UNIVERSE+ Online Seminar

Eiichiro Komatsu

“Does the Universe distinguish between left and right?”

A Tantalizing Hint of Cosmological Parity Violation

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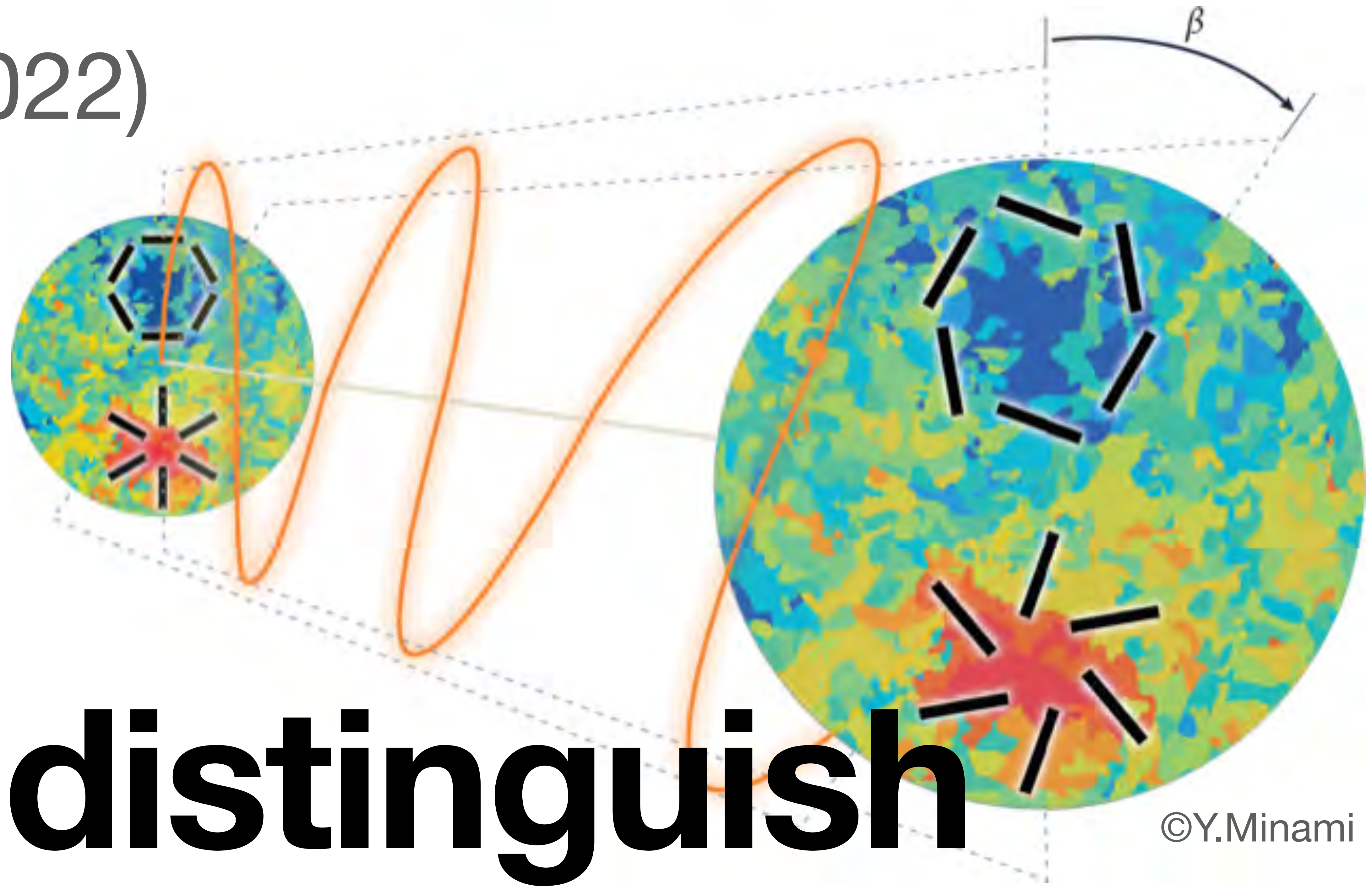
Reference: EK, Nature Rev. Phys. **4**, 452 (2022)

$$I_{\mathrm{CS}} = \int \mathrm{d}^4x \sqrt{-g}\left(-\frac{\alpha}{4f}\chi F\tilde{F}\right)$$



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Does the Universe distinguish between left and right?

A Tantalizing Hint of Cosmological Parity Violation

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

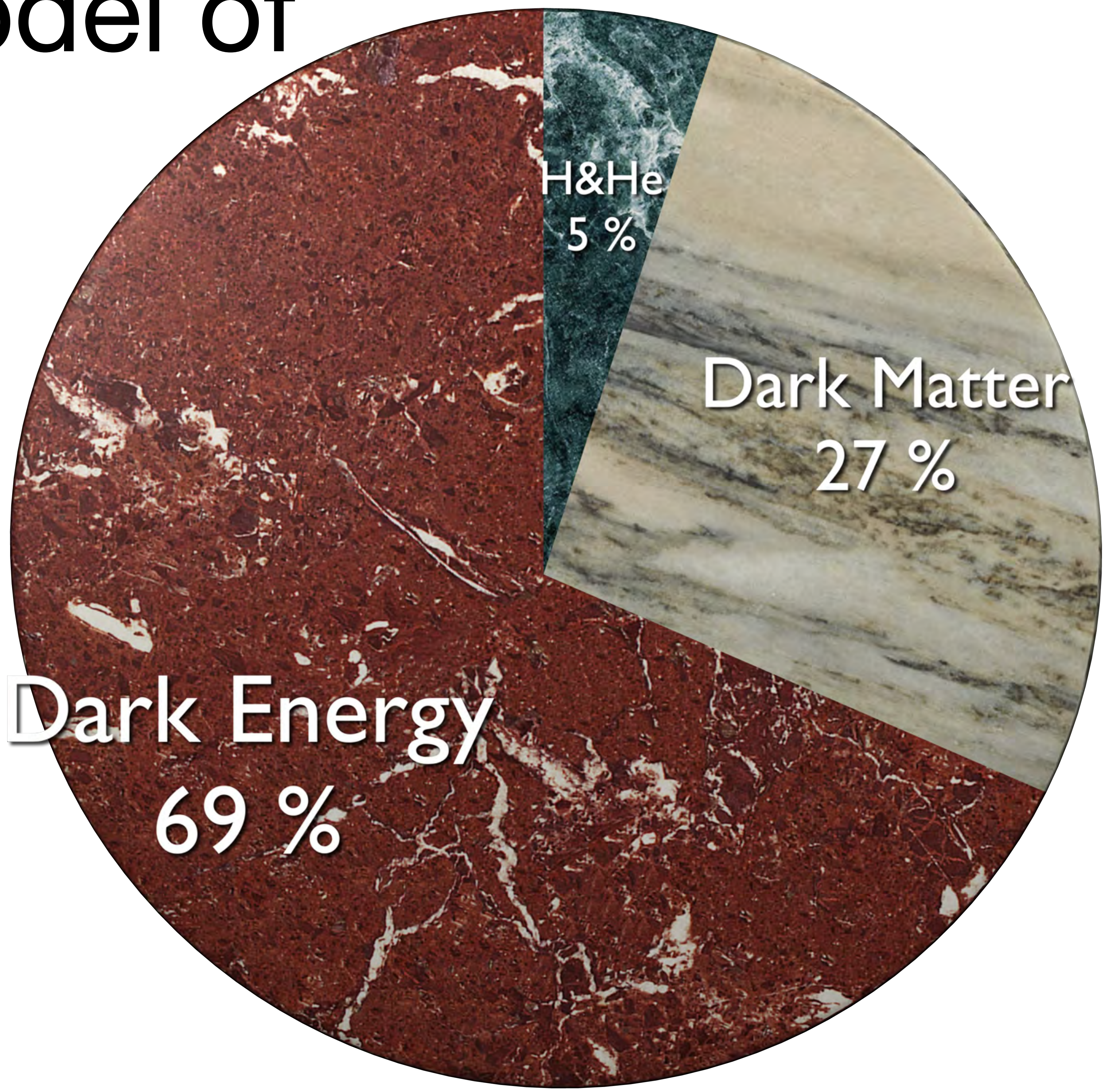
Universe+ Online Seminar, July 15, 2026

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

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)?



New in cosmology!

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

Overarching Goal: Find New Physics

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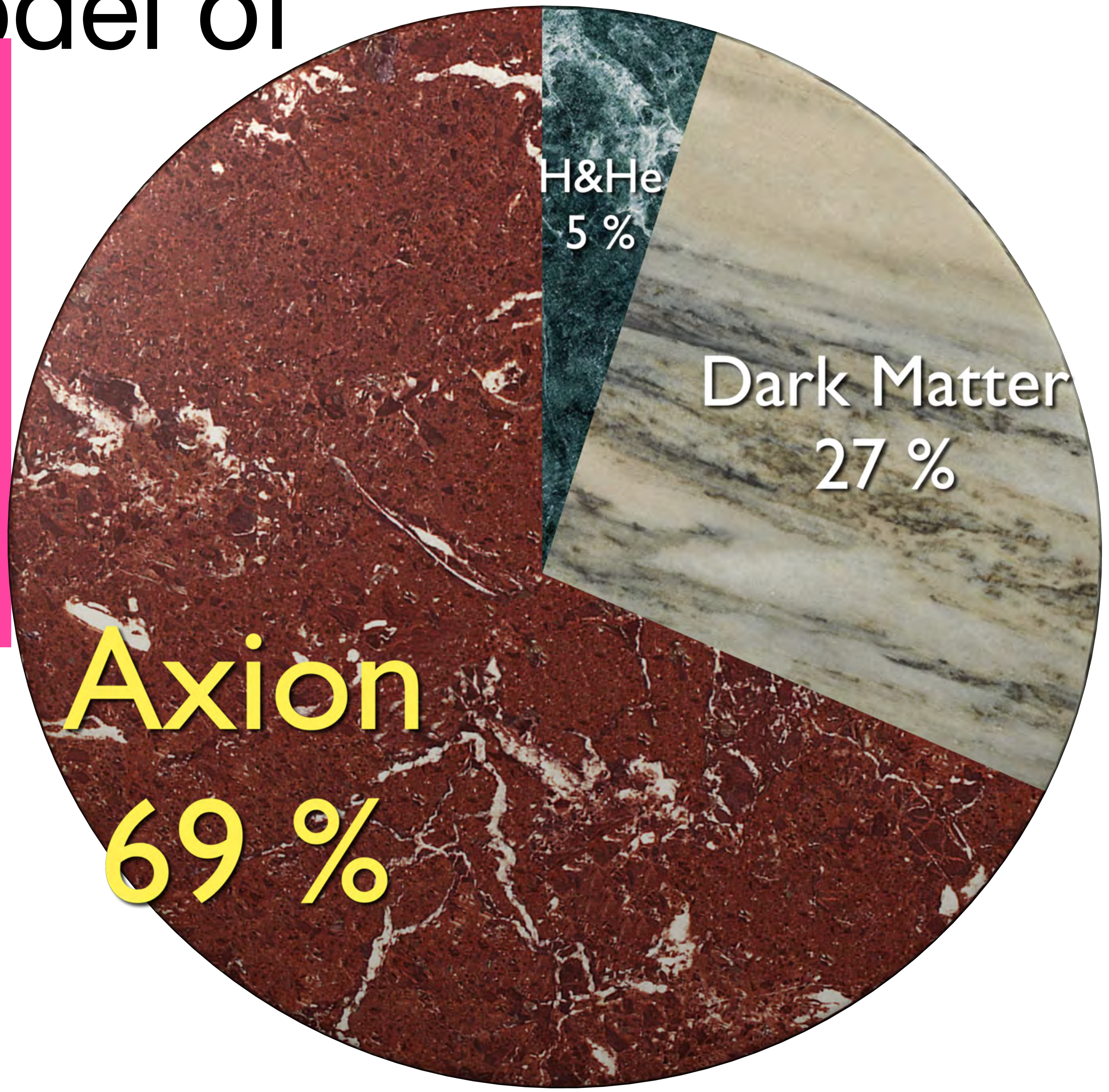
    - What is dark matter

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



<u>New in cosmology!</u>

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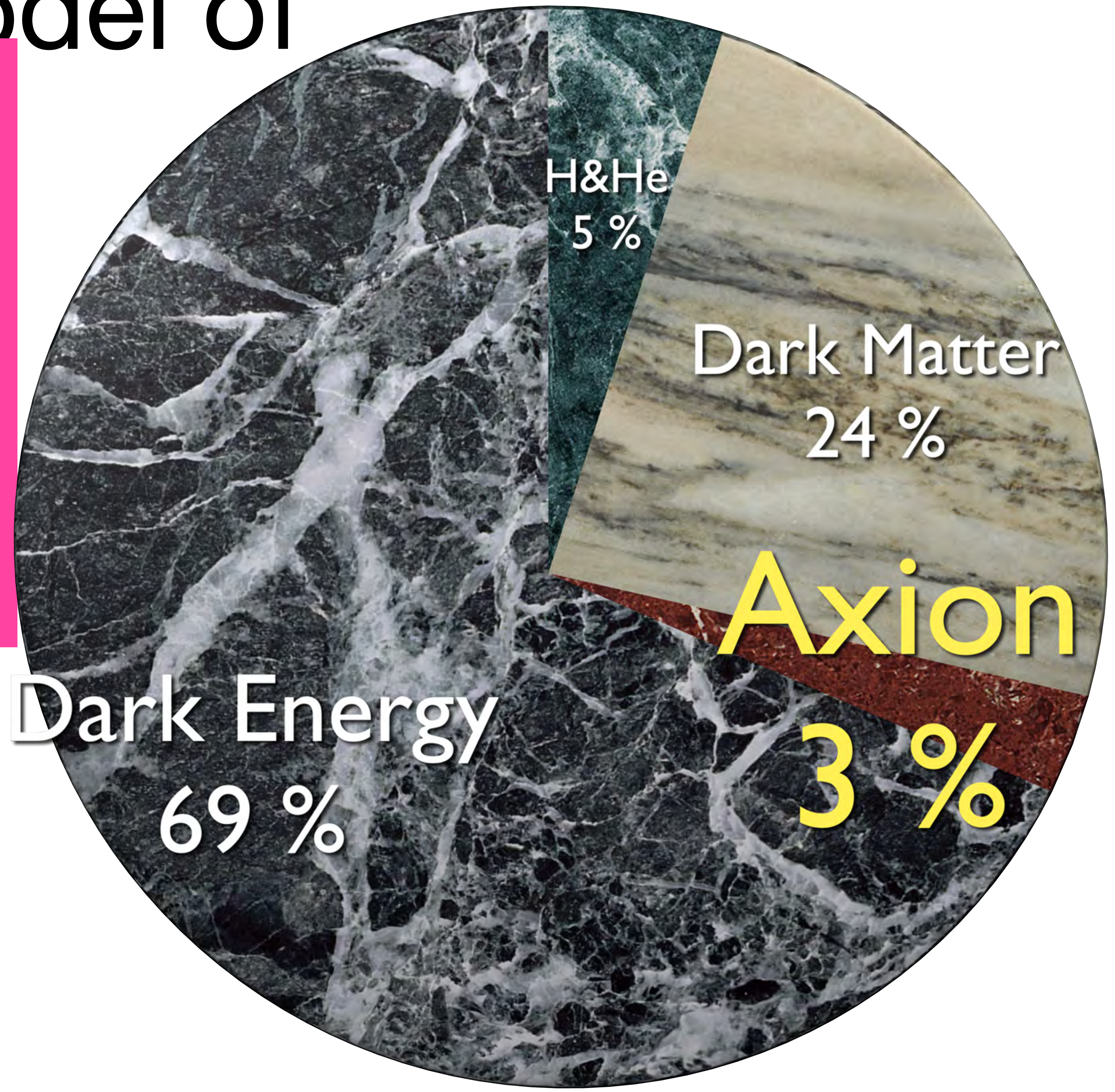


__New in cosmology!__

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

Reference:

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

Available also at arXiv:2202.13919

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 **<u>not</u>** invariant under…
- We ask, “***When we observe a certain phenomenon in nature, do we also observe its mirror image with equal probability?***”

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

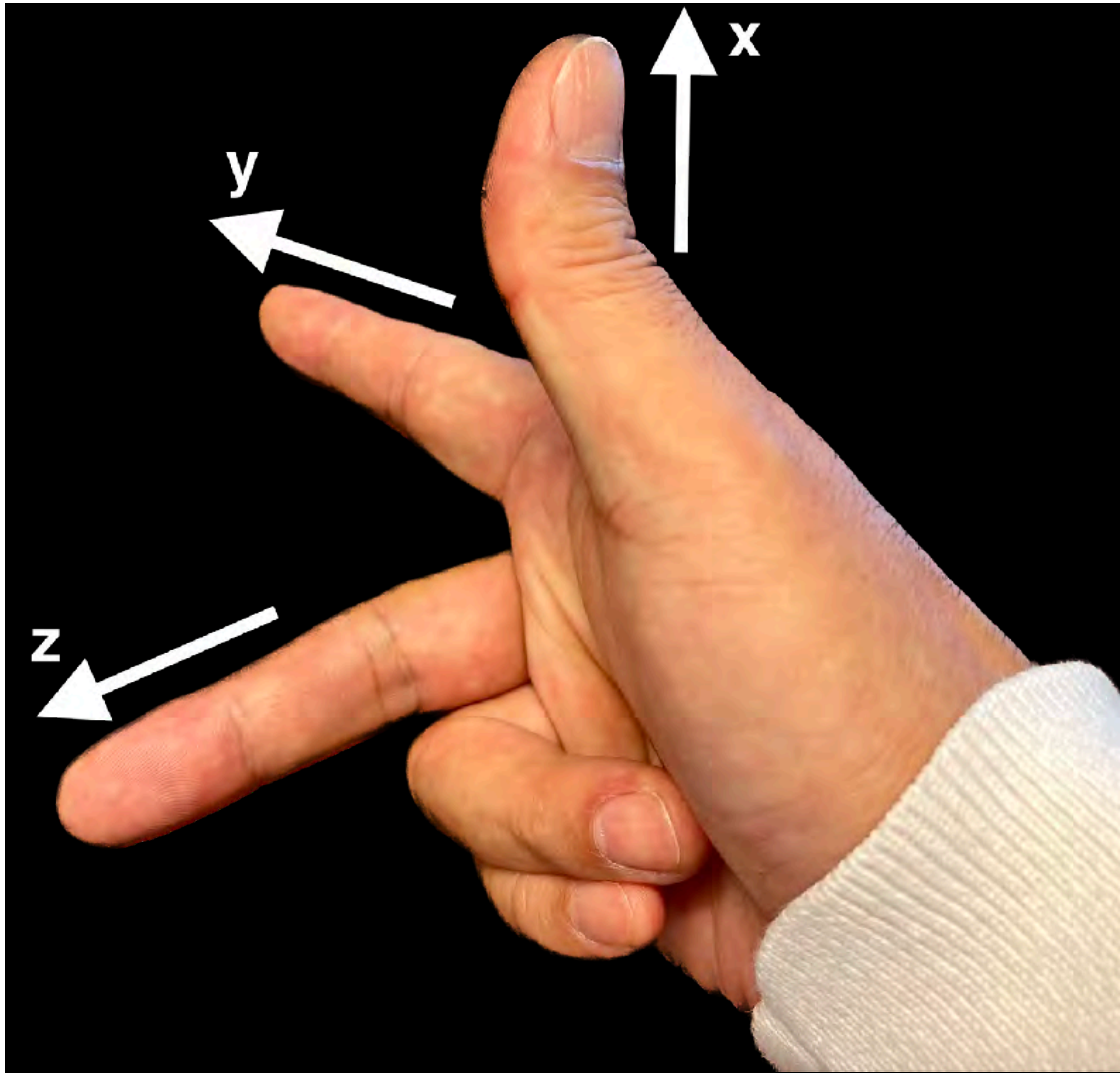
$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

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

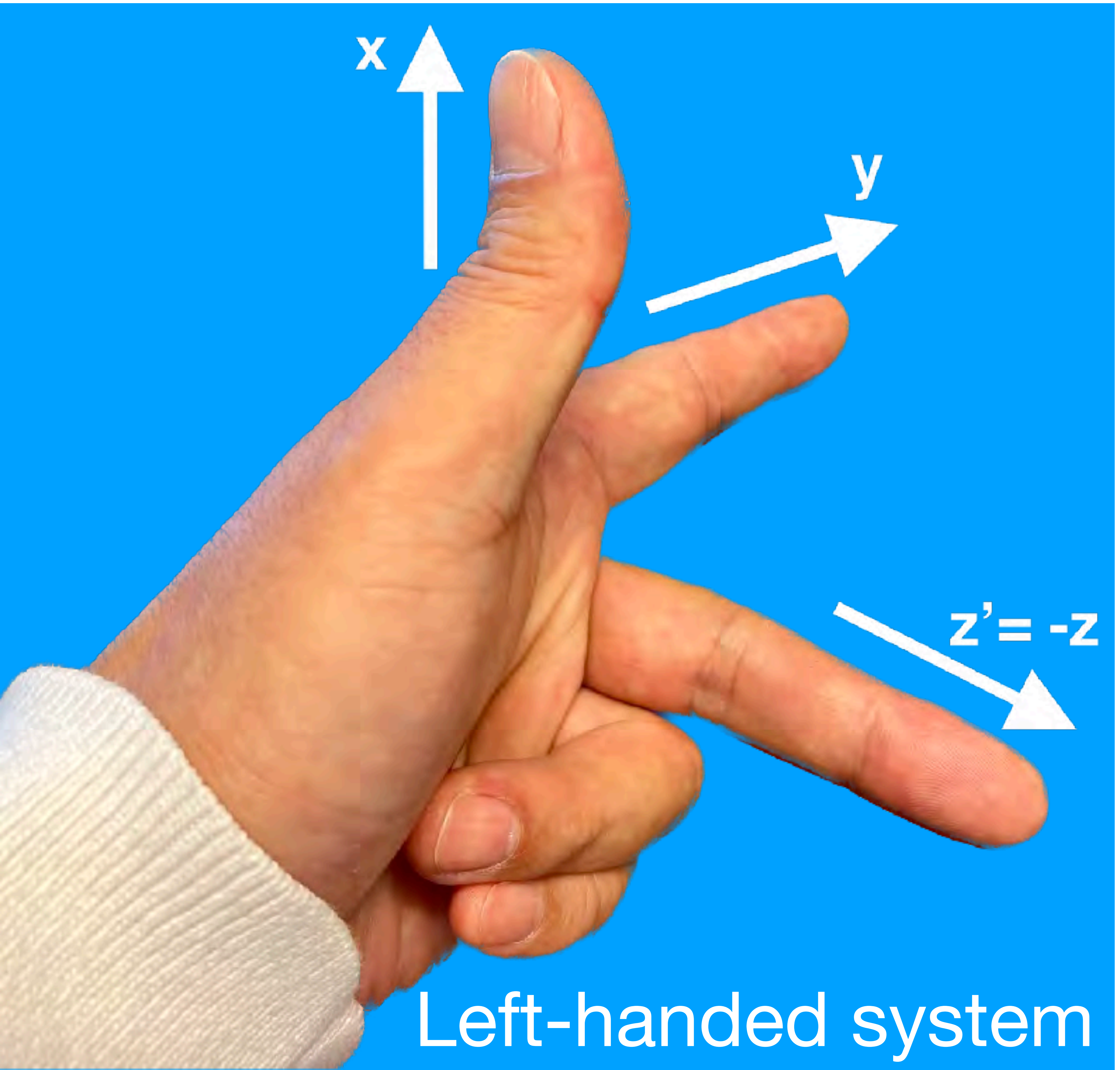
Parity = Mirror + 2d Rotation

- 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.

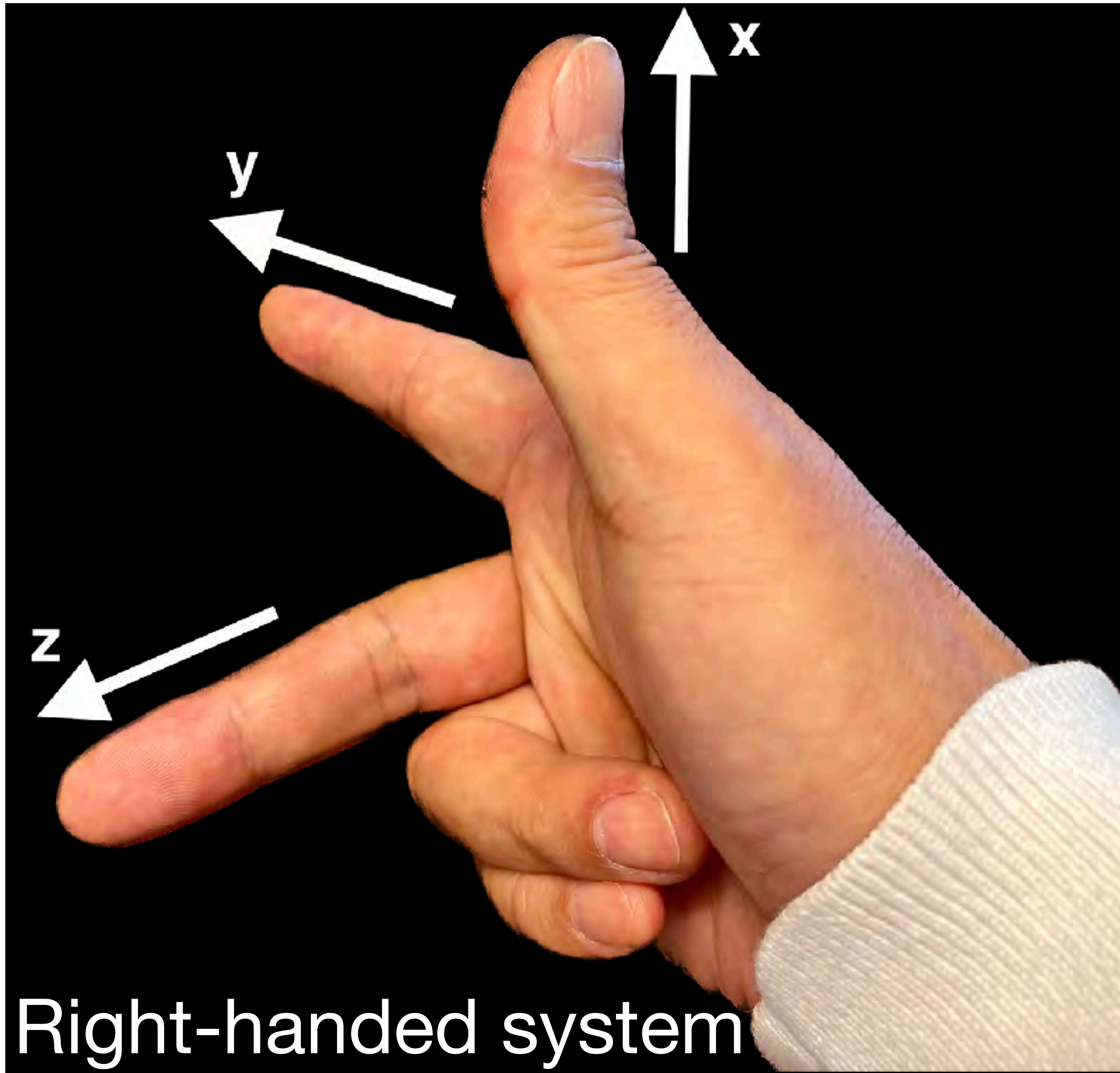
- Let’s demonstrate it!



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



z -> z’ = -z



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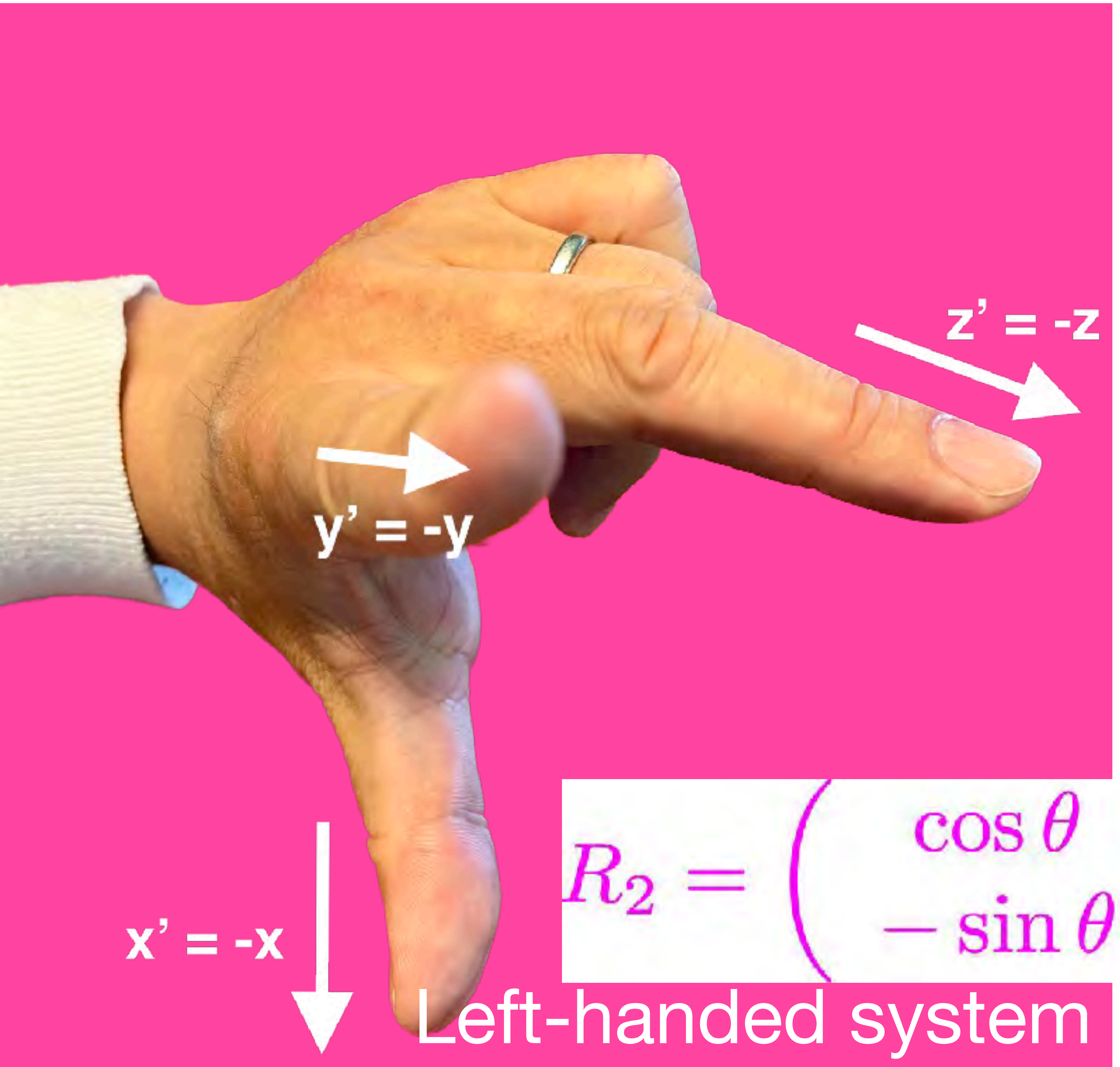
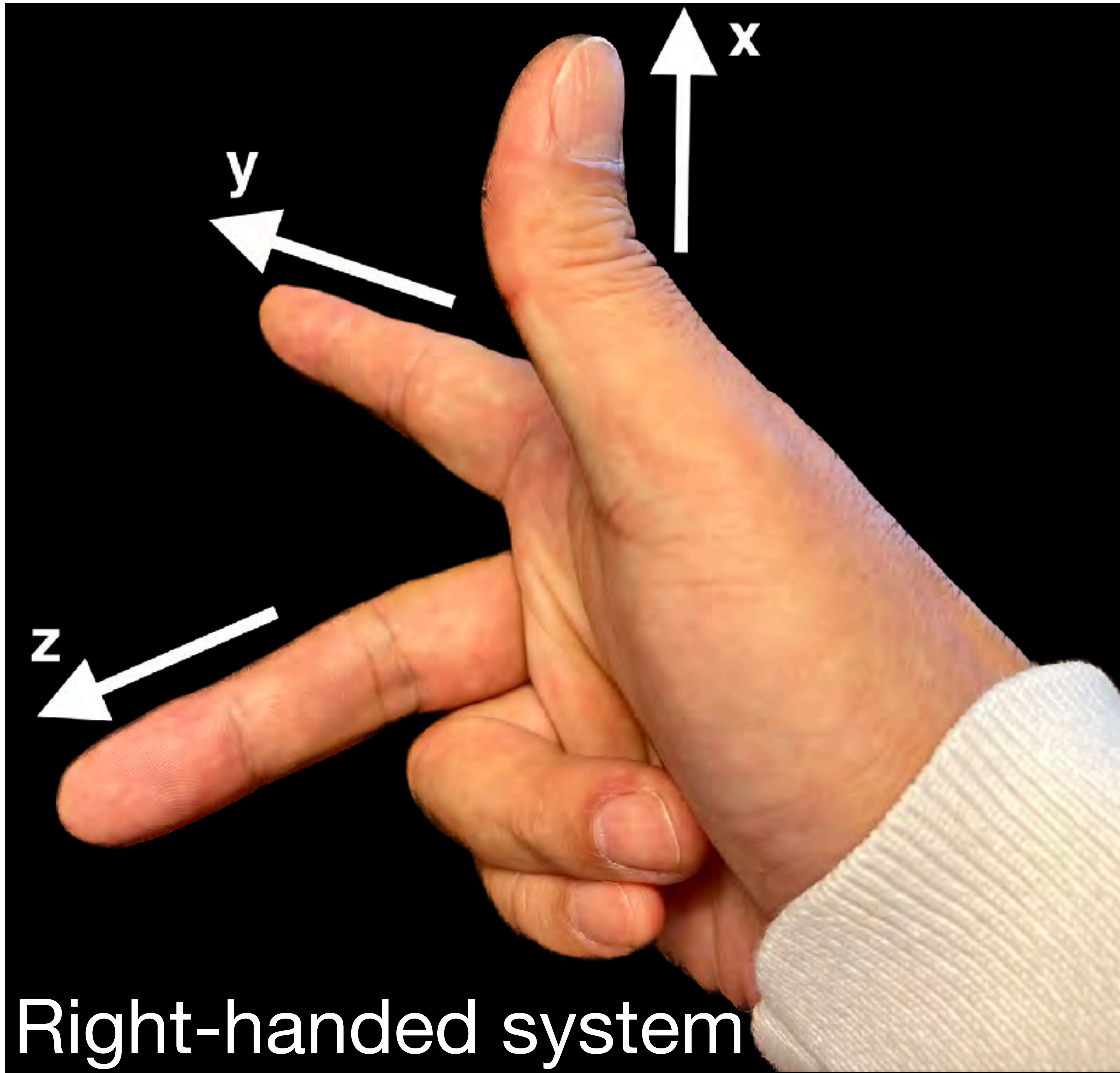


Rotation
In x-y

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

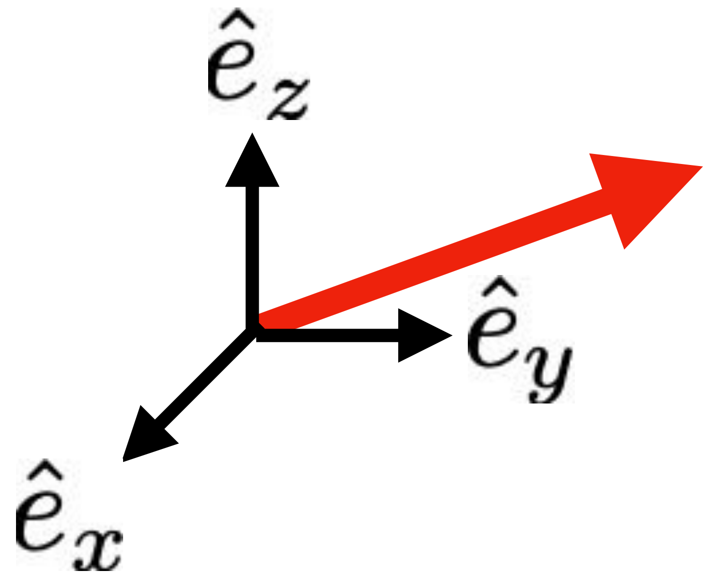
with θ = π



I.2 Pseudovector, Pseudoscalar

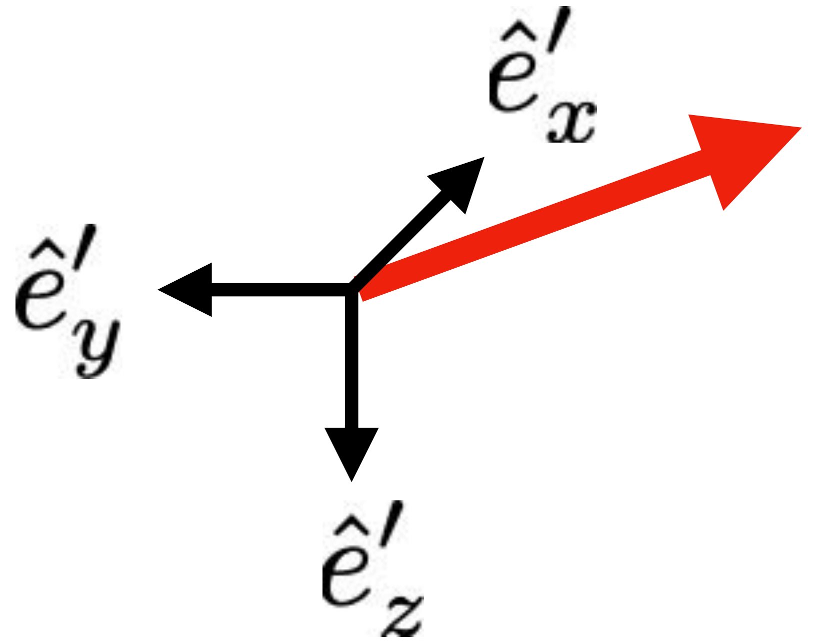
Parity Transformation: Vector

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.



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

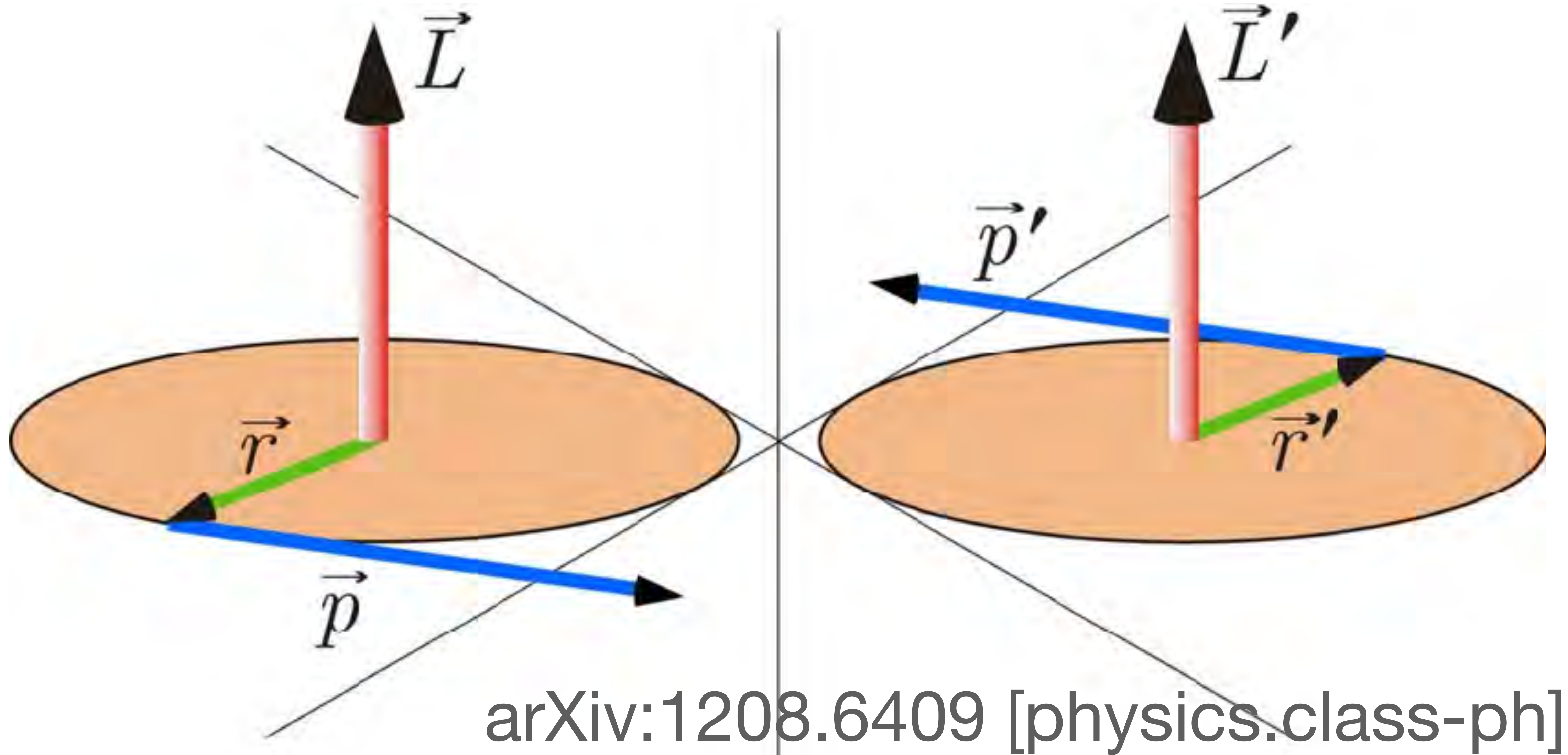
- **p** is the same vector, written using two different basis vectors.
- Therefore, **p**'s components are transformed as $(p'_x, p'_y, p'_z) = (-p_x, -p_y, -p_z)$

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.,

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



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*

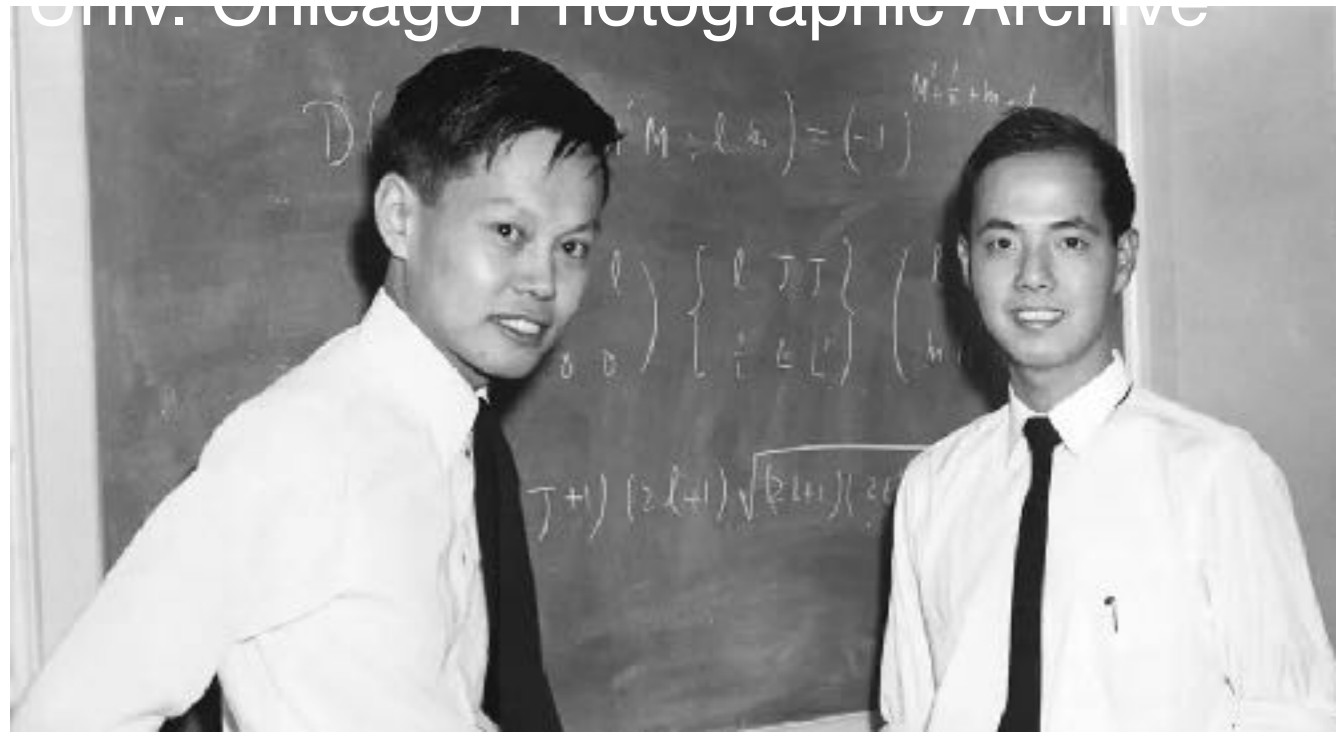
AND

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

Wu Chien-Shiung
吳健雄



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

Initial reaction

Bildarchiv der ETH-Bibliothek

Many physicists did not believe it initially.

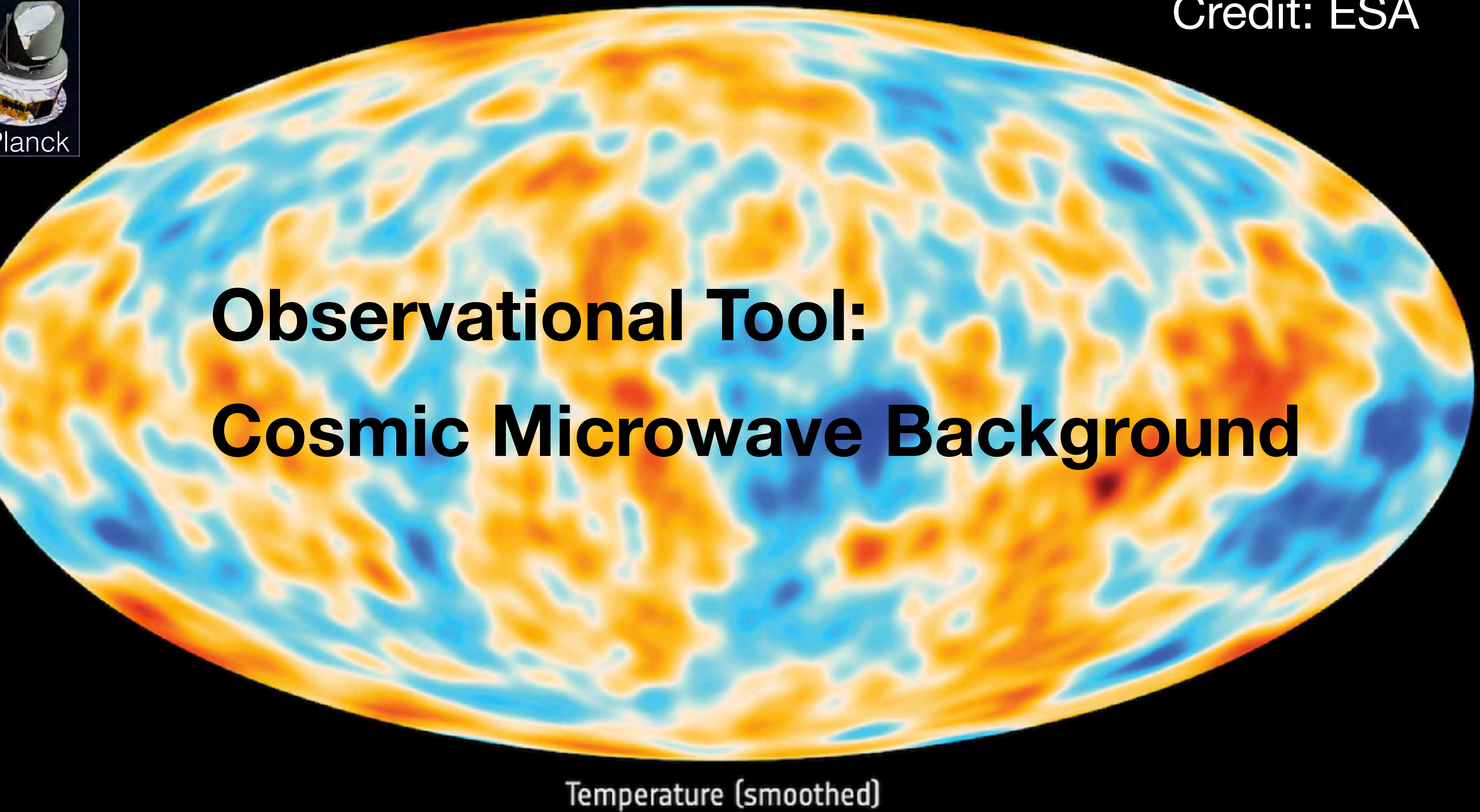
- To Lee and Yang’s theoretical paper on parity violation in β-decay:
    - Wolfgang Pauli said, “*Ich glaube aber nicht, daß der Herrgott ein schwacher Linkshänder ist*” (I do not believe that the Lord is a weak left-hander).
- To Wu’s discovery paper:
    - Wolfgang Pauli said, “*Sehr aufregend. Wie 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?*”

Part II: A Hint of New Physics

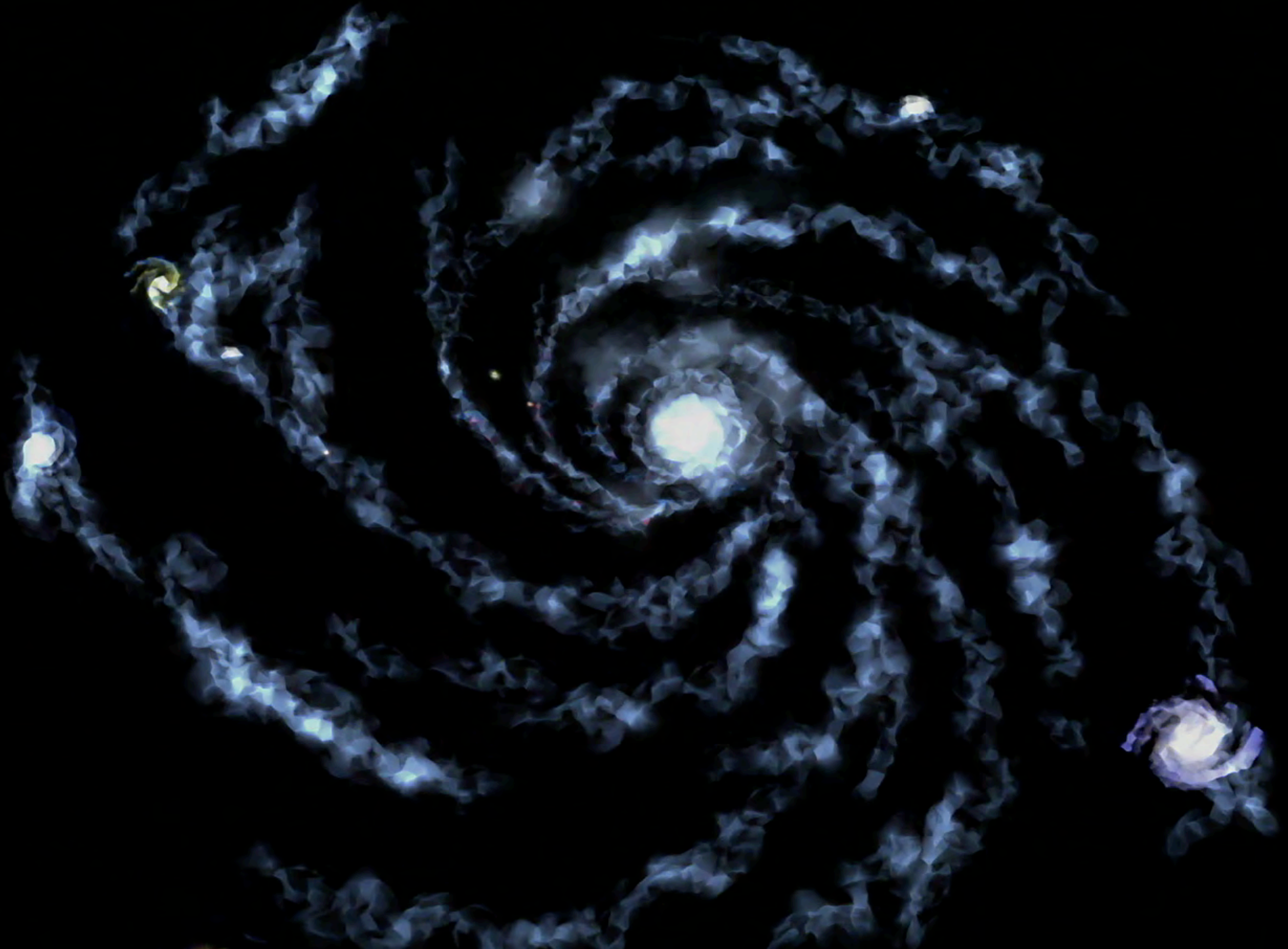
II.1 Parity Violation in the Cosmic Microwave Background (CMB)

Credit: ESA

Observational Tool:
Cosmic Microwave Background



Credit: WMAP Science Team



The sky in various wavelengths

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

Planck

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

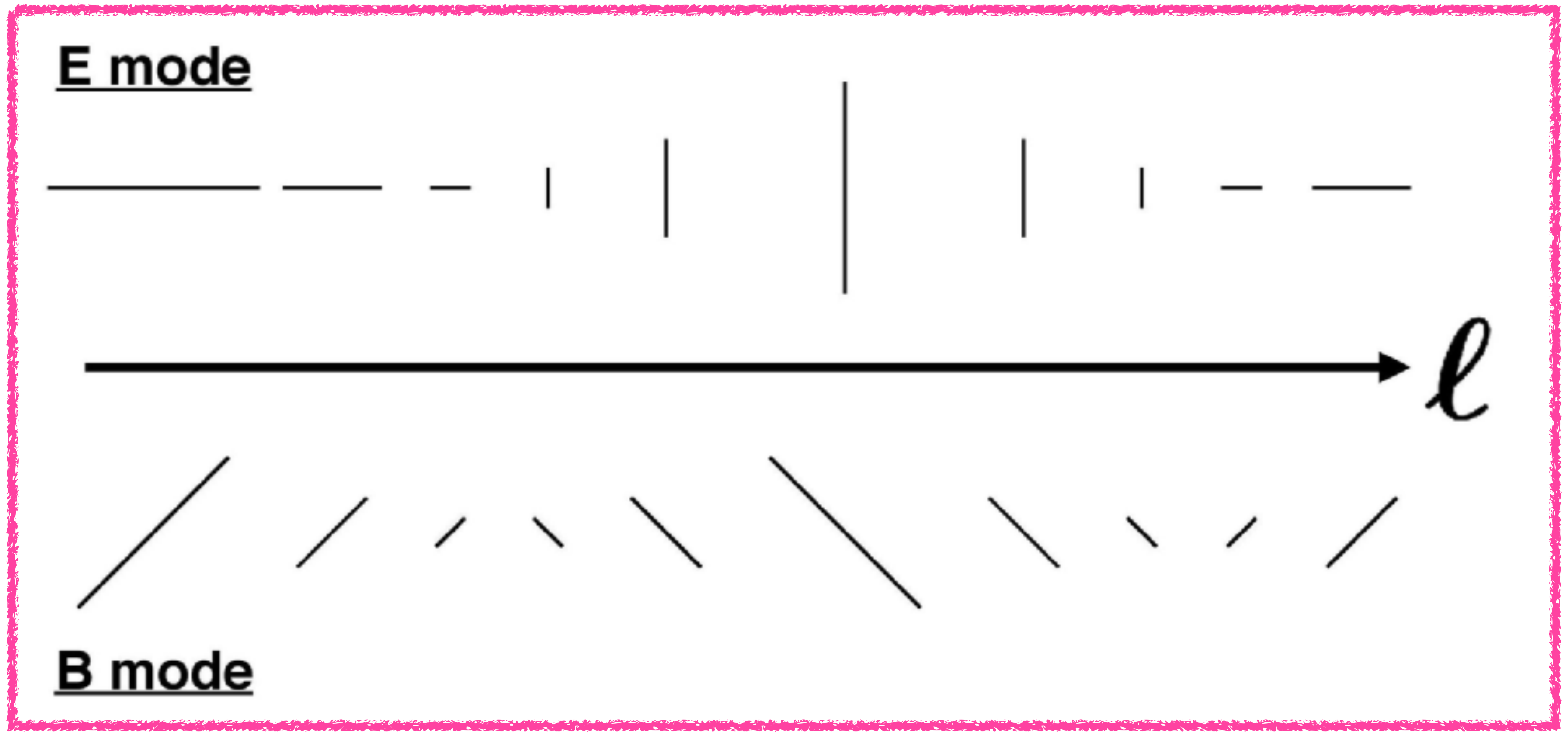
Pseudoscalar: EB correlation

- 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!**

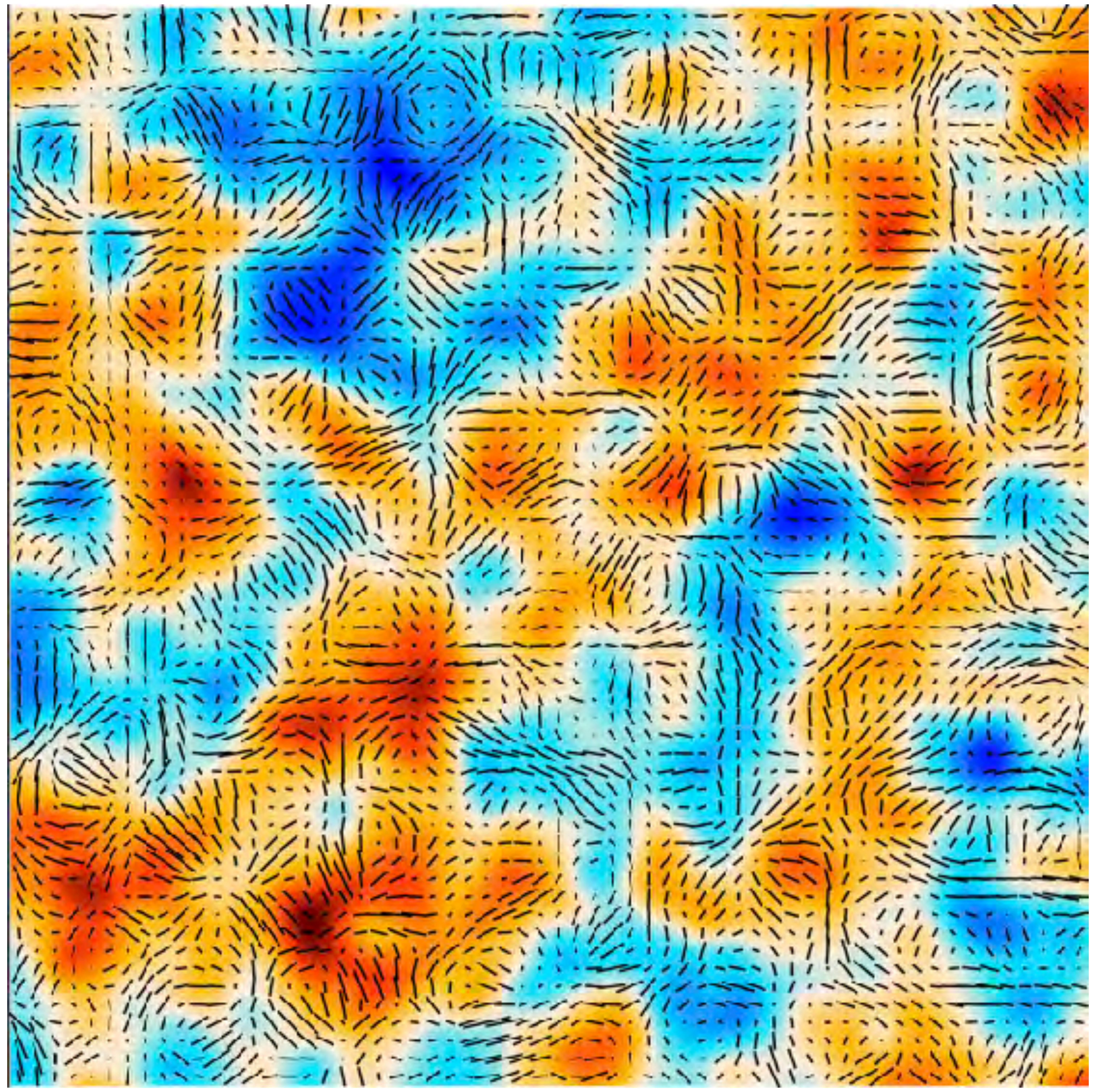
Zaldarriaga, Seljak (1997); Kamionkowski, Kosowsky, Stebbins (1997)

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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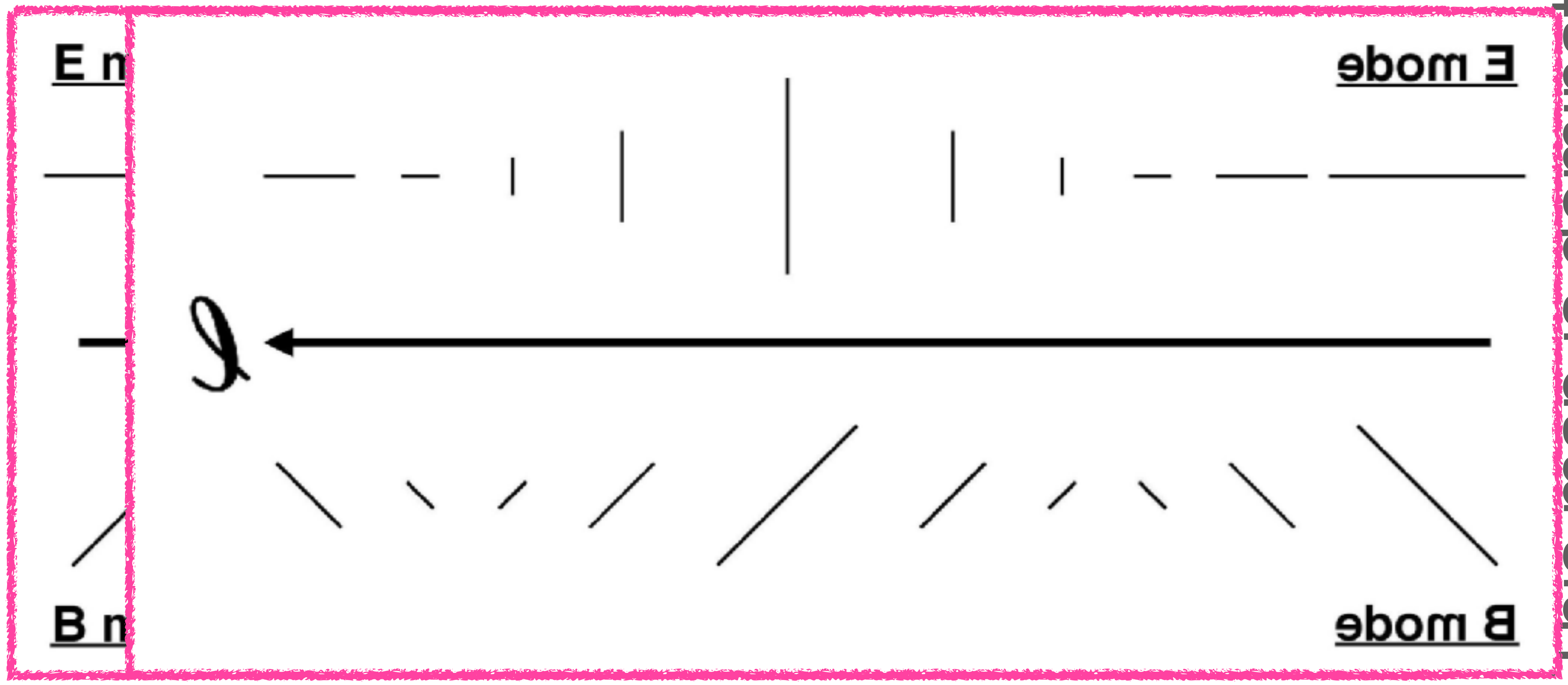

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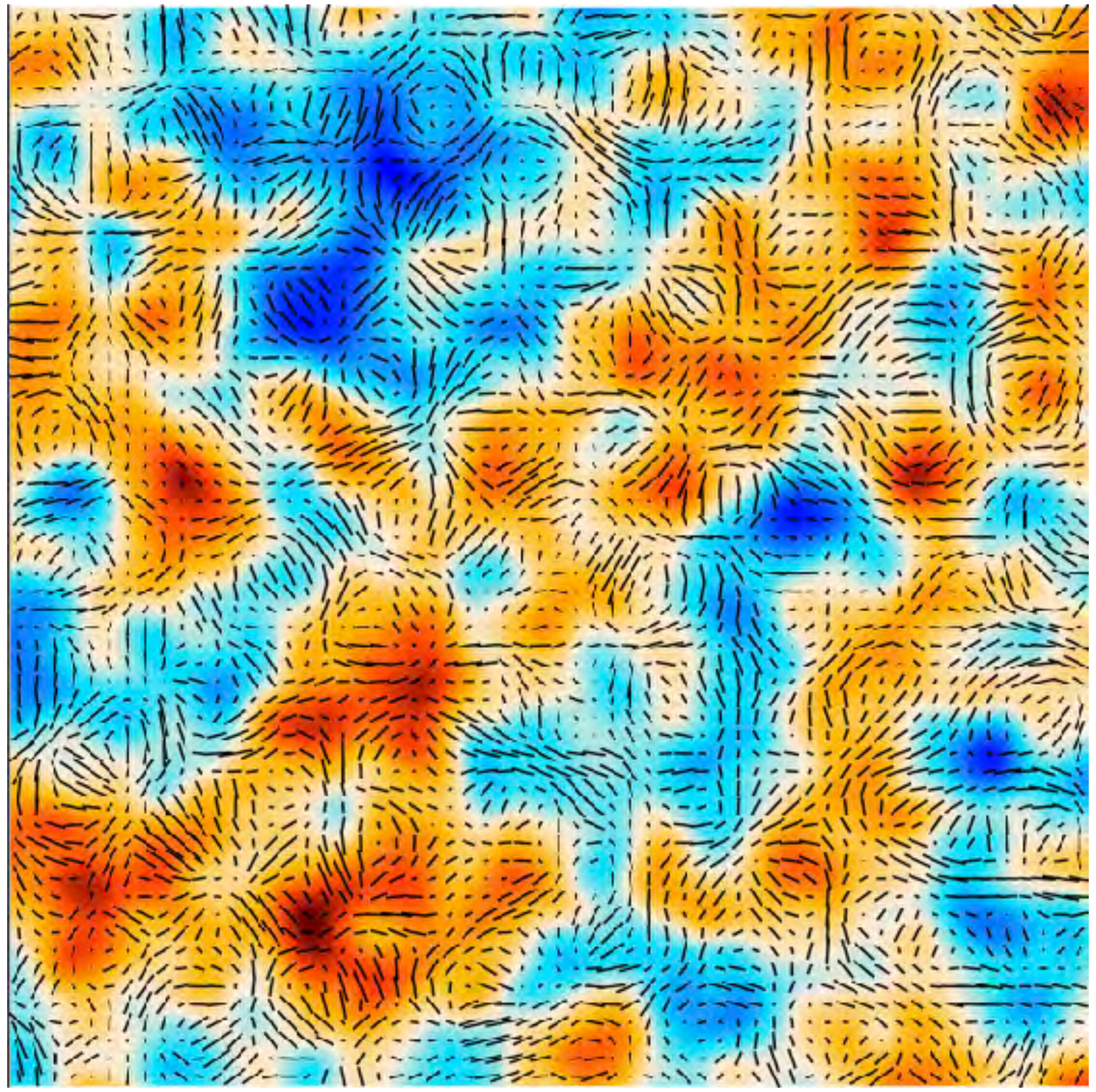

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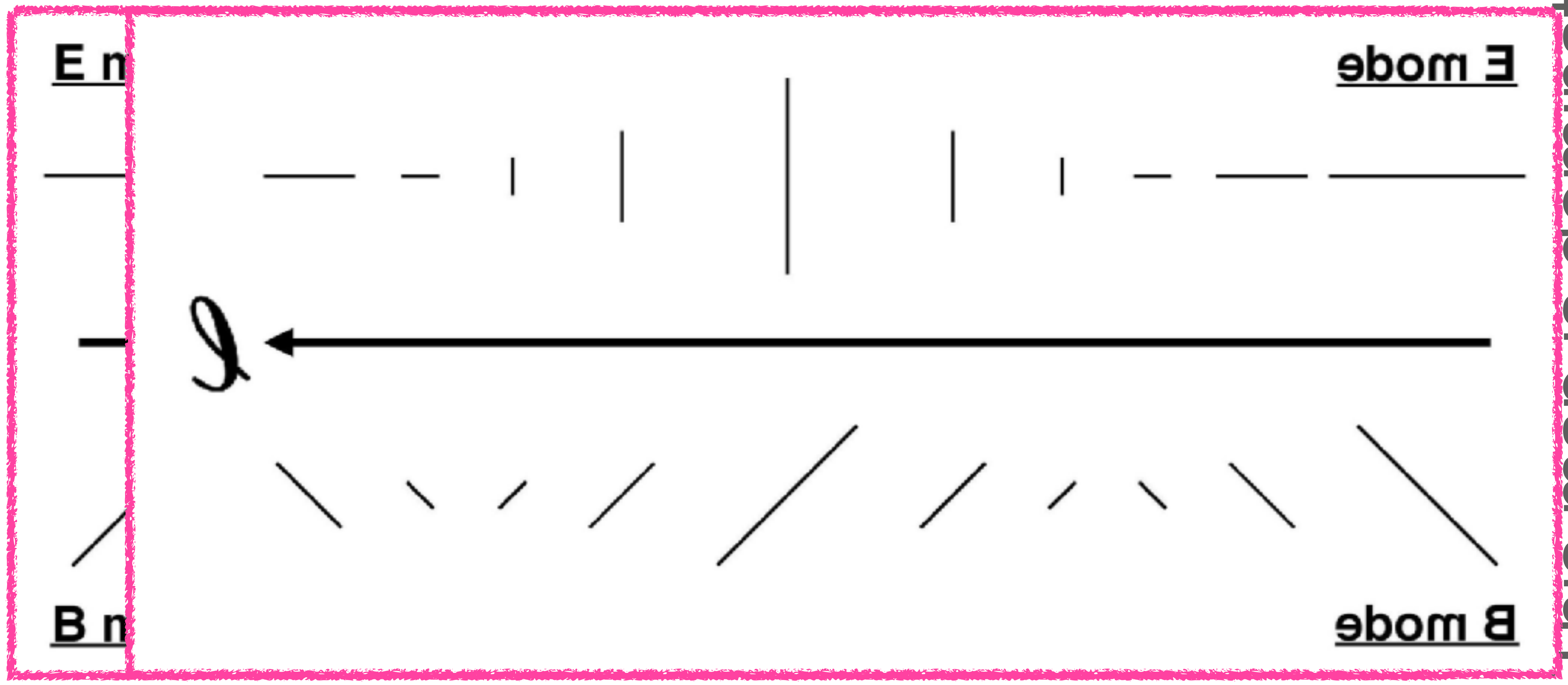

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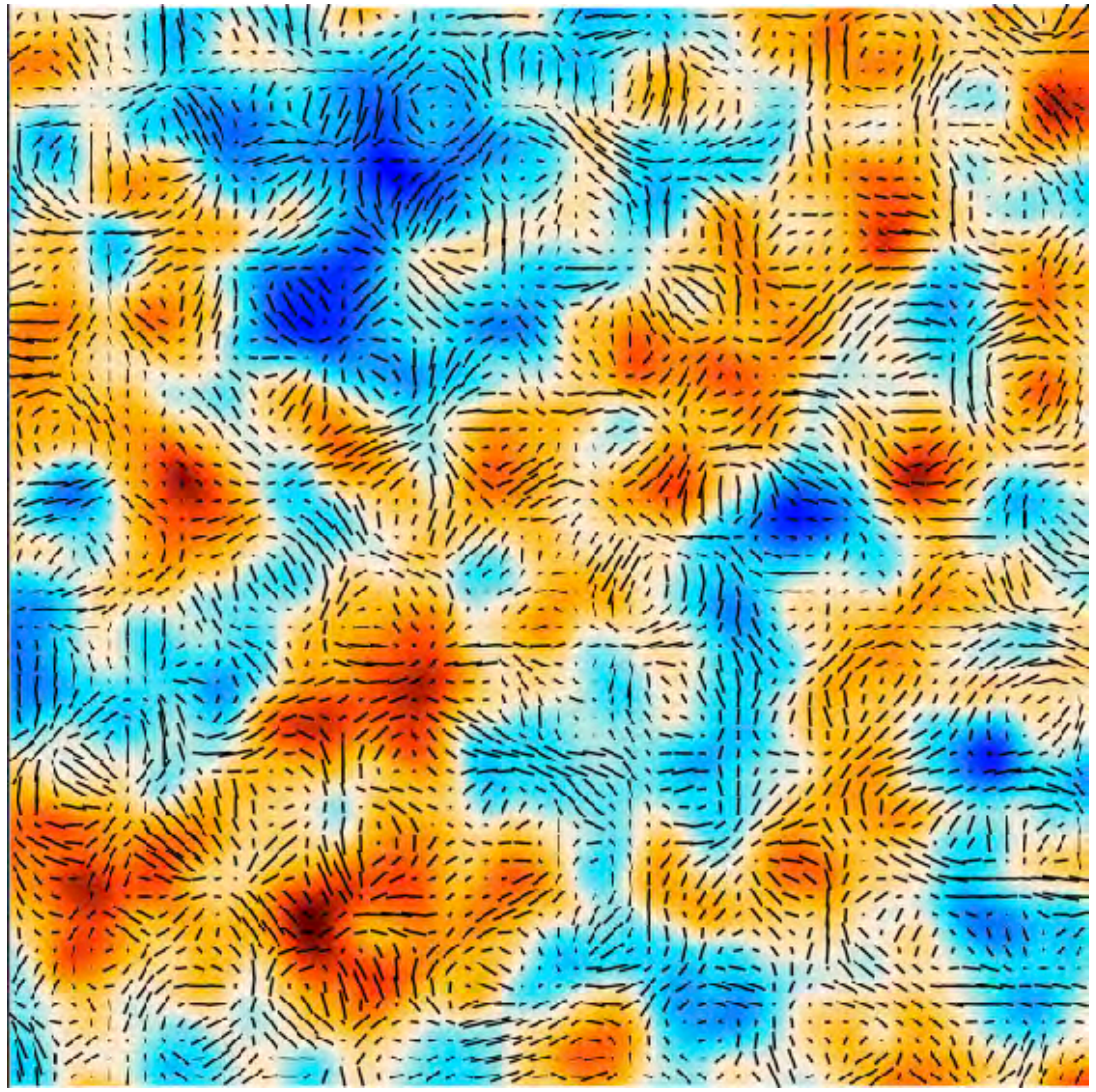


$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

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

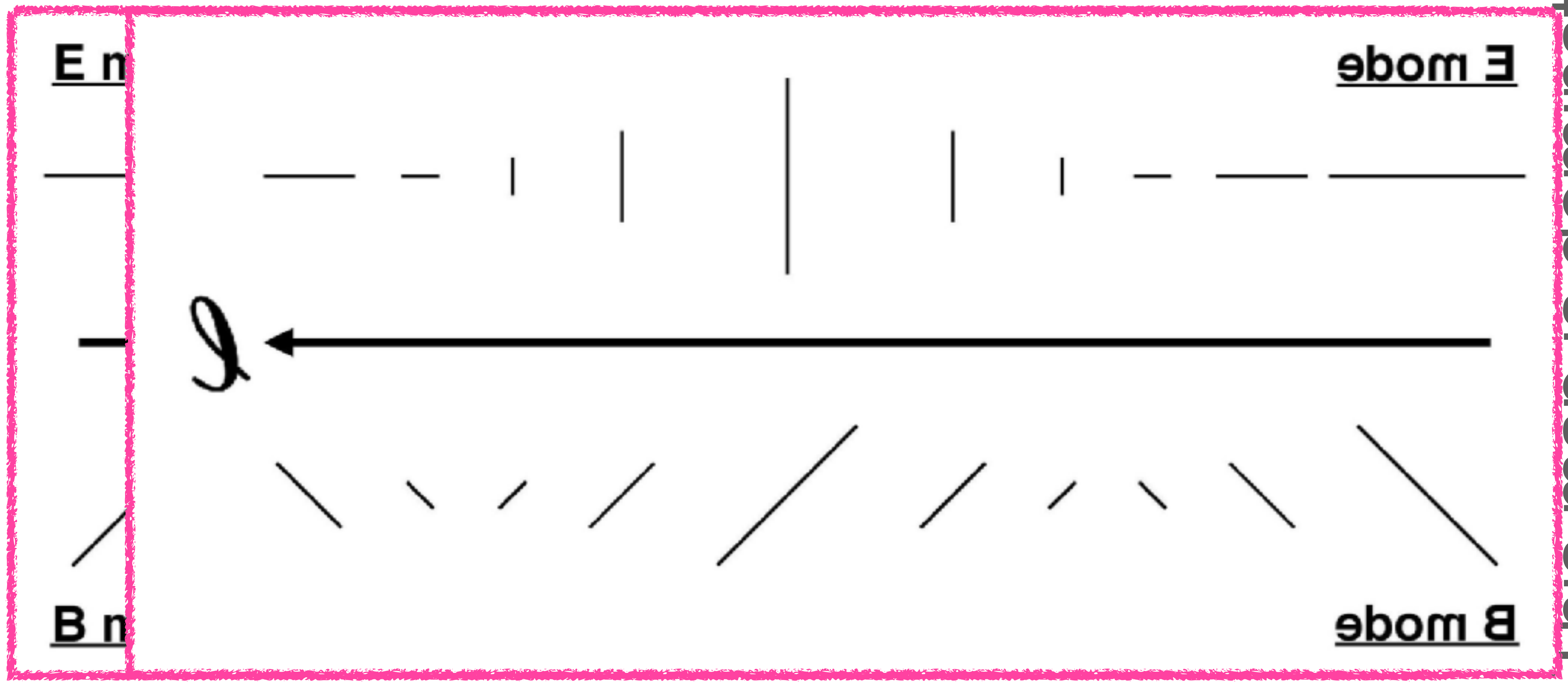
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

These are scalars and insensitive to parity violation.

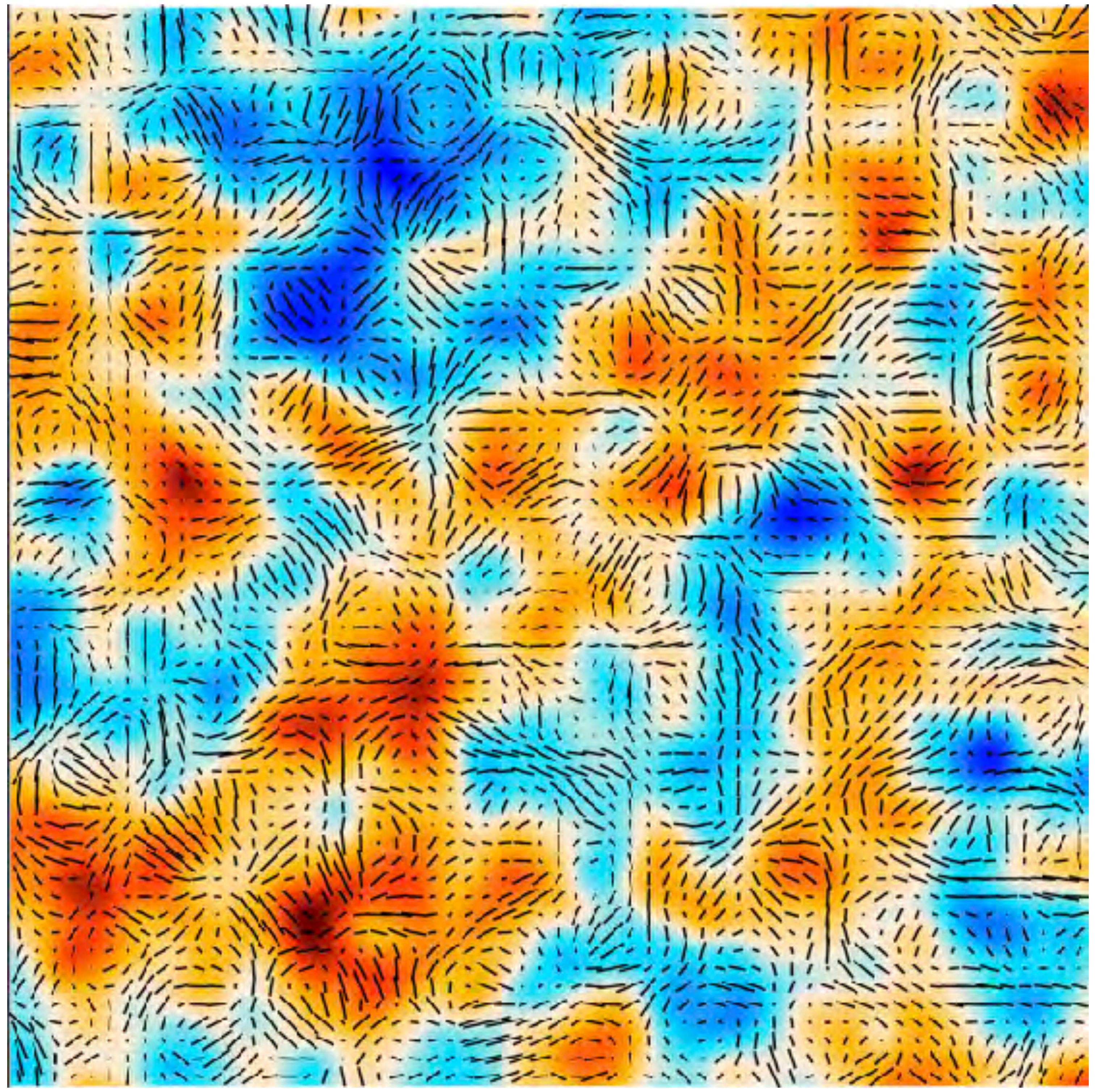
Lue, Wang, Kamionkowski (1999); Feng et al. (2005, 2006)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

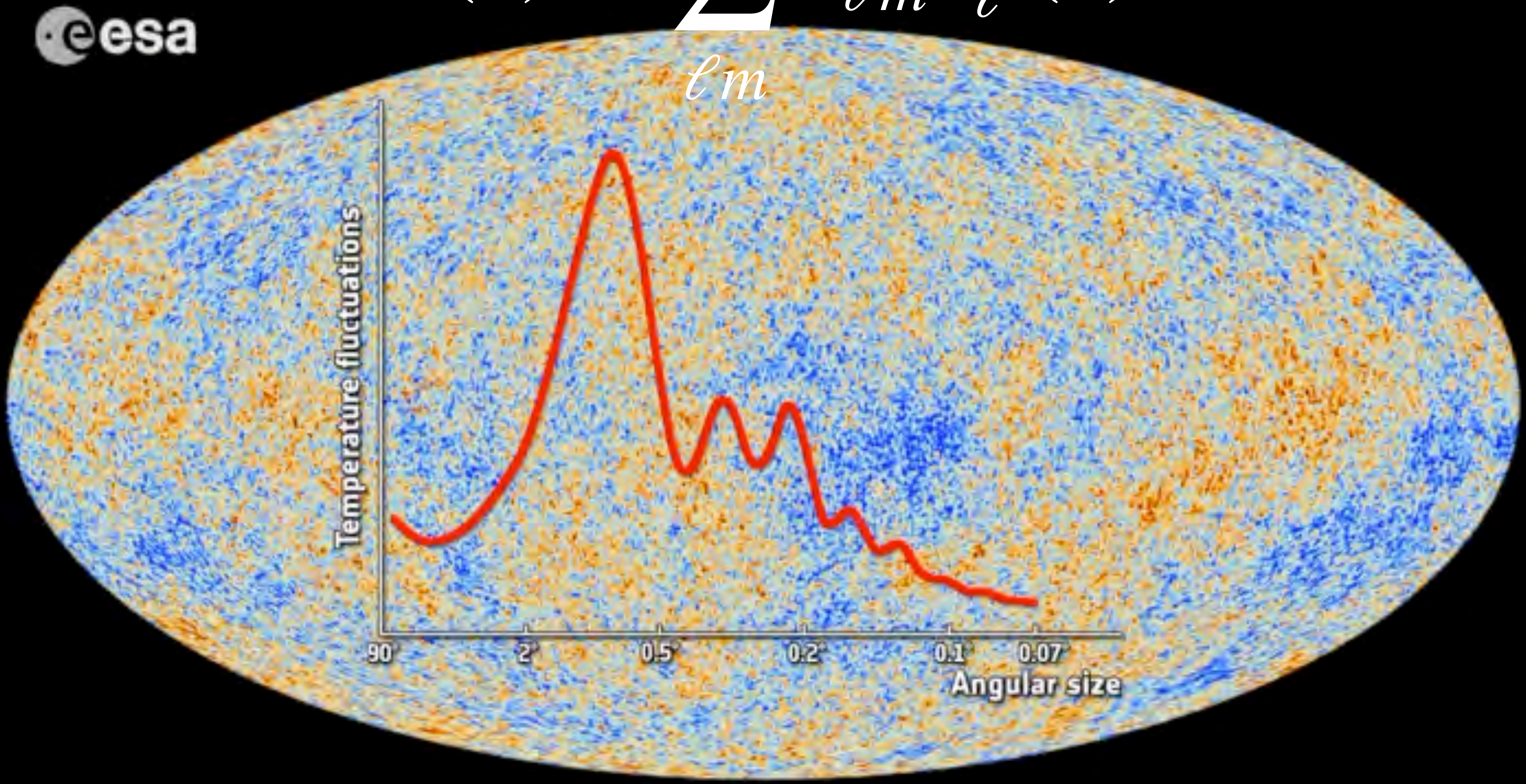
$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} -$$

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

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

Spherical Harmonics Decomposition

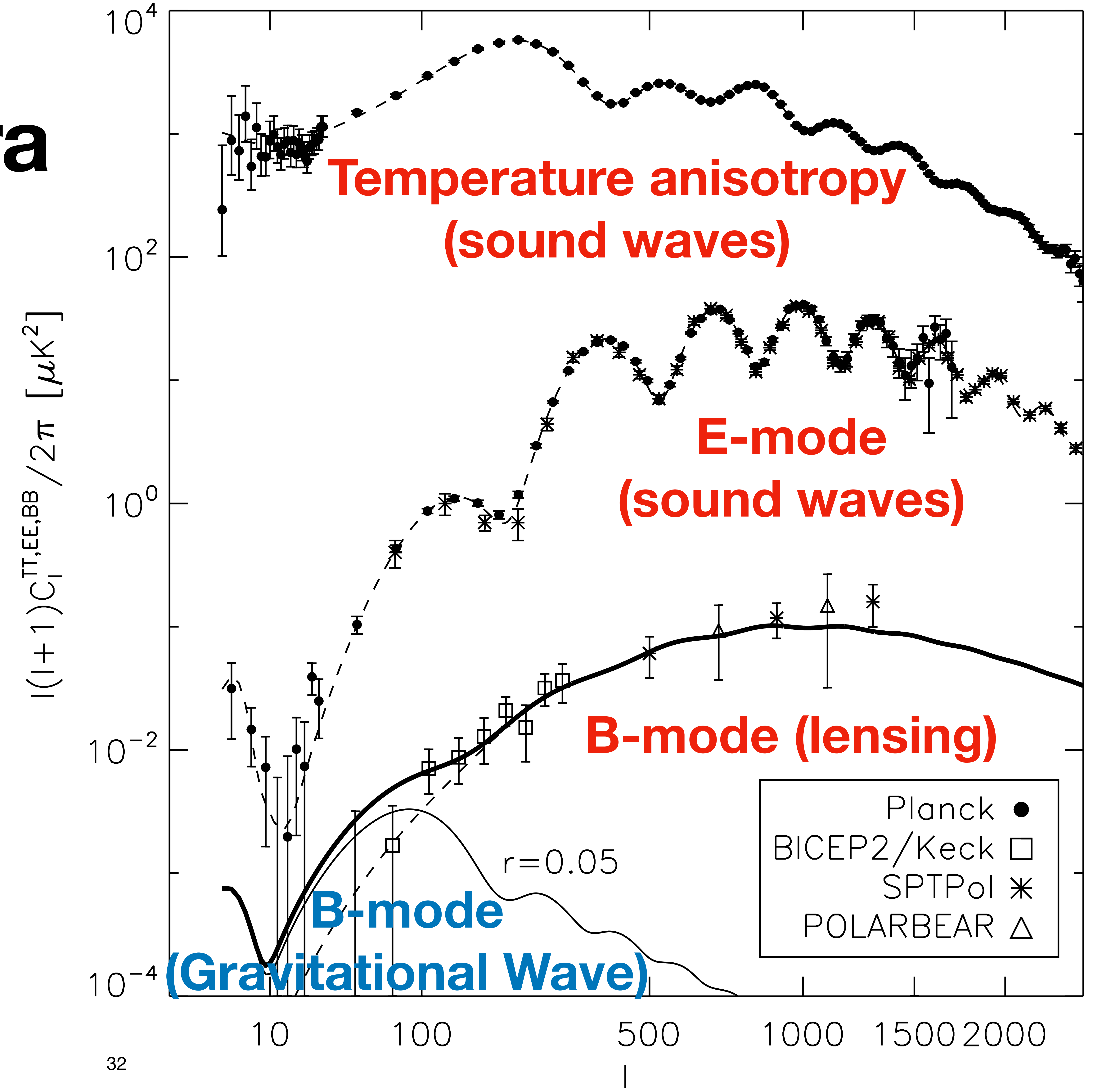
$$\Delta T(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_\ell^m(\hat{n})$$



CMB Power Spectra

Progress over 30 years

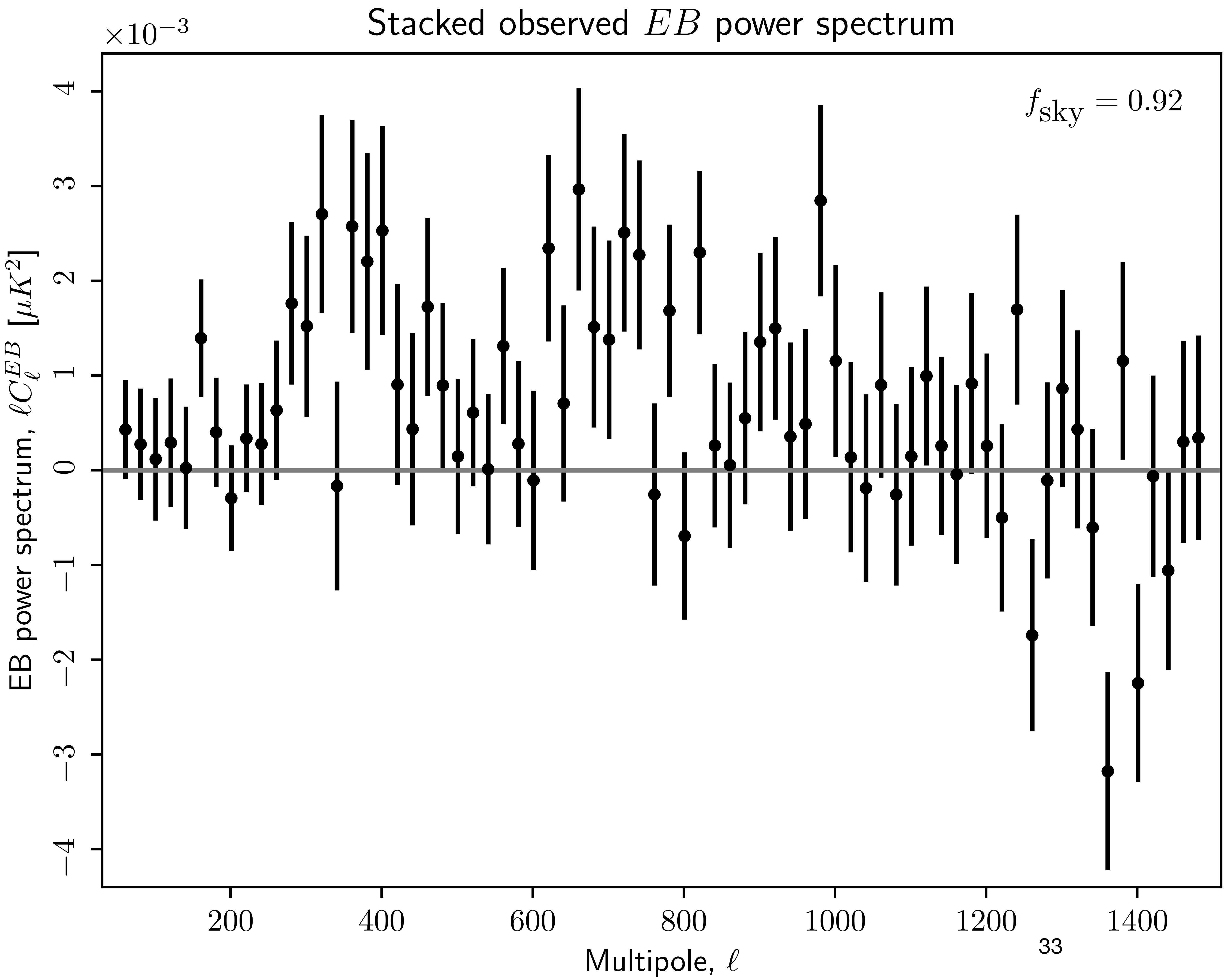
- This is the typical figure seen in talks and lectures on the CMB.
  - The temperature and the E- and B-mode polarization power spectra are well measured.
- **Parity violation appears in the TB and EB power spectra, not shown here.**

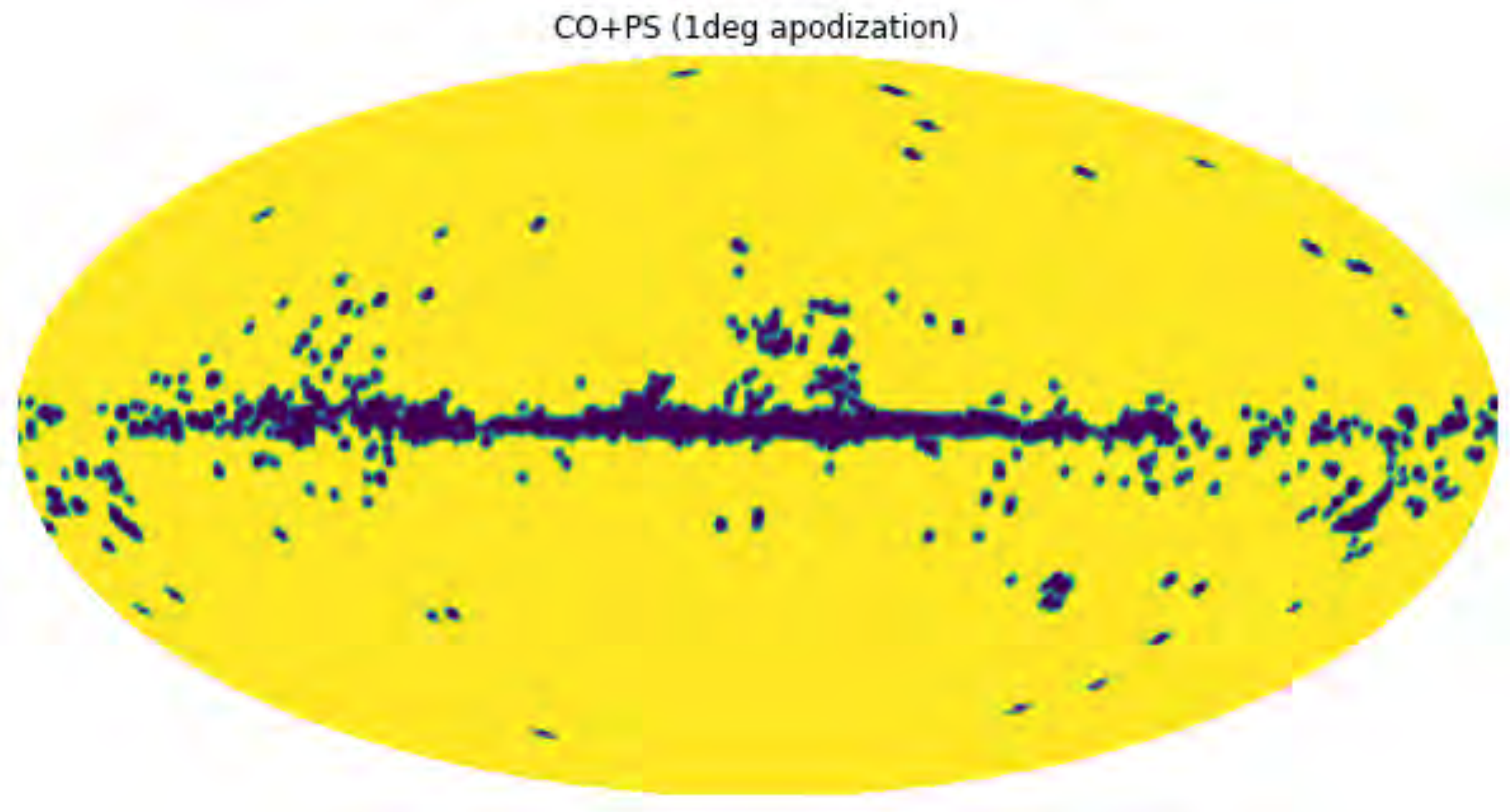


Eskilt, EK (2022)

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

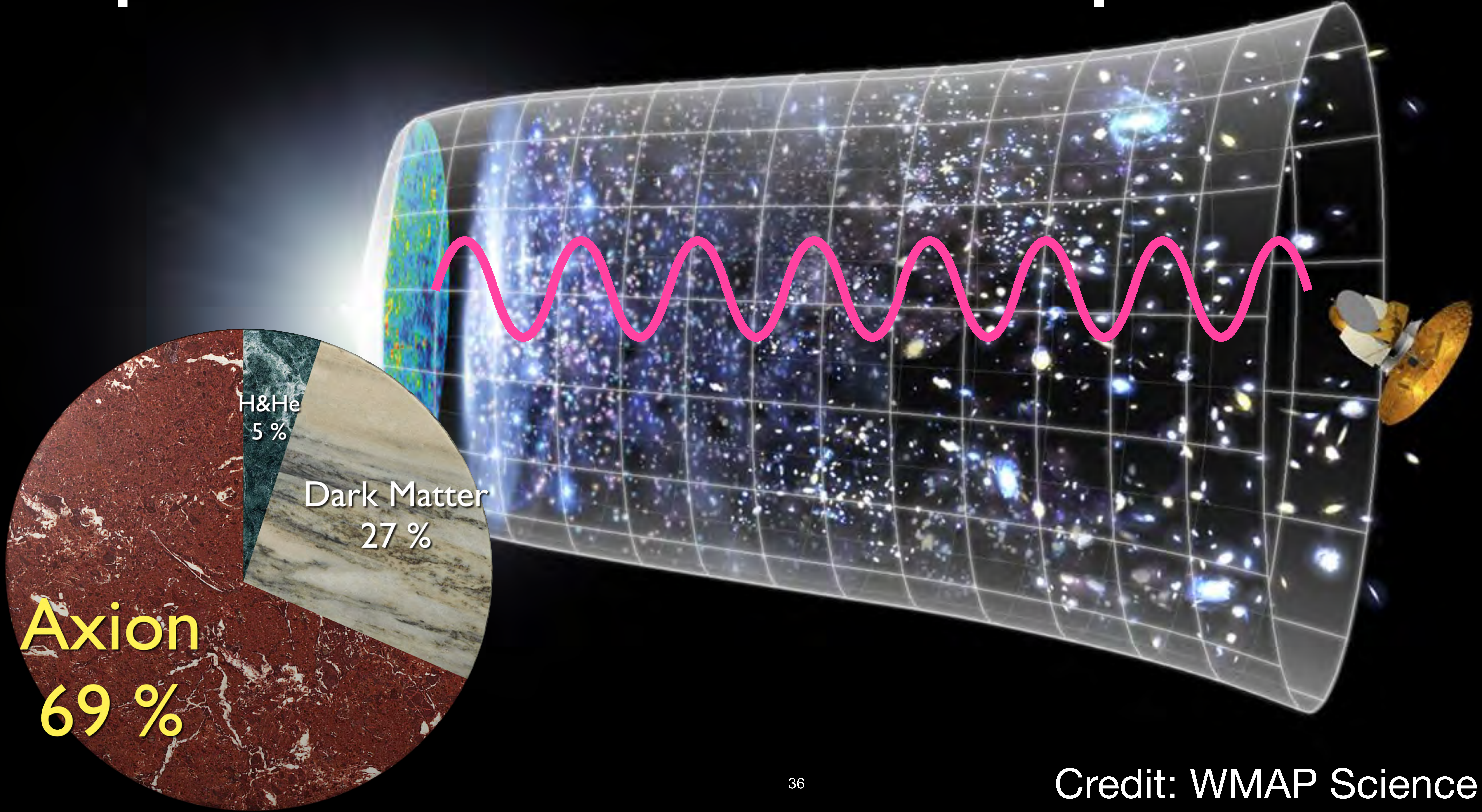
How does the EM wave of the CMB propagate?

The surface of "last scattering" by electrons

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

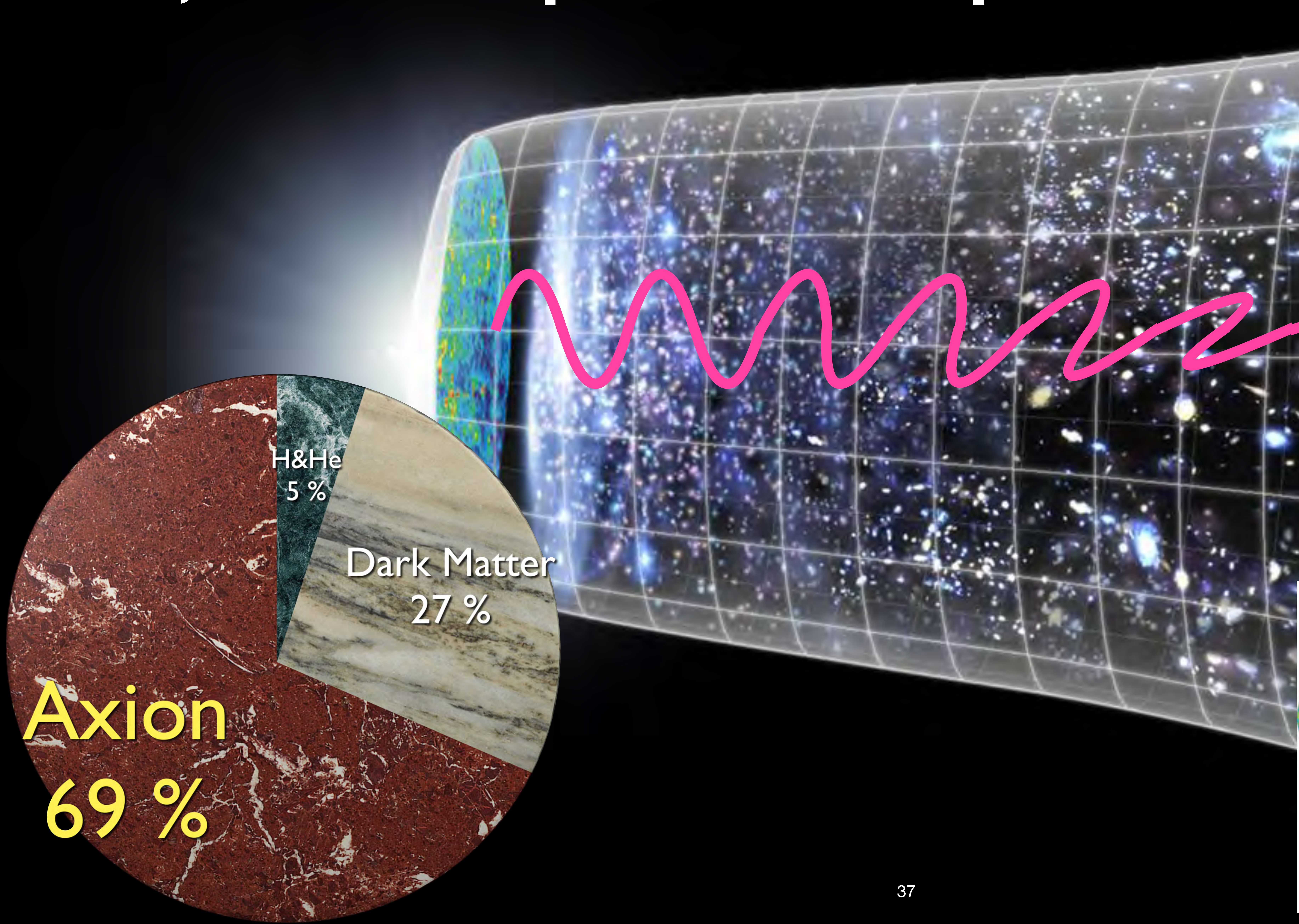
Credit: WMAP Science Team

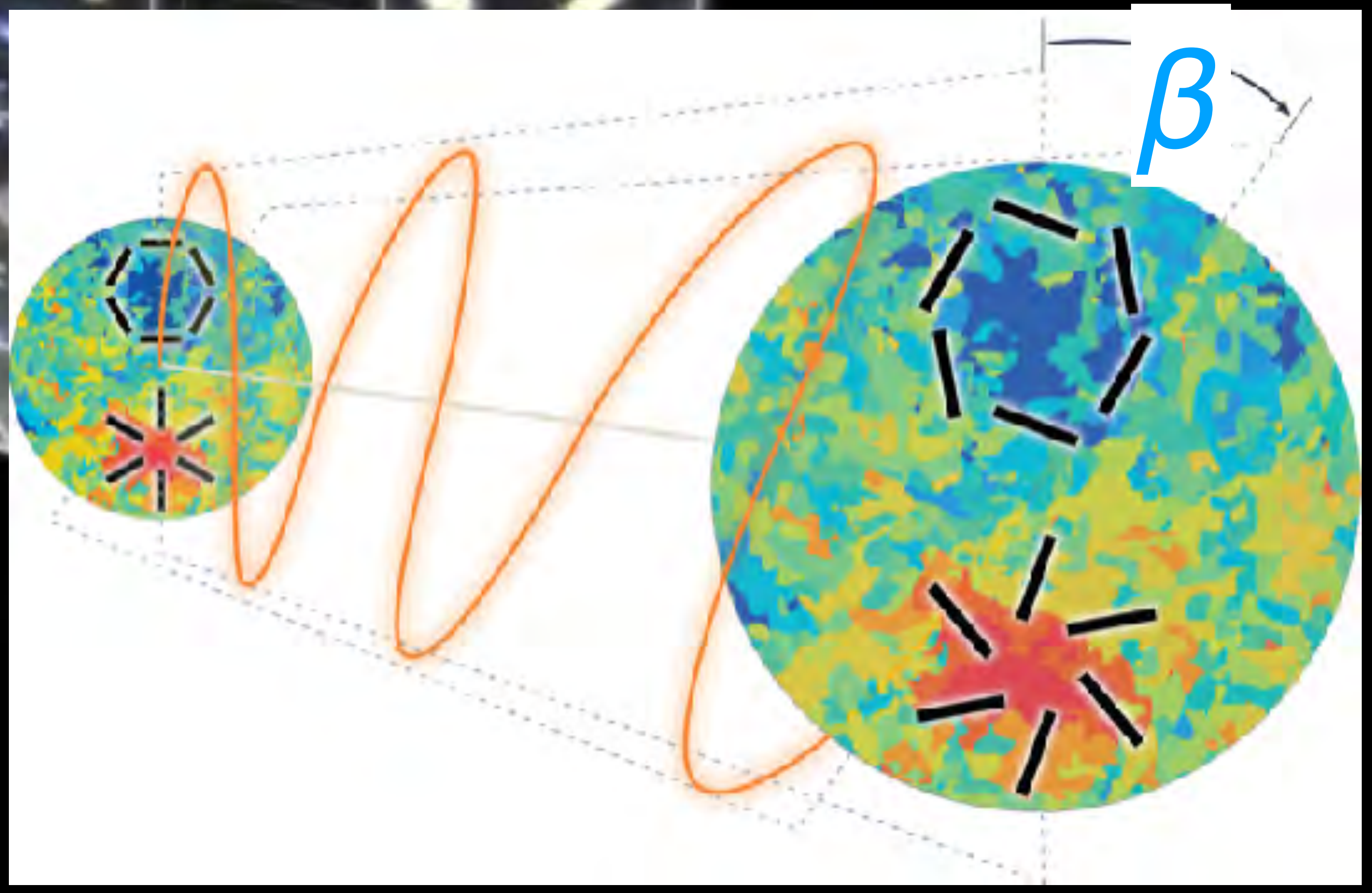
If space were filled with axionlike particles…



Credit: WMAP Science Team

then, the CMB polarization plane would be rotated!



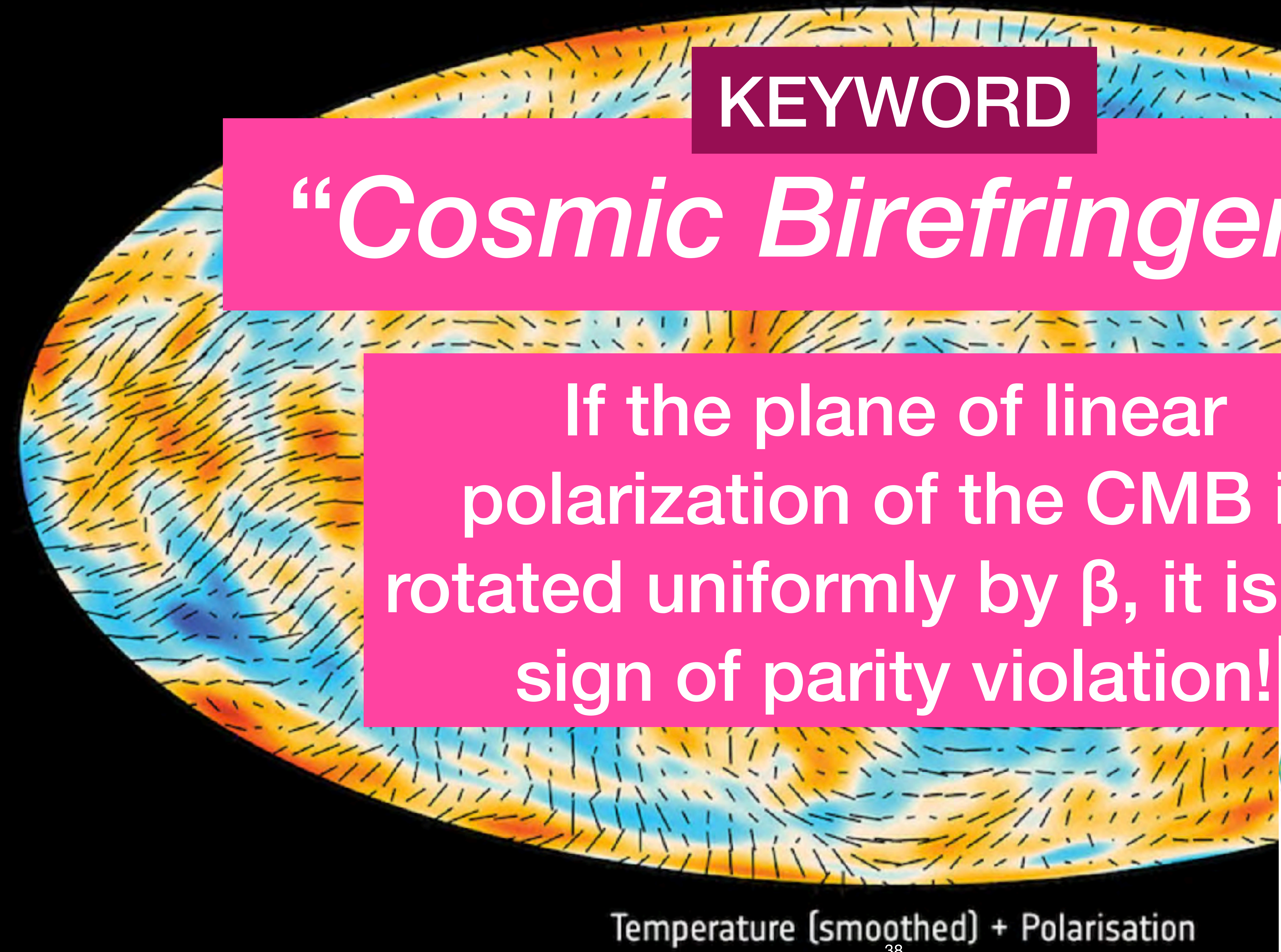


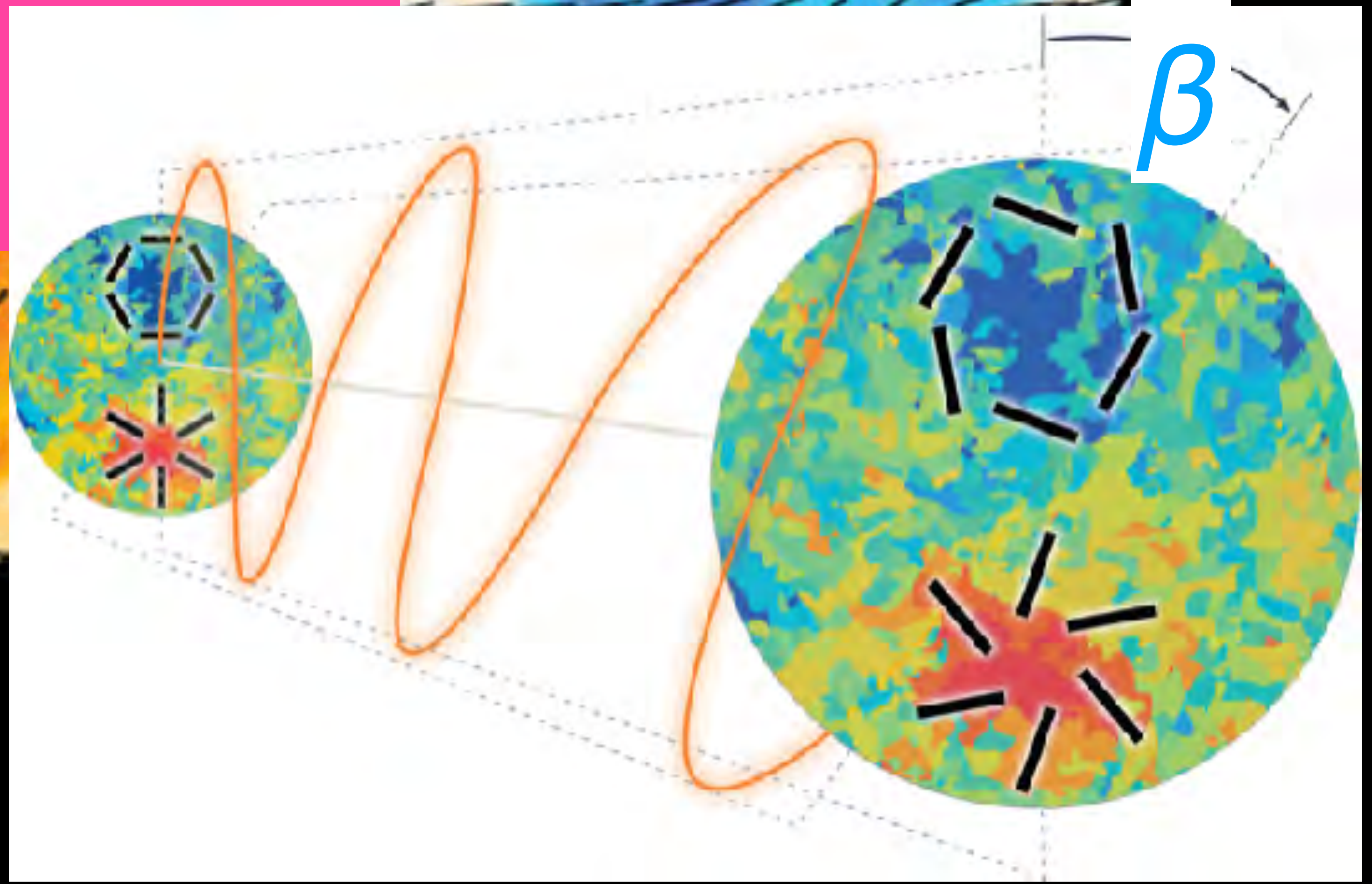
Credit: ESA

KEYWORD

“*Cosmic Birefringence*”

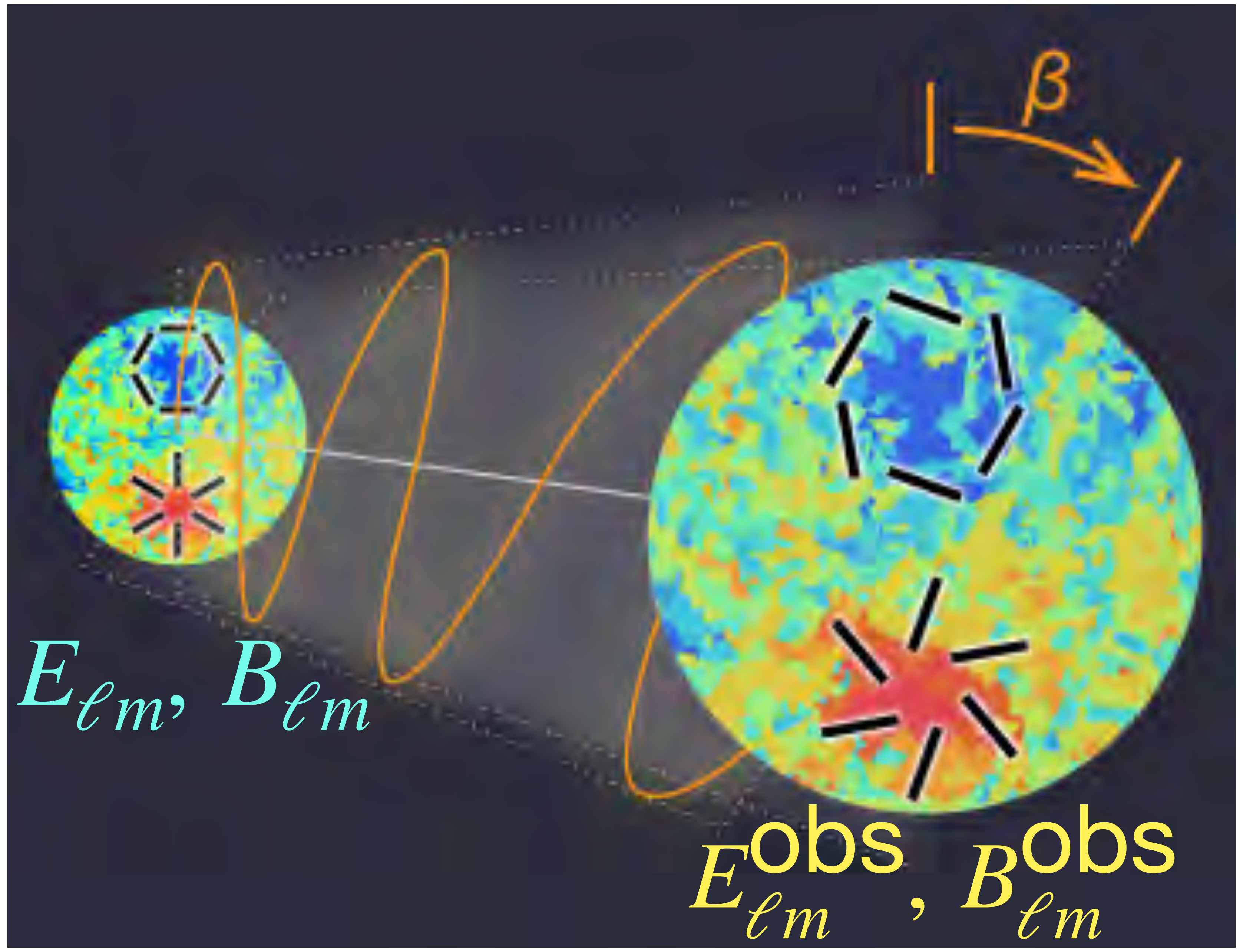
If the plane of linear polarization of the CMB is rotated uniformly by β, it is the sign of parity violation!





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

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

$$E^{\text{obs}}_{\ell m} \pm i B^{\text{obs}}_{\ell m} = (E_{\ell m} \pm i B_{\ell m}) e^{\pm 2i\beta}$$

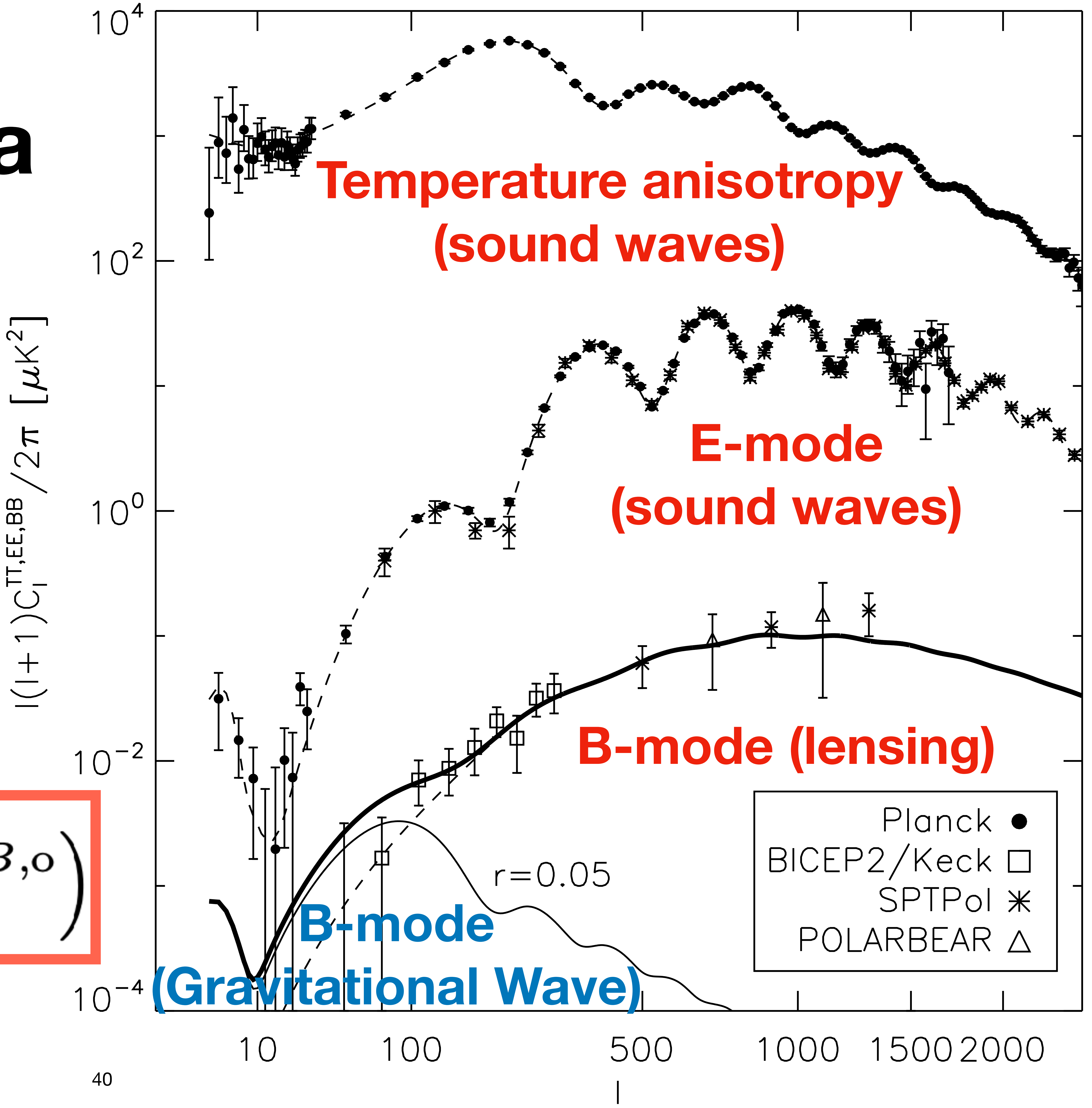
- which gives

$$E^{\text{obs}}_{\ell m} = E_{\ell m}\cos(2\beta) - B_{\ell m}\sin(2\beta)$$
$$B^{\text{obs}}_{\ell m} = E_{\ell m}\sin(2\beta) + B_{\ell m}\cos(2\beta)$$

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!

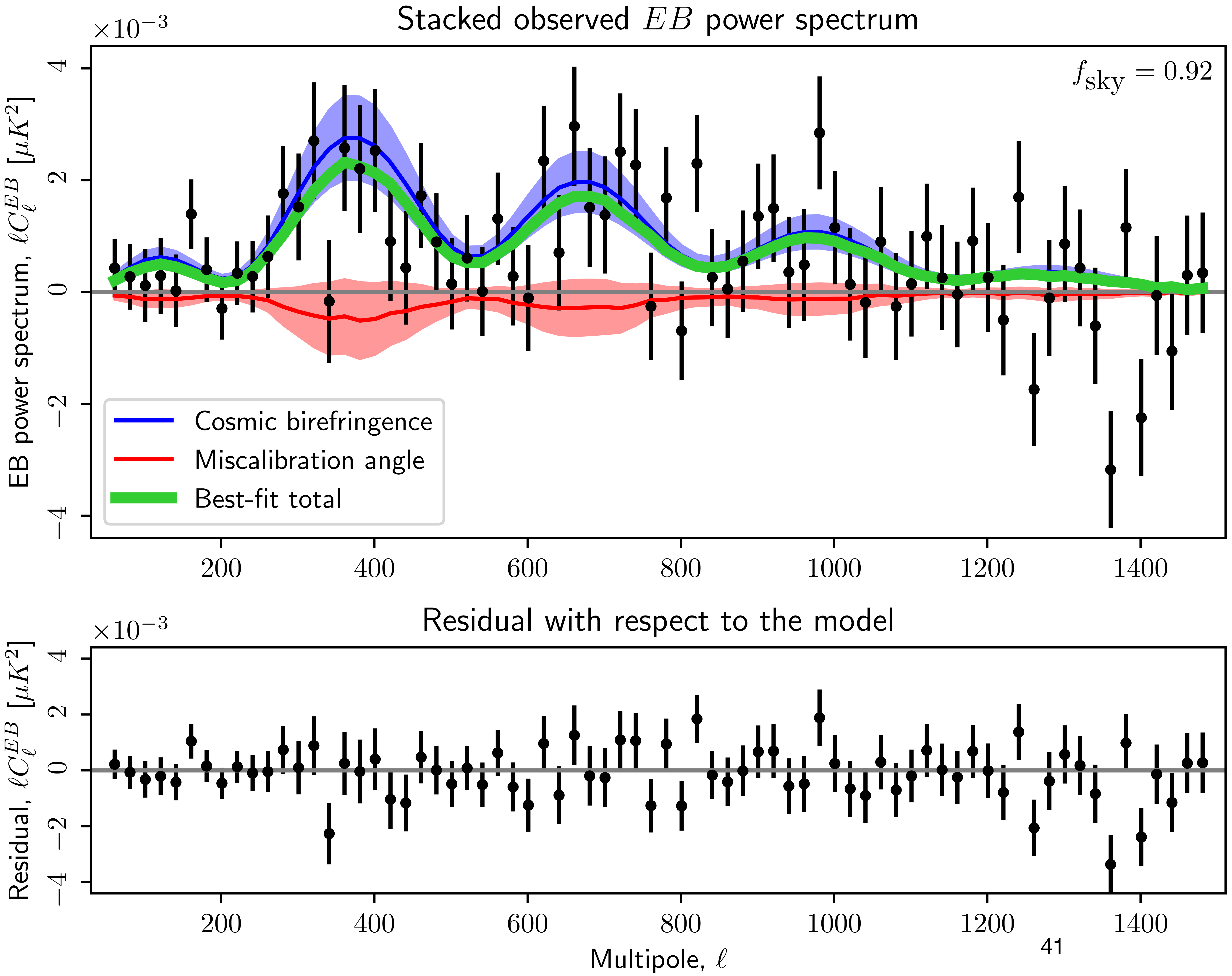
$$\boxed{C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)}$$

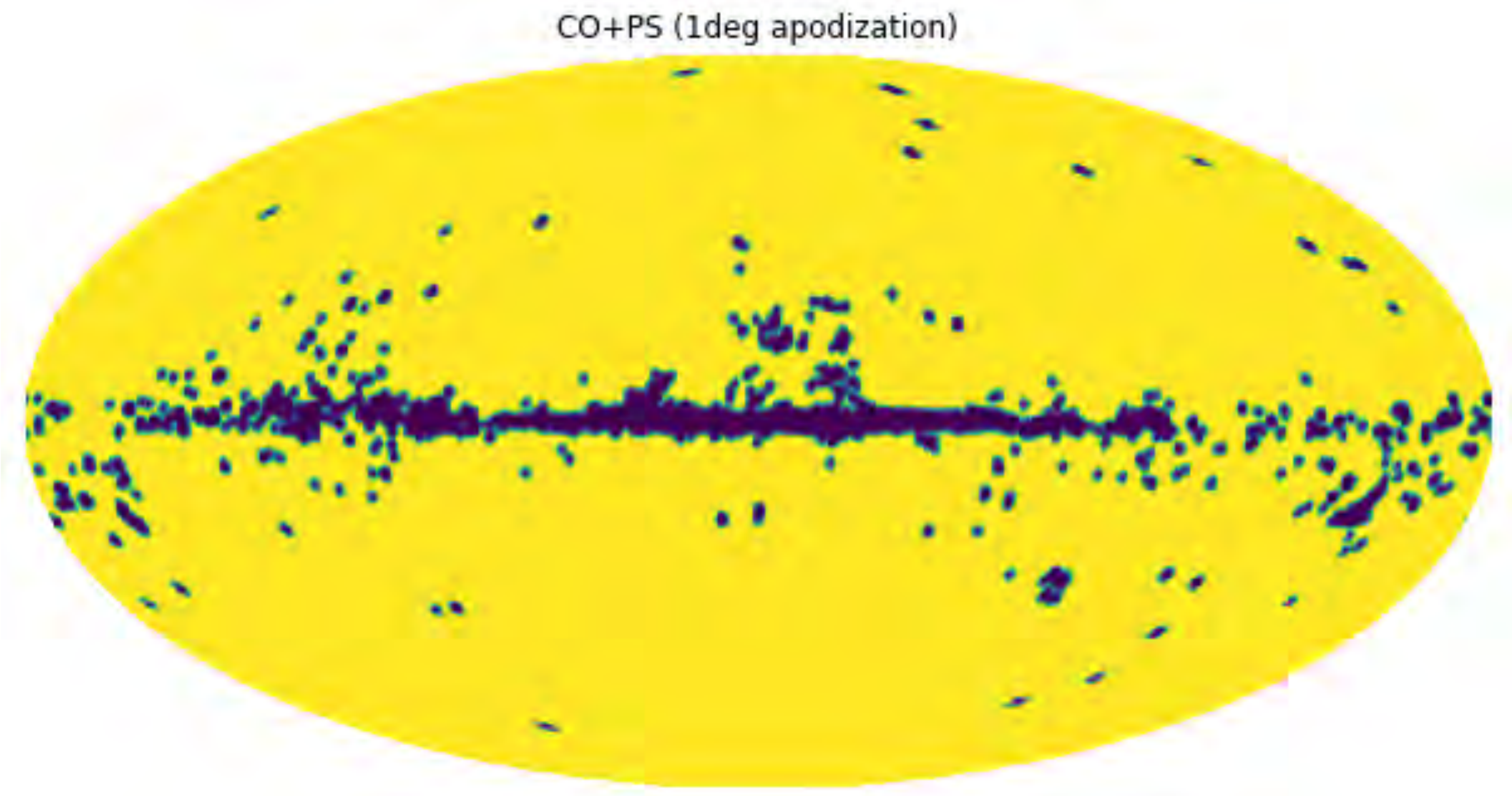


Minami, EK (2020); Diego-Palazuelos et al. (2022); Eskilt, EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

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



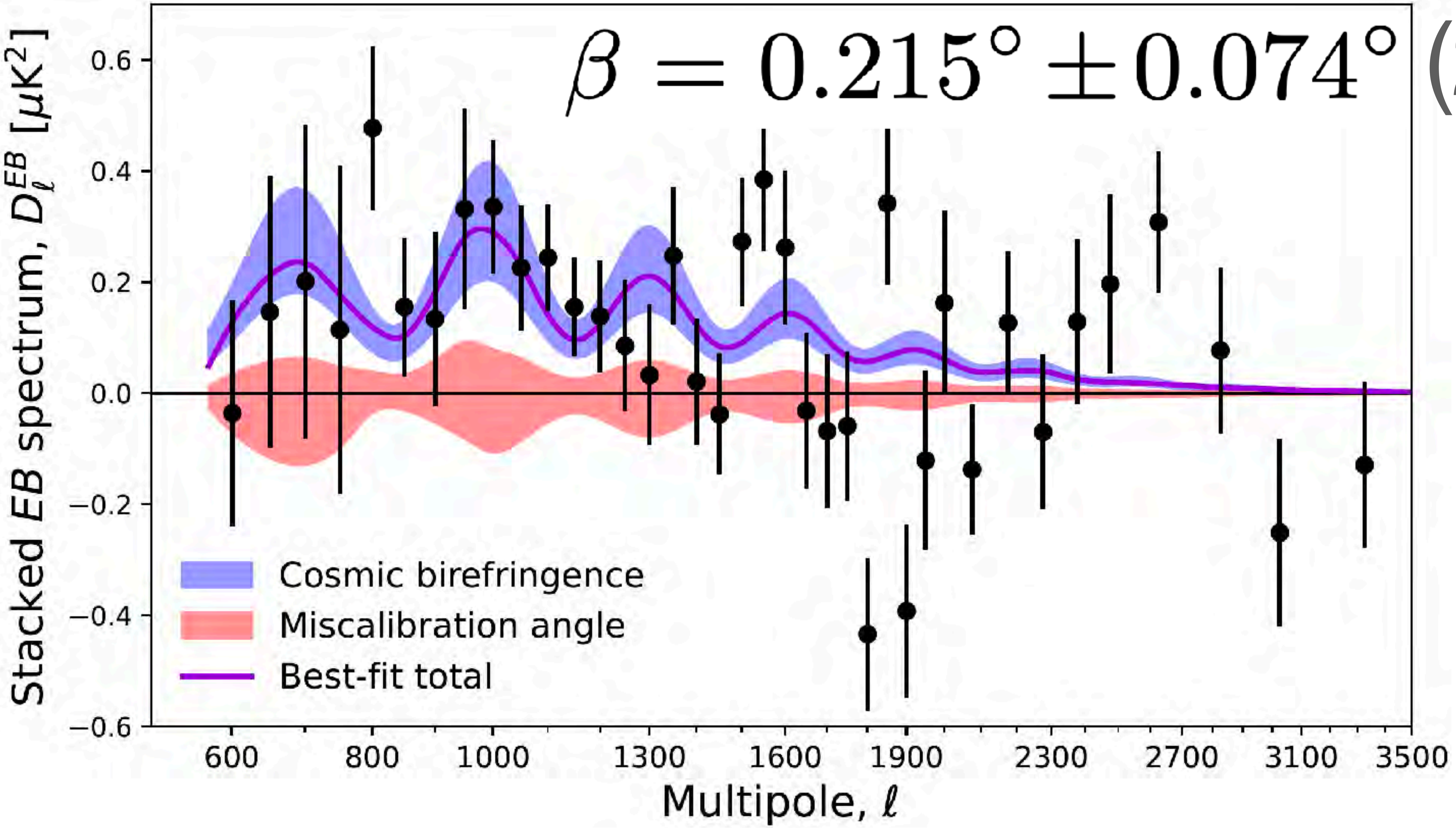


- **β = 0.34 ± 0.09 deg**
- $\chi^2 = 65.3$
  - Good fit! The statistical significance is 3.6σ.

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

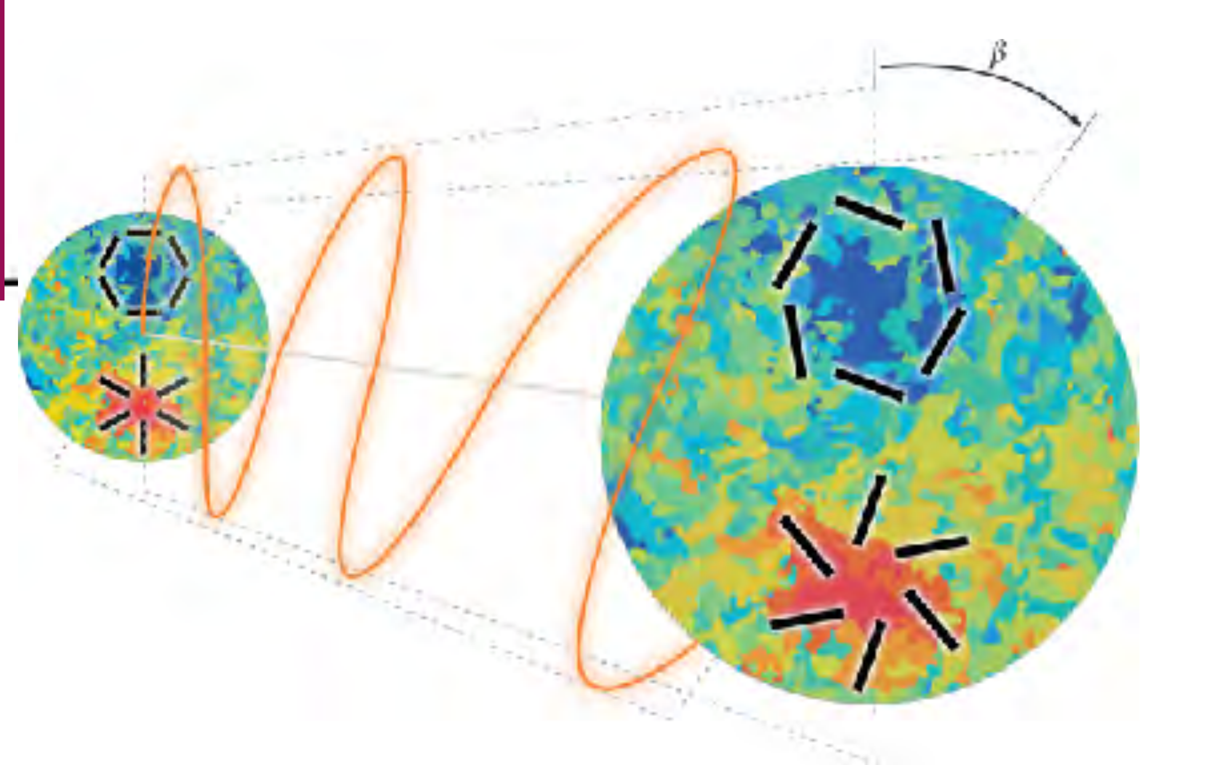
Atacama Cosmology Telescope (DR6)

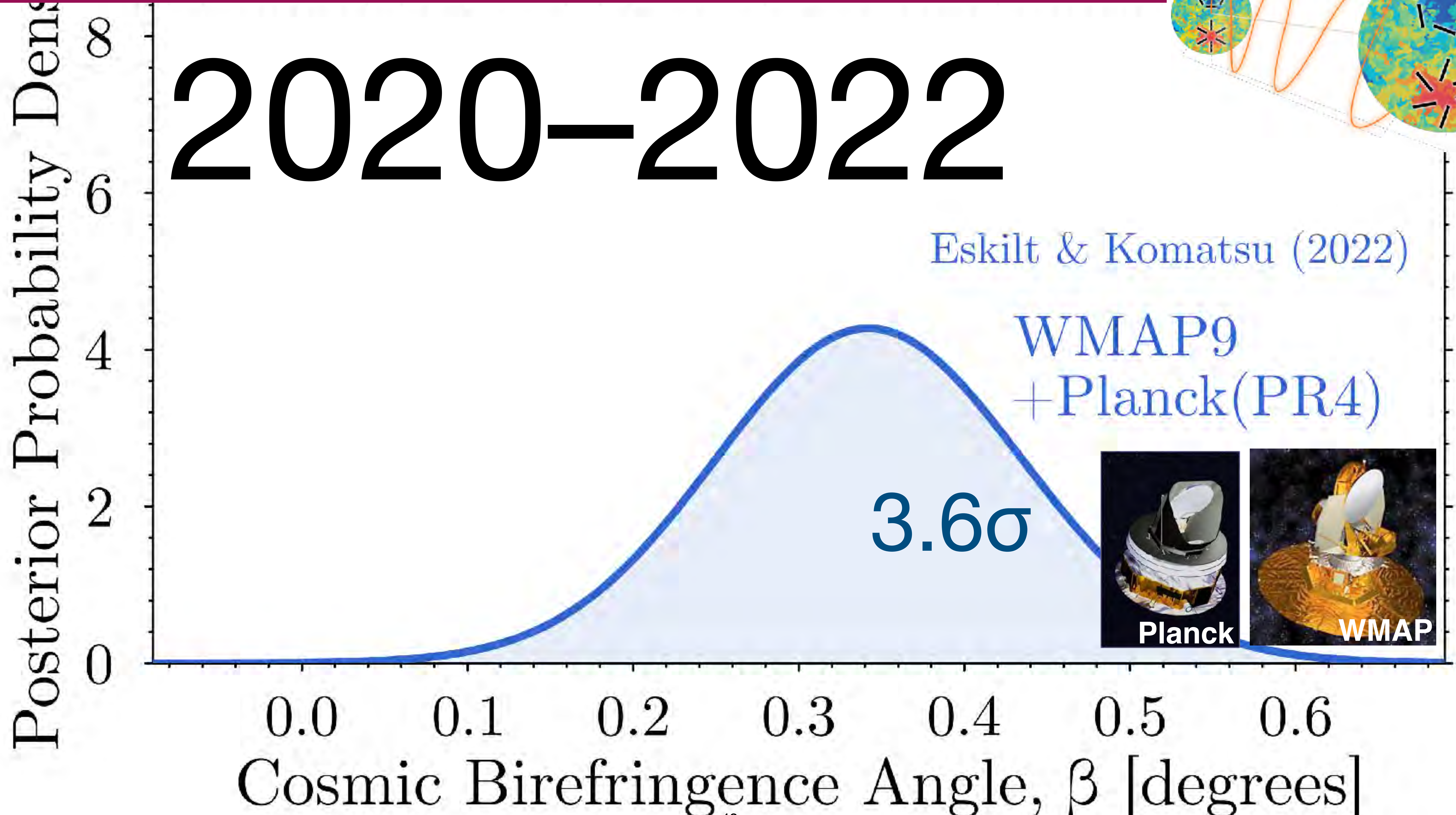
***We needed to measure it in independent experiments* -> here it is!**



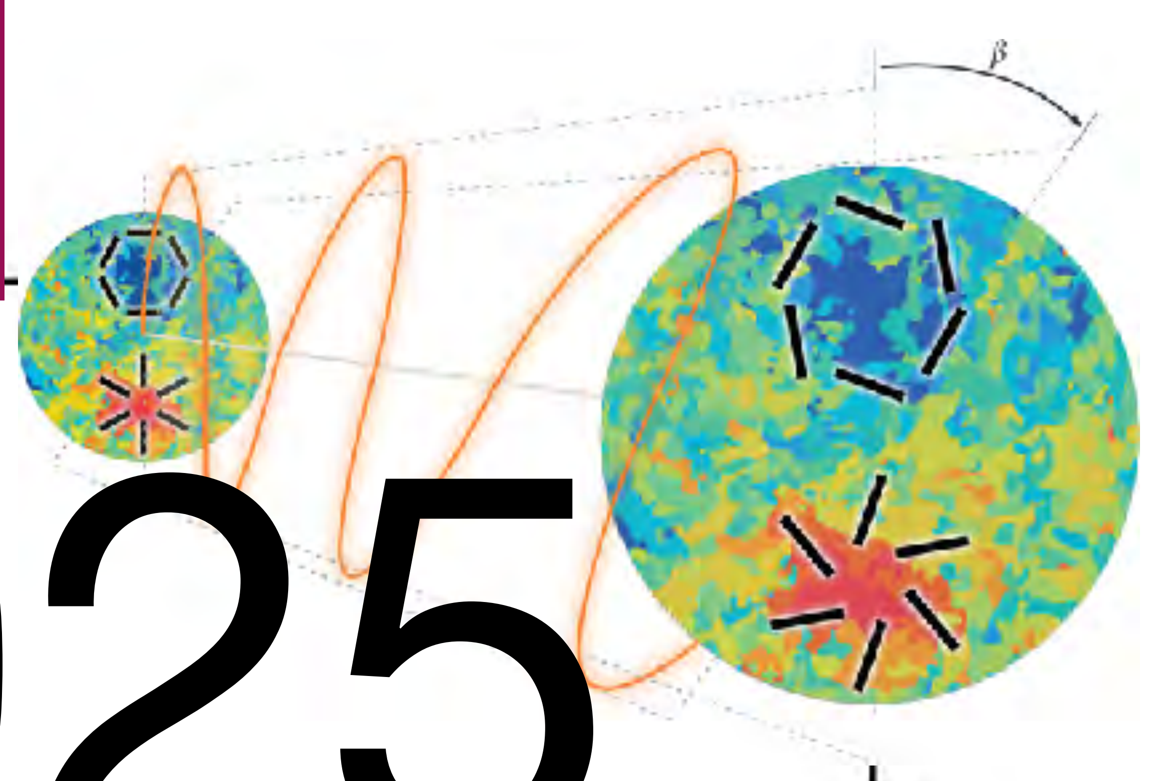
(2.9σ)

A tantalizing hint of cosmic birefringence!

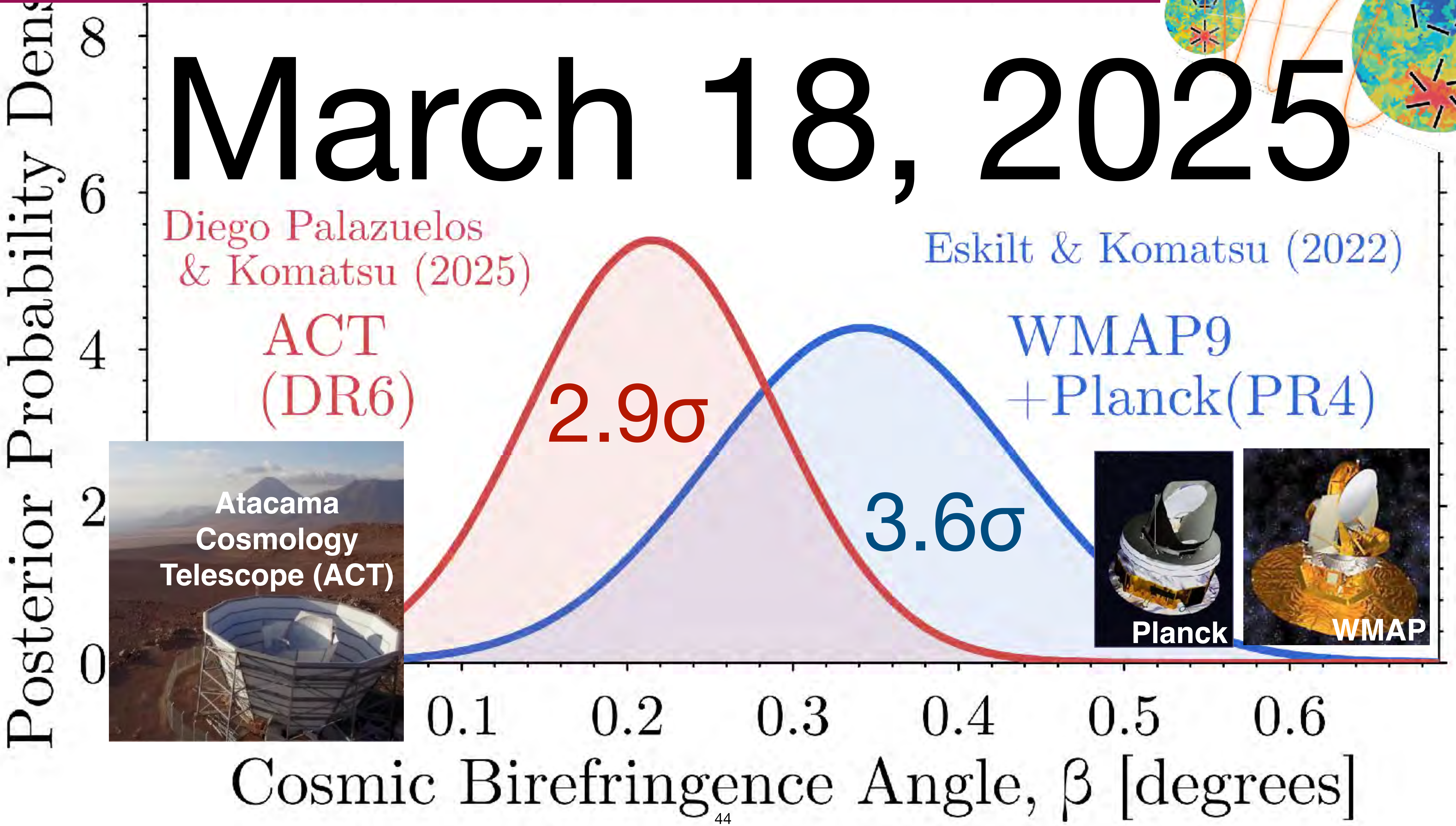




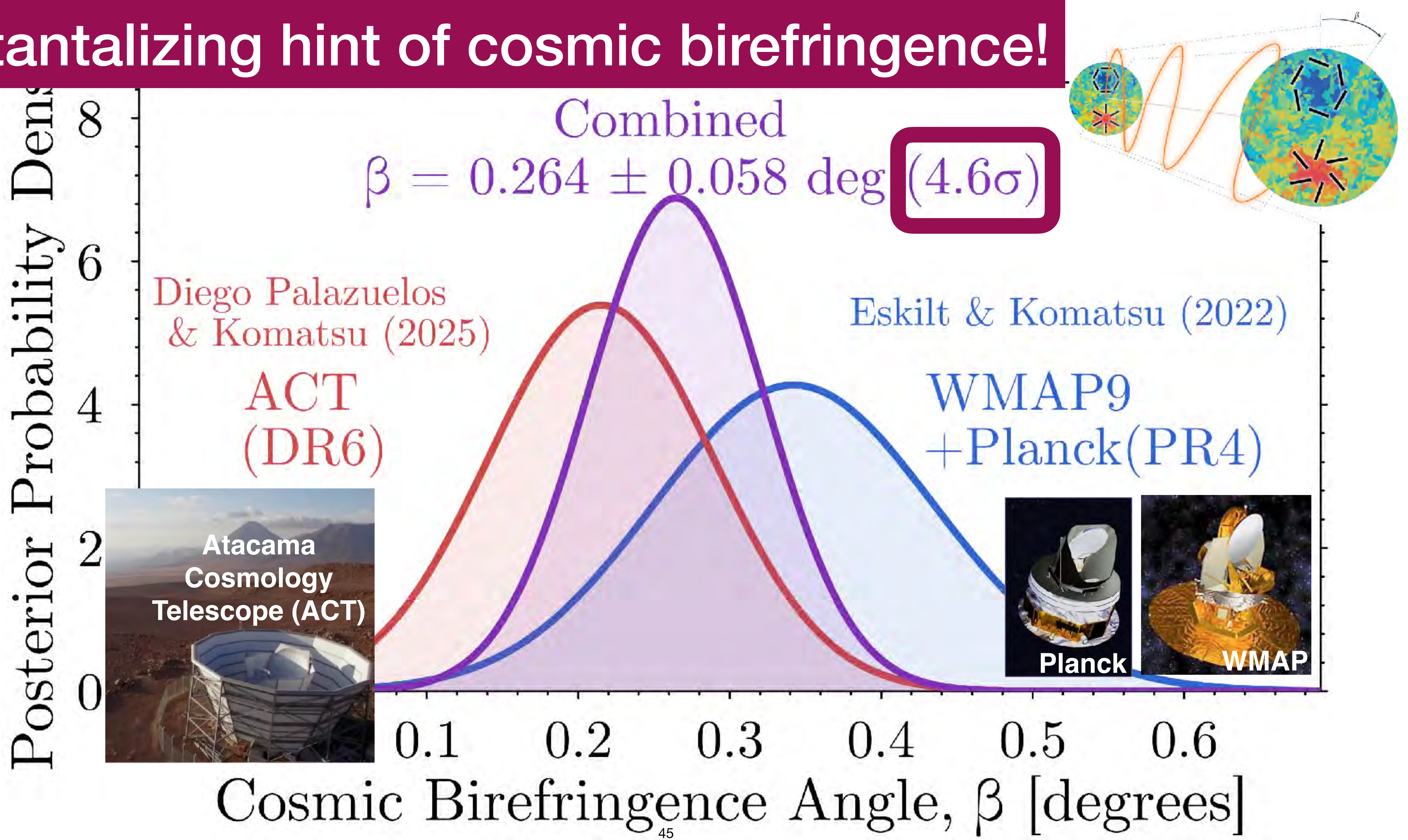
A tantalizing hint of cosmic birefringence!



March 18, 2025



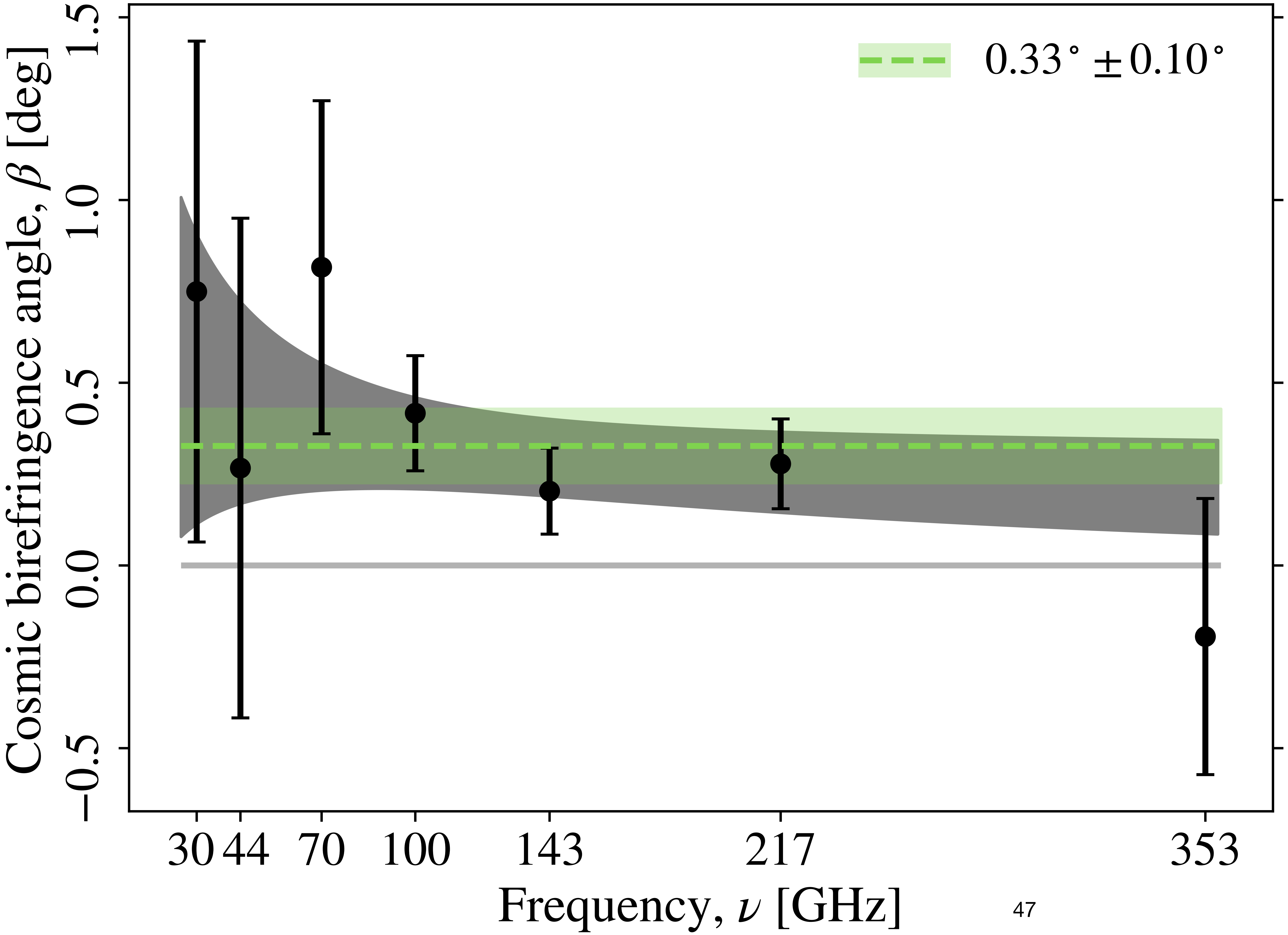
A tantalizing hint of cosmic birefringence!



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

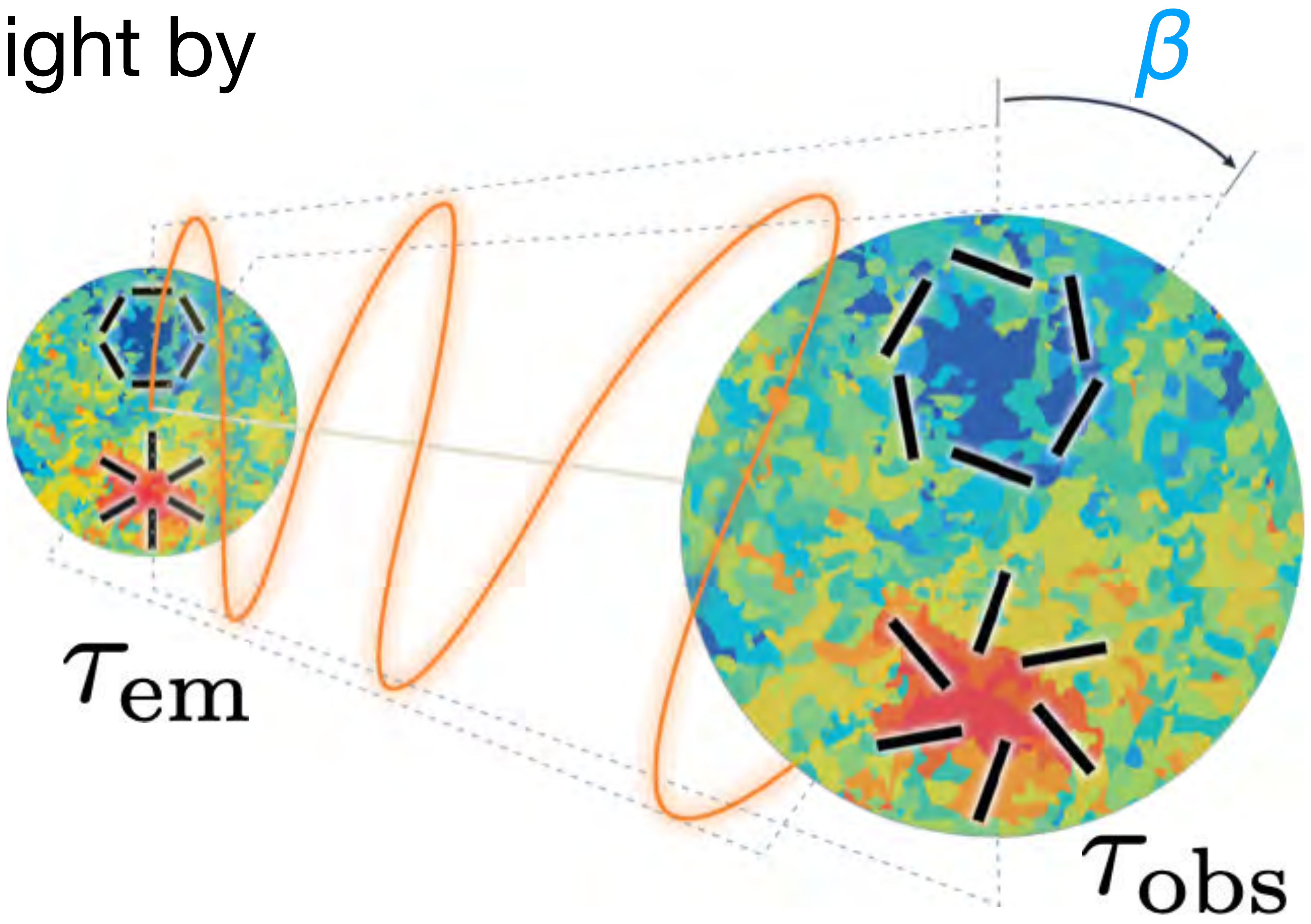
Scalar field-photon coupling

$$\boxed{F\tilde{F} \equiv F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}}$$

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

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

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



Adler (1969); Bell, Jackiw (1969); Fujikawa (1979)

Is there a known example of this term in particle physics?

Yes, a pion. The ABJ anomaly!

Credit: HiggsTan

- A pion is a composite meson composed of a quark and an antiquark.
  - A neutral pion, π^0, is composed of either $u\bar{u}$ or $d\bar{d}$, and **is a pseudoscalar**.
    (Chinowsky & Steinberger, 1954)
  - π^0 is coupled to photons via l_{CS} where
    - $\theta = \pi^0 / f_\pi$ with $f_\pi \sim 184$ MeV (pion decay constant)
    - $\alpha = 2\alpha_{EM} N_c / (3\pi)$ with $N_c = 3$ (the number of quark colors) and $\alpha_{EM} \sim 1/137$ (EM fine structure constant)
- **π^0 decays into 2 photons via this term, which has been observed.** So, this possibility is not completely crazy!

Ni (1977); Sikivie (1983); Turner, Widrow (1987)
Carroll, Field, Jackiw (1990)

$F\tilde{F}$ in the action

Chern-Simons term

- Consider $I_{\rm CS} = -\frac{1}{4}\alpha \int d^4x\ \theta F\tilde{F}$ with $F\tilde{F} = 2\partial_\mu(A_\nu \tilde{F}^{\mu\nu})$
  - α: a dimensionless constant
  - θ: a dimensionless (pseudo)scalar field
- **This is not a surface term!** Integration by parts gives

$$I_{\rm CS} = \frac{1}{2}\alpha \int d^4x\ (\partial_\mu\theta) A_\nu \tilde{F}^{\mu\nu}$$

Jim Simons in 2023

https://einstein-chair.github.io/simons2023/

- This is a special case of the so-called *Chern-Simons term(*)*, $p_\mu A_\nu \tilde{F}^{\mu\nu}$ with $p_\mu = \partial_\mu\theta$

(*) Strictly speaking, Chern-Simons 3-form for an Abelian gauge field is $A_\nu \tilde{F}^{0\nu} = A_i \epsilon^{ijk}\partial_j A_k$

Multiple discoveries of $I_{\mathrm{CS}} = -\frac{1}{4}\alpha \int d^4x \; \theta F\tilde{F}$

The presence of this term is well motivated.

- This electromagnetic coupling term has been discovered at least 4 times in the past.
  - **1969**: The ABJ anomaly [Adler, Bell, Jackiw]
  - **1974**: Chern-Simons 3-form [Chern, Simons]
    - Promoted to 4-dimensional theory in 1990 [Carroll, Field, Jackiw]
  - **1977**: Equivalence Principle [Ni]
  - **1983**: Axion electrodynamics [Sikivie]

Correction to Maxwell's equations

In Minkowski space, Heaviside units and *c*=1

- We now derive the correction to Maxwell's equations from

$$\boxed{d^4x = dtd^3\mathbf{x}}$$

$$I = -\frac{1}{4}\int d^4x \; \left(F^2 + \alpha\theta F\tilde{F}\right) + \int d^4x \; A_\mu j^\mu$$

- Finding the path that gives a stationary point,

$$\boxed{\partial_\nu F^{\mu\nu} + \alpha(\partial_\nu\theta)\tilde{F}^{\mu\nu} = j^\mu}$$

As expected, only the <u>space-time dependence</u> of the θ field affects Maxwell's equation.

Correction to the EM wave equation in vacuum

With the Chern-Simons term

$$\partial_\nu F^{\mu\nu} + \alpha(\partial_\nu \theta)\tilde{F}^{\mu\nu} = 0$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

- With $A^0=\phi=0$ in the Lorenz gauge, we find

$$-\Box A^i + \alpha(\partial_\nu \theta)\tilde{F}^{i\nu} = 0$$

$$\boxed{\begin{aligned}\Box &= \eta^{\alpha\beta}\partial_\alpha\partial_\beta = -\frac{\partial^2}{\partial t^2} + \nabla^2 \\ A^\mu &= \eta^{\mu\alpha}A_\alpha = (\phi, \mathbf{A})\end{aligned}}$$

$$\Rightarrow \ddot{\mathbf{A}} - \nabla^2\mathbf{A} + \underbrace{\alpha\left[-\dot{\theta}(\nabla\times\mathbf{A}) + (\nabla\theta)\times\dot{\mathbf{A}}\right]}_{\text{Correction to the EM wave equation!}} = 0$$

Helicity basis to probe parity symmetry

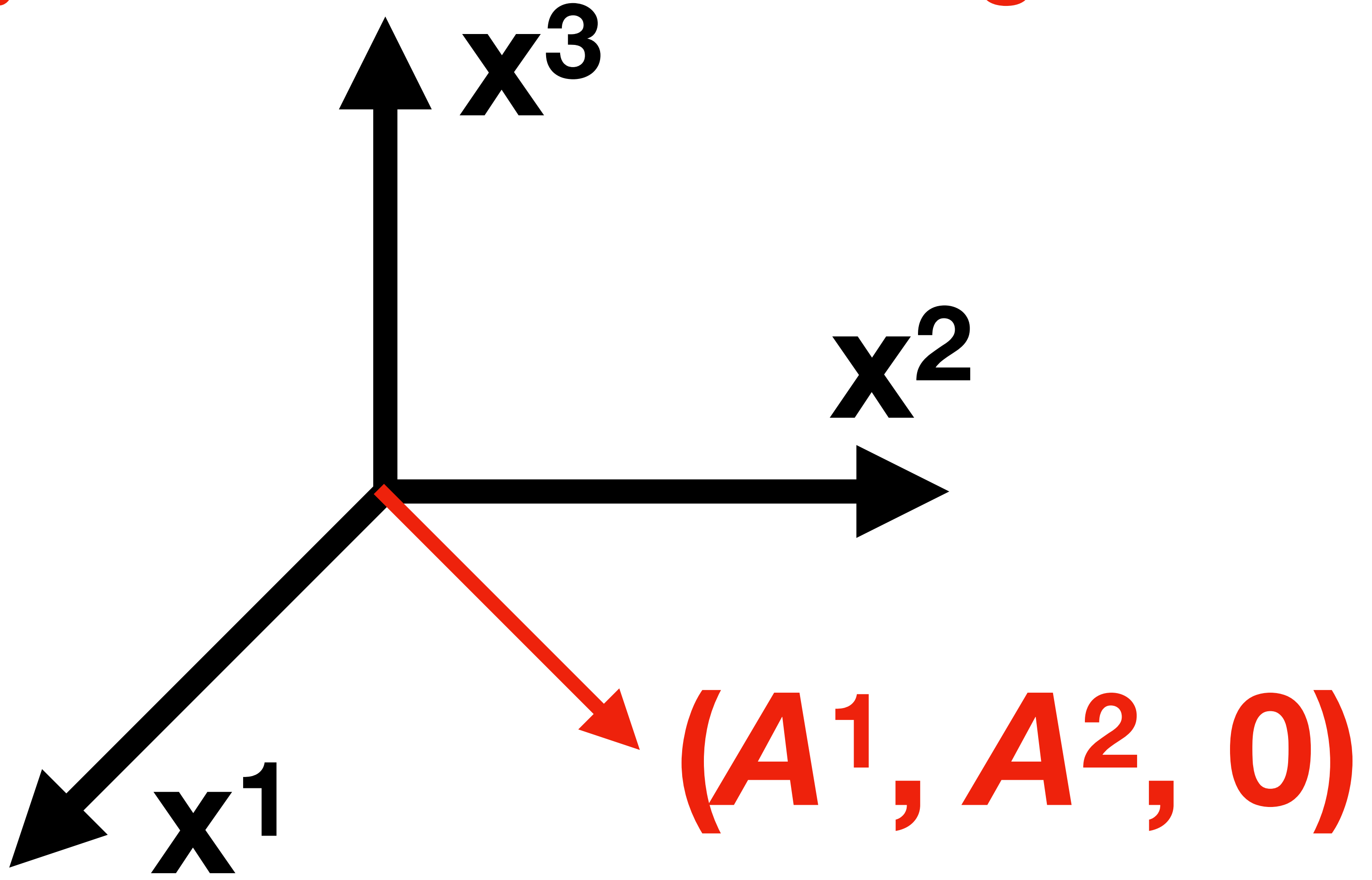
Going to Fourier space

- Fourier transform of **A**(t,**x**) is $\mathbf{A}(t,\mathbf{x}) = (2\pi)^{-3/2} \int d^3\mathbf{k}\ \mathbf{A}_\mathbf{k}(t) e^{i\mathbf{k}\cdot\mathbf{x}}$
    - The EM wave propagates in the direction of **k**. The change in $\mathbf{A}_\mathbf{k}$ is perpendicular to **k**.

"Coulomb gauge" $\nabla \cdot \mathbf{A}(t,\mathbf{x}) = 0 \rightarrow \mathbf{k} \cdot \mathbf{A}_\mathbf{k}(t) = 0$

- Choose **k** to be on the z(=x^3) axis. The helicity states, λ=±1, are given for each Fourier mode by

$$A_\pm = \frac{A^1_\mathbf{k} \mp i A^2_\mathbf{k}}{\sqrt{2}}$$



Correction to the EM wave equation

In the helicity basis

$$\ddot{\mathbf{A}} - \nabla^2 \mathbf{A} + \underbrace{\alpha \left[-\dot{\theta} (\nabla \times \mathbf{A}) + (\nabla \theta) \times \dot{\mathbf{A}} \right]}_{\text{Correction to the EM wave equation!}} = 0$$

- If θ has a time-dependent vacuum expectation value, $\theta(t,\mathbf{x})$ –> $\bar{\theta}(t)$, we find in Fourier space

$$\ddot{\mathbf{A}}_{\mathbf{k}} + k^2 \mathbf{A}_{\mathbf{k}} - i\alpha \dot{\bar{\theta}} (\mathbf{k} \times \mathbf{A}) = 0$$

$$\Rightarrow \quad \ddot{A}_{\pm} + \left(k^2 \boxed{\mp} k \alpha \dot{\bar{\theta}} \right) A_{\pm} = 0$$

Parity violation

The equation of motion depends on handedness!

Imagine that space is filled with a pseudoscalar field coupled to photons via the CS term.

Scalar field DM/DE coupled to the CS term

DM = Dark Matter; DE = Dark Energy

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

We wrote

$$\theta = \frac{\chi}{f}$$

- χ is a neutral pseudoscalar field (spin 0).
- Why consider χ as a good DM/DE candidate?
  - *Why not*? We have an example in the Standard Model: a neutral pion.
  - We expect $\alpha \simeq \alpha_{\text{EM}} \simeq 10^{-2}$ and $f < M_{\text{Pl}} \simeq 2.4 \times 10^{18}$ GeV.
- χ can be composed of fermions like a pion, or a fundamental pseudoscalar like an "axion" field.

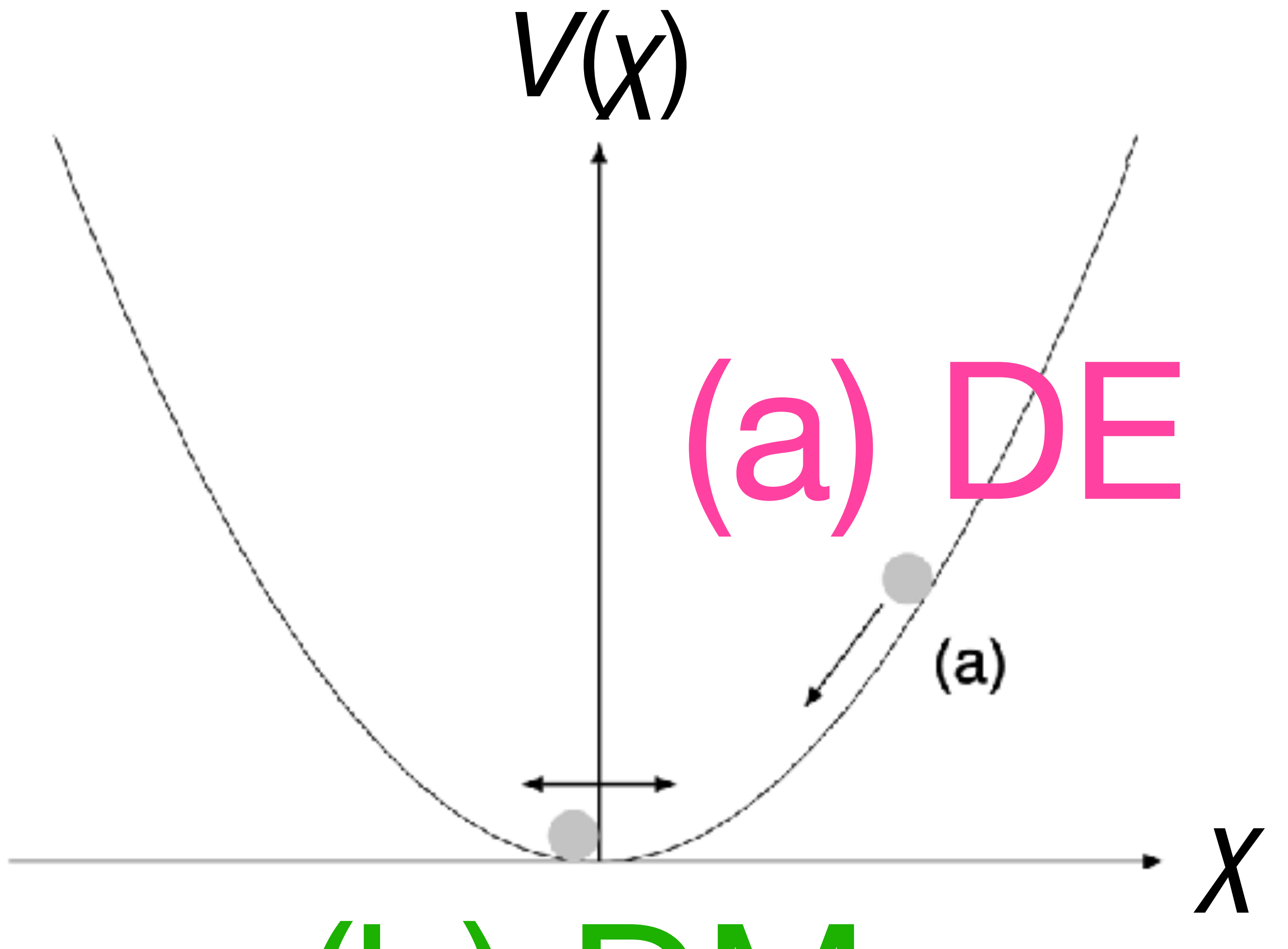
Distinction between DE and DM

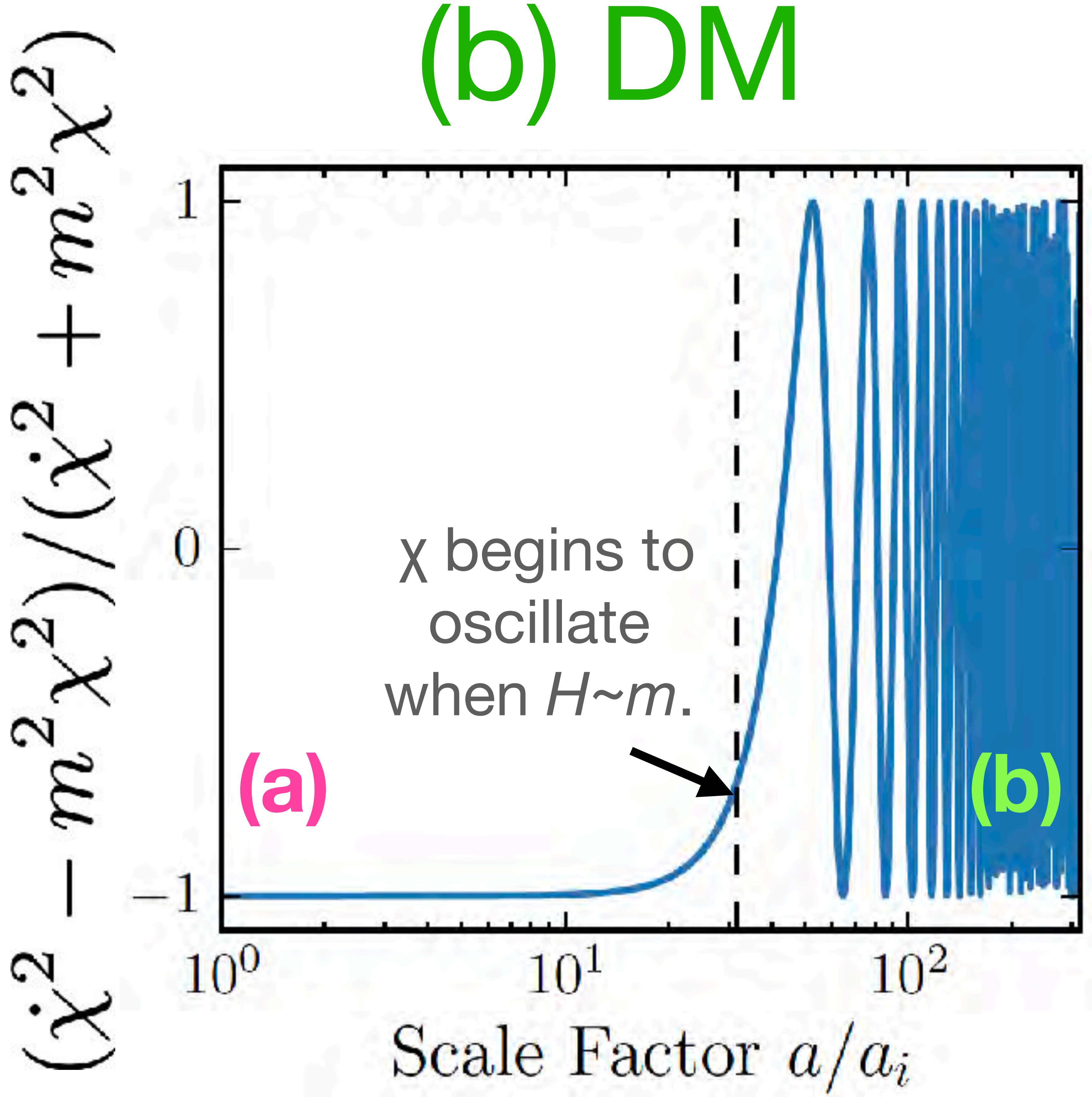
How small is its mass? Example of $V(\chi) = m^2\chi^2/2$

- The useful criterion is the equation of state parameter, *w*.

$$w = \frac{P}{\rho} = \frac{\langle \dot{\chi}^2 \rangle - m^2 \langle \chi^2 \rangle}{\langle \dot{\chi}^2 \rangle + m^2 \langle \chi^2 \rangle}$$

- $w \simeq -1$: Dark Energy (DE)
    - $m \lesssim H_0 \simeq 10^{-33}$ eV
- $w \simeq 0$: Dark Matter (DM)
    - $m \gtrsim H_0$





Phase velocity of circular polarization states

Expanding space, *c*=1

where $' = \frac{\partial}{\partial \tau} = a\frac{\partial}{\partial t}$

τ : conformal time

- We write

$$A''_\pm + \omega_\pm^2 A_\pm = 0, \quad \omega_\pm^2 = k^2 \mp \frac{k\alpha\chi'}{f}$$

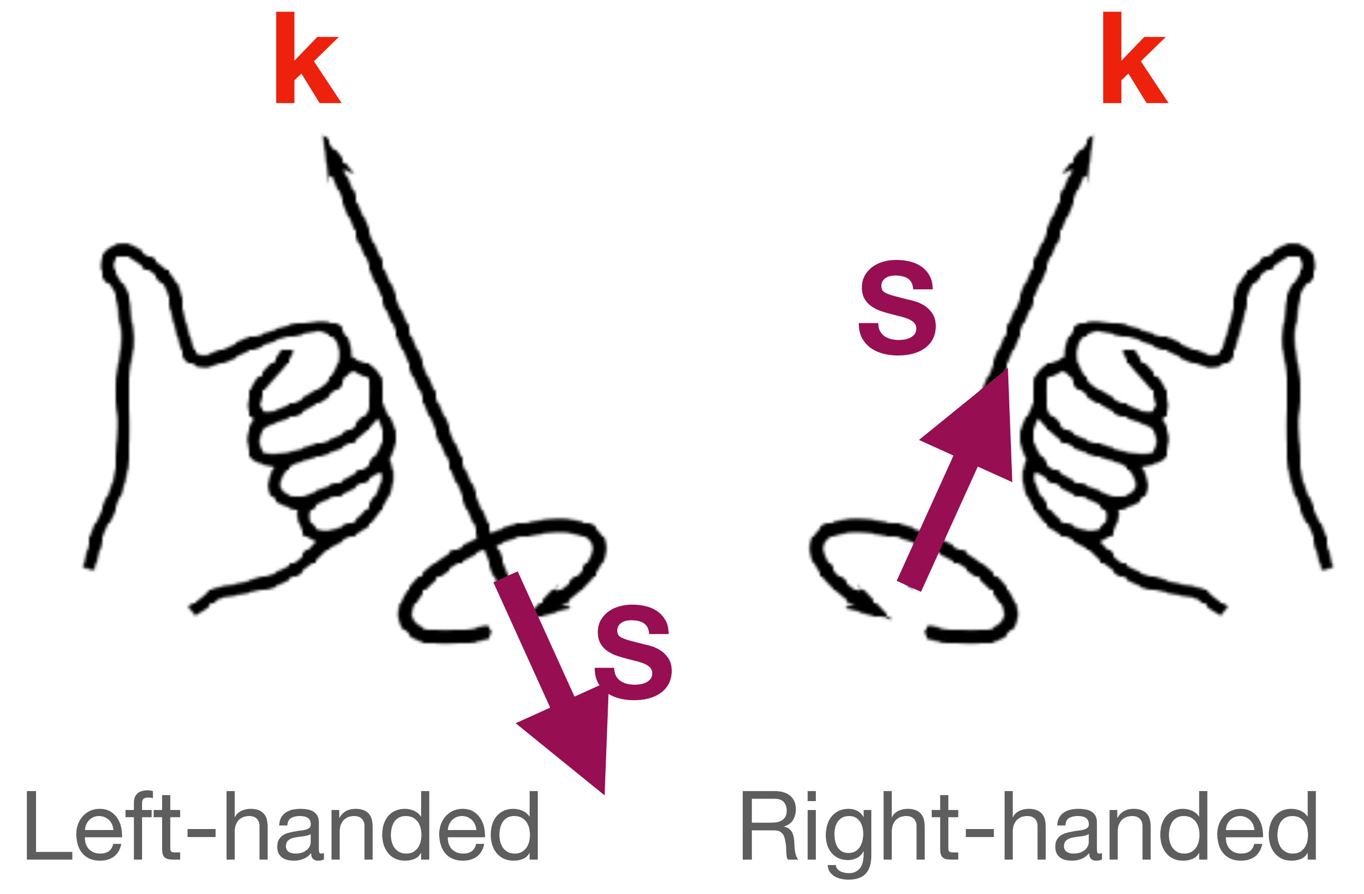
- We work in the limit of $k^2 \gg k\alpha\chi'/f$. This approximation is accurate for the photons we observe today.

- The phase velocity of circular polarization states, $\omega_\pm/k$, is

$$\frac{\omega_\pm}{k} \simeq 1 \mp \frac{\alpha\chi'}{2kf}$$

+: Right-handed state

–: Left-handed state



Plane-wave (WKB) Solution

Expanding space, *c*=1

$$A''_\pm + \omega_\pm^2 A_\pm = 0, \qquad \omega_\pm \simeq k \mp \frac{\alpha\chi'}{2f}$$

- For $|\omega'_\pm| \ll \omega_\pm^2$, which is satisfied here, an accurate solution is given by

$$A_\pm \simeq C_\pm \frac{\exp\left(-i\int d\tau\ \omega_\pm + i\delta_\pm\right)}{\boxed{\sqrt{2\omega_\pm}} \simeq \sqrt{2k}}$$

We can replace $\omega_\pm$ in amplitude (but not in phase) with k.

where $C_\pm$ is the initial amplitude and $\delta_\pm$ is the initial phase.

Carroll, Field, Jackiw (1990); Carroll, Field (1991); Harari, Sikivie (1992)

Cosmic Birefringence

Rotation of the plane of linear polarization

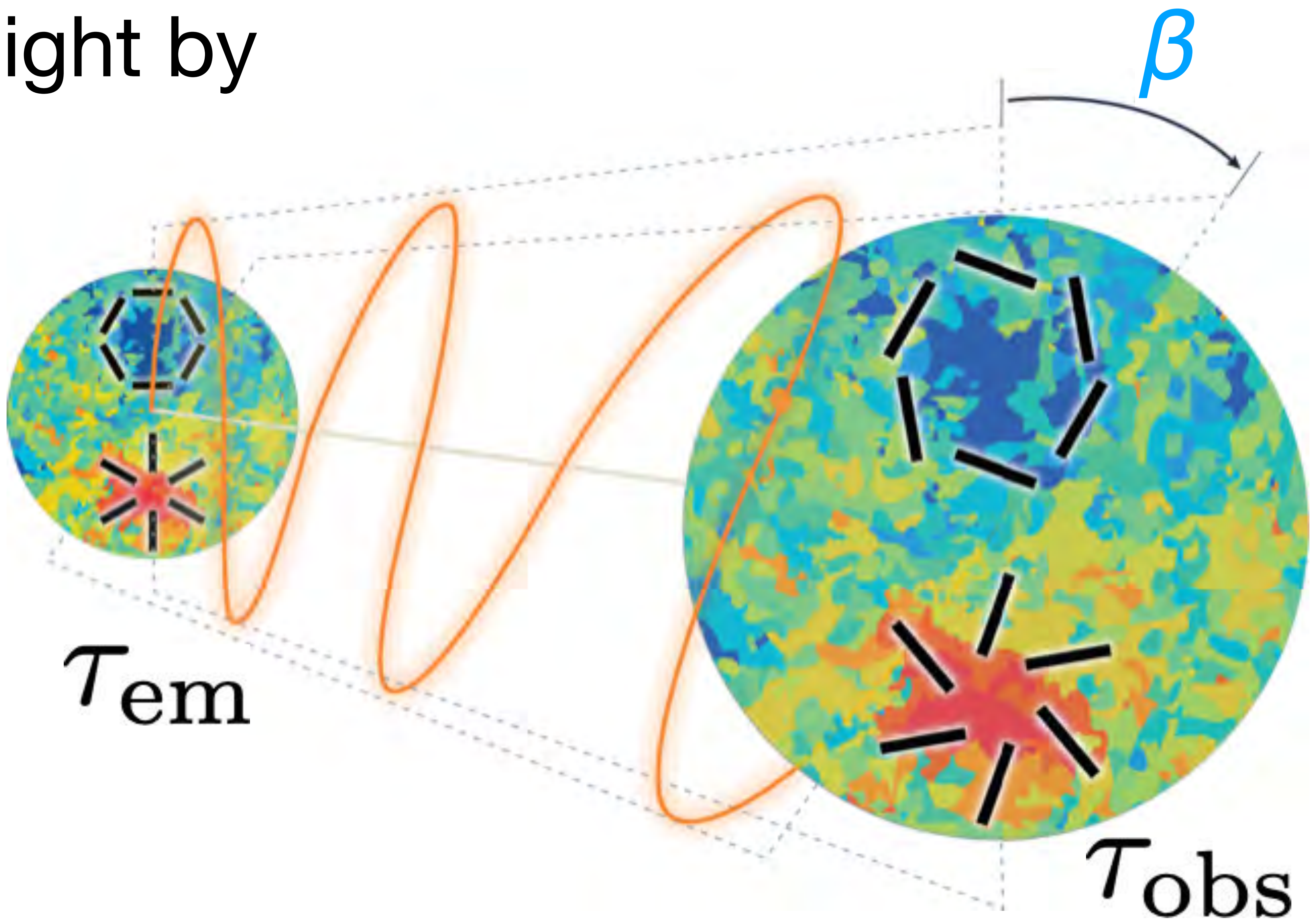
$$A_\pm \simeq C_\pm \frac{\exp\left(-i\int d\tau\ \omega_\pm + i\delta_\pm\right)}{\boxed{\sqrt{2\omega_\pm}} \simeq \sqrt{2k}}$$

with

$$\frac{\omega_\pm}{k} \simeq 1 \mp \frac{\alpha\chi'}{2kf}$$

- 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

DM = Dark Matter; DE = Dark Energy

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

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

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

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

Axionlike particle?

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

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

©HiggsTan

So, space may be filled with axionlike particles…

II.4: What Comes Next?

What are we worried about now?

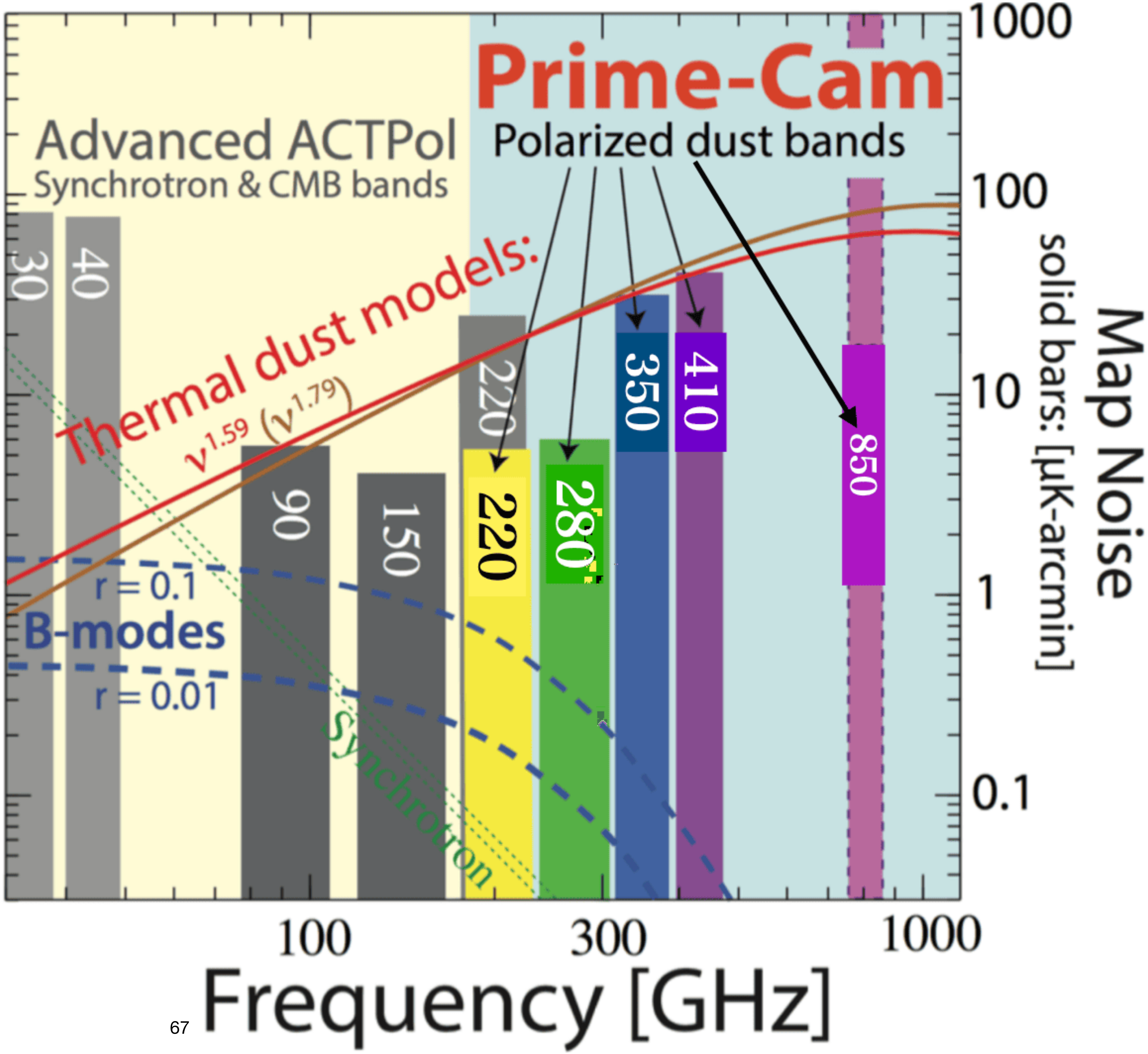
“Unknown Unknowns”

- **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!

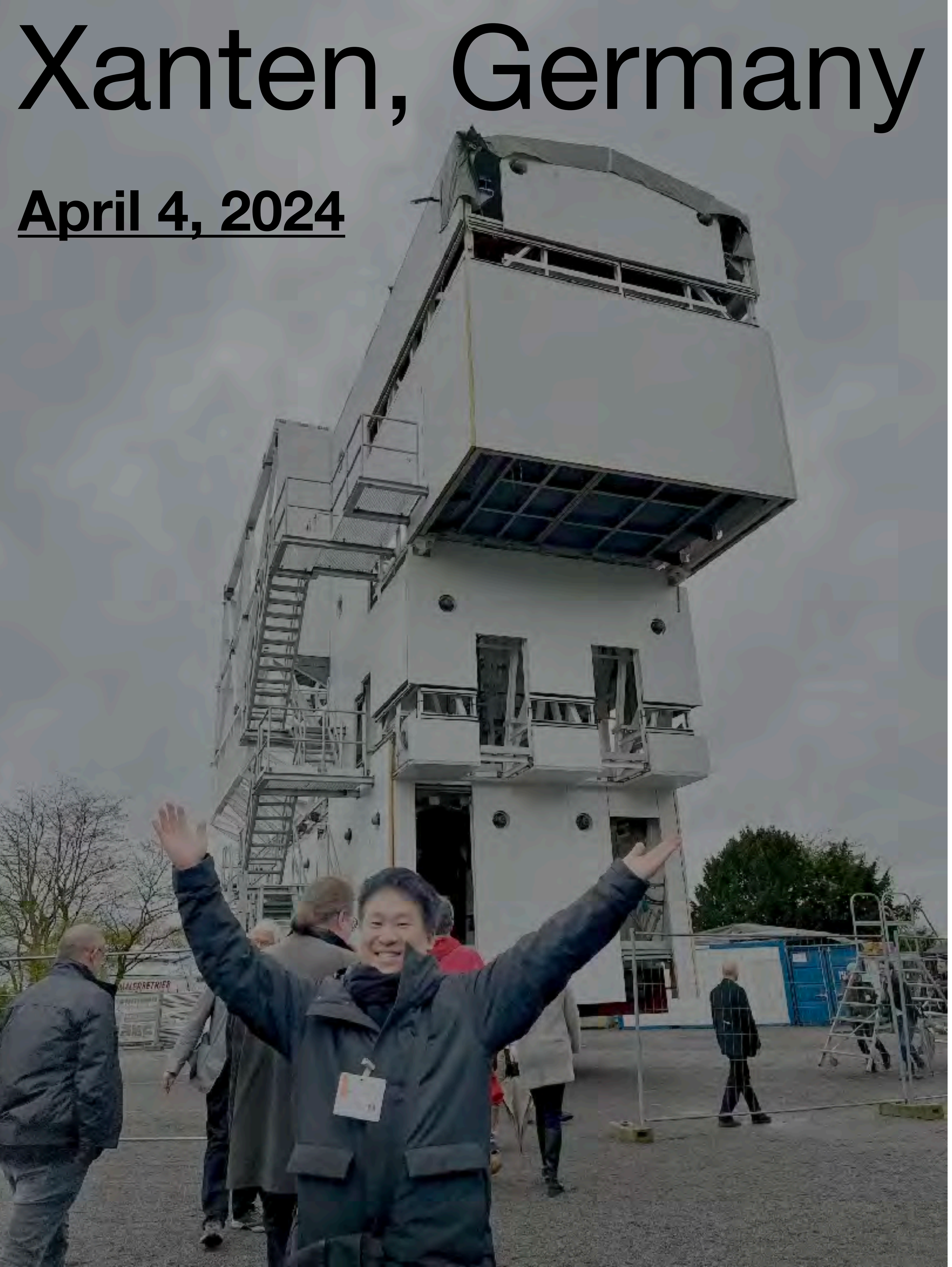
CPI vertex



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

Xanten, Germany

April 4, 2024



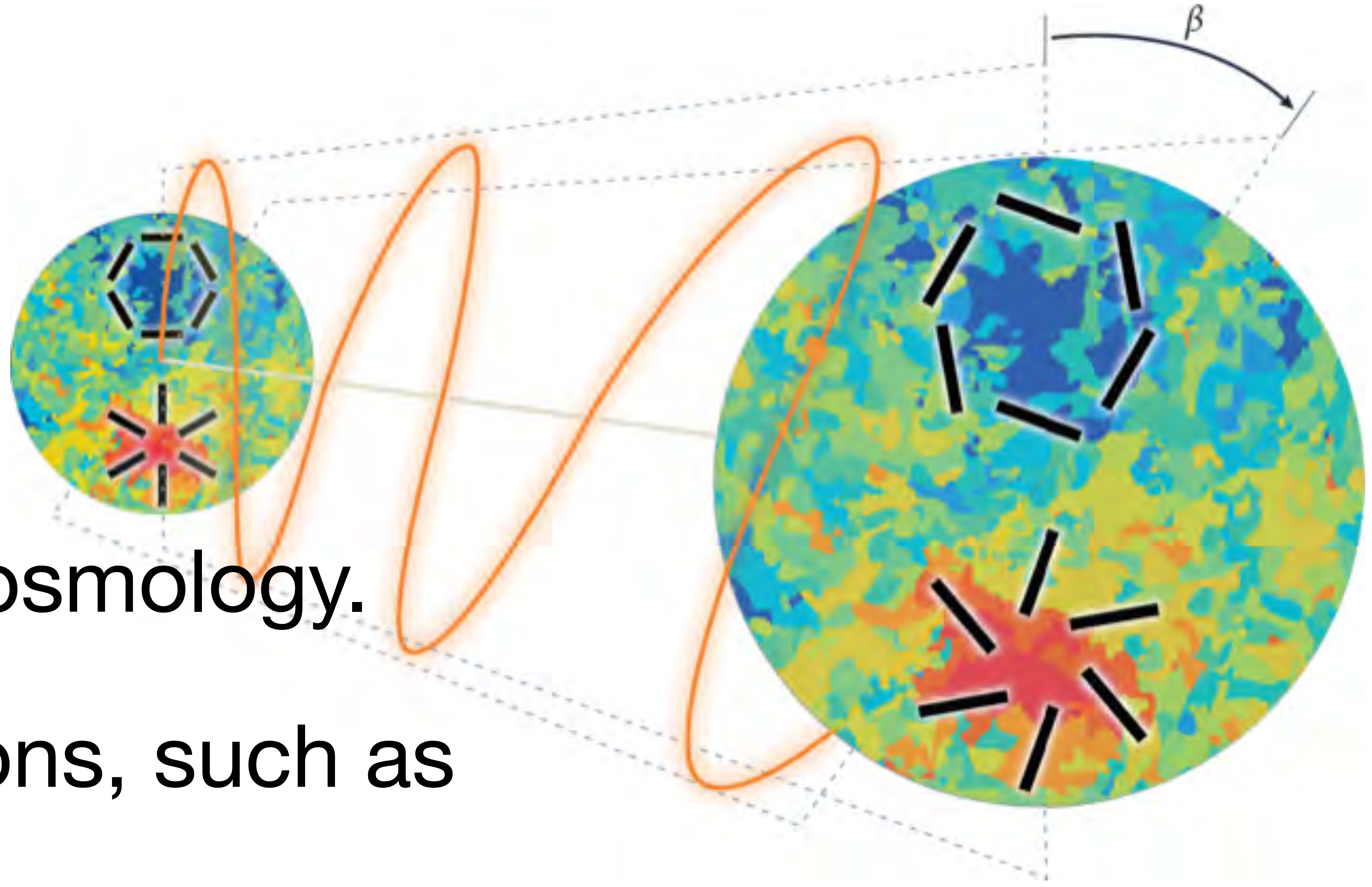
Cerro Chajnantor

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!