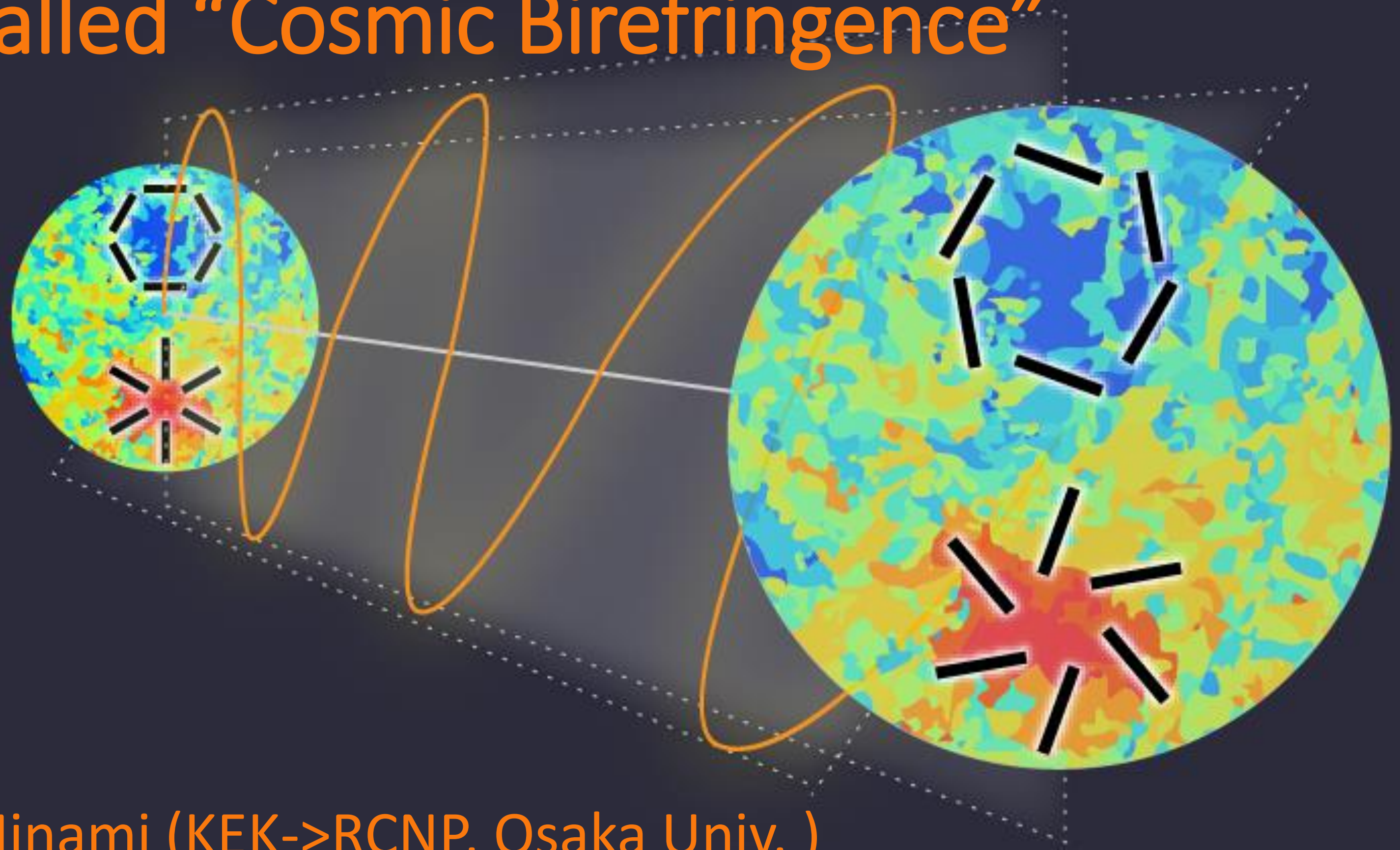
Search for parity-violating physics in the polarisation of the cosmic microwave background, so called "Cosmic Birefringence"



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PHYSICAL REVIEW LETTERS

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

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.

Issue
Vol. 125, Iss. 22 — 27 November 2020

The methodology papers that led to this search

We worked for about 2 years

1. **"Simultaneous determination of miscalibration angles and cosmic birefringence"**, [PTEP, 2019, 8, August (2019)]
   - ➢ The original paper to describe the basic idea, methodology, and validation
   - ➢ Full-sky data
2. **"Determination of miscalibrated polarisation angles from observed CMB and foreground EB power spectra: Application to partial-sky observation"**, [PTEP, 2020, 6, June (2020)]
   - ➢ Extension to partial sky data
   - ➢ Use prior knowledge of CMB power spectra to determine foreground EB correlation
3. **"Simultaneous determination of the cosmic birefringence and miscalibrated polarisation angles II: Including cross-frequency spectra"**, [PTEP, 2020, 10, October (2020)]
   - ➢ The compete methodology for multi-channel observations
   - ➢ This method is used for analysing Planck's PR3 and PR4 data

Cosmic Birefringence

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

The Universe filled with a "birefringent material"

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

$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$

Chern-Simons term

$$\mathcal{L} \supset -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}\boxed{g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}} \quad \cdots (1)$$

Turner & Widrow (1988)

In electromagnetic fields:

Parity Even

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

Parity Odd

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

*The axion field, ϕ, is a "pseudo scalar", which is parity odd; thus, the last term in Eq (1) is parity even as a whole.

Cosmic Birefringence

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

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Chern-Simons term

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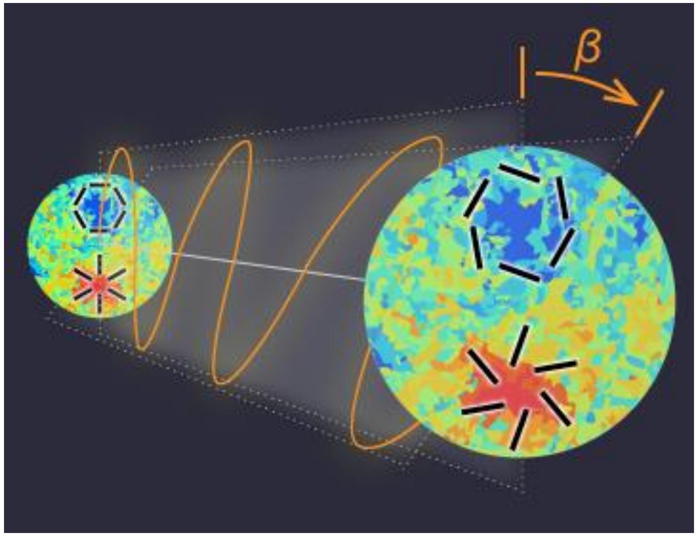
Turner & Widrow (1988)

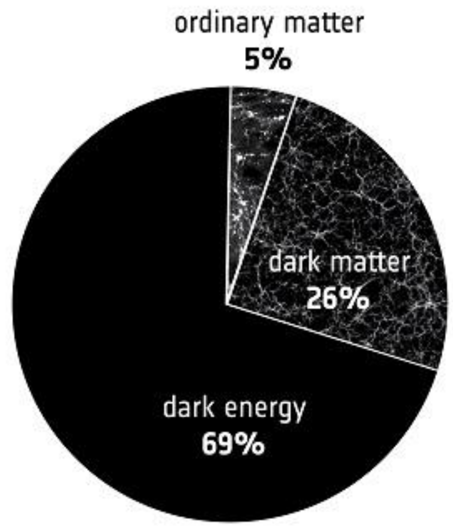
$$\beta = \frac{g_{\phi\gamma}}{2}\int_{emission}^{observer} dt\,\dot{\phi}$$
$$= \frac{g_{\phi\gamma}}{2}(\phi_{observer} - \phi_{emission}) \quad \cdots (2)$$

Difference of the field values rotates the linear polarization!



Motivation

- The Universe's energy budget is dominated by two dark components:
  - Dark Energy
  - Dark Matter



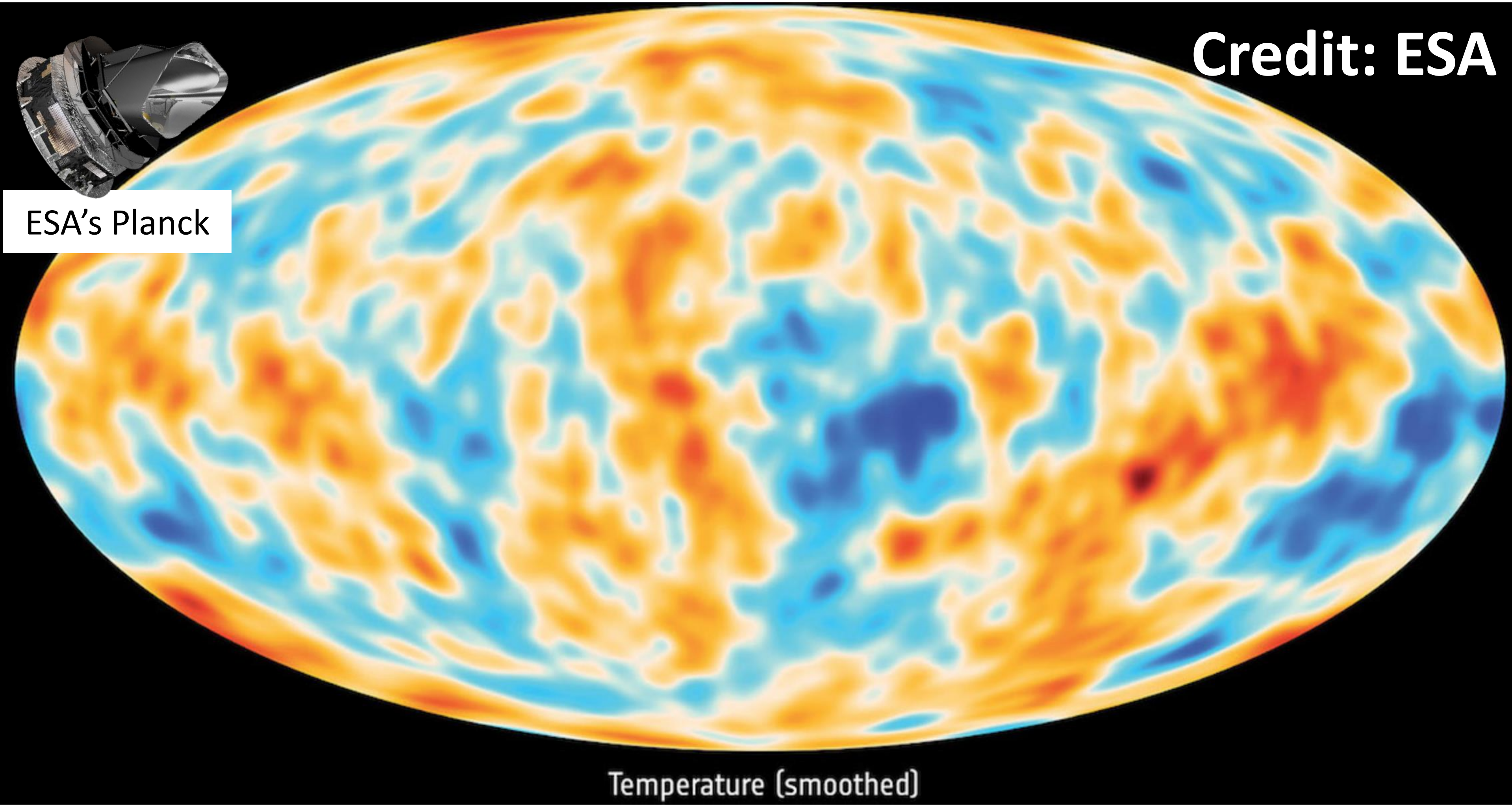
Credit: ESA

- 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?

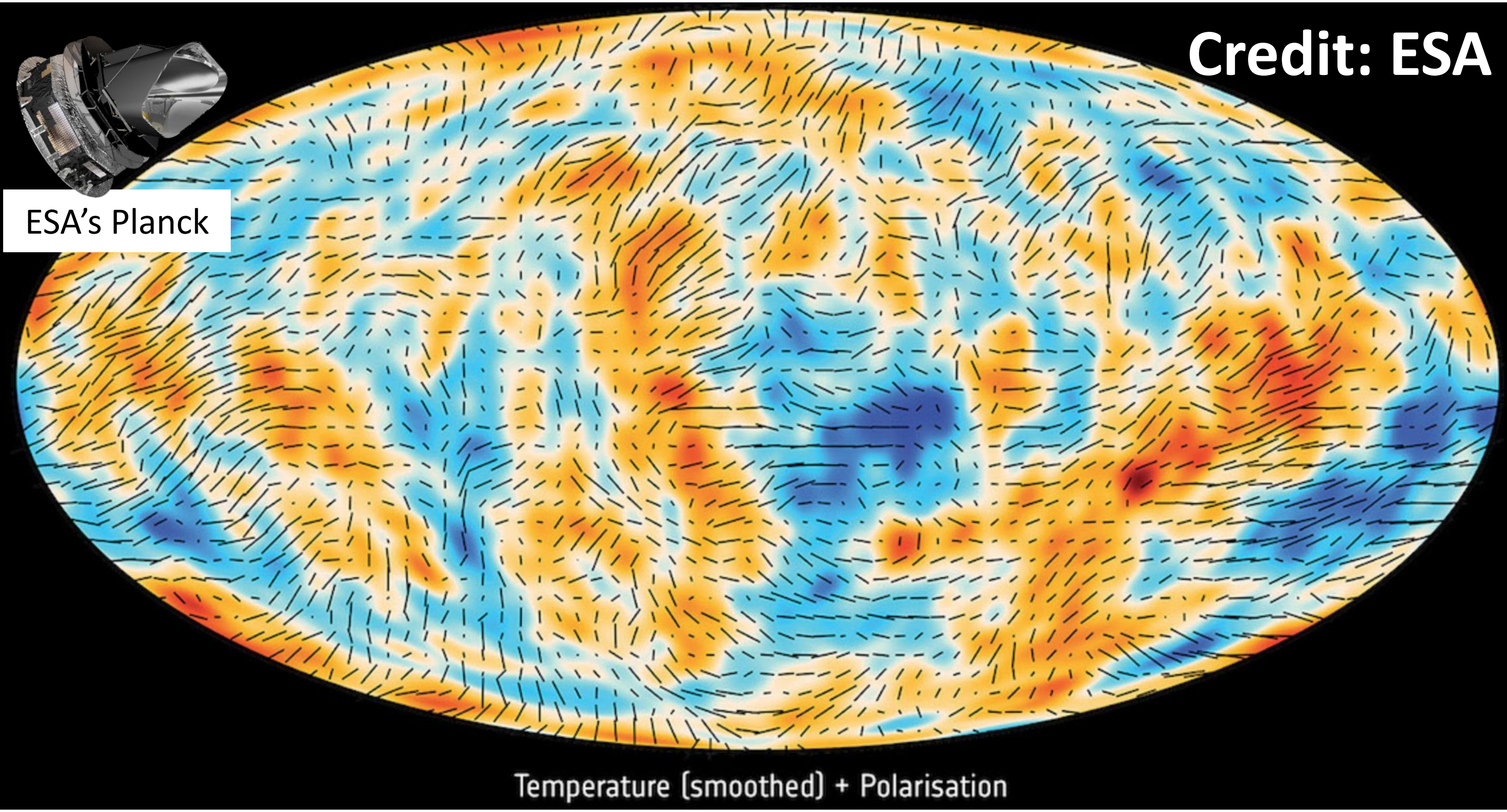
Let's look using
cosmic microwave background (CMB)

Searching for cosmic birefringence with CMB



Emitted 13.8 billions years ago
at the last scattering surface (LSS)

Temperature anisotropy + polarisaion

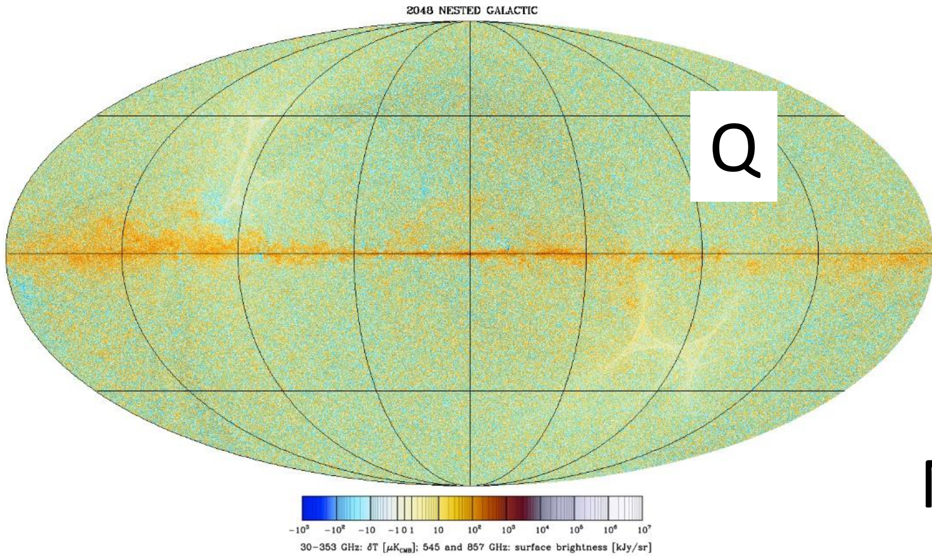


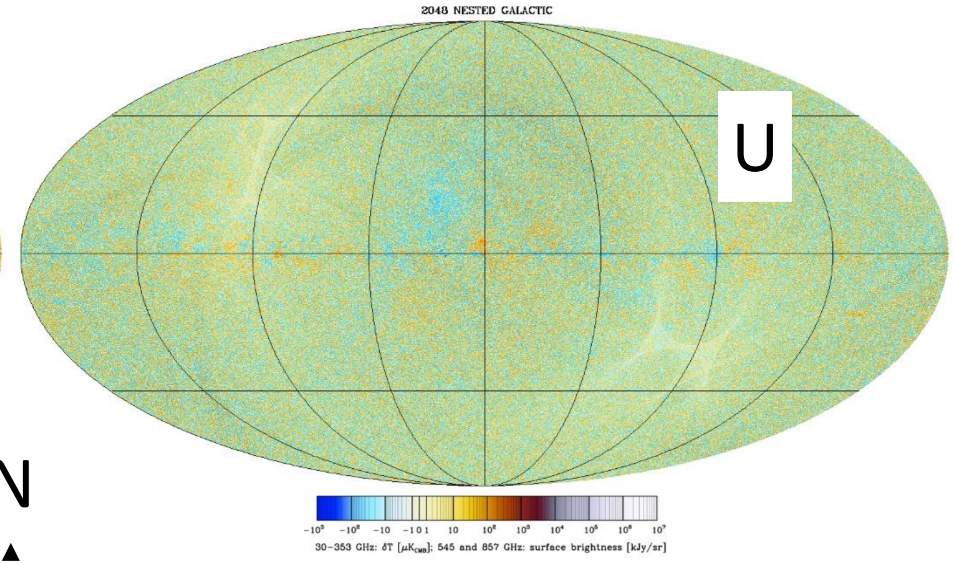
We know the initial $\beta = 0$

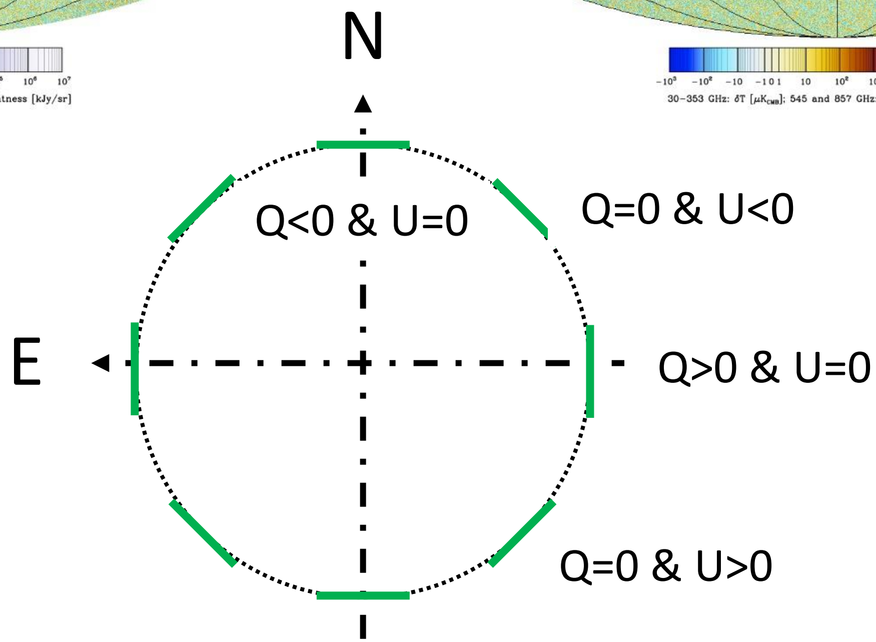
Measurement of the polarisation

Credit: ESA

We measure linear polarisation with two orthogonal parameters



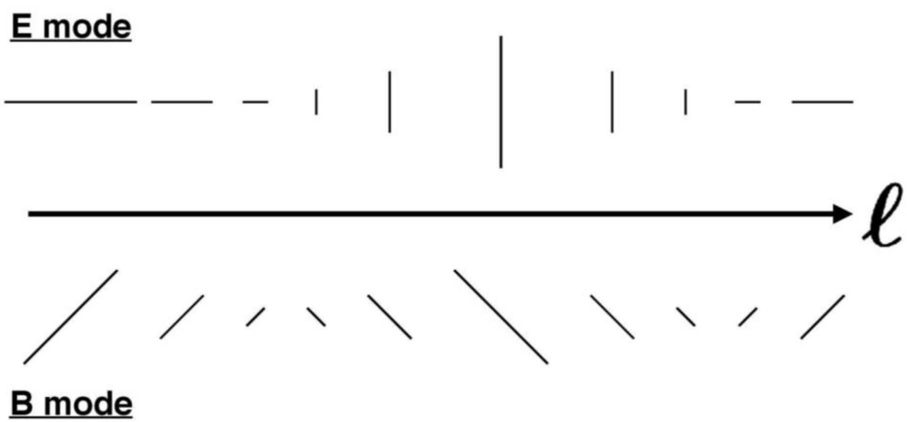




E- and B-mode: decomposition of linear polarisation

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

$$E(\ell) \pm iB(\ell) = e^{\mp 2i\phi_\ell} \int d\hat{\boldsymbol{n}}\, [Q(\hat{\boldsymbol{n}}) + iU(\hat{\boldsymbol{n}})] e^{-i\ell\cdot\hat{\boldsymbol{n}}}$$



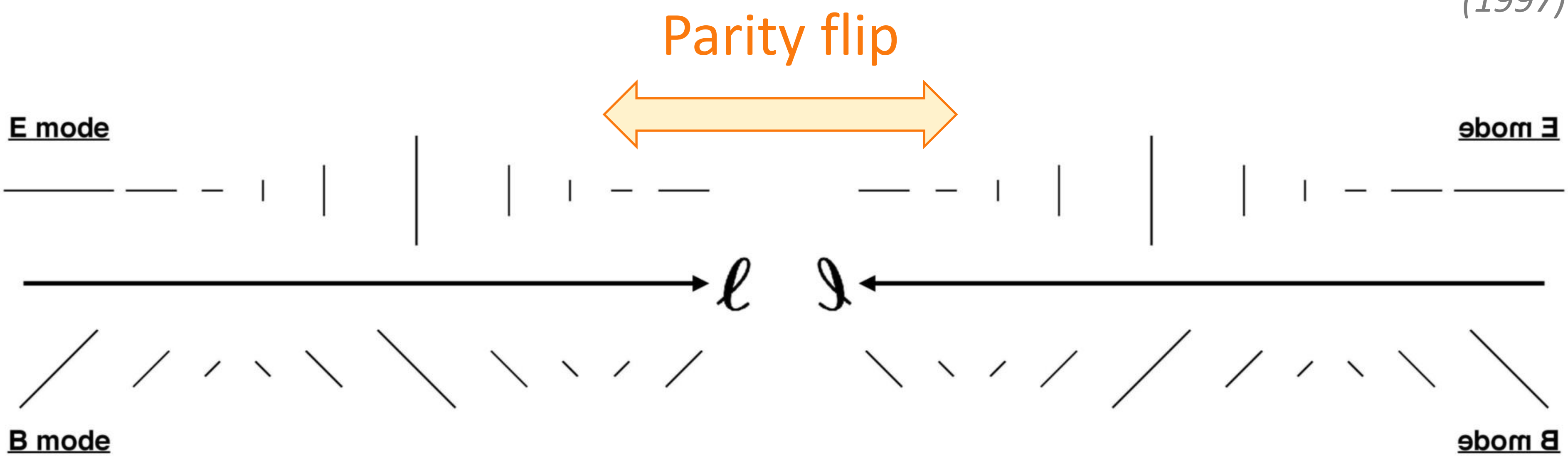
Direction of the Fourier wavenumber vector

- 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 transformation

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



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

auto correlation $\left\{\begin{aligned} \langle E_\ell E^*_{\ell'} \rangle &= (2\pi)^2 \delta^{(2)}(\ell - \ell') C_\ell^{EE} \\ \langle B_\ell B^*_{\ell'} \rangle &= (2\pi)^2 \delta^{(2)}(\ell - \ell') C_\ell^{BB} \end{aligned}\right.$

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

$\cdots (3)$

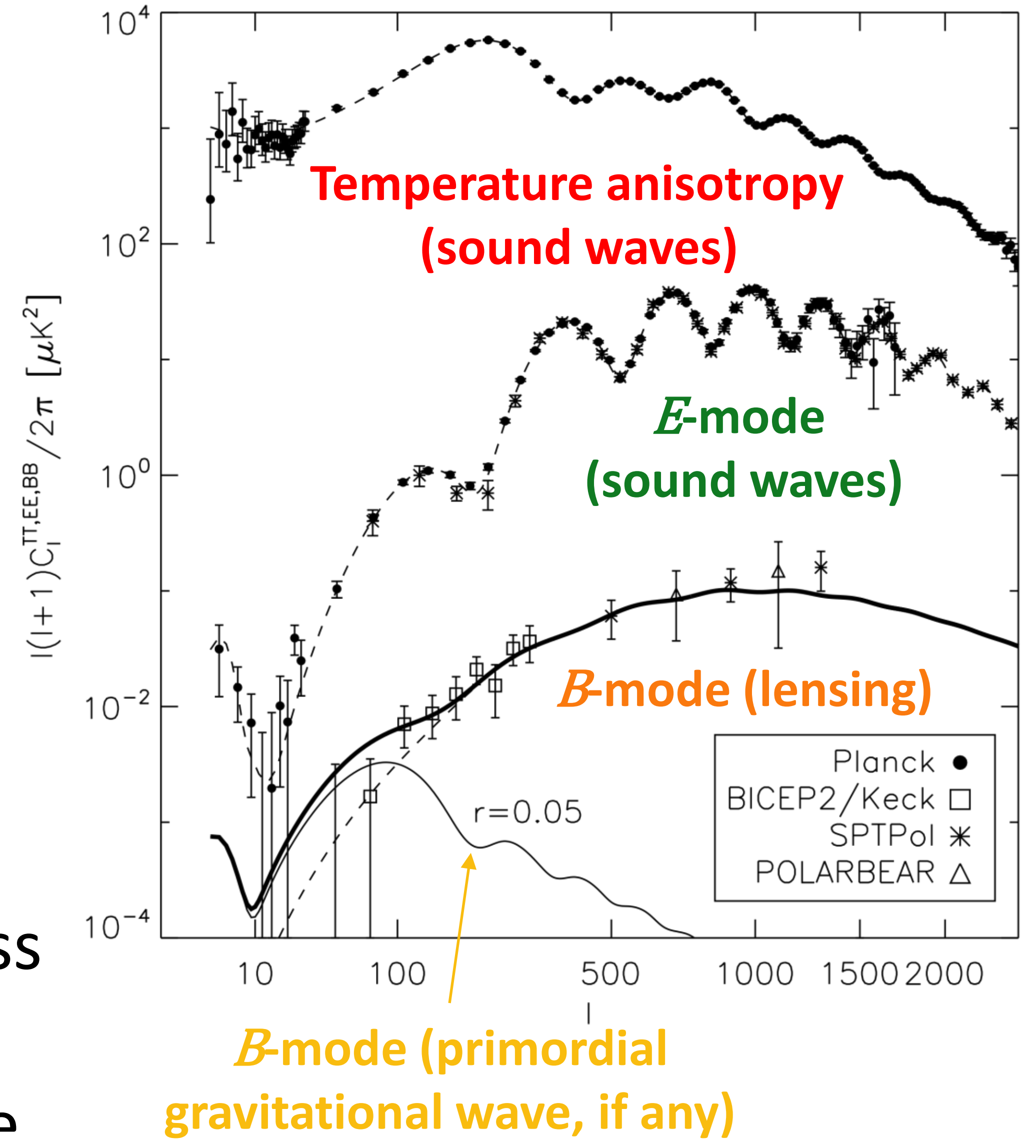
- The others, e.g., $\langle T_\ell B^*_{\ell'} \rangle$ and $\langle E_\ell B^*_{\ell'} \rangle$, are not invariant
  - We can use these to probe parity-violating physics!

Power spectra

- This is the typical figure that you find in many talks on the CMB

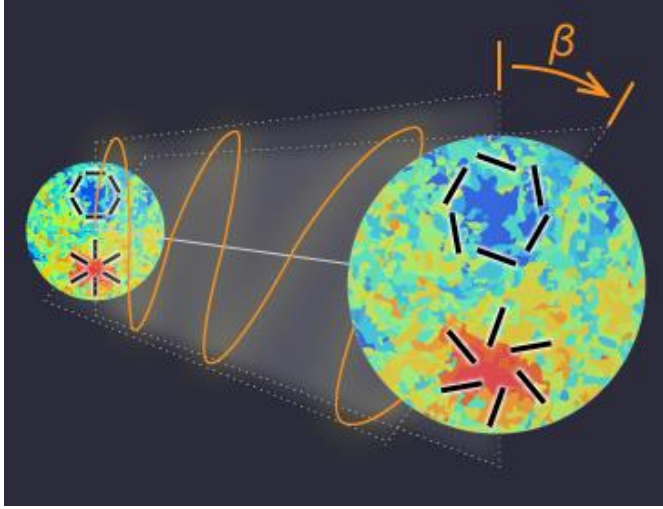
- The temperature anisotropy and E- and B-mode polarisation power spectra have been measured well

- Our focus is the EB cross spectrum, which is not shown here



$\boldsymbol{EB}$ correlation from the cosmic birefringence

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



- Cosmic birefringence convert E<-> B as

$$\begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{obs} = \begin{pmatrix} \cos(2\boldsymbol{\beta}) & -\sin(2\boldsymbol{\beta}) \\ \sin(2\boldsymbol{\beta}) & \cos(2\boldsymbol{\beta}) \end{pmatrix} \begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix} \quad \cdots (4)$$

- In power spectra:

$$\langle C_\ell^{EB,obs} \rangle = \frac{1}{2} \boxed{\left(\langle C_\ell^{EE} \rangle - \langle C_\ell^{BB} \rangle \right)} \sin(4\beta) + \langle \cancelto{0}{C_\ell^{EB}} \rangle \cos(4\beta) \quad \cdots (5)$$

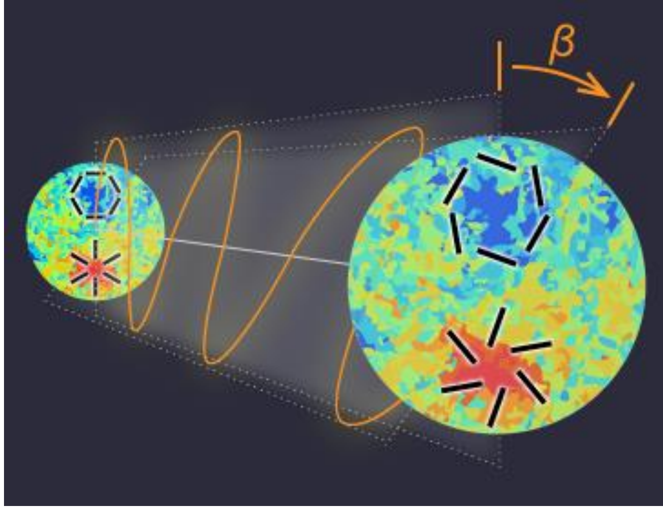
Need to assume a model!

Vanish at the LSS

- Traditionally, one would find β by fitting $C_\ell^{EE,CMB} - C_\ell^{BB,CMB}$ to the observed $C_\ell^{EB,obs}$ using the best-fitting CMB model
  - Assuming the intrinsic $\langle C_\ell^{EB} \rangle = 0$, at the last scattering surface (LSS) (justified in the standard cosmology)

Only with observed data

Zhao et al. 2015;(Minami et al. 2019)



- Cosmic birefringence convert E<-> B as

$$\begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{obs} = \begin{pmatrix} \cos(2\boldsymbol{\beta}) & -\sin(2\boldsymbol{\beta}) \\ \sin(2\boldsymbol{\beta}) & \cos(2\boldsymbol{\beta}) \end{pmatrix} \begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix} \quad \cdots (4)$$

- We find additional relations

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

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

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

$$\langle C_\ell^{EB,o} \rangle = \frac{1}{2}\boxed{\left(\langle C_\ell^{EE,o} \rangle - \langle C_\ell^{BB,o} \rangle\right)}\tan(4\beta) + \frac{\cancelto{0}{\langle C_\ell^{EB} \rangle}}{\cos(4\beta)} \quad \cdots (6)$$

No need to assume a model   Vanish at the LSS

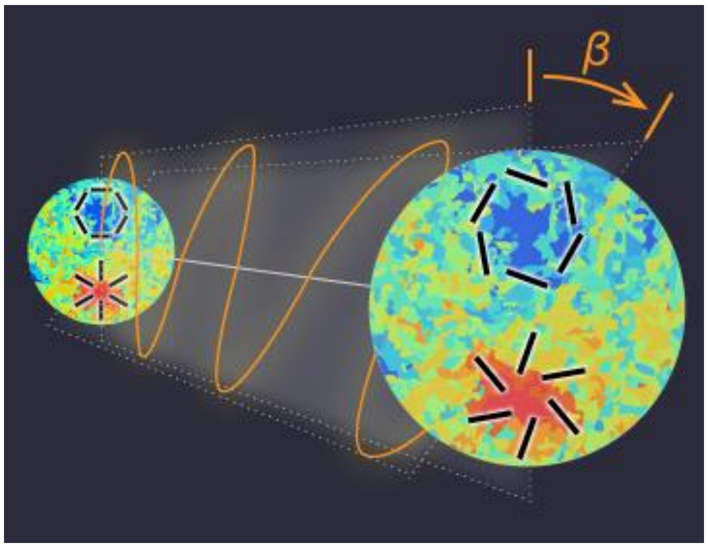
The Biggest Problem: Miscalibration of detectors

Miscalibration of detectors

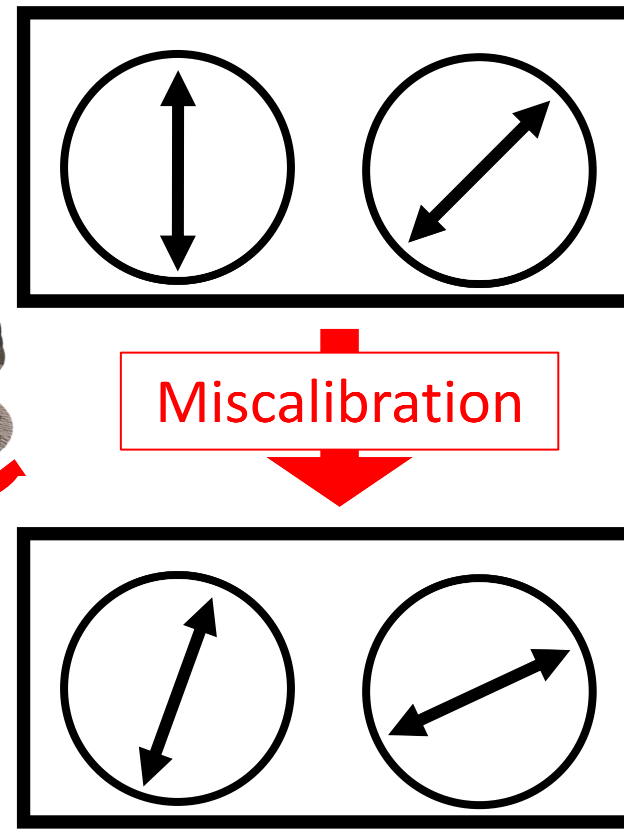
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

Cosmic or Instrumental?

Polarisation-sensitive detectors on the focal plane



OR



rotated by an angle "α" (but we do not know it)

- Is the polarization plane rotated by the genuine cosmic birefringence, β ?
- Are the polarisation-sensitive detectors rotated by miscalibration, α, on the sky coordinate (and we did not know)?

We can only measure the sum, $\alpha + \beta$

The past measurements

The quoted uncertainties are all statistical only (68% C.L.)

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

First measurement

Why not yet discovered?

The past measurements

Now including the estimated systematic errors on $\boldsymbol{\alpha}$

Measurement	β + stat. + sys. (deg.)
Feng et al. 2006	$-6.0 \pm 4.0 \pm$**??**
WMAP Collaboration, Komatsu et al. 2009; 2011	$-1.1 \pm 1.4 \pm \mathbf{1.5}$
QUaD Collaboration, Wu et al. 2009	$-0.55 \pm 0.82 \pm \mathbf{0.5}$
…	…
Planck Collaboration 2016	$0.31 \pm 0.05 \pm \mathbf{0.28}$
POLARBEAR Collaboration 2020	$-0.61 \pm 0.22 +$**??**
SPT Collaboration, Bianchini et al. 2020	$0.63 \pm 0.04 +$**??**
ACT Collaboration, Namikawa et al. 2020	$0.12 \pm 0.06 +$**??**
ACT Collaboration, Choi et al. 2020*	$0.09 \pm 0.09 +$**??**

First measurement

Uncertainty in the calibration of α has been the major limitation

*used optical model , "as-designed" angles

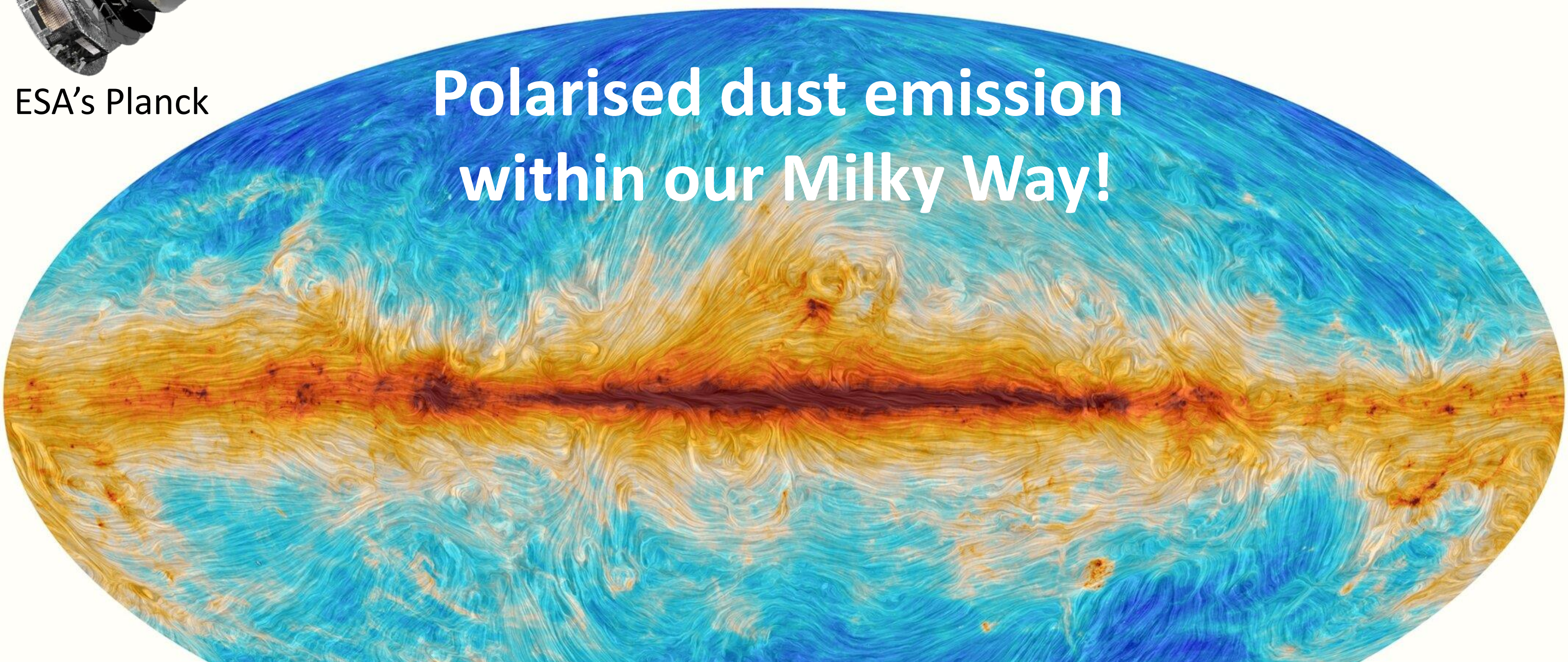
- Other way to calibrate?

Crab nebula, Tau A (Celestial source)	0.27 deg. (Aumont et al.(2018))
Wire grid	1.00 deg. ? (Planck pre launch)

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

ESA's Planck

Credit: ESA



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 birefringence

Minami et al. (2019)

Idea: Miscalibration of the polarization angle α rotates both the FG and CMB, but β affects only the CMB

$$\left.\begin{aligned} E^{\mathrm{o}}_{\ell,m} &= E^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) - B^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) - B^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + \underbrace{E^{\mathrm{N}}_{\ell,m}}_{\text{noise}} \\ B^{\mathrm{o}}_{\ell,m} &= E^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + B^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + B^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) + B^{\mathrm{N}}_{\ell,m} \end{aligned}\right. \cdots (7)$$

From them, we derived

$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\Big(\underbrace{\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle}_{\text{Measured}}\Big) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\Big(\underbrace{\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle}_{\text{Known accurately}}\Big) \quad \cdots (8)$$

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

- For the baseline result, we ignore the intrinsic EB correlations of the FG and the CMB
  - The latter is justified but the former is not
  - We will revisit this important issue at the end

Likelihood for determination of α and β

Minami et al. (2019)

Single frequency case, full sky data

$$-2\ln\mathcal{L} = \sum_{\ell=2}^{\ell_{\max}} \frac{\left[C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right) - \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}}\right)\right]^2}{\mathrm{Var}\left(C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)\right)} \quad \cdots (9)$$

- We determine α and β simultaneously using this likelihood

Estimate Variance (Information for experts)

- With full-sky power spectra (not cut-sky pseudo power spectra), we can calculate variance exactly as

$$
\begin{aligned}
&\mathrm{Var}\left[C_\ell^{EB,\mathrm{o}} - (C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}})\tan(4\alpha)/2\right] \\
&= \left\langle\left[C_\ell^{EB,\mathrm{o}} - (C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}})\tan(4\alpha)/2\right]^2\right\rangle - \langle C_\ell^{EB,\mathrm{o}} - (C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}})\tan(4\alpha)/2\rangle^2 \\
&= \frac{1}{2\ell+1}\langle C_\ell^{EE}\rangle\langle C_\ell^{BB}\rangle + \frac{\tan^2(4\alpha)}{4}\frac{2}{2\ell+1}\left(\langle C_\ell^{EE}\rangle^2 + \langle C_\ell^{BB}\rangle^2\right) \\
&\quad - \tan(4\alpha)\frac{2}{2\ell+1}\langle C_\ell^{EB}\rangle\left(\langle C_\ell^{EE}\rangle - \langle C_\ell^{BB}\rangle\right) + \underbrace{\boxed{\frac{1}{2\ell+1}\left(1-\tan^2(4\alpha)\right)\langle C_\ell^{EB}\rangle^2.}}_{=\ 0}
\end{aligned}
\qquad \cdots (9)
$$

- We approximate $\langle C_\ell^{XY}\rangle \approx C_\ell^{XY,o}$
- We ignore $\langle C_\ell^{EB}\rangle^2$ term because it's small and yields bias
  - Even if $\langle C_\ell^{EB}\rangle \approx 0$, $C_\ell^{EB,o}$ has a small non-zero value with fluctuation, and ${C_\ell^{EB,o}}^2$ yields bias

Likelihood for determination of α and β

Minami et al. (2019)

Single frequency case, full sky data

$$-2\ln\mathcal{L} = \sum_{\ell=2}^{\ell_{\max}} \frac{\left[C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right) - \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}}\right)\right]^2}{\mathrm{Var}\left(C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)\right)} \cdots (9)$$

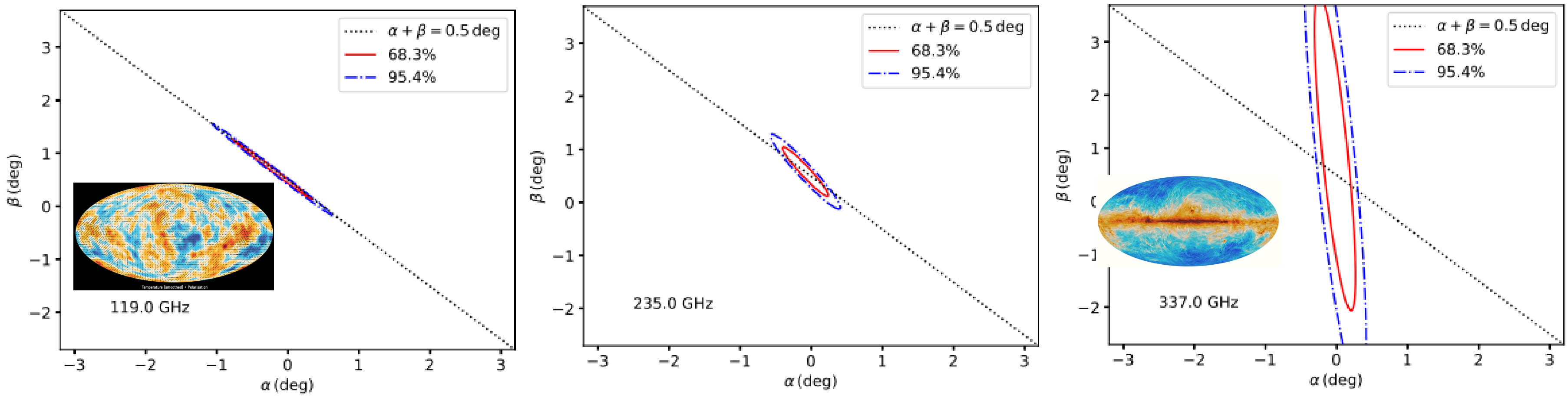
- We determine α and β simultaneously using this likelihood
- For analysing the Planck data, we use the multi-frequency likelihood developed in Minami and Komatsu (2020a)
- We first validate the algorithm using simulated data

How does it work?

How does it work?

Minami et al. (2019)

Simulation with future CMB data (LiteBIRD)



CMB channel (119 GHz) **Mid freq. (235 GHz)** **Dust FG channel (337 GHz)**

- The CMB signal determines the sum of two angles, $\alpha + \beta$
  - Diagonal line
- The FG determines only α
- Mid freq. : breaking the degeneracy with FG signal!
  - $\sigma(\beta) \sim \sigma(\alpha)$, since $\sigma(\alpha + \beta) \ll \sigma(\alpha)$

Application to the Planck Data (PR3, released in 2018)

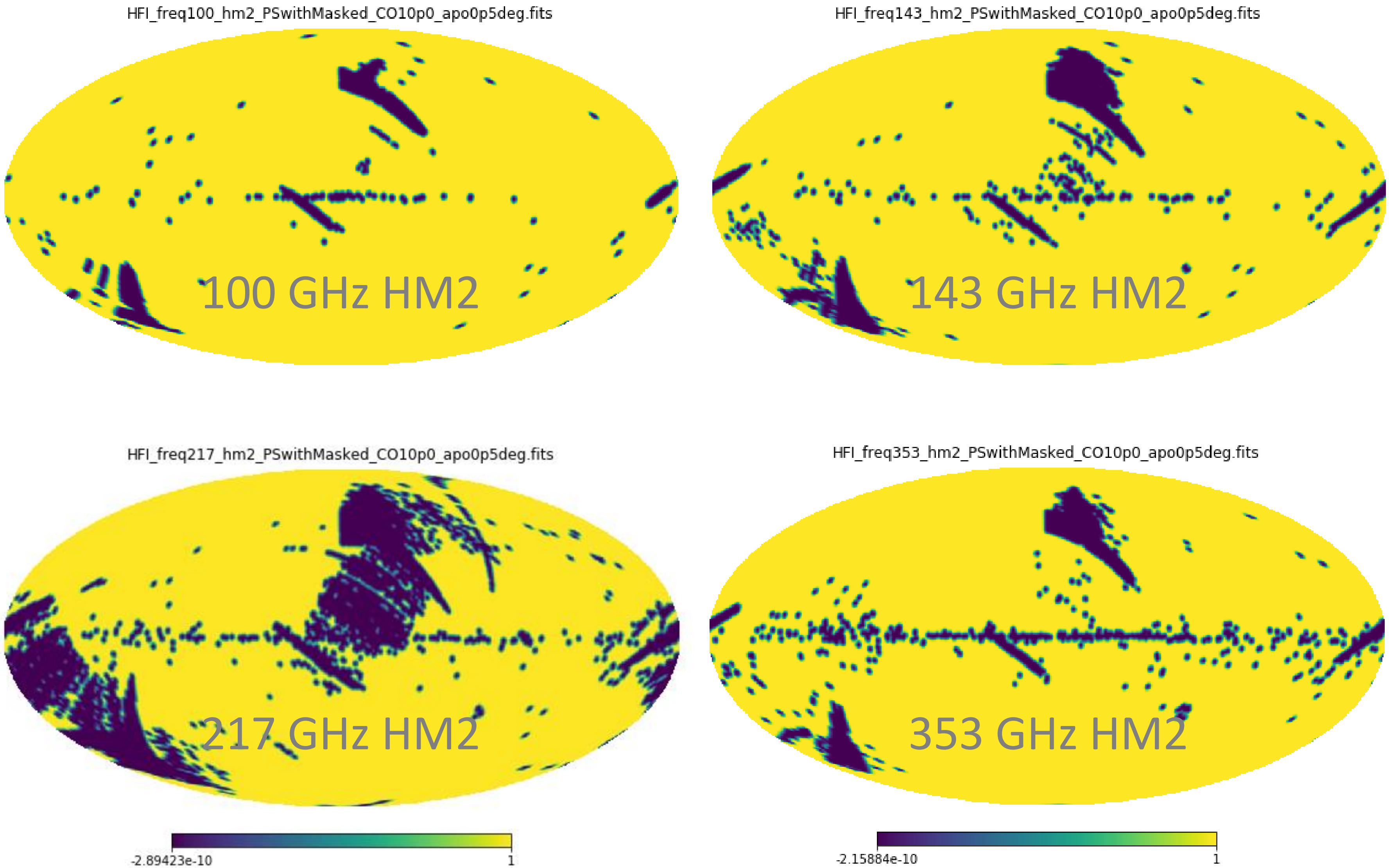
$\boldsymbol{\ell_{\mathbf{min}} = 51, \ell_{\mathbf{max}} = 1500}$ **(the same values used by Planck team)**

- We used Planck High Frequency Instrument (HFI) data
  - 4 channels: 100, 143, 217, and 353 GHz

Information for experts

- Power spectra calculated from "Half Missions" (HM1 and HM2 maps)
- Mask (using NaMaster [Alonso et al.]), apodization by "Smooth" with 0.5 deg
  - Bright CO regions. Bright point sources. Bad pixels.
- $I \to P$ leakage due to the beam is corrected using QuickPol [Hivon et al.]
  - It does not change the result even if we ignore this correction: good news!

Masks


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
-2.89423e-10
1
HFI_freq353_hm2_PSwithMasked_CO10p0_apo0p5deg.fits
353 GHz HM2
-2.15884e-10
1

Validation with FFP10

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

- There are 4 α_ν's and one β
- 10 simulations, without foreground samples because no beam systematics is applied them
  - We can check only $\beta(\alpha_\nu = 0)$ and only $\alpha_\nu(\beta = 0)$

Angles	$\alpha_\nu = 0$ (deg.)	$\beta = 0$ (deg.)
β	0.010 ± 0.030	-
α_{100}	-	-0.008 ± 0.047
α_{143}	-	0.013 ± 0.033
α_{217}	-	0.017 ± 0.065
α_{353}	-	0.14 ± 0.41

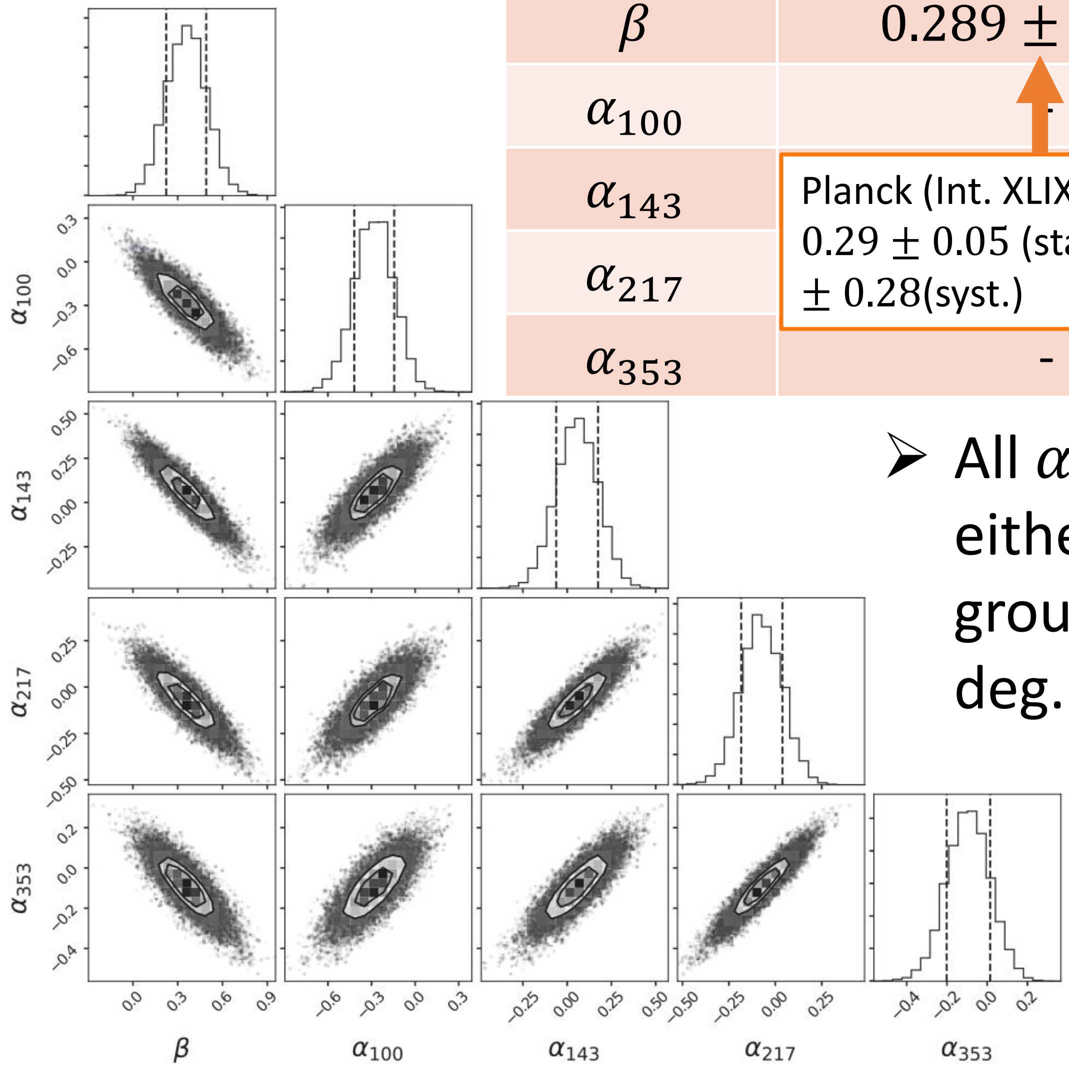
- No bias found. The test passed.

Main Results

Main results: $\beta > 0$ at 99.2% (2.4σ)

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

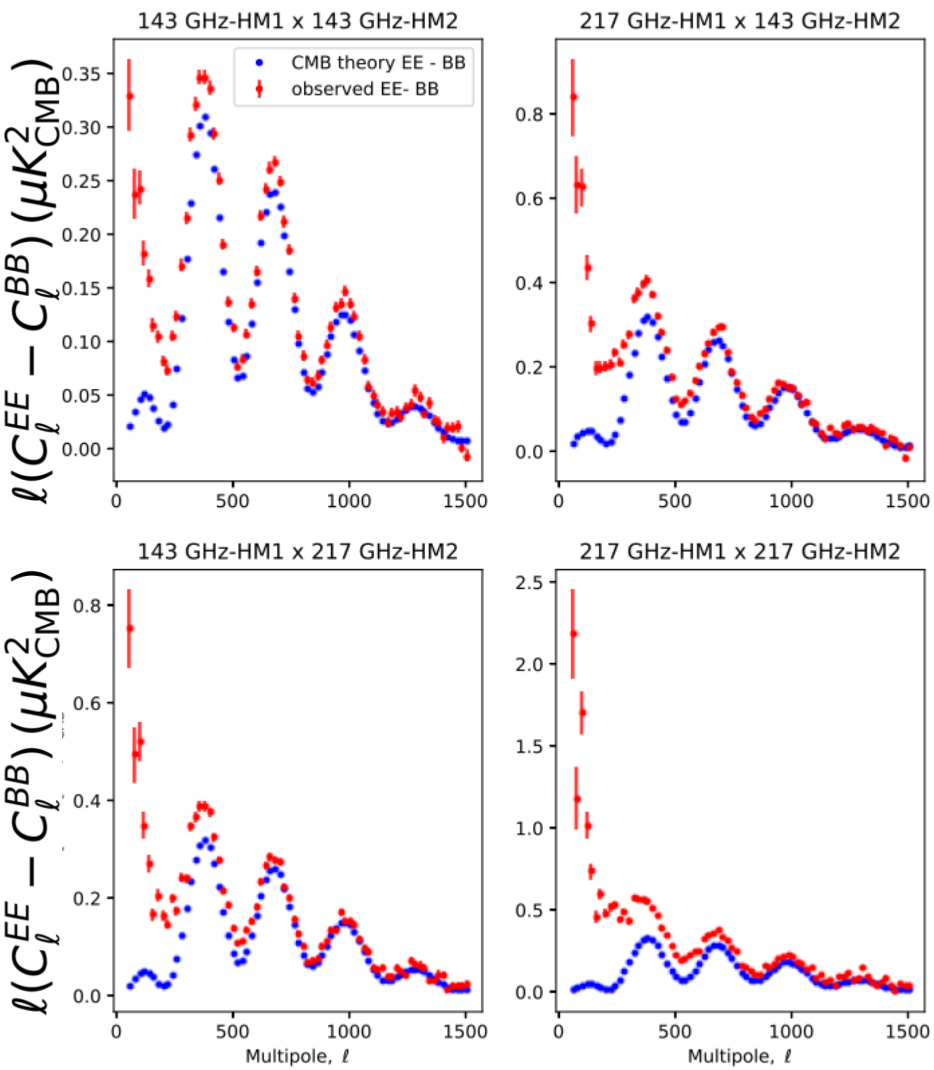
Planck (Int. XLIX):
0.29 ± 0.05 (stat.)
$\pm\ 0.28$(syst.)



- All α_ν are consistent with zero either statistically, or within the ground calibration error of 0.28 deg.
  - Removing α_{100} did not change β
  - $\beta = 0.35$ is consistent with the Planck's result

$EE - BB$ power spectra

Minami & Komatsu (2020b)

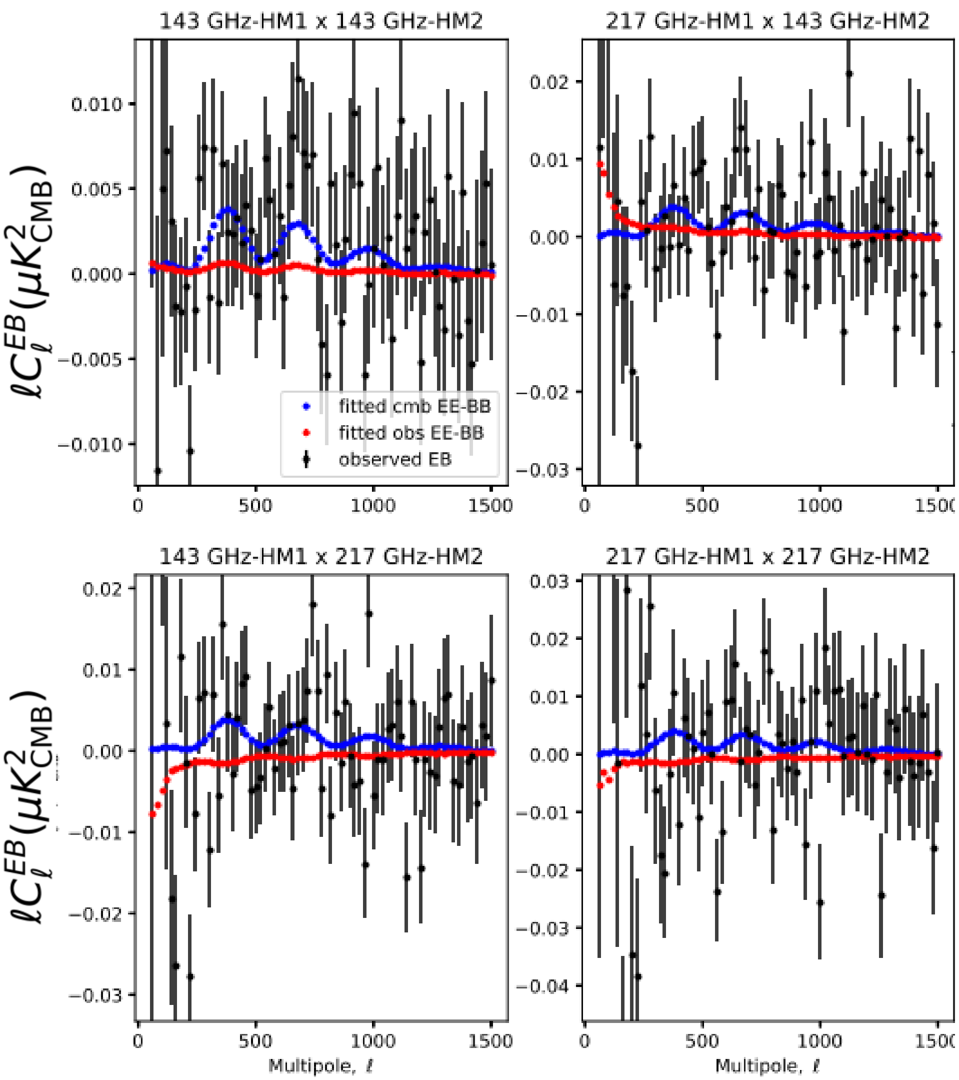


- Can we see $\beta = 0.35 \pm 0.14$ by eyes?
- First, take a look at the observed $EE - BB$ spectra
- Red: Observed total
- Blue: The best-fitting CMB model

*The difference is due to the FG (and potentially systematics)

EB power spectra (Black dots)

Minami & Komatsu (2020b)



- Can we see $\beta = 0.35 \pm 0.14$ by eyes?
- Red: The observed signal attributed to the miscalibration angle, α_ν
- Blue: The CMB signal attributed to the cosmic birefringence, β
- Red + Blue is the best-fitting model for explaining the data points (black dots)

How about the foreground $\boldsymbol{EB}$?

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

If the intrinsic foreground (FG) *EB* exists, our method interprets it as a miscalibration angle $\boldsymbol{\alpha}$

- Thus, $\alpha \to \alpha + \gamma$, where γ is the parameter of the intrinsic EB
  - The sign of γ is the same as the sign of the foreground EB
- We thus can determine:

FG: $\alpha + \gamma$

CMB: $\alpha + \beta$

$$\boldsymbol{\beta - \gamma = 0.35 \pm 0.14} \textbf{ deg.}$$

- There is evidence for the dust-induced $TE_{dust} > 0$ & $TB_{dust} > 0$; then, we'd expect $EB_{dust} > 0$ [Huffenberger et al.], i.e., $\gamma > 0$. If so, β increased further…
  - We can give a lower bound on β

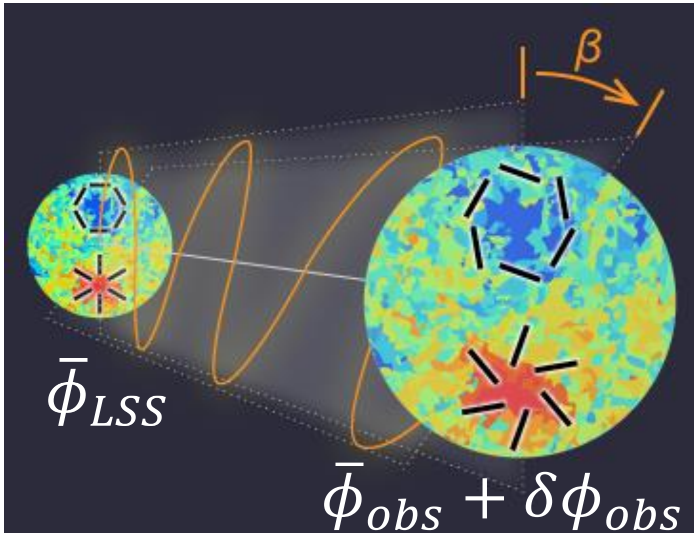
Implications

Minami & Komatsu (2020b)

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

- When a Lagrangian density includes a Chern-Simons coupling between a pseudo-scalar field and the electromagnetics tensor as:

$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \cdots (10)$$



- The birefringence angle is

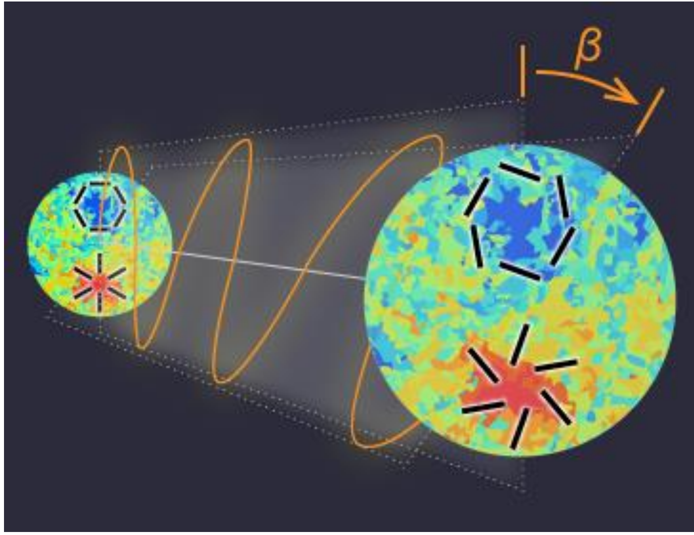
$$\beta = \frac{g_{\phi\gamma}}{2} \left(\bar{\phi}_{obs} - \bar{\phi}_{LSS} + \delta\phi_{obs} \right) \quad \cdots (11)$$

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); Fujita, Minami, et al. (2020)

- Our measurement yields

$$g_{\phi\gamma} \left(\bar{\phi}_{obs} - \bar{\phi}_{LSS} + \delta\phi_{obs} \right) = (1.2 \pm 0.5) \times 10^{-2} \text{ rad.} \quad \cdots (12)$$

Conclusion



- We find a hint of the parity violating-physics in the CMB polarization:

$\beta = 0.35 \pm 0.14$ deg. (68% C.L.)

*Higher statistical significance is needed to confirm this signal

- Our new method finally makes “impossible” to possible:
  - Use foreground signal to calibrate detector rotations
  - Our method can be applied to any of the **existing** and **future** CMB experiments
- We should be possible to test the signal is true or only a coincidence immediately
  - If confirmed, it would have important implications for the dark matter/energy.