Cosmic Birefringence: Searching for Parity Violation with CMB Polarization

1st BiCoQ Conference

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Parity Transformation

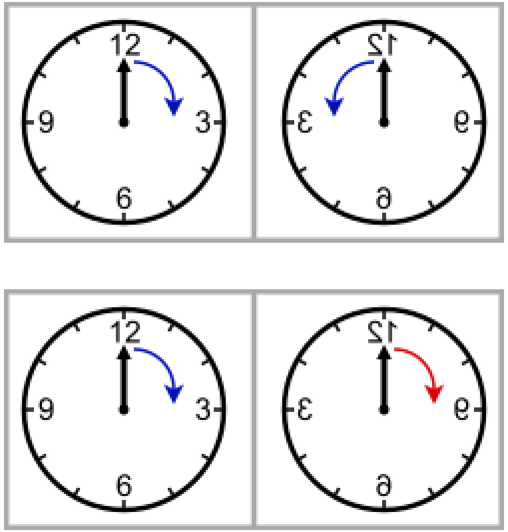


Fig. 1: *Parity Clocks - P-Violation.*

Top —P-symmetry

A clock built as the mirror image of the original ***will*** behave like its mirror image.

Bottom — P-asymmetry

A clock built as the mirror image of the original will ***not*** behave like its mirror image.

Parity Violation: Wu Experiment

- **QED & QCD** → parity invariant
- **Wu experiment:** cobalt-60 nuclei aligned by a magnetic field (1956)
- **β-decay asymmetry** for spin-up vs spin-down
- **Weak interactions** → parity violation
- *Parity symmetry at cosmological scales?*

Fig. 2: *Chien-Shiung Wu, 1912-1997*

Extension to Standard Electromagnetism: Chern-Simons Interaction

A pseudoscalar field, χ, can couple to the electromagnetic field through a Chern-Simons term. In this scenario, the standard Maxwell Lagrangian density is modified with an extra term:

$$\mathcal{L} = \mathcal{L}_{EM} + \mathcal{L}_{CS} ,$$

where

$$\mathcal{L}_{CS} = -\frac{\alpha_{em}}{4f} \chi F\tilde{F} ,$$

and

$$F\tilde{F} \equiv \sum_{\mu\nu} F_{\mu\nu} \sum_{\mu'\nu'} \frac{\varepsilon^{\mu\nu\mu'\nu'}}{2\sqrt{-g}} F_{\mu'\nu'} .$$

- α_{em} : coupling constant
- f : decay constant, with the dimension of energy
- $\varepsilon^{\mu\nu\mu'\nu'}$: Levi-Civita symbol
- g : is the determinant of $g_{\mu\nu}$, metric tensor, where $g_{\mu\nu} = a^2(\eta)\mathrm{diag}(-1,1,1,1)$ (in natural units).

The parity violation arises because:
$F\tilde{F} = -4\mathbf{B}\cdot\mathbf{E}$, where **E** (electric field vector) has odd parity and **B** (magnetic field vector) has even parity.

Extension to Standard Electromagnetism: Chern-Simons Interaction

EM field propagating in a birefringent background; DM or DE?

The **phase velocity**, describing how the wave propagates, is approximately:

$$\frac{\omega_{\pm}}{k} \simeq 1 \mp \frac{\alpha_{em}\chi'}{2kf}$$

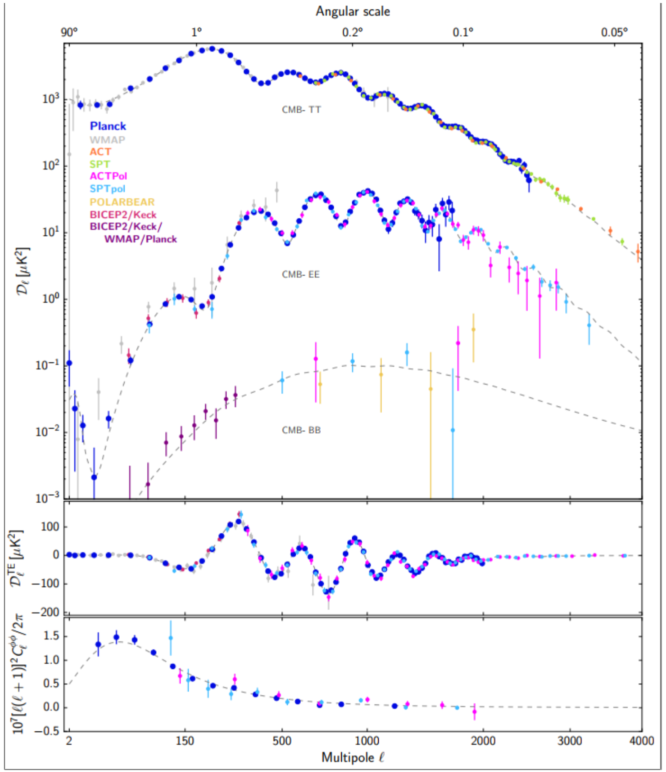
The **isotropic birefringence** is related to the field χ in the following way:

$$\alpha = \frac{\alpha_{em}}{2f}\int_{\eta_{LS}}^{\eta_0} d\eta\,\chi'$$

η_{LS} : conformal time at the last scattering surface

η_0 : conformal time today

Cosmic Birefringence and CMB Polarization



$$E^{o}_{\ell m} \pm iB^{o}_{\ell m} = (E_{\ell m} \pm iB_{\ell m})e^{\pm 2i\beta}$$

$$C_\ell^{TB,\,o} = C_\ell^{TE}\sin(2\beta)$$

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

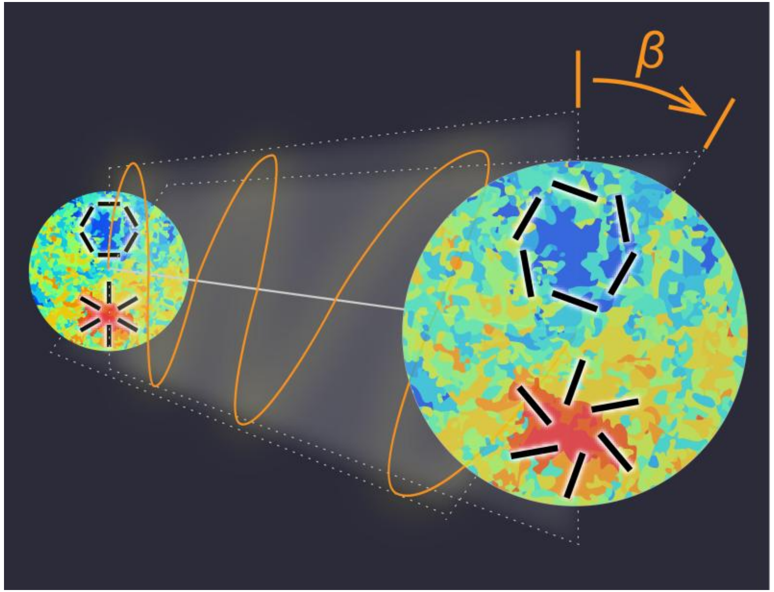


__Fig. 3: Left__: Observed CMB polarization power spectra (Planck 2018 results: I. Overview and the cosmological legacy of Planck, 2020).
__Right:__ Rotation of the Linear Polarization Plane of the CMB photons by Cosmic Birefringence (Adapted from Komatsu, 2022. Credit: Y. Minami).

β = 0.31° ± 0.05° (stat.) ± 0.28° (syst.)

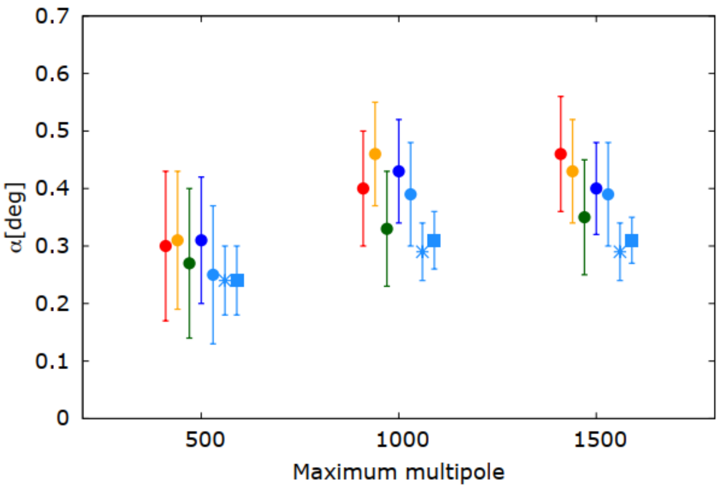


***Fig. 4:** Adapted from Planck intermediate results. XLIX. Parity-violation constraints from polarization data, 2016.*

Birefringence angle estimates (in degrees) versus the maximum multipole considered. Only $(1\,\sigma)$ statistical uncertainties are shown here; with systematic errors discussed later. `Commander` is shown in red, `NILC` in orange, `SEVEM` in green, `SMICA` (full-mission data) in blue, and `SMICA` (half-mission data) in cyan. Dot symbols refer to the estimates obtained with the D_ℓ^{TB} estimator. Star symbols refer to estimates coming from D_ℓ^{EB} and squares are obtained through the combination of D_ℓ^{TB} and D_ℓ^{EB}.

β = 0.215° ± 0.074° (2.9σ)

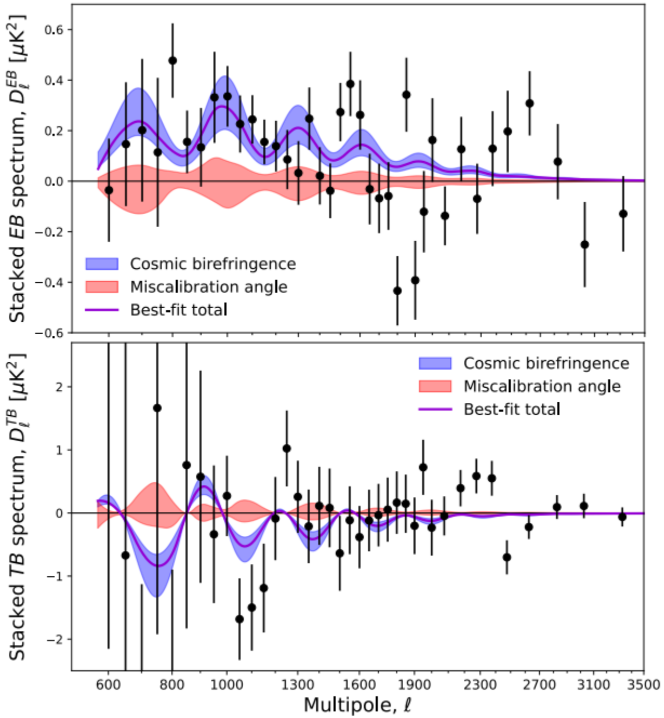


***Fig. 5:** Adapted from Cosmic Birefringence from the Atacama Cosmology Telescope Data Release 6, 2026, P. Diego-Palazuelos and E. Komatsu.*

Stacked EB (upper) and TB (lower) power spectra observed by ACT DR6's PA4 f220, PA5 f090, PA5 f150, PA6 f090, and PA6 f150 in the baseline multipole cut. The red and blue bands show, respectively, the $1\,\sigma$ confidence contours from the polarization angle miscalibration and cosmic birefringence contributions to our joint EB and TB fit with $\Pi^{\rm PA}$. The purple line shows the total best-fitting model.

β = 0.215°–0.342°, excluding β = 0 at 3.6σ

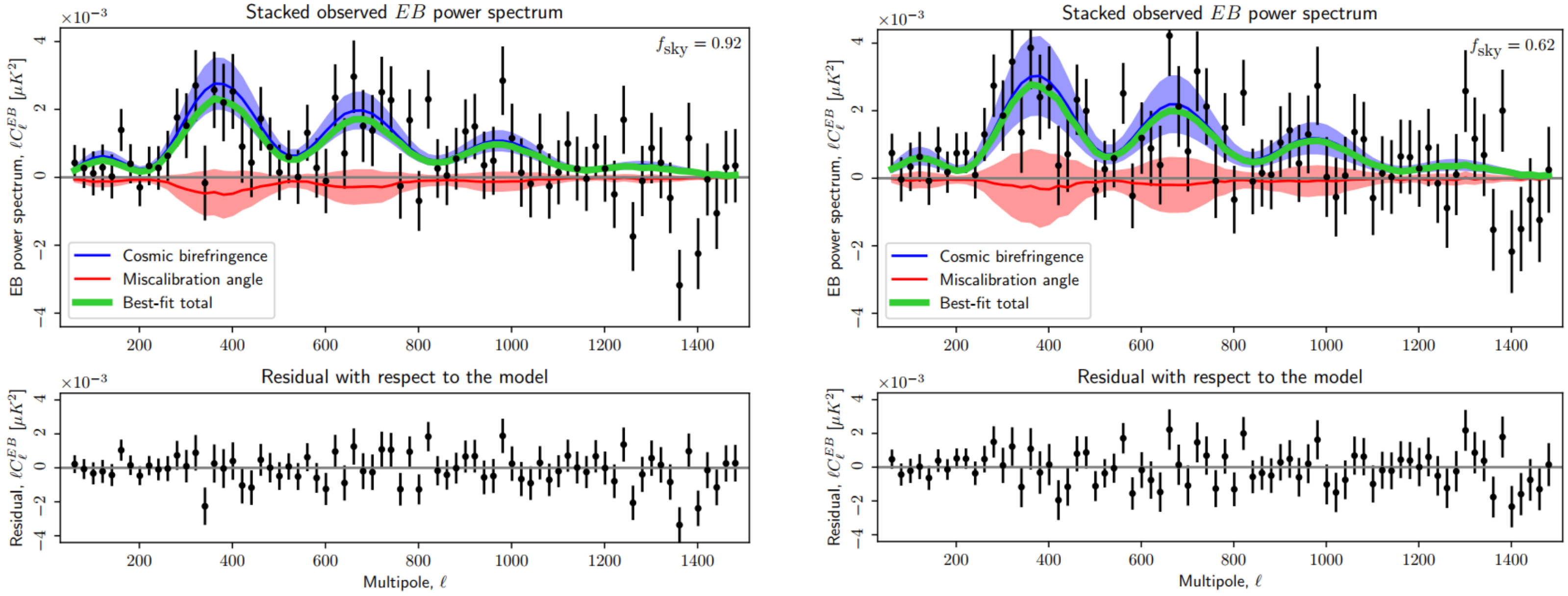


Fig. 6: Adapted from Improved Constraints on Cosmic Birefringence from the WMAP and Planck Cosmic Microwave Background Polarization Data, Eskilt & Komatsu 2022.

Stacked observed *EB* power spectrum (upper) and residuals with respect to the best-fitting model (lower) for nearly full-sky data *f*sky = 0,92 (left) and for fsky = 0.62 (right). The blue and red shaded areas show the 1*σ* bands for the cosmic birefringence and miscalibration contributions, respectively. The green solid line shows the total best-fitting model.

Does the Universe have a preferred handedness?

Degeneracy with the Miscalibration Angle

- **Anisotropic birefringence → not degenerate with the instrumental rotation**
  - A spatially varying rotation angle across the sky; mixes CMB modes of different angular scales
  - Produces off-diagonal correlations at $\ell \neq \ell'$ in the CMB covariance matrix; not mimicked by a uniform instrumental rotation
- **Isotropic birefringence → degenerate with the instrumental rotation**
  - **Self-calibration**
    - Minami-Komatsu method using foregrounds
  - **External calibration**
    - Wire grid
    - Drone-based artificially polarised source

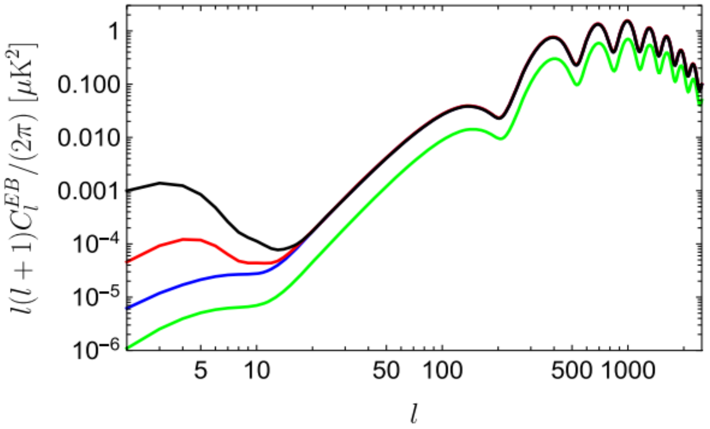
Fig. 7: *POLOCALC (Nati et al. 2017, Coppi et al. 2025) in operation at the Simons Observatory site*

Uncertainty Budget of the Cosmic Birefringence Angle Estimation

$$\sigma^2(\beta) \simeq \sigma^2\_sys + \sigma^2\_fg + \sigma^2\_stat$$

- **Instrumental systematics**
  - Polarization angle miscalibration
  - Beam asymmetries, I → P leakage, correlated noise, and detector and HWP non-idealities
- **Galactic foreground emission**
  - **Dust EB contamination and modeling: not well understood!** (from the geometry of magnetic field alignment with filamentary dust structures)
  - **Synchrotron EB contamination:** negligible
- **Statistical uncertainties**
  - Limited sky coverage and E-to-B mode mixing from masking
  - Uncorrelated noise
  - Gravitational delensing residuals

Dark Energy-like vs. Dark Matter-like Field



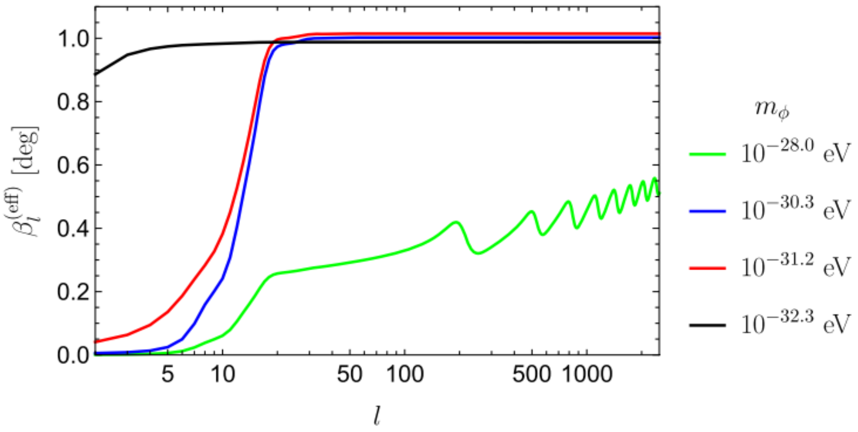


Fig. 8: *EB spectrum & effective angle — lighter fields*

Is cosmic birefringence due to dark energy or dark matter? A tomographic approach. *Nakatsuka, Namikawa, Komatsu, Phys. Rev. D, 2022.*

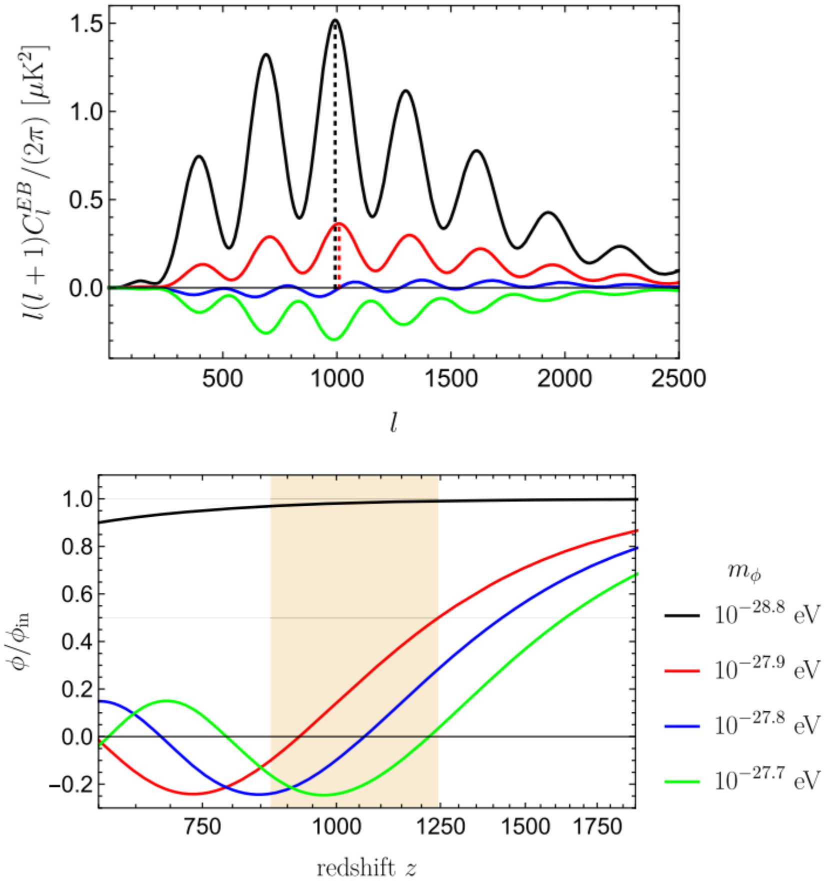
DARK ENERGY–LIKE ($m_\varphi \lesssim 10^{-33}$ eV)

- Field frozen during the entire CMB polarization generation
- Constant birefringence angle at all redshifts
- $C_\ell^{EB} \propto C_\ell^{EE}$ (scale-independent)

ULTRA-LIGHT DARK MATTER ($10^{-32} \lesssim m_\varphi \lesssim - 10^{-31}$ eV)

- Slowly evolves before reionization (no oscillation)
- Recombination vs. reionization photons acquire different birefringence
- Different C_ℓ^{EB} amplitudes at low ($\ell \lesssim 10$) vs high ℓ

Dark Energy-like vs. Dark Matter-like Field



Is cosmic birefringence due to dark energy or dark matter? A tomographic approach. *Nakatsuka, Namikawa, Komatsu, Phys. Rev. D, 2022.*

DARK MATTER–LIKE ($m_\varphi \gtrsim 10^{-28}$ eV)

- Oscillates during or before recombination
- C_ℓ^{EB} acoustic peaks shift to higher ℓ
- Amplitude grows strongly with mass

Fig. 9: *Heavy dark matter: EB acoustic peaks at high ℓ & field oscillation vs redshift*

Conclusions

C_ℓ^{EB} is not just a probe of parity violation; its shape is a window into the fundamental nature of dark matter and dark energy.

Simons Observatory · LAT
High-multipole reach — small-scale (high-ℓ) sensitivity

LiteBIRD
Full-sky coverage at low multipoles (low ℓ)

Together, these two surveys have the potential to bring cosmic birefringence within reach; opening a new window on the symmetries and new physics of the Universe.

Thank you!