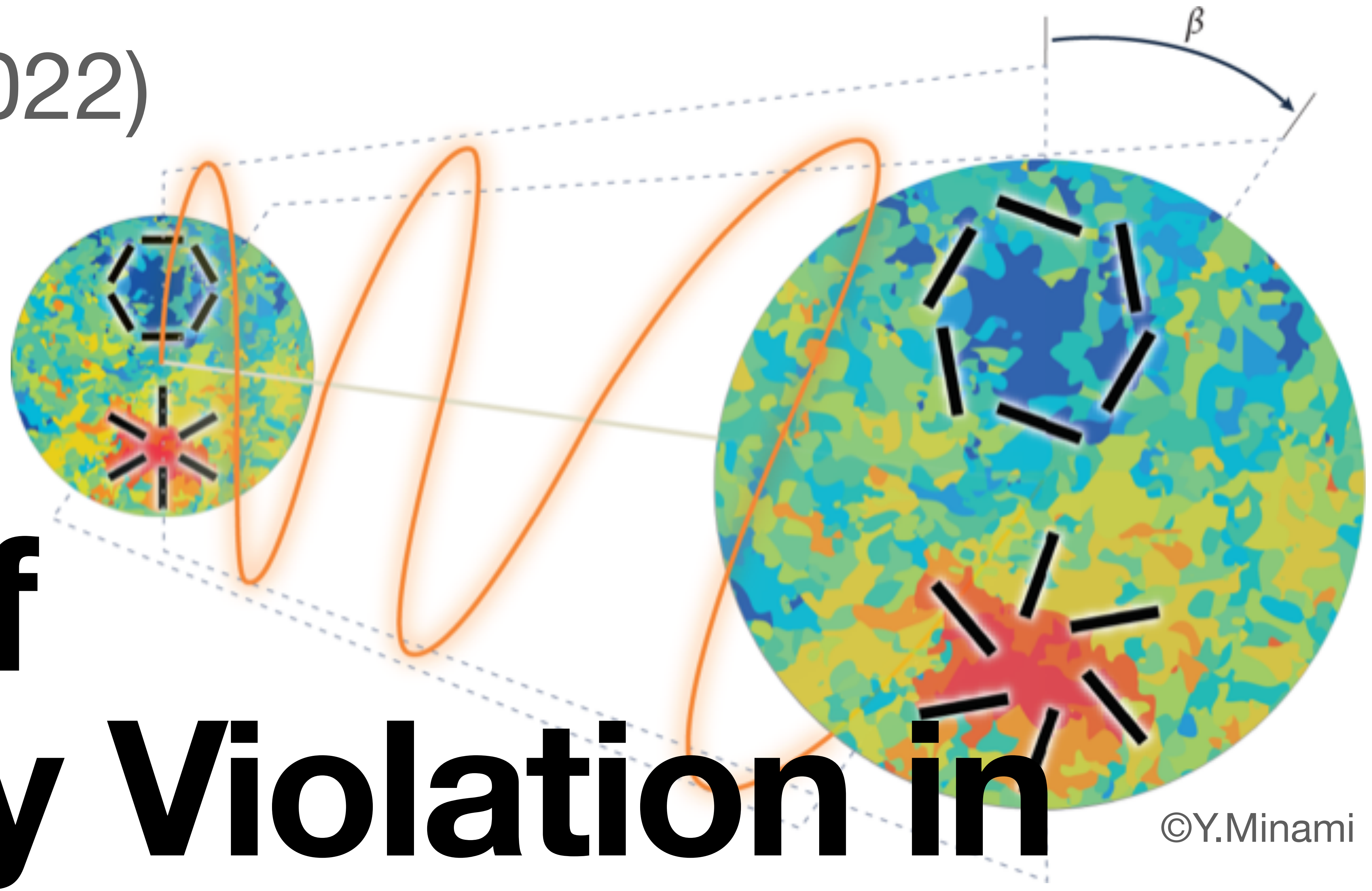
Reference: EK, Nature Rev. Phys. **4**, 452 (2022)



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A Tantalizing Hint of Cosmological Parity Violation in the Polarized Light of the CMB

Does the Universe distinguish between left and right?

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

HEP/Astro Results Forum, May 23, 2025

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

Overarching Theme

Let's find new physics!

- The current cosmological model (*ΛCDM*) **requires** new physics beyond the standard model of elementary particles and fields.
    - What is dark matter (*CDM*)?
    - What is dark energy (*Λ*)?

Overarching Theme

There are many ideas, but how can we make progress?

- The current cosmological model (*ΛCDM*) **requires** new physics beyond the standard model of elementary particles and fields.
  - What is dark matter (*CDM*)? => CDM, WDM, FDM, …
  - What is dark energy (*Λ*)? => Dynamical field, modified gravity, quantum gravity, …

New in cosmology!

Violation of parity symmetry may hold the answer to these fundamental questions.

Reference:

Nature Rev. Phys. **4**, 452 (2022)

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Review Article | Published: 18 May 2022

New physics from the polarized light of the cosmic microwave background

Eiichiro Komatsu

Nature Reviews Physics **4**, 452–469 (2022) | Cite this article

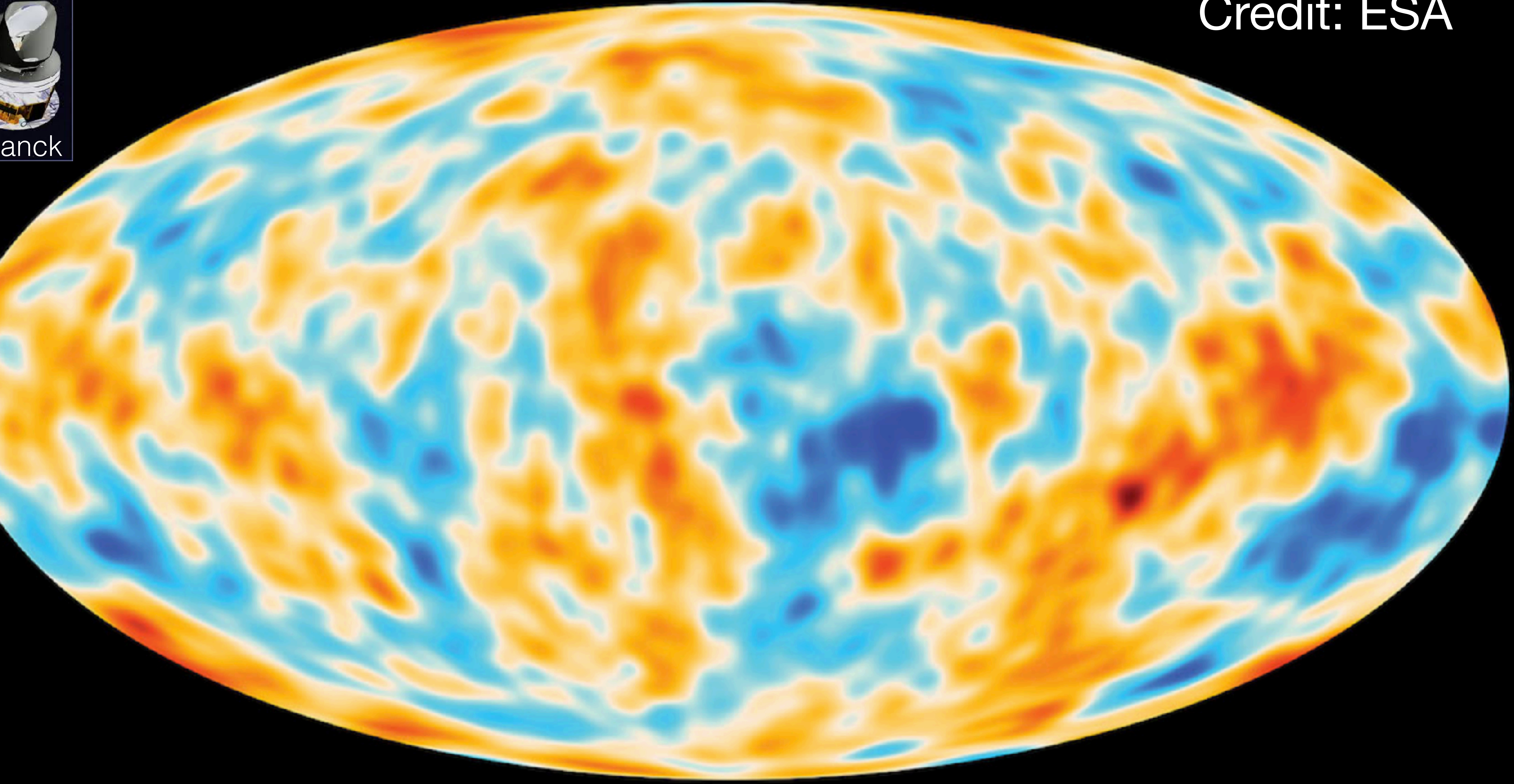
Key Words:

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

I have been told that you are all familiar with parity and CMB.

So, let’s get right to the point!

Credit: ESA



Temperature (smoothed)

Credit: ESA

Key Point

Pseudoscalar: EB correlation

- The observed pattern of the CMB polarization can be decomposed into eigenstates of parity, called "E modes" and "B modes".

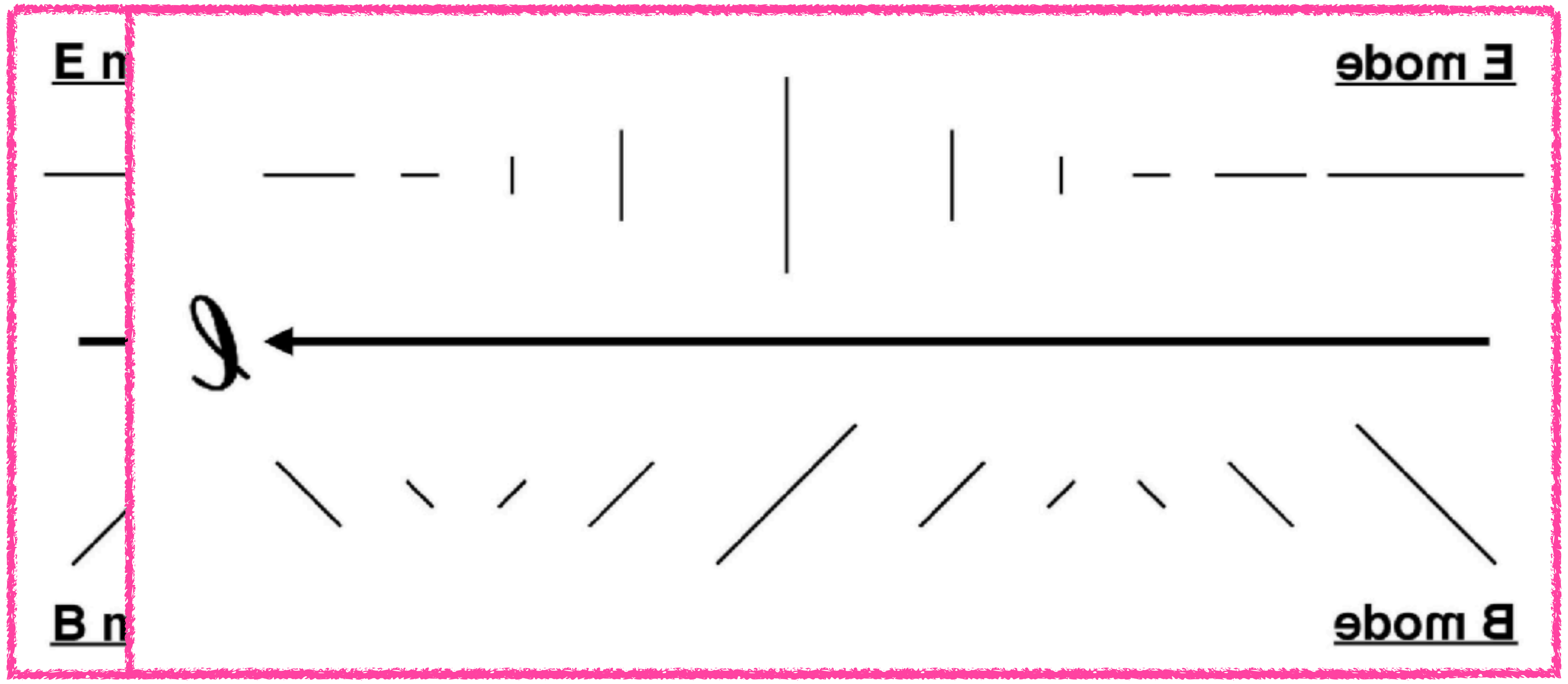
- E and B modes are transformed differently under the parity transformation. Therefore, the product of the two, **the "EB correlation", is a pseudoscalar**.

- **The full-sky average of the EB correlation must vanish (to within the measurement uncertainty), if there is no parity violation!**

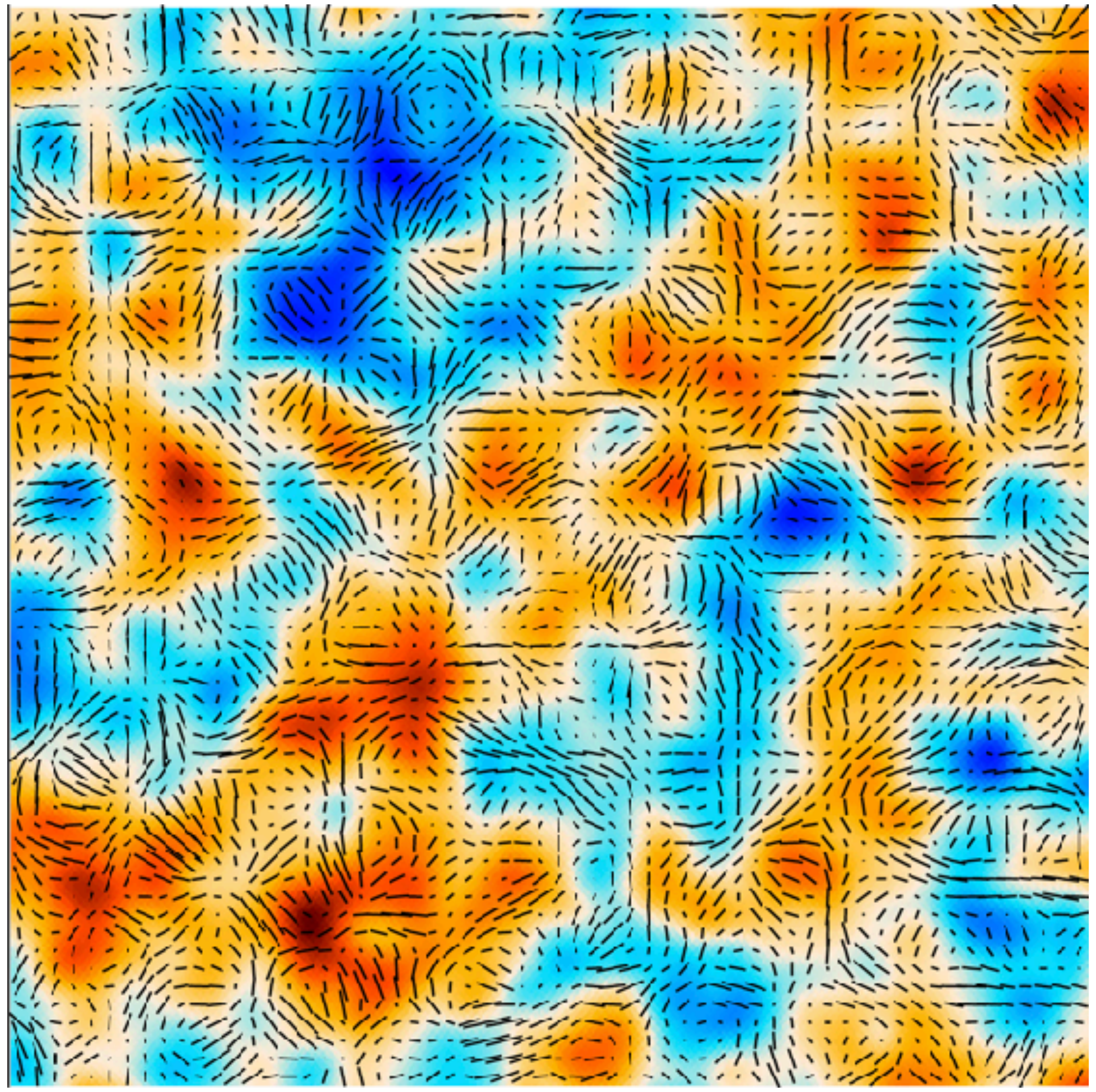
Zaldarriaga, Seljak (1997); Kamionkowski, Kosowsky, Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

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

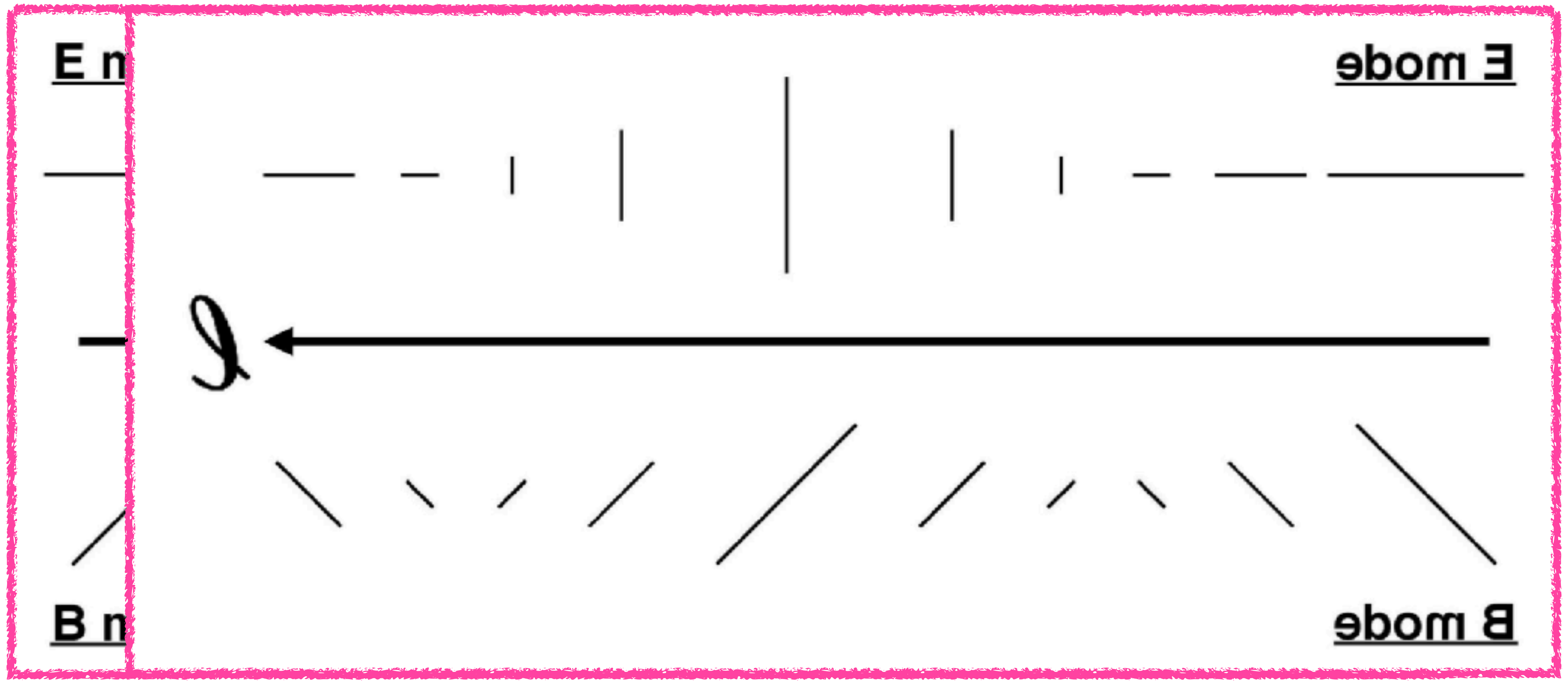
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

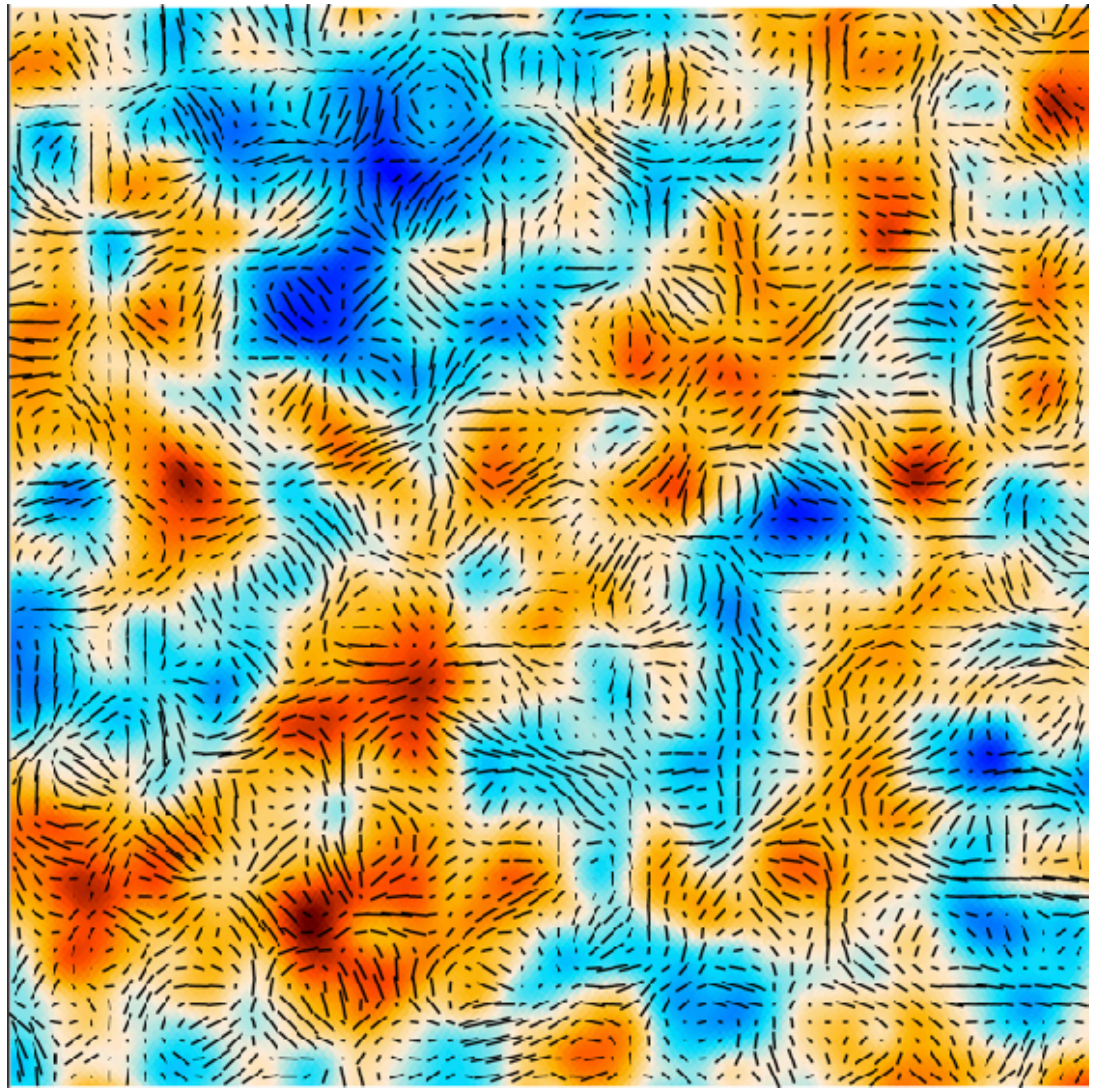
These are scalars and insensitive to parity violation.

Lue, Wang, Kamionkowski (1999); Feng et al. (2005, 2006)

Parity eigenstates: E and B modes

Concept defined in Fourier space





This map is dominated by E-mode polarization

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

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

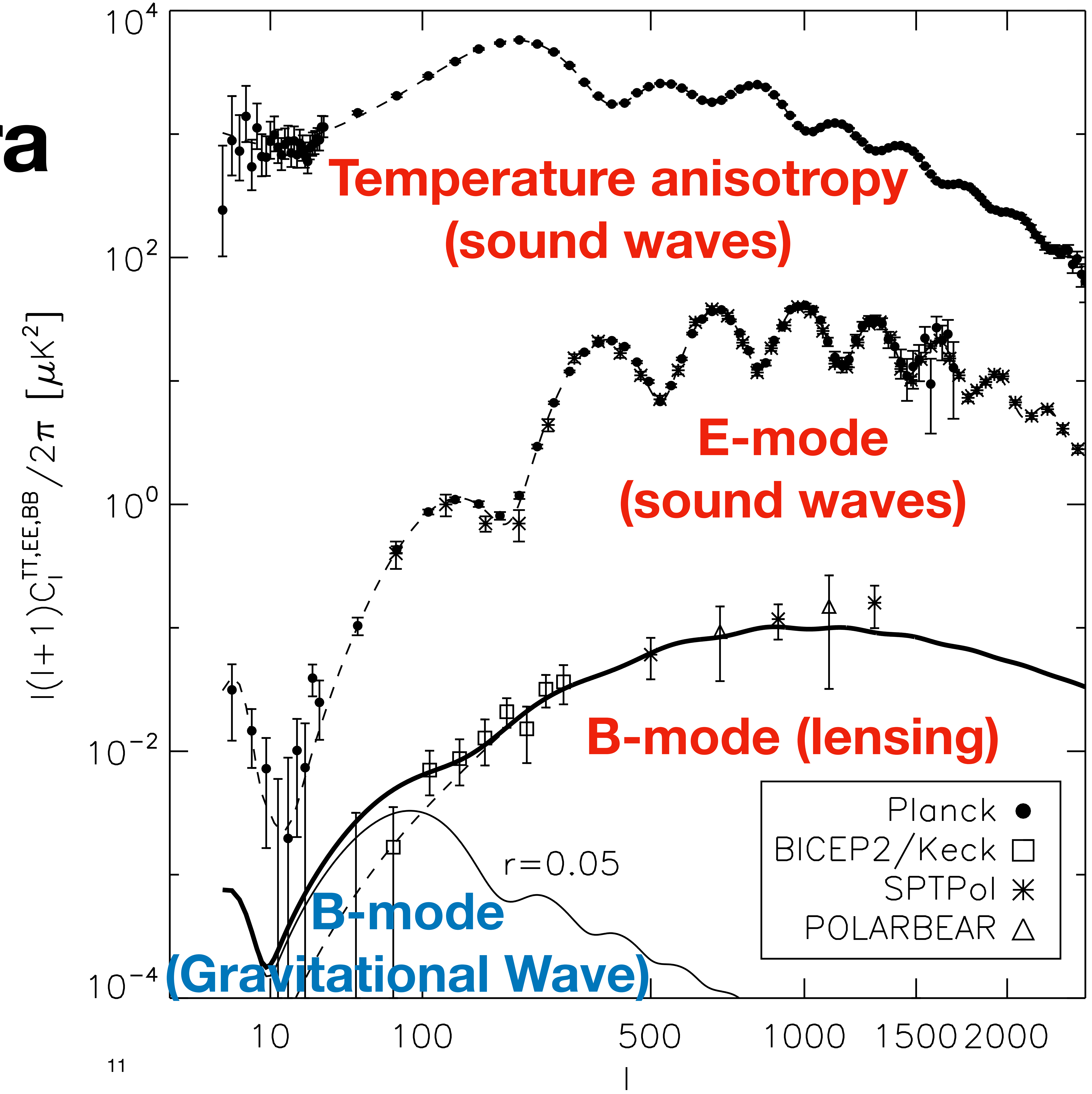
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

The other combinations, <TB> and <EB>,
are pseudoscalars and
sensitive to parity violation!

CMB Power Spectra

Progress over 30 years

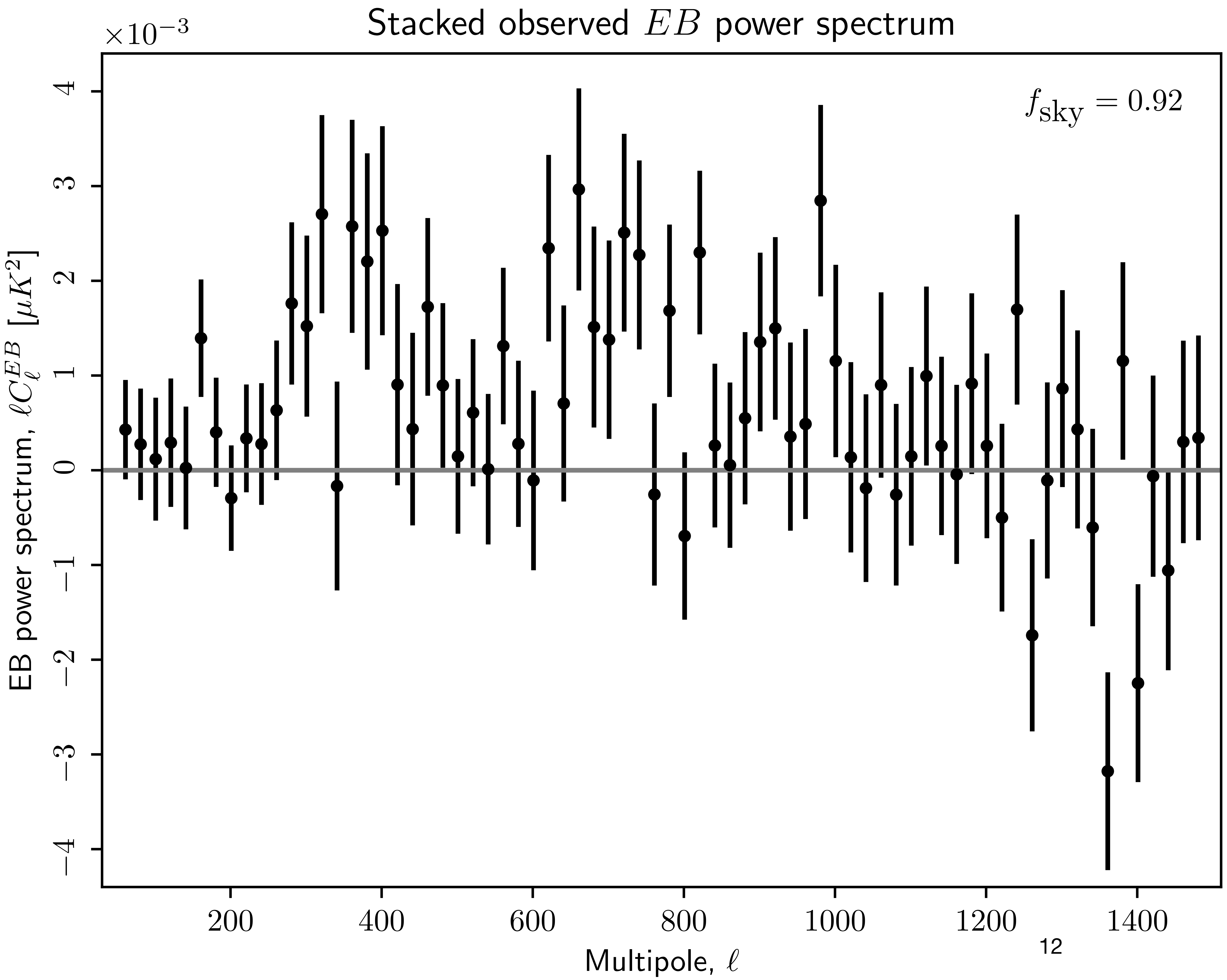
- This is the typical figure seen in talks and lectures on the CMB.
    - The temperature and the E- and B-mode polarization power spectra are well measured.
- **Parity violation appears in the TB and EB power spectra, not shown here.**

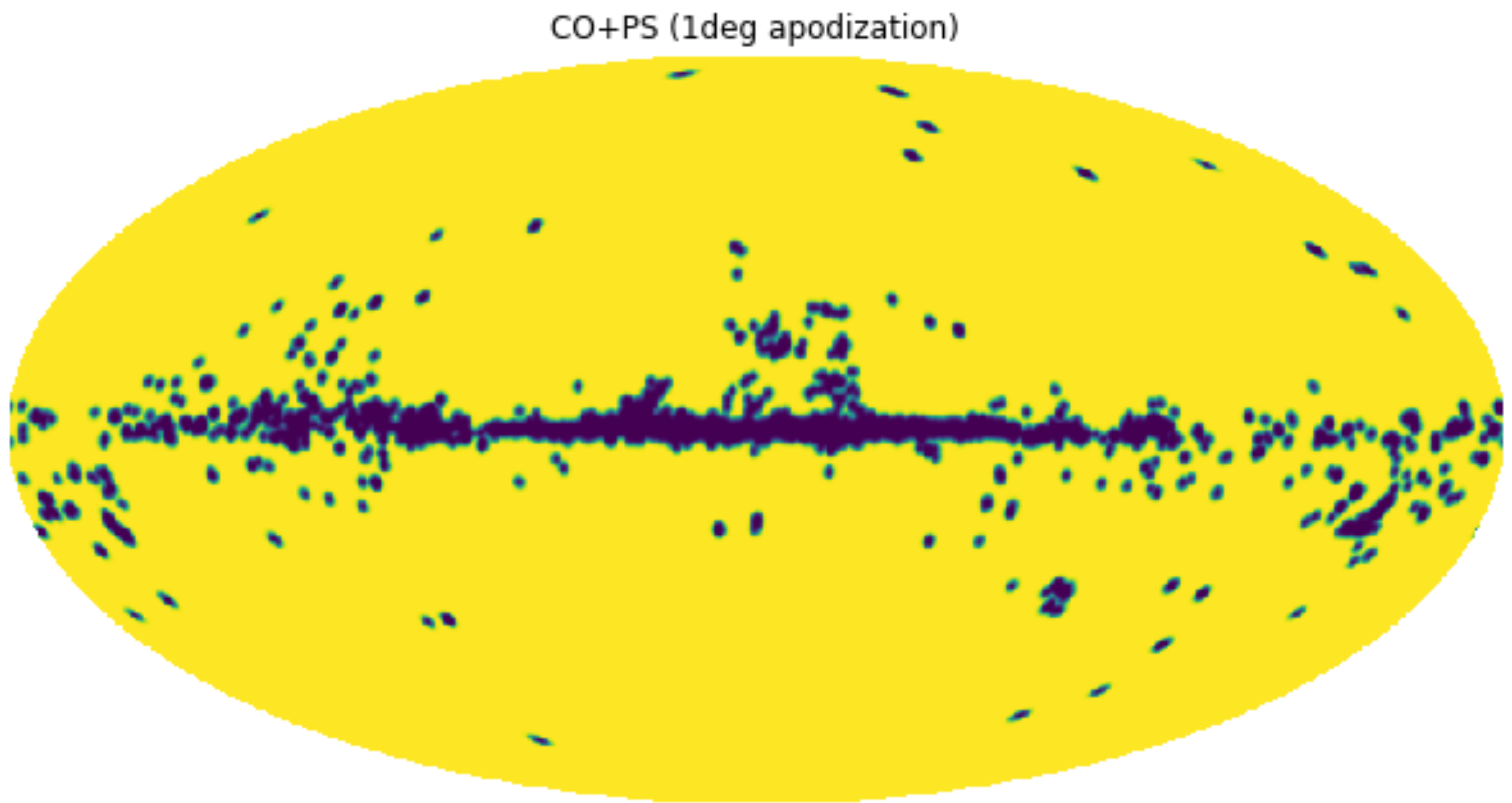


Eskilt, EK (2022)

This is the EB power spectrum (WMAP+Planck)

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

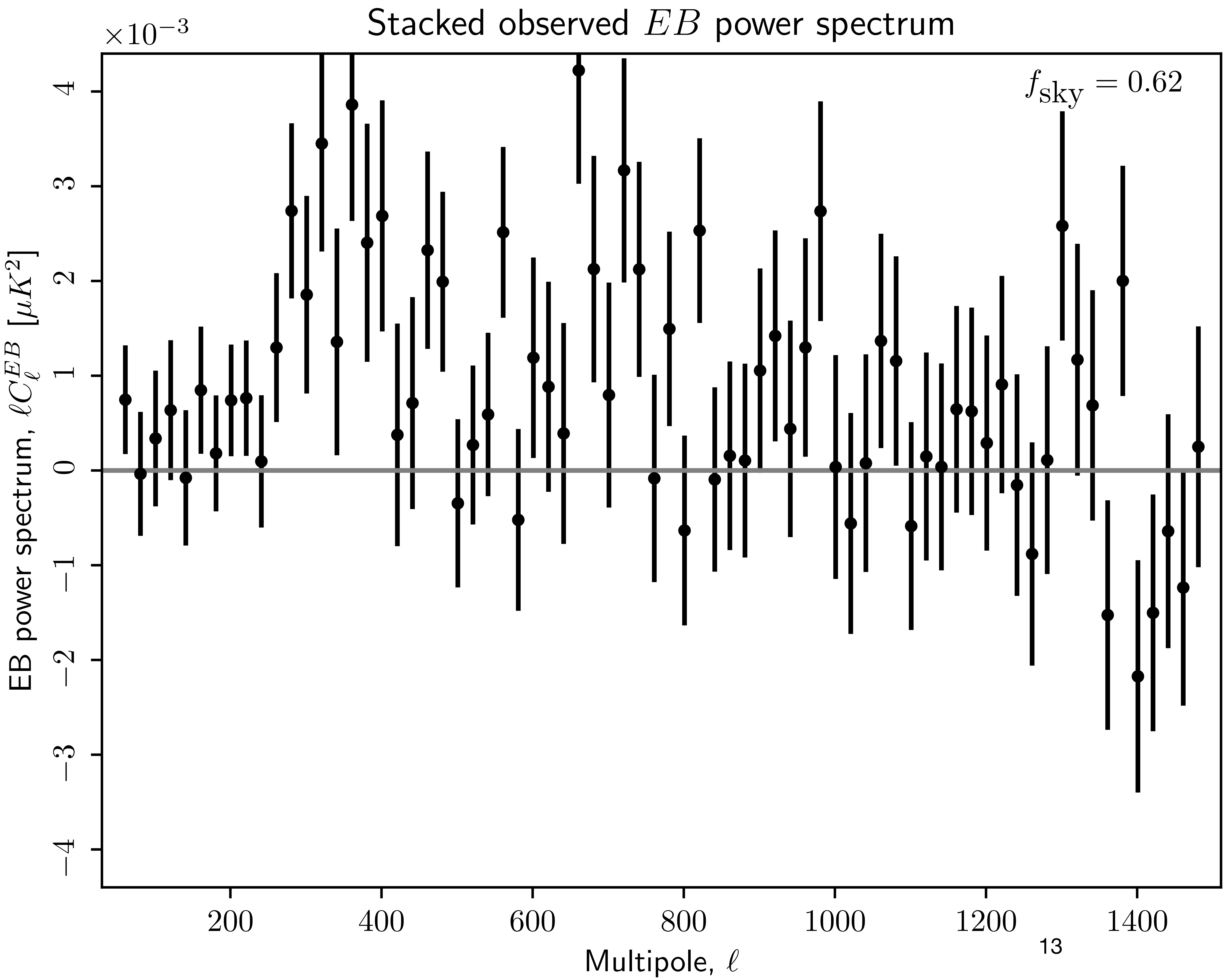


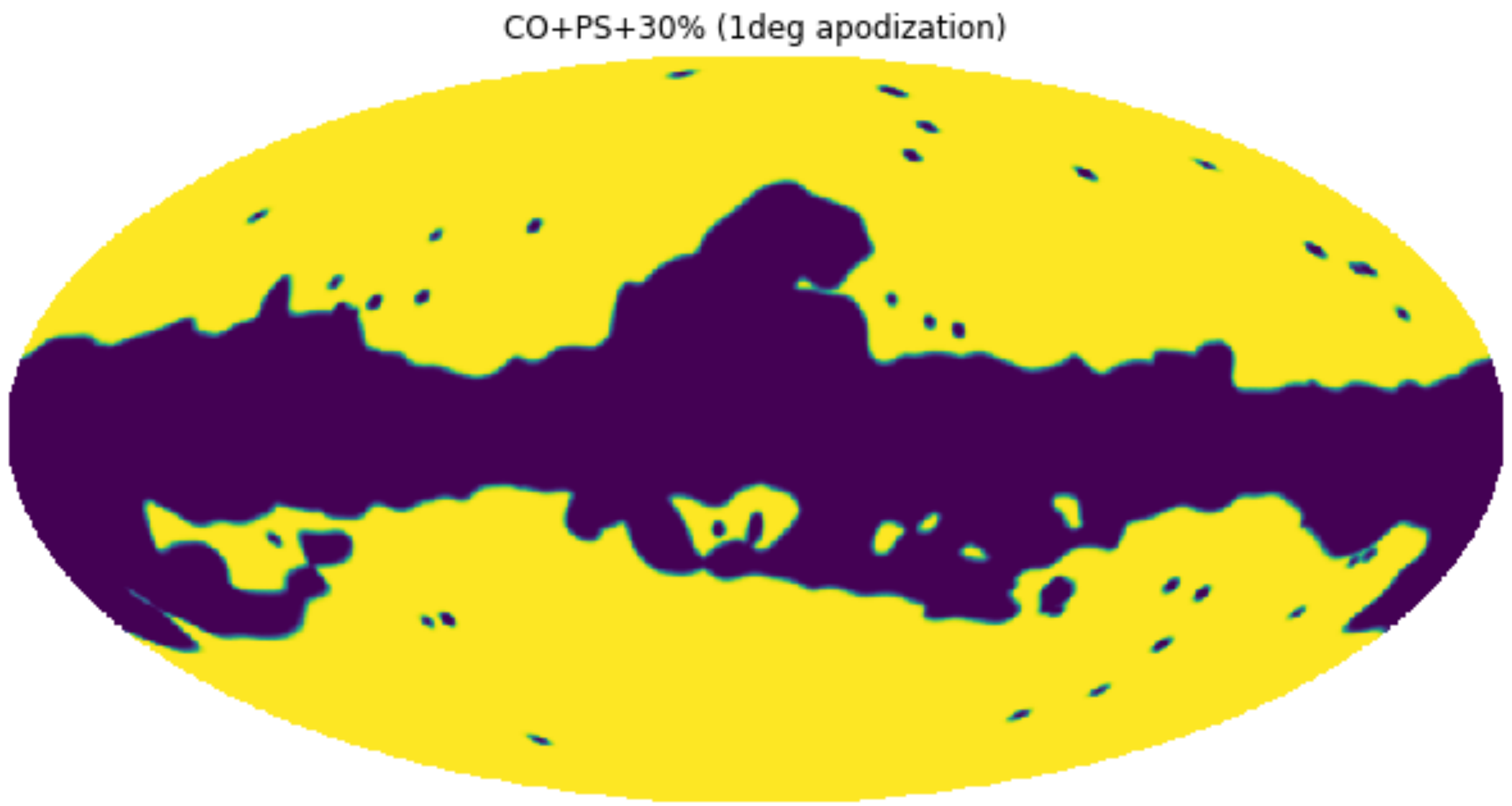


- χ^2 = 125.5 for DOF=72
  - Unambiguous signal of something!

This is the EB power spectrum (WMAP+Planck)

Galactic plane removed (62% of the sky)

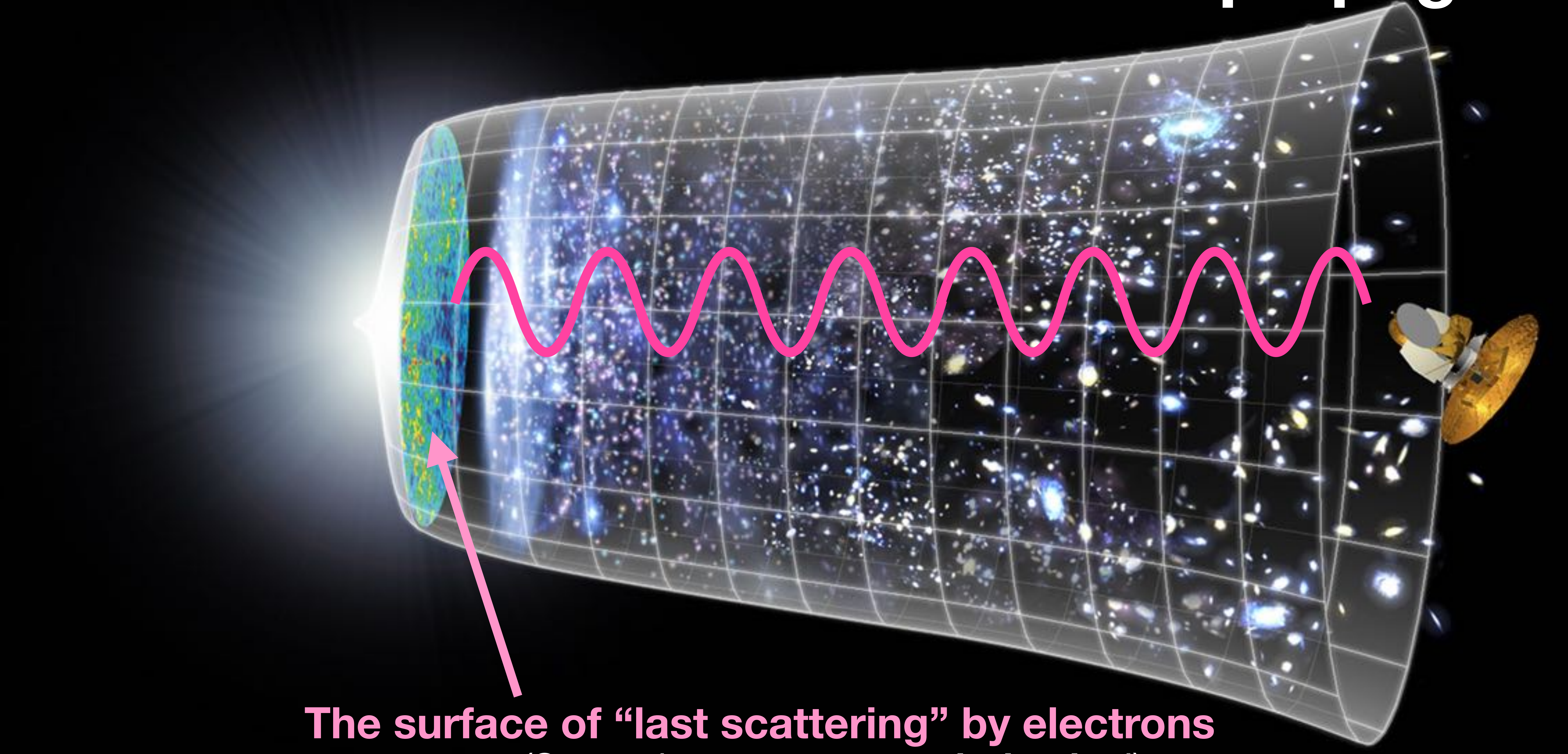




- $\chi^2 = 138.4$
  - The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

Cosmic Birefringence: Rotation of the Plane of Linear Polarization

How does the EM wave of the CMB propagate?



The surface of "last scattering" by electrons

(Scattering generates ***polarization***!)

Credit: WMAP Science Team

How does the EM wave of the CMB propagate?

Credit: ESA

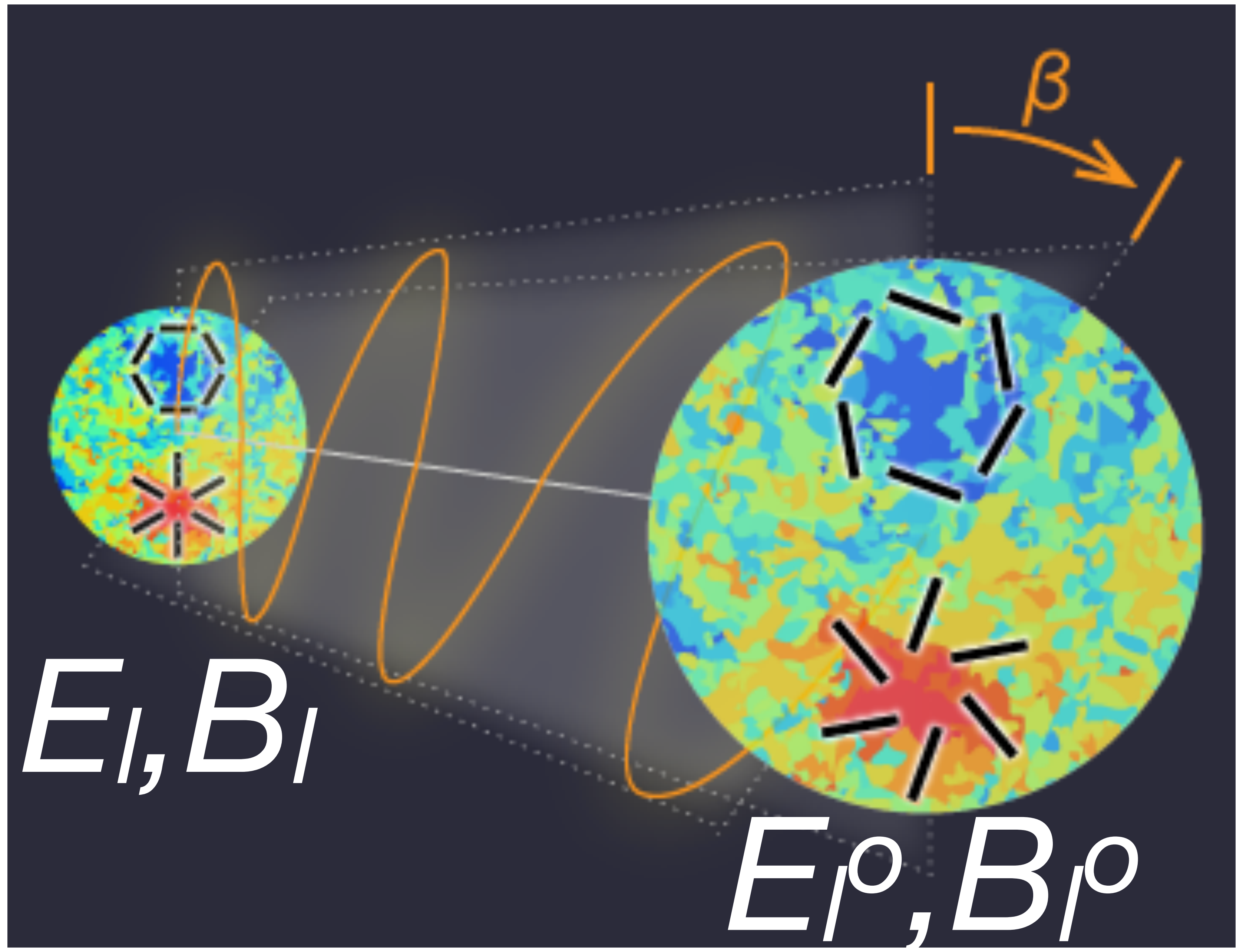
“*Cosmic Birefringence*”

If the plane of linear polarization of the CMB is rotated uniformly by β, it is the sign of parity violation!

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

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

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



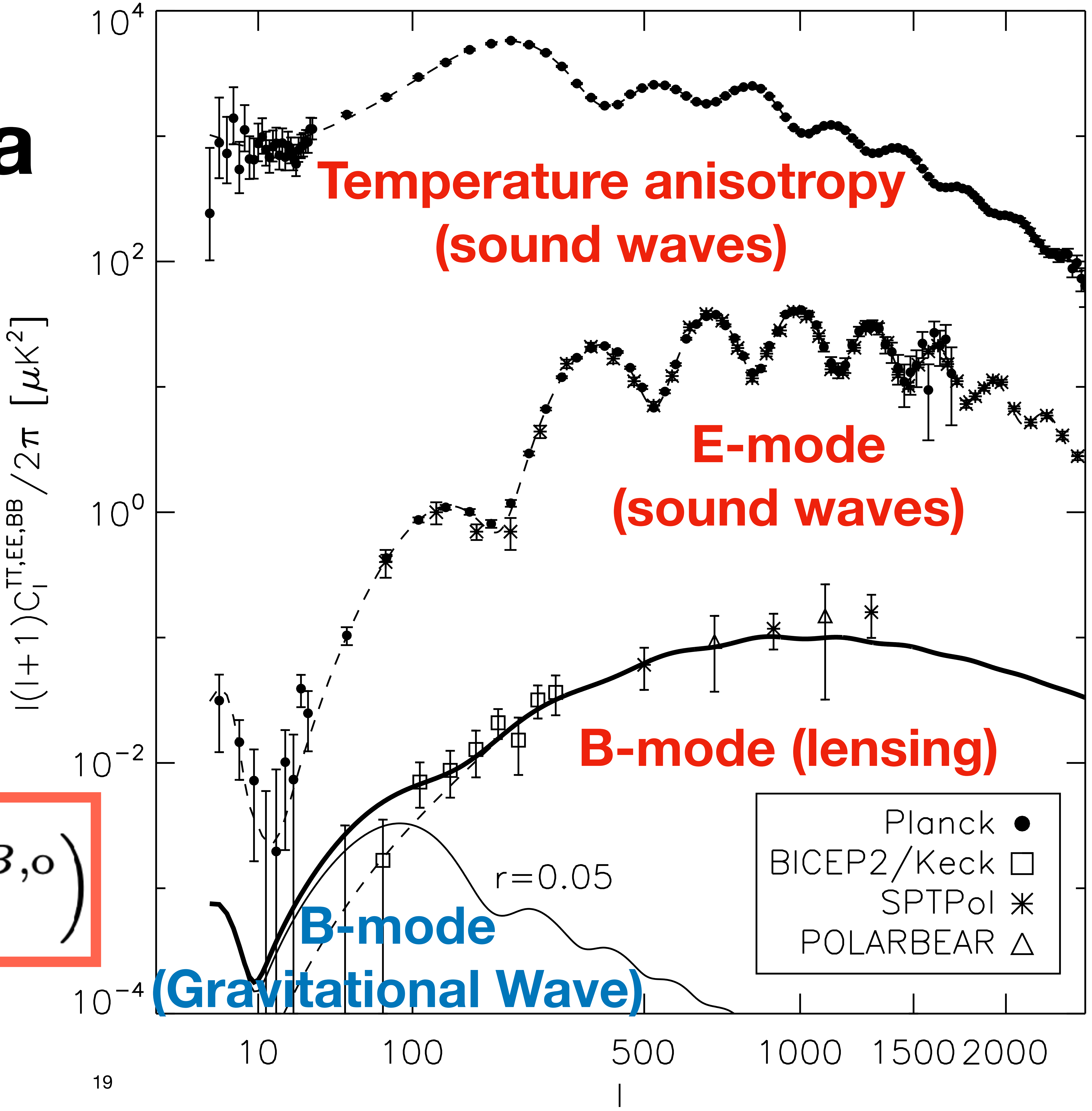
- which gives

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

CMB Power Spectra

- Rotation of the plane of linear polarization **mixes** E and B modes.
- Therefore, the EB correlation will be given by the difference between the EE and BB correlations.
- Observed EE is much greater than BB. We expect EB to look like EE!

$$C_\ell^{EB,o} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,o} - C_\ell^{BB,o}\right)$$

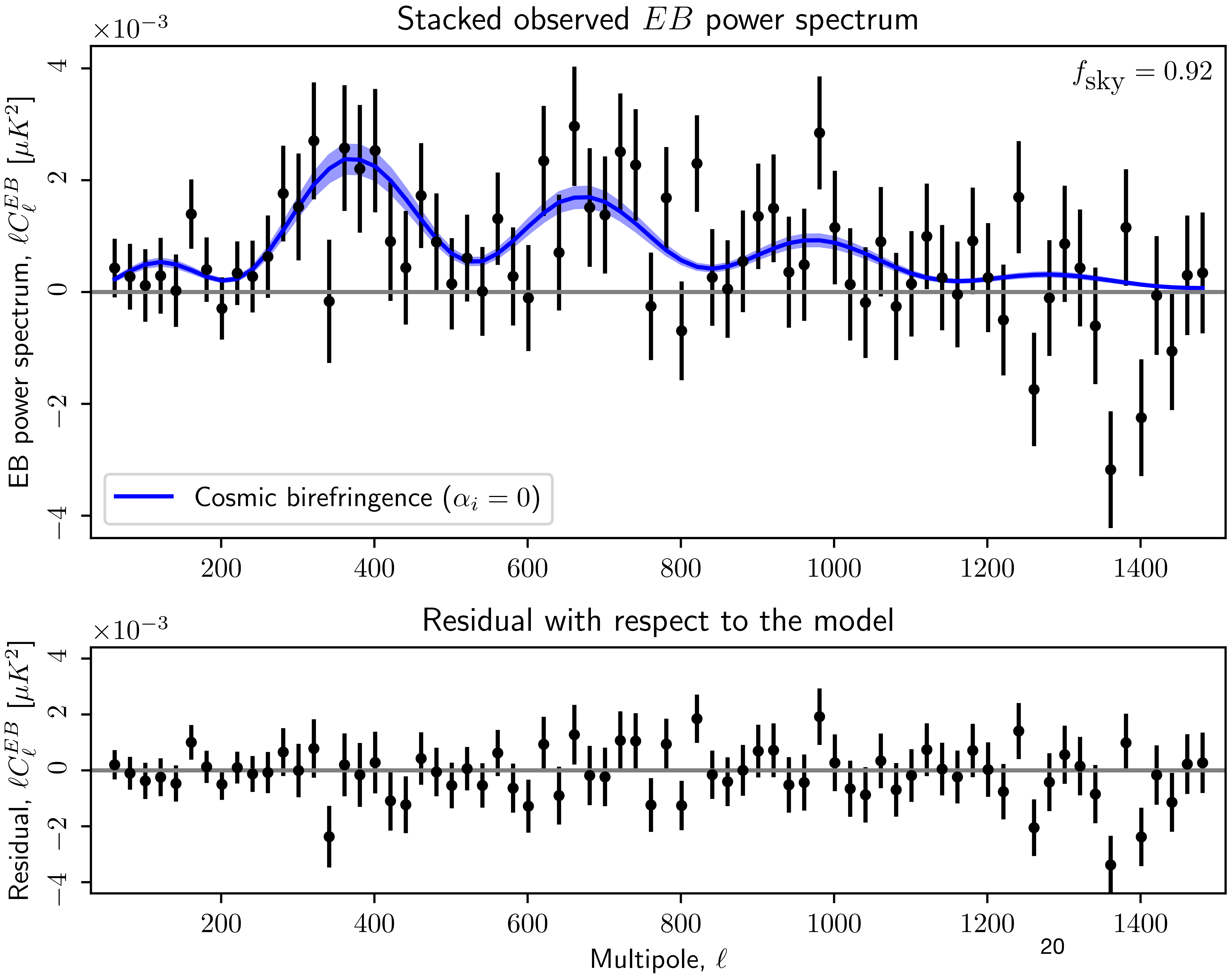


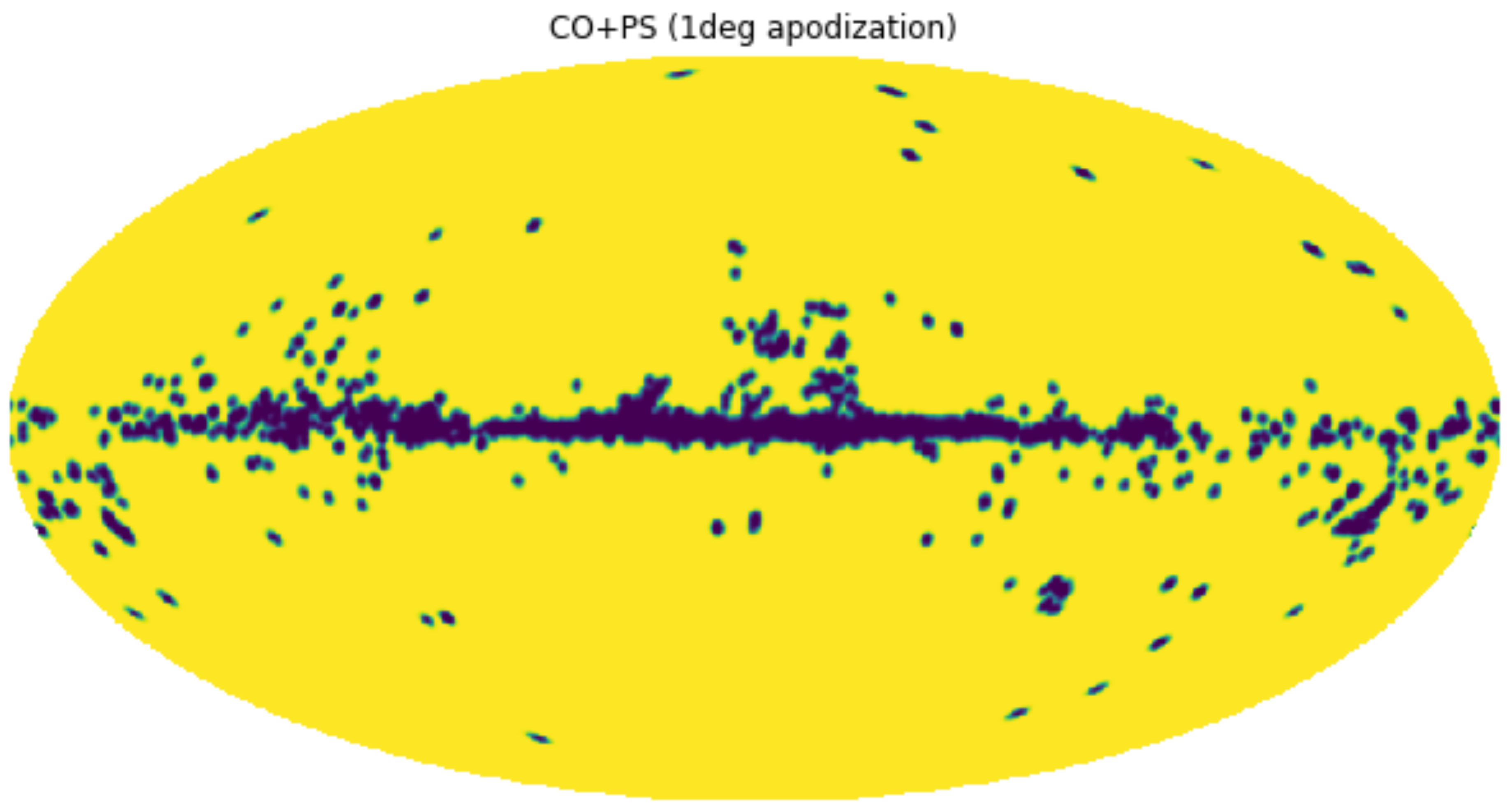
Eskilt, EK (2022)

Cosmic Birefringence fits well(?)

$$C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)$$

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



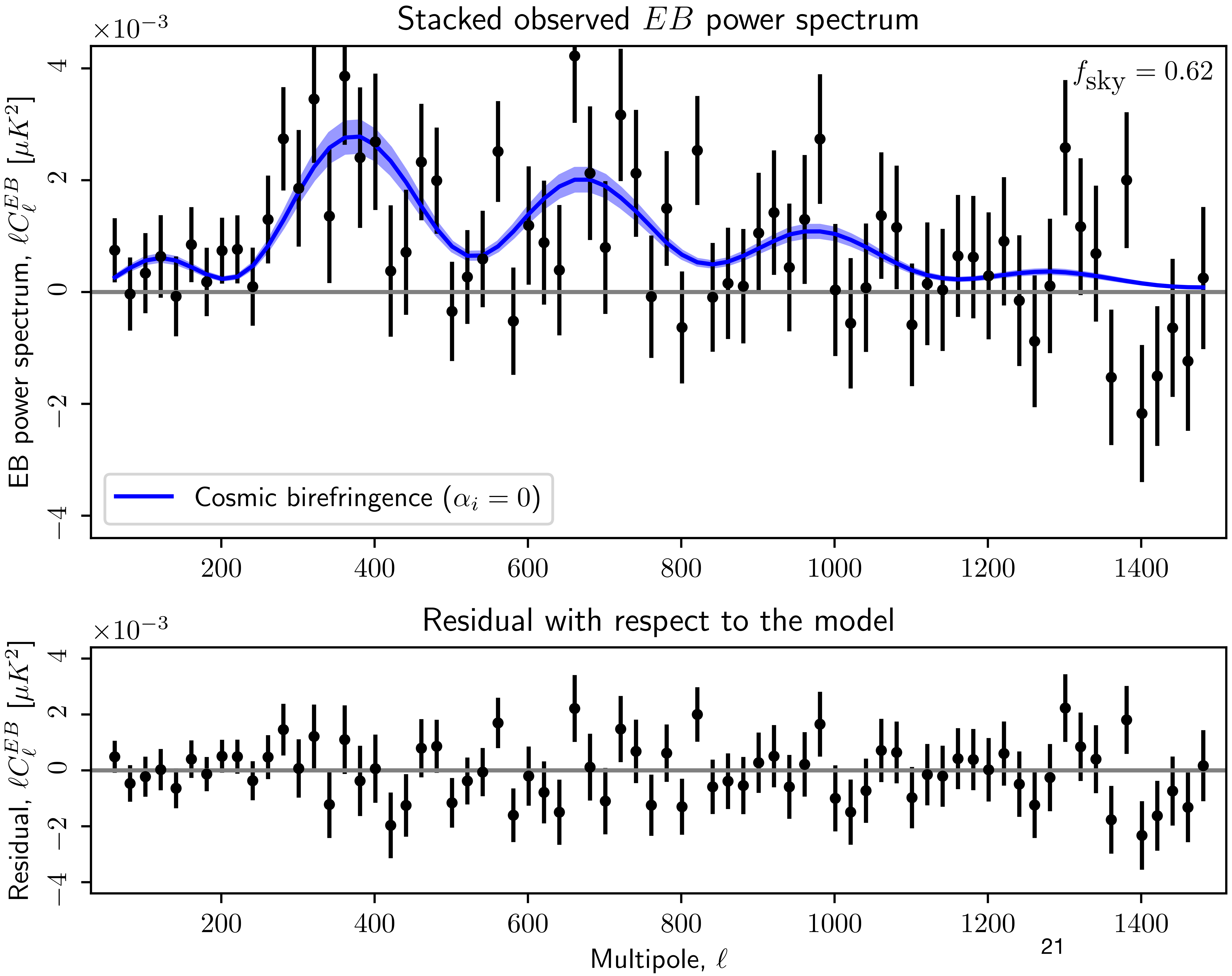


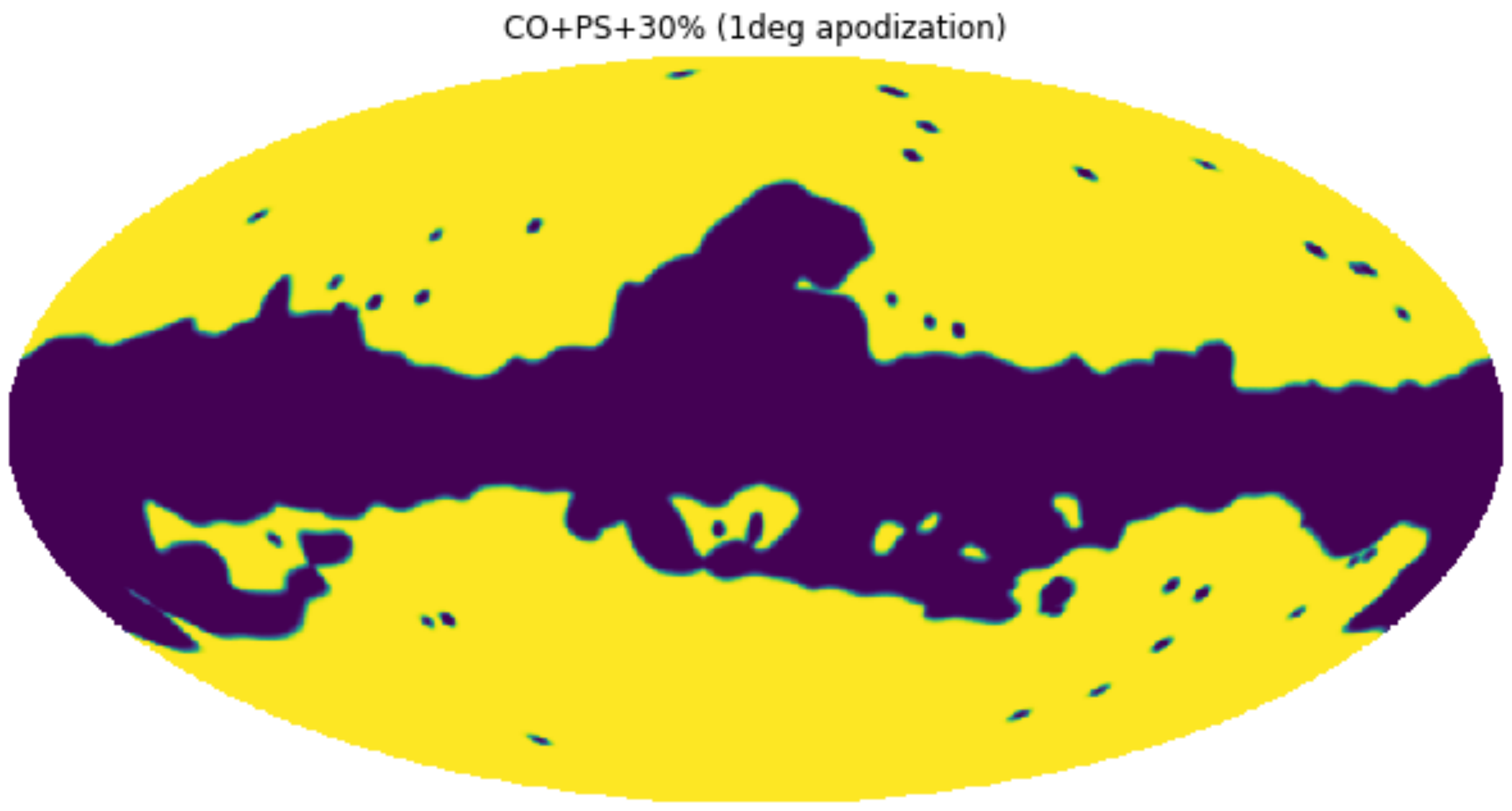
- $\beta = 0.288 \pm 0.032$ deg
- $\chi^2 = 66.1$ for DOF=71
  - Good fit! 9σ detection?

Cosmic Birefringence fits well(?)

$$C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)$$

Galactic plane removed (62% of the sky)





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

The Biggest Problem: Miscalibration of detectors

Impact of miscalibration of polarization angles

Cosmic or Instrumental?

- Is the plane of linear polarization rotated by the genuine cosmic birefringence effect, or simply because the polarization-sensitive directions of the 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

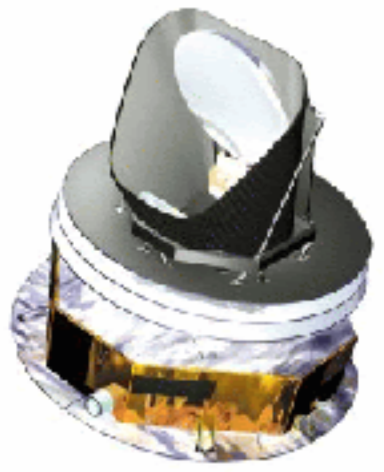
- $\beta = -6.0 \pm 4.0 \pm$ **??** deg (Feng et al. 2006)
- $\beta = -1.1 \pm 1.4 \pm$ **1.5** deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- $\beta = 0.55 \pm 0.82 \pm$ **0.5** deg (QUaD Collaboration, Wu et al. 2009)
- …
- $\beta = 0.31 \pm 0.05 \pm$ **0.28** deg (Planck Collaboration 2016)
- $\beta = -0.61 \pm 0.22 \pm$ **??** 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

Minami et al. (2019); Minami, EK (2020)

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

Credit: ESA



ESA’s Planck

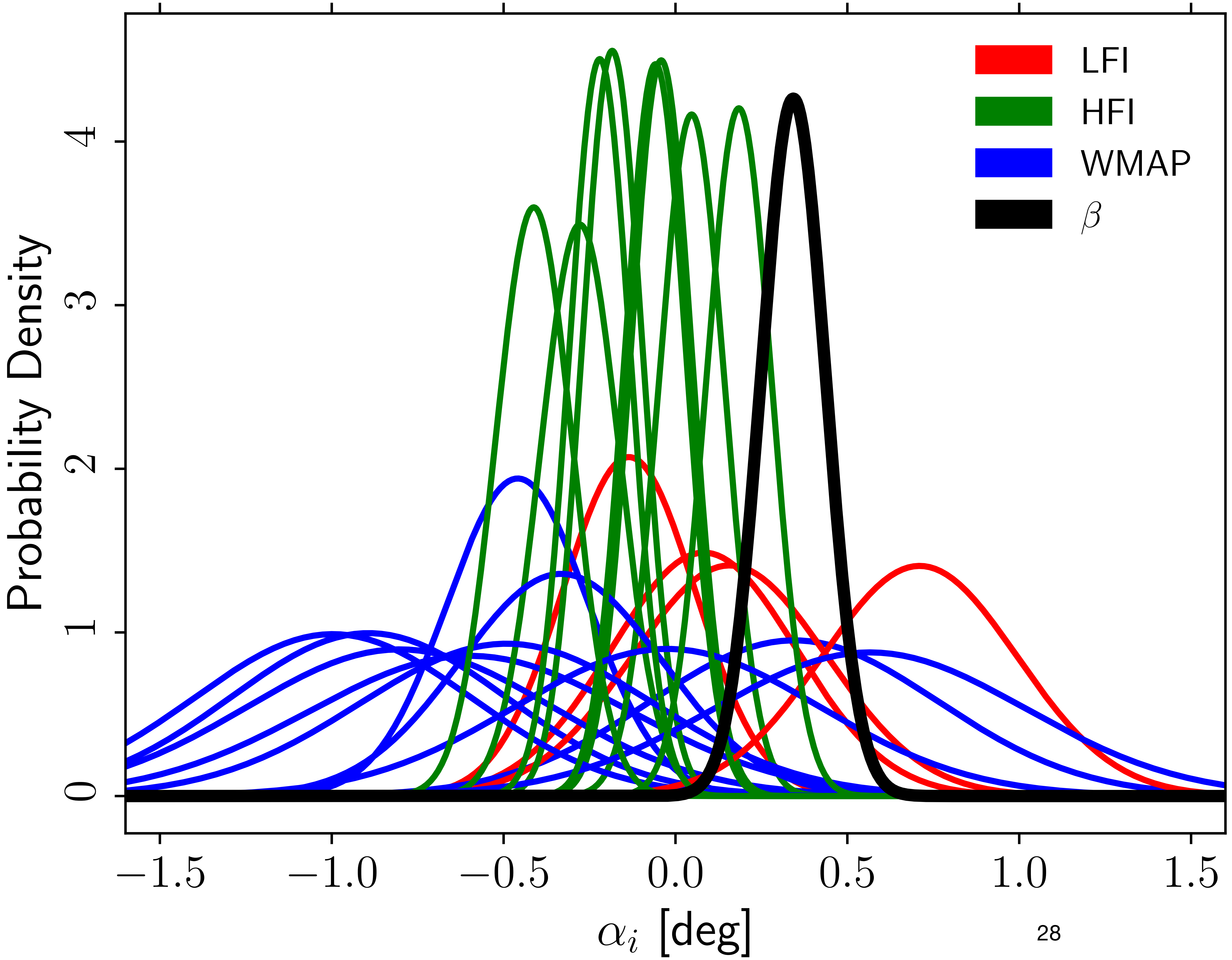
Polarized dust emission within our Milky Way!

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

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

Miscalibration angles (WMAP and Planck)

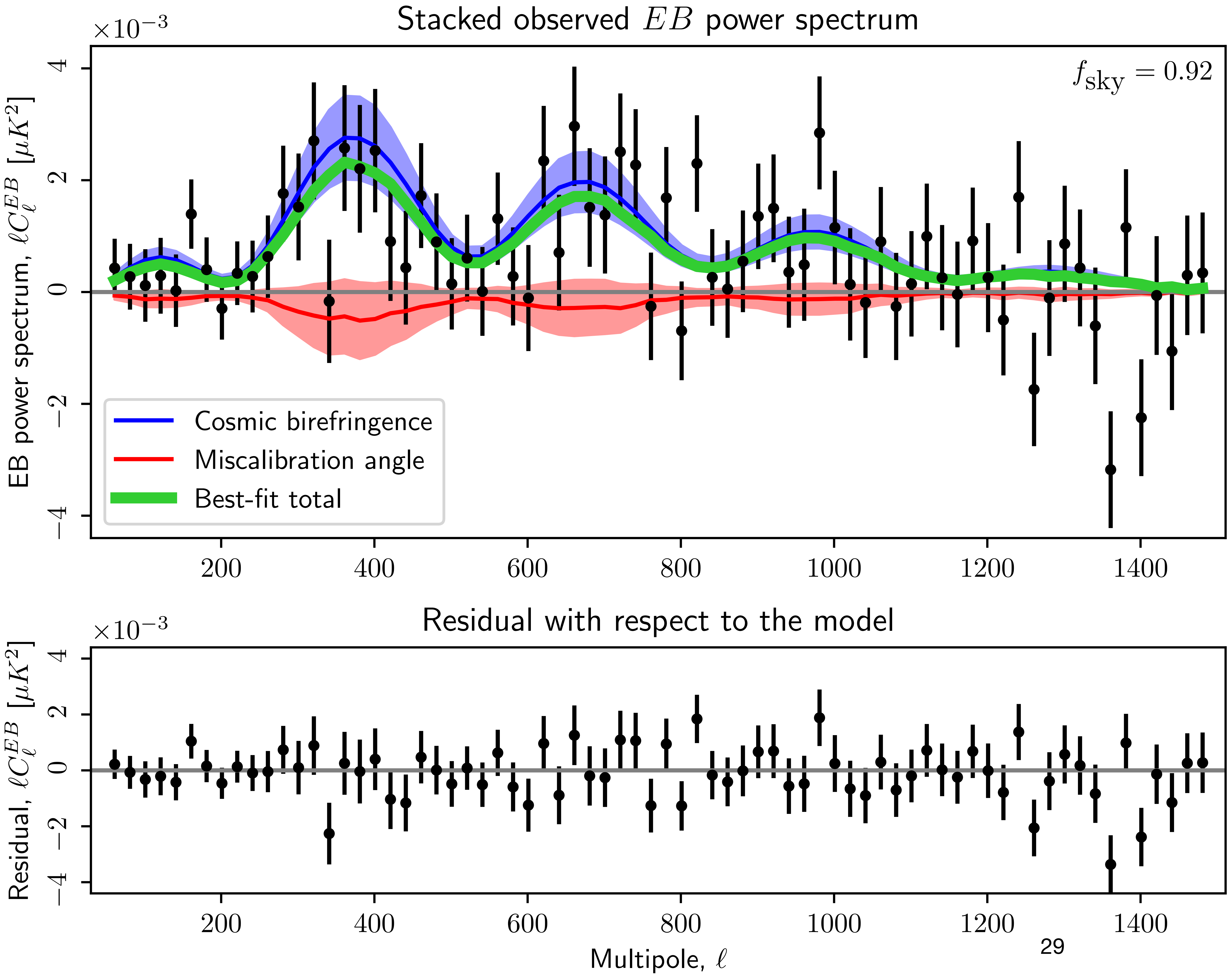
Nearly full-sky data (92% of the sky)

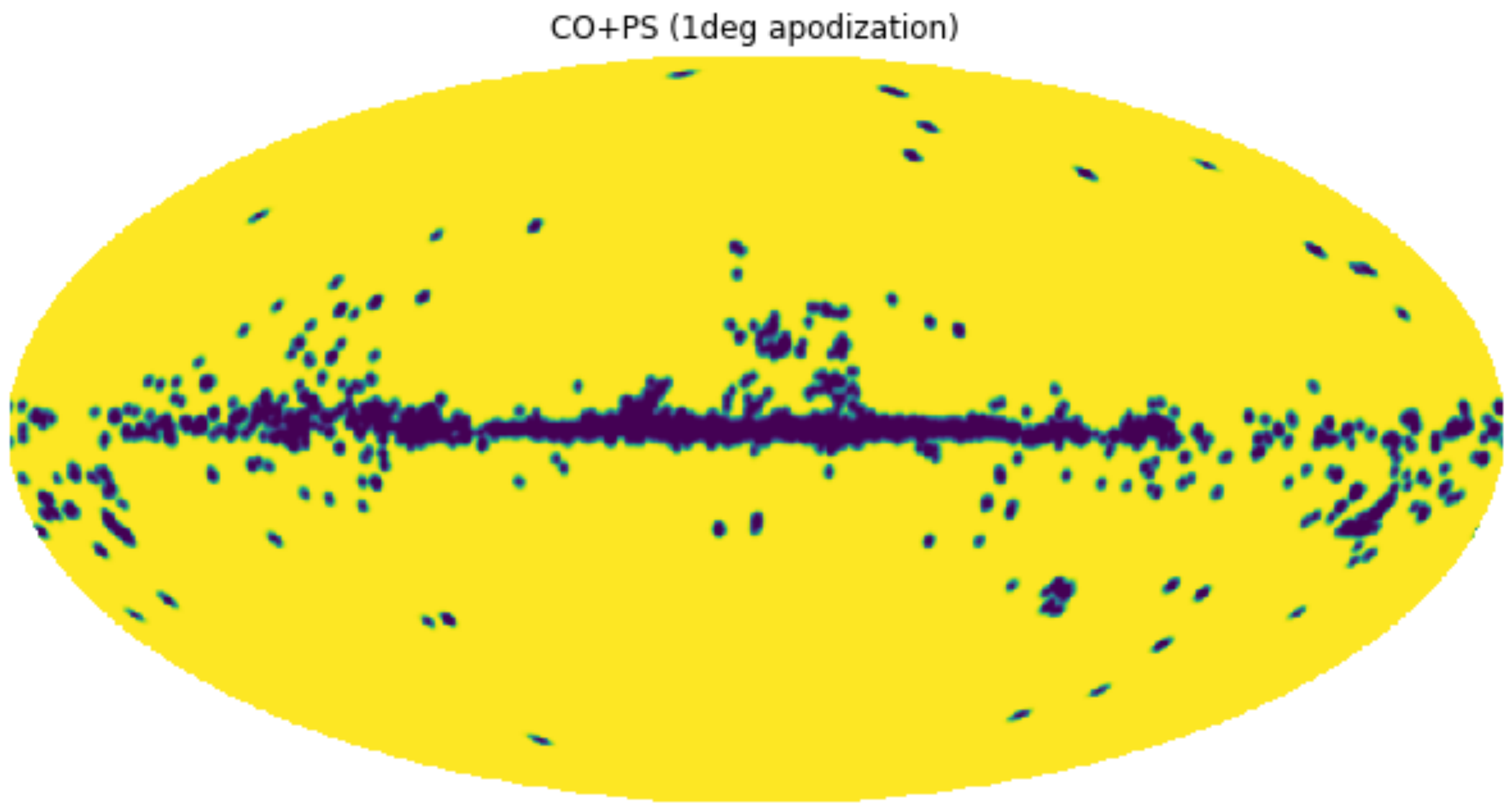


- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

Cosmic Birefringence fits well (WMAP+Planck)

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



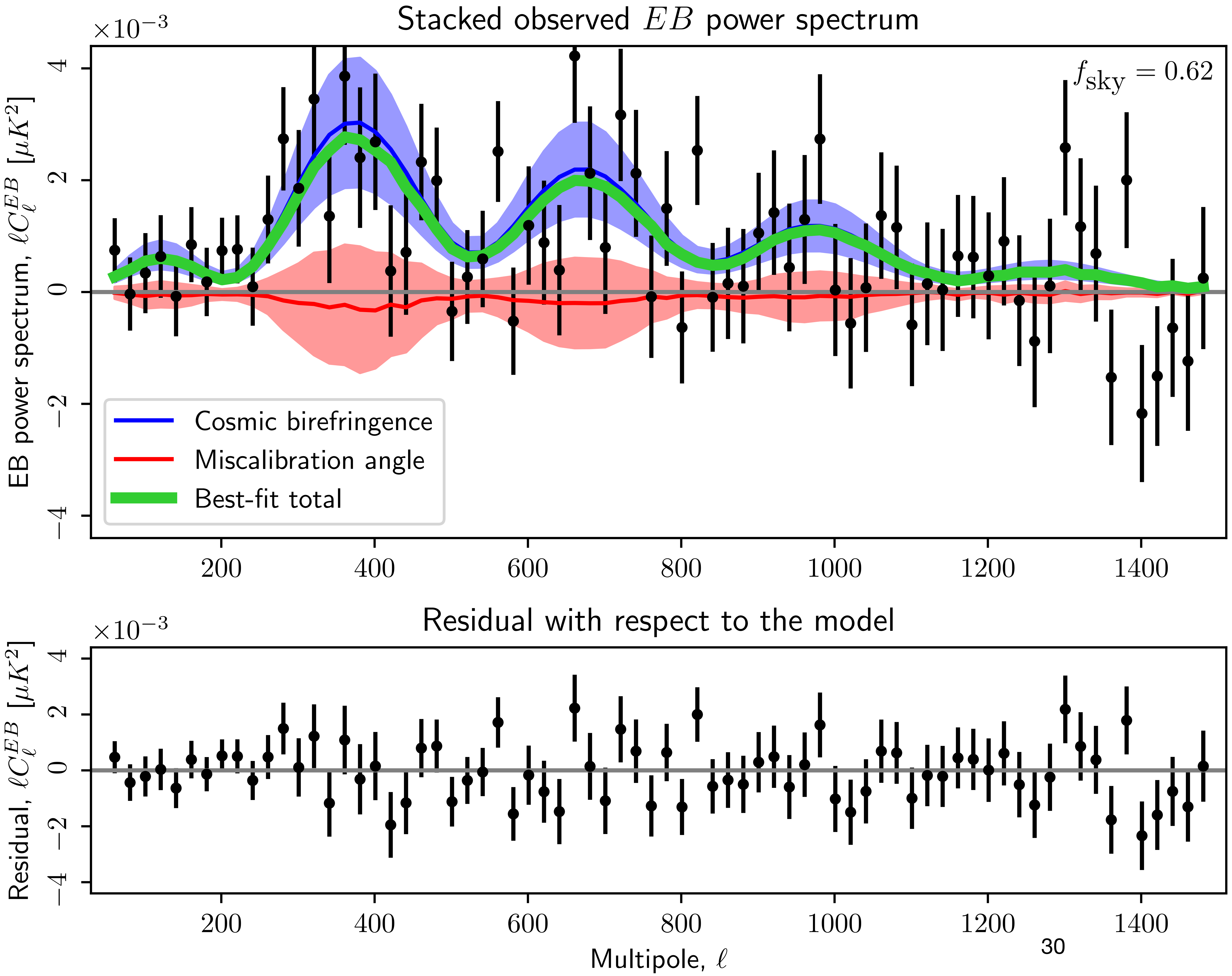


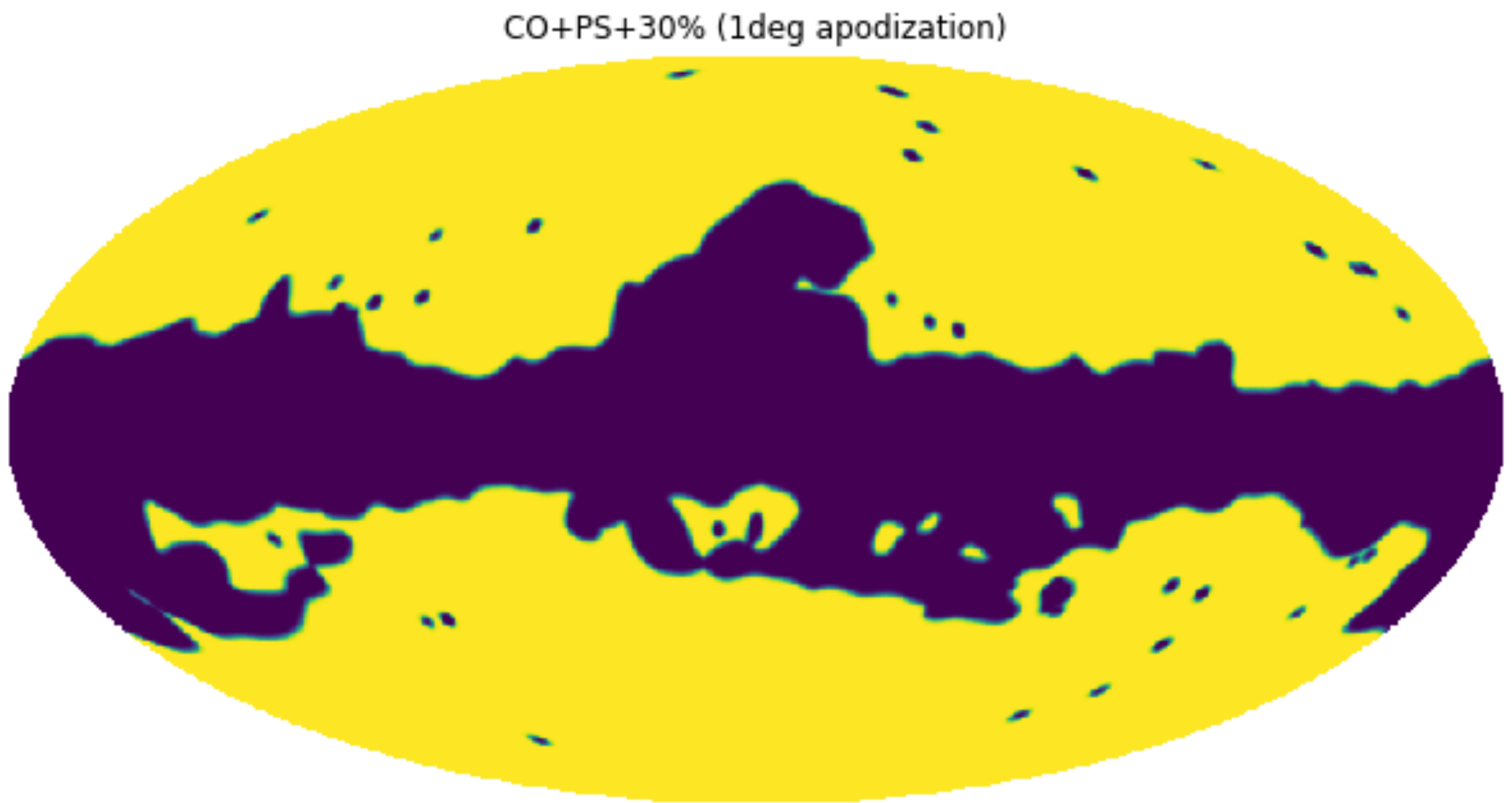
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- $\chi^2 = 65.3$

Minami, EK (2020); Diego-Palazuelos et al. (2022); Eskilt, EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

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

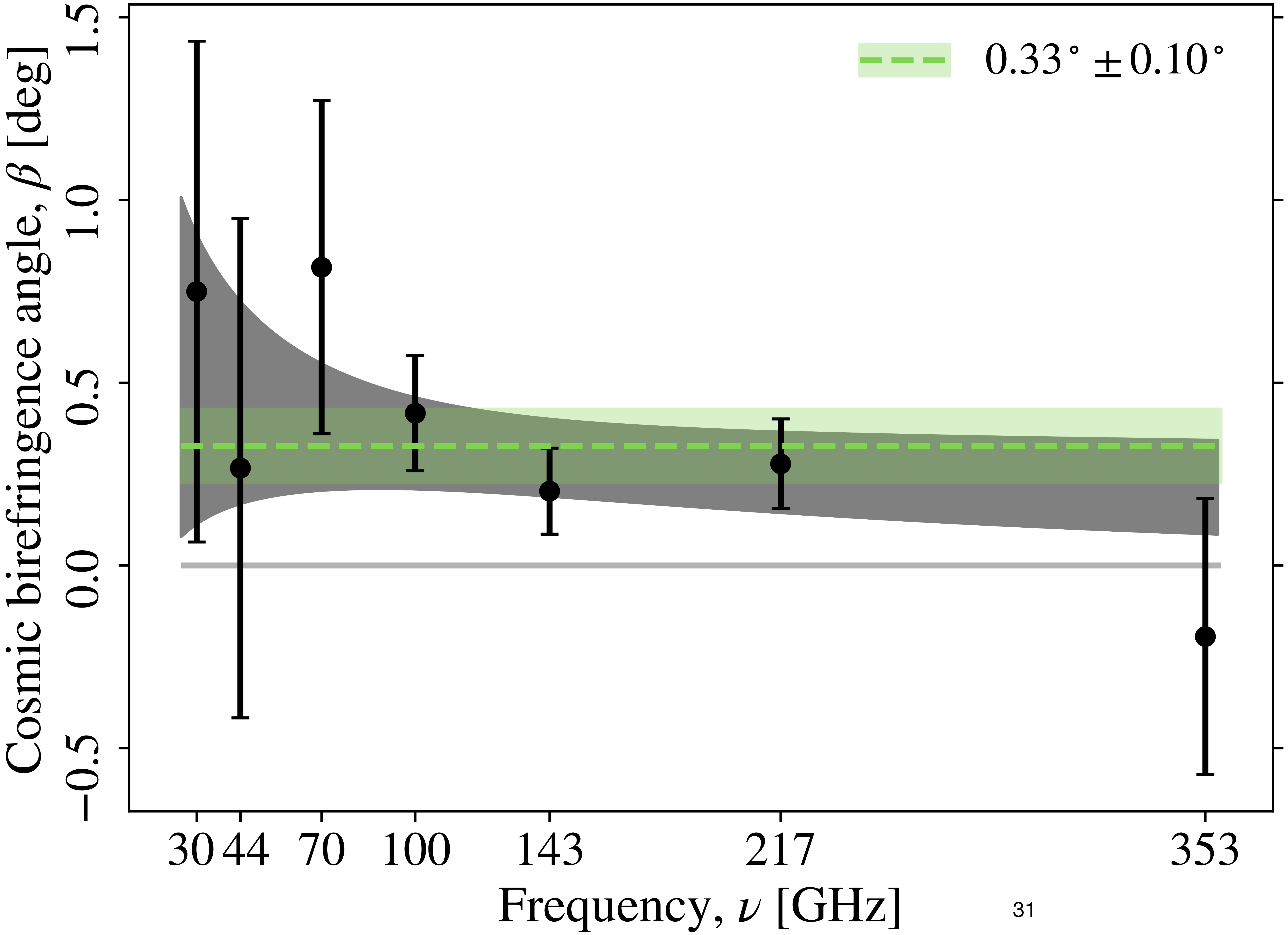




- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- $\chi^2 = 65.8$

No frequency dependence is found

It is not due to Faraday rotation.



- Light traveling in a uniform magnetic field also experiences a rotation of the plane of linear polarization, called "**Faraday rotation**". However, the rotation angle depends on the frequency, as $\beta(\nu) \propto \nu^{-2}$.
- No evidence for frequency dependence is found!
  - For $\beta \propto \nu^n$, $n = -0.20^{+0.41}_{-0.39}$ (68% CL)
  - **Faraday rotation ($n = -2$) is disfavoured.**

Is β caused by non-cosmological effects?

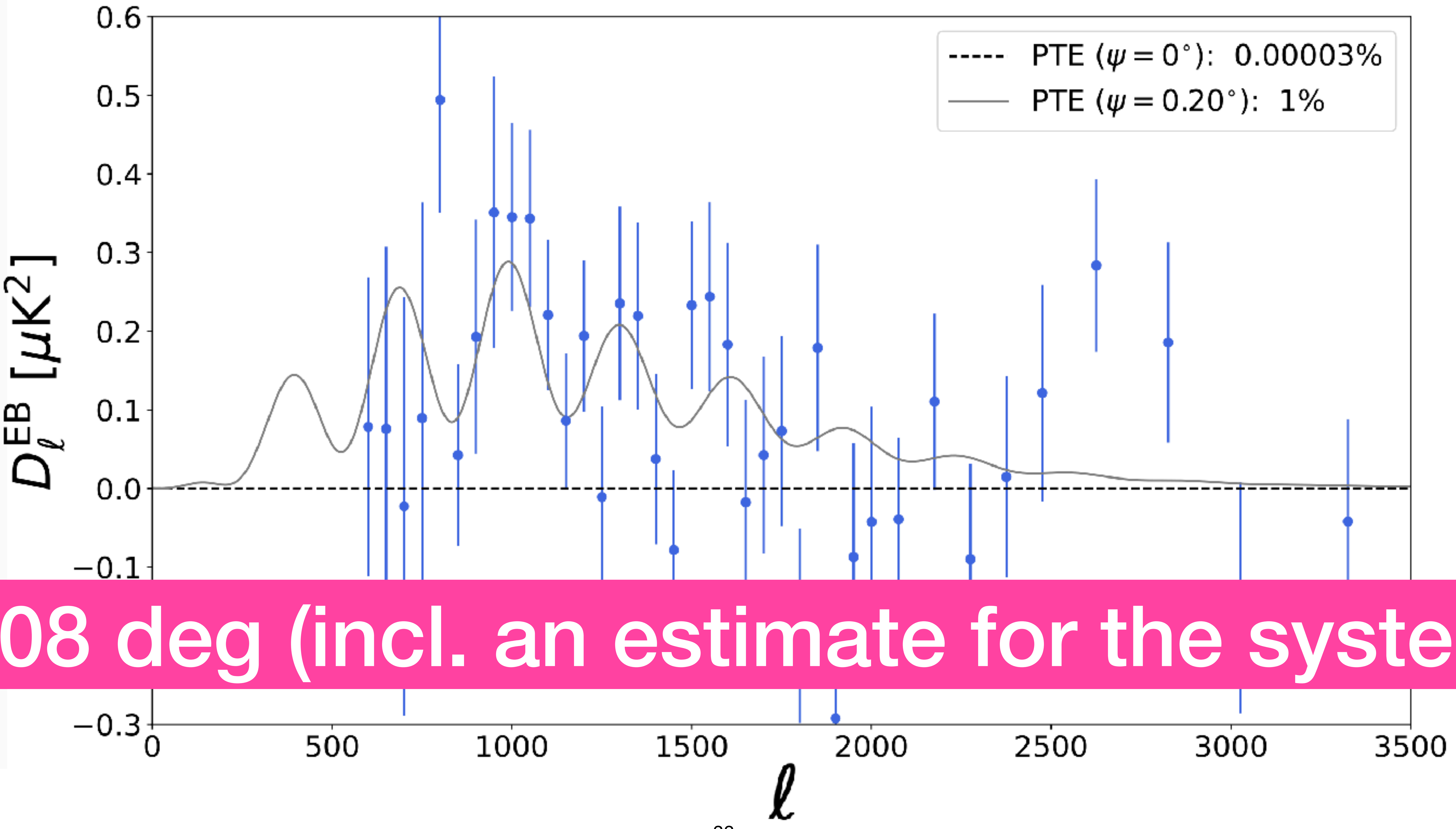
We need to measure it in independent experiments.

- The **known** instrumental effects of the WMAP and Planck missions are shown to have negligible effects on β.
  - However, we can never rule out **unknown** instrumental effects… We need to measure β in independent experiments.
- The polarized Galactic foreground emission was used to calibrate the instrumental polarization angles, α. The intrinsic EB correlations of the Galactic foreground emission (**polarized dust and synchrotron emission**) could affect the results.
  - We need to measure β without relying on the foreground by calibrating α well, e.g., Murata et al. (Simons Observatory), arXiv:2309.02035; Murphy et al. (ACT), arXiv:2403.00763; Cornelison et al. (BICEP3), arXiv:2410.12089; Ritacco et al. (COSMOCal), arXiv:2405.12135.

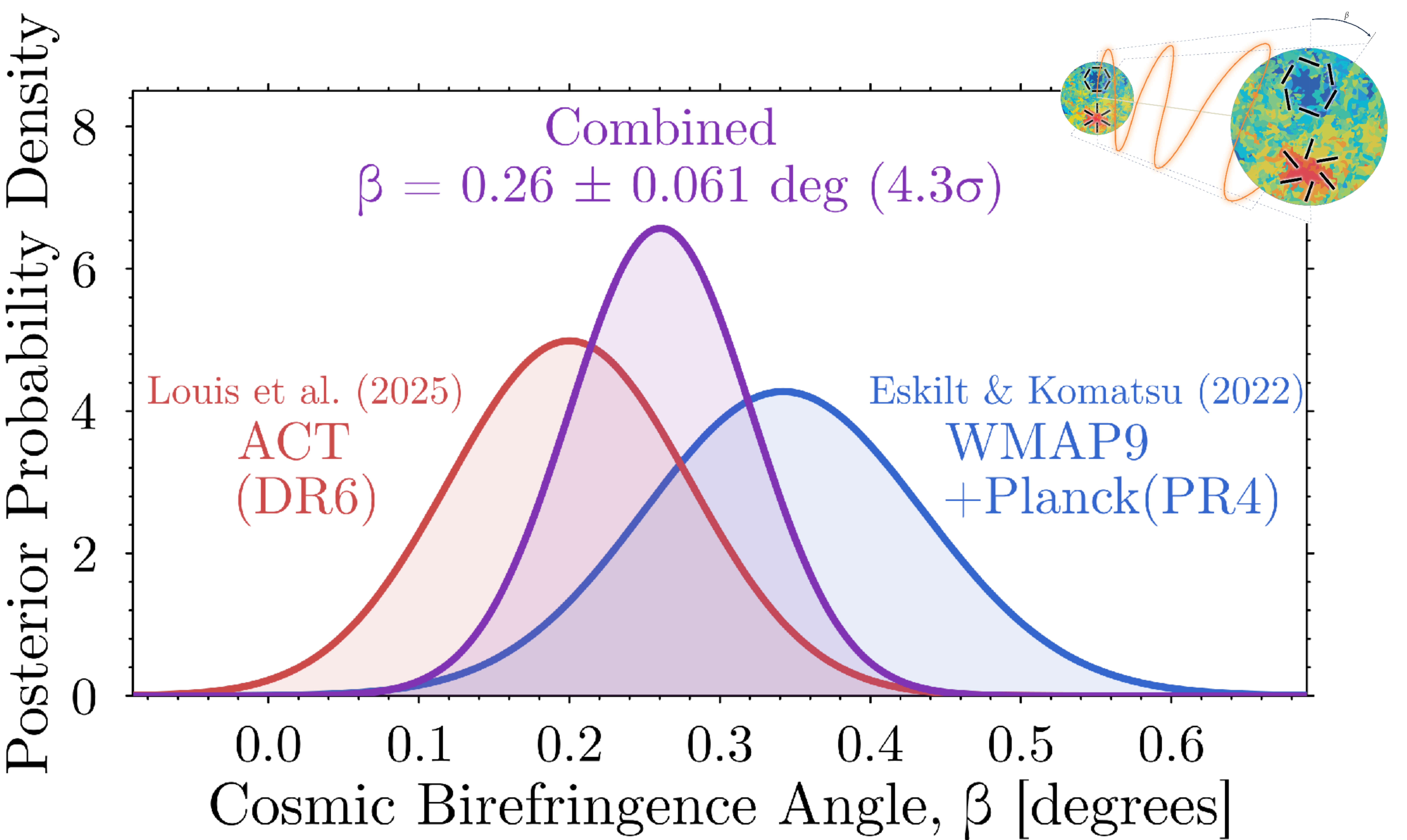
ACT Collaboration, arXiv:2503.14452

Atacama Cosmology Telescope (DR6)

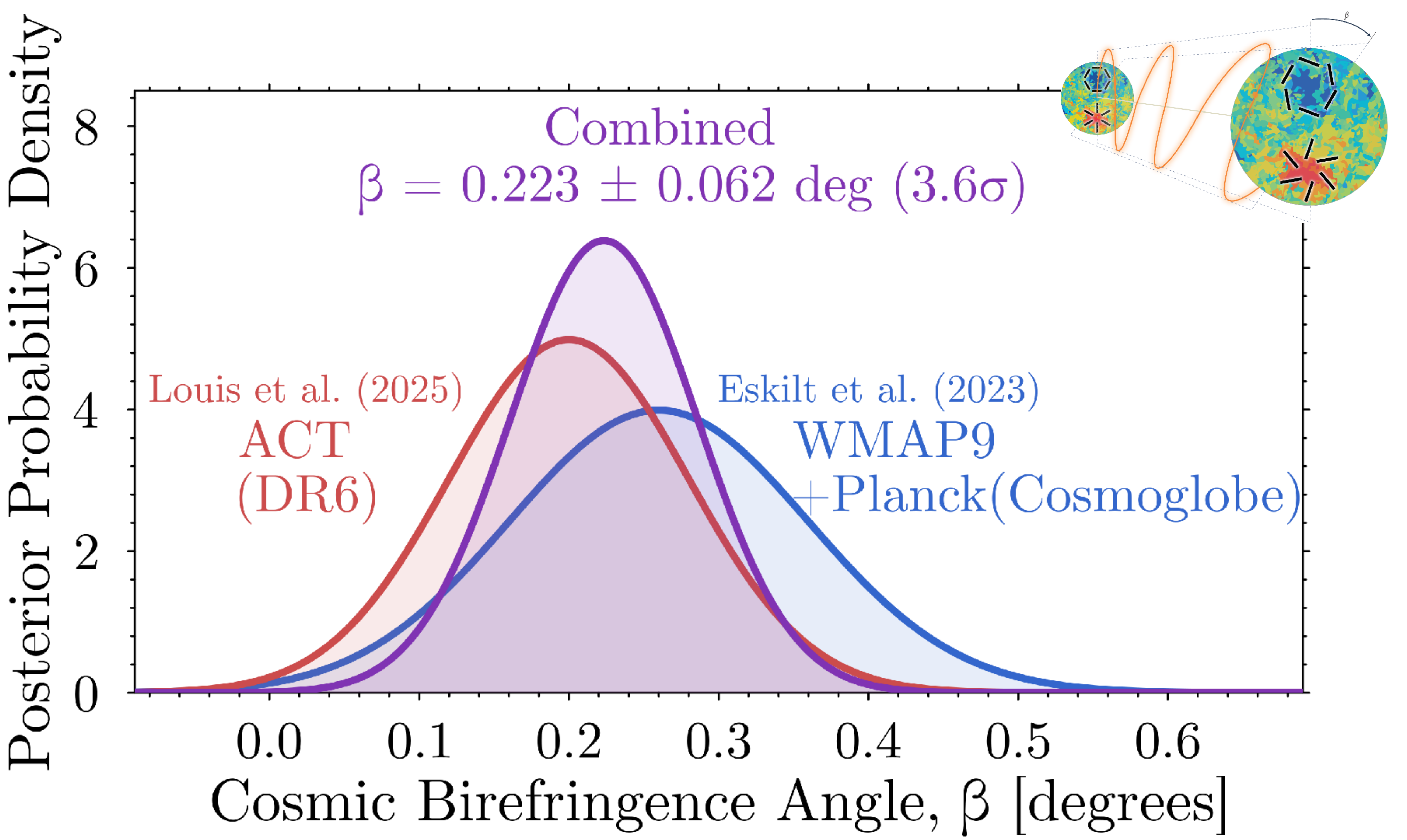
***We need to measure it in independent experiments* -> here it is!**



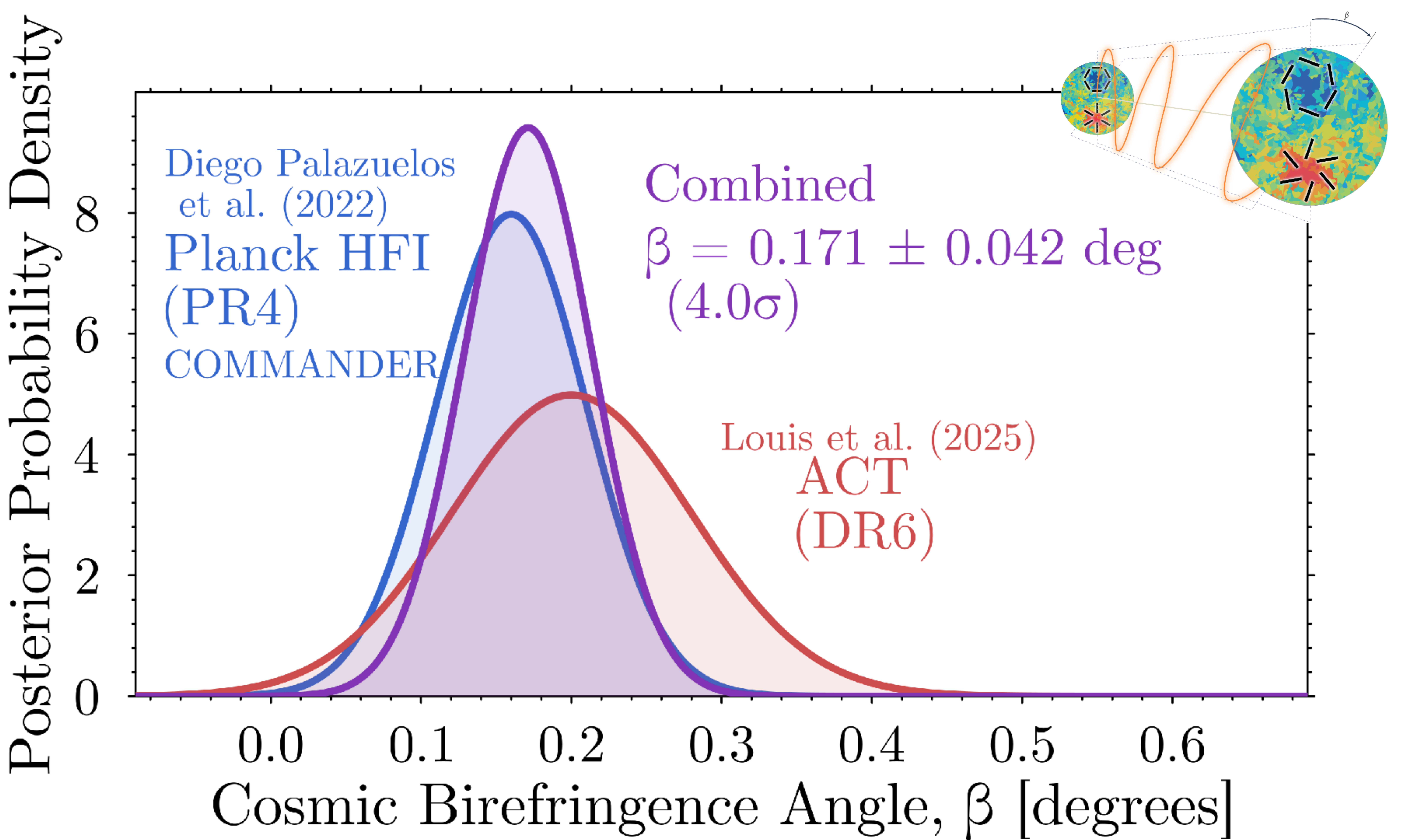
0.2 ± 0.08 deg (incl. an estimate for the systematics)



Combined
$\beta = 0.26 \pm 0.061$ deg (4.3σ)
Louis et al. (2025)
ACT
(DR6)
Eskilt & Komatsu (2022)
WMAP9
+Planck(PR4)
Posterior Probability Density
0
2
4
6
8
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Cosmic Birefringence Angle, β [degrees]
β



Combined
β = 0.223 ± 0.062 deg (3.6σ)
Louis et al. (2025)
ACT
(DR6)
Eskilt et al. (2023)
WMAP9
+Planck(Cosmoglobe)
Posterior Probability Density
0
2
4
6
8
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Cosmic Birefringence Angle, β [degrees]


Posterior Probability Density
Diego Palazuelos et al. (2022)
Planck HFI
(PR4)
COMMANDER
Combined
β = 0.171 ± 0.042 deg
(4.0σ)
Louis et al. (2025)
ACT
(DR6)
0
2
4
6
8
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Cosmic Birefringence Angle, β [degrees]

What are we worried about now?

“Unknown Unknowns”

- **WMAP+Planck**
  - The biggest worry: Unknown systematics in the Planck HFI at 353 GHz, since our results depend crucially on it.
- **ACT**
  - The biggest worry: The model for the optics of the ACT telescope and instruments may not capture all the systematics.
- The way forward: We will need another independent measurement, using an **artificial polarization source**. This will remove the dependence on any models.
  - BICEP3 (Cornelison et al., arXiv:2410.12089) and the Simons Observatory (Murata et al., arXiv:2309.02035) are doing exactly that. The final word is coming soon!

Implications

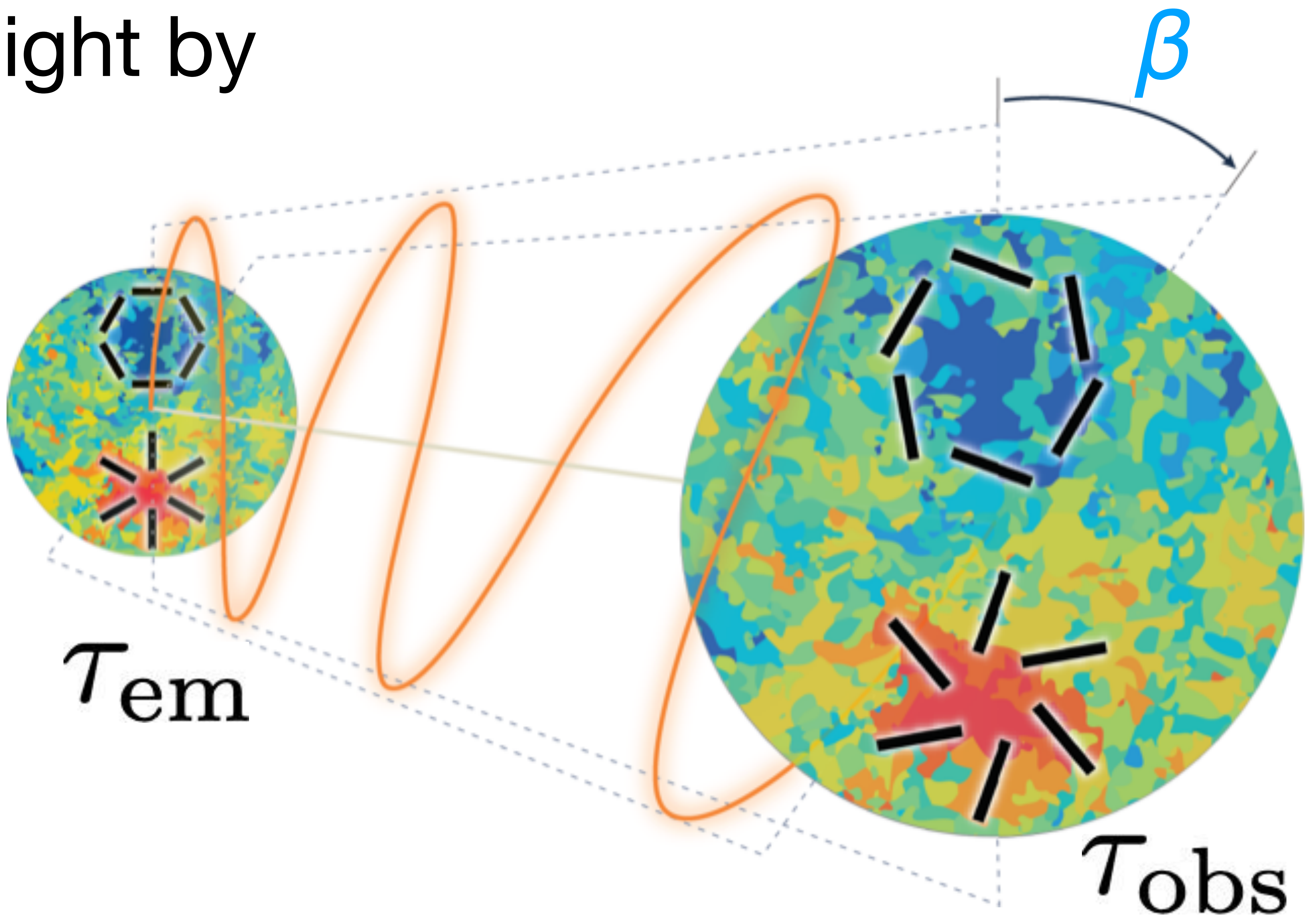
DM = Dark Matter; DE = Dark Energy

This term exists for a pion.
What if DM/DE is "pion-like particle"

$$I = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\partial\chi)^2 - V(\chi) - \frac{1}{4}F^2 - \frac{\alpha}{4f}\chi F\tilde{F}\right]$$

- This **rotates** the plane of linear polarization of light by

$$\beta = -\int_{\tau_{\rm em}}^{\tau_{\rm obs}} d\tau\,(\omega_+ - \omega_-)$$
$$= \frac{\alpha}{2f}\left[\chi(\tau_{\rm obs}) - \chi(\tau_{\rm em})\right]$$



Implications

DM = Dark Matter; DE = Dark Energy

This term exists for a pion.
What if DM/DE is "pion-like particle"

$$I = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\partial\chi)^2 - V(\chi) - \frac{1}{4}F^2 - \frac{\alpha}{4f}\chi F\tilde{F}\right]$$

- The measured angle, β, implies that the field has evolved by

$$\Delta\chi = \chi(\tau_{\rm obs}) - \chi(\tau_{\rm em}) \simeq \frac{10^{-2}}{\alpha}f$$

Axionlike particle?

- If it is due to DE: this measurement rules out DE being a cosmological constant.

- If it is due to DM: at least a fraction of DM violates parity symmetry.

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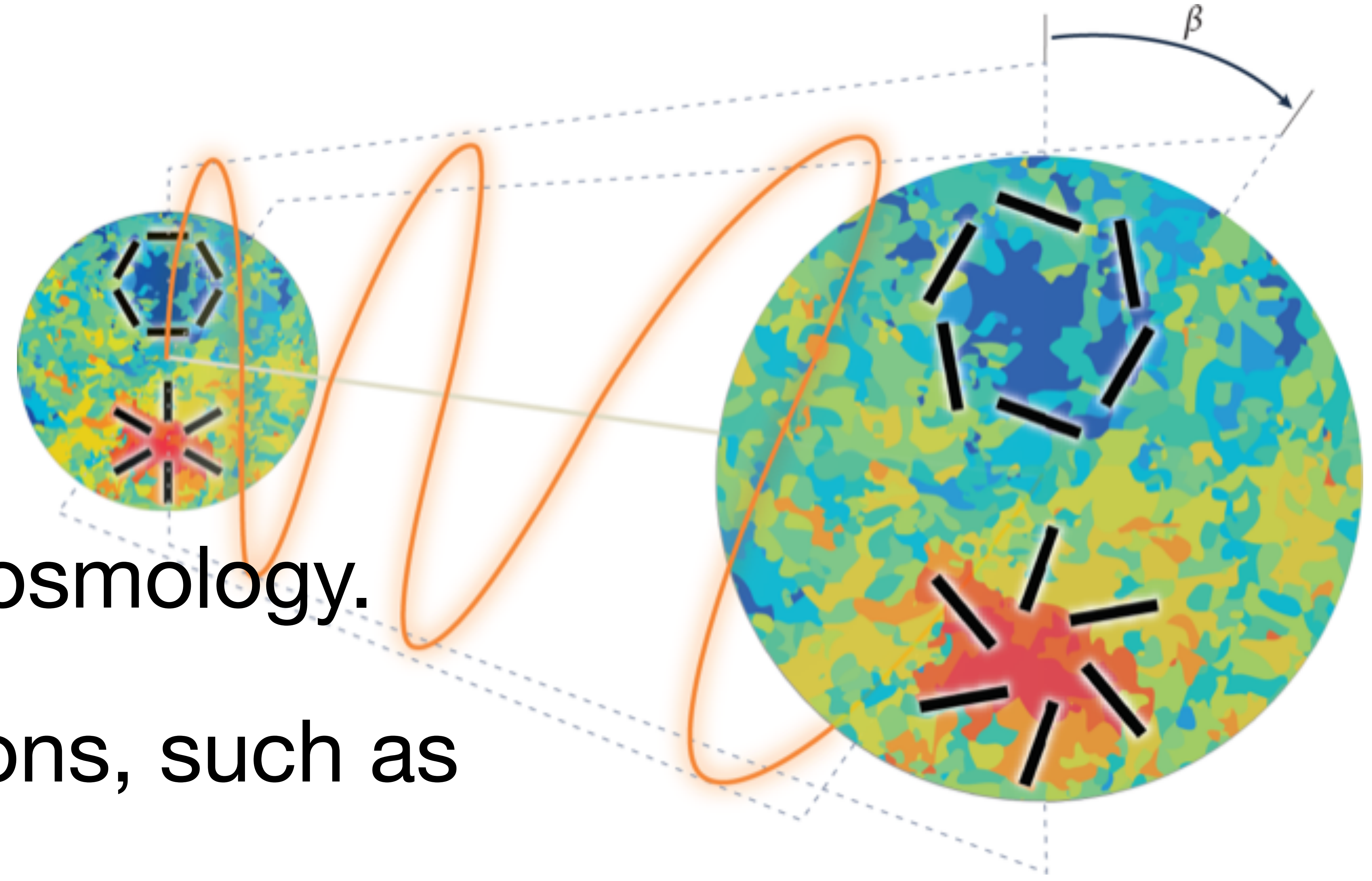
So, space may be filled with axionlike particles…



Summary

Let's find new physics!

- Violation of parity symmetry is a new topic in cosmology.
- It may hold the answers to fundamental questions, such as
    - *What is Dark Matter?*
    - *What is Dark Energy?*
- Since parity is violated in the weak interaction, it seems natural to expect that **parity is also violated in the Dark Sector**.
    - **4σ hint of Cosmic Birefringence**: Space may be filled with parity-violating DM and DE fields?
- **What else should we be looking? New and exciting research topics.**