B06: DM–CMB

The Dark Matter (DM) Search using the Cosmic Microwave Background (CMB)

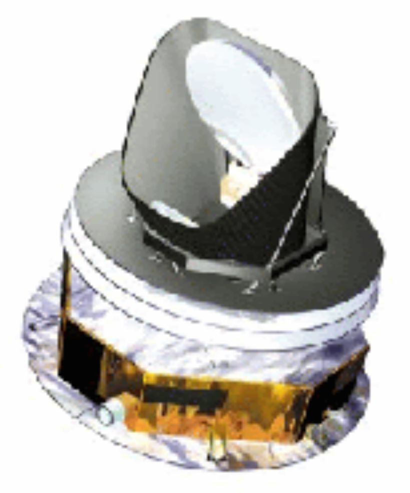
Eiichiro Komatsu (Max Planck Institute for Astrophysics / Kavli IPMU)

Symposium, March 29, 2022

ESA's Planck

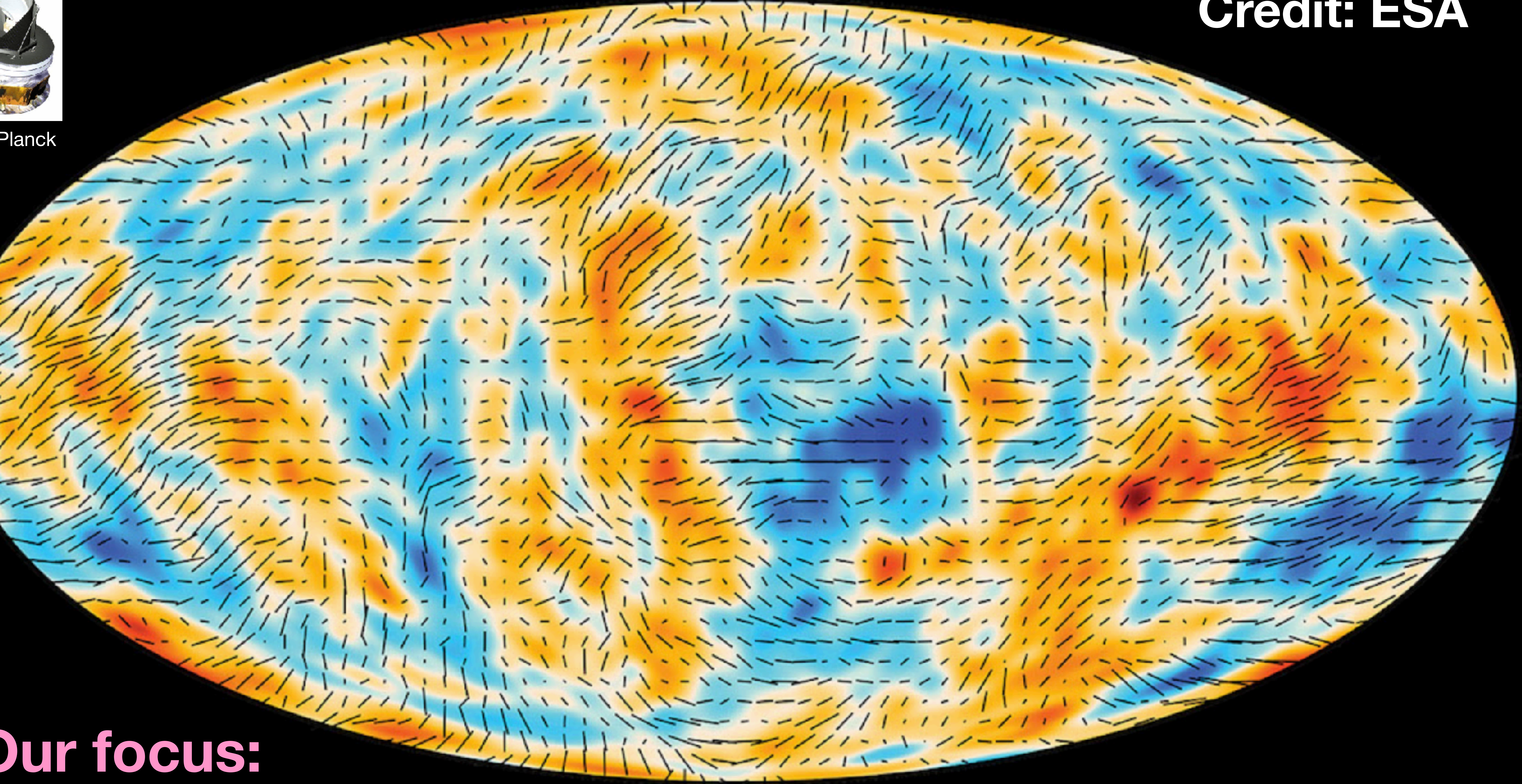
Credit: ESA


Temperature (smoothed)



ESA's Planck

Credit: ESA



Temperature (smoothed) + Polarisation

Our focus:
Polarisation!

Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (*Λ*)?
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
- *Polarisation* of the CMB may hold the answers to these questions.

Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (*Λ*)?
  - **Cosmic birefringence** in cross-correlation of E- and B-mode polarisation
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
  - Imprint of **primordial gravitational waves** in B-mode polarisation
- *Polarisation* of the CMB may hold the answers to these questions.

New physics from the polarised light of the cosmic microwave background

To appear in Nature Reviews Physics.

arXiv:2202.13919

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Many of the B06 activities are explained in this article.

ABSTRACT

The current cosmological model requires new physics beyond the standard model of elementary particles and fields such as dark matter and dark energy. Their nature is unknown and so is that of the initial fluctuations in the early Universe that led to the creation of the cosmic structure we see today. Polarised light of the cosmic microwave background (CMB) may hold the answer to these fundamental questions and we discuss two phenomena that could be uncovered in CMB observations. First, if the physics behind dark matter and dark energy violates parity symmetry, their coupling to photons rotated the plane of linear polarisation as the CMB photons have been travelling for more than 13 billion years. This effect is known as 'cosmic birefringence'. A tantalising hint for such a signal has been found with a statistical significance of 3σ. Second, the period of accelerated expansion in the very early Universe, called 'cosmic inflation', might have produced a (yet unobserved) stochastic background of primordial gravitational waves. These might have been generated by vacuum fluctuations in spacetime or by matter fields and could be measured in the CMB polarisation. The goal of observing these two phenomena will influence how data from future CMB experiments are collected, calibrated, and analysed.

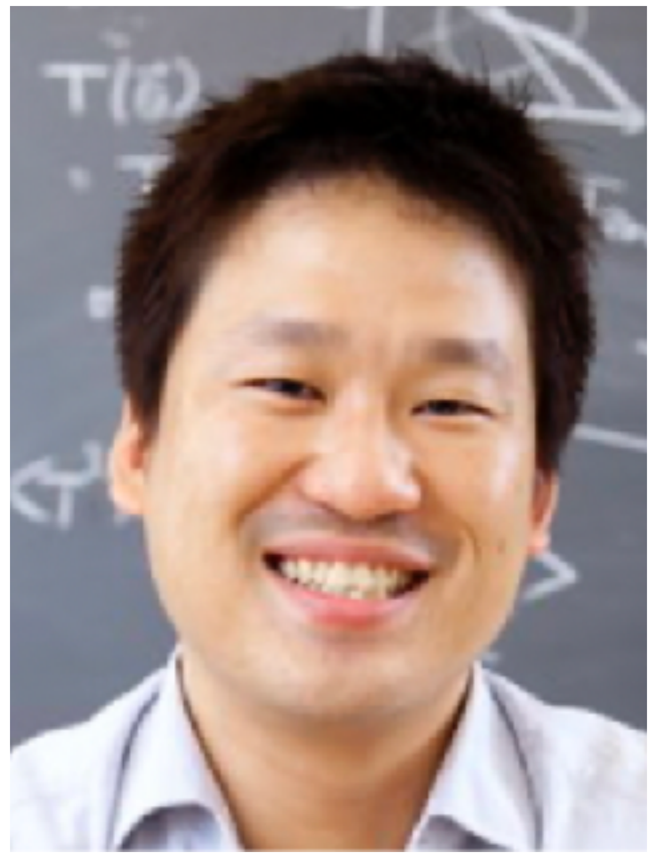
The Science Targets: Examples

How can we use the CMB polarisation to learn about the DM?

- **Do the DM fields violate parity symmetry?**
  - Why not? The weak interaction violates parity symmetry.
  - E.g., axion-like fields.
  - **Example project:** *How does the parity-violating DM field affect the propagation of polarised light of the CMB?*
- **Do the DM fields have a higher spin?**
  - Why not? The Higgs field is the only known field of elementary particles with zero spin.
  - **Example project:** *Do higher-spin fields generate new features in the gravitational waves which can be observed in the CMB polarisation?*

The Team

A small yet “dream team”



Eiichiro Komatsu
(MPA / Kavli IPMU)

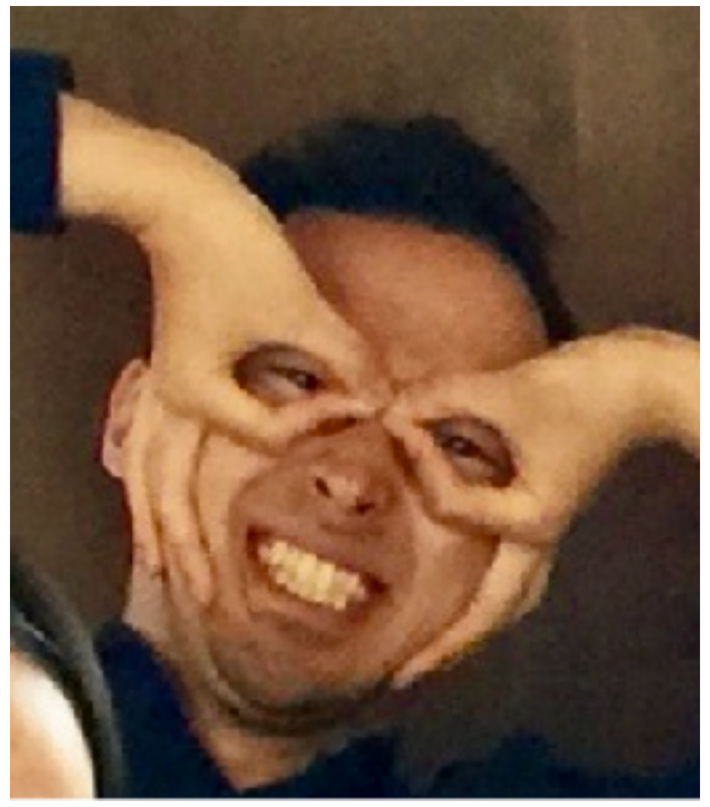
Analysis

- 研究代表者

Maresuke Shiraishi
(NIT Kagawa
-> **Suwa Univ. Sci.**)

Analysis
+ Theory

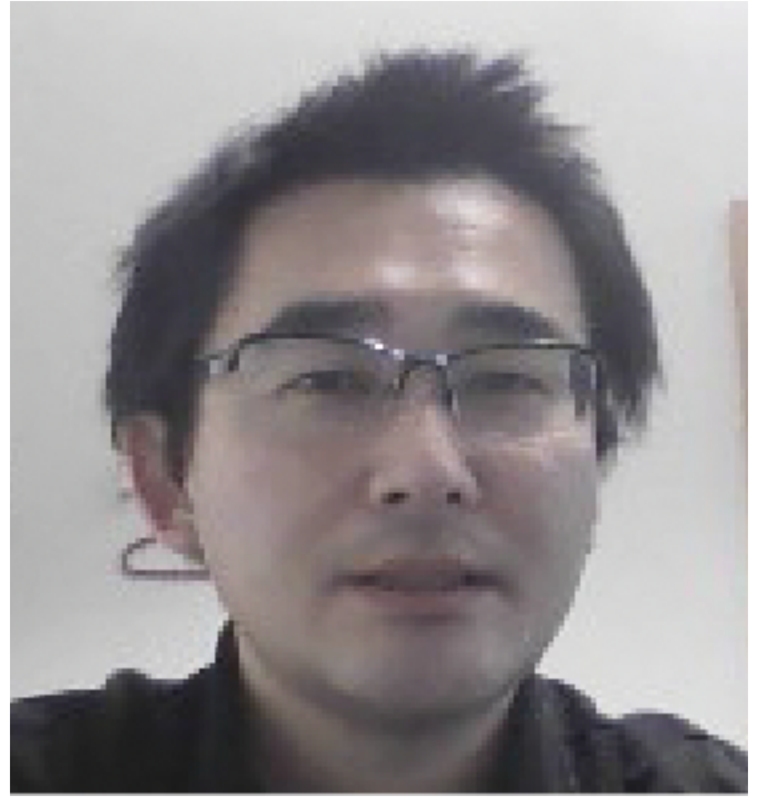
- 研究分担者



Ippei Obata
(MPA ->
Kavli IPMU)

Theory

- 研究協力者



Toshiya Namikawa
(Kavli IPMU)

Analysis

- 研究協力者


Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates polarisation!)
What powered the Big Bang?
What is dark matter/energy?

Achievements: Highlight (4.2021 – 3.2022)

Do the DM fields violate parity symmetry?

- **New measurement and interpretation of "cosmic birefringence"**
  - Diego-Palazuelos et al. (incl. **EK**), "*Cosmic birefringence from the Planck Data Release 4*", published in PRL.

This Talk

  - **Namikawa**, "*CMB mode coupling with isotropic polarization rotation*", published in MNRAS.

  - **Obata**, "*Implications of the cosmic birefringence measurement for the axion dark matter search*", arXiv:2108.02150.

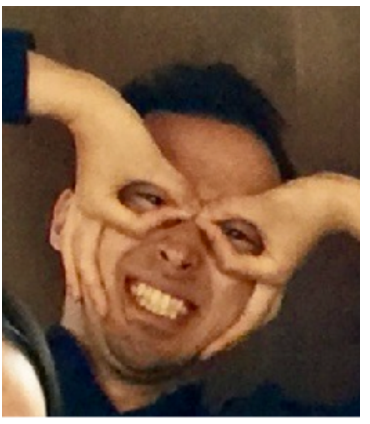
  - Nakatsuka, **Namikawa**, **EK**, "*Is cosmic birefringence due to dark energy or dark matter? A tomographic approach*", arXiv:2203.08560.
  - Gasparotto, **Obata**, "Cosmic birefringence from monodromic axion dark energy", arXiv:2203.09409.

The following talks

Achievements: Highlight (4.2021 – 3.2022)

Do the DM fields have a higher spin?

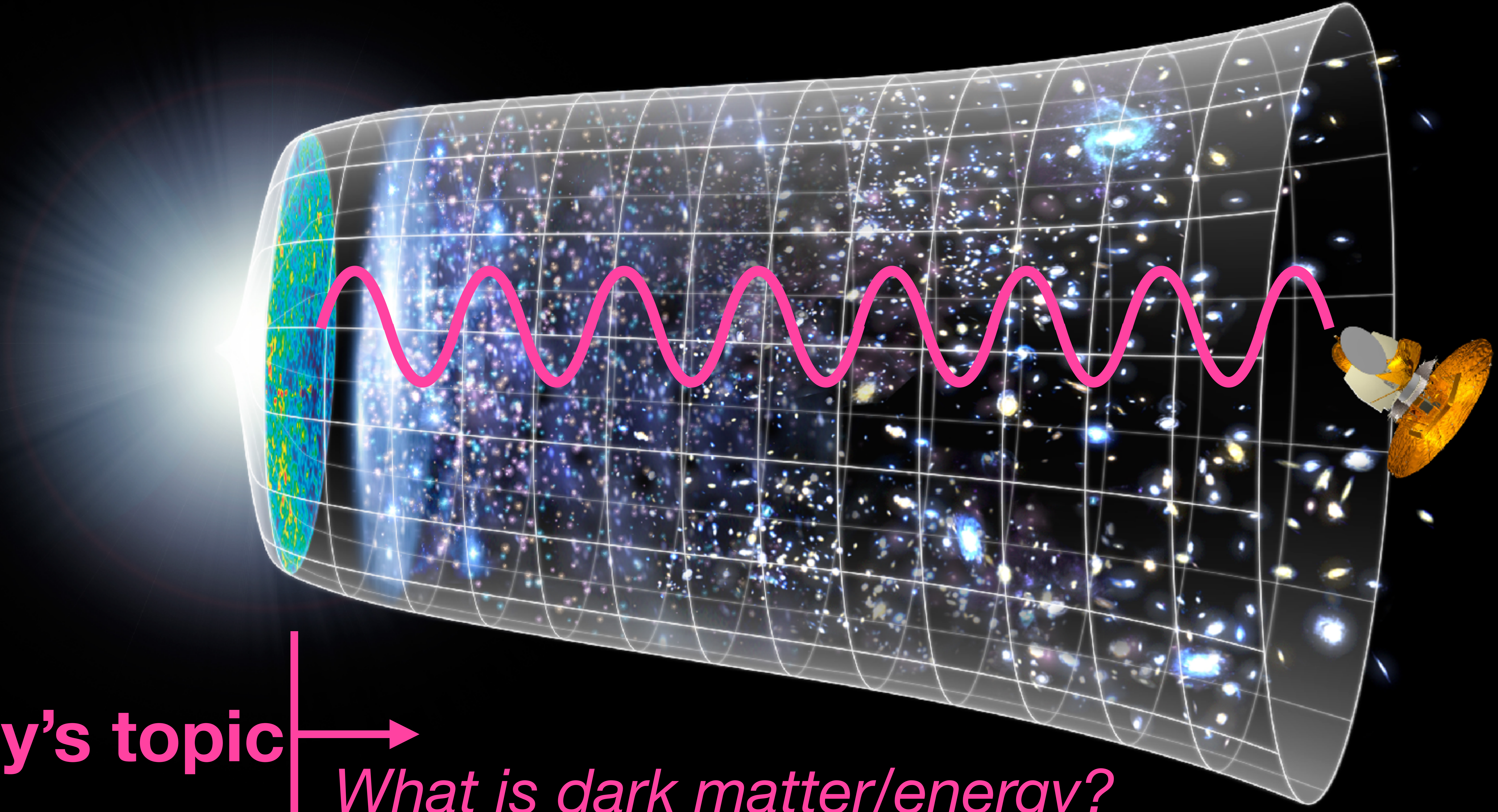
- **Axion-SU(2) & U(1) systems during inflation and predictions for GWs**
  - Ishiwata, **EK**, **Obata**, "*Axion-gauge field dynamics with backreaction*", published in JCAP.



  - Fujita, Murai, **Obata, Shiraishi**, "*Gravitational wave trispectrum in the axion-SU(2) model*", published in JCAP.

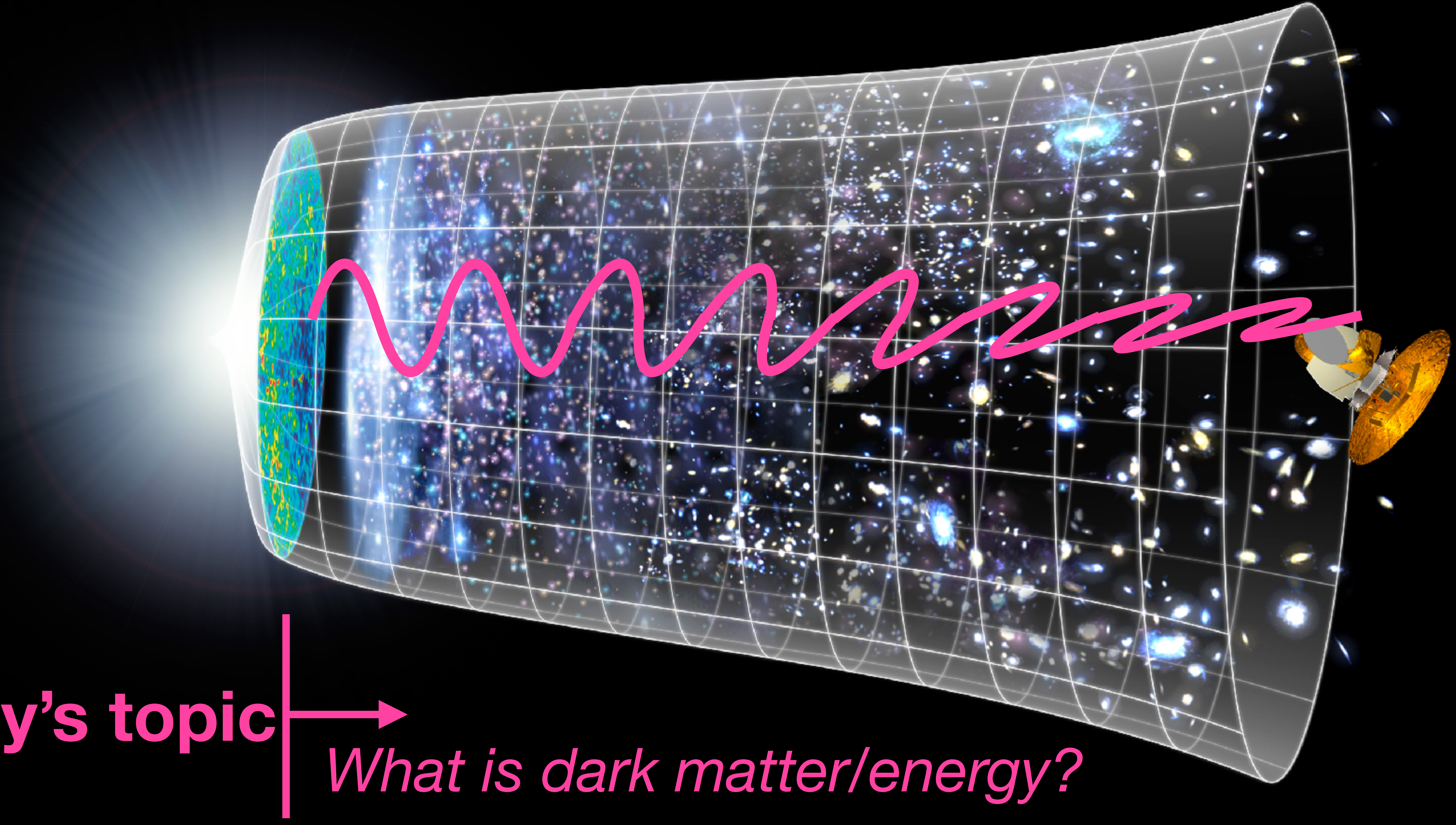
  - Campeti, Öszoy, **Obata, Shiraishi,** "*New constraints on axion-gauge field dynamics during inflation from Planck and BICEP/Keck data sets*", arXiv:2203.03401.

How does the electromagnetic wave of the CMB propagate?



Today's topic → *What is dark matter/energy?*

How does the electromagnetic wave of the CMB propagate?



Today's topic

What is dark matter/energy?

Cosmic Birefringence

The Universe filled with a "birefringent material"

This "axion" field can be dark matter or dark energy!

- If the Universe is filled with a pseudoscalar field (e.g., an axion field) coupled to the electromagnetic 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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad \sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E}) \qquad \sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$

Parity Even **Parity Odd**

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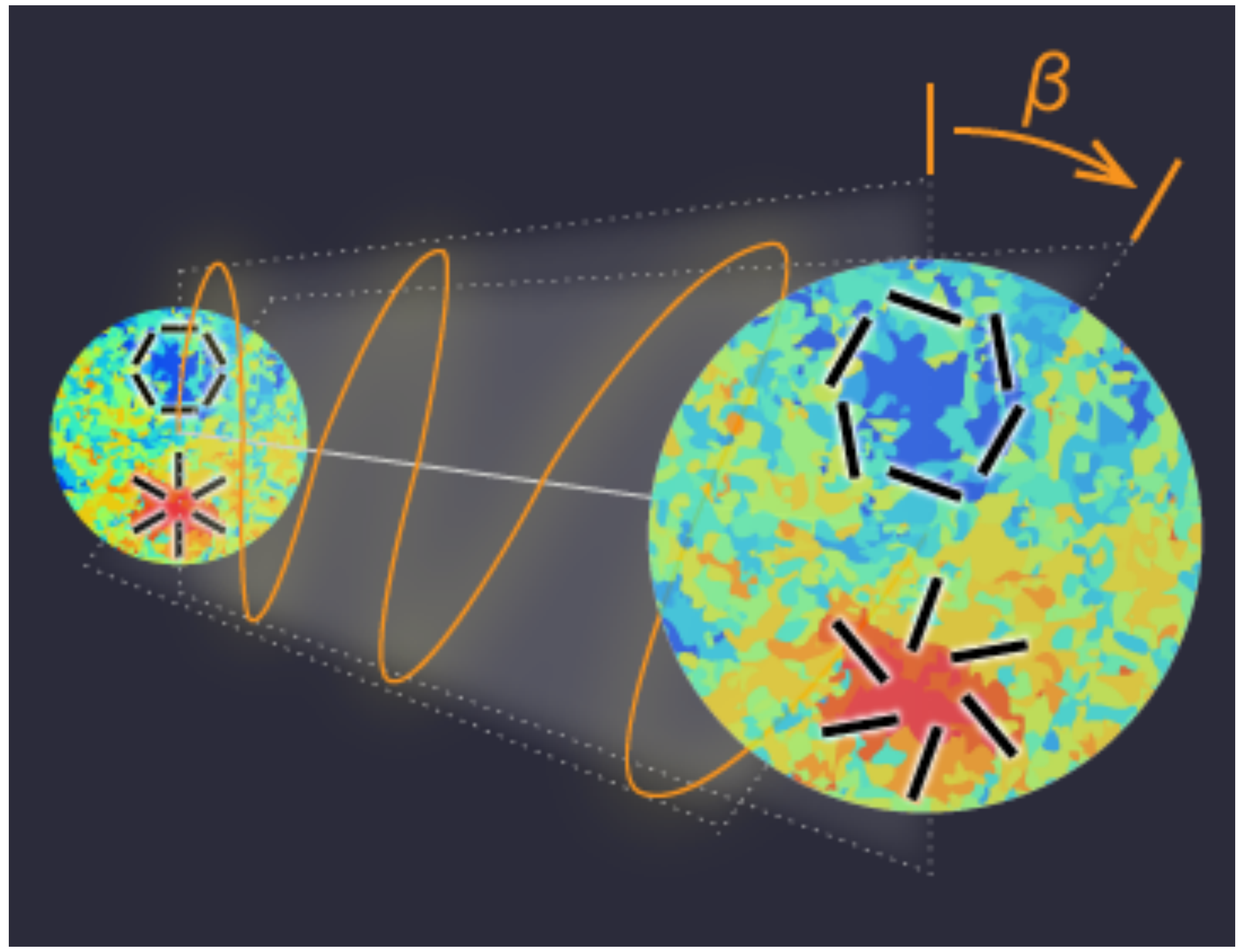


"Cosmic Birefringence"

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to **rotation of the linear polarisation direction.**

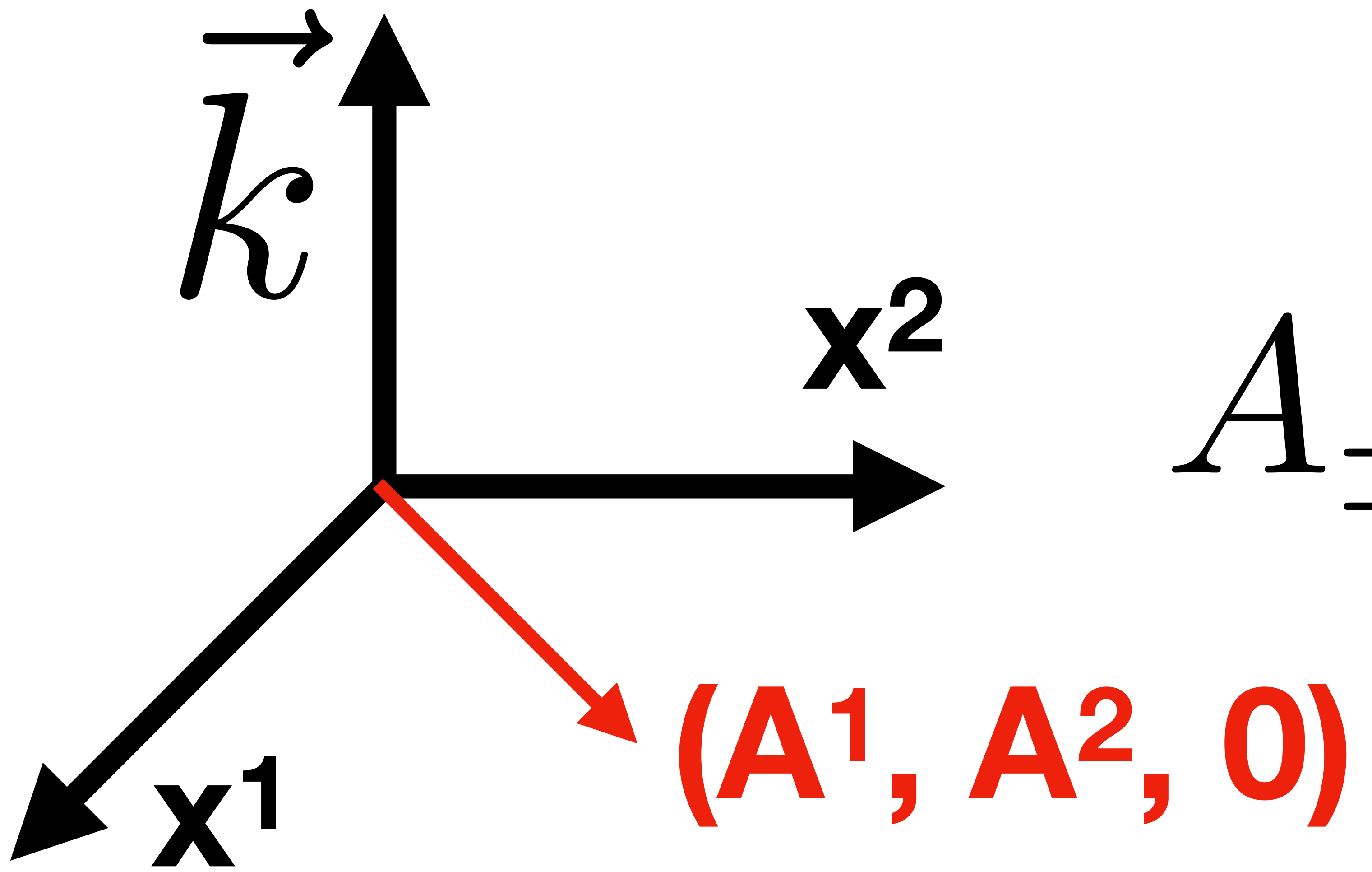
Standard Maxwell Theory

Warm up (1)

- To isolate a transverse wave, we require A_0=0 and div(A_i)=0. Then, in vacuum,

$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0 \qquad\qquad ds^2 = a^2(-d\eta^2 + d\mathbf{x}^2)$$

- Go to Fourier space, choose the propagation direction of A_i to be in z-axis, and define right- and left-handed polarisation states as



$$A_\pm = \frac{A_1 \mp iA_2}{\sqrt{2}}$$

- A_+: Right-handed state
- A_-: Left-handed state

Standard Maxwell Theory

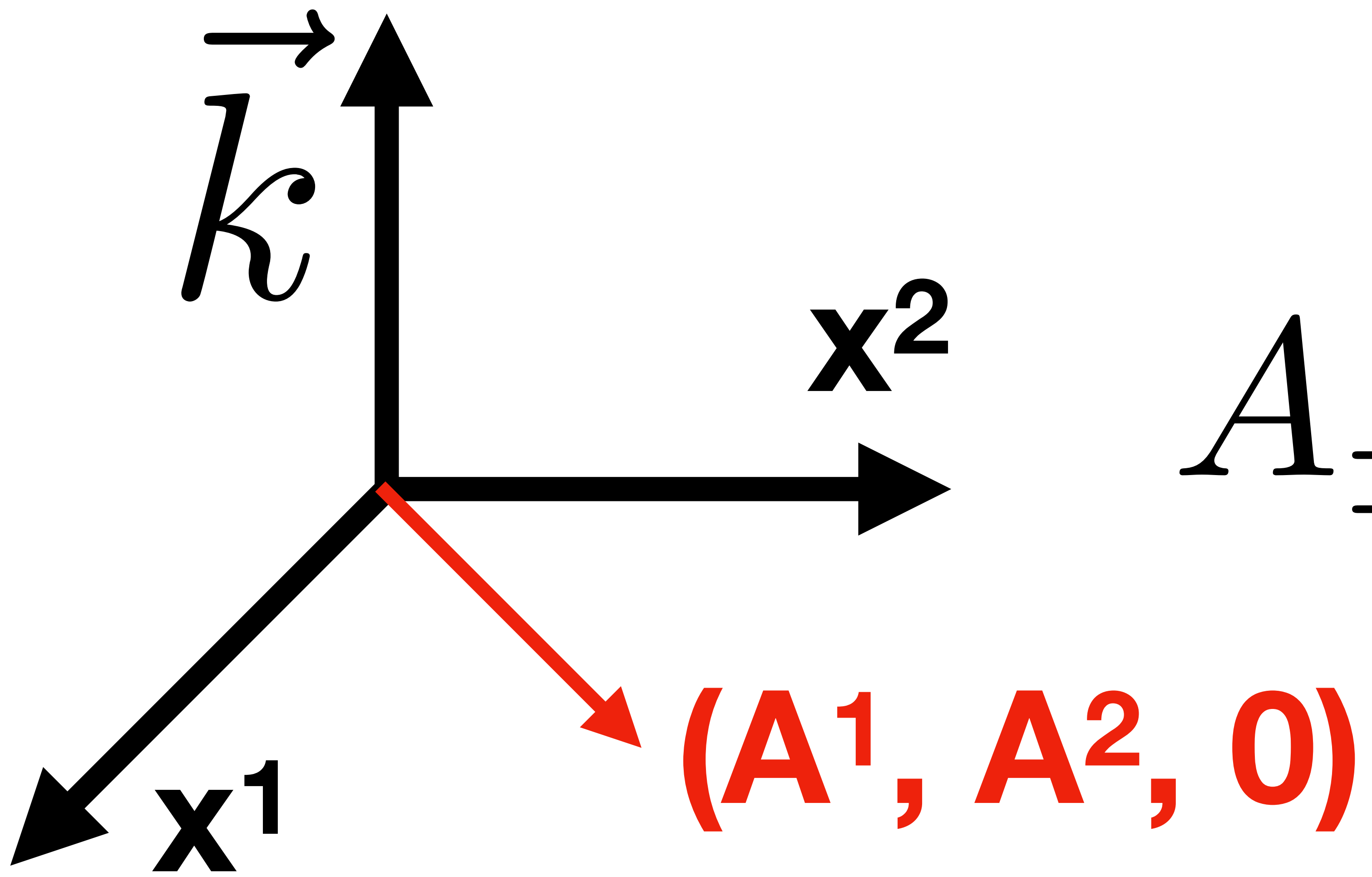
Warm up (2)

- To isolate a transverse wave, we require $A_0=0$ and $\mathrm{div}(A_i)=0$. Then, in vacuum,

$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0 \quad \Rightarrow \quad \left(-\omega_\pm^2 + k^2\right) A_\pm(\eta) = 0$$

Same dispersion relation for right- and left-handed states

- Go to Fourier space, choose the propagation direction of A_i to be in z-axis, and define right- and left-handed polarisation states as



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

Cosmic Birefringence

Derivation (1)

- Now, include **the Chern-Simons term**!

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

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

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 equation of motion is modified to

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

$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k} \quad (\theta' = \partial\theta/\partial\eta)$$

Cosmic Birefringence

Derivation (1)

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$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k} = \left(1 \pm \frac{2g_a\theta'}{k}\right)^2 - \frac{4g_a^2\theta'^2}{k^2}$$

Cosmic Birefringence

Derivation (1)

- Now, include **the Chern-Simons term**!

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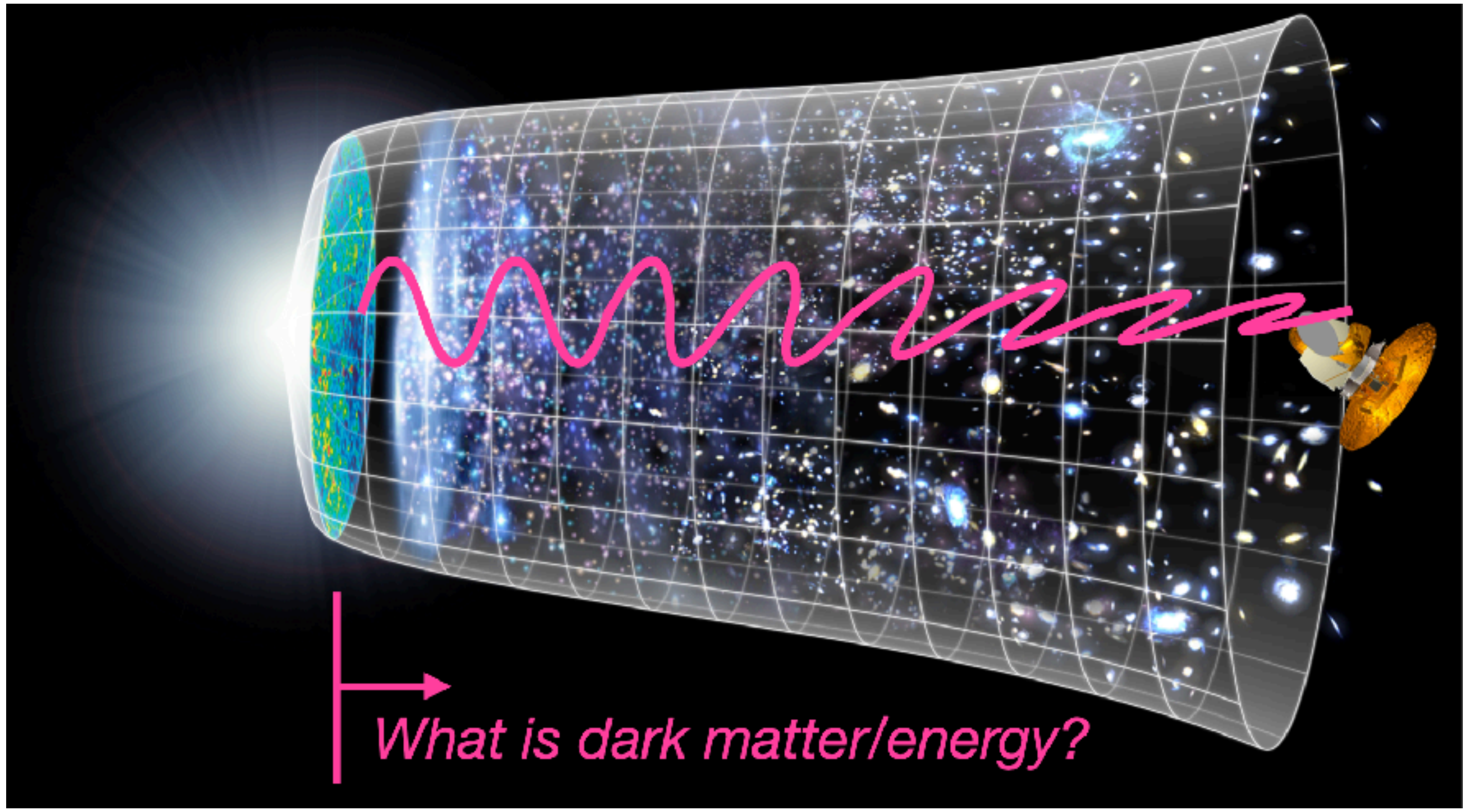
$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

Phase velocities of right- and left-handed states are slightly different!

Cosmic Birefringence

Derivation (2)



- With

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

Phase velocities of right- and left-handed states are slightly different!

- The plane of linear polarisation rotates clockwise on the sky by an angle β:

$$-\beta = \int d\eta \, \frac{\omega_+ - \omega_-}{2} = 2g_a \int d\eta \, \theta' = 2g_a \int dt \, \dot{\theta}$$

The effect accumulates over the distance!
=> CMB polarisation is sensitive to this effect

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

Cosmic Birefringence

Recap

This "axion" field can be dark matter or dark energy!

- If the Universe is filled with a pseudoscalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

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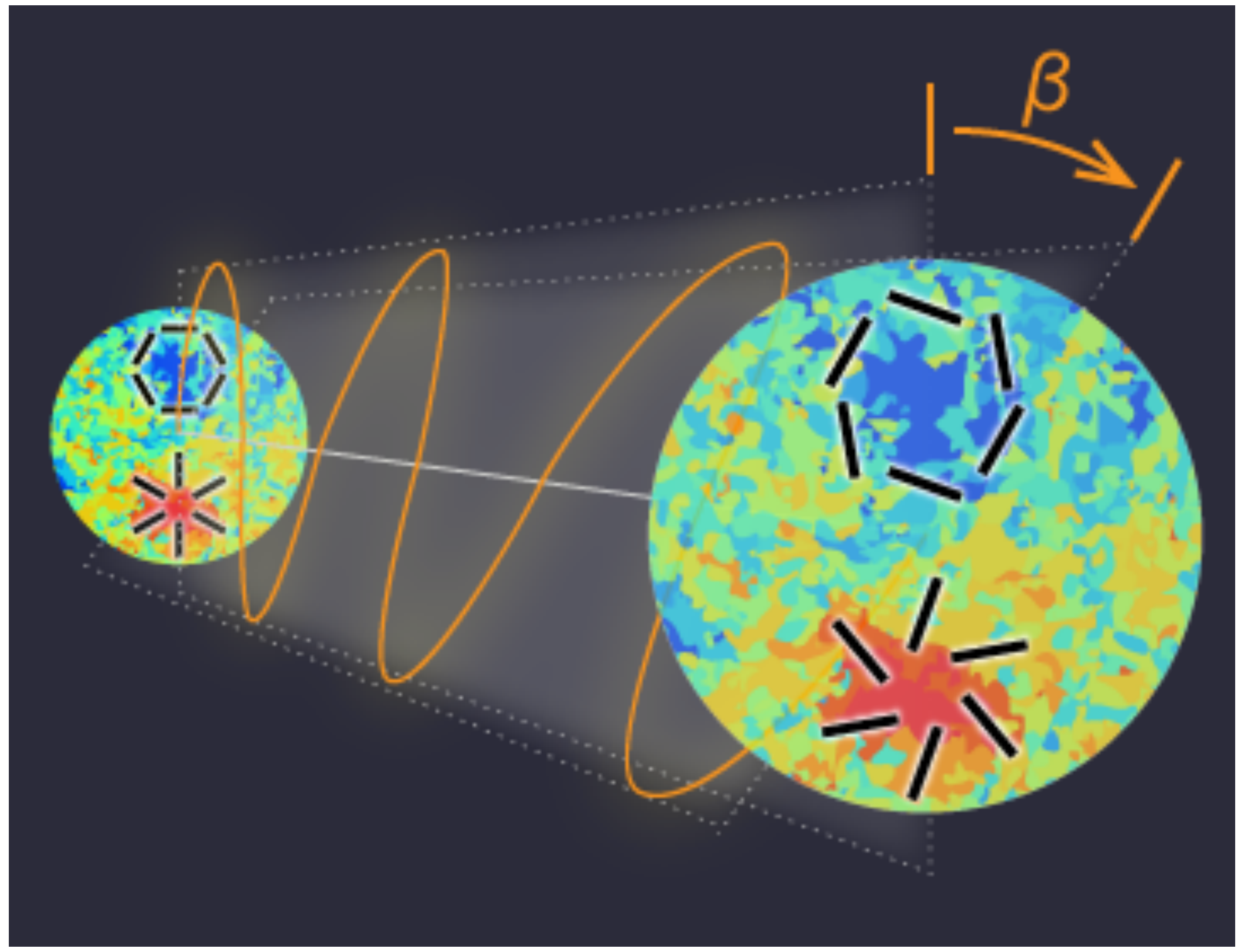
$$\beta = -2g_a\int_{t_\mathrm{emitted}}^{t_\mathrm{observed}} dt\,\dot{\theta} = 2g_a\left[\theta(t_\mathrm{e}) - \theta(t_\mathrm{o})\right]$$



The difference between the fields values at the end points gives β.

Cosmic Birefringence

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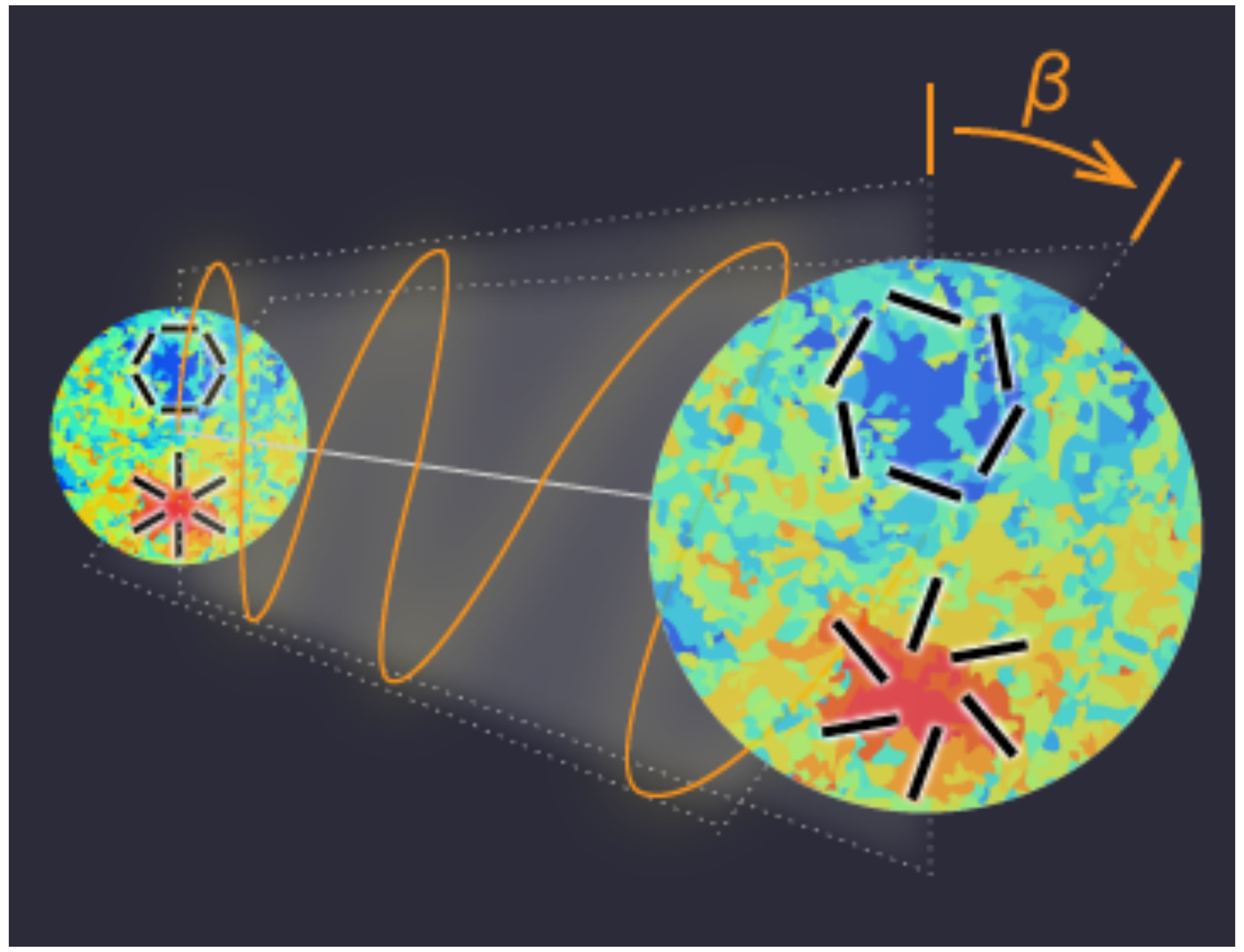


If θ varies over space:

$$\beta(\hat{n},\tau) = -2g_a\int_{t_\mathrm{emitted}}^{t_\mathrm{observed}} dt\,\frac{d\theta}{dt} = 2g_a\left[\theta(t_\mathrm{e},\hat{n}r_\mathrm{oe}) - \theta(t_\mathrm{o},\tau)\right]$$

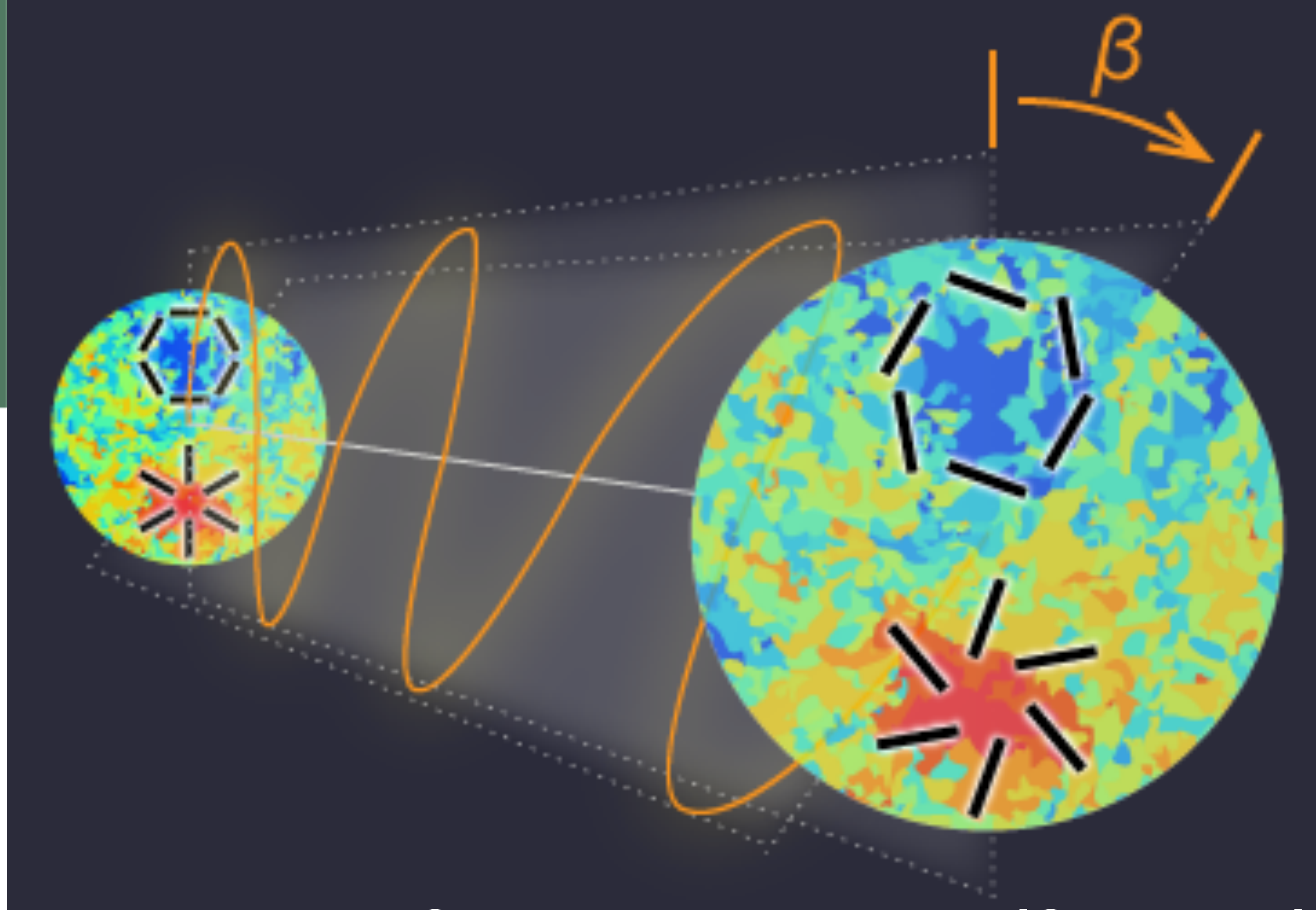
PHYSICAL REVIEW LETTERS

Featured in Physics Editors' Suggestion

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

Yuto Minami and Eiichiro Komatsu
Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

Physics See synopsis: Hints of Cosmic Birefringence?



Credit: Yuto Minami (Osaka U.)

First measurement: 2.4σ

$\beta = 0.35 \pm 0.14$ (68%CL)

ABSTRACT

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.

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Cosmic Birefringence from the *Planck* Data Release 4

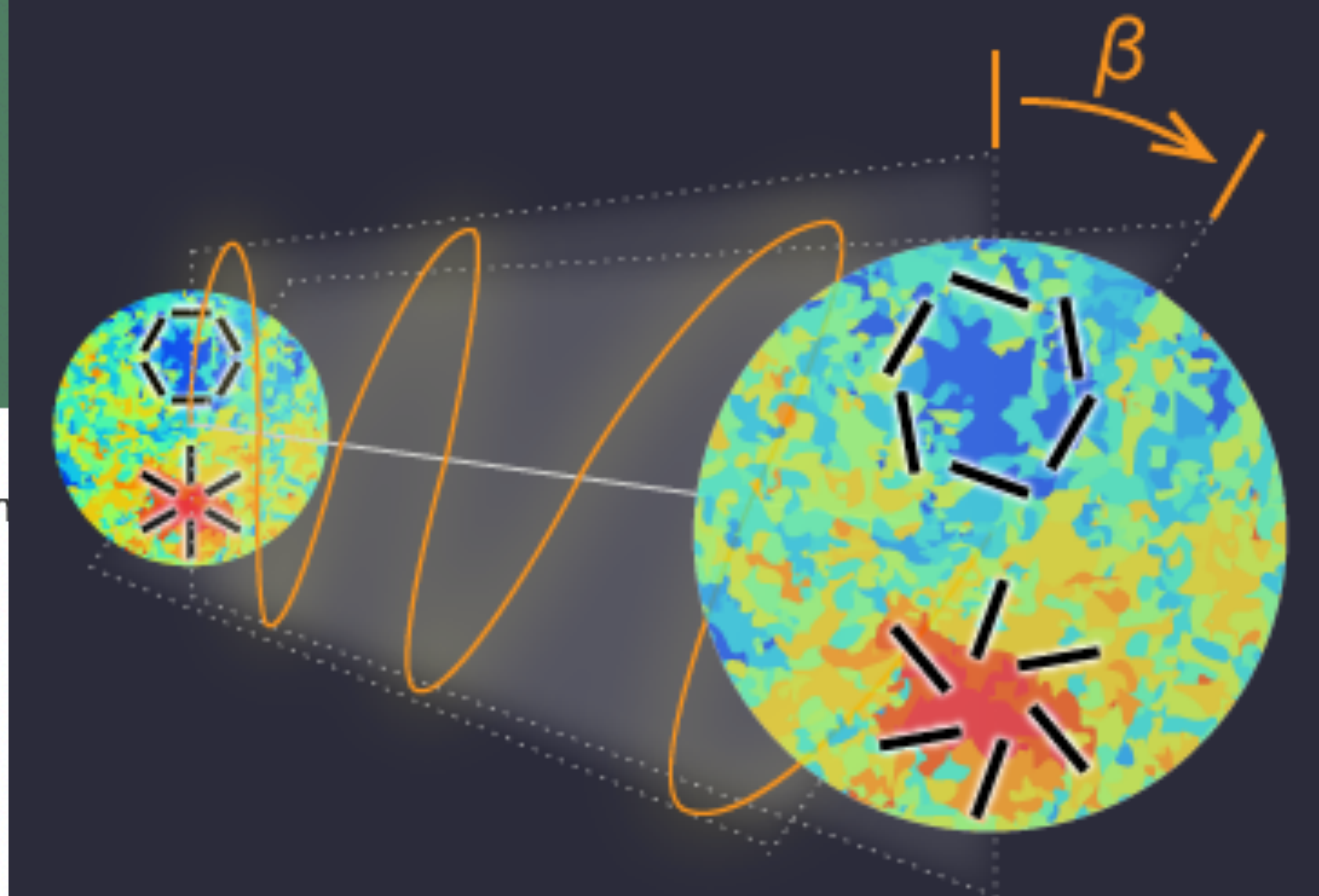
P. Diego-Palazuelos, J. R. Eskilt, Y. Minami, M. Tristram, R. M. Sullivan, A. J. Banday, R. B. Barreiro, H. K. Eriksen, K. M. Górski, R. Keskitalo, E. Komatsu, E. Martínez-González, D. Scott, P. Vielva, and I. K. Wehus

Phys. Rev. Lett. **128**, 091302 – Published 1 March 2022

Article | References | No Citing Articles | PDF | HTML | Export Citation

ABSTRACT

We search for the signature of parity-violating physics in the cosmic microwave background, called cosmic birefringence, using the *Planck* data release 4. We initially find a birefringence angle of $\beta = 0.30^\circ \pm 0.11^\circ$ (68% C.L.) for nearly full-sky data. The values of β decrease as we enlarge the Galactic mask, which can be interpreted as the effect of polarized foreground emission. Two independent ways to model this effect are used to mitigate the systematic impact on β for different sky fractions. We choose not to assign cosmological significance to the measured value of β until we improve our knowledge of the foreground polarization.



Credit: Yuto Minami (Osaka U.)

With the latest Planck data release:

$\beta = 0.30 \pm 0.11$ (68%CL)

Accounting for the effect of Galactic foreground:

$\beta = 0.36 \pm 0.11$ (68%CL)

Now it is 3.3σ.

Interpretation and the possible way forward

- See the following presentations by Toshiya and Ippei.

arXiv:2203.08560

Is cosmic birefringence due to dark energy or dark matter? A tomographic approach

Hiromasa Nakatsuka,[1] Toshiya Namikawa,[2] and Eiichiro Komatsu[3,2]

[1] *ICRR, University of Tokyo, Kashiwa, 277-8582, Japan*
[2] *Kavli IPMU (WPI), UTIAS, University of Tokyo, Kashiwa, 277-8583, Japan*
[3] *Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*

arXiv:2108.02150

Implications of the Cosmic Birefringence Measurement for the Axion Dark Matter Search

Ippei Obata[1]

[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*

Workshop! (If approved by Kavli IPMU)

Main organiser: Elisa Ferreira (Kavli IPMU)

- *Workshop Title*: ***Recent Topics on Dark Matter, Gravitational Waves, and the Cosmic Microwave Background***
- Target dates: June 27-30, 2022
- Co-sponsored by:
  - This 学術変革(A).
  - JSPS Core-to-core Program (PI: Akito Kusaka), involving international institutions working on the CMB research.
  - European Commission RISE Program “CMB-INFLATE”, involving international institutions working on the CMB research.