Cosmic Birefringence Triggered by Dark Matter Domination

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in collaboration with

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Cosmic birefringence and Planck data

- Minami and Komatsu have found hints of a faint birefringence signal in the Planck data by developing an approach to mitigate certain systematic errors.

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

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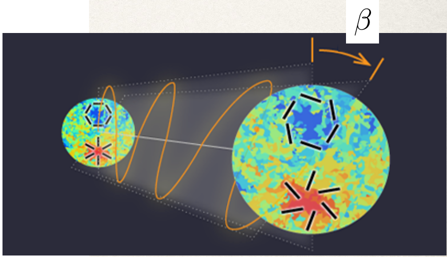
(Dated: November 24, 2020)

We search for evidence of parity-violating physics in the Planck 2018 polarization data, and report on a new measurement of the cosmic birefringence angle, β. The previous measurements are limited by the systematic uncertainty in the absolute polarization angles of the Planck detectors. We mitigate this systematic uncertainty completely by simultaneously determining β and the angle miscalibration using the observed cross-correlation of the E- and B-mode polarization of the cosmic microwave background and the Galactic foreground emission. We show that the systematic errors are effectively mitigated and achieve a factor-of-2 smaller uncertainty than the previous measurement, finding $\beta = 0.35 \pm 0.14$ deg (68% C.L.), which excludes $\beta = 0$ at 99.2% C.L. This corresponds to the statistical significance of 2.4σ.

Y. Minami and E. Komatsu, Phys. Rev. Lett. 125, 221301 (2020)



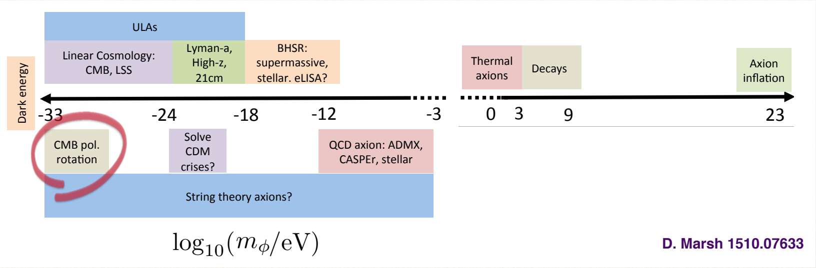
Y. Minami /KEK

Cosmic birefringence from axion

- The string theory predicts very light particles, called axions, in the low-energy effective field theory. They may couple to photons via the Chern-Simons coupling:

$$\mathcal{L} \supset -c_\gamma \frac{\alpha}{4\pi} \frac{\phi}{f_\phi} F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad f_\phi \sim 10^{16}\ \mathrm{GeV}$$

- They lead to rich phenomenology in cosmology and particle physics, depending on their masses.



Cosmic birefringence from axion

- Cosmic birefringence can be induced if an axion moves before present and after the recombination epoch.

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - c_\gamma \frac{\alpha}{4\pi} \frac{\phi}{f_\phi} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$\simeq \frac{1}{2} \left[\Big(\underbrace{\vec{E} + c_\gamma \frac{\alpha}{2\pi} \frac{\phi}{f_\phi} \vec{B}}_{\equiv \vec{D}} \Big)^2 - \Big(\underbrace{\vec{B} - c_\gamma \frac{\alpha}{2\pi} \frac{\phi}{f_\phi} \vec{E}}_{\equiv \vec{H}} \Big)^2 \right]$$

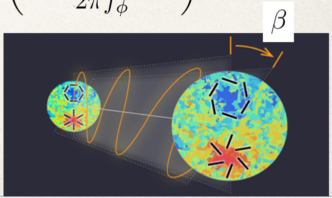
S.M.Carroll, G.B.Field, R.Jackiw '90
D.Harari, P.Sikivie '92
S.M.Carroll, '98

Recent works:
T.Fujita, K.Murai, H.Nakatsuka, S.Tsujikawa, 2011.11894
F.Takahashi, W.Yin, 2012.11576
M.Jain, A.J.Long, M.A.Amin 2103.10962

- $\vec{D}$ and $\vec{H}$ (rather than $\vec{E}$ and $\vec{B}$) satisfy free wave equations.

  The polarization plane is rotated by $\beta = c_\gamma \frac{\alpha}{2\pi} \frac{\Delta\phi}{f_\phi} \simeq 0.42\, c_\gamma \left(\frac{\phi_{\rm today} - \phi_{\rm LSS}}{2\pi f_\phi} \right) {\rm deg}$

- Planck data: $\beta = 0.35 \pm 0.14$ deg ⟷ $\Delta\phi / f_\phi = \mathcal{O}(1)$
  - No fine-tuning is required to explain the Planck data.
  - f_ϕ can be the string or GUT scale.



Cosmic birefringence from axion

- Cosmic birefringence can be induced if an axion moves before present and after the recombination epoch.

$$m_\phi \lesssim 10^{-28}\ \text{eV} \qquad\qquad m_\phi \gtrsim 10^{-33}\ \text{eV}$$

S.M.Carroll, G.B.Field, R.Jackiw '90
D.Harari, P.Sikivie '92
S.M.Carroll, '98

Why does the axion start to oscillate just before the present epoch?
(another cosmic coincidence problem or "why now" problem)

- We can address this question by introducing an effective mass that is proportional to the dark matter density.

$$V(\phi) = \frac{1}{2} c_H H_{\rm DM}^2(t) \phi^2 \qquad\qquad H_{\rm DM}^2 \equiv \frac{\rho_{\rm DM}}{3M_{\rm Pl}^2}, \quad c_H = \mathcal{O}(1)$$

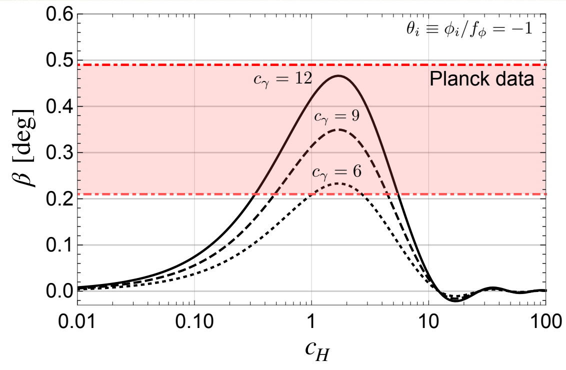
- This triggers the axion oscillation after the matter-radiation equality, which is just before the recombination epoch.

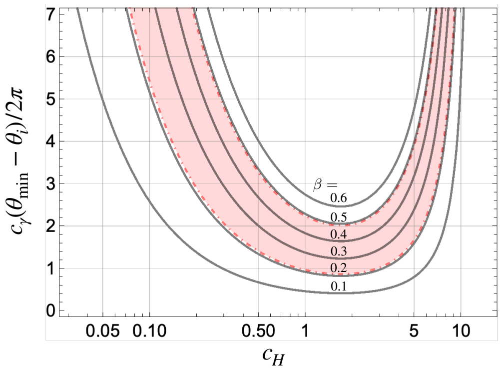
S. Nakagawa, F. Takahashi, M.Y., 2103.08153

"Why now" problem of axion oscillation ⟷ Coincidence of matter-radiation equality and recombination epoch

Cosmic birefringence triggered by DM domination

- Low-energy EFT: $\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}c_H H_{\rm DM}^2(t)\phi^2 - c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi}F_{\mu\nu}\tilde{F}^{\mu\mu}$





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Cosmic birefringence triggered by DM domination

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Are there any simple UV origins of the effective mass term?

- Yes, there are. We proposed a couple of models.

Cosmic birefringence triggered by DM domination

- Low-energy EFT: $\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}c_H H_{\rm DM}^2(t)\phi^2 - c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi}F_{\mu\nu}\tilde{F}^{\mu\mu}$

- UV origin 1: non-minimal gravitational coupling

$$\mathcal{L} \supset -\xi R\phi^2 \sim 3\xi H_{\rm DM}^2(t)\phi^2$$

- In the radiation-dominated era, it is negligible because $R \ll H^2$ due to the conformal symmetry of radiation.
- In the matter-dominated era, it gives the effective mass of $\sqrt{6\xi}H$.

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Cosmic birefringence triggered by DM domination

- Low-energy EFT: $\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}c_H H_{\rm DM}^2(t)\phi^2 - c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi}F_{\mu\nu}\tilde{F}^{\mu\mu}$

- UV origin 2: Witten effect on hidden monopole DM

  - We introduce an SU(2)H gauge theory, which is spontaneously broken to U(1)H by an adjoint Higgs field. Then a hidden monopole is a good candidate for DM.
  - If the axion couples to U(1)H, the monopole has an electric charge of $\phi/(2\pi f_\phi)$ by the Witten effect:

$$\mathcal{L} \supset -\frac{1}{4}F_{H,\mu\nu}F_H^{\mu\nu} - \frac{\alpha_H \phi}{8\pi f_\phi}F_{H,\mu\nu}\tilde{F}_H^{\mu\mu} \;\Rightarrow\; {\rm div}\vec{E}_H = -\frac{\alpha_H\phi}{2\pi f_\phi}{\rm div}\vec{B}_H$$

E. Witten '79

  - The axion acquires an effective mass in the monopole plasma to minimize the energy of the electric field around monopoles.

$$m_\phi^2 \simeq \left(\frac{\alpha_H}{4\pi f_\phi}\right)^2 \rho_M(t)$$

Fischler, Presskill '83

$$= c_H H_{\rm DM}^2(t) \quad \text{where} \quad c_H = 3\left(\frac{\alpha_H}{4\pi}\frac{M_{\rm pl}}{f_\phi}\right)^2 = \mathcal{O}(1) \;\; \text{for} \;\; f_\phi = 10^{16}\ {\rm GeV} \;\; \text{and} \;\; \alpha_H = \mathcal{O}(0.01)$$

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Summary

- The birefringence signal in Planck data implies an axion moves after the recombination epoch.

"Why now" problem of axion oscillation ⟷ Coincidence of matter-radiation equality and recombination epoch

- This can be addressed if an axion couples to dark matter density.

$$V(\phi) = \frac{1}{2} c_H H_{\rm DM}^2(t) \phi^2$$

- UV origins:
  - Non-minimal coupling to gravity

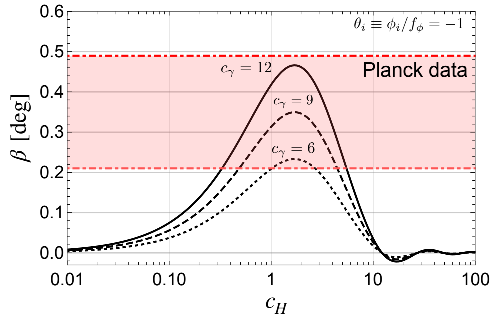
$$\mathcal{L} \supset -\xi R \phi^2 \quad \sim -3\xi H_{\rm DM}^2(t)\phi^2$$

  - Hidden monopole dark matter

$$\mathcal{L} \supset -\frac{1}{4} F_{H,\mu\nu} F_H^{\mu\nu} - \frac{\alpha_H \theta_H}{8\pi} F_{H,\mu\nu} \tilde{F}_H^{\mu\mu}$$

$\rightarrow$ $c_H = 3 \left(\frac{\alpha_H}{4\pi} \frac{M_{\rm pl}}{f_\phi} \right)^2$ for monopole DM

$= \mathcal{O}(1)$ for $f_\phi = 10^{16}$ GeV and $\alpha_H = \mathcal{O}(0.01)$



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