

# Cosmic Birefringence

Hunting for new parity-violating physics

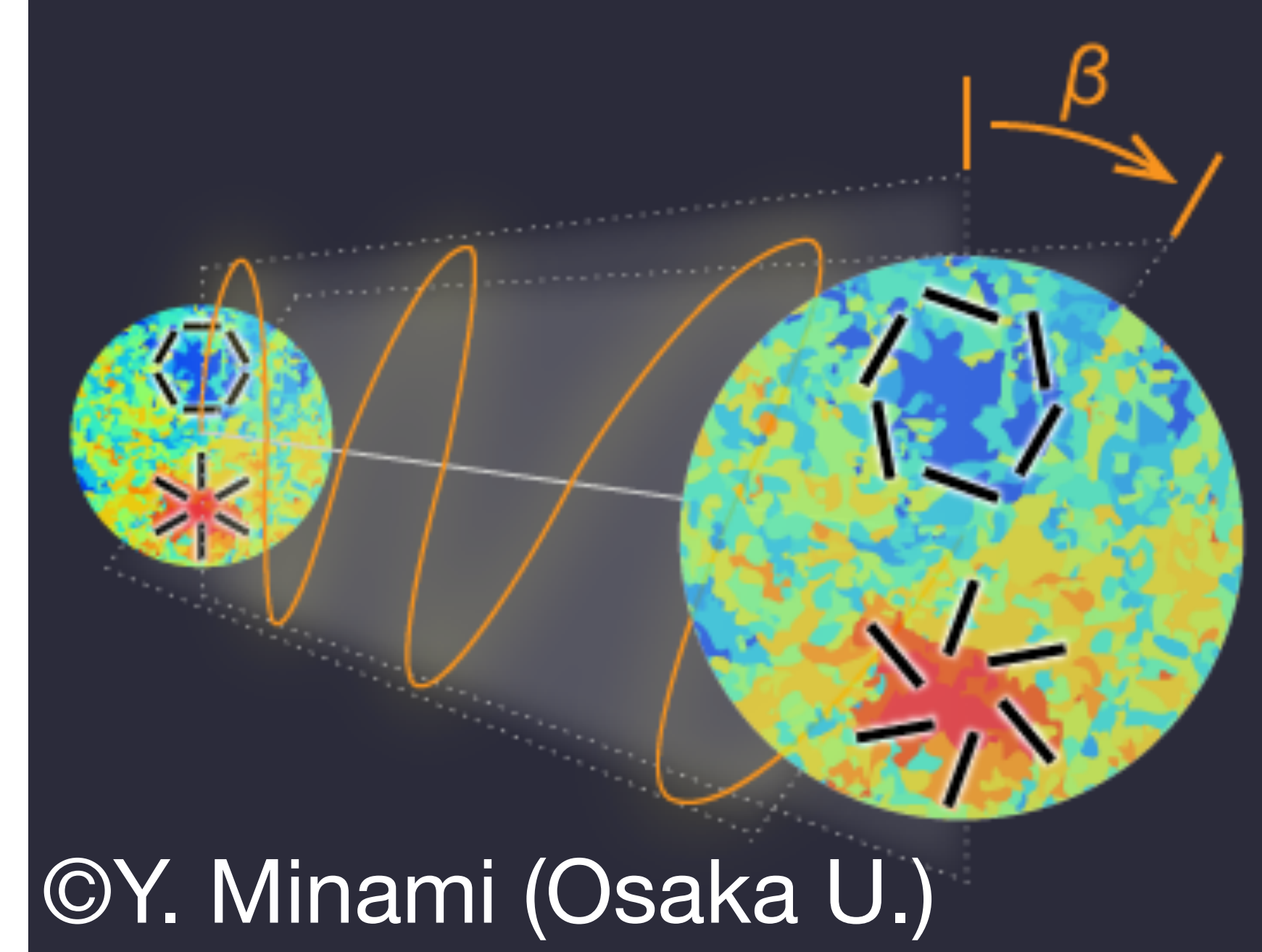
based on

- *Minami & EK, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, Minami, et al., arXiv:2201.07682*

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# Standard Cosmological Model ( $\Lambda$ CDM) Requires New Physics

## Physics beyond Standard Model of elementary particles and fields

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

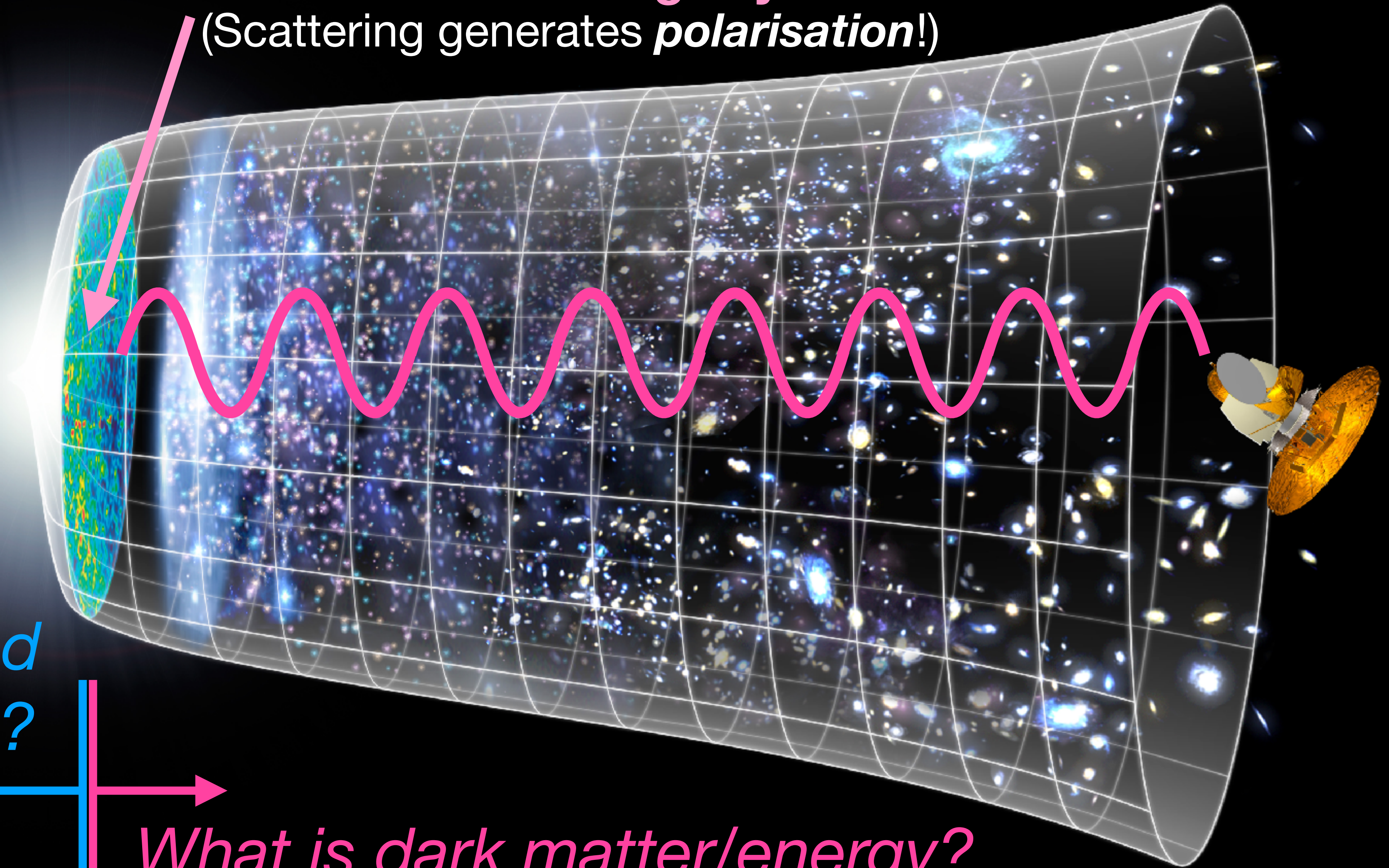
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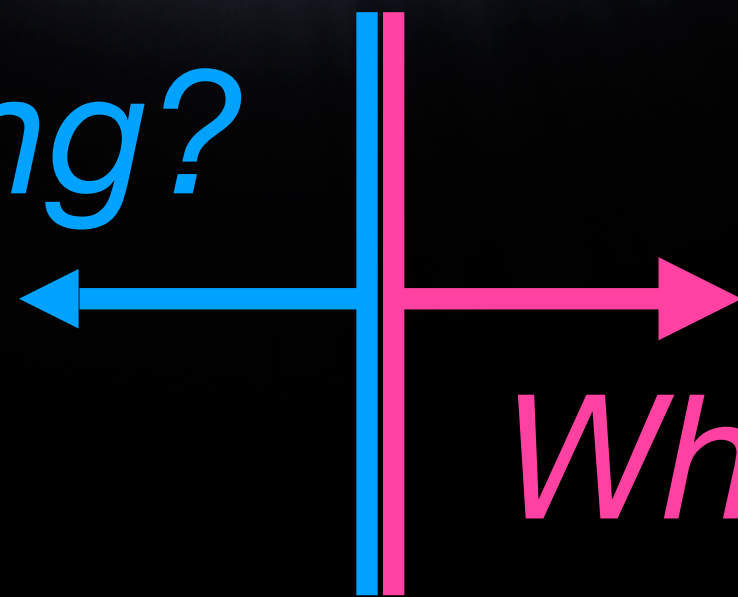
- **Dark Sector:** What is dark matter ( $CDM$ )? What is dark energy ( $\Lambda$ )?
  - **Cosmic birefringence** in cross-correlation of E- and B-mode polarisation
- **Early Universe:** What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
  - Imprint of **primordial gravitational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

The surface of “last scattering” by electrons

(Scattering generates *polarisation*!)

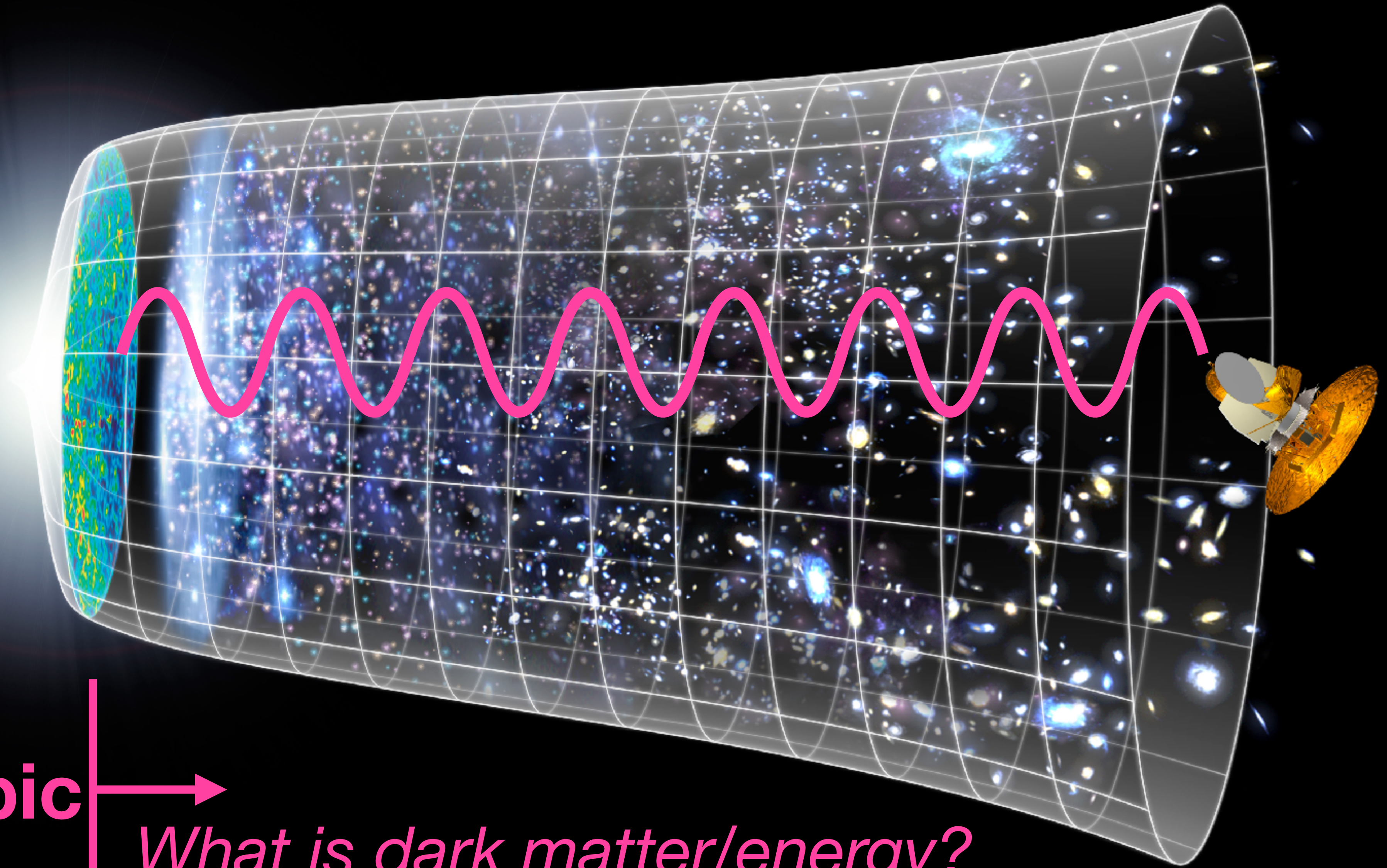


*What powered  
the Big Bang?*



*What is dark matter/energy?*

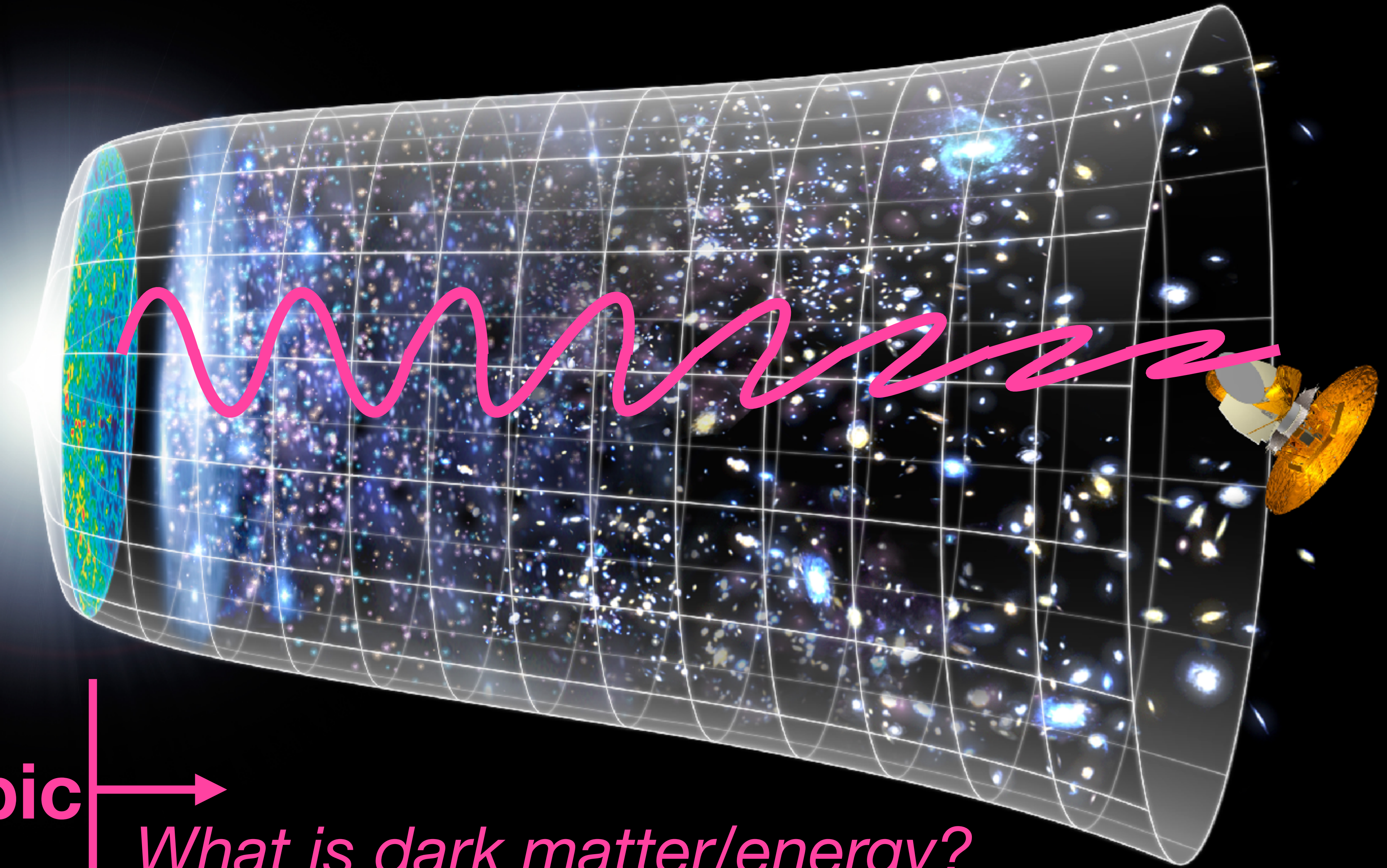
# How does the electromagnetic wave of the CMB propagate?



**Today's topic**

*What is dark matter/energy?*

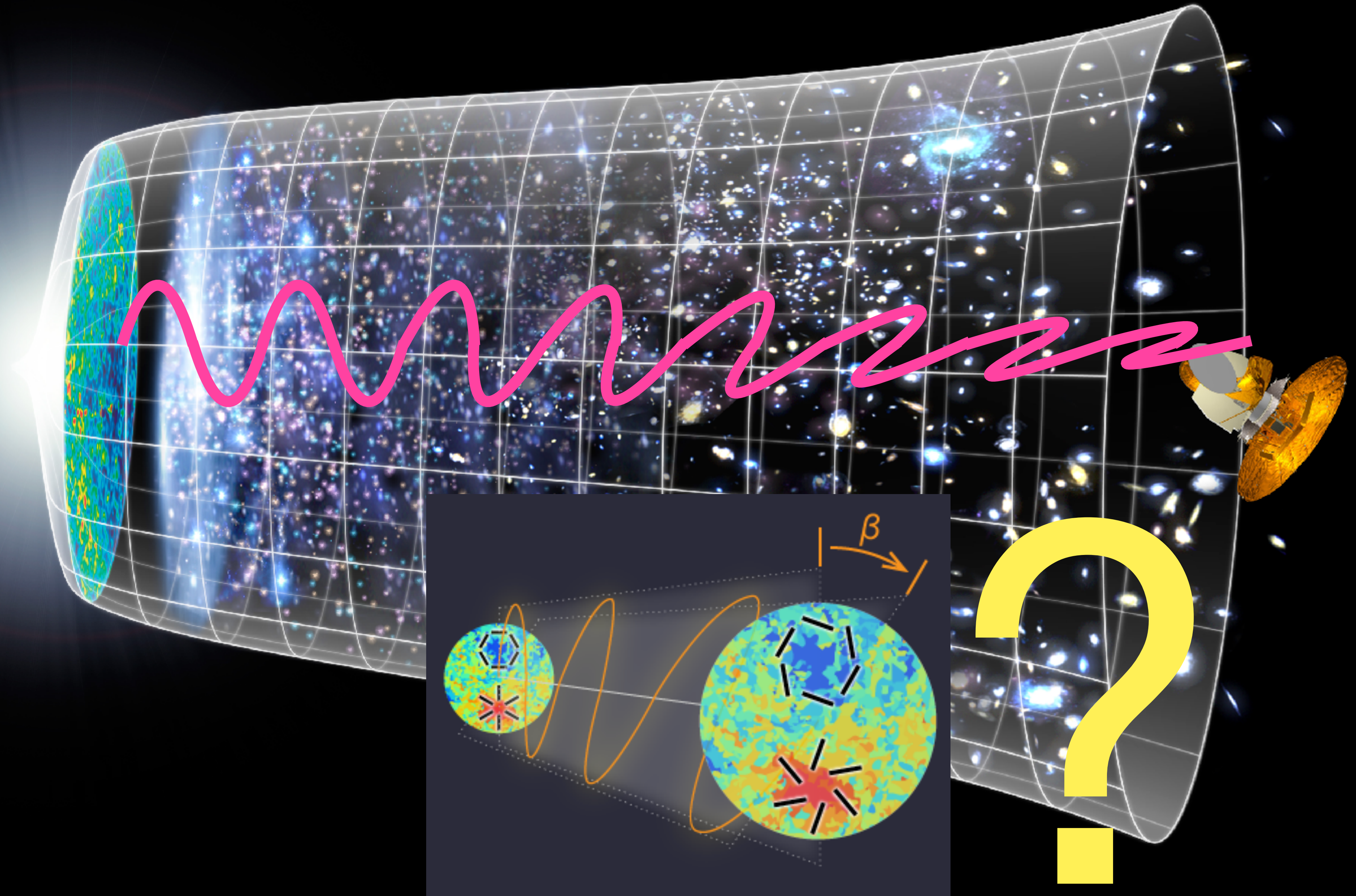
# How does the electromagnetic wave of the CMB propagate?



**Today's topic**

*What is dark matter/energy?*

# How does the electromagnetic wave of the CMB propagate?



# The methodology papers that led to our measurements

**Methodology development took 2 years. We now have results from data!**

1. **Minami**, Ochi, Ichiki, Katayama, Komatsu & Matsumura, “*Simultaneous determination of the cosmic birefringence and miscalibrated polarization angles from CMB experiments*”, PTEP, 083E02 (2019)

- The original paper to describe the basic idea, methodology, and validation
- Assumed full-sky data



*Yuto Minami*  
(Osaka U.)

2. **Minami**, “*Determination of miscalibrated polarization angles from observed CMB and foreground EB power spectra: Application to partial-sky observation*”, PTEP, 063E01 (2020)

- Extension to partial-sky data

3. **Minami** & Komatsu, “*Simultaneous determination of the cosmic birefringence and miscalibrated polarization angles II: Including cross-frequency spectra*”, PTEP, 103E02 (2020)

- The complete methodology for multi-frequency data, used for analysing Planck data

# 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

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

Chern-Simons term

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

where  $g_a$  is a coupling constant of the order  $\alpha$ , and the vacuum angle  $\theta = \phi_a / f_a$  ( $\phi_a$  = axion field). The equations

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

Parity Even Parity Odd

# Cosmic Birefringence

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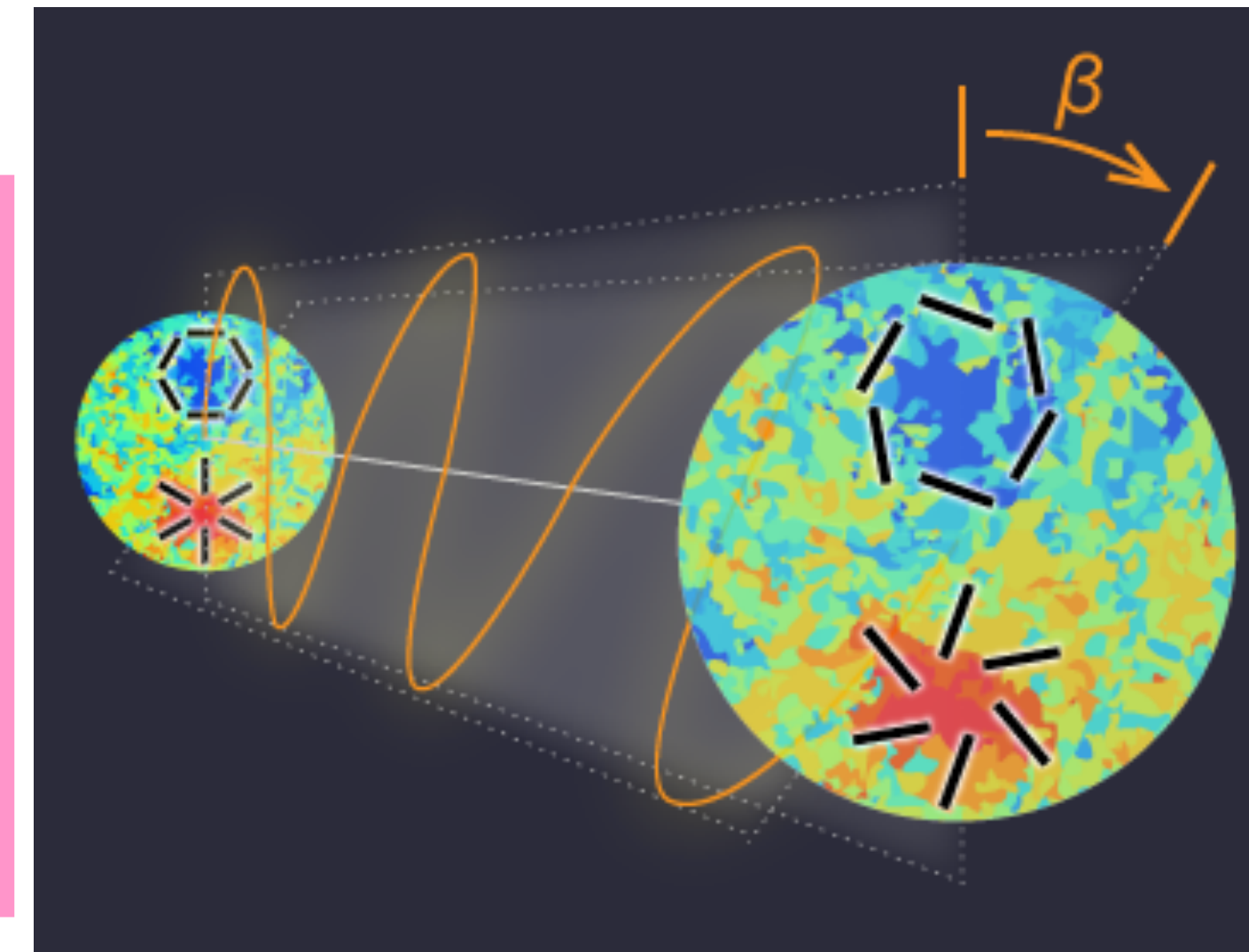
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“Cosmic Birefringence”

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



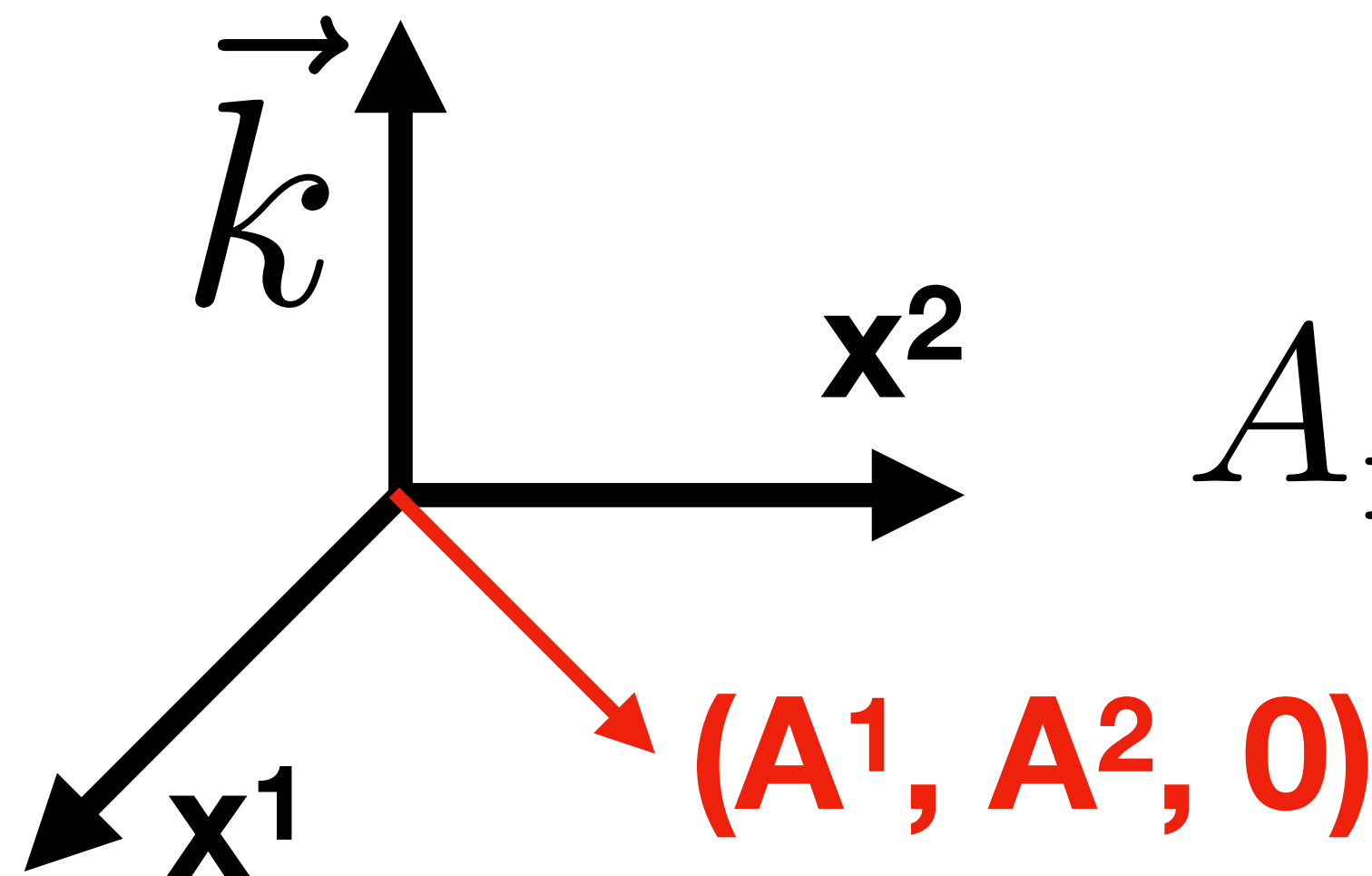
# Standard Maxwell Theory

## Warm up (1)

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

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

- 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



$$A_{\pm} = \frac{A_1 \mp i A_2}{\sqrt{2}}$$

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

# Standard Maxwell Theory

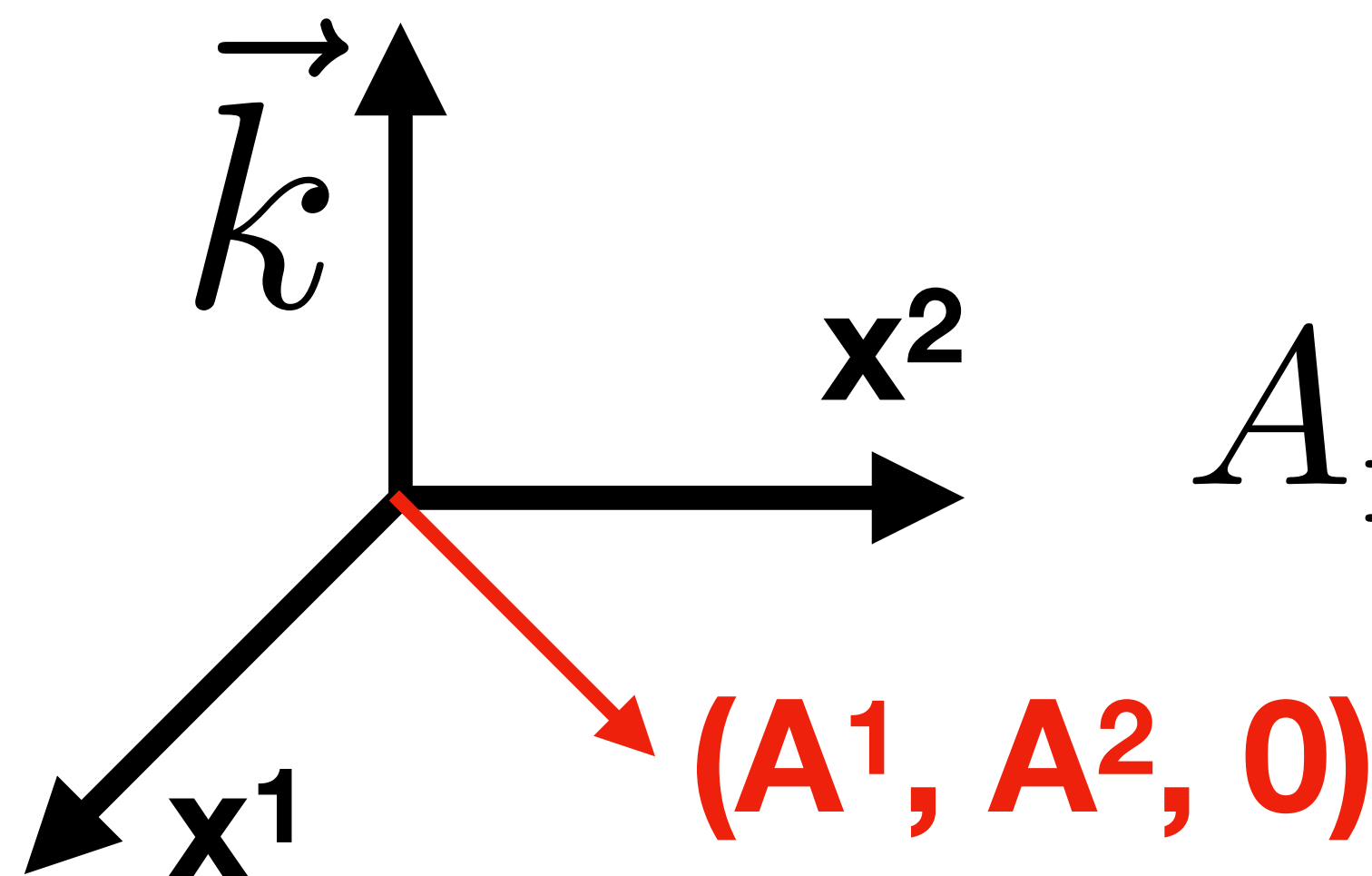
## Warm up (2)

- To isolate a transverse wave, we require  $A_0=0$  and  $\text{div}(\mathbf{A}_i)=0$ . 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

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# Cosmic Birefringence

## Derivation (1)

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

the effective Lagrangian for axion electrodynamics is

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- The equation of motion is modified to

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

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

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# Cosmic Birefringence

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

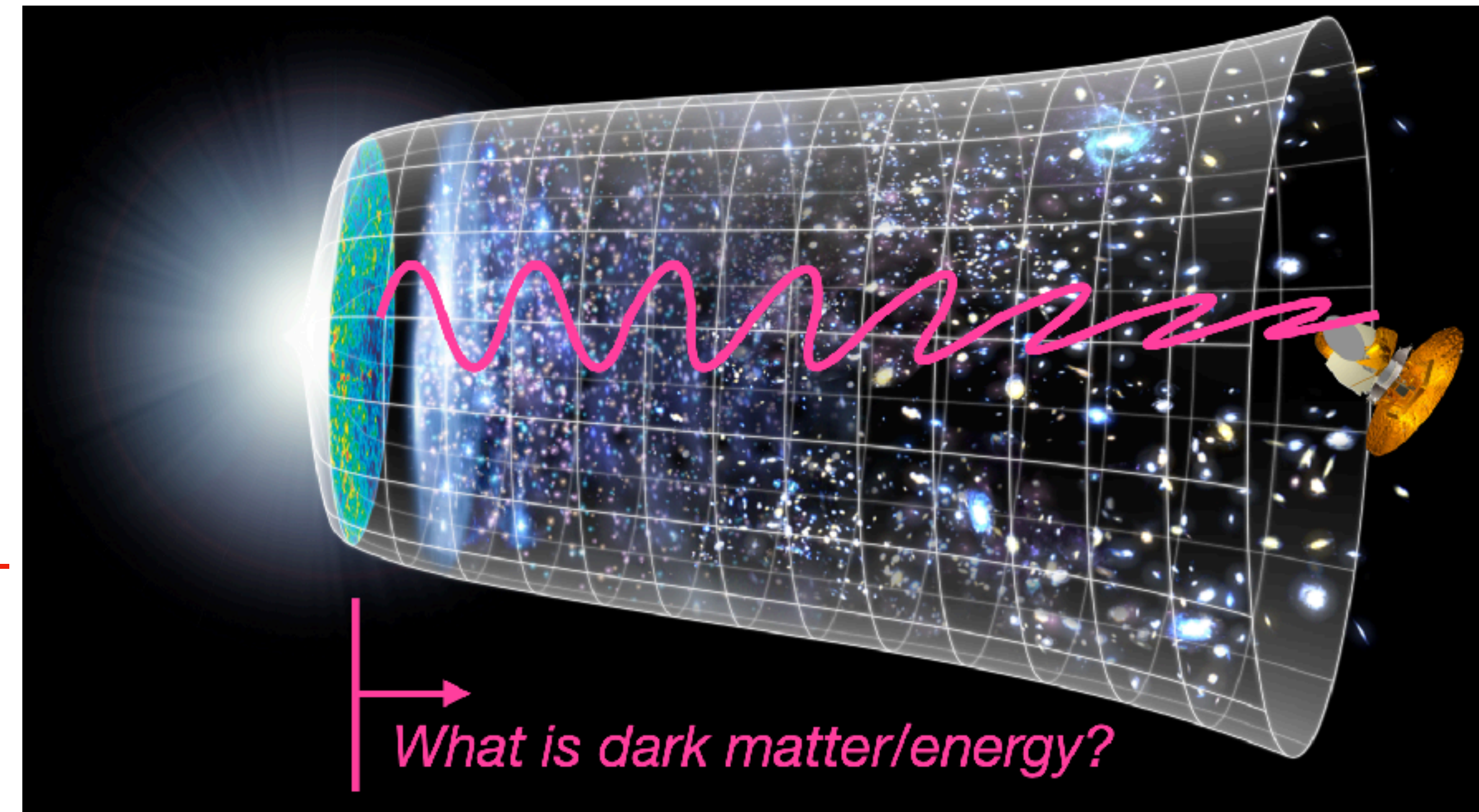
# Cosmic Birefringence

## 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 by an angle  $\psi$ :

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

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

# Cosmic Birefringence

## Derivation (3)

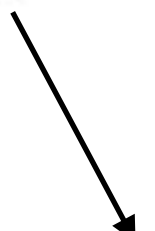
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 This is the convention  
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# Cosmic Birefringence

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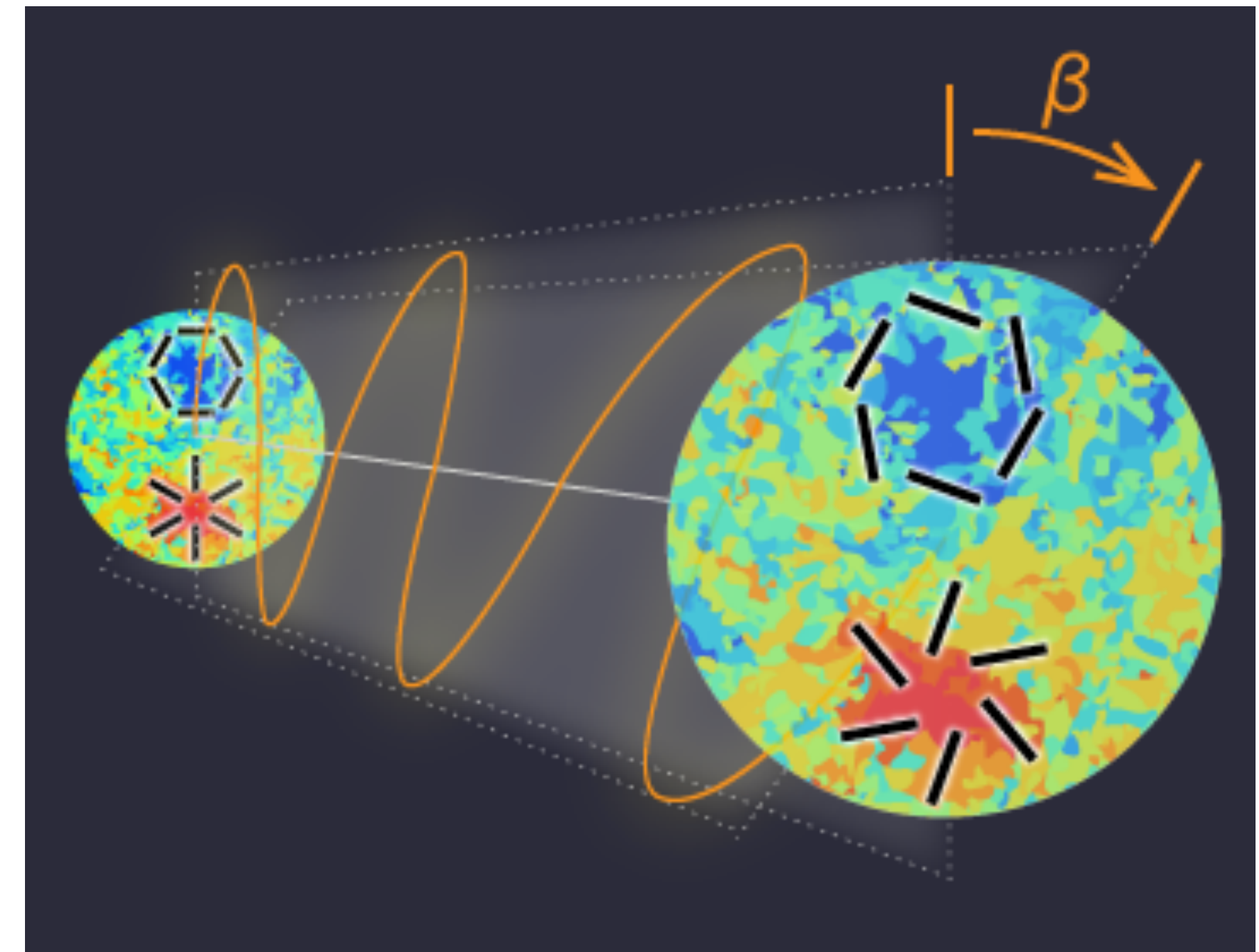
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This is the convention for polarisation direction adopted by IAU

**However!**

The CMB community adopted the opposite sign convention...  
Thus, we shall use  $\beta = -\psi$



# Cosmic Birefringence

## Recap

- 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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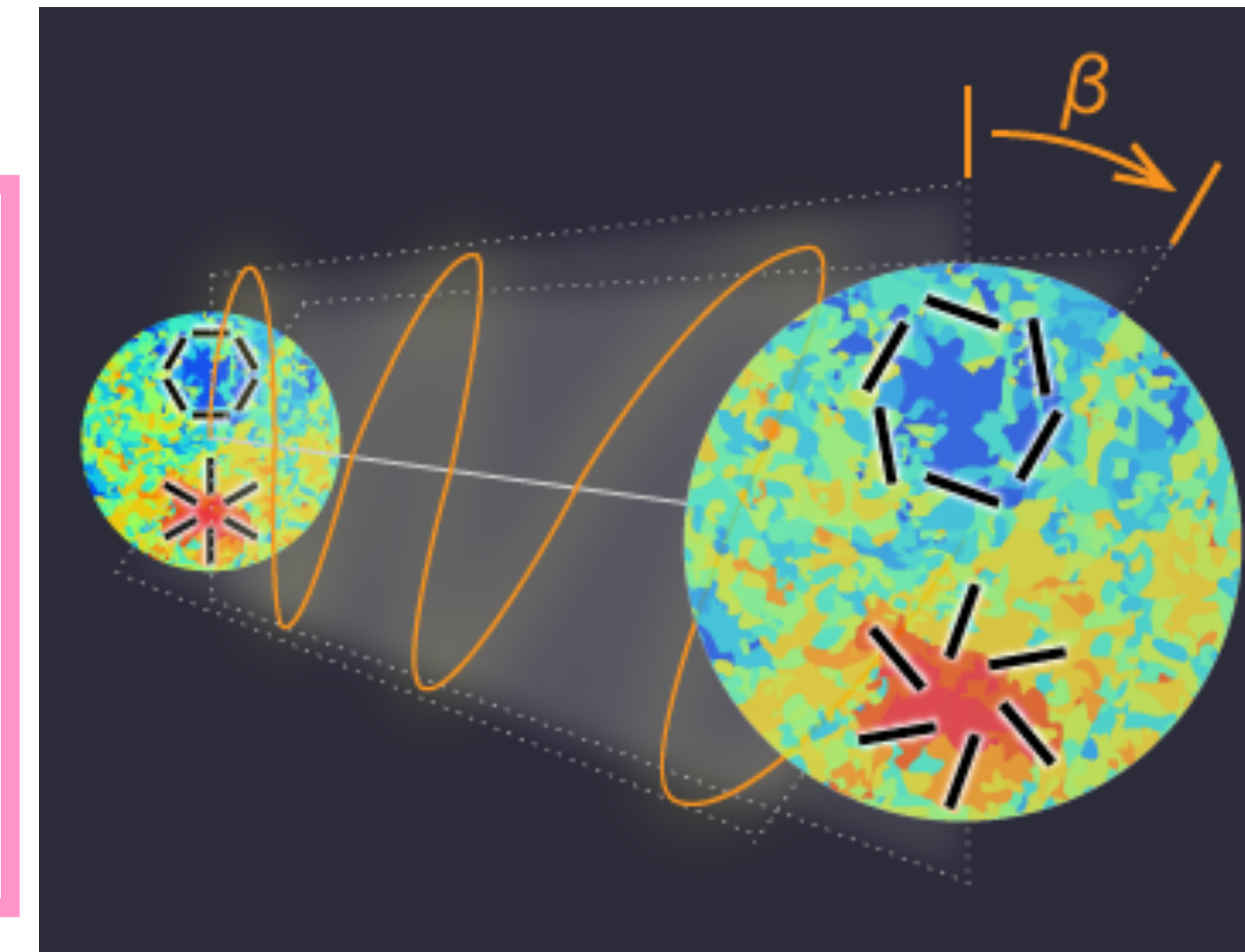
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where  $g_a$  is a coupling constant of the order  $\alpha$ , and the vacuum angle  $\theta = \phi_a / f_a$  ( $\phi_a$  = axion field). The equations



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

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

# Motivation

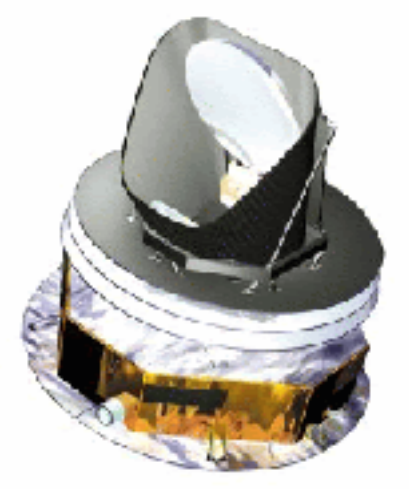
## Why study the cosmic birefringence?

- 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.

# **(Simpler) Motivation**

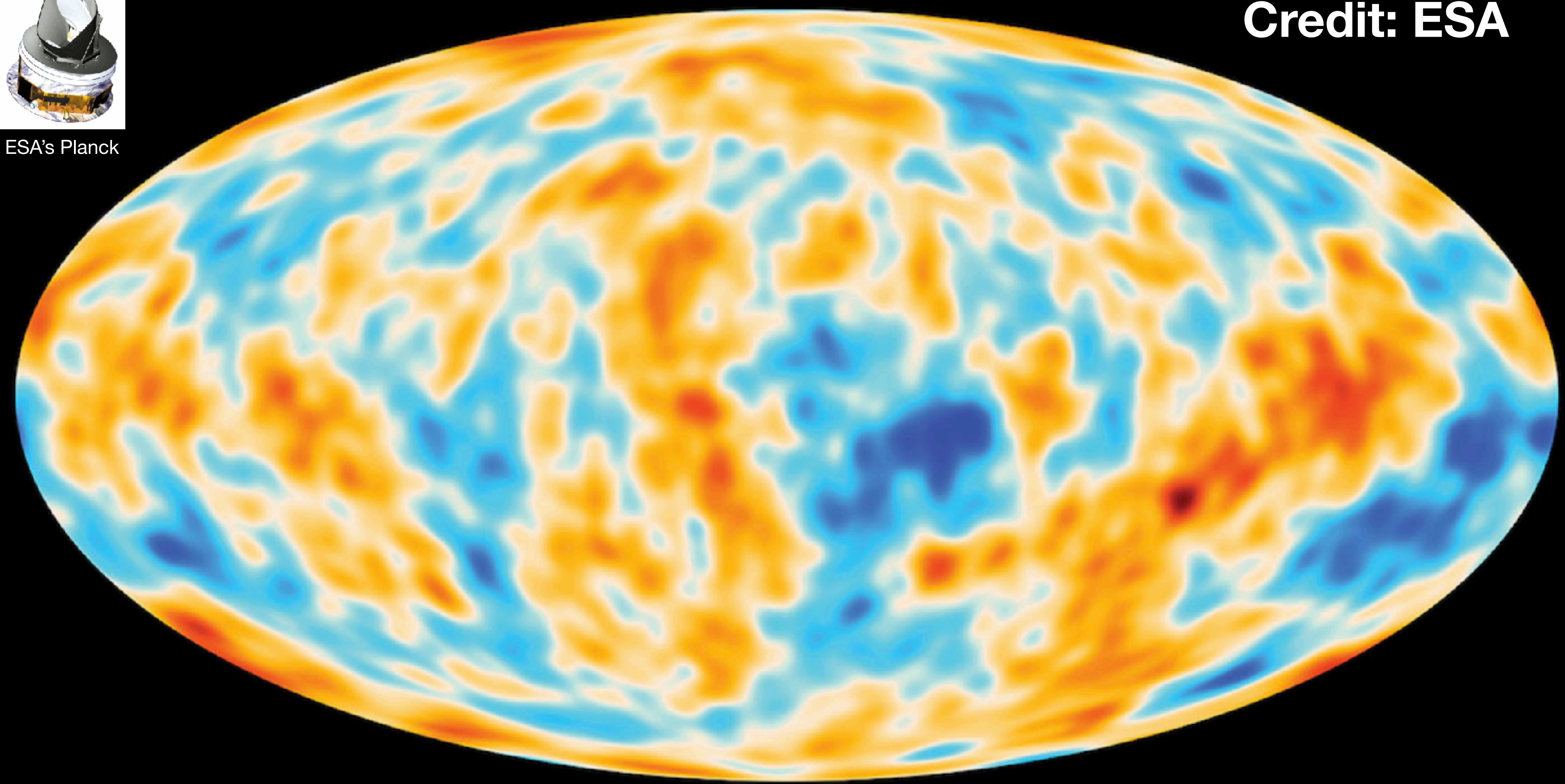
## **Why study the cosmic birefringence?**

- We know that the weak interaction violates parity (Lee & Yang 1956; Wu et al. 1957).
  - Why should the laws of physics governing the Universe conserve parity?
- Let's look!



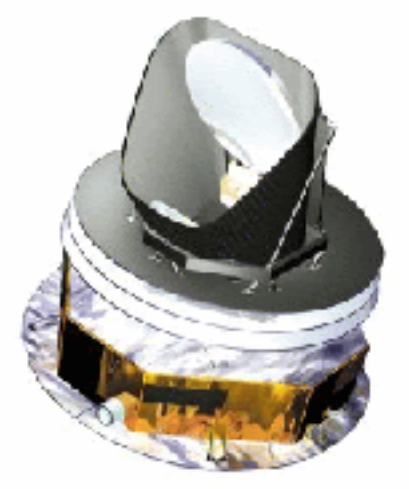
ESA's Planck

Credit: ESA



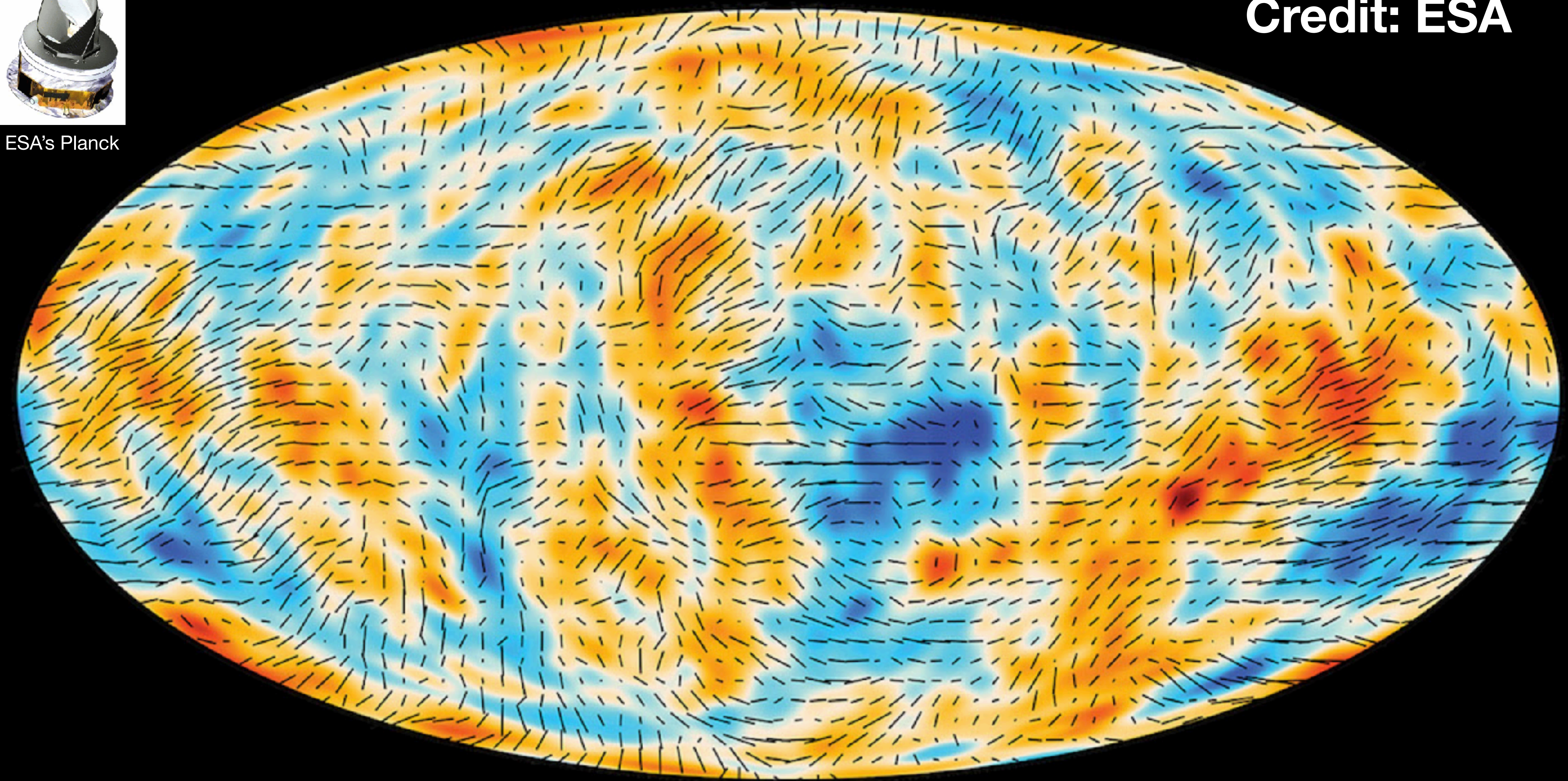
Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



ESA's Planck

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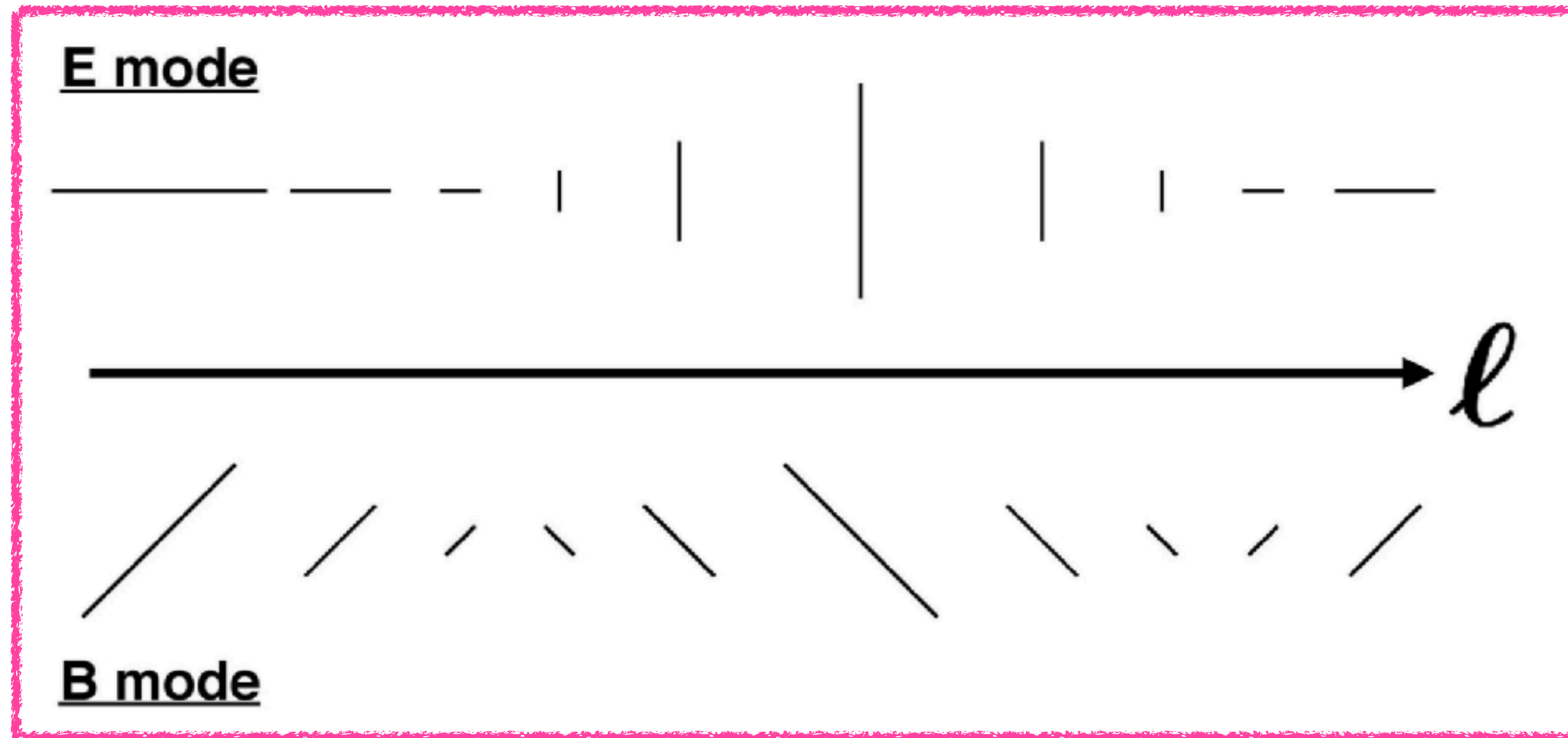


Foreground-cleaned Temperature (smoothed) + Polarisation

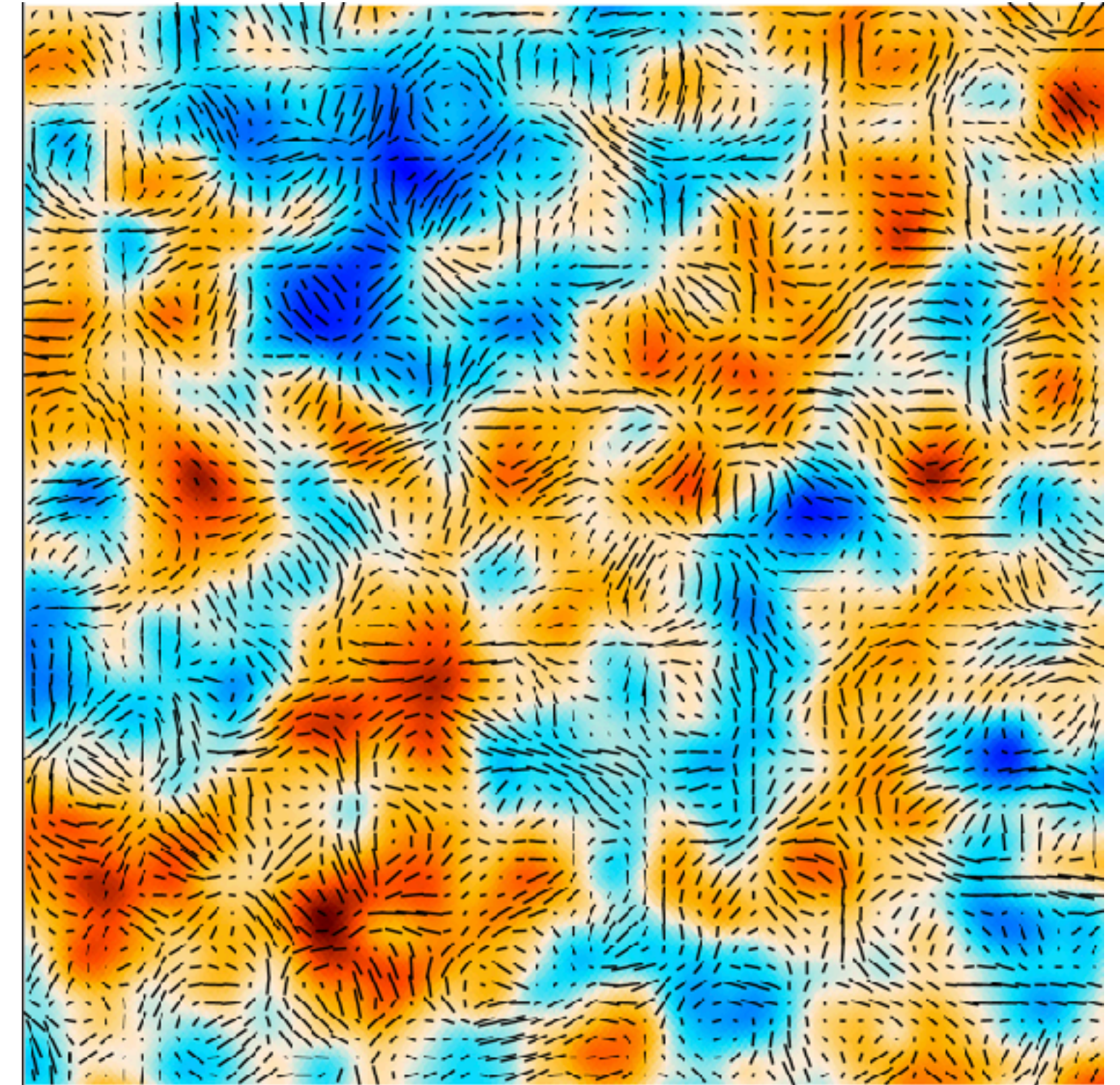
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# Parity eigenstates: E and B modes

Concept defined in Fourier space



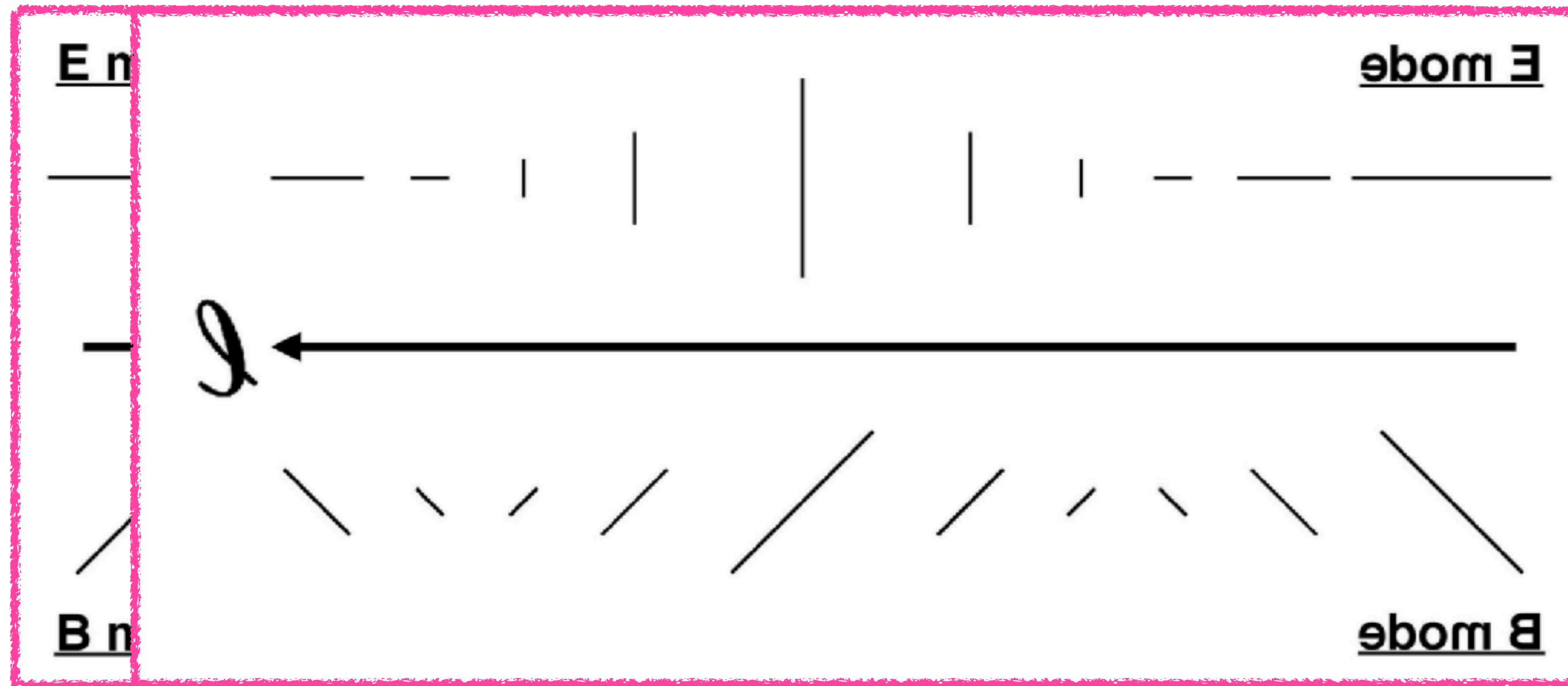
This map is dominated  
by E-mode polarisation



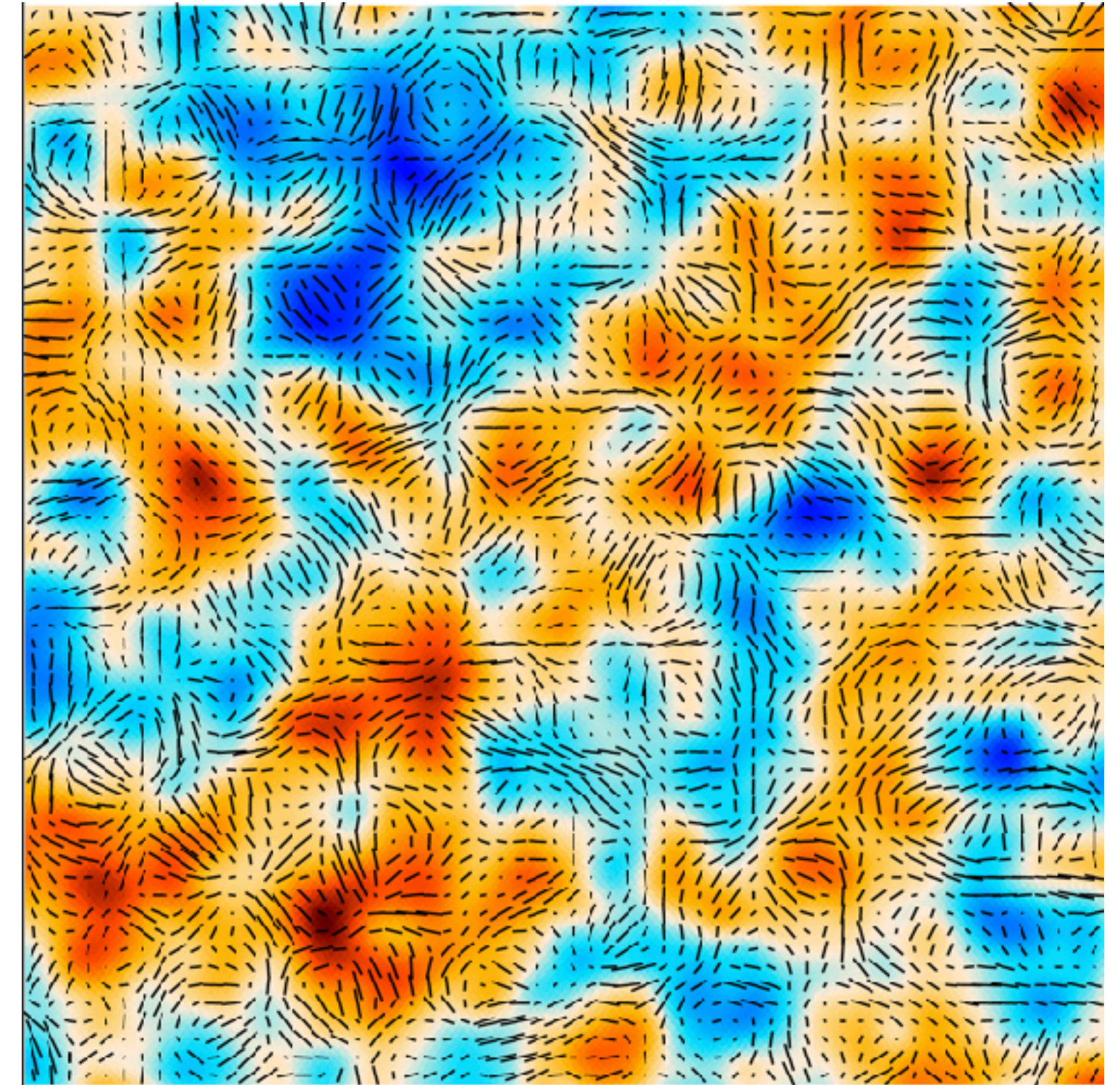
- **E-mode** : Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode** : Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

# Parity eigenstates: E and B modes

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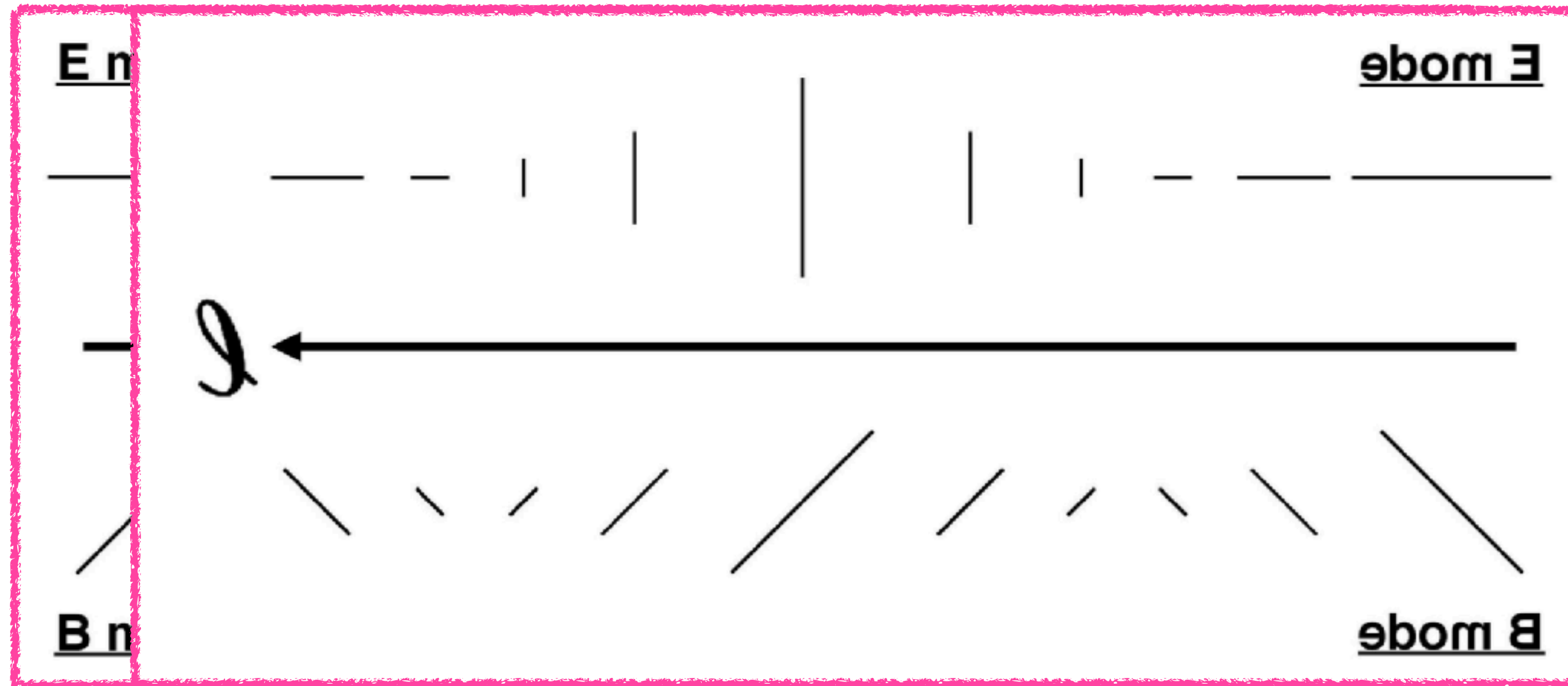
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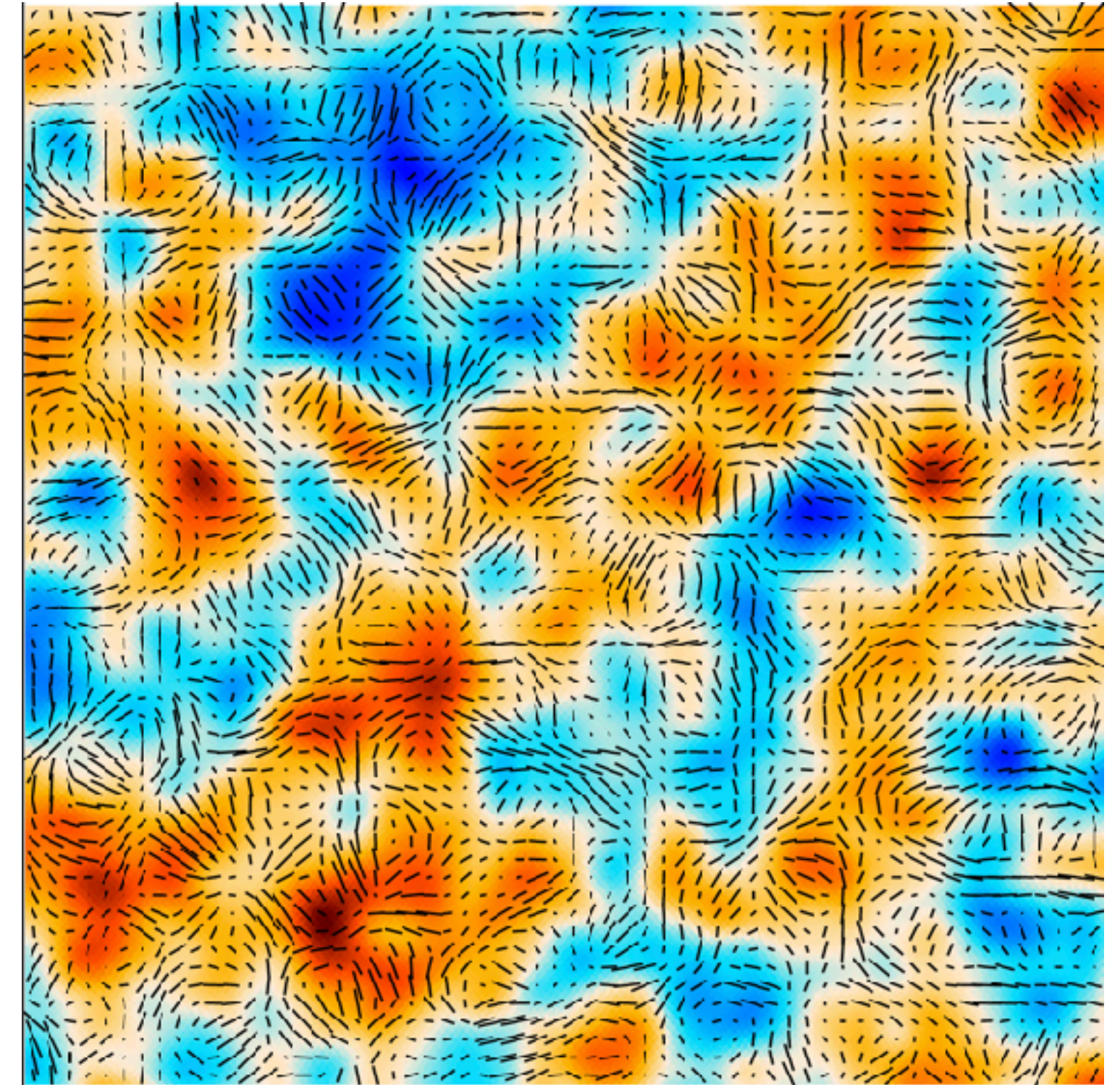
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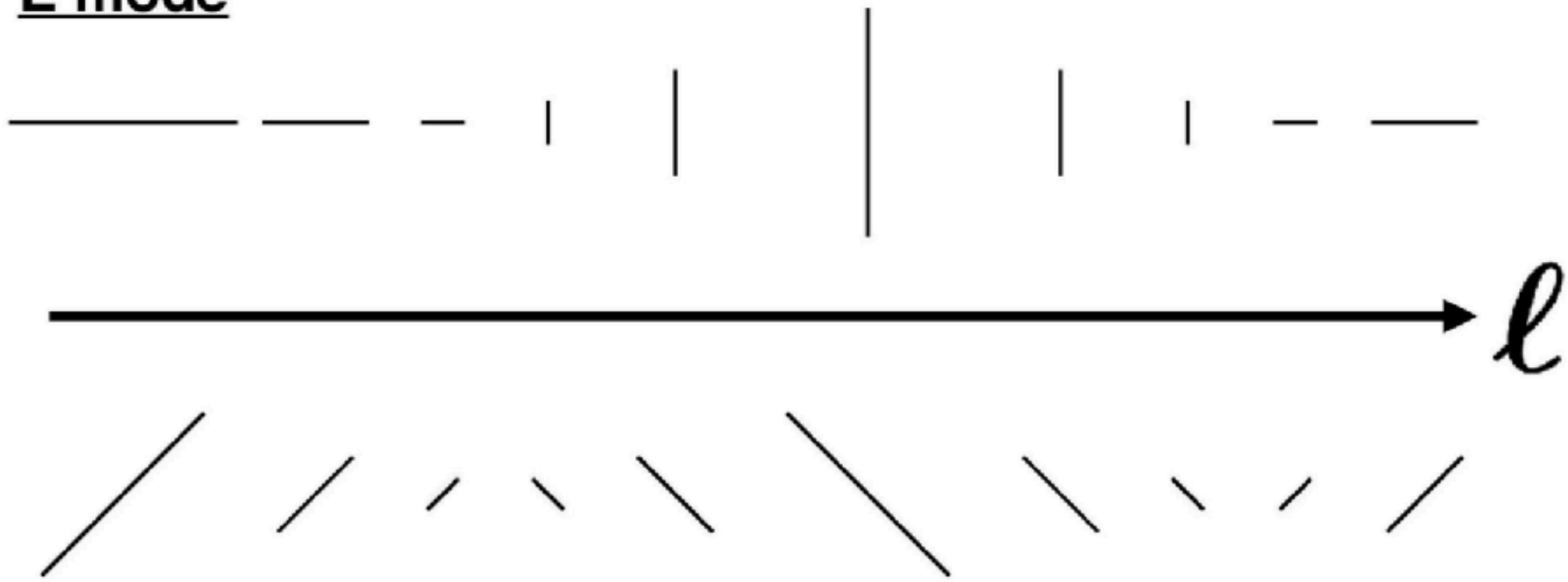
- **E-mode** : Polarisation directions are **parallel or perpendicular** to the wavenumber direction
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**IMPORTANT**: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

# Parity Flip

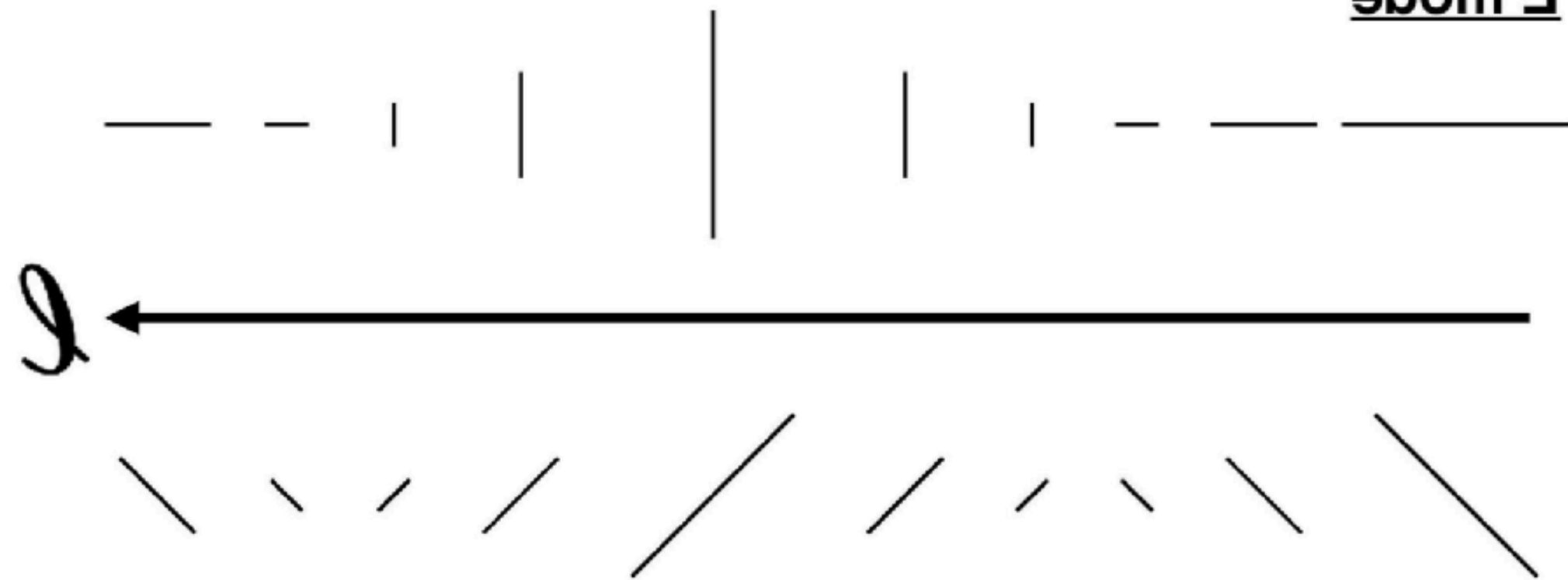
**E-mode remains the same, whereas B-mode changes the sign**

E mode



B mode

E mode



B mode

- Two-point correlation functions invariant under the parity flip are

$$\langle E_{\ell} E_{\ell'}^* \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{EE}$$

$$\langle B_{\ell} B_{\ell'}^* \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{BB}$$

$$\langle T_{\ell} E_{\ell'}^* \rangle = \langle T_{\ell}^* E_{\ell'} \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{TE}$$

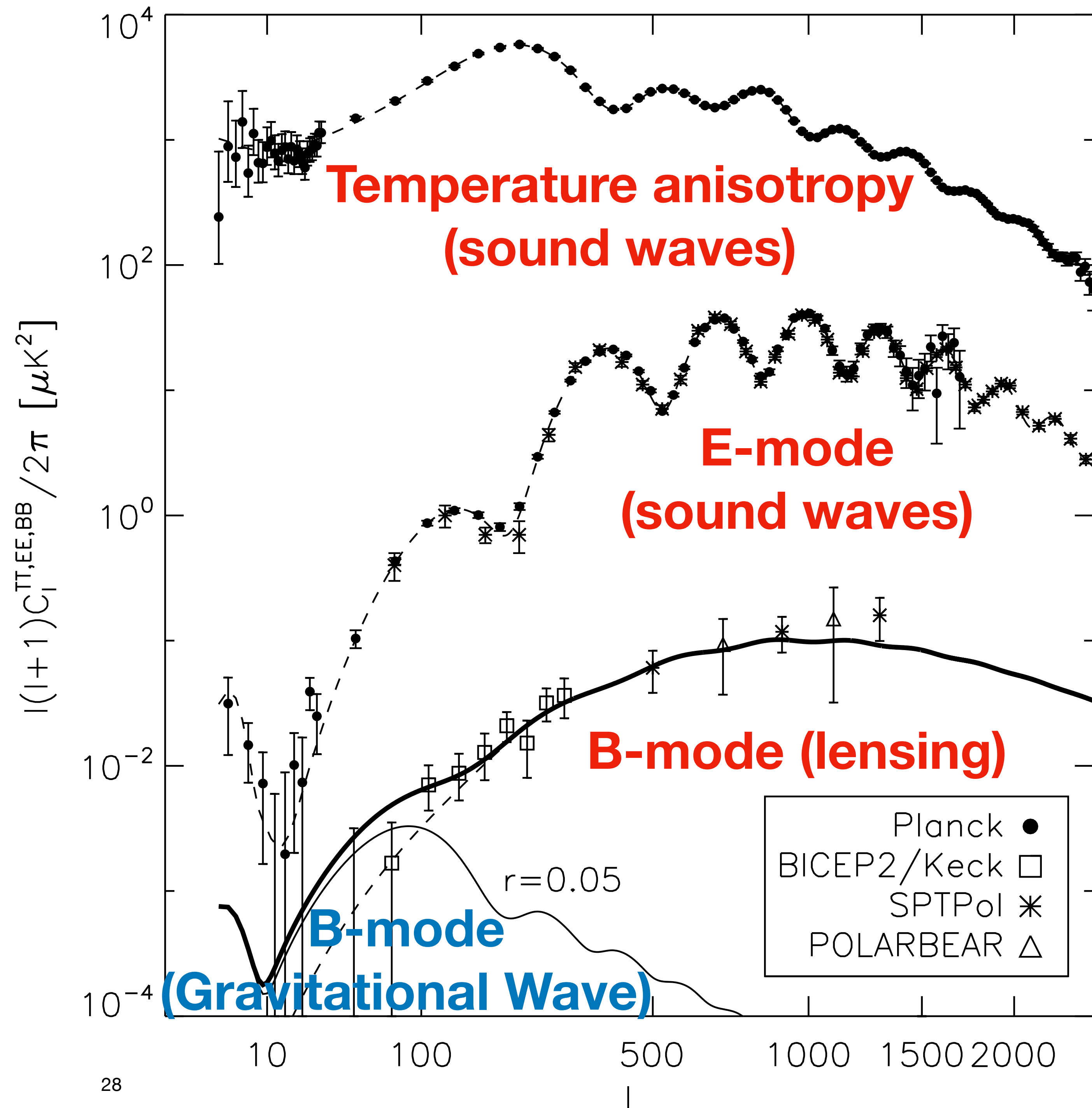
- The other combinations  $\langle TB \rangle$  and  $\langle EB \rangle$  are not invariant under the parity flip.

- We can use these combinations to probe parity-violating physics (e.g., axions)**

# Power Spectra

A lot have been measured

- This is the typical figure that you find in talks and lectures on CMB.
- The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**



# E-B mixing by rotation of the plane of linear polarisation

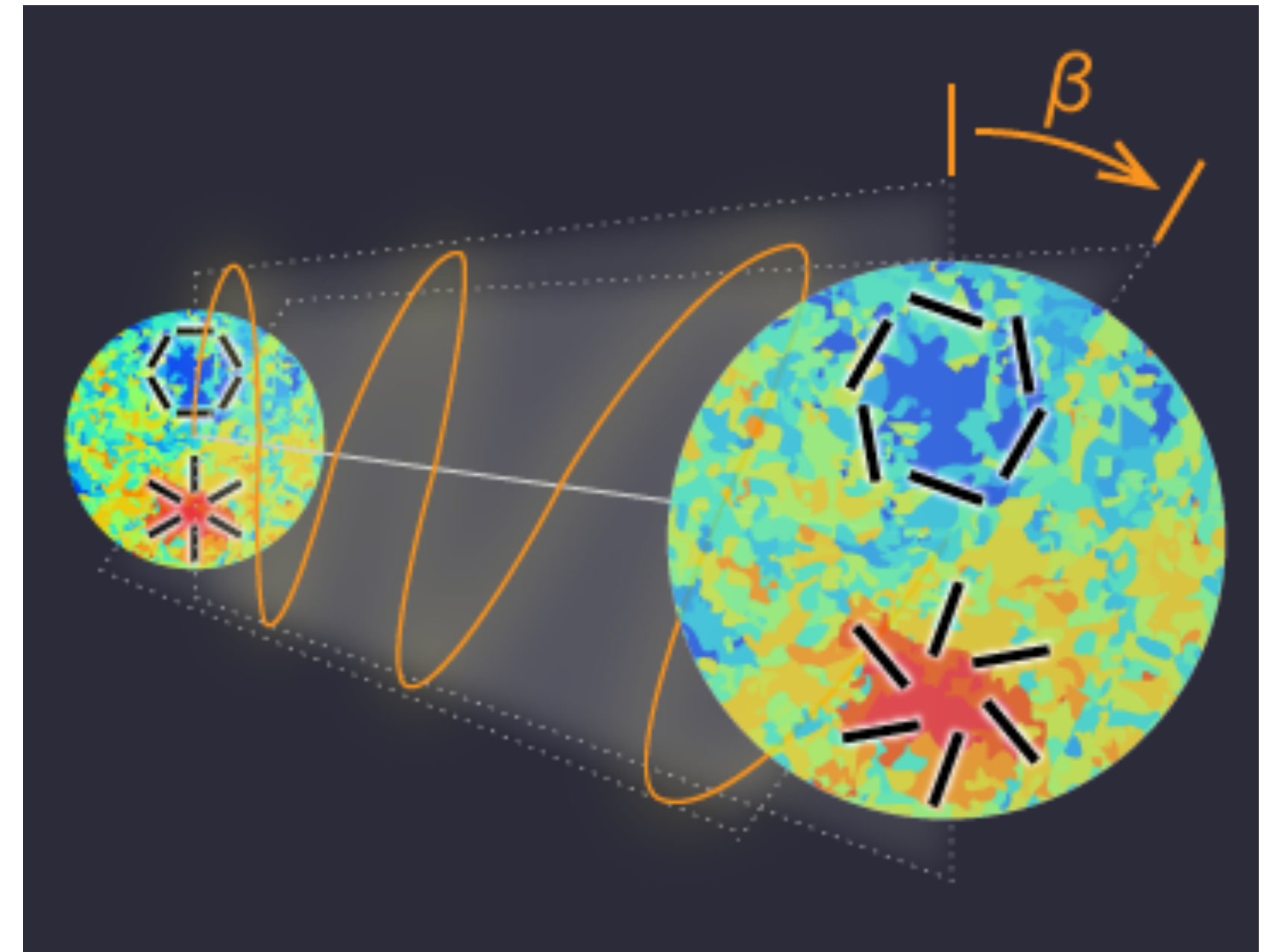
- Observed E- and B-mode polarisation,  $E_\ell^\circ$  and  $B_\ell^\circ$ , are related to those before rotation as

$$E_\ell^\circ \pm iB_\ell^\circ = (E_\ell \pm iB_\ell)e^{\pm 2i\beta}$$

- which gives

$$E_\ell^\circ = E_\ell \cos(2\beta) - B_\ell \sin(2\beta)$$

$$B_\ell^\circ = E_\ell \sin(2\beta) + B_\ell \cos(2\beta)$$



# Searching for the birefringence

- Computing observed difference between EE and BB spectra,

$$C_{\ell}^{EE,\text{obs}} = C_{\ell}^{EE} \cos^2(2\beta) + C_{\ell}^{BB} \sin^2(2\beta) - C_{\ell}^{EB} \sin(4\beta)$$

$$C_{\ell}^{BB,\text{obs}} = C_{\ell}^{EE} \sin^2(2\beta) + C_{\ell}^{BB} \cos^2(2\beta) + C_{\ell}^{EB} \sin(4\beta)$$

$$C_{\ell}^{EE,\text{obs}} - C_{\ell}^{BB,\text{obs}} = (C_{\ell}^{EE} - C_{\ell}^{BB}) \cos(4\beta) - 2C_{\ell}^{EB} \sin(4\beta)$$

- We find

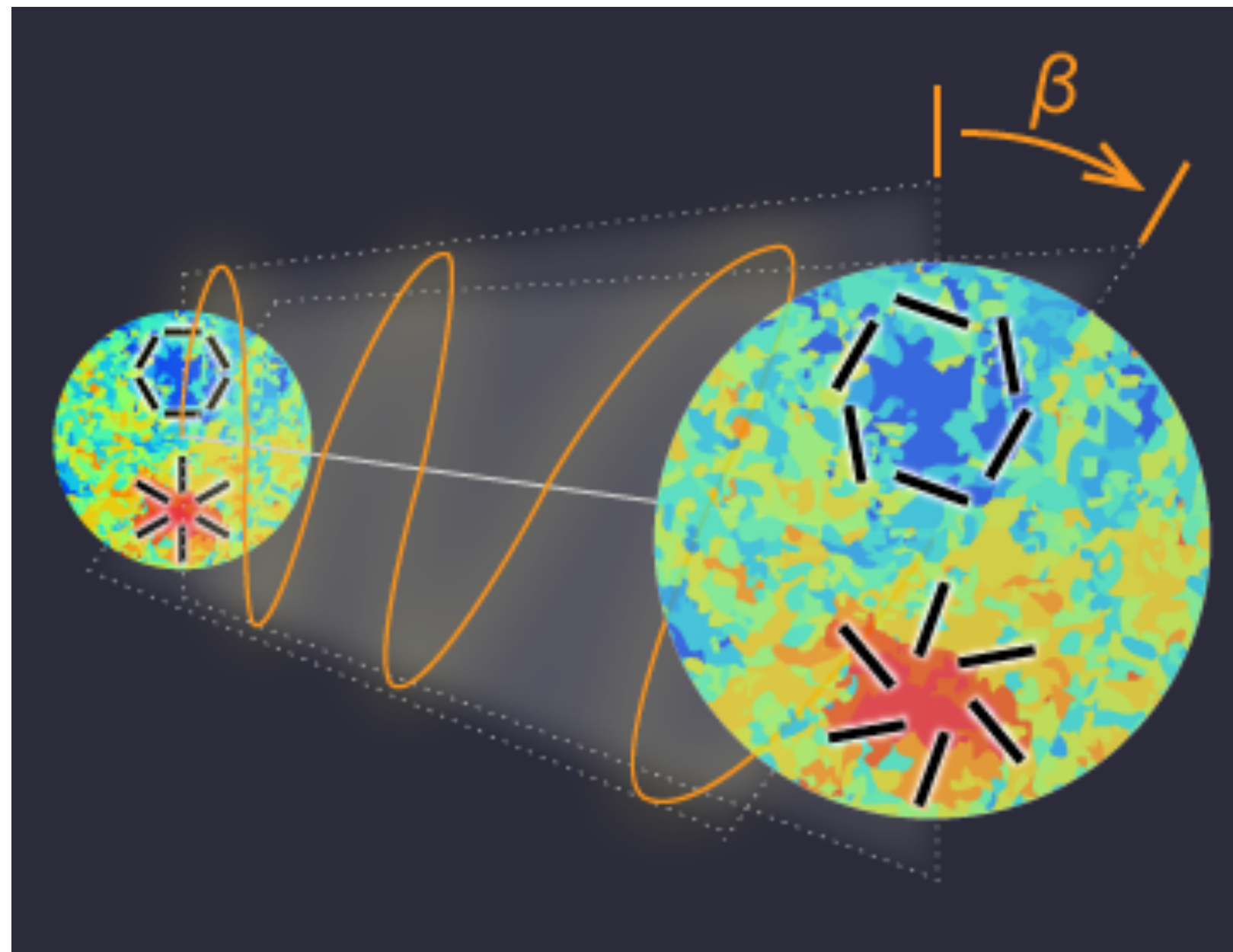
$$\begin{aligned} C_{\ell}^{EB,\text{obs}} &= \frac{1}{2} (C_{\ell}^{EE} - C_{\ell}^{BB}) \sin(4\beta) + C_{\ell}^{EB} \cos(4\beta) \\ &= \frac{1}{2} (\underline{C_{\ell}^{EE,\text{obs}} - C_{\ell}^{BB,\text{obs}}}) \tan(4\beta) + \frac{C_{\ell}^{EB}}{\cos(4\beta)} \end{aligned}$$

EB is generated  
by the *difference*  
between EE and  
BB spectra.

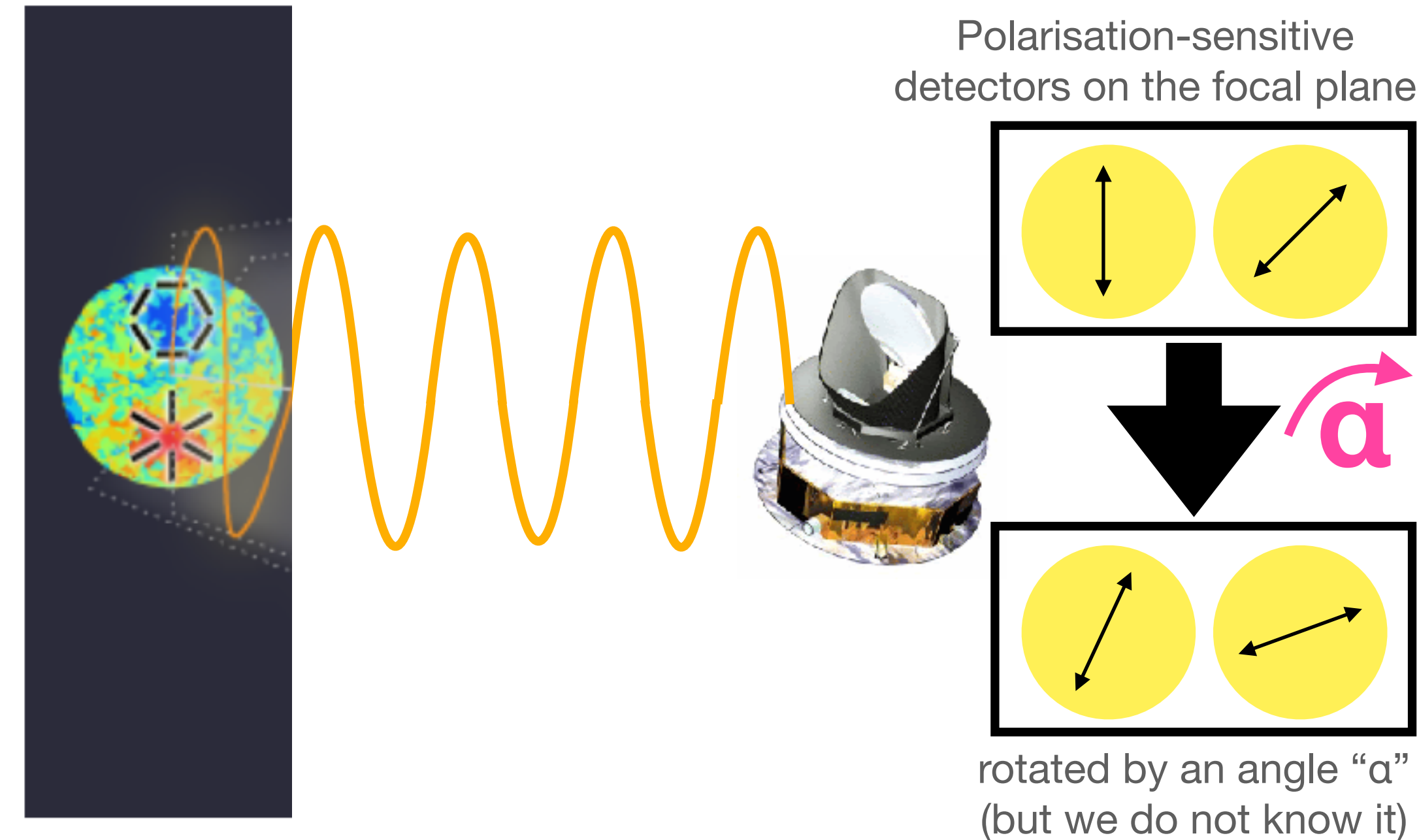
# **The Biggest Problem: Miscalibration of detectors**

# Impact of miscalibration of polarisation angles

## Cosmic or Instrumental?



OR



- Is the plane of linear polarisation rotated by the genuine cosmic birefringence effect, or simply because the polarisation-sensitive directions of detectors are rotated with respect to the sky coordinates (and we did not know it)?
- If the detectors are rotated by  $\alpha$ , it seems that we can measure only the **sum  $\alpha + \beta$** .

# The past measurements

The quoted uncertainties are all statistical only (68%CL)

- $\alpha + \beta = -6.0 \pm 4.0$  deg (Feng et al. 2006) first measurement
- $\alpha + \beta = -1.1 \pm 1.4$  deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- $\alpha + \beta = 0.55 \pm 0.82$  deg (QUaD Collaboration, Wu et al. 2009)
- ...
- $\alpha + \beta = 0.31 \pm 0.05$  deg (Planck Collaboration 2016)
- $\alpha + \beta = -0.61 \pm 0.22$  deg (POLARBEAR Collaboration 2020)
- $\alpha + \beta = 0.63 \pm 0.04$  deg (SPT Collaboration, Bianchini et al. 2020)
- $\alpha + \beta = 0.12 \pm 0.06$  deg (ACT Collaboration, Namikawa et al. 2020)
- $\alpha + \beta = 0.07 \pm 0.09$  deg (ACT Collaboration, Choi et al. 2020)

**Why not yet  
discovered?**

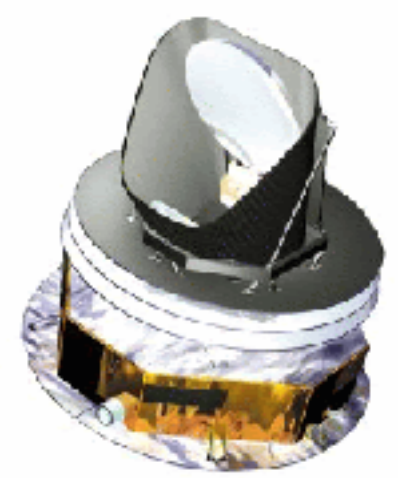
# The past measurements

Now including the estimated systematic errors on  $\alpha$

- $\beta = -6.0 \pm 4.0 \pm ??$  deg (Feng et al. 2006)
- $\beta = -1.1 \pm 1.4 \pm 1.5$  deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- $\beta = 0.55 \pm 0.82 \pm 0.5$  deg (QUaD Collaboration, Wu et al. 2009)
- ...
- $\beta = 0.31 \pm 0.05 \pm 0.28$  deg (Planck Collaboration 2016)
- $\beta = -0.61 \pm 0.22 \pm ??$  deg (POLARBEAR Collaboration 2020)
- $\beta = 0.63 \pm 0.04 \pm ??$  deg (SPT Collaboration, Bianchini et al. 2020)
- $\beta = 0.12 \pm 0.06 \pm ??$  deg (ACT Collaboration, Namikawa et al. 2020)
- $\beta = 0.07 \pm 0.09 \pm ??$  deg (ACT Collaboration, Choi et al. 2020)

**Uncertainty in the calibration of  $\alpha$  has been the major limitation**

**The Key Idea: The polarised Galactic foreground emission as a calibrator**



ESA's Planck

**Credit: ESA**

# Polarised dust emission within our Milky Way!

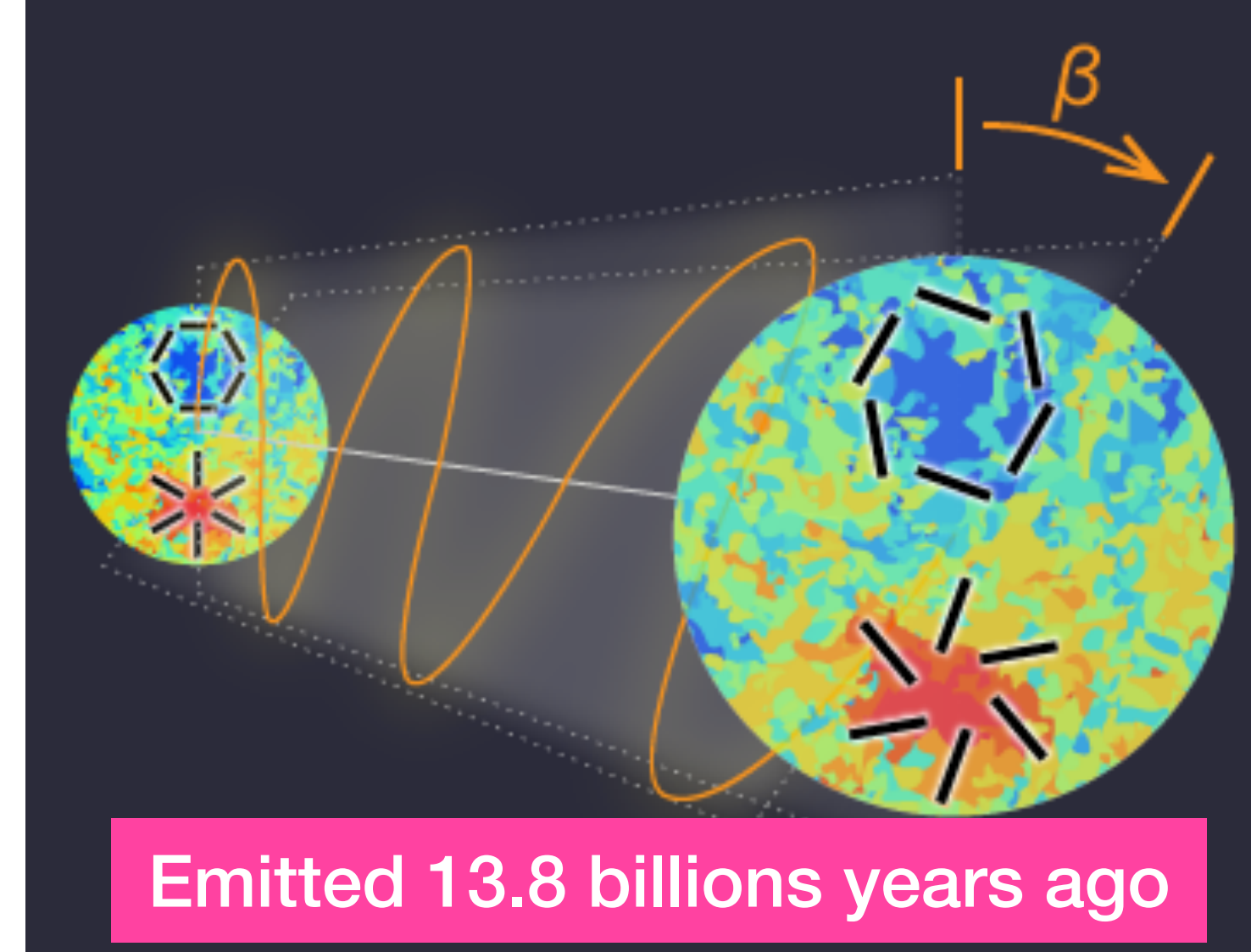
Emitted “right there” - it would  
not be affected by the cosmic  
birefringence.

Directions of the magnetic field inferred from polarisation of the thermal dust emission in the Milky Way

# Searching for the birefringence

## Improvement #2 (Minami et al. 2019)

- **Idea:** Miscalibration of the polarization angle  $\alpha$  rotates both the foreground and CMB, but  $\beta$  affects only the CMB.



But the source of foreground is much closer!

$$E_{\ell,m}^o = E_{\ell,m}^{\text{fg}} \cos(2\alpha) - B_{\ell,m}^{\text{fg}} \sin(2\alpha) + E_{\ell,m}^{\text{CMB}} \cos(2\alpha + 2\beta) - B_{\ell,m}^{\text{CMB}} \sin(2\alpha + 2\beta) + \boxed{E_{\ell,m}^{\text{N}}}$$

$$B_{\ell,m}^o = E_{\ell,m}^{\text{fg}} \sin(2\alpha) + B_{\ell,m}^{\text{fg}} \cos(2\alpha) + E_{\ell,m}^{\text{CMB}} \sin(2\alpha + 2\beta) + B_{\ell,m}^{\text{CMB}} \cos(2\alpha + 2\beta) + \boxed{B_{\ell,m}^{\text{N}}}$$

noise

- Thus,

$$\langle C_{\ell}^{EB,o} \rangle = \frac{\tan(4\alpha)}{2} \left( \underbrace{\langle C_{\ell}^{EE,o} \rangle - \langle C_{\ell}^{BB,o} \rangle}_{\text{measured}} \right) + \frac{\sin(4\beta)}{2 \cos(4\alpha)} \left( \underbrace{\langle C_{\ell}^{EE,\text{CMB}} \rangle - \langle C_{\ell}^{BB,\text{CMB}} \rangle}_{\text{known accurately}} \right) + \frac{1}{\cos(4\alpha)} \langle C_{\ell}^{EB,\text{fg}} \rangle + \frac{\cos(4\beta)}{\cos(4\alpha)} \langle C_{\ell}^{EB,\text{CMB}} \rangle .$$

Key: No explicit modelling of the foreground EE and BB is necessary

# Assumption for the baseline result

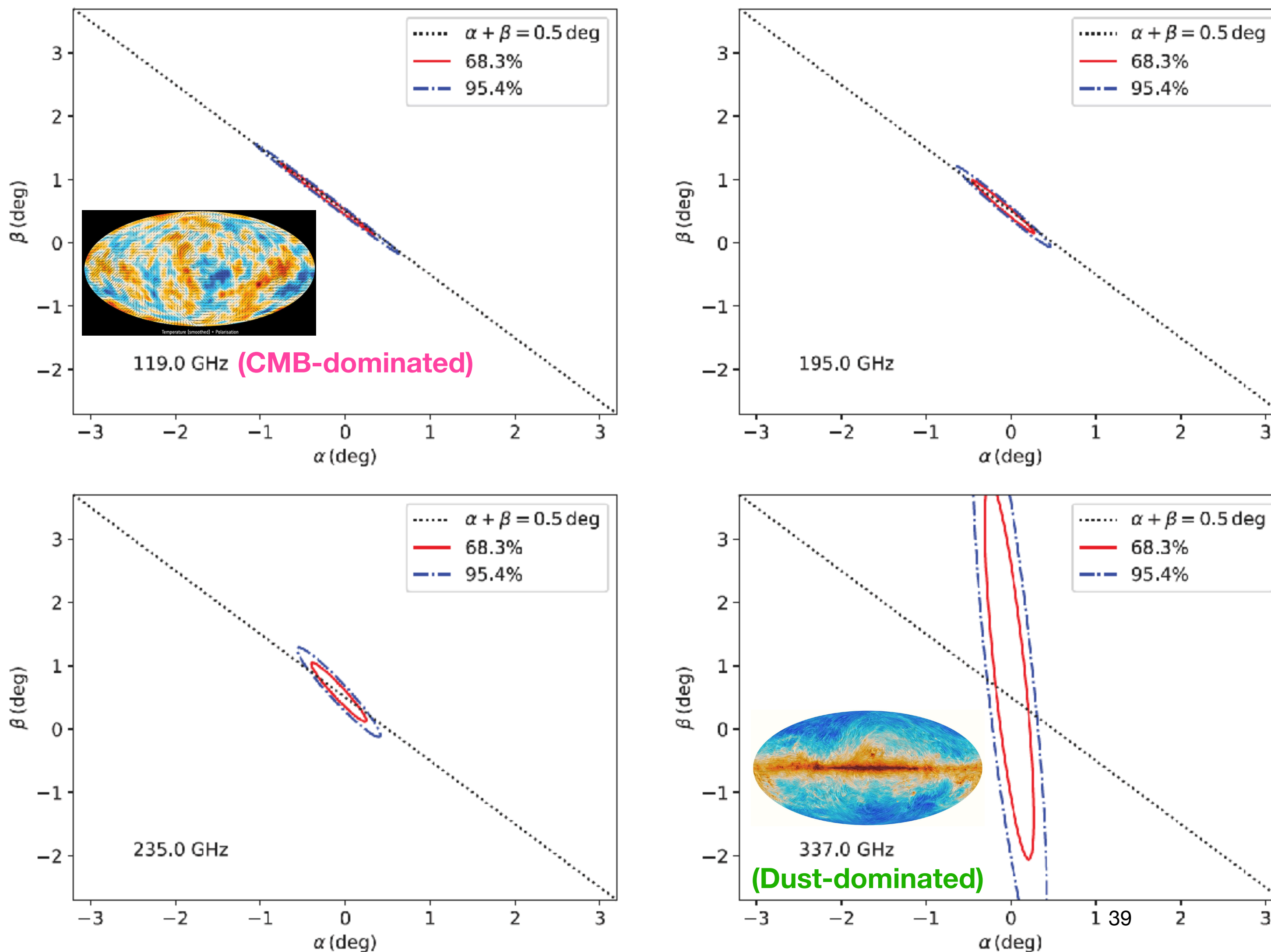
What about the intrinsic EB correlation of the foreground emission?

$$\begin{aligned} \langle C_{\ell}^{EB,o} \rangle = & \frac{\tan(4\alpha)}{2} \left( \langle C_{\ell}^{EE,o} \rangle - \langle C_{\ell}^{BB,o} \rangle \right) + \frac{\sin(4\beta)}{2 \cos(4\alpha)} \left( \langle C_{\ell}^{EE,CMB} \rangle - \langle C_{\ell}^{BB,CMB} \rangle \right) \\ & + \frac{1}{\cos(4\alpha)} \langle C_{\ell}^{EB,fg} \rangle + \frac{\cos(4\beta)}{\cos(4\alpha)} \langle C_{\ell}^{EB,CMB} \rangle. \end{aligned}$$

- For the baseline result, we ignore the intrinsic EB correlations of the foreground  $\langle C_{\ell}^{EB,fg} \rangle$  and the CMB  $\langle C_{\ell}^{EB,CMB} \rangle$ .
- The latter is justifiable but the former is not. We will revisit this important issue at the end.

# How does it work?

## Simulation of future CMB data (LiteBIRD)



- When the data are dominated by CMB, the sum of two angles,  $\alpha + \beta$ , is determined precisely.
  - This is the diagonal line.
- The foreground determines  $\alpha$  with some uncertainty, breaking the degeneracy. Then  $\sigma(\beta) \sim \sigma(\alpha)$  because  $\sigma(\alpha + \beta) \ll \sigma(\alpha)$ .
- When the data are dominated by the foreground, it can determine  $\alpha$  but not  $\beta$  due to the lack of sensitivity to the CMB.

# PHYSICAL REVIEW LETTERS

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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?](#)

Yuto Minami  
(Osaka U.)



# Application to the Planck Public Data Release 3 (PR3)

$l_{\min} = 51$ ,  $l_{\max} = 1490$  (same as those used by the Planck team)

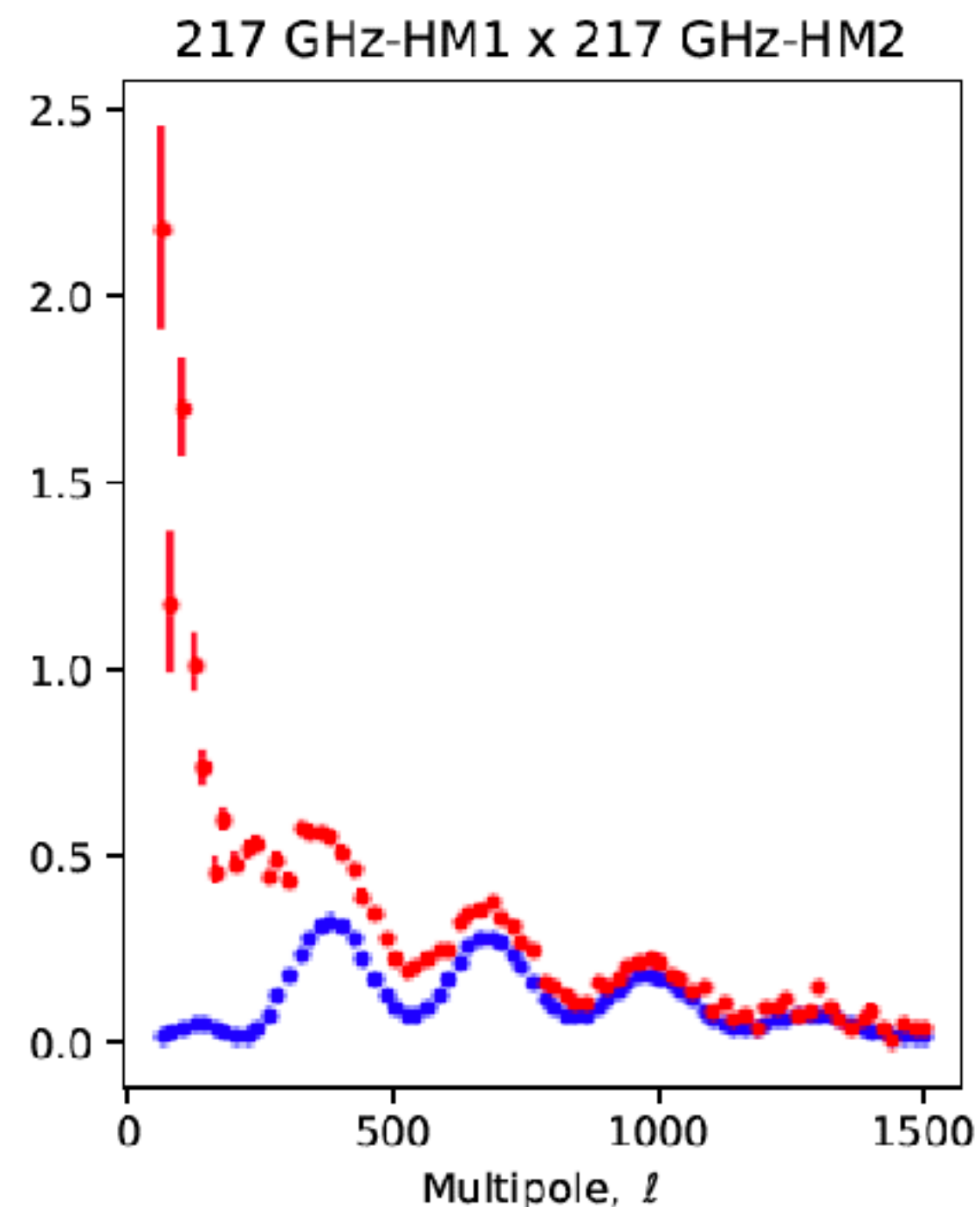
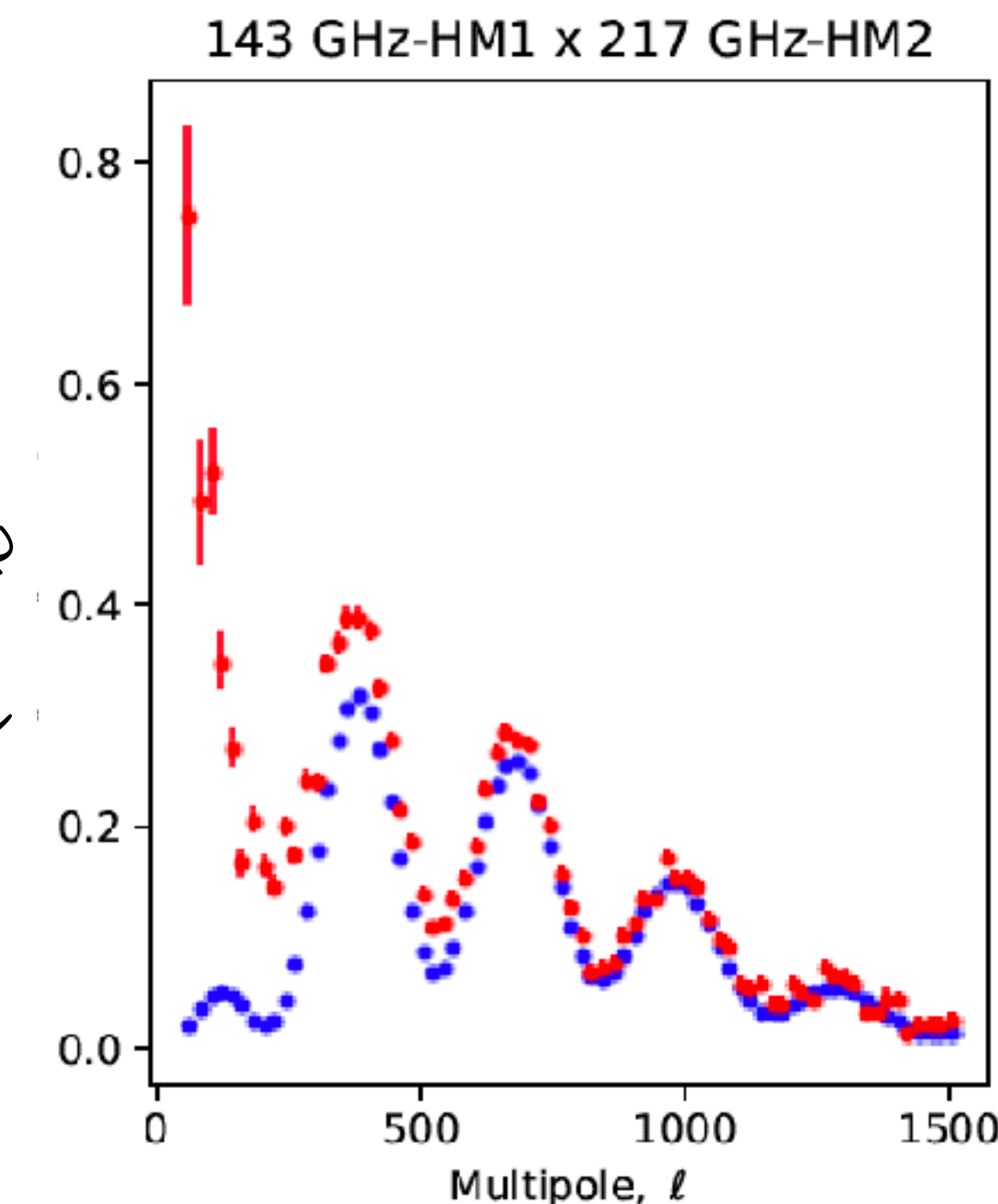
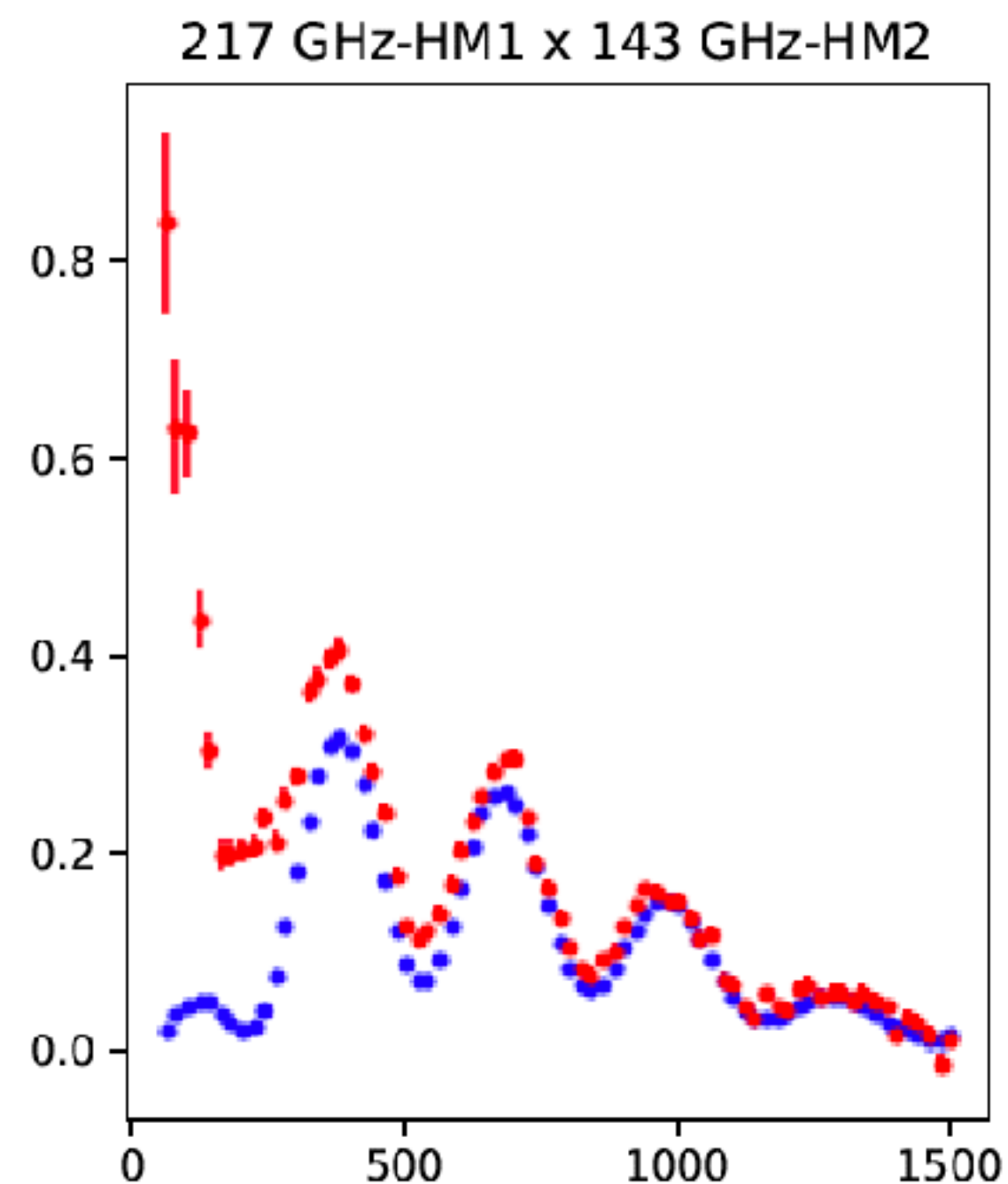
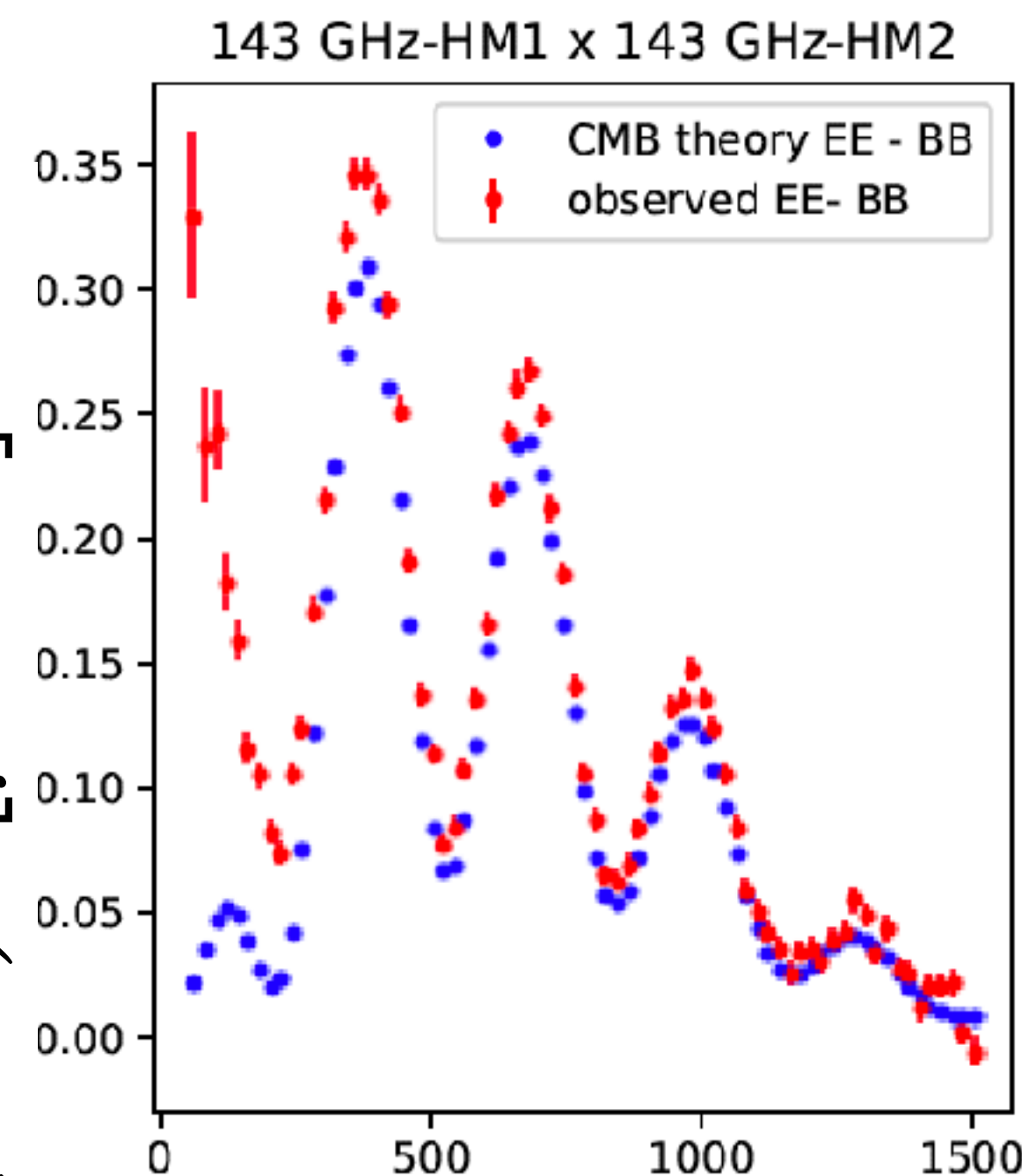
- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz)

## Main Result: $\beta > 0$ at $2.4\sigma$ for nearly full-sky data

TABLE I. Cosmic birefringence and miscalibration angles from the Planck 2018 polarization data with  $1\sigma$  (68%) uncertainties

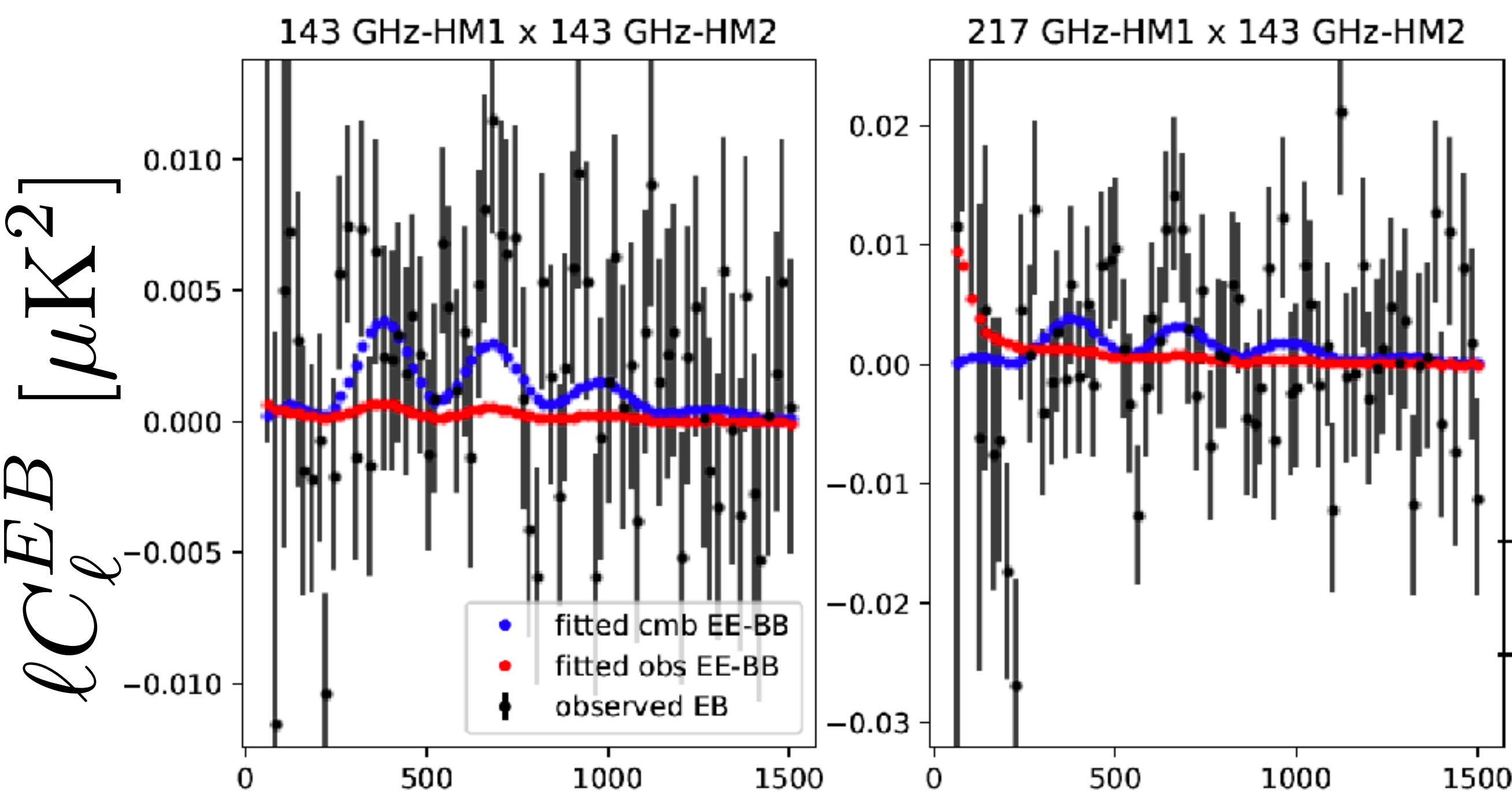
| Angles         | $\alpha_v=0$                                     | Results (deg)    |
|----------------|--------------------------------------------------|------------------|
| $\beta$        | $0.289 \pm 0.048$                                | $0.35 \pm 0.14$  |
| $\alpha_{100}$ | (This agrees with the result of the Planck team) | $-0.28 \pm 0.13$ |
| $\alpha_{143}$ |                                                  | $0.07 \pm 0.12$  |
| $\alpha_{217}$ |                                                  | $-0.07 \pm 0.11$ |
| $\alpha_{353}$ |                                                  | $-0.09 \pm 0.11$ |

$\ell(C_\ell^{EE} - C_\ell^{BB}) [\mu K^2]$



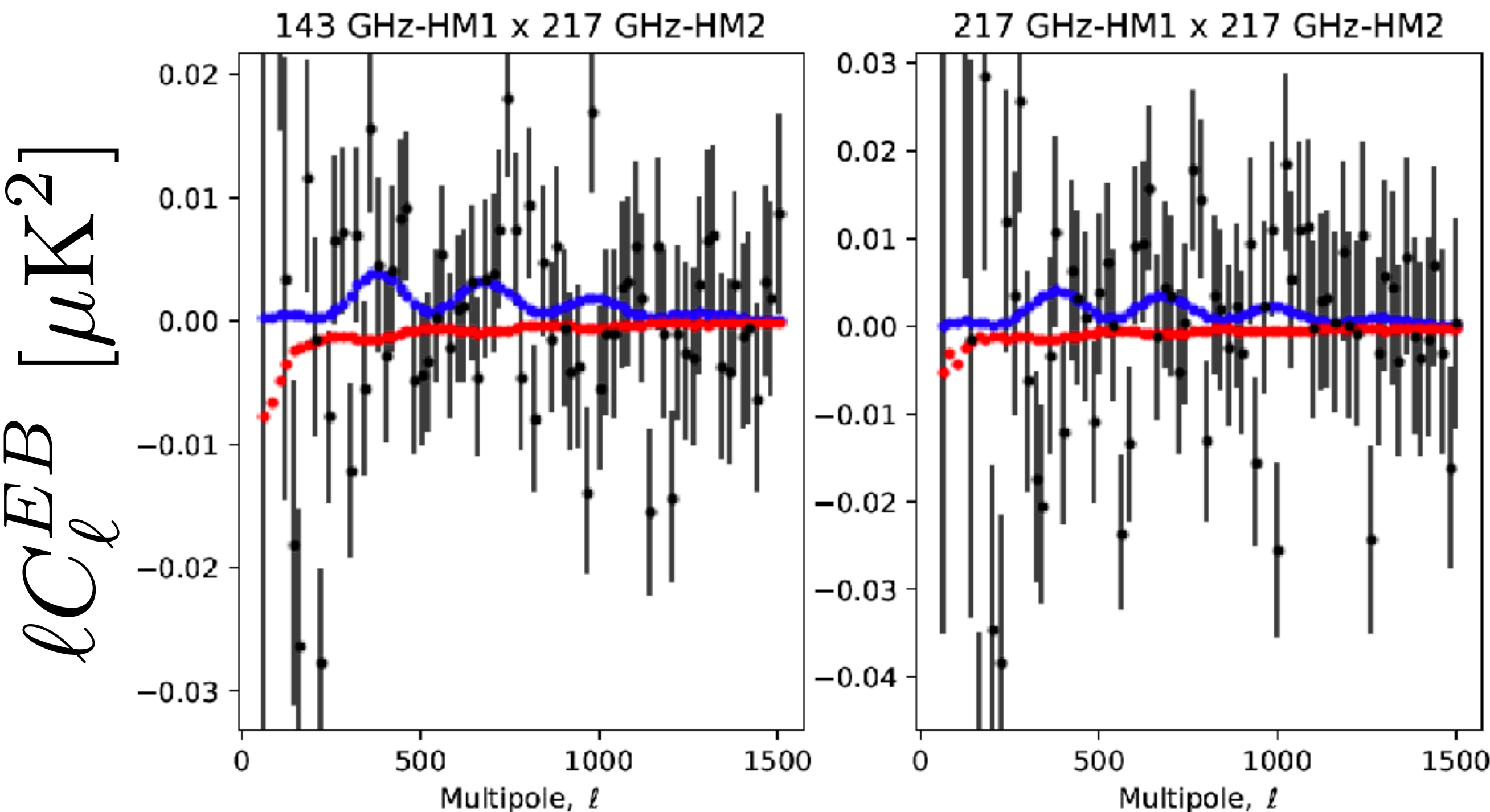
$$\langle C_\ell^{EB,o} \rangle = \frac{\tan(4\alpha)}{2} \left( \langle C_\ell^{EE,o} \rangle - \langle C_\ell^{BB,o} \rangle \right) + \frac{\sin(4\beta)}{2 \cos(4\alpha)} \left( \langle C_\ell^{EE,CMB} \rangle - \langle C_\ell^{BB,CMB} \rangle \right)$$

- Can we see  $\beta = 0.35 \pm 0.14$  deg by eyes?
- First, take a look at the observed EE-BB spectra.
- Red: Total
- Blue: The best-fitting CMB model
- *The difference is due to the FG (and maybe unknown systematics)*



$$\langle C_l^{EB,o} \rangle = \frac{\tan(4\alpha)}{2} \left( \langle C_l^{EE,o} \rangle - \langle C_l^{BB,o} \rangle \right) + \frac{\sin(4\beta)}{2 \cos(4\alpha)} \left( \langle C_l^{EE,CMB} \rangle - \langle C_l^{BB,CMB} \rangle \right)$$

- Can we see  $\beta = 0.35 \pm 0.14$  deg by eyes?
- Red: The signal attributed to the miscalibration angle,  $\alpha_v$
- Blue: The signal attributed to the cosmic birefringence,  $\beta$
- Red + Blue is the best-fitting model for explaining the data points



# How about the foreground EB?

- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle  $\alpha$ .
- Thus,  $\alpha \rightarrow \alpha + \gamma$ , where  $\gamma$  is the contribution from the intrinsic EB.
  - The sign of  $\gamma$  is the same as the sign of the foreground EB.
- From FG:  $\alpha + \gamma$ . From CMB:  $\alpha + \beta$ .
  - Thus, our method yields  **$\beta - \gamma = 0.35 \pm 0.14$  deg.**
- There is evidence for the dust-induced  $TE_{\text{dust}} > 0$  and  $TB_{\text{dust}} > 0$ . Then, we'd expect  $EB_{\text{dust}} > 0$  (Huffenberger et al. 2020), i.e.,  $\gamma > 0$ . If so,  $\beta$  increases further...

Accepted Paper

# Cosmic birefringence from the *Planck* data release 4

Phys. Rev. Lett.

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

**Accepted** 4 February 2022

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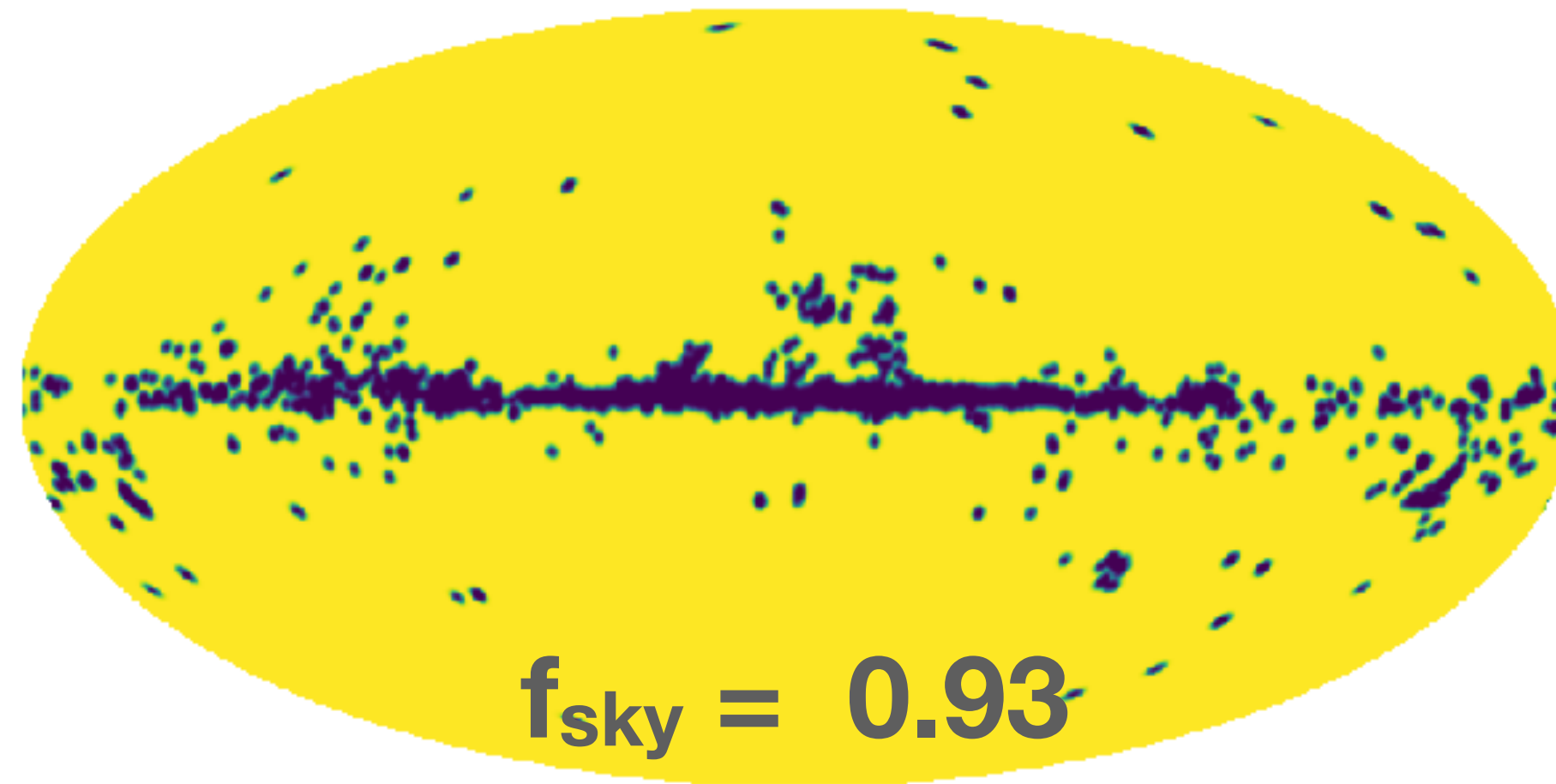
Double corresponding authors.  
PhD students. *Young power!*

# Application to the Public Data Release 4 (PR4)

**PR4 = “NPIPE” reprocessing of all the Planck data (Planck Collaboration 2020)**

- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz).
  - **These maps have lower noise** and better-characterised systematics than PR3.
  - We measure power spectra from A/B splits (each frequency band has 2 sets of detectors), to avoid possible correlated noise.
- Masks
  - Unlike for the PR3 analysis, we use the common mask for all frequencies.
  - Bright CO regions, Bright point sources, and four Galactic masks.
  - Fraction of sky used = 0.93, 0.90, 0.85, 0.75 and 0.63.

CO+PS (1deg apodization)

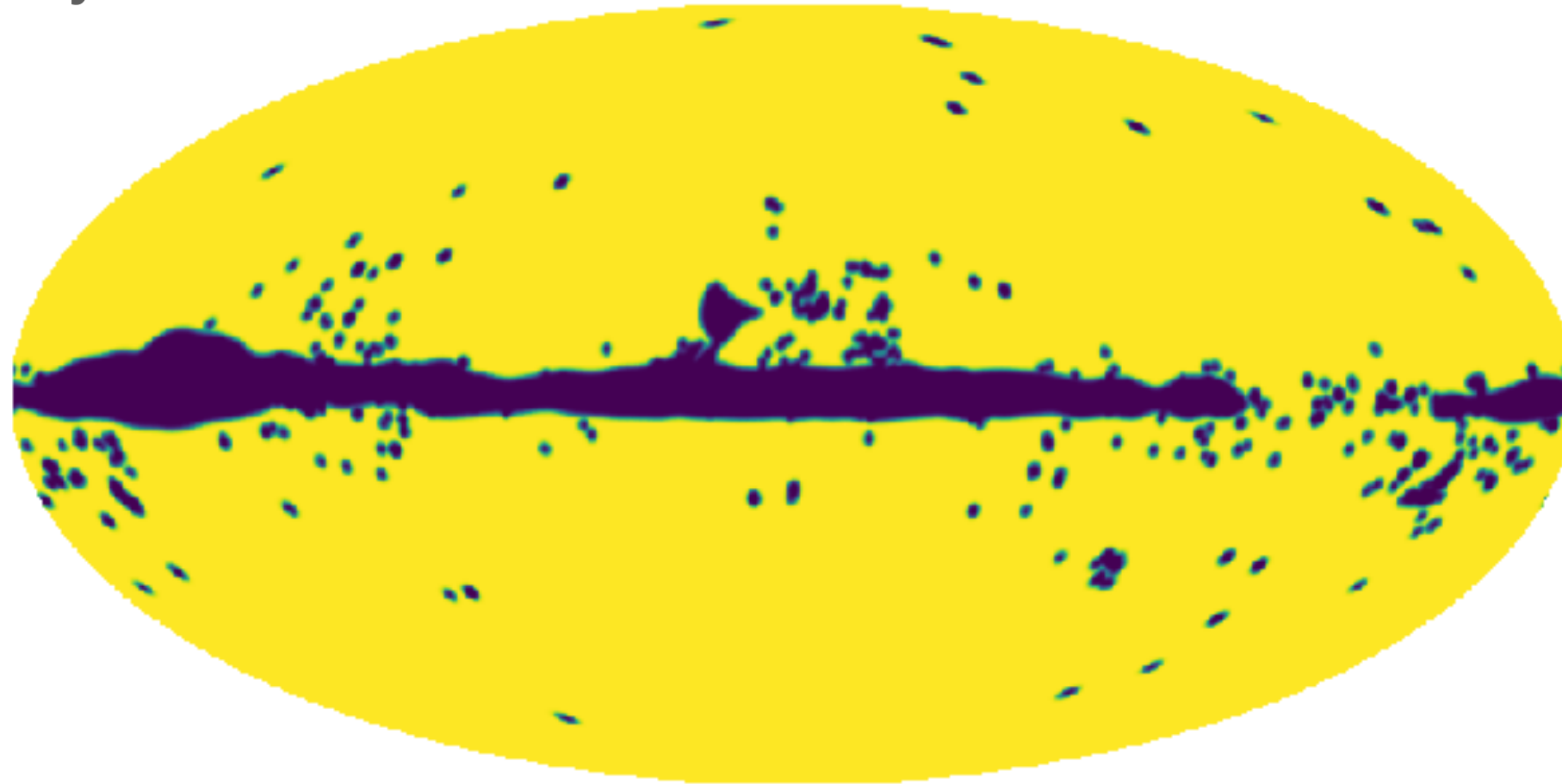


$f_{\text{sky}} = 0.93$

= nearly full sky

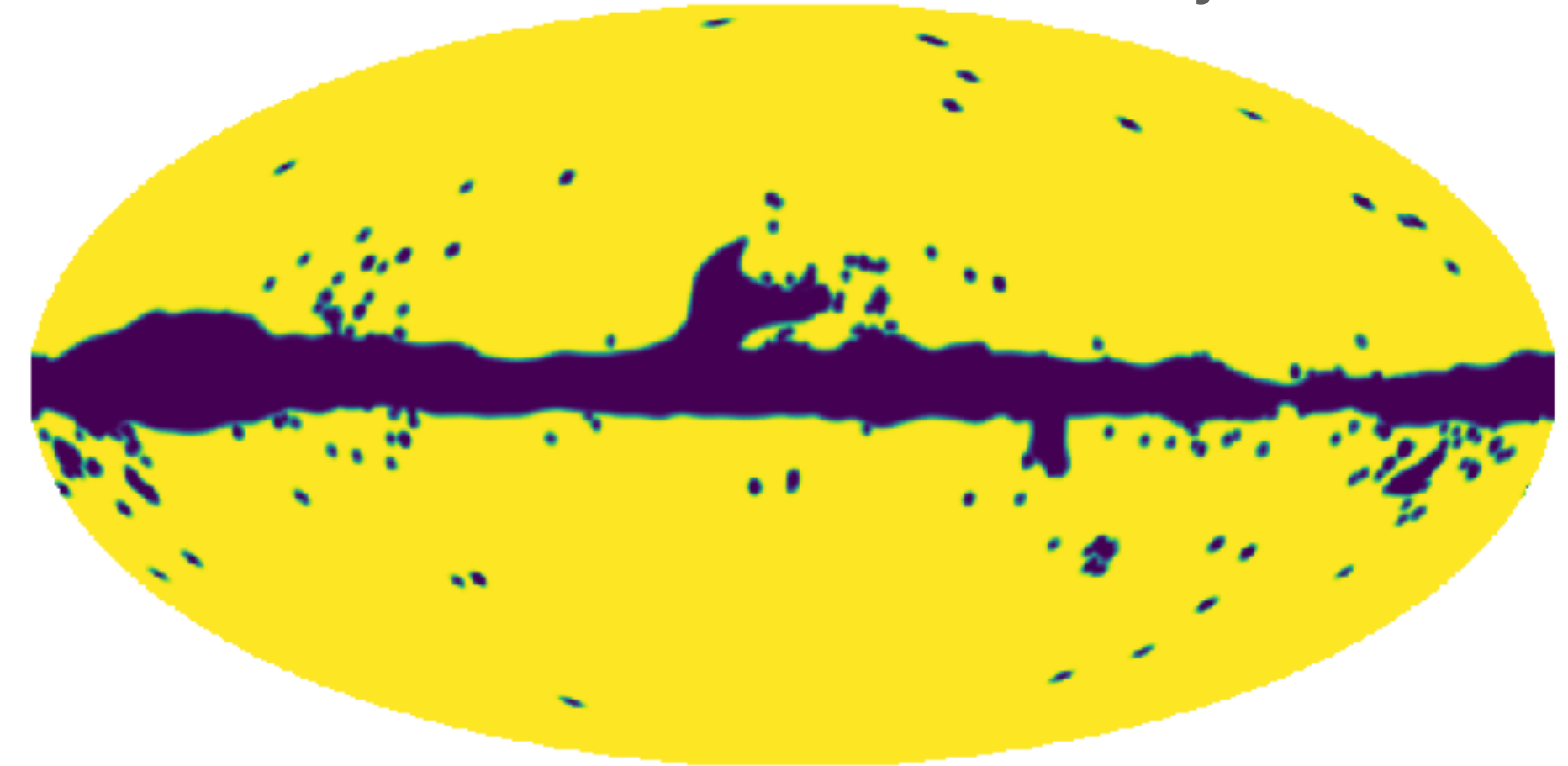
$f_{\text{sky}} = 0.90$

CO+PS+5% (1deg apodization)



CO+PS+10% (1deg apodization)

$f_{\text{sky}} = 0.85$



CO+PS+20% (1deg apodization)



$f_{\text{sky}} = 0.75$

CO+PS+30% (1deg apodization)



$f_{\text{sky}} = 0.63$

# Full-sky result, without accounting for foreground EB

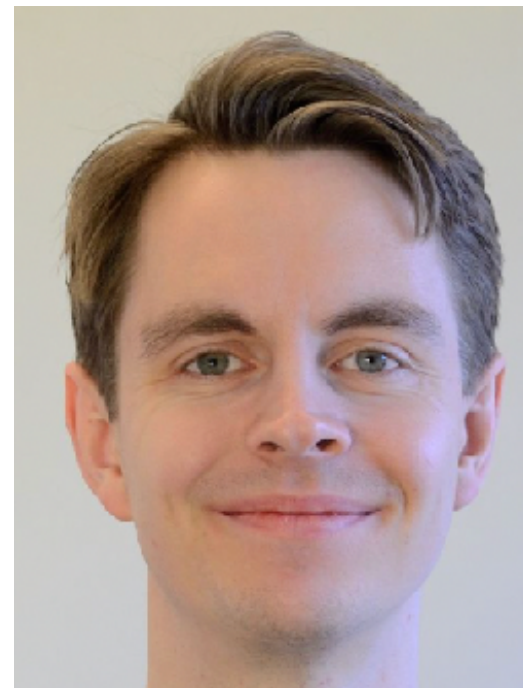
The PR3 result confirmed, with smaller statistical uncertainty

- We find  $\beta = 0.30 \pm 0.11$  deg (68% CL) for nearly full sky  $\rightarrow$  a  $2.7\sigma$  result
- Four independent pipelines were compared and the results agreed.

PDP



JRE



YM



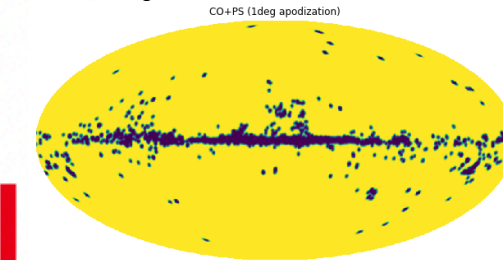
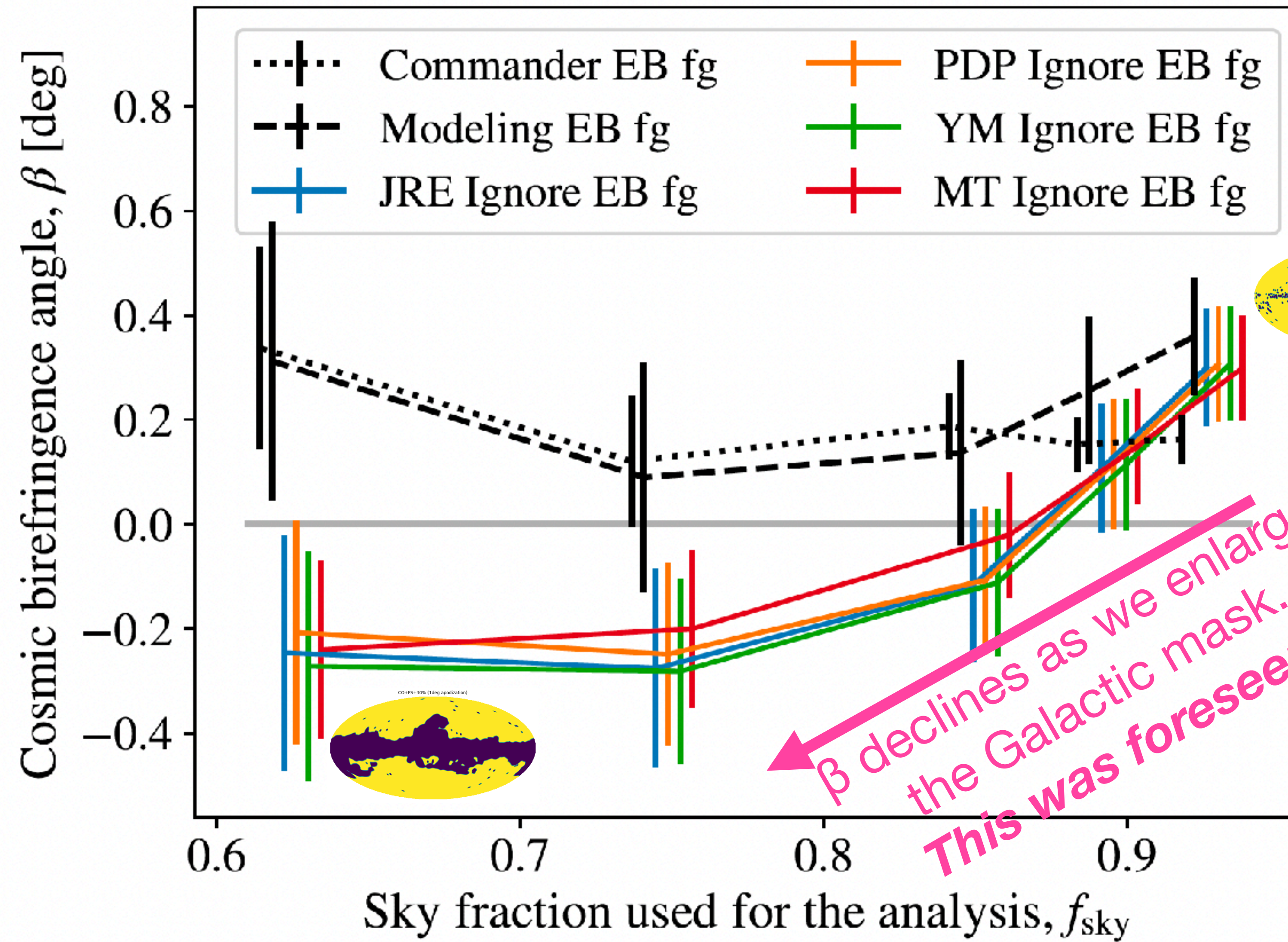
MT



- More statistical significance than the  $2.4\sigma$  result of the PR3,  $0.35 \pm 0.14$  deg.

# How do the results change with $f_{\text{sky}}$ ?

Hint for the foreground EB for smaller  $f_{\text{sky}}$



PDP



JRE



YM



MT



# Including the foreground EB

## Introducing a new angle, “ $\gamma$ ”

- When we do not ignore the intrinsic foreground EB, the *observed* foreground EB (including the miscalibration angle contribution,  $\alpha$ ) is given by

$$C_{\ell}^{EB,FG,o} = \frac{1}{2} \sin(4\alpha) \left( C_{\ell}^{EE,FG} - C_{\ell}^{BB,FG} \right) + \underbrace{C_{\ell}^{EB,FG} \cos(4\alpha)}_{\text{new term}}$$

- Using a formula for trigonometric functions,

$$A \sin \varphi + B \cos \varphi = \sqrt{A^2 + B^2} \sin(\varphi + \theta), \quad \tan \theta = B/A$$

- We obtain

$$C_{\ell}^{EB,FG,o} = \sqrt{J_{\ell}^2 + (C_{\ell}^{EB,FG})^2} \sin(4\alpha + 4\gamma_{\ell}) \left\{ \begin{array}{l} J_{\ell} \equiv \frac{1}{2} \left( C_{\ell}^{EE,FG} - C_{\ell}^{BB,FG} \right) \\ \tan(4\gamma_{\ell}) \equiv C_{\ell}^{EB,FG} / J_{\ell} \end{array} \right. \quad \alpha \rightarrow \alpha + \gamma$$

# Remember this slide?

## How about the foreground EB?

- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle  $\alpha$ .
- Thus,  $\alpha \rightarrow \alpha + \gamma$ , where  $\gamma$  is the contribution from the intrinsic EB.
  - The sign of  $\gamma$  is the same as the sign of the foreground EB.
- From FG:  $\alpha + \gamma$ . From CMB:  $\alpha + \beta$ .
  - Thus, our method yields  $\beta - \gamma = 0.35 \pm 0.14$  deg.
- There is evidence for the dust-induced  $TE_{\text{dust}} > 0$  and  $TB_{\text{dust}} > 0$ . Then, we'd expect  $EB_{\text{dust}} > 0$  (Huffenberger et al. 2020), i.e.,  $\gamma > 0$ . If so,  $\beta$  increases further...

We expected  $\beta$  to decrease towards smaller  $f_{\text{sky}}$  due to the foreground EB.

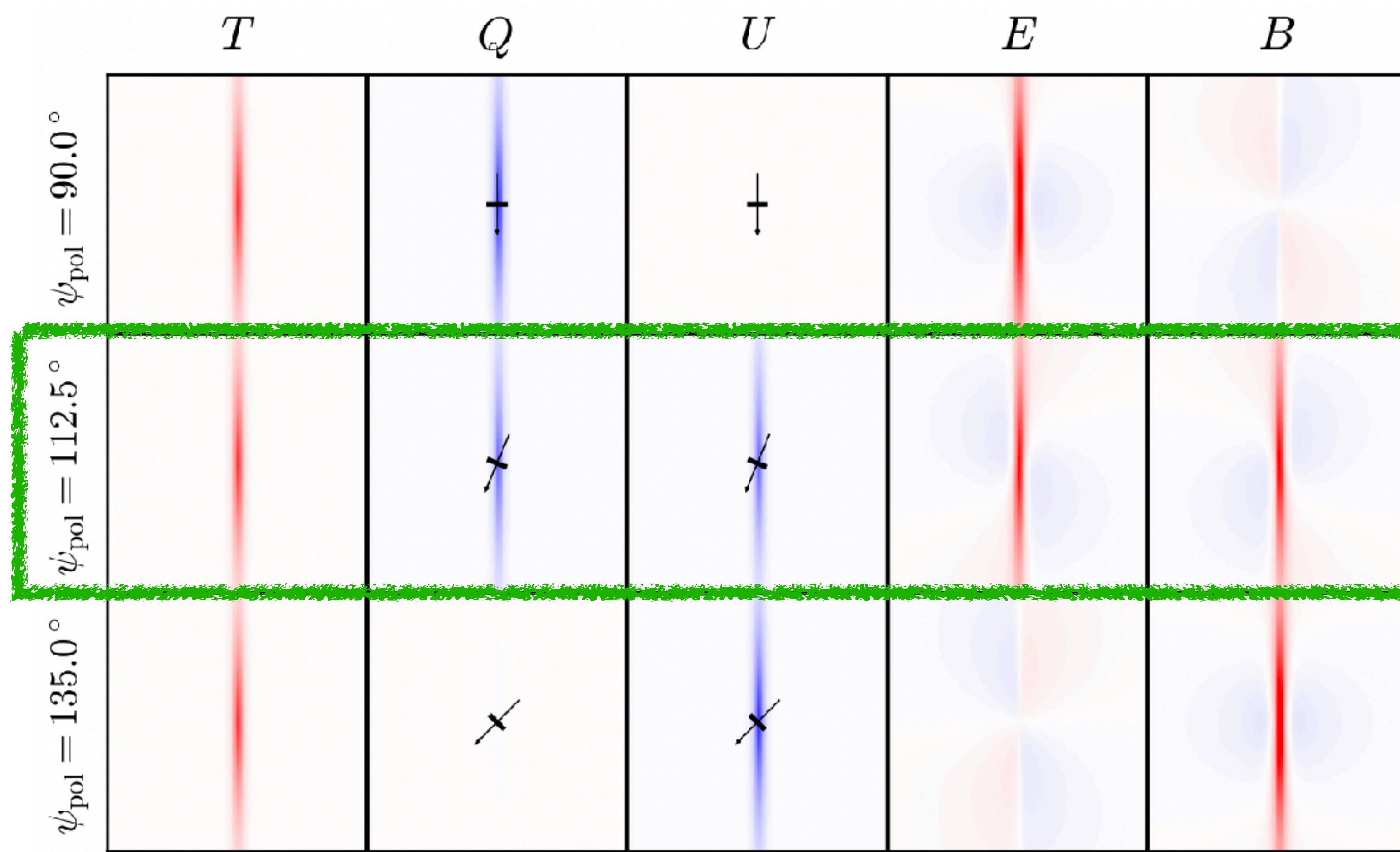
# Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- **How do we model the new angle  $\gamma$ ?**
  - We don't really know for sure yet. *This is a fascinating opportunity for Galactic science!*
- Nonetheless, there may be a clue from the dust TB correlation.
  - **Discovery of a non-zero (positive) dust TB correlation** by the Planck collaboration was a surprise.
  - We still do not know its origin (see Huppenberger et al. 2020 and Clark et al. 2021 for the first attempts to explain it).
  - However, it seems reasonable to relate the possible dust EB correlation to the dust TB correlation.

# TE, TB, and EB correlation from a filament

Huffenberger, Rotti & Collins (2020)



- Misalignment of filaments and magnetic fields creates  $TE > 0$ ,  $TB > 0$  and  $EB > 0$

# Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- How do we model the new angle  $\gamma$ ?

- Our *ansatz*, motivated by a physical consideration of Clark et al. (2021):

$$\left\{ \begin{array}{l} C_{\ell}^{EB,\text{dust}} = A_{\ell} C_{\ell}^{EE,\text{dust}} \sin(4\psi_{\ell}^{\text{dust}}) \\ \psi_{\ell}^{\text{dust}} = \frac{1}{2} \arctan(C_{\ell}^{TB,\text{dust}} / C_{\ell}^{TE,\text{dust}}) \end{array} \right.$$

Free  $\ell$ -dependent amplitude parameters

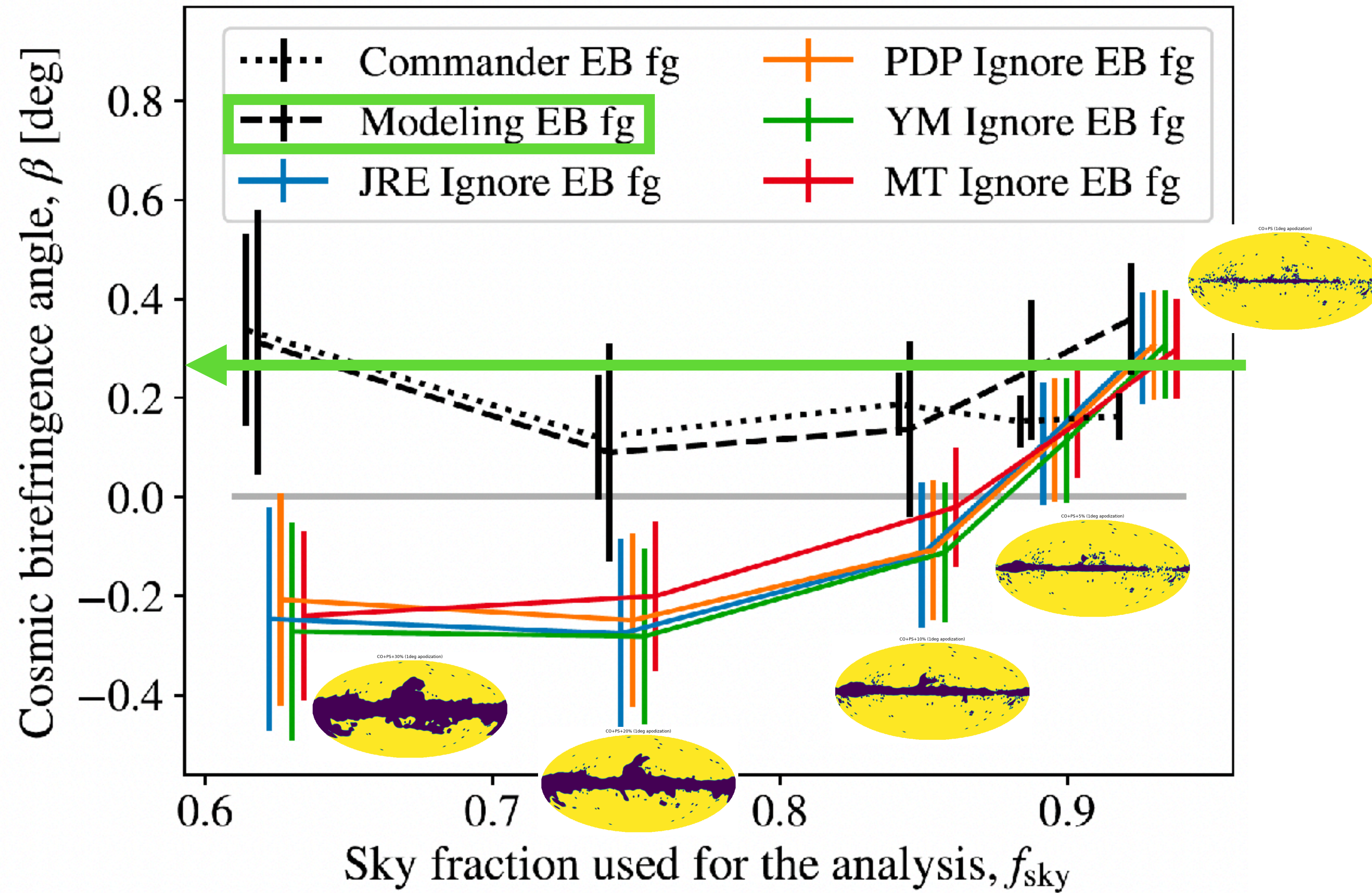
- Then

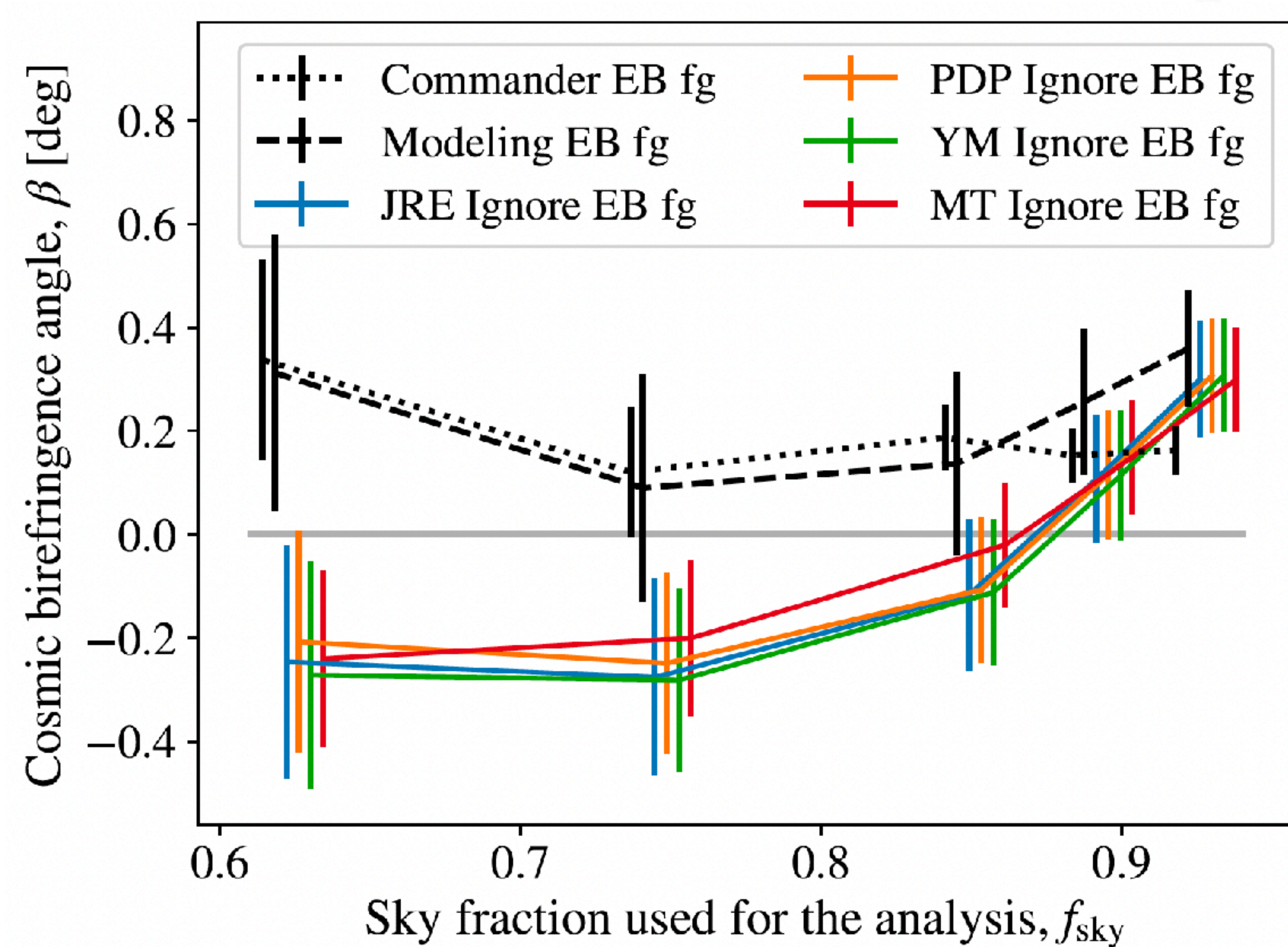
$$\gamma_{\ell} \simeq \frac{A_{\ell} C_{\ell}^{EE,\text{dust}}}{C_{\ell}^{EE,\text{dust}} - C_{\ell}^{BB,\text{dust}}} \frac{C_{\ell}^{TB,\text{dust}}}{C_{\ell}^{TE,\text{dust}}}$$

for small angles.

# Dashed line: Modeling the foreground EB

Trend for declining  $\beta$  is largely gone. But which  $f_{\text{sky}}$  we should choose?





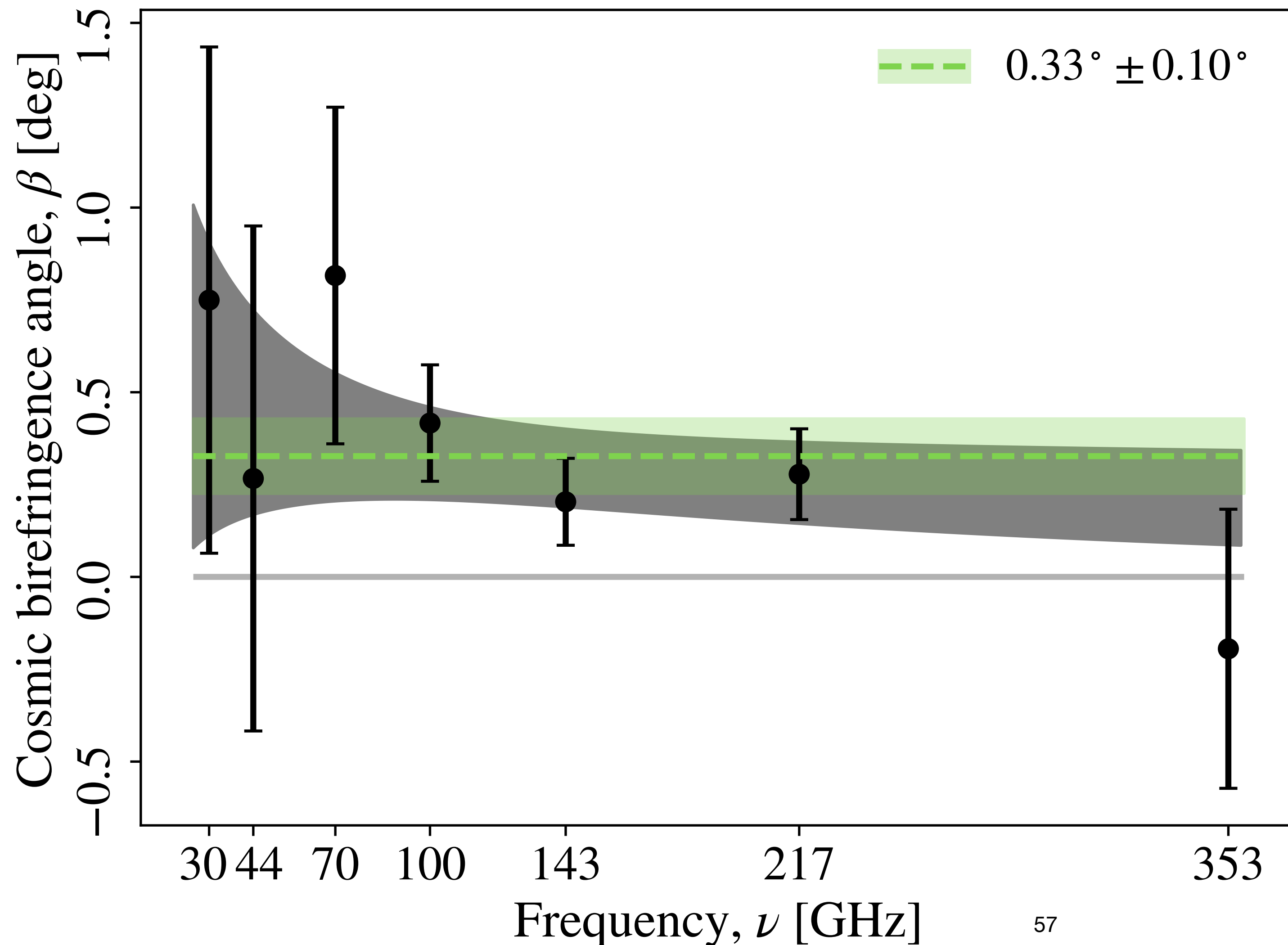
- As foreseen, accounting for the foreground EB **increased**  $\beta$  from 0.30 to 0.36 for nearly full-sky data.
- Which  $f_{\text{sky}}$  we should choose for the final result?  
**We do not know yet.** We need more investigation.
- We need help from Galactic astrophysics! It is a fascinating subject.

| $f_{\text{sky}}$    | 0.93                              |
|---------------------|-----------------------------------|
| $\beta$             | <b><math>0.36 \pm 0.11</math></b> |
| $\alpha_{100A}$     | $-0.32 \pm 0.13$                  |
| $\alpha_{100B}$     | $-0.43 \pm 0.13$                  |
| $\alpha_{143A}$     | $0.03 \pm 0.11$                   |
| $\alpha_{143B}$     | $0.15 \pm 0.11$                   |
| $\alpha_{217A}$     | $-0.06 \pm 0.11$                  |
| $\alpha_{217B}$     | $-0.07 \pm 0.11$                  |
| $\alpha_{353A}$     | $-0.19 \pm 0.10$                  |
| $\alpha_{353B}$     | $-0.23 \pm 0.11$                  |
| $10^2 A_{51-130}$   | $2.5^{+1.6}_{-1.4}$               |
| $10^2 A_{131-210}$  | $0.8^{+1.2}_{-0.6}$               |
| $10^2 A_{211-510}$  | $1.5^{+2.4}_{-1.1}$               |
| $10^2 A_{511-1490}$ | $6.2^{+5.7}_{-4.1}$               |



# No frequency dependence is found

## Consistent with the expectation from cosmic birefringence



- Johannes R. Eskilt measured  $\beta$  separately at all of 7 Planck polarised frequency bands.
- No evidence for frequency dependence:
  - For  $\beta \sim (\nu/150\text{GHz})^n$ ,  
 $n = -0.35^{+0.48}_{-0.47}$  (68% CL)
  - Faraday rotation ( $n=-2$ ) is disfavoured.

# Conclusion

$\beta = 0.30 \pm 0.11$  (68%CL; nearly full sky)

- Modeling the foreground EB, we find  $\beta=0.36 \pm 0.11$  deg.
  - “ $\pm 0.11$ ” is the **statistical-only uncertainty**. What is the systematic uncertainty due to the modelling of foreground EB?  
*This is the key question now!*
  - Good news: **The impact of the known instrumental systematics is negligible.** We found this using the NPIPE simulations of the PR4 data.
- No evidence for frequency dependence of  $\beta$ . Evidence for a cosmological signal?
  - With all of the Planck frequency bands (30–353 GHz),  $\beta=0.33 \pm 0.10$  deg (Eskilt, no correction for foreground EB)
- If the measured  $\beta$  is confirmed as cosmological, it would have profound implications for the fundamental physics behind dark matter and energy.

