Cosmic Birefringence Triggered by Dark Matter Domination

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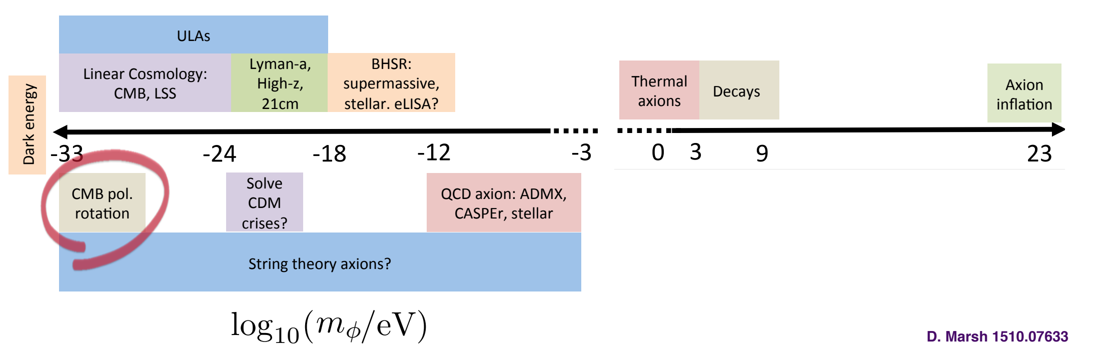
Cosmic birefringence from axion

- Axion-like particles (axions) have rich phenomenology in cosmology!

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi) - c_\gamma \frac{\alpha}{4\pi}\frac{\phi}{f_\phi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



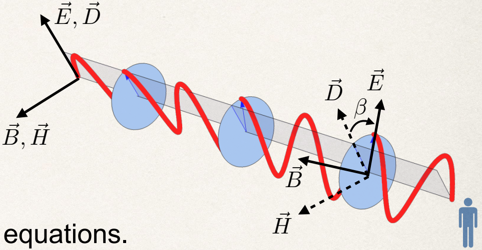
Cosmic birefringence from axion

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

- The polarization plane of CMB photon is rotated when an axion moves after the recombination epoch.

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

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

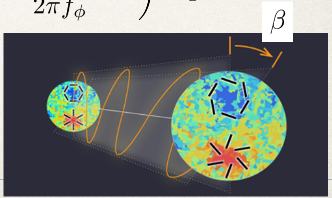


- $\vec{D}$ and $\vec{H}$ (rather than $\vec{E}$ and $\vec{B}$) satisfy free wave equations.

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

- $\Delta\phi/f_\phi = \mathcal{O}(1) \Longleftrightarrow \beta = \mathcal{O}(1)$

  String axion can have an observable effect.



Cosmic birefringence from axion

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

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

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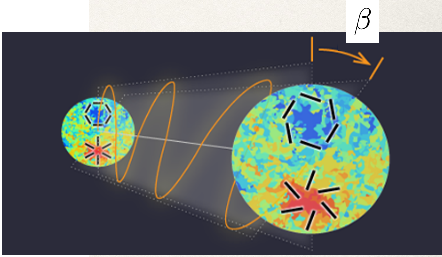
Todai Institutes for Advanced Study, The University of Tokyo, Kashiwa 277-8583, Japan
(Dated: November 24, 2020)

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 /KEK

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

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

Axion oscillation triggered by DM domination

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

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

This is another cosmic coincidence problem or "why now" problem.

✓ Is this related to dark matter?

Naively, the answer is negative because the recombination epoch is (just) after the matter-radiation equality.

- We have positive answers if the axion has an effective mass that triggers its oscillation after the matter-radiation equality.

Cosmic history

- BBN ($z \sim 10^{10}$)
- Matter-radiation equality ($z \sim 3400$)
- Recombination ($z \sim 1100$)
- Now ($z = 0$)

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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?

- Suppose that the axion has an effective mass that is proportional to the dark matter density.

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

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

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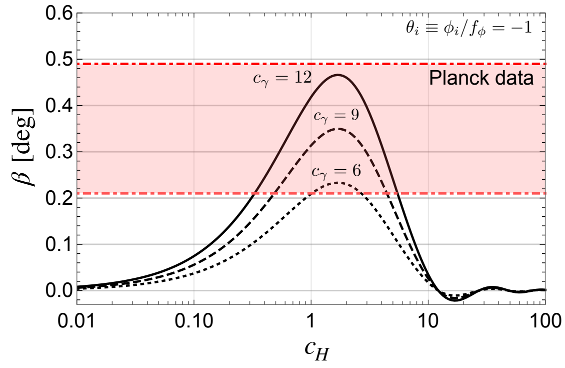
Cosmic history

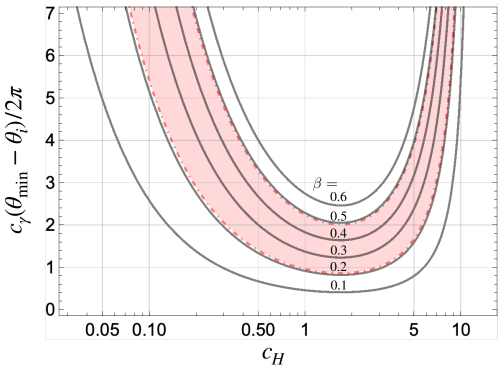
- BBN ($z \sim 10^{10}$)
- Matter-radiation equality ($z \sim 3400$)
- Recombination ($z \sim 1100$)

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

Axion oscillation 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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UV models for the DM-induced mass

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

Is there a complete UV model for the effective mass term?

- Yes, there is.

UV models for the DM-induced mass

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- UV origin: 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.

    Murayama, Shu '09, Baek, Ko, Park '13, Khoze, Ro '14

  - If the axion couples to U(1)H, the monopole has an electric charge of $\phi/(2\pi f_\phi)$ by the Witten effect:

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

E. Witten '79

UV models for the DM-induced mass

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    E. Witten '79

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

    Fischler, Presskill '83

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

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Summary

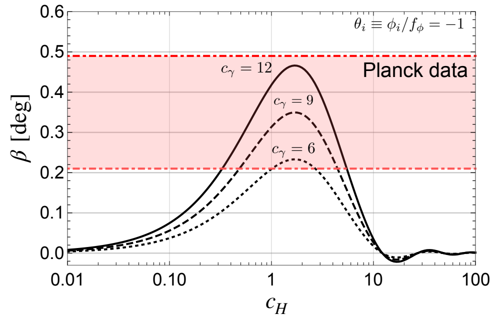
- The birefringence signal in Planck data implies an axion moves after the recombination epoch.

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

- The "why now" problem 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 complete model:
  - Hidden monopole dark matter
    - can explain DM density for $m_M = 10^{4\text{-}10}$ GeV
    - has a self-interaction via U(1)$_H$
    - may have mini-electric charge via kinetic mixing
    - predicts dark radiation from U(1)$_H$ gauge fields



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Appendix: related works

- Studies for the effect of fluctuations generated during inflation
  - Pospelov, Ritz, Skordis 0808.0673 (Considering massless axion)
  - Fujita, Minami, Murai, Nakatsuka 2008.02473 (Taking into account local fluctuations of axion)

- Studies that relates the axion and DM
  - Fedderke, Graham, Rajendran 1903.02666 (Considering the washout effect by axion oscillation)
  - Nakagawa, Takahashi, Yamada 2103.08153 (This work!)

- Studies that relates the axion and dark energy
  - Fujita, Murai, Nakatsuka, Tsujikawa 2011.11894 (Considering early dark energy to solve H_0 tension simultaneously)
  - Choi, Lin, Visinelli, Yanagida 2106.12602 (Providing a small mass by a small EW instanton effect)
  - Obata 2108.02150 (Considering two-axion alignment mechanism and also relating DM)
  - Gasparotto, Obata 2203.09409 (Considering monodromic axion dark energy)

- Studies considering the formation of topological defects
  - Agrawal, Hook, Huang 1912.02823 (Considering anisotropic birefringence from cosmic strings)
  - Jain, Long, Amin 2103.10962 (Considering anisotropic birefringence from cosmic strings)
  - Takahashi, Yin 2012.11576 (Considering isotropic and anisotropic birefringence from domain walls without cosmic strings)