On the impact of the H_0 tension on the primordial tilt

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In collaboration with
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FO, T. Takahashi, in prep

2023/1/ Yonsei - Saga Partnership Program

Hubble constant (H_0)problem

- Direct measurements

  ex) SH0ES Collaboration

$$H_0 = 73.04 \pm 1.04 \ \text{km/s/Mpc}$$

A.G.Riess et al., Astrophys. J. Lett (arXiv:2112.04510)

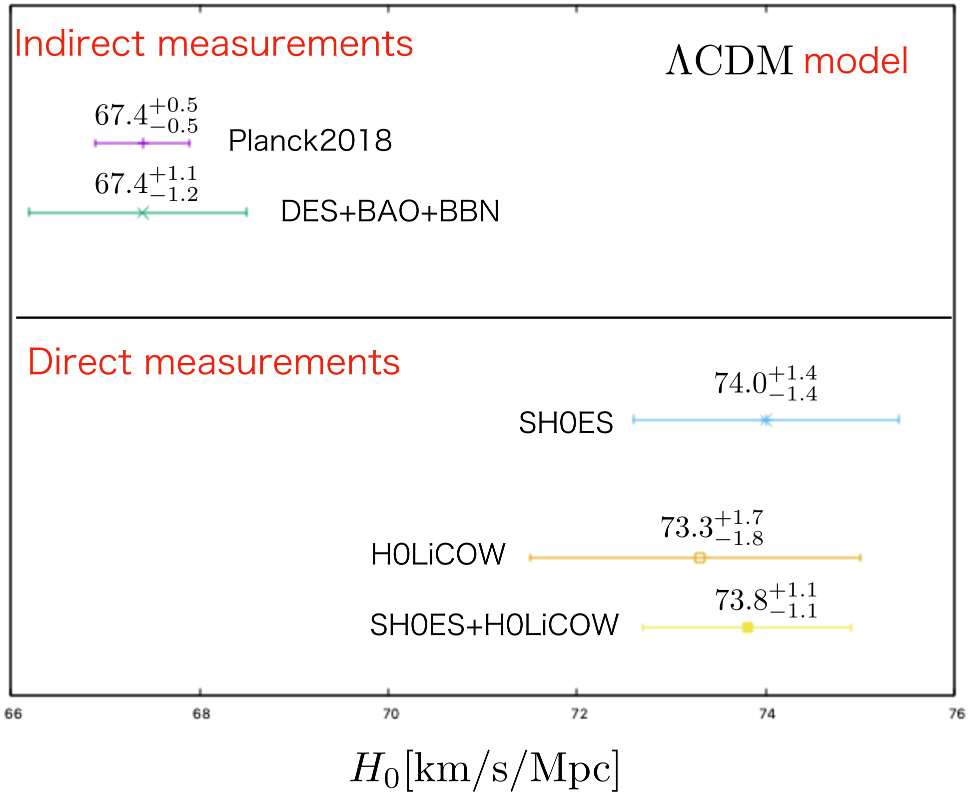
- Indirect measurements

  ex) Cosmic Microwave Background (CMB) ：

$$H_0 \simeq 67.36 \pm 0.54 \ \mathrm{km/s/Mpc}$$

Planck Collaboration., A&A (arXiv:1807.06209)

Wong et al., MNRAS (arXiv1907.04869)



There is a statistically significant tension between direct and indirect measurements

- What's the origin of the tension?
  - Systematic error？ → It may be difficult to explain the origin of the tension because independent measurements are consistent within either direct and indirect ones
  - Need to extend the LCDM model? → Various models have been proposed to solve the H_0tension

Purpose

- Various models have been proposed to solve the H_0 problem

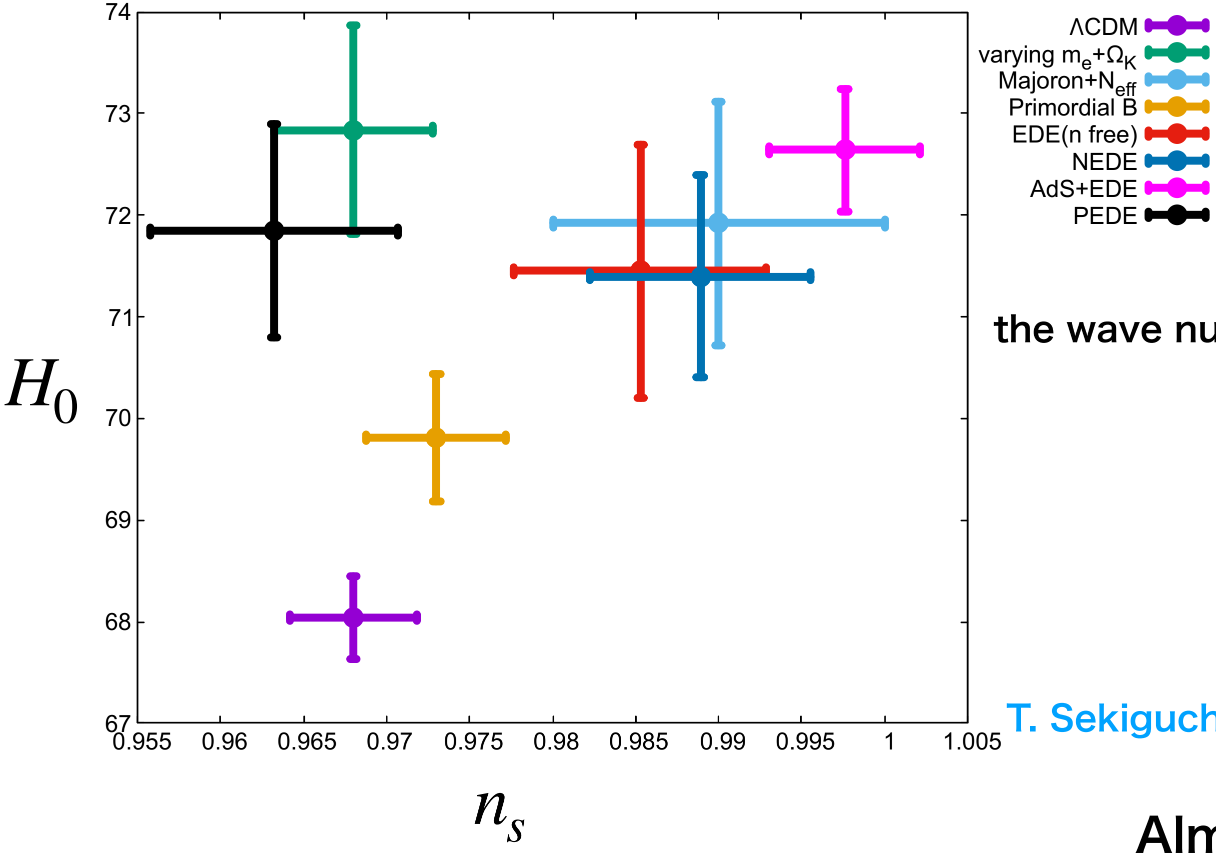
  ex) Early Dark Energy, varying m_e ・・・

  → Such models affect cosmological parameters other than H_0

Purpose

- In particular,

we investigated the effect on the spectral index n_s of the primordial power spectrum



ex) Early Dark Energy

$n_s \simeq 0.98$

T L Smith et al., Phys. Rev. D(arXiv:1908.06995)

the wave number dependence of the primordial power spectrum become almost **scale invariant**

ex) varying $m_e + \Omega_K$ model

$n_s \simeq 0.96$

T. Sekiguchi and T. Takahashi., Phys. Rev. D (arXiv:2007.03381)

Almost the same as for the ΛCDM model

Purpose

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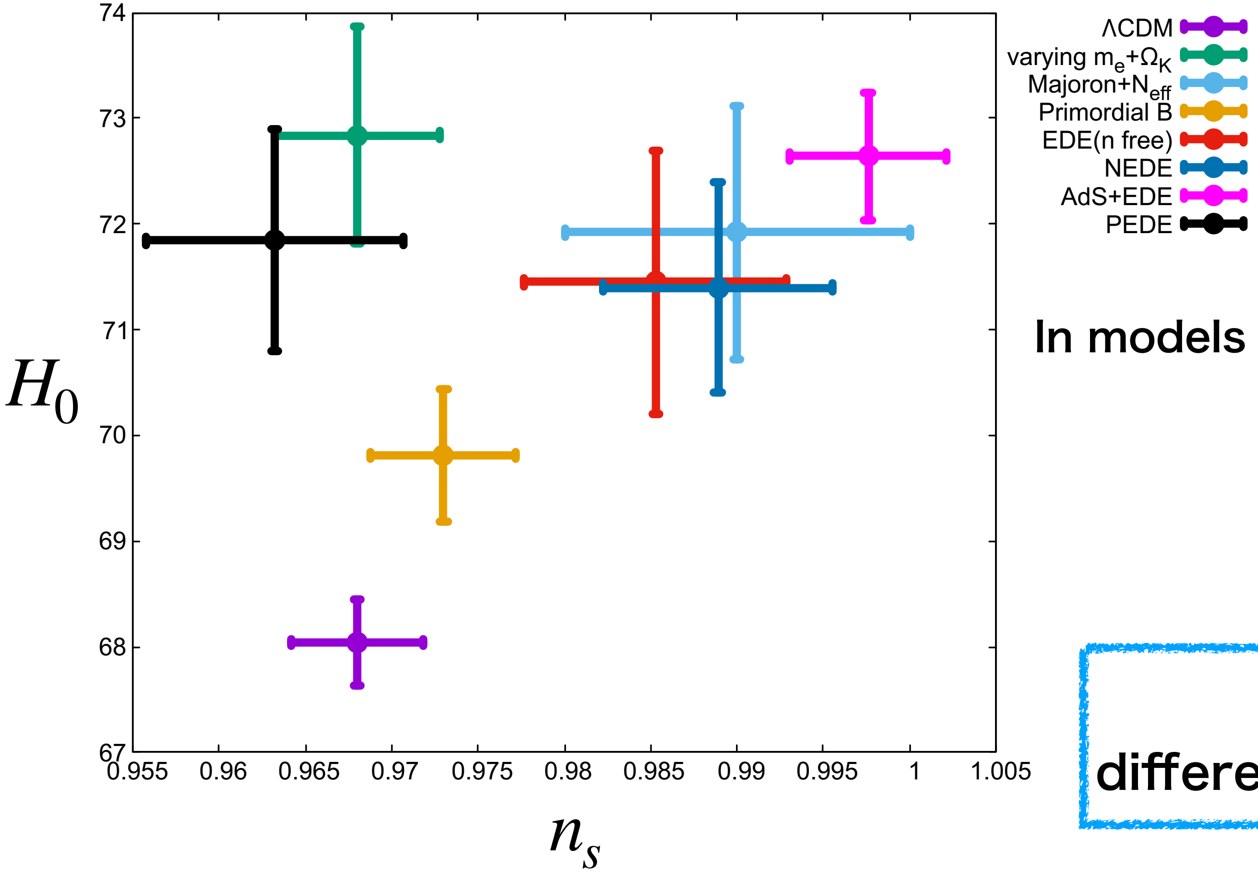
  we investigated the effect on the spectral index n_s of the primordial power spectrum



In models that are supposed to resolve the H_0 tension,

some of them affect n_s

Models are separated by differences of effect on diffusion damping.

Purpose

- Various models have been proposed to solve the H_0 problem

  ex) Early Dark Energy, varying m_{e} ・・・

  → Such models affect cosmological parameters other than H_0

- we investigated the effect on n_s of the primordial power spectrum

  ex) Early Dark Energy $n_s \simeq 0.98$ T L Smith et al., Phys. Rev. D(arXiv:1908.06995)

  the wave number dependence of the primordial power spectrum become almost scale invariant

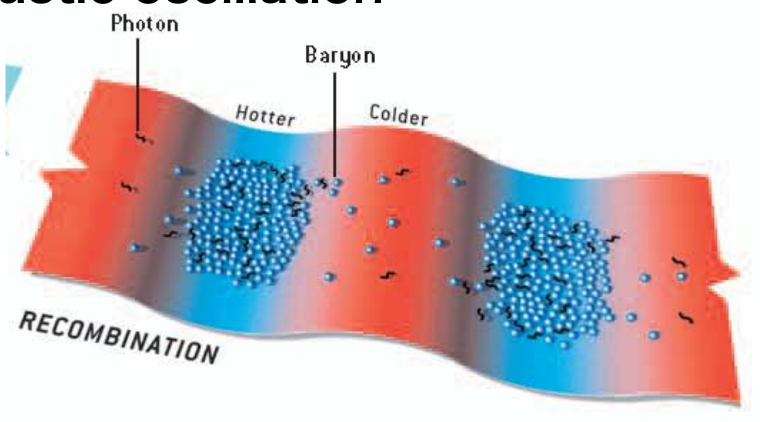
  ex) varying $m_{\mathrm{e}} + \Omega_{\mathrm{K}}$ model $n_s \simeq 0.96$ Almost the same as for the ΛCDM model

  T. Sekiguchi and T. Takahashi., Phys. Rev. D (arXiv:2007.03381)

- We discuss what models influence n_s

Sound horizon

- One of the methods to solve the H_0 problem is decreasing the sound horizon at the recombination period.
- sound horizon
  - In the early universe, baryons and photons behave as mixed fluid
  - The mixed fluid participate in acoustic oscillation
  - The sound horizon is the distance
    at which fluctuations propagate as waves of acoustic oscillation



$$r_s = \int_0^t \frac{c_s}{a} dt \quad = \frac{1}{\sqrt{3}} \int_0^a \frac{1}{\sqrt{1+R}} \frac{da'}{a'^2 H}$$

$$R = \frac{3}{4} \frac{\bar{\rho}_b}{\bar{\rho}_\gamma}$$

c_s : the sound speed of the mixed fluid

http://background.uchicago.edu/~whu/SciAm/sym3b.html

Diffusion damping (Silk damping)

- In photon decoupling, photons diffuse in a random walk, and fluctuations below the diffusion scale erase

➡ **Diffusion damping or Silk damping**

- k_D : Wave number of the scale at which diffusion damping becomes effective

$$[k_D(\tau)]^{-2} \equiv \frac{1}{6}\int \frac{\tau_c}{1+R}\left(\frac{16}{15}+\frac{R^2}{1+R}\right)d\tau$$

$\tau_c \equiv 1/an_e\sigma_T$: optical depth

n_e : the number density of electrons σ_T : Thomson scattering cross-section

➡ The amplitude of acoustic oscillation is significantly damp on small scales for wave numbers larger than k_D.

The ratio $1/k_D(=\lambda_D)$ to sound horizon r_{s*} determines the damping scale

Example 1) Early Dark Energy (EDE) model

- Introduce a scalar field
- increase the total energy density before the recombination era due to the additional contribution from the scalar field
- Therefore the sound horizon decreases and H_0 increases

$$H(z) = H_0\sqrt{\Omega_{\rm m}(z) + \Omega_{\rm r}(z) + \Omega_\Lambda + \Omega_\phi(z)}$$

The additional contribution from the scaler field

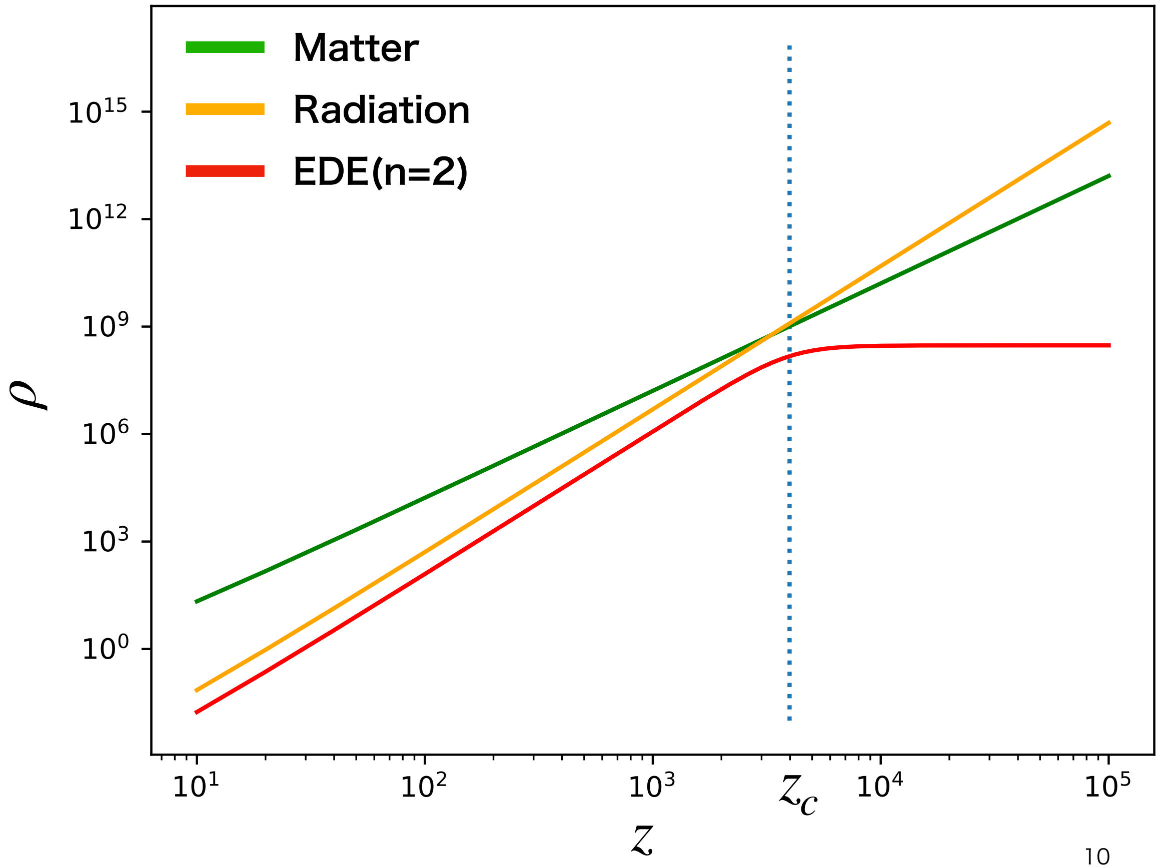
$$r_s = \int_z^\infty \frac{c_s dz'}{H(z')}$$

Adding a scalar field leads to an increase of $H(z)$

- In general, we introduce a scalar field with the potential $V \propto (1+\cos\Theta)^n$

Example 1) Early Dark Energy (EDE) model

we use a model discussed in Poulin et al, **Phys. Rev. D (arXiv:1806.10608)**



Example 2) Varying m_e model

T. Sekiguchi and T. Takahashi., Phys. Rev. D (arXiv:2007.03381)

- we consider the time-varying electron mass m_e
- A model that attempts to solve the H_0 problem
  by making the recombination epoch earlier with a larger m_e

- The energy level of hydrogen R_g is proportional to m_e $\quad R_g \propto m_e$
- The recombination temperature is determined by R_g $\quad R_g \propto T_{\gamma *}$

$$\left.\begin{array}{l} R_g \propto m_e \\ R_g \propto T_{\gamma *} \end{array}\right\} m_e \propto T_{\gamma *} \propto \frac{1}{a_*}$$

$$r_s(z_*) = \frac{1}{\sqrt{3}} \int_0^{a_*} \frac{1}{\sqrt{1+R}} \frac{da}{a^2 H}$$

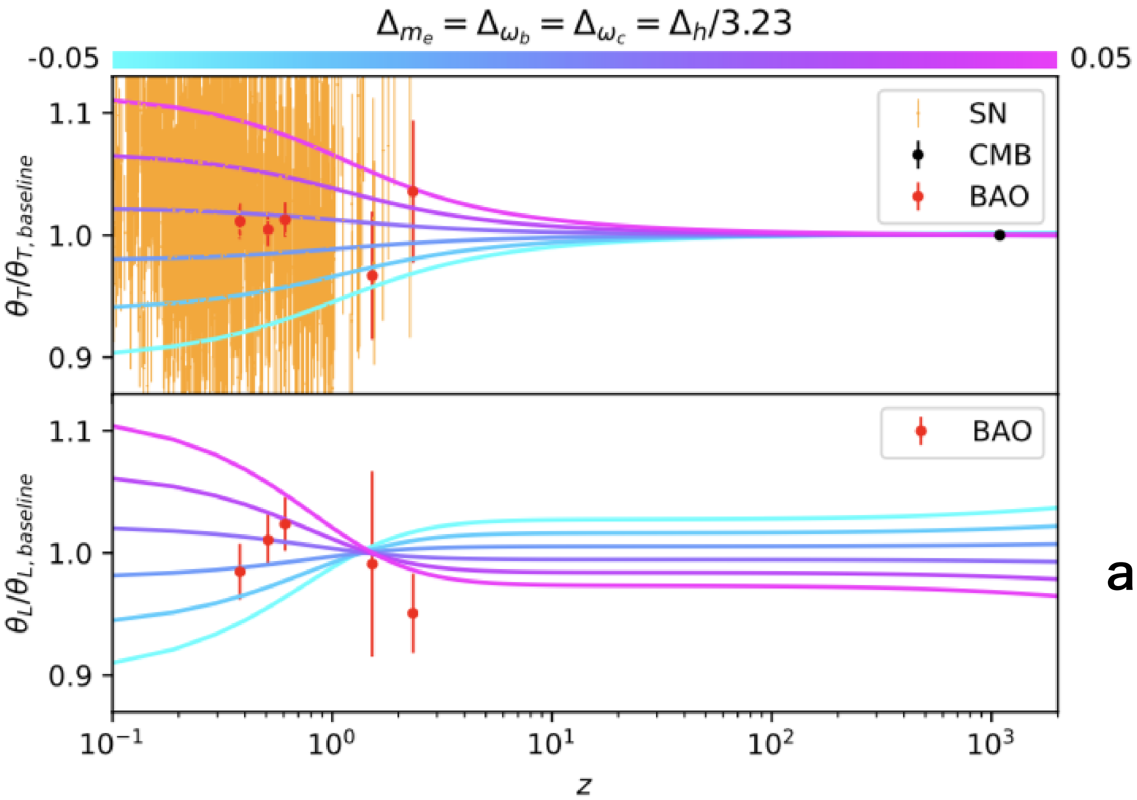
($*$: recombination era)

In the varying m_e model, we show the fit to BAO, and other low-z distance measures

Example 2) Varying $m_e + \Omega_K$ model

BAO scale measured along the horizontal and line-of-sight directions, respectively

$$\theta_T(z) \equiv \frac{r_s(z_*)}{D_M(z)}, \quad \theta_L(z) \equiv r_s(z_*)H(z)$$



In varying m_e model,

combine CMB with BAO/SNeIa

Even if m_e increases,

CMB is not affected by adjusting other cosmological parameters, but the fit to BAO is not good

$$\Delta_{m_e} = \log(m_e/m_{e,\mathrm{baseline}})$$

T. Sekiguchi and T. Takahashi., Phys. Rev. D (arXiv:2007.03381)

Example 2) Varying $m_e + \Omega_K$ model

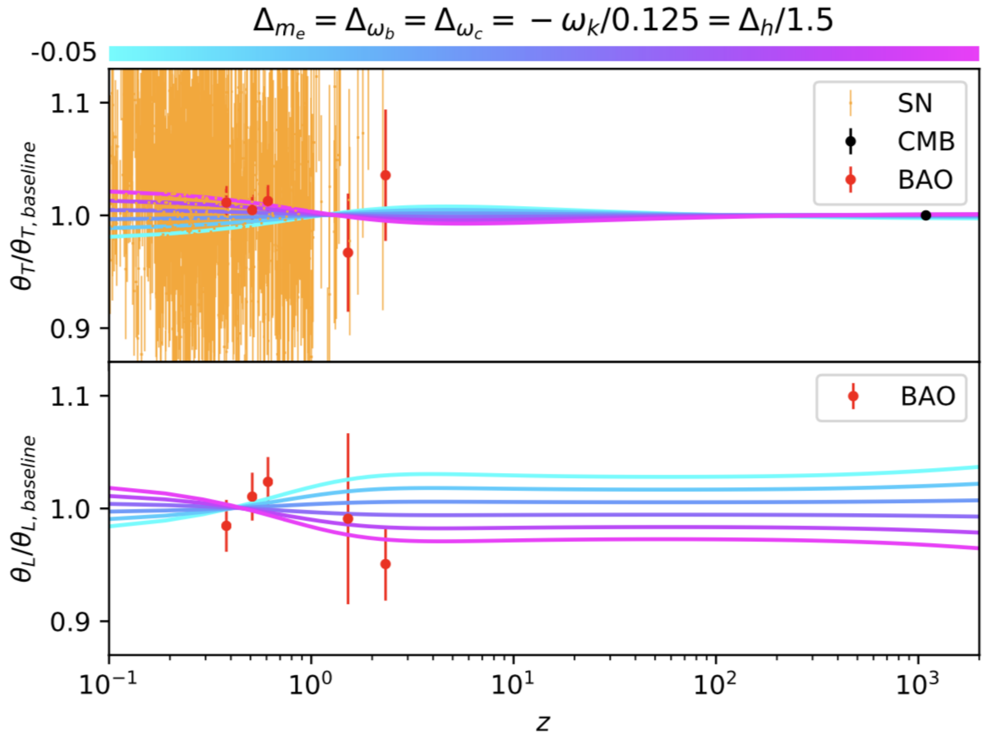
Extending the background model from the ΛCDM model gives an even better fit while achieving a larger H_0

When $\Omega_K \neq 0$(varying $m_e + \Omega_K$)

$$D_M(z) = \begin{cases} \chi(z) = \int_0^z \frac{dz'}{H(z')} & \Omega_K = 0 \text{ (flat)} \\ \frac{1}{\sqrt{-\Omega_K} H_0} \sin[\sqrt{-\Omega_K} H_0 \chi(z)] & \Omega_K < 0 \text{ (closed)} \\ \frac{1}{\sqrt{\Omega_K} H_0} \sinh[\sqrt{\Omega_K} H_0 \chi(z)] & \Omega_K > 0 \text{ (open)} \end{cases}$$

When $\Omega_K < 0$,

➡ **this model can solve the H_0 problem**



T. Sekiguchi and T. Takahashi., Phys. Rev. D (arXiv:2007.03381)

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$$\left.\begin{array}{l} R_g \propto m_e \\ R_g \propto T_{\gamma *} \end{array}\right\} m_e \propto T_{\gamma *} \propto \frac{1}{a_*}$$

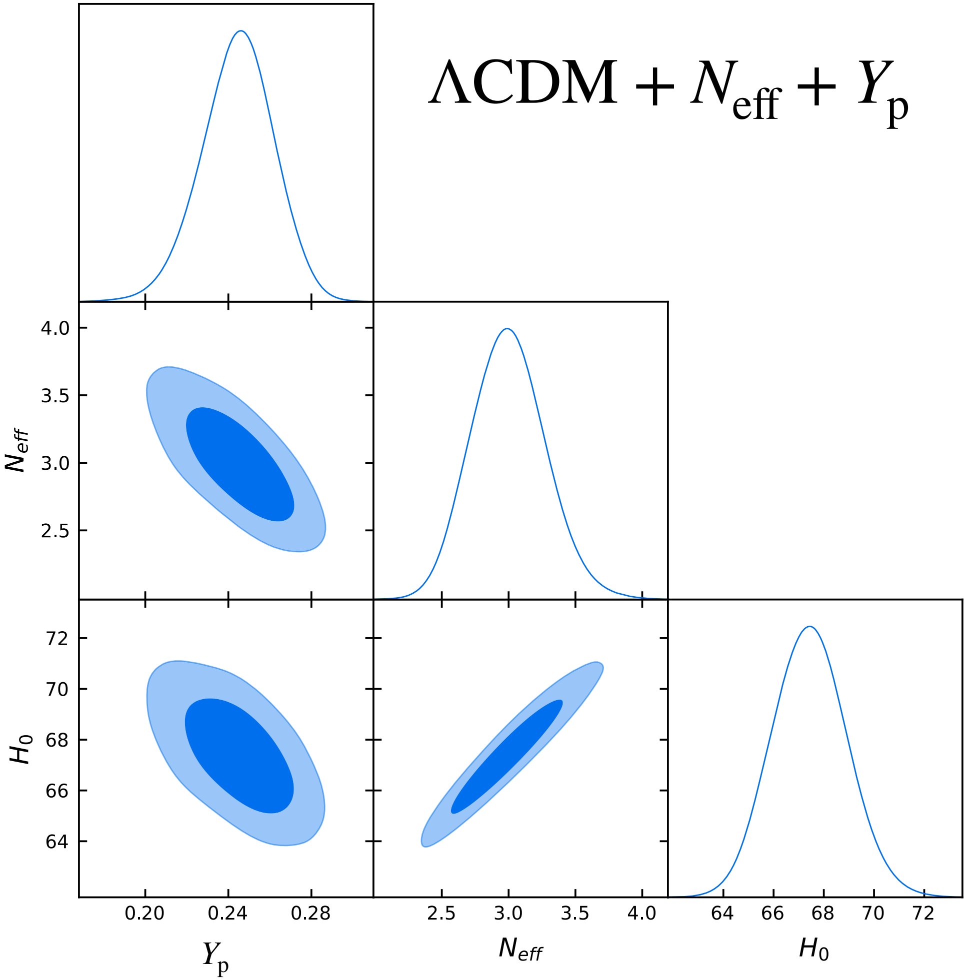
$$r_s(z_*) = \frac{1}{\sqrt{3}} \int_0^{a_*} \frac{1}{\sqrt{1+R}} \frac{da}{a^2 H}$$

($*$: recombination era)

We consider varying m_e + Ω_K proposed by

T. Sekiguchi and T. Takahashi., Phys. Rev. D (arXiv:2007.03381)

Example 3) ΛCDM+$N_{\rm eff}$ ($Y_{\rm p} = 0.16,\ 0.18$)



We consider a **"Toy model"** fixing $Y_{\rm p} = 0.16,\ 0.18$

to get a larger H_0

※we use as a simple example to solve the H_0 problem

In the analysis of ΛCDM+$N_{\rm eff} + Y_{\rm p}$

smaller helium-4 abundance

→ larger the effective species of neutrino ($N_{\rm eff}$)

→ Larger the Hubble constant(H_0)

Analysis

- the Markov chain Monte Carlo method (MCMC) (CosmoMC)
    - Planck 2018 (including TTTEEE and lensing) N. Aghanim et al. , A&A (arXiv:1807.06209)
- BAO
    - SDSS-III BOSS DR12 galaxy samples (z=0.38, 0.51, 0.61) S. Alam et al., MNRAS (arXiv:1607.03155)
    - SDSS DR7 Main Galaxy Sample (z=0.15) J. Ross et al, . MNRAS (arXiv:1409.3242)
    - 6dF Galaxy Survey F. Beutler et al., MNRAS (arXiv:1106.3366)
- SNeIa
    - Pantheon sample D. M. Scolnic et al., ApJ (arXiv:1710.00845)
- H_0 prior

$H_0 = 74.03 \pm 1.42$ km/s/Mpc Riess et al., Astrophys. J. (arXiv:1903.07603)

Result(ΛCDM model)

- **Derived parameters**

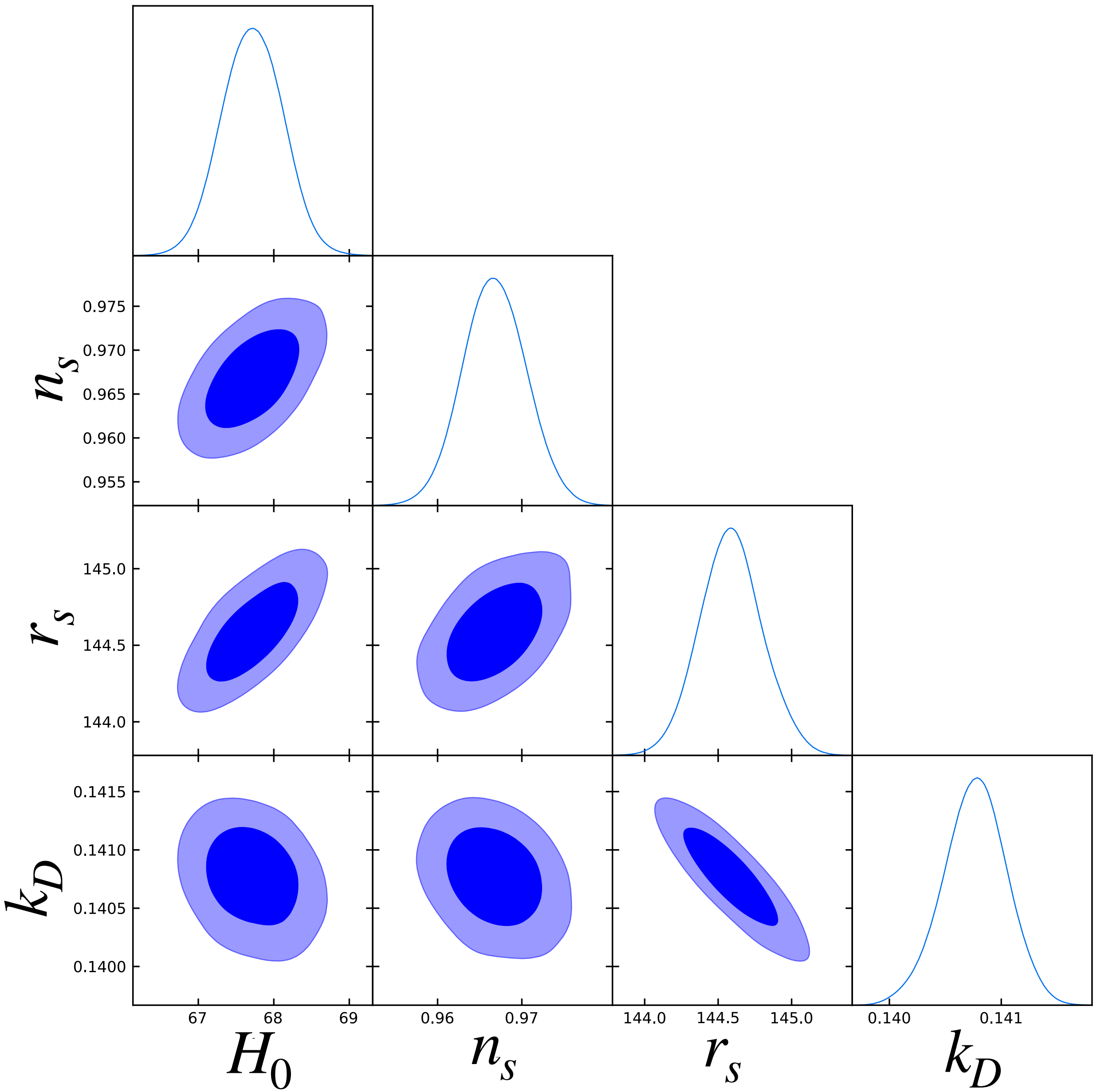
$$H_0 = 67.71 \pm 0.40, \quad n_s = 0.967 \pm 0.0038$$

$$r_{s*} = 144.59 \pm 0.212, \quad k_D = 0.141 \pm 0.0003$$

k_D : Wave number of the scale at which diffusion damping becomes effective

⬇

We compare other models with the ΛCDM model



Result(EDE (n=2) model)

- Derived parameters

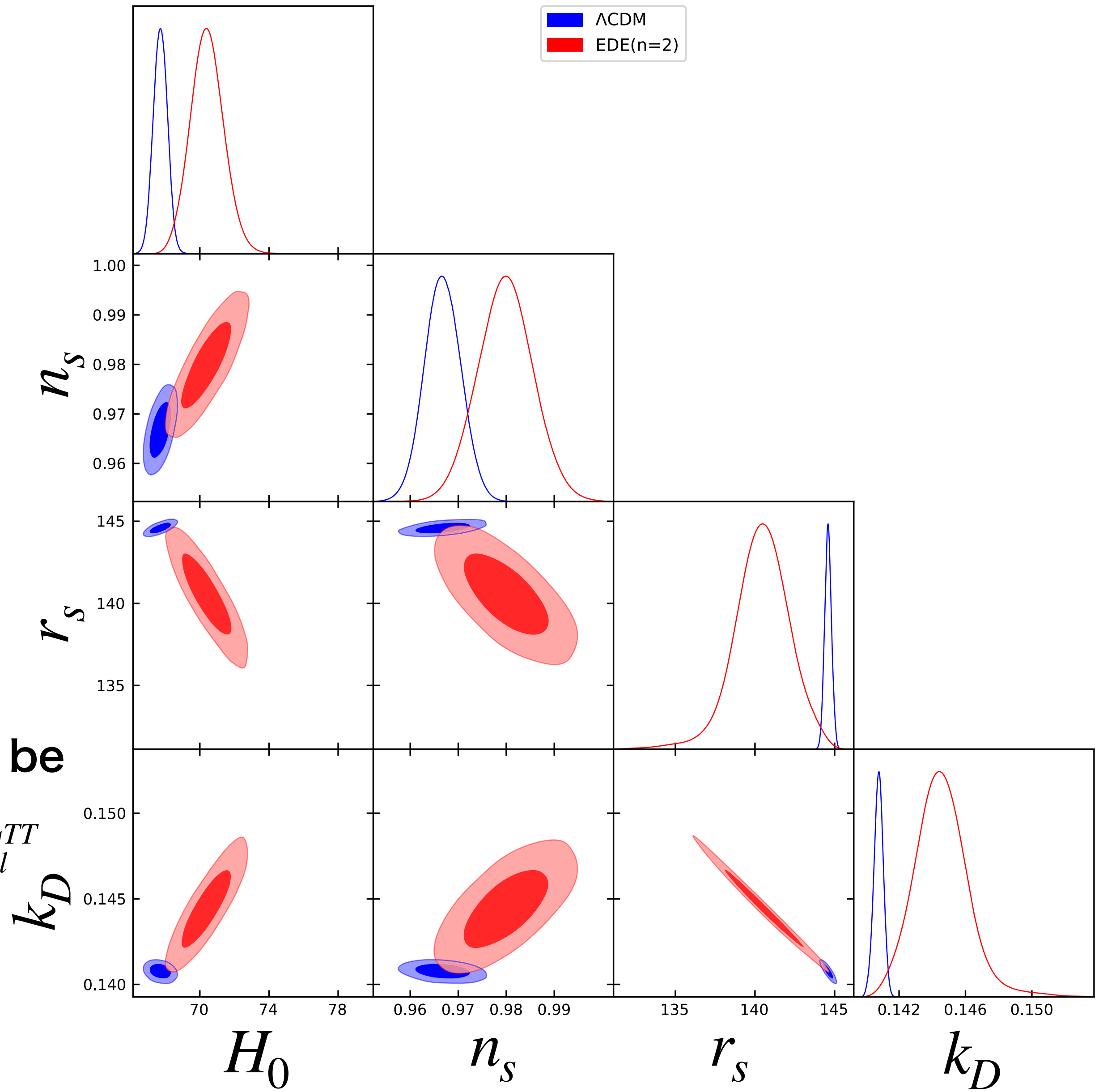
$H_0 = 70.42 \pm 0.92, \quad n_s = 0.980 \pm 0.0056$

$r_{s*} = 140.47 \pm 1.59, \quad k_D = 0.144 \pm 0.0015$

⬇

EDE model gives a larger value of n_s

we explain that the value of n_s needs to be large using the CMB power spectrum C_l^{TT}



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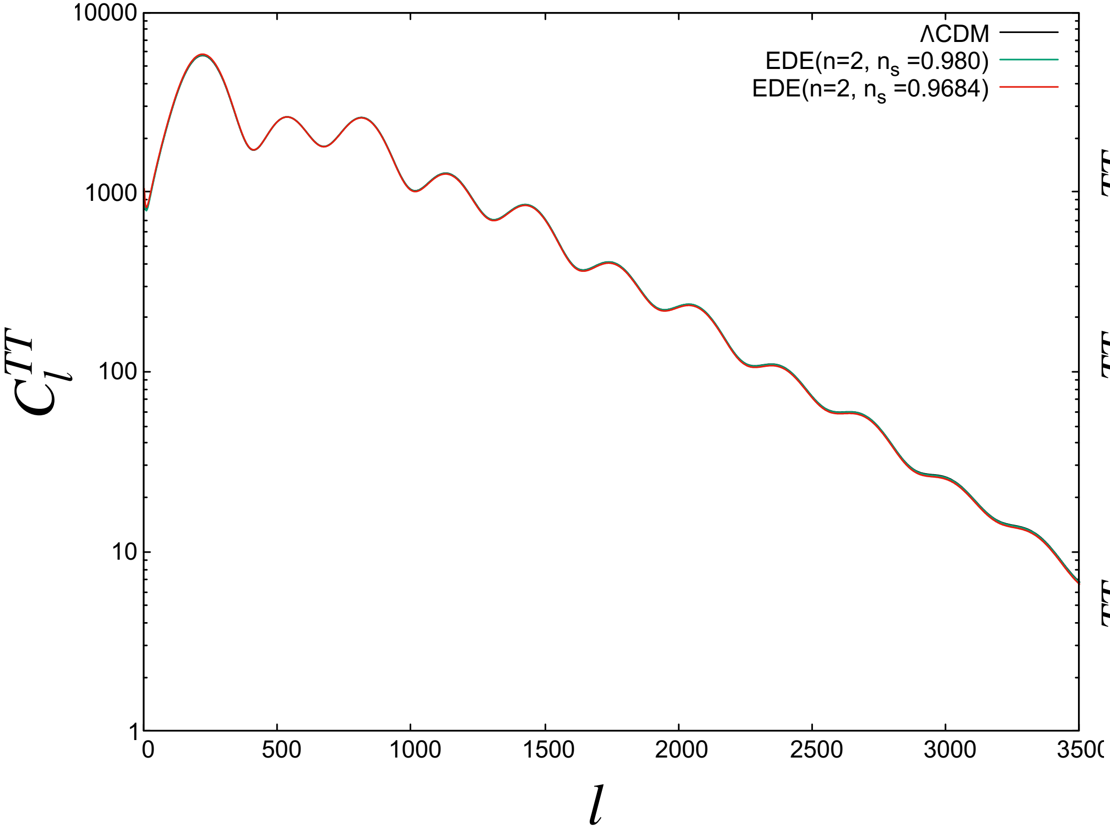
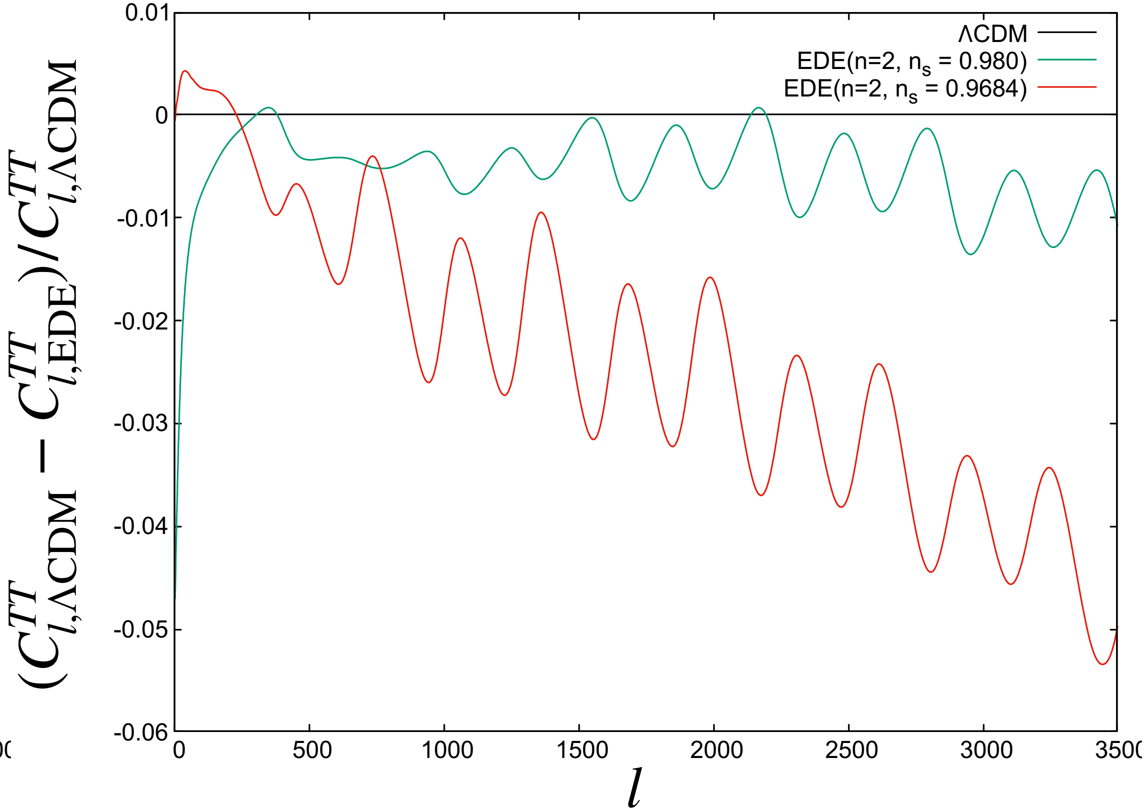




➡ The EDE model affects only r_s

keeping the fit to CMB by increasing n_s

Result(varying $m_e + \Omega_K$ model)

- Derived parameters

$H_0 = 72.84 \pm 1.04,$ $n_s = 0.968 \pm 0.0048$

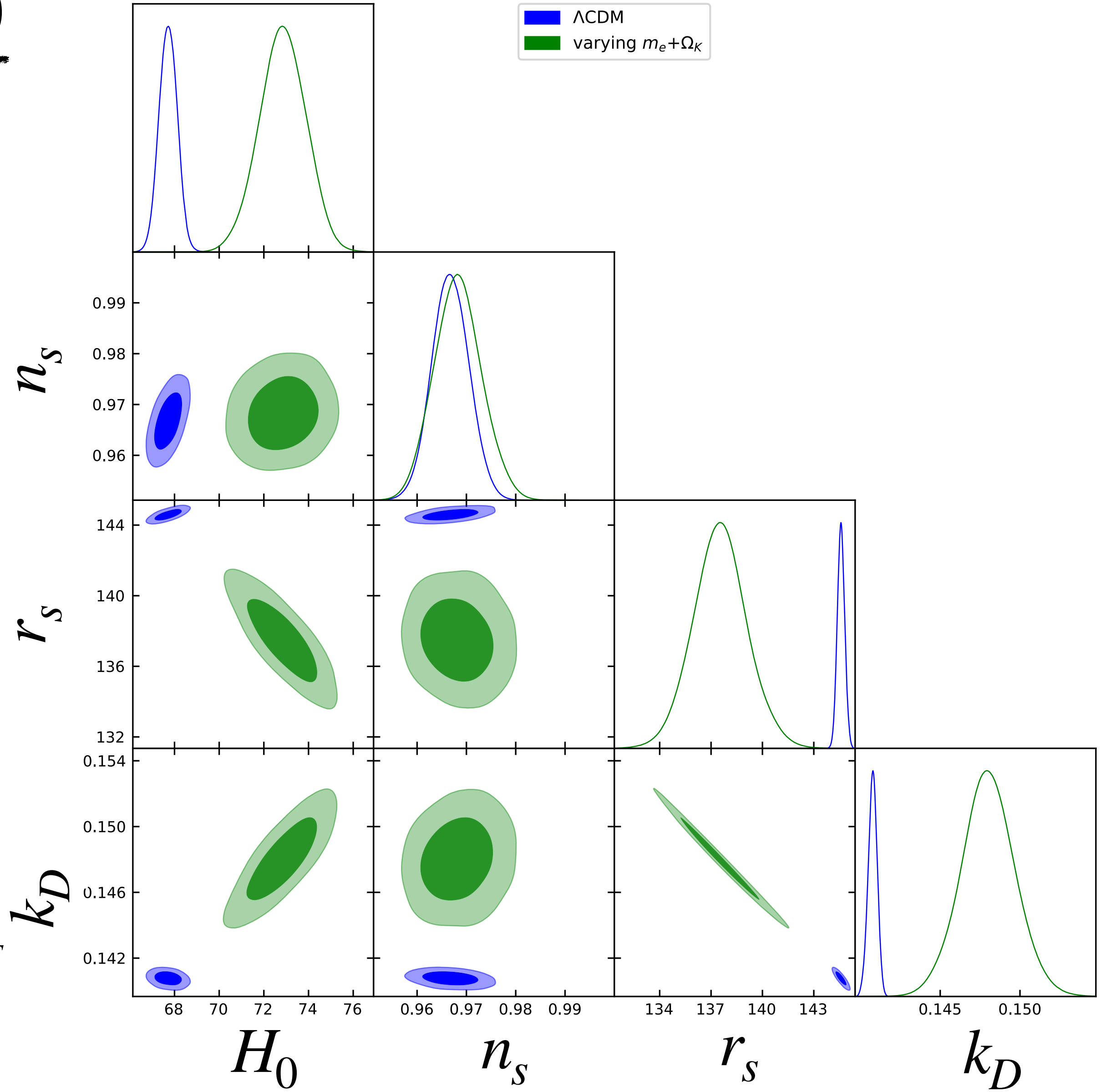
$r_{s*} = 137.52 \pm 1.57,$ $k_D = 0.148 \pm 0.0017$

n_s is almost the same as ΛCDM

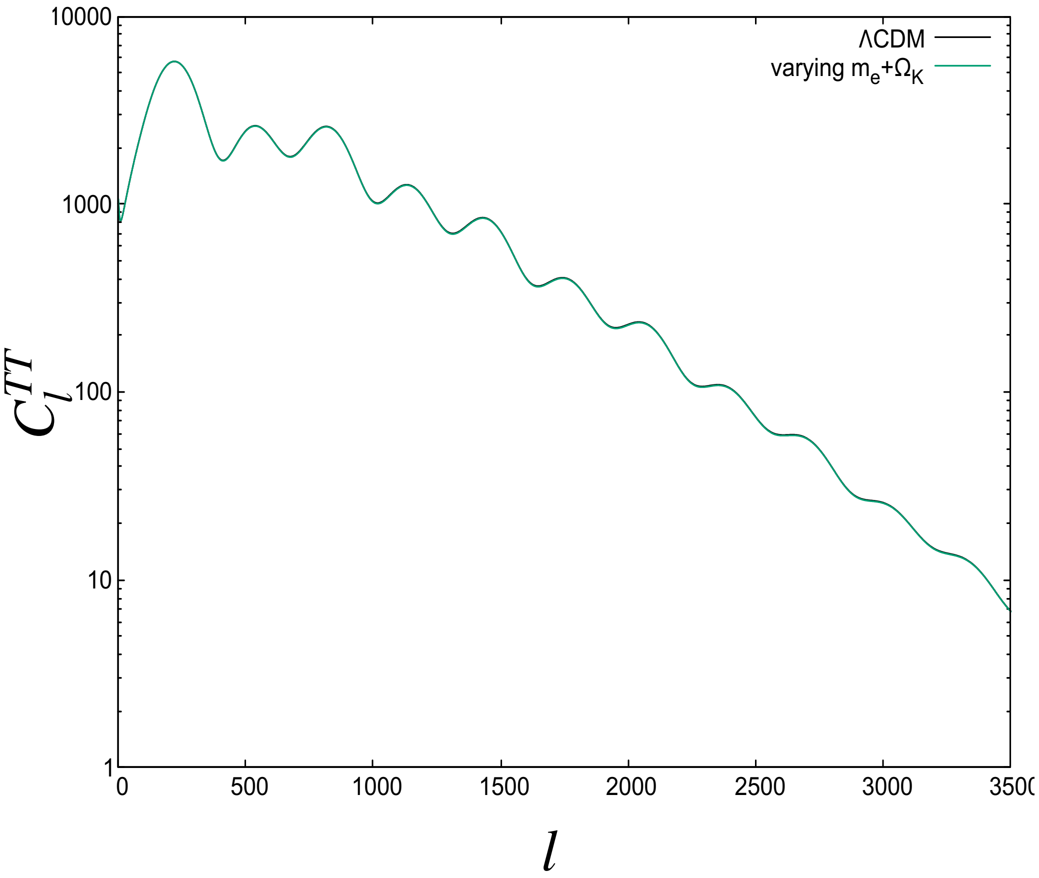
k_D becomes larger compared to ΛCDM

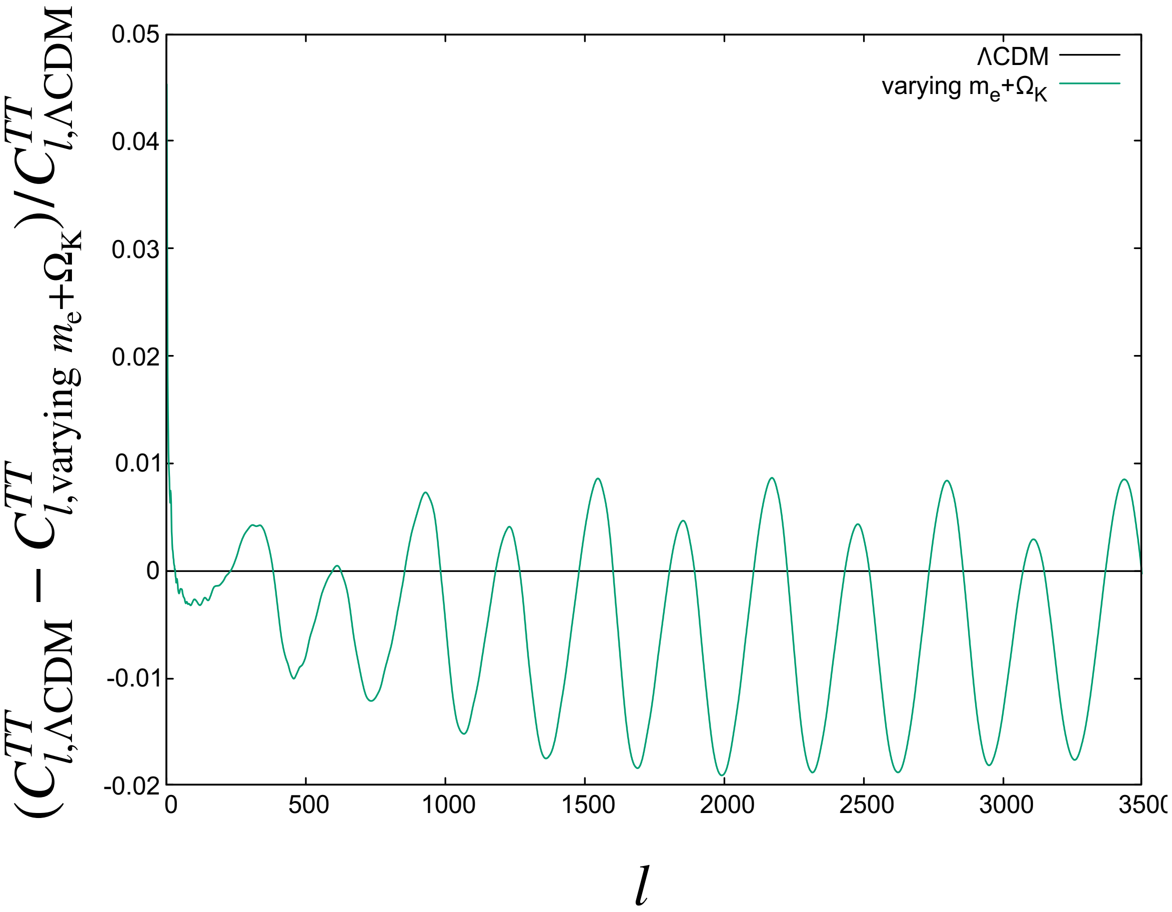
We show the CMB power spectrum C_l^{TT}

In this model



Result(varying $m_e + \Omega_K$ model)





→ n_s doesn't need to be increased due to the increase k_D

Result(ΛCDM+$N_{\rm eff}$ ($Y_{\rm p} = 0.16,\ 0.18$))

- obtained parameters

- $Y_{\rm p} = 0.16$

$H_0 = 71.90 \pm 1.39,\quad n_s = 0.961 \pm 0.0069$

$r_{s*} = 136.79 \pm 1.98,\quad k_D = 0.149 \pm 0.0018$

- $Y_{\rm p} = 0.18$

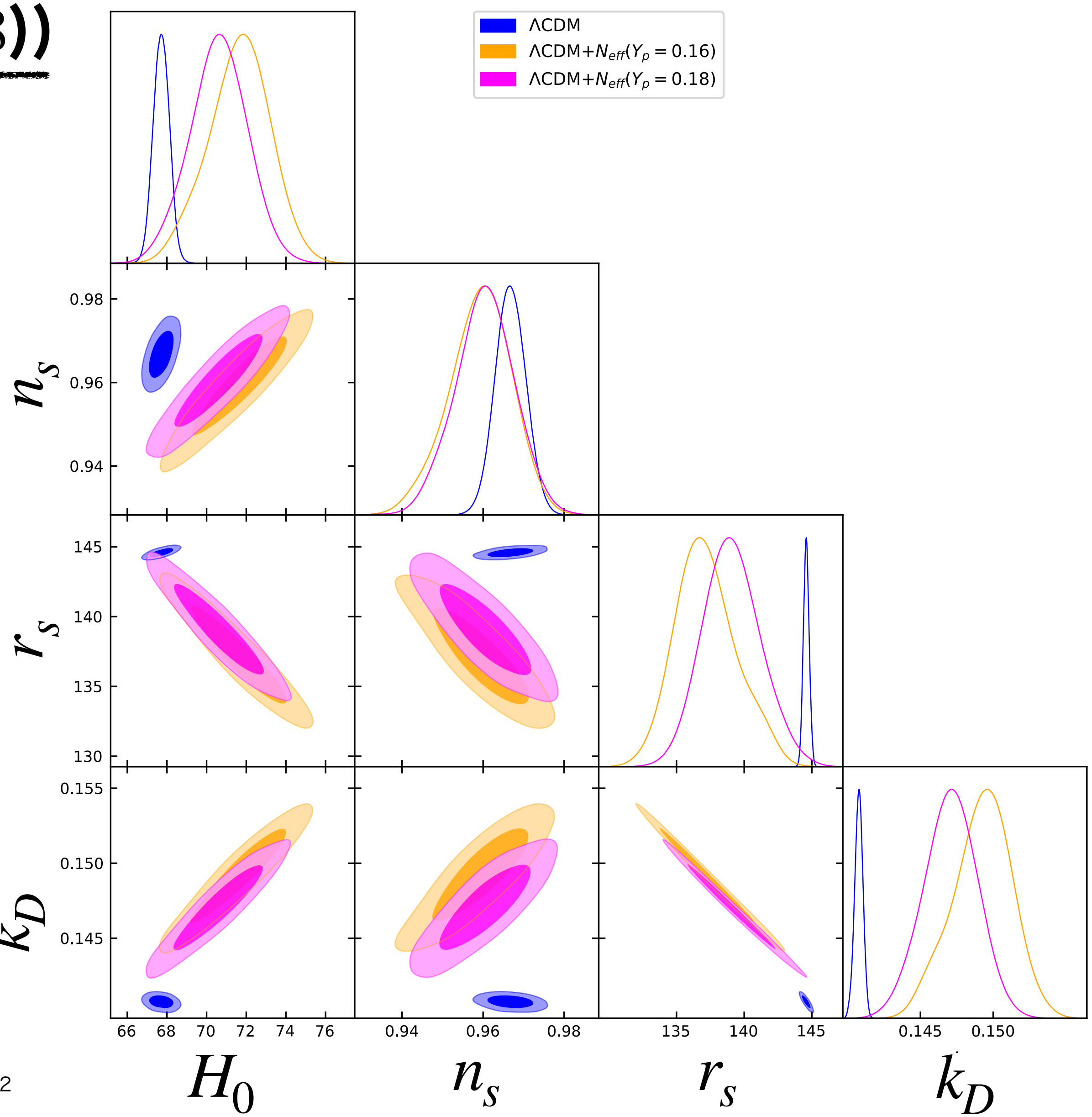
$H_0 = 70.78 \pm 1.39,\quad n_s = 0.961 \pm 0.0070$

$r_{s*} = 138.80 \pm 2.00,\quad k_D = 0.147 \pm 0.0017$

n_s is almost the same as ΛCDM model

k_D gives a larger value

compared to ΛCDM



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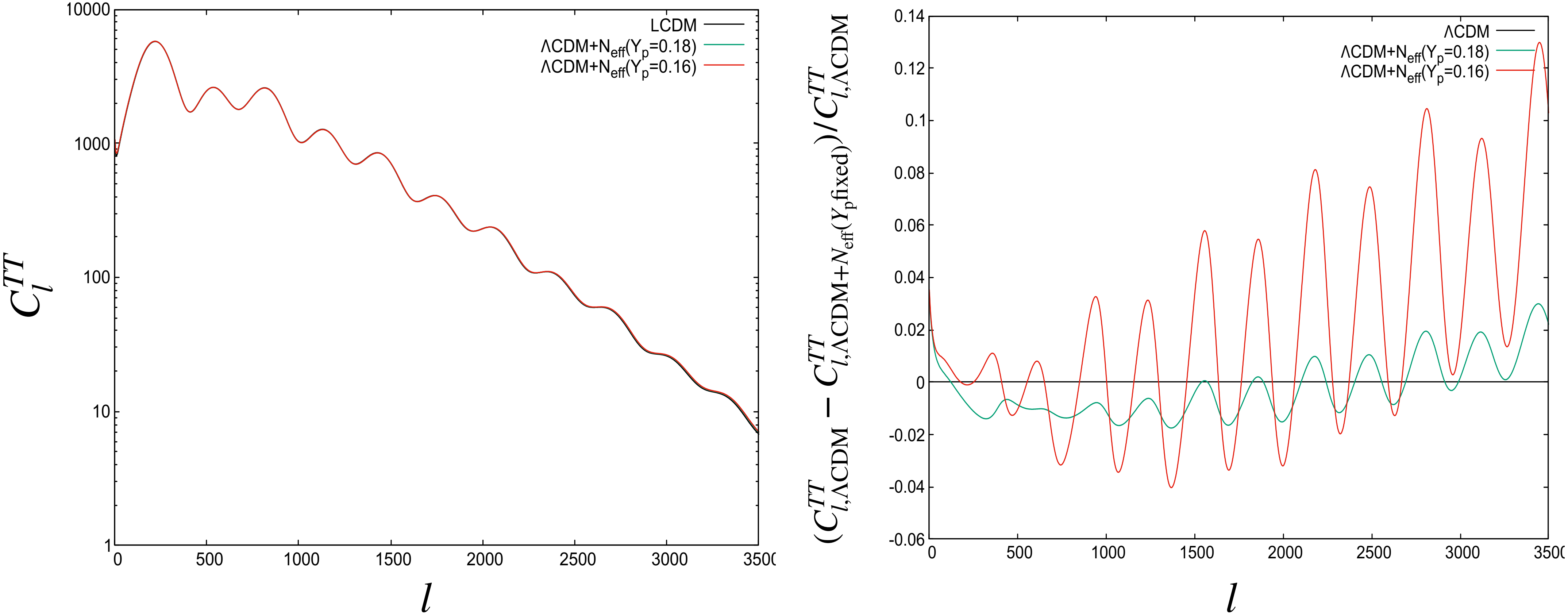
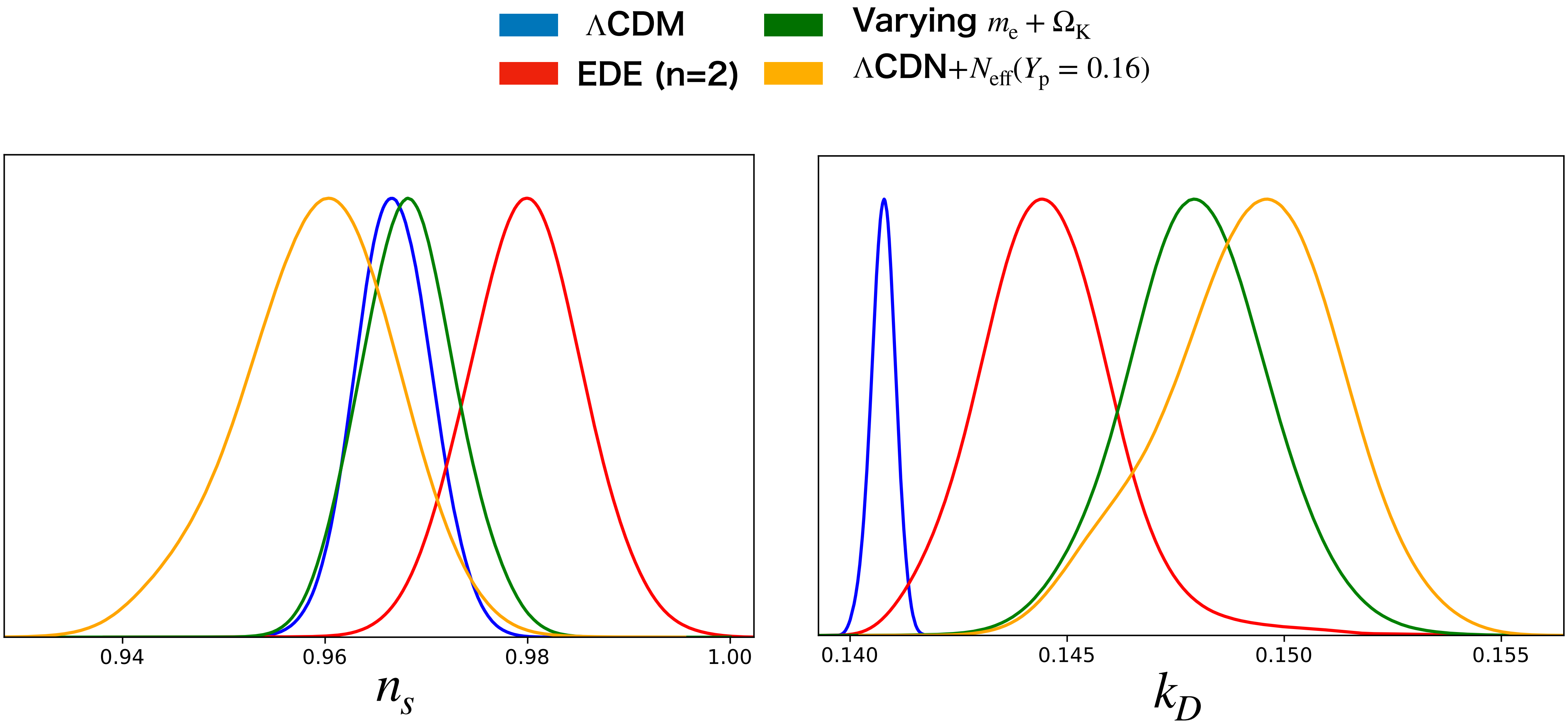


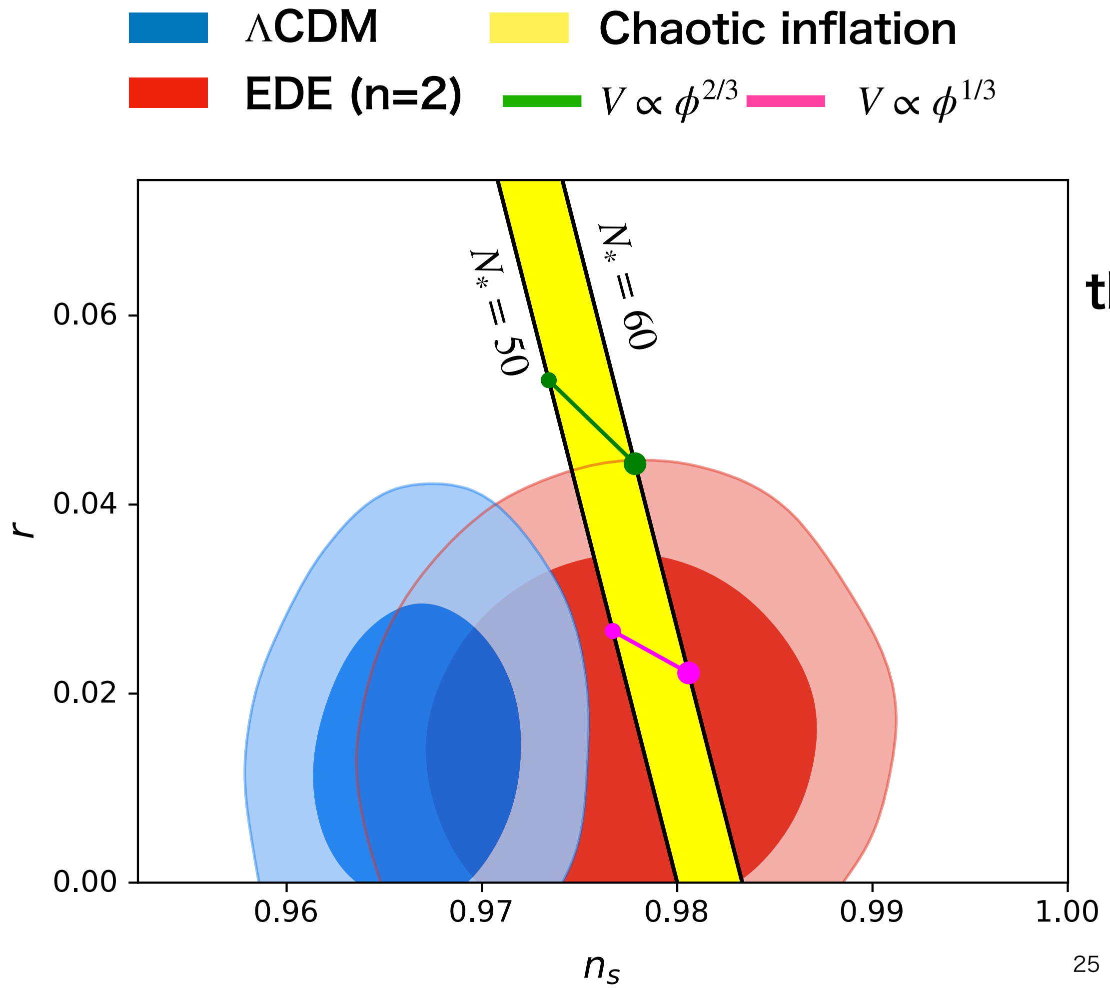
→ n_s doesn't need to be increased due to the increase of k_D

Result (plot summary)



Result (n_s – r plot)

- The bottom figure shows the n_s – r plot for the EDE (n=2) model



Compared to the ΛCDM model,
the EDE model obtains a larger value of n_s

In the model which
obtains a larger value of n_s ・・・

Such a model could allow
Some chaotic inflation model

Conclusion

- We investigated the effect on the spectral index n_s of the primordial power spectrum in a model suggested to solve the H_0 problem

- Models that can solve the H_0 problem are classified as follows:

  - Models which obtain a larger value of n_s
  - Models that can obtain almost the same n_s value as ΛCDM

  → The difference of effects on diffusion damping

- Models that obtain a larger value of n_s could allow some chaotic inflation model

Thank you for your attention!

Example) varying m_e

Barrow, John D. and Magueijo, Joao., Phys. Rev. D (arXiv:astro-ph/0503222)

- Dynamical electron mass
  - Dirac lagrangian $\mathscr{L}_\Psi = i\bar{\Psi}\gamma^\mu\partial_\mu\Psi - m\bar{\Psi}\Psi$
    - "dilaton" field ϕ control electron mass $m = m_0 \exp \phi$ m_0 : current electron mass

$\longrightarrow$ Consider the varying m_e

- Dirac equation with varying mass $(i\gamma^\mu\partial_\mu - m)\Psi = 0$

- minimal dynamics of ϕ $\mathscr{L}_\phi = \frac{w}{2}\partial_\mu\phi\partial^\mu\phi$ w : coupling constant

- dynamical equation of the logarithm ($\phi = \ln(m/m_0)$) of mass $\partial^2\phi = -\frac{m}{w}\bar{\Psi}\Psi$

Example) varying m_e

Barrow, John D. and Magueijo, Joao., Phys. Rev. D (arXiv:astro-ph/0503222)

- Dynamical electron mass
  - "dilaton" field ϕ control electron mass $m = m_0 \exp\phi$ m_0 : current electron mass

→ Consider the varying m_e

- the exact solution of m

$$m = \exp[\phi] = -\frac{2C^2}{Mt}\left(\frac{t}{T}\right)^{\pm C}\frac{1}{[1-(t/T)^{\pm C}]^2}$$

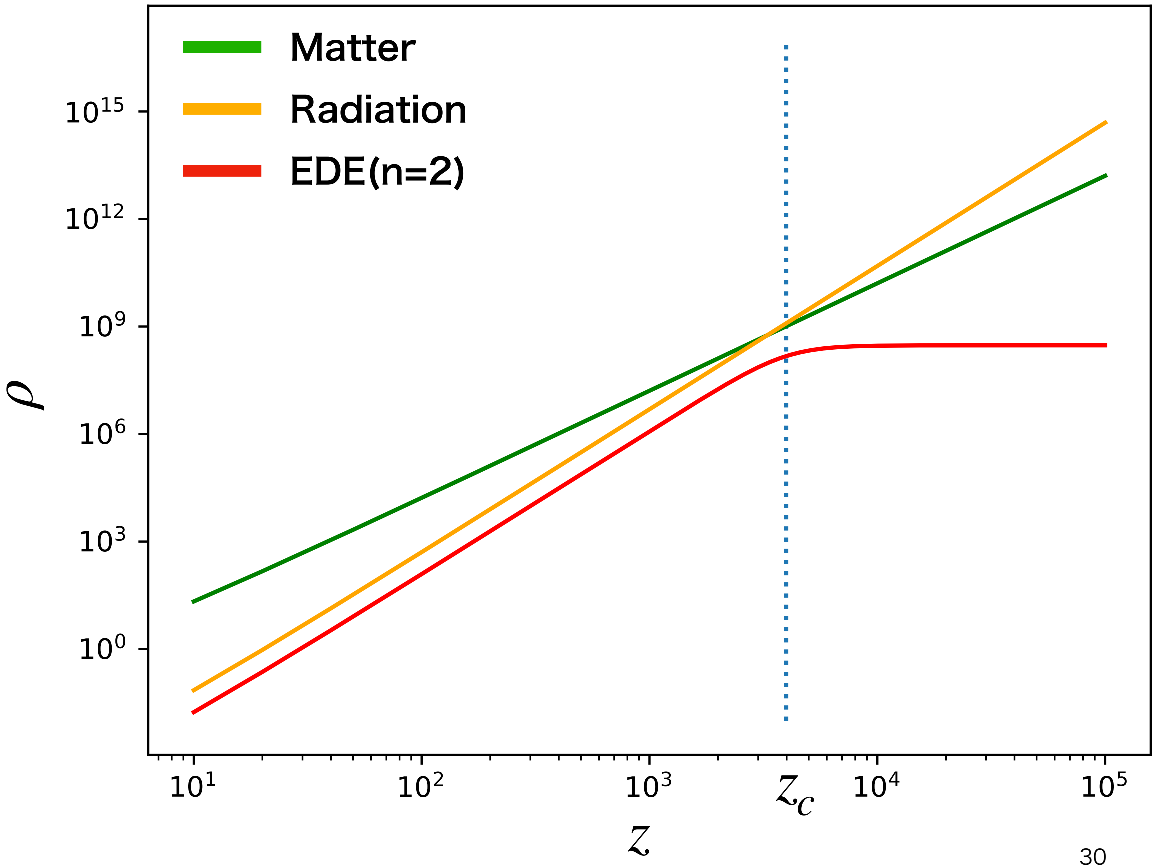
$$M = \frac{a^3 n_L m_0}{w} \simeq \frac{\rho_{e0} a_0^3}{w}$$

C : Constant n_L : lepton number density

ρ_{e0} : current electron energy density

Example) Early Dark Energy (EDE) model

we use the model proposed by Poulin et al, Phys. Rev. D (arXiv:1806.10608)



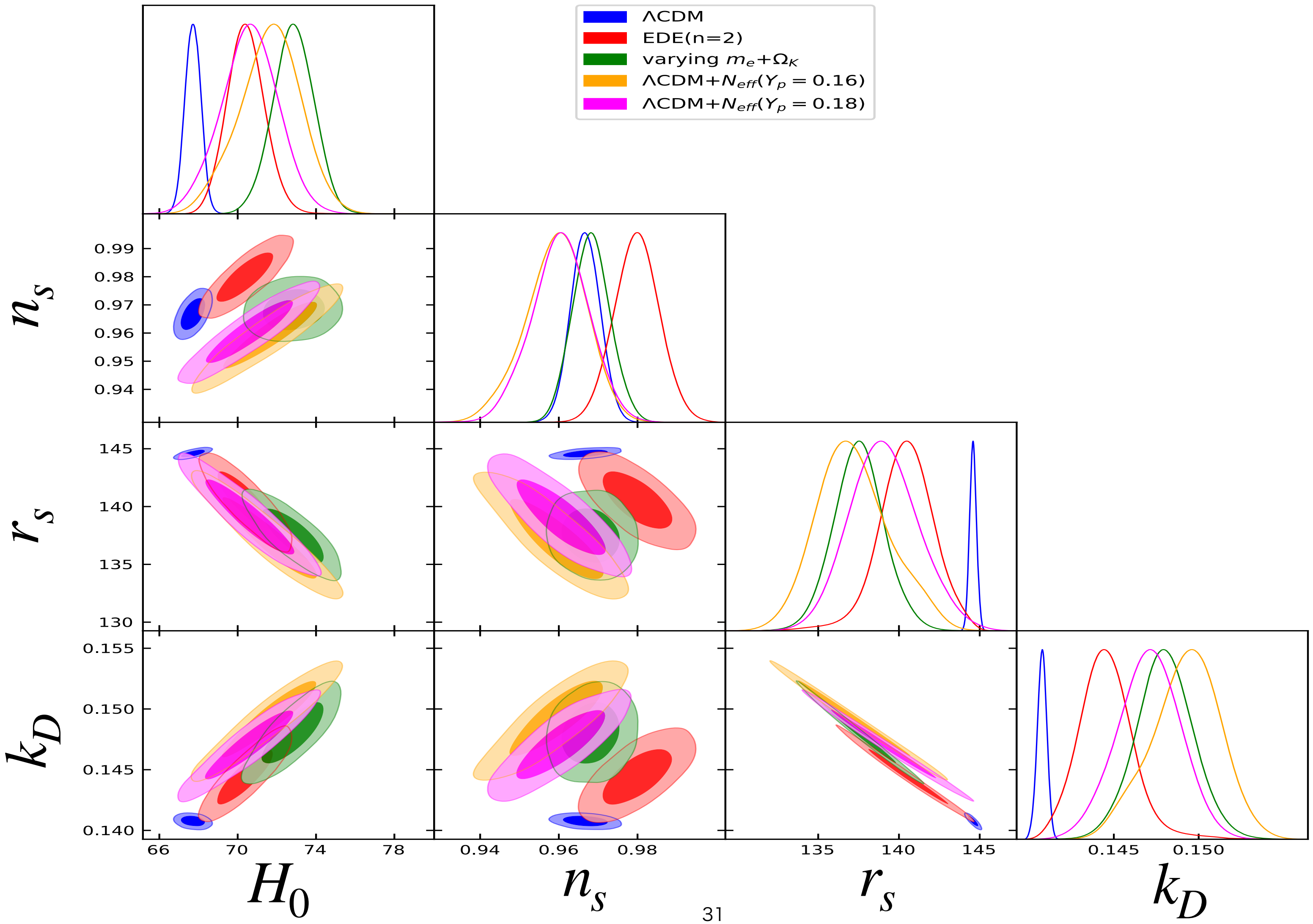
$$w_a(z) = \frac{1 + w_n}{1 + [(1+z)/1+z_c)]^{3(1+w_n)}} - 1,$$

$$\Omega_a(z) = \frac{2\Omega_a(z_c)}{[(1+z_c)/1+z)]^{3(1+w_n)} + 1}$$

$$w_n \equiv \frac{n-1}{n+1}$$

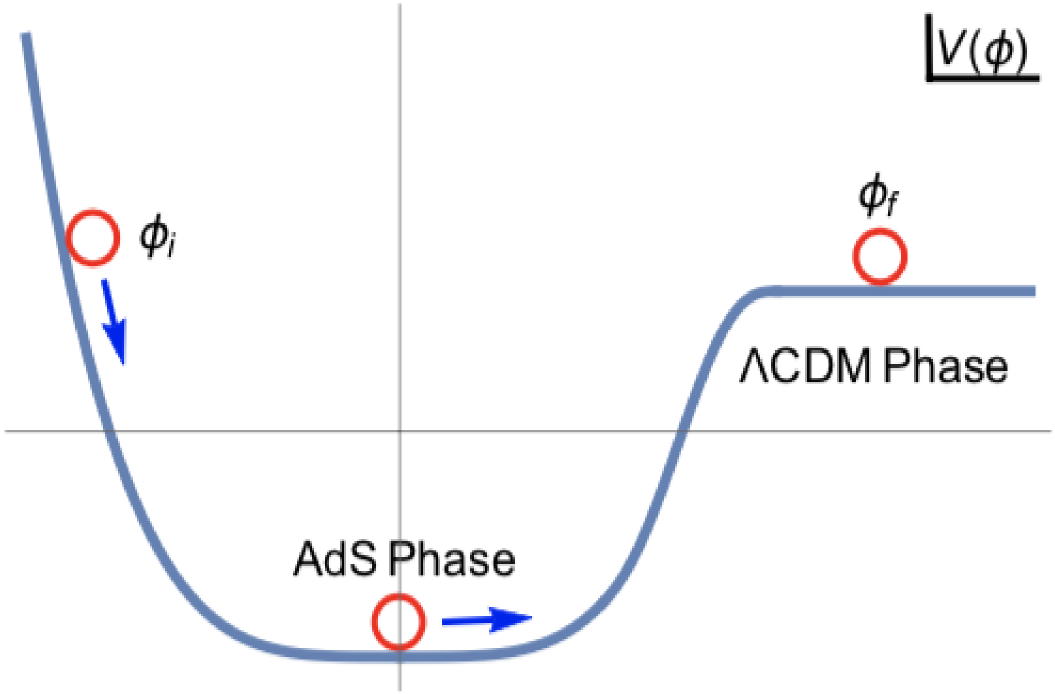
z_c : The critical redshift

Result(triangle plot summary)



AdS phase + EDE model

Gen Ye and Yun-Song Piao., Phys. Rev. D(arXiv:2001.02451)

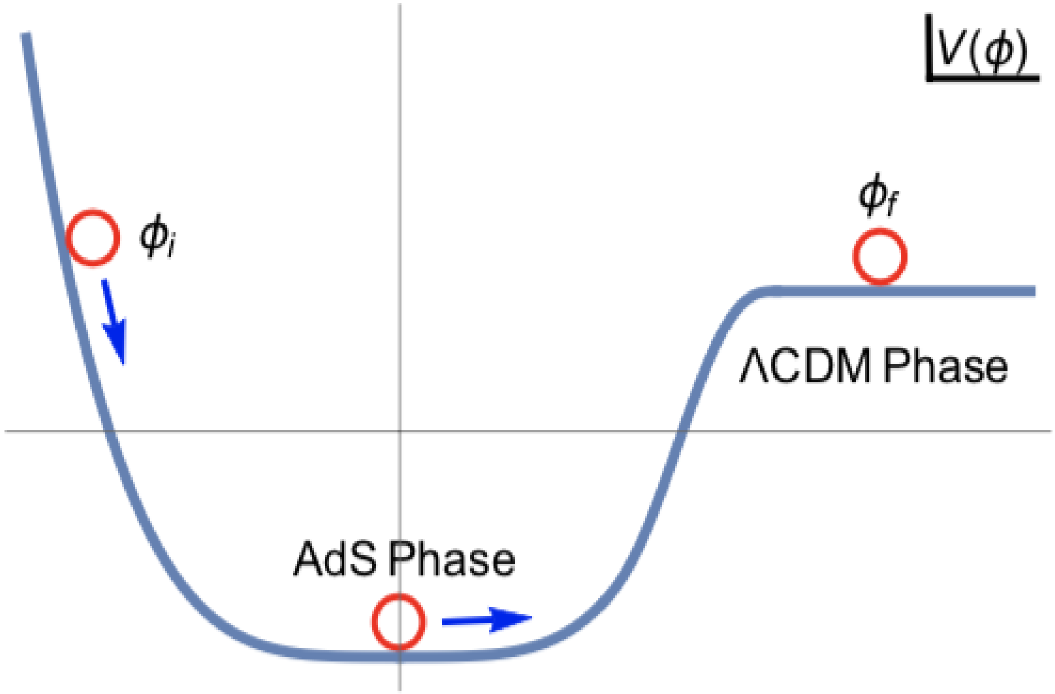


Example of potential

$$V(\phi) = \begin{cases} V_0\left(\dfrac{\phi}{M_p}\right)^4 - V_{ads} & \dfrac{\phi}{M_p} < \left(\dfrac{v_{ads}}{V_0}\right)^{1/4} \\ 0 & \dfrac{\phi}{M_p} > \left(\dfrac{v_{ads}}{V_0}\right)^{1/4} \end{cases}$$

V_{ads} **: the depth of AdS well,** $M_p = \dfrac{c\hbar}{G}$

AdS phase + EDE モデル



1. The scalar field ϕ is in the middle of the potential.
   That energy density ρ_ϕ is negligible

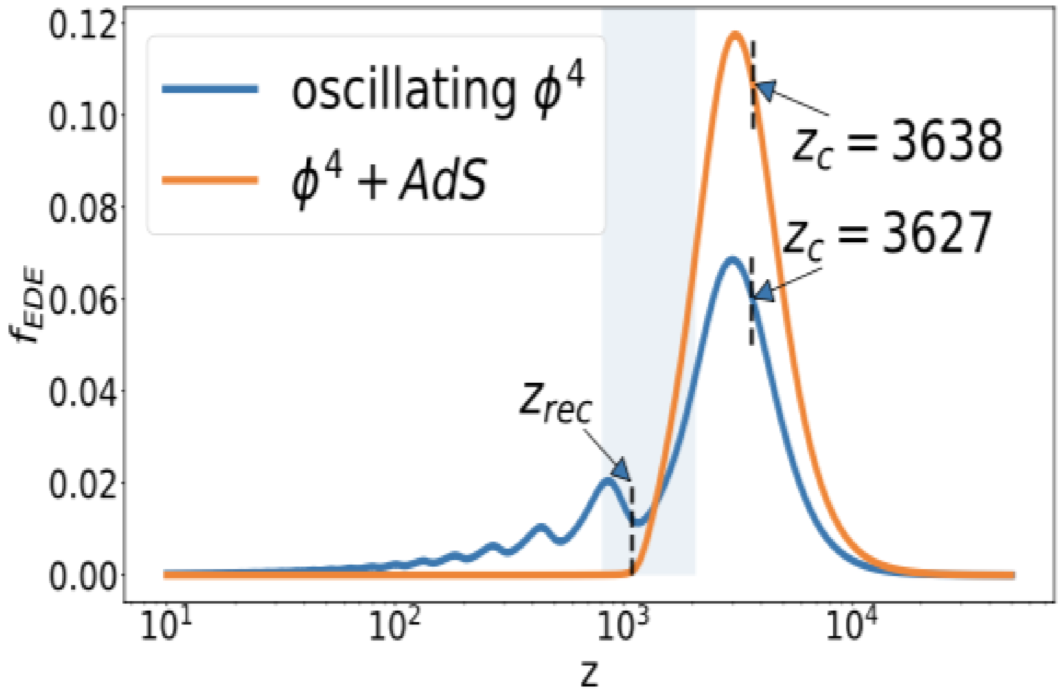
2. As expanding the universe,
   the radiation, and matter dilute.
   When $H^2 \simeq \partial_\phi^2 V$ before the recombination,
   the field starts to roll the potential,
   and that ρ_ϕ isn't negligible.

3. The field rolls the AdS phase,
   and ρ_ϕ quickly redshifts during this period.

4. The field rises to the region of $\Lambda > 0$,
   and the universe settles in the ΛCDM phase until now

AdS phase + EDE model

The contribution of energy density



ϕ^4 + AdS model

$f_{\rm EDE}$ is very small in the recombination period

Majoron+N_{eff}

Escudero et al., Phys. J. C (arXiv:1909.04044)

- A model that attempts to solve the Hubble tension
  by giving an additional contribution due to the interaction of Majoron and neutrinos.

- New parameters

m_ϕ : Majoron mass Γ_{eff} : Effective decay width

N_{eff} : The effective number of neutrinos

Phenomenologically Emergent Dark Energy (PEDE)

Weiqiang Yang et al., Phys. Dark Univ.(arXiv:2007.02927)

- This model is motivated that dark energy could be an emergent phenomenon only arising at low redshift.

- Some transition forms can obtain a larger value of H_0

- parameters

$$\Omega_{\rm ED}(z) = \Omega_{\rm DE,0}\left[1 - \tanh(\log_{10}(1+z))\right]$$

$\Omega_{\rm DE,0}$: The present-day value of $\Omega_{\rm DE}$

$$w_{\rm DE}(z) = \frac{1}{3}\frac{d\ln\Omega_{\rm DE}}{dz}(1+z) - 1 :$$

The reason k_D is large in the ΛCDM+$N_{\rm eff}$ ($Y_{\rm p} = 0.16,\ 0.18$) model

decreasing the helium-4 abundance

Decreasing $Y_{\rm p}$

➡ increasing the number density of free electron

Increasing $n_{\rm e}$

➡ diffusion distance $\lambda_D = \sqrt{\frac{ct}{n_{\rm e}\sigma_{\rm T}}}$

Decreasing λ_D

➡ $\lambda_D = 1/k_D$

Increasing k_D

The reason k_D is large in the varying $m_{\rm e} + \Omega_{\rm K}$ model

$$1/k_D(z_*) \propto a_* \qquad m_{\rm e} \propto T_{\gamma *} \propto \frac{1}{a_*}$$

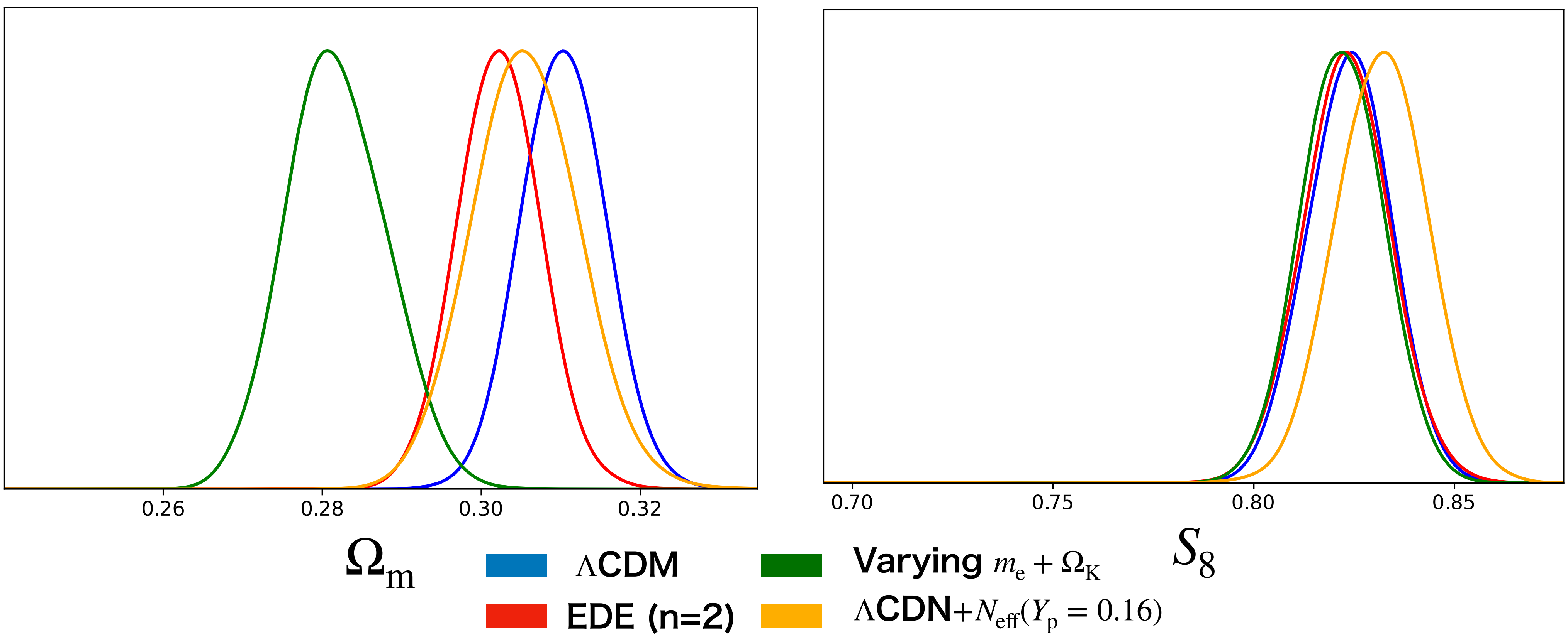
➡ $$k_D(z_*) \propto m_{\rm e}$$

a larger $m_{\rm e}$ leads to a larger k_D

Result(plot summary)

$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$$

$$\sigma_8^2 = \frac{A_0}{2\pi^2}\int dk k^{n+2} W^2\left(k \cdot 8h^{-1}\mathrm{Mpc}\right) T^2(k, t_0)$$



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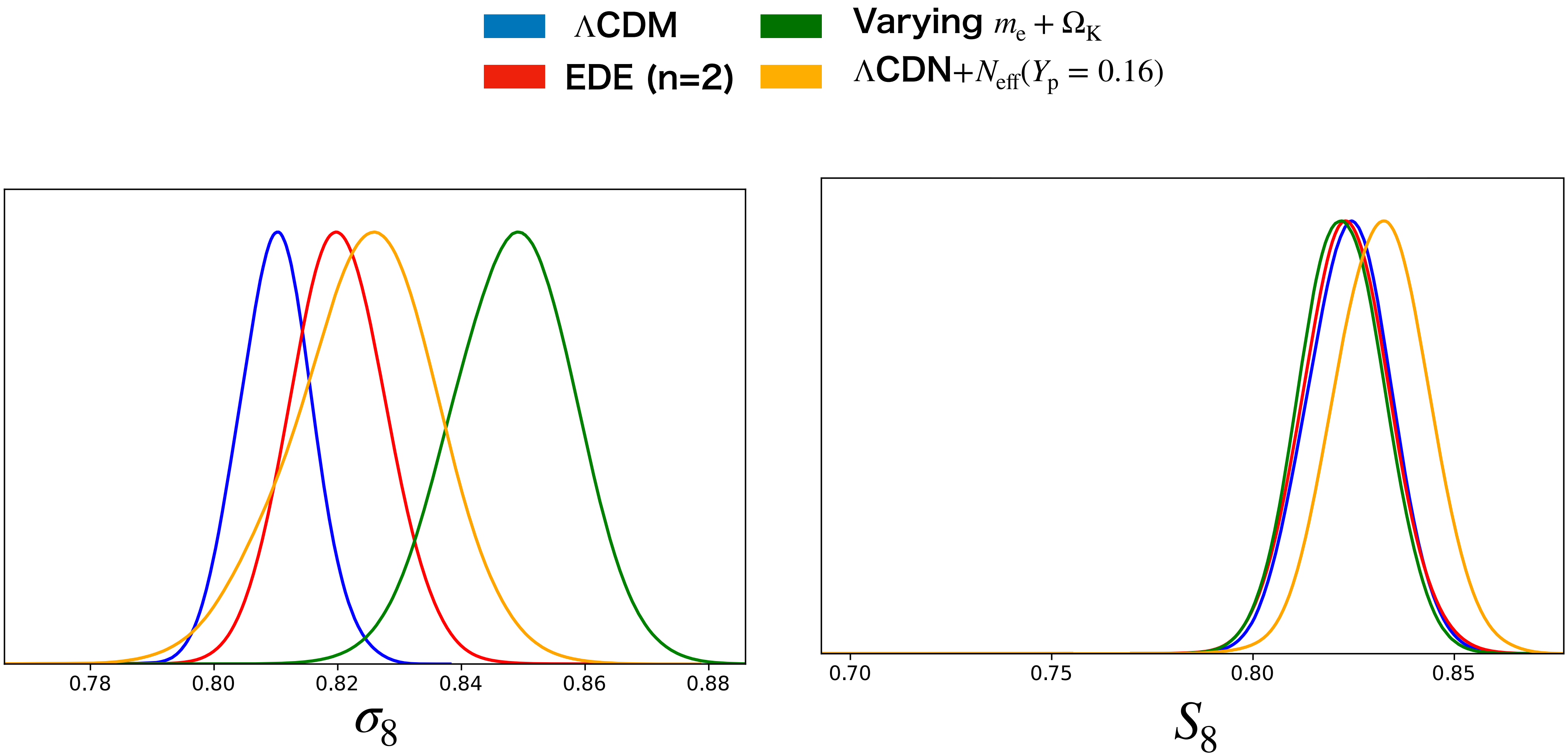
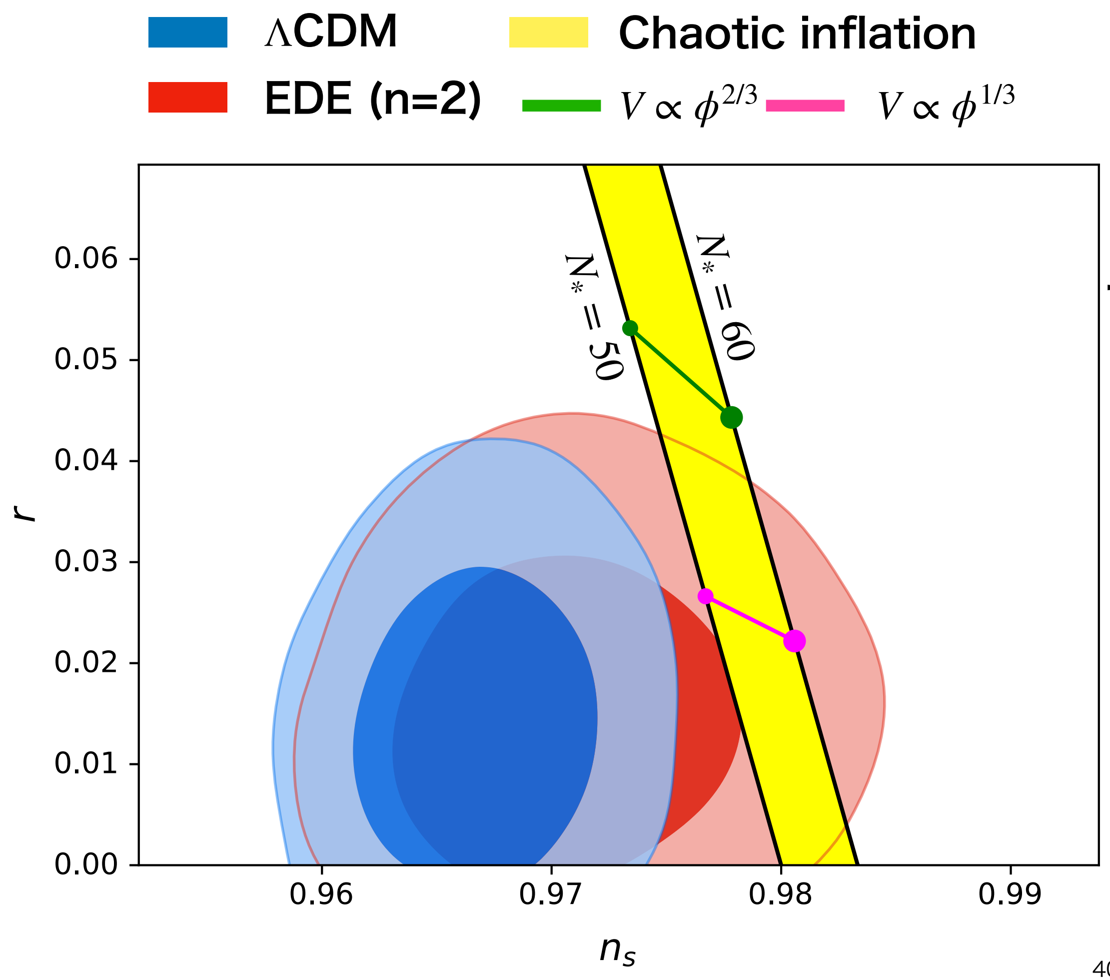


Result(n_s − r plot)

- The bottom figure shows n_s − r plot of the EDE (n=2) model



Compared to the ΛCDM model,
the EDE model obtains a larger value of n_s

↓

In the model which
obtains a larger value of n_s・・・

Such a model could allow
a chaotic inflation model