Big Bang nucleosynthesis(BBN) and early dark energy(EDE) in light of the EMPRESS Y_p results and the Hubble tension

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Based on Takahashi and S.Y. (2211.04087)

What’s is BBN?

- ⋆ Light elements’ creation in the early universe ($T \sim 1$ MeV $\sim 10^{10}$ K).
  - ► Neutron number determines the created elements’ abundance.
  - ► Mainly ^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{7}Li are created.
  - ► BBN prediction is almost consistent with observations.

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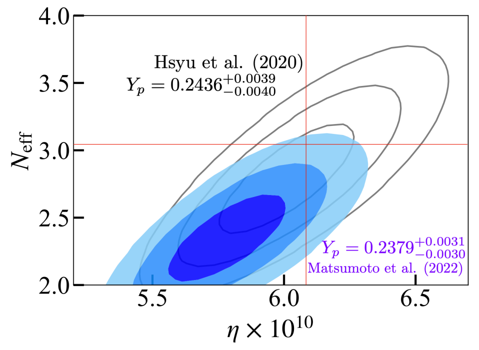
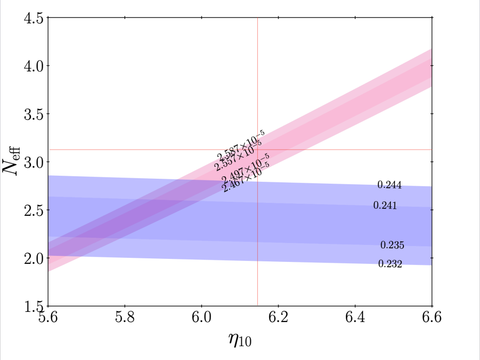
EMPRESS Y_p result vs BBN (helium anomaly)

EMPRESS Y_p result (Matsumoto et al. 2022): $Y_p = 0.2379^{+0.0031}_{-0.0030}$



(Dp+Yp)　Matsumoto et al. 2022



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What is the Hubble tension?

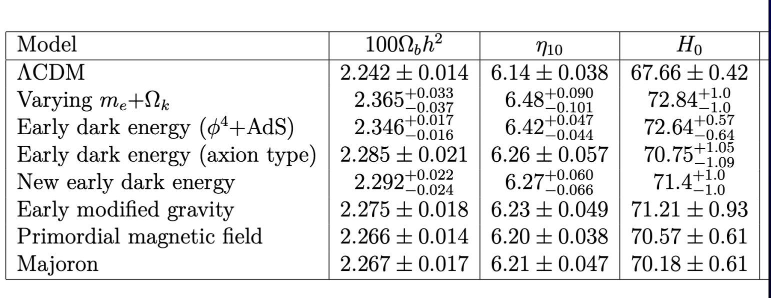
$\star$ 4σ difference between direct and indirect measurement.

Direct measurement	*Indirect measurement*
$H_0 = 73.04 \pm 1.04$ km/s/Mpc	$H_0 = 67.66 \pm 0.42$ km/s/Mpc

→ Many modified models are proposed to resolve the Hubble tension.

Models to resolve the Hubble tension

Modified ΛCDM models affect the baryon abundance.



Model	$100\Omega_b h^2$	η_{10}	H_0
ΛCDM	2.242 ± 0.014	6.14 ± 0.038	67.66 ± 0.42
Varying m_e+Ω_k	$2.365^{+0.033}_{-0.037}$	$6.48^{+0.090}_{-0.101}$	$72.84^{+1.0}_{-1.0}$
Early dark energy (ϕ^4+AdS)	$2.346^{+0.017}_{-0.016}$	$6.42^{+0.047}_{-0.044}$	$72.64^{+0.57}_{-0.64}$
Early dark energy (axion type)	2.285 ± 0.021	6.26 ± 0.057	$70.75^{+1.05}_{-1.09}$
New early dark energy	$2.292^{+0.022}_{-0.024}$	$6.27^{+0.060}_{-0.066}$	$71.4^{+1.0}_{-1.0}$
Early modified gravity	2.275 ± 0.018	6.23 ± 0.049	71.21 ± 0.93
Primordial magnetic field	2.266 ± 0.014	6.20 ± 0.038	70.57 ± 0.61
Majoron	2.267 ± 0.017	6.21 ± 0.047	70.18 ± 0.61

Takahashi and S.Y. (2022)

A larger baryon abundance is required!!

$$\eta_{10} \overset{\text{def}}{=} n_b/n_\gamma \times 10^{10} > 6.14$$

Models to resolve the Hubble tension

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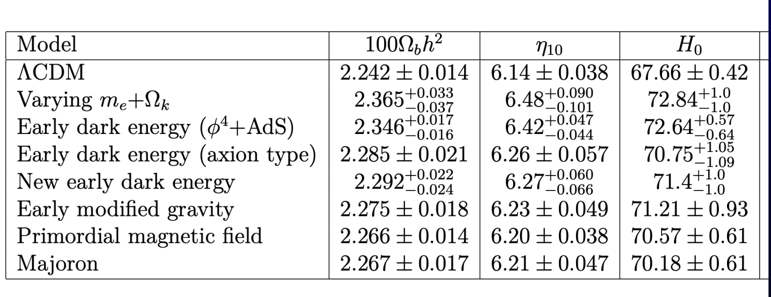

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Analysis

$$\chi^2 = \frac{(Y_p^{\rm obs} - Y_p^{\rm th})^2}{\sigma^2_{Y_p,{\rm obs}} + \sigma^2_{Y_p,{\rm sys}}} + \frac{(D_p^{\rm obs} - D_p^{\rm th})^2}{\sigma^2_{D_p,{\rm obs}} + \sigma^2_{D_p,{\rm sys}}} + \frac{(\eta_{10}^{\rm ref} - \eta_{10})^2}{\sigma^2_{\eta_{10}}}$$

$$Y_p^{\rm obs} = 0.2379,\ \sigma_{Y_p,{\rm obs}} = 0.0031,\ \sigma^2_{Y_p,{\rm sys}} = (0.0003)^2 + (0.00012)^2$$

$$D_p^{\rm obs} = 2.527 \times 10^{-5},\ \sigma_{D_p,{\rm obs}} = 0.030 \times 10^{-5},\ \sigma^2_{D_p,{\rm sys}} = (0.05 \times 10^{-5})^2$$

We consider two cases for the prior on η_{10}:

$$\eta_{10}^{\rm ref,1} = 6.14, \qquad \sigma_{\eta_{10},1} = 0.038,$$

$$\eta_{10}^{\rm ref,2} = 6.40, \qquad \sigma_{\eta_{10},2} = 0.060.$$

Helium and Deuterium abundances

Observational value of $Y_p \cdots$ Matsumoto et al. (2022):

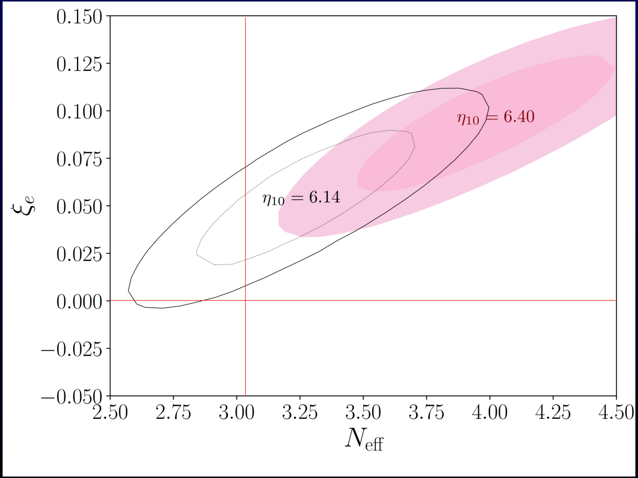
$$Y_p = 0.2379^{+0.0031}_{-0.0030}.$$

Observational value of $D_p \cdots$ Cooke et al. (2018):

$$D_p = (2.527 \pm 0.0030) \times 10^{-5}.$$

Theoretical errors $\sigma_{Y_p,\mathrm{sys}}$ & $\sigma_{D_p,\mathrm{sys}}$ are determined with neutron lifetime & model parameters η_{10}.

Effects of baryon density on N_{eff} and ξ_e constraints



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If EDE is present in BBN era, can we resolve the helium anomaly?

Energy density is:

$$\rho_{\text{total}} = \rho_\gamma + \rho_\nu + \rho_{e^+e^-} + \rho_b + \rho_{\text{EDE}}.$$

Energy density affects Hubble parameter:

$$\frac{8\pi G}{3}\rho = H^2 \overset{\text{def}}{=} \left(\frac{\dot{a}}{a}\right)^2 .$$

Thus, effects of ρ_{EDE} on $H(T)$ follow :

$$\rho_{\text{EDE}} > 0 \Rightarrow H_{\text{noEDE}}(T) < H_{+\text{EDE}}(T)$$ (neutron freezes out earlier)

$$\rho_{\text{EDE}} < 0 \Rightarrow H_{\text{noEDE}}(T) > H_{+\text{EDE}}(T)$$ (neutron freezes out later)

EDE models we consider

- ⋆ EDE1 (e.g. Poulin et al. 2018) :

$$\rho_\Lambda = \rho_0 \qquad (T > T_t),$$
$$\rho_\Lambda = \rho_0 \left(\frac{T}{T_t}\right)^n \qquad (T \leq T_t).$$

$n = 6$ is fixed in our computation.

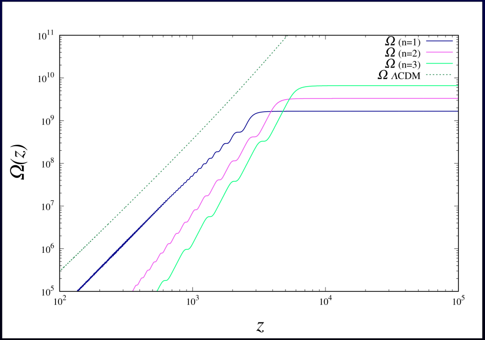
- ⋆ EDE2 (e.g. Ahmed et al. 2002 & Zwane et al. 2017) :

$$\rho_\Lambda = -\rho_0 \qquad (T > T_t),$$
$$\rho_\Lambda = 0 \qquad (T \leq T_t).$$

Parameters are ρ_0 & T_t.

Examples of the EDE (1)

$V_n(\phi) = V_0(1 - \cos(\phi/f))^n$ (Poulin et al. 2018) : “Ultra-light axion-like field.”



Poulin et al. 2018

The field equation shows :

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

Initially, $3H\dot{\phi}$ is dominant. But $dV/d\phi$ increases and come to be dominant gradually.

$$3H\dot{\phi} > \frac{dV}{d\phi} \rightarrow 3H\dot{\phi} < \frac{dV}{d\phi}$$

The reversal starts an energy density dilution.

Examples of the EDE (2)

Ahmed et al. 2002 & Zwane et al. 2017 : "Everpresent Λ"

If spacetime is discrete, its elements' number would depend on Poisson fluctuation :

$$N \sim V \pm \sqrt{V}.$$

While the uncertainty principle would show :

$$\Delta\Lambda \times \Delta V = \Delta\Lambda \times \sqrt{V} \sim 1$$
$$\therefore \Delta\Lambda \sim 1/\sqrt{V} \sim H^2 = \frac{1}{3}\rho_c$$

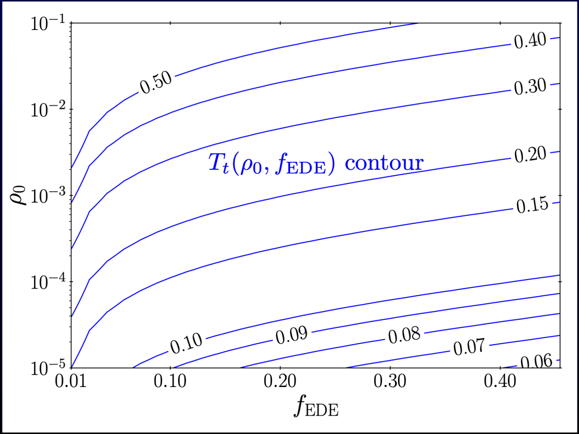
This means negative dark energy of $O(\rho_c)$ can exist with $\langle\Lambda\rangle = 0$.

Definitions of energy density fraction

Energy density fraction f_{EDE} :

$$f_{\mathrm{EDE}} \overset{\mathrm{def}}{=} \left.\frac{\rho_{\mathrm{EDE}}}{\rho_{\mathrm{total}}}\right|_{T=T_t} = \frac{\rho_0}{\rho_0 + \rho_{erB}(T_t)}$$

Two of $\{\rho_0,\ T_t,\ f_{\mathrm{EDE}}\}$ determine the other.



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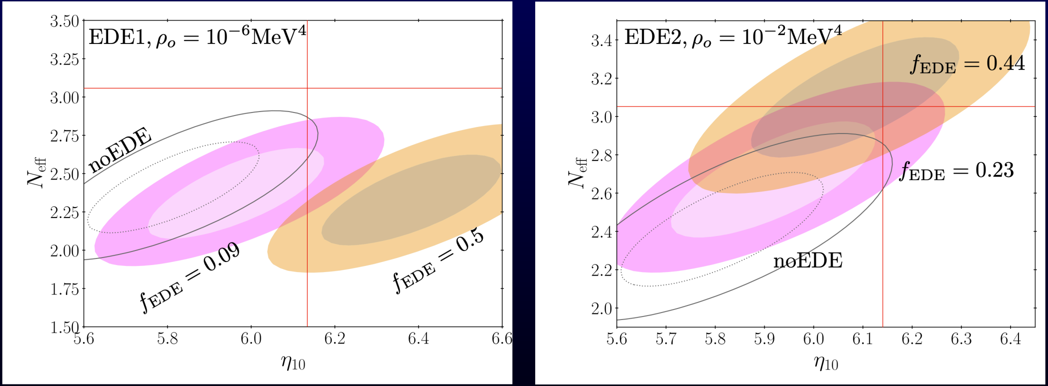
Result: η_{10} vs $N_{\rm eff}$ $(\xi_e = 0)$



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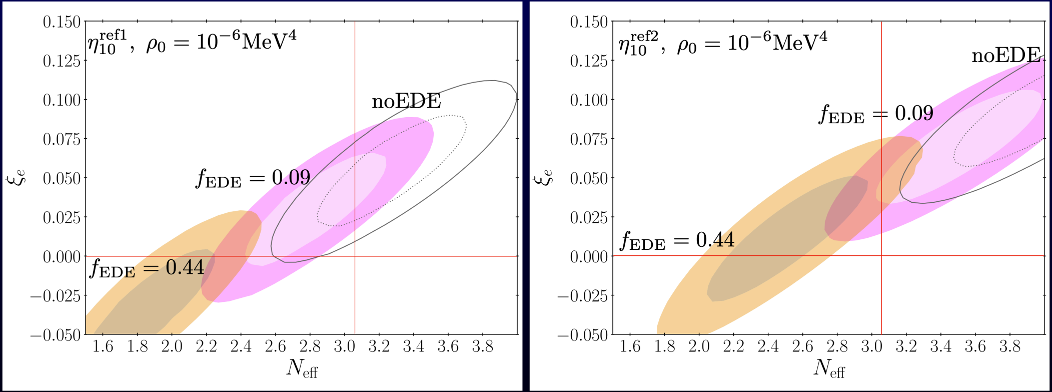
Able to tune the η_{10} value by adding EDEs.

Result: EDE1 N_{eff} vs ξ_e $(\eta_{10}$ prior$)$



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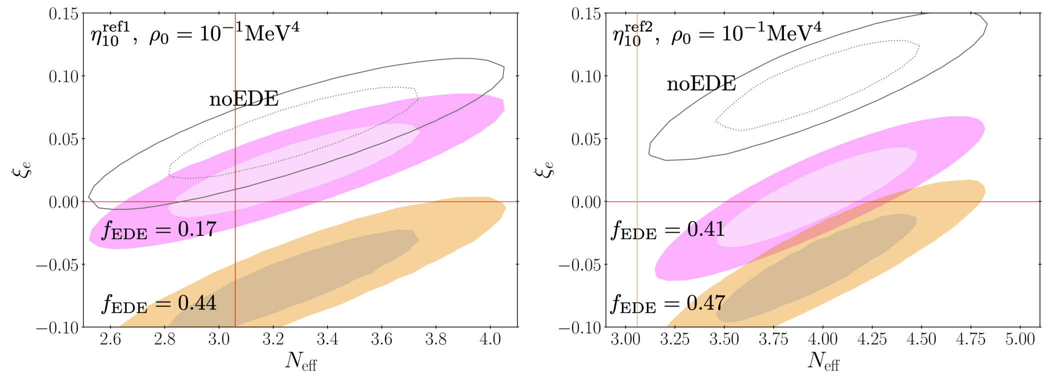
Ether ξ_e or N_{eff} can be fixed to a standard scenario.

Result: EDE2 $N_{\rm eff}$ vs ξ_e (η_{10} prior)



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In $\eta_{10}^{\rm ref1}$ prior, both $N_{\rm eff}$ and ξ_e can be fixed to standard scenario.

In $\eta_{10}^{\rm ref2}$ prior, ξ_e can be fixed to a standard scenario.

Conclusion

- ⋆ Standard parameters cannot explain Empress Y_p observation (Matsumoto et al. 2022).

  $\longrightarrow$ helium anomaly

- ⋆ Modified models to resolve the Hubble tension make η_{10} larger.

- ⋆ An EDE in BBN era makes helium anomaly better.

  Especially, an EDE2 explained observation with standard scenario

$N_{\rm eff} = 3.046, \;\; \xi_e = 0.$

  An EDE1 also explained with either $N_{\rm eff} = 3.046$ or $\xi_e = 0$ fixed.