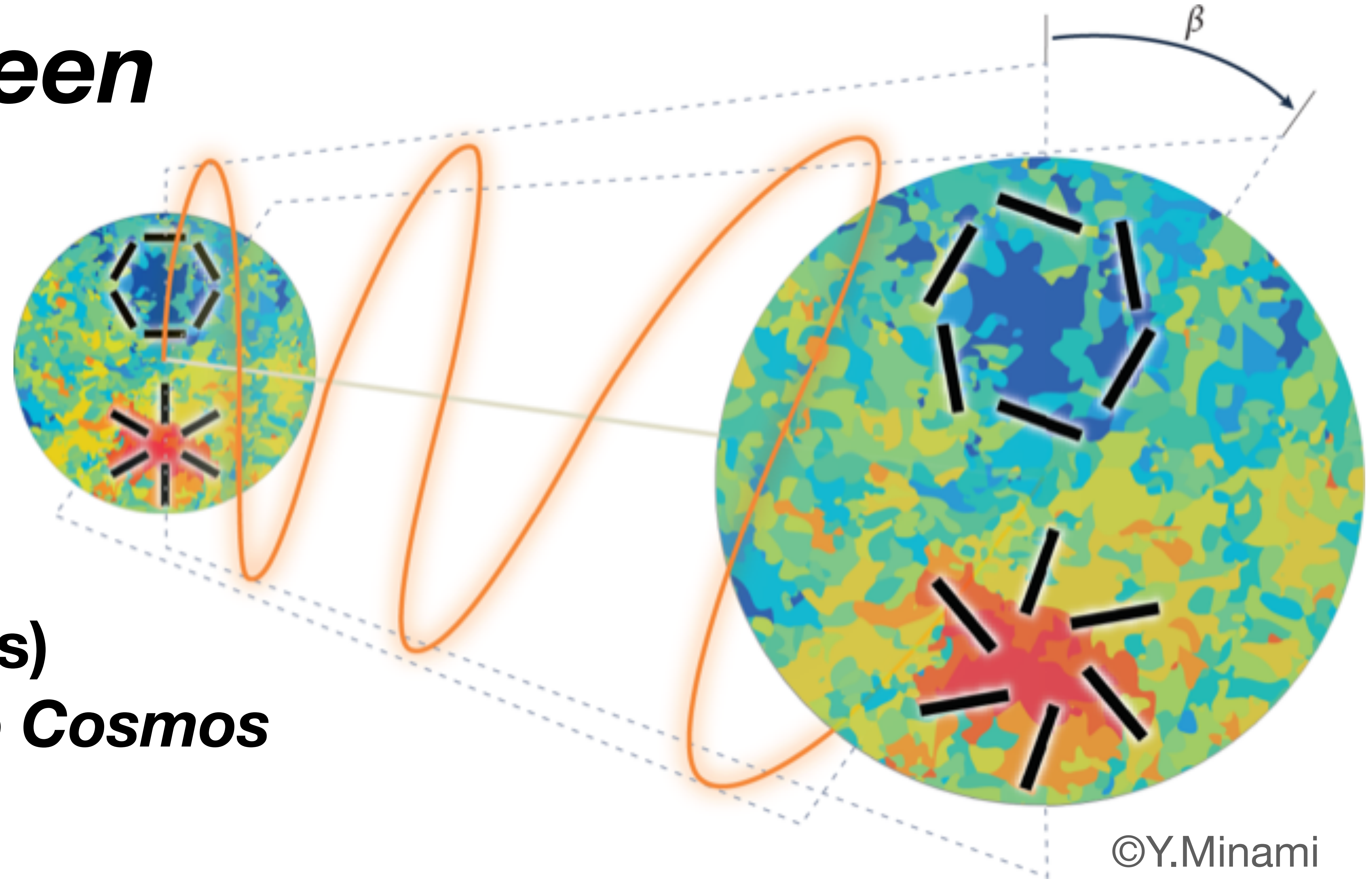
Reference: EK, Nature Rev. Phys. **4**, 452 (2022)

Parity Violation in Cosmology

Does the Universe distinguish between left and right?



Eiichiro Komatsu (Max Planck Institute for Astrophysics)

550 Years of the Copernican Universe: Our Place in the Cosmos

November 10, 2023

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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

https://wwwmpa.mpa-garching.mpg.de/~komatsu/lectures--reviews.html

Lectures & Reviews

2023

- Lecture Slides: **"Parity Violation in Cosmology" [7 x 85 min]**
  - MC Specialized Course, Department of Physics, Nagoya University (June 6–30)
    - The syllabus is available **here**.
    - Reference: "*New Physics from the Polarized Light of the Cosmic Microwave Background*"
      - **Nature Reviews Physics, 4, 452-469 (2022 May 18)**. You can have access to the full text via **this link**. Supplementary information is available **here**.
  - **Lecture 1**: What is parity symmetry? (PDF 3.9 MB; last updated, June 5, 2023)
    - 1.1 Parity
    - 1.2 Vector and pseudovector
    - 1.3 Discovery of parity violation in β-decay
    - 1.4 Helicity
  - **Lecture 2**: Chern-Simons interaction (PDF 1.6 MB; last updated, June 8, 2023)
    - 2.1 Parity symmetry in electromagnetism (EM)

⋮

Probing Parity Symmetry

Definition

- **Parity transformation = Inversion of all spatial coordinates**
  - (x, y, z) –> (-x, -y, -z)
- Parity symmetry in physics states:
  - *The laws of physics are invariant under inversion of all spatial coordinates.*
- Violation of parity symmetry = The laws of physics are **not** invariant under…
- Ask "***When we observe a certain phenomenon in nature, do we also observe its mirror image(*) with equal probability?***"
  - (*) "Mirror image" is an ambiguous word. A parity transformation is (x, y, z) –> (-x, -y, -z), whereas a "mirror image" often refers to, e.g., (x, y, z) –> (-x, y, z), where only one of (x,y,z) is flipped.

Do we also observe this with equal probability?

Note that this is not full parity transformation, as only one axis is flipped.

Parity and Rotation

- Parity transformation (***x*** –> -***x***) and 3d rotation (***x*** –> R***x***) are different.
  - R is a continuous transformation and the determinant of R is det(R) = +1.
  - Parity is a discrete transformation and the **determinant is –1**, as

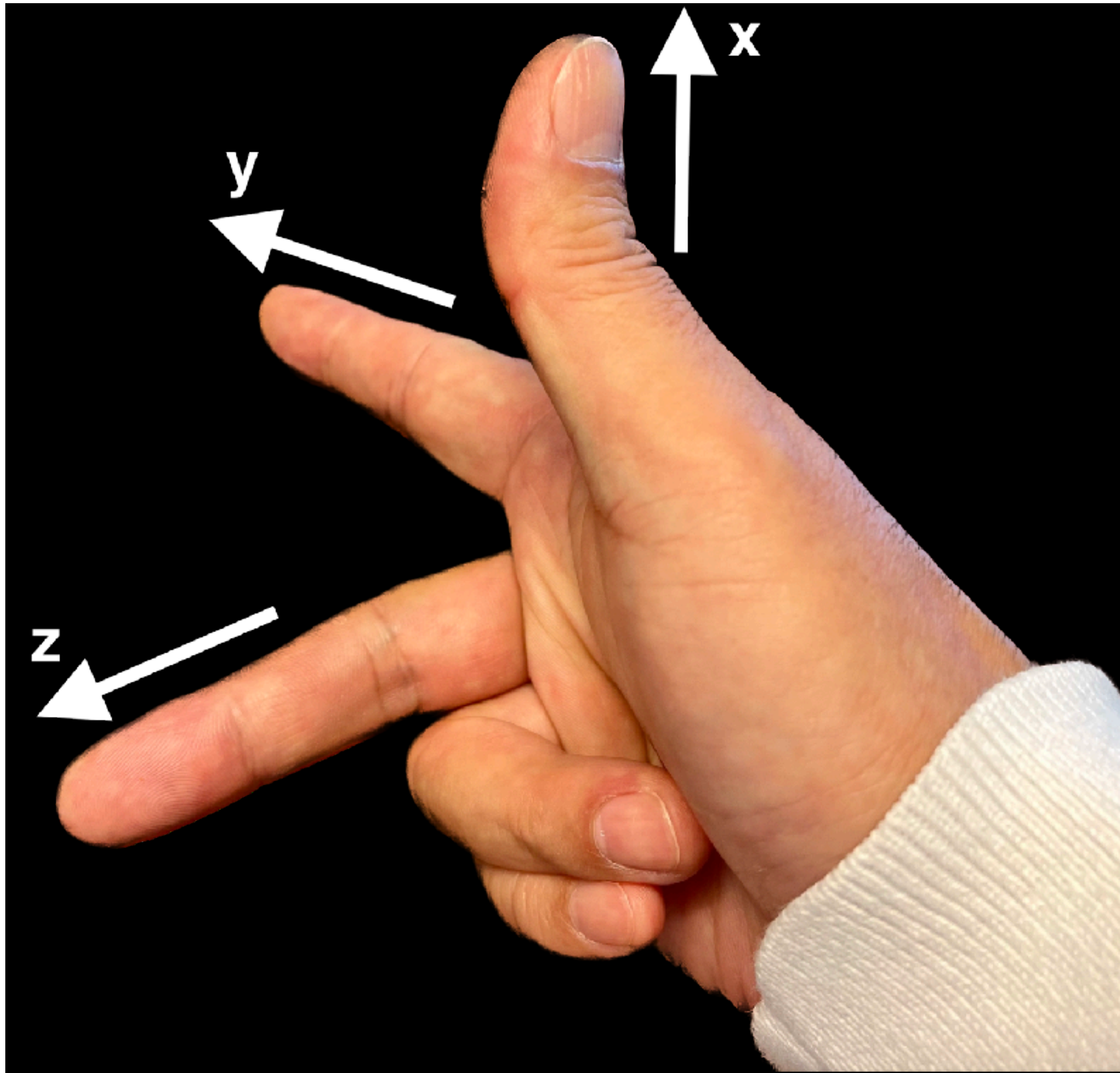
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

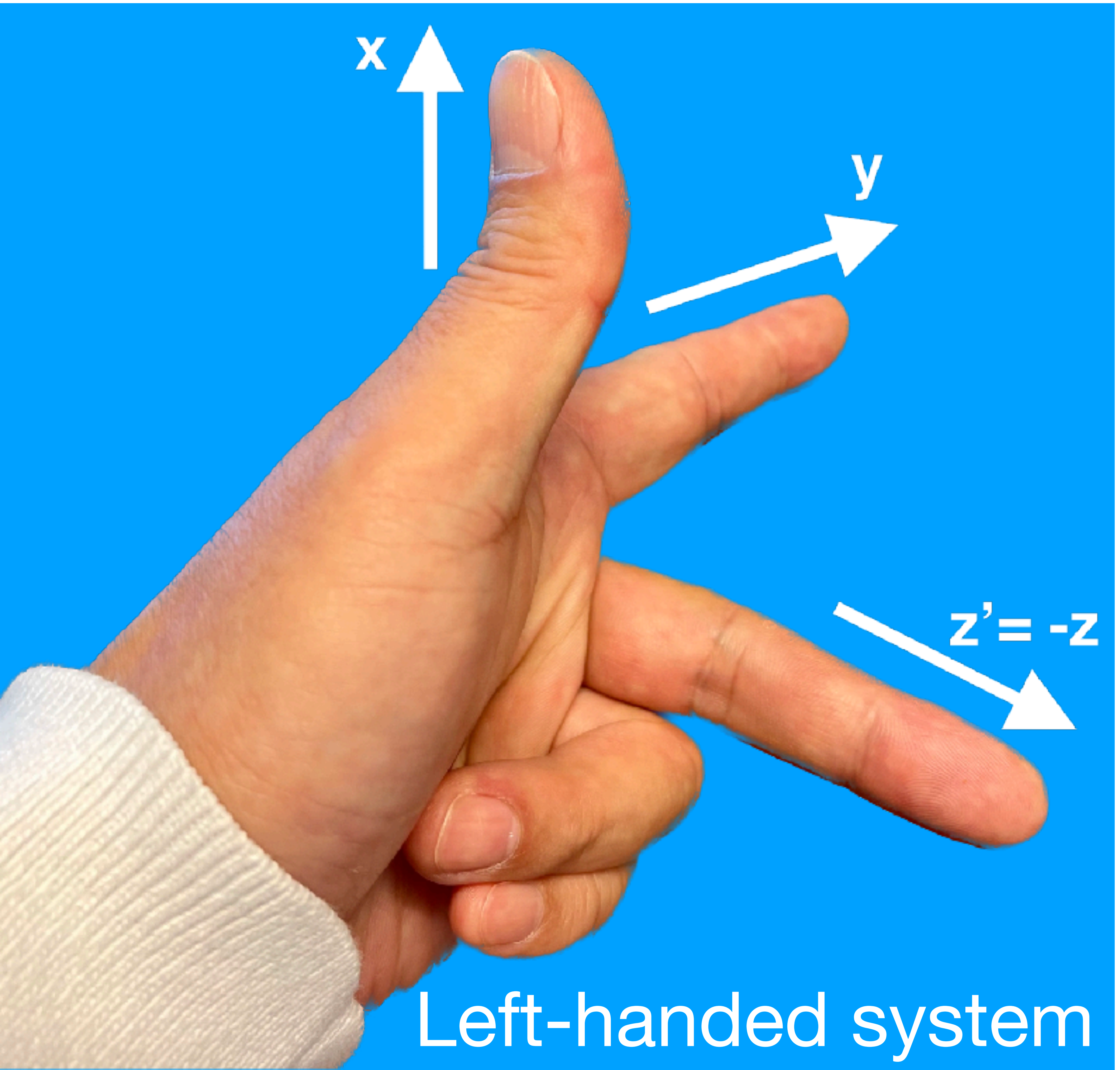
Parity = Mirror + 2d Rotation

- One may think of parity transformation as a mirror in one of the coordinates (e.g., z –> -z) and **2d** rotation by π in the others.

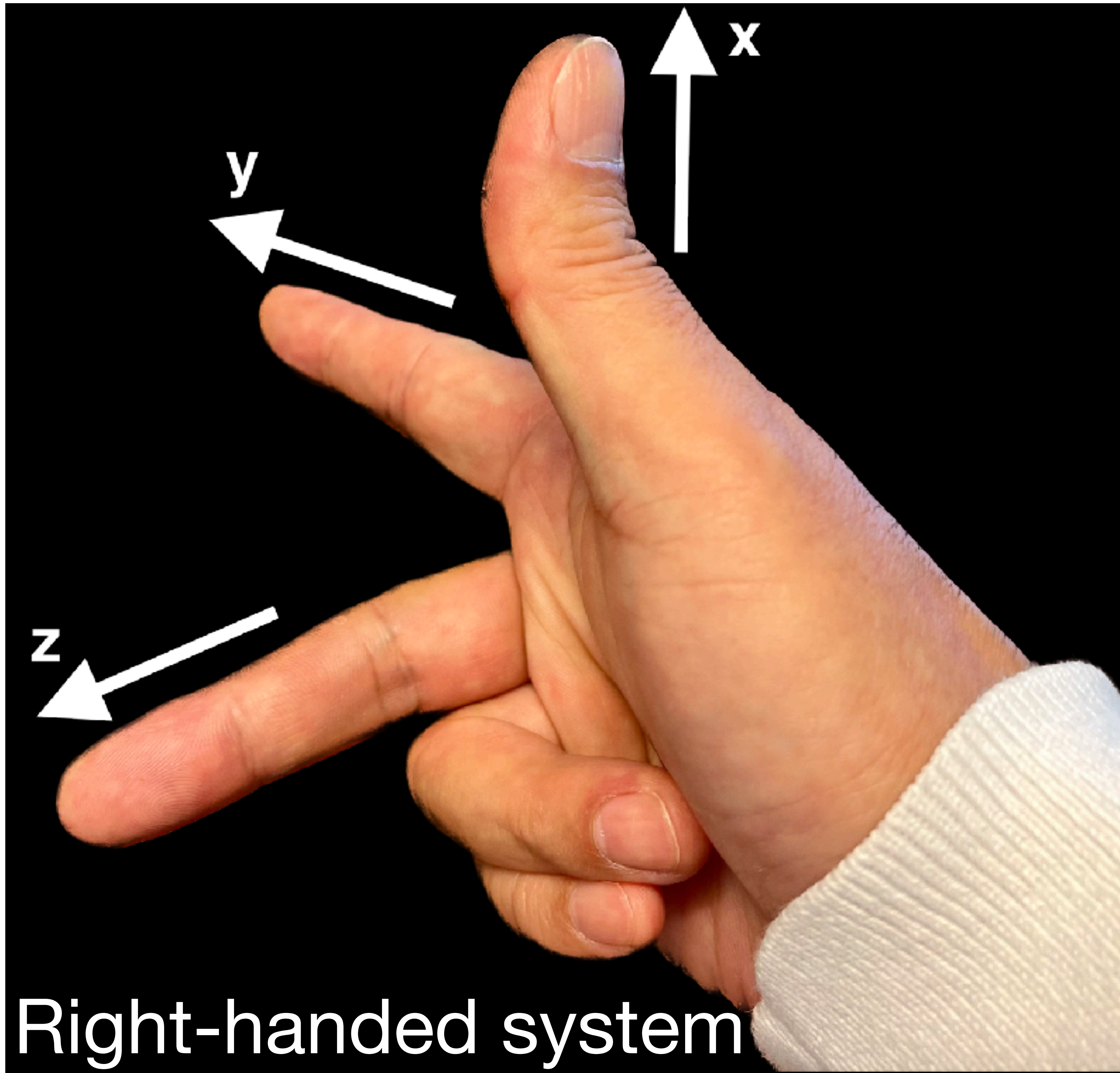
- Let’s demonstrate it!



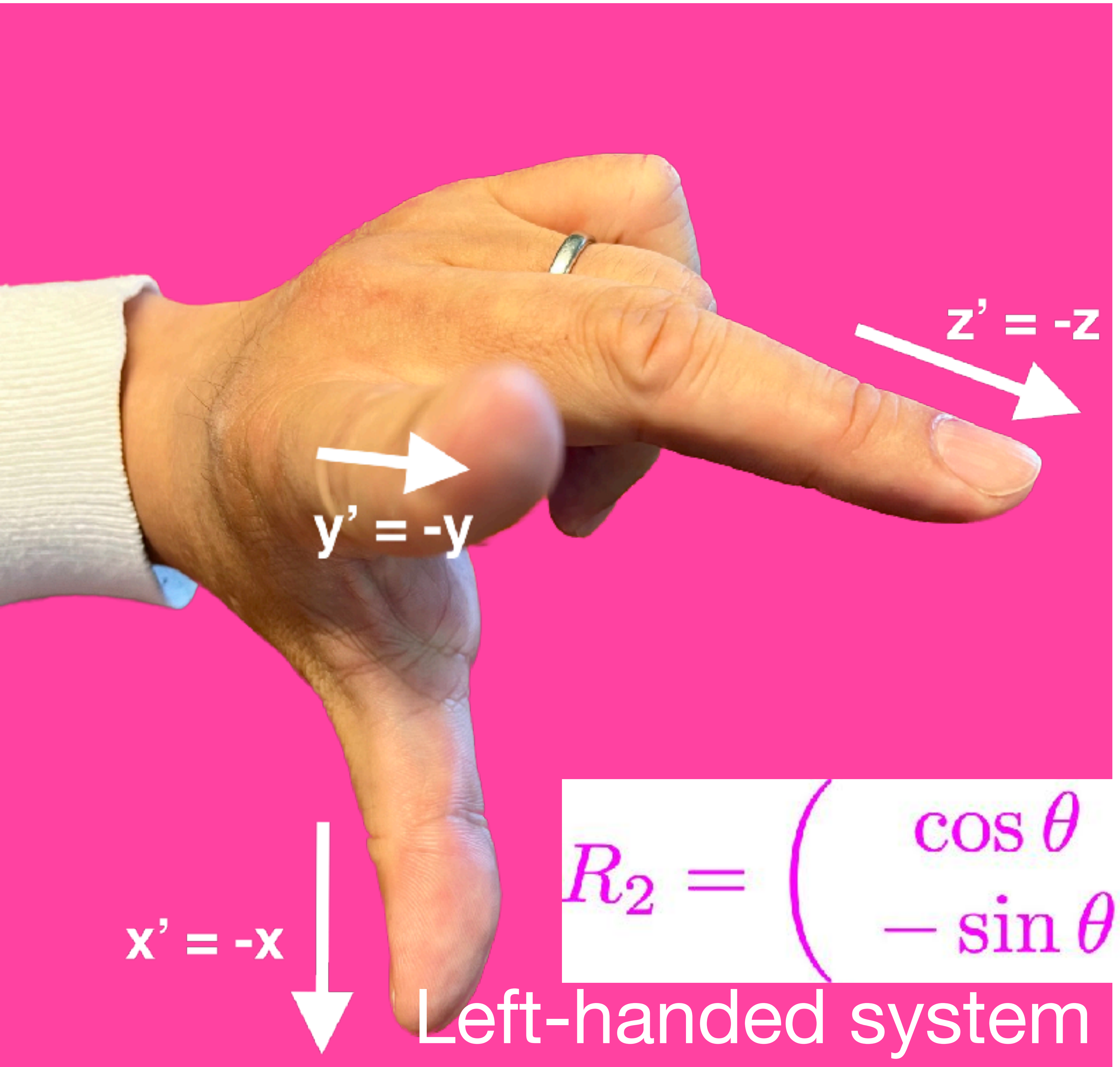
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & \boxed{-1} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$



z -> z' = -z



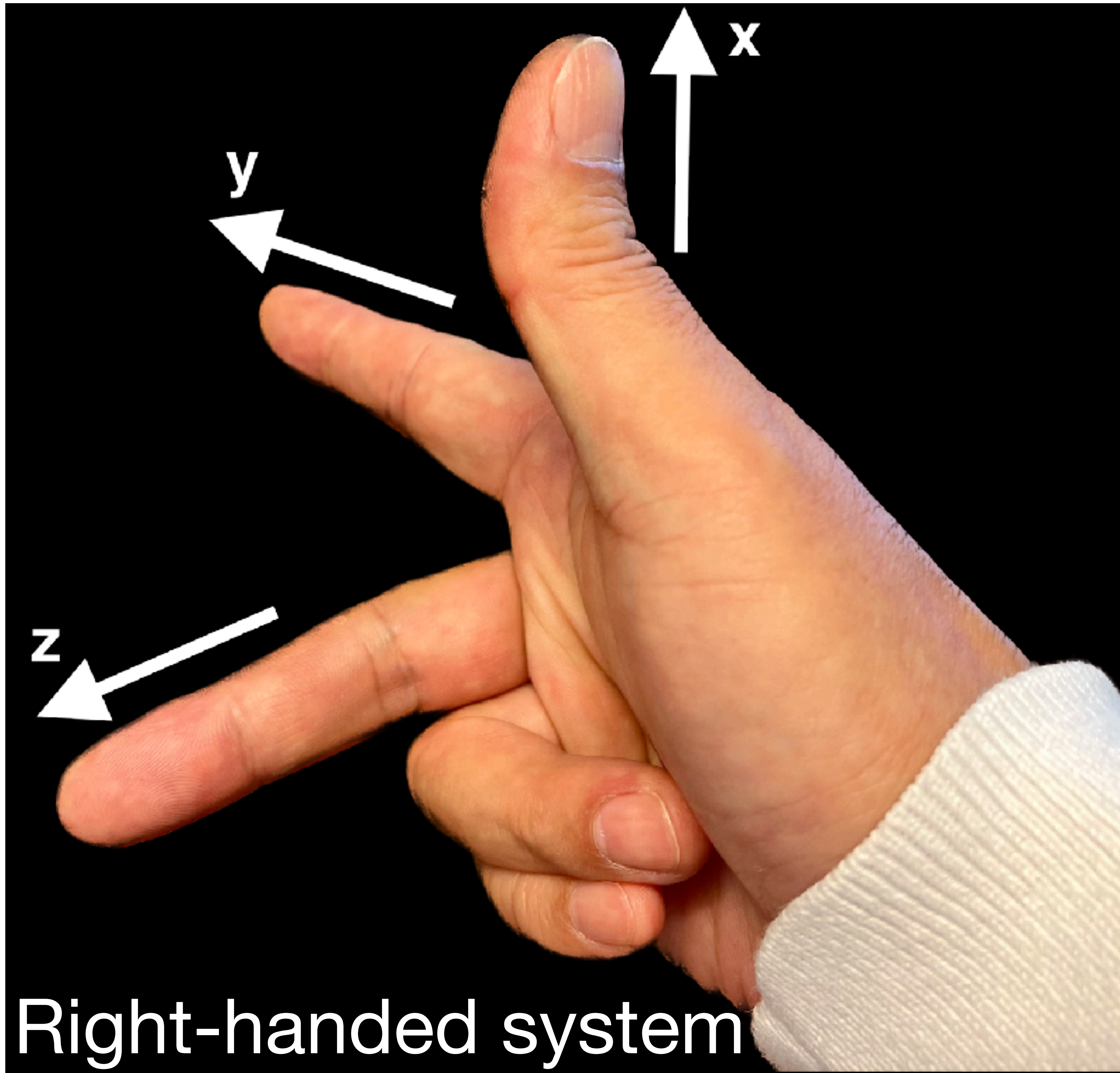
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$



Rotation
In x-y

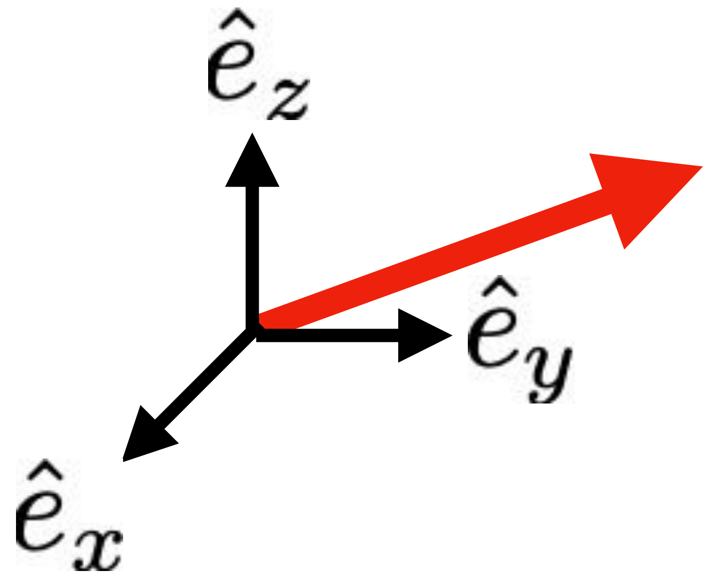
$$R_2 = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

with θ = π



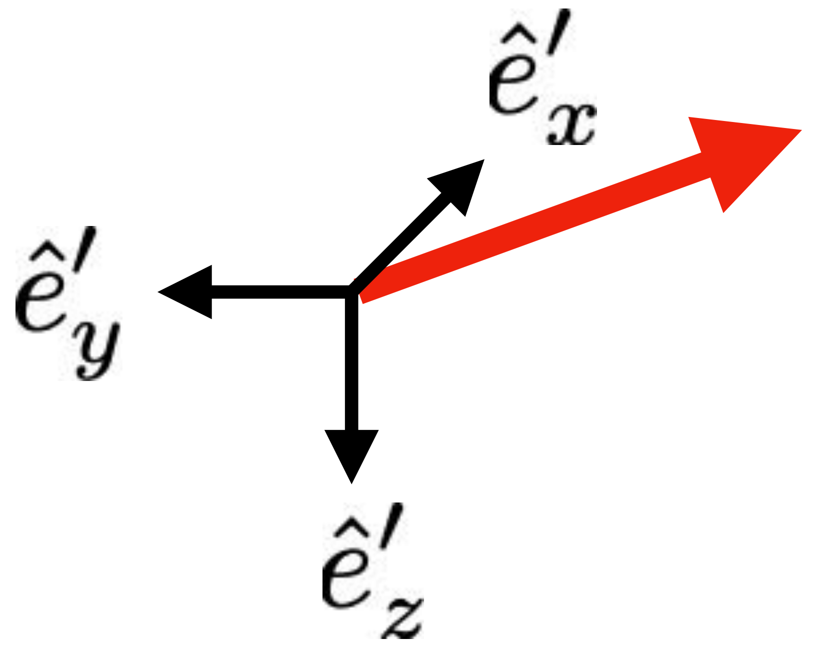
Parity Transformation: Vector

E.g., momentum, electric field



$$\mathbf{p} = p_x \hat{e}_x + p_y \hat{e}_y + p_z \hat{e}_z$$

$\hat{e}_i$ is a unit vector.



$$\begin{aligned}\mathbf{p} &= p'_x \hat{e}'_x + p'_y \hat{e}'_y + p'_z \hat{e}'_z \\ &= -p'_x \hat{e}_x - p'_y \hat{e}_y - p'_z \hat{e}_z\end{aligned}$$

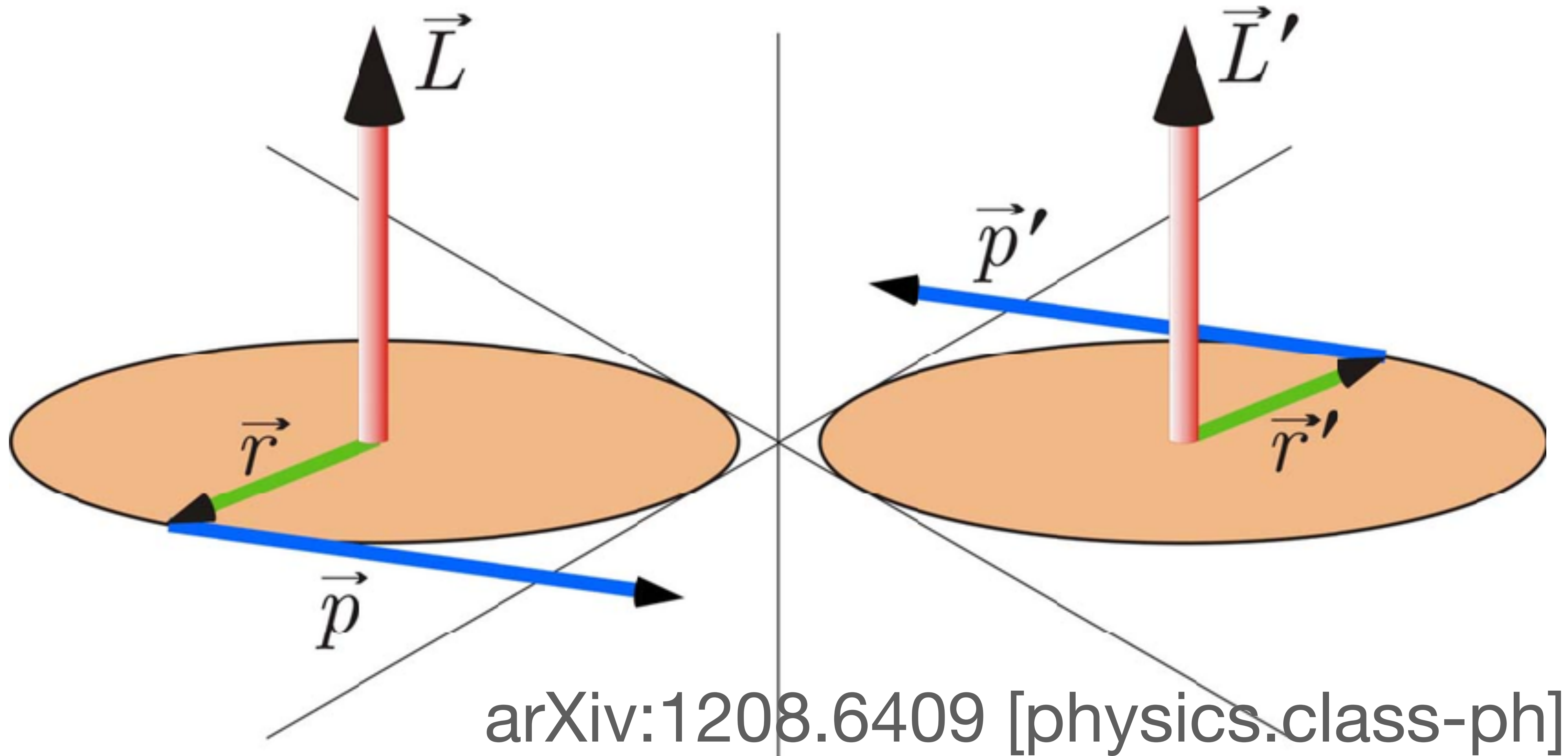
- **p** is the same vector, written using two different basis vectors.
- Therefore, **p**'s components are transformed as $(p'_x, p'_y, p'_z) = (-p_x, -p_y, -p_z)$

Parity Transformation: Pseudovector

E.g., angular momentum, magnetic field

- Orbital angular momentum, $\mathbf{L} = \mathbf{r} \times \mathbf{p}$, is a *pseudovector*. Its *components* do **not** change under parity transformation: $(L'_x, L'_y, L'_z) = (L_x, L_y, L_z)$
  - Both $\mathbf{r} = (X, Y, Z)$ and $\mathbf{p} = (p_x, p_y, p_z)$ are vectors whose components change sign. Thus, their products do not change, e.g.,

$$
\begin{aligned}
L'_x &= Y' p'_z - Z' p'_y \\
&= (-Y)(-p_z) - (-Z)(-p_y) \\
&= L_x
\end{aligned}
$$



arXiv:1208.6409 [physics.class-ph]

Key Point

Parity Transformation: Pseudoscalar

How to test parity symmetry?

- A dot product of a vector and a pseudovector is a **pseudoscalar**.
  - Like a scalar, a pseudoscalar is invariant under rotation.
  - But, a pseudoscalar changes sign under parity transformation.
- **Experimental test of parity symmetry**: Construct a pseudoscalar and see if the average value is zero. If not, the system violates parity symmetry!
  - *Example*: a dot product of particle A's momentum and particle B's angular momentum: $\mathbf{p}_\mathrm{A} \cdot \mathbf{L}_\mathrm{B}$. Measure this and average over many trials. Does the average vanish, $\langle \mathbf{p}_\mathrm{A} \cdot \mathbf{L}_\mathrm{B} \rangle = 0$?

Letters to the Editor,
Physical Review, 105, 1413 (1957)

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

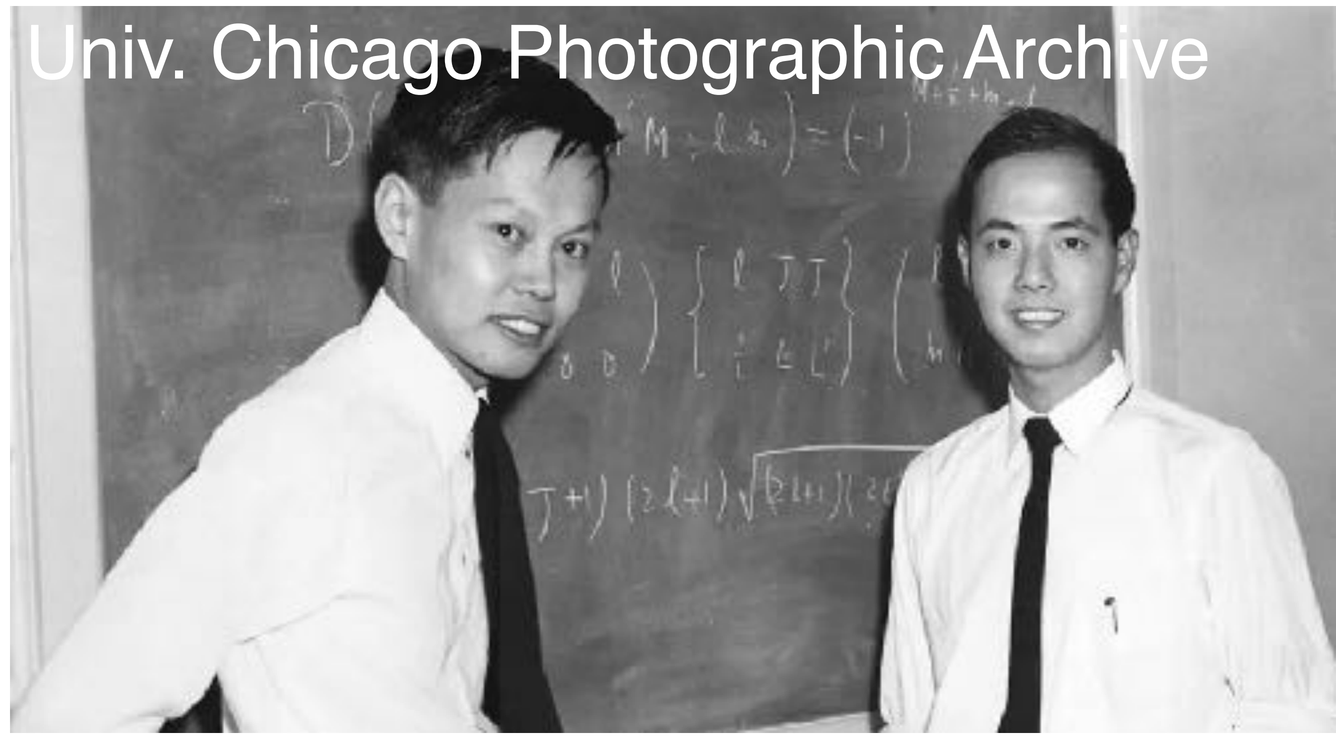
AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the

Chien-Shiung Wu



Chen-Ning Yang Tsung-Dao Lee

The Wu Experiment of β-decay

$^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e + 2\gamma$

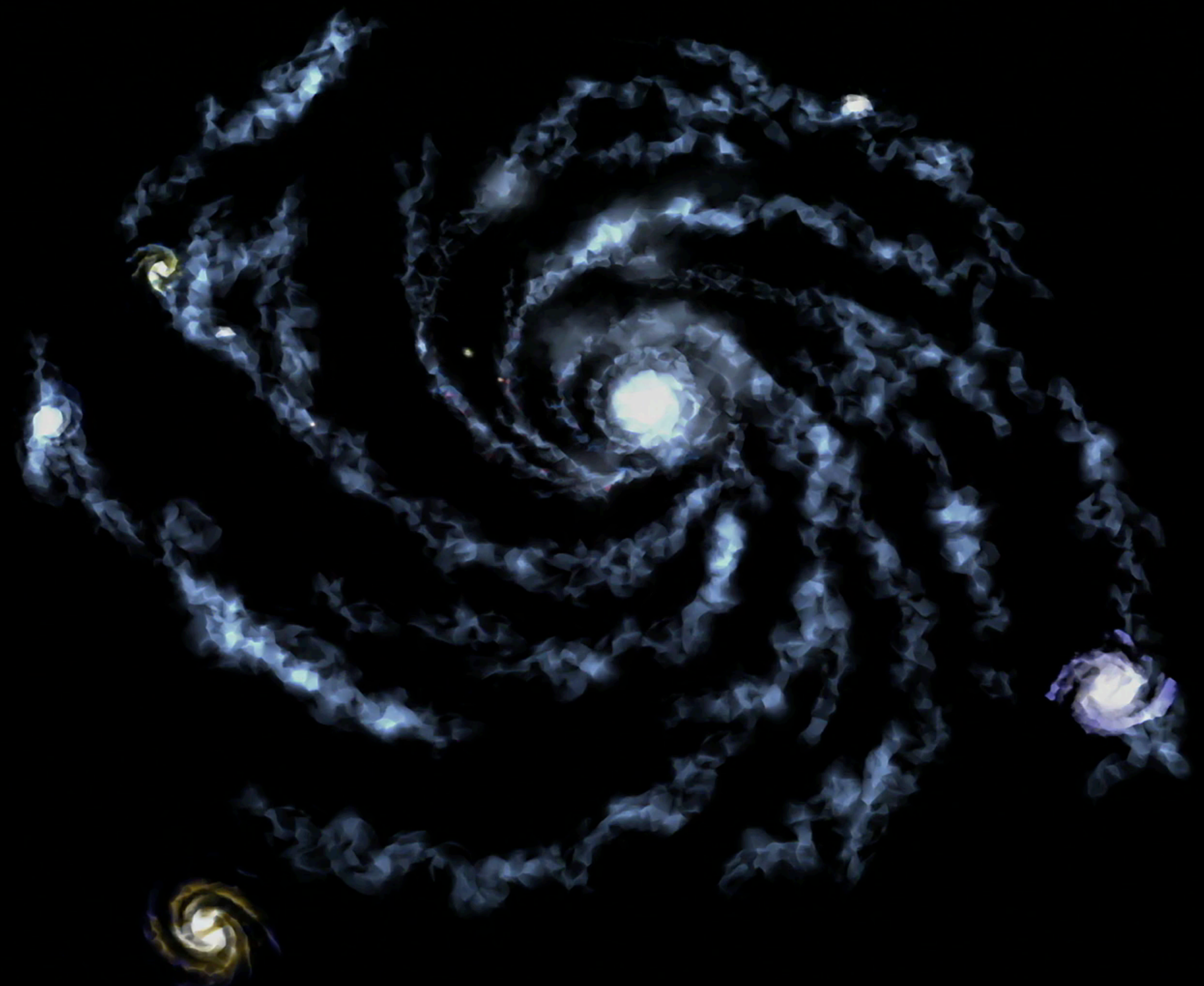
- Electrons must be emitted with equal probability in all directions relative to **J**, if parity symmetry is respected in β-decay.
  - This was not observed: $\langle \mathbf{p}_e \cdot \mathbf{J} \rangle \neq 0$. **Parity symmetry is violated in β-decay!**

Initial reaction

Bildarchiv der ETH-Bibliothek

Many physicists did not believe it initially.

- To Lee and Yang's theoretical paper on parity violation in β-decay:
  - Wolfgang Pauli said, "*Ich glaube aber nicht, daß der Herrgott ein schwacher Linkshänder ist*" (I do not believe that the Lord is a weak left-hander).
- To Wu's discovery paper:
  - Wolfgang Pauli said, "*Sehr aufregend. Wie sicher ist die Nachricht?*" (Very exciting. How sure is this news?)
- **This was shocking news. The weak interaction distinguishes between left and right!**
- In this talk we ask, "*Does the Universe distinguish between left and right?*" Most scientists answer, "No, of course it doesn't". **That may well be true, but one must at least have a look to be sure!**

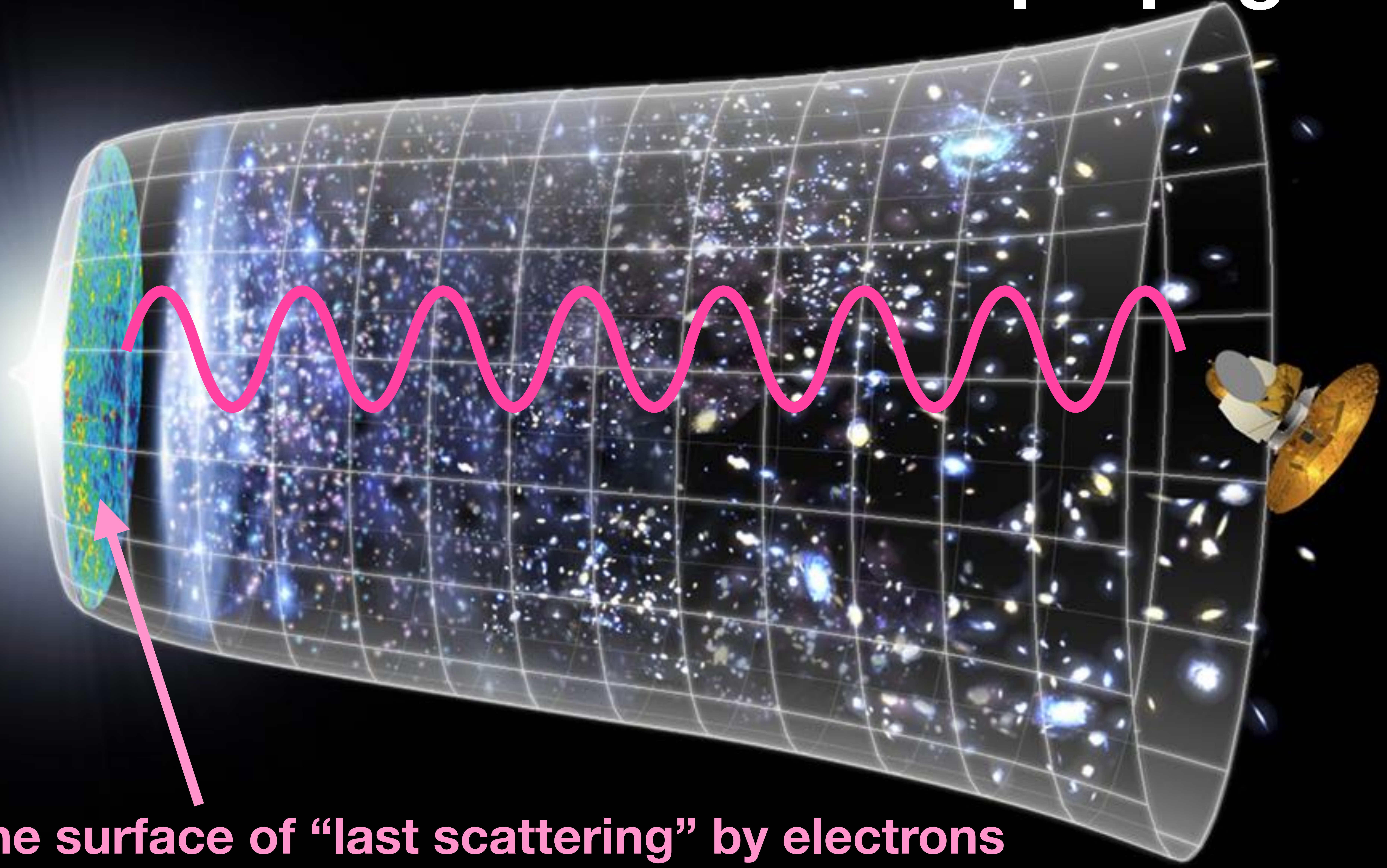


Emitted 13.8 billions years ago

Credit: ESA

Emitted 13.8 billions years ago

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?

Key Point

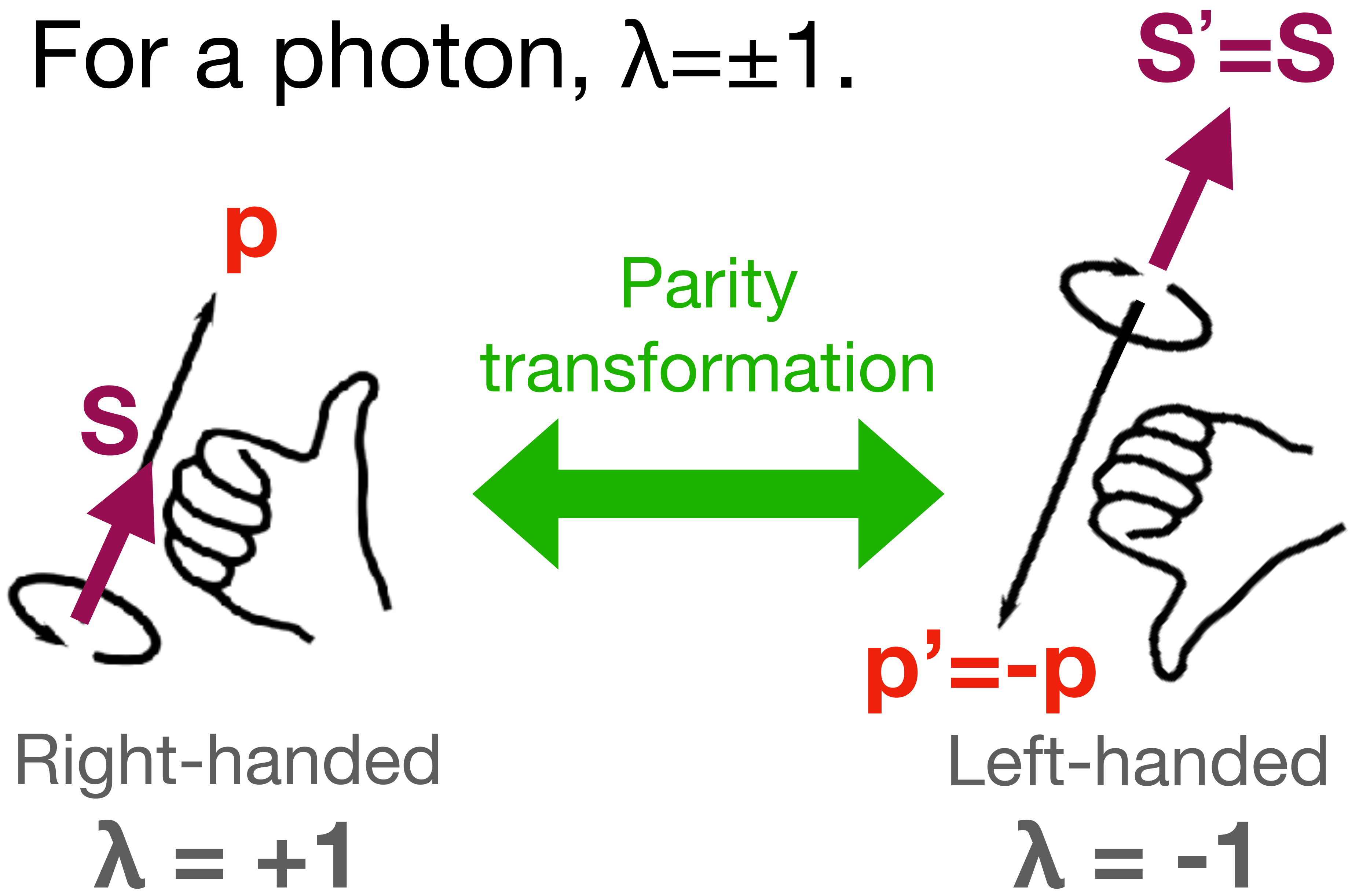
Helicity is a pseudoscalar

Party transformation changes “right-handed” to “left-handed” and vice versa

- For massless particles, we define the “helicity”, λ, as

$$\mathbf{S} \cdot \frac{\mathbf{p}}{|\mathbf{p}|} = \lambda\hbar$$

- For a photon, λ=±1.



- **λ is a pseudoscalar** because it is a product of a momentum vector (**p**) and a spin pseudovector (**S**).
  - On the other hand, “scalar”, such as $\mathbf{p}^2$ and $\mathbf{S}^2$, does not change sign.
- For a graviton, λ=±2.
- **Asymmetry between λ=±1 and ±2 is the sign of parity violation!**

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!

Key Point

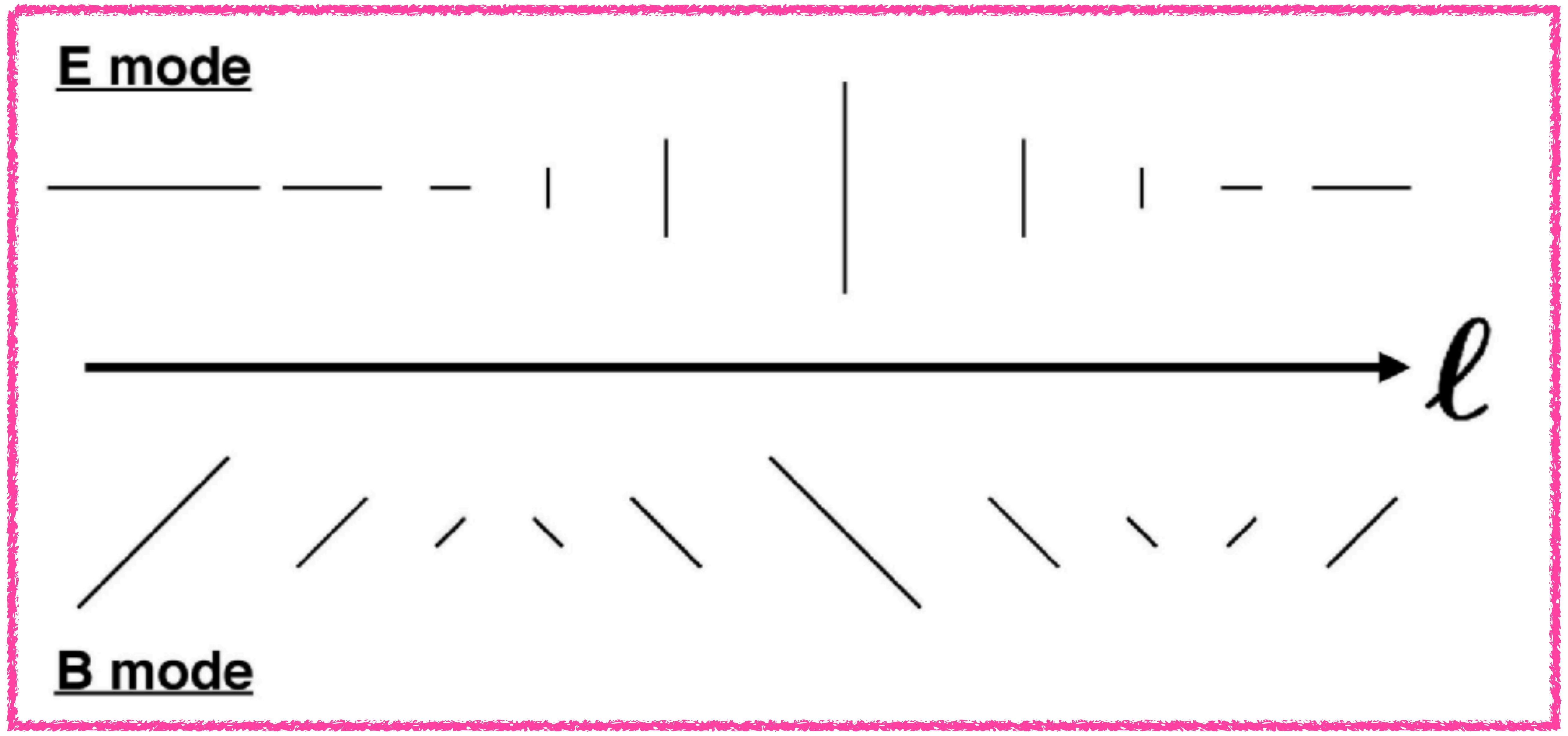
Pseudoscalar: EB correlation

- 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!**

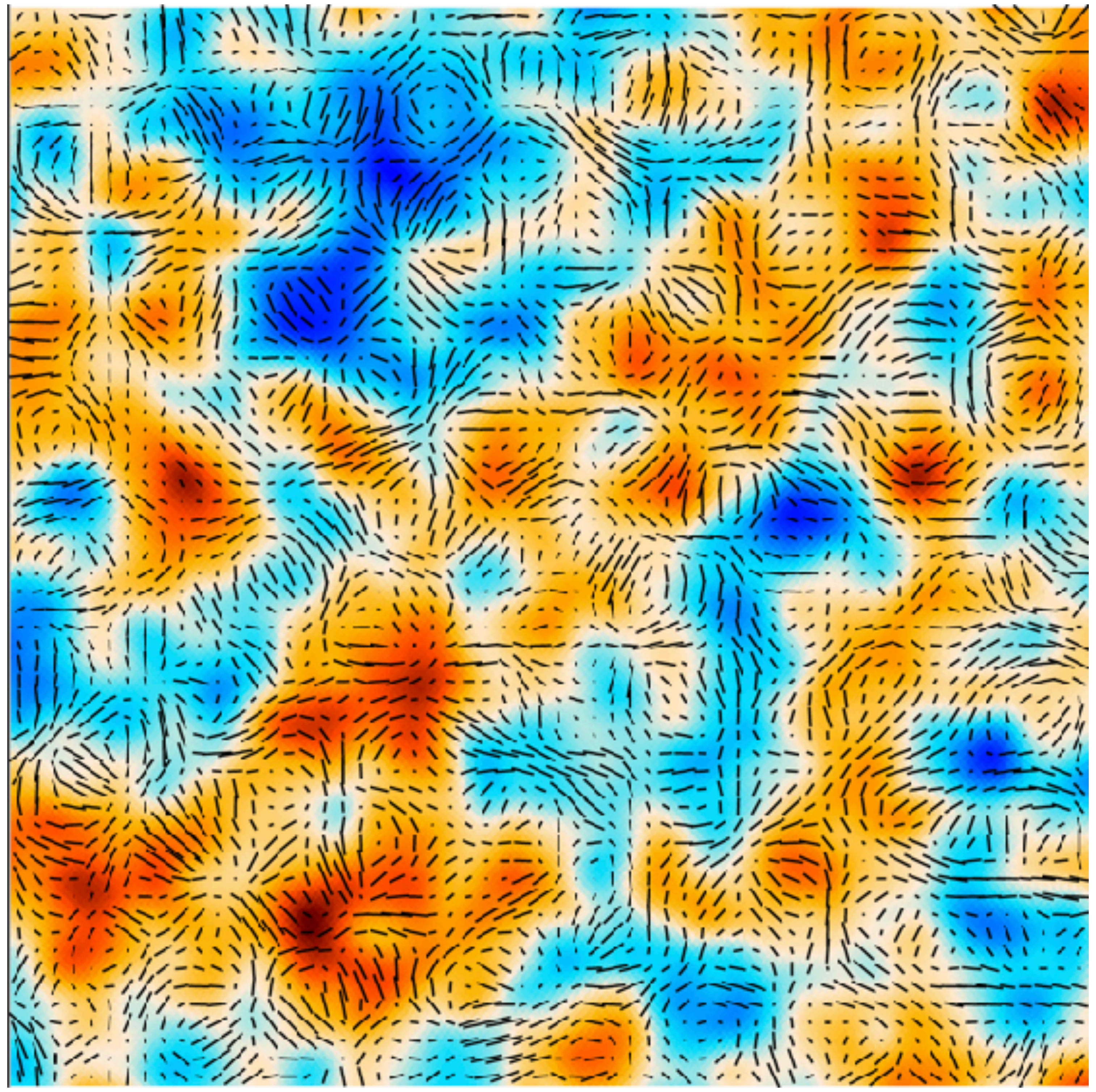
Zaldarriaga, Seljak (1997); Kamionkowski, Kosowsky, Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



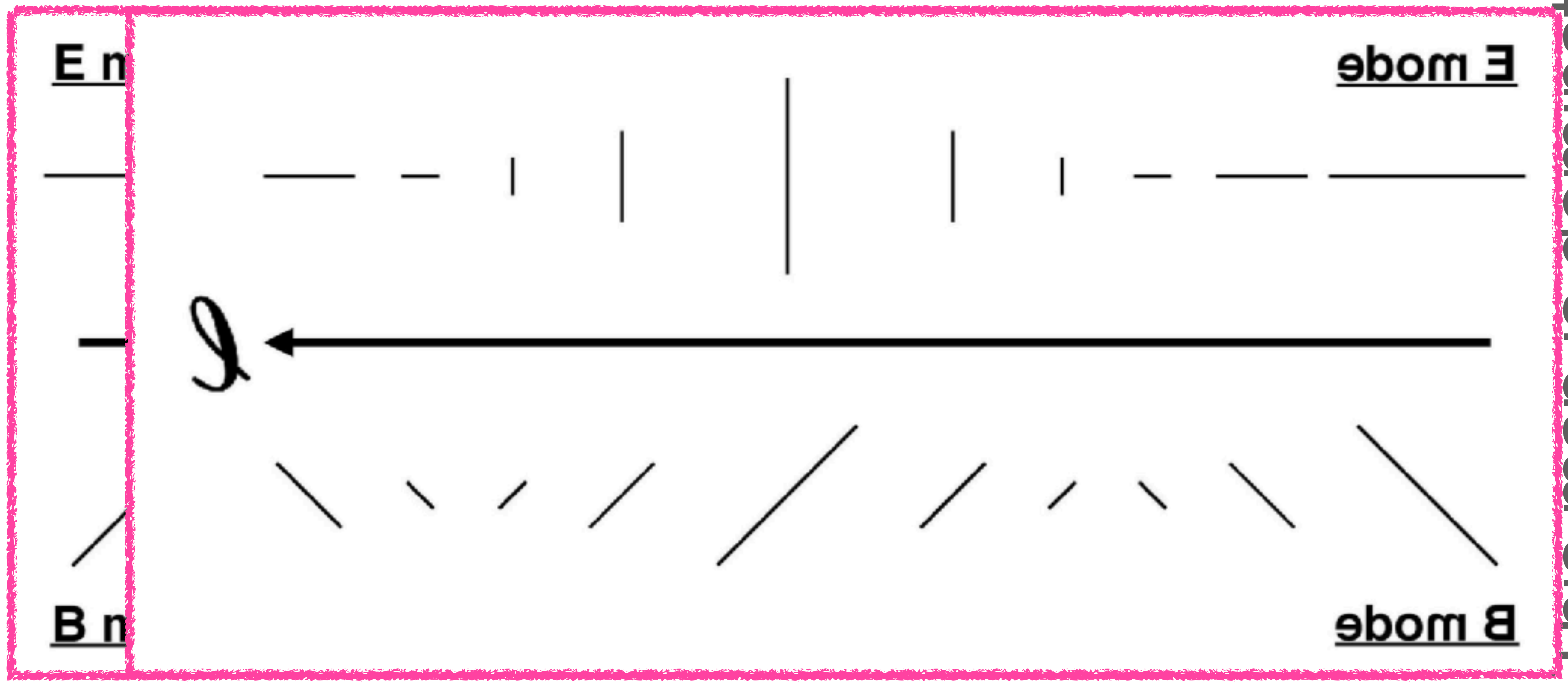
- **E-mode**：Polarization directions are **parallel or perpendicular** to the wavenumber direction

- **B-mode**：Polarization directions are **45 degrees tilted** w.r.t the wavenumber direction

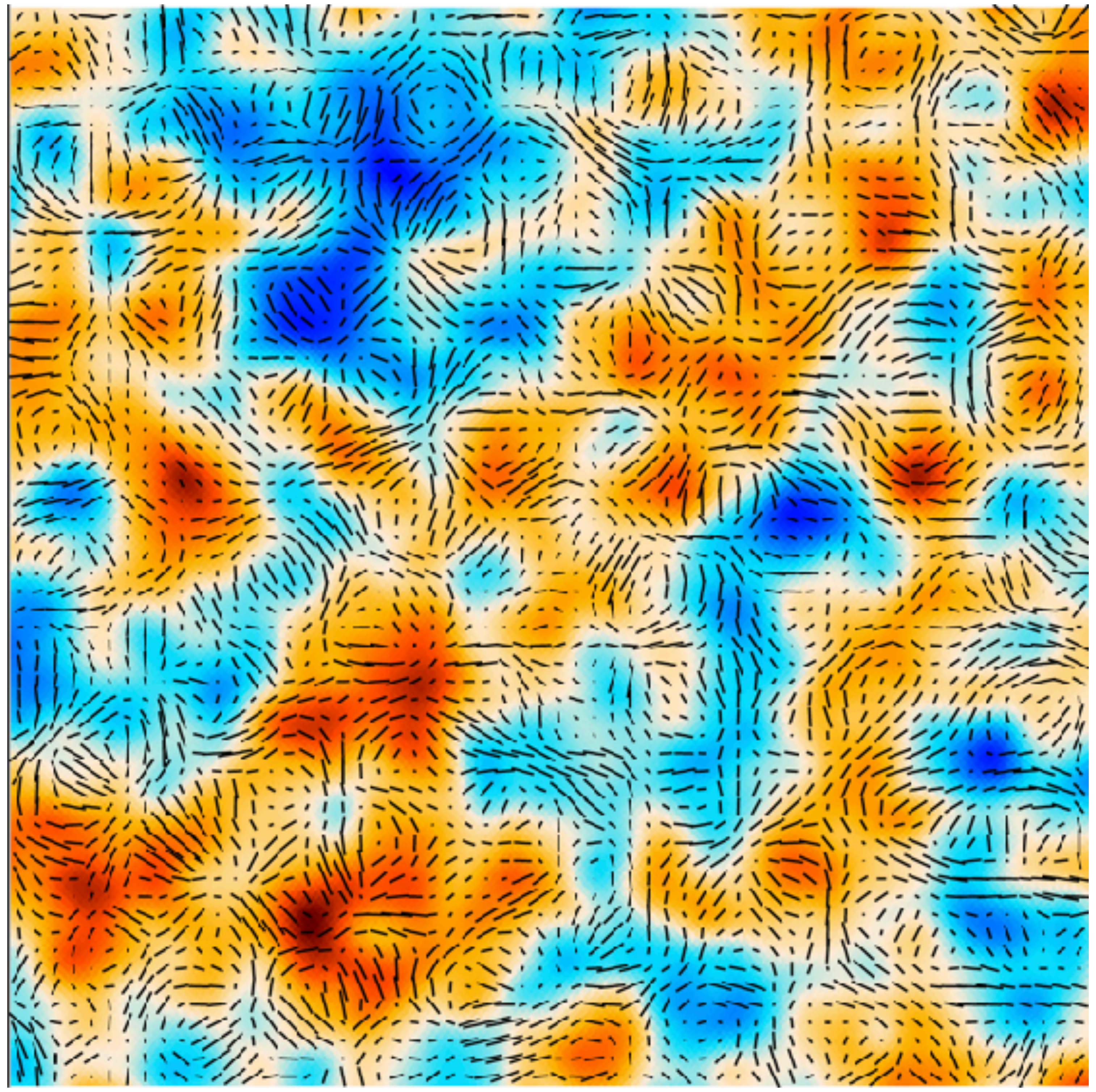
Zaldarriaga, Seljak (1997); Kamionkowski, Kosowsky, Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization

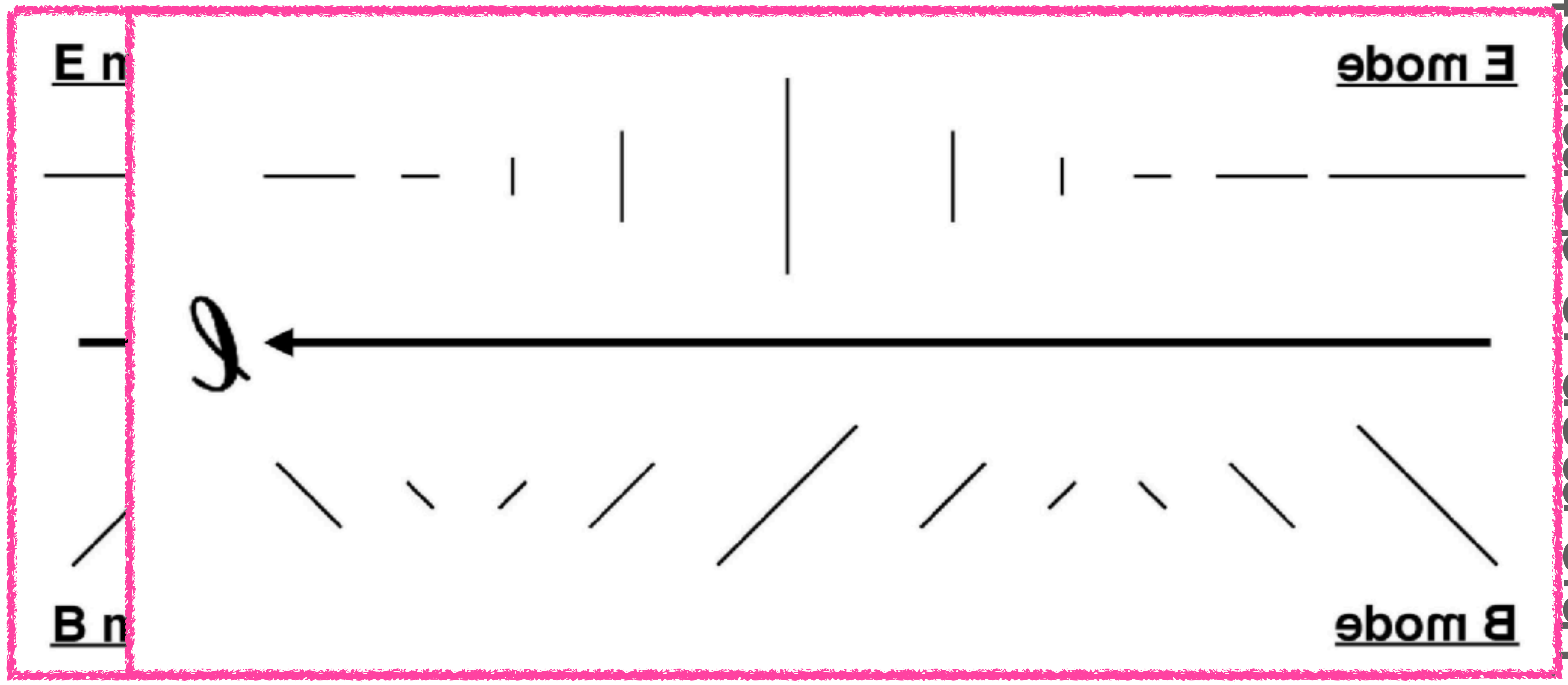


- **E-mode**：Polarization directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarization directions are **45 degrees tilted** w.r.t the wavenumber direction

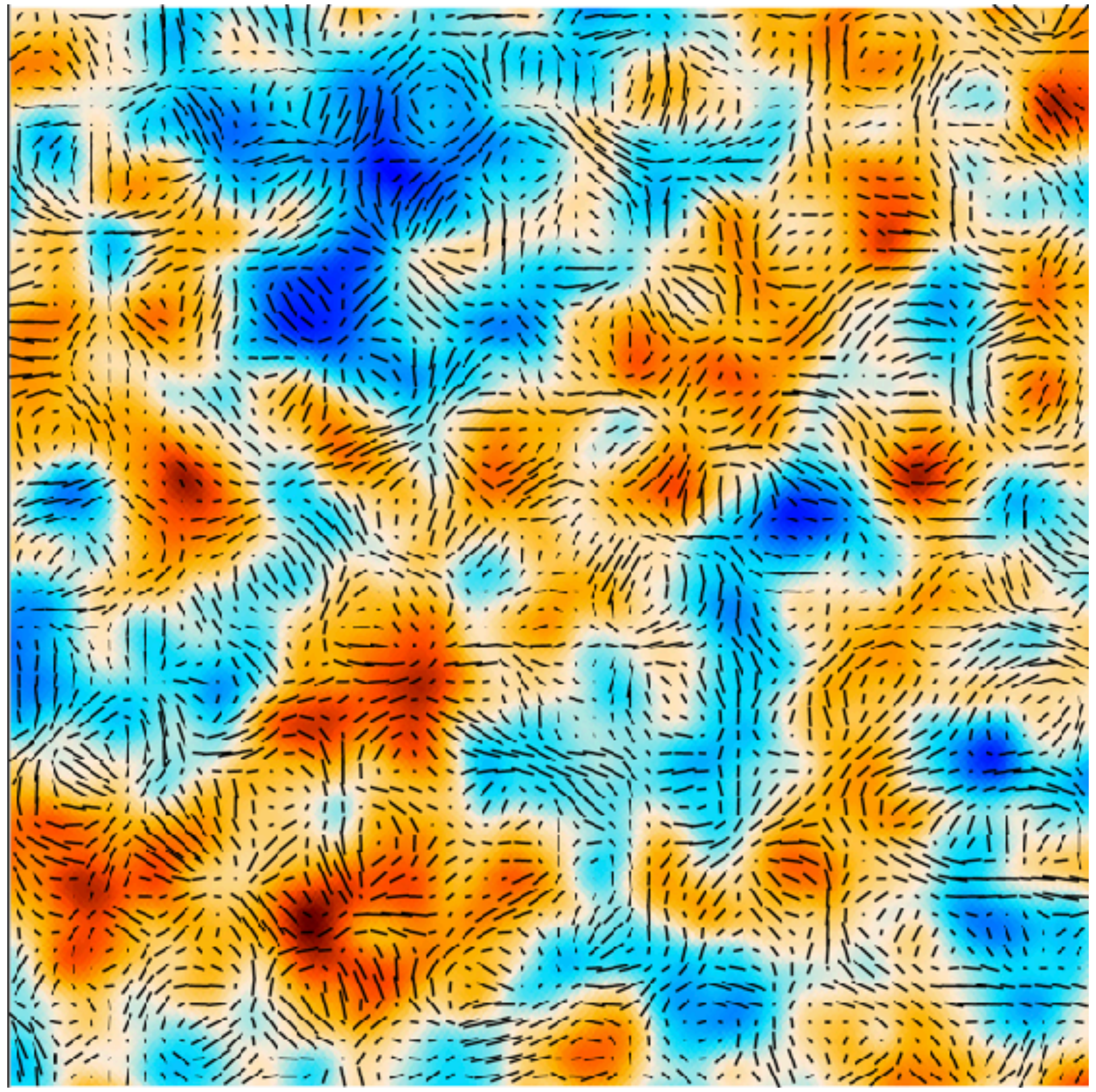
Zaldarriaga, Seljak (1997); Kamionkowski, Kosowsky, Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

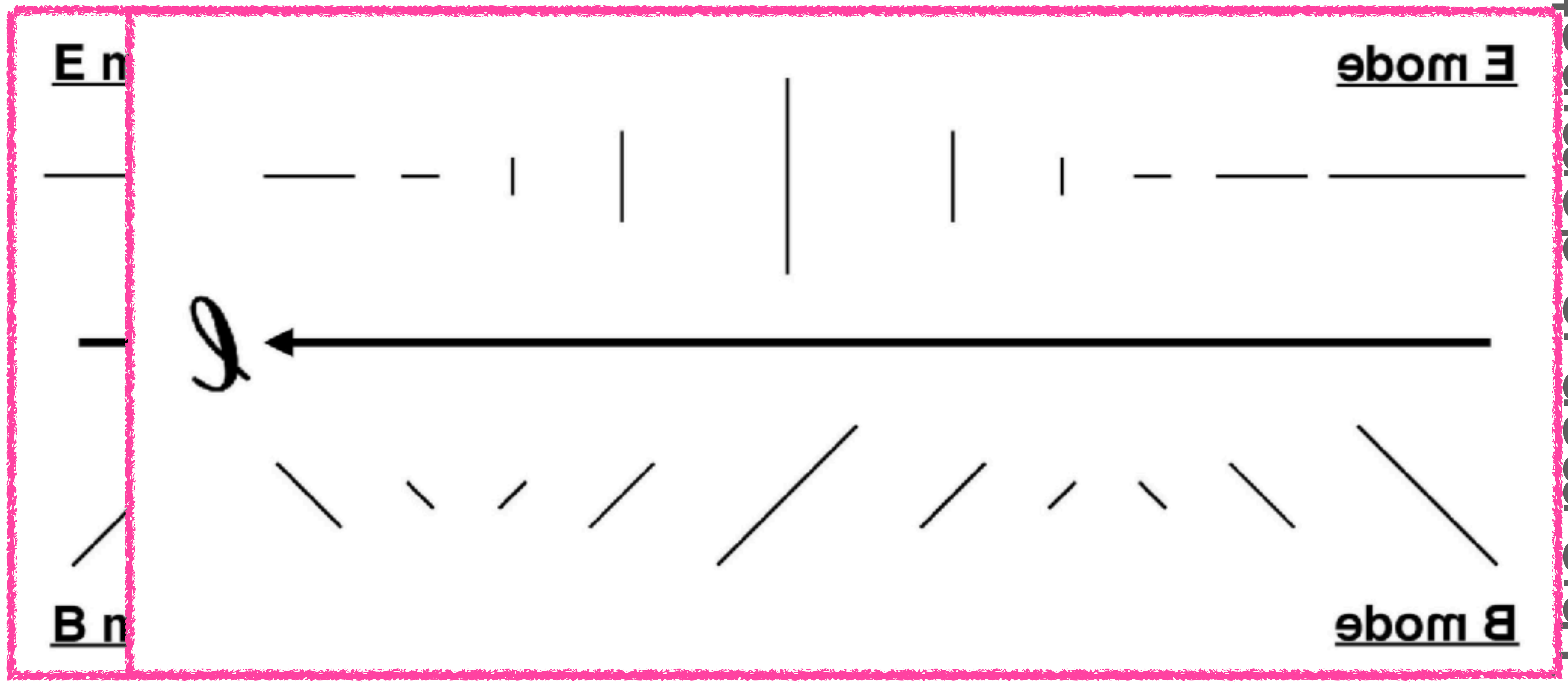
$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

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

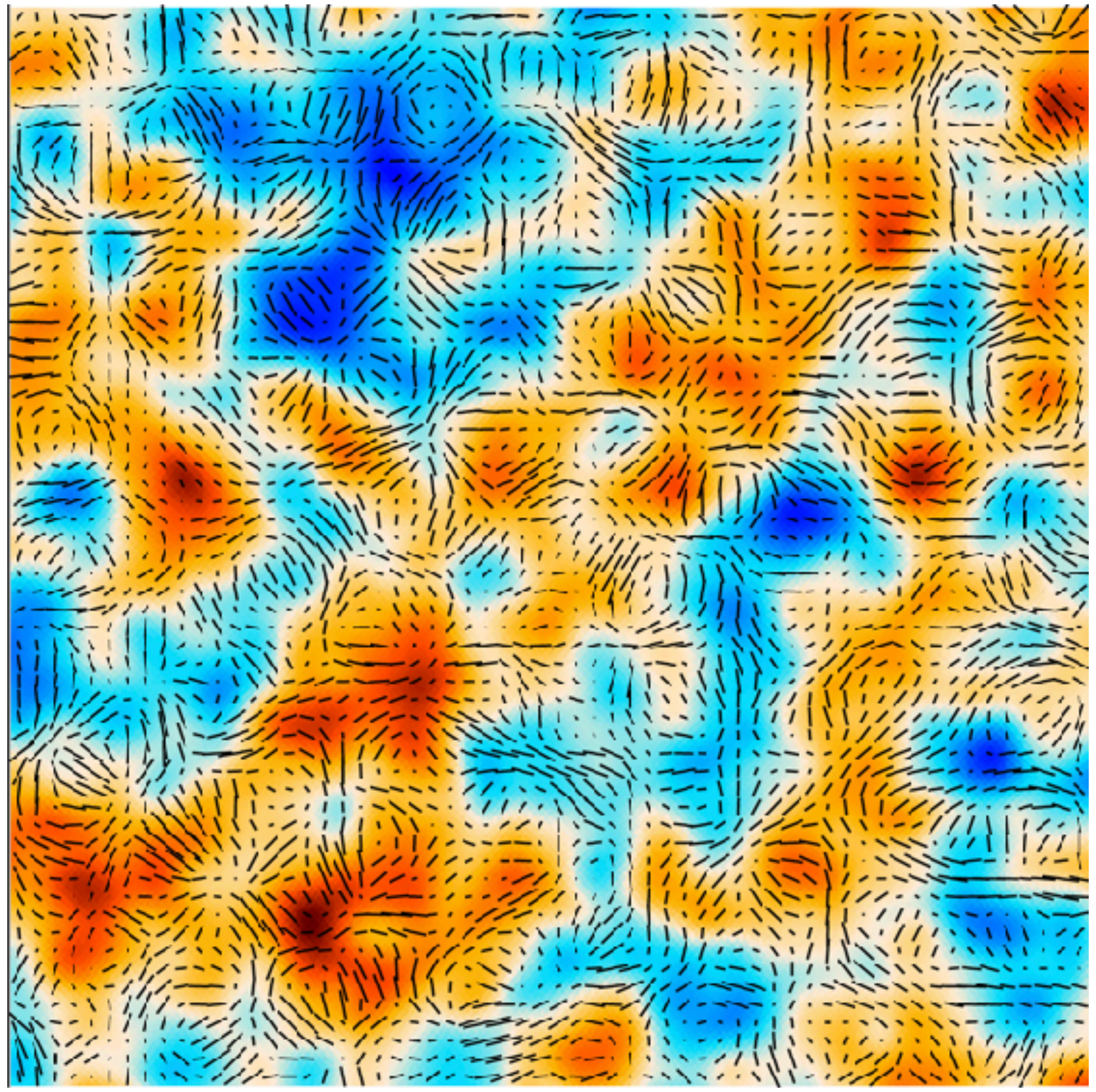
These are scalars and insensitive to parity violation.

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

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

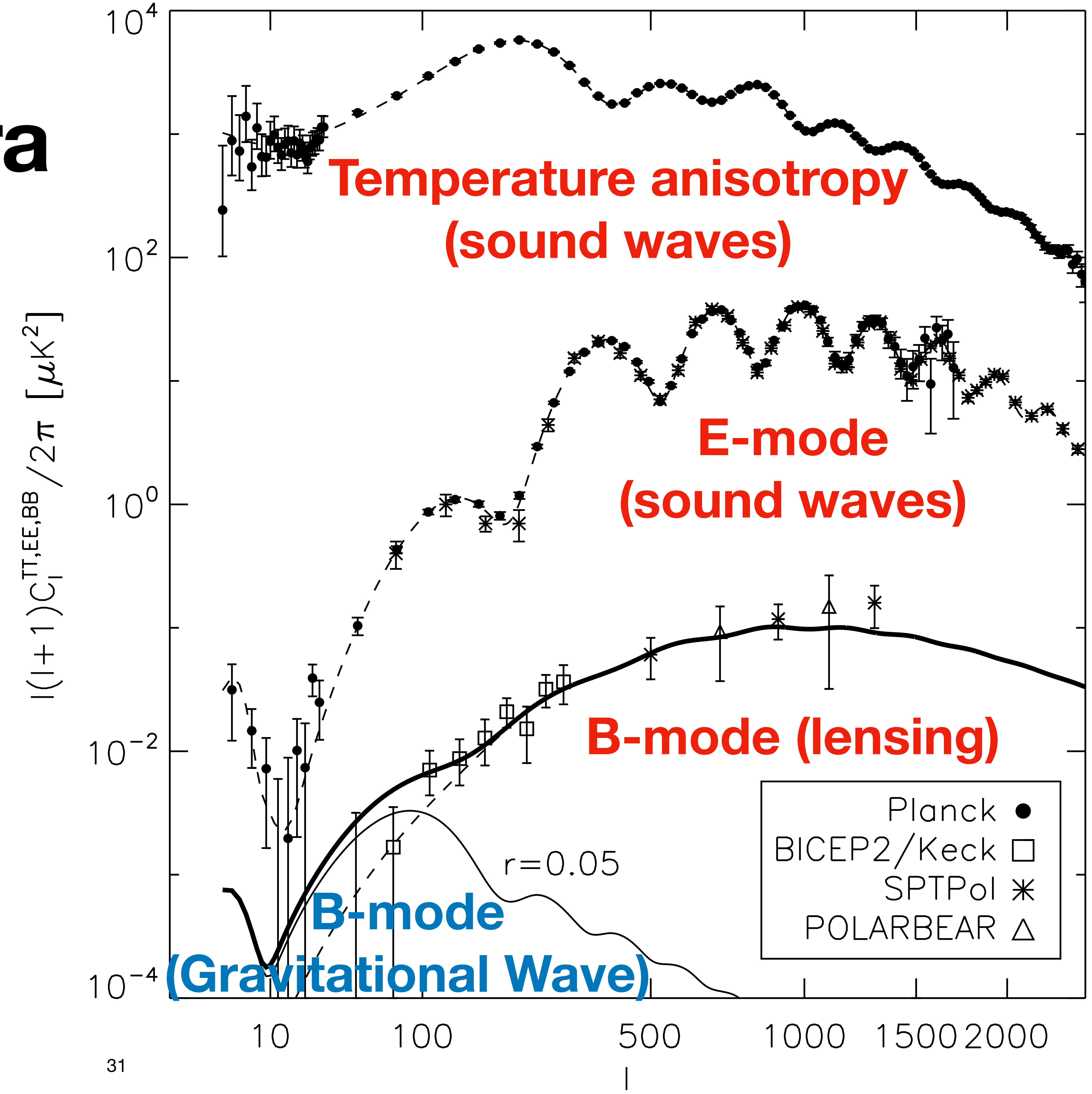
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C^{TE}_{\ell}$$

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

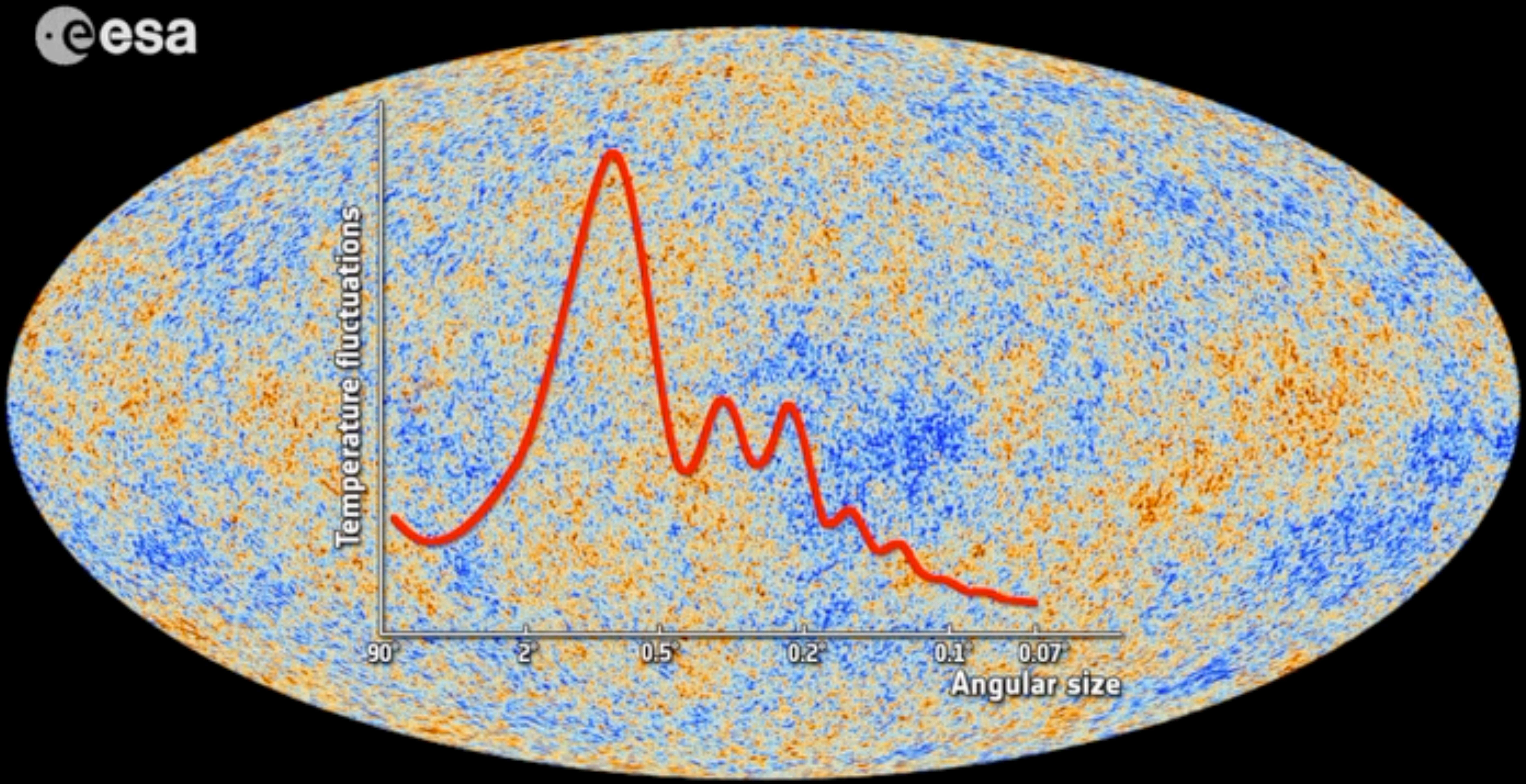
CMB Power Spectra

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.**

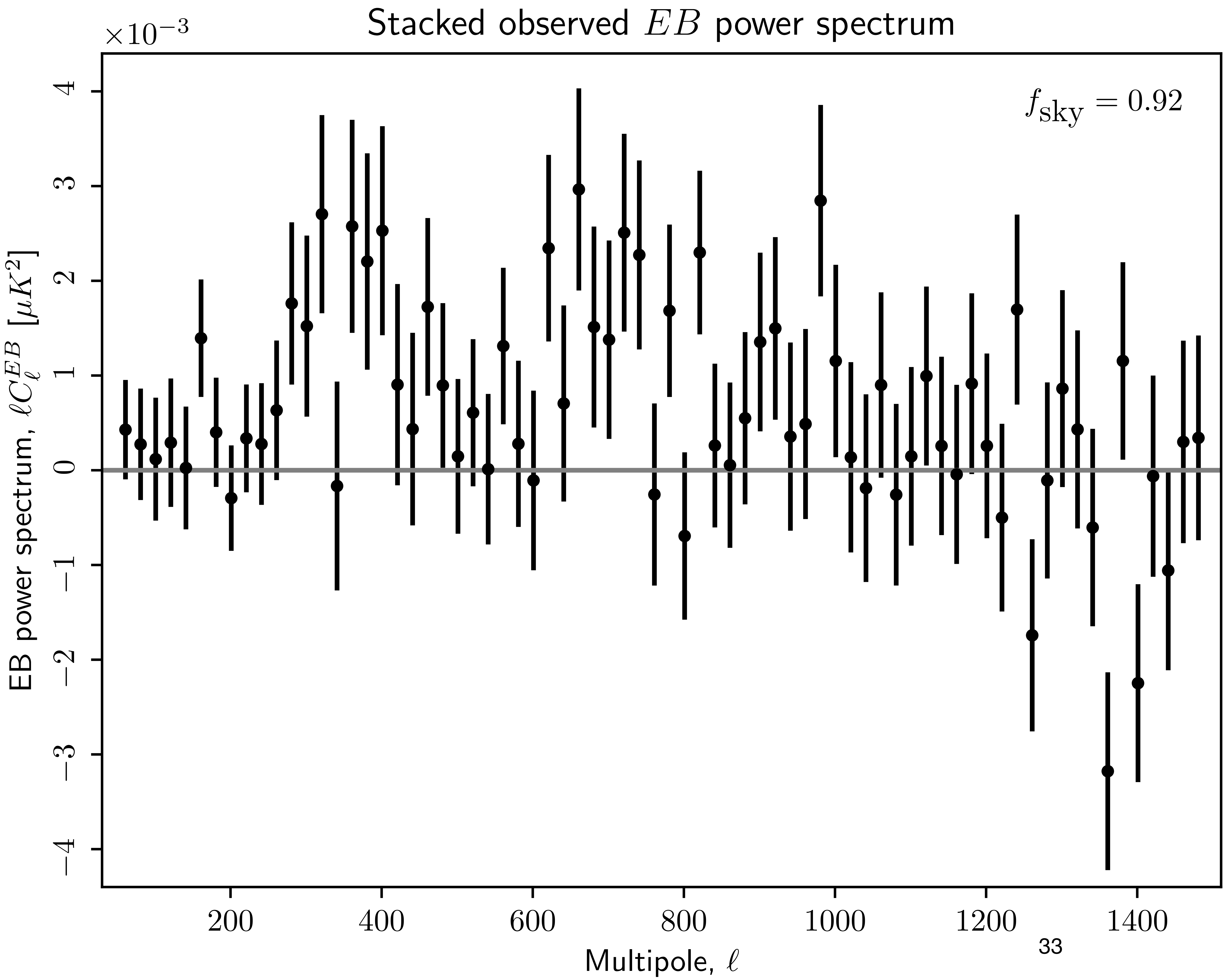


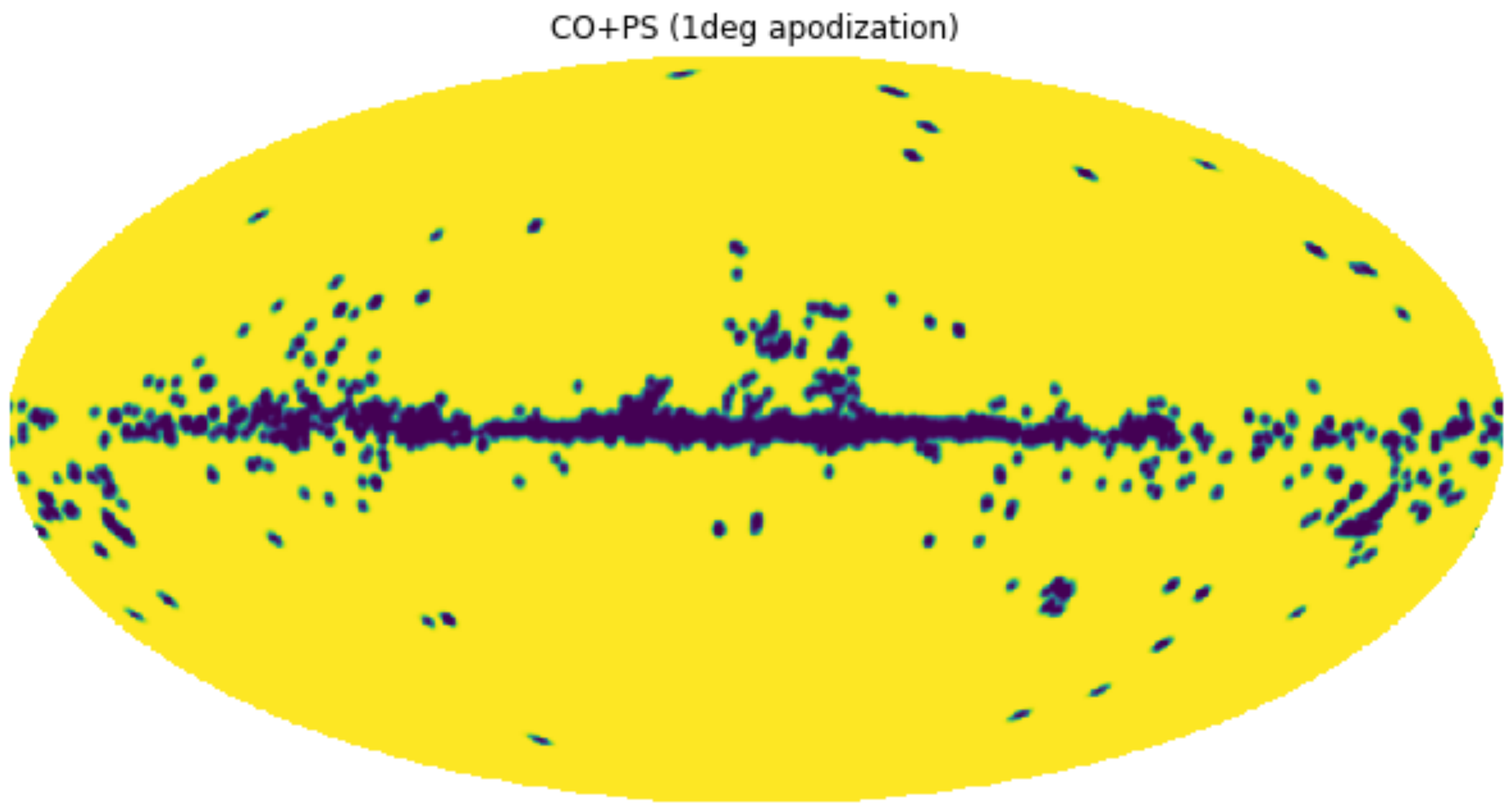
Power Spectrum, Explained



This is the EB power spectrum (WMAP+Planck)

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

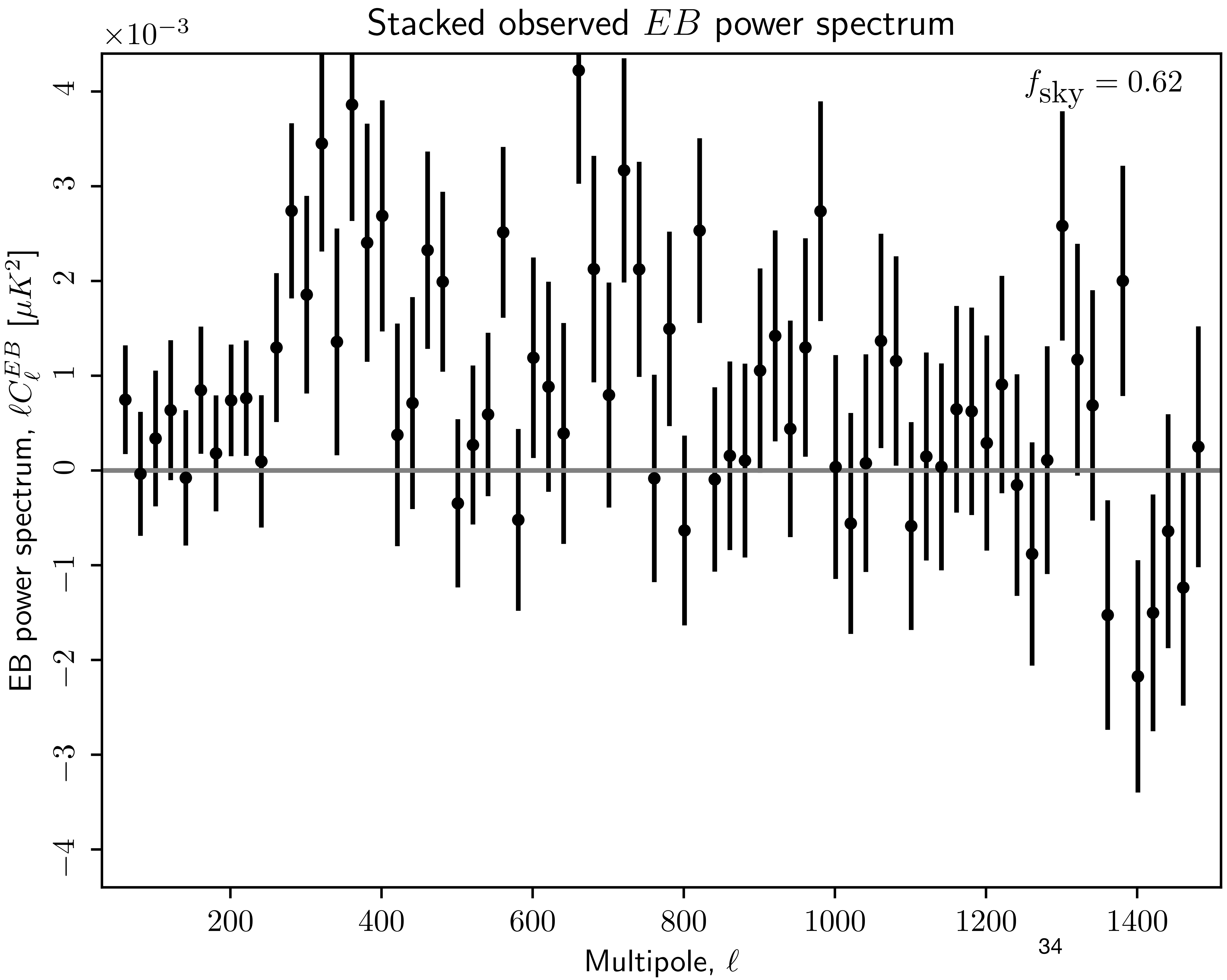


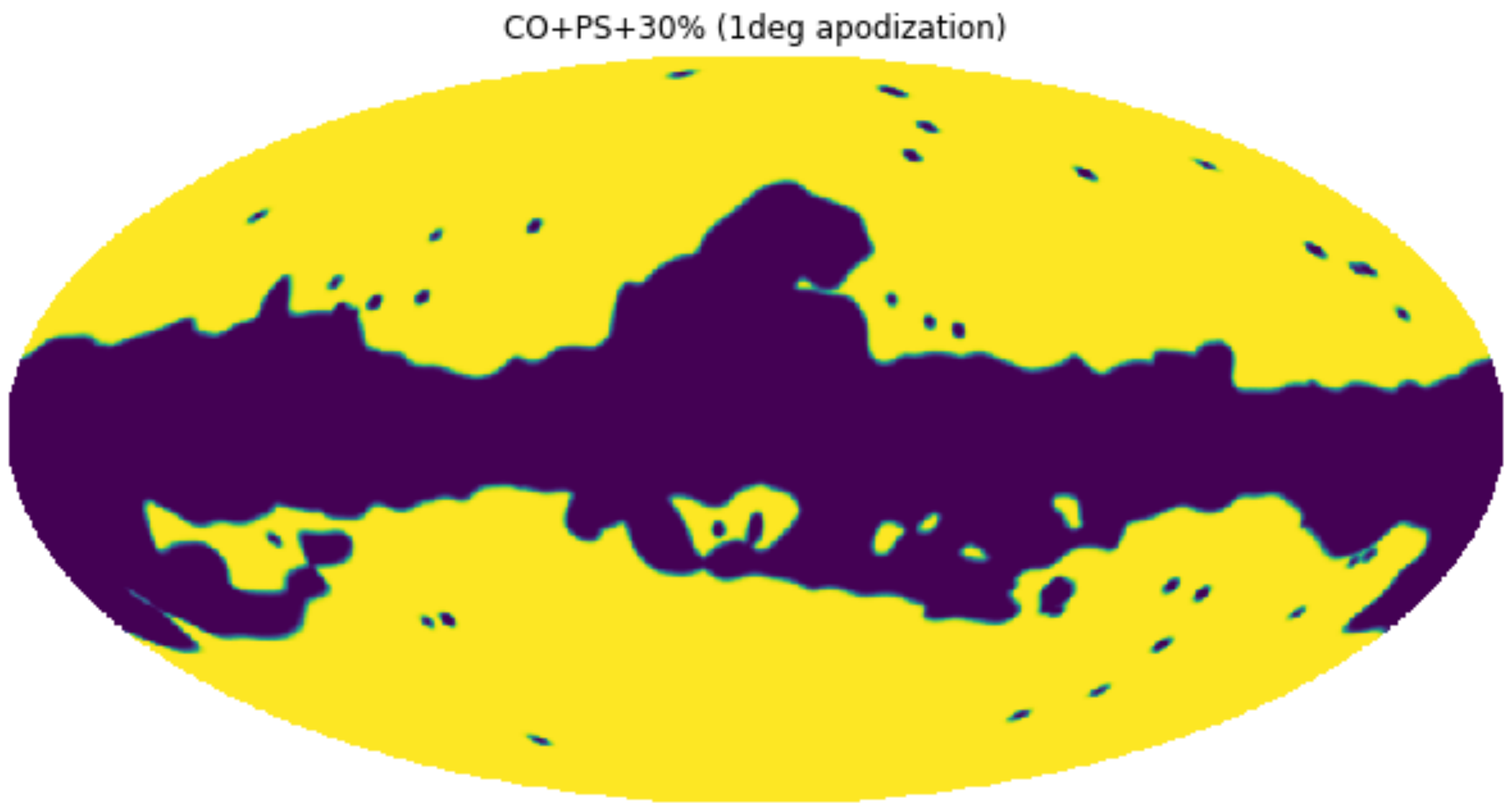


- χ^2 = 125.5 for DOF=72
  - Unambiguous signal of something!

This is the EB power spectrum (WMAP+Planck)

Galactic plane removed (62% of the sky)



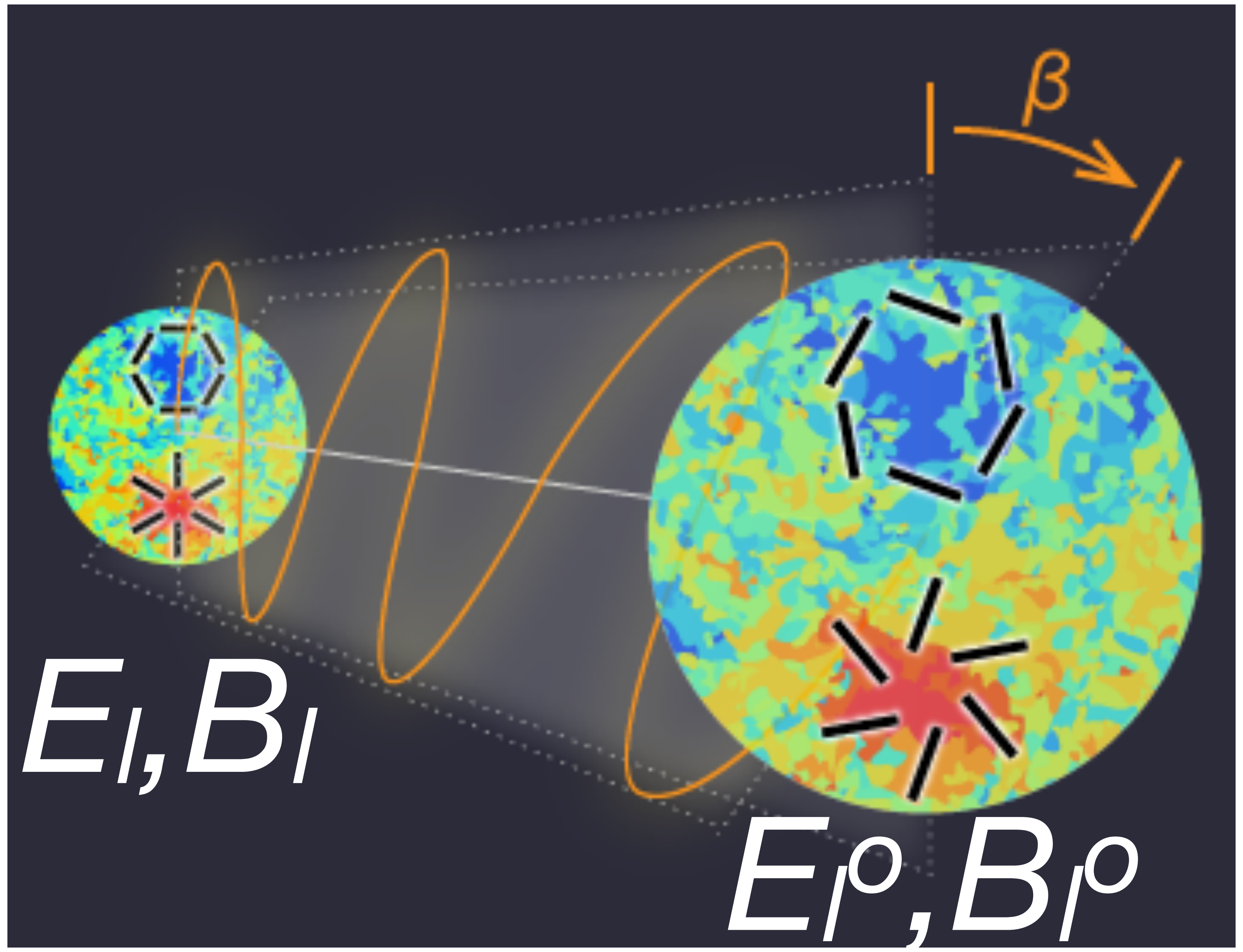


- $\chi^2 = 138.4$
  - The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

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

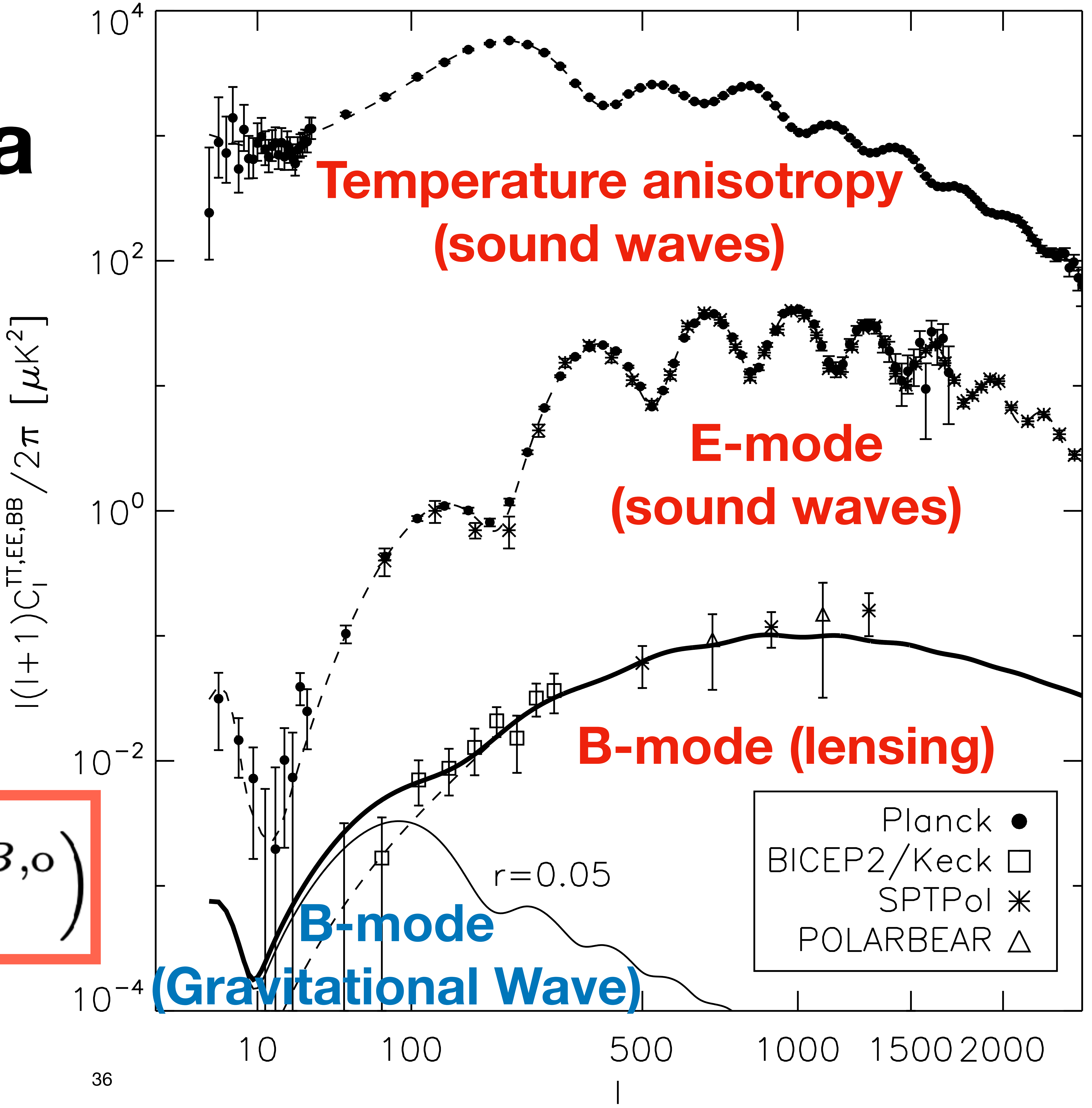
$$E_\ell^{\rm o} = E_\ell \cos(2\beta) - B_\ell \sin(2\beta)$$

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

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!

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

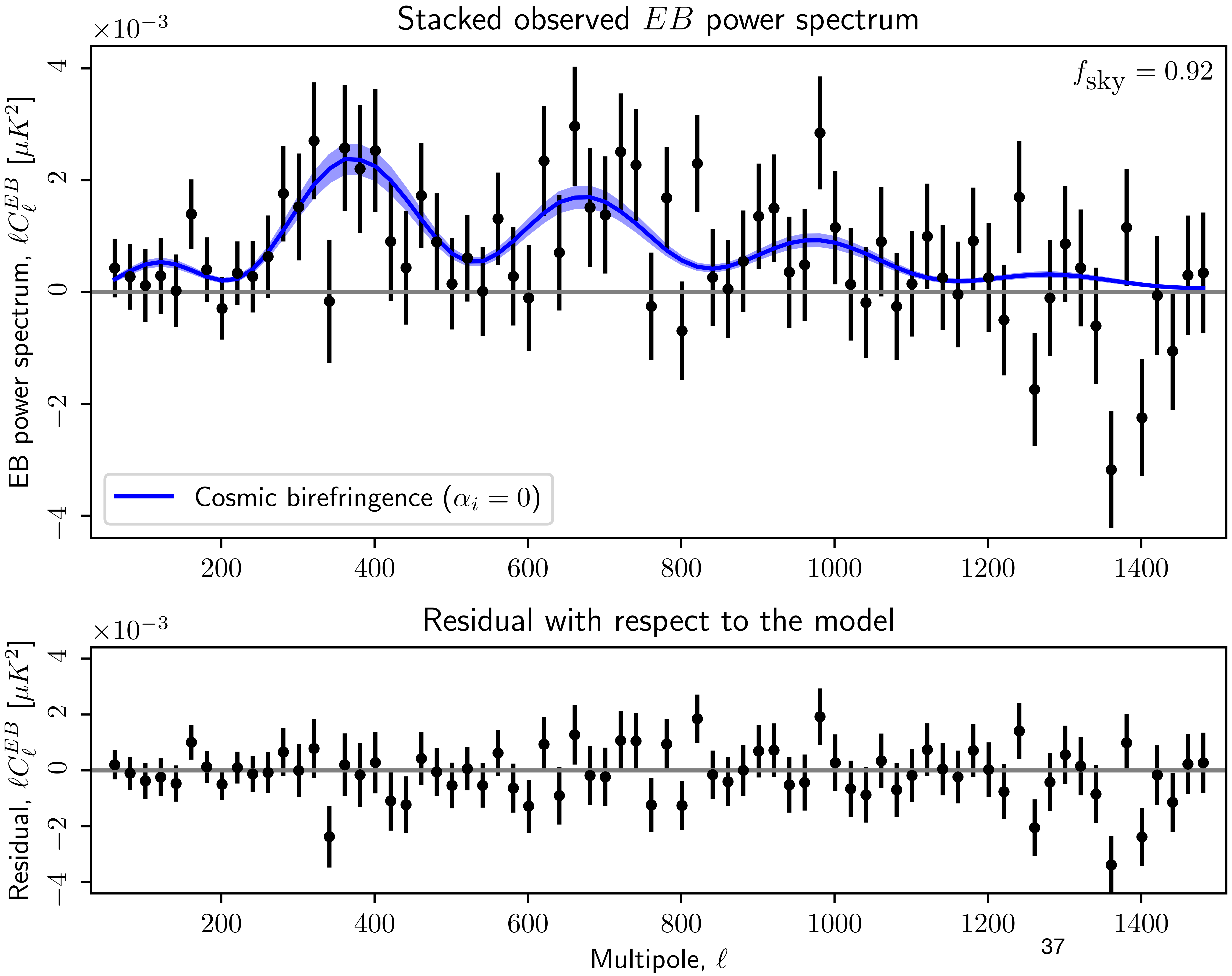


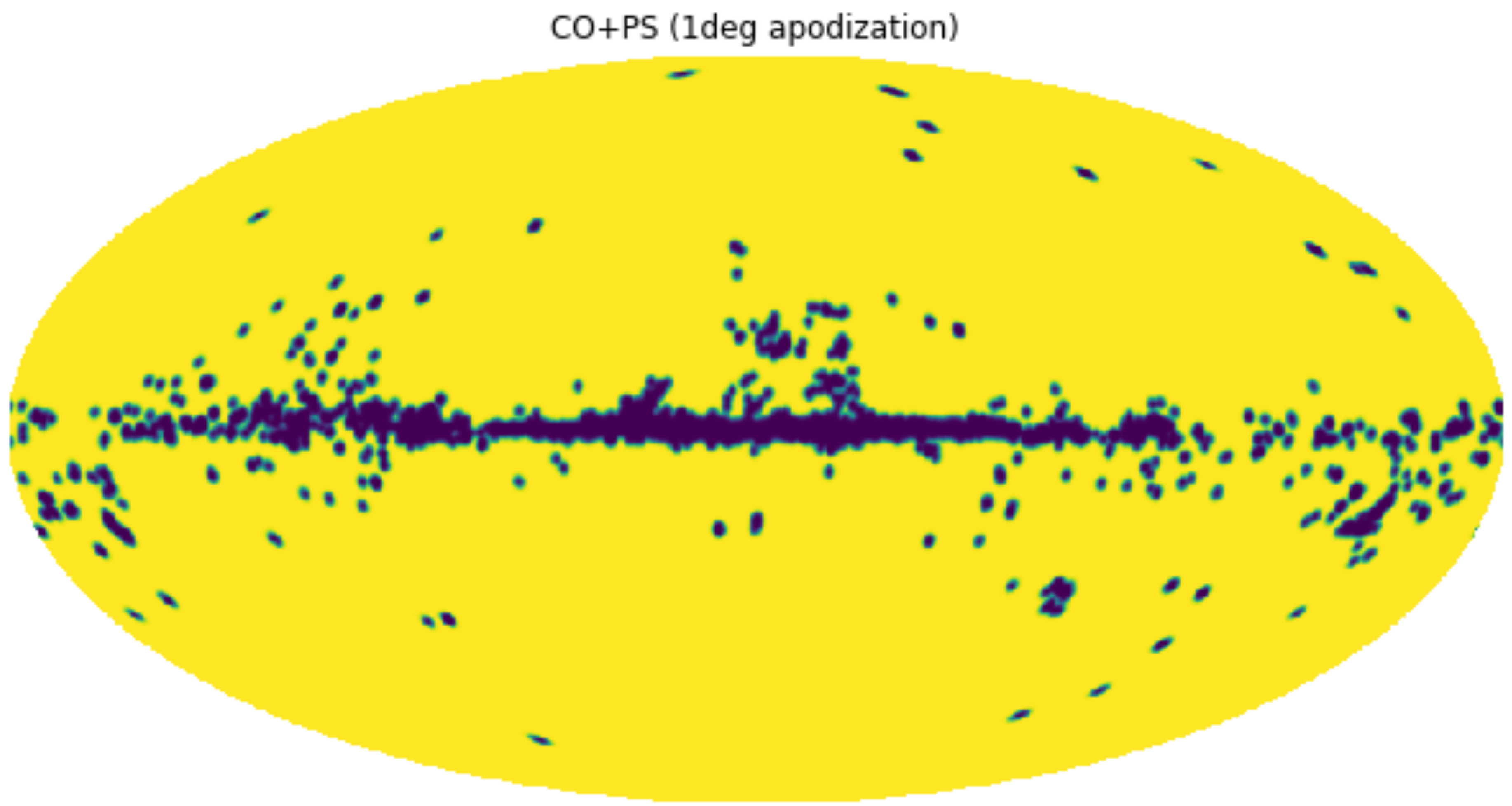
Eskilt, EK (2022)

Cosmic Birefringence fits well(?)

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

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





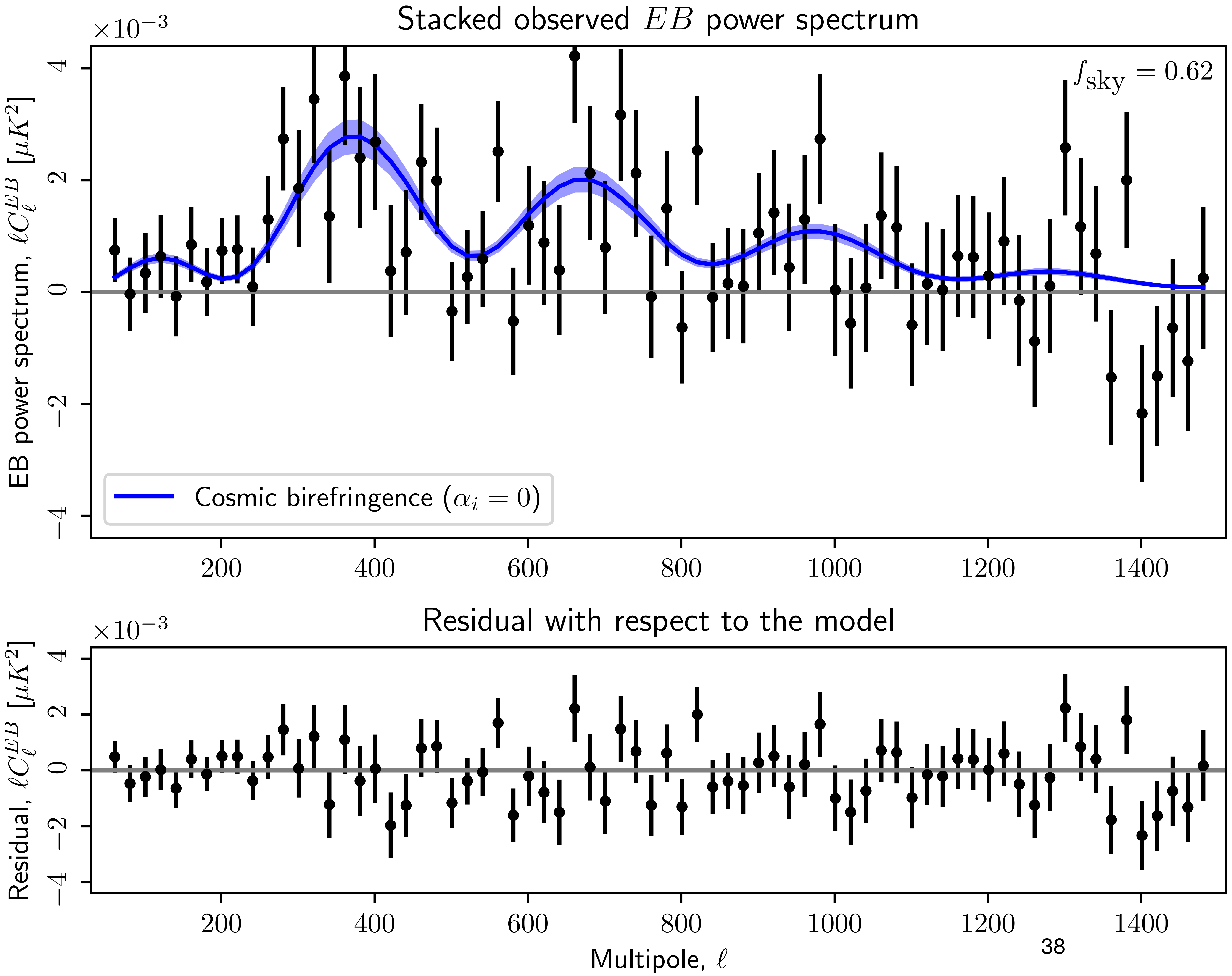
- $\beta = 0.288 \pm 0.032$ deg
- $\chi^2 = 66.1$ for DOF=71
  - Good fit! 9σ detection?

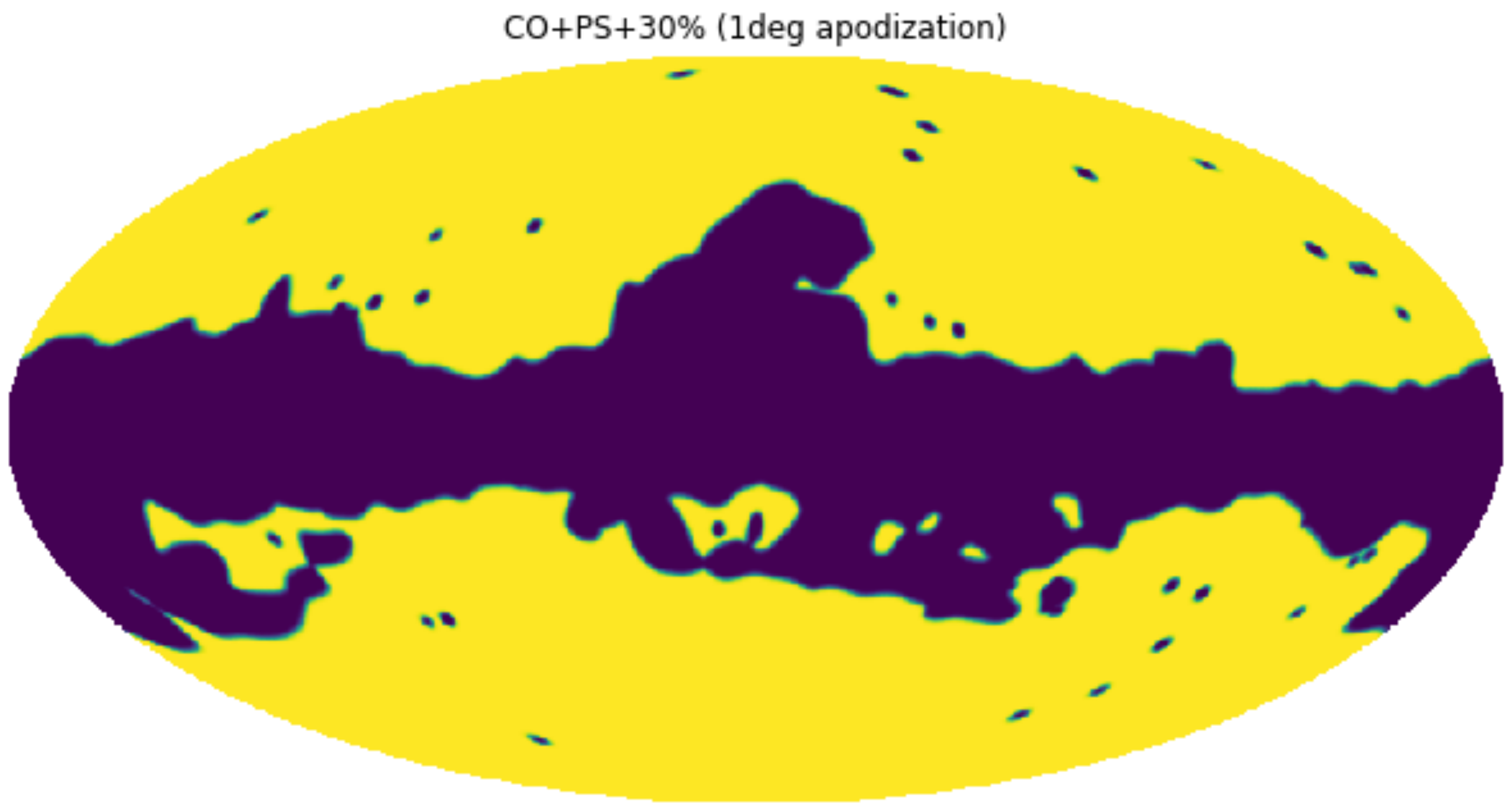
Eskilt, EK (2022)

Cosmic Birefringence fits well(?)

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

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

- 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)

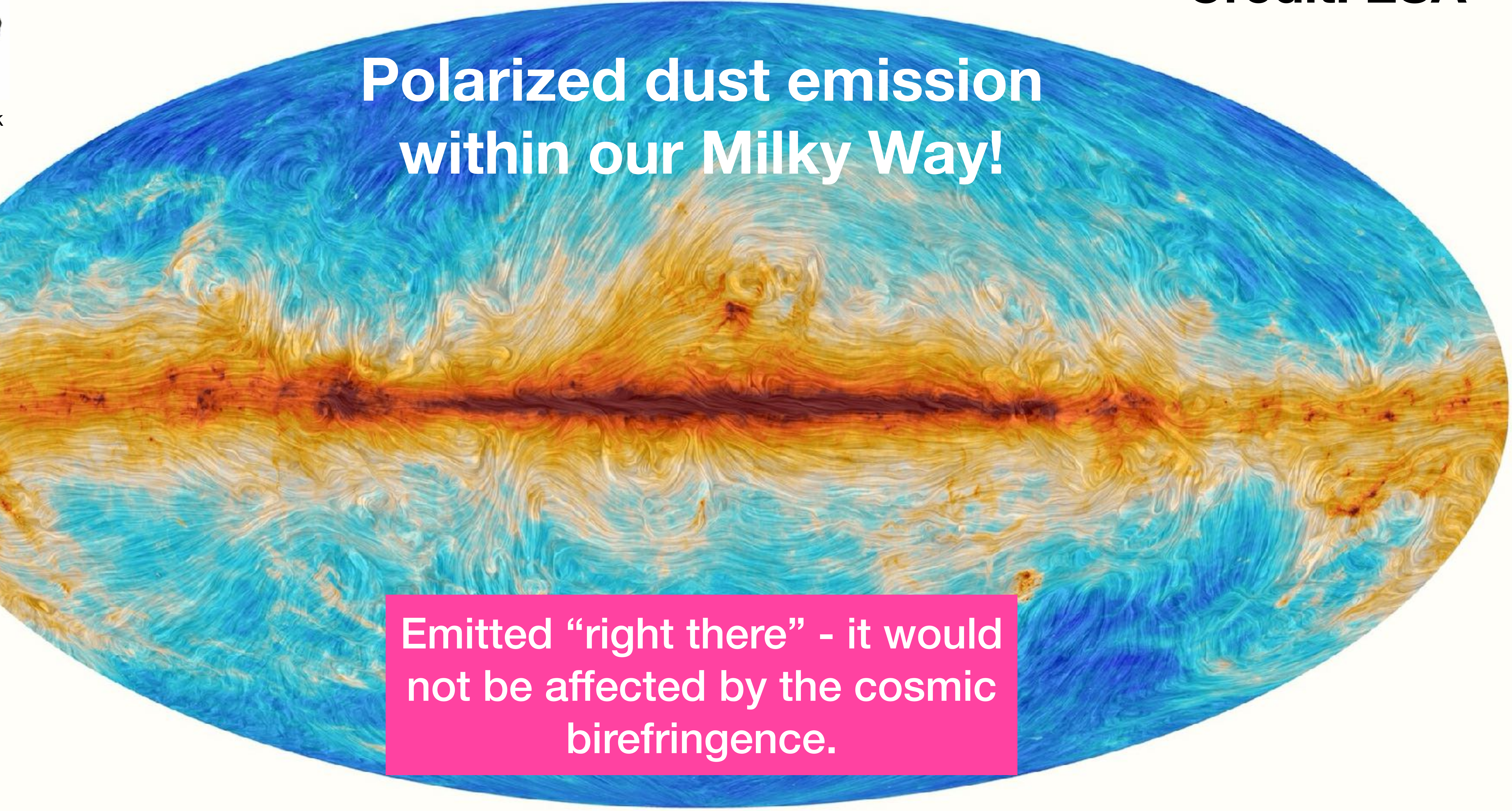
Uncertainty in the calibration of α has been the major limitation

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

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

ESA's Planck

Credit: ESA



Polarized dust emission within our Milky Way!

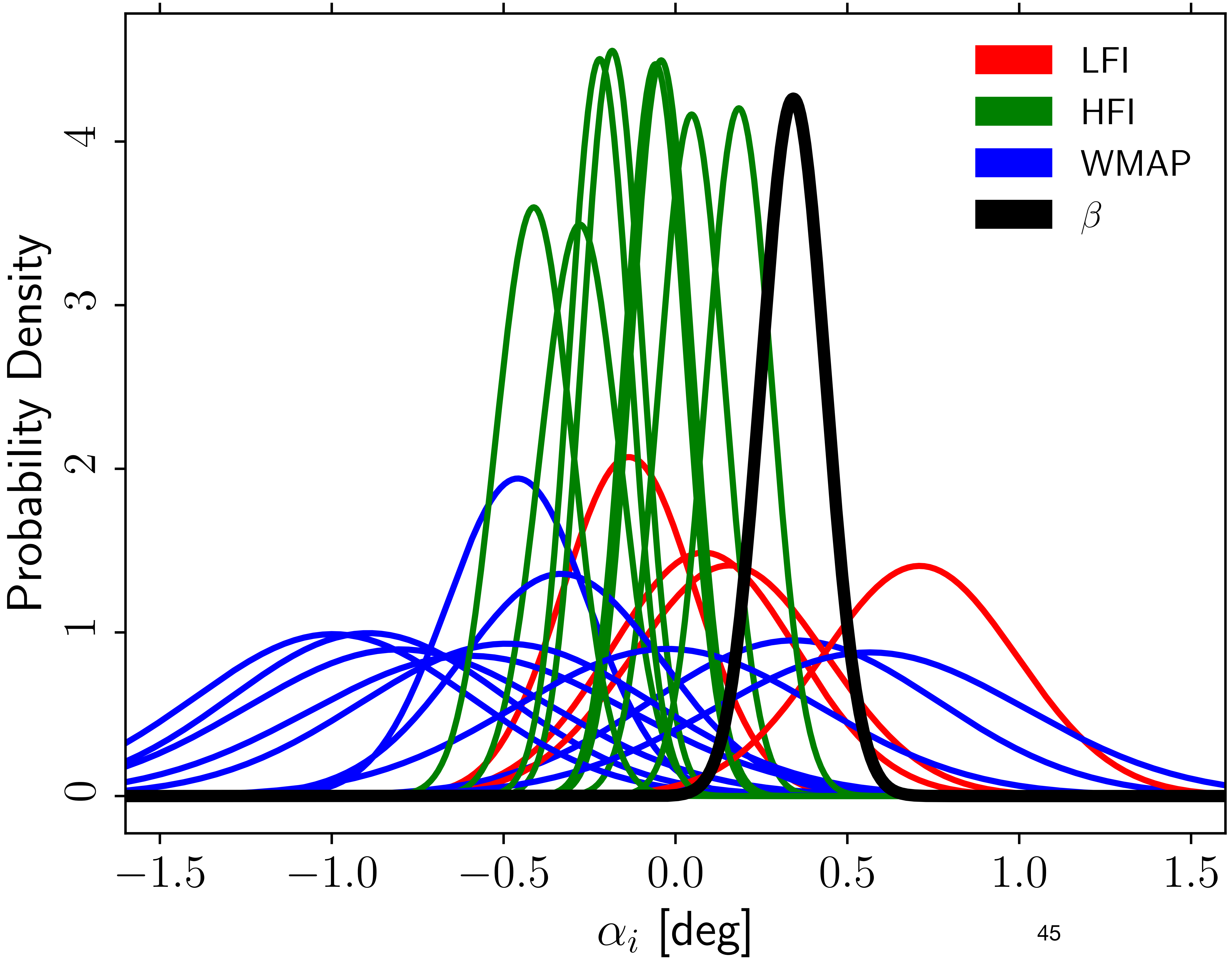
Emitted "right there" - it would not be affected by the cosmic birefringence.

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

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

Miscalibration angles (WMAP and Planck)

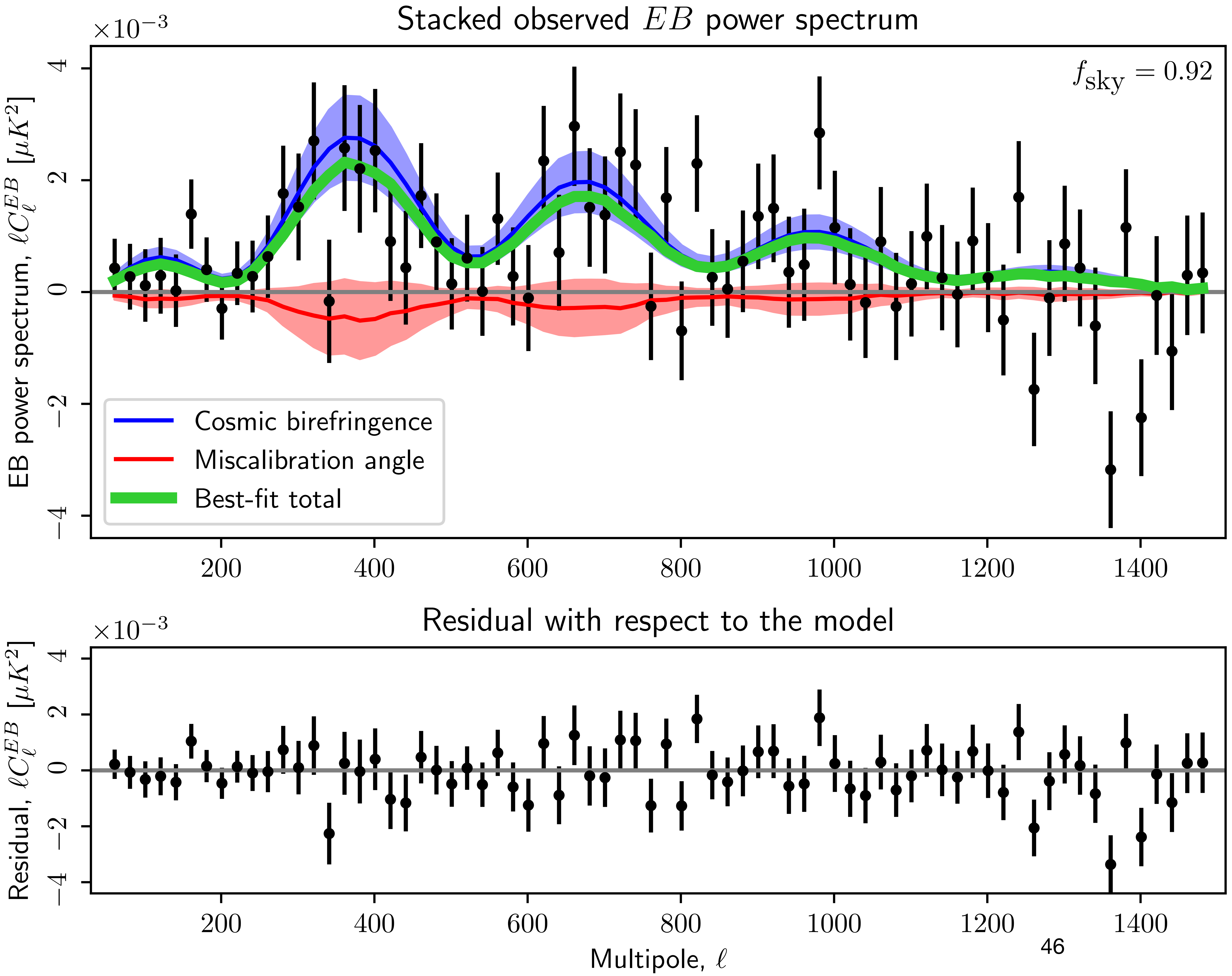
Nearly full-sky data (92% of the sky)

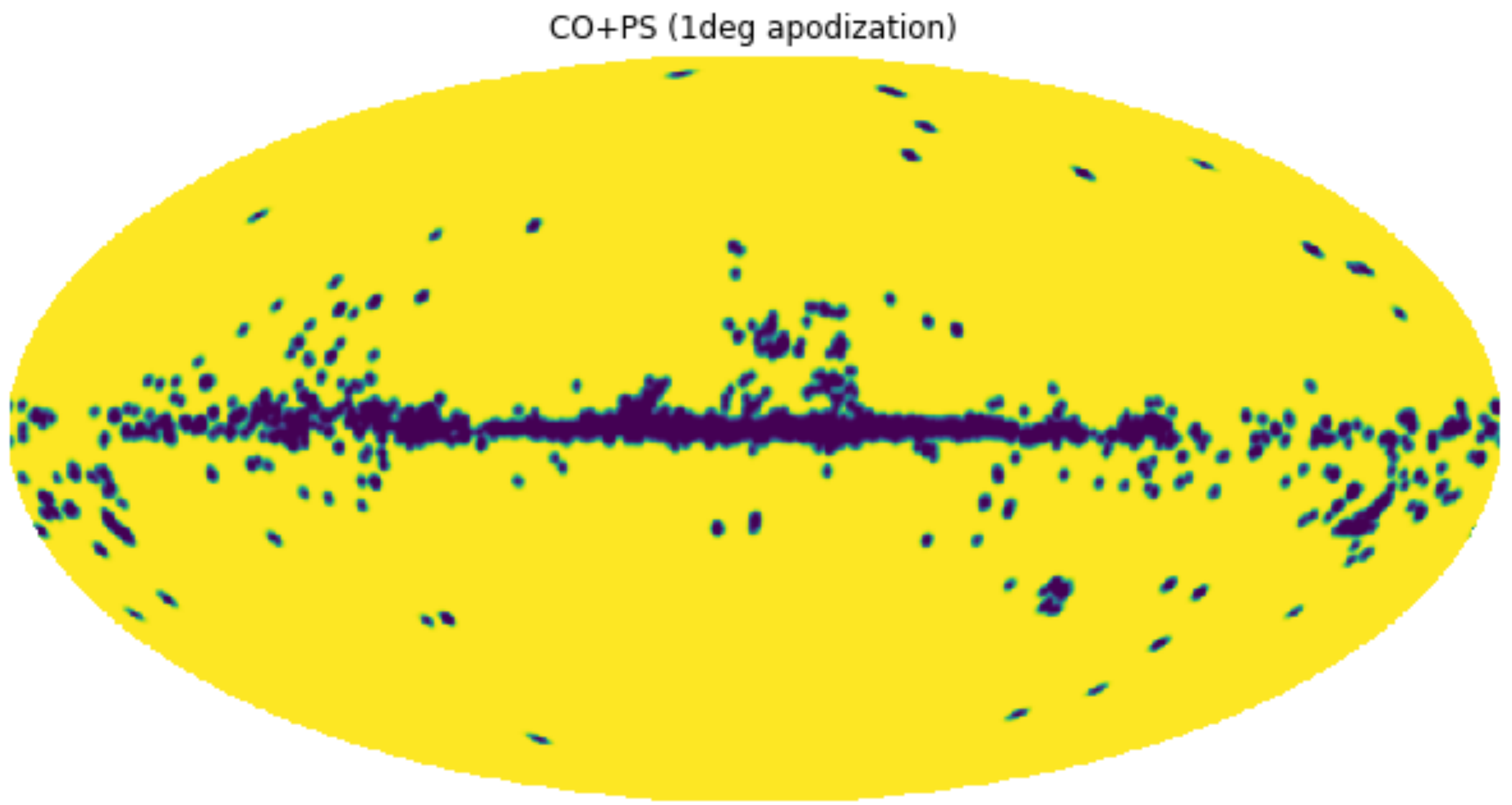


- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

Cosmic Birefringence fits well (WMAP+Planck)

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

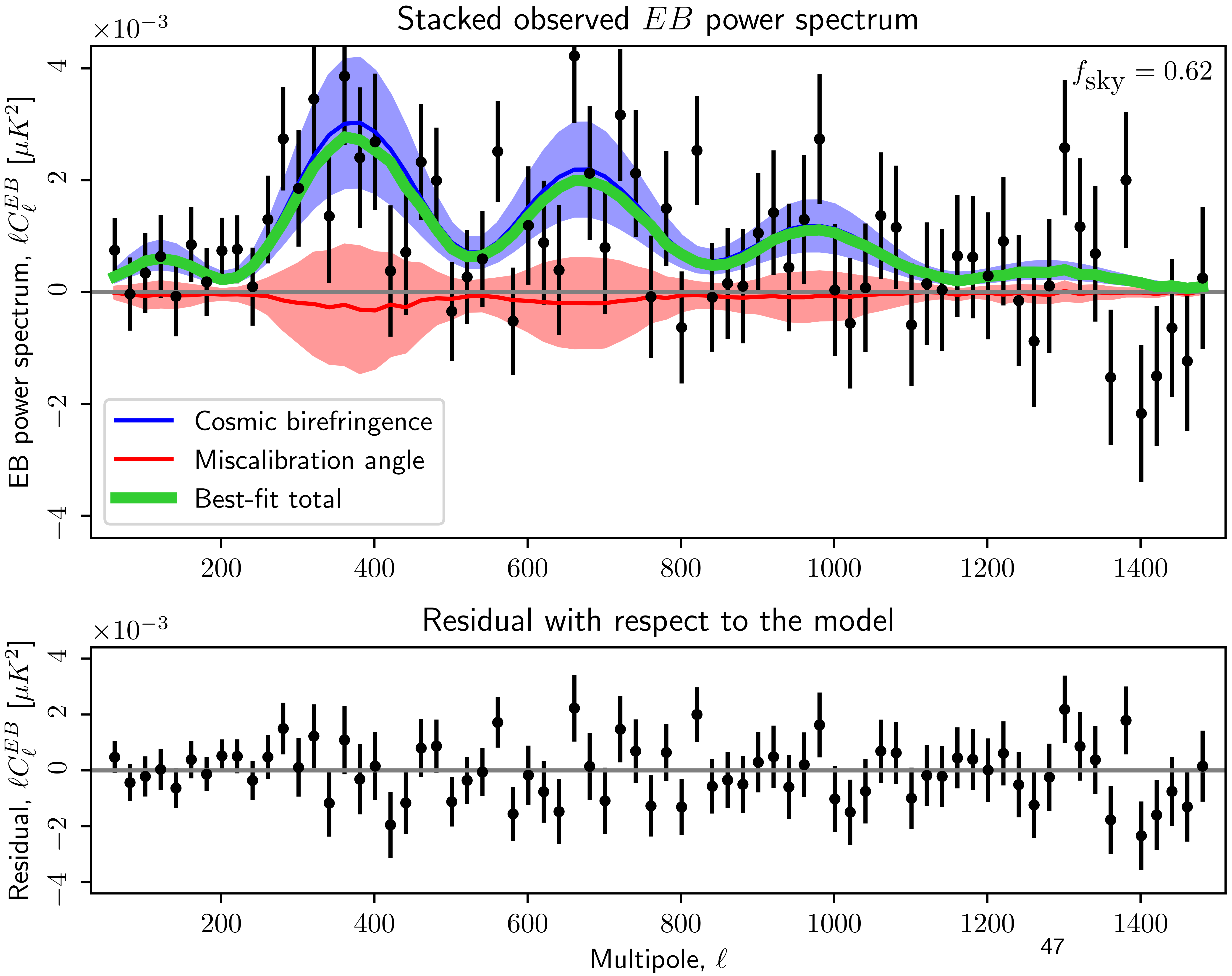


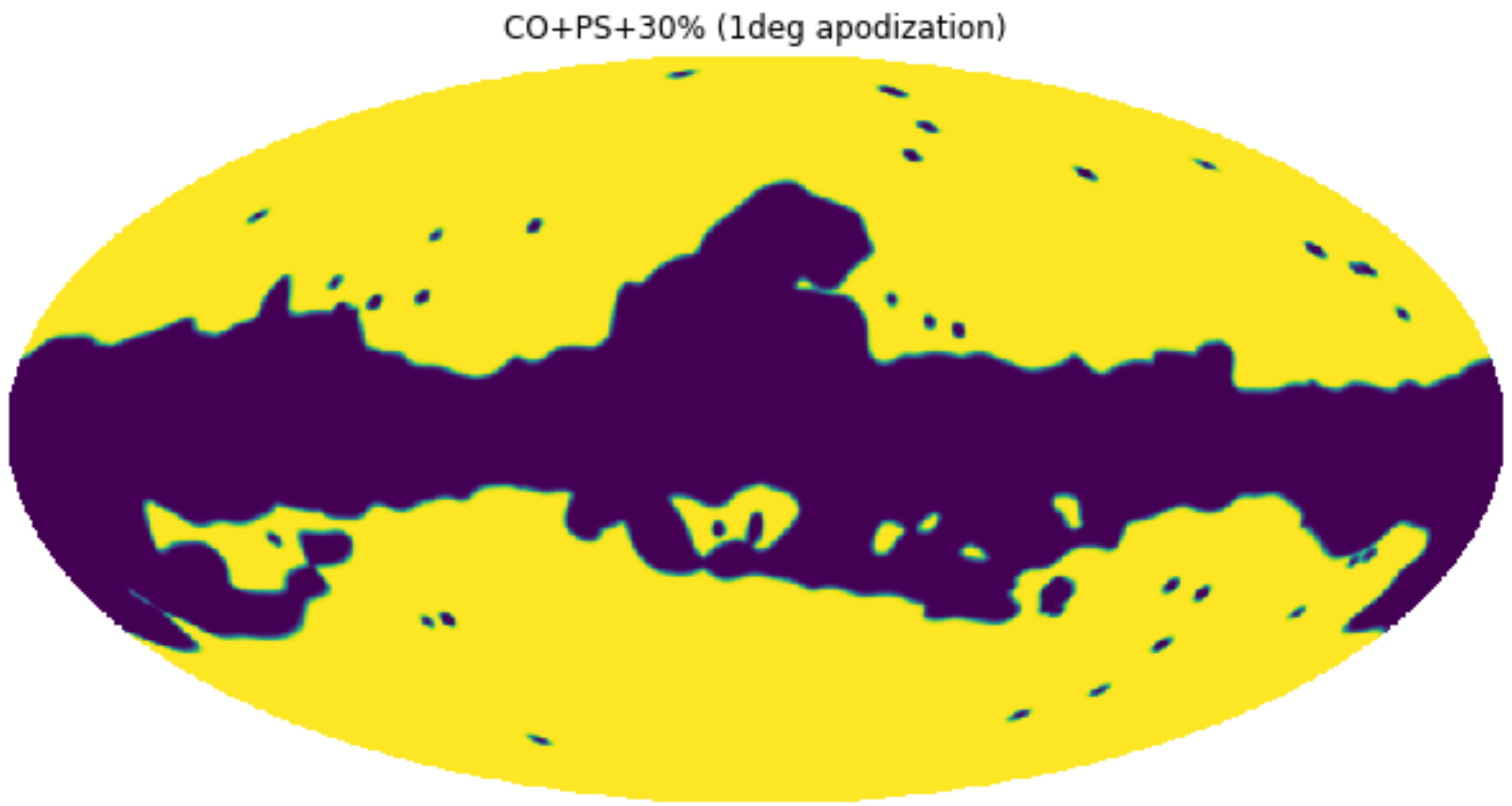


- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- $\chi^2 = 65.3$

Cosmic Birefringence fits well (WMAP+Planck)

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

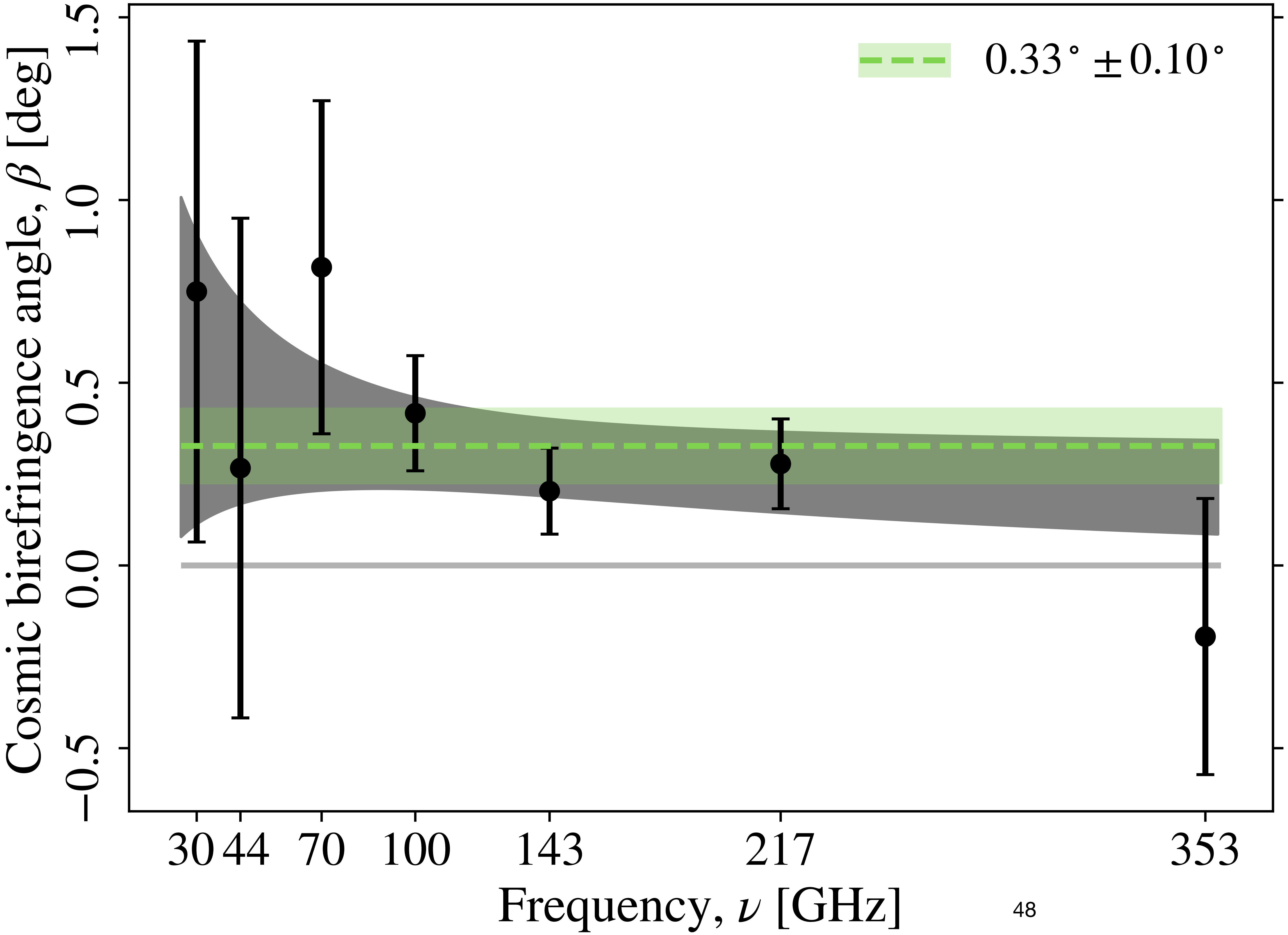




- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- $\chi^2 = 65.8$

No frequency dependence is found

Consistent with the expectation from cosmic birefringence



- 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., Cornelison et al. (BICEP3 Collaboration), arXiv:2207.14796.

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

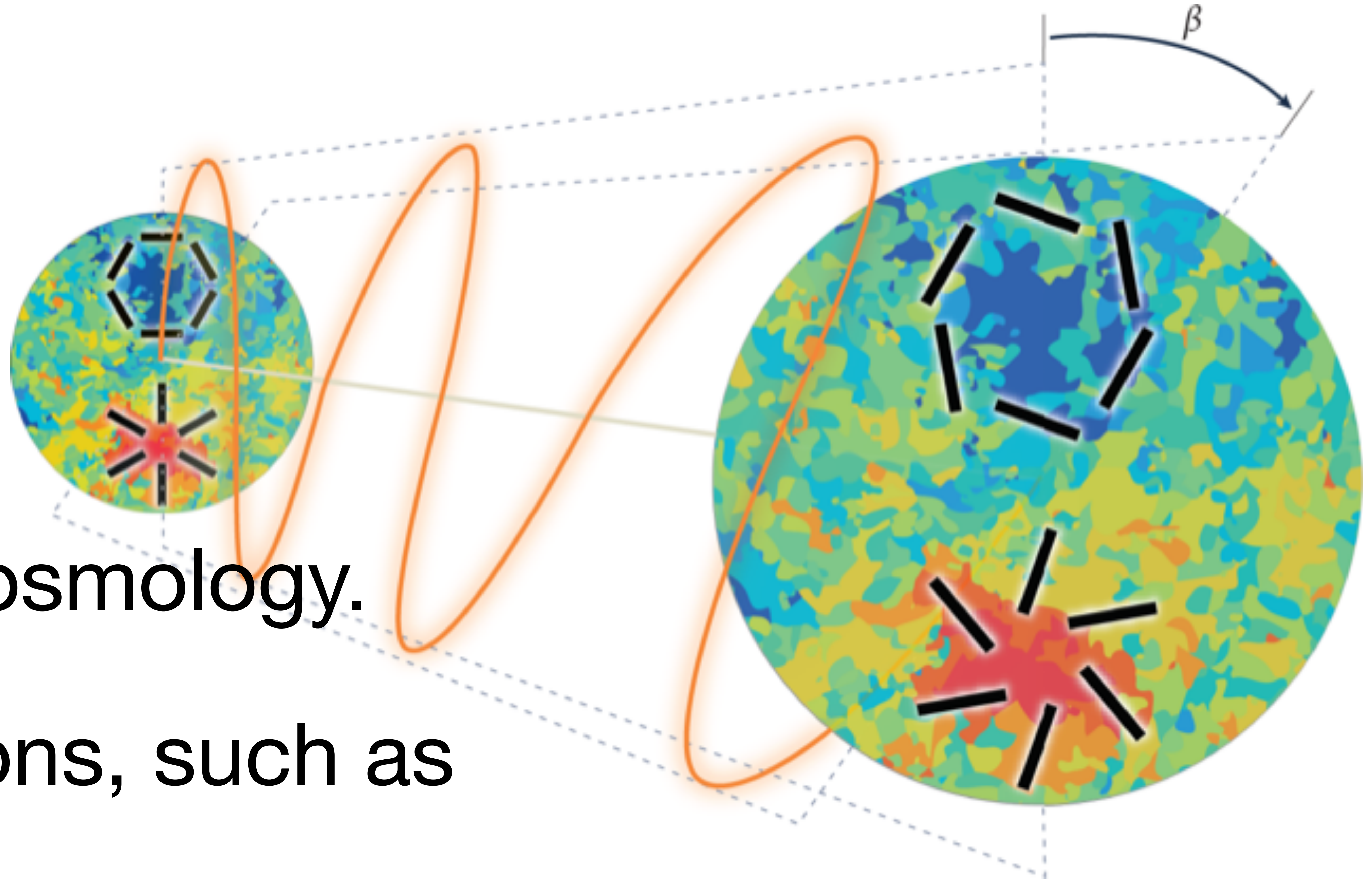
$$\Delta\chi = \chi(\tau_{\rm obs}) - \chi(\tau_{\rm em}) \simeq \frac{10^{-2}}{\alpha} f$$

- 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.

Summary

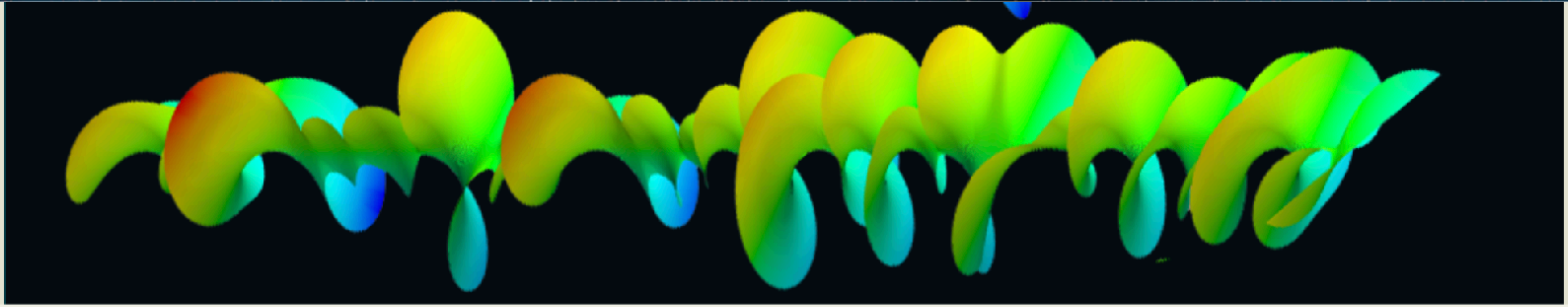
Let's find new physics!



- 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**.
    - **3.6σ hint of Cosmic Birefringence**: Space may be filled with parity-violating DM and DE fields?
- **What else should we look at? New and great topics of research.**

中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics

The registration will be open around middle of July.



Large-scale Parity Violation Workshop

December 4(Mon)-7(Thu), 2023

ASIAA, Taipei, Taiwan

December 4-7 in Taipei

https://events.asiaa.sinica.edu.tw/workshop/20231204/index.php

Purpose

In recent few years, studies of parity violation at cosmological scales have been attracting a lot of attention, with the observations of birefringence in CMB, galaxy spins, and four-point correlation functions of galaxies and CMB. Investigating violation of parity at such scales enables us to probe new physics beyond the standard model of cosmology, potentially nature of dark matter and dark energy. This workshop aims to bring together experts in numerical, observational and theoretical aspects of parity violation in cosmology.

The registration will be open around middle of July.