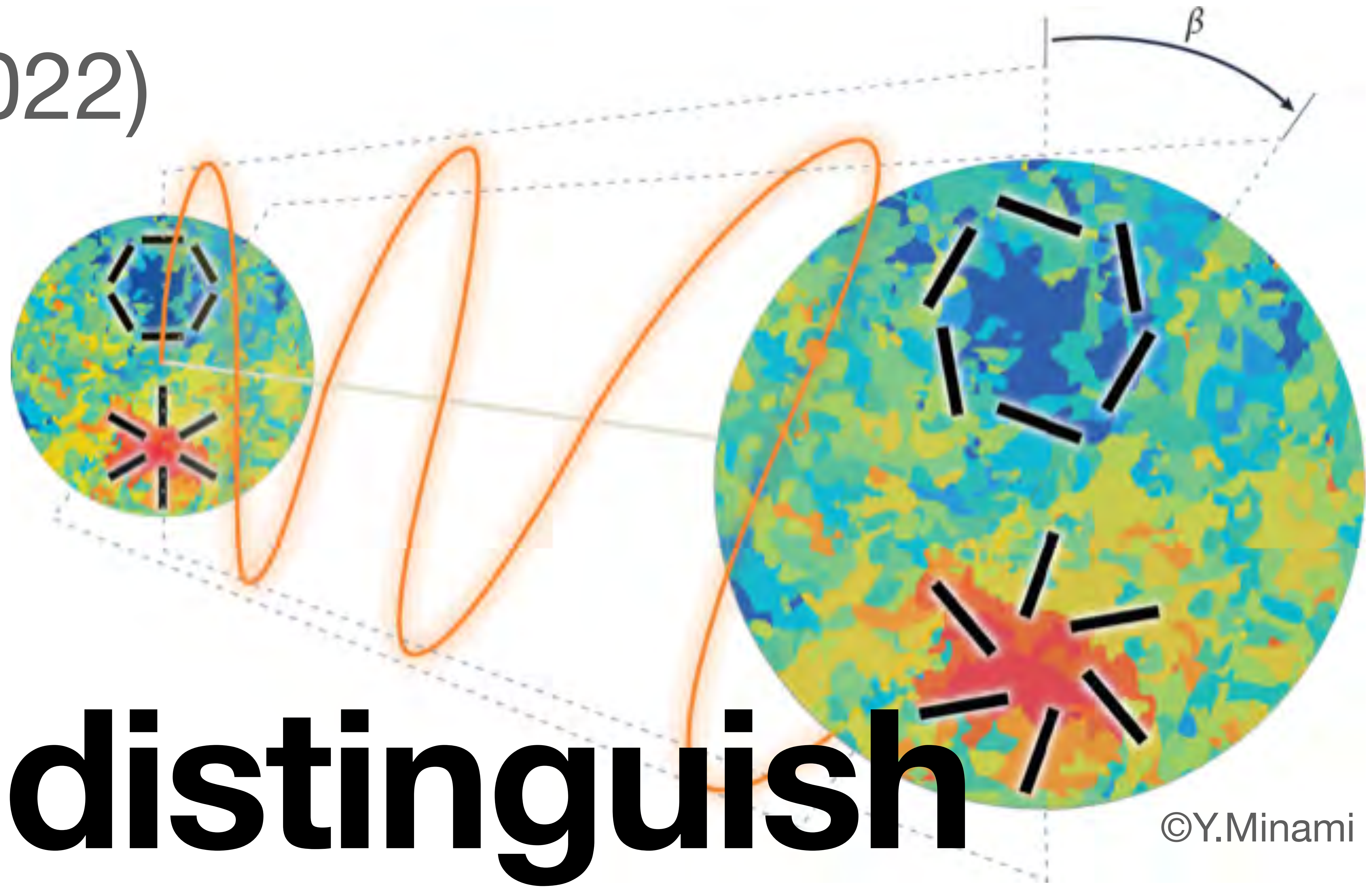
Reference: EK, Nature Rev. Phys. **4**, 452 (2022)



©Y.Minami

Does the Universe distinguish between left and right?

A Tantalizing Hint of Cosmological Parity Violation

Eiichiro Komatsu (Max Planck Institute for Astrophysics)
"From Inflation to Dark Energy", YITP, May 21, 2026

MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

Guys, great to see you all!

Princeton, Jan. 31, 1999

Philadelphia, Jan. 5, 2002

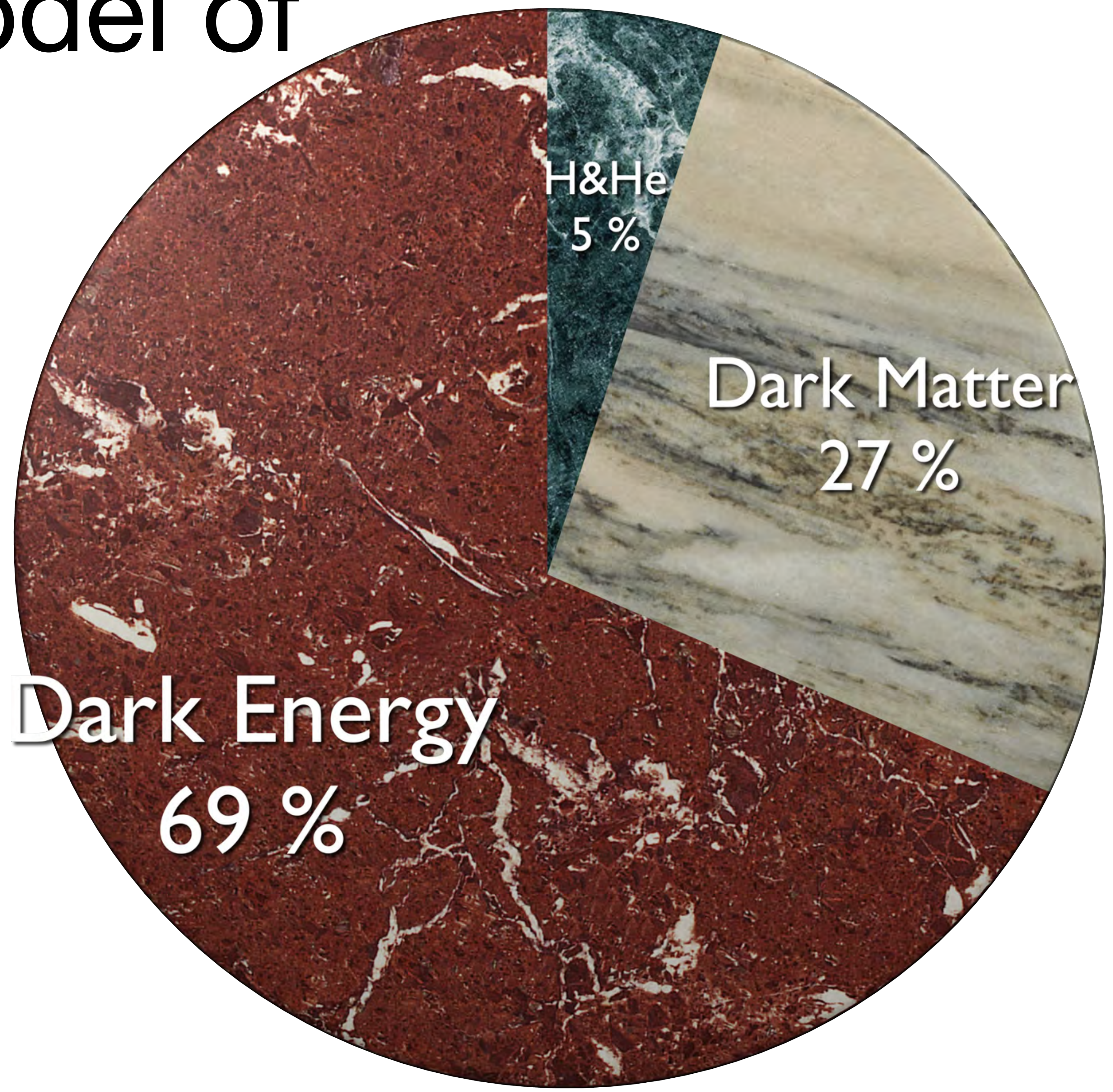
We were young and stupid ;)

Wait, maybe
we still are…?

Overarching Goal: Find New Physics

The physical nature of dark energy and dark matter

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



<u>New in cosmology!</u>

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

Overarching Goal: Find New Physics

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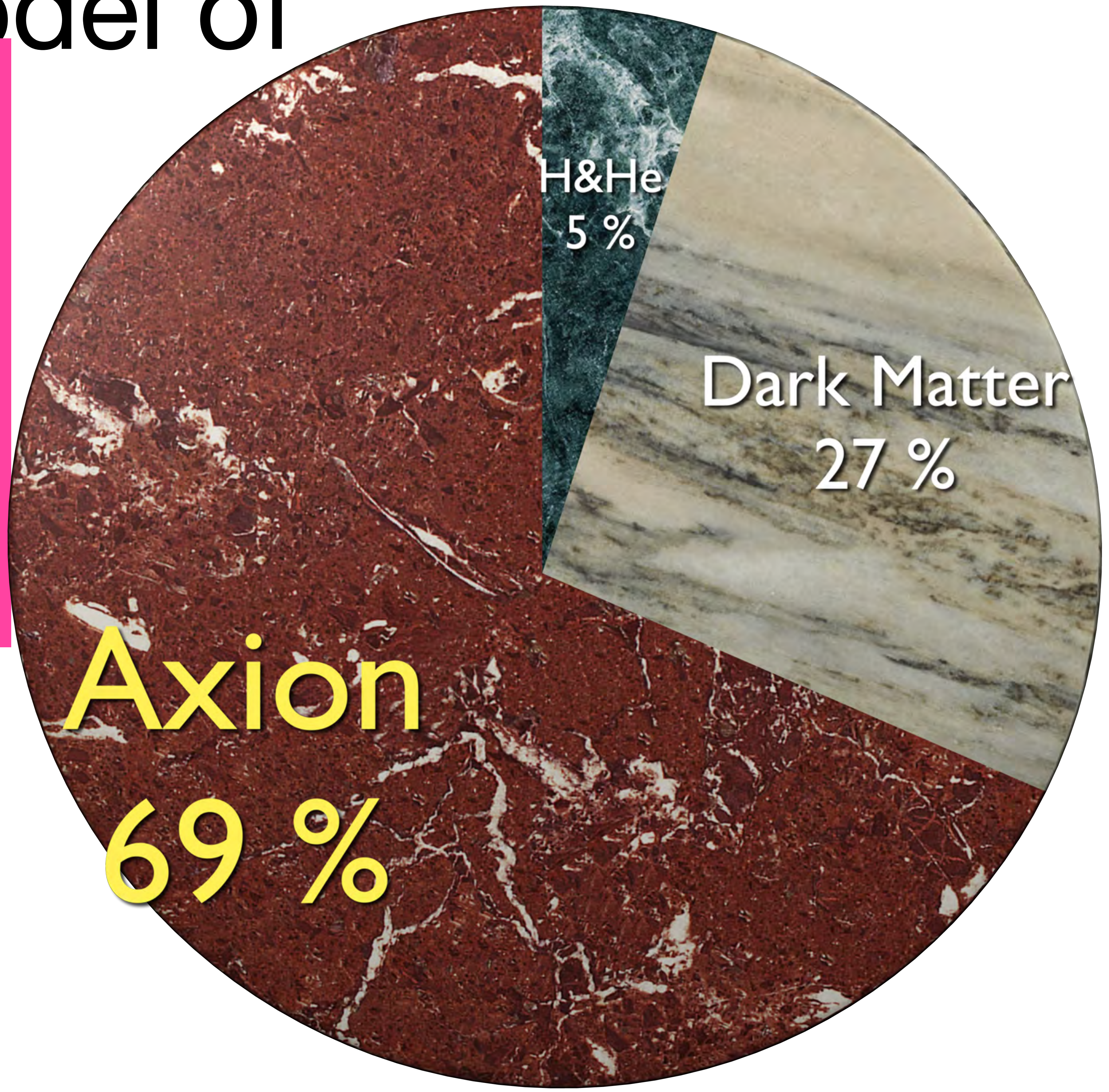
  - What is dark matter

It would be wonderful to give it a name, instead of calling it “dark something”.



New in cosmology!

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The physical nature of dark energy and dark matter

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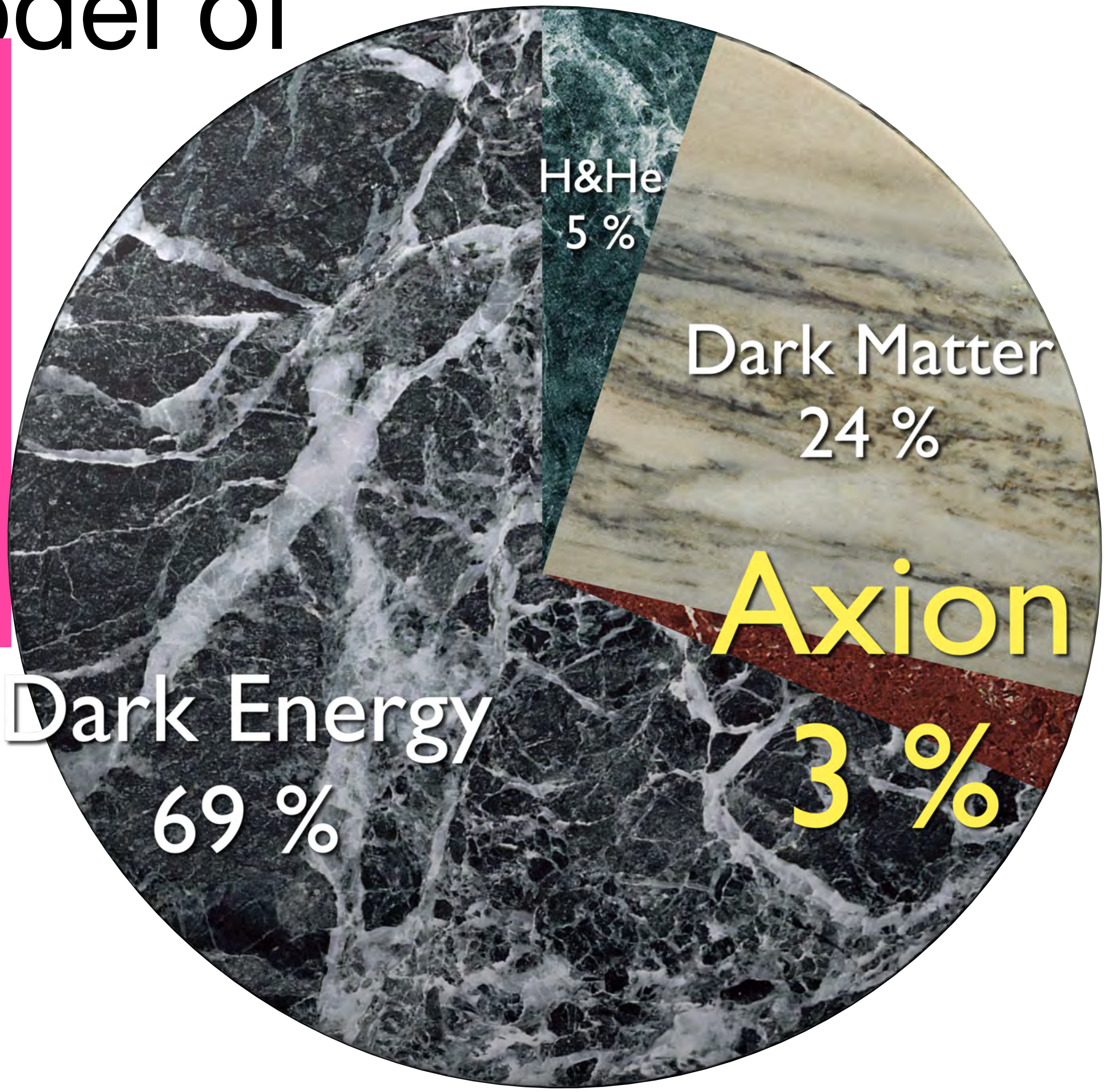

New in cosmology!

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

Part I: Known Physics

I.1 Parity

“Never underestimate the joy people derive from hearing something they already know.”

Enrico Fermi

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…
- We ask, "***When we observe a certain phenomenon in nature, do we also observe its mirror image with equal probability?***"

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

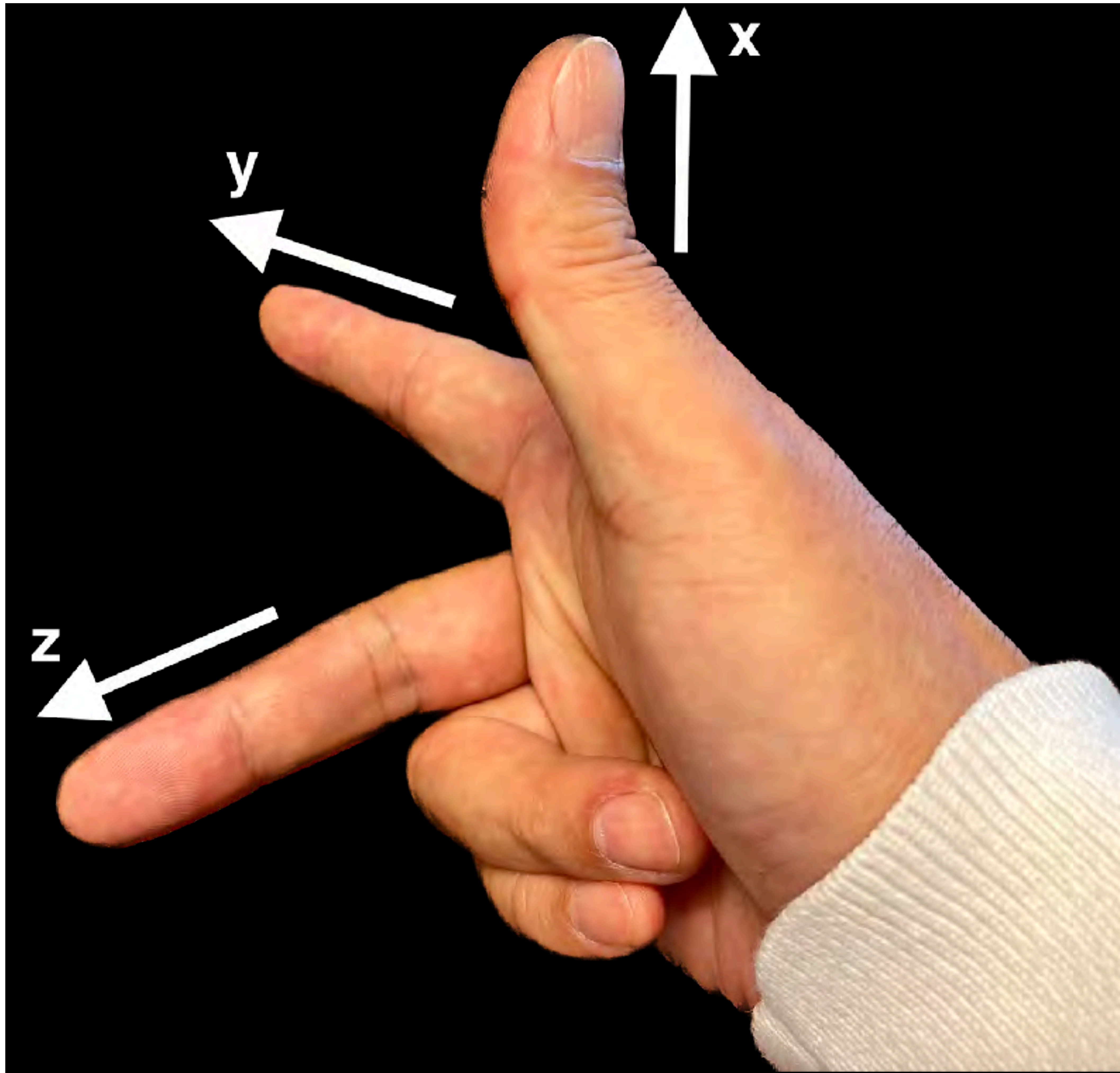
- Parity transformation (***x*** –> -***x***) and 3d rotation (***x*** –> R***x***) are different.
  - R is a continuous transformation and the determinant of R is det(R) = +1.
  - Parity is a discrete transformation and the **determinant is –1**, as

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

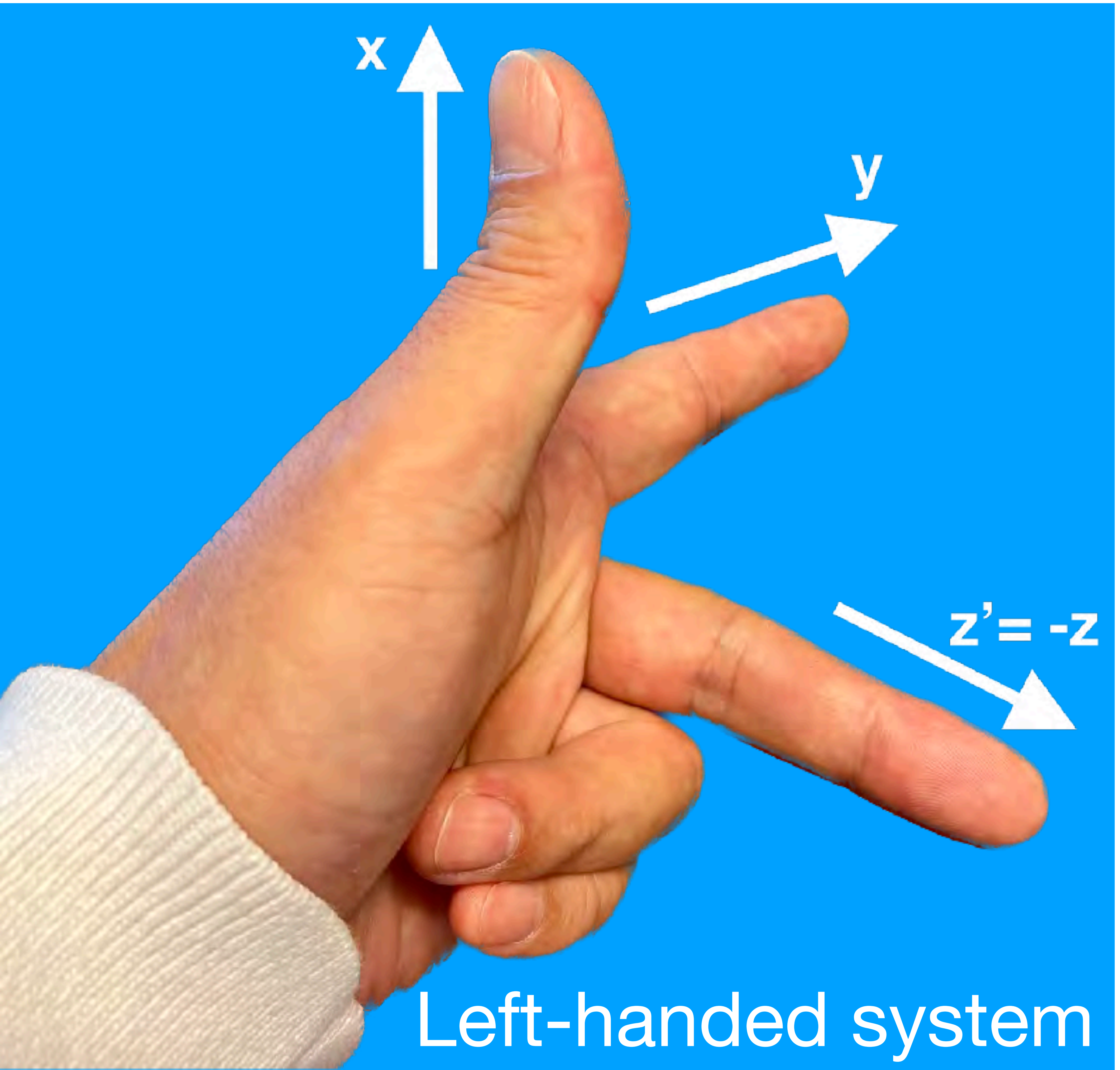
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

Parity = Mirror + 2d Rotation

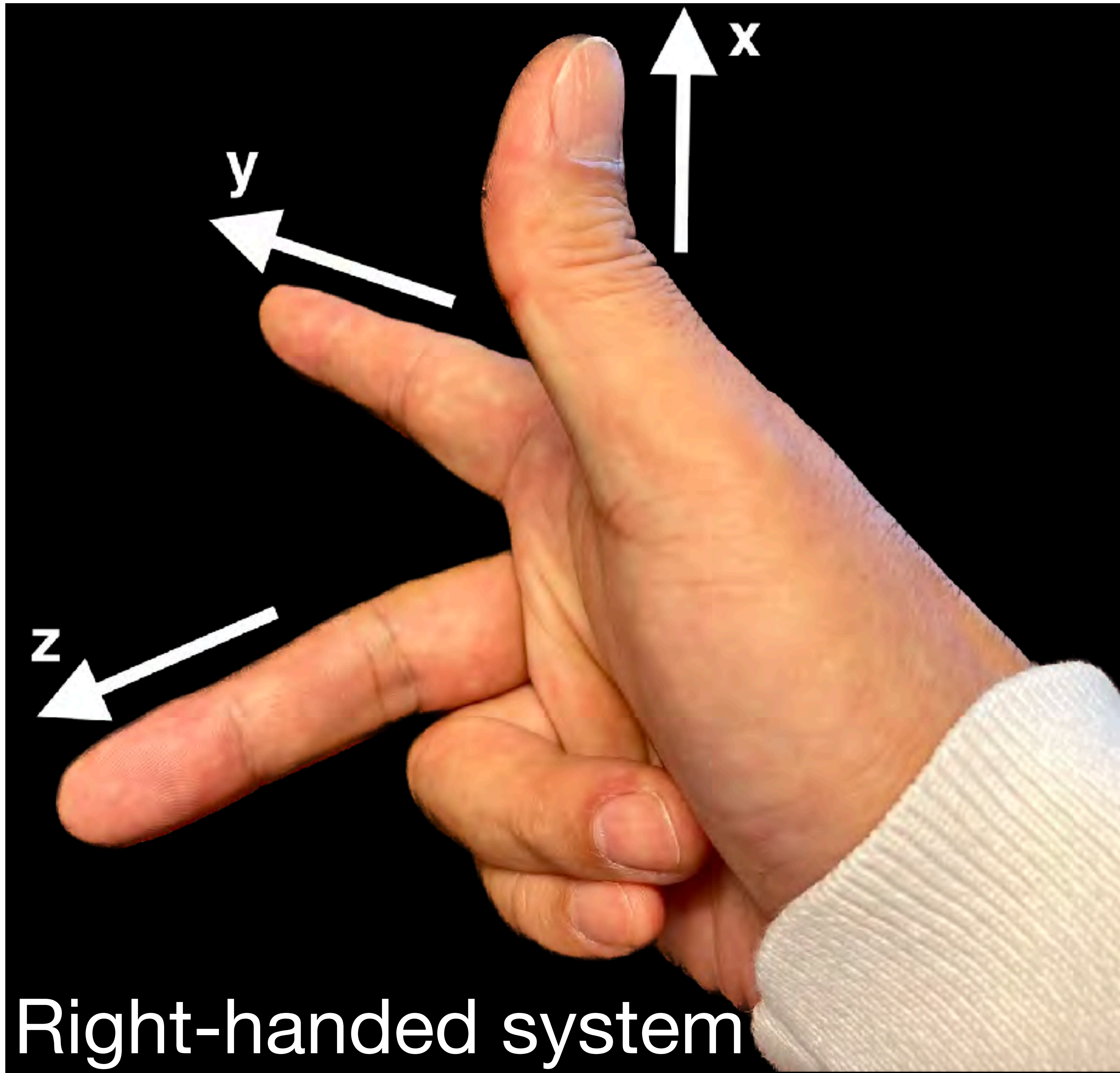
- One may think of parity transformation as a mirror in one of the coordinates (e.g., z –> -z) and **2d** rotation by π in the others.
- Let's demonstrate it!



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



z -> z’ = -z



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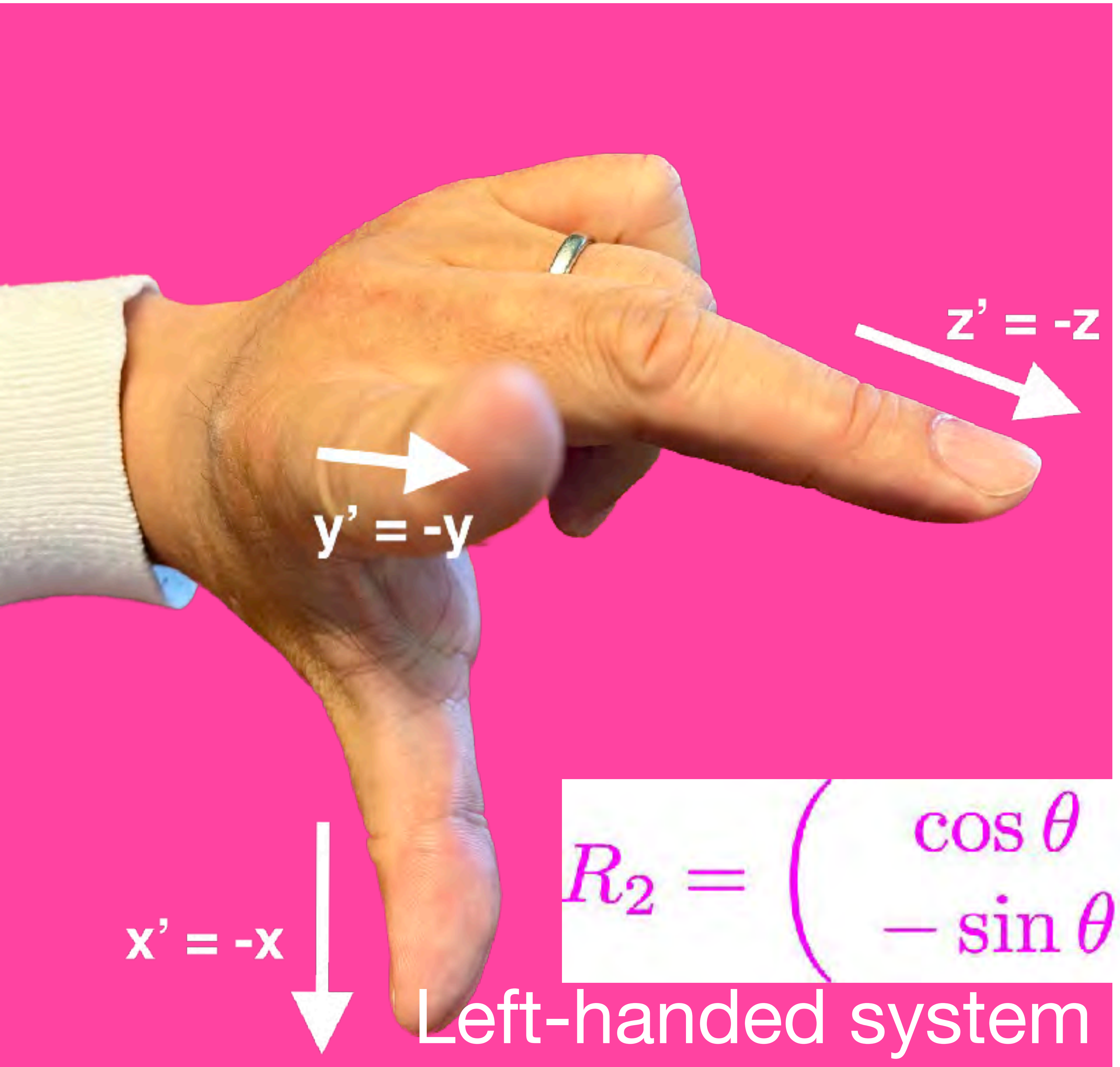
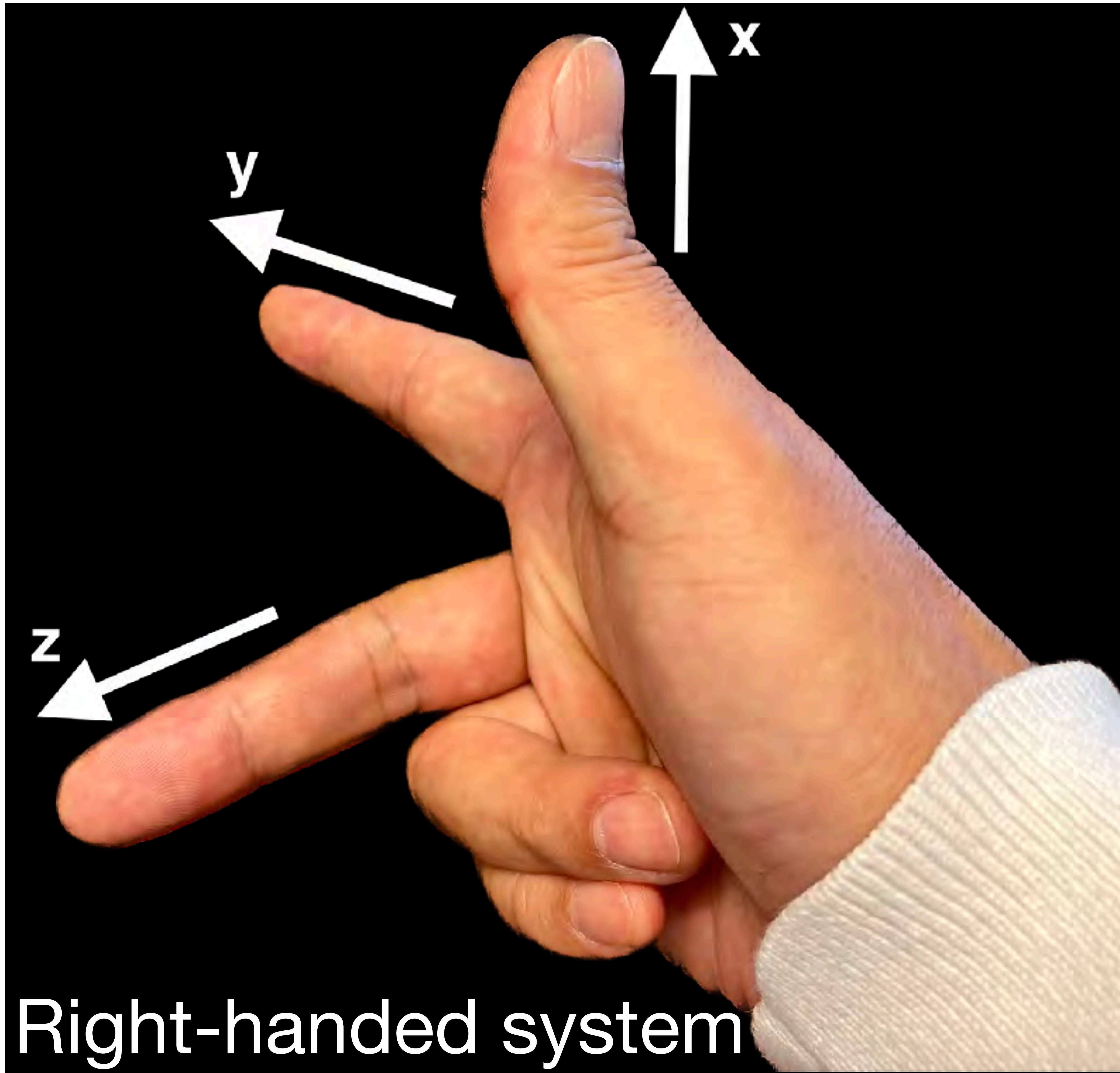


Rotation In x-y

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

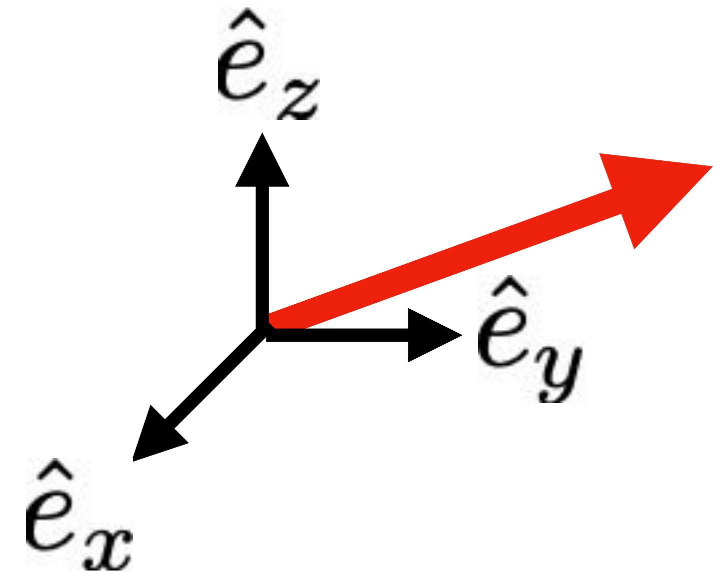
with θ = π



I.2 Pseudovector, Pseudoscalar

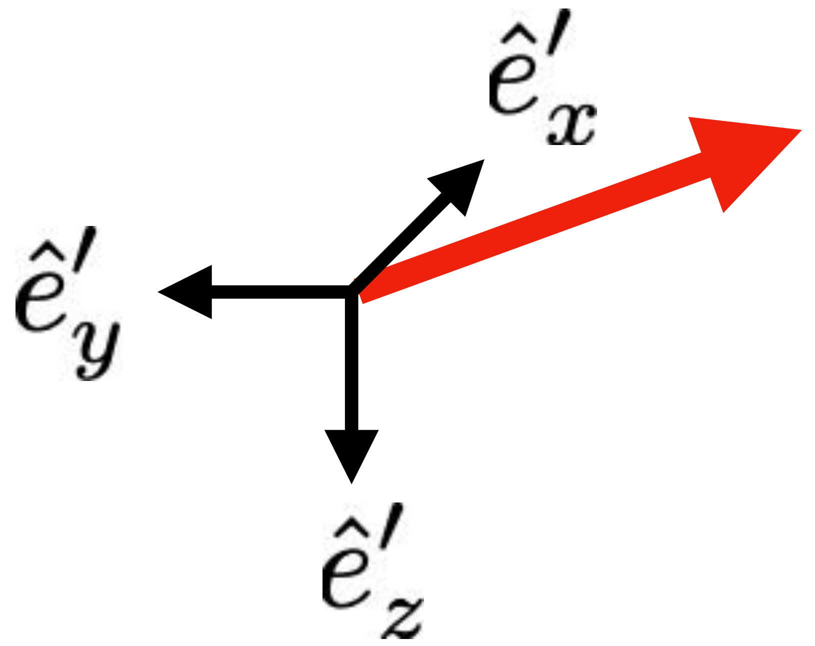
Parity Transformation: Vector

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.



$$\mathbf{p} = p'_x \hat{e}'_x + p'_y \hat{e}'_y + p'_z \hat{e}'_z$$
$$= -p'_x \hat{e}_x - p'_y \hat{e}_y - p'_z \hat{e}_z$$

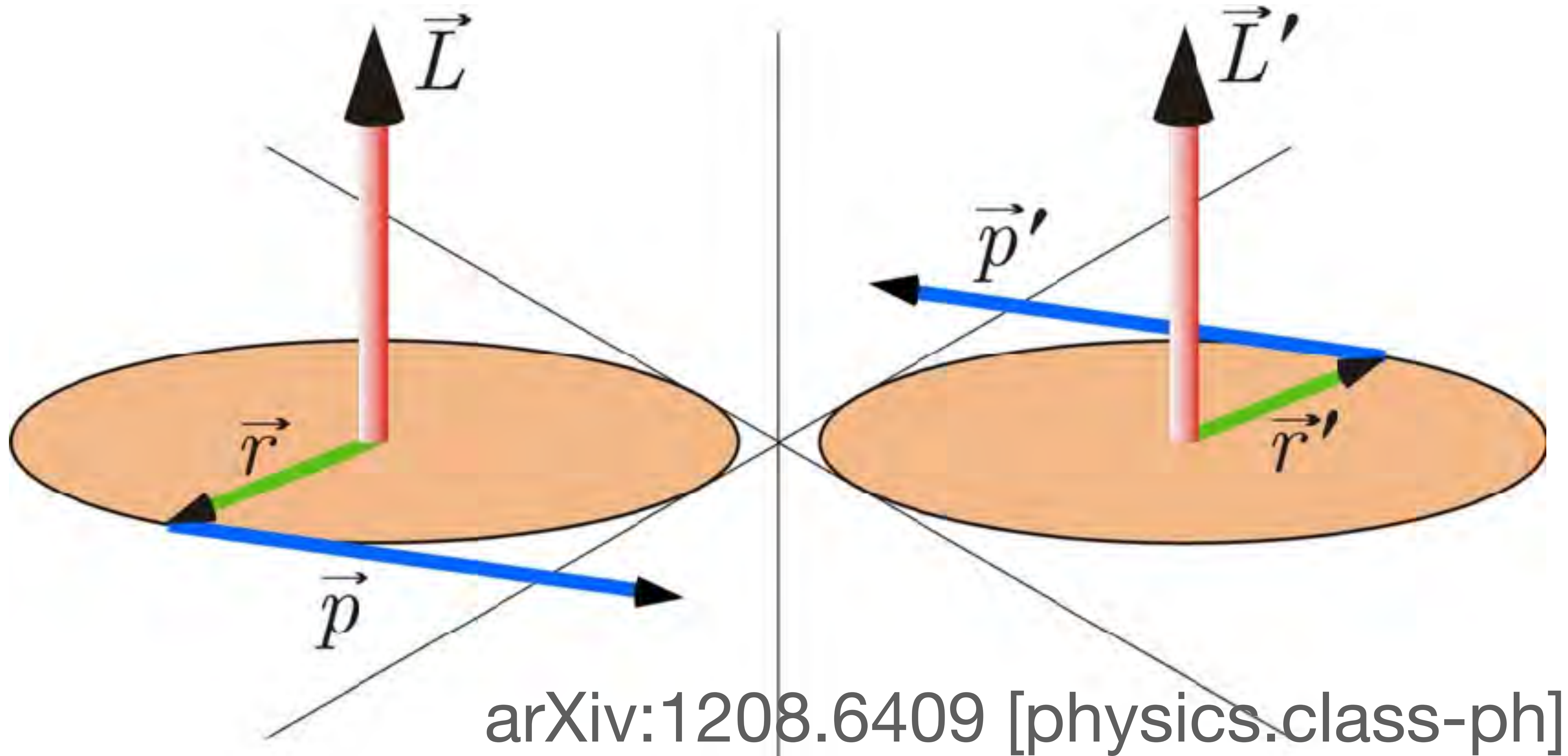
- **p** is the same vector, written using two different basis vectors.
- Therefore, **p**'s components are transformed as $(p'_x, p'_y, p'_z) = (-p_x, -p_y, -p_z)$

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

I.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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吳健雄

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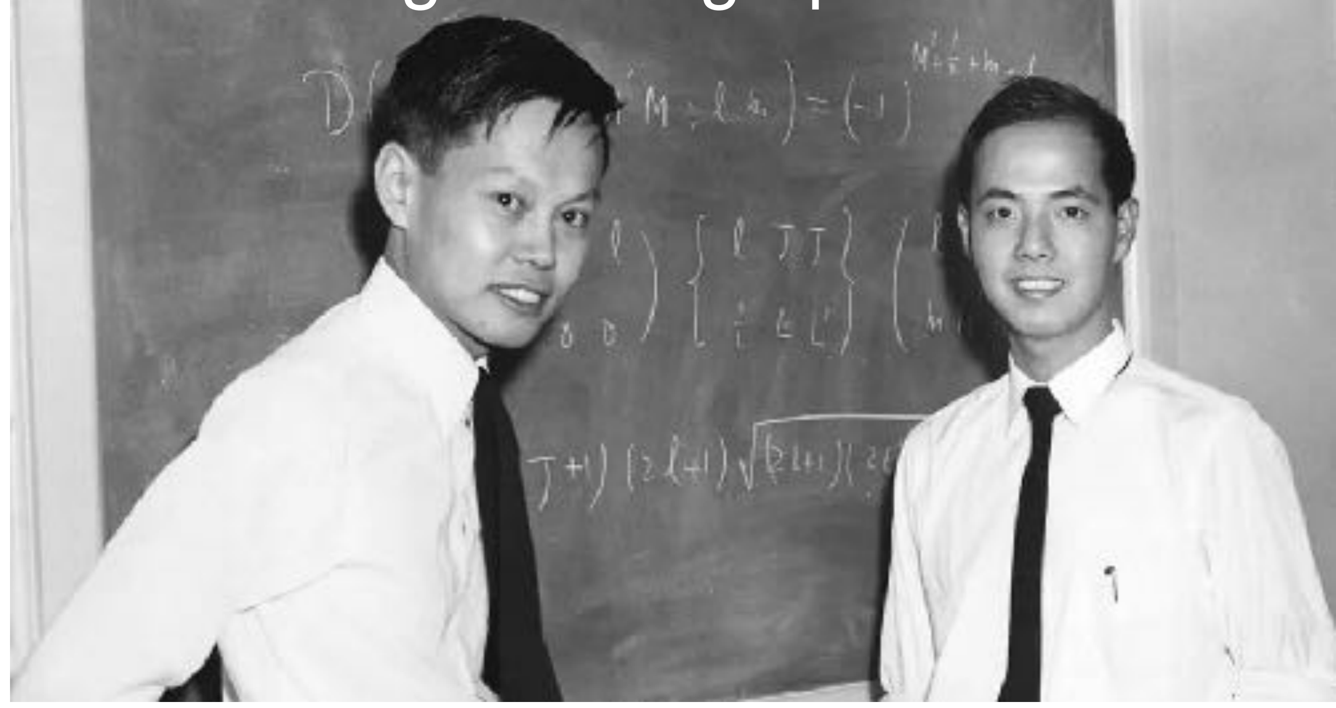

Yang Chen-Ning
楊振寧

Lee Tsung-Dao
李政道

Wu et al. (1957)

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: $\langle \mathbf{p}_\mathrm{e} \cdot \mathbf{J} \rangle \neq 0$. **Parity symmetry is violated in β-decay!**

Initial reaction

Many physicists did not believe it initially.

Bildarchiv der ETH-Bibliothek

- 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?*”

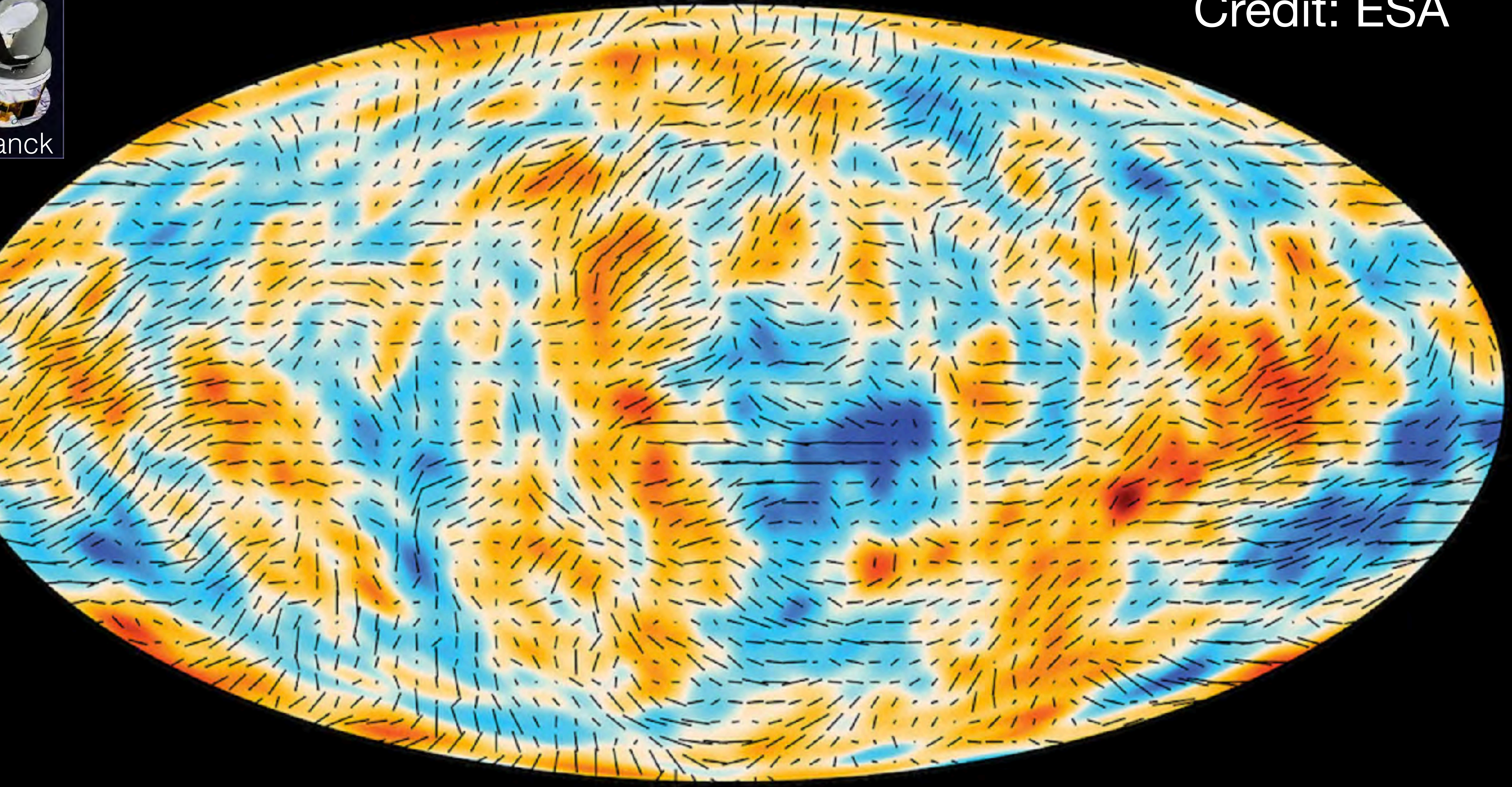
Part II: A Hint of New Physics

II.1 Parity Violation in the Cosmic Microwave Background (CMB)

Credit: ESA

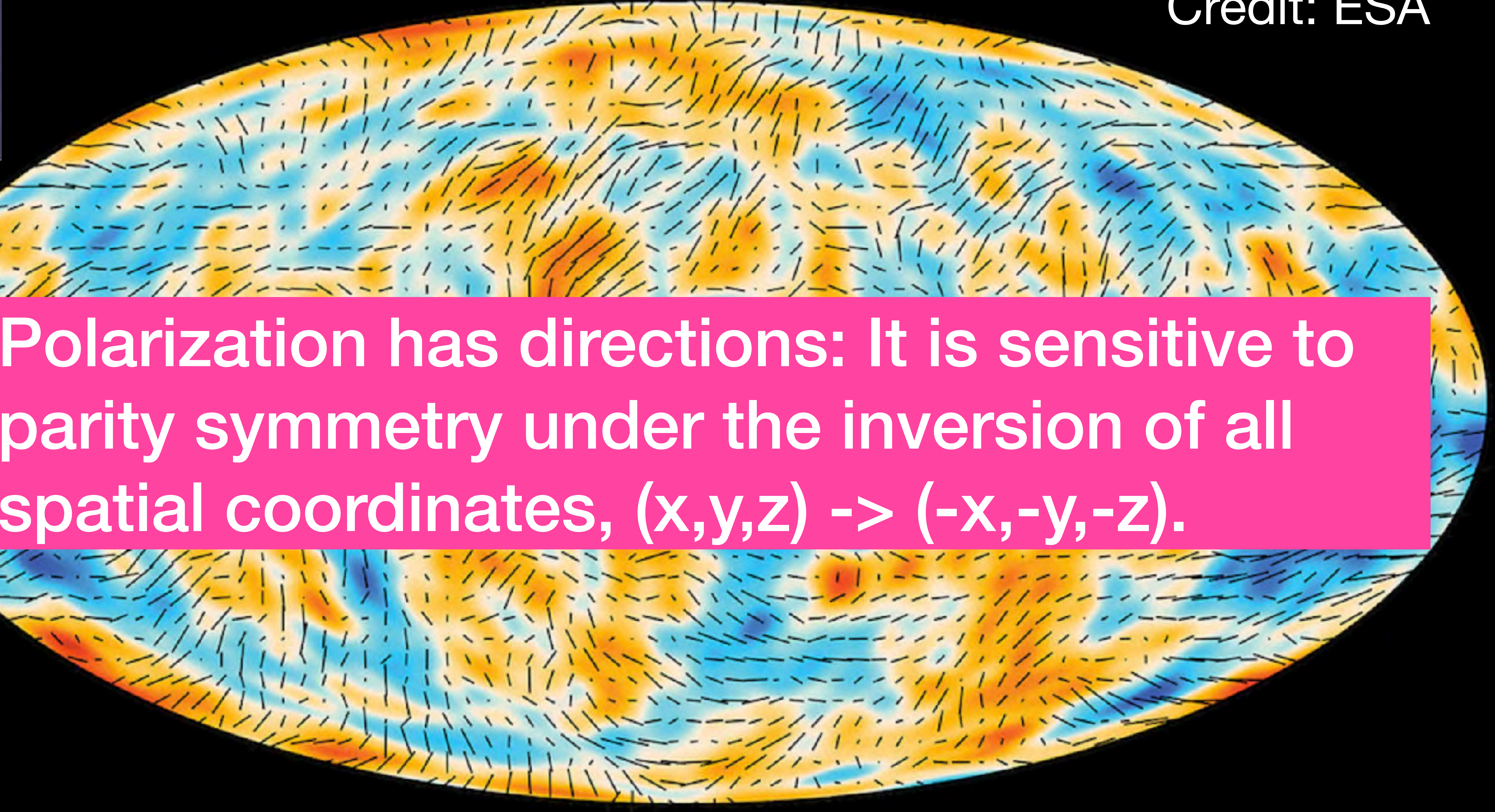
Observational Tool: Cosmic Microwave Background

Credit: ESA



Temperature (smoothed) + Polarisation

Credit: ESA



Polarization has directions: It is sensitive to parity symmetry under the inversion of all spatial coordinates, (x,y,z) -> (-x,-y,-z).

Temperature (smoothed) + Polarisation

Key Point

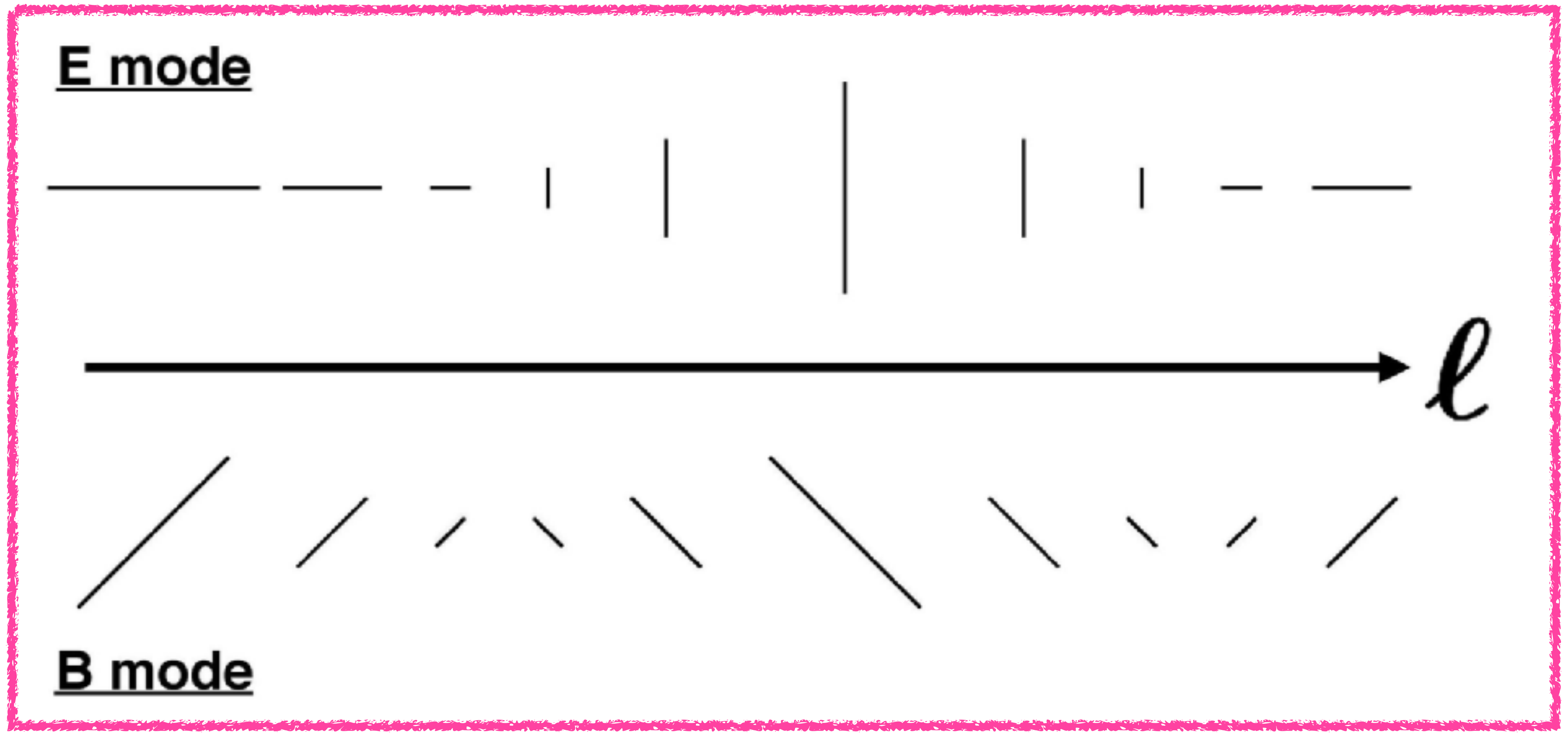
Pseudoscalar: EB correlation

- 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!**

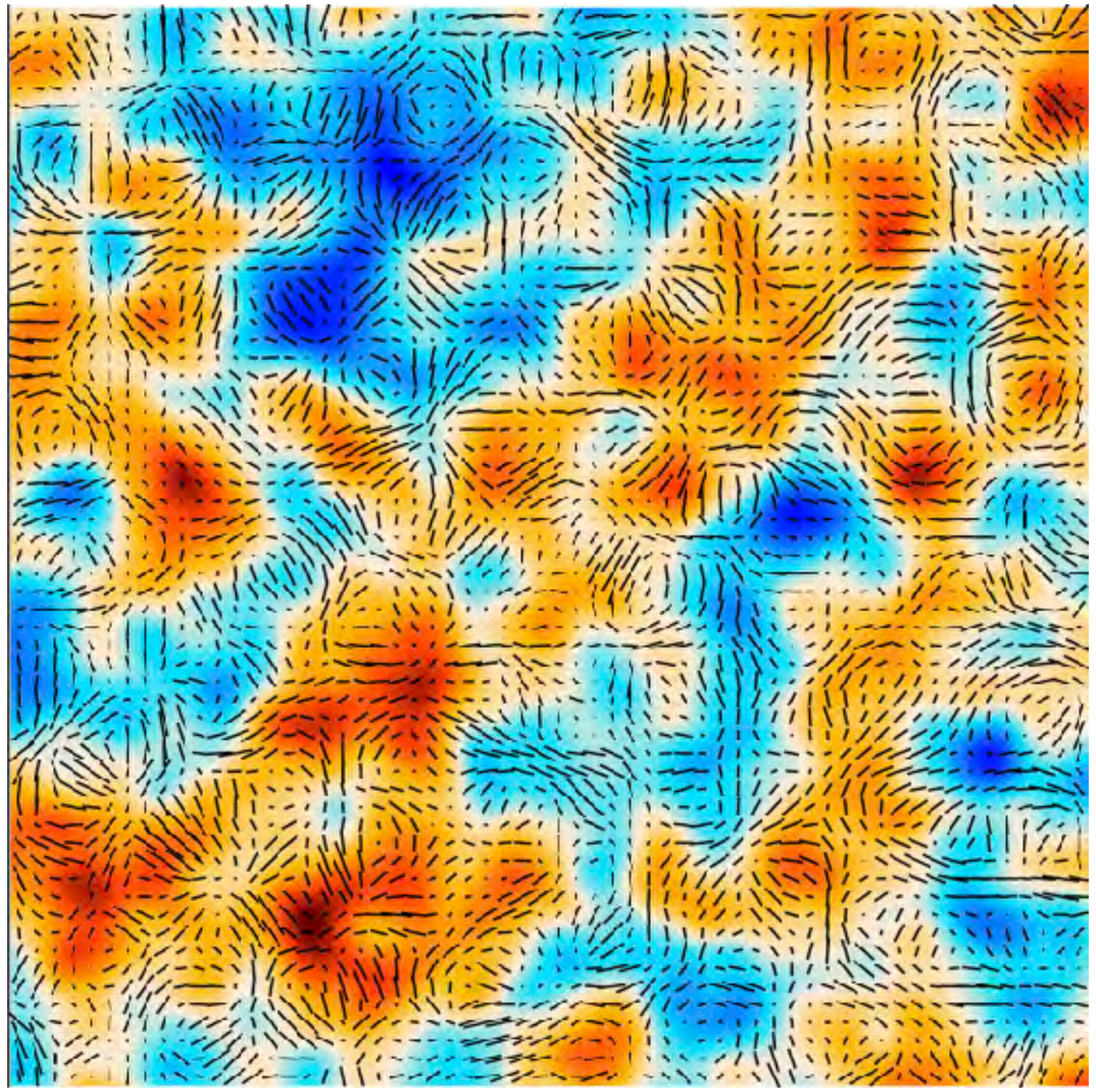
Zaldarriaga, Seljak (1997); Kamionkowski, Kosowsky, Stebbins (1997)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



- **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)

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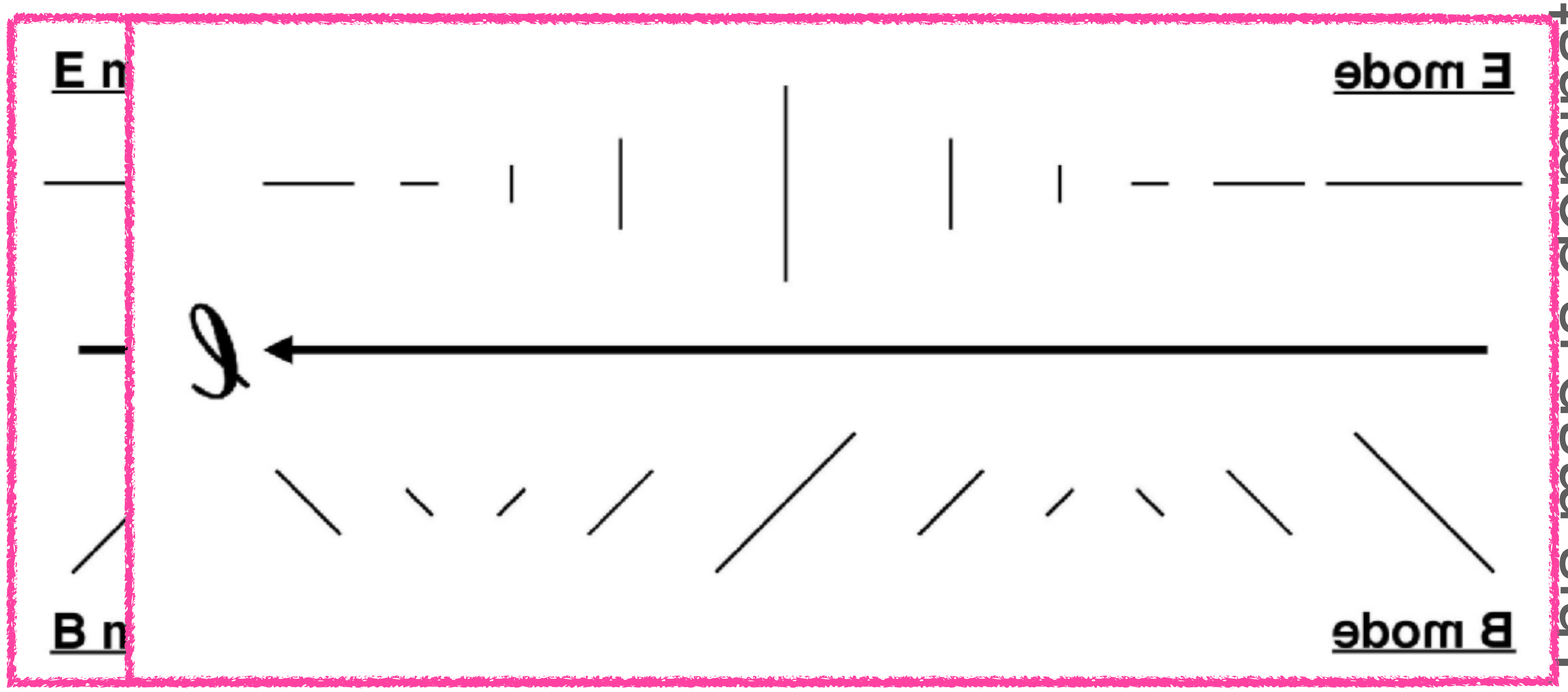

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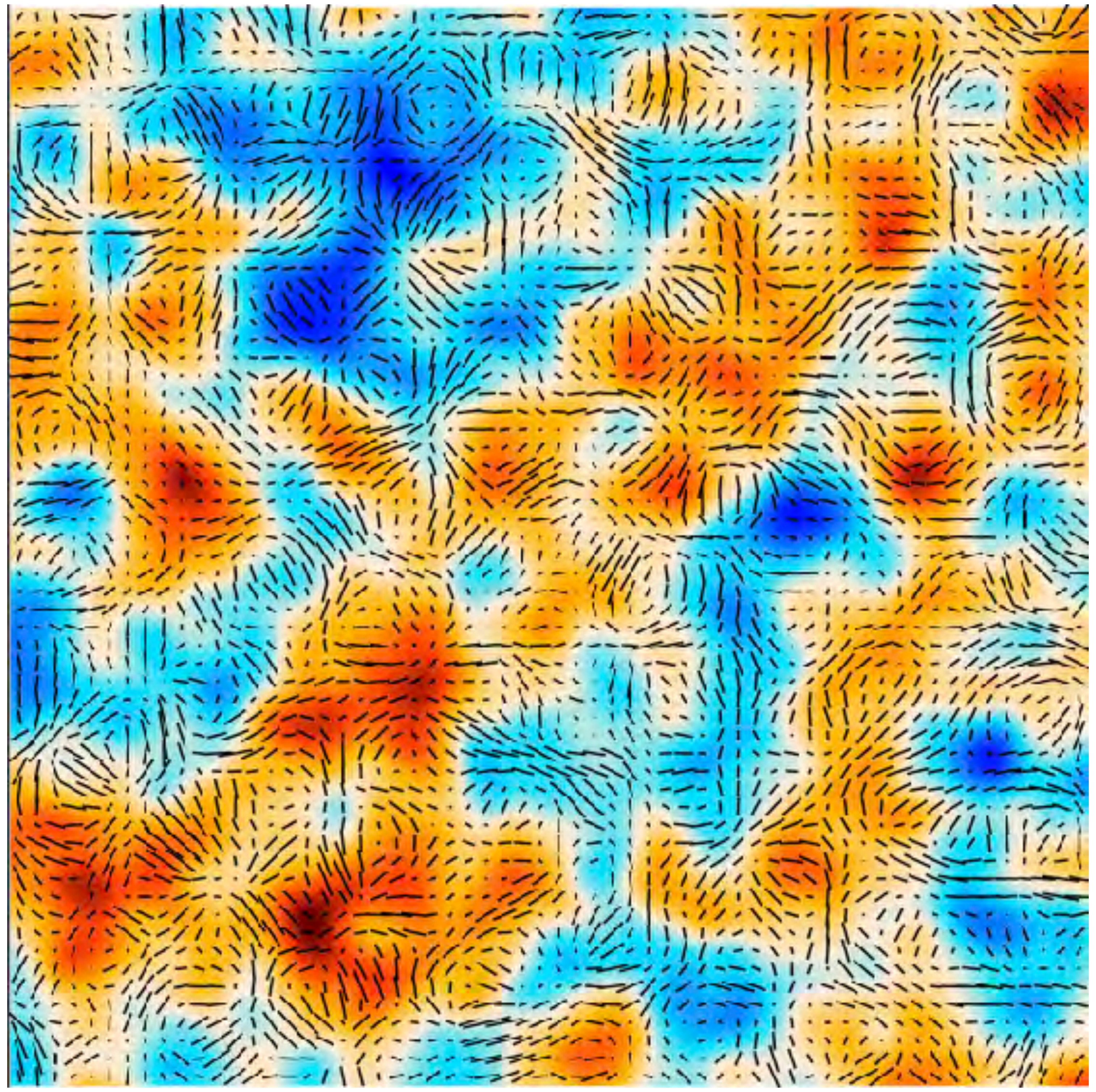

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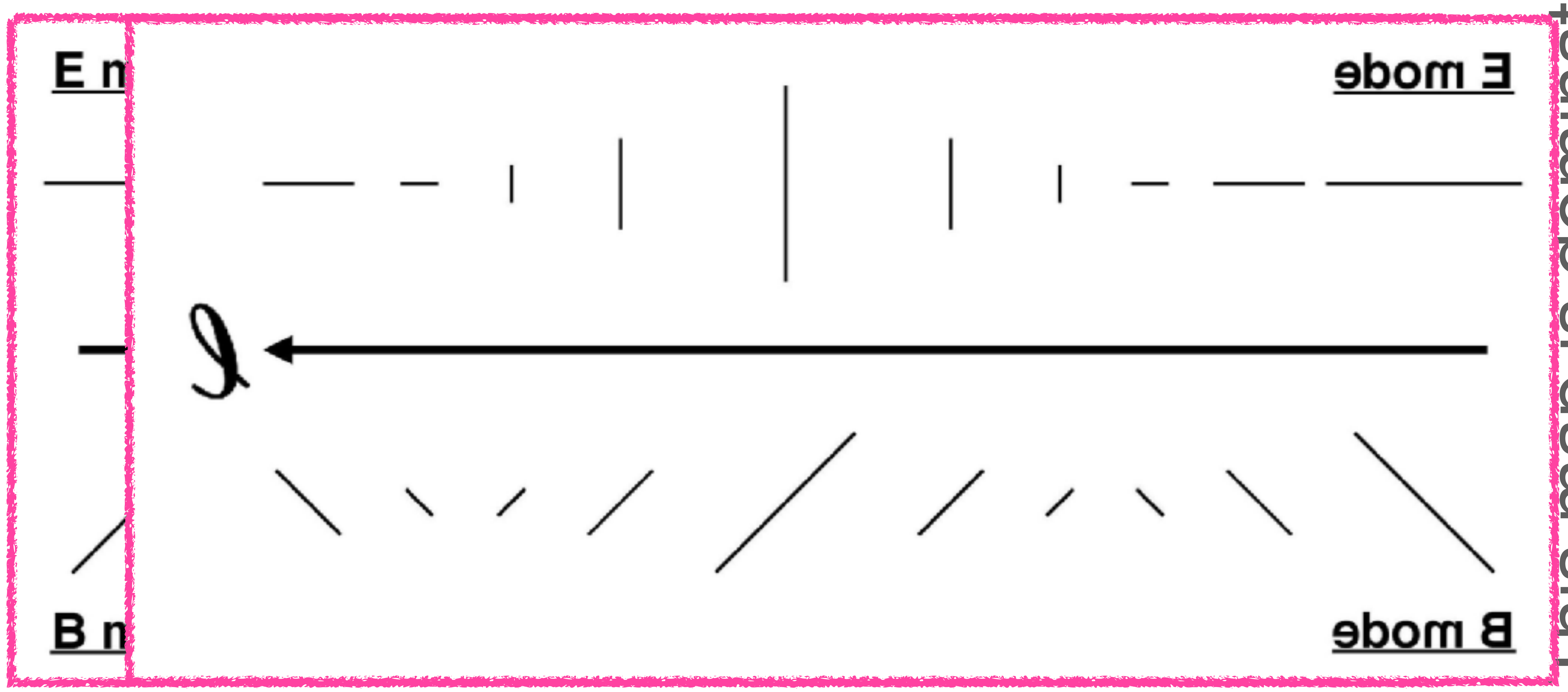
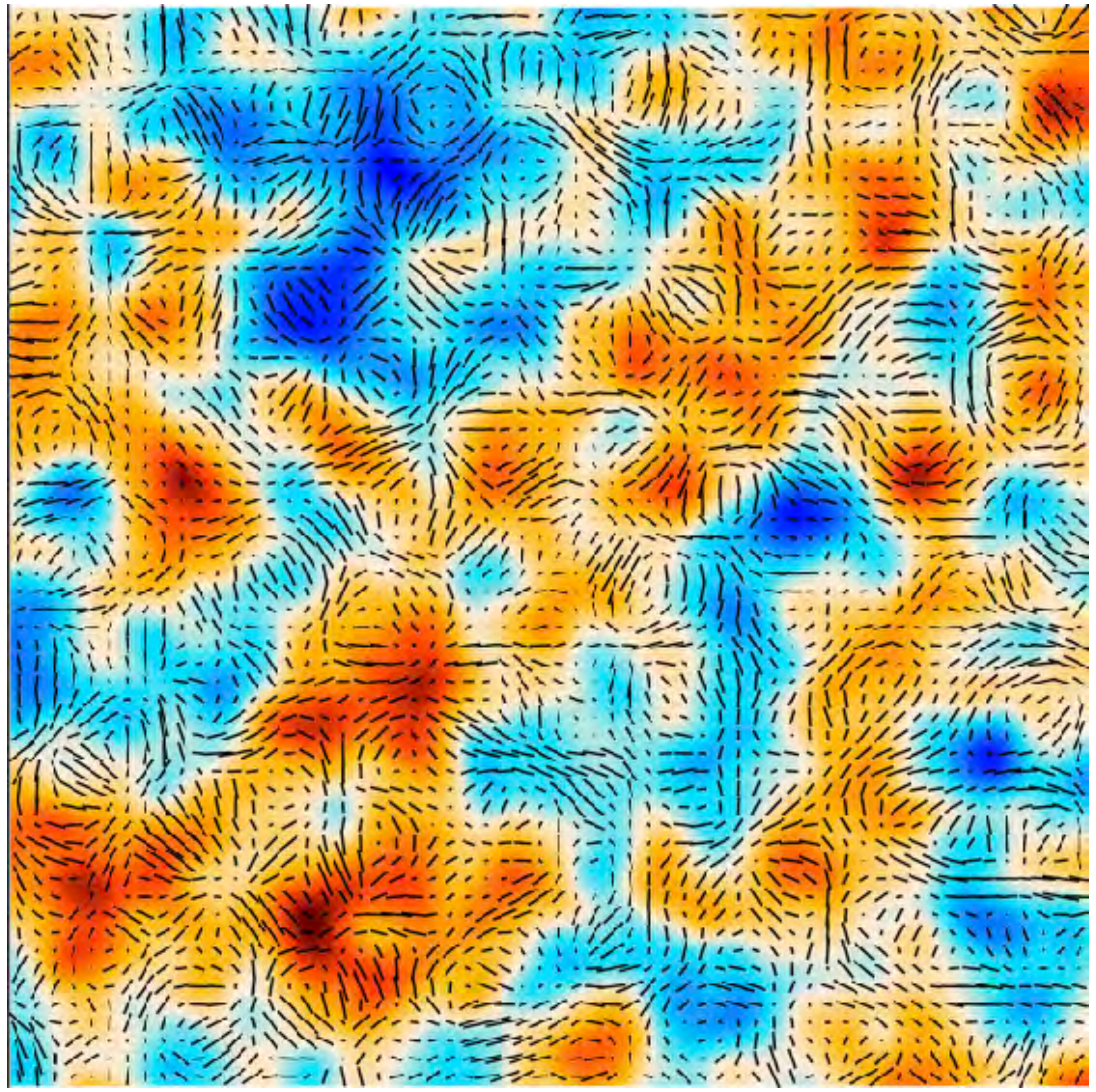


This map is dominated by E-mode polarization



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

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

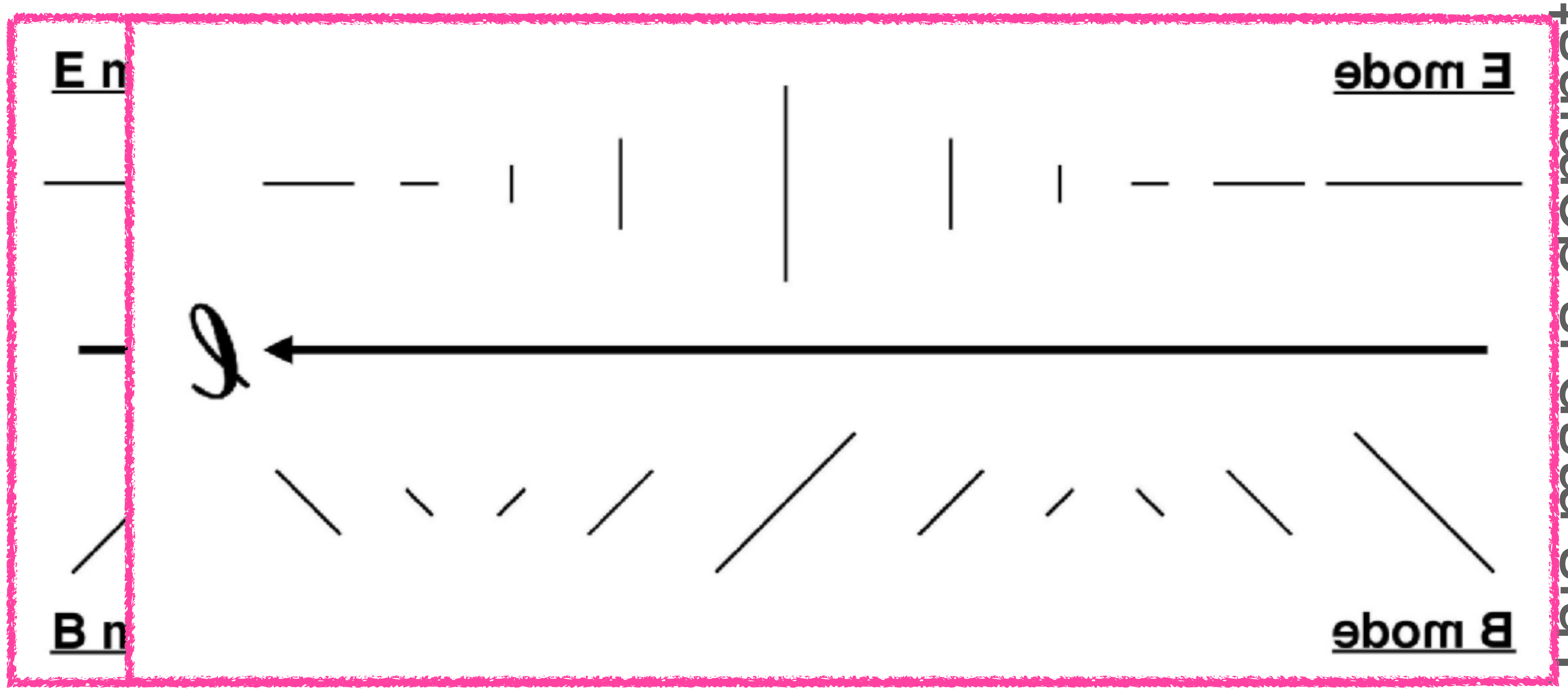
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

These are scalars and insensitive to parity violation.

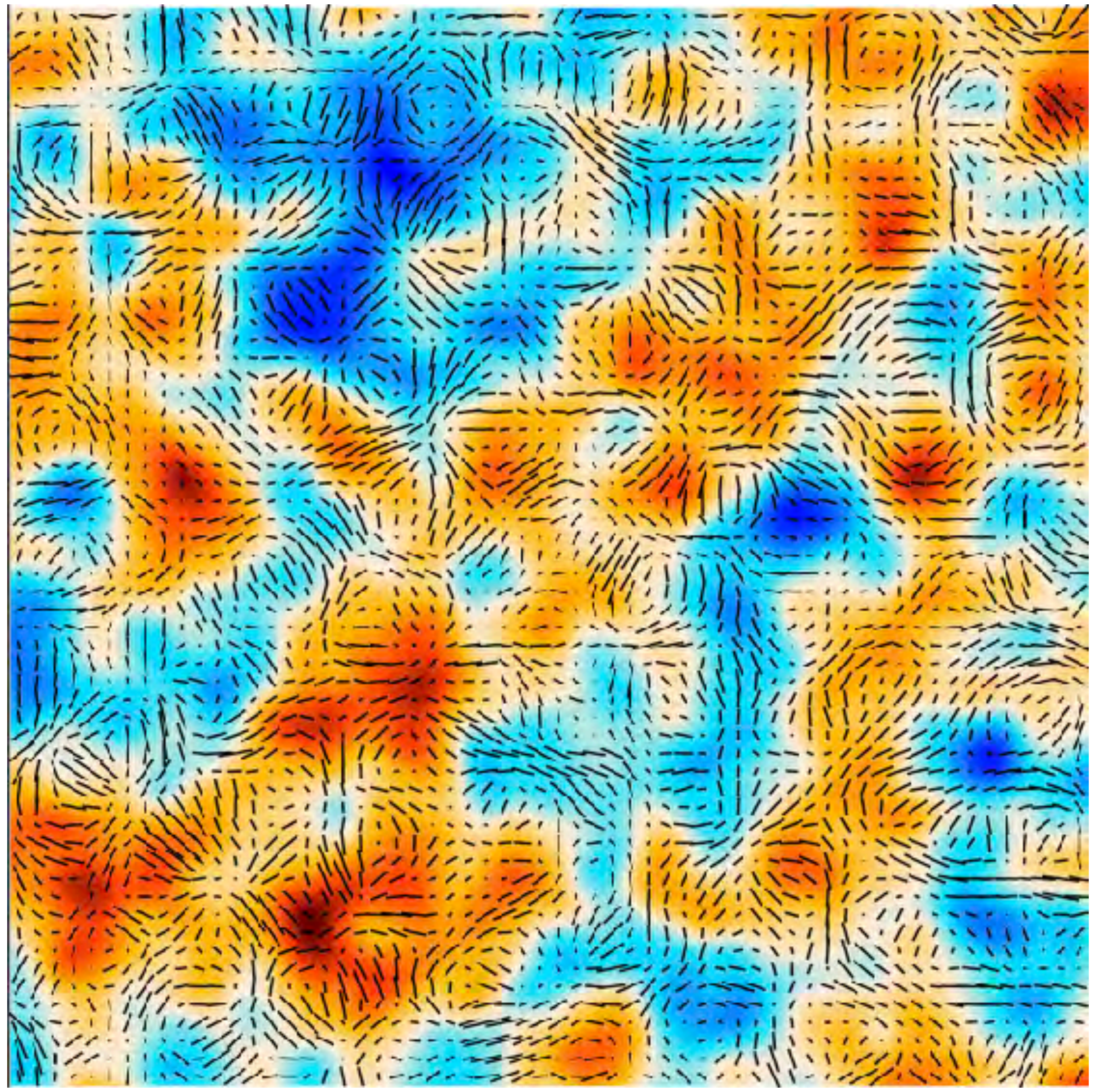
Lue, Wang, Kamionkowski (1999); Feng et al. (2005, 2006)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

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

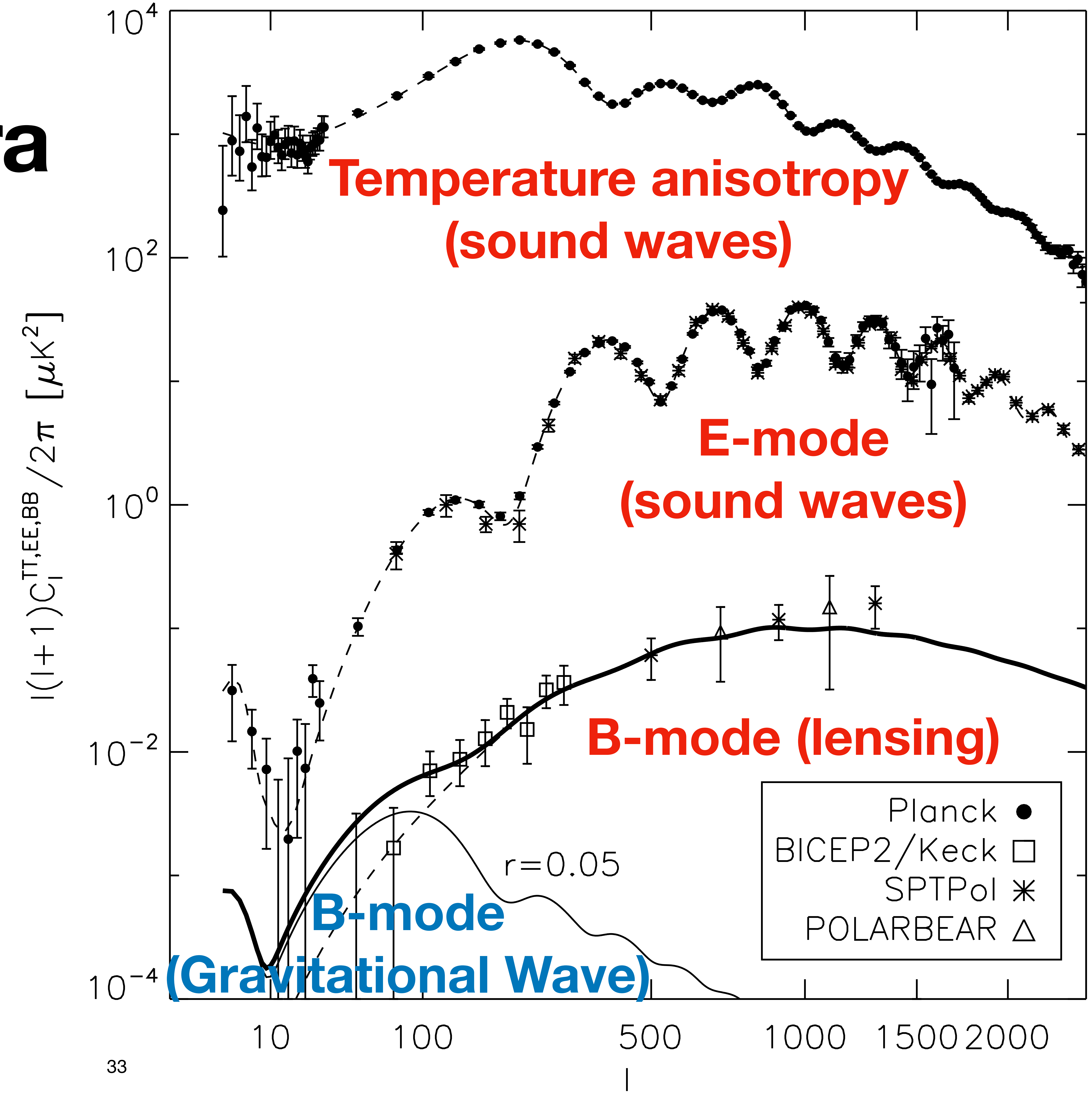
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'}\rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'}\rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell}-\boldsymbol{\ell}')C_\ell^{TE}$$

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

CMB Power Spectra

Progress over 30 years

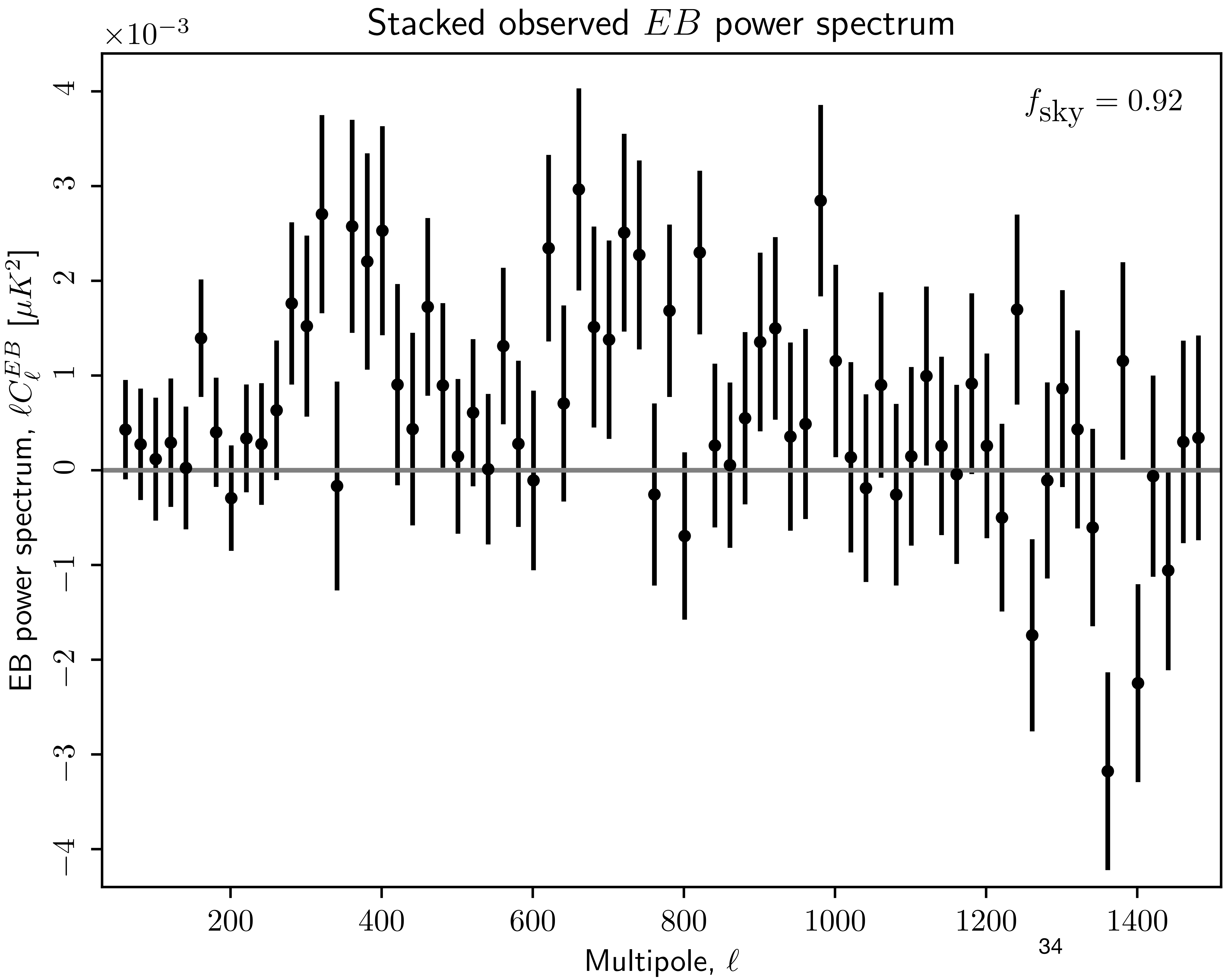
- This is the typical figure seen in talks and lectures on the CMB.
  - The temperature and the E- and B-mode polarization power spectra are well measured.
- **Parity violation appears in the TB and EB power spectra, not shown here.**

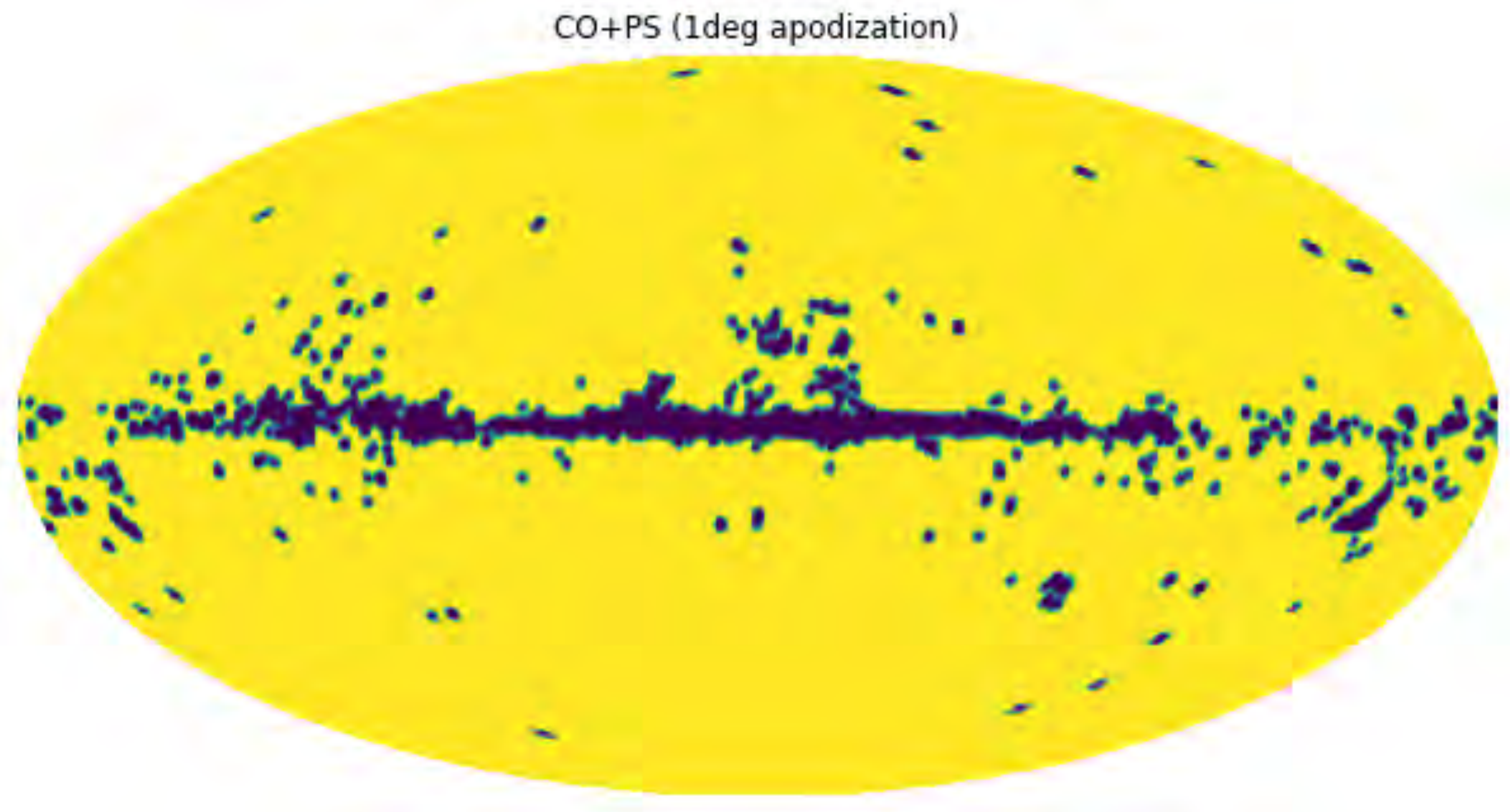


Eskilt, EK (2022)

This is the EB power spectrum (WMAP+Planck)

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

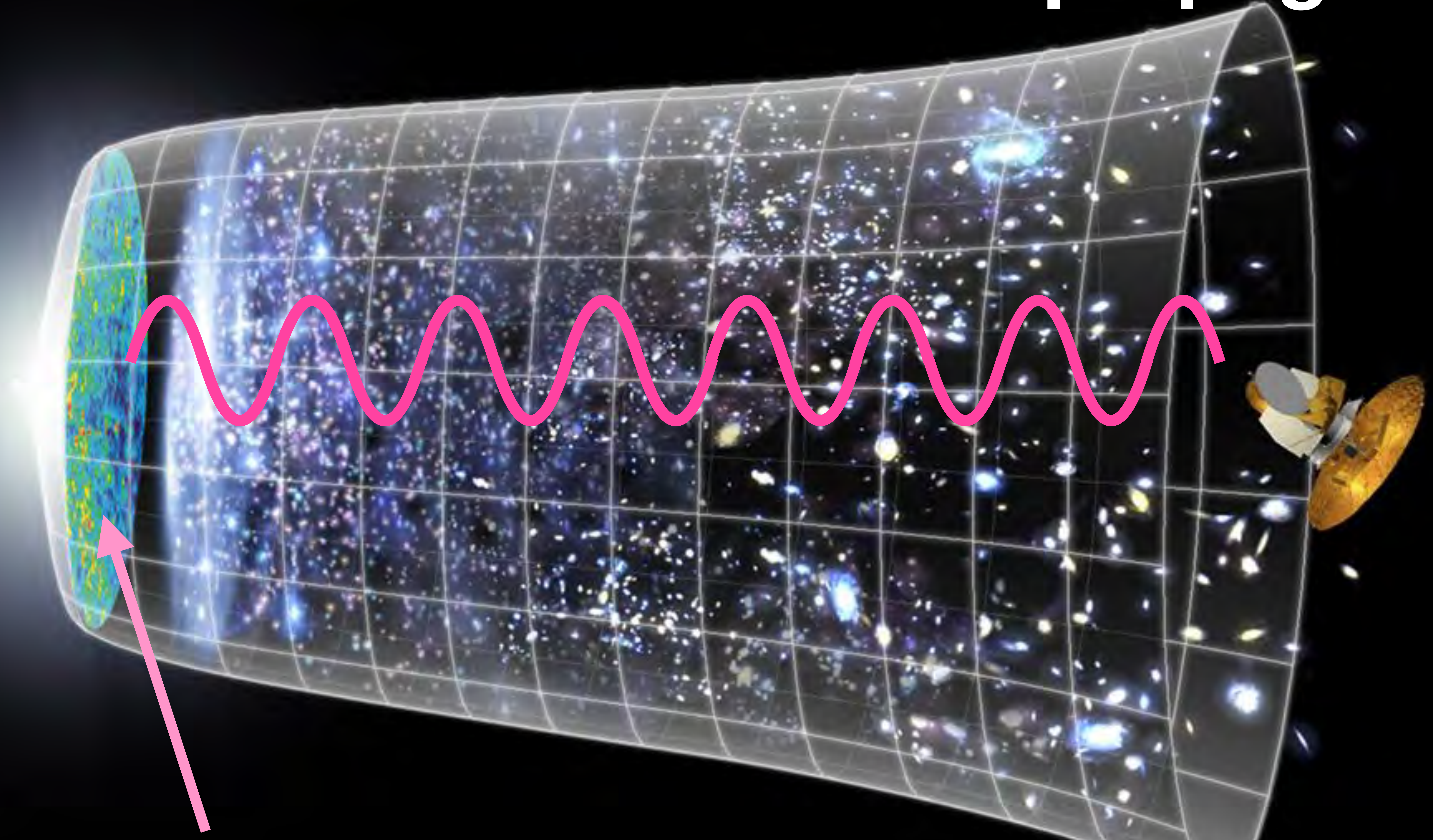




- $\chi^2 = 125.5$ for DOF=72
  - Unambiguous signal of something!

II.2: Cosmic Birefringence

How does the EM wave of the CMB propagate?

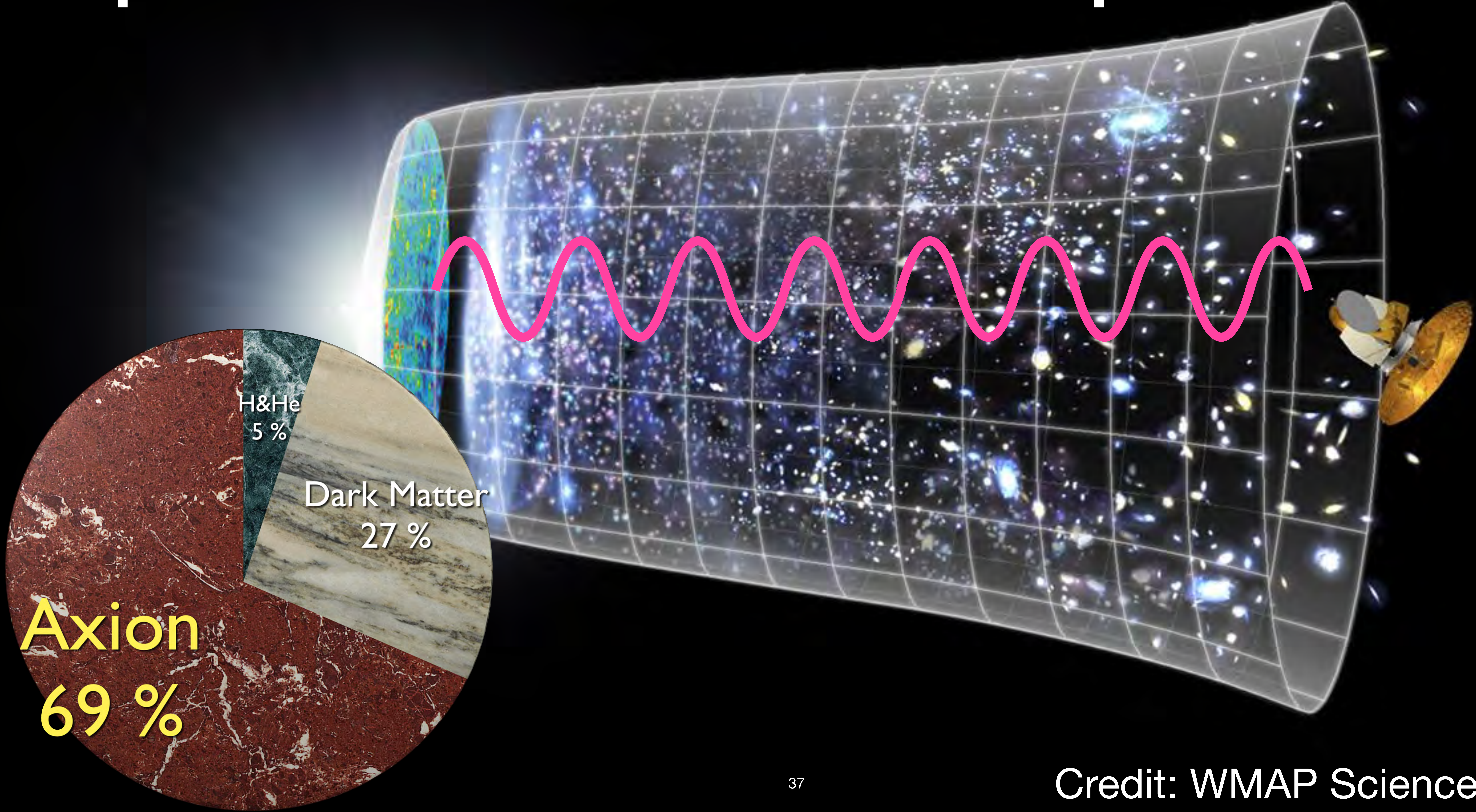


The surface of “last scattering” by electrons

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

Credit: WMAP Science Team

If space were filled with axionlike particles…



Credit: WMAP Science Team

then, the CMB polarization plane would be rotated!

Credit: ESA

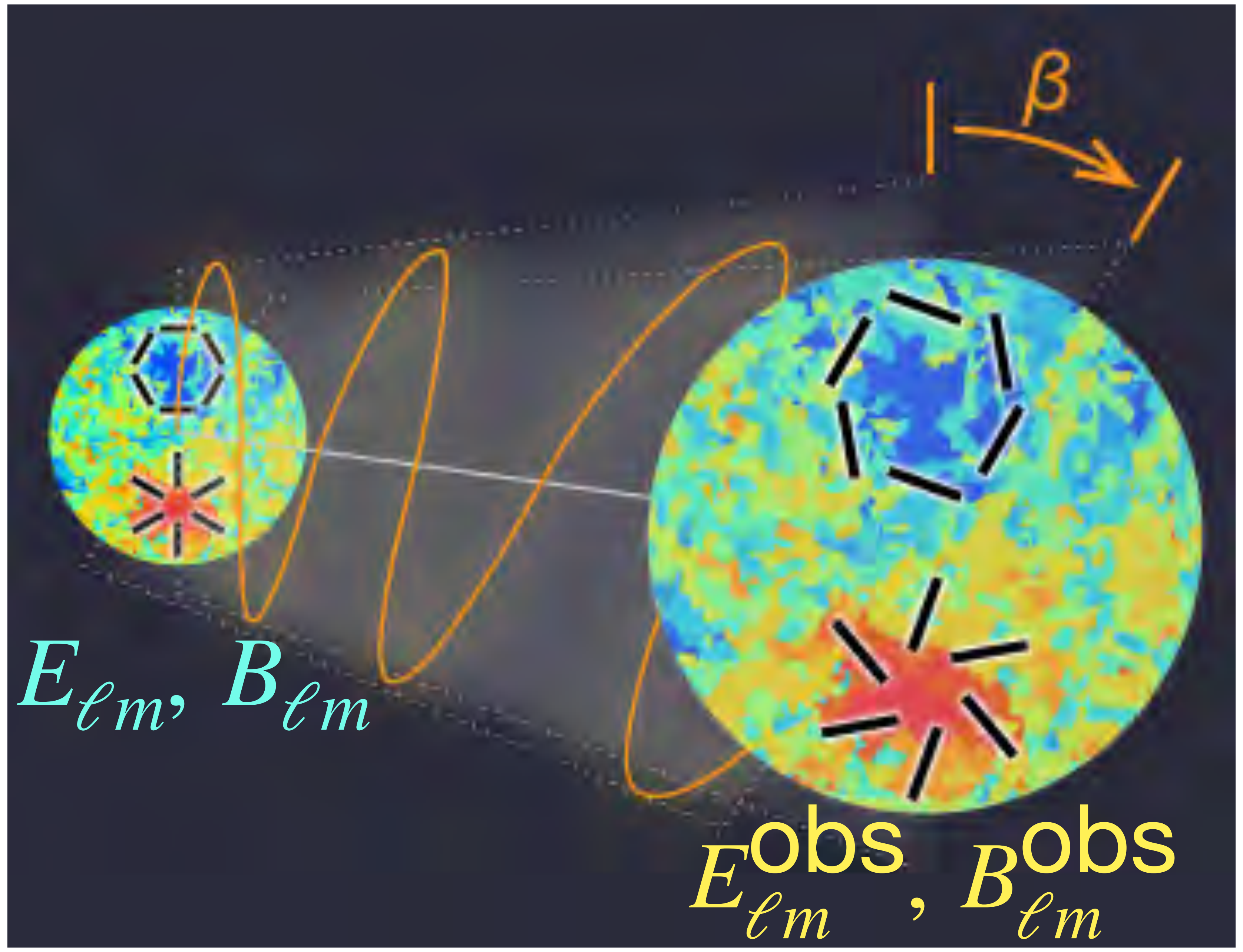
KEYWORD

“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^o and B_l^o, are related to those before rotation as

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

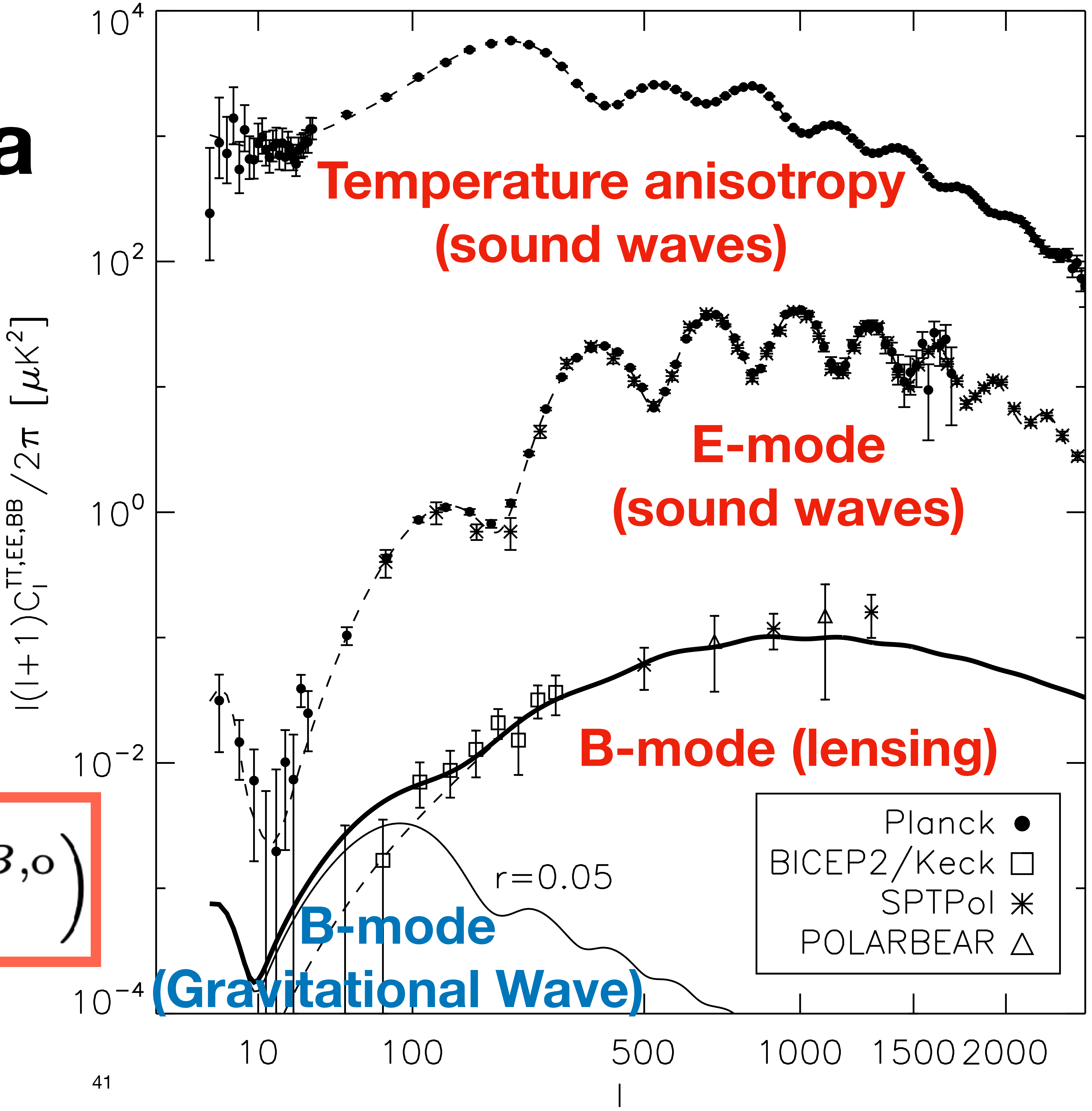
- which gives

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

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!

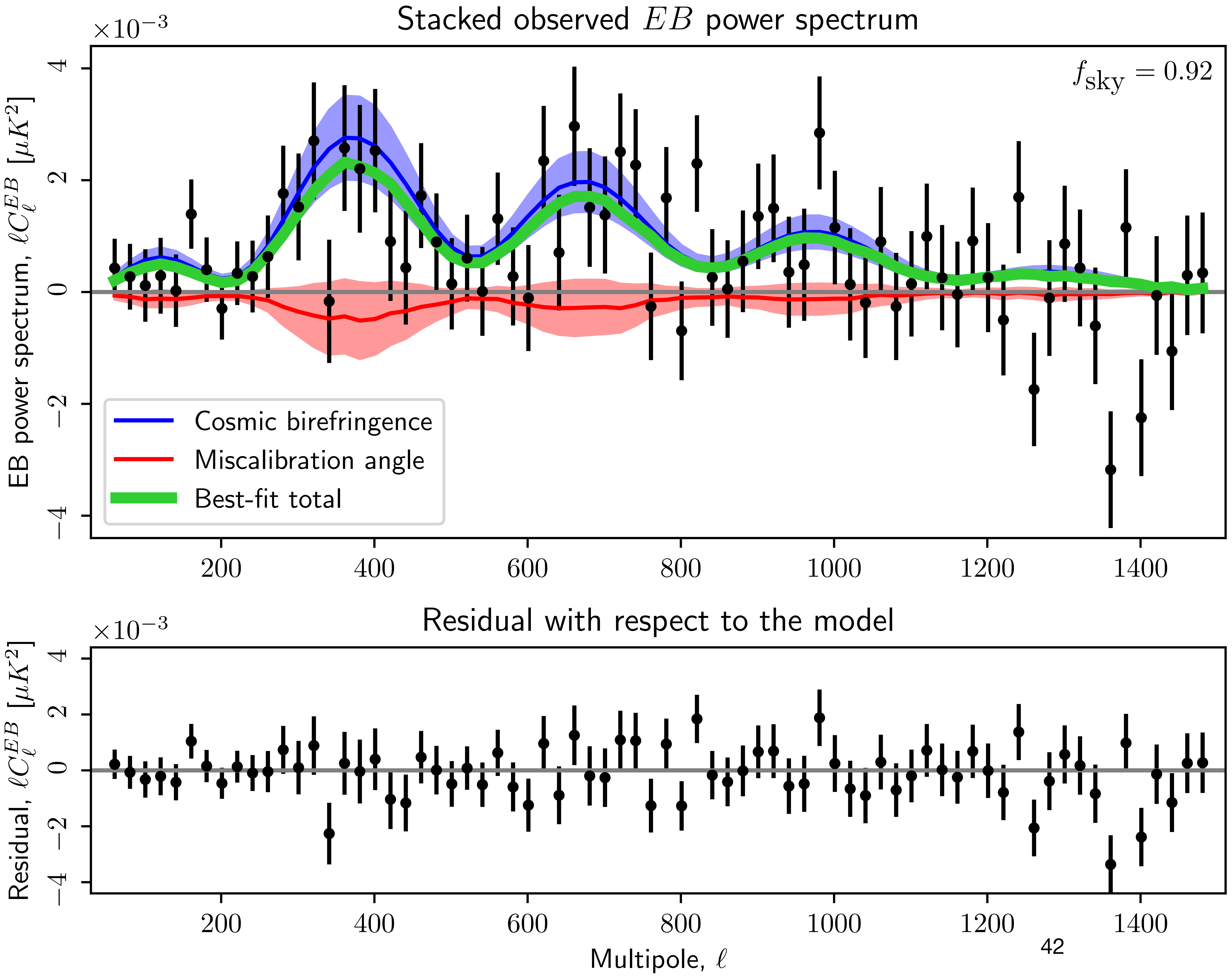
$$C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)$$

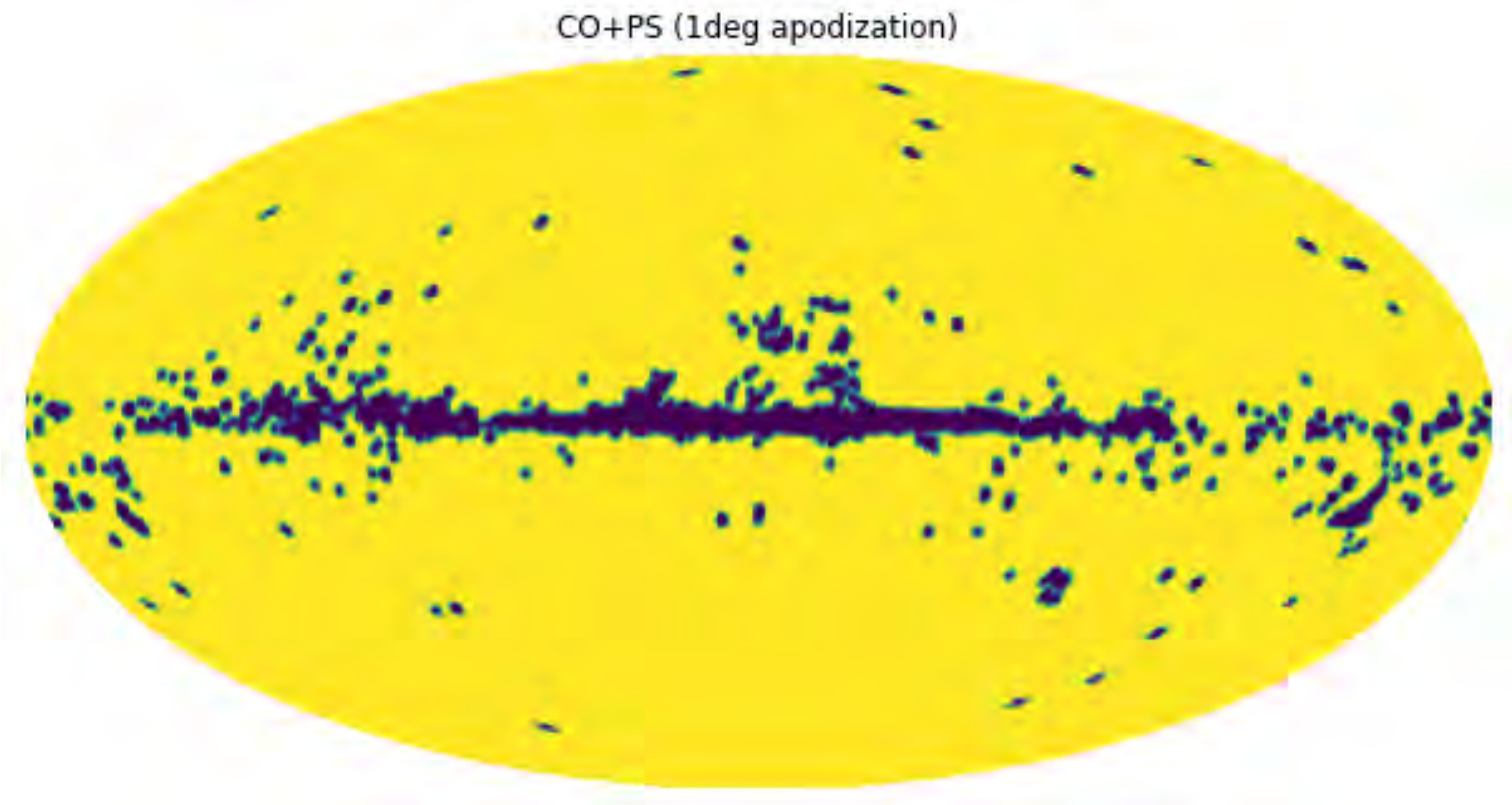


Minami, EK (2020); Diego-Palazuelos et al. (2022); Eskilt, EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

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



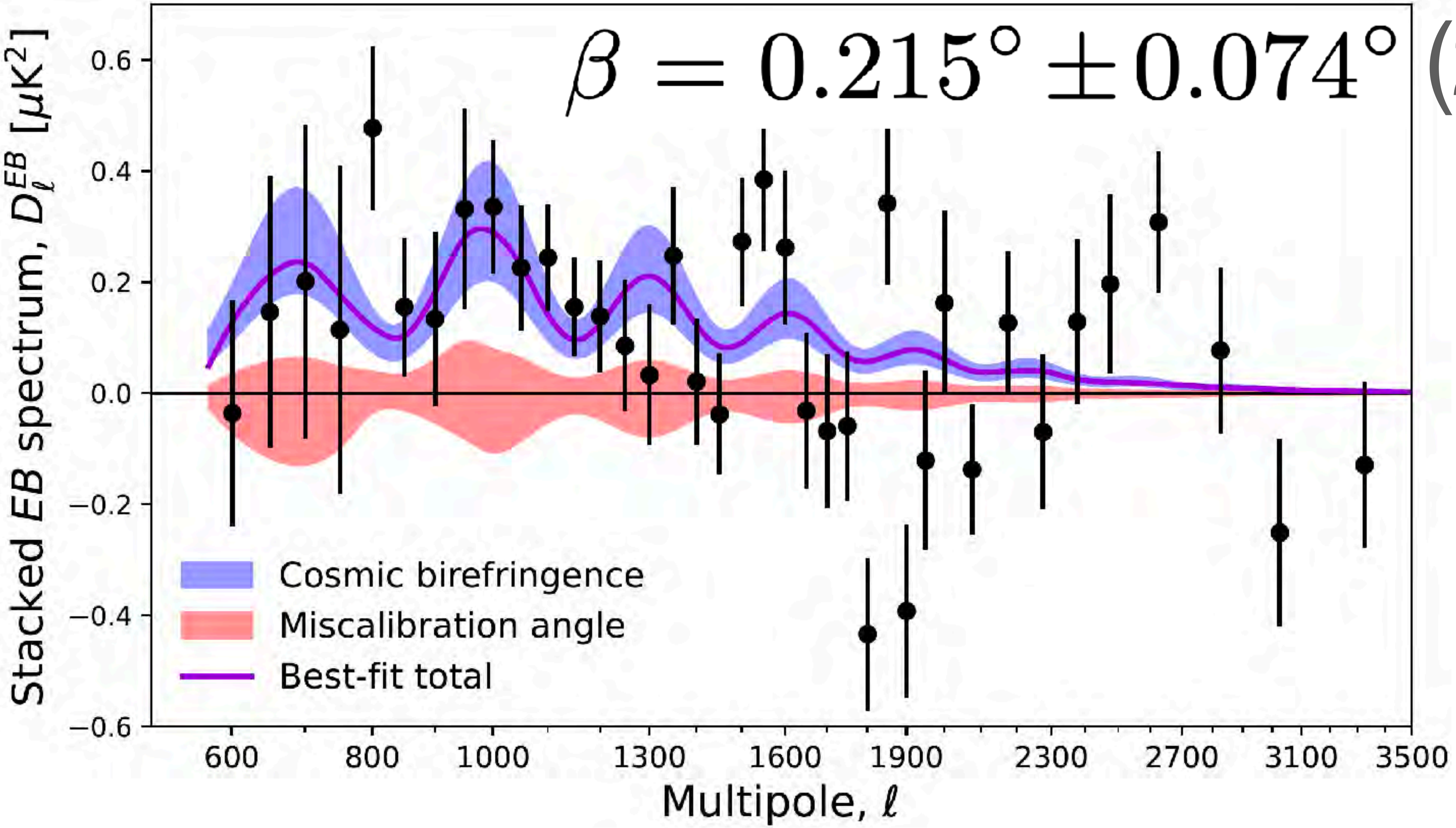


- **β = 0.34 ± 0.09 deg**
- χ^2 = 65.3
    - Good fit! The statistical significance is 3.6σ.

ACT Collaboration, arXiv:2503.14452; Diego Palazuelos, EK, arXiv:2509.13654

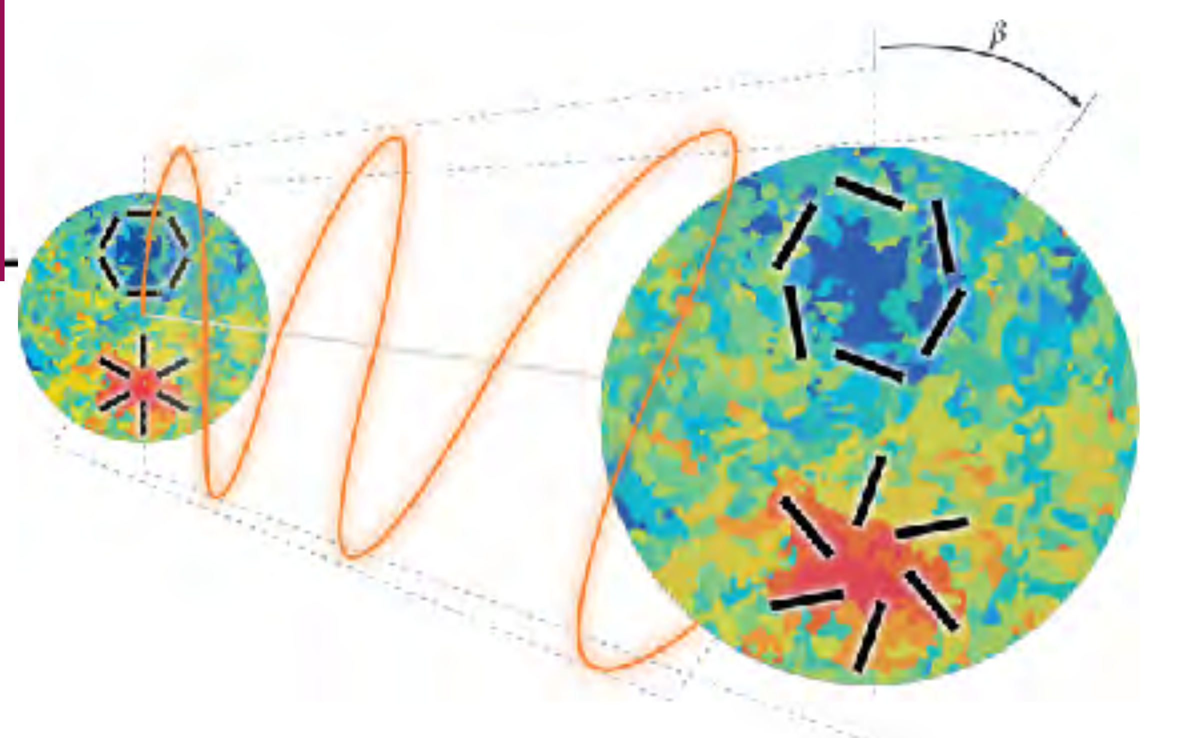
Atacama Cosmology Telescope (DR6)

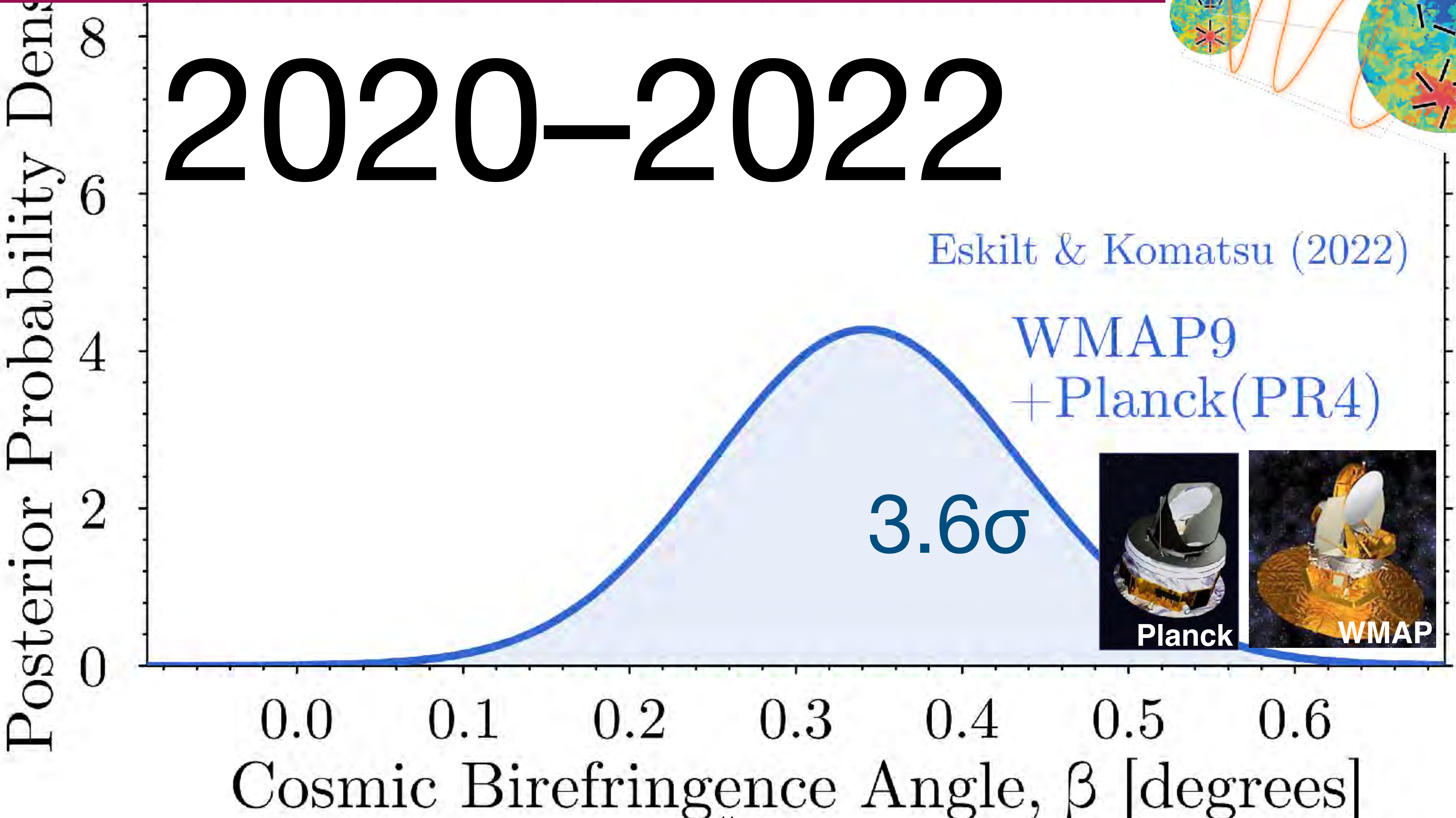
***We needed to measure it in independent experiments* -> here it is!**



(2.9σ)

A tantalizing hint of cosmic birefringence!





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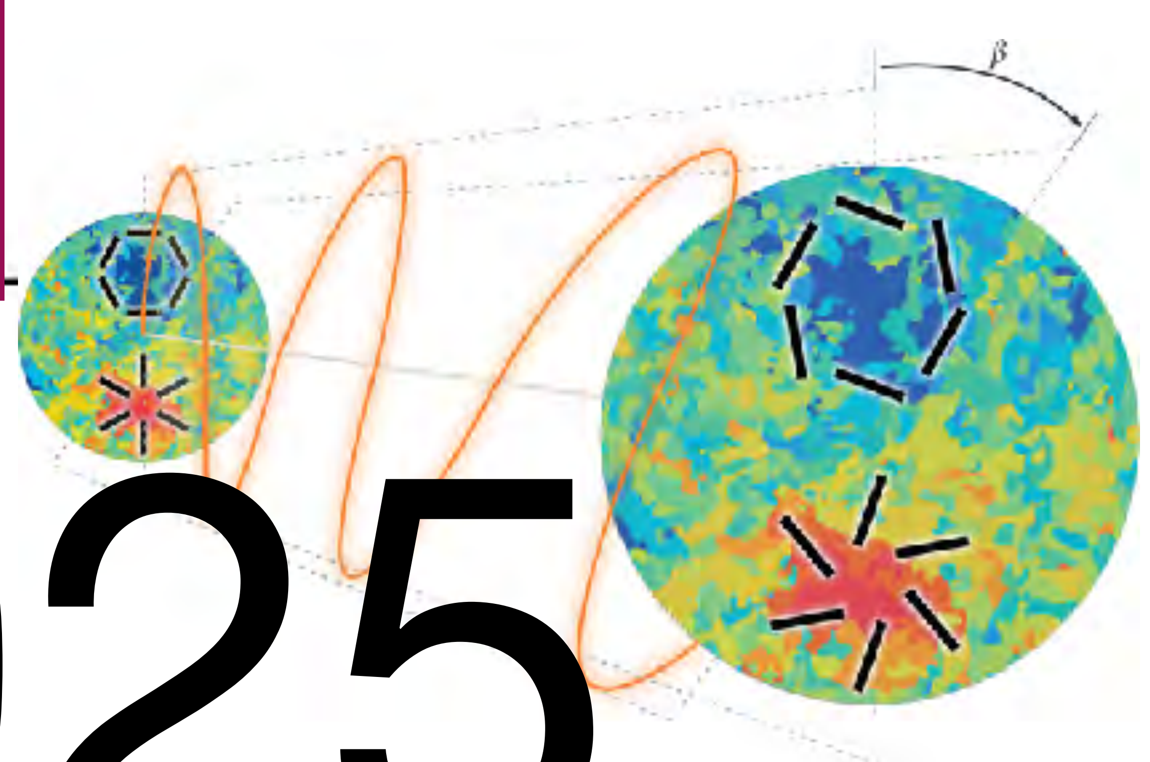
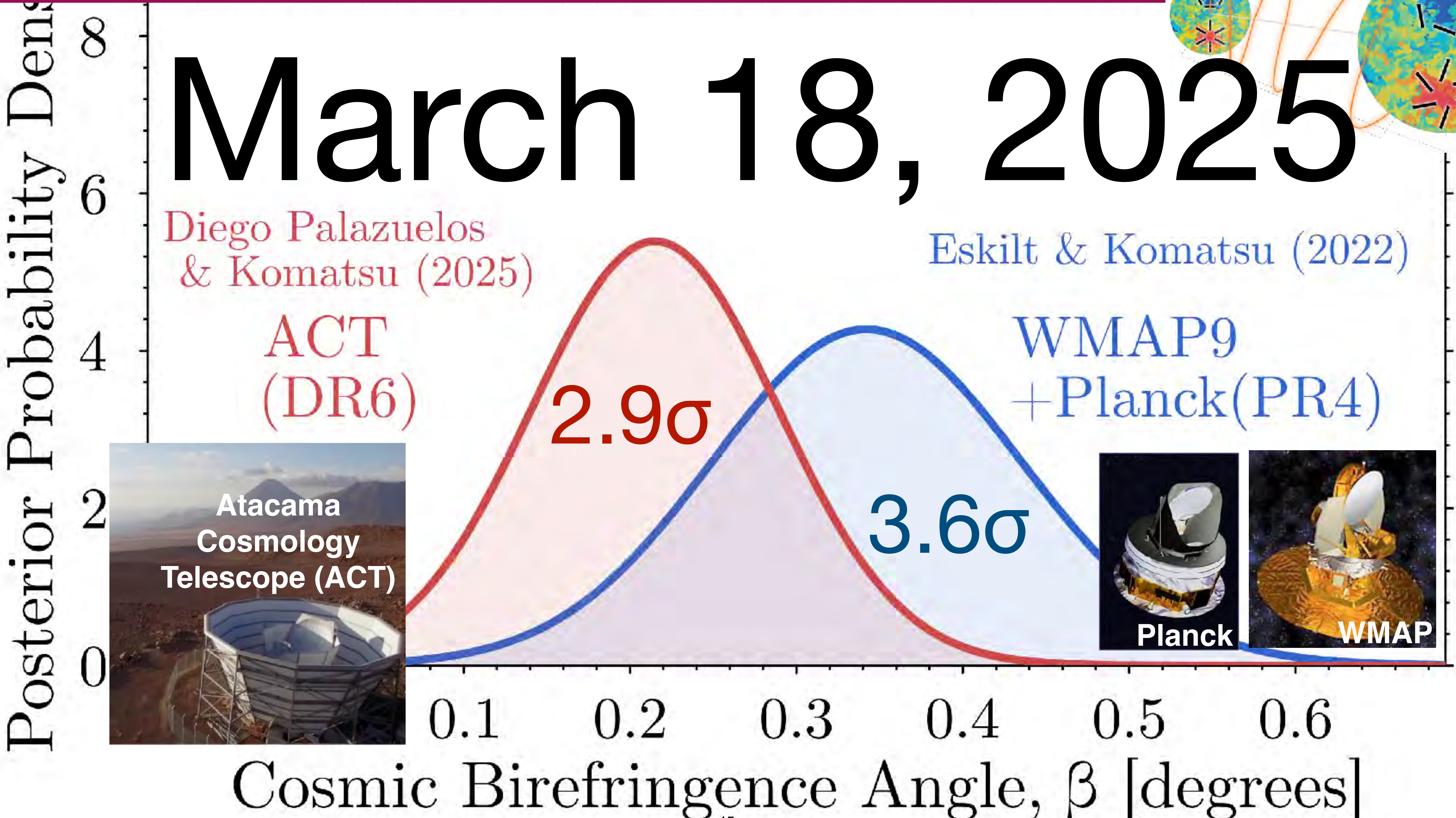
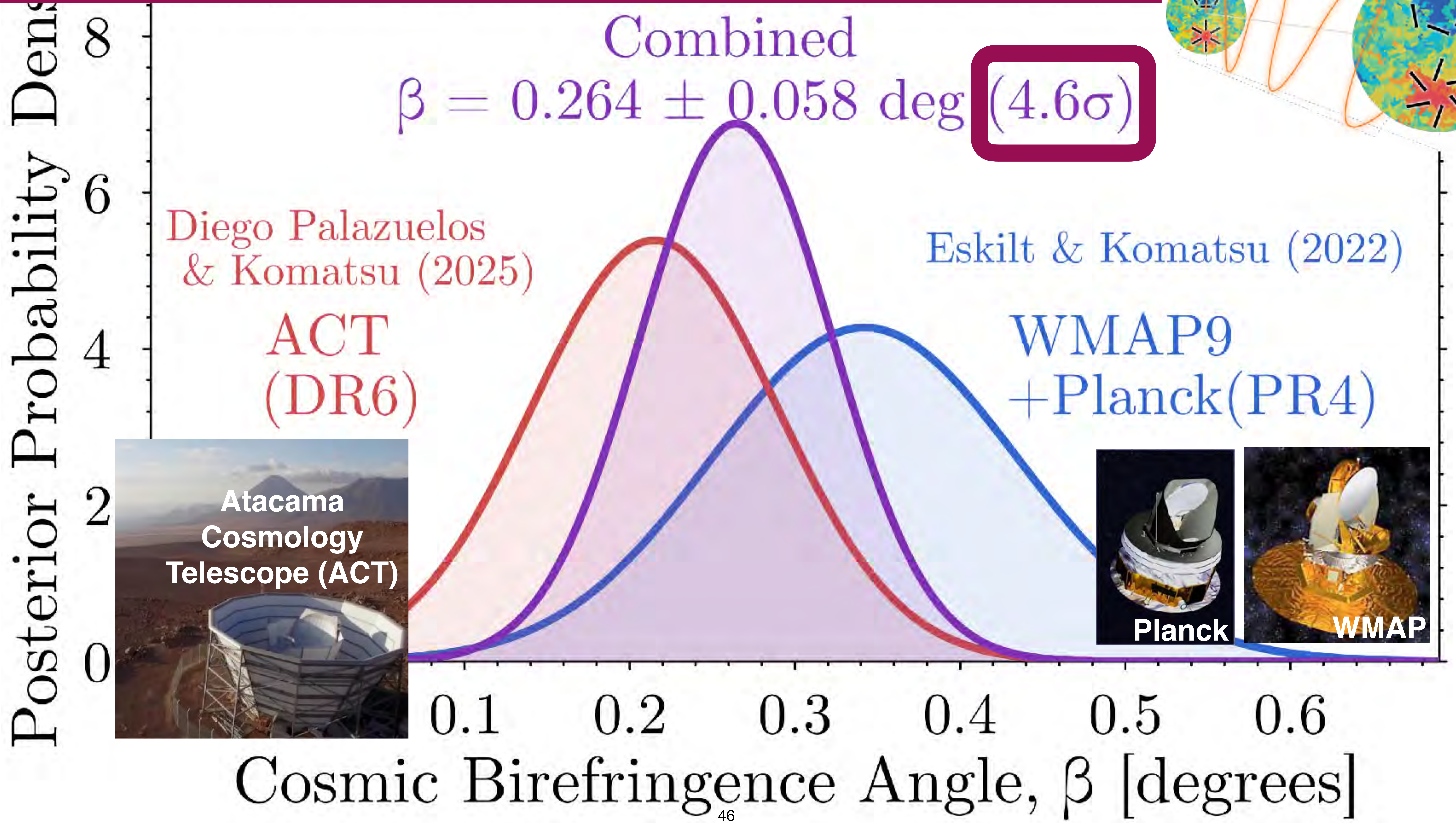
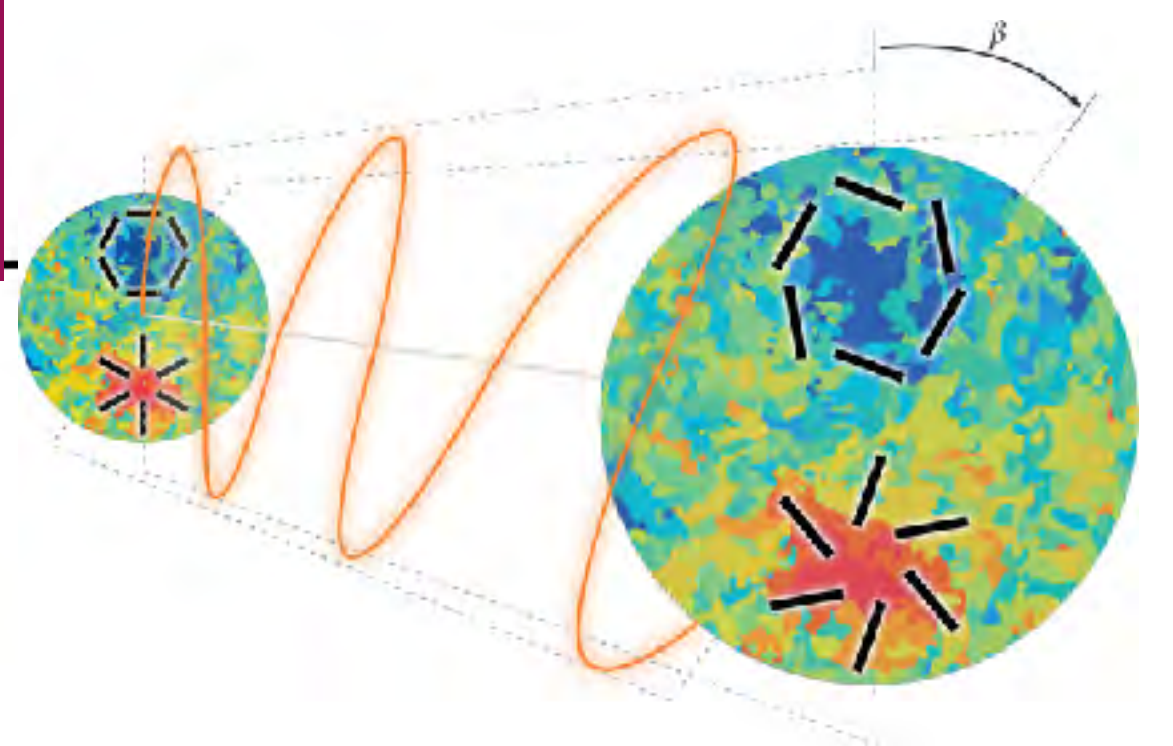


March 18, 2025



A tantalizing hint of cosmic birefringence!

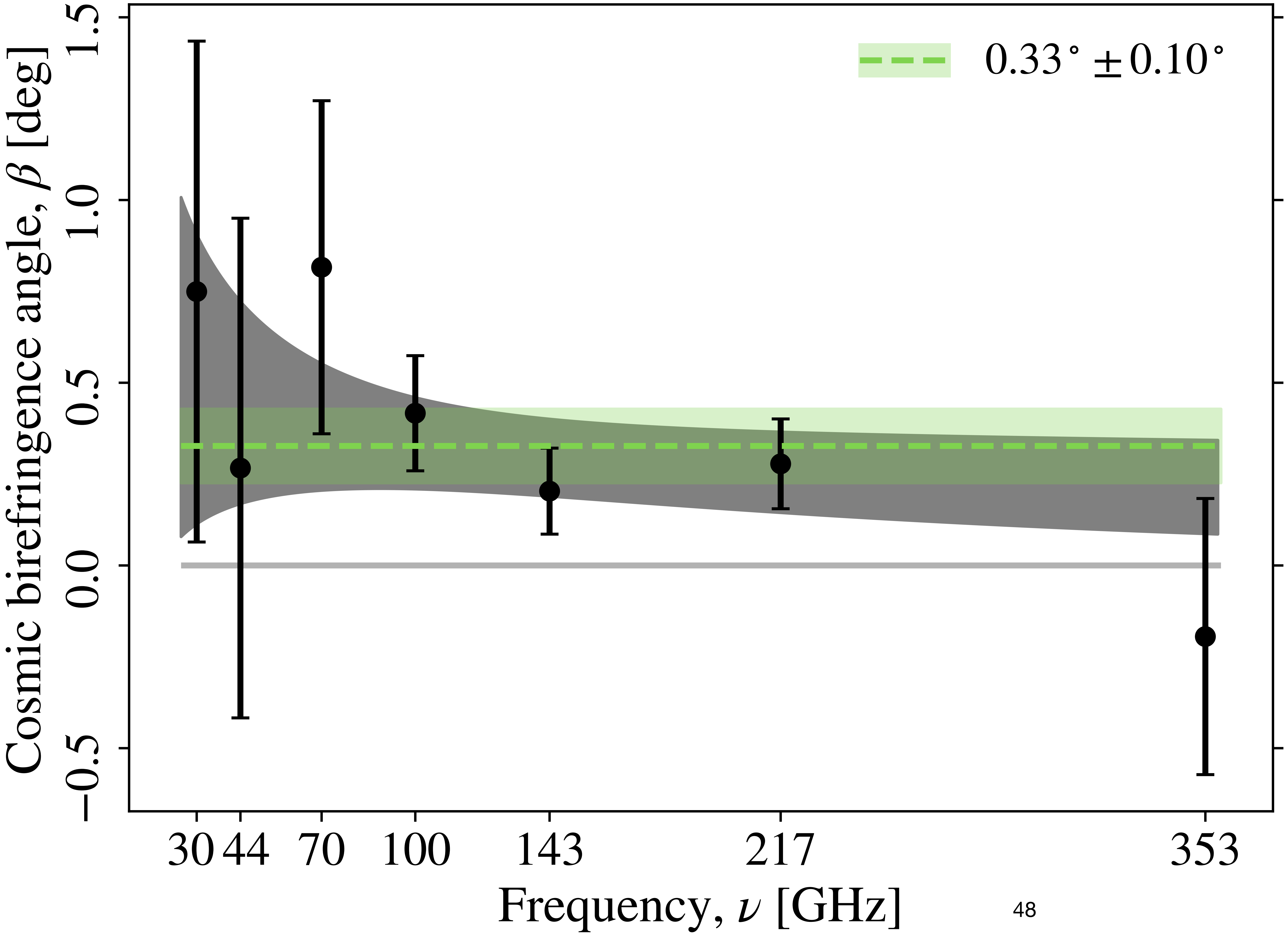




II.3: Cosmological Origin

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.**

Implications

DM = Dark Matter; DE = Dark Energy

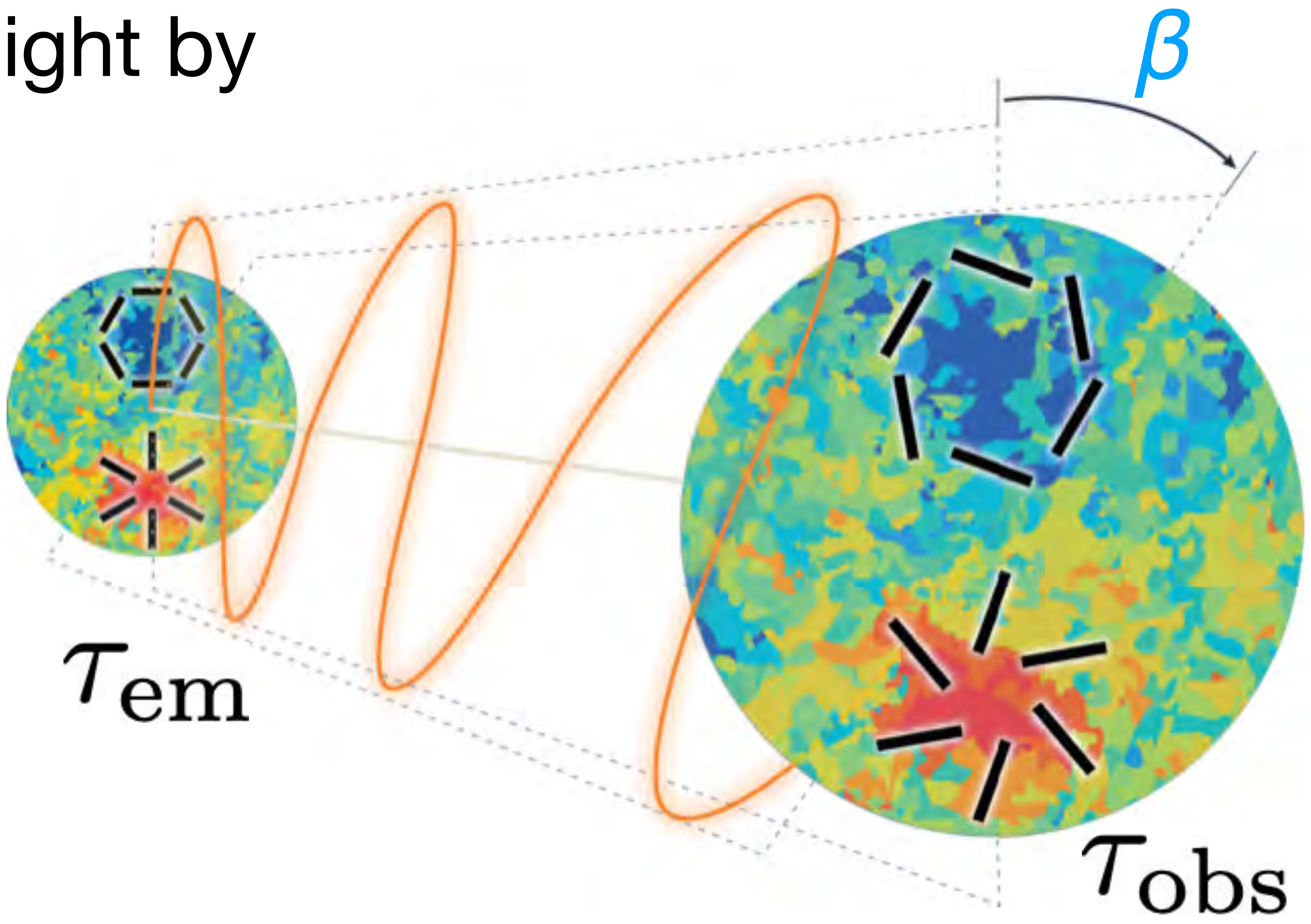
This term exists for a pion.
What if DM/DE is "pion-like particle"?

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

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

$$\beta = -\int_{\tau_{\rm em}}^{\tau_{\rm obs}} d\tau\,(\omega_+ - \omega_-)$$

$$= \frac{\alpha}{2f}\left[\chi(\tau_{\rm obs}) - \chi(\tau_{\rm em})\right]$$



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

Implications

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

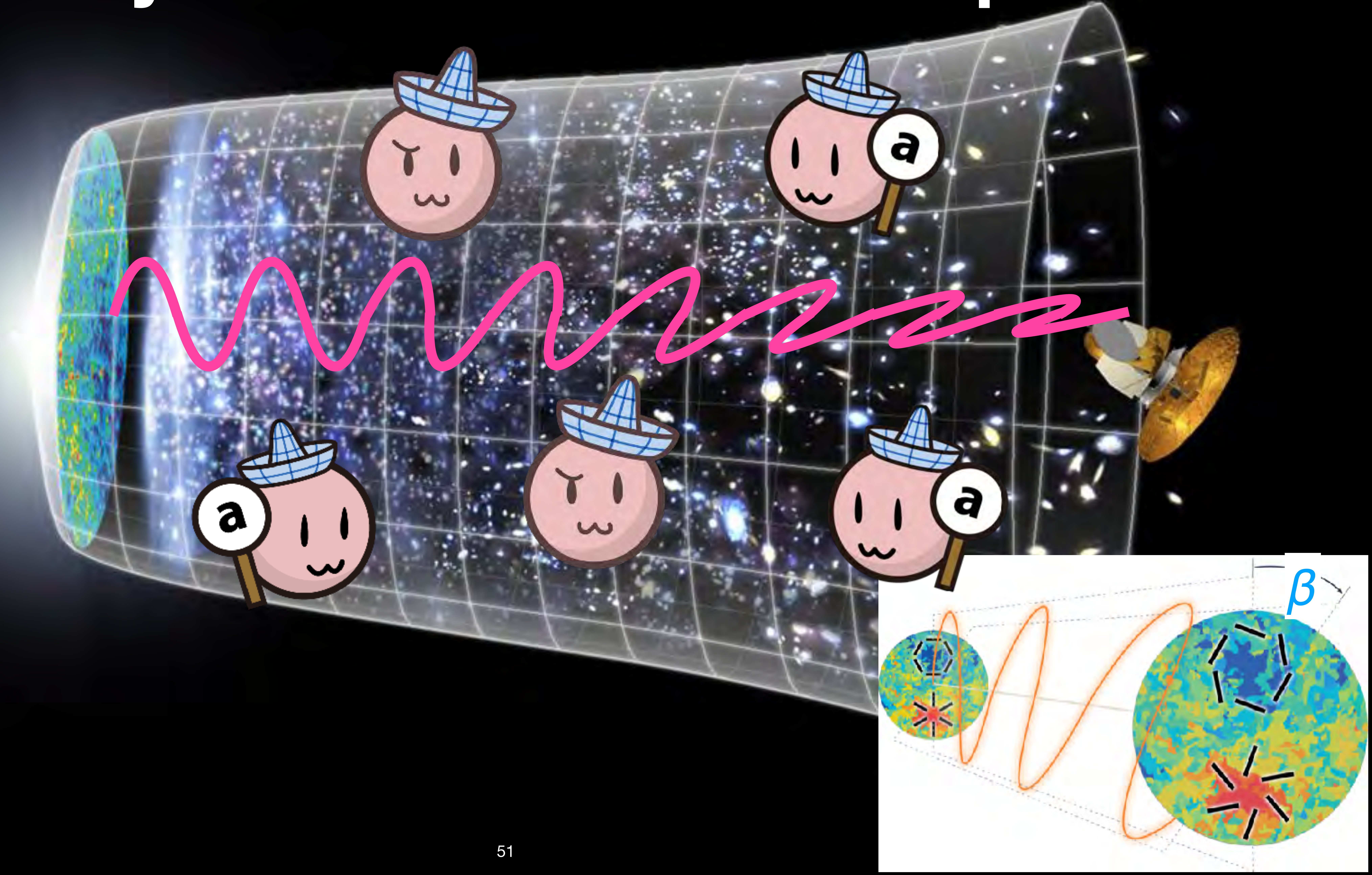
$$\Delta\chi = \chi(\tau_{\rm obs}) - \chi(\tau_{\rm em}) \simeq \frac{10^{-2}}{\alpha} f$$

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.

So, space may be filled with axionlike particles…



II.4: What Comes Next?

What are we worried about now?

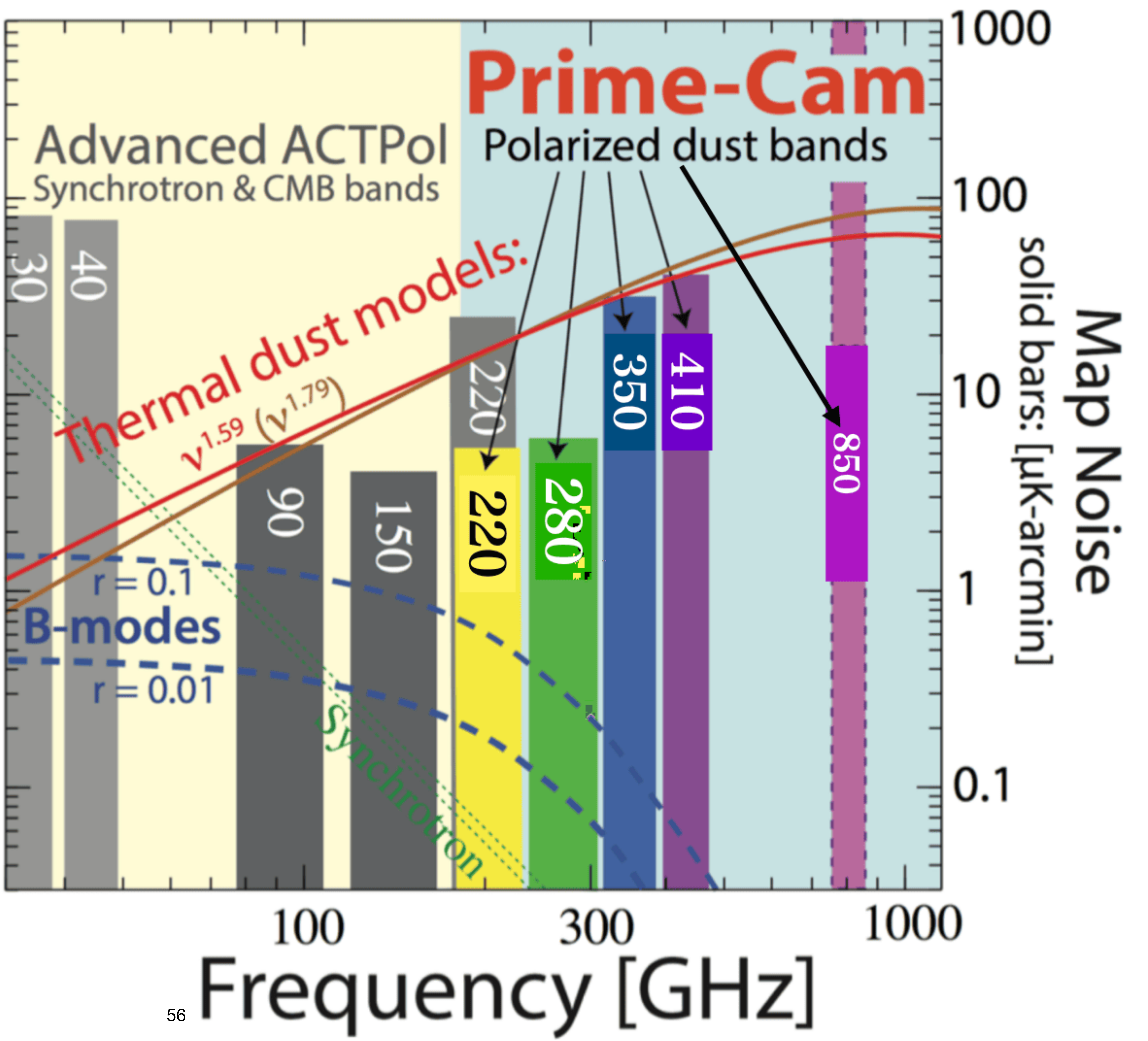
"Unknown Unknowns"

- **WMAP+Planck**
  - Unknown systematics in the Planck instruments.
- **ACT**
  - 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.
  - Both **BICEP3** (Cornelison et al., arXiv:2410.12089) and the **Simons Observatory** (Murata et al., arXiv:2309.02035) are doing exactly that. We will probably have the final answer in a couple of years!

Fred Young Sub-mm Telescope!

Fred Young Sub-mm Telescope!

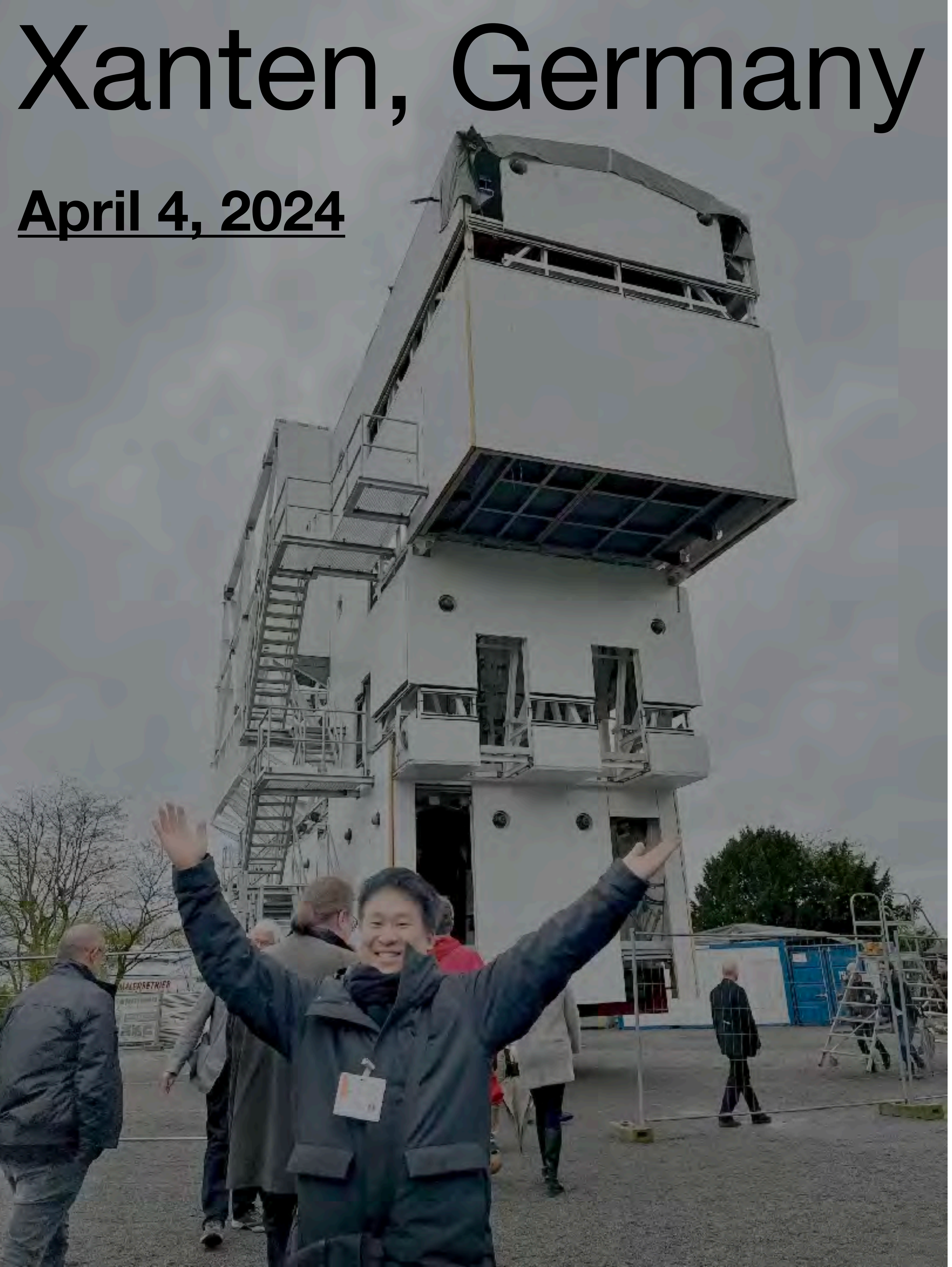
CPi vertex



Prime-Cam
Polarized dust bands
Advanced ACTPol
Synchrotron & CMB bands
Thermal dust models:
$\nu^{1.59}$ ($\nu^{1.79}$)
r = 0.1
B-modes
r = 0.01
Synchrotron
30
40
90
150
220
220
280
350
410
850
1000
100
10
1
0.1
Map Noise
solid bars: [μK-arcmin]
100
300
1000
Frequency [GHz]

Xanten, Germany

April 4, 2024



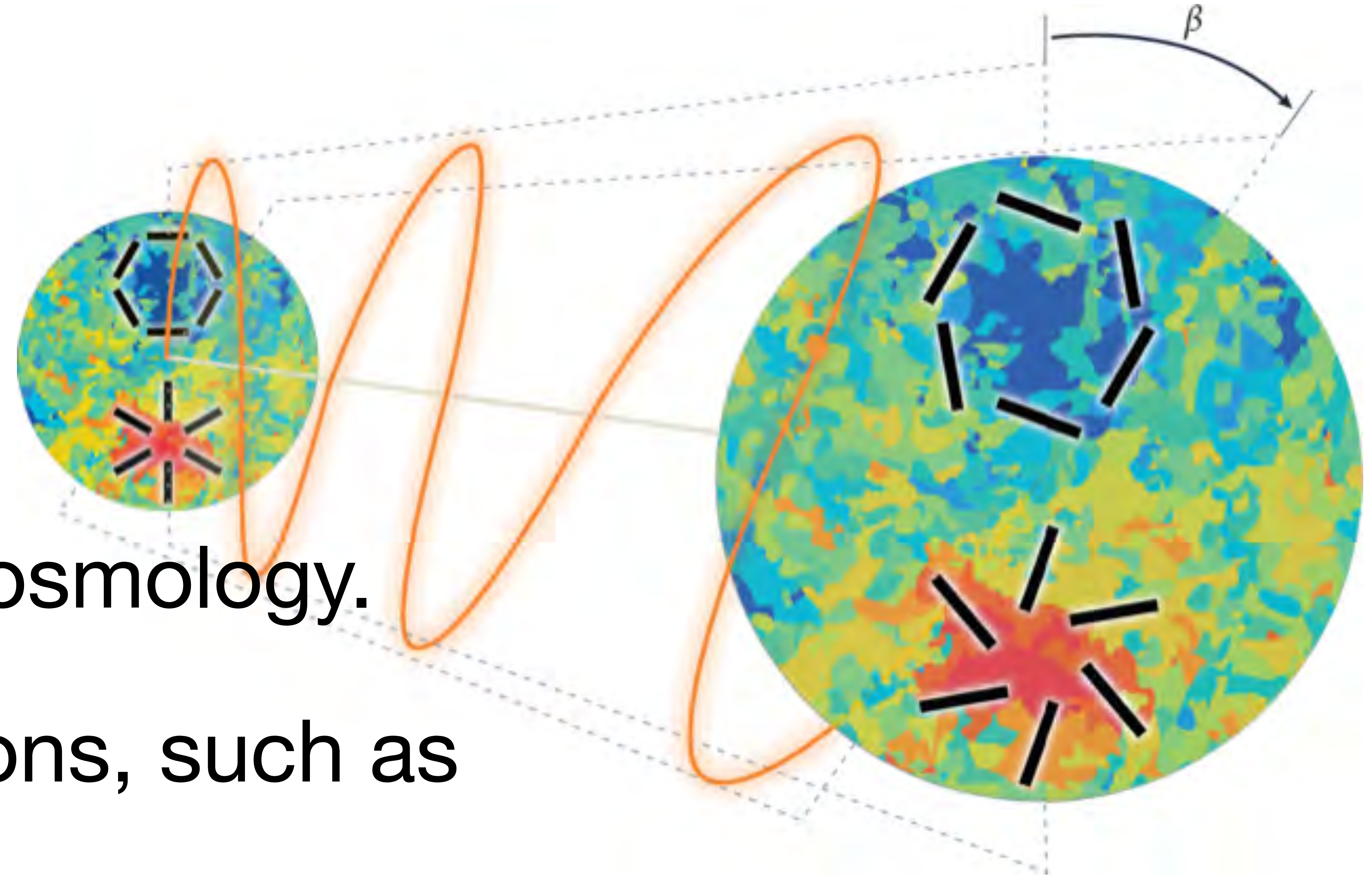
Cerro Chajnantor

April 9, 2026


ALMA@5,000m

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 dark matter and dark energy fields?
- **What do we need? Yet another independent confirmation.**
  - BICEP3, Simons Observatory, and FYST!