Cosmic Birefringence in Light of Discrete Symmetries

Nils A. Nilsson (CTPU-CGA, Institute for Basic Science, Daejeon, Korea)

August 13, 2024

Light Dark World 2024 KAIST

Based on Nilsson+Le Poncin-Lafitte, Phys.Rev.D 109 (2024) 1, 015032 (2311.16368),

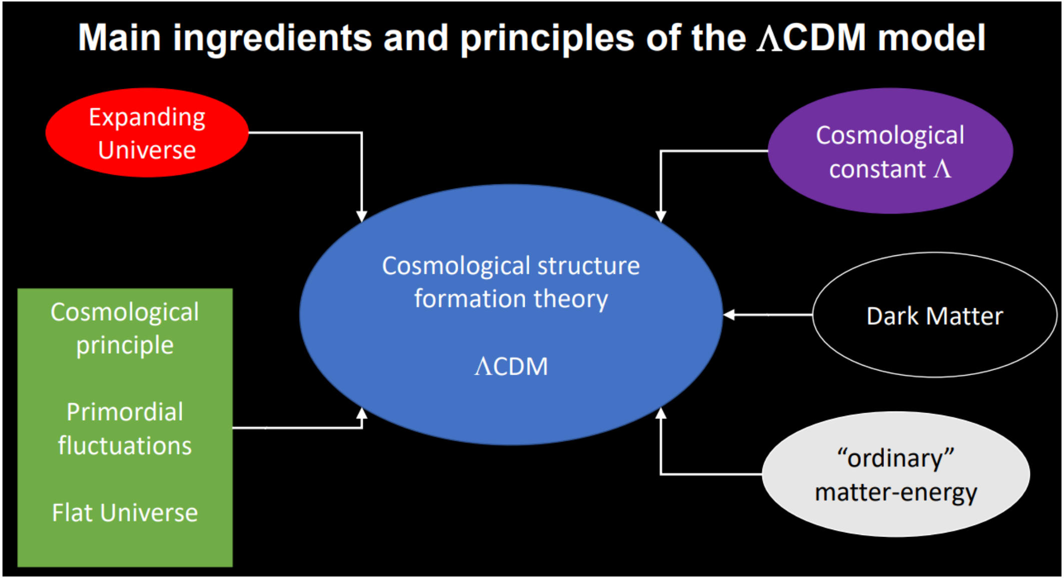
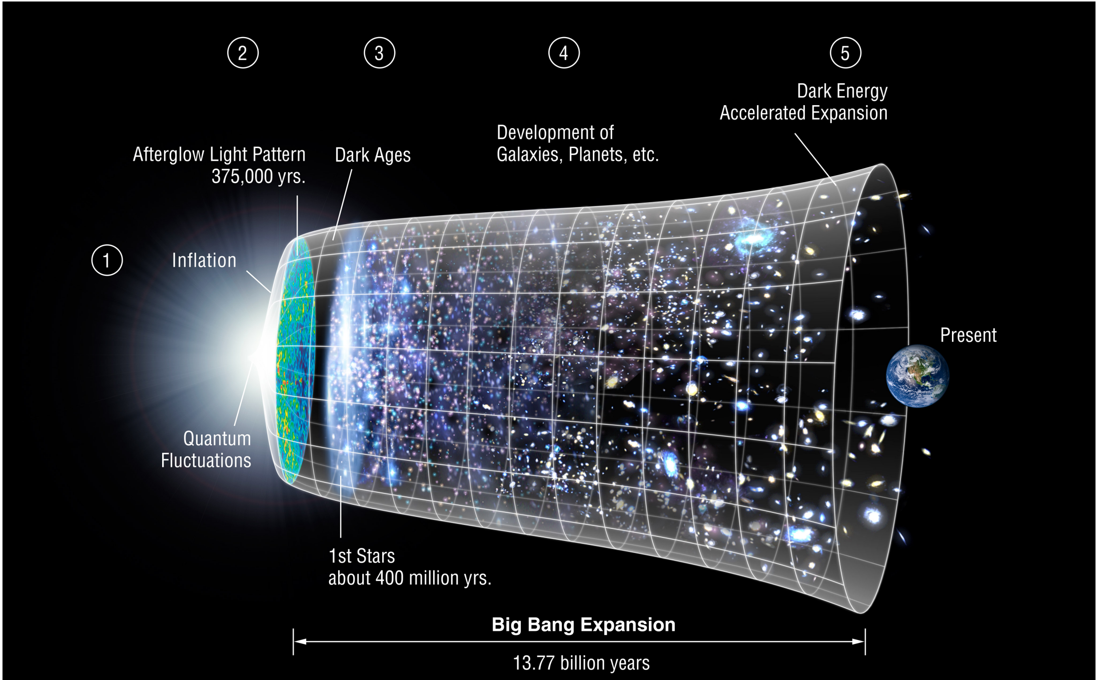
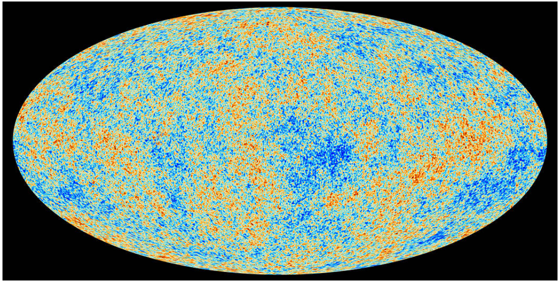
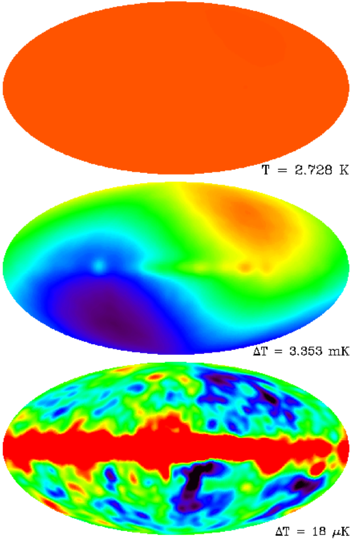


Image credit: Jesús Zavala Franco, U.Iceland



1
2
3
4
5
Dark Energy
Accelerated Expansion
Development of
Galaxies, Planets, etc.
Afterglow Light Pattern
375,000 yrs.
Dark Ages
Inflation
Quantum
Fluctuations
Present
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years





Credit: NASA; Planck/COBE

Hints of anisotropy

Cherry-picked signs of new physics/anisotropies

- Quadrupole-Octopole Alignment
  - A. Oliveira Costa et al., Phys. Rev. D 69 (2004)
- Anomalous Bulk Flow
  - C. Howlett et al., Mon. Not. Roy. Astron. Soc. 515 (2022)
- Radio-Galaxy Dipoles
  - D. J. Schwarz et al.,Phys. Rev. Lett. 93 (2004)
- Variation of Fine-Structure Constant
  - J. A. King et al., Mon. Not. Roy. Astron. Soc. 422 (2012)
- Cosmic Birefringence - Rotation of the Polarisation Plane of CMB Photons
  - E. Komatsu, Nature Rev. Phys. 4 (2022)

See 2207.05765 for an extensive review.

ΛCDM problems

- Lots of hints of anisotropy!

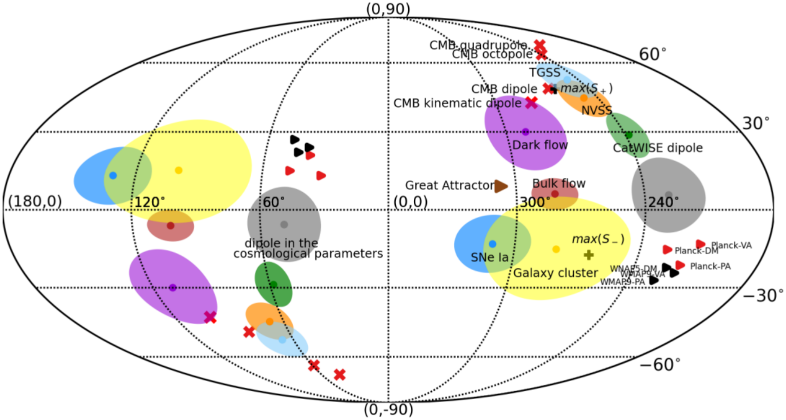


Image credit: 2207.05765

Axion electrodynamics

- Turner & Widrow PRD 1988:

Next consider axion electrodynamics. For energies well below the Peccei-Quinn symmetry-breaking scale f_a, the effective Lagrangian for axion electrodynamics is

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

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

- Carroll 1998: "Cosmic birefringence"

Cosmic birefringence

- We can write Mawwell's equations as

$$\partial_\nu F^{\mu\nu} = j^\mu, \qquad \partial_\nu \widetilde{F}^{\mu\nu} = 0$$

- The field strength[2] must be parity invariant, but $F\widetilde{F}$ is a pseudoscalar

$$F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E}), \quad \widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta} \Longrightarrow F\widetilde{F} = -4\mathbf{B}\cdot\mathbf{E}$$

- Surface term

$$S_{\rm EM} = -\frac{1}{4}\int d^x \left[F^2 - A_\mu j^\mu\right] + \int d^4x \underbrace{F\widetilde{F}}_{\to 2\partial_\mu(A_\nu \widetilde{F}^{\mu\nu})}$$

Chern-Simons term

- If this is all that's stopping us, add a Chern-Simons term

$$S_{\mathrm{CS}} = -\frac{1}{4}\alpha \int d^4x\,\theta F\widetilde{F} \quad \Longrightarrow S_{\mathrm{CS}} = \tfrac{1}{2}\alpha \int d^4x(\partial_\mu\theta)A_\nu\widetilde{F}^{\mu\nu}$$

Review Article | Published: 18 May 2022

New physics from the polarized light of the cosmic microwave background

Eiichiro Komatsu

Nature Reviews Physics **4**, 452–469 (2022) | Cite this article

Cosmic birefringence

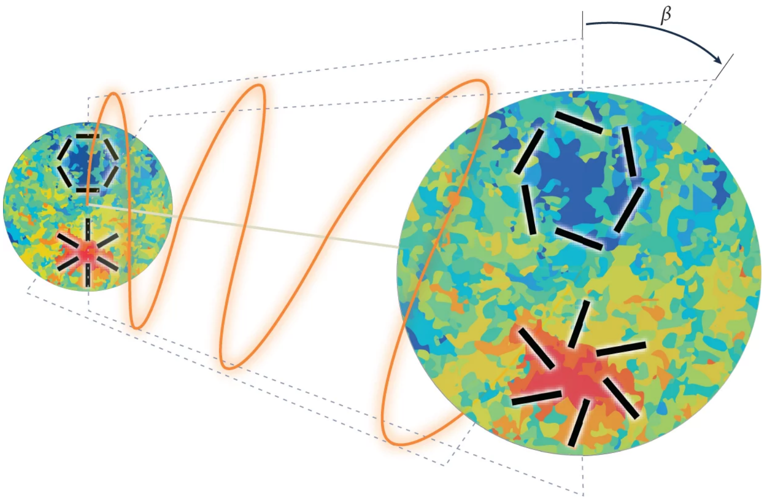


Image credit: Minami 2022

CMB signals of parity violation

- Recent series of papers by Komatsu, Eskilt, et al
- Cosmic birefringence angle $\beta \approx 0.35^\circ$, non-zero at 3.6σ.

See for example: 2011.11254, 2202.13919, 2205.13962.

CMB signals of parity violation

- Recent series of papers by Komatsu, Eskilt, et al
- Cosmic birefringence angle $\beta \approx 0.35^\circ$, non-zero at 3.6σ.
- Signal independent of foreground and Faraday rotation; consistent with generation through an axion-photon coupling

$$\mathcal{L}_{\rm int} \sim \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

See for example: 2011.11254, 2202.13919, 2205.13962.

CMB signals of parity violation

- Recent series of papers by Komatsu, Eskilt, et al
- Cosmic birefringence angle $\beta \approx 0.35^\circ$, non-zero at 3.6σ.
- Signal independent of foreground and Faraday rotation; consistent with generation through an axion-photon coupling

$$\mathcal{L}_{\rm int} \sim \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

- Generates non-zero $C_\ell^{\rm EB}$, breaks parity
- Phase velocities different: $\omega_\pm / k \approx 1 \pm 2 g_a \theta' / k$

See for example: 2011.11254, 2202.13919, 2205.13962.

Cosmic birefringence from EFT

- We can write the photon sector of the Standard-Model Extension EFT as

$$\mathcal{L} \sim -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \underbrace{\frac{1}{2}\epsilon^{\alpha\beta\mu\nu} A_\beta (\hat{k}_{\mathrm{AF}})_\alpha F_{\mu\nu}}_{\text{CPT odd}} - \underbrace{\frac{1}{4}(\hat{k}_{\mathrm{F}})^{\alpha\beta\mu\nu} F_{\alpha\beta} F_{\mu\nu}}_{\text{CPT even}}$$

See by Kostelecky + Mewes PRL 2007

Cosmic birefringence from EFT

- We can write the photon sector of the Standard-Model Extension EFT as

$$\mathcal{L} \sim -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \underbrace{\frac{1}{2}\epsilon^{\alpha\beta\mu\nu}A_\beta(\hat{k}_{\mathrm{AF}})_\alpha F_{\mu\nu}}_{\text{CPT odd}} - \underbrace{\frac{1}{4}(\hat{k}_{\mathrm{F}})^{\alpha\beta\mu\nu}F_{\alpha\beta}F_{\mu\nu}}_{\text{CPT even}}$$

$$(\hat{k}_{\mathrm{F}})^{\kappa\lambda\mu\nu} \equiv \sum_{d\in 2\mathbb{Z}} (k_{\mathrm{F}}^{(d)})^{\kappa\lambda\mu\nu\alpha_1\ldots\alpha_{d-4}}\partial_{\alpha_1}\ldots\partial_{\alpha_4}$$

$$(\hat{k}_{\mathrm{AF}})_\kappa \equiv \sum_{d\in 2\mathbb{Z}+1} (k_{\mathrm{AF}}^{(d)})_\kappa{}^{\alpha_1\ldots\alpha_{d-3}}\partial_{\alpha_1}\ldots\partial_{\alpha_3}$$

See by Kostelecky + Mewes PRL 2007

Cosmic birefringence from EFT

- We can write the photon sector of the Standard-Model Extension EFT as

$$\mathcal{L} \sim -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \underbrace{\frac{1}{2}\epsilon^{\alpha\beta\mu\nu}A_\beta(\hat{k}_{\mathrm{AF}})_\alpha F_{\mu\nu}}_{\text{CPT odd}} - \underbrace{\frac{1}{4}(\hat{k}_{\mathrm{F}})^{\alpha\beta\mu\nu}F_{\alpha\beta}F_{\mu\nu}}_{\text{CPT even}}$$

$$(\hat{k}_{\mathrm{F}})^{\kappa\lambda\mu\nu} \equiv \sum_{d\in 2\mathbb{Z}} (k_{\mathrm{F}}^{(d)})^{\kappa\lambda\mu\nu\alpha_1\ldots\alpha_{d-4}}\partial_{\alpha_1}\ldots\partial_{\alpha_4}$$

$$(\hat{k}_{\mathrm{AF}})_\kappa \equiv \sum_{d\in 2\mathbb{Z}+1} (k_{\mathrm{AF}}^{(d)})_\kappa^{\ \alpha_1\ldots\alpha_{d-3}}\partial_{\alpha_1}\ldots\partial_{\alpha_3}$$

- We obtain the CS term with the CPT odd EFT correction, leads to a modified Ampere-Maxwell relation

$$(k_{\mathrm{AF}}^{(3)})_\kappa \to \chi^{ij} = -2i\frac{c}{\omega}\epsilon_{ikj}(k_{\mathrm{AF}})^k - 2i\left(\frac{c}{\omega}\right)^2(k_{\mathrm{AF},0})k^k$$

See by Kostelecky + Mewes PRL 2007

Cosmic birefringence from EFT

- Susc. tensor $\chi^{ij} \longrightarrow$ mixing matrix between the Stokes parameters U, V, Q (see Lembo et al PRL 2021)

$$Q(\hat{n}) \pm iU(\hat{n}) = -\sum_{lm}(E_{lm} + iB_{lm})\, {}_{\pm 2}Y_{lm}(\hat{n})$$

$$E_{lm} \to (-1)^l E_{lm}, \quad B_{lm} \to (-1)^{l+1} B_{lm}, \quad \text{as } \hat{n} \to -\hat{n}$$

- We can define the angular power spectra as[1]

$$C_l^{XX'} = (2l+1)^{-1} \sum_m X_{lm} X'^{*}_{lm} \quad \Rightarrow \quad \boxed{C_l^{EB,k} = 4c\sqrt{((\bar{k}_{AF})_0)^2}(\widetilde{C}_l^{EE} - \widetilde{C}_l^{BB})}$$

$$(\bar{k}_{AF})_0 = \int_{\eta_0}^{\eta_{LSS}} (k_{AF})_0 \, d\eta$$

[1] See Caloni et al JCAP 2022 for derivation

Cosmic birefringence angle

- CPT-odd term from EFT versus axion-photon coupling:

$$C_l^{EB,k} = 4c\sqrt{((\bar{k}_{AF})_0)^2}(\widetilde{C}_l^{EE} - \widetilde{C}_l^{BB}), \qquad C_l^{EB,\phi} = \frac{1}{2} 4 \sin 4\beta(\widetilde{C}_l^{EE} - \widetilde{C}_l^{BB}),$$

- Massage $\bar{k}_{\mathrm{AF}}$ to different form

$$|k_{V,00}^{(3)}| = \sqrt{\frac{\pi}{4c^2}}\frac{1}{\eta_0 - \eta_{\mathrm{LSS}}}\sqrt{\gamma}, \quad \gamma = 16c^2((\bar{k}_{\mathrm{AF}})_0)^2$$

- Best constraints before Cosmic Birefringence

$$\boxed{\begin{aligned} |k_{(V),00}^{(3)}| &< 6.81 \cdot 10^{-44}\ \text{GeV}, \quad \textit{Planck} \\ |k_{(V),00}^{(3)}| &< 1.54 \cdot 10^{-44}\ \text{GeV}, \quad \textit{Planck} + \mathrm{BCII} + \mathrm{ACT} \end{aligned}}$$

Current best constraint

- Using the (not the most stringent) cosmic birefringence angle: $\beta = 0.35^\circ \pm 0.14^\circ$ (1σ), non-zero at 2.4σ :

$$|k^{(3)}_{(V),00}| = (7.32 \pm 2.94) \cdot 10^{-45}\ \text{GeV} \quad (1\sigma)$$

- $\beta \neq 0$ **and** $|k^{(3)}_{(V),00}| \neq 0$ at 2.4σ, indicating *CPT*-odd interaction.
- Miscalibration angle!
- Other possible sources: Intrinsic sources of primordial EB correlations; foreground contamination; Faraday rotation: ruled out! (papers by Komatsu, Eskilt, Minami)

NAN + Le-Poncin Lafitte PRD 2024, included in the Data Tables: 0801.0287

Summary

- Signals of cosmic birefringence indicate the presence of a parity-odd interaction.
- The Maxwell dual shows up naturally in the CPT-odd photon sector of the Standard-Model Extension
- Cosmic-birefringence angle $\Longrightarrow$ strongest photon constraint on CPT violation (and therefore local Lorentz violation)