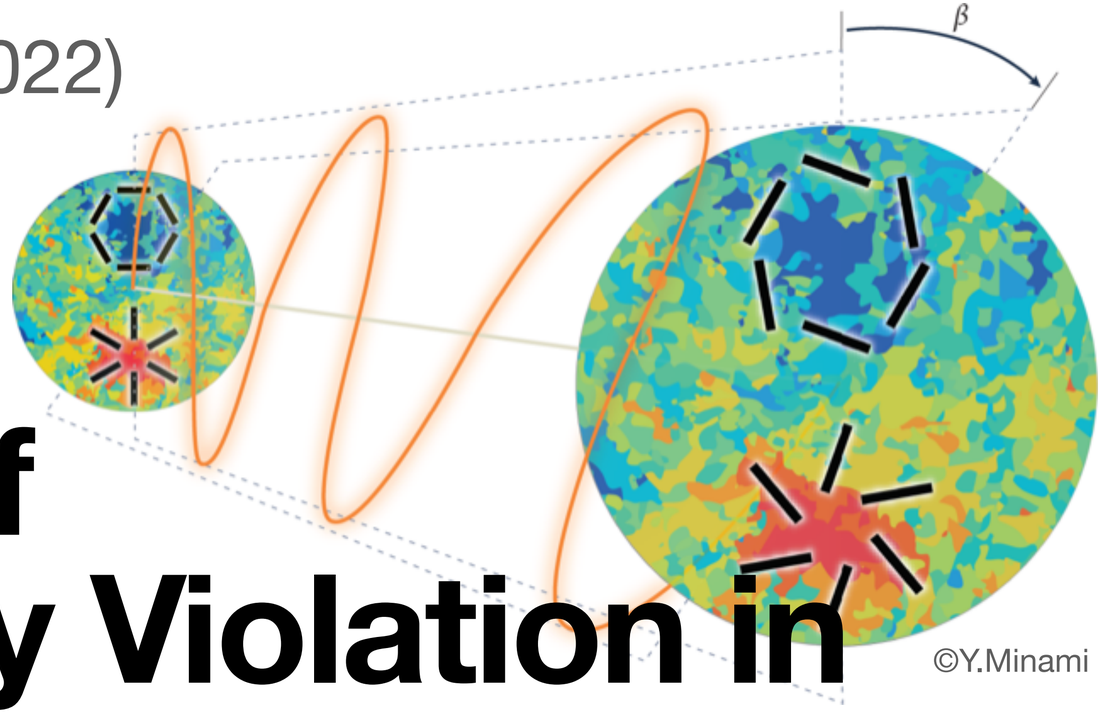
Reference: EK, Nature Rev. Phys. **4**, 452 (2022)



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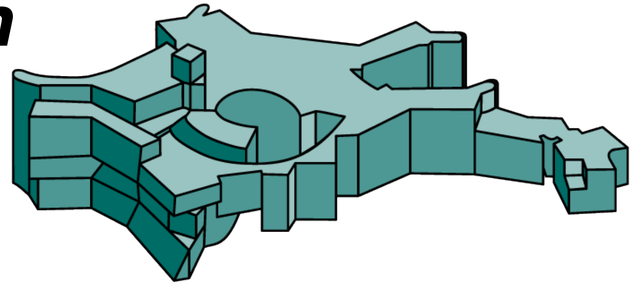
A Tantalizing Hint of Cosmological Parity Violation in the Polarized Light of the CMB

Does the Universe distinguish between left and right?



Eiichiro Komatsu (Max Planck Institute for Astrophysics)

"Gravitational Waves, Cosmology and Fundamental Physics", Hangzhou Institute for Advanced Study, Nov. 1, 2025

MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

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 reviews physics

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

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…

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

Parity and Rotation

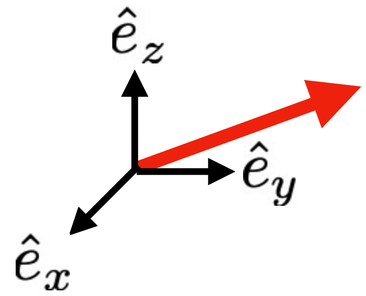
- Parity transformation (***x*** –> -***x***) and 3d rotation (***x*** –> R***x***) are different.
  - R is a continuous transformation and the determinant of R is det(R) = +1.
  - Parity is a discrete transformation and the **determinant is –1**, as

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

2. Pseudovector, Pseudoscalar

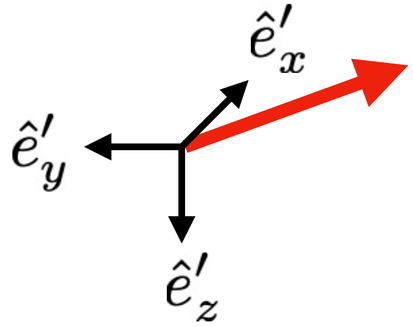
Parity Transformation: Vector

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.



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

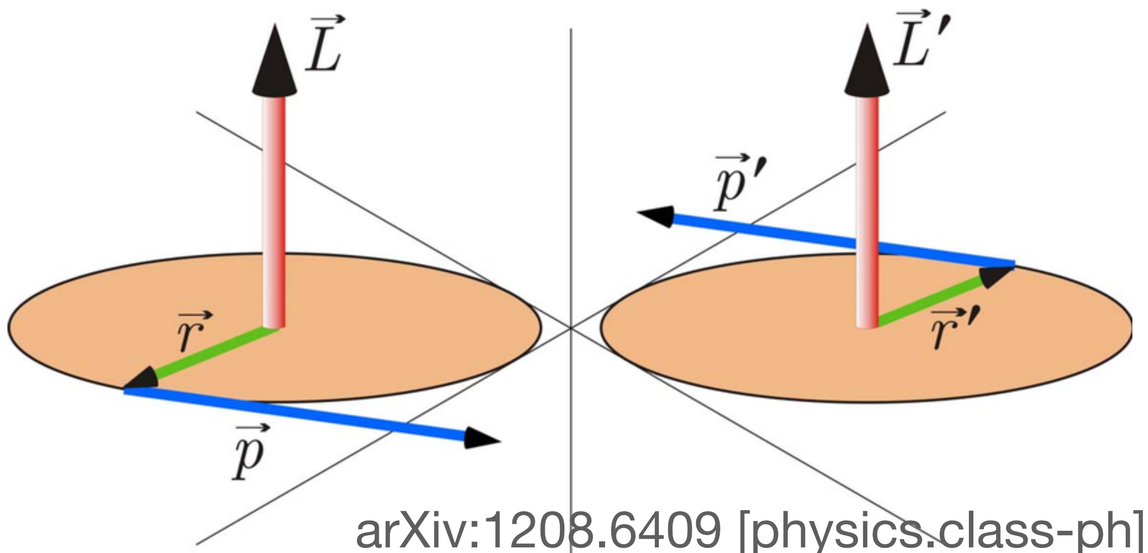
- **p** is the same vector, written using two different basis vectors.
- Therefore, **p**'s components are transformed as $(p'_x, p'_y, p'_z) = (-p_x, -p_y, -p_z)$

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.,

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



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

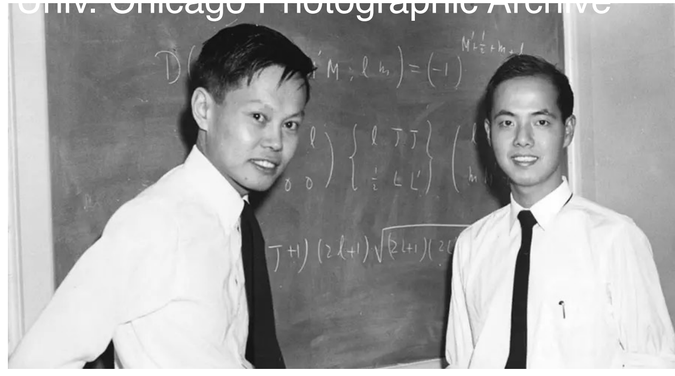
E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

(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

Smithsonian Institution Archives

Chien-Shiung Wu
吳健雄



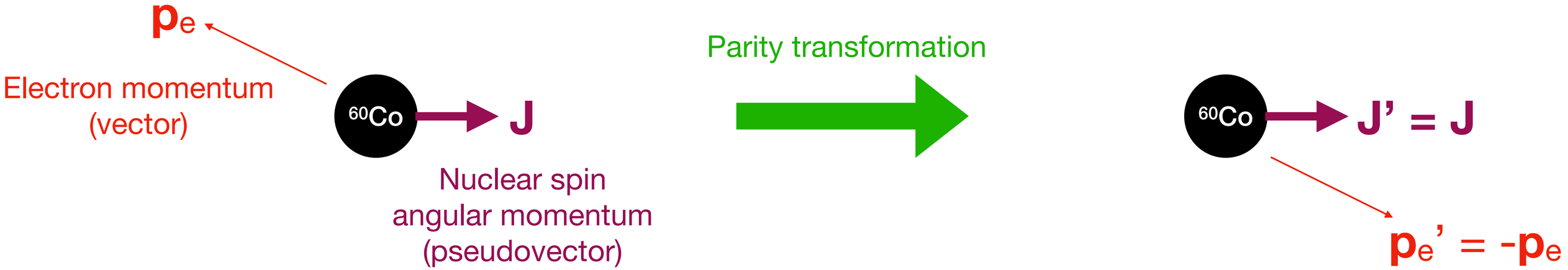
Chen-Ning Yang
楊振寧

Tsung-Dao Lee
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

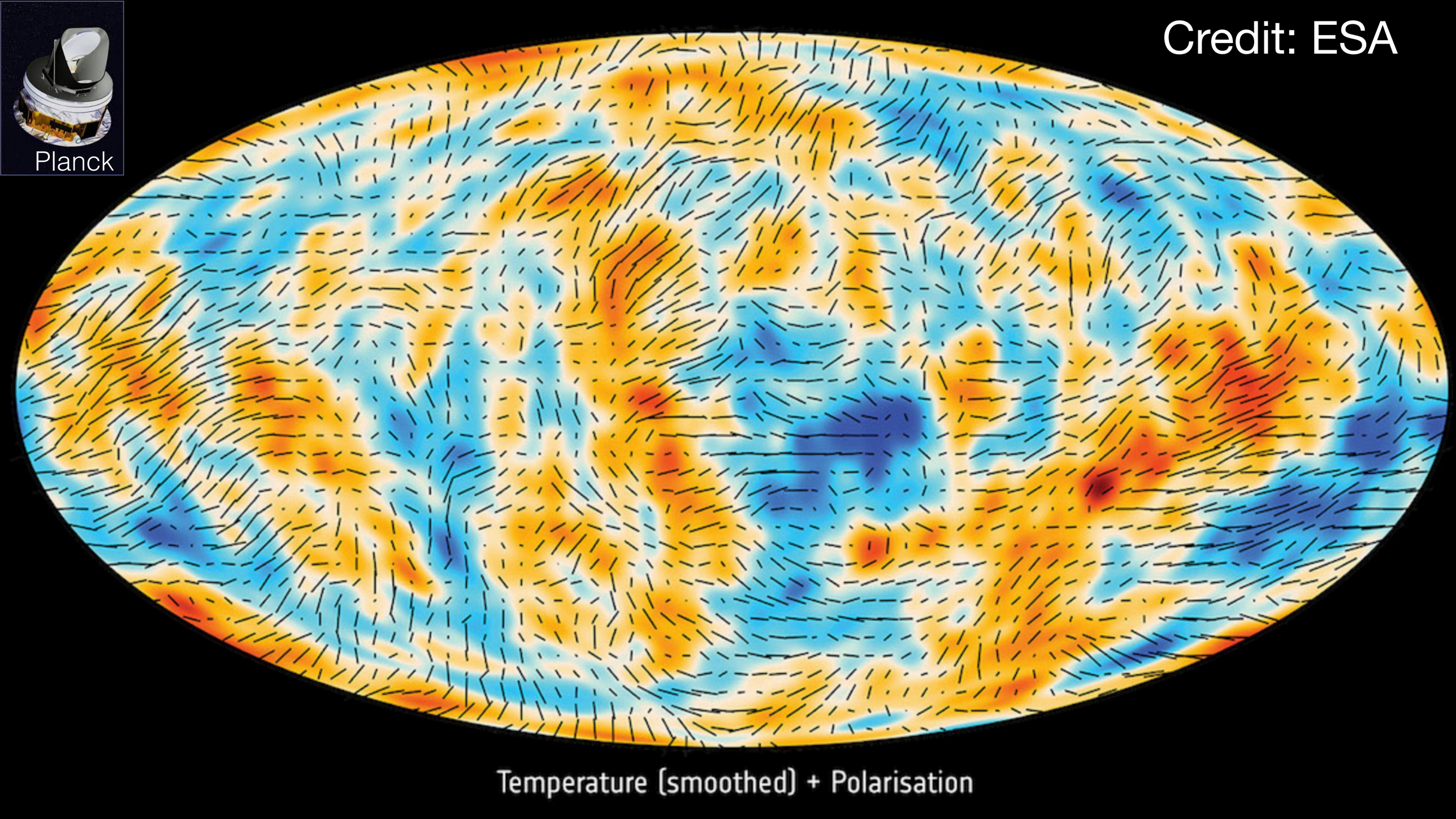
Many physicists did not believe it initially.

- 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?*”

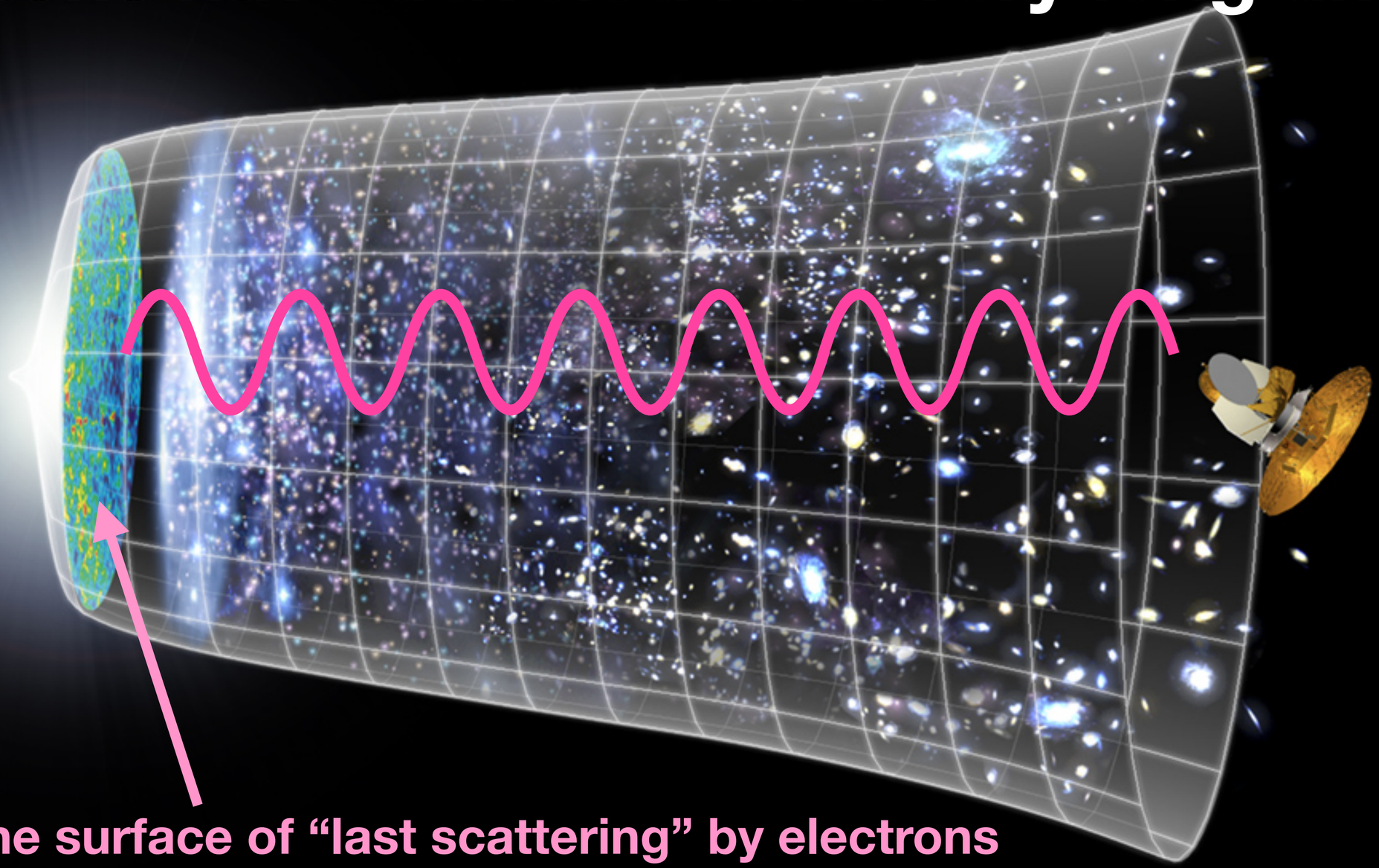
4. Parity Violation in the Cosmic Microwave Background (CMB)

Credit: ESA

Temperature (smoothed)


Planck
Credit: ESA
Temperature (smoothed) + Polarisation

CMB photons have traveled for a very long time!



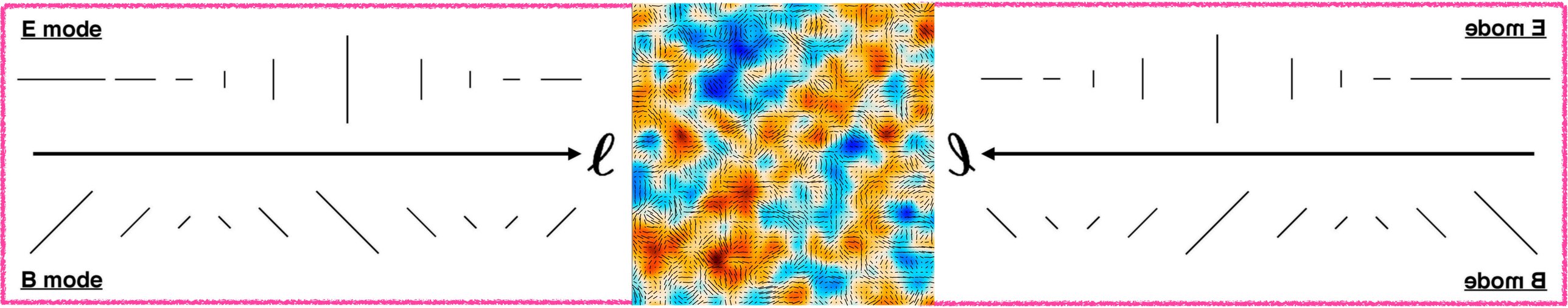
The surface of "last scattering" by electrons
(Scattering generates ***polarization***!)

Credit: WMAP Science Team

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”.



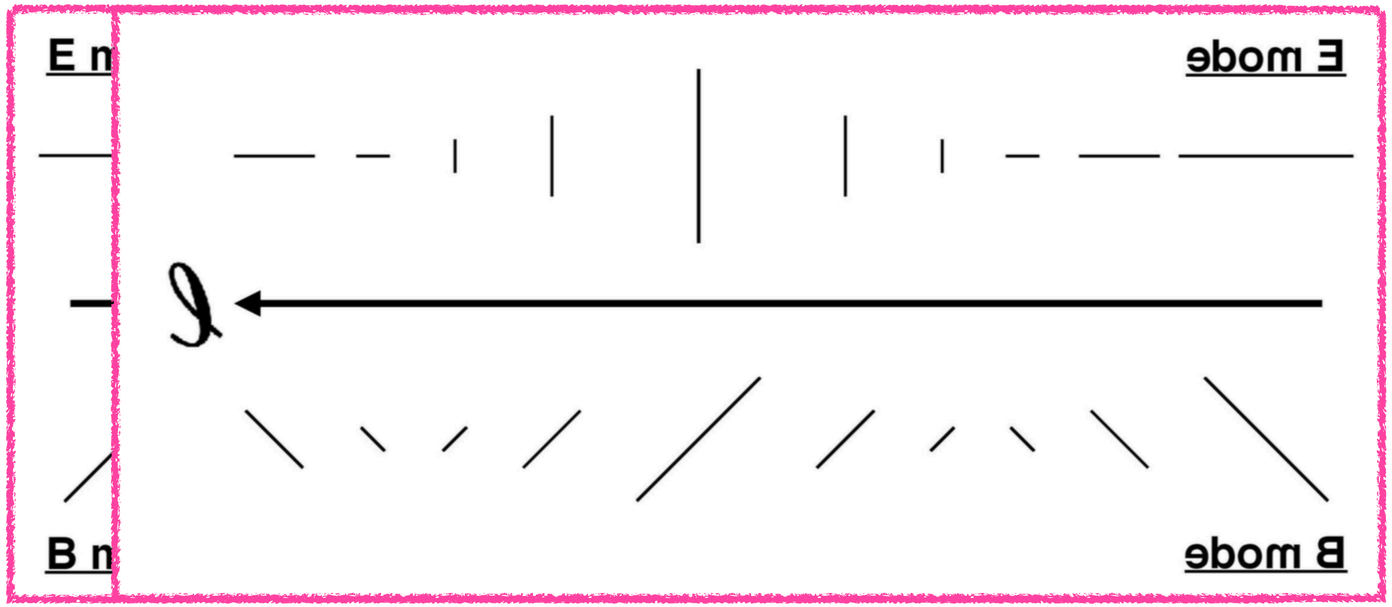
- E and B modes are transformed differently under the parity transformation. Therefore, the product of the two, **the “EB correlation”, is a pseudoscalar**.

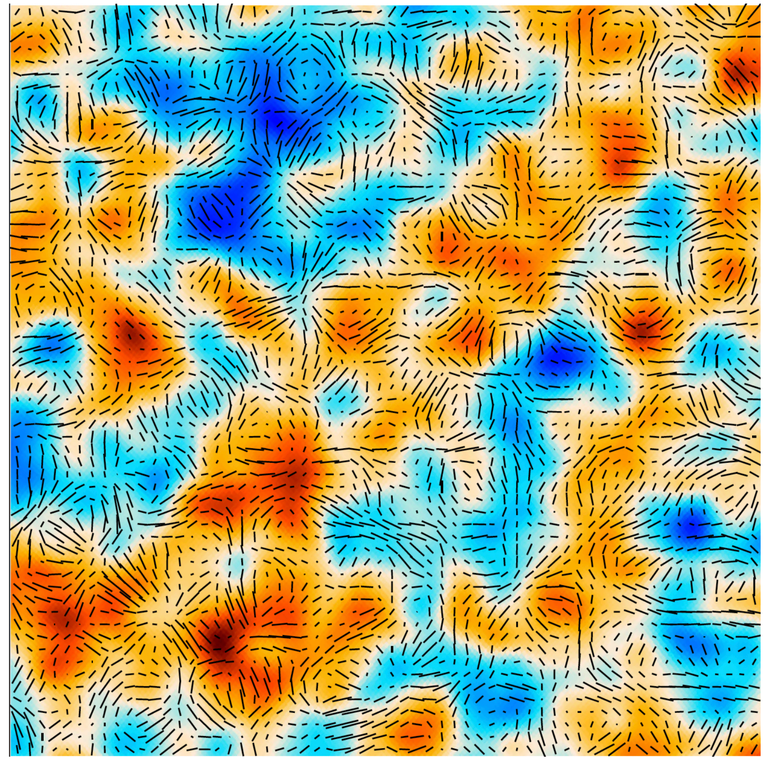
- **The full-sky average of the EB correlation must vanish (to within the measurement uncertainty), if there is no parity violation!**

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

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

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

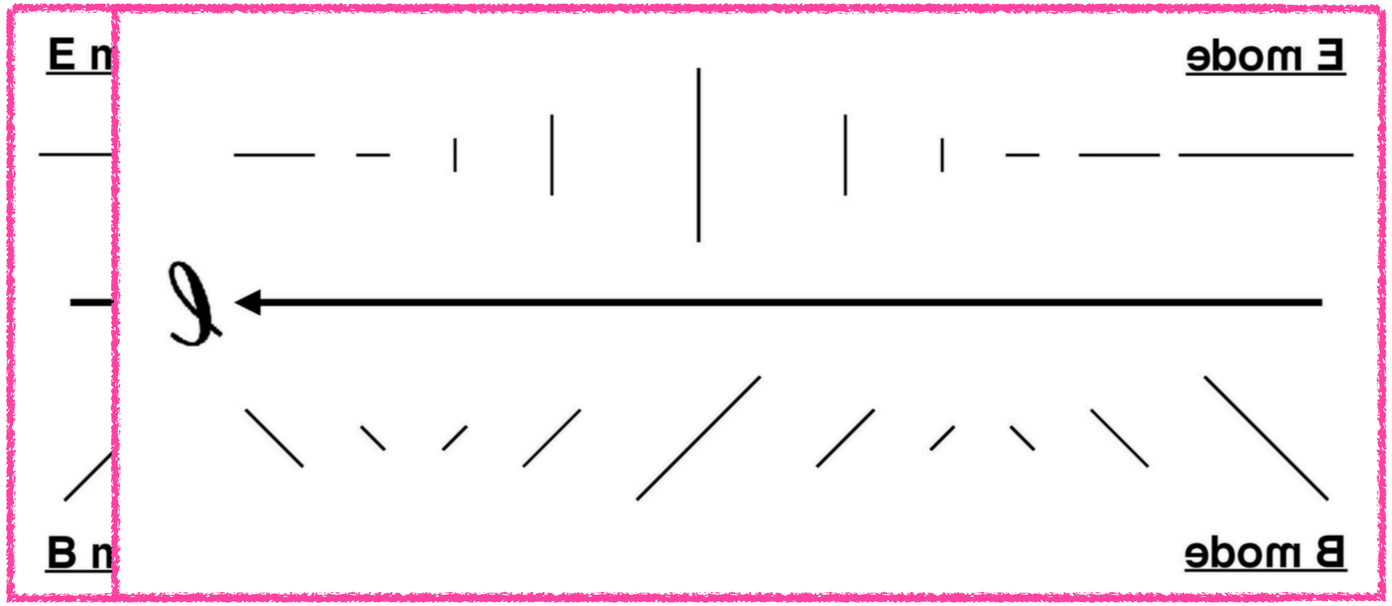
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta^{(2)}_D(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

These are scalars and insensitive to parity violation.

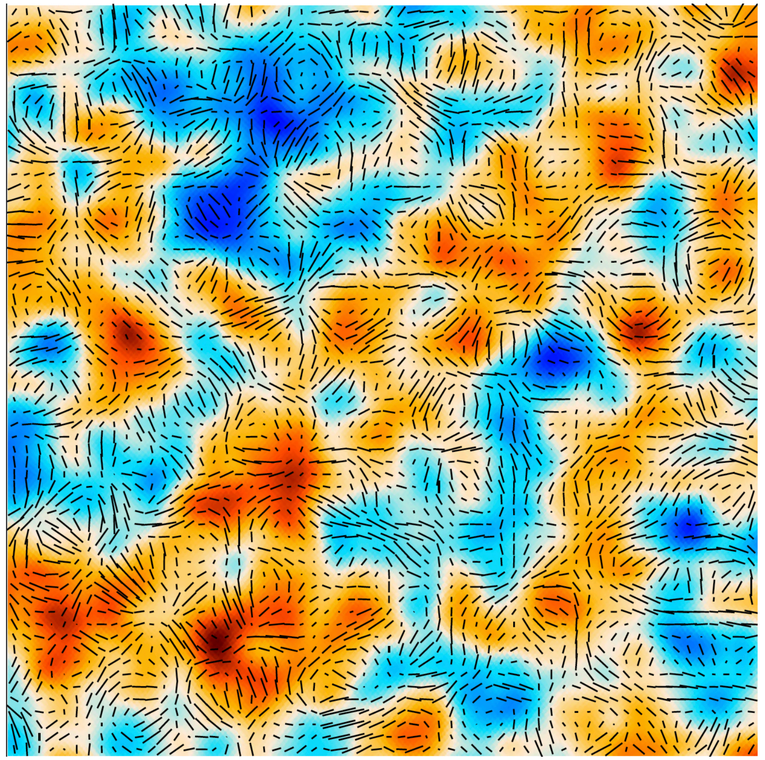
Lue, Wang, Kamionkowski (1999); Feng et al. (2005, 2006)

Parity eigenstates: E and B modes

Concept defined in Fourier space



This map is dominated by E-mode polarization



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

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

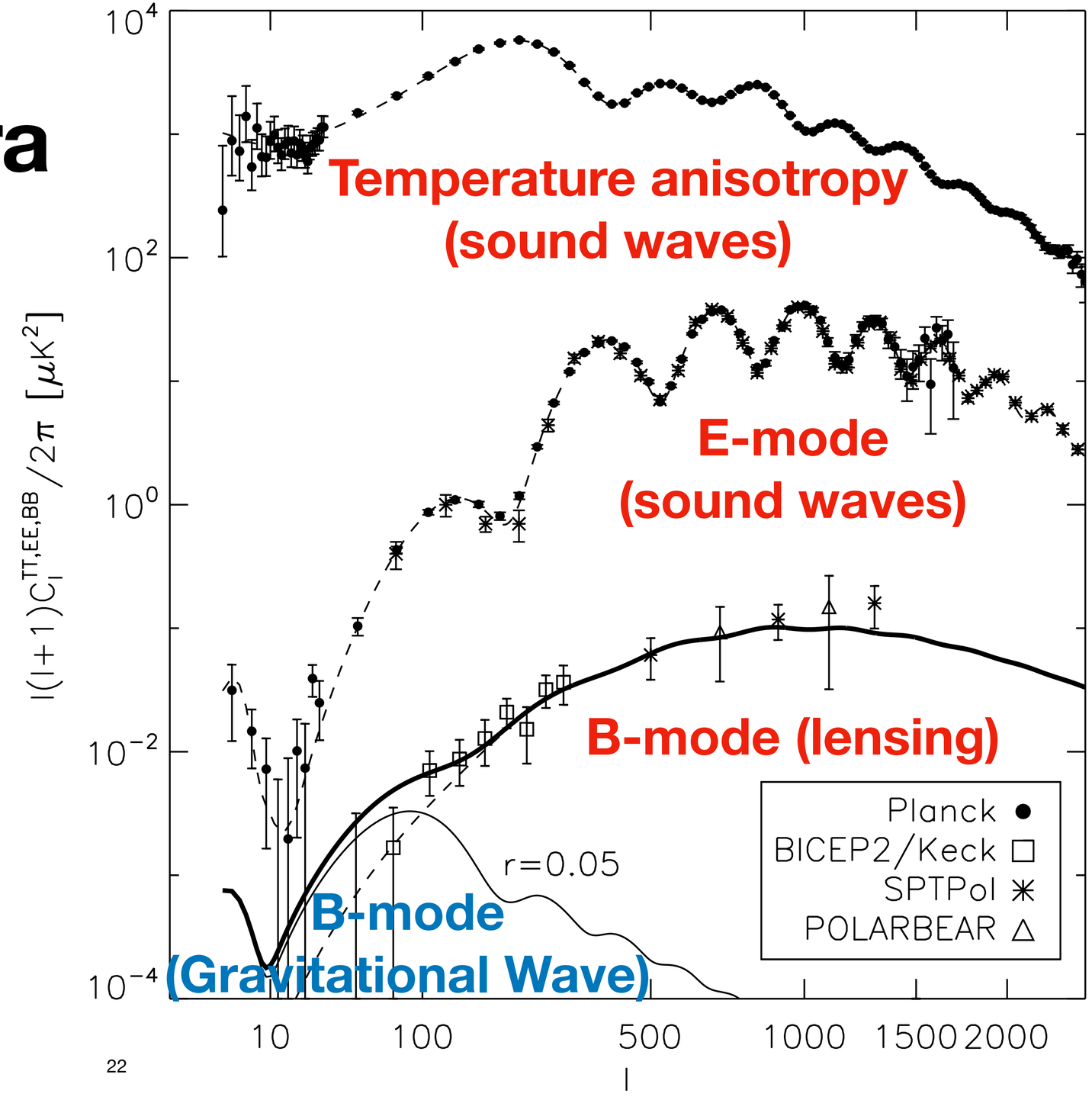
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

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

CMB Power Spectra

Progress over 30 years

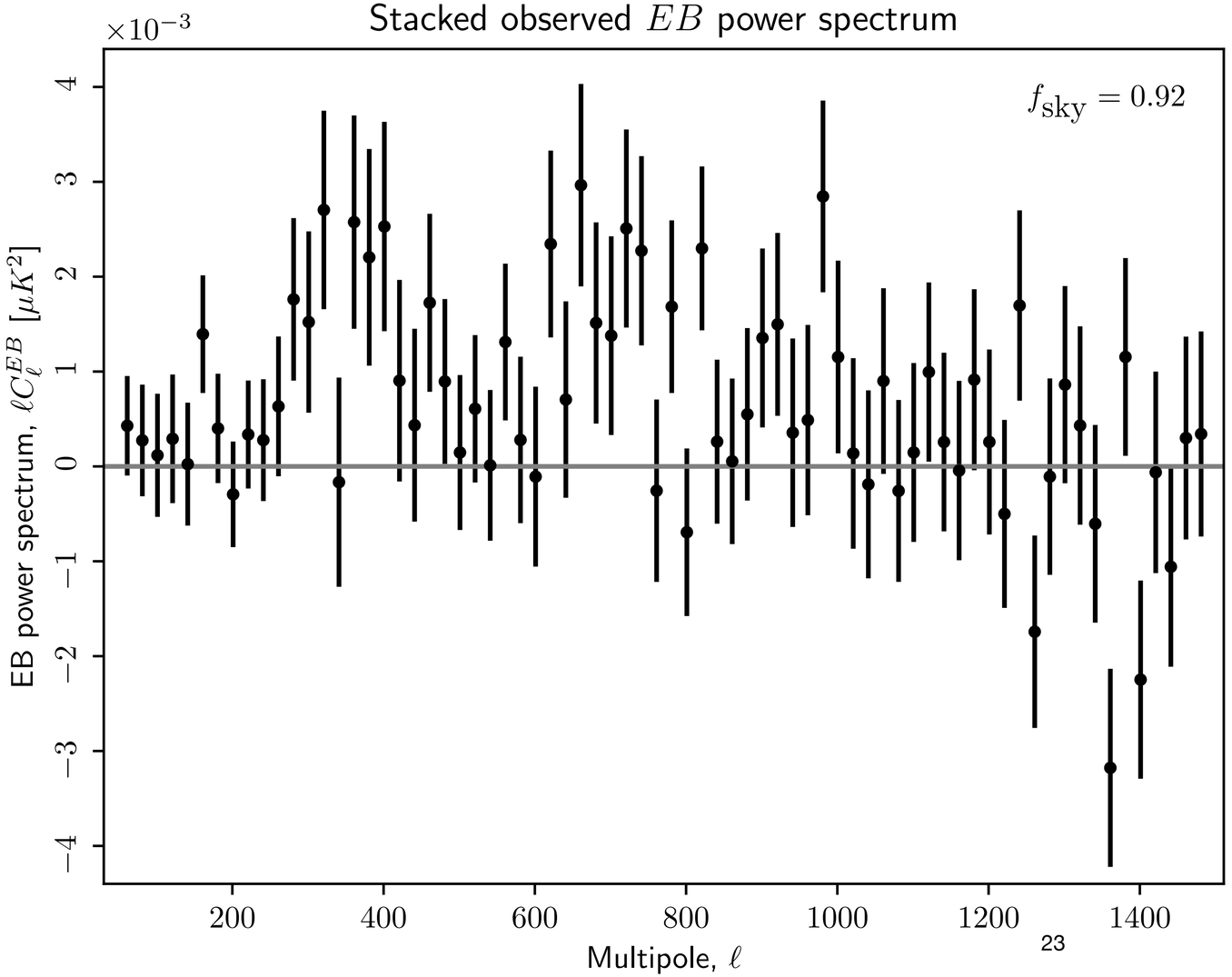
- This is the typical figure seen in talks and lectures on the CMB.
  - The temperature and the E- and B-mode polarization power spectra are well measured.
- **Parity violation appears in the TB and EB power spectra, not shown here.**

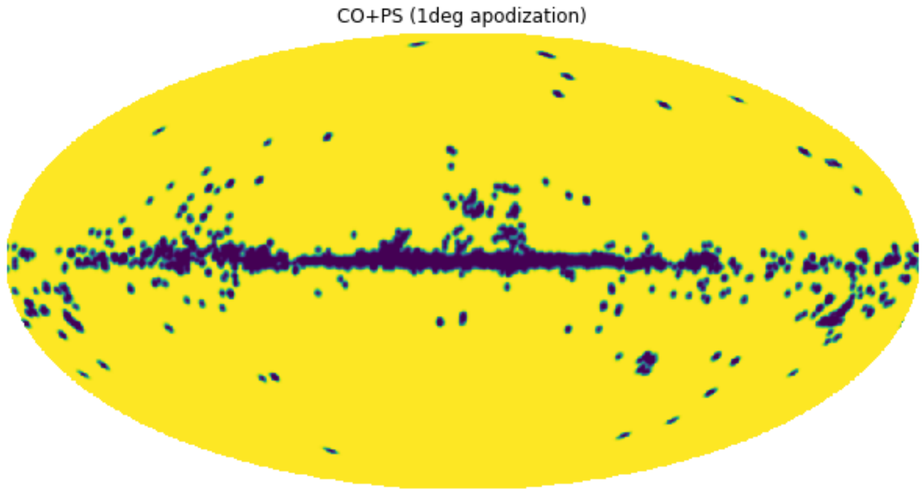


Eskilt, EK (2022)

This is the EB power spectrum (WMAP+Planck)

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

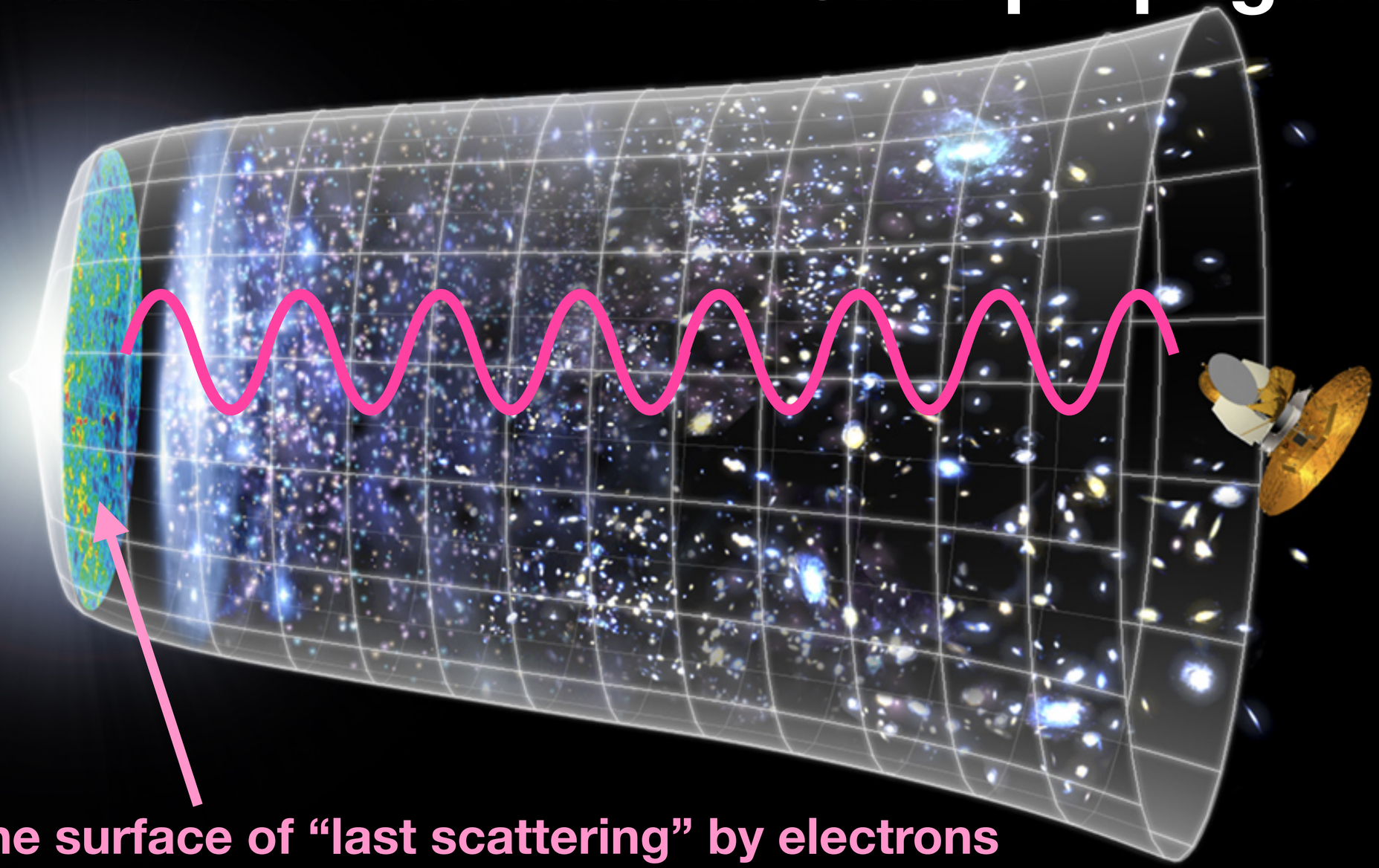




- χ^2 = 125.5 for DOF=72
  - Unambiguous signal of something!

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

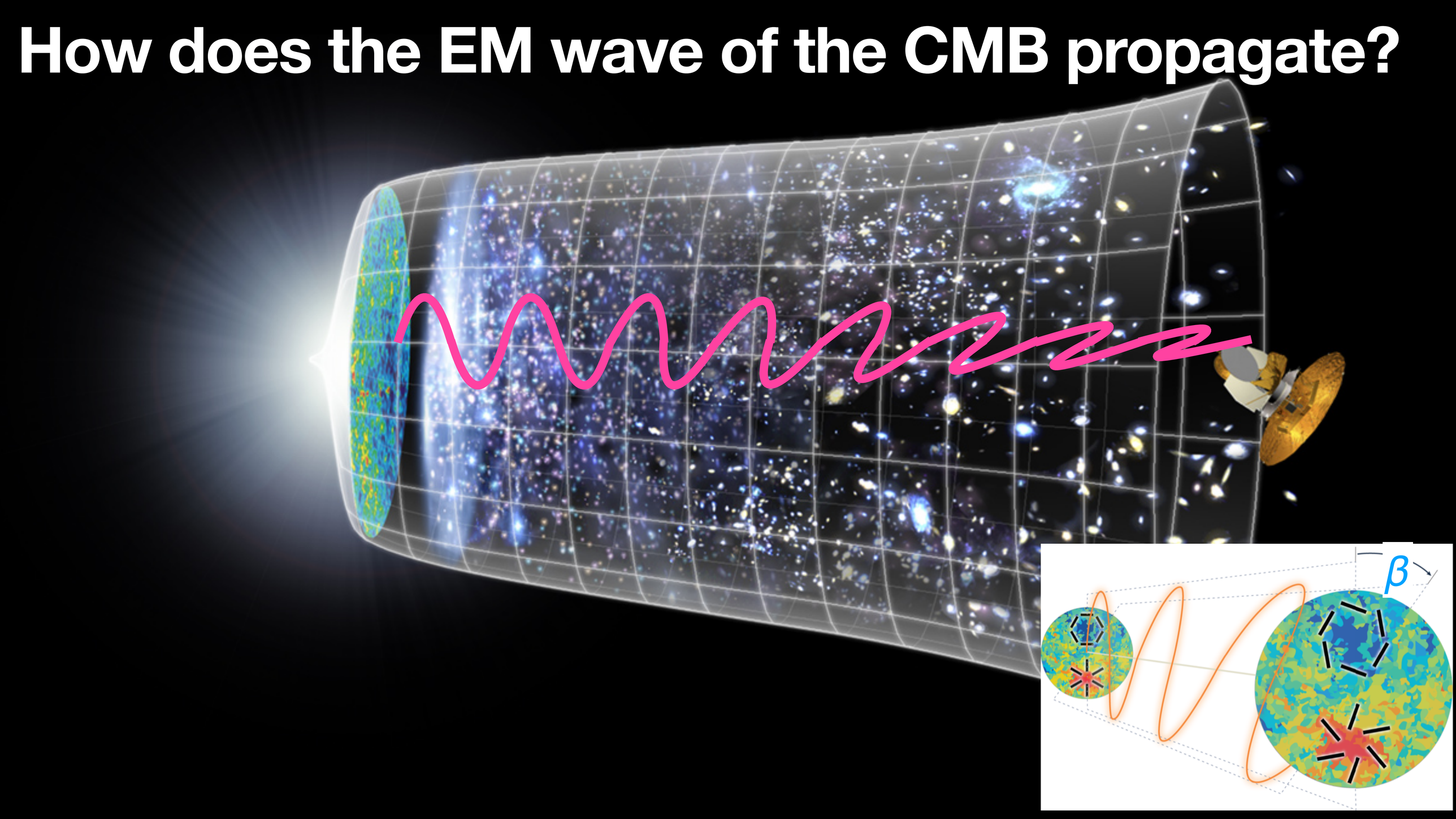
How does the EM wave of the CMB propagate?



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

Credit: WMAP Science Team

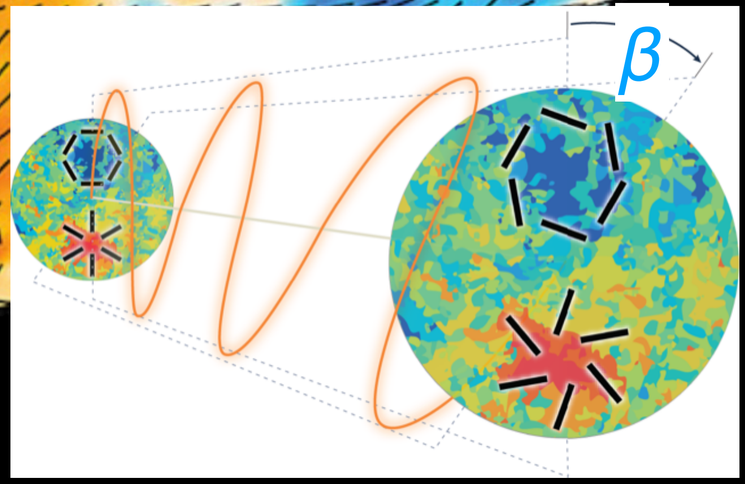
How does the EM wave of the CMB propagate?



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!



Temperature (smoothed) + Polarisation

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

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

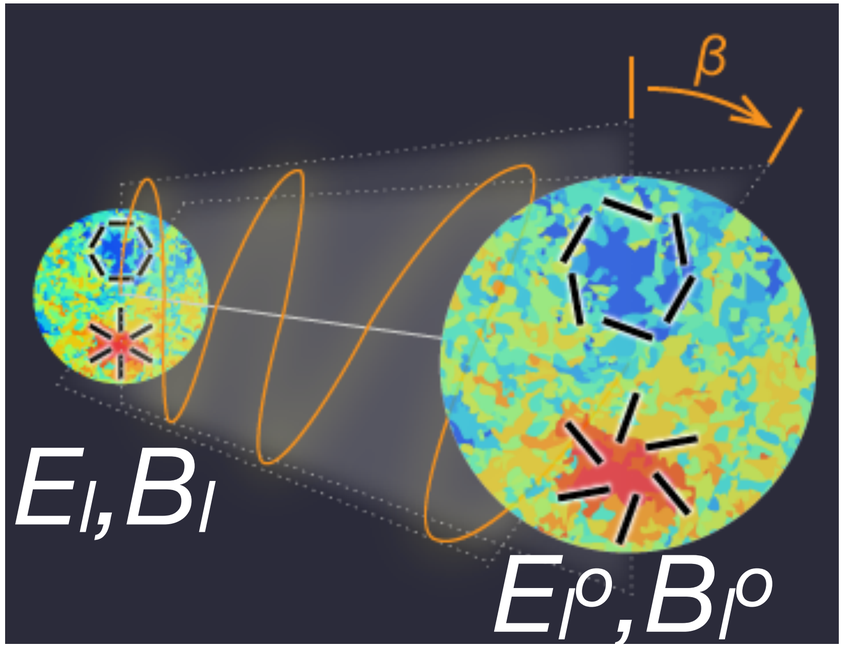
- Observed E- and B-mode polarization, E_l^o and B_l^o, are related to those before rotation as

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

- which gives

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

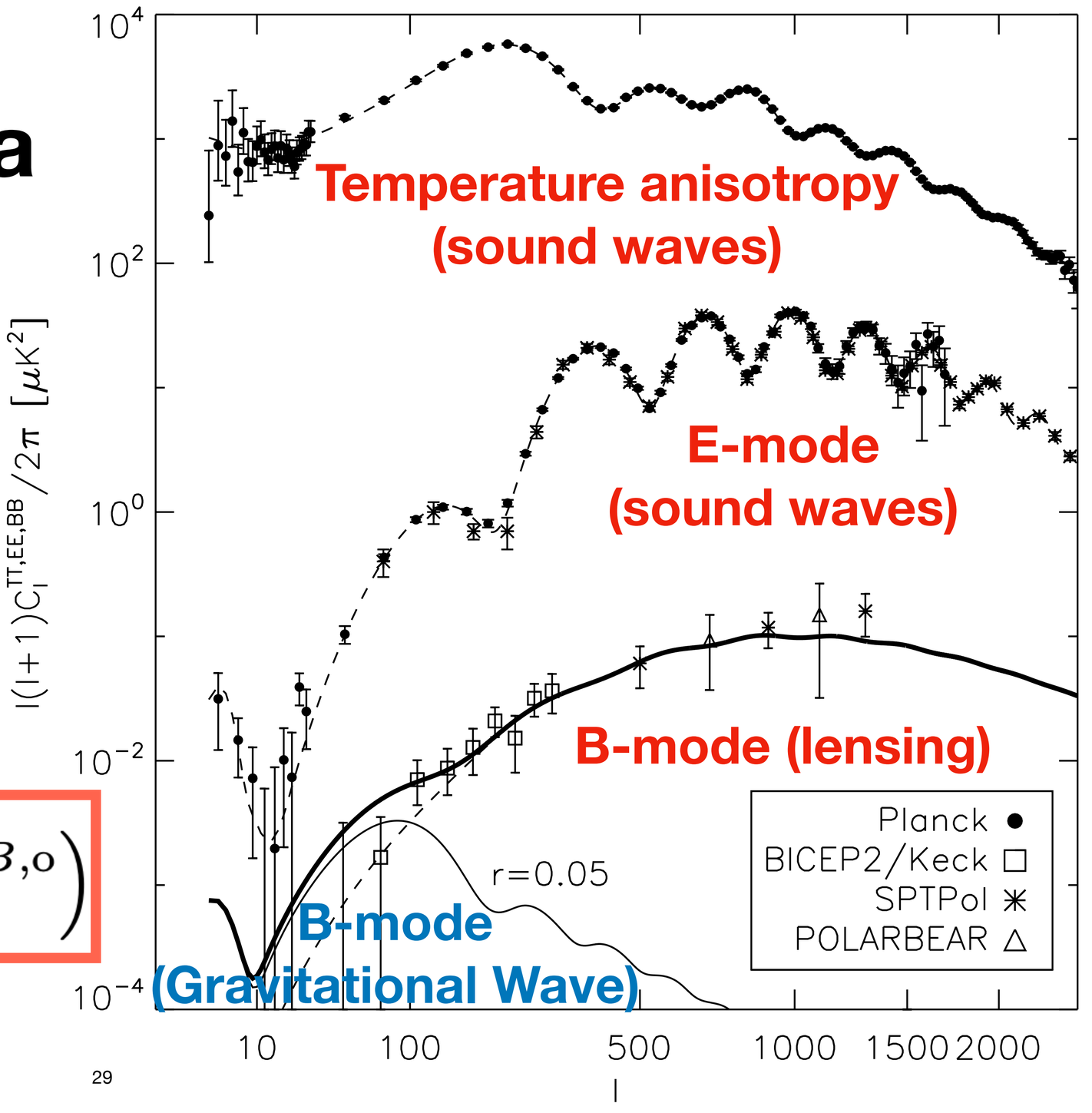
$$B_\ell^{\rm o} = E_\ell \sin(2\beta) + B_\ell \cos(2\beta)$$



CMB Power Spectra

- Rotation of the plane of linear polarization **mixes** E and B modes.
- Therefore, the EB correlation will be given by the difference between the EE and BB correlations.
- Observed EE is much greater than BB. We expect EB to look like EE!

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

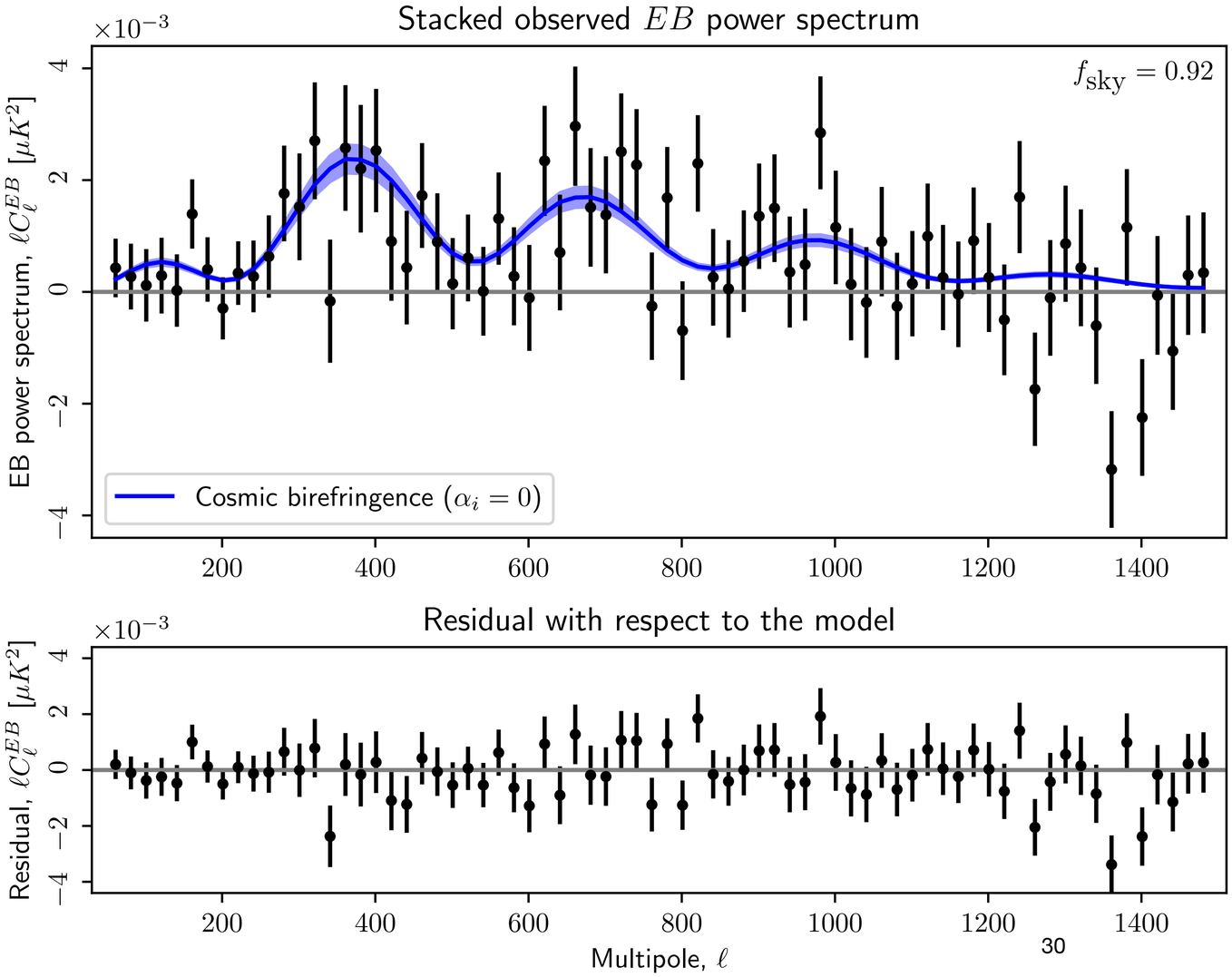


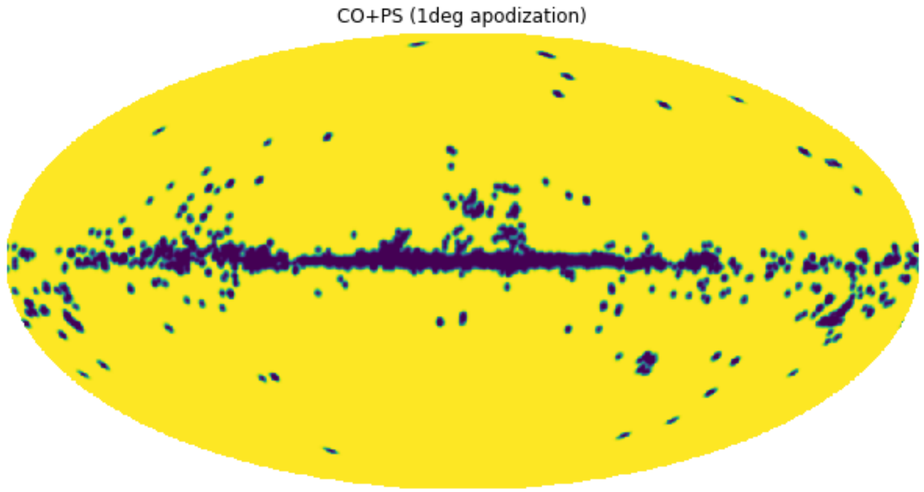
Eskilt, EK (2022)

Cosmic Birefringence fits well(?)

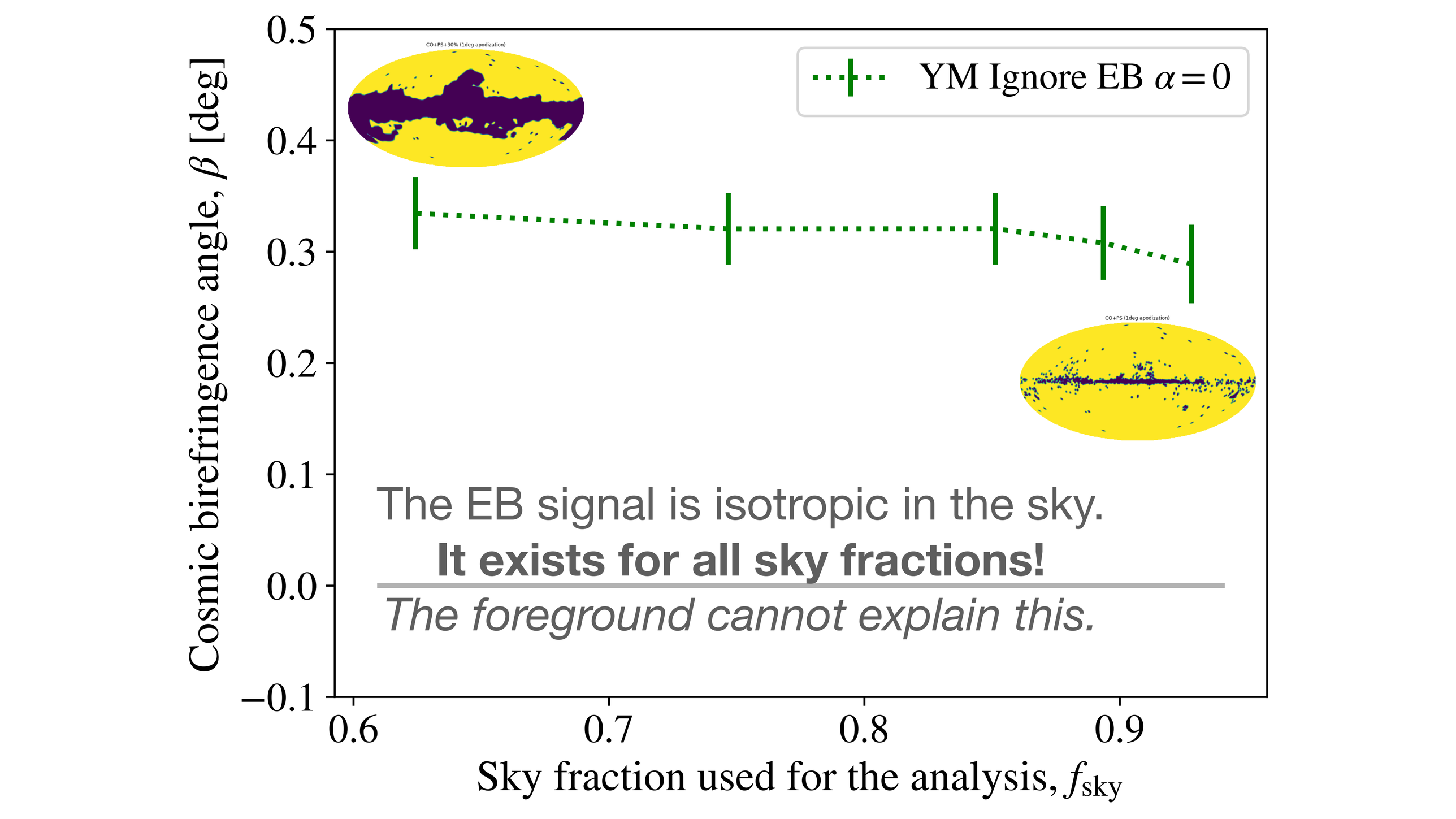
$$C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)$$

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





- β = 0.288 ± 0.032 deg
- χ^2 = 66.1 for DOF=71
  - Good fit! 9σ detection?

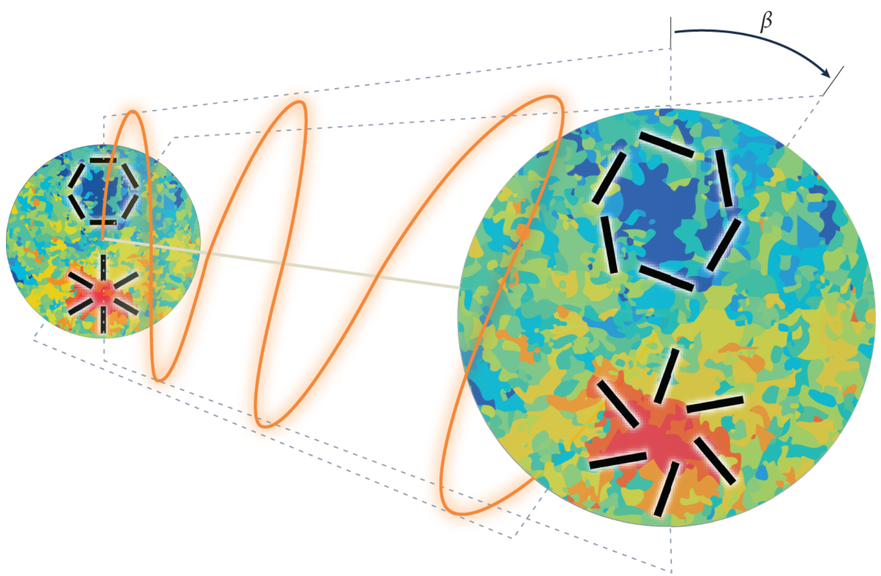

YM Ignore EB $\alpha = 0$
CO+PS+30% (1deg apodization)
CO+PS (1deg apodization)
The EB signal is isotropic in the sky.
It exists for all sky fractions!
The foreground cannot explain this.
Cosmic birefringence angle, β [deg]
Sky fraction used for the analysis, $f_{\rm sky}$
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
0.6
0.7
0.8
0.9

The Biggest Problem: Miscalibration of detectors

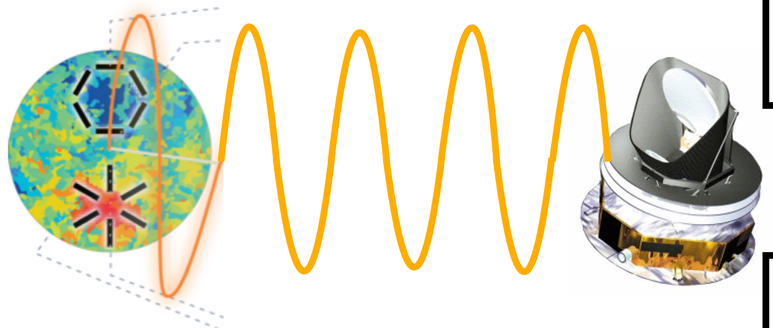
Wu et al. (2009); Miller, Shimon, Keating (2009); EK et al. (2011)

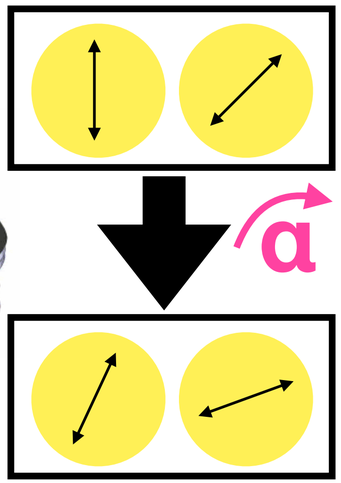
Impact of miscalibration of polarization angles

Cosmic or Instrumental?



OR



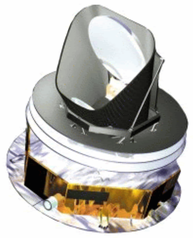


- Is the plane of linear polarization rotated by the genuine cosmic birefringence effect, or simply because the polarization-sensitive directions of the detectors are rotated with respect to the sky coordinates (and we did not know it)?

- If the detectors are rotated by α, it seems that we can measure only the **sum α+β**.

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!

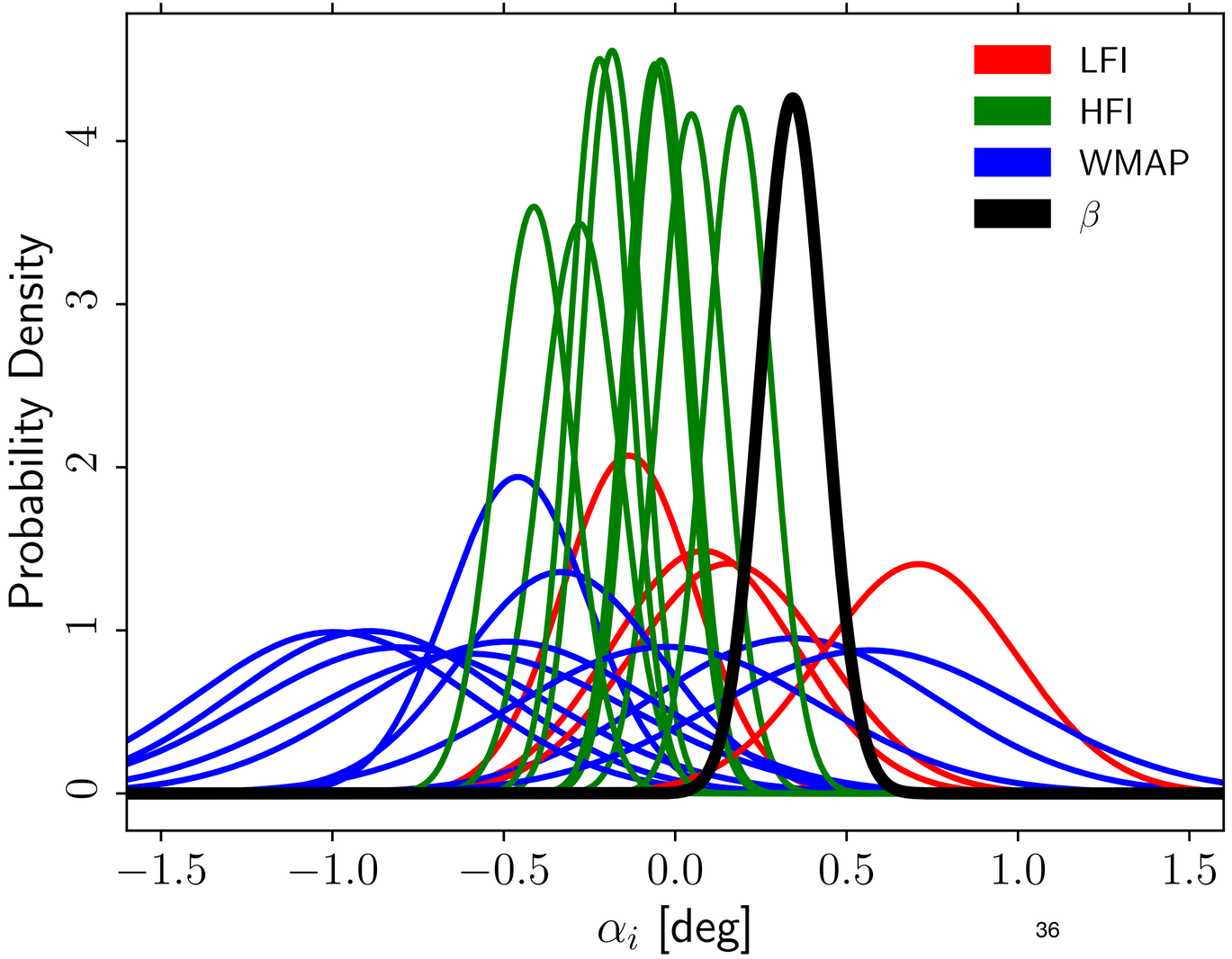
Emitted "right there" - it would not be affected by cosmic birefringence.

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

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

Miscalibration angles (WMAP and Planck)

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

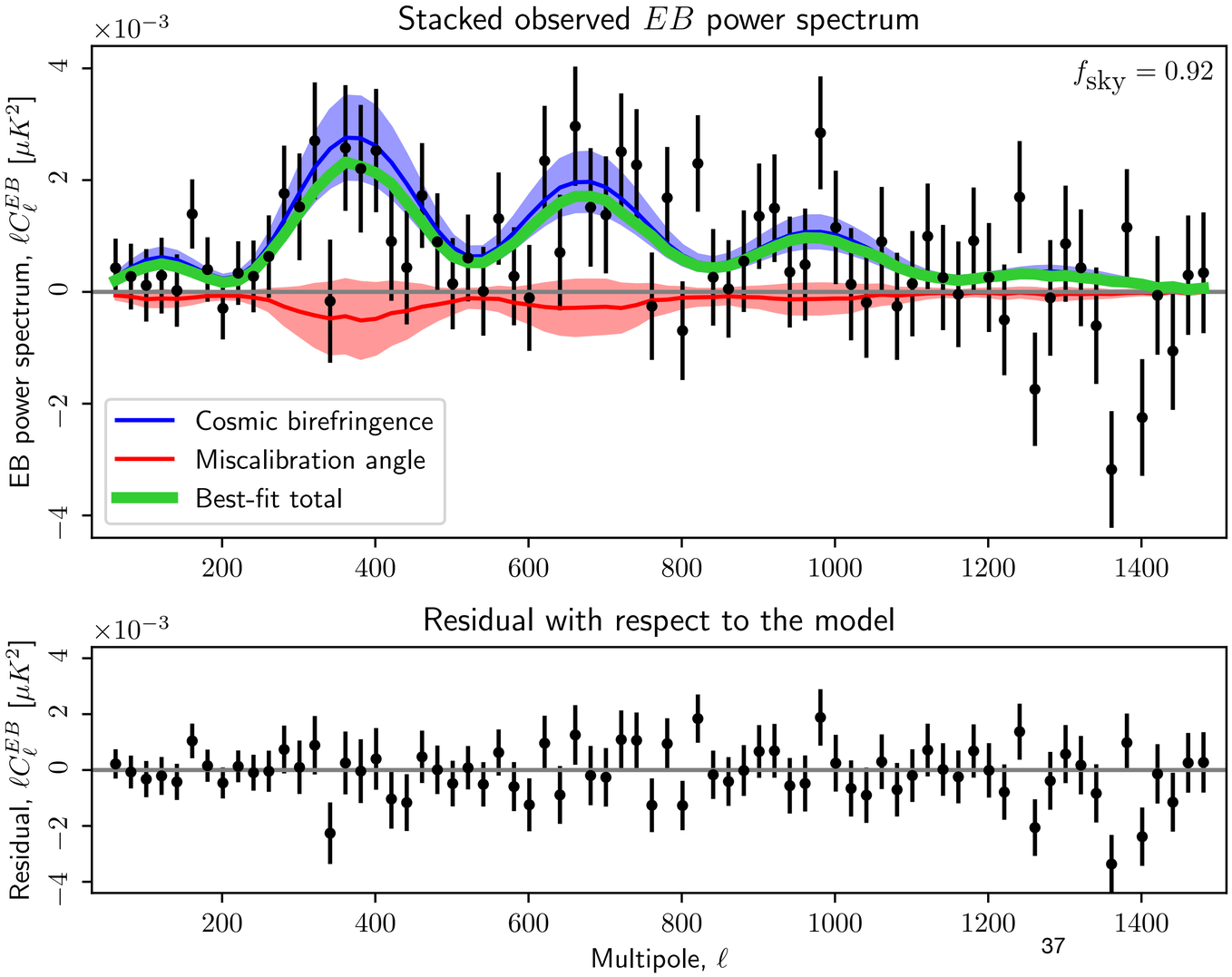


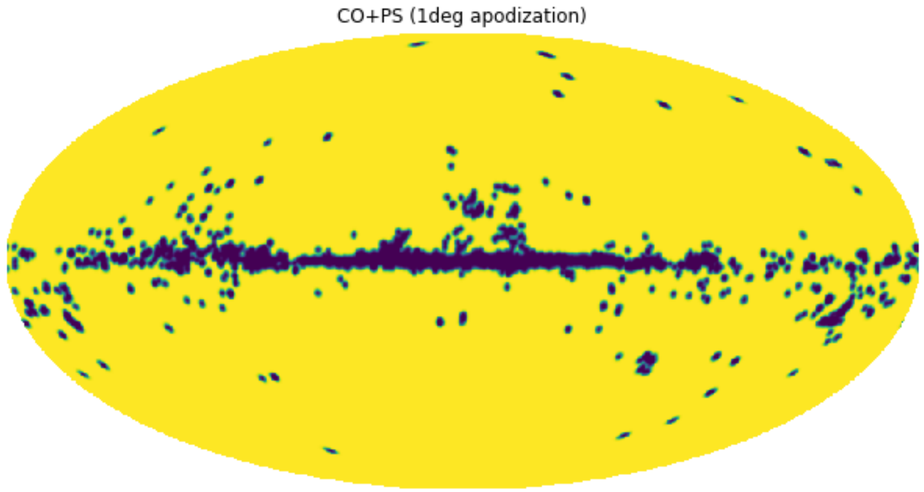
- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

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)



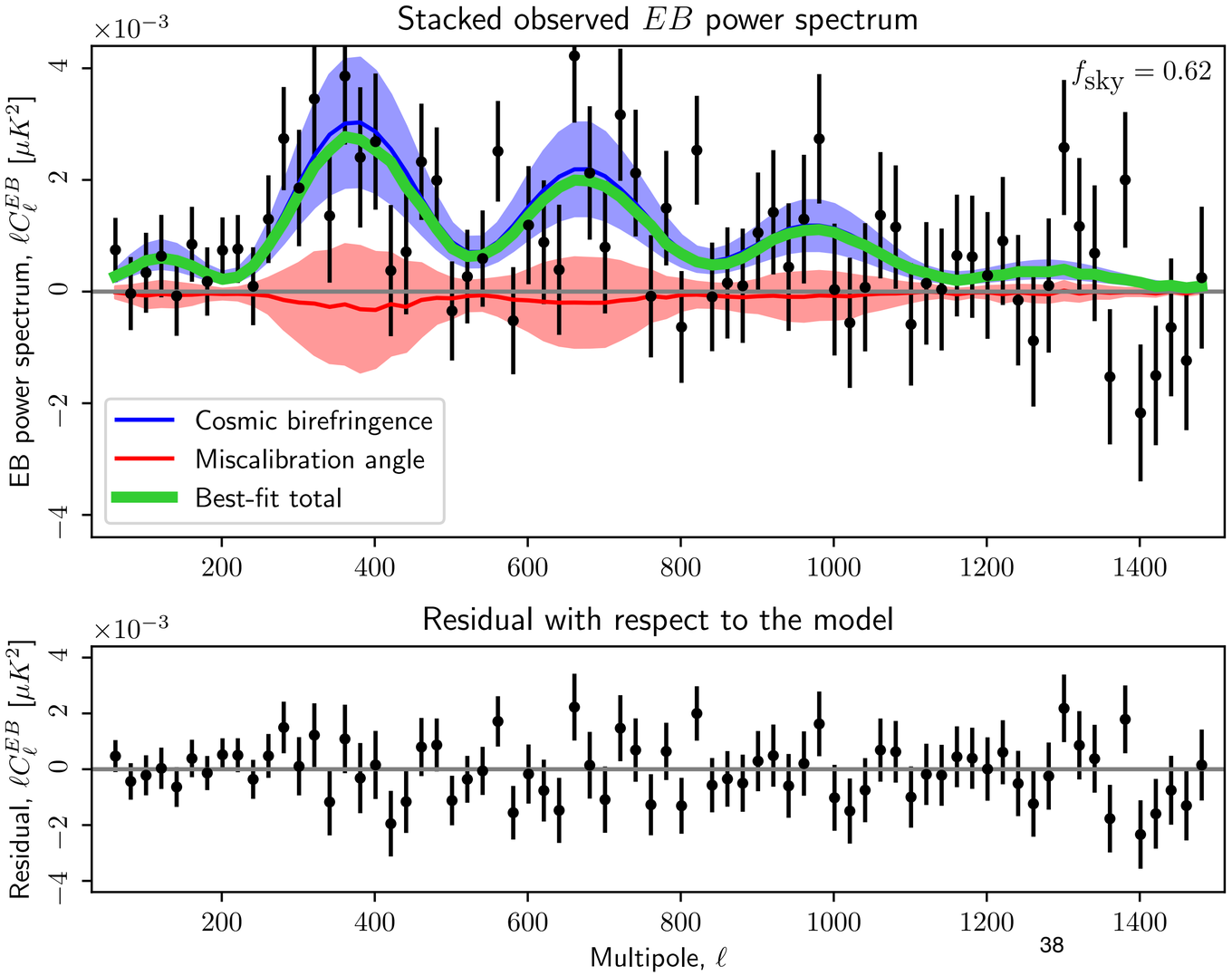


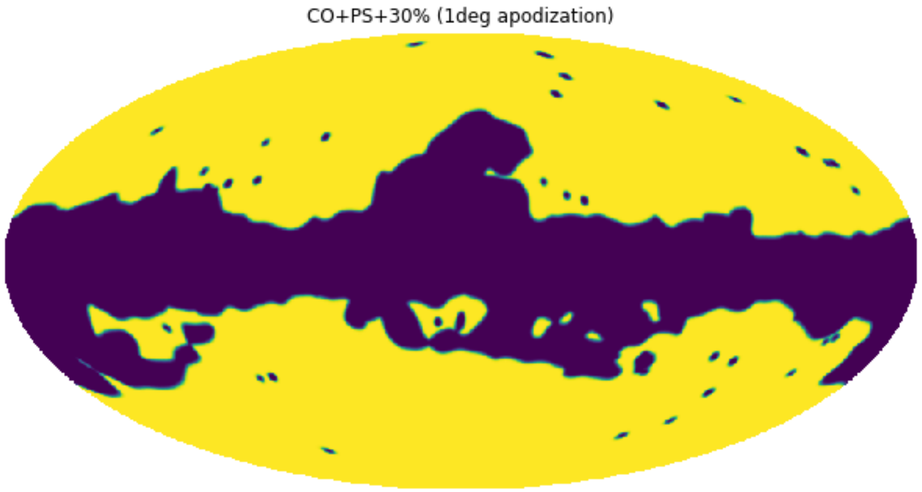
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- $\chi^2 = 65.3$

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

Cosmic Birefringence fits well (WMAP+Planck)

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



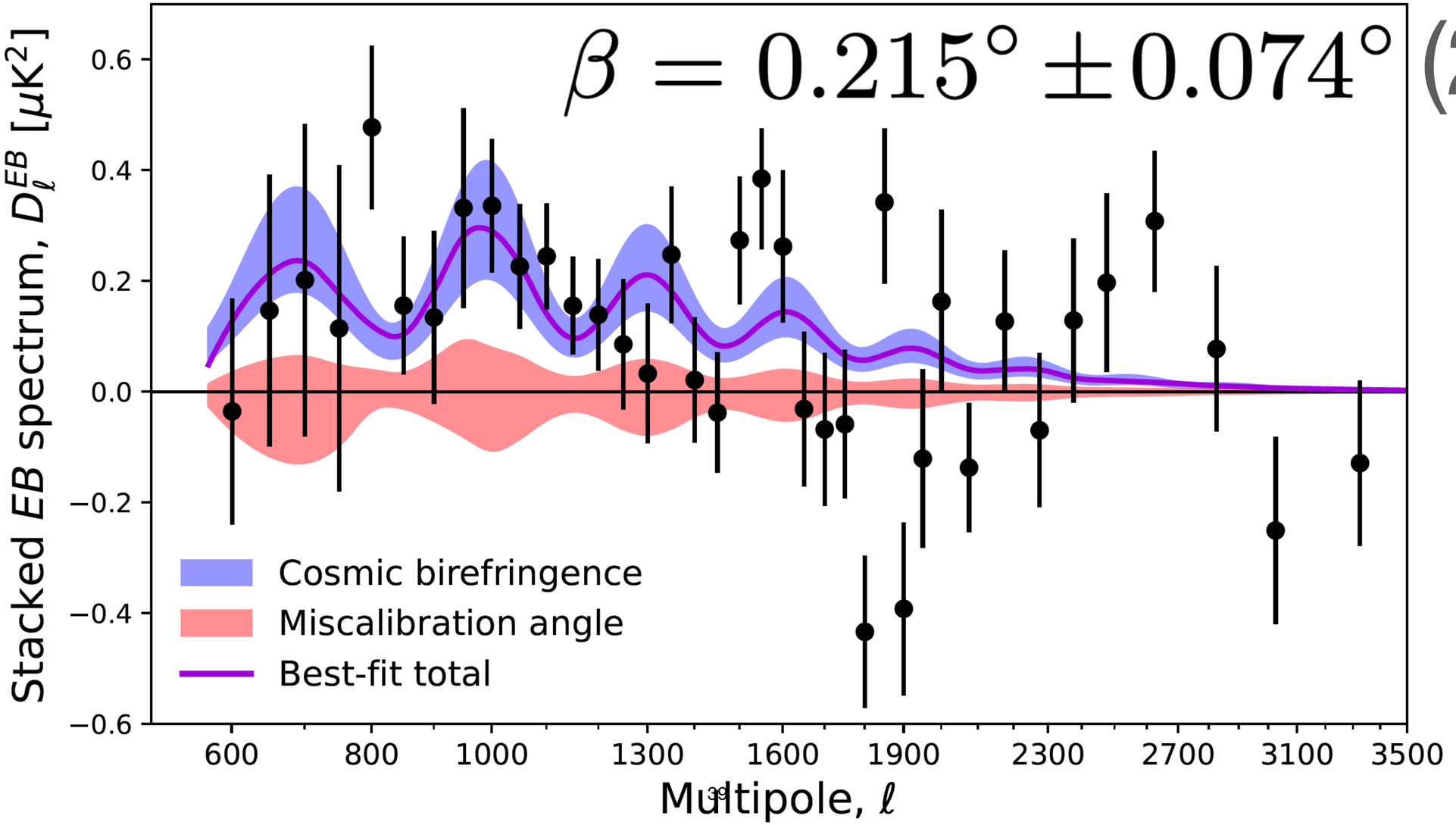


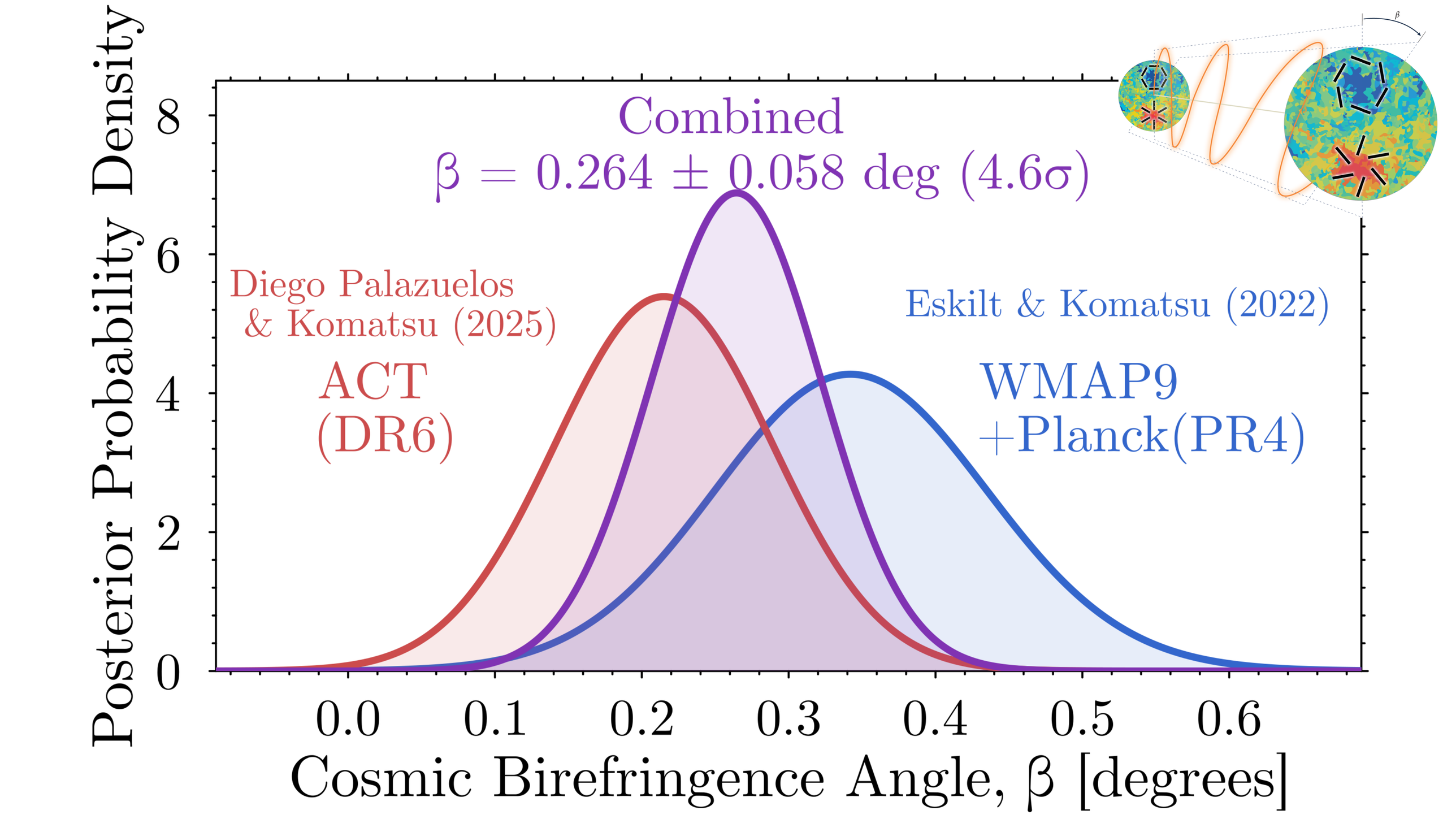
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- $\chi^2 = 65.8$

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

Atacama Cosmology Telescope (DR6)

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

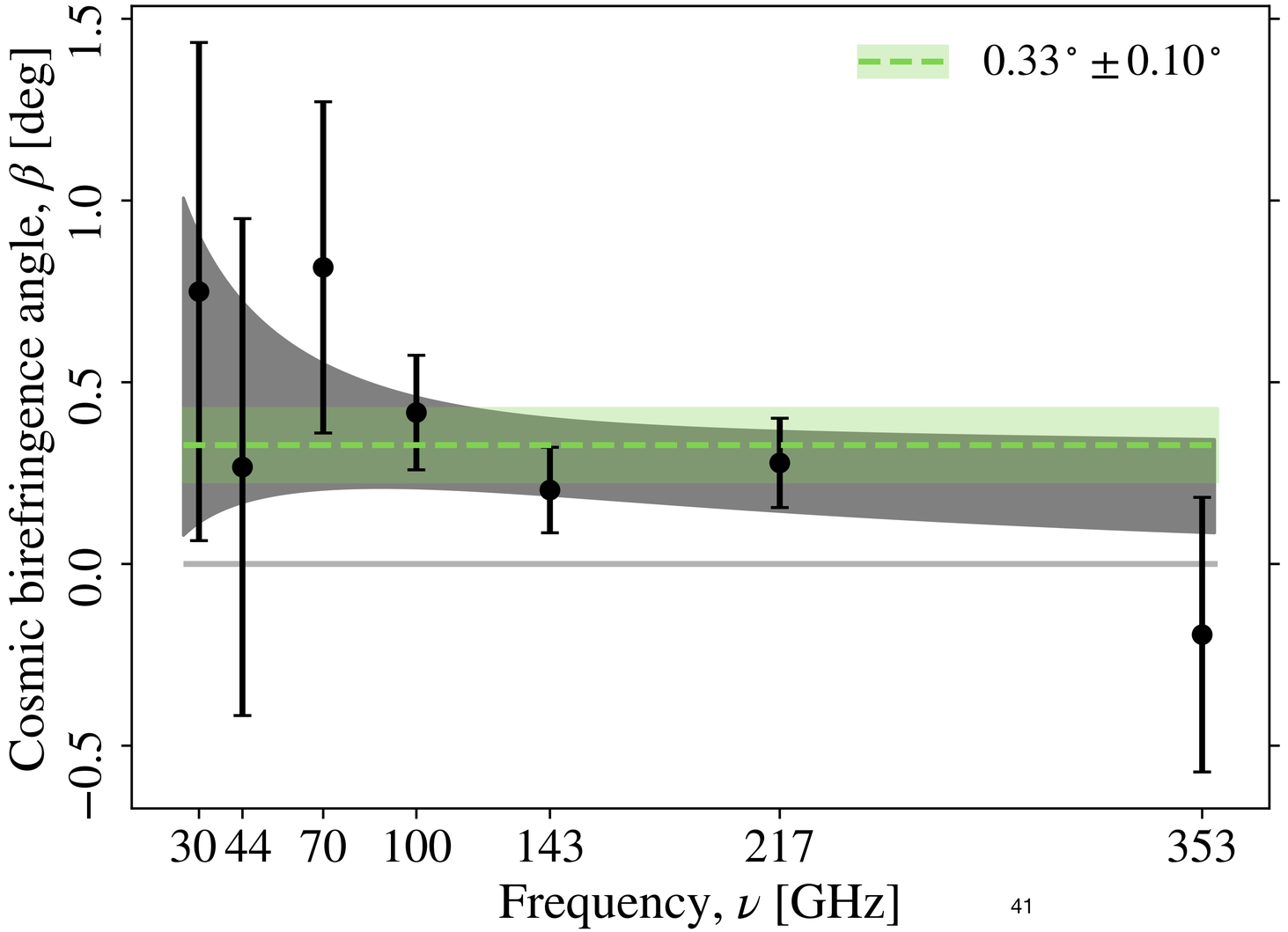



Combined
$\beta = 0.264 \pm 0.058$ deg (4.6σ)
Diego Palazuelos
& Komatsu (2025)
ACT
(DR6)
Eskilt & Komatsu (2022)
WMAP9
+Planck(PR4)
Posterior Probability Density
0
2
4
6
8
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Cosmic Birefringence Angle, β [degrees]

Eskilt (2022); Eskilt, EK (2022)

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.**

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 Dark Matter and Dark Energy

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

Scalar field DM/DE coupled to photons

DM = Dark Matter; DE = Dark Energy

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

The scalar field sector: DM or DR.

- 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 $\alpha \simeq \alpha_{\rm EM} \simeq 10^{-2}$ and $f < M_{\rm Pl} \simeq 2.4 \times 10^{18}$ GeV.
- χ can be composed of fermions like a pion, or a fundamental pseudoscalar like an “axion” field.

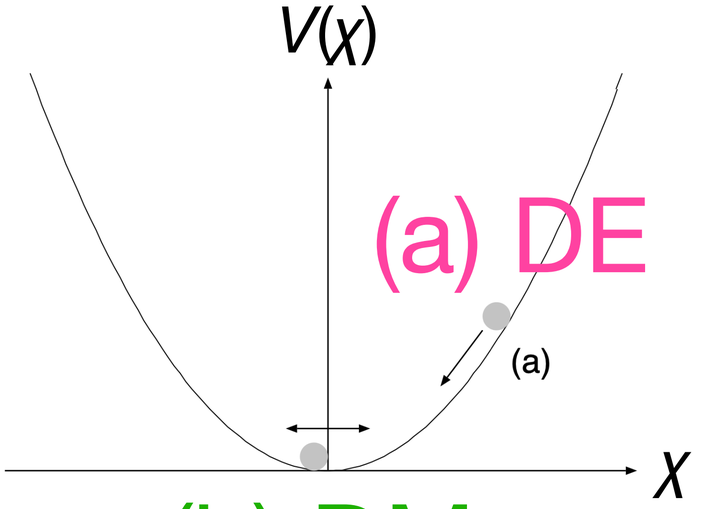
Distinction between DE and DM

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

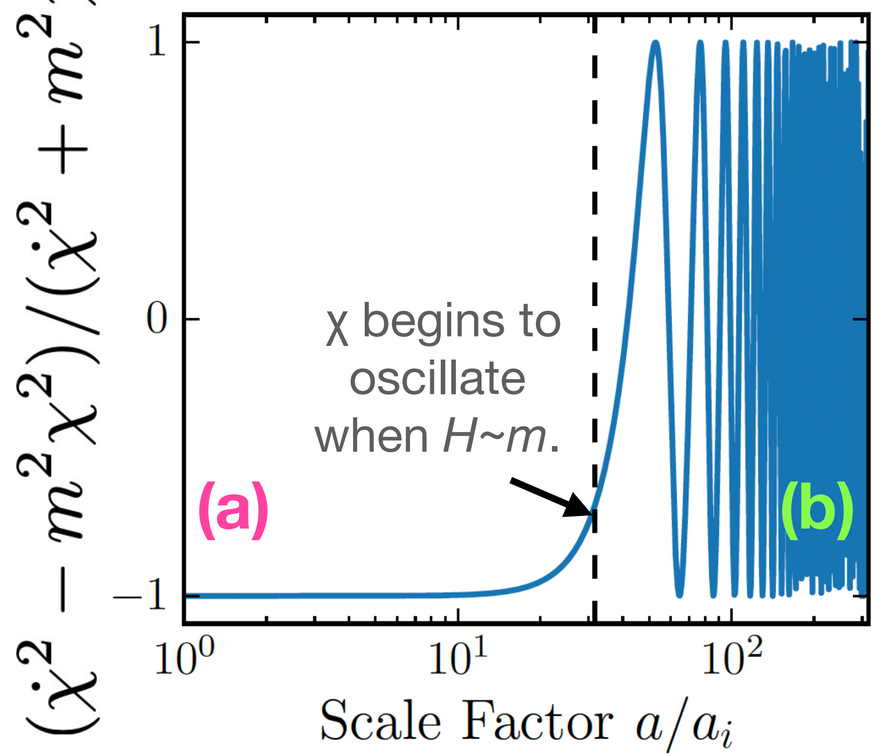
- The useful criterion is the equation of state parameter, *w*.

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

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



(b) DM



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

Scalar field DM/DE coupled to photons

DM = Dark Matter; DE = Dark Energy

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

The electromagnetic sector: Coupling to photons via the "Chern-Simons term".

$$F^2 \equiv F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E})$$

This is a *scalar* and is invariant under parity transformation.

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

This is a *pseudoscalar* and changes sign under parity transformation!

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

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

Jim Simons in 2023
https://einstein-chair.github.io/simons2023/

- **This is not a surface term!** Integration by parts gives

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

- 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 $A_\nu \tilde{F}^{0\nu} = A_i \epsilon^{ijk} \partial_j A_k$

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 I_{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!

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 (倪維斗)]
  - **1983**: Axion electrodynamics [Sikivie]

Implications

DM = Dark Matter; DE = Dark Energy

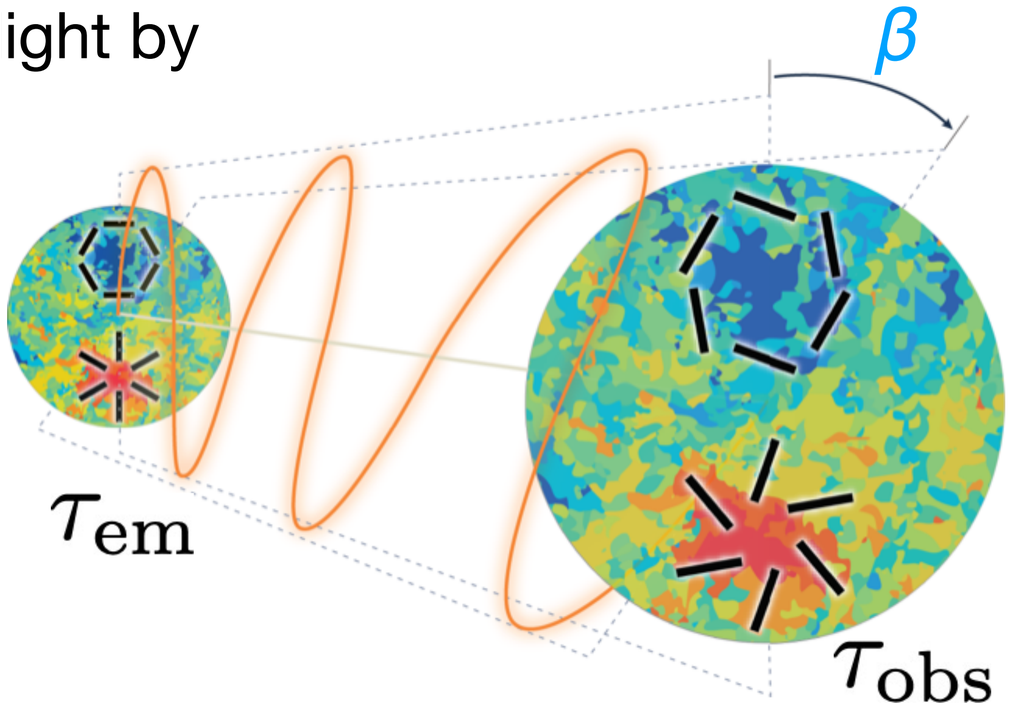
This term exists for a pion.
What if DM/DE is “pion-like particle”?

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

- 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

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

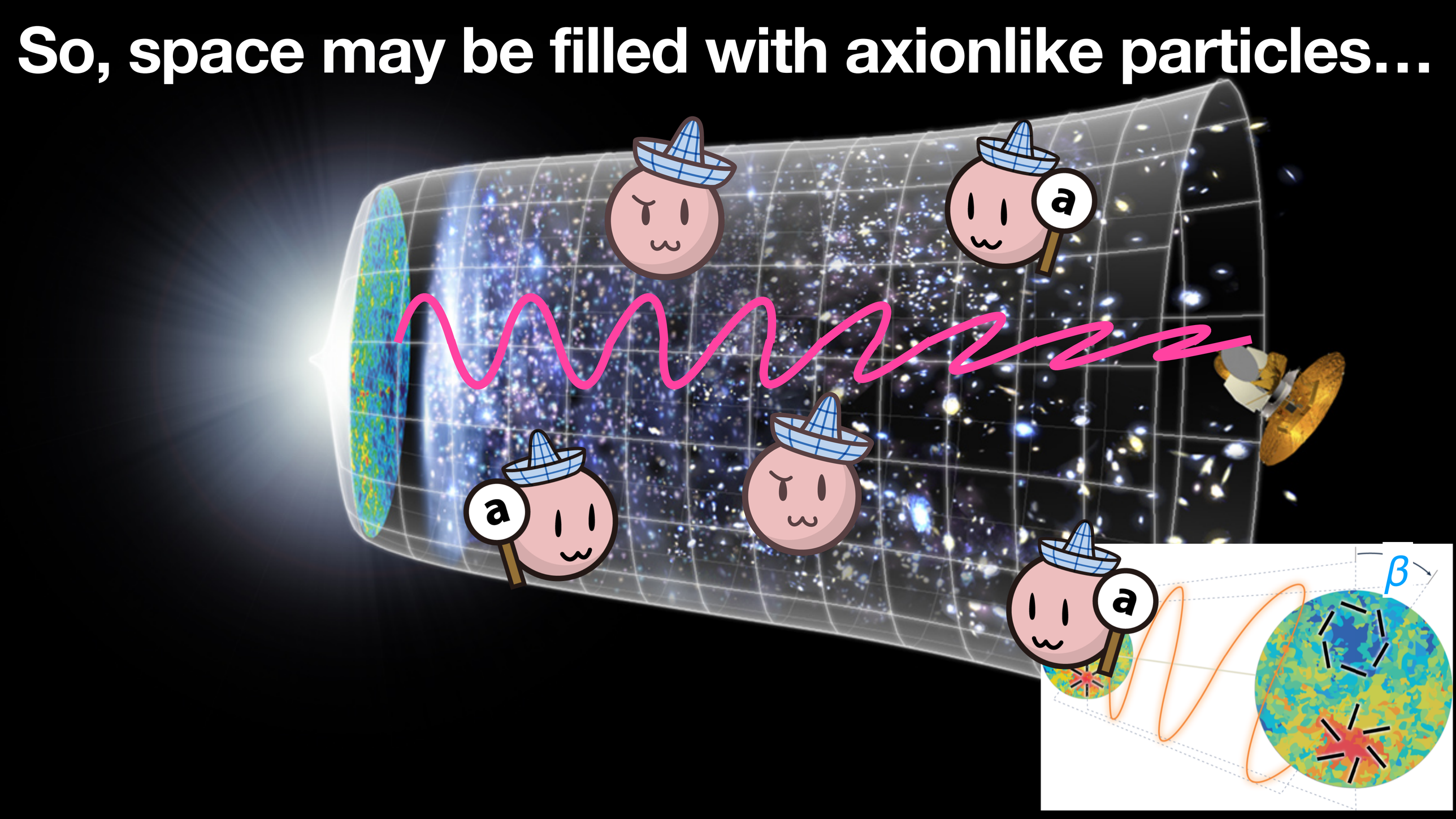
$$\Delta\chi = \chi(\tau_{\rm obs}) - \chi(\tau_{\rm em}) \simeq \frac{10^{-2}}{\alpha} f$$

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.

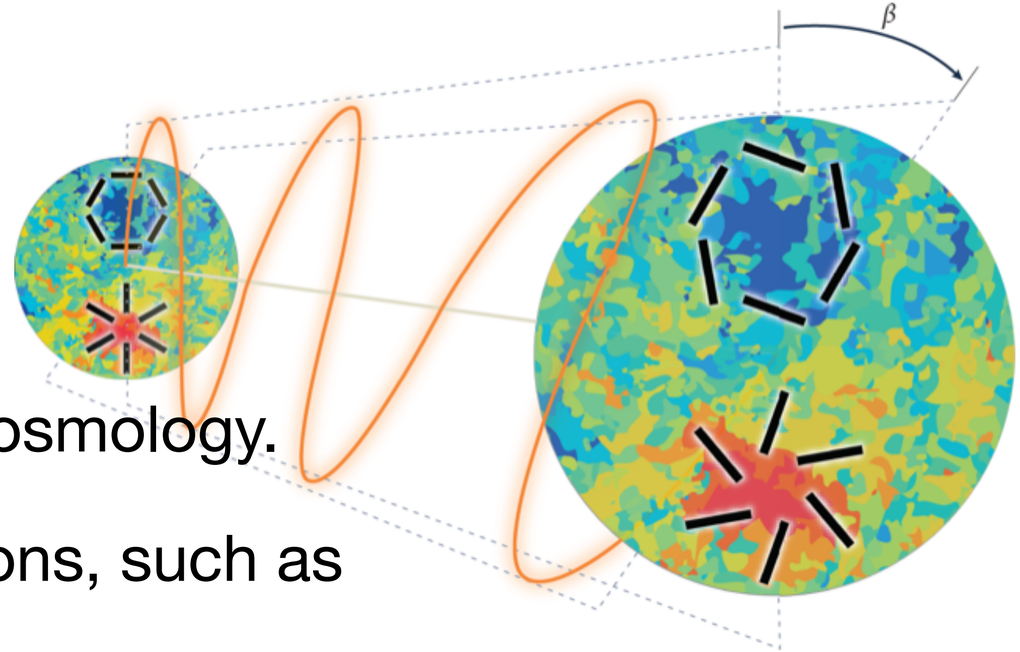
©Higgstan

So, space may be filled with axionlike particles…



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 DM and DE fields?
- **What else should we be looking? New and exciting research topics.**

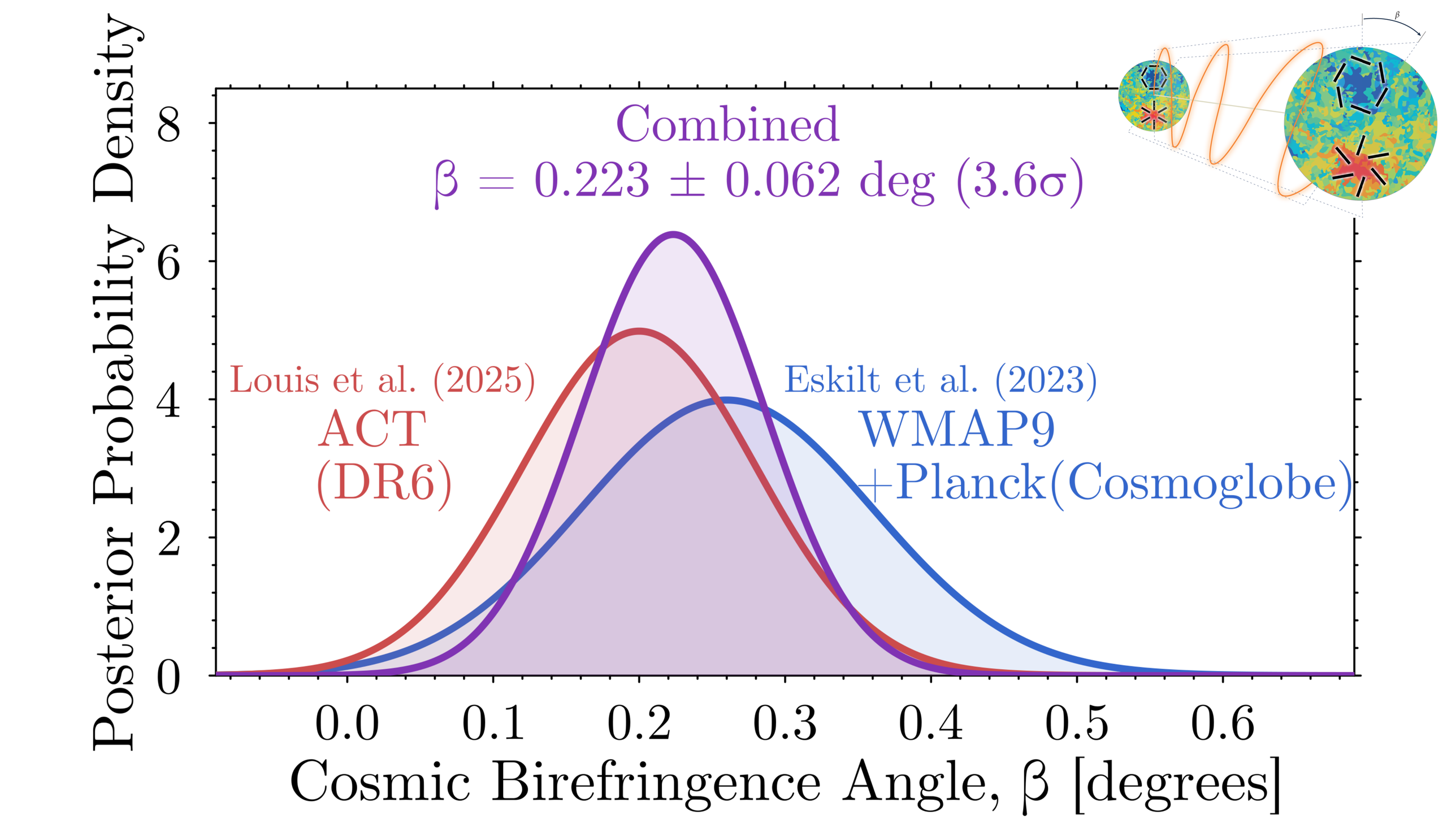
Back up slides

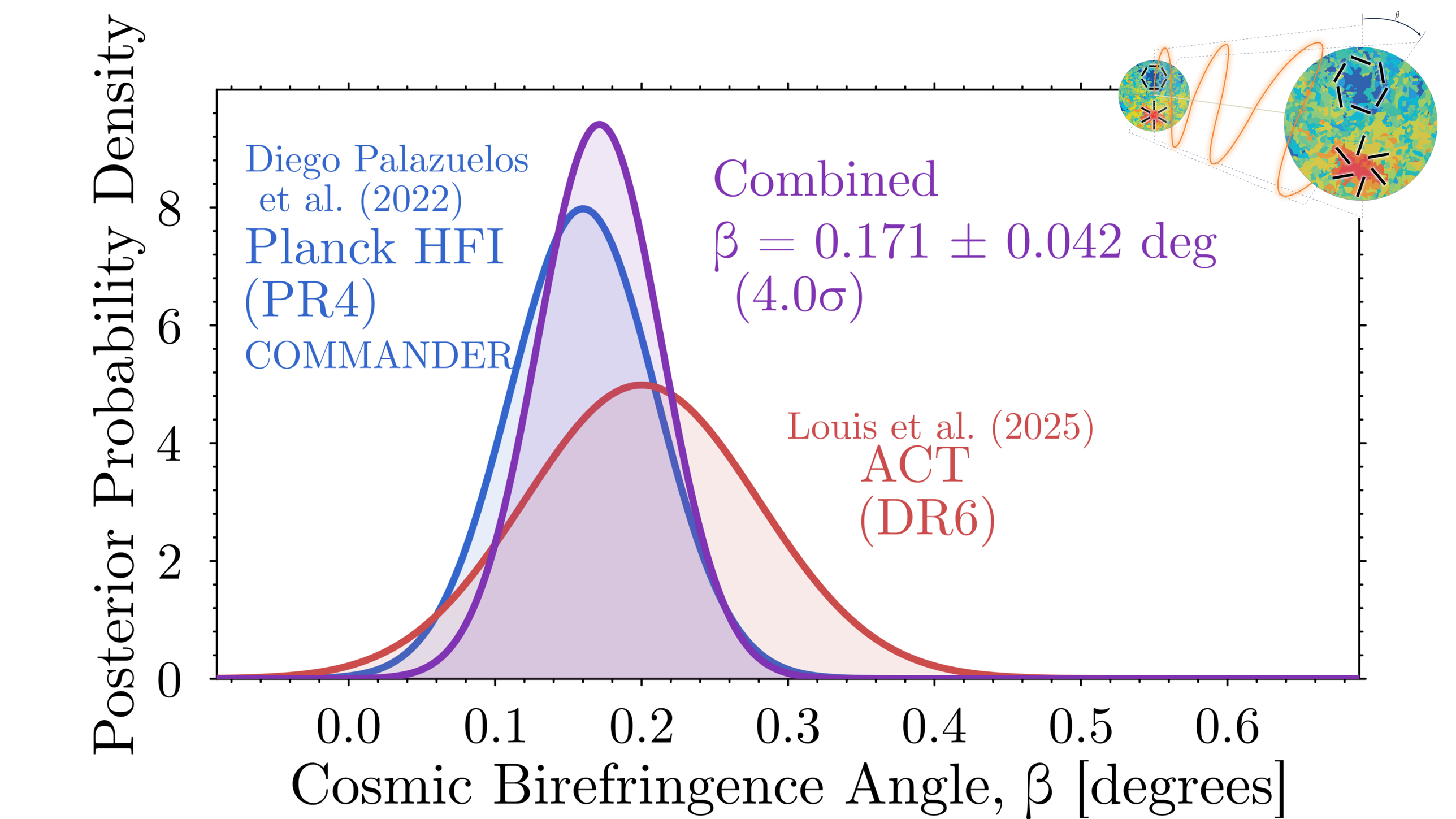
Diego-Palazuelos et al. (2022, 2023); Eskilt et al. [Cosmoglobe] (2023)

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.

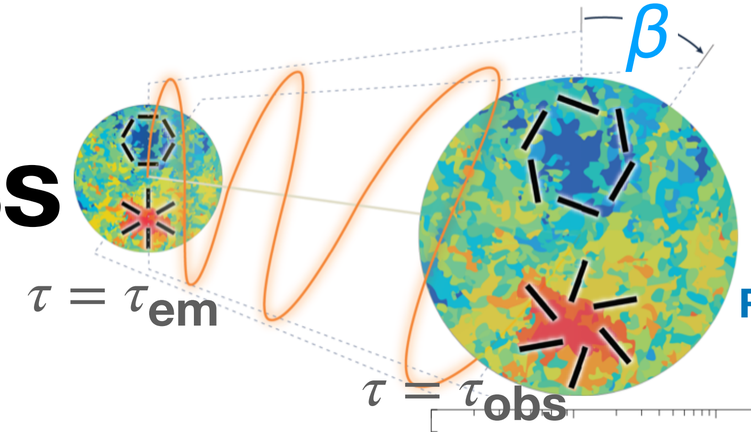

Combined
β = 0.223 ± 0.062 deg (3.6σ)
Louis et al. (2025)
ACT
(DR6)
Eskilt et al. (2023)
WMAP9
+Planck(Cosmoglobe)
Posterior Probability Density
0
2
4
6
8
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Cosmic Birefringence Angle, β [degrees]
β


Posterior Probability Density
0
2
4
6
8
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Cosmic Birefringence Angle, β [degrees]
Diego Palazuelos
et al. (2022)
Planck HFI
(PR4)
COMMANDER
Combined
β = 0.171 ± 0.042 deg
(4.0σ)
Louis et al. (2025)
ACT
(DR6)
β

Is cosmic birefringence due to dark matter or dark energy?

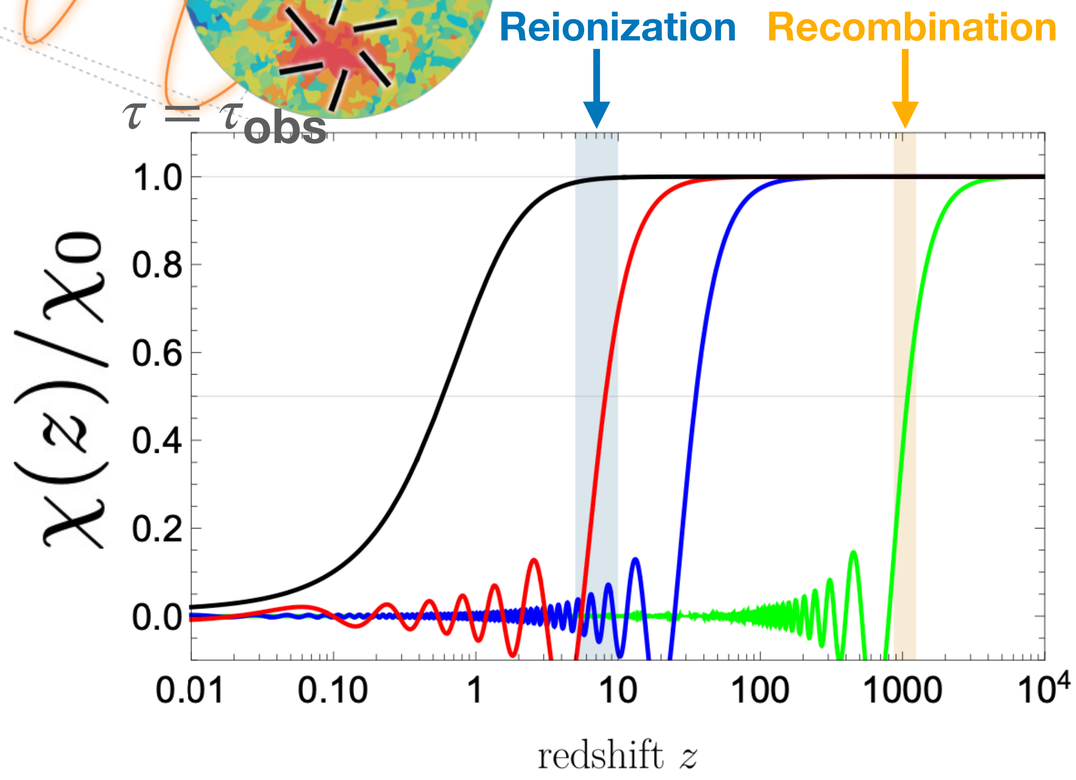
Nakatsuka, Namikawa, EK (2022)

How to measure mass



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

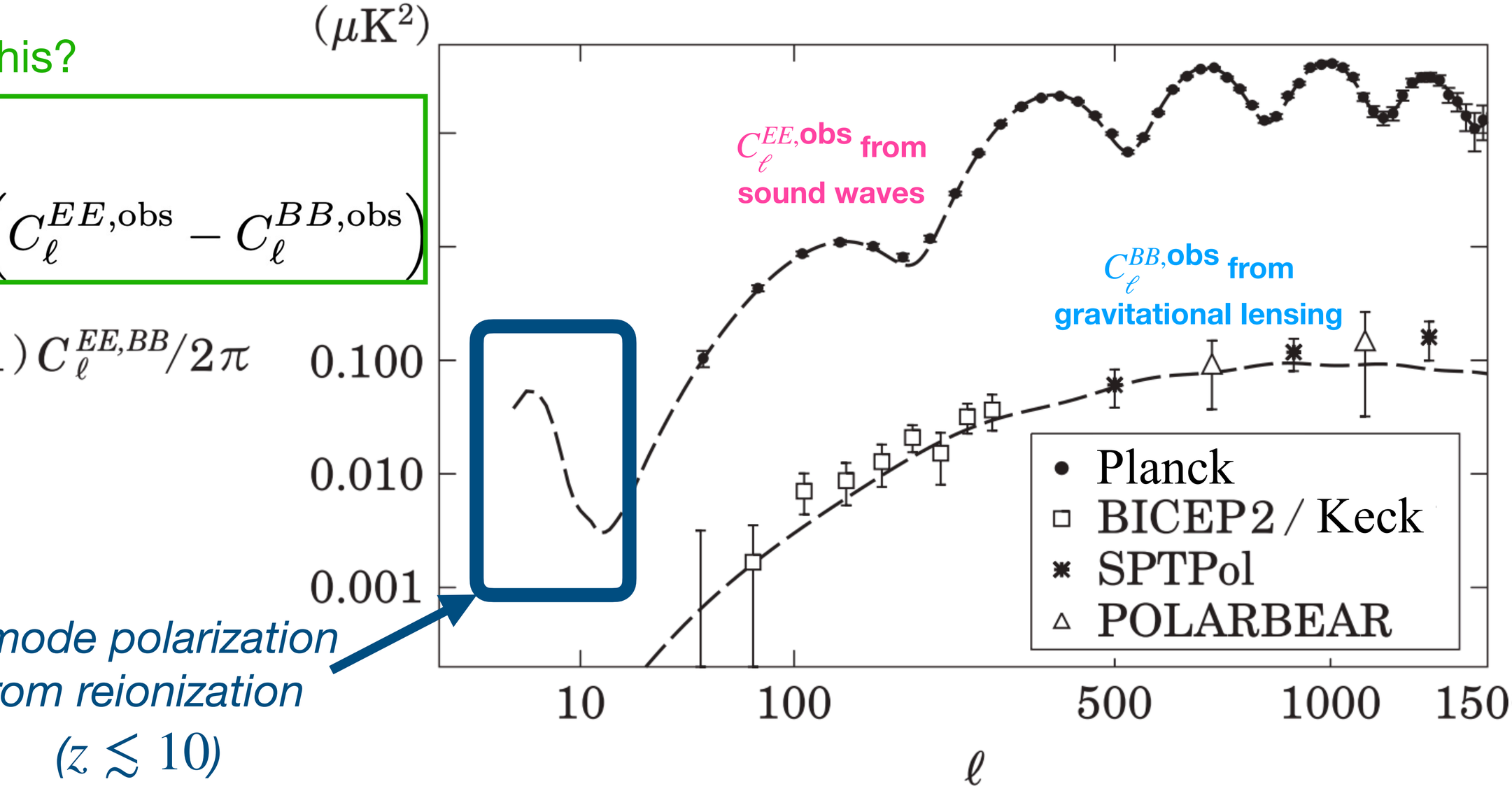
- There are 2 epochs when the CMB polarization was produced.
  - ***z*~1100: Recombination**
  - ***z*~10: Reionization**
- β from these 2 epochs can be different!



“Reionization bump” at low multipoles ($\ell \lesssim 10$)

Do we find this?

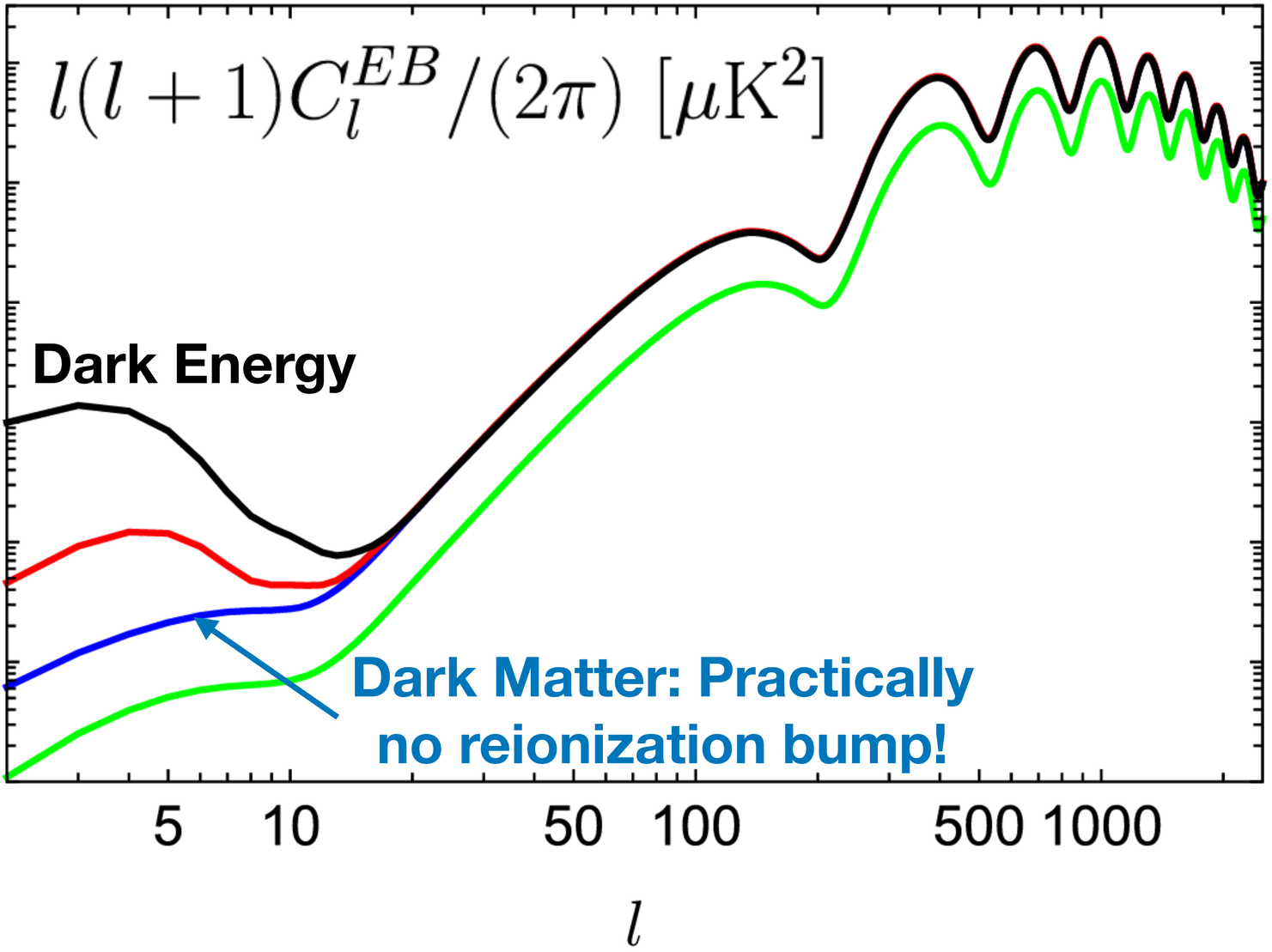
$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right)$$

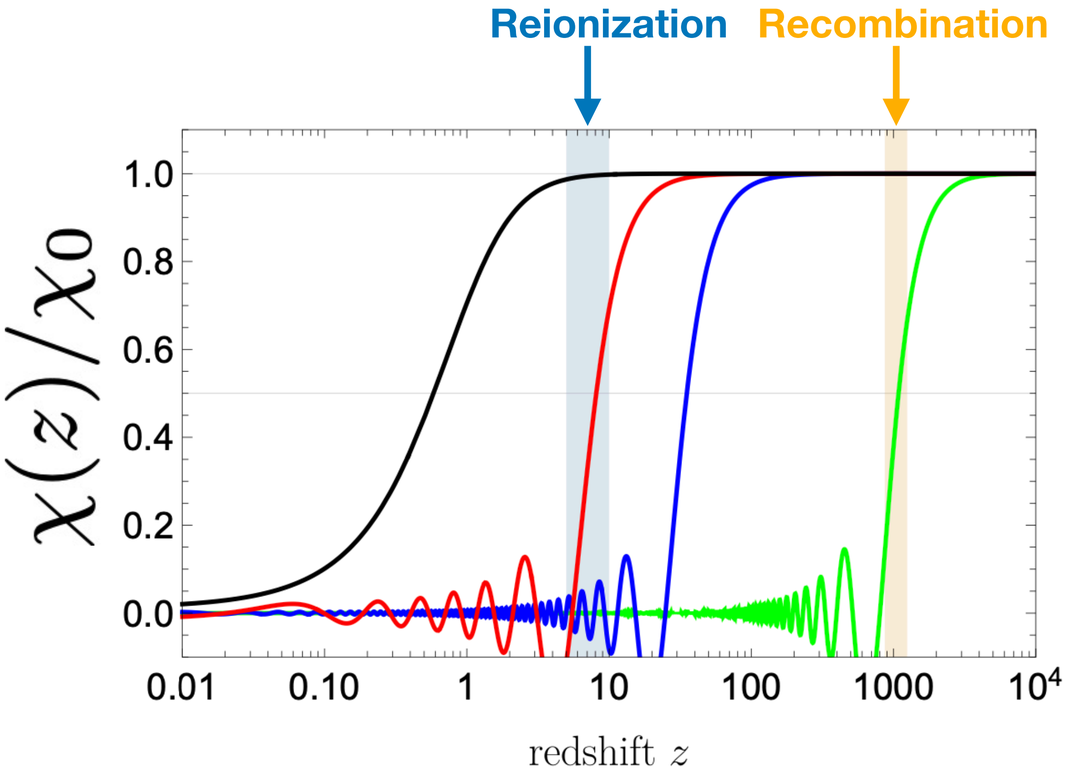


E-mode polarization from reionization ($z \lesssim 10$)

Nakatsuka, Namikawa, EK (2022)

Cosmic Birefringence "Tomography"





$10^{-28.0}$ eV
$10^{-31.2}$ eV
$10^{-30.3}$ eV
$10^{-32.3}$ eV

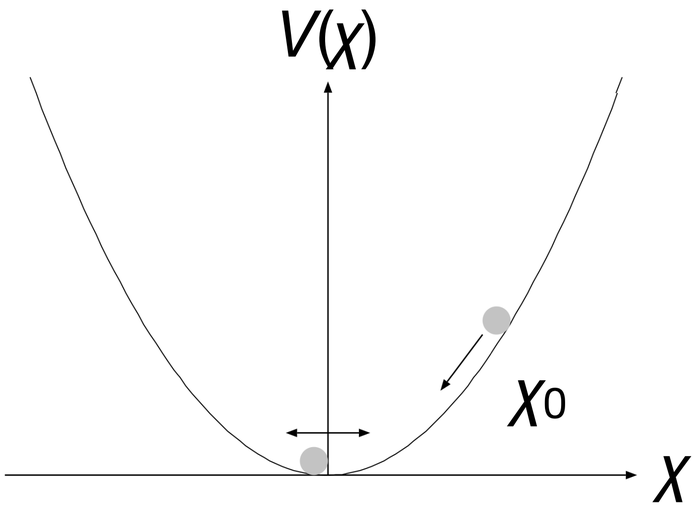
Time-dependent Rotation Angle

Pressure of a massive free scalar field

$V(\chi) = m^2\chi^2/2$ ($c=1$ and $\hbar=1$)

- To simplify notation, we will omit the overline, $\bar{\chi}(t)$ –> $\chi(t)$.
- The equation of motion for a massive free scalar field is

$$\ddot{\chi} + m^2\chi = 0$$



- The solution with $\chi(0) = \chi_0$ and $\dot{\chi}(0) = 0$ is

$$\chi(t) = \chi_0 \cos(mt)$$

Oscillations with the period $T = 2\pi/m$.

$$\rho = \frac{1}{2}m^2\chi_0^2\,, \quad P = 0$$

Pressureless –> CDM!

Obata, Fujita, Michimura (2018); Fedderke, Graham, Rajendran (2019)

CDM-induced parity violation in EM waves

"Time-domain cosmology"

- The Chern-Simons interaction between photons and CDM gives

$$\ddot{A}_\pm + \left(k^2 \mp \frac{k\alpha\dot{\chi}}{f}\right) A_\pm = 0$$

$$\ddot{A}_\pm + \left[k^2 \pm \frac{k\alpha\chi_0 m}{f}\sin(mt)\right] A_\pm = 0$$

Periodic change for parity violation in EM waves

$$T = \frac{2\pi}{m}$$

$$\simeq 1\ \mathrm{day}\left(\frac{5\times10^{-20}\ \mathrm{eV}}{m}\right)$$

This is a human timescale!!