素粒子

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1. Introduction

BBN (Big Bang Nucleosynthesis)

- Important process leading to success of the big bang model
- BBN determines baryon density of the Universe
  - Before CMB provide better estimation
  - Goal which baryogenesis must achieves
- BBN is very sensitive to physical conditions at T~ 1MeV
  - Prove to the early universe
  - Unstable particles,
  - Extra species contributing to cosmic density …..

今日の話

1. Introduction
2. BBN constraints on unstable particles
    - A. Gravitino problem
    - B. Annihilation of dark matter
    - C. MeV reheating
3. Baryogenesis and dark matter
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1.1 Standard Big Bang Nucleosynthesis (BBN)

- In the early universe (T=1-0.01 MeV)

$$\boxed{2p + 2n \rightarrow {}^4\mathrm{He}}$$ + small D $\;{}^3\mathrm{He}$ $\;{}^7\mathrm{Li}$

- Initial Condition
  p and n interchange via weak interaction

$$\boxed{\begin{aligned} \nu_e + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu}_e \\ n &\leftrightarrow p + e^- + \bar{\nu}_e \end{aligned}}$$

Reaction Rate $\Gamma \sim \sigma v n_e \sim G_F^2 T^2 T^3 \sim G_F^2 T^5$

- Γ >> H → Chemical equilibrium

$$\boxed{\mu_{\nu_e} + \mu_n = \mu_p + \mu_{e^-}}$$

$$n_{e^-} - n_{e^+} = \frac{1}{3}\mu_e T^2 = n_p$$

$\mu_e/T \ll 1 (\Leftarrow\ n_{e^-} - n_{e^+} \ll n_\gamma)$ $\mu_\nu \ll 1$ (assumption)

→ $$\boxed{\mu_n = \mu_p}$$

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} \exp[-(m-\mu)/T]$$

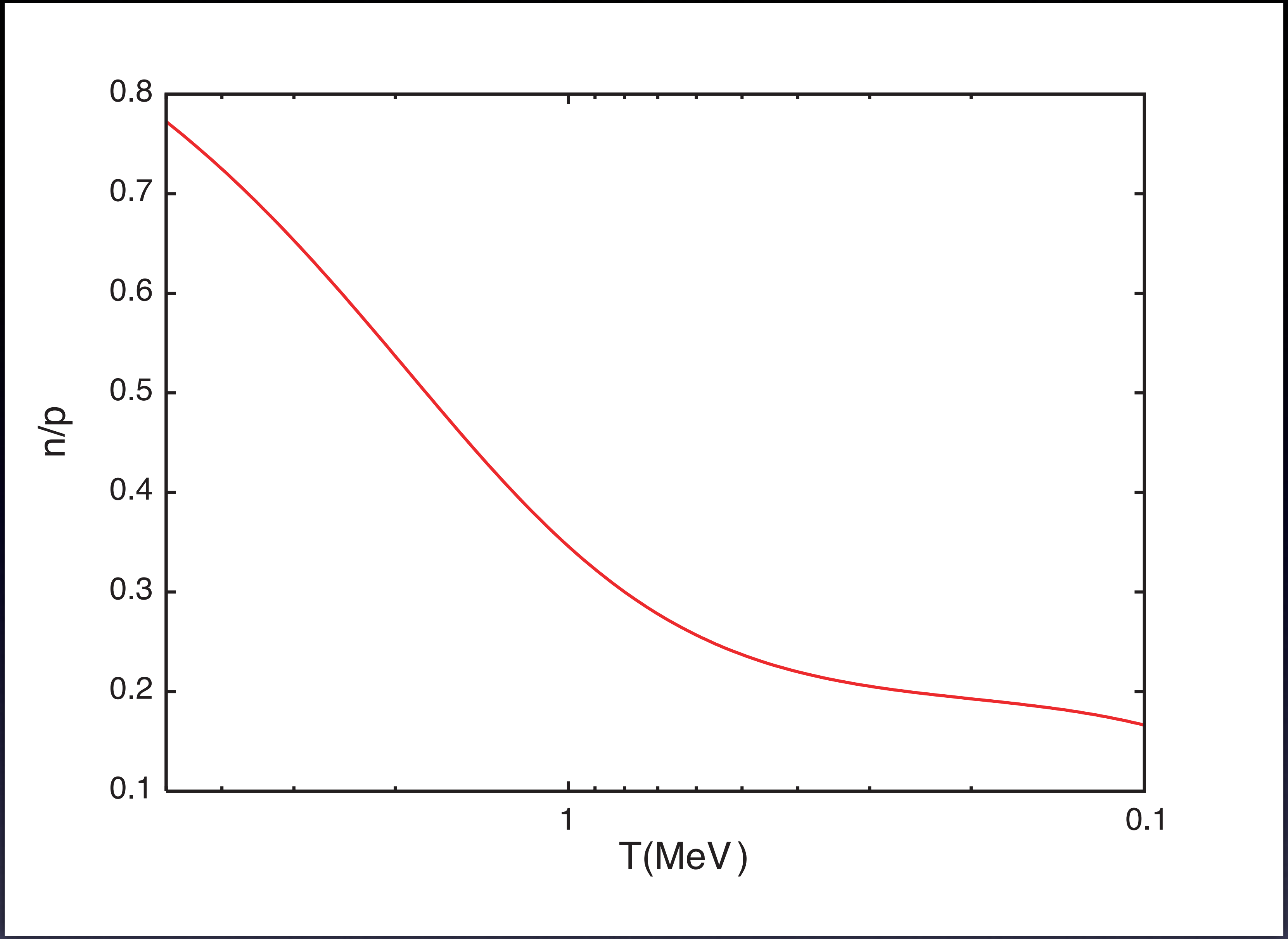
$$\left(\frac{n_n}{n_p}\right)_{\text{eq}} = \exp\left(-\frac{Q}{T}\right)$$

$$Q = m_n - m_p = 1.293\ \text{MeV}$$

- Γ = H weak interactions freeze out → $T_f \sim 1$ MeV

freeze-out temp.

→ $$\boxed{\frac{n_n}{n_p} \simeq \exp\left(-\frac{Q}{T_f}\right) \simeq \frac{1}{7}}$$



- Almost all neutrons that exist at that time are synthesized into He4

$$\Rightarrow \quad \frac{\rho_{^4\mathrm{He}}}{\rho_{\mathrm{H}}+\rho_{^4\mathrm{He}}} = \frac{4(n_n/2)}{n_n+n_p} = 2\frac{n_n/n_p}{1+n_n/n_p} \simeq 0.25$$

- 0.1 MeV < T < 1 MeV

$$p + n \;\leftrightarrow\; D + \gamma \qquad\qquad Q_d = 2.22 \text{ MeV}$$

$$n_\gamma \sim 10^{10} n_B \gg n_B$$

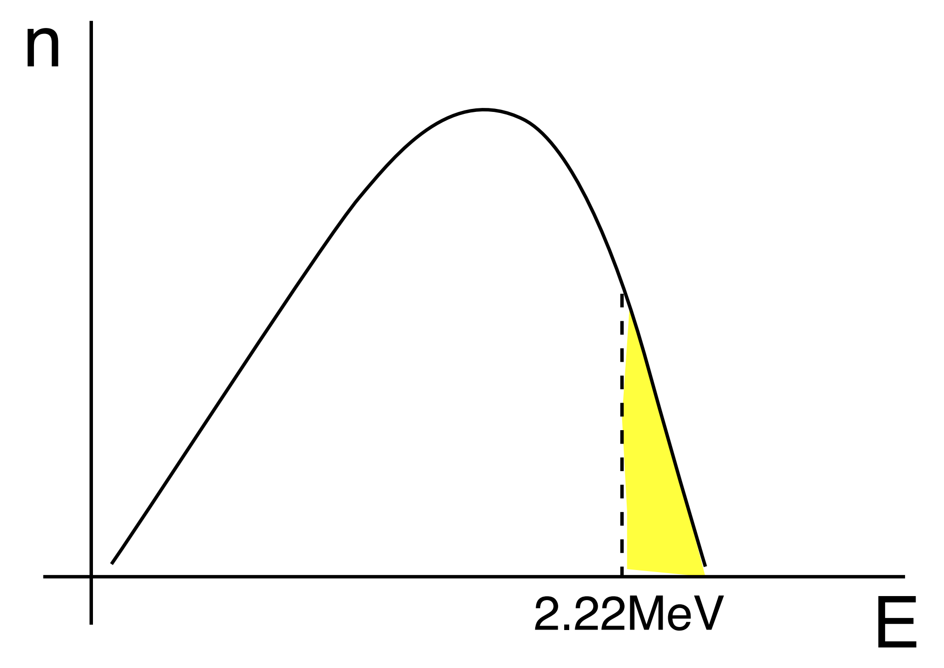
Produced D is destroyed

$$D + \gamma \to p + n$$

$$T \simeq 0.1 \text{ MeV}$$

$$n_\gamma(E_\gamma > 2.22\text{MeV}) \searrow$$

$$\Rightarrow \boxed{p + n \;\to\; D + \gamma}$$



- T < 0.1 MeV

$$\boxed{\begin{aligned} \mathrm{D} + \mathrm{D} &\;\to\; {}^3\mathrm{He} + n \\ {}^3\mathrm{He} + n &\;\to\; {}^3\mathrm{He} + p \\ {}^3\mathrm{He} + \mathrm{D} &\;\to\; {}^4\mathrm{He} + n \end{aligned}}$$

$${}^4\mathrm{He}$$

$$\Rightarrow \; + \text{ small amount of } D,\ {}^3\mathrm{He},\ {}^3\mathrm{H}$$

$$({}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e, \quad \tau_{1/2} \sim 12\text{yr})$$

- Heavier Light Elements?

  ➡ No

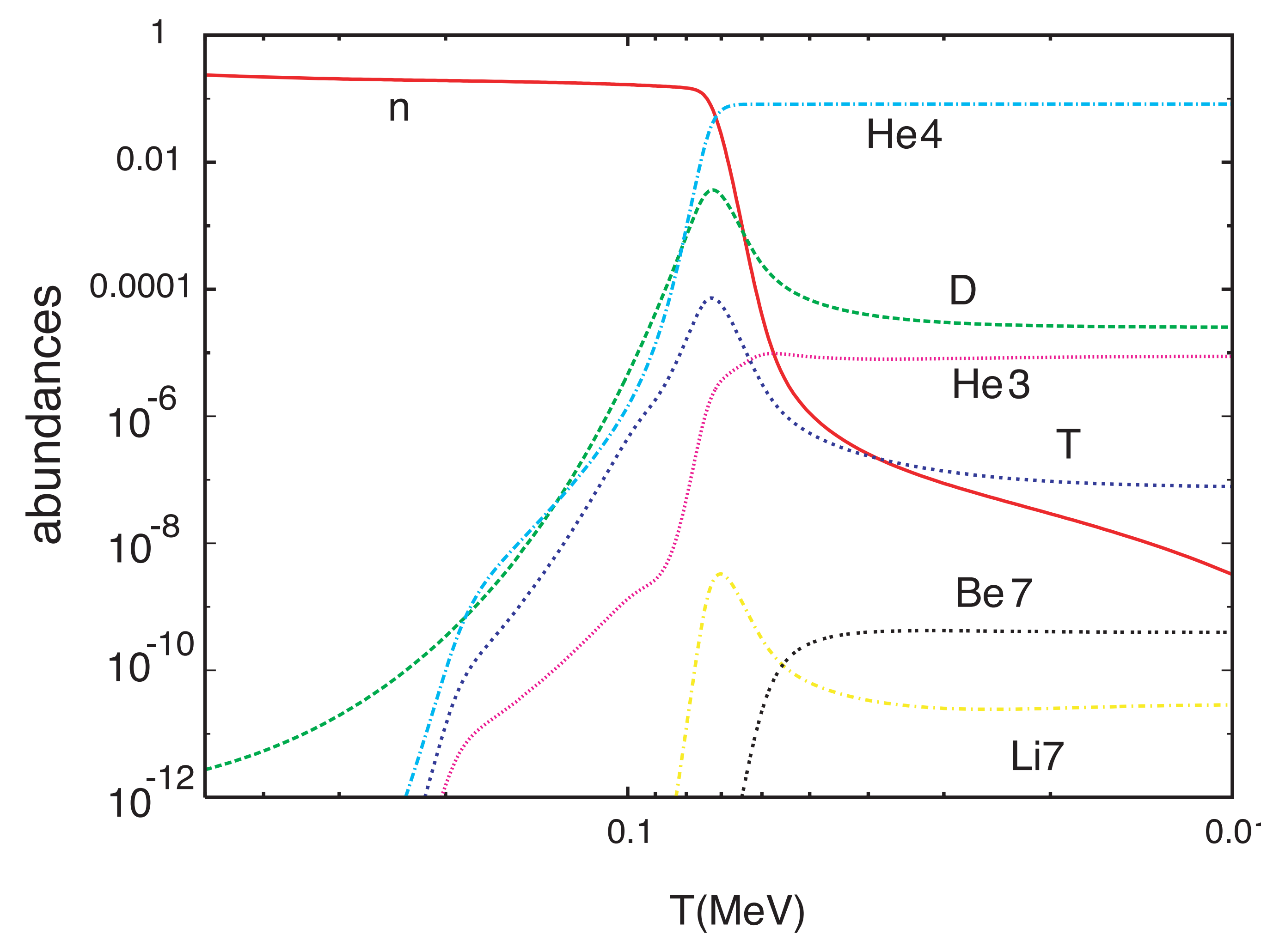
  - ▷ No stable nuclei with A=5 or 8
  - ▷ Coulomb Barrier

- But tiny amount of Li7

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

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

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



Abundances of Light Elements only depend on baryon-to-photon ratio

$$\boxed{\eta_B \equiv \frac{n_B}{n_\gamma}}$$

Prediction vs Observation

- Abundance

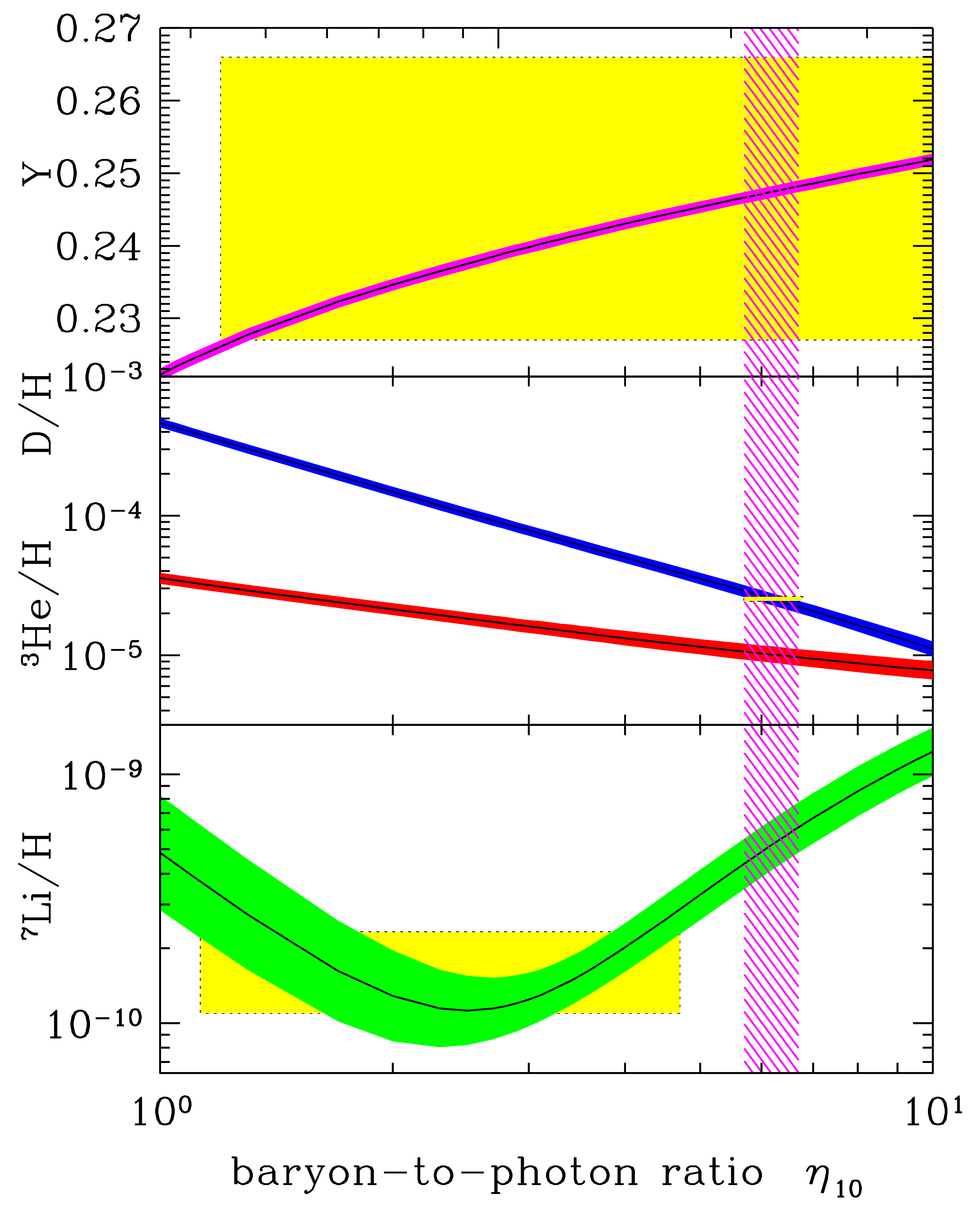
$$Y_p = \frac{\rho_{^4\mathrm{He}}}{\rho_{\mathrm{H}} + \rho_{^4\mathrm{He}}}$$

$$\frac{\mathrm{A}}{\mathrm{H}} = \frac{n_{\mathrm{A}}}{n_{\mathrm{H}}}$$

- Baryon-photon ratio
  - D/H observation

$$\boxed{\eta_B \simeq 6 \times 10^{-10}}$$

- Lithium problem



Observational abundances of light elements

- He4 [Extragalactic HII region]

  $Y_p = 0.254 \pm 0.003$ Izotov, Stasinska, Guseva (2013)

  $Y_p = 0.2465 \pm 0.0097$ PDG (2013)

- D [Damped Ly alpha system]

  $(\mathrm{D/H})_p = (2.53 \pm 0.04) \times 10^{-5}$ Cooke et al, (2013)

- Li7 [Metal poor halo stars]

  $(^7\mathrm{L/H})_p = (1.6 \pm 0.3) \times 10^{-10}$ Sbordone et al, (2010)

- Li6 [Metal poor halo stars]

  $(^6\mathrm{L}/^7\mathrm{Li})_p < 0.5$ Asplund et al, (2006)

- He3 [Solar system]

  $(^3\mathrm{He}/^7\mathrm{D})_p < 0.83 \pm 0.27$ Geiss, Gloeckler (2003)

2. BBN constraints on unstable particles

- Long-lived unstable particles might spoil success of BBN
- High energy particles from decay destroy light elements
  - Radiative decay (photons, electrons)
  - Hadronic decay (quarks, gluons)
- Candidates
  - Gravitino (SUSY partner of graviton)
  - Moduli fields (predicted in superstring)
  - Dark matter annihilation

2.1 Gravitino Problem

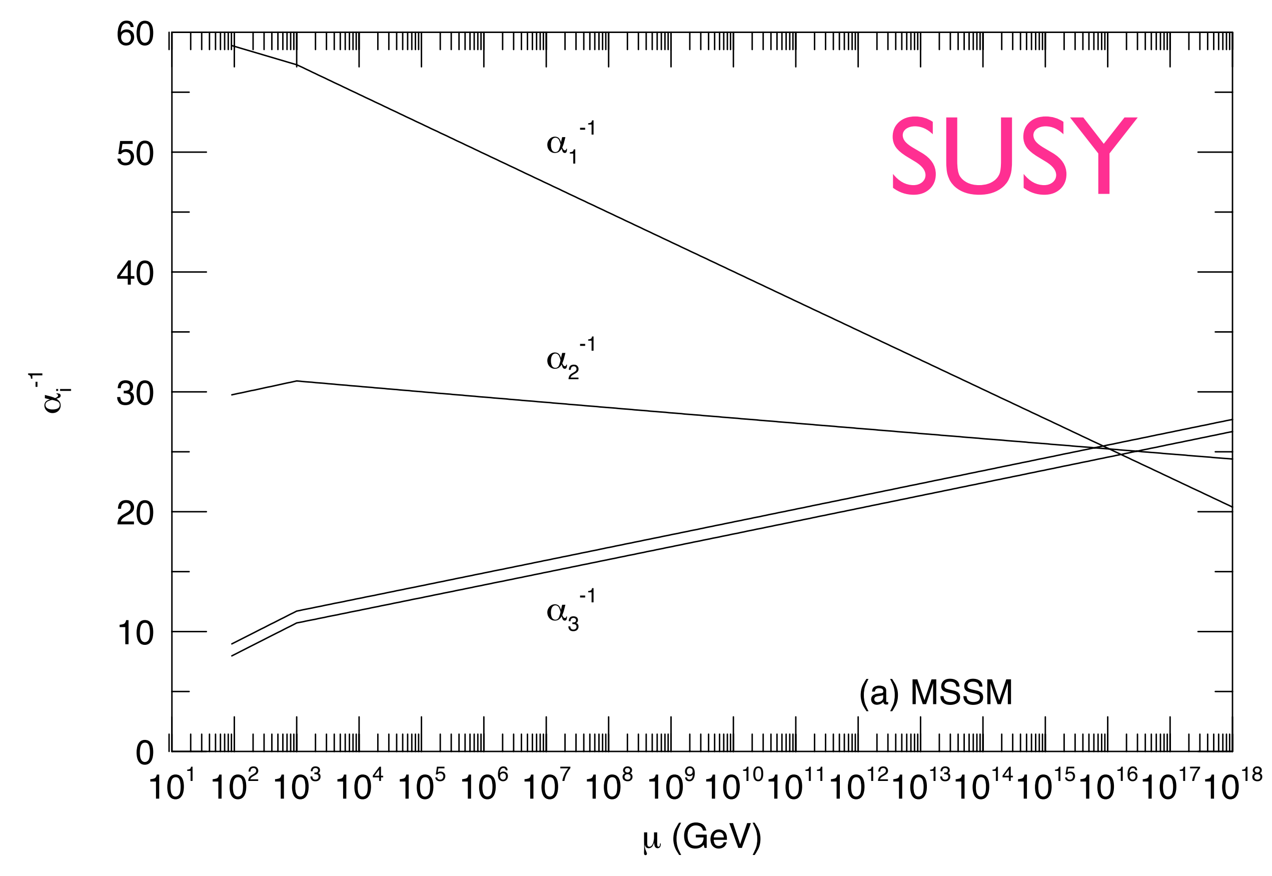
- Supersymmetry (SUSY)
  - Hierarchy Problem
    Keep electroweak scale against radiative correction
  - Coupling Constant Unification in GUT

- SUSY particles

quark	$\longleftrightarrow$	squarks
lepton	$\longleftrightarrow$	slepton
photon	$\longleftrightarrow$	photino

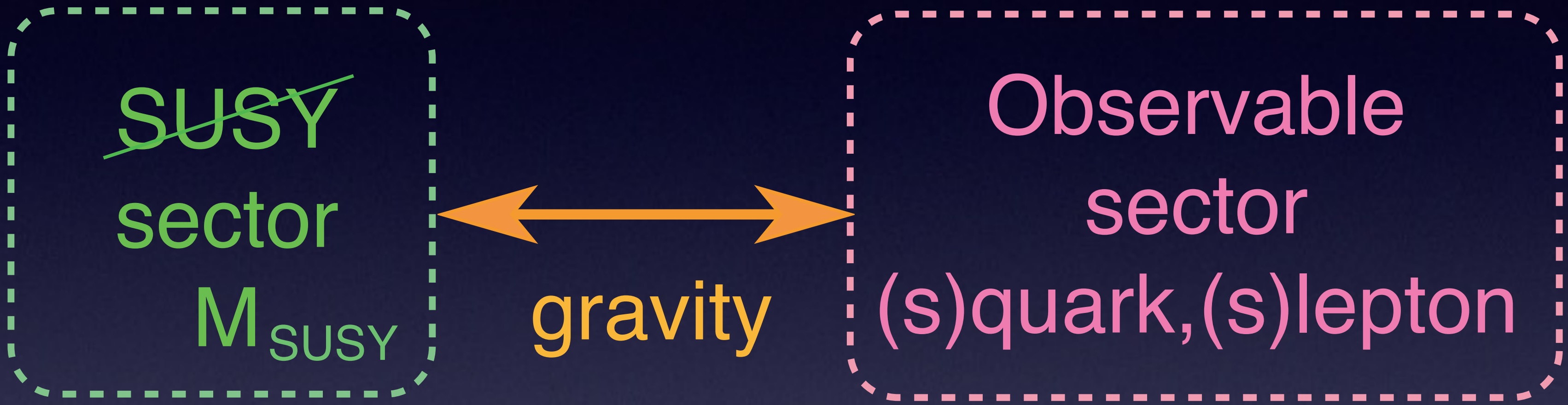
- Gravitino
  superpartner of graviton

Gravitino $\psi_{3/2}$



SUSY Breaking Scheme

- At low energy ~~SUSY~~ $(m_{\tilde{q}}, m_{\tilde{\ell}} \sim 1\mathrm{TeV} \gg m_q, m_\ell)$
- Gravity Mediated SUSY Breaking (GMSB)



~~SUSY~~ sector M_{SUSY}

gravity

Observable sector (s)quark,(s)lepton

- Squark, slepton masses

$$m_{\tilde{q}}, m_{\tilde{\ell}} \sim \frac{M_{\mathrm{SUSY}}^2}{M_p} \sim 10^{2-3}\ \mathrm{GeV}$$

$$M_{\mathrm{SUSY}} \sim 10^{11-13}\ \mathrm{GeV}$$

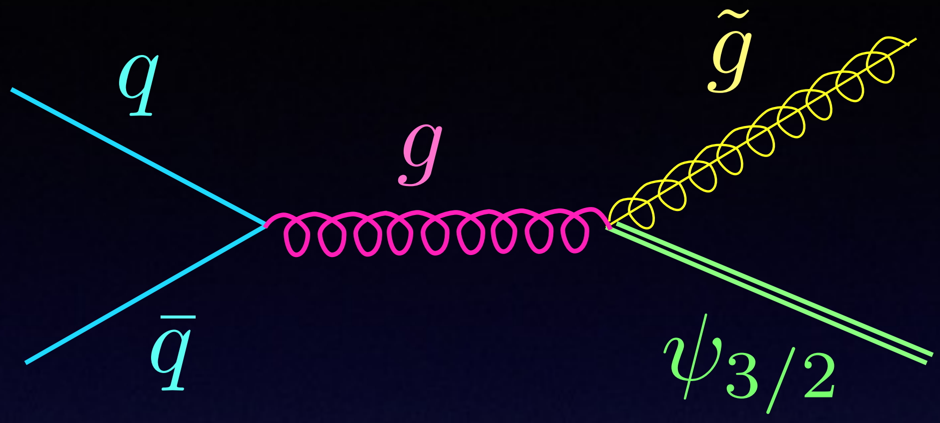
- Gravitino

$$\boxed{m_{3/2} \sim 10^{2-3}\ \mathrm{GeV}}$$

Gravitino production and decay

- Gravitinos are produced during reheating after inflation

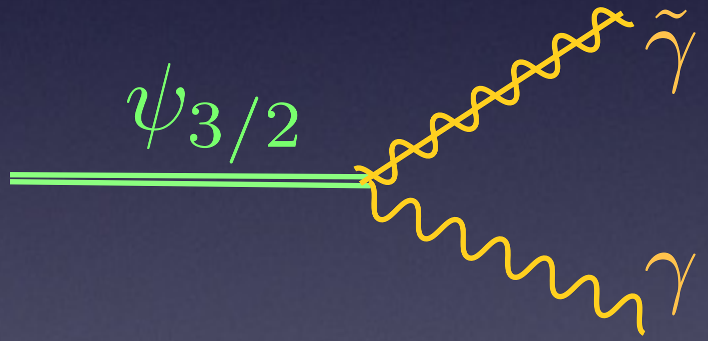
$$\boxed{\frac{n_{3/2}}{n_\gamma} \simeq 10^{-11}\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)}$$



Bolz, Brandenburg, Buchmüller (2001); MK, Moroi (1995)

$$n_{3/2}/n_\gamma \sim \sigma n_q t \sim (1/M_p^2)T_R^3(M_p/T_R^2)$$

- Gravitino decay



  - Radiative decay e.g. $\psi_{3/2} \to \tilde{\gamma} + \gamma$

$$\tau(\psi_{3/2} \to \tilde{\gamma} + \gamma) \simeq 4 \times 10^8\,\mathrm{sec}\left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)^{-3}$$

  - Hadronic decay e.g. $\psi_{3/2} \to \tilde{g} + g$

$$\tau(\psi_{3/2} \to \tilde{g} + g) \simeq 6 \times 10^7\,\mathrm{sec}\left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)^{-3}$$

Gravitino problem and constraint on reheating temperature

Decay Products (photons, hadrons)

↓

Serious Effect on Big Bang Nucleosynthesis

Gravitino Problem

↓

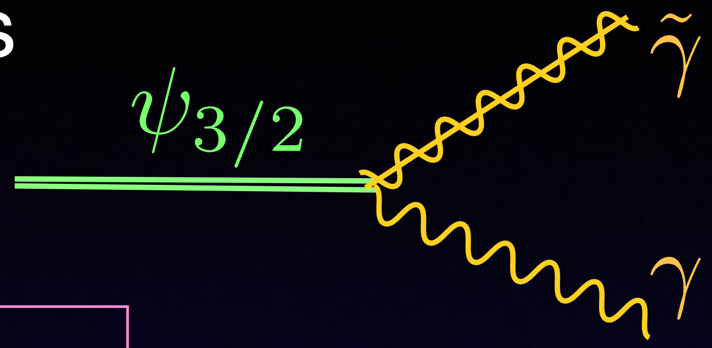
$$Y_{3/2} \equiv \frac{n_{3/2}}{s} \simeq 1.9 \times 10^{-12} \left(\frac{T_R}{10^{10}\,\mathrm{GeV}} \right)$$

Stringent Constraint on T_R

Ellis, Nanopoulos,Sarkar (1985)
Reno, Seckel (1988)
Dimopoulos et al (1989)
MK, Moroi (1995)

2.2 Radiative decay and BBN

- Radiative decay → High energy photons



→ Electromagnetic shower

$$\gamma + \gamma_{\rm BG} \rightarrow e^+ + e^-$$

$$\epsilon_\gamma > m_e^2/22T$$

$$e^\pm + \gamma_{\rm BG} \rightarrow e^\pm + \gamma$$

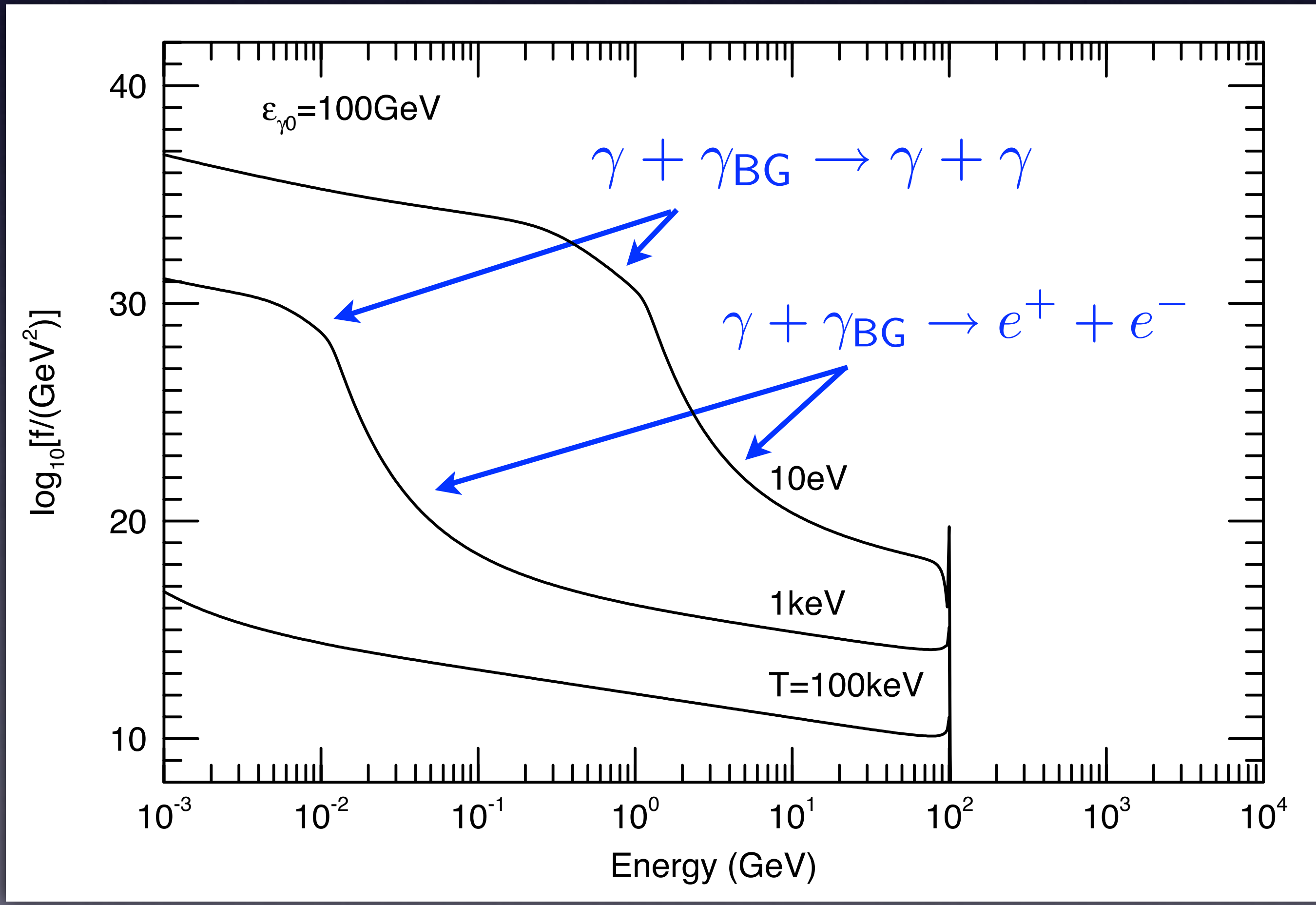
$$\gamma + \gamma_{\rm BG} \rightarrow \gamma + \gamma$$

→ Many soft photons

$$\epsilon_\gamma \gtrsim 2.2\text{MeV} \quad (T \lesssim 10\text{keV})$$

$$\epsilon_\gamma \gtrsim 20\text{MeV} \quad (T \lesssim 1\text{keV})$$

→ Destruct light elements



MK, Moroi (1995)

- Destruction of light elements

$$\begin{aligned}
&\mathrm{D}+\gamma\rightarrow n+p && [2.2\mathrm{MeV}]\\
&\mathrm{T}+\gamma\rightarrow \mathrm{D}+n && [6.2\mathrm{MeV}]\\
&{}^{3}\mathrm{He}+\gamma\rightarrow \mathrm{D}+p && [5.5\mathrm{MeV}]\\
&{}^{4}\mathrm{He}+\gamma\rightarrow \mathrm{T}+n && [19.8\mathrm{MeV}]\\
&{}^{4}\mathrm{He}+\gamma\rightarrow{}^{3}\,\mathrm{He}+n && [20.5\mathrm{MeV}]\\
&{}^{4}\mathrm{He}+\gamma\rightarrow \mathrm{D}+n+p && [26.1\mathrm{MeV}]
\end{aligned}$$

→ Non thermal production of D and He3

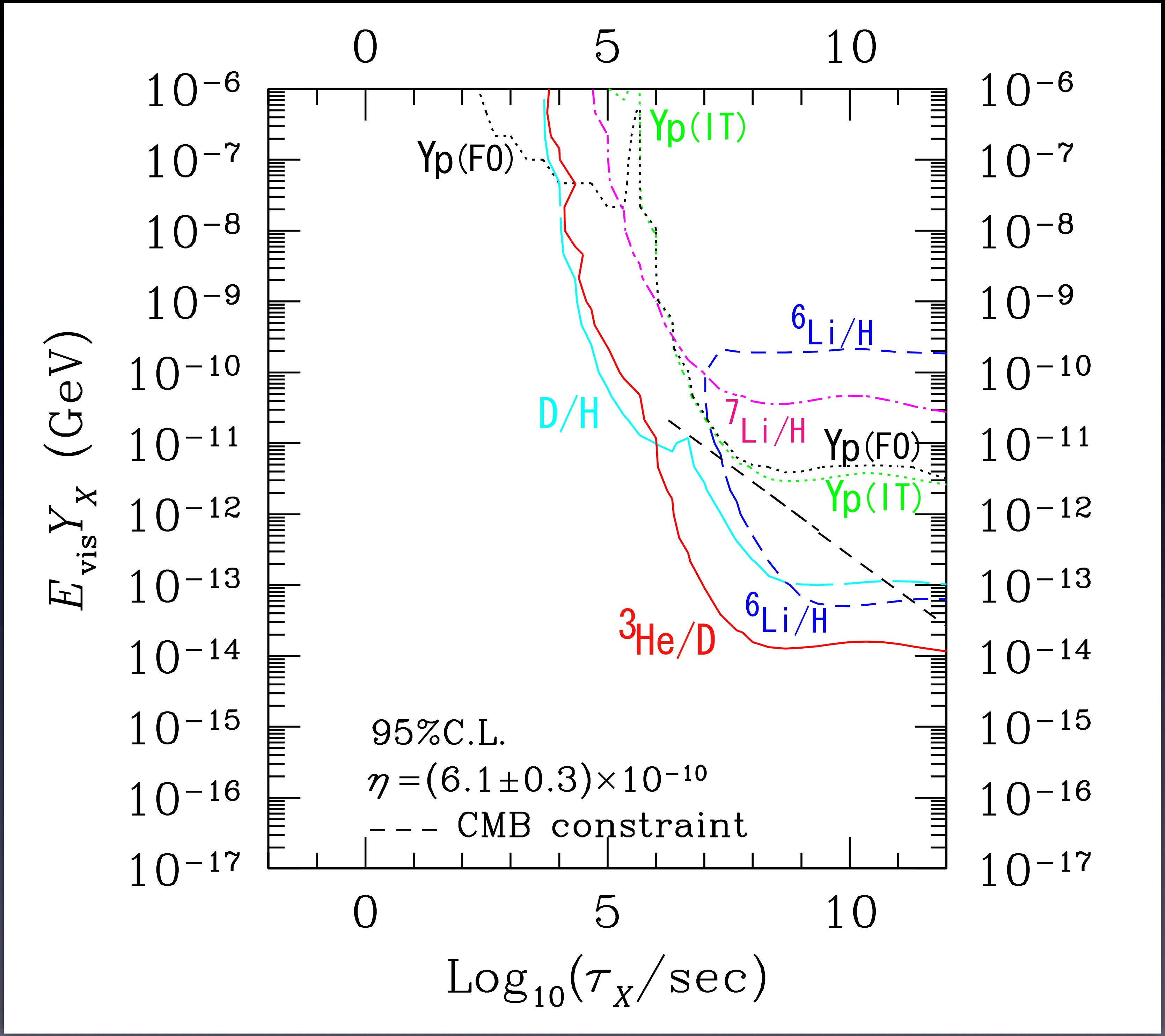
→ Non thermal production of Li6

Dimopoulos et al (1989)
Jedamzik (2000)

$$\begin{aligned}
&\mathrm{T}+\ {}^{4}\mathrm{He}\rightarrow\ {}^{6}\mathrm{Li}+n && [4.0\mathrm{MeV}]\\
&{}^{3}\mathrm{He}+\ {}^{4}\mathrm{He}\rightarrow\ {}^{6}\mathrm{Li}+p && [4.8\mathrm{MeV}]
\end{aligned}$$

Constraint on radiative decay

MK, Kohri, Moroi (2005)



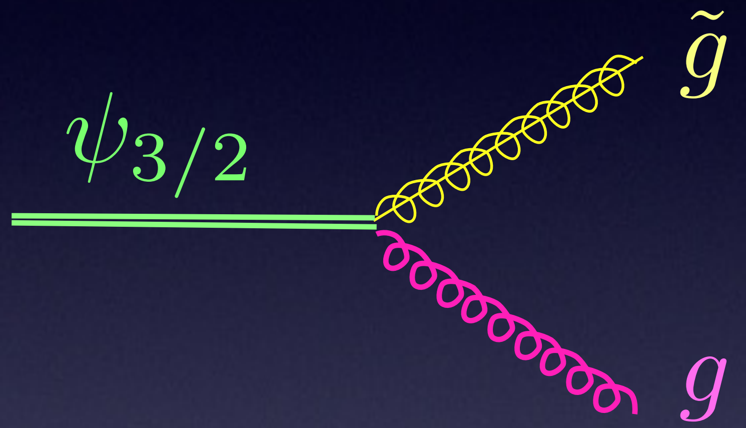
- He3/D gives the most stringent constraint

2.3 Haronic decay and BBN

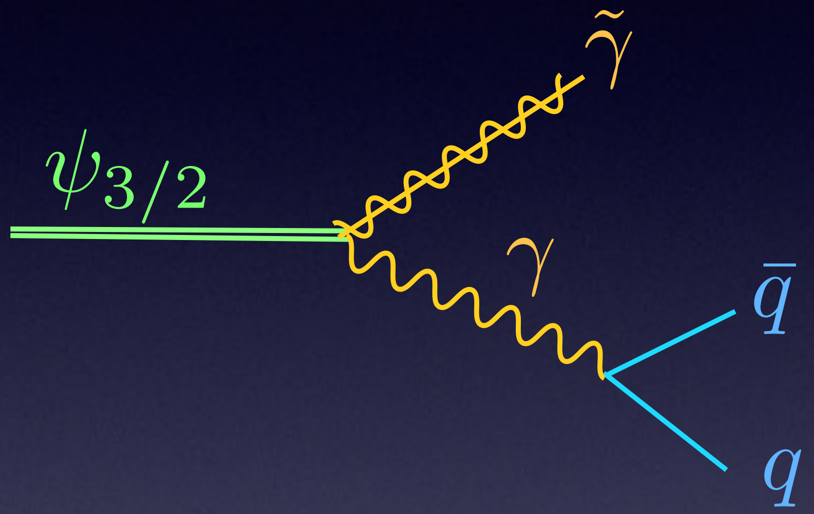
Reno, Seckel (1988)
Dimopoulos et al (1989)

MK, Kohri, Moroi (2005)
Jedamzik (2006)

- Hadronic decay takes place even if gravitino only couples to photon and photino

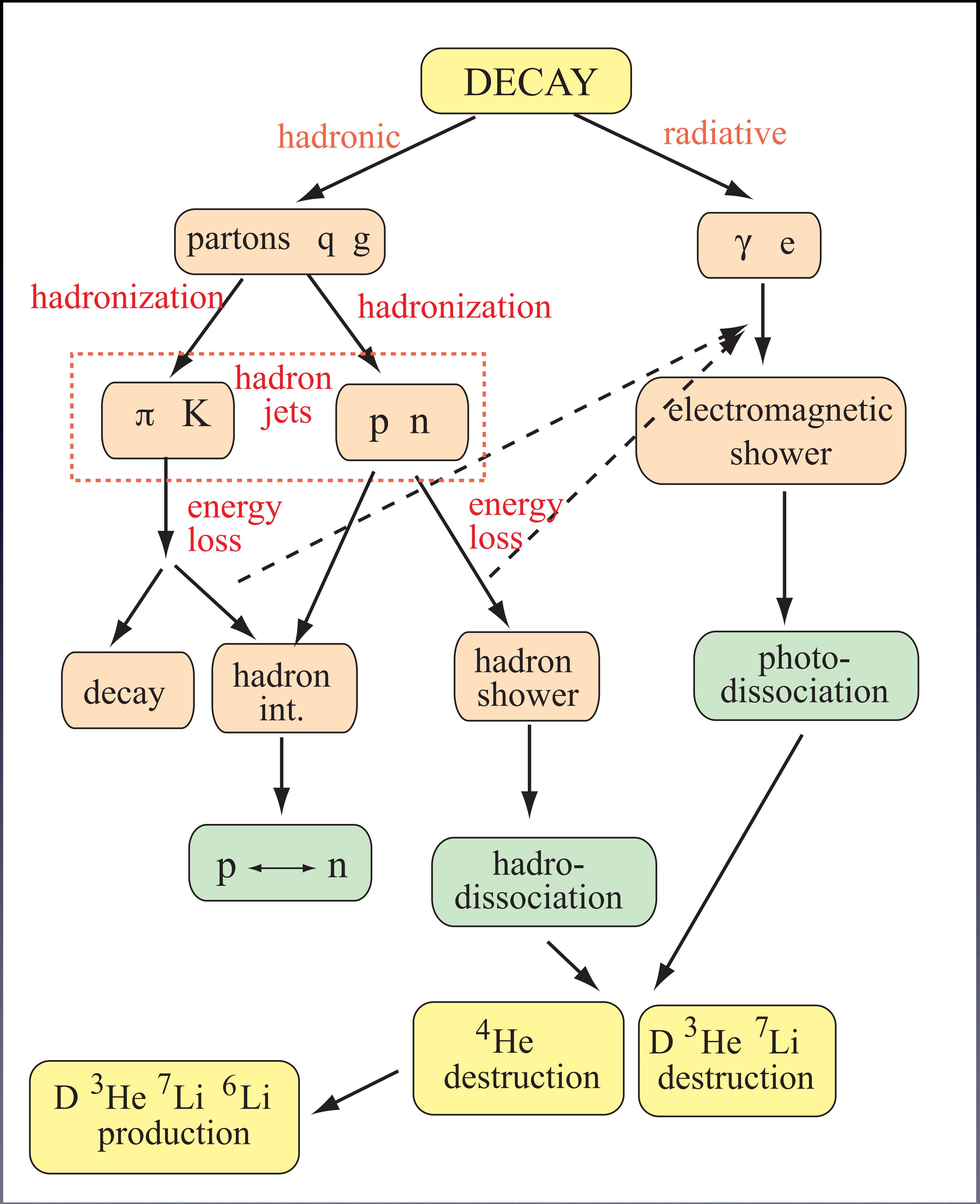


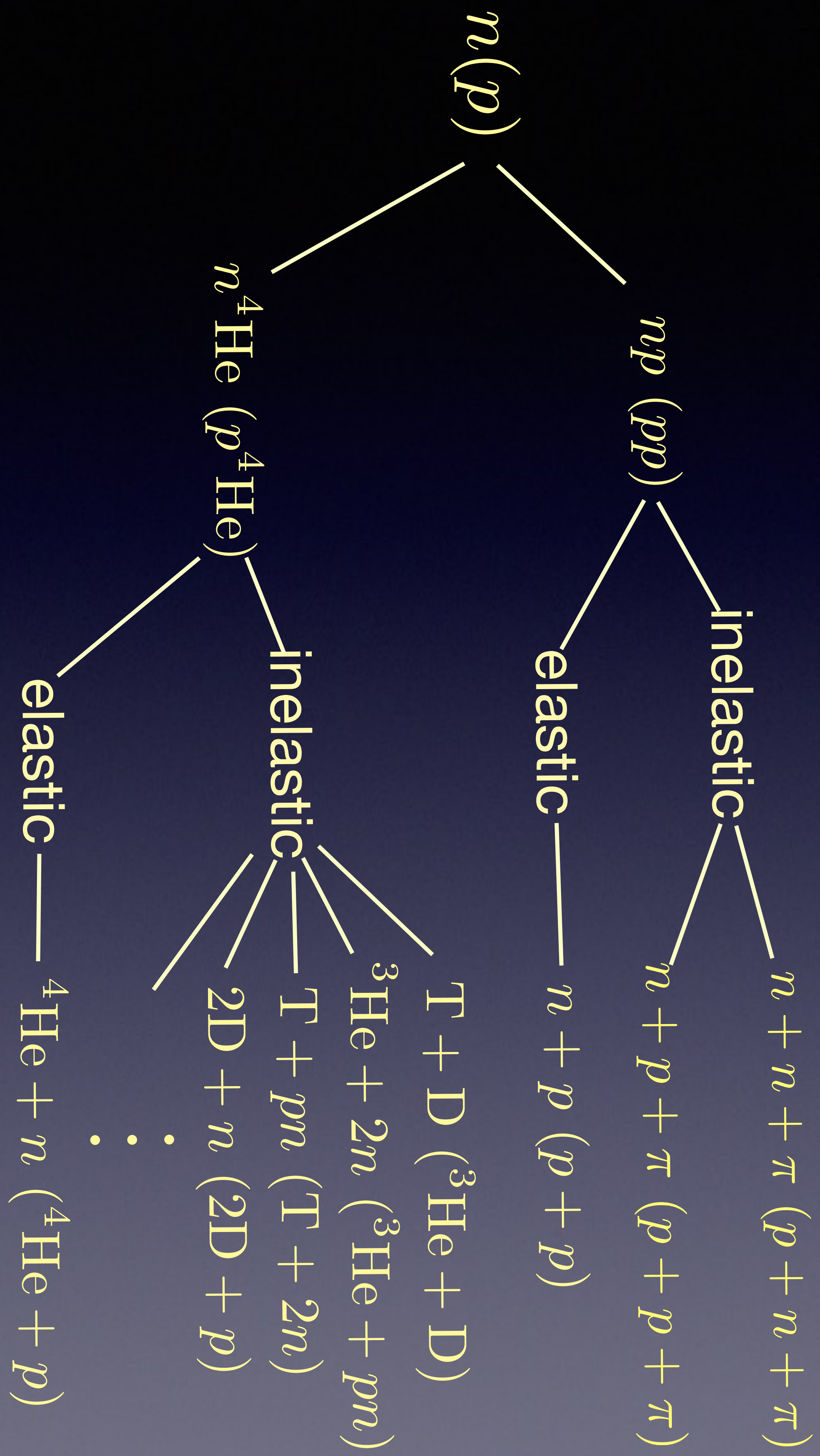
$B_h \sim 1$



$B_h \sim \alpha/4\pi \sim 0.001$

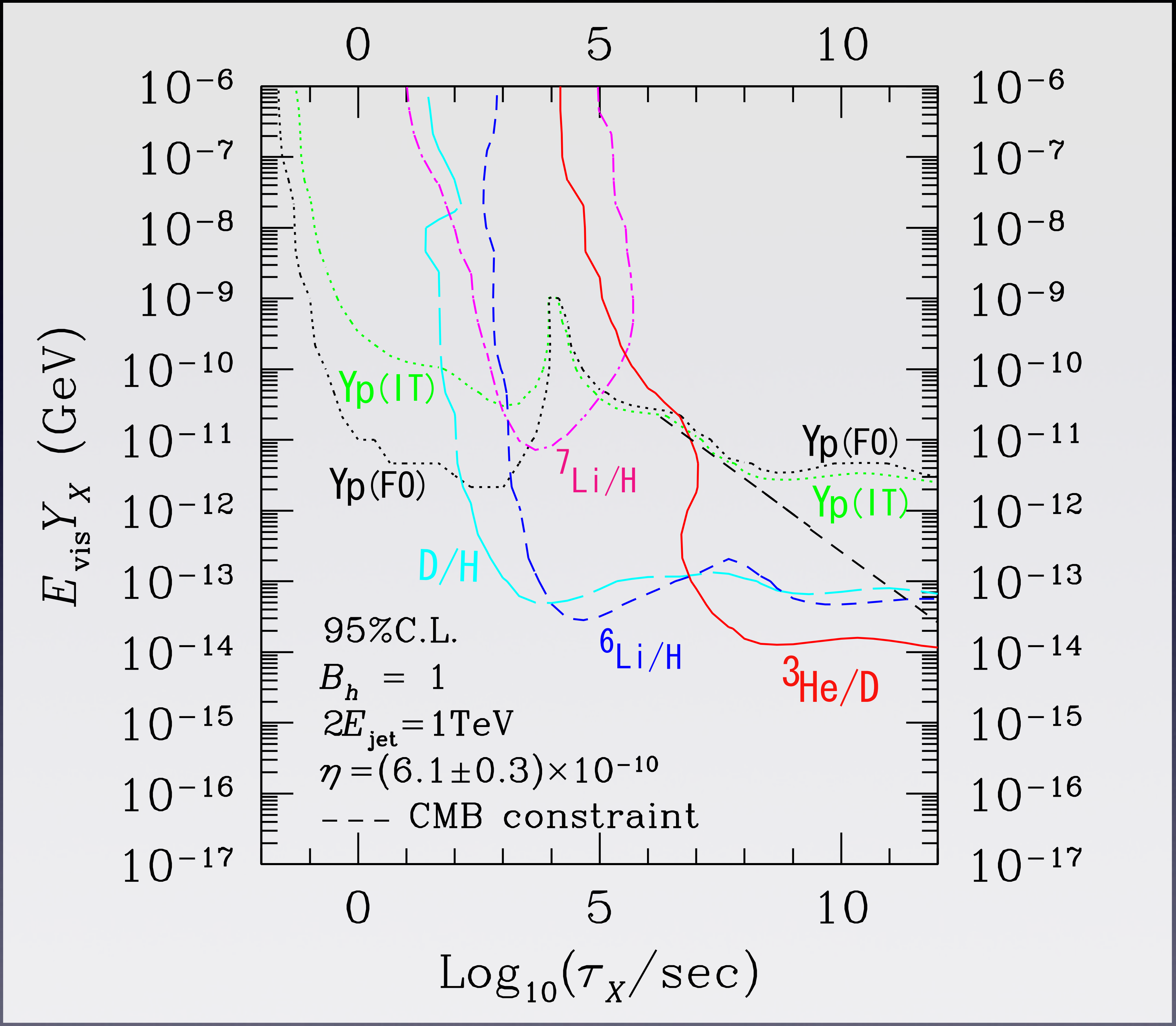
quarks, gluons → energetic hadrons → hadro-dissociation → destruction & production of Light elements


DECAY
hadronic
radiative
partons q g
γ e
hadronization
hadronization
hadron jets
π K
p n
electromagnetic shower
energy loss
energy loss
decay
hadron int.
hadron shower
photo-dissociation
p ⟷ n
hadro-dissociation
^{4}He destruction
D ^{3}He ^{7}Li destruction
D ^{3}He ^{7}Li ^{6}Li production


$p(n)$
$n\,^4\mathrm{He}$ $(p\,^4\mathrm{He})$
np (pp)
elastic
inelastic
elastic
inelastic
$^4\mathrm{He}+n$ $(^4\mathrm{He}+p)$
⋮
$2\mathrm{D}+n$ $(2\mathrm{D}+p)$
$\mathrm{T}+pn$ $(\mathrm{T}+2n)$
$^3\mathrm{He}+2n$ $(^3\mathrm{He}+pn)$
$\mathrm{T}+\mathrm{D}$ $(^3\mathrm{He}+\mathrm{D})$
$n+p$ $(p+p)$
$n+p+\pi$ $(p+p+\pi)$
$n+n+\pi$ $(p+n+\pi)$

Constraint on hadronic decay

MK, Kohri, Moroi (2005)



- D/H ($\tau < 10^7$ sec) or He3/D ($\tau > 10^7$ sec) gives the most stringent constraint

2.4 Constraint on reheating temperature

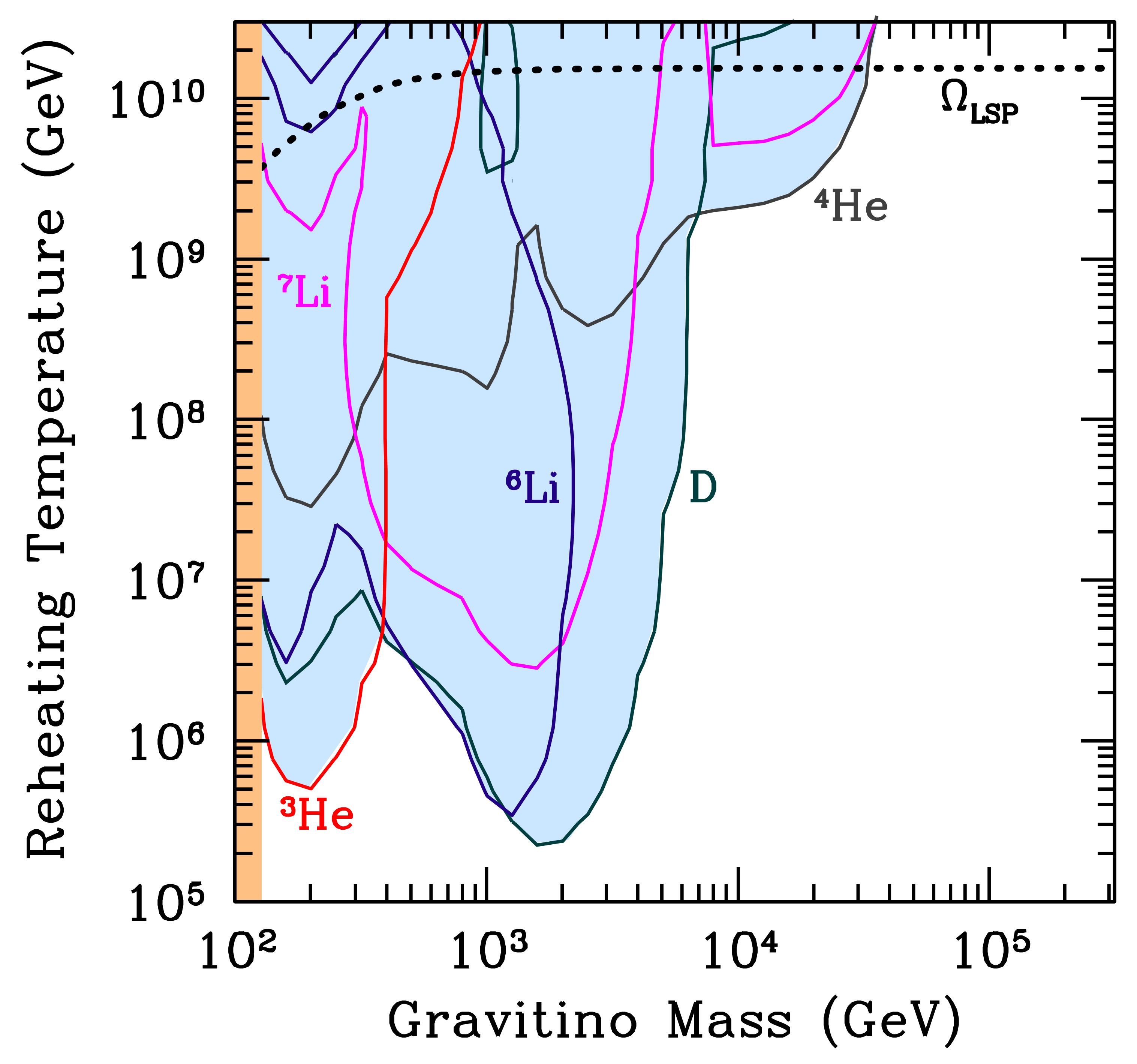
MK, Kohri, Moroi, Yotsuyanagi (2008)

- Gravitino lifetime ← $m_{3/2}$ decay modes
- Gravitino abundance ← T_{R}

$$Y_{3/2} \equiv \frac{n_{3/2}}{s} \simeq 1.9 \times 10^{-12} \left(\frac{T_R}{10^{10}\mathrm{GeV}} \right)$$

- SUSY mass spectrum
  - adopt CMSSM (constrained minimal susy standard model)
    - Universal gaugino mass $m_{1/2}$
    - Universal scalar mass m_0
    - Universal trilinear coupling A_0
    - ratio of VEV of the two Higgs fields $\tan\beta$

MK Kohri Moroi Yotsuyanagi (2008)



- Reheating temperature T_R should be less than ~ 10^6 GeV for $m_{3/2}$ = 0.1 - 40 TeV

2.3 Constraint on annihilation of dark matter

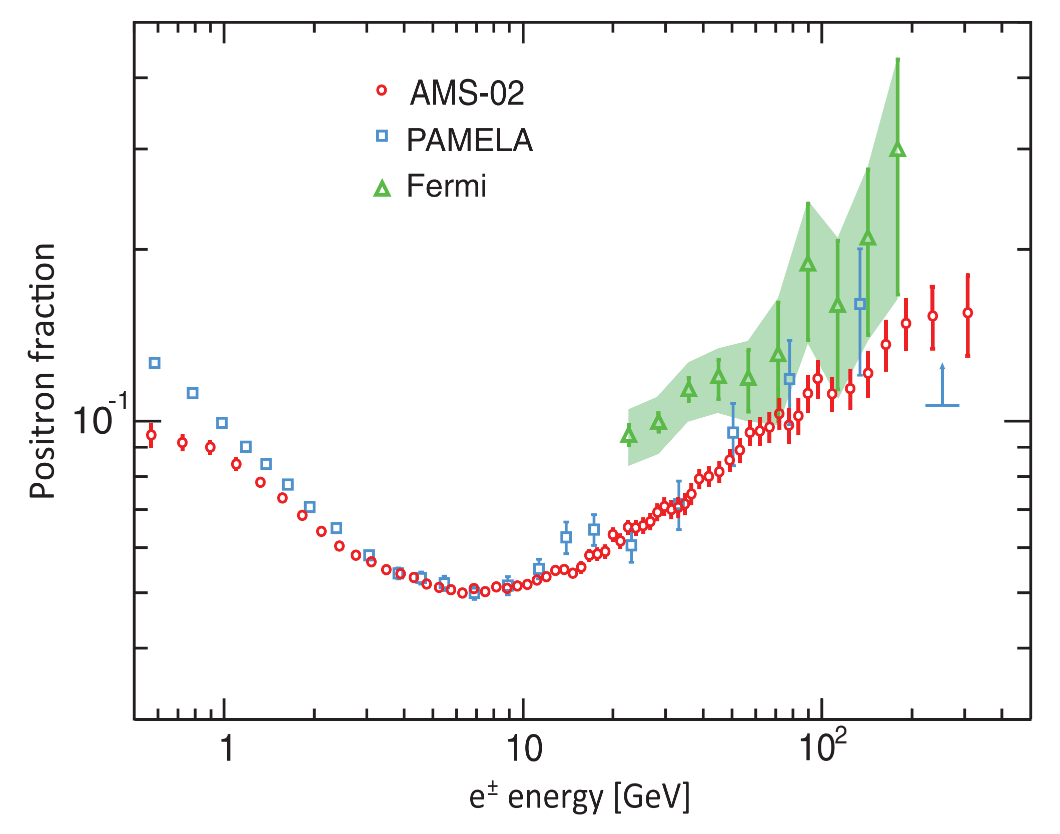
- Motivated by the observation of cosmic ray positrons and electrons by the PAMELA satellite

➡ $\mathrm{DM} + \mathrm{DM} \longrightarrow e^+ + e^-$

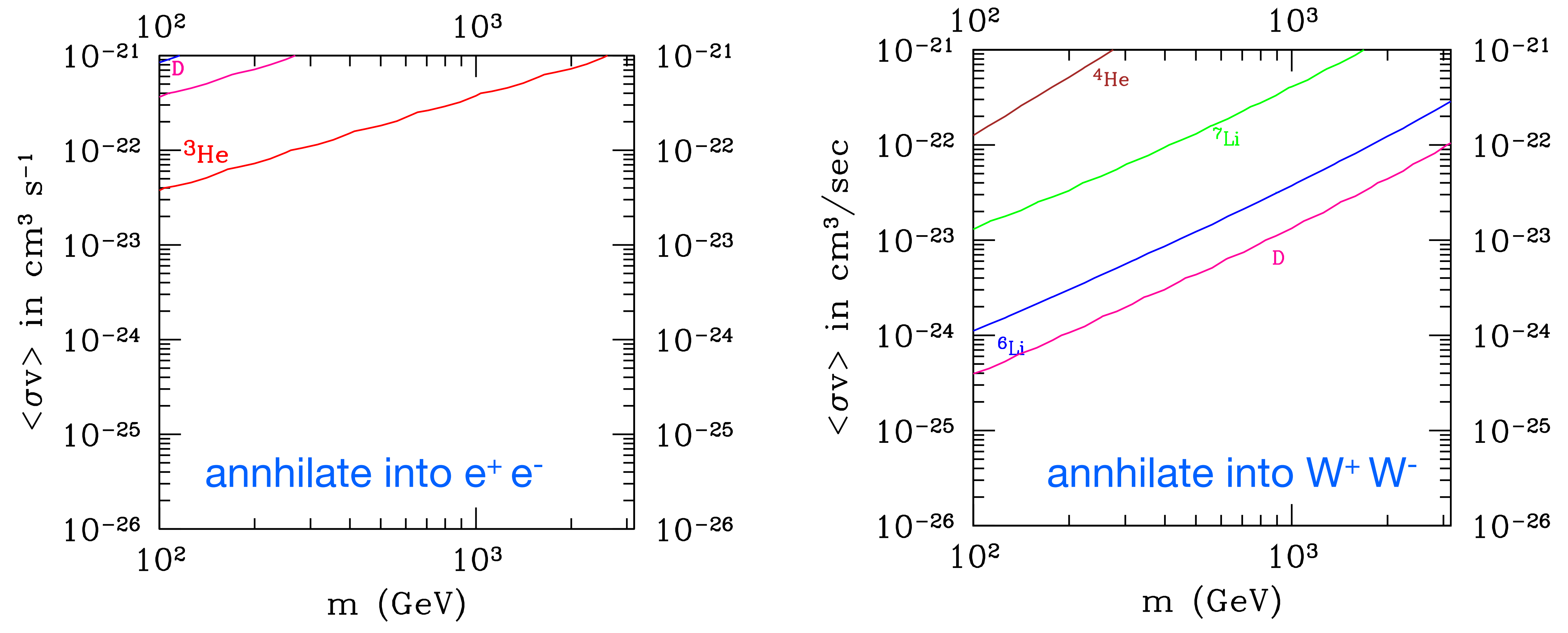
$$\boxed{\langle\sigma v\rangle \sim 10^{-23}\mathrm{cm}^{-3}\mathrm{s}^{-1}}$$

- DM annihilation also affects BBN

AMS(2013)

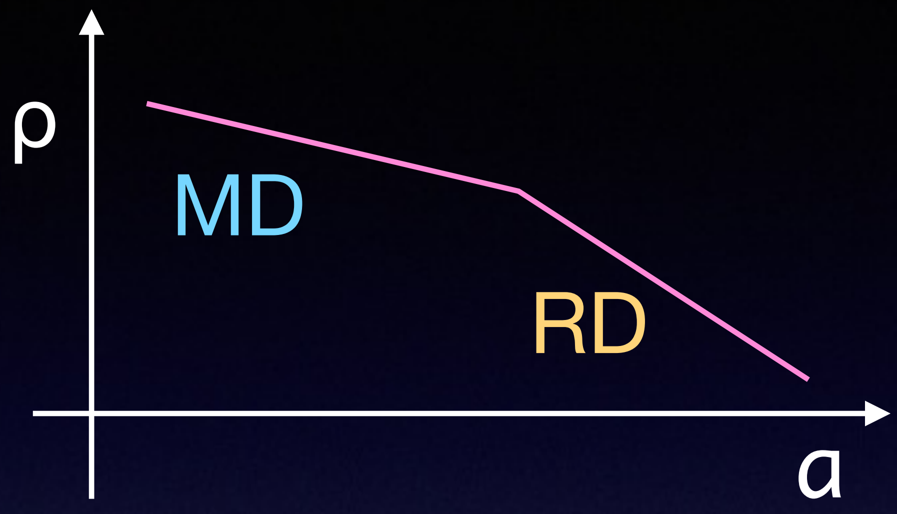


Hisano, Kawasaki, Kohri, Moroi, Nakayama (2009)



2.4 MeV reheating (lower bound on reheating temperature)

- Low reheating temperature after inflation
- Late-time decay of massive particles



→ Reheating temperature =O(1)MeV

- Inflaton decay into standard model particles
- All particles except neutrinos are quickly thermalized

→ Insufficient neutrino thermalization

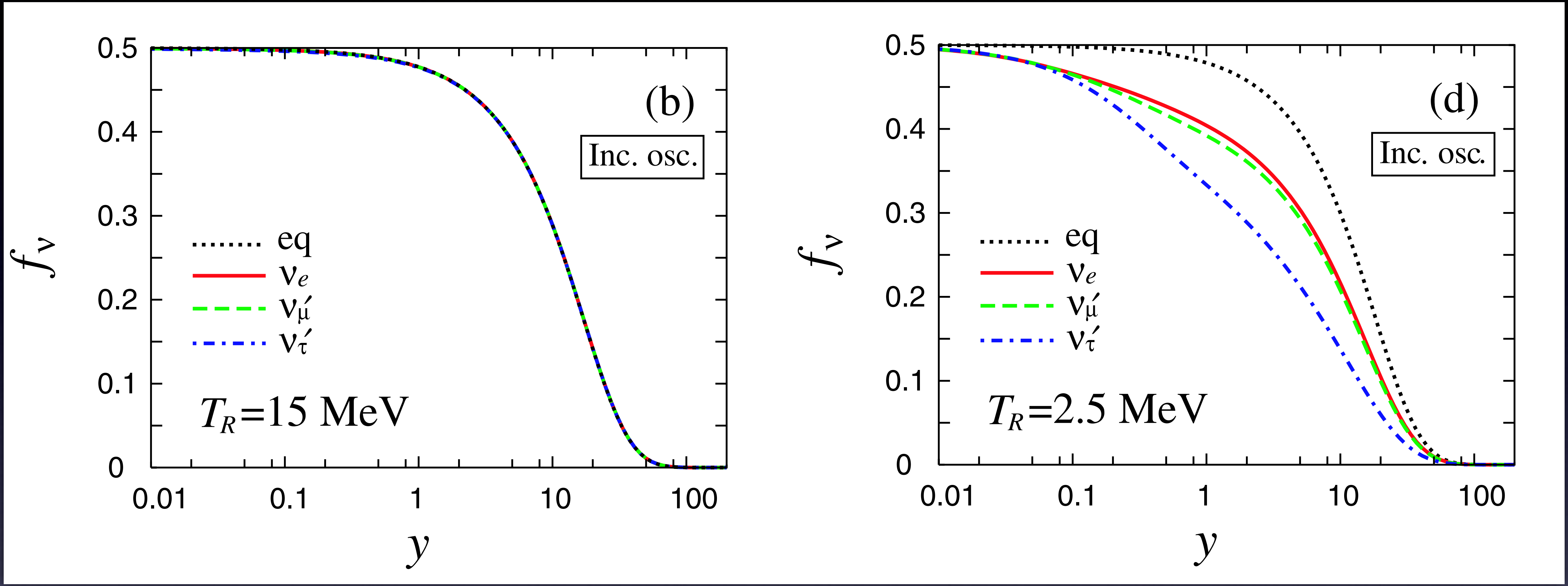
- small number of electron neutrinos
- small effective number of neutrino species

→ BBN

→ **Constraint on T_R**

- Momentum distribution of neutrinos

Ichikawa, Kawasaki, F.Takahashi (2005)



- BBN (p/n) ⬅ $p + e^- \leftrightarrow n + \nu_e$
  - small number of ν_e ➡ weak interaction ↘ ➡ $n/p \nearrow$
  - small ν density ➡ cosmic expansion ↘ ➡ $n/p \searrow$

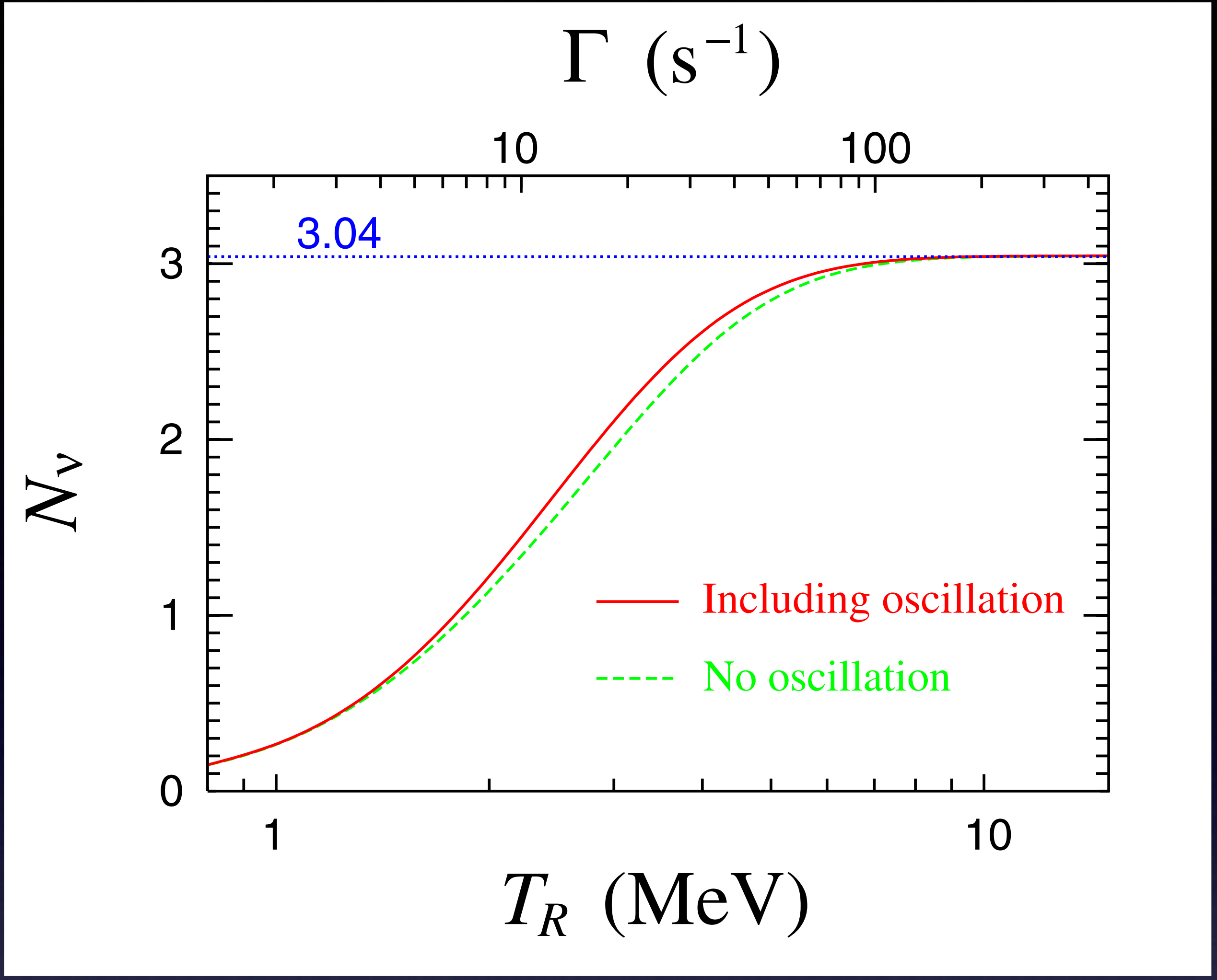
- Effective number of neutrinos

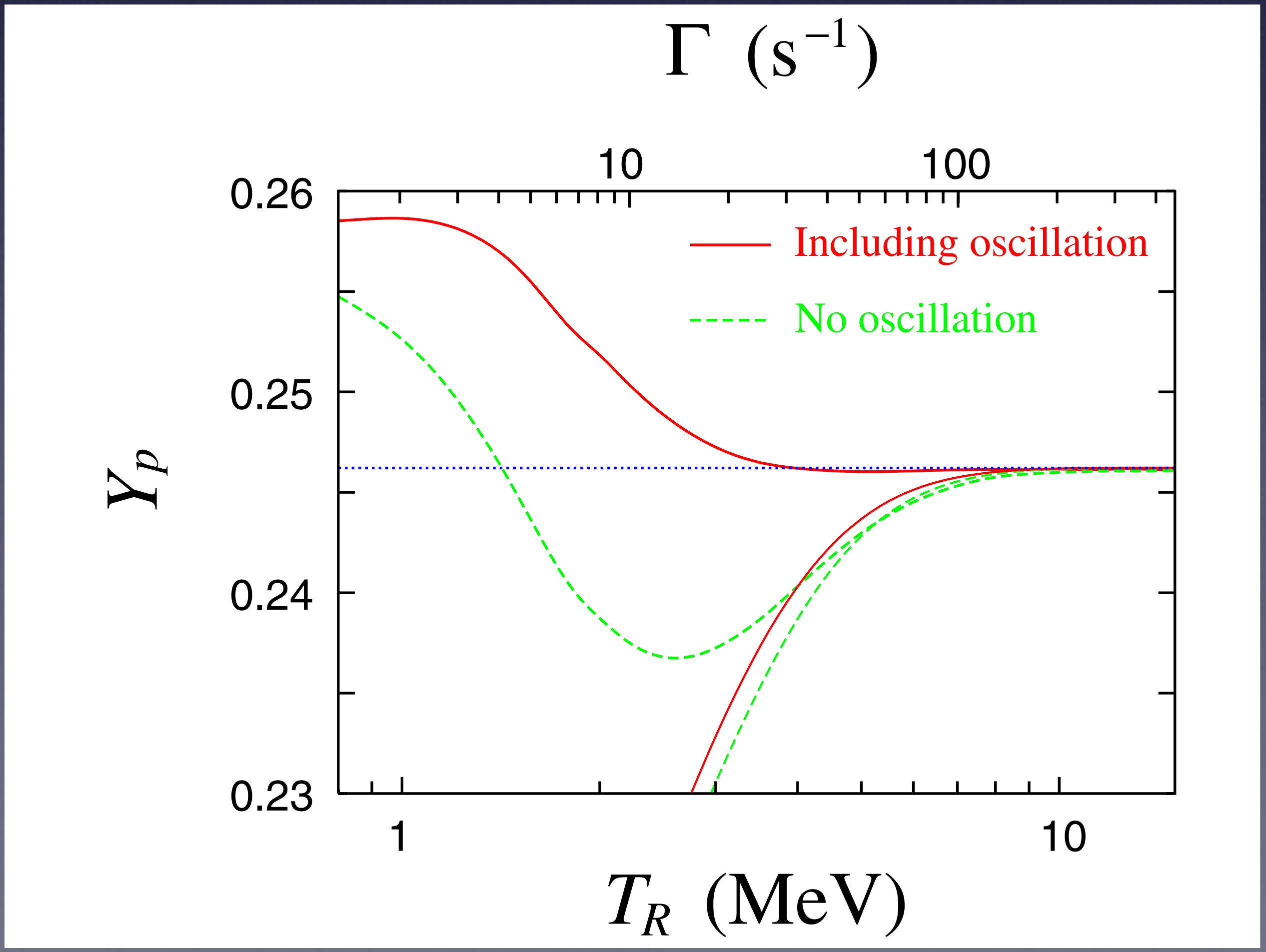
$$\boxed{N_\nu = \frac{\sum \rho_{\nu_i}}{\rho_{\text{std}}}}$$

- He4 abundance

$$n/p \nearrow \quad \Rightarrow \quad Y_p \nearrow$$

Lowering T_R only acts to delay the p-n ratio freeze-out and decreases Y_p

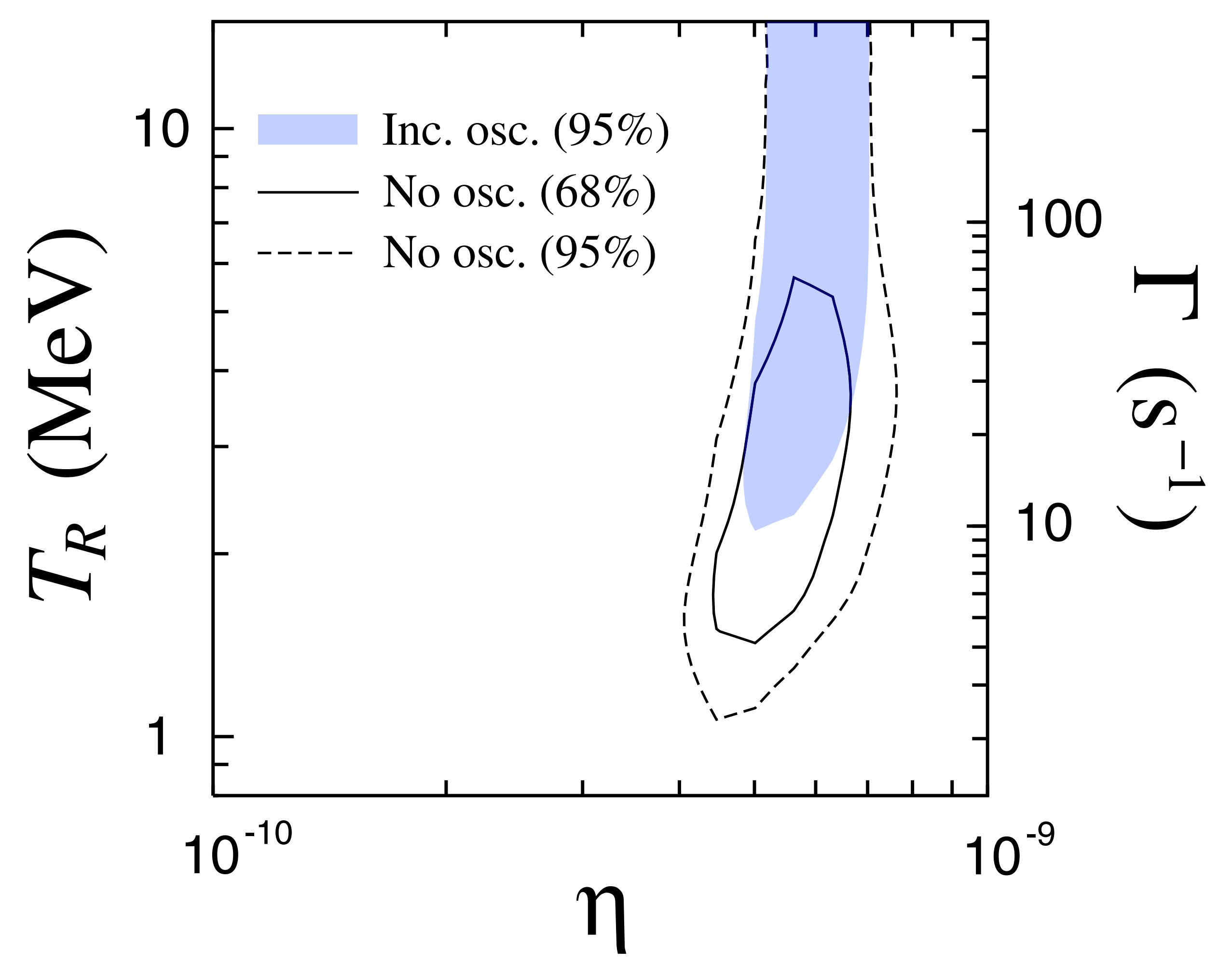




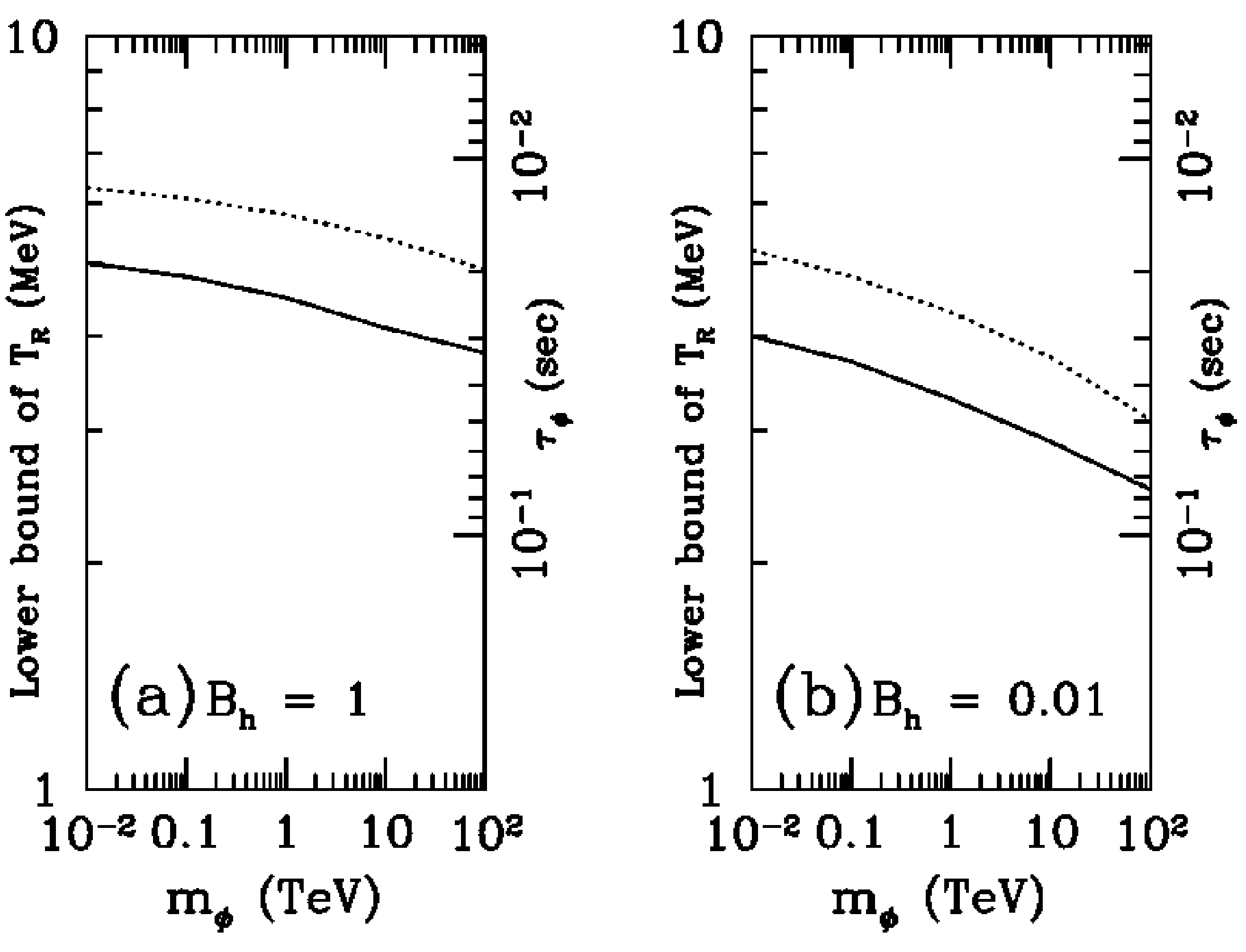
Constrain on reheating temperature

- BBN constraint → $T_R > 2$ MeV
- If hadronic decay occurs ($\pi^\pm$ $K^\pm$ . . .) it changes n/p

→ $T_R >$ 3-5 MeV



Ichikawa, Kawasaki, F.Takahashi (2005)

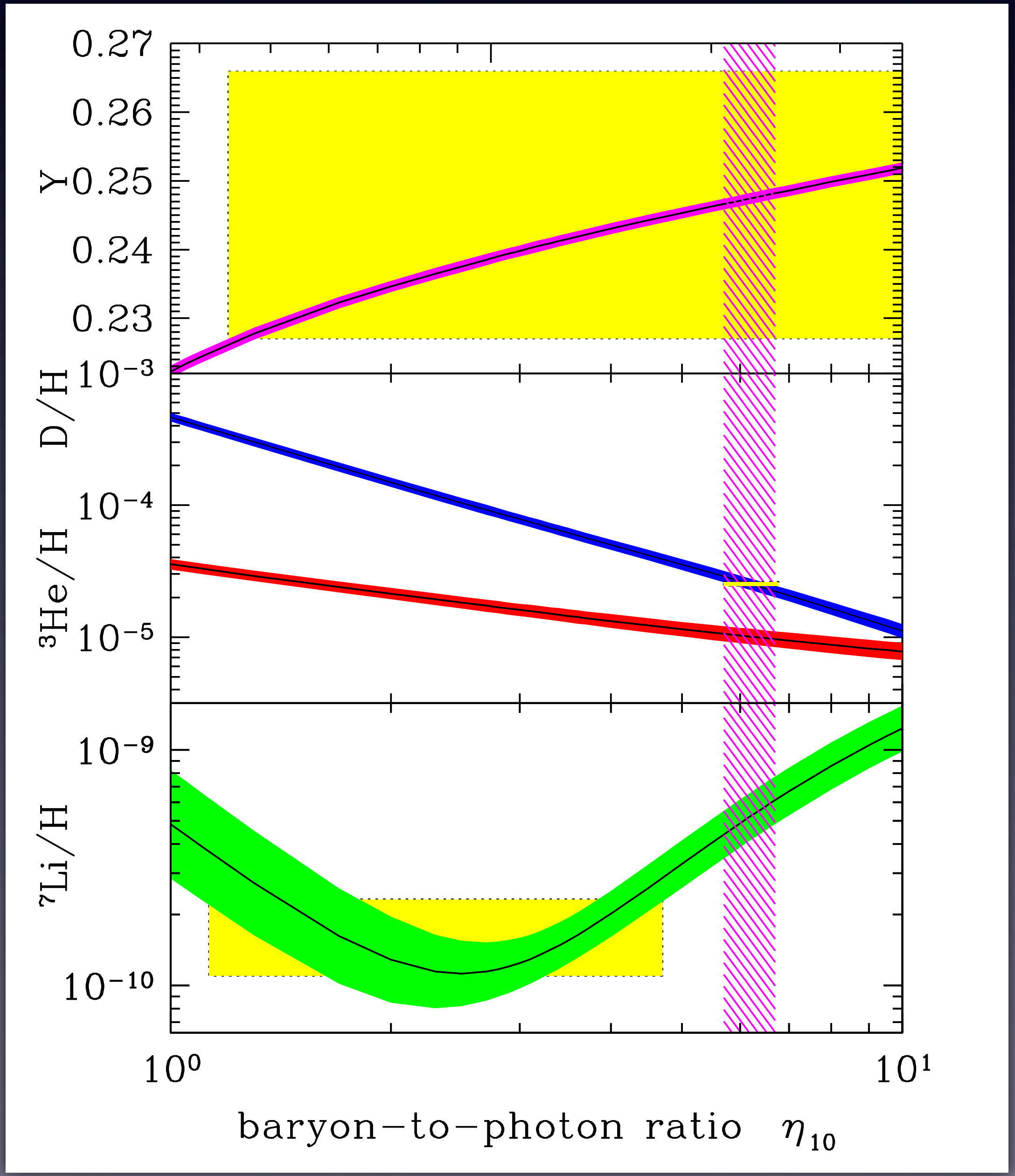


Kawasaki, Kohri, Sugiyama (2000)

3. Baryogenesis and dark matter

- Our universe is made of baryons (not anti-baryons)
- Asymmetry between matter and ant-matter
- How large asymmetry? →

$$\boxed{n_B - n_{\bar{B}}?}$$



Big Bang Nucleosynthesis

$$\boxed{\frac{n_B}{s} = (6-8)\times 10^{-11}}$$

s: entropy density

Baryogenesis

before BBN after inflation

3.1 Sakharov's condition

- For successful baryogenesis

(1) B violation (L-B violation)

(2) C and CP violation

(3) Out of equilibrium

(2) CP transformation

$$\mathrm{A} + \mathrm{B} \to \mathrm{C} + \mathrm{D} \;\Rightarrow\; \mathrm{A}^{CP} + \mathrm{B}^{CP} \to \mathrm{C}^{CP} + \mathrm{D}^{CP}$$

If the theory is CP invariant

$$\Gamma[\mathrm{A} + \mathrm{B} \to \mathrm{C} + \mathrm{D}] = \Gamma[\mathrm{A}^{CP} + \mathrm{B}^{CP} \to \mathrm{C}^{CP} + \mathrm{D}^{CP}]$$

→ B = 0

(3) Thermal distribution is determined by T and m

CPT invariance $m_{\mathrm{A}} = m_{\bar{\mathrm{A}}}$ → B = 0

3.2 Baryogenesis mechanism

- Electroweak baryogenesis
  - In the standard model
    - too small CP (Kobayashi-Maskawa)
    - EW phase transition is not 1st order

→ not working

- Leptogenesis
  - Lepton number generation from heavy right-handed ν
  - L → B by sphaleron process
    - Requires high reheating temperature $T > 10^9$ GeV

→ graviton problem?

- Affleck-Dine baryogenesis

3.2 Affleck-Dine Mechanism

Affleck, Dine (1985)

- Scalar potential (squark, slepton, higgs) in MSSM (minimal supersymmetric standard model)

  Flat Directions = Affleck-Dine fields Φ ← baryon (lepton) number

  (flat if SUSY and no cut-off)

- In the inflationary universe, dynamics of some AD field produces baryon asymmetry of the universe

- Scalar potential

$$\boxed{V(\Phi) = m_\Phi^2|\Phi|^2 + \frac{|\Phi|^{2(n-1)}}{M^{2(n-3)}} + a\frac{m_{3/2}}{M^{n-3}}(\Phi^n + \Phi^{*n})}$$

SUSY breaking

U(1) symmetry

Non-renormalizable term

A-term

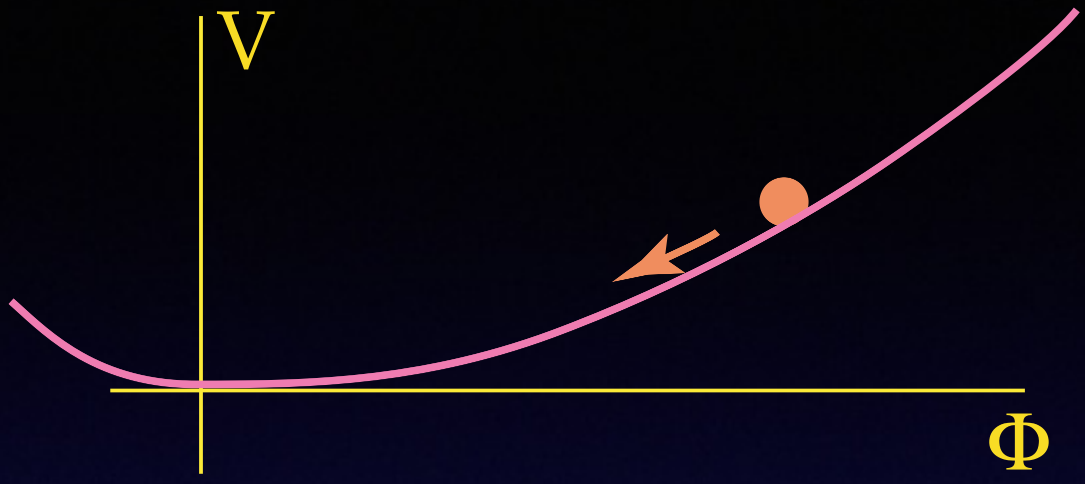
$\cancel{\mathrm{U}}(1)$

$$\boxed{\Rightarrow \cancel{U}_B(1)}$$

Dynamics of Affleck-Dine Field

- During Inflation Φ has a large value

  $\langle |\Phi| e^{i\theta} \rangle \neq 0 \;\Rightarrow$ CP, out of eq.



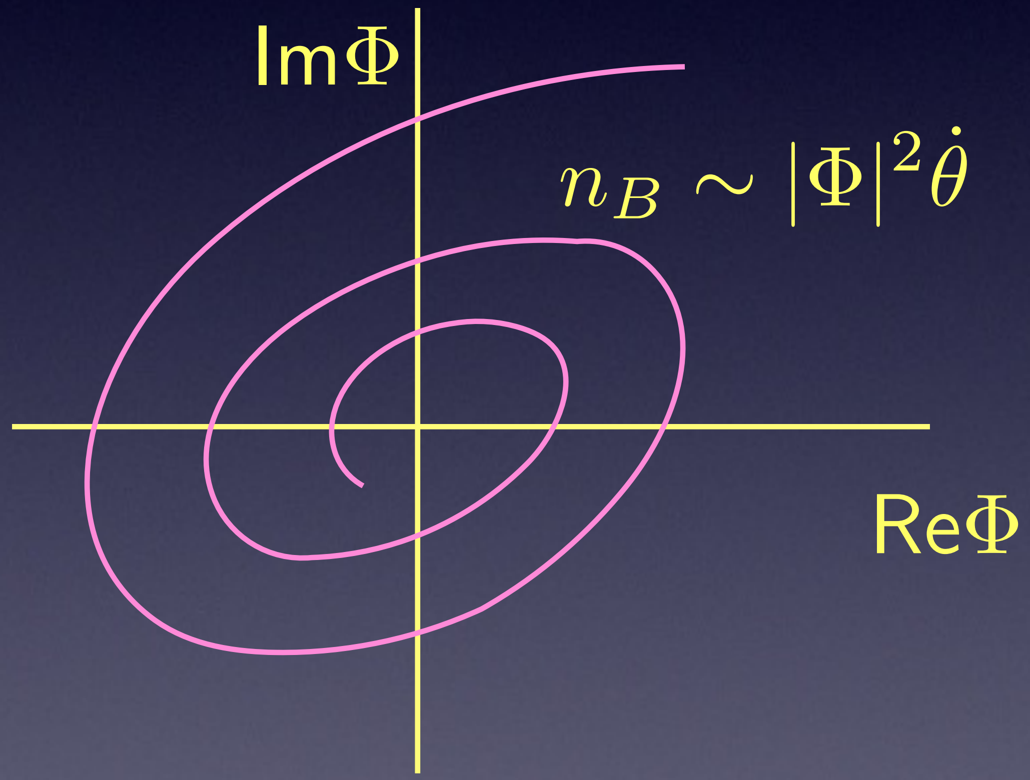
- $H \lesssim m_\Phi$ ➡ Φ Oscillation

A-term

⬇

Kick in phase direction

➡ Baryon Number Generation



$$\boxed{n_B = -i(\dot{\Phi}^* \Phi - \Phi^* \dot{\Phi})}$$

$$\sim \dot{\theta} |\Phi|^2$$

Noether current

$$j_{B,\mu} = i(\Phi^* \partial_\mu \Phi - \Phi \partial_\mu \Phi^*)$$

3.3 Affleck-Dine mechanism and Q-ball formation

- However, Dynamics of AD-field is complicated by the existence of Q-ball

Kusenko Shaposhnikov (1998) Enqvist McDonald (1998)
Kasuya MK (2000)

- Q-ball : Non-topological Soliton in Scalar Field Theory with Global U(1)

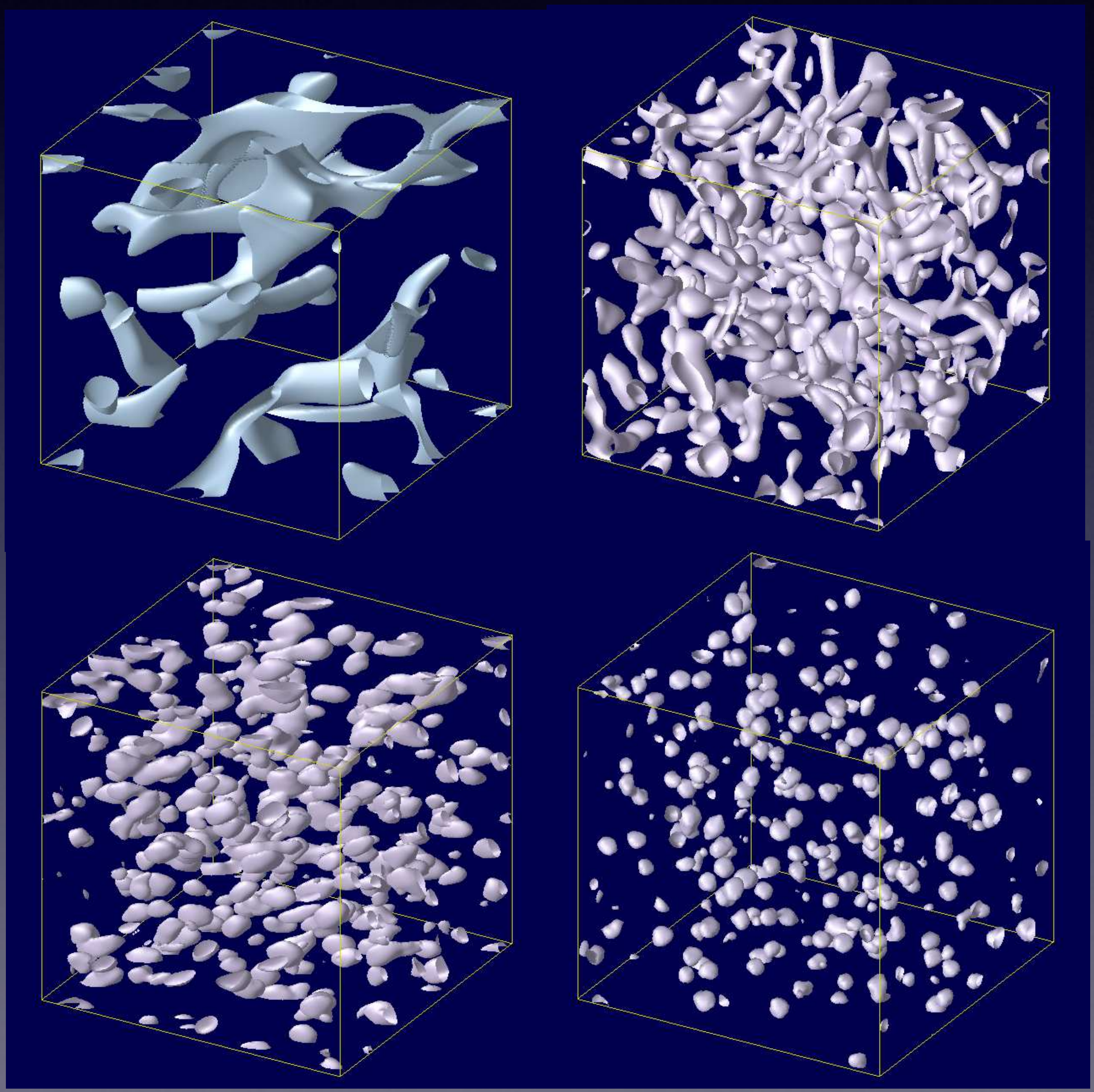
S. Coleman (1984)

AD Field $\Phi \neq 0$

Oscillation

Q-Ball Formation

Q-Ball Decay → Baryon Number



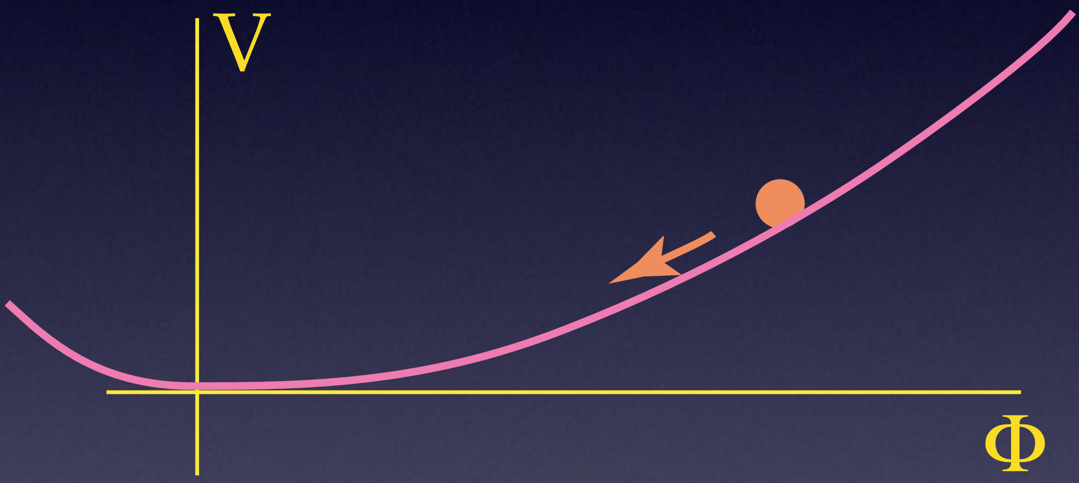
Hiramatsu MK Takahashi (2009)

3.4 Cogenesis with Q Balls

- Affleck-Dine mechanism for baryogenesis
- Flat directions (=AD fields Φ) in scalar potential of SUSY extensions of the standard model

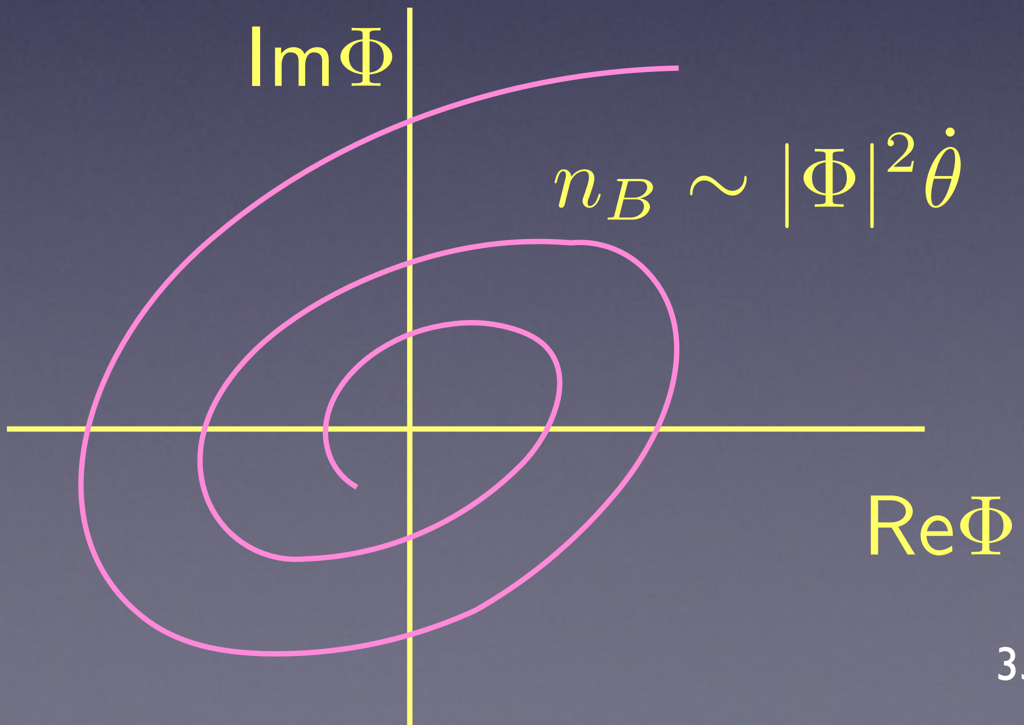
$\tilde{q}$ (squarks), $\tilde{l}$ (sleptons), H

  - Large field value during inflation
  - Start oscillation after inflation



→ Baryon number generation

  - Formation of Q Balls
    AD field produces spherical condensates through instabilities



- LSPs (lightest SUSY particles) can be dark matter

- Q balls are unstable in gravity mediated SUSY breaking
  - Q balls decay into quarks and LSPs ($\tilde{\chi}$)
  - Q-ball decay into quarks is saturated by Pauli blocking

Simple relation among decay rates

→ $\Gamma(Q \to q_i + q_j) \simeq 8\Gamma(Q \to q_i + \tilde{\chi})$ MK Yamada (2012)

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{B}}} = \frac{m_{\tilde{\chi}}}{m_p/3} \frac{\mathrm{Br}(\mathrm{Q\ ball} \to \mathrm{sparticles})}{\mathrm{Br}(\mathrm{Q\ ball} \to \mathrm{quarks})} = \frac{m_{\tilde{\chi}}}{m_p/3} \frac{\sum_s g_s f(m_s)}{8 n_q}$$

- n_q : number of species of quarks interacting with Q-ball
- g_s : number of degrees of freedom of sparticles
- f(m) =1 for $m_\Phi \gg m_s$

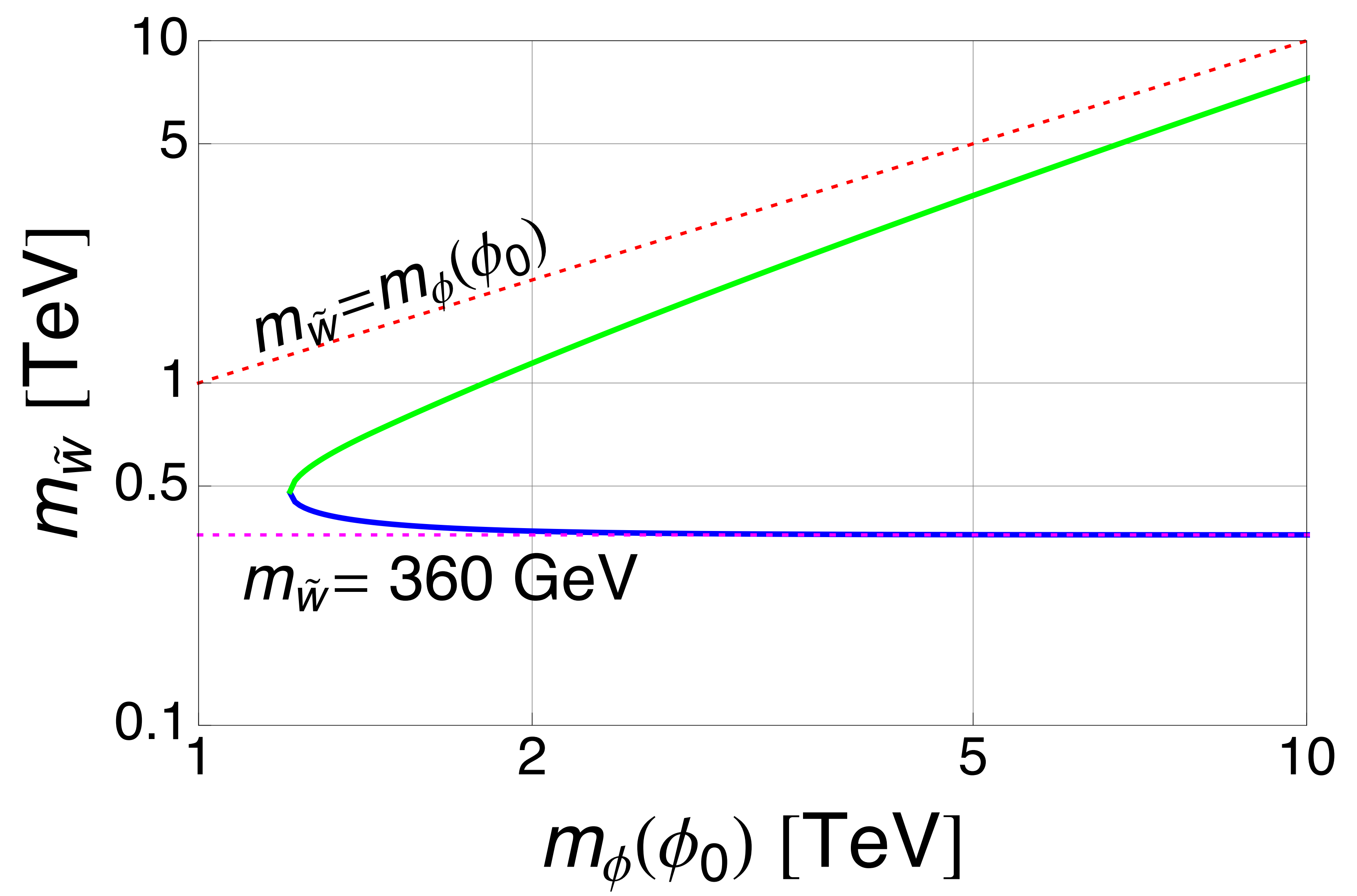
→ $n_B \simeq 72\ n_{\tilde{\chi}}$ (n_q = 27 for udd-flat direction)

$$\boxed{m_{\tilde{\chi}} \simeq 360\mathrm{GeV} \ \Rightarrow \ \rho_B = \rho_{\tilde{\chi}}/5}$$

IF $m_\Phi \simeq m_{\tilde{\chi}} \ \Rightarrow \ n_{\tilde{\chi}} \searrow \ \Rightarrow \ m_{\tilde{\chi}} \nearrow$

- To keep Ω_{DM}/Ω_B relation, produced LSPs should not annihilate
  - Late decay of Q balls
  - Low reheating temperature T_R < 1 GeV
- For example, LSP = winos NLSP = bono

Q balls ➡ winos ➡ bins



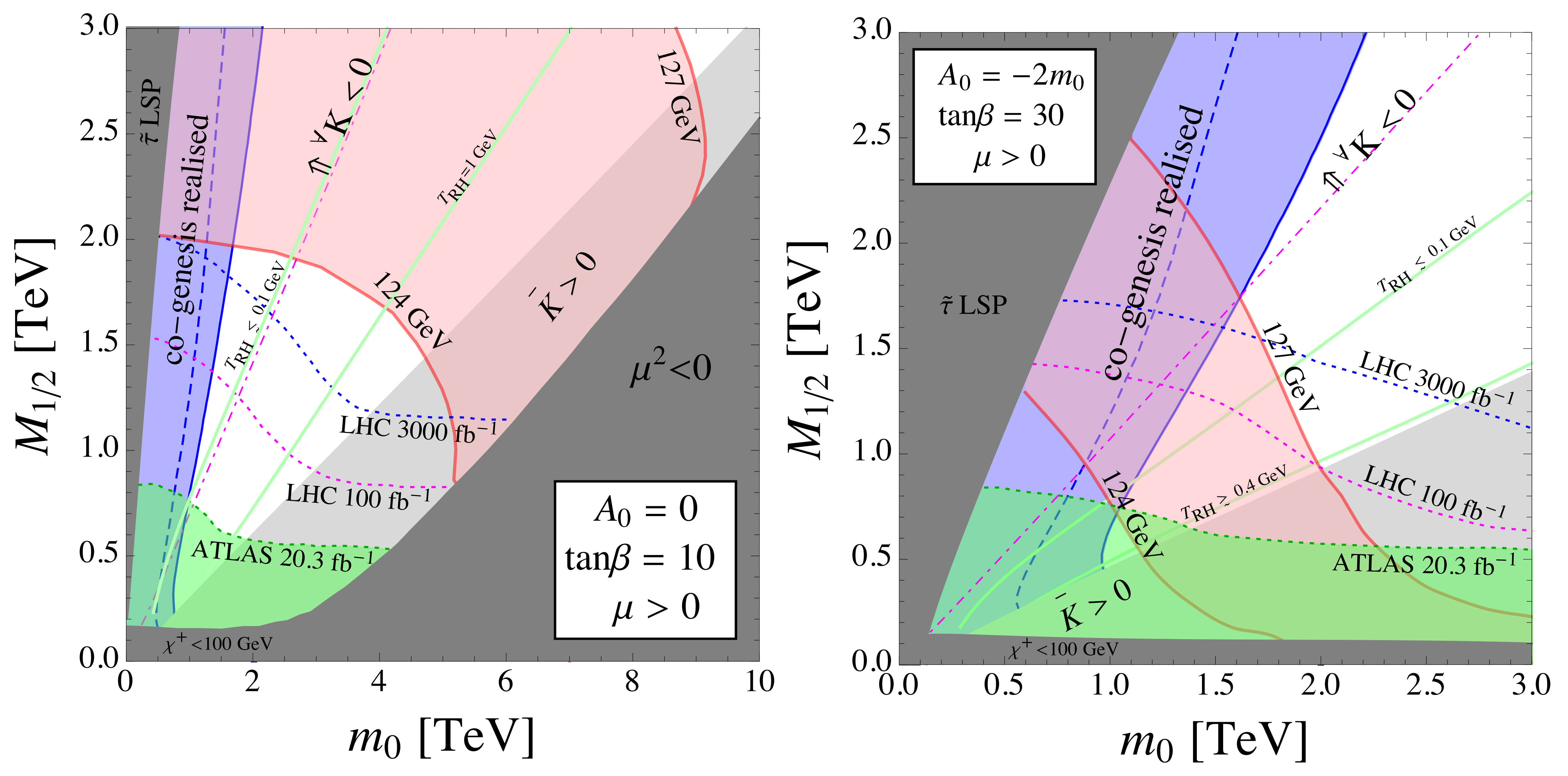
Kamada MK Yamada (2012)

Q ball cogenesis in CMSSM

Kamada MK Yamada (2014)

- Low reheating temperature $T_R < 1$ GeV
- sparticle mass spectrum in CMSSM

- Cogenesis is consistent with 126 GeV Higgs



Backup

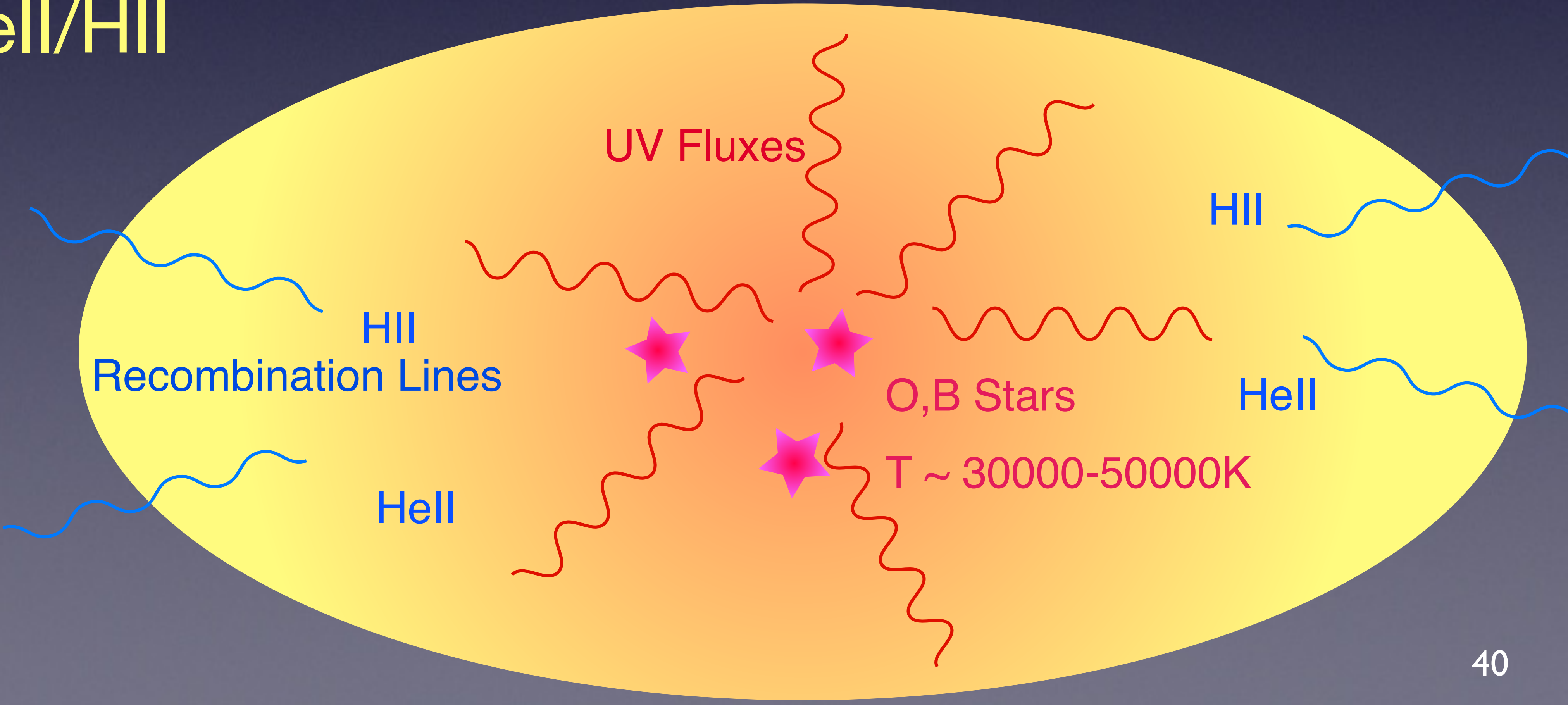
Measurement of He in HII region

- HII region
  - OB stars ionize H and He
  - E(HI)= 13.6eV, E(HeI)= 24.6eV,E(HeII)= 56.4eV
- Recombination lines

H II HeII

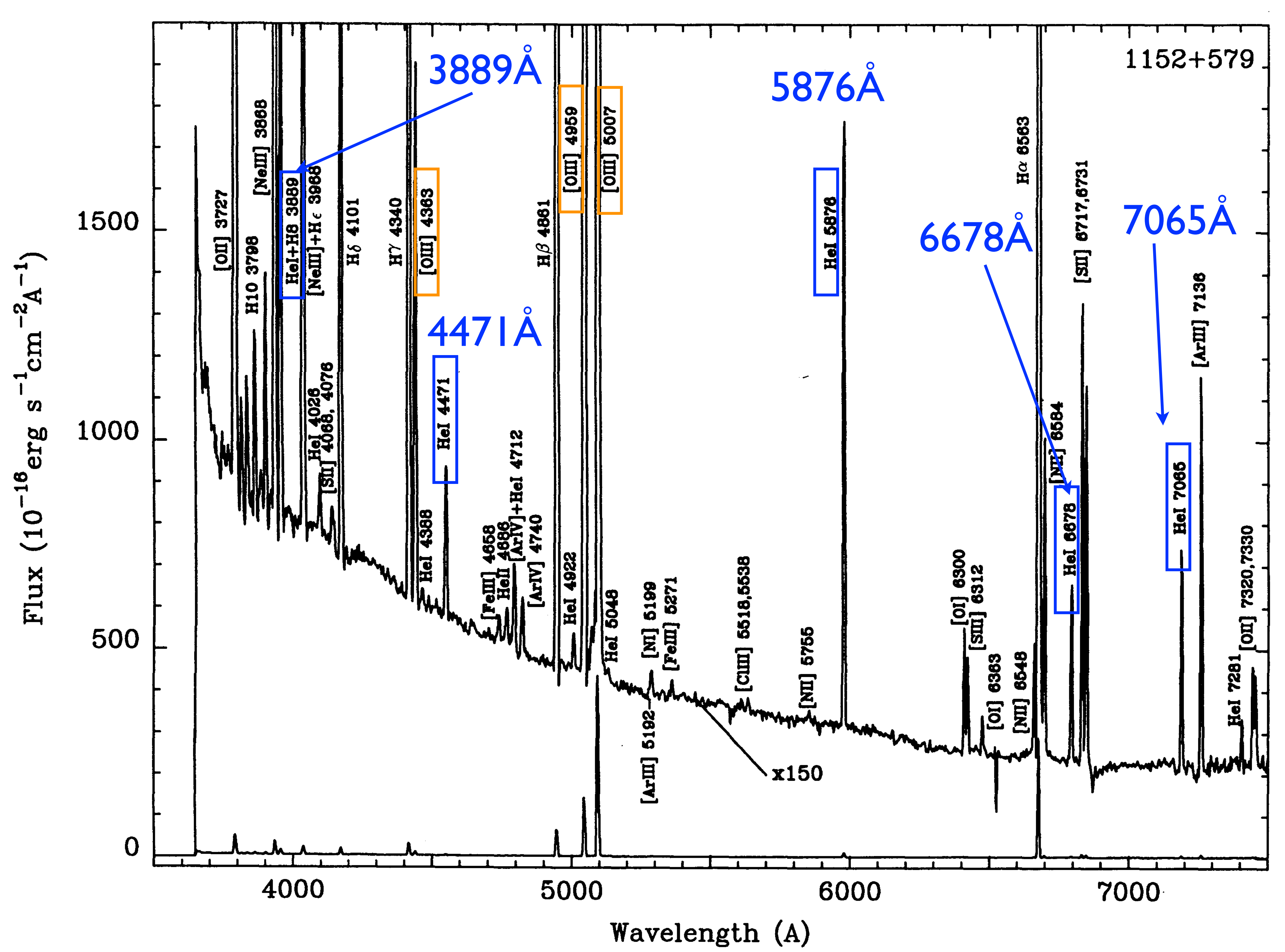
- measure HeII/HII

NGC 6611



Spectrum

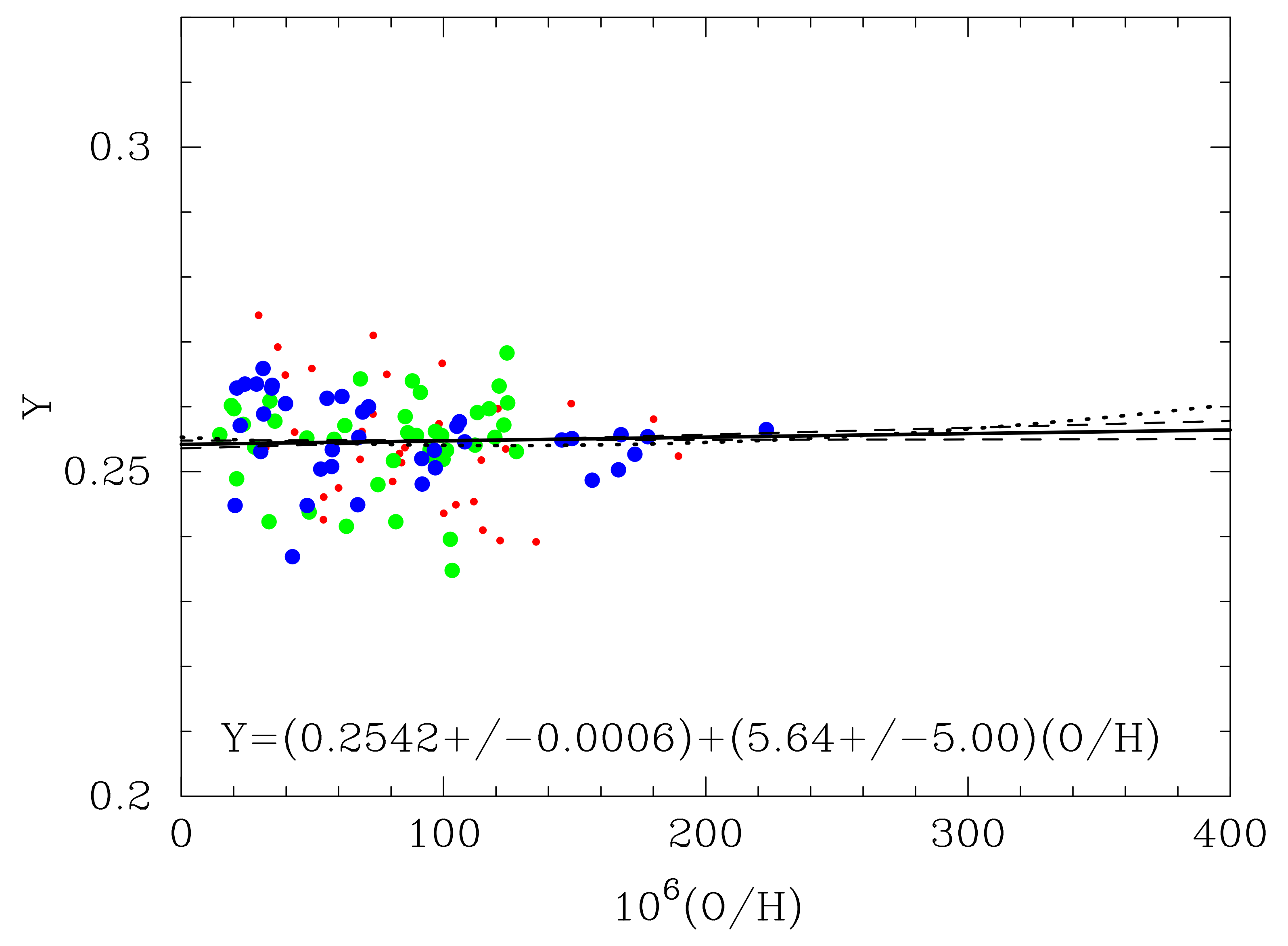
MRK 193 Izotov, Thuan, Lipovetsky (1994)



Determination of Yp

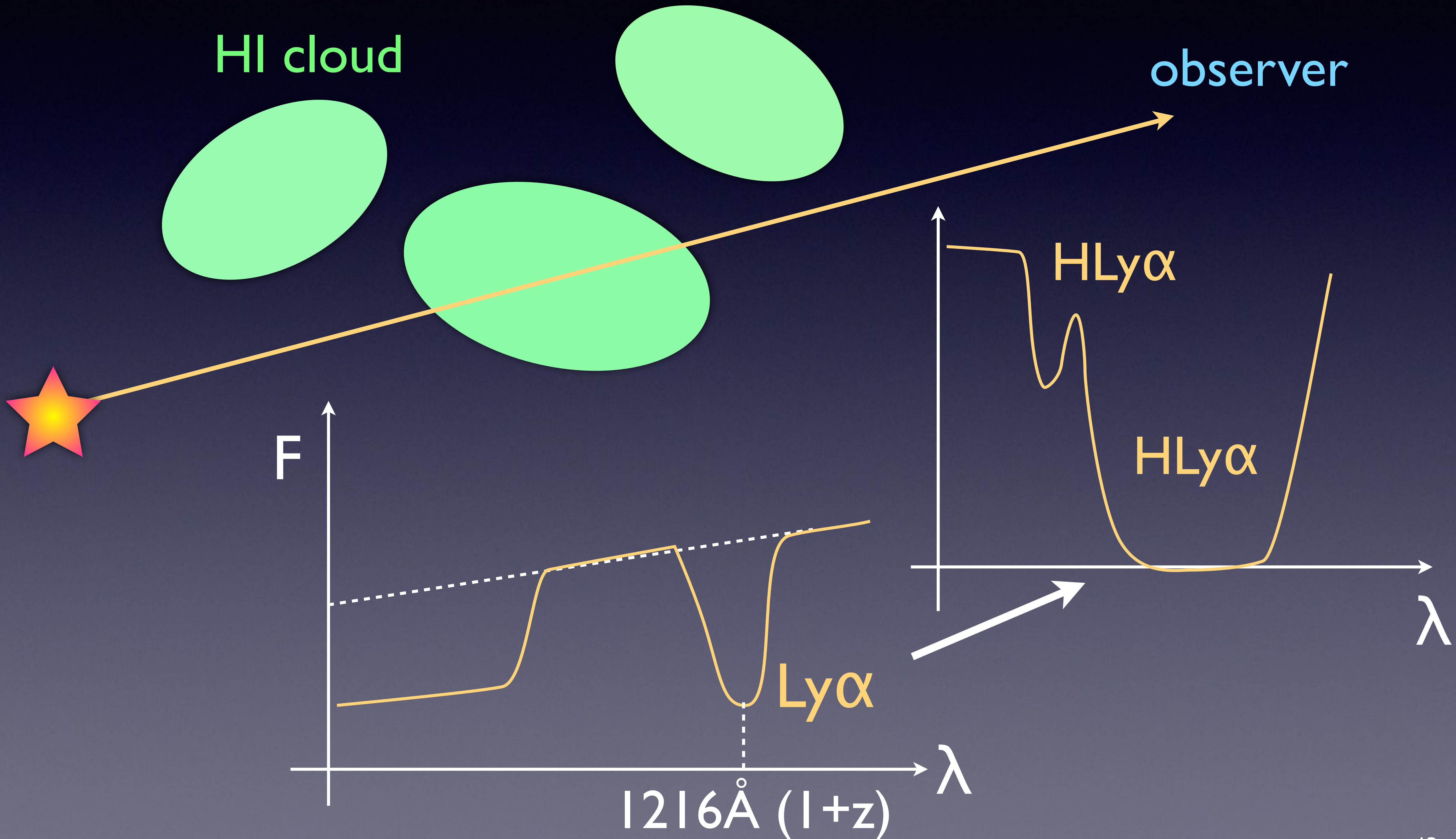
- Izotov & Thuan (2010)
  - 111 HII regions (from 1610 samples)
  - Taking into systematic effects

$$Y_p = 0.254 \pm 0.003$$



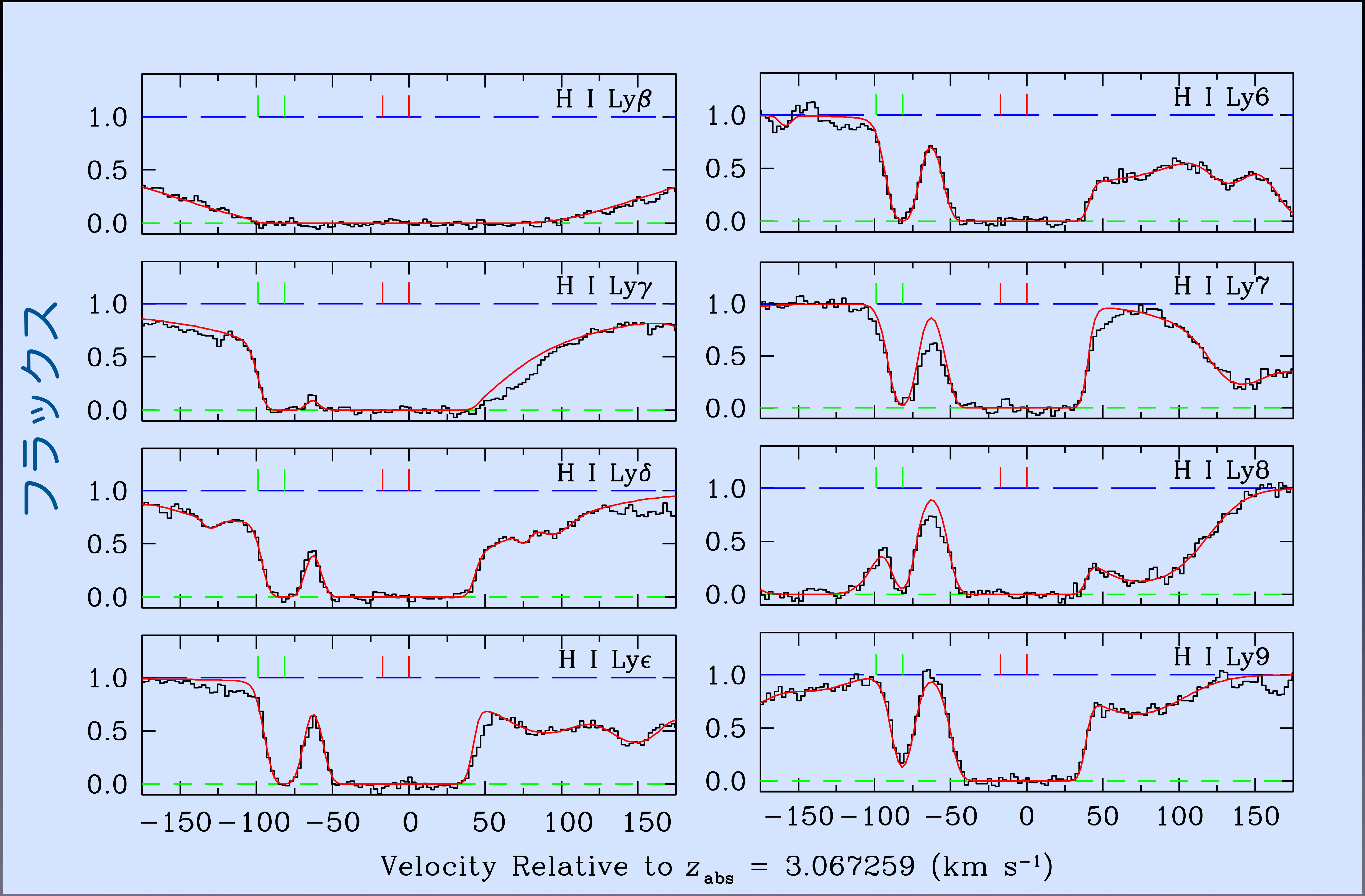
D abundance

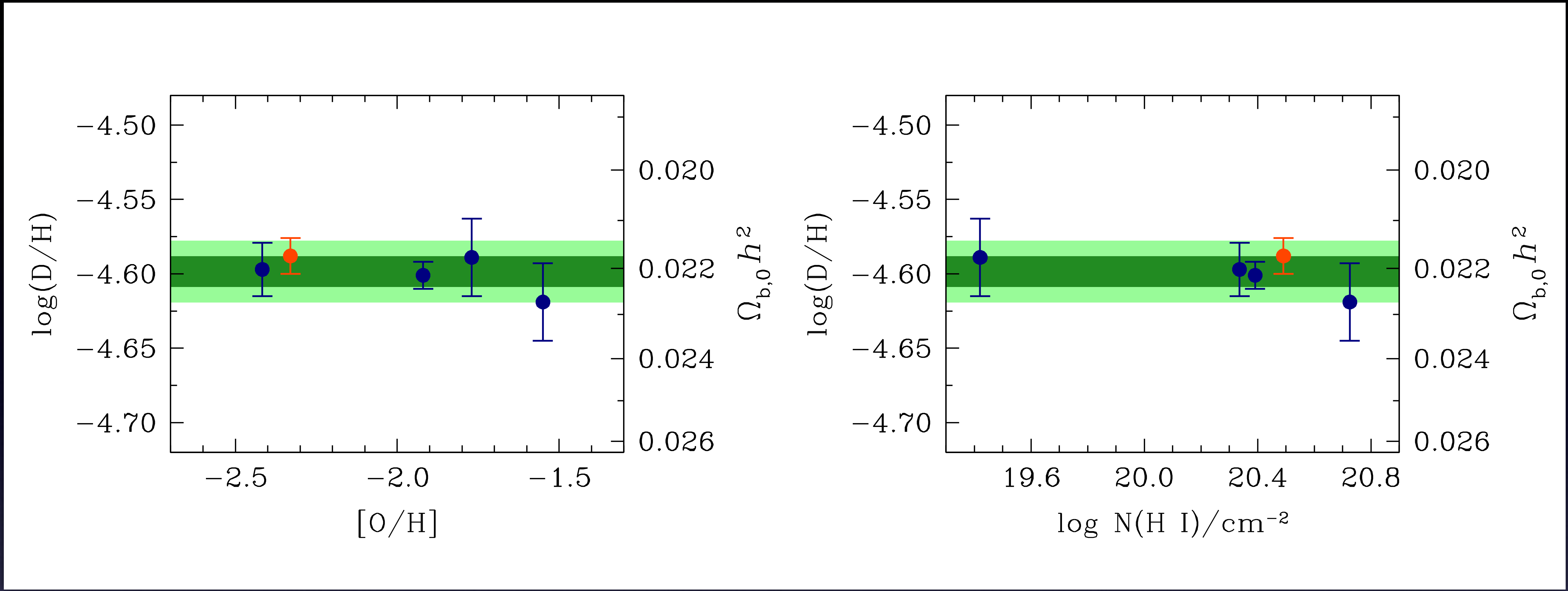
- Lyman α, β, γ, δ . . . absorption in QSOs spectrum



- DLAS at $z_{abs} = 3.067$ toward QSO SDSS J1358+6522

Cooke et al, (2013)





weighted mean

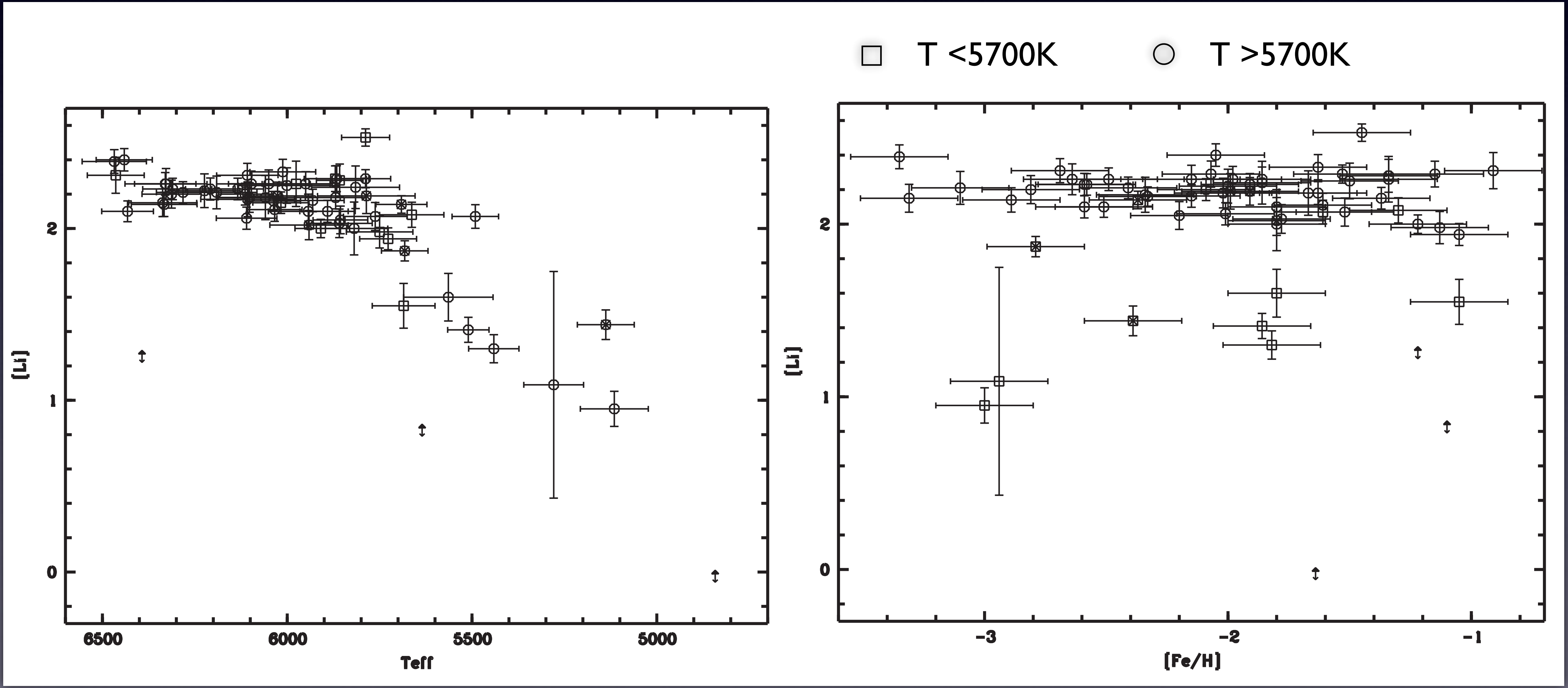
$$(\mathrm{D/H})_p = (2.53 \pm 0.04) \times 10^{-5}$$

Li7 Abundance

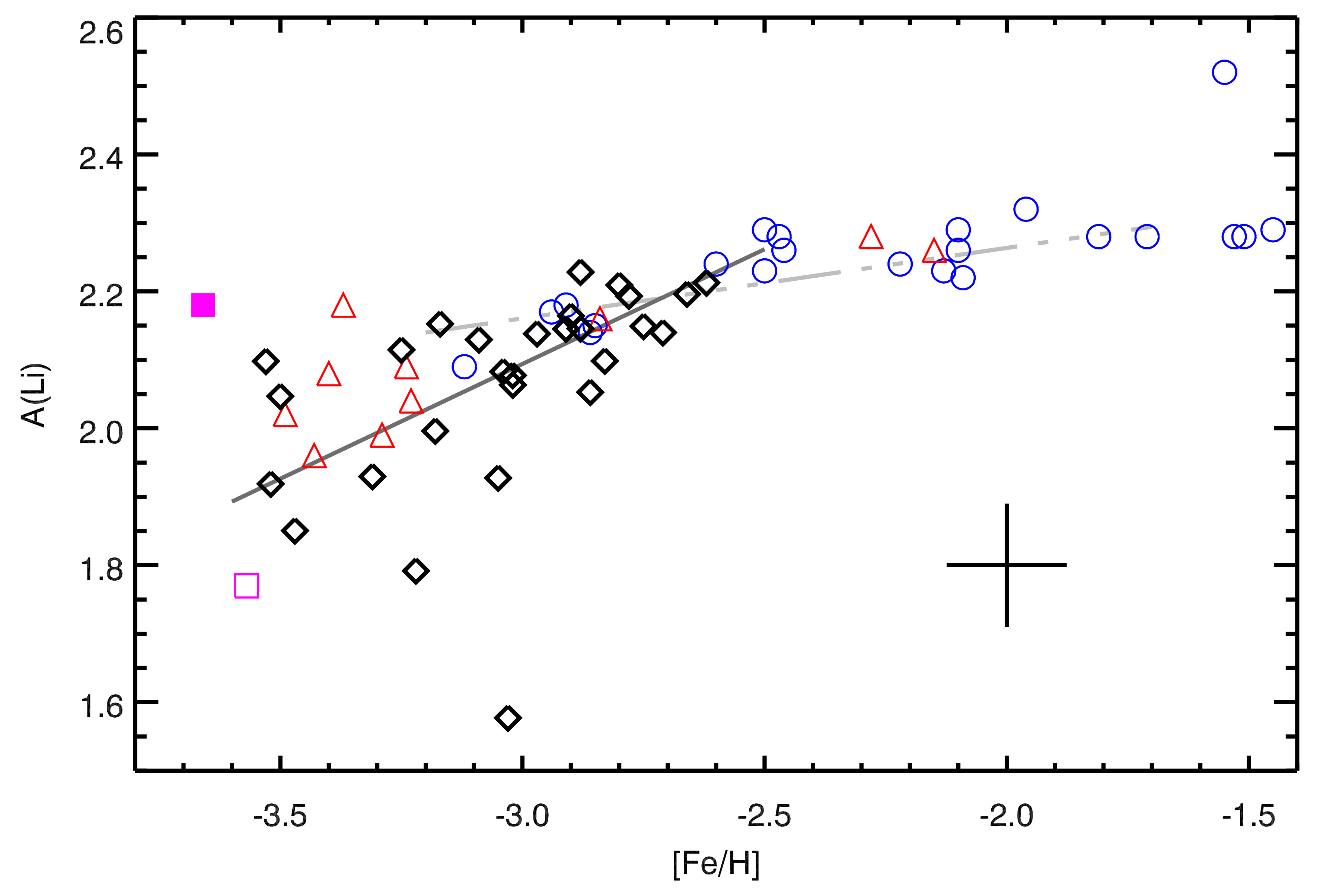
- Spite plateau [Spite & Spite (1987)]

  constant Li7 abundance in warmest metal-poor stars

→ Primordial abundance of Li 7



Bonifacio, Molaro 1997



$$({}^7\mathrm{L}/\mathrm{H})_p = (1.6 \pm 0.3) \times 10^{-10}$$

Sbordone et al, (2010)