Hunting for parity-violating physics in polarisation of the cosmic microwave background

a.k.a. "Cosmic Birefringence"

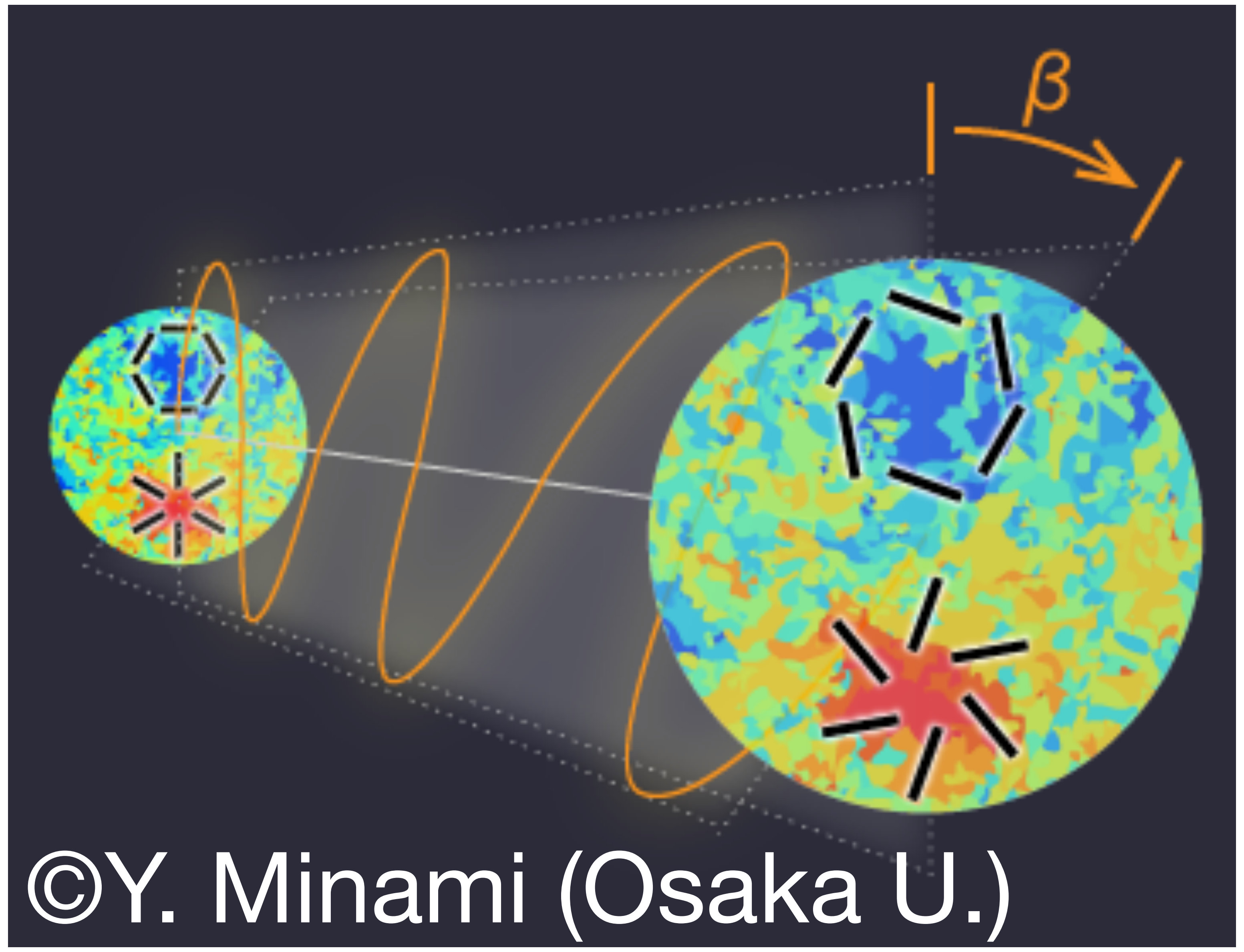
based on

- *Minami & EK, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, Minami, et al., arXiv:2201.07682*

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)

Cosmology and Particle Astrophysics Seminar@LeCosPA

January 24, 2022



Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (*Λ*)?

- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?

- *Polarisation* of the CMB may hold the key to the answers.

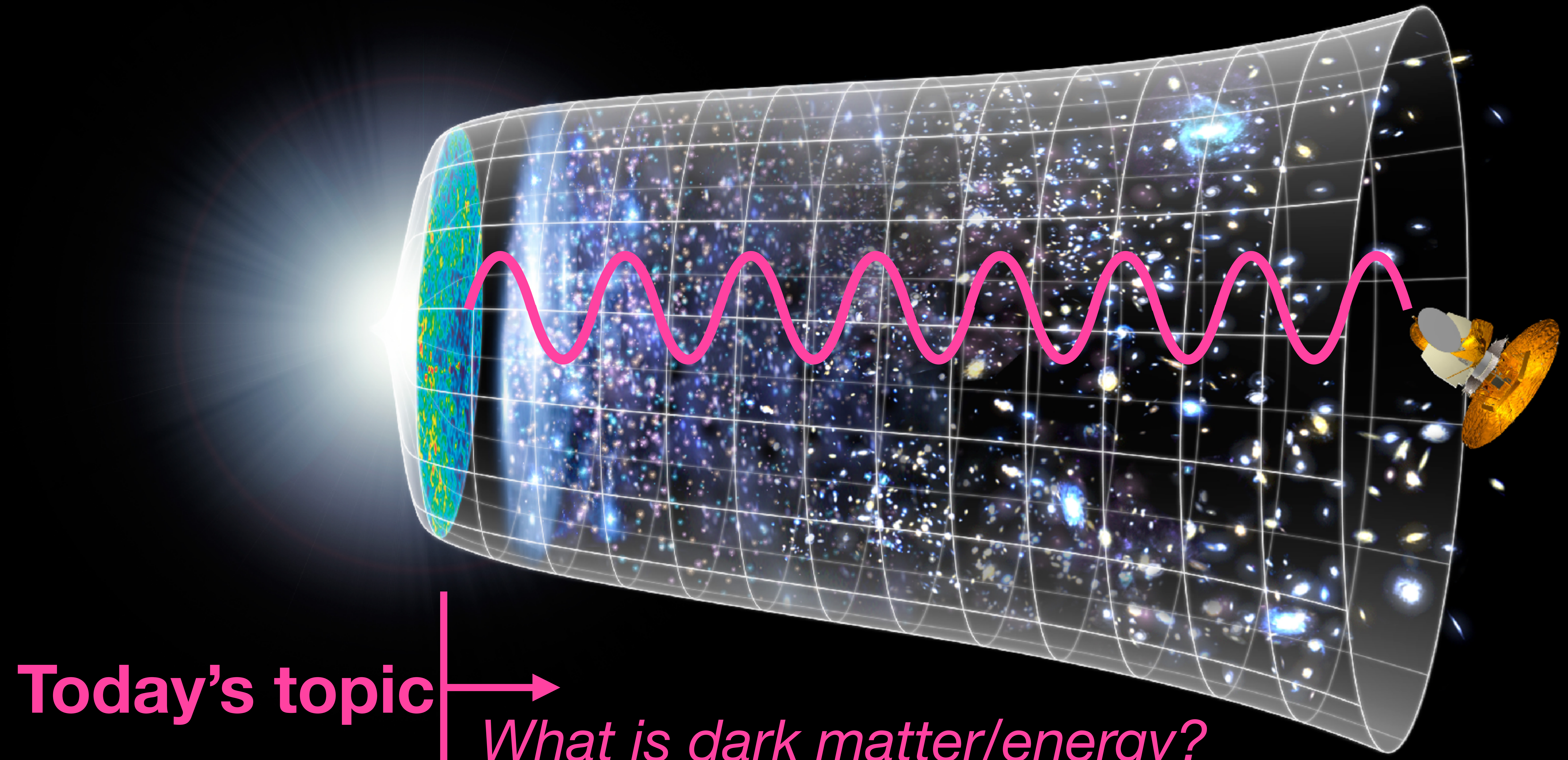
Standard Cosmological Model (ΛCDM) Requires New Physics

Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (Λ)?
  - **Cosmic birefringence** in cross-correlation of E- and B-mode polarisation
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
  - Imprint of **primordial gravitational waves** in B-mode polarisation
- *Polarisation* of the CMB may hold the key to the answers.

Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates **polarisation**!)
What powered the Big Bang?
What is dark matter/energy?

How does the electromagnetic wave of the CMB propagate?



Today's topic

What is dark matter/energy?

How does the electromagnetic wave of the CMB propagate?

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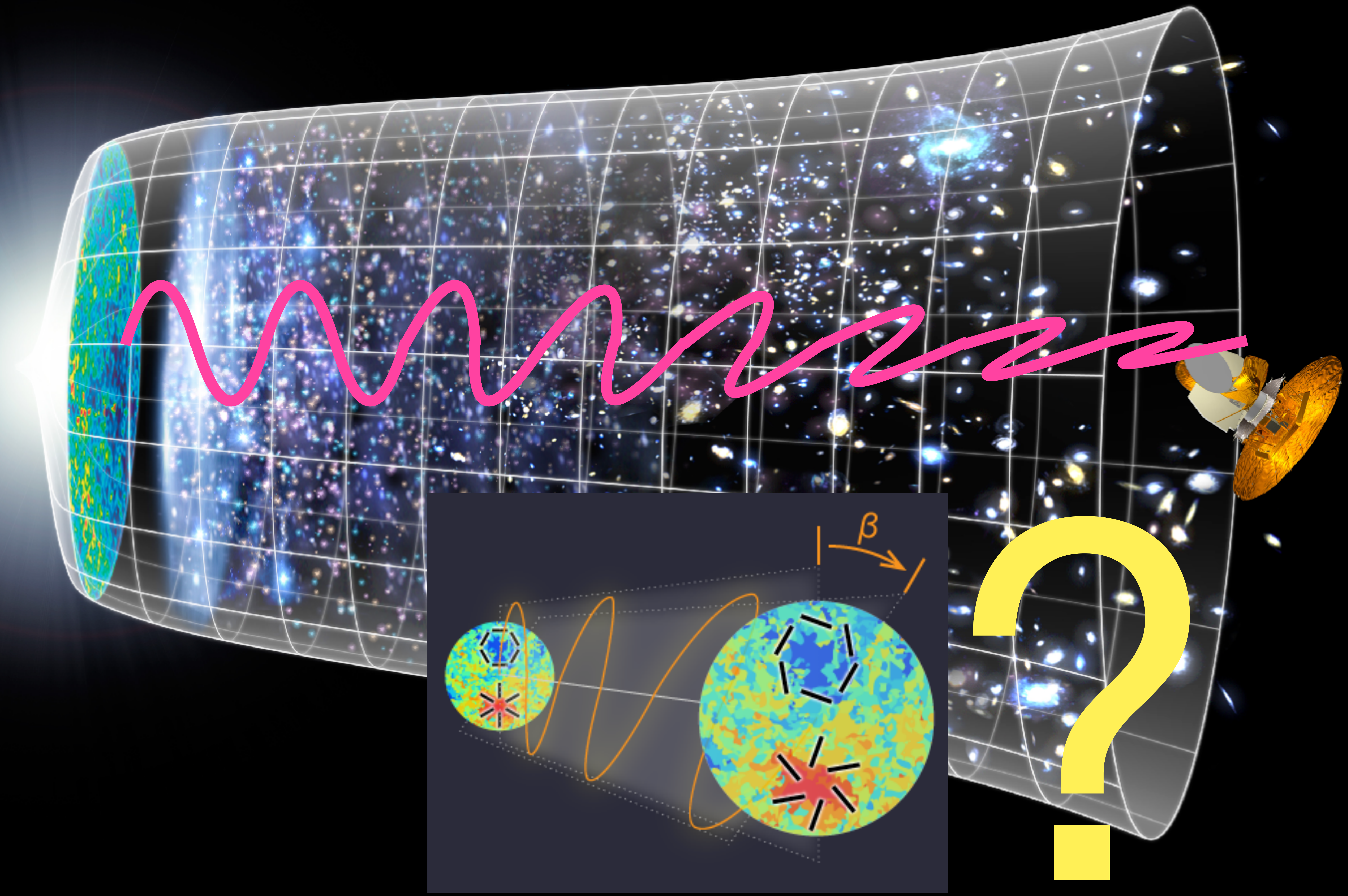

The methodology papers that led to our measurements

Methodology development took 2 years. We now have results from data!

1. **Minami**, Ochi, Ichiki, Katayama, Komatsu & Matsumura, "*Simultaneous determination of the cosmic birefringence and miscalibrated polarization angles from CMB experiments*", PTEP, 083E02 (2019)
    - The original paper to describe the basic idea, methodology, and validation
    - Assumed full-sky data

Yuto Minami
(Osaka U.)

2. **Minami**, "*Determination of miscalibrated polarization angles from observed CMB and foreground EB power spectra: Application to partial-sky observation*", PTEP, 063E01 (2020)
    - Extension to partial-sky data
3. **Minami** & Komatsu, "*Simultaneous determination of the cosmic birefringence and miscalibrated polarization angles II: Including cross-frequency spectra*", PTEP, 103E02 (2020)
    - The complete methodology for multi-frequency data, used for analysing Planck data

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

Cosmic Birefringence

The Universe filled with a "birefringent material"

This "axion" field can be dark matter or dark energy!

- If the Universe is filled with a pseudoscalar field (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

Ni (1977); Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}}, \quad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$

where g_a is a coupling constant of the order α, and the vacuum angle $\theta = \phi_a/f_a$ (ϕ_a = axion field). The equations

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

$$\sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E})$$ **Parity Even**

$$\sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$ **Parity Odd**

- The axion field, θ, is a "pseudoscalar", which is parity odd; thus, the last term in Eq.3.7 is parity even as a whole.

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

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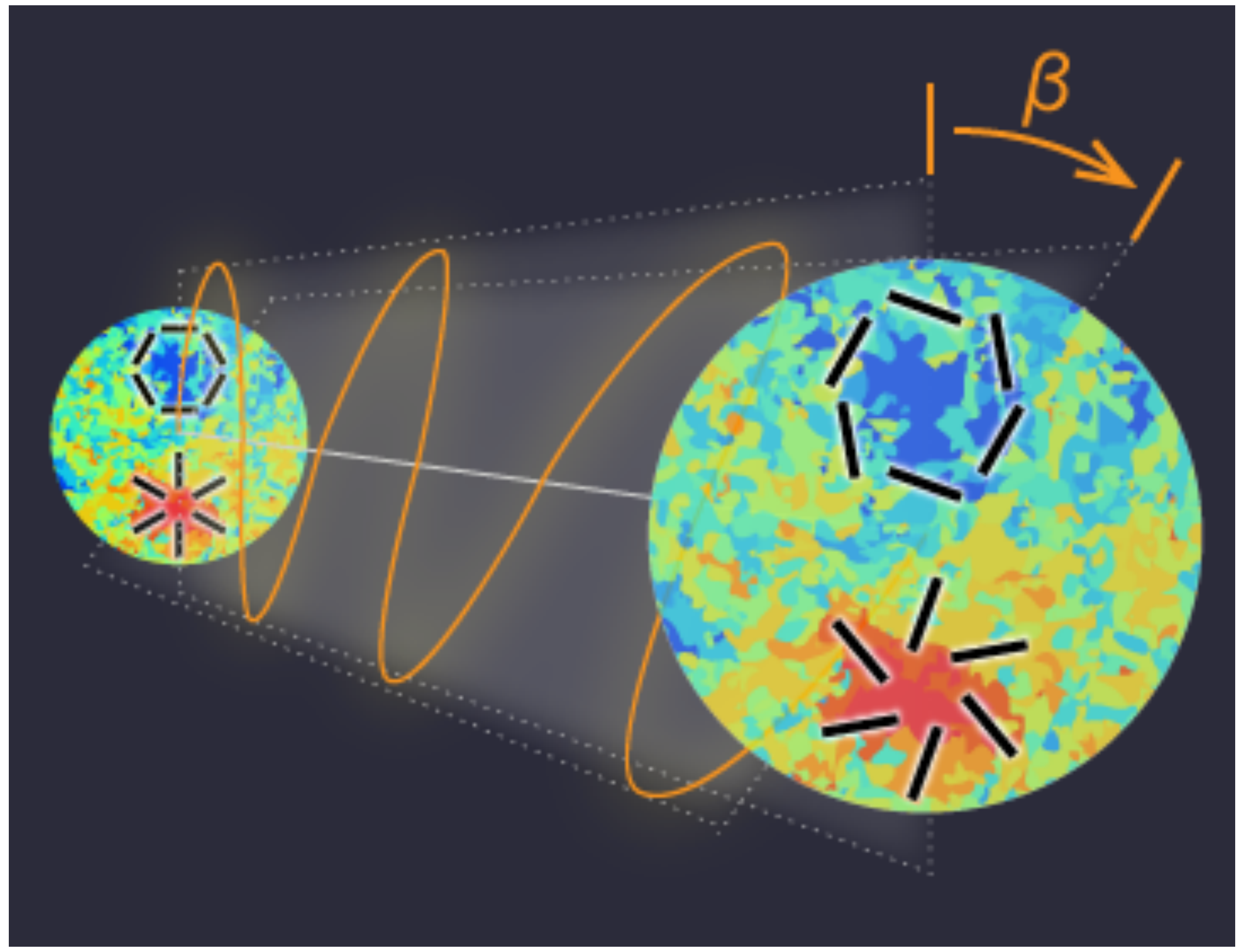


"Cosmic Birefringence"

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to **rotation of the linear polarisation direction.**

Standard Maxwell Theory

Warm up (1)

- ***Technical, but an important note***: the standard electromagnetic theory is invariant under conformal transformation of the metric tensor:

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

- To make the full advantage of this, we write the metric using the conformal time, η, rather than the physical time, t. That is to say,

$$ds^2 = a^2(-d\eta^2 + d\mathbf{x}^2) \text{ i.e., } g_{\mu\nu} = a^2(\eta)\mathrm{diag}(-1,1,1,1)$$

- What is this good for? If we choose Ω=1/a, **we can undo(*) expansion**, and the equation takes the same form as in Minkowski space!

(*) The effect of expansion is still remembered by the conformal time, $\eta = \int dt/a(t)$

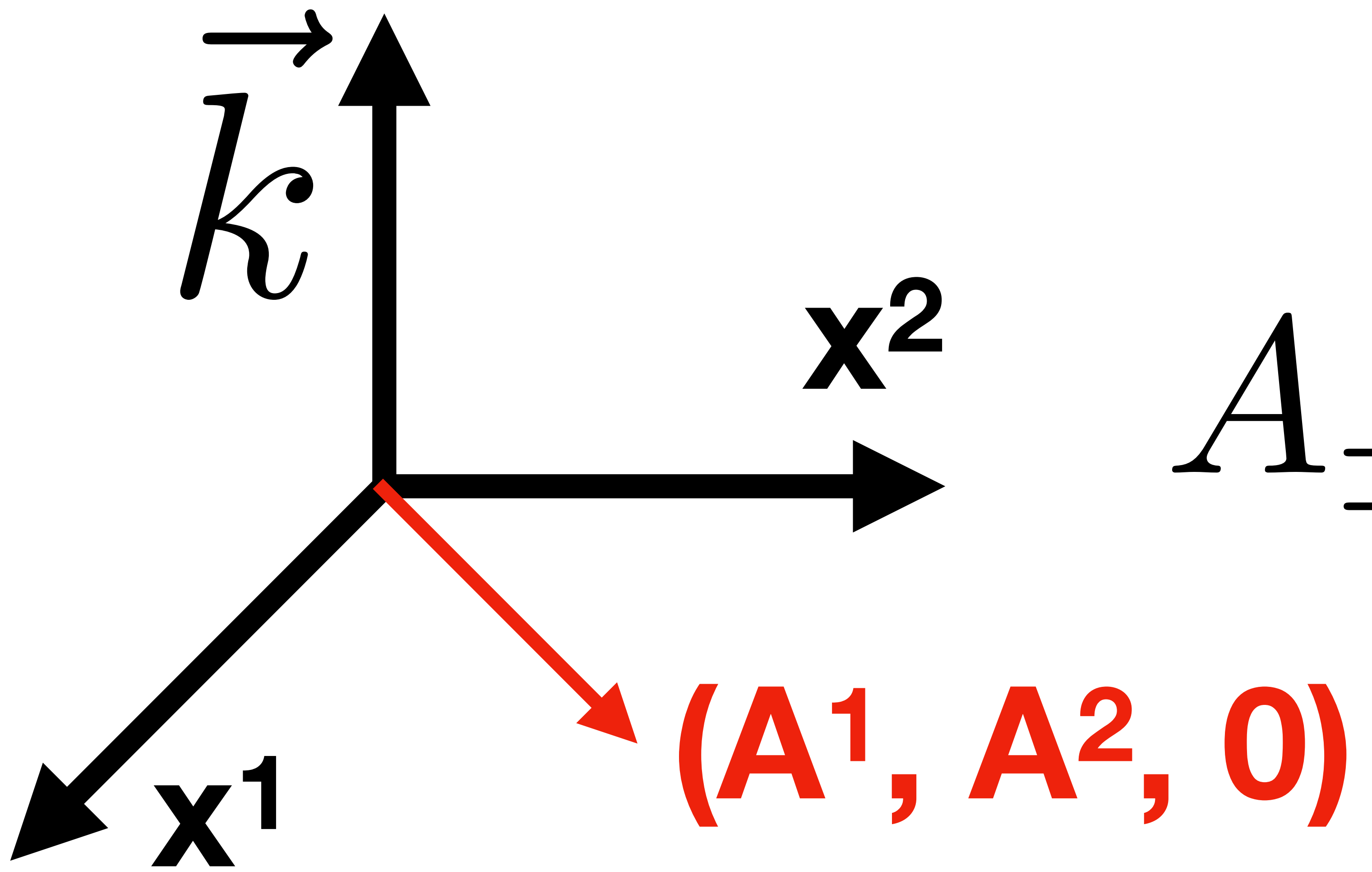
Standard Maxwell Theory

Warm up (2)

- To isolate a transverse wave, we require A_0=0 and div(A_i)=0. Then, in vacuum,

$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0$$

- Go to Fourier space, choose the propagation direction of A_i to be in z-axis, and define right- and left-handed polarisation states as



$$A_\pm = \frac{A_1 \mp iA_2}{\sqrt{2}}$$

- A_+: Right-handed state
- A_-: Left-handed state

Standard Maxwell Theory

Warm up (3)

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$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0 \qquad \left(-\omega_\pm^2 + k^2\right) A_\pm(\eta) = 0$$

Same dispersion relation for right- and left-handed states

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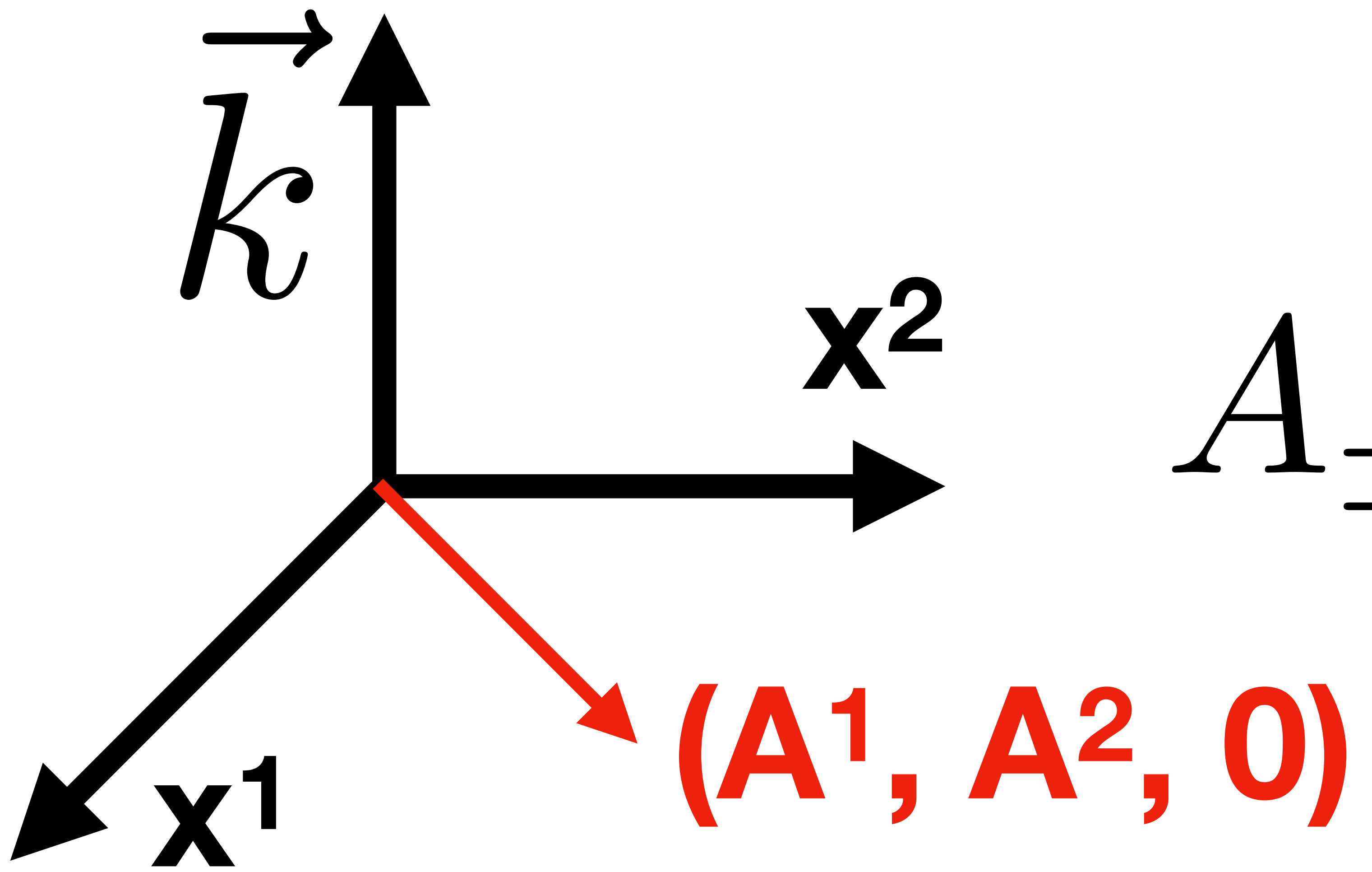

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Cosmic Birefringence

Derivation (1)

- Now, include **the Chern-Simons term**!

the effective Lagrangian for axion electrodynamics is

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- The equation of motion is modified to

$$\left(-\omega_\pm^2 + k^2\right)A_\pm(\eta) = 0 \quad \Rightarrow \quad \left(-\omega_\pm^2 + k^2 \boxed{\pm 4g_a k\theta'}\right)A_\pm(\eta) = 0$$

$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k} \qquad (\theta' = \partial\theta/\partial\eta)$$

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

Cosmic Birefringence

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$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k} = \left(1 \pm \frac{2g_a\theta'}{k}\right)^2 - \cancel{\frac{4g_a^2\theta'^2}{k^2}}$$

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Phase velocities of right- and left-handed states are slightly different!

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

Cosmic Birefringence

Derivation (2)

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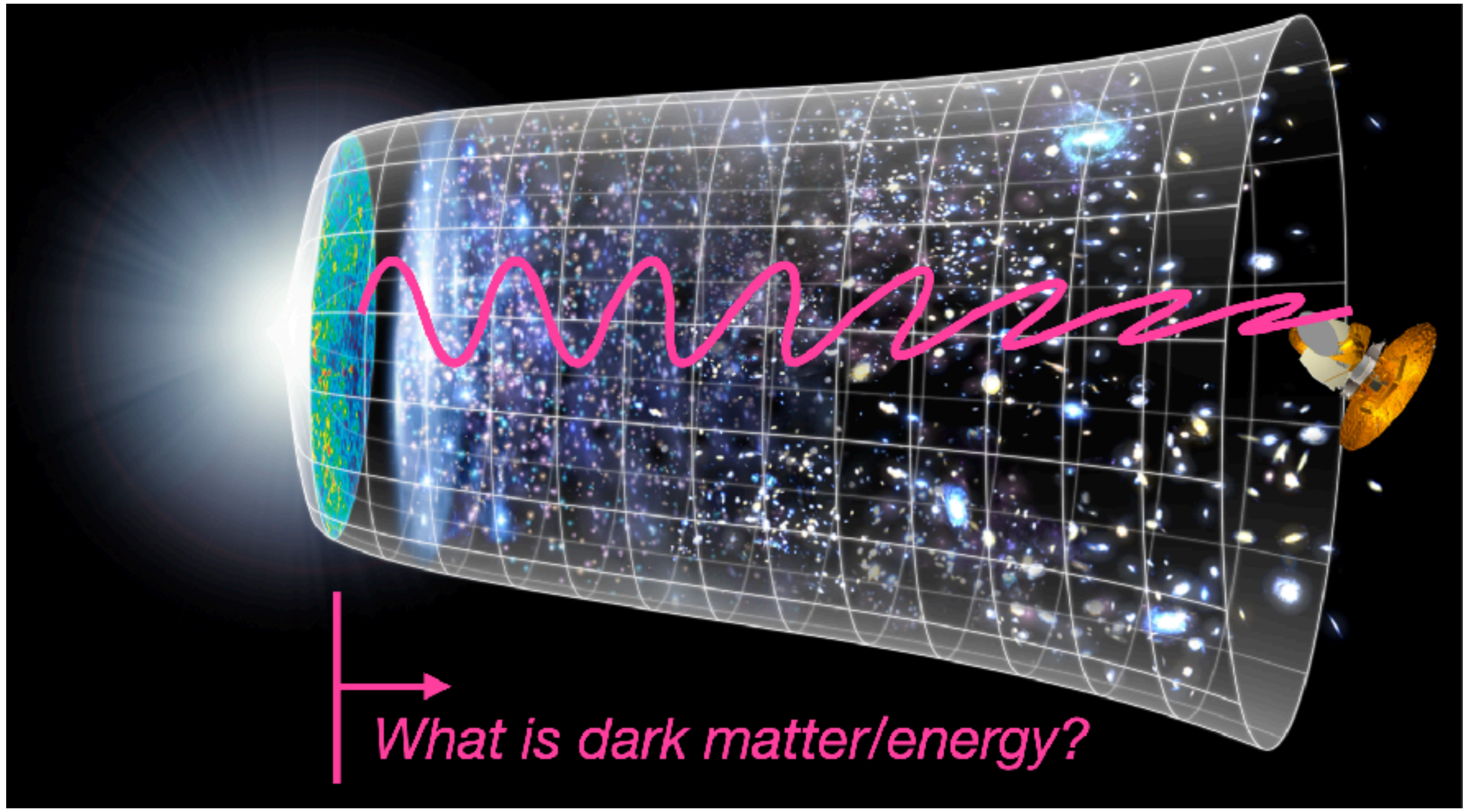
Phase velocities of right- and left-handed states are slightly different!



- The plane of linear polarisation rotates by an angle ψ:

$$\psi = \int d\eta \, \frac{\omega_+ - \omega_-}{2} = 2g_a \int d\eta \, \theta' = 2g_a \int dt \, \dot{\theta}$$

The effect accumulates over the distance!
=> CMB polarisation is sensitive to this effect

Cosmic Birefringence

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This is the convention for polarisation direction adopted by IAU

Cosmic Birefringence

Derivation (3)

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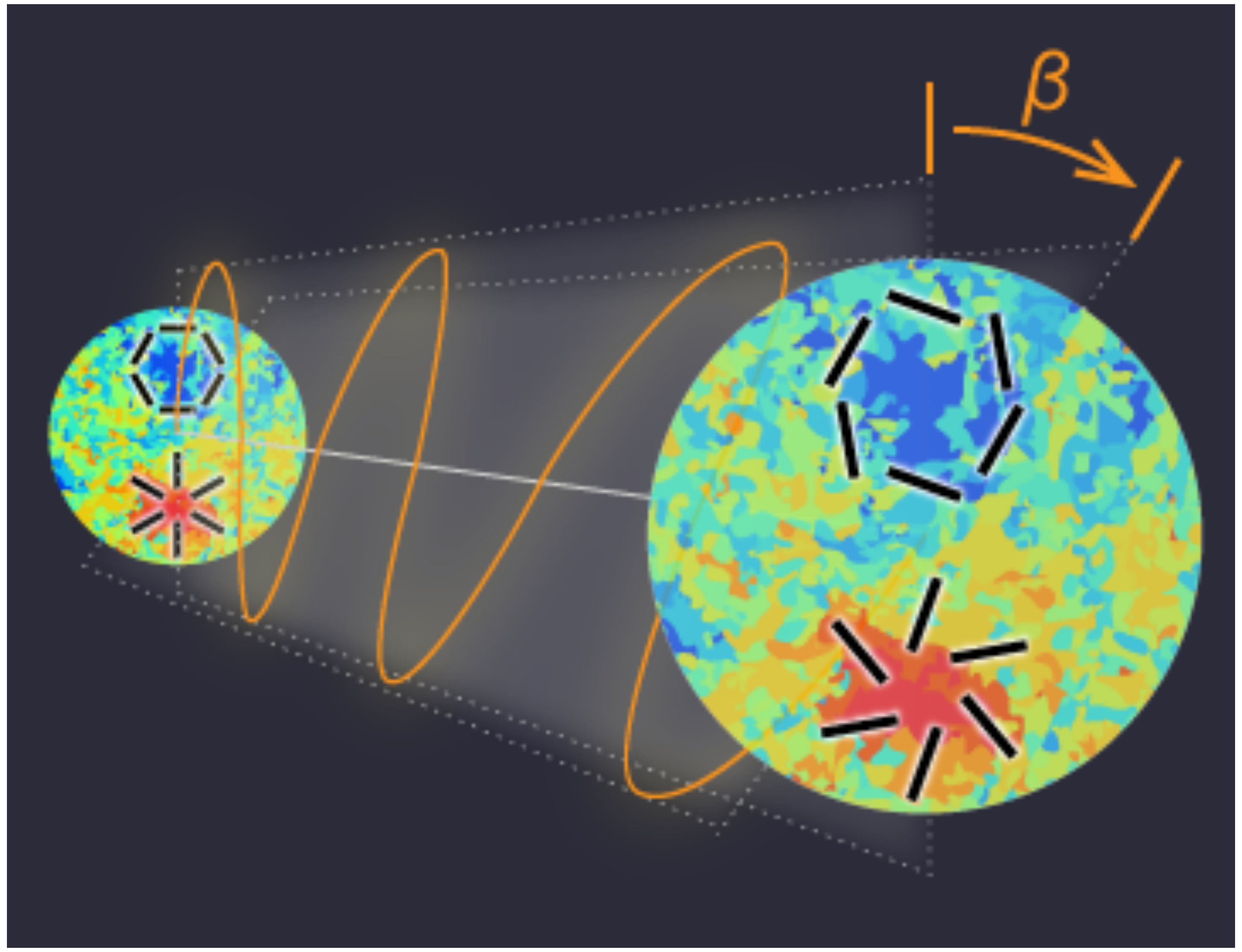

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This is the convention for polarisation direction adopted by IAU

However!

The CMB community adopted the opposite sign convention…
Thus, we shall use β = −ψ

Cosmic Birefringence

Recap

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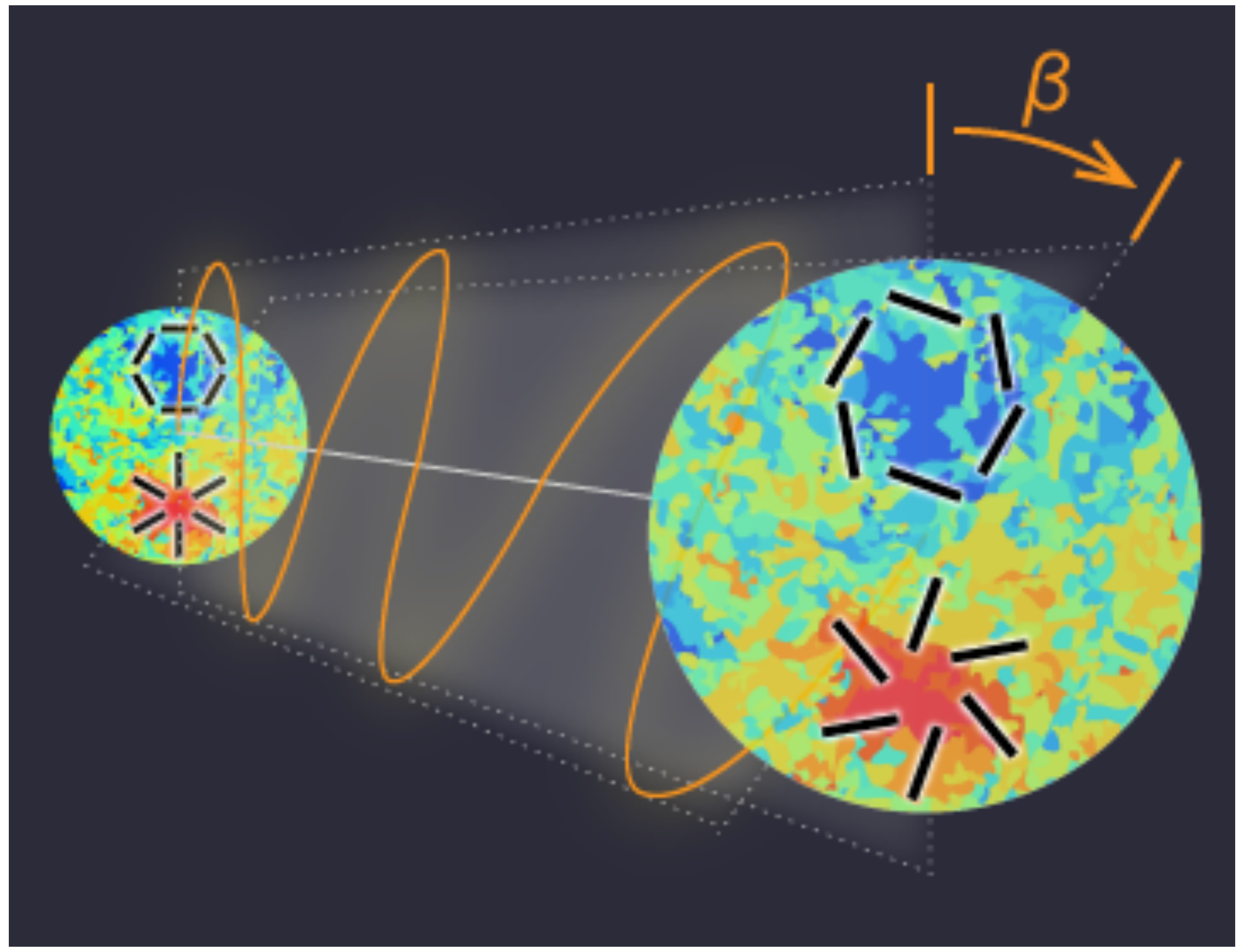
$$\beta = -2g_a\int_{t_{\mathrm{emitted}}}^{t_{\mathrm{observed}}} dt\ \dot{\theta}$$



The larger the distance the photon travels, the larger the effect becomes.

Motivation

Why study the cosmic birefringence?

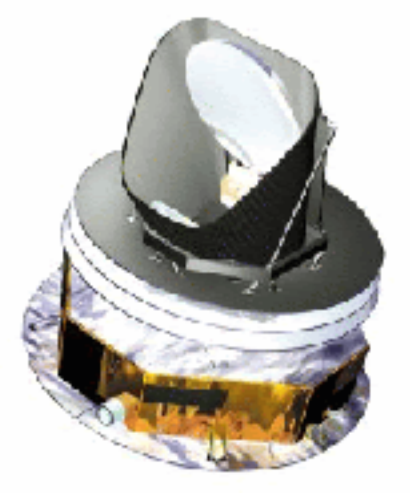
- The Universe's energy budget is dominated by two dark components:
  - Dark Matter
  - Dark Energy
- Either or both of these can be an axion-like field!
  - See Marsh (2016) and Ferreira (2020) for reviews.
- Thus, detection of parity-violating physics in polarisation of the cosmic microwave background can transform our understanding of Dark Matter/ Energy.

(Simpler) Motivation

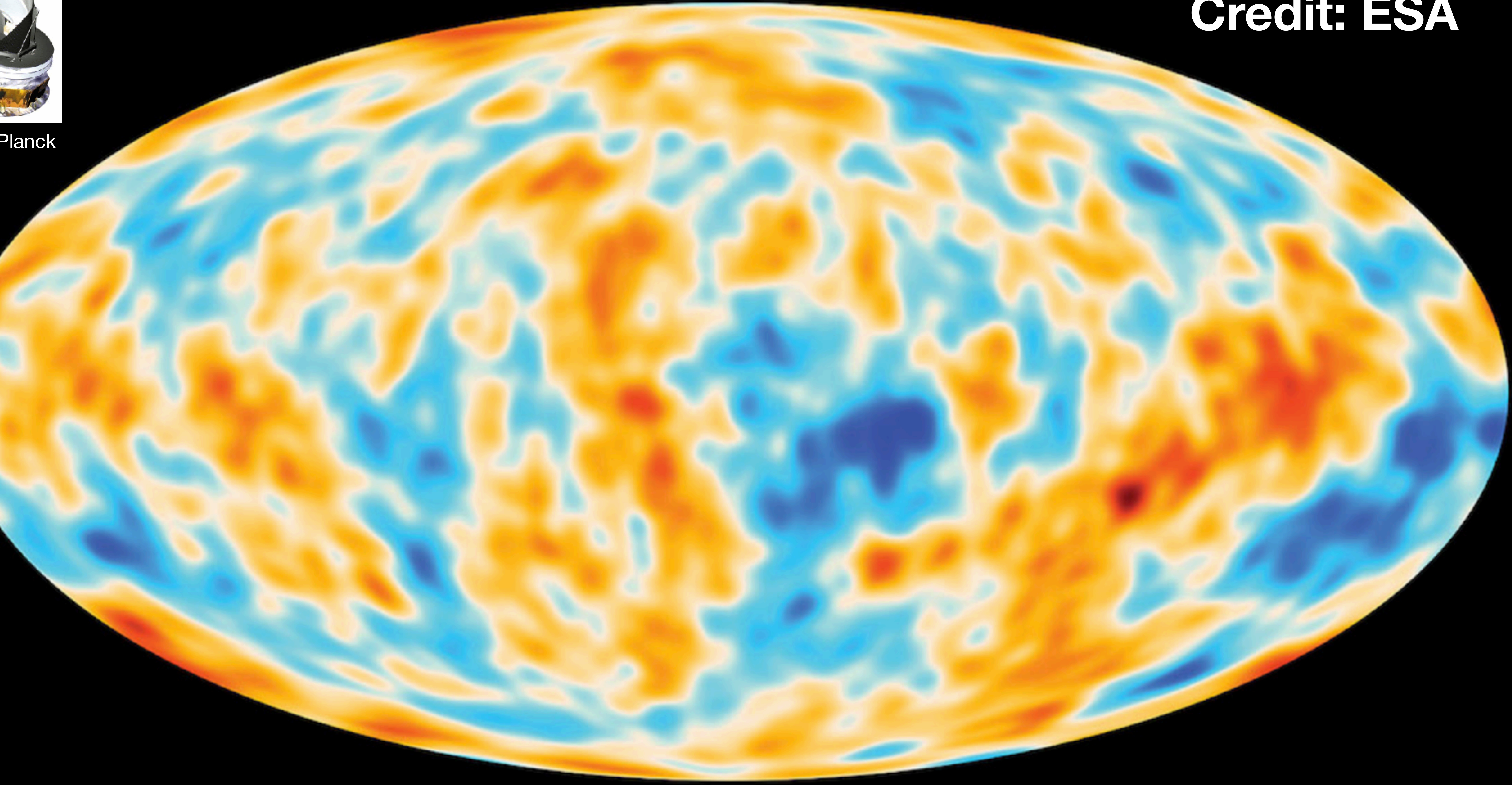
Why study the cosmic birefringence?

- We know that the weak interaction violates parity (Lee & Yang 1956; Wu et al. 1957).
    - Why should the laws of physics governing the Universe conserve parity?

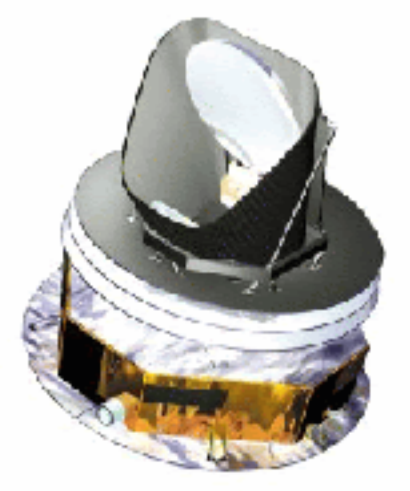
- Let's look!


ESA’s Planck

Credit: ESA


Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



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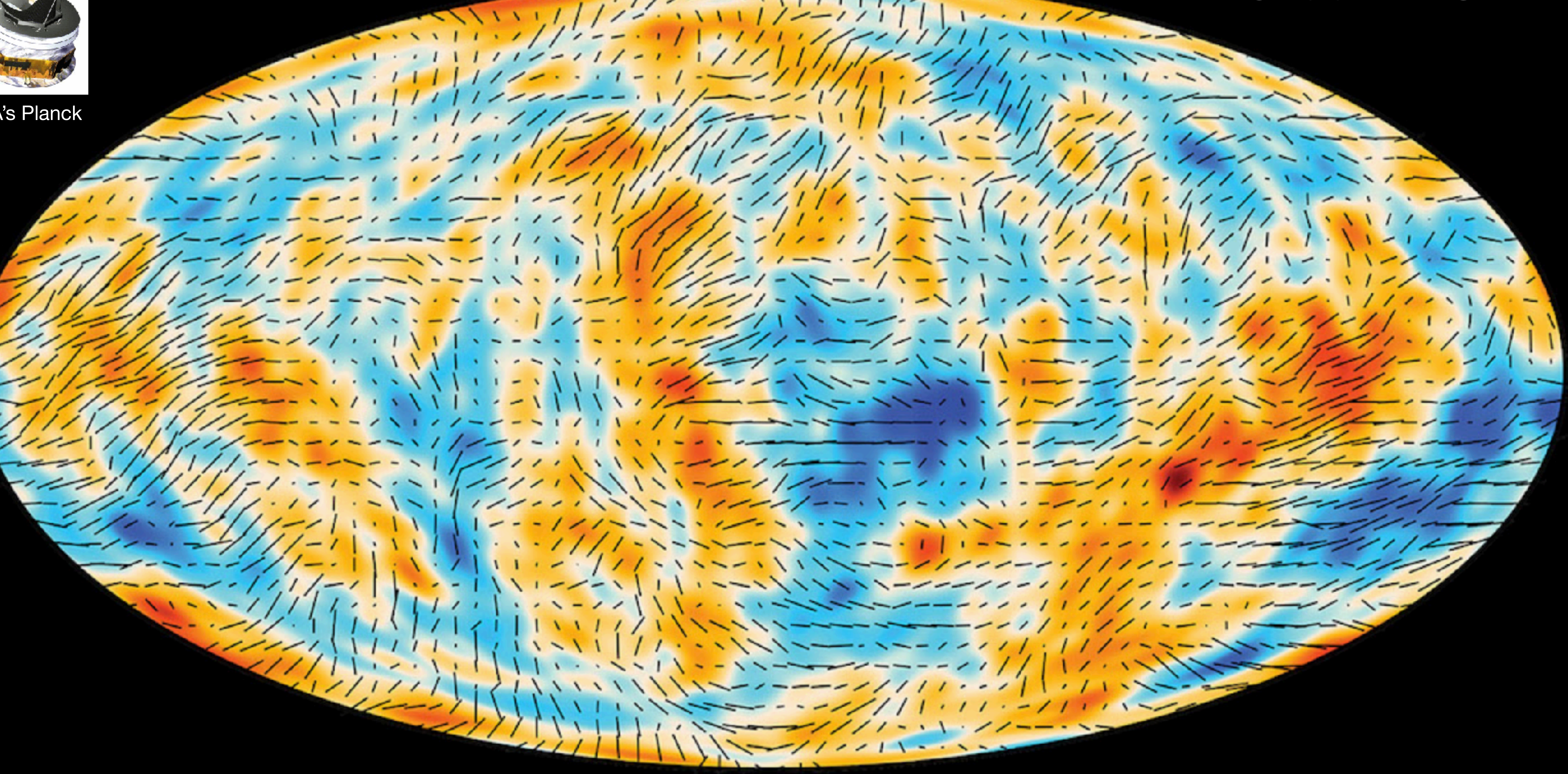


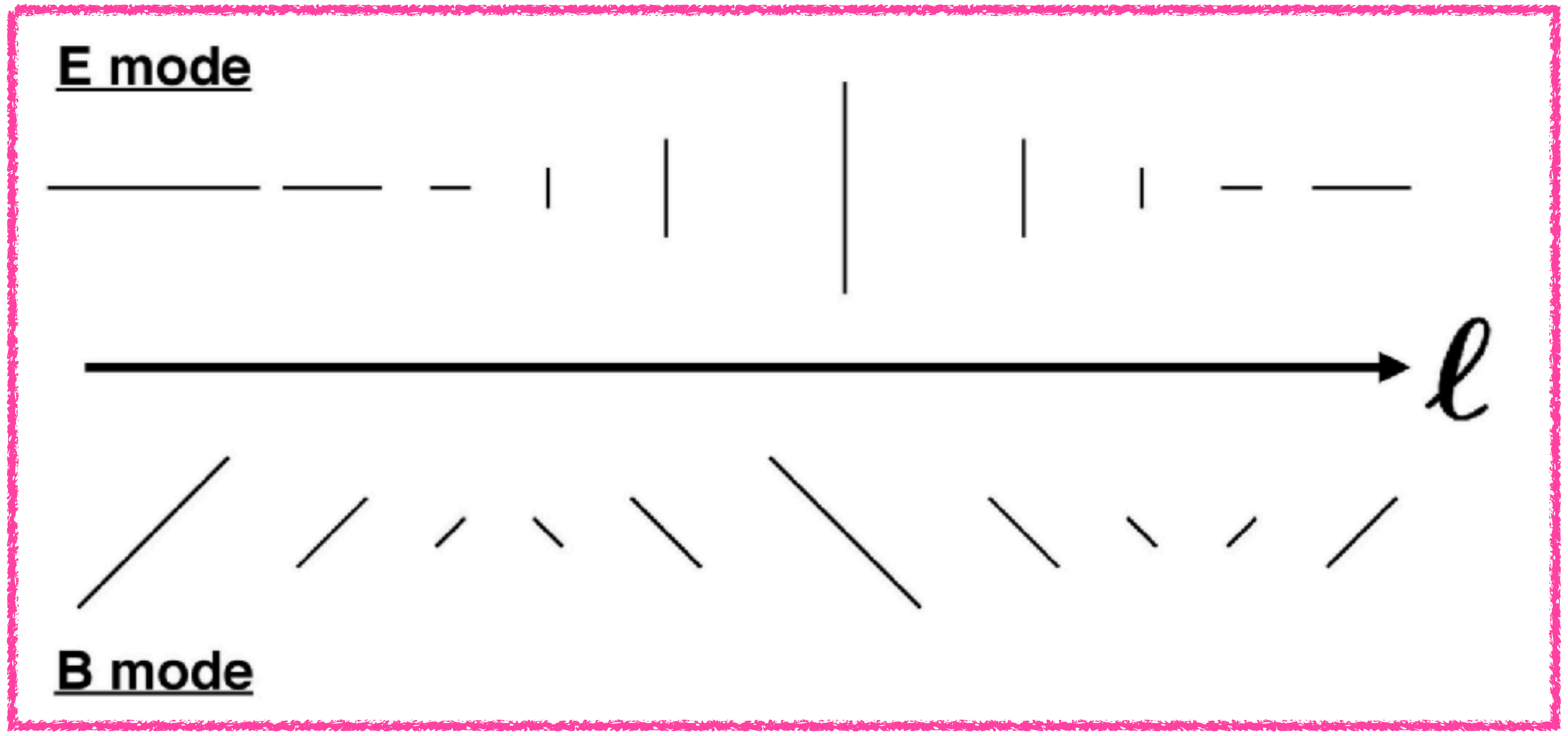
Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

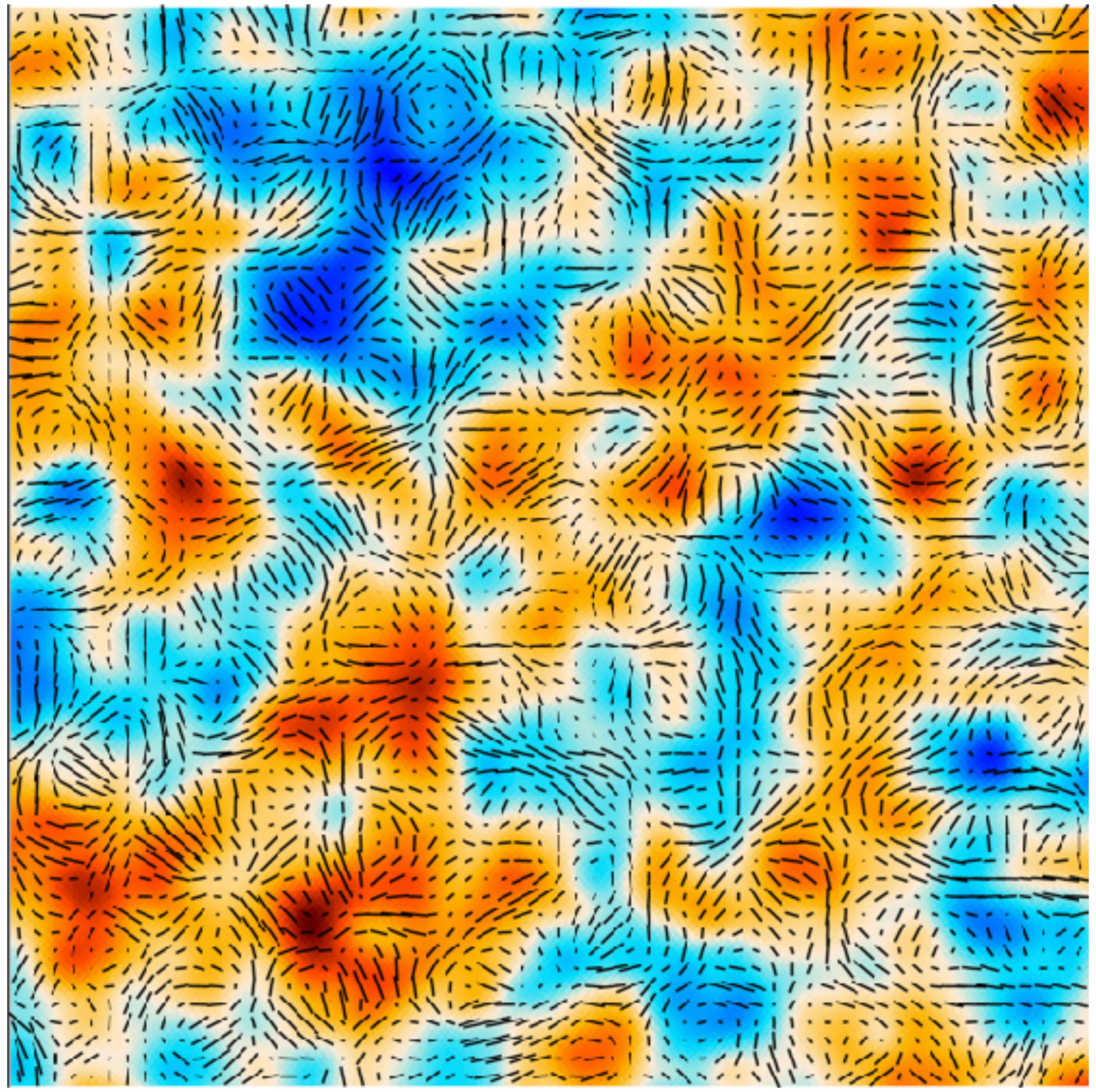
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

E- and B-mode decomposition of linear polarisation

Concept defined in Fourier space



This map is dominated by E-mode polarisation



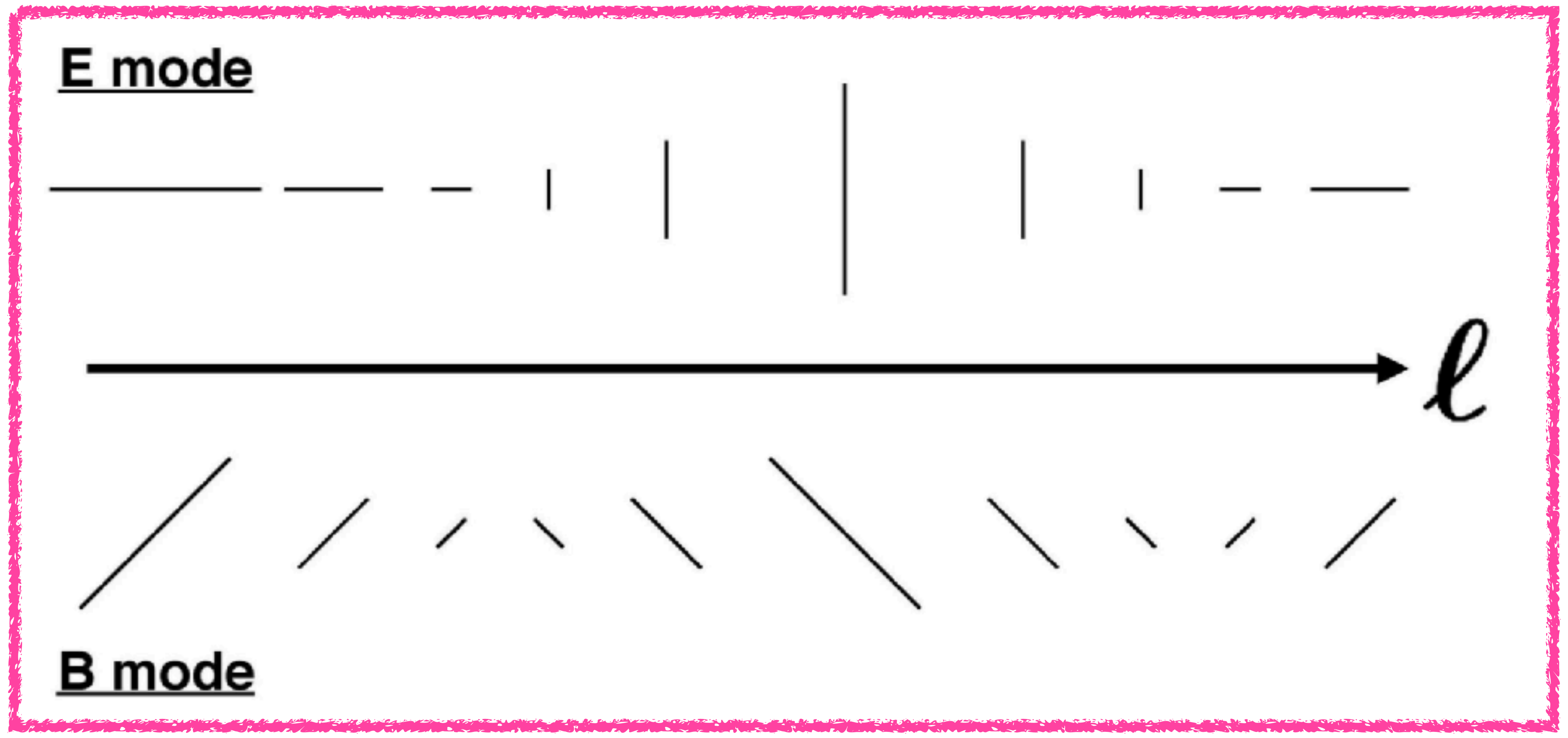
- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

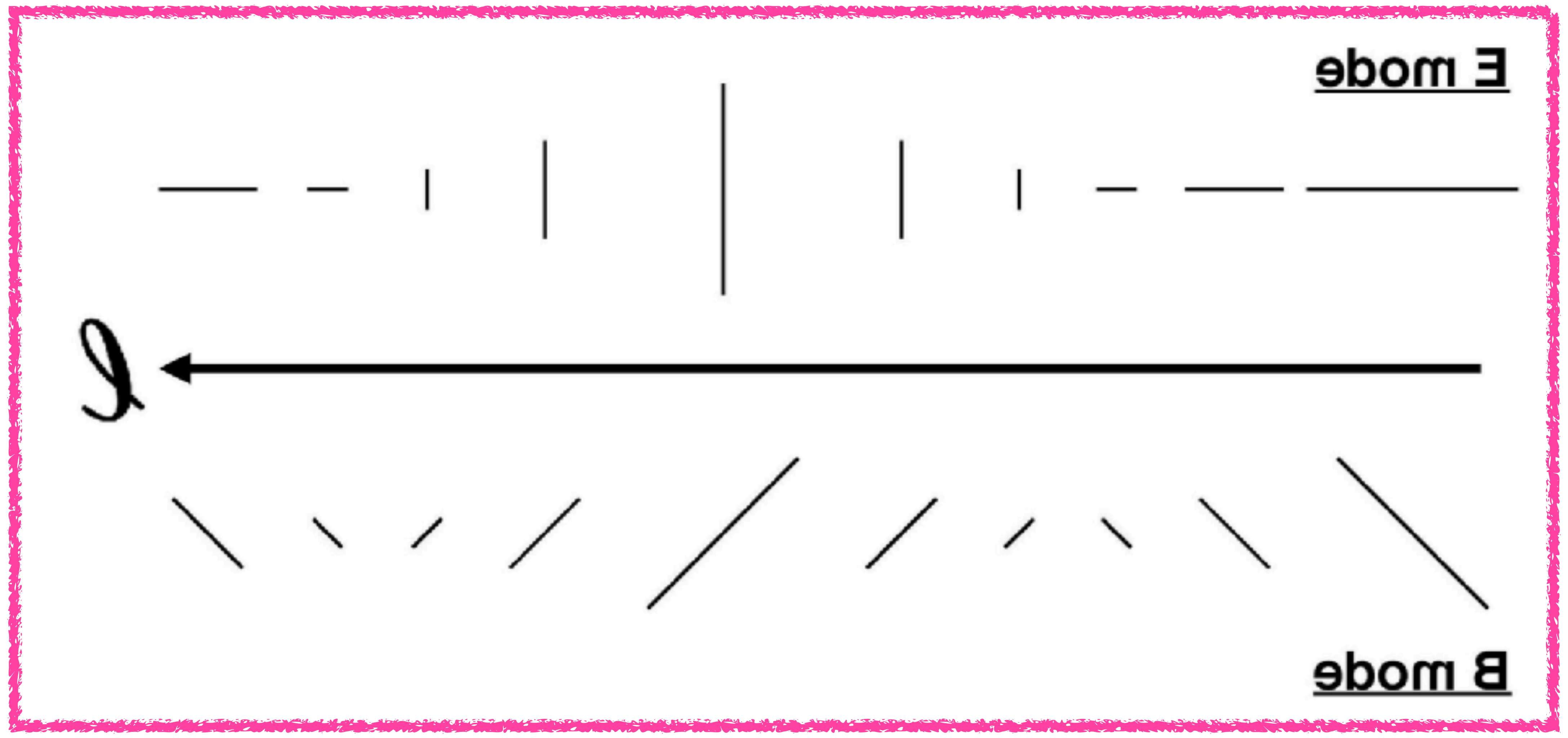
IMPORTANT”: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

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

Parity Flip

E-mode remains the same, whereas B-mode changes the sign





- Two-point correlation functions invariant under the parity flip are

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

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

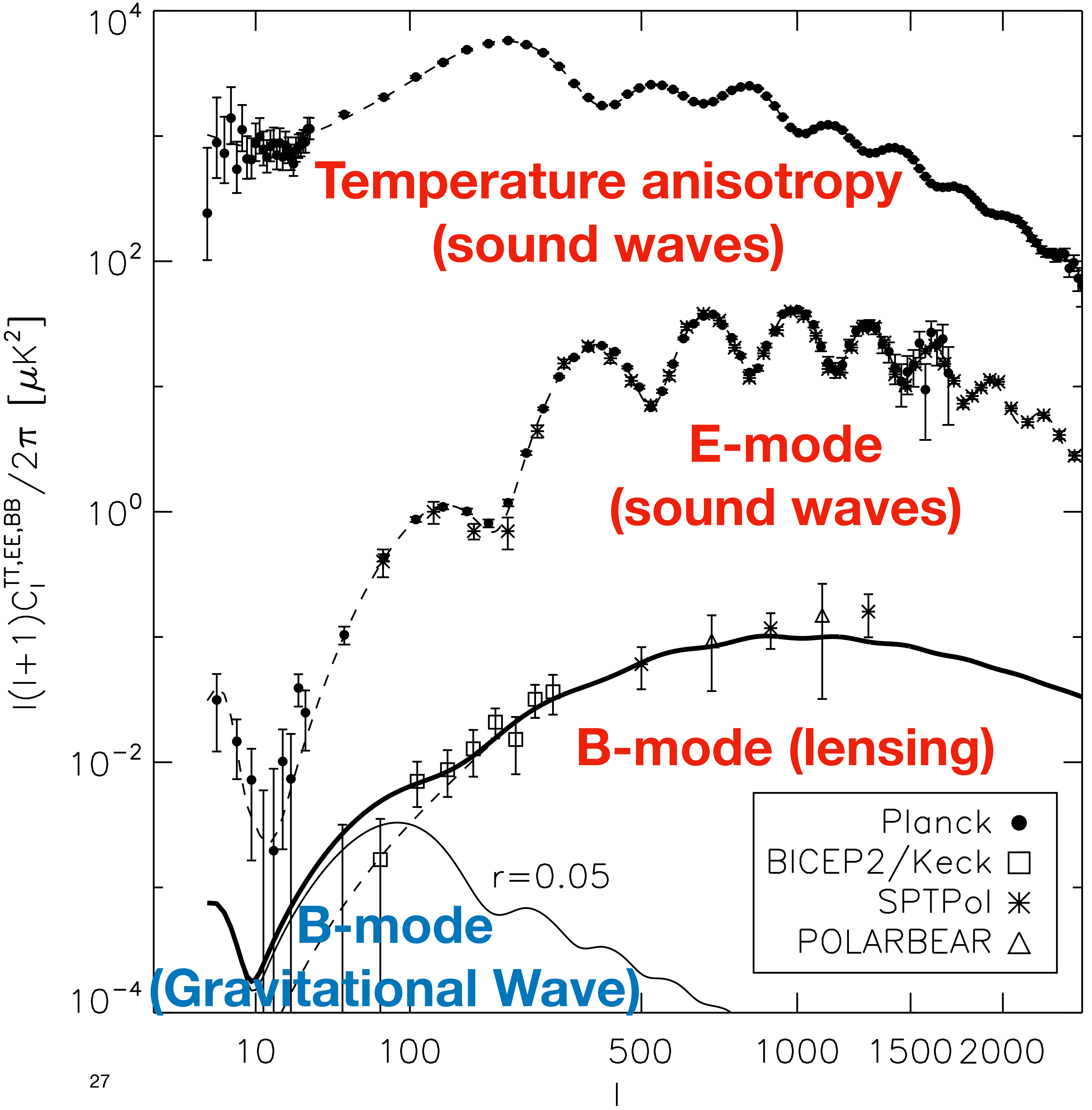
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **We can use these combinations to probe parity-violating physics (e.g., axions)**

Power Spectra

A lot have been measured

- This is the typical figure that you find in talks and lectures on CMB.
    - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**

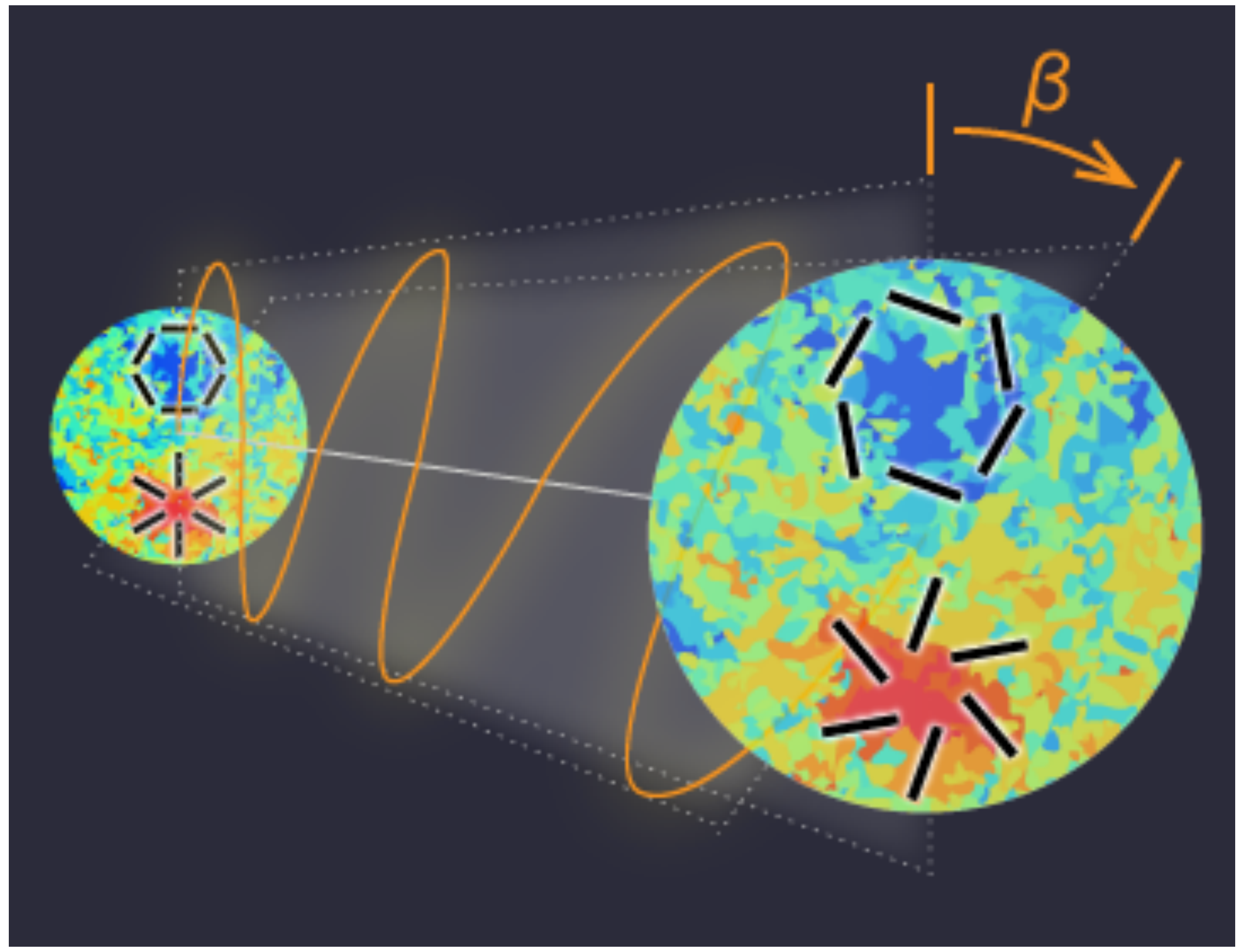


Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

EB correlation from the cosmic birefringence

E <-> B conversion by rotation of the linear polarisation plane

- The intrinsic EE, BB, and EB power spectra 13.8 billion years ago would yield the observed EB as



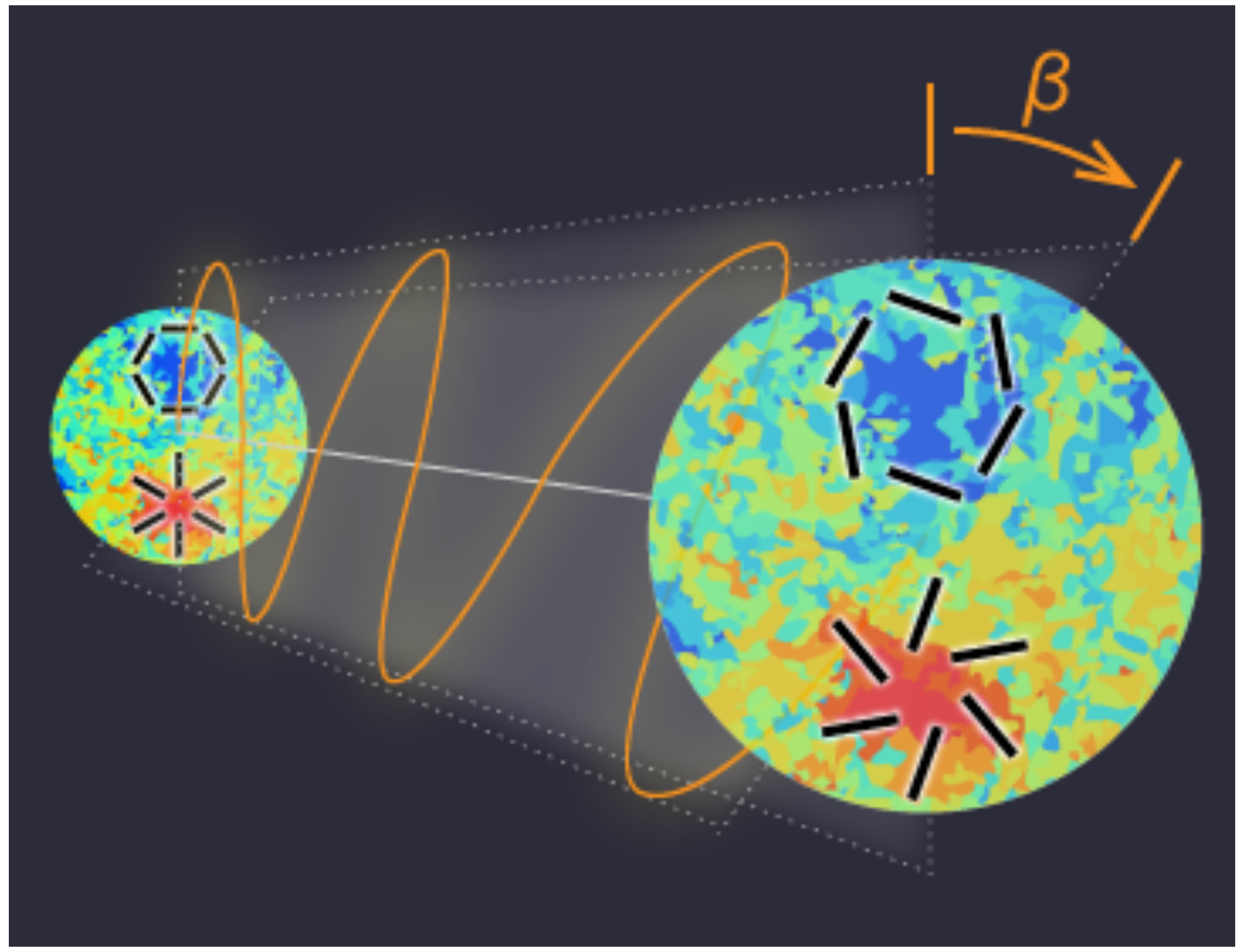
$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

- **How do we infer β from the observational data?**

- Traditionally, one would find β by fitting $C_l^{EE,CMB} - C_l^{BB,CMB}$ to the observed $C_l^{EB,obs}$ using the best-fitting CMB model, and assuming the intrinsic EB to vanish, $C_l^{EB}=0$.

Searching for the birefringence

Improvement #1 (Zhao et al. 2015)



- If we look at how EE and BB spectra are also modified,

$$C_\ell^{EE,\mathrm{obs}} = C_\ell^{EE}\cos^2(2\beta) + C_\ell^{BB}\sin^2(2\beta) - C_\ell^{EB}\sin(4\beta)$$

$$C_\ell^{BB,\mathrm{obs}} = C_\ell^{EE}\sin^2(2\beta) + C_\ell^{BB}\cos^2(2\beta) + C_\ell^{EB}\sin(4\beta)$$

- We find

$$C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}} = (C_\ell^{EE} - C_\ell^{BB})\cos(4\beta) - 2C_\ell^{EB}\sin(4\beta)$$

- Thus,

$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

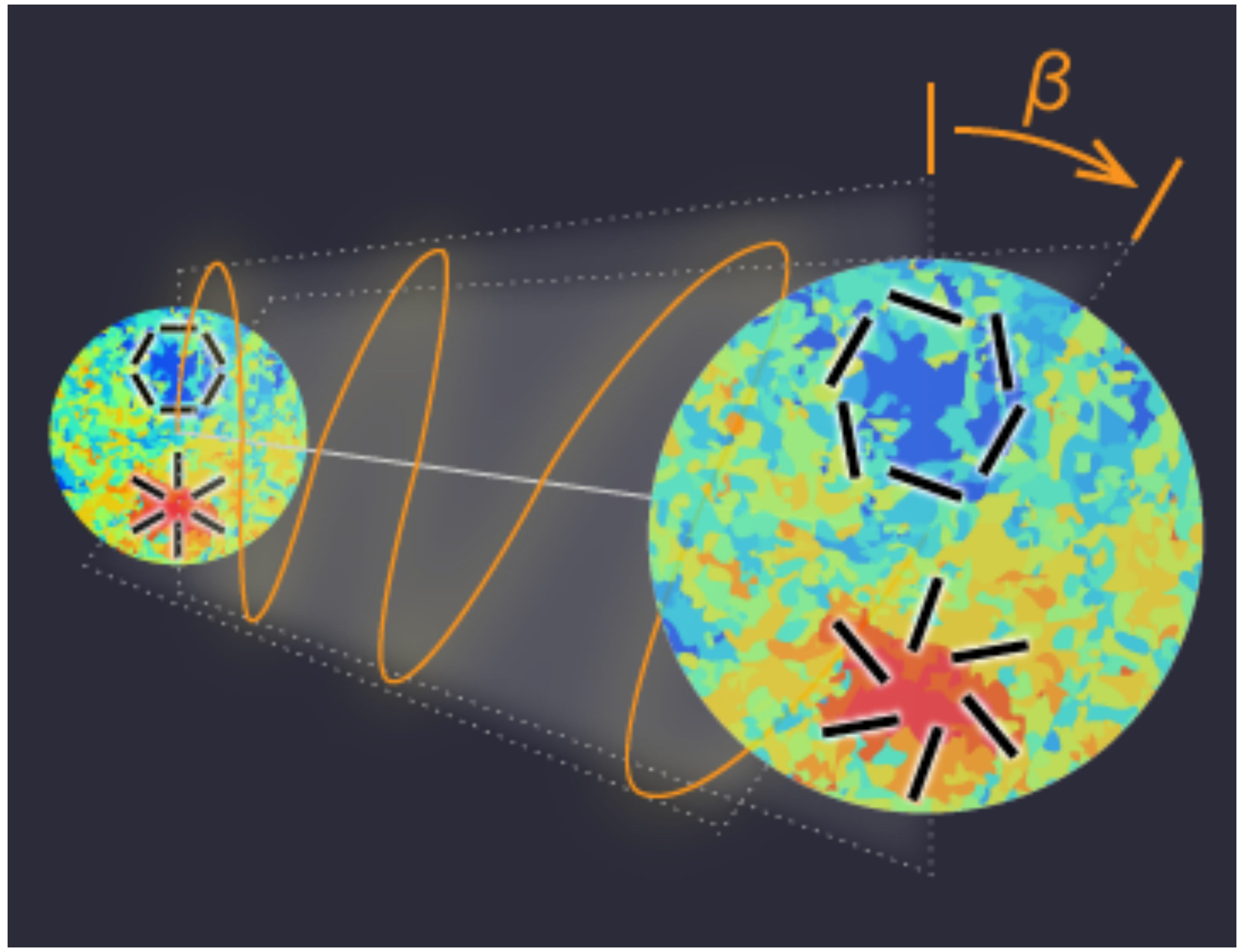
$$= \frac{1}{2}\boxed{(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}})}\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

No need to assume a model

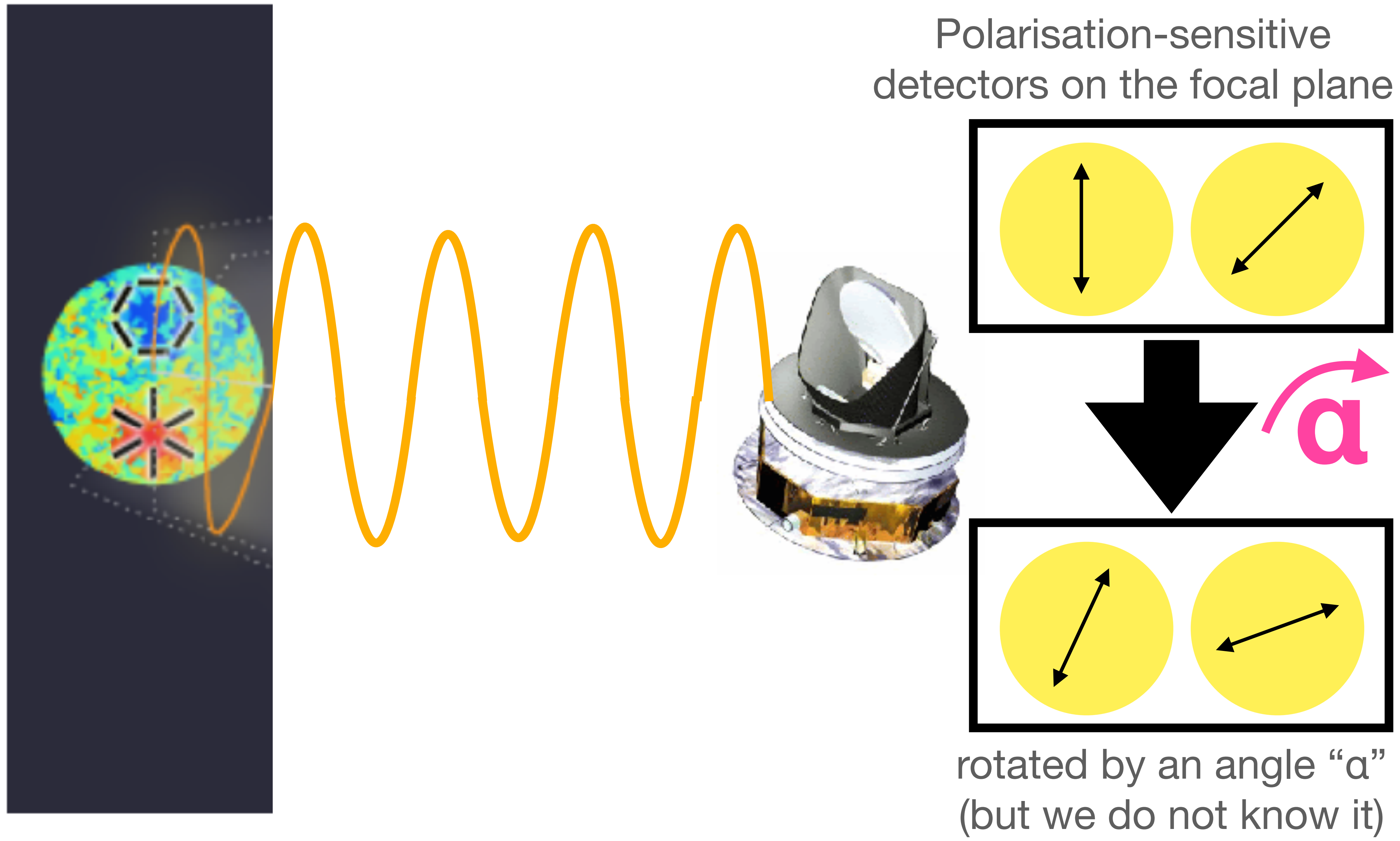
The Biggest Problem: Miscalibration of detectors

Impact of miscalibration of polarisation angles

Cosmic or Instrumental?



OR



- Is the plane of linear polarisation rotated by the genuine cosmic birefringence effect, or simply because the polarisation-sensitive directions of 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**.

The past measurements

The quoted uncertainties are all statistical only (68%CL)

- $\alpha+\beta = -6.0 \pm 4.0$ deg (Feng et al. 2006) first measurement
- $\alpha+\beta = -1.1 \pm 1.4$ deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- $\alpha+\beta = 0.55 \pm 0.82$ deg (QUaD Collaboration, Wu et al. 2009)
- …
- $\alpha+\beta = 0.31 \pm 0.05$ deg (Planck Collaboration 2016)
- $\alpha+\beta = -0.61 \pm 0.22$ deg (POLARBEAR Collaboration 2020)
- $\alpha+\beta = 0.63 \pm 0.04$ deg (SPT Collaboration, Bianchini et al. 2020)
- $\alpha+\beta = 0.12 \pm 0.06$ deg (ACT Collaboration, Namikawa et al. 2020)
- $\alpha+\beta = 0.07 \pm 0.09$ deg (ACT Collaboration, Choi et al. 2020)

Why not yet discovered?

The past measurements

Now including the estimated systematic errors on α

- β = –6.0 ± 4.0 ± **??** deg (Feng et al. 2006)
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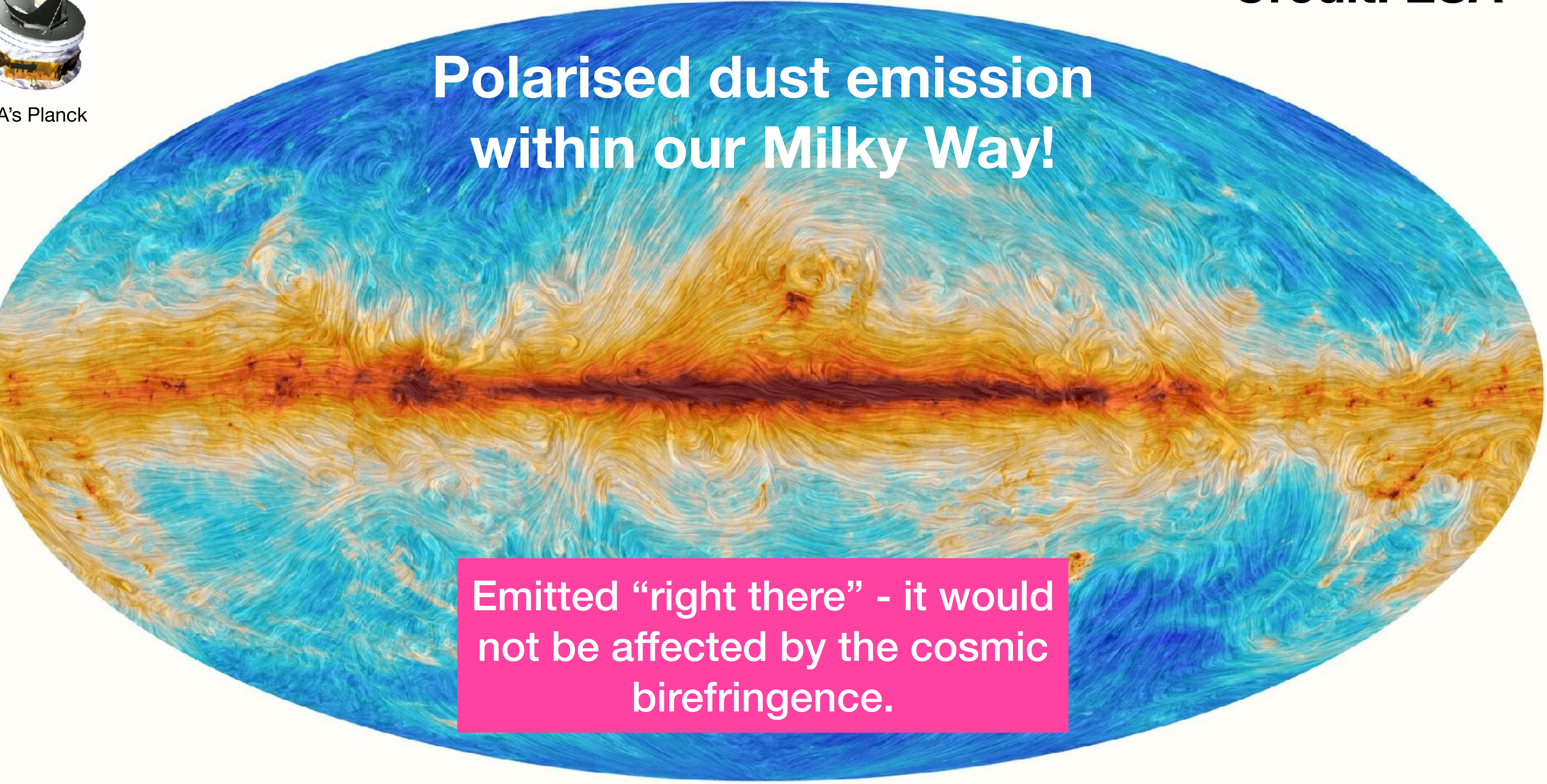
- β = –0.61 ± 0.22 ± **??** deg (POLARBEAR Collaboration 2020)
- β = 0.63 ± 0.04 ± **??** deg (SPT Collaboration, Bianchini et al. 2020)
- β = 0.12 ± 0.06 ± **??** deg (ACT Collaboration, Namikawa et al. 2020)
- β = 0.07 ± 0.09 ± **??** deg (ACT Collaboration, Choi et al. 2020)

Uncertainty in the calibration of α has been the major limitation

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

ESA's Planck

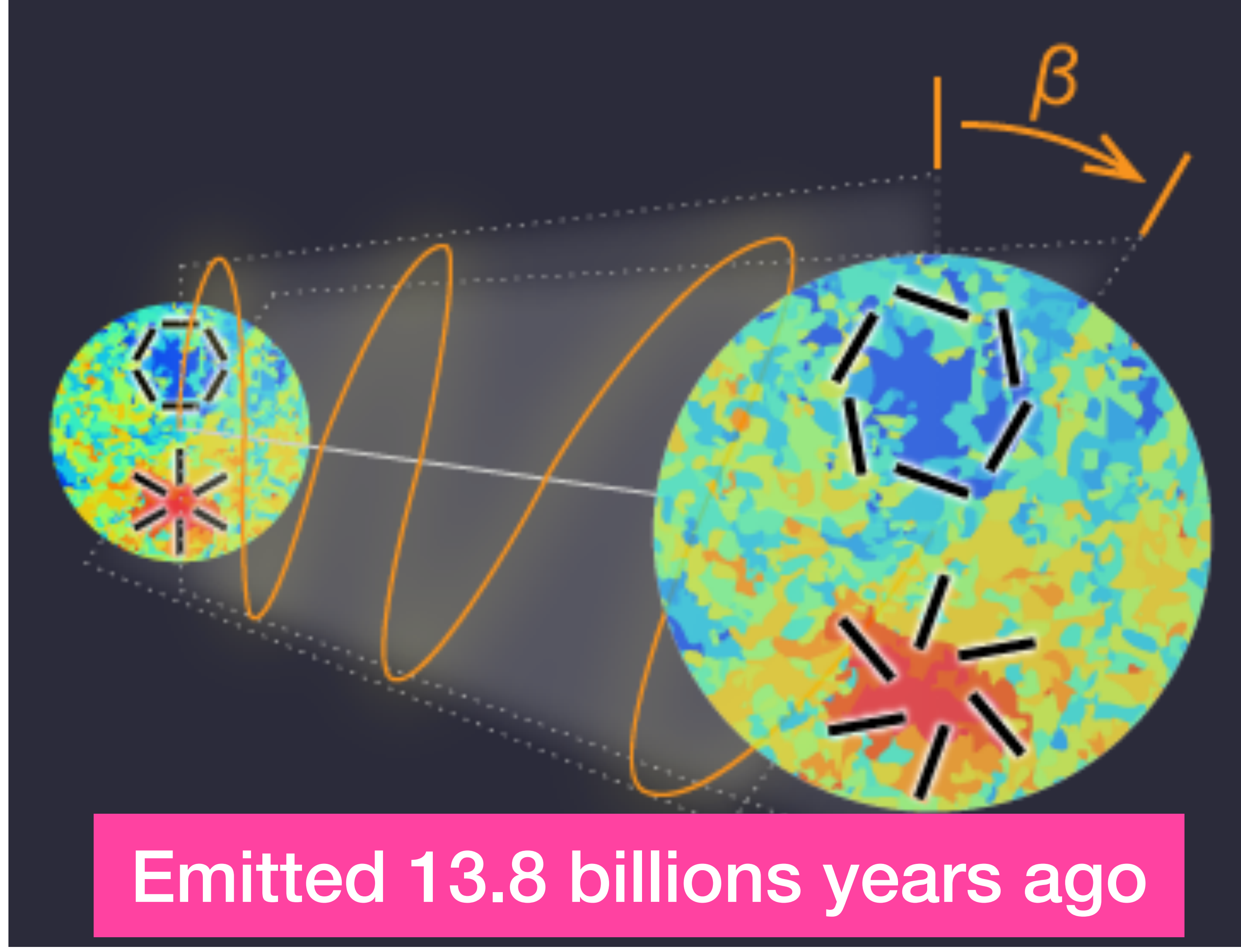
Credit: ESA



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

Searching for the birefringence

Improvement #2 (Minami et al. 2019)



But the source of foreground is much closer!

- **<u>Idea:</u>** *Miscalibration of the polarization angle α rotates both the foreground and CMB, but β affects only the CMB.*

$$E^{\rm o}_{\ell,m} = E^{\rm fg}_{\ell,m}\cos(2\alpha) - B^{\rm fg}_{\ell,m}\sin(2\alpha) + E^{\rm CMB}_{\ell,m}\cos(2\alpha+2\beta) - B^{\rm CMB}_{\ell,m}\sin(2\alpha+2\beta) + \boxed{E^{\rm N}_{\ell,m}}$$

$$B^{\rm o}_{\ell,m} = E^{\rm fg}_{\ell,m}\sin(2\alpha) + B^{\rm fg}_{\ell,m}\cos(2\alpha) + E^{\rm CMB}_{\ell,m}\sin(2\alpha+2\beta) + B^{\rm CMB}_{\ell,m}\cos(2\alpha+2\beta) + \boxed{B^{\rm N}_{\ell,m}}$$

noise

- Thus,

$$\langle C_\ell^{EB,{\rm o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\underbrace{\langle C_\ell^{EE,{\rm o}}\rangle - \langle C_\ell^{BB,{\rm o}}\rangle}_{\text{measured}}\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\underbrace{\langle C_\ell^{EE,{\rm CMB}}\rangle - \langle C_\ell^{BB,{\rm CMB}}\rangle}_{\text{known accurately}}\right)$$

$$+ \frac{1}{\cos(4\alpha)}\langle C_\ell^{EB,{\rm fg}}\rangle + \frac{\cos(4\beta)}{\cos(4\alpha)}\langle C_\ell^{EB,{\rm CMB}}\rangle\,.$$

Key: No explicit modelling of the foreground EE and BB is necessary

Assumption for the baseline result

What about the intrinsic EB correlation of the foreground emission?

$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right) + \frac{1}{\cos(4\alpha)}\boxed{\langle C_\ell^{EB,\mathrm{fg}}\rangle} + \frac{\cos(4\beta)}{\cos(4\alpha)}\boxed{\langle C_\ell^{EB,\mathrm{CMB}}\rangle}.$$

- For the baseline result, we ignore the intrinsic EB correlations of the foreground $\langle C_\ell^{EB,\mathrm{fg}}\rangle$ and the CMB $\langle C_\ell^{EB,\mathrm{CMB}}\rangle$.
    - The latter is justifiable but the former is not. We will revisit this important issue at the end.

Likelihood for the simplest case

Single-frequency case, full sky data

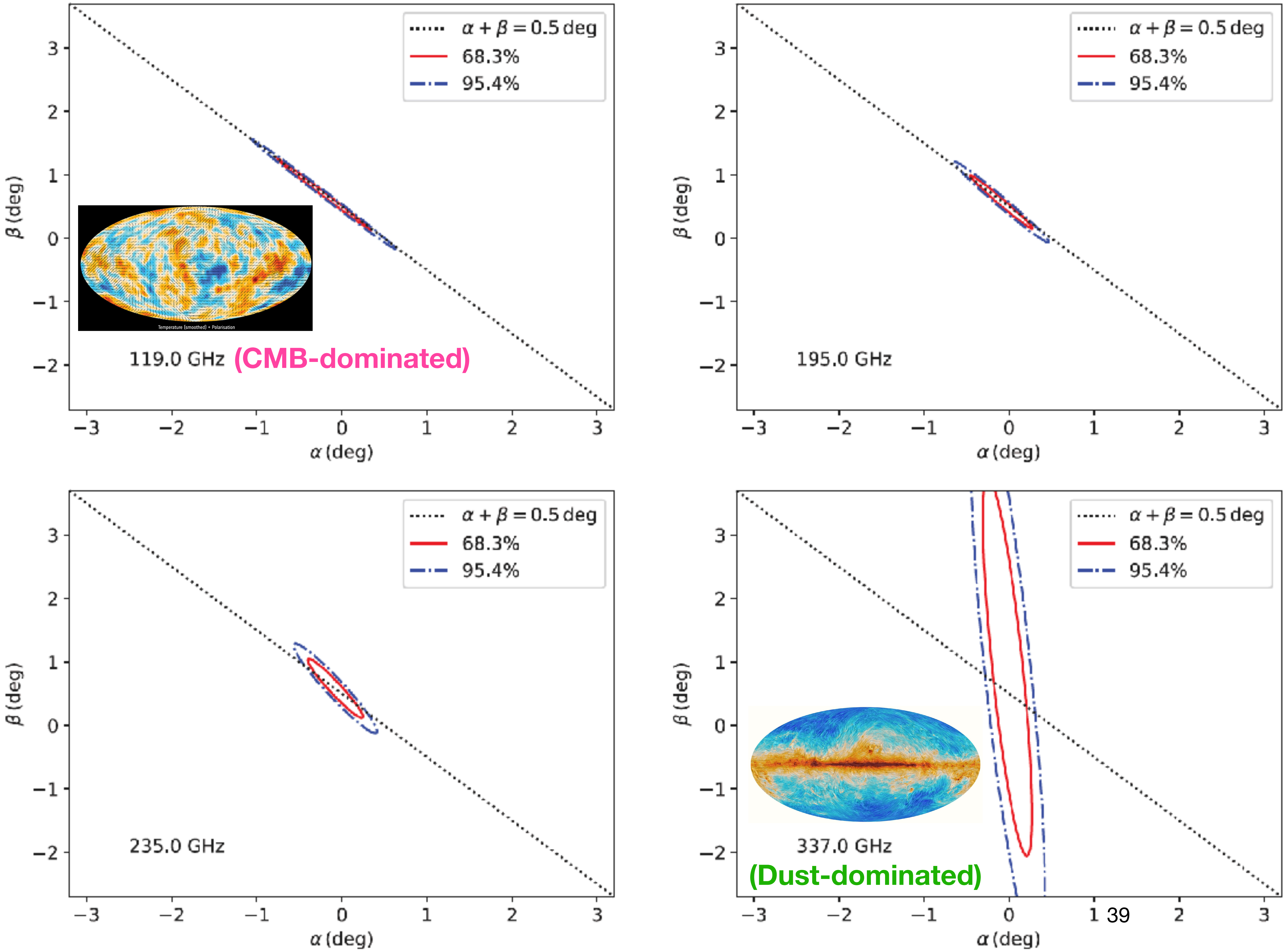
$$-2\ln\mathcal{L} = \sum_{\ell=2}^{\ell_{\max}} \frac{\left[C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right) - \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}}\right)\right]^2}{\mathrm{Var}\left(C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)\right)}$$

- We determine α and β simultaneously from this likelihood.
- We first validate the algorithm using simulated data.
- For analysing the Planck data, we use the multi-frequency likelihood developed in Minami and Komatsu (2020a).

Minami et al. (2019)

How does it work?

Simulation of future CMB data (LiteBIRD)



- When the data are dominated by CMB, the sum of two angles, α+β, is determined precisely.
    - This is the diagonal line.
- The foreground determines α with some uncertainty, breaking the degeneracy. Then σ(β) ~ σ(α) because σ(α+β) << σ(α).
- When the data are dominated by the foreground, it can determine α but not β due to the lack of sensitivity to the CMB.

PHYSICAL REVIEW LETTERS

Featured in Physics   Editors' Suggestion

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

Yuto Minami and Eiichiro Komatsu
Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

Physics See synopsis: Hints of Cosmic Birefringence?

ABSTRACT

We search for evidence of parity-violating physics in the Planck 2018 polarization data and report on a new measurement of the cosmic birefringence angle β. The previous measurements are limited by the systematic uncertainty in the absolute polarization angles of the Planck detectors. We mitigate this systematic uncertainty completely by simultaneously determining β and the angle miscalibration using the observed cross-correlation of the E- and B-mode polarization of the cosmic microwave background and the Galactic foreground emission. We show that the systematic errors are effectively mitigated and achieve a factor-of-2 smaller uncertainty than the previous measurement, finding $\beta = 0.35 \pm 0.14$ deg (68% C.L.), which excludes $\beta = 0$ at 99.2% C.L. This corresponds to the statistical significance of 2.4σ.

Yuto Minami
(Osaka U.)

Application to the Planck Data (PR3)

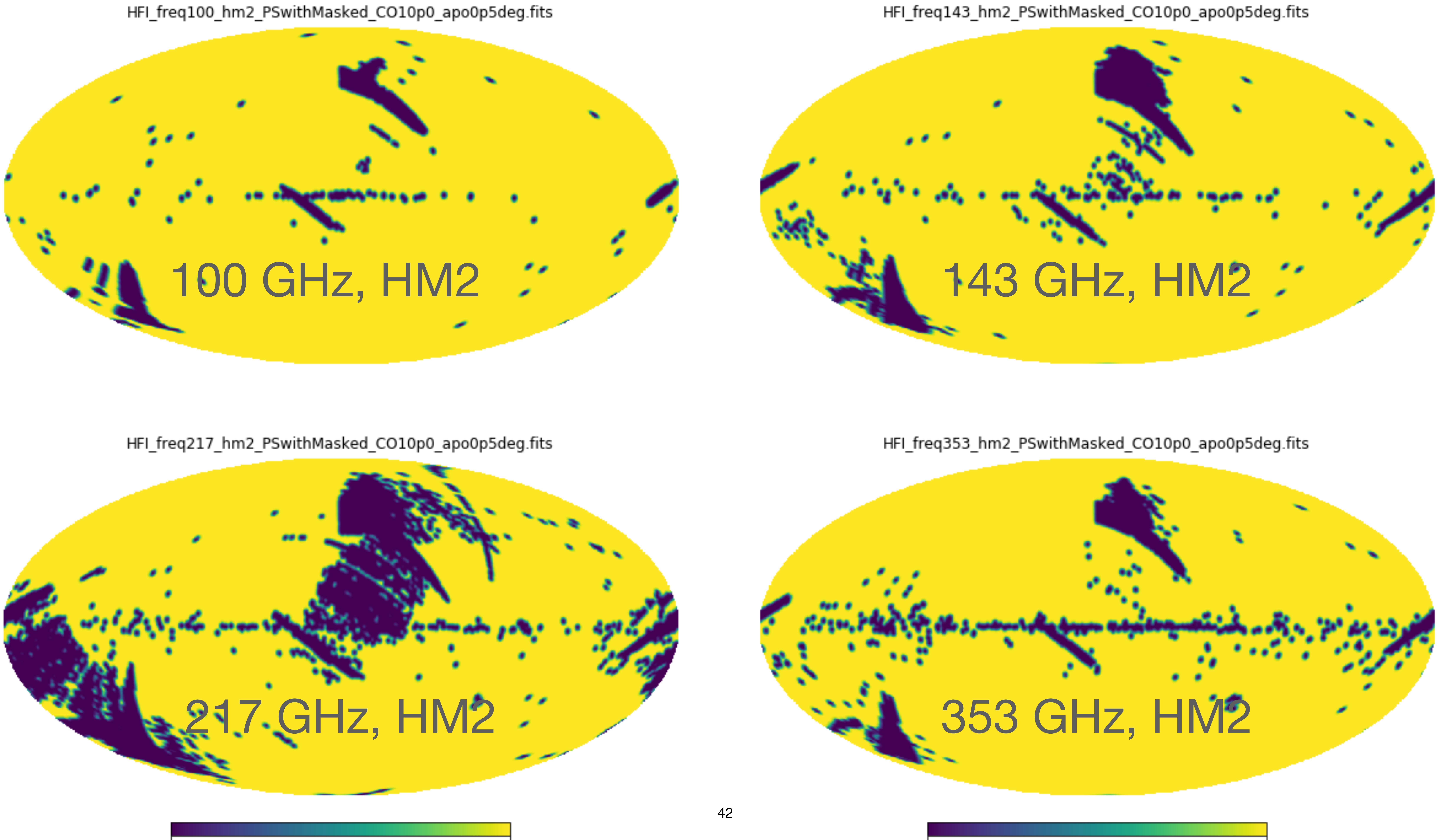
lmin = 51, lmax = 1490 (same as those used by the Planck team)

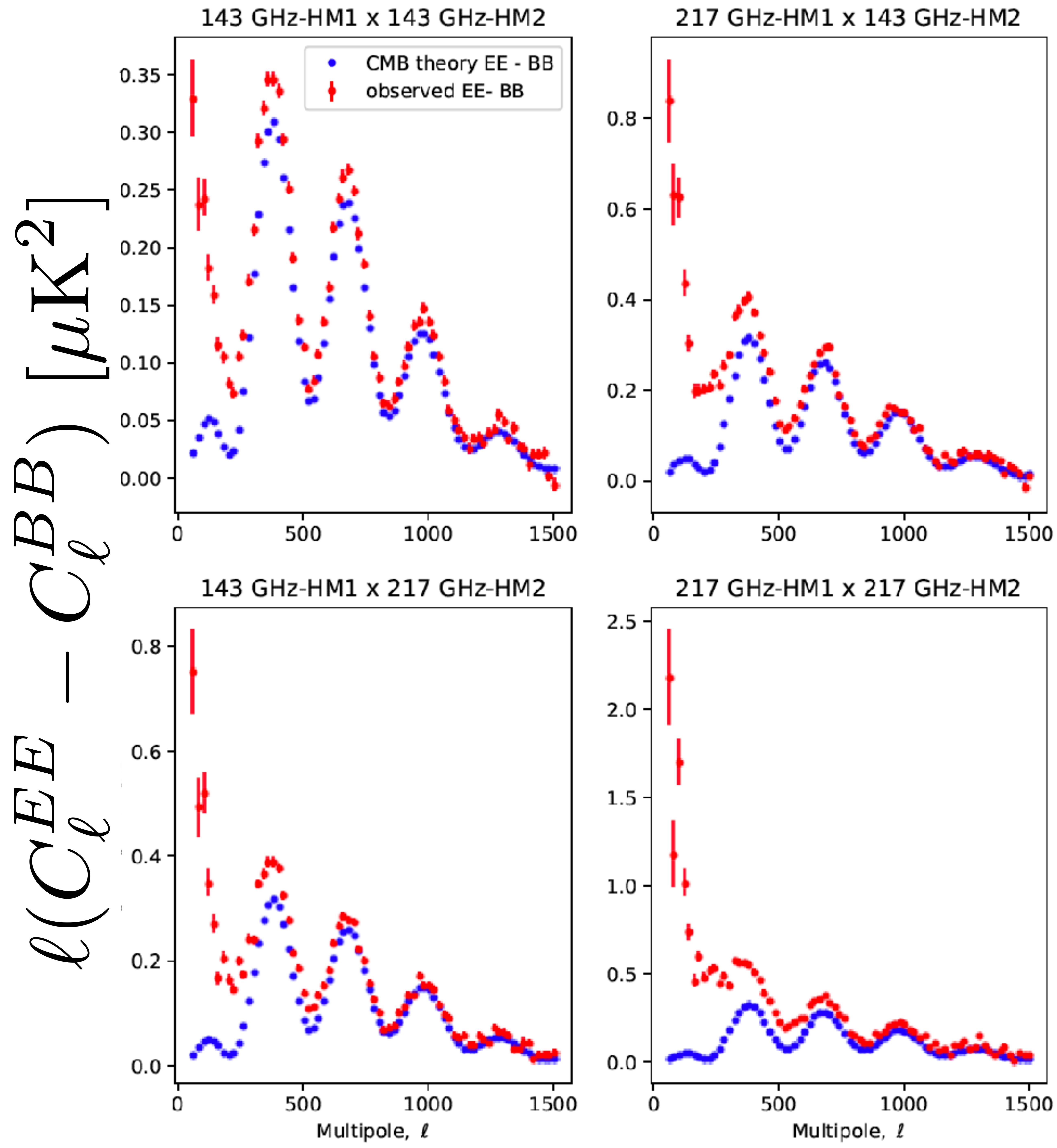
- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz)

Main Result: β > 0 at 2.4σ for nearly full-sky data

TABLE I. Cosmic birefringence and miscalibration angles from the Planck 2018 polarization data with 1σ (68%) uncertainties

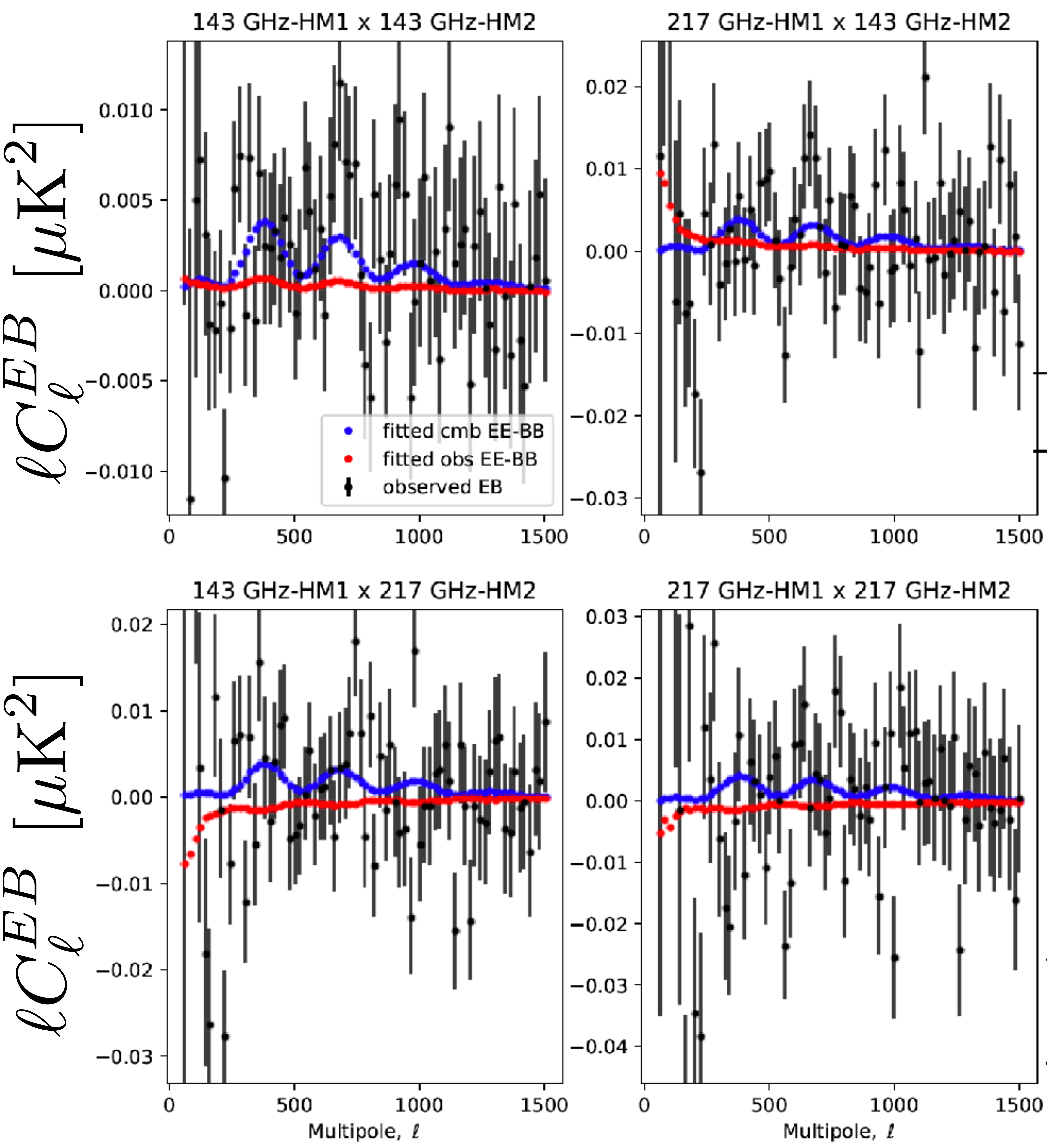
Angles	$\alpha_\nu=0$	Results (deg)
β	0.289 ± 0.048 (This agrees with the result of the Planck team)	0.35 ± 0.14
α_{100}		-0.28 ± 0.13
α_{143}		0.07 ± 0.12
α_{217}		-0.07 ± 0.11
α_{353}		-0.09 ± 0.11


HFI_freq100_hm2_PSwithMasked_CO10p0_apo0p5deg.fits
100 GHz, HM2
HFI_freq143_hm2_PSwithMasked_CO10p0_apo0p5deg.fits
143 GHz, HM2
HFI_freq217_hm2_PSwithMasked_CO10p0_apo0p5deg.fits
217 GHz, HM2
HFI_freq353_hm2_PSwithMasked_CO10p0_apo0p5deg.fits
353 GHz, HM2



$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\boxed{\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right)} + \frac{\sin(4\beta)}{2\cos(4\alpha)}\boxed{\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)}$$

- Can we see β = 0.35 ± 0.14 deg by eyes?
- First, take a look at the observed EE–BB spectra.
  - Red: Total
  - Blue: The best-fitting CMB model
- *The difference is due to the FG (and maybe unknown systematics)*



Minami & Komatsu (2020b)

$$\langle C_\ell^{EB,o}\rangle = \boxed{\frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,o}\rangle - \langle C_\ell^{BB,o}\rangle\right)} + \boxed{\frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)}$$

- Can we see β = 0.35 ± 0.14 deg by eyes?
  - Red: The signal attributed to the miscalibration angle, α_ν
  - Blue: The signal attributed to the cosmic birefringence, β
- Red + Blue is the best-fitting model for explaining the data points

How about the foreground EB?

- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle α.
- Thus, α -> $\alpha+\gamma$, where γ is the contribution from the intrinsic EB.
  - The sign of γ is the same as the sign of the foreground EB.
- From FG: $\alpha+\gamma$. From CMB: $\alpha+\beta$.
  - Thus, our method yields **$\beta-\gamma = 0.35 \pm 0.14$ deg.**
- There is evidence for the dust-induced $TE_{dust} > 0$ and $TB_{dust} > 0$. Then, we'd expect $EB_{dust} > 0$ (Huffenberger et al. 2020), i.e., $\gamma>0$. If so, β increases further…

Diego-Palazuelos, Eskilt, et al., arXiv:2201.07682, to appear in PRL

More data and more analysis innovation were needed. Now we have them!

Cosmic birefringence from *Planck* data release 4

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Double corresponding authors.
PhD students. Young power!

Johannes Røsok Eskilt
(Univ. Oslo)

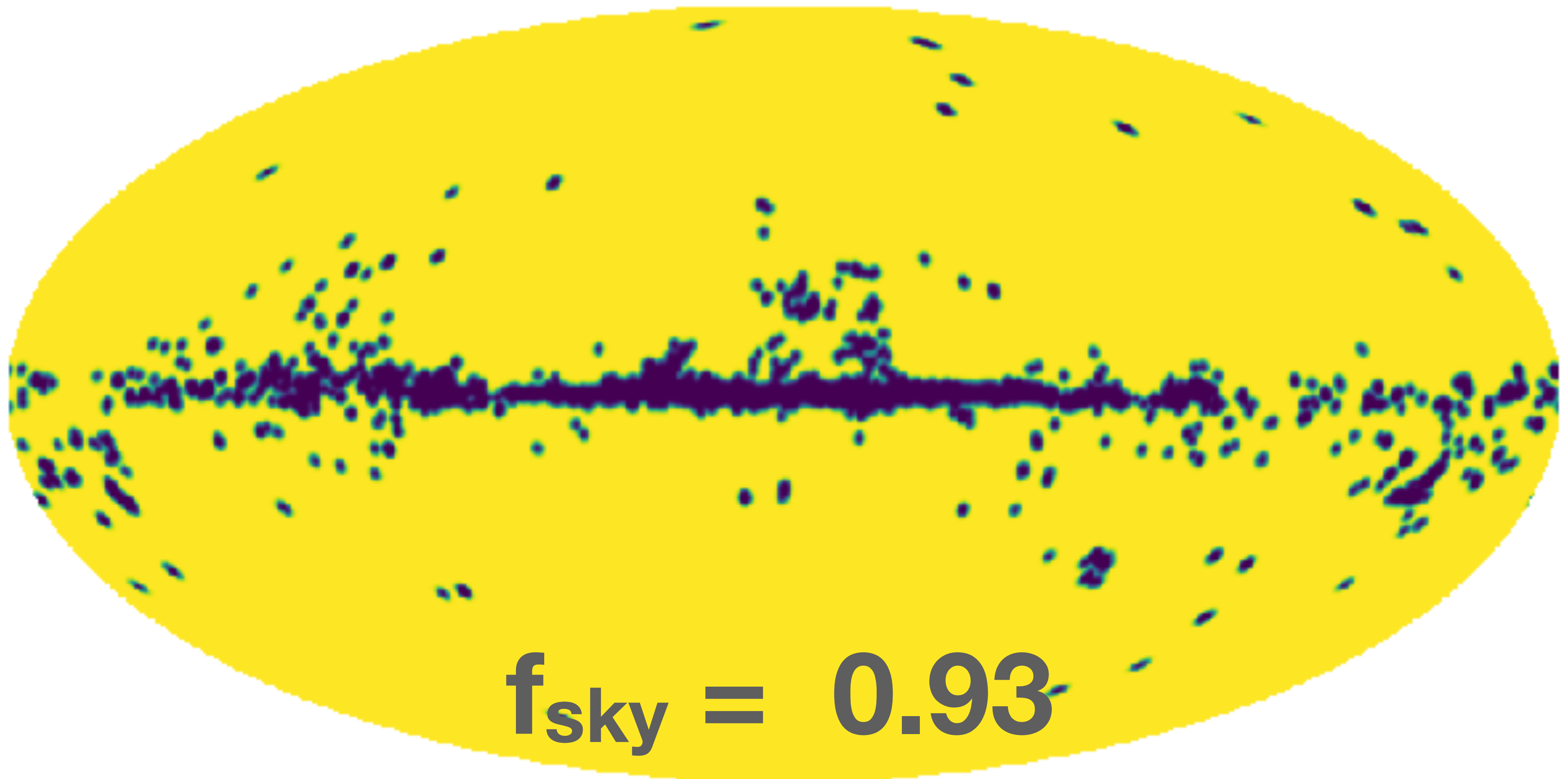
Diego-Palazuelos, Eskilt, et al. (2022)

Application to the Public Data Release 4 (PR4)

PR4 = "NPIPE" reprocessing of all the Planck data (Planck Collaboration 2020)

- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz).
  - **These maps have <u>lower noise</u>** and better-characterised systematics than PR3.
  - We measure power spectra from A/B splits (each frequency band has 2 sets of detectors), to avoid possible correlated noise.
- Masks
  - Unlike for the PR3 analysis, we use the common mask for all frequencies.
  - Bright CO regions, Bright point sources, and four Galactic masks.
  - Fraction of sky used = 0.93, 0.90, 0.85, 0.75 and 0.63.

CO+PS (1deg apodization)



f_{sky} = 0.93

= nearly full sky

f_{sky} = 0.90

CO+PS+5% (1deg apodization)

CO+PS+10% (1deg apodization)

f_{sky} = 0.85

CO+PS+20% (1deg apodization)

f_{sky} = 0.75

CO+PS+30% (1deg apodization)

f_{sky} = 0.63

Full-sky result, without accounting for foreground EB

The PR3 result confirmed, with smaller statistical uncertainty

- We find **β = 0.30 ± 0.11 deg** (68% CL) for nearly full sky -> a 2.7σ result
    - Four independent pipelines were compared and the results agreed.

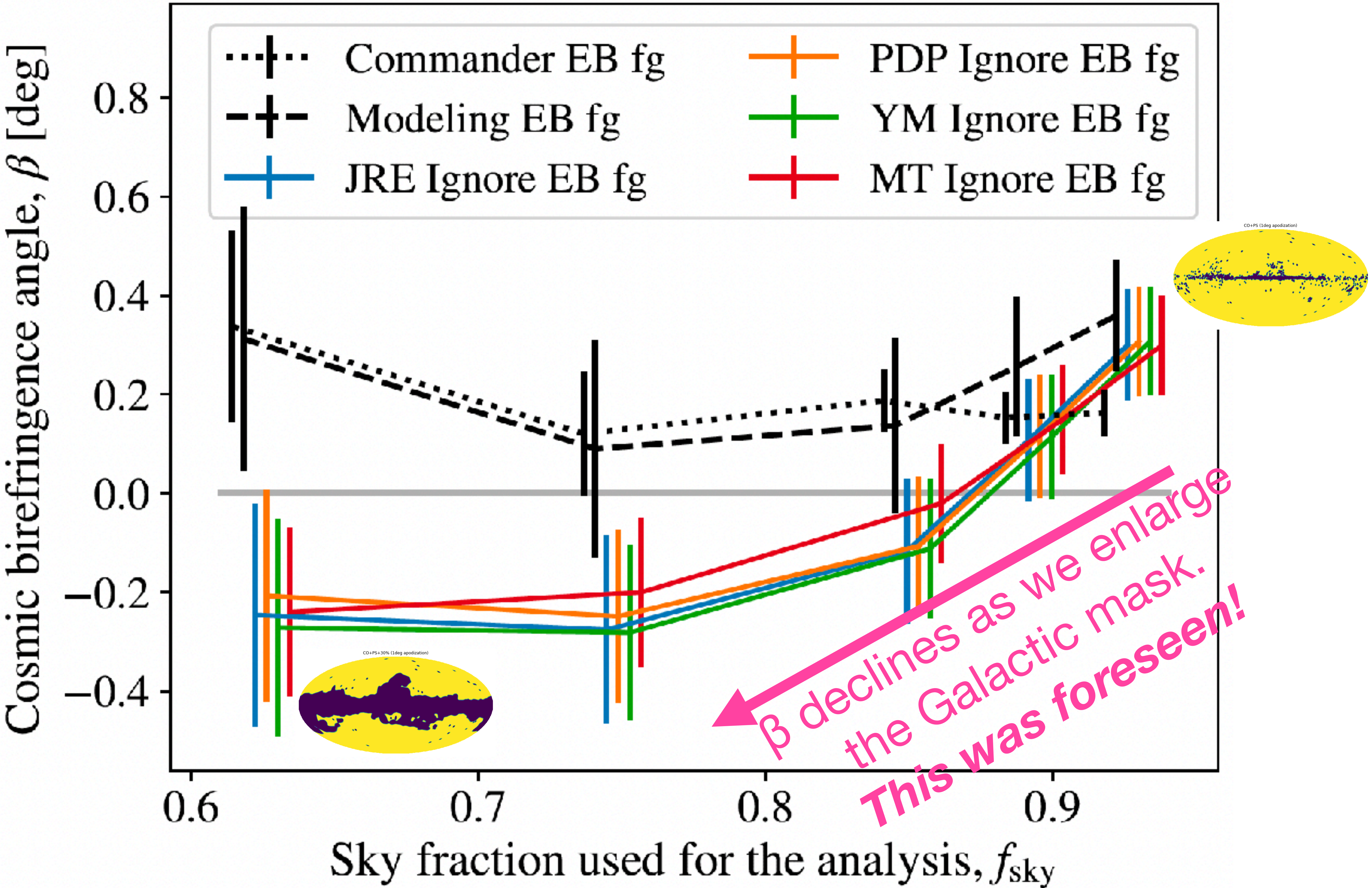
PDP JRE YM MT



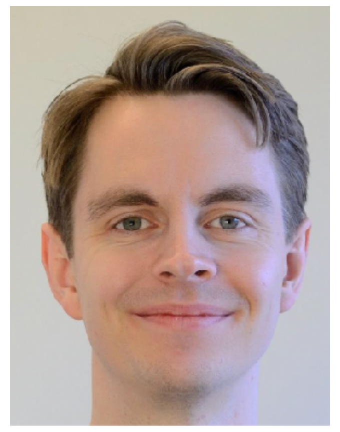

- More statistical significance than the 2.4σ result of the PR3, 0.35 ± 0.14 deg.

How do the results change with f_{sky}?

Hint for the foreground EB for smaller f_{sky}



PDP

JRE

YM

MT


Including the foreground EB

Introducing a new angle, "γ"

- When we do not ignore the intrinsic foreground EB, the *observed* foreground EB (including the miscalibration angle contribution, α) is given by

$$C_\ell^{EB,\mathrm{FG,o}} = \frac{1}{2}\sin(\boxed{4\alpha})\left(C_\ell^{EE,\mathrm{FG}} - C_\ell^{BB,\mathrm{FG}}\right) + \underbrace{C_\ell^{EB,\mathrm{FG}}\cos(4\alpha)}_{\text{new term}}$$

- Using a formula for trigonometric functions,

$$A\sin\varphi + B\cos\varphi = \sqrt{A^2+B^2}\sin(\varphi+\theta), \quad \tan\theta = B/A$$

- We obtain

α -> α+γ

$$C_\ell^{EB,\mathrm{FG,o}} = \sqrt{J_\ell^2 + (C_\ell^{EB,\mathrm{FG}})^2}\sin(\boxed{4\alpha + 4\gamma_\ell}) \quad \begin{cases} J_\ell \equiv \frac{1}{2}\left(C_\ell^{EE,\mathrm{FG}} - C_\ell^{BB,\mathrm{FG}}\right) \\ \tan(4\gamma_\ell) \equiv C_\ell^{EB,\mathrm{FG}}/J_\ell \end{cases}$$

Minami et al. (2019); Minami & Komatsu (2020b)

Remember this slide?

How about the foreground EB?

- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle α.
- Thus, α -> α+γ, where γ is the contribution from the intrinsic EB.
  - The sign of γ is the same as the sign of the foreground EB.
- From FG: α+γ. From CMB: α+β.
  - Thus, our method yields **β–γ = 0.35 ± 0.14 deg.**
- There is evidence for the dust-induced $TE_{dust} > 0$ and $TB_{dust} > 0$. Then, we'd expect $EB_{dust} > 0$ (Huffenberger et al. 2020), i.e., **γ>0. If so, β increases further…**

We expected β to decrease towards smaller f_{sky} due to the foreground EB.

Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- **How do we model the new angle γ?**
  - We don’t really know for sure yet. *This is a fascinating opportunity for Galactic science!*
- Nonetheless, there may be a clue from the dust TB correlation.
  - Discovery of a non-zero (positive) dust TB correlation by the Planck collaboration was a surprise.
  - We still do not know its origin (see Huffenberger et al. 2020 and Clark et al. 2021 for the first attempts to explain it).
  - However, it seems reasonable to relate the possible dust EB correlation to the dust TB correlation.
- Long story short…

Relating EB to TB

Here comes fascinating (unknown) physics of dust polarisation

- **How do we model the new angle γ?**
  - Our *ansatz*, motivated by a physical consideration of Clark et al. (2021):

$$\begin{cases} C_\ell^{EB,\mathrm{dust}} = A_\ell C_\ell^{EE,\mathrm{dust}} \sin(4\psi_\ell^{\mathrm{dust}}) \\ \psi_\ell^{\mathrm{dust}} = \frac{1}{2}\arctan(C_\ell^{TB,\mathrm{dust}}/C_\ell^{TE,\mathrm{dust}}) \end{cases}$$

  - Then

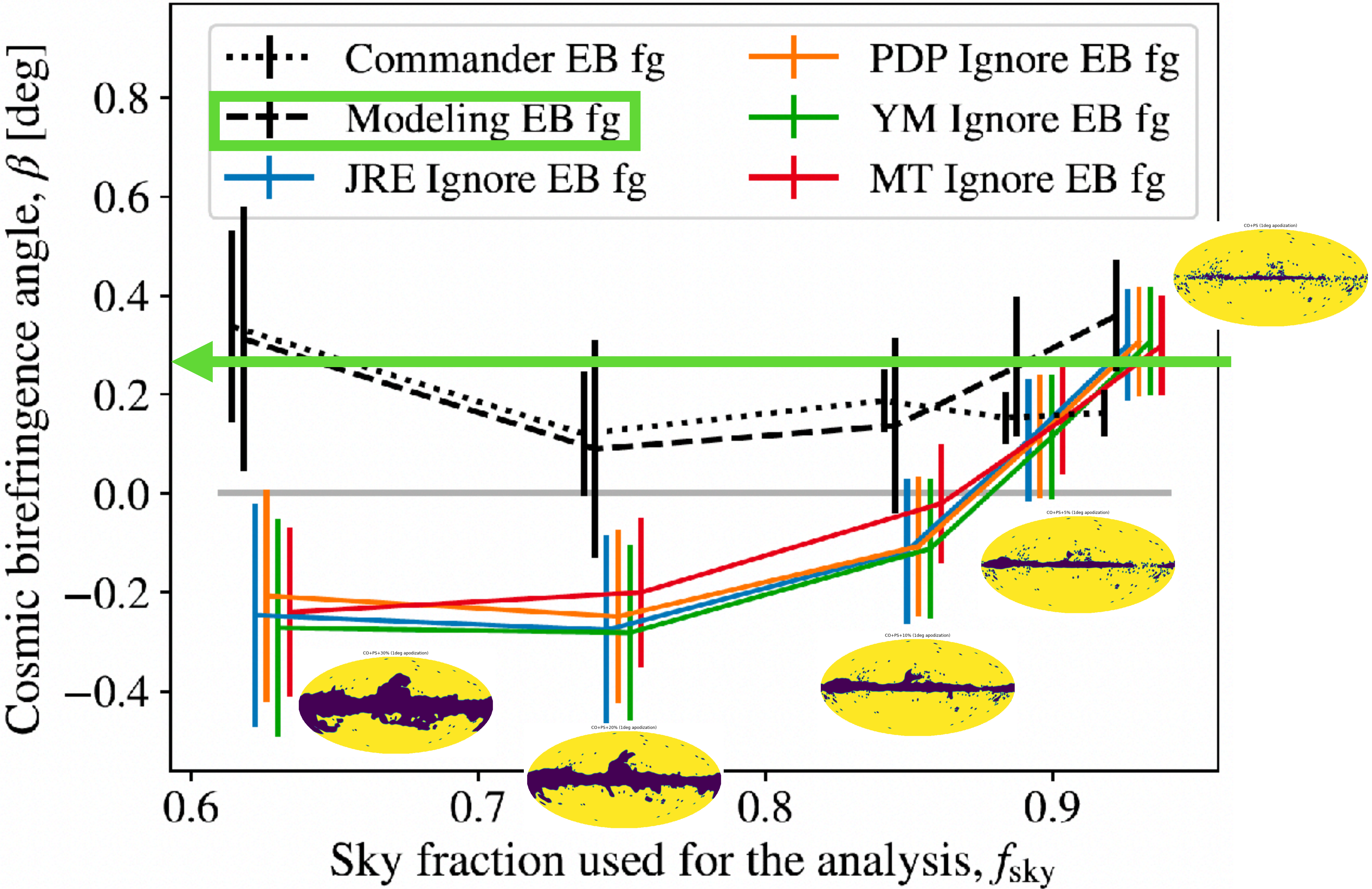
$$\boxed{\gamma_\ell \simeq \frac{A_\ell C_\ell^{EE,\mathrm{dust}}}{C_\ell^{EE,\mathrm{dust}} - C_\ell^{BB,\mathrm{dust}}} \frac{C_\ell^{TB,\mathrm{dust}}}{C_\ell^{TE,\mathrm{dust}}}}$$

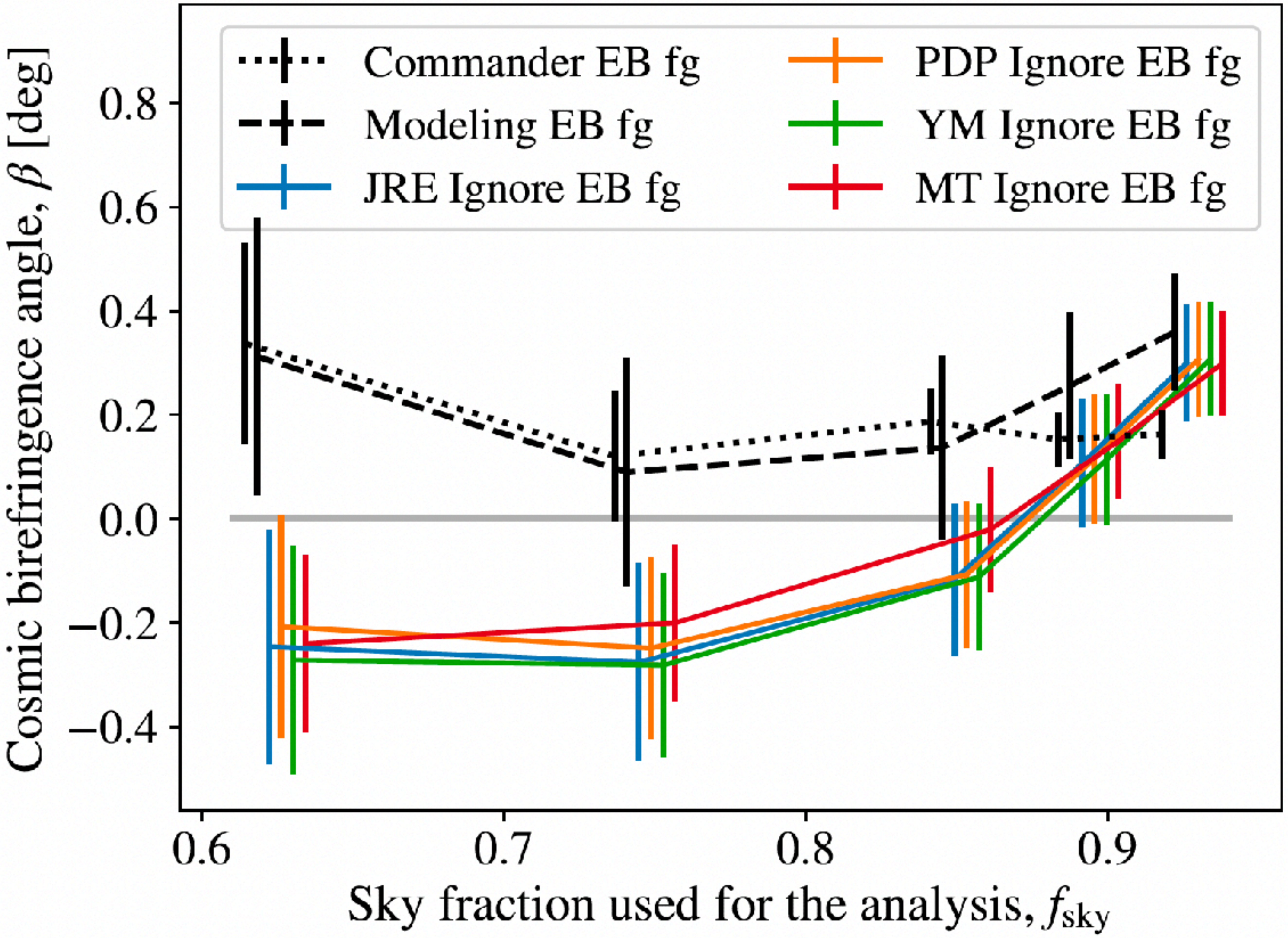
for small angles.

Diego-Palazuelos, Eskilt, et al. (2022)

Dashed line: Modeling the foreground EB

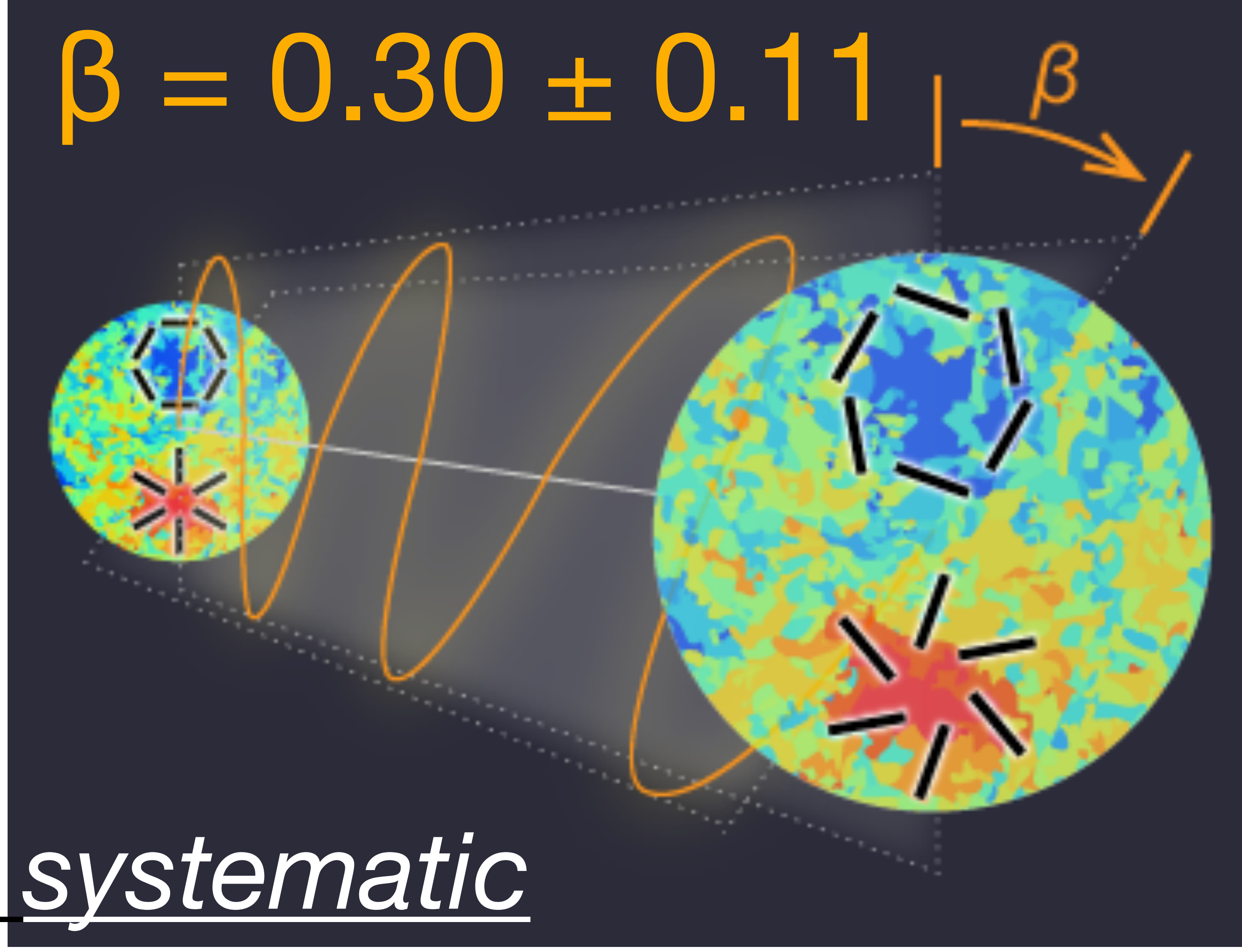
Trend for declining β is largely gone. But which f_{sky} we should choose?





$f_{\rm sky}$	0.93
β	$\boxed{0.36 \pm 0.11}$
α_{100A}	-0.32 ± 0.13
α_{100B}	-0.43 ± 0.13
α_{143A}	0.03 ± 0.11
α_{143B}	0.15 ± 0.11
α_{217A}	-0.06 ± 0.11
α_{217B}	-0.07 ± 0.11
α_{353A}	-0.19 ± 0.10
α_{353B}	-0.23 ± 0.11
$10^2 A_{51-130}$	$2.5^{+1.6}_{-1.4}$
$10^2 A_{131-210}$	$0.8^{+1.2}_{-0.6}$
$10^2 A_{211-510}$	$1.5^{+2.4}_{-1.1}$
$10^2 A_{511-1490}$	$6.2^{+5.7}_{-4.1}$

- As foreseen, accounting for the foreground EB **increased** β from 0.30 to 0.36 for nearly full-sky data.
  - Which $f_{\rm sky}$ we should choose for the final result? **We do not know yet.** We need more investigation.
  - We need help from Galactic astrophysics! It is a fascinating subject.



Conclusion

β = 0.30 ± 0.11 (68%CL; nearly full sky)

- Modeling the foreground EB, we find β=0.36 ± 0.11 deg.
    - **"± 0.11" is the statistical-only uncertainty.** What is *the systematic uncertainty* due to the modelling of foreground EB? *This is the key question now!*
    - Good news: **The impact of the known instrumental systematics is negligible.** We found this using the NPIPE simulations of the PR4 data.
- If the measured β is confirmed as cosmological, it would have profound implications for the fundamental physics behind dark matter and energy.

Spoiler!

- *More results coming soon (J. R. Eskilt): Constraints on photon-energy dependence of β, using all of the Planck data including 30, 44 and 70 GHz.*