Title: Hadronic Mass Variation in Big Bang Nucleosynthesis

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Abstract: I will present a brief introduction to Big Bang Nucleosynthesis theory and observation. I will then discuss BBN as a probe of hadronic mass variation in the very early universe, including comparison with the observed Li7 discrepancy. Finally I want to explore the possibility of overproducing Li6 by three orders of magnitude in order to match reported observations.

Hadronic Mass Variation in Big Bang Nucleosynthesis

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16 July 2008

THE UNIVERSITY OF
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SYDNEY · AUSTRALIA

Outline

1. Standard BBN
2. Deuterium Binding Energy
    - Sensitivity
    - Results
3. Variation of nuclear binding energy
    - Effect on BBN
    - Variation of light quark mass

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Overview

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\begin{aligned}
\frac{\dot{R}}{R} = H &= \sqrt{\frac{8\pi G_N}{3}\rho} \\
\frac{\ddot{R}}{R} &= -\frac{4\pi G_N}{3}(\rho + 3p) \\
\dot{\rho} &= -3H(\rho + p)
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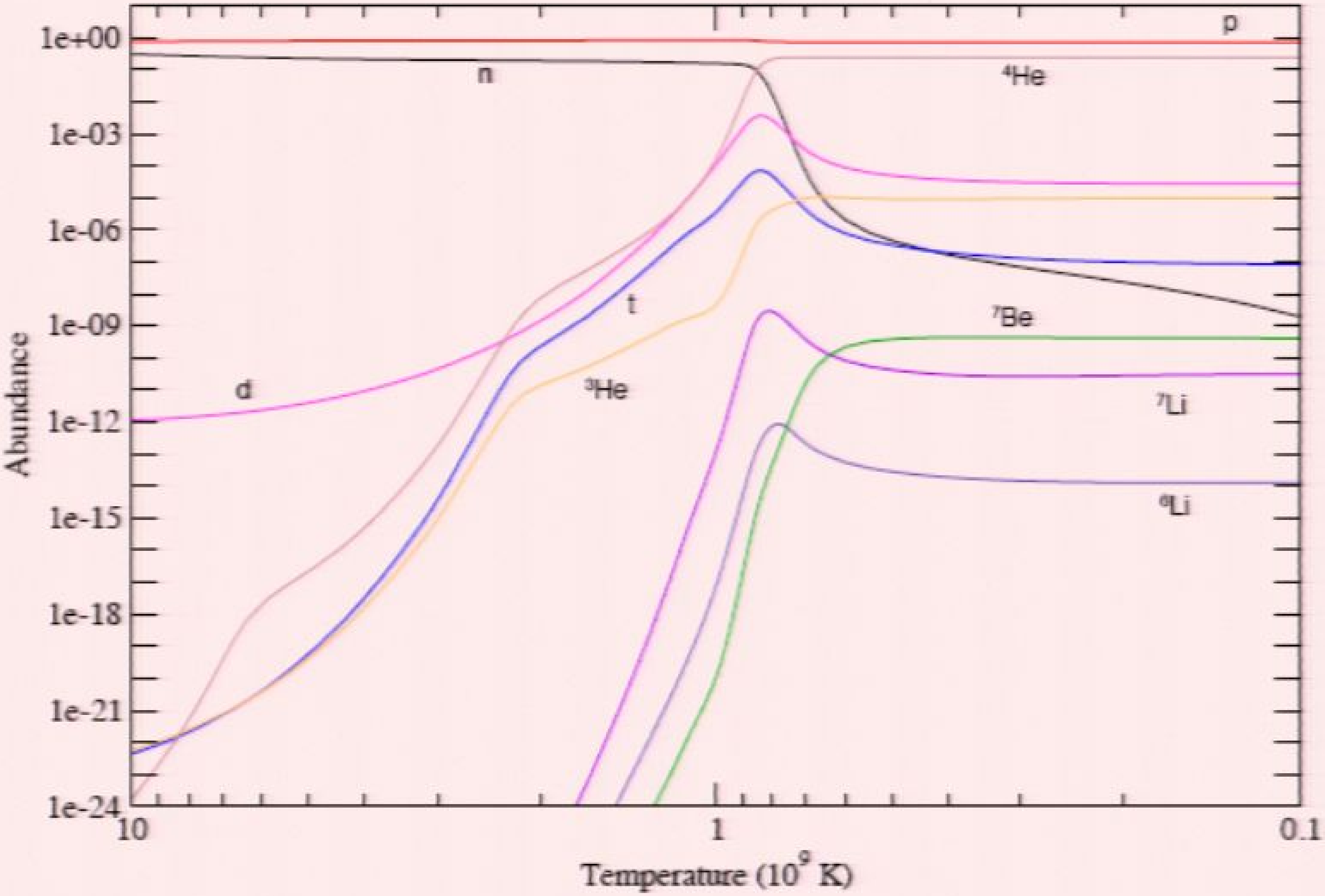
\dot{Y}_i &= \sum_{j,k,l} N_i \left(\Gamma_{kl\to ij} \frac{Y_l Y_k}{N_l! N_k!} - \Gamma_{ij\to kl} \frac{Y_i Y_j}{N_i! N_j!} \right) \\
n_- - n_+ &= n_B \sum_j Z_j Y_j \\
\frac{\dot{n}_B}{n_B} &= -3H
\end{aligned}$$

$$(1\,\mathrm{MeV} = 11.6 \times 10^9\,\mathrm{K})$$

SBBN evolution of light abundances



Stages of BBN

- $n \leftrightarrow p$ equilibrium:

$$n + \nu \rightleftharpoons p + e^-, \quad n + e^+ \rightleftharpoons p + \bar{\nu}$$

Freeze-out $t \sim 1$ s ~ 1 MeV $\sim 10^{10}$ K

- D bottleneck:

$$\begin{aligned} p + n \quad &\rightleftharpoons \quad d + \gamma \\ (\text{meanwhile} \quad n \quad &\rightarrow \quad p + e^- + \bar{\nu}) \end{aligned}$$

- Nucleosynthesis from $t \sim 3 \rightarrow 10$ min

$$d \rightarrow ({}^3\text{He},\ t) \rightarrow {}^4\text{He}$$

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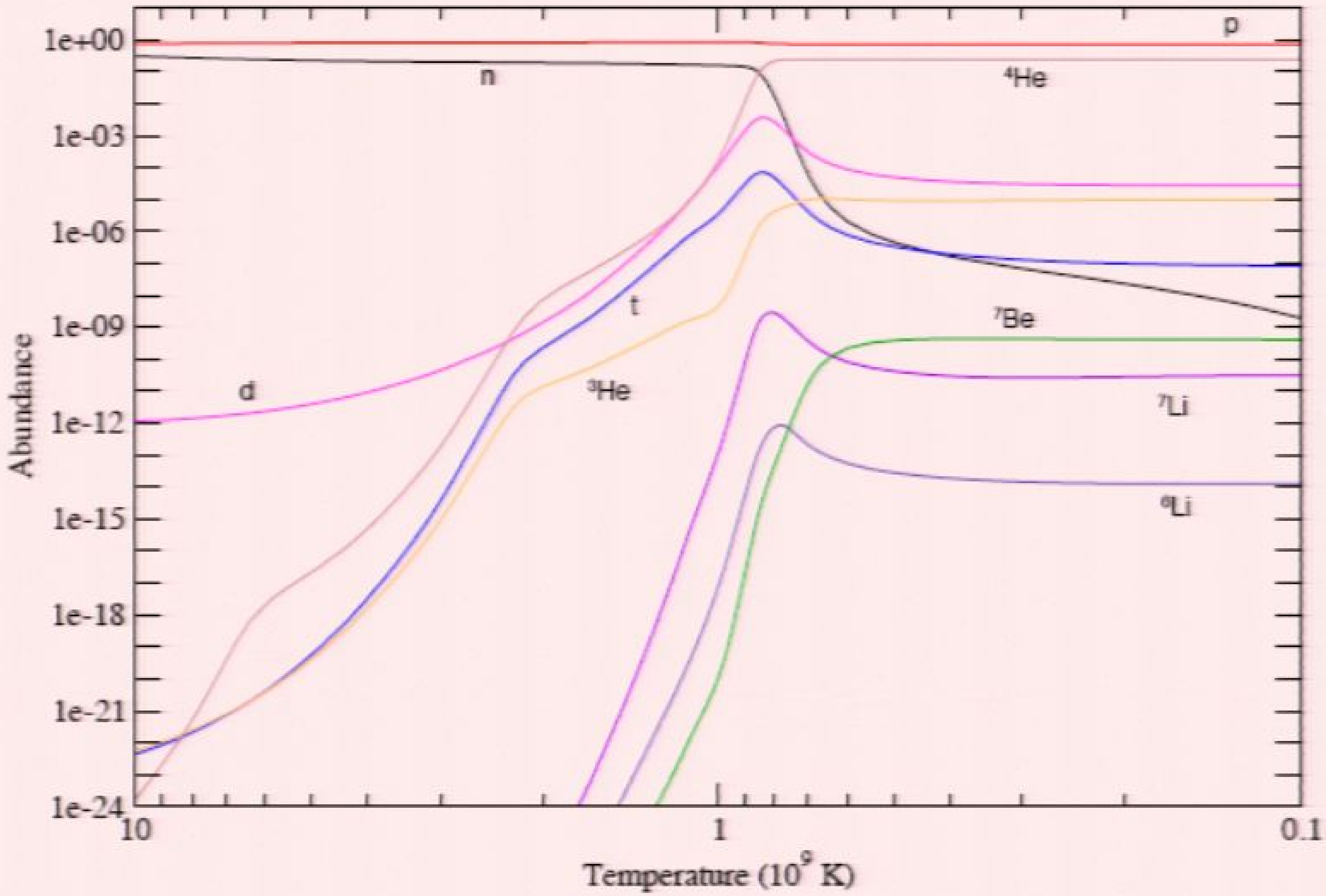

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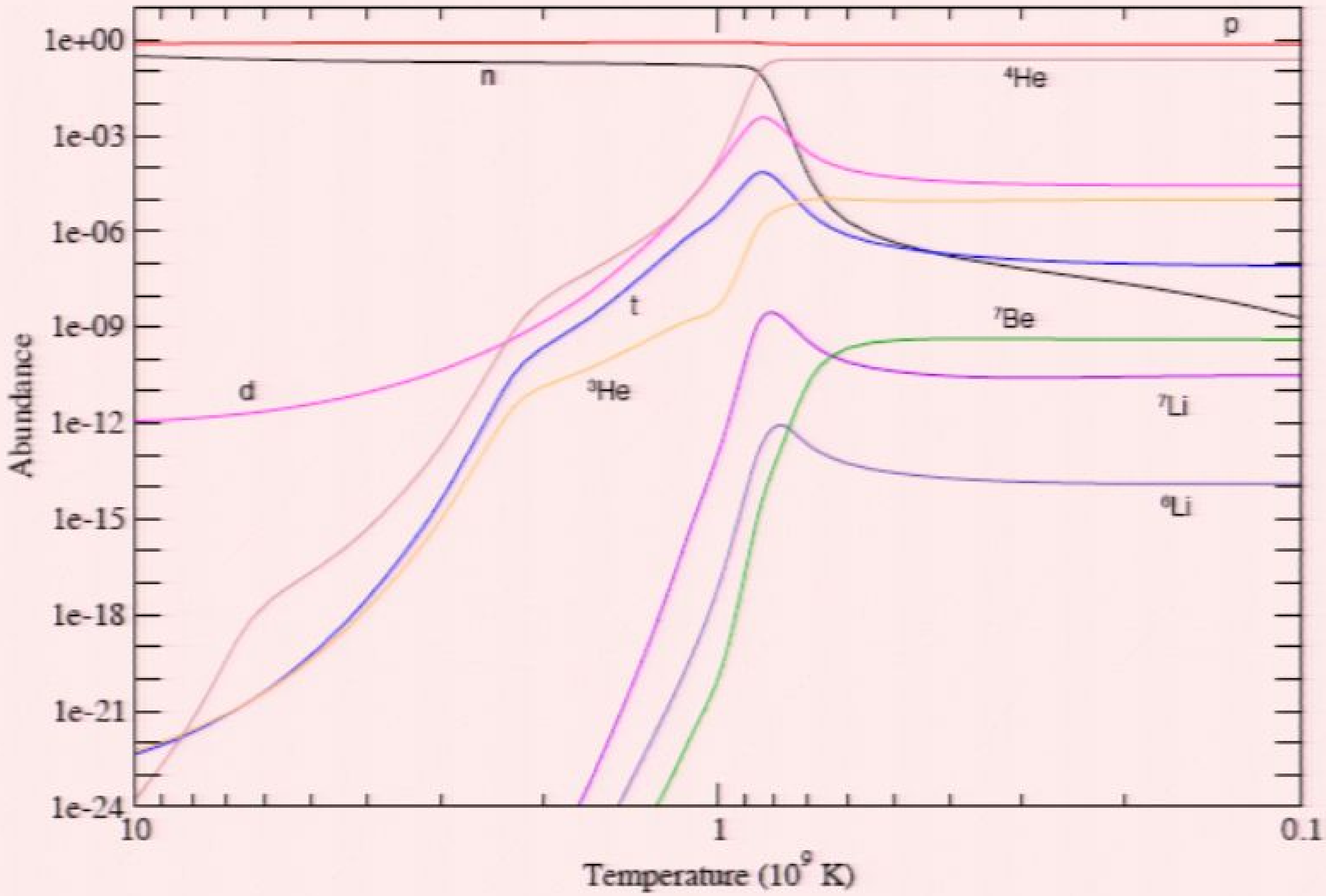

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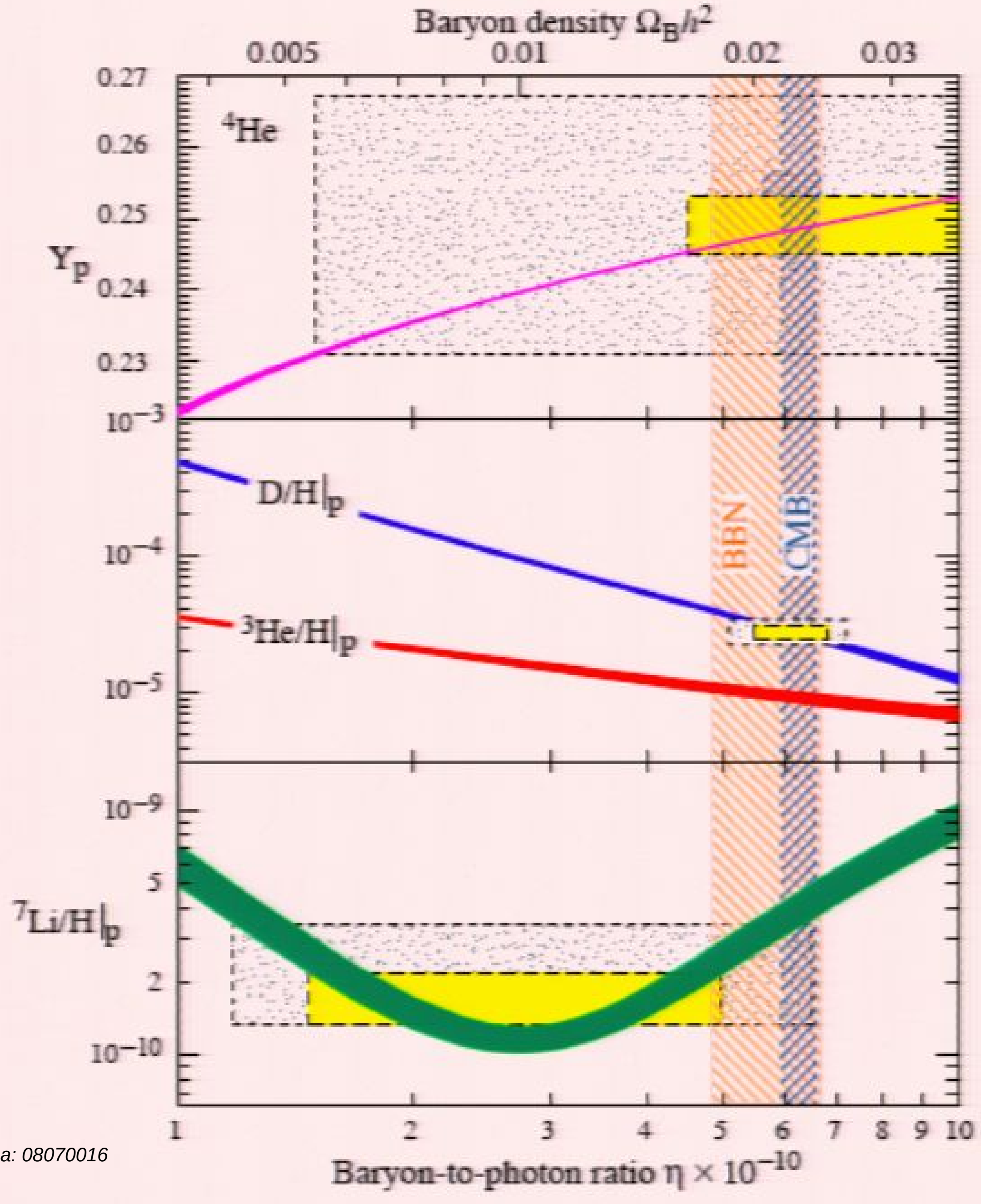

PDG 2007

B. D. Fields and S. Sarkar

2σ confidence intervals

Theory results

1σ ranges at $\eta = 6.14 \times 10^{-10}$ (WMAP)

	Dent[1]	Cyburt[2]	This work
D/H	$2.61\ (4) \times 10^{-5}$	$2.55^{+0.20}_{-0.20} \times 10^{-5}$	$2.77{\times}10^{-5}$
^{3}He/H	$10.3\ (3) \times 10^{-6}$	$10.12^{+0.67}_{-0.66} \times 10^{-6}$	$10.09{\times}10^{-5}$
Y_p	$0.2478\ (2)$	$0.2485\ (5)$	0.2457
^{7}Li/H	$4.5\ (4) \times 10^{-10}$	$4.26^{+0.91}_{-0.86} \times 10^{-10}$	$4.43{\times}10^{-10}$

[1] Dent, Stern, Wetterich (2007); errors from Serpico *et al.* (2004)

[2] Cyburt (2004)

Observation

$Y_{^4\mathrm{He}}$ (usually denoted Y_p):

- Observed in H II regions, extrapolated to zero metallicity. Systematics debated.
- 0.249 (9) – Olive and Skillman, 2004
- 0.2477 (29) – Peimbert *et al.*, 2007
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Observation

D/H:

- Detected in QAS via isotope shifted damped Ly-α (no astrophysical sources)
- Averaging six precise observations in QAS gives (PDG 2007): $2.84\,(14)\times 10^{-5}$
- Including dispersion (systematic errors): $2.84\,(26)\times 10^{-5}$

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- ^{7}Li does not vary in Pop II stars with low metallicity (Spite plateau)
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- Others: $2.34\,(32)^{1}$, $1.26\,(26)^{2}\times 10^{-10}$
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- Upper bound: 3.0×10^{-10}
  possibility of Li destruction by mixing of stellar atmospheres

[1] Meléndez and Ramirez, 2004 [2] Bonifacio *et al.*, 2007

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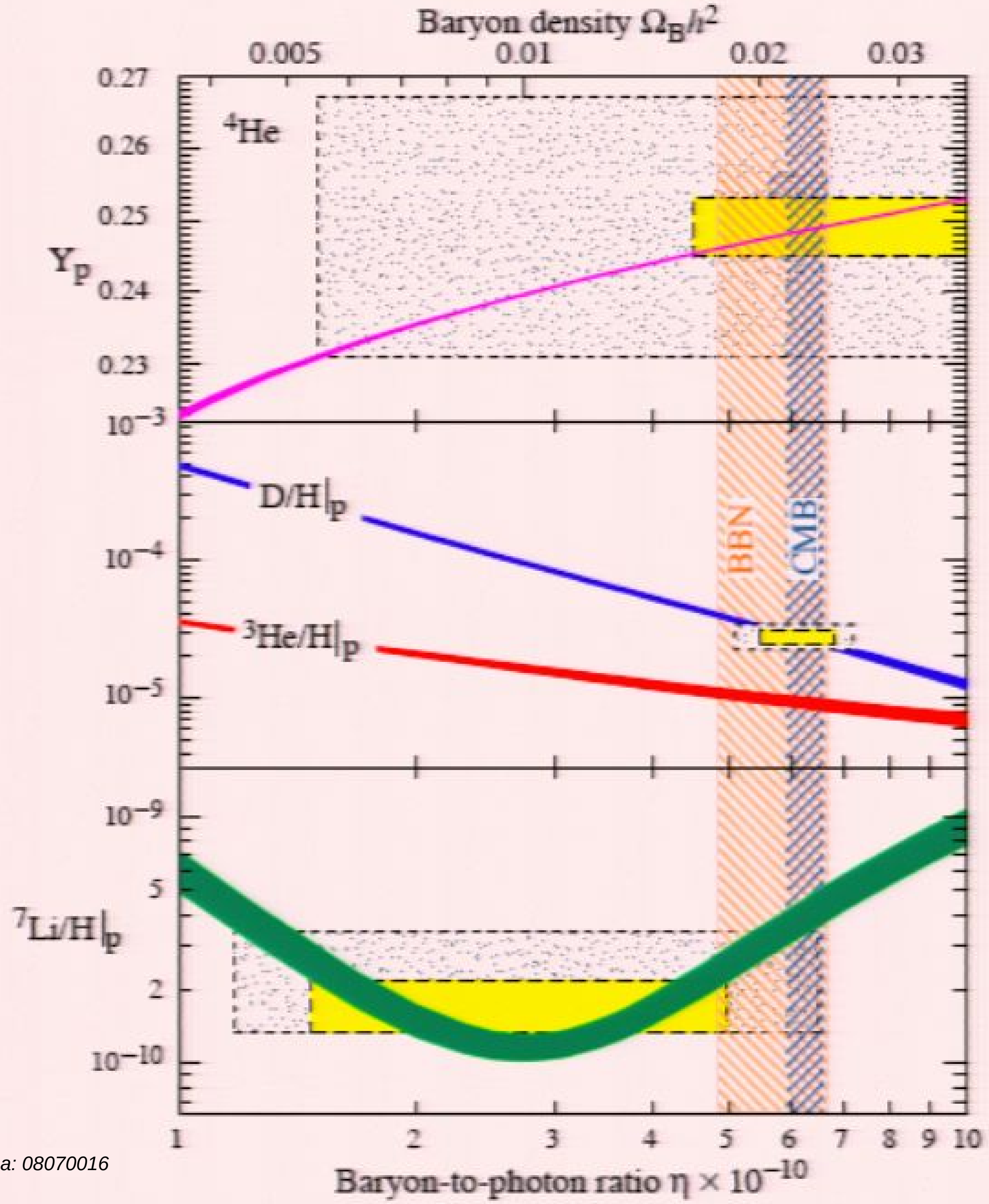

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BBN modifications

- n freeze-out temperature depends on expansion rate
- more light species → higher freeze-out temperature → more neutrons will survive after decoupling → more ^{4}He
- neutron lifetime $\tau_n = 886$ s. Freeze-out is at ~ 1 s.
  D bottleneck opens at ~ 200 s.
  $\therefore \tau_n$ affects neutron survival until BBN and therefore ^{4}He abundance.

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Variation of mass scales

GUTs consistently predicts much larger variation of strong interaction than electromagnetic:

$$\frac{\delta m_q}{m_q} \sim 35 \frac{\delta \alpha}{\alpha}$$

(Marciano 1984, Calmet and Fritzsch 2002, Wetterich 2003, ...)

d production sensitivity

- The first step in nucleosynthesis is

$$p + n \rightleftharpoons d + \gamma$$

with binding energy $B_d = 2.22\ \mathrm{MeV} = 25.82 \times 10^9\ \mathrm{K}$.

- The rate $\Gamma_{p(n,\gamma)d}$ is sensitive to Q (Dmitriev, Flambaum, Webb 2004)

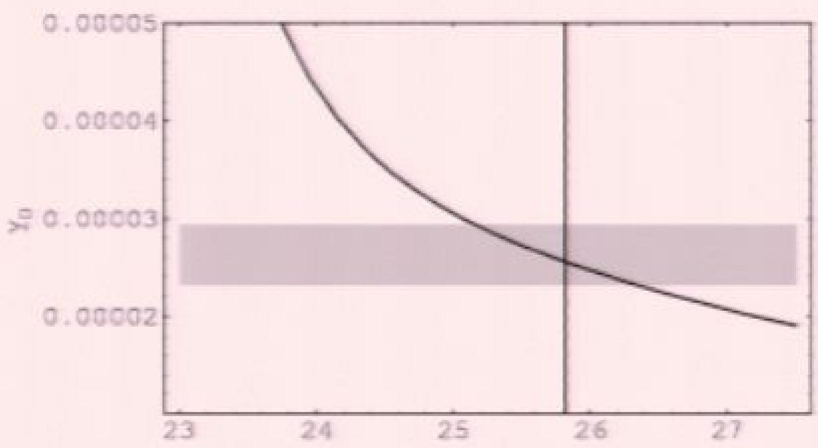
$$\Gamma_{p(n,\gamma)d} \sim 1 + \left(\frac{5}{2} + \sqrt{\frac{Q}{\epsilon_v}} \right) \frac{\delta Q}{Q}$$

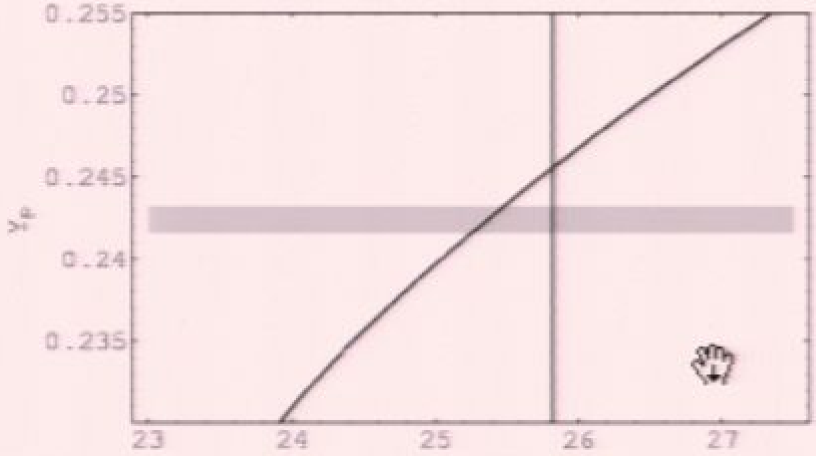
where the second term accounts for variation in the position of the virtual level with energy $\epsilon_v \sim 0.07$ MeV

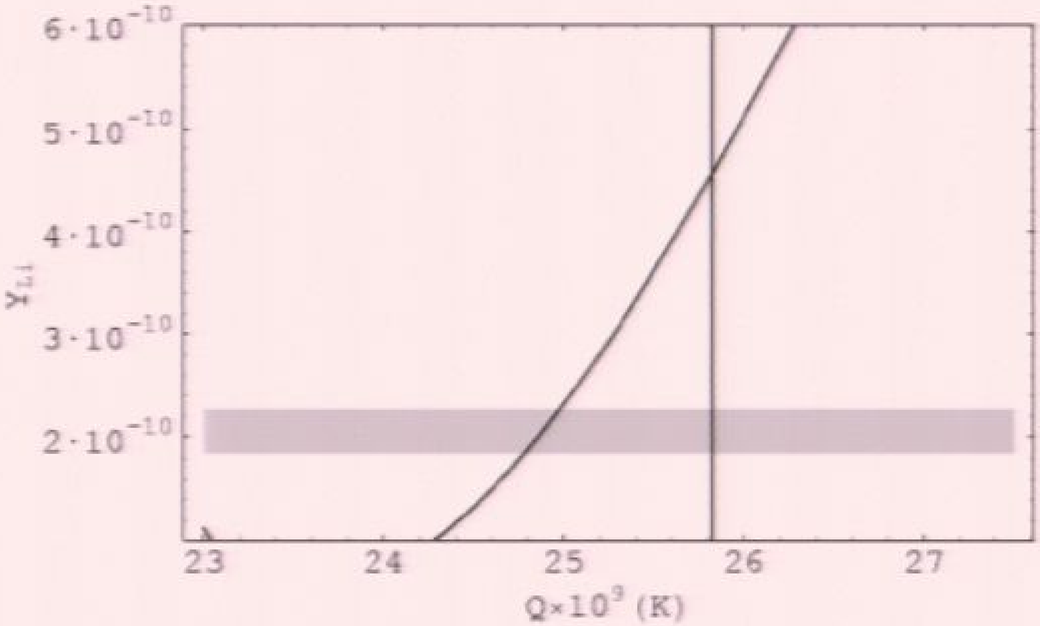
- The inverse reaction

$$\Gamma_{d(\gamma,n)p} \sim e^{-Q/T}$$

Q variation results







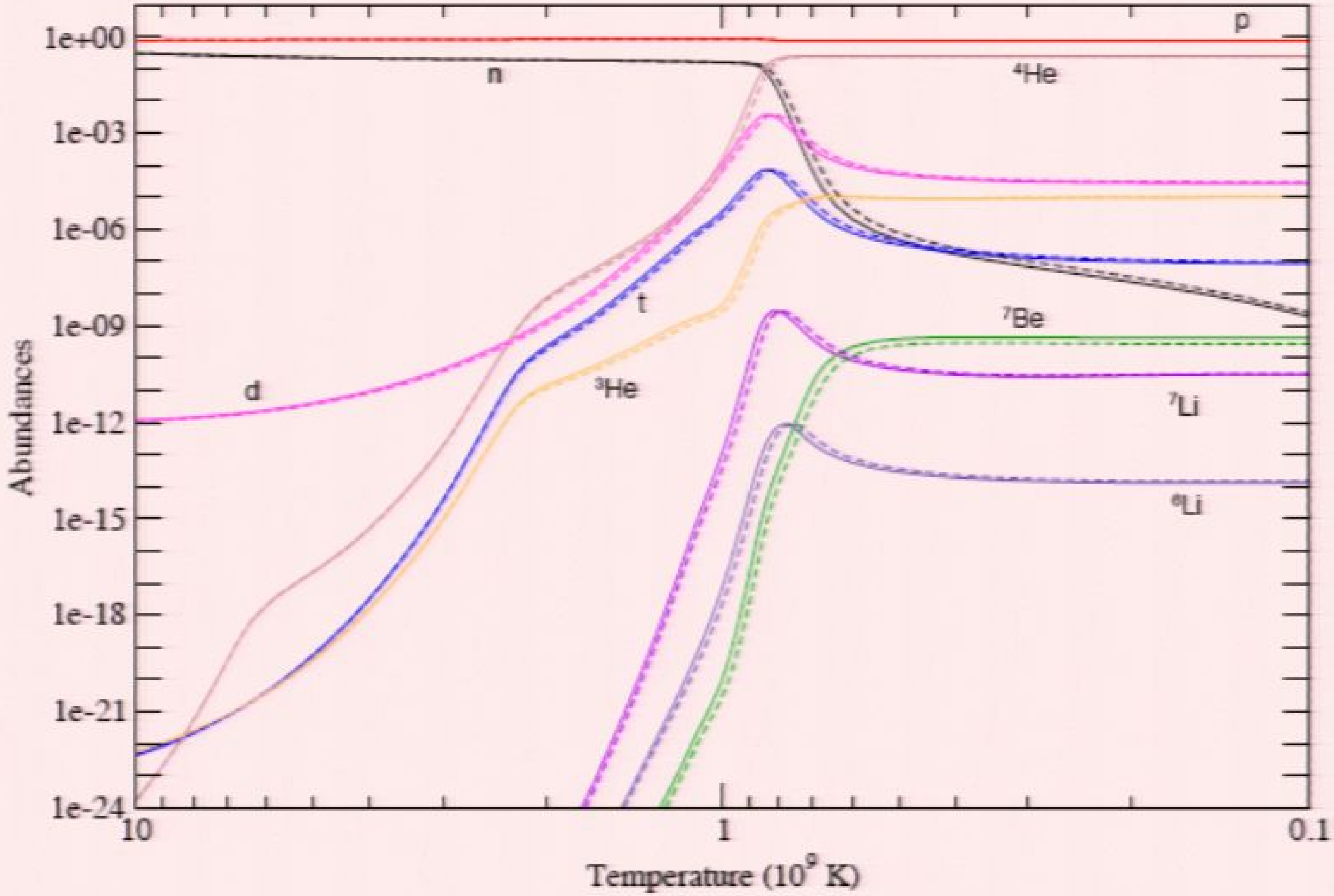
Q variation results

Concordance with experiment (DFW 2004):

$$\delta Q/Q = -0.019\,(5)$$

- Q reduced, D bottleneck opens later
- More n, p, D, ^{3}He, ^{6}Li, ^{7}Li
- Less ^{4}He, less ^{7}Be

Q variation results



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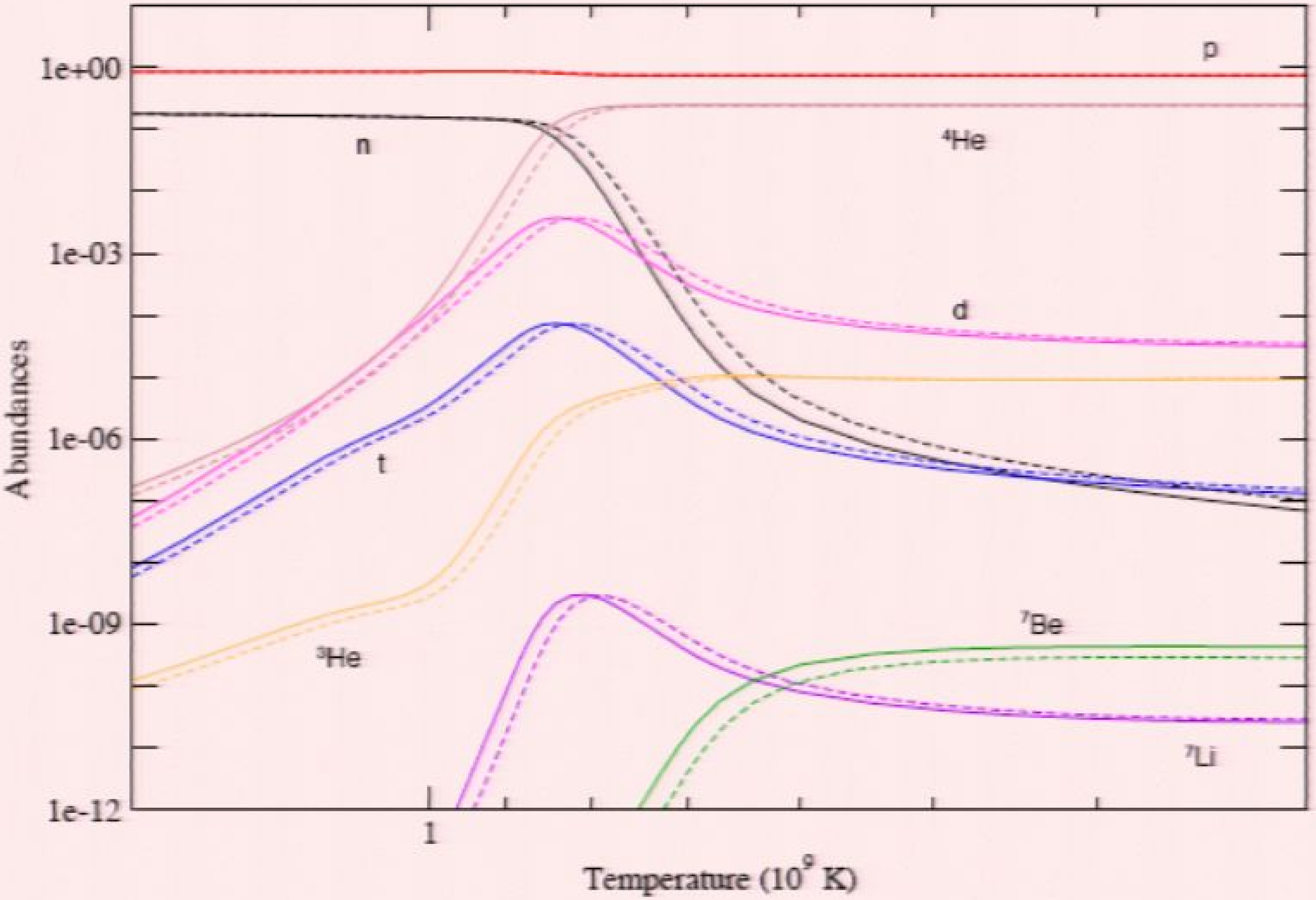

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Mechanisms for change

Modification of binding energies → change in Q → reaction rates

- For $2 \rightarrow 2$ inelastic scattering reactions,

$$\sigma \sim (Q+E)^{1/2}$$

- For $E1$ radiative capture reactions,

$$\sigma \sim (Q+E)^{3}$$

- Reverse reaction $\sim e^{-Q/T}$

(Dent *et al.* 2007)

Linear variation

$\partial \ln Y_a / \partial \ln X_i$	D	^{3}He	^{4}He	^{6}Li	^{7}Li
G	0.94	0.33	0.36	1.4	−0.72
α	2.3	0.79	0.00	4.6	−8.1
τ_n	0.41	0.15	0.73	1.4	0.43
m_e	−0.16	−0.02	−0.71	−1.1	−0.82
Q_N	0.83	0.31	1.55	2.9	1.00
m_N	3.5	0.11	−0.07	2.0	−12
B_D	−2.8	−2.1	0.68	−6.8	8.8
B_T	−0.22	−1.4	0	−0.20	−2.5
$B_{^3\mathrm{He}}$	−2.1	3.0	0	−3.1	−9.5
$B_{^4\mathrm{He}}$	−0.01	−0.57	0	−59	−57
$B_{^6\mathrm{Li}}$	0	0	0	69	0
$B_{^7\mathrm{Li}}$	0	0	0	0	−6.9
$B_{^7\mathrm{Be}}$	0	0	0	0	81
η	−1.6	−0.57	0.04	−1.5	2.1

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Linear variation of B_D

1. Dent *et al.* 2007; ϵ_ν resonance not considered
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1.	-2.8	-2.1	0.68	-6.8	8.8	
2.	-4.98	-1.39	0.71	-4.08	17.88	
3.	-3.99	-1.78	0.70	-7.63	16.72	

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3.	-3.99	-1.78	0.70	-7.63	-1.93	18.14

Reanalysis of B_D variation

Linear reanalysis of DFW 2004 work:

$$1 + \frac{\partial \ln Y_a}{\partial \ln B_D} x = \frac{Y_a\,(\mathrm{obs})}{Y_a\,(\mathrm{theory})}$$

where $x = \delta B_D / B_D$.

$$\begin{array}{rlcr} \mathrm{D:} & 1 - 4.98\,x = 1.09 \pm 0.10 & & -0.018\,(20) \\ {}^4\mathrm{He:} & 1 + 0.71\,x = 1.005 \pm 0.036 & \rightarrow & 0.007\,(51) \\ {}^7\mathrm{Li:} & 1 + 17.88\,x = 0.33 \pm 0.11 & & -0.037\,(6) \end{array}$$

Consistent solution: $x = -0.035\,(6)$ dominated by ${}^7\mathrm{Li}$
c.f. original paper $x = -0.019\,(5)$

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Not consistent with tight bounds on ^{4}He $(1.8\sigma$ *deviation*$)$.

Dependence of nuclear binding on hadronic mass variation

Flambaum and Wiringa, 2007

- Calculate dependence of binding energies w.r.t. hadrons: N, π, Δ, ρ- and ω-mesons
- Use Argonne models of nuclear Hamiltonian + Urbana model IX for three-nucleon potential.

Result is tabulated values of

$$\frac{\partial(\ln B)}{\partial(\ln m_H)}$$

Dependence of nuclear binding on hadronic mass variation

- Use Dyson-Schwinger equation (DSE) to map variation of light quark mass, $m_q = (m_u + m_d)/2$, to hadron masses (Flambaum *et al.* 2006).

$$\frac{\delta m_H}{m_H} = \frac{\sigma_H}{m_H}\frac{\delta m_q}{m_q}$$

with $\frac{\sigma_H}{m_H}$ value of 0.498 for pion, etc.

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- Put it together:

$$\frac{\partial B/B}{\partial m_q/m_q} = \sum_H \frac{\partial(\ln B)}{\partial(\ln m_H)}\frac{\sigma_H}{m_H}$$

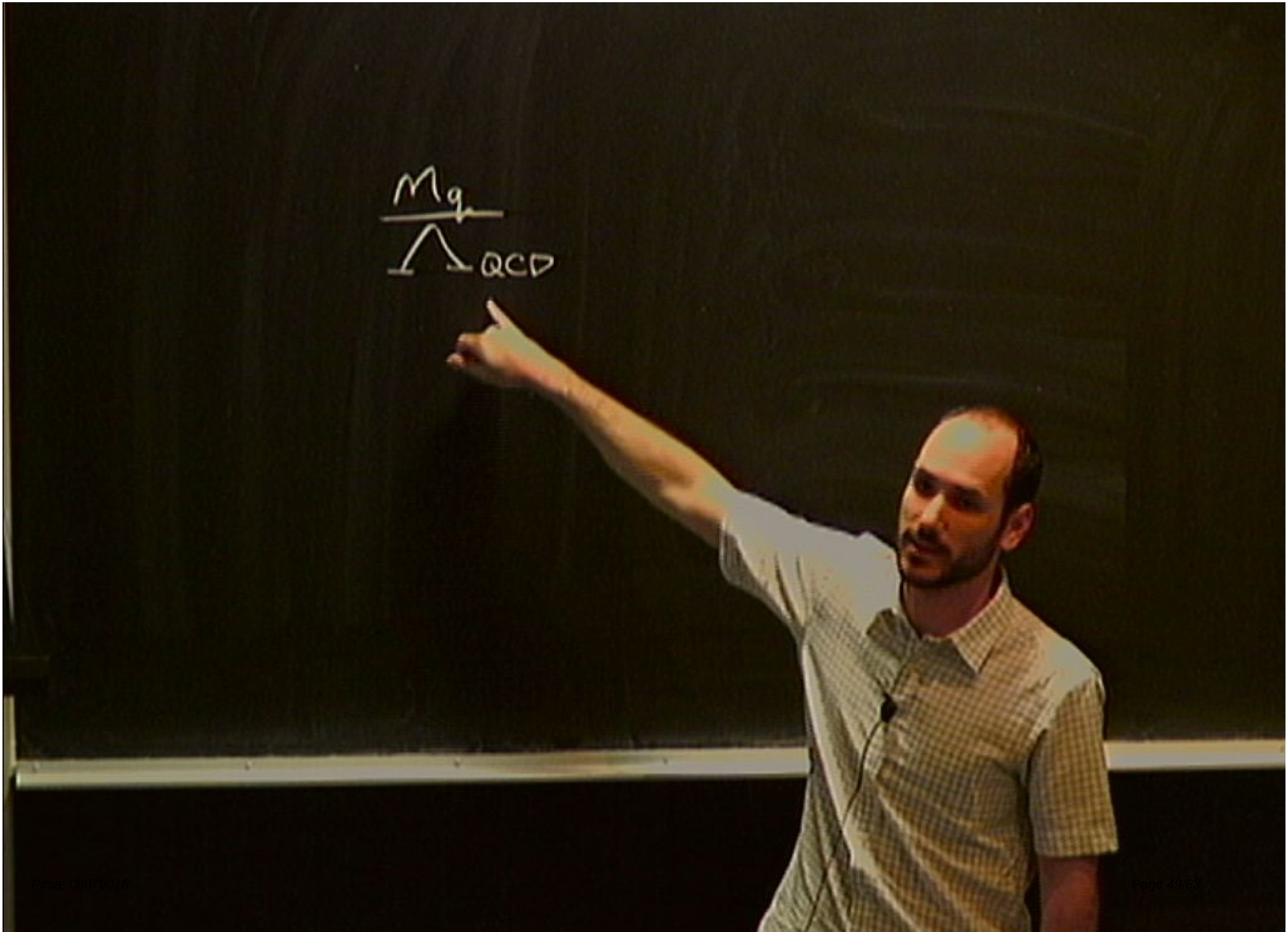
tabulated for all light species (up to ^{7}Be).

Linear variation of m_q

Now $x = \delta m_q / m_q$

$$\begin{array}{rlcr}
\text{D:} & 1 + 9.34\,x = 1.09 \pm 0.10 & & 0.009\,(11) \\
{}^4\text{He:} & 1 - 1.00\,x = 1.005 \pm 0.036 & \rightarrow & -0.005\,(36) \\
{}^7\text{Li:} & 1 - 60\,x = 0.33 \pm 0.11 & & 0.011\,(2)
\end{array}$$

Consistent solution: $x = 0.011\,(2)$ dominated by ^{7}Li
c.f. Flambaum and Wiringa, 2007: $x = 0.013\,(2)$



$$\frac{M_q}{\Lambda_{QCD}}$$

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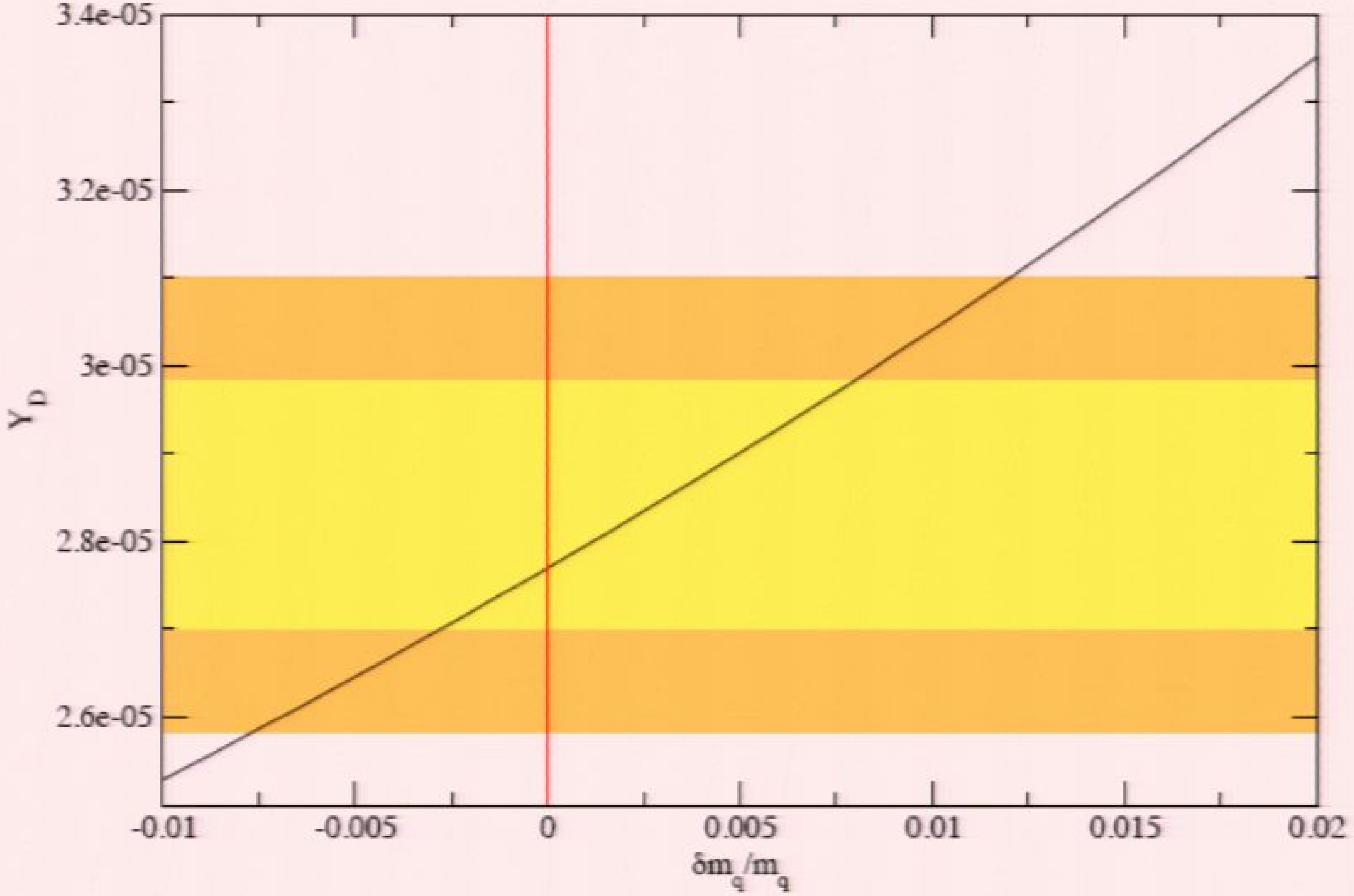
Now $x = \delta m_q / m_q$

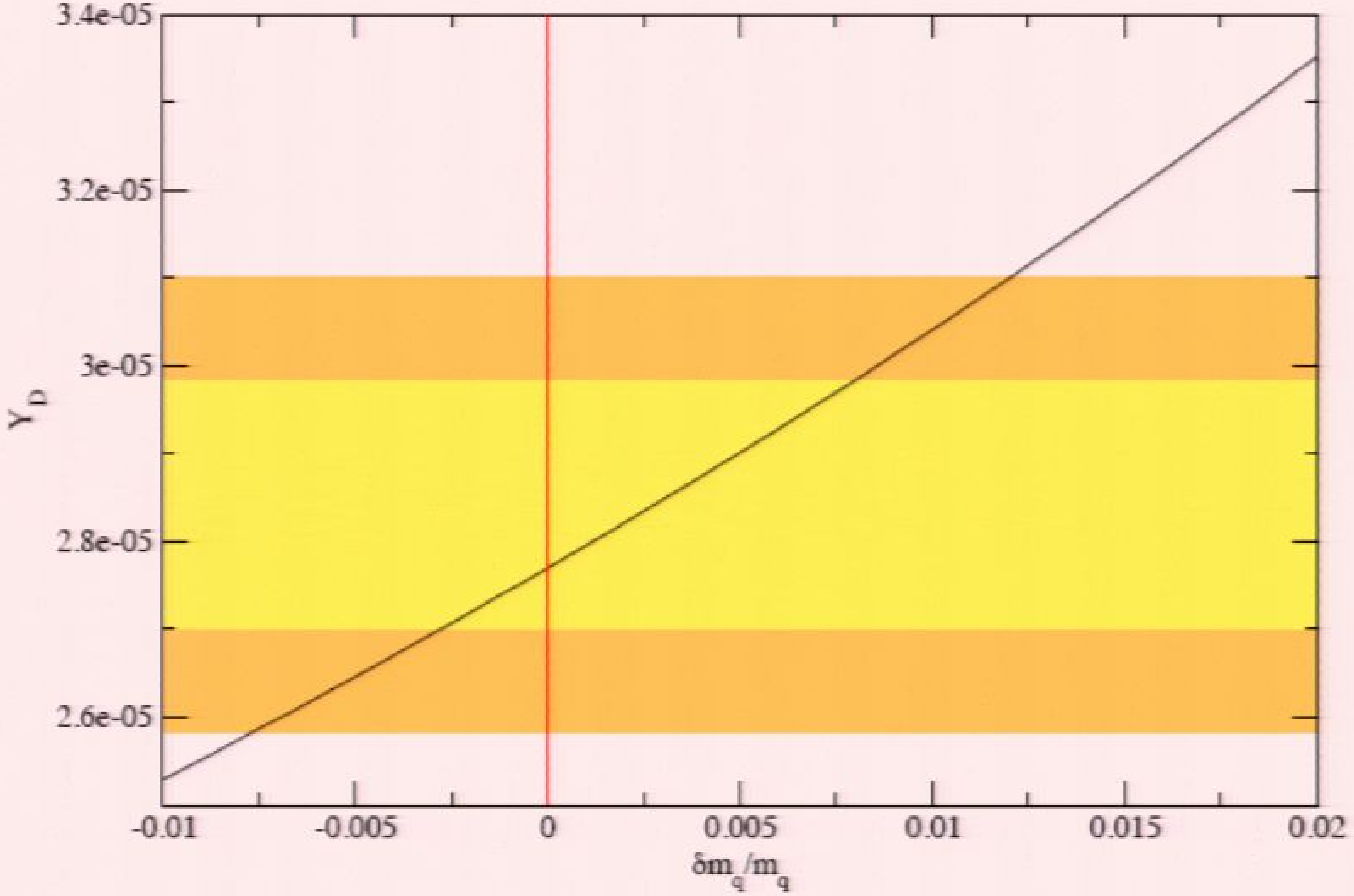
$$\begin{array}{rlcr} \text{D:} & 1 + 9.34\,x = 1.09 \pm 0.10 & & 0.009\,(11) \\ {}^4\text{He:} & 1 - 1.00\,x = 1.005 \pm 0.036 & \rightarrow & -0.005\,(36) \\ {}^7\text{Li:} & 1 - 60\,x = 0.33 \pm 0.11 & & 0.011\,(2) \end{array}$$

Consistent solution: $x = 0.011\,(2)$ dominated by ^{7}Li
c.f. Flambaum and Wiringa, 2007: $x = 0.013\,(2)$

Nonlinear variation of m_q: D constraint



Nonlinear variation of m_q: D constraint



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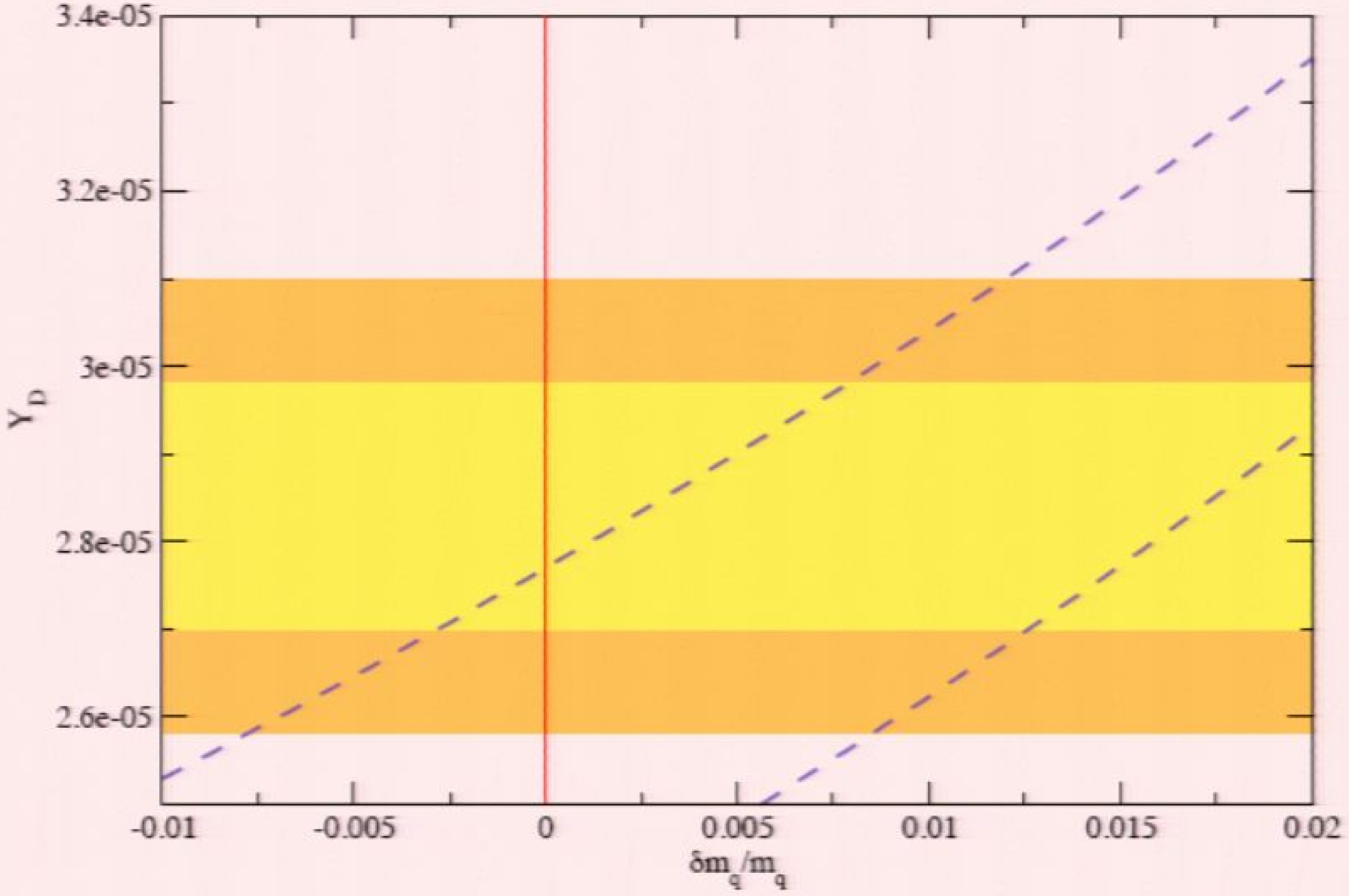
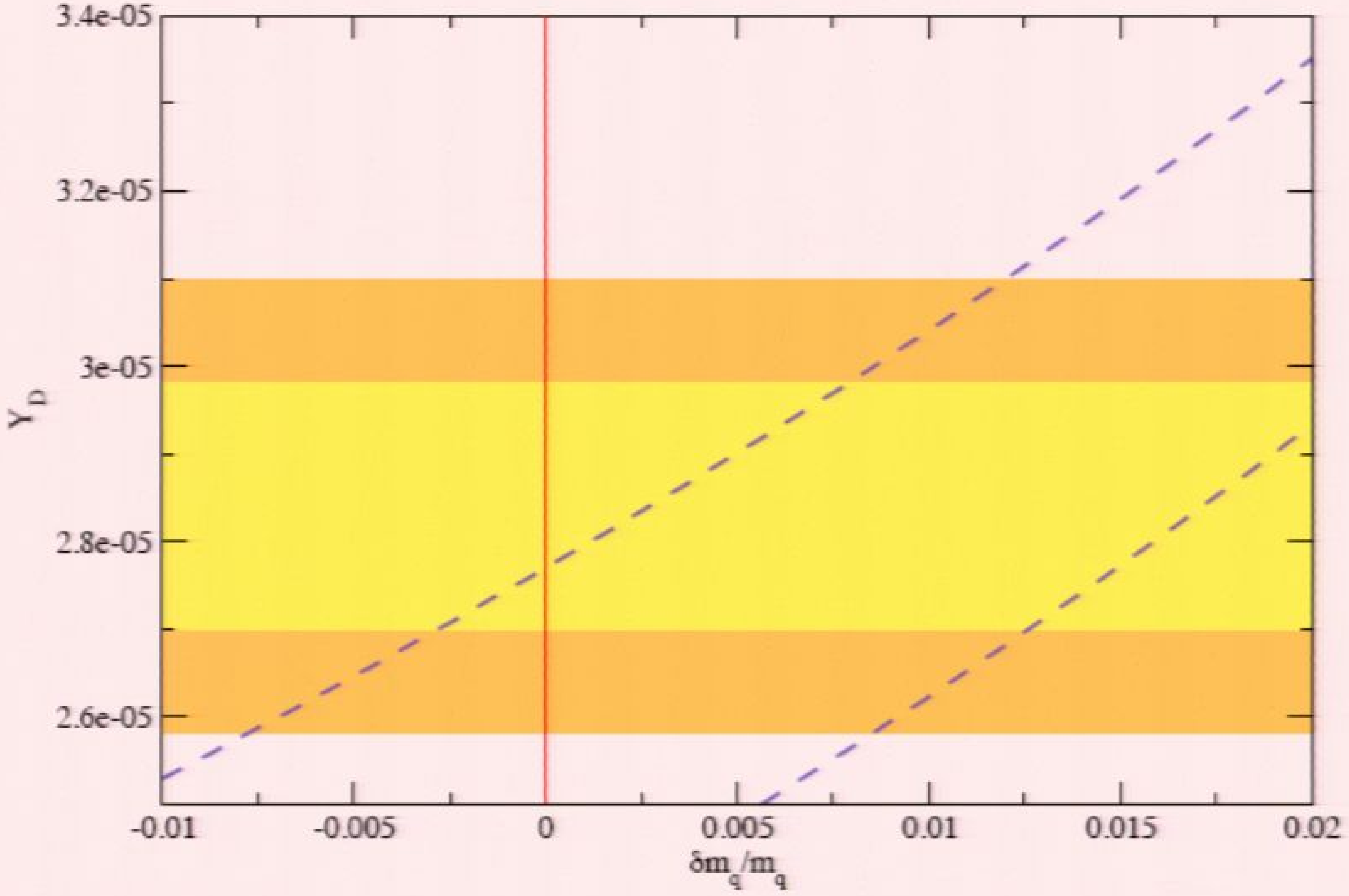
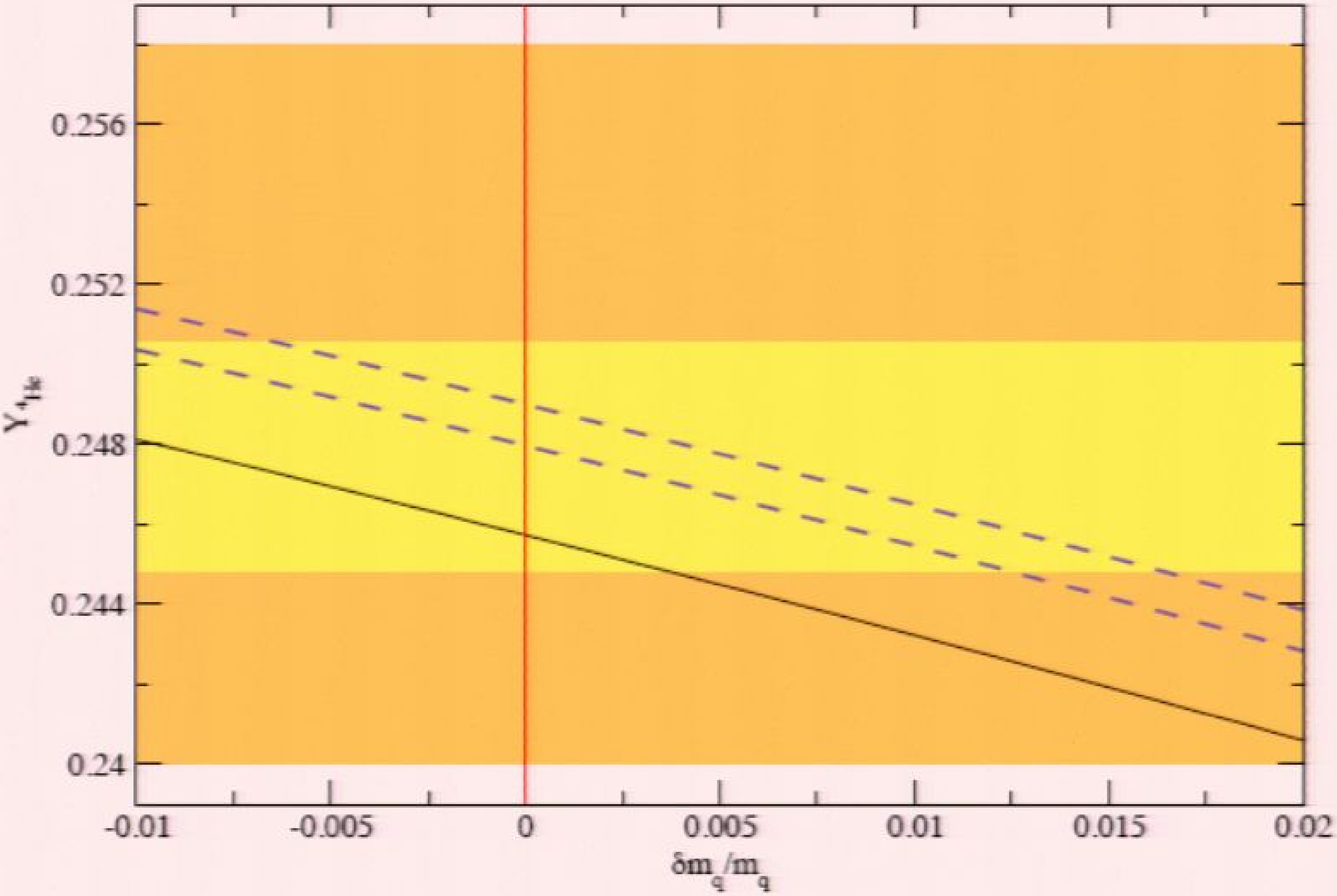


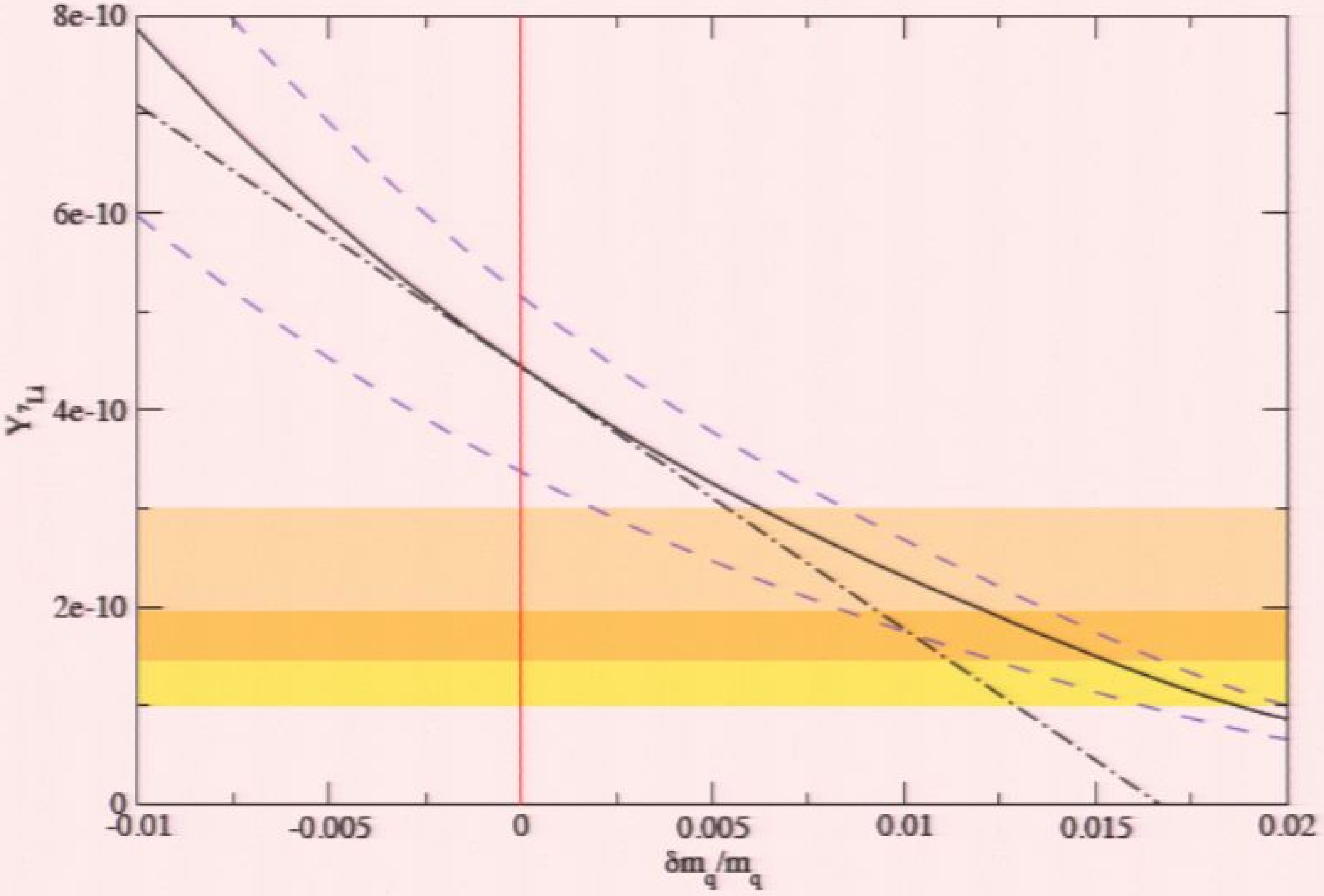
Nonlinear variation of m_q: D constraint



Nonlinear variation of m_q: ^{4}He constraint



Nonlinear variation of m_q: ^{7}Li constraint

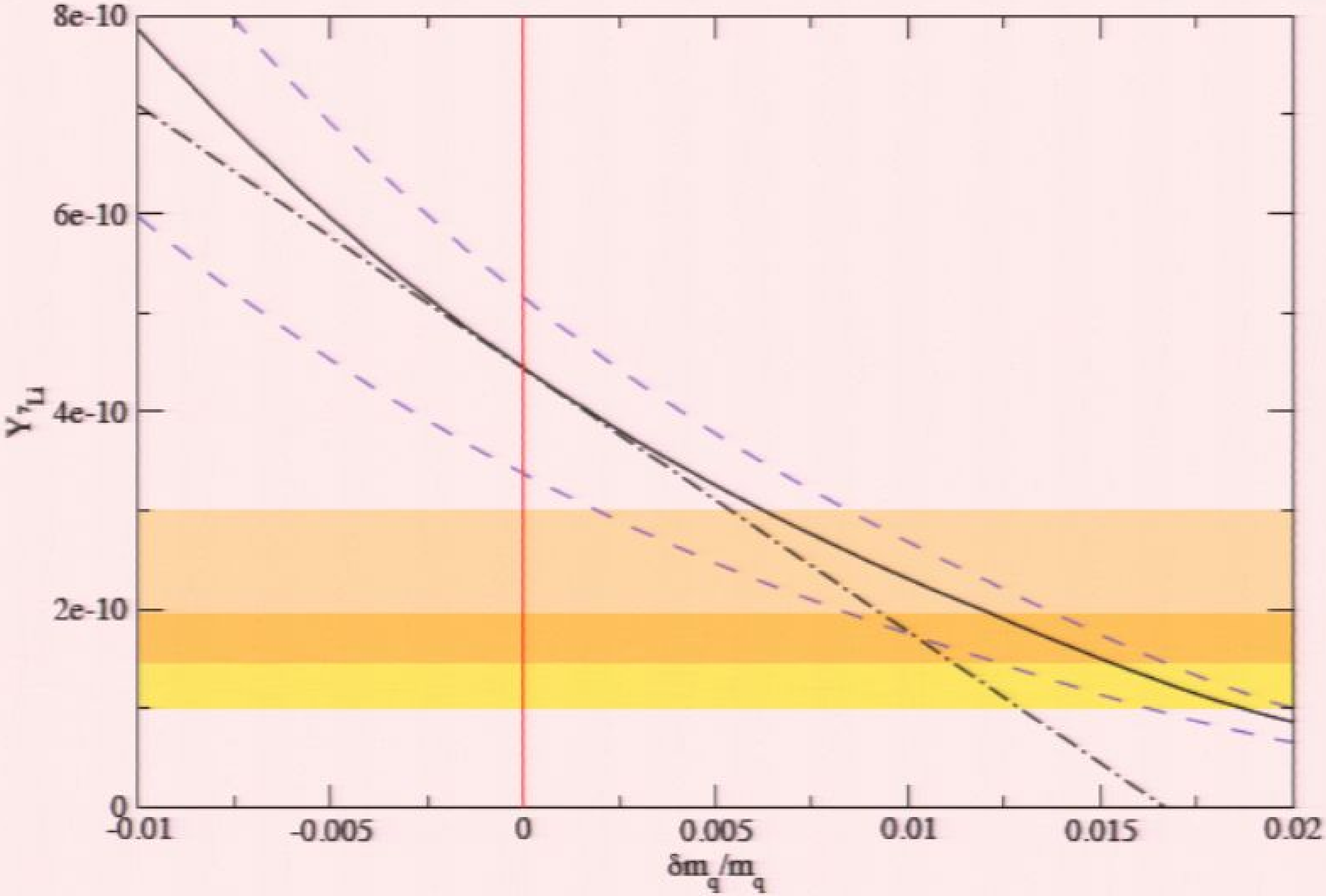


Results from ^{7}Li

Only observational uncertainty	
Bonifacio *et al.* 2007	$\delta m_q/m_q = 0.017\,(2)$
PDG 2007	$\delta m_q/m_q = 0.013\,(2)$
Bonifacio + PDG	$\delta m_q/m_q = 0.015\,(3)$
Lower limit	$\delta m_q/m_q > 0.006$

- Large theory errors (Cyburt) increase uncertainty to ~ 0.007
- Nonlinear effect is ~ 0.005

Nonlinear variation of m_q: ^{7}Li constraint



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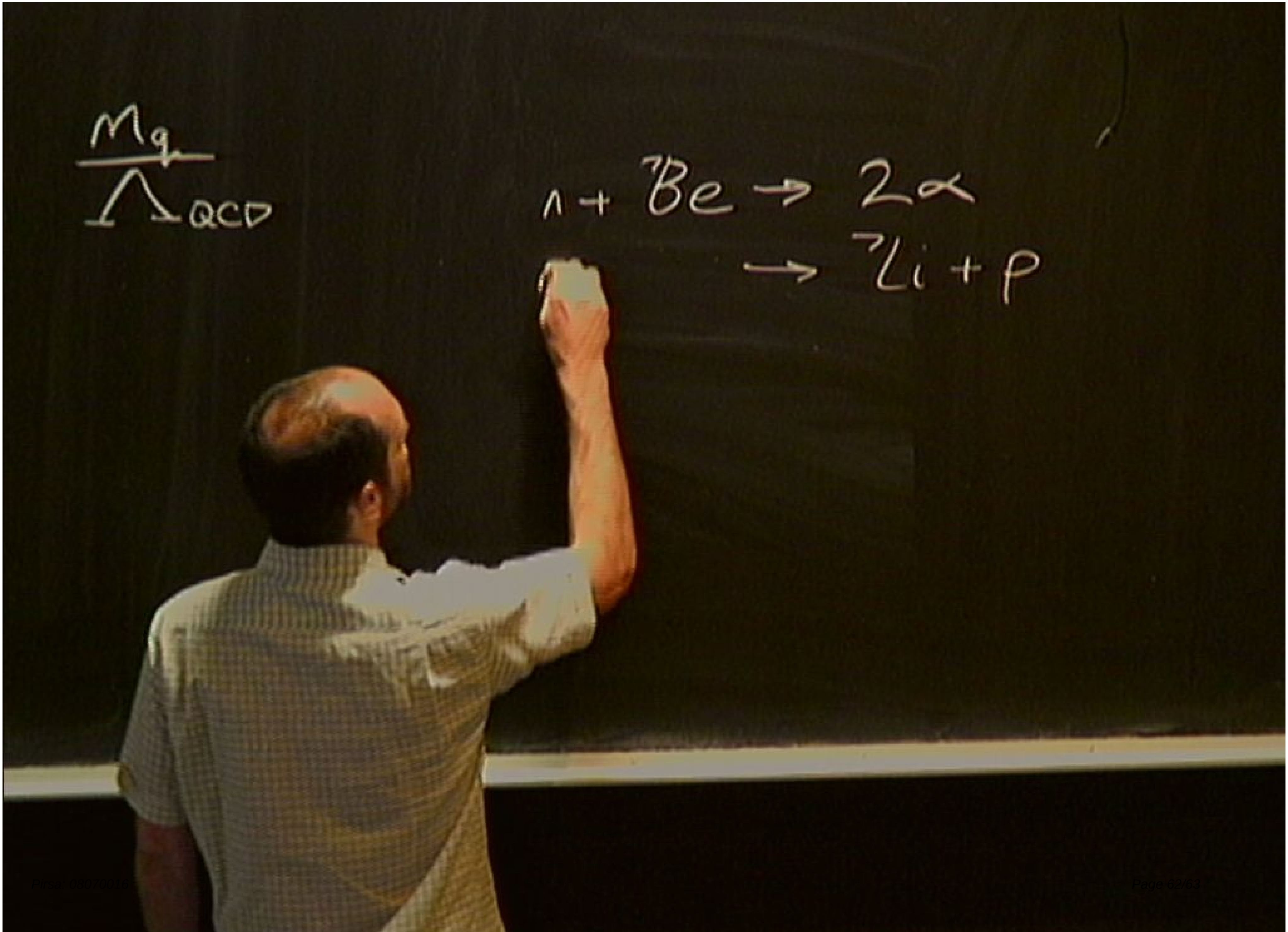
- Large theory errors (Cyburt) increase uncertainty to ~ 0.007
- Nonlinear effect is ~ 0.005
- $\delta m_q / m_q$ is not small!
  e.g. Q goes negative for some minor reactions
  - $^{10}\mathrm{Be}\,(p,\alpha)\,^{7}\mathrm{Be}$
  - $^{9}\mathrm{Be}\,(p,d\alpha)\,^{4}\mathrm{He}$

Summary

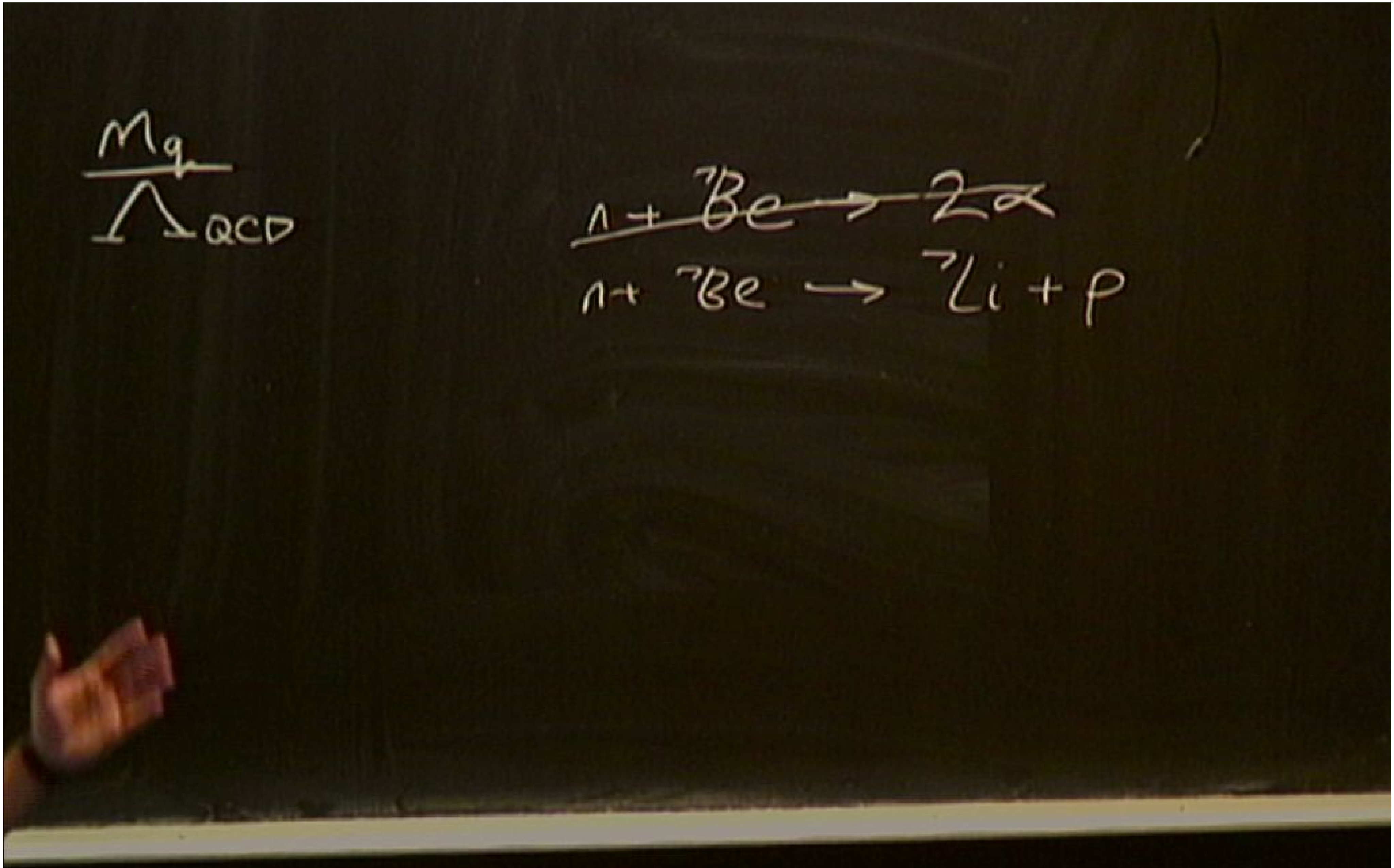
- BBN is a useful probe of hadronic mass variation in the early universe
- Improvements in observational constraints (incl. ^{3}He) and nuclear reactions will further constrain hadron mass variation
- Nonlinear effects have some importance



$$\frac{M_q}{\Lambda_{QCD}}$$

$$n + {}^7Be \to 2\alpha$$

$$\to {}^7Li + p$$



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