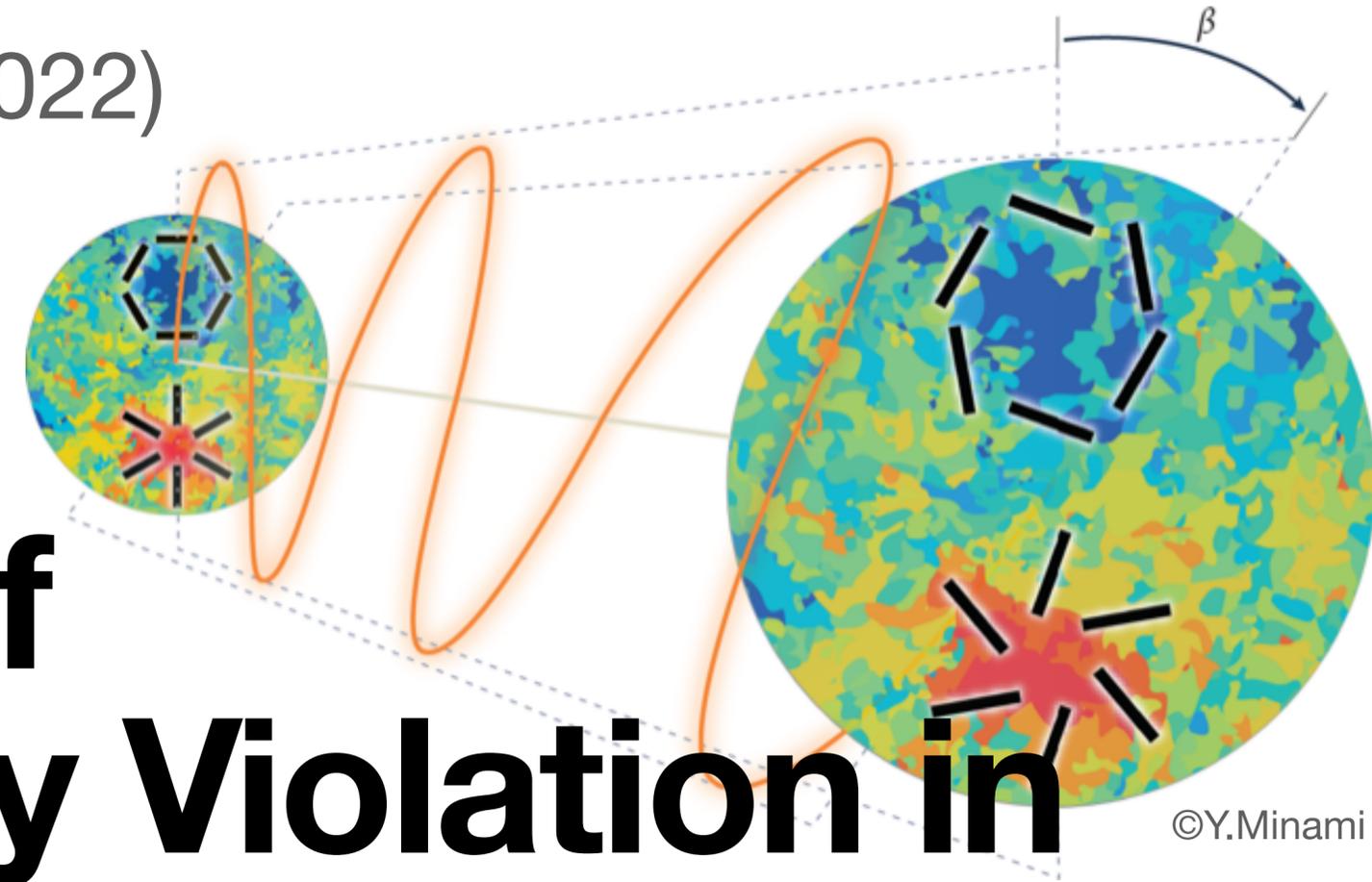


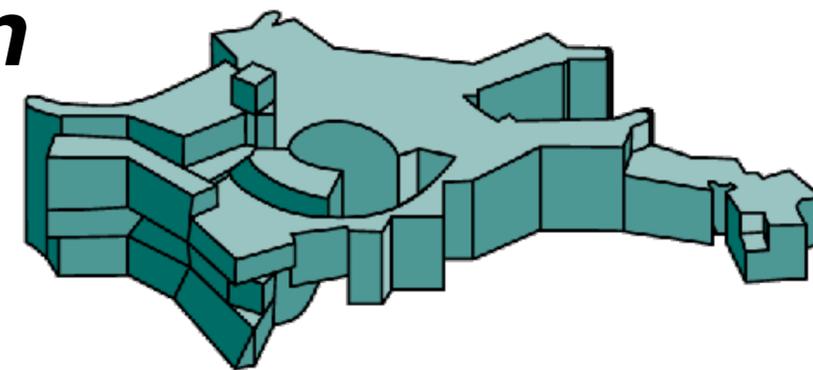
Reference: EK, Nature Rev. Phys. 4, 452 (2022)

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



©Y.Minami

*Does the Universe distinguish between
left and right?*



Eiichiro Komatsu (Max Planck Institute for Astrophysics)
Axions in Stockholm, NORDITA, July 1, 2025

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

Overarching Theme

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

- The current cosmological model (Λ CDM) **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.

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Review Article | [Published: 18 May 2022](#)

New physics from the polarized light of the cosmic microwave background

[Eiichiro Komatsu](#) 

Key Words:

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

[Nature Reviews Physics](#) 4, 452–469 (2022) | [Cite this article](#)

1. Parity

Probing Parity Symmetry

Definition

- **Parity transformation = Inversion of all spatial coordinates**
 - $(x, y, z) \rightarrow (-x, -y, -z)$
- 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...

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 $(x, y, z) \rightarrow (-x, -y, -z)$, whereas a “mirror image” often refers to, e.g., $(x, y, z) \rightarrow (-x, y, z)$, 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

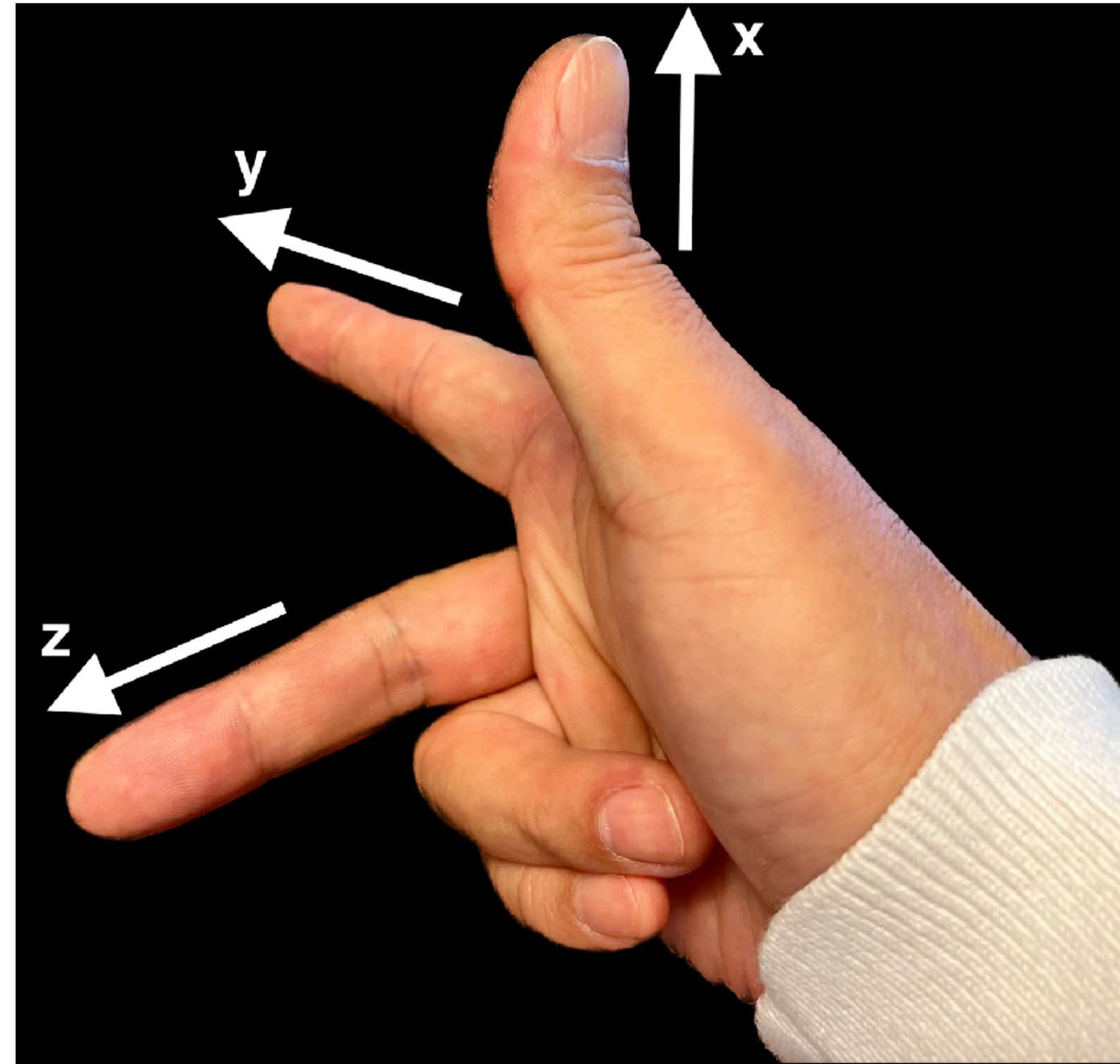
- Parity transformation ($\mathbf{x} \rightarrow -\mathbf{x}$) and 3d rotation ($\mathbf{x} \rightarrow R\mathbf{x}$) are different.
 - R is a continuous transformation and the determinant of R is $\det(R) = +1$.
 - Parity is a discrete transformation and the **determinant is -1**, as

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

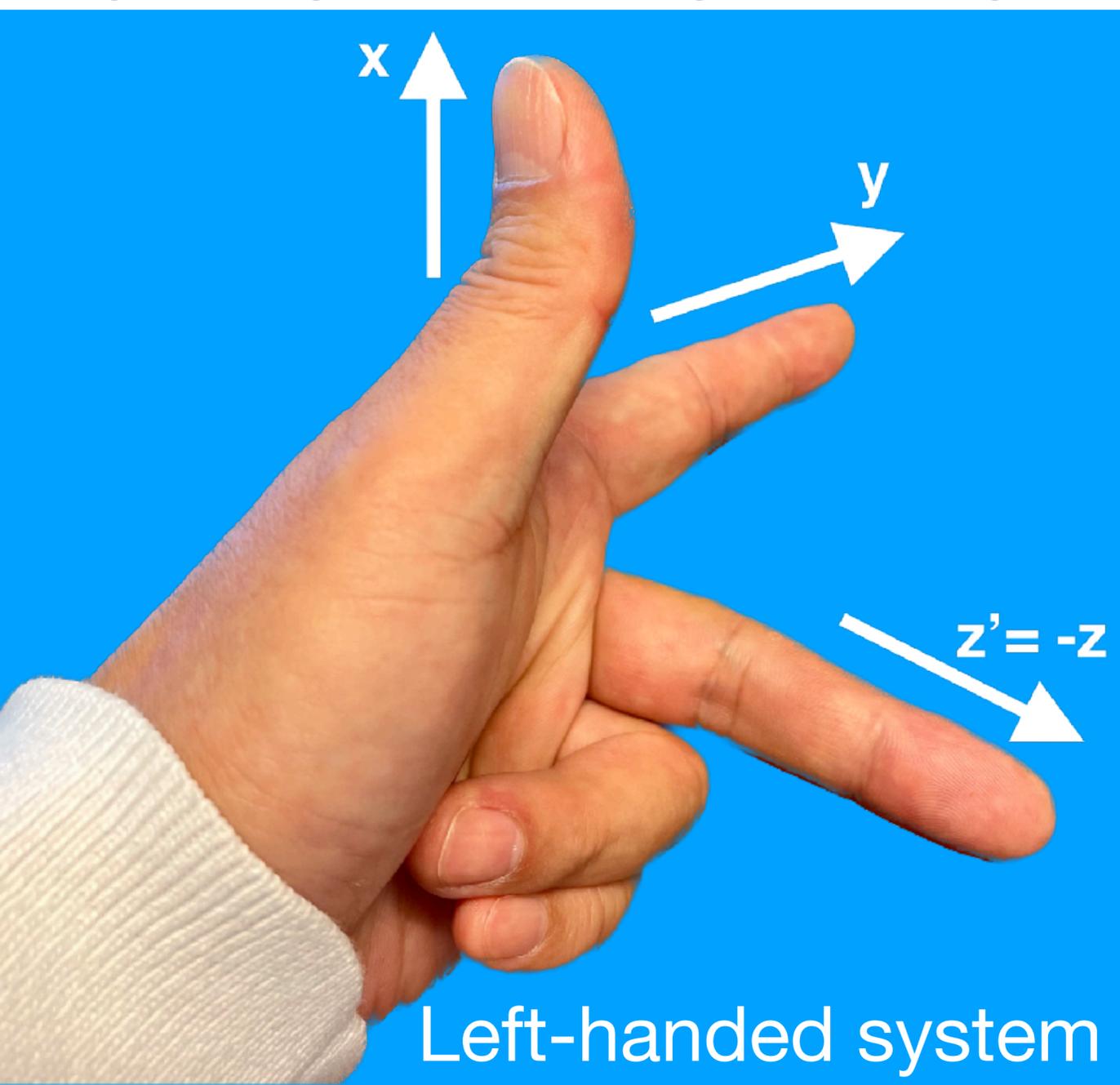
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Parity = Mirror + 2d Rotation

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

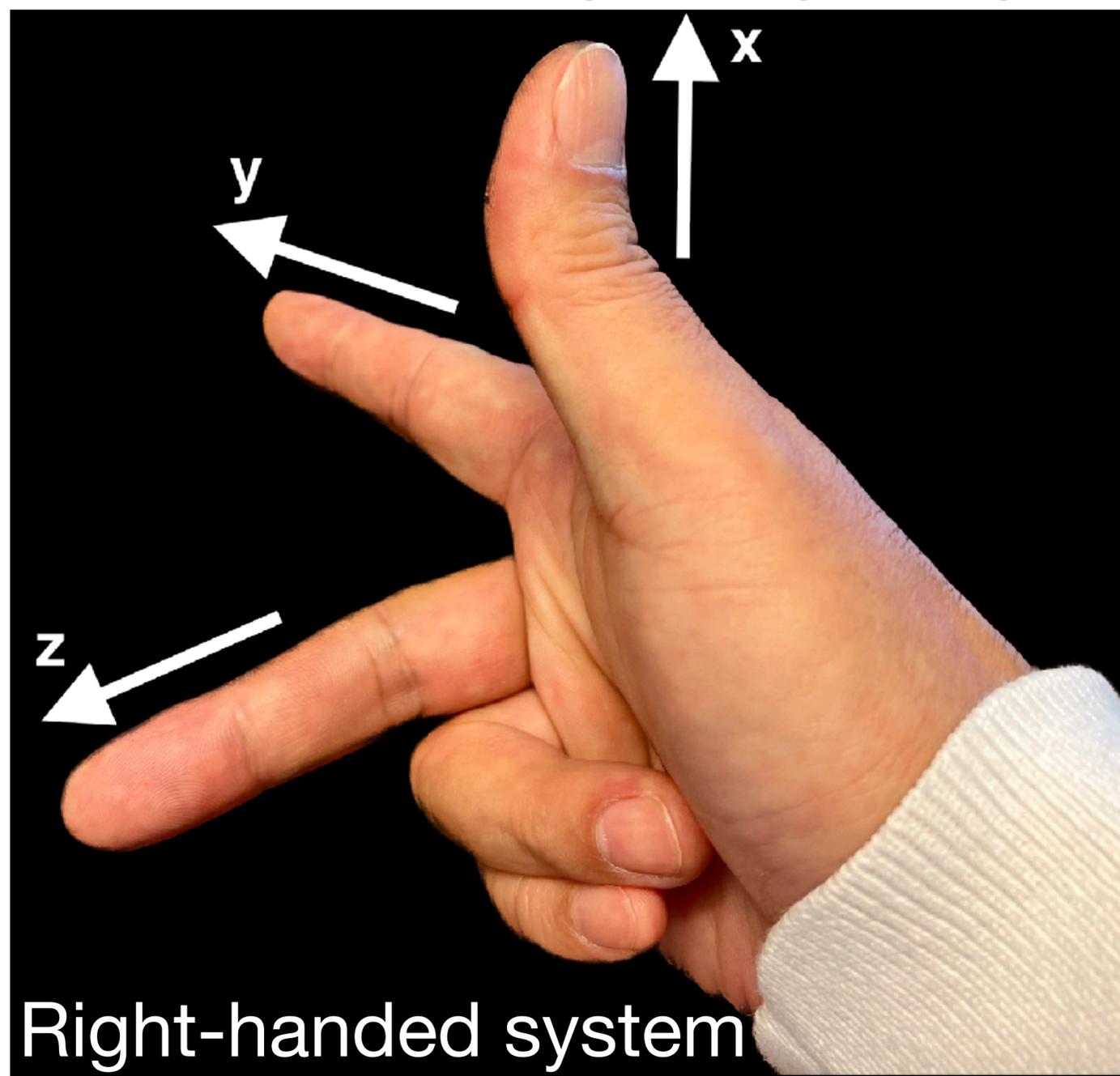


$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

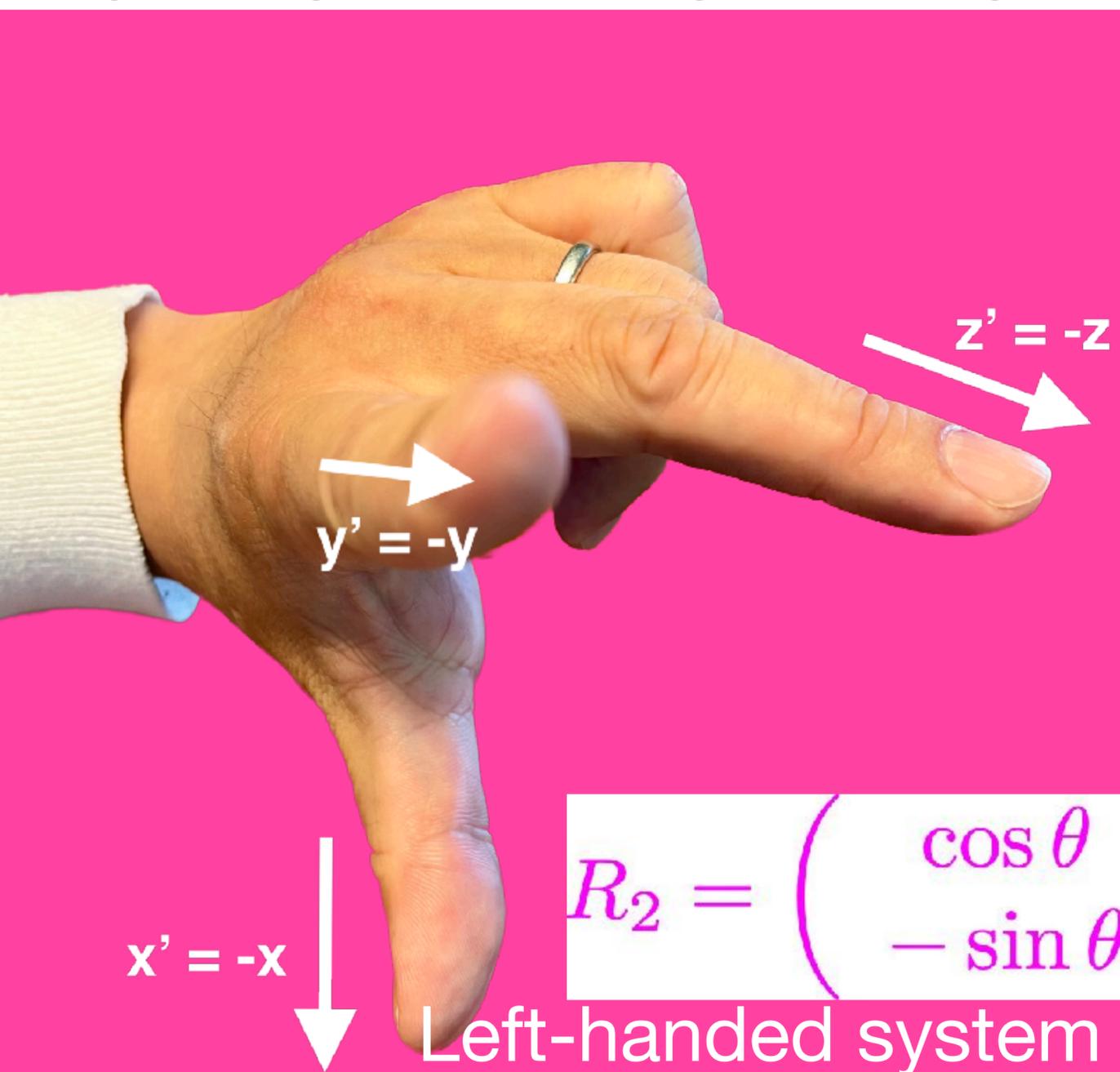


$$\longleftrightarrow$$

$$z \rightarrow z' = -z$$

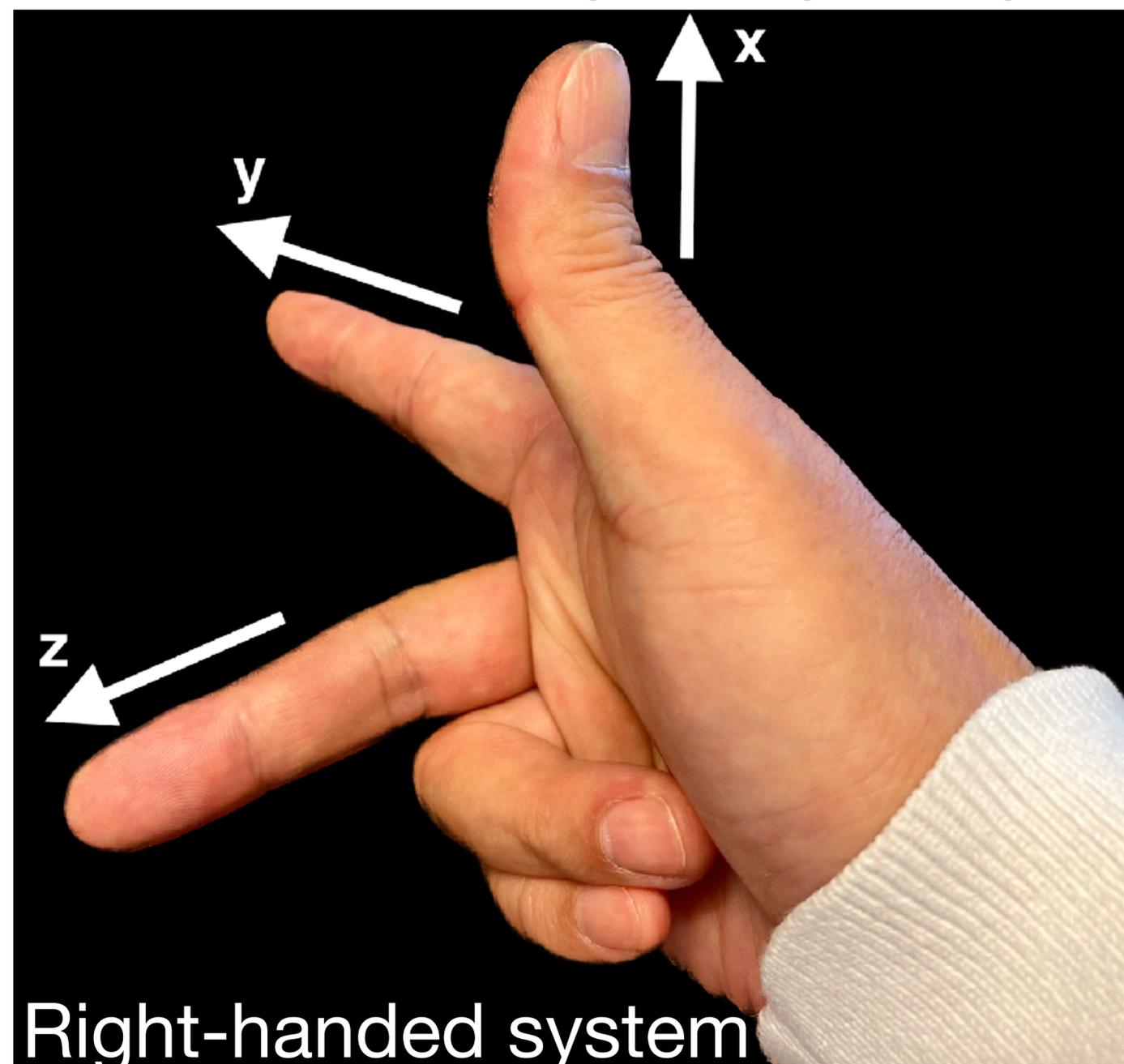


$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} \boxed{-1} & \boxed{0} & 0 \\ \boxed{0} & \boxed{-1} & 0 \\ 0 & 0 & \boxed{-1} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$



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

Left-handed system with $\theta \stackrel{!}{=} \pi$

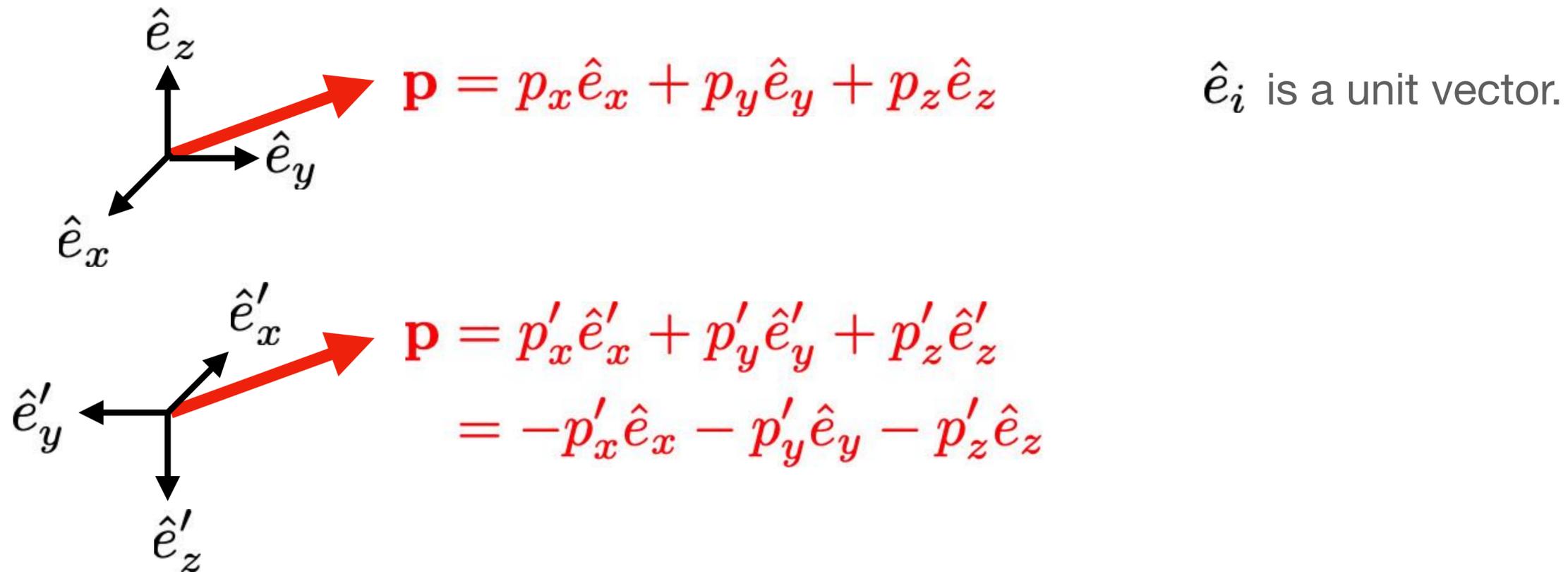


Right-handed system

2. Pseudovector, Pseudoscalar

Parity Transformation: Vector

E.g., momentum, electric field



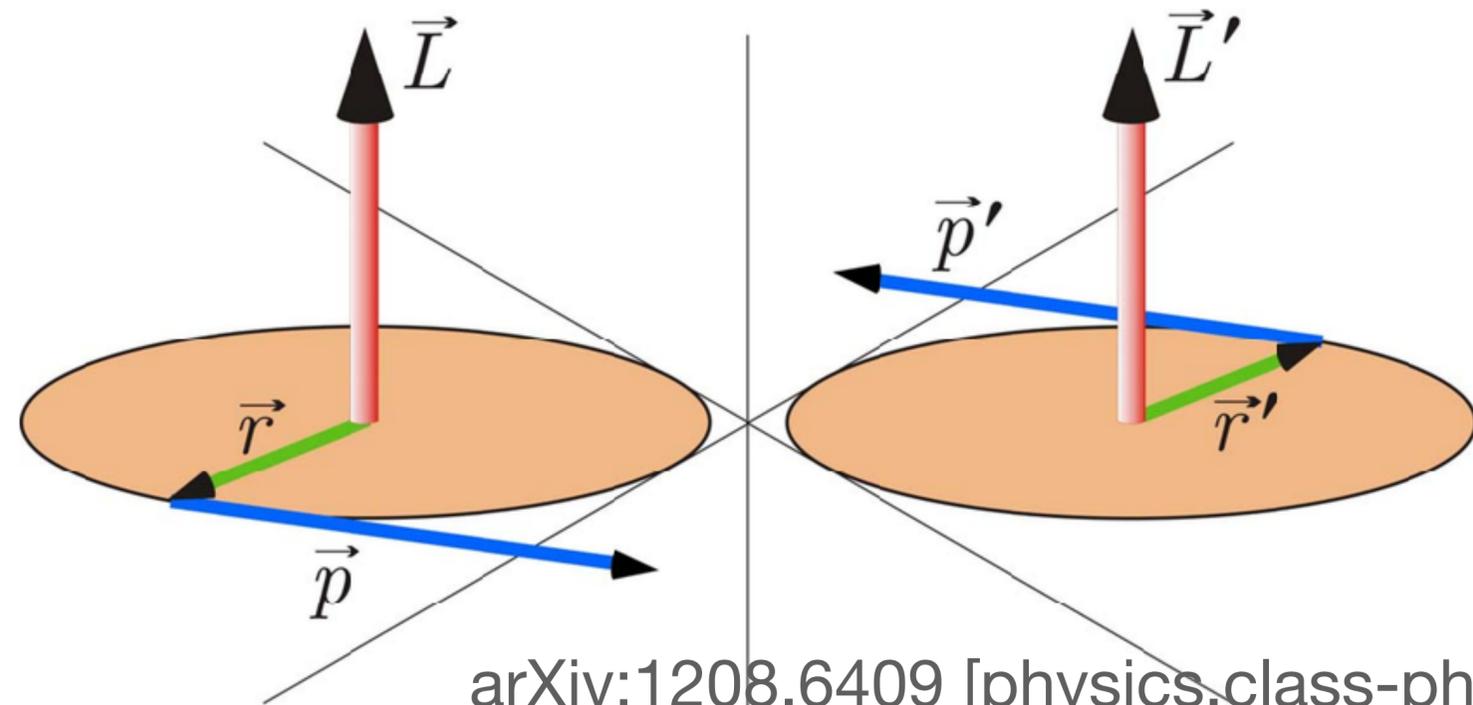
- \mathbf{p} is the same vector, written using two different basis vectors.
- Therefore, \mathbf{p} 's components are transformed as $(p'_x, p'_y, p'_z) = (-p_x, -p_y, -p_z)$

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.,

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



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: $\mathbf{p}_A \cdot \mathbf{L}_B$. Measure this and average over many trials. Does the average vanish, $\langle \mathbf{p}_A \cdot \mathbf{L}_B \rangle = 0$?

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

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.

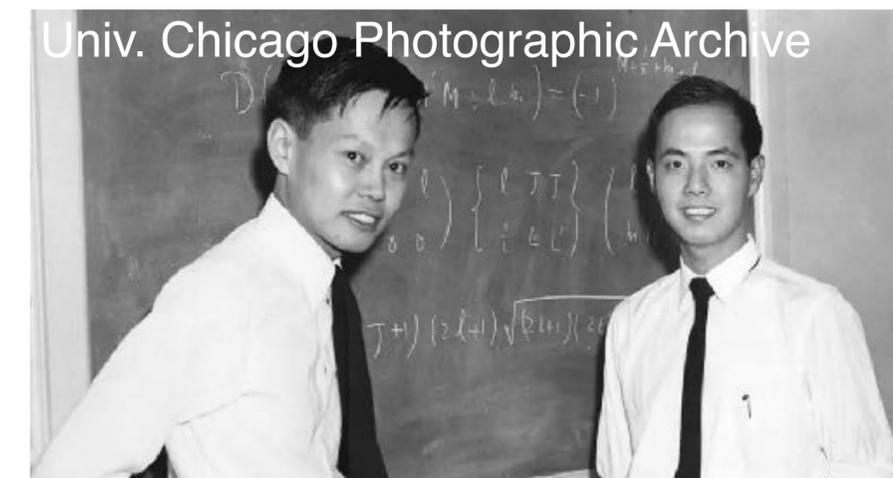
(Received January 15, 1957)

IN a recent paper¹ 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



Smithsonian Institution Archives

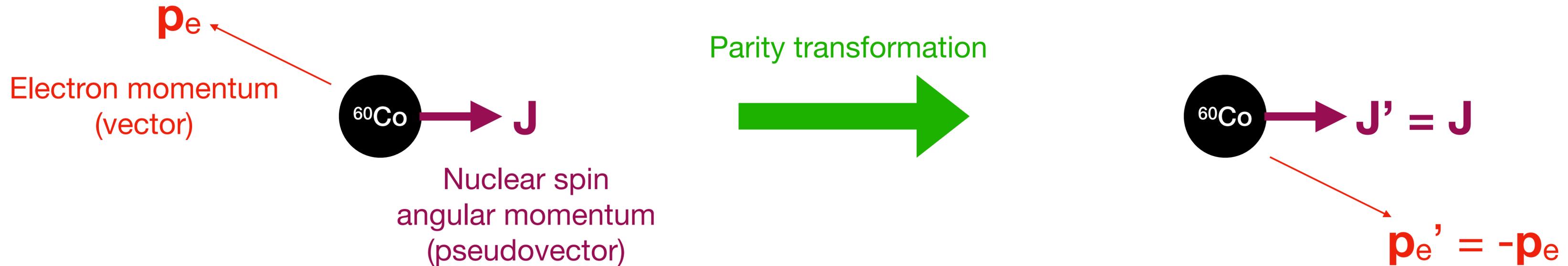
Chien-Shiung Wu



Chen-Ning Yang

Tsung-Dao Lee

The Wu Experiment of β -decay



- Electrons must be emitted with equal probability in all directions relative to \mathbf{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

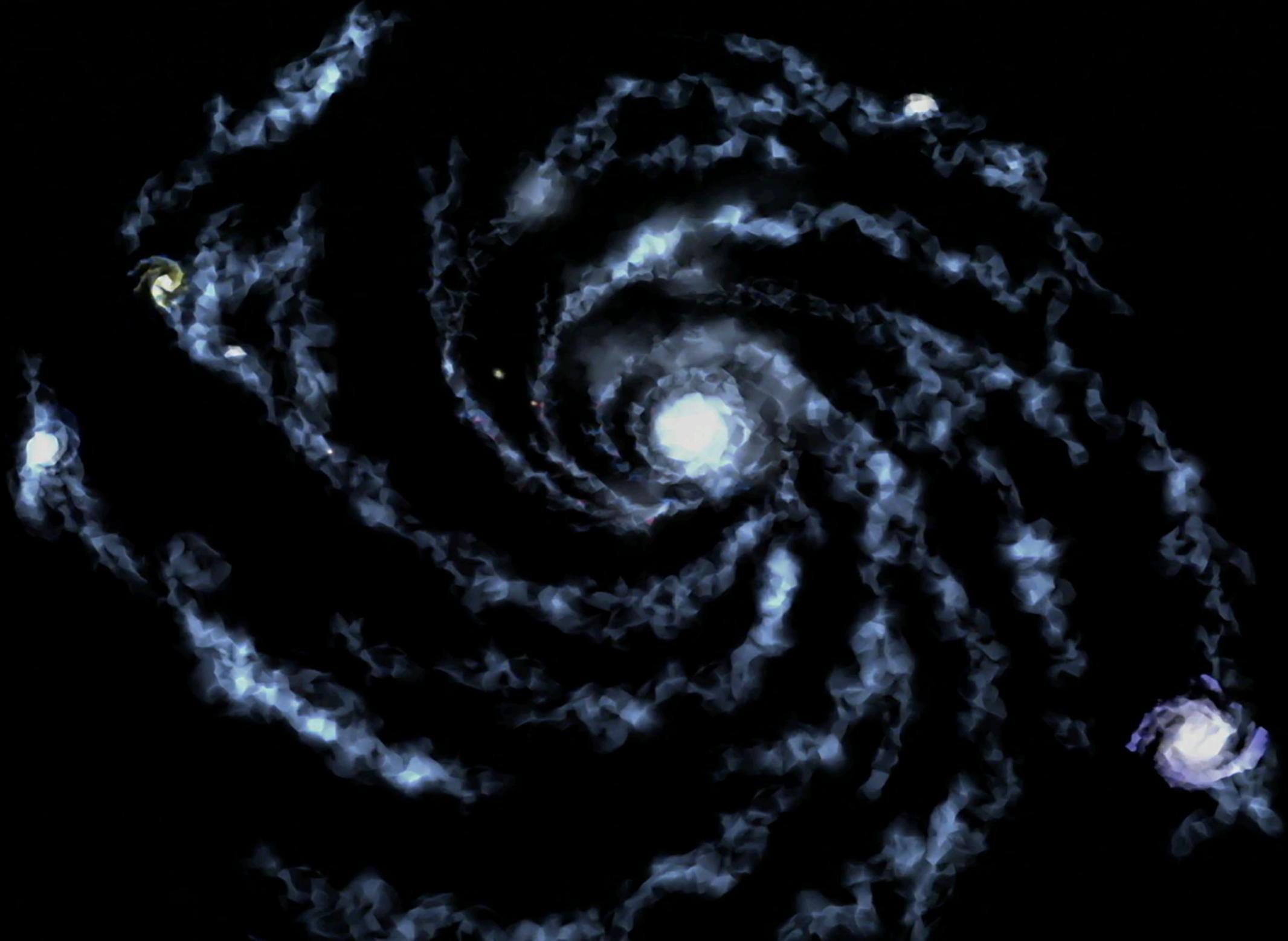
Many physicists did not believe it initially.



- 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)

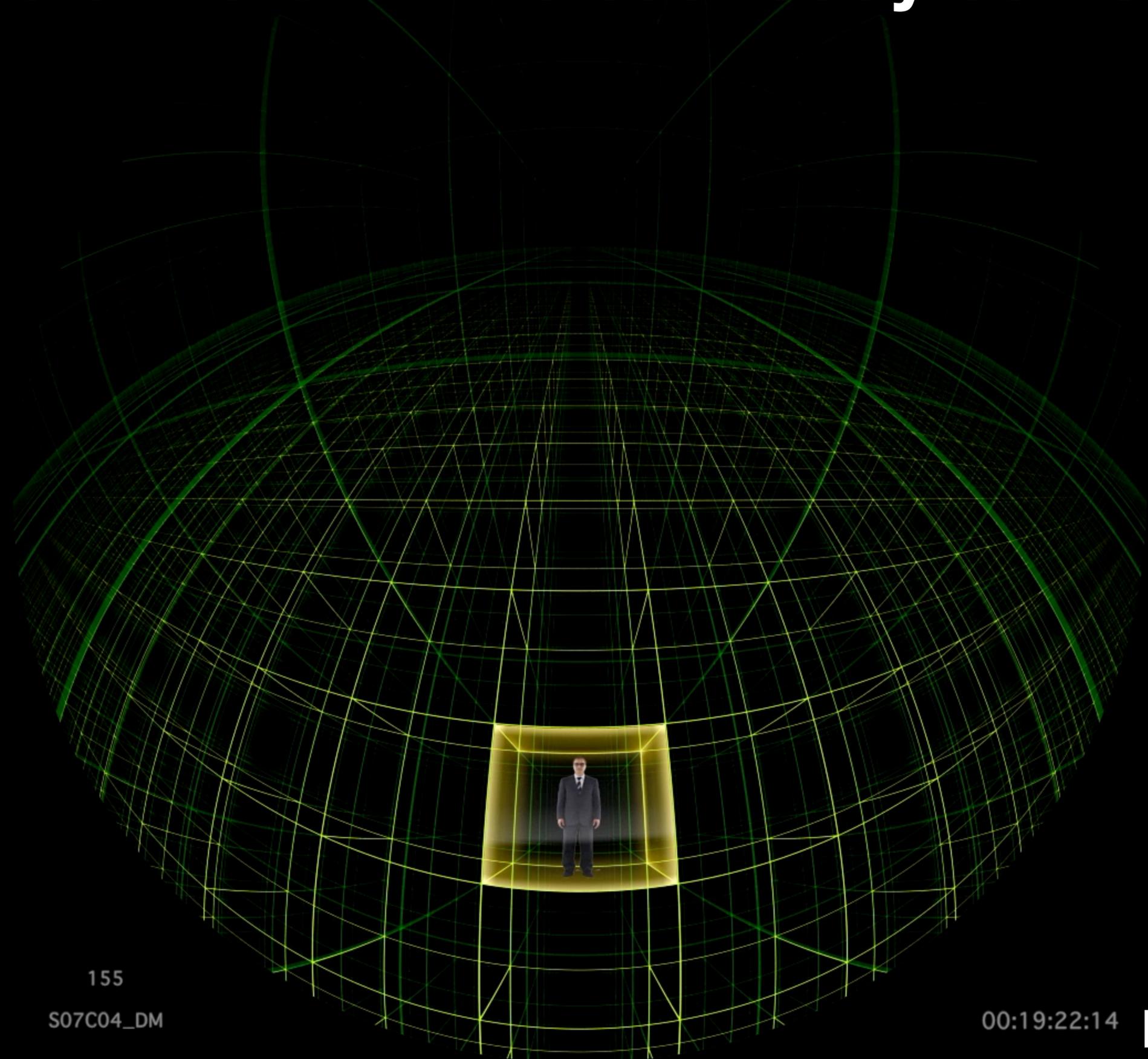
Credit: WMAP Science Team



The sky in various wavelengths

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

Where did the CMB we see today come from?



155

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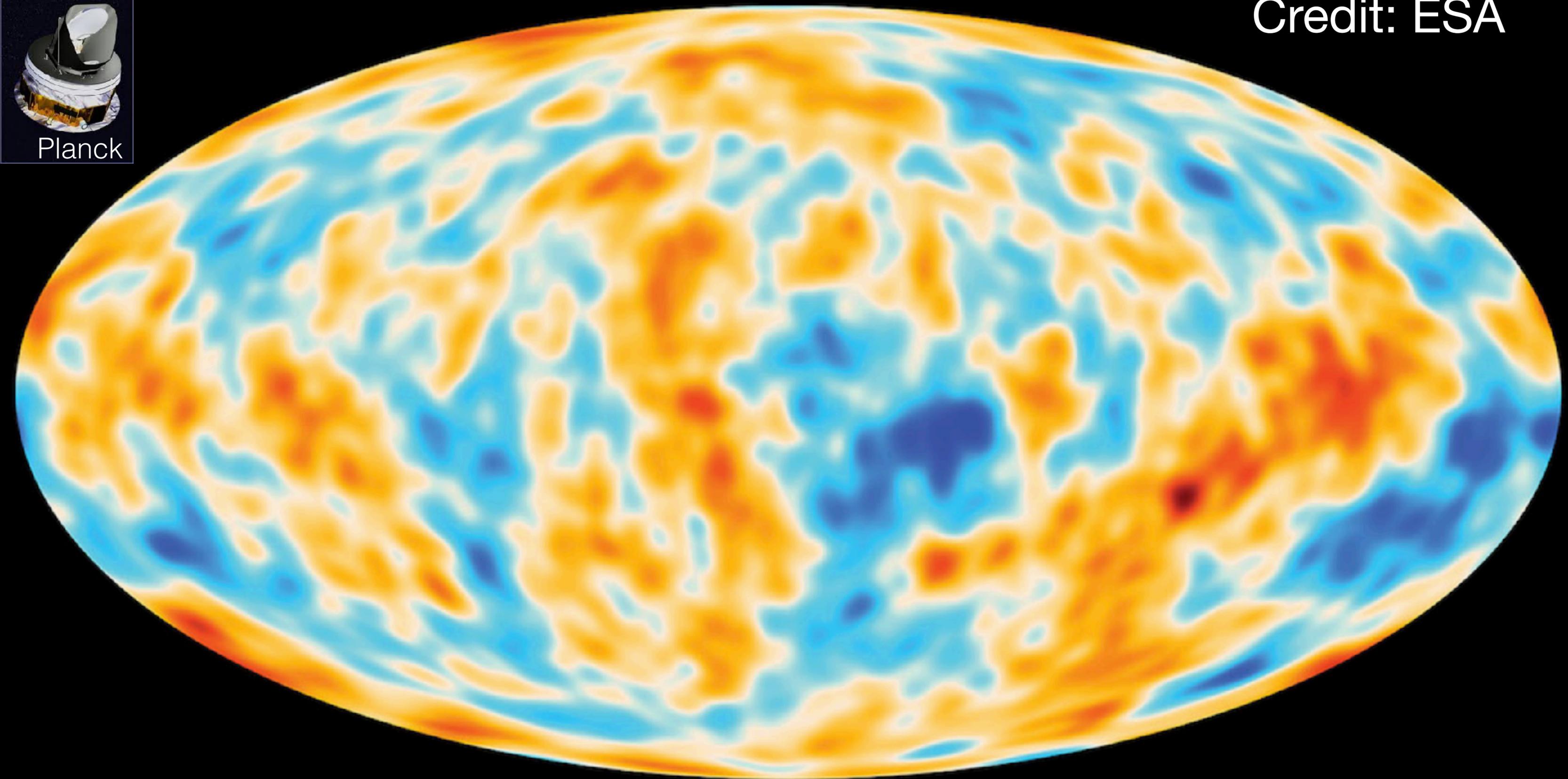
00:19:22:14

From "HORIZON"

Credit: ESA



Planck

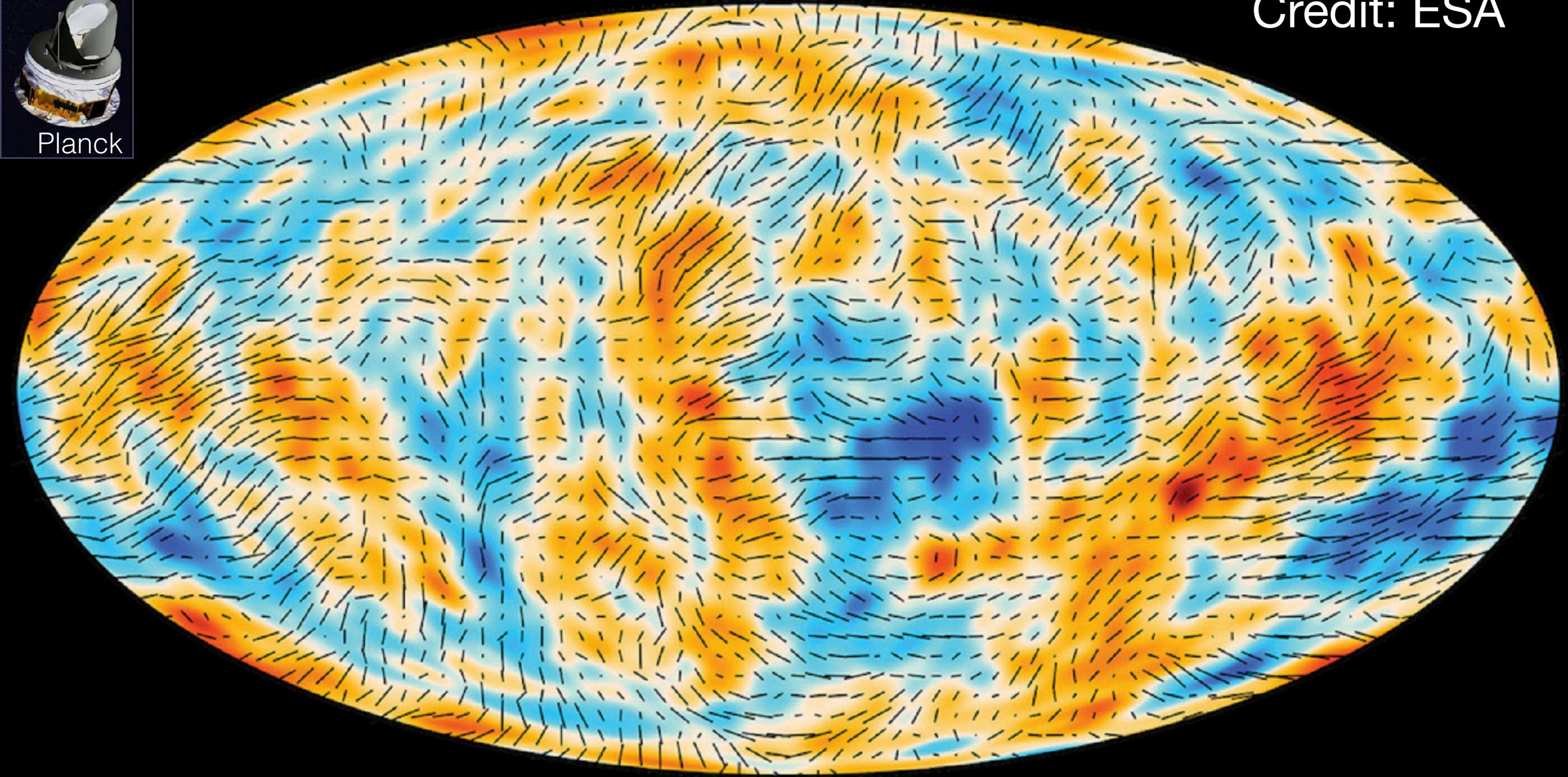


Temperature (smoothed)

Credit: ESA

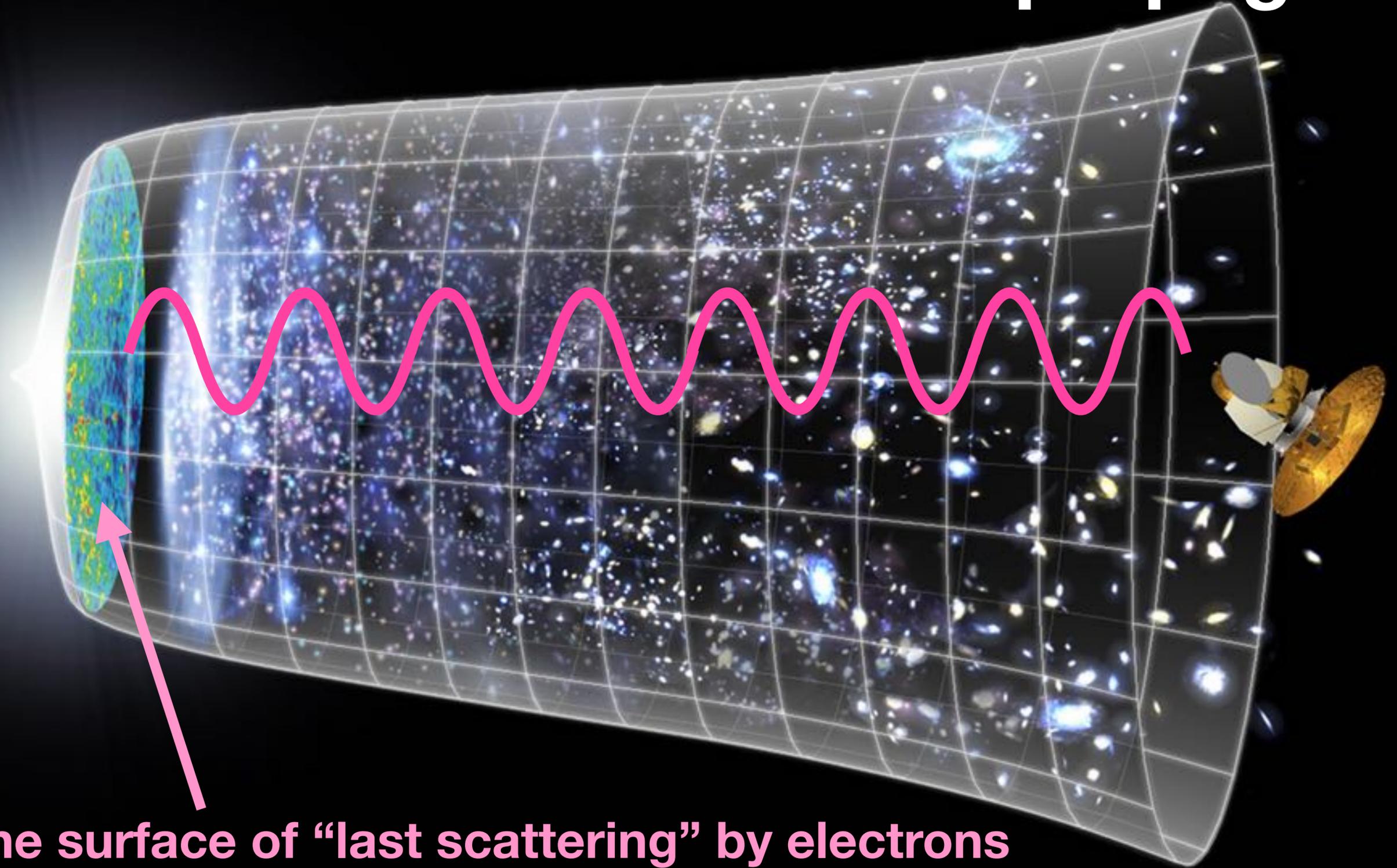


Planck



Temperature (smoothed) + Polarisation

How does the EM wave of the CMB propagates?

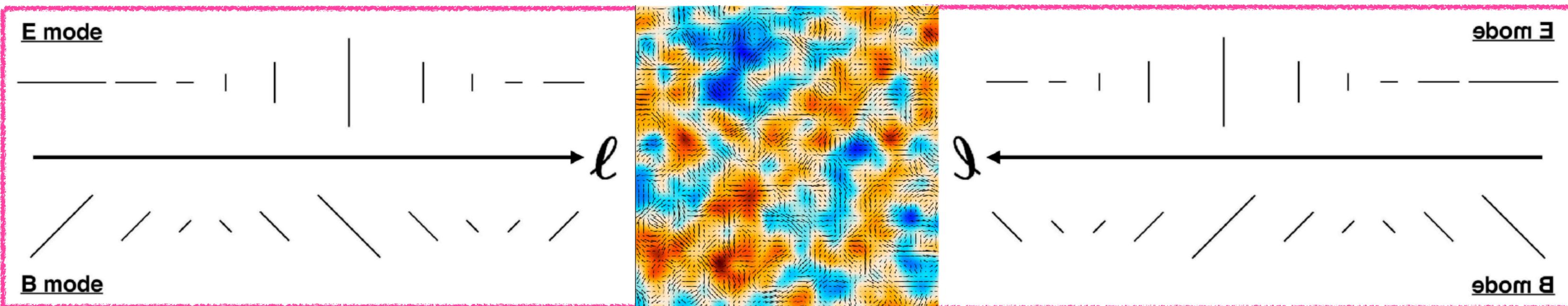


The surface of “last scattering” by electrons
(Scattering generates *polarization*!)

Credit: WMAP Science Team

Pseudoscalar: EB correlation

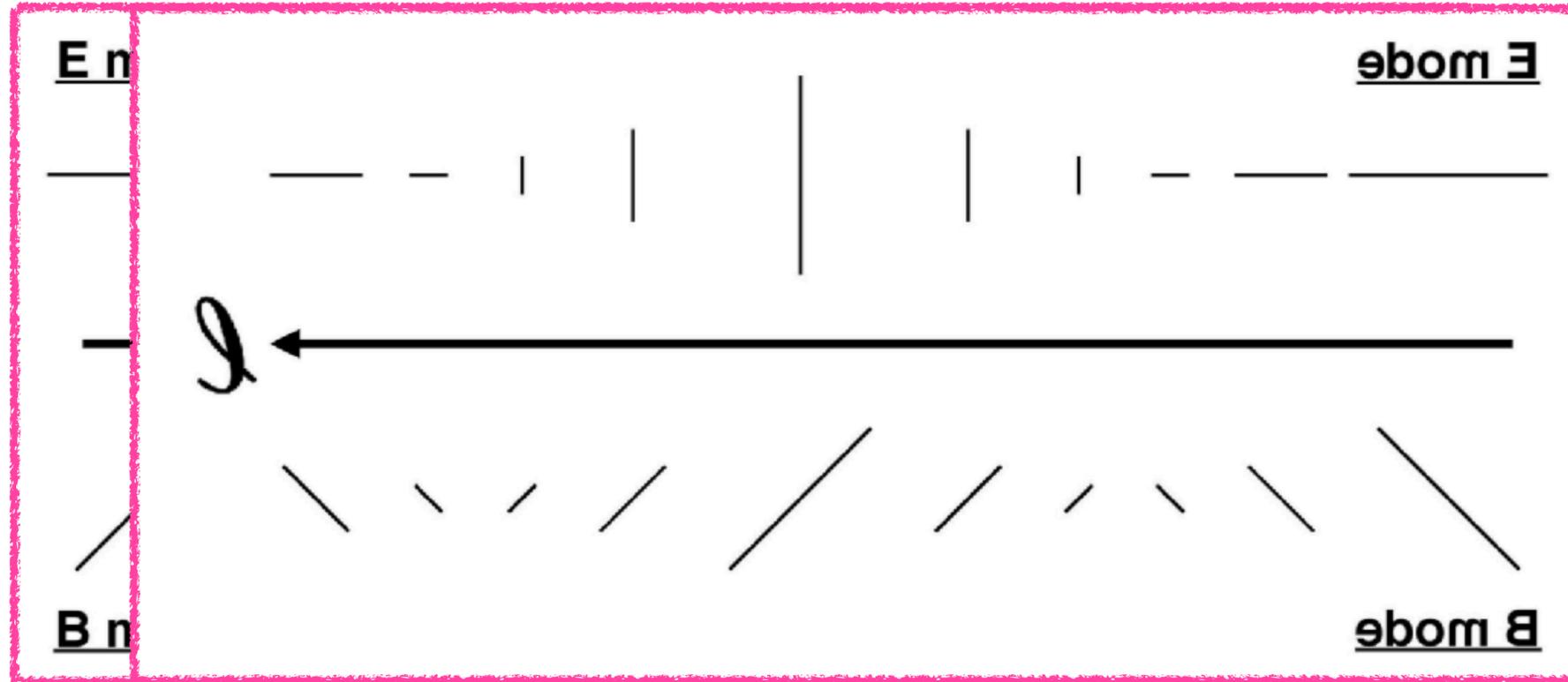
- The observed pattern of the CMB polarization can be decomposed into eigenstates of parity, called “E modes” and “B modes”.



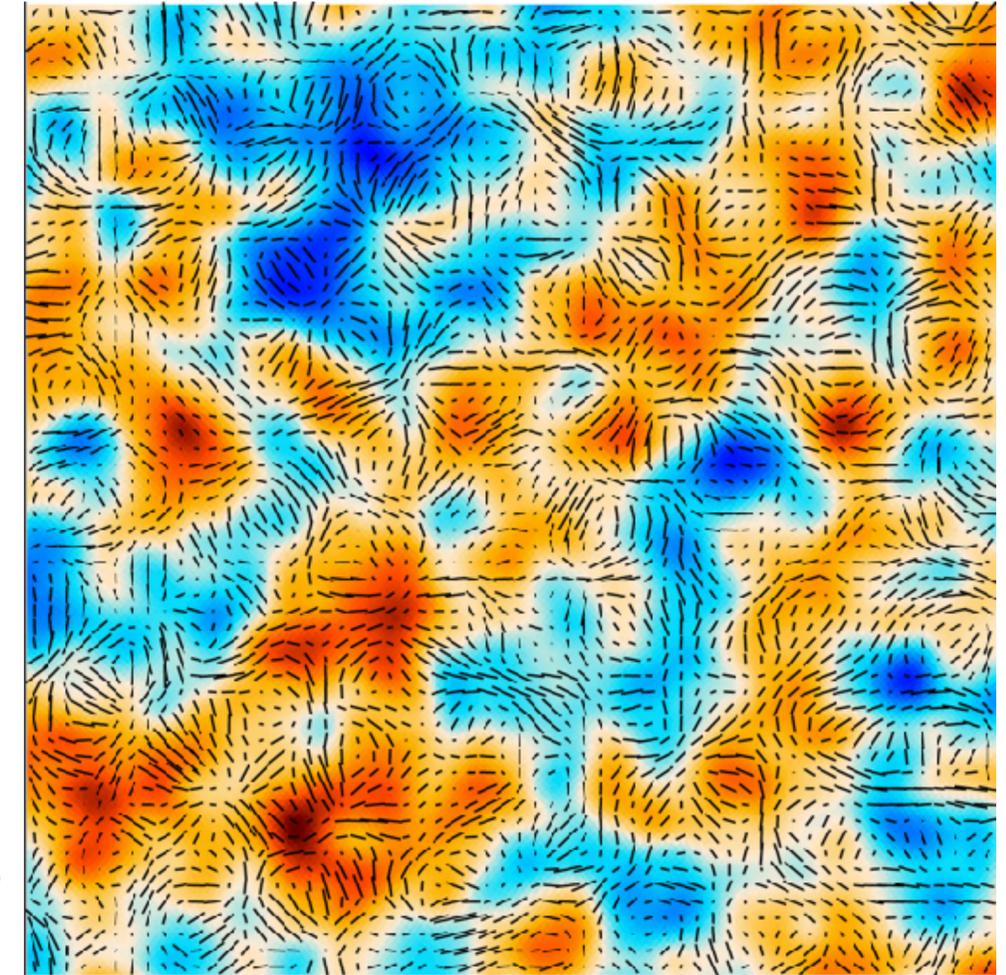
- E and B modes are transformed differently under the parity transformation. Therefore, the product of the two, **the “EB correlation”, is a pseudoscalar.**
- The full-sky average of the EB correlation must vanish (to within the measurement uncertainty), if there is no parity violation!**

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated
by E-mode polarization



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

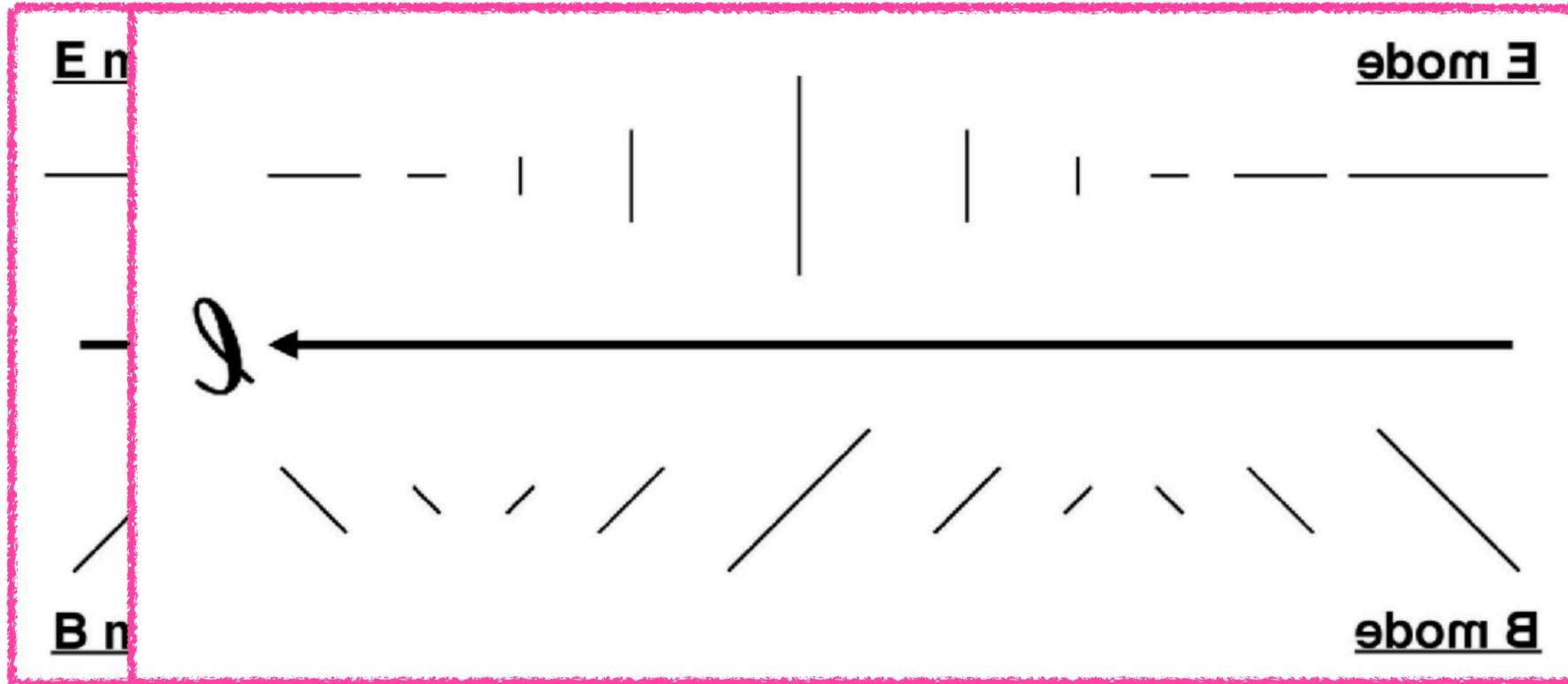
$$\langle B_{\ell} B_{\ell'}^* \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{BB}$$

$$\langle T_{\ell} E_{\ell'}^* \rangle = \langle T_{\ell'}^* E_{\ell} \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{TE}$$

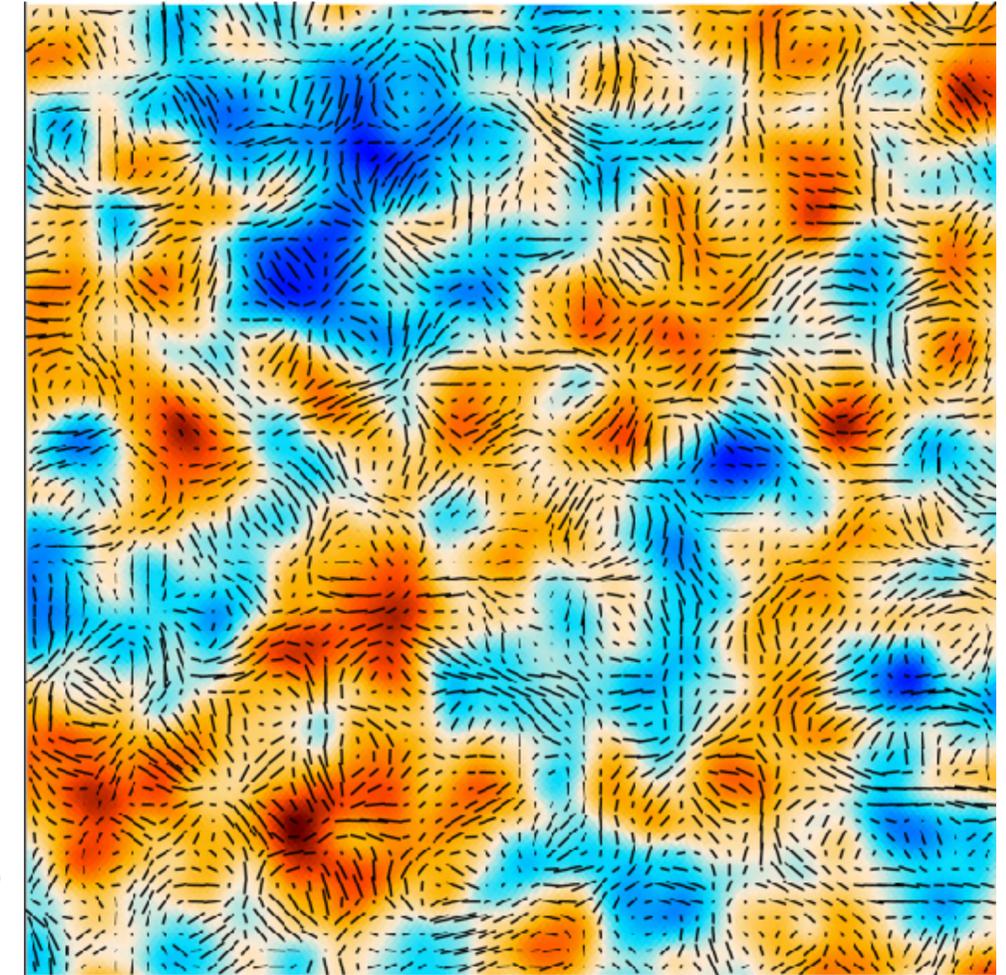
These are scalars and
insensitive to parity violation.

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

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

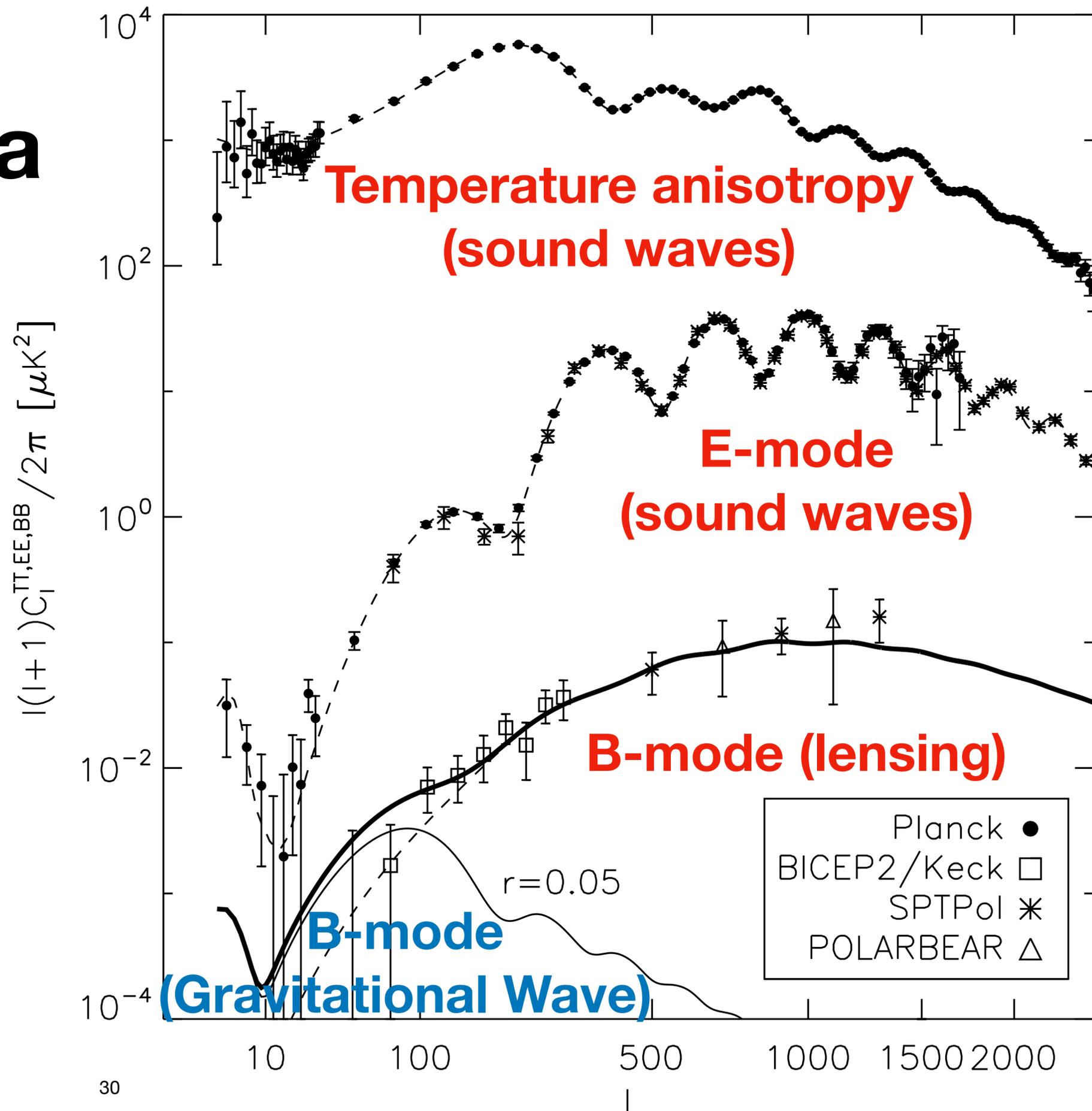
$$\langle T_{\ell} E_{\ell'}^* \rangle = \langle T_{\ell'}^* E_{\ell} \rangle = (2\pi)^2 \delta_D^{(2)}(\ell - \ell') C_{\ell}^{TE}$$

The other combinations, $\langle TB \rangle$ and $\langle EB \rangle$, are pseudoscalars and sensitive to parity violation!

CMB Power Spectra

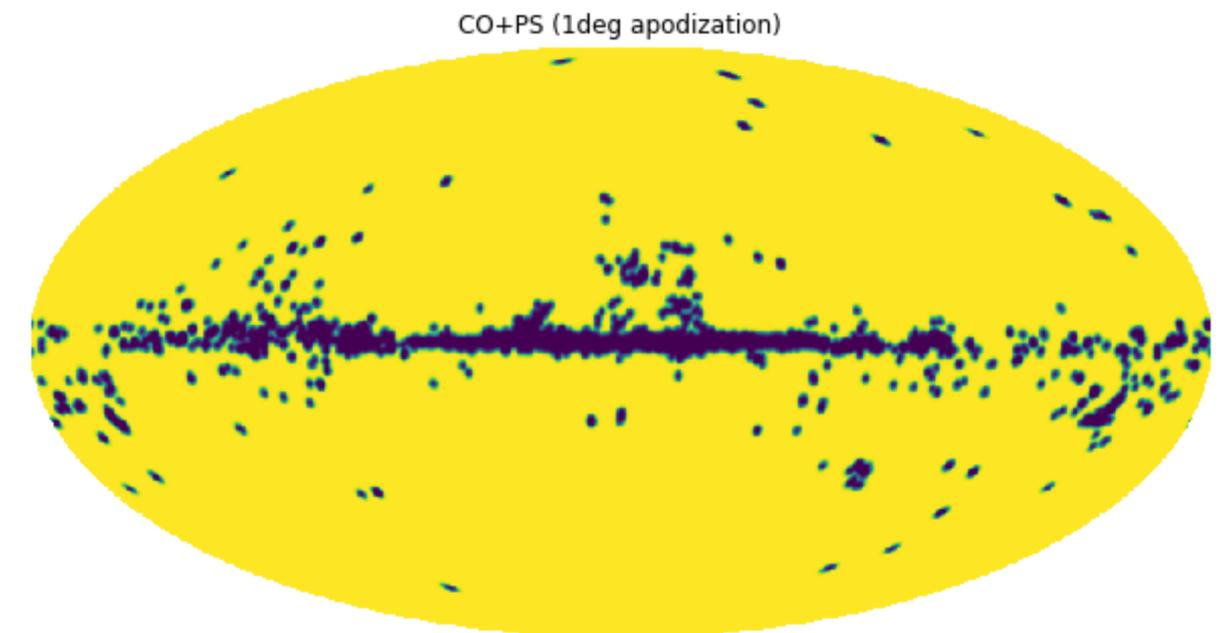
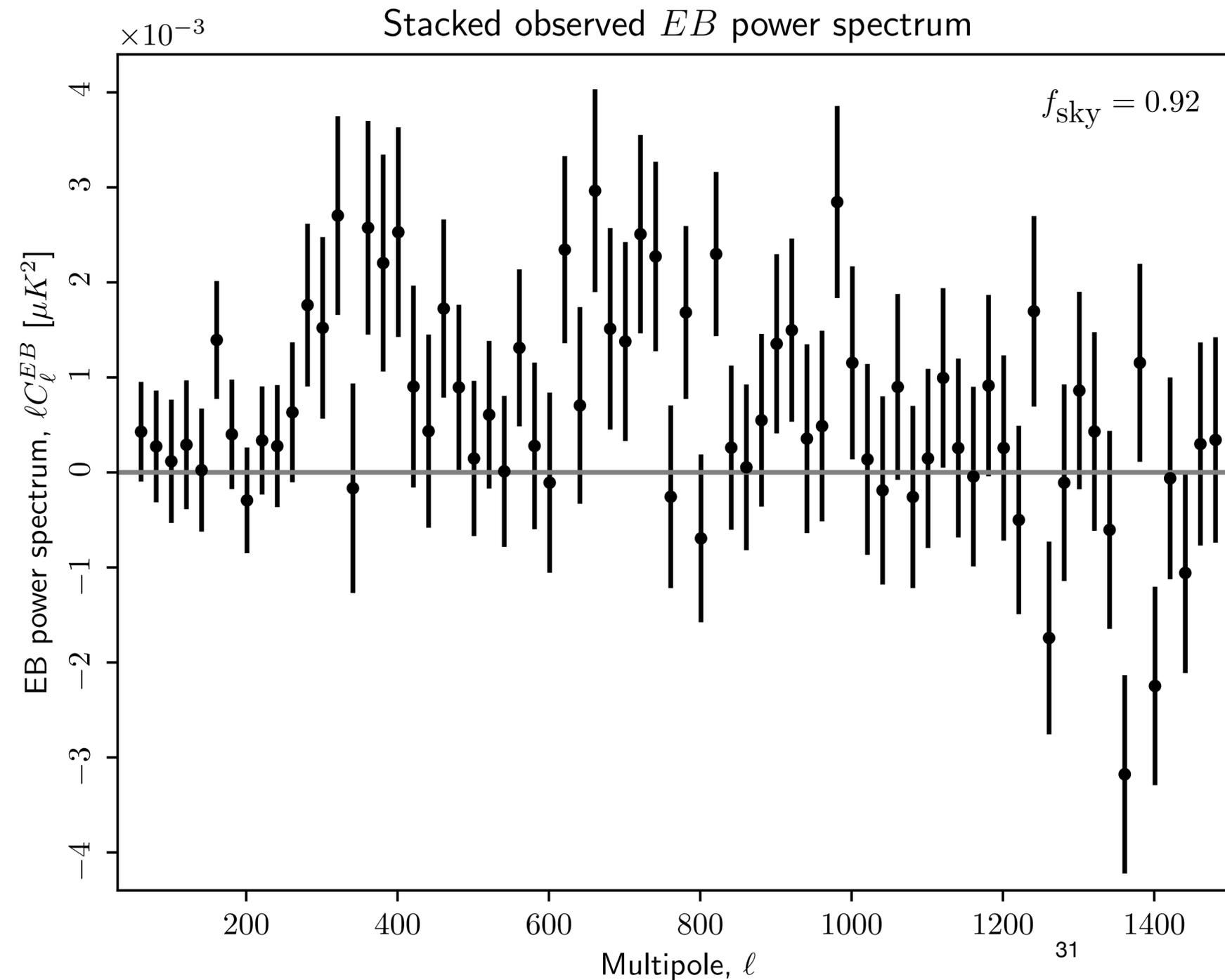
Progress over 30 years

- 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.**



This is the EB power spectrum (WMAP+Planck)

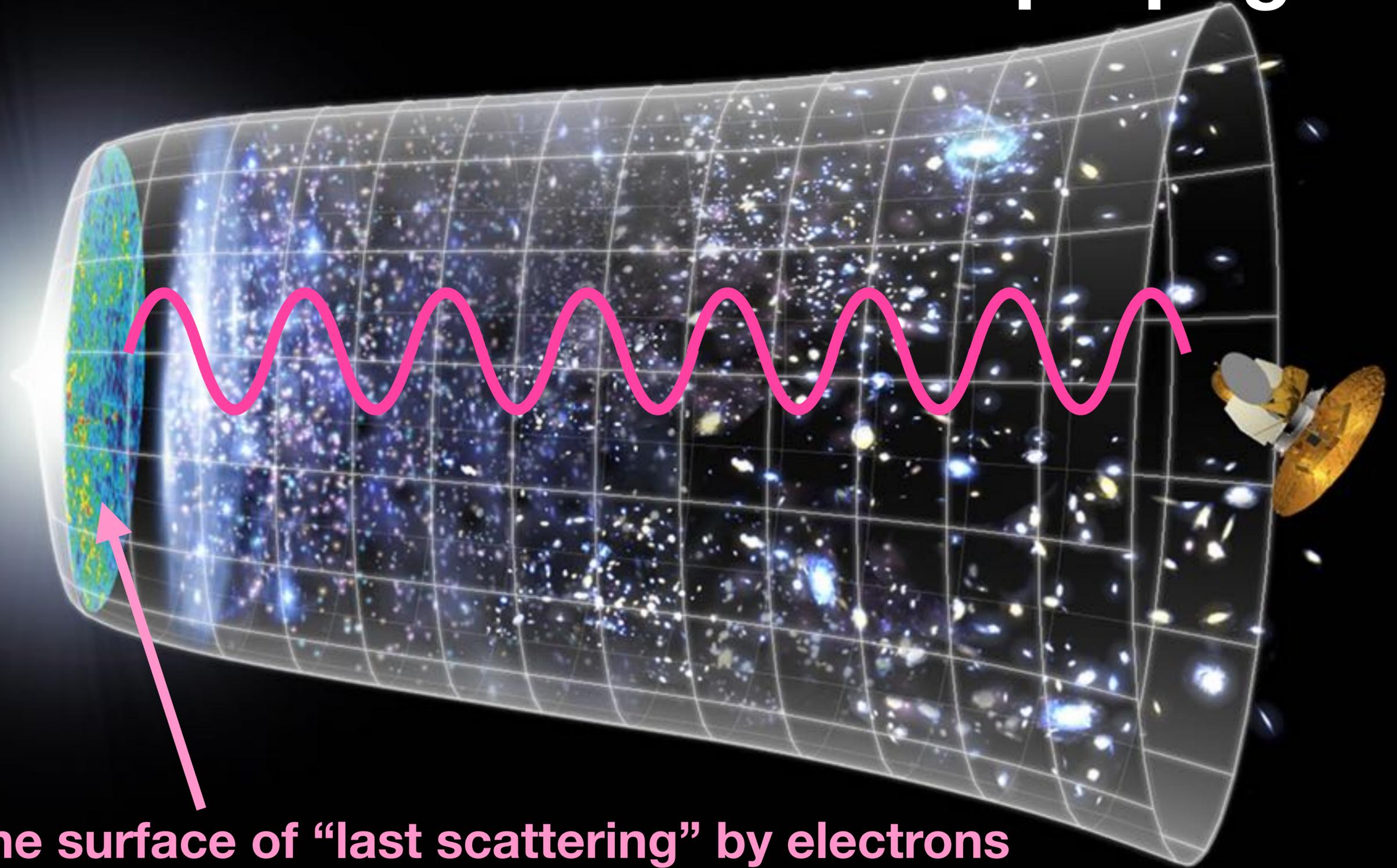
Nearly full-sky data (92% of the sky)



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

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

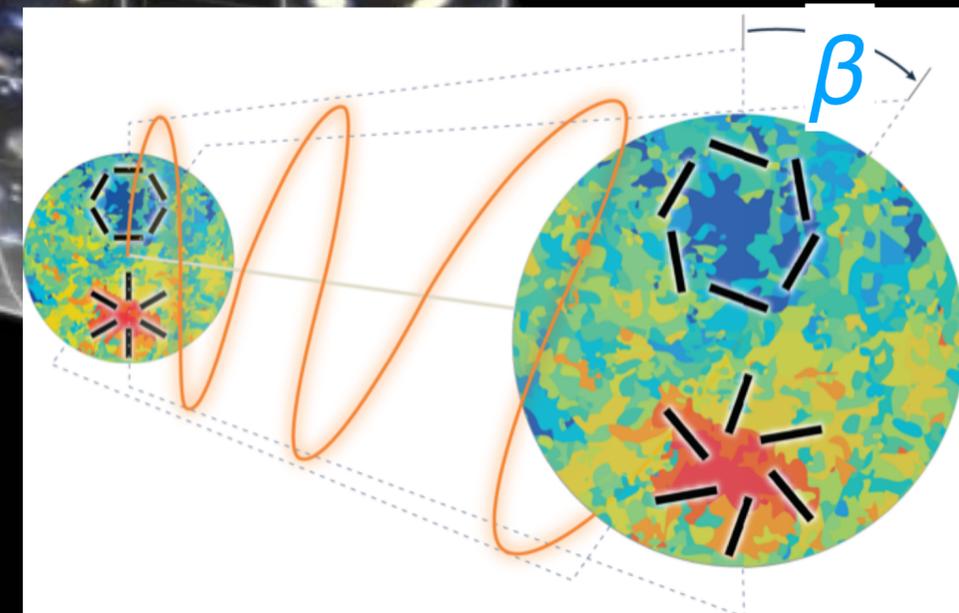
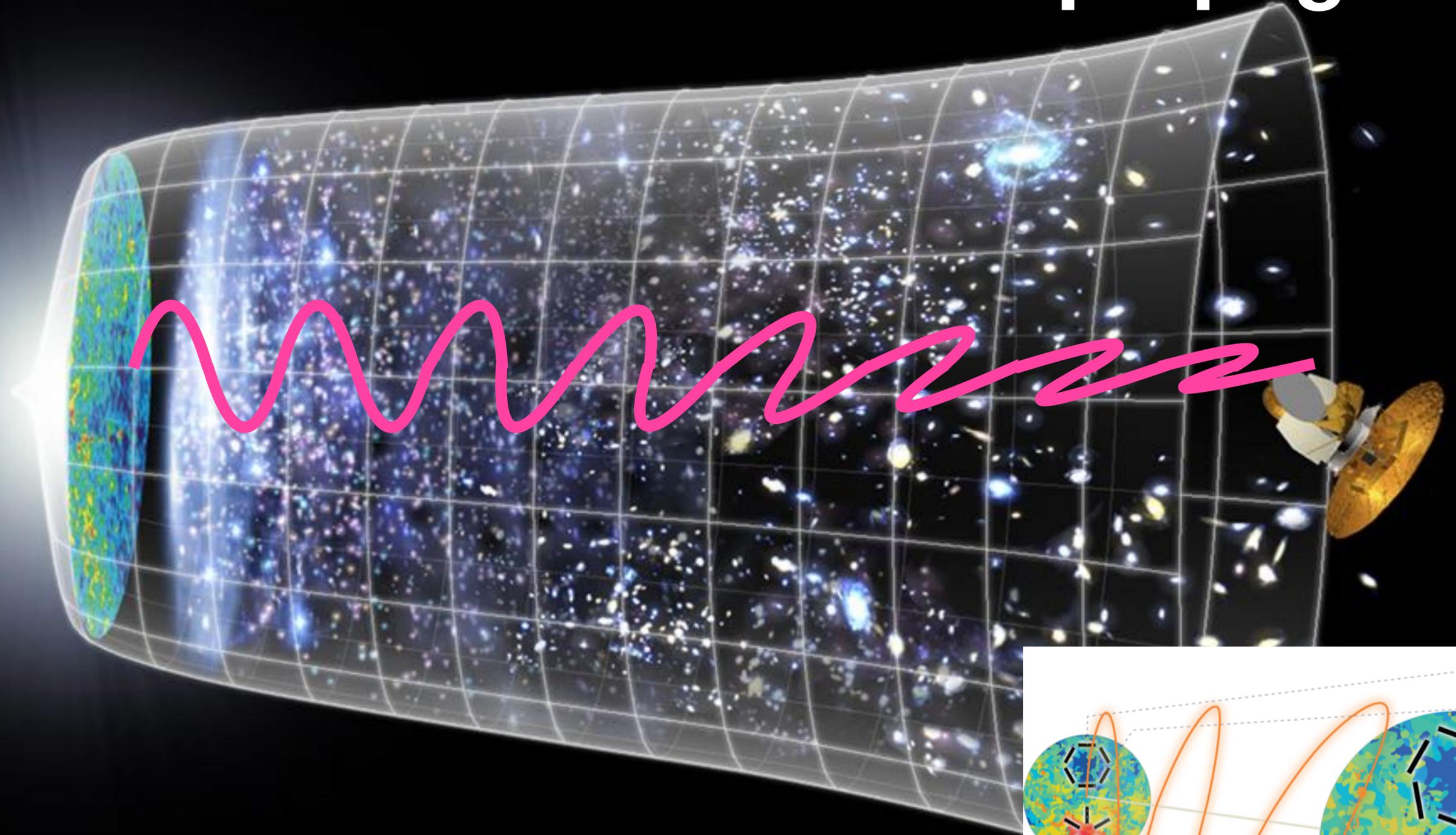
How does the EM wave of the CMB propagates?



The surface of “last scattering” by electrons
(Scattering generates *polarization*!)

Credit: WMAP Science Team

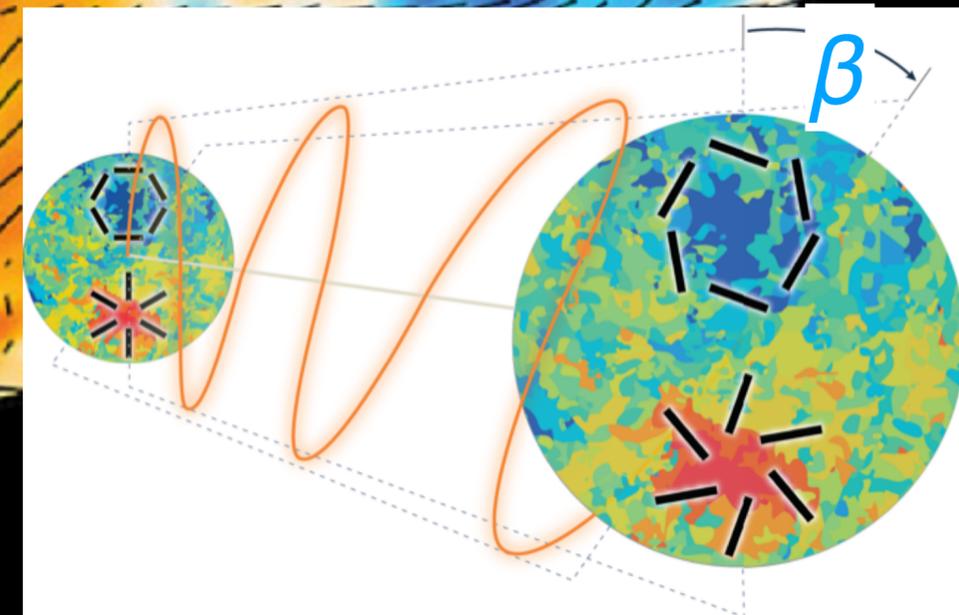
How does the EM wave of the CMB propagates?



“Cosmic Birefringence”

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

Temperature (smoothed) + Polarisation



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

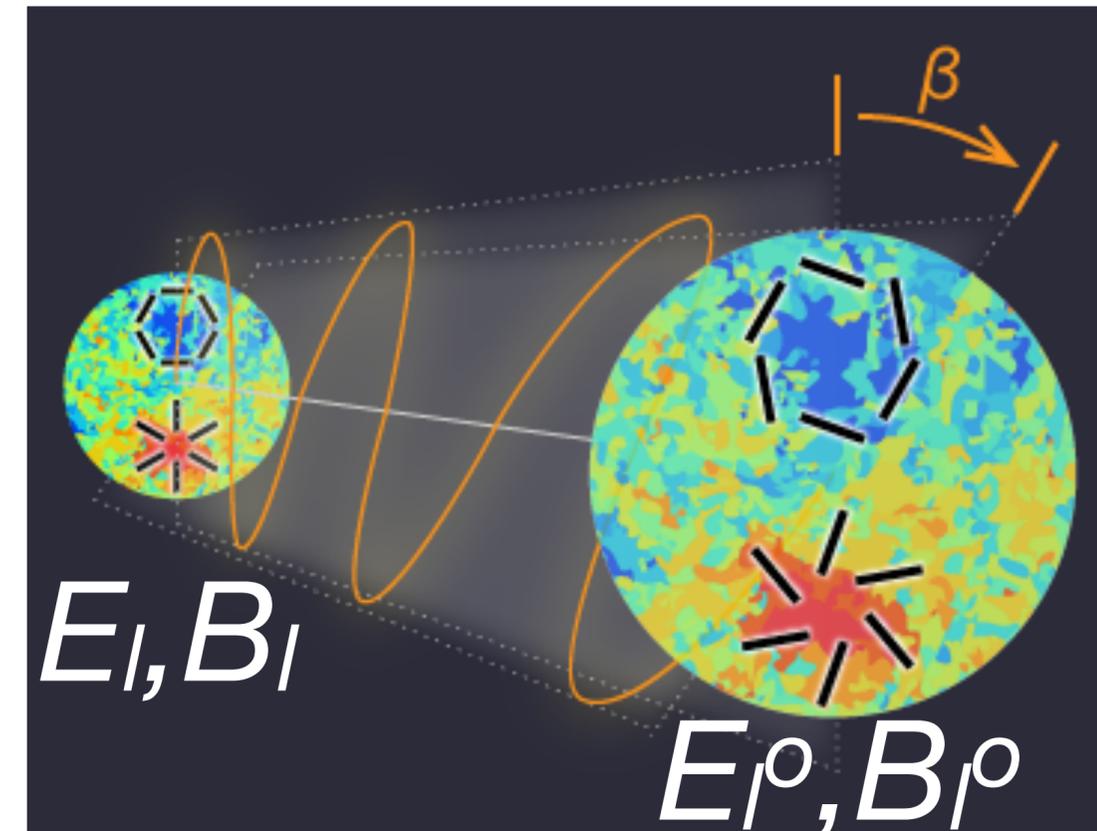
- Observed E- and B-mode polarization, E_l° and B_l° , are related to those before rotation as

$$E_l^\circ \pm iB_l^\circ = (E_l \pm iB_l)e^{\pm 2i\beta}$$

- which gives

$$E_l^\circ = E_l \cos(2\beta) - B_l \sin(2\beta)$$

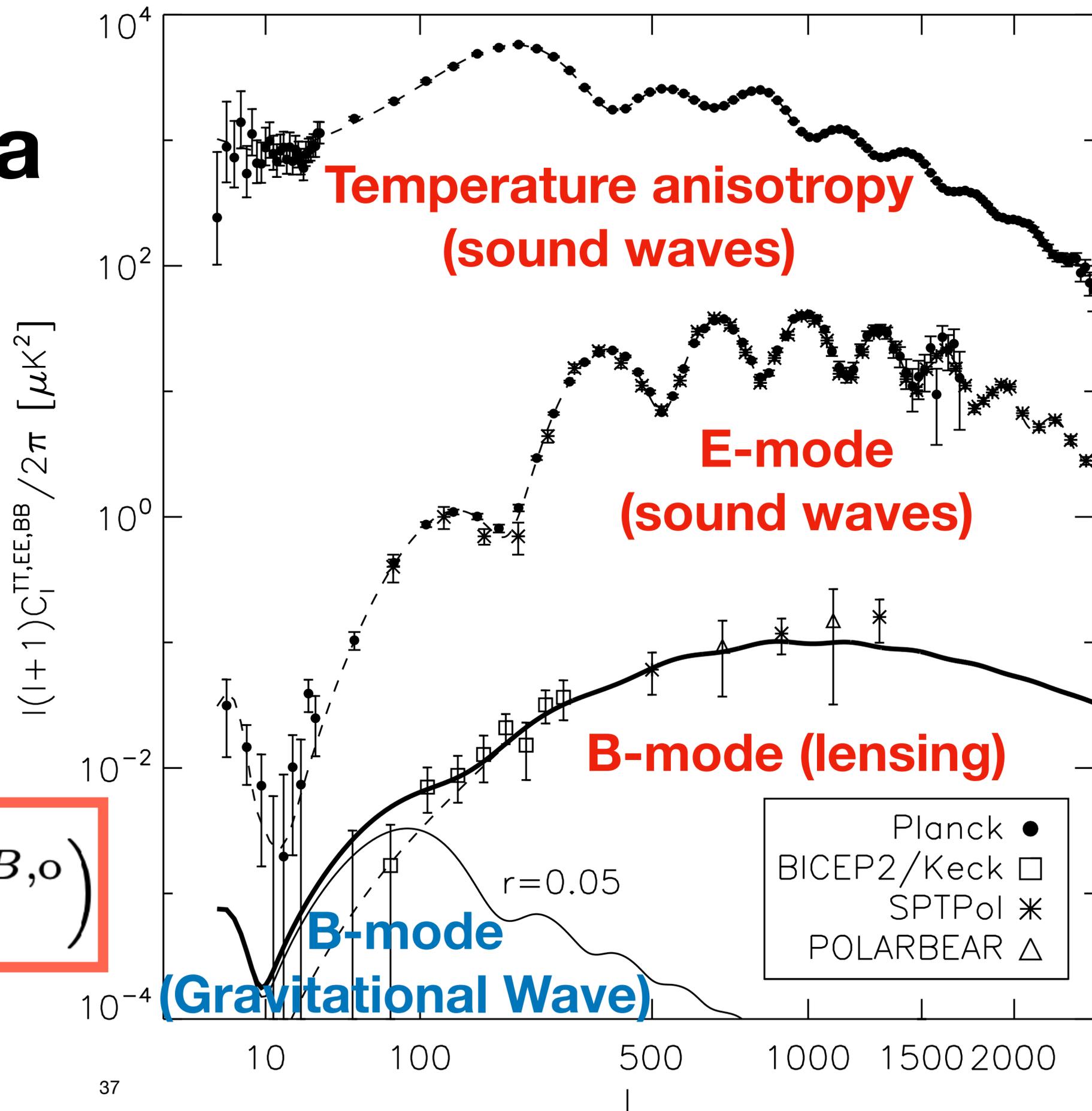
$$B_l^\circ = E_l \sin(2\beta) + B_l \cos(2\beta)$$



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!

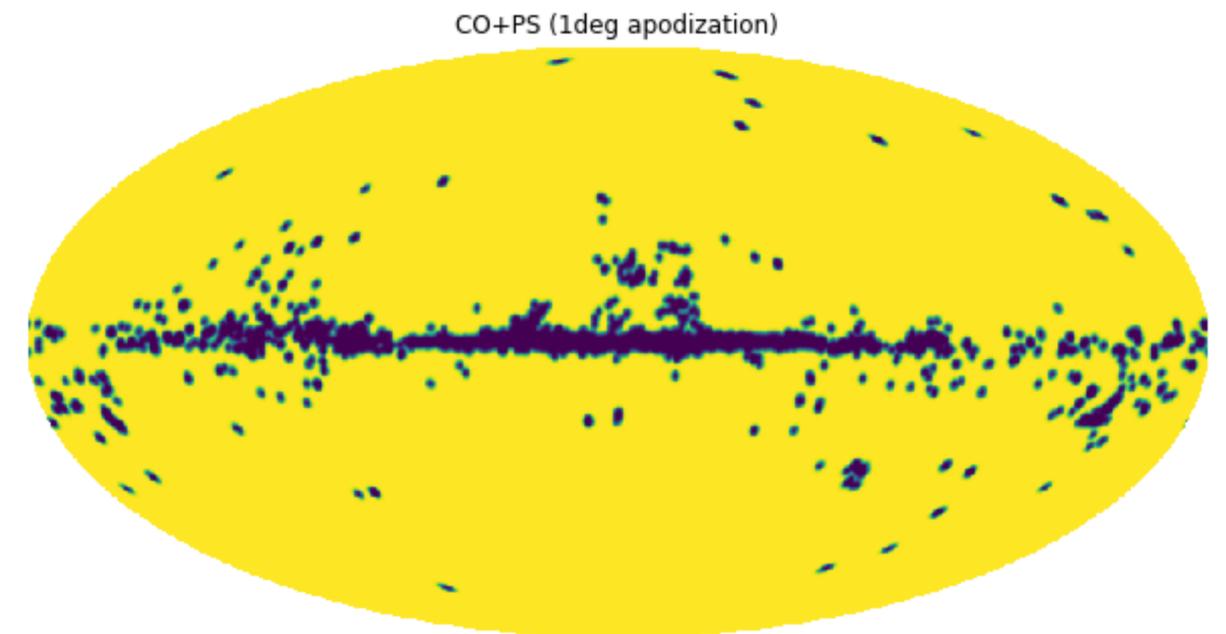
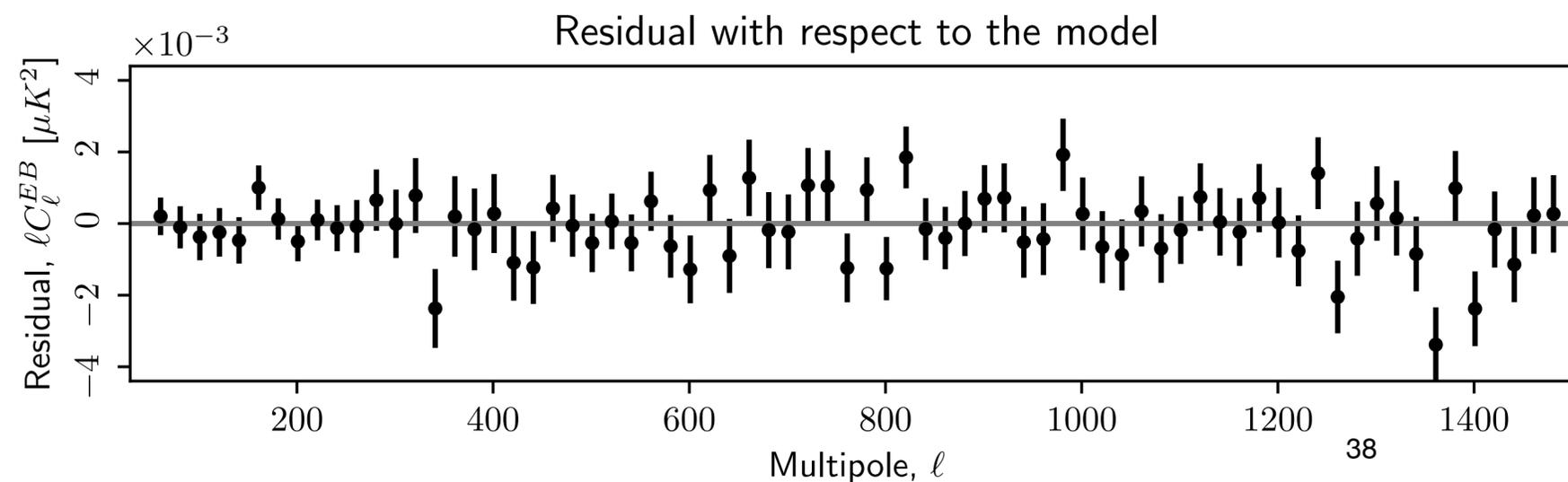
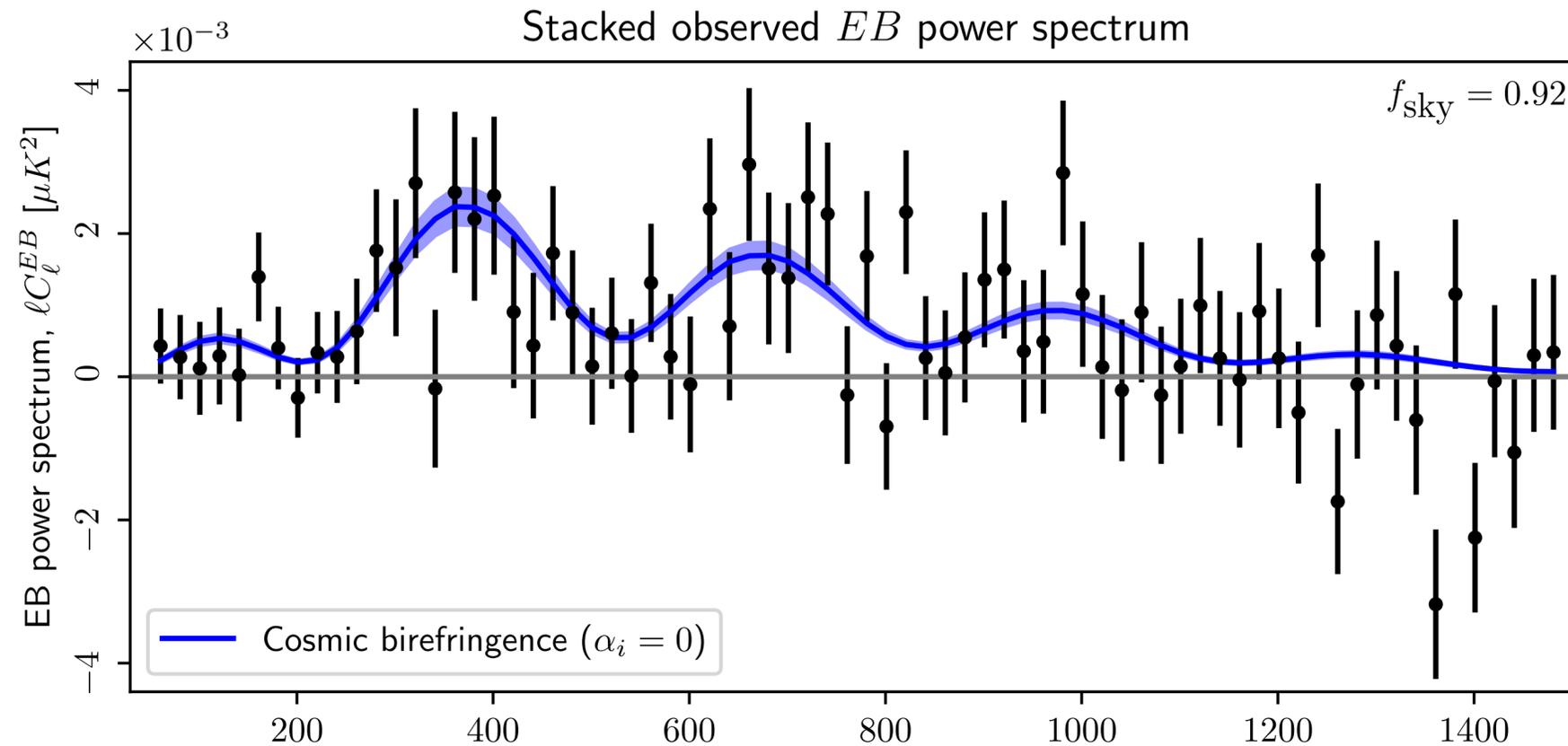
$$C_l^{EB,o} = \frac{\tan(4\beta)}{2} \left(C_l^{EE,o} - C_l^{BB,o} \right)$$



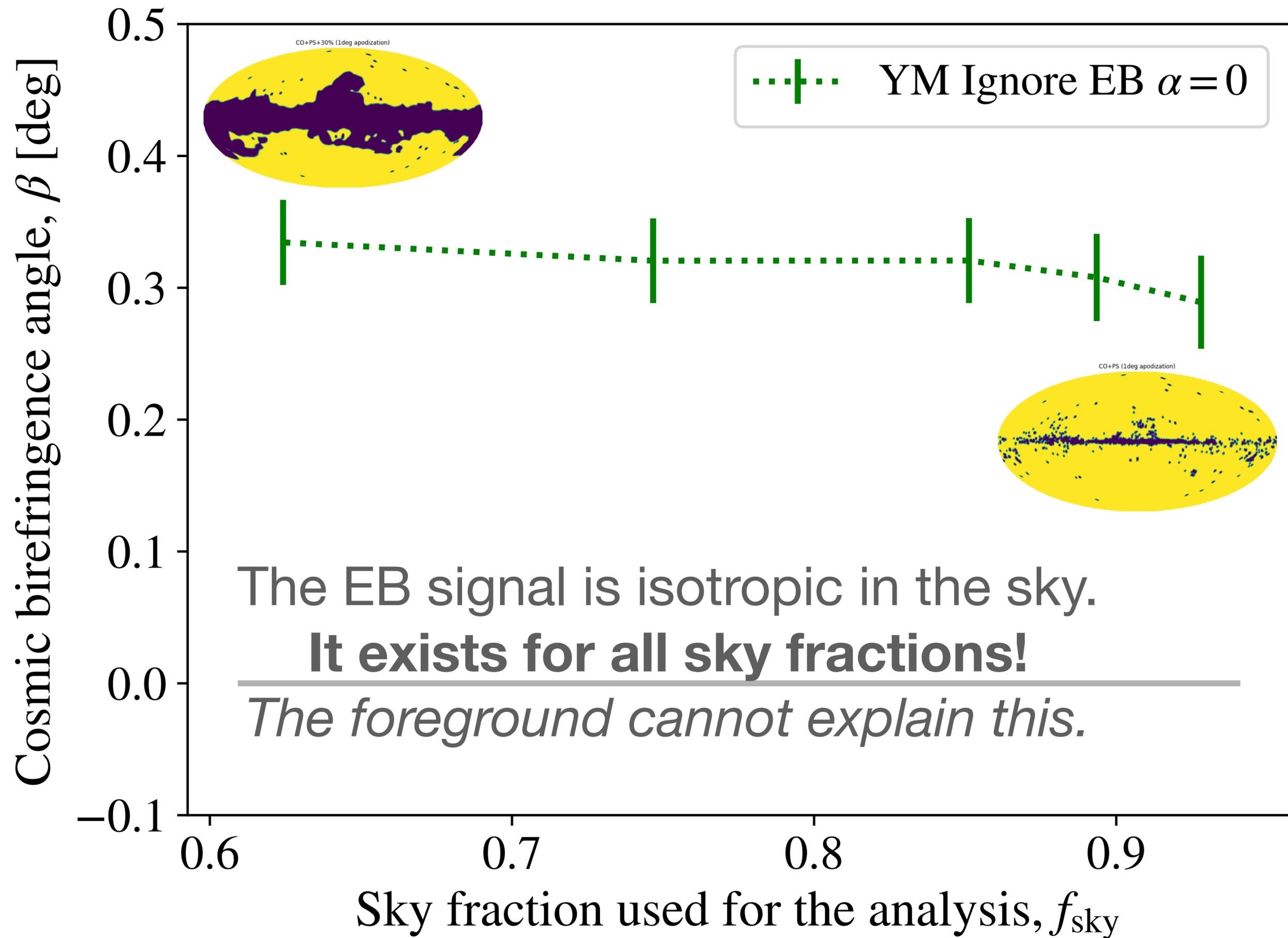
Cosmic Birefringence fits well(?)

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

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?



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 $\alpha + \beta$** .

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



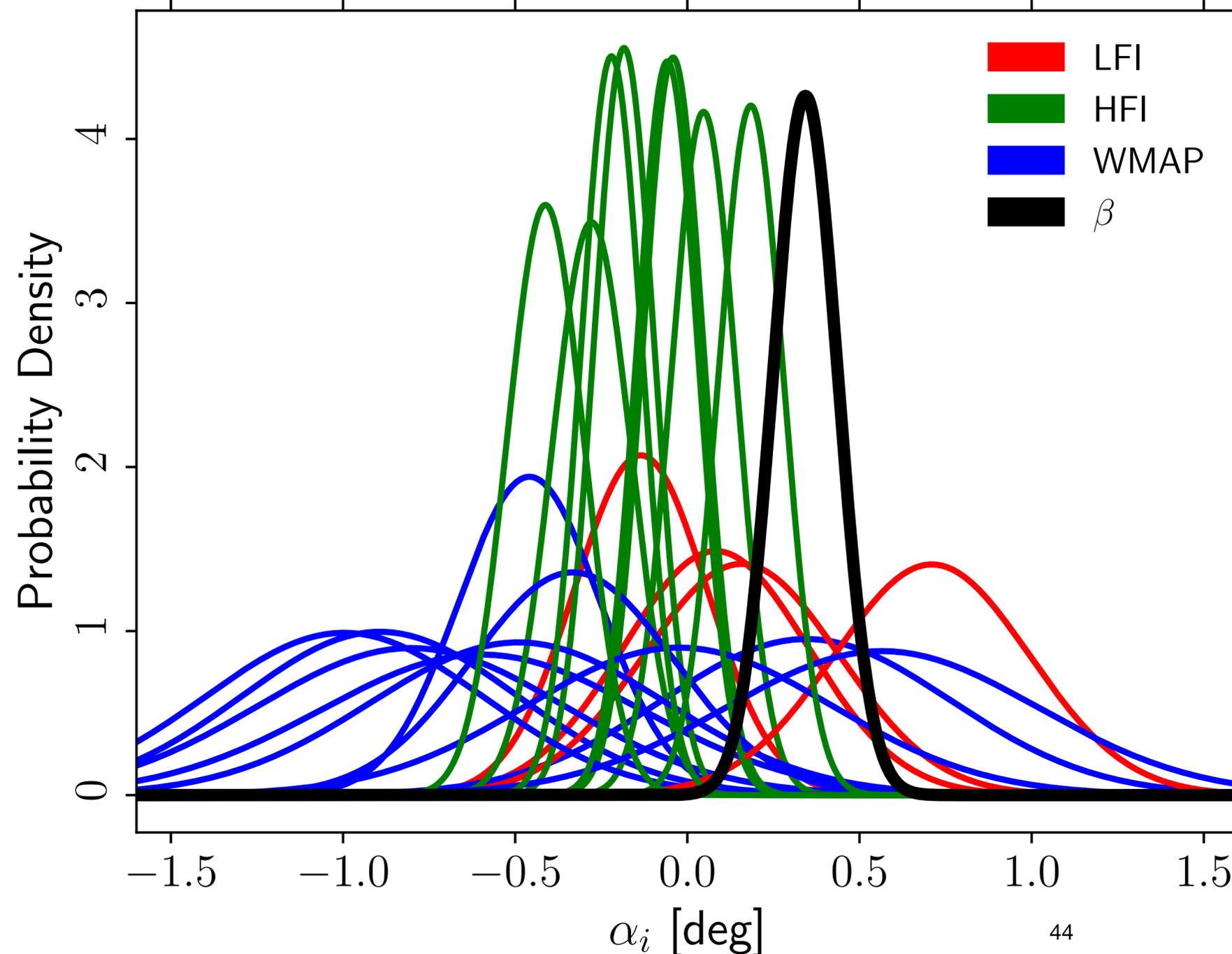
ESA's Planck

Polarized dust emission within our Milky Way!

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

Miscalibration angles (WMAP and Planck)

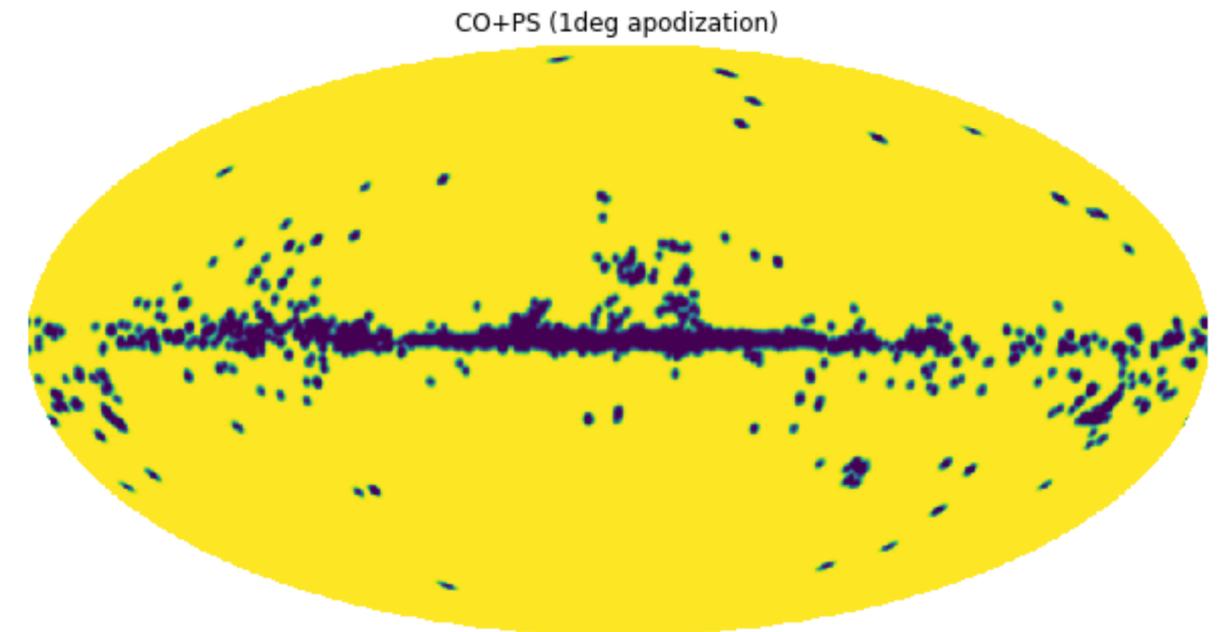
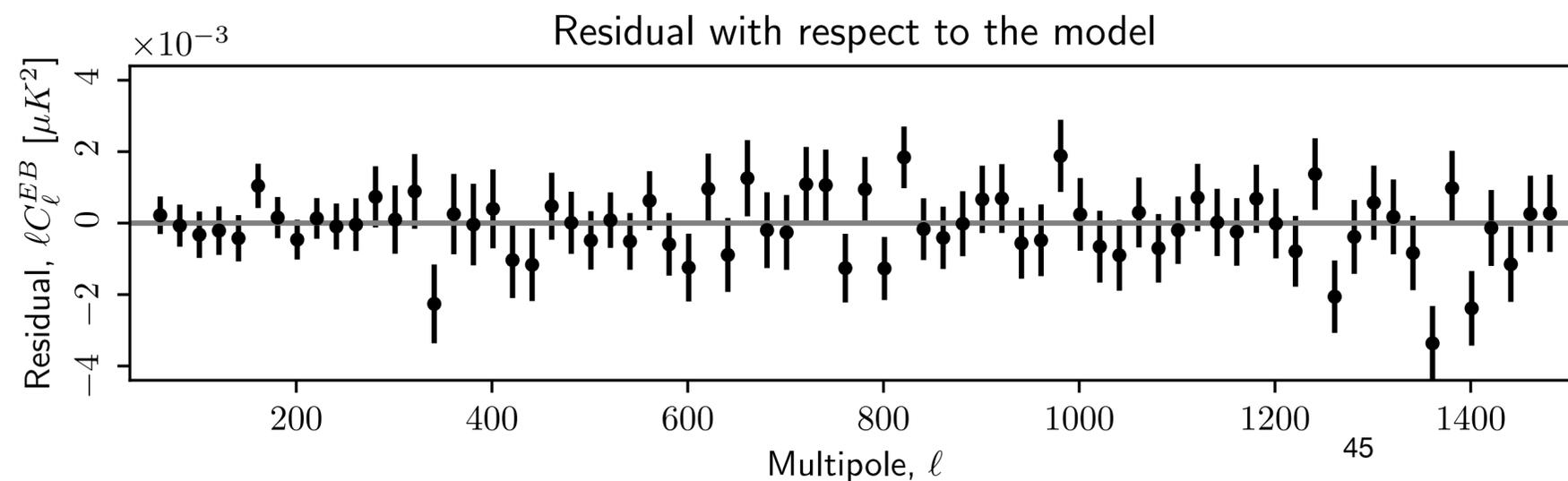
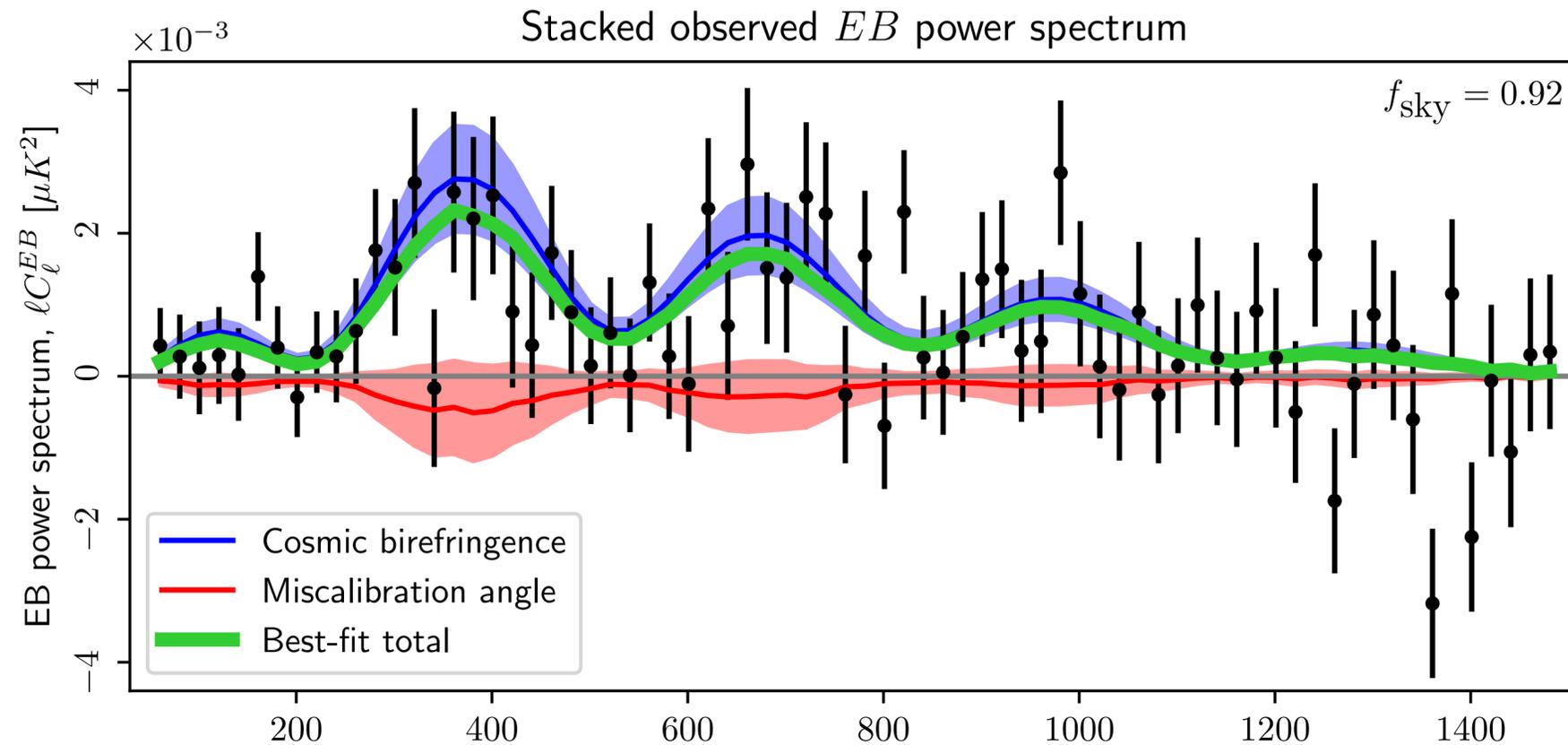
Nearly full-sky data (92% of the sky)



- 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)



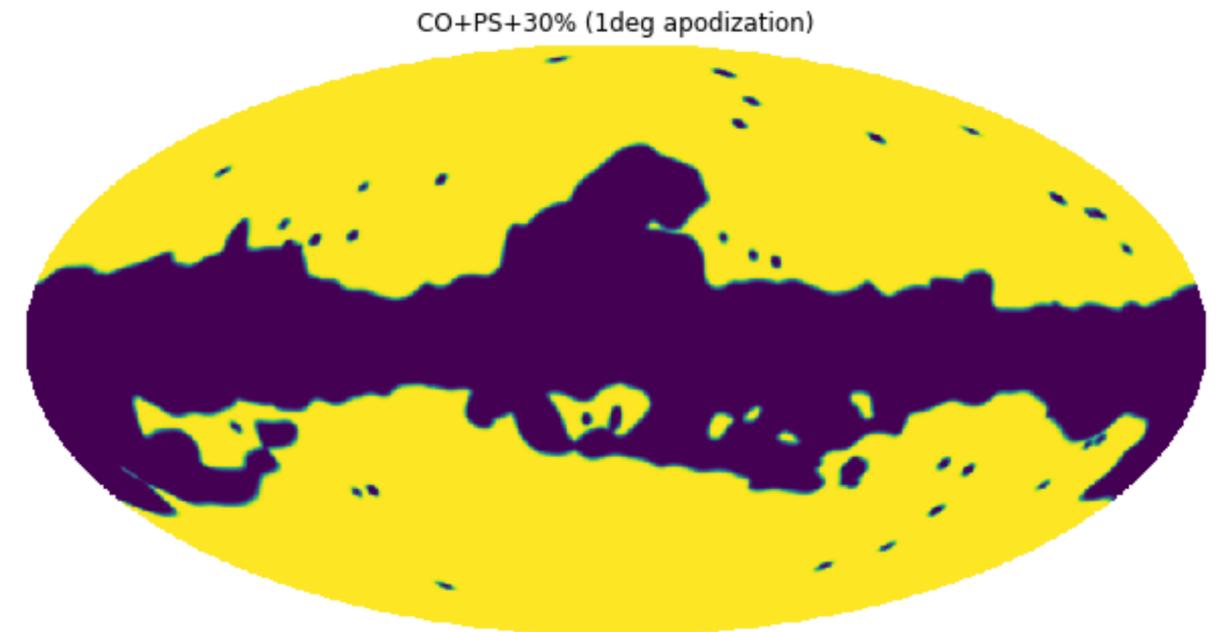
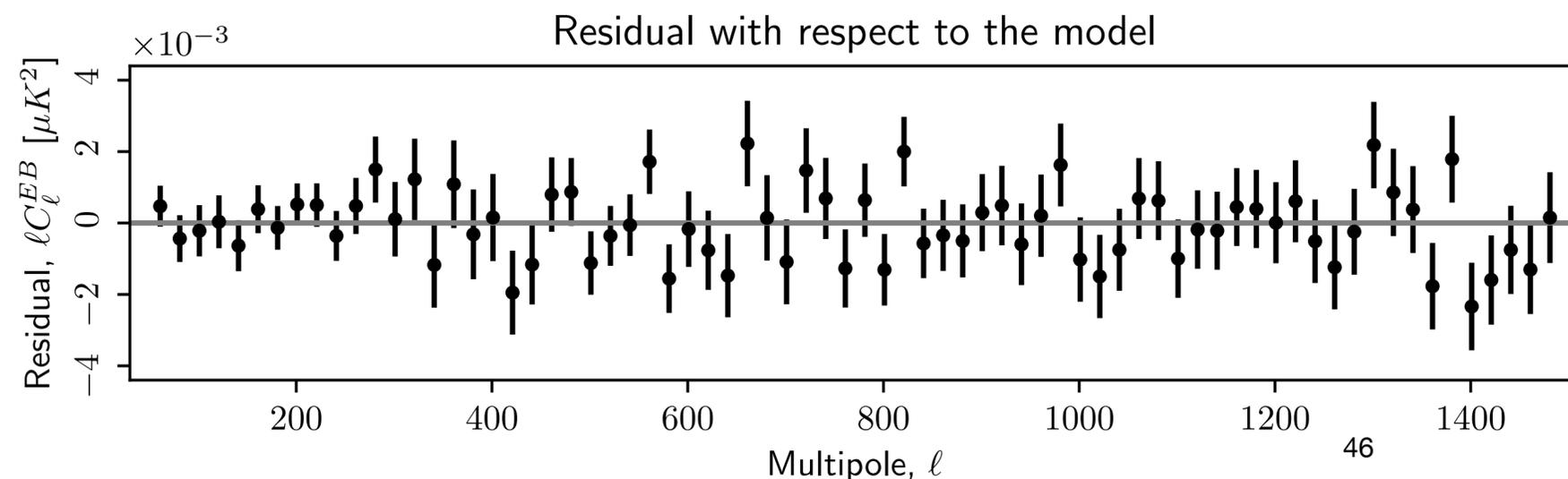
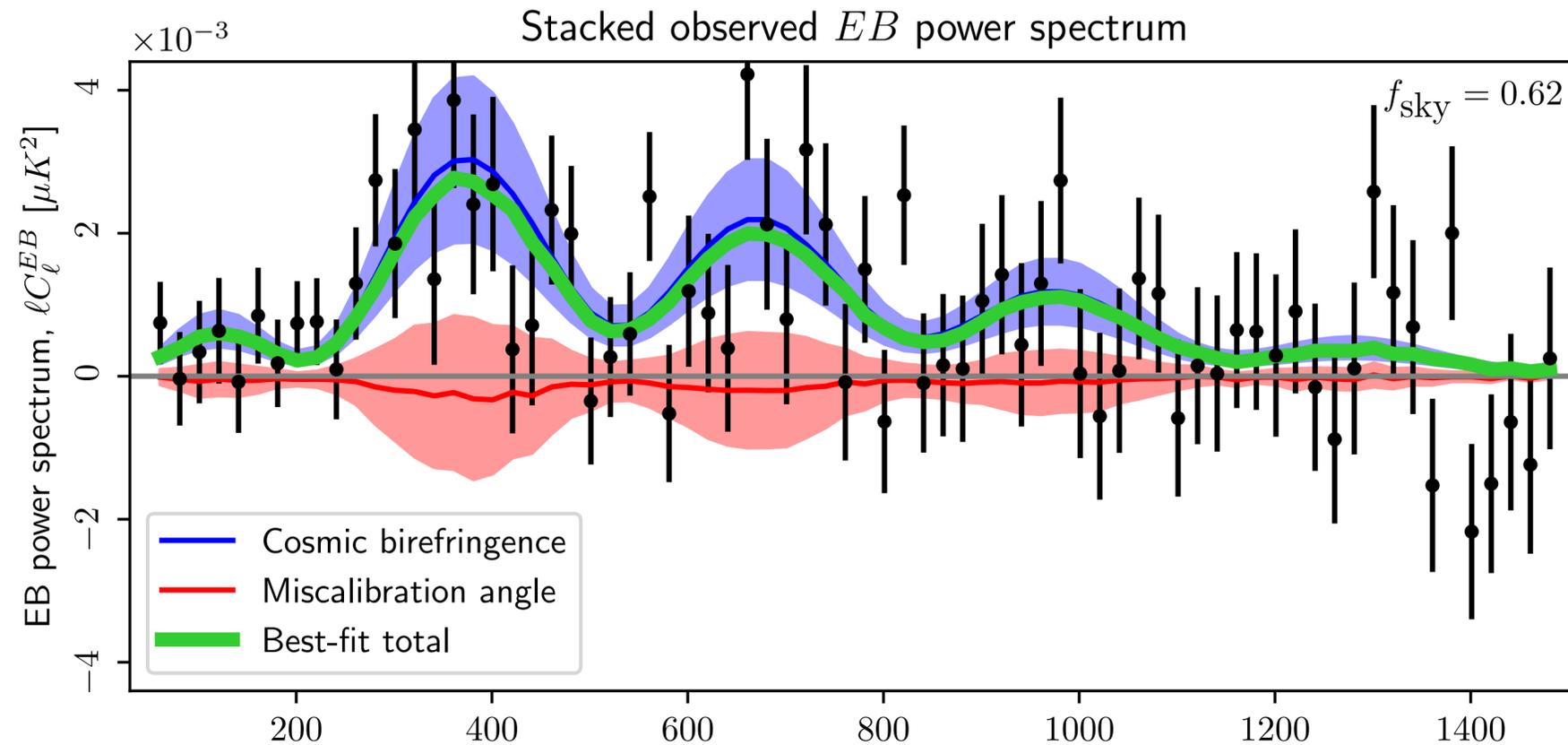
- **Miscalibration angles** make only small contributions thanks to the cancellation.

- $\beta = 0.34 \pm 0.09$ deg

- $\chi^2 = 65.3$

Cosmic Birefringence fits well (WMAP+Planck)

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



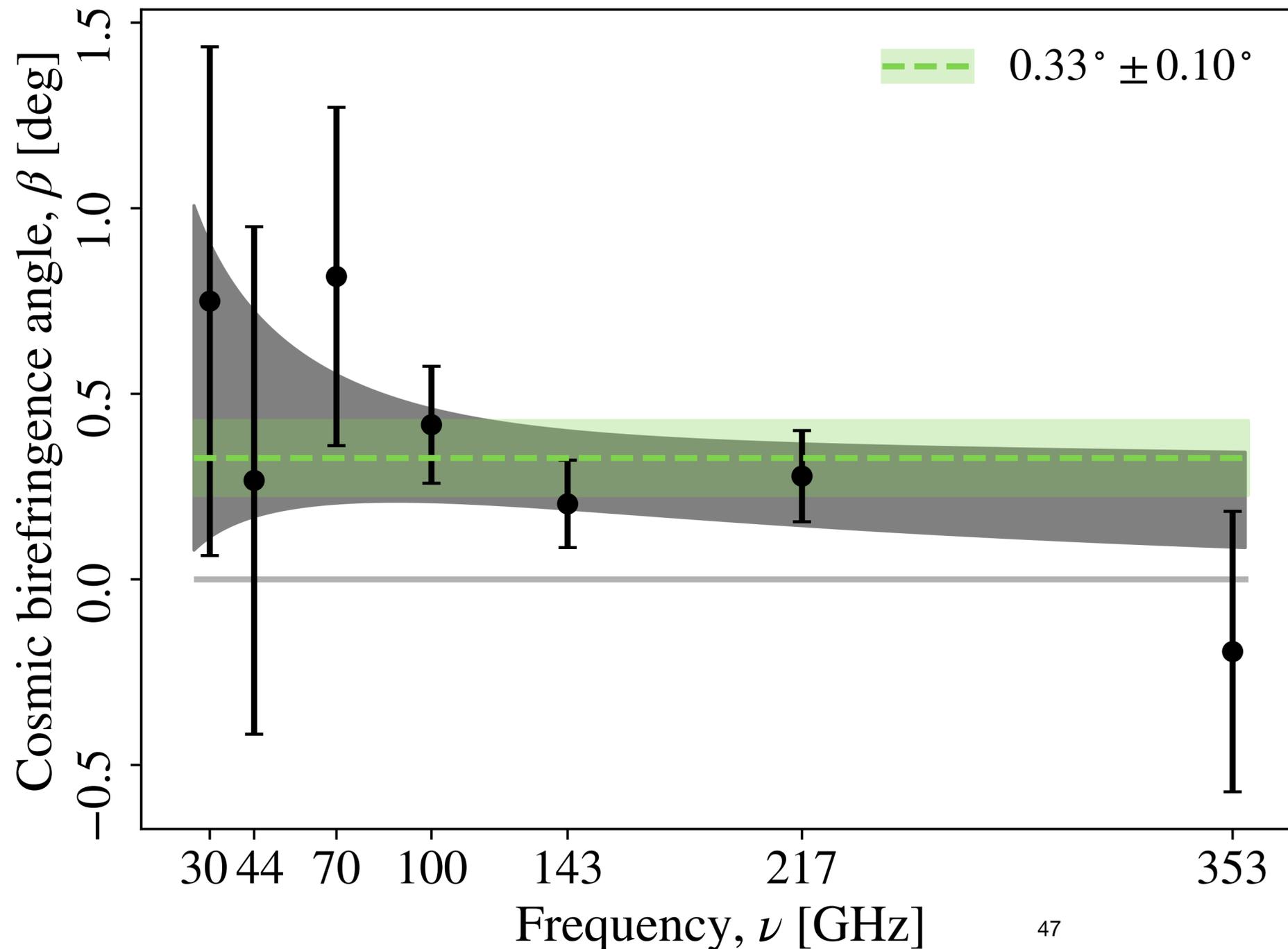
- **Miscalibration angles** make only small contributions thanks to the cancellation.

- $\beta = 0.37 \pm 0.14$ 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.**

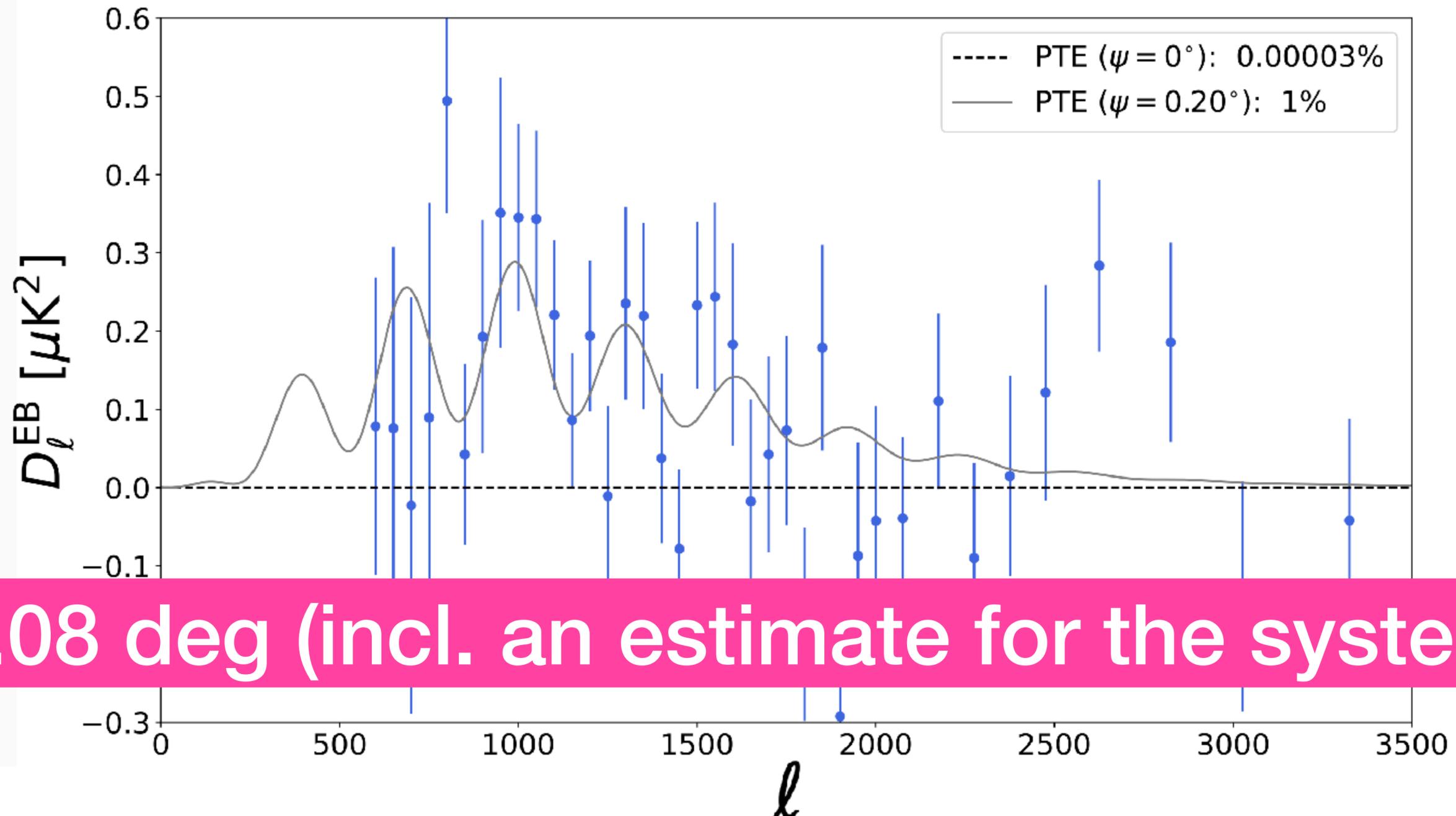
Is β caused by non-cosmological effects?

We need to measure it in independent experiments.

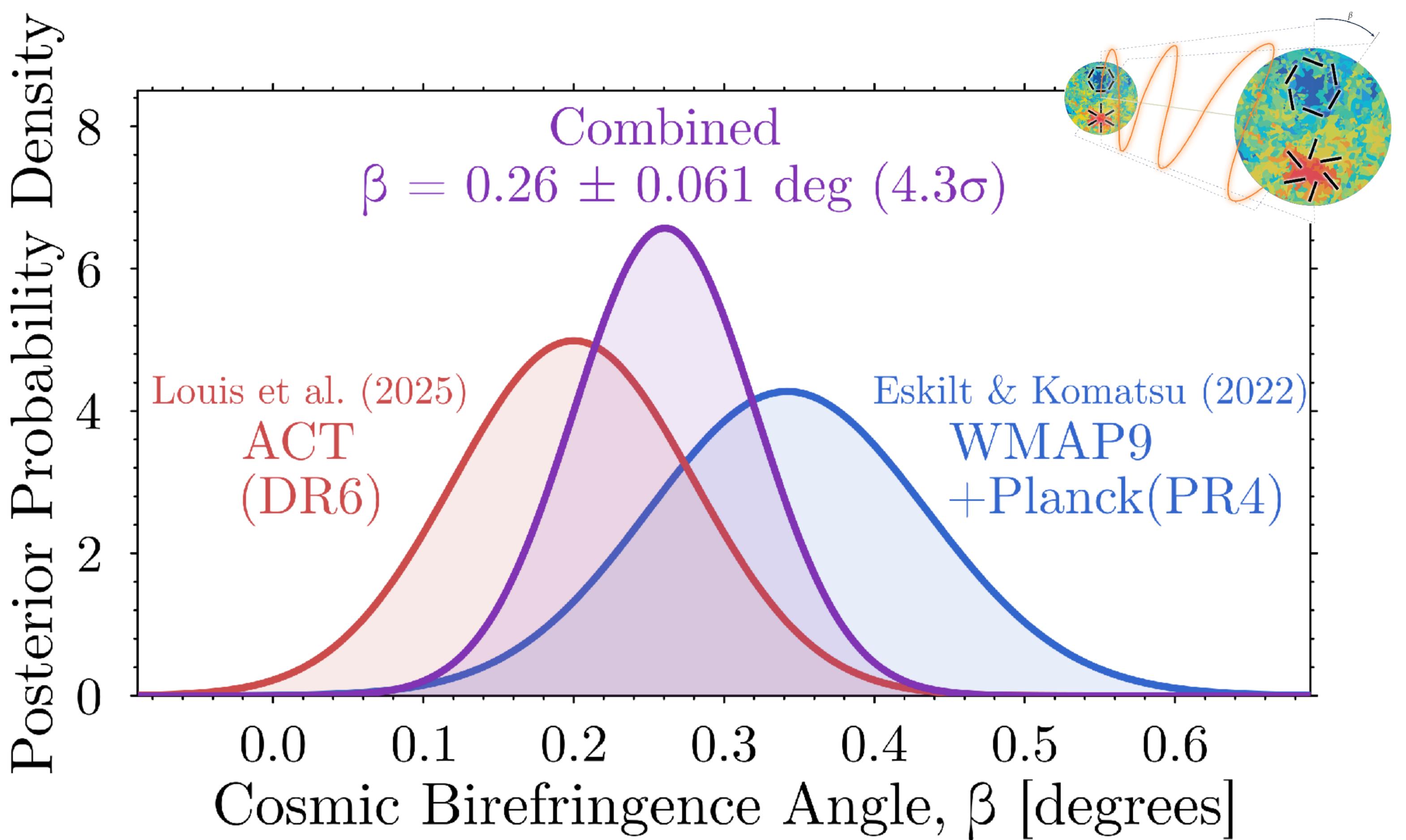
- The **known** instrumental effects of the WMAP and Planck missions are shown to have negligible effects on β .
 - However, we can never rule out **unknown** instrumental effects... We need to measure β in independent experiments.
- The polarized Galactic foreground emission was used to calibrate the 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. (COSMOCaI), arXiv:2405.12135.

Atacama Cosmology Telescope (DR6)

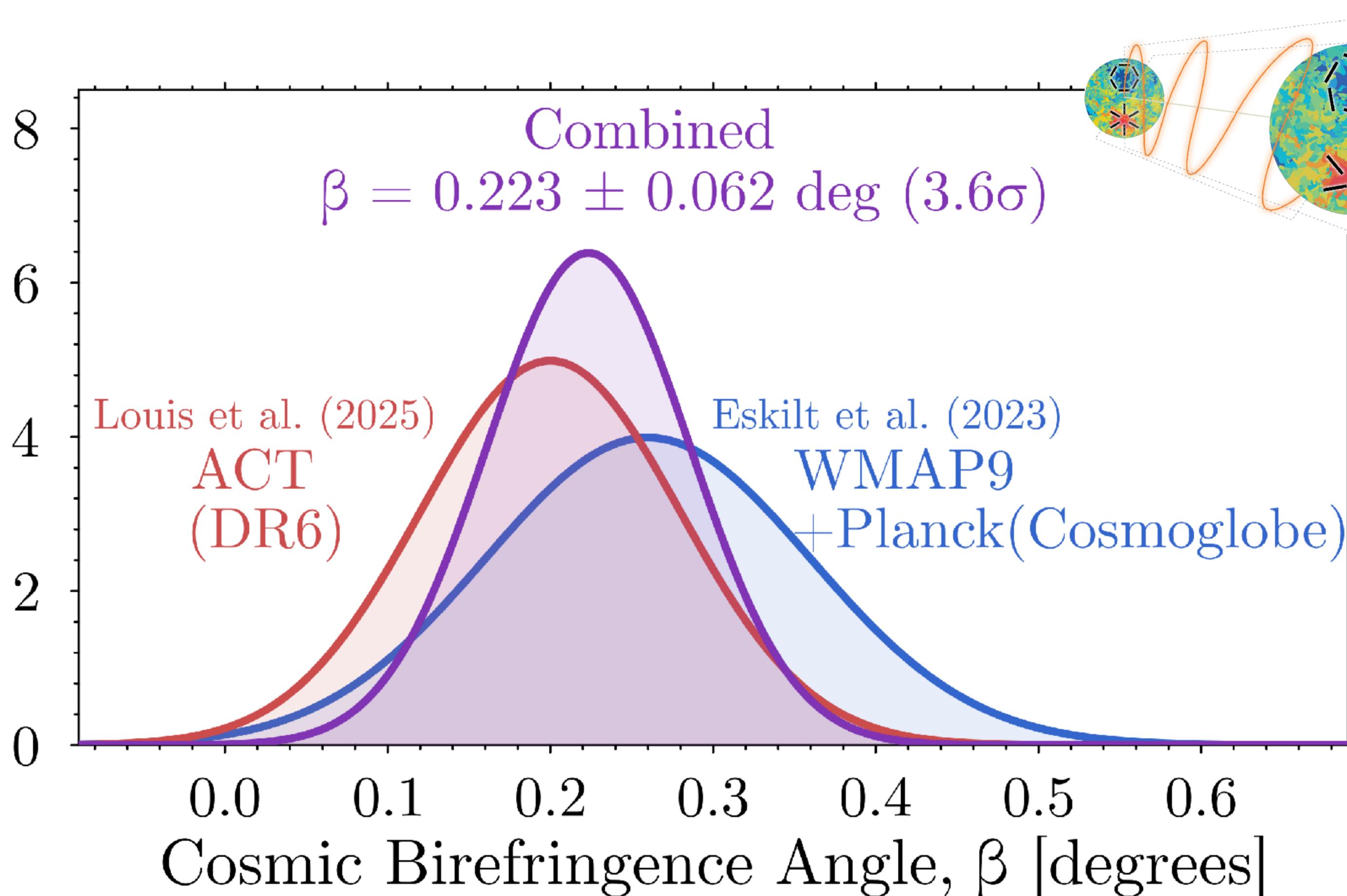
We need to measure it in independent experiments -> here it is!



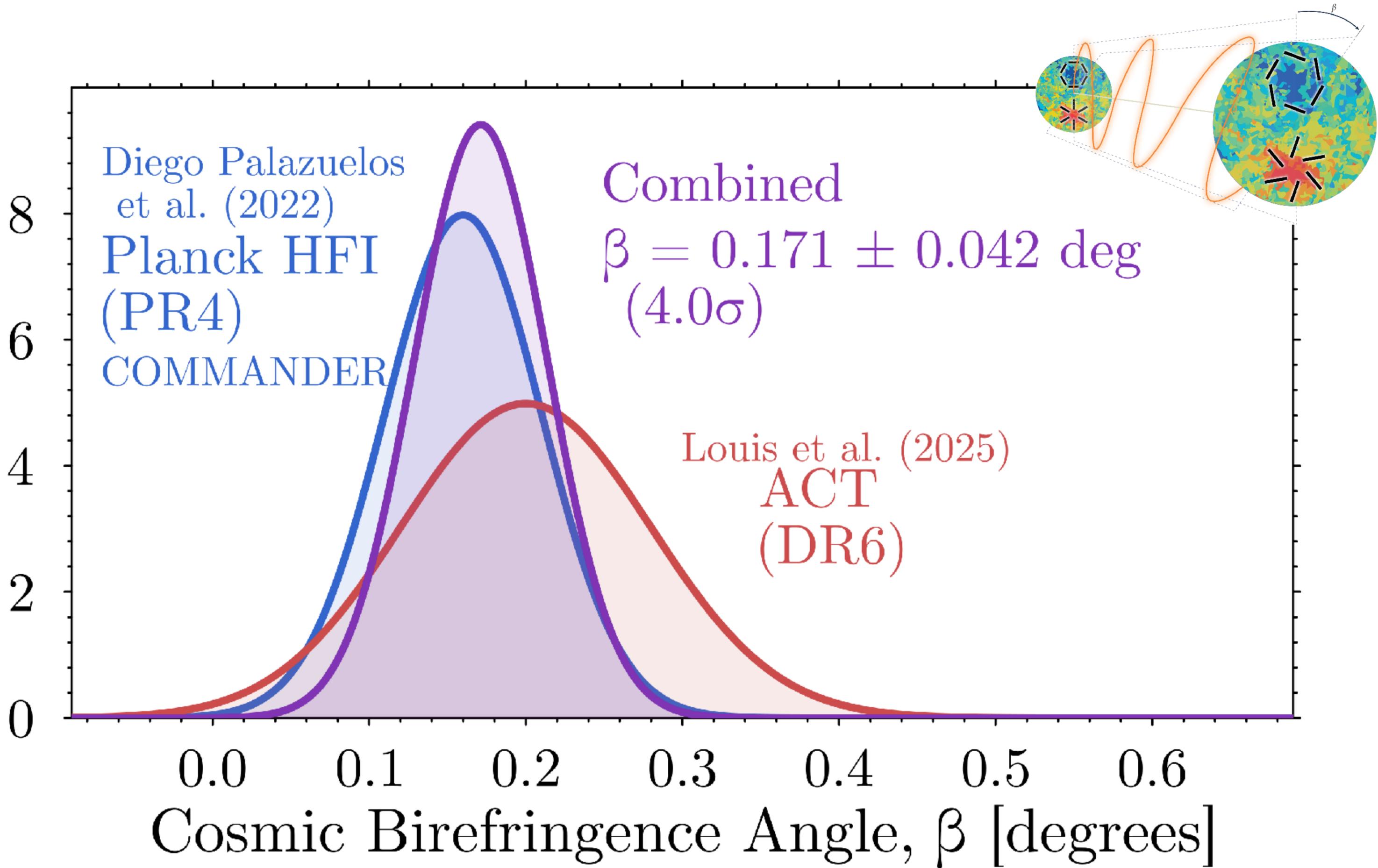
0.2 ± 0.08 deg (incl. an estimate for the systematics)



Posterior Probability Density



Posterior Probability Density



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!

6. Implications for Axioms

Implications

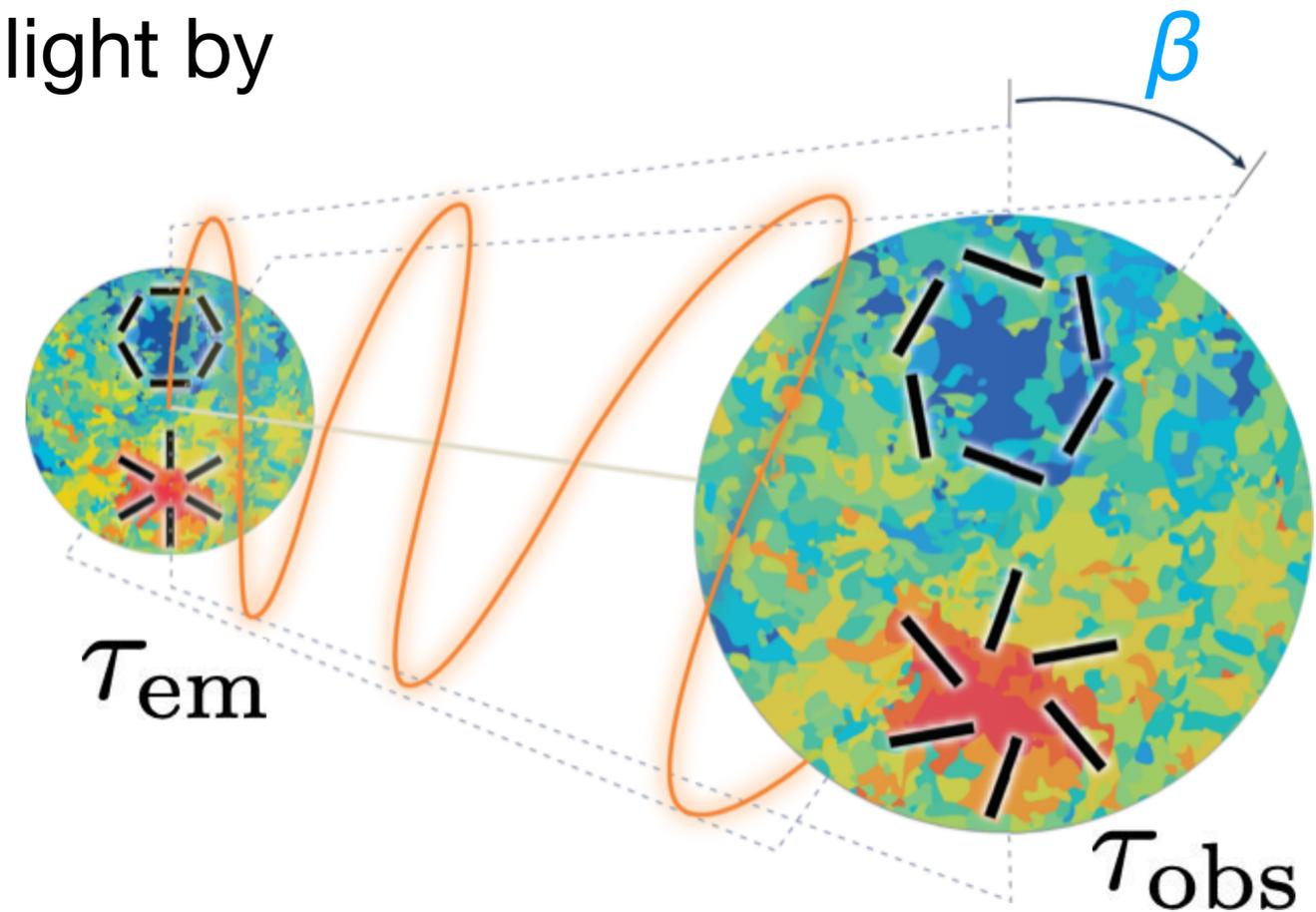
DM = Dark Matter; DE = Dark Energy

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

$$\begin{aligned} \beta &= - \int_{\tau_{\text{em}}}^{\tau_{\text{obs}}} d\tau (\omega_+ - \omega_-) \\ &= \frac{\alpha}{2f} [\chi(\tau_{\text{obs}}) - \chi(\tau_{\text{em}})] \end{aligned}$$



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

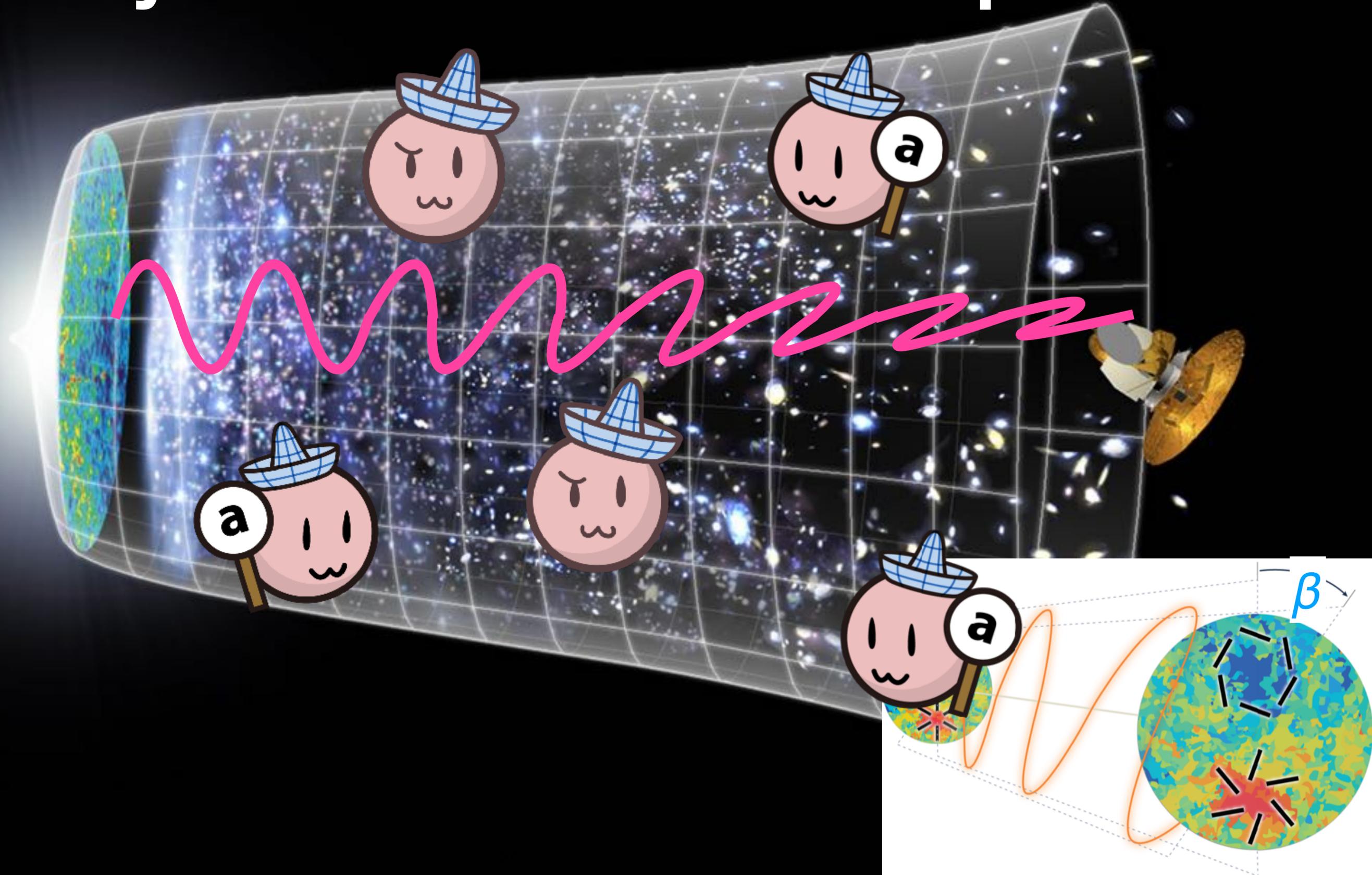
$$\Delta\chi = \chi(\tau_{\text{obs}}) - \chi(\tau_{\text{em}}) \simeq \frac{10^{-2}}{\alpha} f$$

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.



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.**
 - **4 σ 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.**

