Patricia Diego-Palazuelos (Univ. Cantabria, Santander)

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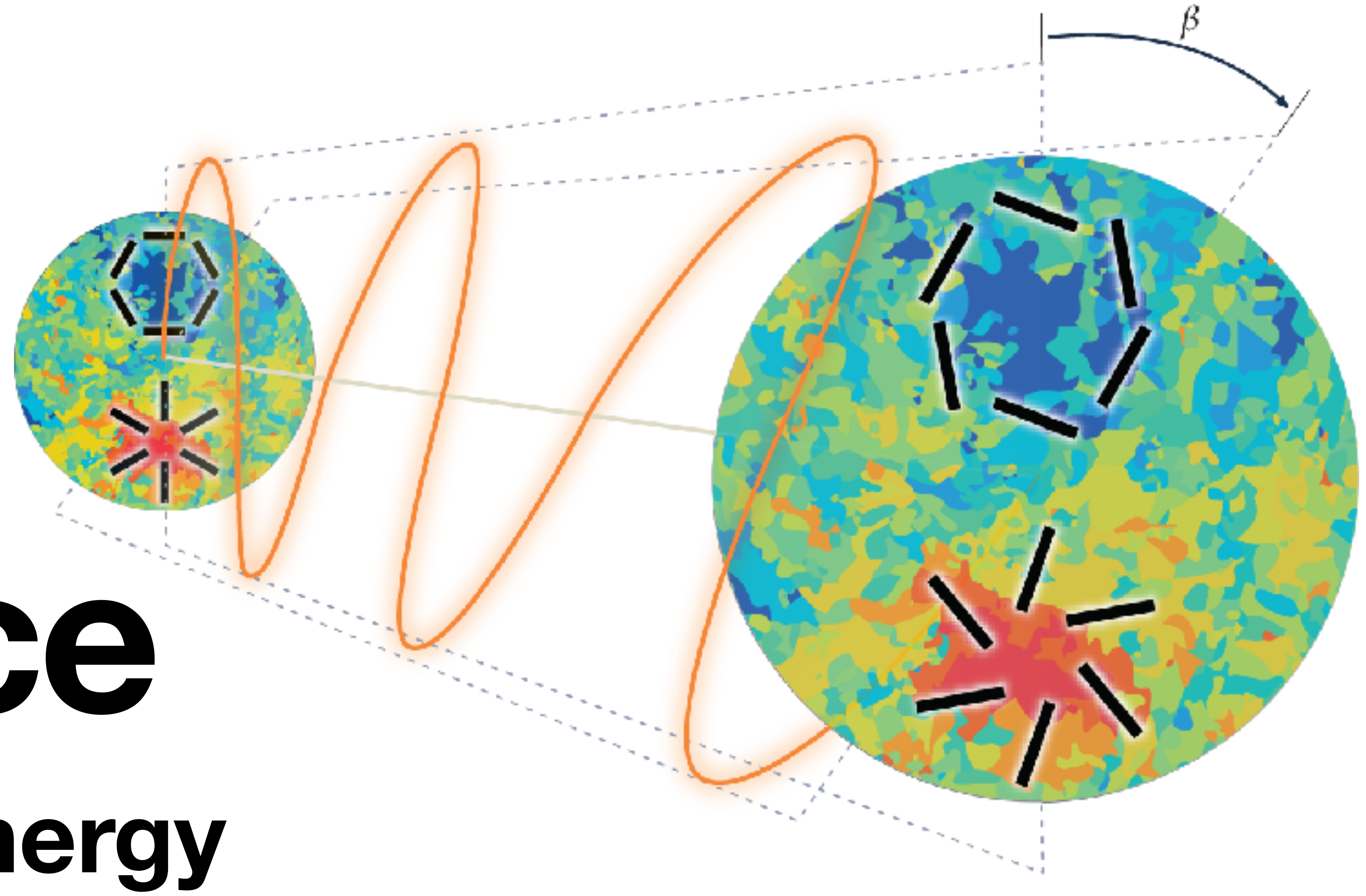
Yuto Minami (Osaka U.)



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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, PRD, 106, 063503 (2022)*
- *Diego-Palazuelos, et al., arXiv:2210.07644*

Eiichiro Komatsu

MPA Institute Seminar, November 14, 2022

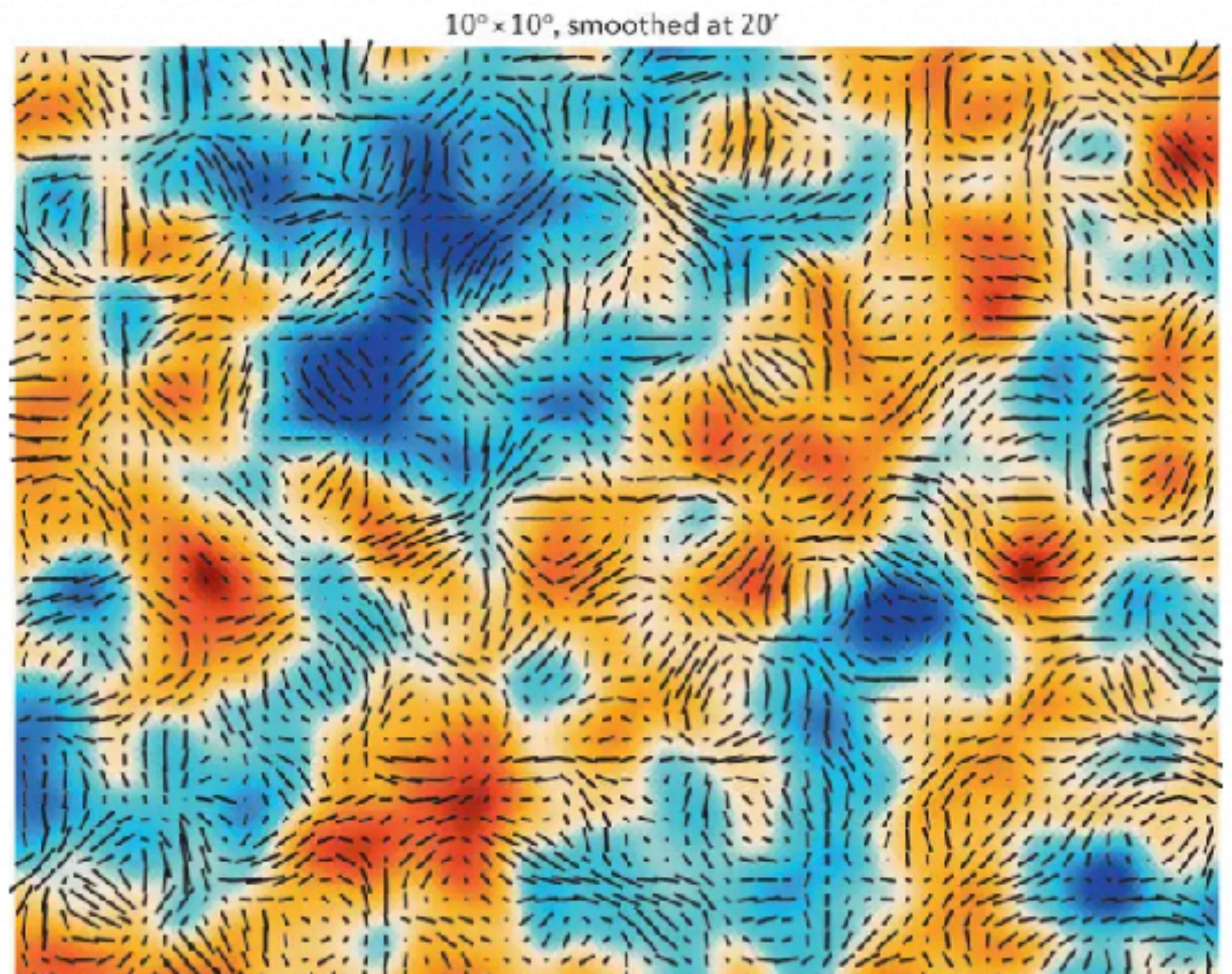
MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

Monthly Highlight June 2022

New analysis strengthens the hint of new physics in polarized radiation from the early Universe

JUNE 01, 2022

In 2020, a tantalizing hint of new physics violating "parity symmetry" was found in polarization data of the cosmic microwave background obtained with the Planck satellite at high frequencies. Based on the Planck data and a simplified assumption about the impact of the polarized dust emission in the Milky Way, the scientists reported a violation of the symmetry of the laws of physics under inversion of spatial coordinates with 99.2% confidence level. An international team led by MPA director Eiichiro Komatsu has now improved the analysis method. By considering the dust emission explicitly and using more data from not only Planck but also from WMAP the astrophysicists measured the parity-violating signal with 99.987% confidence level. If this should be confirmed in the future as a genuine cosmological signal, it would have profound implications for the fundamental physics behind dark matter, dark energy, and quantum gravity.



Photons of the cosmic microwave background (CMB), the afterglow of the primordial fireball Universe, are linearly polarized (Figure 1). This pattern can be used to search for new physics violating "parity symmetry" – the symmetry of the laws of physics under an inversion of spatial coordinates. For example, electromagnetism works the same way whether one is in the original system or in a mirrored system with all spatial coordinates flipped. A violation of parity symmetry has only been observed in the weak interaction of the standard model of elementary particles and fields – so far. Can the Universe also violate parity symmetry?

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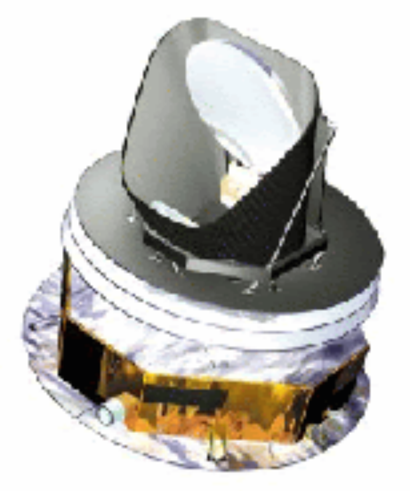
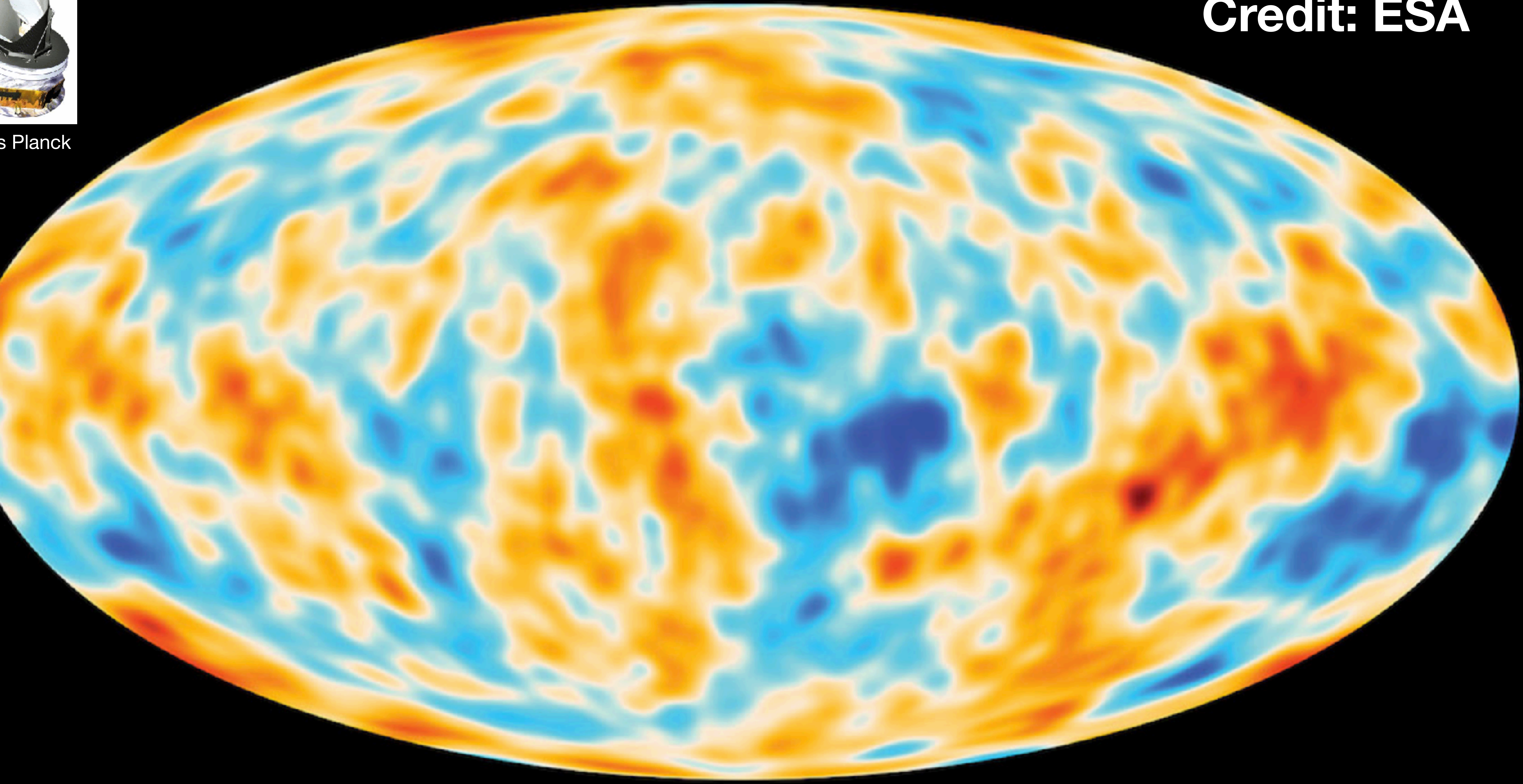
Original publications

ay a menu



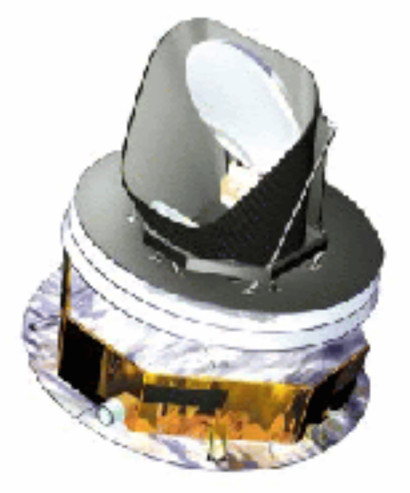
ESA's Planck

Credit: ESA



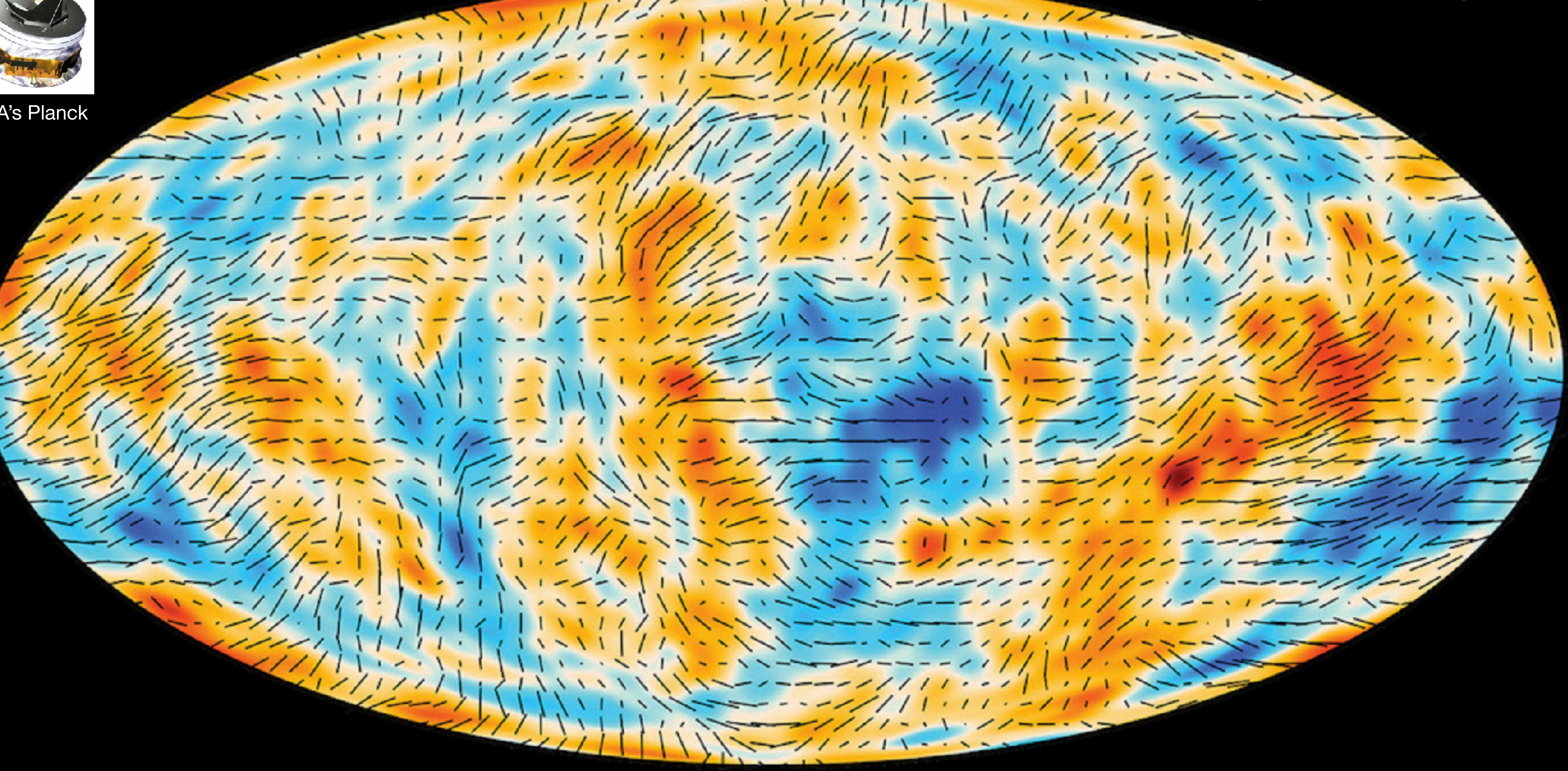
Foreground-cleaned Temperature (smoothed)

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 (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.

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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

Nature Reviews Physics (2022) | Cite this article

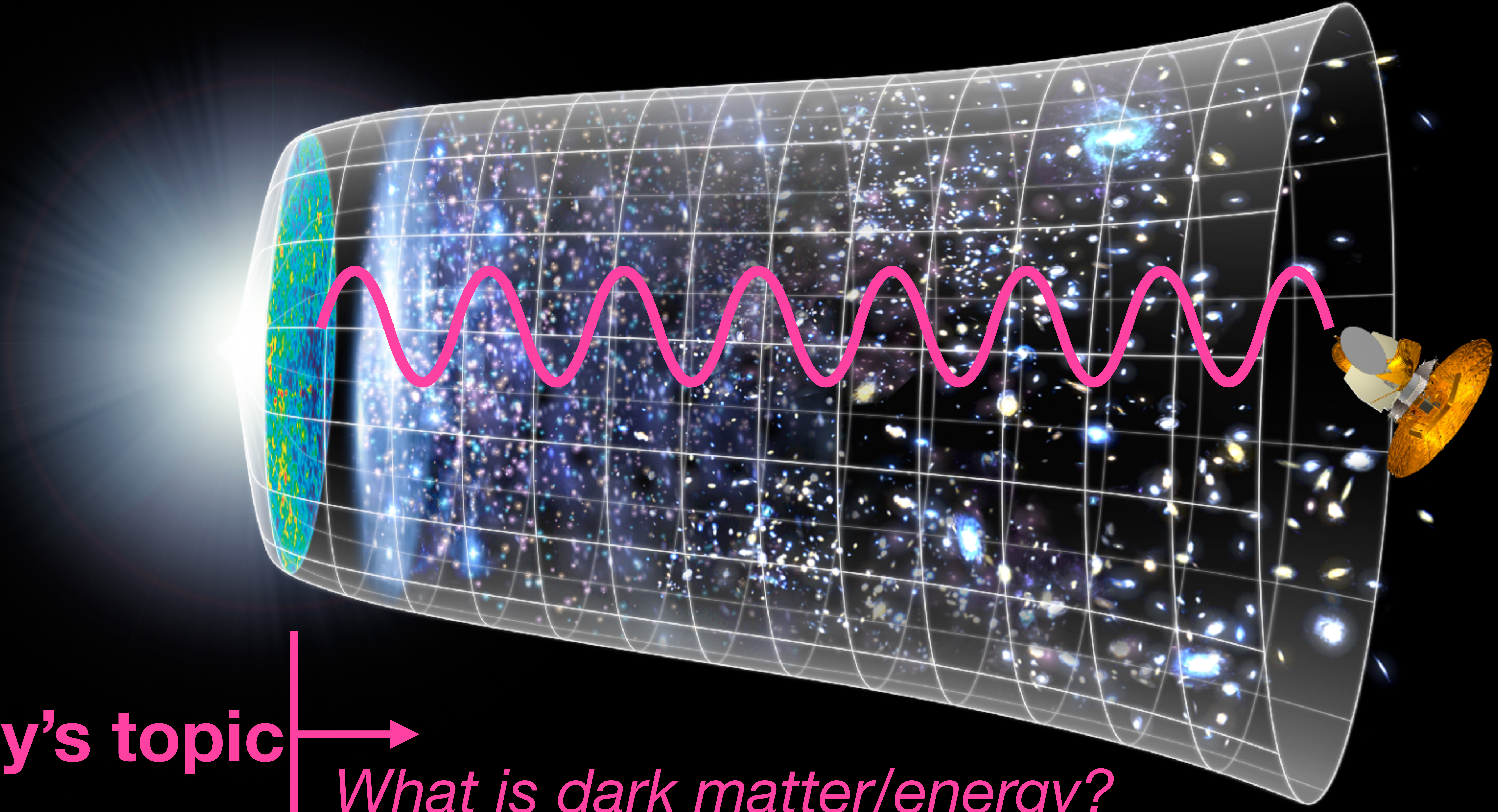
Metrics

Key Words:

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

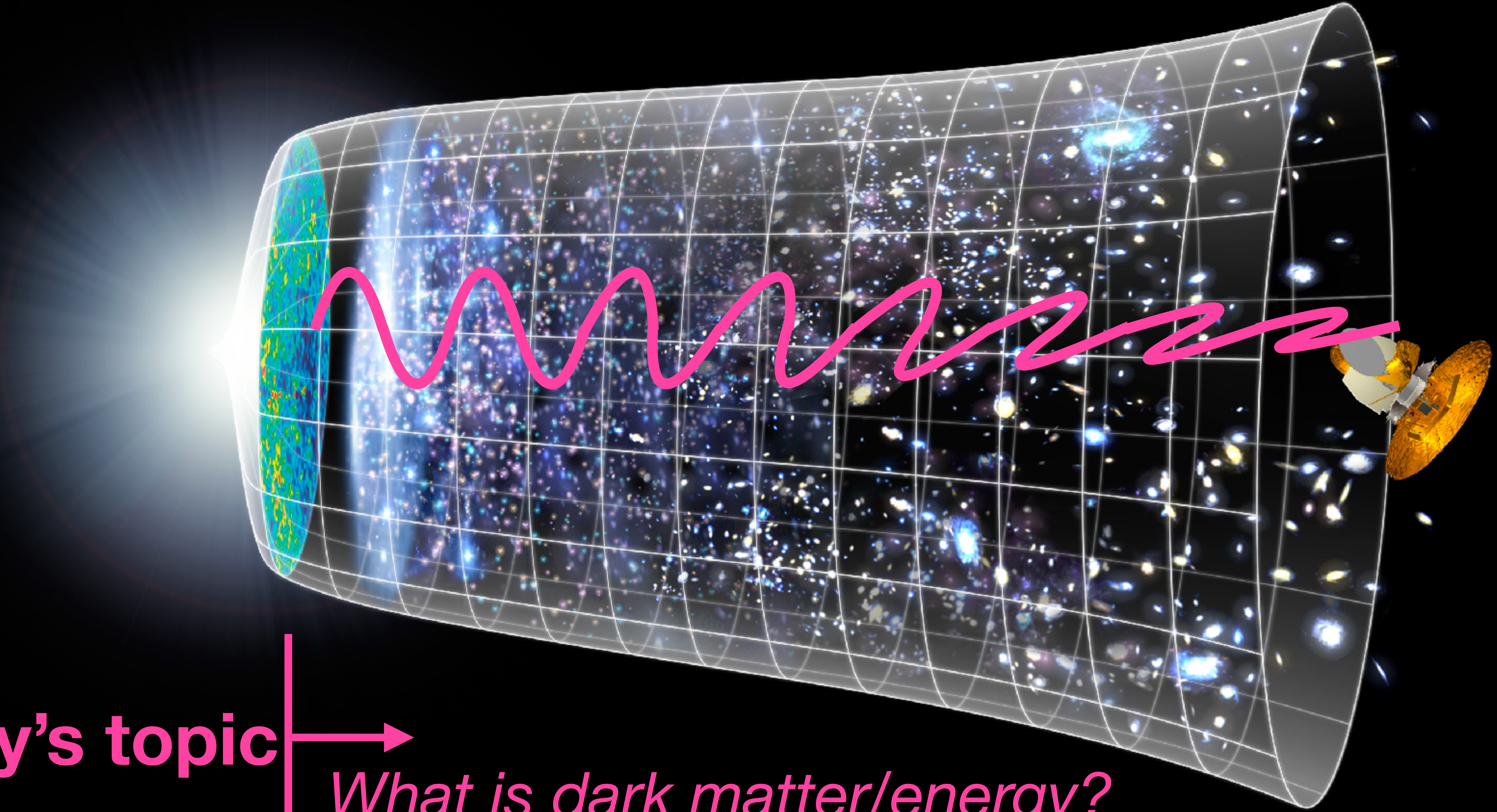

Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates *polarisation*!)
What powered the Big Bang?
What is dark matter/energy?

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

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

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

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)

Cosmic Birefringence

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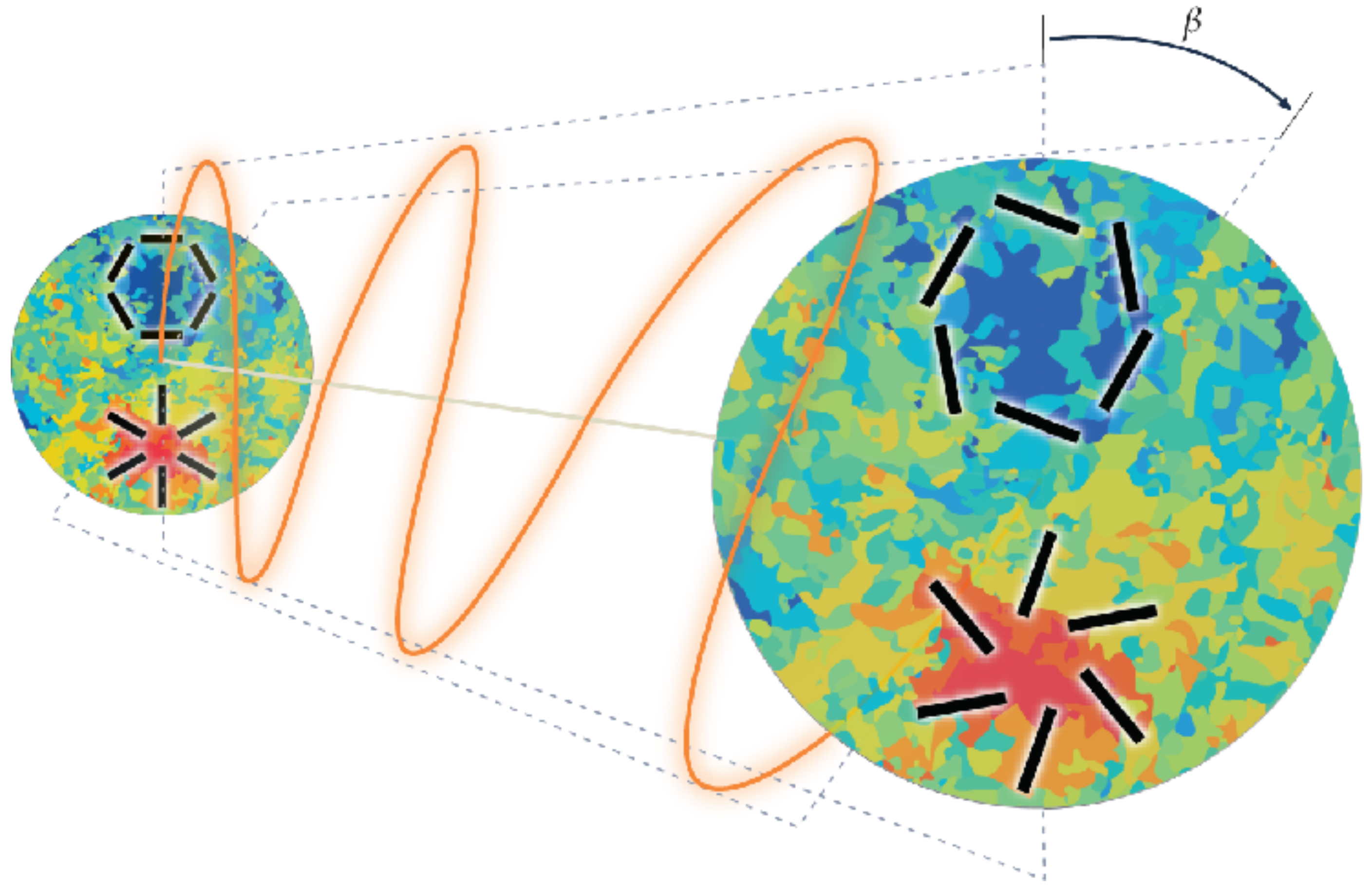


"Cosmic Birefringence"

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

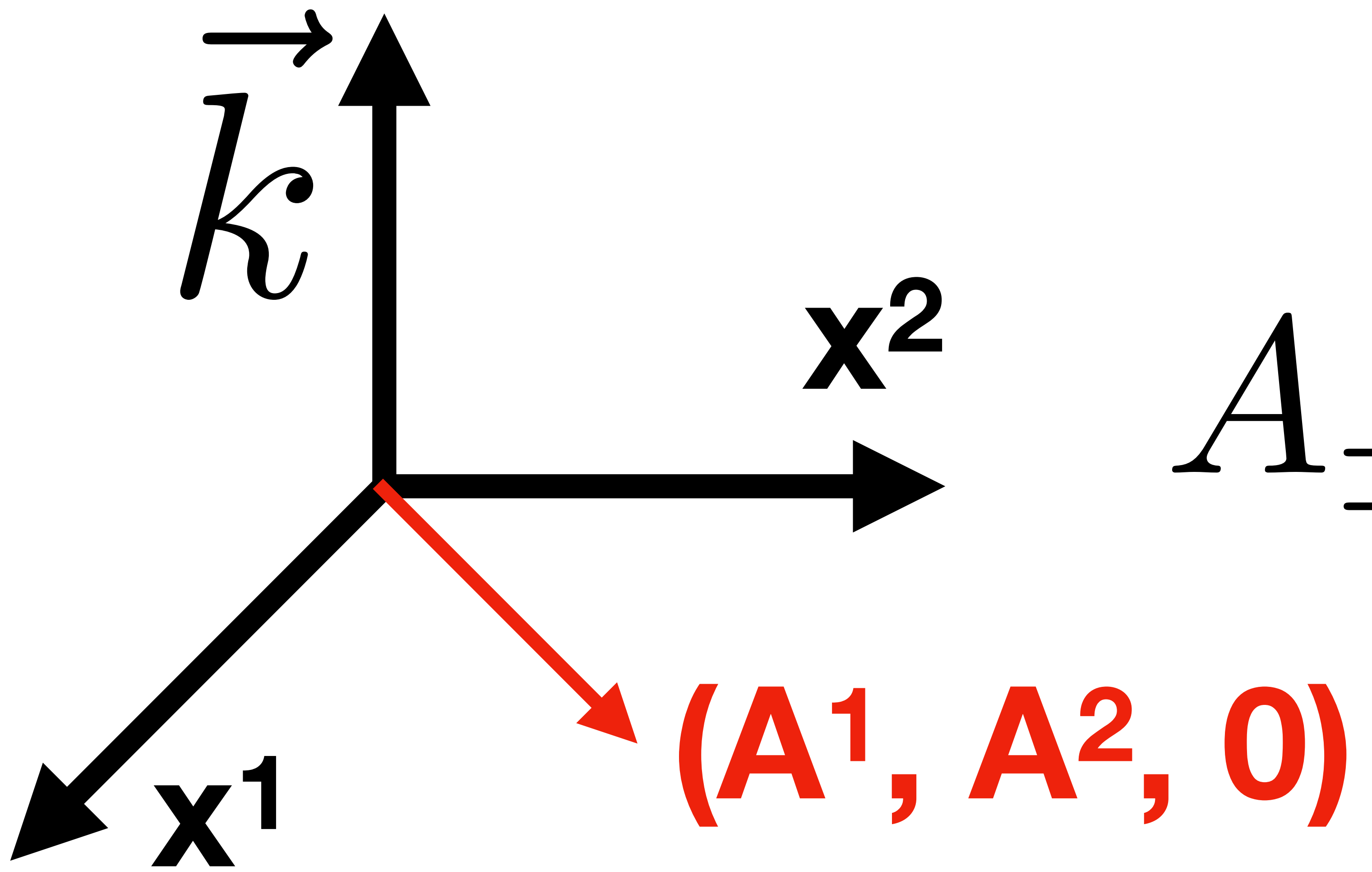
Standard Maxwell Theory

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

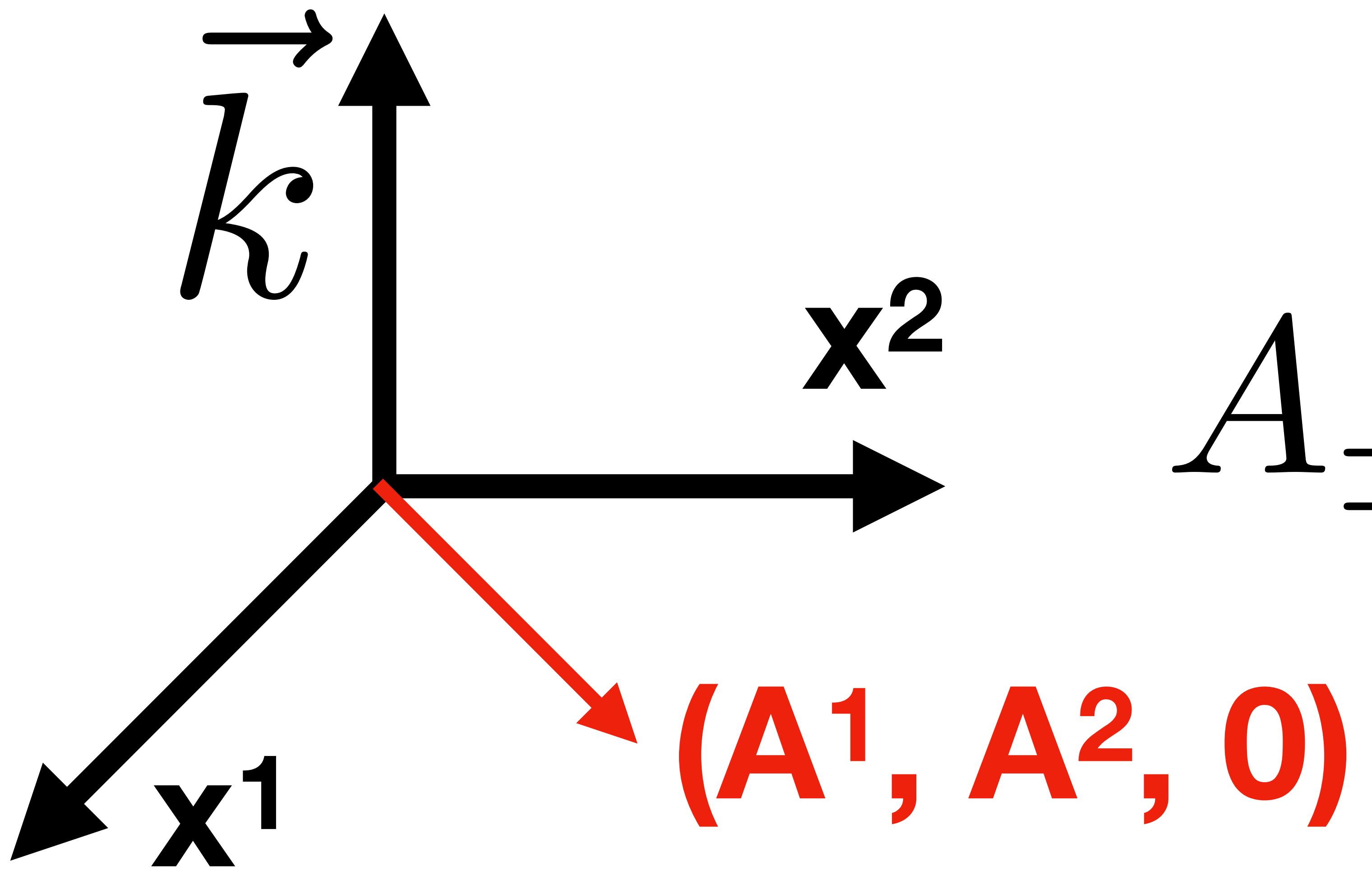
Warm up (2)

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

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

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

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

Cosmic Birefringence

Derivation (1)

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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

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

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

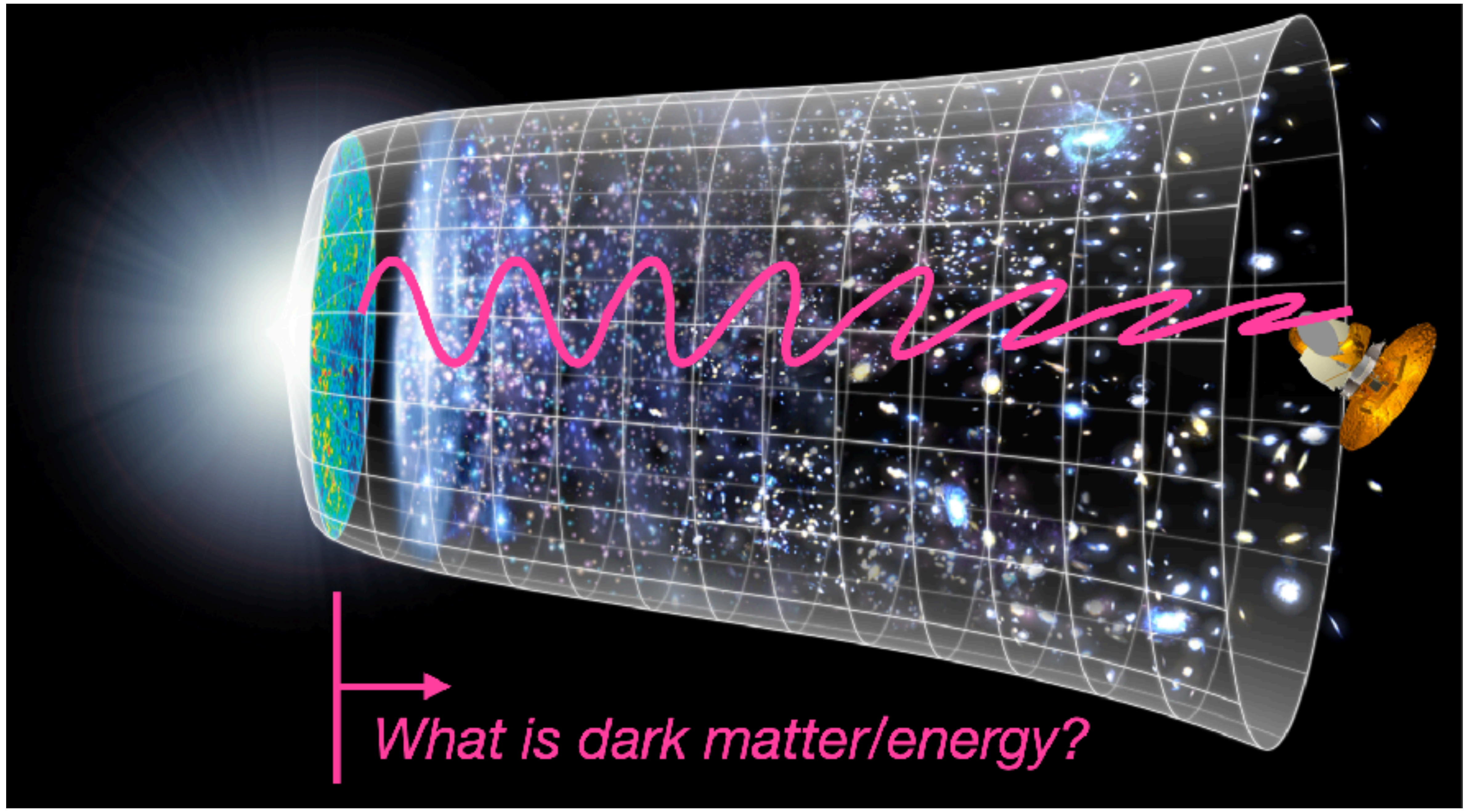
Cosmic Birefringence

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

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

Cosmic Birefringence

Recap

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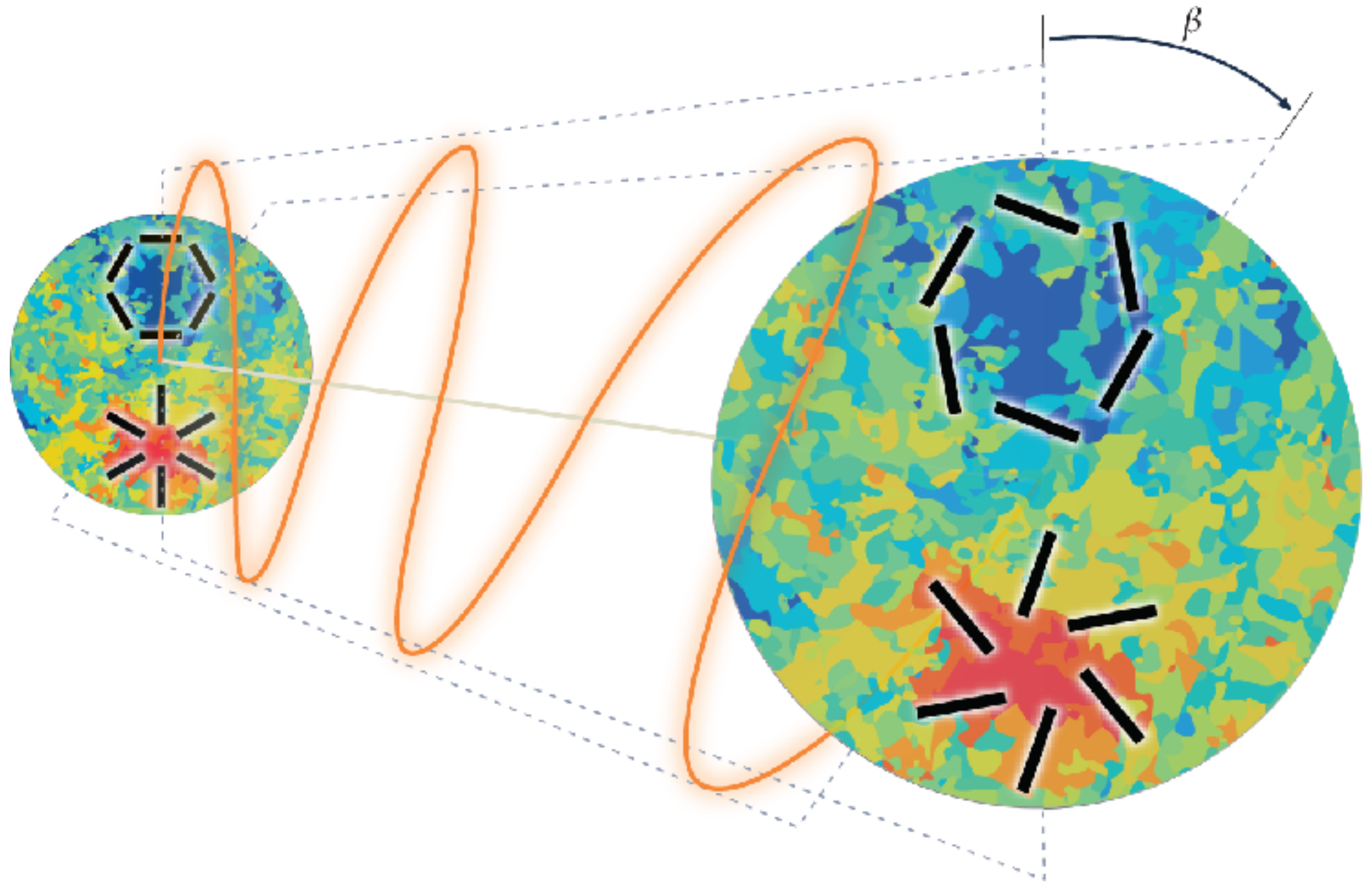
$$\beta = -2g_a\int_{t_\mathrm{emitted}}^{t_\mathrm{observed}} dt\,\dot{\theta} = 2g_a\left[\theta(t_\mathrm{e}) - \theta(t_\mathrm{o})\right]$$



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

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

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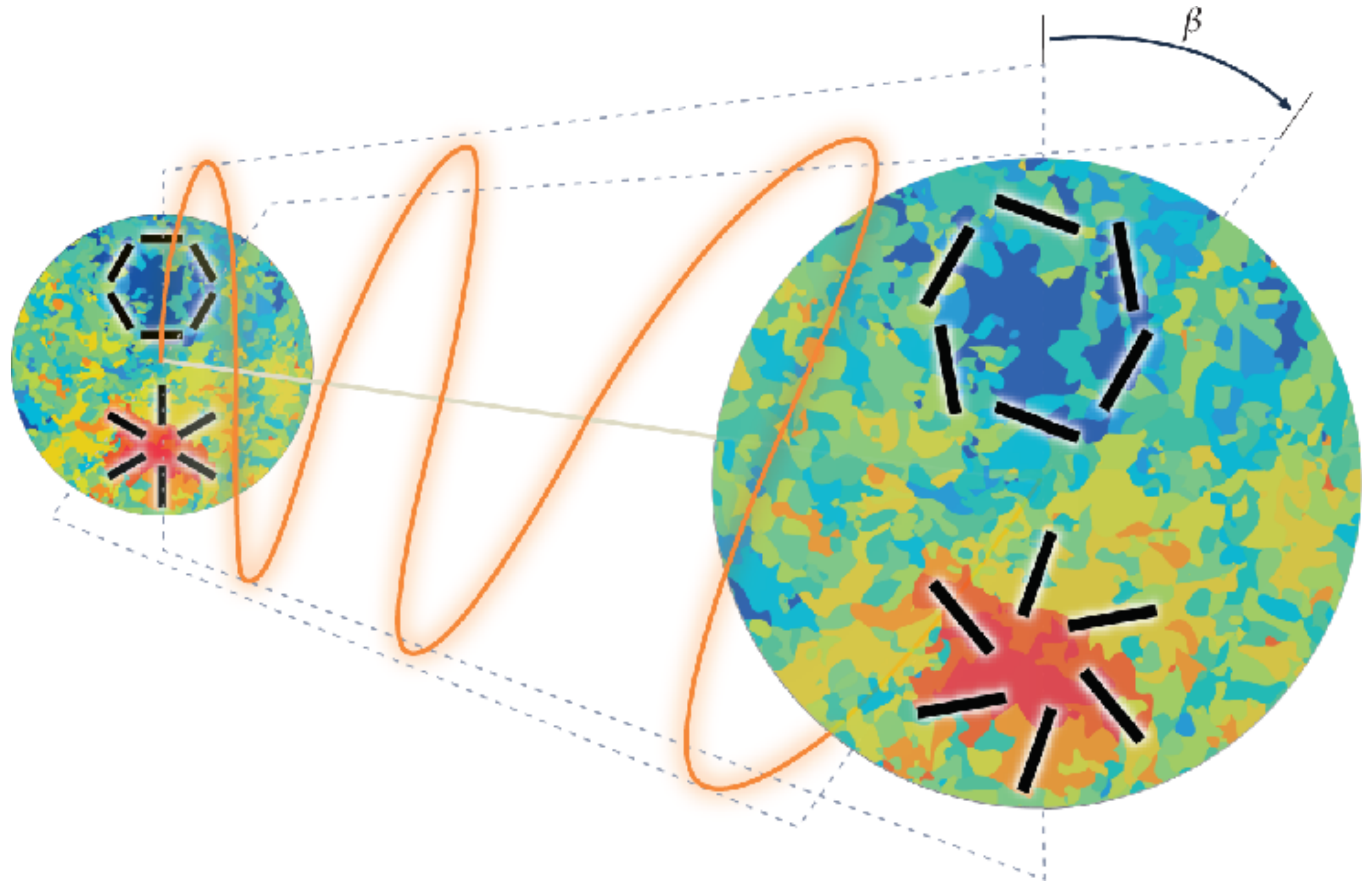


If θ varies over space:

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

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

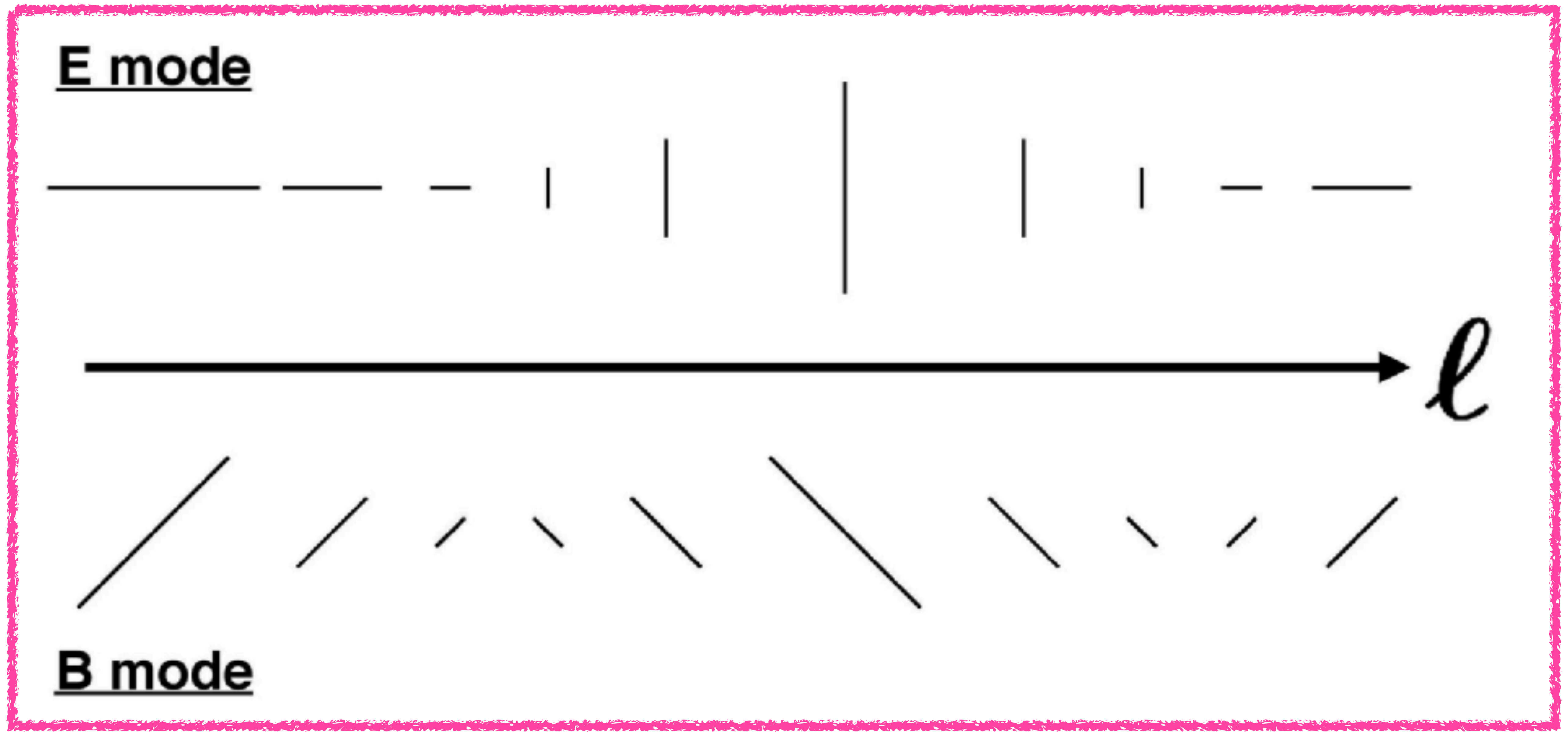
Why study the cosmic birefringence?

- 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!

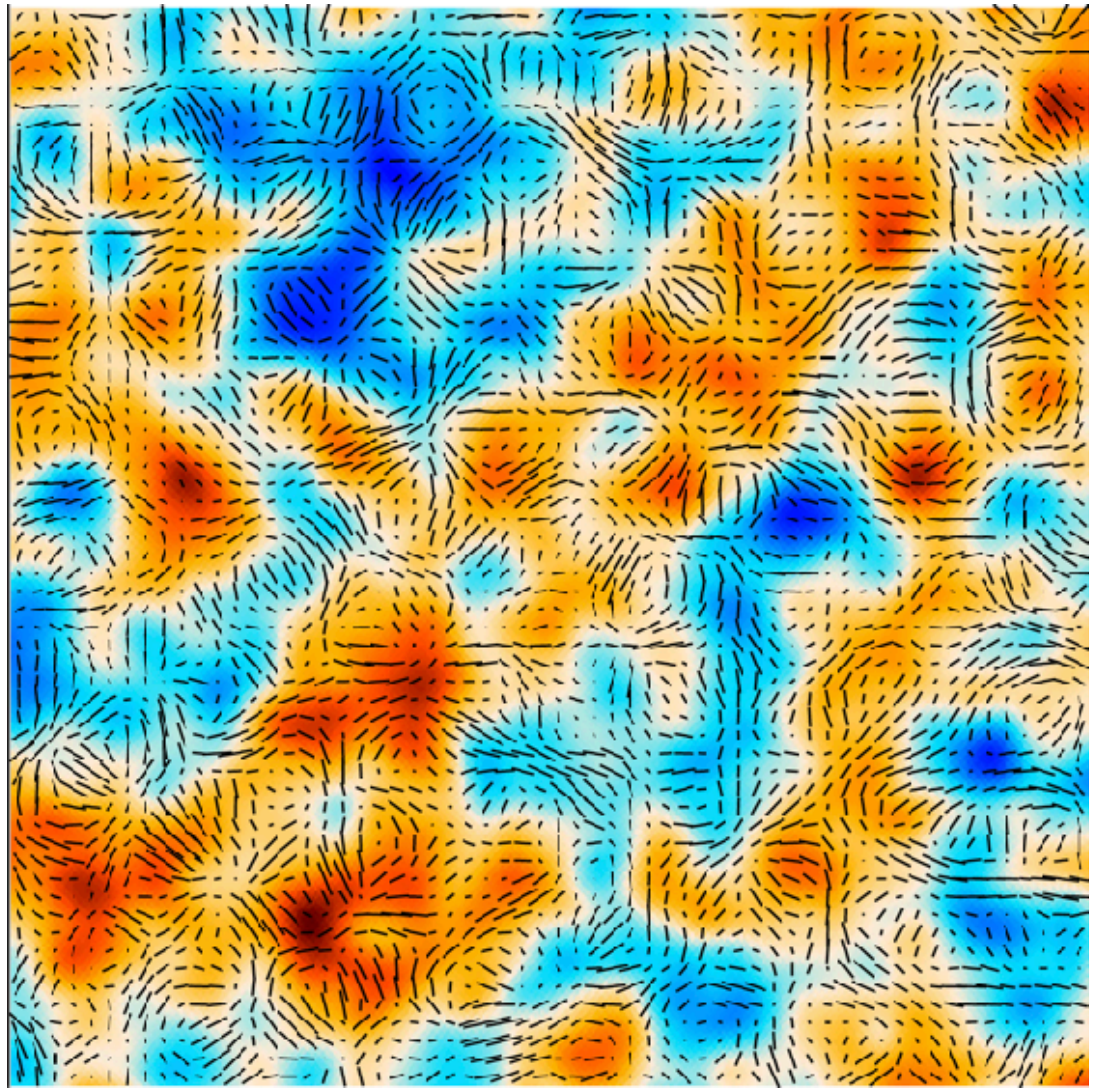
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation

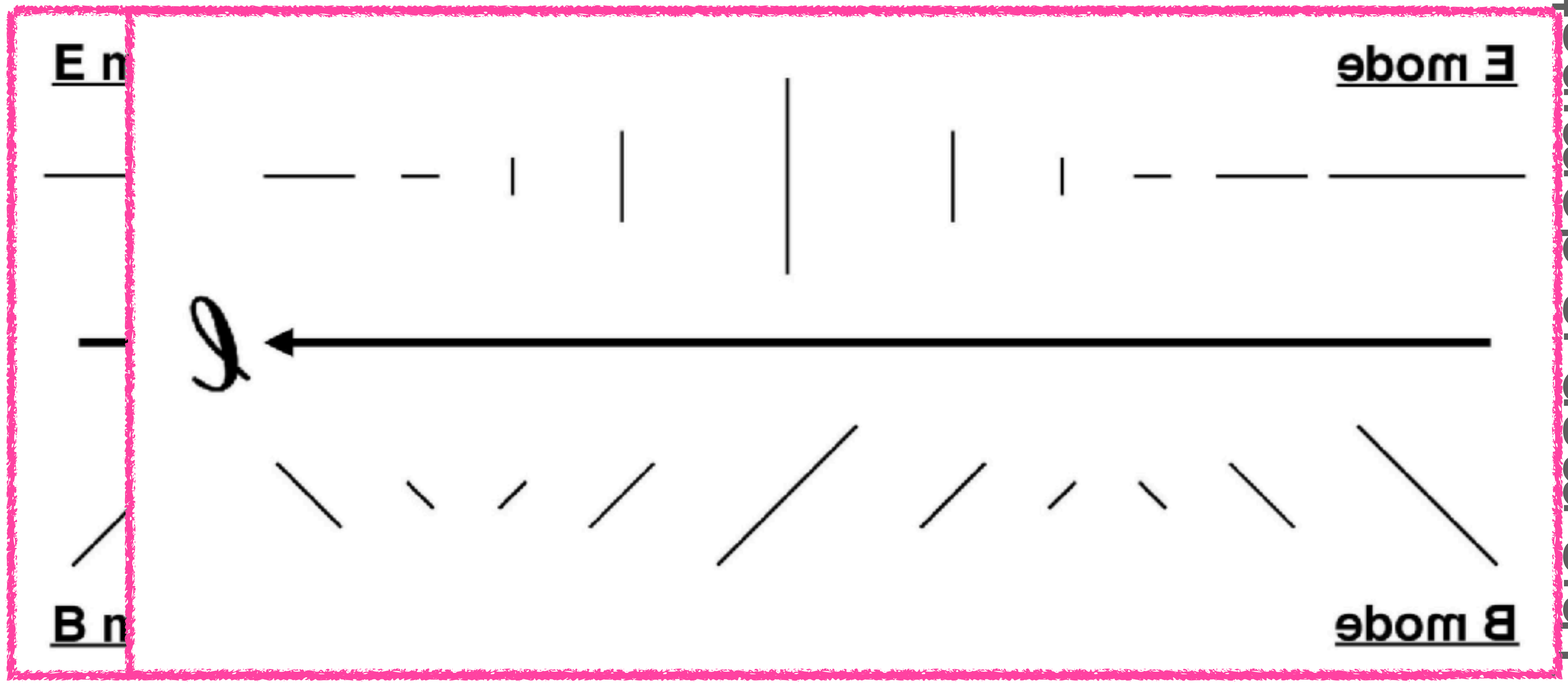


- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

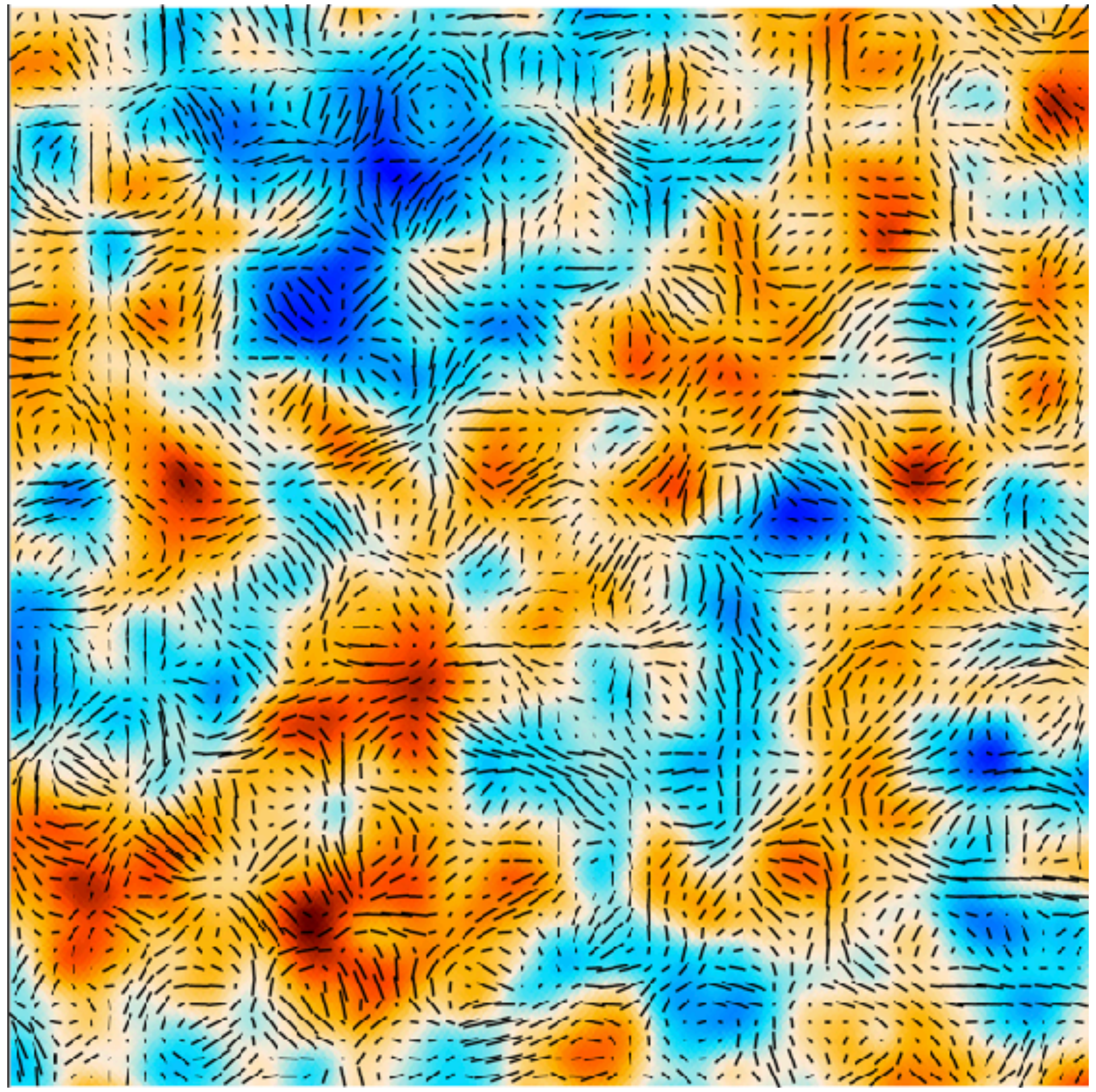
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarisation



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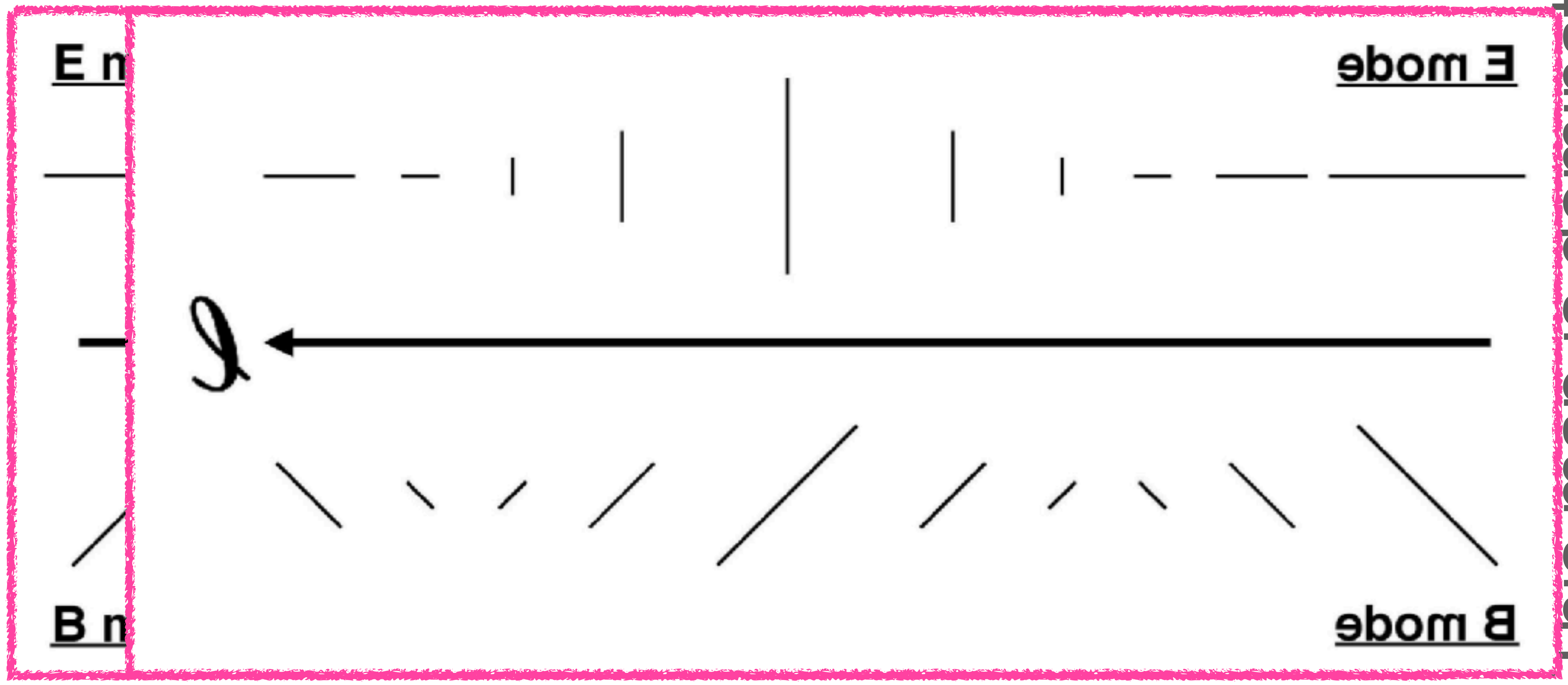
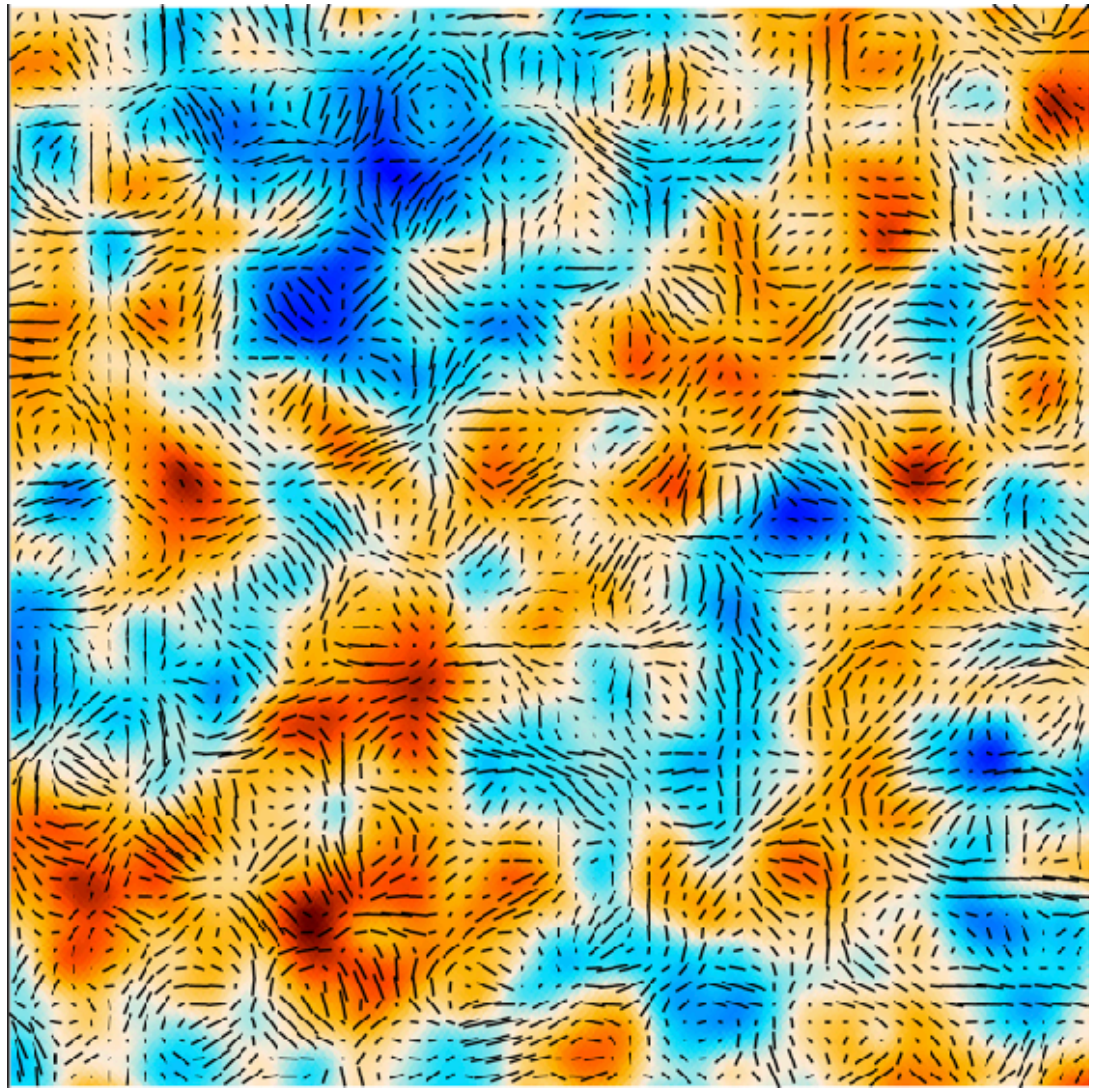


This map is dominated by E-mode polarisation



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

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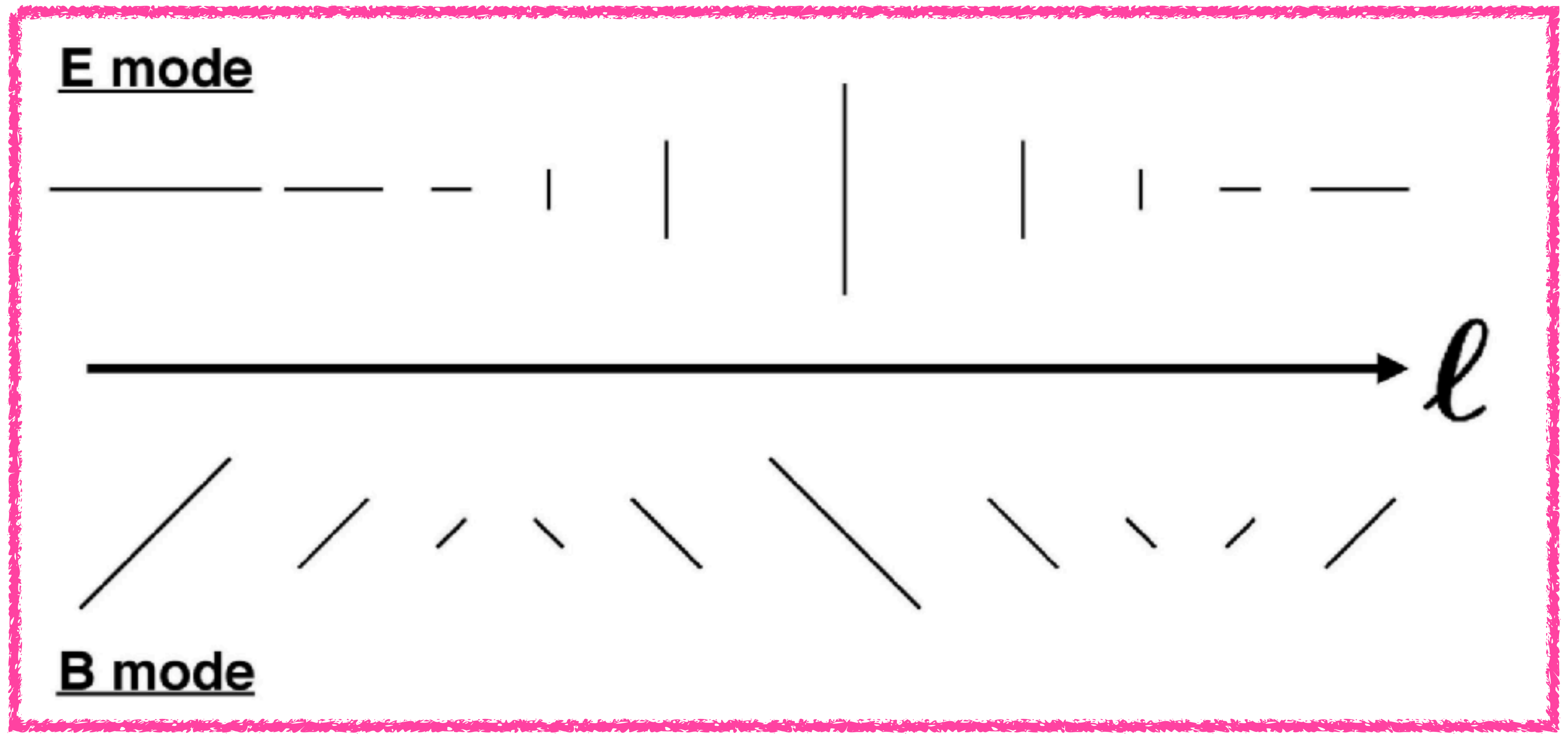
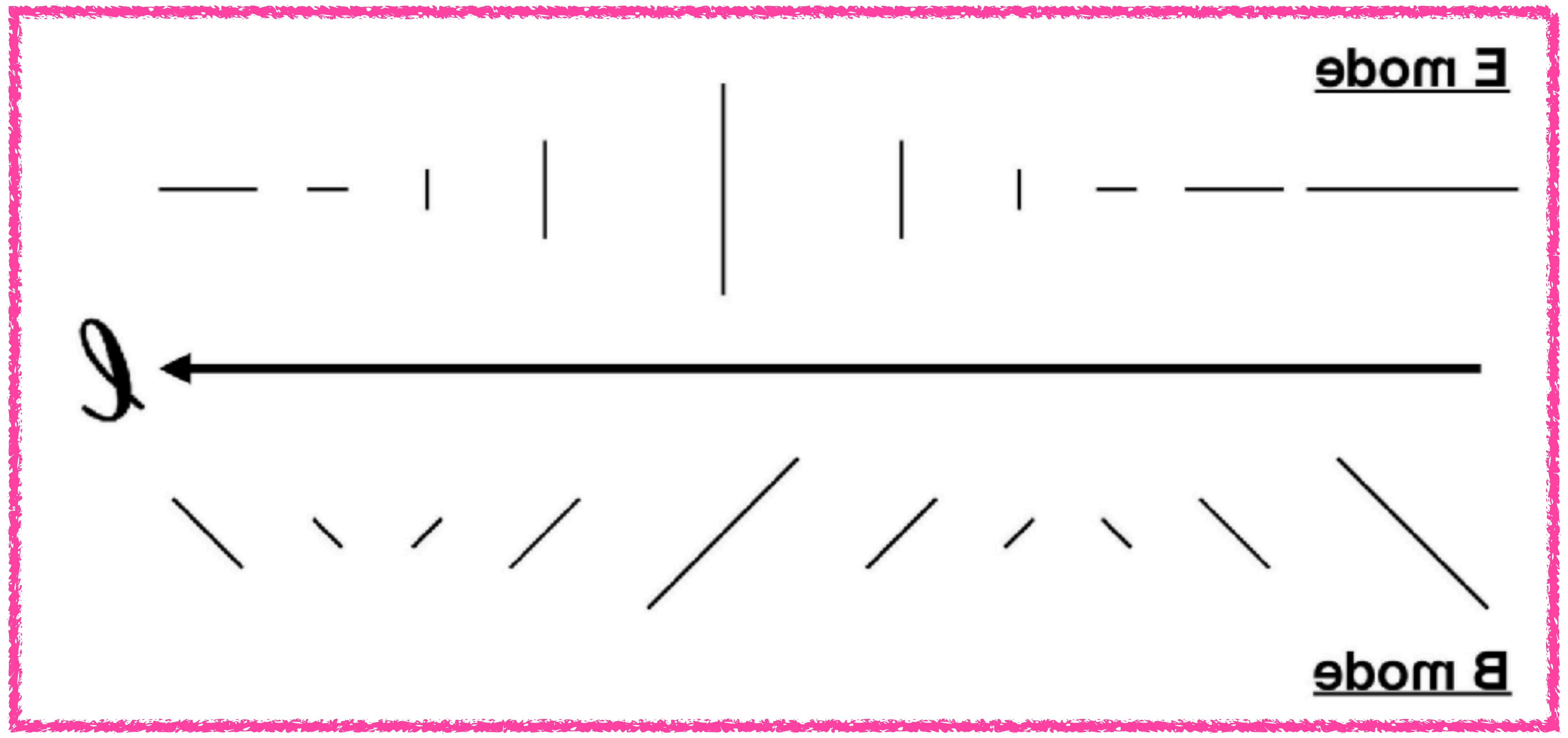
IMPORTANT”: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

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

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

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

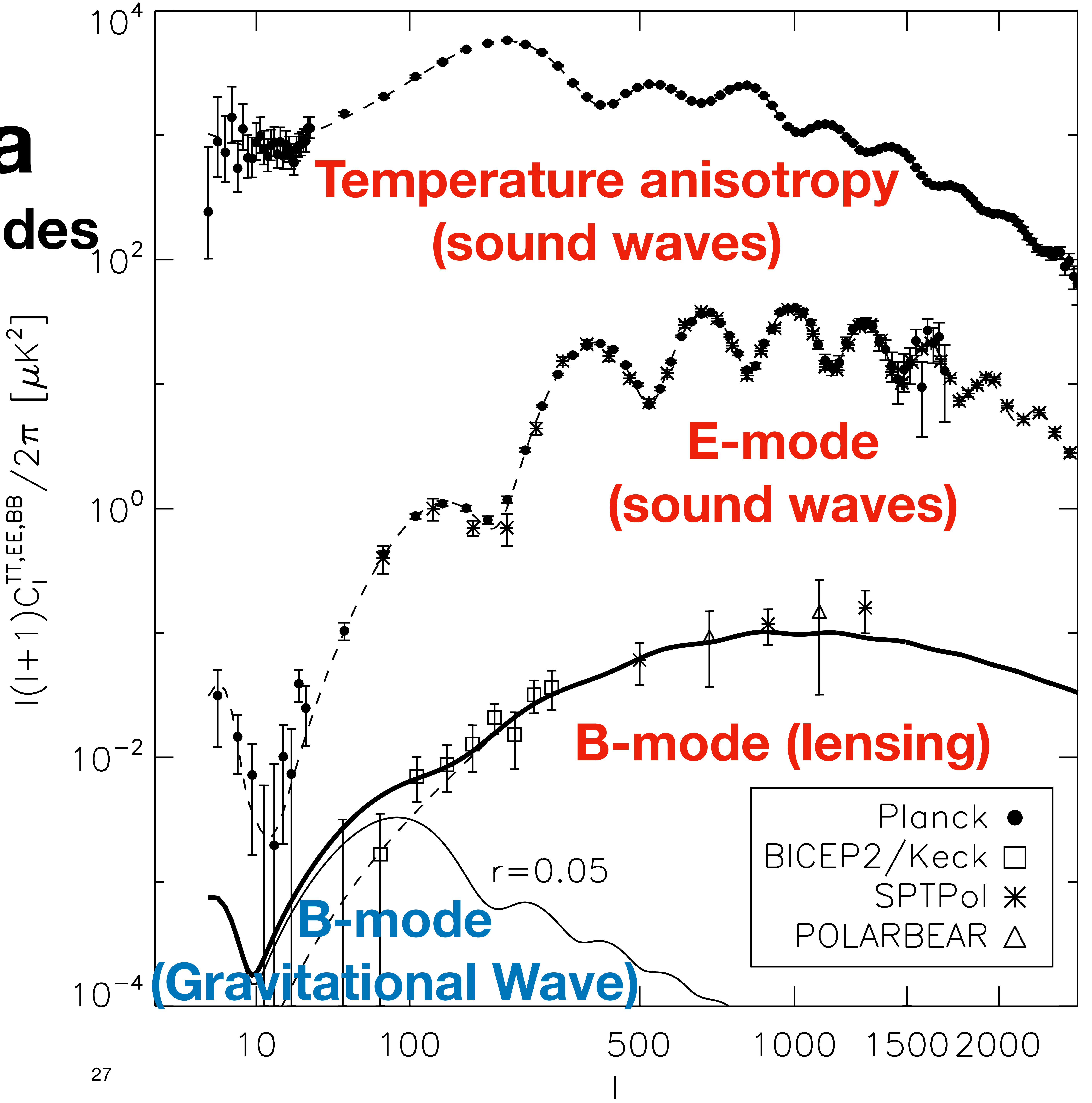
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- 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)**

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.**

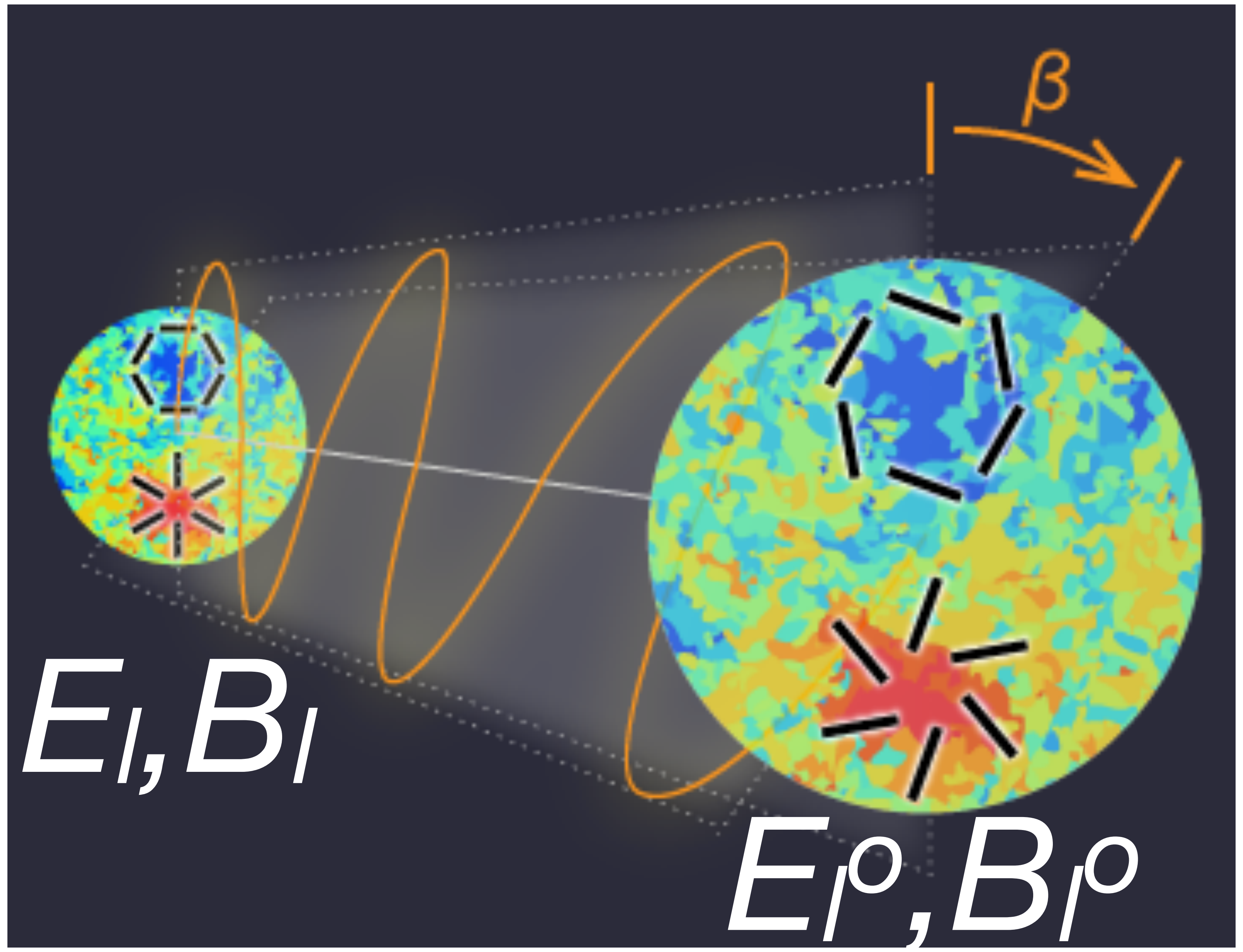


Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

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

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

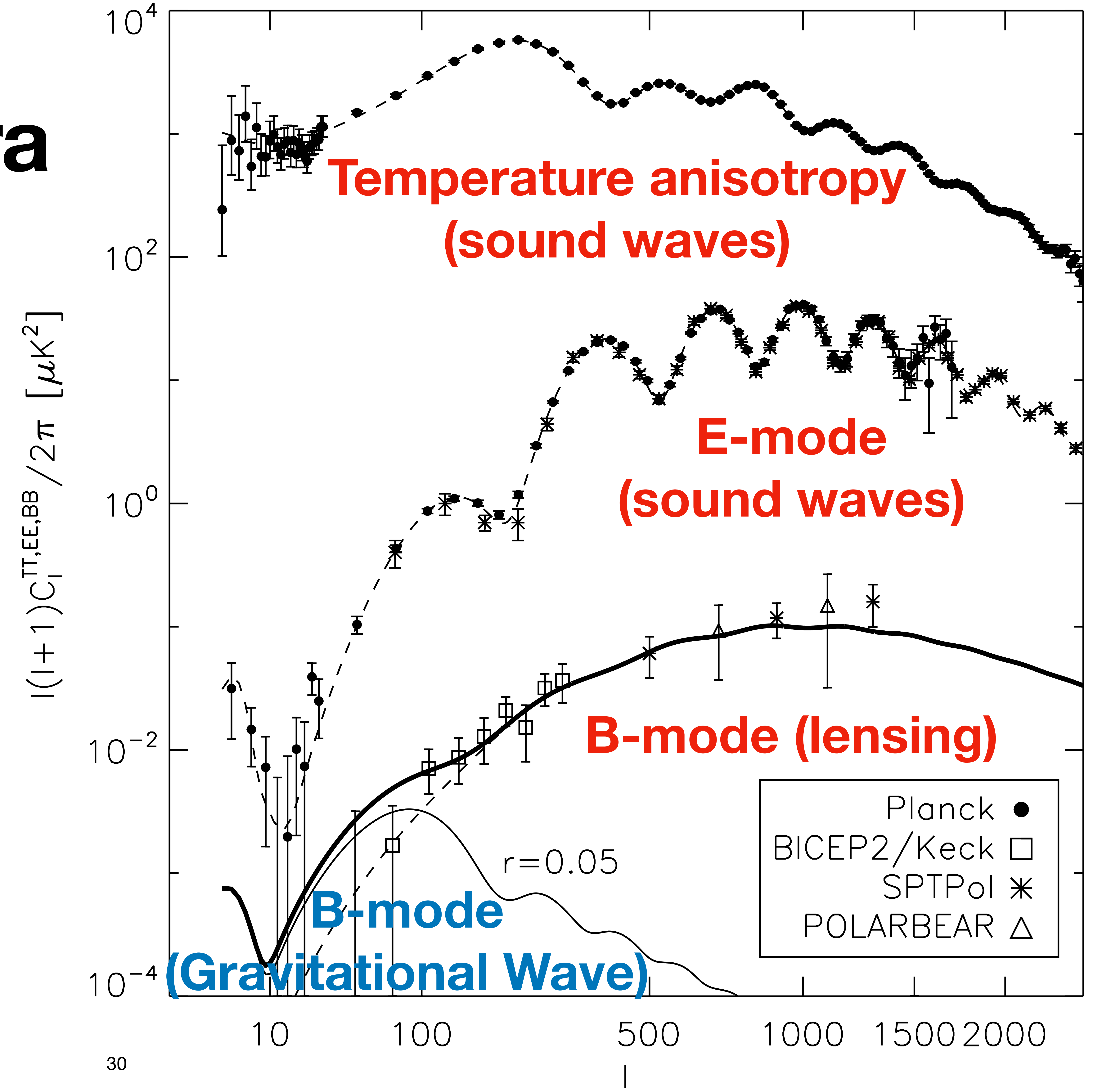
$$= \frac{1}{2}\underline{(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}})}\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

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

CMB Power Spectra

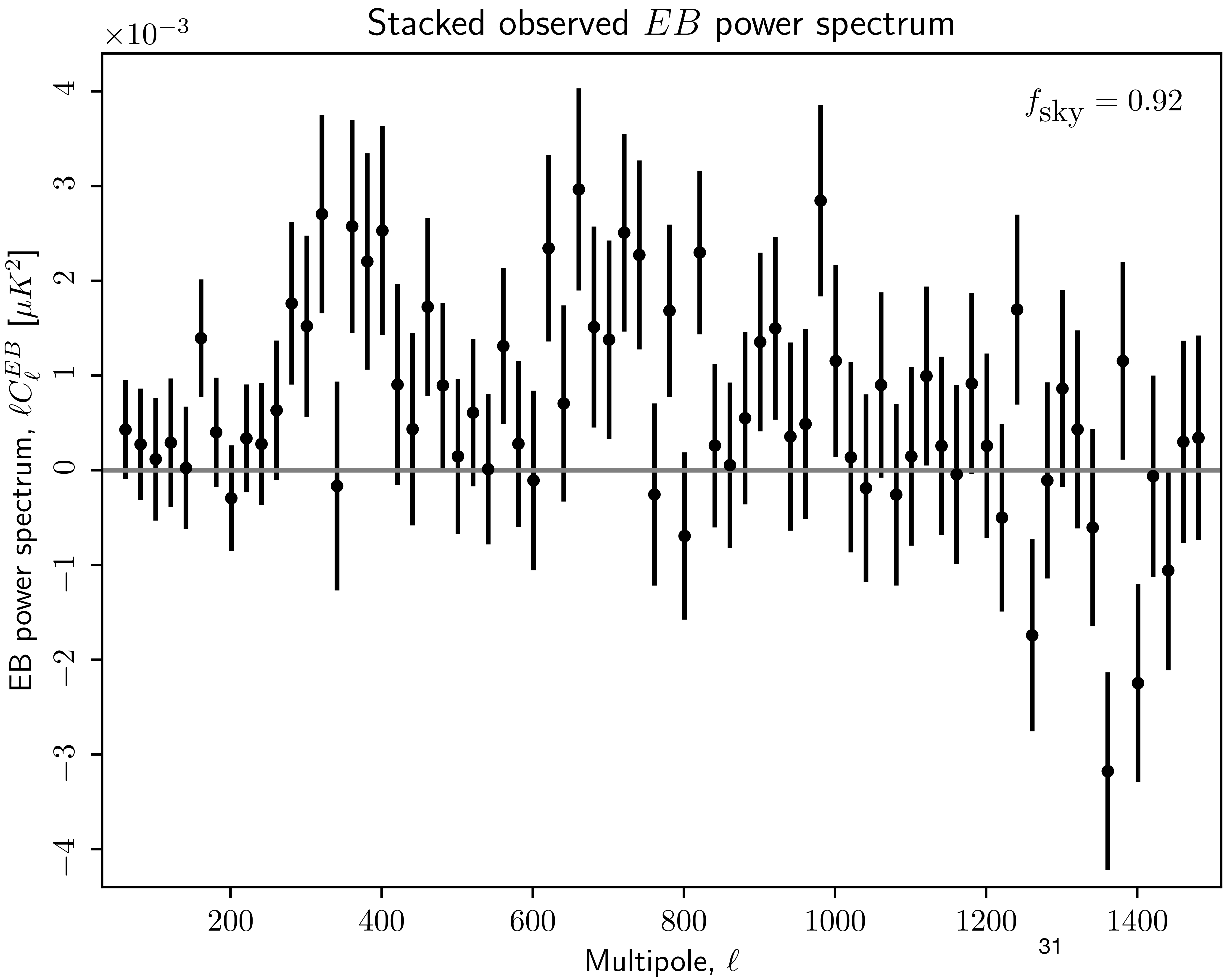
EE >> BB!

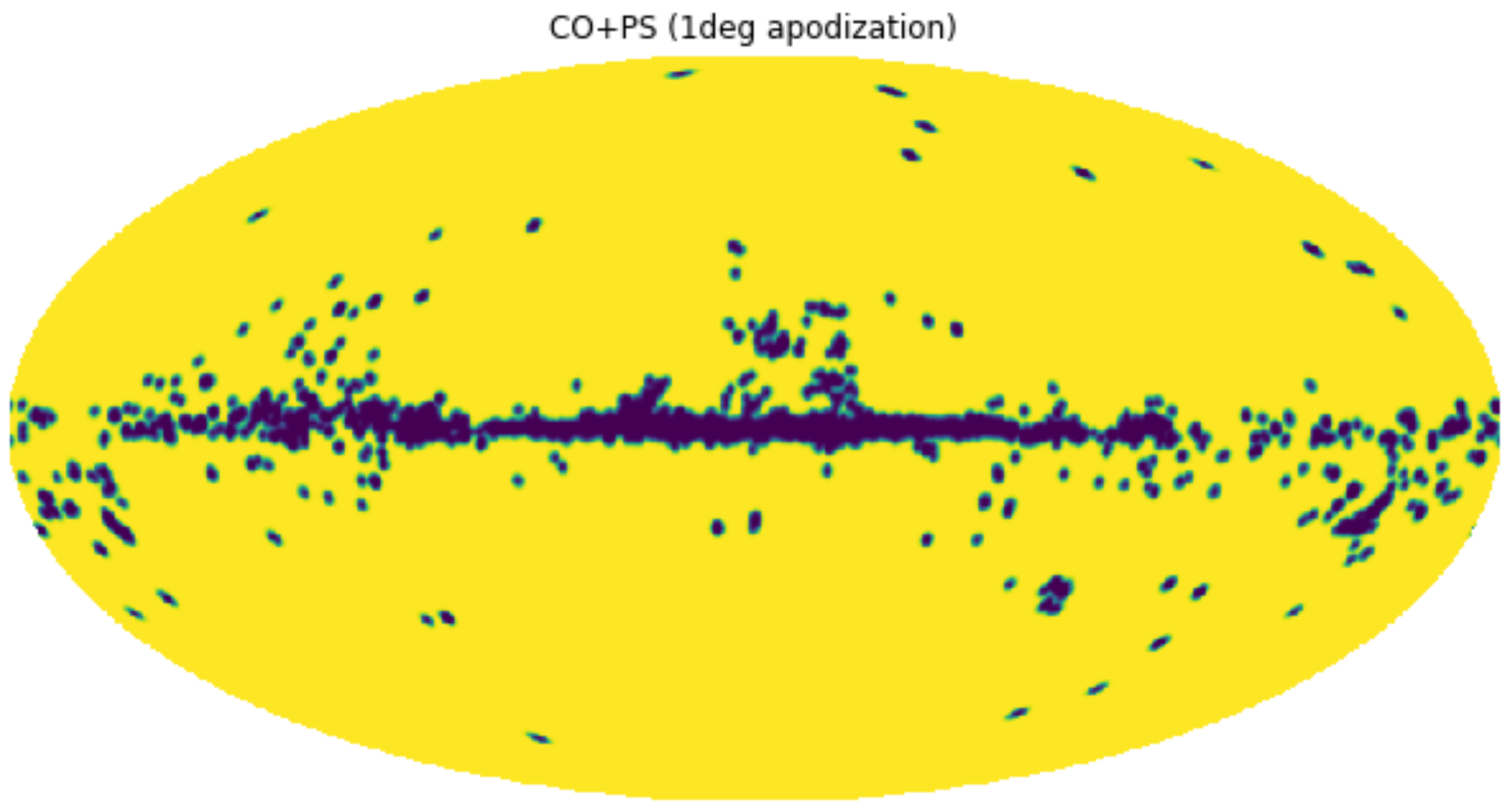
- **In our Universe, CMB EE is much greater than BB. This makes CMB sensitive to birefringence.**
- This is the typical figure that you find in talks and lectures on CMB.
  - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the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



This is the EB power spectrum (WMAP+Planck)

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

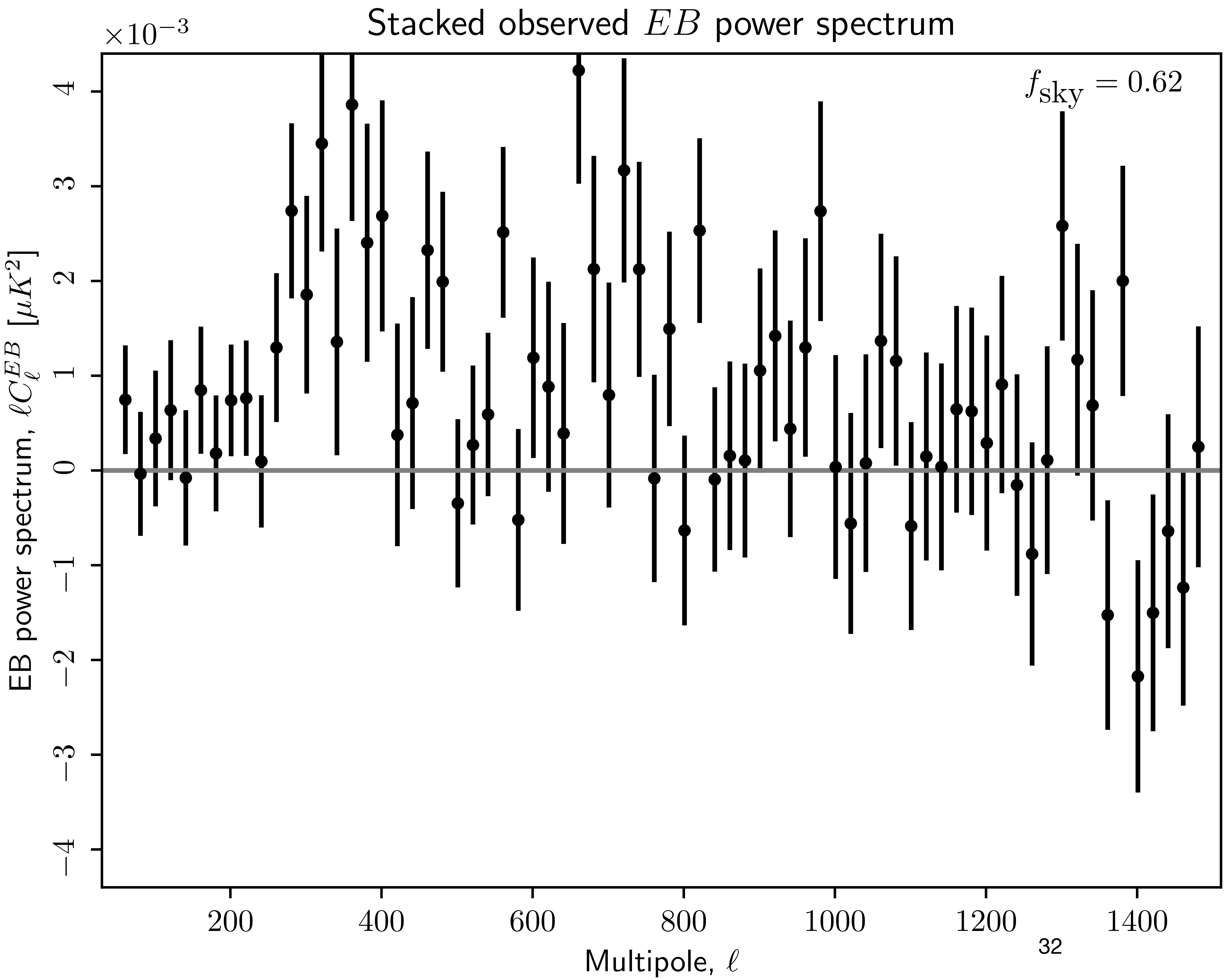


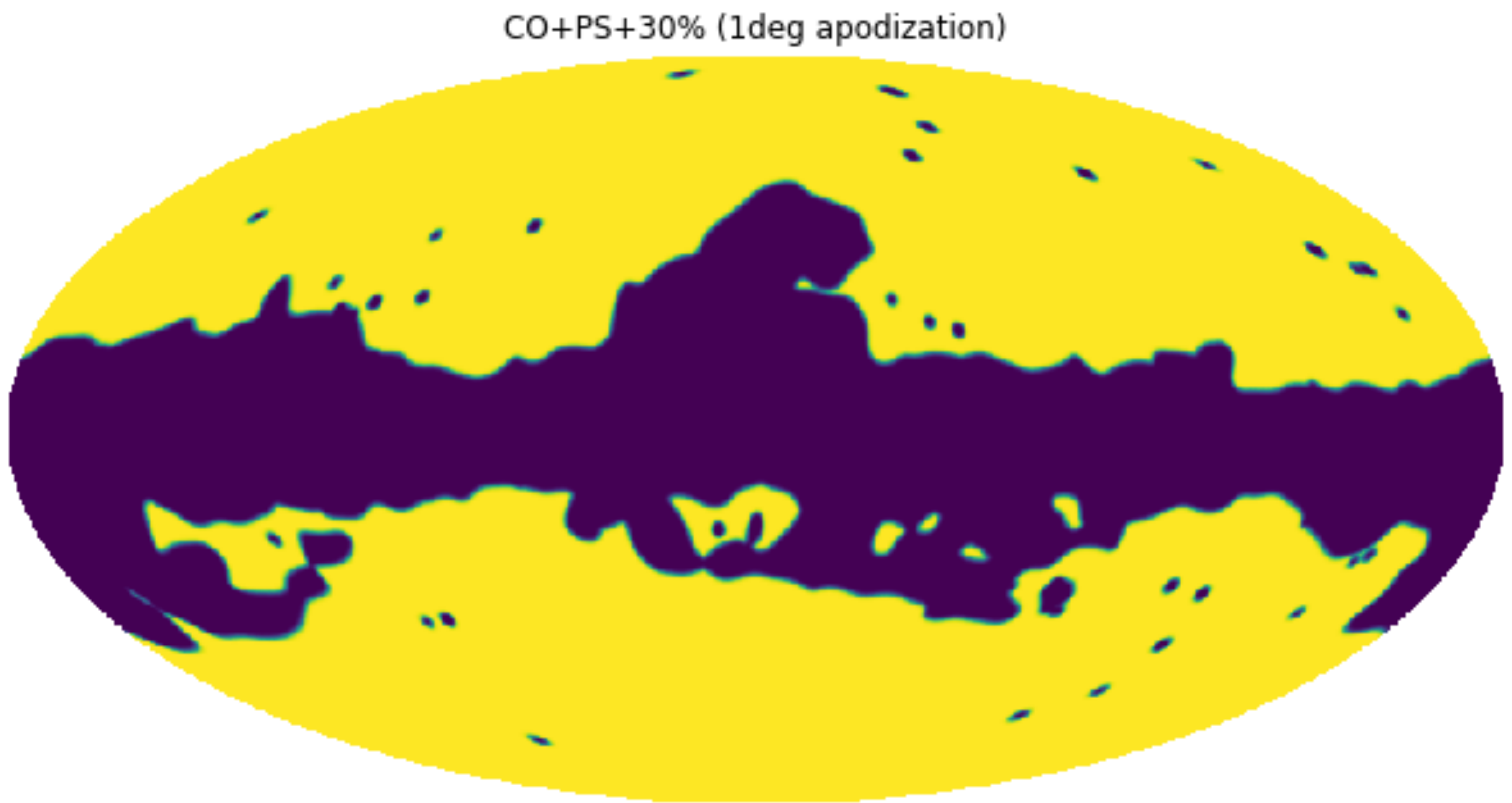


- χ^2 = 125.5 for DOF=72
    - Unambiguous signal of something!

This is the EB power spectrum (WMAP+Planck)

Galactic plane removed (62% of the sky)

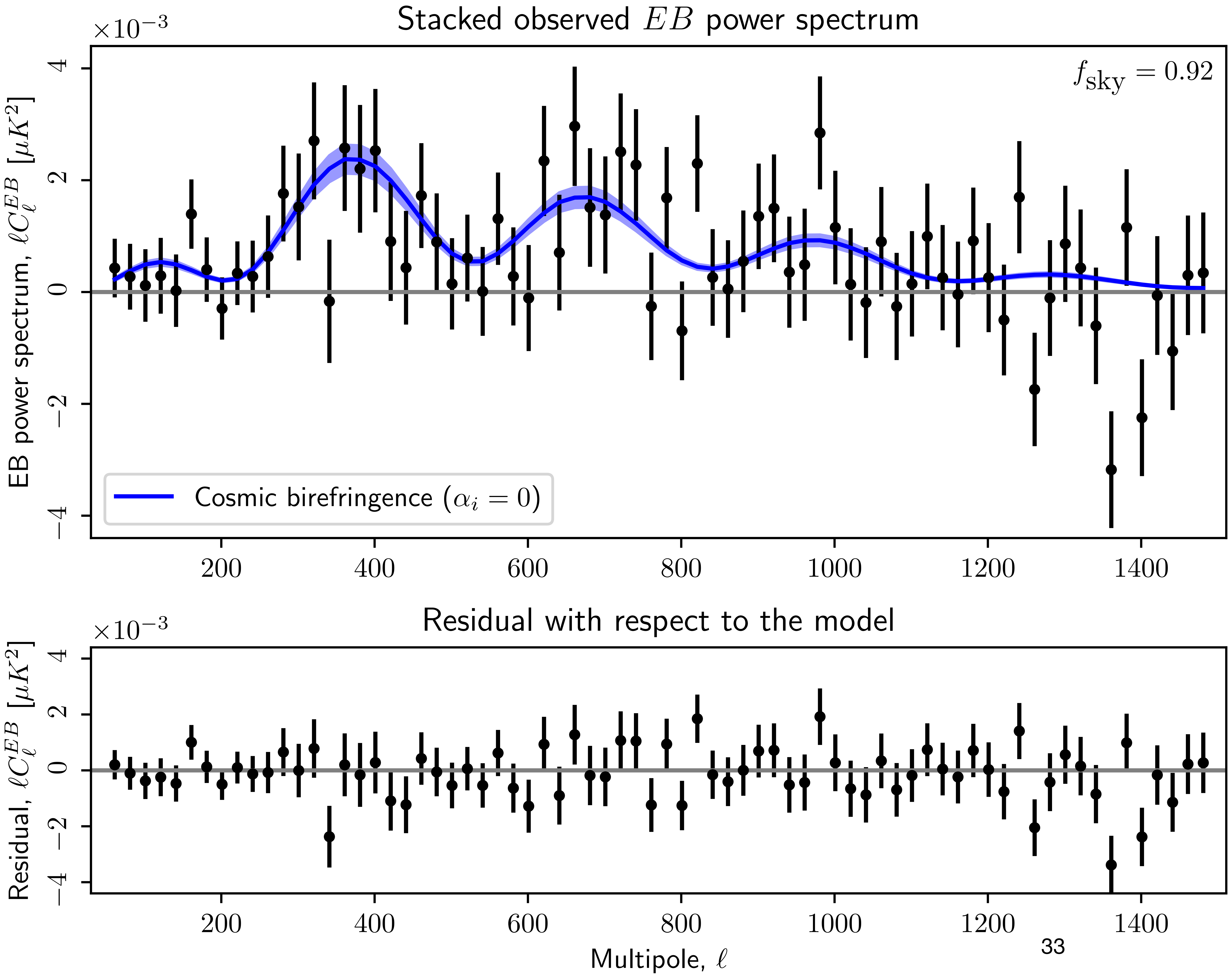


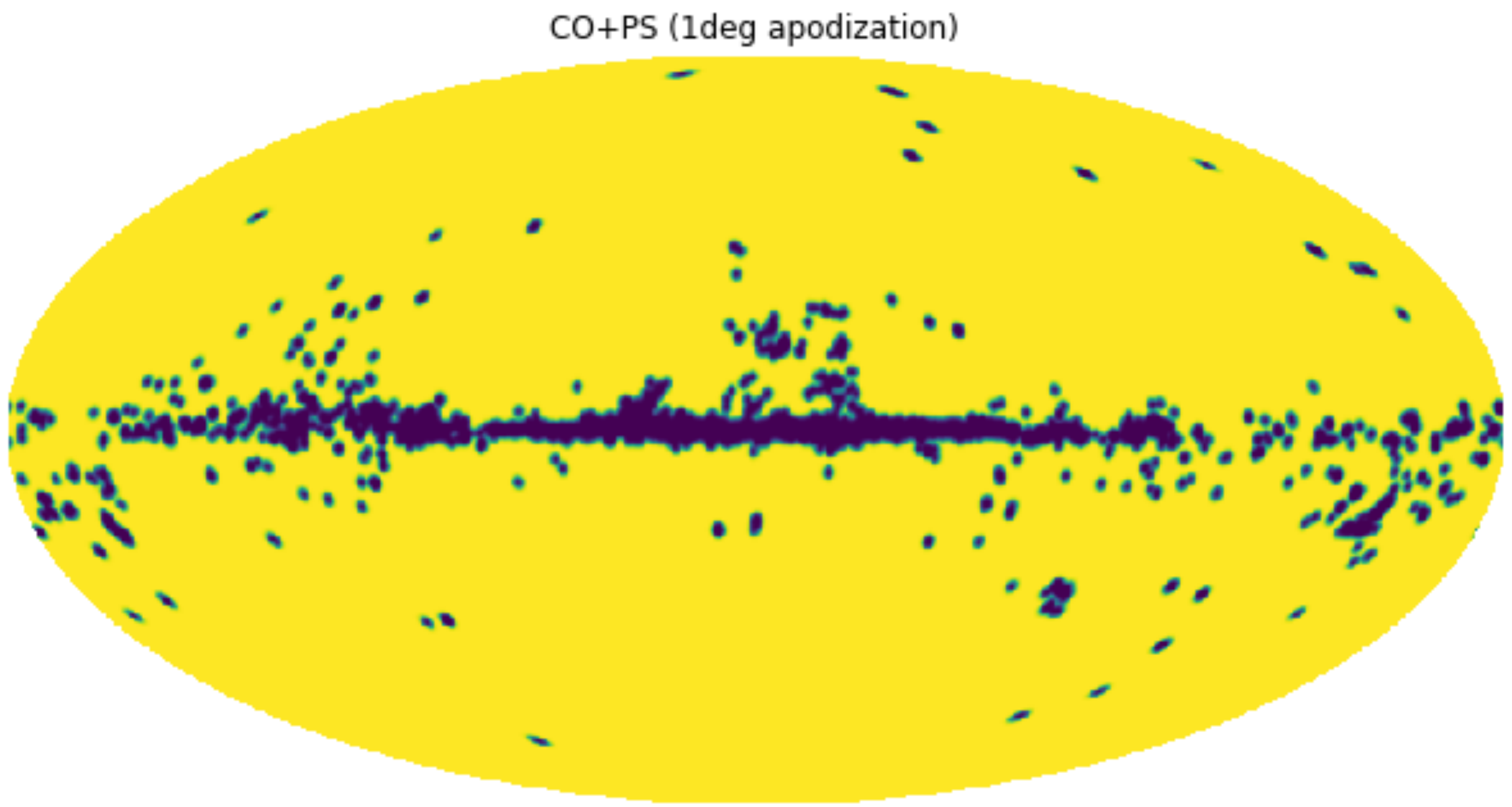


- χ^2 = 138.4 for DOF=72
  - The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

Cosmic Birefringence fits well(?)

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

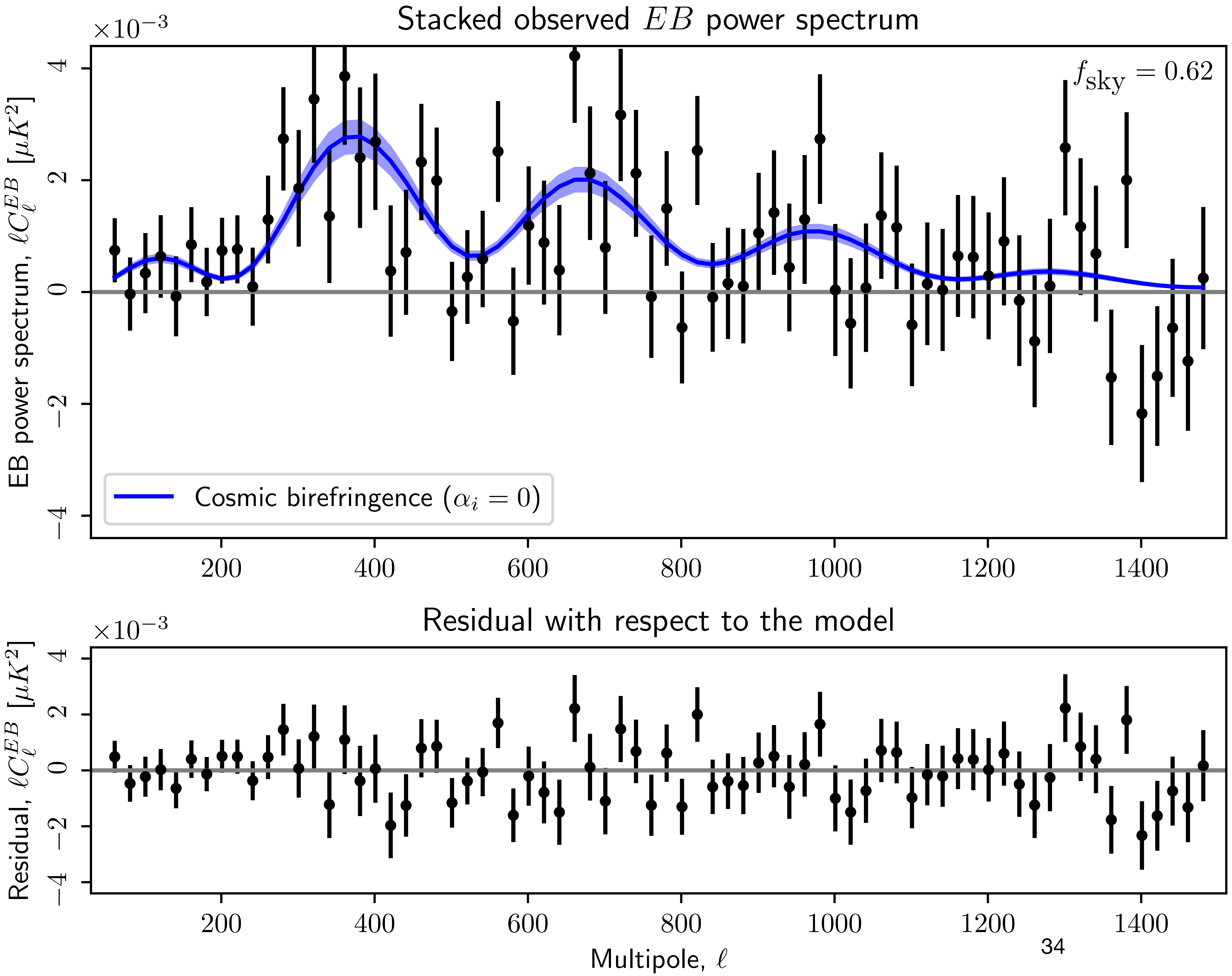


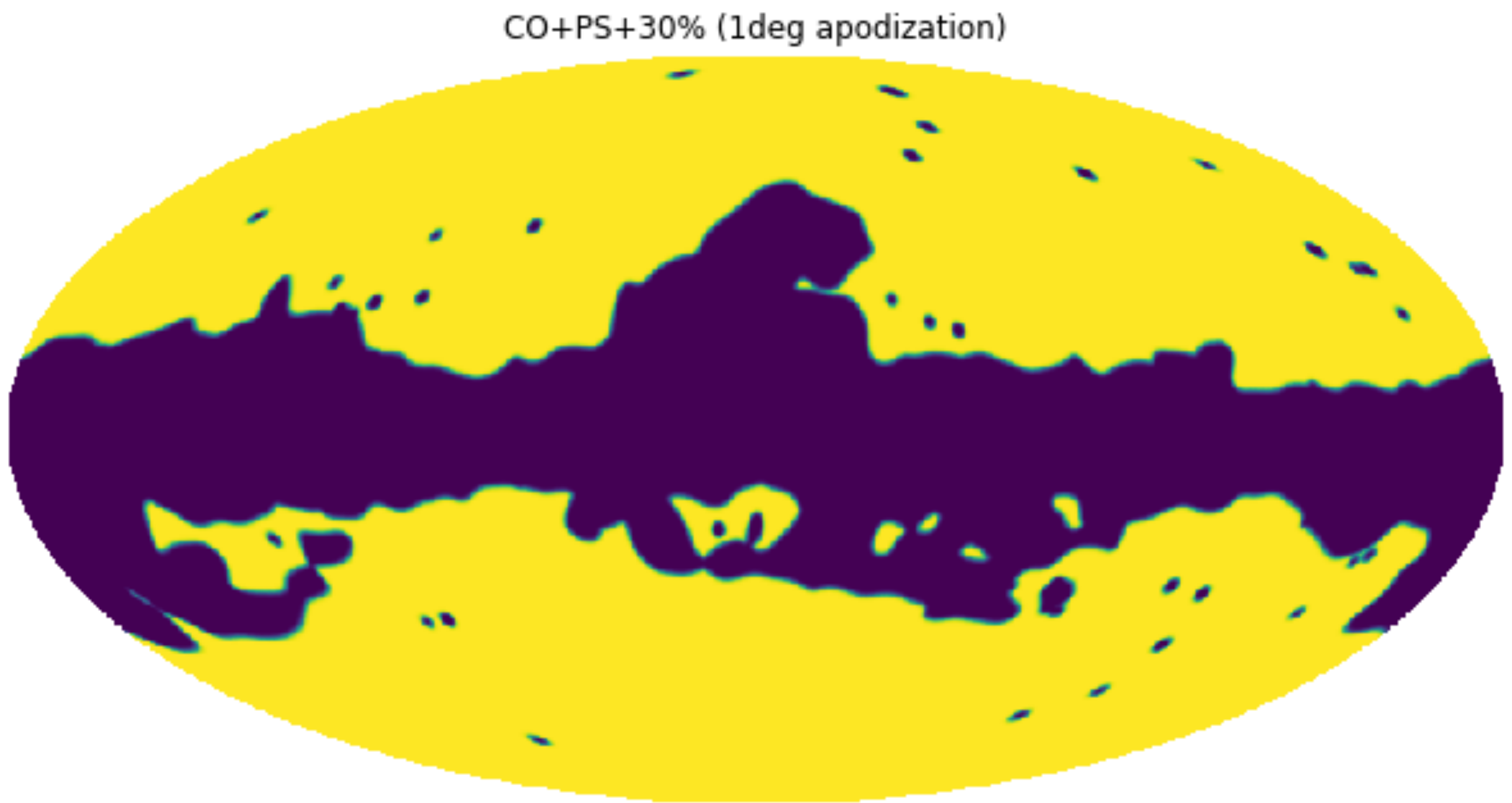


- β = 0.288 ± 0.032 deg
- $\chi^2 = 66.1$
  - Good fit! 9σ detection?

Cosmic Birefringence fits well(?)

Galactic plane removed (62% of the sky)



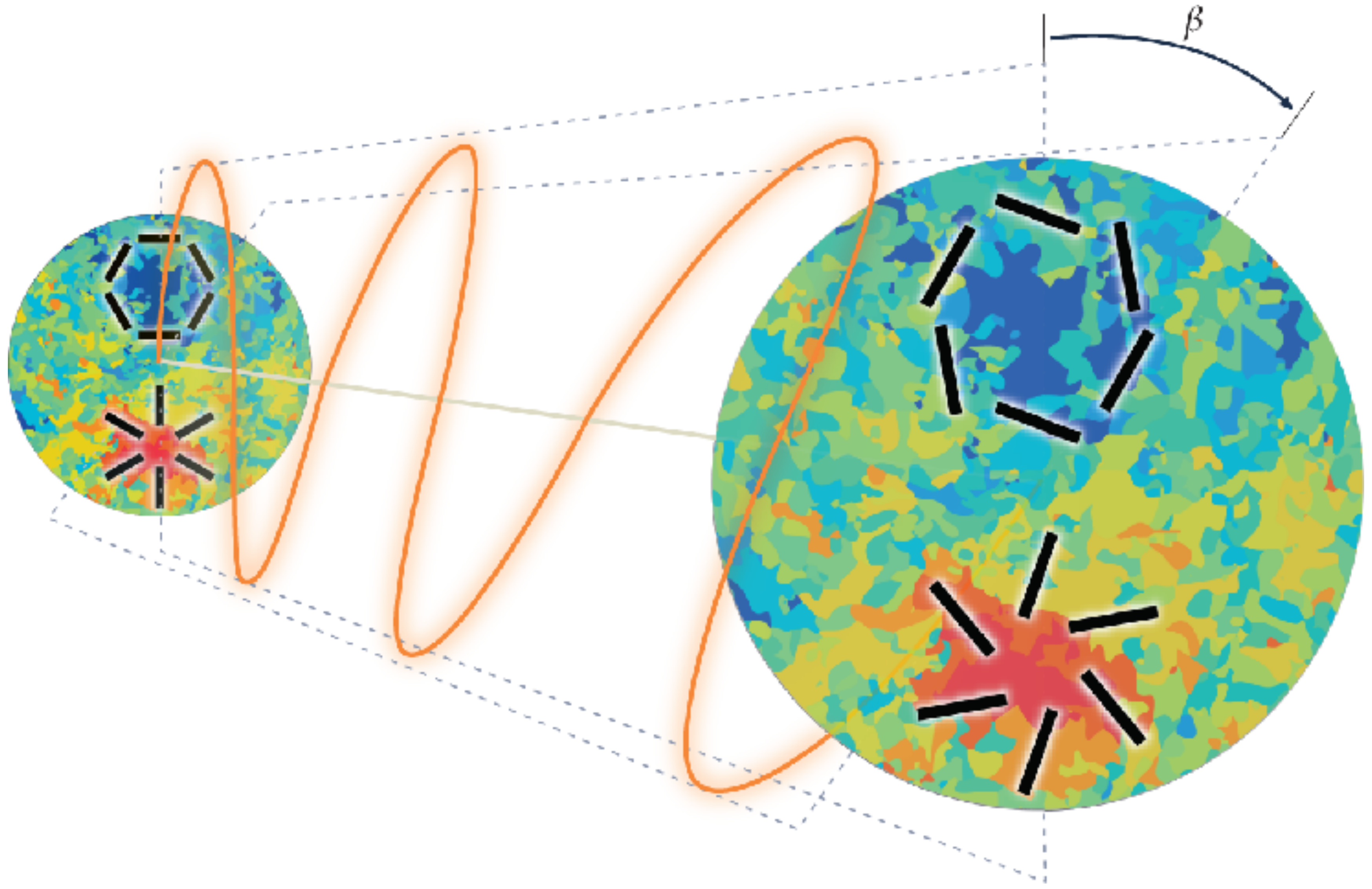


- $\beta = 0.330 \pm 0.035$ deg
- $\chi^2 = 64.5$
- Signal is robust with respect to the Galactic mask.

The Biggest Problem: Miscalibration of detectors

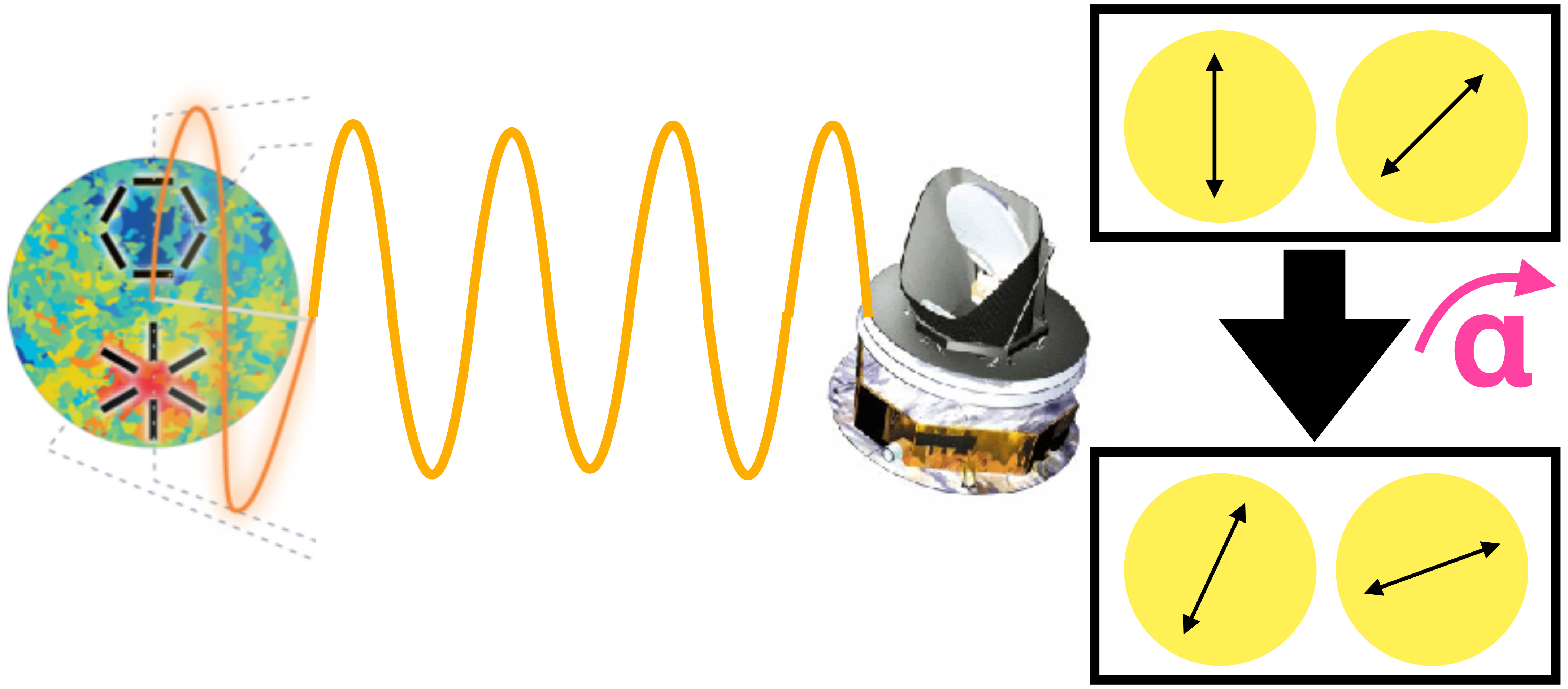
Impact of miscalibration of polarisation angles

Cosmic or Instrumental?



OR

Polarisation-sensitive
detectors on the focal plane



rotated by an angle “α”
(but we do not know it)

- 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)

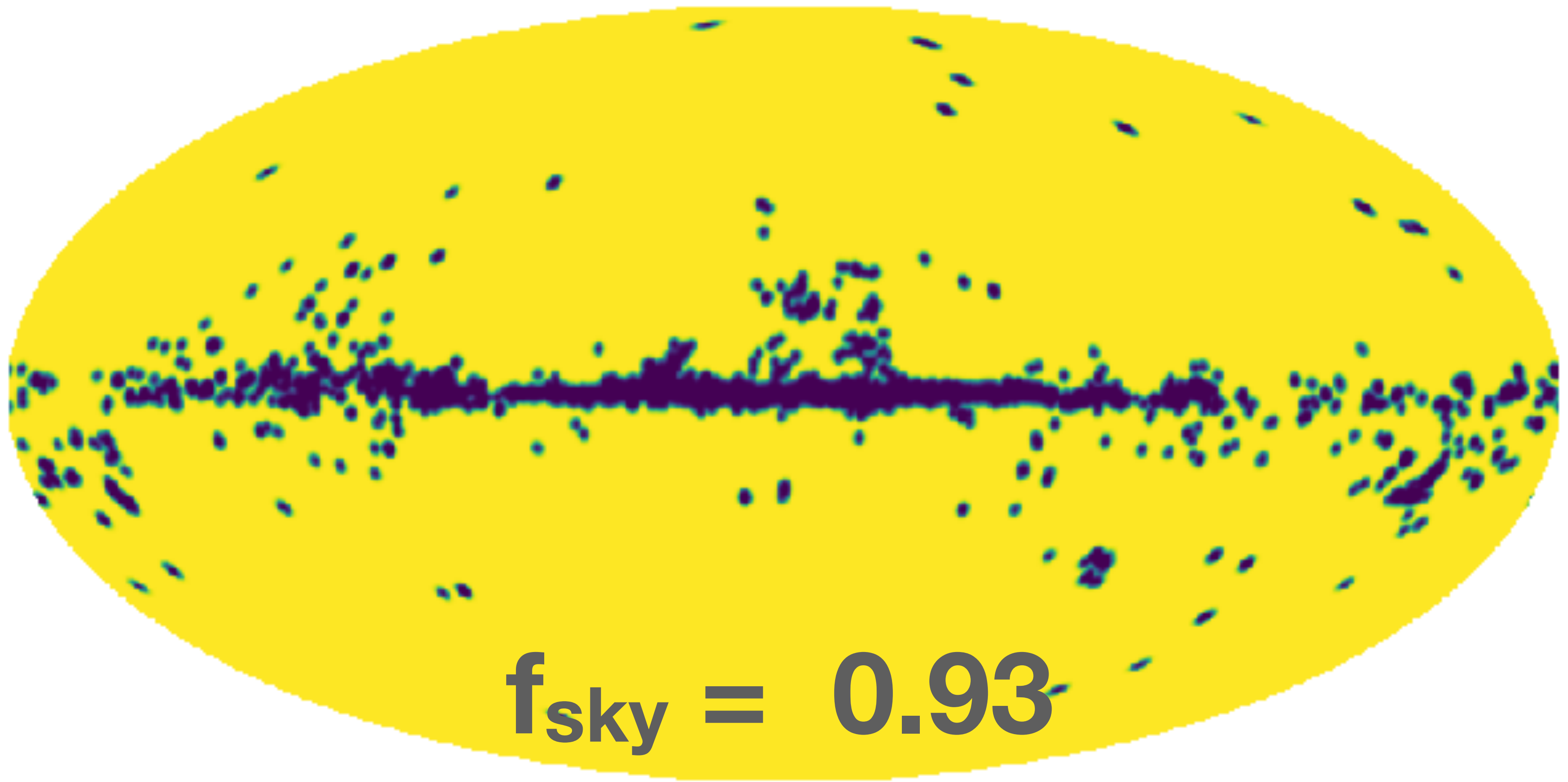
Why not yet discovered?

The past measurements

Now including the estimated systematic errors on α

- $\beta = -6.0 \pm 4.0 \pm$ **??** 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)

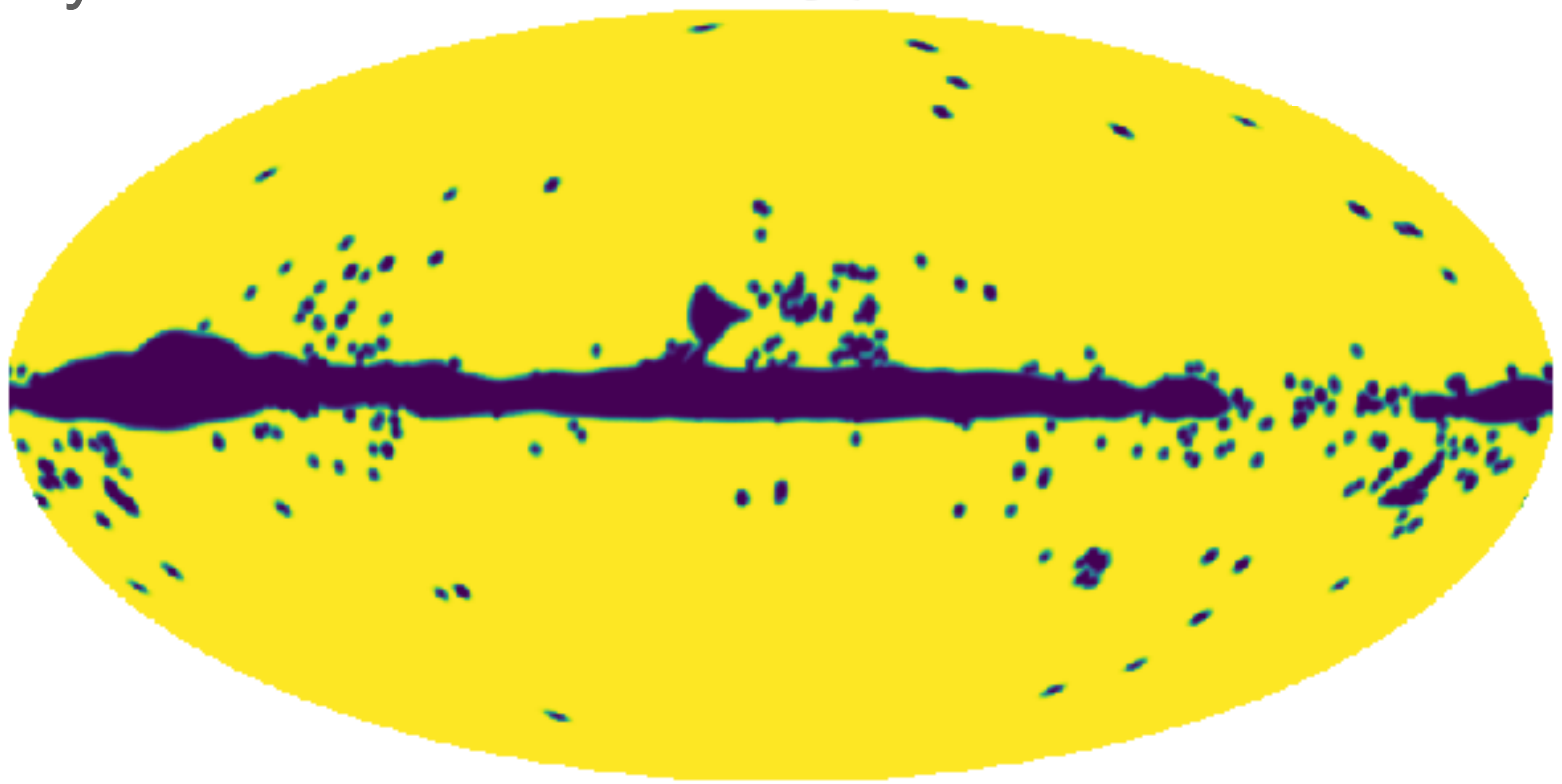
Uncertainty in the calibration of α has been the major limitation



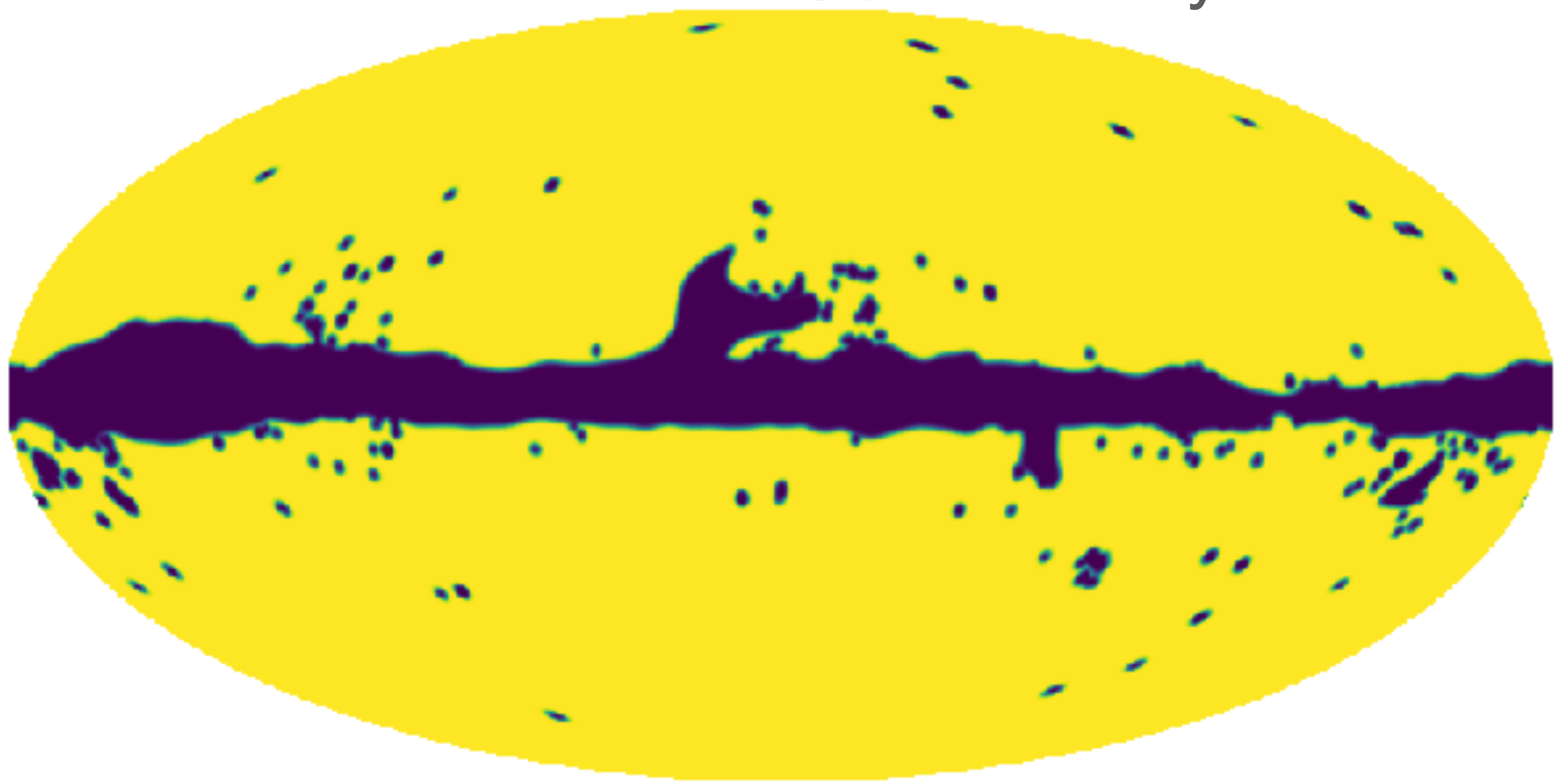
f_{sky} = 0.93

= nearly full sky

f_{sky} = 0.90

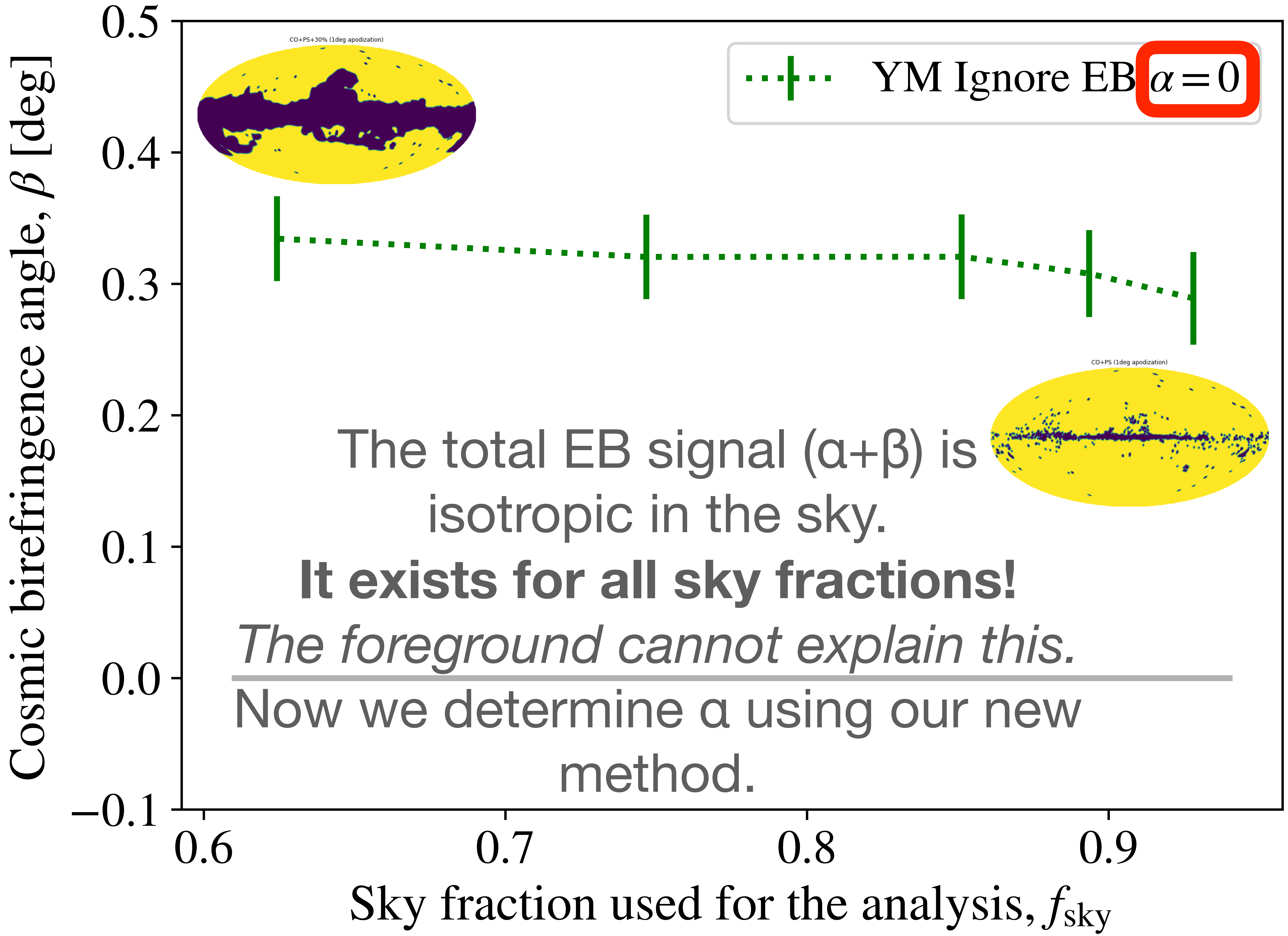


f_{sky} = 0.85



f_{sky} = 0.75

f_{sky} = 0.63



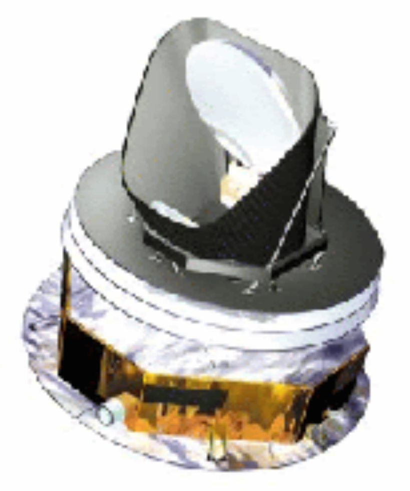
Cosmic birefringence angle, β [deg]
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.6
0.7
0.8
0.9
Sky fraction used for the analysis, $f_{\rm sky}$
YM Ignore EB $\alpha=0$
CO+PS+30% (1deg apodization)
CO+PS (1deg apodization)
The total EB signal (α+β) is isotropic in the sky.
It exists for all sky fractions!
The foreground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

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

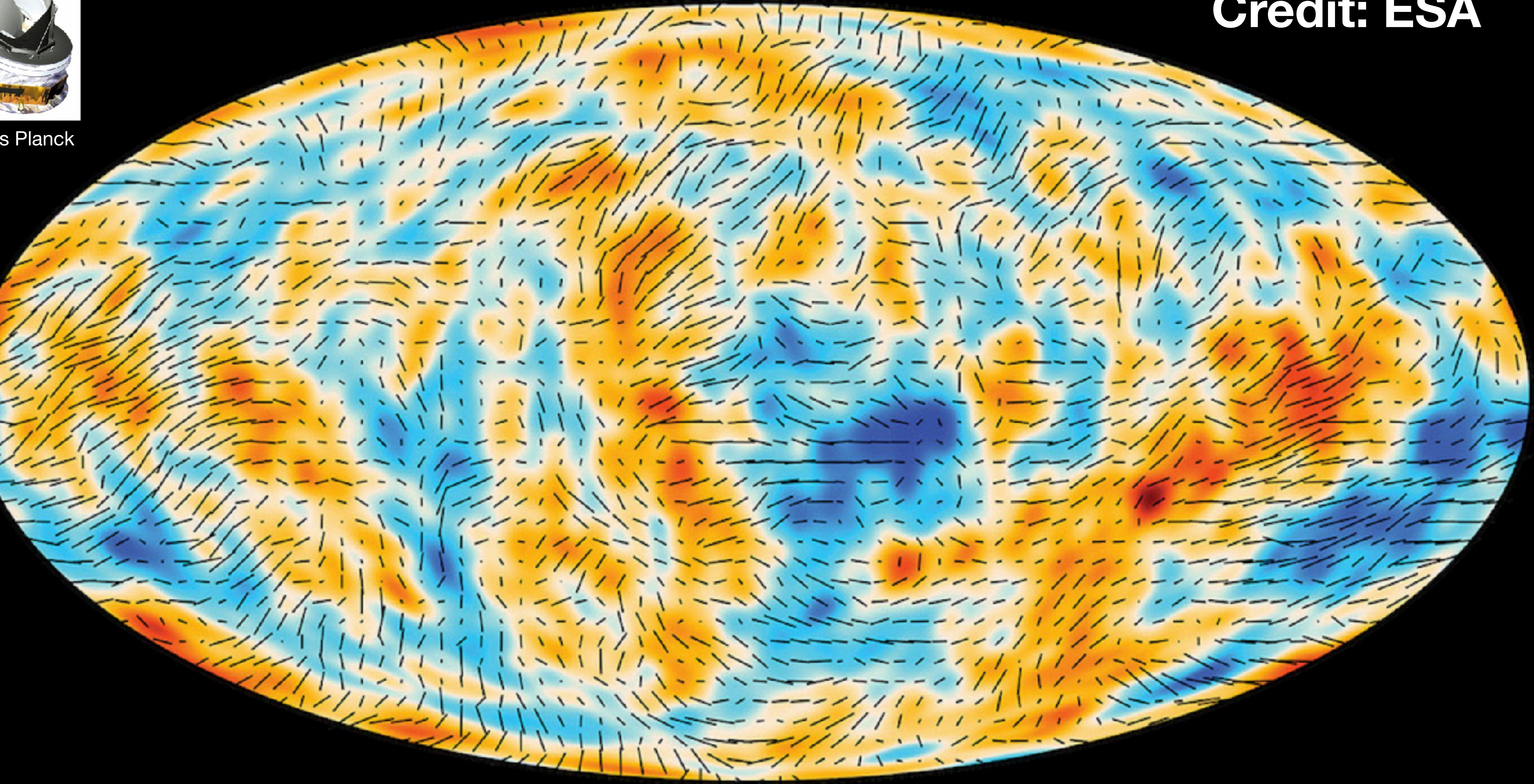
Credit: ESA

ESA's Planck

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


ESA's Planck

Credit: ESA

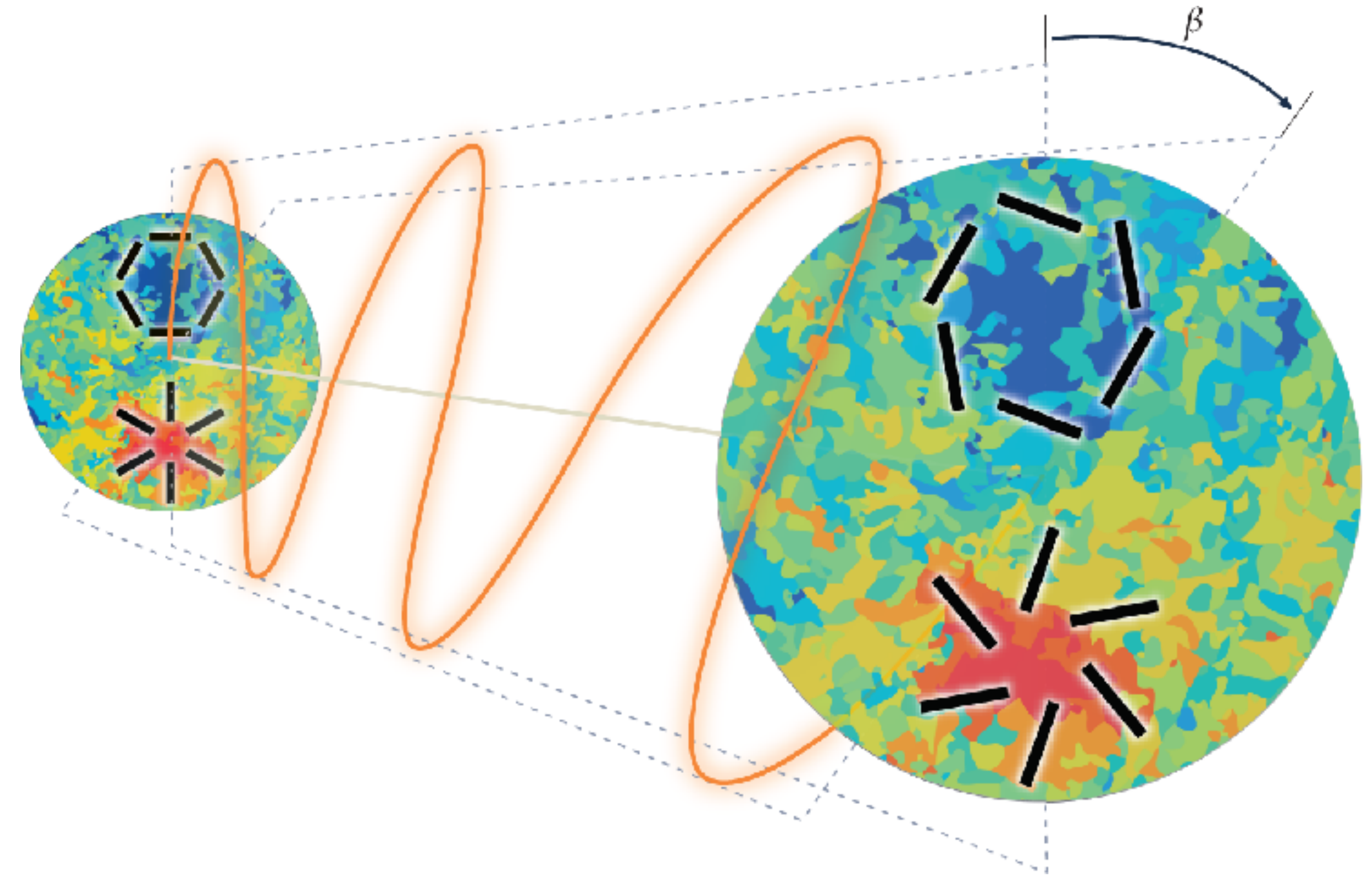


Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Searching for the birefringence

Including the miscalibration angle



- **<u>Idea:</u>** *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!

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

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

noise

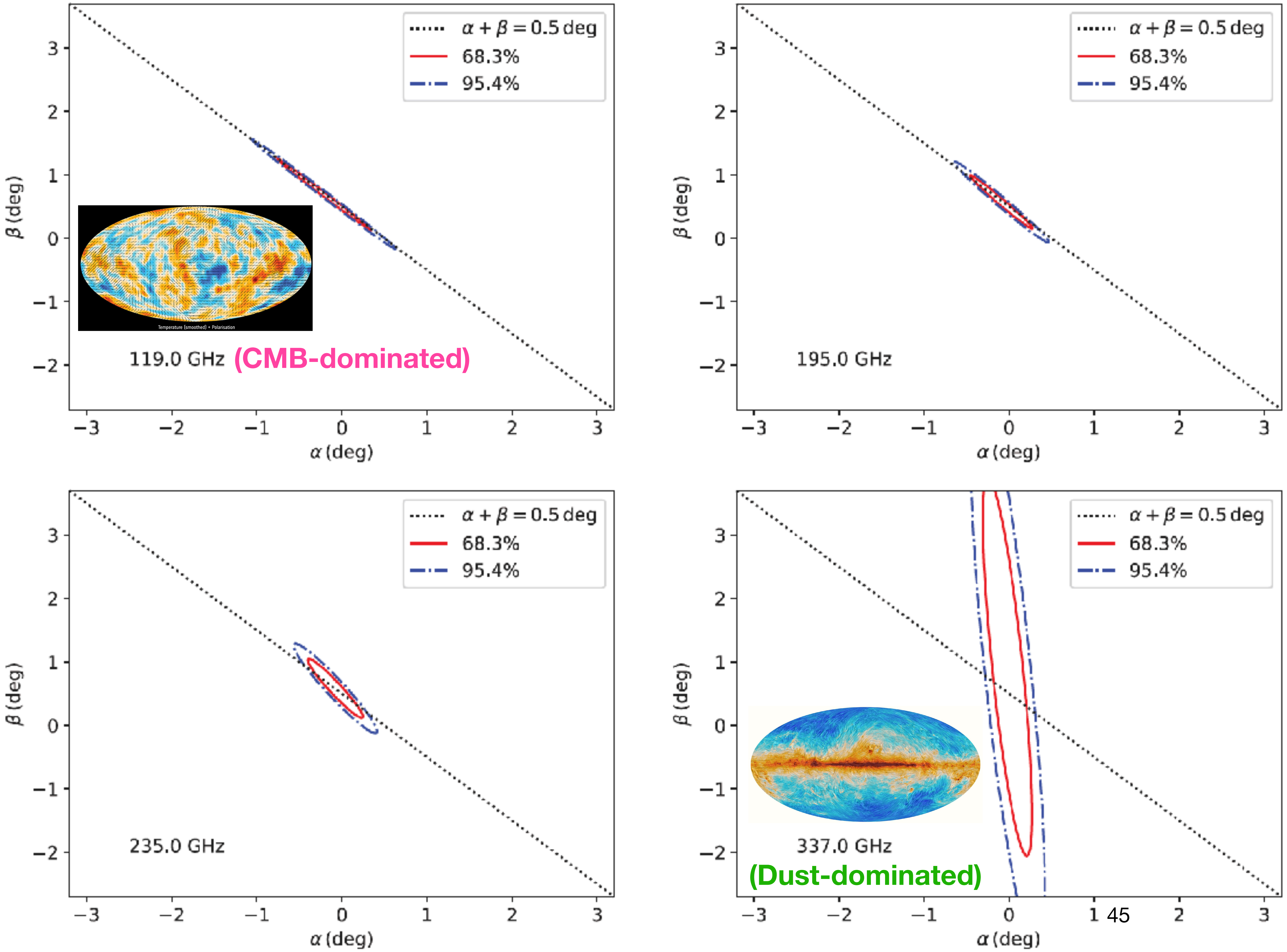
- Thus,

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

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

How does it work?

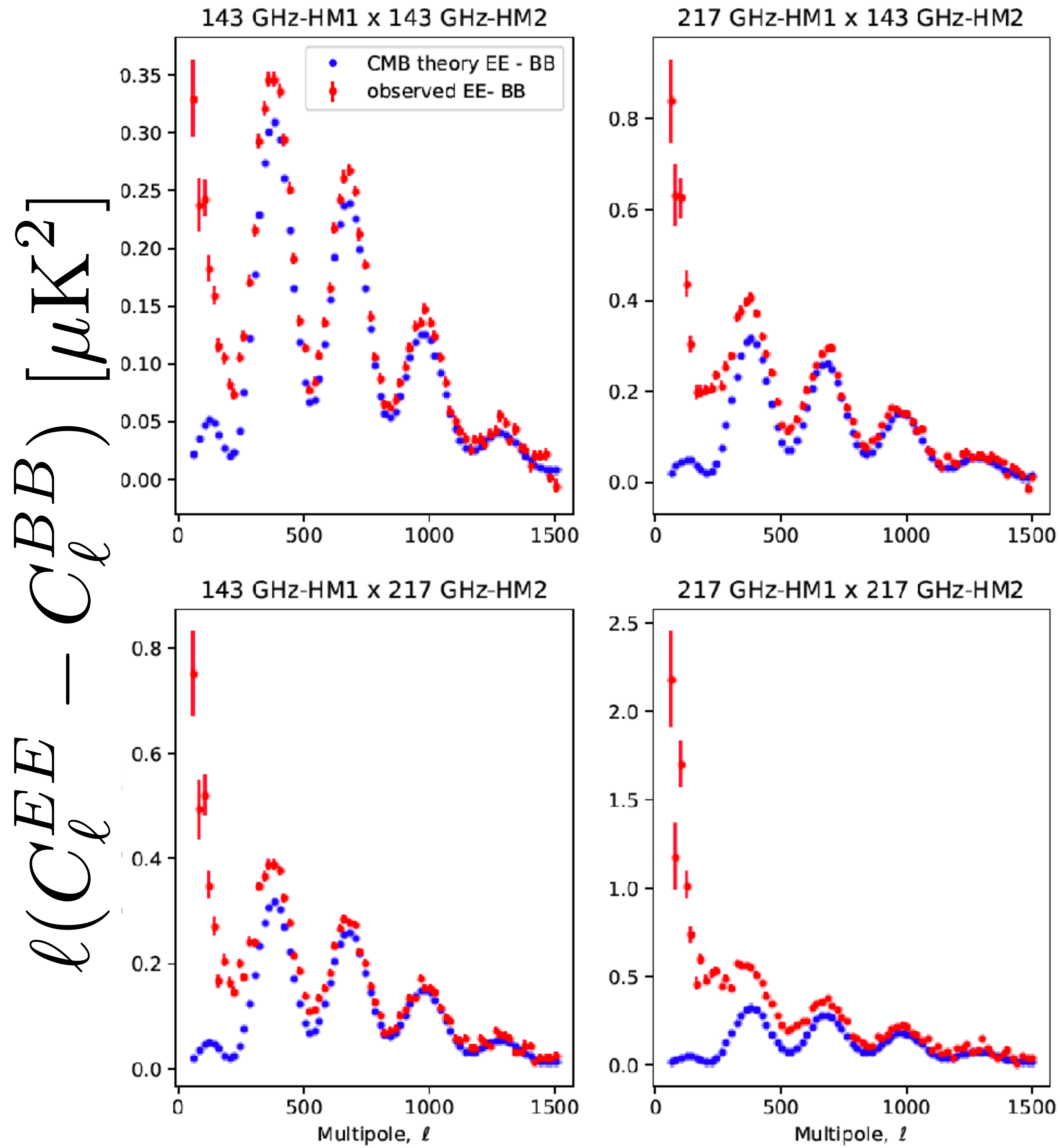
Simulation of future CMB data (LiteBIRD)



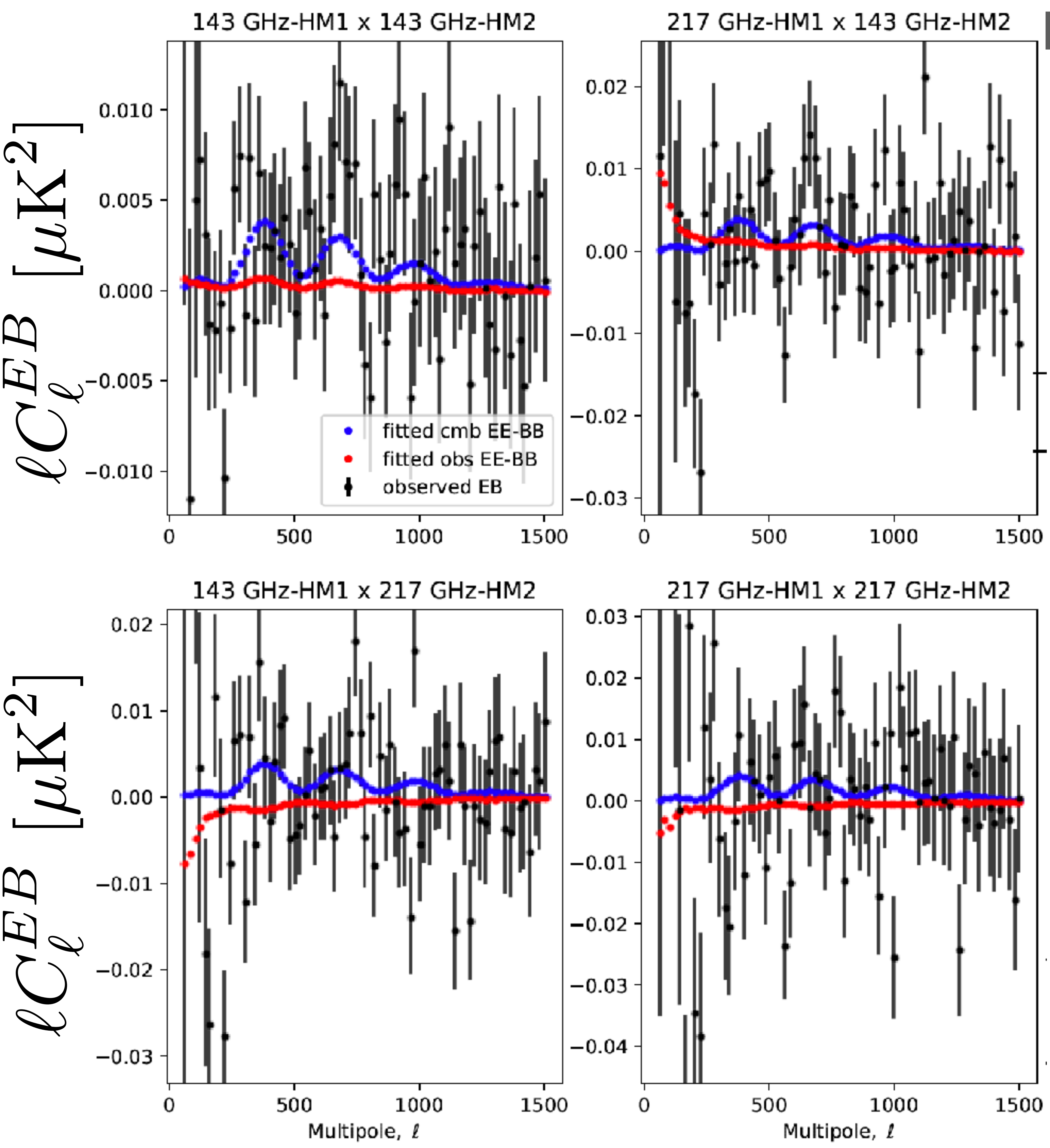
- When the data are dominated by CMB, the sum of two angles, α+β, is determined precisely.
  - This is the diagonal line.
- The foreground determines α with some uncertainty, breaking the degeneracy. Then σ(β) ~ σ(α) because σ(α+β) << σ(α).
- When the data are dominated by the foreground, it can determine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

From Planck HFI Data (Minami & EK 2020)

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



- Can we see β 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)

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

- Can we see β 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)

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

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

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!

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):

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

Free l-dependent amplitude parameters

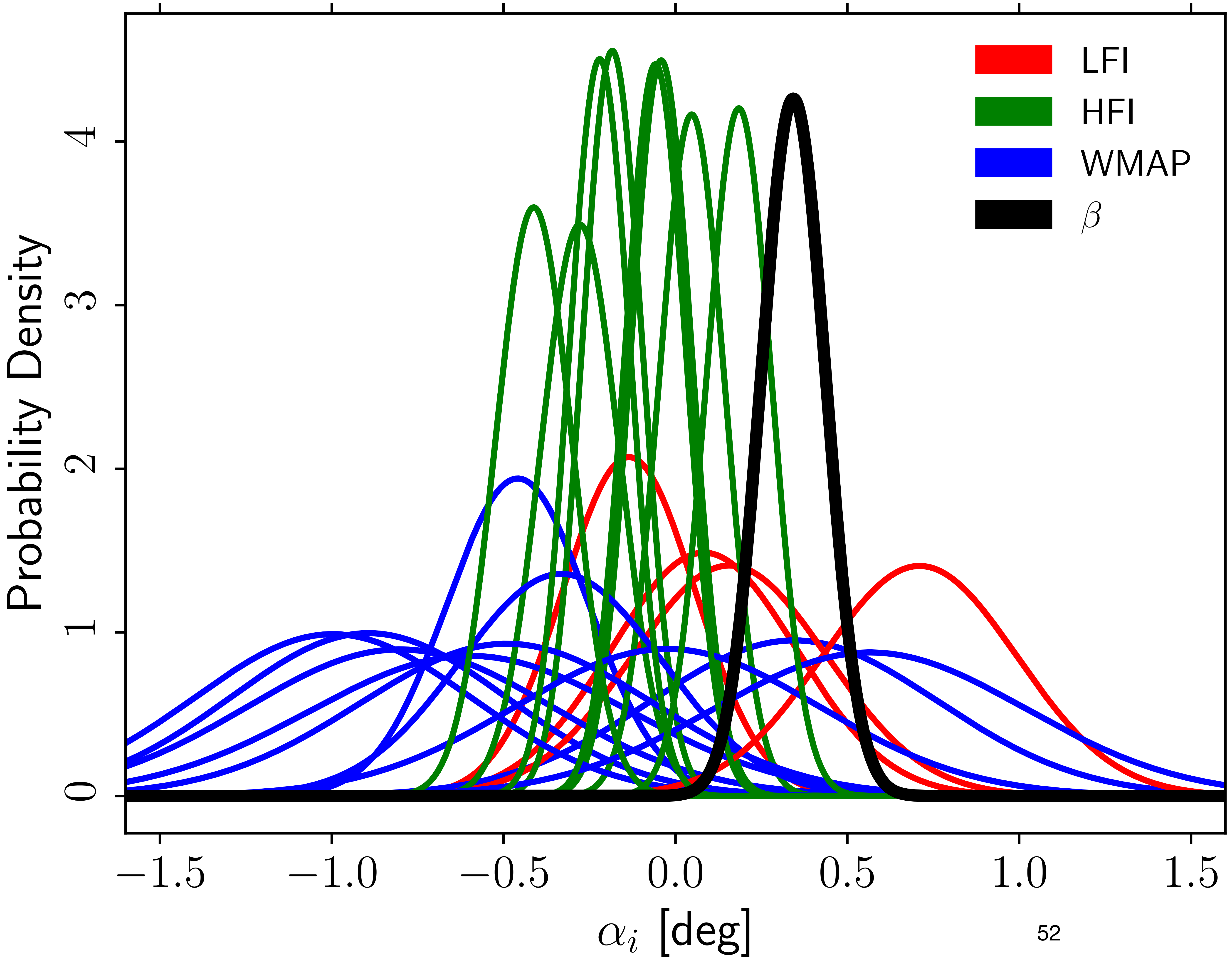
  - Then

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

for small angles.

Miscalibration angles (WMAP and Planck)

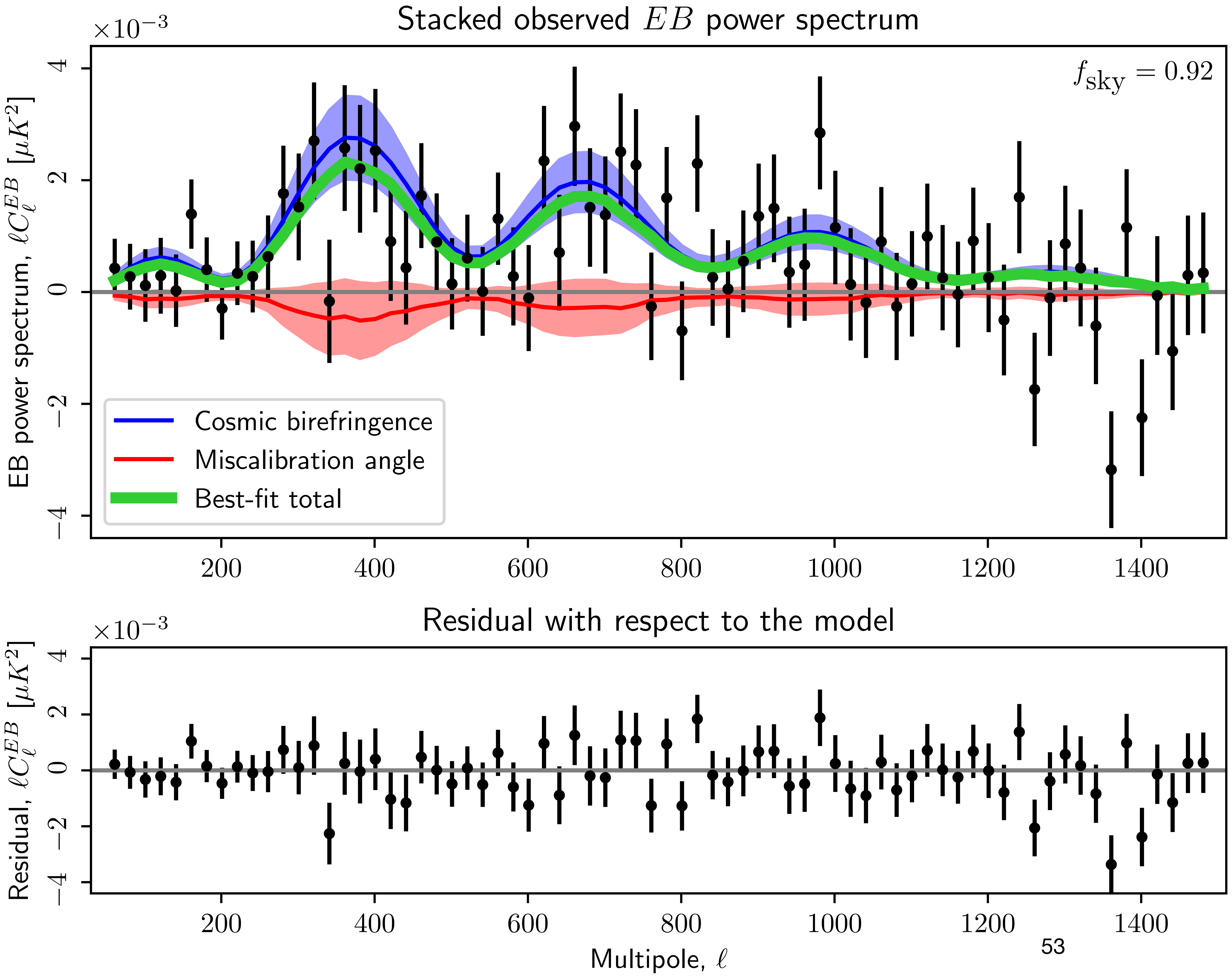
Nearly full-sky data (92% of the sky)

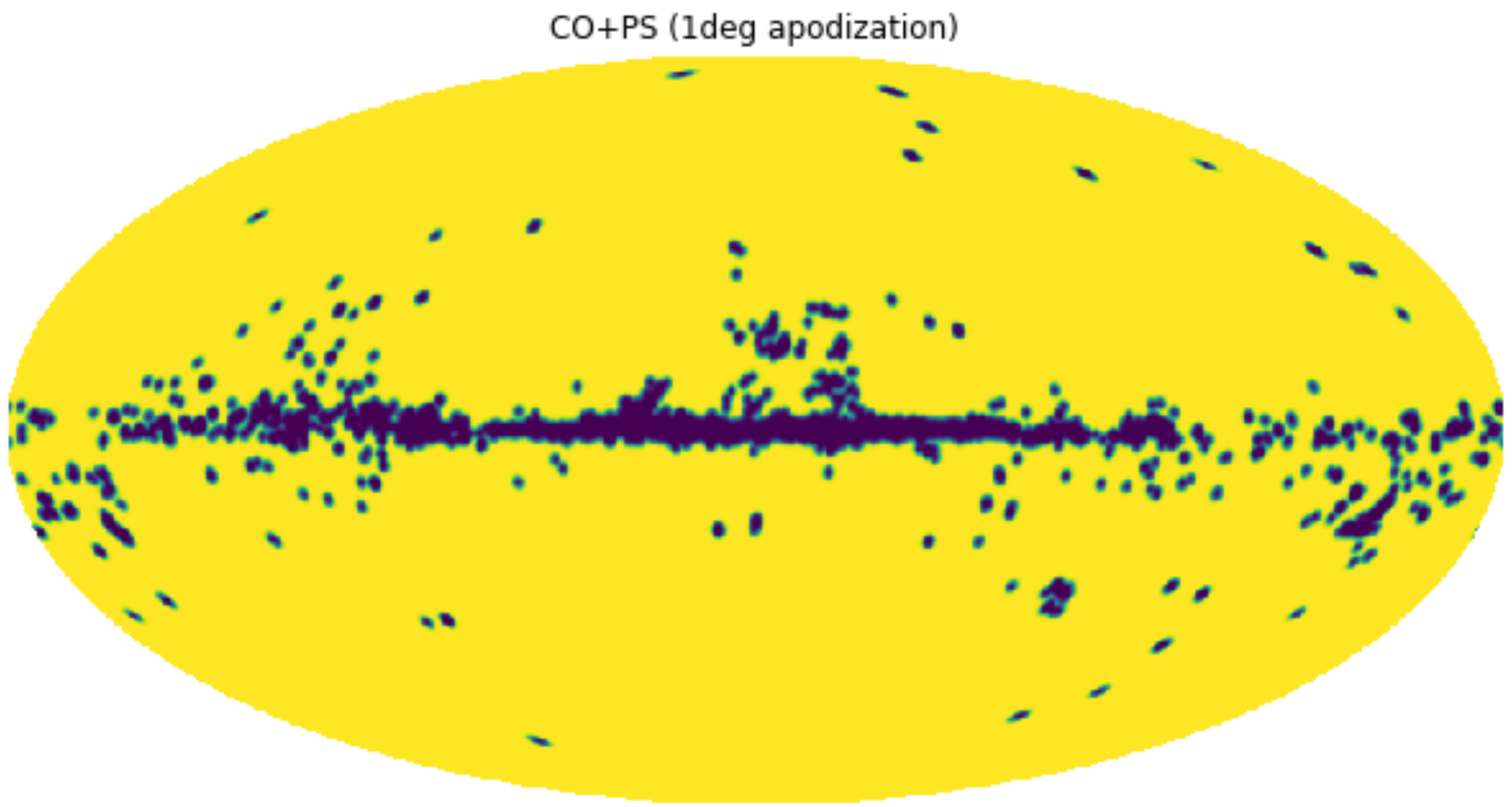


- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

Cosmic Birefringence fits well (WMAP+Planck)

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



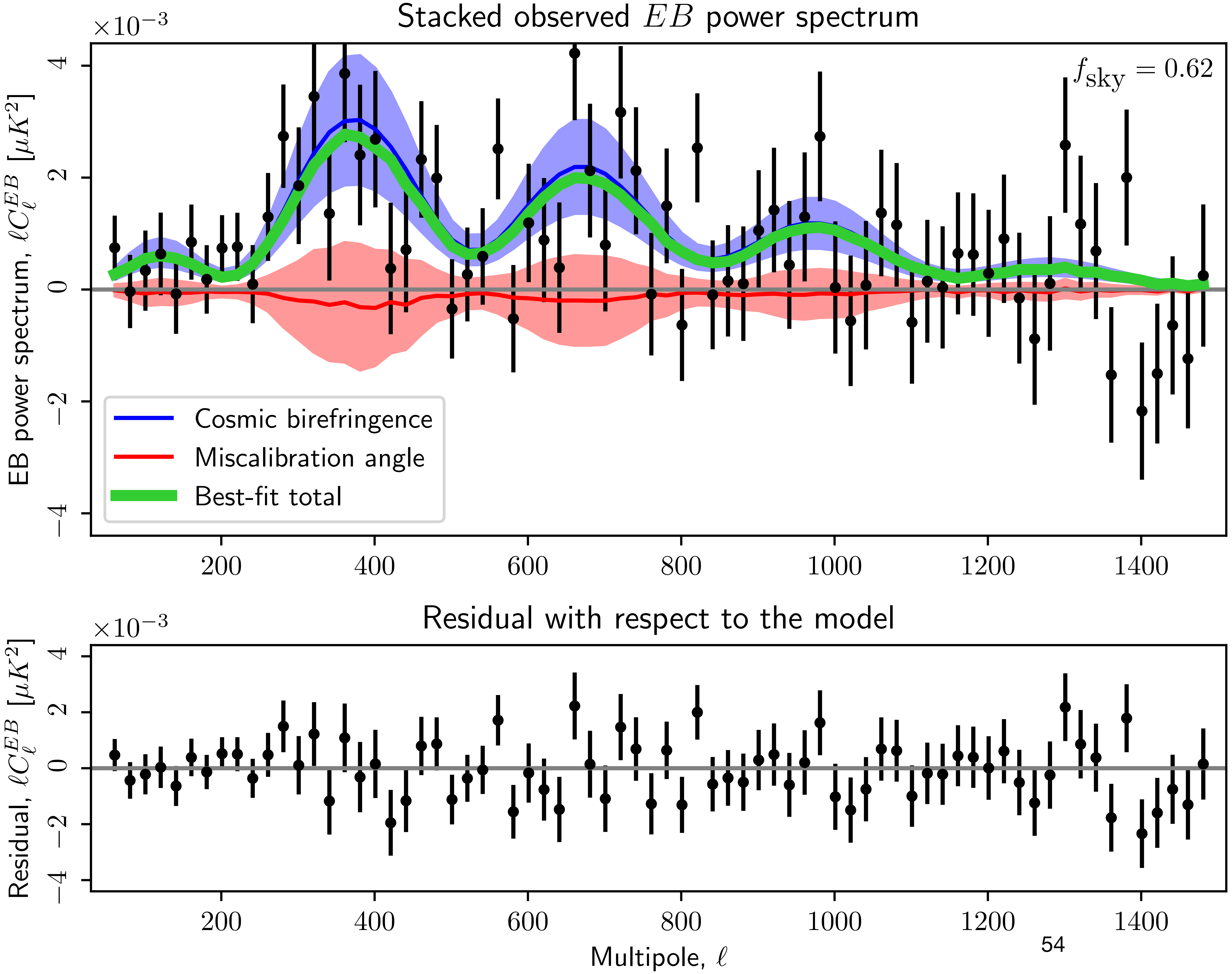


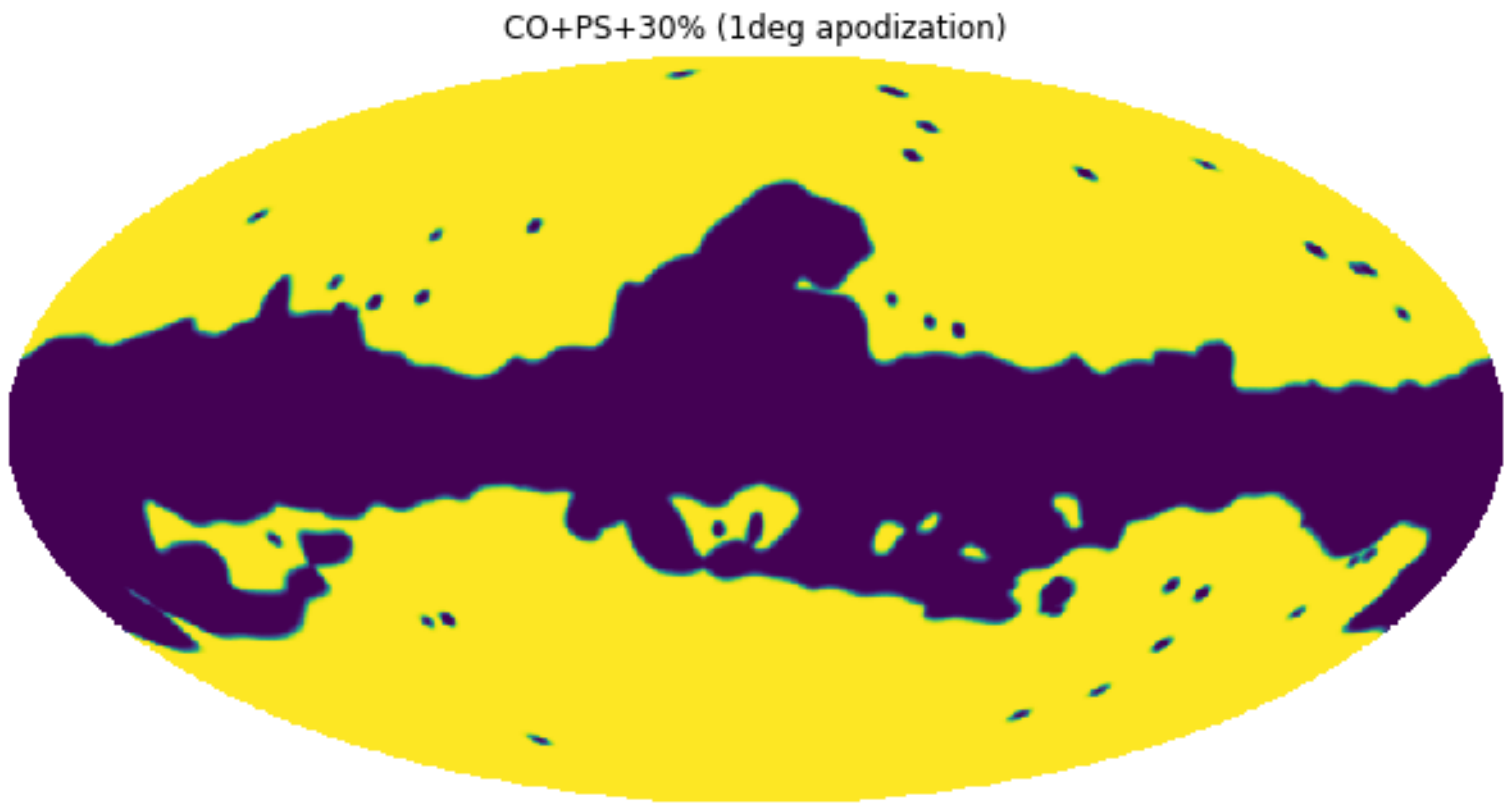
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- χ^2 = 65.3 for DOF=72

Eskilt & EK, arXiv:2205.13962

Cosmic Birefringence fits well (WMAP+Planck)

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

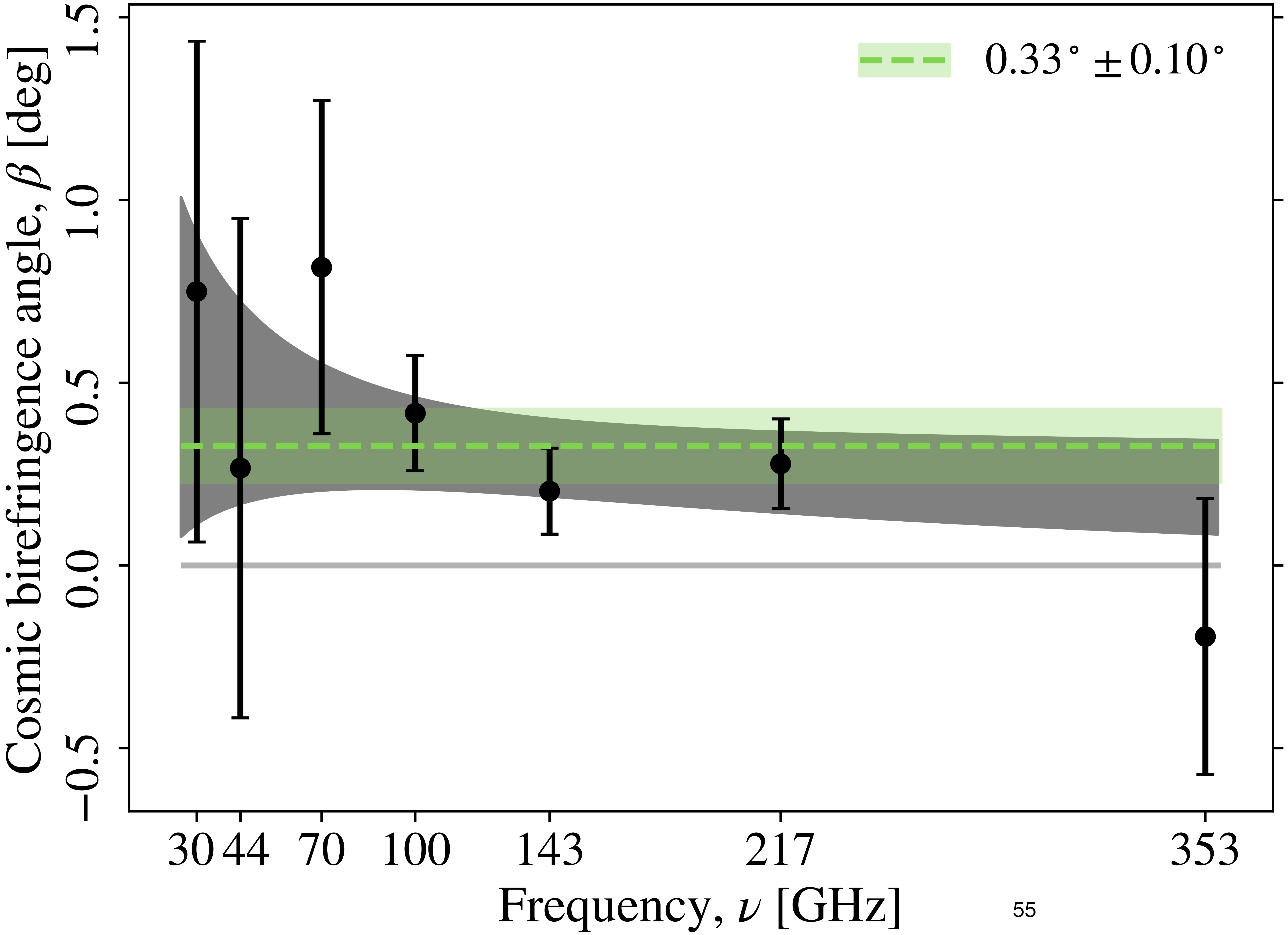




- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- χ^2 = 65.8 for DOF=72

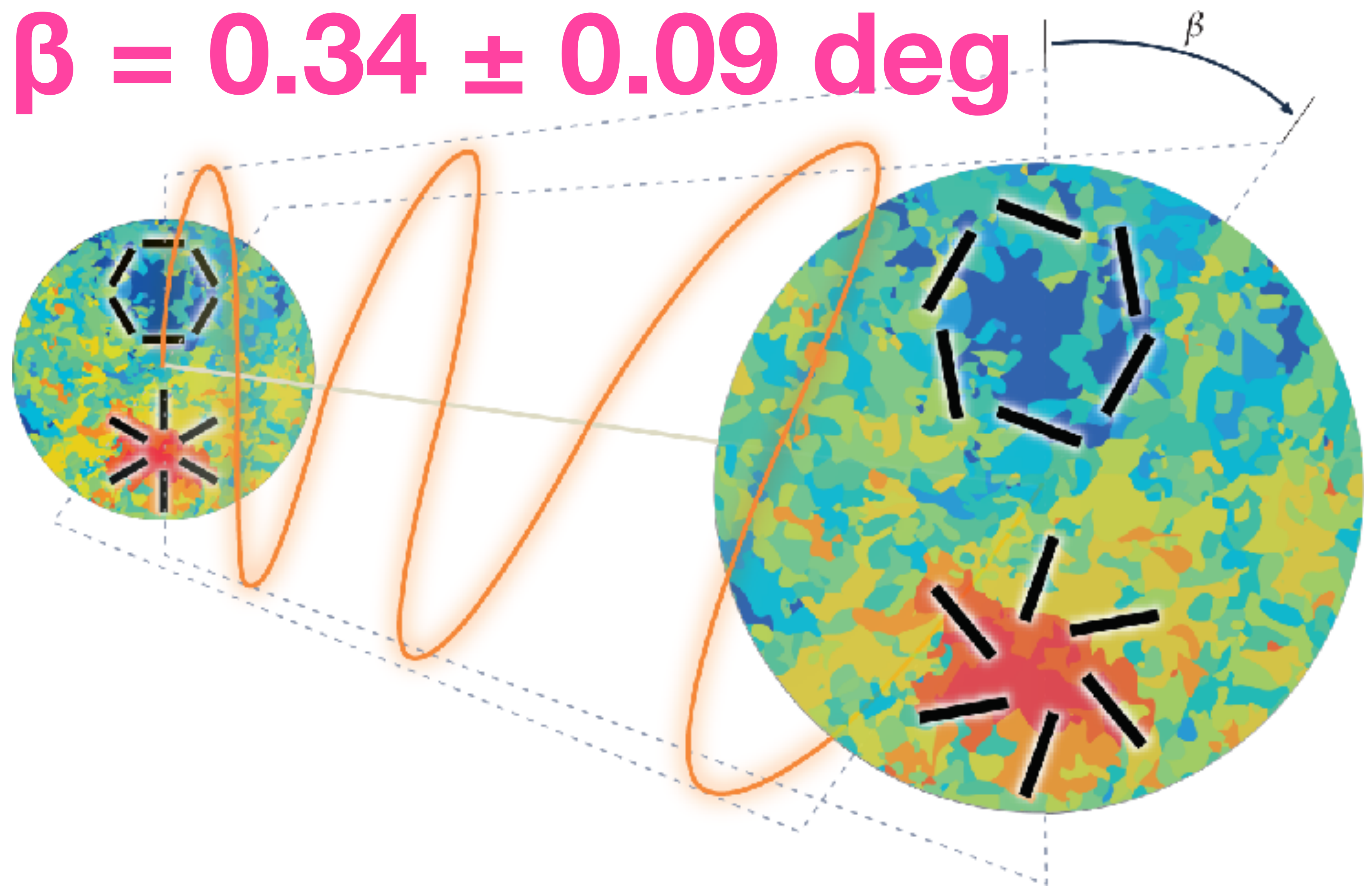
No frequency dependence is found

Consistent with the expectation from cosmic birefringence



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

Conclusion



β = 0.34 ± 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 (*Diego-Palazuelos et al., arXiv:2210.07655*).
- 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 something in the Planck data. No evidence for significant impacts of the Galactic foreground or the known systematics.**
  - But we keep investigating!

Relating EB to TB

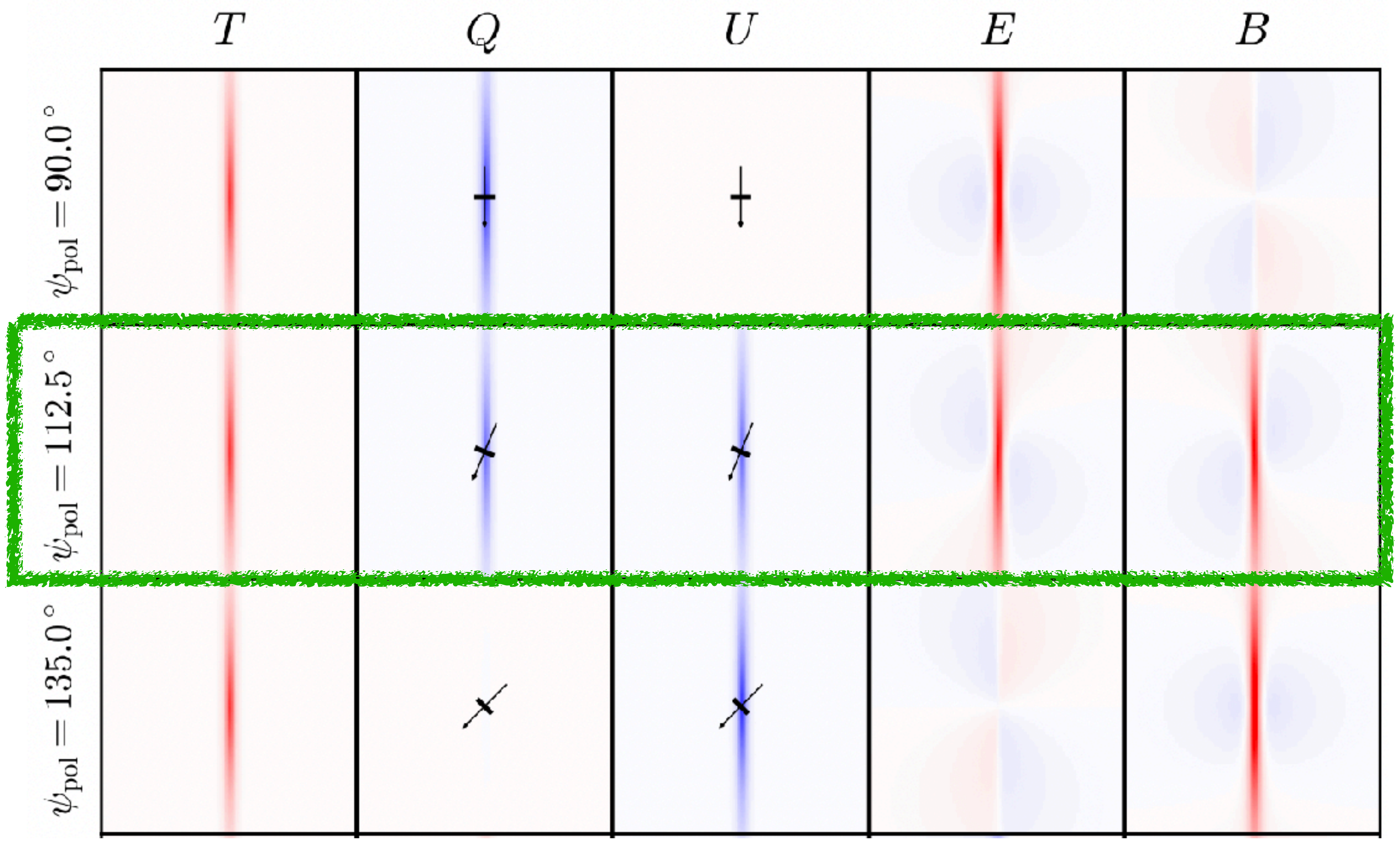
A physical justification for this assumption

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

- **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**