Electron mass variation from dark sector interaction and compatibility with cosmological observation

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D2　Yo Toda

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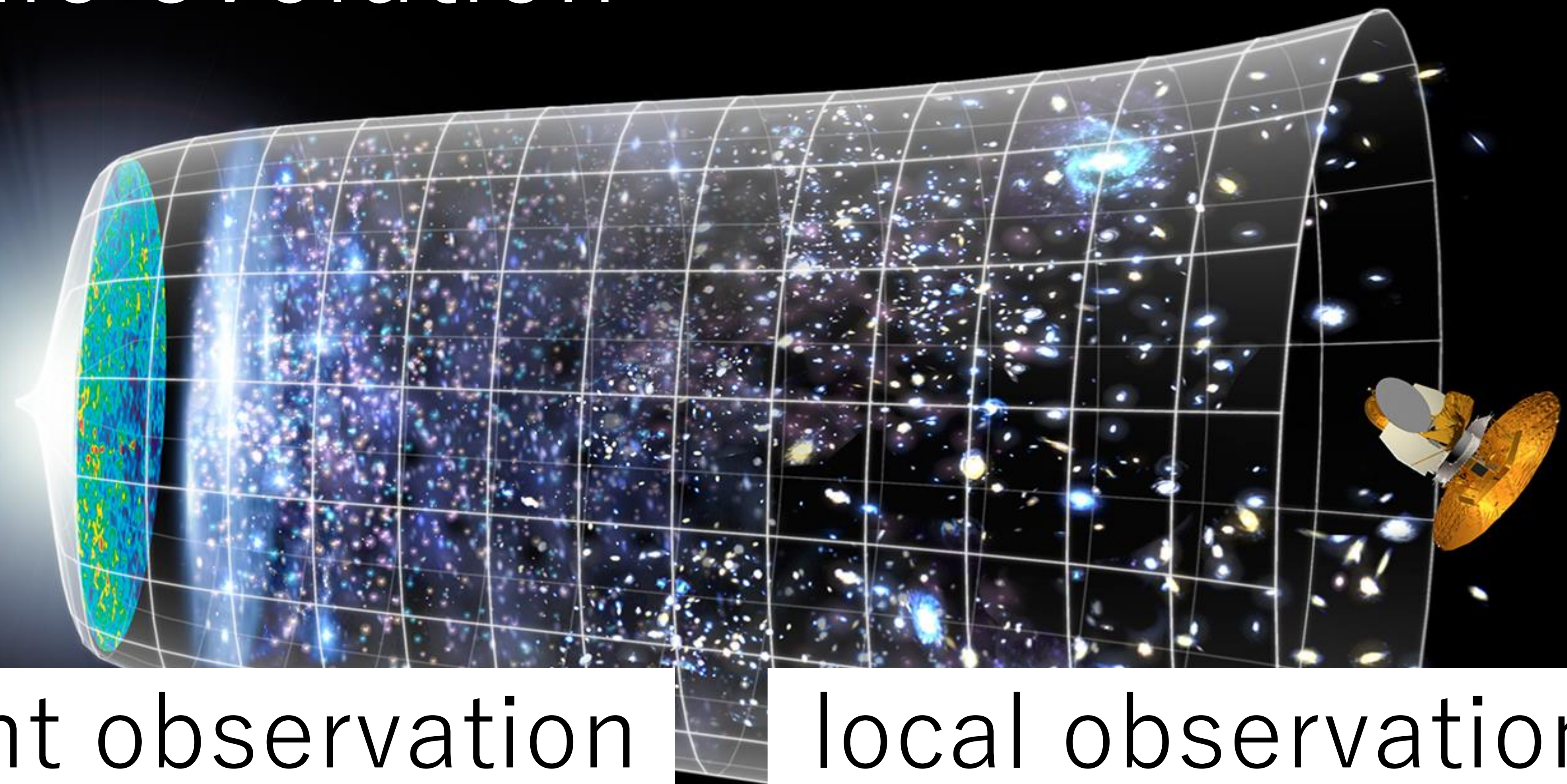
Cosmic evolution



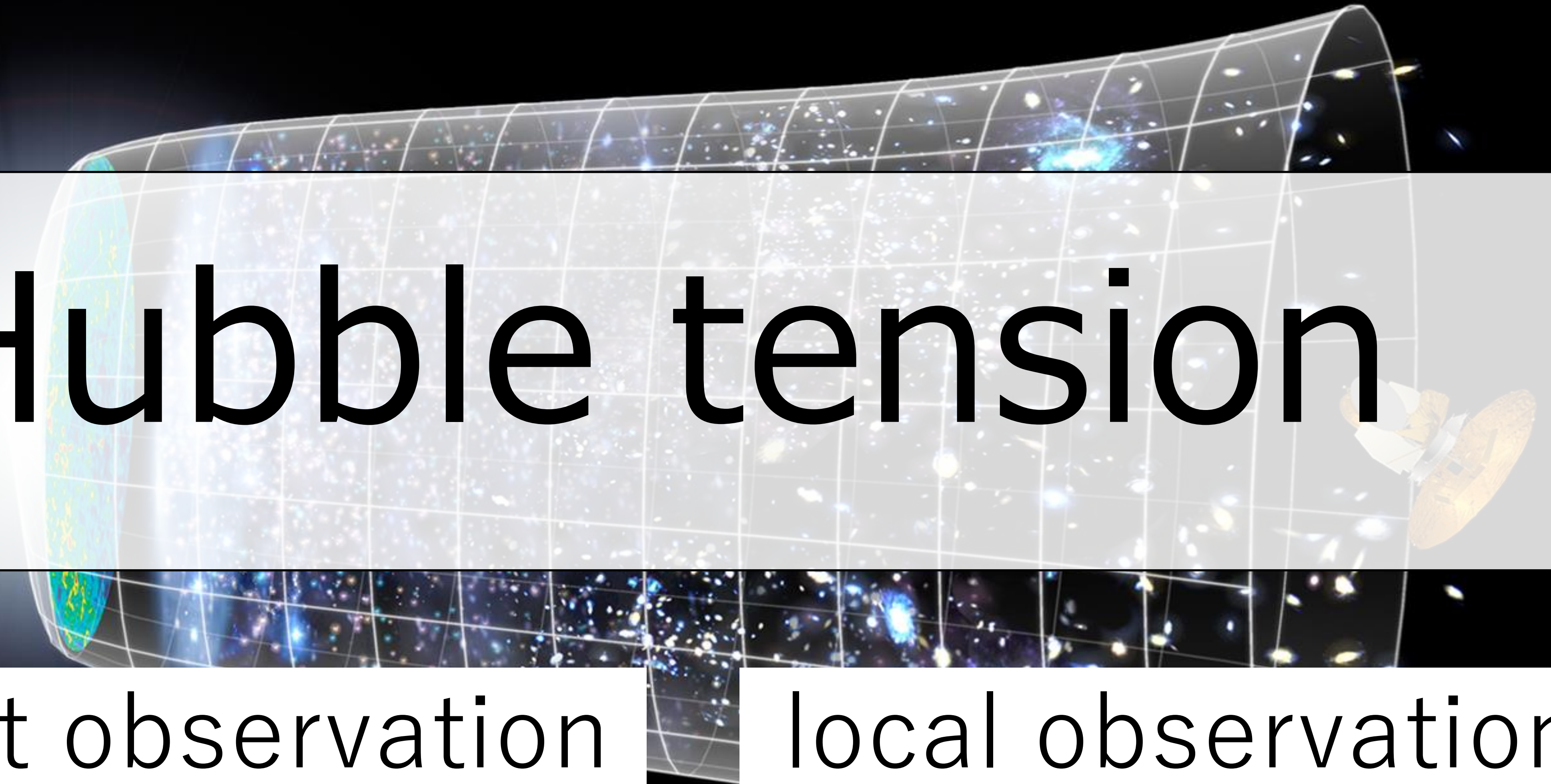
distant observation

$H_0 \fallingdotseq 67$km/s/Mpc

local observation

$H_0 \fallingdotseq 73$km/s/Mpc

Cosmic evolution



Hubble tension

distant observation

$H_0 \fallingdotseq 67$km/s/Mpc

local observation

$H_0 \fallingdotseq 73$km/s/Mpc

HUBBLE TENSION SOLUTION

Model	$\Delta N_{\rm param}$	$\Delta\chi^2$	Finalist
ΛCDM	0	0.00	X
$\Delta N_{\rm ur}$	1	−6.10	X
SIDR	1	−9.57	✓ ③
mixed DR	2	−8.83	X
DR-DM	2	−8.92	X
SIν+DR	3	−4.98	X
Majoron	3	−15.49	✓ ②
primordial B	1	−11.42	✓ ③
varying m_e	1	−12.27	✓ ①
varying m_e+Ω_k	2	−17.26	✓ ①
EDE	3	−21.98	✓ ②
NEDE	3	−18.93	✓ ②
EMG	3	−18.56	✓ ②
CPL	2	−4.94	X
PEDE	0	2.24	X
GPEDE	1	−0.45	X
DM $\to$ DR+WDM	2	−0.19	X
DM $\to$ DR	2	−0.53	X

Phys.Rept. 984 (2022) 1-55
Nils Schoneberg *et al.*

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electron mass variation

▼

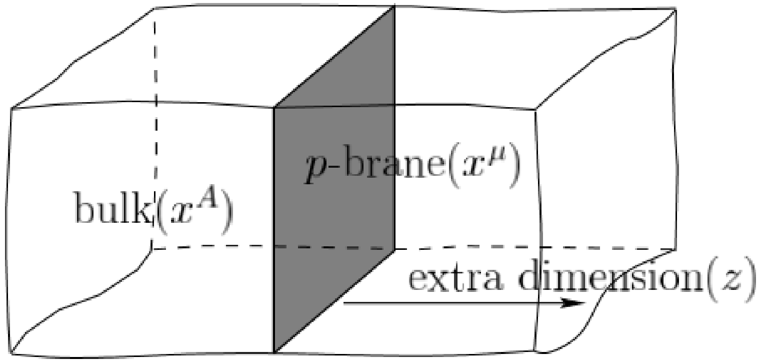
fewer additional parameters
large improvement in $\Delta\chi^2$

Mass variation from extra dimensional theory

- inspired by the models with extra dimensions

Randall-Sundrum model

heterotic M-theory



J.Korean Astron.Soc. 37 (2004) 1-14

- bulk scalar field ϕ (dark energy)

interacts with electrons and dark matter as $m \propto m_0 \mathrm{e}^{\beta\phi}$

・masses of nucleons are not varied

(since the masses of the quarks are generally much less than the masses of the nucleons)

In this presentation

・We investigate the model that dark energy couples to dark matter and electron

・In our model, mass of dark matter and electron in the early universe get greater

・We also fit our model to the cosmological data and find that the Hubble tension is relieved in our model

Setup of the model

Action

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{R}{2\kappa^2} - \underbrace{\frac{1}{2}g^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi) - V(\phi)}_{\text{Dark Energy}}\right] + S_{\mathrm{matter}}(\psi, A(\phi)g_{\mu\nu}),$$

$$A = \exp\left(2\beta\phi\right),$$

Friedman equation and energy conservation

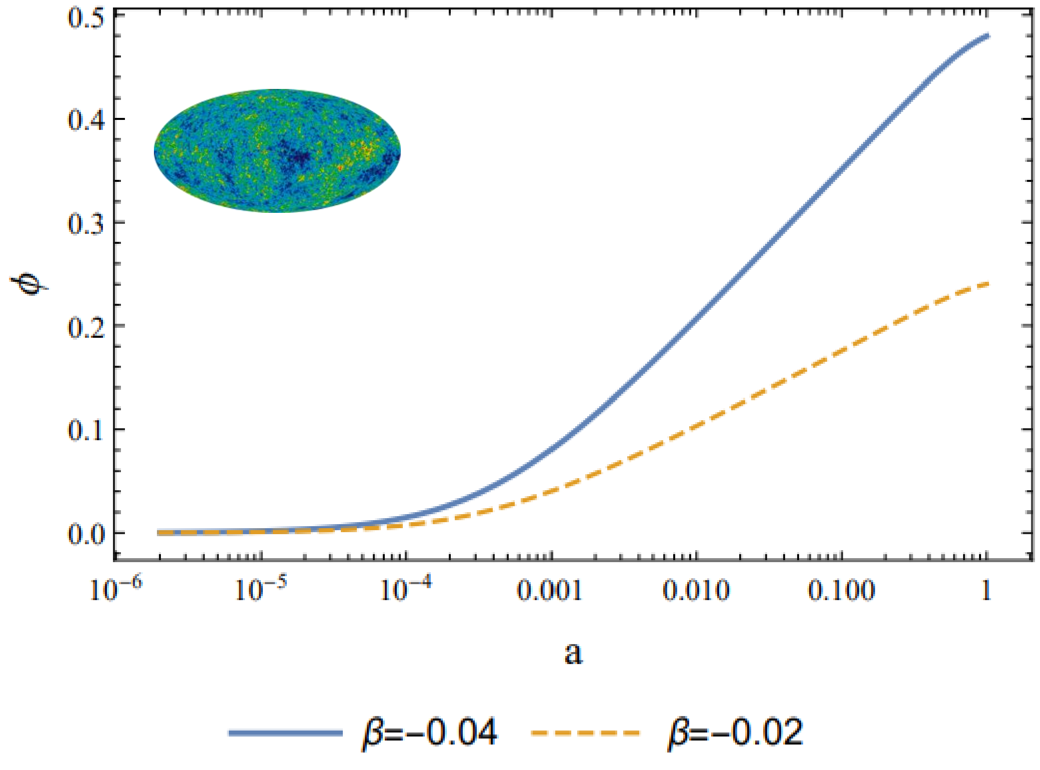
$$\mathcal{H}^2 = \frac{1}{3}a^2\left(\rho_{\mathrm{total}} + \frac{1}{2a^2}\dot{\phi}^2 + V(\phi)\right);$$

(β denotes the interaction magnitude)

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} = \beta(\rho_{(\mathrm{i})} - 3p_{(\mathrm{i})})a^2;$$

$$\dot{\rho}_{(\mathrm{i})} + 3\mathcal{H}(\rho_{(\mathrm{i})} + p_{(\mathrm{i})}) = \beta(\rho_{(\mathrm{i})} - 3p_{(\mathrm{i})})\dot{\phi}, \Rightarrow \quad m \propto m_0 \mathrm{e}^{\beta\phi}$$

Numerical solution of the model



(a) Evolution of the scalar field ϕ

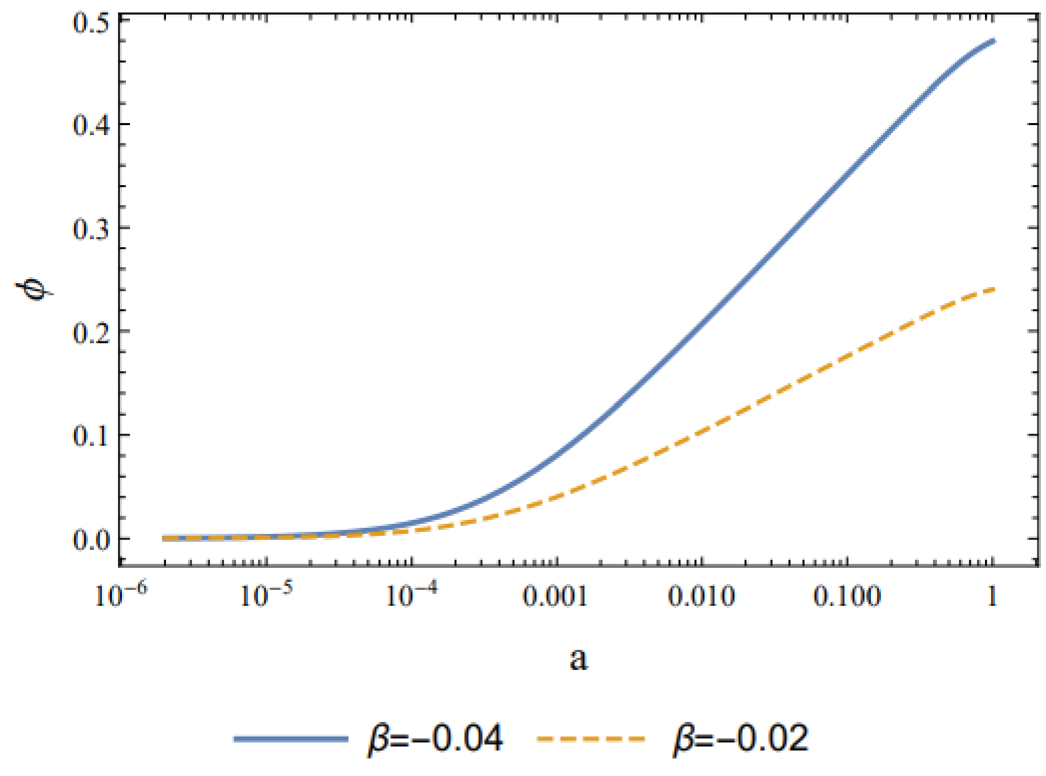
$$\mathcal{H}^2 = \frac{1}{3}a^2\left(\rho_{\rm total} + \frac{1}{2a^2}\dot{\phi}^2 + V(\phi)\right);$$

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} = -\sum_{\rm (i)}\beta(\rho_{\rm (i)} - 3p_{\rm (i)})a^2;$$

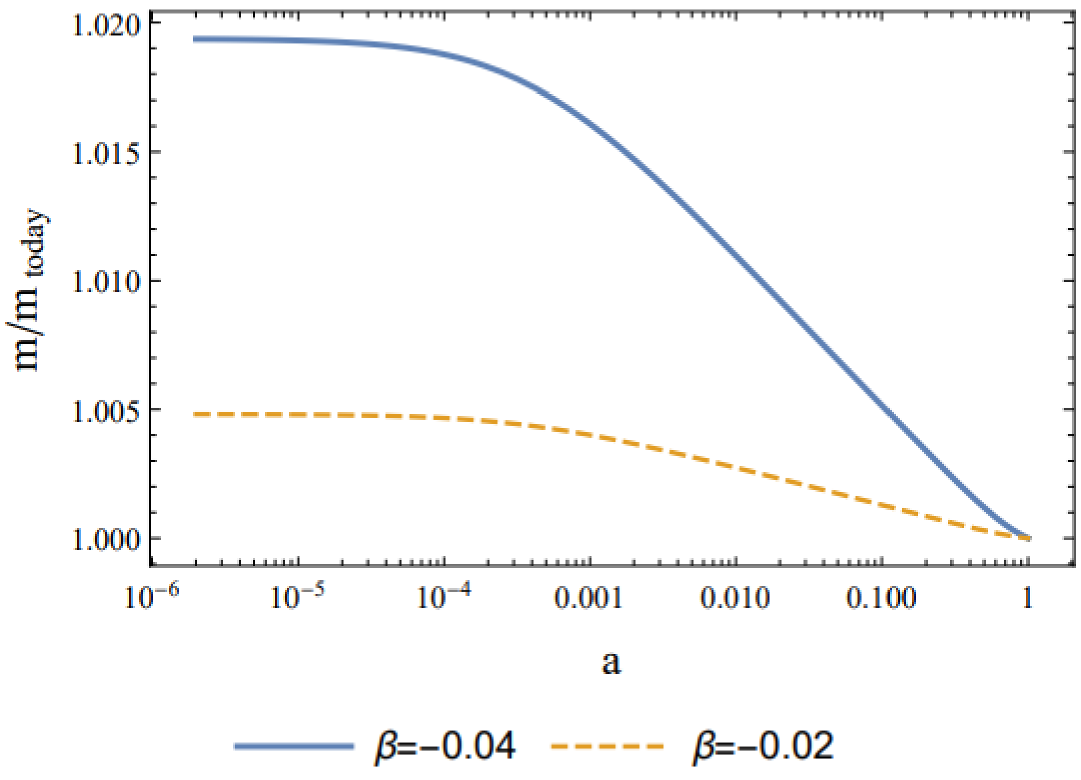
$$\dot{\rho}_{\rm (i)} + 3\mathcal{H}(\rho_{\rm (i)} + p_{\rm (i)}) = \beta(\rho_{\rm (i)} - 3p_{\rm (i)})\dot{\phi}, \Rightarrow \quad m \propto m_0 e^{\beta\phi}$$

Numerical solution of the model

$$m \propto m_0 e^{\beta\phi}$$

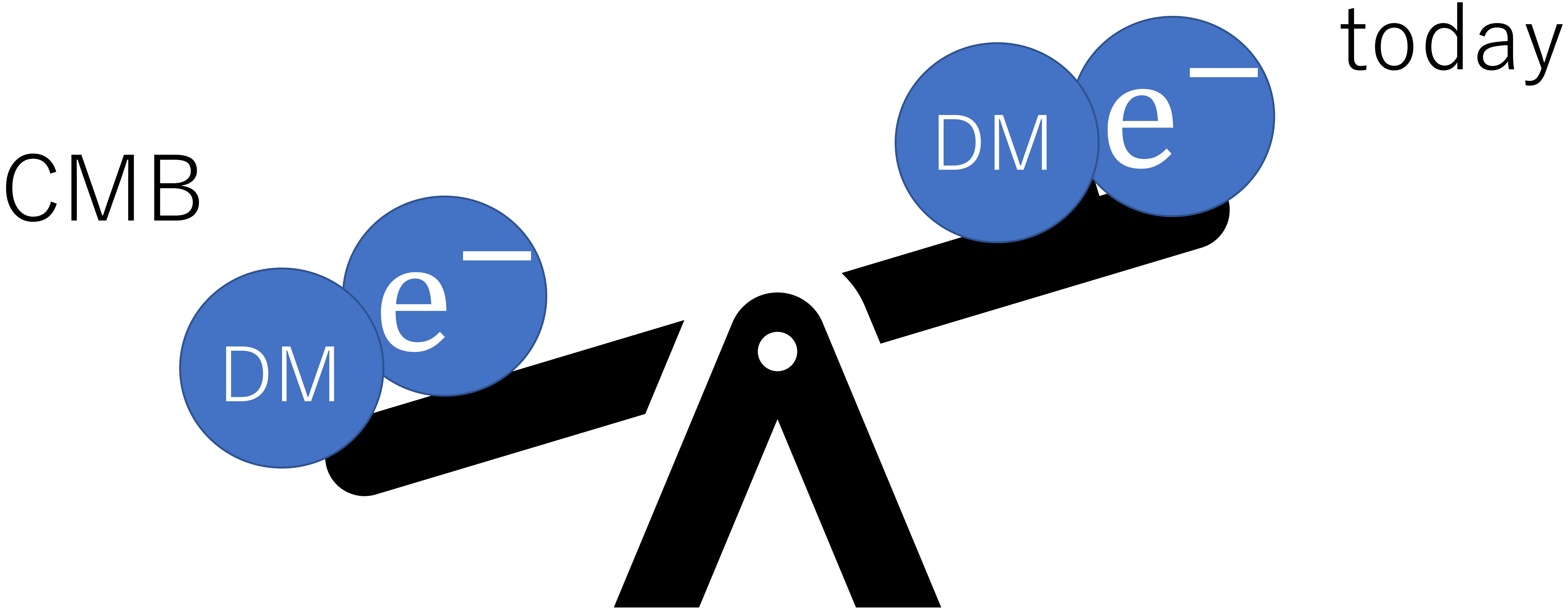


(a) Evolution of the scalar field ϕ



(b) Evolution of the mass

FEATURE OF THE MODEL



ELECTRON MASS AND CMB

Electron mass at last scattering was greater than today

▼ $m_{\mathrm{e}\,|\mathrm{Last\ Scatter}}/m_{\mathrm{e}\,|\mathrm{today}} > 1$

Photons lose energy earlier
to excite electrons in hydrogen

▼ ∵ energy level of hydrogen: $E \propto m_{\mathrm{e}}$

Recombination occurs earlier

▼

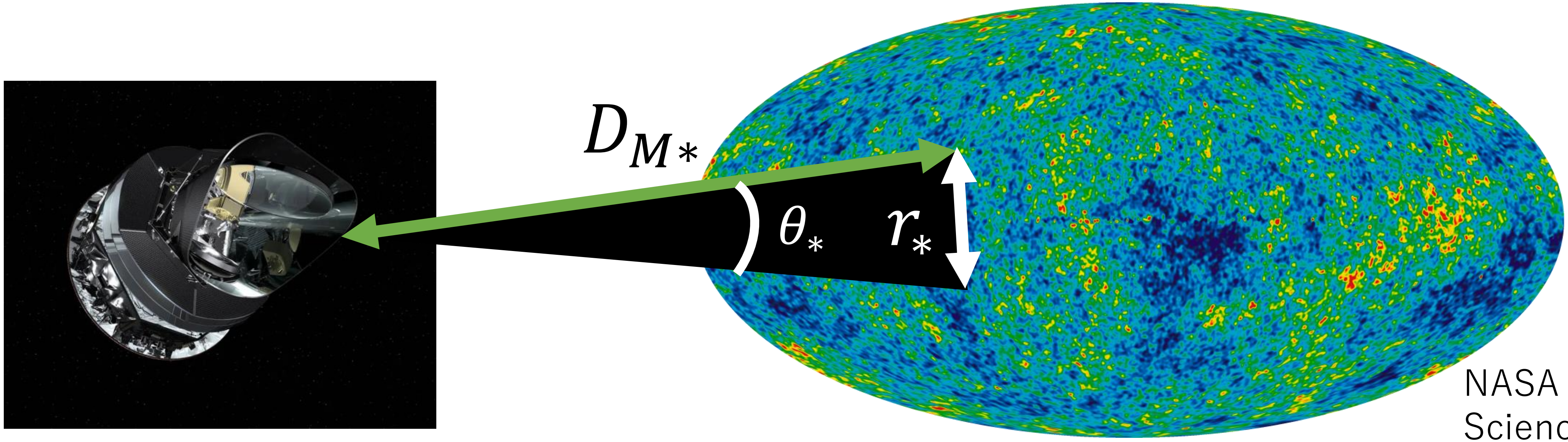
Last scattering time t_* gets shorter

ELECTRON MASS AND CMB

Angular Size : $\theta_* = \frac{r_*}{D_{M*}} = (1.0411 \pm 0.0003) \times 10^{-2}$

$r_* = \int_0^{t_*} \frac{c_s d\tilde{t}}{a(\tilde{t})}$: comoving sound horizon at recombination

$D_{M*} = \int_{t_*}^{t_0} \frac{d\tilde{t}}{a(\tilde{t})}$: comoving angular diameter distance



NASA / WMAP
Science Team

ELECTRON MASS AND CMB

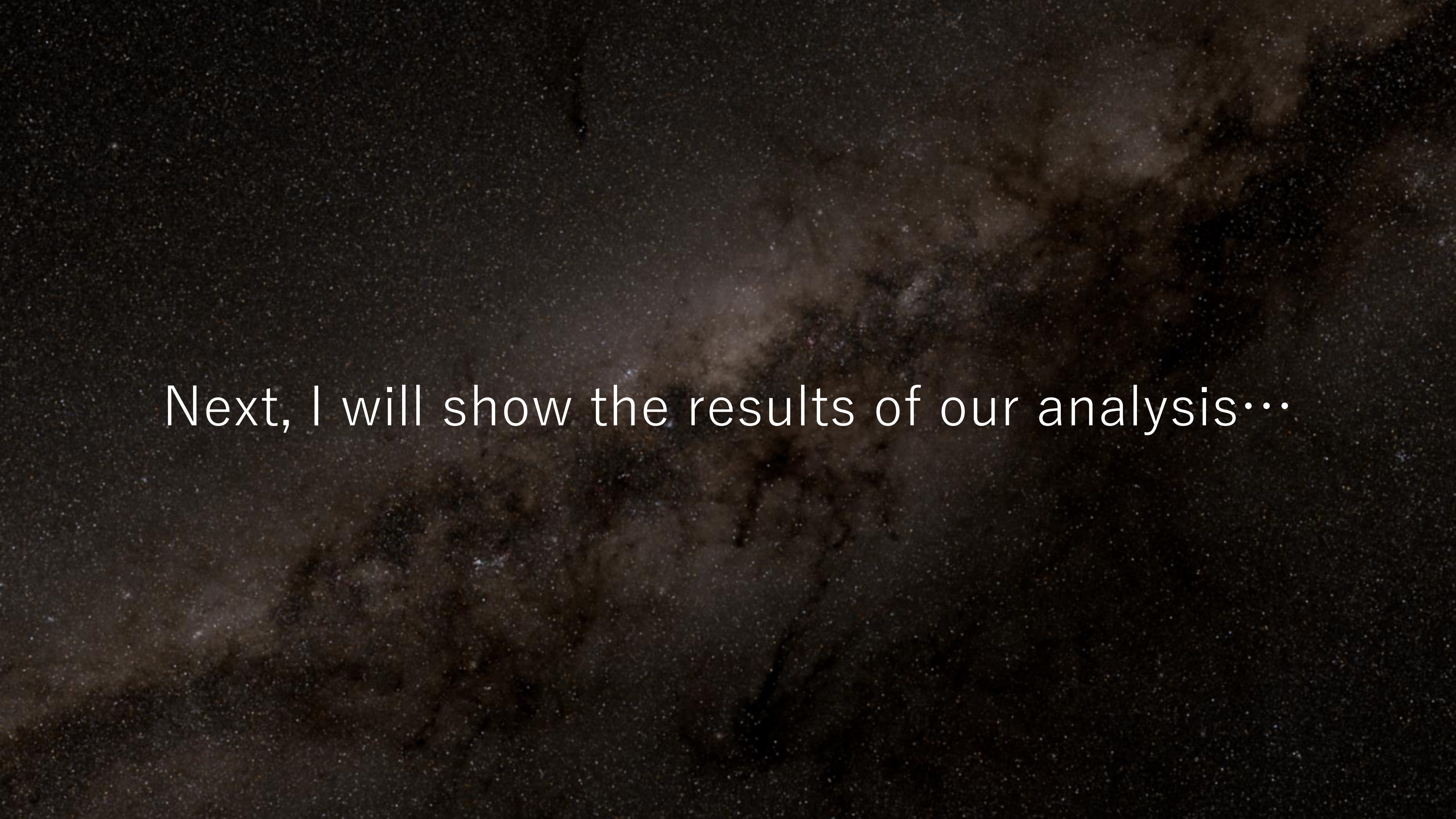
Angular Size : $\theta_* = \frac{r_*}{D_{M*}} = (1.0411 \pm 0.0003) \times 10^{-2}$

$\propto H_0 \times r_*$

Electron mass was greater than today and last scattering time t_* gets shorter

▼ $r_* = \int_0^{t_*} \frac{c_s d\tilde{t}}{a(\tilde{t})}$: comoving sound horizon at recombination

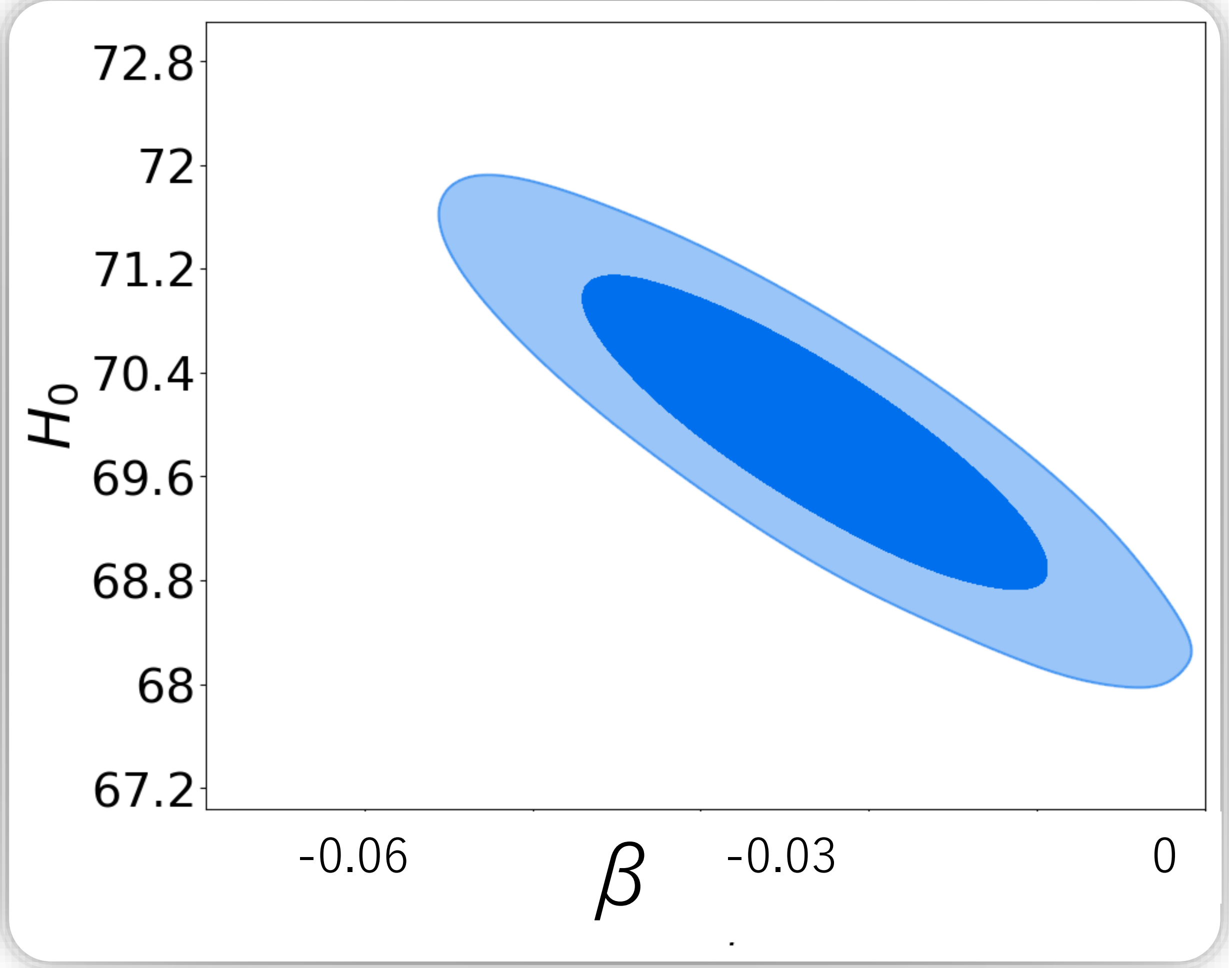
Horizon r_* decreases and Hubble constant H_0 increases


Next, I will show the results of our analysis…

DATA SETS

- CMB from Planck
- BAO from 6dF, MGS and DR12
- light curves from Pantheon
- local measurement of the Hubble constant from SH0ES (R19)

SOLVING HUBBLE TENSION



$$\dot{\rho}_{(i)} + 3\mathcal{H}(\rho_{(i)} + p_{(i)}) = \beta(\rho_{(i)} - 3p_{(i)})\dot{\phi}, \Rightarrow \quad m \propto m_0 e^{\beta\phi}$$

Interaction parameter β ↓

▼

m_e/m_{e0} ↑

▼

Hubble constant H_0 ↑

Planck + BAO + Pantheon + SH0ES

BEST-FIT

Parameter	ΛCDM	our model
β	0	-0.03515
H_0 [km/s/Mpc]	68.17	69.54
$\chi^2_{\mathrm{CMB\ high}l}$	2346.31	2345.61
$\chi^2_{\mathrm{CMB\ low}l}$	22.62	23.293
$\chi^2_{\mathrm{CMB\ low}E}$	398.180	398.760
$\chi^2_{\mathrm{CMB\ lensing}}$	8.595	8.852
$\chi^2_{\mathrm{H074p03}}$	16.983	9.980
χ^2_{JLA}	1034.80	1034.77
χ^2_{prior}	1.795	2.105
χ^2_{BAO}	5.200	6.386
χ^2_{todal}	3834.47	3829.75

Interaction parameter β ↓

▼

H_0 ↑

▼

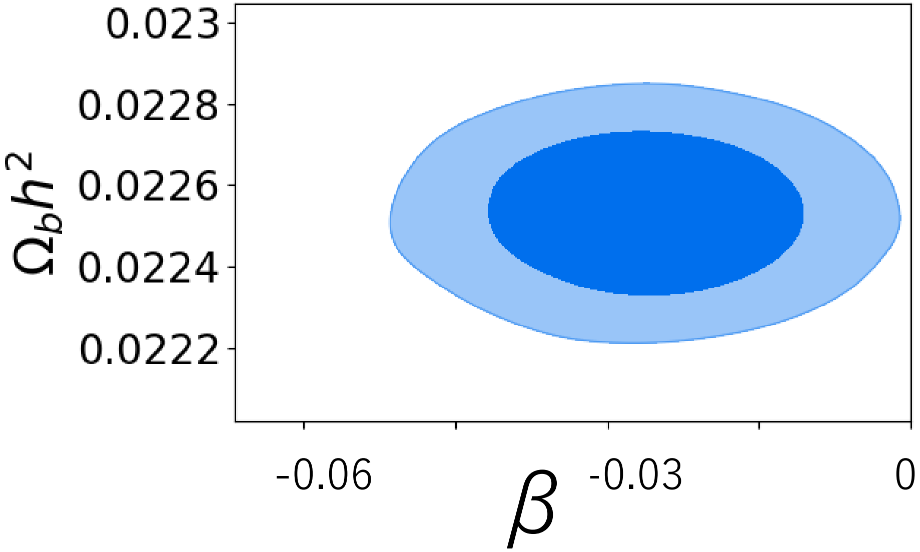
improve χ^2

ADDITIONAL COMMENTS

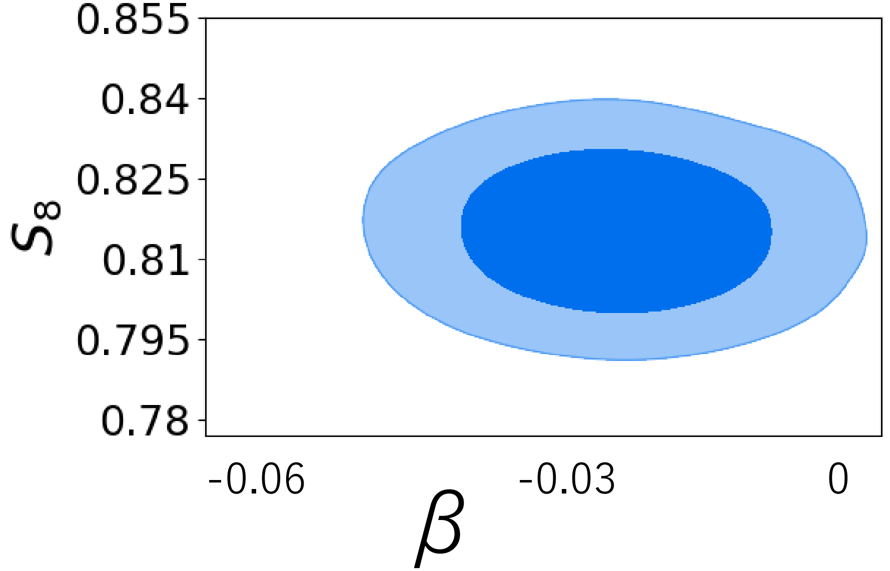
- $\Omega_b h^2$ does not increase

⇒ Not to spoil BBN's success.

(the simple electron mass varying model leads to the larger $\Omega_b h^2$ and too small D/H)



- S_8 tension does not relieved



TAKE-HOME MESSAGE

・Electron mass variation from dark sector interaction is a promising solution to the Hubble tension.

($\beta \lesssim$ -0.03 ($\Delta m_{\mathrm{e}}/m_{\mathrm{e0}}$ $\gtrsim$1.5%) can solve the Hubble tension)

・ In this model, the scalar field of DE is rolled by the DE-DM interaction, and the electron mass is varied due to the coupling between electrons and DE $m = m_0 \mathrm{e}^{\beta\phi}$.

The combination of rolling by the potential $V(\phi)$ and the coupling $m_0 \mathrm{e}^{\beta\phi}$ is also worth considering.

Thank you
for your kind attention!

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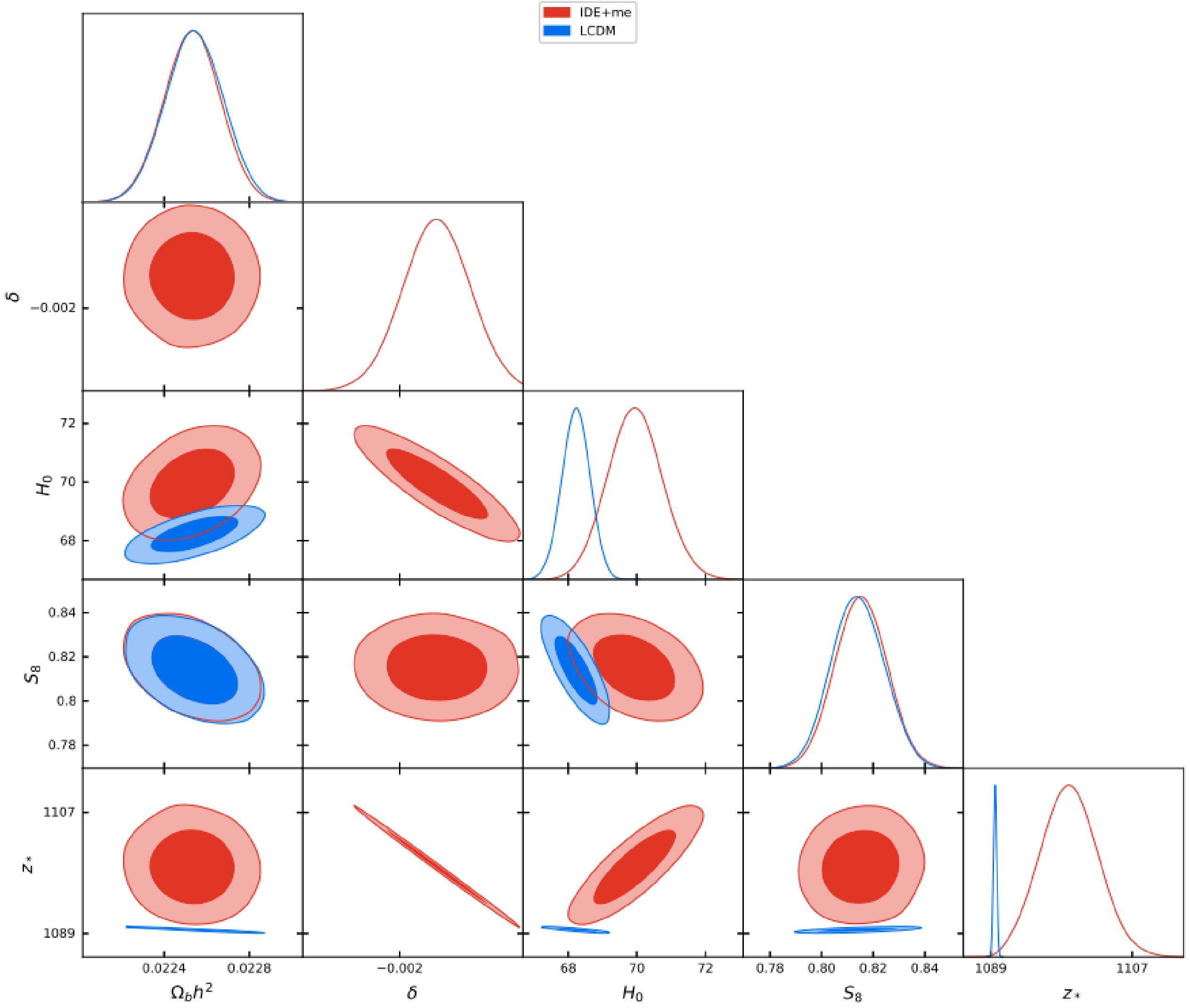
Other parameters



perturbation

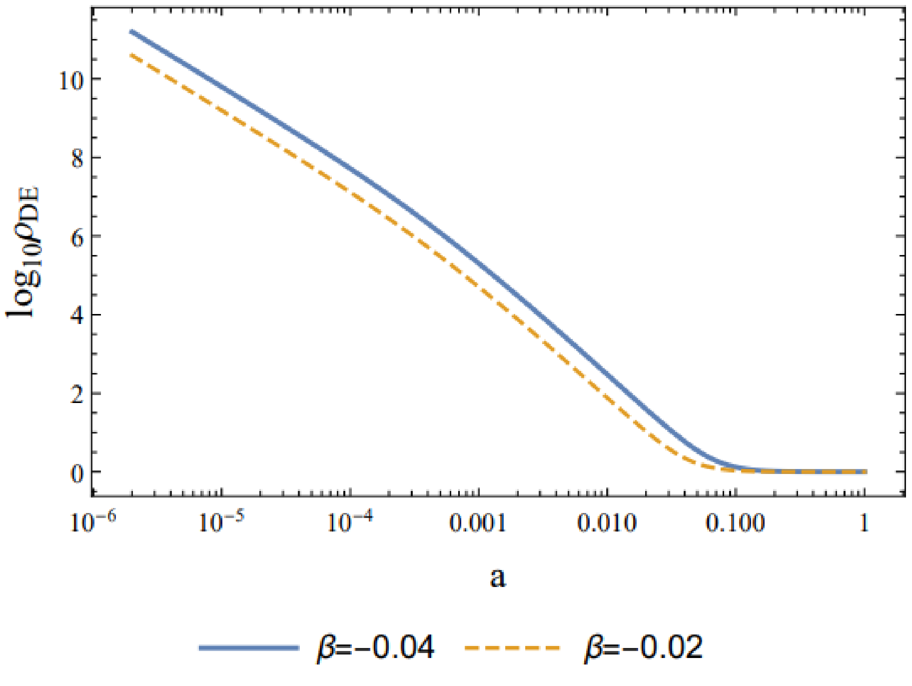
$$\dot{\delta}_{\rm de} = -3\mathcal{H}(1-w_{\rm de})\delta_{\rm de} - (1+w_{\rm de})kv_{\rm de} - (1+w_{\rm de})\frac{\dot{h}}{2}$$
$$- 9\mathcal{H}^2(1-c_{\rm a}^2)(1+w_{\rm de})\frac{v_{\rm de}}{k} - \beta\delta_{\rm de}\frac{a^2\rho_{\rm c}}{\dot{\phi}} + \beta\frac{\rho_{\rm c}}{\rho_{\rm de}}\dot{\phi}(\delta_{\rm de}-\delta_{\rm c})$$

$$\dot{v}_{\rm de} = 2\mathcal{H}v_{\rm de} + \frac{\delta_{\rm de}}{1+w_{\rm de}}k + \beta\dot{\phi}\frac{\rho_{\rm c}}{\rho_{\rm de}}v_{\rm de}\frac{c_a^2}{1+w_{\rm de}}$$

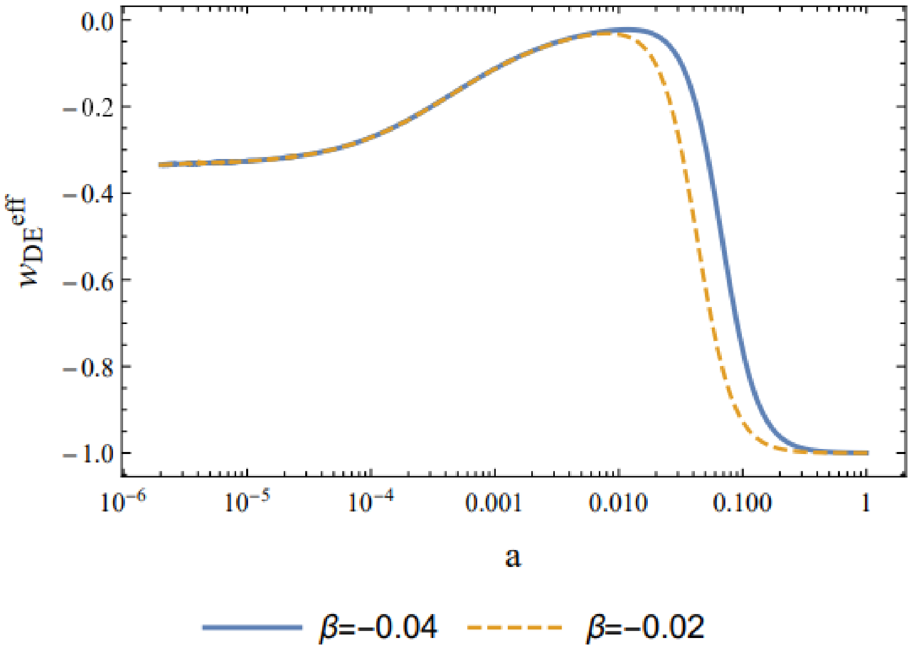
$$\dot{\delta}_{\rm c} = -\left(kv_{\rm c} + \frac{\dot{h}}{2}\right) + \beta\delta\dot{\phi}$$

$$\dot{v}_{\rm c} = -\mathcal{H}v_{\rm c} + \beta k\delta\phi - \beta\dot{\phi}v_{\rm c}$$

$$w_{\rm DE}^{\rm eff} = -1 - \frac{1}{3\rho_{\rm DE}} \frac{\partial \rho_{\rm DE}}{\partial (\ln a)},$$



(a)



(b)

Other parameters