Is Cosmic Birefringence model-dependent?

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Lu Yin, Joby Kochappan, Tuhin Ghosh, Bum-Hoon Lee.
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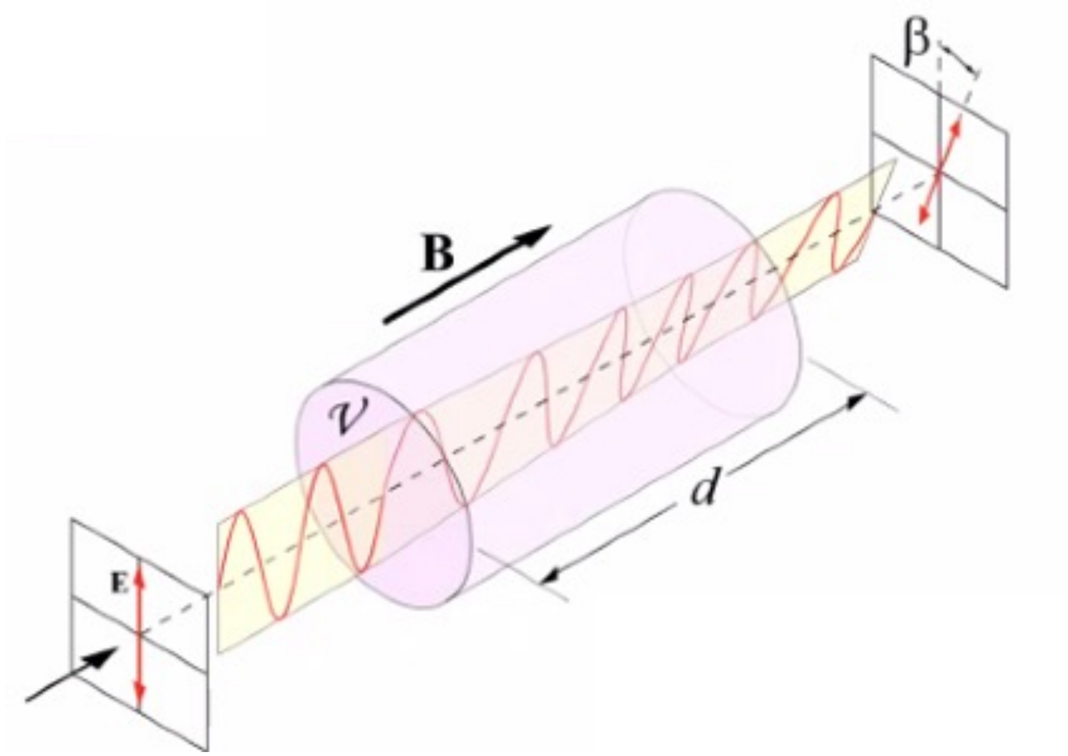
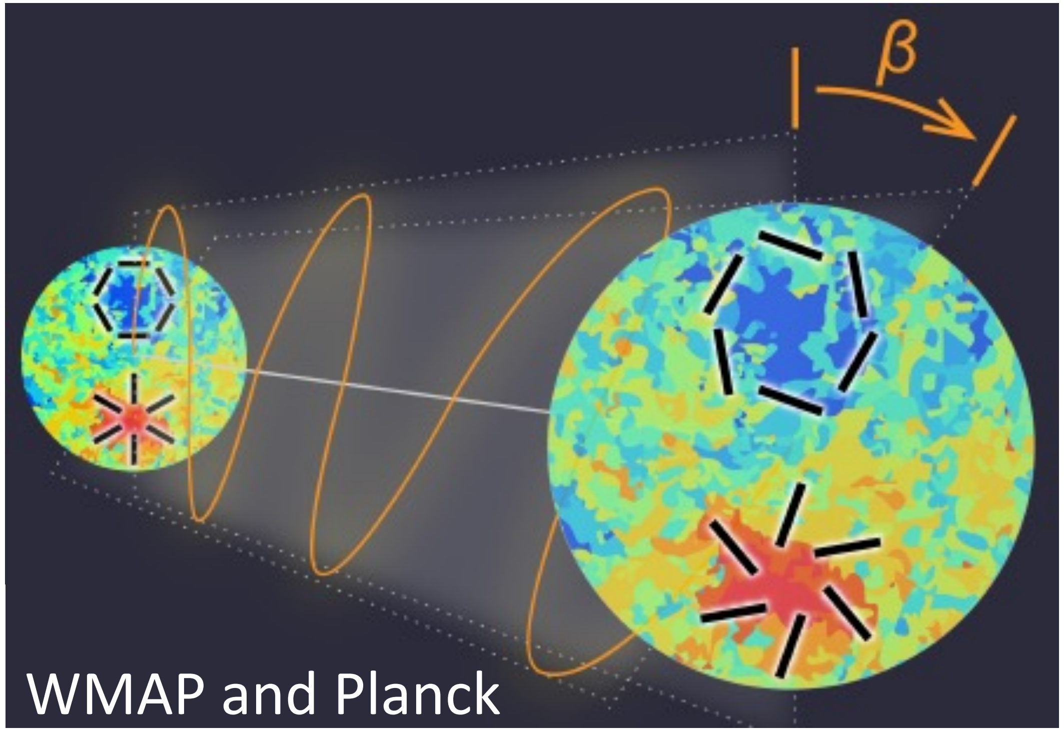
Gravity and Cosmology 2024
01/29–03/01, 2024

What is Cosmic Birefringence?

The rotation of the plane of linear polarization of photons





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

3.6σ

J.R.Eskilt, E.Komatsu, PRD 106 (2022) 6

Introduction to Cosmic Birefringence

- **Cosmic birefringence** is a parity-violating phenomenon, which might indicate the new physics beyond the standard cosmology (ΛCDM).

- Traditional explanation involves an axion coupled to the EM tensor via a Chern-Simons coupling.

Ni (1977); Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a / f_a$ (ϕ_a = axion field). The equations

- The axion can be dark matter or dark energy, which act as a “birefringence material” filling in our Universe

Introduction to Cosmic Birefringence

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\theta\partial^\mu\theta - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$$

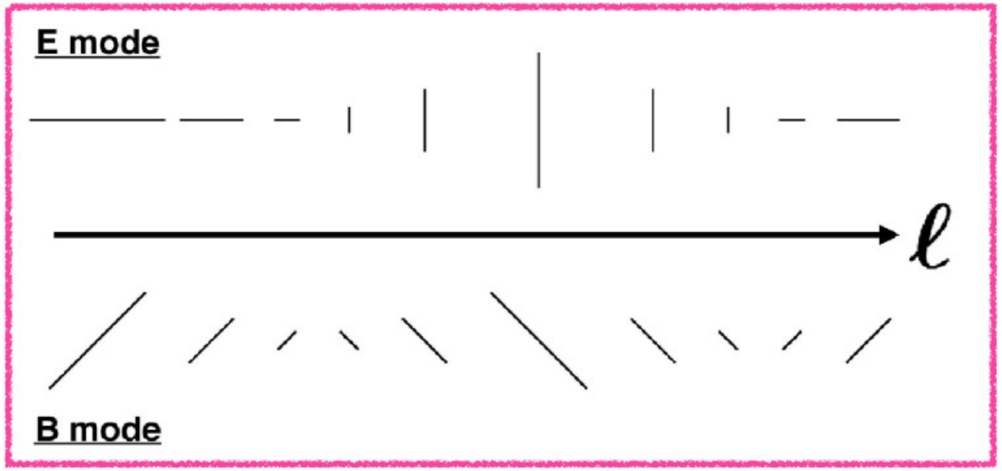
$$\sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$

Parity Odd

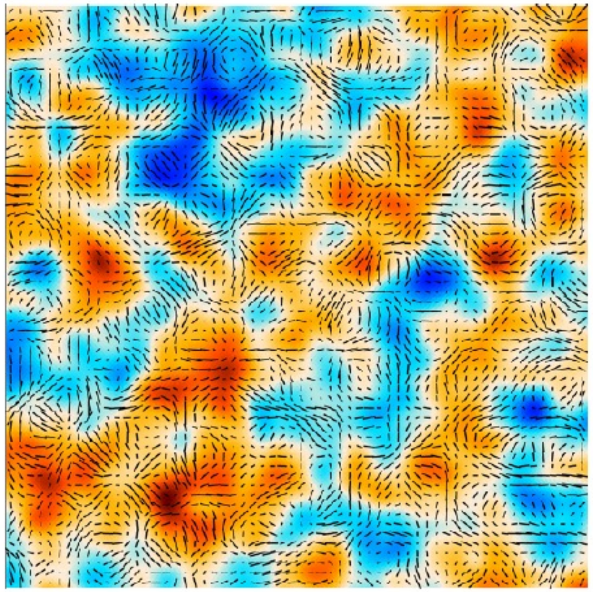
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation



- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

Introduction to Cosmic Birefringence

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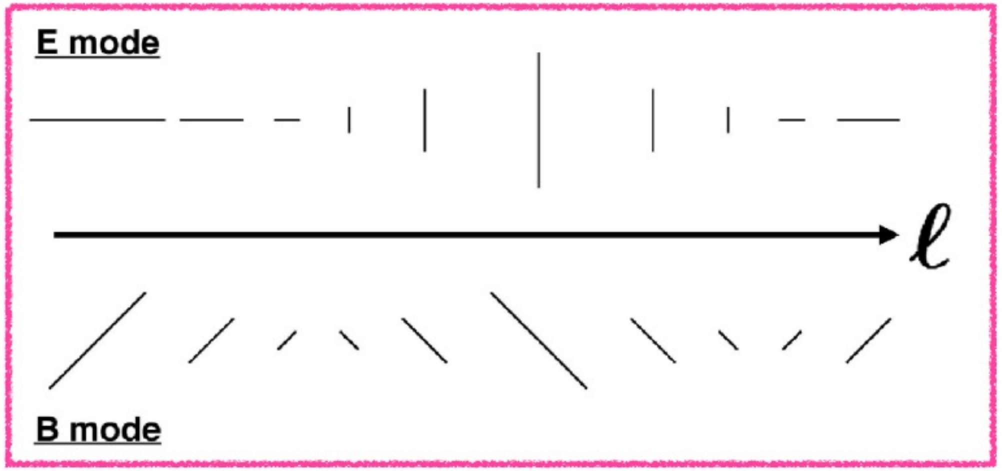

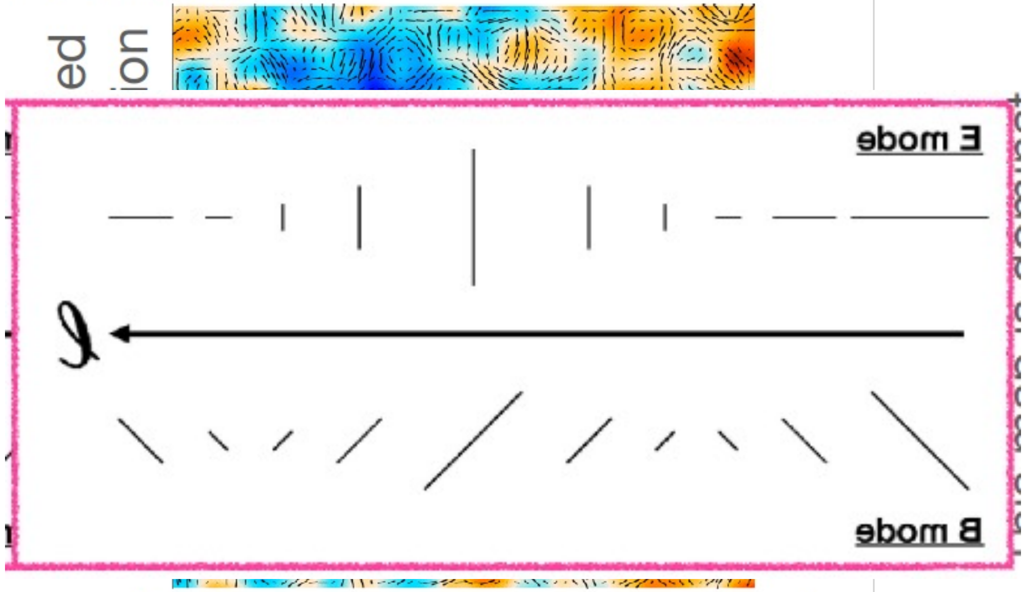

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$$\sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$

Parity Odd

The Equation of Motion modified to

$$\left(-\omega_\pm^2 + k^2\right) A_\pm(\eta) = 0 \quad \Rightarrow \quad \left(-\omega_\pm^2 + k^2 \pm 4g_a k\theta'\right) A_\pm(\eta) = 0$$

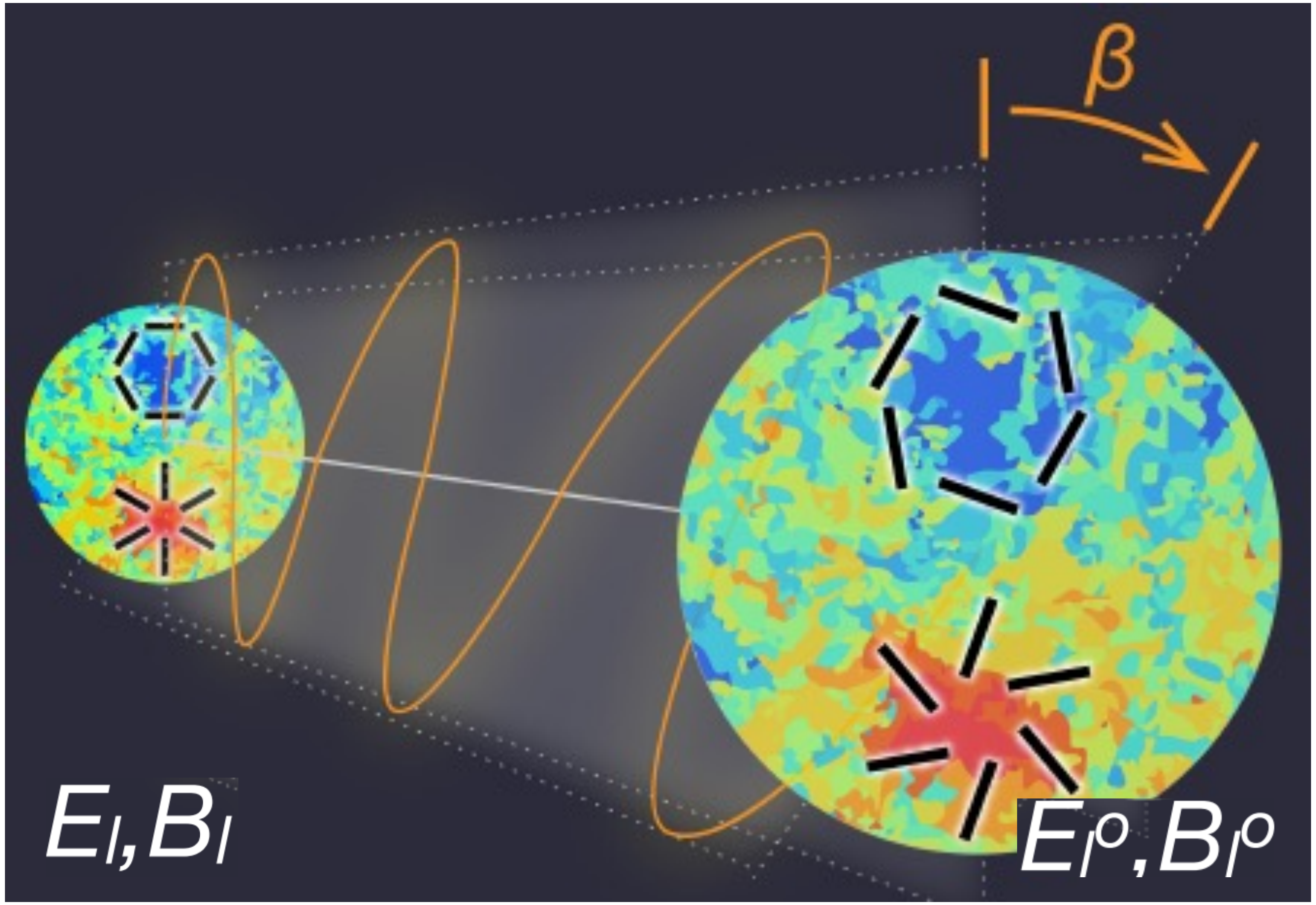
Different phase velocities for RH(+) and LH(-) photon polarizations

$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

Introduction to Cosmic Birefringence

- CB rotation angle $\beta = -2g_a \int_{t_{emitted}}^{t_{obs}} dt\dot{\theta} = 2g_a\left[\theta(t_e) - \theta(t_o)\right]$



E-B mixing by rotation of the linear polarization plane in CMB

$$E_\ell^{\rm o} = E_\ell \cos(2\beta) - B_\ell \sin(2\beta)$$
$$B_\ell^{\rm o} = E_\ell \sin(2\beta) + B_\ell \cos(2\beta)$$

$$E_\ell^{\rm o} \pm iB_\ell^{\rm o} = (E_\ell \pm iB_\ell)e^{\pm 2i\beta}$$

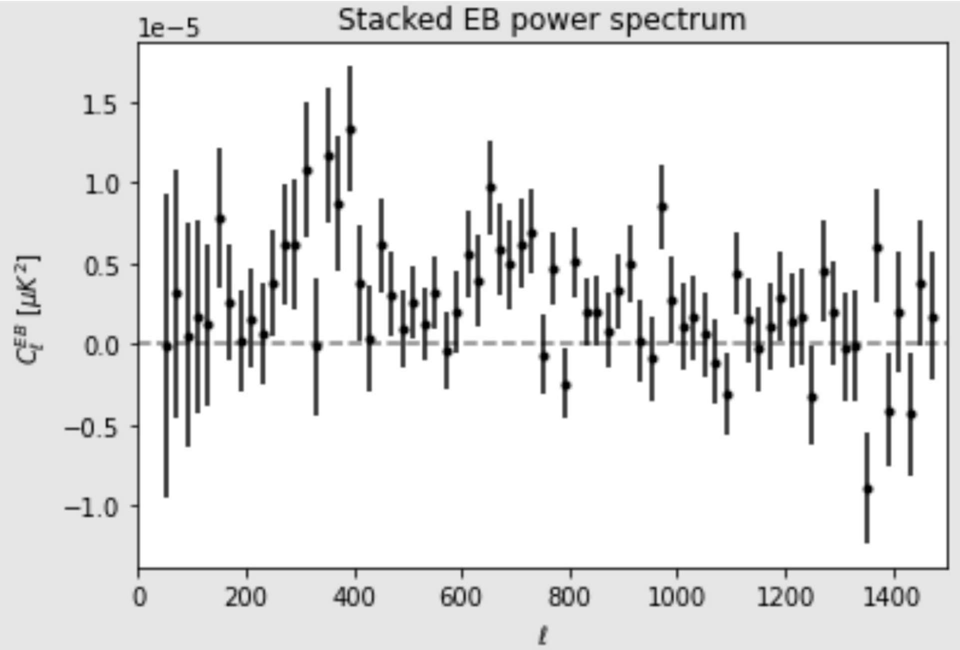
Cosmic Birefringence in the CMB

<E*B> correlation measures

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

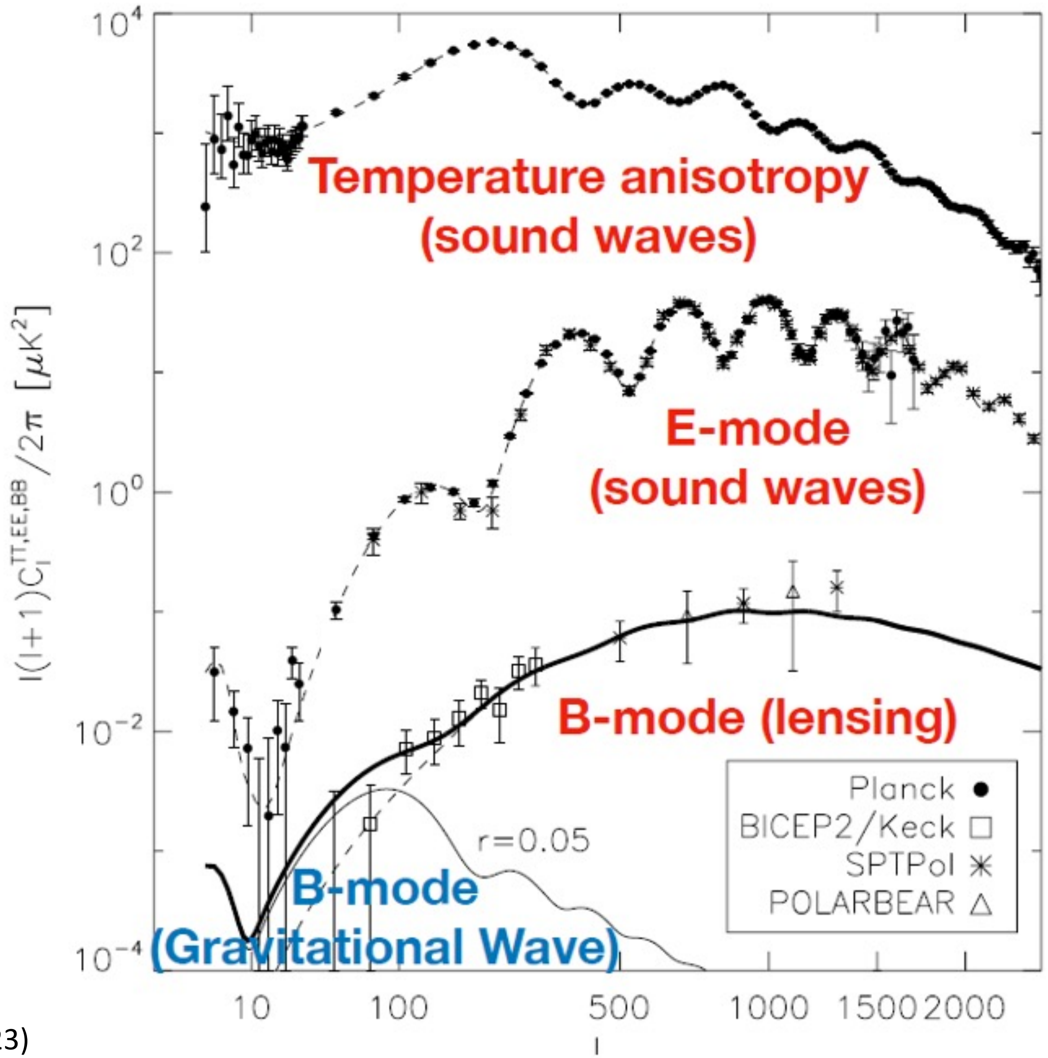
EB is generated by the difference between EE and BB spectra

If $\beta = 0$, the $C_l^{EB} = 0$, EB power spectra is 0.



J. R. Eskilt et al. (2023)
Planck Collaboration Int. LVII, Astron. Astrophys. 643, A42 (2020)

Observed EB Power Spectrum of Planck

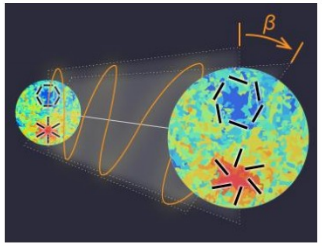


Planck Collaboration Int. LVII, Astron. Astrophys. 643, A42 (2020)

The past measurements

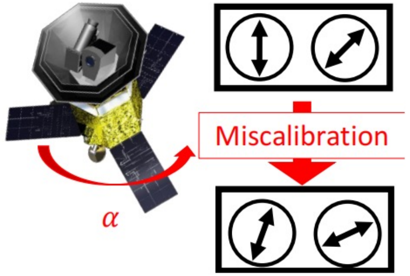
Measured of $\alpha + \beta$

- α+β = –6.0 ± 4.0 deg (Feng et al. 2006) first measurement
- α+β = –1.1 ± 1.4 deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- α+β = 0.55 ± 0.82 deg (QUaD Collaboration, Wu et al. 2009)
- …
- α+β = 0.31 ± 0.05 deg (Planck Collaboration 2016)
- α+β = –0.61 ± 0.22 deg (POLARBEAR Collaboration 2020)
- α+β = 0.63 ± 0.04 deg (SPT Collaboration, Bianchini et al. 2020)
- α+β = 0.12 ± 0.06 deg (ACT Collaboration, Namikawa et al. 2020)
- α+β = 0.07 ± 0.09 deg (ACT Collaboration, Choi et al. 2020)



Cosmic birefringence

OR



The past measurements

Now including the estimated systematic errors on α

- β = –6.0 ± 4.0 ± **??** deg (Feng et al. 2006)
- β = –1.1 ± 1.4 ± **1.5** deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- β = 0.55 ± 0.82 ± **0.5** deg (QUaD Collaboration, Wu et al. 2009)
- ...
- β = 0.31 ± 0.05 ± **0.28** deg (Planck Collaboration 2016)
- β = –0.61 ± 0.22 ± **??** deg (POLARBEAR Collaboration 2020)
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Motivation

Important question:

Is Cosmic Birefringence

model-dependent ?

Cosmic Birefrigence from Early Dark Energy

The pseudoscalar fields of early dark energy

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

$$V_{\rm EDE}(\phi) = m^2 f^2 [1 - \cos(\phi/f)]^n$$

UL Early Dark Energy model

V. Poulin et al. (2018)

$$V_{\rm R\&R}(\phi) = V_0 \left(\frac{\phi}{M_{\rm Pl}}\right)^{2n}$$

Rocl ‘n’ Roll model

P. Agrawal et al.(2019)

$$V_\alpha(\phi) = V_0 \frac{(1+\alpha_2)^{2n} \tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)^{2p}}{\left[1+\alpha_2 \tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)\right]^{2n}}$$

α -attractor model

M. Braglia et al. (2020)

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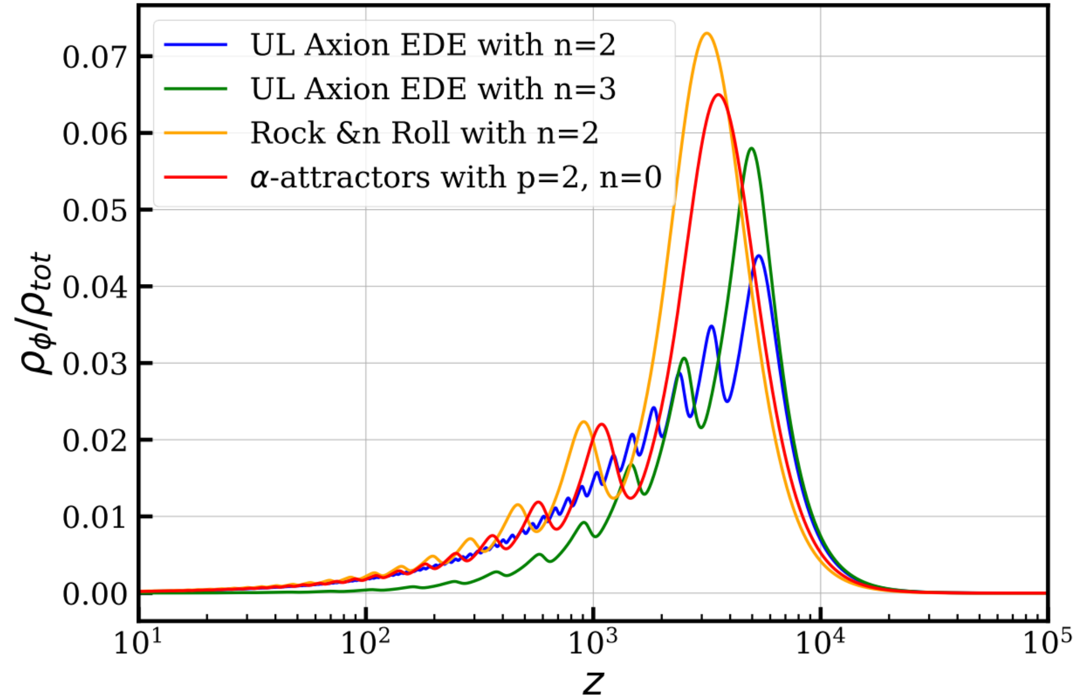
↑

$$V_{\rm EDE}(\phi) = m^2 f^2[1-\cos(\phi/f)]^n \qquad V_{\rm R\&R}(\phi) = V_0\left(\frac{\phi}{M_{\rm Pl}}\right)^{2n} \qquad V_\alpha(\phi) = V_0\frac{(1+\alpha_2)^{2n}\tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)^{2p}}{\left[1+\alpha_2\tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)\right]^{2n}}$$



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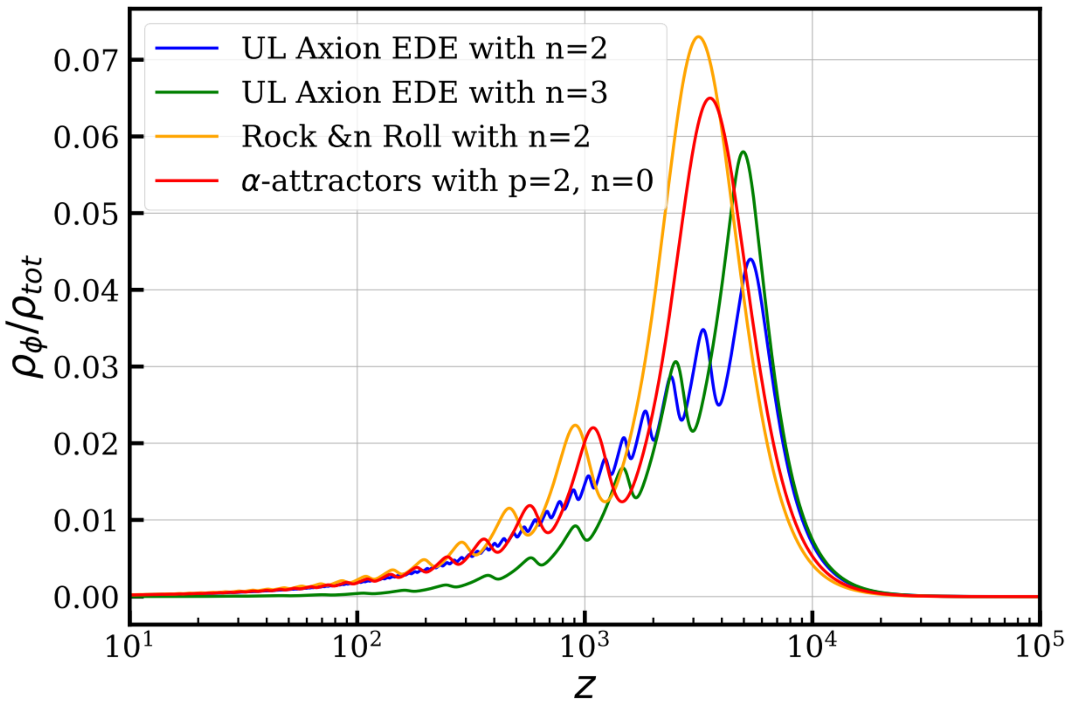
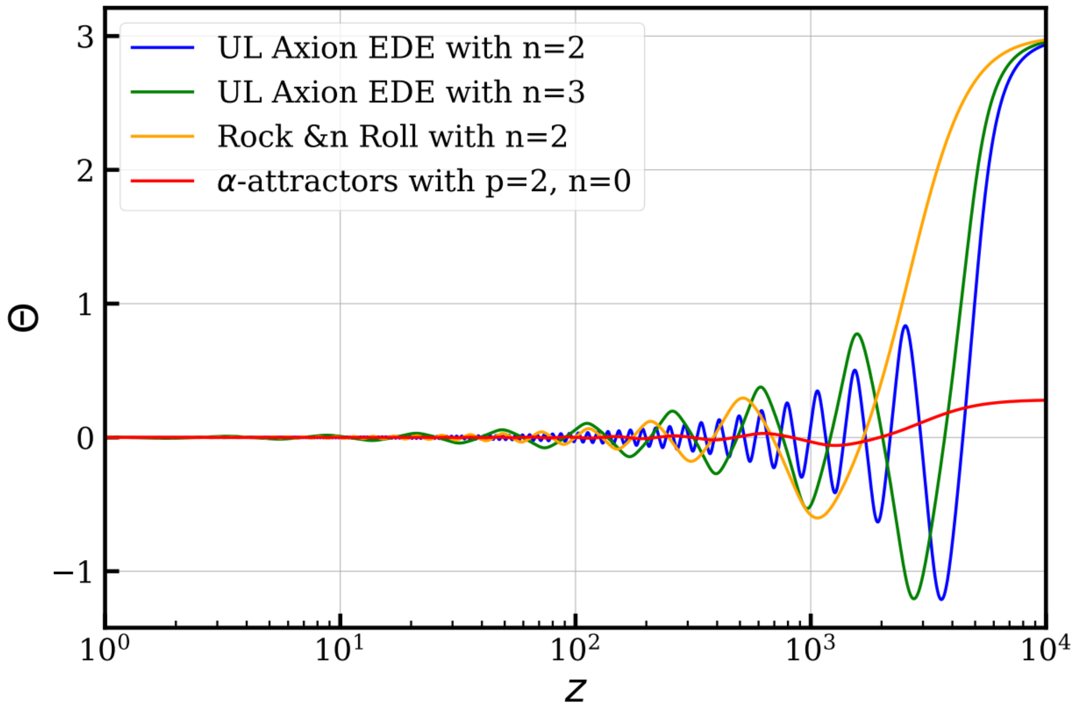
$$\Theta_\alpha \equiv \phi/\left(\sqrt{6\alpha_1}M_{\rm pl}\right)$$

$$V_{\rm EDE}(\phi) = m^2 f^2[1-\cos(\phi/f)]^n \qquad V_{\rm R\&R}(\phi) = V_0\left(\frac{\phi}{M_{\rm Pl}}\right)^{2n} \qquad V_\alpha(\phi) = V_0\frac{(1+\alpha_2)^{2n}\tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)^{2p}}{\left[1+\alpha_2\tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)\right]^{2n}}$$

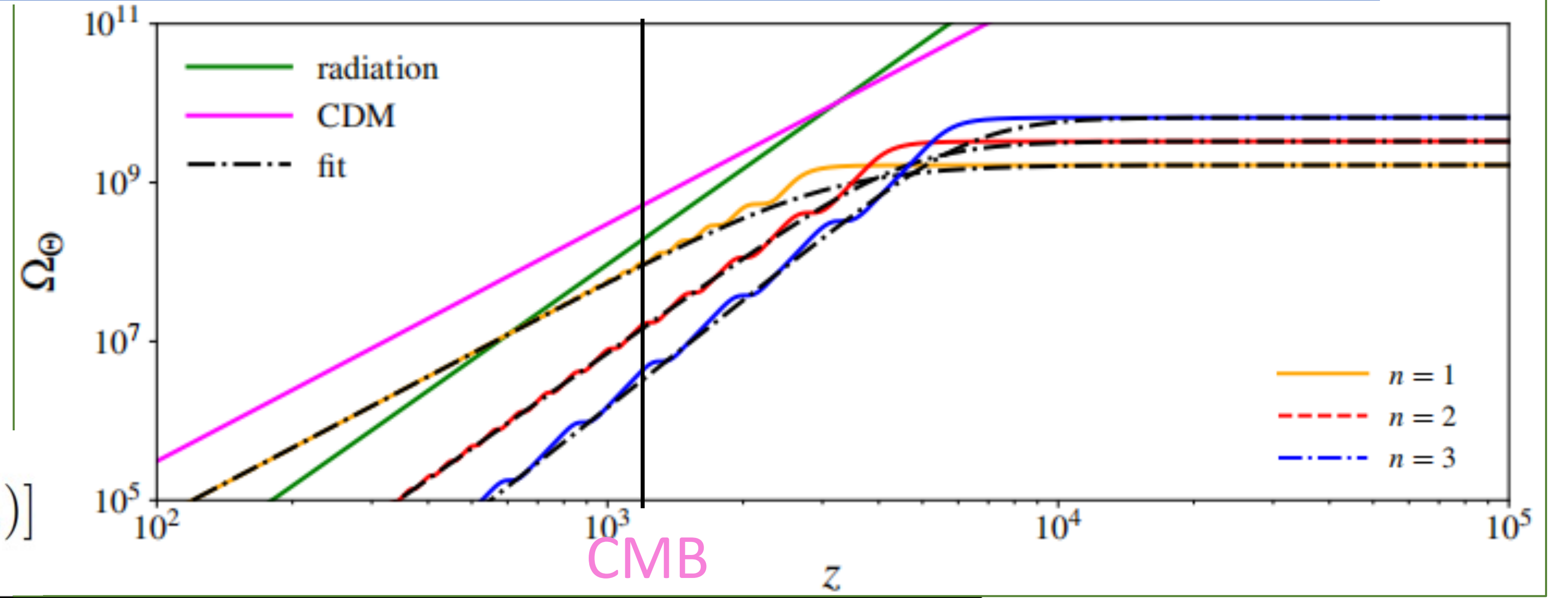


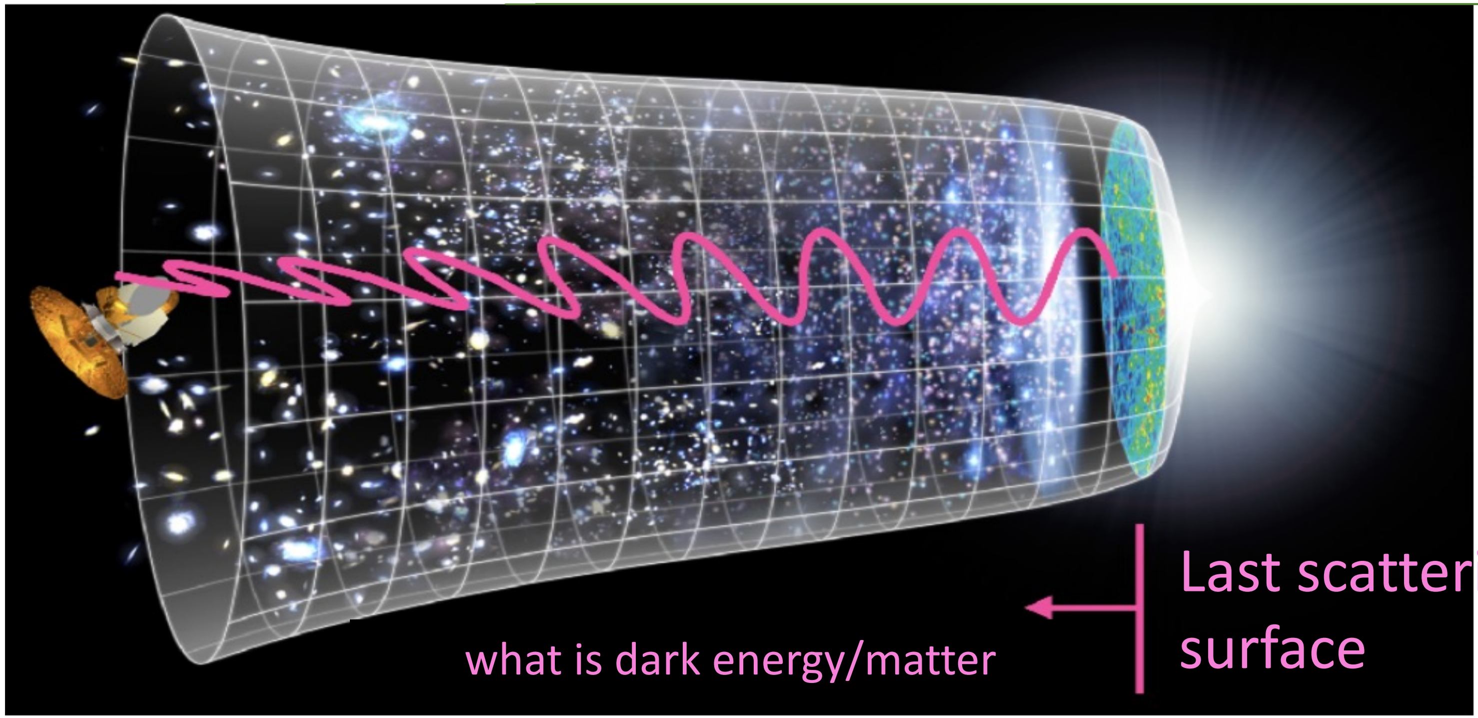


Cosmic Birefrigence from Early Dark Energy

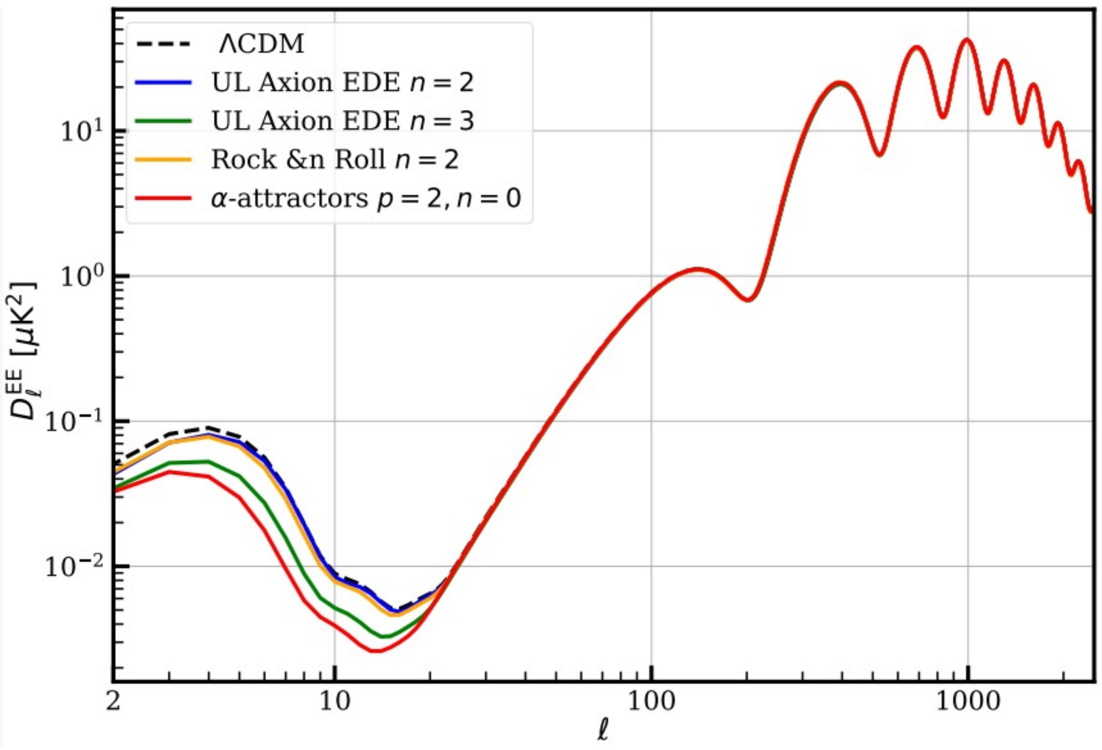
UL Early Dark Energy Model

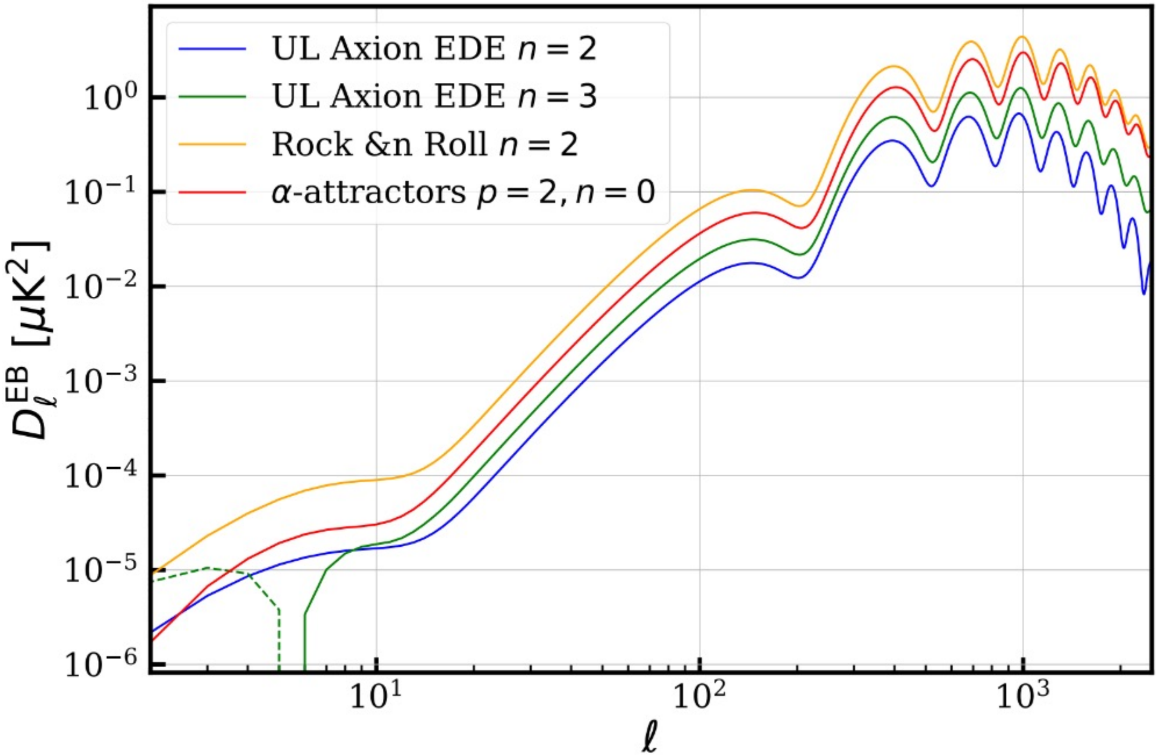
$$\beta = -2g_a \int_{t_{emitted}}^{t_{obs}} dt\dot{\theta} = 2g_a\left[\theta(t_e) - \theta(t_o)\right]$$





Difference in EE and EB power spectra





gM_Pl=1

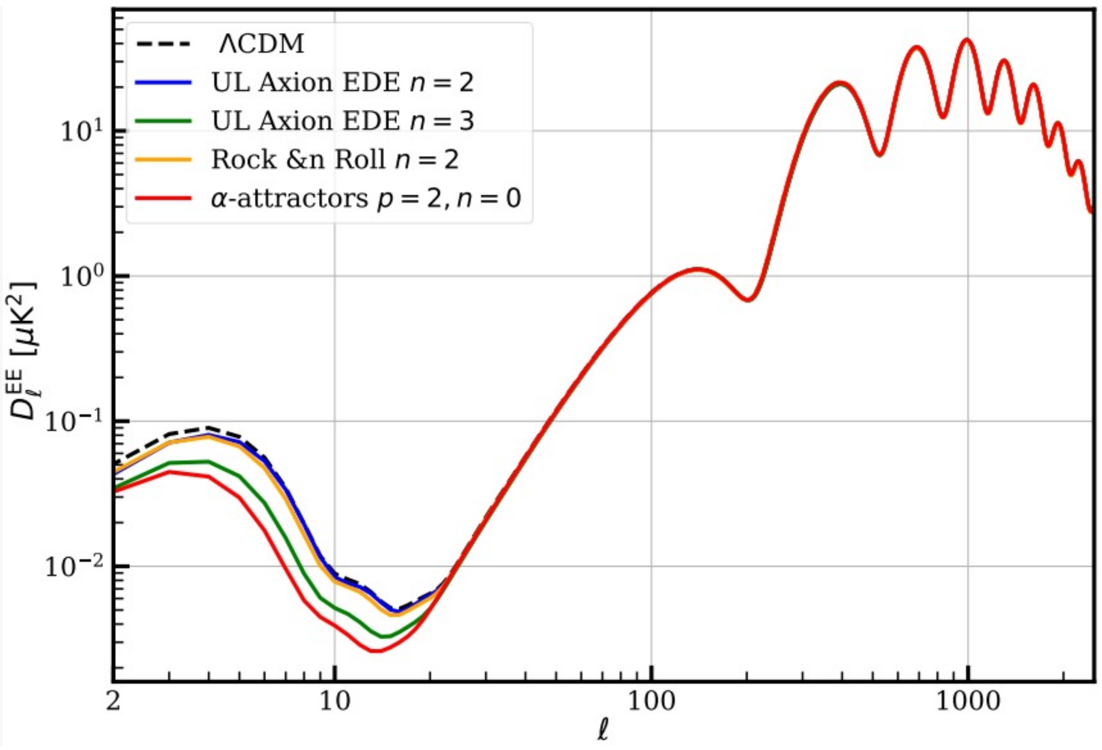
$$\beta(t) = -\frac{1}{2}\int_t^{t_0} d\tilde{t}\,(\omega_+ - \omega_-) = \frac{g}{2}\left[\phi(t_0) - \phi(t)\right]$$

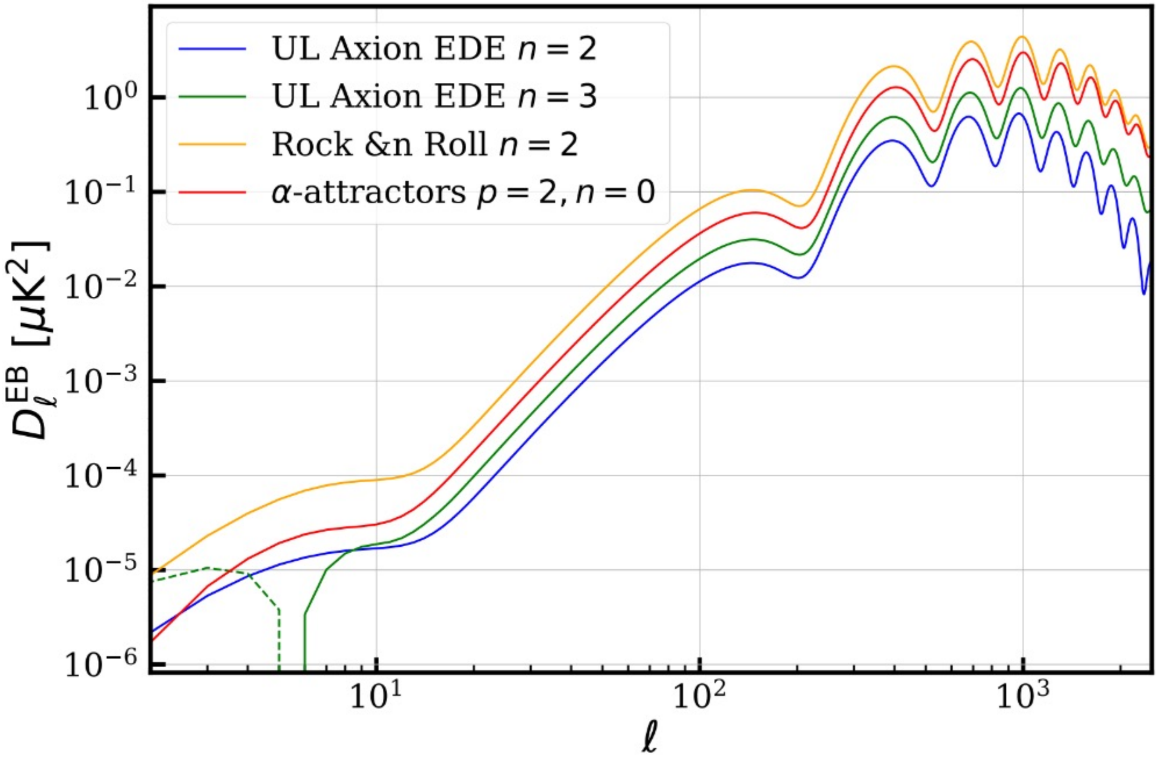
$$_{\pm2}\Delta_{P,l}(\eta_0, q) = -\frac{3}{4}\sqrt{\frac{(l+2)!}{(l-2)!}}\int_0^{\eta_0} d\eta\,\tau' e^{-\tau(\eta)}\Pi(\eta, q) \times \frac{j_\ell(x)}{x^2}\boxed{e^{\pm 2i\beta(\eta)}},$$

new term

$$C_\ell^{XY} = 4\pi\int d(\ln q)\mathcal{P}_s(q)\Delta_{X,l}(q)\Delta_{Y,l}(q),$$

Difference in EE and EB power spectra





EB power spectra is an important smoking gun for different early dark energy models, beyond the EE spectra

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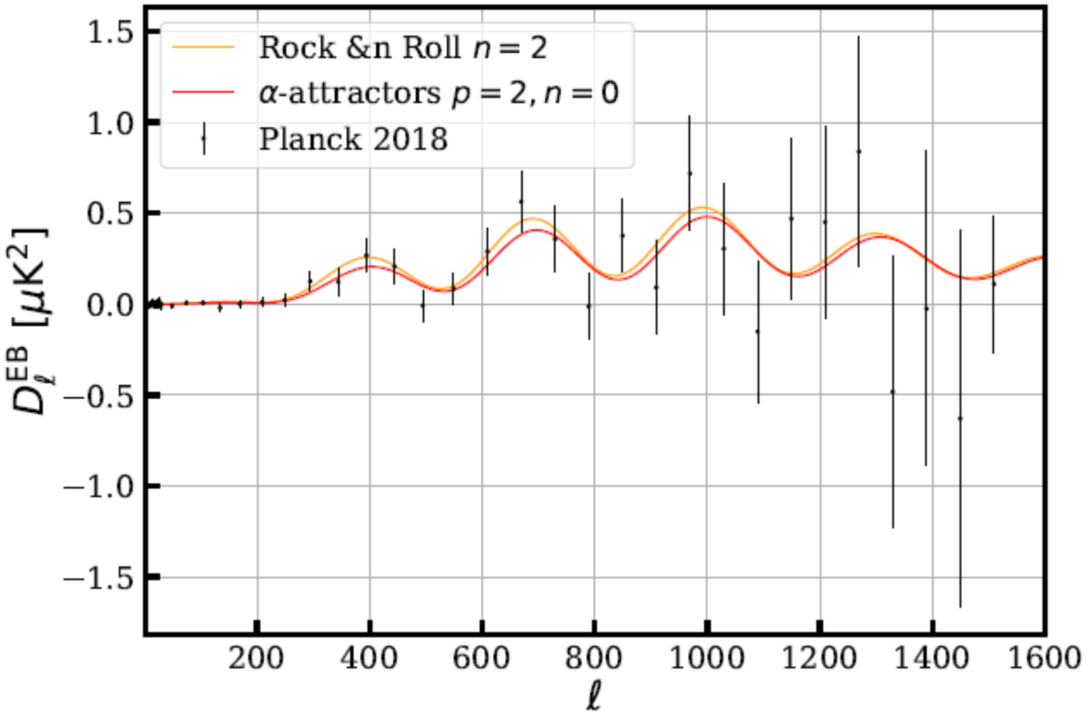
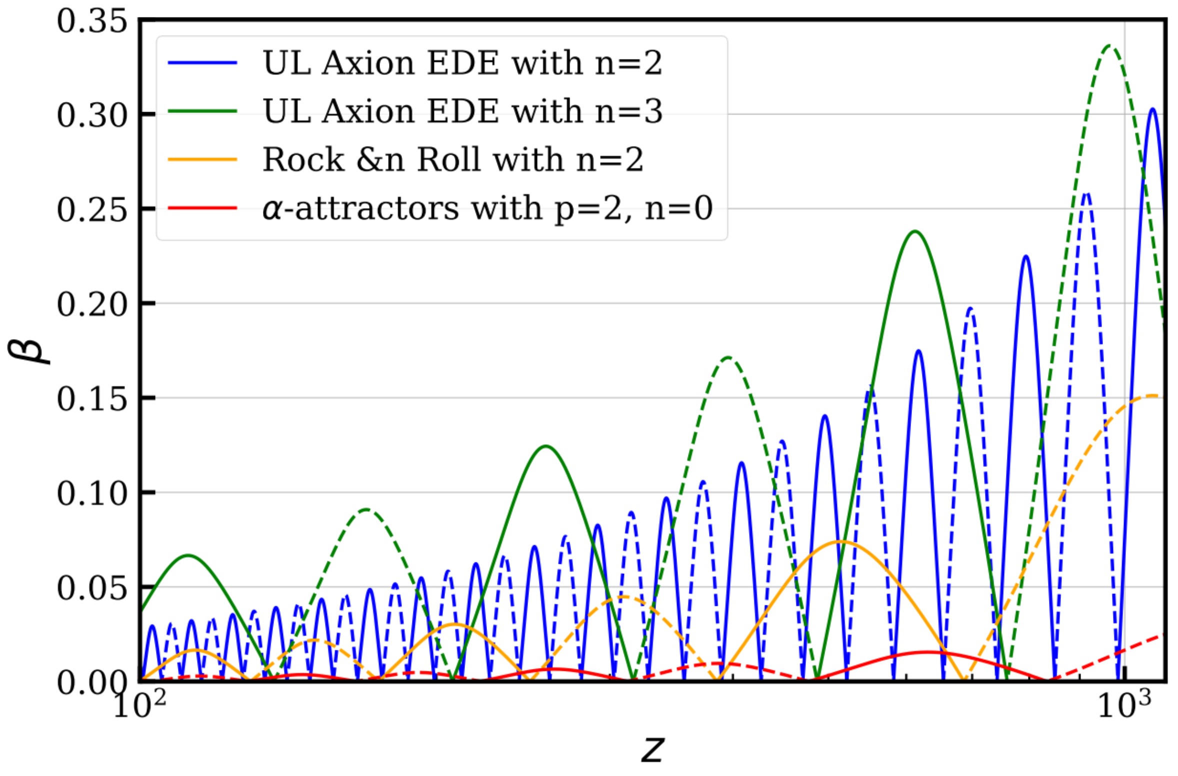
Best fit results form Planck observation

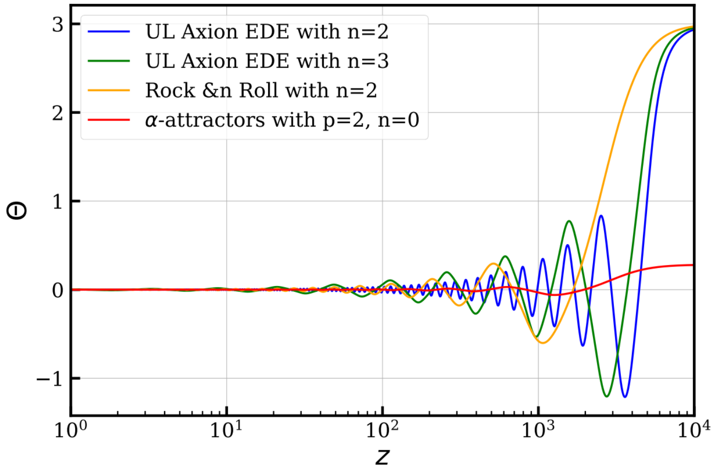


Parameter	ΛCDM	α-attractor	Rock 'n' Roll
gM_{Pl}	0	0.16	0.12
β at CMB	0	0.02°	0.15°

1. value of Chern-Simons constant term is model-dependent
2. current data can not distinguish the two models

The rotation of the plane results from best fit of g





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β at CMB	0	0.02°	0.15°

The value of g is model dependent.

Moreover, the rotation angle β is also highly model dependent.

Conclutions

- **Cosmic Birefringence** is a remarkable parity-violating effect, which is beyond the standard cosmology prediction;
- Recently, new breakthrough in CMB data analysis leads to a hint towards a nonzero CB rotation angle, $\beta = 0.34 \pm 0.09$ deg (68%CL; nearly full sky)
- We studied EB mode of Rock `n' Roll, and α-attractor scalar models for the first time. The value of g is model dependent. Moreover, the rotation angle β is also highly model dependent.
- The EB spectra alone can not distinguish the two models based on current data. It is an important smoking gun for different early dark energy models, beyond the EE spectra.

Thank you