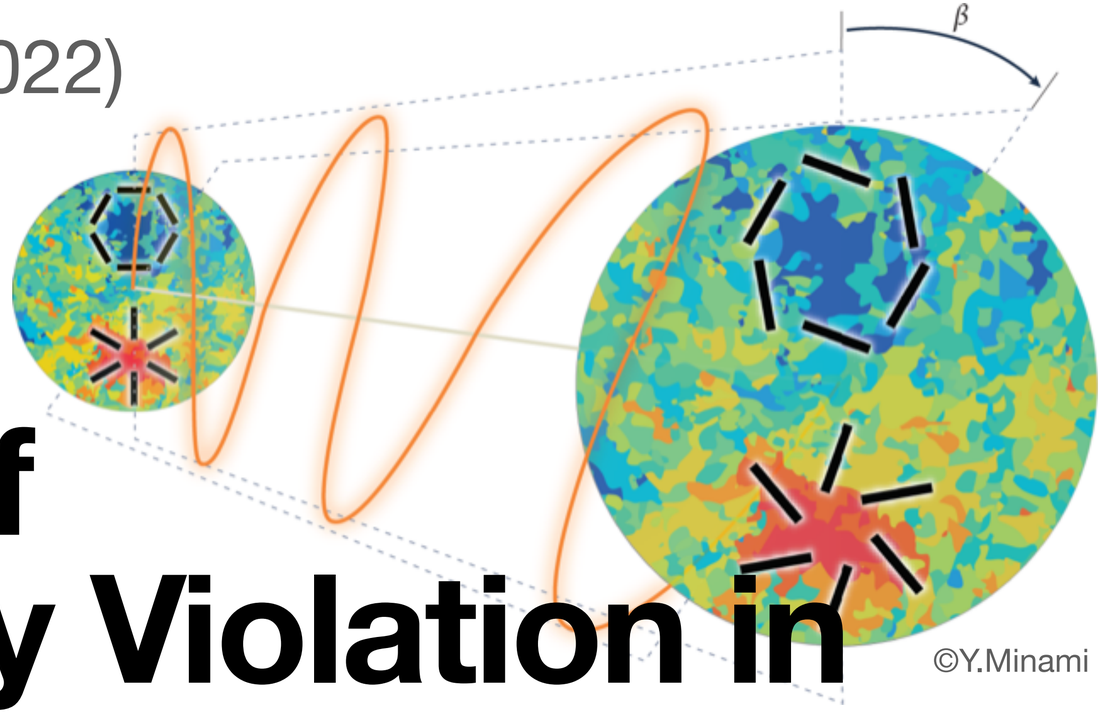
Reference: EK, Nature Rev. Phys. **4**, 452 (2022)



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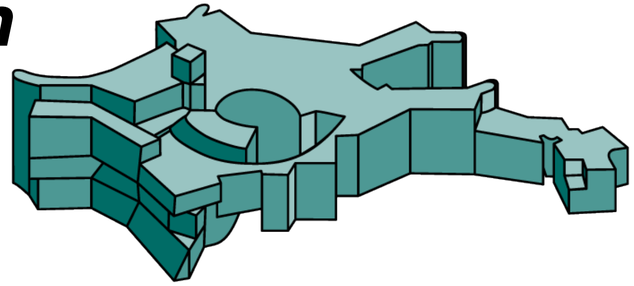
A Tantalizing Hint of Cosmological Parity Violation in the Polarized Light of the CMB

Does the Universe distinguish between left and right?



Eiichiro Komatsu (Max Planck Institute for Astrophysics)

CMB@60, Accademia delle Scienze di Torino, May 30, 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 ✉

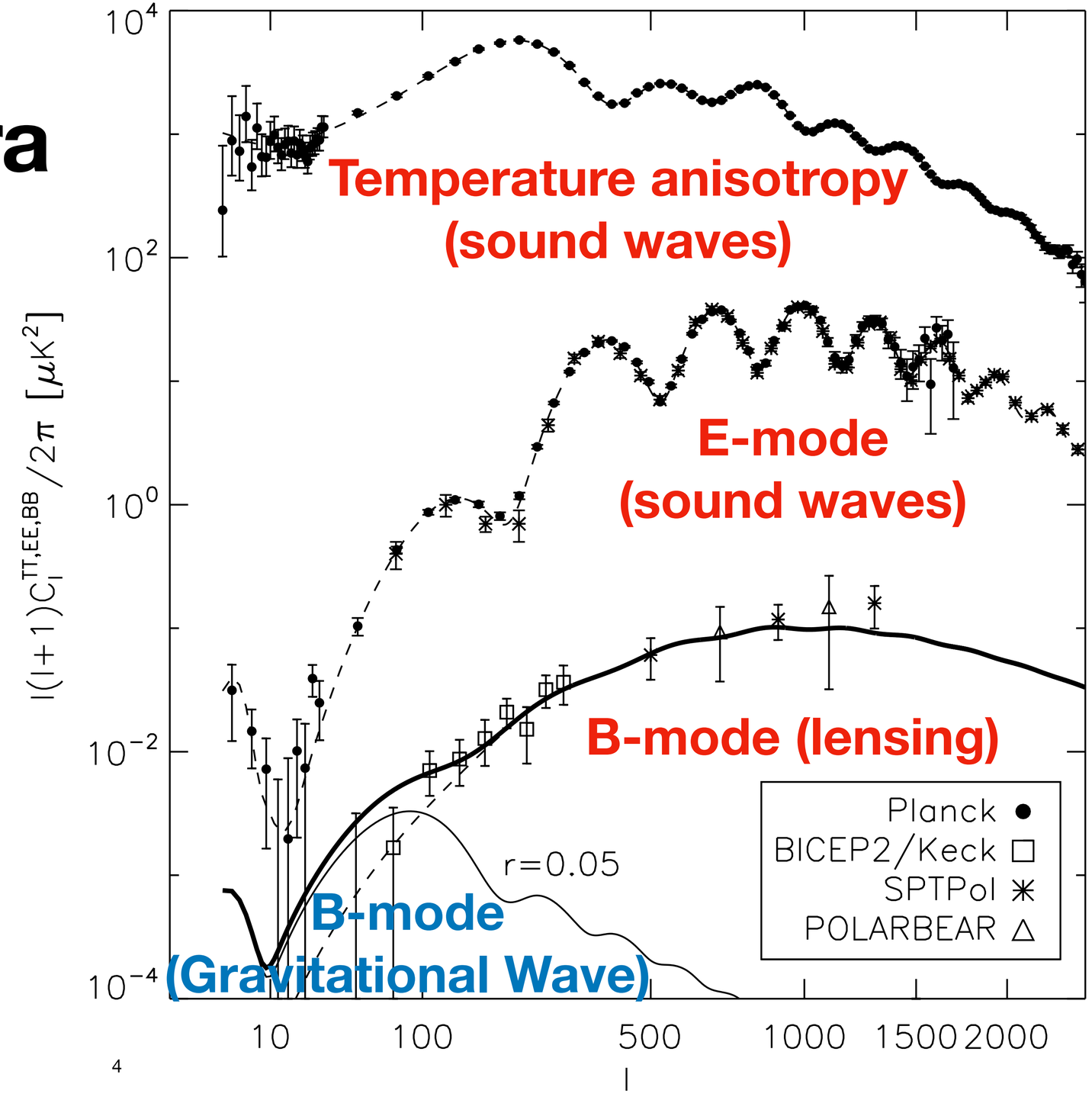
Nature Reviews Physics **4**, 452–469 (2022) | Cite this article

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

CMB Power Spectra

Progress over 30 years

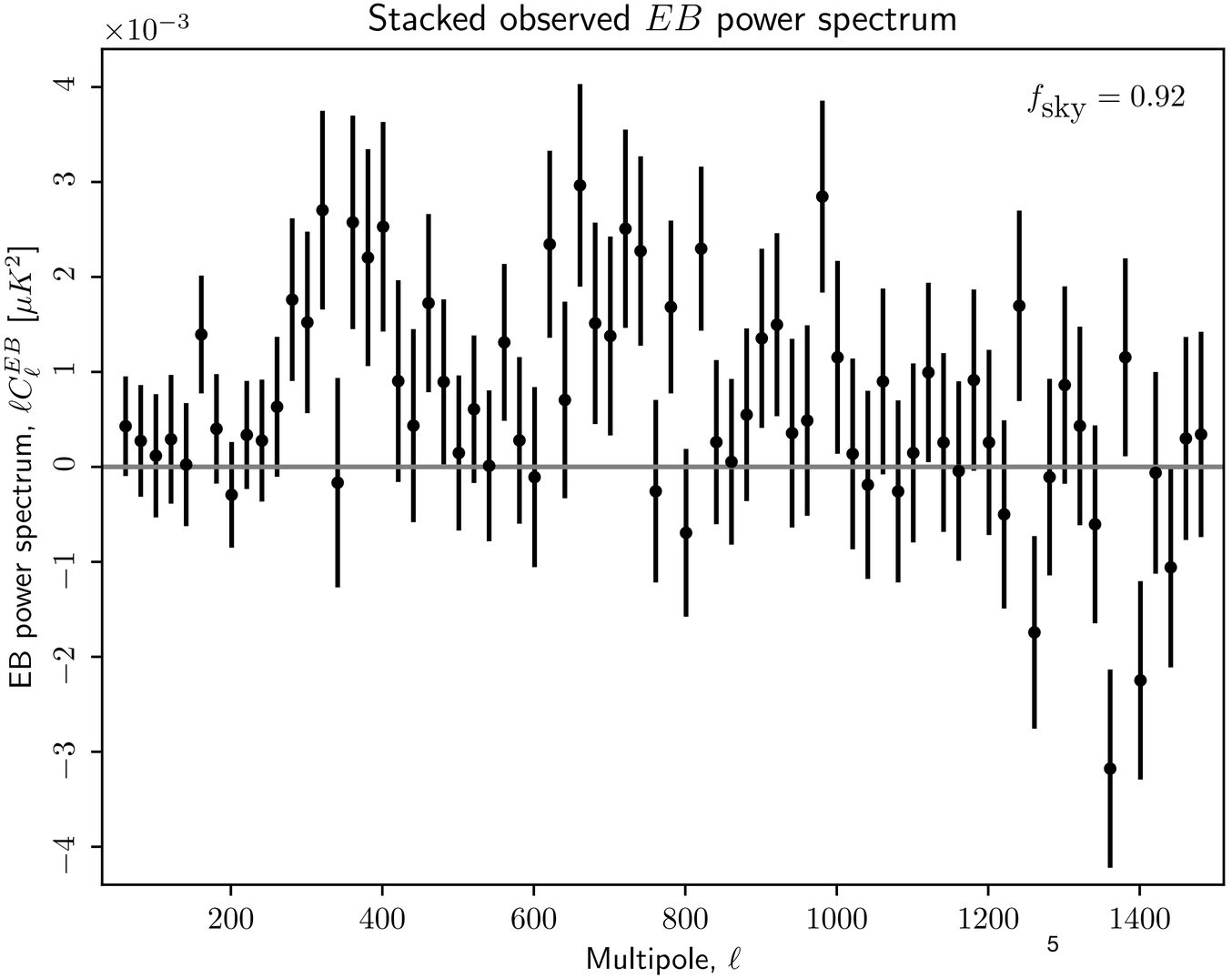
- This is the typical figure seen in talks and lectures on the CMB.
  - The temperature and the E- and B-mode polarization power spectra are well measured.
- **Parity violation appears in the TB and EB power spectra, not shown here.**

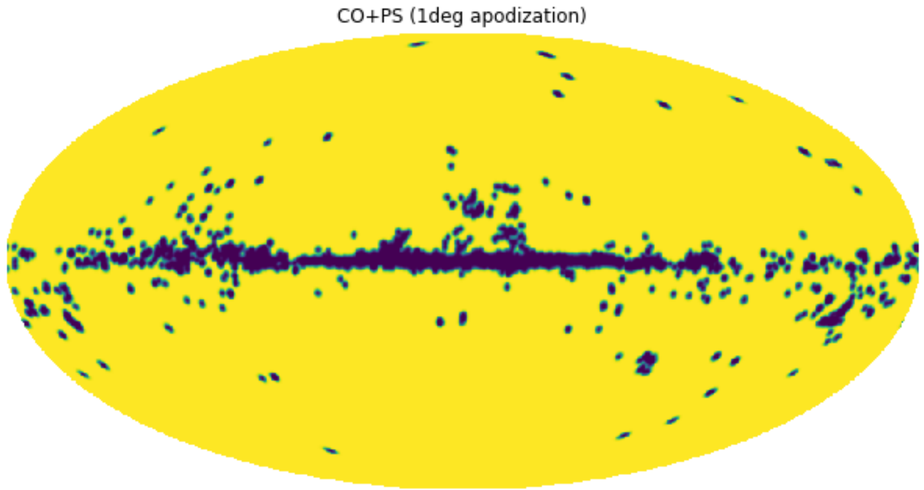


Eskilt, EK (2022)

This is the EB power spectrum (WMAP+Planck)

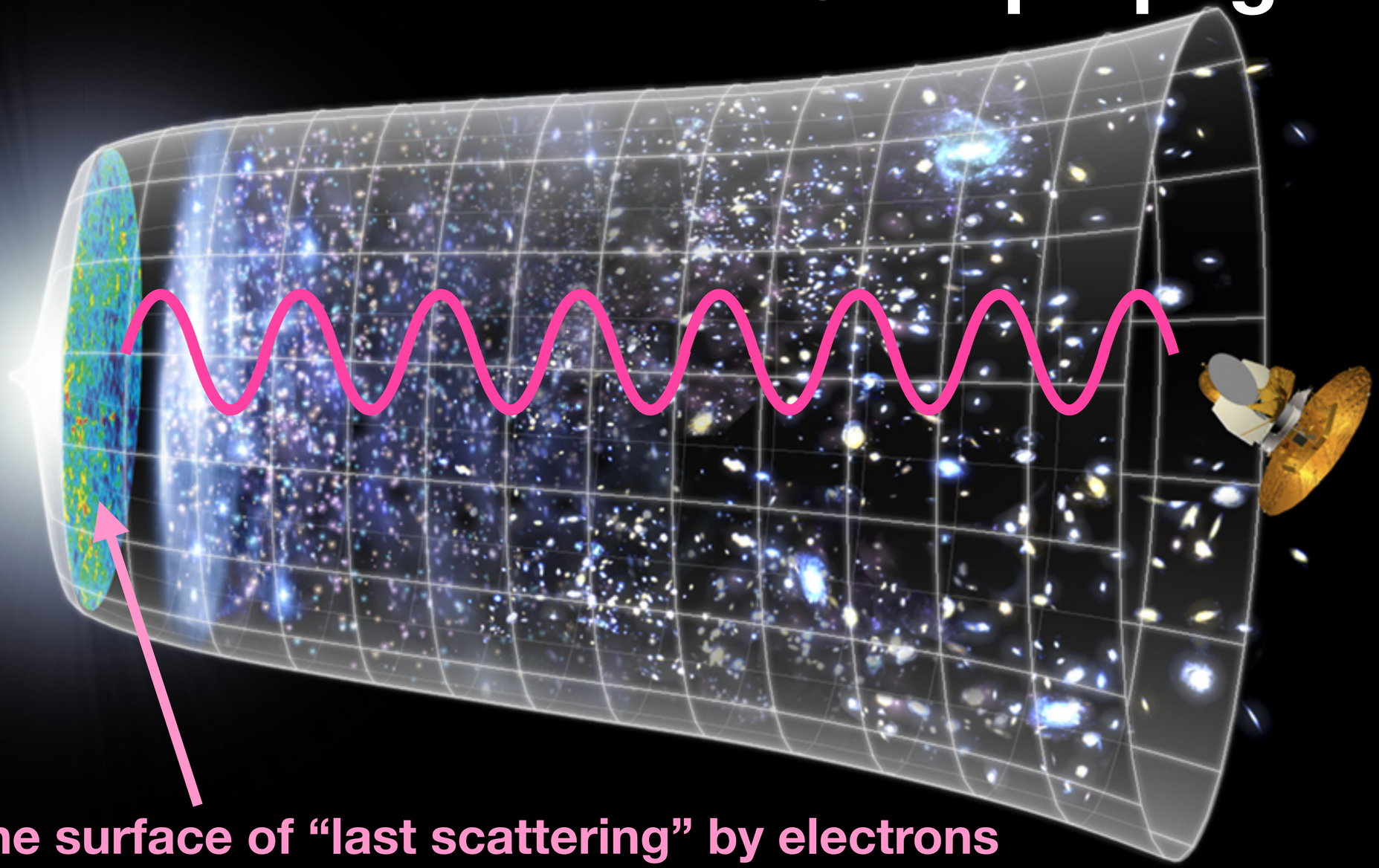
Nearly full-sky data (92% of the sky)





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

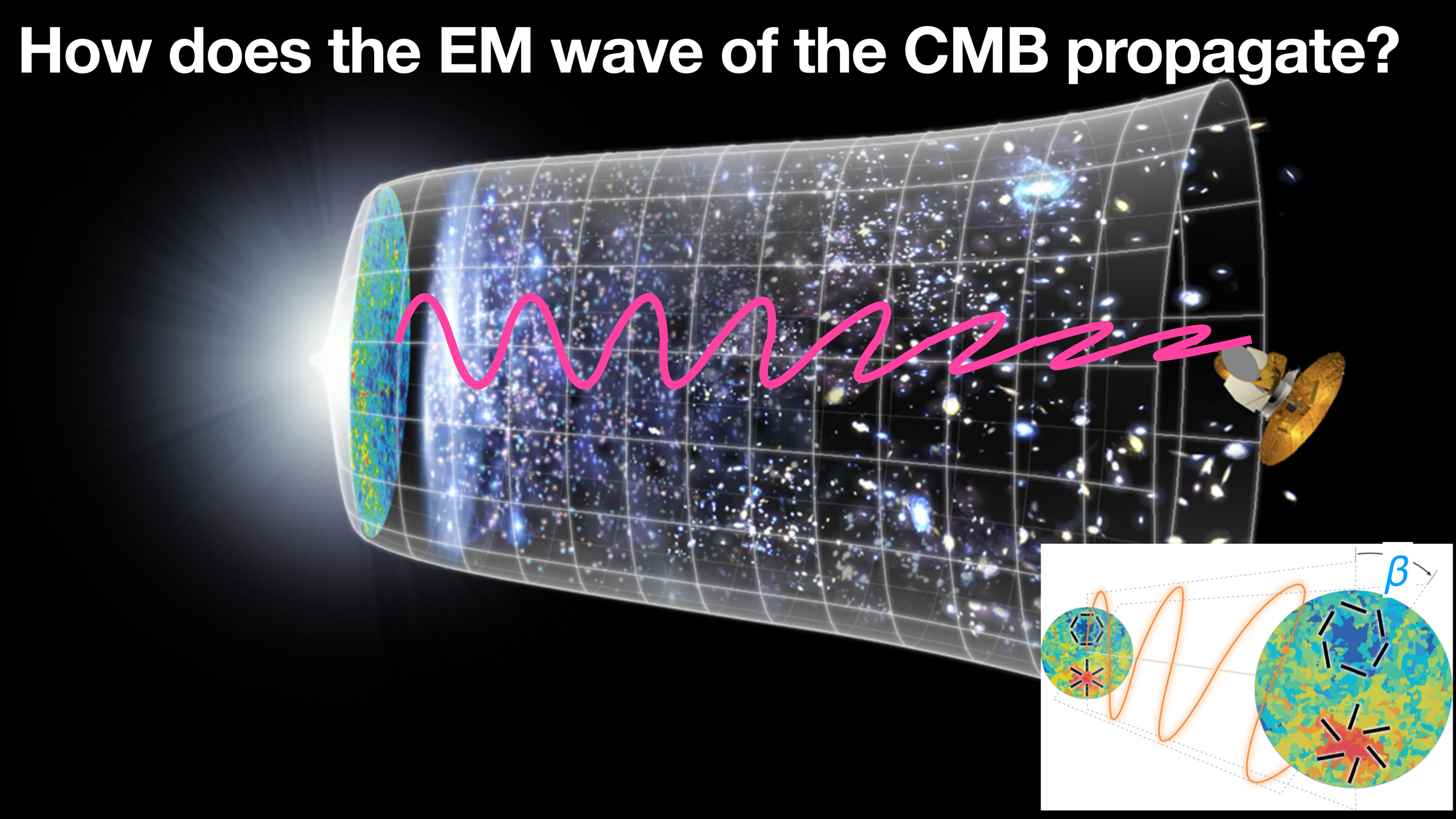
How does the EM wave of the CMB propagate?



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

Credit: WMAP Science Team

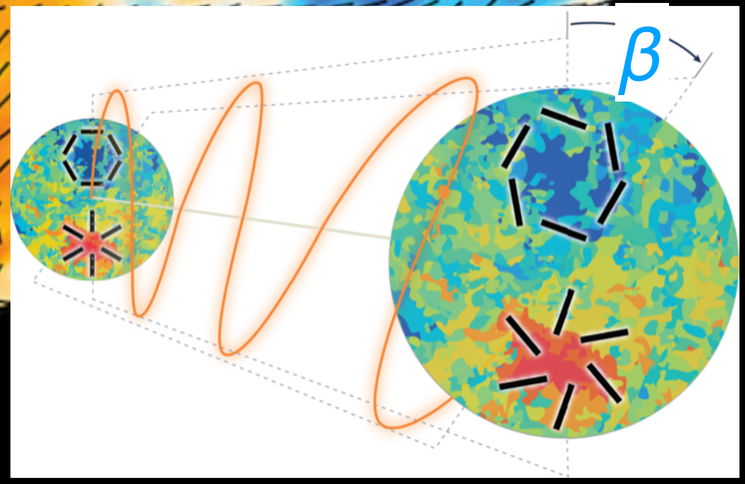
How does the EM wave of the CMB propagate?



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

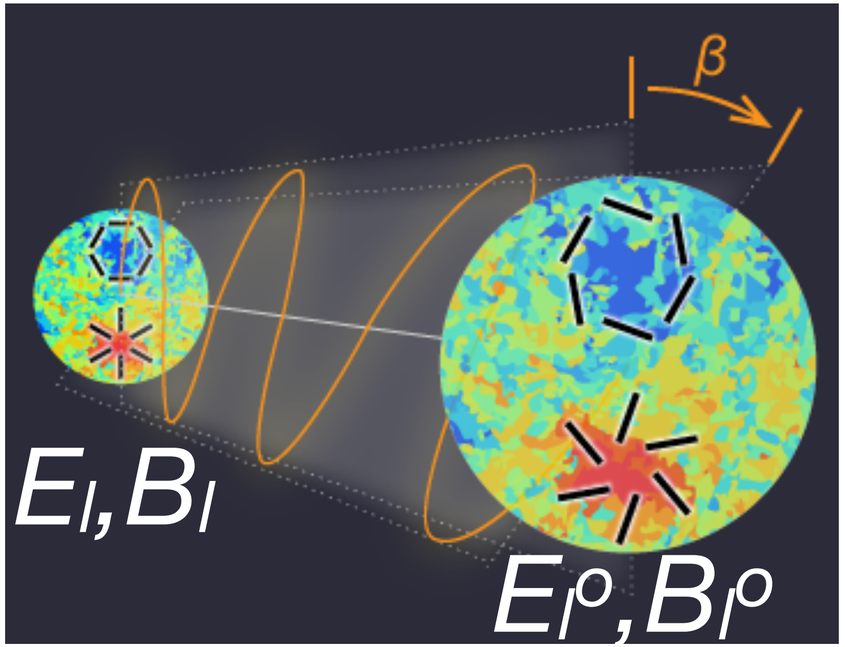
- Observed E- and B-mode polarization, E_l^o and B_l^o, are related to those before rotation as

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

- which gives

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

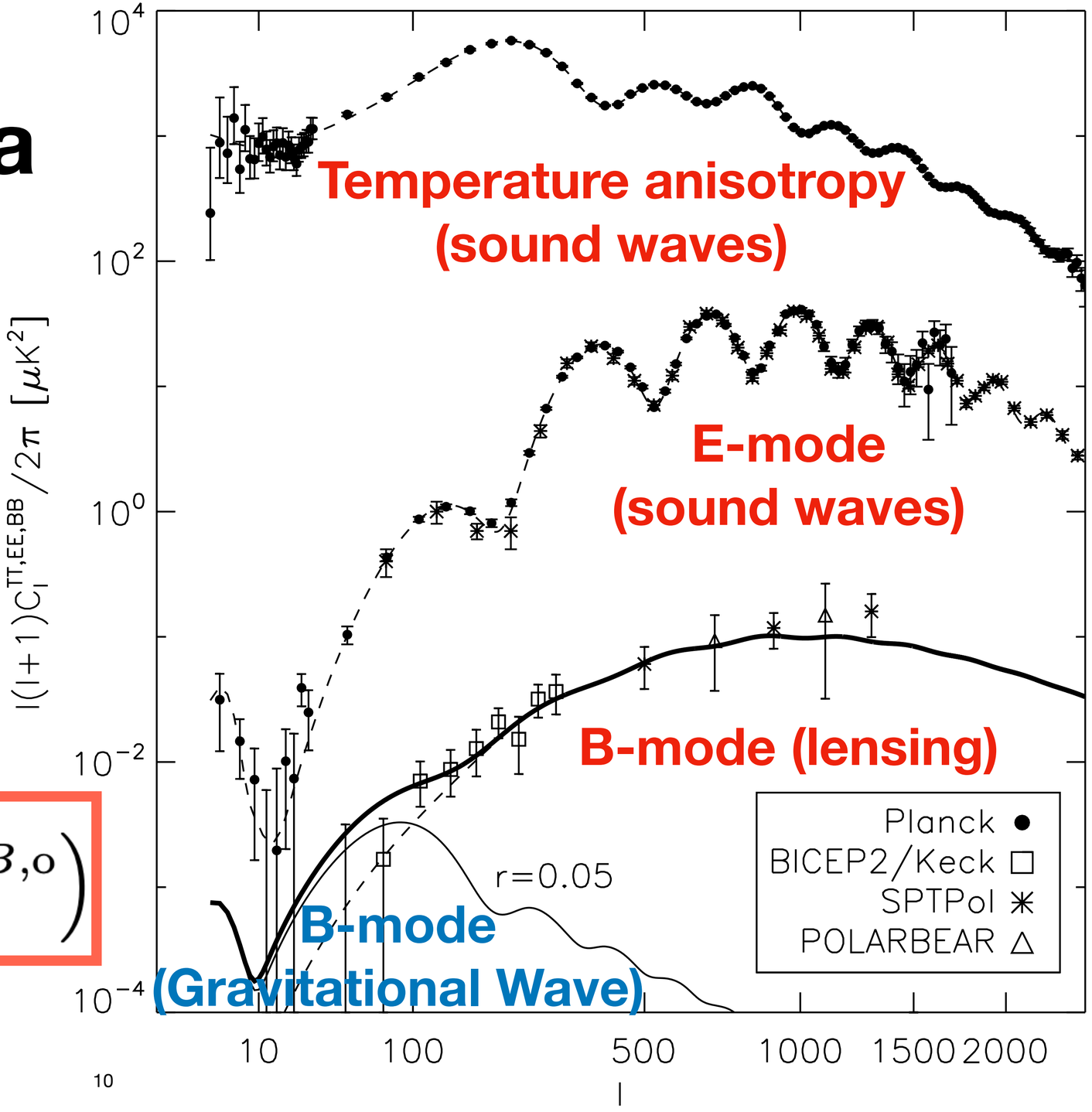
$$B_\ell^{\rm o} = E_\ell \sin(2\beta) + B_\ell \cos(2\beta)$$



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!

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

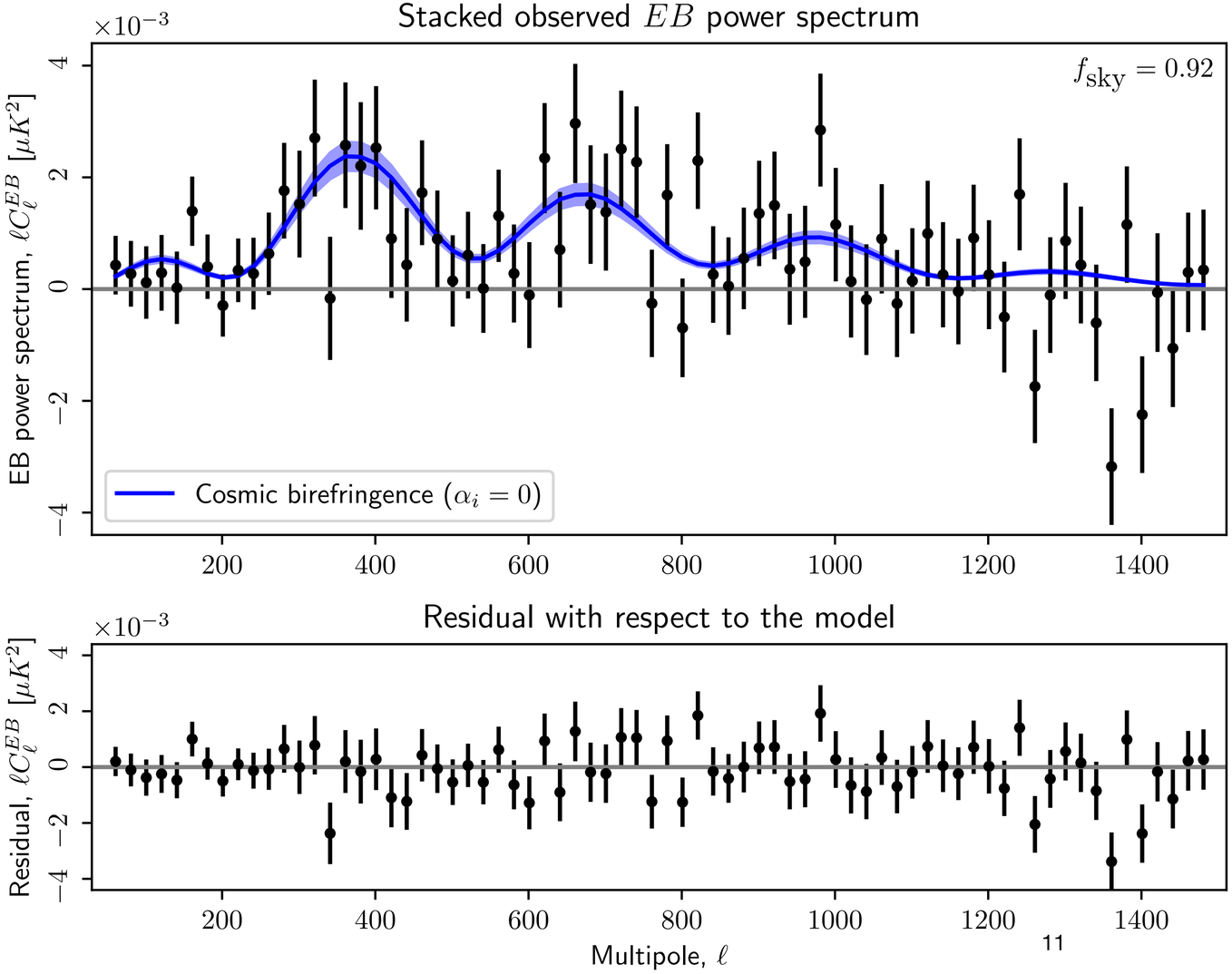


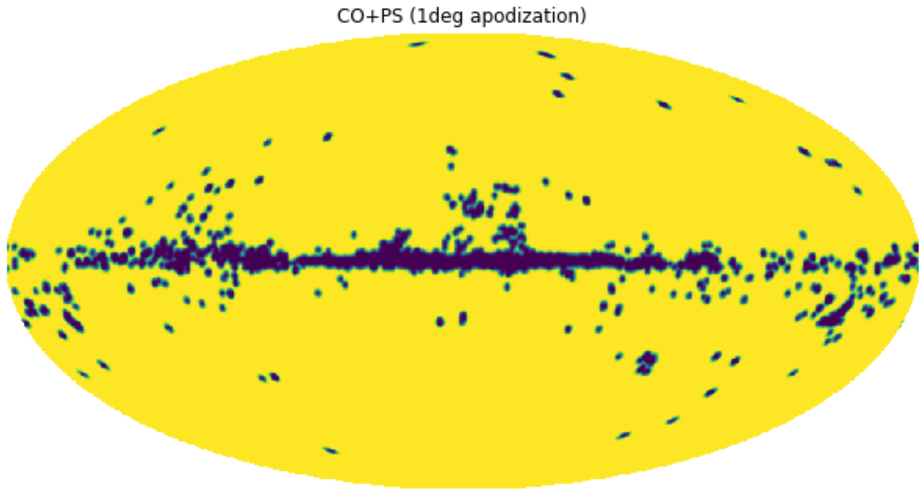
Eskilt, EK (2022)

Cosmic Birefringence fits well(?)

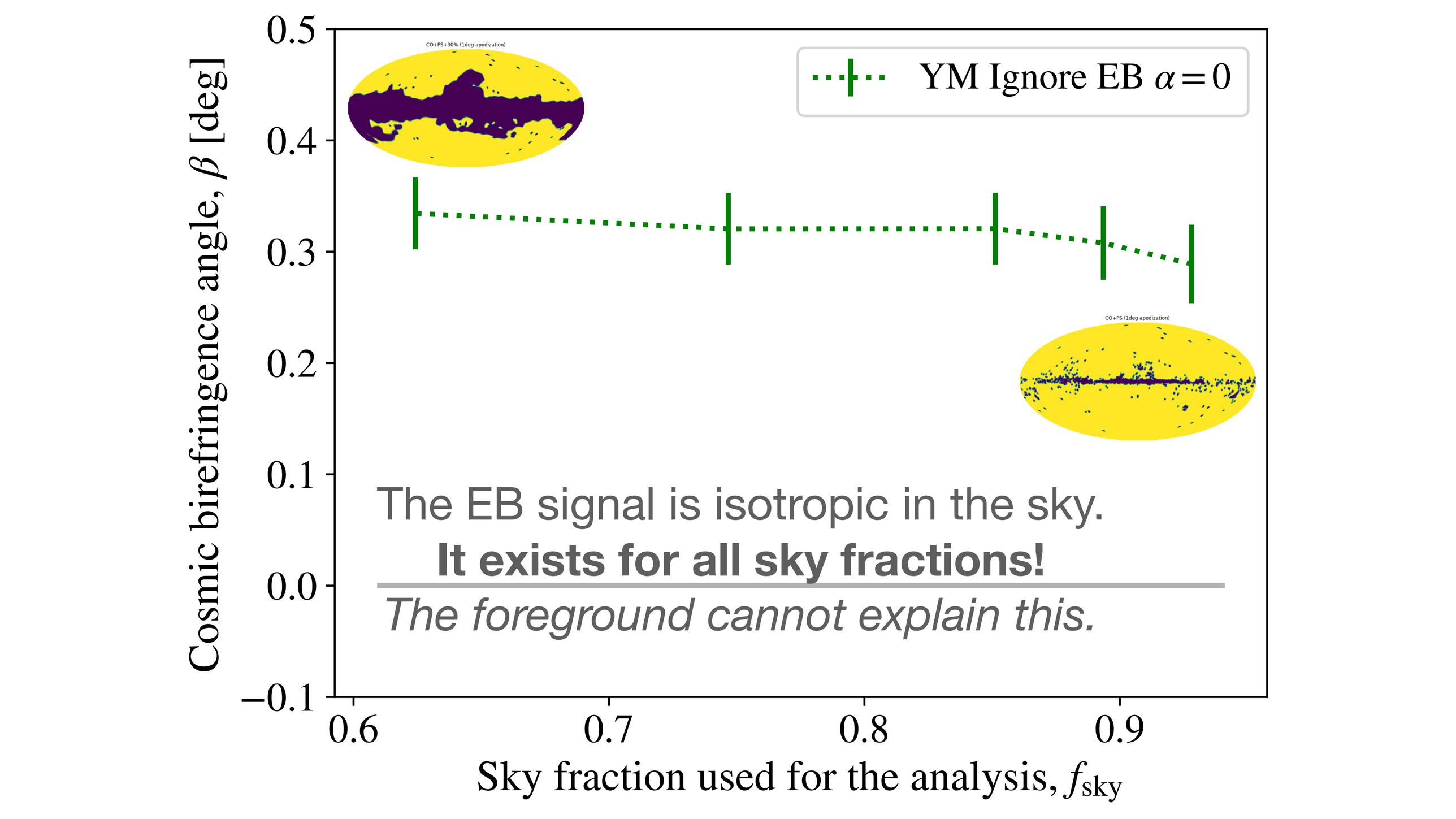
$$C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)$$

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





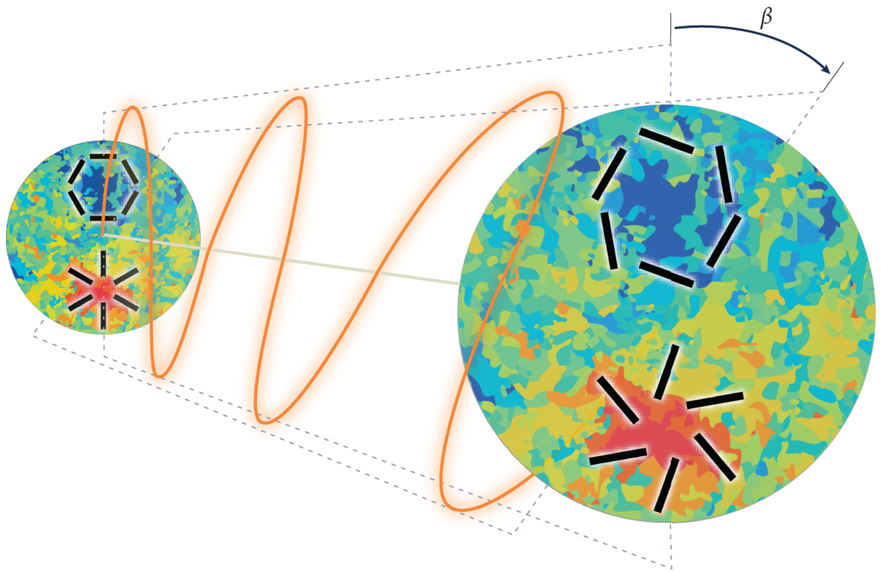
- β = 0.288 ± 0.032 deg
- χ^2 = 66.1 for DOF=71
  - Good fit! 9σ detection?


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

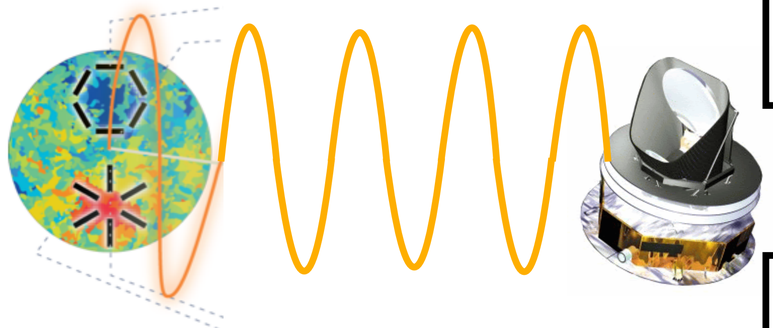
Wu et al. (2009); Miller, Shimon, Keating (2009); EK et al. (2011)

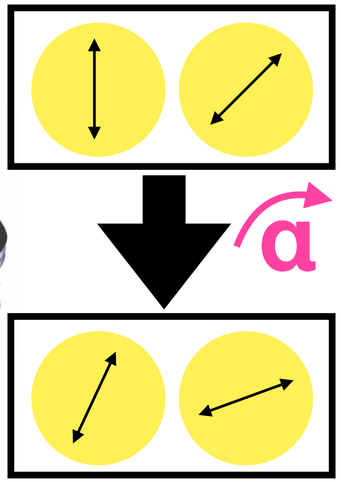
Impact of miscalibration of polarization angles

Cosmic or Instrumental?



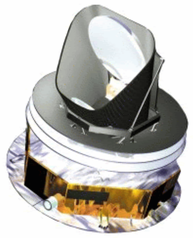
OR





- 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**.



ESA's Planck

Credit: ESA

Polarized dust emission within our Milky Way!

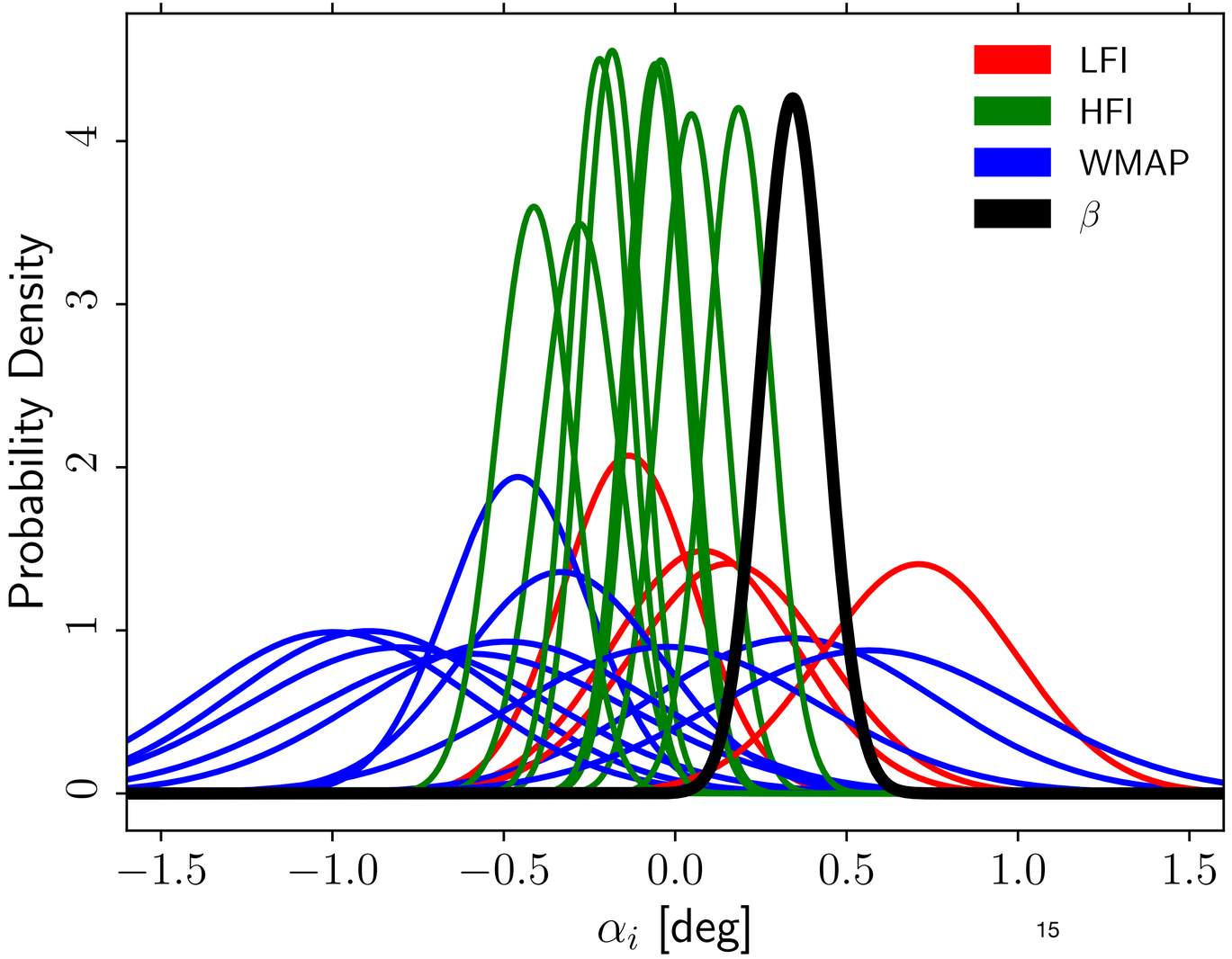
Emitted "right there" - it would not be affected by cosmic birefringence.

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)

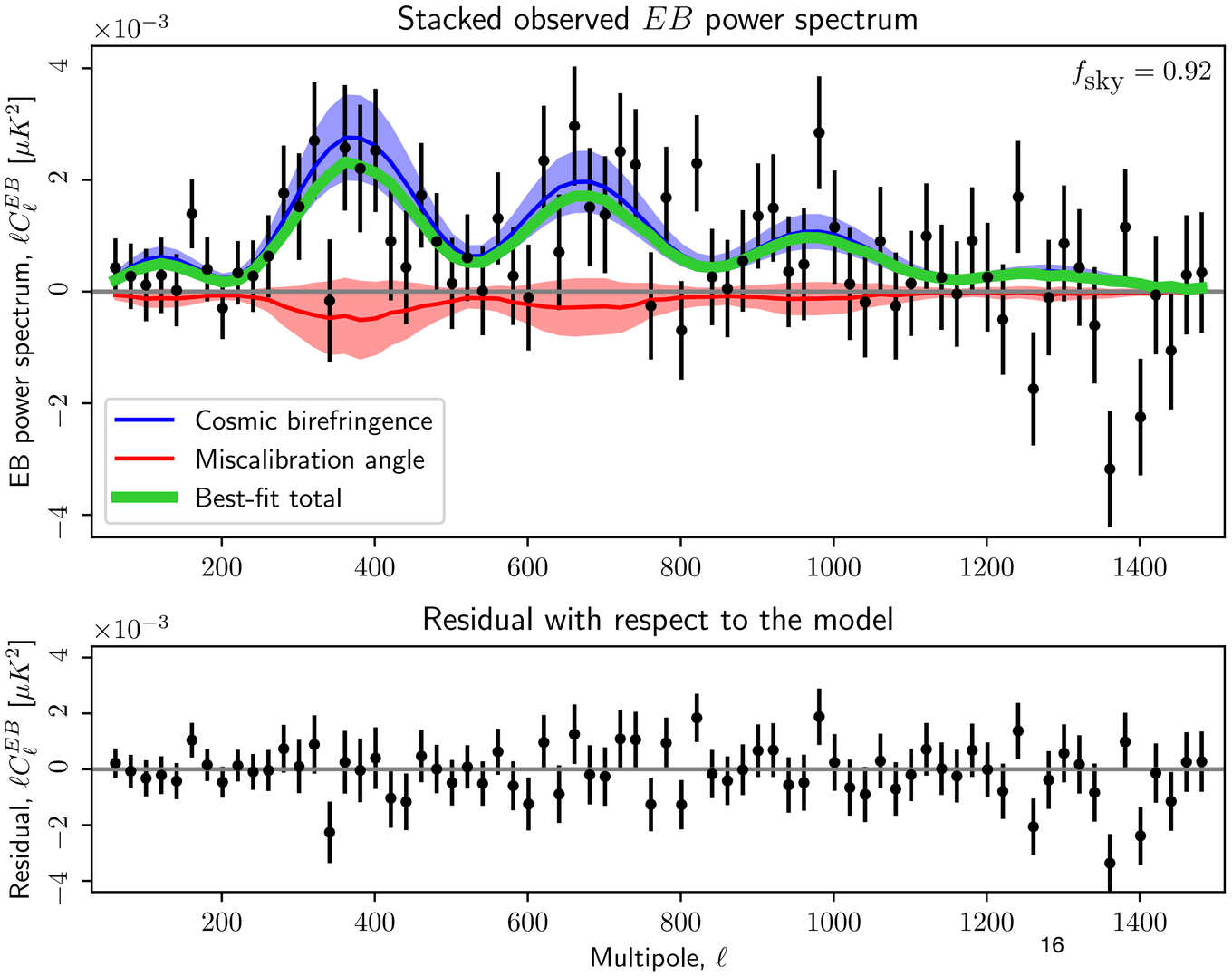


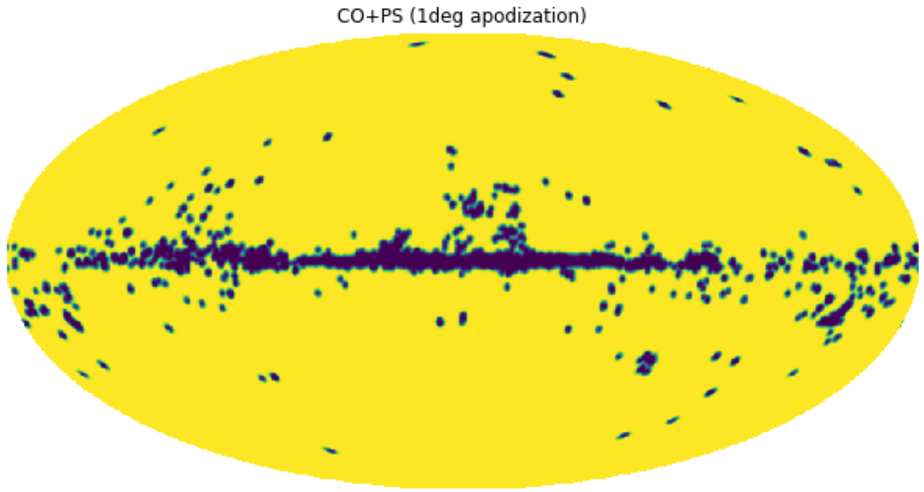
- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

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)



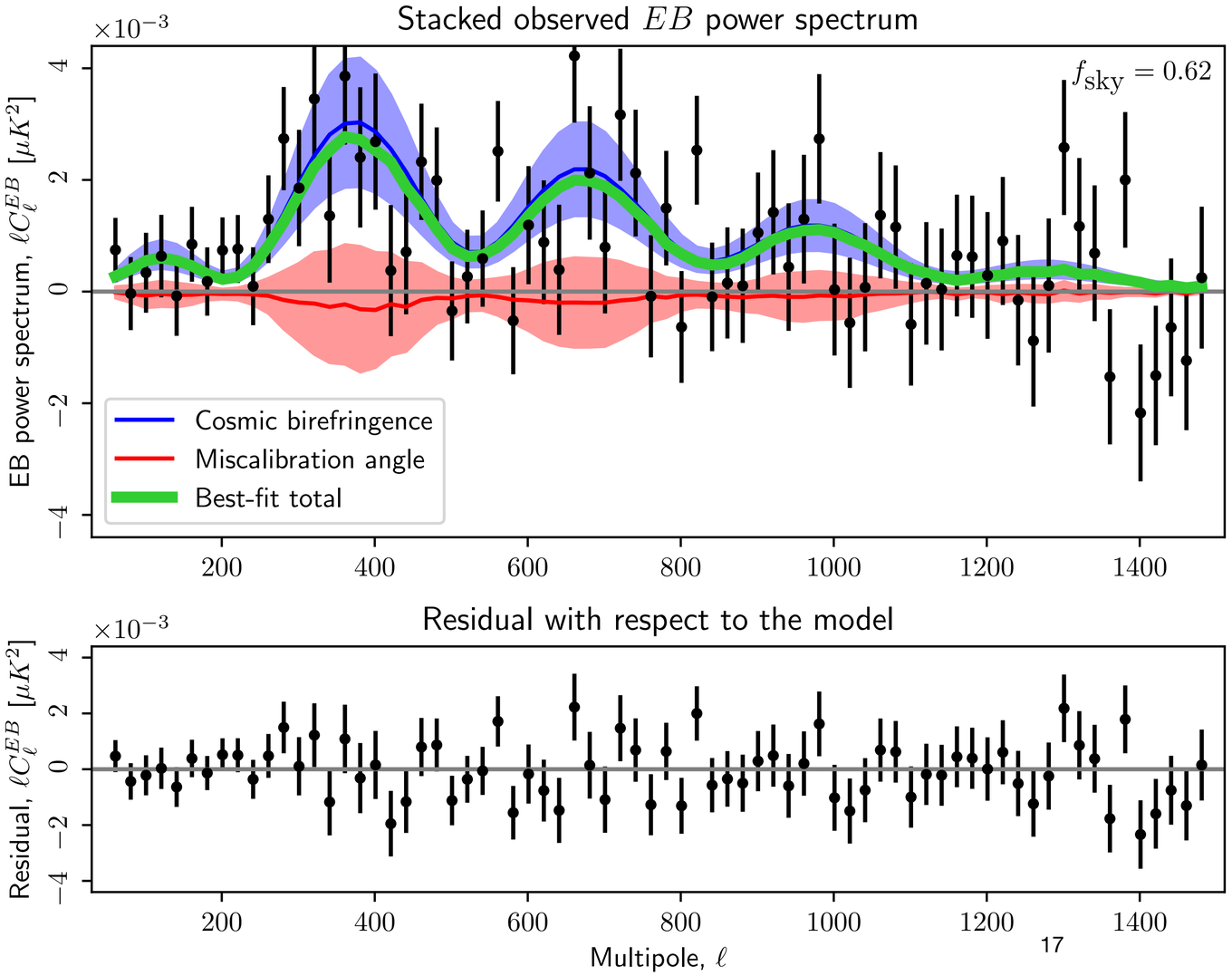


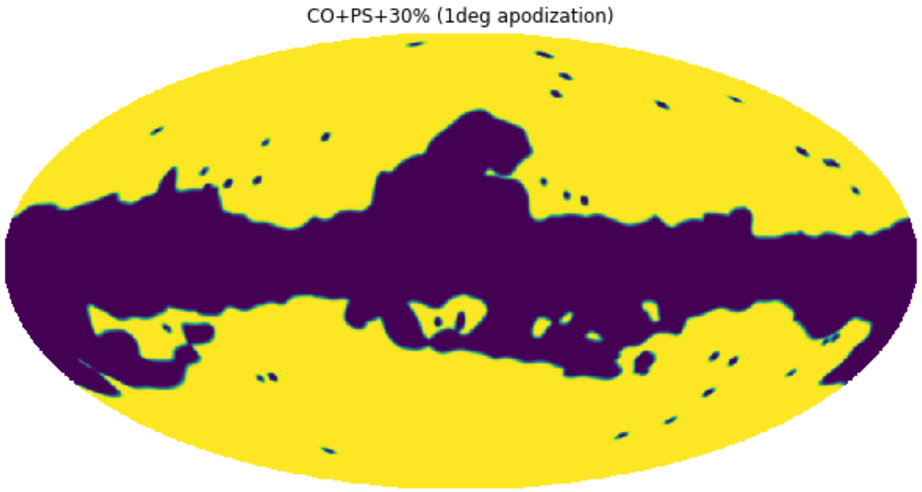
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- $\chi^2 = 65.3$

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)



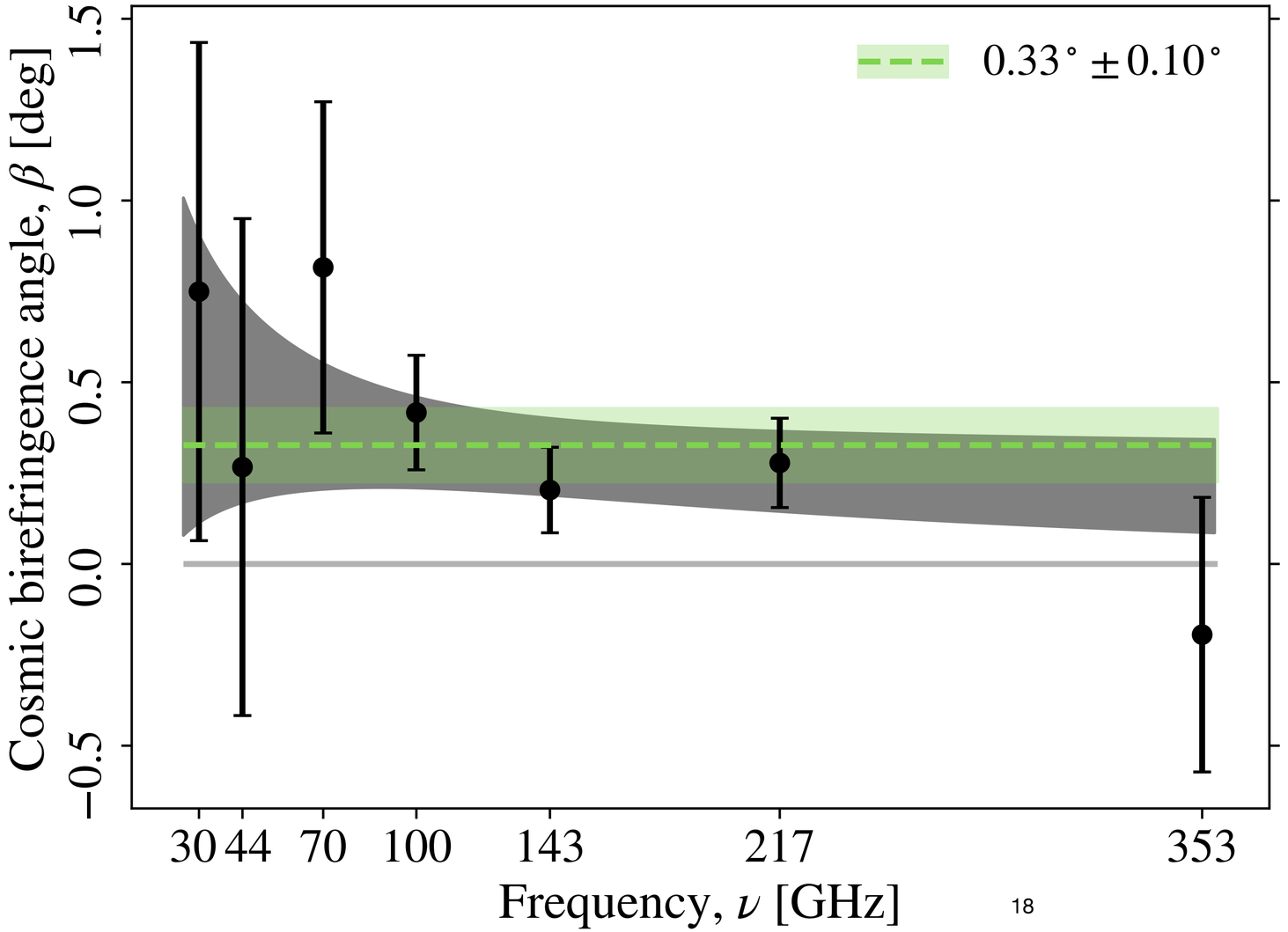


- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- $\chi^2 = 65.8$

Eskilt (2022); Eskilt, EK (2022)

No frequency dependence is found

It is not due to Faraday rotation.

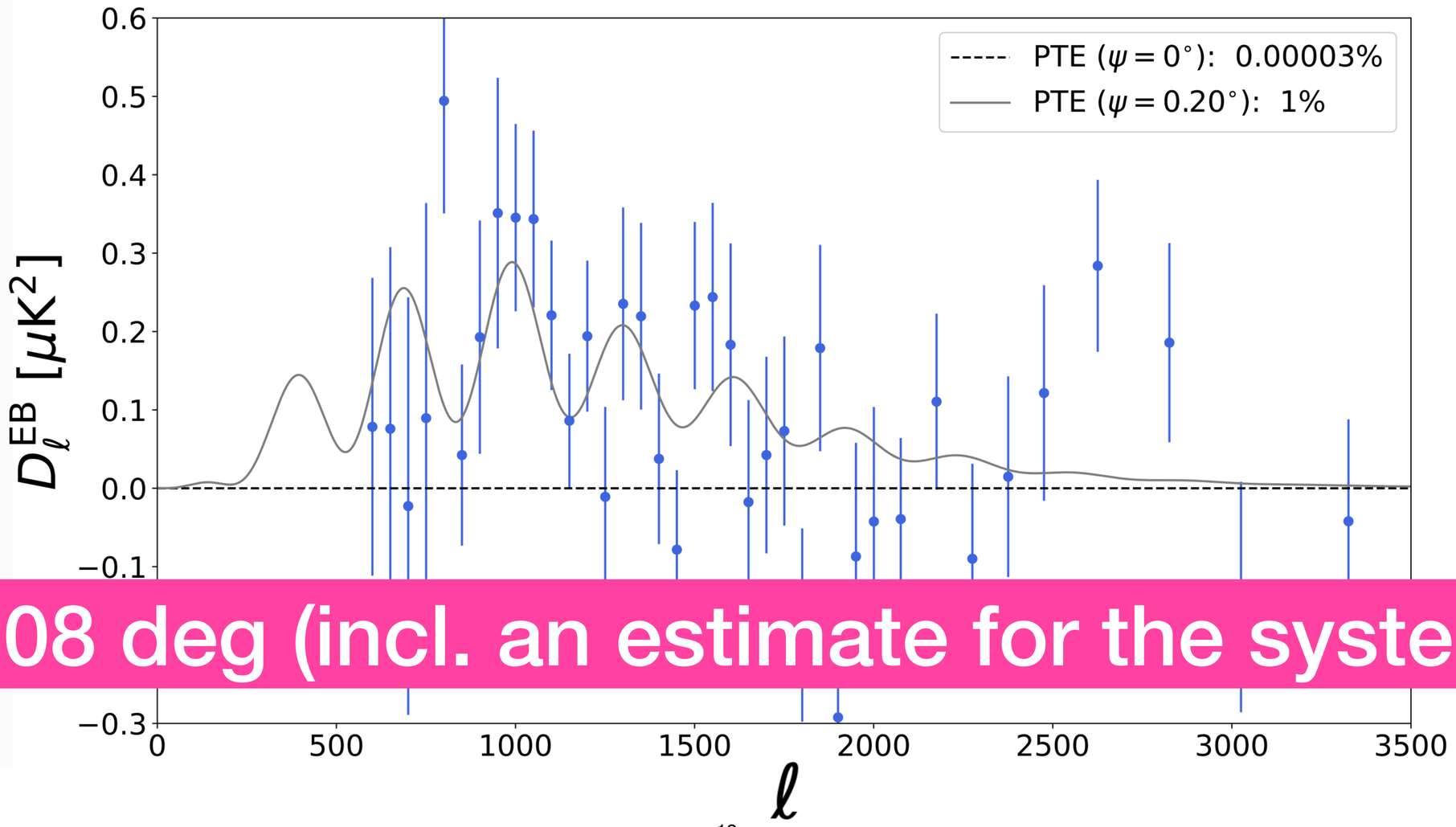


- Light traveling in a uniform magnetic field also experiences a rotation of the plane of linear polarization, called "**Faraday rotation**". However, the rotation angle depends on the frequency, as $\beta(\nu) \propto \nu^{-2}$.
- No evidence for frequency dependence is found!
  - For $\beta \propto \nu^n$, $n = -0.20^{+0.41}_{-0.39}$ (68% CL)
  - **Faraday rotation ($n = -2$) is disfavoured.**

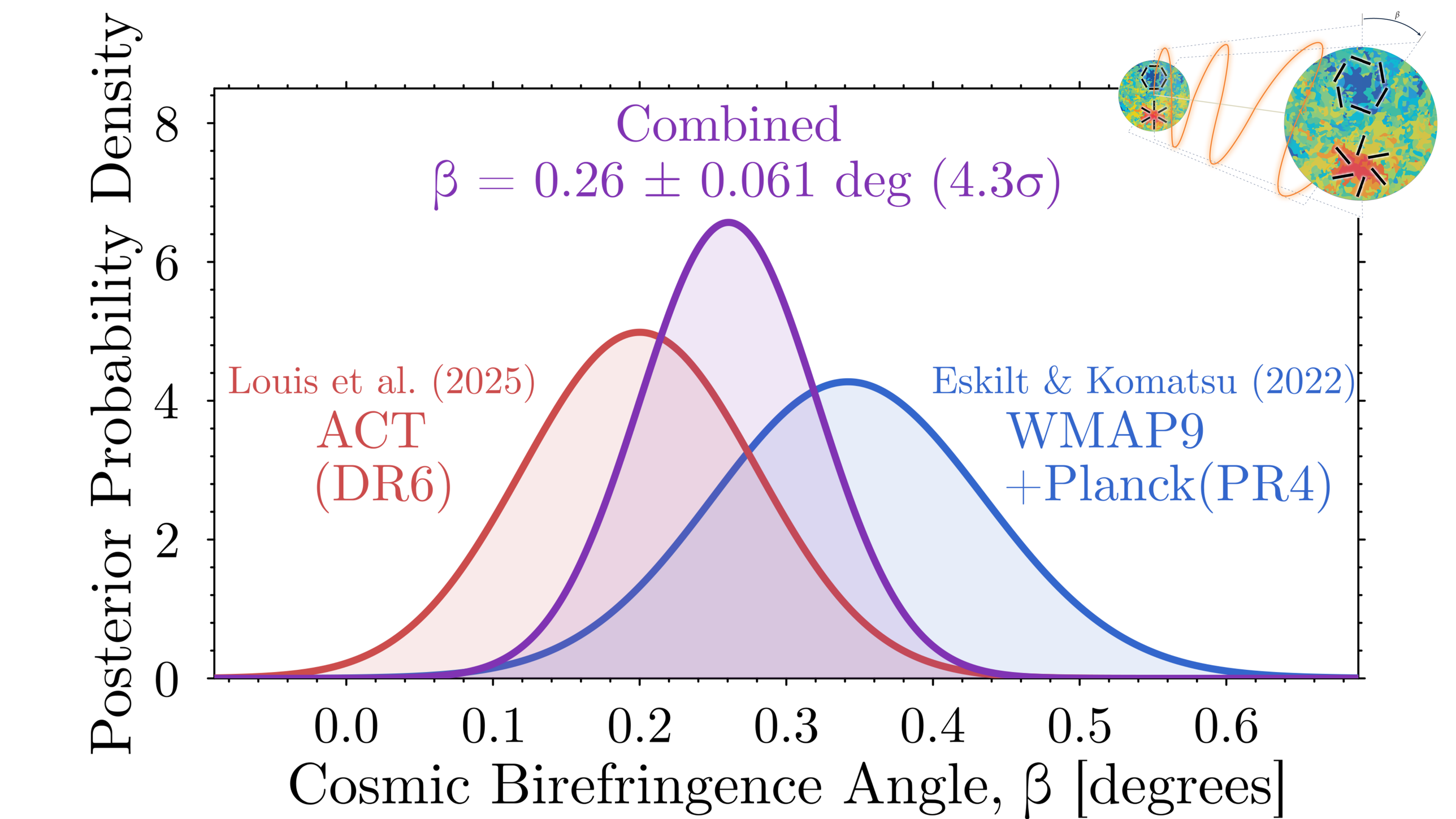
ACT Collaboration, arXiv:2503.14452

Atacama Cosmology Telescope (DR6)

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



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


Combined
β = 0.26 ± 0.061 deg (4.3σ)
Louis et al. (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]

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!

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

Implications

DM = Dark Matter; DE = Dark Energy

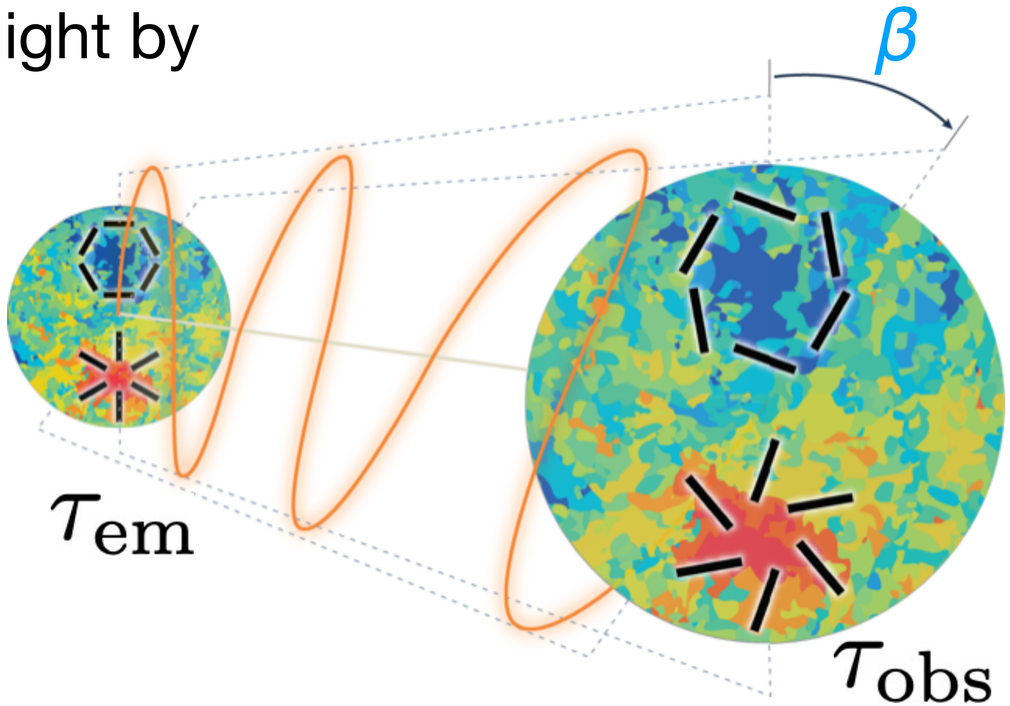
This term exists for a pion.
What if DM/DE is “pion-like particle”

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

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

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

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



Implications

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

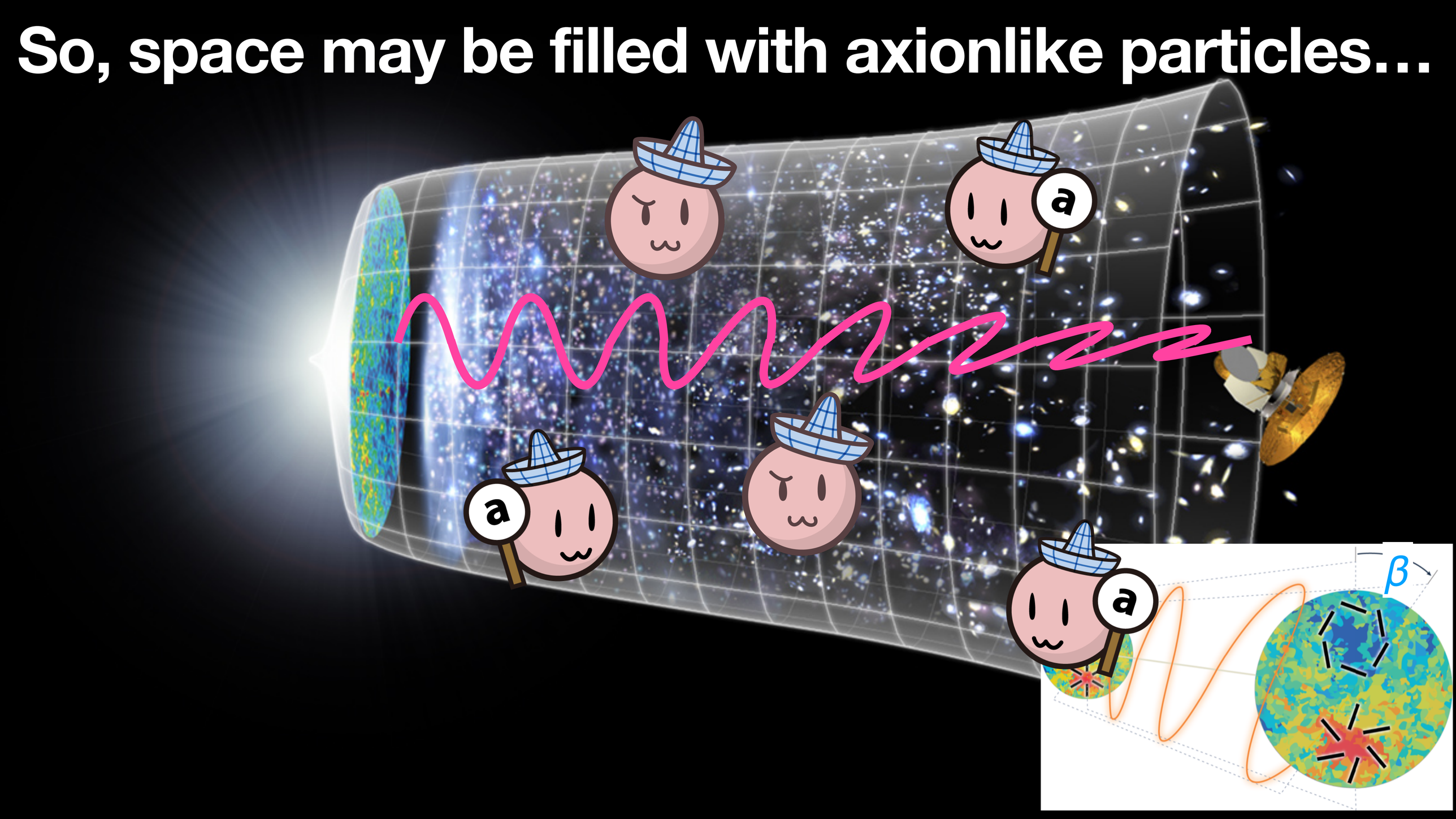
$$\Delta\chi = \chi(\tau_{\rm obs}) - \chi(\tau_{\rm em}) \simeq \frac{10^{-2}}{\alpha} f$$

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.

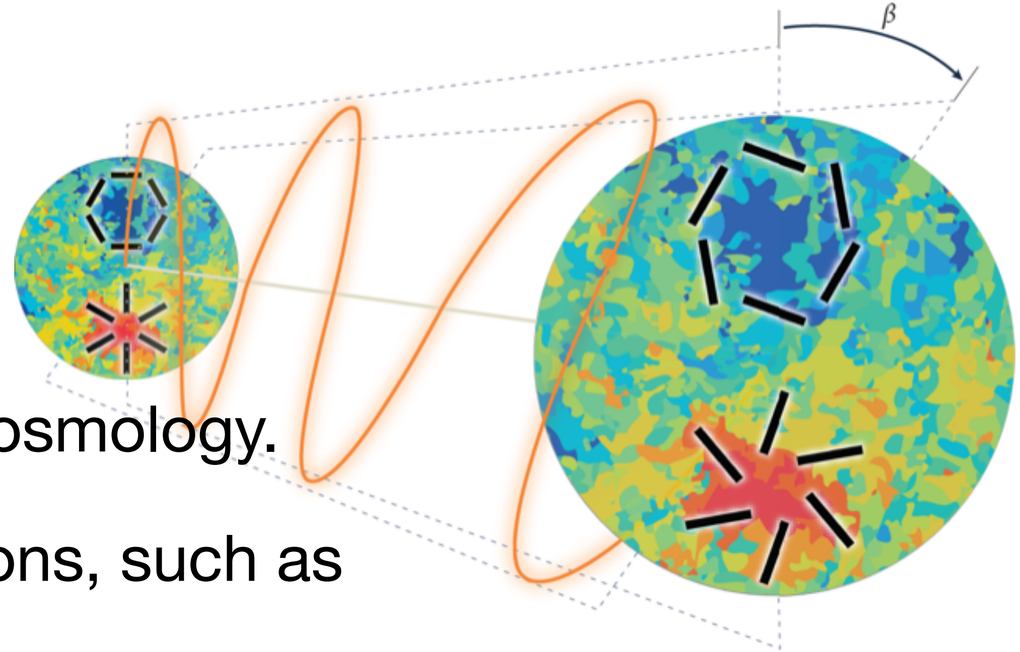
©Higgstan

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.**

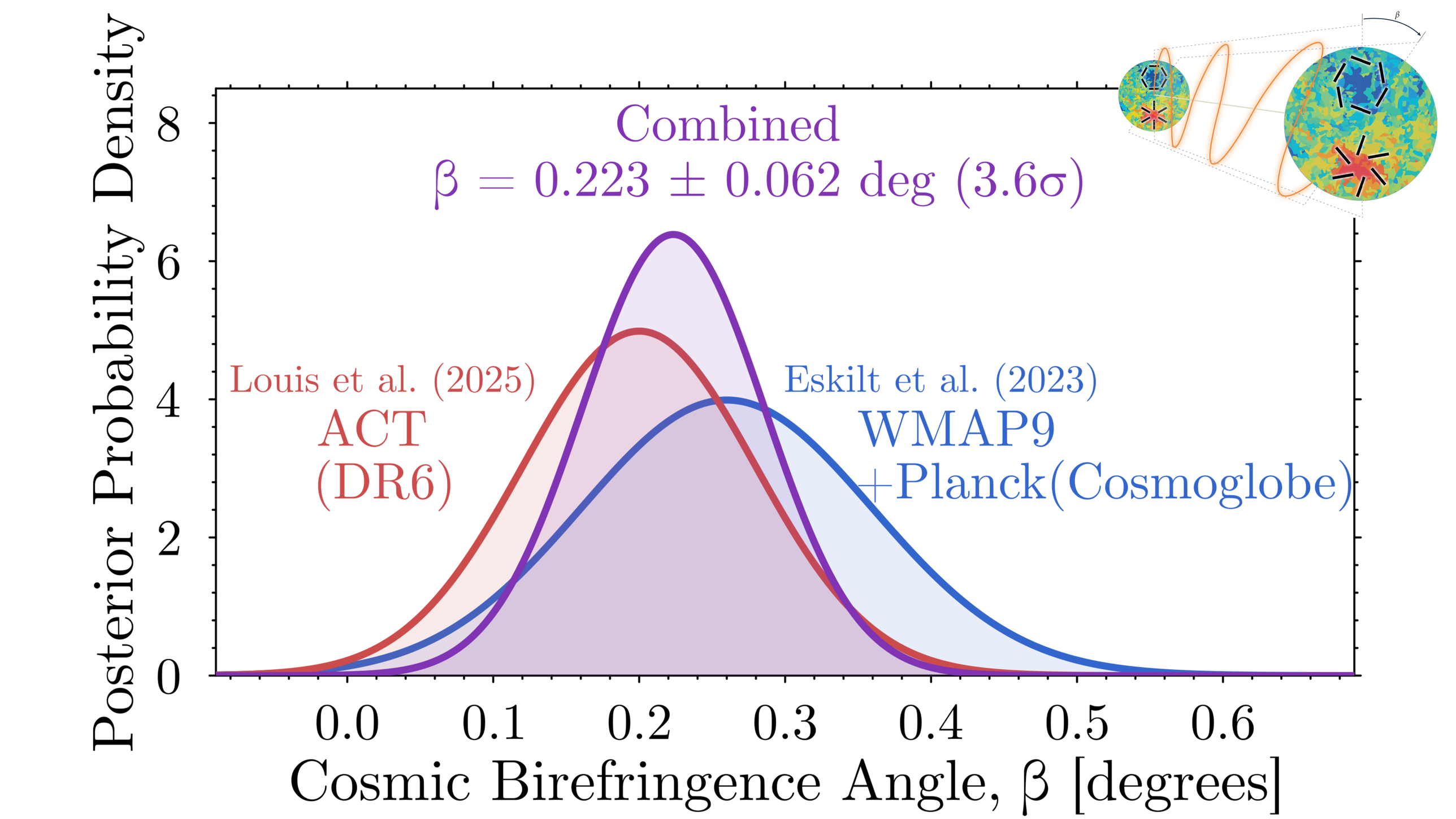
Back up slides

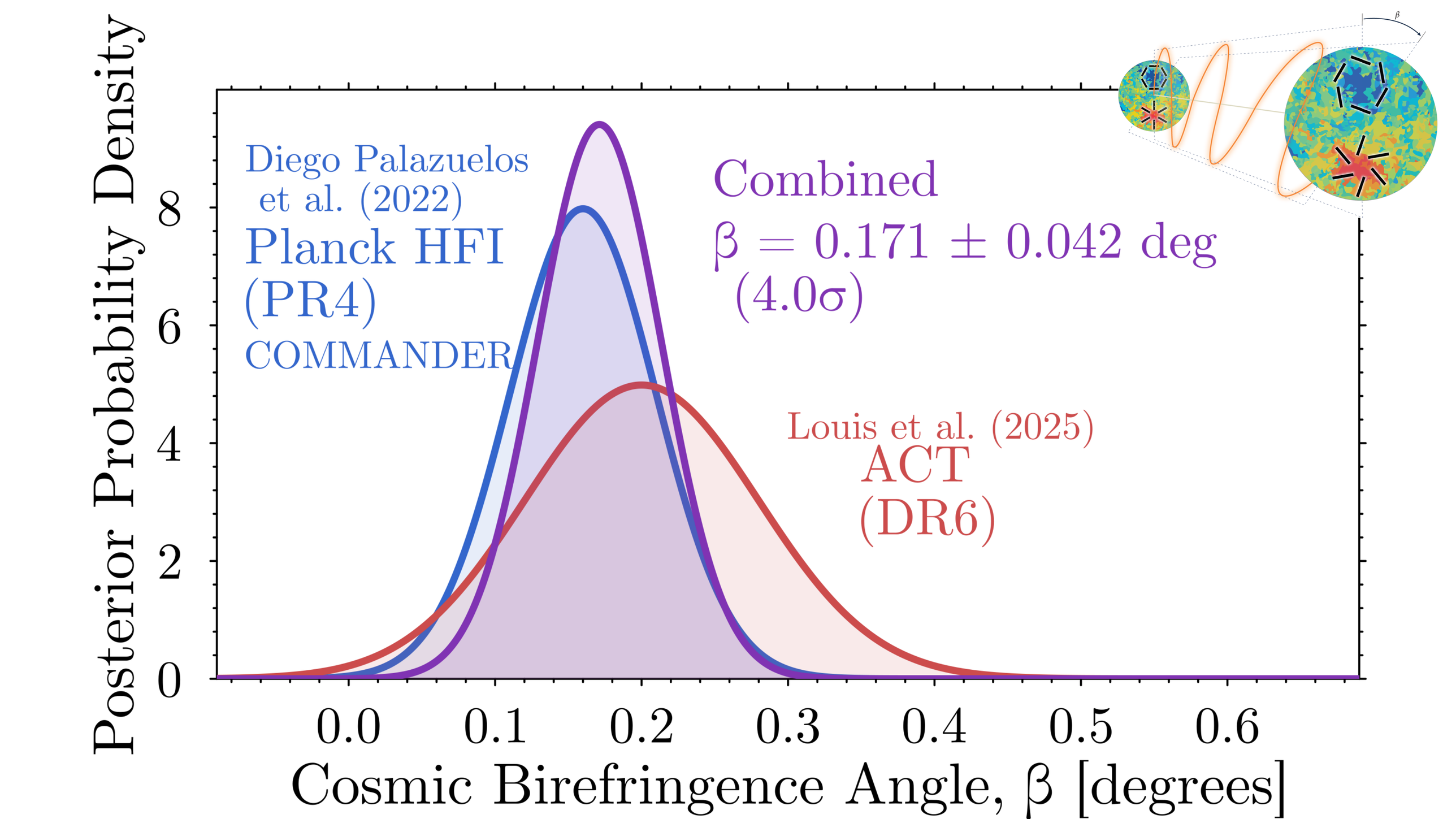
Diego-Palazuelos et al. (2022, 2023); Eskilt et al. [Cosmoglobe] (2023)

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