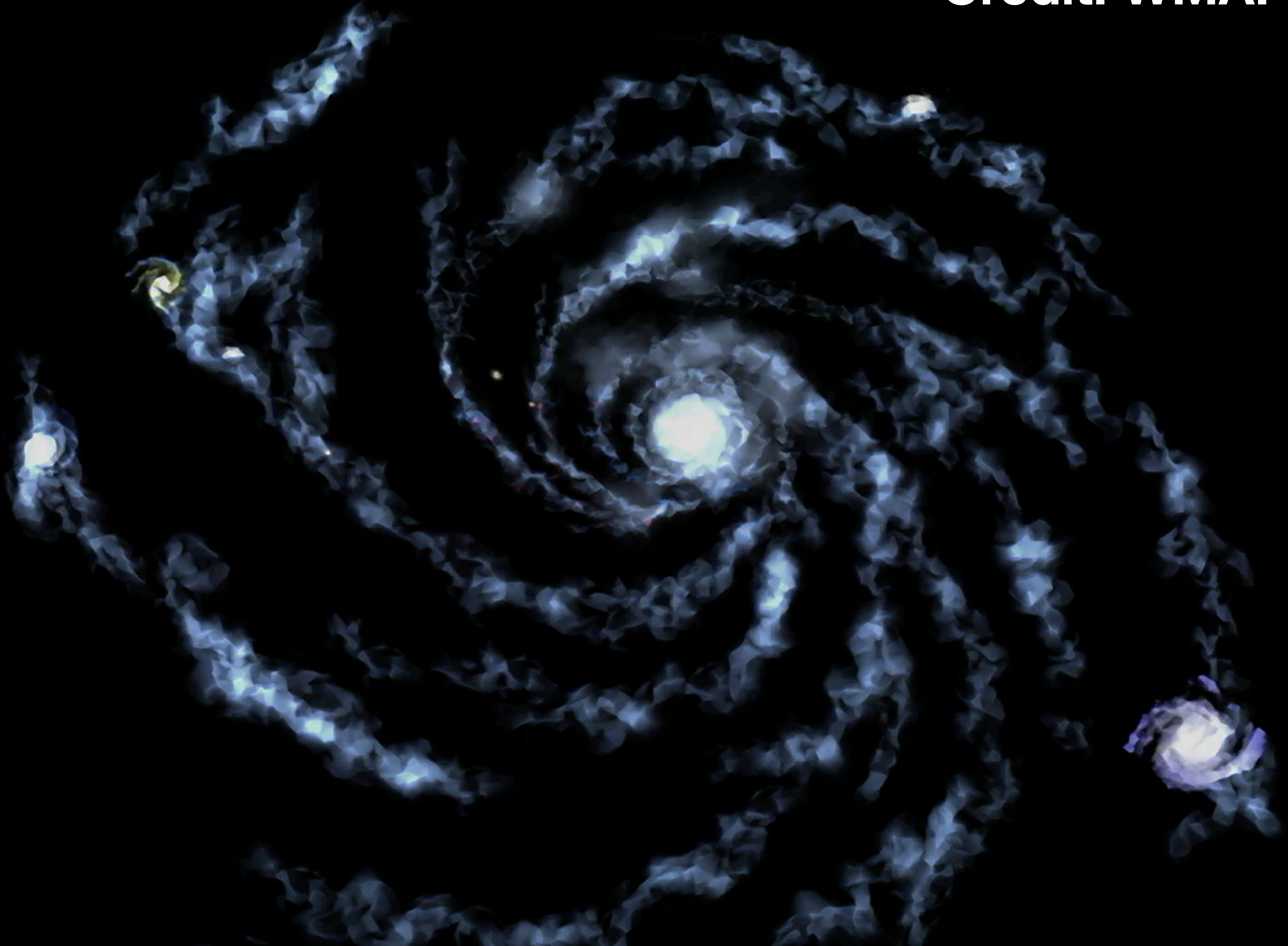
B06: DM–CMB

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

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

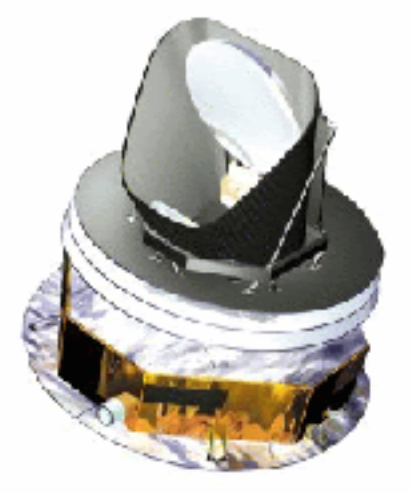
The Kick-off Symposium, February 6, 2021

Credit: WMAP Science Team



The sky in various wavelengths

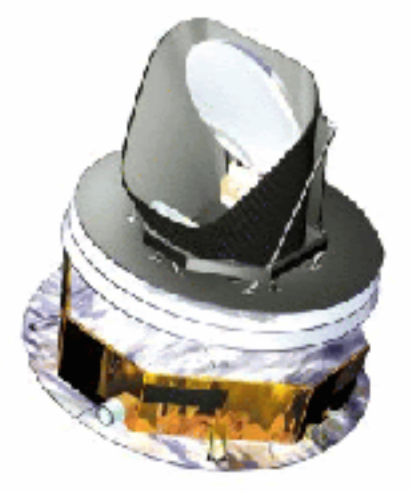
Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave



ESA’s Planck

Credit: ESA

Temperature (smoothed)


ESA's Planck

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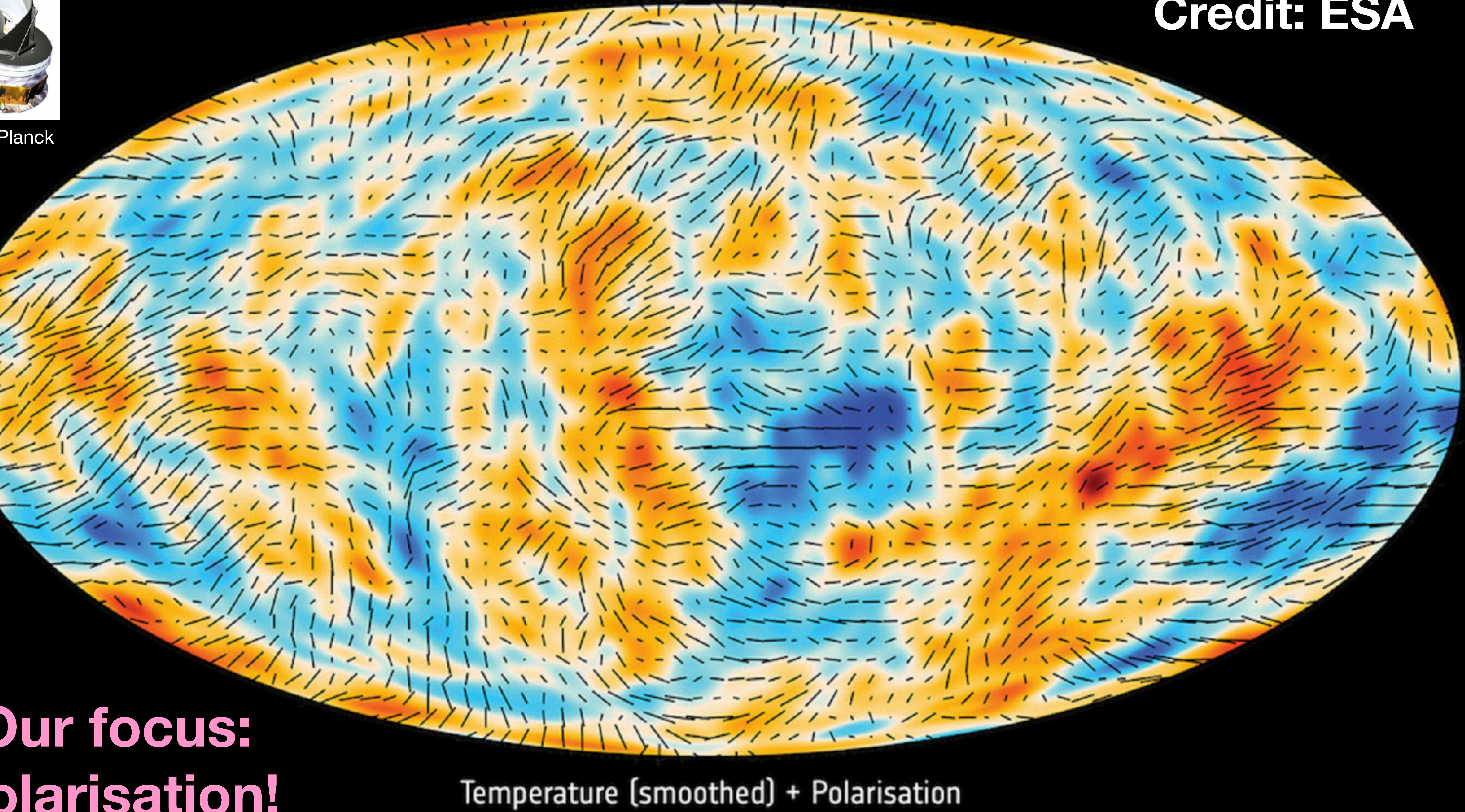


Our focus: Polarisation!

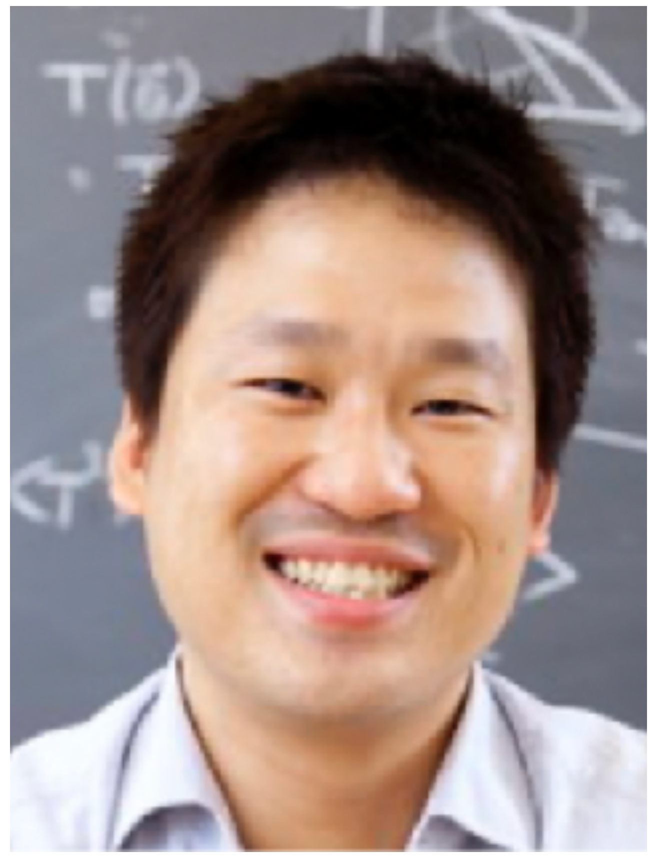
The Science Targets: Examples

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

- **Do the DM fields violate parity?**
    - Why not? The weak interaction violates parity.
    - 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)

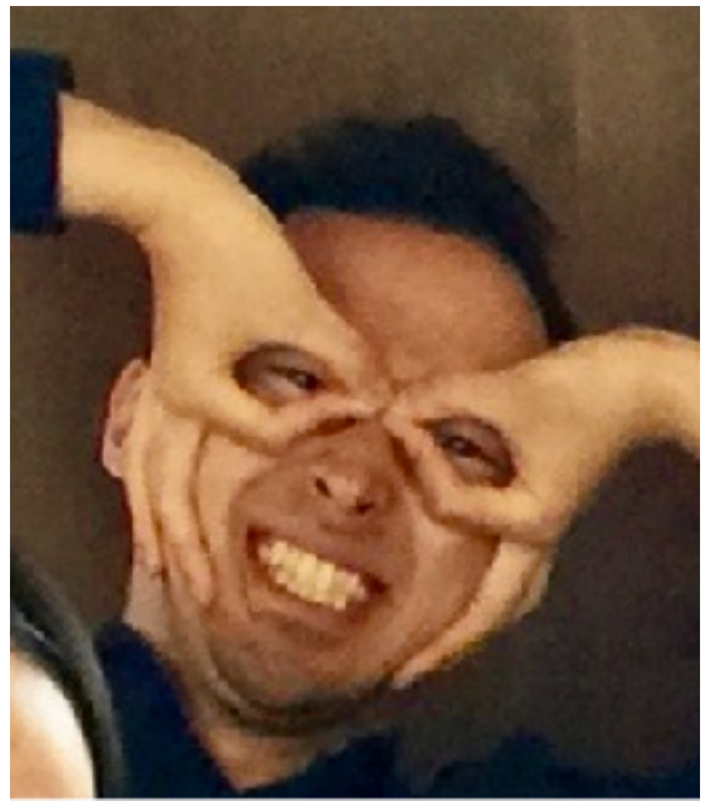
Analysis

- 研究代表者

Maresuke Shiraishi
(NIT Kagawa)

Analysis
+ Theory

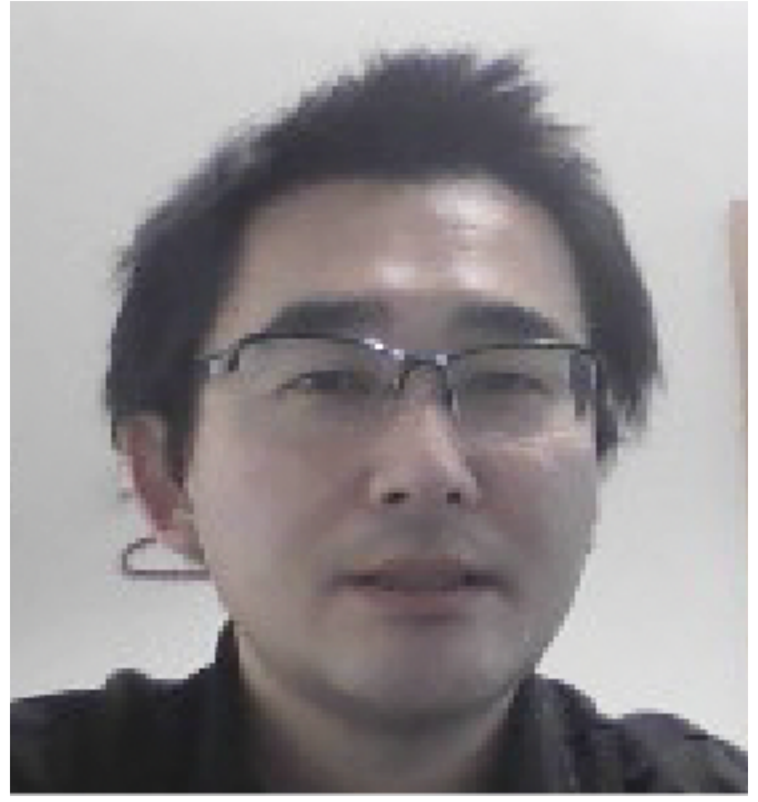
- 研究分担者



Ippei Obata
(MPA)

Theory

- 研究協力者



Toshiya Namikawa
(Cambridge Univ. ->
Kavli IPMU on Aug 1)

Analysis

- 研究協力者

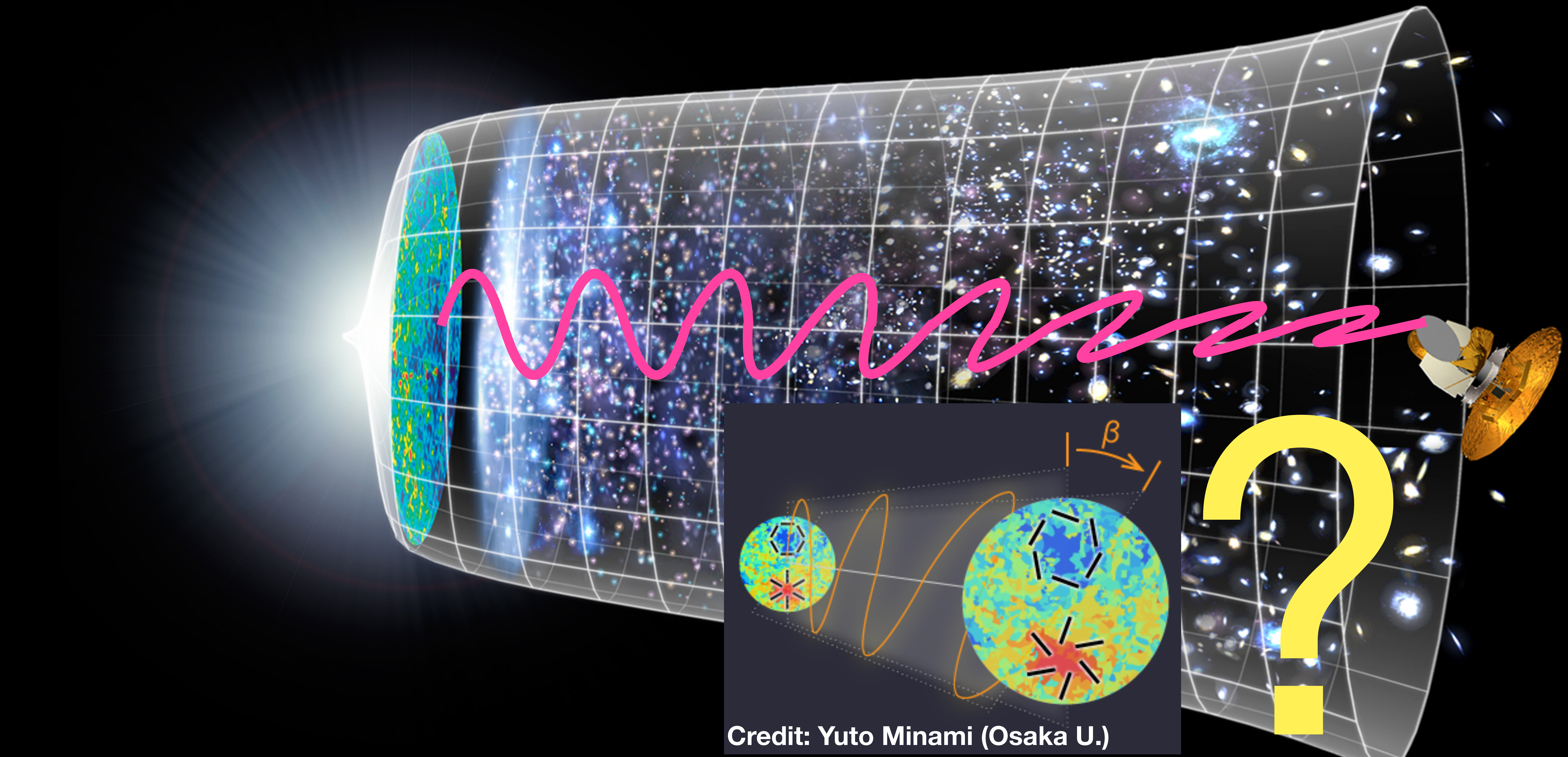
Credit: WMAP Science Team

How does the electromagnetic wave of the CMB reach us?

Now shown: The cosmological redshift due to the expansion of the Universe

Credit: WMAP Science Team

How does the electromagnetic wave of the CMB reach us?



Note: rotation of the polarisation plane is massively exaggerated!

Cosmic Birefringence

The Universe filled with a "birefringent material"

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

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

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

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

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

$$\sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E})$$ **Parity Even**

$$\sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$ **Parity Odd**

- The axion field, θ, is a "pseudo scalar", which is parity odd; thus, the last term in Eq.3.7 is parity even as a whole.

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998)

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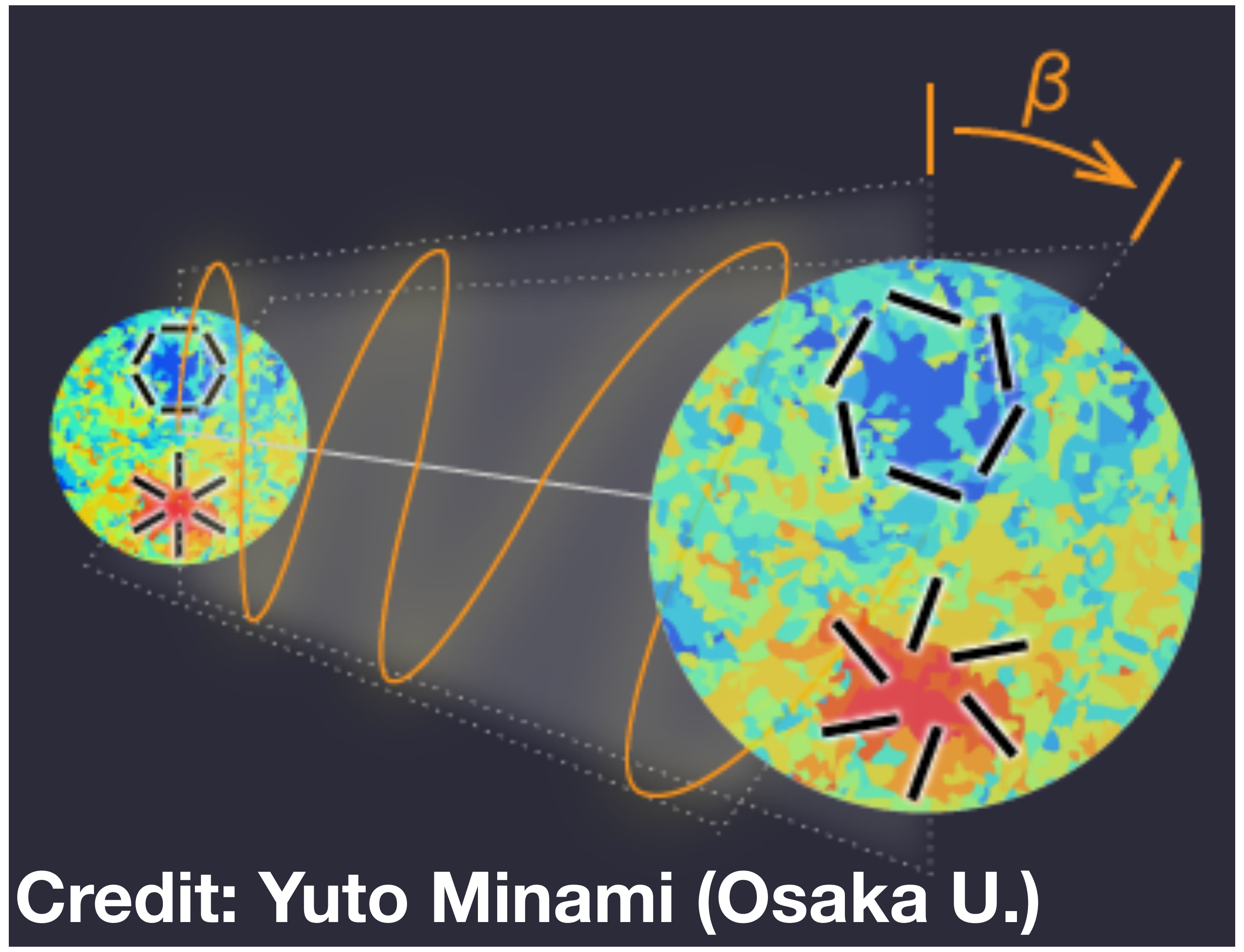


Credit: Yuto Minami (Osaka U.)

The "Cosmic Birefringence" (Carroll 1998)

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

Cosmic Birefringence

The effect accumulates over the distance

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

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

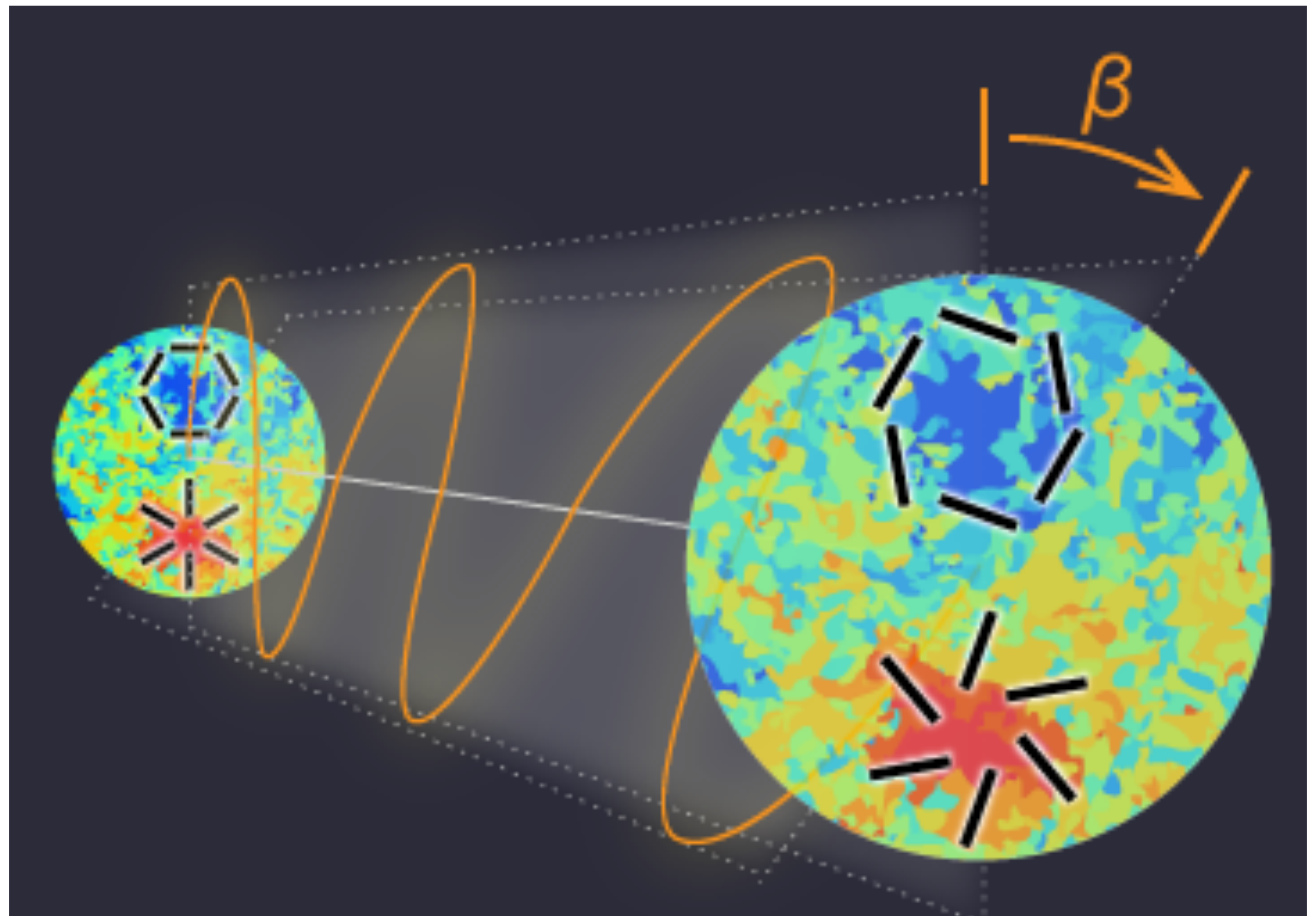
Chern-Simons term

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

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

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

$$\beta = 2g_a \int_{t_{\text{emission}}}^{t_{\text{observed}}} dt\ \dot{\theta}$$



Credit: Yuto Minami (Osaka U.)

The larger the distance the photon travels, the larger the effect becomes.

Motivation

Why study the cosmic birefringence?

- The Universe's energy budget is dominated by two dark components:
    - Dark Matter
    - Dark Energy
- Either or both of these can be an axion-like field!
    - See Marsh (2016) and Ferreira (2020) for reviews.
- Thus, detection of parity-violating physics in polarisation of the cosmic microwave background can transform our understanding of Dark Matter/ Energy.

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

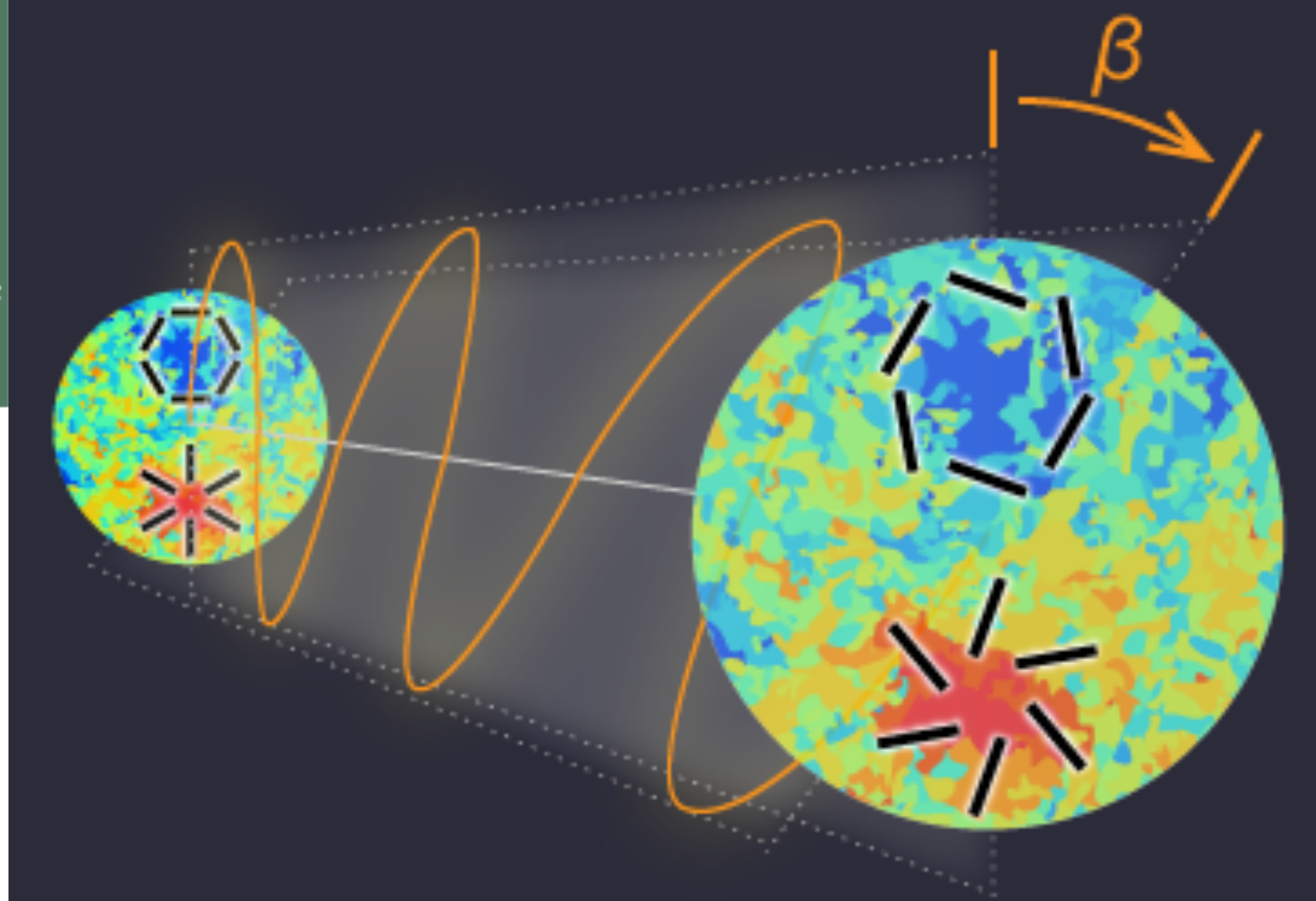
Yuto Minami and Eiichiro Komatsu
Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

Physics See synopsis: Hints of Cosmic Birefringence?

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

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.



Credit: Yuto Minami (Osaka U.)

State-of-the-art: 2.4σ

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

Confirmed by at least 3 teams using independent codes.

Next Steps:

1. **To increase the statistical significance.**
2. **To understand the origin of the signal.**

Primordial gravitational waves from gauge fields

The New Paradigm

$$S = S_{\rm EH} + S_{\rm dilaton} + S_{\rm axion} + S_{\rm gauge} + S_{\rm CS}$$

$$= \int dx^4 \sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}(\partial_\mu\varphi)^2 - V(\varphi) - \frac{1}{2}(\partial_\mu\sigma)^2 - W(\sigma) - \frac{1}{4}I(\varphi)^2 F^{a\mu\nu}F^a_{\mu\nu} - \frac{1}{4}\lambda\frac{\sigma}{f}\tilde{F}^{a\mu\nu}F^a_{\mu\nu}\right]$$

The set up given in, e.g., Obata and Soda (2016)

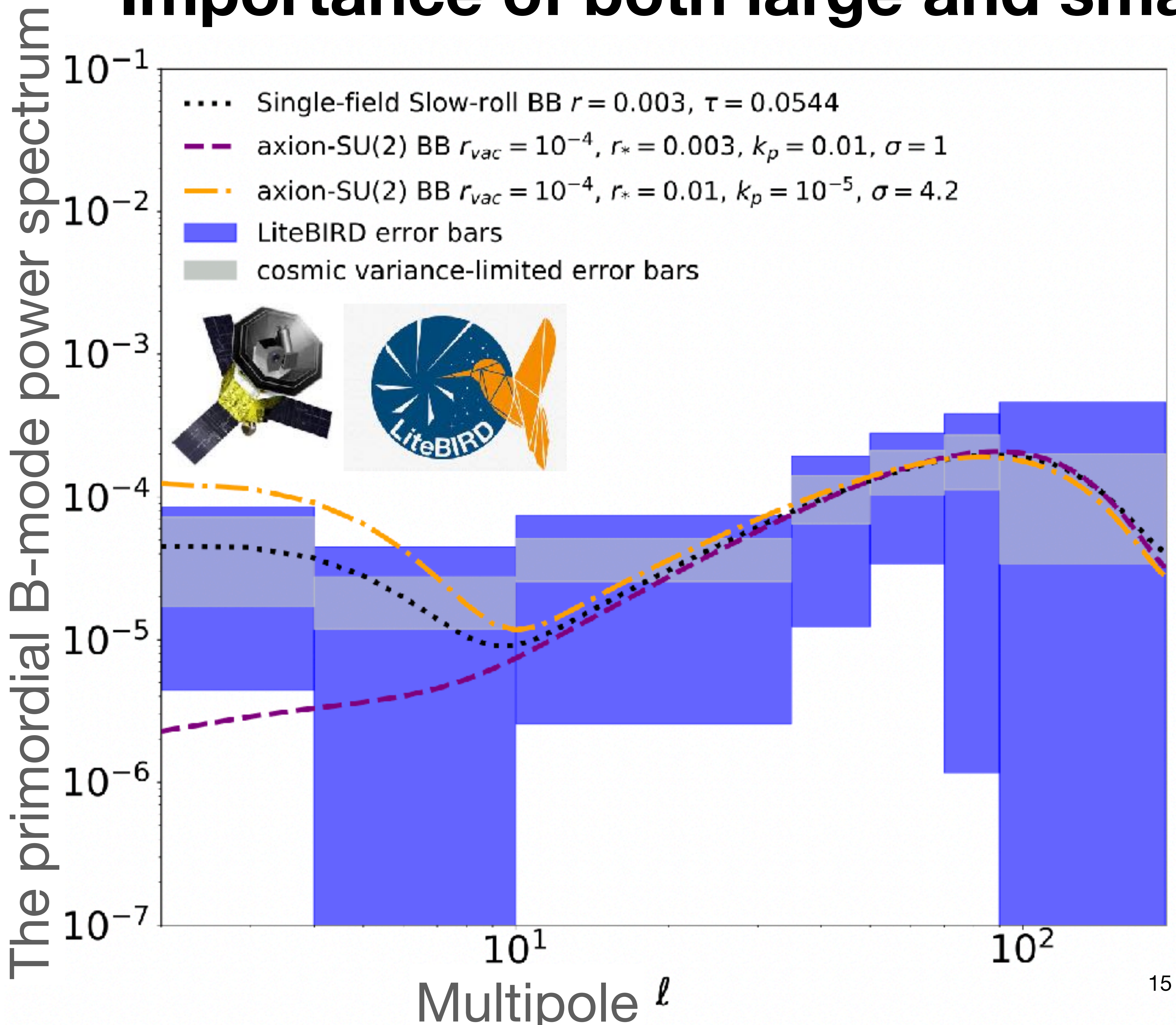
- This set up can produce the primordial gravitational waves that can be:
  - Highly **scale-dependent**
  - **Statistically anisotropic**
  - Highly **non-Gaussian**
  - Completely **chiral**

⟷

Opposite of the predictions of the standard scenario without gauge fields

Testing the gauge field scenario with future CMB experiments

Importance of both large and small angular scale experiments



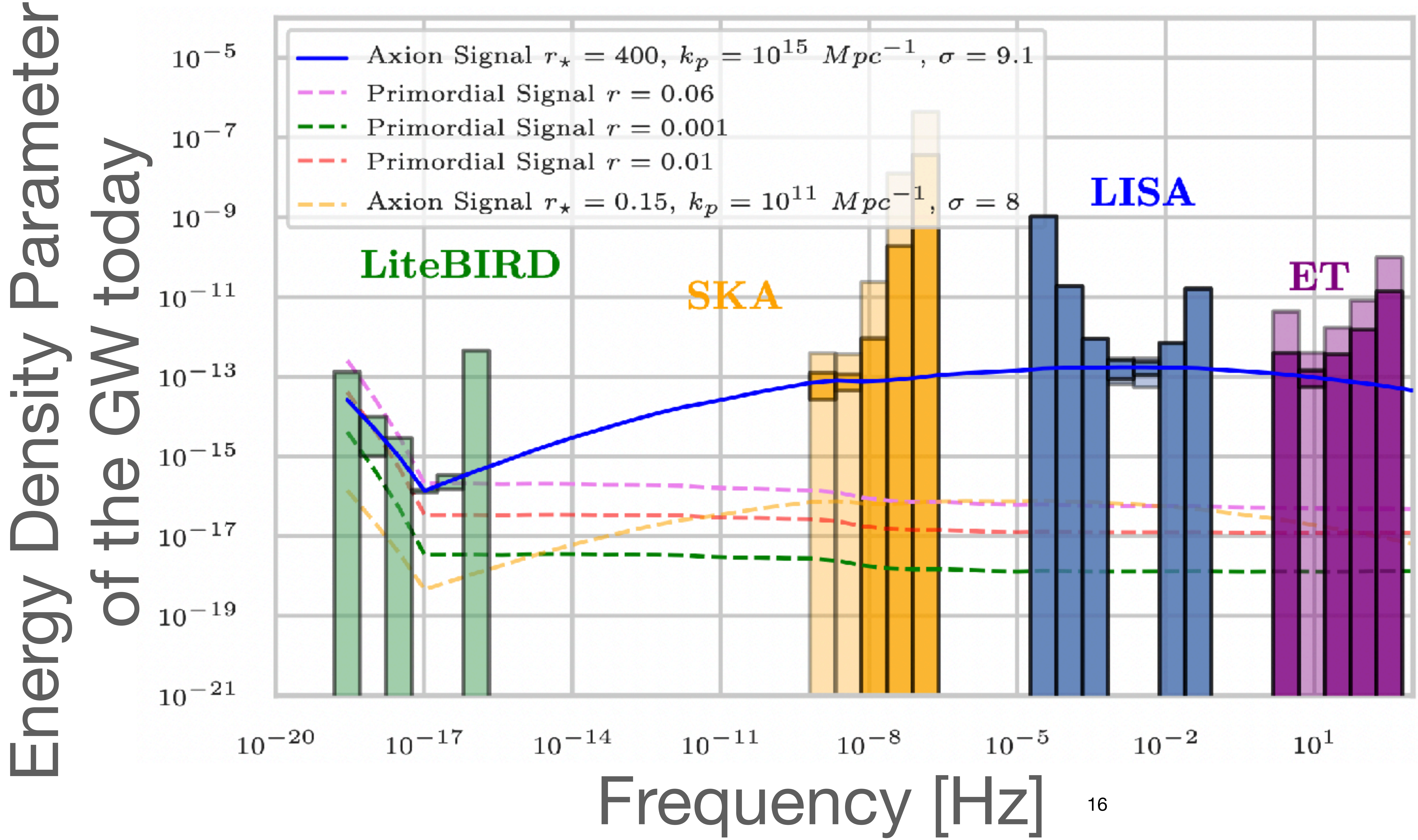
- Even if the small angular scale experiments (Simons Array, Simons Observatory, CMB S-4) detect the B-mode polarisation power spectrum at the multipole of ell ~ 80 (about 2 degrees in the sky), **we must also measure it on large angular scales (ell < 10) to probe the shape of the power spectrum** before making a conclusion about its origin!

Figure Credit: Paolo Campeti (MPA) and the LiteBIRD Collaboration

Campeti, Komatsu et al. (2021)

Not just CMB: Pulsar Timing Array and Laser Interferometers

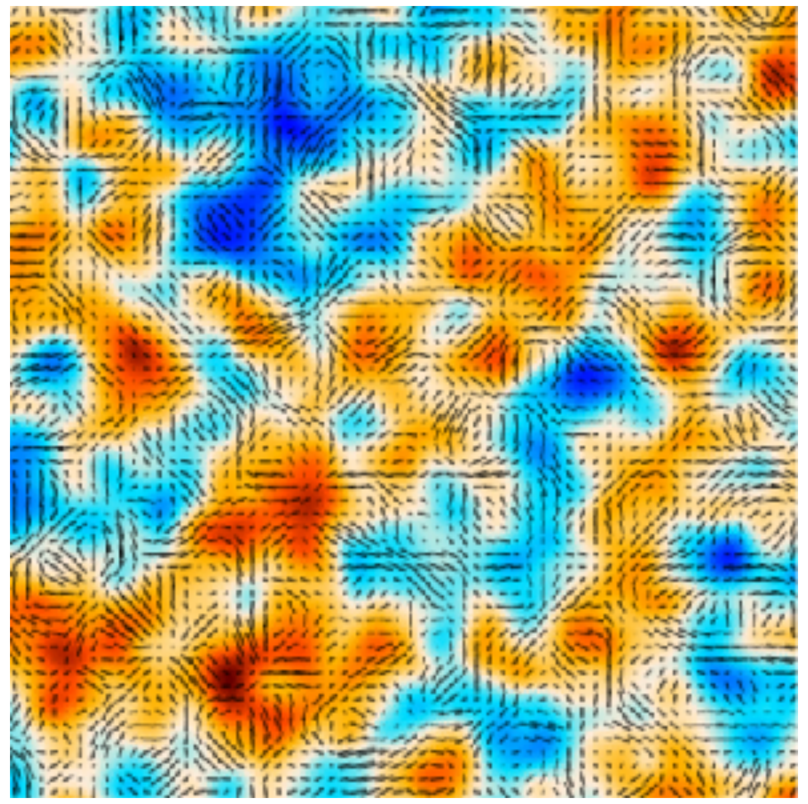
Across *21 decades* in frequency!



- **The gauge field model** can make completely different predictions for the spectrum of the gravitational wave.
- **Importance of the multi-frequency experiments** using completely different techniques!

Summary of B06

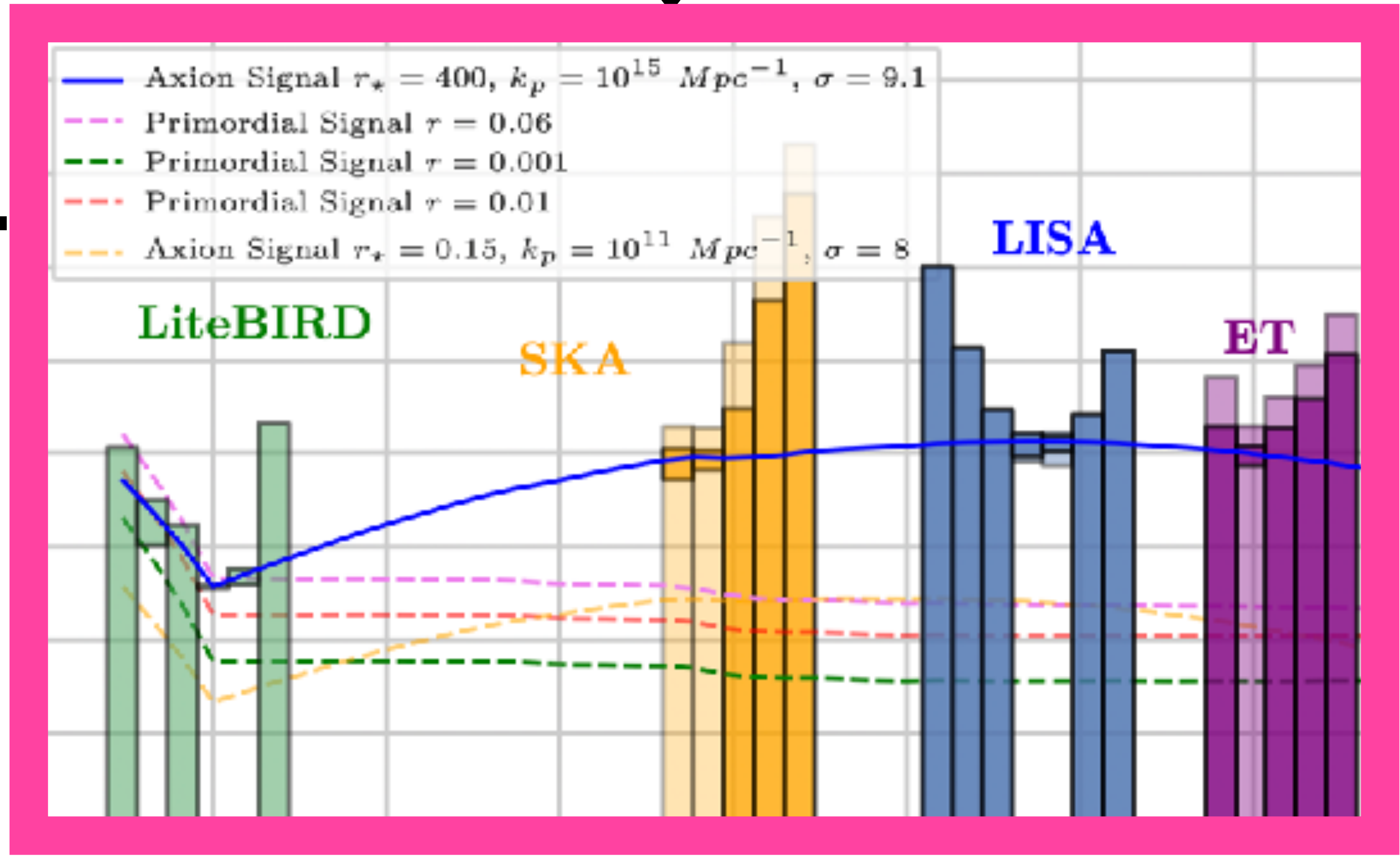
The DM search using the CMB polarisation



- We use polarisation of the CMB to probe new physics of the DM fields.
    - Do they violate parity symmetry?
    - Do they have a higher spin?

$$S = S_{\mathrm{EH}} + S_{\mathrm{dilaton}} + S_{\mathrm{axion}} + S_{\mathrm{gauge}} + S_{\mathrm{CS}}$$
$$= \int dx^4 \sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}(\partial_\mu\varphi)^2 - V(\varphi) - \frac{1}{2}(\partial_\mu\sigma)^2 - W(\sigma) - \frac{1}{4}I(\varphi)^2 F^{a\mu\nu}F^a_{\mu\nu} - \frac{1}{4}\lambda\frac{\sigma}{f}\tilde{F}^{a\mu\nu}F^a_{\mu\nu}\right]$$

- Two approaches:
    - **Theoretical projects** to refine predictions.
    - **Analysis projects** to measure the predicted properties.



- Going beyond CMB: PTA and laser interferometers:
- *Let's discovery something new!*