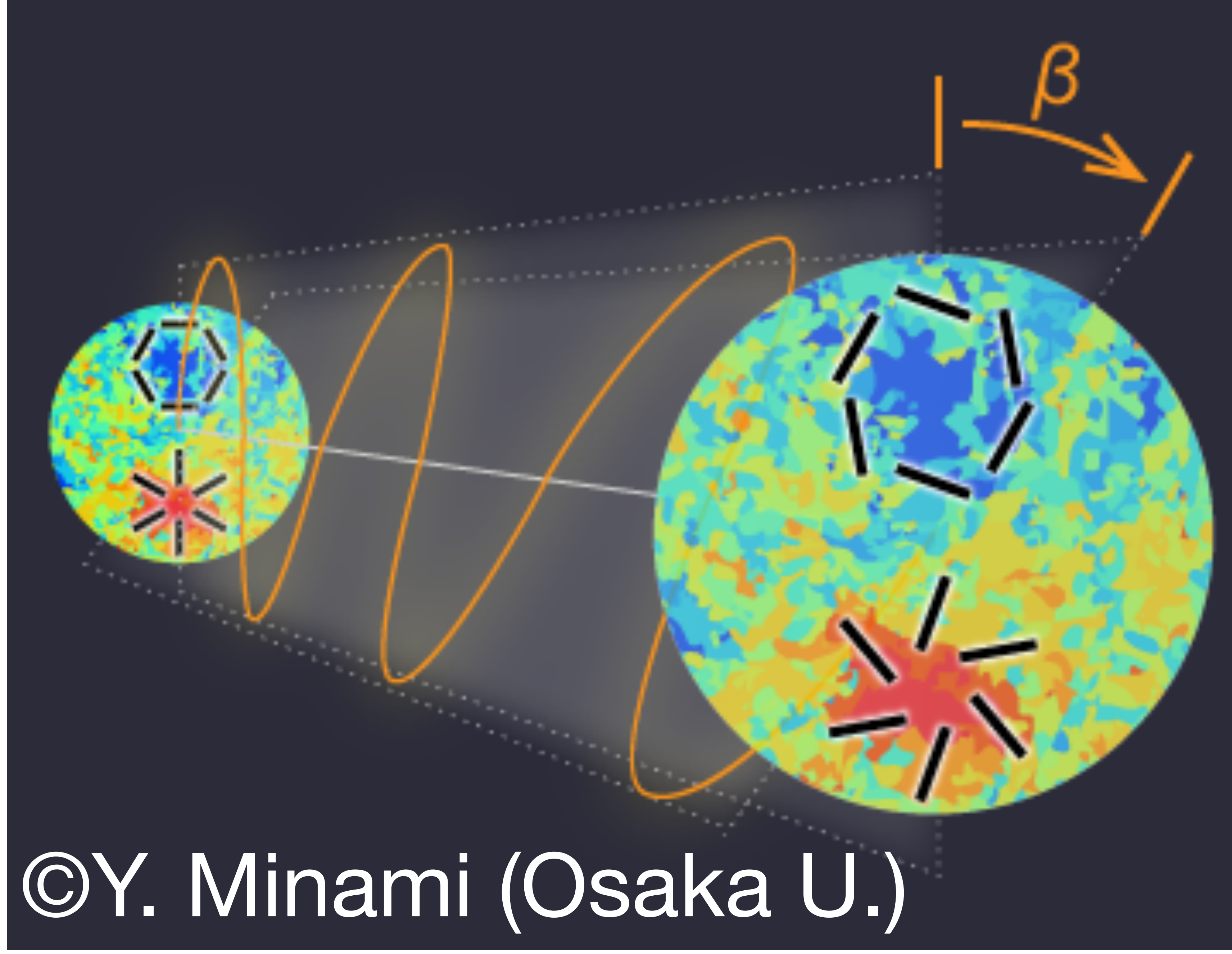
Cosmic Birefringence

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)

Gravity - The Next Generation@YKIS2022a

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MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

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 key to the answers.

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 key to the answers.


Credit: WMAP Science Team
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?

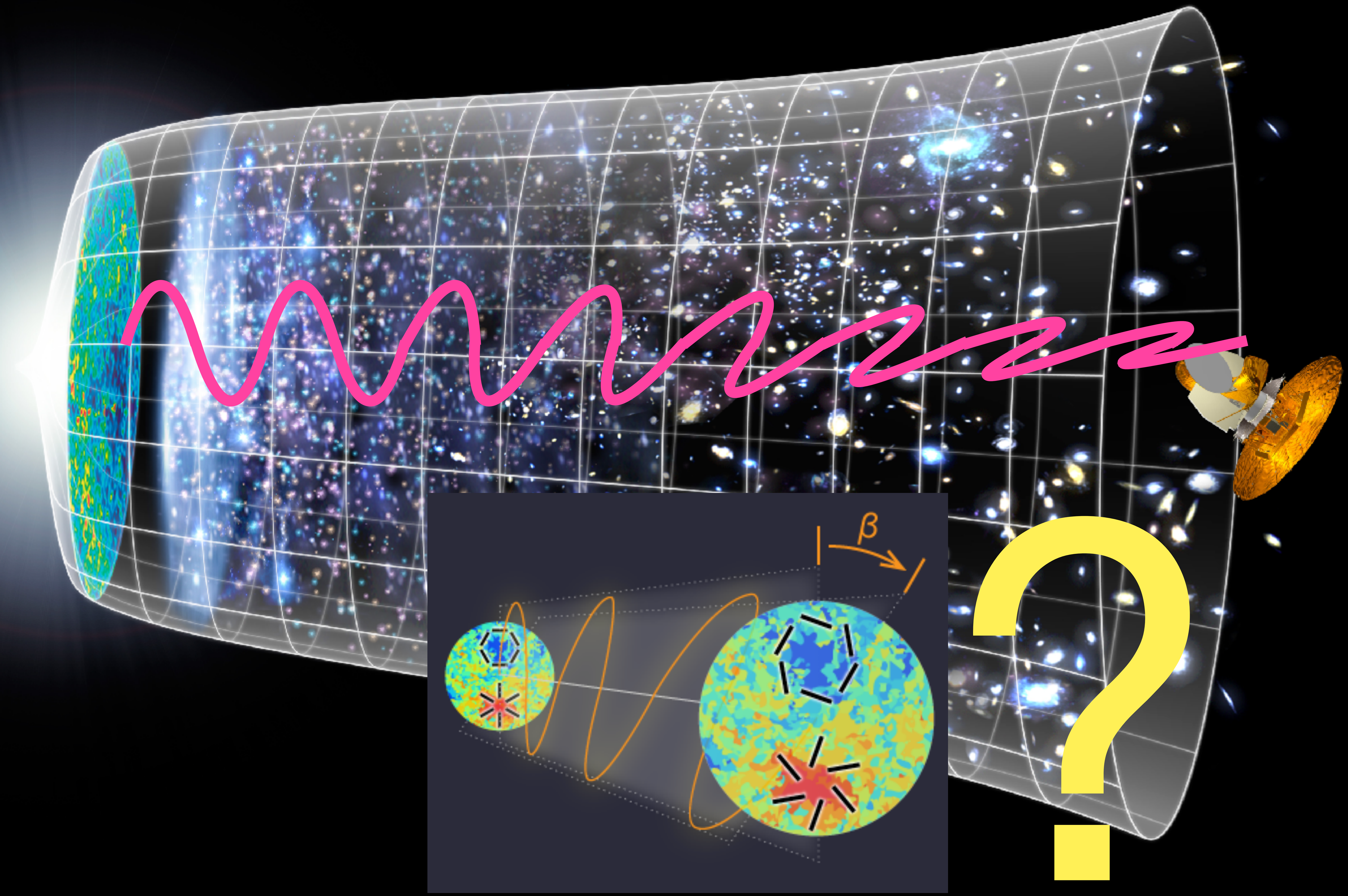
Today's topic → *What is dark matter/energy?*

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

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

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

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

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

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**

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

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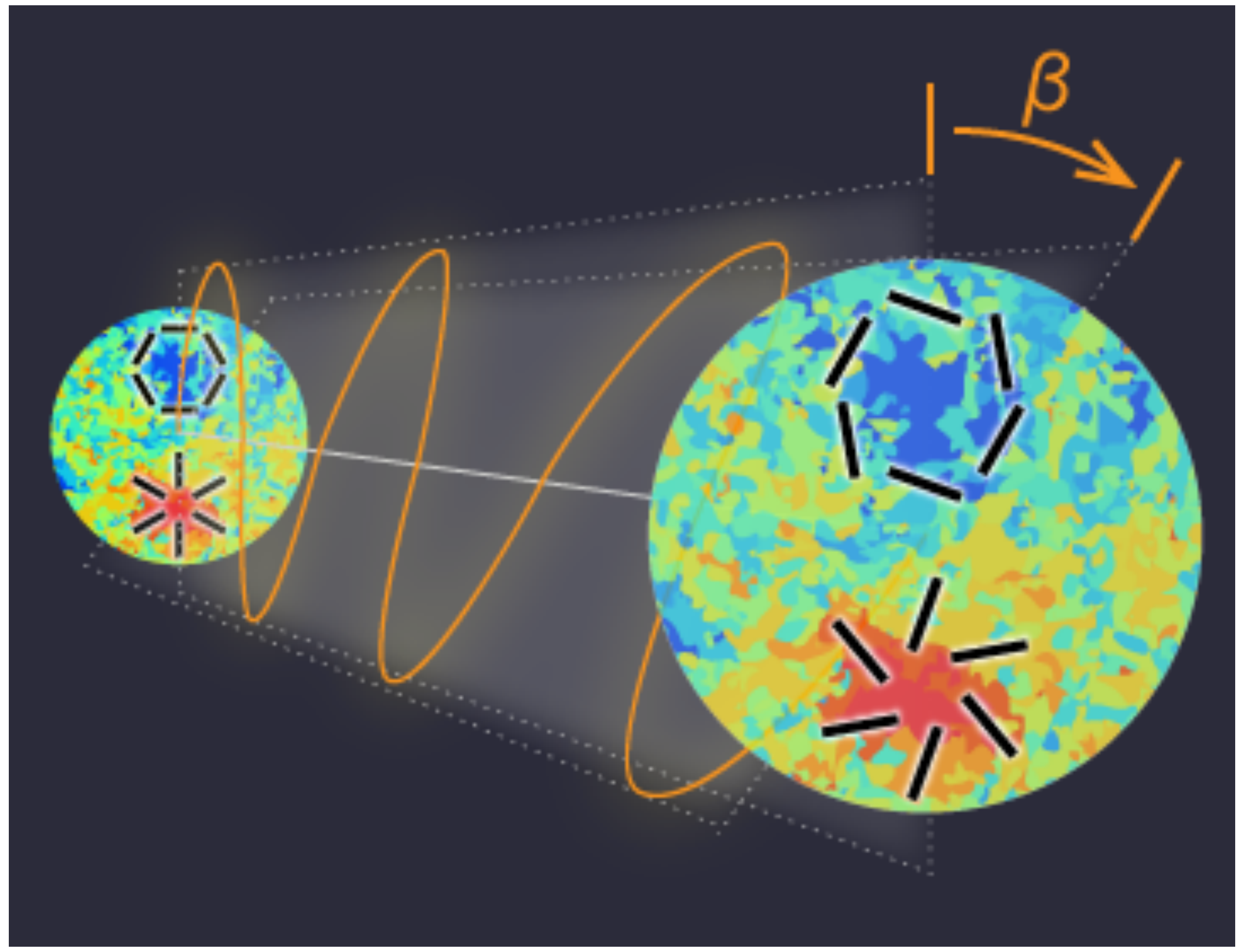


"Cosmic Birefringence"

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

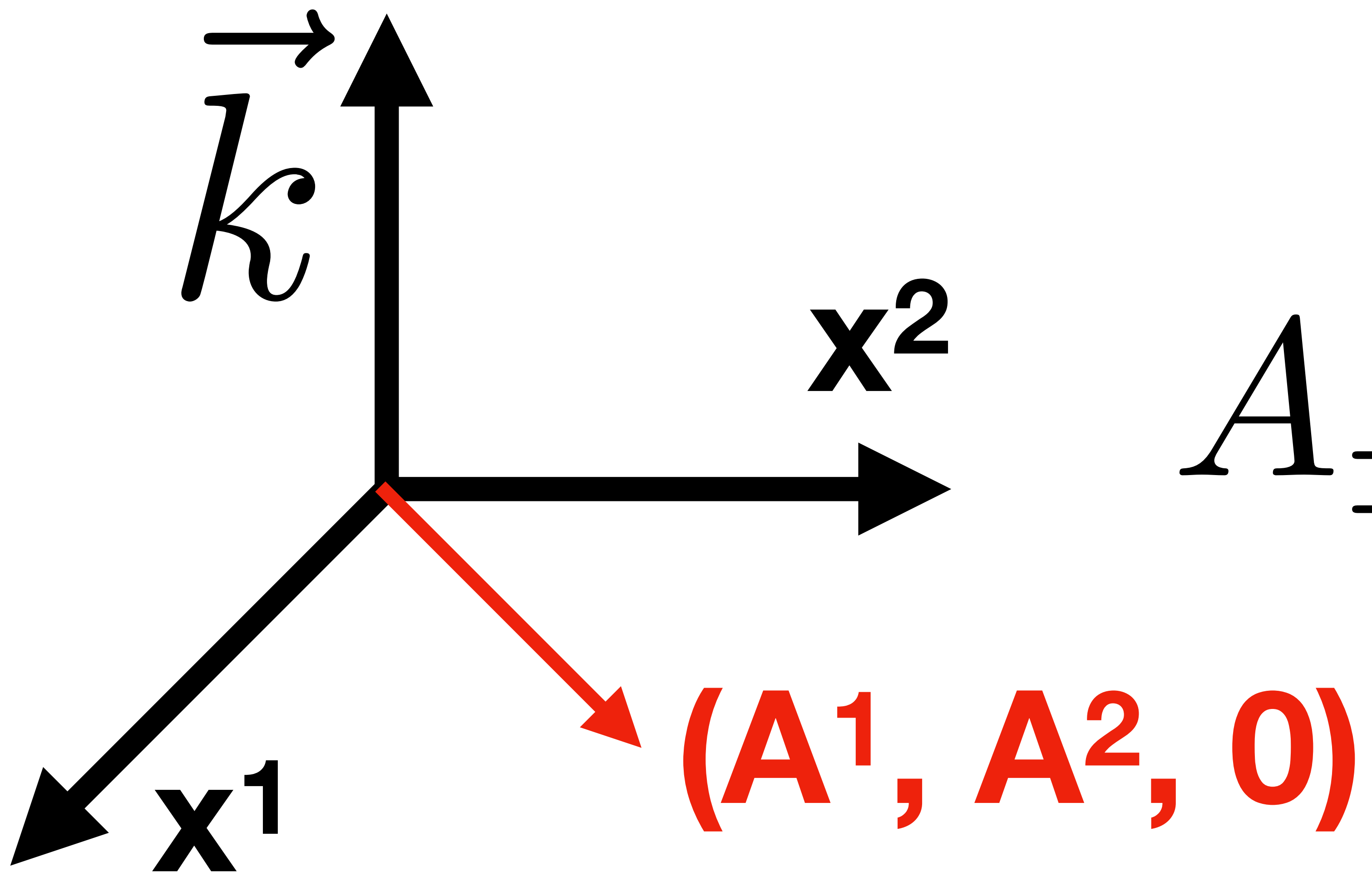
Standard Maxwell Theory

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 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

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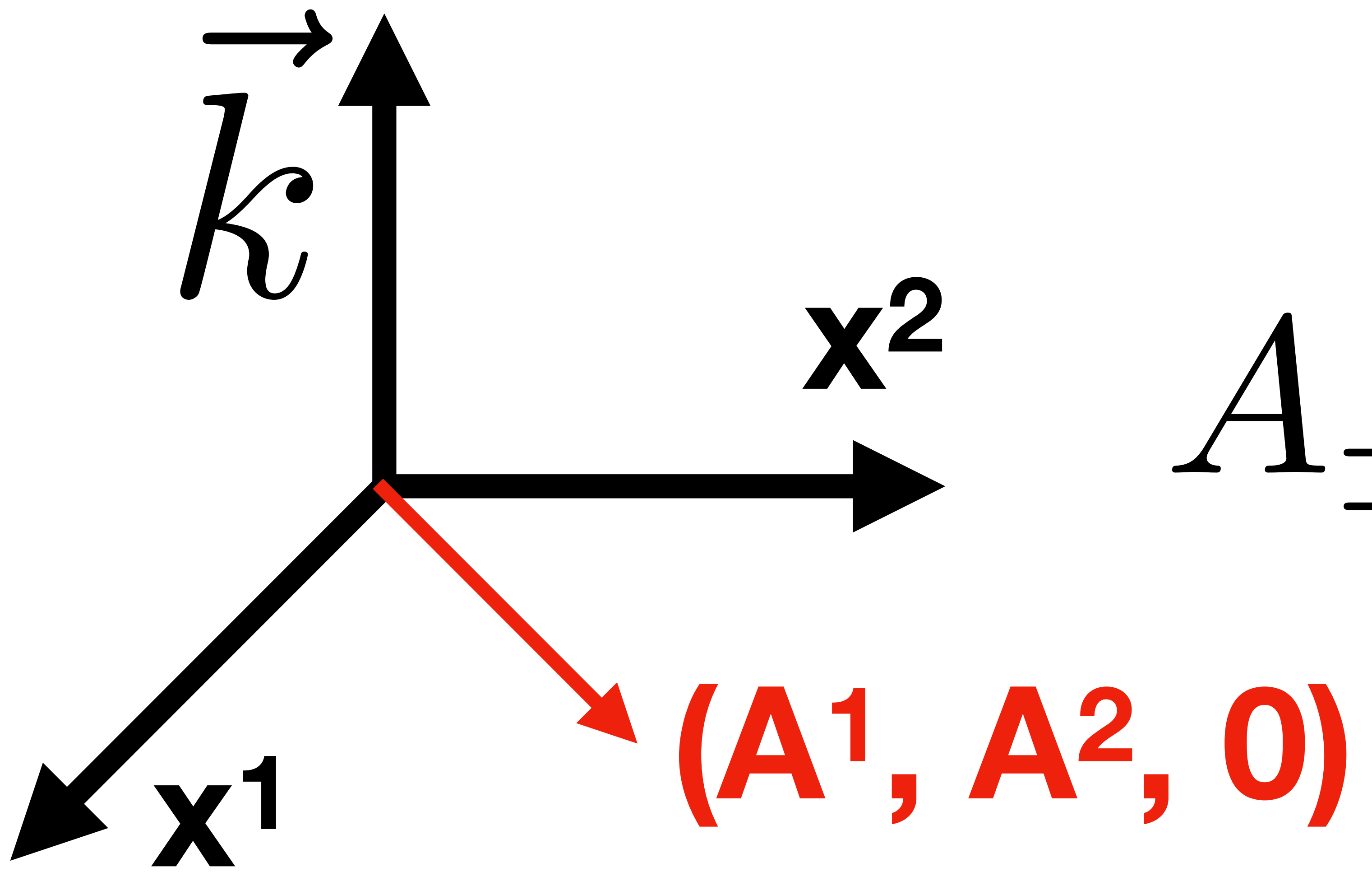

$$A_\pm = \frac{A_1 \mp i A_2}{\sqrt{2}}$$

- A_+: Right-handed state
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Cosmic Birefringence

Derivation (1)

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

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

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

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- The equation of motion is modified to

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

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

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

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Cosmic Birefringence

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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!

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

Cosmic Birefringence

Derivation (2)

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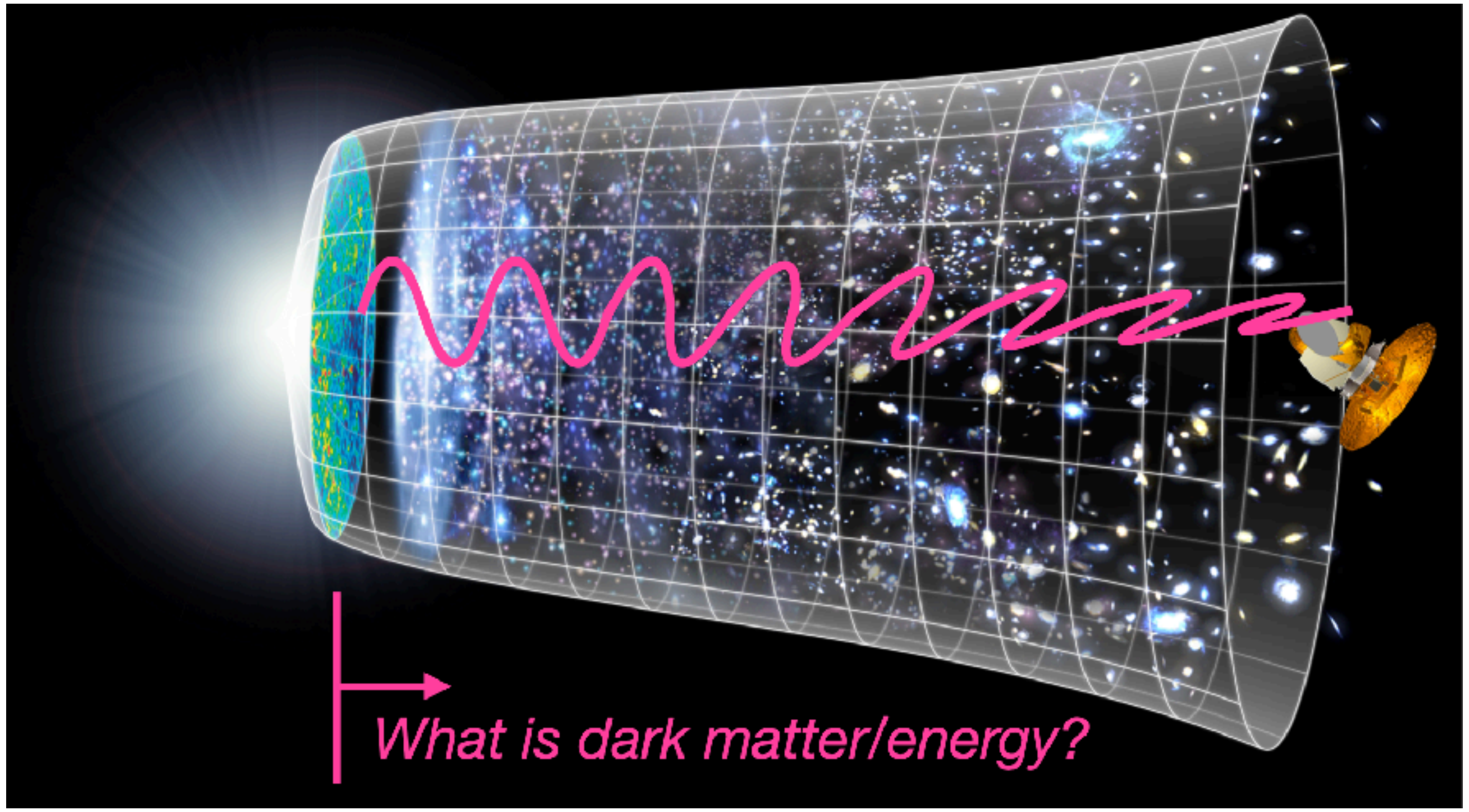

- The plane of linear polarisation rotates by an angle ψ:

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

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

Cosmic Birefringence

Derivation (3)

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This is the convention for polarisation direction adopted by IAU

Cosmic Birefringence

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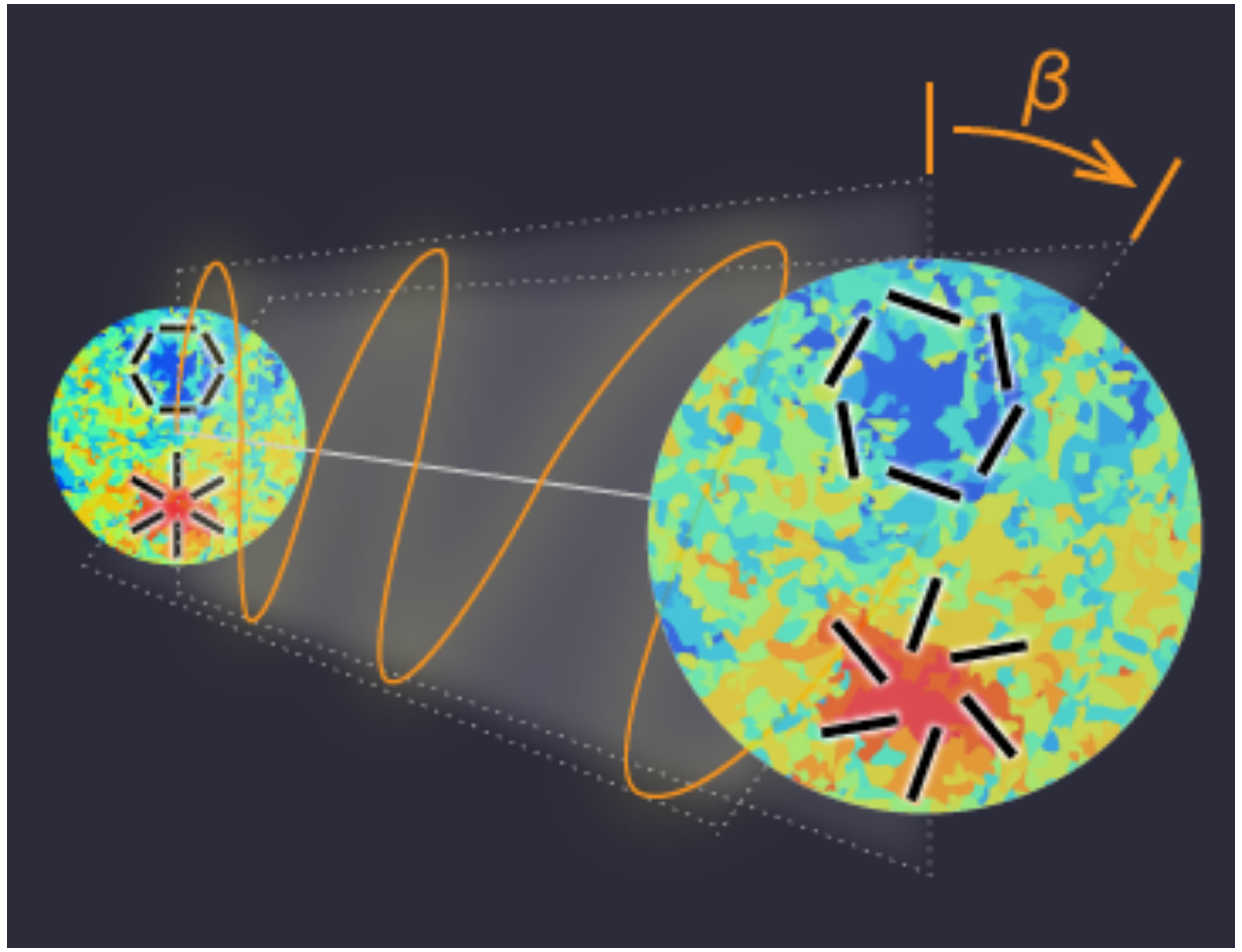

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However!

The CMB community adopted the opposite sign convention…
Thus, we shall use β = −ψ

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

Cosmic Birefringence

Recap

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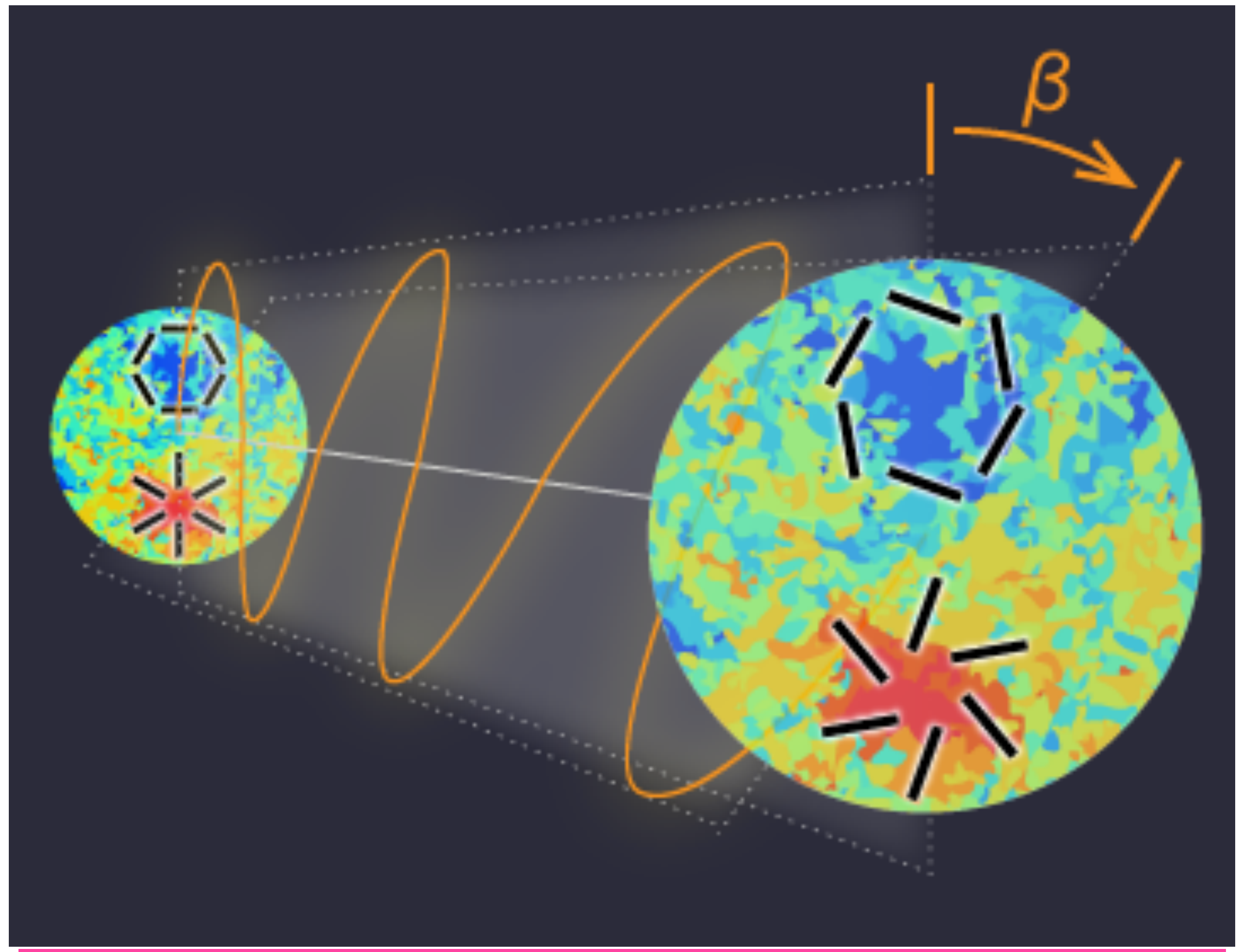
$$\beta = -2g_a \int_{t_\mathrm{emitted}}^{t_\mathrm{observed}} dt\,\dot{\theta} = 2g_a\left[\theta(t_\mathrm{e}) - \theta(t_\mathrm{o})\right]$$



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

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

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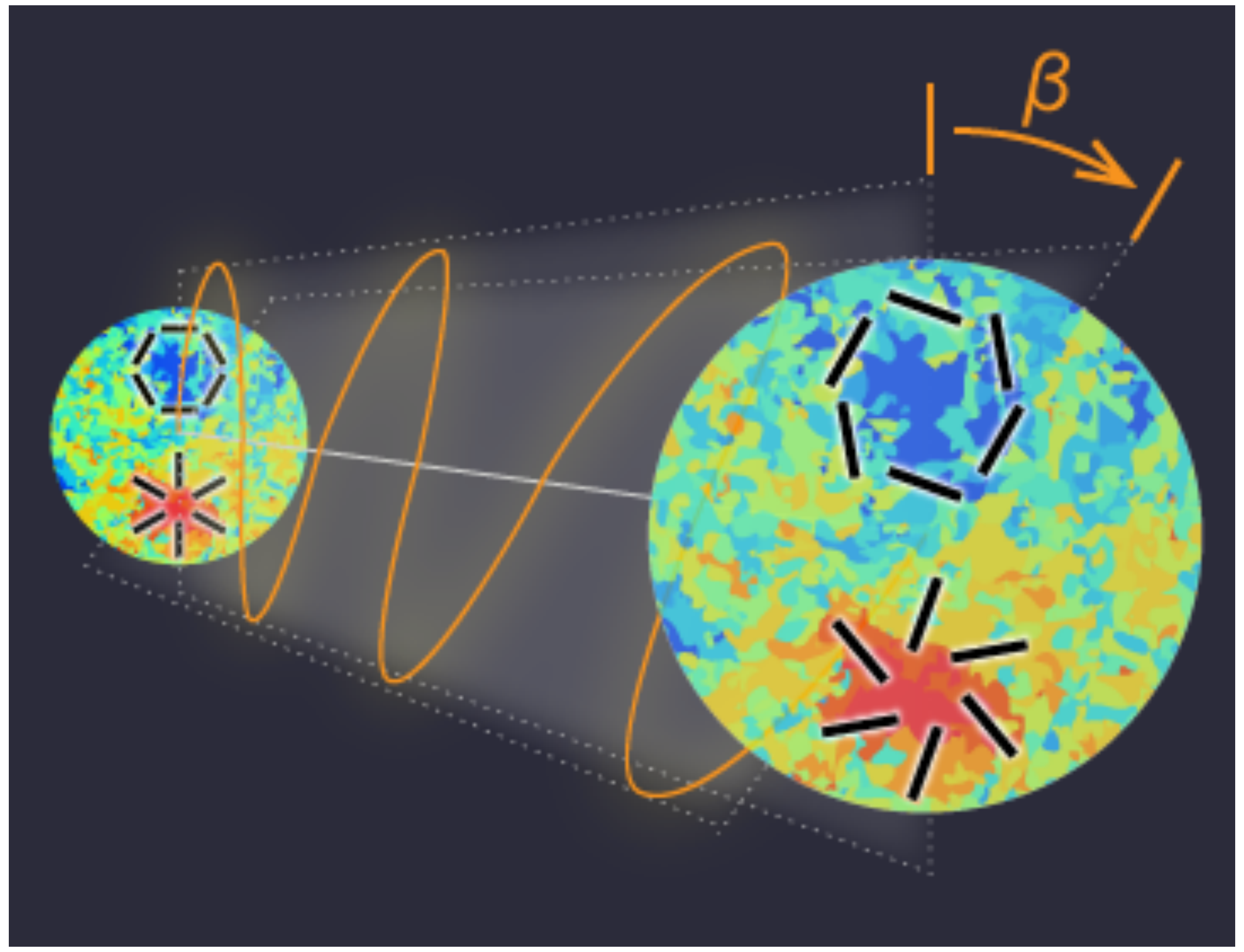


If θ varies over space:

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

Motivation

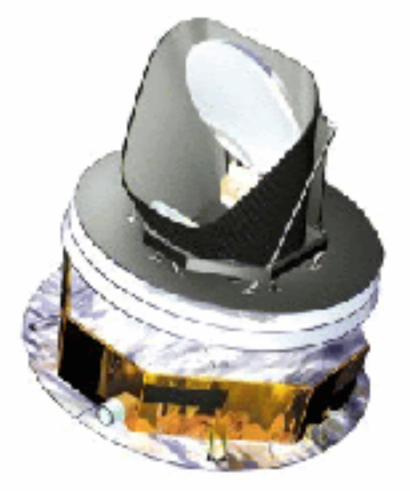
Why study the cosmic birefringence?

- 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!

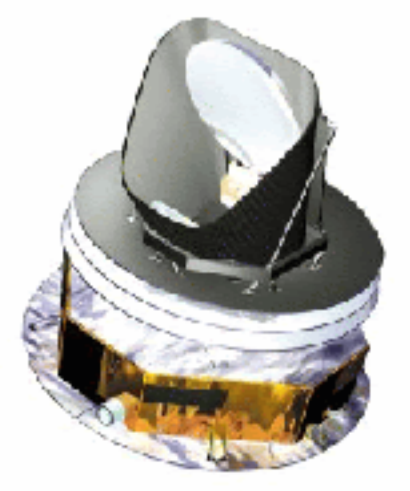


ESA’s Planck

Credit: ESA

Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago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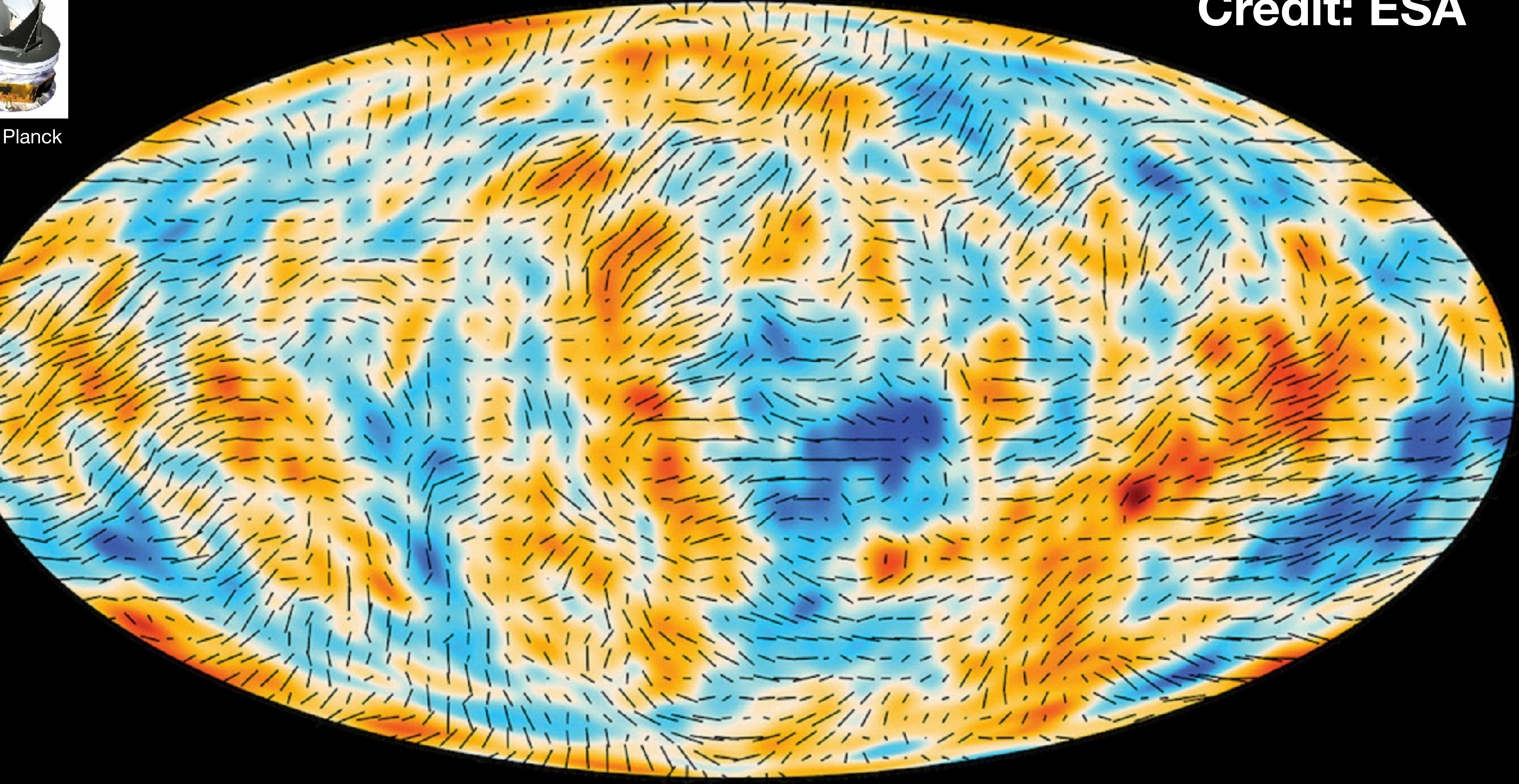

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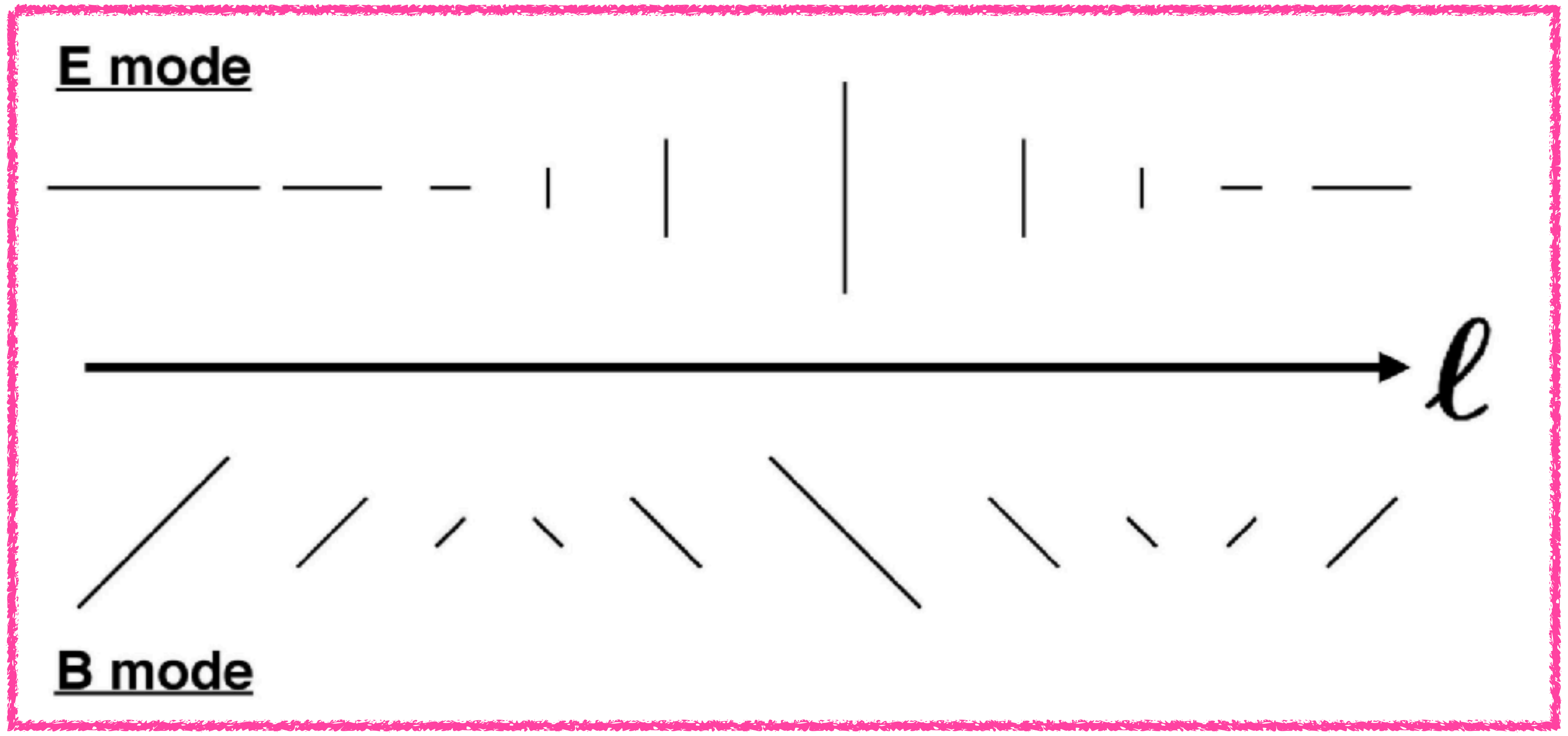
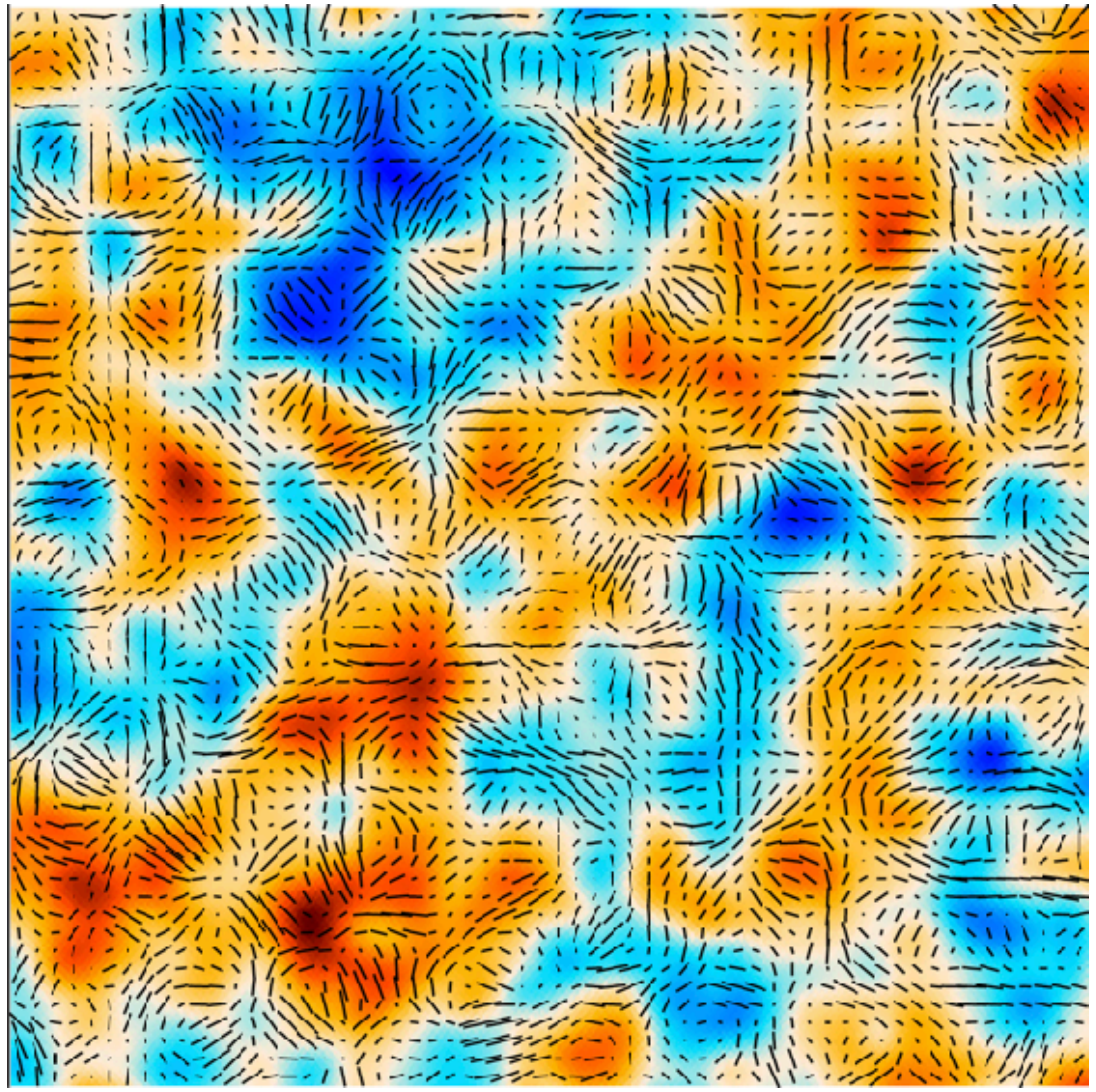
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

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

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

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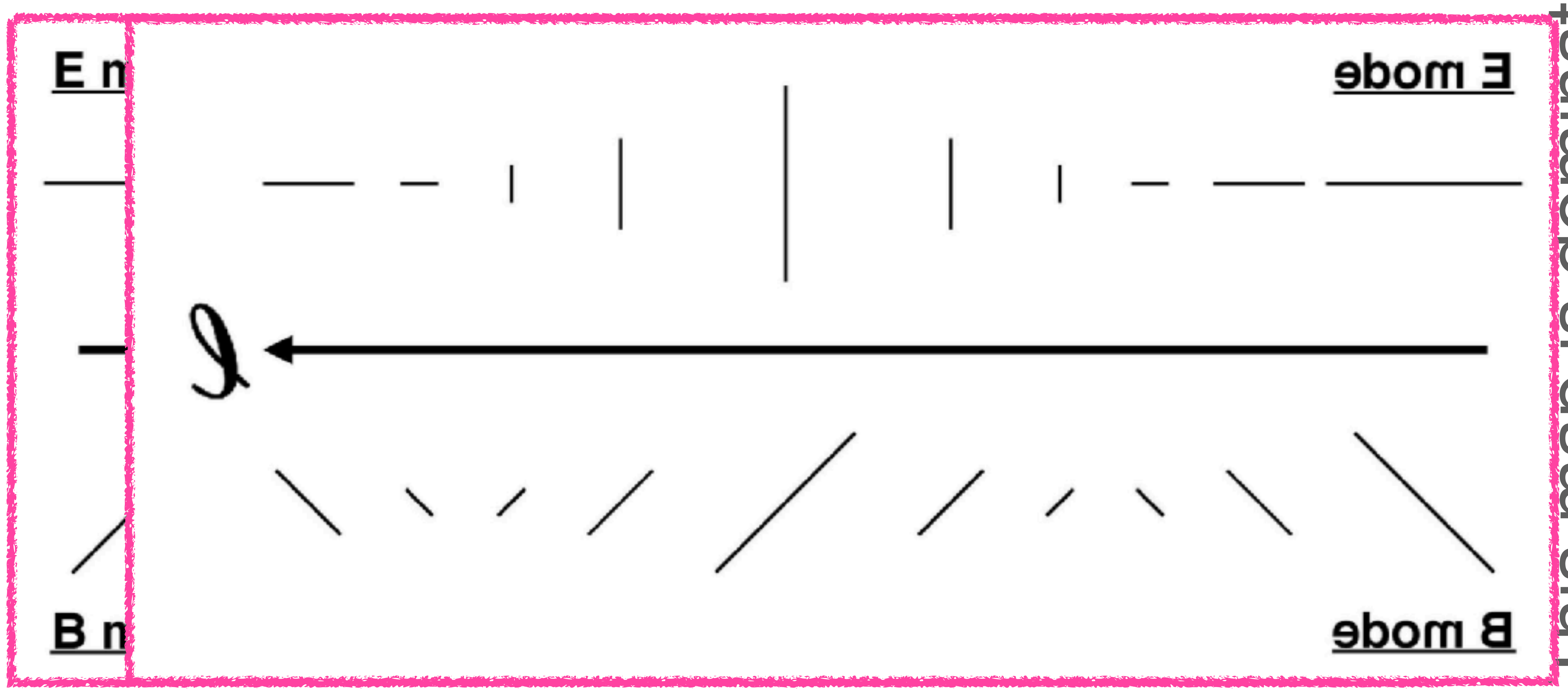
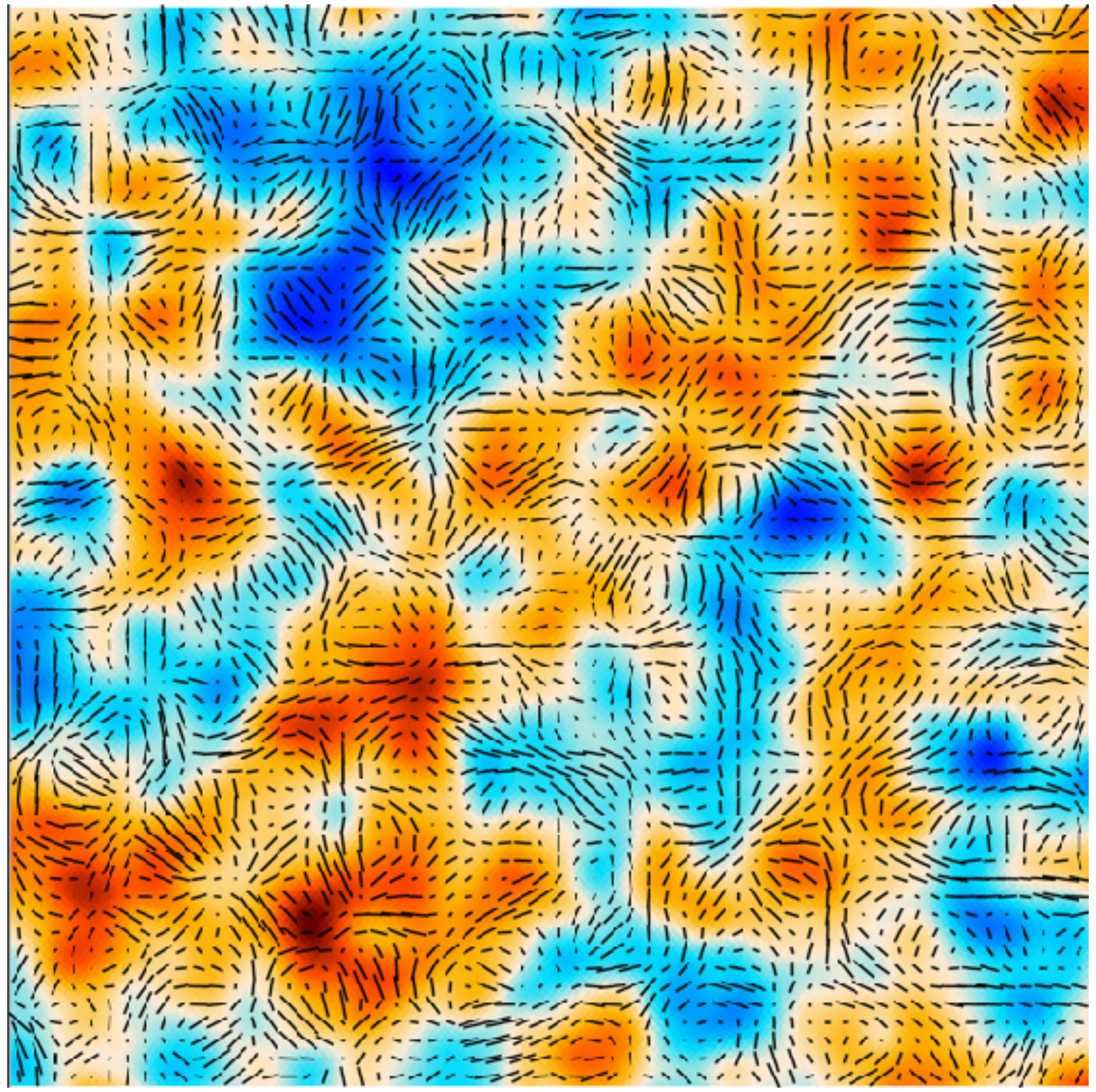


This map is dominated by E-mode polarisation



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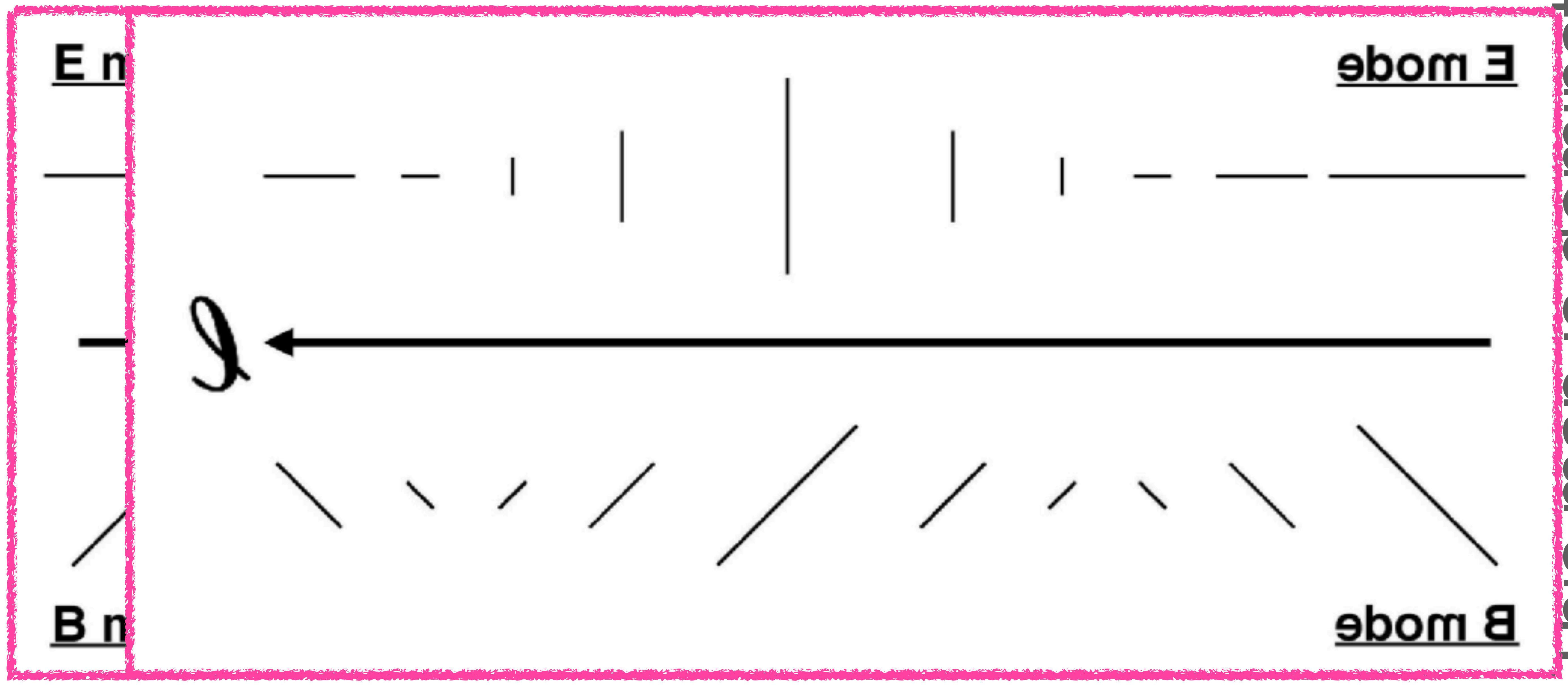
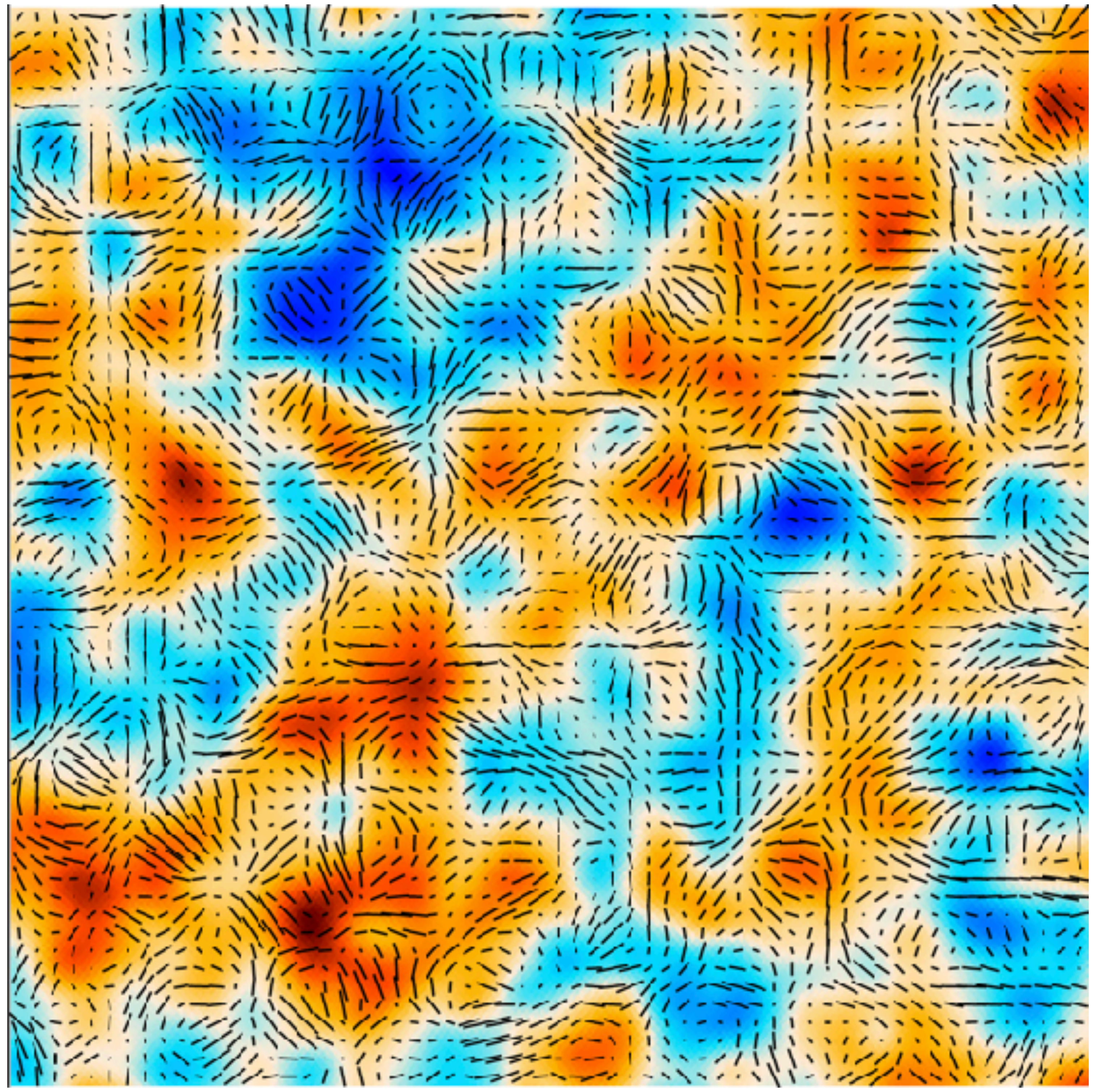


This map is dominated
by E-mode polarisation



- **E-mode**： Polarisation directions are **parallel or perpendicular** to the wavenumber direction

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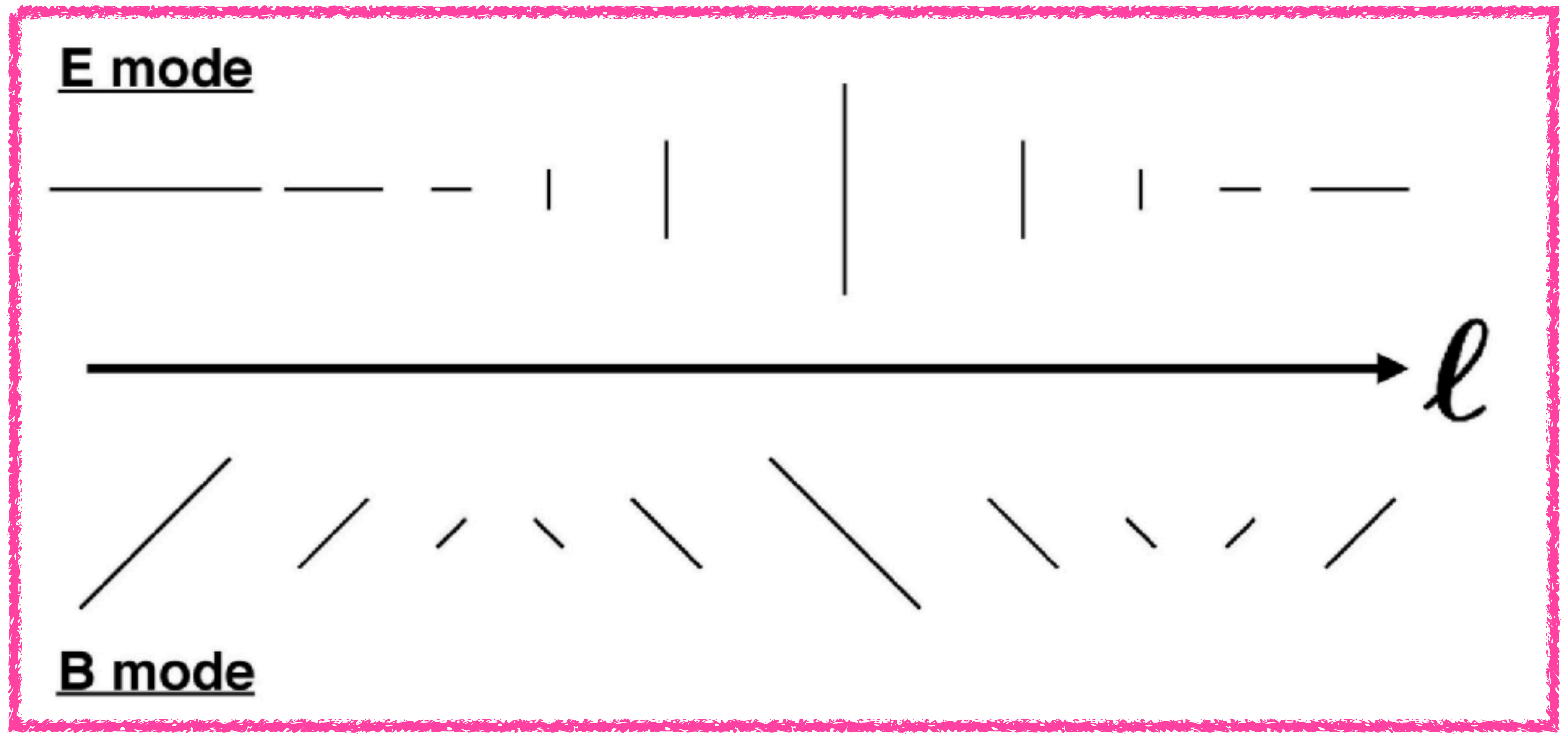
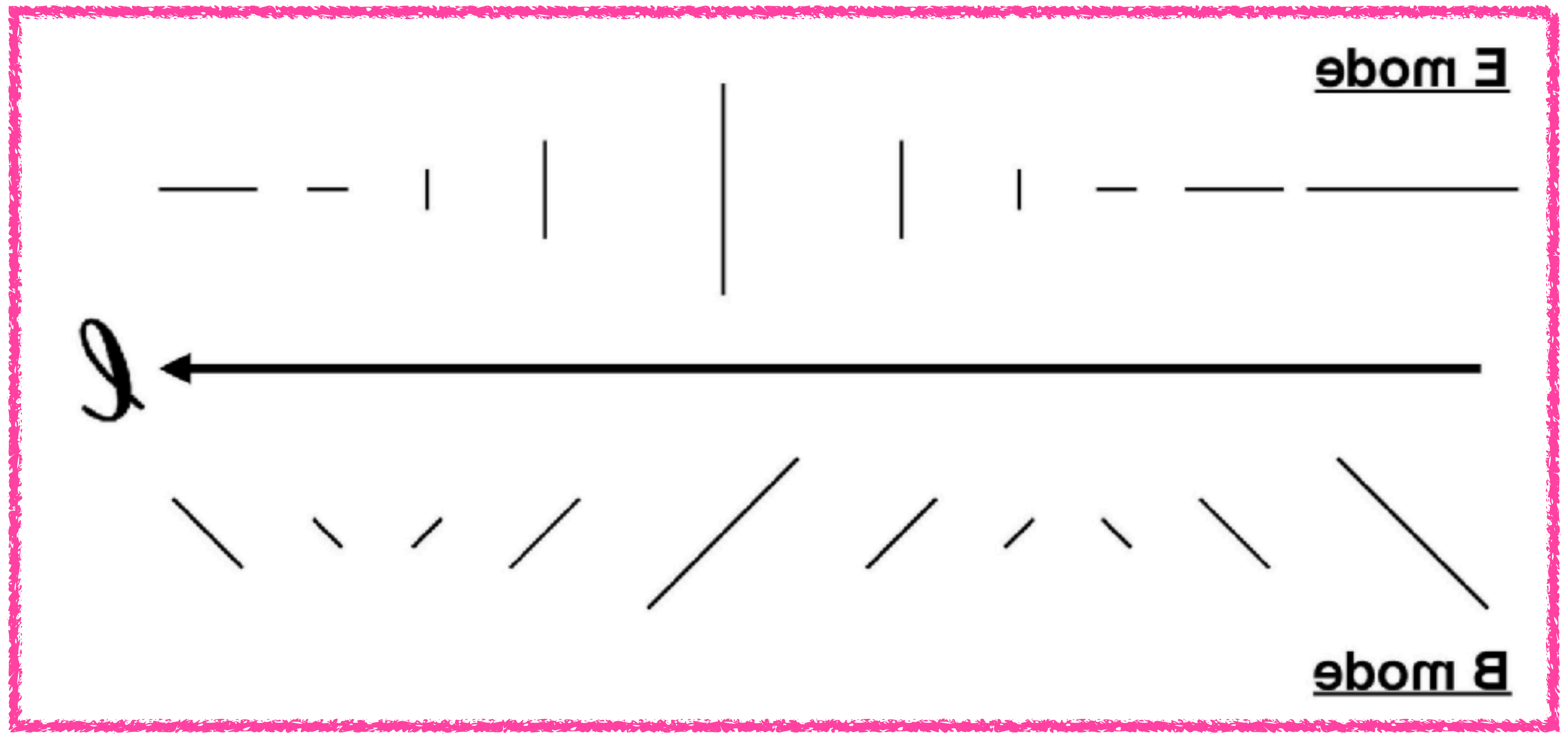
IMPORTANT”: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity Flip

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





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

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

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

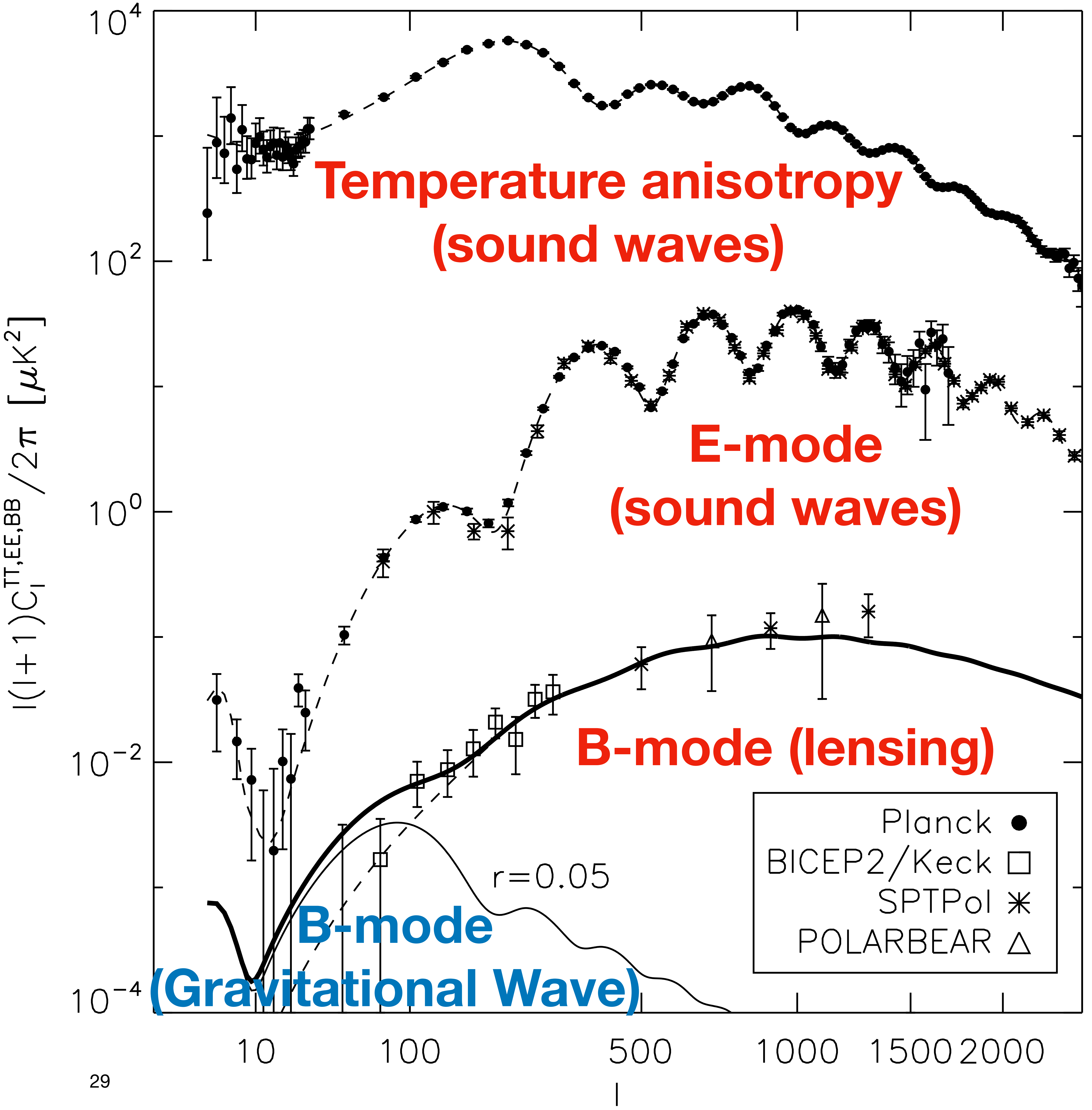
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **We can use these combinations to probe parity-violating physics (e.g., axions)**

Power Spectra

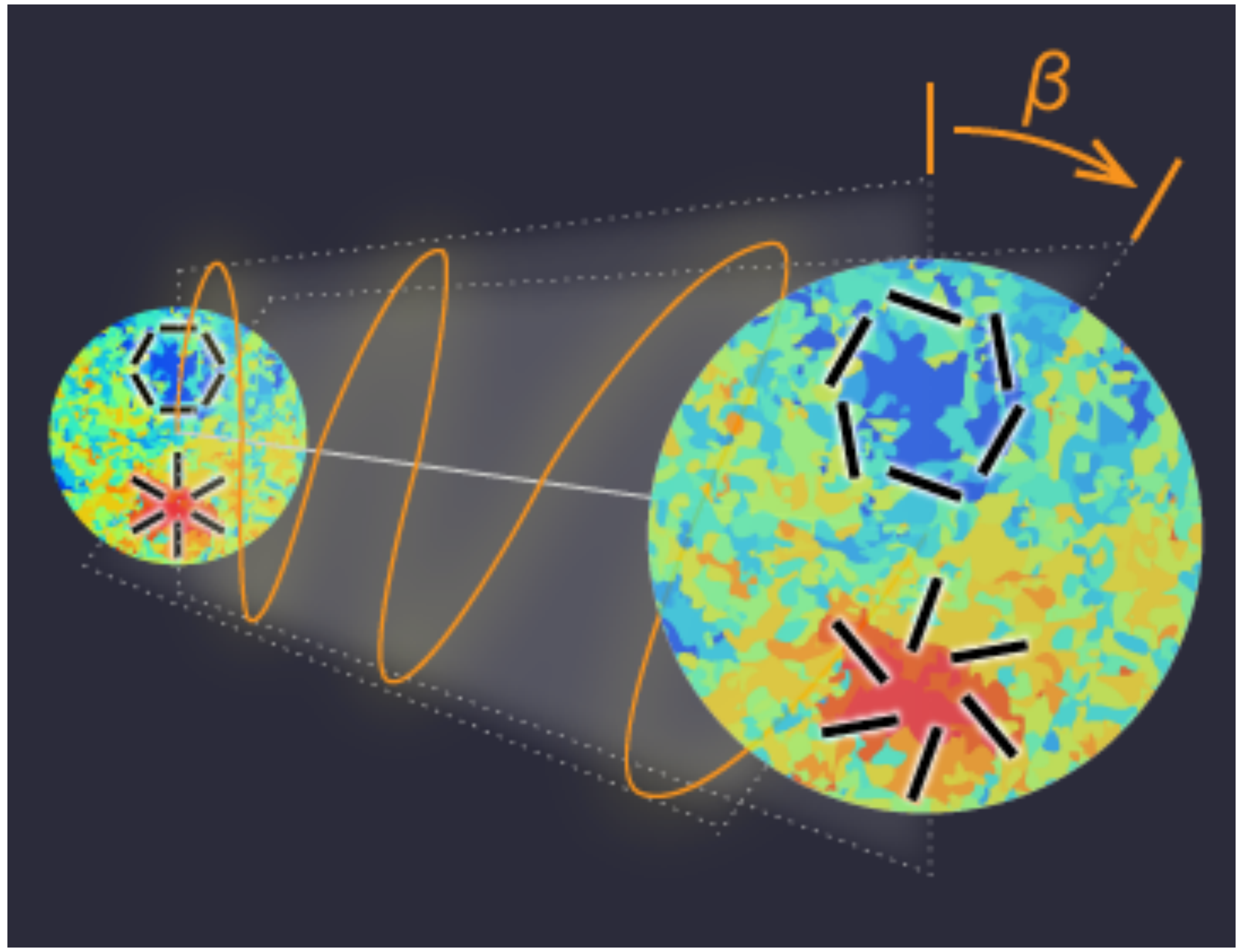
A lot have been measured

- 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.**



Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

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



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

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

- which gives

$$E_\ell^{\rm o} = E_\ell \cos(2\beta) - B_\ell \sin(2\beta)$$

$$B_\ell^{\rm o} = E_\ell \sin(2\beta) + B_\ell \cos(2\beta)$$

Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)
Zhao et al. (2015)

Searching for the birefringence

- Computing observed difference between EE and BB spectra,

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

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

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

- We find

$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

$$= \frac{1}{2}(\underline{C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}})\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

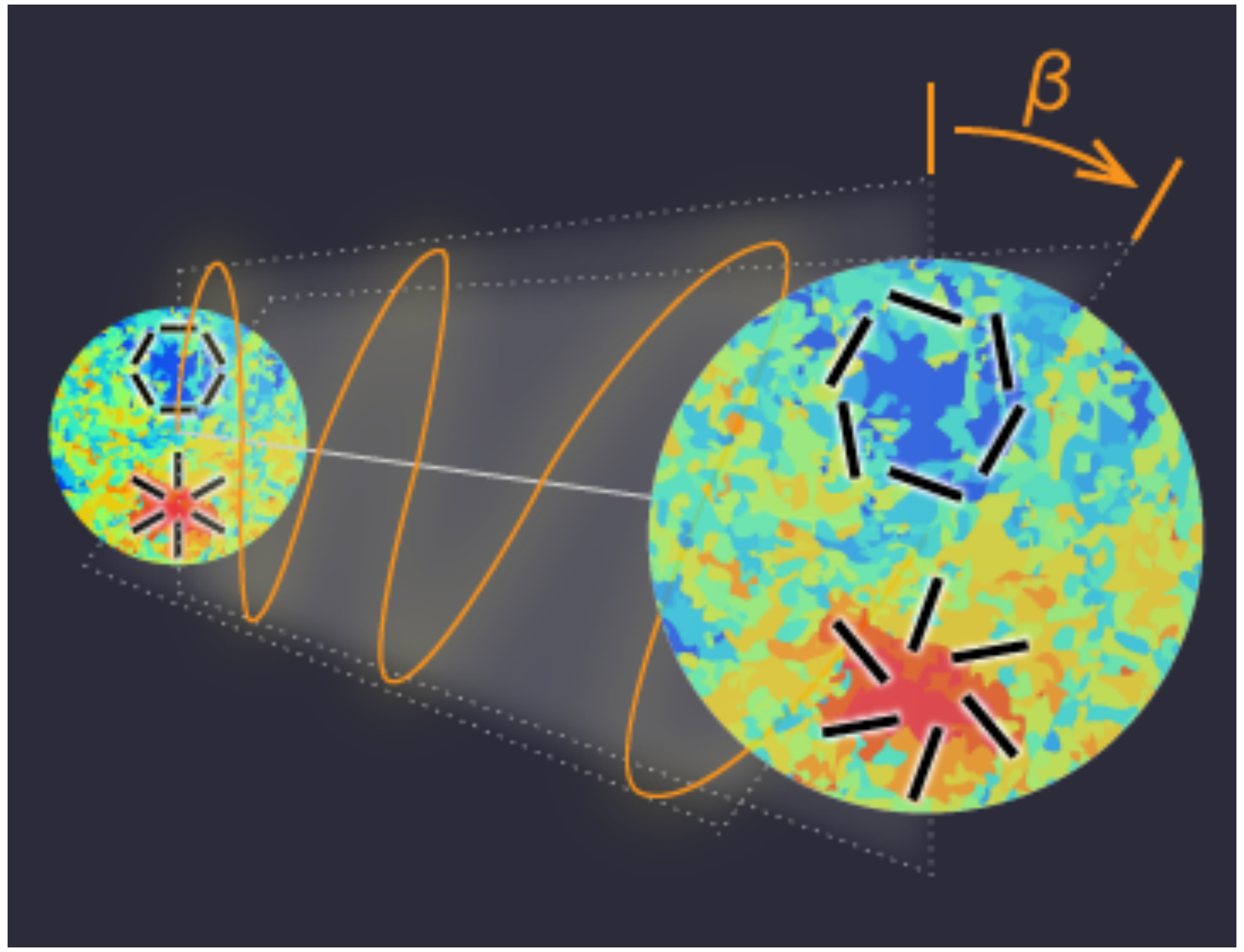
EB is generated by the *difference* between EE and BB spectra.

The Biggest Problem: Miscalibration of detectors

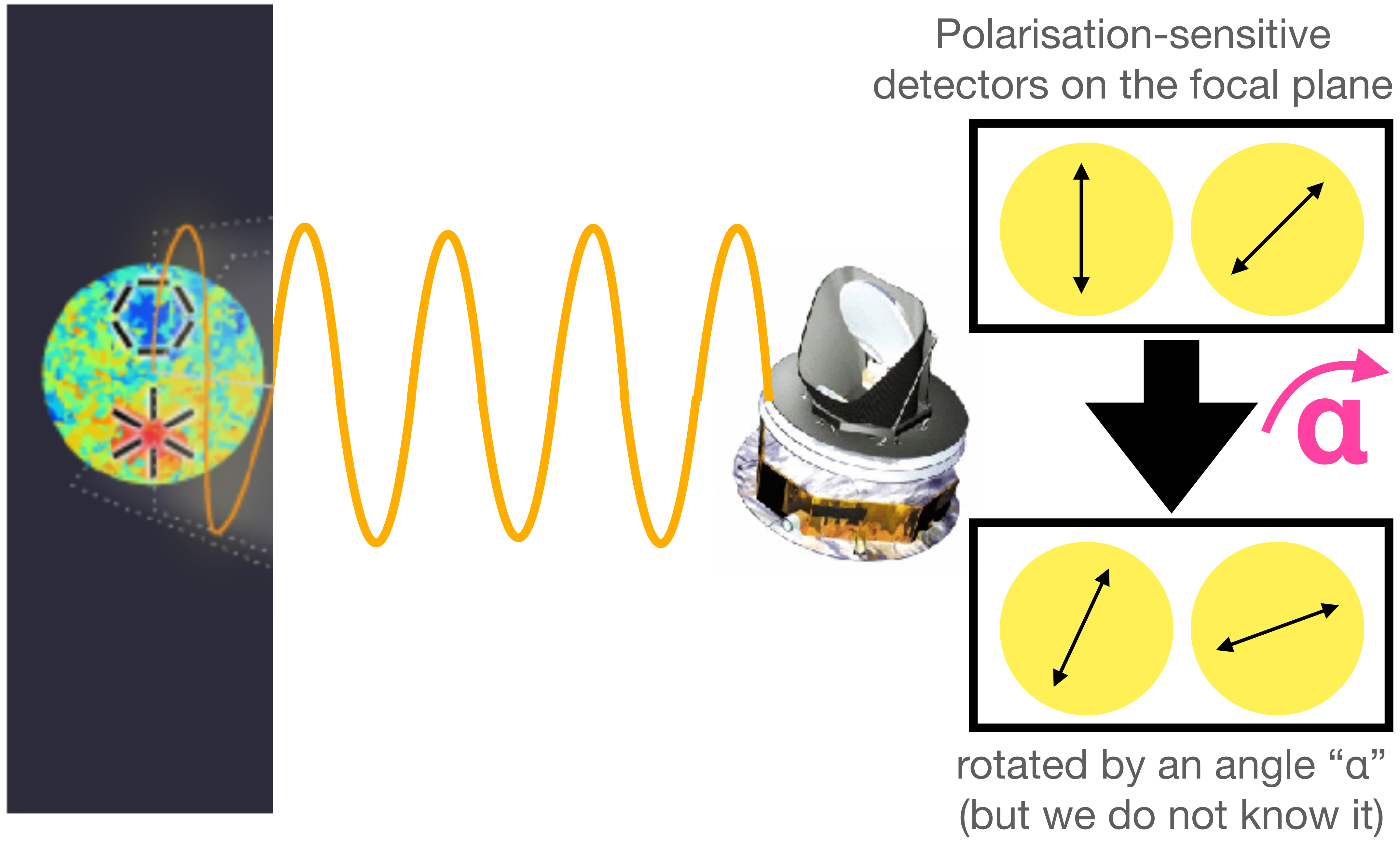
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

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 α+β**.

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

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

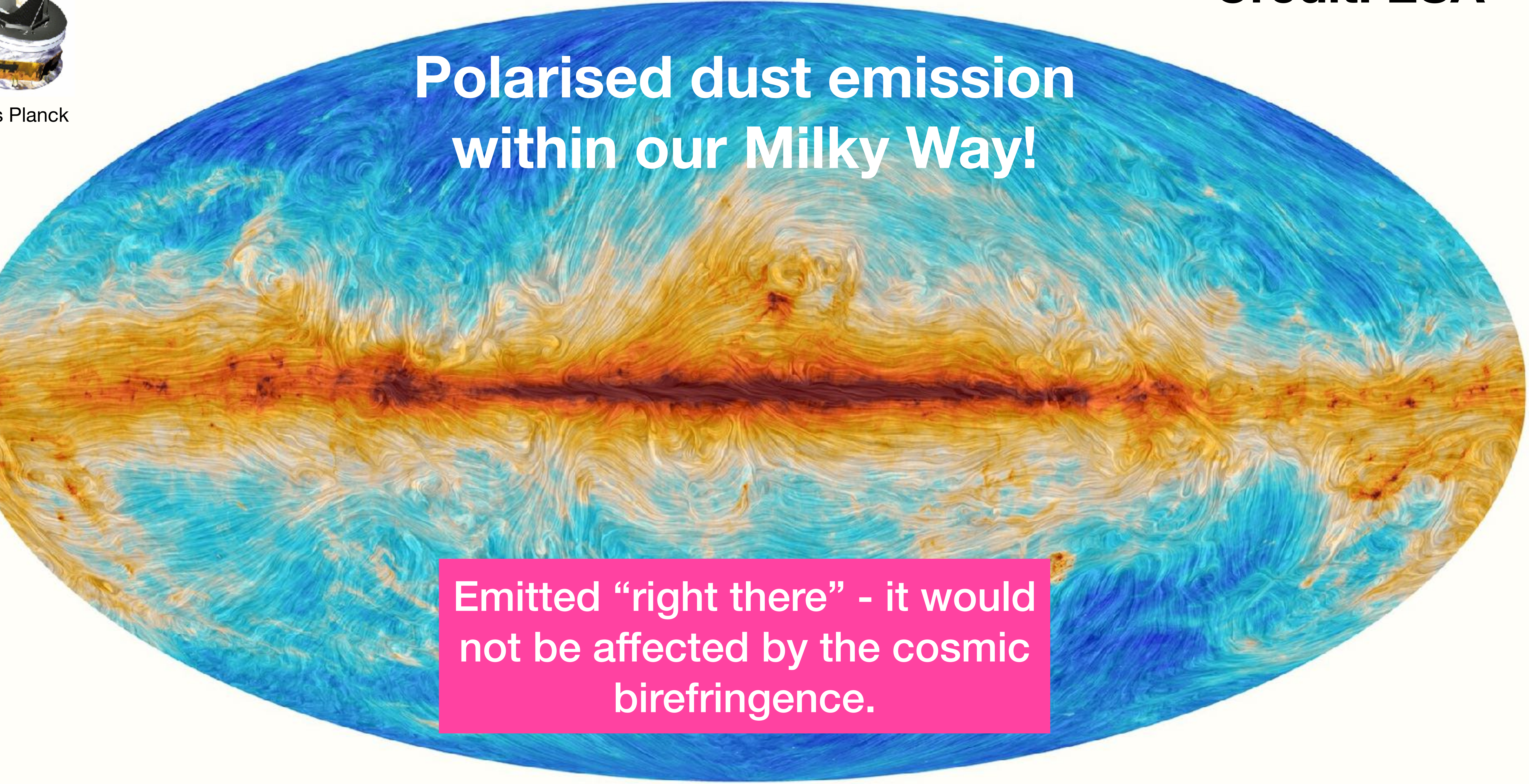
Uncertainty in the calibration of α has been the major limitation

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

Credit: ESA

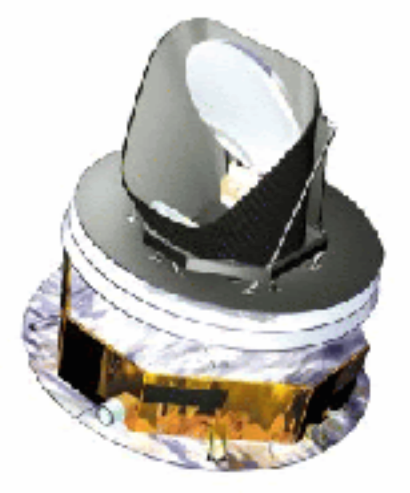
ESA’s Planck

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



ESA's Planck

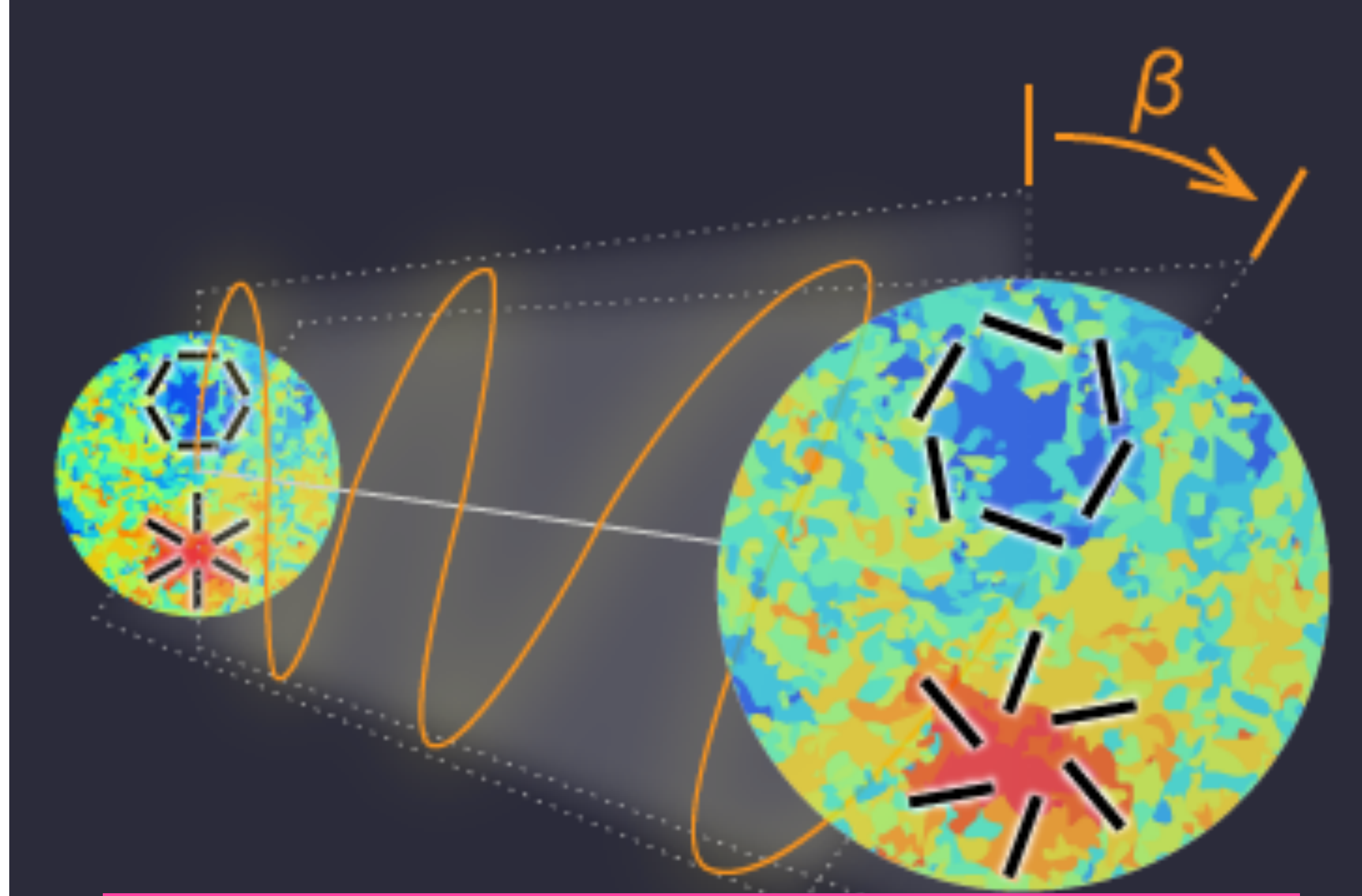
Credit: ESA

Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Searching for the birefringence

Improvement #2 (Minami et al. 2019)



Emitted 13.8 billions years ago

But the source of foreground is much closer!

- **<u>Idea:</u>** *Miscalibration of the polarization angle α rotates both the foreground and CMB, but β affects only the CMB.*

$$E^{\mathrm{o}}_{\ell,m} = E^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) - B^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) - B^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + E^{\mathrm{N}}_{\ell,m}$$

$$B^{\mathrm{o}}_{\ell,m} = E^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + B^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + B^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) + B^{\mathrm{N}}_{\ell,m}$$

noise

- Thus,

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

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

Assumption for the baseline result

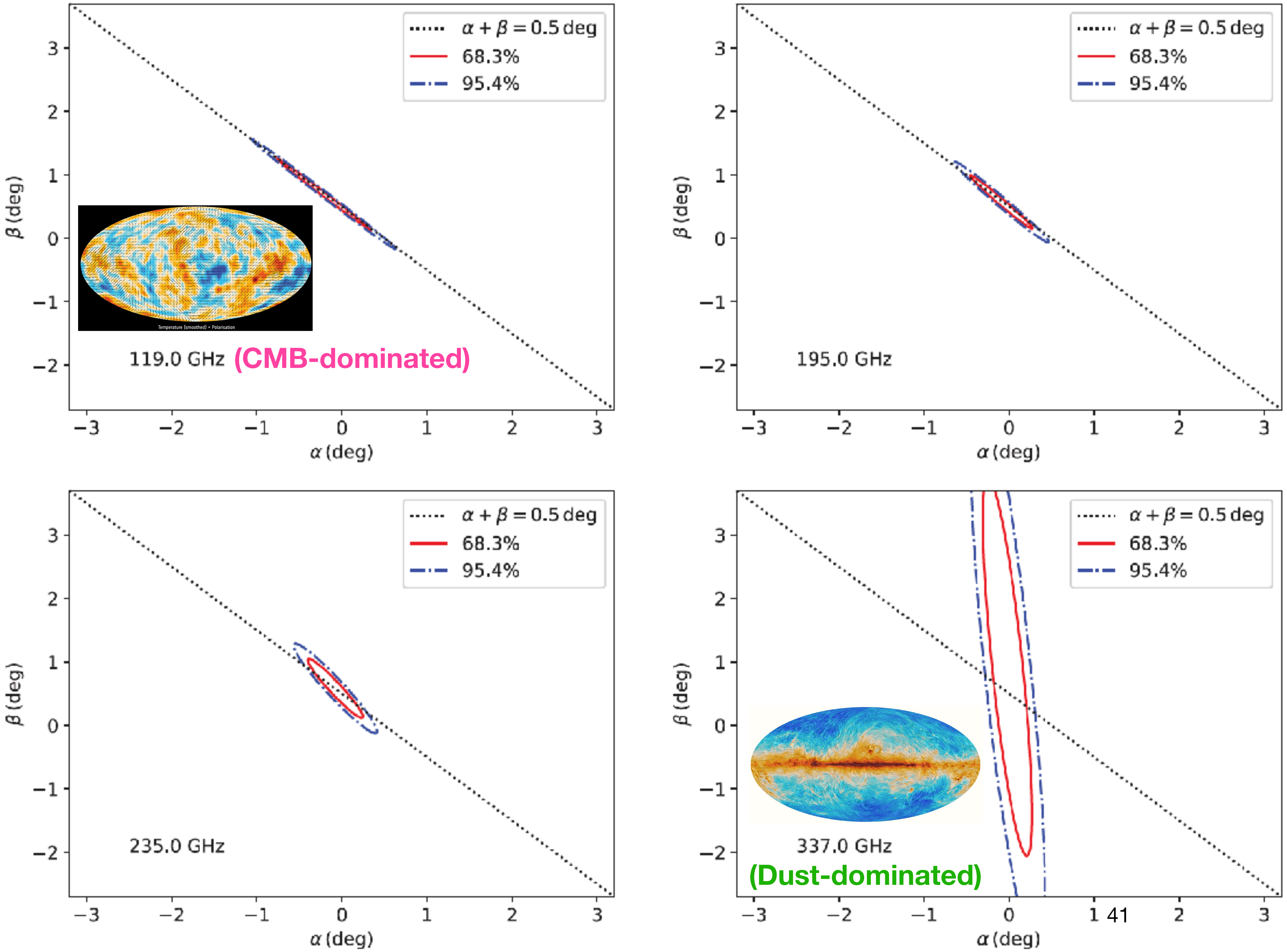
What about the intrinsic EB correlation of the foreground emission?

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

- For the baseline result, we ignore the intrinsic EB correlations of the foreground $\langle C_\ell^{EB,\mathrm{fg}}\rangle$ and the CMB $\langle C_\ell^{EB,\mathrm{CMB}}\rangle$.
  - 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, α+β, is determined precisely.
  - This is the diagonal line.
- The foreground determines α with some uncertainty, breaking the degeneracy. Then σ(β) ~ σ(α) because σ(α+β) << σ(α).
- When the data are dominated by the foreground, it can determine α but not β 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)

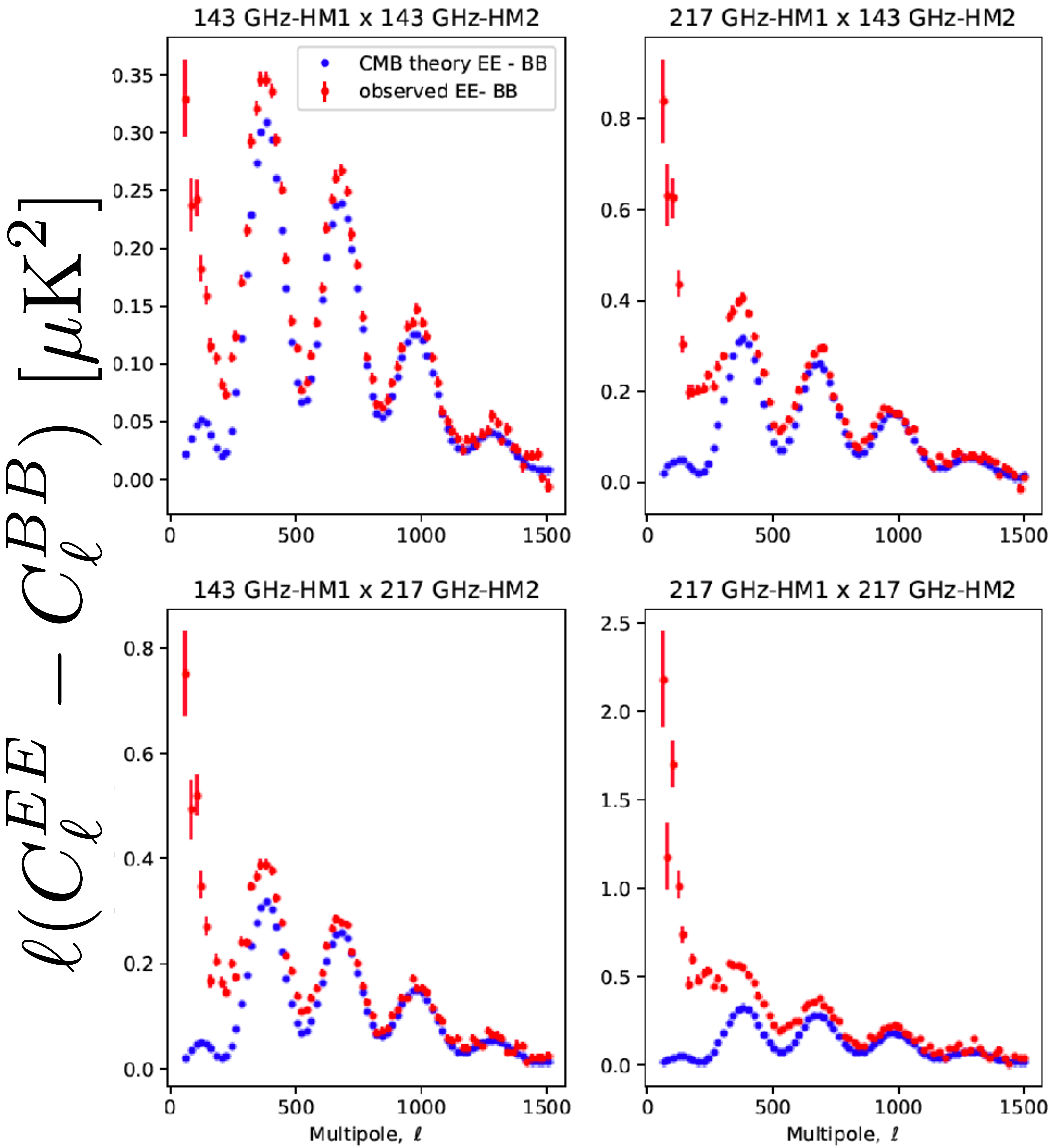
lmin = 51, lmax = 1490 (same as those used by the Planck team)

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

Main Result: β > 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

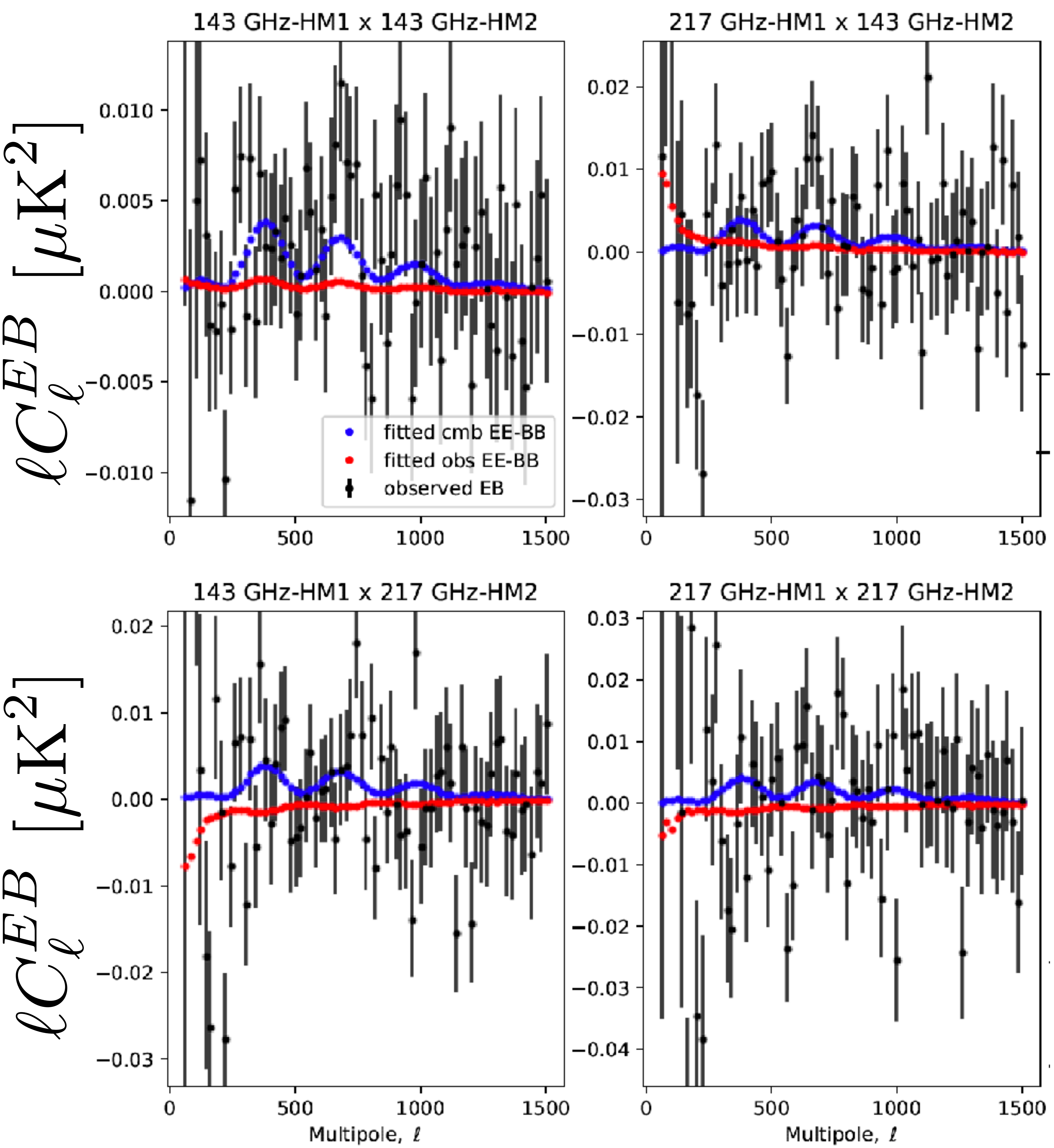
Angles	$\alpha_\nu=0$	Results (deg)
β	0.289 ± 0.048	0.35 ± 0.14
α_{100}	(This agrees with the result of the Planck team)	-0.28 ± 0.13
α_{143}		0.07 ± 0.12
α_{217}		-0.07 ± 0.11
α_{353}		-0.09 ± 0.11



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

- Can we see β = 0.35 ± 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)*

Minami & Komatsu (2020b)



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

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

Angles	Results (deg)
β	0.35 ± 0.14
α_{100}	-0.28 ± 0.13
α_{143}	0.07 ± 0.12
α_{217}	-0.07 ± 0.11
α_{353}	-0.09 ± 0.11

How about the foreground EB?

- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle α.
- Thus, α -> $\alpha+\gamma$, 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 $TE_{dust} > 0$ and $TB_{dust} > 0$. Then, we'd expect $EB_{dust} > 0$ (Huffenberger et al. 2020), i.e., $\gamma>0$. If so, β increases further…

Diego-Palazuelos, Eskilt, et al., arXiv:2201.07682, to appear in PRL

PHYSICAL REVIEW LETTERS

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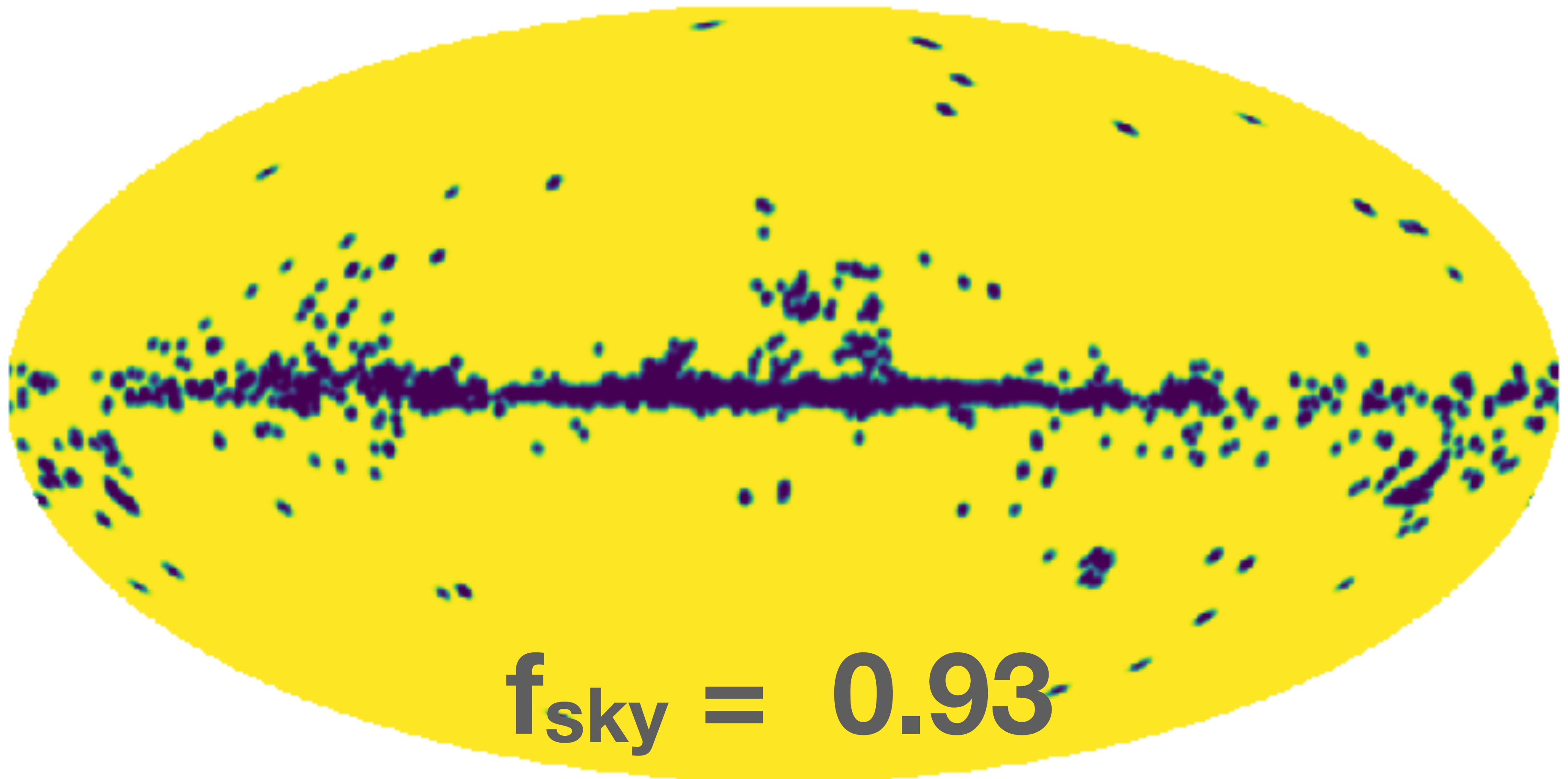
Double corresponding authors.
PhD students. *Young power!*

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 <u>lower noise</u>** 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)

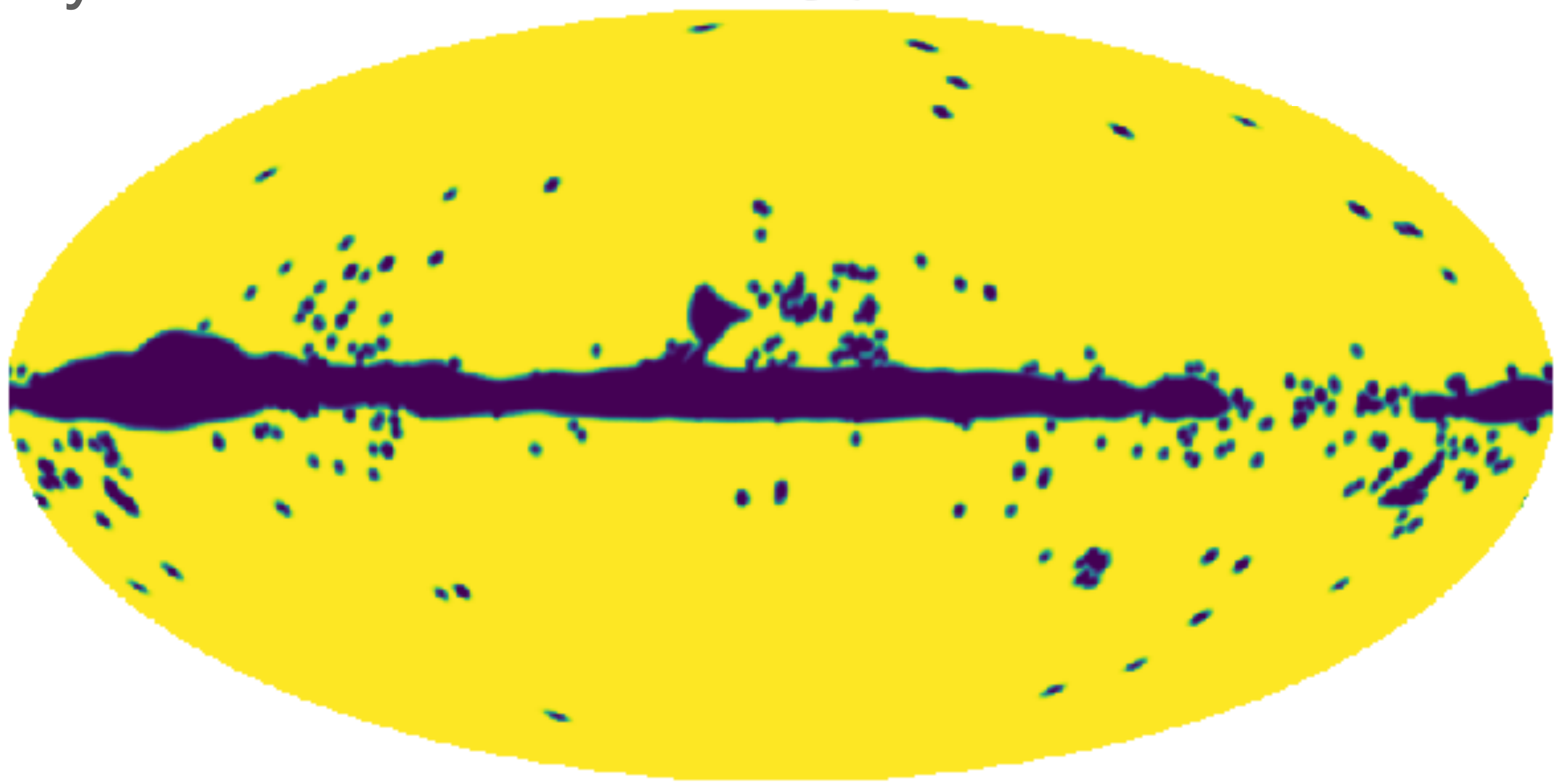


f_{sky} = 0.93

= nearly full sky

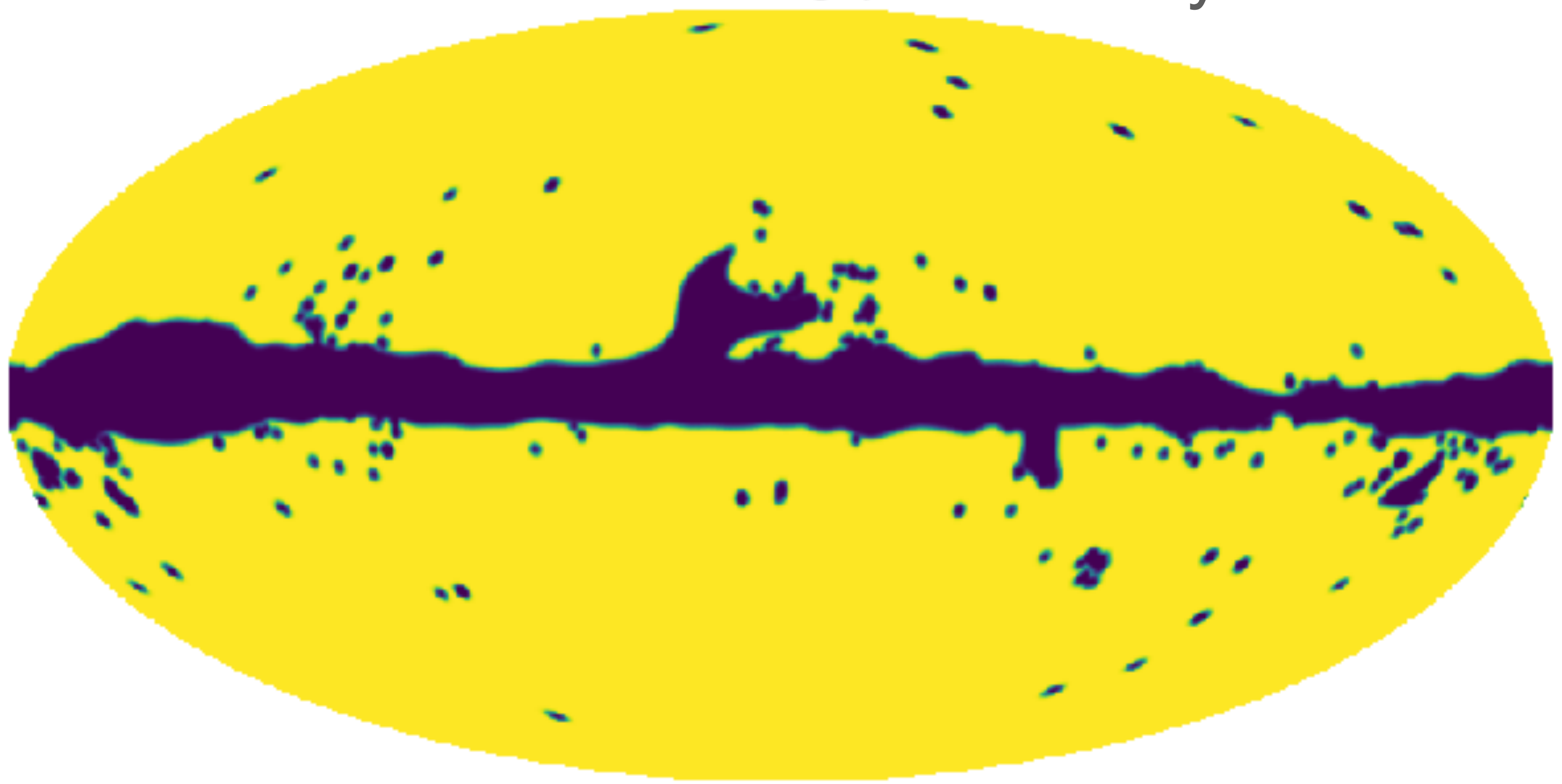
f_{sky} = 0.90

CO+PS+5% (1deg apodization)



CO+PS+10% (1deg apodization)

f_{sky} = 0.85



CO+PS+20% (1deg apodization)

f_{sky} = 0.75

CO+PS+30% (1deg apodization)

f_{sky} = 0.63

Diego-Palazuelos, Eskilt, et al. (2022)

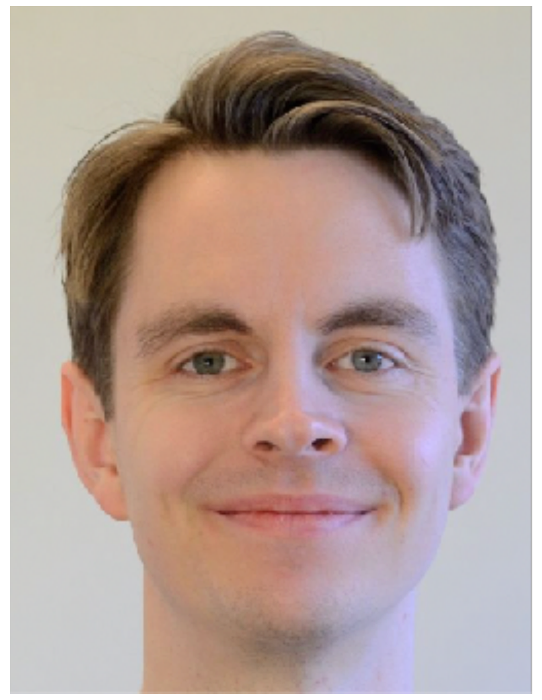
Full-sky result, without accounting for foreground EB

The PR3 result confirmed, with smaller statistical uncertainty

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

PDP

JRE



YM

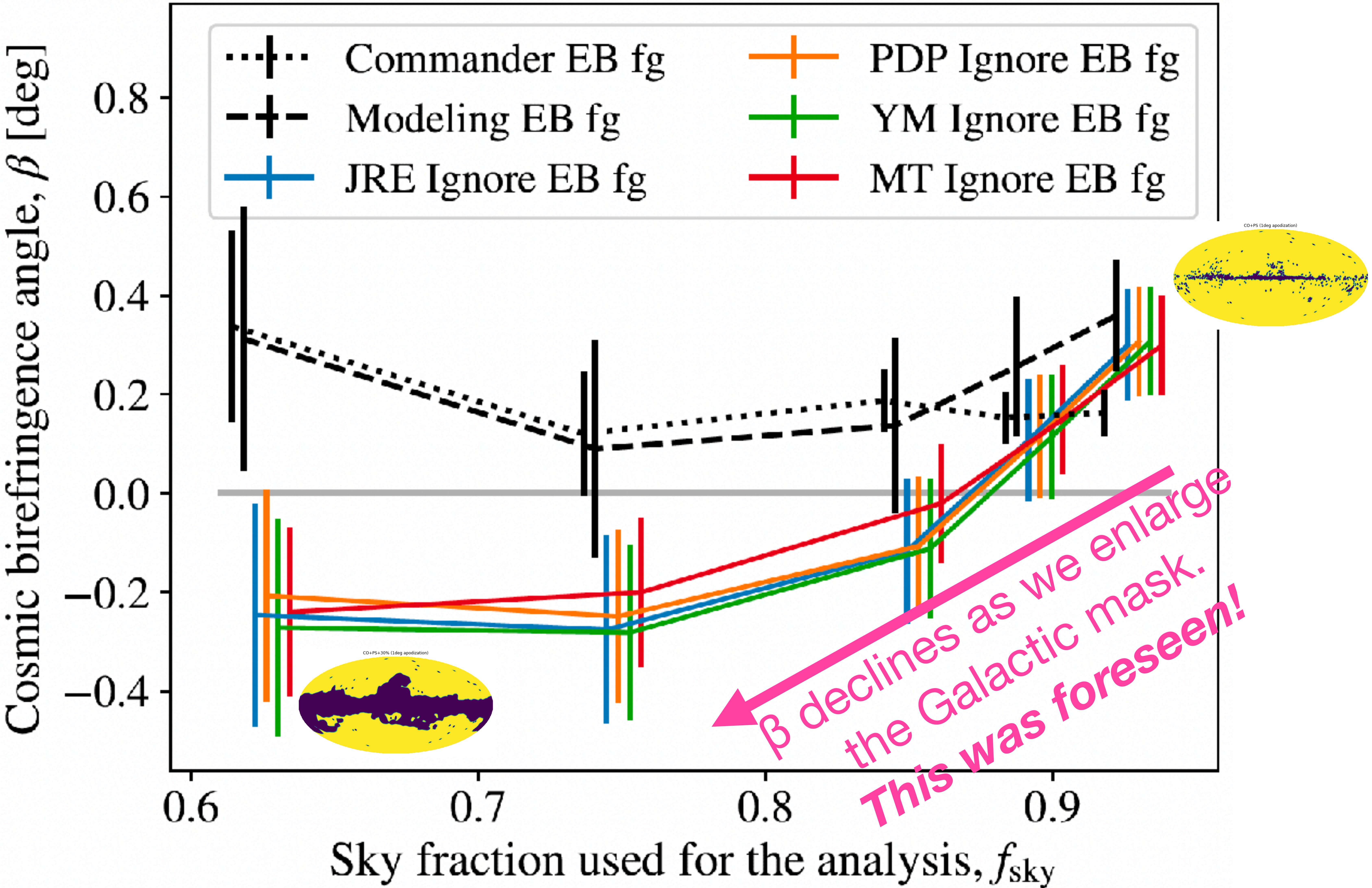
MT

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

Diego-Palazuelos, Eskilt, et al. (2022)

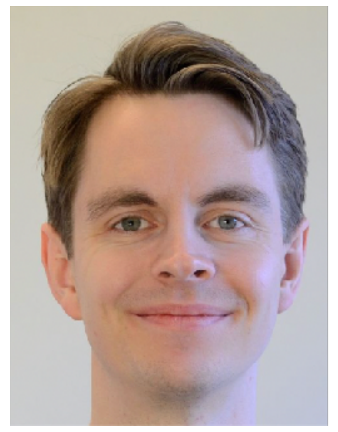
How do the results change with f_{sky}?

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

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

- 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

α -> α+γ

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

Minami et al. (2019); Minami & Komatsu (2020b); Diego-Palazuelos, Eskilt, et al. (2022)

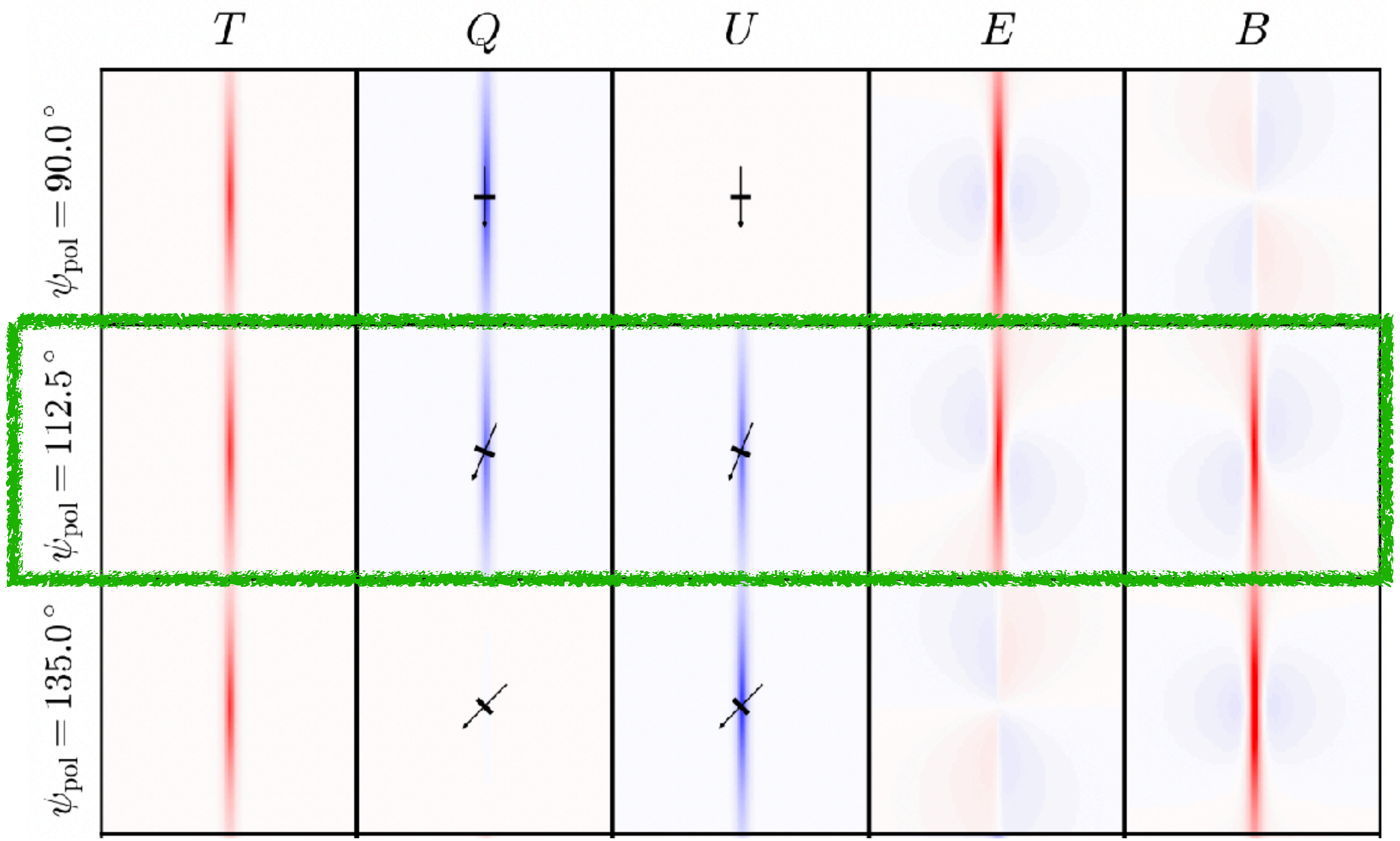
Relating EB to TB

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 Huffenberger 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 & Colins (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):

$$\begin{cases} C_\ell^{EB,\mathrm{dust}} = \boxed{A_\ell} C_\ell^{EE,\mathrm{dust}} \sin(4\psi_\ell^{\mathrm{dust}}) \\ \psi_\ell^{\mathrm{dust}} = \frac{1}{2}\arctan(C_\ell^{TB,\mathrm{dust}}/C_\ell^{TE,\mathrm{dust}}) \end{cases}$$

Free l-dependent amplitude parameters

  - Then

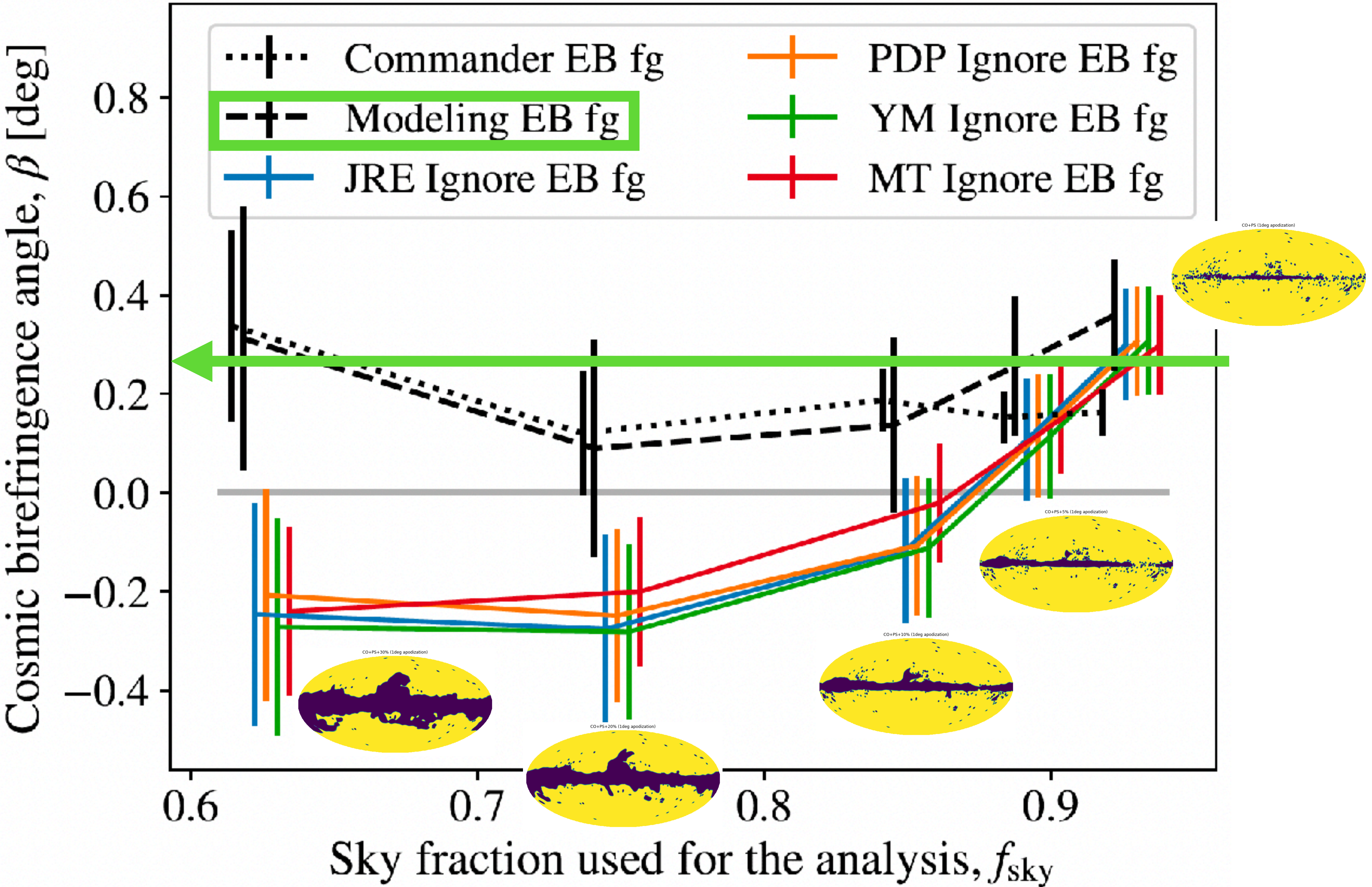
$$\boxed{\gamma_\ell \simeq \frac{A_\ell C_\ell^{EE,\mathrm{dust}}}{C_\ell^{EE,\mathrm{dust}} - C_\ell^{BB,\mathrm{dust}}} \frac{C_\ell^{TB,\mathrm{dust}}}{C_\ell^{TE,\mathrm{dust}}}}$$

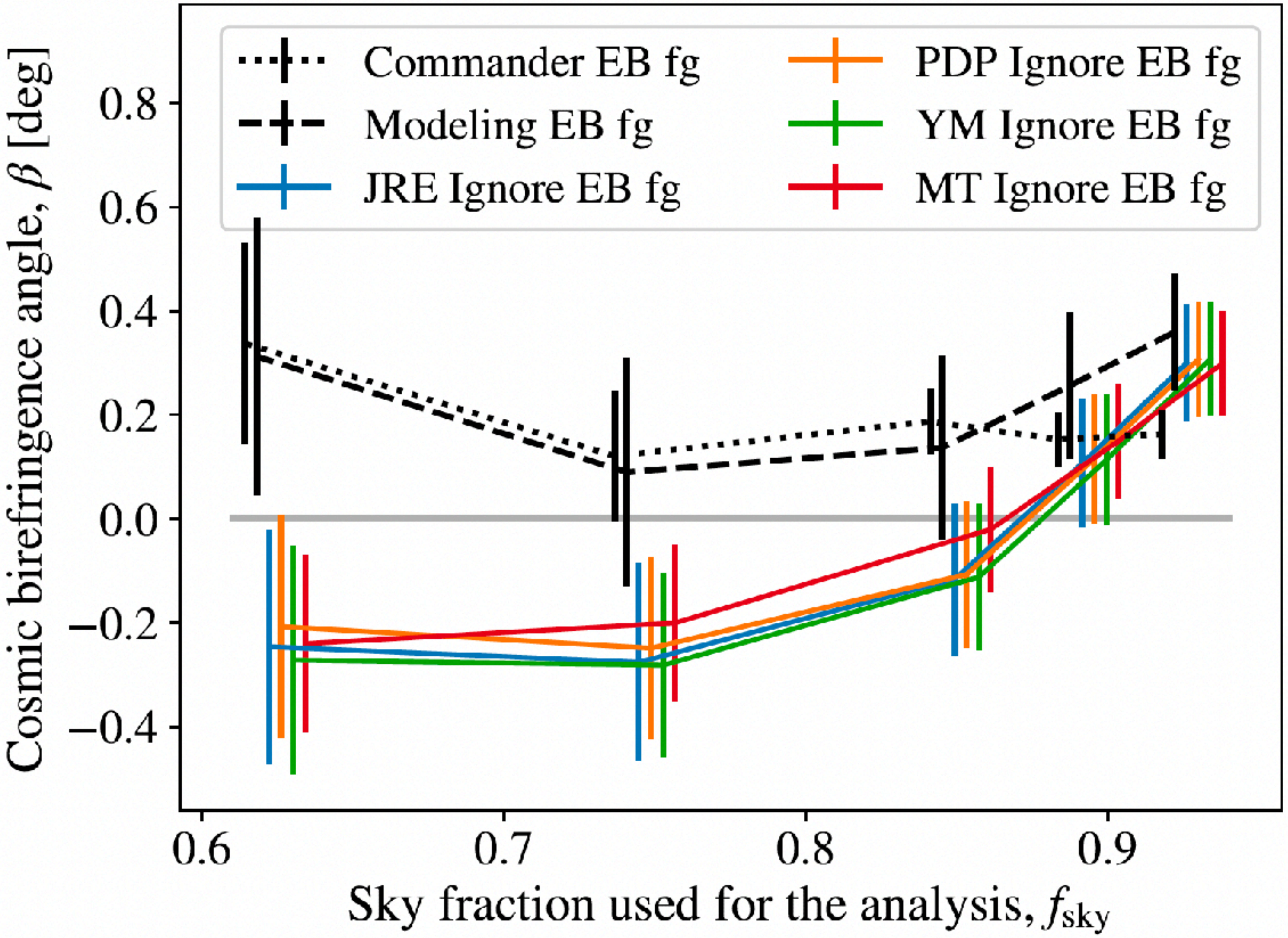
for small angles.

Diego-Palazuelos, Eskilt, et al. (2022)

Dashed line: Modeling the foreground EB

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





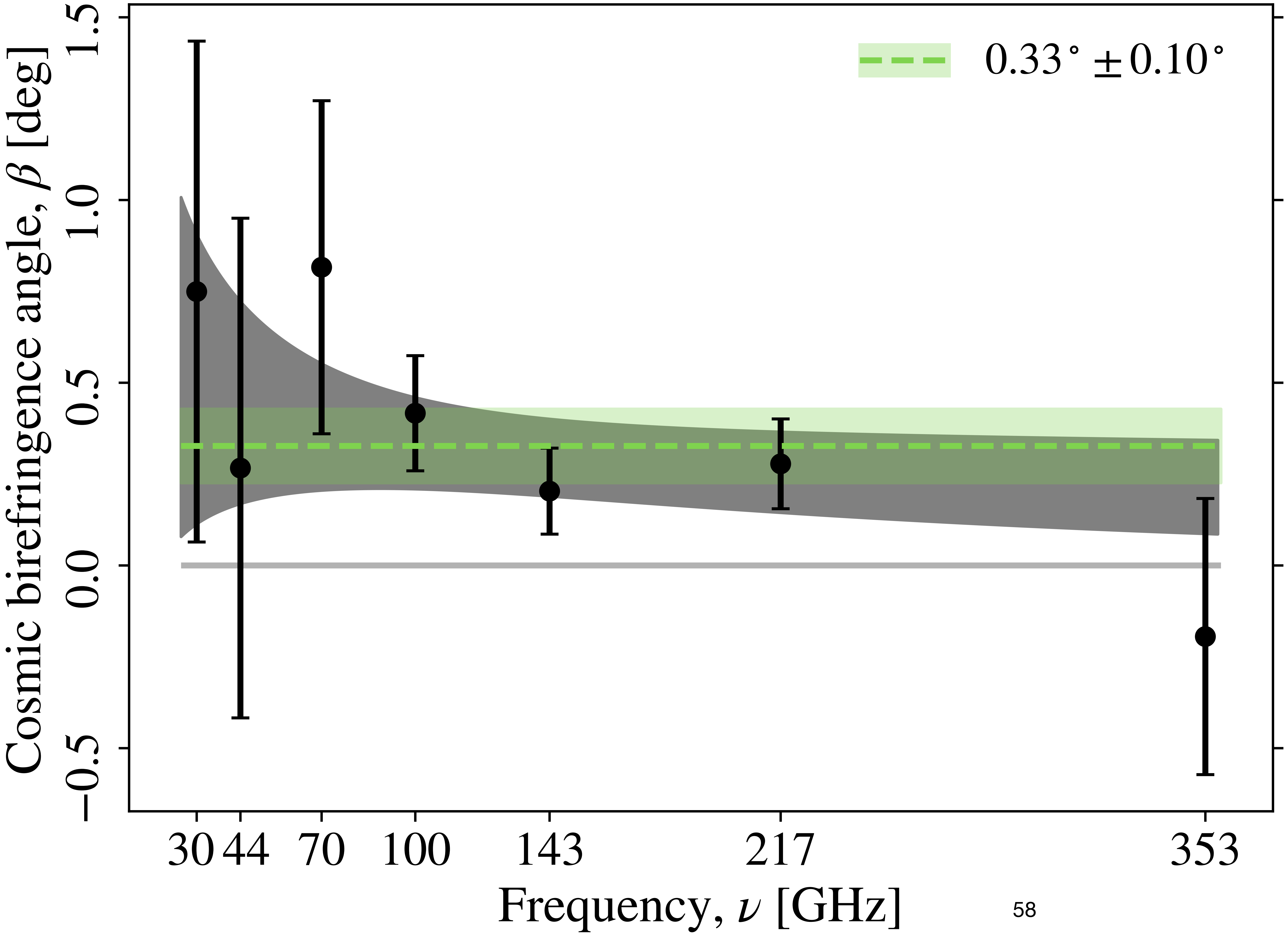
$f_{\rm sky}$	0.93
β	$\boxed{0.36 \pm 0.11}$
α_{100A}	-0.32 ± 0.13
α_{100B}	-0.43 ± 0.13
α_{143A}	0.03 ± 0.11
α_{143B}	0.15 ± 0.11
α_{217A}	-0.06 ± 0.11
α_{217B}	-0.07 ± 0.11
α_{353A}	-0.19 ± 0.10
α_{353B}	-0.23 ± 0.11
$10^2 A_{51-130}$	$2.5^{+1.6}_{-1.4}$
$10^2 A_{131-210}$	$0.8^{+1.2}_{-0.6}$
$10^2 A_{211-510}$	$1.5^{+2.4}_{-1.1}$
$10^2 A_{511-1490}$	$6.2^{+5.7}_{-4.1}$

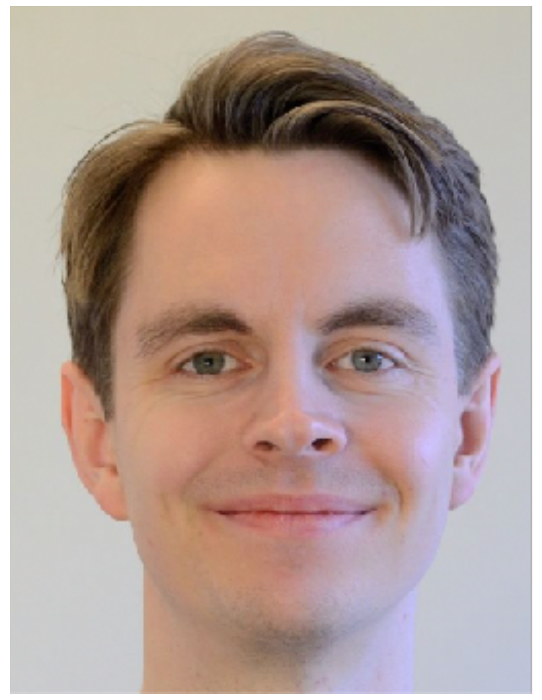
- As foreseen, accounting for the foreground EB **increased** β from 0.30 to 0.36 for nearly full-sky data.
  - Which $f_{\rm sky}$ we should choose for the final result? **We do not know yet.** We need more investigation.
  - We need help from Galactic astrophysics! It is a fascinating subject.

Eskilt, arXiv:2201.13347

No frequency dependence is found

Consistent with the expectation from cosmic birefringence

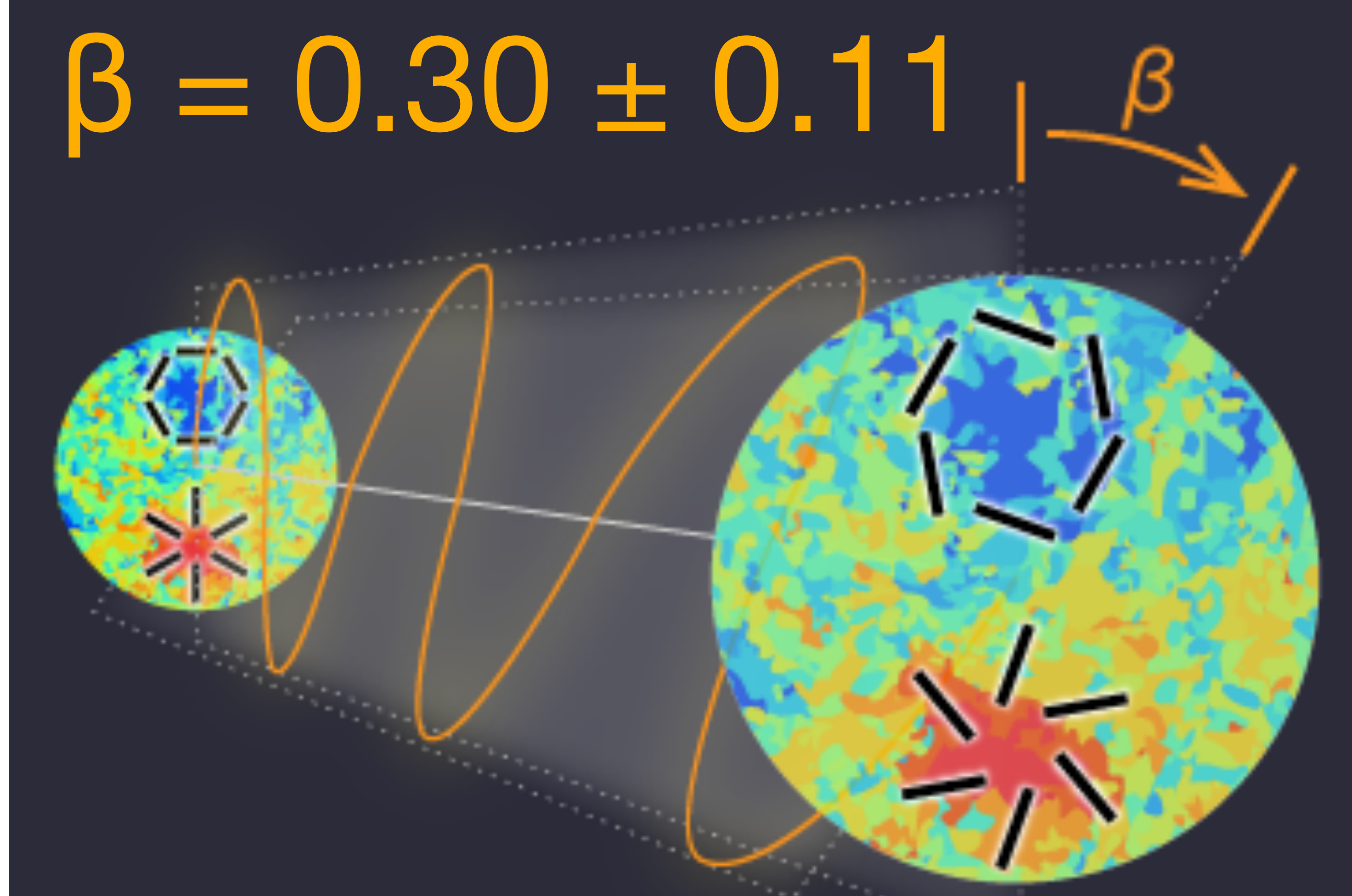




- Johannes R. Eskilt measured β separately at all of 7 Planck polarised frequency bands.
- No evidence for frequency dependence:
  - For $\beta \sim (\nu/150\text{GHz})^n$, $n = -0.35^{+0.48}_{-0.47}$ (68% CL)
  - Faraday rotation (n=–2) is disfavoured.

Conclusion

β = 0.30 ± 0.11 (68%CL; nearly full sky)



- Modeling the foreground EB, we find β=0.36 ± 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), *β=0.33 ± 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.