Is Cosmic Birefringence model-dependent?

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arXiv:2305.07937 [astro-ph.CO]

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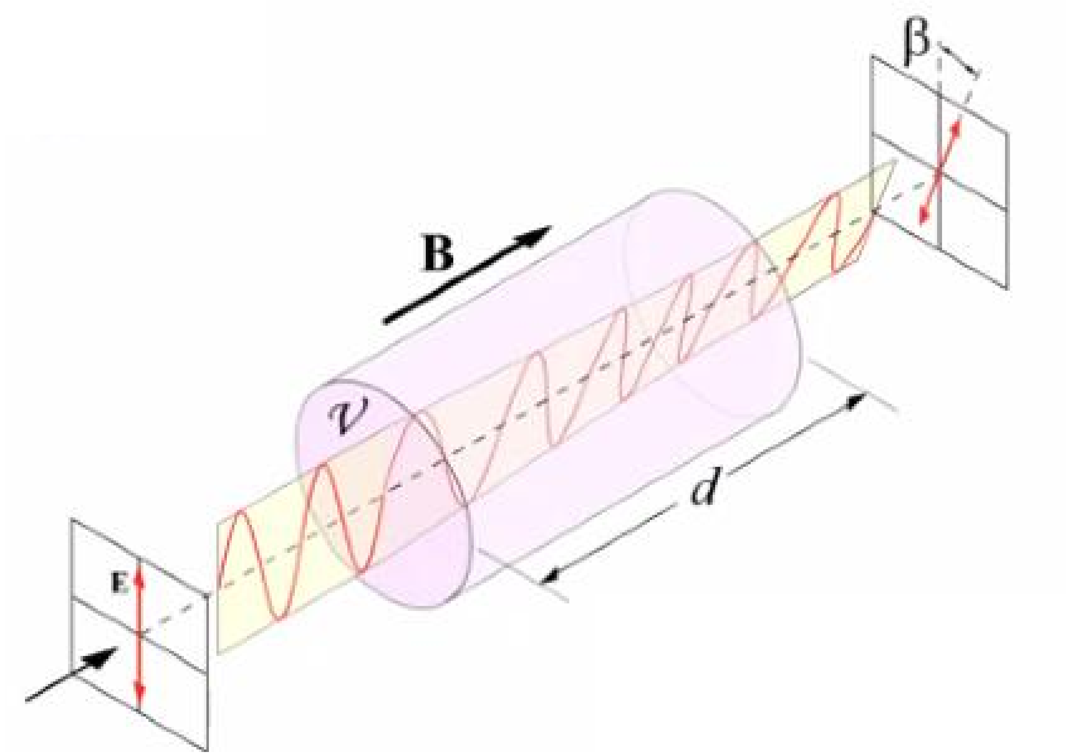
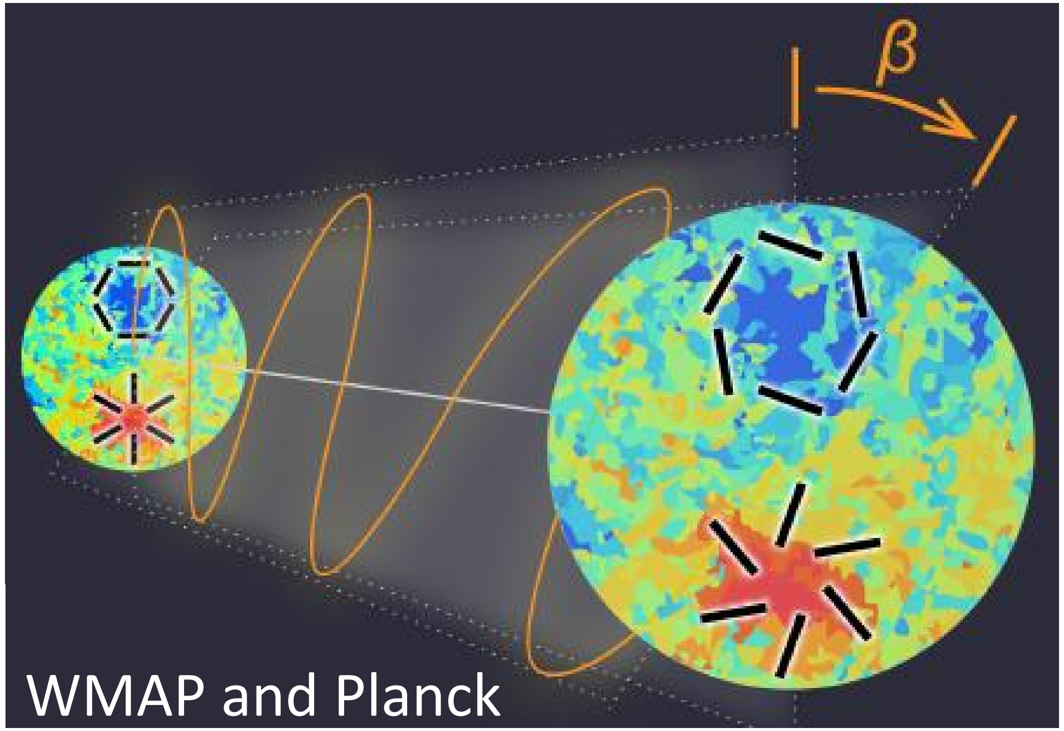
What is Cosmic Birefringence?

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

The Equation of Motion modified to

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

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

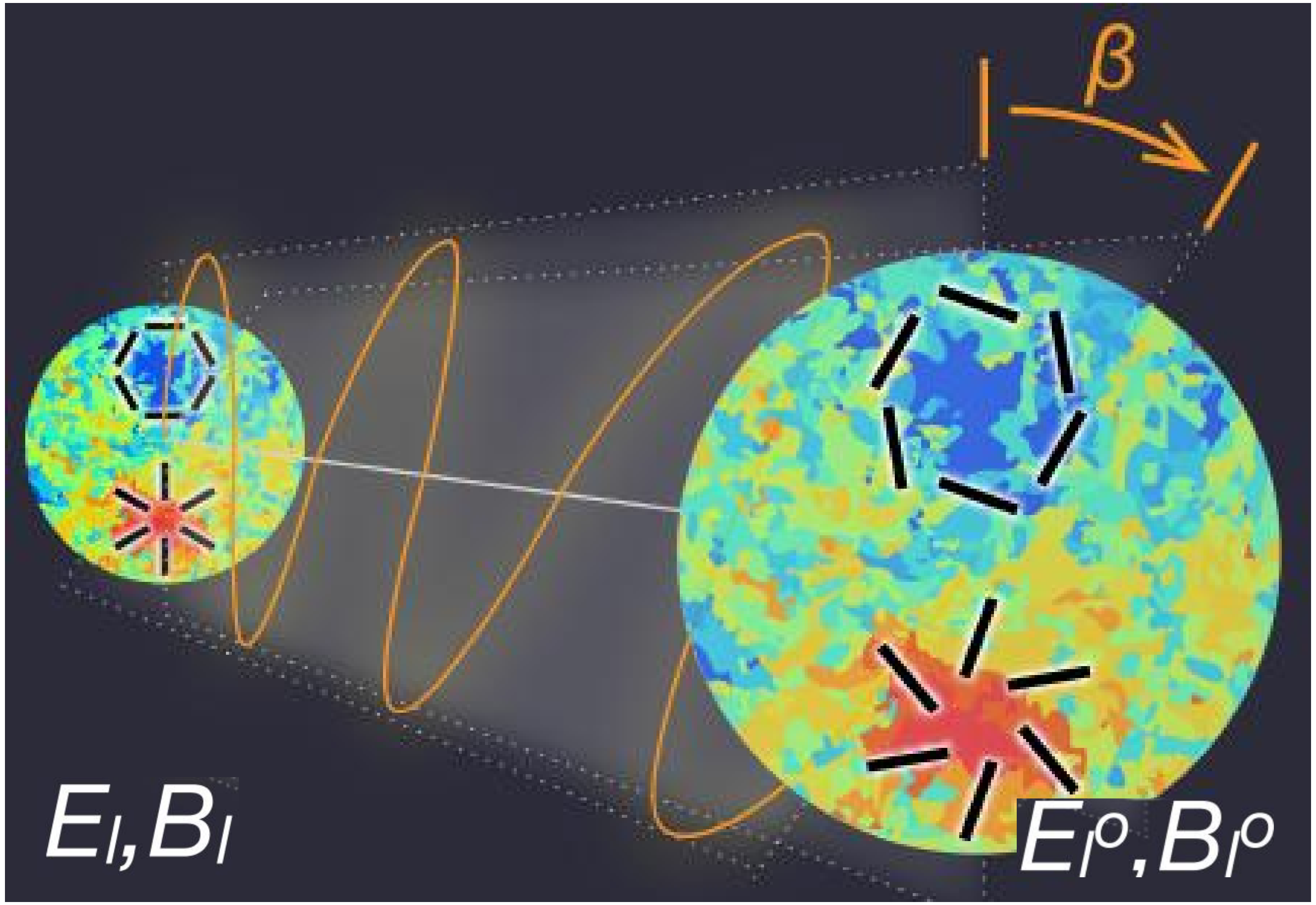
$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

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

Introduction to Cosmic Birefringence

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

- 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

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

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

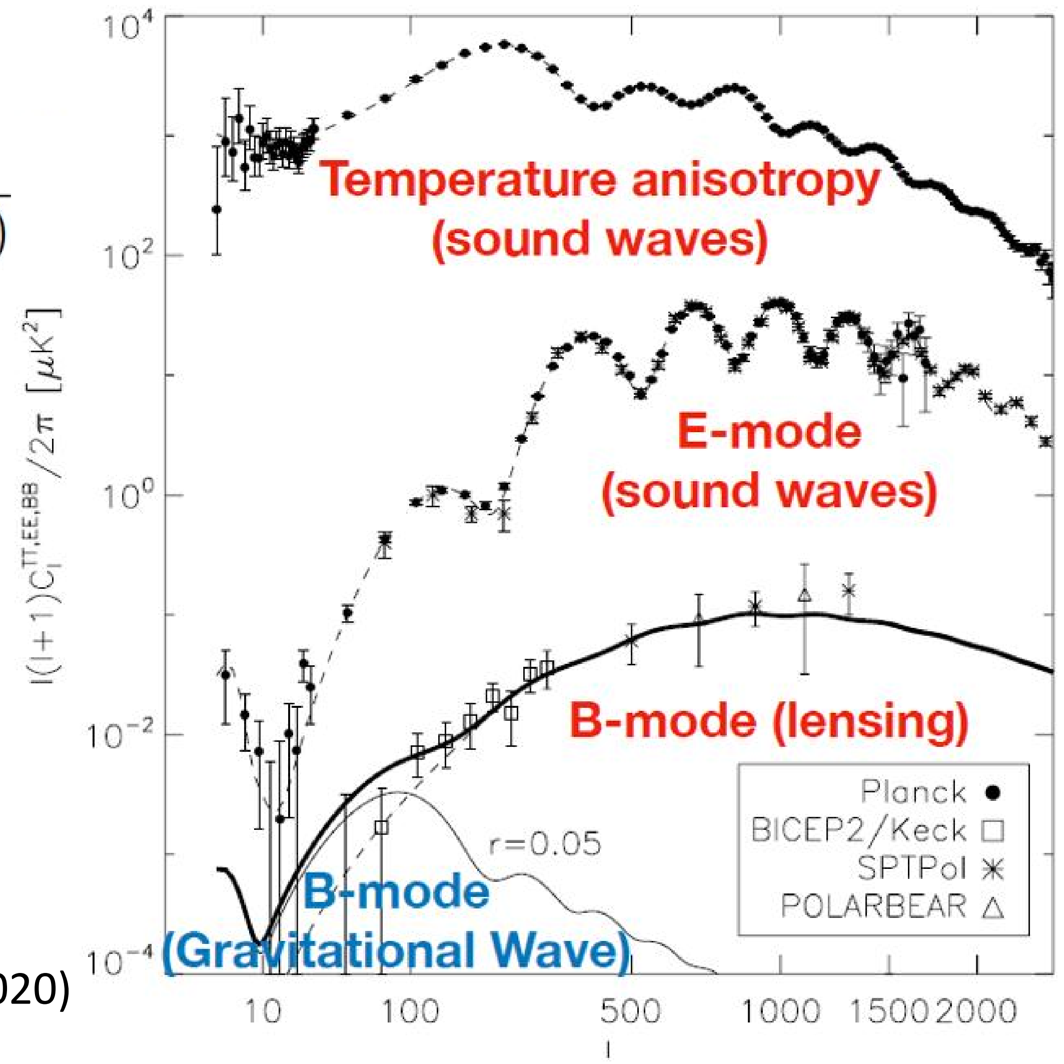
Cosmic Birefringence in the CMB

<E*B> correlation measures β

$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$
$$= \frac{1}{2}(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}})\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

EB is generated by the difference between EE and BB spectra

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



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

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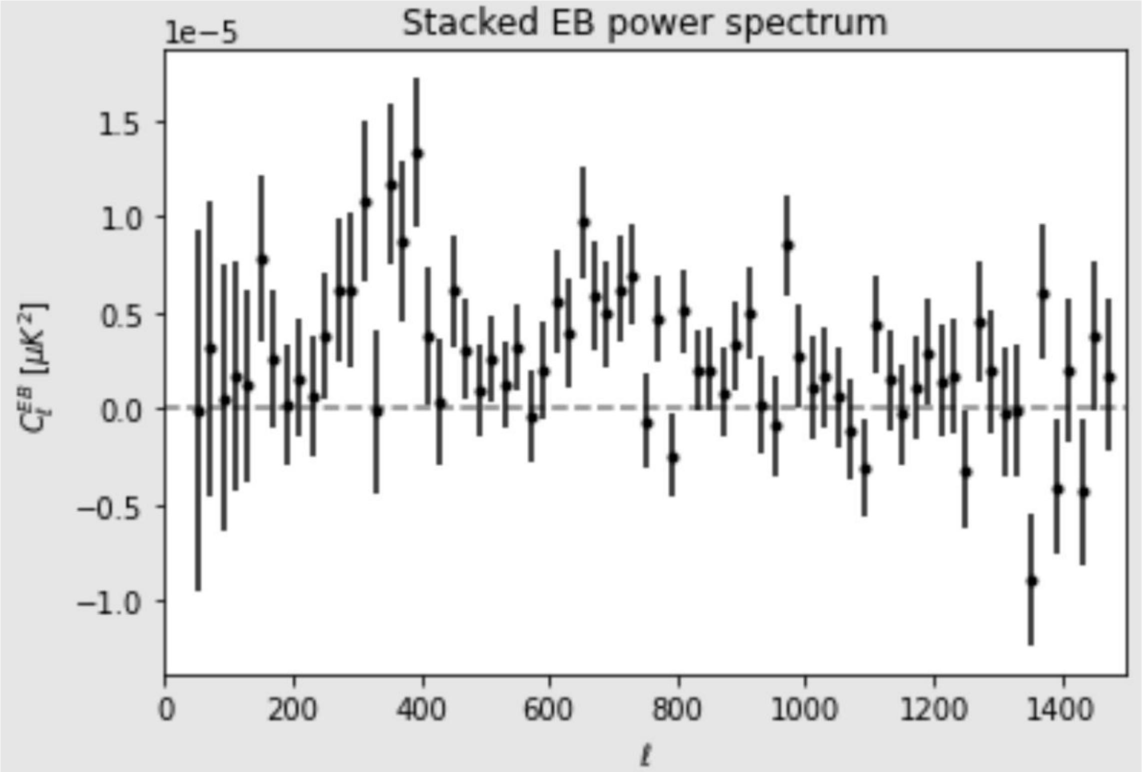
Observed EB Power Spectrum of the High Frequency Instrument of Planck

If β= 0, the $C_l^{EB} = 0.$



J. R. Eskilt et al. (2023)
Planck Collaboration Int. LVII,
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Motivation

Importent question:

Is Cosmic Birefringence

model-dependent ?

Cosmic Birefrigence from Early Dark Energy

The pseudoscalar fields of early dark energy

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

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

Early Dark Energy model

V. Poulin et al. (2018)

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

Rocl ‘n’ Roll model

P. Agrawal et al.(2019)

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

α-attractor model

M. Braglia et al. (2020)

Cosmic Birefrigence from Early Dark Energy

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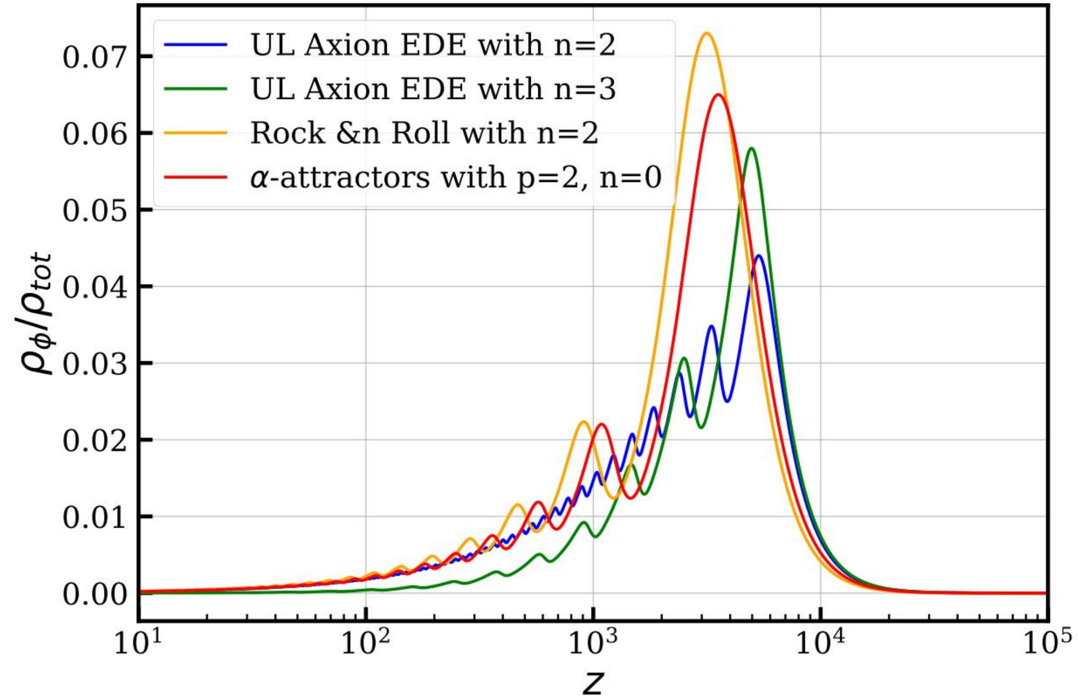
$$V_{\mathrm{EDE}}(\phi) = m^2 f^2 [1 - \cos(\phi/f)]^n \qquad V_{\mathrm{R\&R}}(\phi) = V_0 \left(\frac{\phi}{M_{\mathrm{Pl}}}\right)^{2n} \qquad V_\alpha(\phi) = V_0 \frac{\left(1+\alpha_2\right)^{2n} \tanh\left(\phi/\sqrt{6\alpha_1}M_{\mathrm{pl}}\right)^{2p}}{\left[1+\alpha_2 \tanh\left(\phi/\sqrt{6\alpha_1}M_{\mathrm{pl}}\right)\right]^{2n}}$$



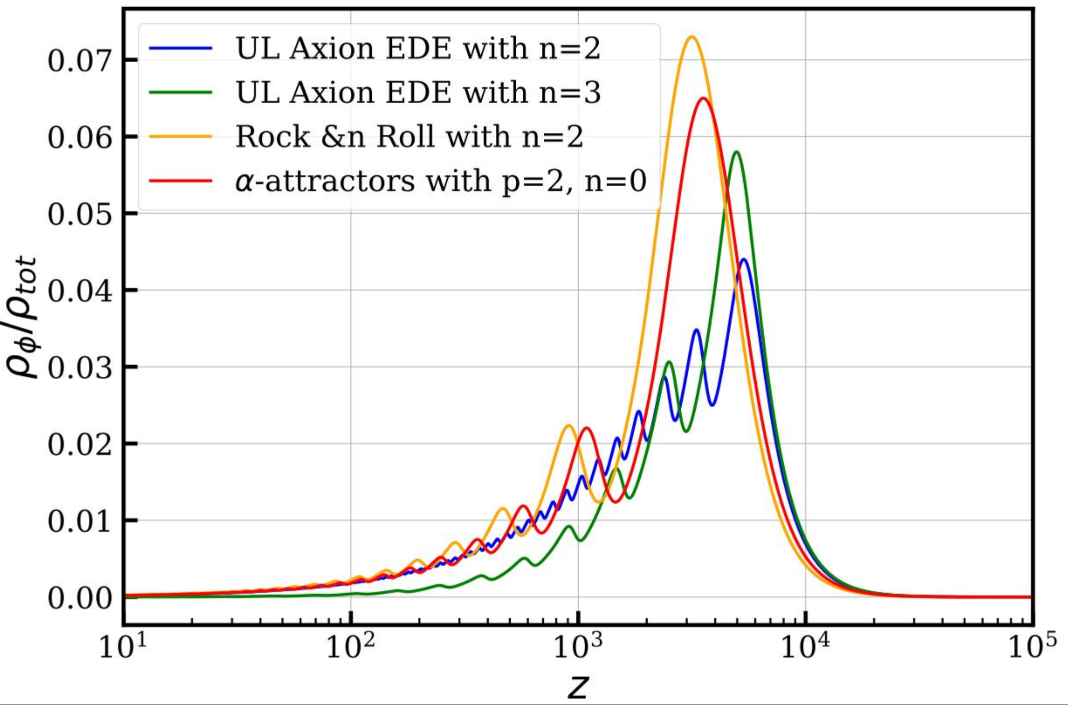
Cosmic Birefrigence from Early Dark Energy

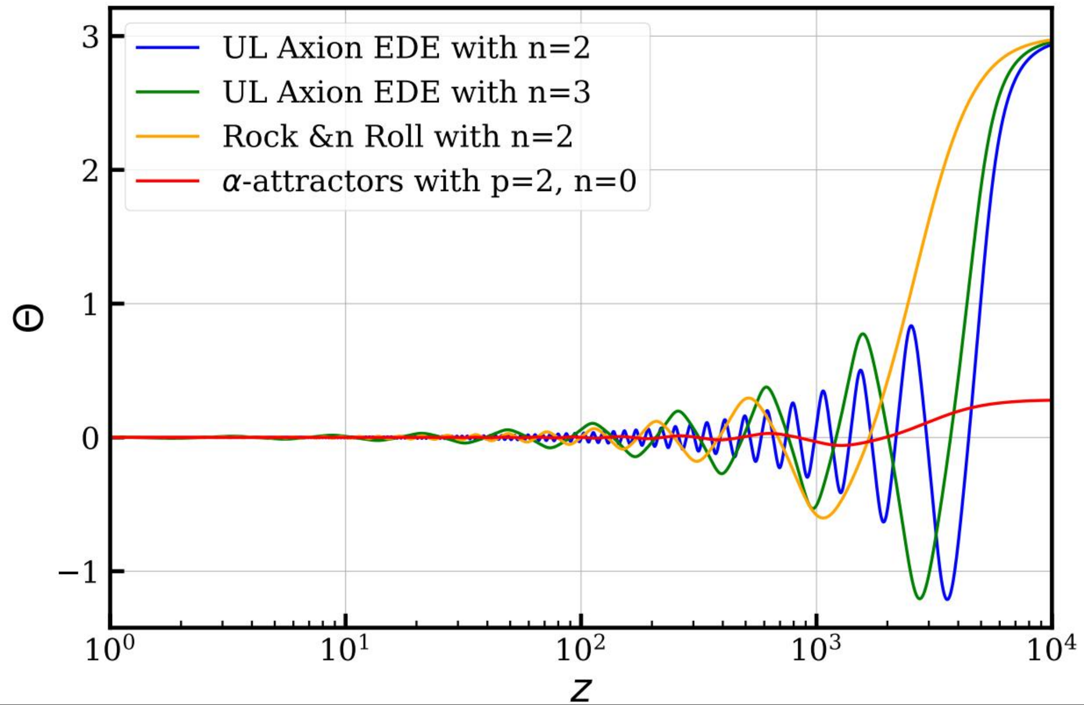
The pseudoscalar fields of early dark energy

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

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

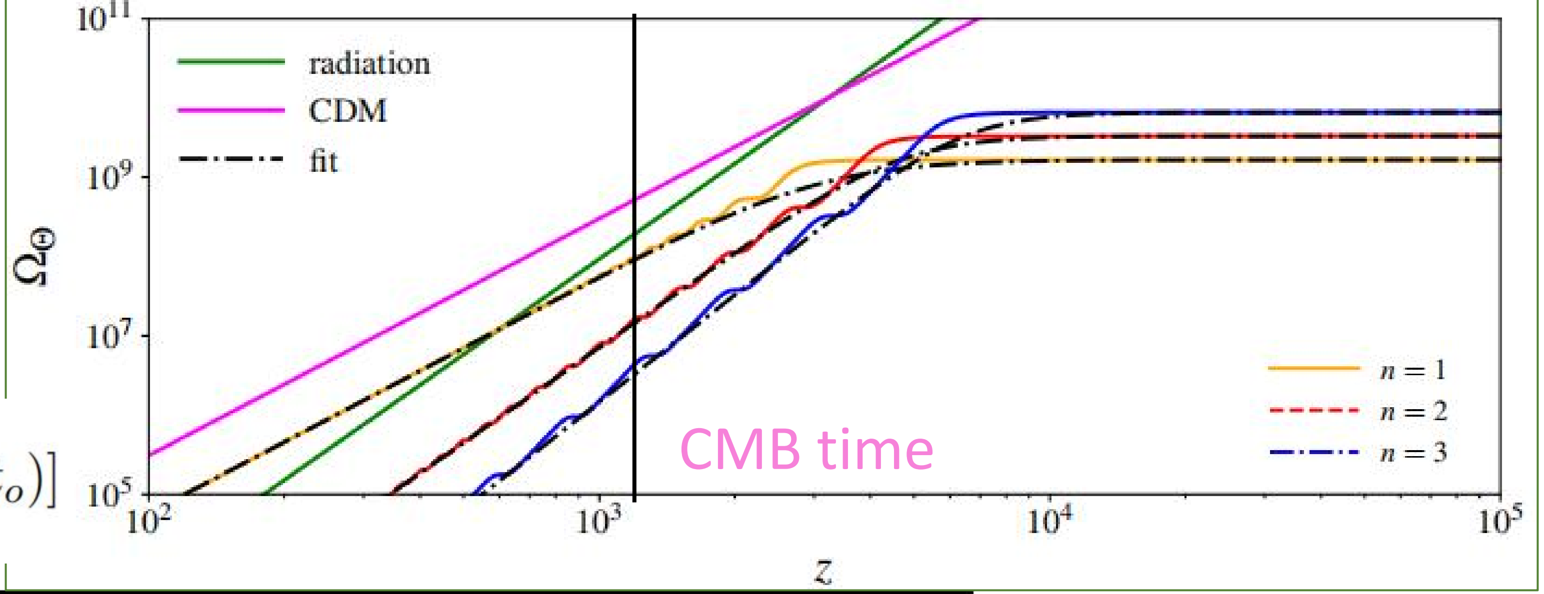
$$V_{\rm EDE}(\phi) = m^2 f^2[1-\cos(\phi/f)]^n \qquad V_{\rm R\&R}(\phi) = V_0\left(\frac{\phi}{M_{\rm Pl}}\right)^{2n} \qquad V_\alpha(\phi) = V_0\frac{(1+\alpha_2)^{2n}\tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)^{2p}}{\left[1+\alpha_2\tanh\left(\phi/\sqrt{6\alpha_1}M_{\rm pl}\right)\right]^{2n}}$$

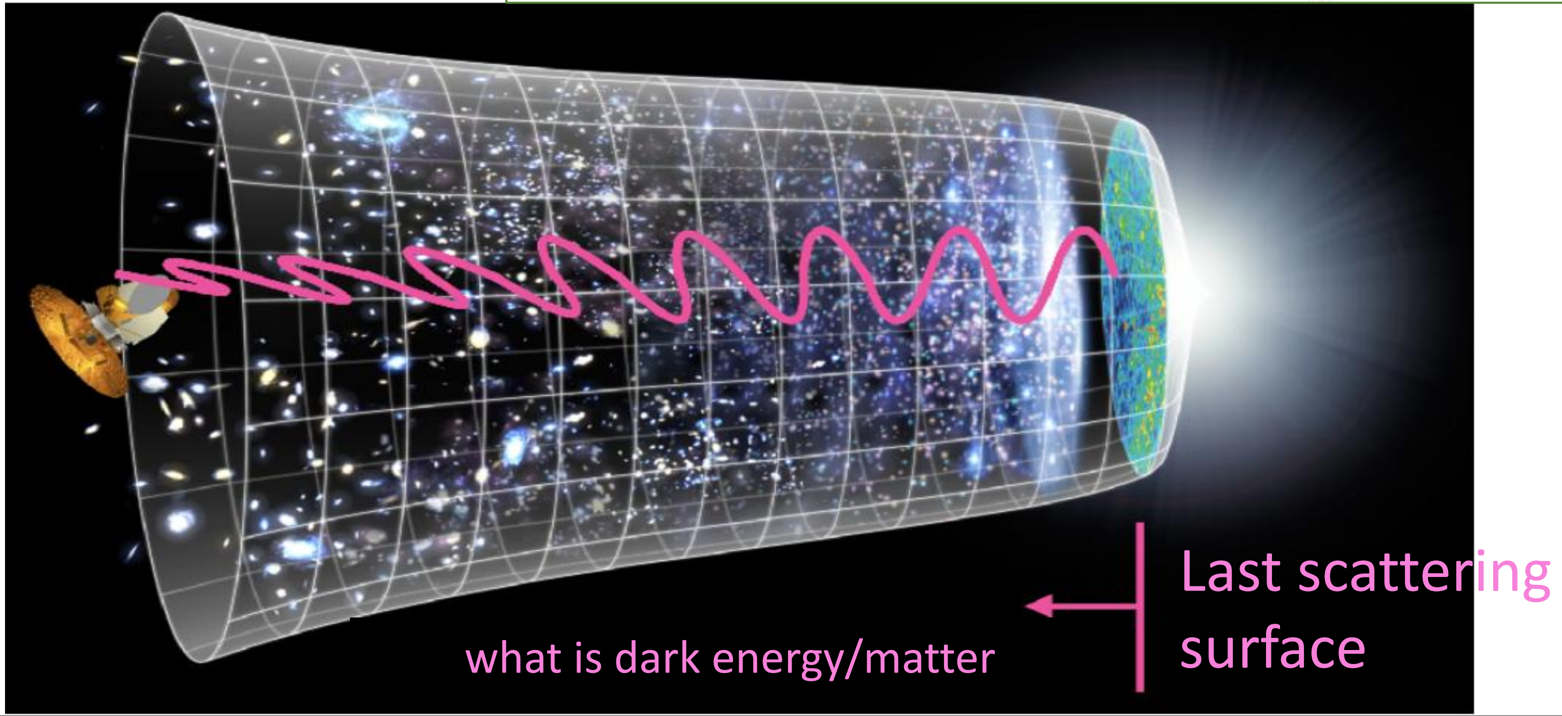




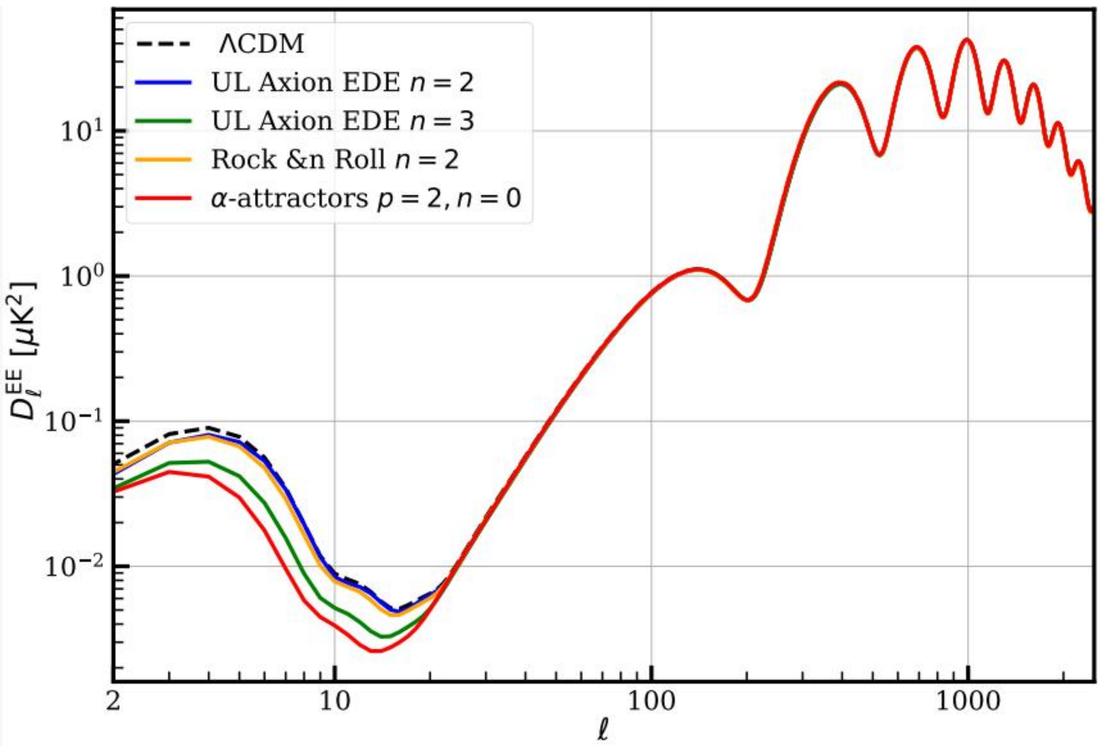
Cosmic Birefrigence from Early Dark Energy

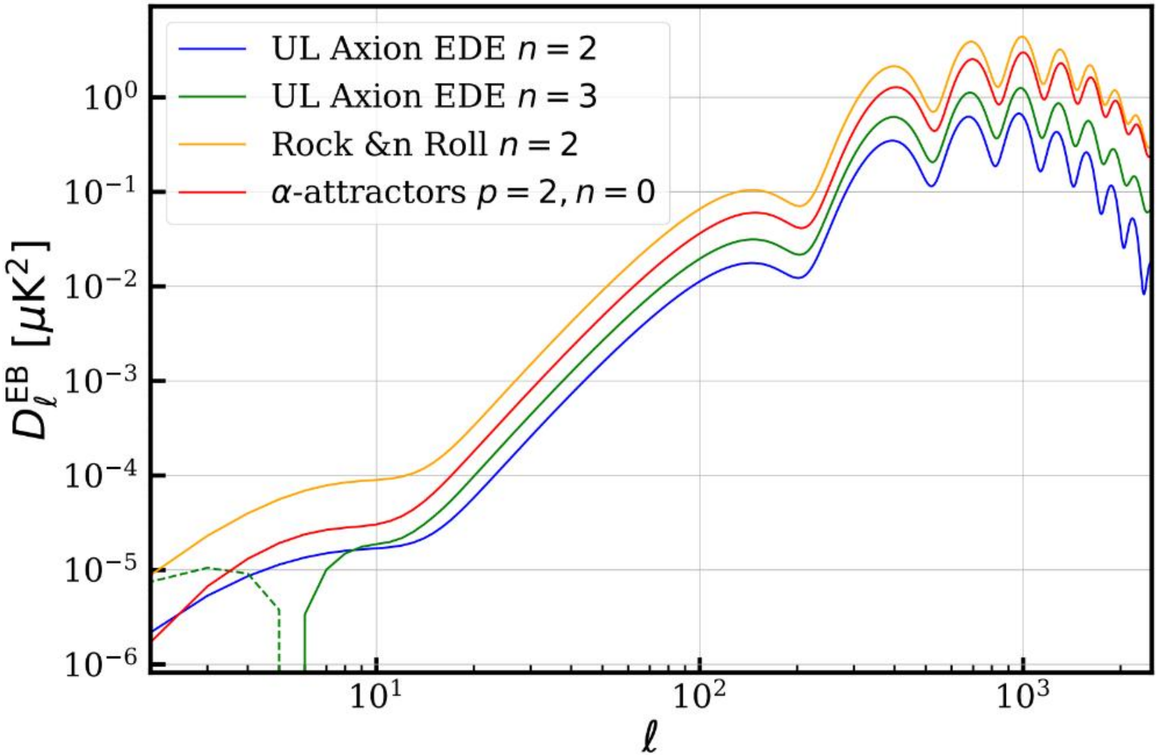
$$\beta = -2g_a \int_{t_{emitted}}^{t_{obs}} dt\dot{\theta} = 2g_a\left[\theta(t_e) - \theta(t_o)\right]$$





Difference in EE and EB power spectra





gM_Pl=1

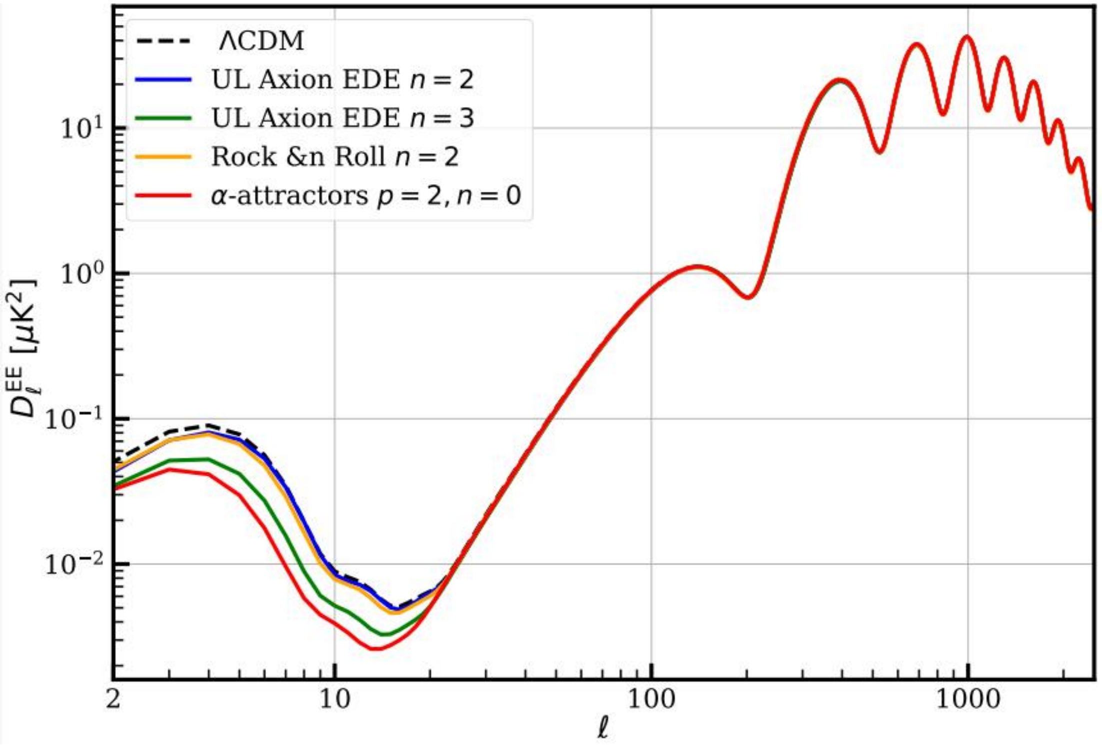
$$\beta(t) = -\frac{1}{2}\int_t^{t_0} \mathrm{d}\tilde{t}\,(\omega_+ - \omega_-) = \frac{g}{2}\left[\phi(t_0) - \phi(t)\right]$$

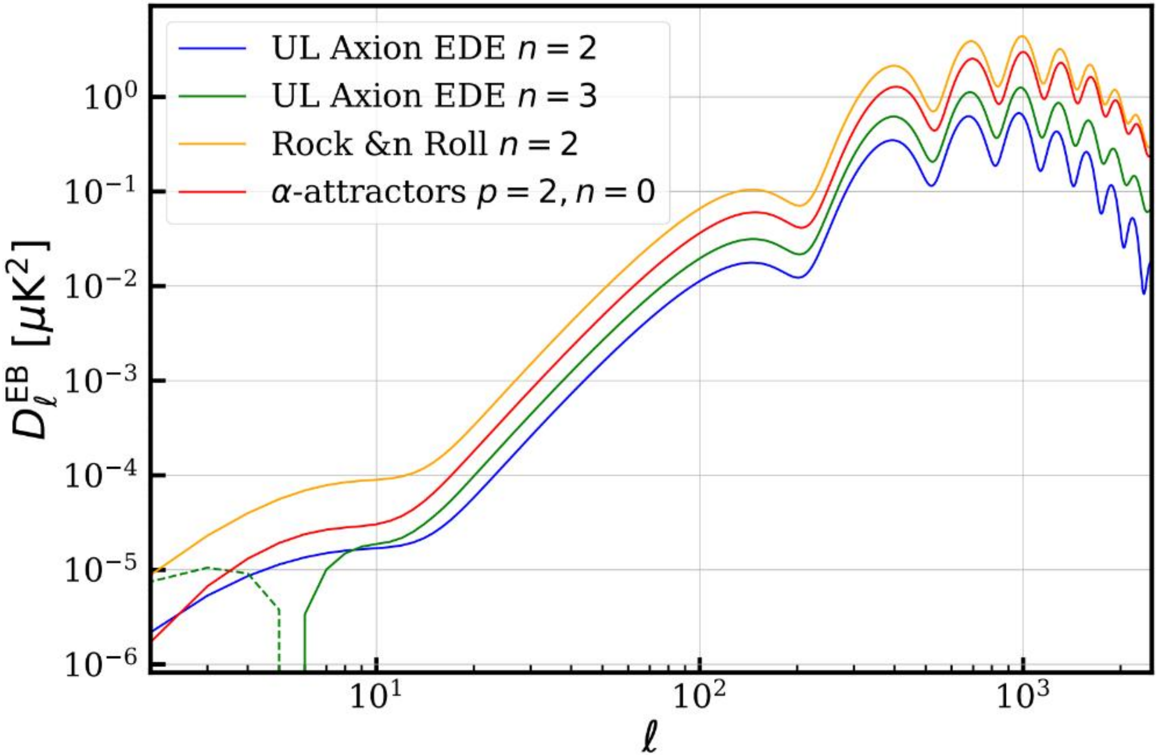
$$_{\pm 2}\Delta_{P,l}(\eta_0, q) = -\frac{3}{4}\sqrt{\frac{(l+2)!}{(l-2)!}}\int_0^{\eta_0} \mathrm{d}\eta\, \tau' e^{-\tau(\eta)}\Pi(\eta, q) \times \frac{j_\ell(x)}{x^2} e^{\pm 2i\beta(\eta)},$$

new term

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

Difference in EE and EB power spectra

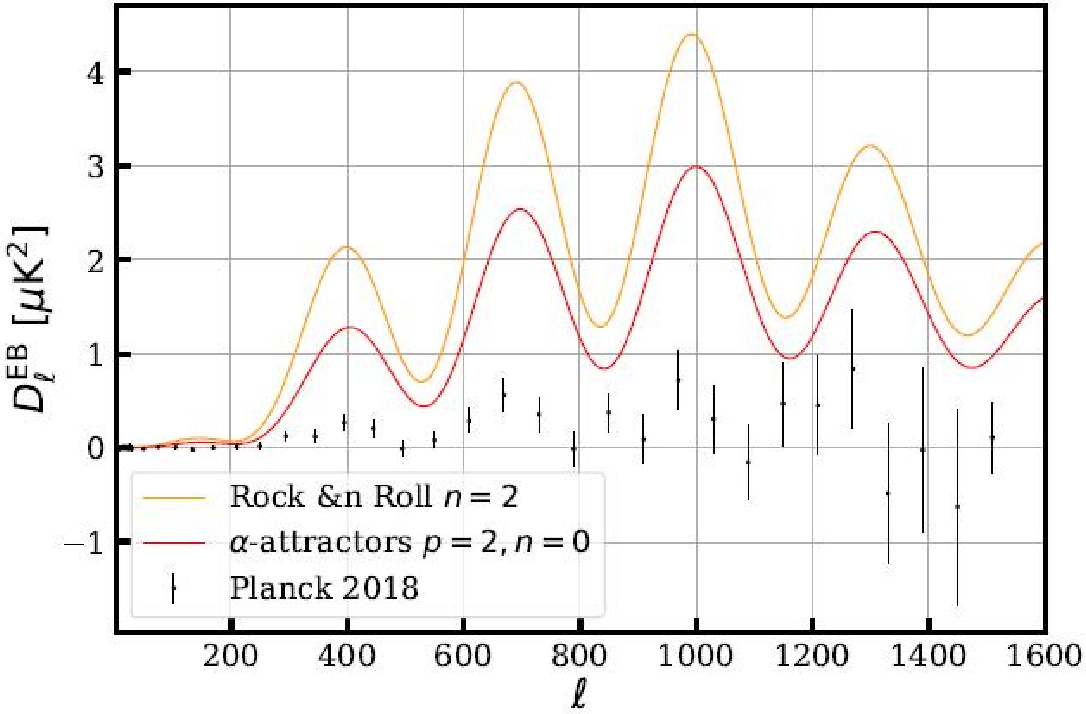


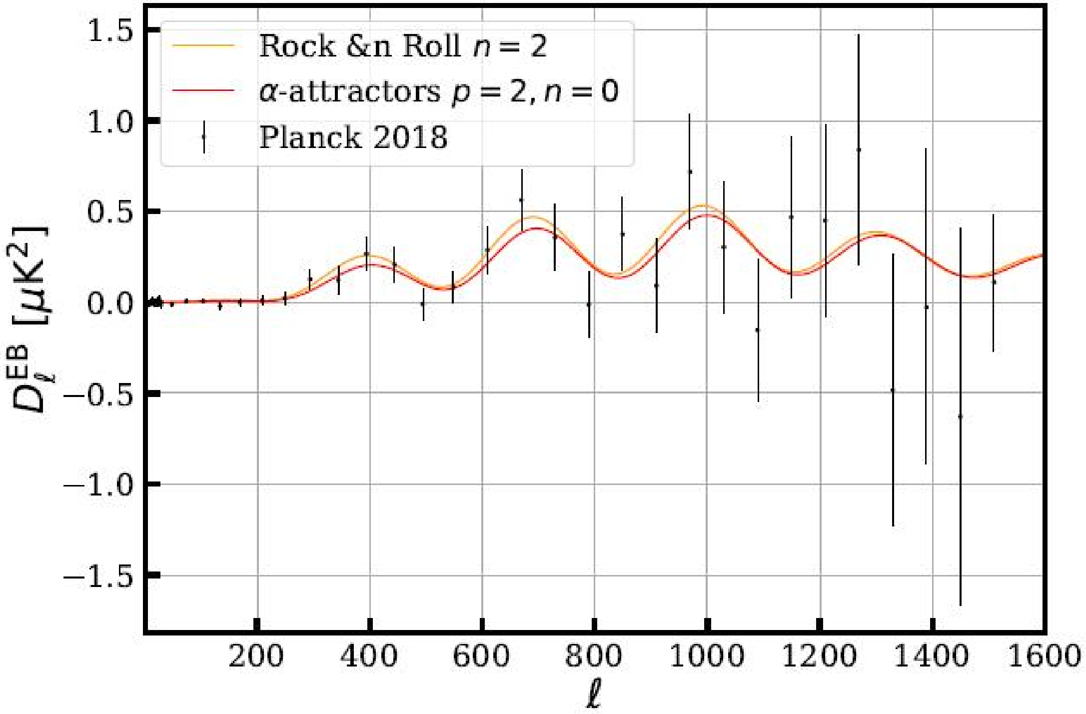


gM_Pl=1

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

Best fit results form Planck observation



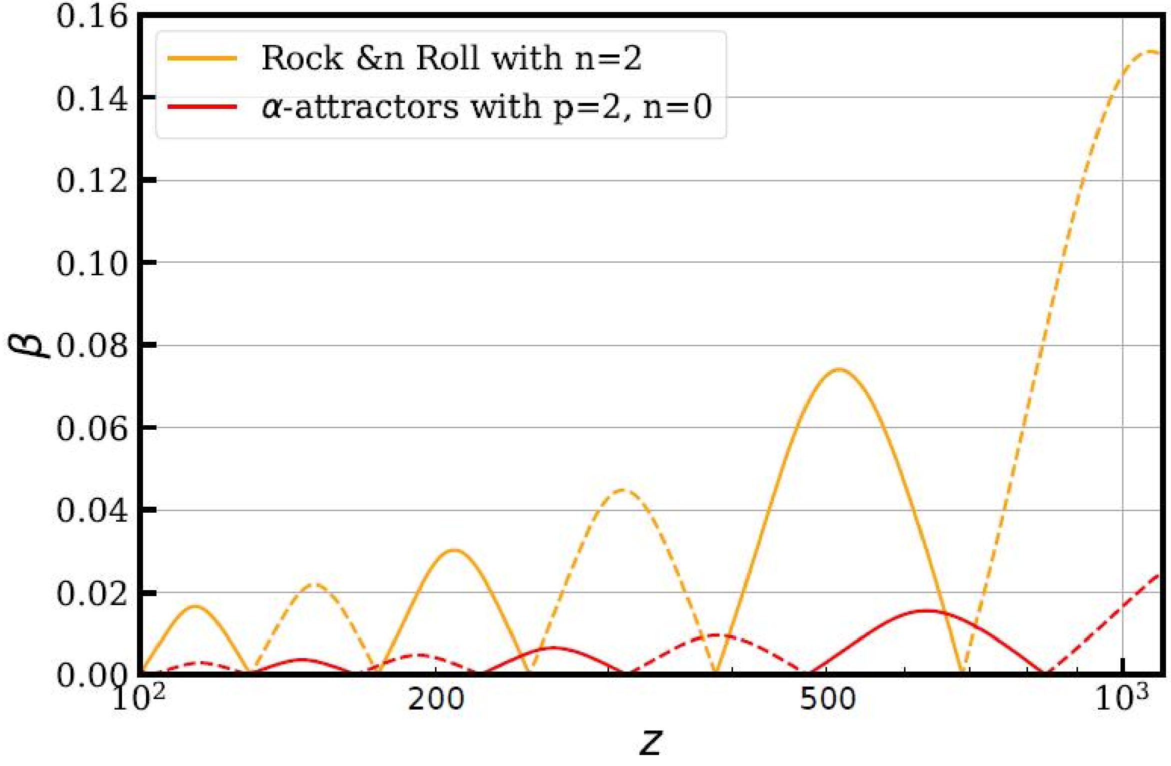


gM_Pl=1

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

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

The rotation of the plane results from best fit of g



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The value of g is model dependent.

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

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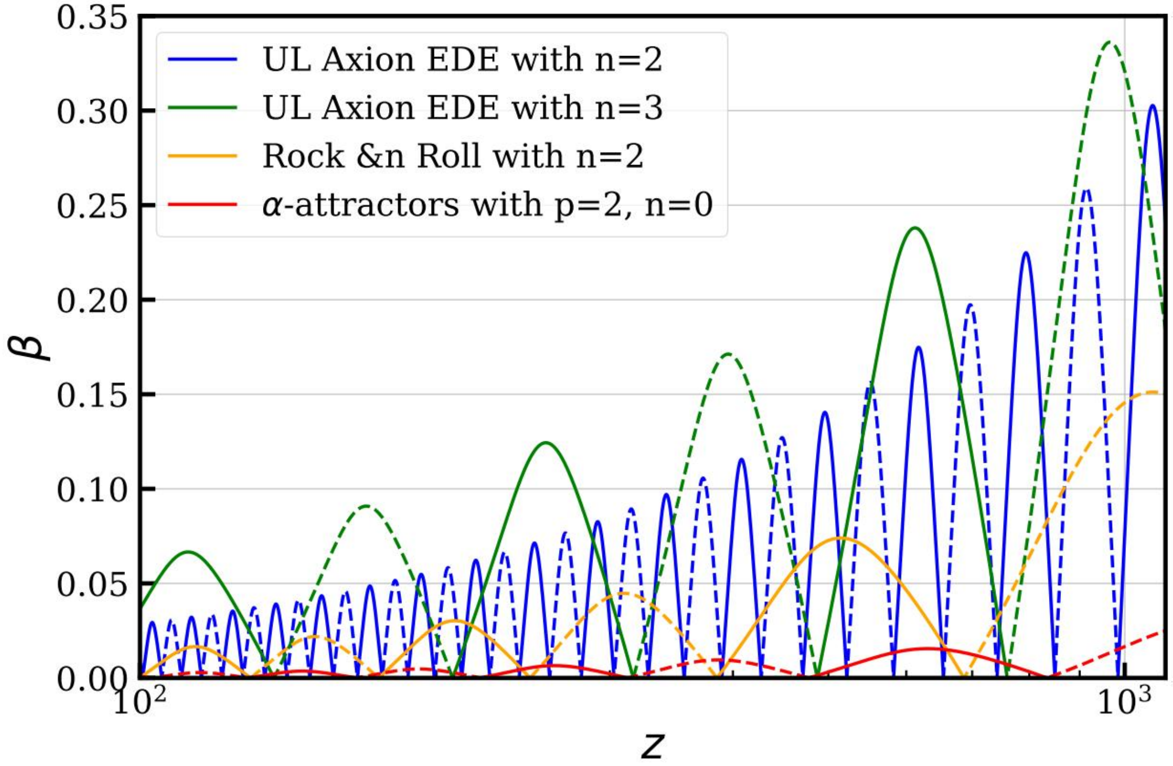

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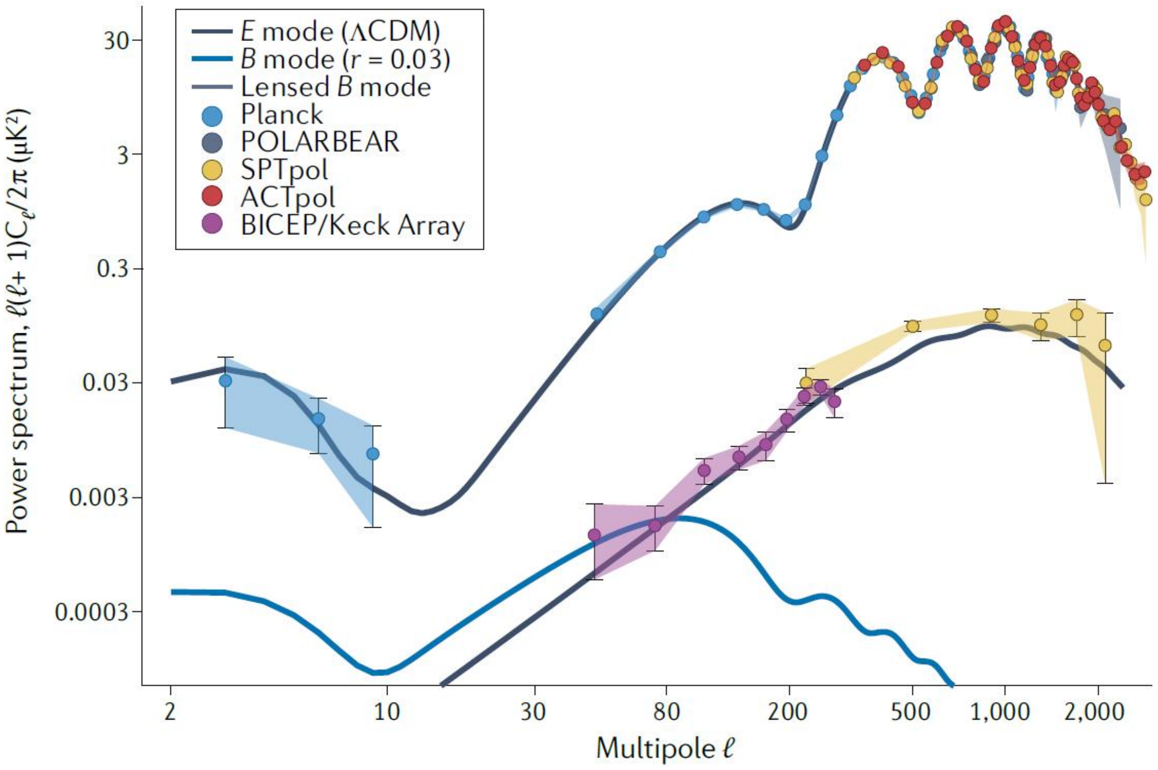
Moreover, the rotation angle β is also highly model dependent.

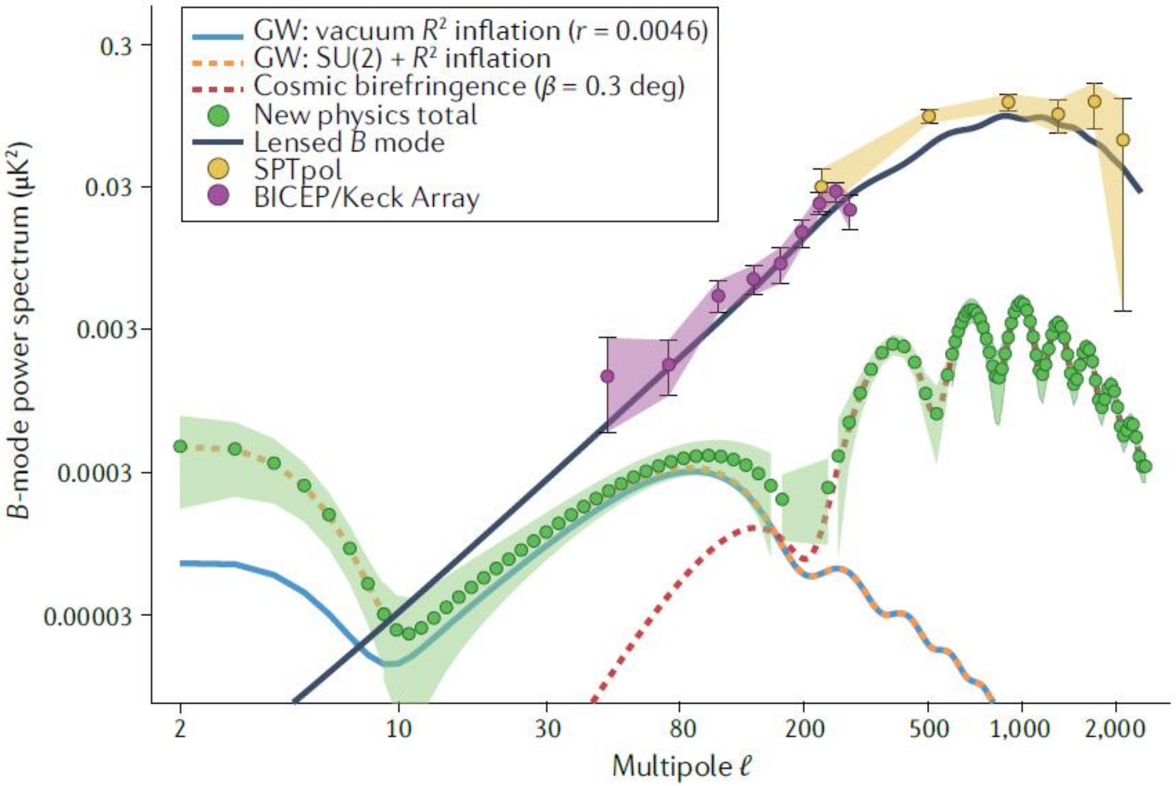
Conclutions

- **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

Accuracy of CMB Power Spectrum Observation





CMB power spectra

B mode to test the primordial gravitational wave