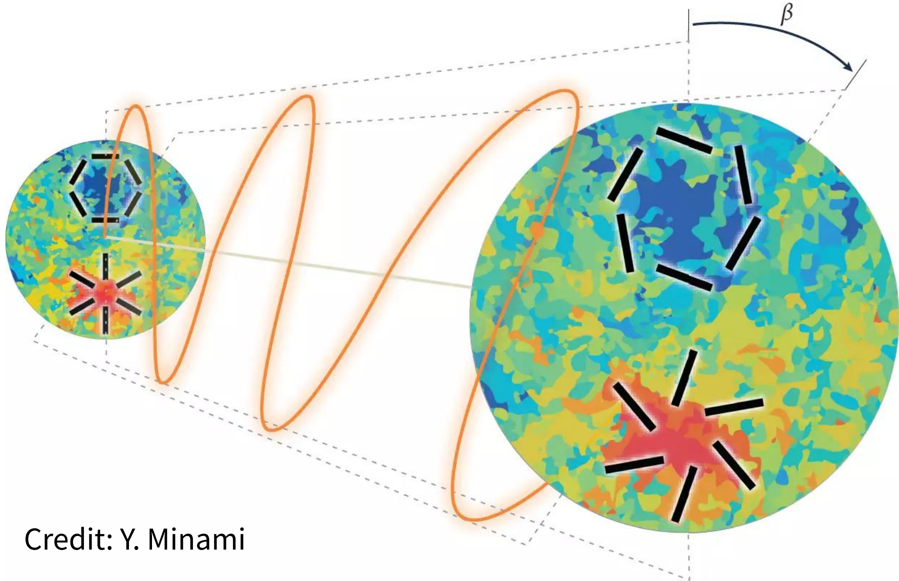
Improved Constraints on Cosmic Birefringence

Johannes R. Eskilt

Recent Progress in Axion Theory and Experiment
6th September 2022

Based on

- JRE & Komatsu: arXiv:2205.13962
- JRE: A&A 662, A10 (2022)
- Diego-Palazuelos, JRE, Minami, Tristram, Sullivan et al: Phys. Rev. Lett. 128, 091302 (2022)



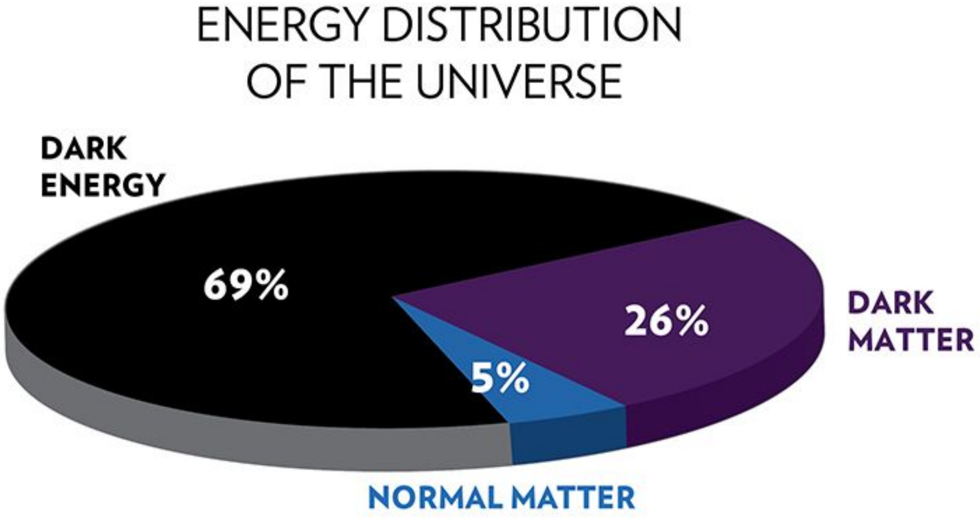
Credit: Y. Minami

What is the content of our universe?

Axions or axion-like fields are candidates for

- Dark matter
- Dark energy
- Inflation

NASA/CXC/K.Divona



An axion-like field can couple to electromagnetism

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

Electromagnetism Chern-Simons term

- Left and right-circular polarization have different phase-velocities
- Causes a rotation of linear polarization
- Parity violation!

$$\begin{aligned}\beta &= -\frac{g_{\gamma\phi}}{2}\int_{\mathrm{emission}}^{\mathrm{observer}} \dot{\phi}\, dt \\ &= -\frac{g_{\gamma\phi}}{2}\left(\phi_{\mathrm{observer}} - \phi_{\mathrm{emission}}\right) \\ &= -\frac{g_{\gamma\phi}}{2}\Delta\phi\end{aligned}$$

Carroll, Field & Jackiw (1990)

Hubble friction causes ultra-light fields to move slowly

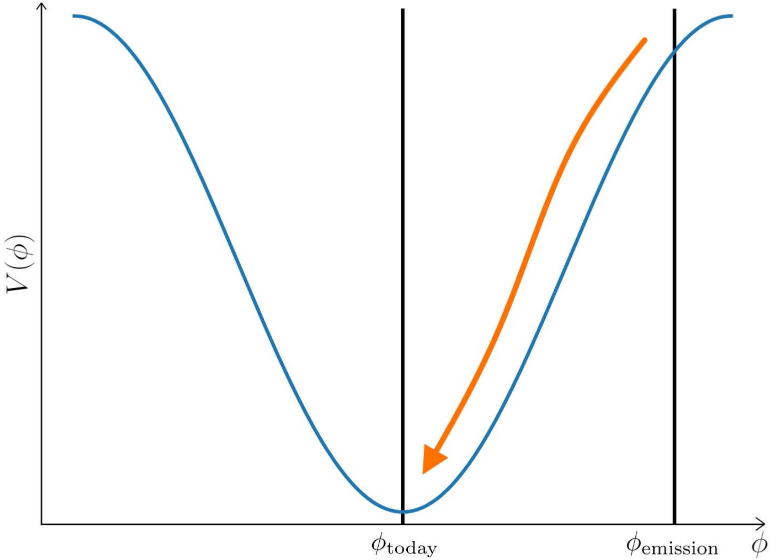
If $H_0 \lesssim m \lesssim H_{\rm CMB}$ $\quad (10^{-33}\,\mathrm{eV} \lesssim m \lesssim 10^{-28}\,\mathrm{eV})$

Then $\phi_{\rm today} \approx 0$

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

$$\beta \approx \frac{g_{\gamma\phi}}{2}\phi_{\rm emission}$$

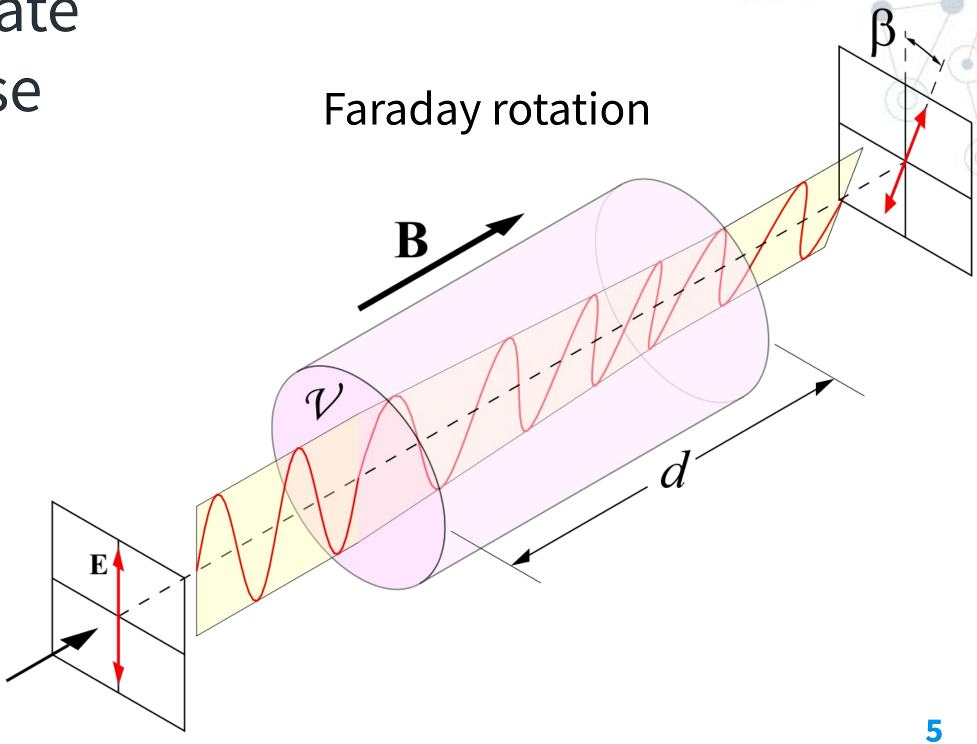
- This effect is called ‘Cosmic Birefringence’



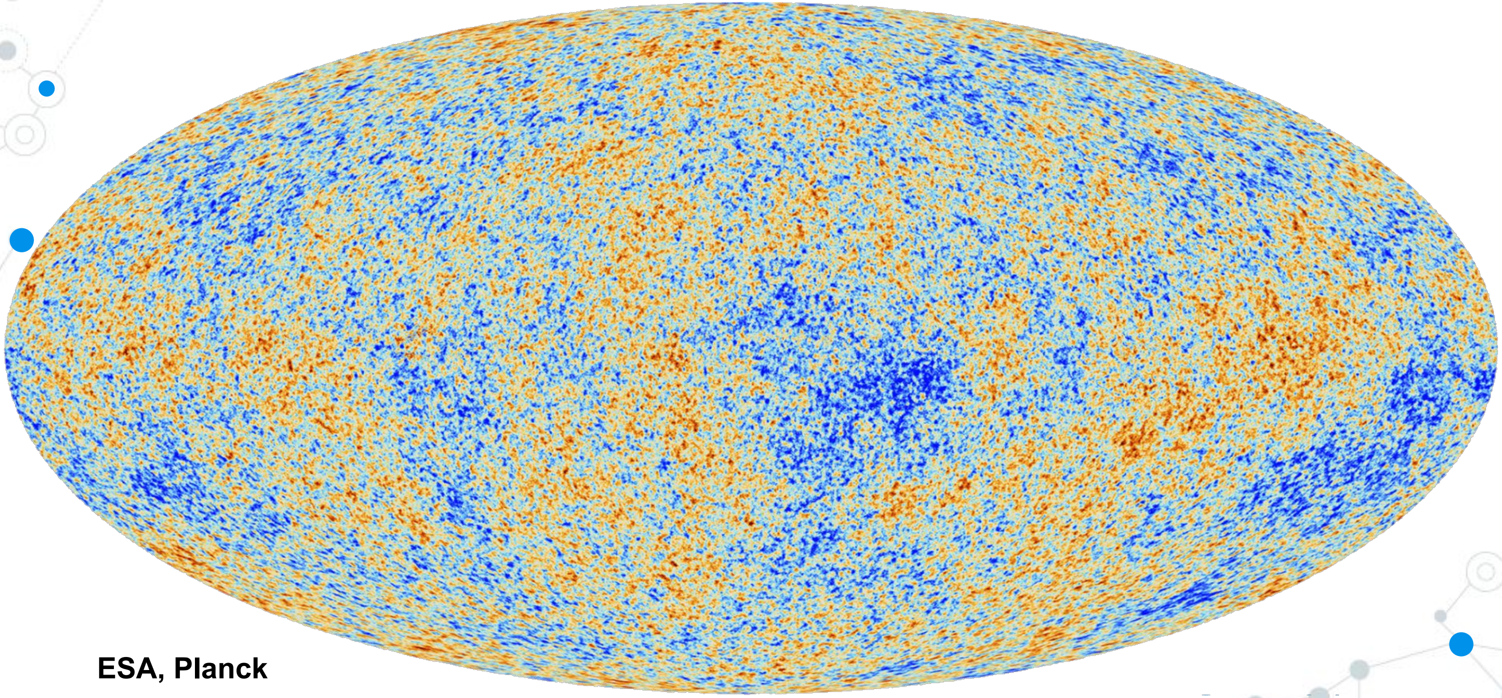
Birefringence

- Birefringent materials cause linearly polarized light to rotate
- Magnetic fields can also cause rotation of linearized light (Faraday rotation)

Faraday rotation

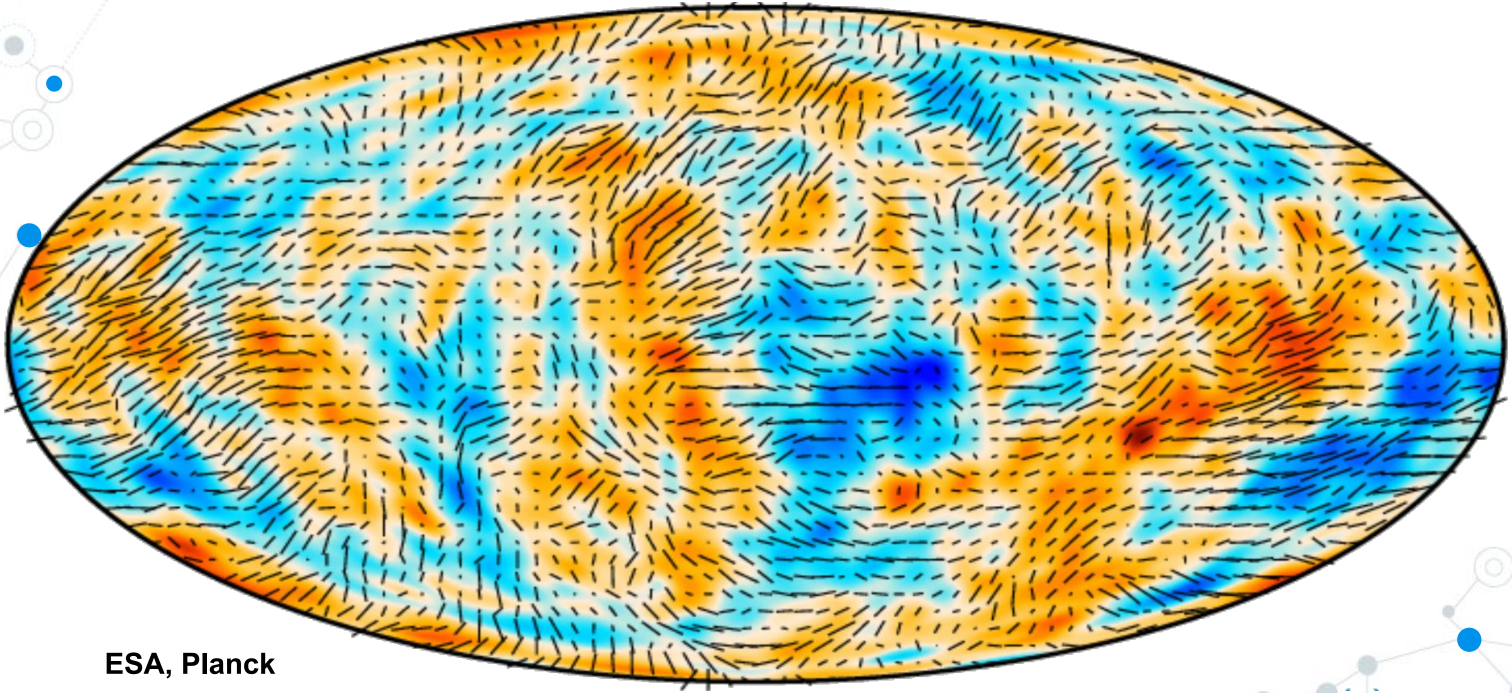


The CMB is *not just* the oldest light in the universe



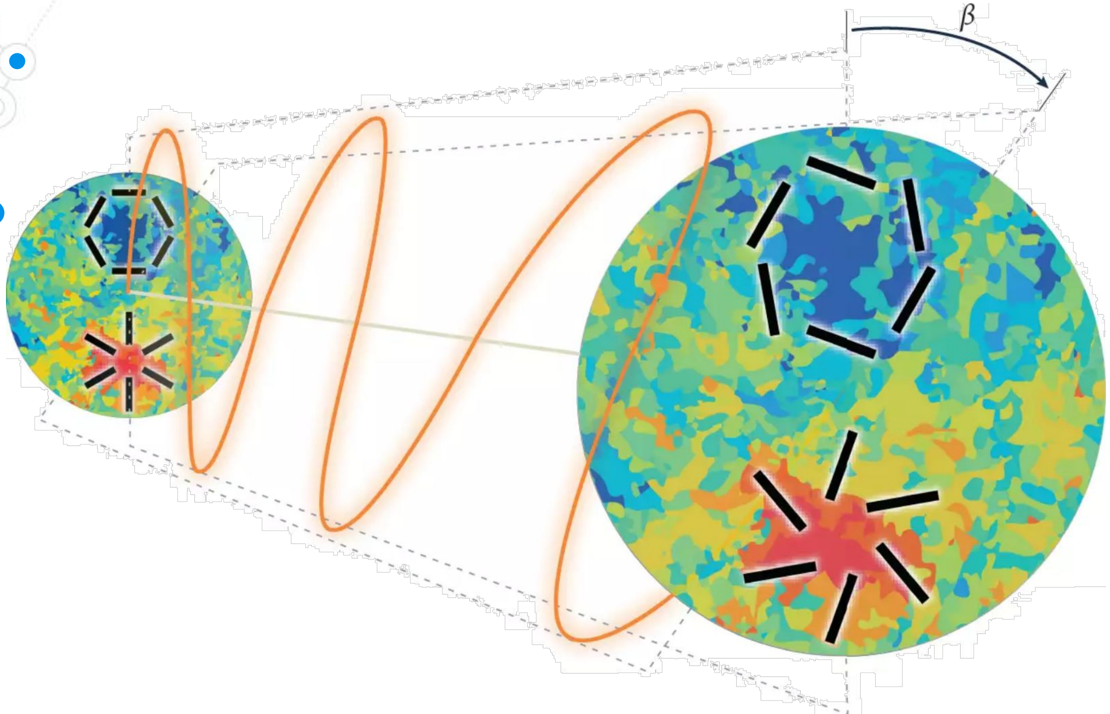
ESA, Planck

The CMB is also the oldest *polarized* light in the universe

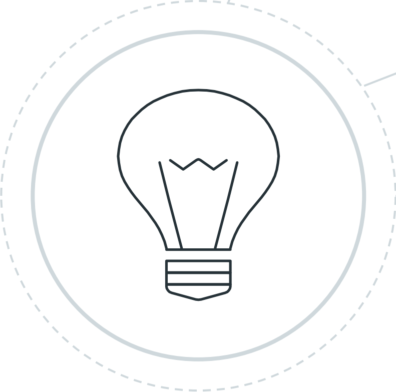


ESA, Planck

The polarized CMB can be used to probe cosmic birefringence!



Spoiler alert



With Planck and WMAP data,
we measure this angle to be

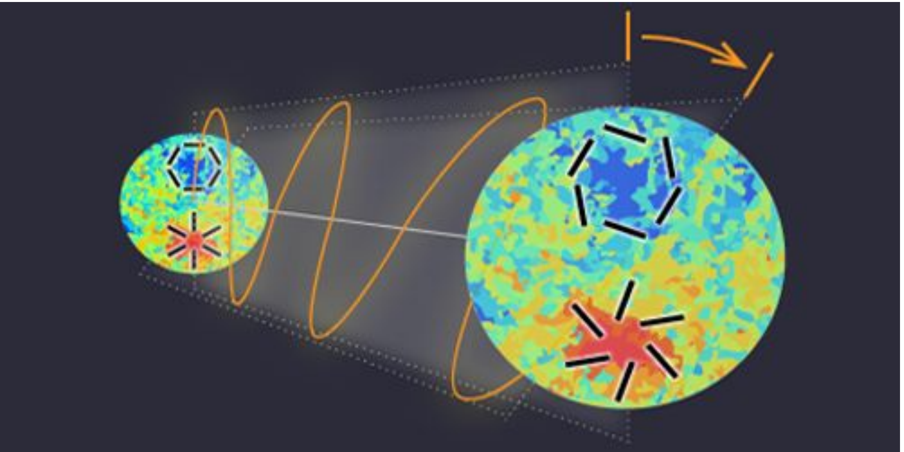
$$\beta = 0.342^\circ\,{}^{+0.094^\circ}_{-0.091^\circ} \quad (68\% \;\; \mathrm{C.L.})$$

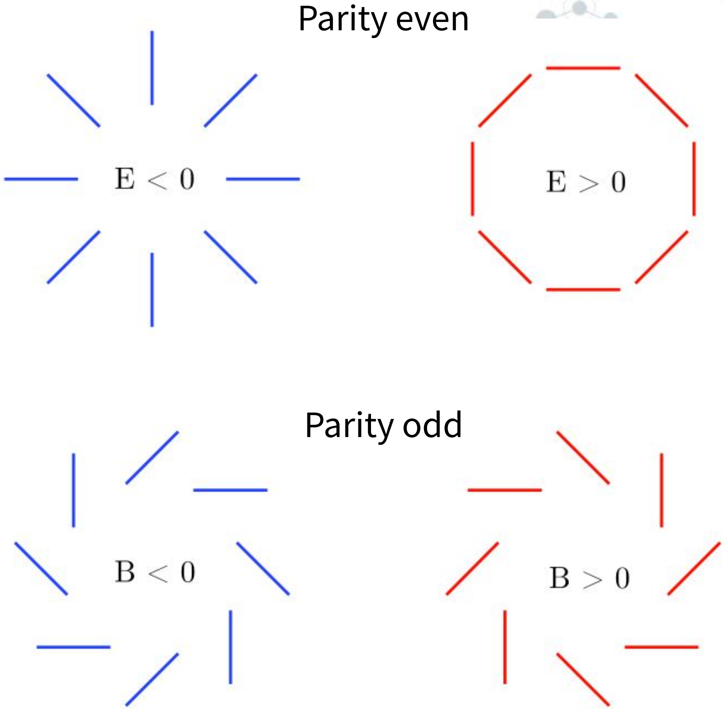
JRE & Komatsu: arXiv:2205.13962

How do we measure isotropic cosmic birefringence?

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

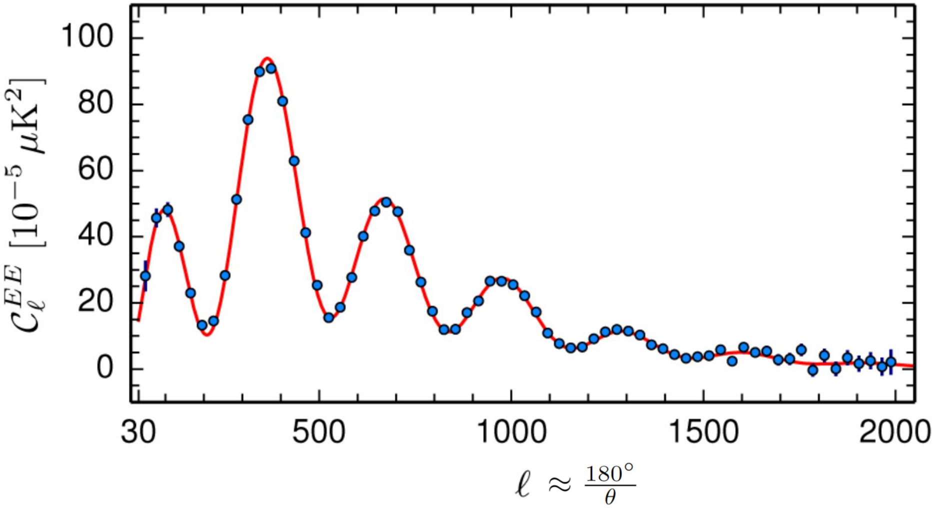
- The linearly polarized CMB is described by the Q and U Stokes parameters
- These are turned into the so-called E- and B-modes
  - NB: Nothing to do with electric and magnetic fields!





Baumann et al. 2009 - arXiv:0811.3919

Amount of E and B-modes are quantified by power spectra in harmonics space

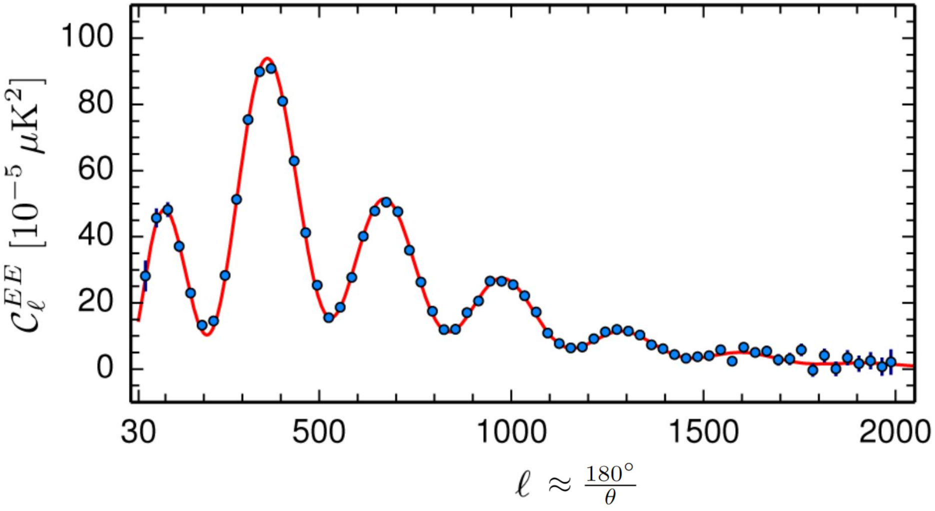


Planck 2015, arXiv:1502.01589

$$C_\ell^{XY} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} X_{\ell m} Y_{\ell m}^*$$

C_ℓ^{EE} EE power spectrum (amount of E-modes)

Amount of E and B-modes are quantified by power spectra in harmonics space



Planck 2015, arXiv:1502.01589

$$C_\ell^{XY} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} X_{\ell m} Y_{\ell m}^*$$

C_ℓ^{EE} EE power spectrum (amount of E-modes)

C_ℓ^{BB} BB power spectrum (amount of B-modes)

Not found

(Lensing found)

C_ℓ^{EB} C_ℓ^{TB} C_ℓ^{TE}

Parity symmetry:

$$C_\ell^{EB} = 0$$

$$C_\ell^{TB} = 0$$

Parity violation:

$$C_\ell^{EB} \neq 0$$

$$C_\ell^{TB} \neq 0$$

E-modes and B-modes get rotated

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

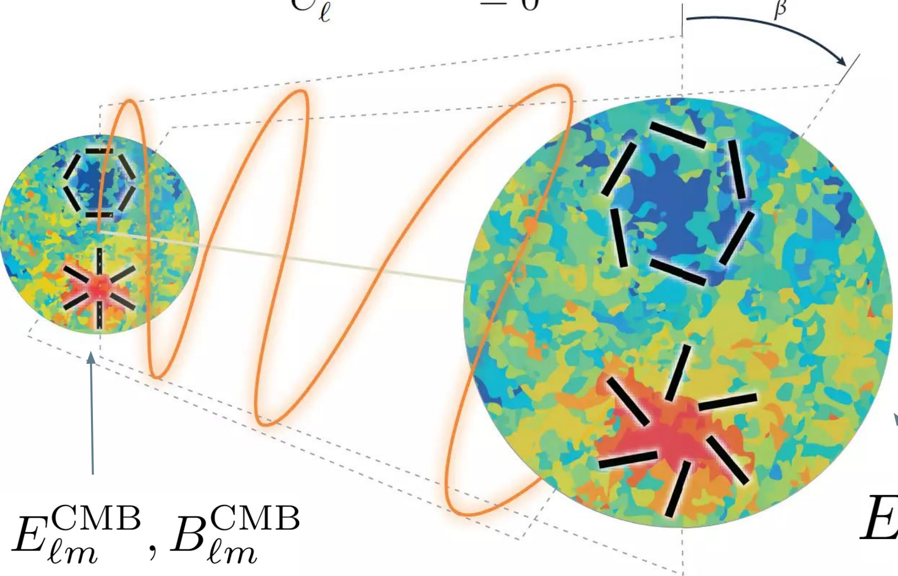
- If we had perfect instruments and no galactic foreground, cosmic birefringence analysis would be easy

- CMB EB correlation not predicted by LCDM $C_\ell^{EB,CMB} = 0$

'o' = observed from our telescopes

$$\begin{bmatrix} E^o_{\ell m} \\ B^o_{\ell m} \end{bmatrix} = \begin{bmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{bmatrix} \begin{bmatrix} E^{CMB}_{\ell m} \\ B^{CMB}_{\ell m} \end{bmatrix}$$

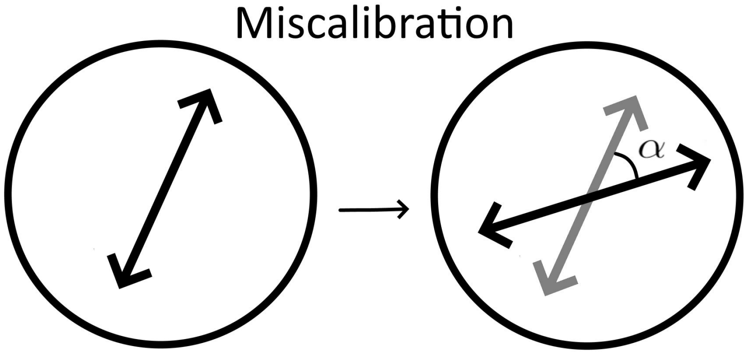
$$C_\ell^{EB,o} = \frac{\sin(2\beta)}{2}\left(C_\ell^{EE,CMB} - C_\ell^{BB,CMB}\right) + \cancel{\frac{C_\ell^{EB,CMB}}{\cos(2\beta)}}$$



$E^{\mathrm{CMB}}_{\ell m}, B^{\mathrm{CMB}}_{\ell m}$

$E^o_{\ell m}, B^o_{\ell m}$

Two problems

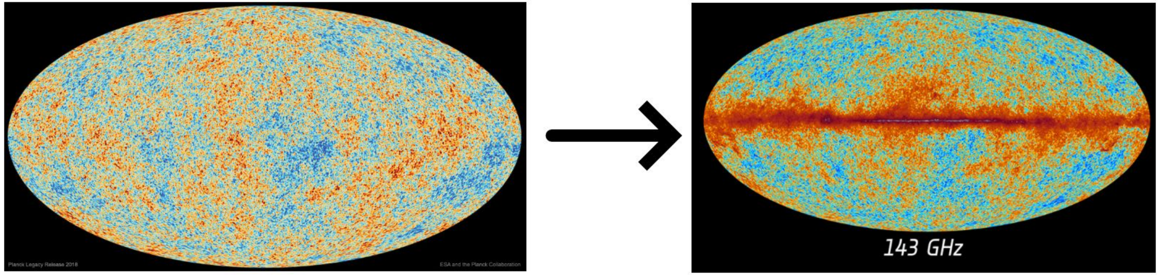


1. Miscalibration angles:

   Measuring the wrong polarization angle

2. Galactic foreground:

   Dust and other stuff in our galaxy ‘contaminates’ our measurement of the CMB



Miscalibration angles

- α = miscalibration angle (different for each experiment)
- β = cosmic birefringence angle (same for all experiments)

$$\alpha + \beta = -0.36 \pm 1.24 \text{ deg}, \text{ (WMAP, Hinshaw et al. 2012, Komatsu et al. 2009)}$$
$$\alpha + \beta = 0.31 \pm 0.05 \text{ deg}, \text{ (Planck Collaboration 2016)}$$
$$\alpha + \beta = -0.61 \pm 0.22 \text{ deg}, \text{ (POLARBEAR Collaboration 2020)}$$
$$\alpha + \beta = 0.63 \pm 0.04 \text{ deg}, \text{ (SPT Collaboration, Bianchi et al. 2020)}$$
$$\alpha + \beta = 0.07 \pm 0.09 \text{ deg}, \text{ (ACT Collaboration, Choi et al. 2020)}$$

What is the miscalibration angle and what is the cosmic birefringence angle?
Uncertainty of β is unknown

New method was developed

Minami et al. 2019, Minami & Komatsu 2020

Assumption: Cosmic birefringence has a negligible impact on foreground polarization!

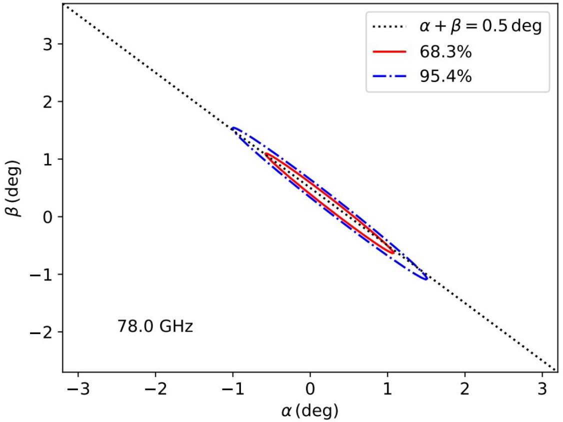
$$\begin{bmatrix} E^{o}_{\ell m} \\ B^{o}_{\ell m} \end{bmatrix} = \begin{bmatrix} \cos(2\alpha) & -\sin(2\alpha) \\ \sin(2\alpha) & \cos(2\alpha) \end{bmatrix} \begin{bmatrix} E^{FG}_{\ell m} \\ B^{FG}_{\ell m} \end{bmatrix} + \begin{bmatrix} \cos(2\alpha+2\beta) & -\sin(2\alpha+2\beta) \\ \sin(2\alpha+2\beta) & \cos(2\alpha+2\beta) \end{bmatrix} \begin{bmatrix} E^{CMB}_{\ell m} \\ B^{CMB}_{\ell m} \end{bmatrix}$$

Foreground is rotated by miscalibration only, while the CMB is rotated by miscalibration plus birefringence

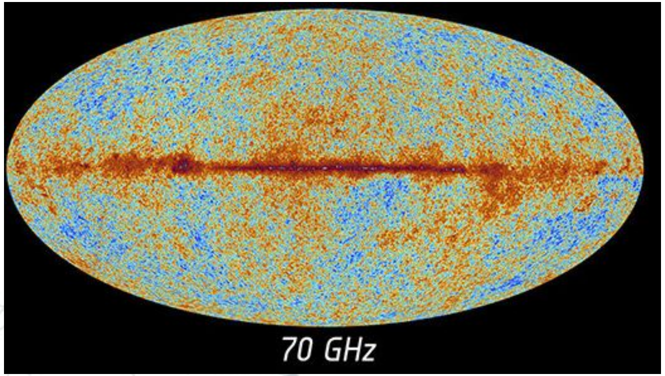
$$C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}} \right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}} \right) + \frac{1}{\cos(4\alpha)} \boxed{C_\ell^{EB,\mathrm{fg}}} + \cancel{\frac{\cos(4\beta)}{\cos(4\alpha)}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

CMB dominated frequency band:
$\alpha + \beta$ is well constrained

β



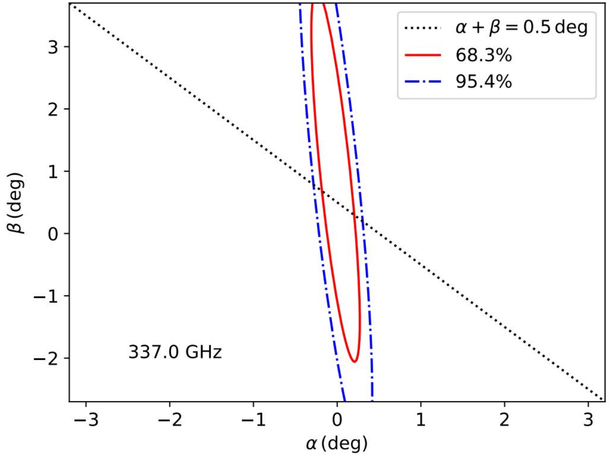
α



ESA and the Planck Collaboration

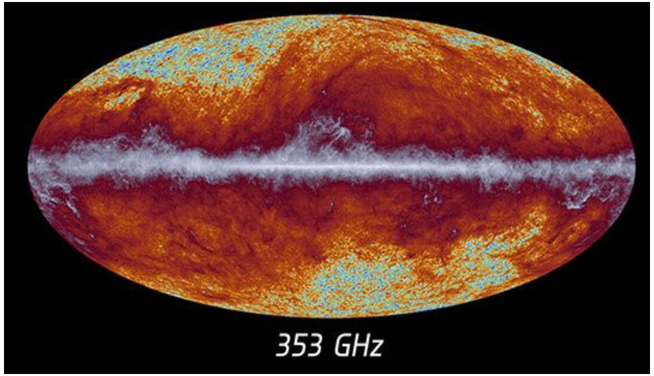
Foreground dominated frequency band:
α is well constrained

β



α

Minami et al. 2019



Featured in Physics Editors' Suggestion

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

$$\beta = 0.35 \pm 0.14\,\mathrm{deg}\ (68\%\ \mathrm{C.L.})$$

Yuto Minami and Eiichiro Komatsu

Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

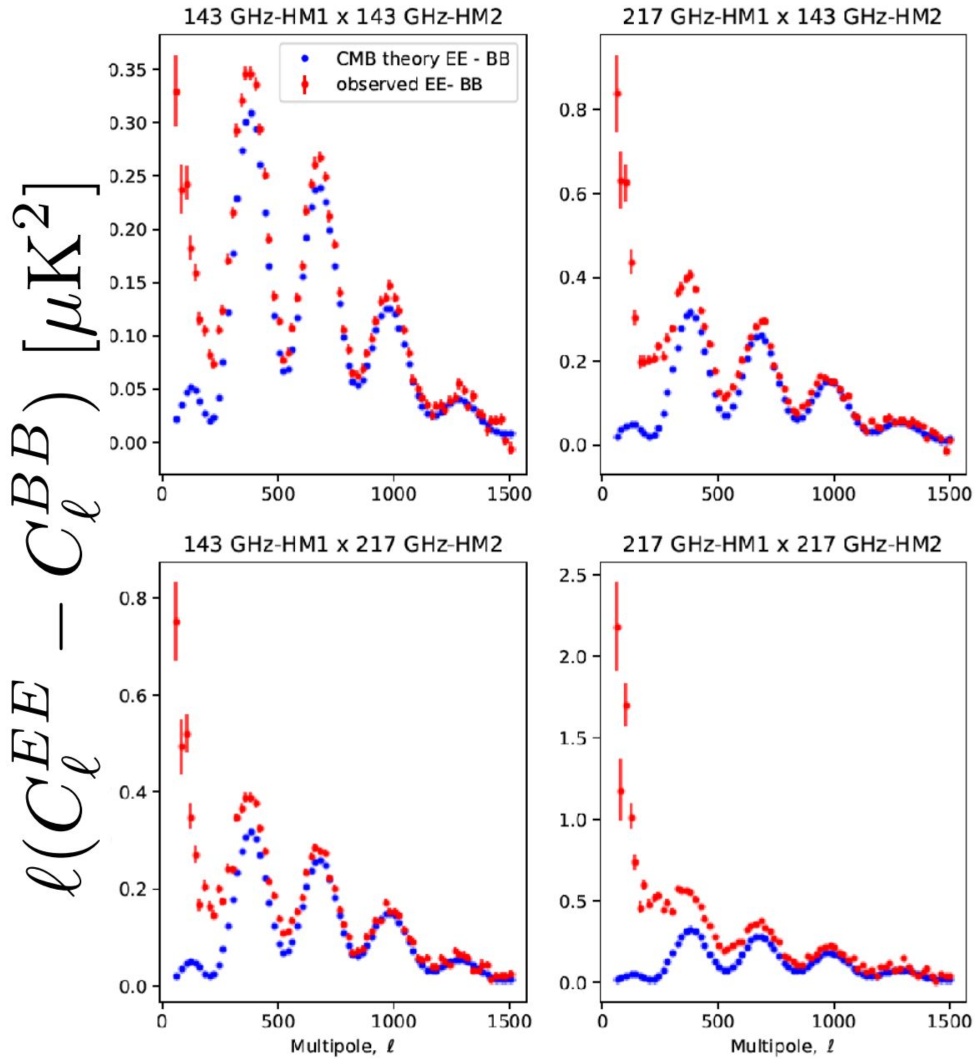
$$2.4\sigma$$

Physics See synopsis: Hints of Cosmic Birefringence?

Article | References | Citing Articles (33) | 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.

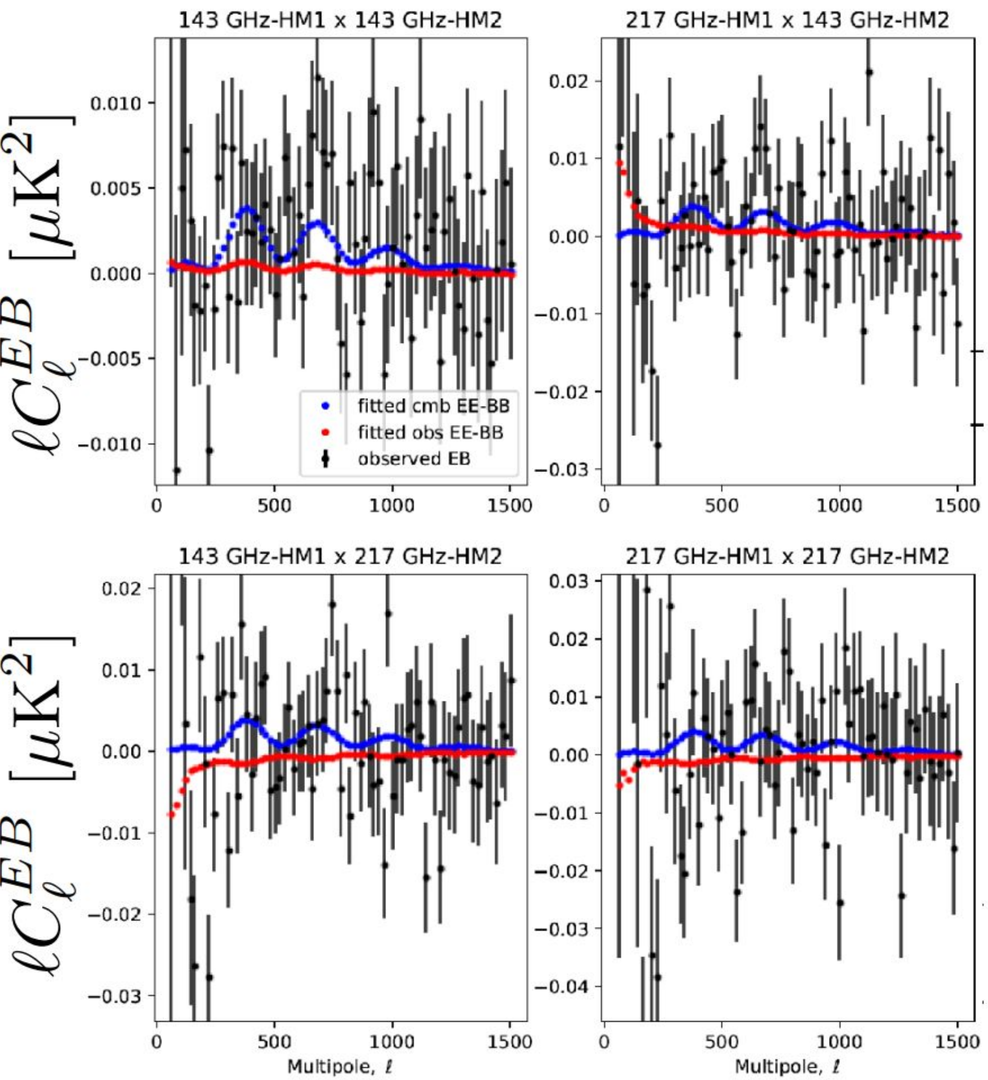


$$C_\ell^{EB,\mathrm{o}} = \frac{\tan(4\alpha)}{2}\boxed{\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)} + \frac{\sin(4\beta)}{2\cos(4\alpha)}\boxed{\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}}\right)}$$

Red = foreground + CMB

Blue = CMB

Minami & Komatsu 2020



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

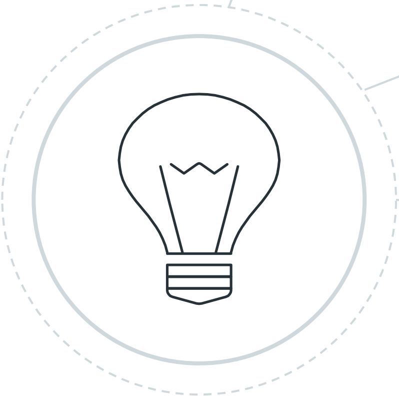
Red = alpha * (foreground + CMB)

Blue = beta * CMB

Best-fit values for beta and alpha

Minami & Komatsu 2020

Initial response

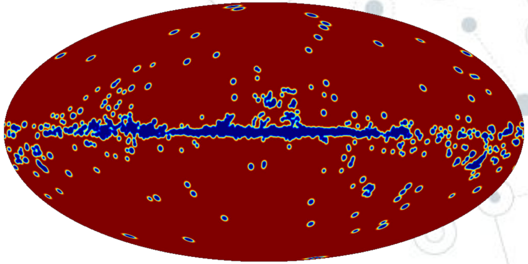


1. 2.4 sigma isn’t that high
2. We don’t understand EB of dust well enough

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

Follow up work

Diego-Palazuelos, JRE, Minami, Tristram et al. Phys. Rev. Lett. **128**, 091302 2022



- We used Planck Data Release 4 rather than 3
  - Higher signal-to-noise
  - Excluding EB of dust: $\beta = 0.30^\circ \pm 0.11^\circ$
- Accounted for EB by using a dust model, but the approach is generic
  - We take EB/EE to be proportional to TB/TE
  - $\beta = 0.36^\circ \pm 0.11^\circ$ (it increases by including dust EB)

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

Not measured by Planck

Measured by Planck

$$\frac{C^{EB,\mathrm{dust}}}{C^{EE,\mathrm{dust}}} \propto \frac{C^{TB,\mathrm{dust}}}{C^{TE,\mathrm{dust}}}$$

Measured by Planck

Measured by Planck

More explicitly

$$C^{EB,\mathrm{dust}} = A_\ell C^{EE,\mathrm{dust}} \sin(4\psi_\ell)$$

$$\psi_\ell = \frac{1}{2}\arctan\left(\frac{C^{TB,\mathrm{dust}}}{C^{TE,\mathrm{dust}}}\right)$$

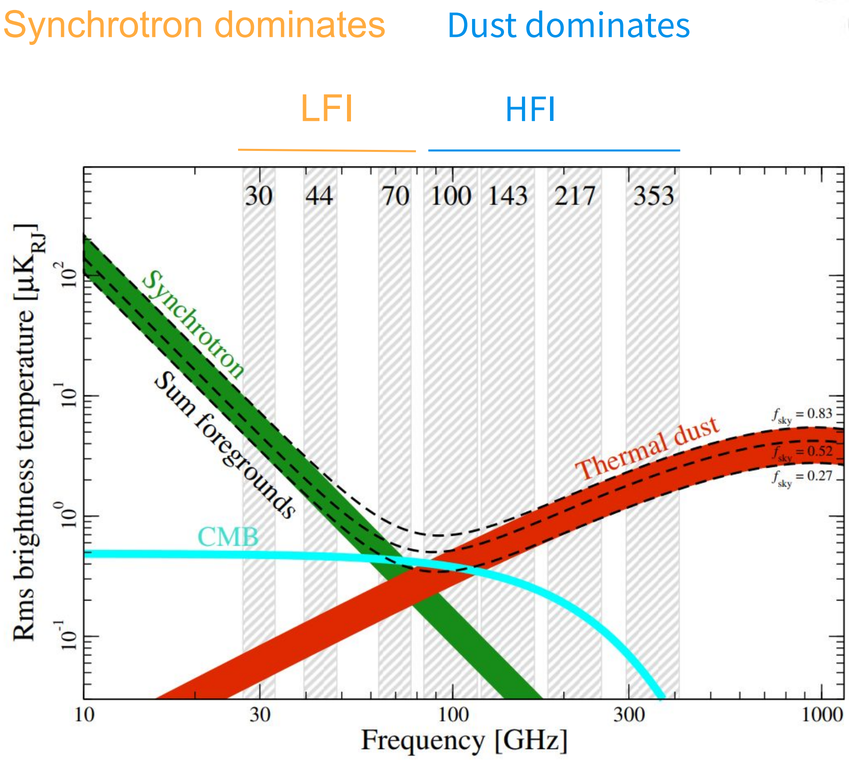
Our ansatz is motivated by the works of Clark et al. (2020)

We calculate ψ_ℓ from 353 GHz channel of Planck where dust dominates.

We fit for A_ℓ in 4 ell-bins simultaneously with β and α

What happens if we include all Planck maps?

- So far we have only looked at HFI where dust dominates
- LFI bands are dominated by synchrotron emission, not dust
- Synchrotron EB has been found to be consistent with zero (Martire et al. 2021)



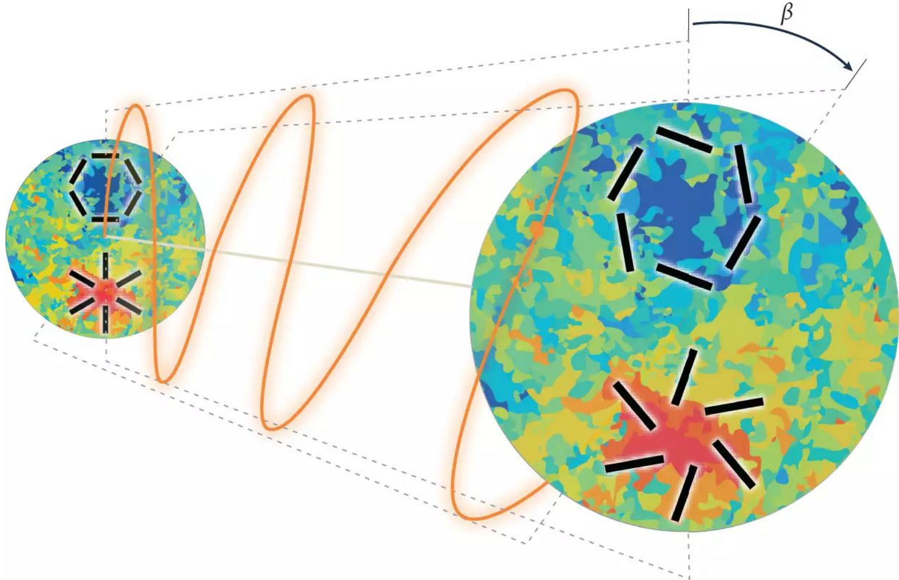
Planck 2018 Results IV

What is the origin of the signal? (if real)

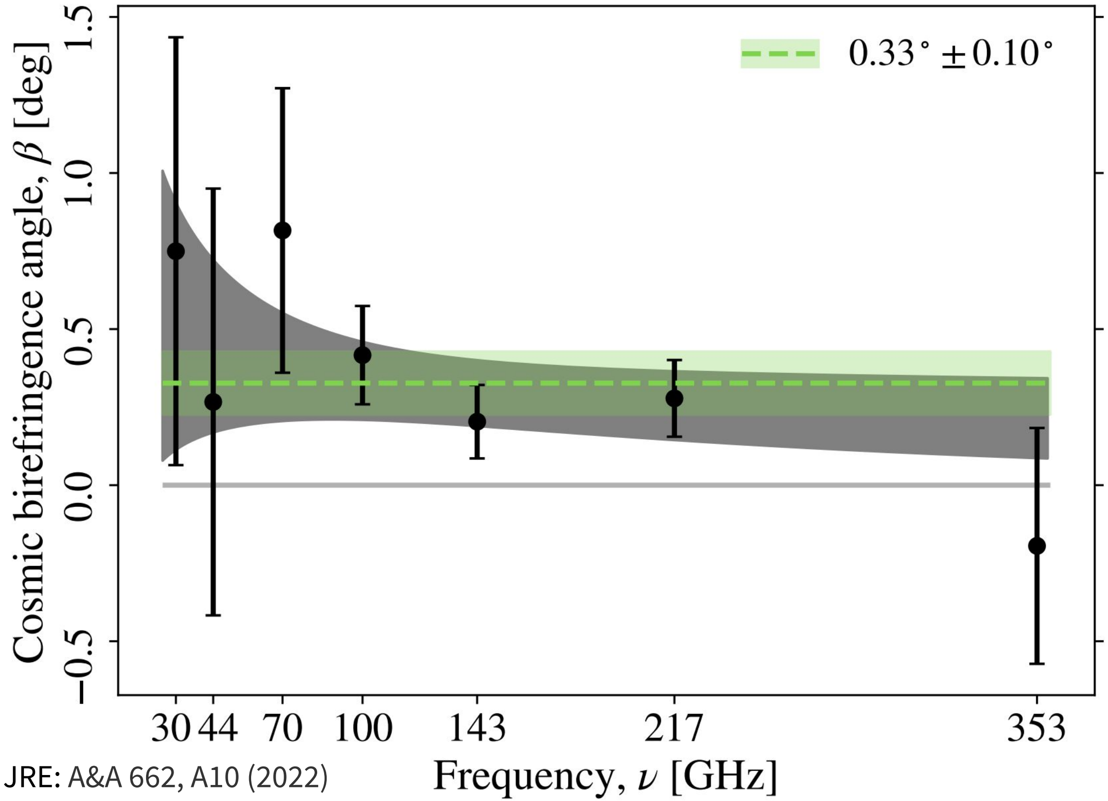
- We can look at the frequency dependence!

- $$\beta_\nu = \beta_0(\nu/\nu_0)^n$$

  - n = 0 for an axion-like field!
  - n = -2 for Faraday rotation
  - n = 1, 2 for quantum gravity theories/Lorentz violating theories



Signal is consistent with being frequency-independent



JRE: A&A 662, A10 (2022)

$$\beta_\nu = \beta_0(\nu/\nu_0)^n$$

$$n = -0.20^{+0.41}_{-0.39}$$ Planck + WMAP, Eskilt&Komatsu 2022

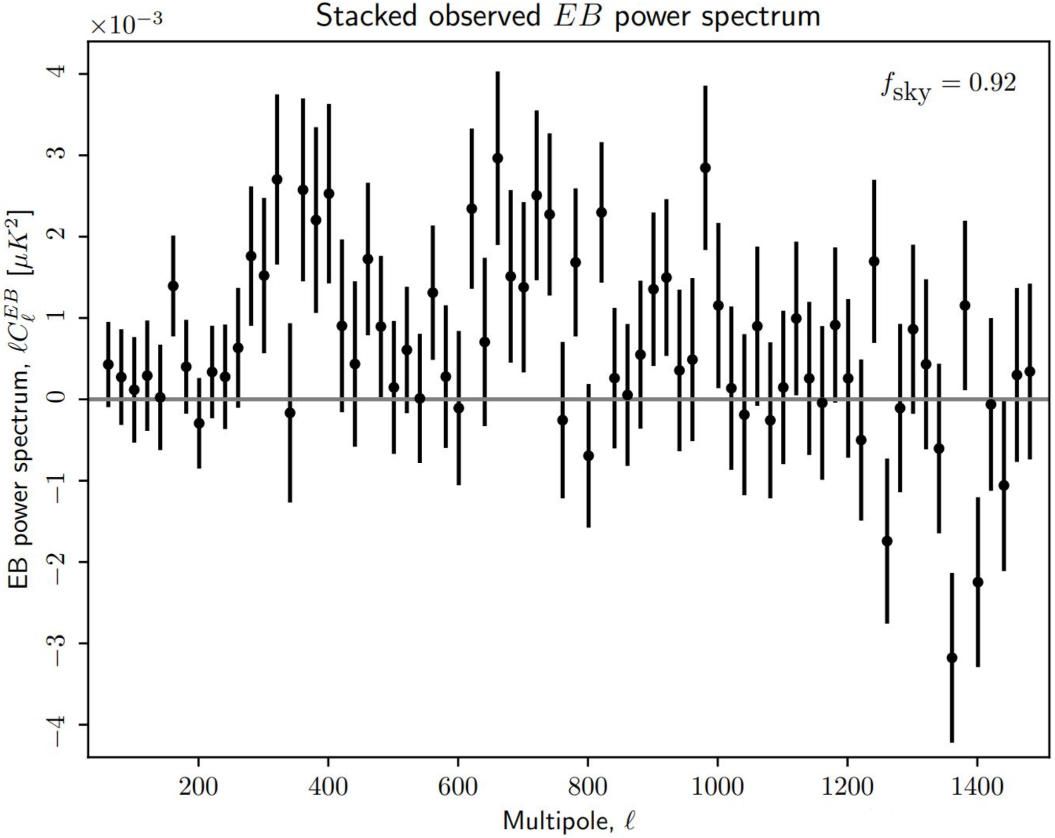
- ◎ Consistent with an axion-like field (n = 0)
- ◎ Faraday rotation caused by magnetic fields are disfavoured (n = -2)

Adding LFI increased the significance!

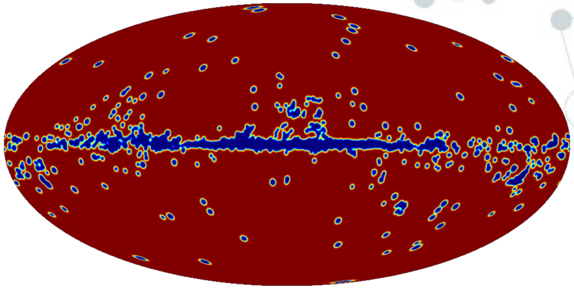
LFI contains little dust, and synchrotron EB has been found to be consistent with zero.

What happens if we also add WMAP?

Adding WMAP increases the significance

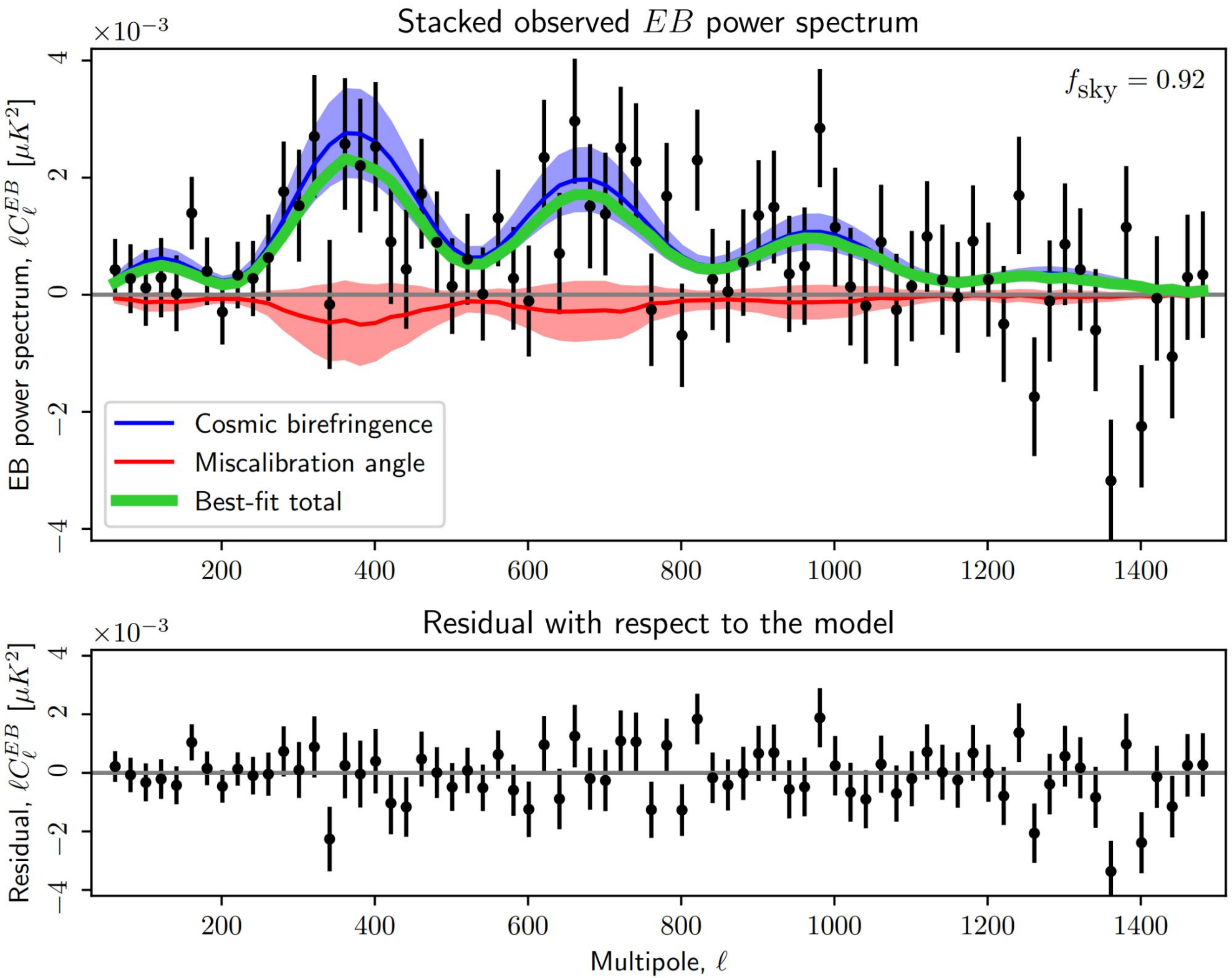


$$\beta = 0.342^\circ {}^{+0.094^\circ}_{-0.091^\circ}$$

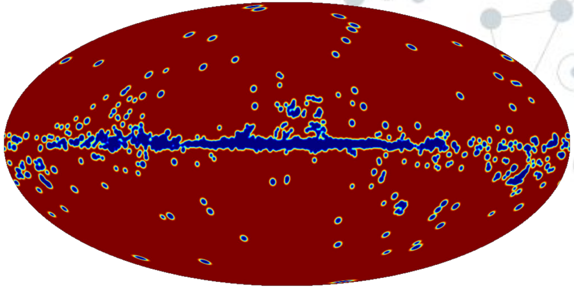


We are seeing something!

$$\chi^2 = 125.5 \text{ for DOF=72}$$

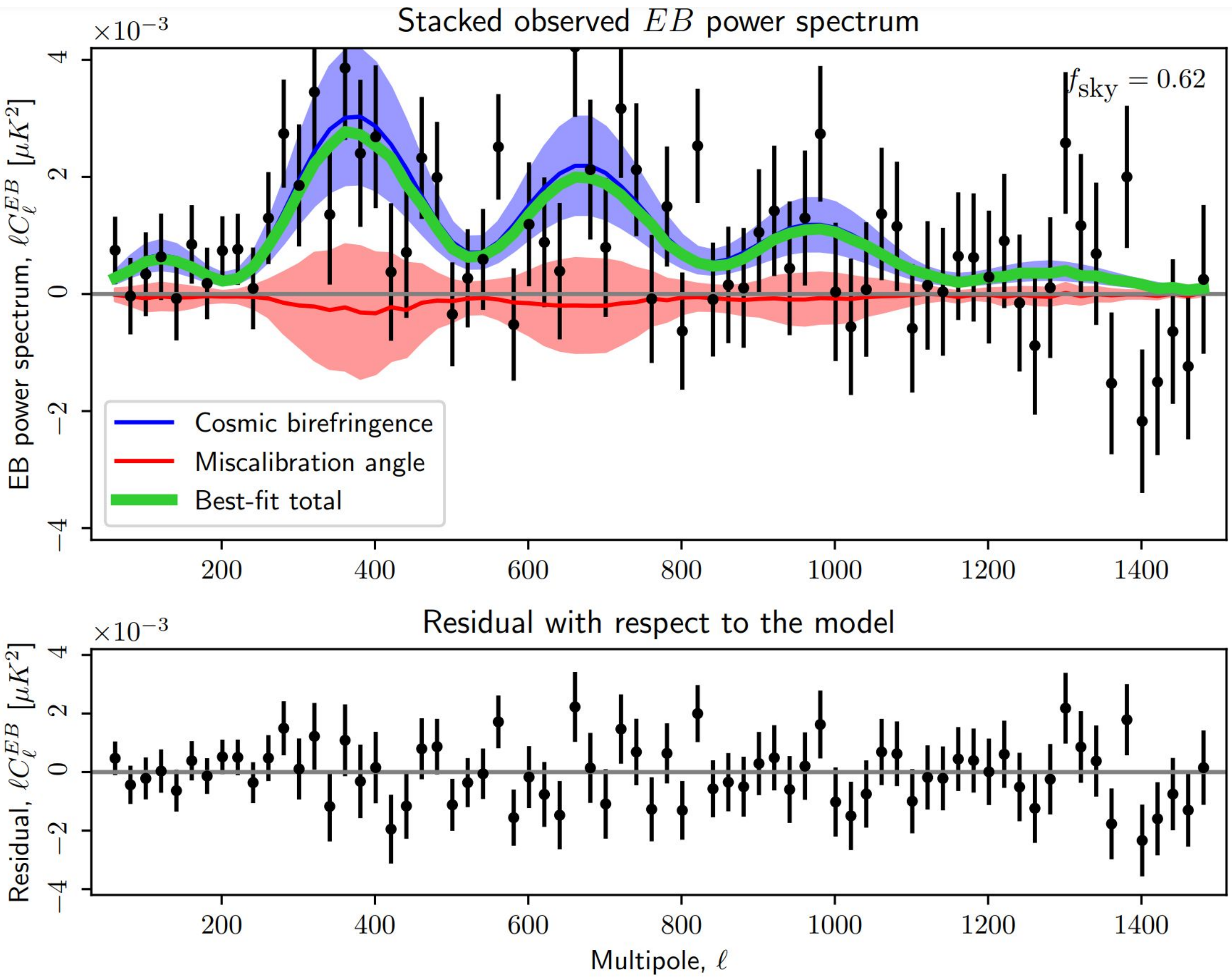


$$\beta = 0.342^\circ {}^{+0.094^\circ}_{-0.091^\circ}$$

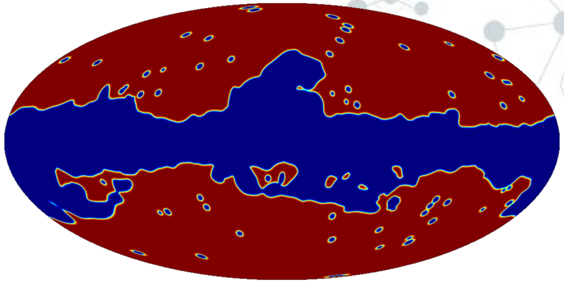


Model fits data well!

$$\chi^2 = 65.3 \text{ for DOF} = 72$$



$$\beta = 0.37^\circ \pm 0.14^\circ$$



Consistent results for larger sky mask!

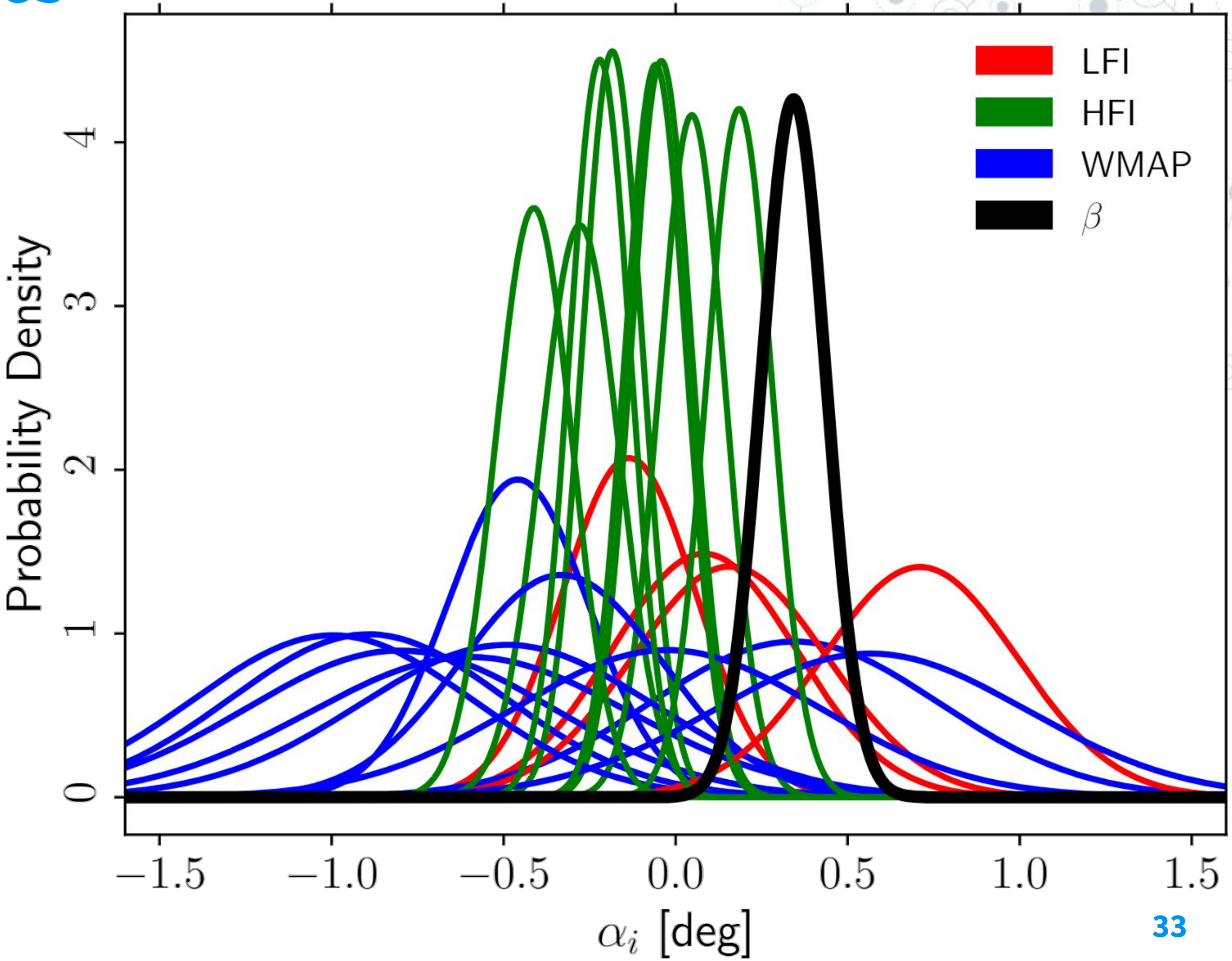
$$\chi^2 = 65.8 \text{ for DOF} = 72$$

Miscalibration angles

Miscalibration angles cancel:
The beauty of adding
independent datasets

A total of 22 miscalibration angles

- 8 HFI
- 4 LFI
- 10 WMAP



Current status

1. We are at 3.6 sigma
2. Dust EB has been taken into account, and we get consistent results for large and small sky masks

FAQ

- When will the statistical significance improve/worsen?
  - When we get better data. We hope ground-based telescopes will search for isotropic CB by calibrating their instruments well.
- Are ultra-light axions the best explanation?
  - We measure the CB signal to be consistent with frequency independence, which is the signature of axions. Other theories where there is little-to-no frequency dependence could also be valid models.

Conclusion

- The past 2 years we have gone from 2.4 sigma to 3.6 sigma by including less noisy and more data.

- EB of dust is much better understood now.

- No evidence of instrumental systematics that would bias our measurement.

- Signal is consistent with being frequency-independent.
  - Good news for axion-like fields.