



Cosmic Birefringence

A New Probe of Dark Matter and Dark Energy

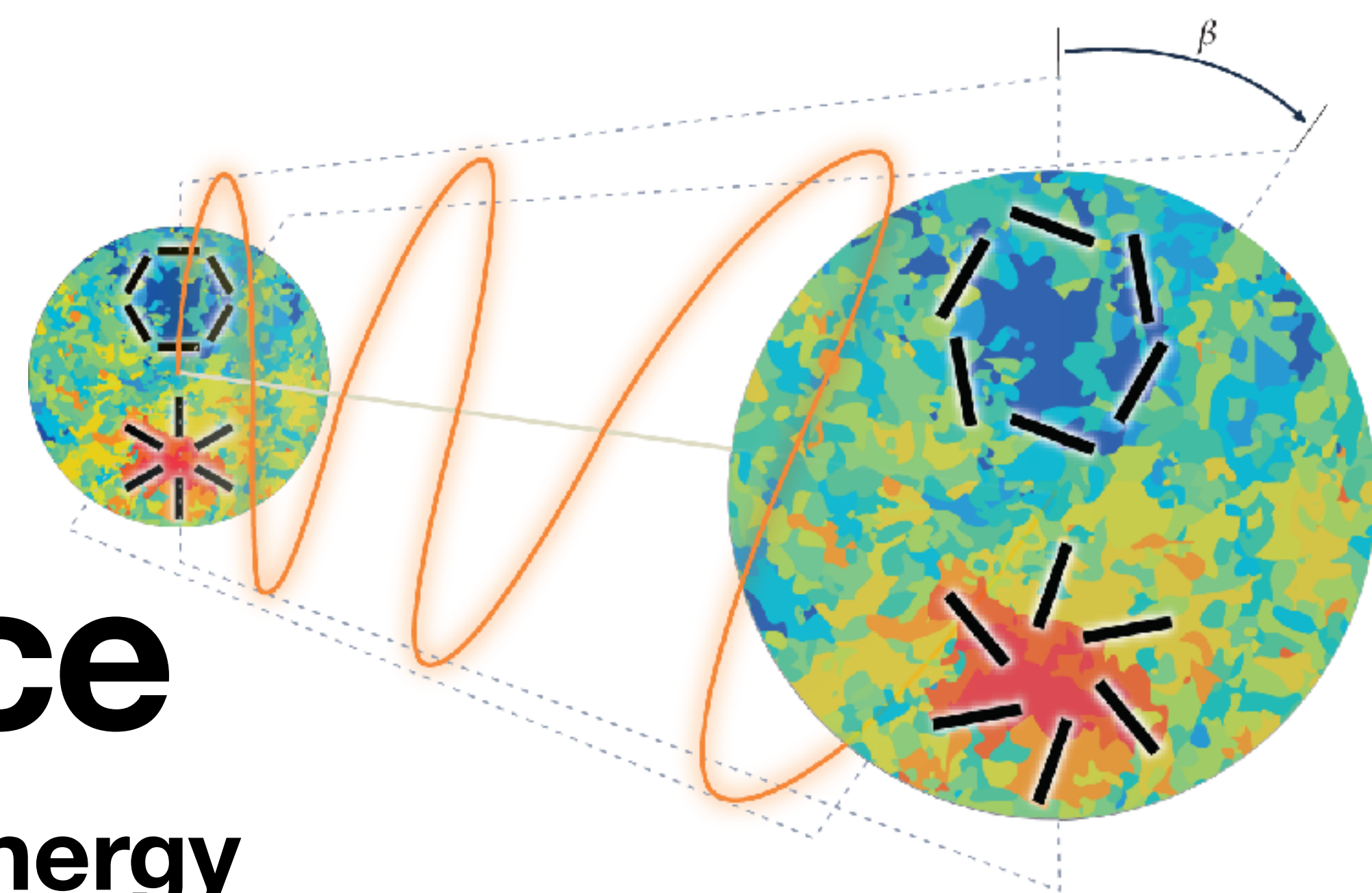
based on

- *Minami & EK, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, Minami, et al., PRL, 128, 091302 (2022)*
- *EK, Nature Reviews Physics, 4 (2022)*
- *Eskilt & EK, arXiv:2205.13962*

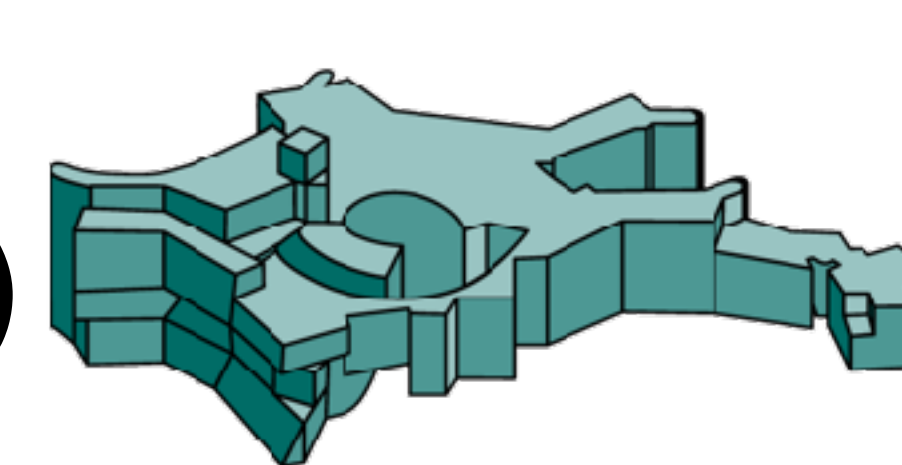
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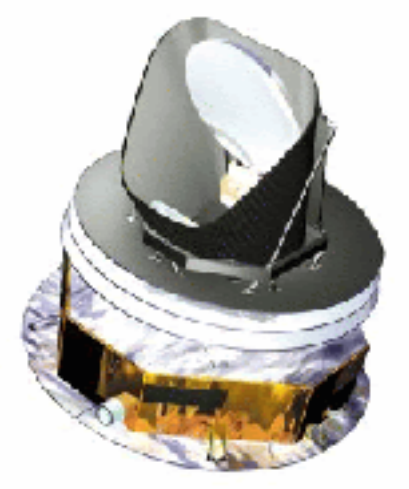
June 29, 2022



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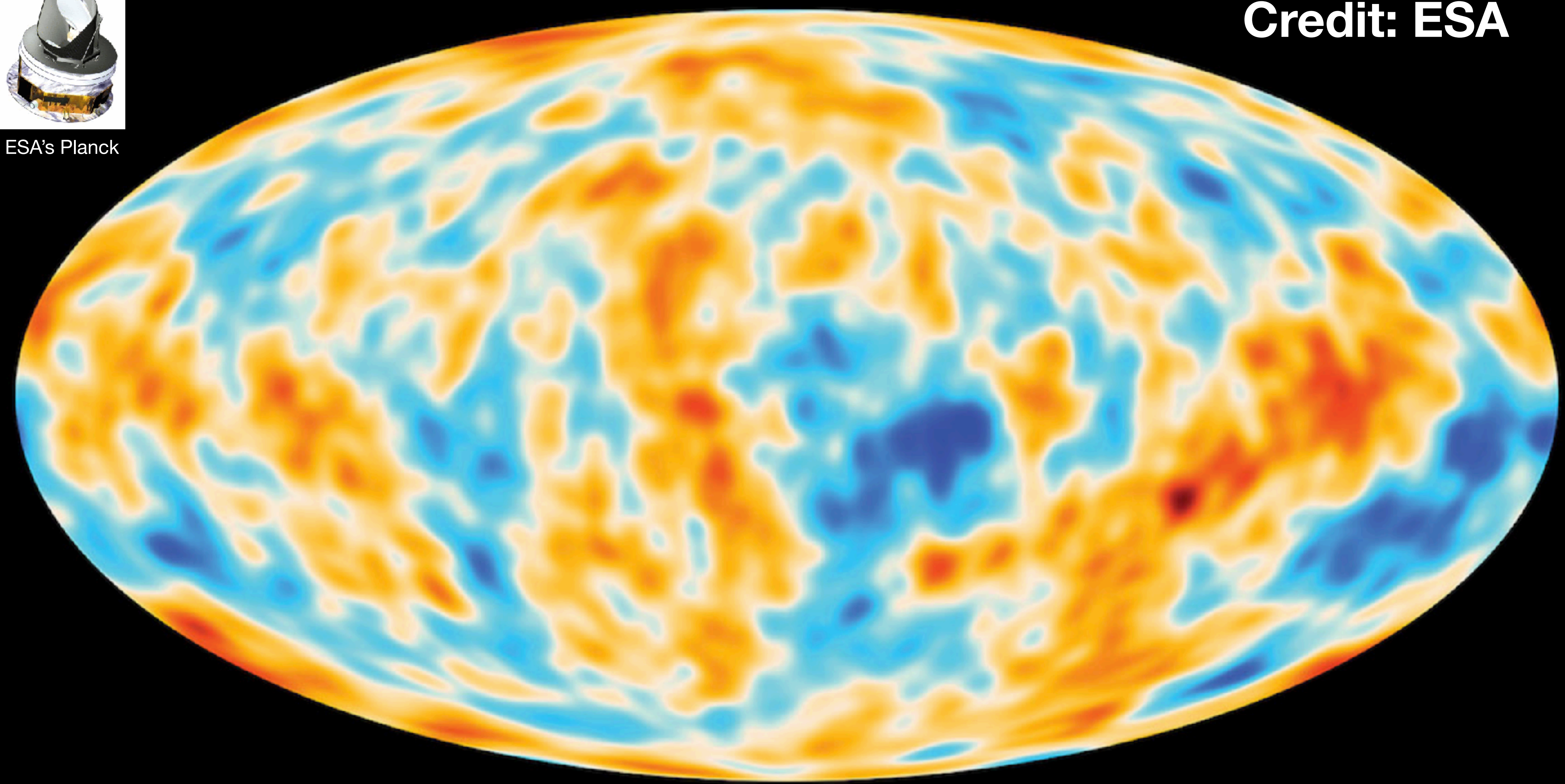


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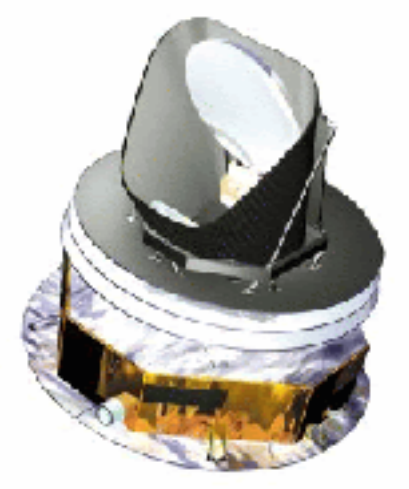
ESA's Planck

Credit: ESA



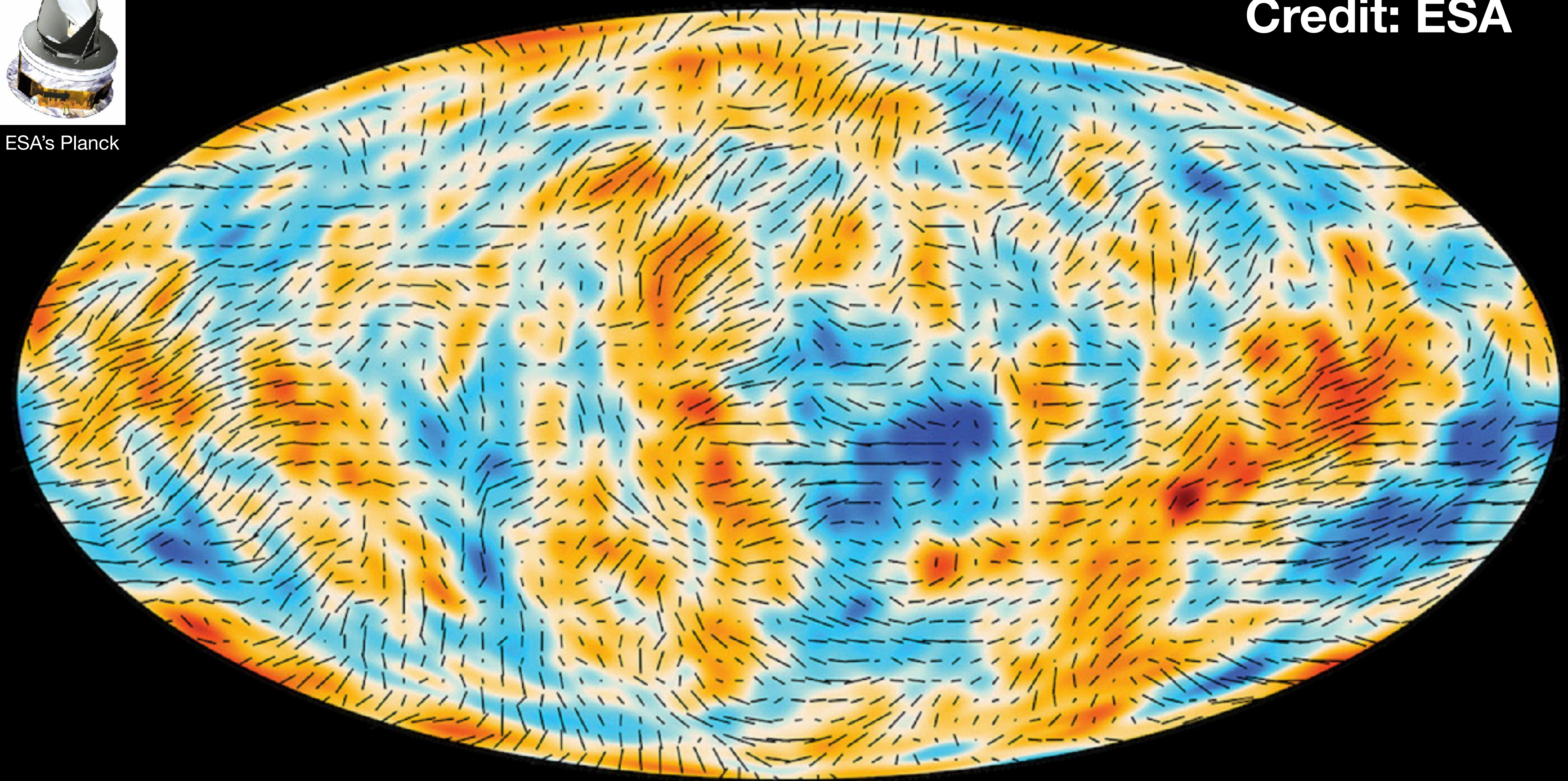
Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



ESA's Planck

Credit: ESA



Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

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

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- **Dark Sector:** What is dark matter (CDM)? What is dark energy (Λ)?
 - **Cosmic birefringence** in CMB polarisation
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- *Polarisation* of the CMB may hold the key to the answers.

[nature](#) > [nature reviews physics](#) > [review articles](#) > article

Review Article | [Published: 18 May 2022](#)

Available also at
arXiv:2202.13919

New physics from the polarized light of the cosmic microwave background

[Eiichiro Komatsu](#) 

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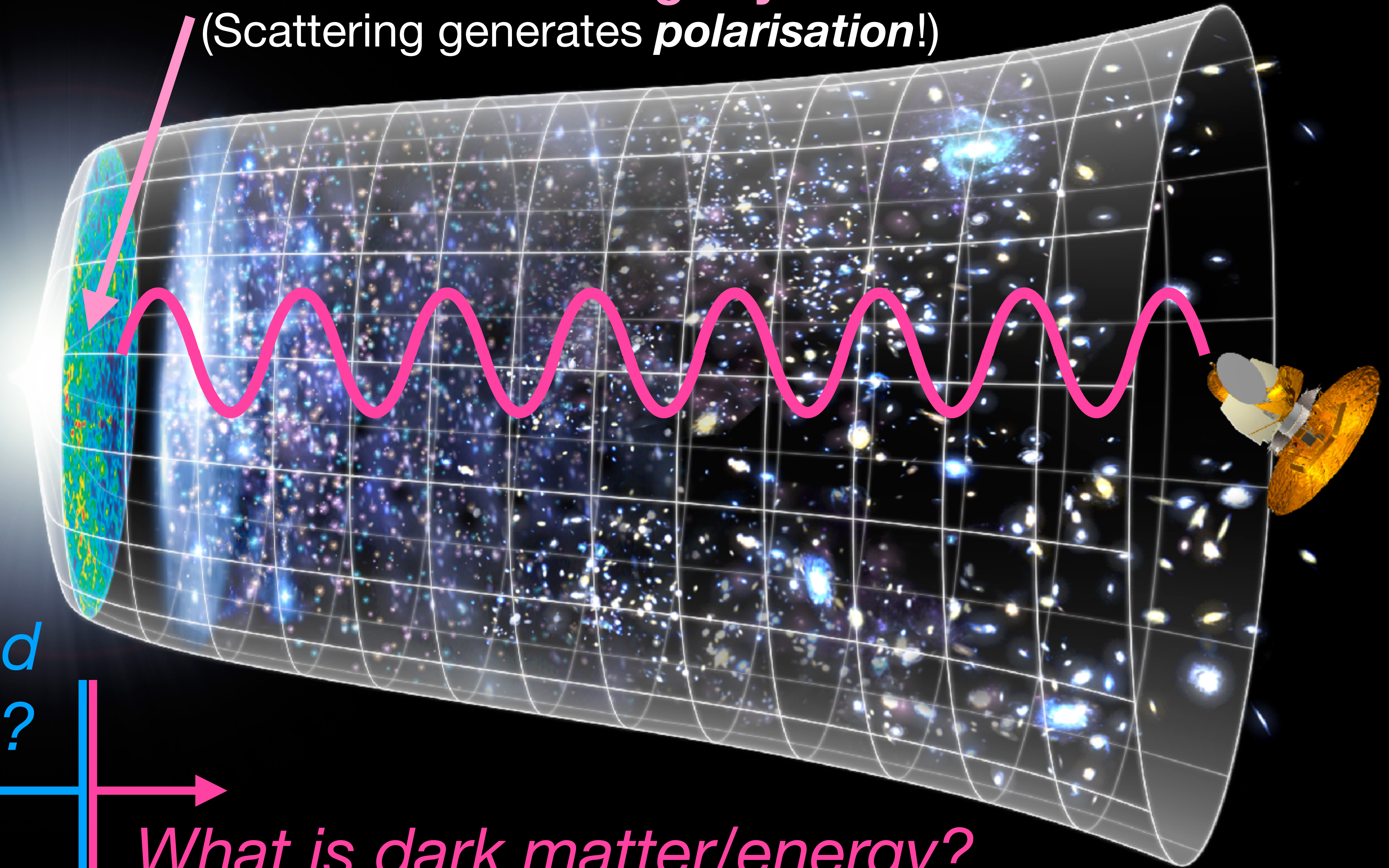
[Metrics](#)

Key Words:

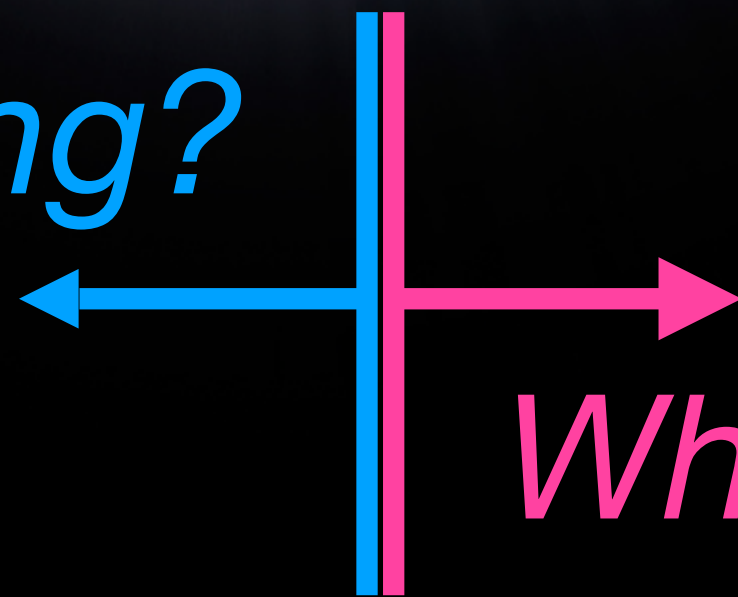
1. Cosmic Microwave Background (CMB)
2. Polarization
3. Parity Symmetry

The surface of “last scattering” by electrons

(Scattering generates *polarisation*!)

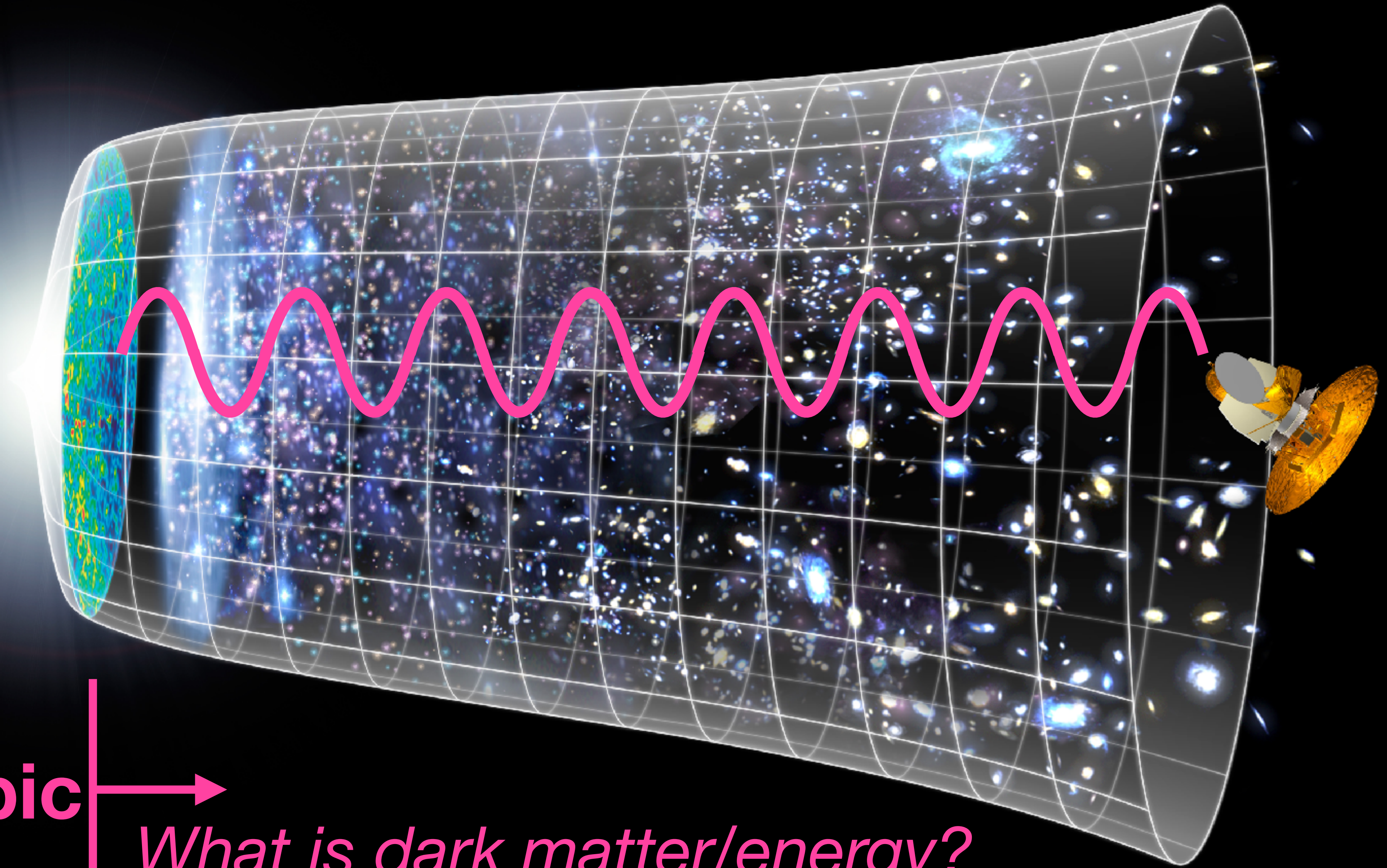


*What powered
the Big Bang?*



What is dark matter/energy?

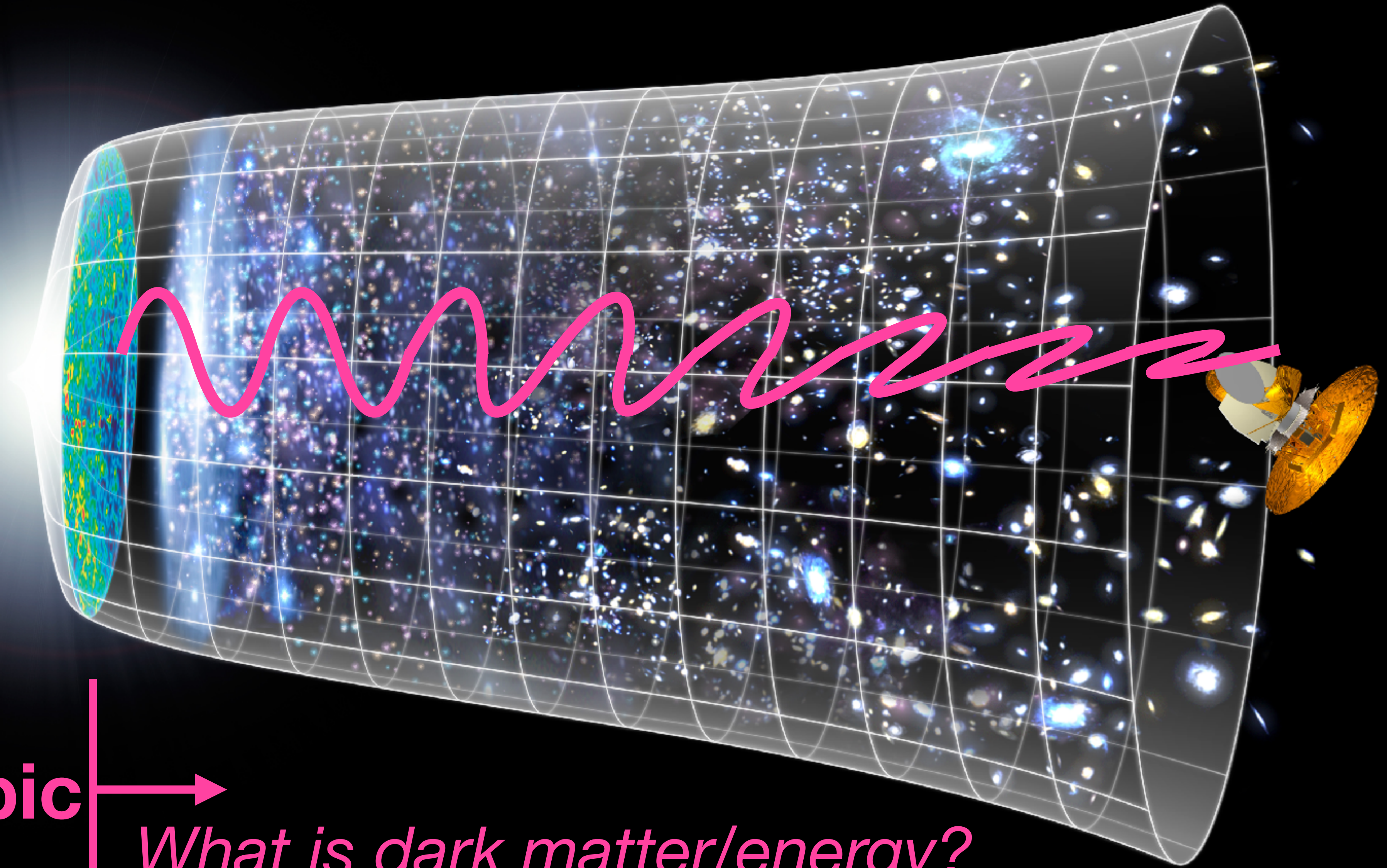
How does the electromagnetic wave of the CMB propagate?



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?*

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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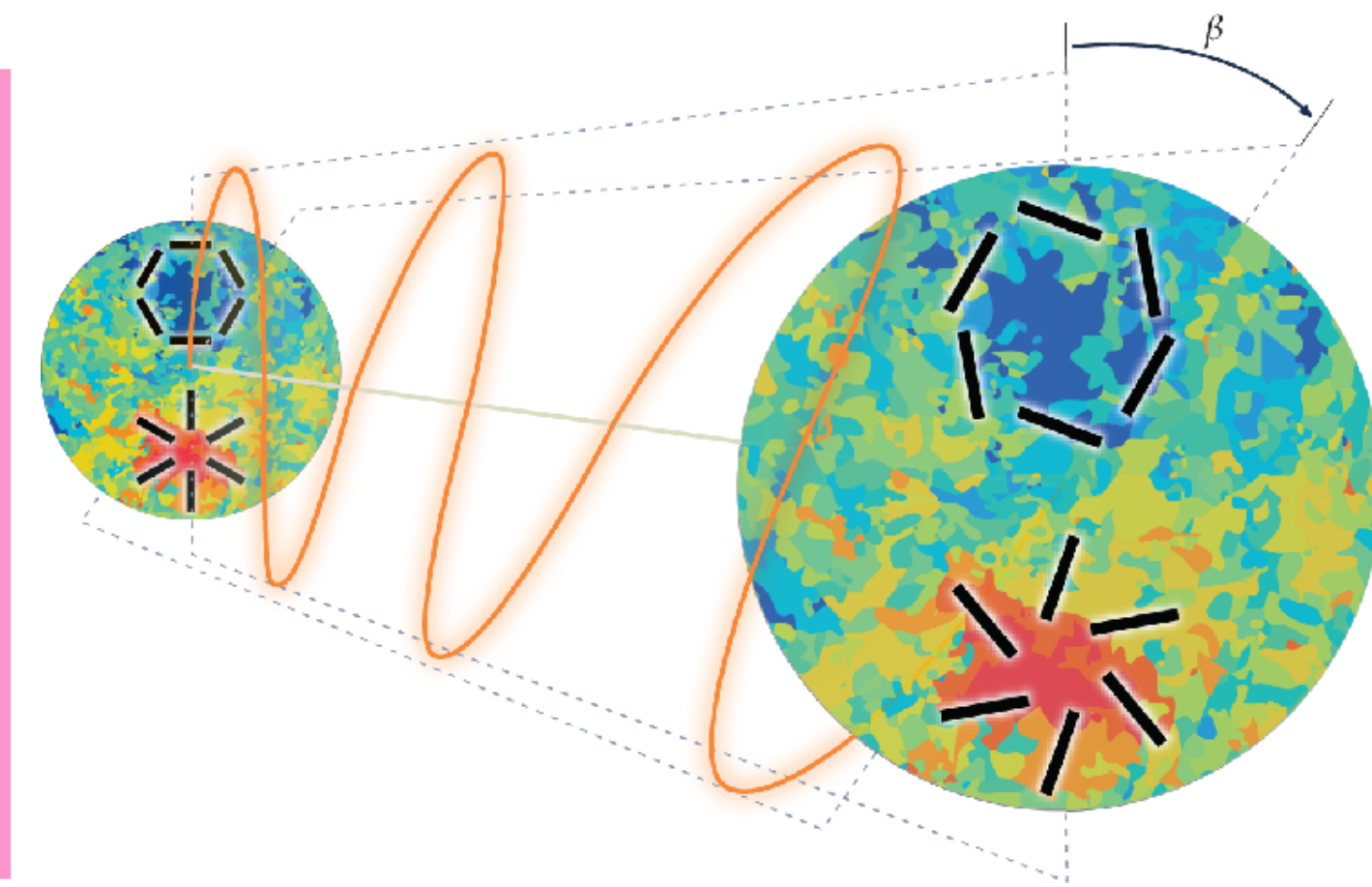
Chern-Simons term

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

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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.**



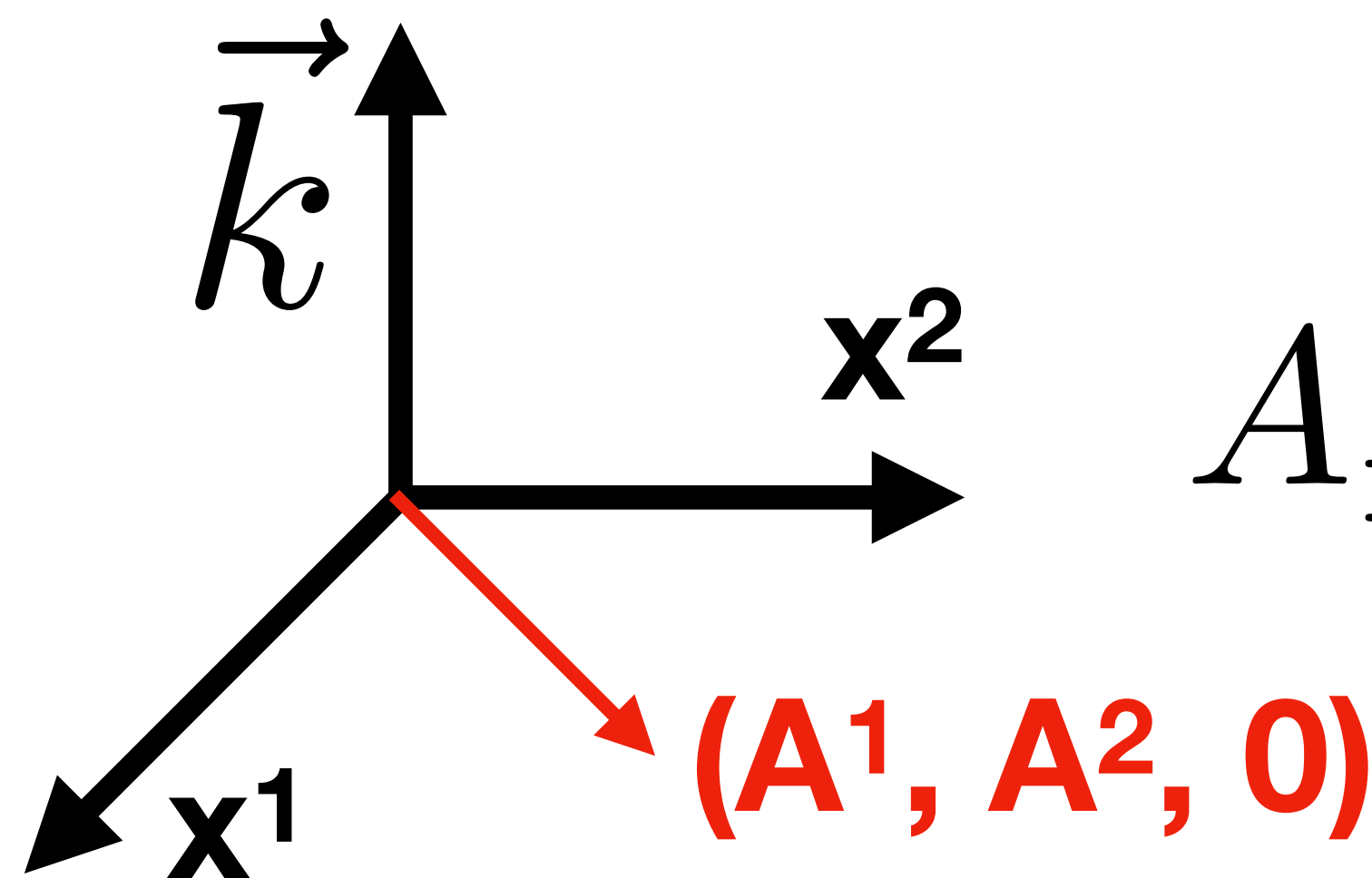
Standard Maxwell Theory

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

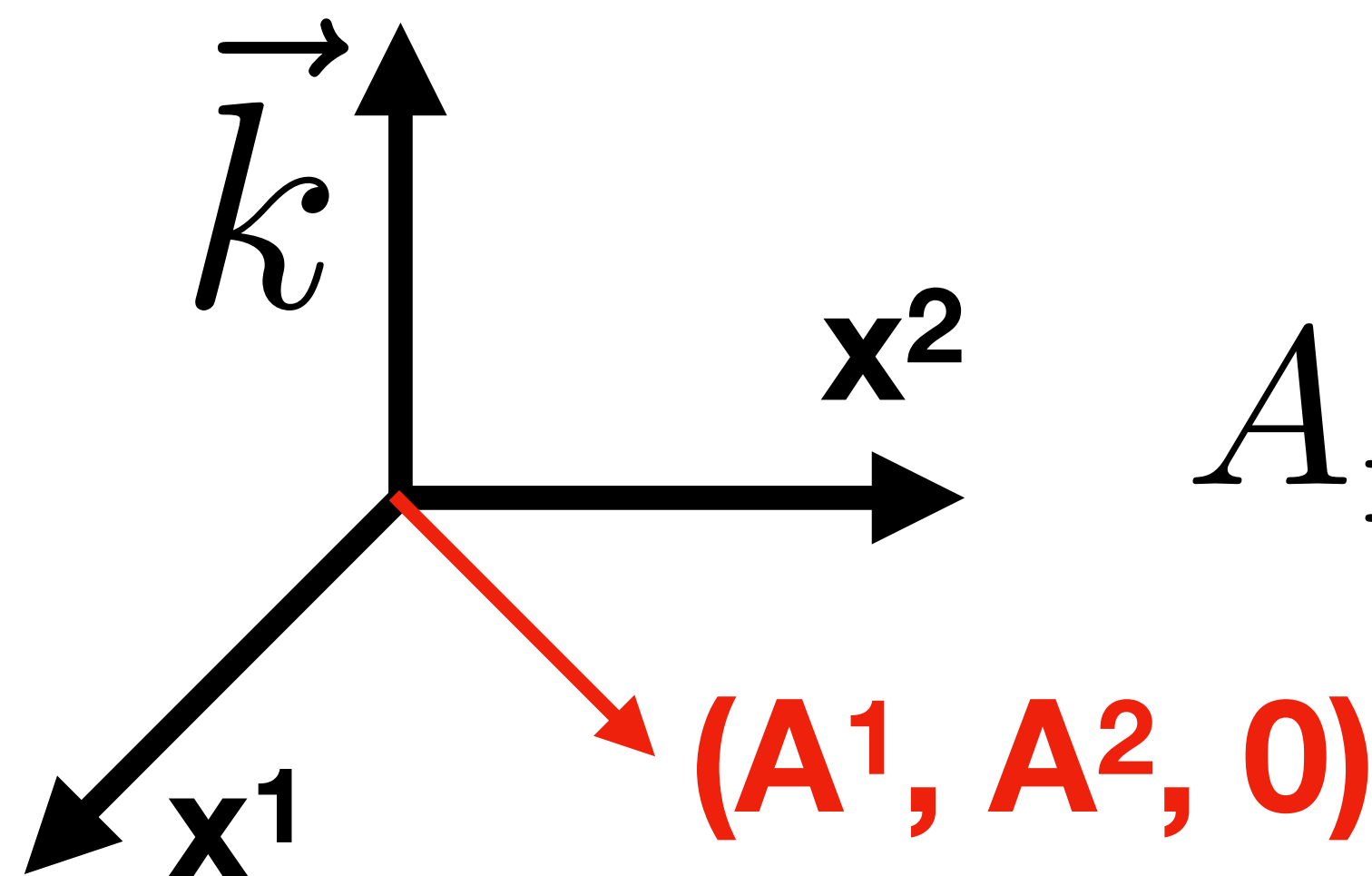
Warm up (2)

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

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

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

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

Cosmic Birefringence

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Cosmic Birefringence

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

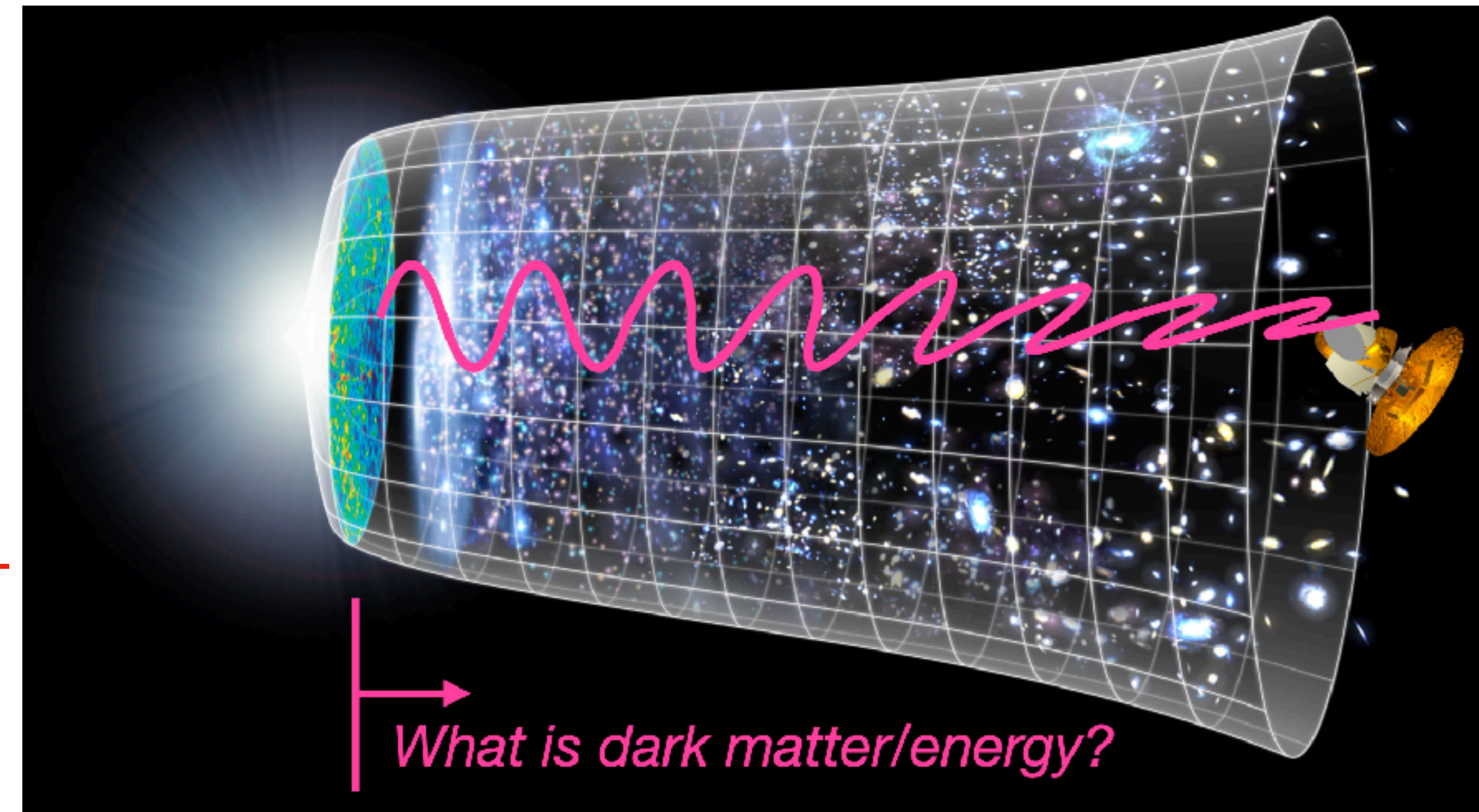
Cosmic Birefringence

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 clockwise on the sky by an angle β :

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

The effect accumulates over the distance!

=> CMB polarisation is sensitive to this effect

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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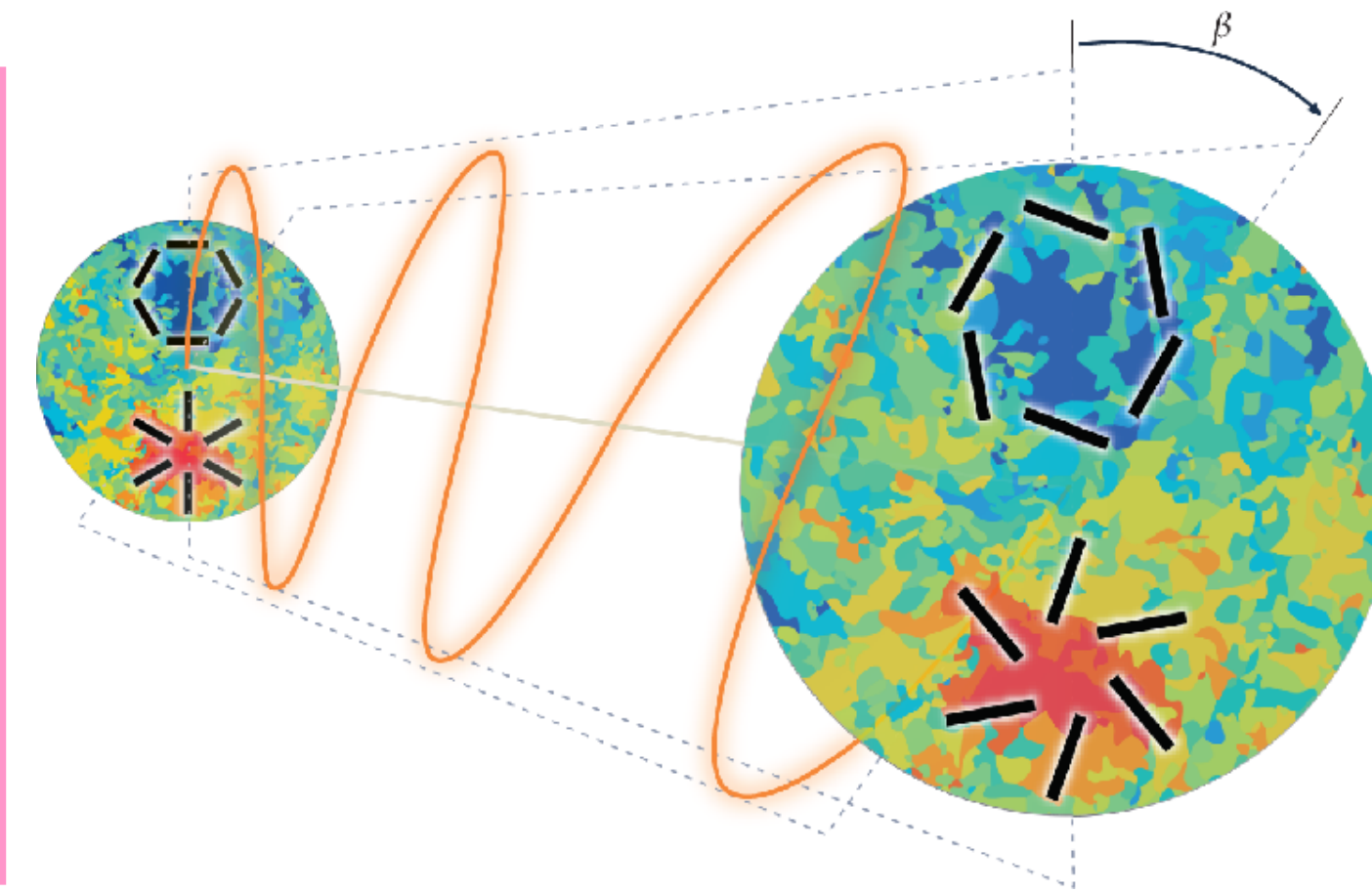
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$$\beta = -2g_a \int_{t_{\text{emitted}}}^{t_{\text{observed}}} dt \dot{\theta} = 2g_a [\theta(t_e) - \theta(t_o)]$$

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



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

Cosmic Birefringence

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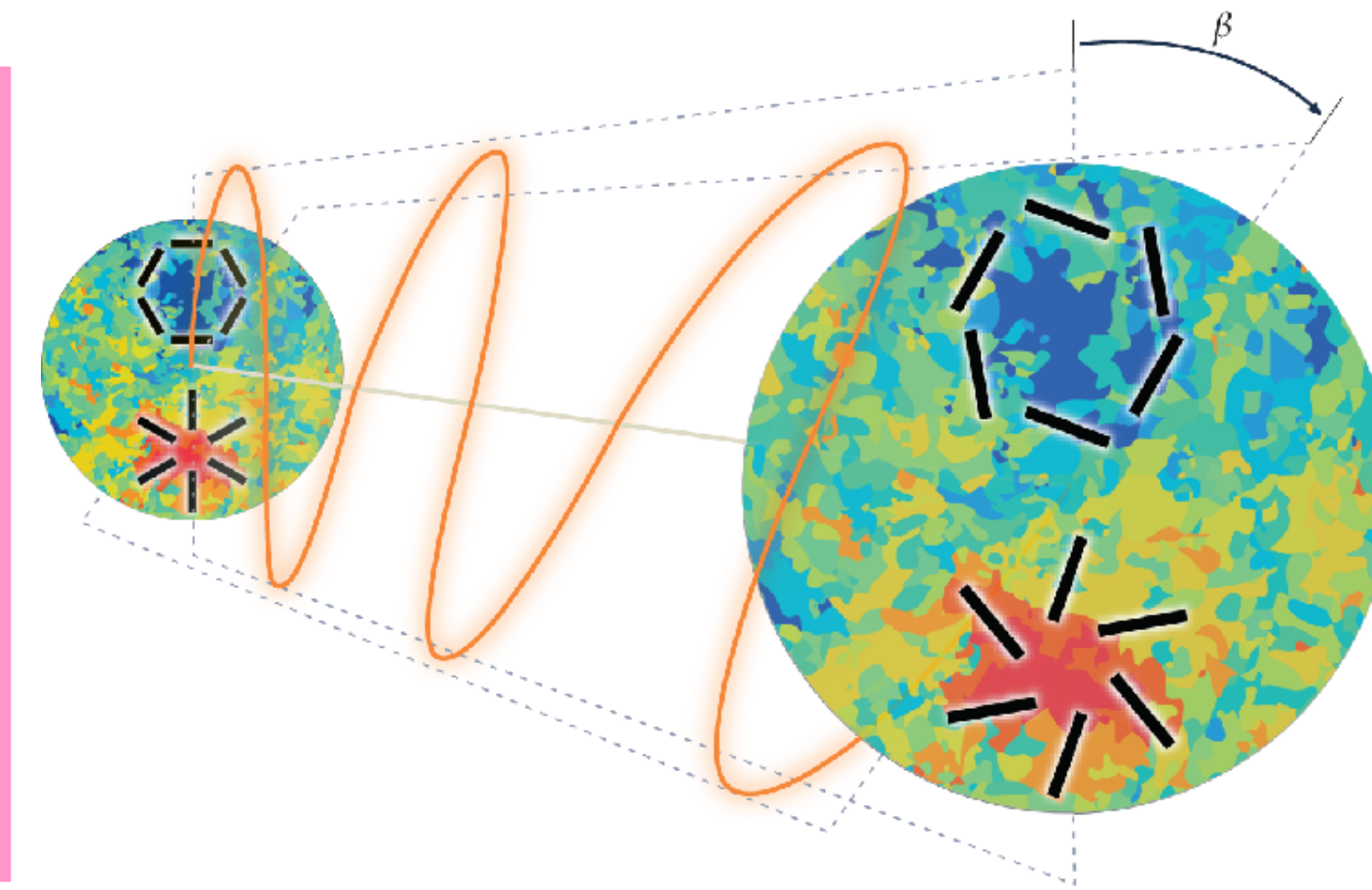
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If θ varies over space:

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

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.

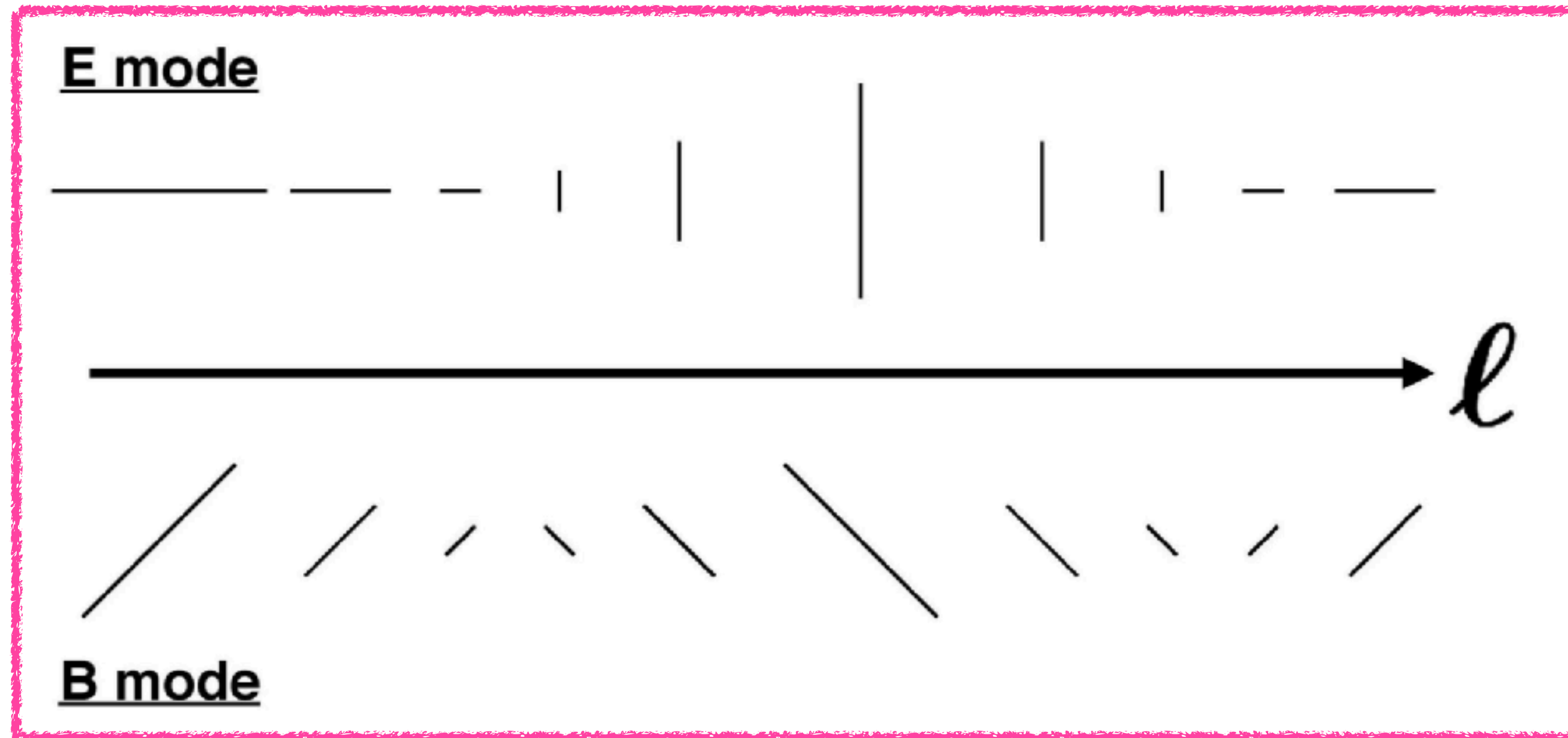
(Simpler) Motivation

Why study the cosmic birefringence?

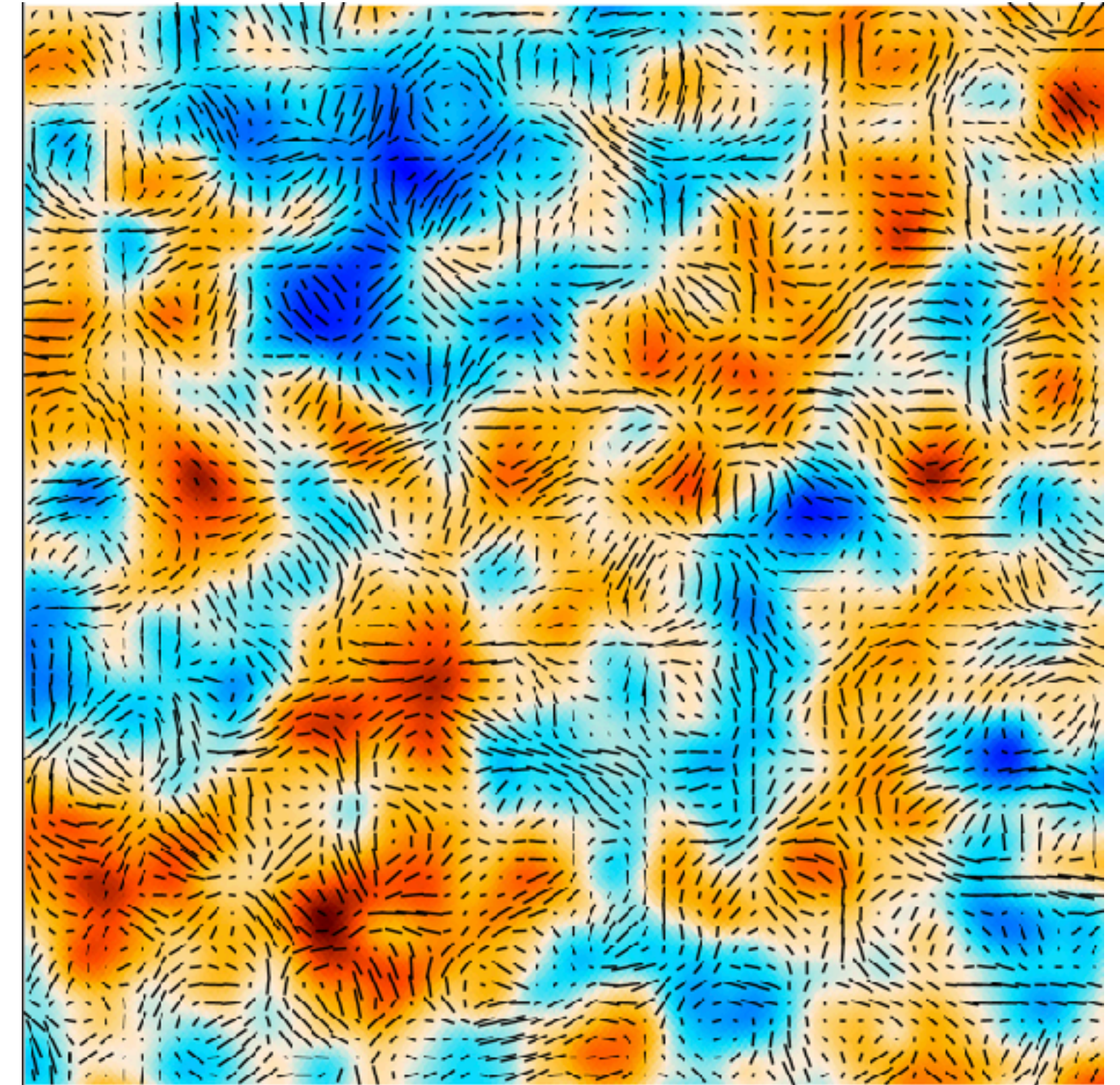
- We know that the weak interaction violates parity (Lee & Yang 1956; Wu et al. 1957).
 - Why should the laws of physics governing the Universe conserve parity?
- Let's look!

Parity eigenstates: E and B modes

Concept defined in Fourier space



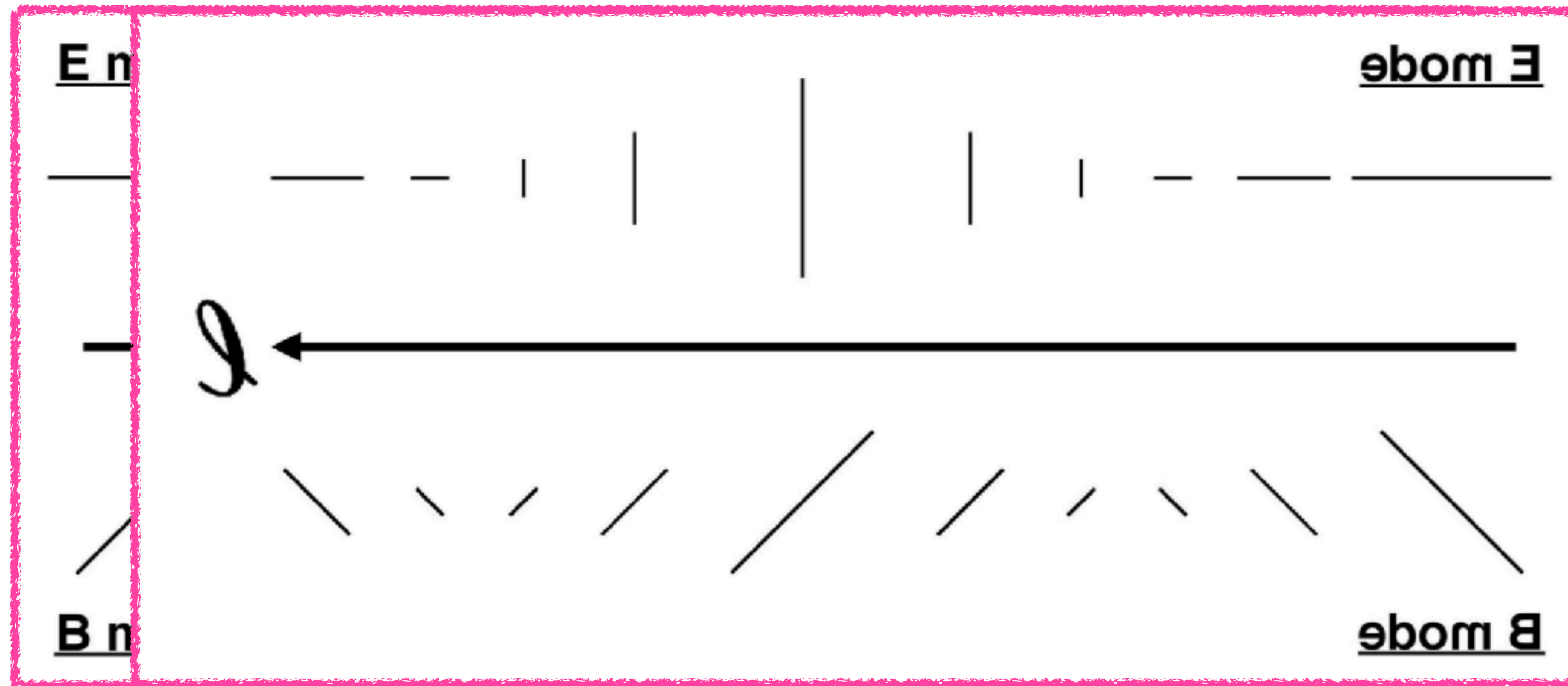
This map is dominated
by E-mode polarisation



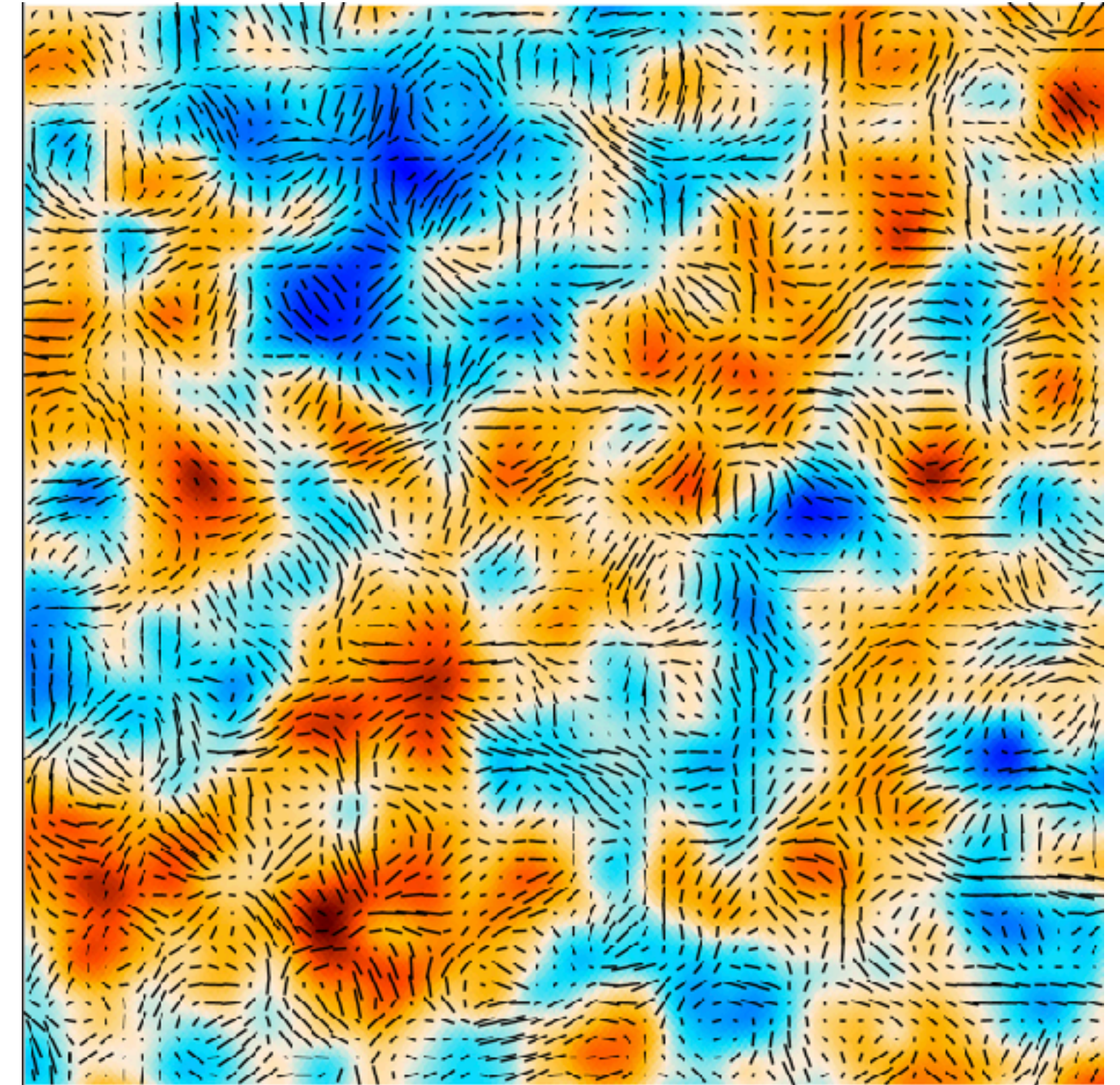
- **E-mode** : Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode** : Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

Parity eigenstates: E and B modes

Concept defined in Fourier space



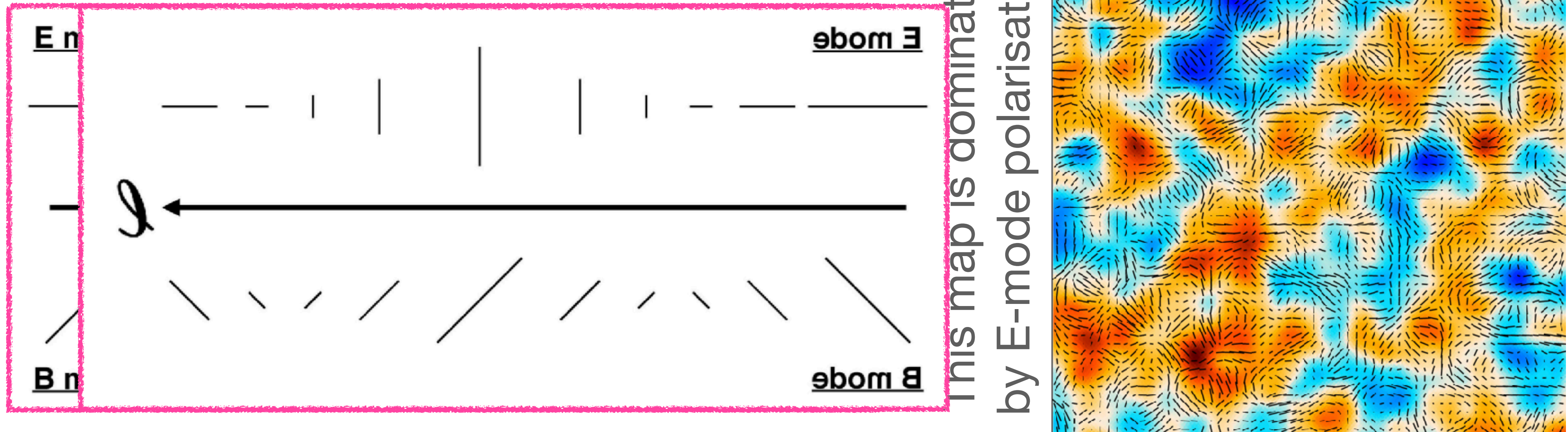
This map is dominated
by E-mode polarisation



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Parity eigenstates: E and B modes

Concept defined in Fourier space



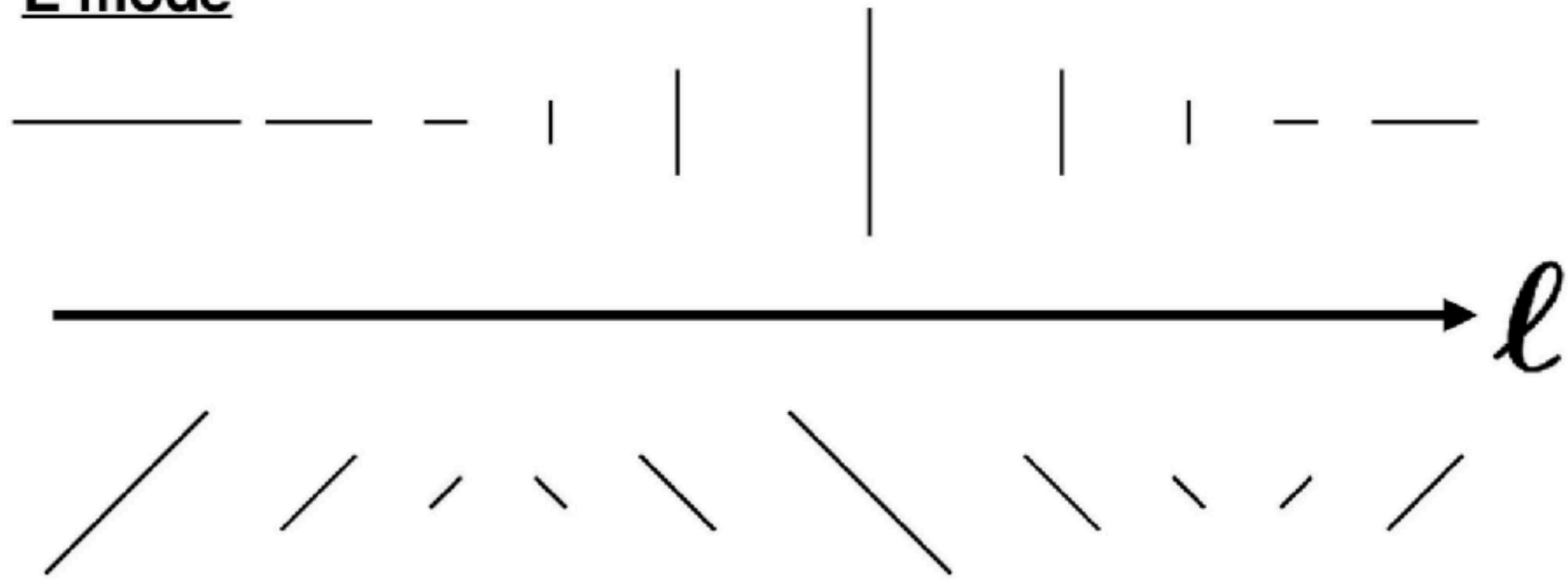
- **E-mode** : Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode** : Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

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

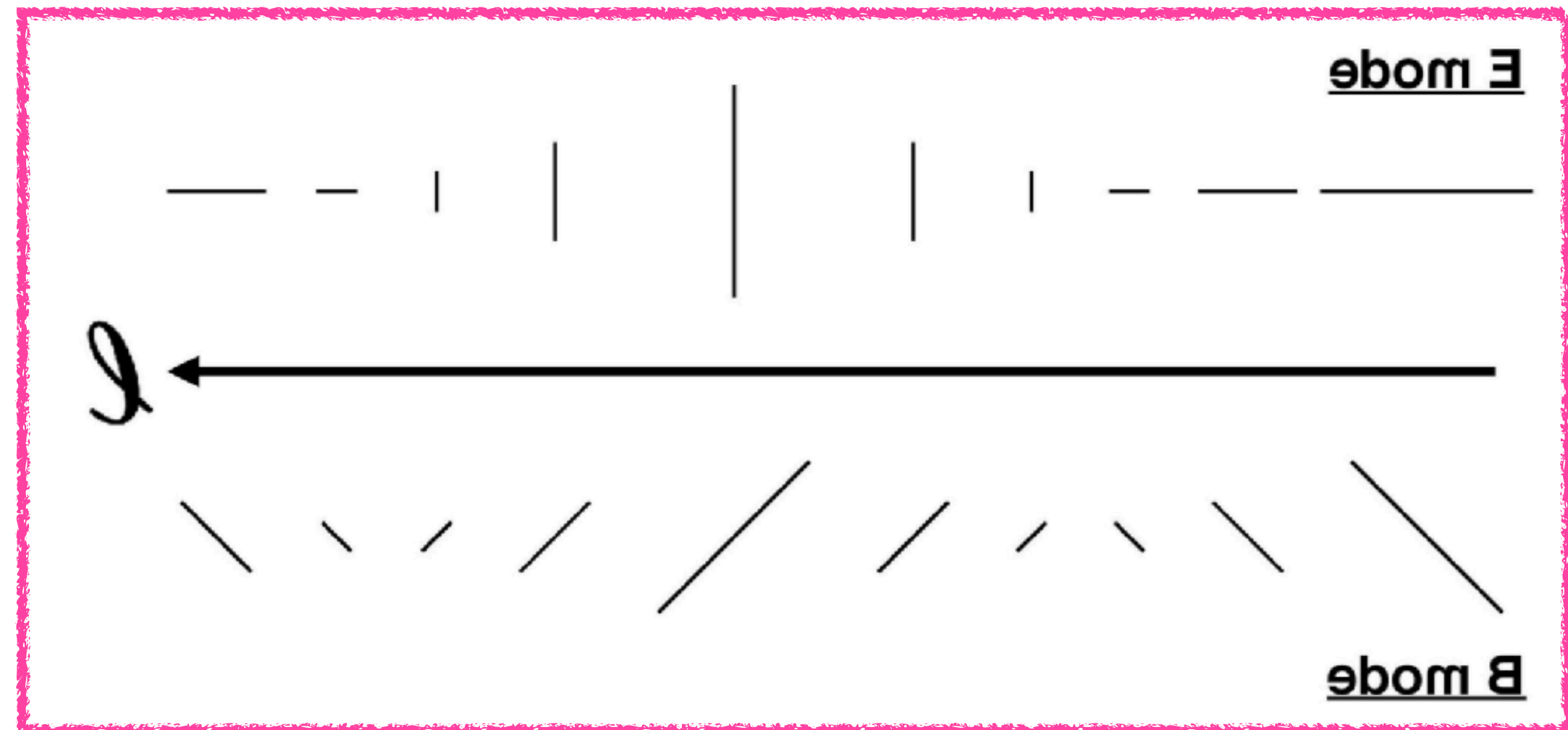
Parity Flip

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

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

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

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

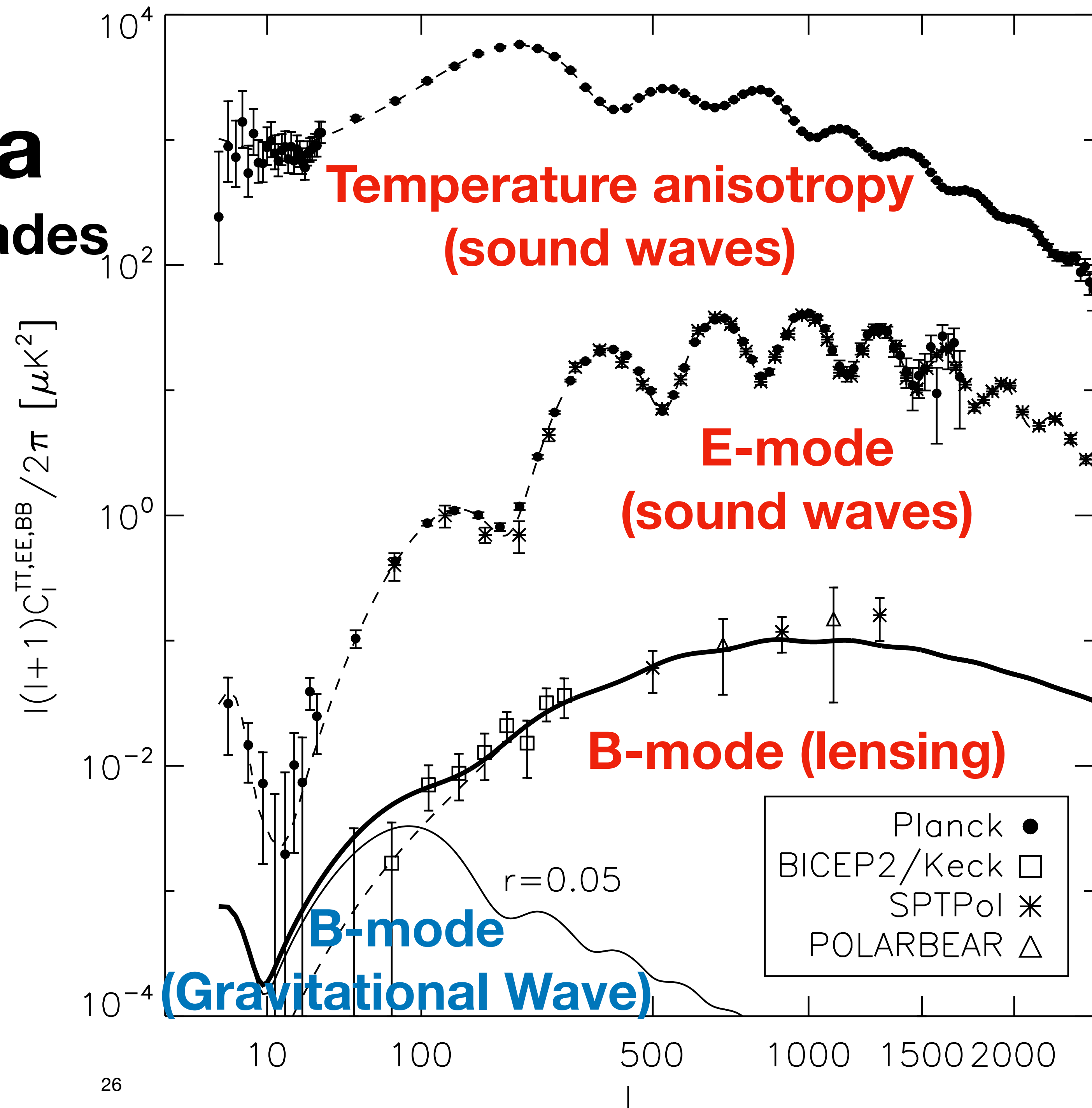
- The other combinations $\langle TB \rangle$ and $\langle EB \rangle$ are not invariant under the parity flip.

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

CMB Power Spectra

Progress over the last 3 decades

- 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

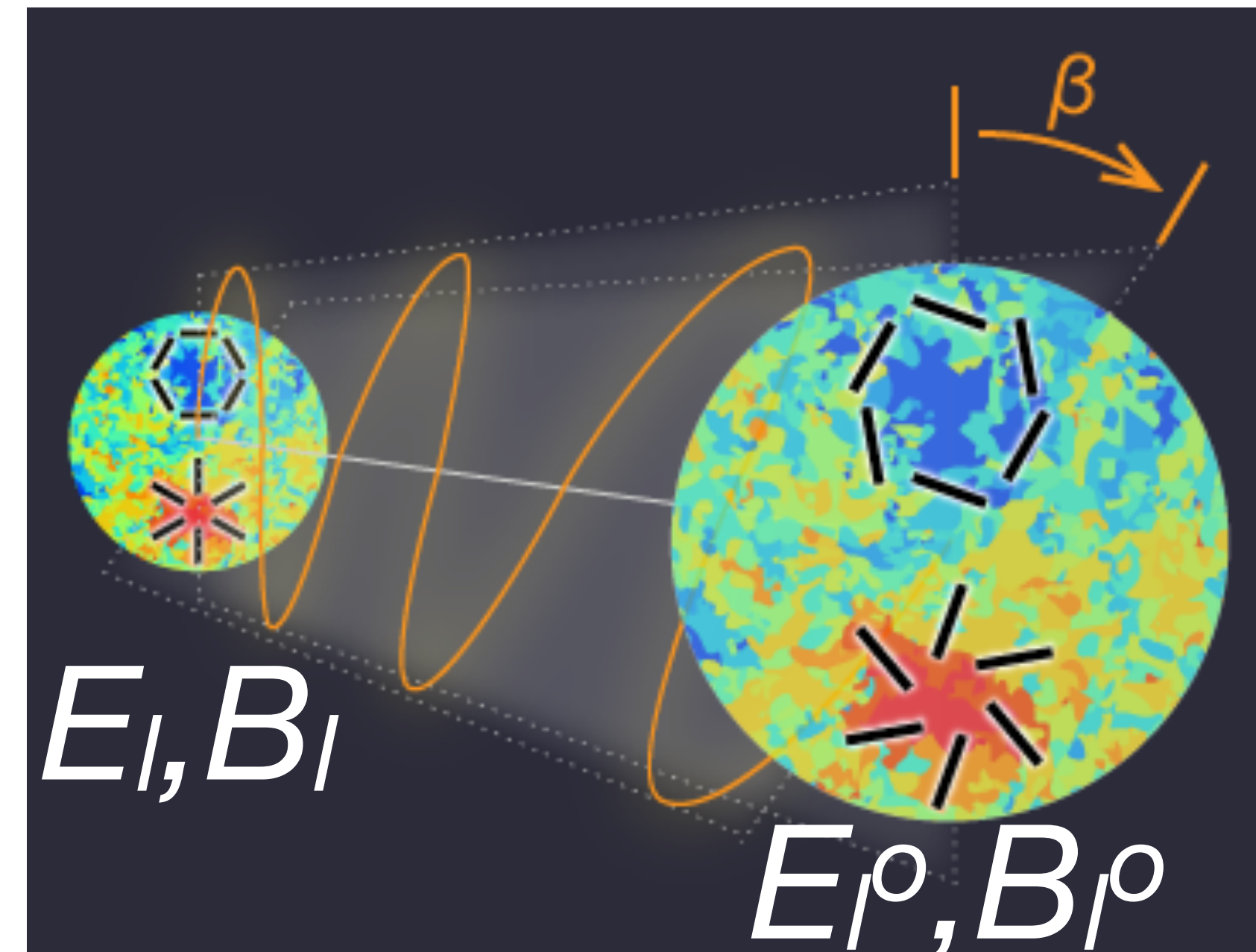
- Observed E- and B-mode polarisation, E_l° and B_l° , are related to those before rotation as

$$E_l^\circ \pm iB_l^\circ = (E_l \pm iB_l)e^{\pm 2i\beta}$$

- which gives

$$E_l^\circ = E_l \cos(2\beta) - B_l \sin(2\beta)$$

$$B_l^\circ = E_l \sin(2\beta) + B_l \cos(2\beta)$$



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

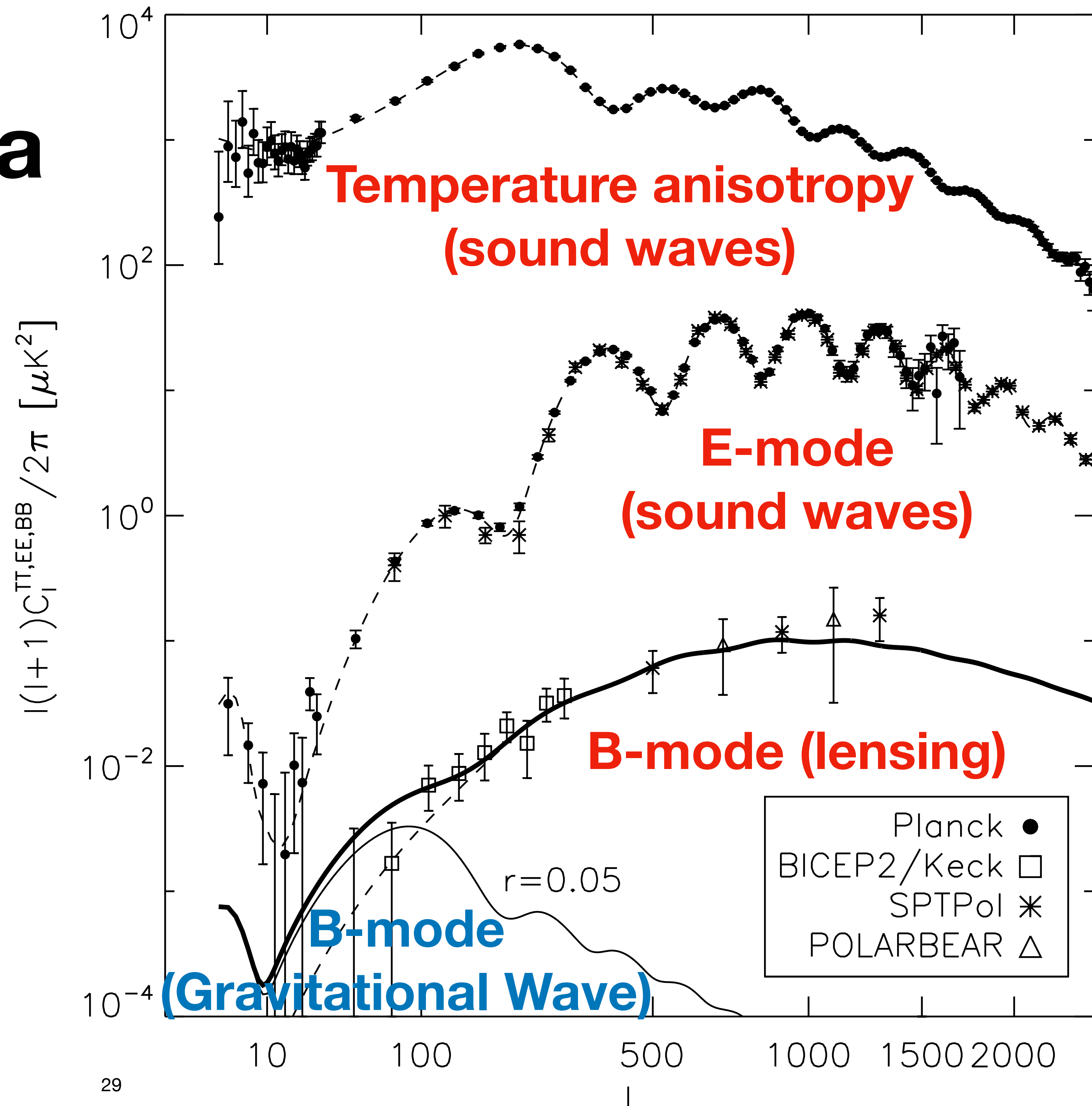
$$\begin{aligned} C_{\ell}^{EB,\text{obs}} &= \frac{1}{2} (C_{\ell}^{EE} - C_{\ell}^{BB}) \sin(4\beta) + C_{\ell}^{EB} \cos(4\beta) \\ &= \frac{1}{2} (\underline{C_{\ell}^{EE,\text{obs}} - C_{\ell}^{BB,\text{obs}}}) \tan(4\beta) + \frac{C_{\ell}^{EB}}{\cos(4\beta)} \end{aligned}$$

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

CMB Power Spectra

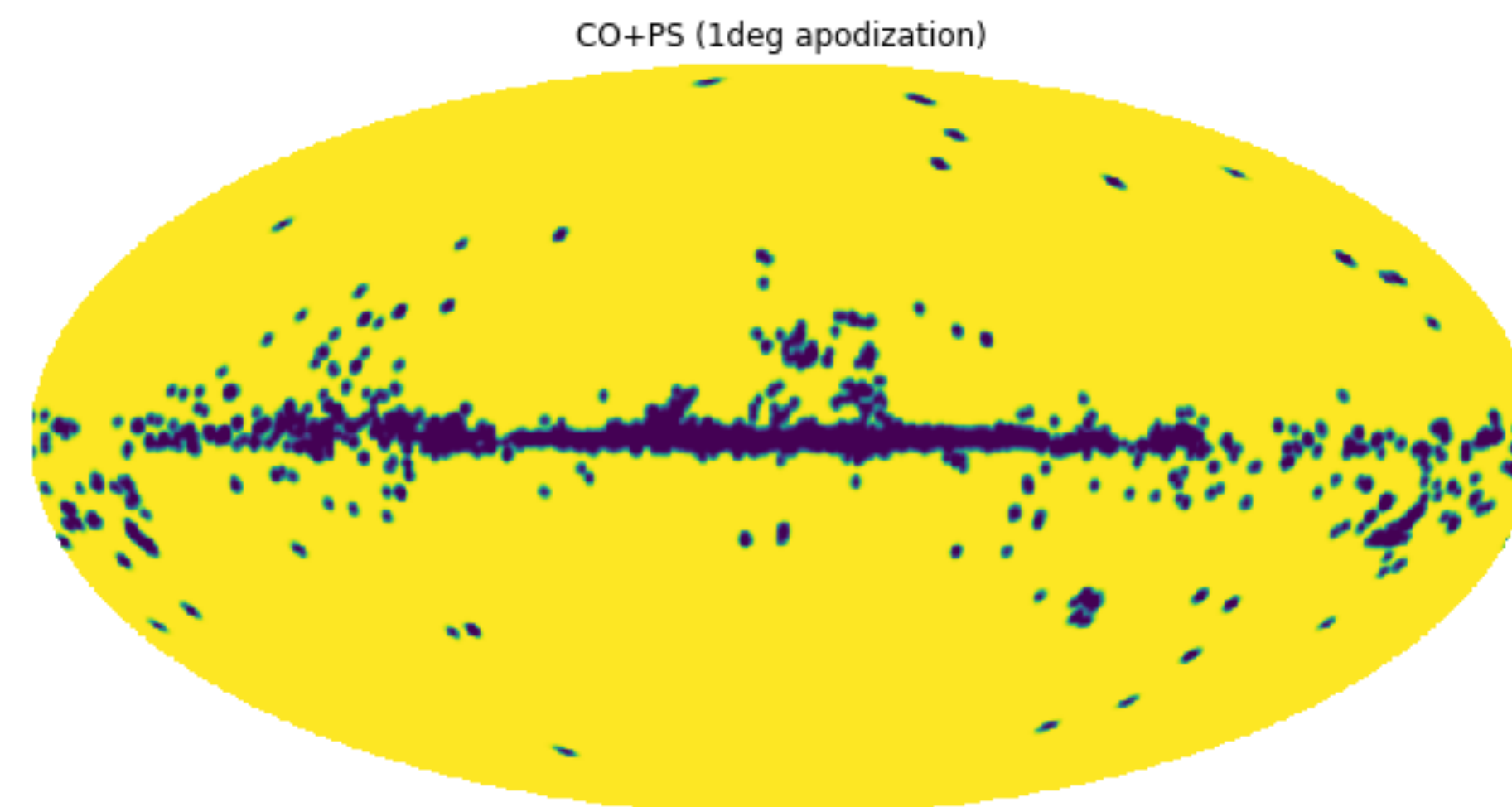
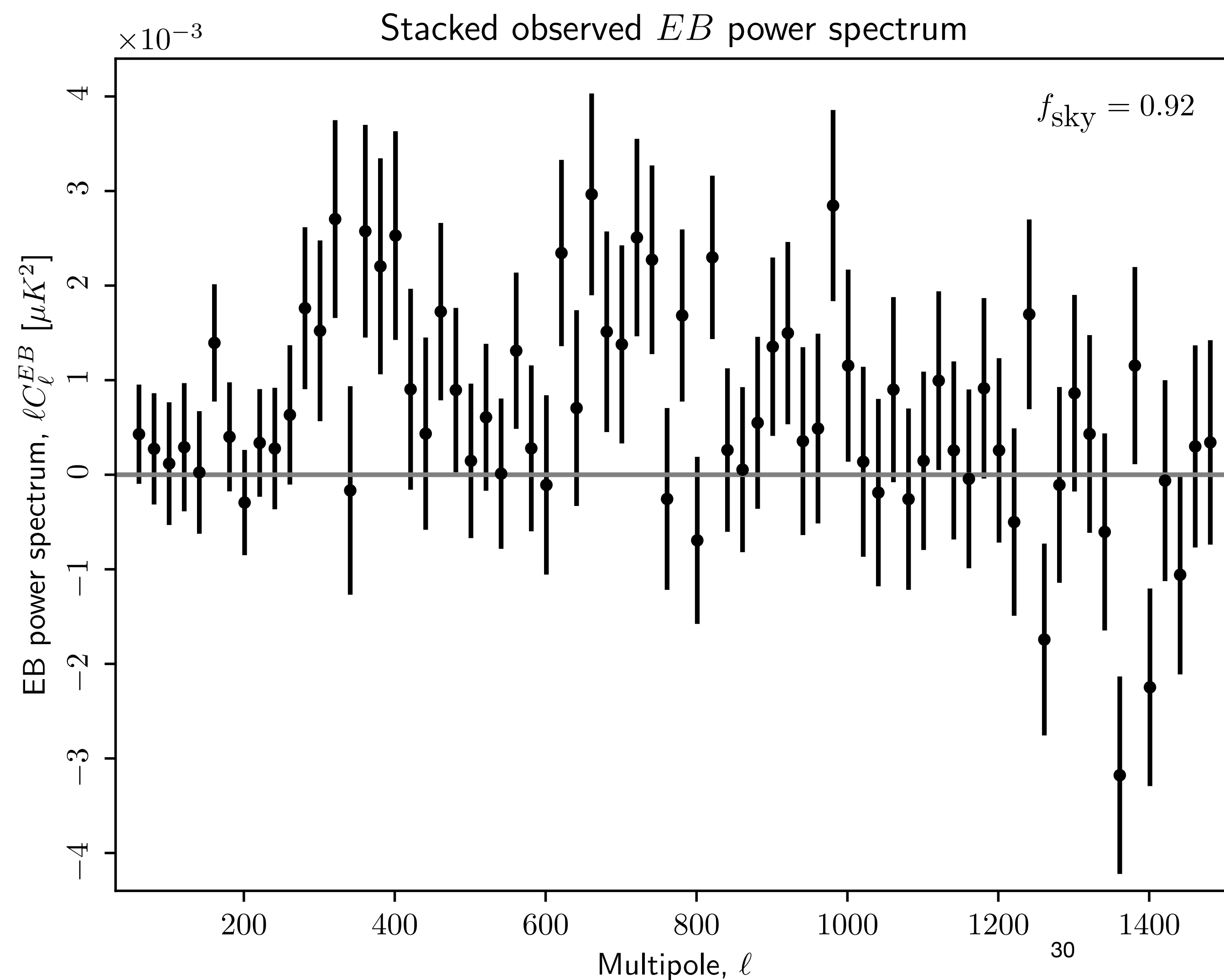
EE >> BB!

- In our Universe, CMB EE is much greater than BB. This makes CMB sensitive to birefringence.
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This is the EB power spectrum (WMAP+Planck)

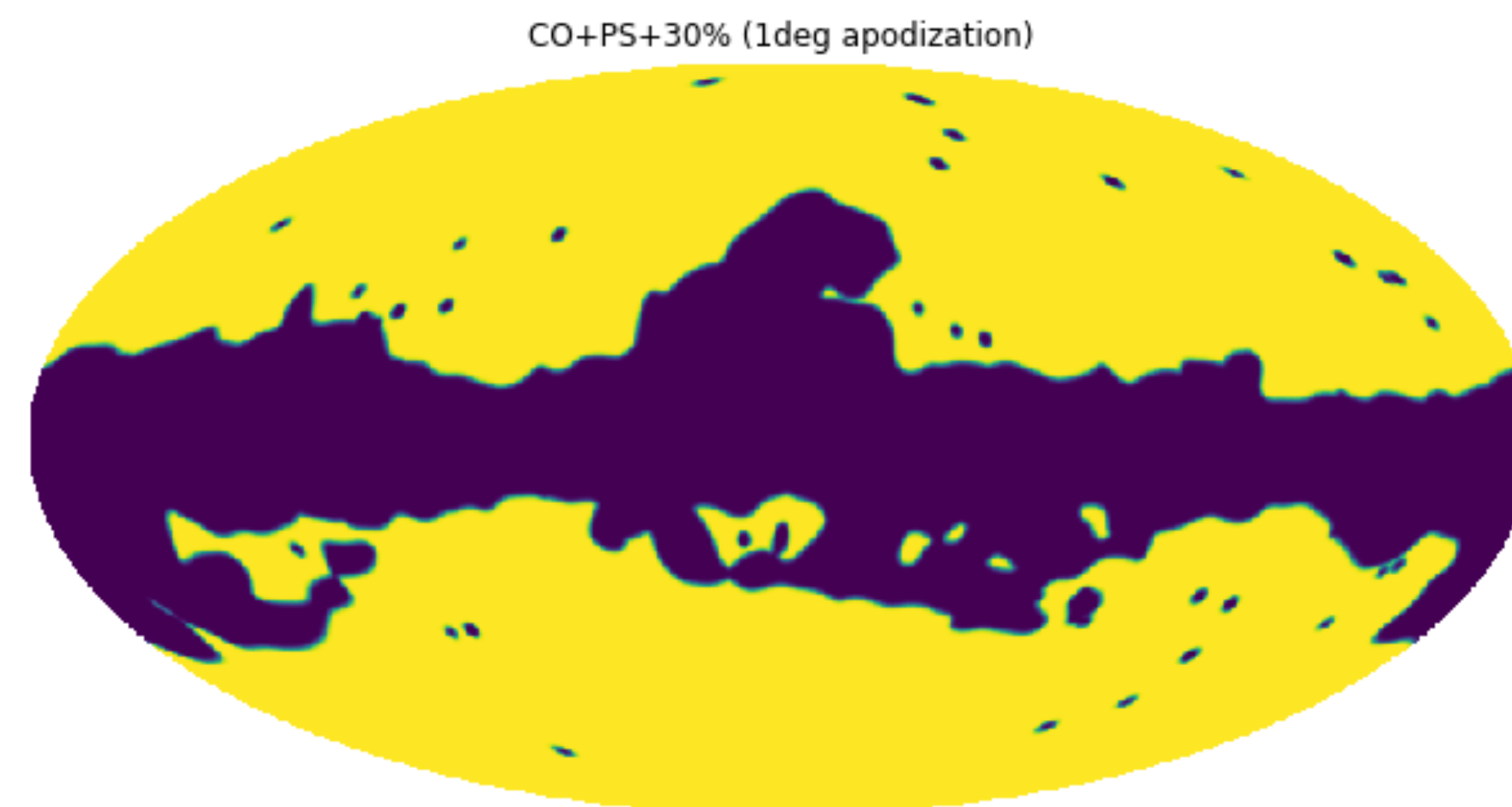
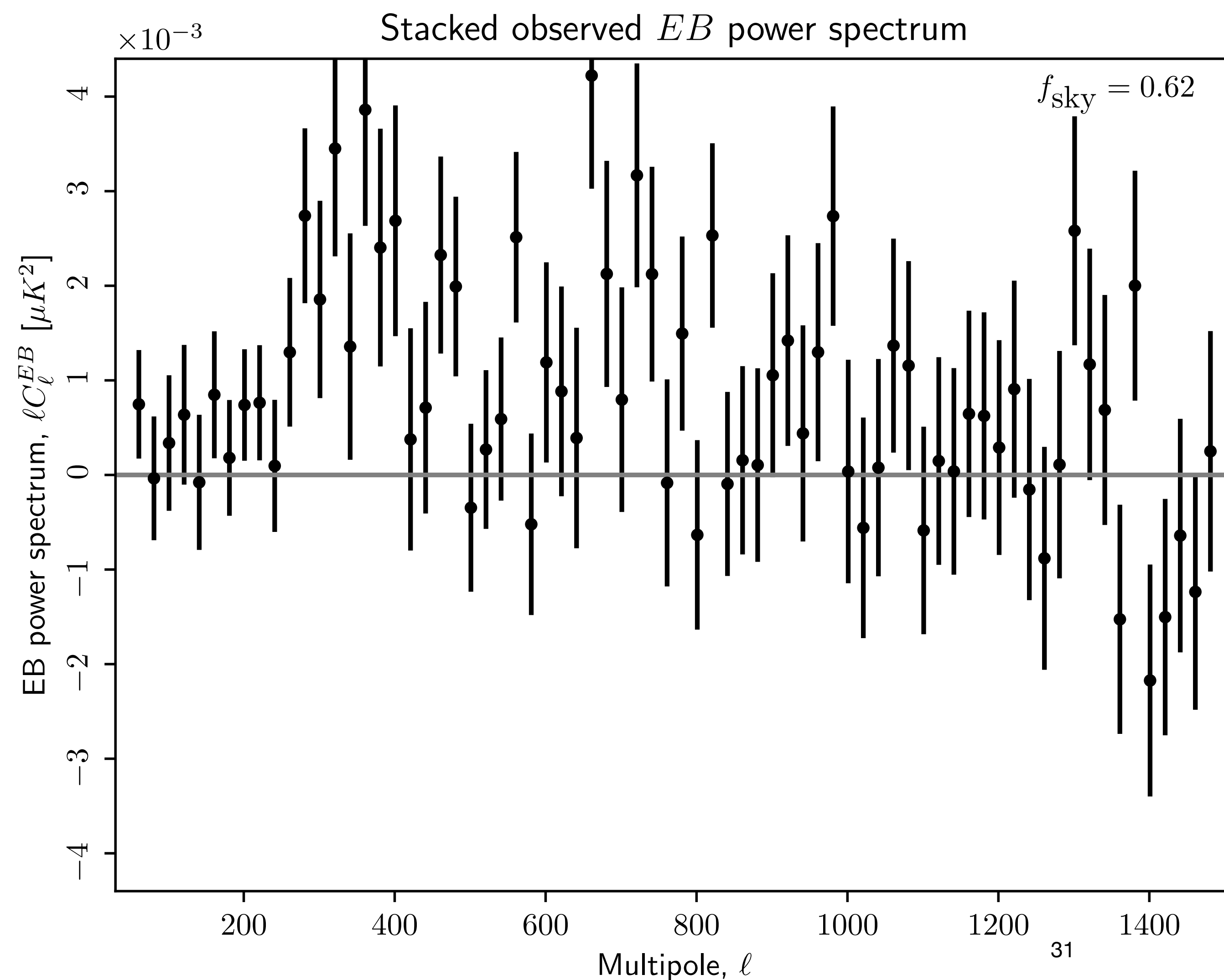
Nearly full-sky data (92% of the sky)



- $\chi^2 = 125.5$ for DOF=72
- Unambiguous signal of something!

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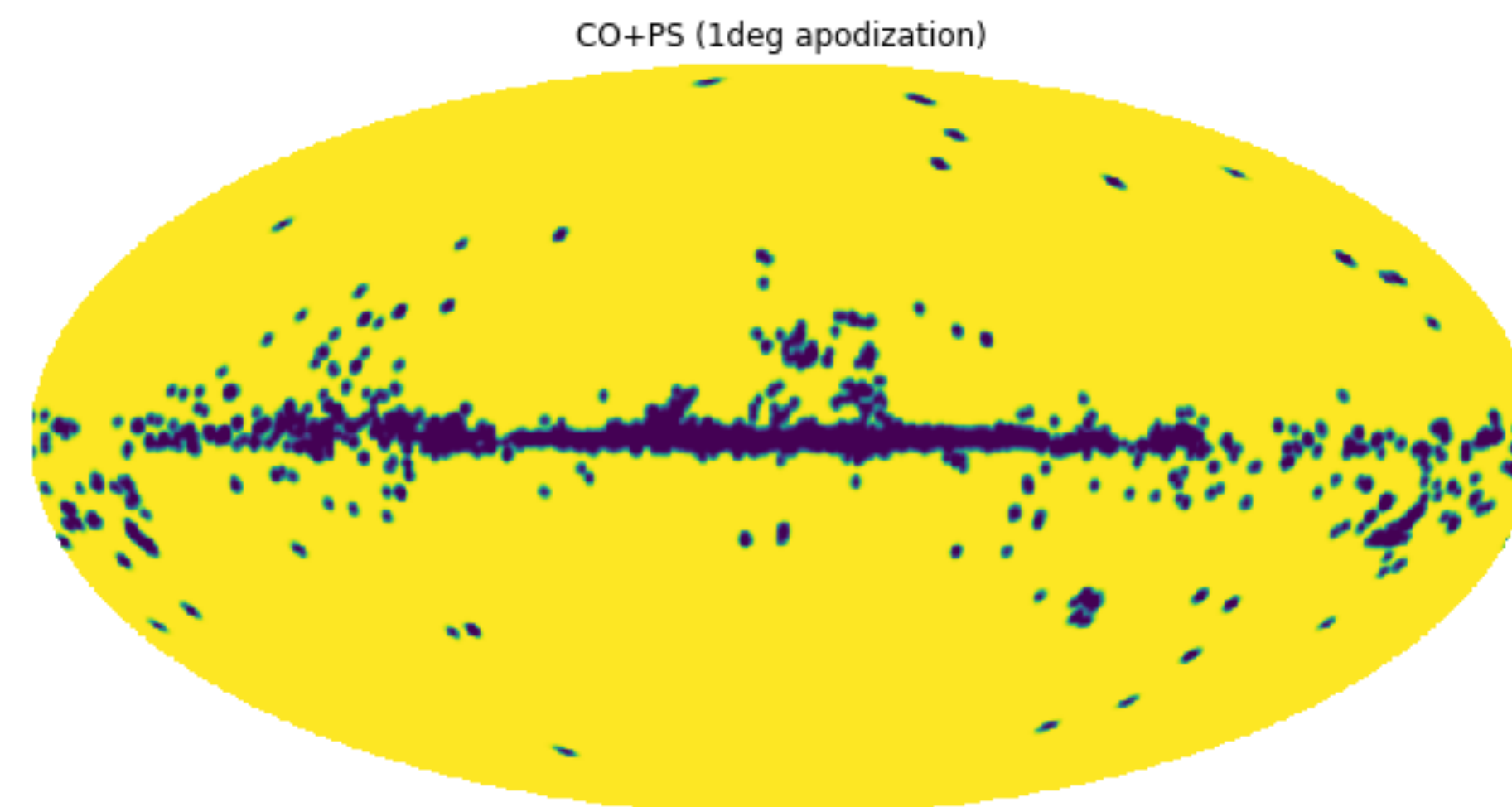
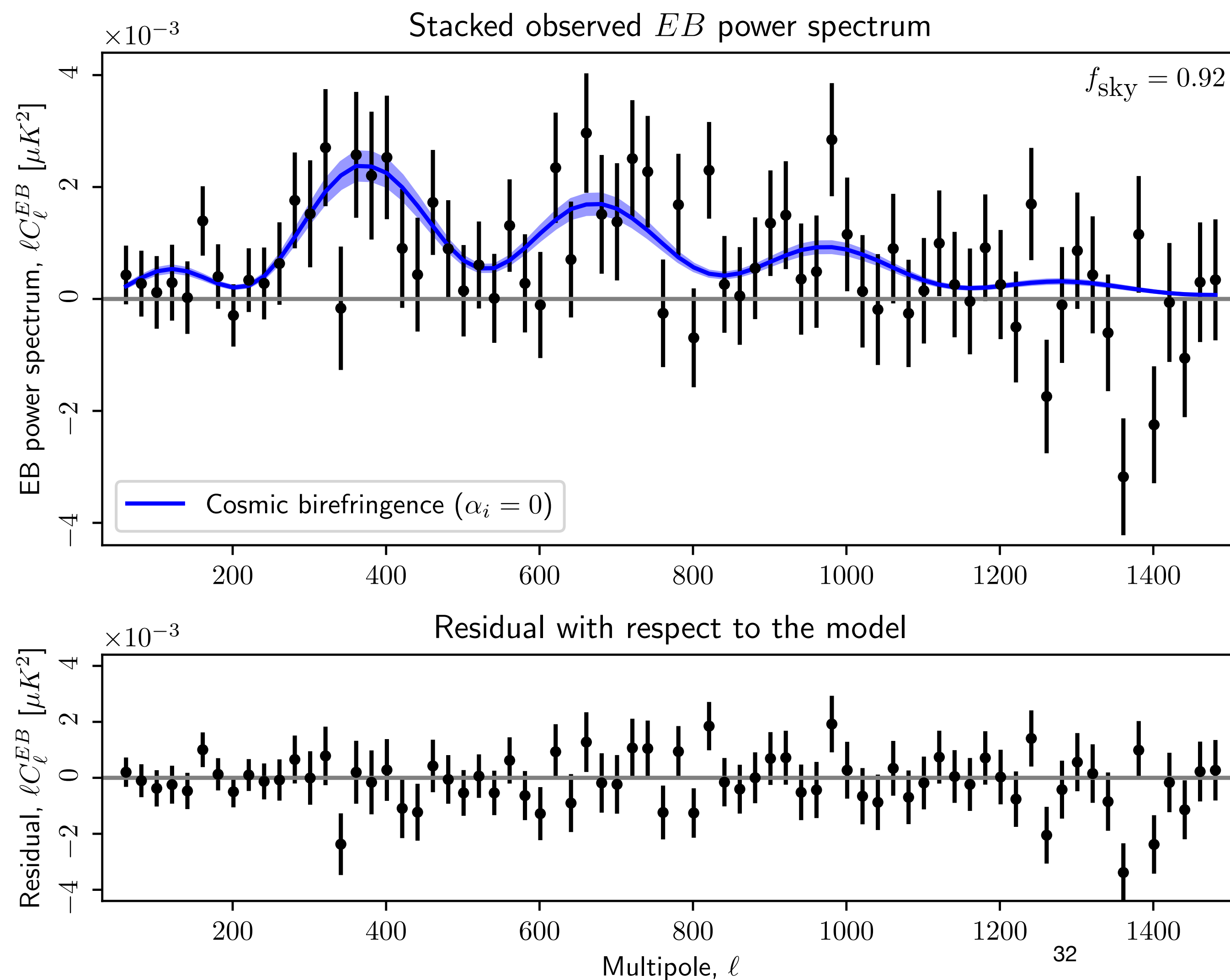
Galactic plane removed (62% of the sky)



- $\chi^2 = 138.4$ for DOF=72
- The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

Cosmic Birefringence fits well(?)

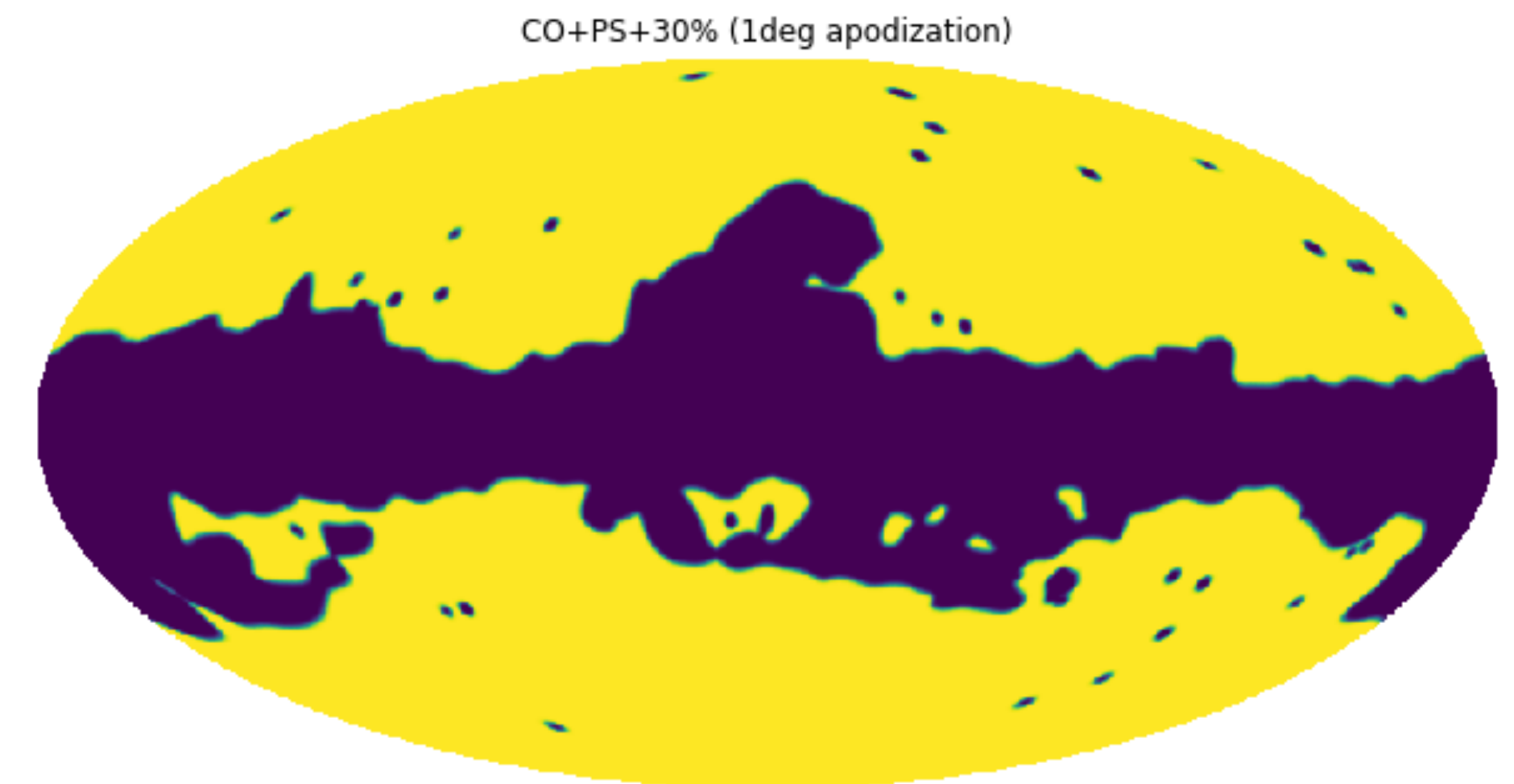
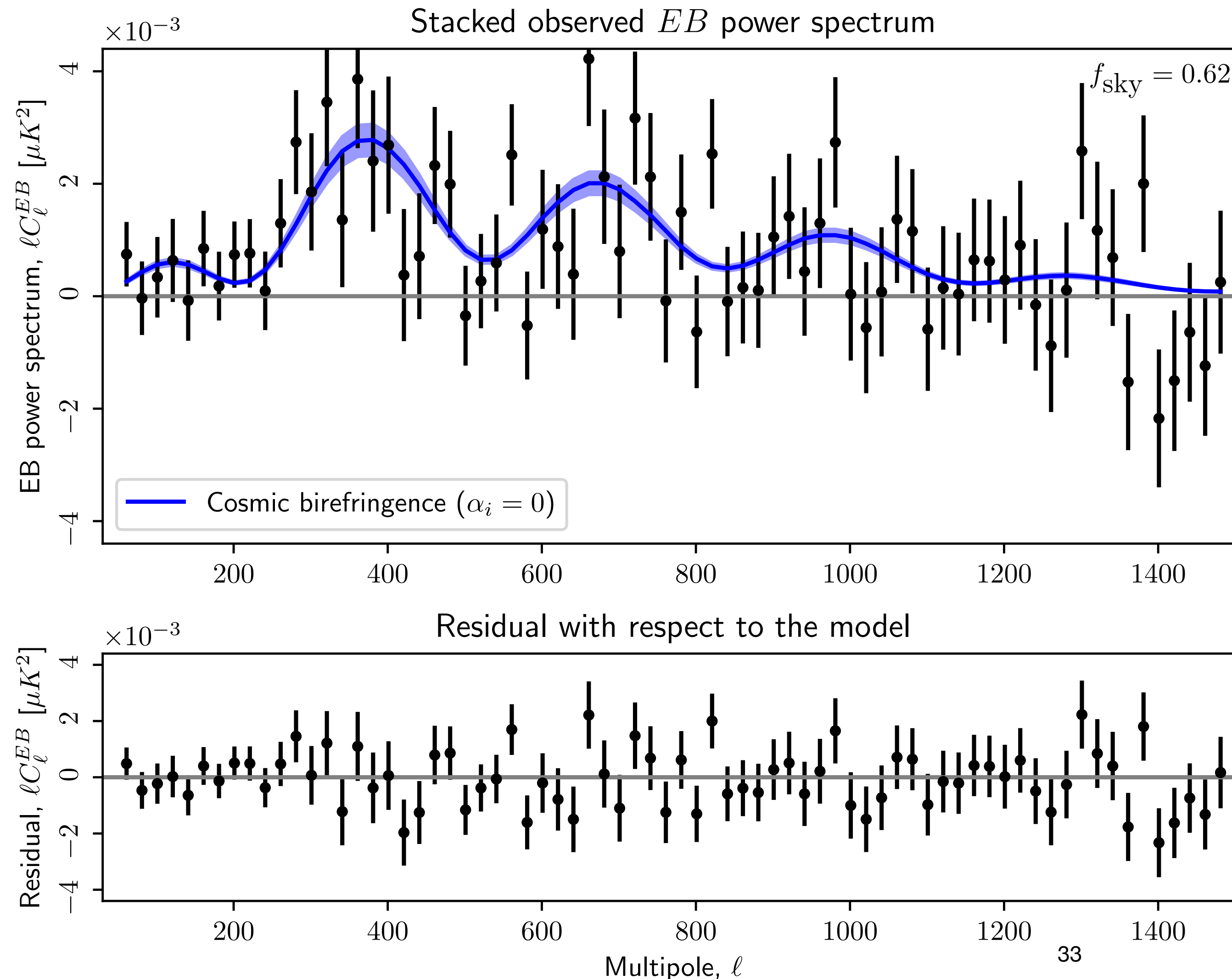
Nearly full-sky data (92% of the sky)



- $\beta = 0.288 \pm 0.032$ deg
- $\chi^2 = 66.1$
- Good fit! 9σ detection?

Cosmic Birefringence fits well(?)

Galactic plane removed (62% of the sky)



- $\beta = 0.330 \pm 0.035$ deg
- $\chi^2 = 64.5$
- Signal is robust with respect to the Galactic mask.

The Biggest Problem: Miscalibration of detectors

Impact of miscalibration of polarisation angles

Cosmic or Instrumental?



- 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?**

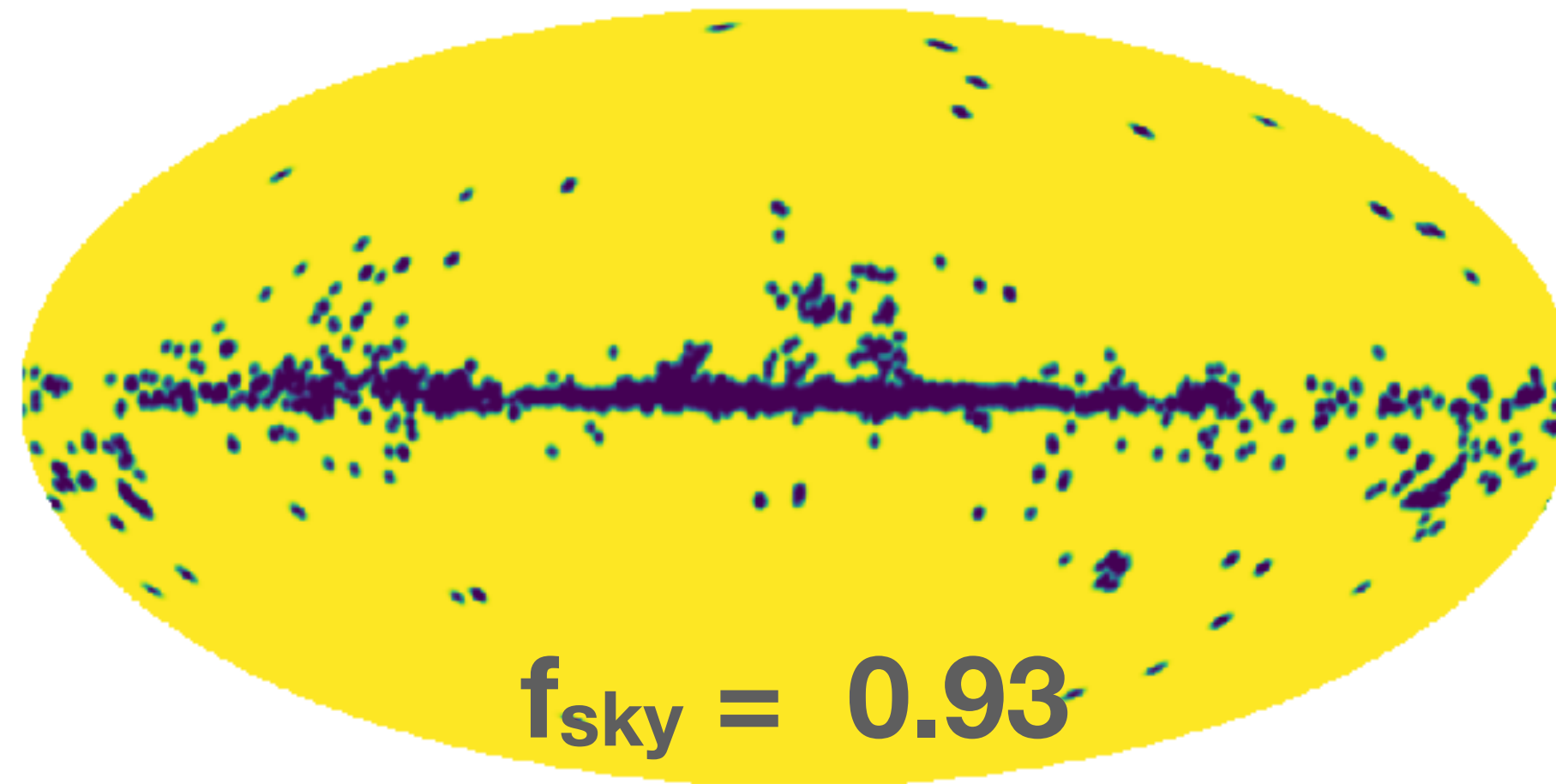
The past measurements

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

CO+PS (1deg apodization)

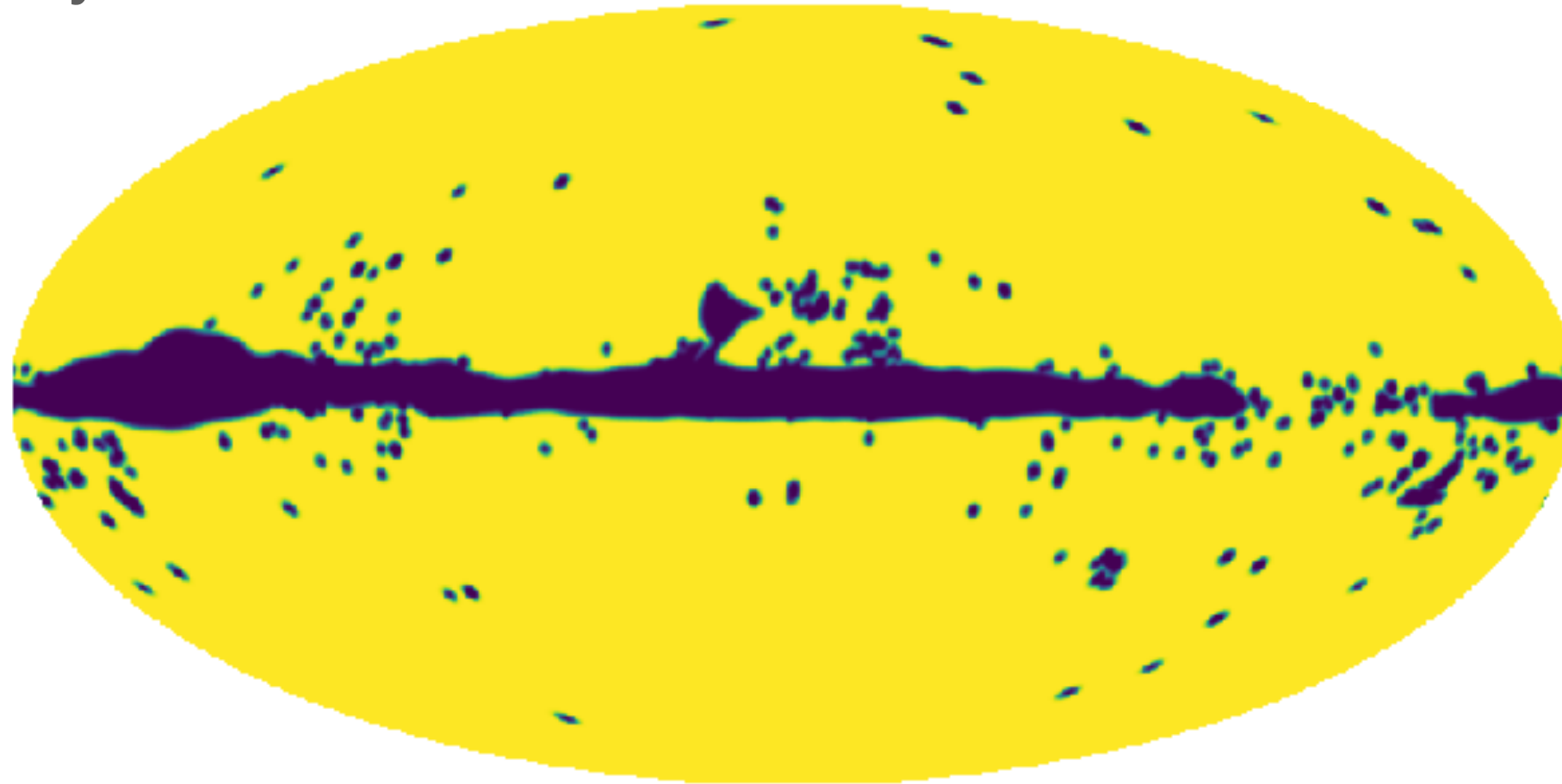


$f_{\text{sky}} = 0.93$

= nearly full sky

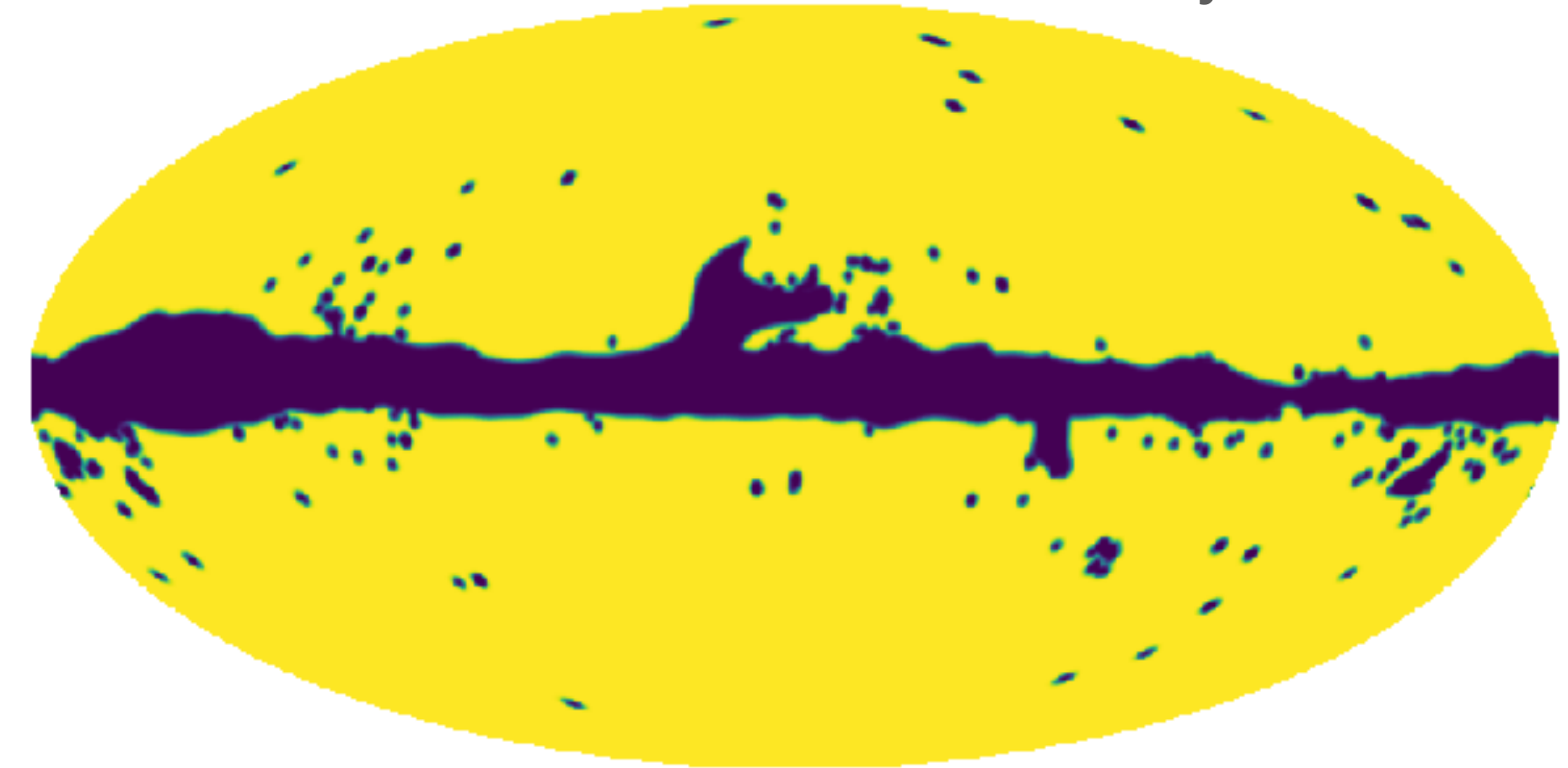
$f_{\text{sky}} = 0.90$

CO+PS+5% (1deg apodization)



CO+PS+10% (1deg apodization)

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



CO+PS+20% (1deg apodization)

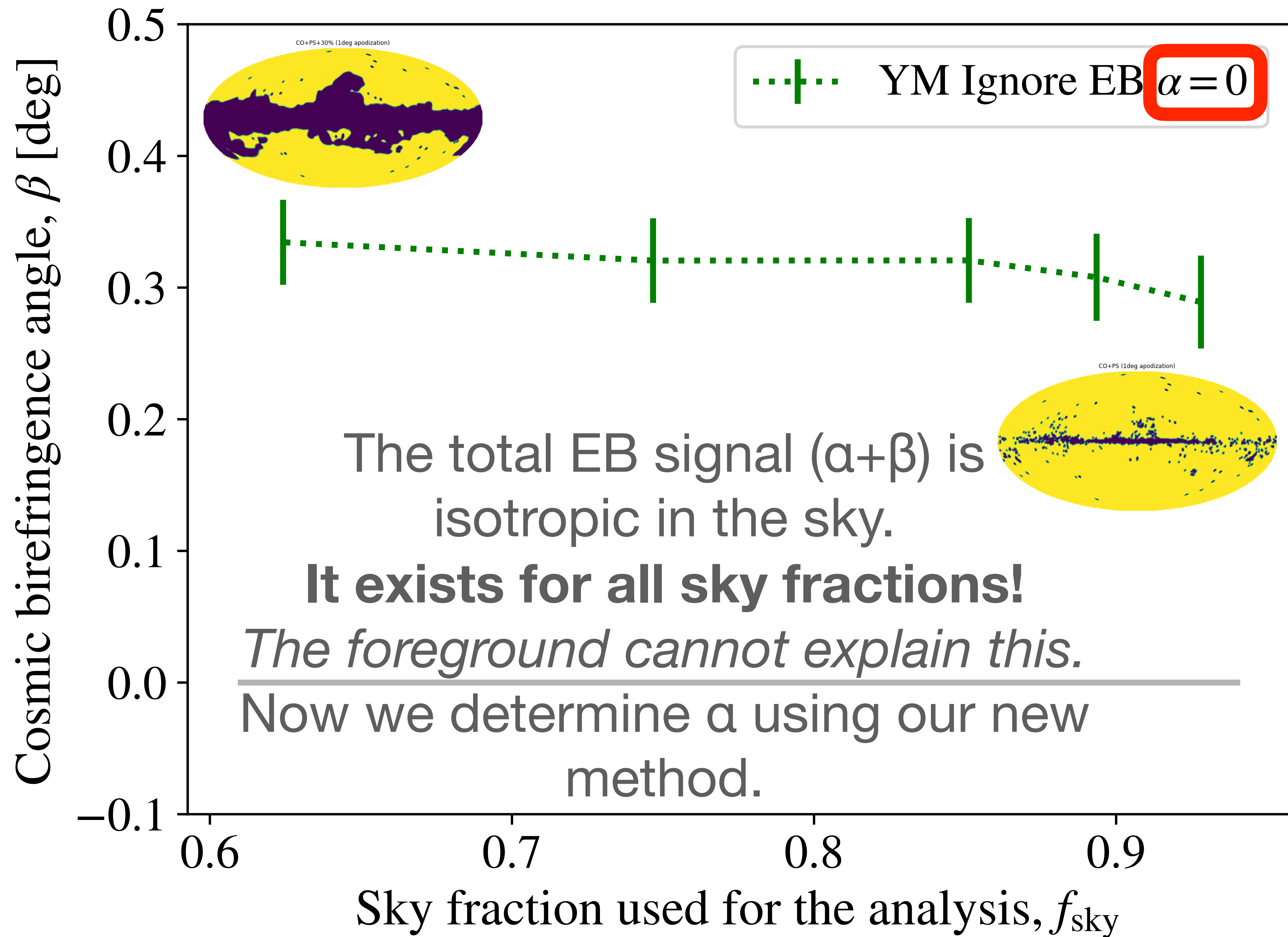


$f_{\text{sky}} = 0.75$

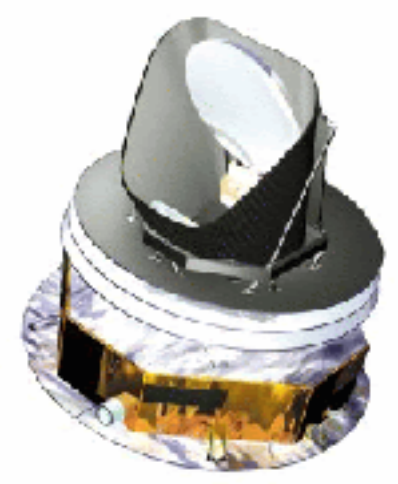
CO+PS+30% (1deg apodization)



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



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



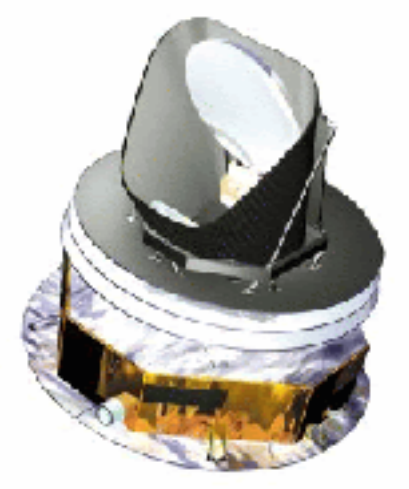
ESA's Planck

Credit: ESA

Polarised dust emission within our Milky Way!

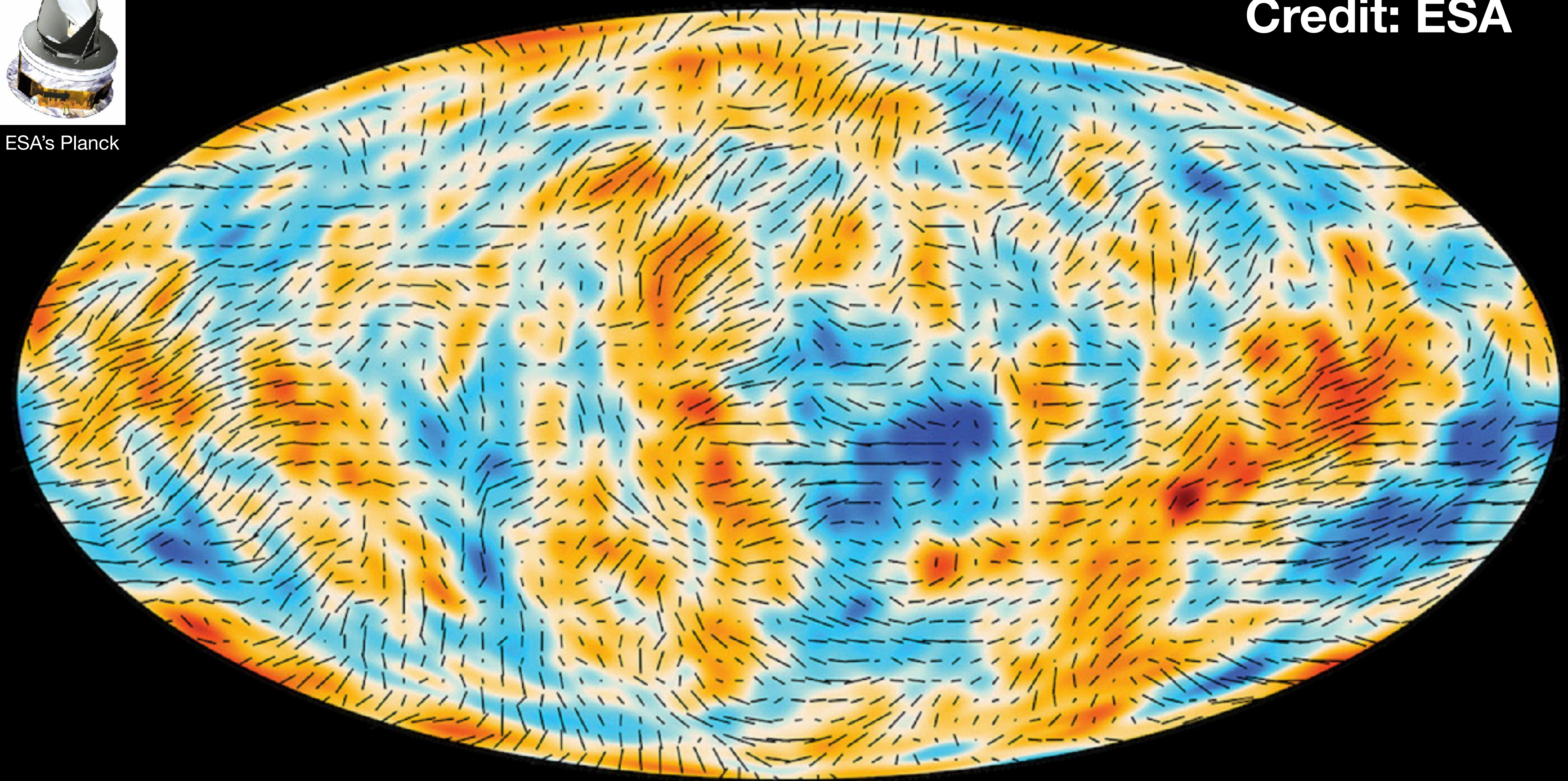
Emitted “right there” - it would
not be affected by the cosmic
birefringence.

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



ESA's Planck

Credit: ESA

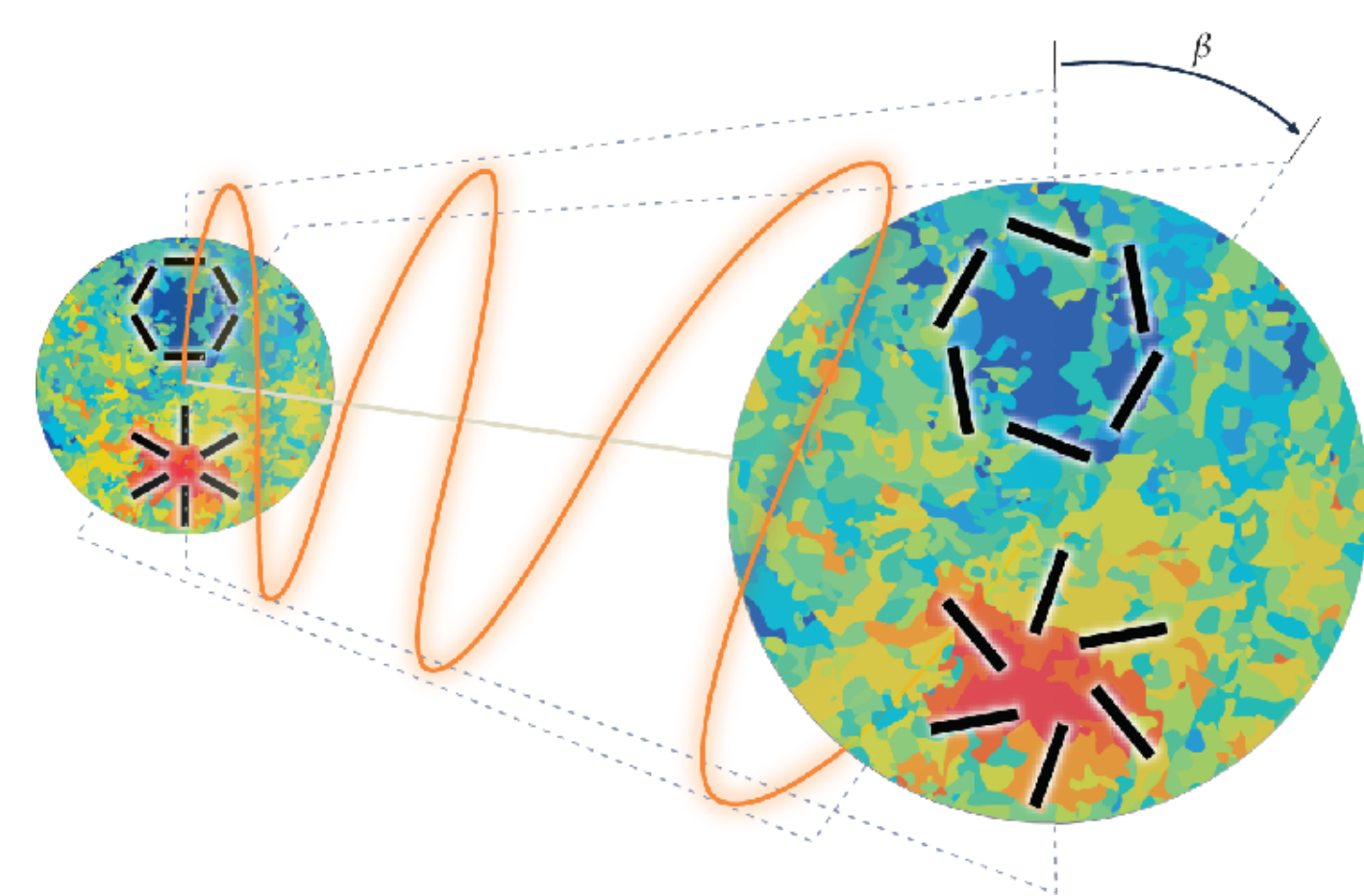


Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Searching for the birefringence

Including the miscalibration angle



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

Emitted 13.8 billions years ago

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

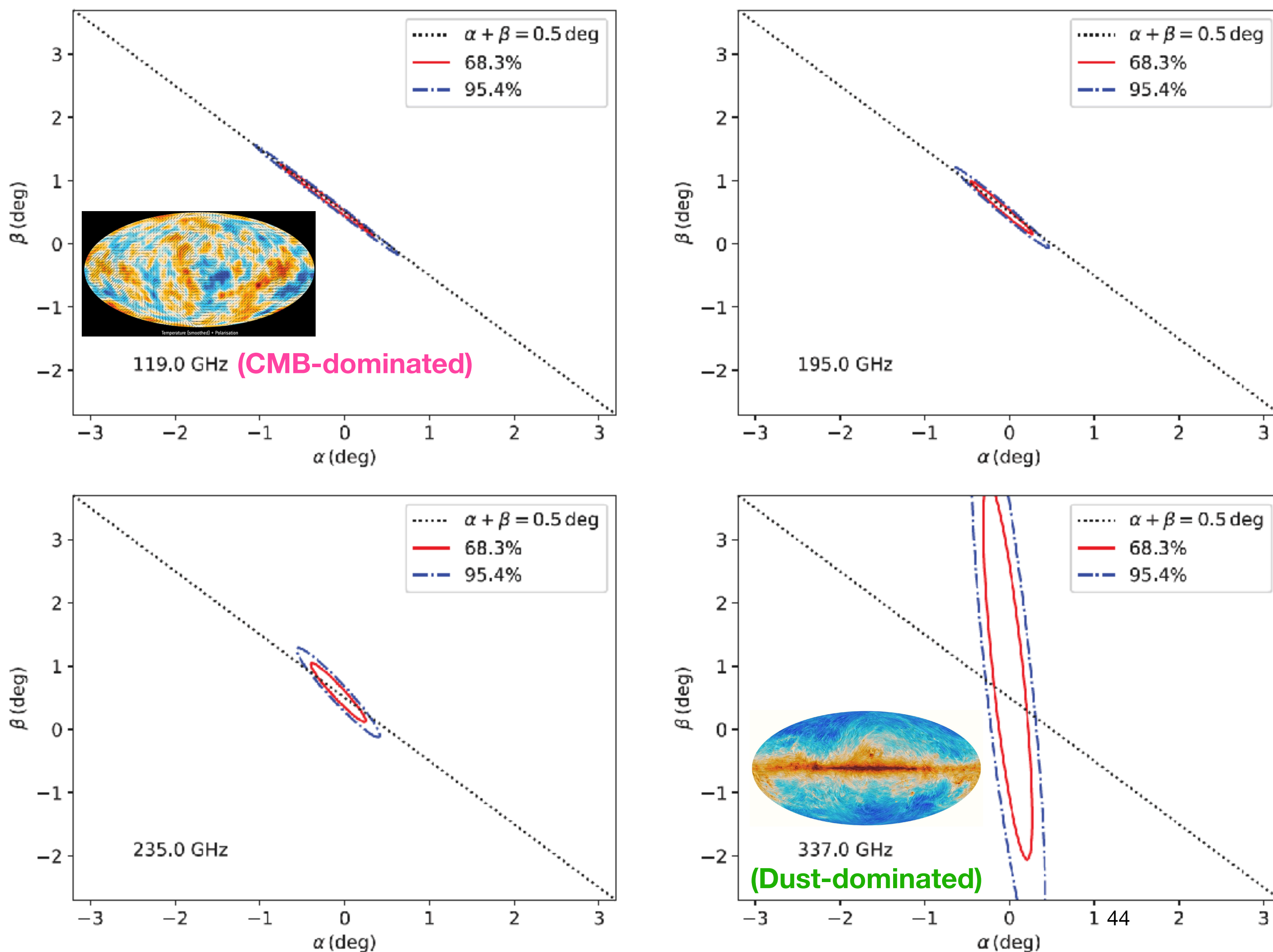
- Thus,

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

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

How does it work?

Simulation of future CMB data (LiteBIRD)



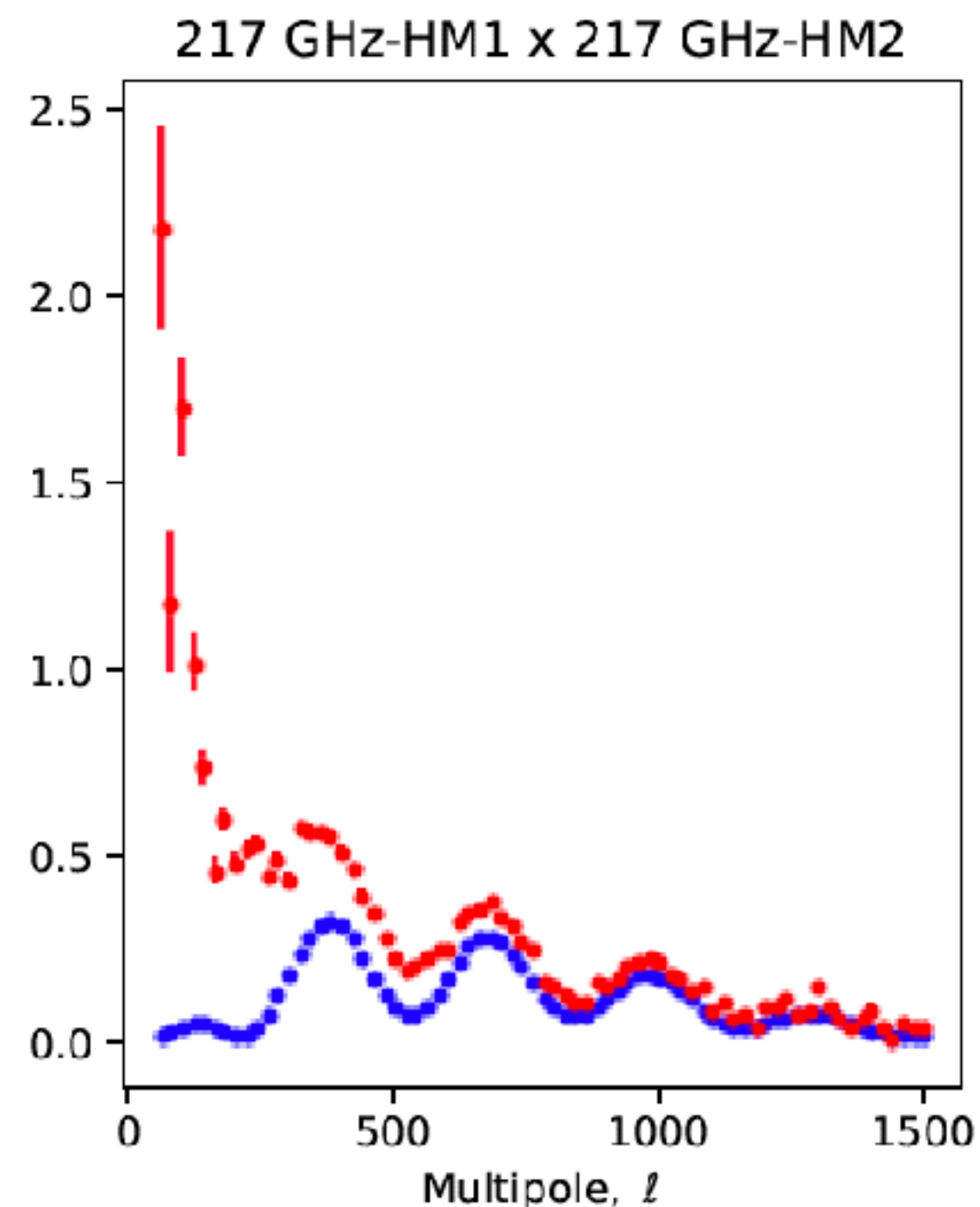
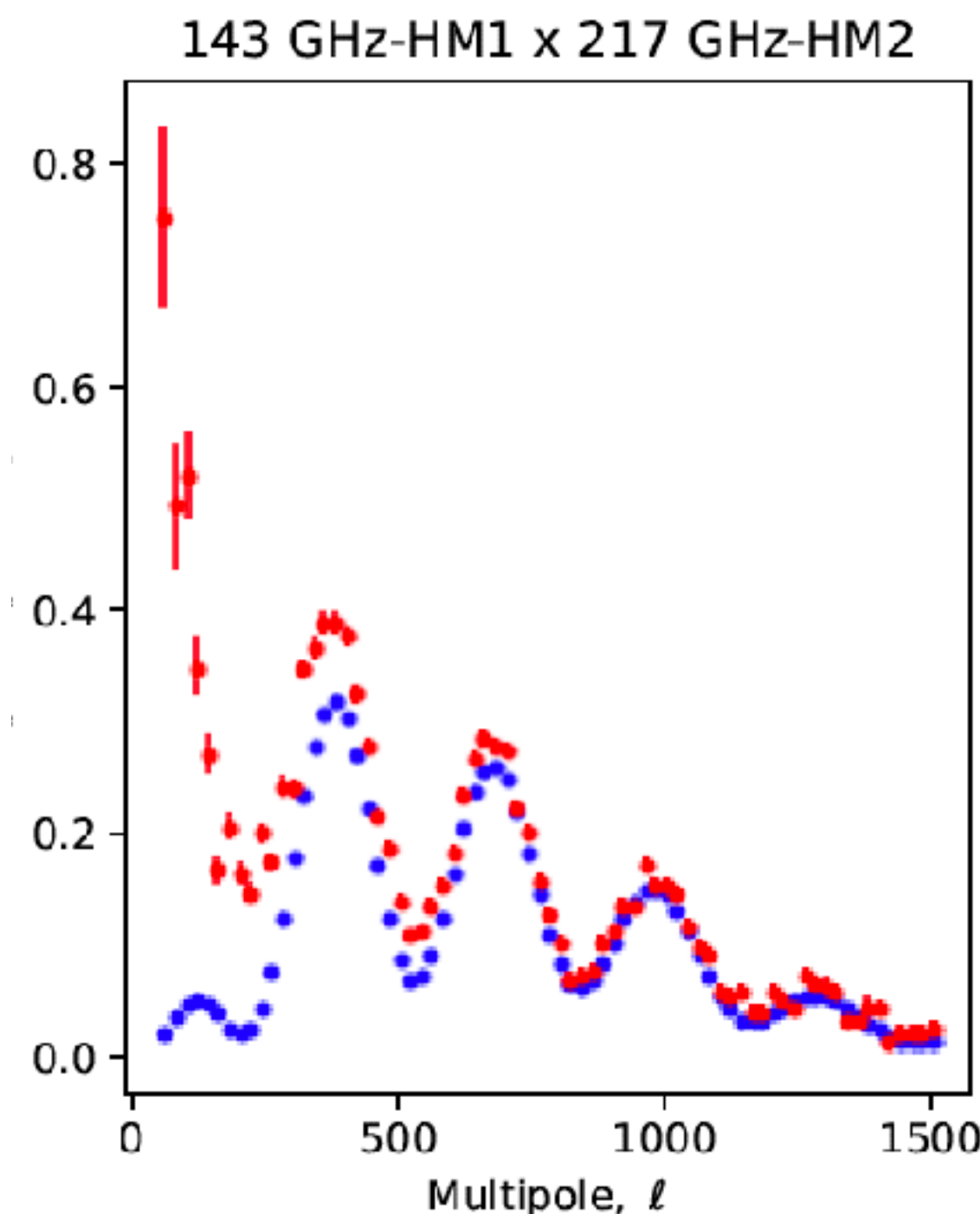
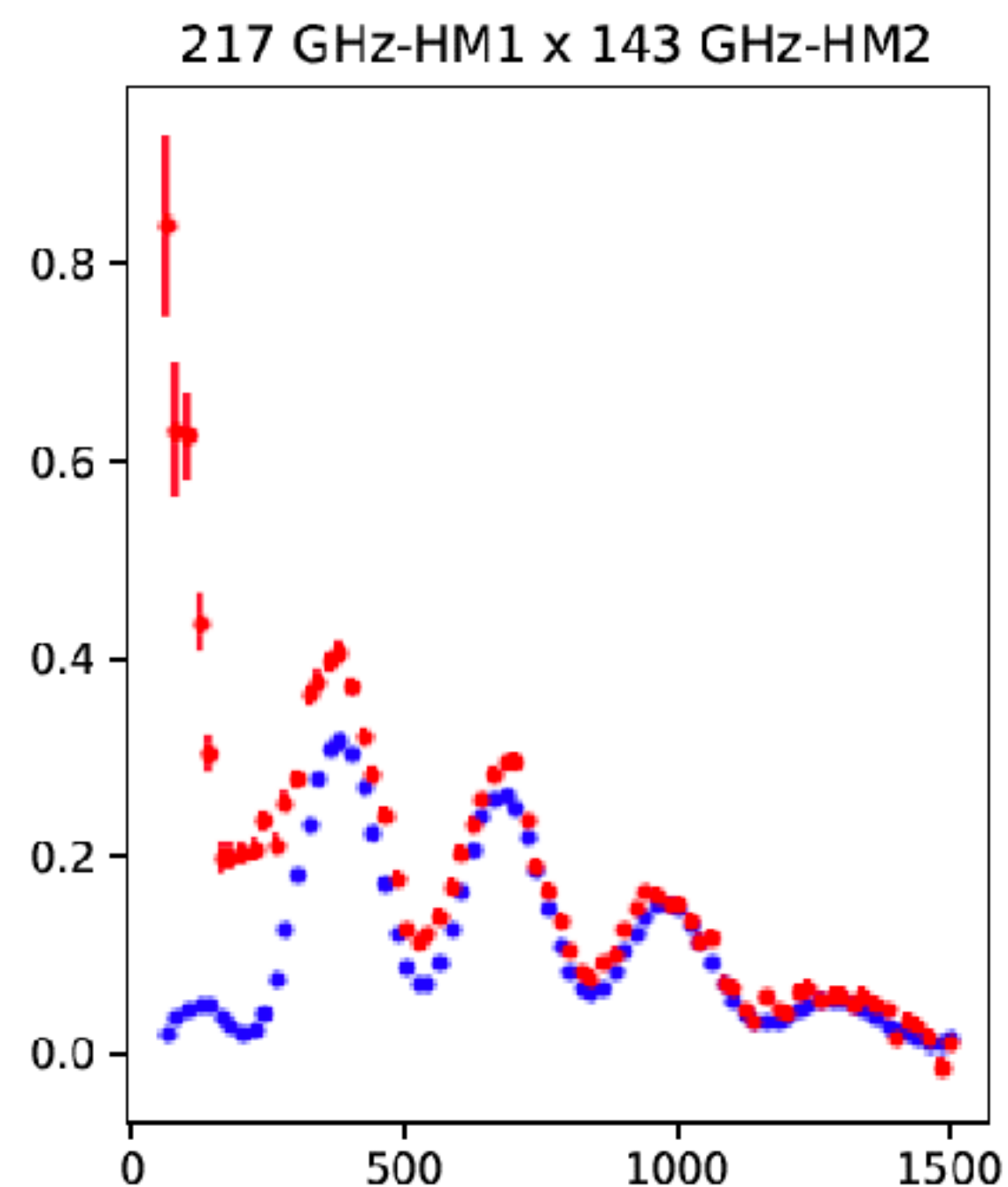
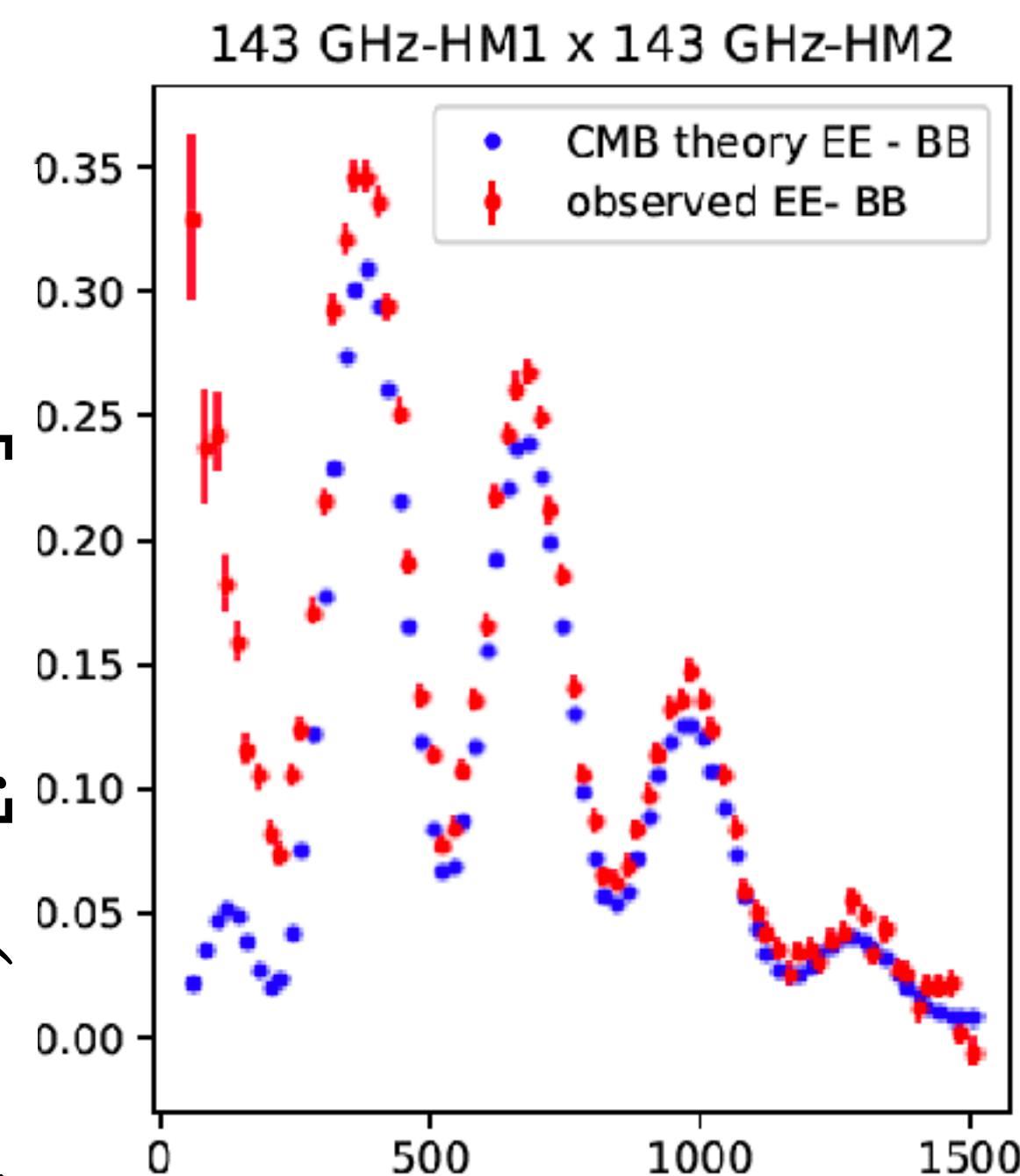
- When the data are dominated by CMB, the sum of two angles, $\alpha + \beta$, is determined precisely.
 - This is the diagonal line.
- The foreground determines α with some uncertainty, breaking the degeneracy. Then $\sigma(\beta) \sim \sigma(\alpha)$ because $\sigma(\alpha + \beta) \ll \sigma(\alpha)$.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

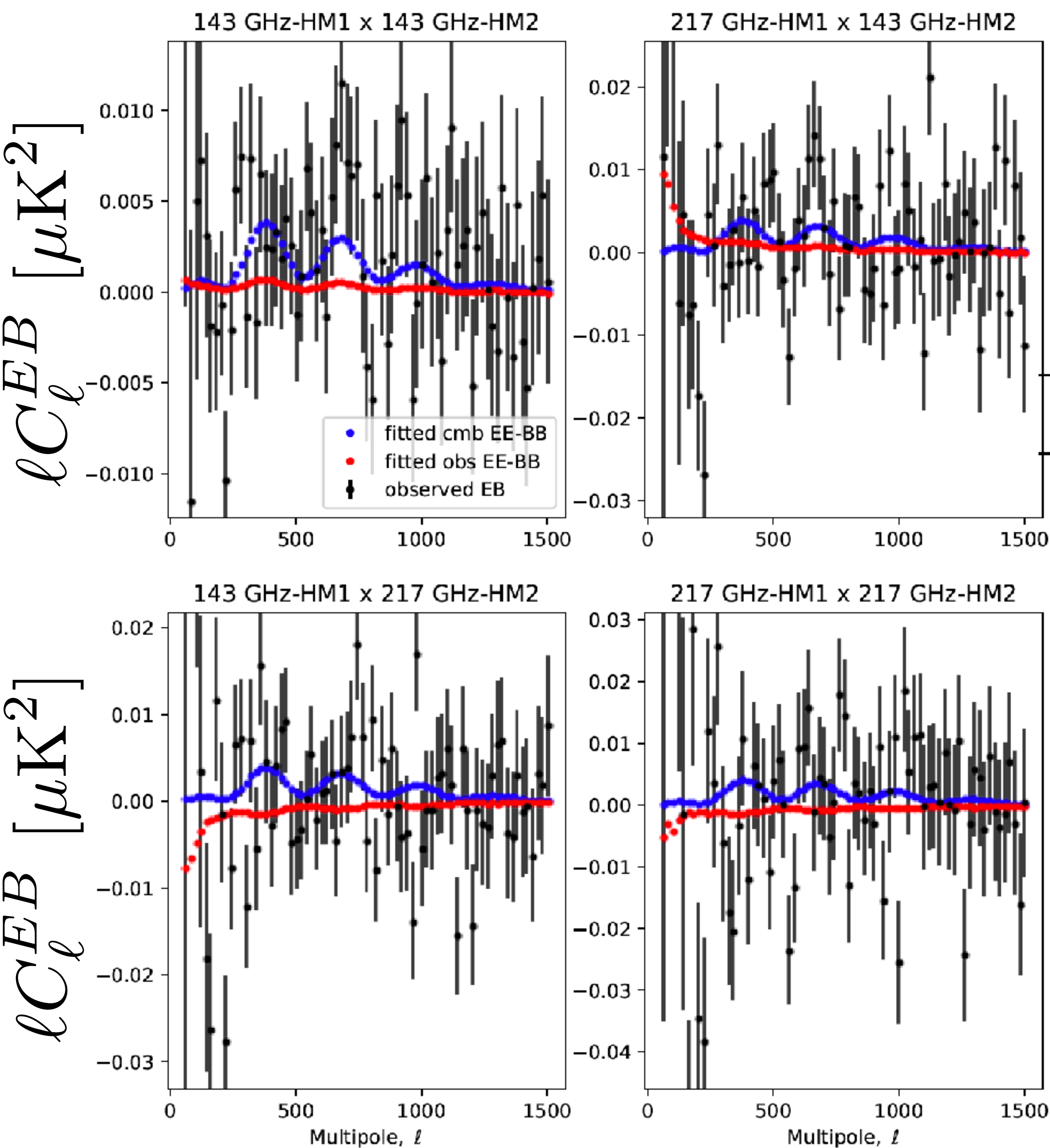
$$\ell(C_\ell^{EE} - C_\ell^{BB}) [\mu K^2]$$

From Planck HFI Data (Minami & EK 2020)

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

- Can we see β 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)*





From Planck HFI Data (Minami & EK 2020)

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

- Can we see β 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

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

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 correlation of the CMB, $\langle C_\ell^{EB,CMB} \rangle$ but we take into account the foreground (dust) EB, $\langle C_\ell^{EB,fg} \rangle$
- We account for the dust EB by assuming that EB/EE is proportional to TB/TE **measured from the data**. Not really a modelling.

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

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

Relating EB to TB

- A generic approach:

$$\frac{C_{\ell}^{EB, \text{dust}}}{C_{\ell}^{EE, \text{dust}}} \propto \frac{C_{\ell}^{TB, \text{dust}}}{C_{\ell}^{TE, \text{dust}}}$$

This is unknown

Measured well!

Measured well!

Relating EB to TB

- How do we model the new angle γ ?

$$\frac{C_{\ell}^{EB,\text{dust}}}{C_{\ell}^{EE,\text{dust}}} \propto \frac{C_{\ell}^{TB,\text{dust}}}{C_{\ell}^{TE,\text{dust}}}$$

- 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

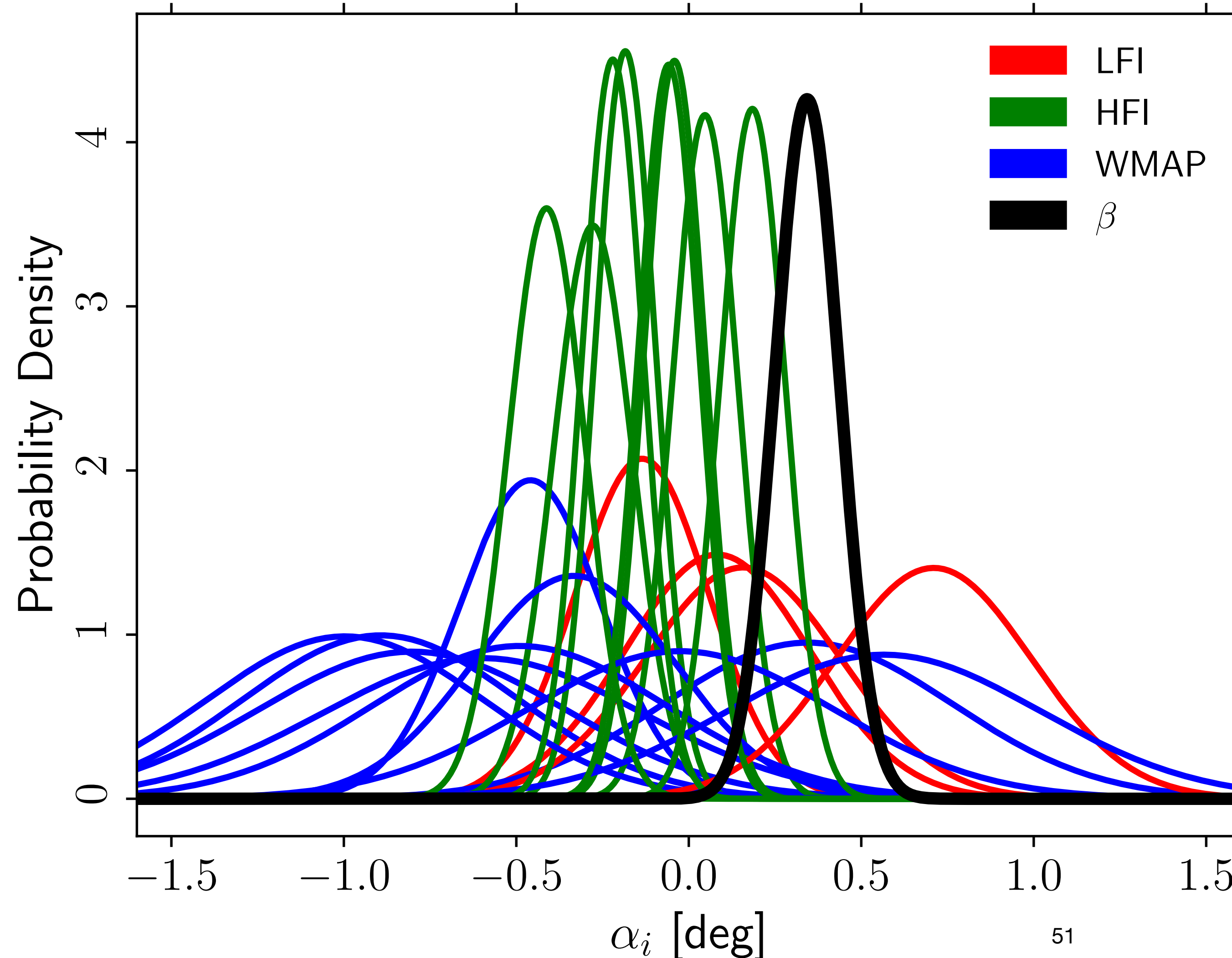
- Then

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

for small angles.

Miscalibration angles (WMAP and Planck)

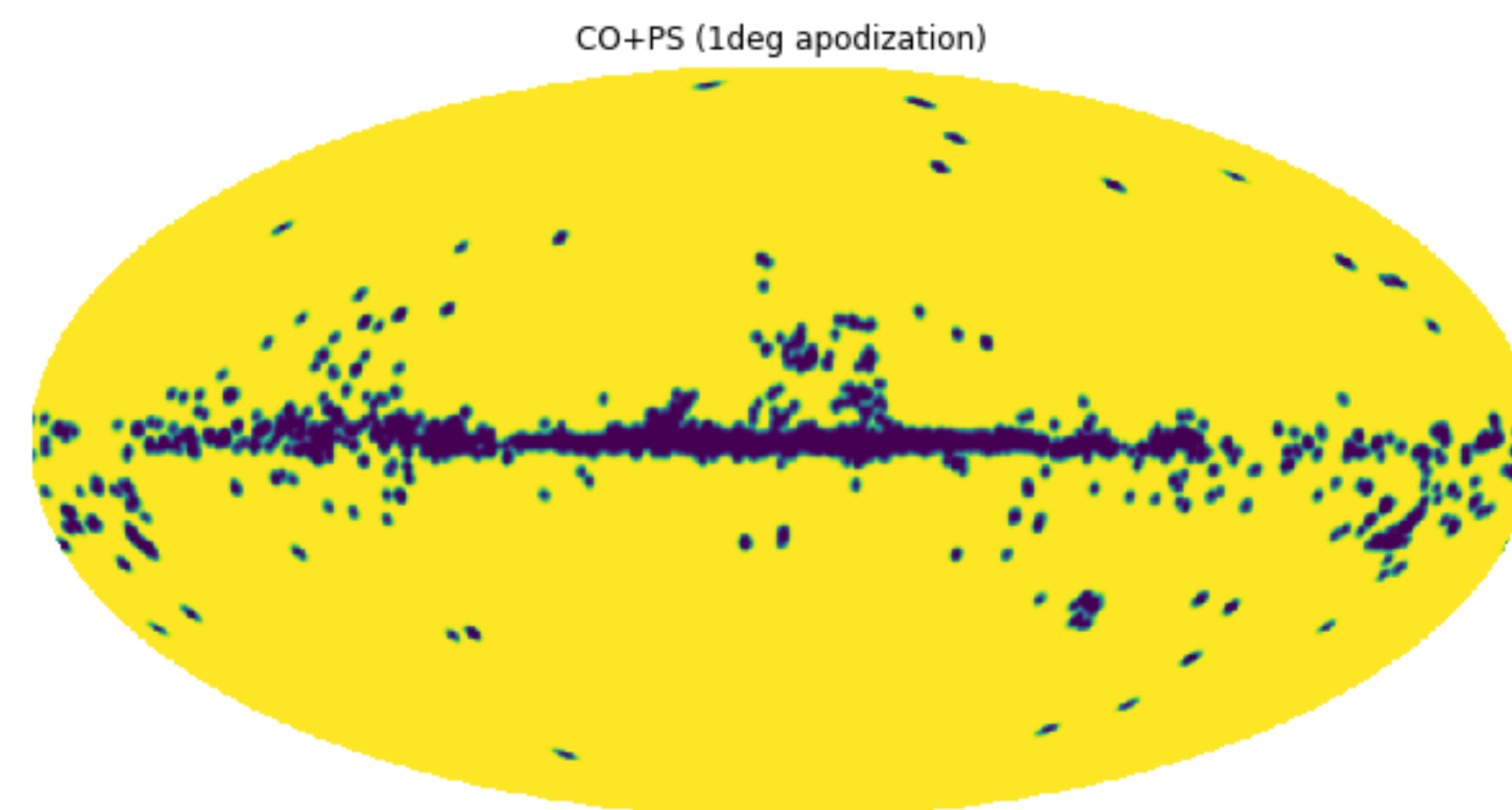
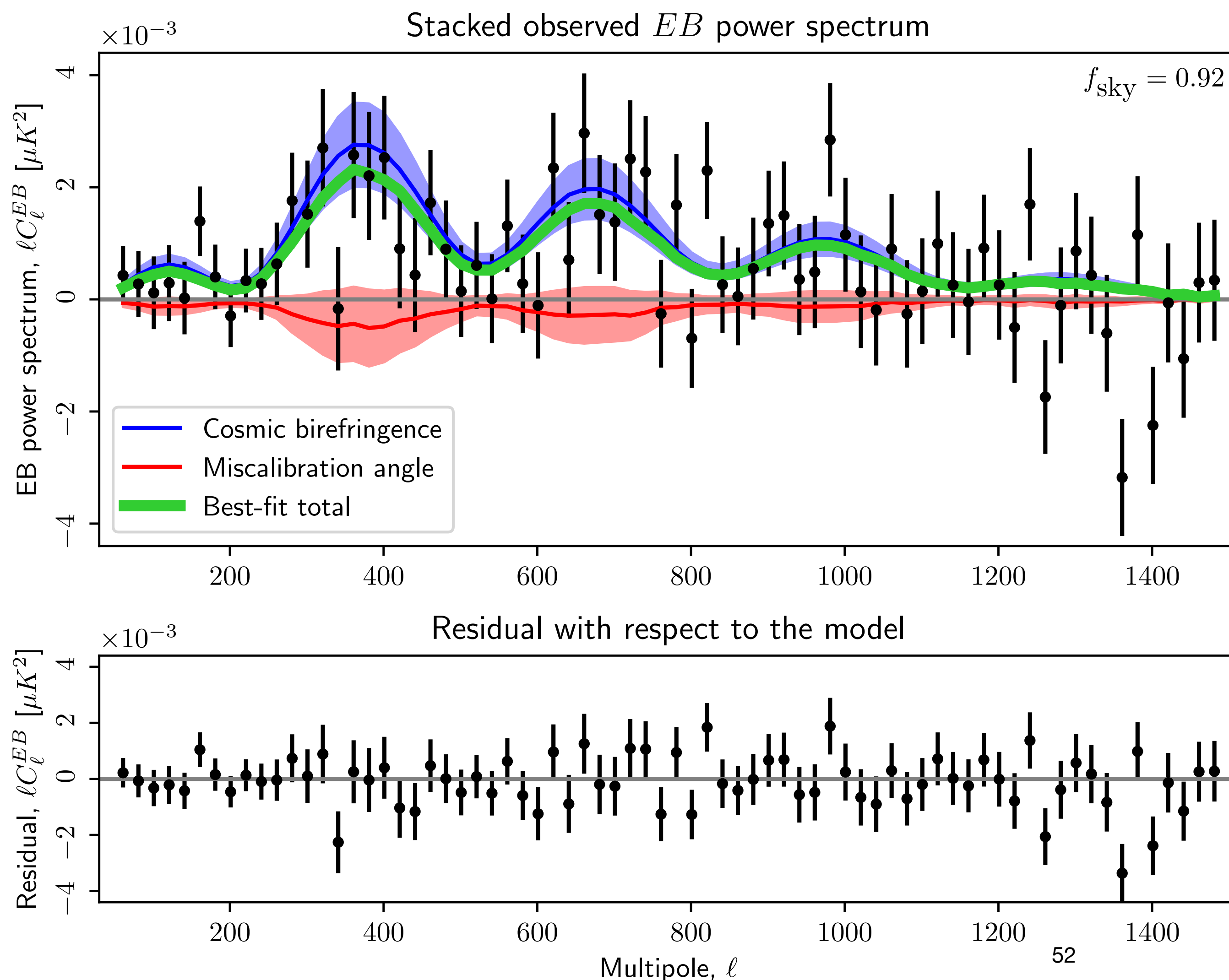
Nearly full-sky data (92% of the sky)



- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
- 1.5 deg for WMAP
- 1 deg for Planck
- They cancel!
- The power of adding independent datasets.

Cosmic Birefringence fits well (WMAP+Planck)

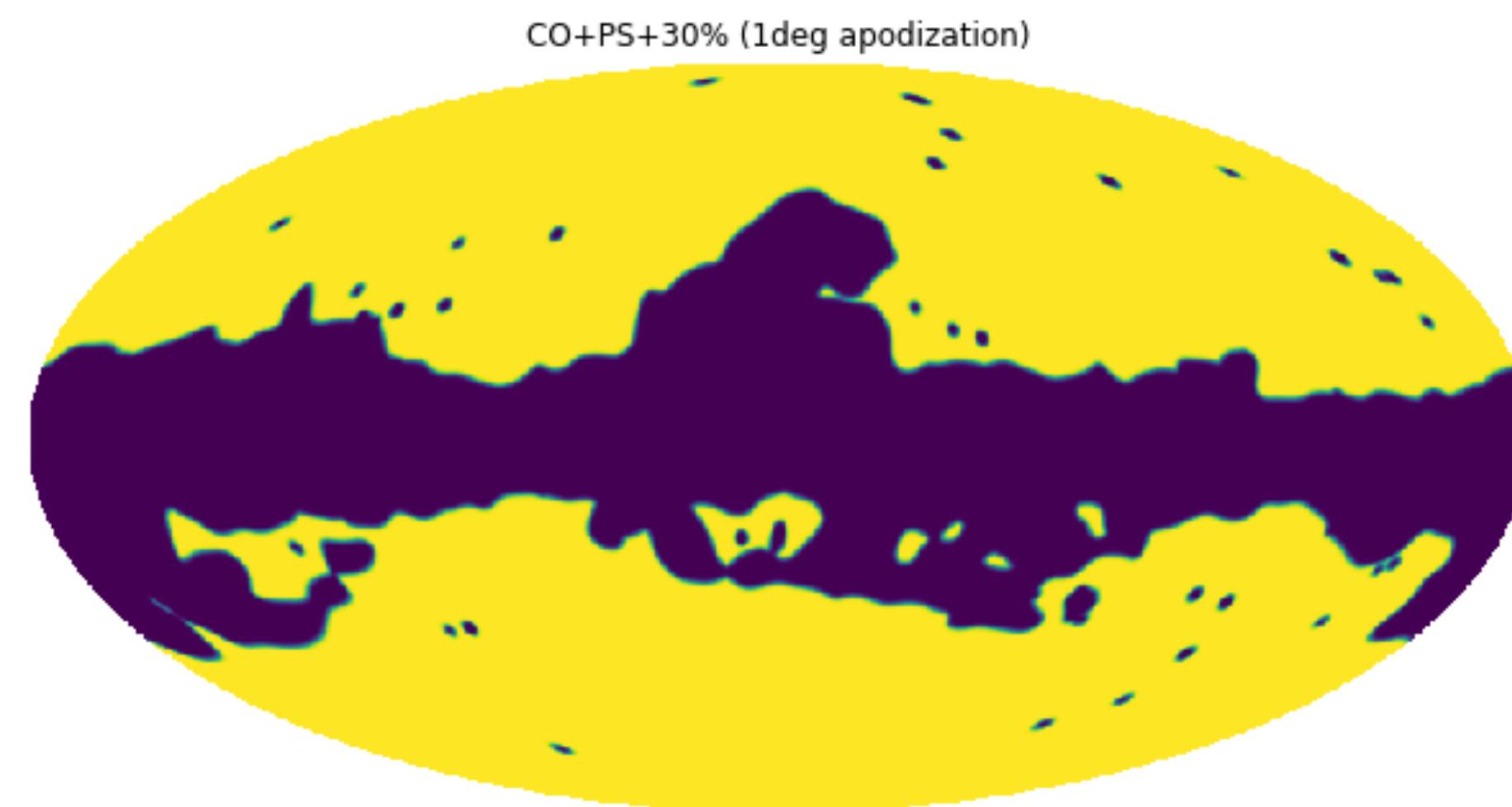
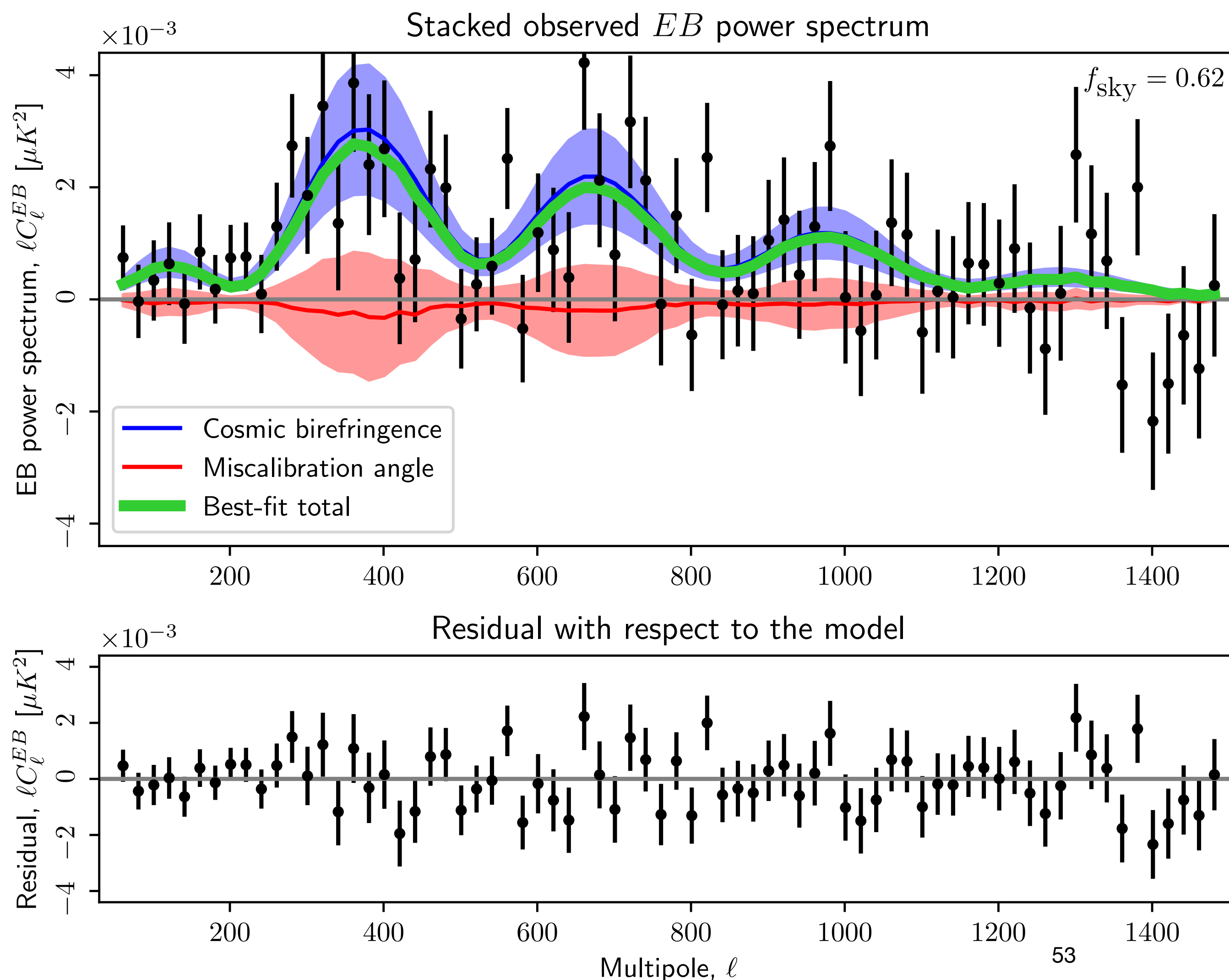
Nearly full-sky data (92% of the sky)



- **Miscalibration angles** make only small contributions thanks to the cancellation.
- $\beta = 0.34 \pm 0.09 \text{ deg}$
- $\chi^2 = 65.3$ for DOF=72

Cosmic Birefringence fits well (WMAP+Planck)

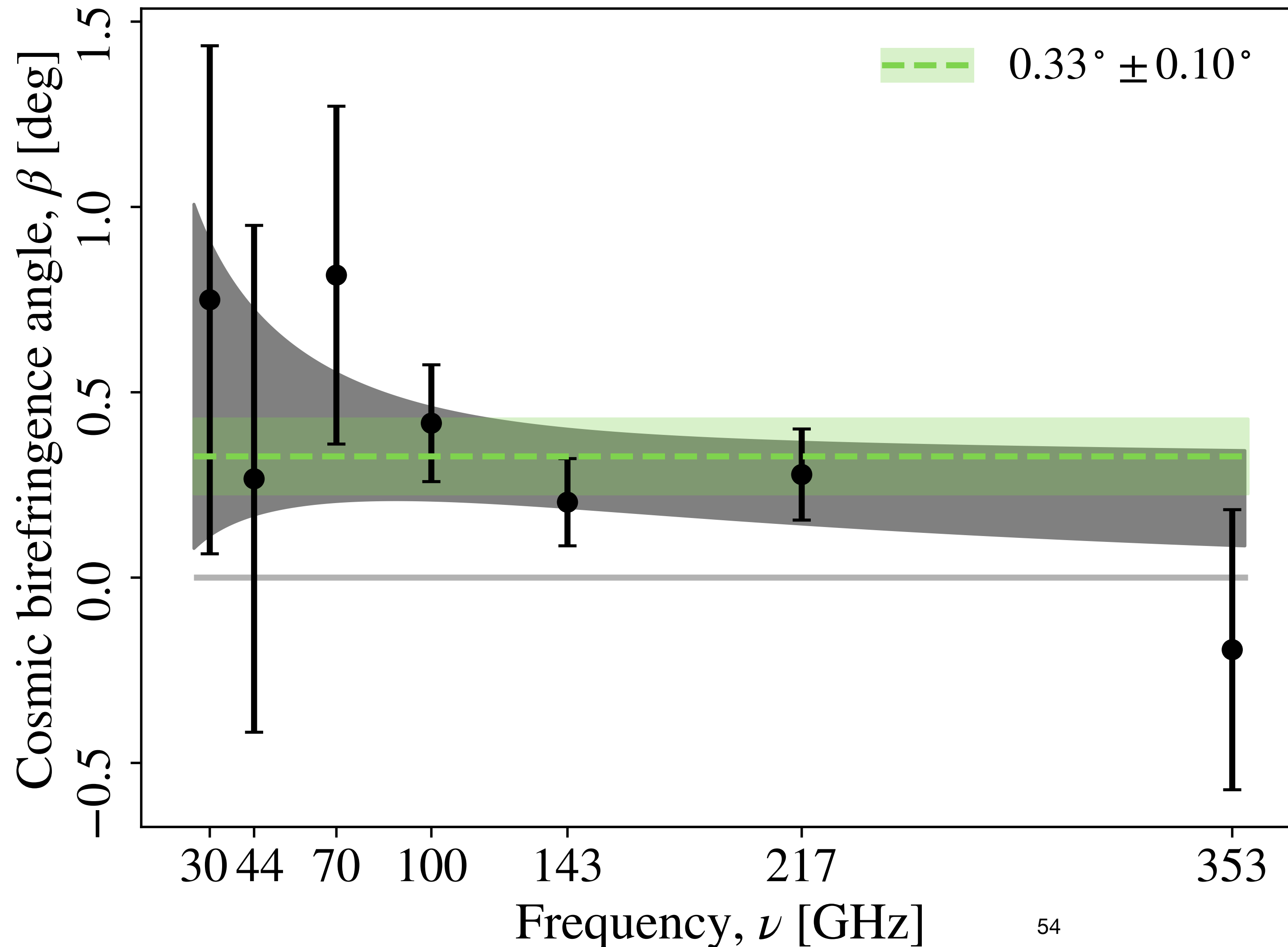
Robust against the Galactic mask (62% of the sky)



- **Miscalibration angles** make only small contributions thanks to the cancellation.
- $\beta = 0.37 \pm 0.14 \text{ deg}$
- $\chi^2 = 65.8$ for DOF=72

No frequency dependence is found

Consistent with the expectation from cosmic birefringence

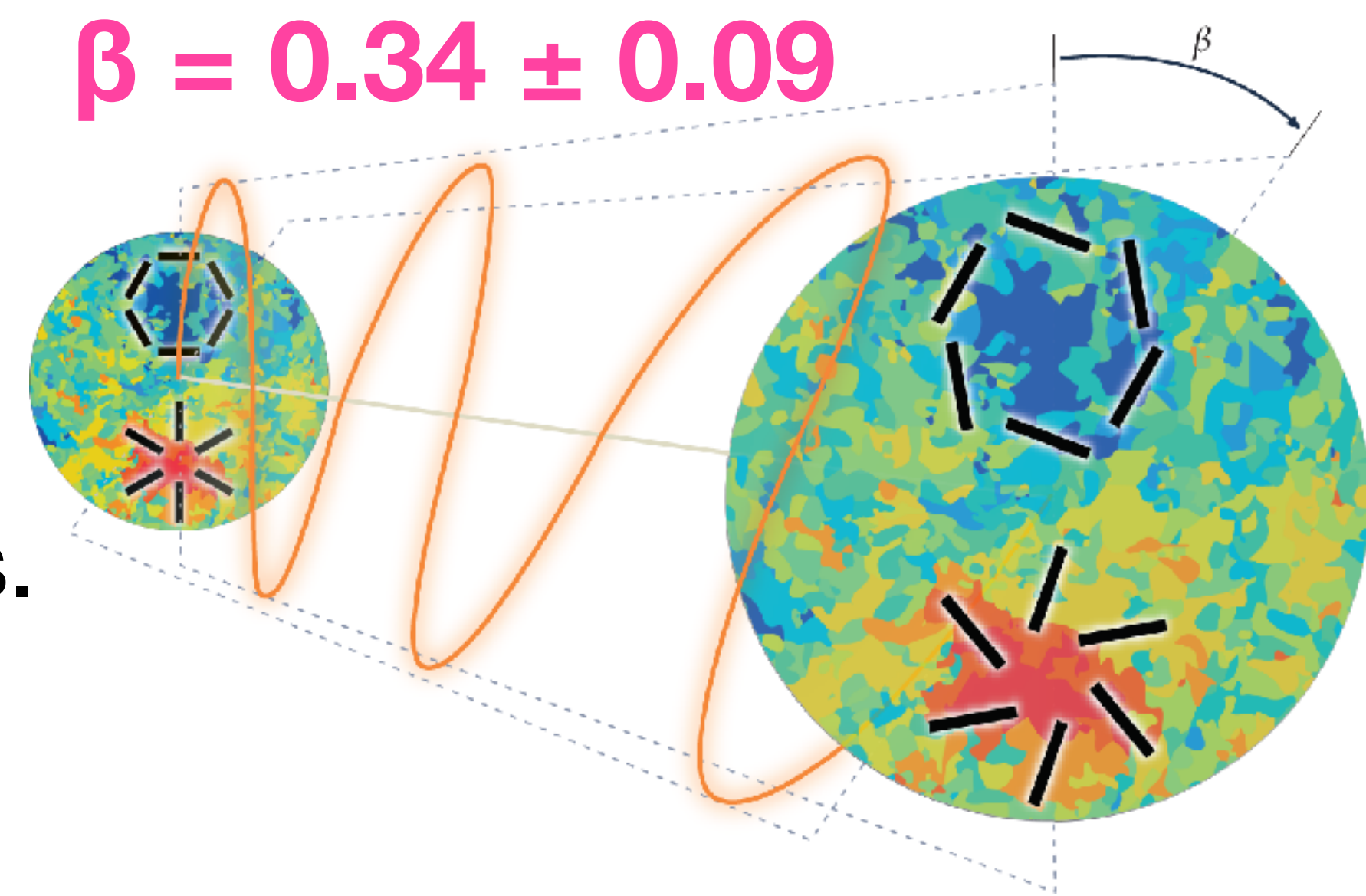


- No evidence for frequency dependence:
- For $\beta \sim (\nu/150\text{GHz})^n$,
 $n = -0.20^{+0.41}_{-0.39}$ (68% CL)
- Faraday rotation ($n=-2$) is disfavoured.

Conclusion

$\beta = 0.34 \pm 0.09$ deg (68%CL; nearly full sky)

- Robust against the sky fraction used for the analysis.
- No evidence for frequency dependence of β .
 - Consistent with a cosmological signal.
- Good news: **The impact of the known instrumental systematics is negligible.** We found this using the Planck simulations.
- If the measured β is confirmed as cosmological, it would have profound implications for the fundamental physics behind dark matter and energy.
- It is fair to say that **there is no evidence for significant impacts of the Galactic foreground or the known systematics.**
 - But we keep investigating!



Relating EB to TB

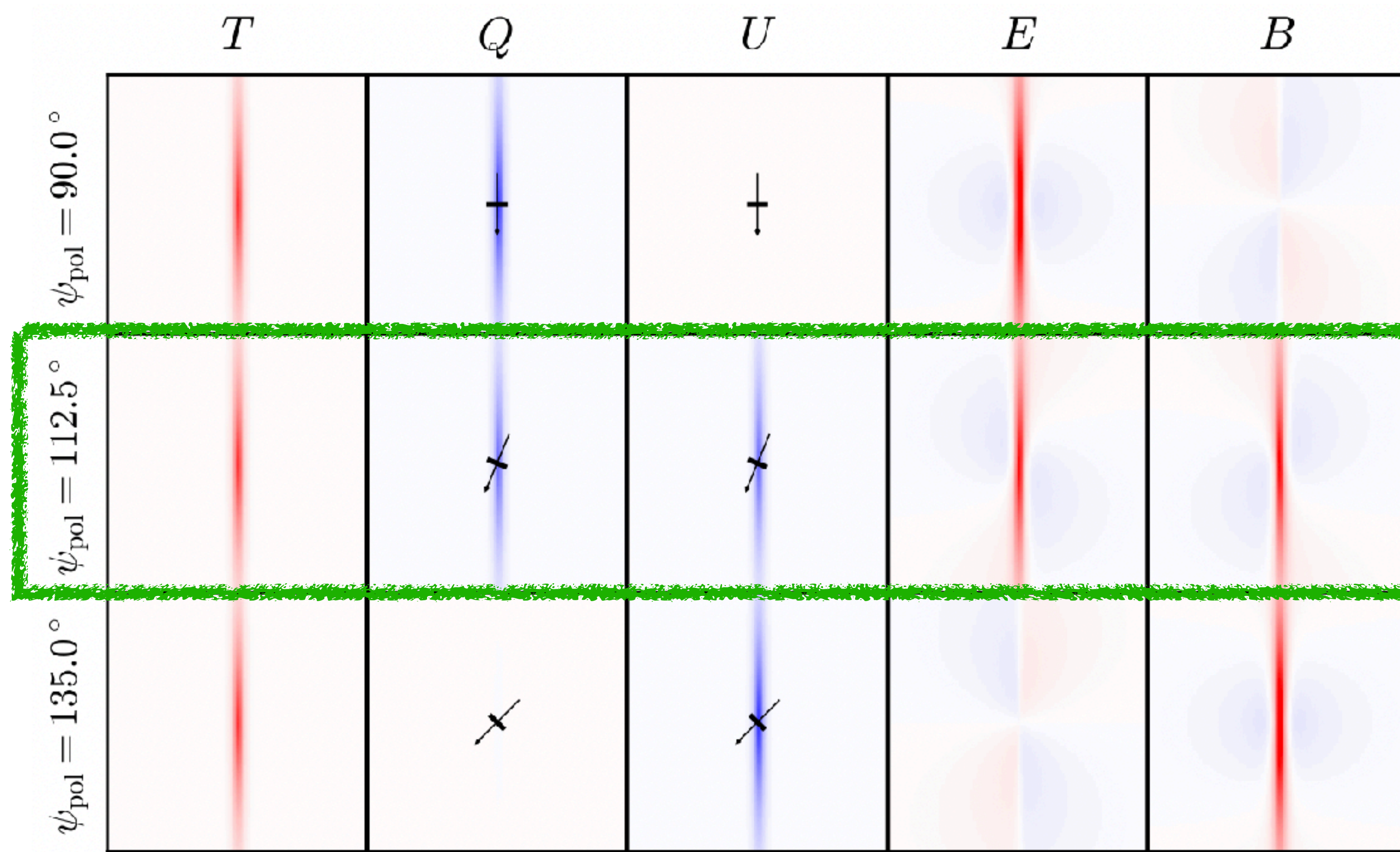
A physical justification for this assumption

$$\frac{C_{\ell}^{EB,\text{dust}}}{C_{\ell}^{EE,\text{dust}}} \propto \frac{C_{\ell}^{TB,\text{dust}}}{C_{\ell}^{TE,\text{dust}}}$$

- **How do we model the new angle γ physically?**
 - 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 $EB > 0$