Lithium Problem in Big Bang Nucleosynthesis and Early Dark Energy

Sora Yamashita (Saga University)

Collaborator : Tomo Takahashi (Saga University)

Big bang nucleosynthesis (BBN)

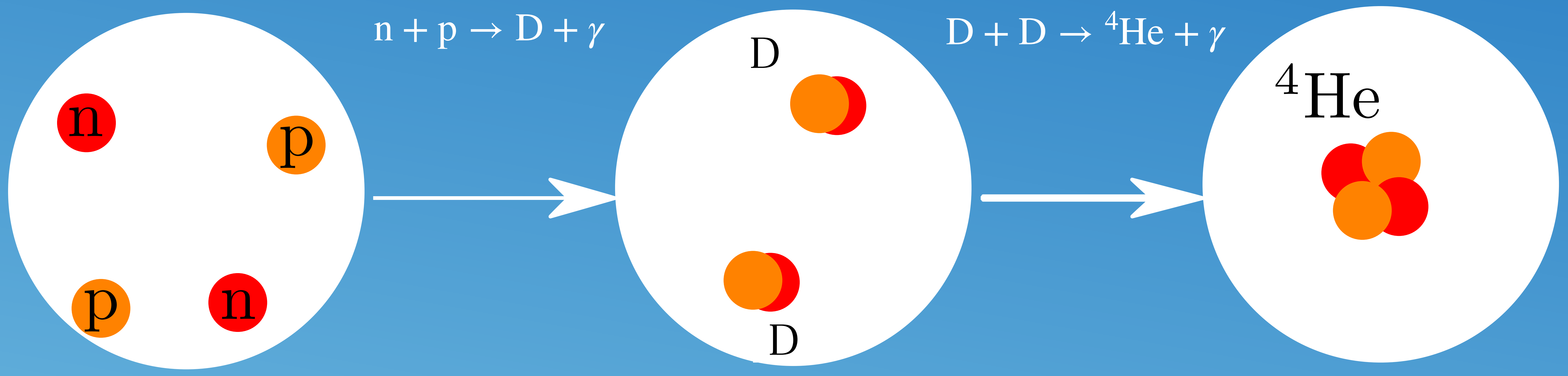
Big bang nucleosynthesis (BBN) (1)

First nucleus' appearance in the Universe

- In big bang cosmology, the Universe was very hot and dense in the early times.
- Nuclei cannot form in high temperature and density!!

Big bang nucleosynthesis (BBN)   (2)

Nuclei can be formed as the Universe cools down.



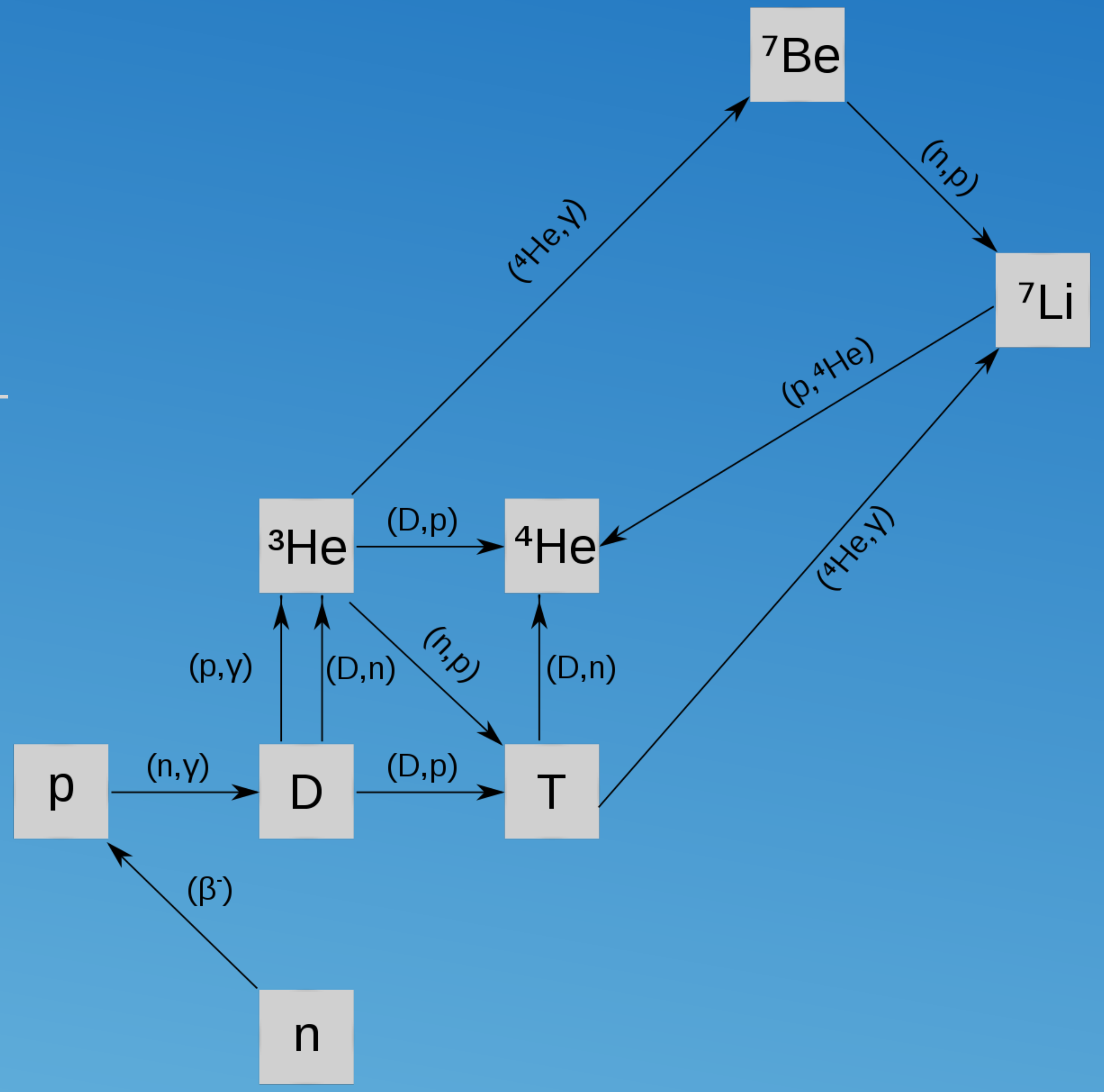
BBN starts at temperature ~ 1 MeV

1. Interactions between neutron and proton freeze out.
   (Isolated neutron starts its decay and decrease.)

$$\mathrm{p} + \mathrm{e}^- \rightleftharpoons \mathrm{n} + \nu_\mathrm{e},\ \mathrm{p} + \bar{\nu}_\mathrm{e} \rightleftharpoons \mathrm{n} + \mathrm{e}^+$$

2. Neutrons interact with protons to produce light nuclei.

e.g.) $\mathrm{n} + \mathrm{p} \rightarrow \mathrm{D} + \gamma$



Nuclear reaction network in BBN

Main equations in the BBN computation.

1. Friedmann equation :

$$\frac{\dot{a}}{a} = H = \sqrt{\frac{8\pi G}{3}\rho}$$

2. Conservation of the baryon number :

$$\frac{\dot{n}_B}{n_B} = -3H$$

3. The continuity equation :

$$\dot{\rho} = -3H(\rho + p)$$

4. Boltzmann equations :

$$\dot{X}_i = \sum_{j,k,l} N_i \left(\Gamma_{kl\to ij} \frac{X_l^{N_l} X_k^{N_k}}{N_l! N_k!} - \Gamma_{ij\to kl} \frac{X_i^{N_i} X_j^{N_j}}{N_i! N_j!} \right)$$

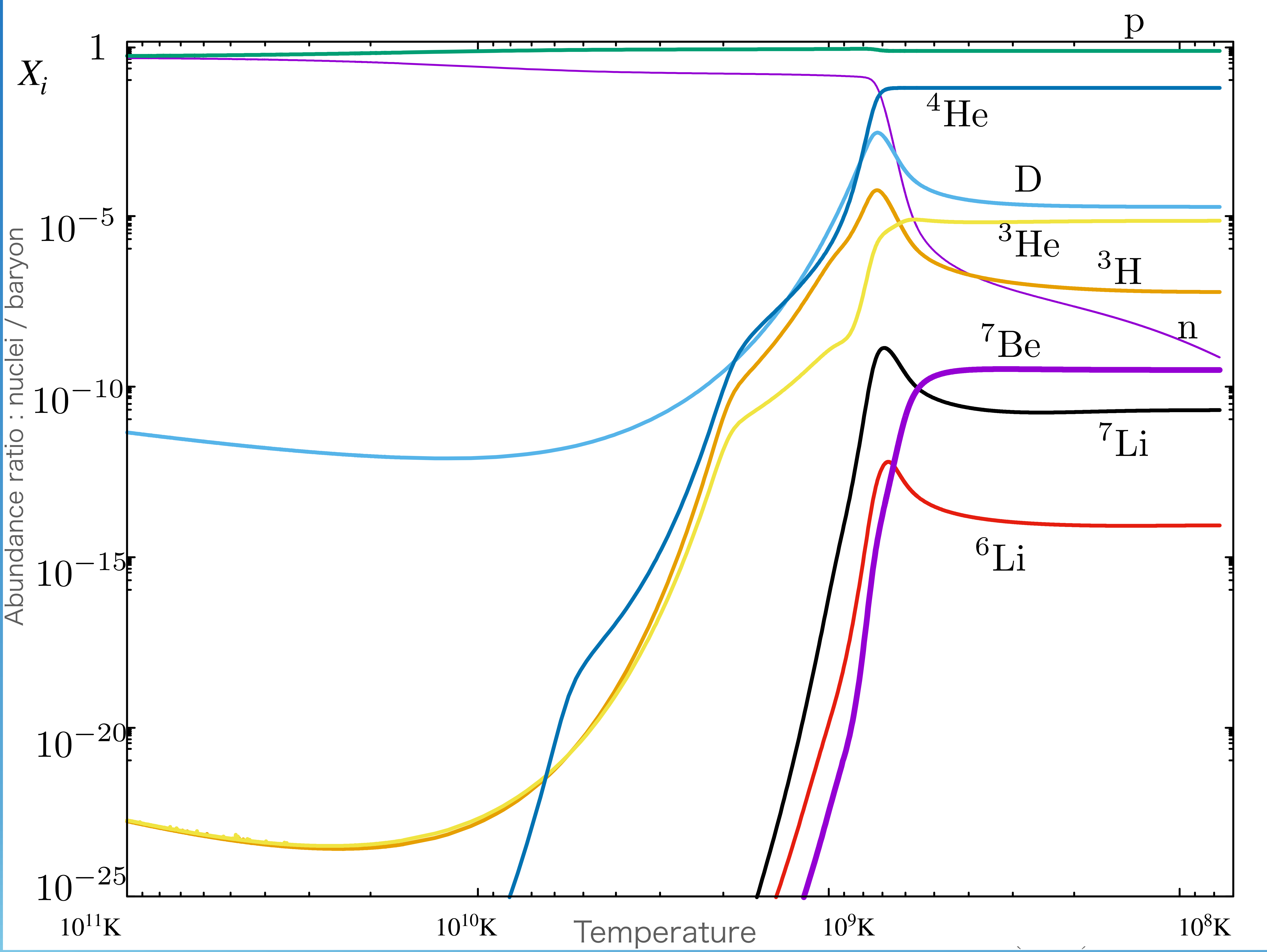
5. The Universe charge neutrality :

$$n_B \sum_j Z_j X_j = n_{e^-} - n_{e^+}$$

How nuclei were formed ?

The picture shows
the evolution of each nuclei
in the BBN.

Calculated with Parthenope (http://parthenope.na.infn.it/)



Evolution of abundance

Lithium problem

The observations show :

$$Y(^4\mathrm{He}) = 0.245 \pm 0.007$$

Fernández et al. 1804.10701

$$\mathrm{D/p} \times 10^5 = 2.55 \pm 0.03$$

Fields et al. 1912.01132

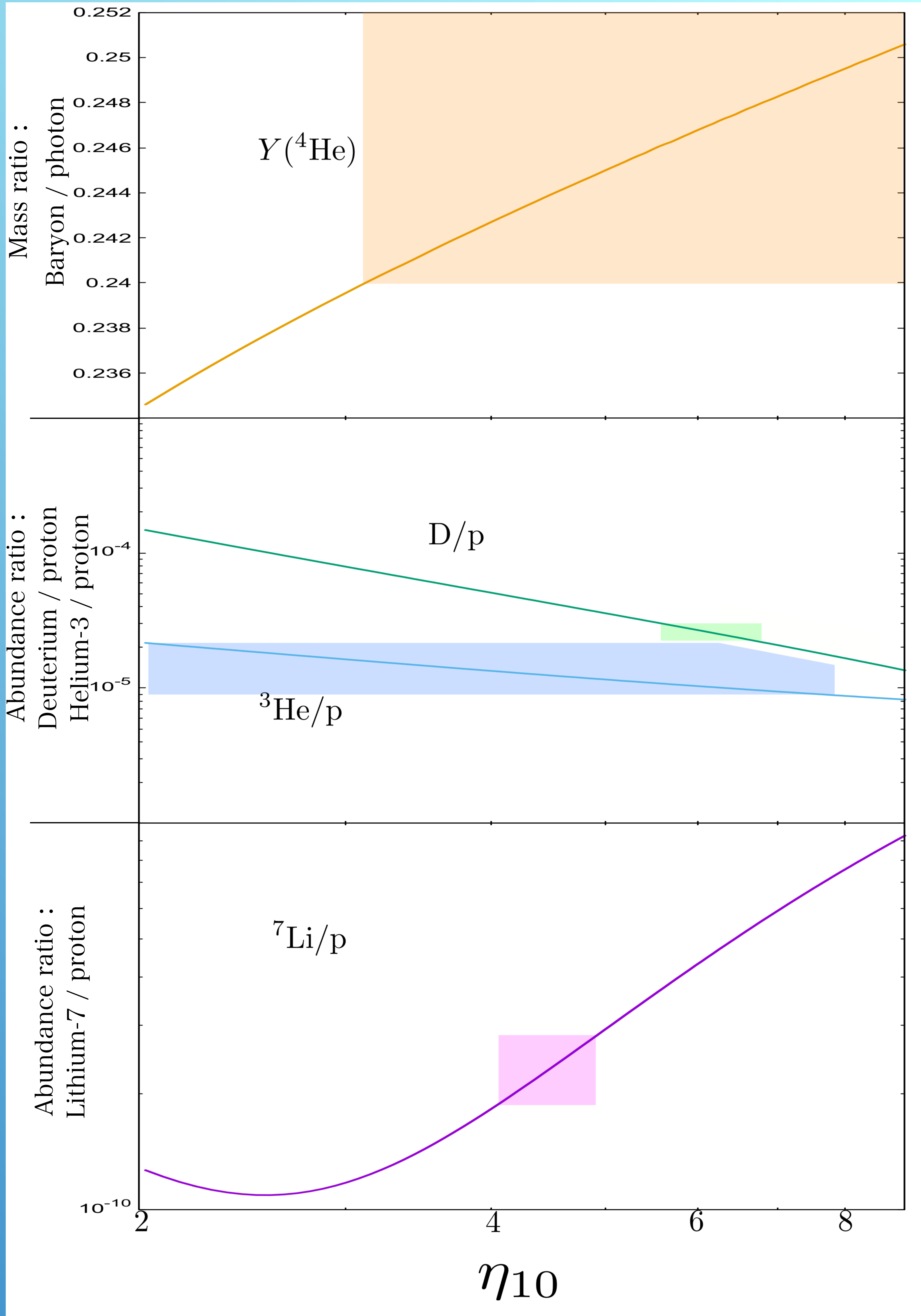
$$^7\mathrm{Li/p} \times 10^{10} = 1.6 \pm 0.3$$

Zyla et al. (PDG),Prog. Theor. Exp. Pays. 2020,083C01(2020)
Sbordone et al. 1003.4510

$$\rightarrow \eta_{10} = n_B/n_\gamma \times 10^{10} \sim 6$$

is corresponding to $\mathrm{D/p}$ and $Y(^4\mathrm{He})$.

However $^7\mathrm{Li/p}$ isn't consistent = Lithium problem



Possible solutions to the Lithium problem :

- Systematic error in observations
- Corrections to nuclear reactions' rate(s)
- Changing fundamental constant such as $\hbar, G, e$
- Introducing X^- particle
- . . .

Early Dark Energy (EDE)

It is one of the idea to resolve Hubble tension

Early Dark Energy (EDE)

The equation of a scalar field ϕ in isotropic and homogeneous background :

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0 \ , \quad H \text{ : Hubble parameter}$$

EDE's potential :

$$V = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)^n \qquad n = 1,2,3,..$$

Poulin et al. Phys.Rev.D 98 (2018) 8, 083525

f, Λ : parameters depend on model

Now, we see how the density parameter of EDE $(n = 1,2,3)$ behaves.

Behavior of EDE

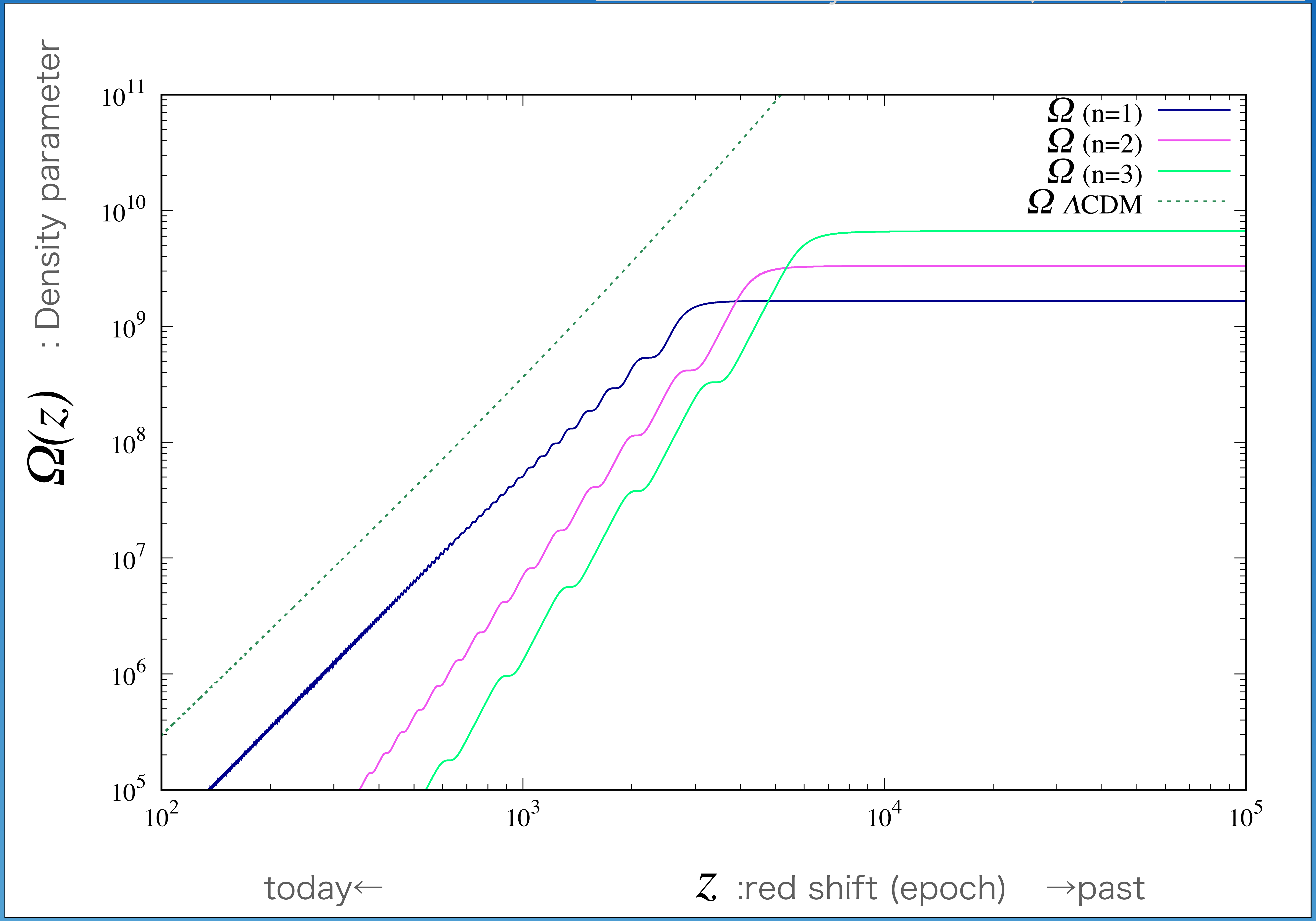
When : $m_{\rm eff}^2 = \frac{d^2V}{d\phi^2} \simeq H^2,$

the field ϕ starts oscillating, and then the density parameter decreases.

We consider EDE during BBN
(Energy density begins to decrease during BBN)

Can EDE resolve
the Lithium problem??

Poulin et al. Phys.Rev.D 98 (2018) 8, 083525



How to add EDE in the BBN calculation

EDE can be simplified as :

$$\rho_{EDE(T>T_0)} = \Lambda \ , \ \ \rho_{EDE(T<T_0)} = \Lambda \left(\frac{T}{T_0}\right)^{2n} \ , \ \ n = 1,2,3,\ldots \ .$$

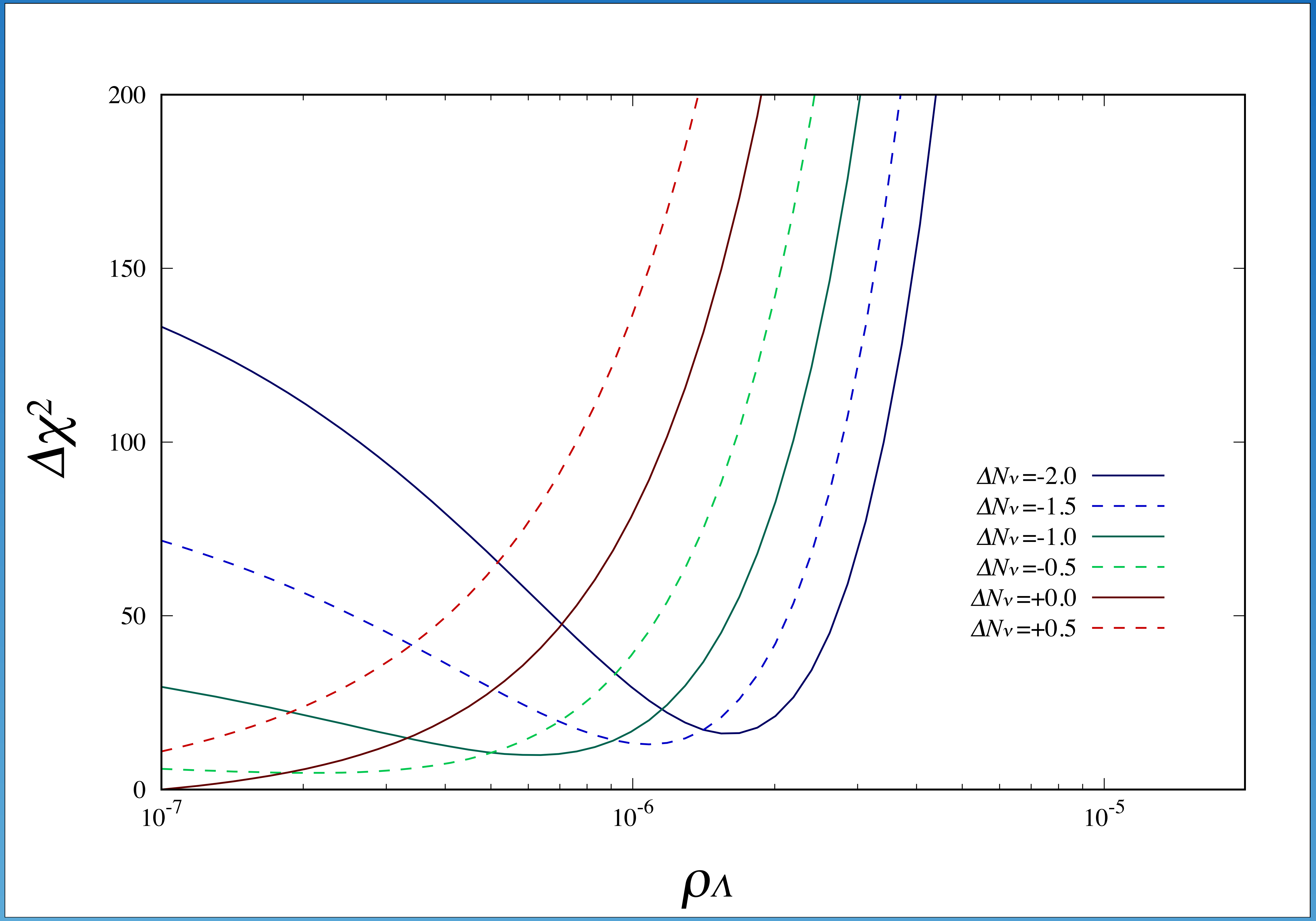
Then total energy density can be modified as :

$$\rho = \rho_\gamma + \rho_\nu + \rho_{baryon} + \rho_{e^\pm} + \rho_{EDE} \ .$$

→ EDE modifies the expansion rate of the Universe during BBN

If $\rho_{EDE} = \Lambda = \text{const}$:

The case with $\Lambda \to 0$ gives a better fit than others.



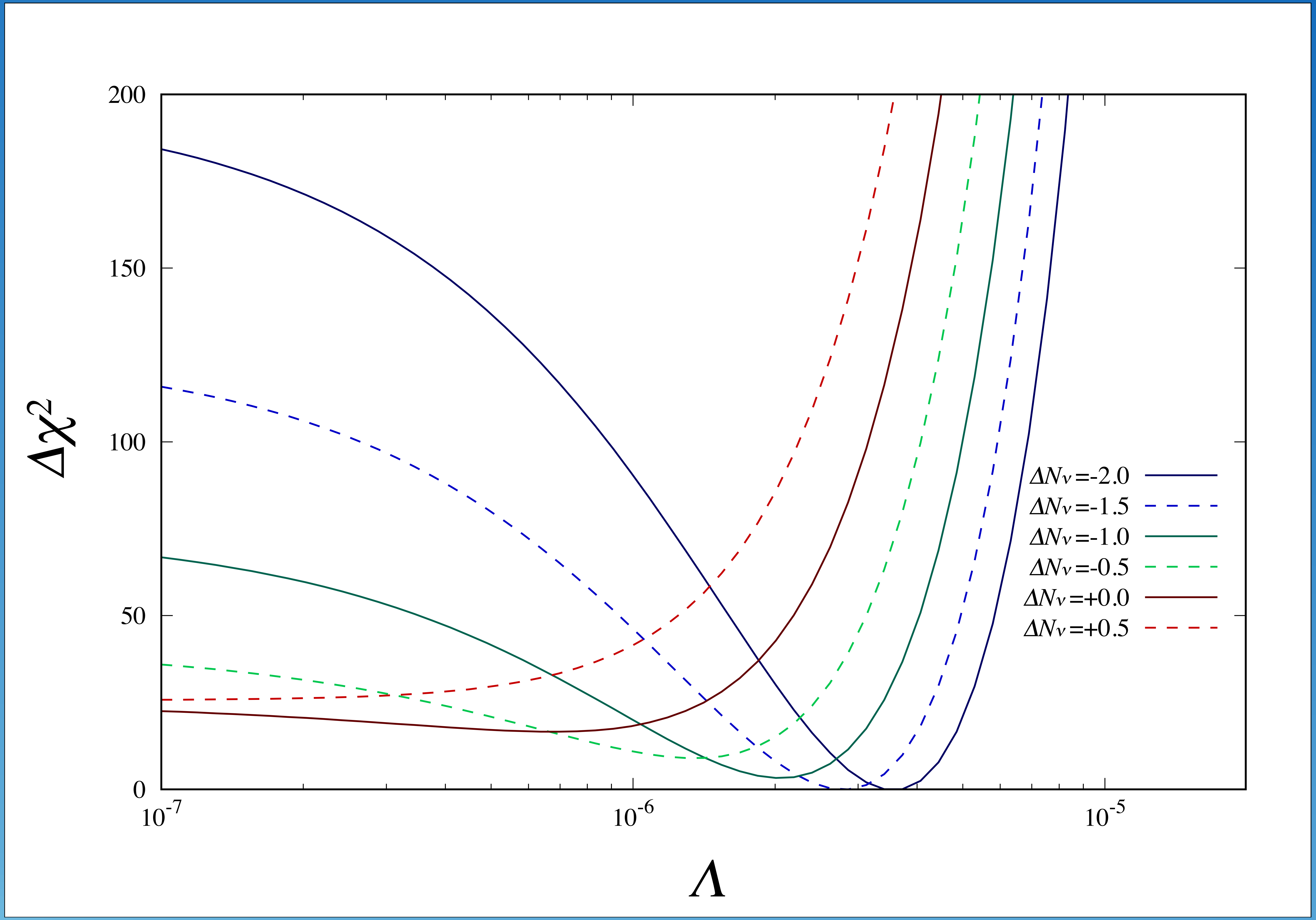
ΔN_ν vs $\chi^2(^2\text{H} + {}^4\text{He} + {}^7\text{Li})$

$$\rho_{EDE(T>T_0)} = \Lambda,\ \rho_{EDE(T<T_0)} = \Lambda\left(\frac{T}{T_0}\right)^{2n},\ n = 3\ , T_0 = 0.043\ \text{MeV},\ \eta_{10} = n_B/n_\gamma \times 10^{10} = 6.12$$

$$\chi^2_{\Delta N=0.0}(\Lambda \to 0)\ -\ \chi^2_{min}(\Lambda \sim 4.0 \times 10^{-6})$$

$$\sim -25$$

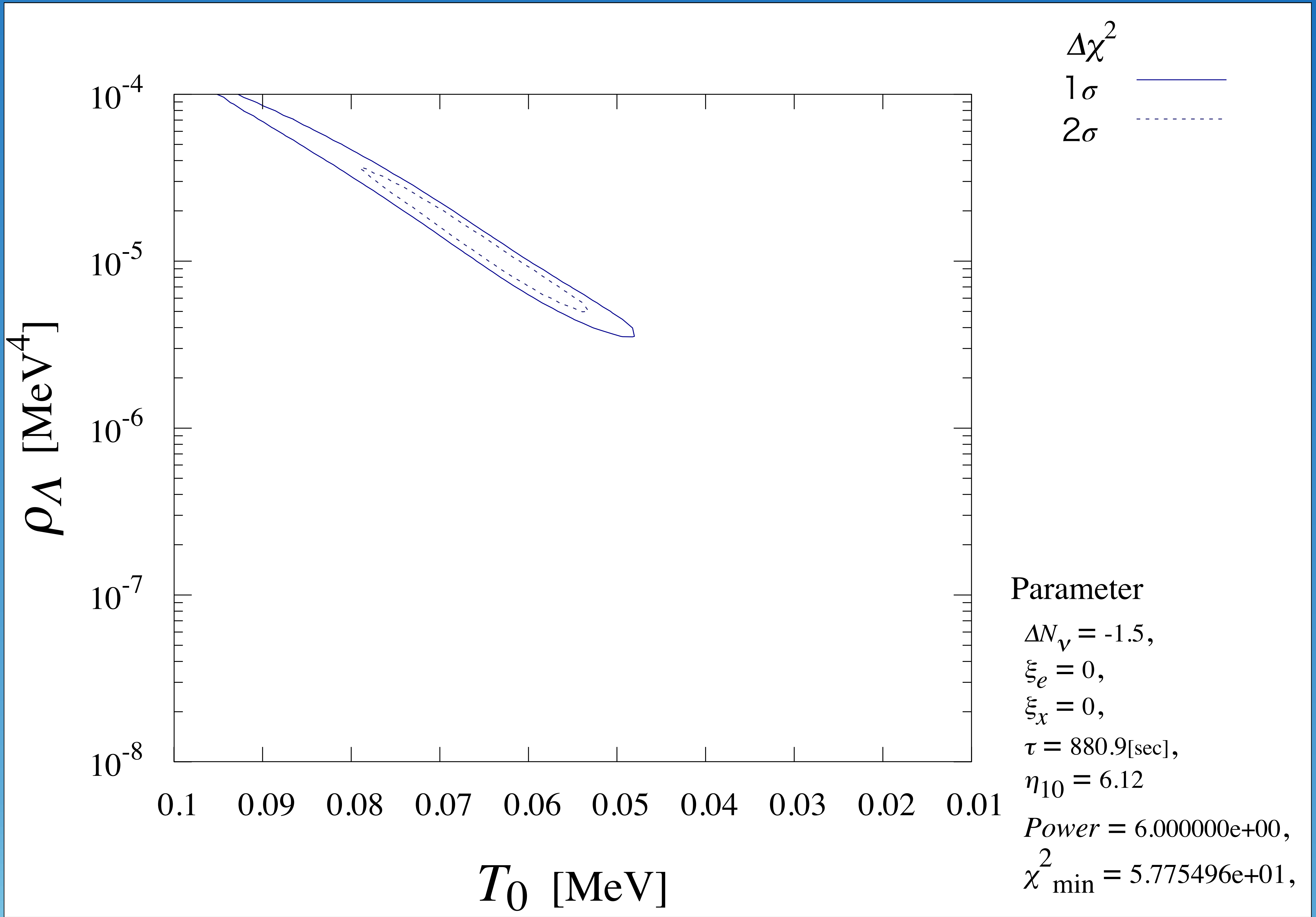
χ^2 can be reduced much.



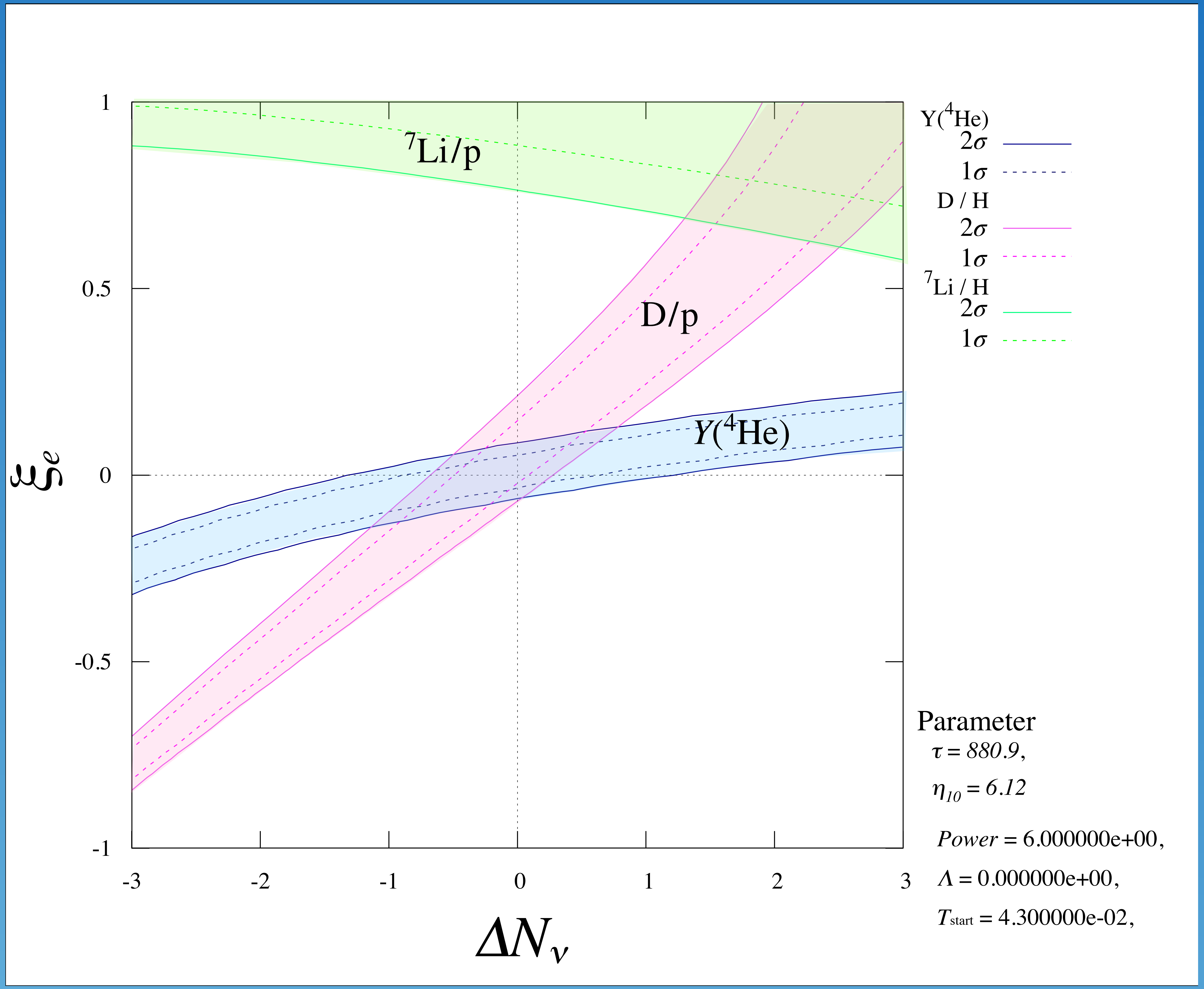
ΔN_ν vs $\chi^2(^2\text{H} + {}^4\text{He} + {}^7\text{Li})$

BBN+EDE

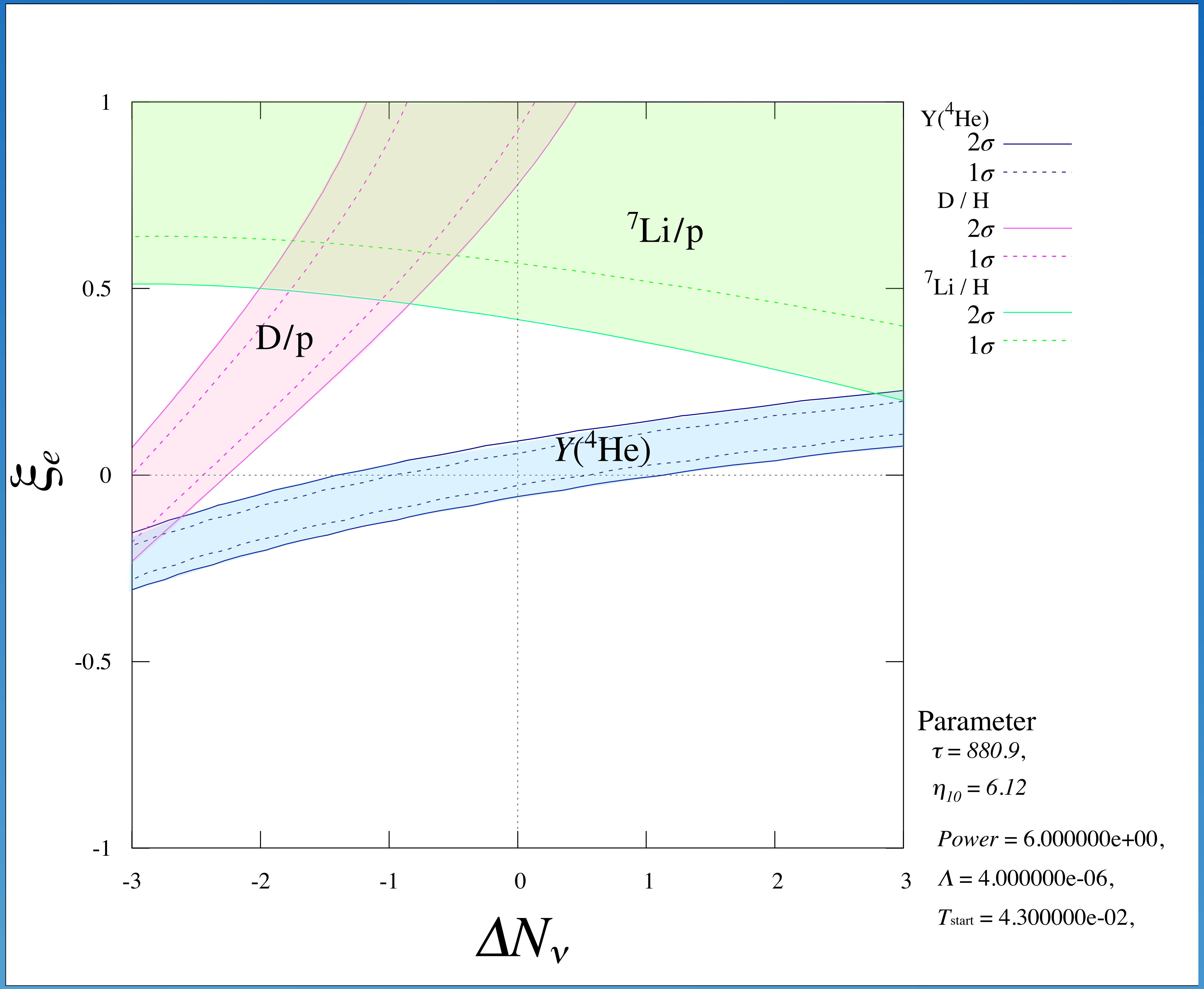
The case with EDE gives a better fit compared to the standard one.



Comparing ΔN_ν vs $\xi_e(=\mu_{\nu e}/m_e)$ plot

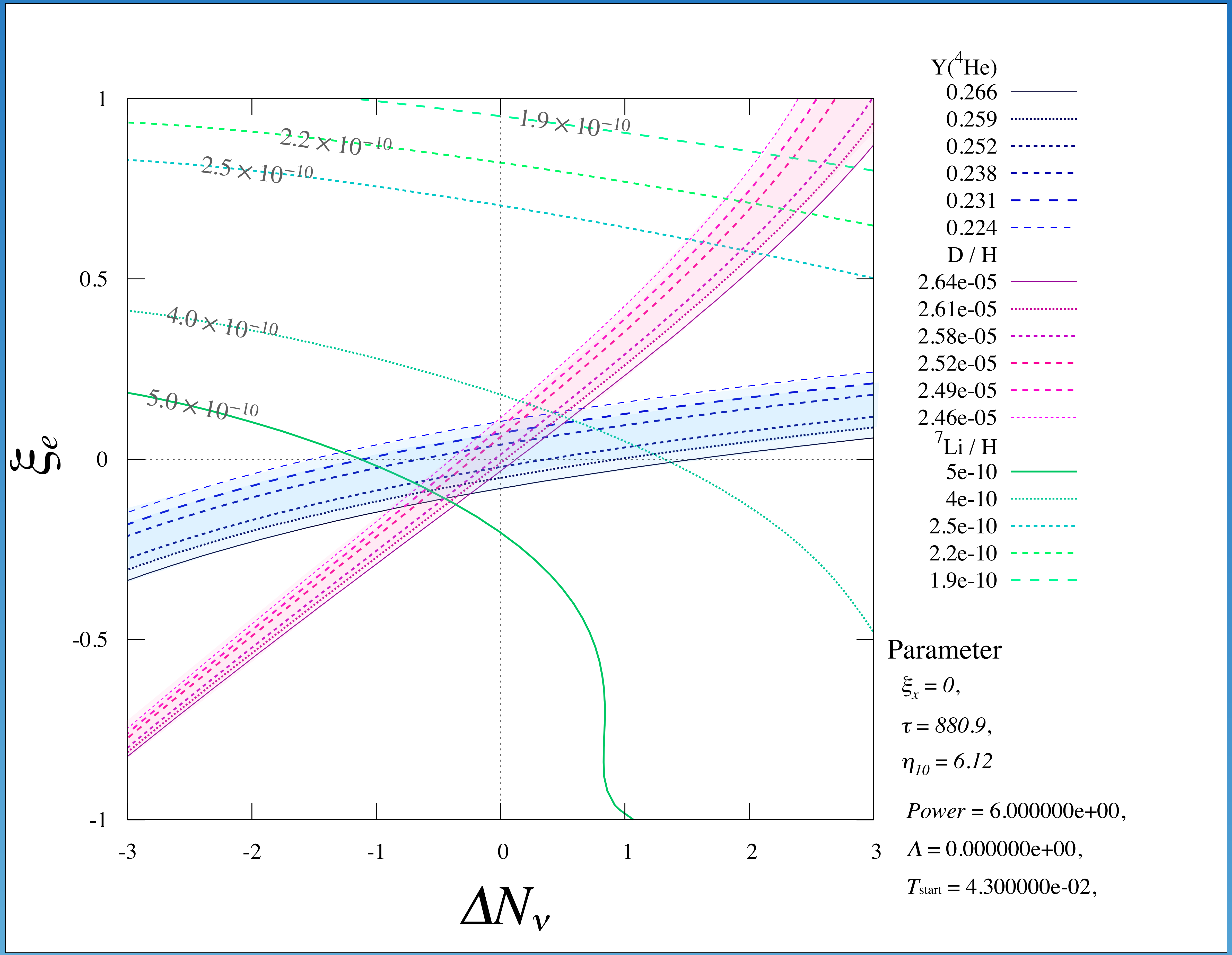


Standard case

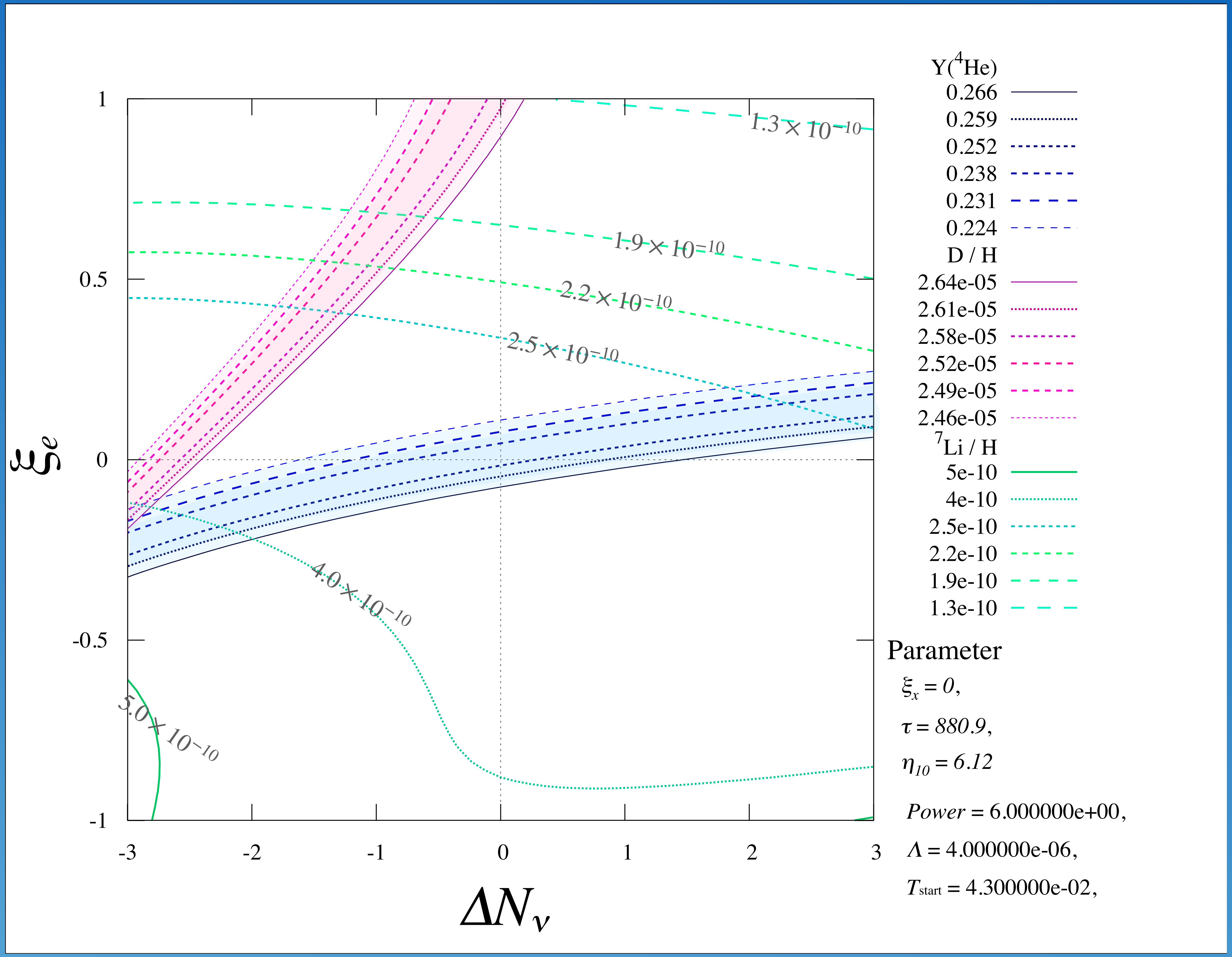


EDE case: $\Lambda = 4.0 \times 10^{-6}$

Abundance of D, ^{4}He, ^{7}Li

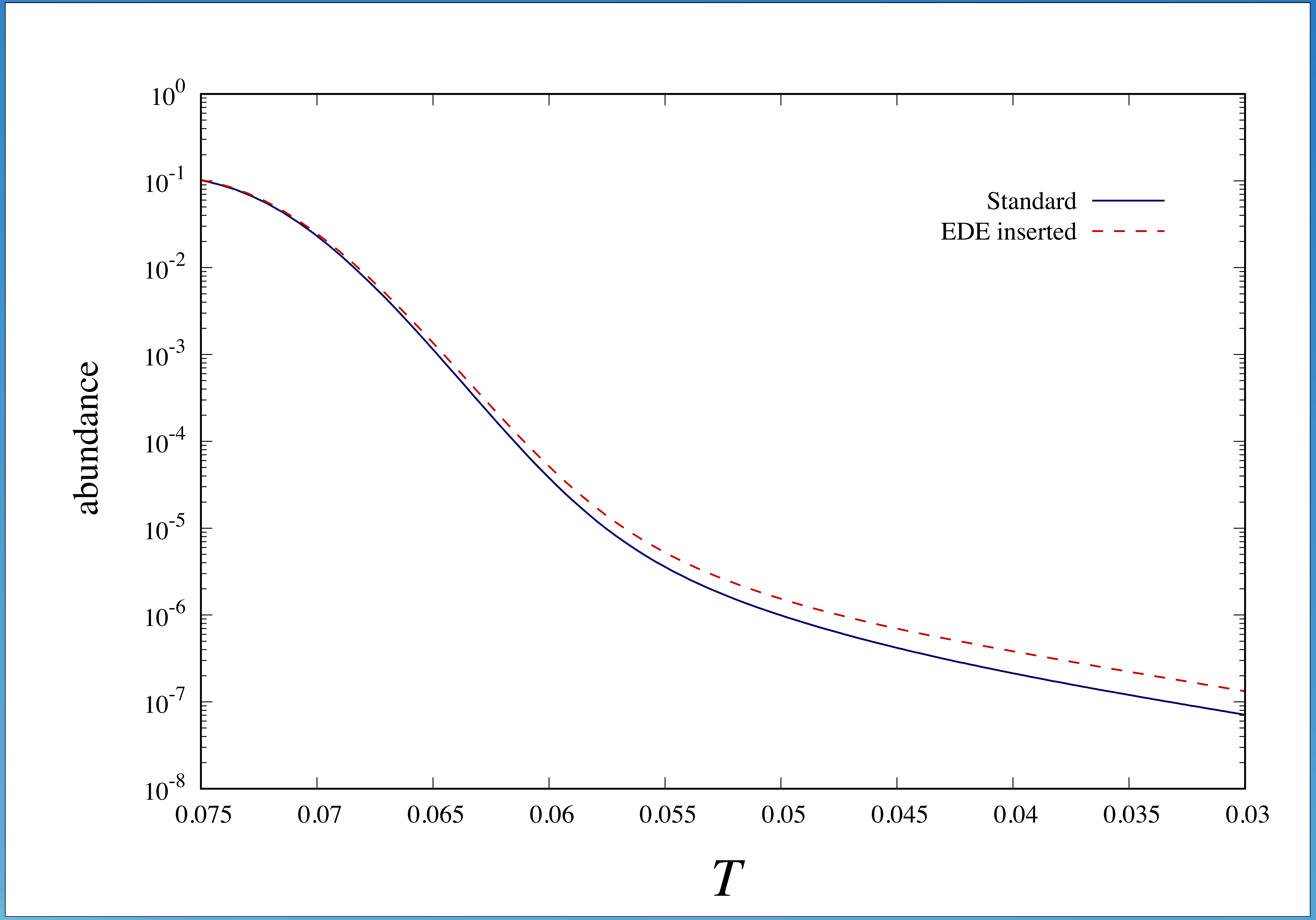


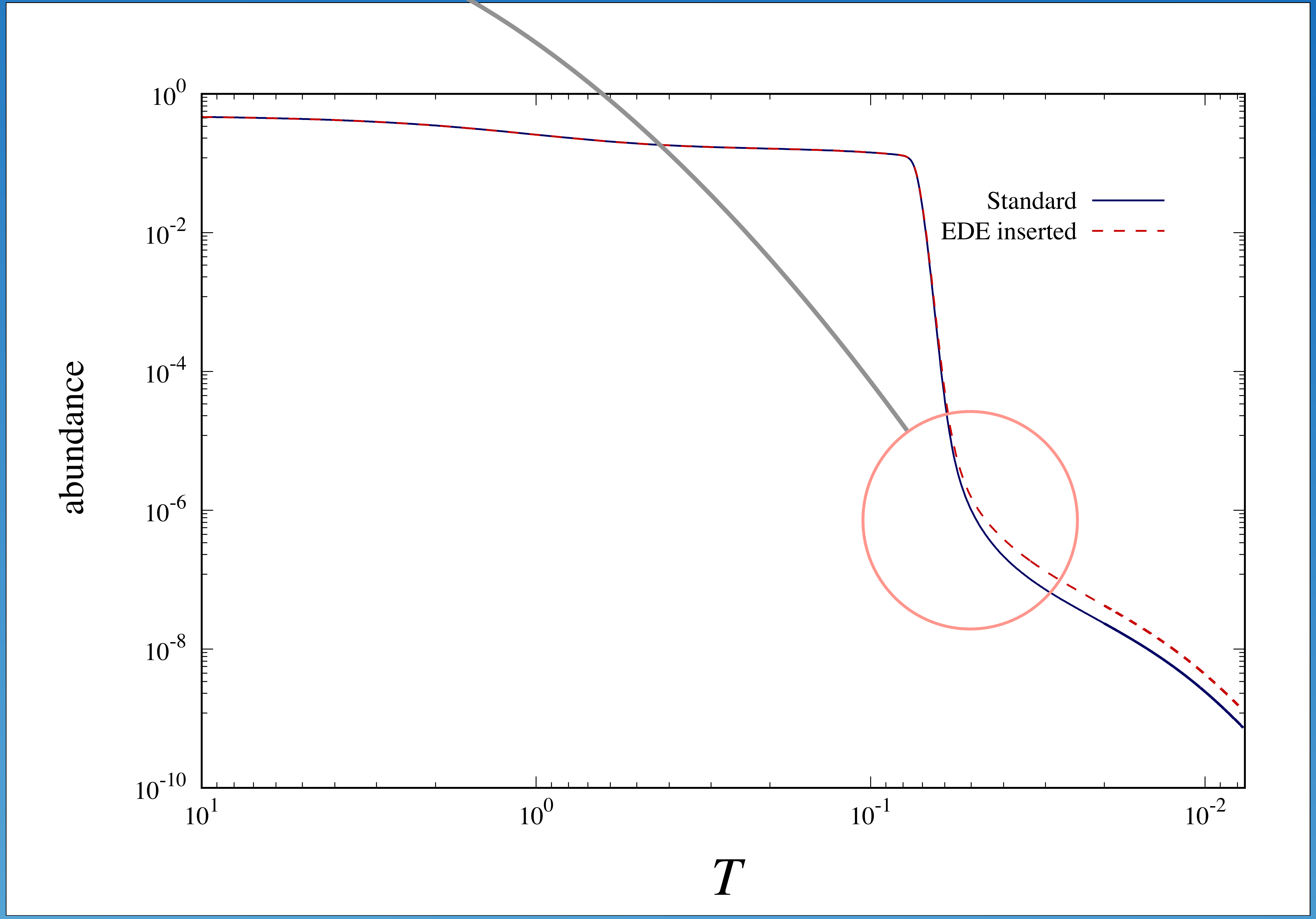
Standard case



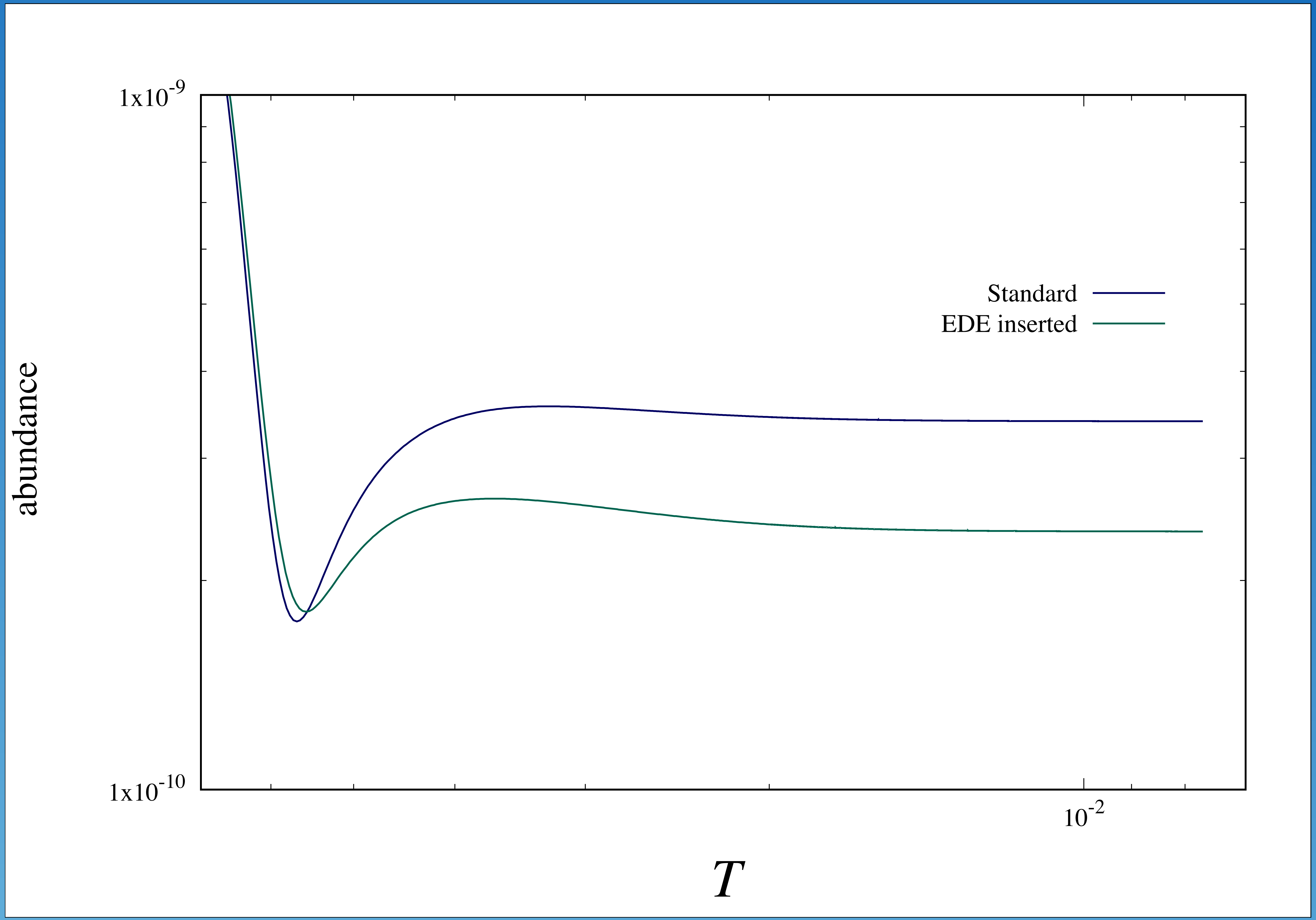
EDE case : $\Lambda = 4.0 \times 10^{-6}$

Evolution of neutron abundance ($\Delta N = 0.0$, $\xi_e = 0.0$) →increased with EDE





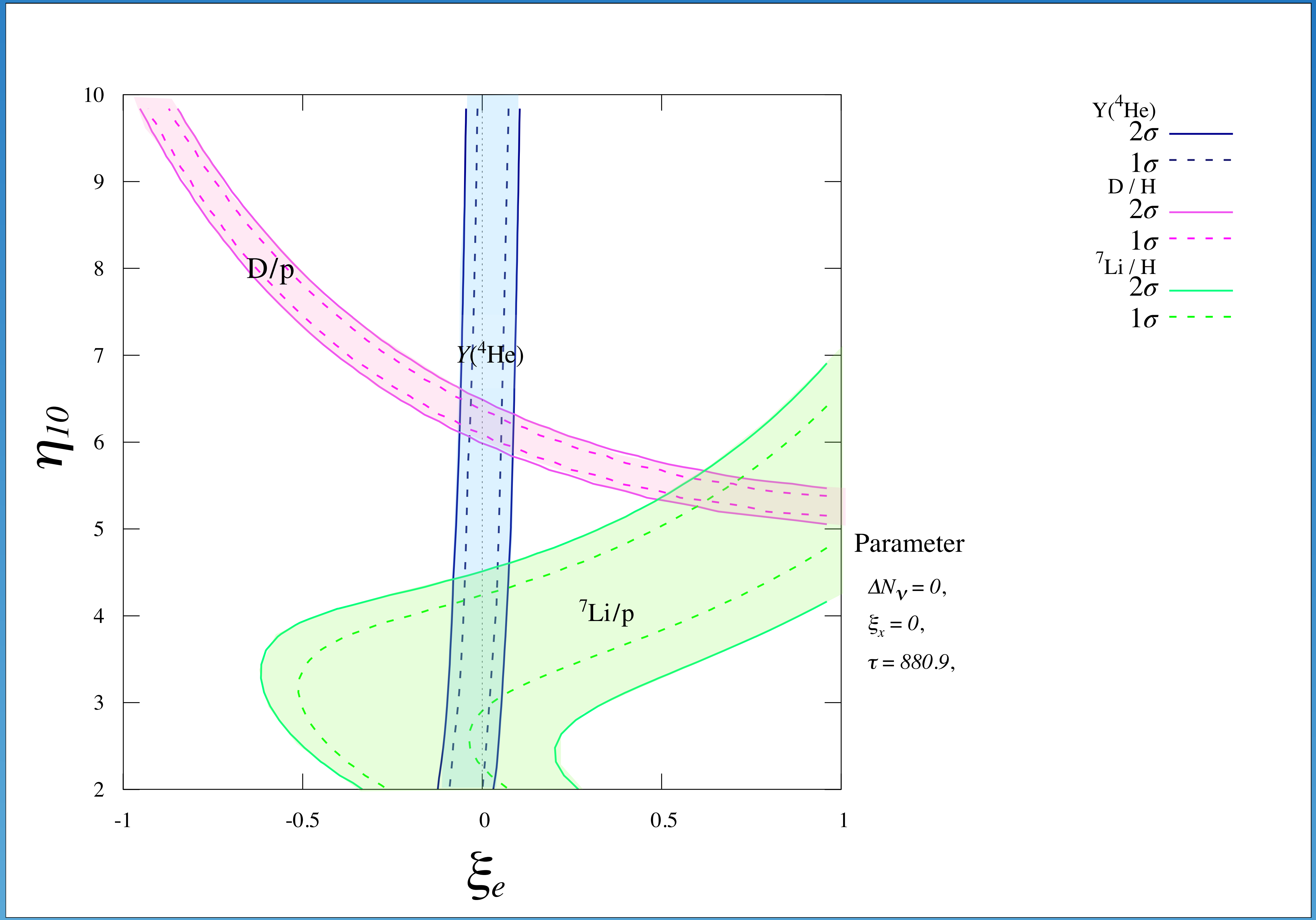
Comparing ^{7}Li(+^{7}Be)'s production ($\Delta N = 0.0$, $\xi_e = 0.0$) →decrease with EDE



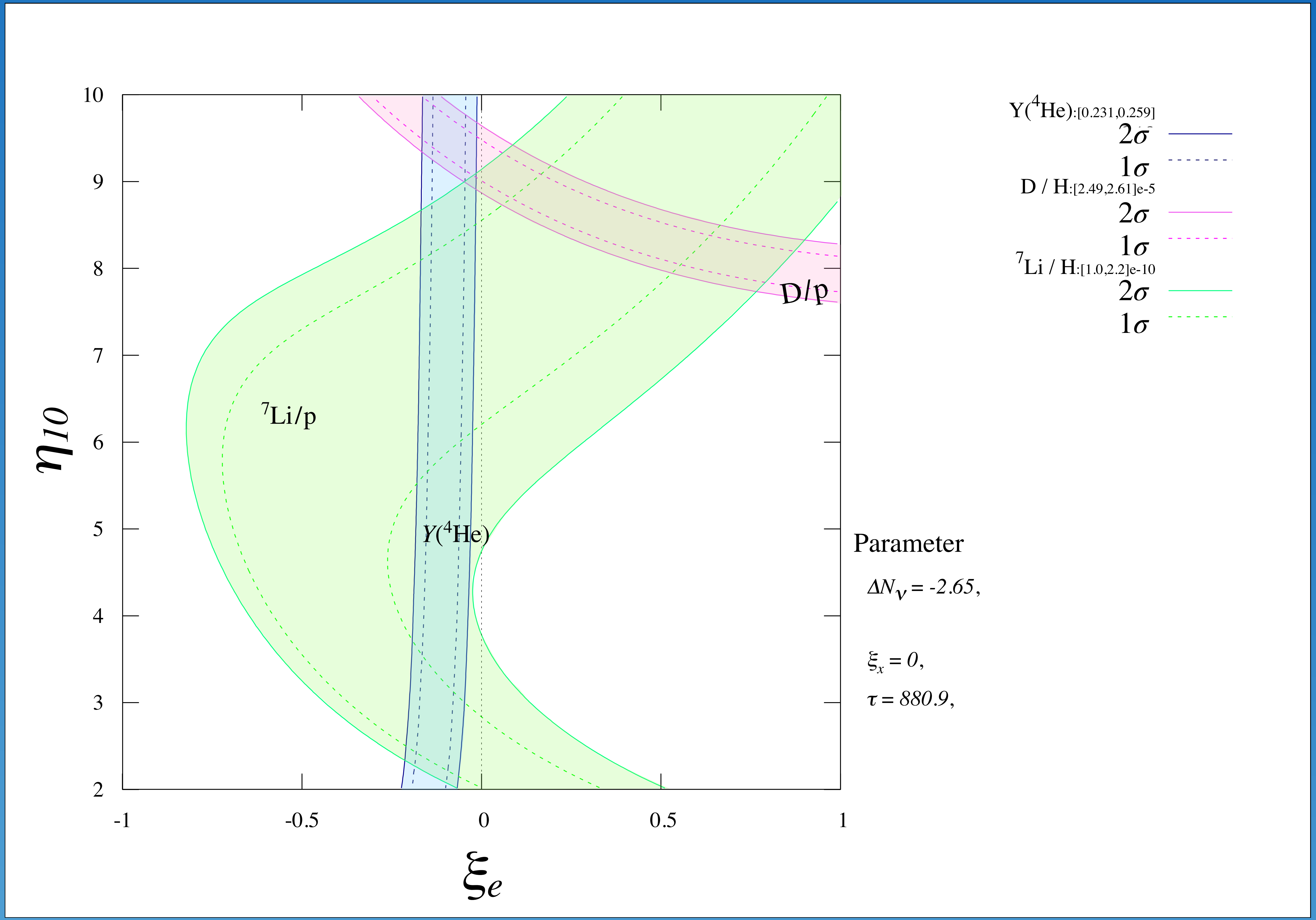
$^7\mathrm{Be} + {}^7\mathrm{Li}$'s evolution

If $\eta_{10} \sim 9$, with EDE, the abundances can be consistent at around 2σ

Here, $\rho_{EDE} = \Lambda_1 \theta(T - T_1) + \Lambda_2 \theta(T - T_2)$



Standard case



$\rho_{EDE} = \Lambda_1 \theta(T - T_1) + \Lambda_2 \theta(T - T_2),\ \Delta N = -2.65$

Summary

Adding EDE makes the abundance of D increased

→Because many neutrons are left by the EDE's effect.

$^7\mathrm{Li} + {}^7\mathrm{Be}$ decrease.

→Because the EDE enhanced the Hubble expansion.

The existence of EDE with $\Delta N_\nu < 0$ can improve somewhat the Lithium problem.

References

- Aghanim et al. Astron.Astrophys. 641 (2020) A6
- Fields et al. Chin.Phys.C 38 (2014) 339-344
- Wagoner et al. Astrophysical Journal, vol. 148, p.3
- L. Sbordone et al., Astron. & Astrophys. 522, A26 (2010)
- http://parthenope.na.infn.it/
- Poulin et al. Phys.Rev.D 98 (2018) 8, 083525
- Zyla et al. (PDG),Prog. Theor. Exp. Pays. 2020,083C01(2020)

- PlanckOBS https://inspirehep.net/literature/1682902
- BBNreview https://inspirehep.net/literature/1333326
- Be->Li https://inspirehep.net/literature/50058
- Fe / Li. https://inspirehep.net/literature/849905
- Parthenope http://parthenope.na.infn.it/
- EDE https://inspirehep.net/literature/1680031
- PDG https://pdg.lbl.gov/2021/reviews/contents_sports.html