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

a.k.a. "Cosmic Birefringence"

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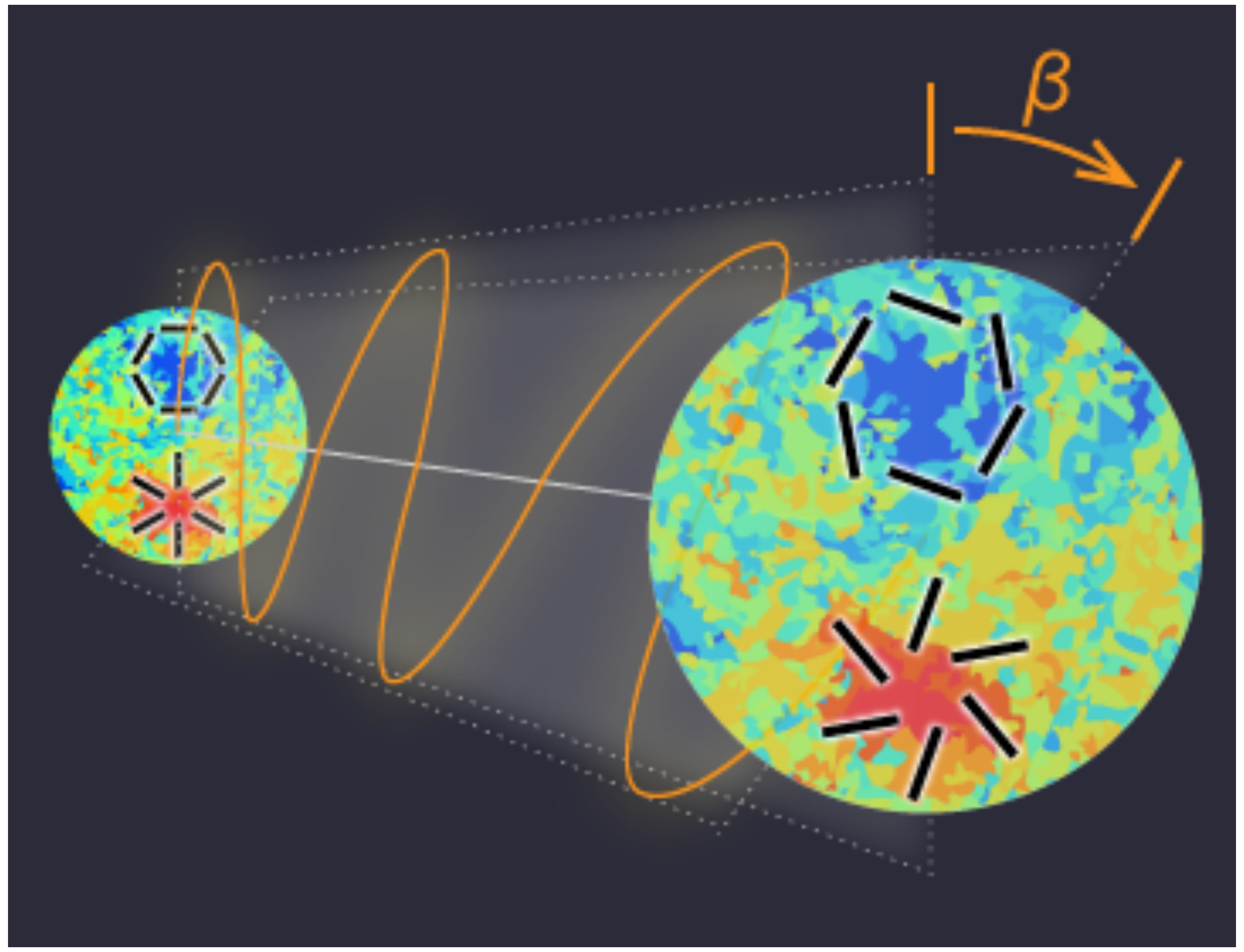
***CEICO Seminar*, November 26, 2020**



Credit: Y. Minami (KEK)

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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

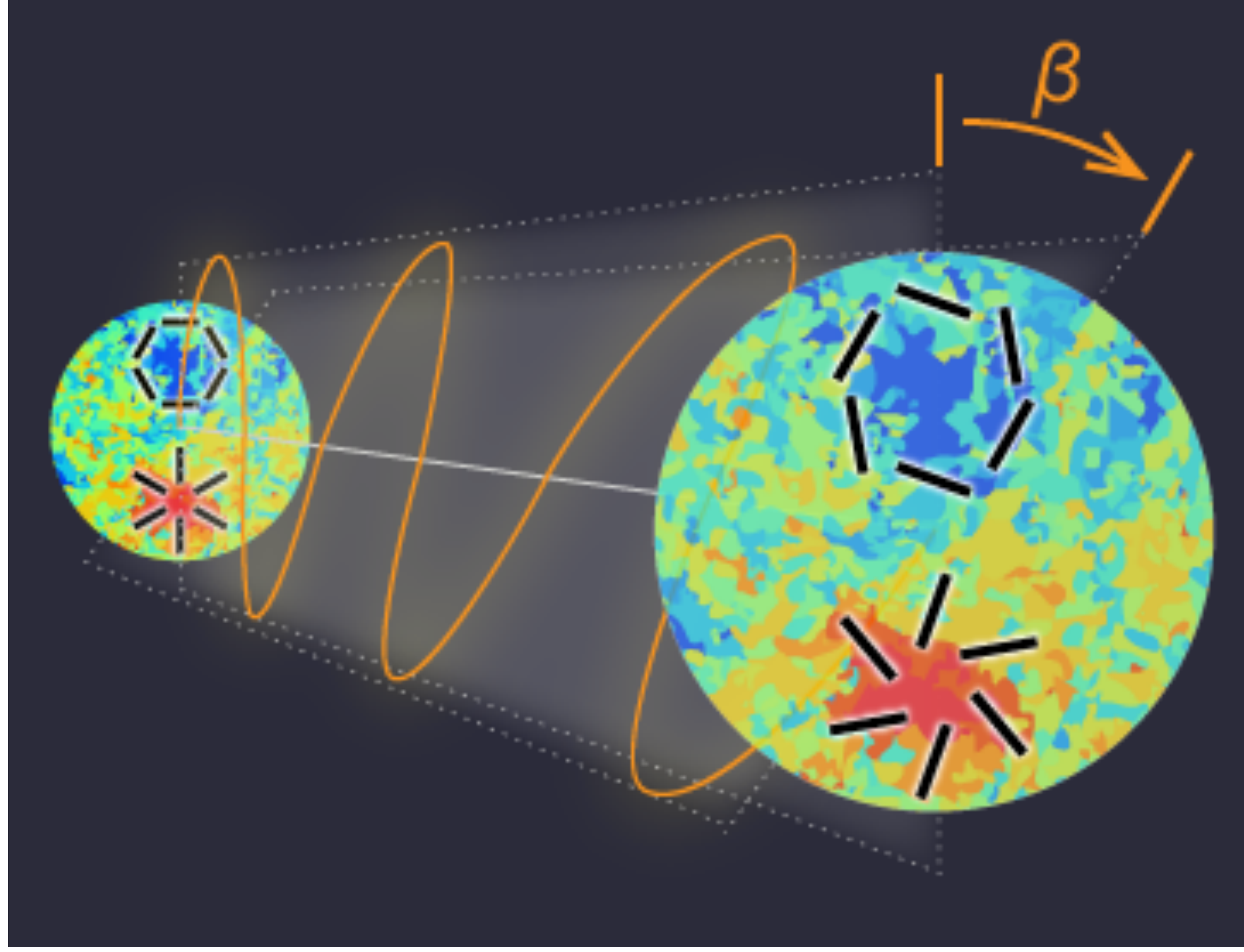
Physics See synopsis: Hints of Cosmic Birefringence?

Article | References | No Citing Articles | PDF | HTML | Export Citation

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.

Credit: Y. Minami (KEK)



Yuto Minami
(KEK -> Osaka U.)

The methodology papers that led to this measurement

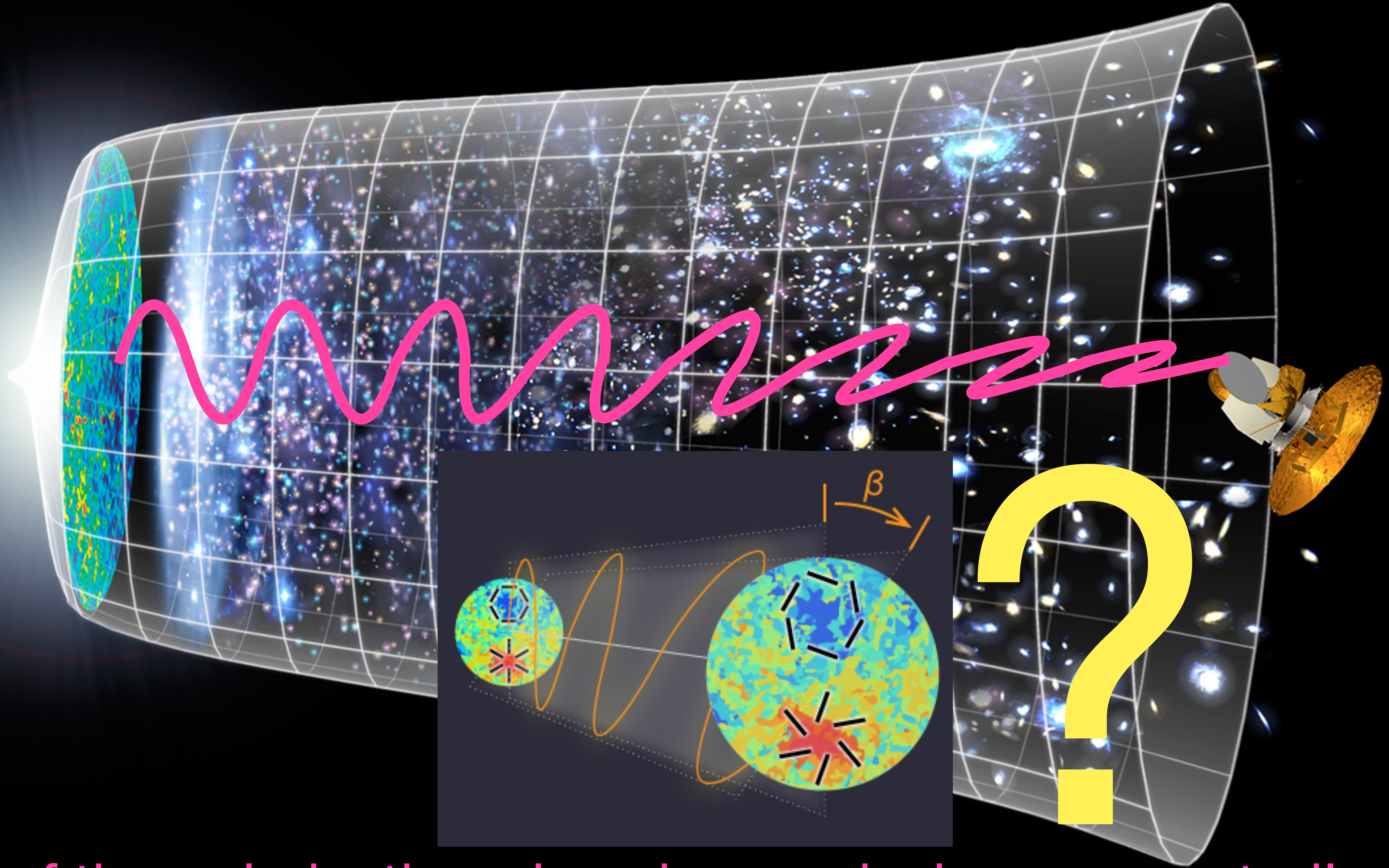
We have been working on this for ~2 years

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
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 PR3

How does the electromagnetic wave of the CMB reach us?

Now shown: The cosmological redshift due to the expansion of the Universe

How does the electromagnetic wave of the CMB reach us?



Note: rotation of the polarisation plane is massively exaggerated!

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998)

Cosmic Birefringence

The Universe filled with a "birefringent material"

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

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

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

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

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

$$\sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E})$$ **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 "pseudo scalar", which is parity odd; thus, the last term in Eq.3.7 is parity even as a whole.

Cosmic Birefringence

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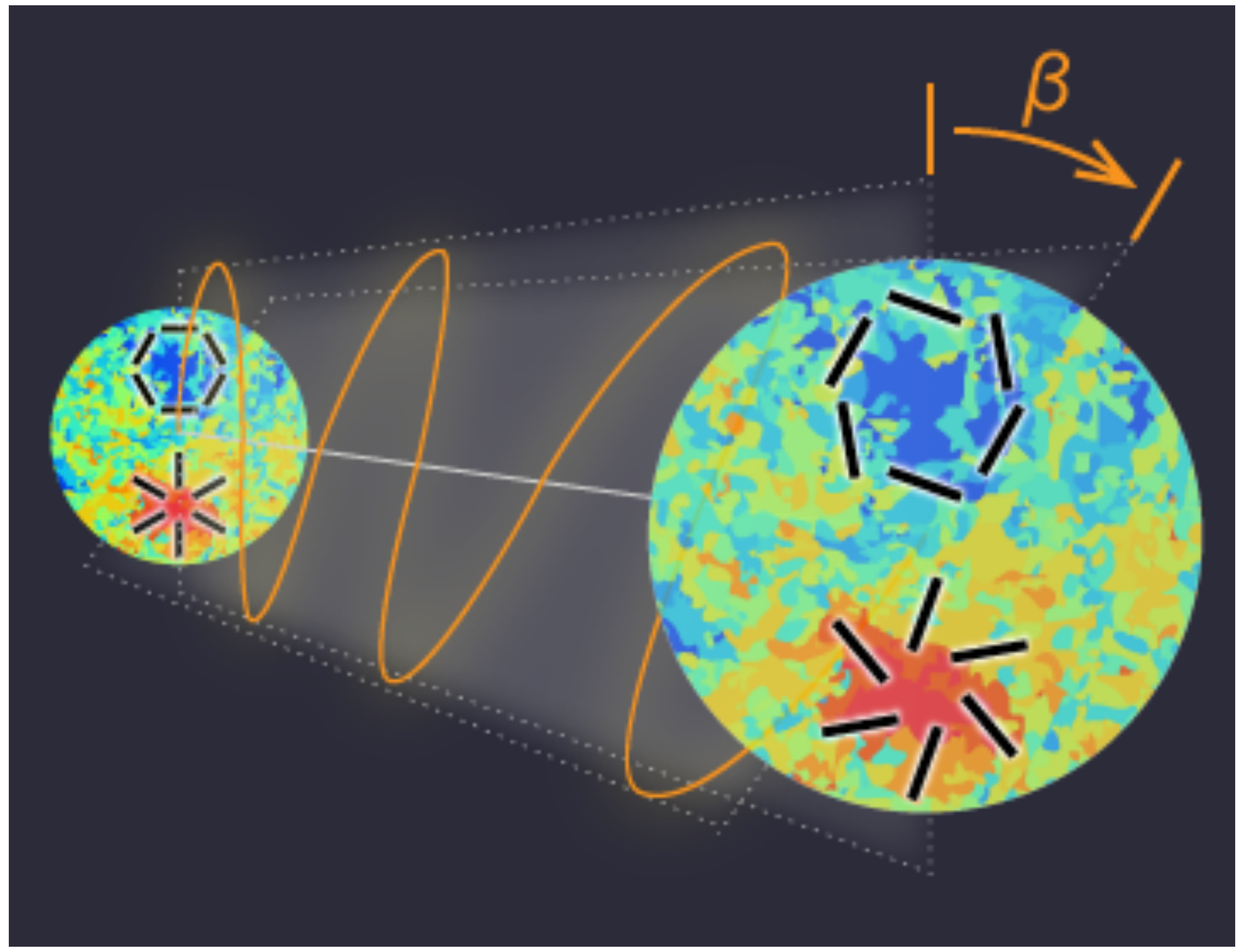

The "Cosmic Birefringence" (Carroll 1998)

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

Cosmic Birefringence

The effect accumulates over the distance

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

Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

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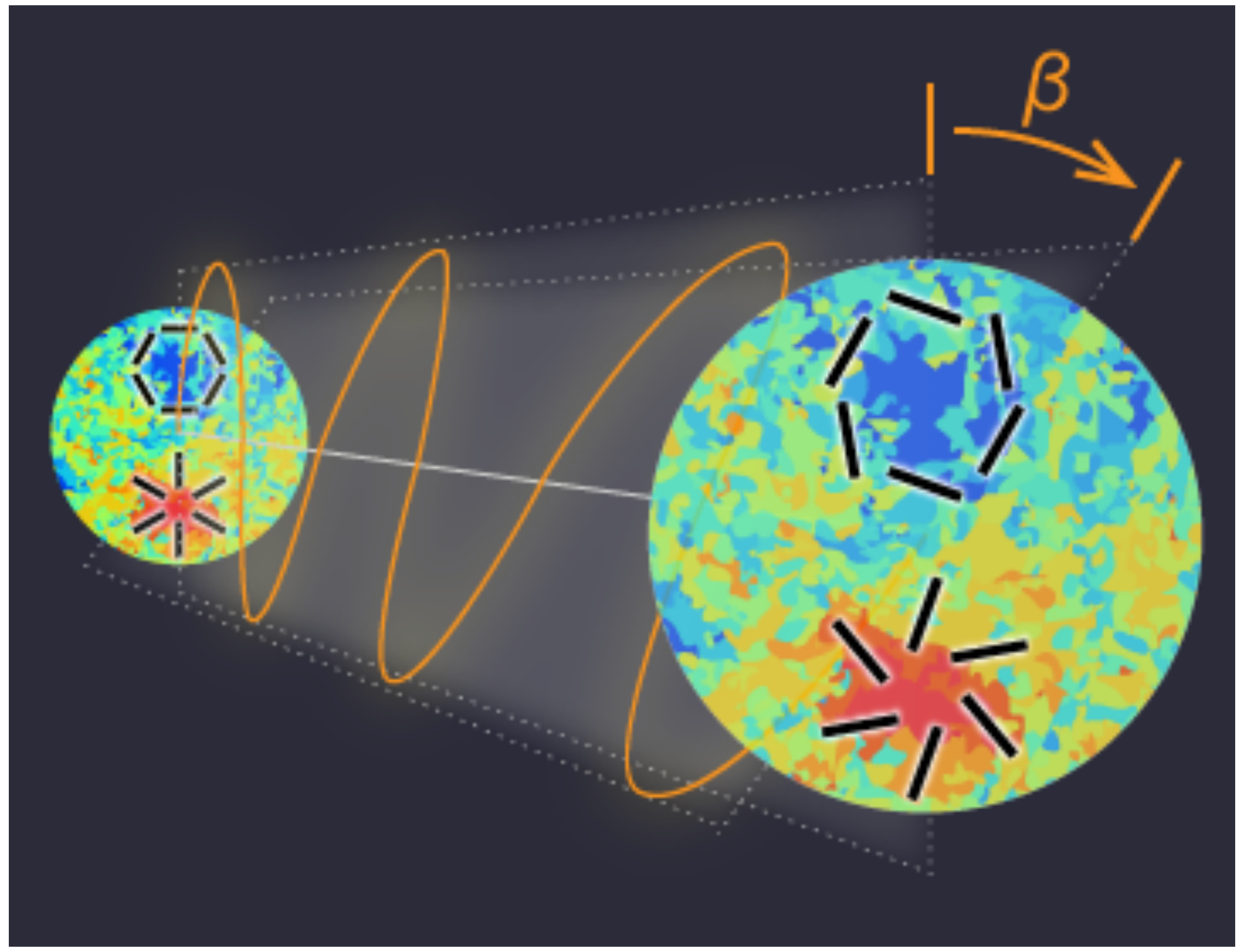


$$\beta = 2g_a \int_{t_{\mathrm{emission}}}^{t_{\mathrm{observed}}} dt \ \dot{\theta}$$

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

Motivation

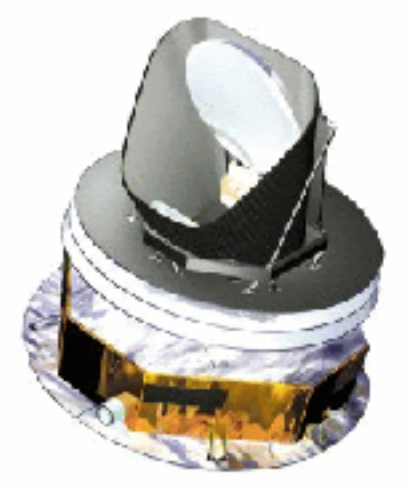
Why study the cosmic birefringence?

- 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!

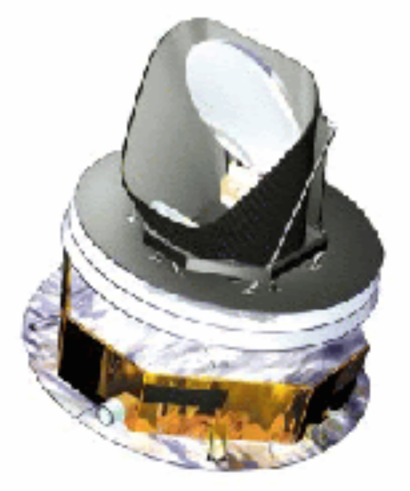


ESA's Planck

Credit: ESA

Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago



ESA's Planck

Credit: ESA

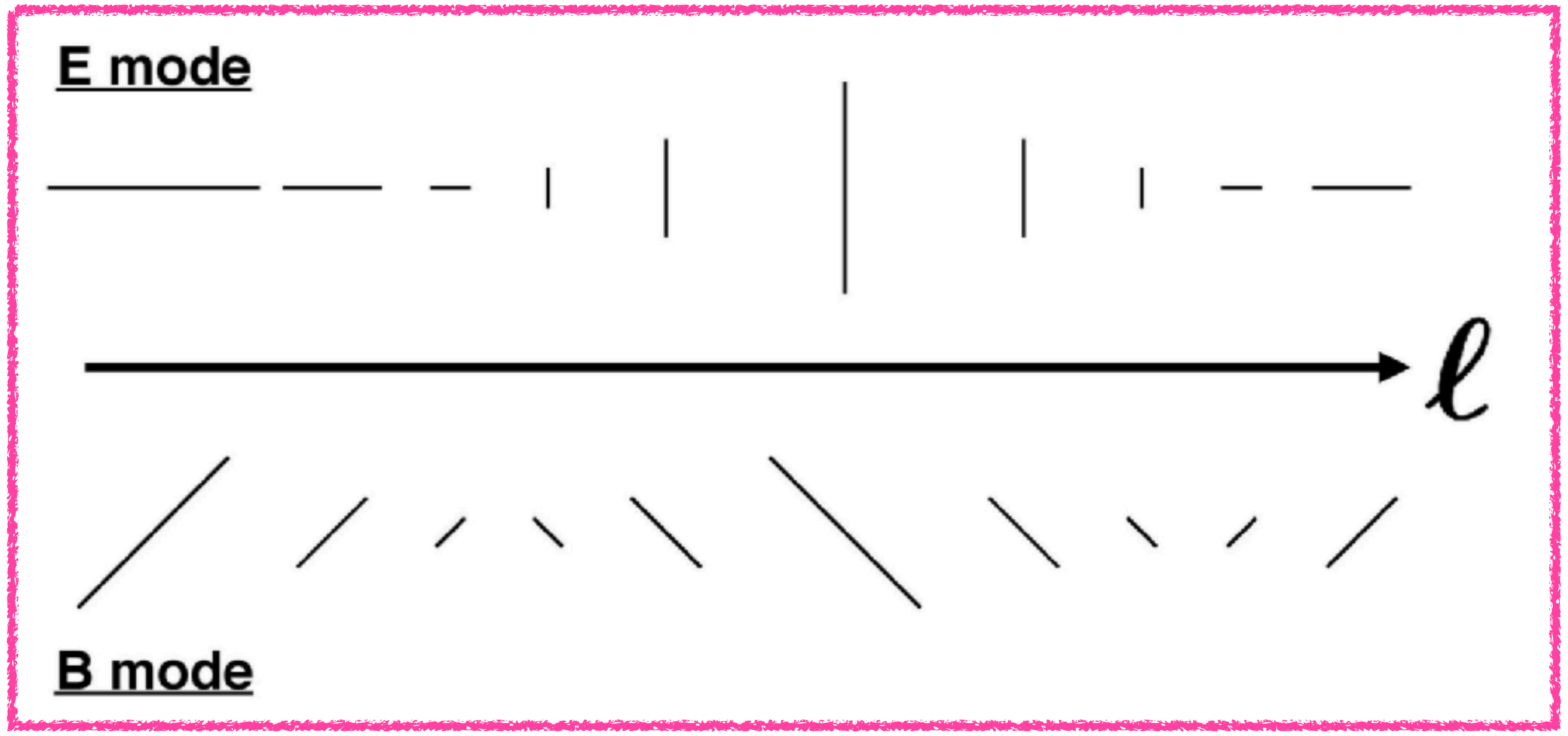
Foreground-cleaned Temperature (smoothed) + Polarisation

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



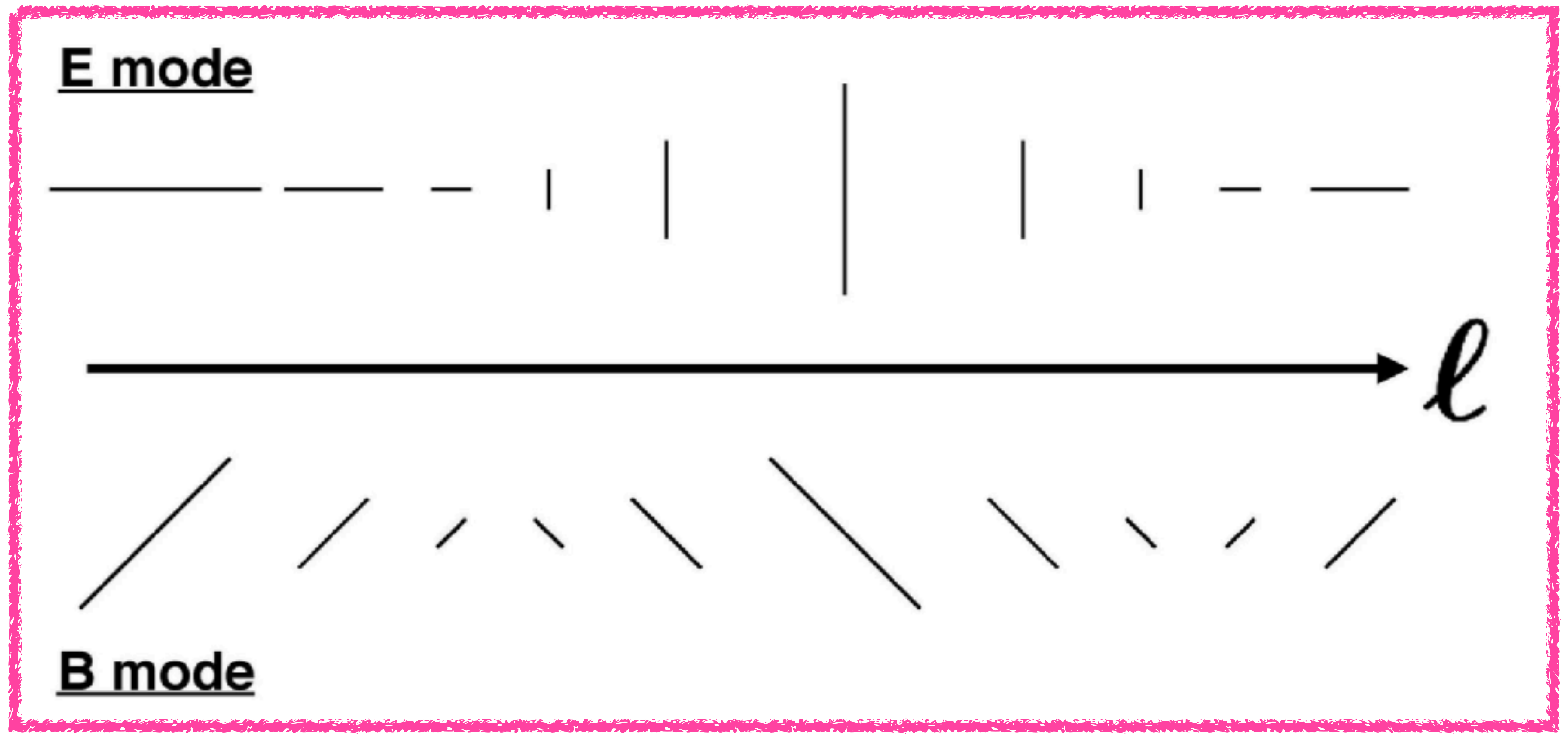
Direction of the Fourier wavenumber vector

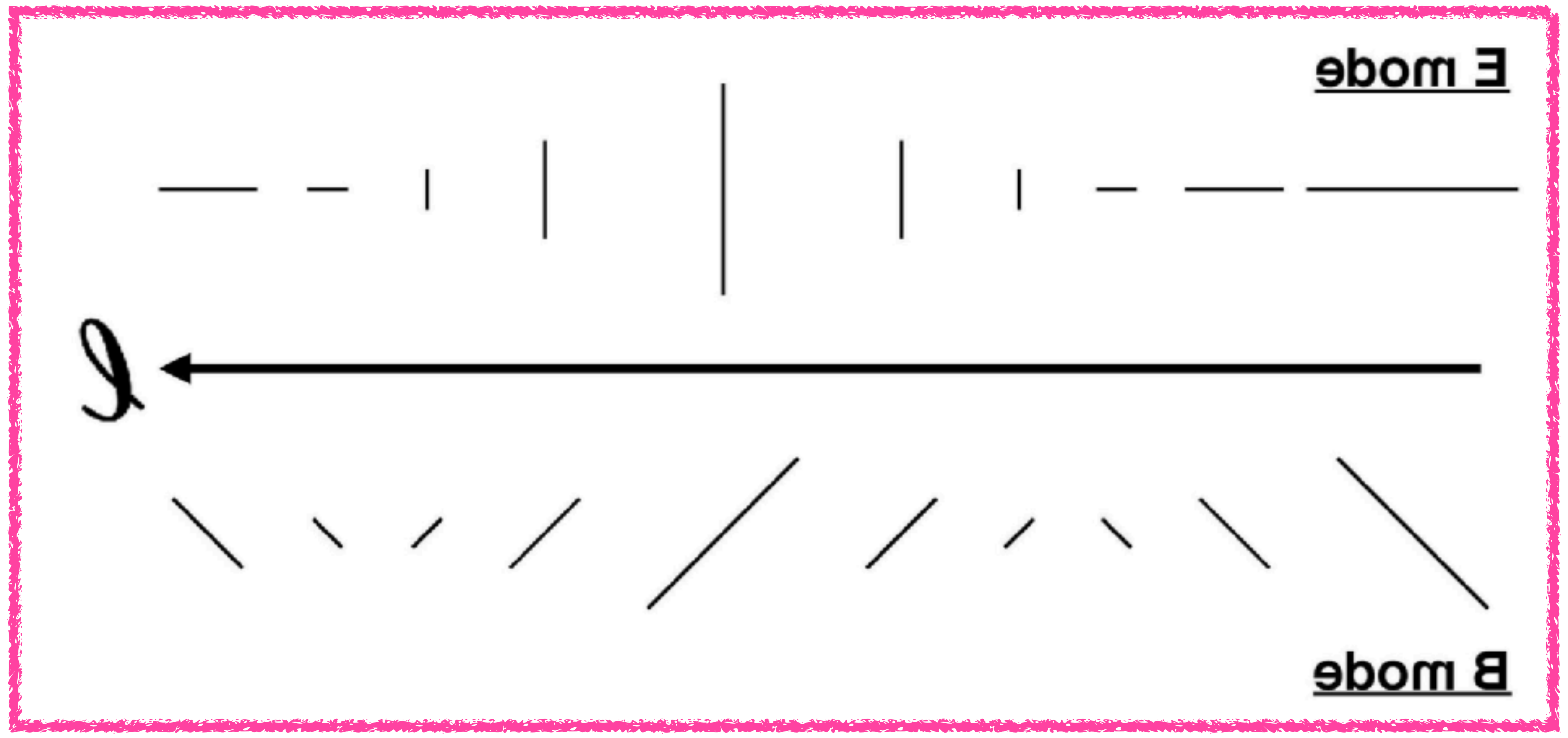
- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

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

Parity Flip

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





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

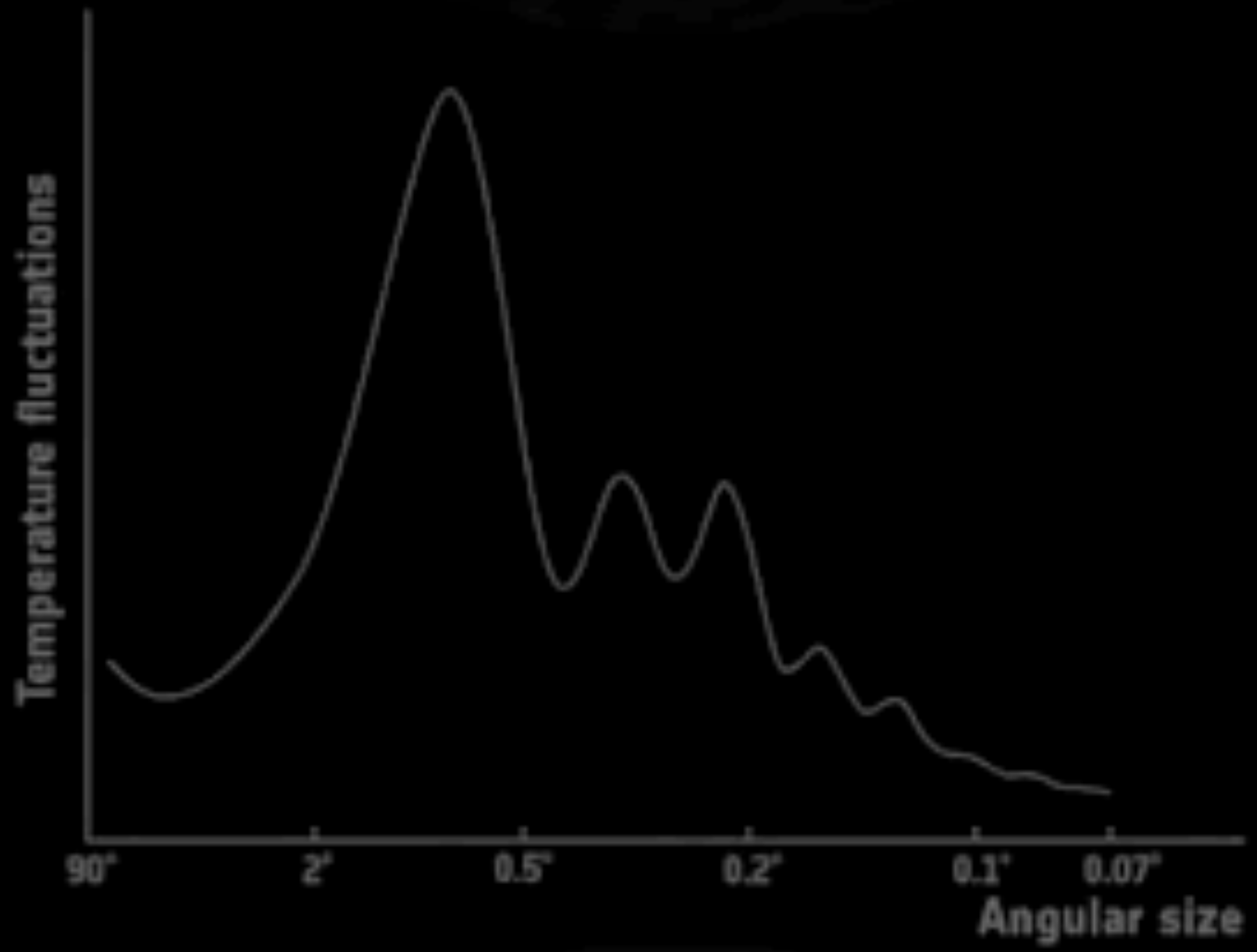
$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

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

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

- 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)**

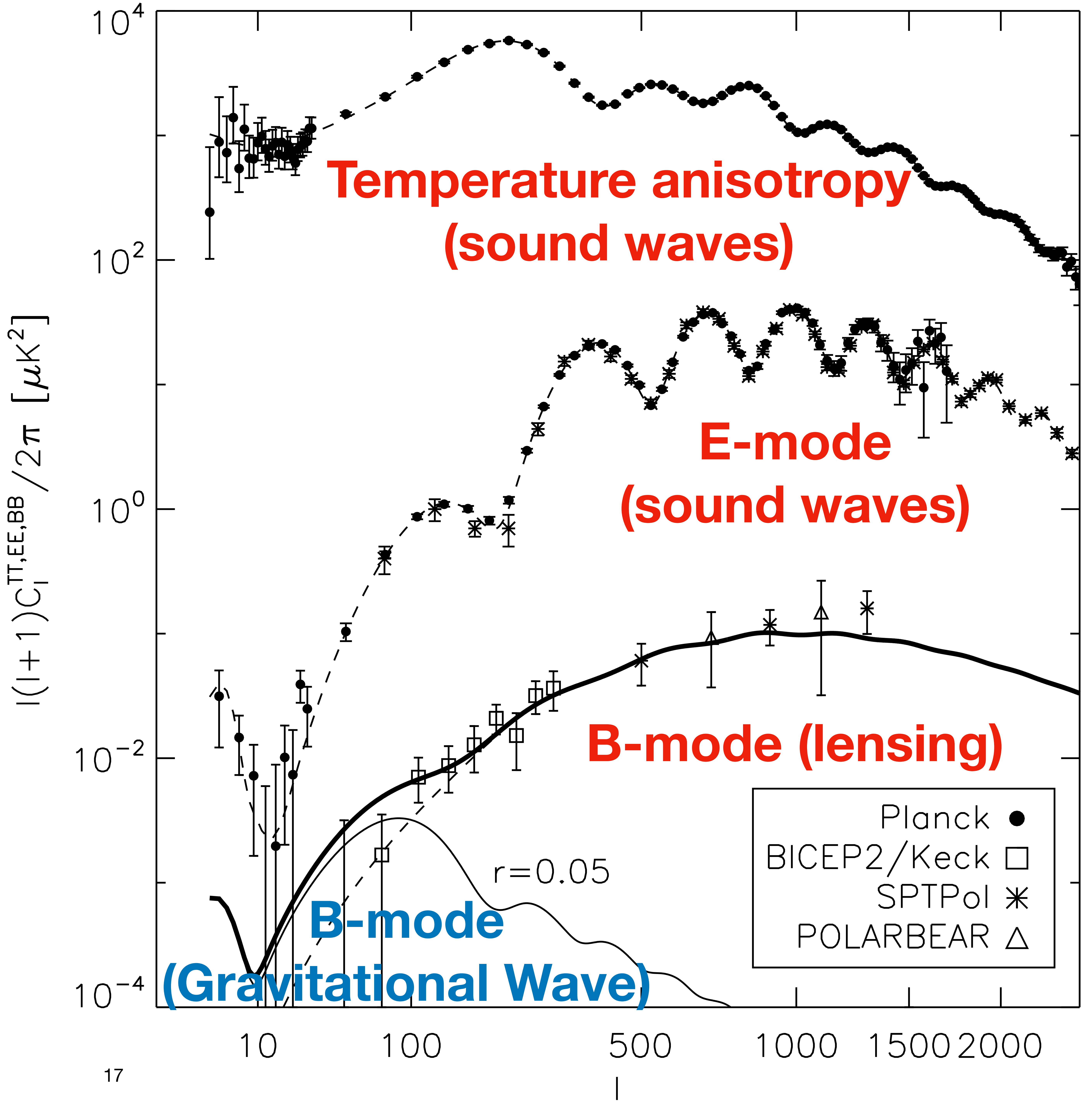
Power spectrum, explained



Power Spectra

A lot have been measured

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



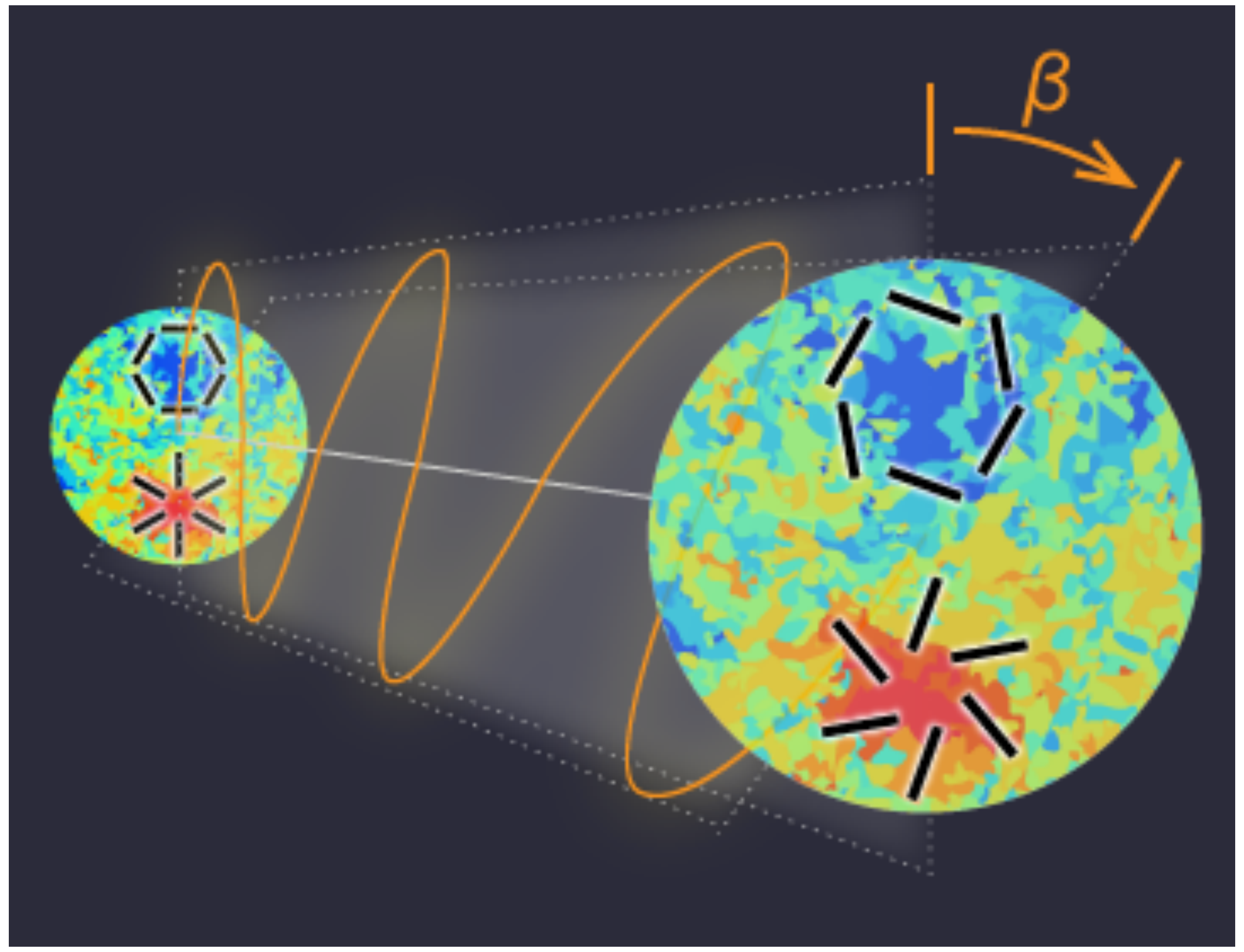
Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

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

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

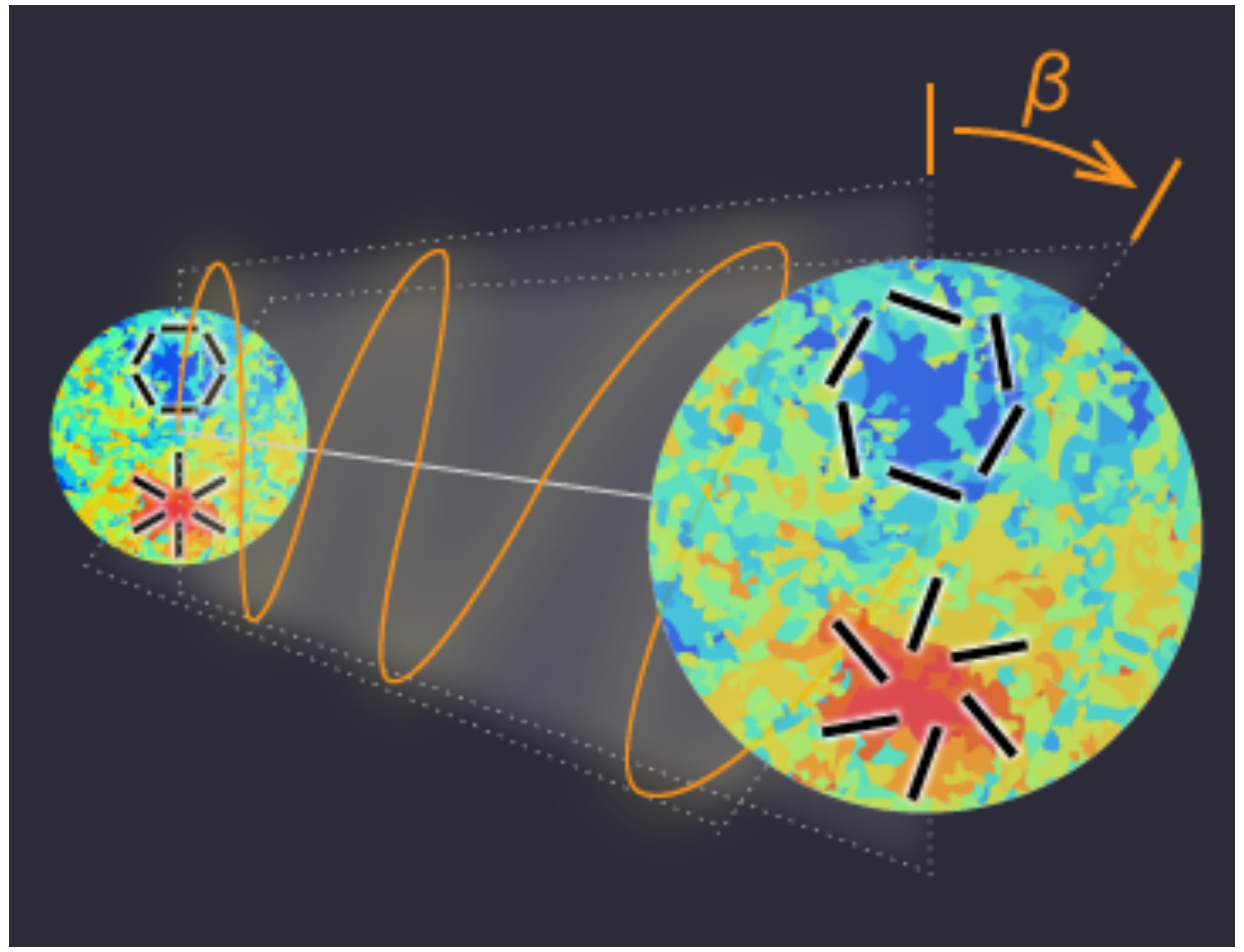


- **How do we infer β from the observational data?**

- 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,

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

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

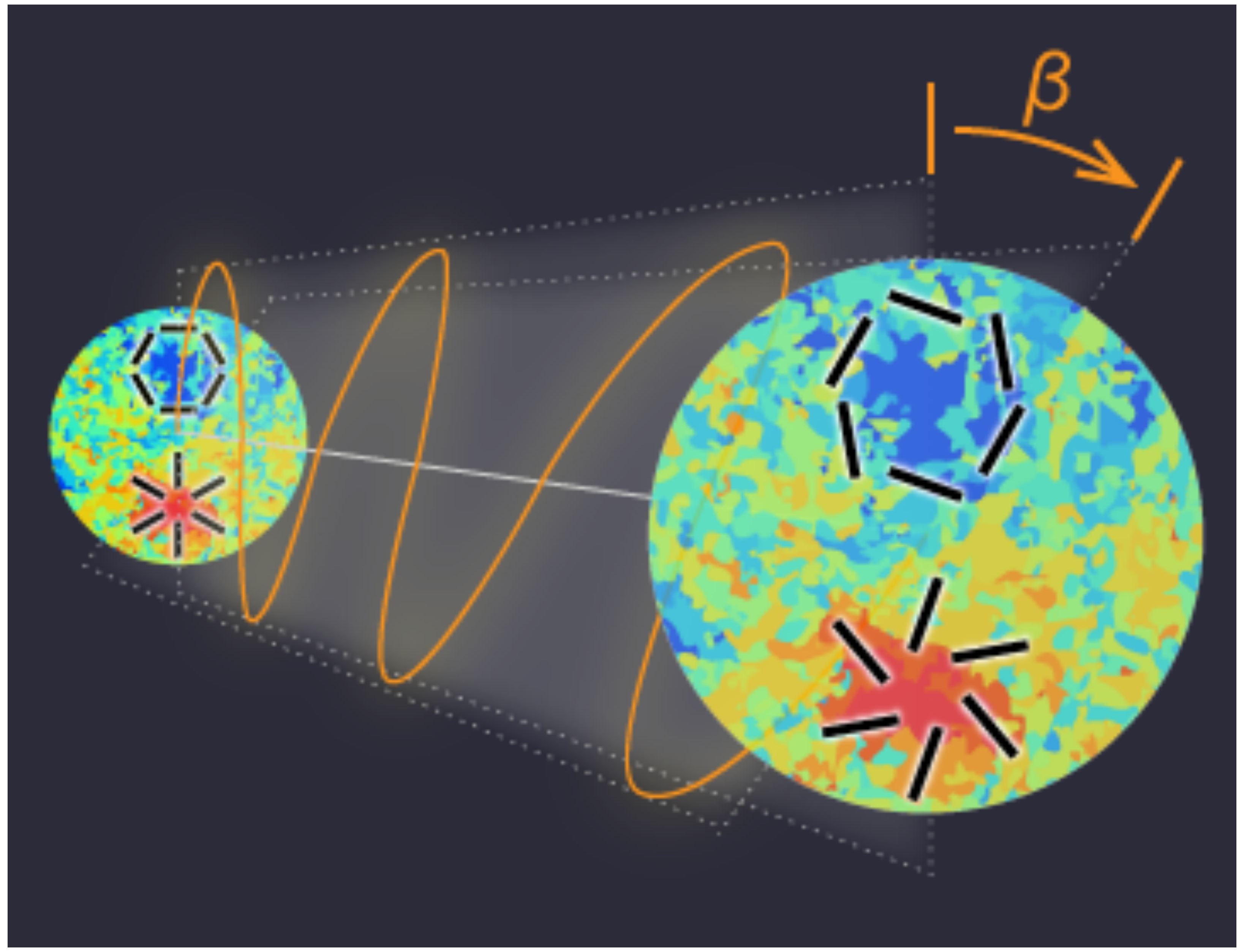
No need to assume a model

The Biggest Problem: Miscalibration of detectors

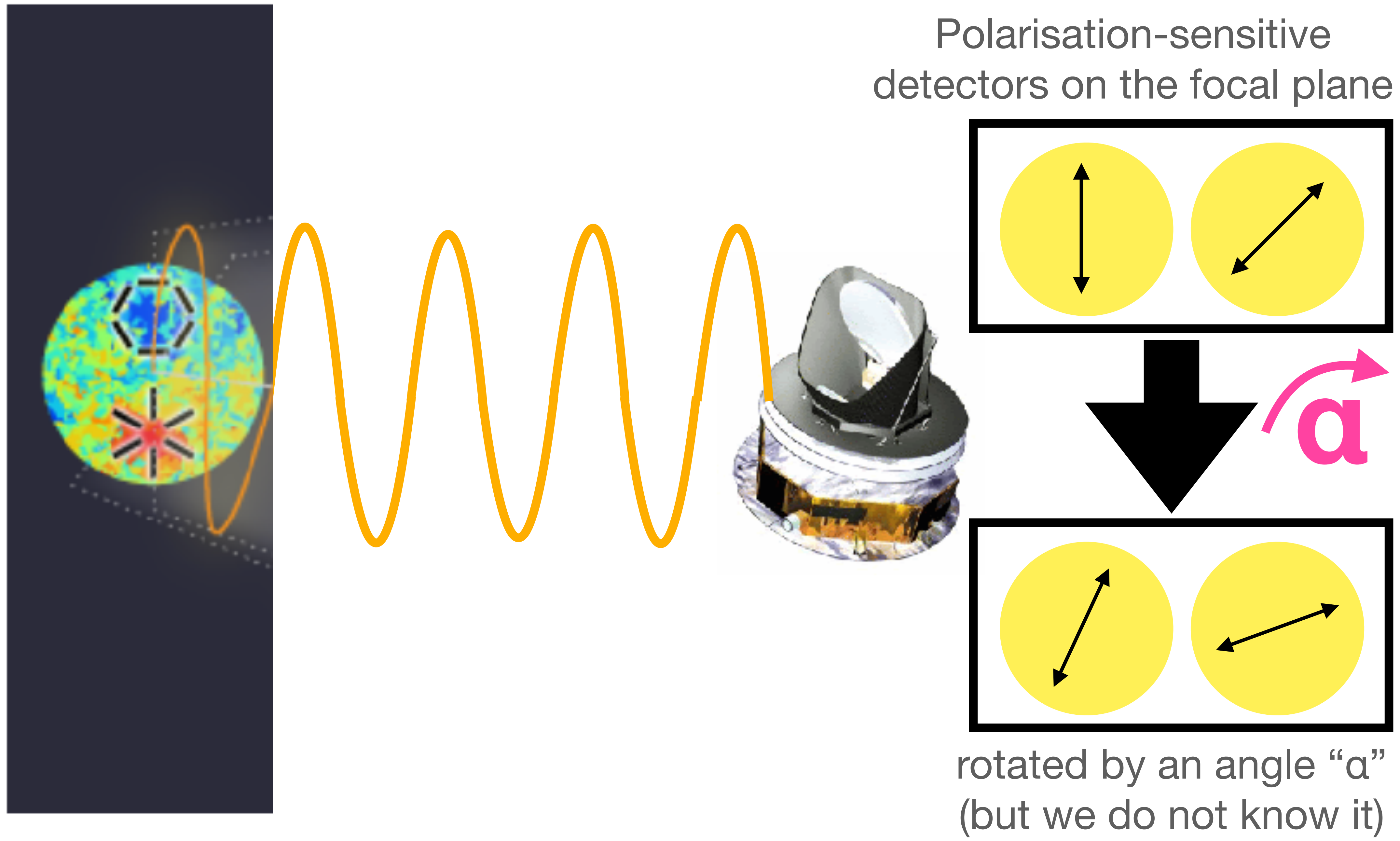
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

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)

- α+β = –6.0 ± 4.0 deg (Feng et al. 2006) first measurement
- α+β = –1.1 ± 1.4 deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- α+β = 0.55 ± 0.82 deg (QUaD Collaboration, Wu et al. 2009)
- …
- α+β = 0.31 ± 0.05 deg (Planck Collaboration 2016)
- α+β = –0.61 ± 0.22 deg (POLARBEAR Collaboration 2020)
- α+β = 0.63 ± 0.04 deg (SPT Collaboration, Bianchini et al. 2020)
- α+β = 0.12 ± 0.06 deg (ACT Collaboration, Namikawa et al. 2020)
- α+β = 0.09 ± 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)
- β = –1.1 ± 1.4 ± **1.5** deg (WMAP Collaboration, Komatsu et al. 2009; 2011)
- β = 0.55 ± 0.82 ± **0.5** deg (QUaD Collaboration, Wu et al. 2009)
- …
- β = 0.31 ± 0.05 ± **0.28** deg (Planck Collaboration 2016)
- 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 = 0.09 ± 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

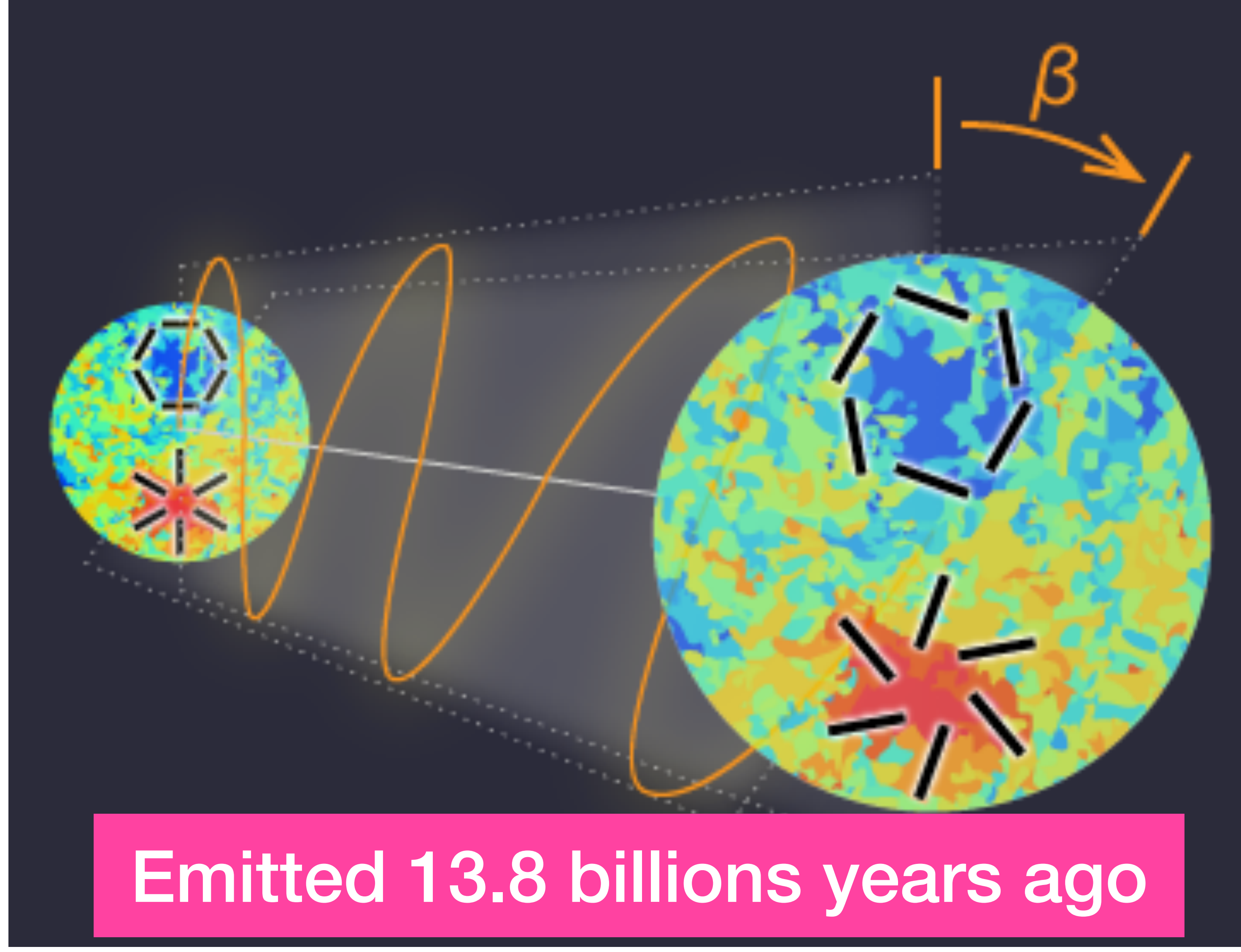
Polarised dust emission within our Milky Way!

Emitted “right there” - it would not be affected by the cosmic birefringence.

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.*

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

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

noise

- Thus,

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

measured — known accurately

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

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.

Minami et al. (2019)

Likelihood for the simplest case

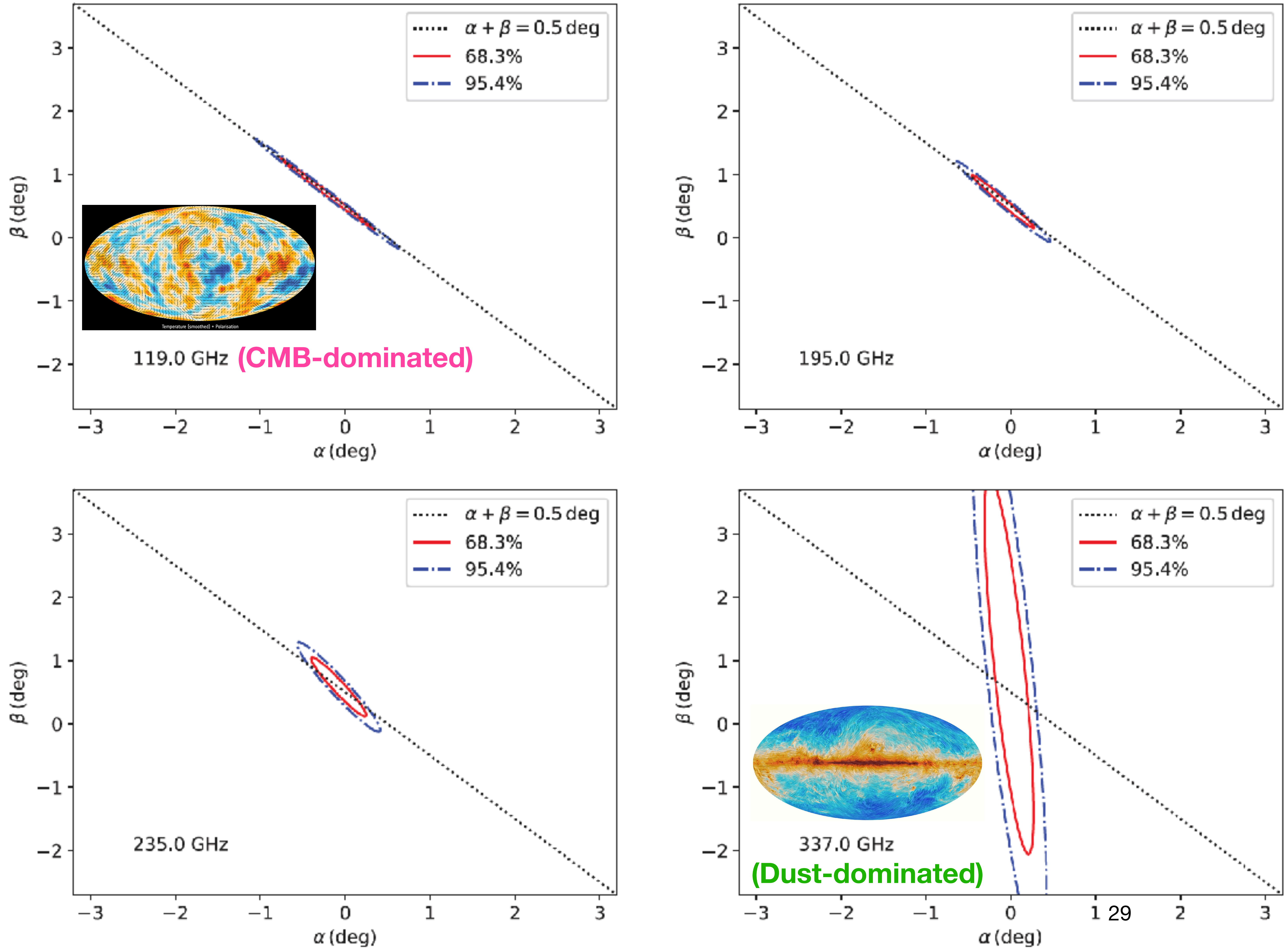
Single-frequency case, full sky data

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

- 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).

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.

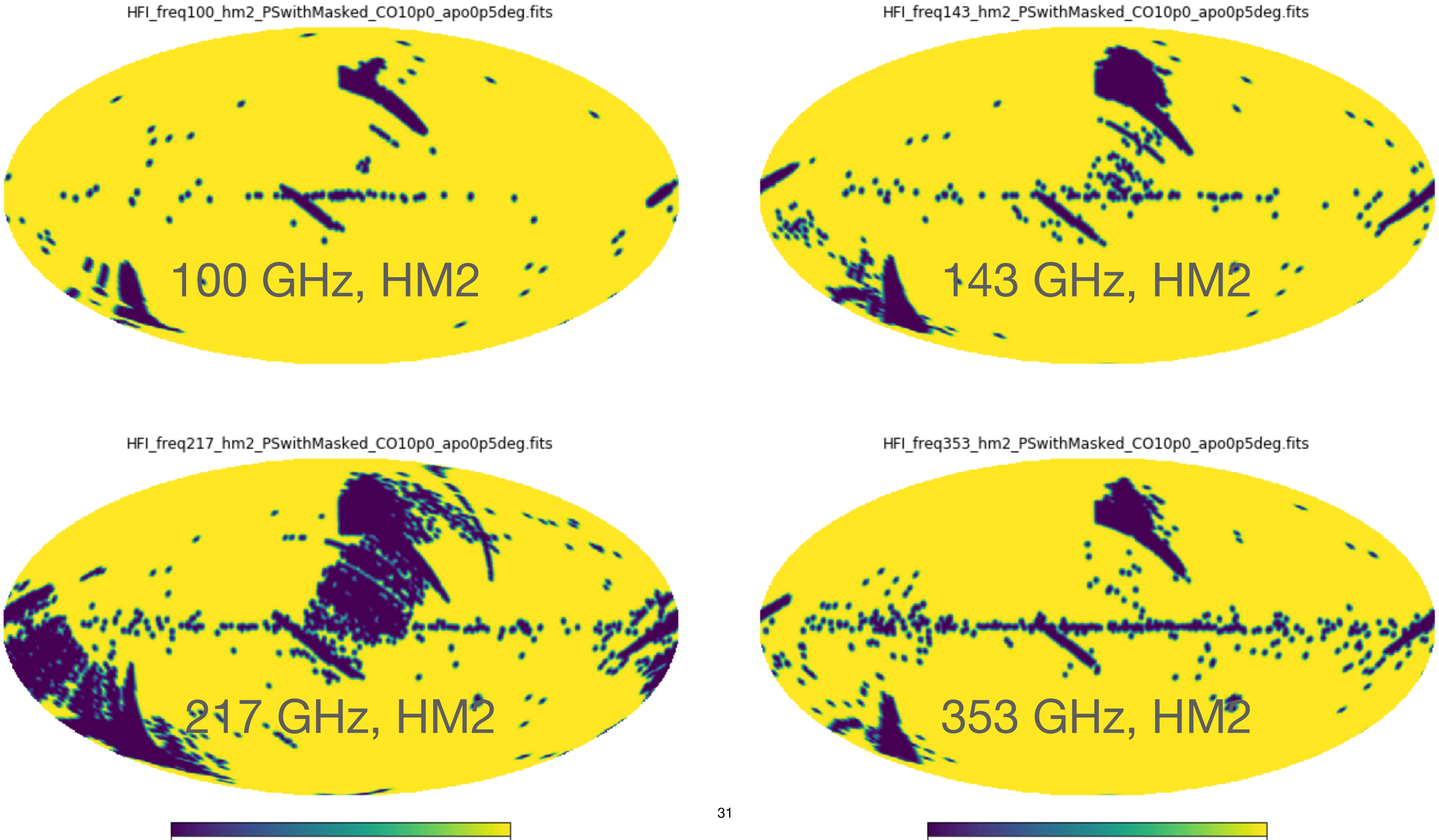
Minami & Komatsu (2020b)

Application to the Planck Data (PR3)

lmin = 51, lmax = 1500 (the same as those used by the Planck team)

Information for experts

- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz)
  - Measure power spectra from "Half Missions" (HM1, HM2)
- Mask (using NaMaster [Alonso et al.], apodization by "Smooth" with 0.5 deg)
  - Bright CO regions, Bright point sources, Bad pixels
- I -> P leakage due to the beam is corrected using QuickPol
  - It does not change the result even if we ignore this correction: good news!


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

Validation by FFP10

FFP10 = Planck team's "Full Focal Plane Simulation"

- There are 4 α_ν's and one β
- 10 simulations, no foreground is included because of the treatment of the beam
  - α-only fit: $\alpha_\nu = \{-0.008 \pm 0.047, 0.013 \pm 0.033, 0.017 \pm 0.065, 0.14 \pm 0.41\}$ deg for $\nu \in \{100, 143, 217, 353\}$ GHz
  - β-only fit: $\beta = 0.010 \pm 0.030$ deg
  - No bias found. The test passed.

Minami & Komatsu (2020b)

Main Results

$\beta > 0$ at 2.4σ

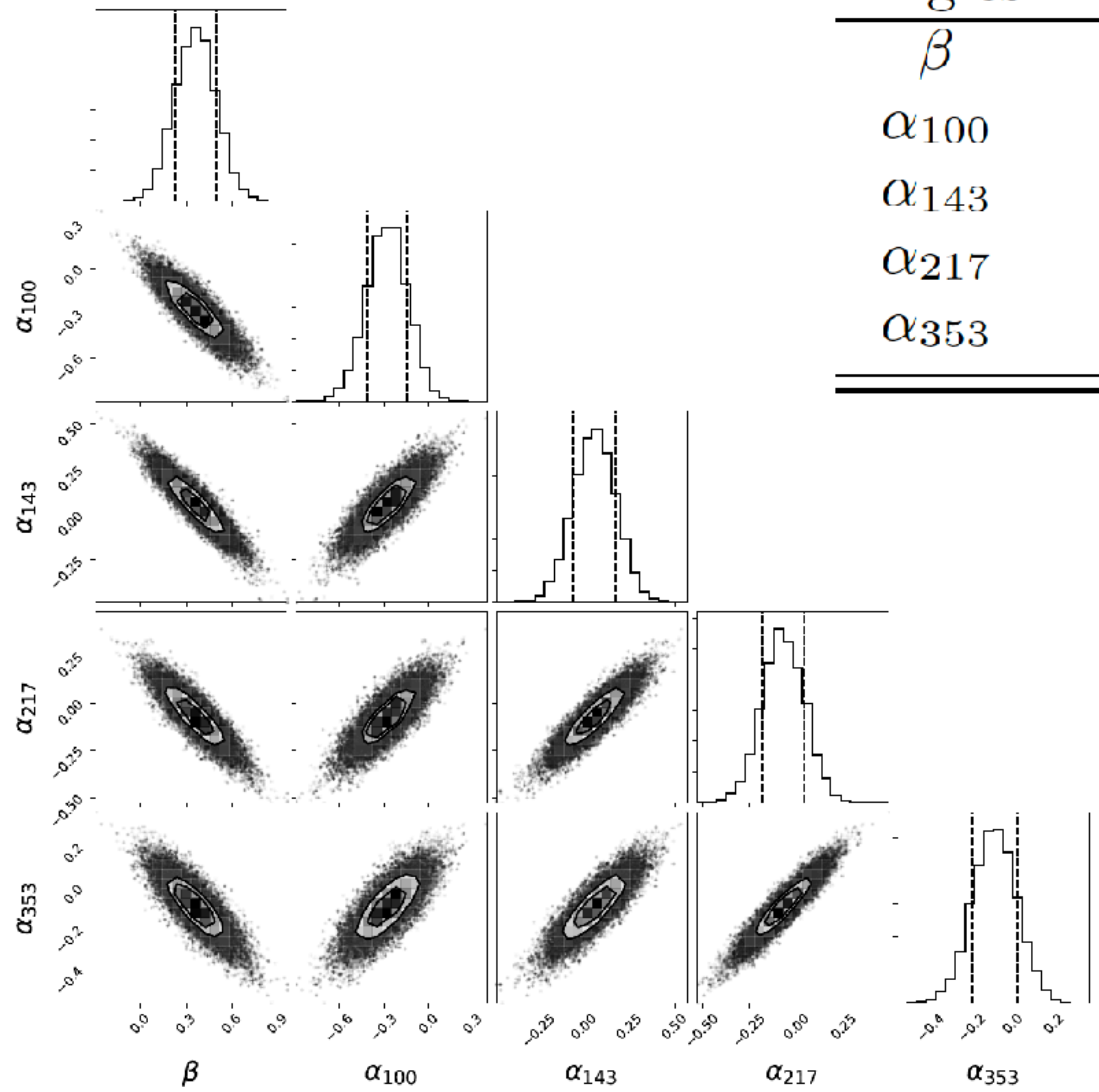
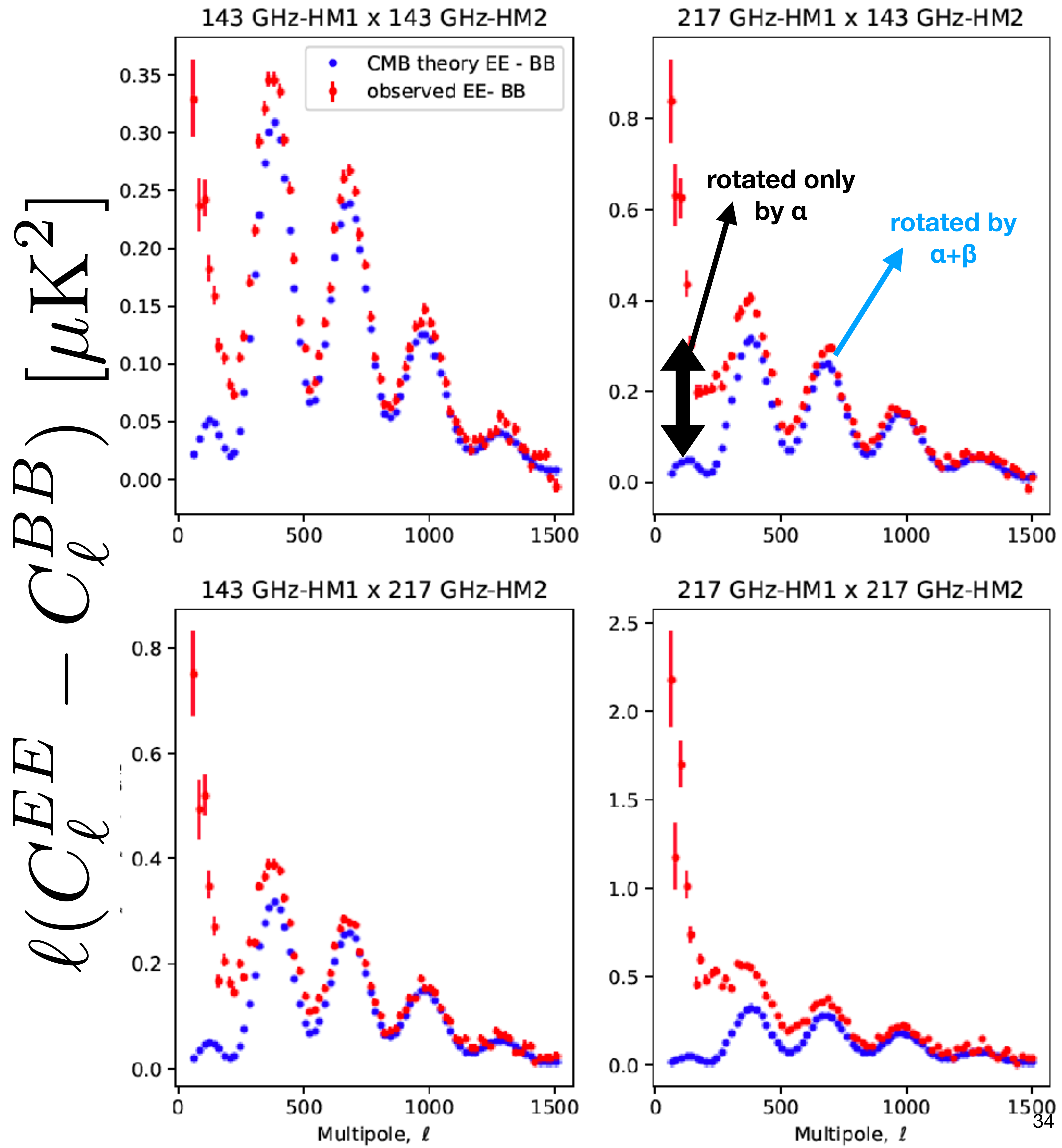


TABLE I. Cosmic birefringence and miscalibration angles from the Planck 2018 polarization data with 1σ (68%) uncertainties

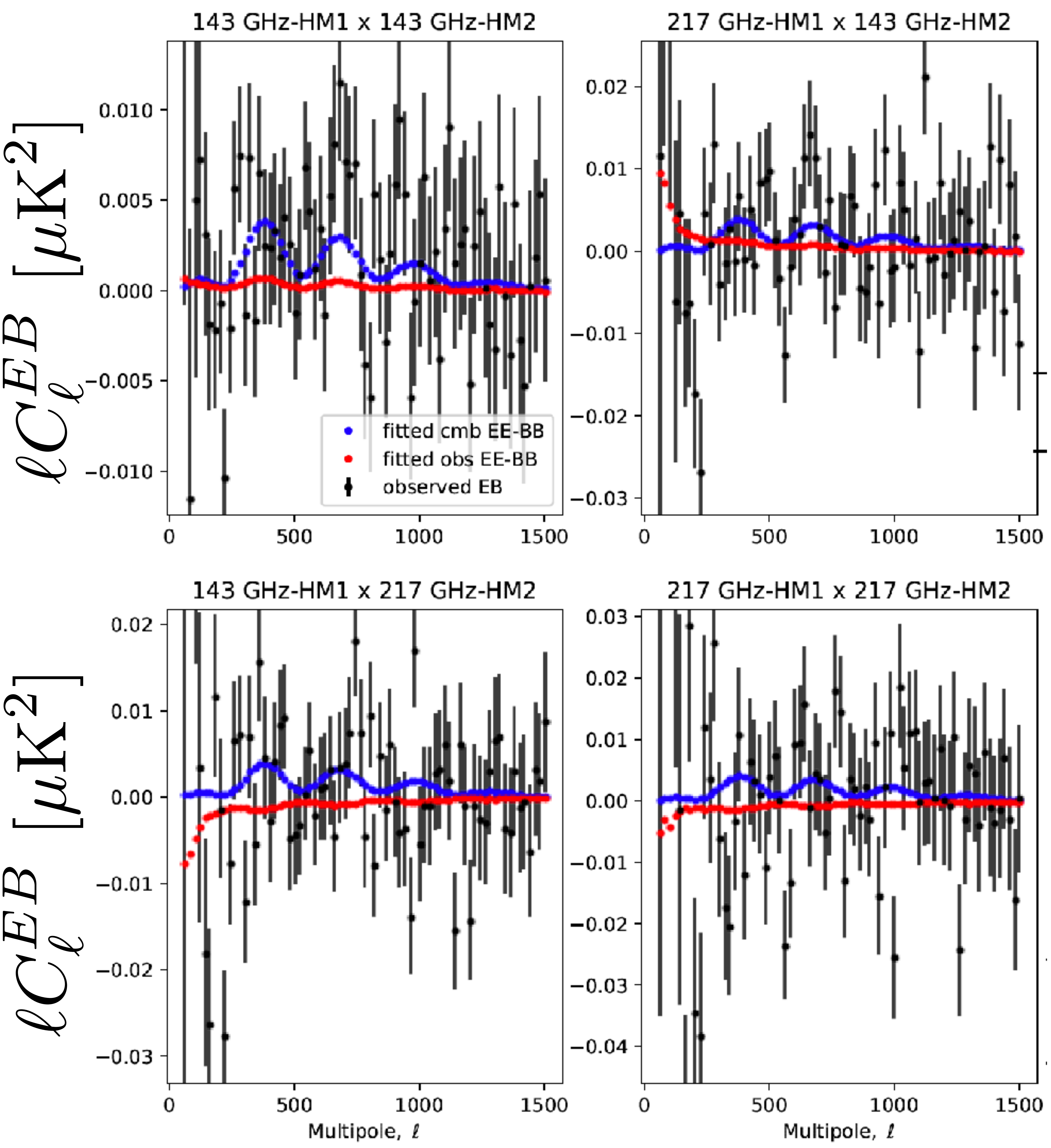
Angles	$\alpha_\nu=0$	Results (deg)
β	0.289 ± 0.048	0.35 ± 0.14
α_{100}		-0.28 ± 0.13
α_{143}		0.07 ± 0.12
α_{217}		-0.07 ± 0.11
α_{353}		-0.09 ± 0.11

- All α_ν's are consistent with zero either statistically, or within the ground calibration error of 0.28 deg.
  - Removing 100 GHz did not change β
- β=0.35 deg also agrees well with the Planck determination assuming $\alpha_\nu=0$:
  - $\beta(\alpha_\nu=0) = 0.29 \pm 0.05$ (stat. from EB) $\pm$ 0.28 (syst.) [Planck Int. XLIX]



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

- 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 potentially systematics)*



Minami & Komatsu (2020b)

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

- 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?

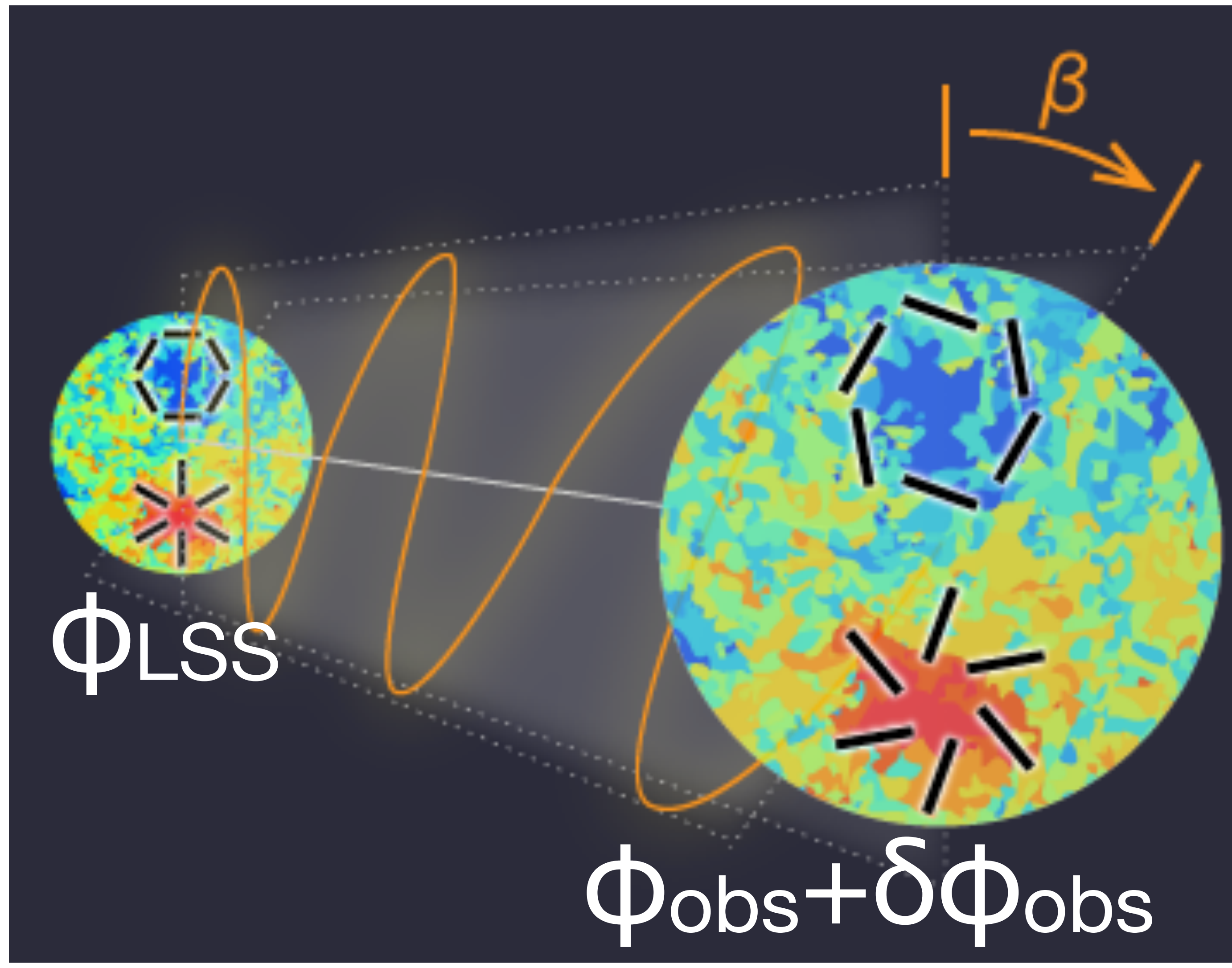
- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle α.
- Thus, α -> α+γ, where γ is the contribution from the intrinsic EB.
  - The sign of γ is the same as the sign of the foreground EB.
- From FG: α+γ. From CMB: α+β.
  - Thus, our method yields **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…

Implications

What does it mean for your models of dark matter and energy?

- When the Lagrangian density includes a Chern-Simons coupling between a pseudo scalar field and the electromagnetic tensor given by

$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

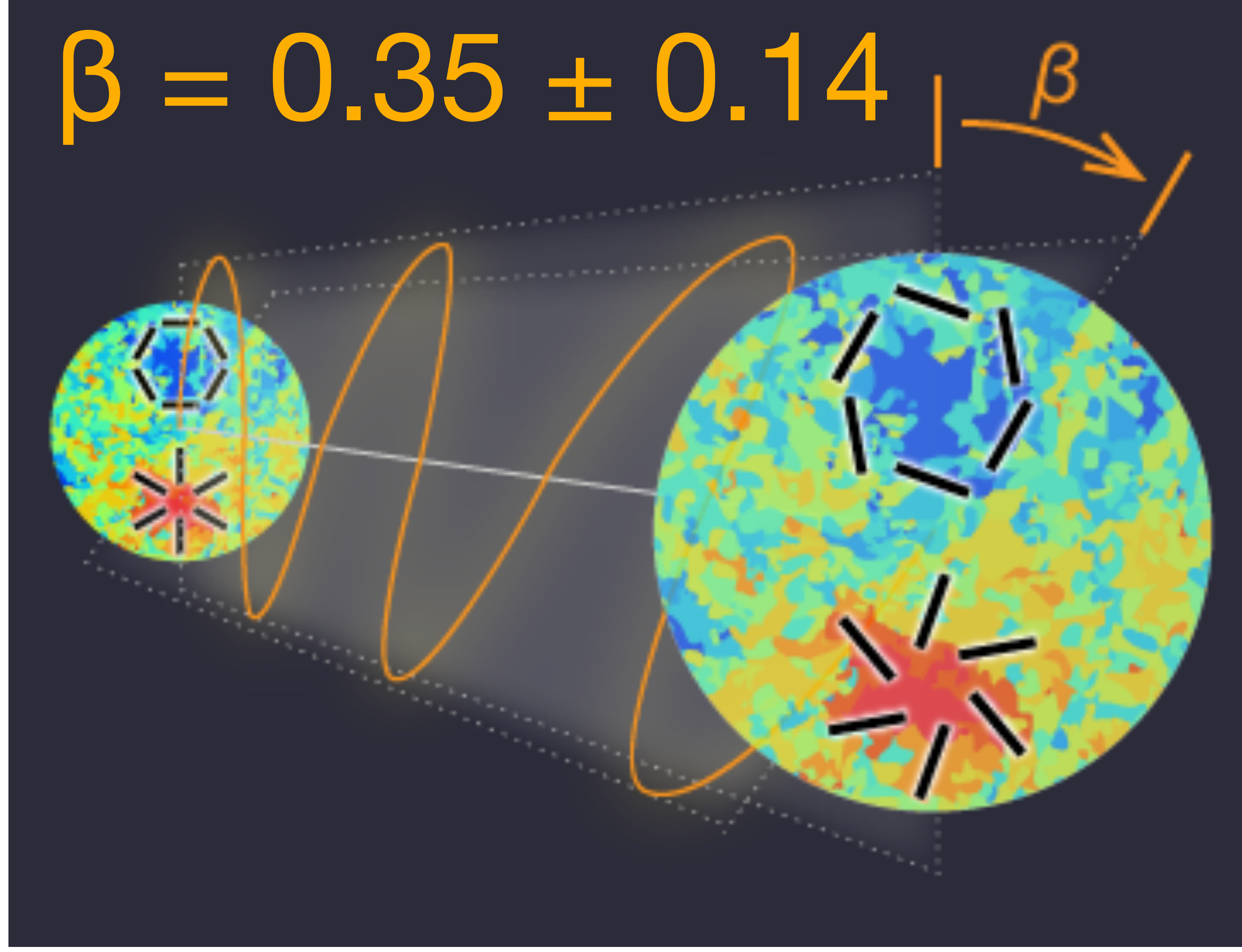


- The birefringence angle is

$$\beta = \tfrac{1}{2} g_{\phi\gamma} (\bar{\phi}_{\rm obs} - \bar{\phi}_{\rm LSS} + \delta\phi_{\rm obs})$$

- Our measurement yields

$$g_{\phi\gamma} (\bar{\phi}_{\rm obs} - \bar{\phi}_{\rm LSS} + \delta\phi_{\rm obs}) = (1.2 \pm 0.5) \times 10^{-2}\,\mathrm{rad}\,.$$



Conclusion

β = 0.35 ± 0.14 (68%CL)

- We perfectly understand what 2.4σ means!
  - Higher statistical significance is need to confirm this signal.
- Our new method finally allowed us to make this “impossible” measurement, which may point to new physics.
  - Our method can be applied to any of the existing and future CMB experiments.
  - The confirmation (or otherwise) of the signal should be possible immediately.
- If confirmed, it would have important implications for dark matter/energy.

Back-up Slides

Likelihood

Partial-sky, Multi-frequency extension

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{\ell=2}^{\ell_{\max}} \left(\mathbf{A}\vec{C}_\ell^{\mathrm{o}} - \mathbf{B}\vec{C}_\ell^{\mathrm{CMB,th}}\right)^{\mathrm{T}} \mathbf{C}^{-1} \left(\mathbf{A}\vec{C}_\ell^{\mathrm{o}} - \mathbf{B}\vec{C}_\ell^{\mathrm{CMB,th}}\right),$$

- where

$$\vec{C}_\ell^{\mathrm{o}} = \begin{pmatrix} C_\ell^{E_iE_j,\mathrm{o}} & C_\ell^{B_iB_j,\mathrm{o}} & C_\ell^{E_iB_j,\mathrm{o}} \end{pmatrix}^{\mathrm{T}}$$

$$\vec{C}_\ell^{\mathrm{CMB,th}} = \begin{pmatrix} C_\ell^{E_iE_j,\mathrm{CMB,th}} b_\ell^i b_\ell^j & C_\ell^{B_iB_j,\mathrm{CMB,th}} b_\ell^i b_\ell^j \end{pmatrix}$$

$$\mathbf{C} = \mathbf{A}\mathrm{Cov}(\vec{C}_\ell^{\mathrm{o}}, \vec{C}_\ell^{\mathrm{o}\,\mathrm{T}})\mathbf{A}^{\mathrm{T}}$$

$$\mathrm{Cov}(\vec{C}_\ell^{\mathrm{o},ij}, \vec{C}_\ell^{\mathrm{o},pq\,\mathrm{T}}) = \begin{pmatrix} \mathrm{Cov}(C_\ell^{E_iE_j,\mathrm{o}}, C_\ell^{E_pE_q,\mathrm{o}}) & \cancel{\mathrm{Cov}(C_\ell^{E_iE_j,\mathrm{o}}, C_\ell^{B_pB_q,\mathrm{o}})} & \cancel{\mathrm{Cov}(C_\ell^{E_iE_j,\mathrm{o}}, C_\ell^{E_pB_q,\mathrm{o}})} \\ \cancel{\mathrm{Cov}(C_\ell^{B_iB_j,\mathrm{o}}, C_\ell^{E_pE_q,\mathrm{o}})} & \mathrm{Cov}(C_\ell^{B_iB_j,\mathrm{o}}, C_\ell^{B_pB_q,\mathrm{o}}) & \cancel{\mathrm{Cov}(C_\ell^{B_iB_j,\mathrm{o}}, C_\ell^{E_pB_q,\mathrm{o}})} \\ \cancel{\mathrm{Cov}(C_\ell^{E_iB_j,\mathrm{o}}, C_\ell^{E_pE_q,\mathrm{o}})} & \cancel{\mathrm{Cov}(C_\ell^{E_iB_j,\mathrm{o}}, C_\ell^{B_pB_q,\mathrm{o}})} & \mathrm{Cov}(C_\ell^{E_iB_j,\mathrm{o}}, C_\ell^{E_pB_q,\mathrm{o}}) \end{pmatrix}$$

Likelihood

Partial-sky, Multi-frequency extension

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{\ell=2}^{\ell_{\max}} \left(\mathbf{A}\vec{C}_\ell^{\mathrm{o}} - \mathbf{B}\vec{C}_\ell^{\mathrm{CMB,th}}\right)^{\mathrm{T}} \mathbf{C}^{-1} \left(\mathbf{A}\vec{C}_\ell^{\mathrm{o}} - \mathbf{B}\vec{C}_\ell^{\mathrm{CMB,th}}\right),$$

- where

$\mathbf{A}$ is a block diagonal matrix of $\begin{pmatrix} -\vec{R}^{\mathrm{T}}(\alpha_i,\alpha_j)\mathbf{R}^{-1}(\alpha_i,\alpha_j) & 1 \end{pmatrix},$

- with

$$\vec{R}(\theta_i,\theta_j) = \begin{pmatrix} \cos(2\theta_i)\sin(2\theta_j) \\ -\sin(2\theta_i)\cos(2\theta_j) \end{pmatrix}$$

$$\mathbf{R}(\theta_i,\theta_j) = \begin{pmatrix} \cos(2\theta_i)\cos(2\theta_j) & \sin(2\theta_i)\sin(2\theta_j) \\ \sin(2\theta_i)\sin(2\theta_j) & \cos(2\theta_i)\cos(2\theta_j) \end{pmatrix}$$

Likelihood

Partial-sky, Multi-frequency extension

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{\ell=2}^{\ell_{\rm max}} \left(\mathbf{A}\vec{C}_\ell^{\rm o} - \mathbf{B}\vec{C}_\ell^{\rm CMB,th}\right)^{\rm T} \mathbf{C}^{-1} \left(\mathbf{A}\vec{C}_\ell^{\rm o} - \mathbf{B}\vec{C}_\ell^{\rm CMB,th}\right),$$

- where

B is a block diagonal matrix of $\left[\vec{R}^{\rm T}(\alpha_i+\beta,\alpha_j+\beta) - \vec{R}^{\rm T}(\alpha_i,\alpha_j)\mathbf{R}^{-1}(\alpha_i,\alpha_j)\mathbf{R}(\alpha_i+\beta,\alpha_j+\beta)\right]$,

- with

$$\vec{R}(\theta_i,\theta_j) = \begin{pmatrix} \cos(2\theta_i)\sin(2\theta_j) \\ -\sin(2\theta_i)\cos(2\theta_j) \end{pmatrix}$$

$$\mathbf{R}(\theta_i,\theta_j) = \begin{pmatrix} \cos(2\theta_i)\cos(2\theta_j) & \sin(2\theta_i)\sin(2\theta_j) \\ \sin(2\theta_i)\sin(2\theta_j) & \cos(2\theta_i)\cos(2\theta_j) \end{pmatrix}$$