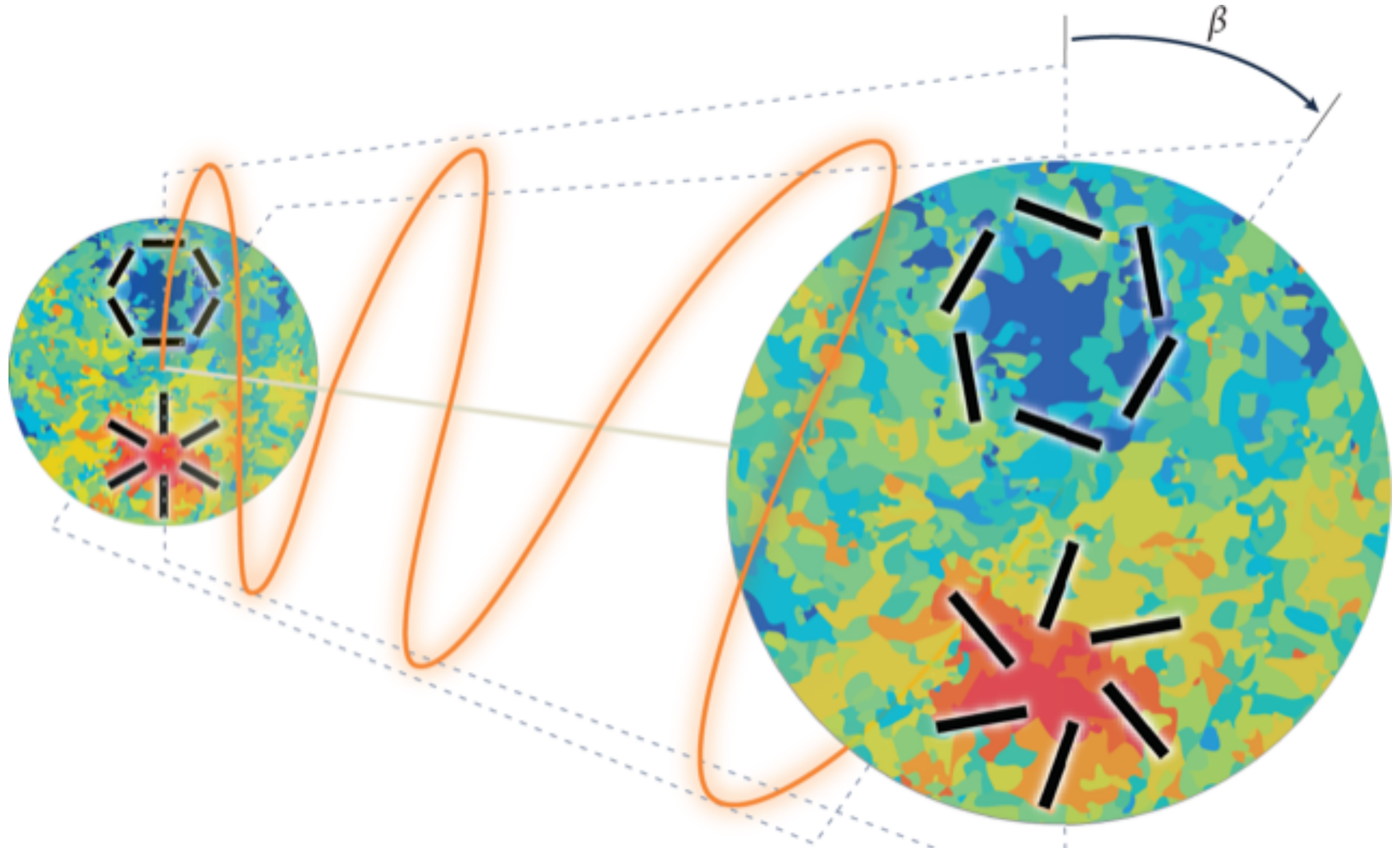
Reference: EK, Nature Rev. Phys. **4**, 452 (2022)



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Parity Violation in Cosmology

Does the Universe distinguish between left and right?

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

EuCAPT Colloquium, November 12, 2024

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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

1. Parity

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…

But, who cares about coordinates?

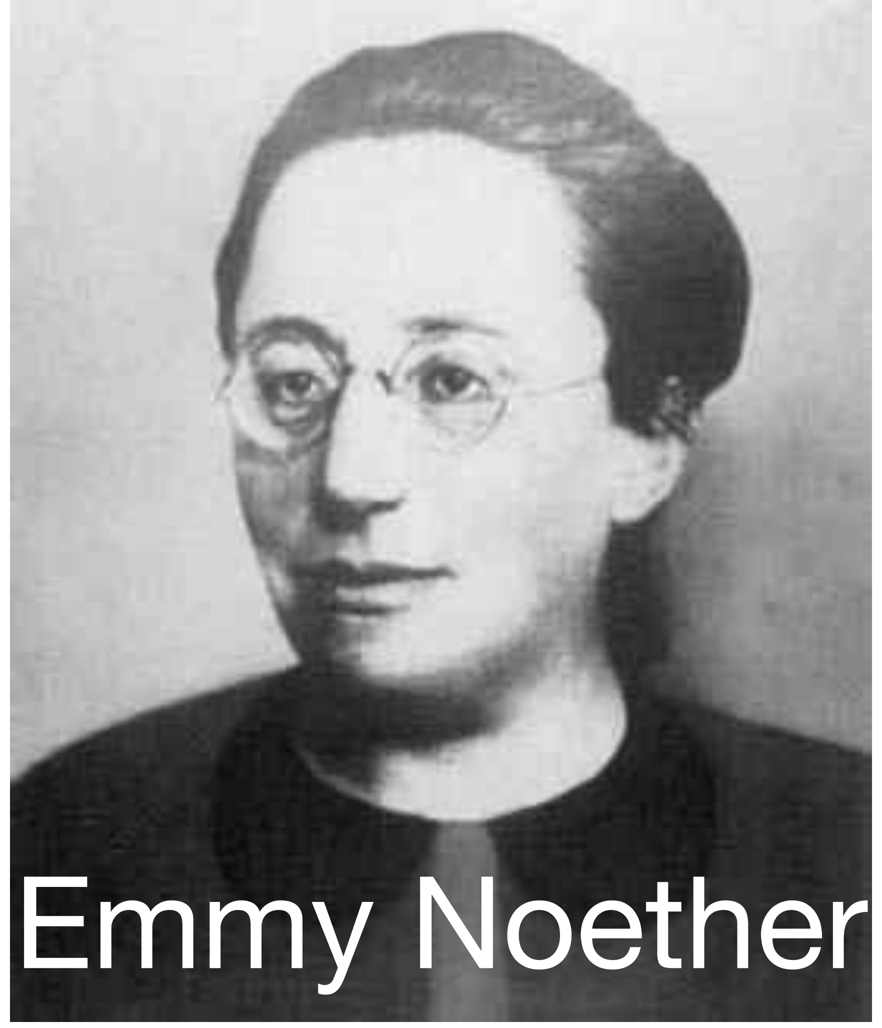
The key is the coordinate *transformation*

- You may say, "*Coordinates are just a convenient mathematical tool. Physics should not depend on how we chart the world with coordinates.*"
  - Yes, that is absolutely correct.
- Coordinate **transformations** are different. The underlying physical principle does not depend on the choice of coordinates. However, "**how a physical system appears to change from one coordinate system to another**" often contains useful information.

Continuous Coordinate Transformation - 1

Spatial translation and homogeneity

- We do an experiment in Sendai, and repeat it in Munich. We find the same answer (to within the uncertainty).
- This is evidence for **invariance under spatial translation**. We shift spatial coordinates by a constant vector ***c***, ***x*** –> ***x*** + ***c***, and the physics relevant to the experiment does not change.
  - There is no special location in space => **homogeneity**.
  - This even implies that the total momentum is conserved!
    - Noether's theorem

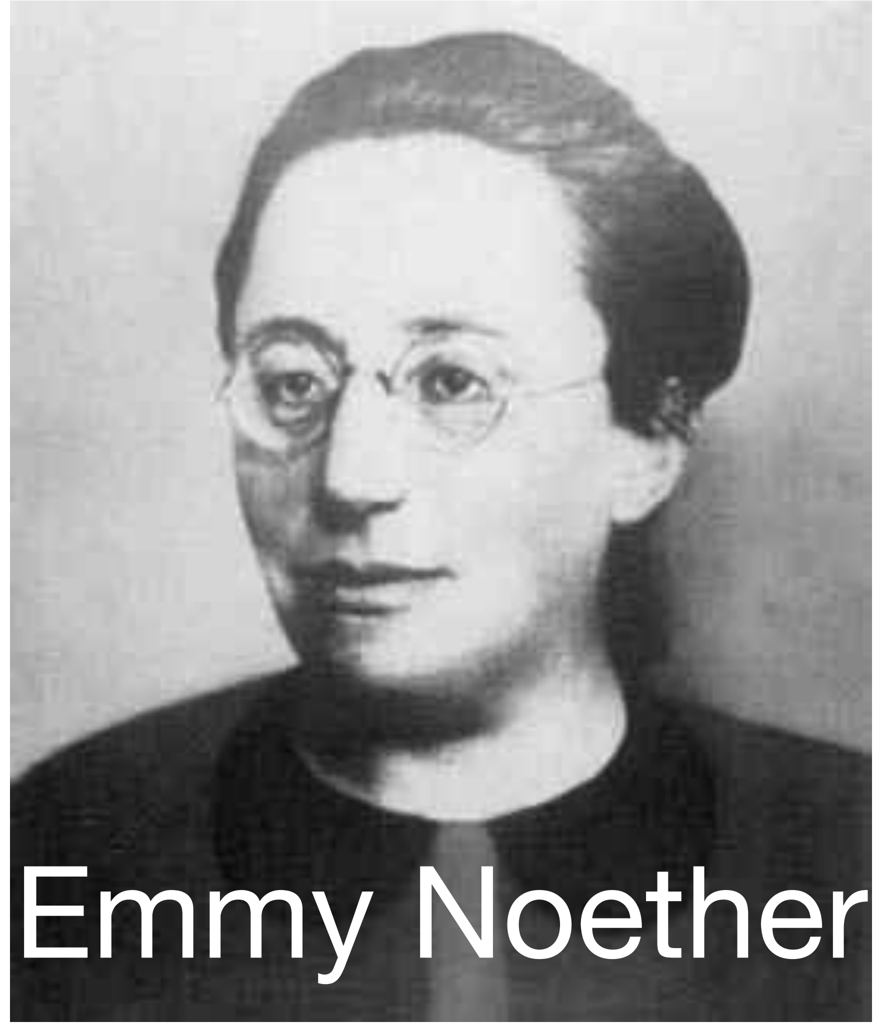


https://mathshistory.st-andrews.ac.uk

Continuous Coordinate Transformation - 2

Spatial rotation and isotropy

- We do an experiment. We repeat it a few times after rotating the experimental apparatus at different angles. We find the same answer (to within the uncertainty).
- This is evidence for **invariance under spatial rotation**. We rotate spatial coordinates by $\boldsymbol{x} \rightarrow R\boldsymbol{x}$, where R is a 3-dimensional rotation matrix, and the physics relevant to the experiment does not change.
  - There is no special direction in space => **isotropy**.
  - This even implies that the total angular momentum is conserved!
    - Noether's theorem



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Parity: Discrete Coordinate Transformation

- We 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

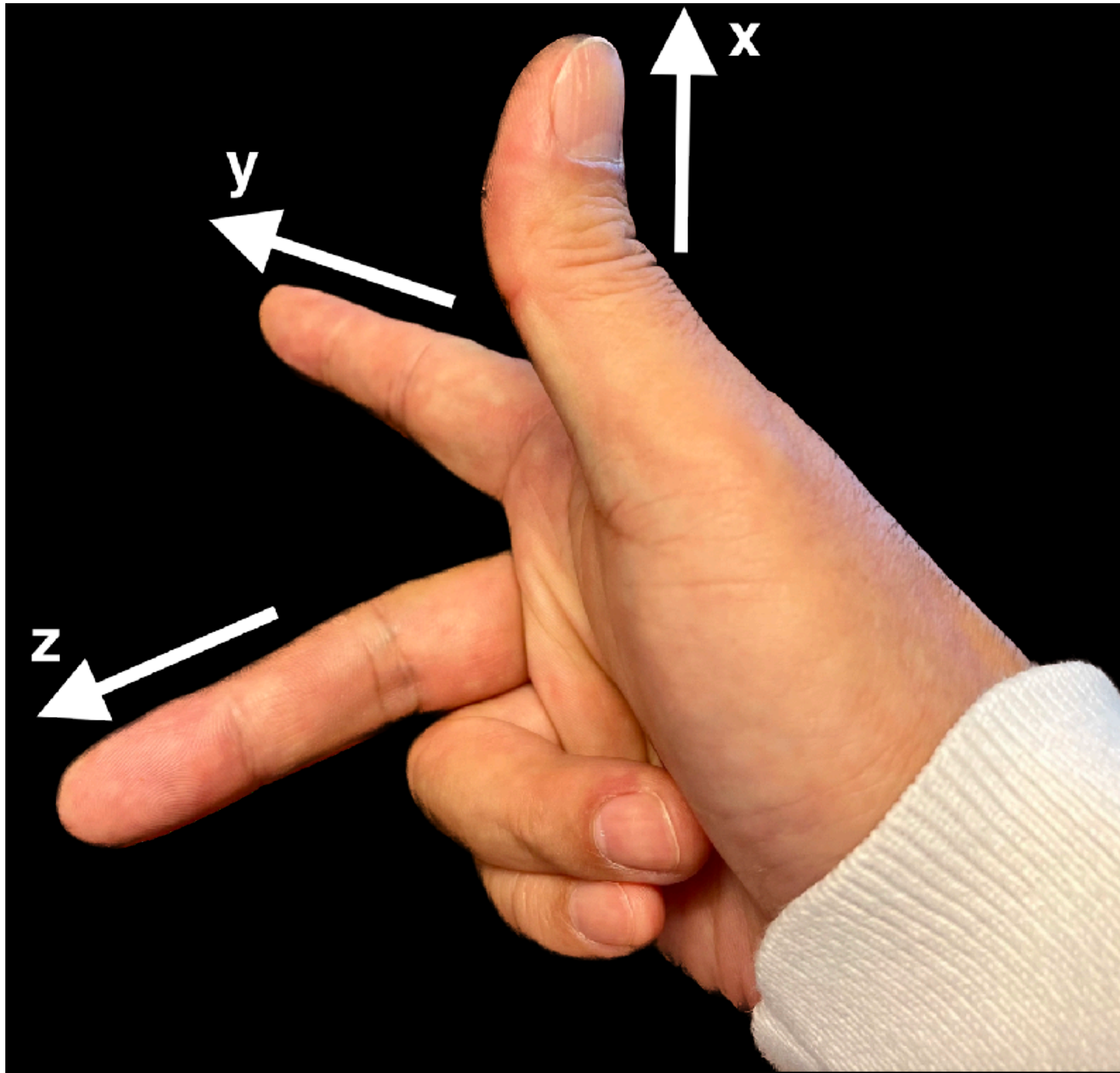
- Parity transformation (***x*** –> -***x***) and 3d rotation (***x*** –> R***x***) are different.
    - R is a continuous transformation and the determinant of R is det(R) = +1.
    - Parity is a discrete transformation and the **determinant is –1**, as

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

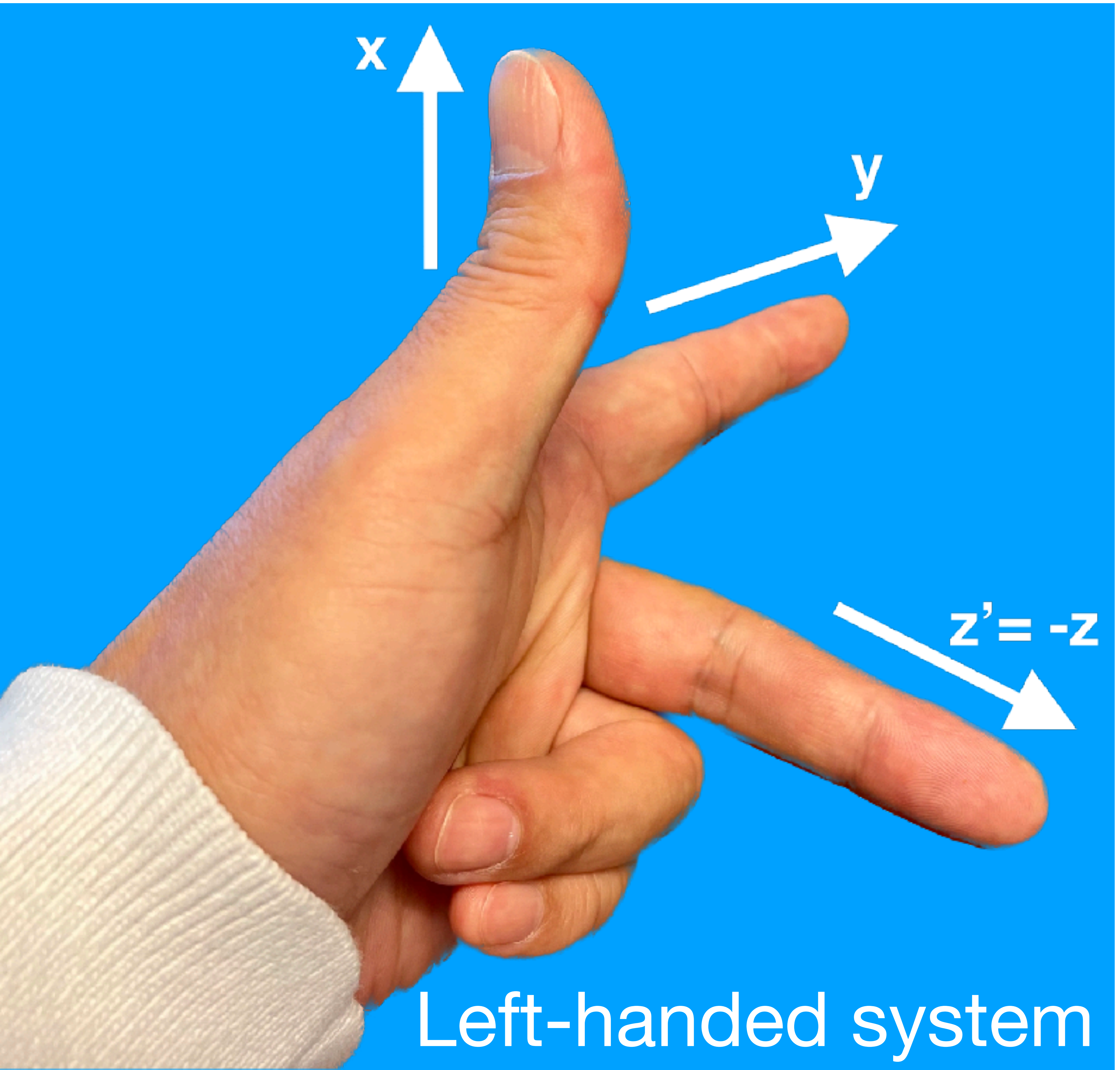
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Parity = Mirror + 2d Rotation

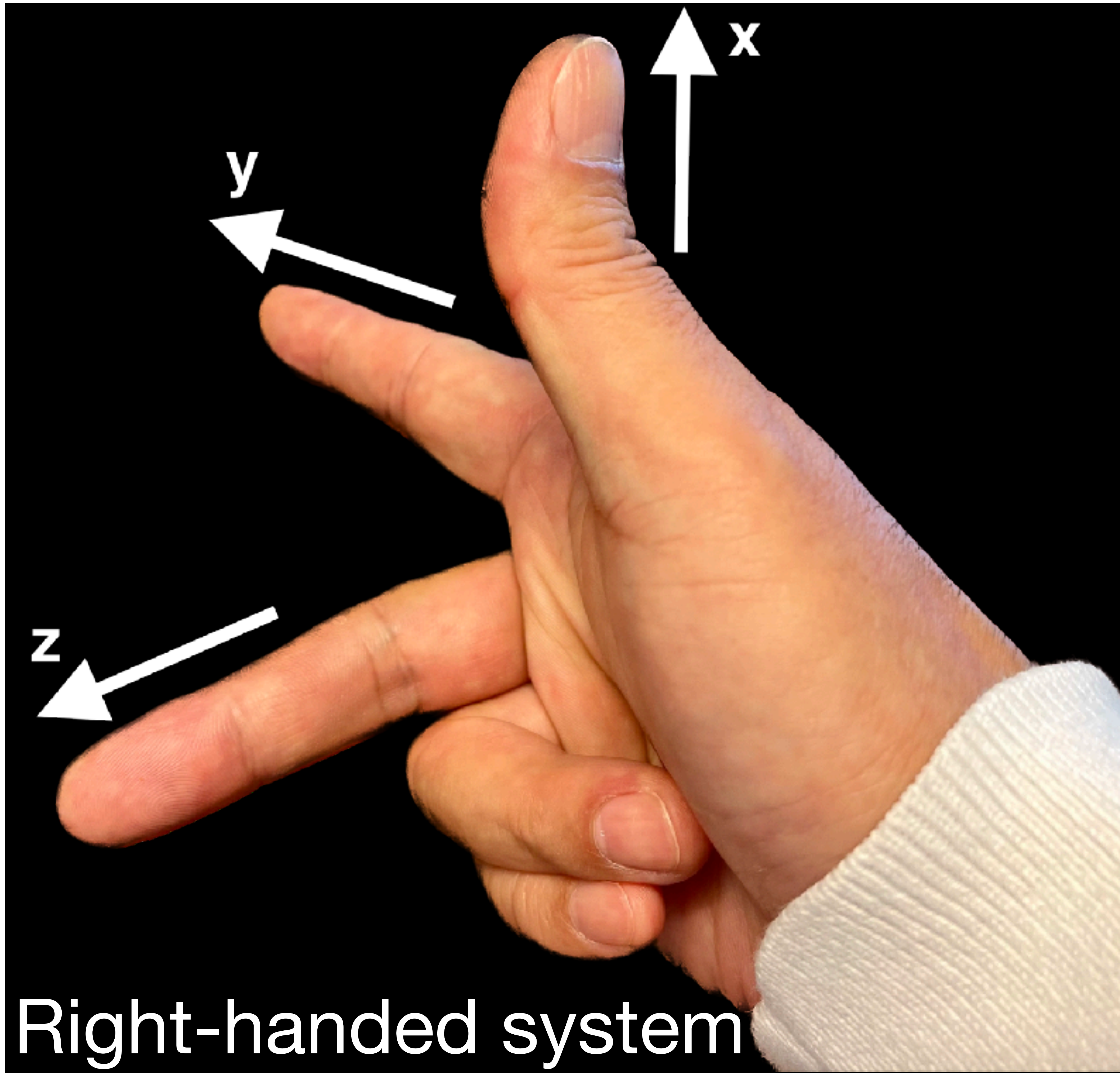
- One may think of parity transformation as a mirror in one of the coordinates (e.g., z –> -z) and **2d** rotation by π in the others.
- Let's demonstrate it!



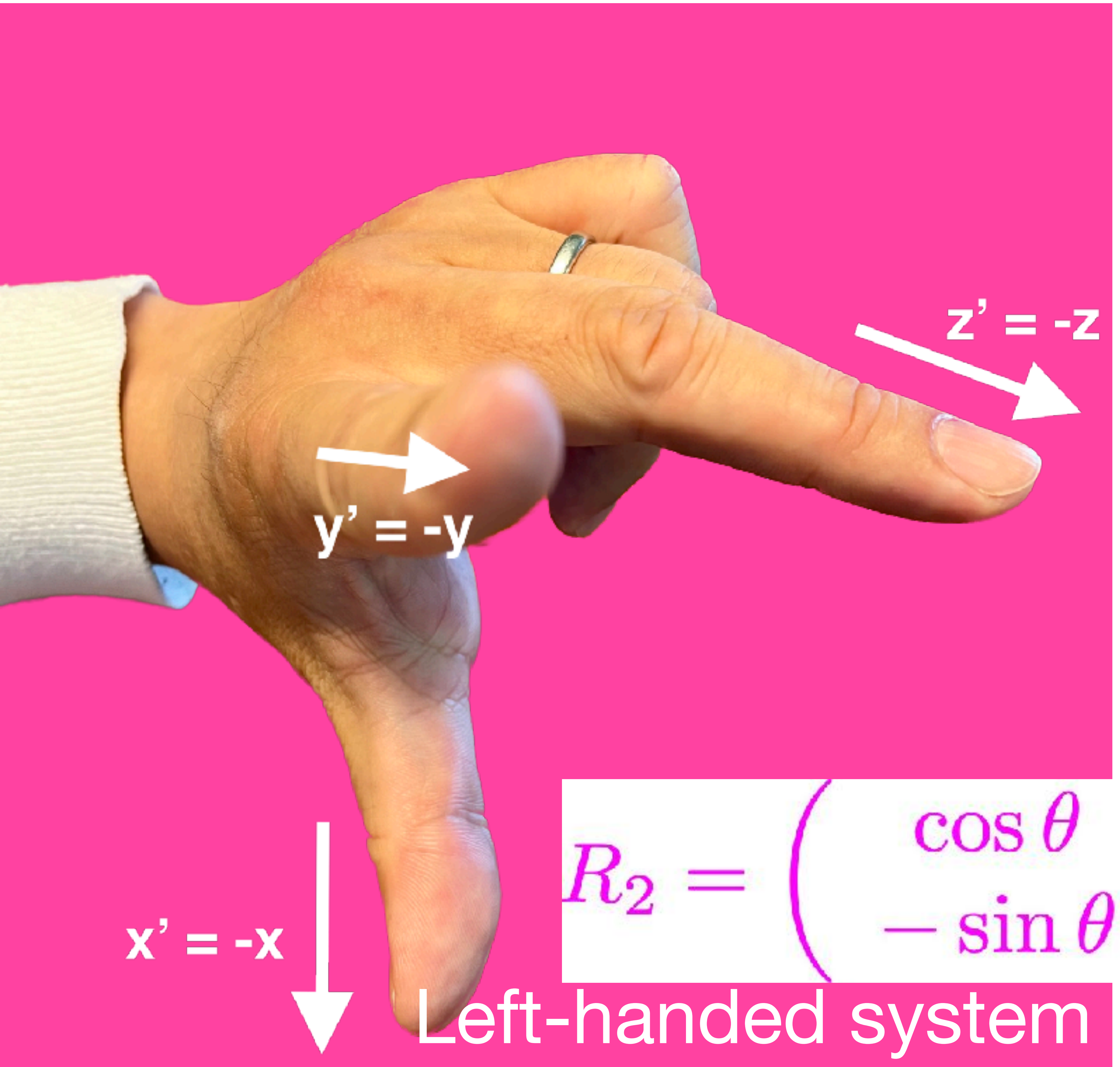
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & \boxed{-1} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$



z -> z' = -z



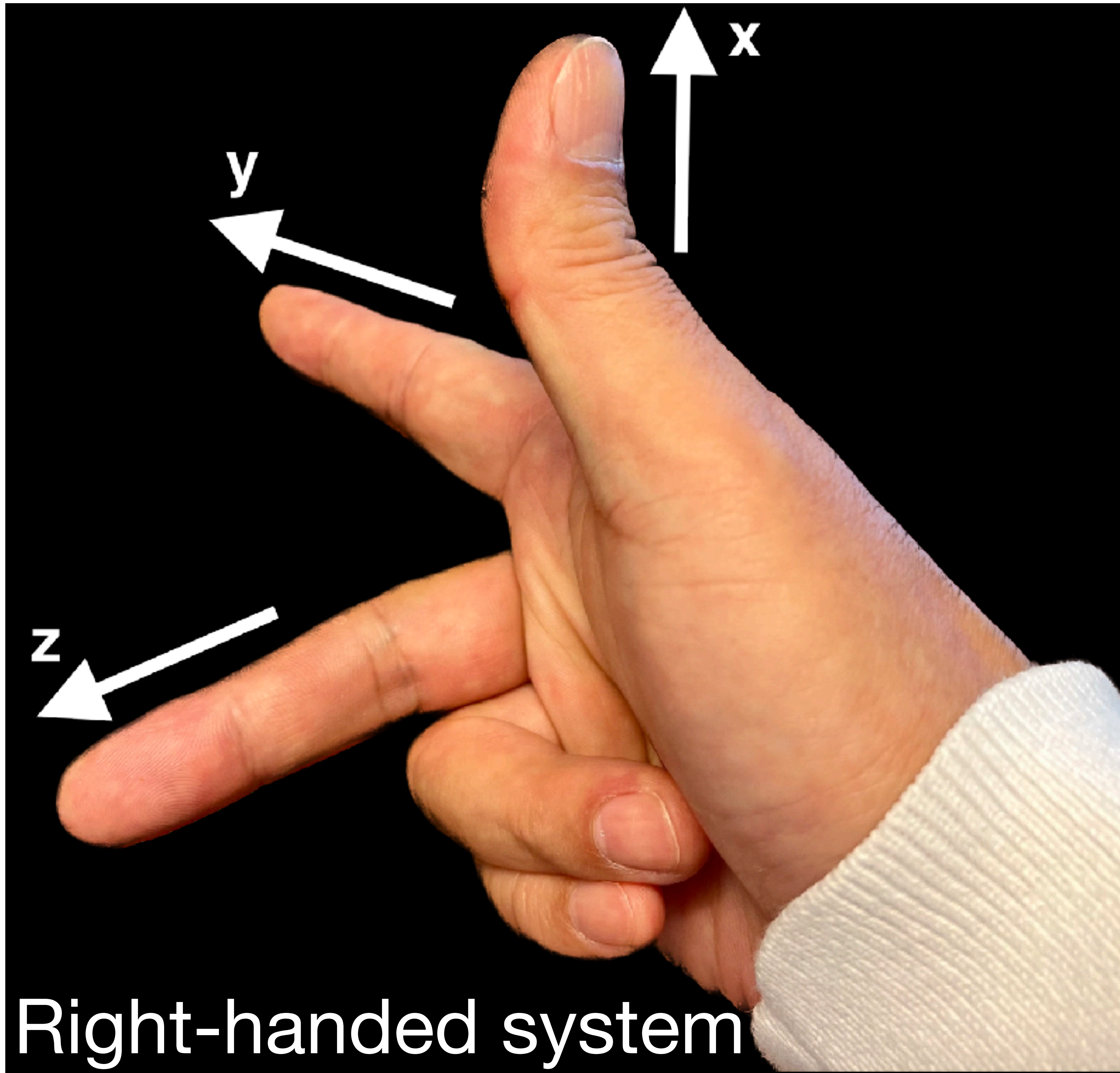
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$



Rotation In x-y

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

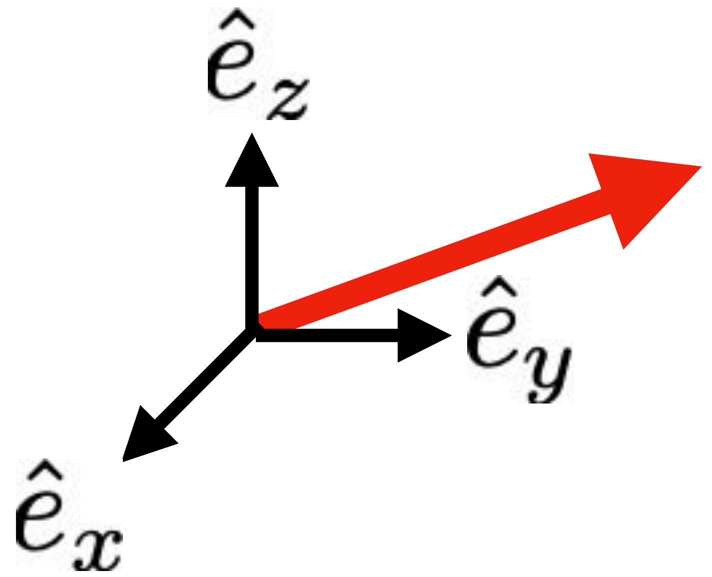
with θ = π



2. Pseudovector, Pseudoscalar

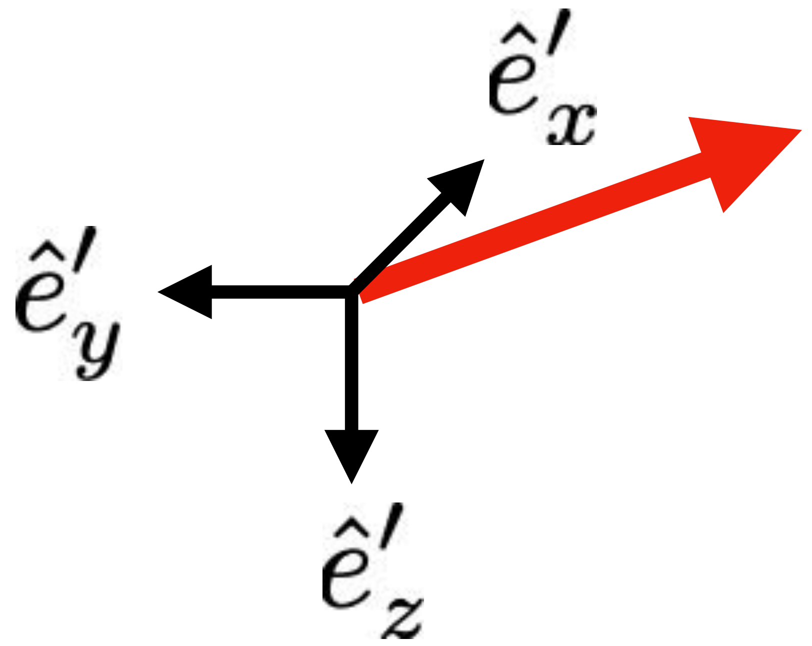
Parity Transformation: Vector

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.



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

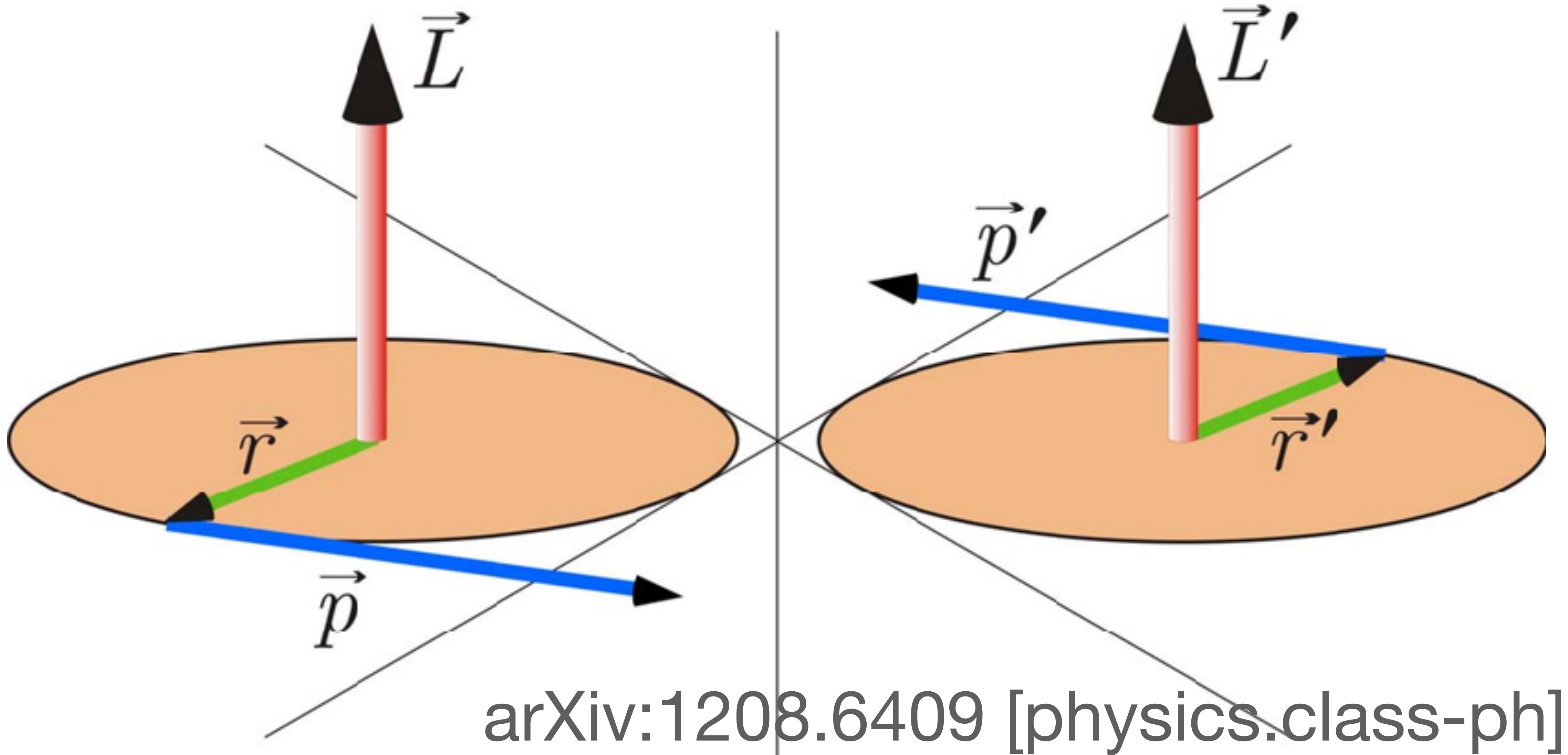
- **p** is the same vector, written using two different basis vectors.
- Therefore, **p**'s components are transformed as $(p'_x, p'_y, p'_z) = (-p_x, -p_y, -p_z)$

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 **<u>not</u>** 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.,

$$L'_x = Y'p'_z - Z'p'_y$$
$$= (-Y)(-p_z) - (-Z)(-p_y)$$
$$= L_x$$



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, $\langle \mathbf{p}_{\mathrm{A}} \cdot \mathbf{L}_{\mathrm{B}} \rangle = 0$?

3. Discovery of Parity Violation in β-decay (weak interaction)

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*

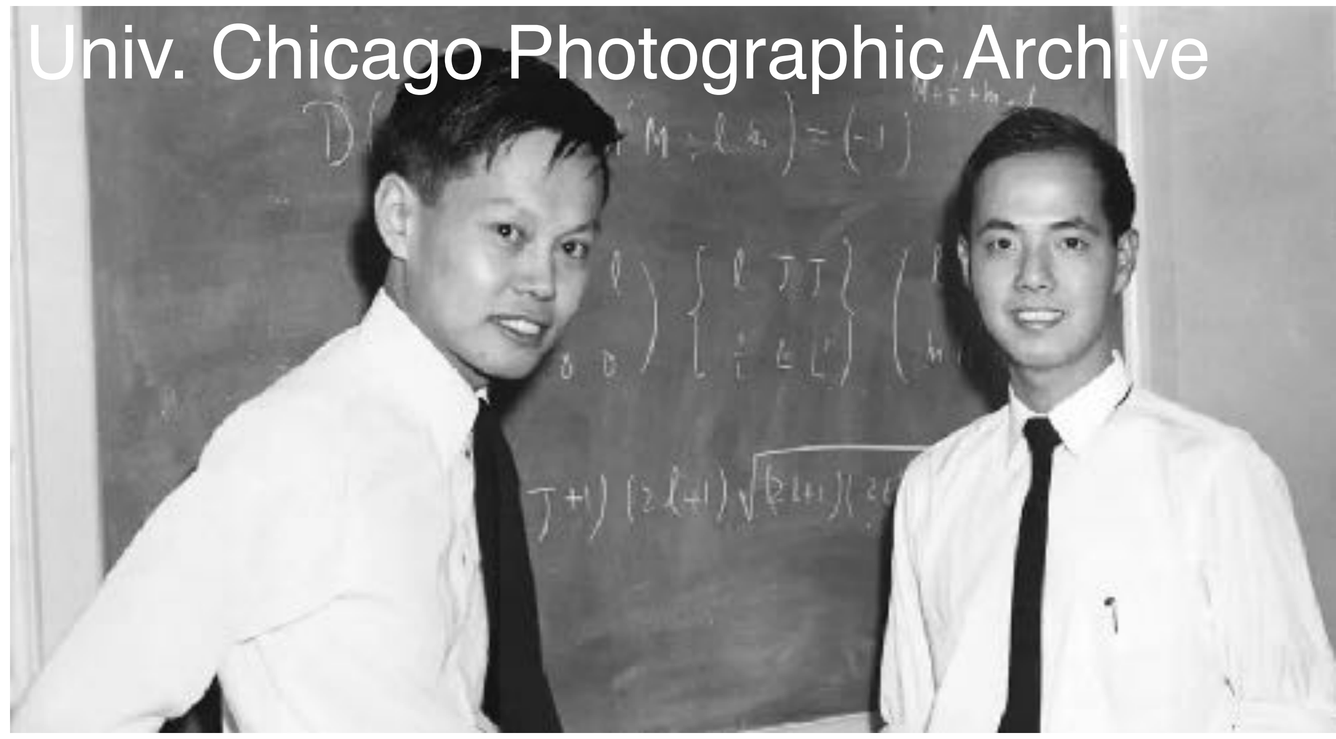
AND

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!**

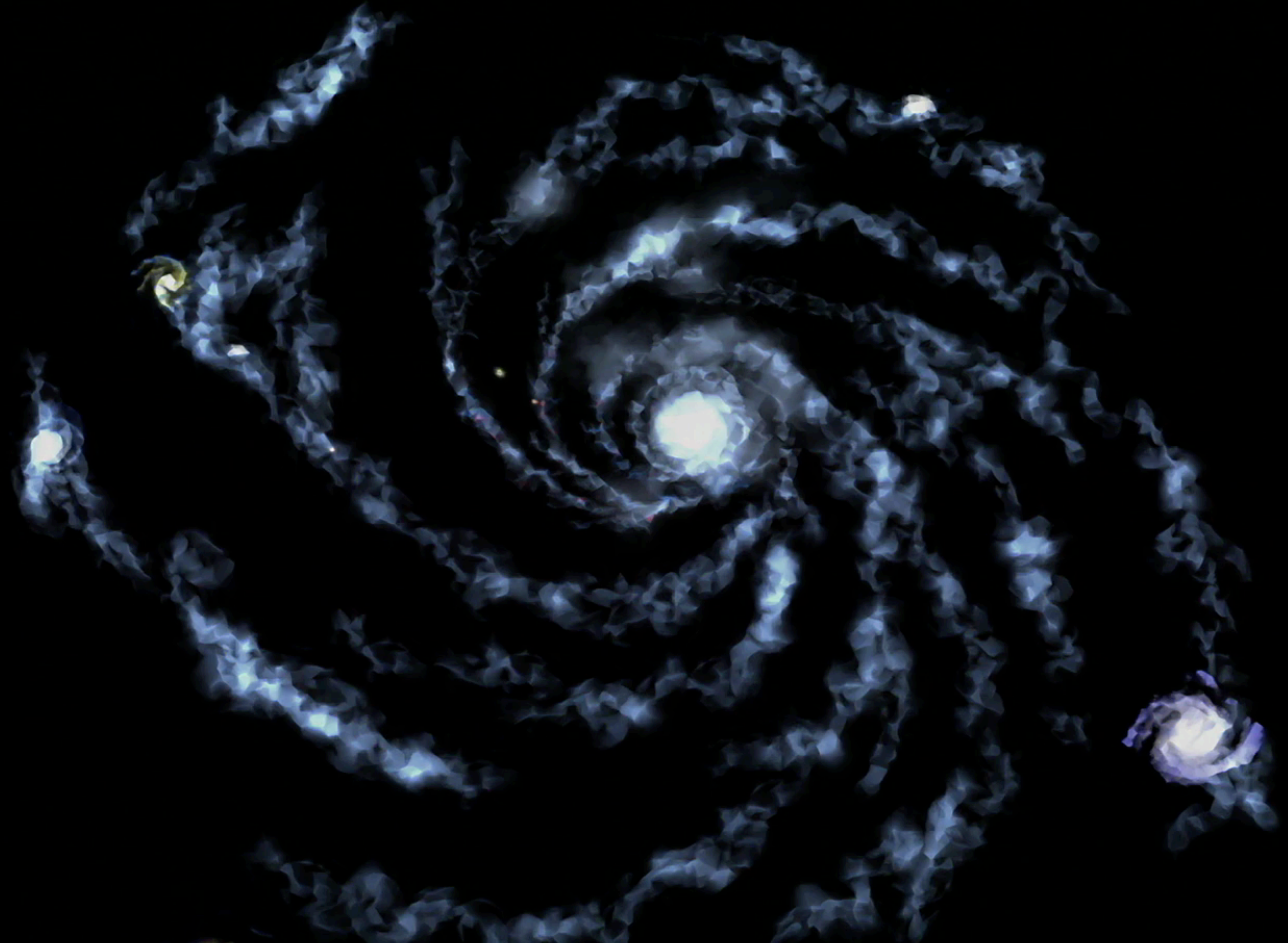
Initial reaction

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?”*

4. Parity Violation in the Cosmic Microwave Background (CMB)

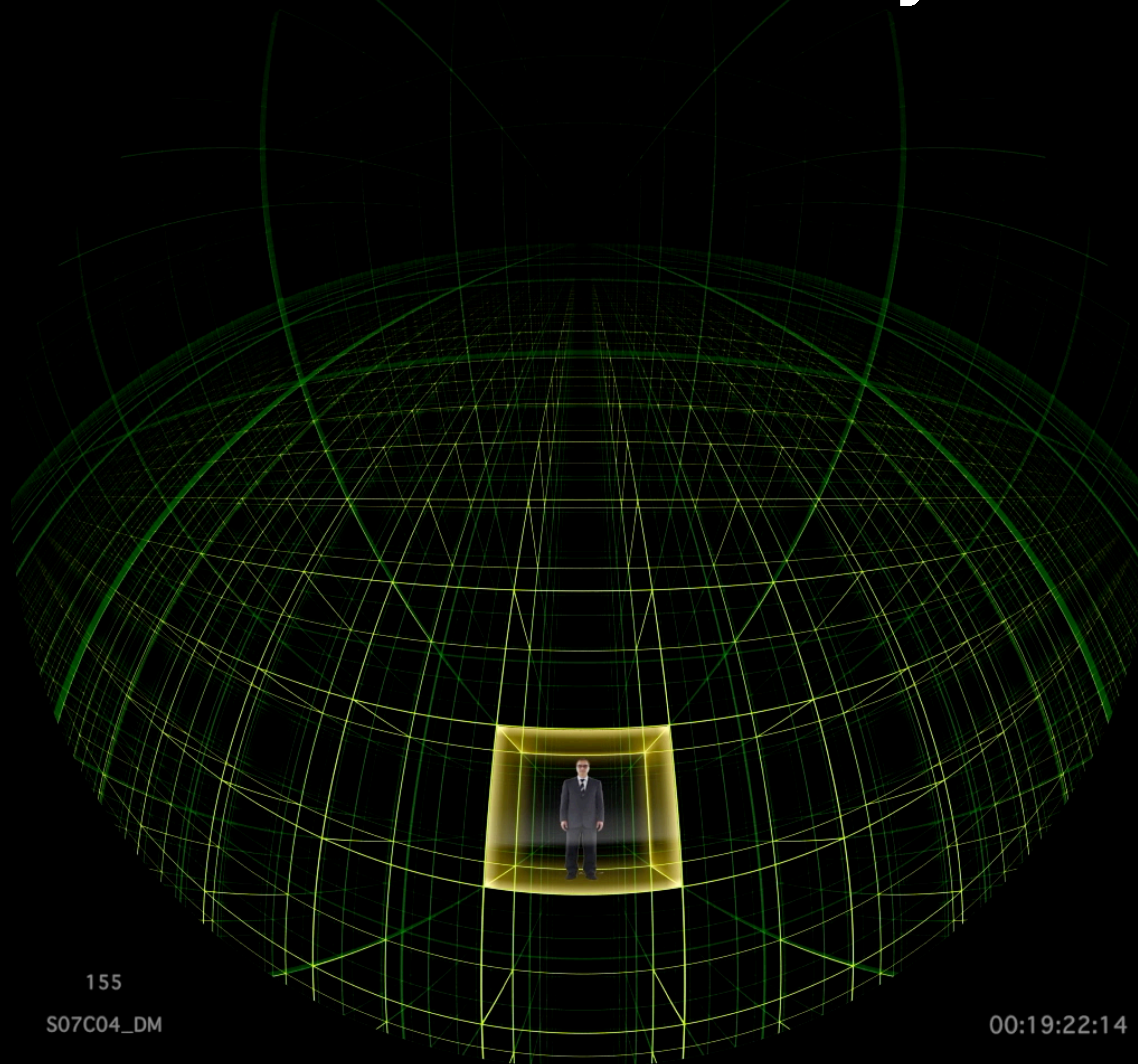
Credit: WMAP Science Team



The sky in various wavelengths

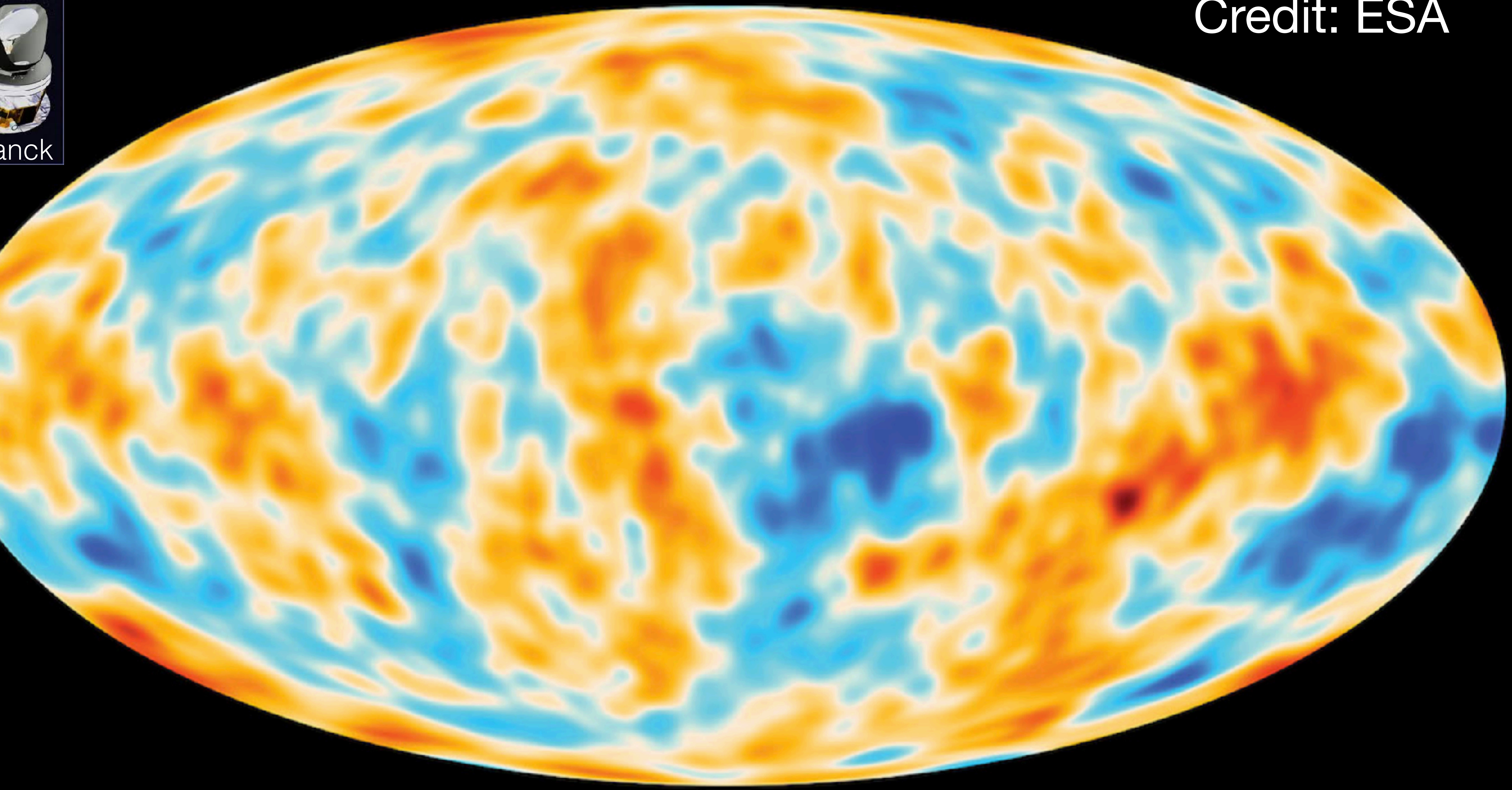
Visible -> Near Infrared -> Far Infrared -> Submillimeter -> Microwave

Where did the CMB we see today come from?



From “HORIZON”

Credit: ESA



Temperature (smoothed)

Credit: ESA

Temperature (smoothed) + Polarisation

Key Point

Pseudoscalar: EB correlation

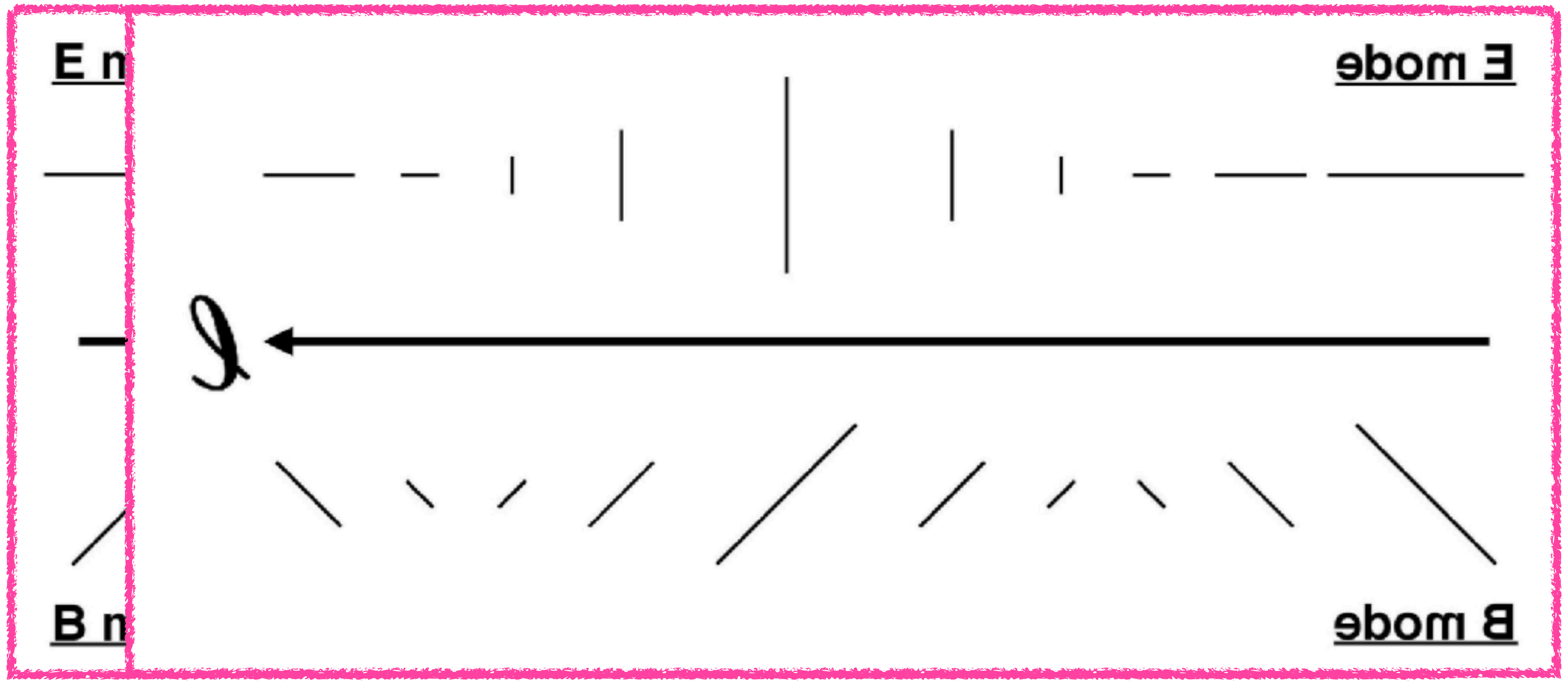
- The observed pattern of the CMB polarization can be decomposed into eigenstates of parity, called “E modes” and “B modes”.

- 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!**

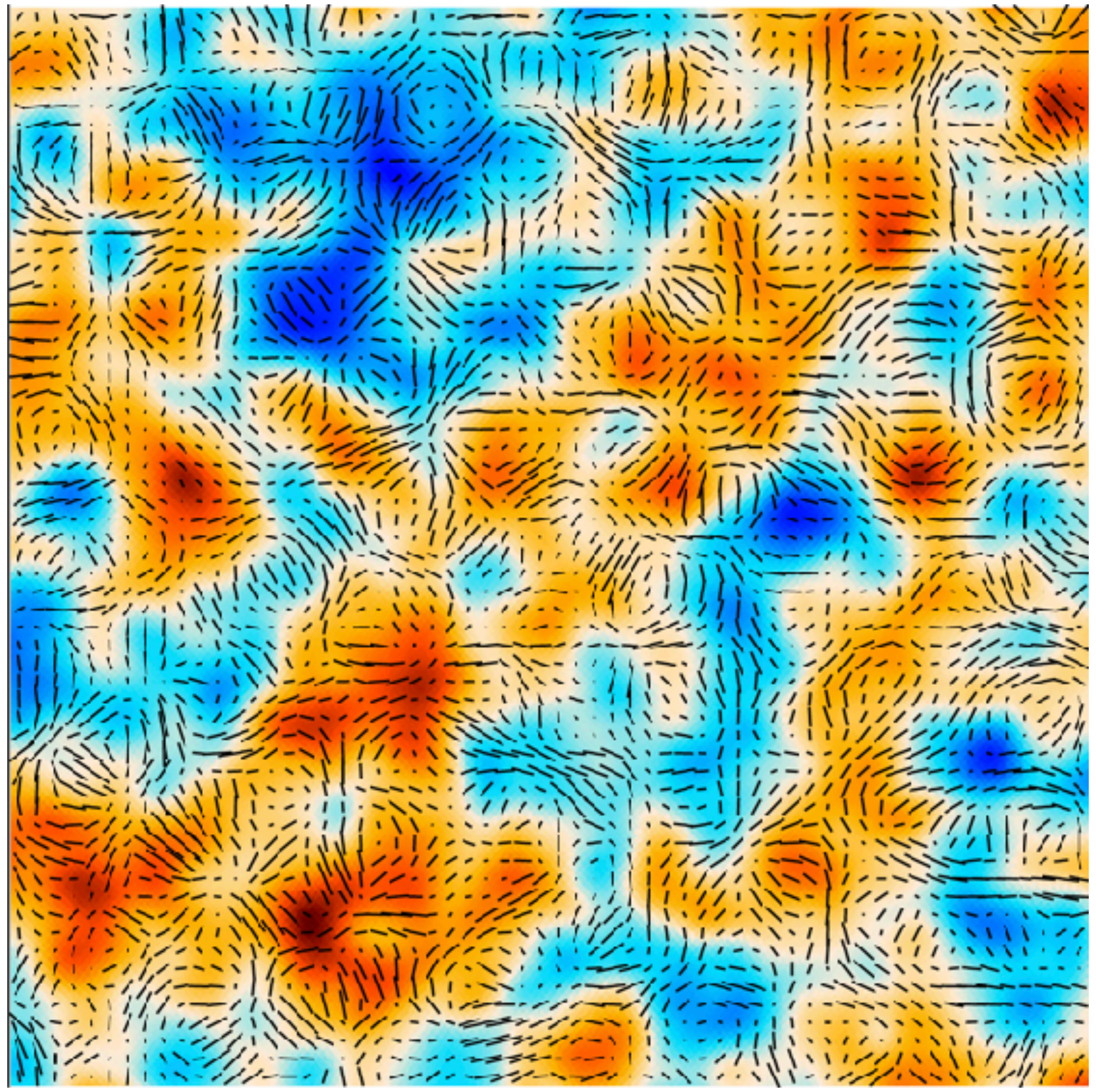
Zaldarriaga, Seljak (1997); Kamionkowski, Kosowsky, Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

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

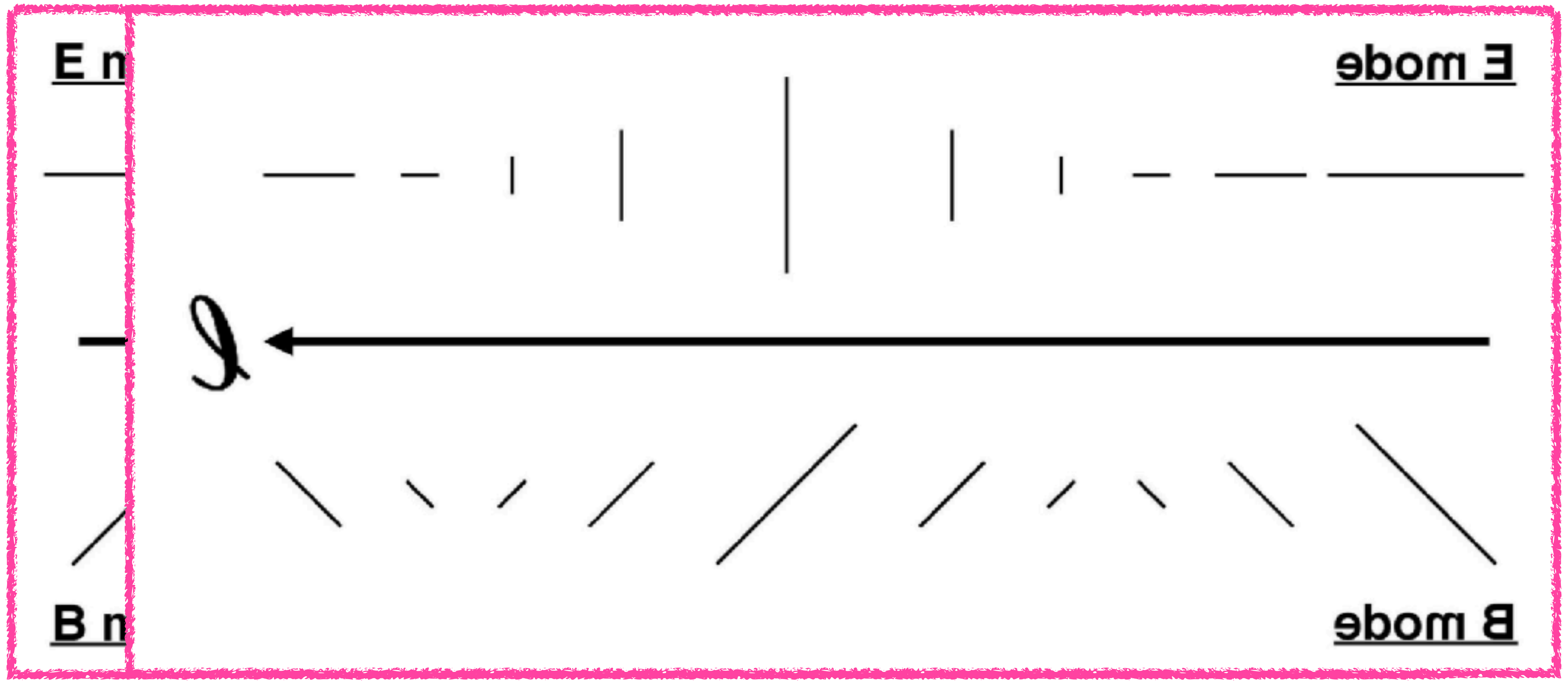
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

These are scalars and insensitive to parity violation.

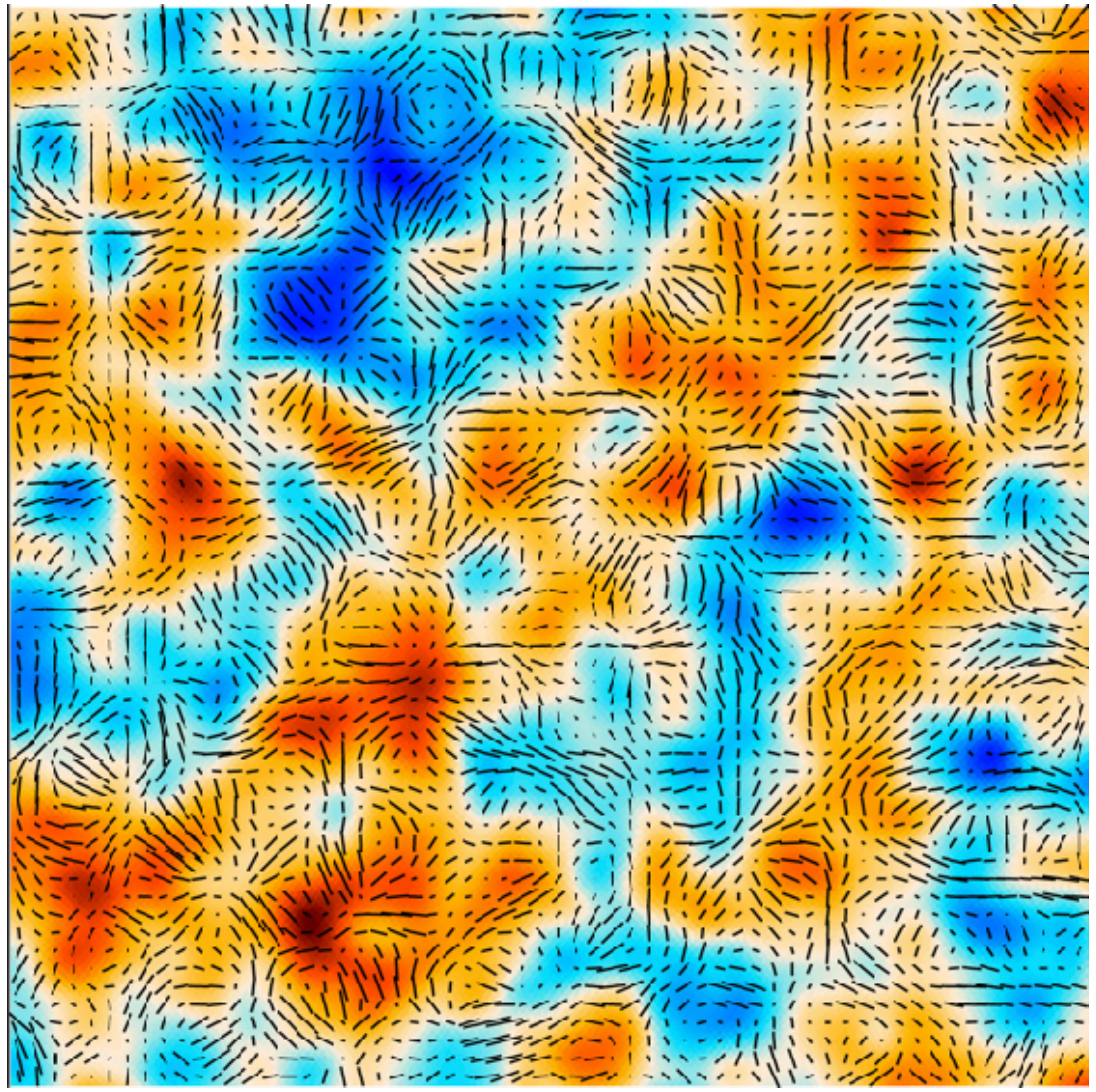
Lue, Wang, Kamionkowski (1999); Feng et al. (2005, 2006)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated
by E-mode polarization



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

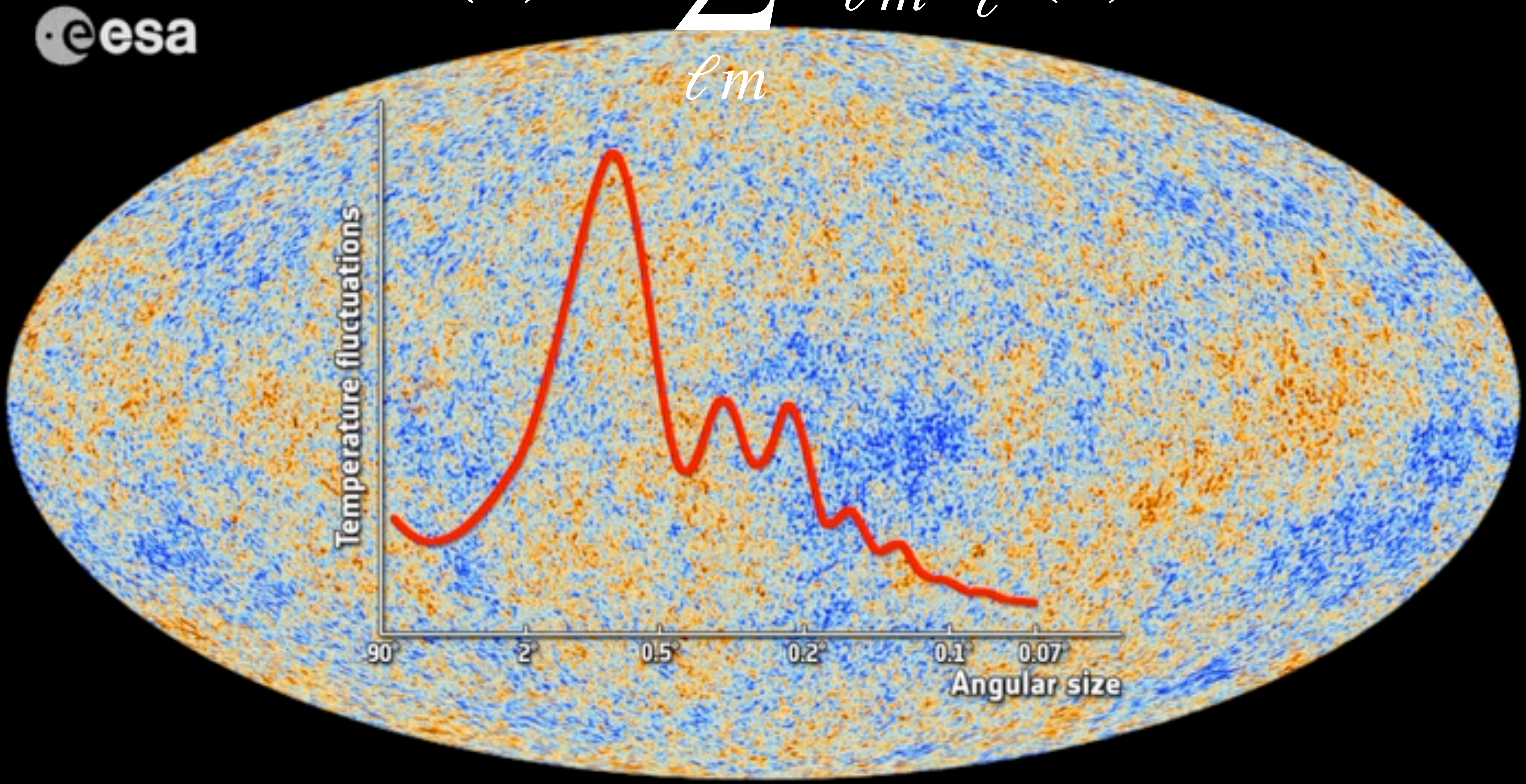
$$\langle B_{\boldsymbol\ell} B^*_{\boldsymbol\ell'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol\ell -$$

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

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

Spherical Harmonics Decomposition

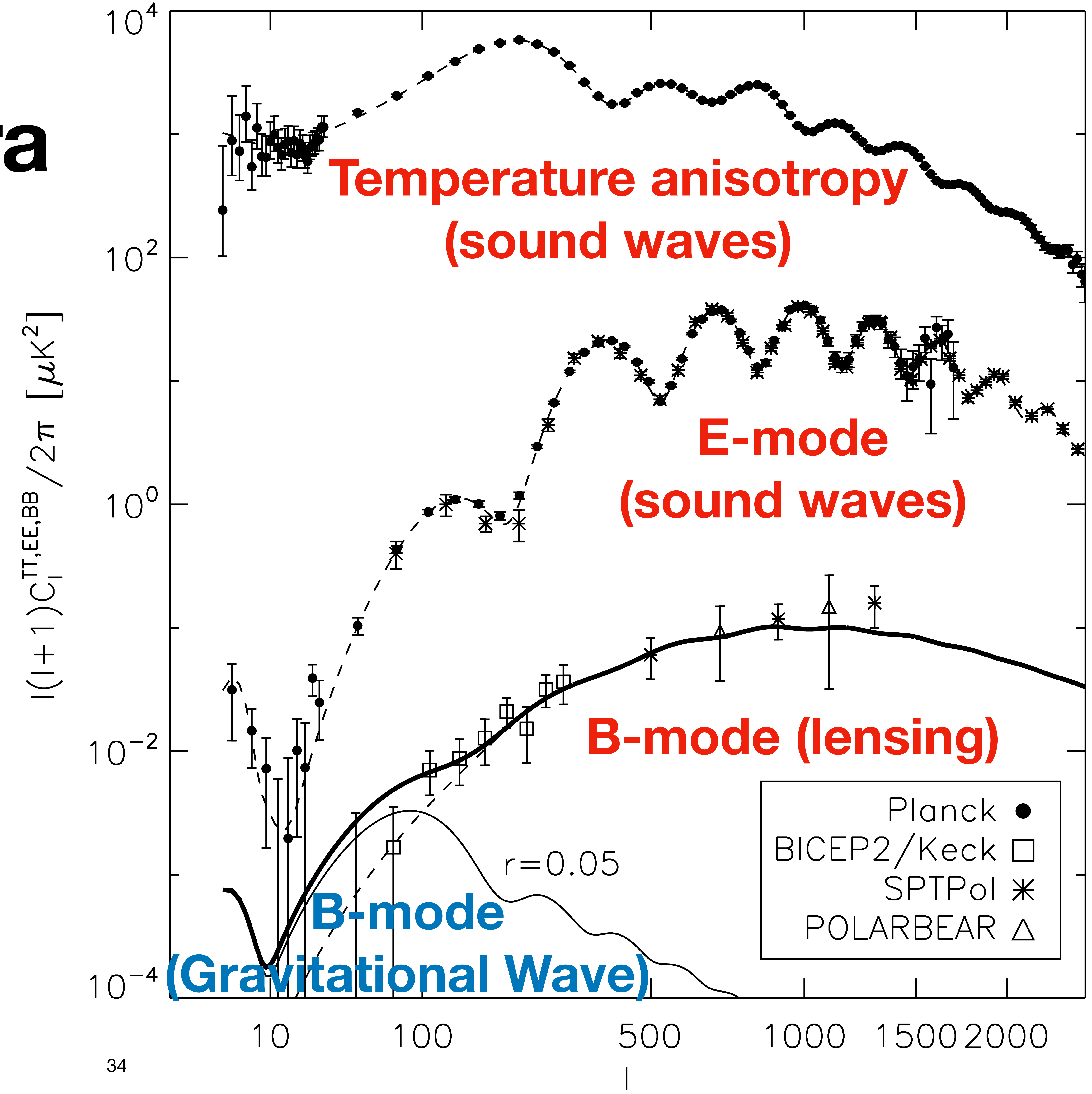
$$\Delta T(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell}^{m}(\hat{n})$$



CMB Power Spectra

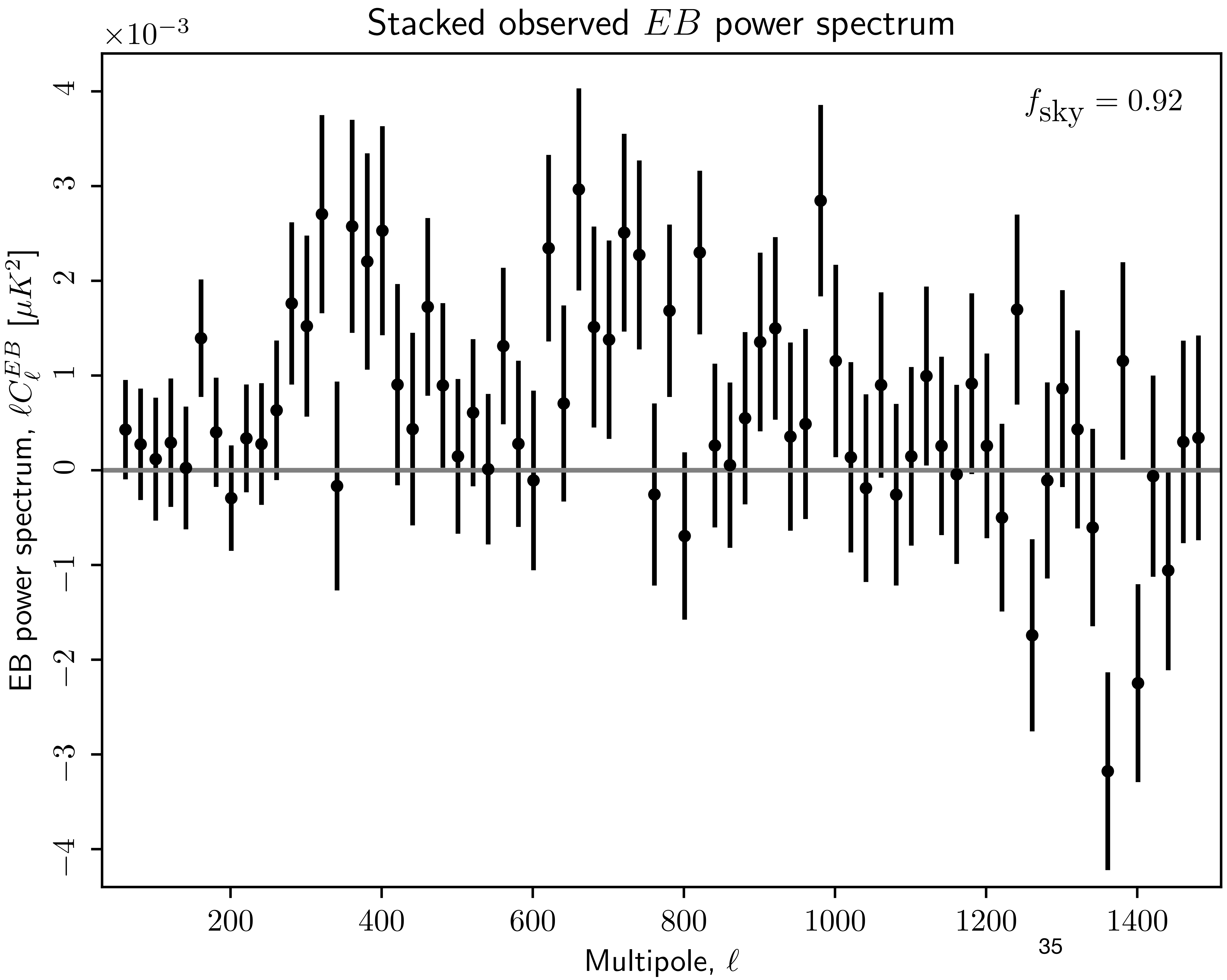
Progress over 30 years

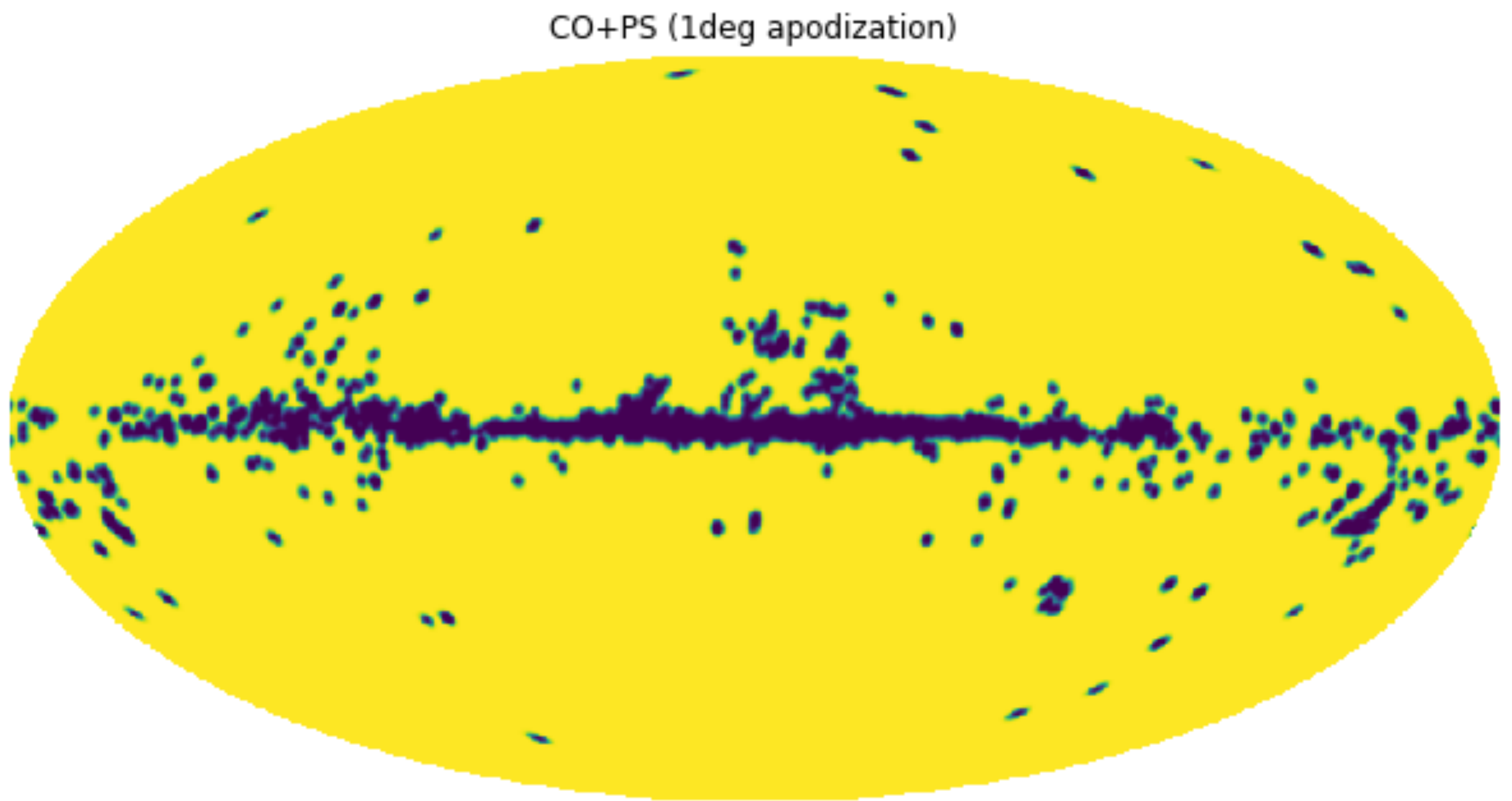
- This is the typical figure seen in talks and lectures on the CMB.
    - The temperature and the E- and B-mode polarization power spectra are well measured.
- **Parity violation appears in the TB and EB power spectra, not shown here.**



This is the EB power spectrum (WMAP+Planck)

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



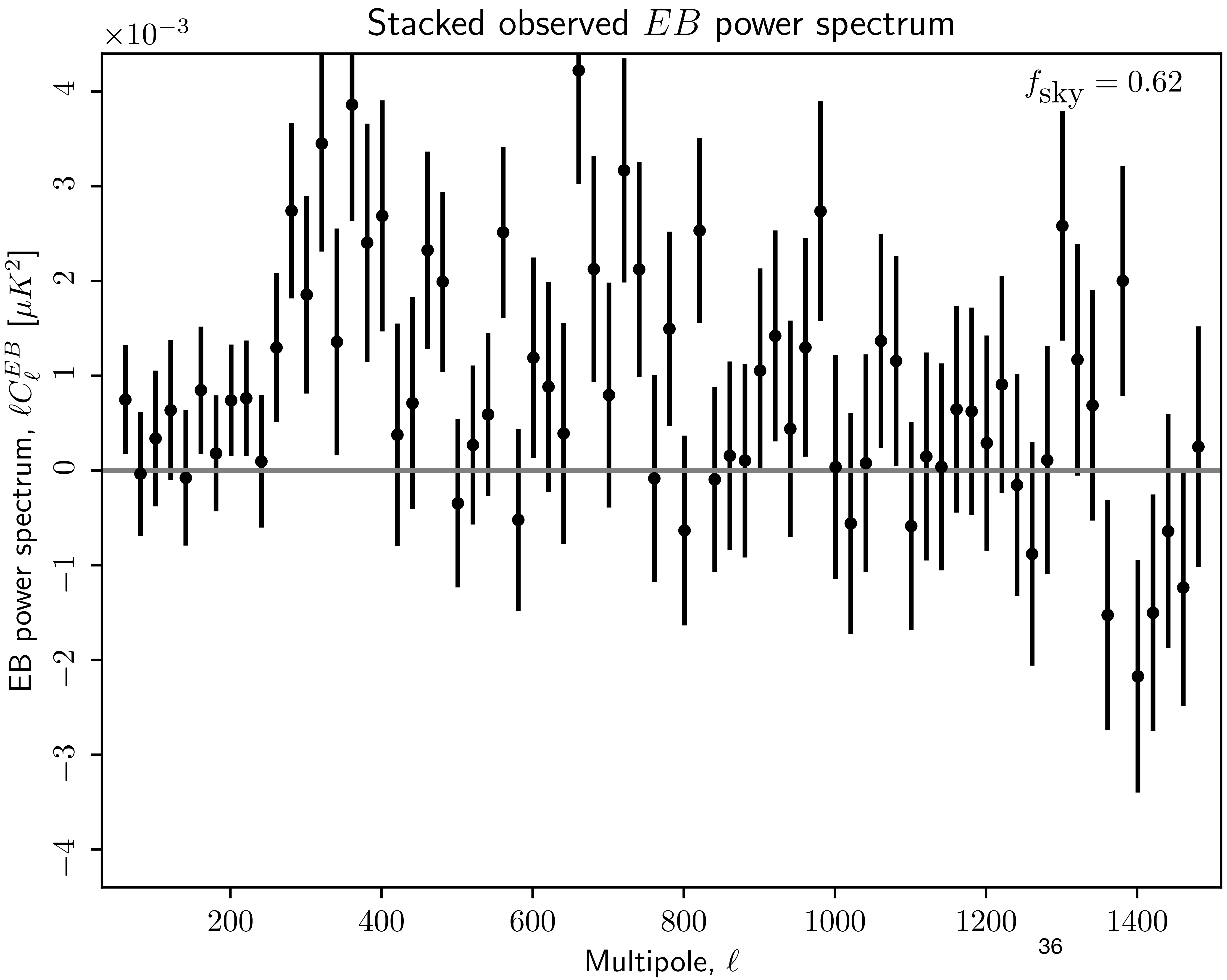


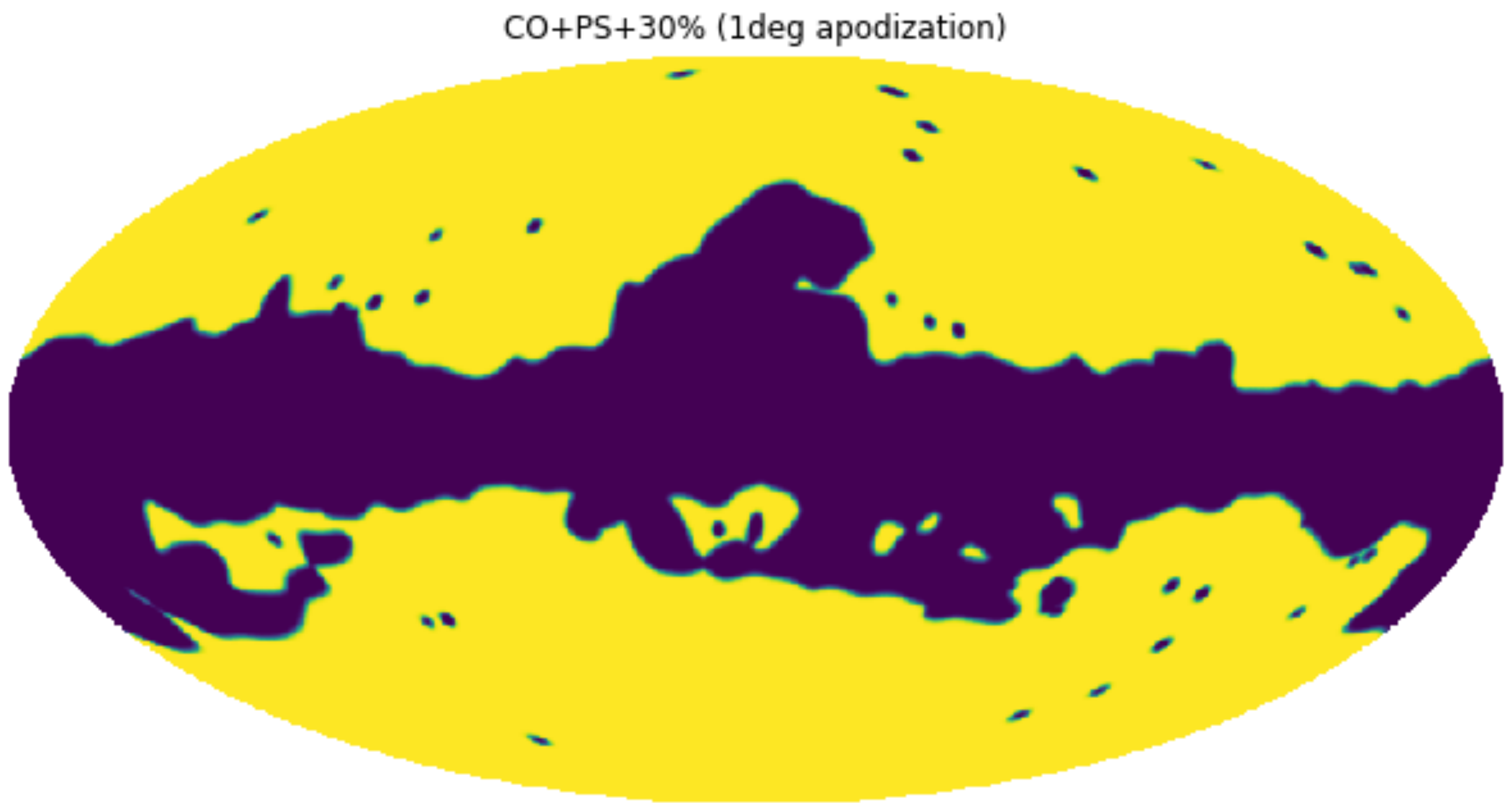
- $\chi^2 = 125.5$ for DOF=72
  - Unambiguous signal of something!

Eskilt, EK (2022)

This is the EB power spectrum (WMAP+Planck)

Galactic plane removed (62% of the sky)



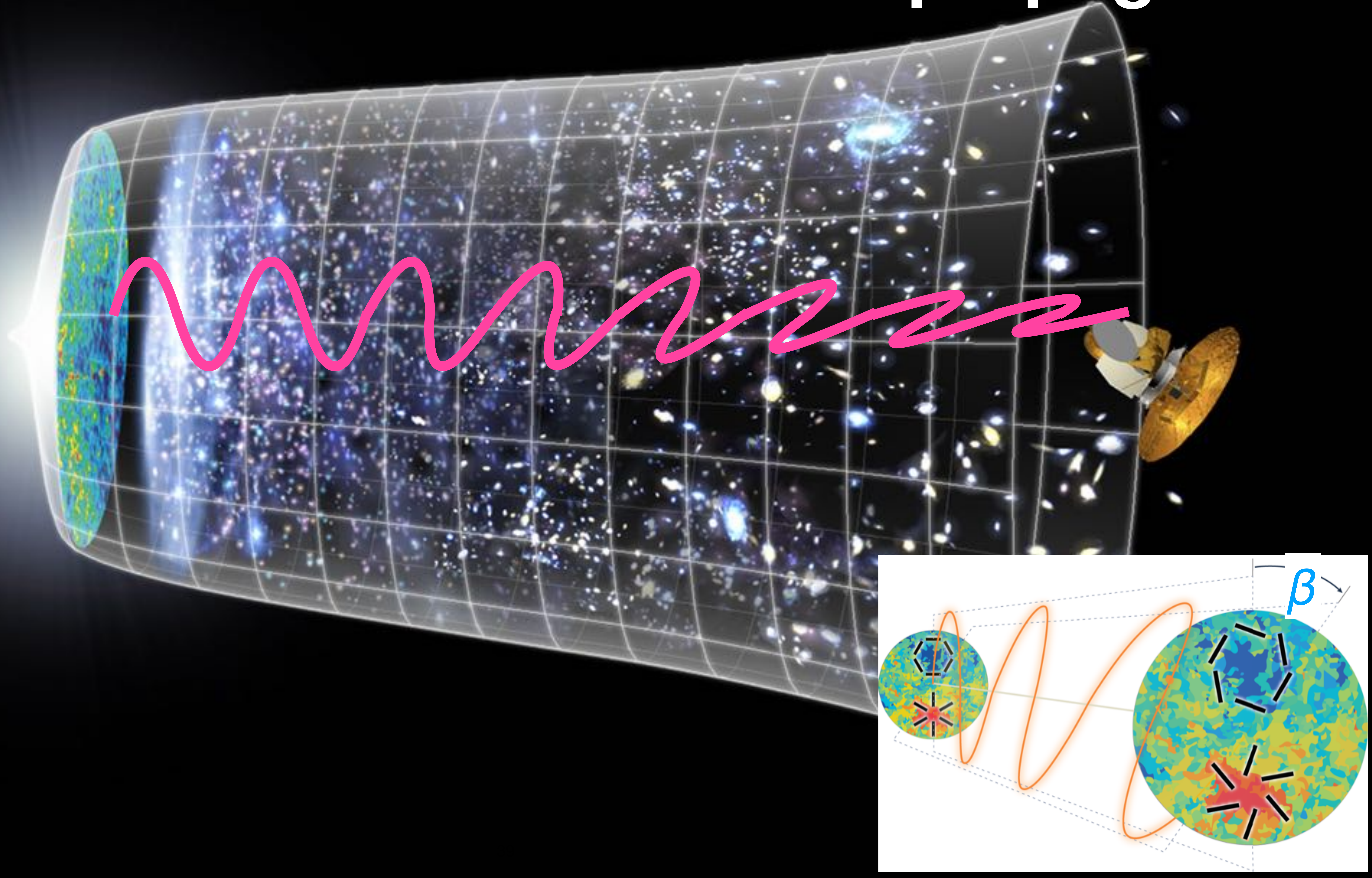


- $\chi^2 = 138.4$
  - The signal exists regardless of the Galactic mask. This rules out the Galactic foreground.

5. Cosmic Birefringence: Rotation of the Plane of Linear Polarization

How does the EM wave of the CMB propagate?

How does the EM wave of the CMB propagate?



Credit: ESA

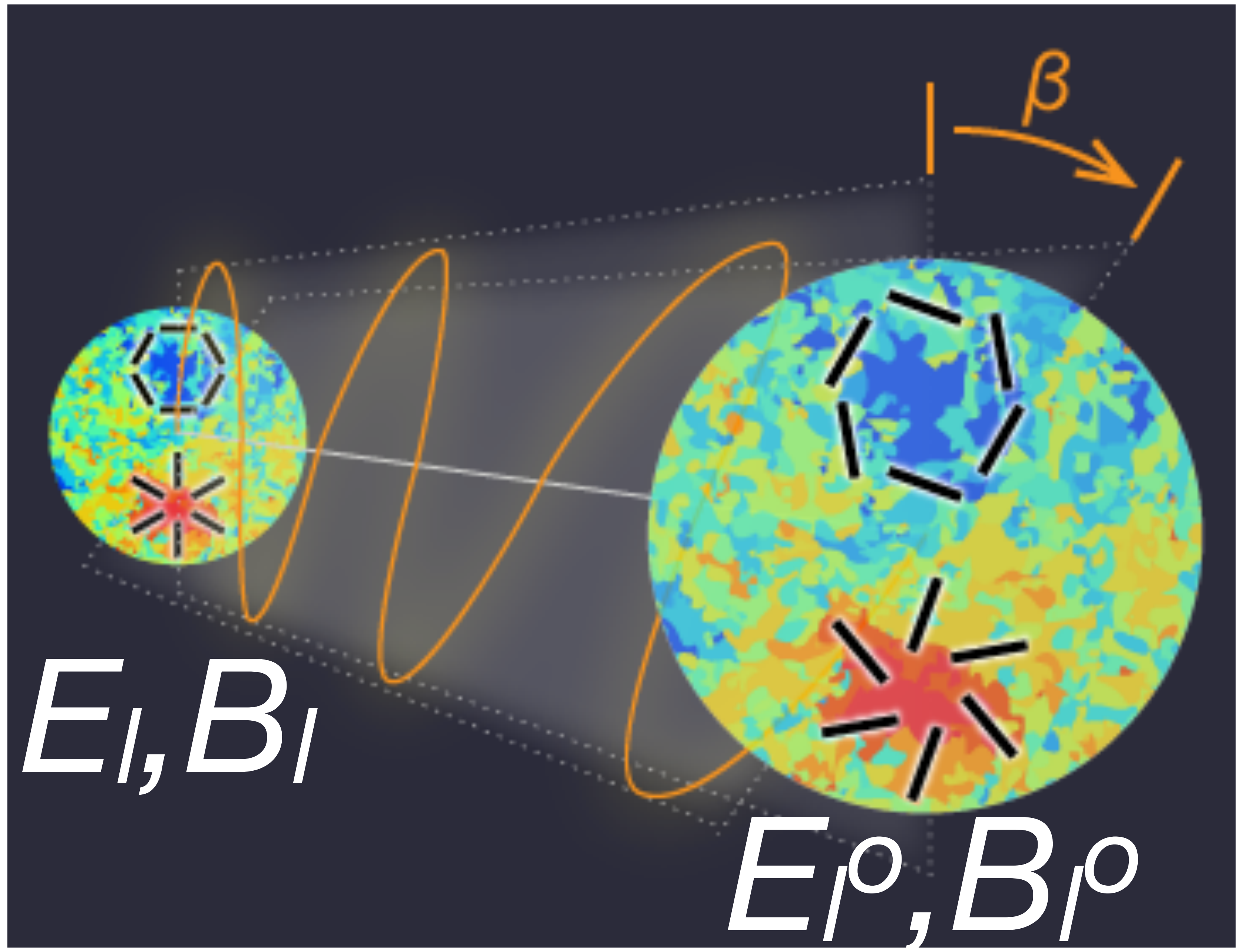
“Cosmic Birefringence”

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

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



- which gives

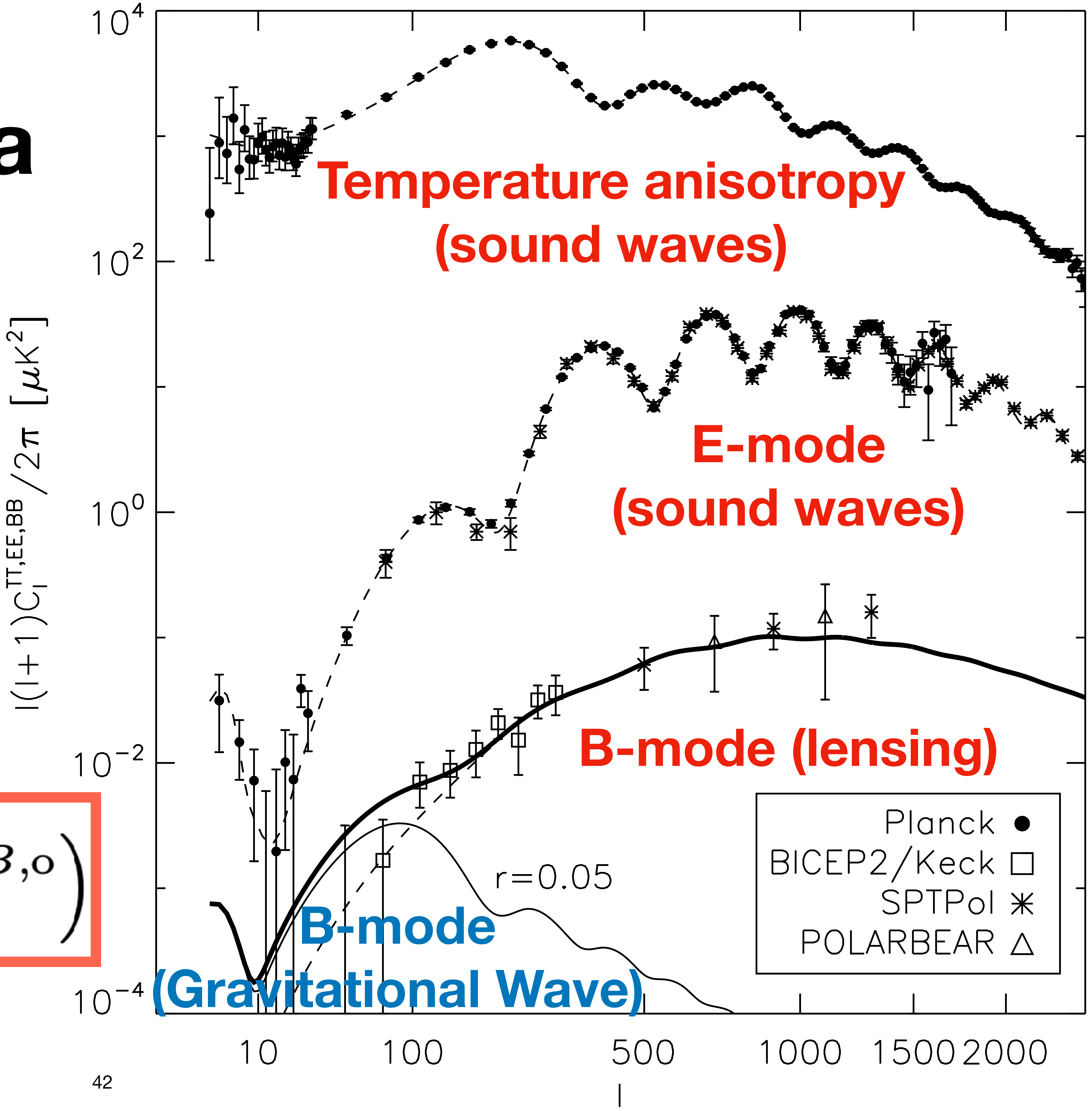
$$E_\ell^{\mathrm{o}} = E_\ell \cos(2\beta) - B_\ell \sin(2\beta)$$

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

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!

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

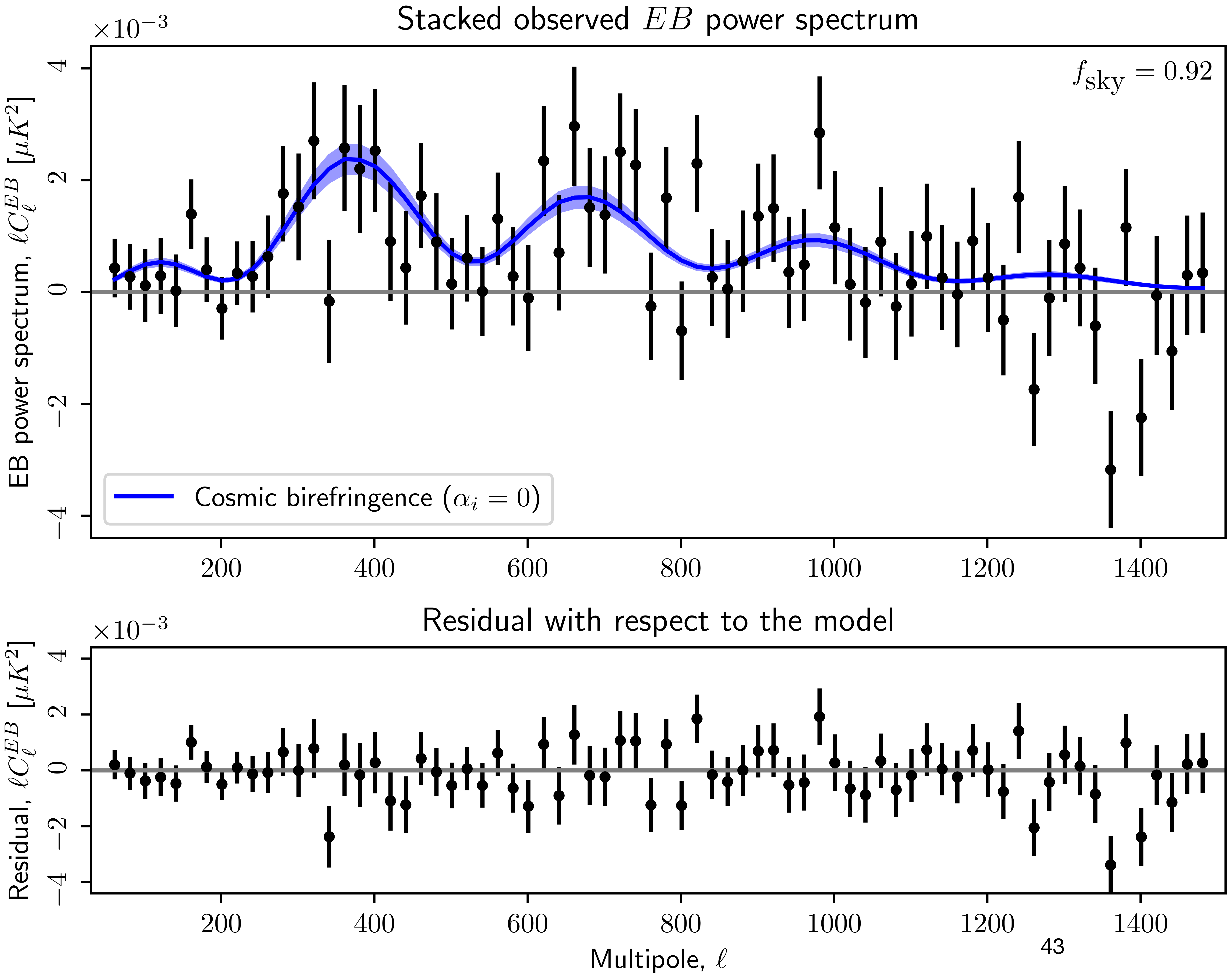


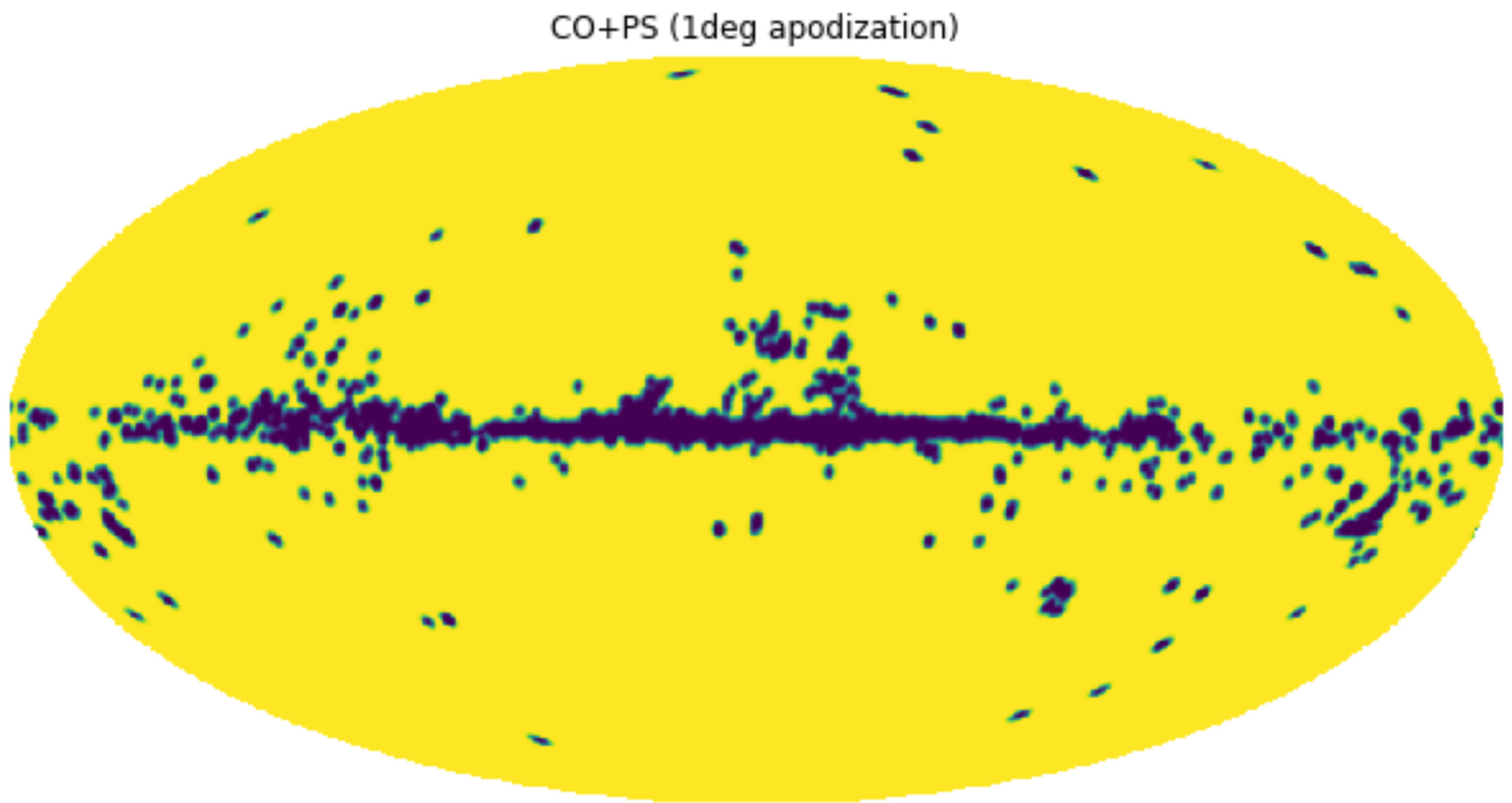
Eskilt, EK (2022)

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)





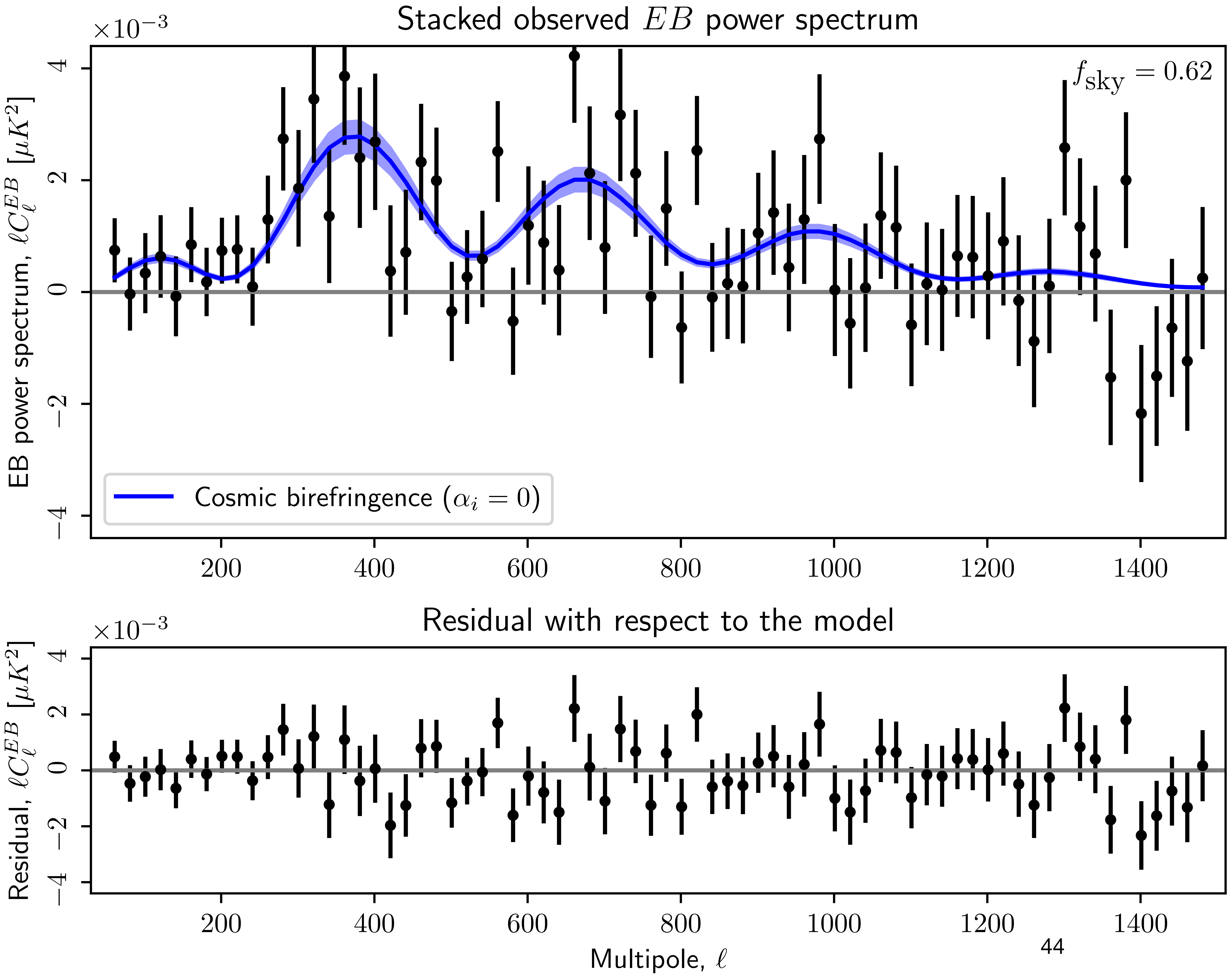
- $\beta = 0.288 \pm 0.032$ deg
- $\chi^2 = 66.1$ for DOF=71
  - Good fit! 9σ detection?

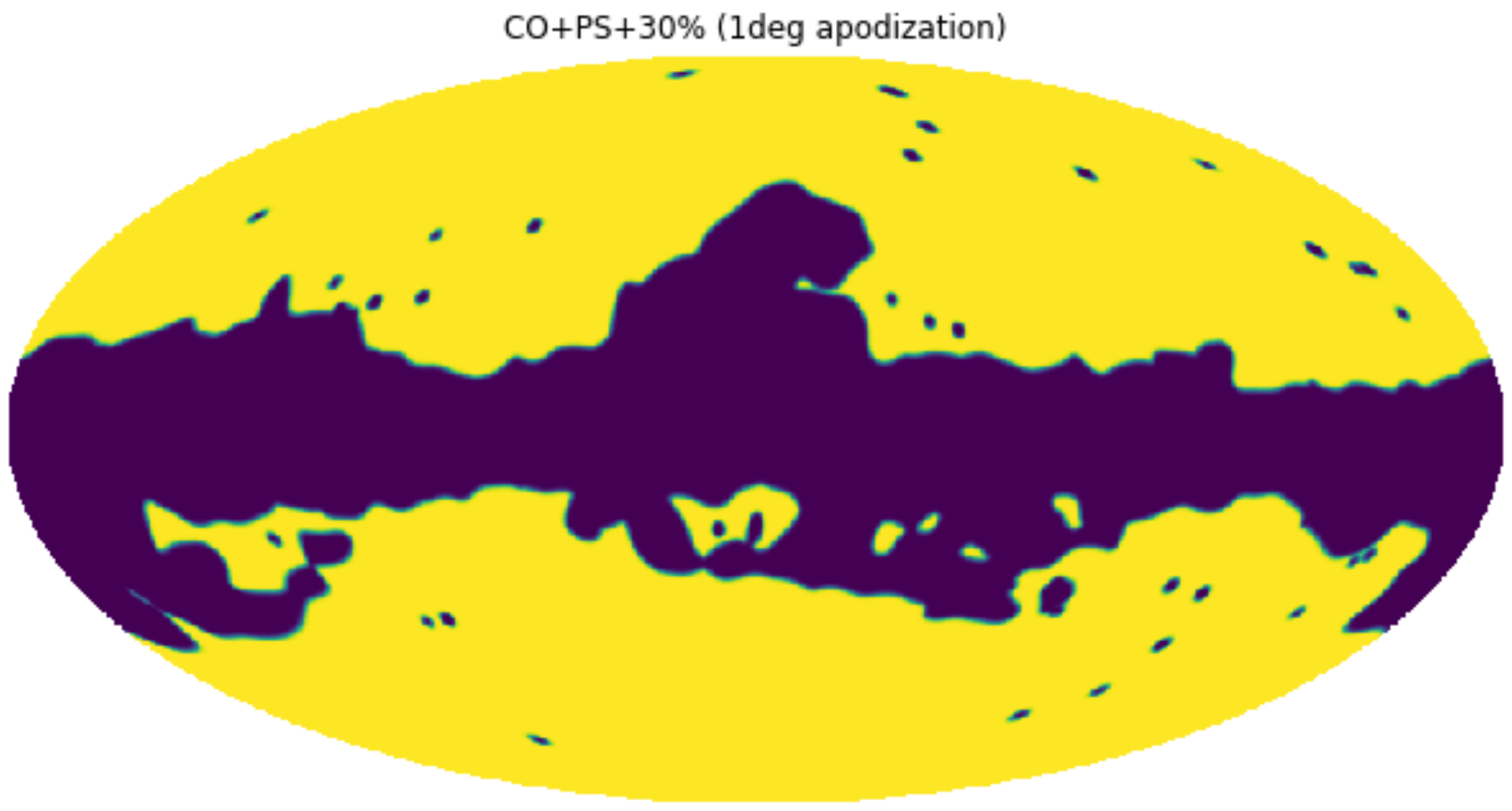
Eskilt, EK (2022)

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)





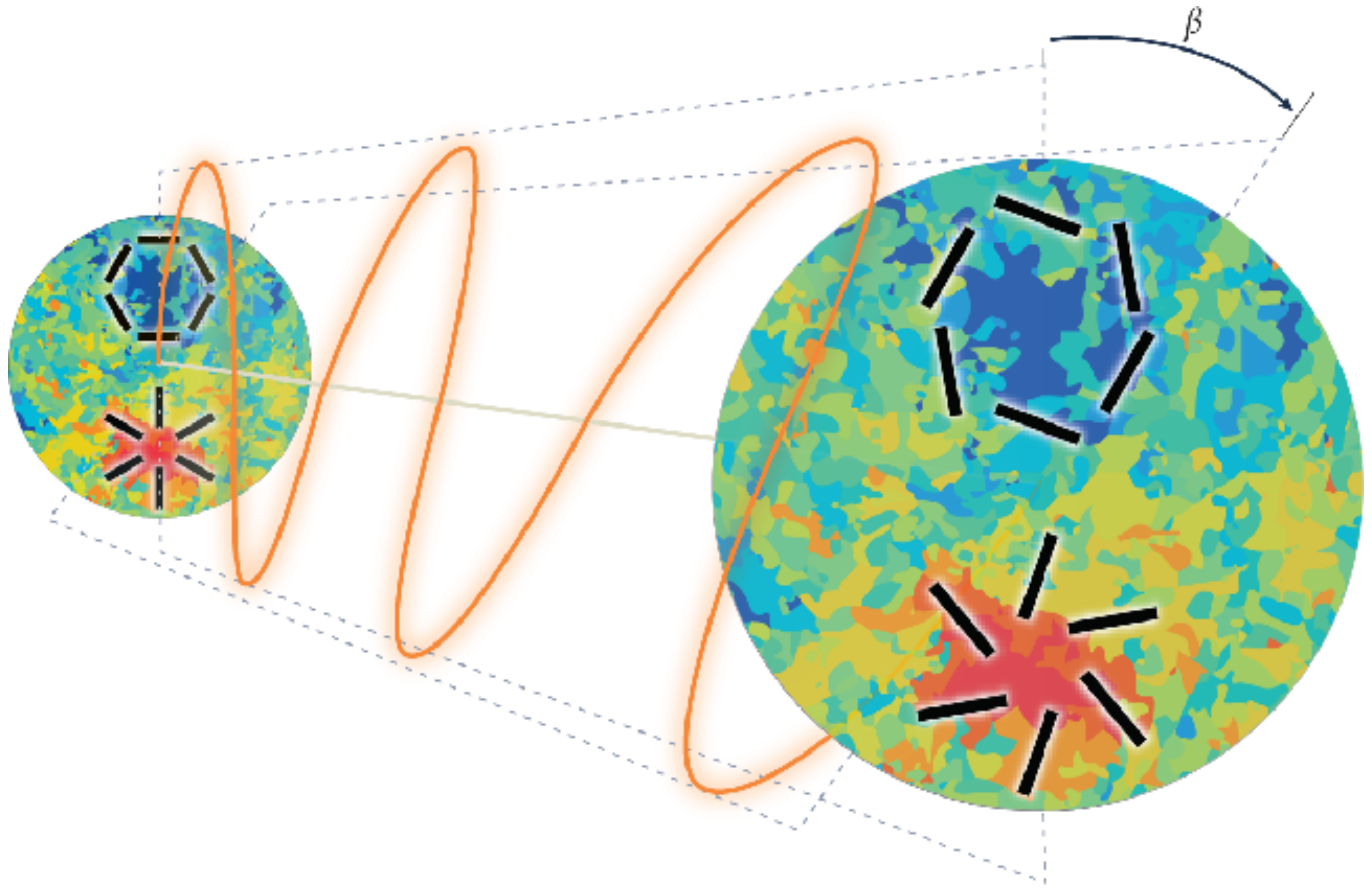
- β = 0.330 ± 0.035 deg
- χ^2 = 64.5
- Signal is robust with respect to the Galactic mask.

The Biggest Problem: Miscalibration of detectors

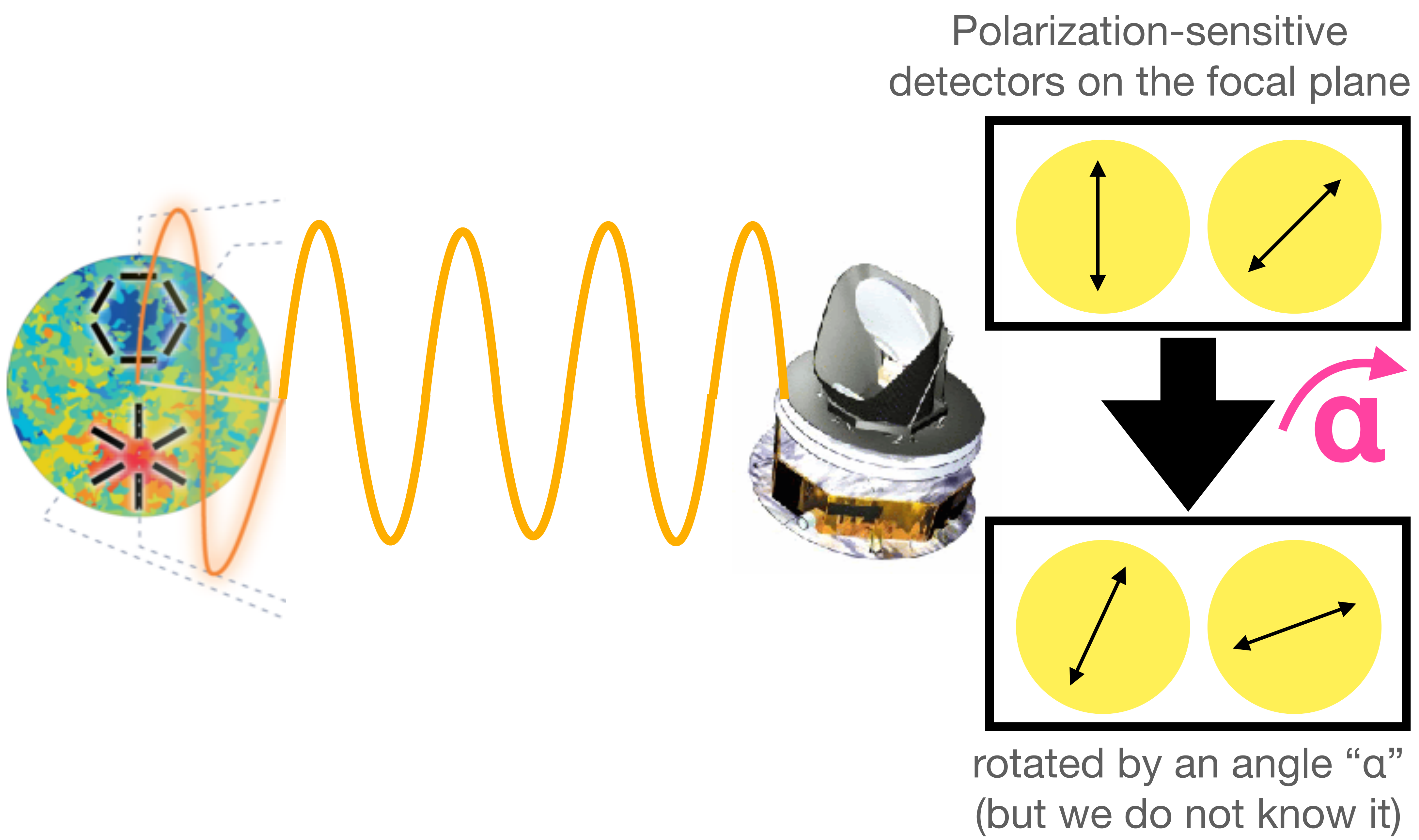
Wu et al. (2009); Miller, Shimon, Keating (2009); EK et al. (2011)

Impact of miscalibration of polarization angles

Cosmic or Instrumental?



OR



- 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)

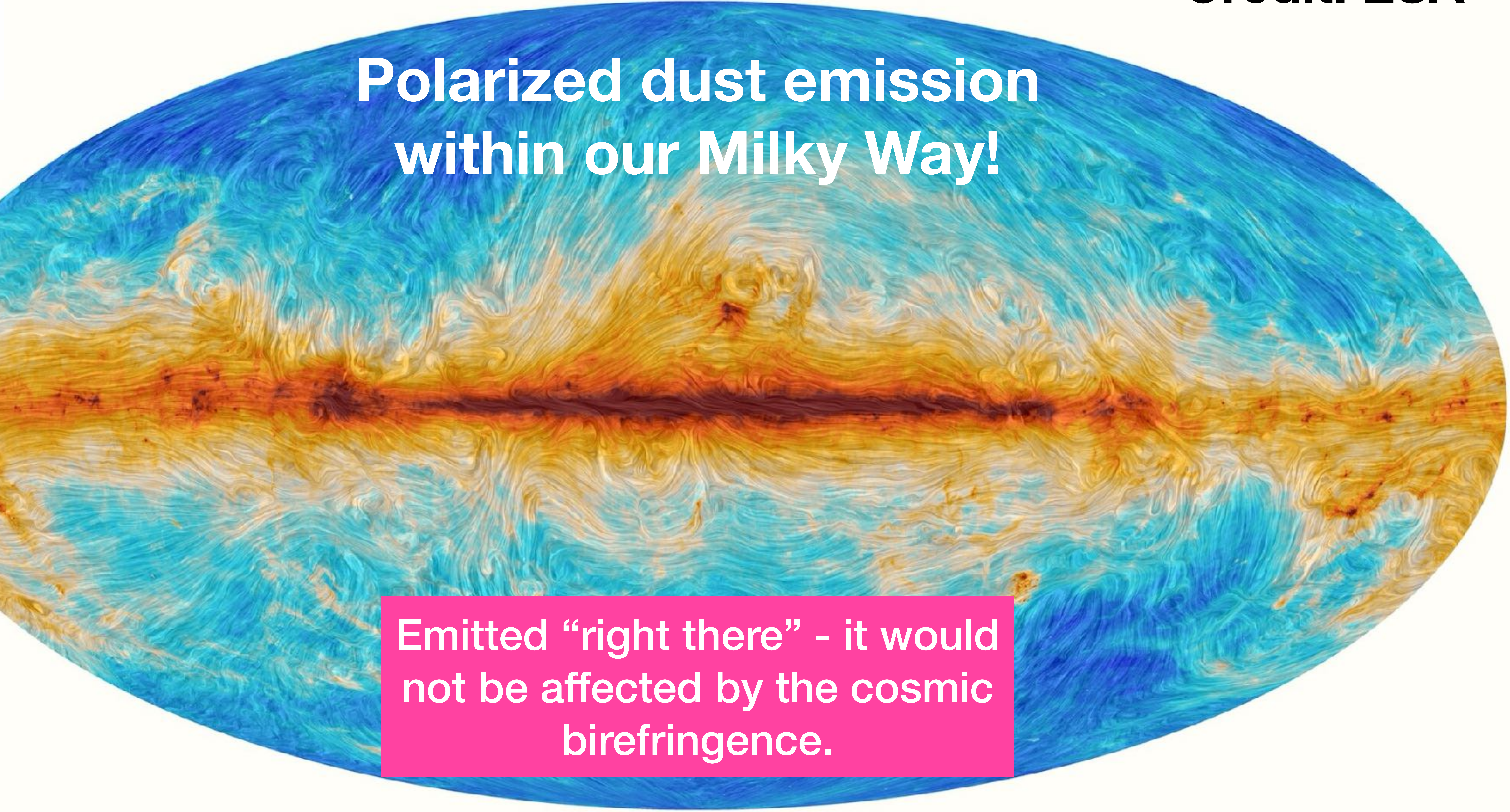
Uncertainty in the calibration of α has been the major limitation

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

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


ESA's Planck

Credit: ESA



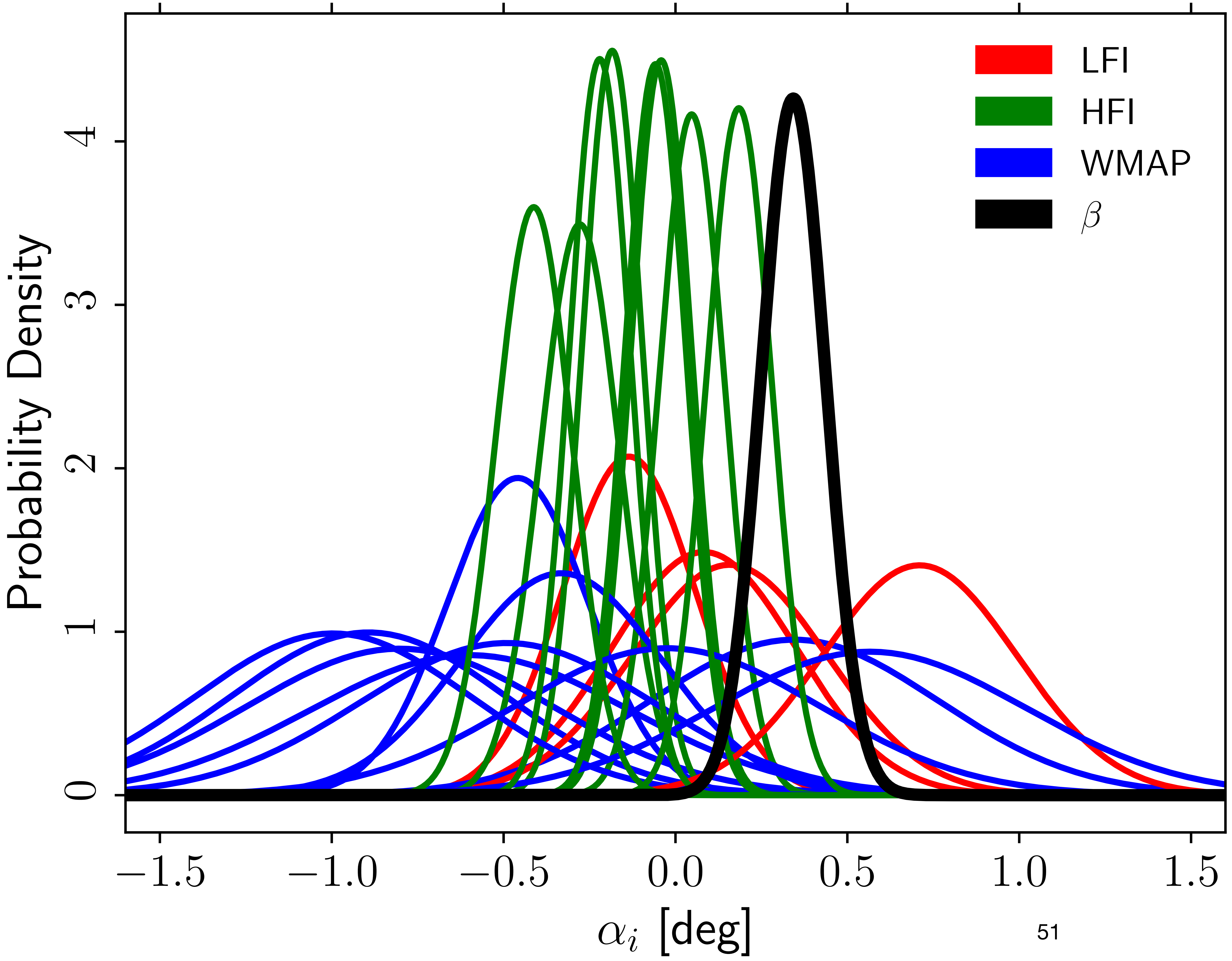
Polarized dust emission within our Milky Way!

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

Miscalibration angles (WMAP and Planck)

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

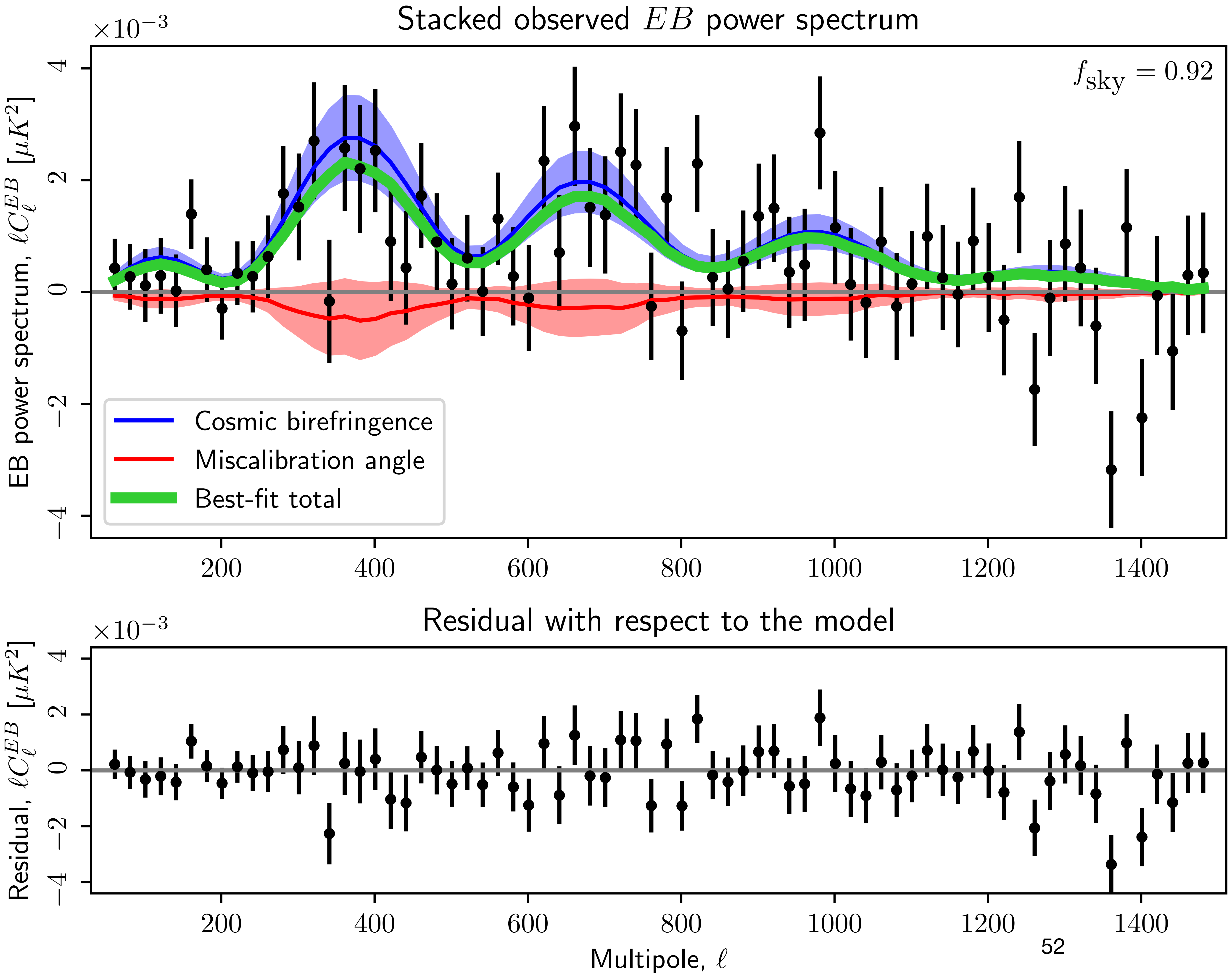


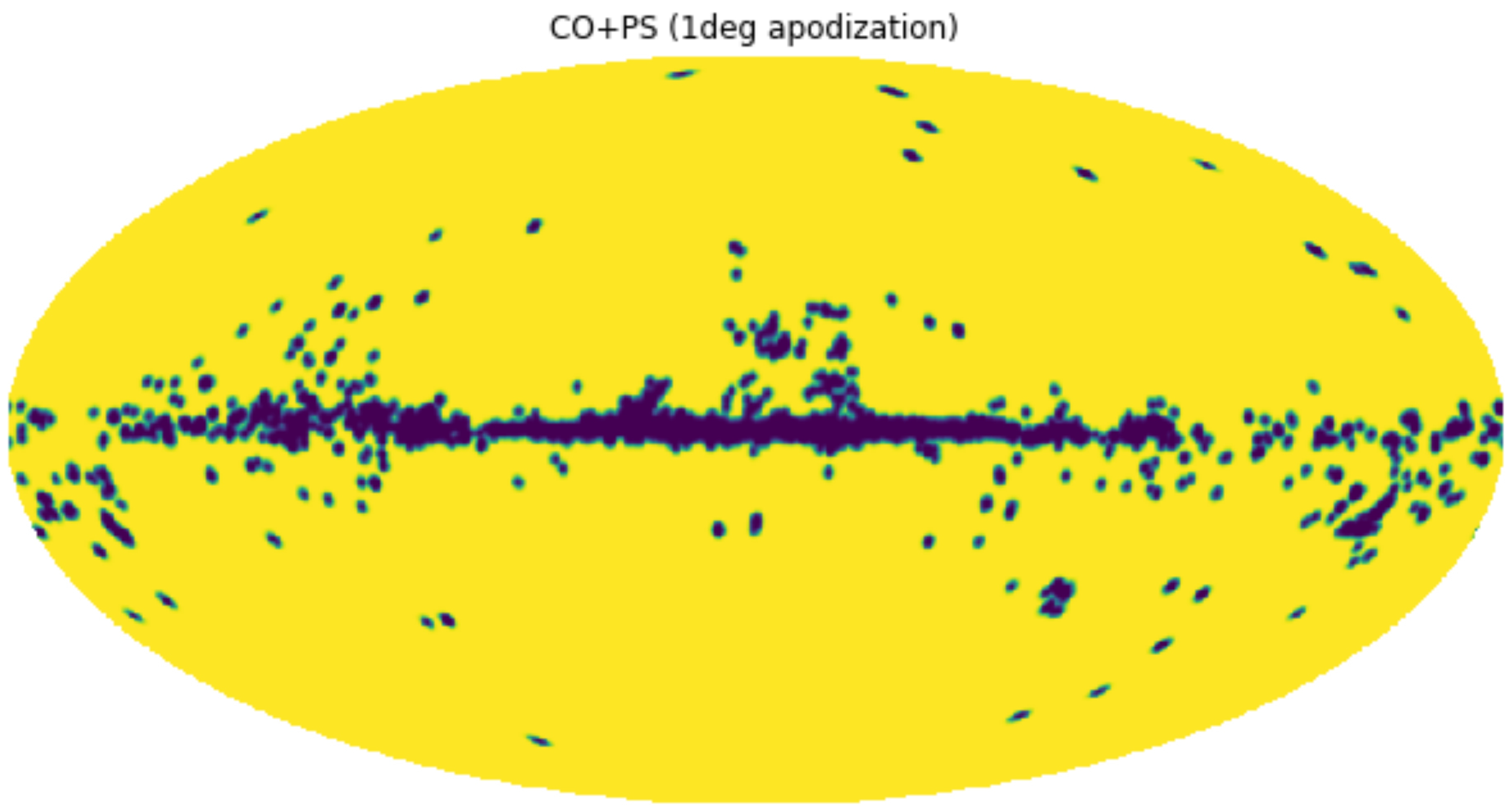
- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

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

Cosmic Birefringence fits well (WMAP+Planck)

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

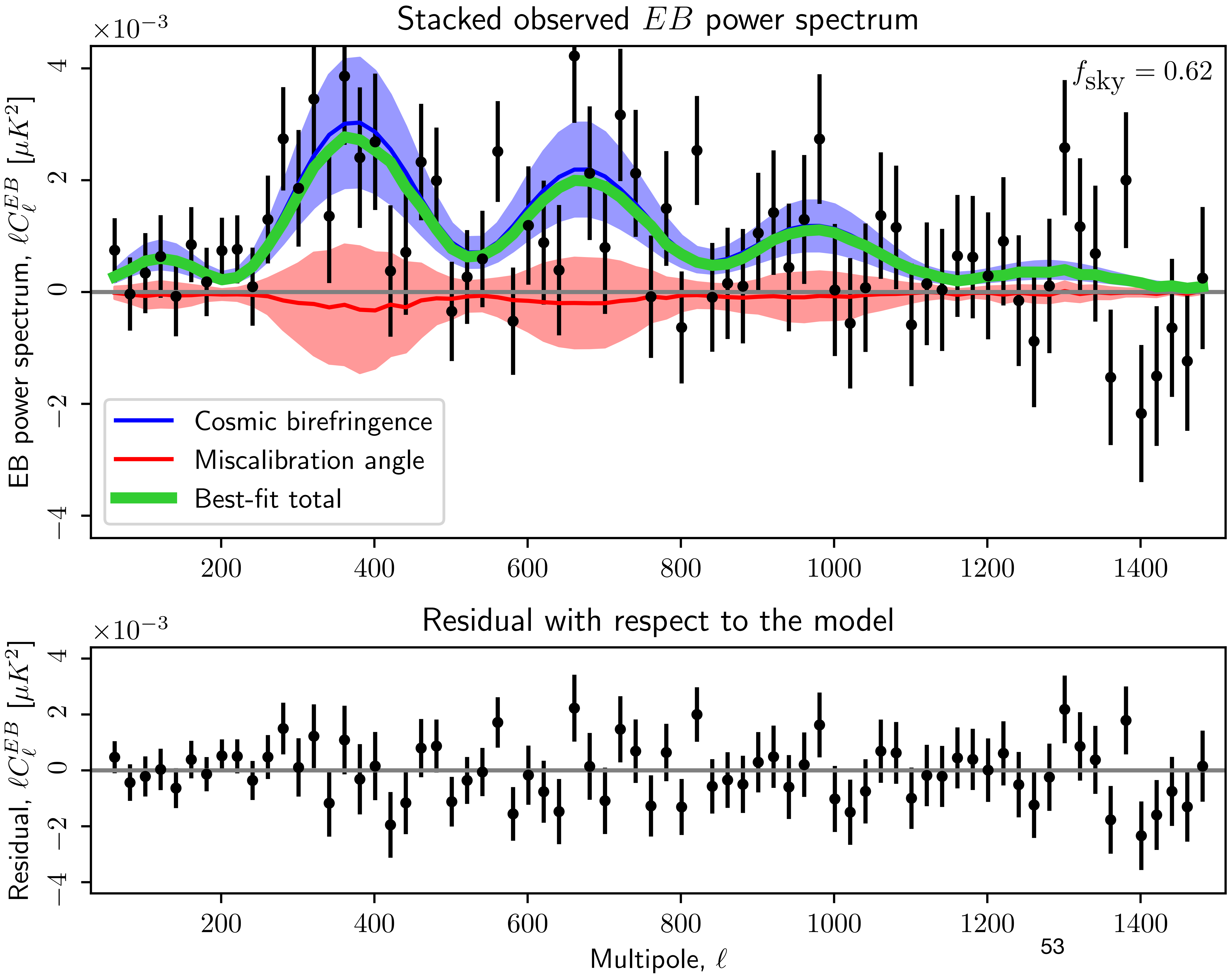


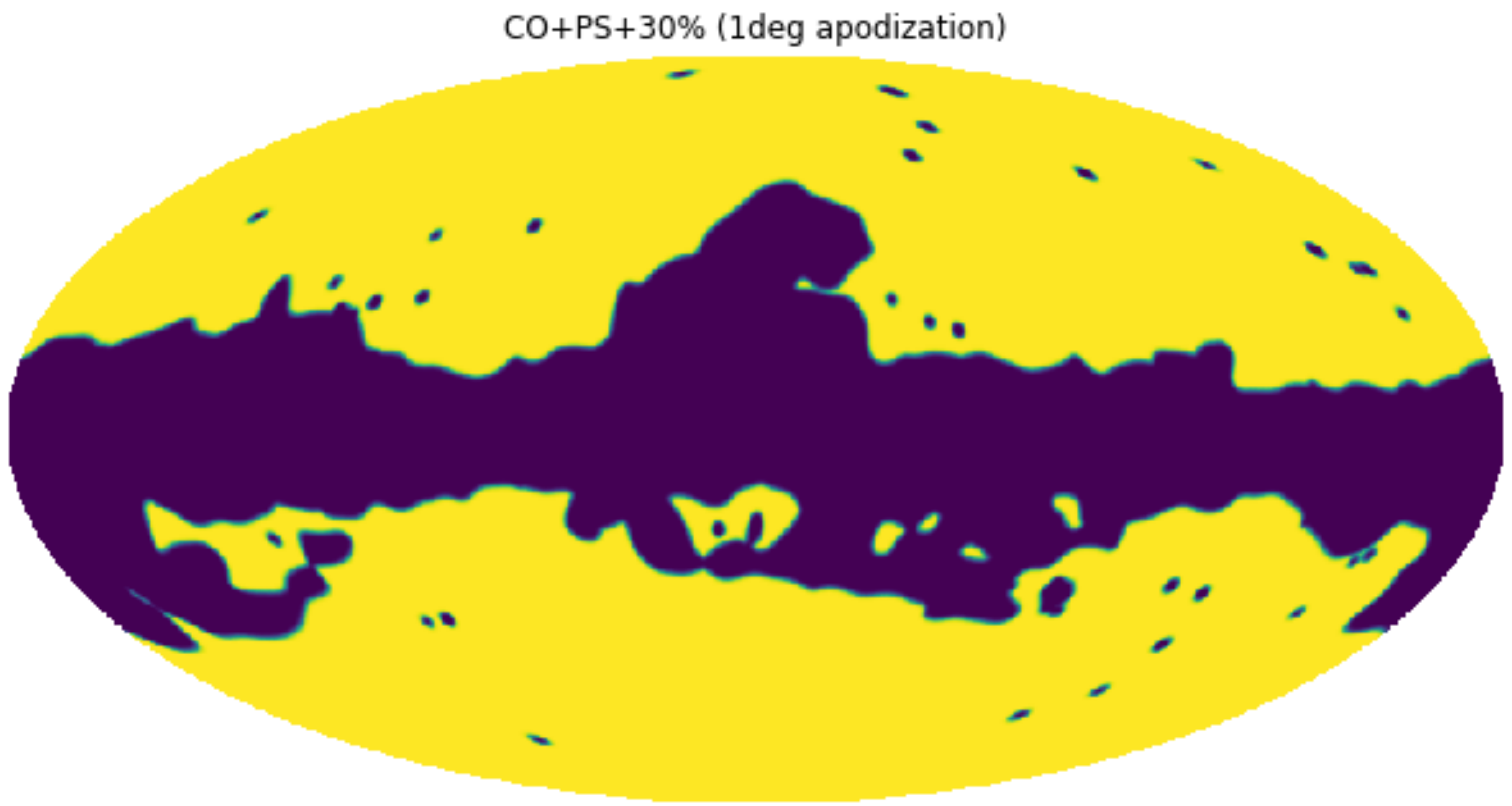


- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- $\chi^2 = 65.3$

Cosmic Birefringence fits well (WMAP+Planck)

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

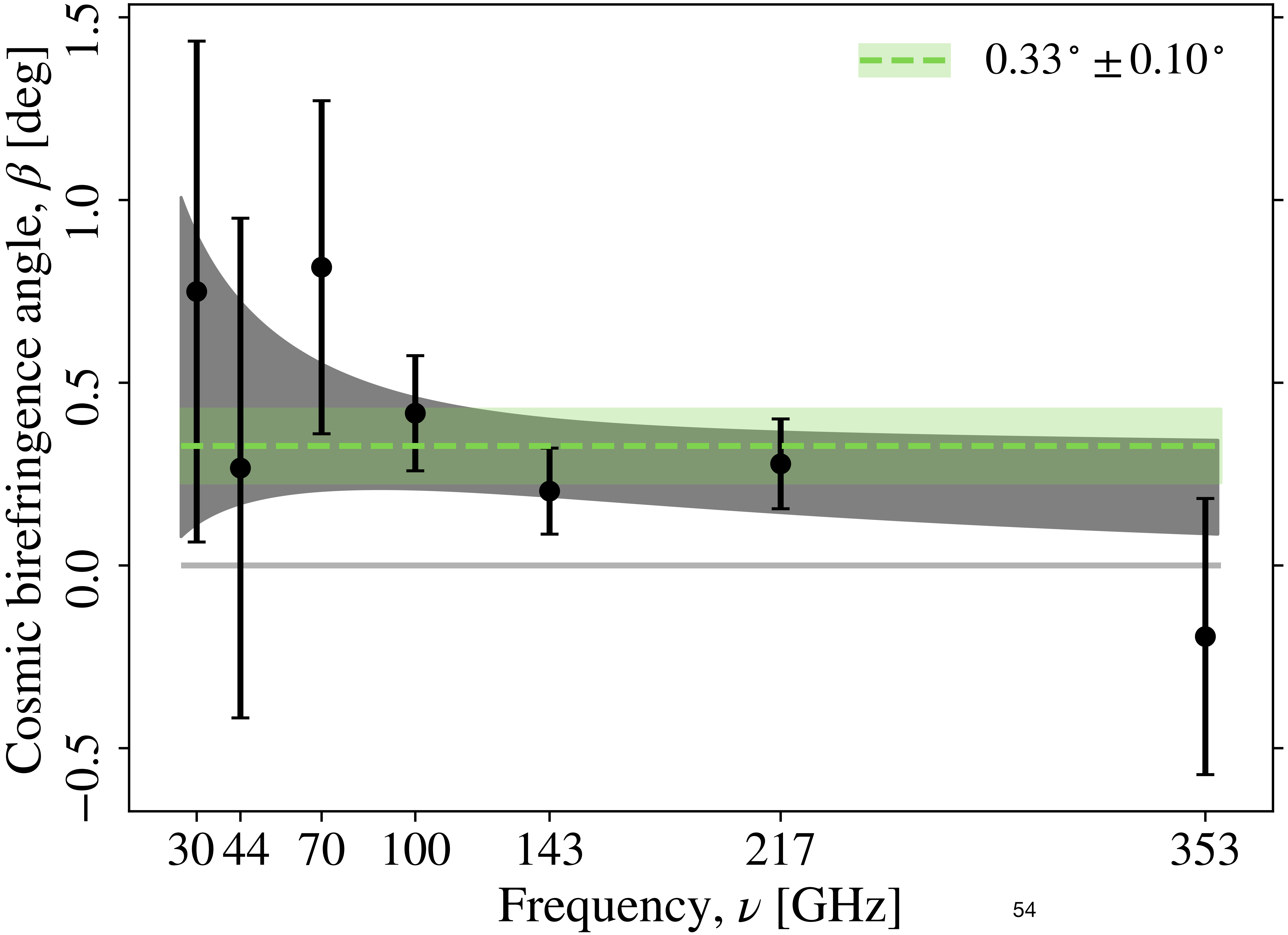




- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- $\chi^2 = 65.8$

No frequency dependence is found

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.**

Diego-Palazuelos et al. (2022, 2023); Eskilt et al., arXiv:2305.02268

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.

Implications

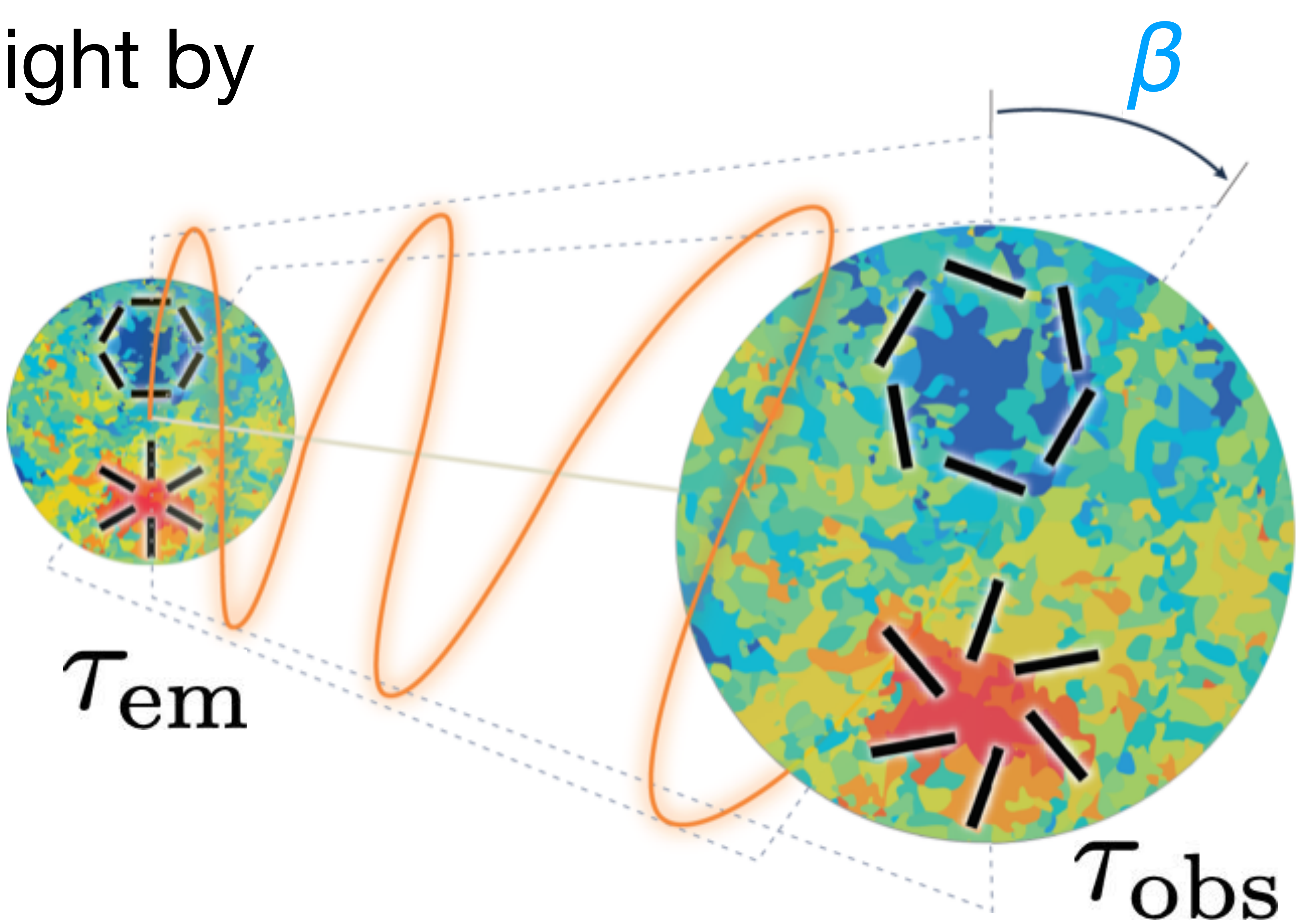
DM = Dark Matter; DE = Dark Energy

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

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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

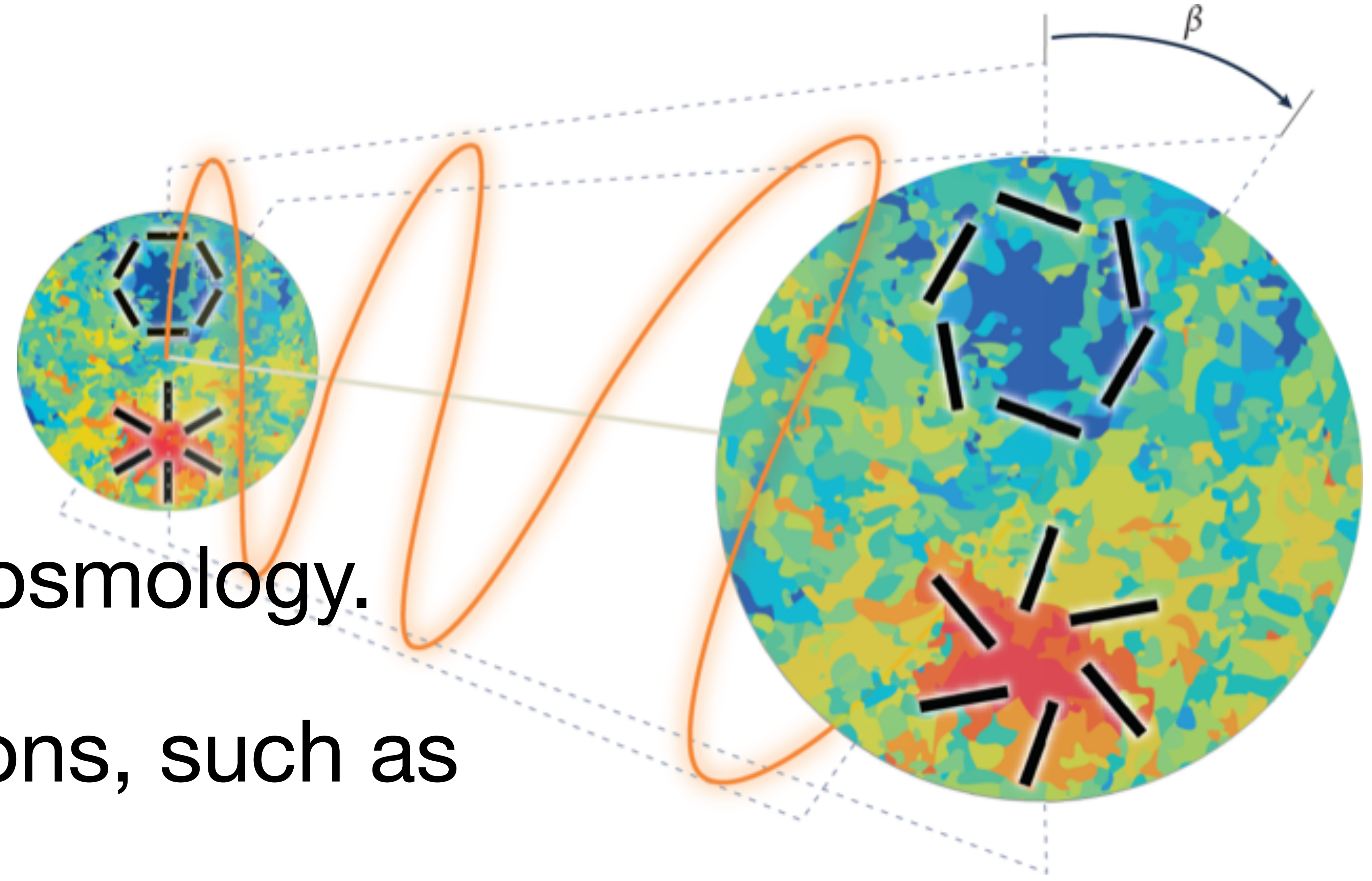
$$\Delta\chi = \chi(\tau_{\rm obs}) - \chi(\tau_{\rm em}) \simeq \frac{10^{-2}}{\alpha}f$$

- 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 be looking? New and exciting research topics.**