Isotropic cosmic birefringence from early dark energy

Kai Murai
(U. Tokyo, final year of PhD course)

Collaborator: Eiichiro Komatsu(MPA), Toshiya Namikawa(IPMU)

Mini-workshop at MPA
2022/7/19

My work

- Rotation of the CMB polarization (= CMB Birefringence)

  T. Fujita, Y. Minami, KM, H. Nakatsuka
  Phys. Rev. D 105 103519, arXiv: 2110.03228

  T. Fujita, KM, H. Nakatsuka, S. Tsujikawa
  Phys. Rev. D 105 103518, arXiv: 2203.03977

  This talk

  "Isotropic cosmic birefringence from early dark energy"
  E. Komatsu, KM, T. Namikawa
  In preparation

- Big Bang Nucleosynthesis
- Primordial black holes
- Axion-gauge dynamics in inflation

Contents

I. Cosmic birefringence

II. Early dark energy

III. CB from EDE

IV. Summary

Contents

I. Cosmic birefringence

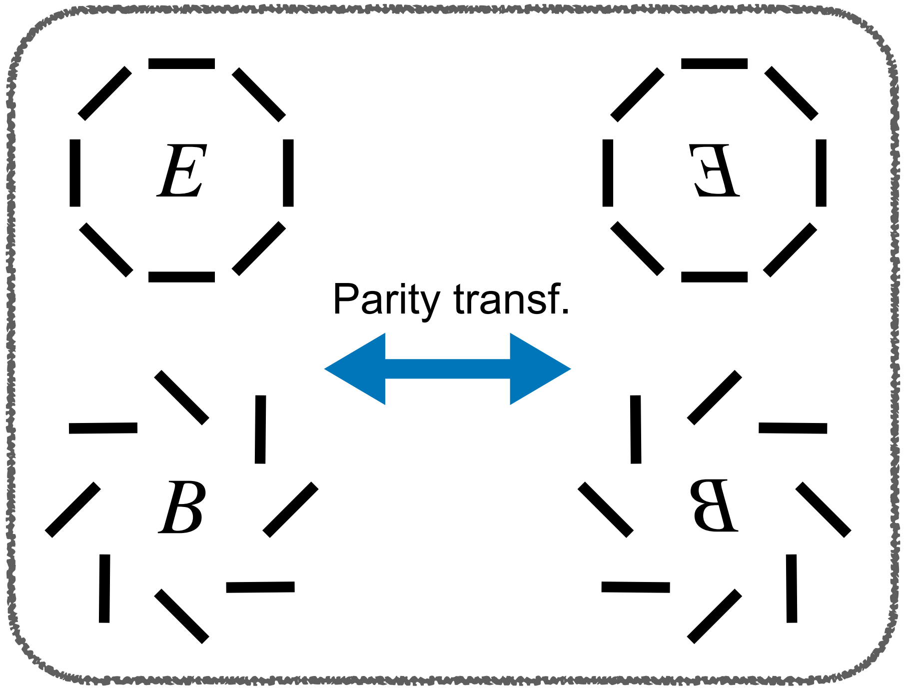
II. Early dark energy

III. CB from EDE

IV. Summary

Cosmic birefringence

Cosmic birefringence is a rotation of the plane on linear polarization in CMB.



CMB polarization is decomposed into

- Parity-even E mode
- Parity-odd B mode

Cosmic birefringence mixes E and B modes:

$$C_l^{EE} = \cos^2(2\beta)\tilde{C}_l^{EE} + \sin^2(2\beta)\tilde{C}_l^{BB}$$

$$C_l^{BB} = \cos^2(2\beta)\tilde{C}_l^{BB} + \sin^2(2\beta)\tilde{C}_l^{EE}$$

$$C_l^{EB} = \frac{1}{2}\sin(4\beta)\left(\tilde{C}_l^{EE} - \tilde{C}_l^{BB}\right)$$

After birefringence

Before birefringence

$$\tilde{C}_l^{BB} \ll \tilde{C}_l^{EE}$$

$$\tilde{C}_l^{EB} = 0$$

Cosmic birefringence

- Parity violating signal in CMB

New analysis of the Planck data reported “cosmic birefringence”.

[Minami & Komatsu(2020)]

The measured cosmic birefringence is considered to be

- isotropic
- independent of the photon frequency

The isotropic rotation angle is estimated as

$$\beta = 0.342^\circ {}^{+0.094^\circ}_{-0.091^\circ} \text{ at 68\% C.L.}$$

[Eskilt & Komatsu (2022)]

This signal indicates the existence of new physics!

Cosmic birefringence

Cosmic birefringence from axion

Axion is a candidate of the origin of β.

$$\mathscr{L} = -\frac{1}{2}\left(\partial_\mu \phi\right)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Dispersion relations for left/right circular polarization photons:

$$\omega_\pm \simeq k \mp \frac{g}{2}\left(\frac{\partial\phi}{\partial t} + \frac{\vec{k}}{k}\cdot\vec{\nabla}\phi\right) = k \mp \frac{g}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

$\rightarrow \beta$ is represented by the difference of the axion field value:

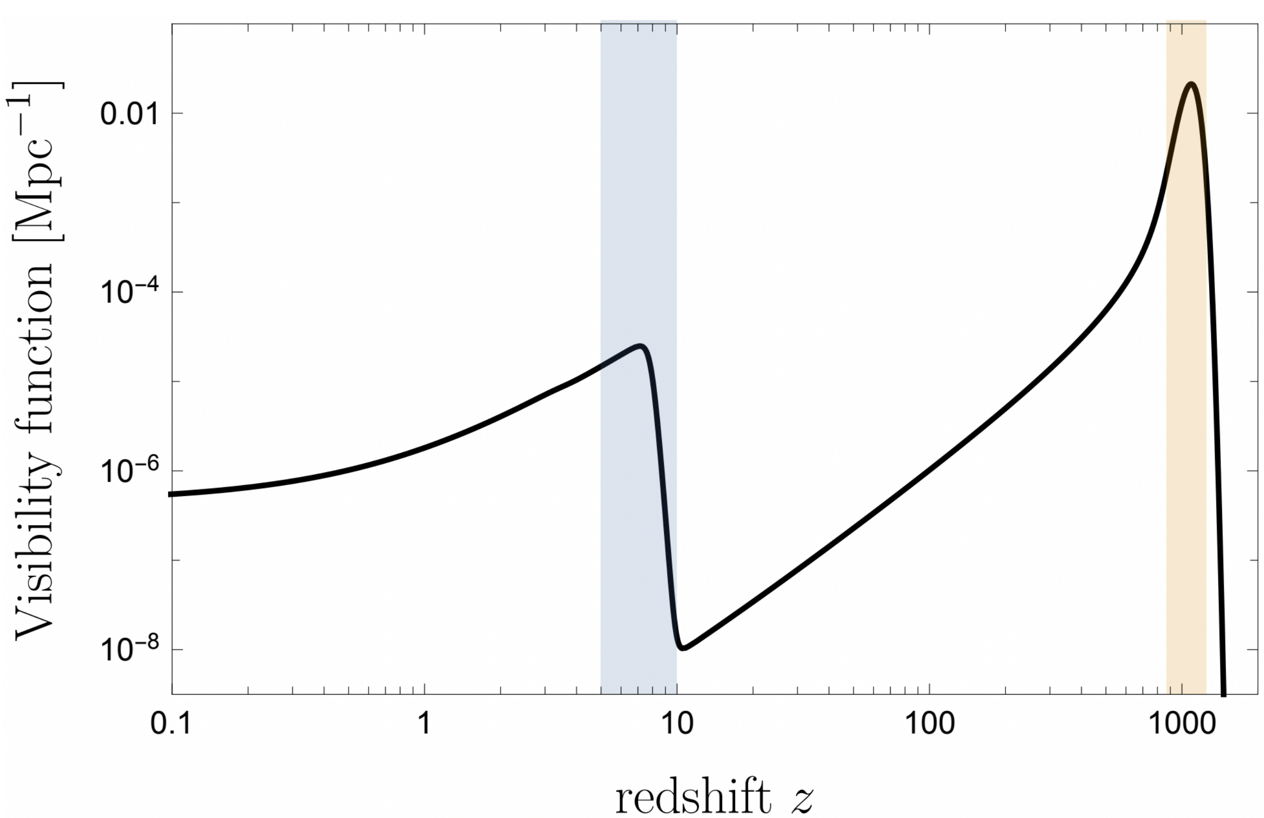
$$\beta(t) = -\frac{1}{2}\int_t^{t_0}\mathrm{d}t\,(\omega_+ - \omega_-) = \frac{g}{2}\left[\phi(t_0) - \phi(t)\right]$$

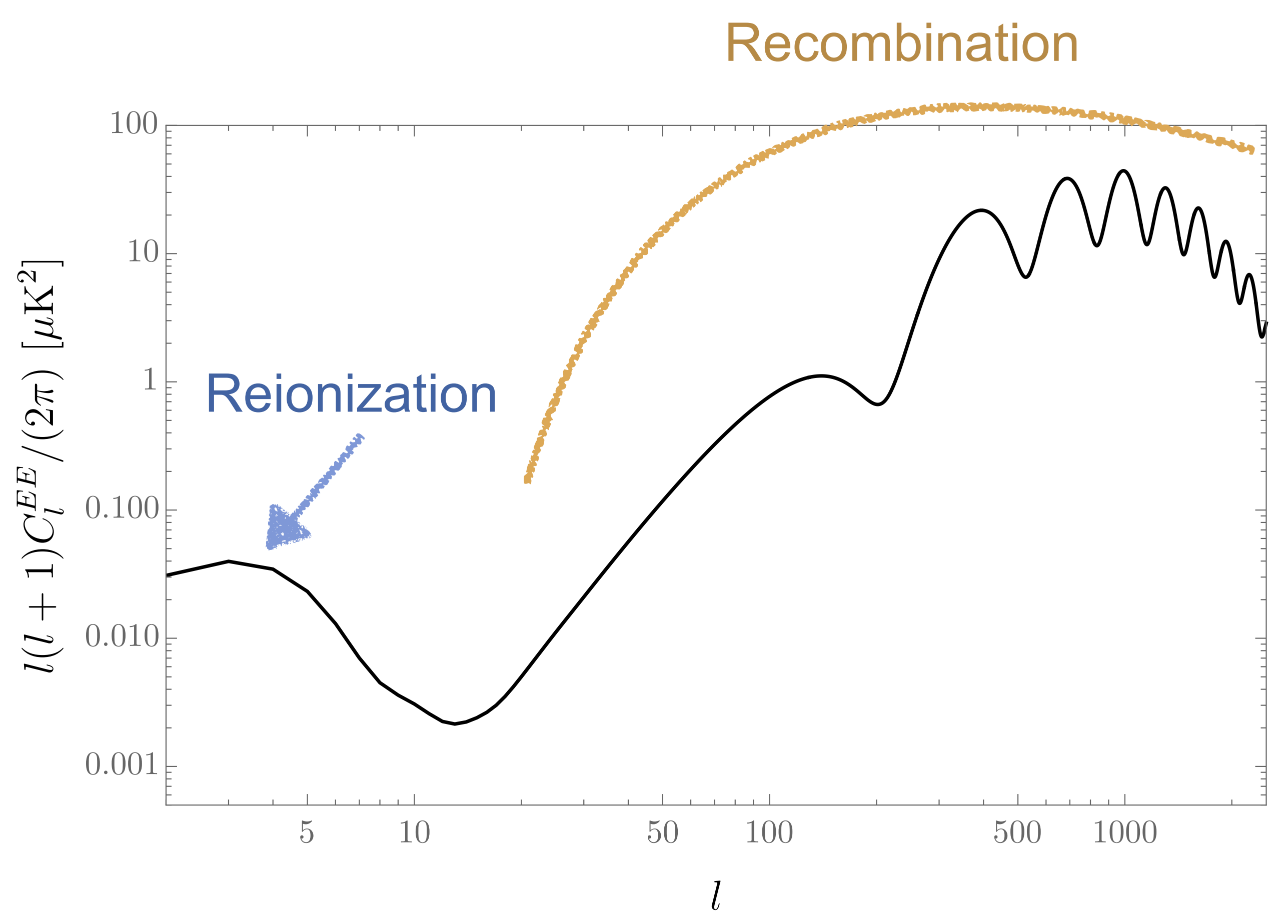
Cosmic birefringence

- Tomographic approach

  CMB polarization mainly comes from

  - Recombination ($z \sim 1090$)
  - Reionization ($z \sim 7$)





Contents

I. Cosmic birefringence

II. Early dark energy

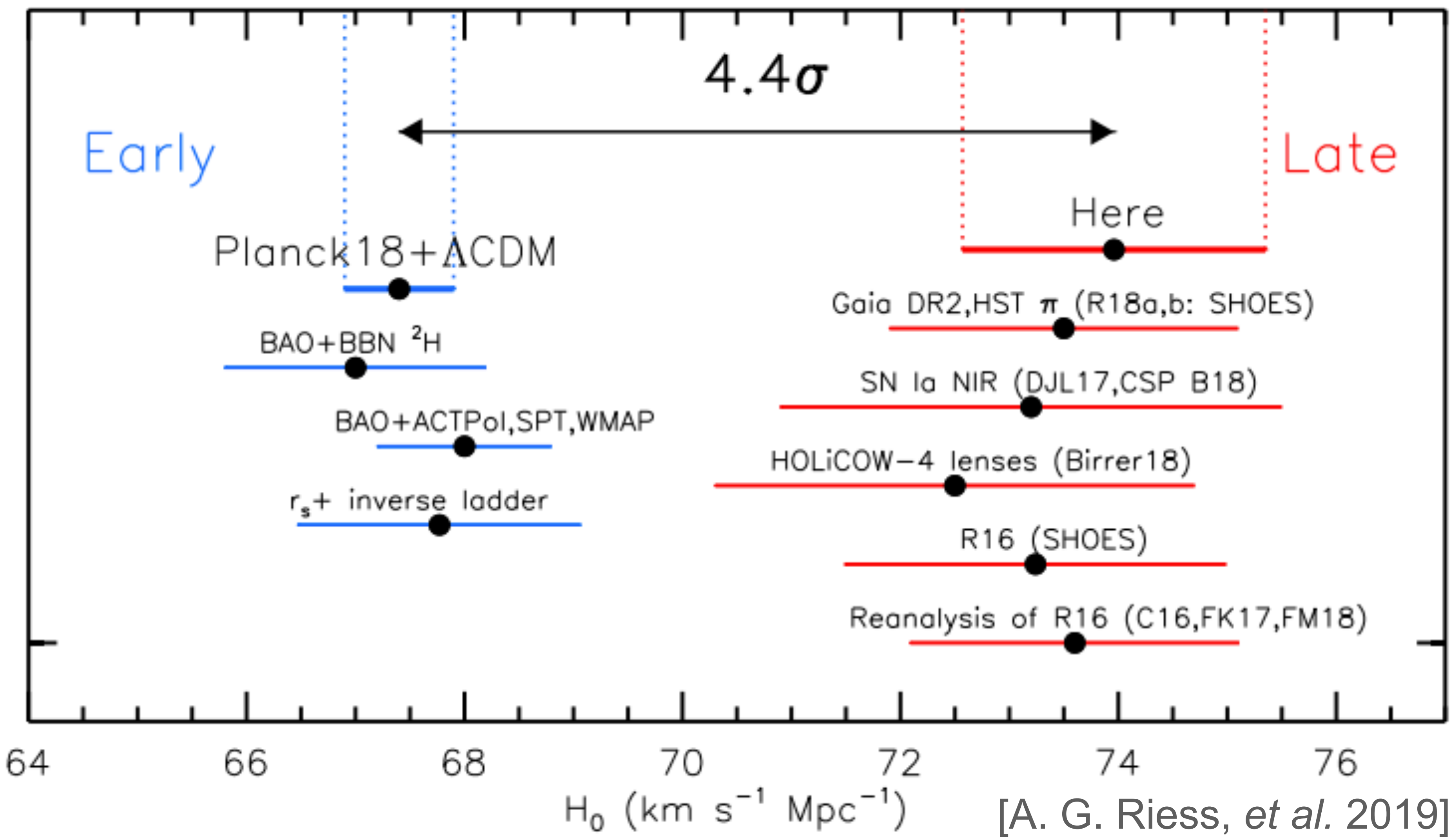
III. CB from EDE

IV. Summary

Early dark energy

■ Hubble tension

Hubble tension is a discrepancy of the value of H_0 between the local measurement and early-universe predictions.



[A. G. Riess, *et al.* 2019]

Hubble Space Telescope

$74.03 \pm 1.42\,\mathrm{km/s/Mpc}$

Planck 2018

$67.4 \pm 0.5\,\mathrm{km/s/Mpc}$

Early dark energy

■ Idea of Early dark energy [Karwal & Kamionkowski (2016)]

Angle of sound horizon

$$\theta_s^\star = \frac{r_s^\star}{D_A^\star}$$

$$\int_{z_\star}^{\infty} \mathrm{d}z \, \frac{c_s(z)}{H(z)}$$: Sound horizon

Recombination

$$\int_0^{z_\star} \frac{\mathrm{d}z}{H(z)}$$: Angular diameter distance

Increase $H(z)$ at $z \gtrsim z_\star$

$\rightarrow$ Decrease $r_s^\star$ and then $D_A^\star$

$\rightarrow$ The inferred value of H_0 increases.

Early dark energy

- Early dark energy model

EDE must satisfy the followings:

- Relevant at matter-radiation equality
- Behaves like dark energy at early times
- Dilutes faster than the matter after $z_\star$

An EDE model includes a field with a potential:

$$V_{\cos}^{(n)} \equiv m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n, \qquad n \geq 2$$

[Poulin, Smith, Karwal, Kamionkowski (2019)]

Around $\phi = 0$, $V(\phi)$ is approximated $\propto \phi^{2n}$.

$$\rho_\phi \propto a^{-6n/(n+1)}$$ [Turner (1983)]

Best-fit for EDE

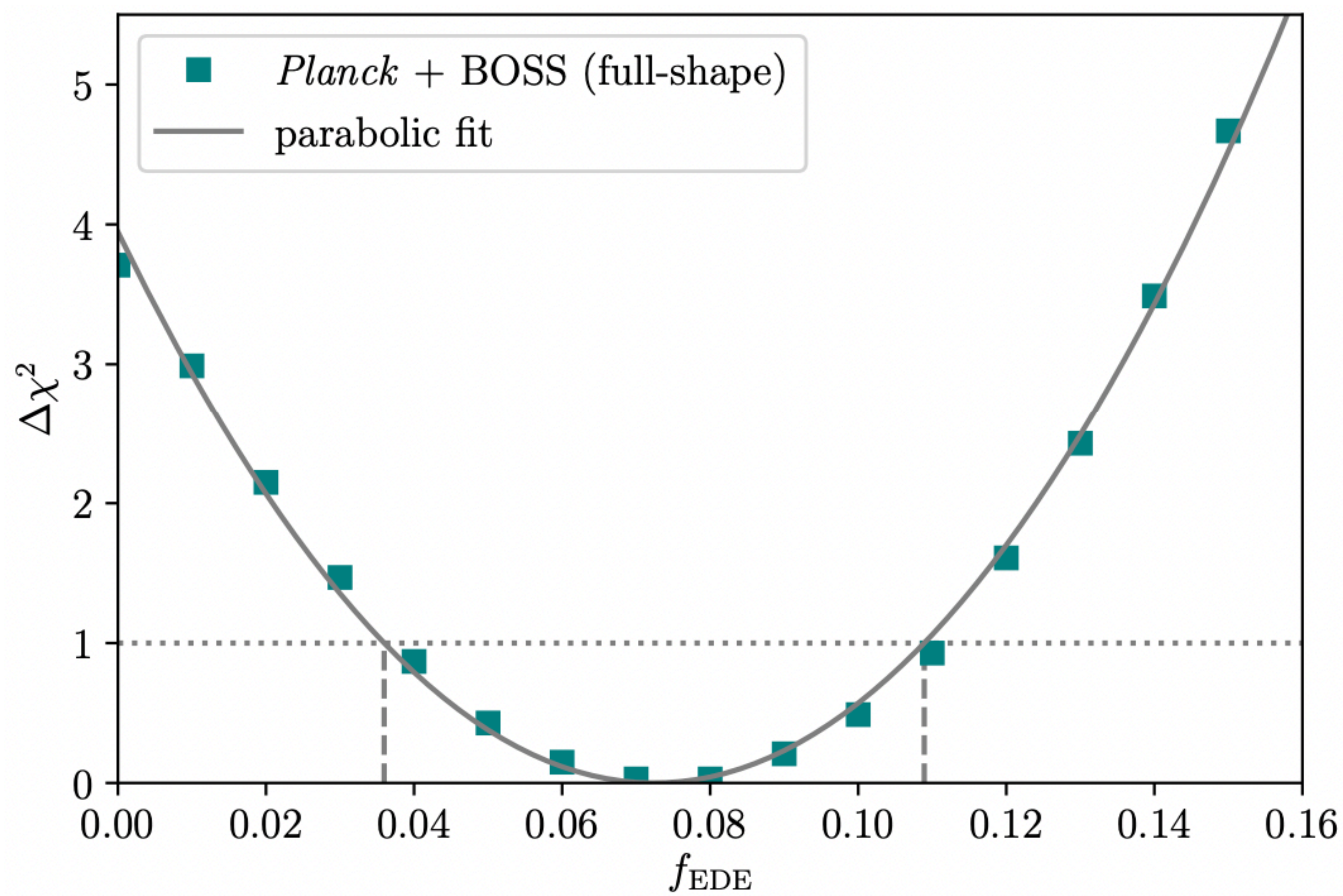
We consider a model with $V = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^3$.

Using a profile likelihood, the favored value of f_{EDE} is estimated:

$$f_{\mathrm{EDE}} = 0.072^{+0.071}_{-0.060}$$

at 95% C.L.

[Herold, Ferreira, Komatsu (2022)]



Contents

I. Cosmic birefringence

II. Early dark energy

III. CB from EDE

IV. Summary

Implementation

In the previous work, the effect of β has been implemented with an input data of $\phi(\eta)$. [Nakatsuka, Namikawa, Komatsu (2022)]

$$\underbrace{{}_{\pm2}\Delta_{P,l}(\eta_0,q)}_{\text{Fourier of } Q,\,U} = -\frac{3}{4}\sqrt{\frac{(l+2)!}{(l-2)!}}\int_0^{\eta_0} \mathrm{d}\eta\, \tau' e^{-\tau(\eta)}\Pi(\eta,q)\frac{j_l(x)}{x^2}e^{\pm 2i\underbrace{\beta(\eta)}_{\beta(\eta)=\frac{g}{2}\left[\phi(\eta_0)-\phi(\eta)\right]}}$$

$$\Delta_{E,l}(q) \pm i\Delta_{B,l}(q) \equiv -\ {}_{\pm2}\Delta_{P,l}(\eta_0,q)$$

To deal with EDE, $\phi(\eta)$ should be solved consistently with the background cosmology.

We extend the code to solve following CLASS_EDE code.

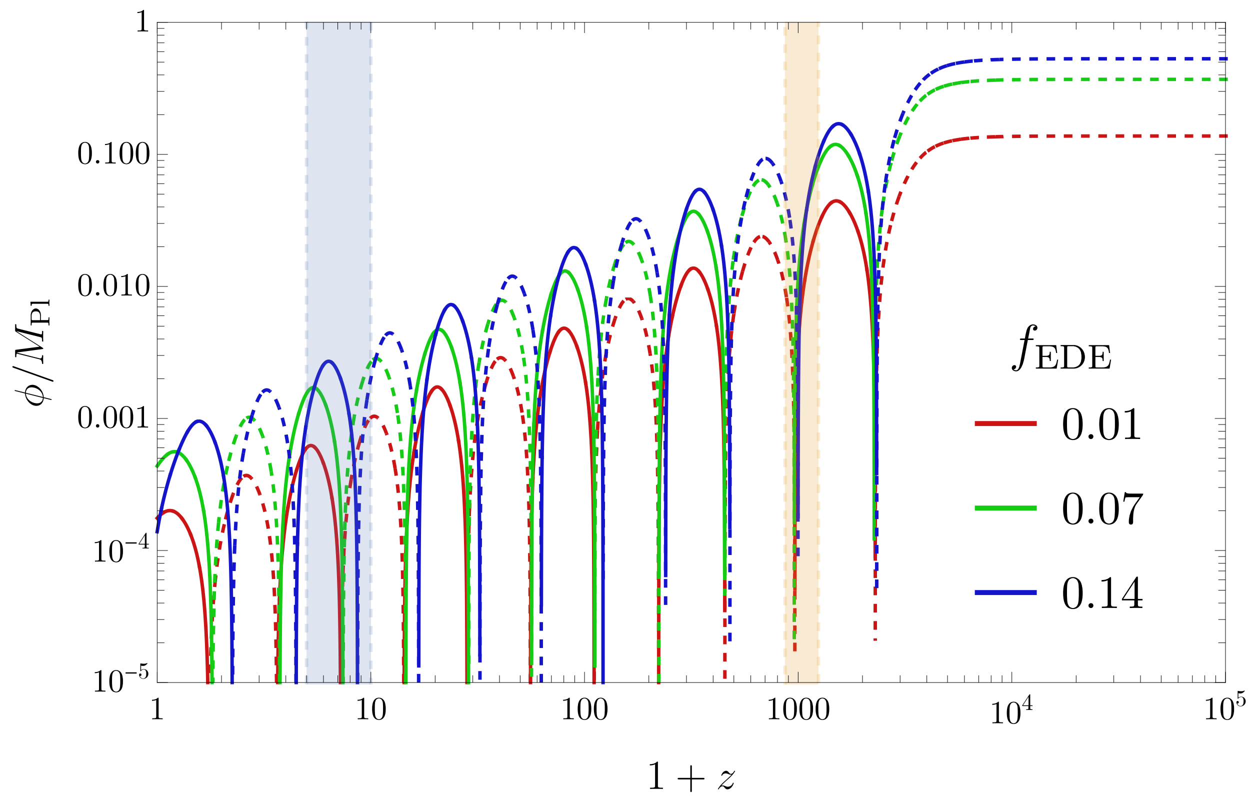
[Hill, McDonough, Toomey, Alexander (2020)]

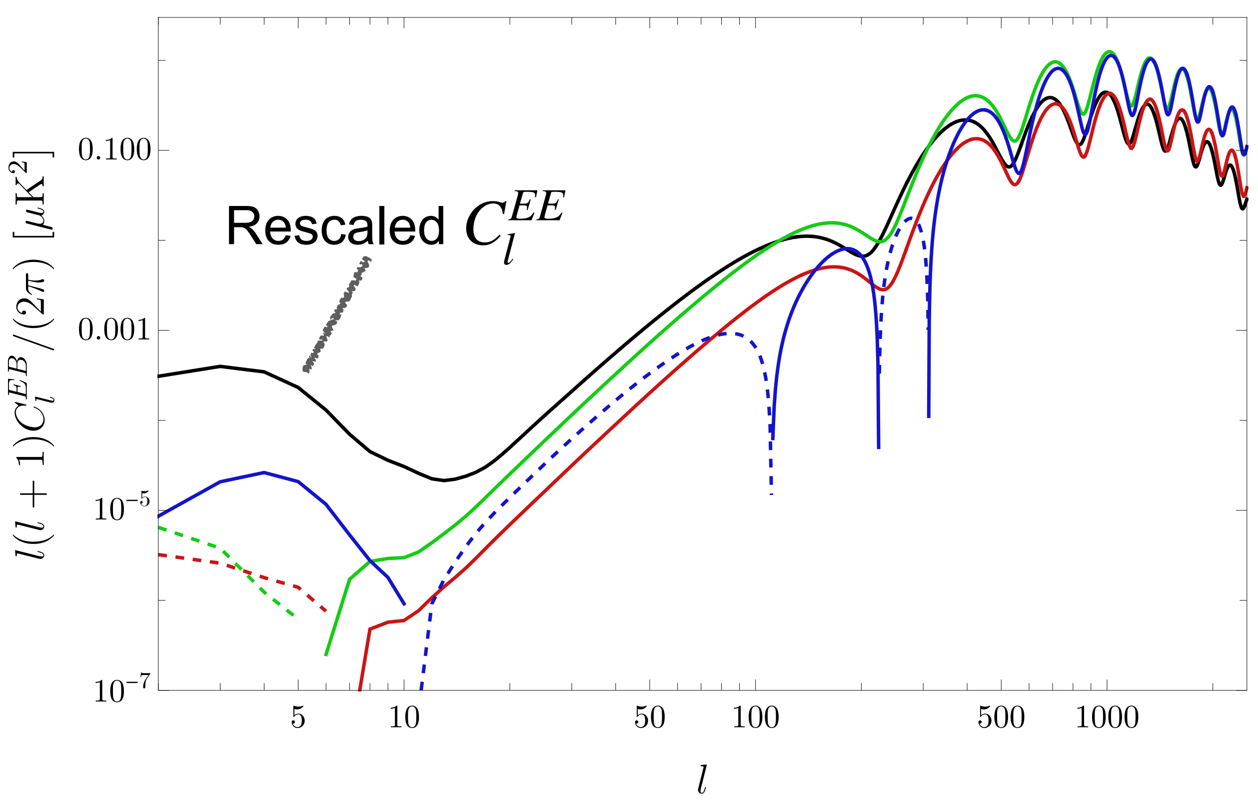
Isotropic CB from EDE

- EB angular power spectrum

We consider the EDE model with the best-fit parameters for $f_{\rm EDE} = 0.01, 0.07$, and 0.14.

Here, we use $g = M_{\rm Pl}^{-1}$ and C_l^{EB} scales as $\propto g$.



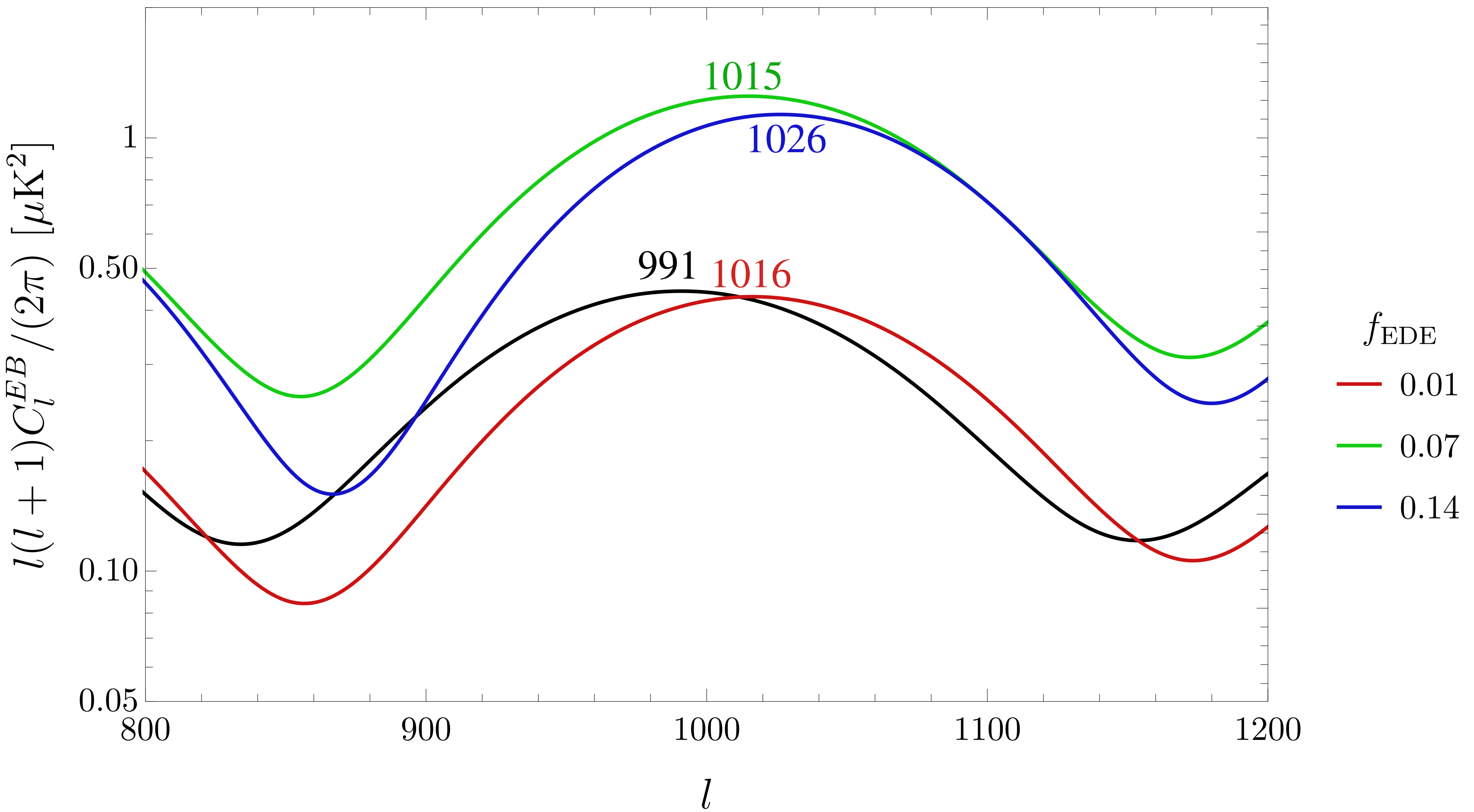


Isotropic CB from EDE

- EB angular power spectrum

C_l^{EB} is not proportional to C_l^{EE}.

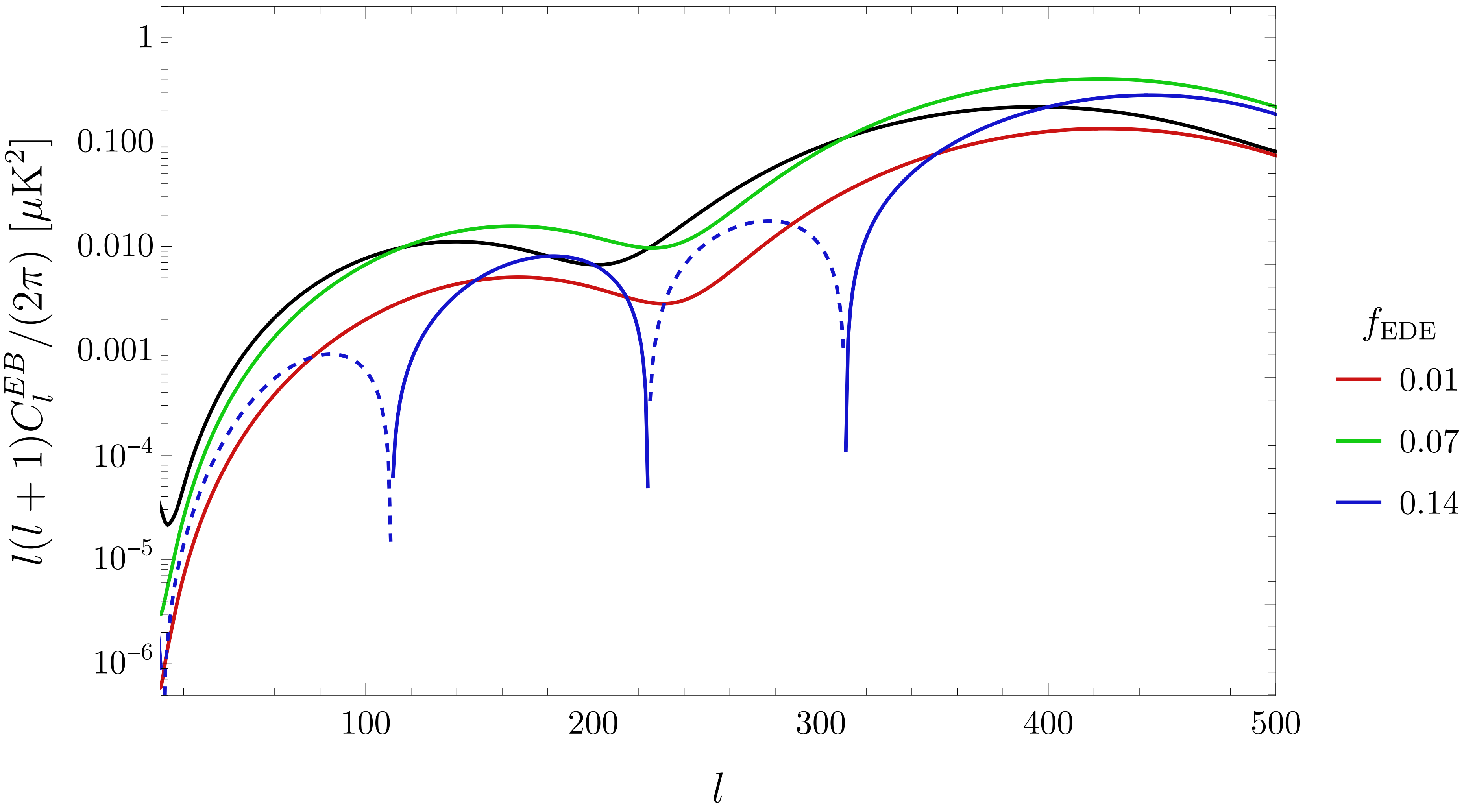
The peak is shifted by $\Delta l \gtrsim 10$.



Isotropic CB from EDE

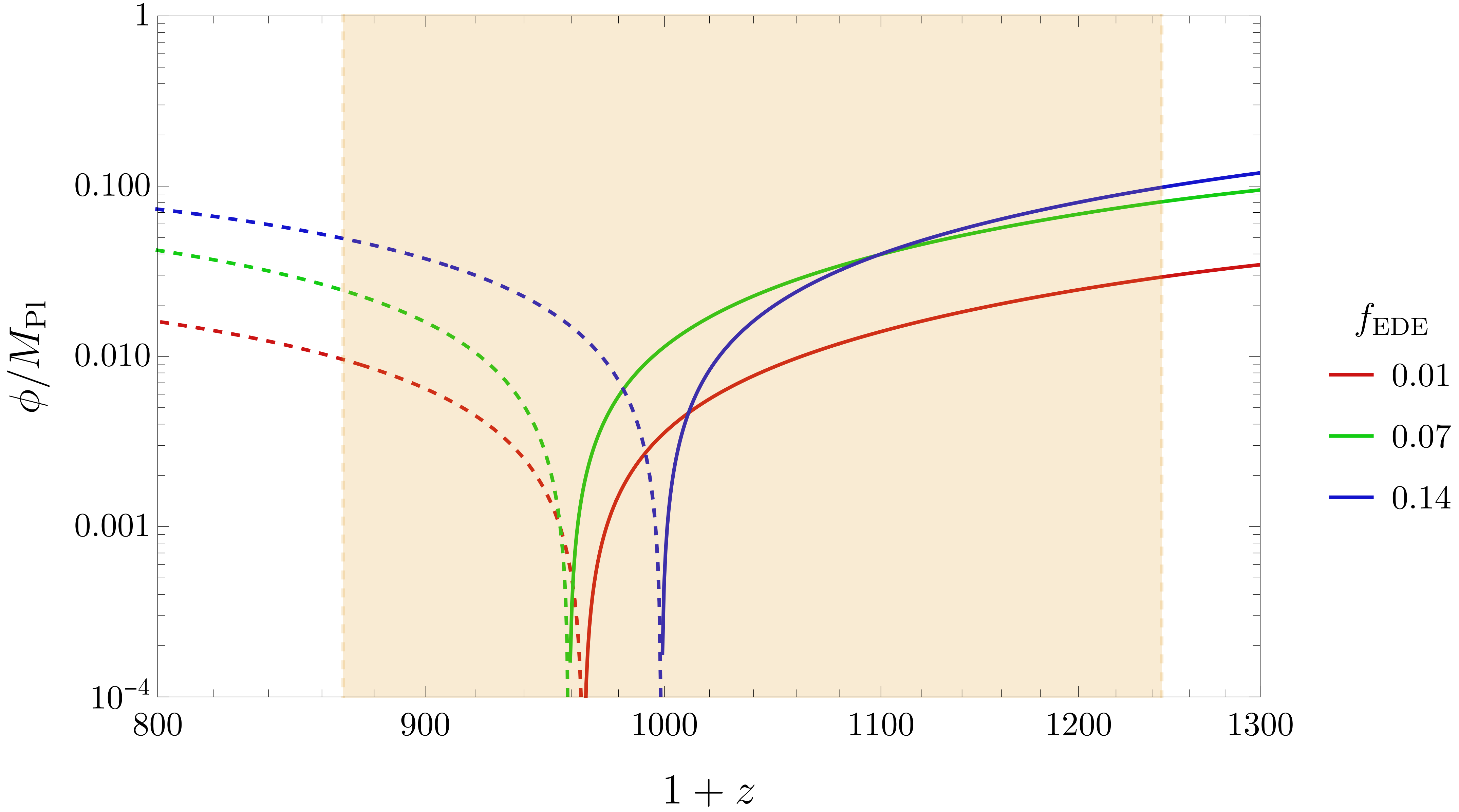
- EB angular power spectrum

For $f_{\mathrm{EDE}} = 0.14$, the sign of C_l^{EB} flips in mid l.



Isotropic CB from EDE

- EB angular power spectrum



Isotropic CB from EDE

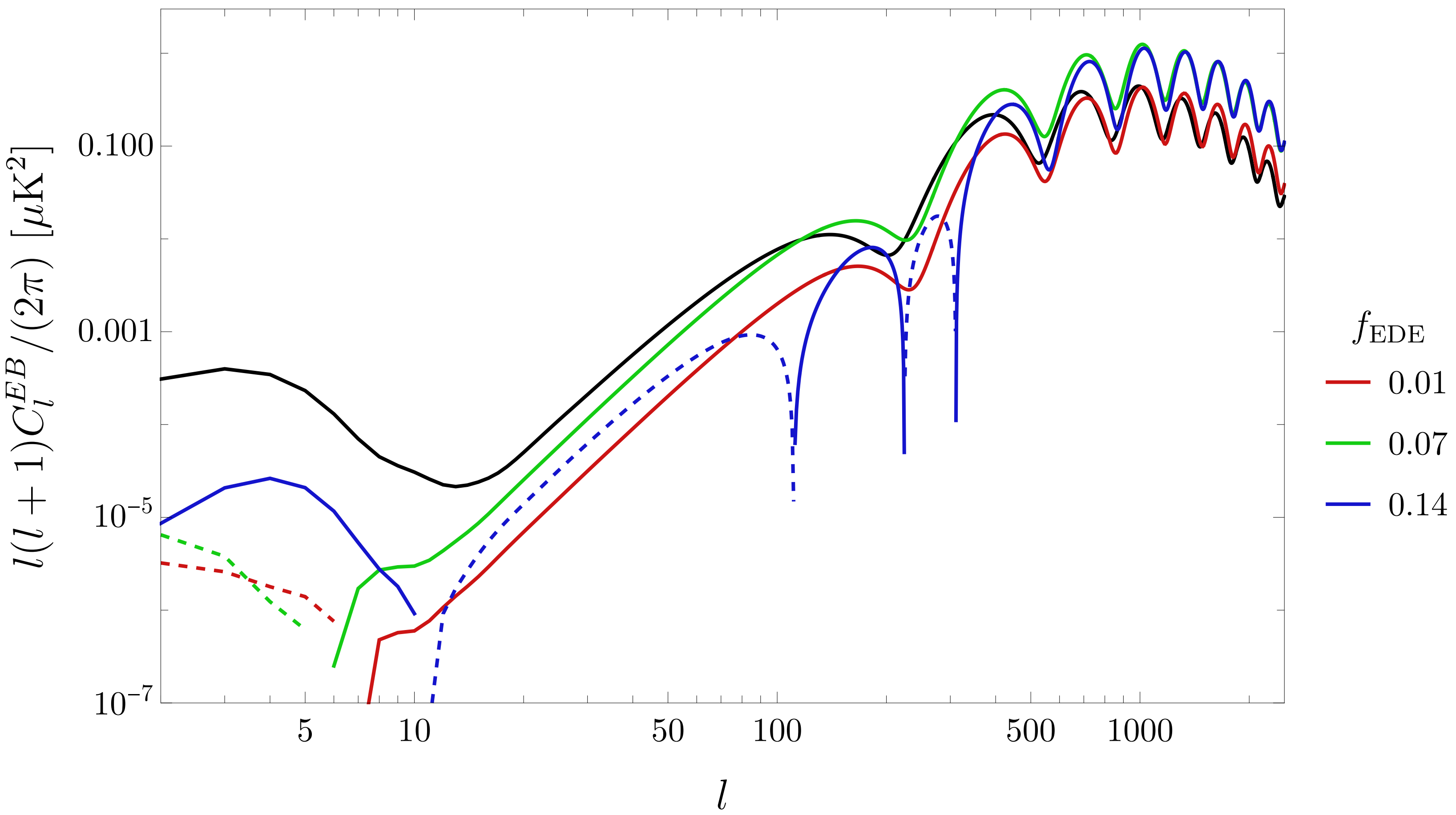
- EB angular power spectrum

Rough translation into β: $$\frac{\mathrm{Max}[C_l^{EB}]}{\mathrm{Max}[C_l^{EE}]} = \frac{1}{2}\sin(4\beta_{\mathrm{eff}})$$

We obtain $\beta_{\mathrm{eff}} = \beta_{\mathrm{obs}}$ with

$$gM_{\mathrm{Pl}} = \{1.2, 0.42, 0.47\}\,.$$

$\rightarrow g = \mathcal{O}\left(M_{\mathrm{Pl}}^{-1}\right)$ is favored.



Contents

I. Cosmic birefringence

II. Early dark energy

III. CB from EDE

IV. Summary

Summary

- I extended the modified CLASS codes and calculated the EB power spectrum when an EDE field induces cosmic birefringence.
- For all f_{EDE} I considered,

  the EB spectrum is not proportional to the EE spectrum.
- Especially, $f_{\mathrm{EDE}} = 0.14$ has a distinct shape.
- Future direction:

  Anisotropic CB

  Including lensing