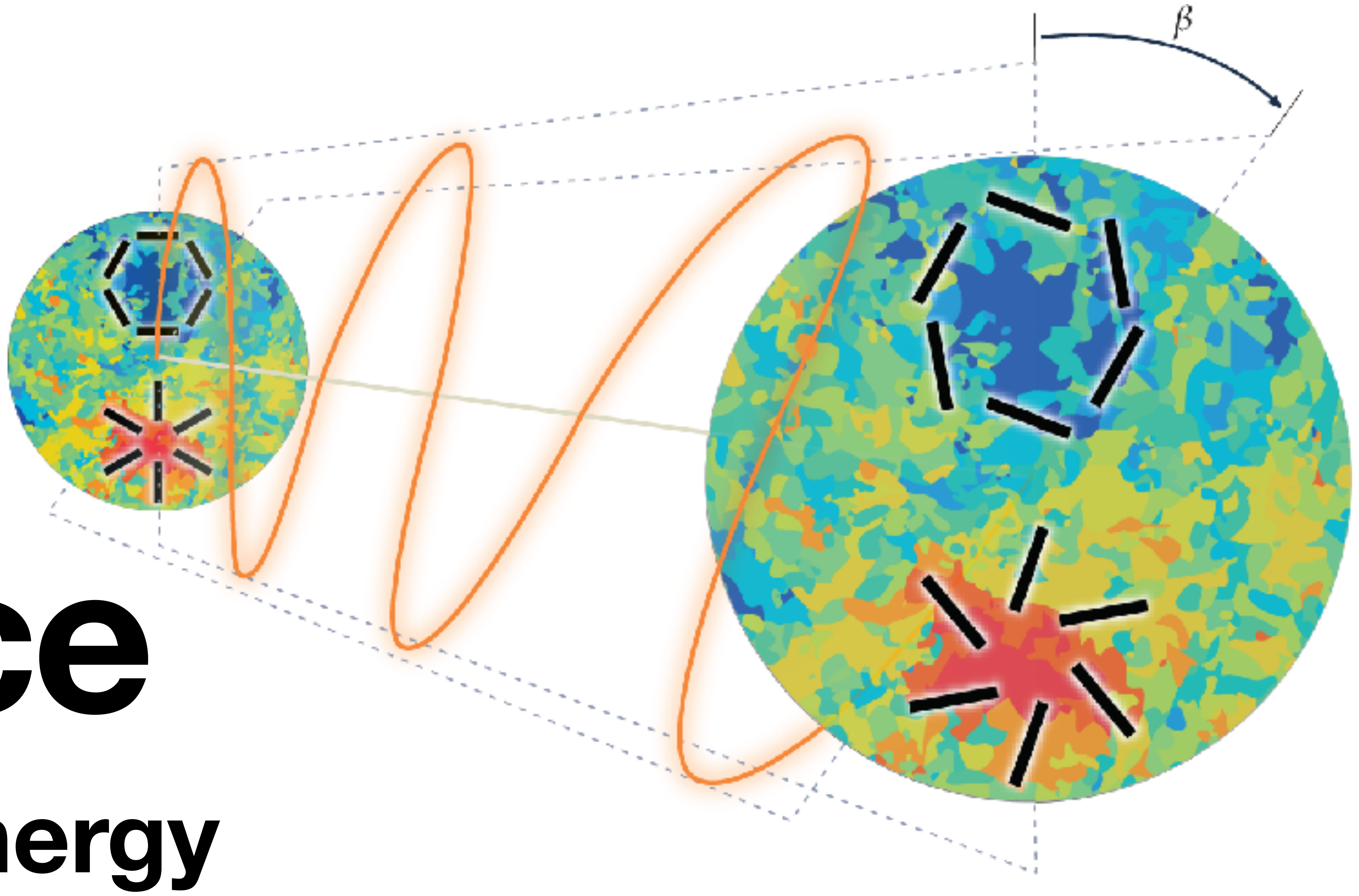
Patricia Diego-Palazuelos (Univ. Cantabria, Santander)

Johannes Røsok Eskilt (Univ. Oslo)

Yuto Minami (Osaka U.)



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Cosmic Birefringence

A New Probe of Dark Matter and Dark Energy

based on

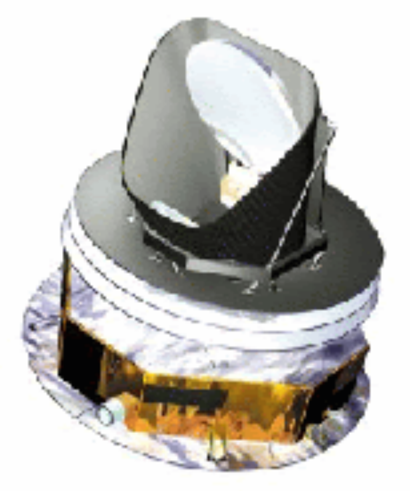
- *Minami & EK, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, Minami, et al., PRL, 128, 091302 (2022)*
- *EK, Nature Reviews Physics, 4 (2022)*
- *Eskilt & EK, arXiv:2205.13962*

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)

UTAP, the University of Tokyo

June 13, 2022

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

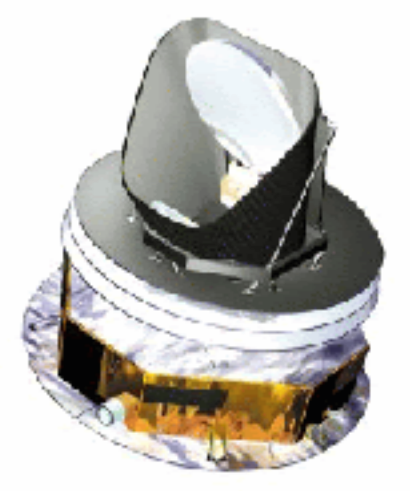


ESA's Planck

Credit: ESA

Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



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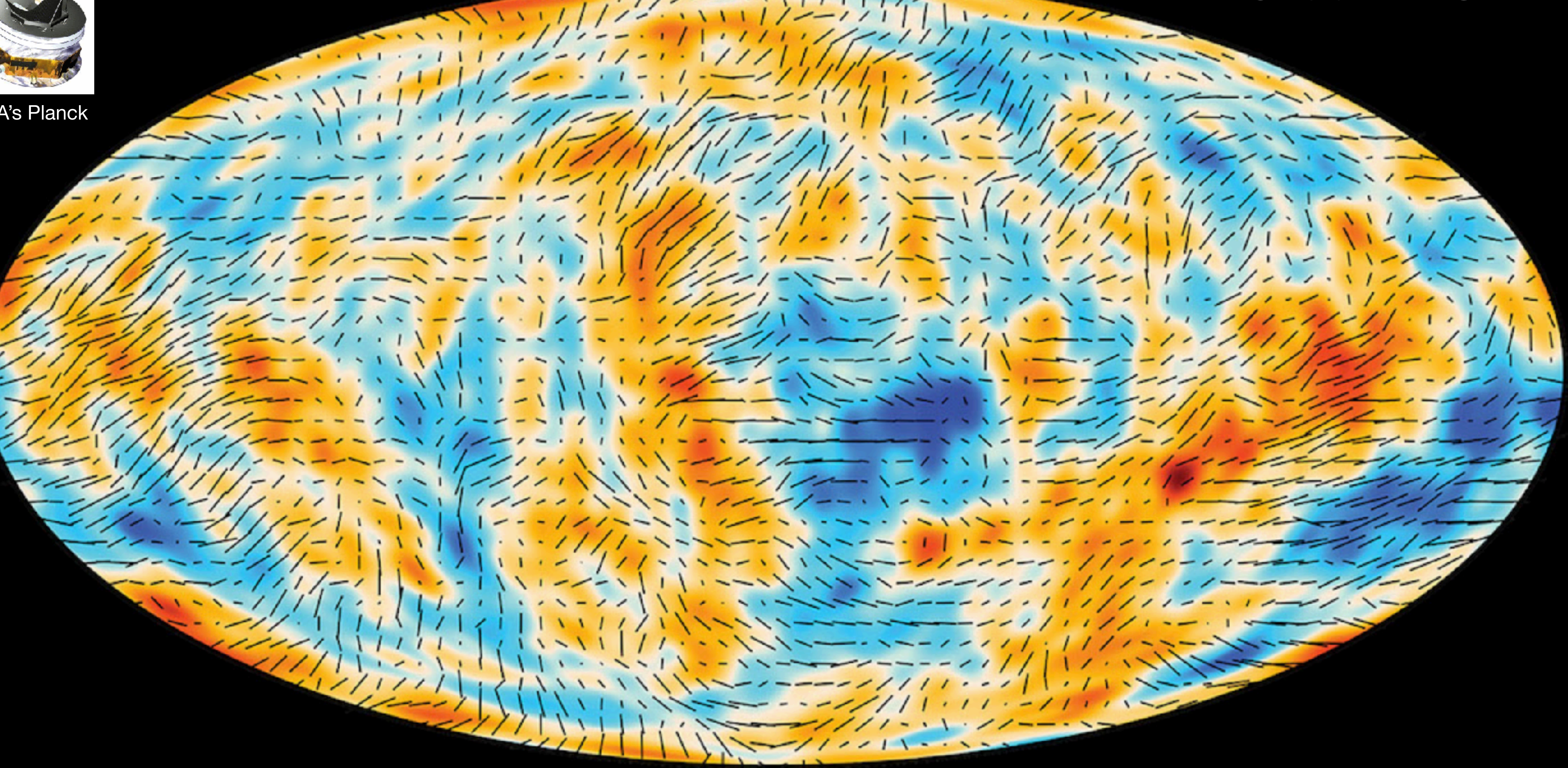
Credit: ESA



Emitted 13.8 billions years ago

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 CMB polarisation
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
  - Imprint of **primordial gravitational waves** in CMB polarisation
- *Polarisation* of the CMB may hold the key to the answers.

nature reviews physics

Available also at arXiv:2202.13919

Review Article | Published: 18 May 2022

New physics from the polarized light of the cosmic microwave background

Eiichiro Komatsu ✉

Nature Reviews Physics (2022) | Cite this article

Key Words:

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

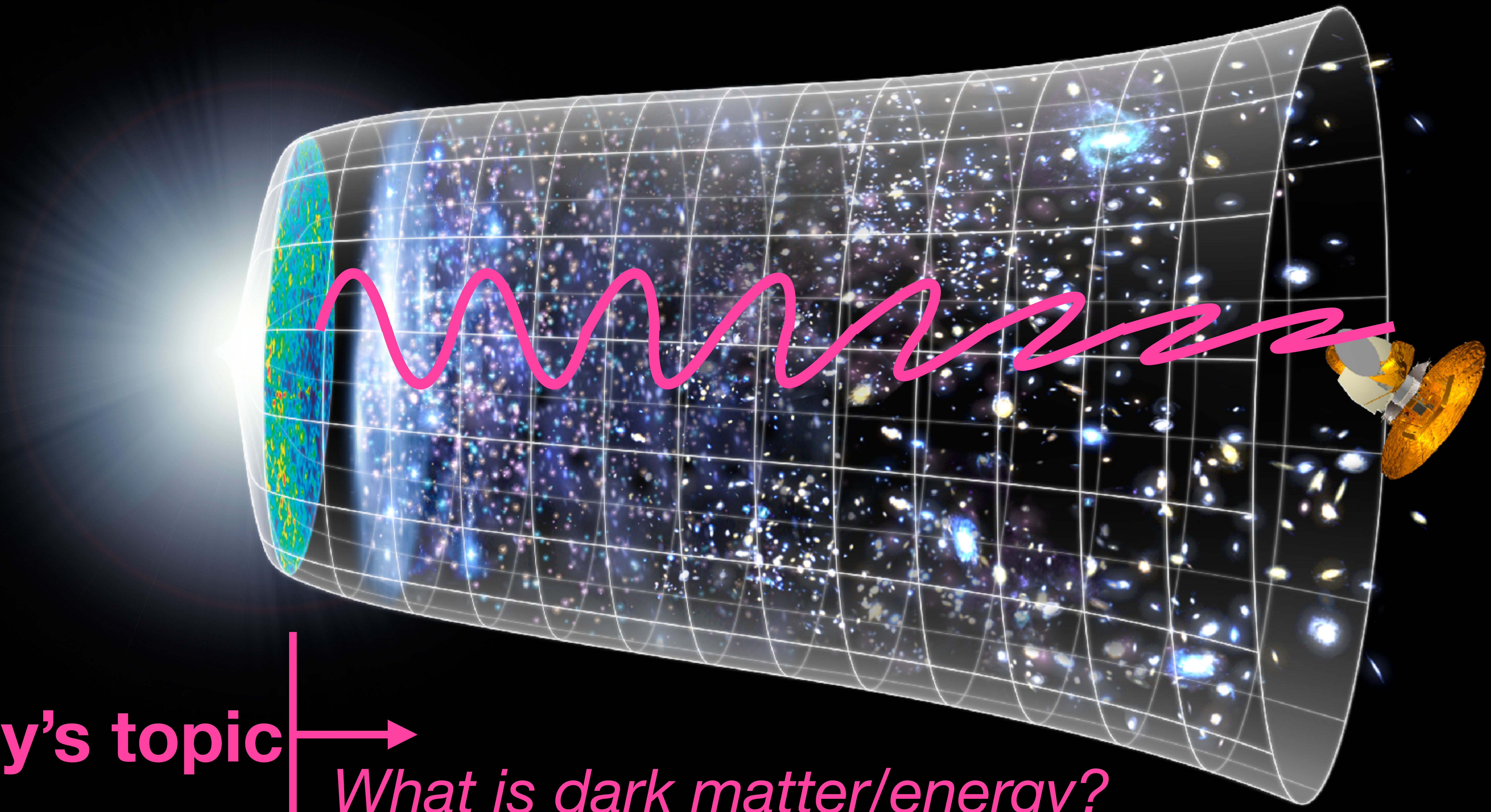
Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates ***polarisation***!)
What powered the Big Bang?
What is dark matter/energy?

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?*

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

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

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

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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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

Parity Even

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

Parity Odd

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

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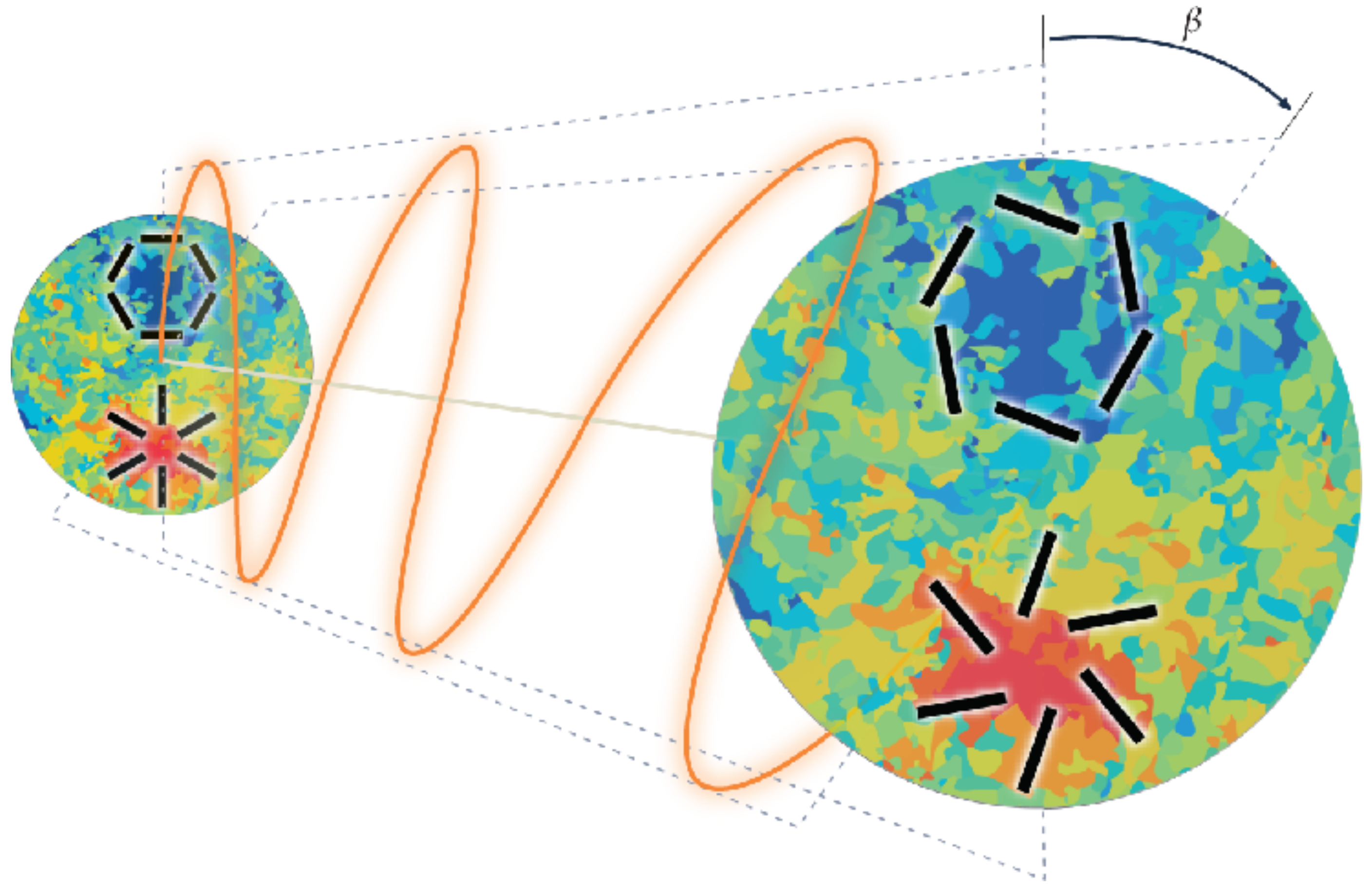


"Cosmic Birefringence"

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

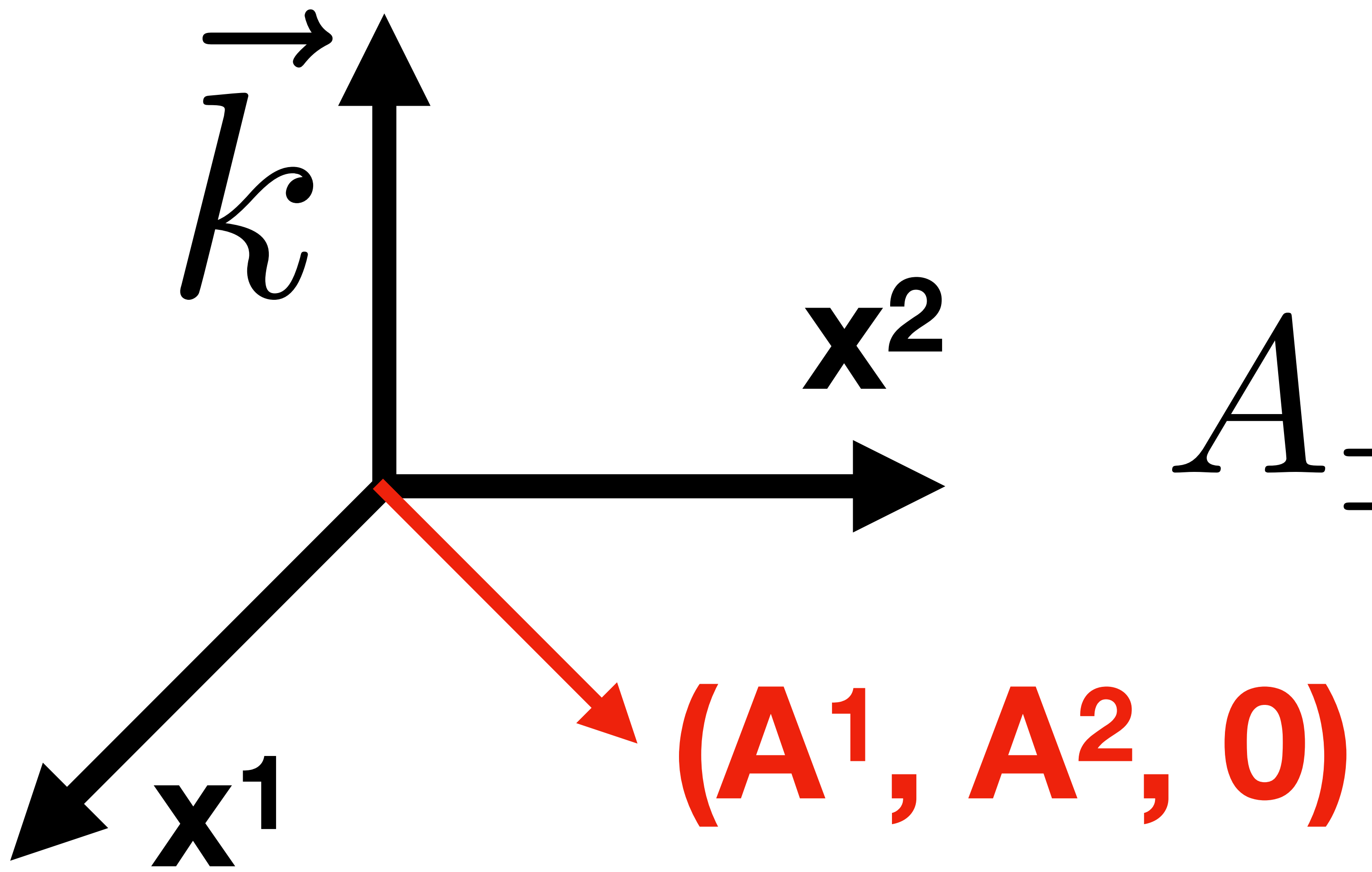
Standard Maxwell Theory

Warm up (1)

- To isolate a transverse wave, we require A_0=0 and div(A_i)=0. Then, in vacuum,

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

- 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

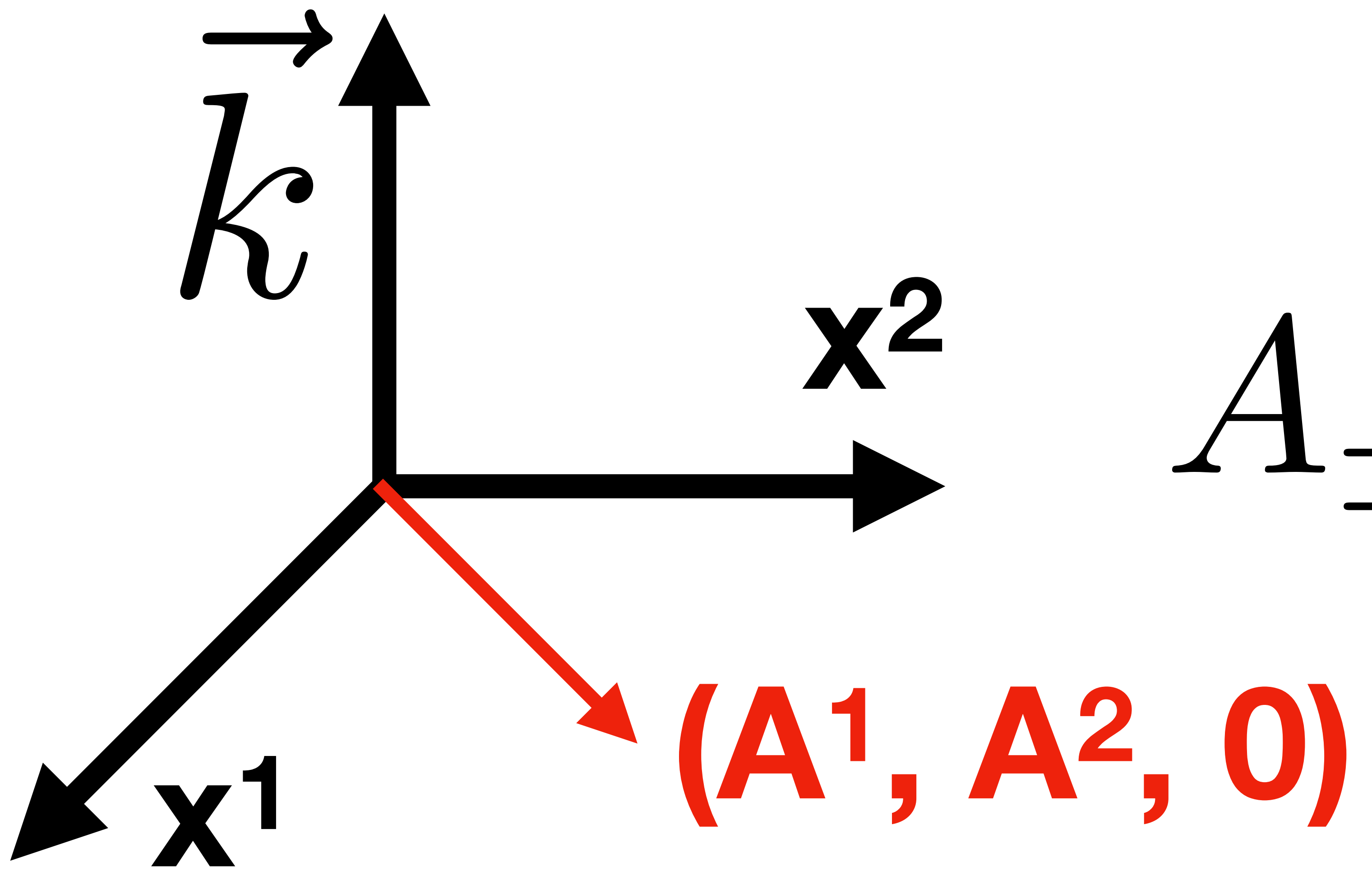
Warm up (2)

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

- 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



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

Cosmic Birefringence

Derivation (1)

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

> the effective Lagrangian for axion electrodynamics is
>
> Chern-Simons term
>
> $$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (3.7)$$
>
> $$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$
>
> 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

- The equation of motion is modified to

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

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

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

Cosmic Birefringence

Derivation (1)

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

the effective Lagrangian for axion electrodynamics is

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$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k} = \left(1 \pm \frac{2g_a\theta'}{k}\right)^2 - \cancel{\frac{4g_a^2\theta'^2}{k^2}}$$

Cosmic Birefringence

Derivation (1)

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

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

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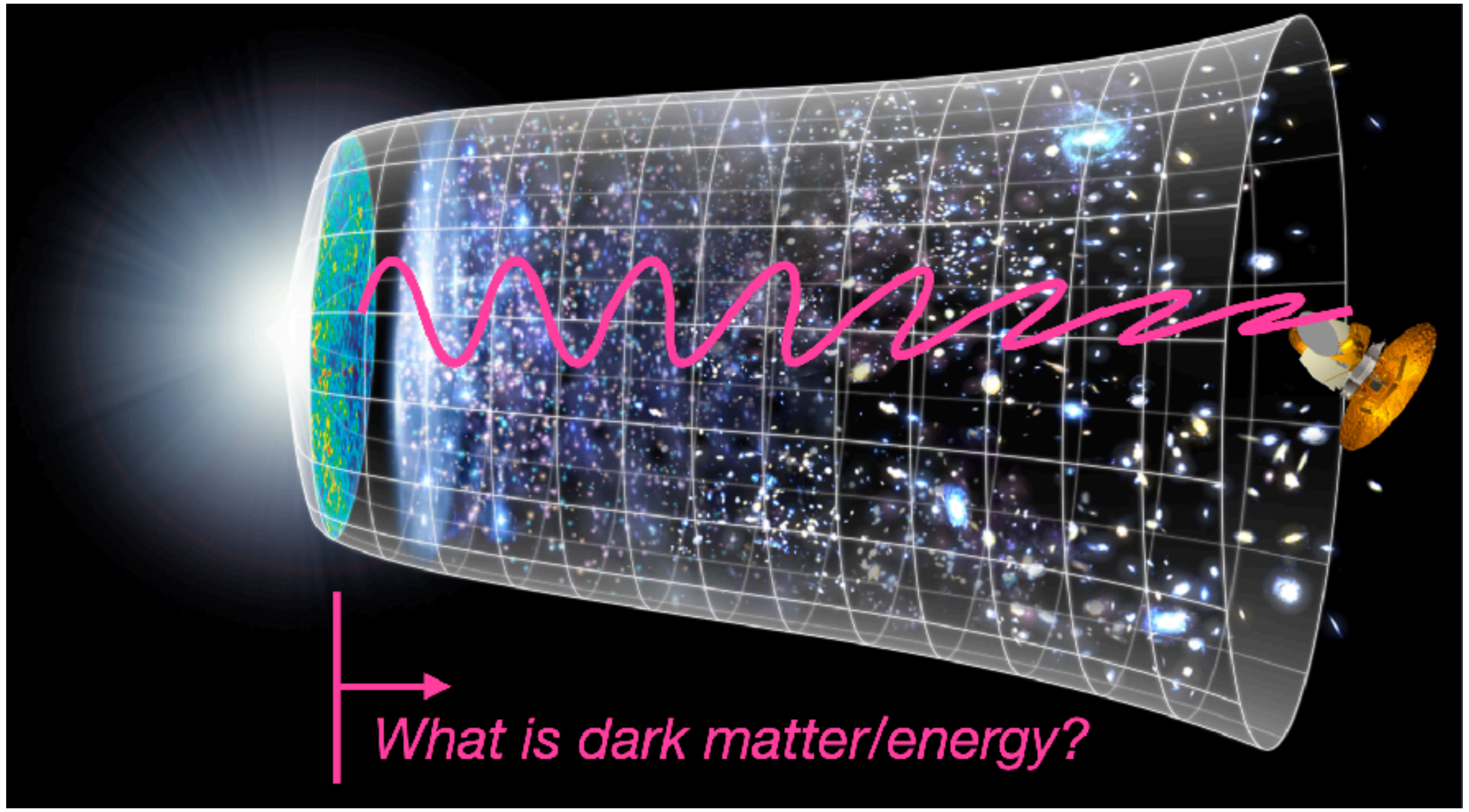
$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

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 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

This "axion" field can be dark matter or dark energy!

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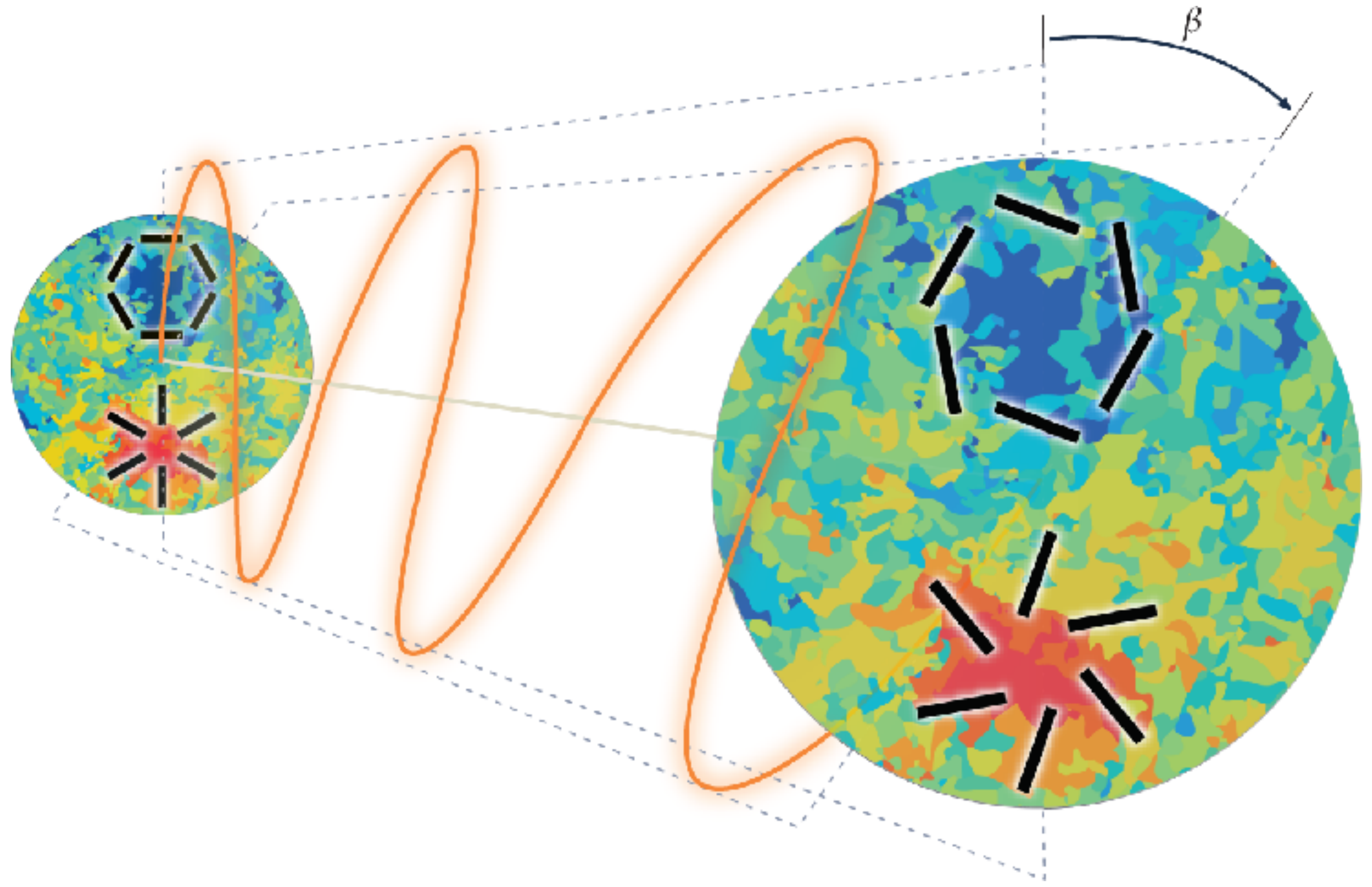
Chern-Simons term: $g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$

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

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

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



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

Cosmic Birefringence

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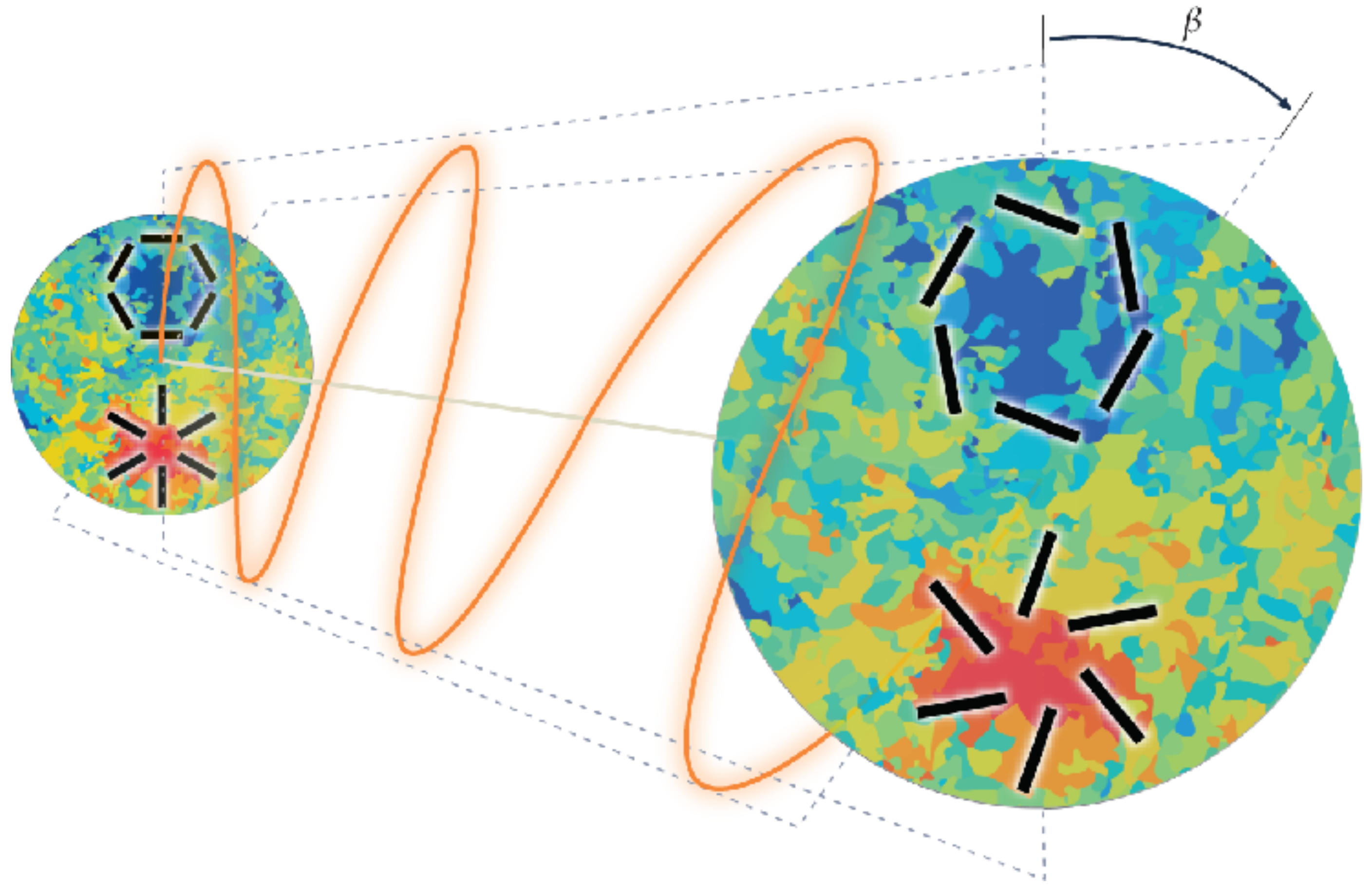


If θ varies over space:

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

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

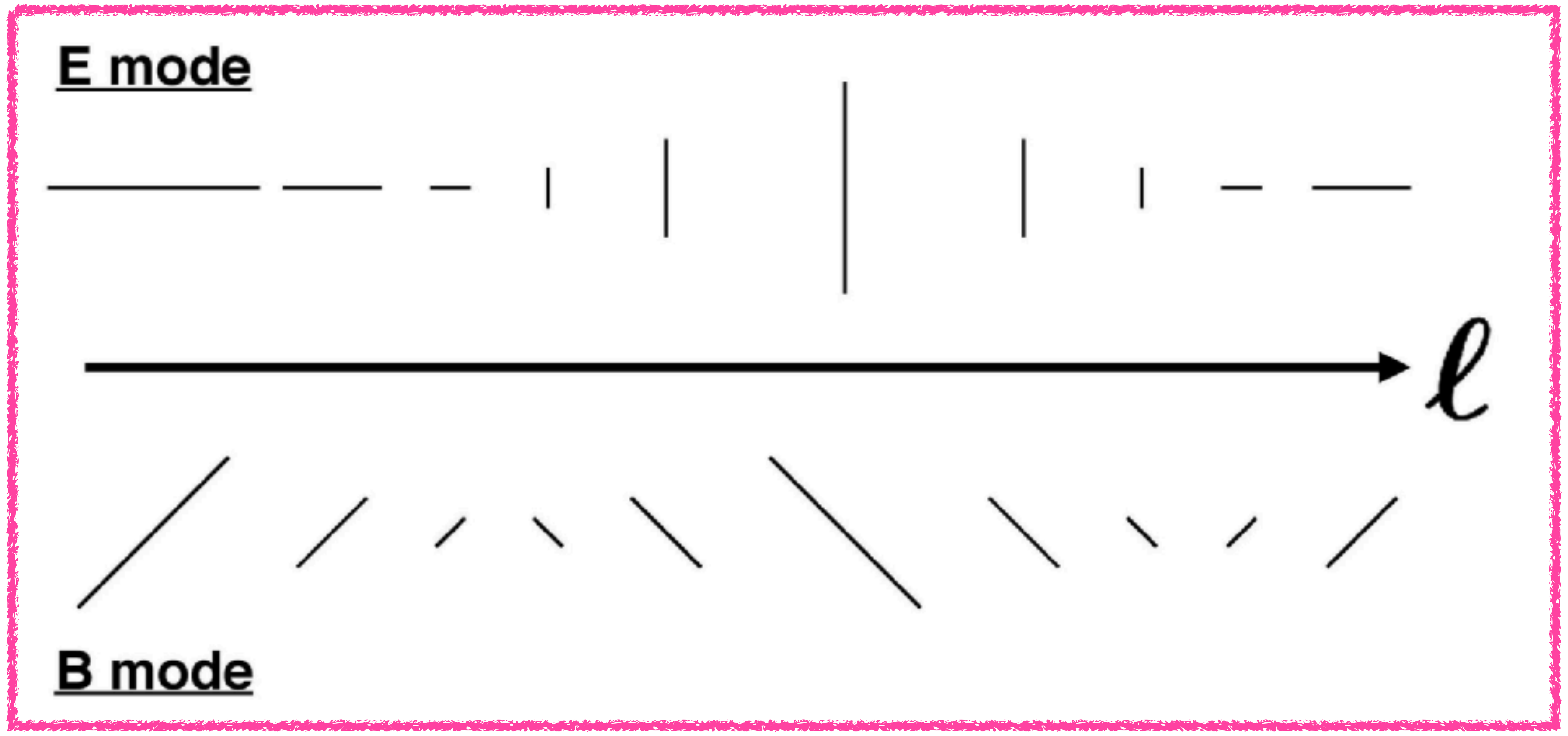
Why study the cosmic birefringence?

- 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!

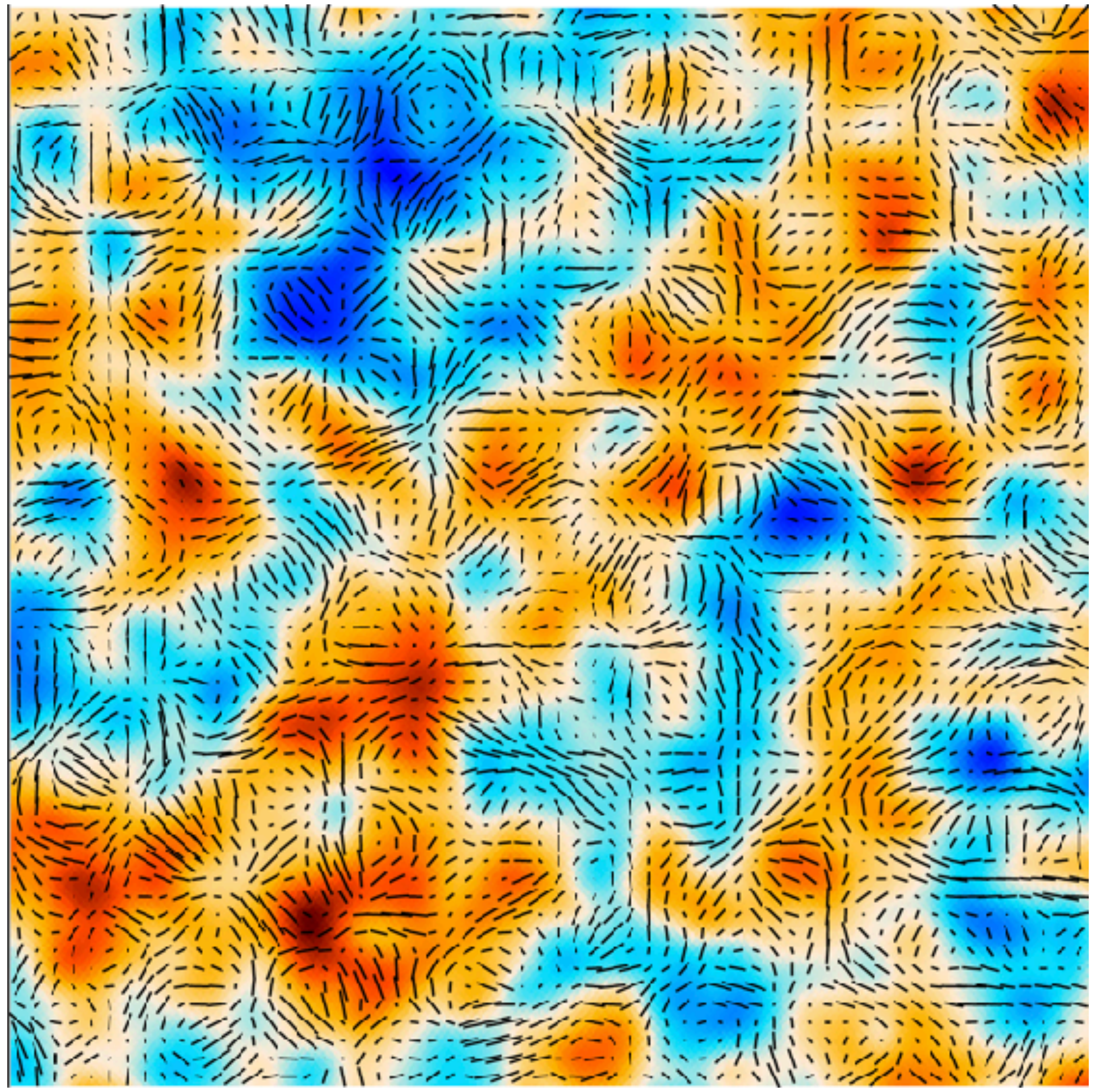
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

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)

Parity eigenstates: E and B modes

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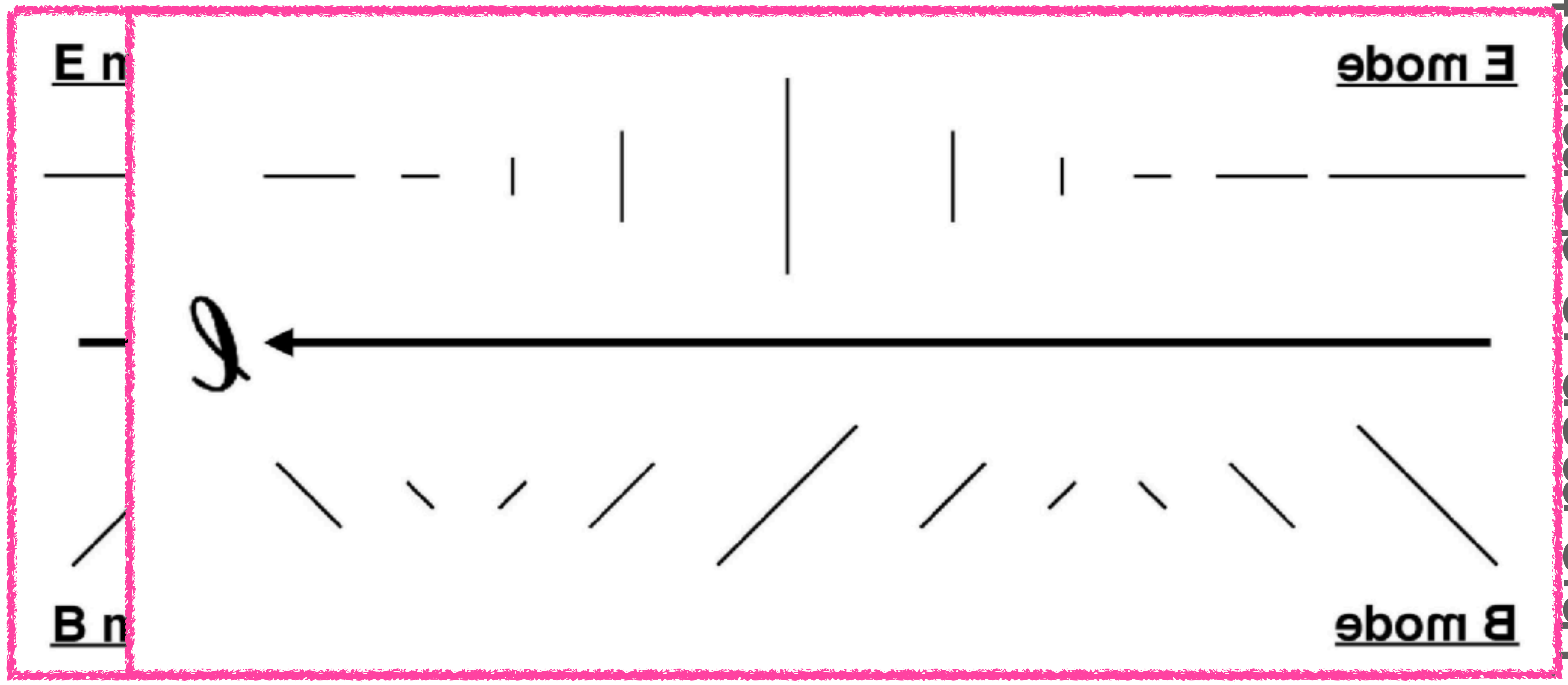
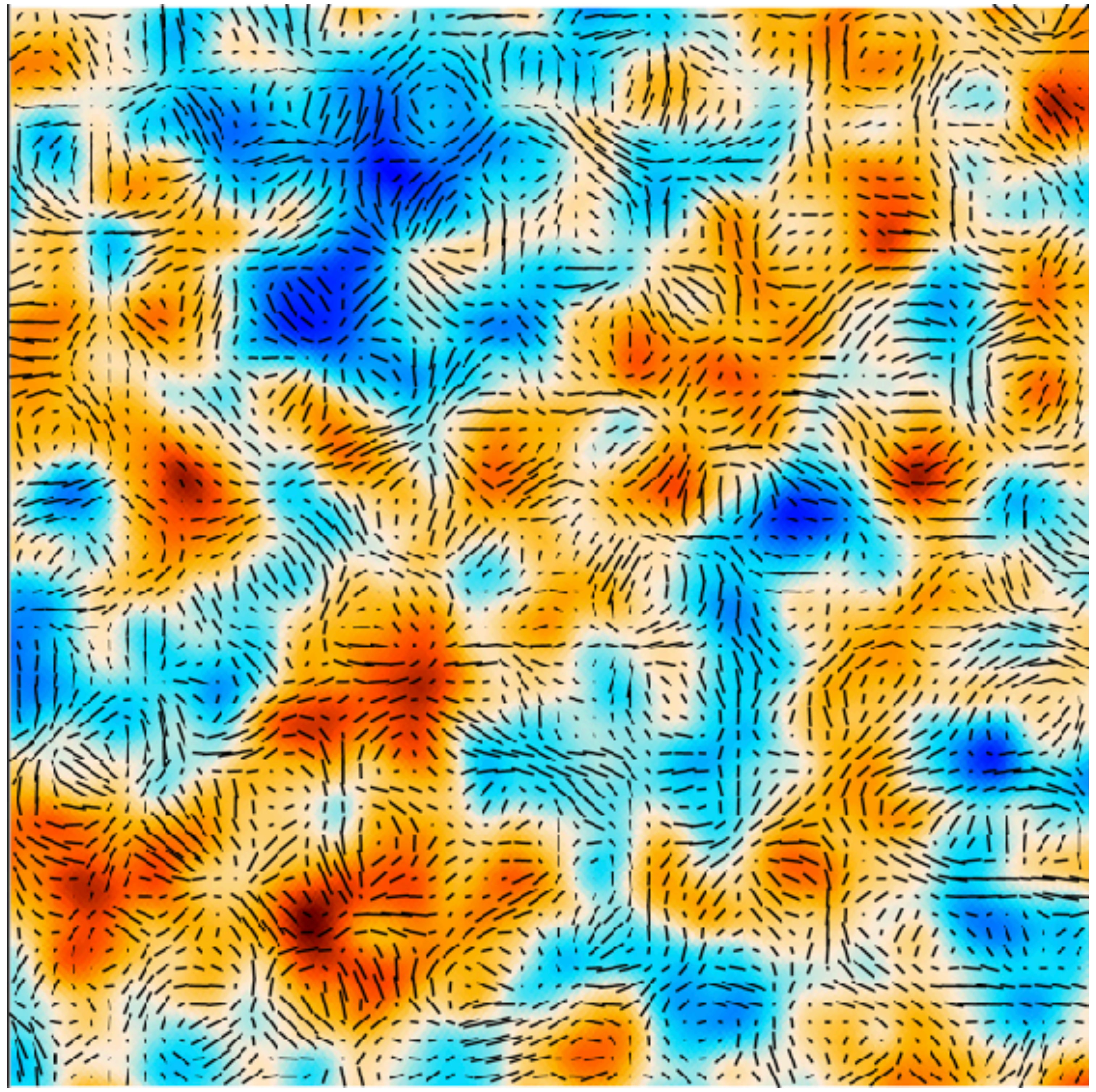


This map is dominated by E-mode polarisation



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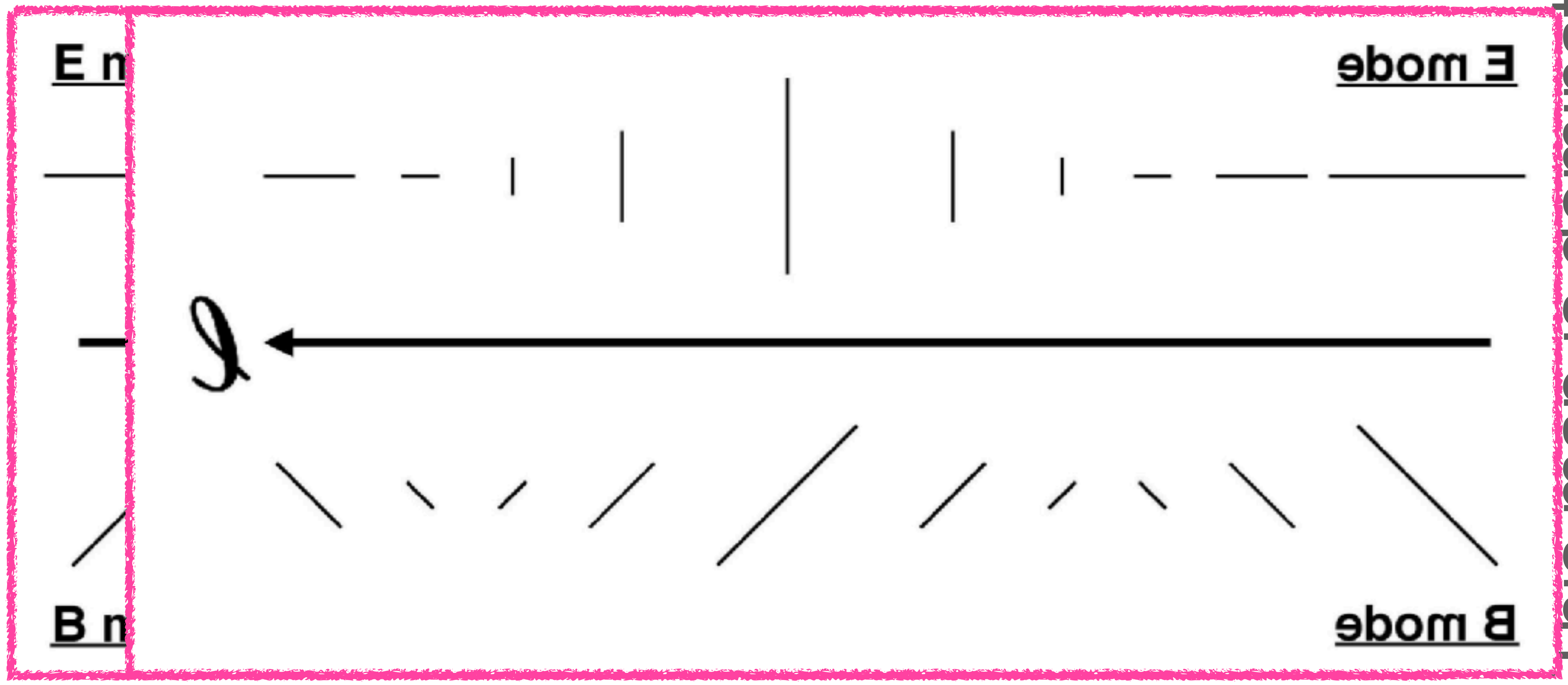
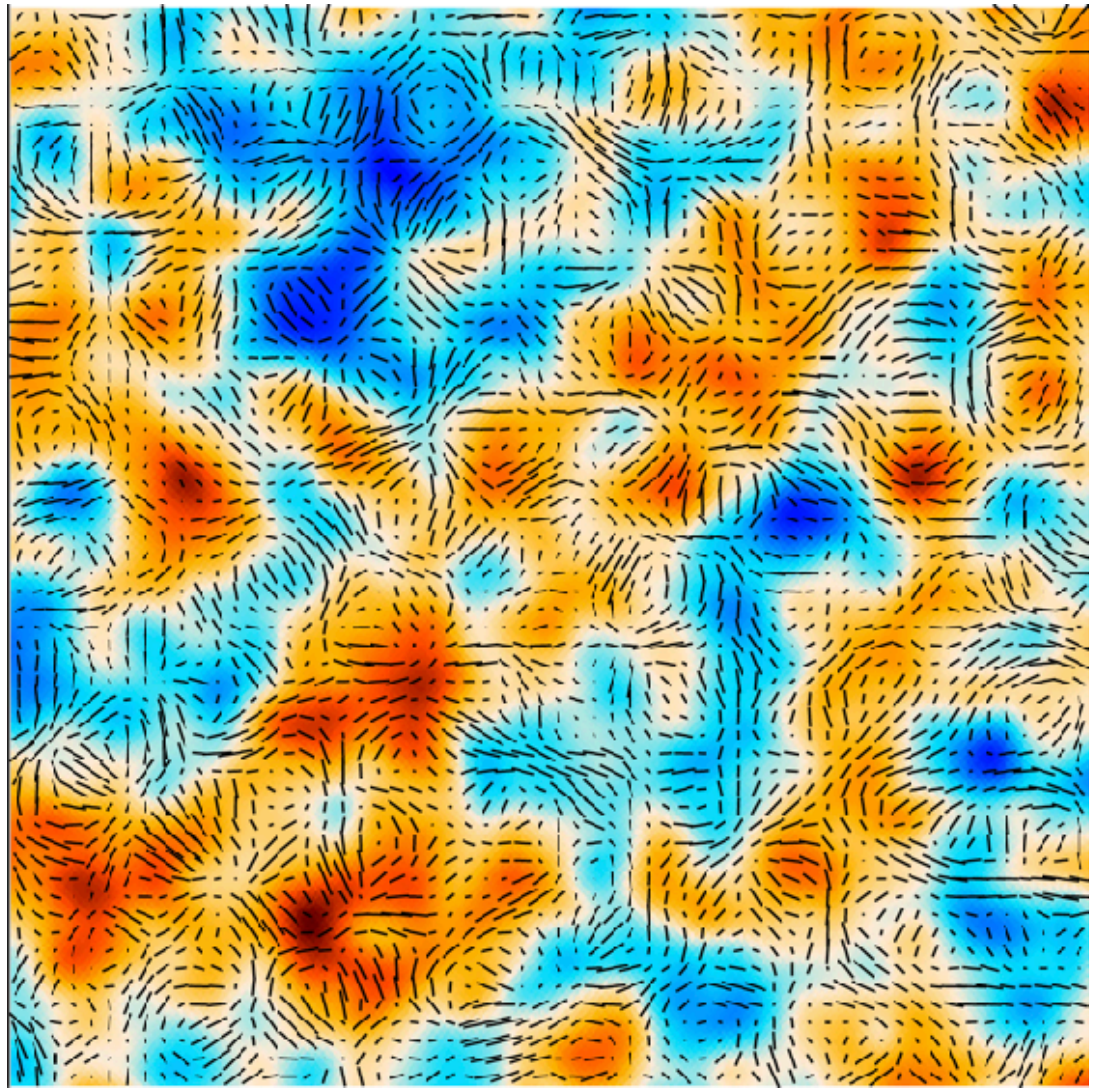
Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation



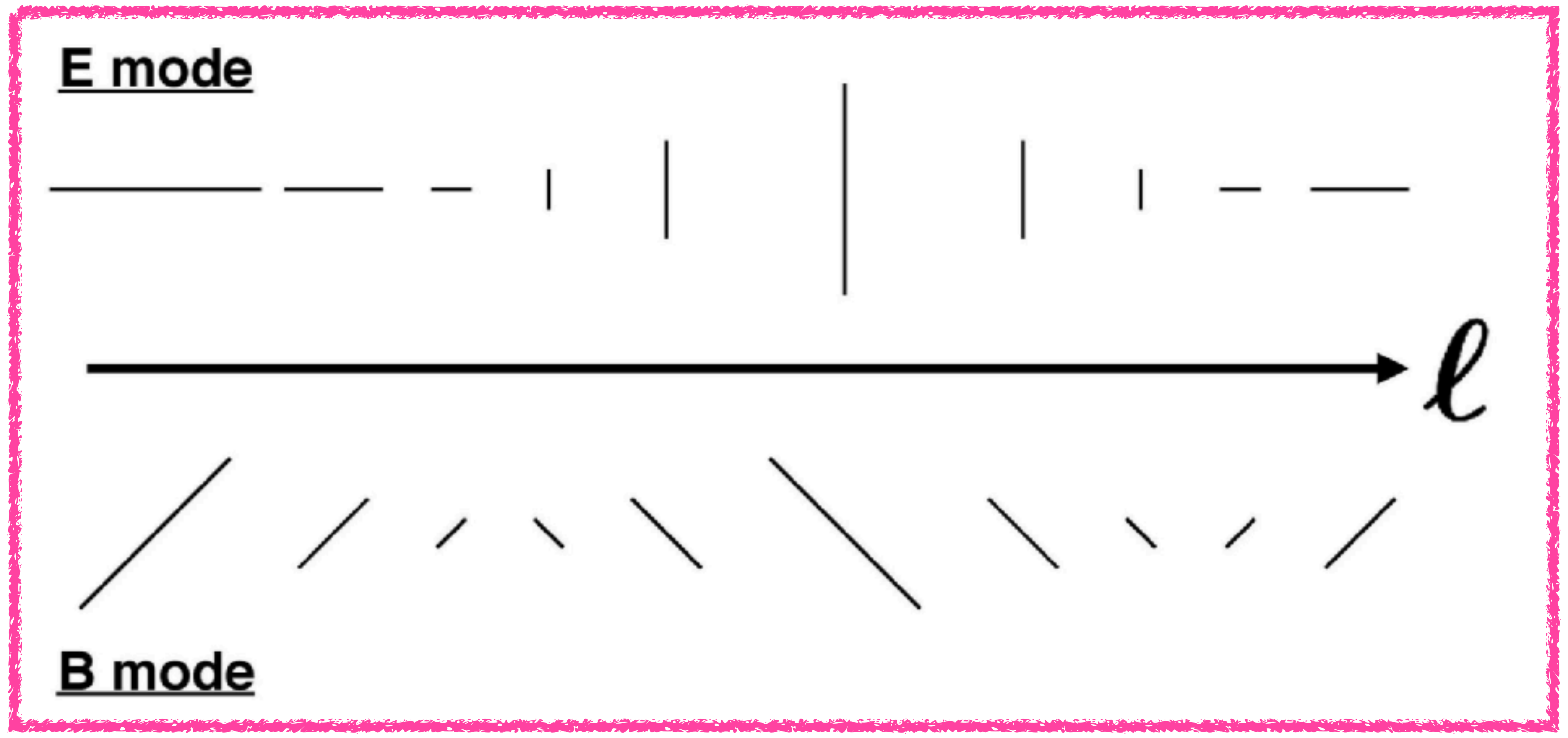
- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

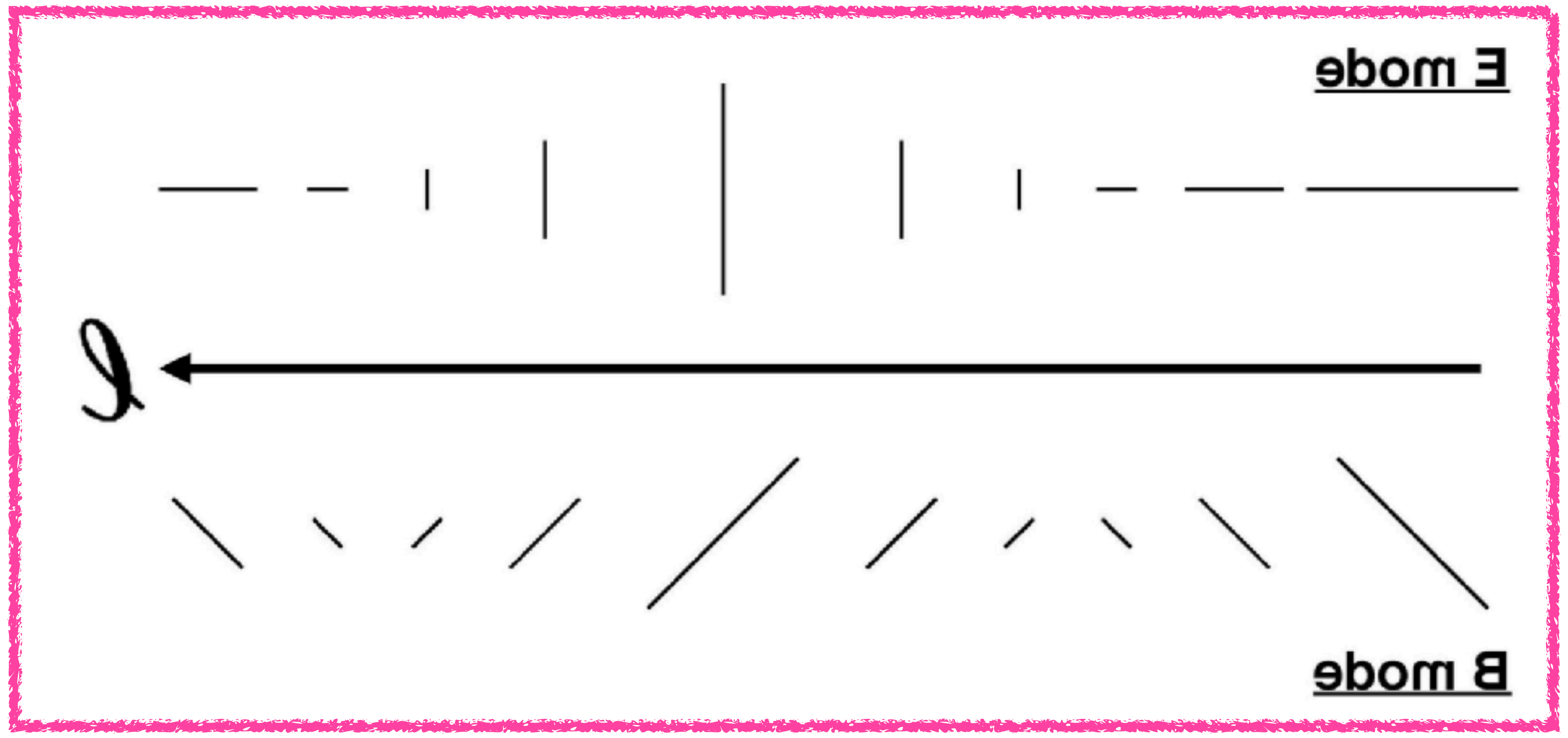
IMPORTANT”: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

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

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

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

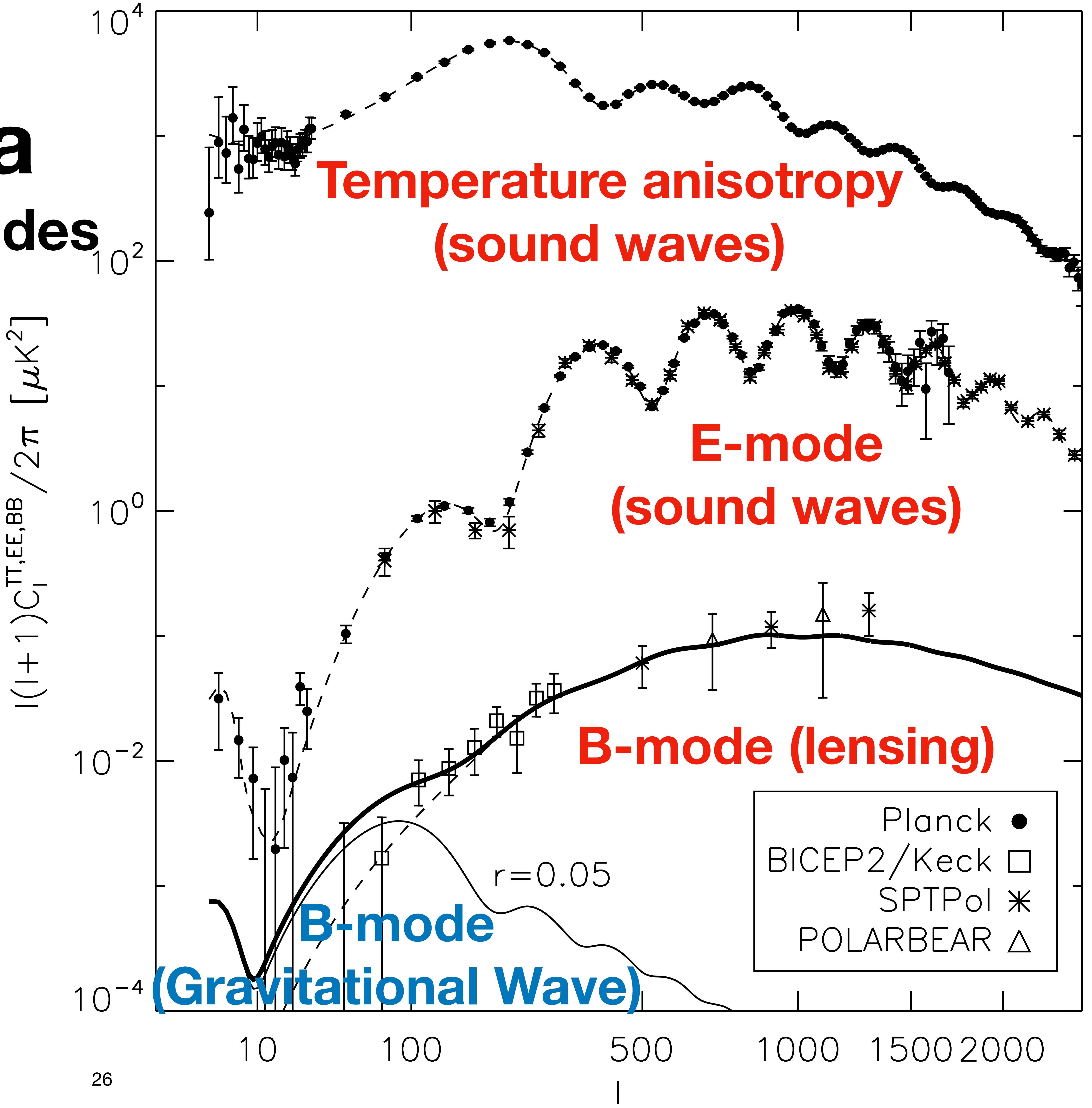
$$\langle T_{\ell} E^*_{\ell'} \rangle = \langle T^*_{\ell} E_{\ell'} \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_\ell^{TE}$$

- The other combinations <TB> and <EB> 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.**

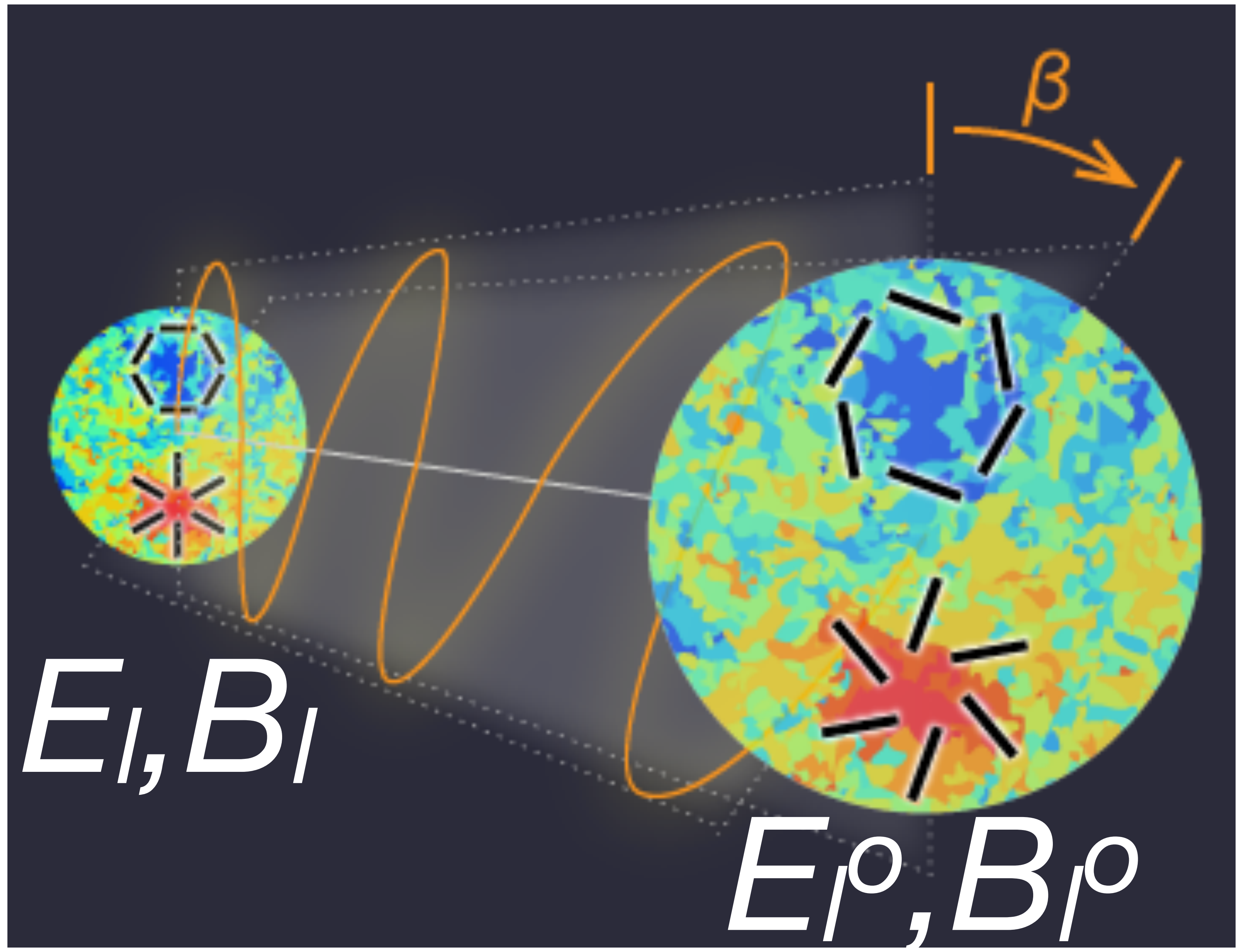


Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

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

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

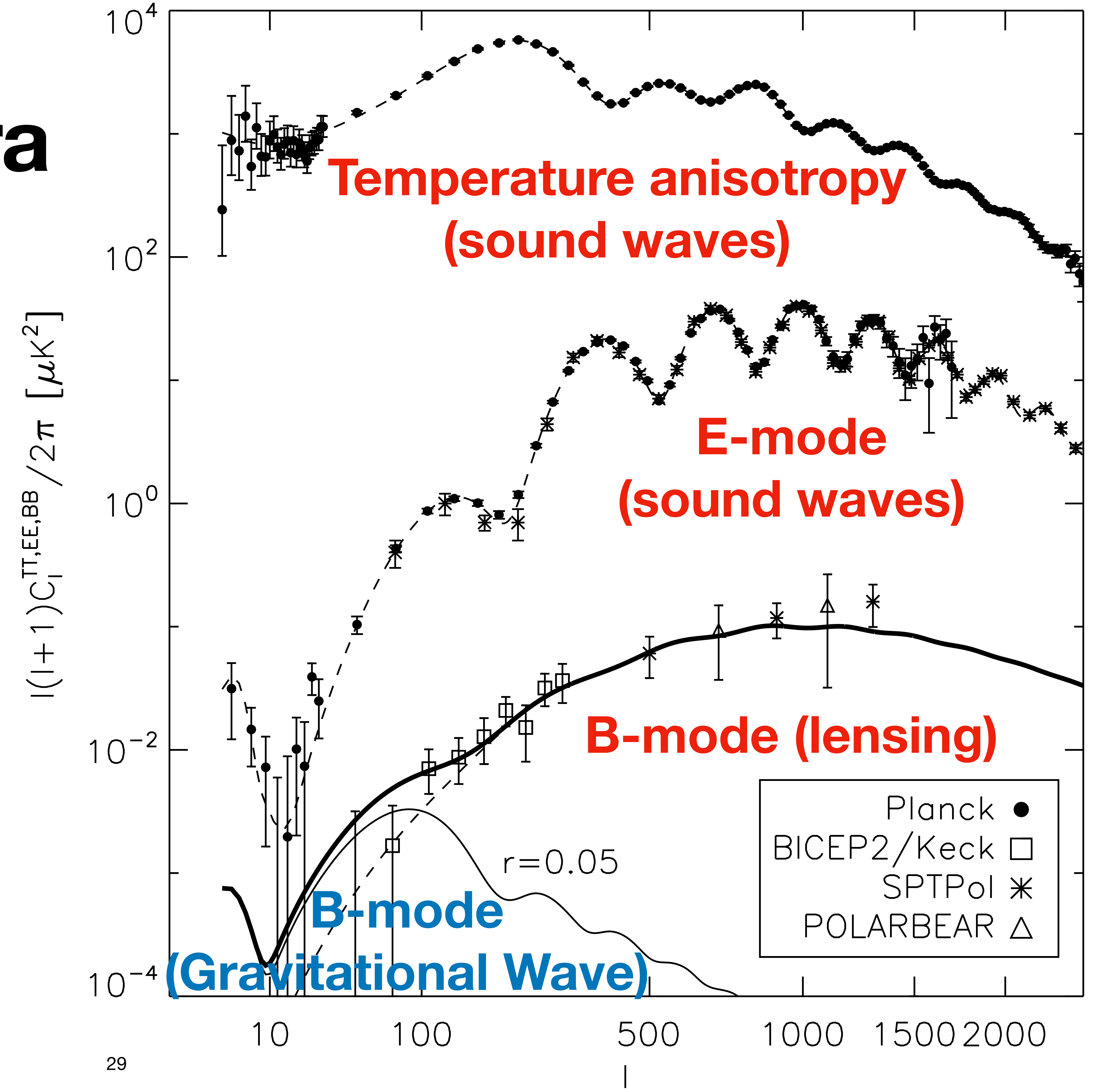
$$= \frac{1}{2}\underline{(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}})}\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

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

CMB Power Spectra

EE >> BB!

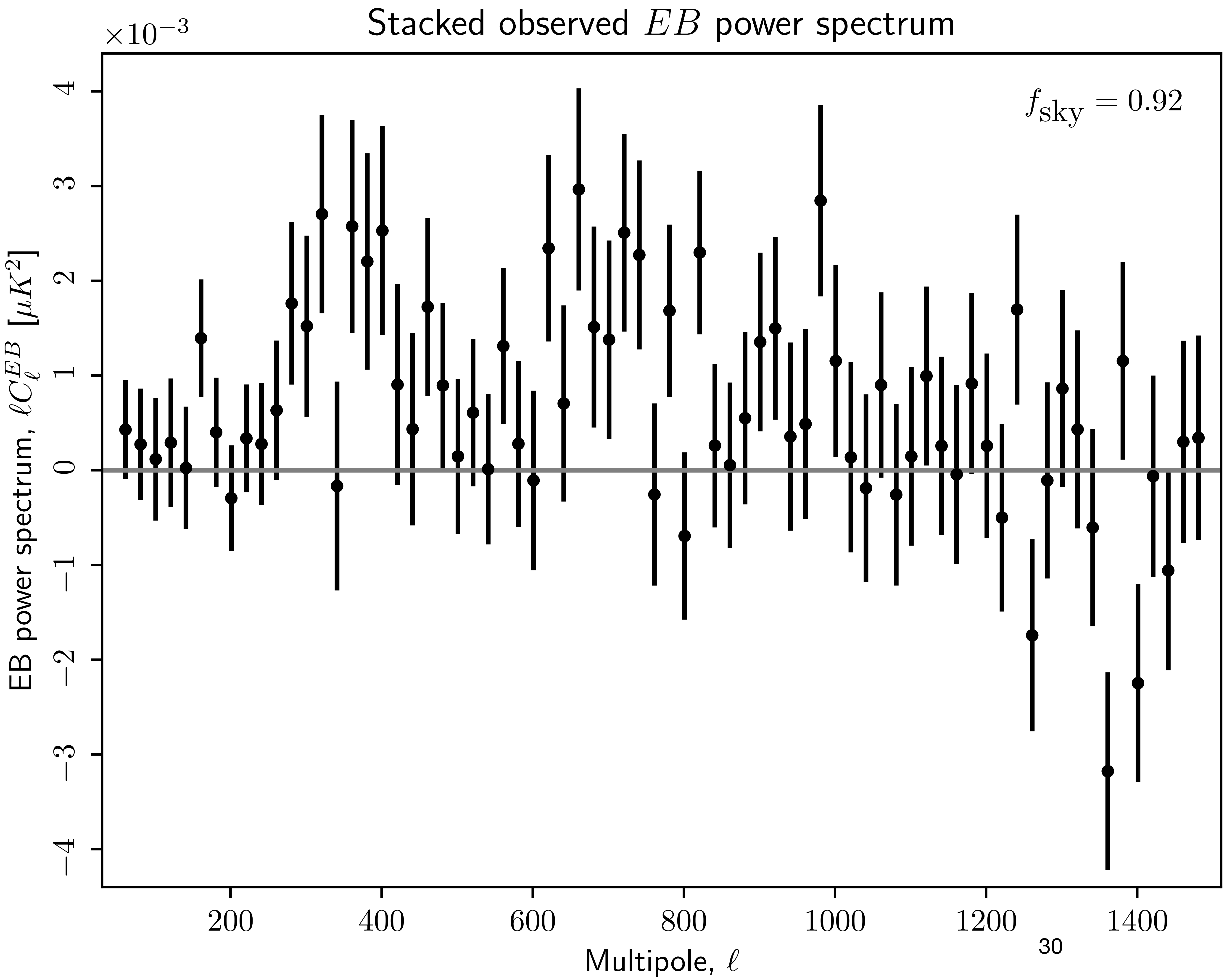
- **In our Universe, CMB EE is much greater than BB. This makes CMB sensitive to birefringence.**
- This is the typical figure that you find in talks and lectures on CMB.
  - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**

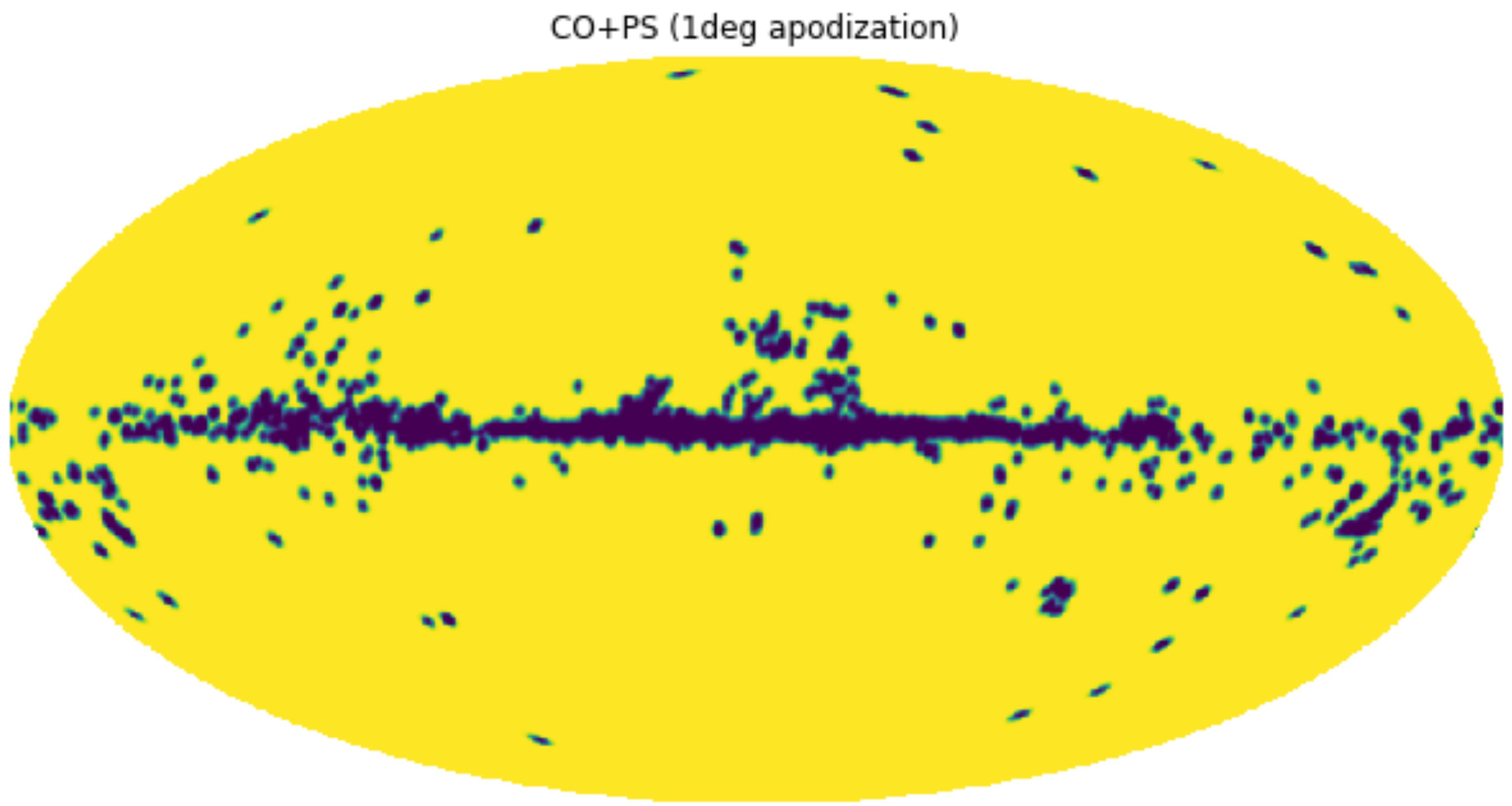


Eskilt & EK, arXiv:2205.13962

This is the EB power spectrum (WMAP+Planck)

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

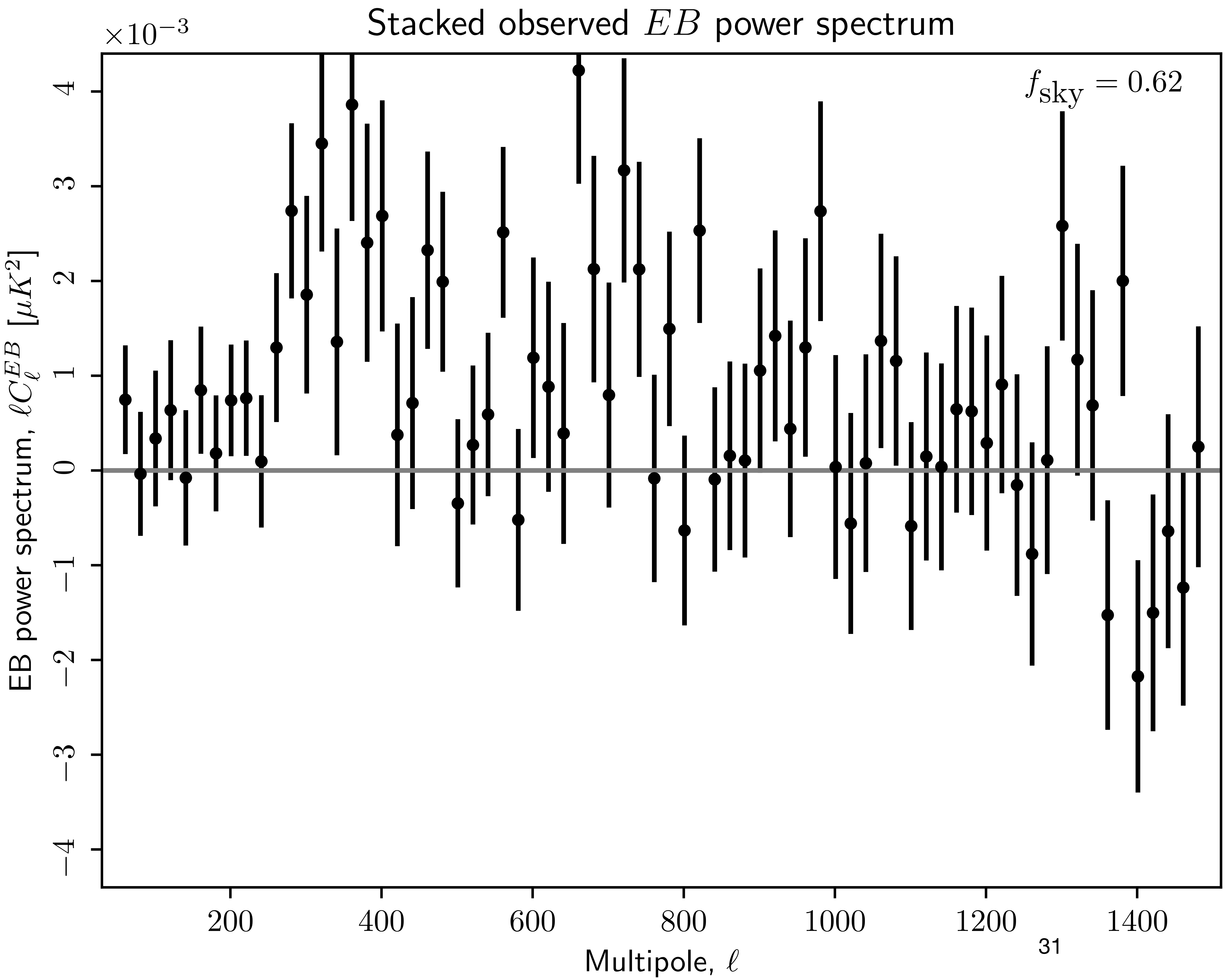


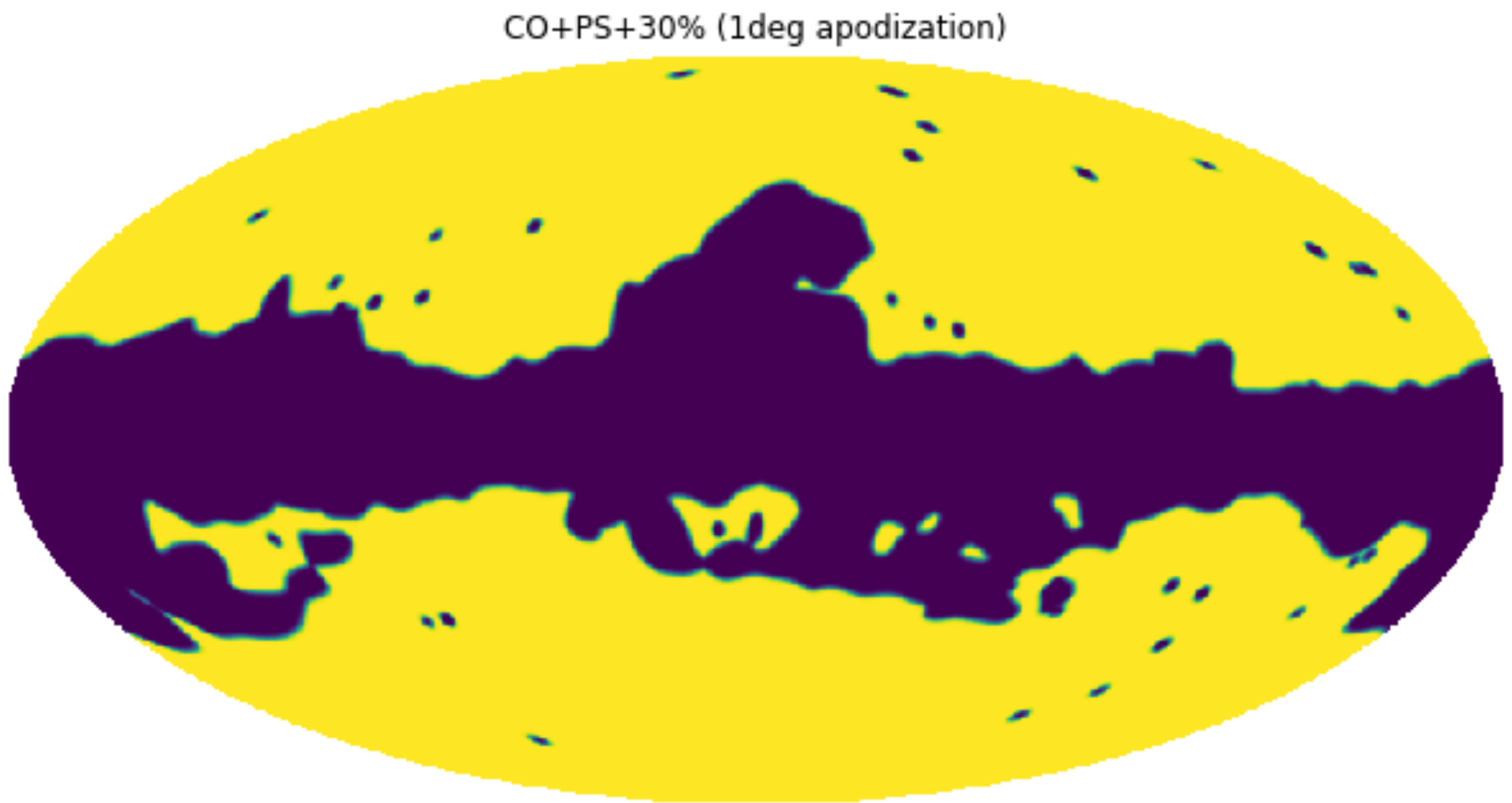


- χ^2 = 125.5 for DOF=72
  - Unambiguous signal of something!

This is the EB power spectrum (WMAP+Planck)

Galactic plane removed (62% of the sky)



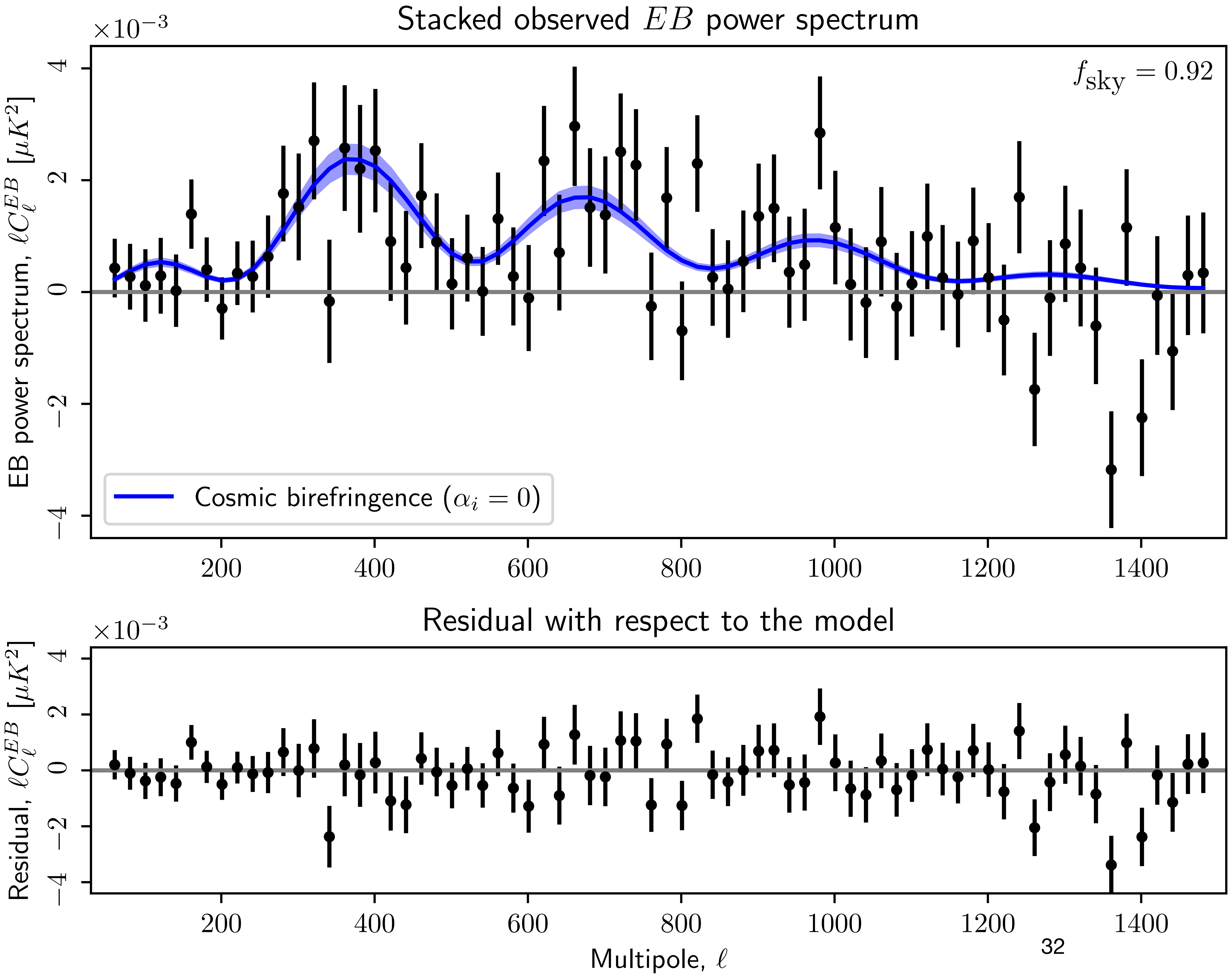


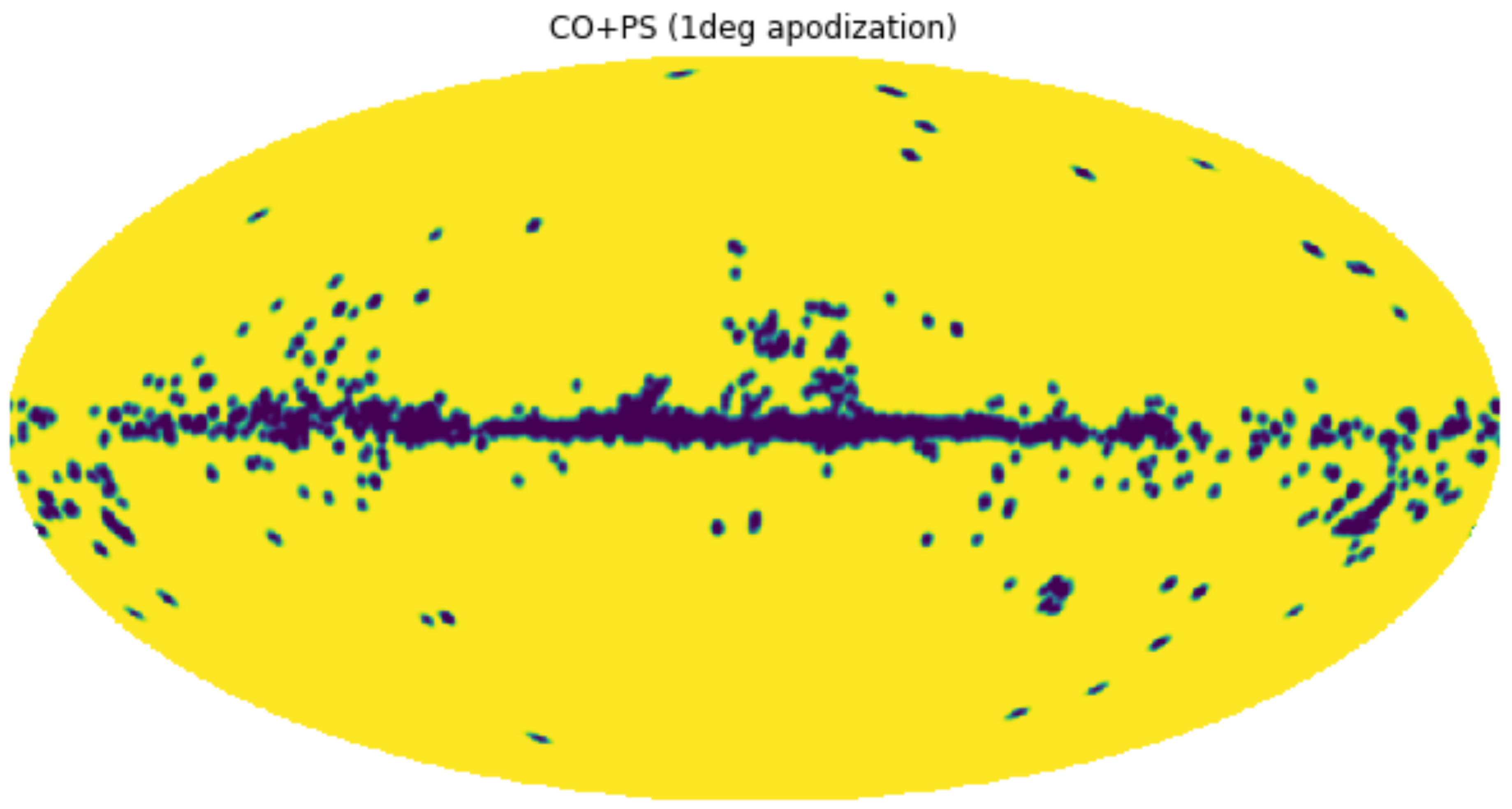
- χ^2 = 138.4 for DOF=72
  - The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

Eskilt & EK, arXiv:2205.13962

Cosmic Birefringence fits well(?)

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

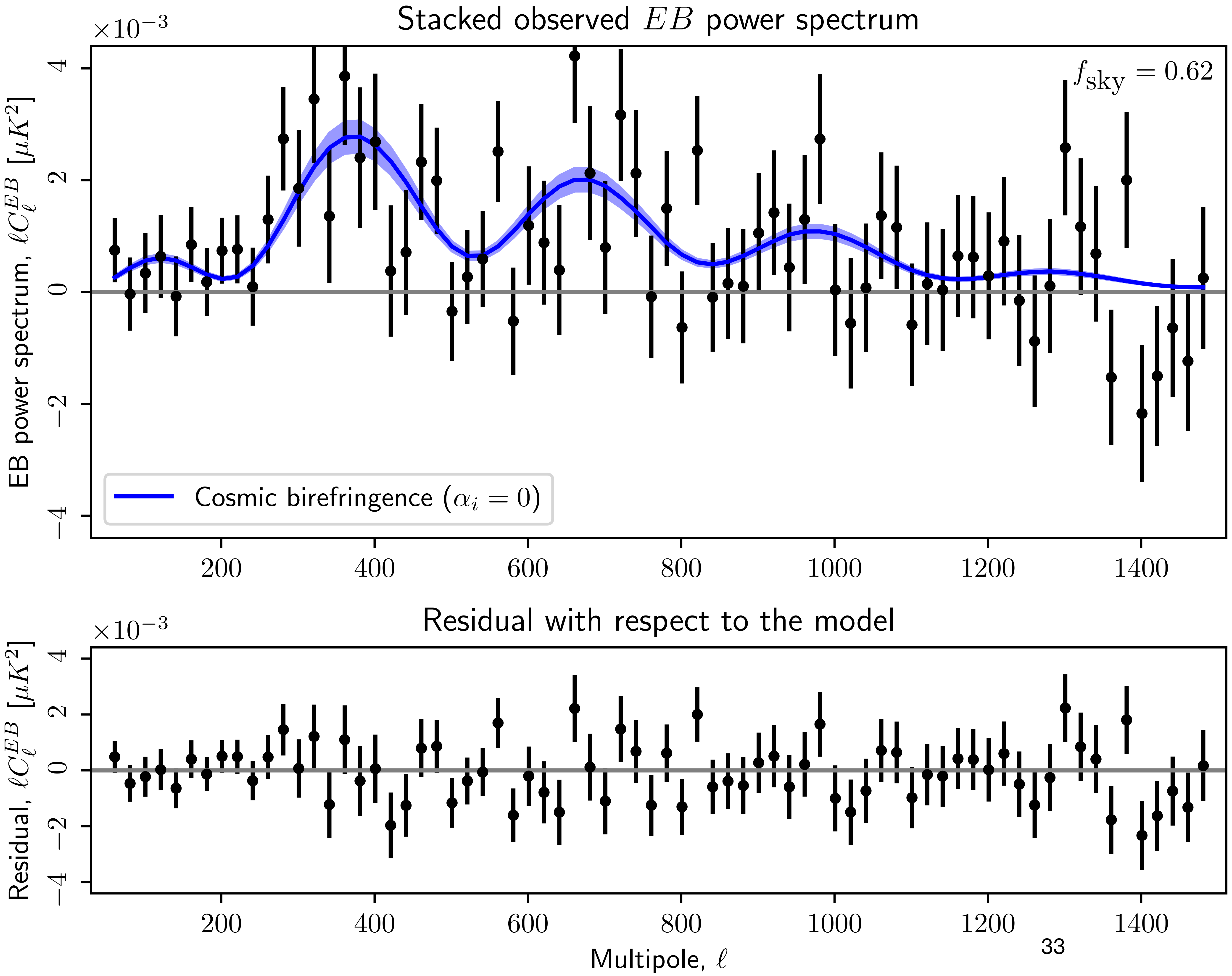


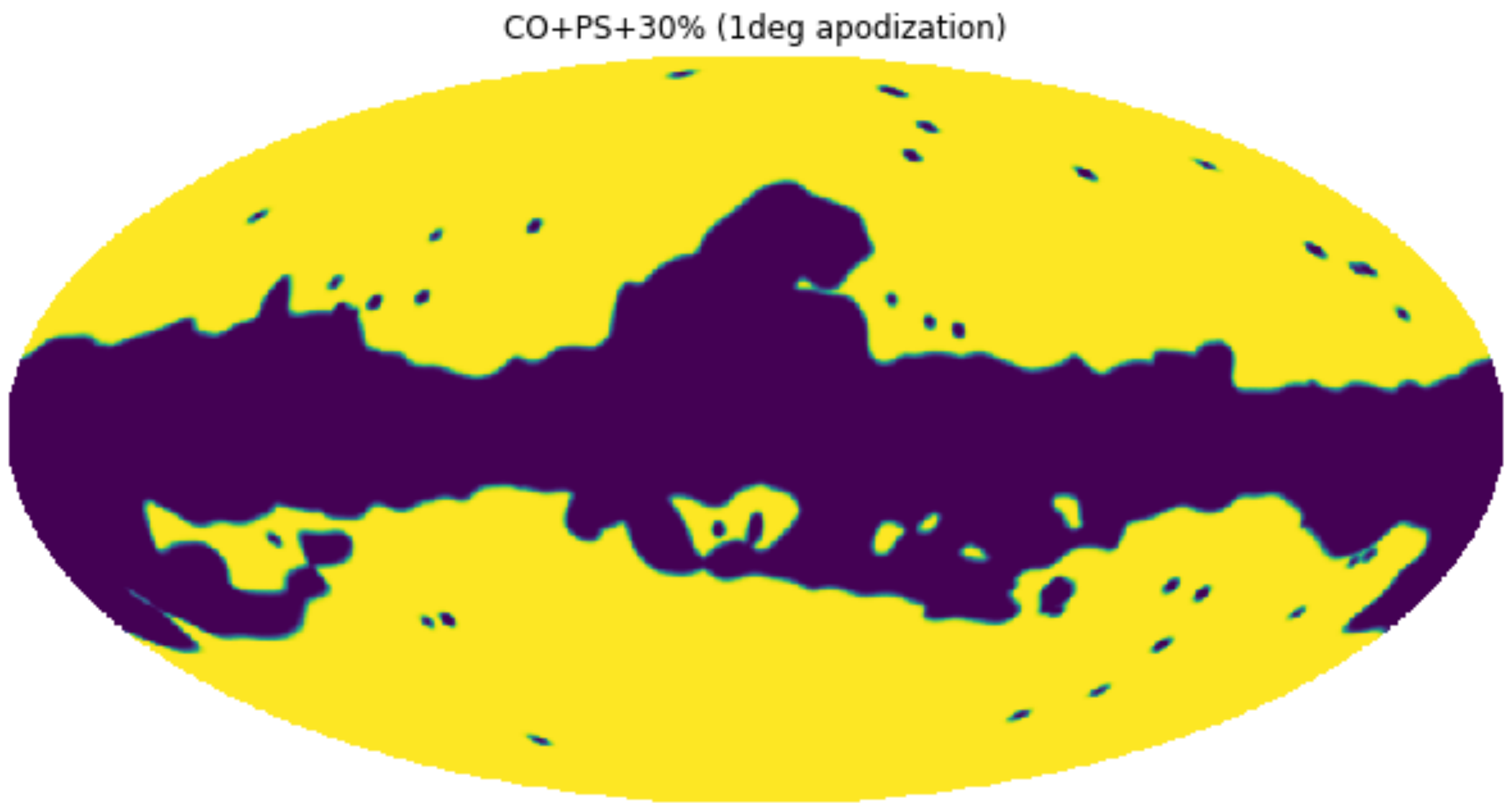


- β = 0.288 ± 0.032 deg
- χ^2 = 66.1 for DOF=72
  - Good fit! 9σ detection?

Cosmic Birefringence fits well(?)

Galactic plane removed (62% of the sky)





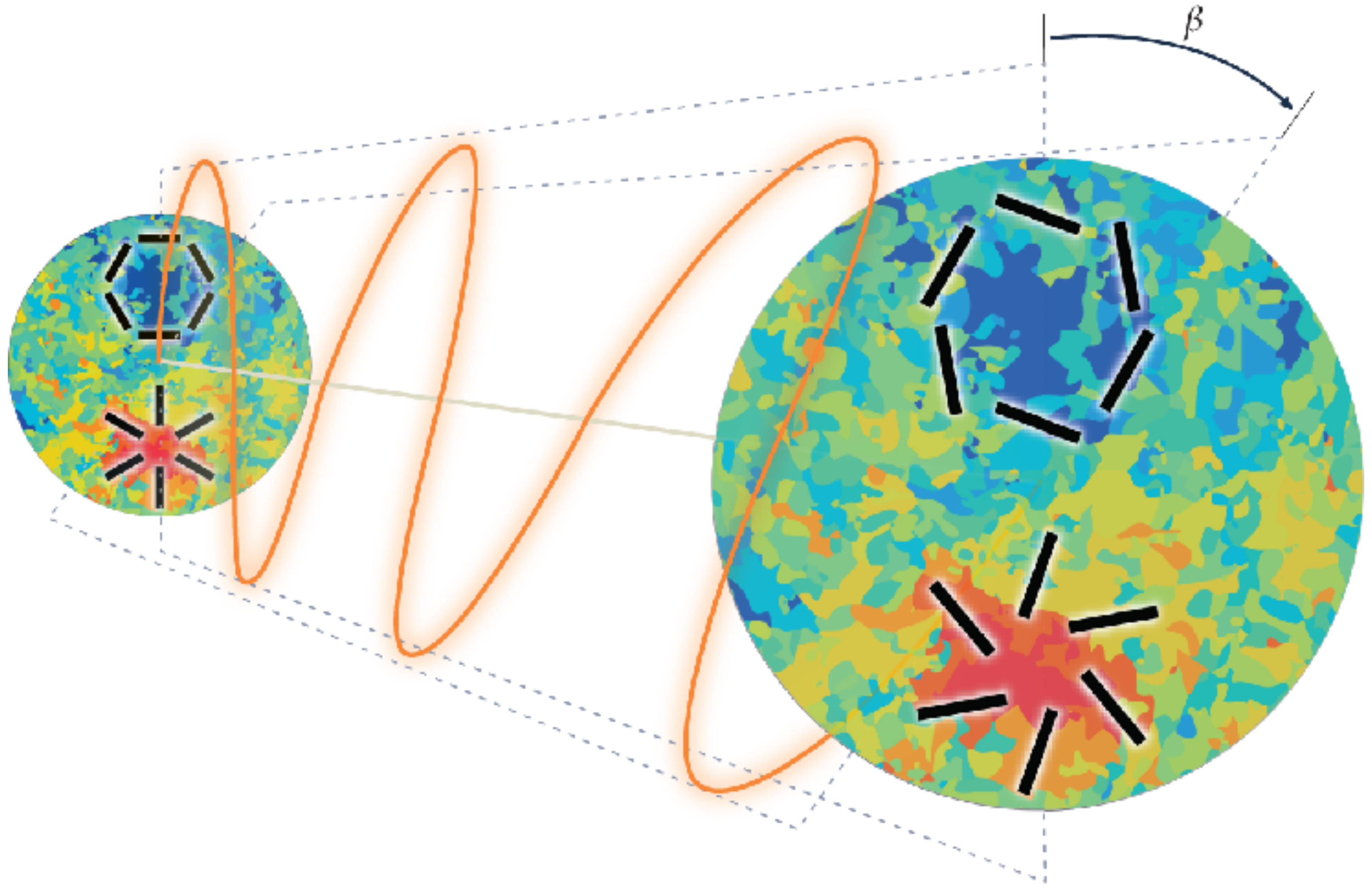
- β = 0.330 ± 0.035 deg
- χ^2 = 64.5 for DOF=72
- Signal is robust with respect to the Galactic mask.

The Biggest Problem: Miscalibration of detectors

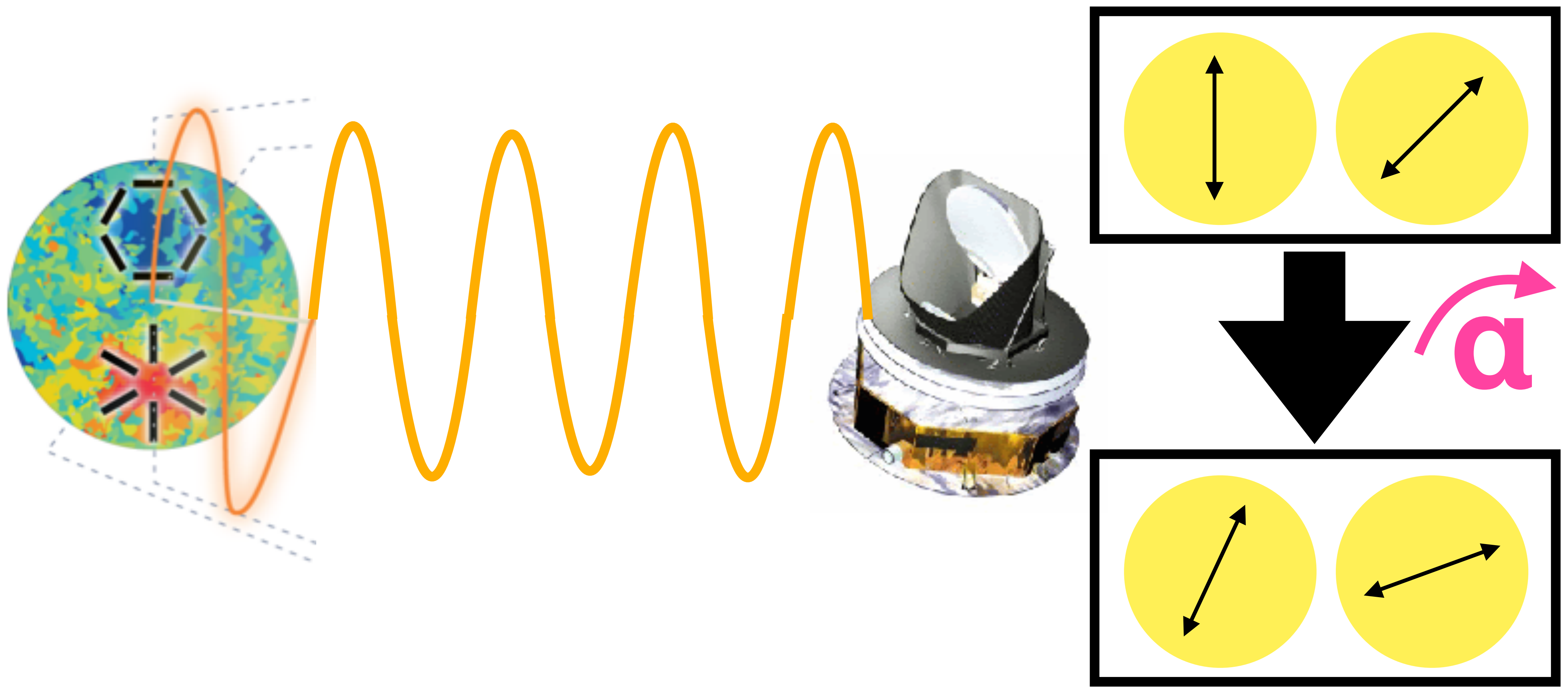
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

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?

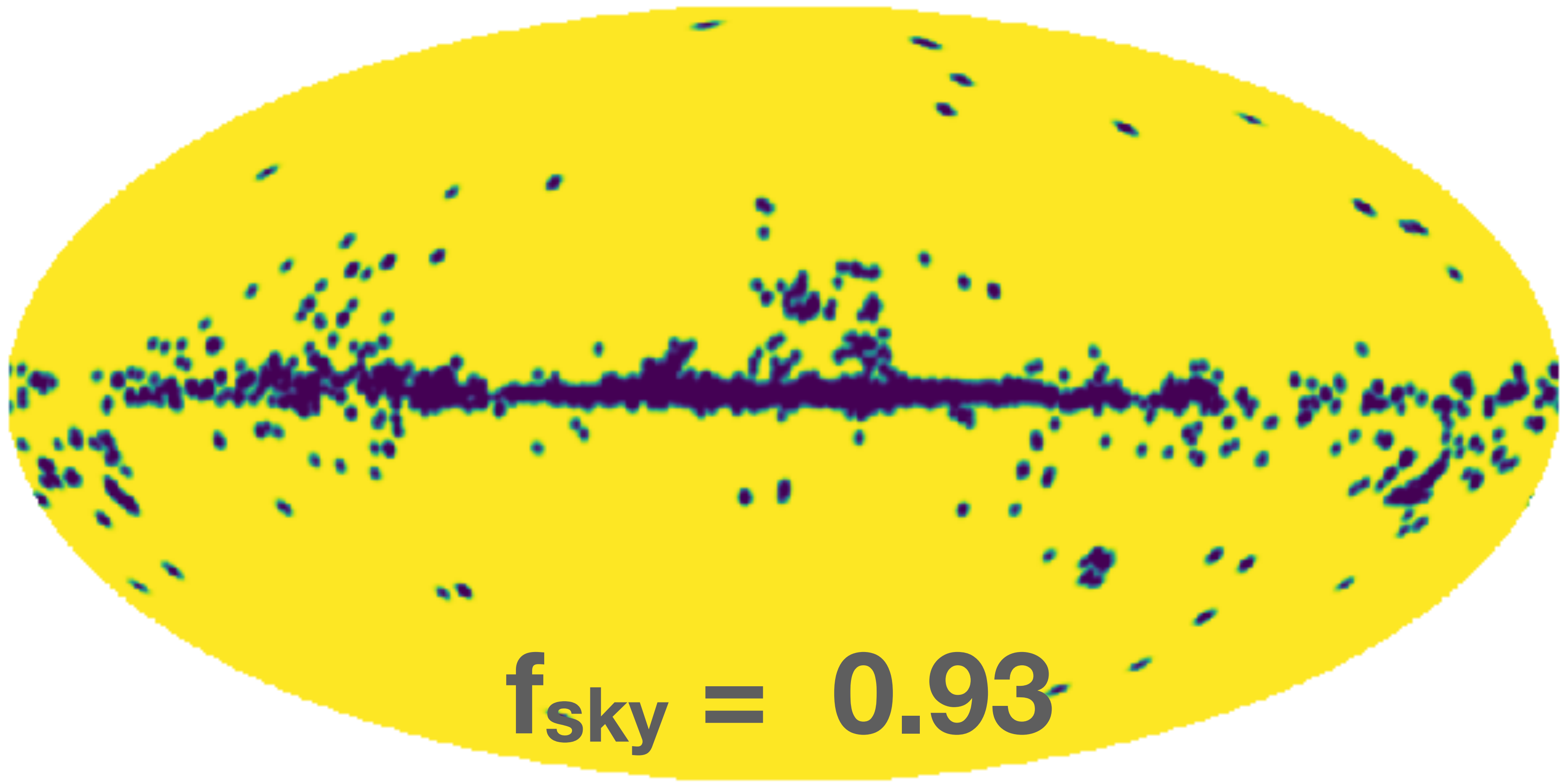
The past measurements

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

CO+PS (1deg apodization)

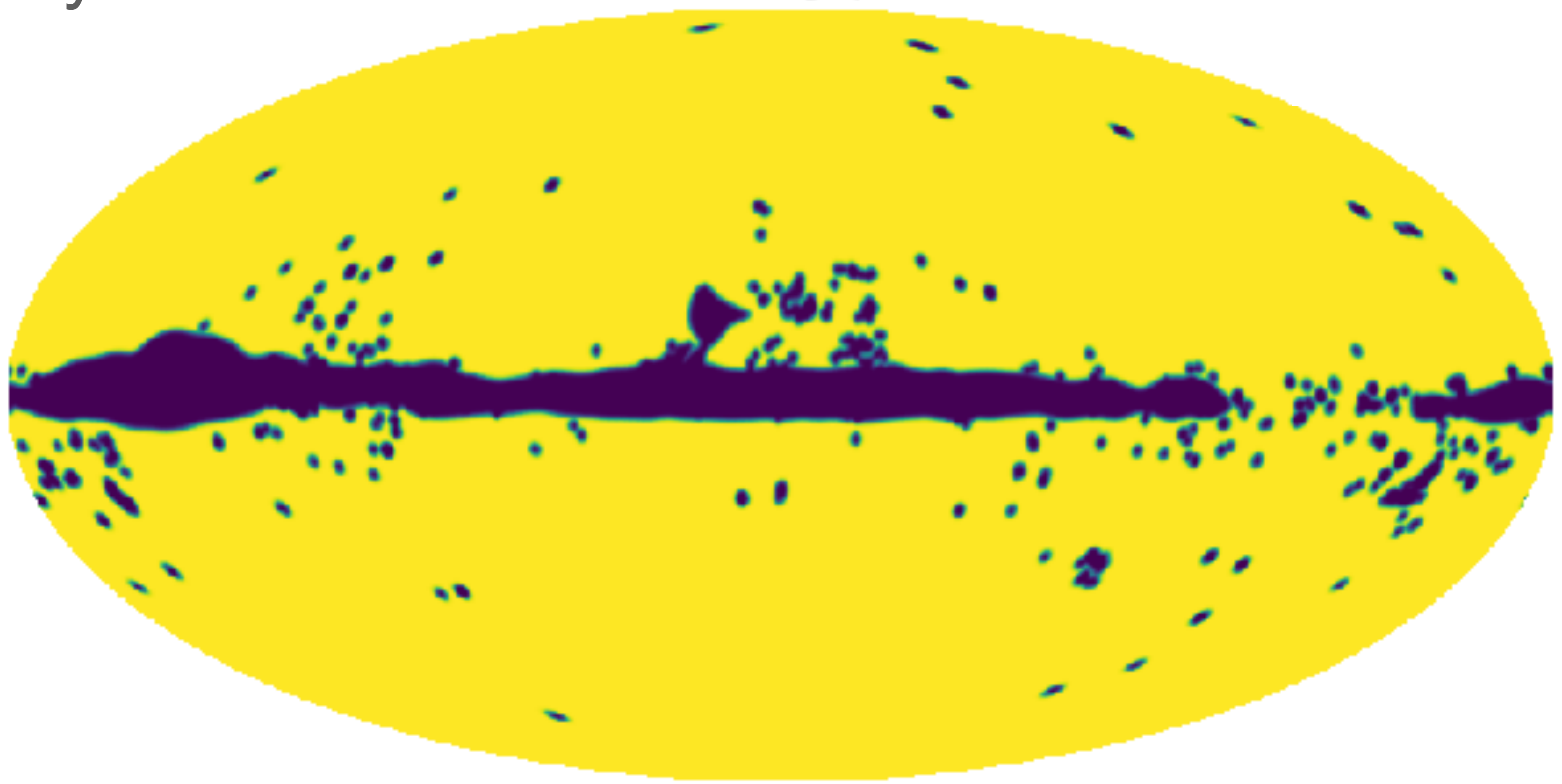


f_{sky} = 0.93

= nearly full sky

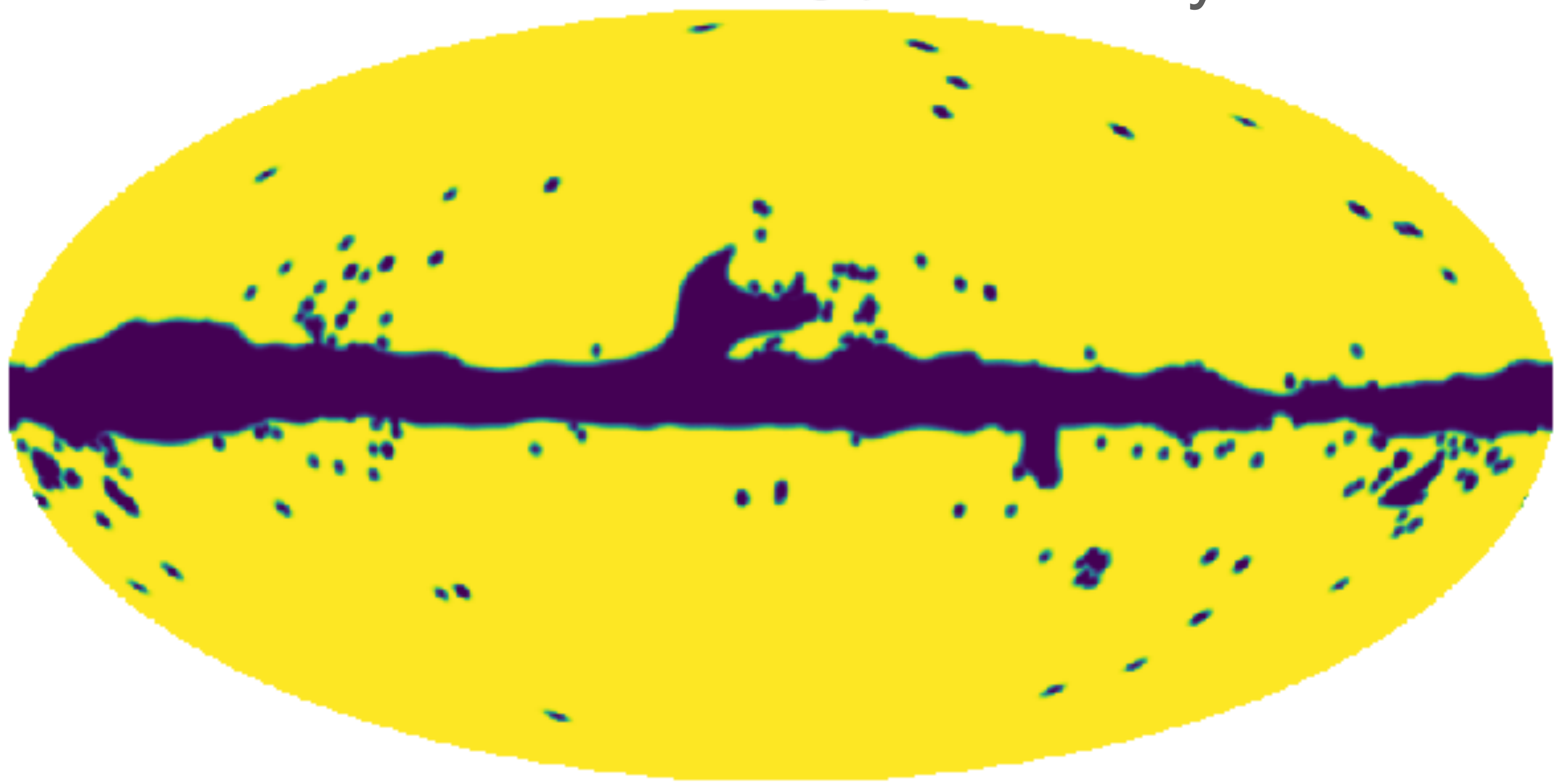
f_{sky} = 0.90

CO+PS+5% (1deg apodization)



CO+PS+10% (1deg apodization)

f_{sky} = 0.85

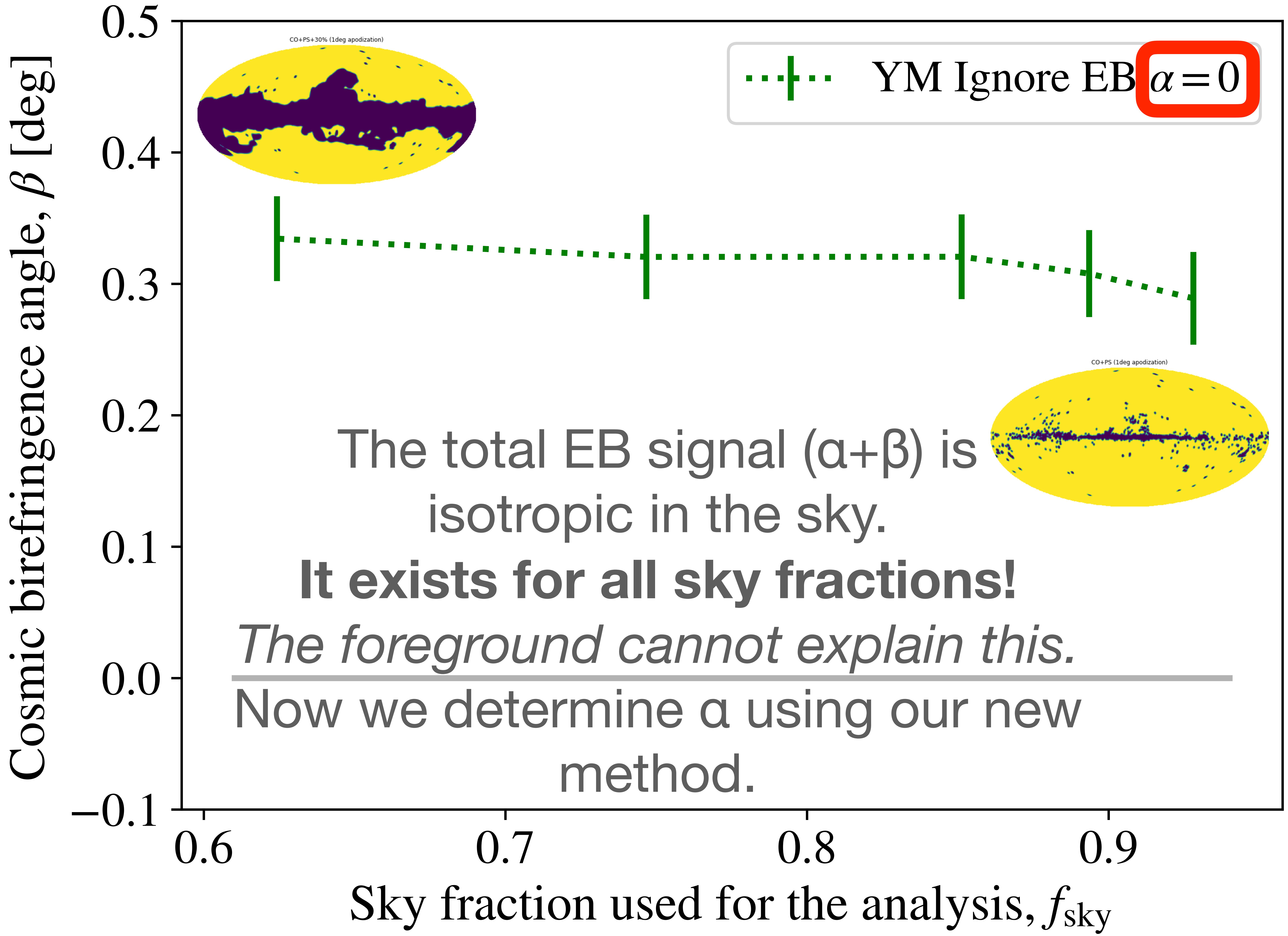


CO+PS+20% (1deg apodization)

f_{sky} = 0.75

CO+PS+30% (1deg apodization)

f_{sky} = 0.63

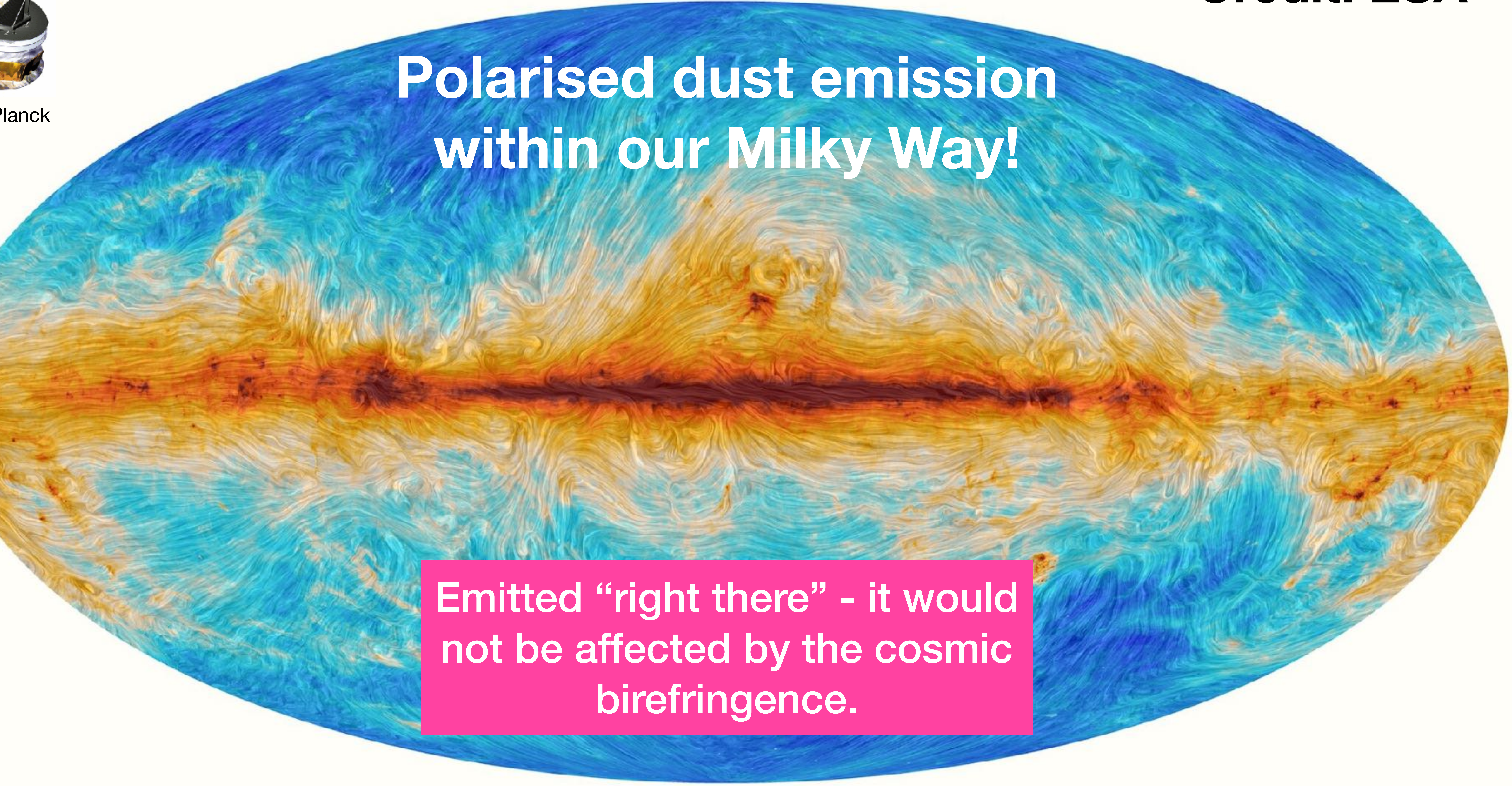

YM Ignore EB $\alpha=0$
CO+PS+30% (1deg apodization)
CO+PS (1deg apodization)
The total EB signal (α+β) is isotropic in the sky.
It exists for all sky fractions!
The foreground cannot explain this.
Now we determine α using our new method.
Cosmic birefringence angle, β [deg]
Sky fraction used for the analysis, f_{sky}
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.6
0.7
0.8
0.9

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

ESA's Planck

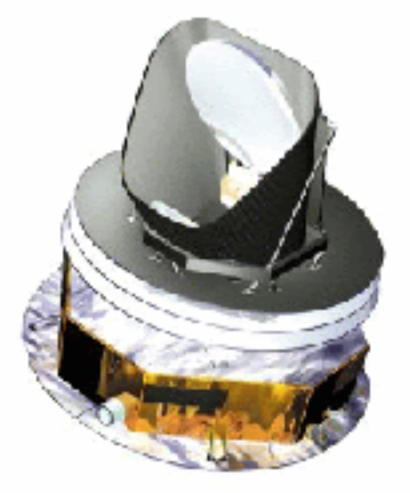
Credit: ESA

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



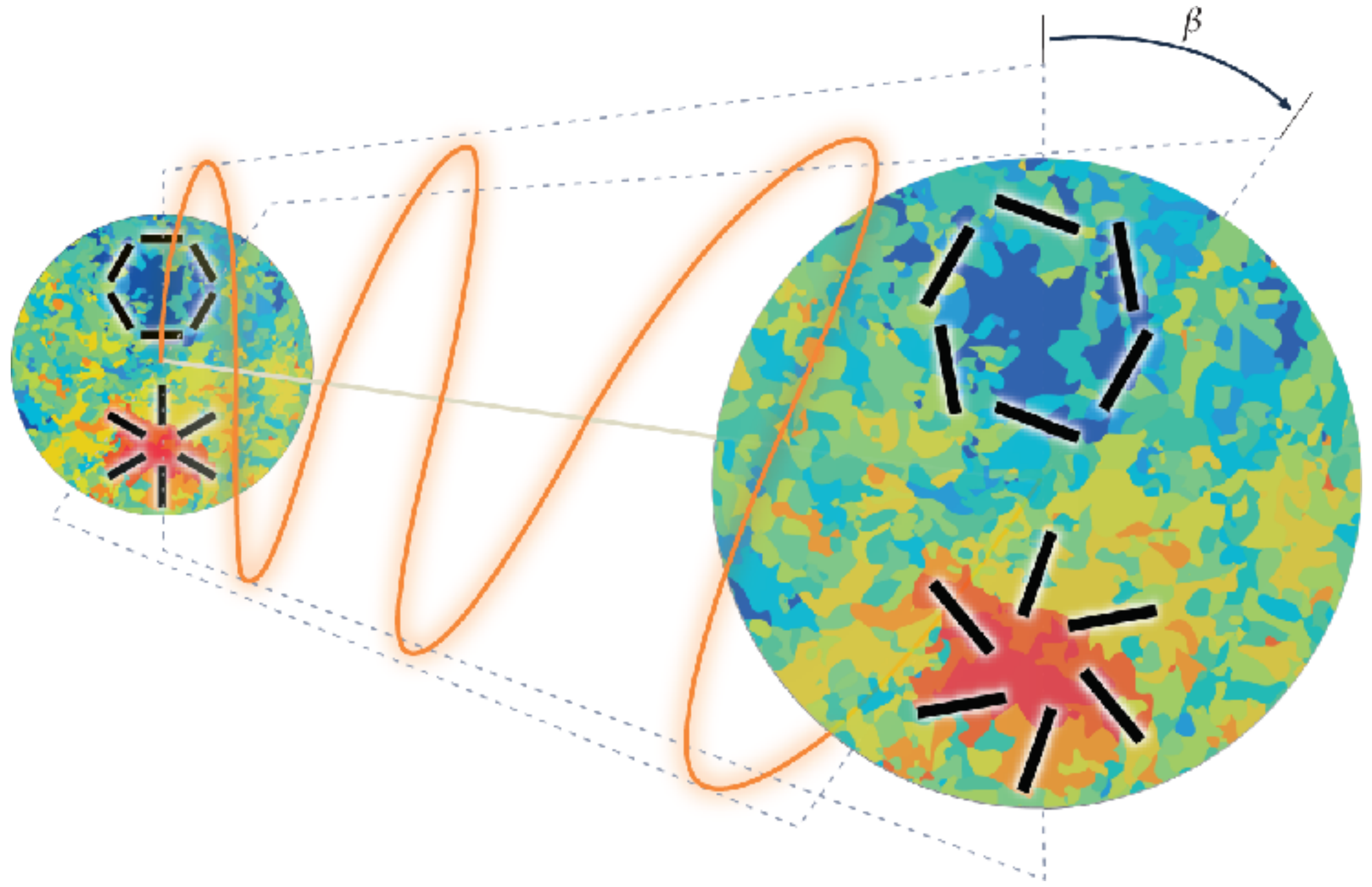
Credit: ESA

Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Searching for the birefringence

Including the miscalibration angle



Emitted 13.8 billions years ago

But the source of foreground is much closer!

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

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

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

noise

- Thus,

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

measured

known accurately

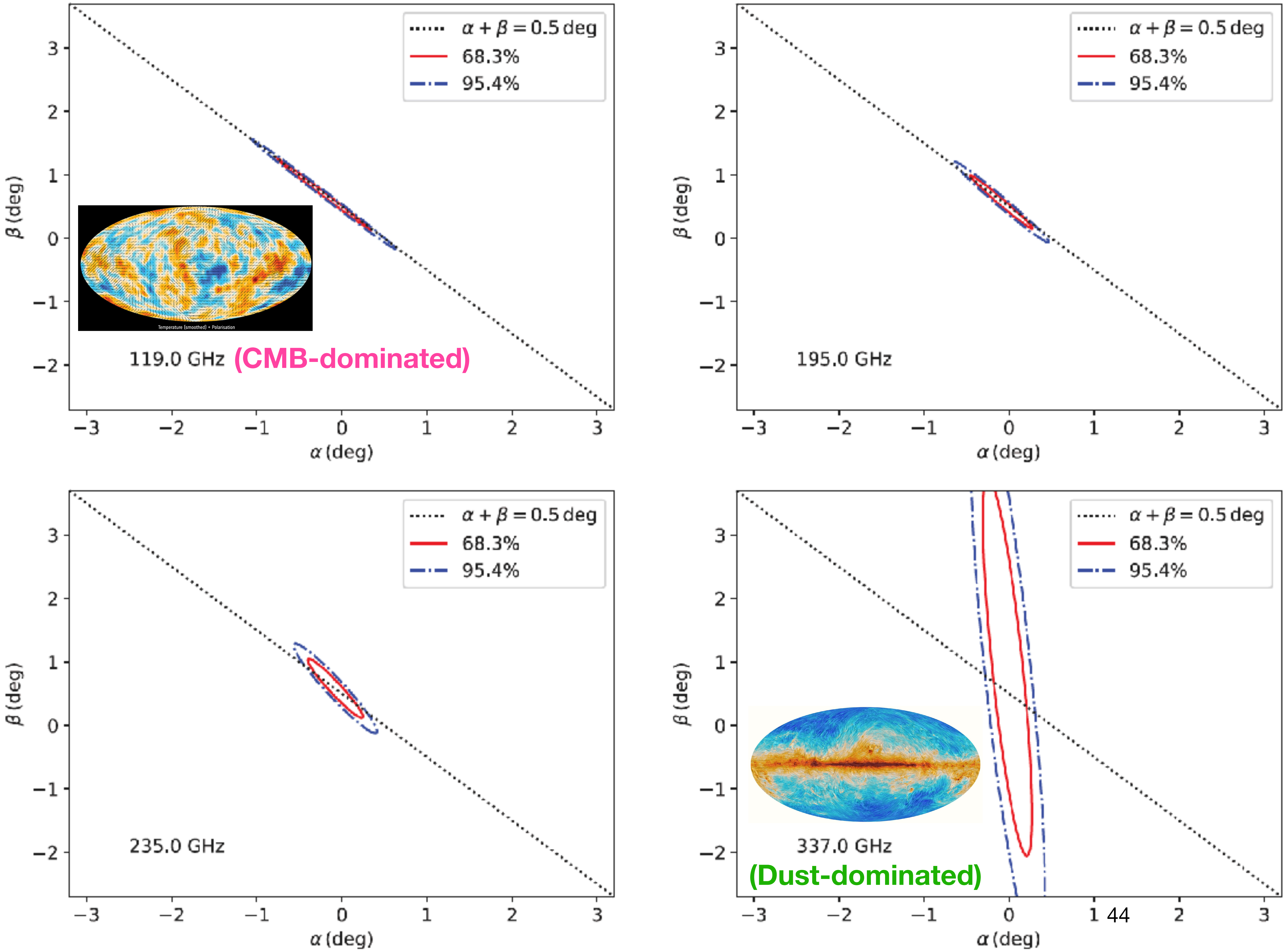
$$+ \frac{1}{\cos(4\alpha)}\langle C_\ell^{EB,\rm fg}\rangle + \frac{\cos(4\beta)}{\cos(4\alpha)}\langle C_\ell^{EB,\rm CMB}\rangle\,.$$

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

Minami et al. (2019)

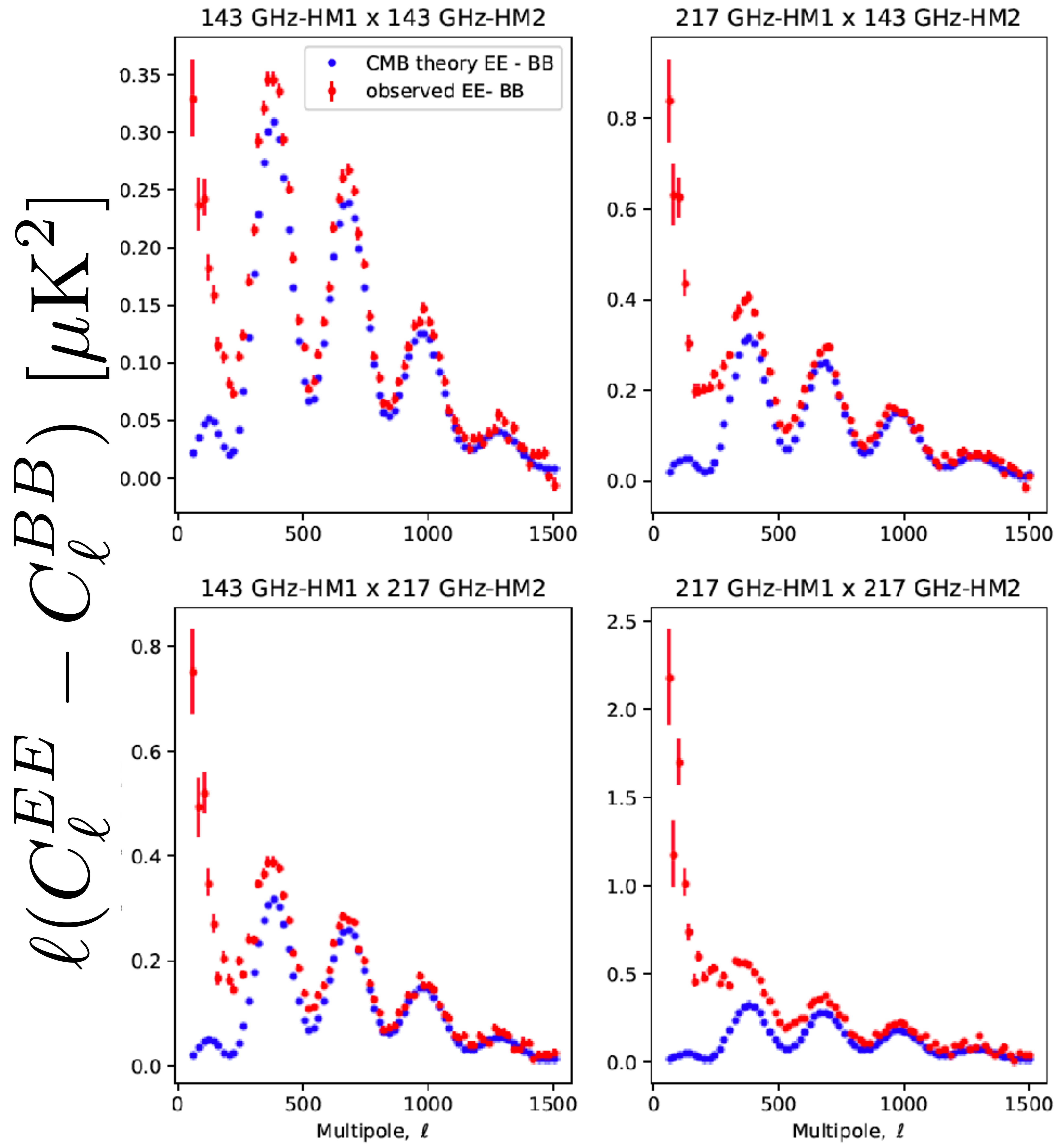
How does it work?

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.

From Planck HFI Data (Minami & EK 2020)

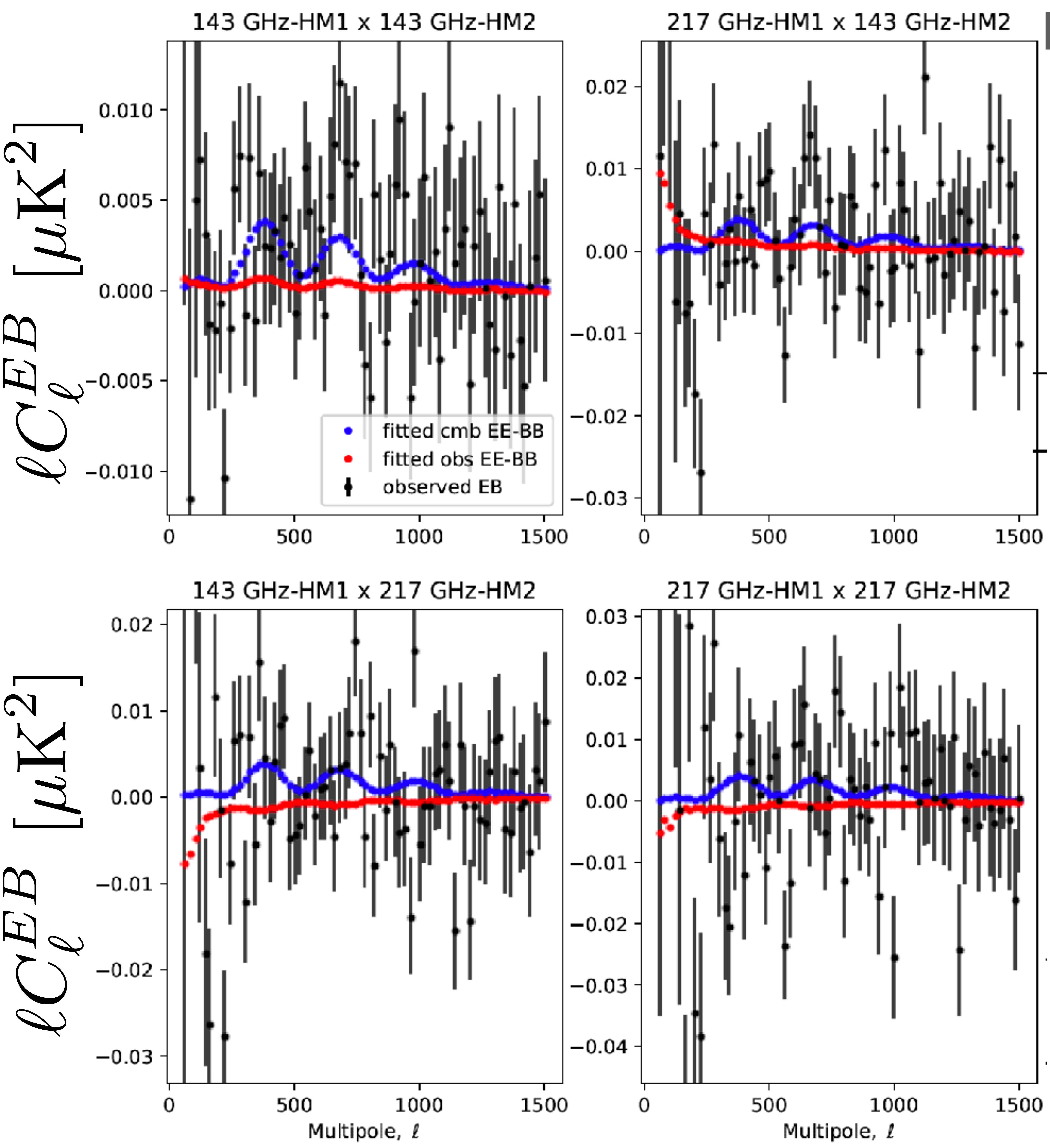


$$\langle C_\ell^{EB,o}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,o}\rangle - \langle C_\ell^{BB,o}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$

- 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)

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



- Can we see β 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

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

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

Relating EB to TB

- **A generic approach:**

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

This is unknown

Measured well!

Measured well!

Measured well!

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

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

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

$$C_\ell^{EB,\mathrm{FG,o}} = \sqrt{J_\ell^2 + (C_\ell^{EB,\mathrm{FG}})^2}\sin(4\alpha + 4\gamma_\ell)$$

$$\begin{cases} J_\ell \equiv \frac{1}{2}\left(C_\ell^{EE,\mathrm{FG}} - C_\ell^{BB,\mathrm{FG}}\right) \\ \tan(4\gamma_\ell) \equiv C_\ell^{EB,\mathrm{FG}}/J_\ell \end{cases}$$

Clark et al. (2021); Diego-Palazuelos, Eskilt, et al. (2022)

Relating EB to TB

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

- **How do we model the new angle γ?**
  - Our *ansatz*, motivated by a physical consideration of Clark et al. (2021):

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

Free l-dependent amplitude parameters

  - Then

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

for small angles.

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

Relating EB to TB

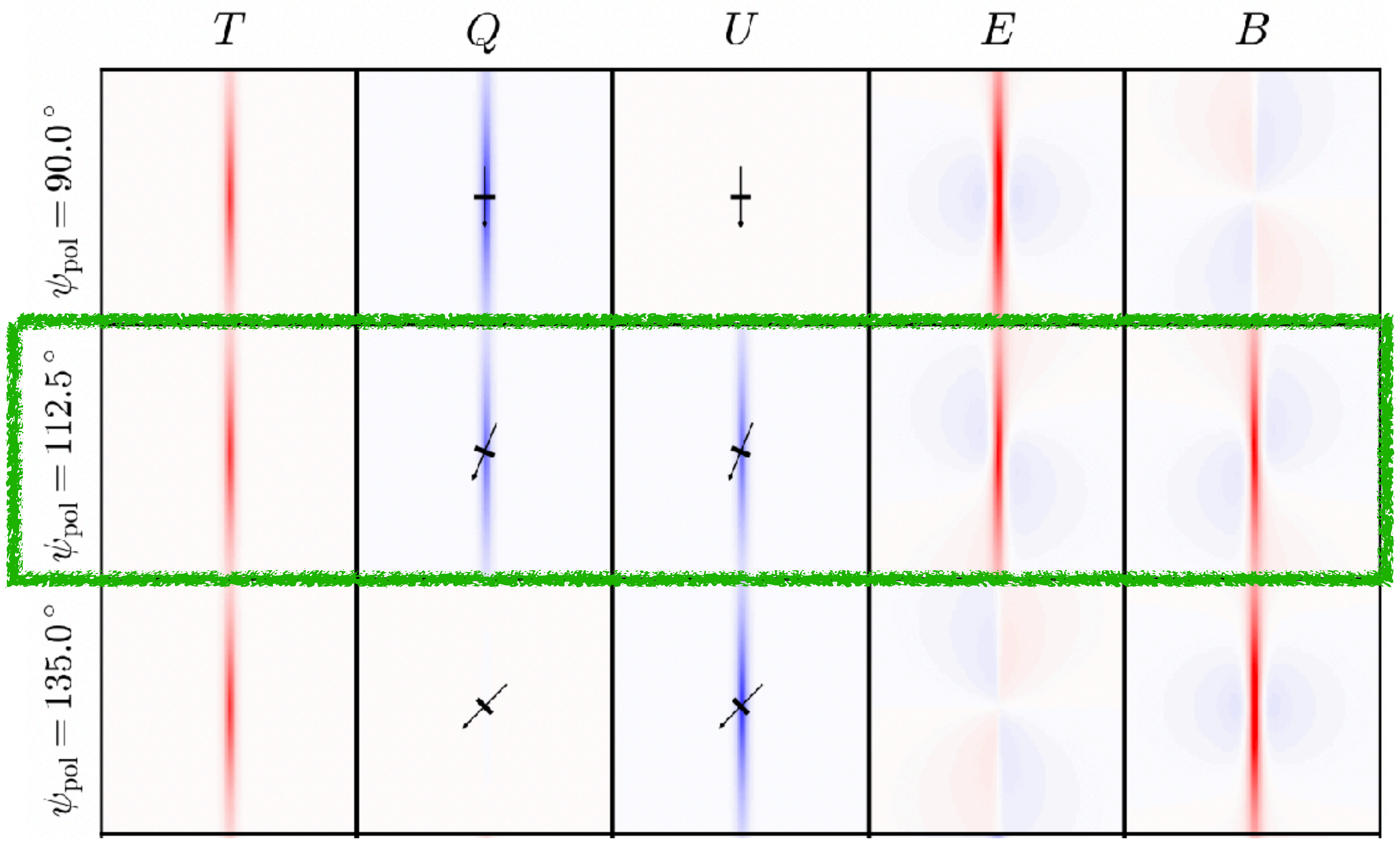
A physical justification for this assumption

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

- **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 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)

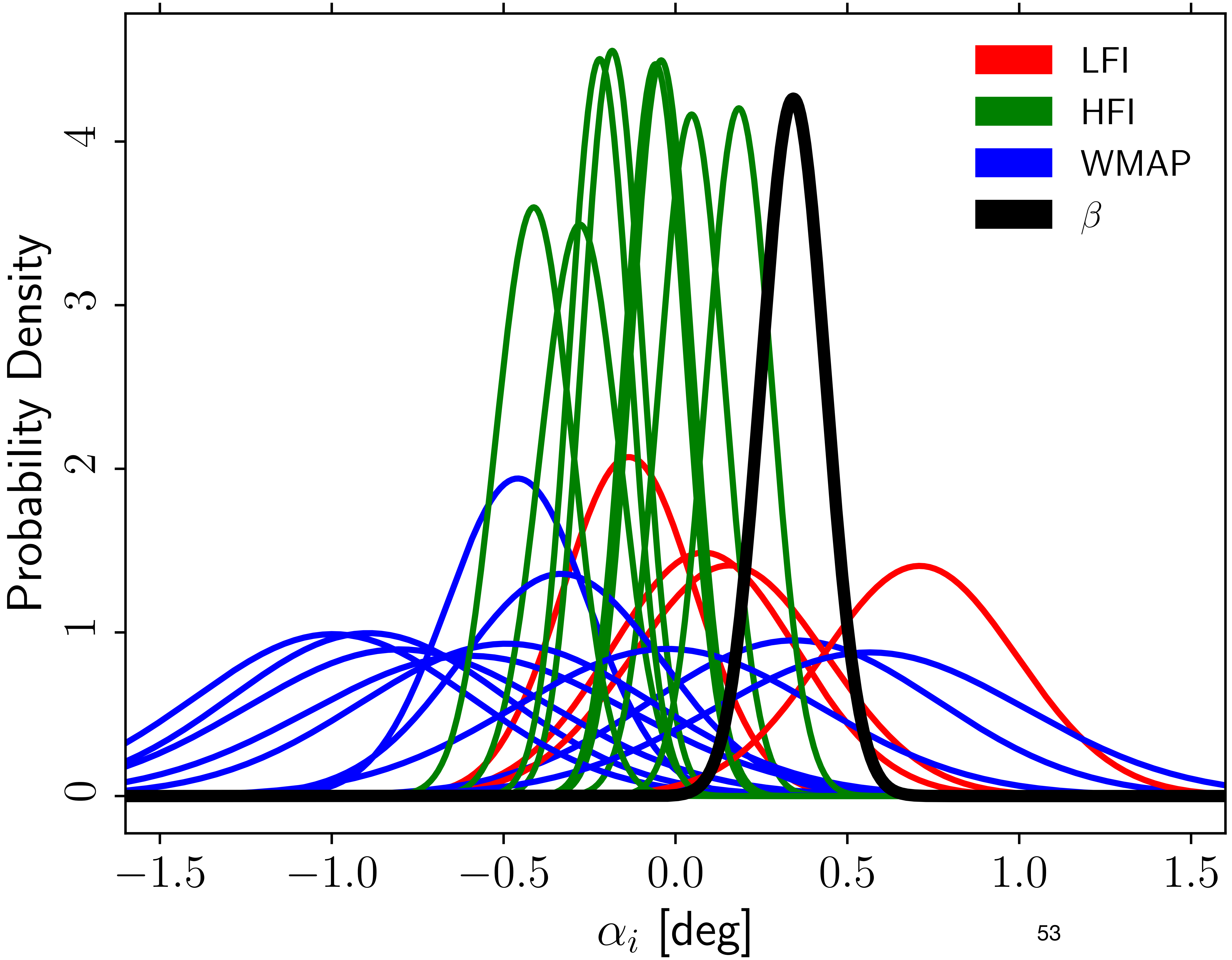


- **Misalignment of filaments and magnetic fields creates TE>0, TB>0 and EB>0**

Eskilt & EK, arXiv:2205.13962

Miscalibration angles (WMAP and Planck)

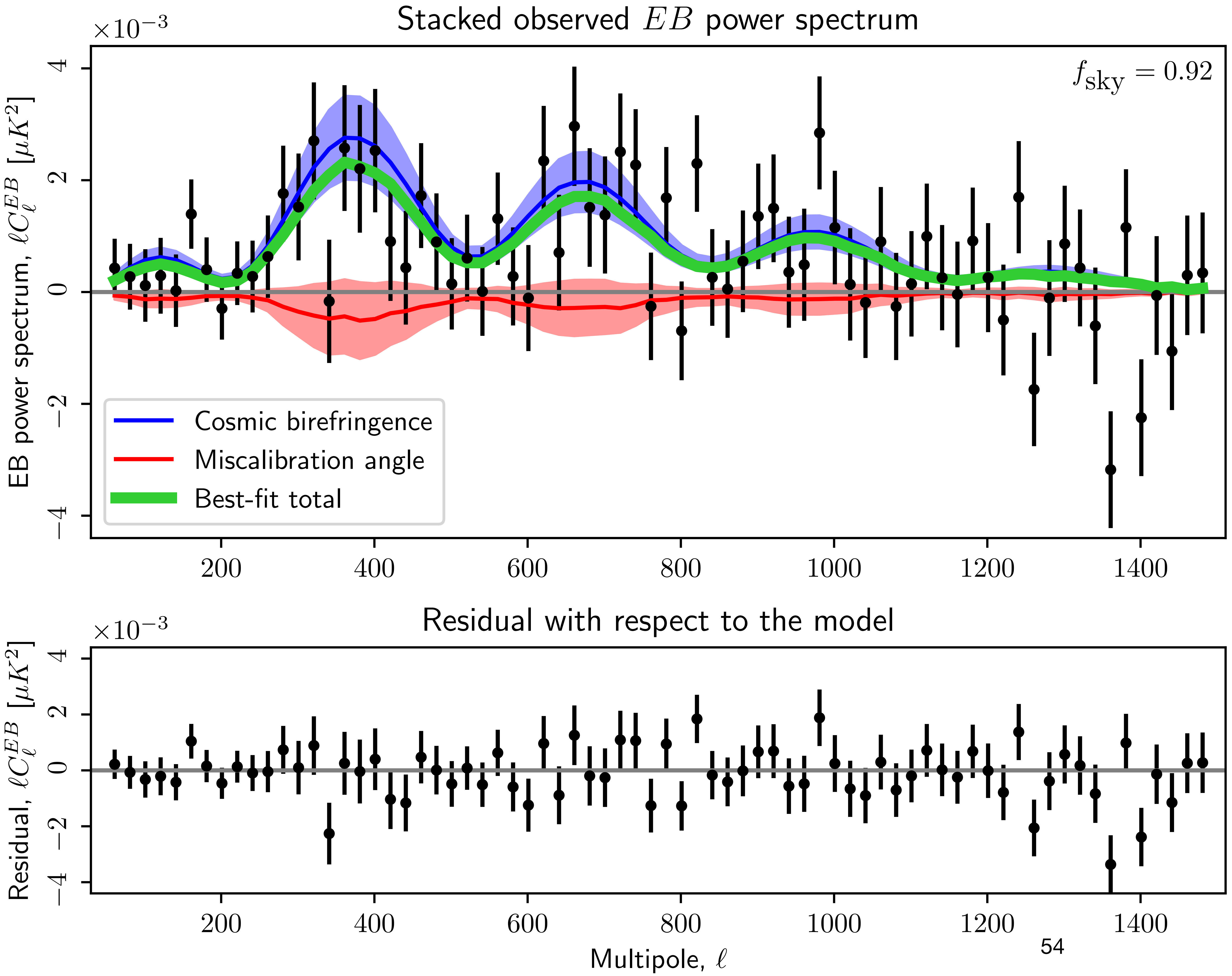
Nearly full-sky data (92% of the sky)

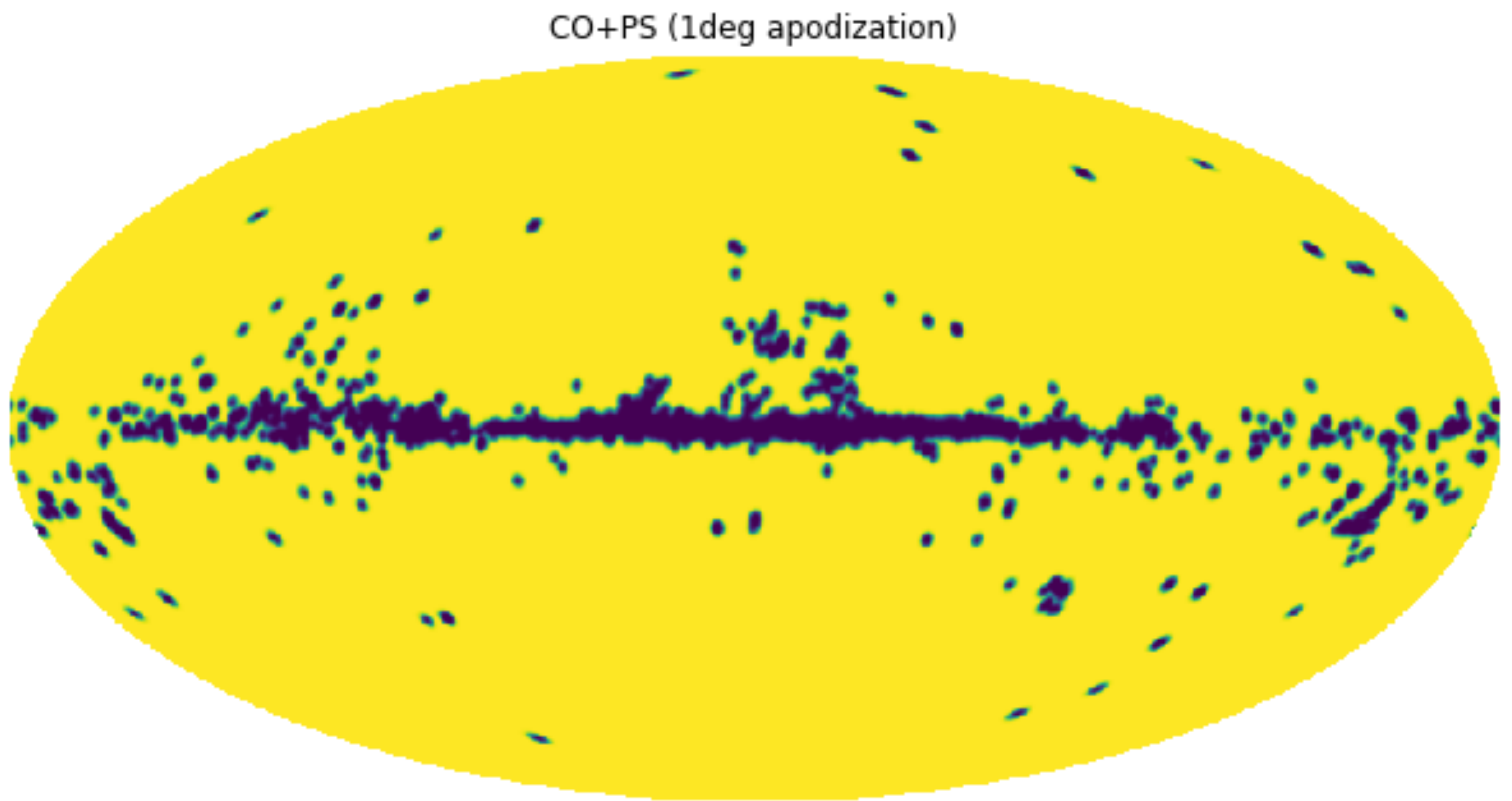


- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

Cosmic Birefringence fits well (WMAP+Planck)

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

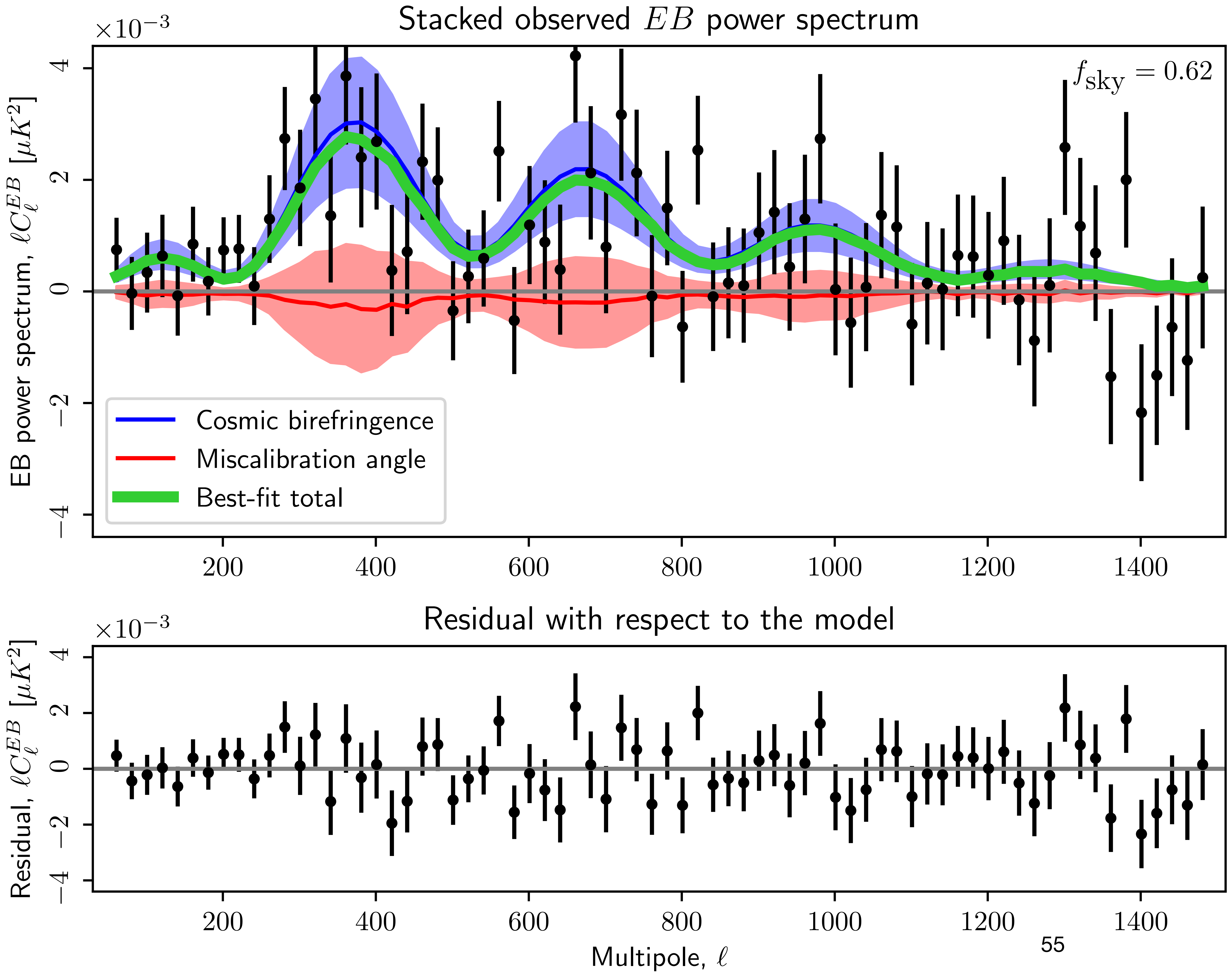


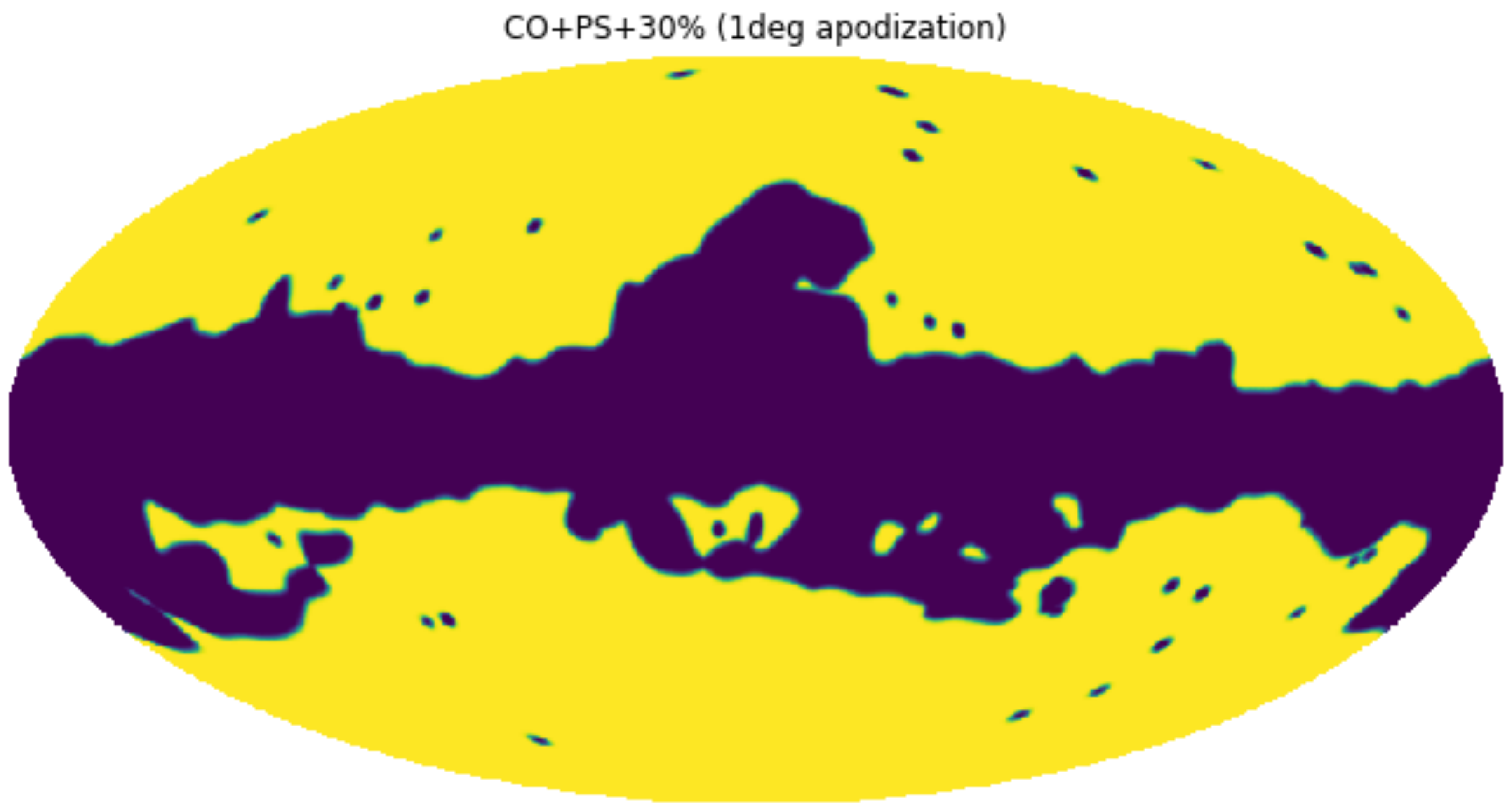


- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- χ^2 = 65.3 for DOF=72

Cosmic Birefringence fits well (WMAP+Planck)

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

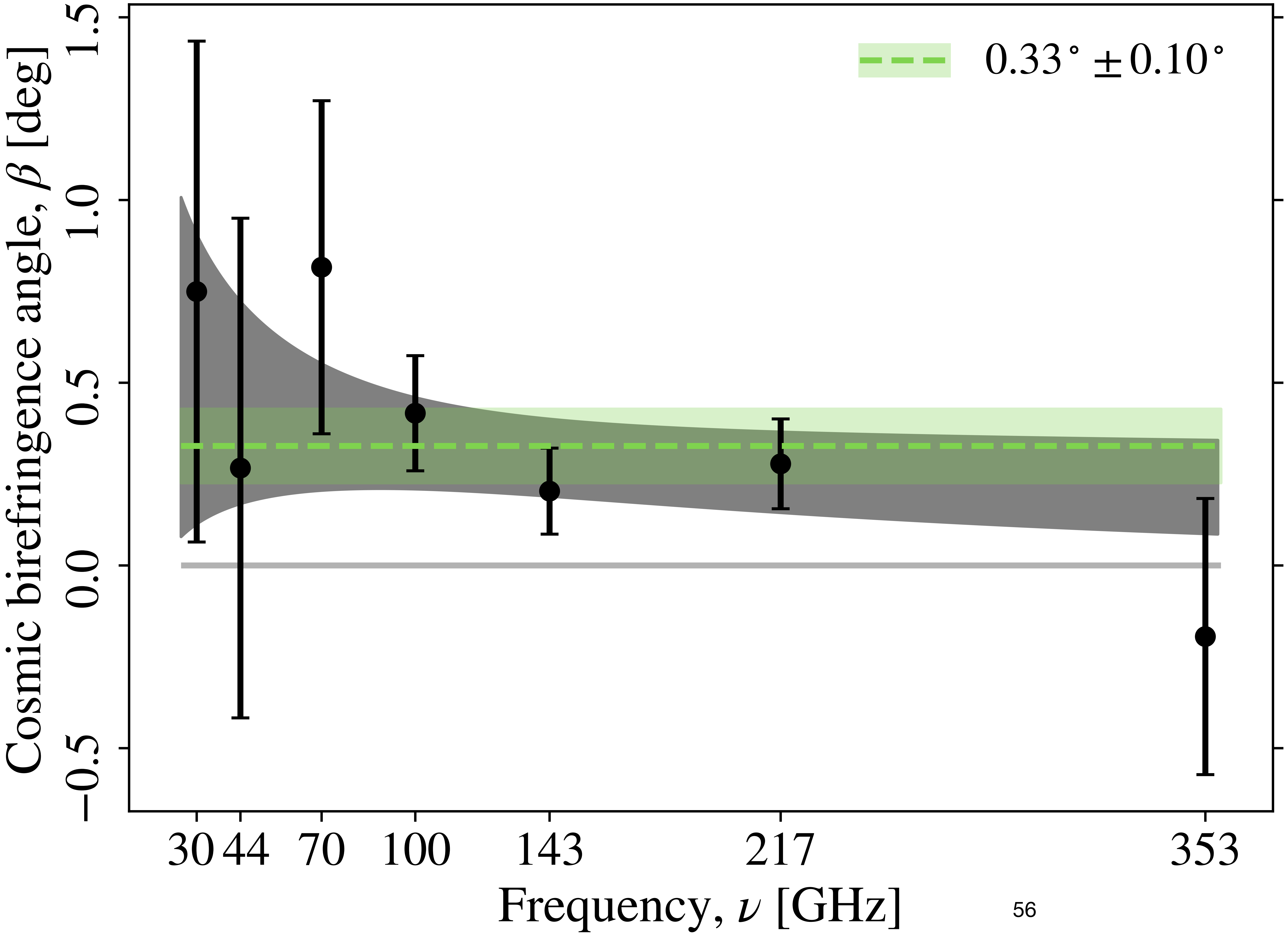




- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **$\beta = 0.37 \pm 0.14$ deg**
- $\chi^2 = 65.8$ for DOF=72

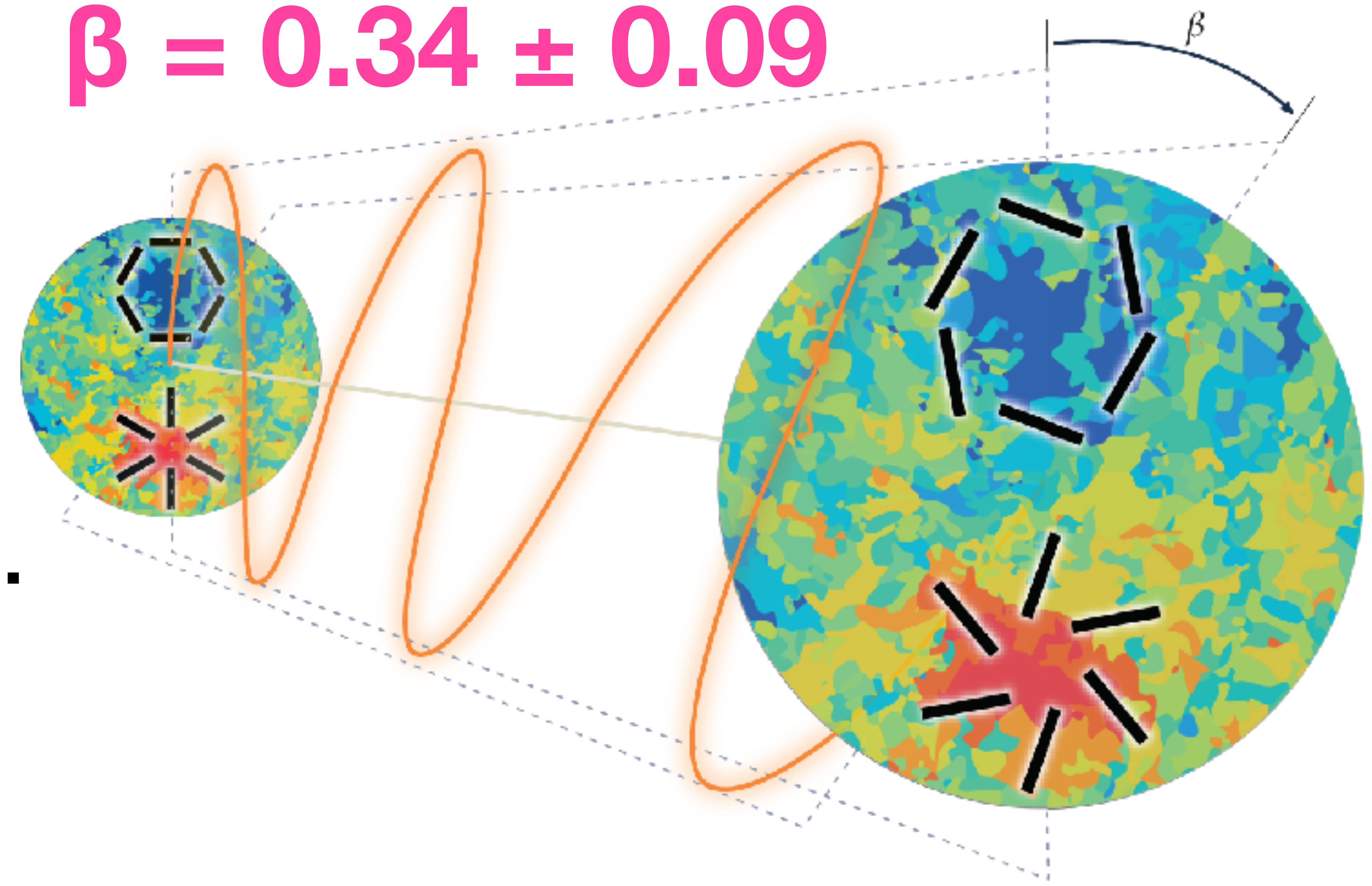
No frequency dependence is found

Consistent with the expectation from cosmic birefringence



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

$\beta = 0.34 \pm 0.09$



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!