

Cosmic Birefringence

Hunting for new parity-violating physics

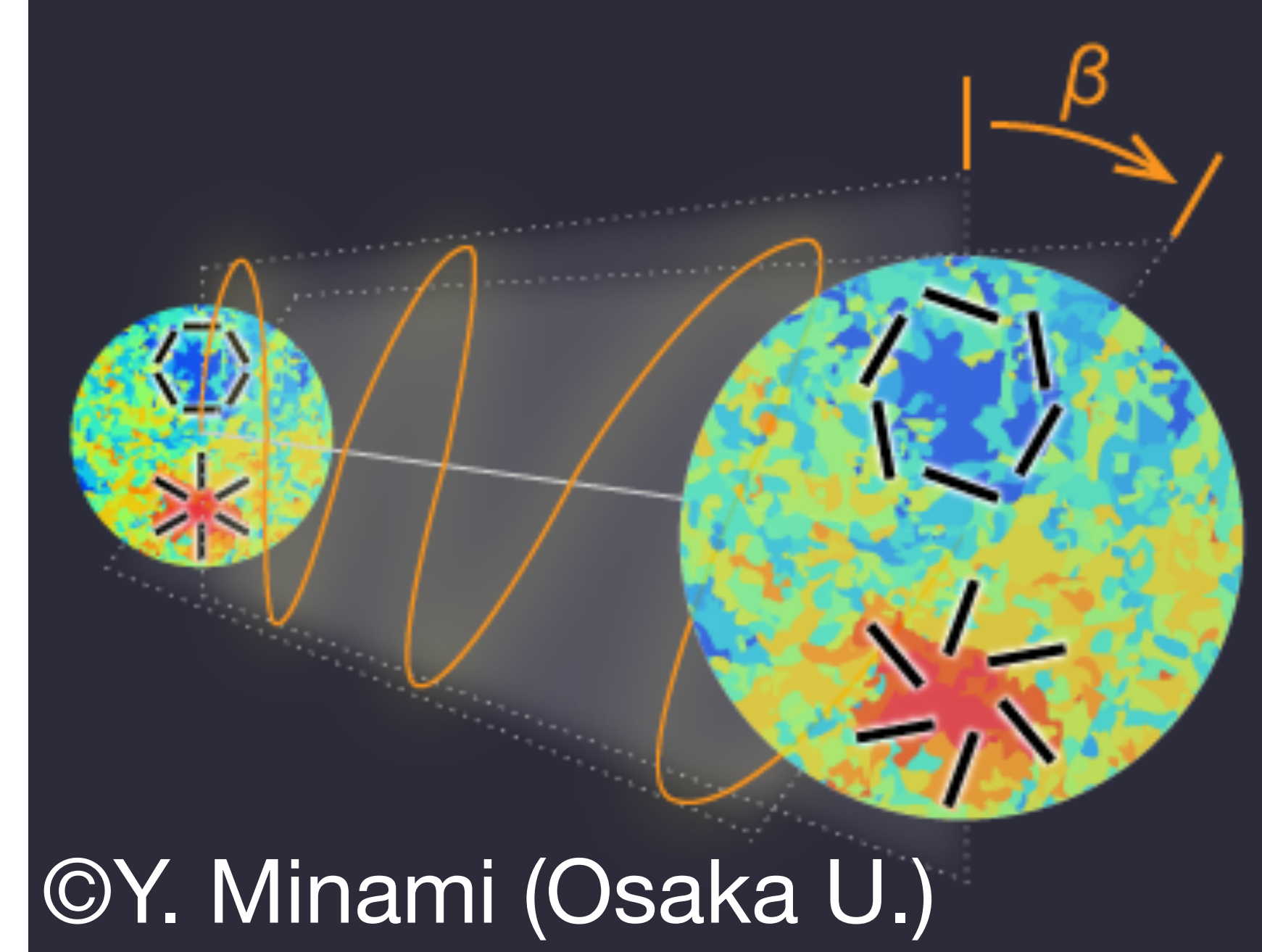
based on

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

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)

Galileo Galilei Institute Tea Break's Seminar

February 2, 2022



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Standard Cosmological Model (Λ CDM) 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 key to the answers.

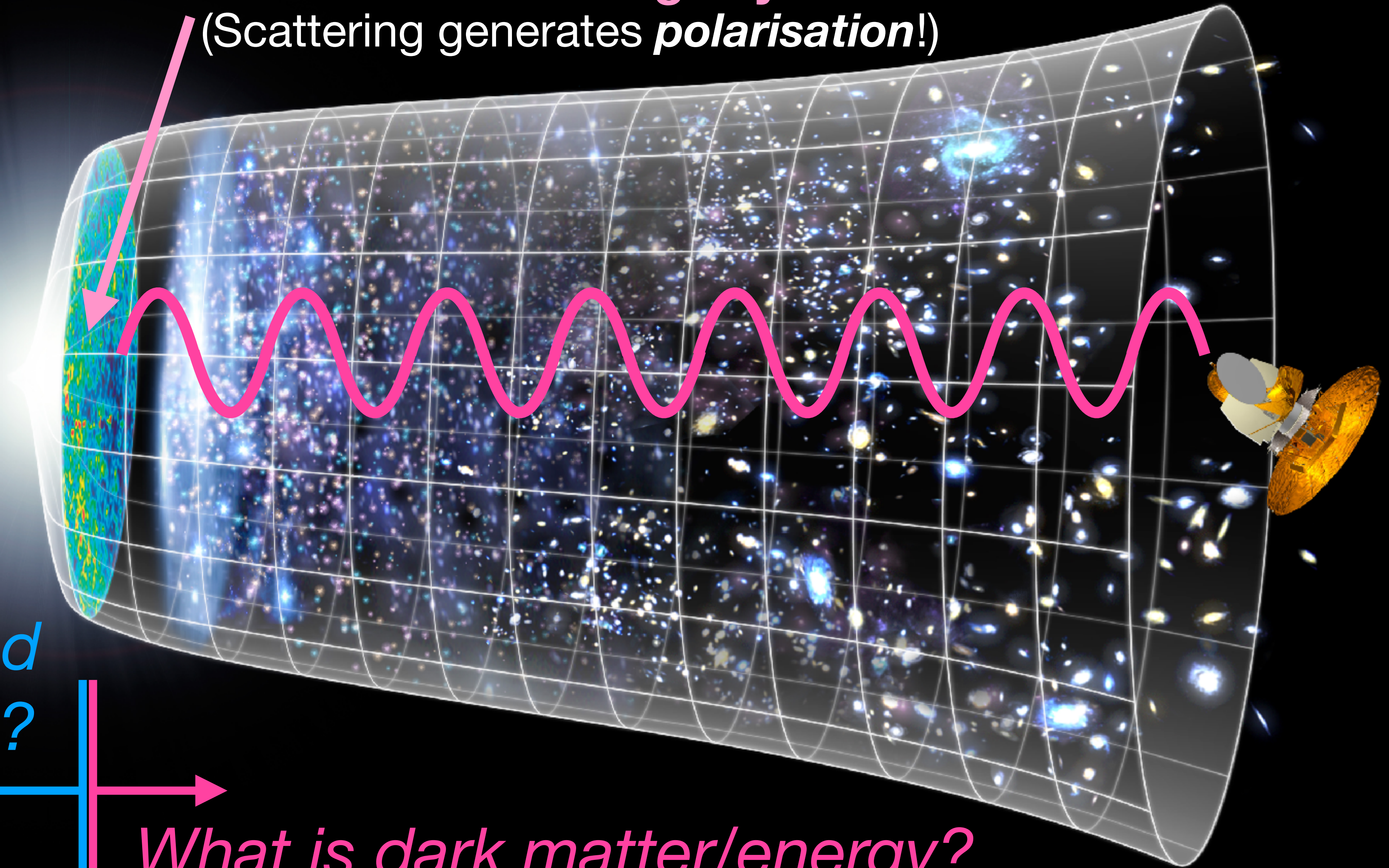
Standard Cosmological Model (Λ CDM) Requires New Physics

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 key to the answers.

The surface of “last scattering” by electrons

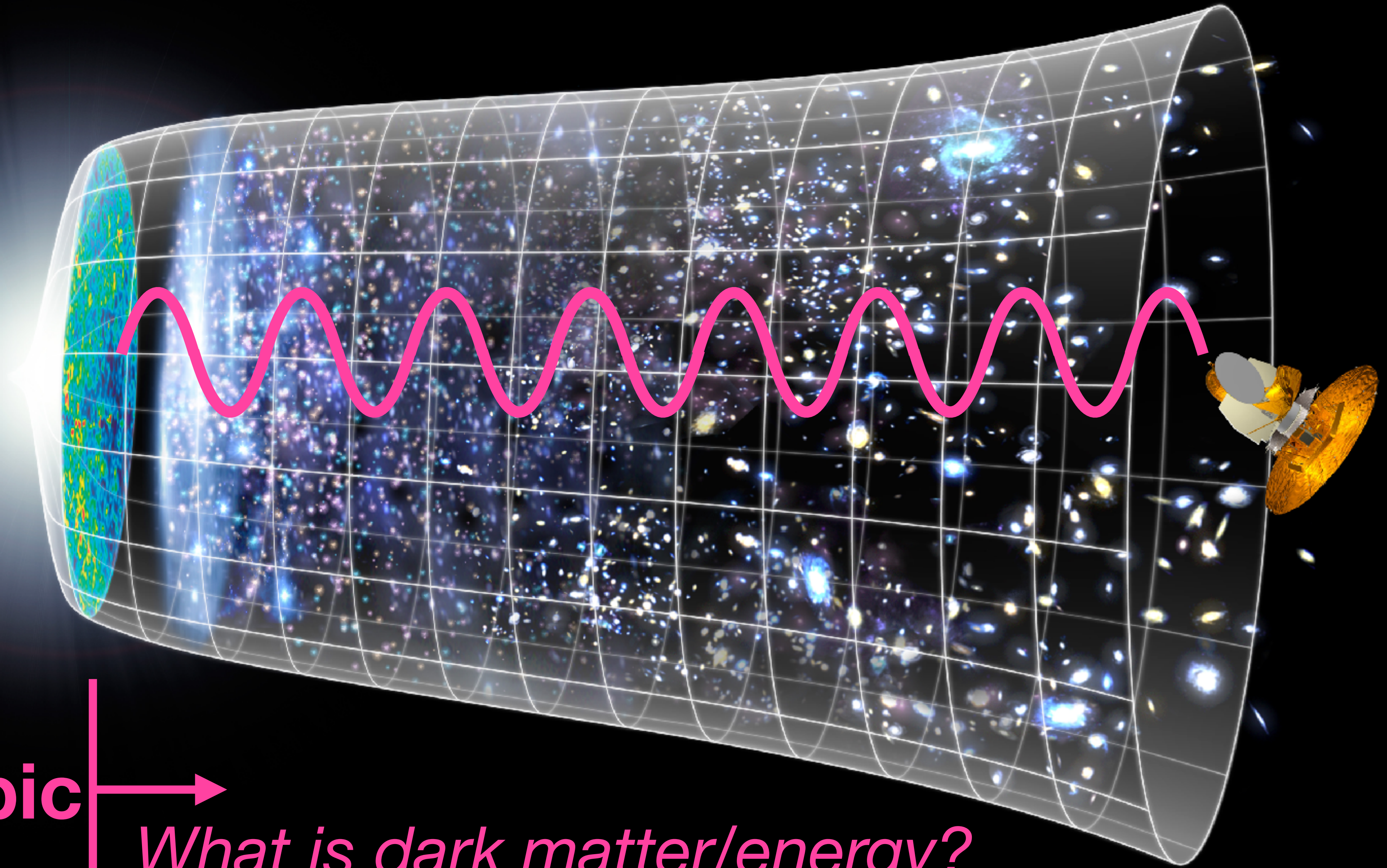
(Scattering generates *polarisation*!)



*What powered
the Big Bang?*

What is dark matter/energy?

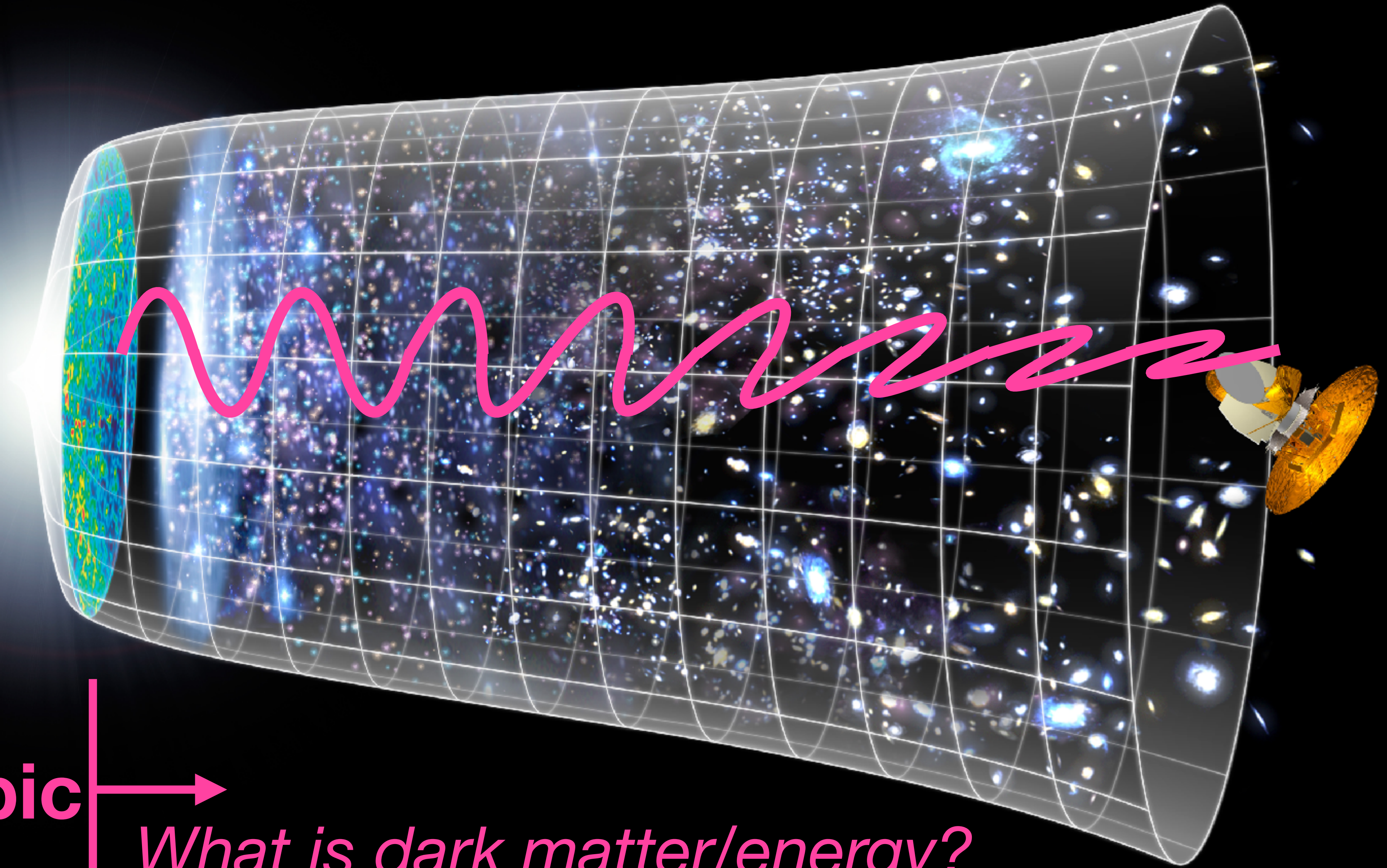
How does the electromagnetic wave of the CMB propagate?



Today's topic

What is dark matter/energy?

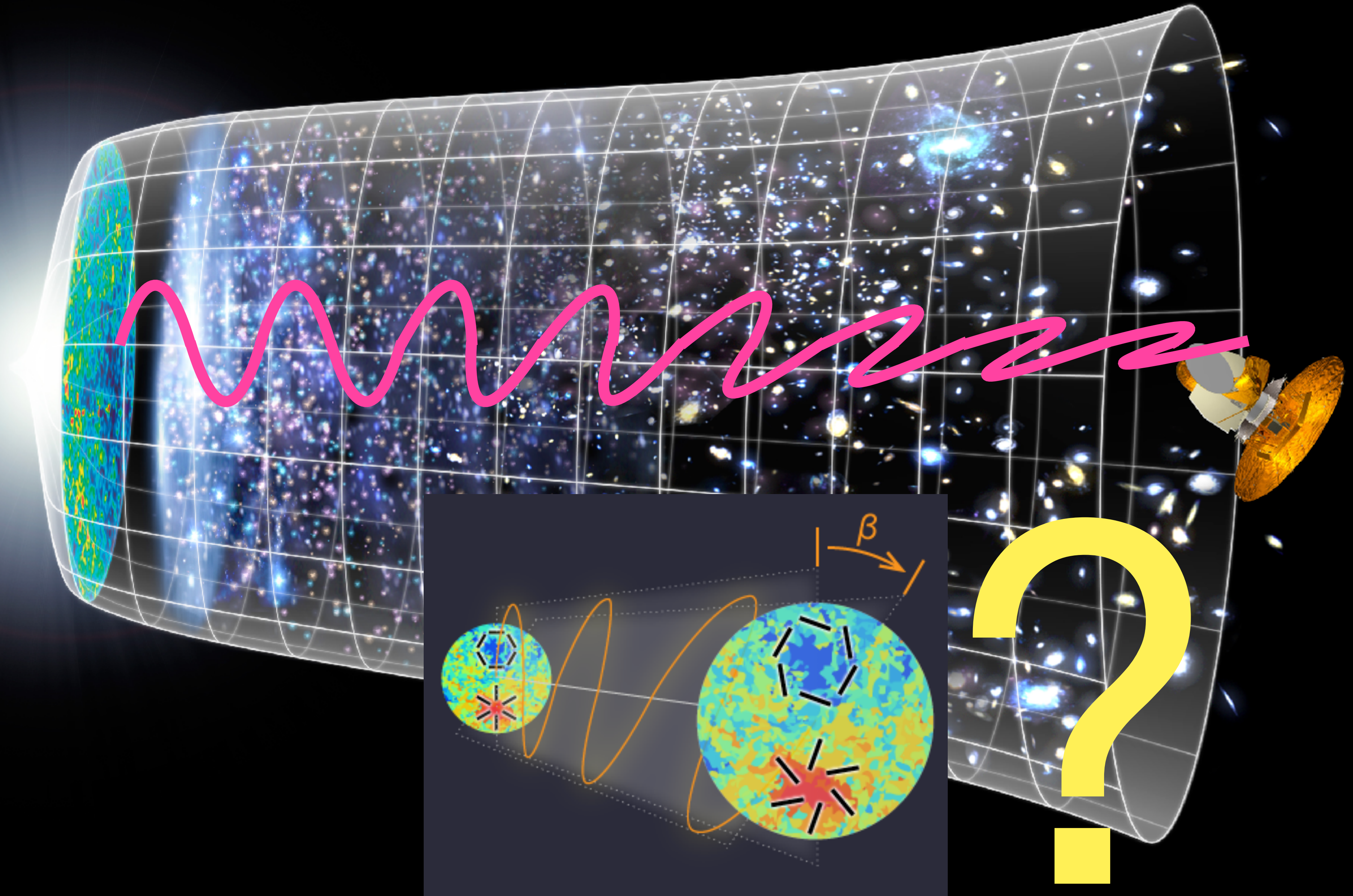
How does the electromagnetic wave of the CMB propagate?



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

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

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

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

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

Parity Even Parity Odd

Cosmic Birefringence

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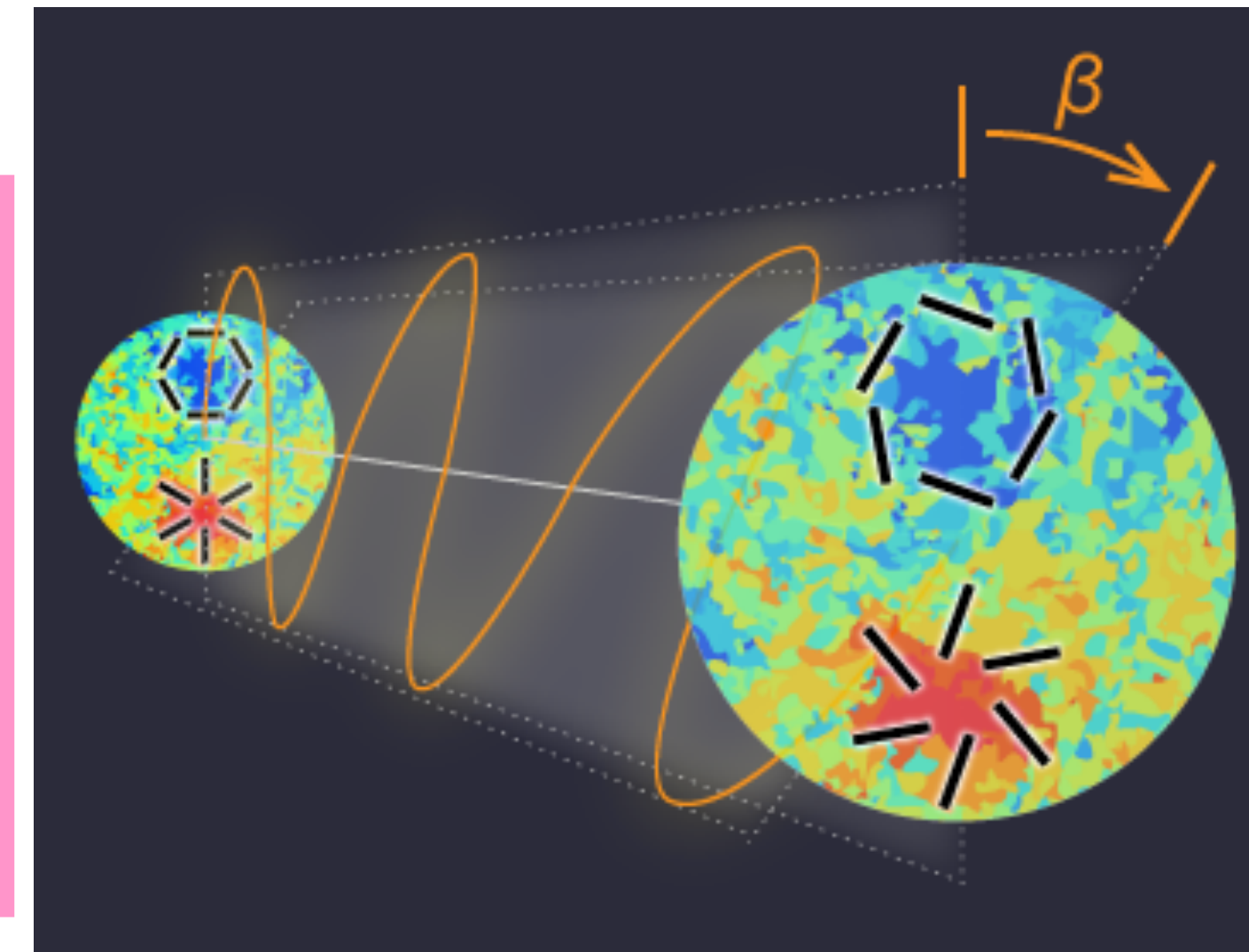
Chern-Simons term

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

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

“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.**



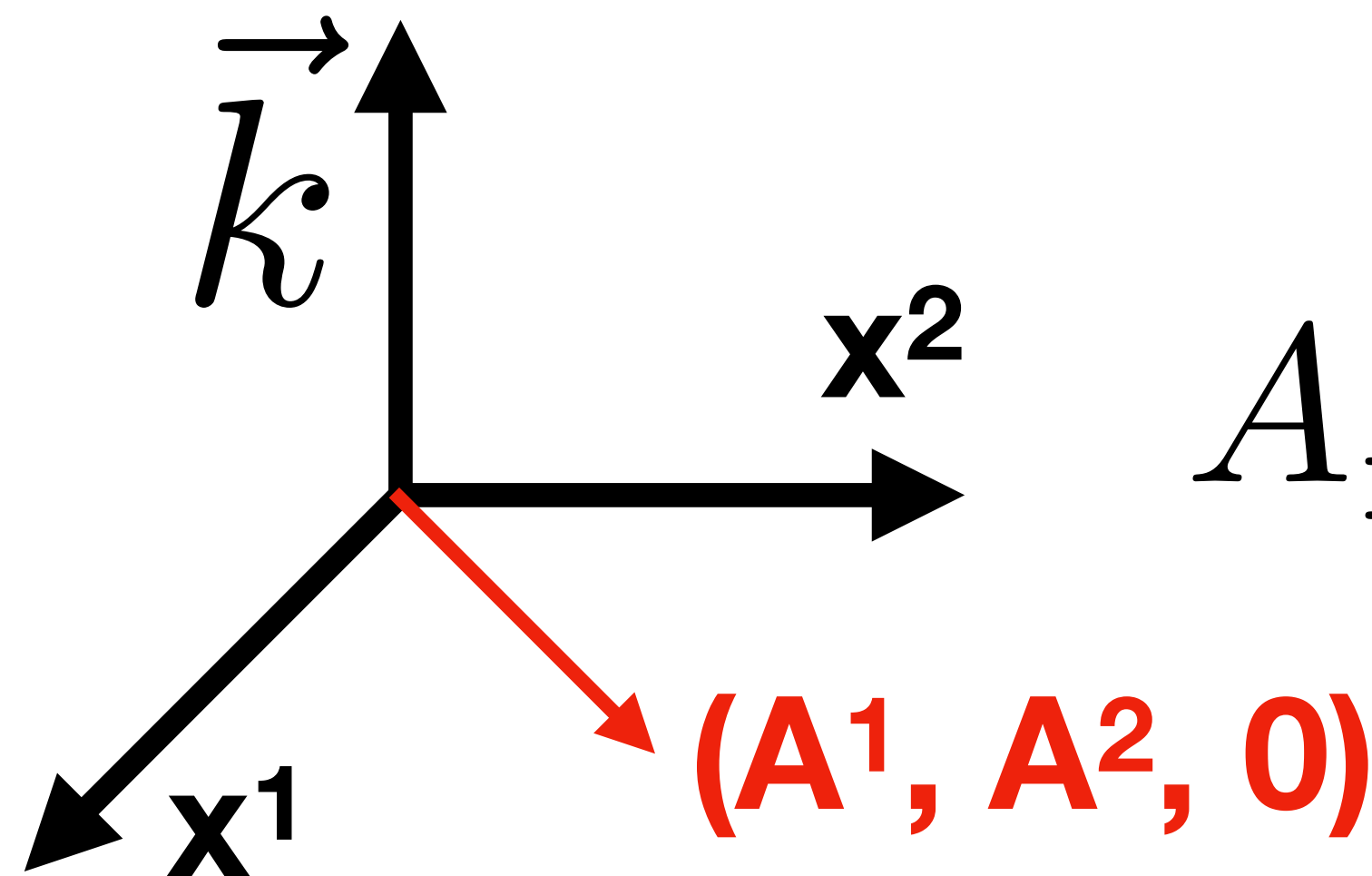
Standard Maxwell Theory

Warm up (1)

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

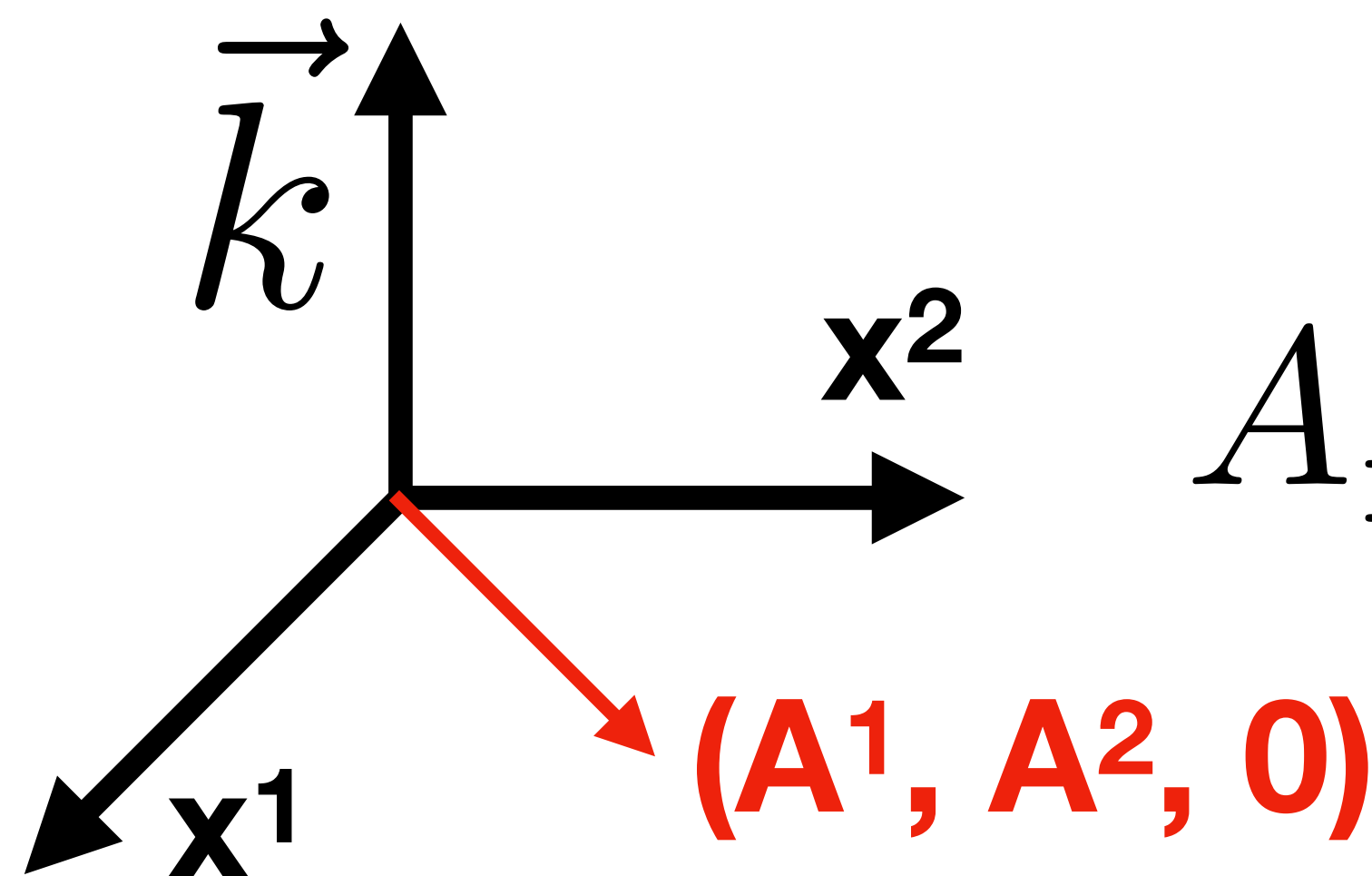
Warm up (2)

- 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

- Go to Fourier space, choose the propagation direction of $\mathbf{A}_i$ to be in z-axis, and define right- and left-handed polarisation states as



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Cosmic Birefringence

Derivation (1)

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

the effective Lagrangian for axion electrodynamics is

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

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- The equation of motion is modified to

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

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

Cosmic Birefringence

Derivation (1)

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

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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!**

the effective Lagrangian for axion electrodynamics is

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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!

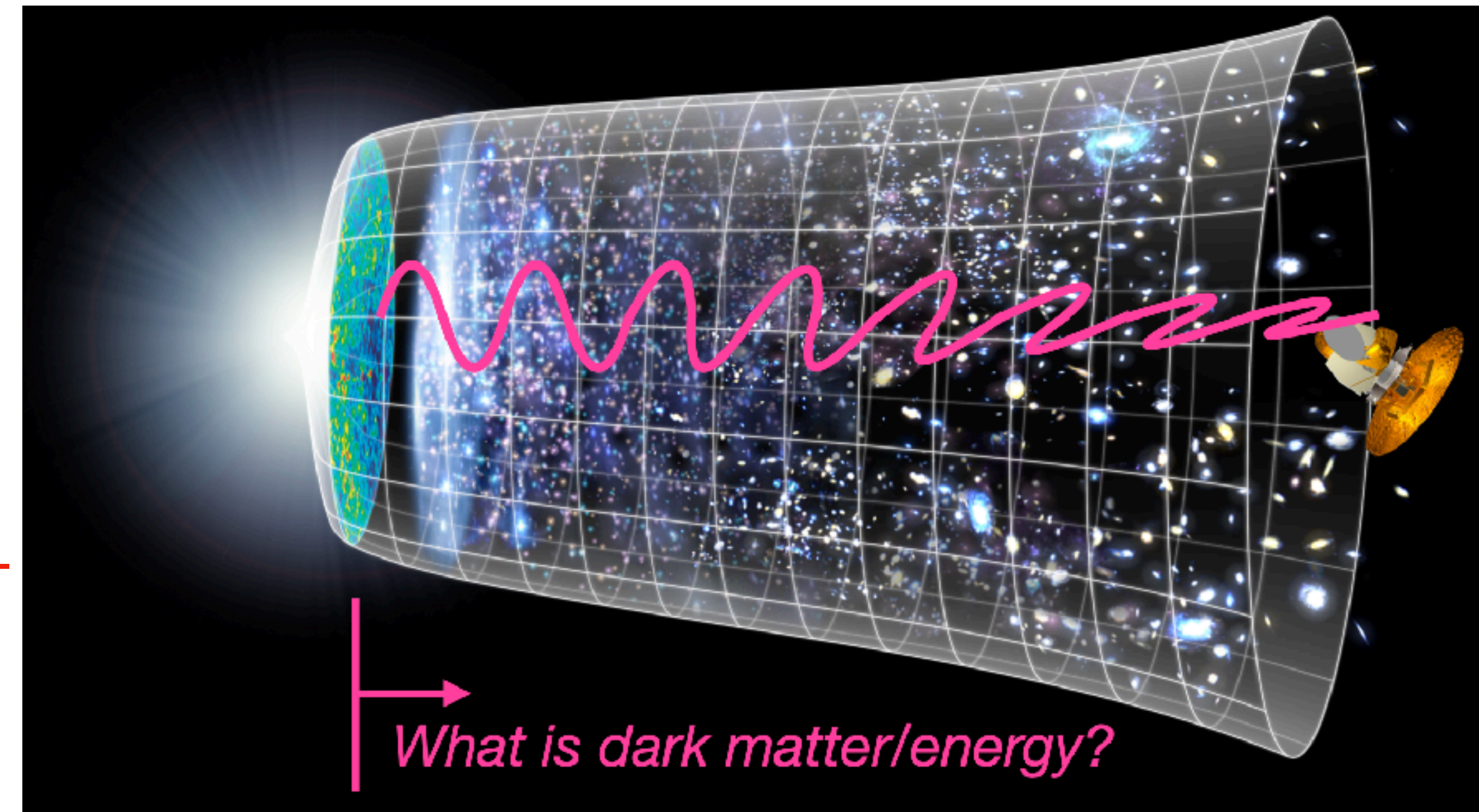
Cosmic Birefringence

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 by an angle ψ :

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

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

Cosmic Birefringence

Derivation (3)

- 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 ψ :

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

↙
This is the convention
for polarisation direction
adopted by IAU

Cosmic Birefringence

Derivation (3)

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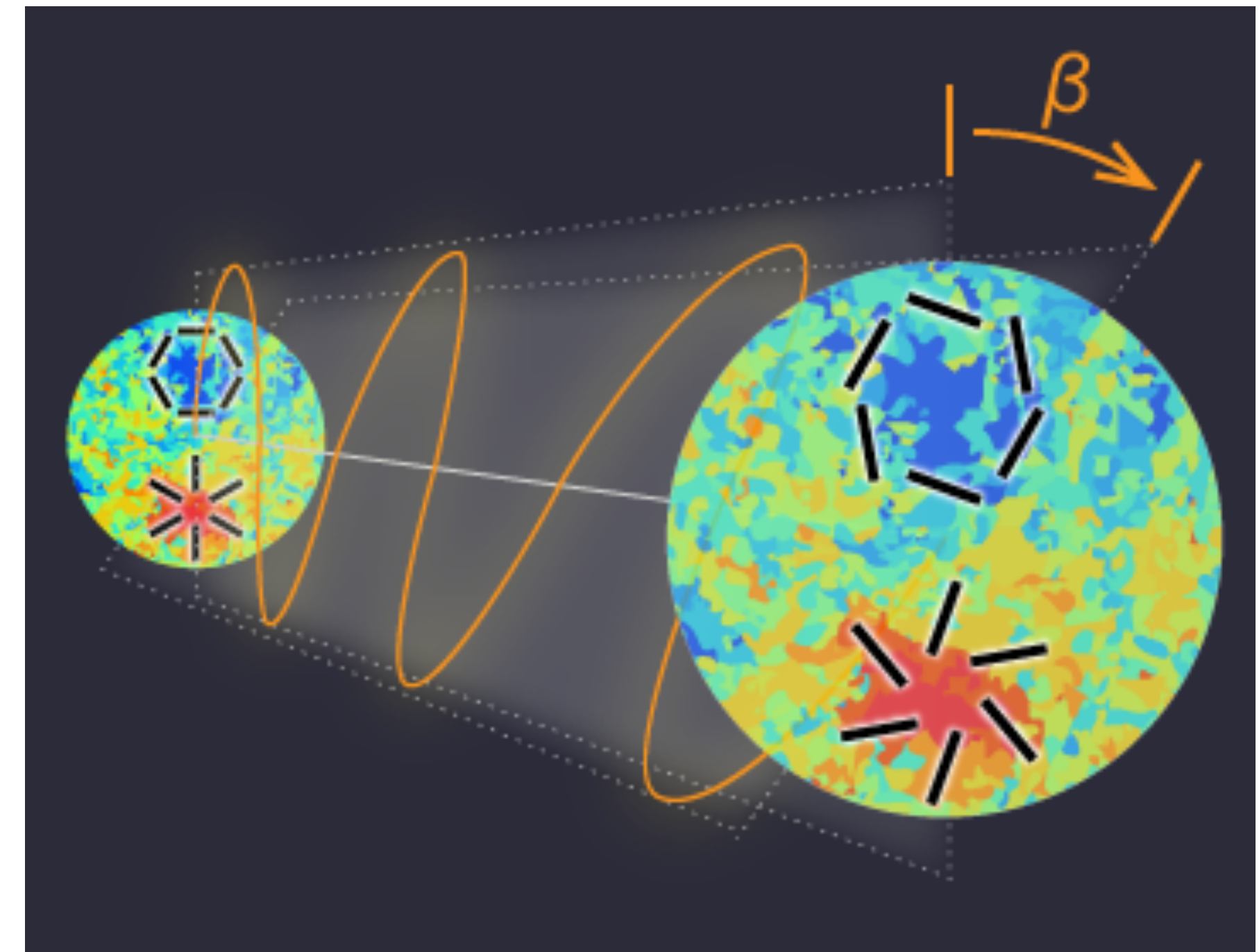
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This is the convention for polarisation direction adopted by IAU

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:

This “axion” field can be dark matter or dark energy!

Ni (1977); Turner & Widrow (1988)

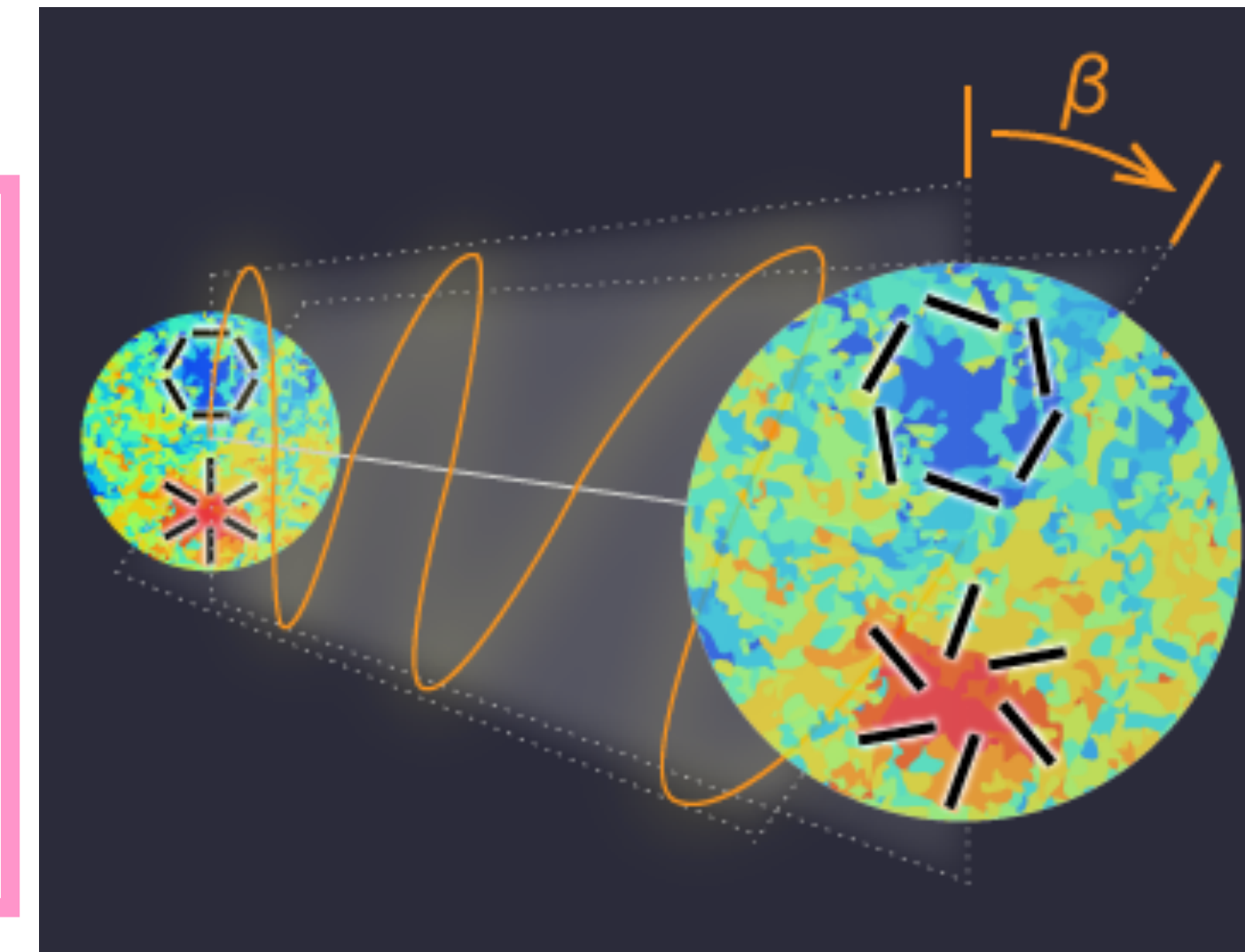
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where g_a is a coupling constant of the order α , and the vacuum angle $\theta = \phi_a / f_a$ (ϕ_a = axion field). The equations



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

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

Motivation

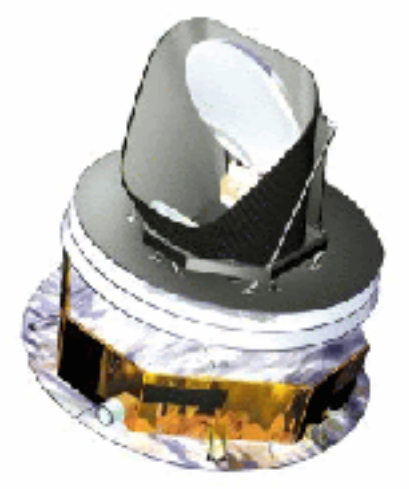
Why study the cosmic birefringence?

- 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

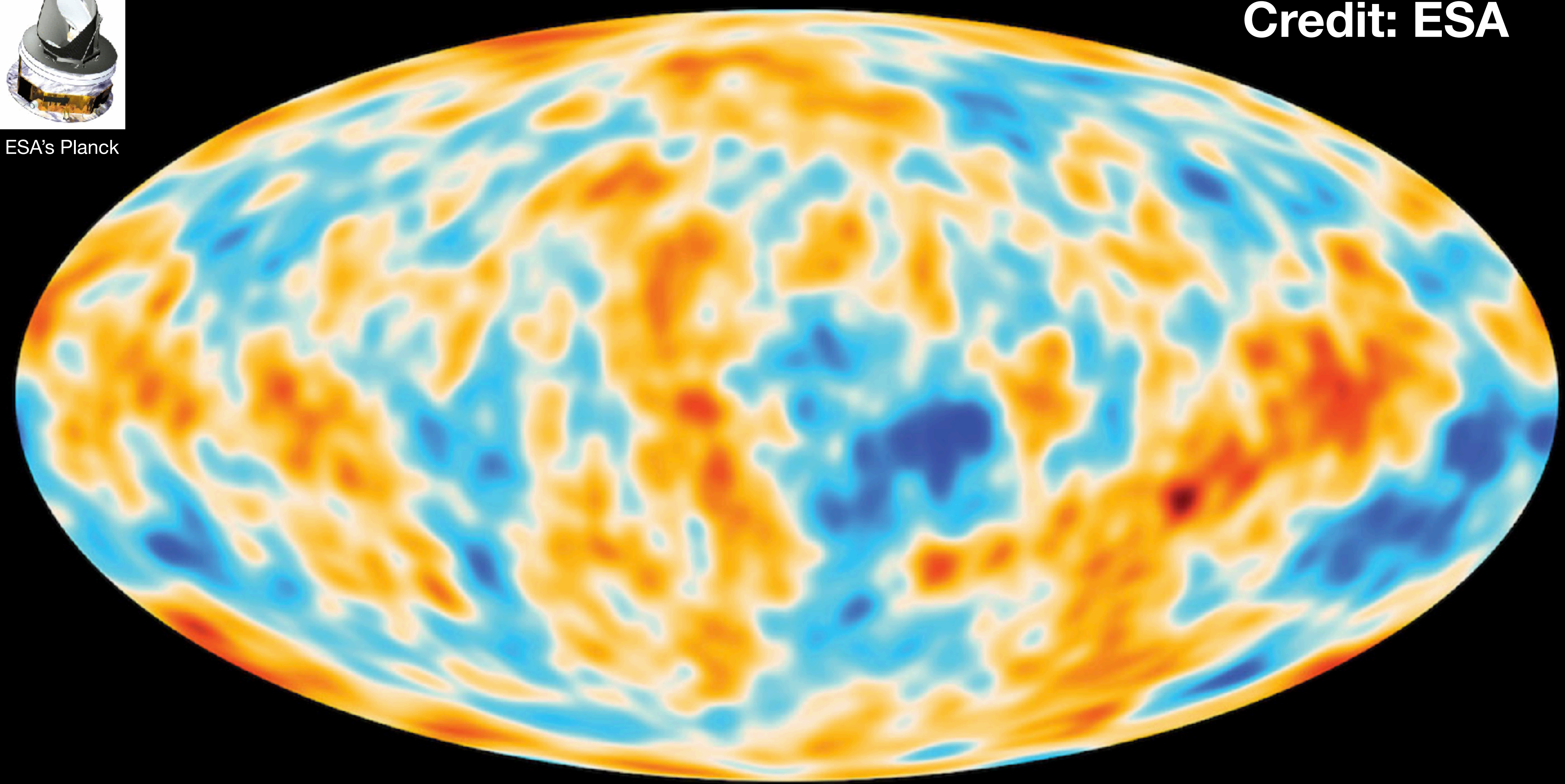
Why study the cosmic birefringence?

- 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!



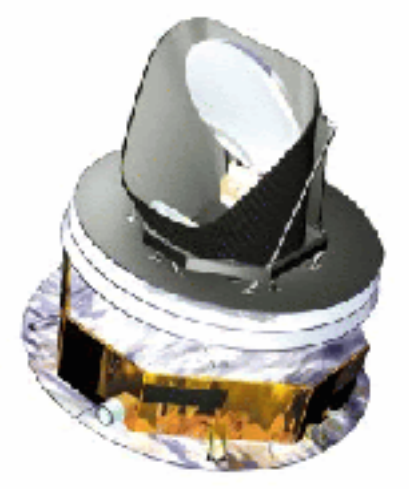
ESA's Planck

Credit: ESA



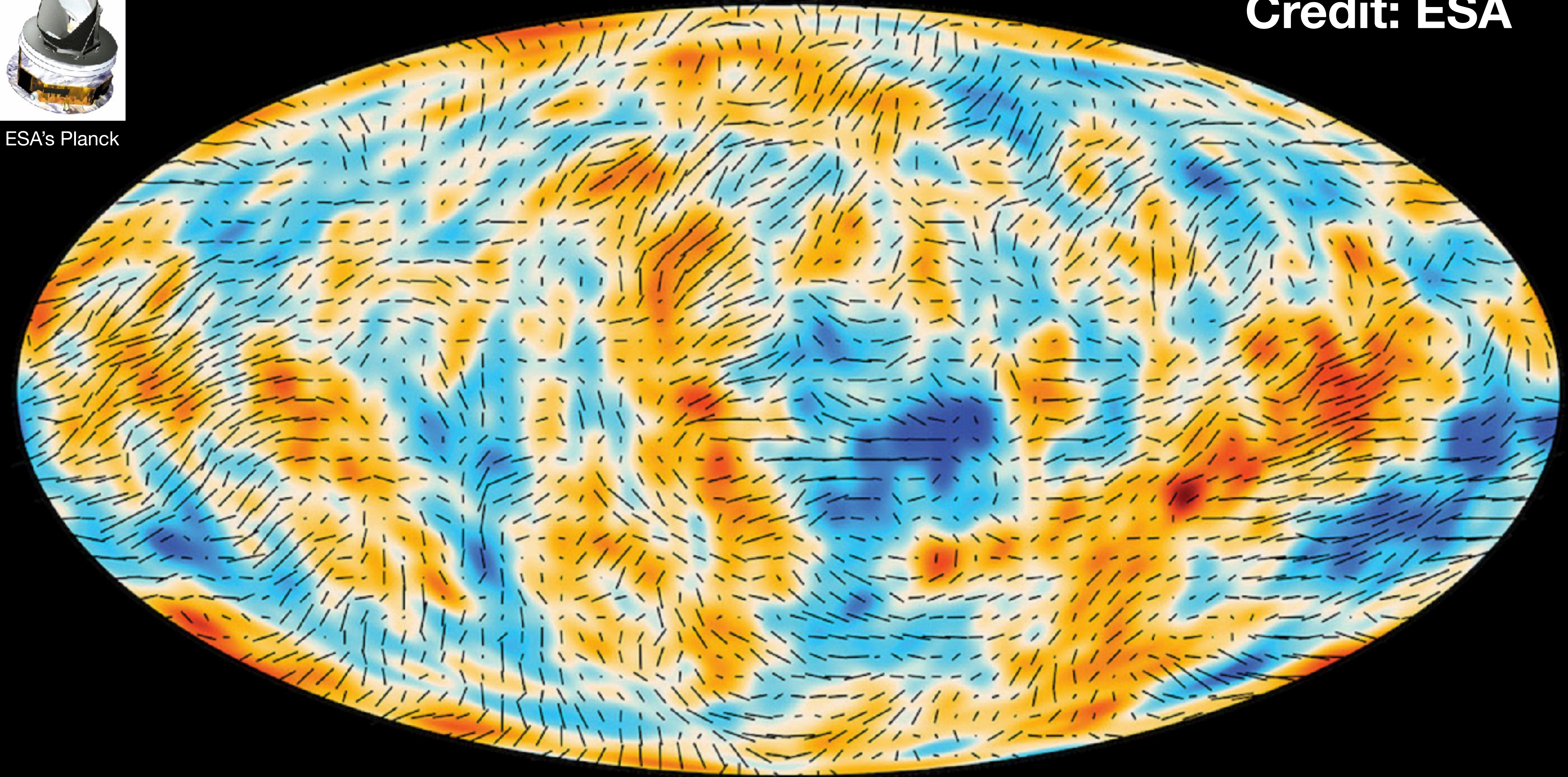
Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



ESA's Planck

Credit: ESA

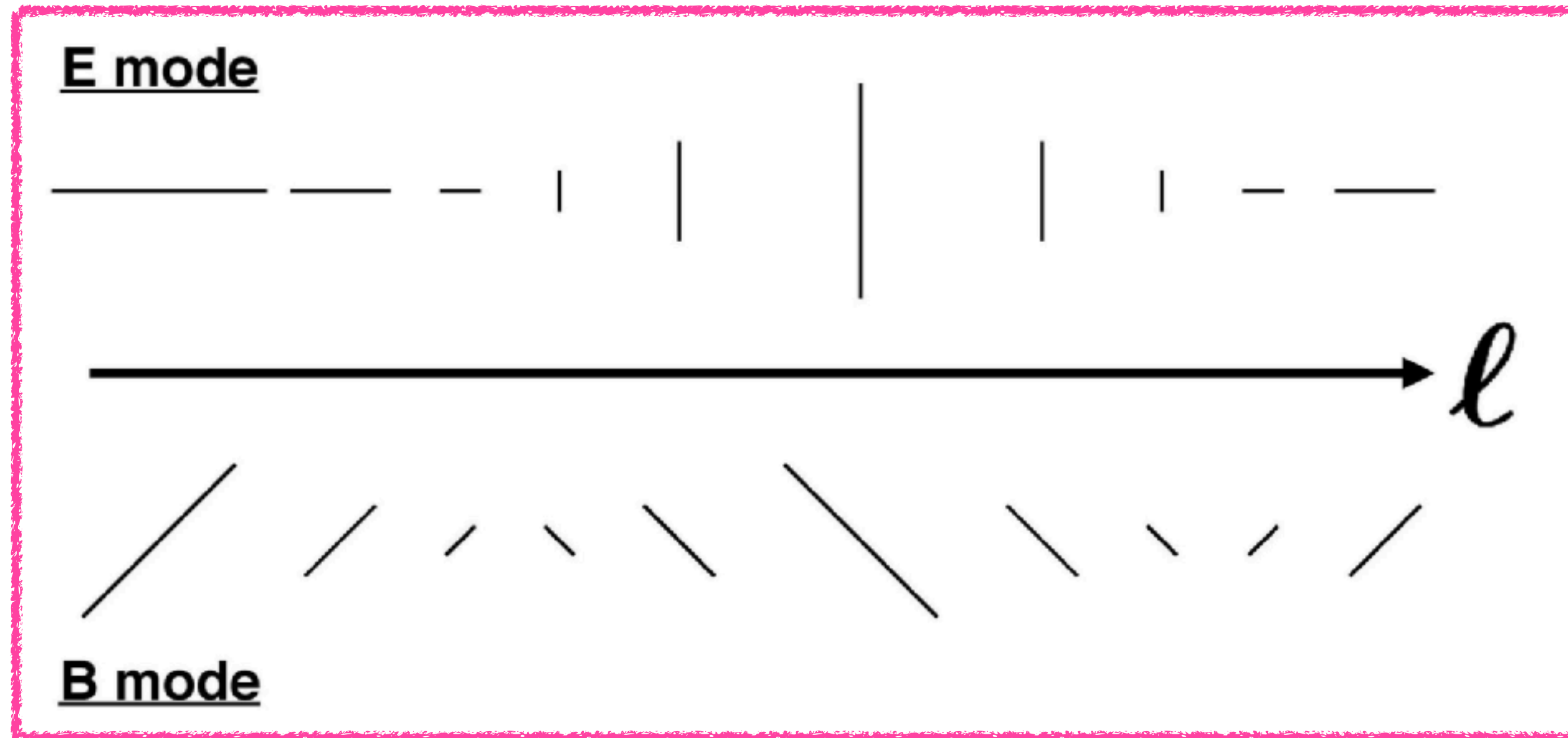


Foreground-cleaned Temperature (smoothed) + Polarisation

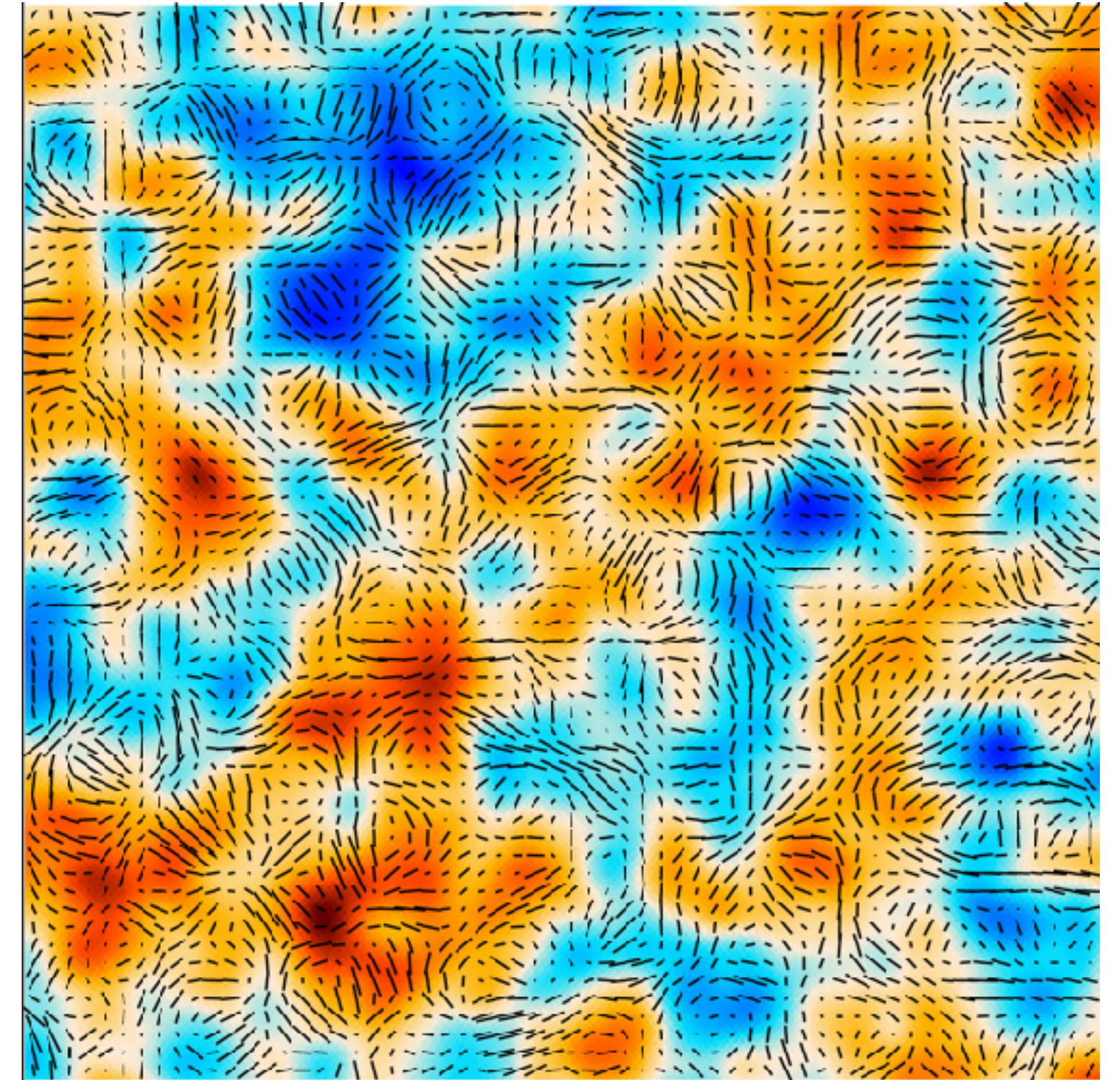
Emitted 13.8 billions years ago

E- and B-mode decomposition of linear polarisation

Concept defined in Fourier space



This map is dominated
by E-mode polarisation



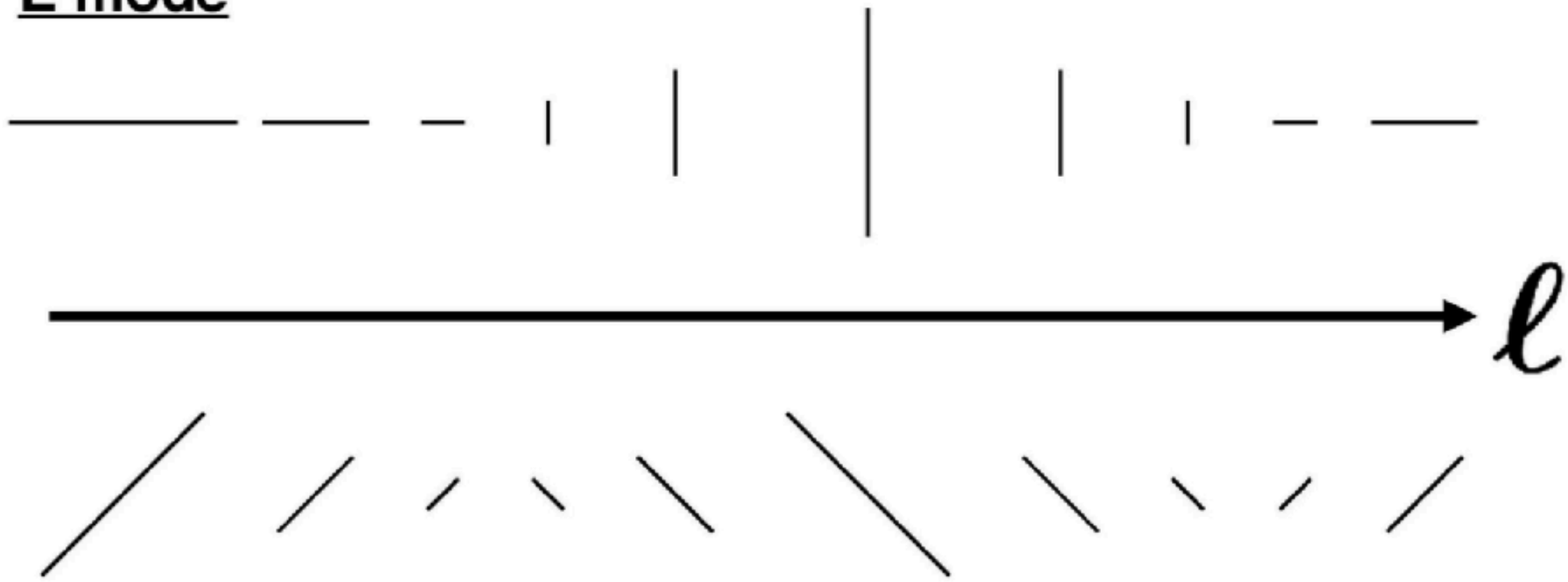
- **E-mode** : Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode** : Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

IMPORTANT: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

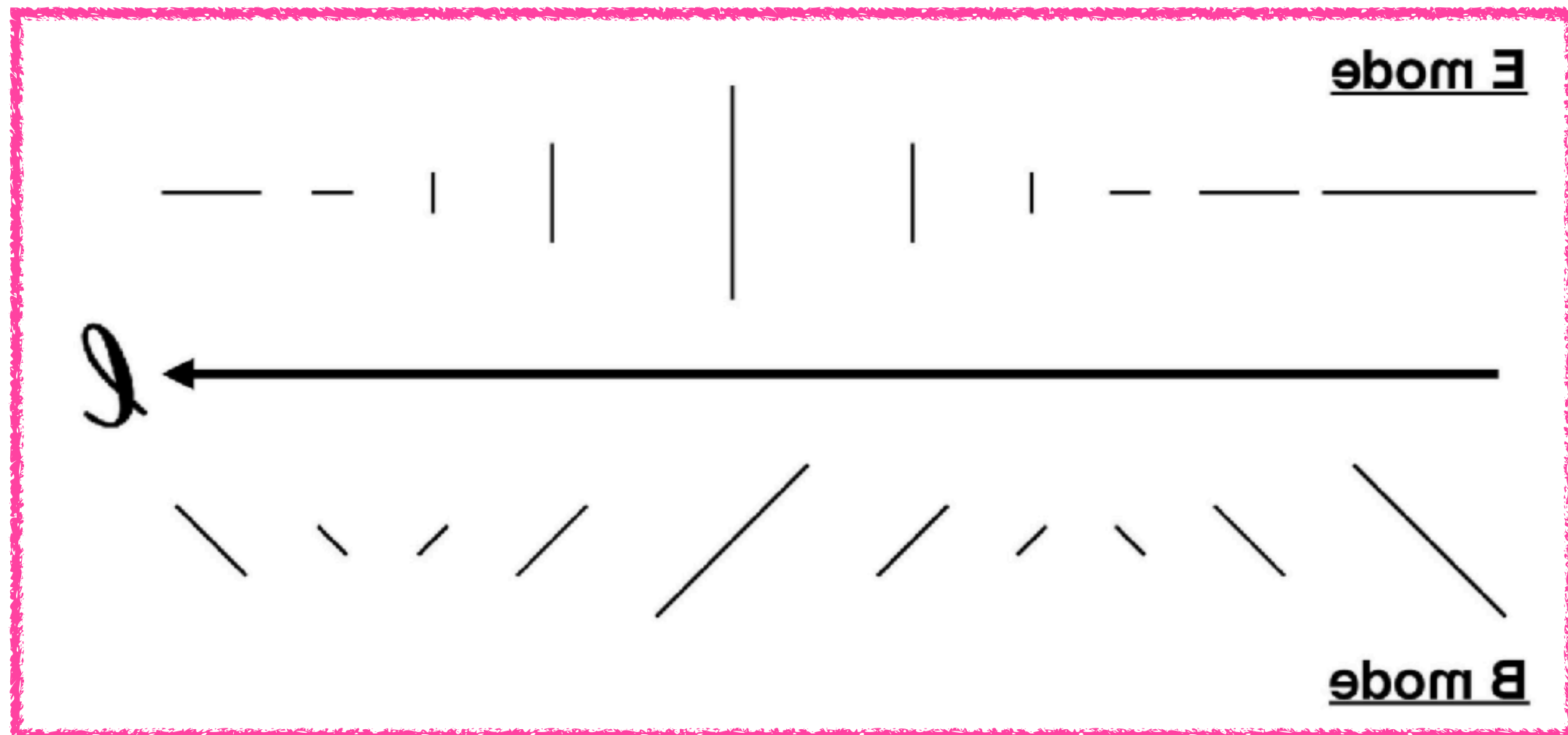
Parity Flip

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

E mode



B mode



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

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

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

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

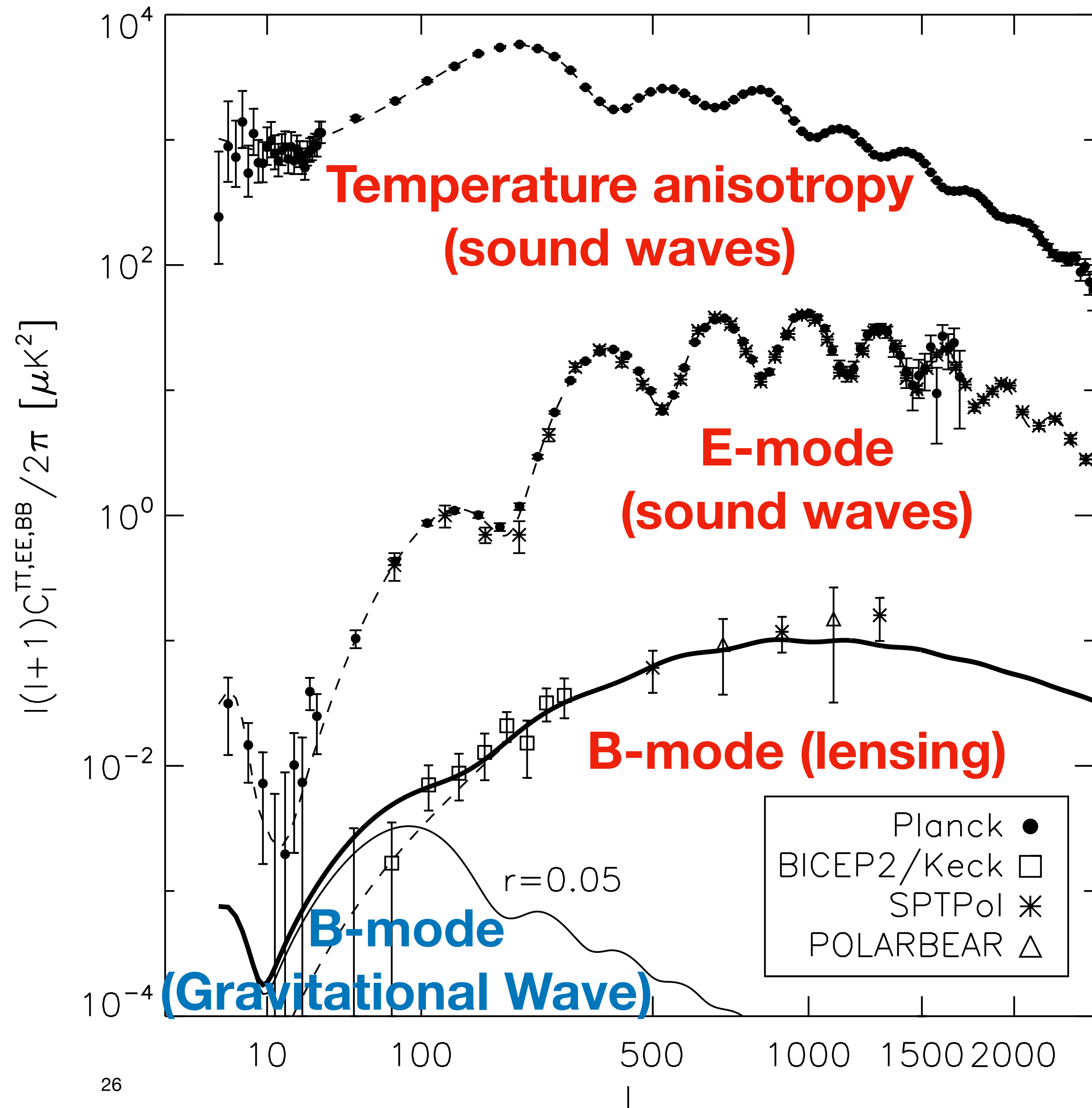
- The other combinations $\langle TB \rangle$ and $\langle EB \rangle$ are not invariant under the parity flip.

- 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

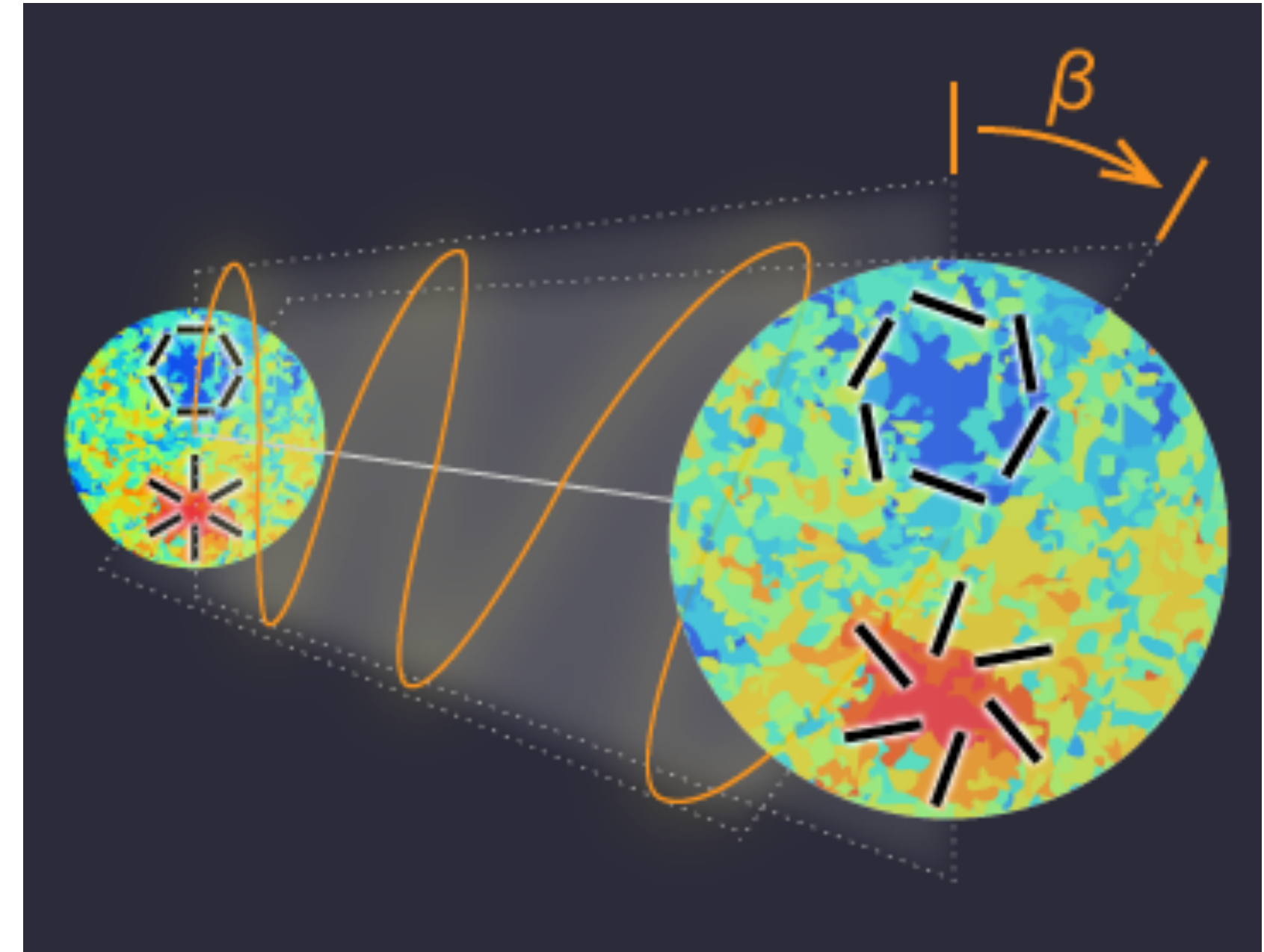
- Observed E- and B-mode polarisation, E_ℓ° and B_ℓ° , are related to those before rotation as

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

- 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

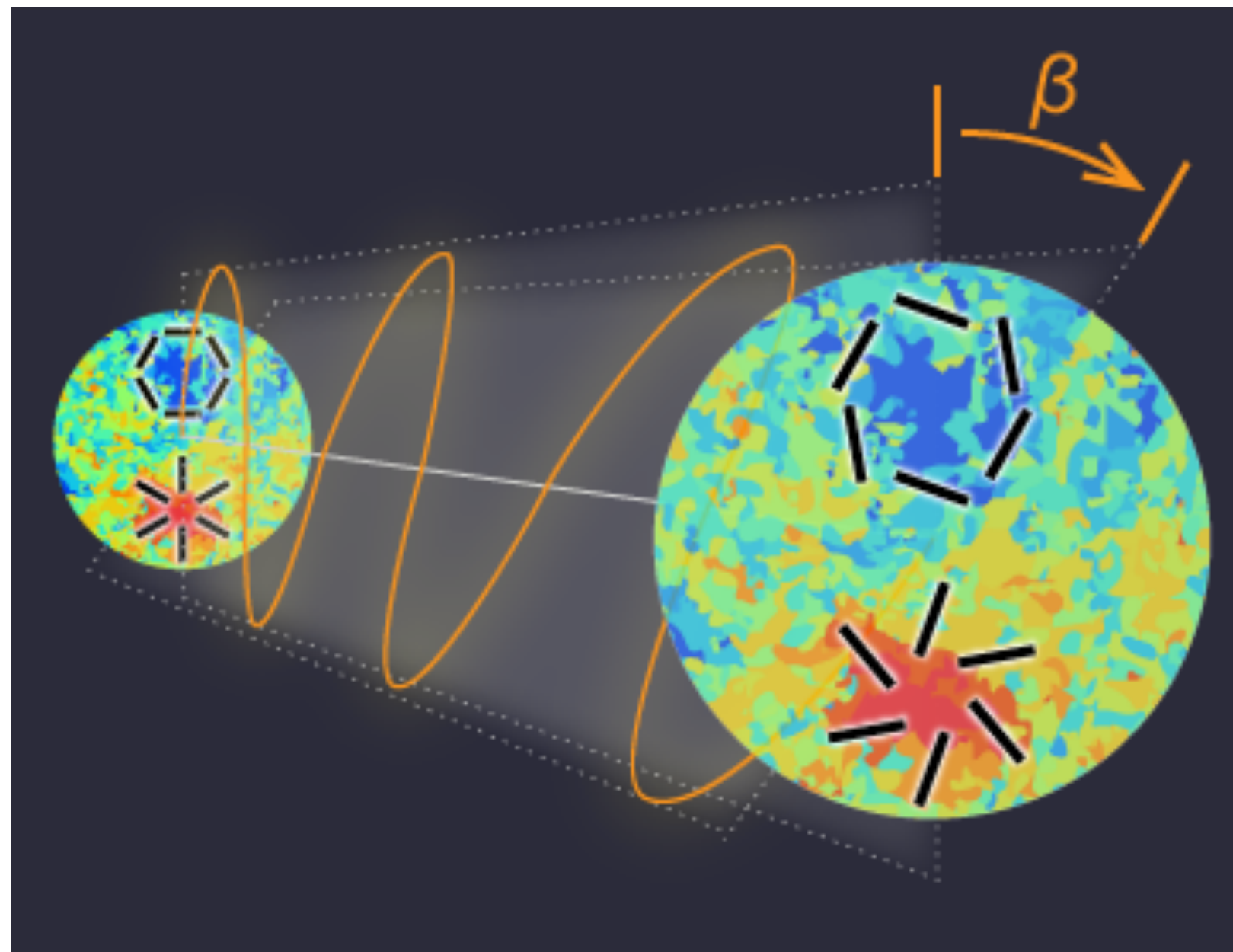
$$\begin{aligned} C_{\ell}^{EB,\text{obs}} &= \frac{1}{2} (C_{\ell}^{EE} - C_{\ell}^{BB}) \sin(4\beta) + C_{\ell}^{EB} \cos(4\beta) \\ &= \frac{1}{2} (\underline{C_{\ell}^{EE,\text{obs}} - C_{\ell}^{BB,\text{obs}}}) \tan(4\beta) + \frac{C_{\ell}^{EB}}{\cos(4\beta)} \end{aligned}$$

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

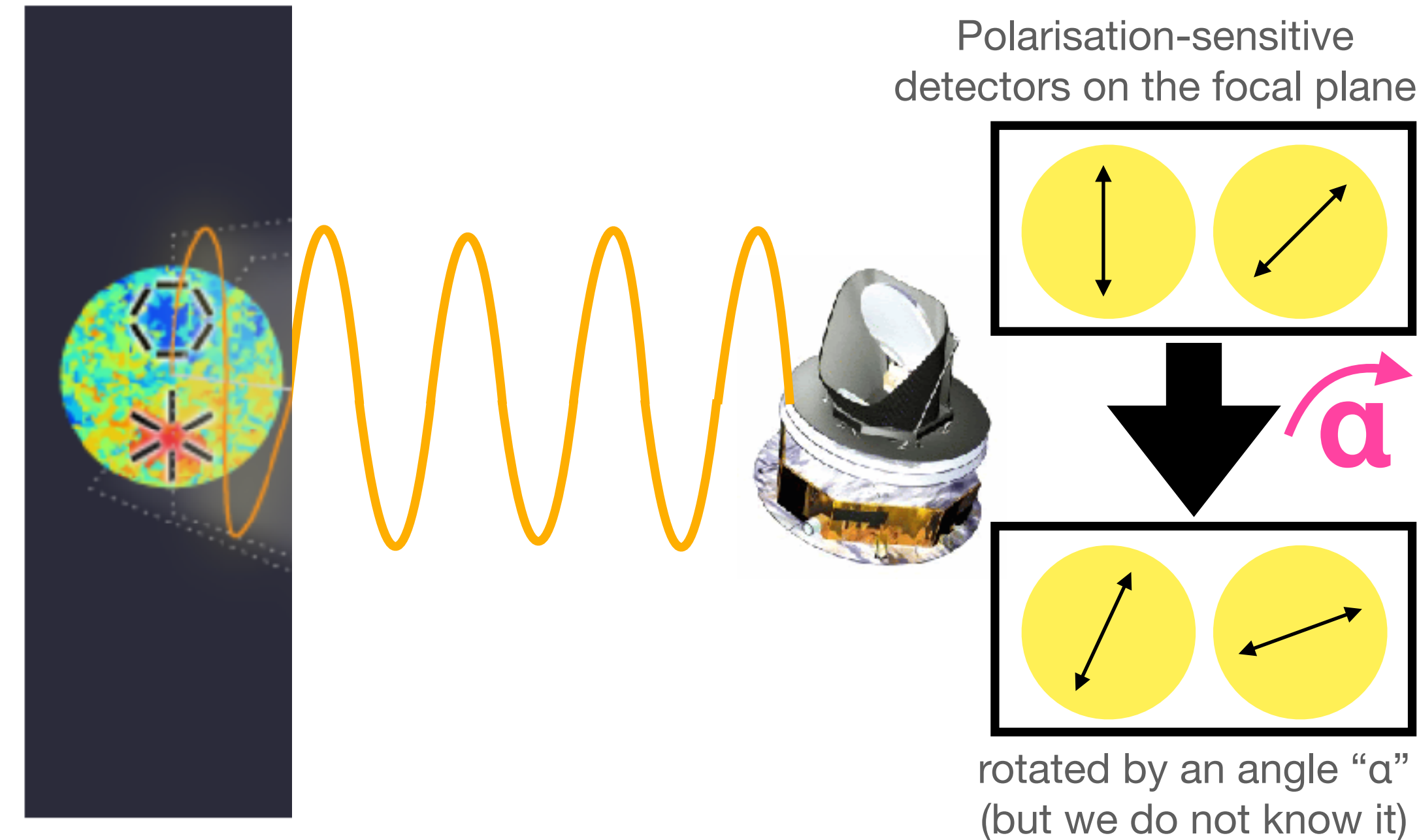
The Biggest Problem: Miscalibration of detectors

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 α , 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?**

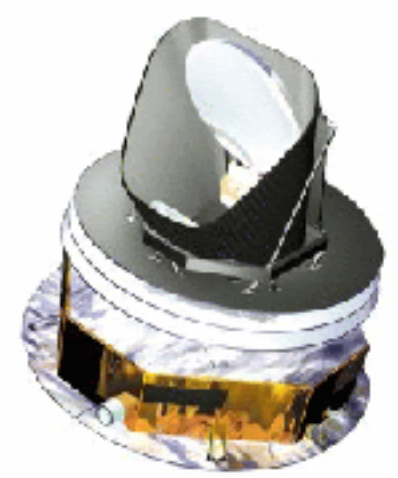
The past measurements

Now including the estimated systematic errors on α

- $\beta = -6.0 \pm 4.0 \pm ??$ 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 α 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!

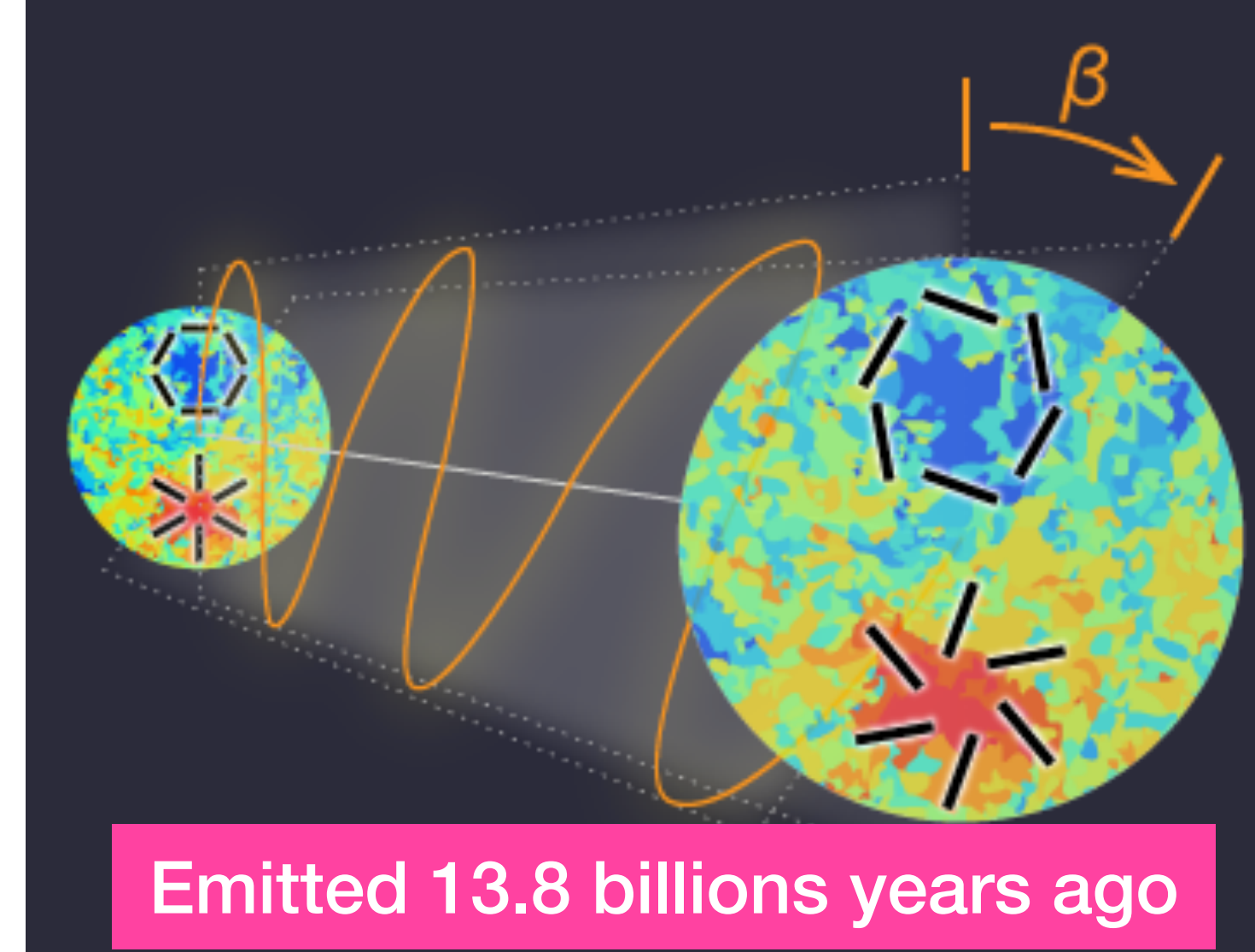
Emitted “right there” - it would
not be affected by the cosmic
birefringence.

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 α rotates both the foreground and CMB, but β affects only the CMB.



But the source of foreground is much closer!

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

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

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

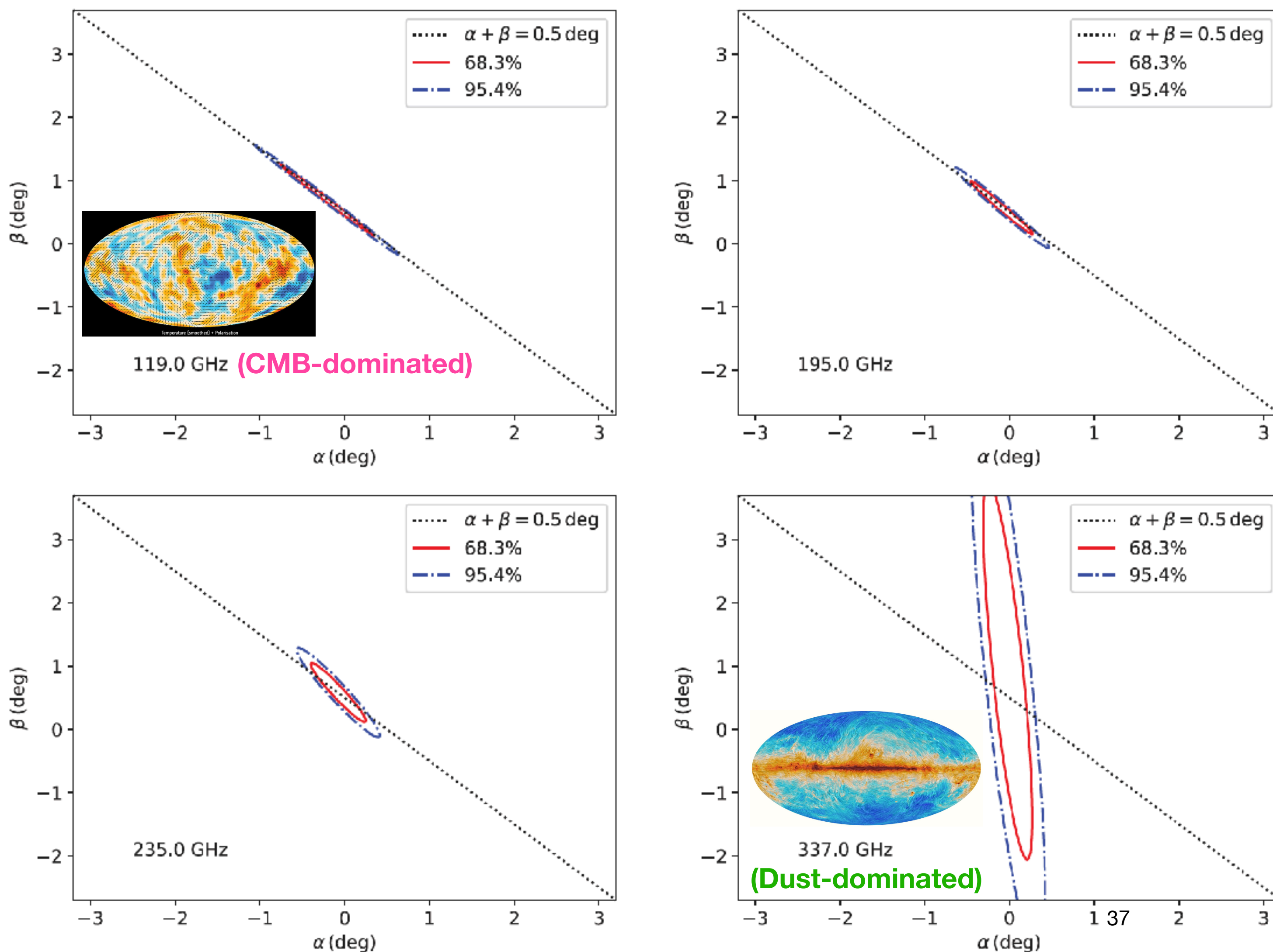
What about the intrinsic EB correlation of the foreground emission?

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

- 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 α 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 α but not β due to the lack of sensitivity to the CMB.

[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?](#)

[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 .



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)

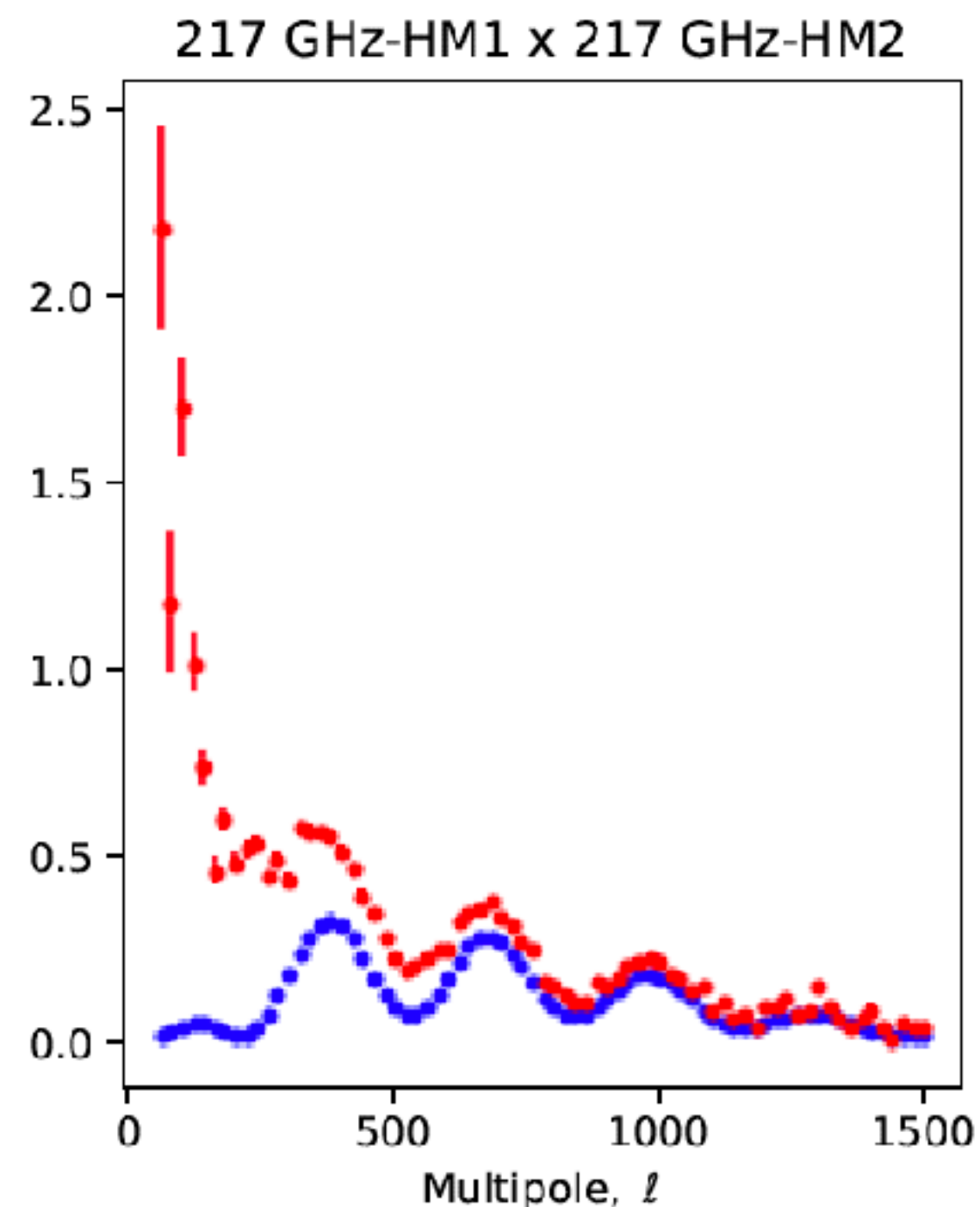
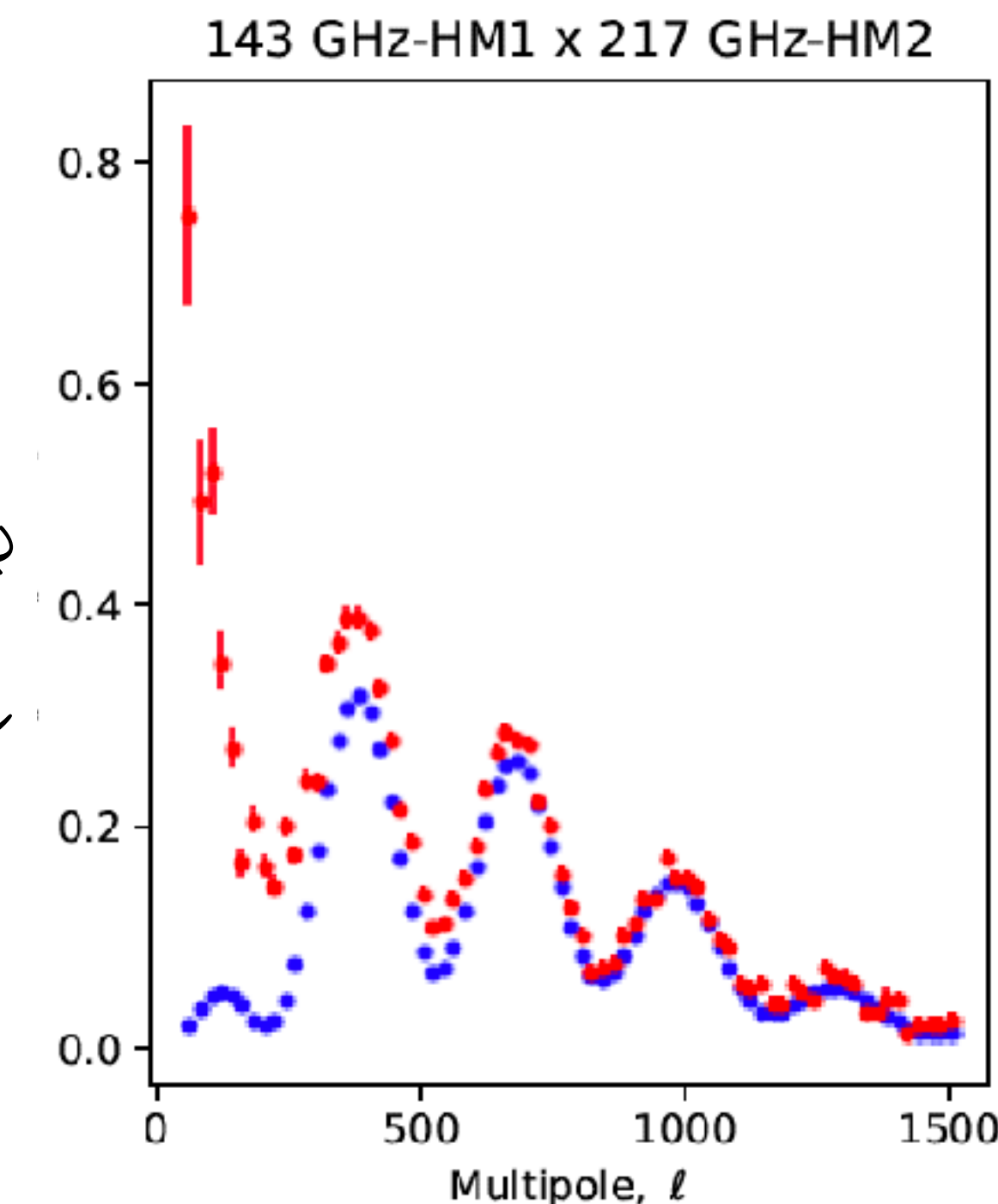
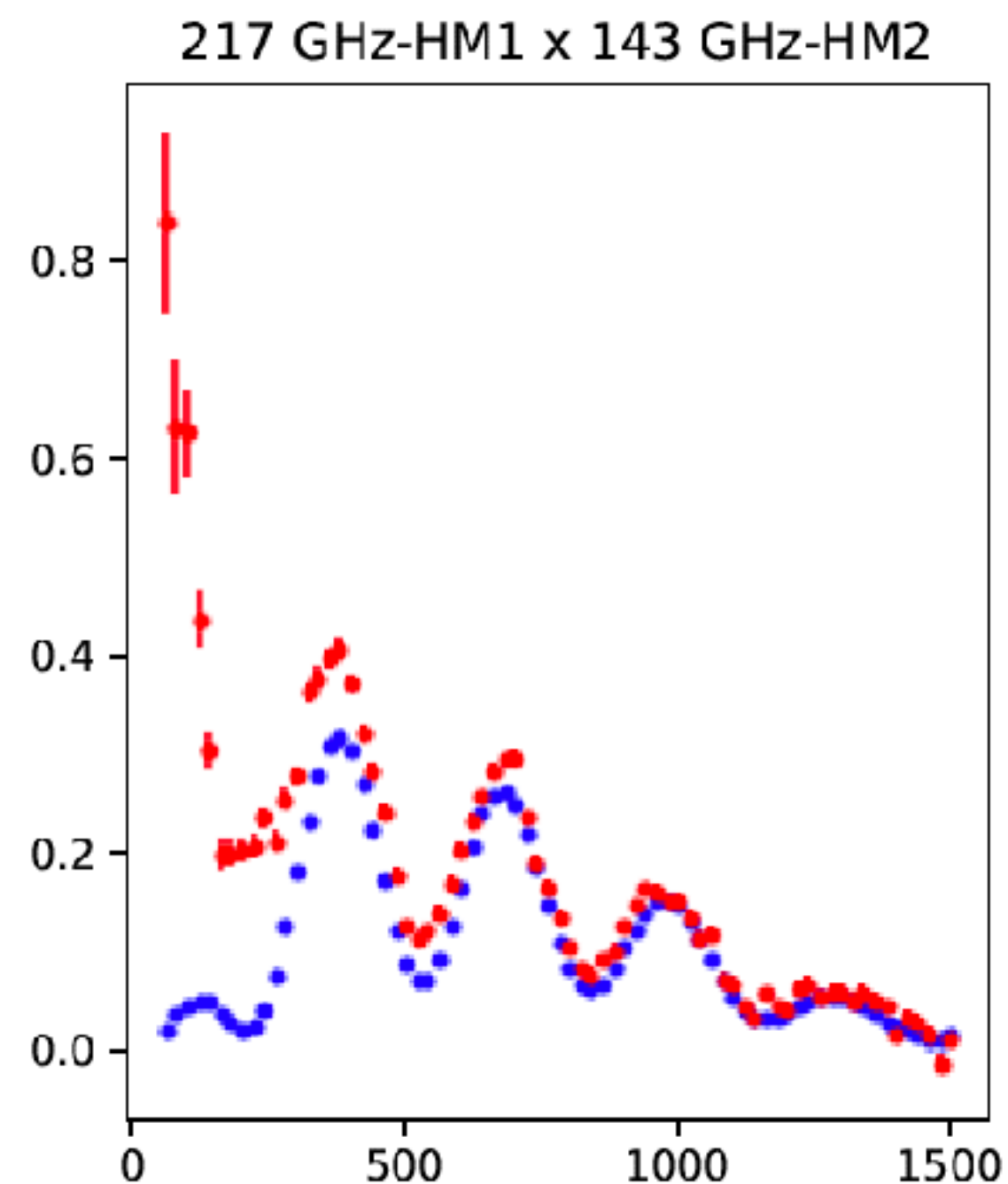
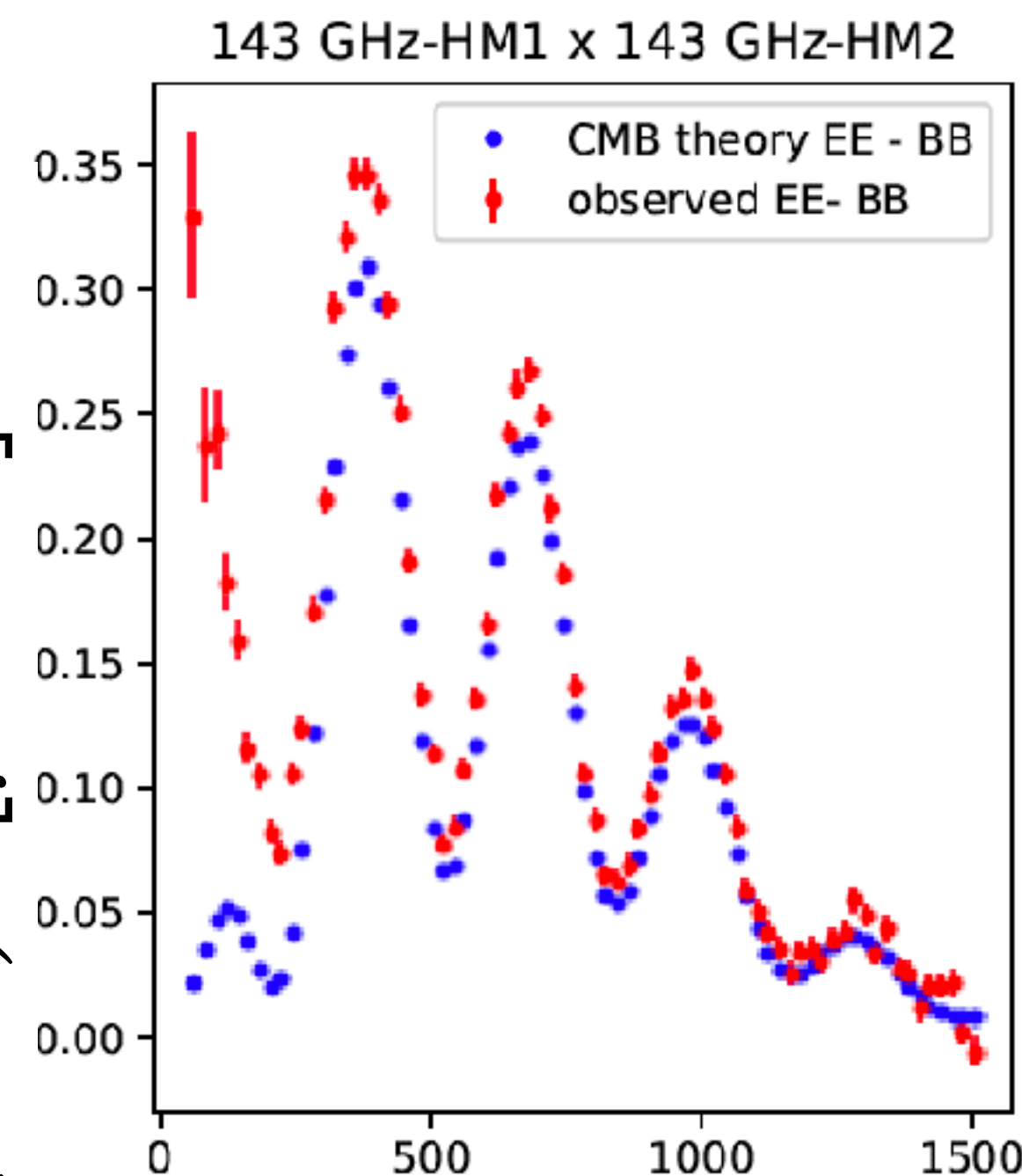
- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz)

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

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

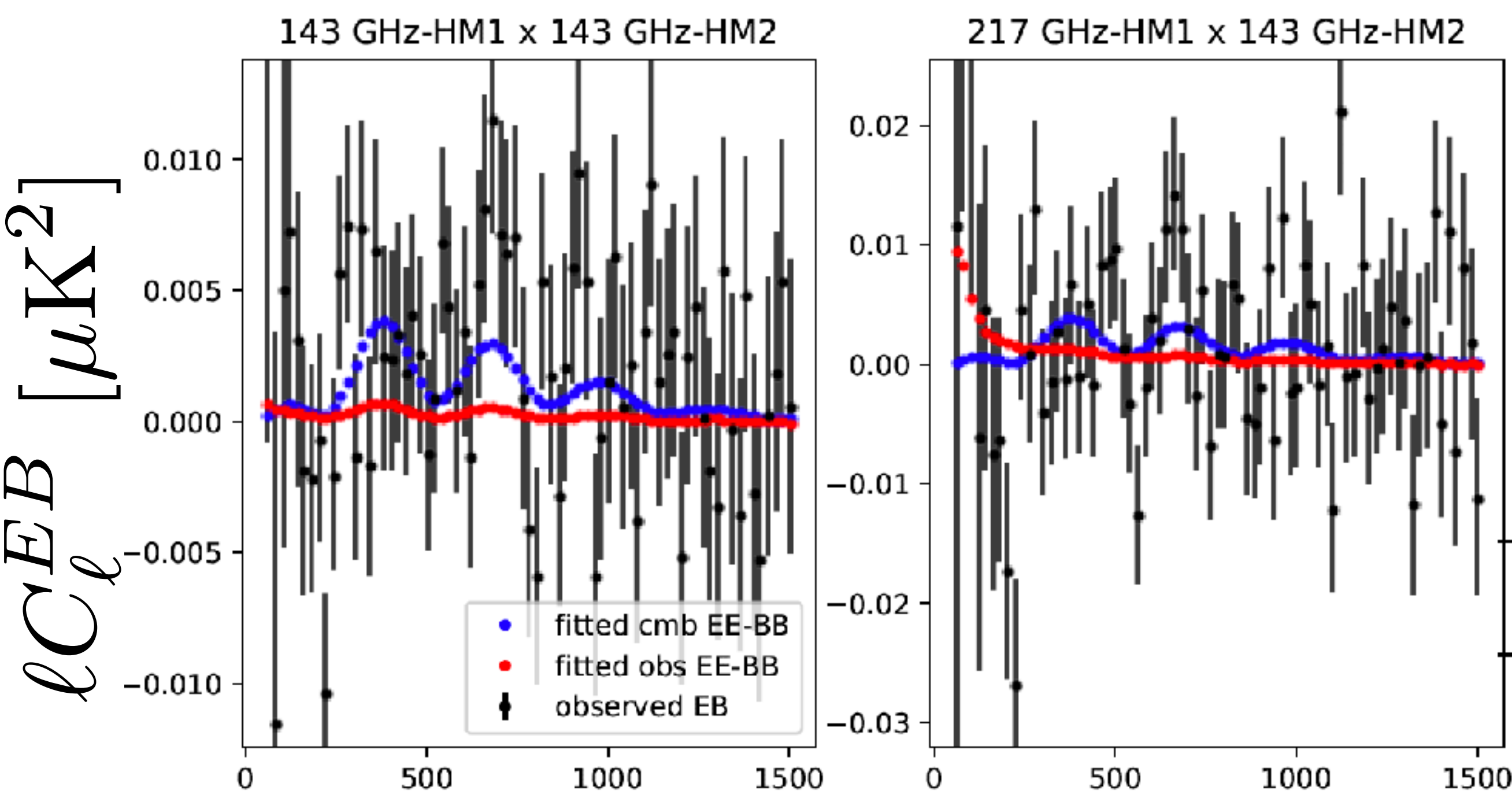
Angles	$\alpha_v=0$	Results (deg)
β	0.289 ± 0.048	0.35 ± 0.14
α_{100}	(This agrees with the result of the Planck team)	-0.28 ± 0.13
α_{143}		0.07 ± 0.12
α_{217}		-0.07 ± 0.11
α_{353}		-0.09 ± 0.11

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



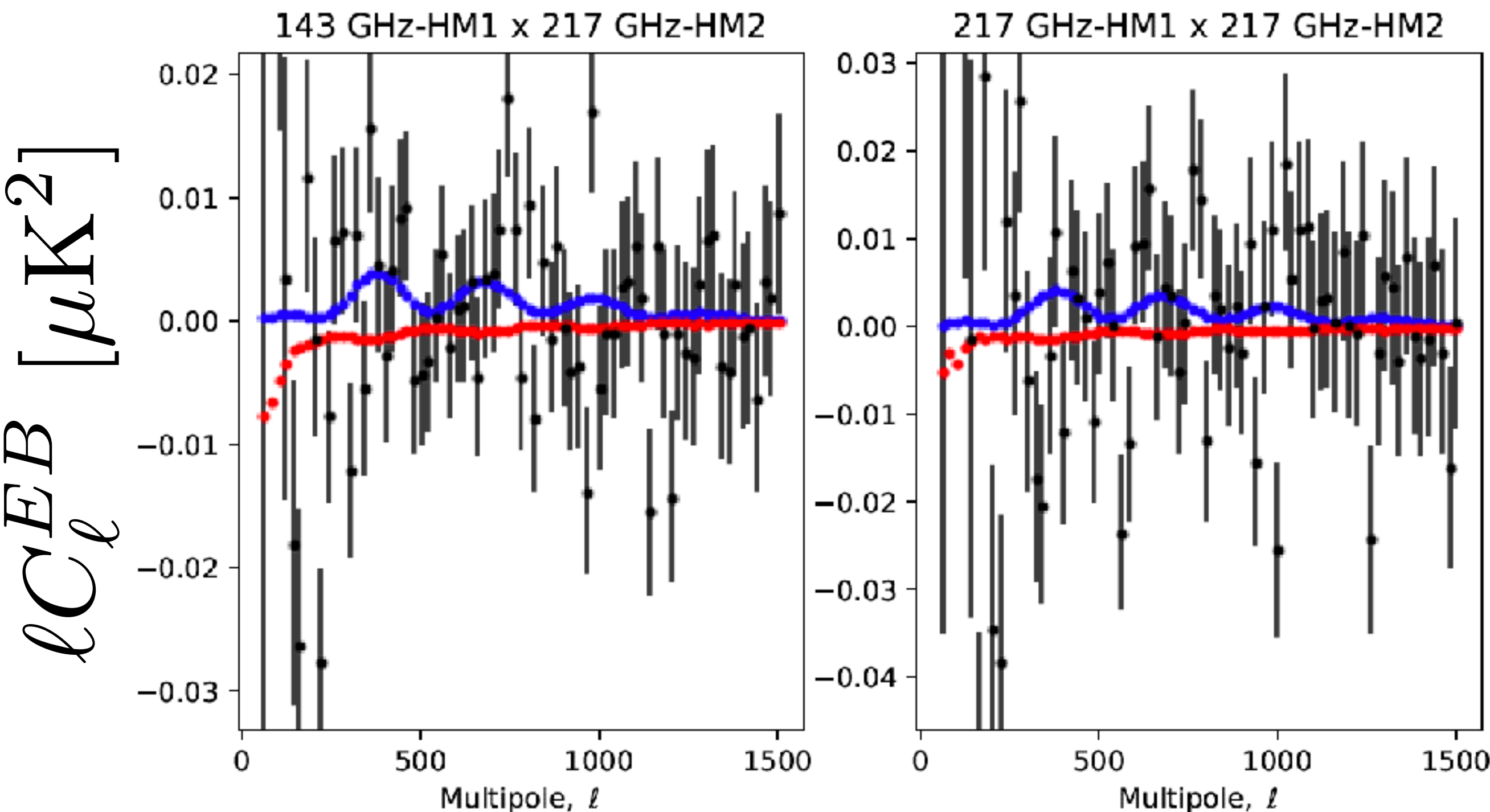
$$\langle C_\ell^{EB,o} \rangle = \frac{\tan(4\alpha)}{2} \left(\langle C_\ell^{EE,o} \rangle - \langle C_\ell^{BB,o} \rangle \right) + \frac{\sin(4\beta)}{2 \cos(4\alpha)} \left(\langle C_\ell^{EE,CMB} \rangle - \langle C_\ell^{BB,CMB} \rangle \right)$$

- 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, α_v
- Blue: The signal attributed to the cosmic birefringence, β
- 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 α .
- Thus, $\alpha \rightarrow \alpha + \gamma$, where γ is the contribution from the intrinsic EB.
 - The sign of γ 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, β increases further...

More data and more analysis innovation were needed. Now we have them!

Cosmic birefringence from *Planck* data release 4

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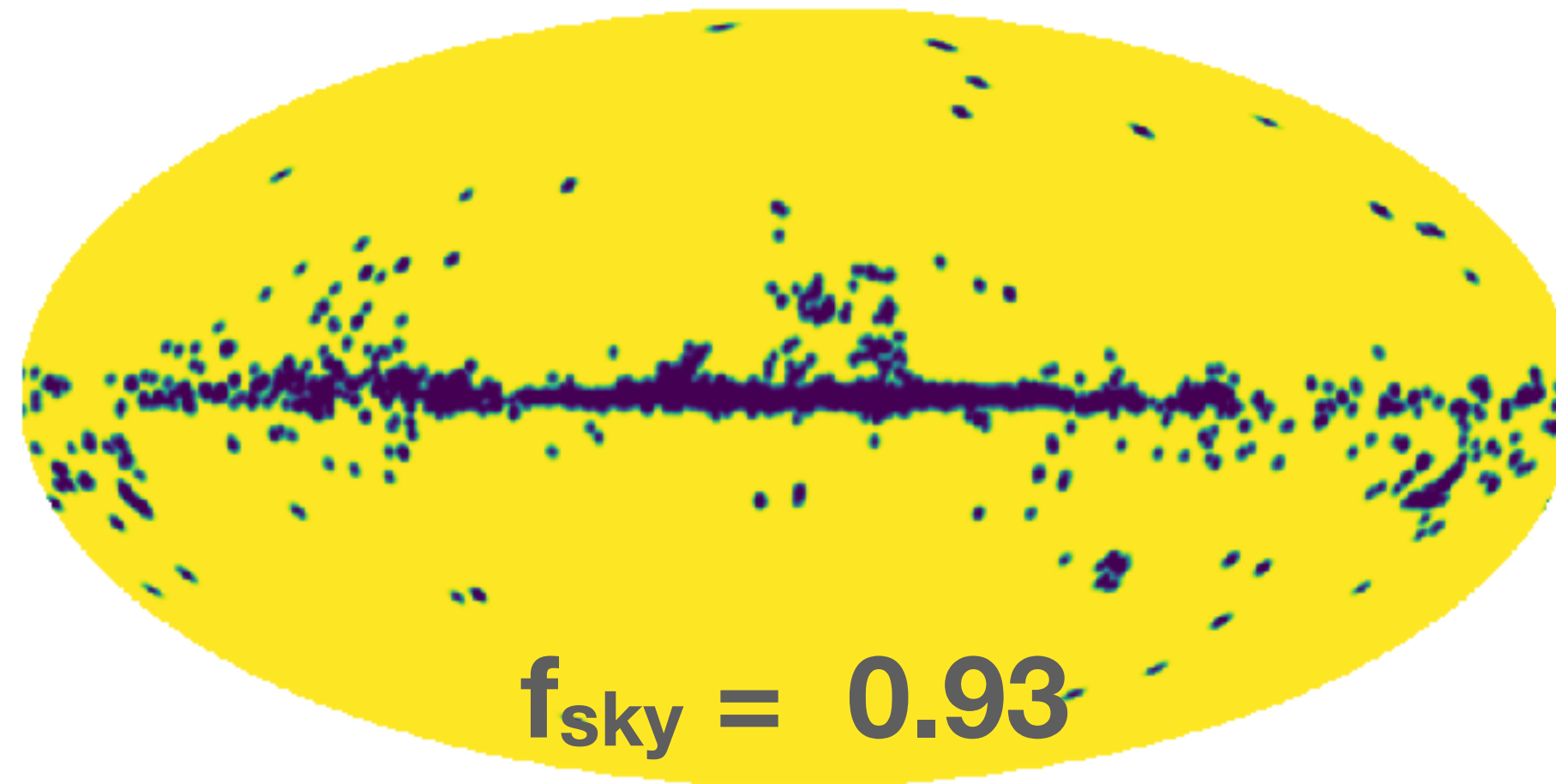
Double corresponding authors.
PhD students. Young power!

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)

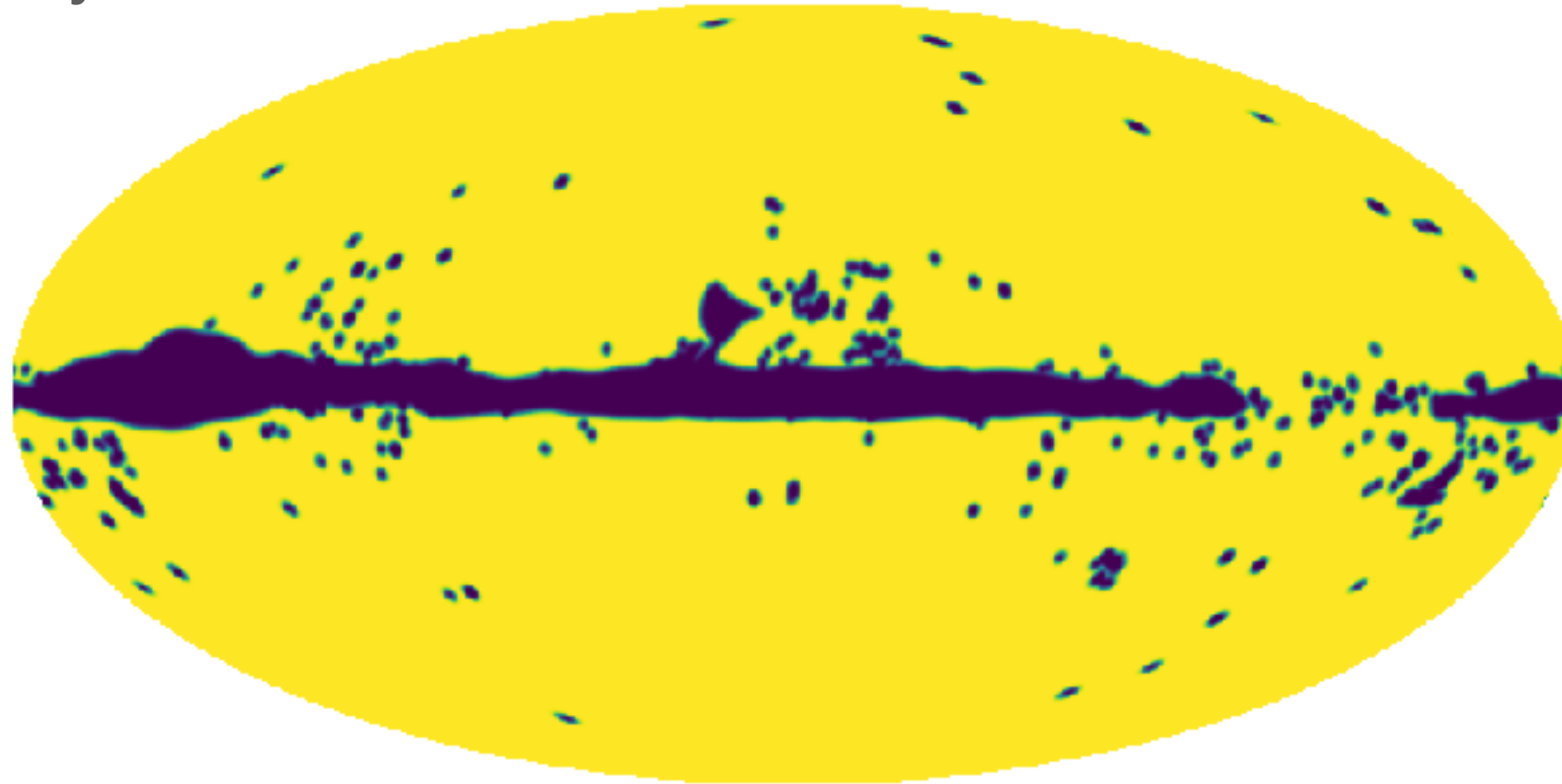


$f_{\text{sky}} = 0.93$

= nearly full sky

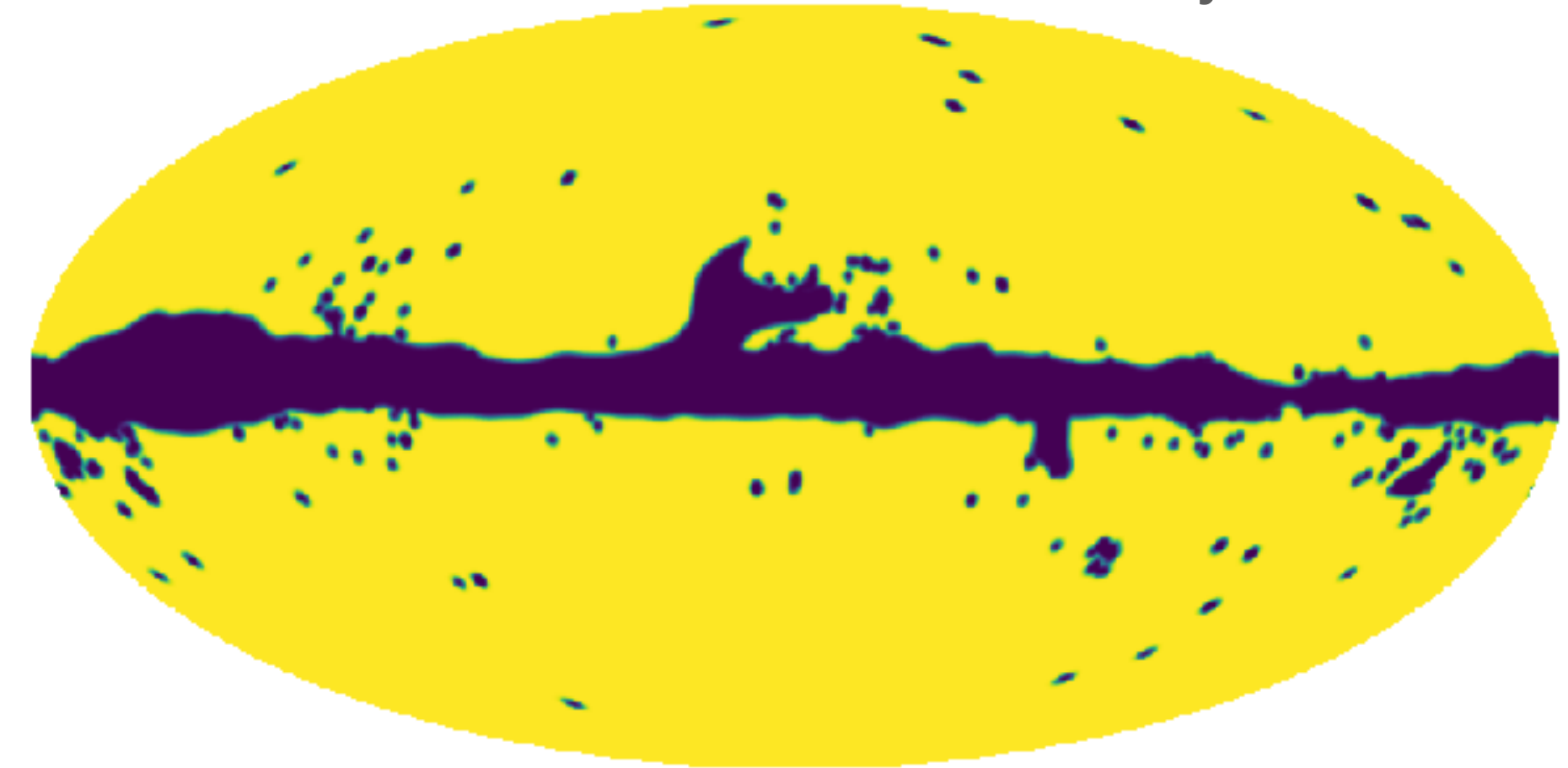
$f_{\text{sky}} = 0.90$

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

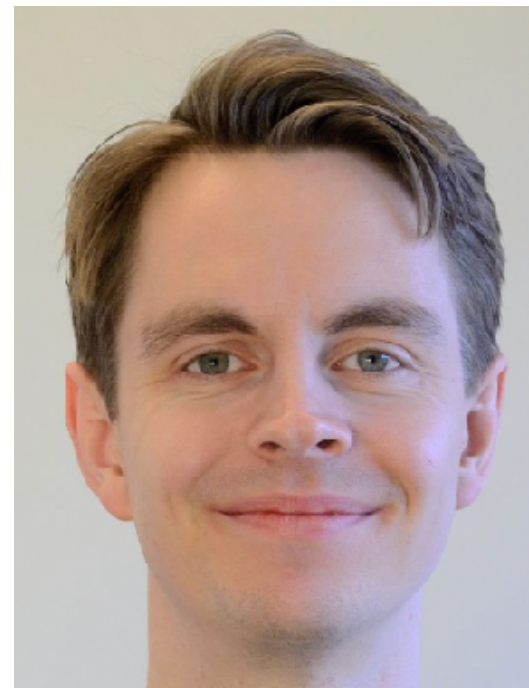
The PR3 result confirmed, with smaller statistical uncertainty

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

PDP



JRE



YM



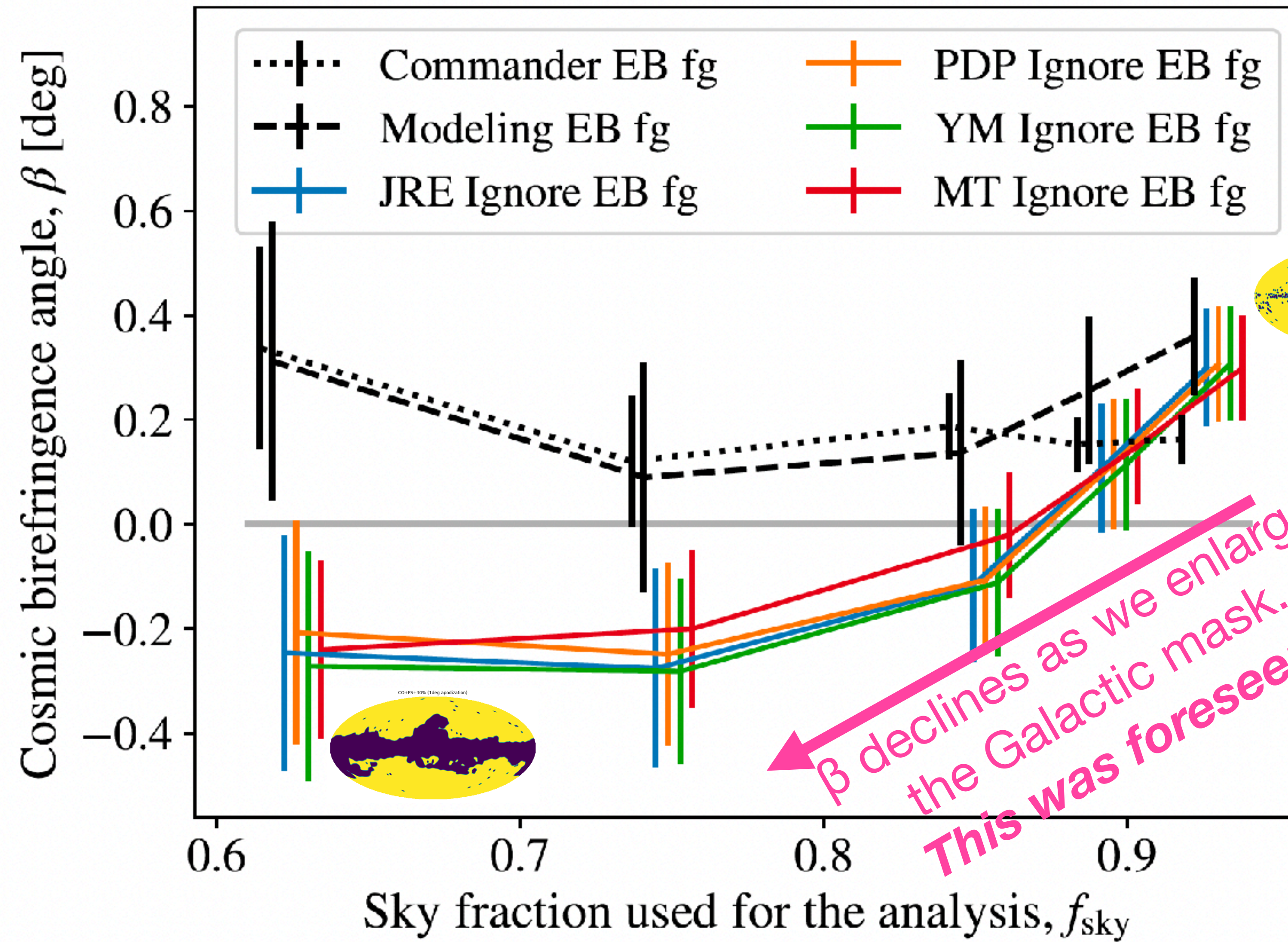
MT



- More statistical significance than the 2.4σ result of the PR3, 0.35 ± 0.14 deg.

How do the results change with f_{sky} ?

Hint for the foreground EB for smaller f_{sky}



PDP



JRE



YM



MT



Including the foreground EB

Introducing a new angle, “ γ ”

- When we do not ignore the intrinsic foreground EB, the *observed* foreground EB (including the miscalibration angle contribution, α) 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 α .
- Thus, $\alpha \rightarrow \alpha + \gamma$, where γ is the contribution from the intrinsic EB.
 - The sign of γ 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, β increases further...

We expected β to decrease towards smaller f_{sky} due to the foreground EB.

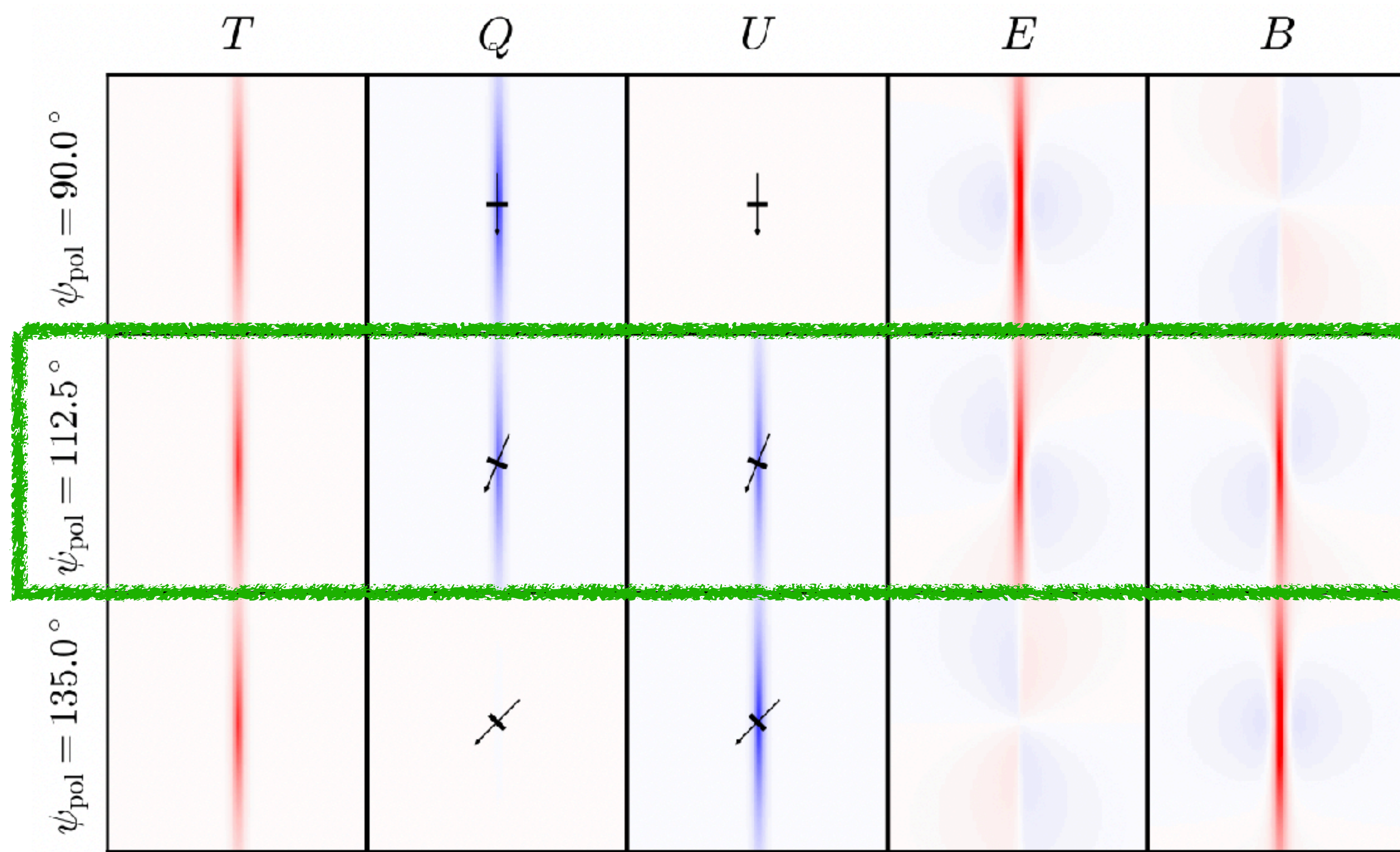
Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- **How do we model the new angle γ ?**
 - 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 γ ?

- 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 ℓ -dependent amplitude parameters

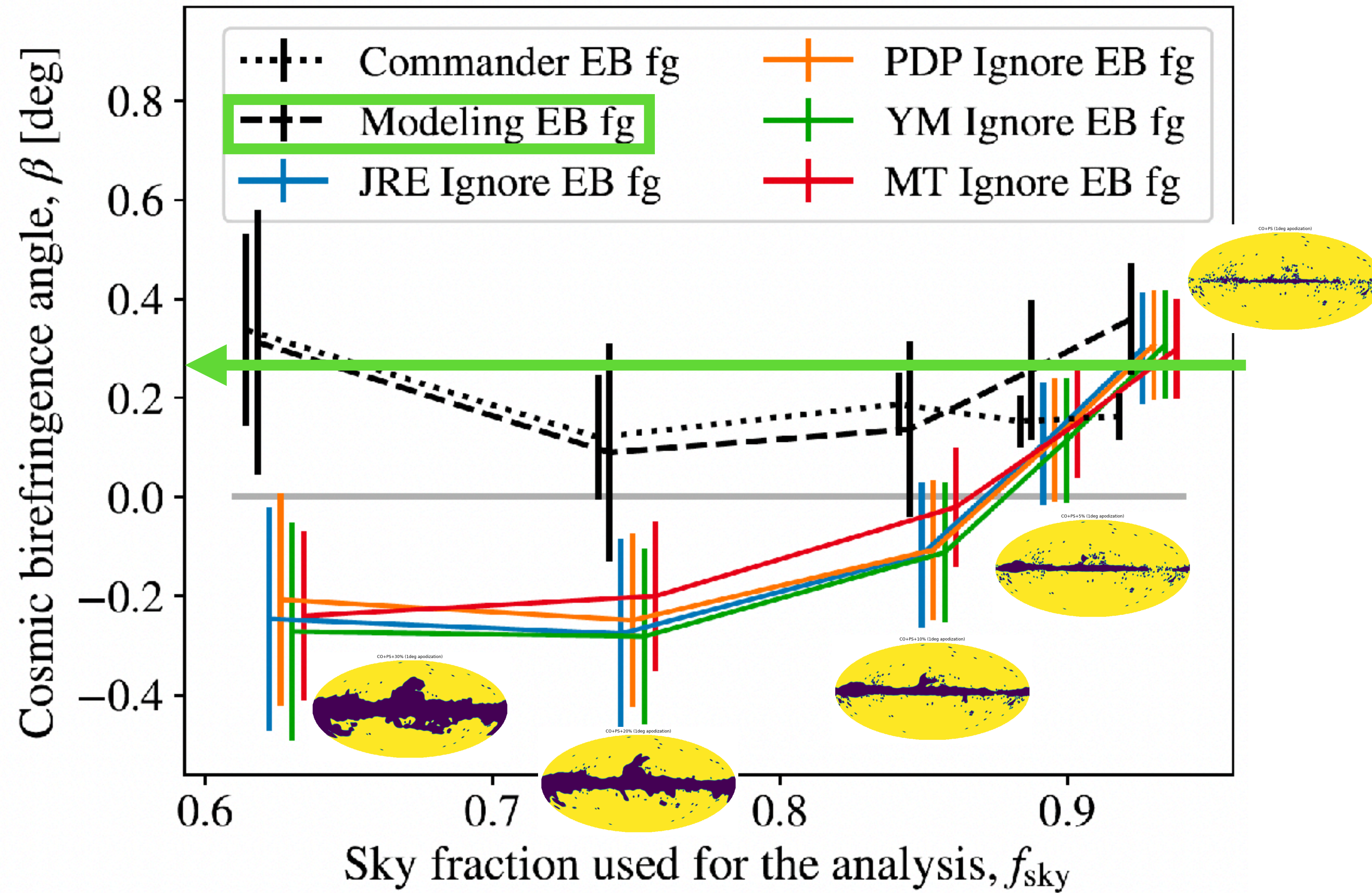
- Then

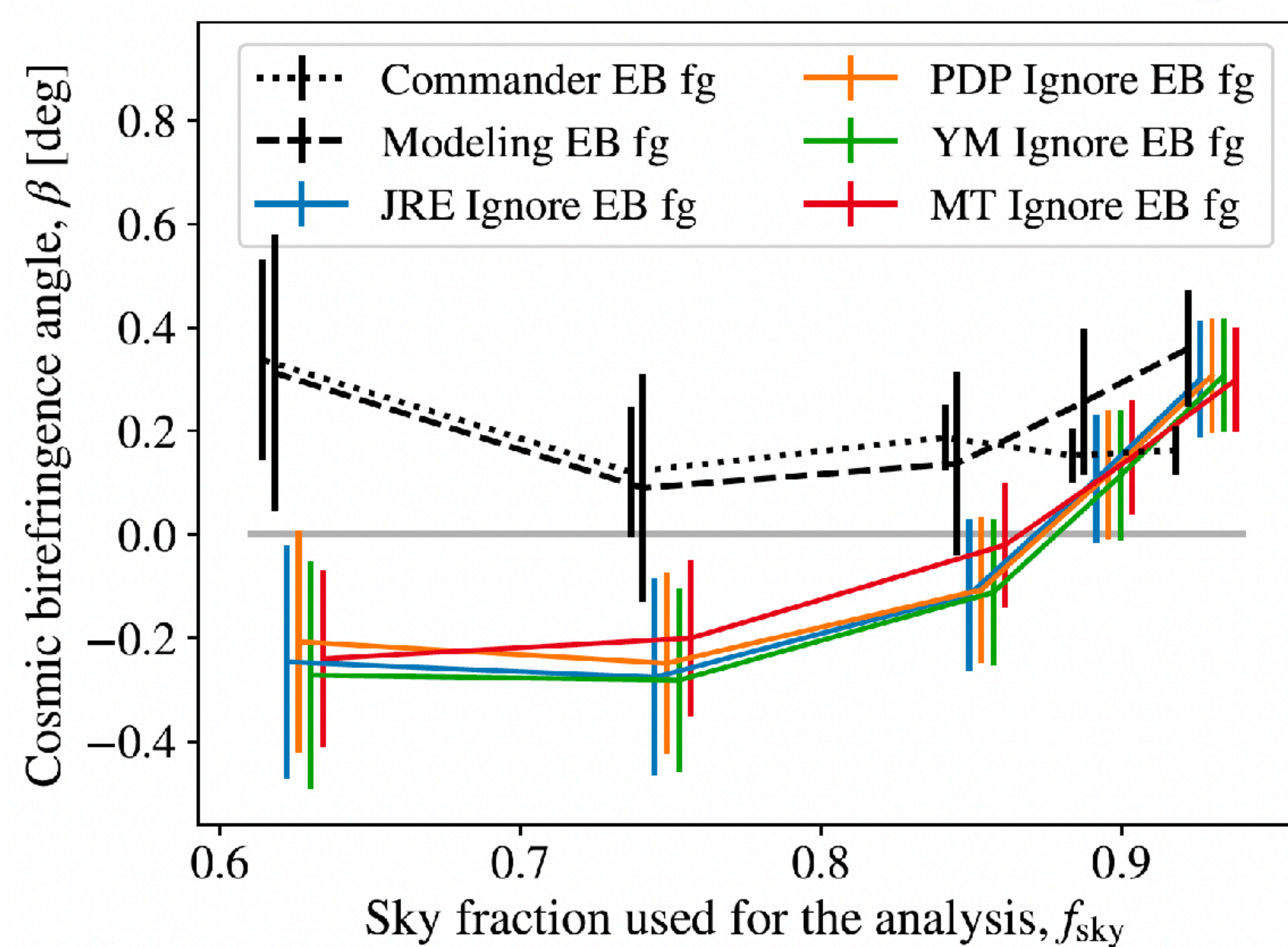
$$\gamma_{\ell} \simeq \frac{A_{\ell} C_{\ell}^{EE,\text{dust}}}{C_{\ell}^{EE,\text{dust}} - C_{\ell}^{BB,\text{dust}}} \frac{C_{\ell}^{TB,\text{dust}}}{C_{\ell}^{TE,\text{dust}}}$$

for small angles.

Dashed line: Modeling the foreground EB

Trend for declining β is largely gone. But which f_{sky} we should choose?





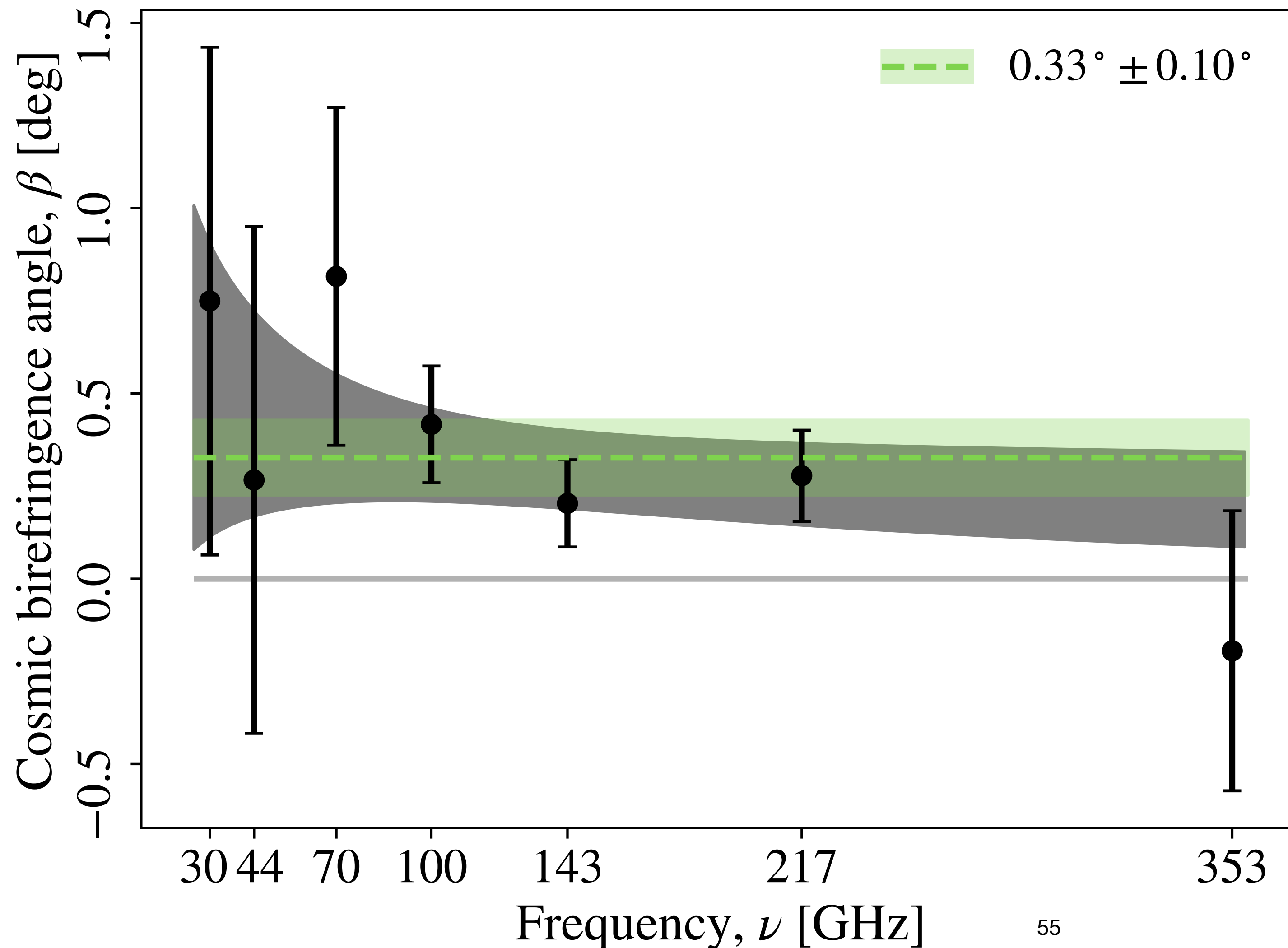
- As foreseen, accounting for the foreground EB **increased** β from 0.30 to 0.36 for nearly full-sky data.
- Which f_{sky} we should choose for the final result?
We do not know yet. We need more investigation.
- We need help from Galactic astrophysics! It is a fascinating subject.

f_{sky}	0.93
β	0.36 ± 0.11
α_{100A}	-0.32 ± 0.13
α_{100B}	-0.43 ± 0.13
α_{143A}	0.03 ± 0.11
α_{143B}	0.15 ± 0.11
α_{217A}	-0.06 ± 0.11
α_{217B}	-0.07 ± 0.11
α_{353A}	-0.19 ± 0.10
α_{353B}	-0.23 ± 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 β 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.
 - “ ± 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 β . 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 β is confirmed as cosmological, it would have profound implications for the fundamental physics behind dark matter and energy.

