Cosmic birefringence:
a hint of new physics in cosmology and fundamental physics

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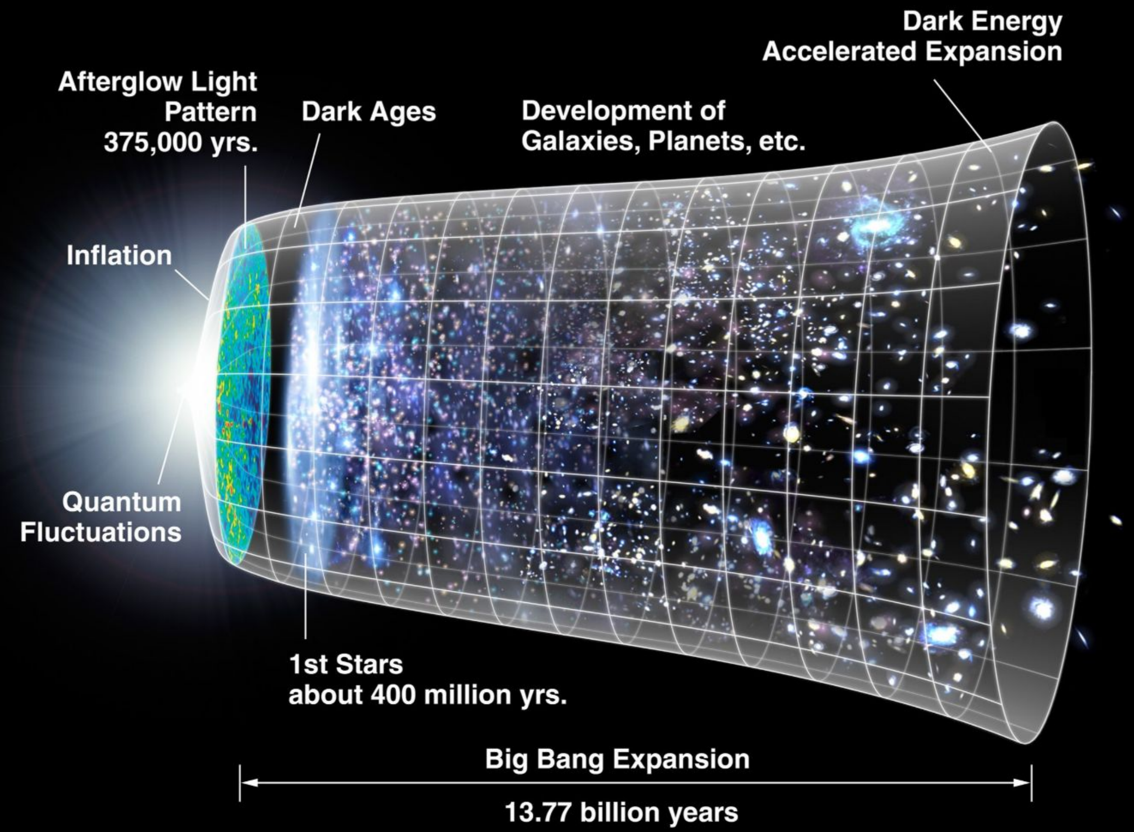
Island of Noirmoutier, France

MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

ΛCDM

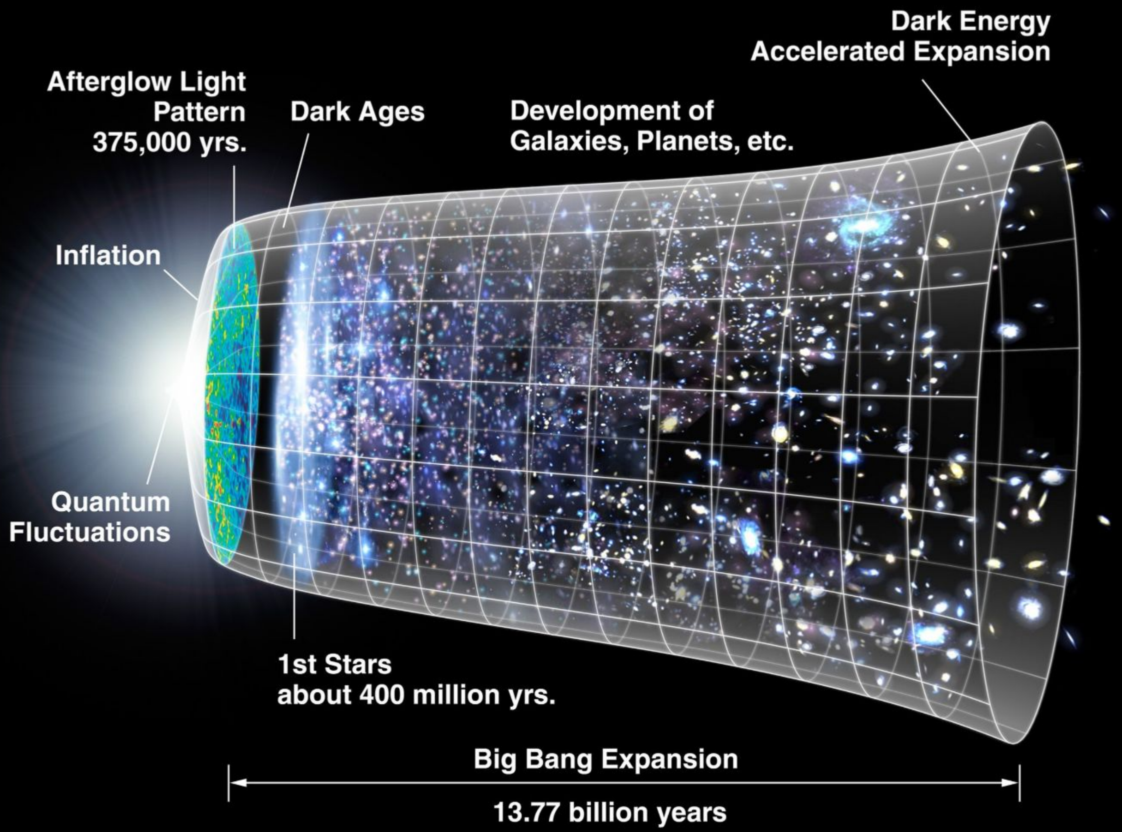


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

ΛCDM

But, what are dark matter and dark energy? Inflation too…

Have we missed something?
Have we used all the information at our disposal?

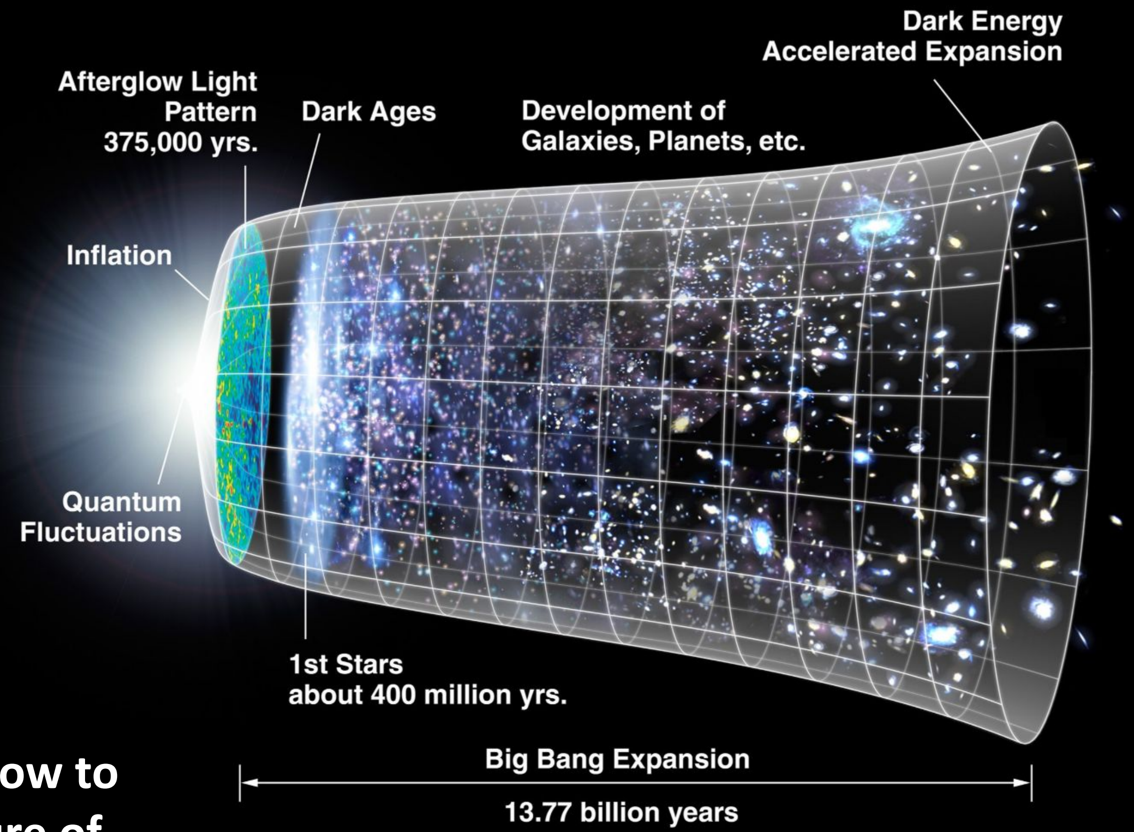


ΛCDM

But, what are dark matter and dark energy? Inflation too…

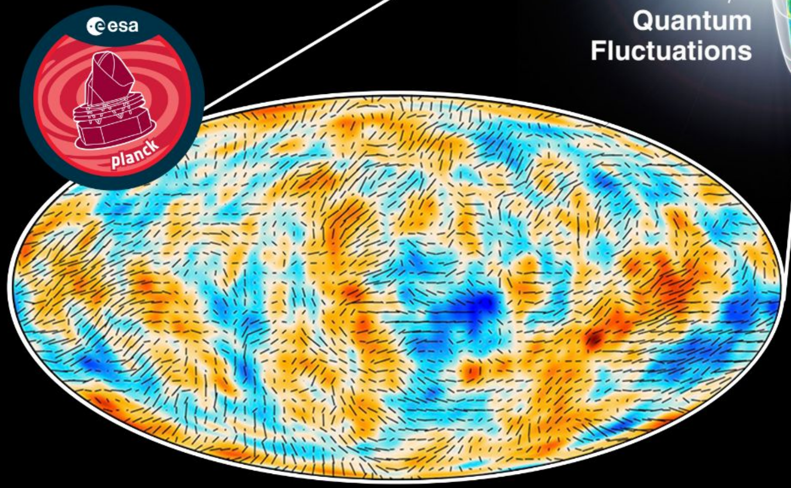
Have we missed something?
Have we used all the information at our disposal?

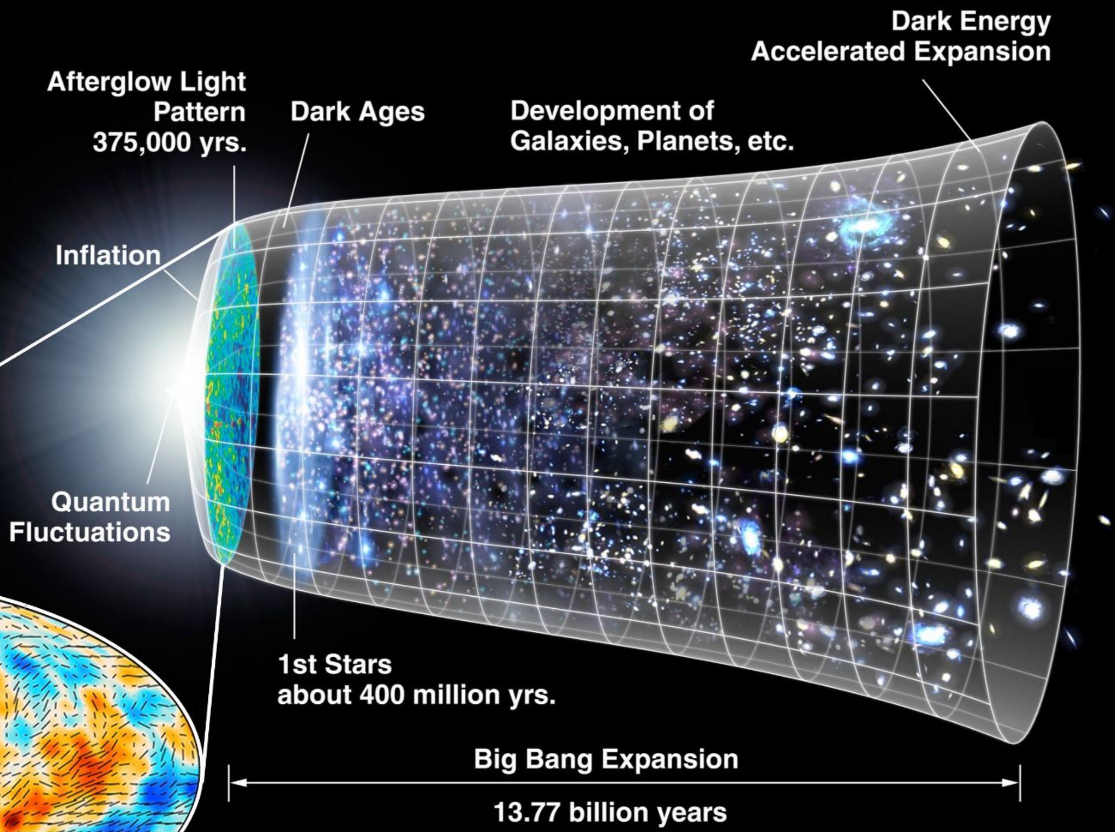
Parity violation opens a window to gain new insights on the nature of dark matter, dark energy, and inflation



ΛCDM

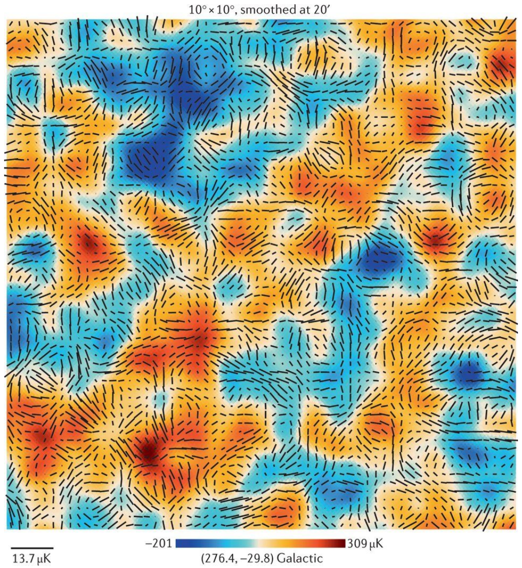
My observable of choice



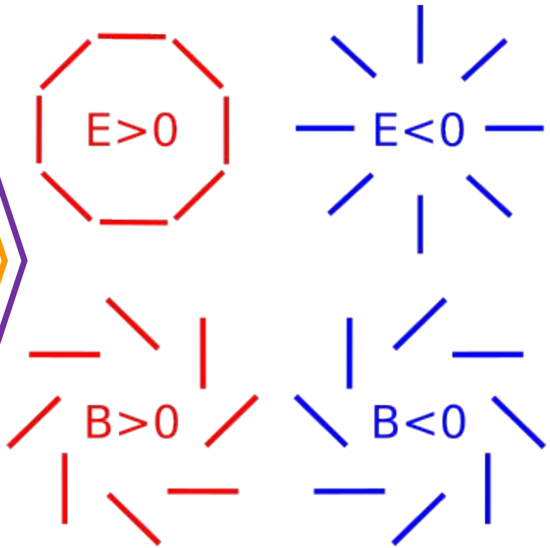


Cosmic microwave background (CMB)

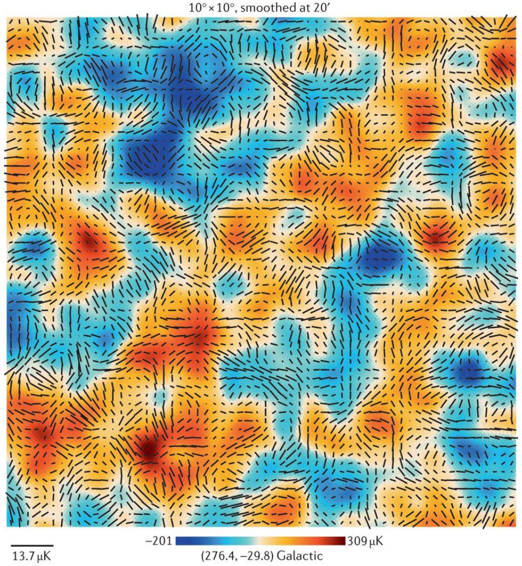
Decompose polarization patterns into *E* and *B* modes



***Planck* I 2020, A&A, 641, A1**

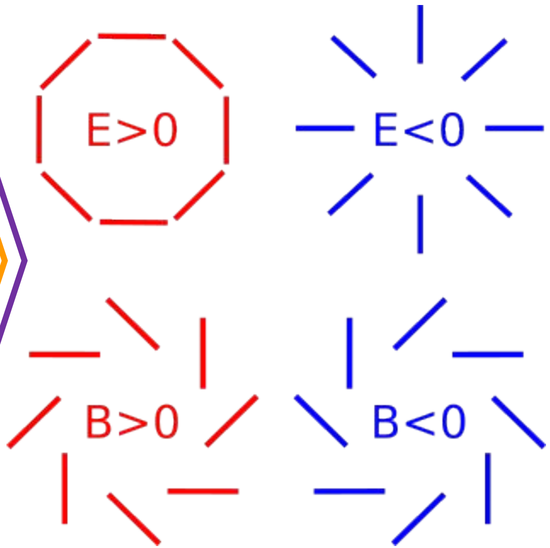


Zaldarriaga & Seljak 1997, PRD, 55, 1830
Kamionkowski et al 1997, PRD, 55, 7368



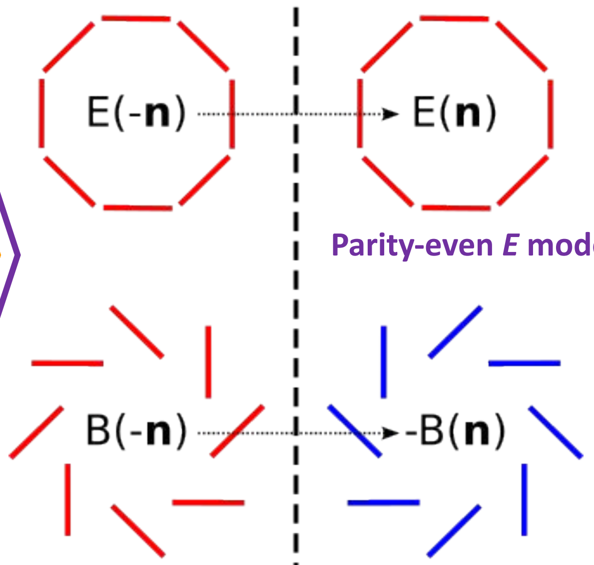
***Planck* I 2020, A&A, 641, A1**

Decompose polarization patterns into *E* and *B* modes



Eigenstates of parity!

Under parity transformation (inversion of spatial coordinates)

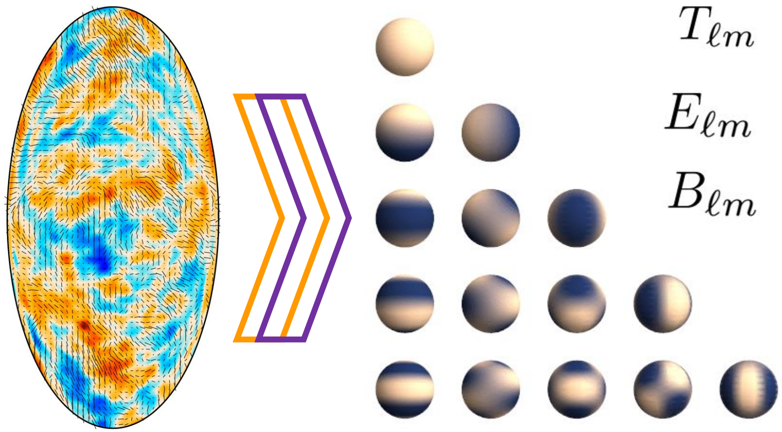


Parity-even *E* modes

Parity-odd *B* modes

Zaldarriaga & Seljak 1997, PRD, 55, 1830
Kamionkowski et al 1997, PRD, 55, 7368

Projecting CMB anisotropies to a series of spherical harmonics

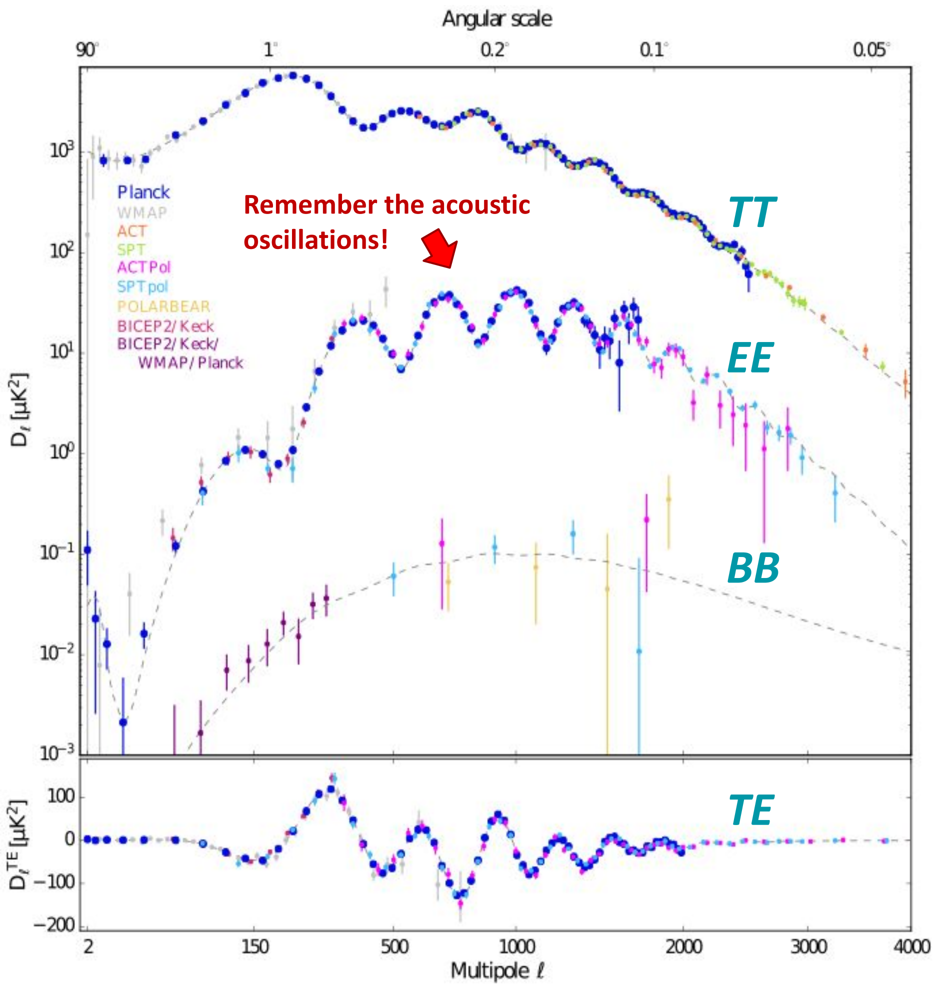


$T_{\ell m}$

$E_{\ell m}$

$B_{\ell m}$

Zaldarriaga & Seljak 1997, PRD, 55, 1830
Kamionkowski et al 1997, PRD, 55, 7368



Planck I 2020, A&A, 641, A1

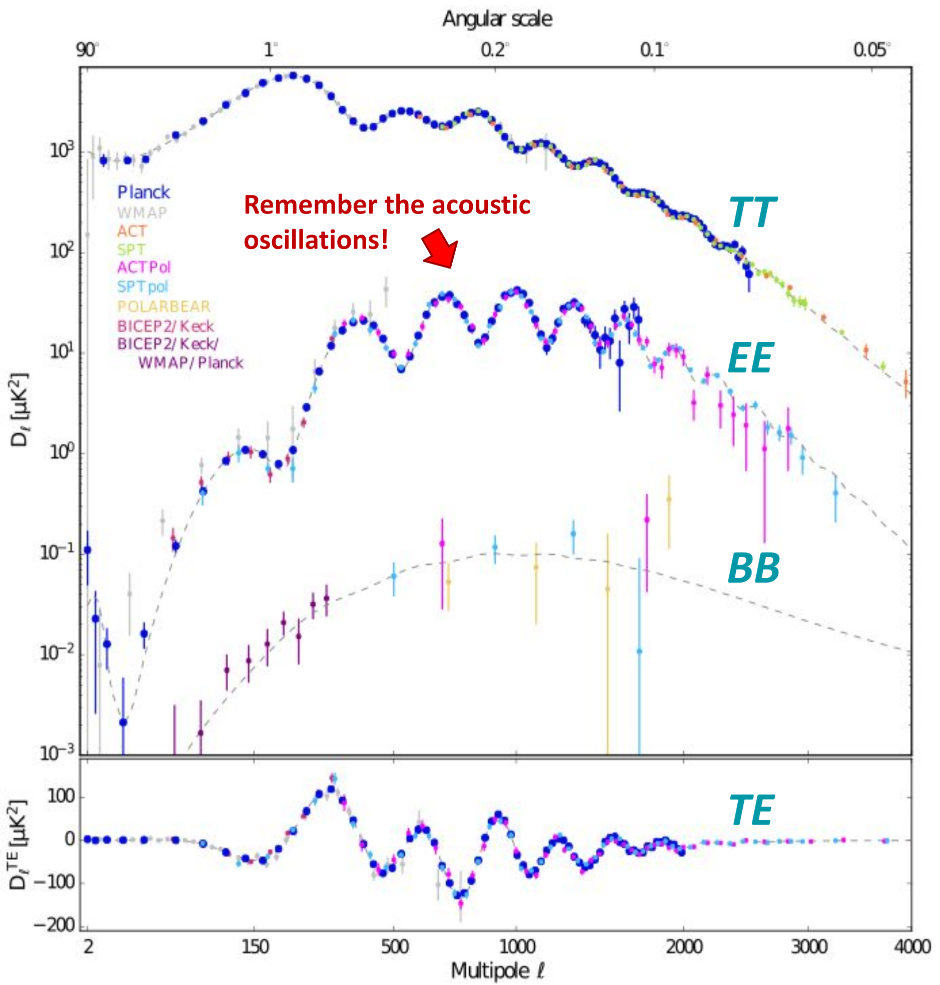
Focusing on the correlations between polarization coefficients

$$\langle E_{\ell m} E^*_{\ell' m'} \rangle = \delta_{mm'} \delta_{\ell\ell'} \boxed{C_\ell^{EE}}$$
$$\langle B_{\ell m} B^*_{\ell' m'} \rangle = \delta_{mm'} \delta_{\ell\ell'} \boxed{C_\ell^{BB}}$$

Parity-even

$$\langle E_{\ell m} B^*_{\ell' m'} \rangle = \delta_{mm'} \delta_{\ell\ell'} \boxed{C_\ell^{EB}}$$

Parity-odd



Planck I 2020, A&A, 641, A1

Focusing on the correlations between polarization coefficients

$$\langle E_{\ell m} E^*_{\ell' m'} \rangle = \delta_{mm'} \delta_{\ell\ell'} \boxed{C^{EE}_\ell}$$
$$\langle B_{\ell m} B^*_{\ell' m'} \rangle = \delta_{mm'} \delta_{\ell\ell'} \boxed{C^{BB}_\ell}$$
Parity-even

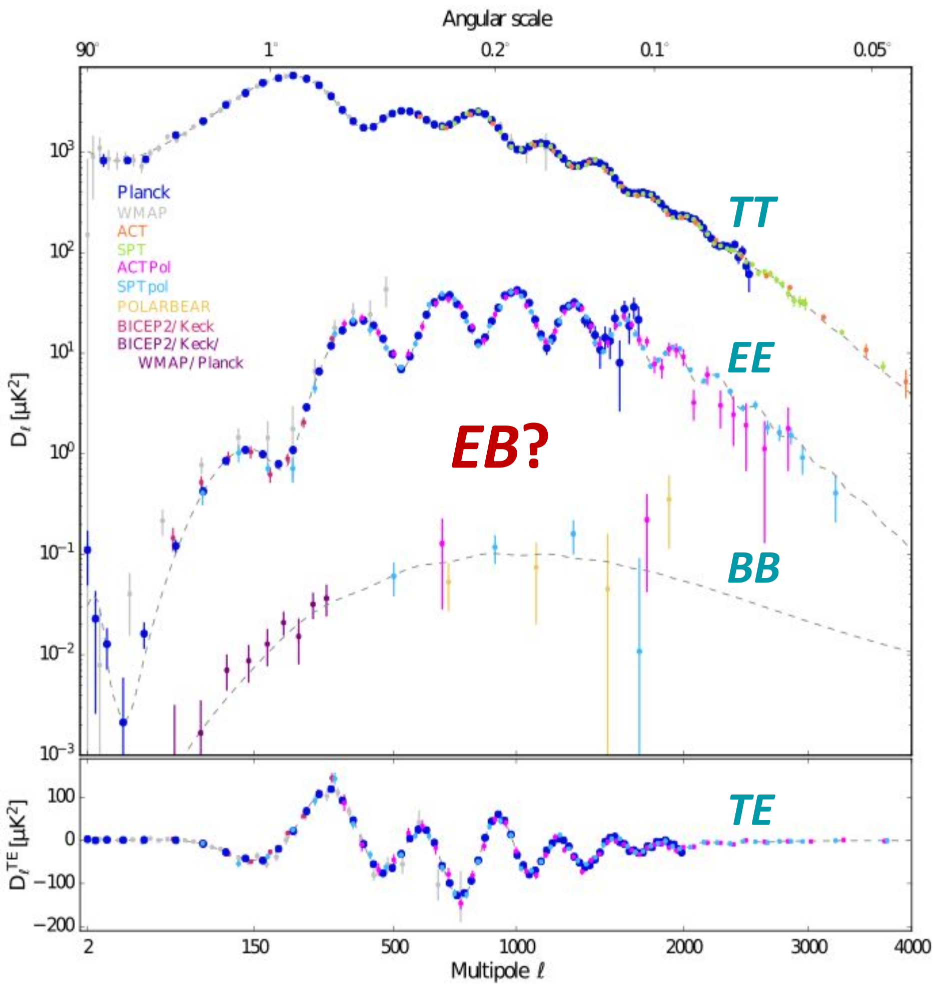
$$\langle E_{\ell m} B^*_{\ell' m'} \rangle = \delta_{mm'} \delta_{\ell\ell'} \boxed{\cancel{C^{EB}_\ell}}$$
Parity-odd

ΛCDM & SM

The statistics of CMB anisotropies must be invariant under parity transformation

$EB \neq 0$ would be evidence of parity-violating physics

Lue et al 1999, PRL, 83, 1506



Planck I 2020, A&A, 641, A1

Dark matter or dark energy could be a parity-violating pseudoscalar field

$$P[\phi(\vec{n})] \to \phi'(\vec{n}') = -\phi(-\vec{n})$$

via Chern-Simons coupling to electromagnetism

$$\frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}_{\mu\nu}$$

Carroll et al 1990, PRD, 41, 1231
Carroll & Field 1991, PRD, 43, 3789
Harari & Sikivie 1992, PLB, 289, 67

rotation of the plane of linear polarization clockwise on the sky

$$\beta = -\frac{1}{2} g_{\phi\gamma} \int \frac{\partial \phi}{\partial t} dt$$

Cosmic birefringence

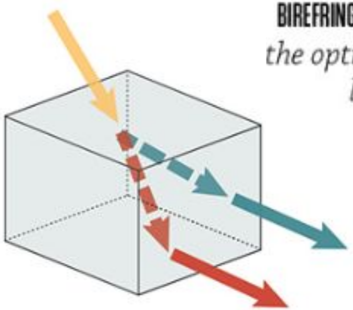
For example:

Axionlike particles

Marsh 2016, Phys Rep, 643, 1

Early Dark Energy

Murai et al 2023, PRD, 107, L041302
Eskilt et al 2023, PRL, 131, 121001
Kochappan et al 2024, PRD, 112, 063562



BIREFRINGENCE *Birefringence describes the optical property where a ray of light is split by polarization into two rays taking slightly different paths.*

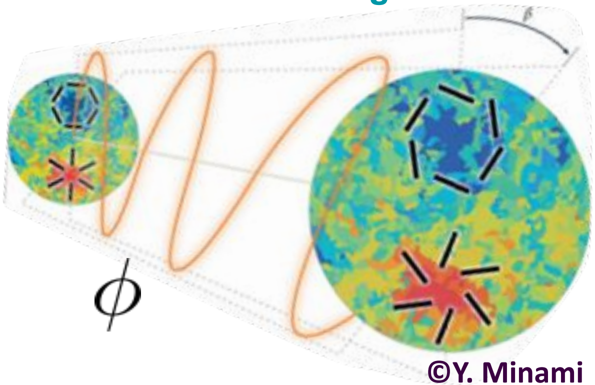
Cosmic birefringence rotates CMB polarization

$$\begin{pmatrix} E_{\ell m}^{\rm obs} \\ B_{\ell m}^{\rm obs} \end{pmatrix} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m}^{\Lambda\rm CDM} \\ B_{\ell m}^{\Lambda\rm CDM} \end{pmatrix}$$

so the observed angular power spectrum becomes

$$C_\ell^{EB,\rm obs} = \frac{1}{2}\tan(4\beta)\left(C_\ell^{EE,\rm obs} - C_\ell^{BB,\rm obs}\right)$$

Cosmic birefringence



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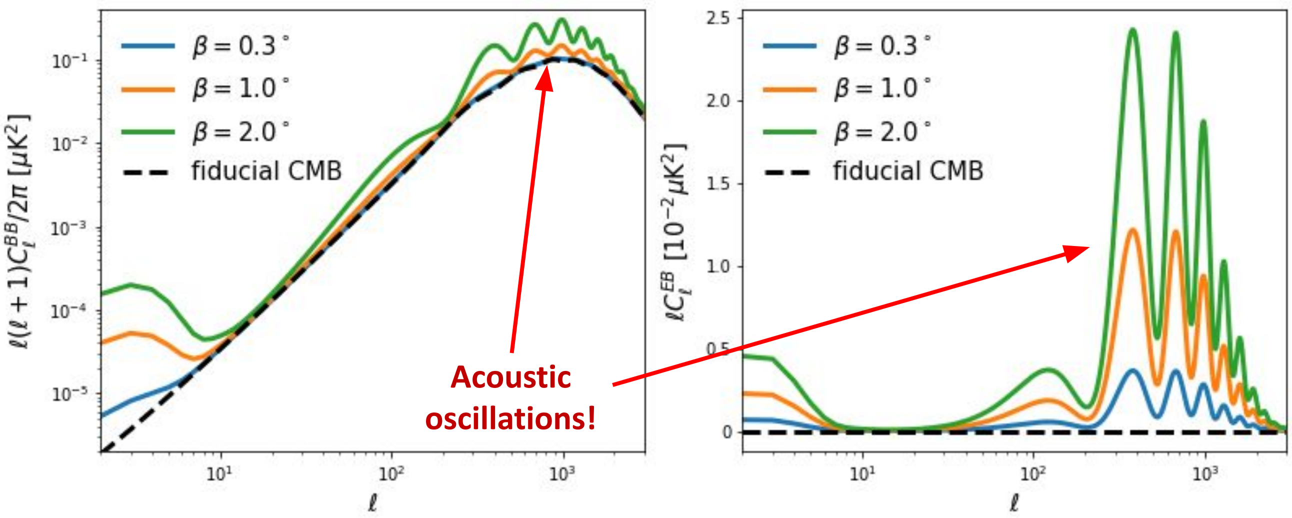
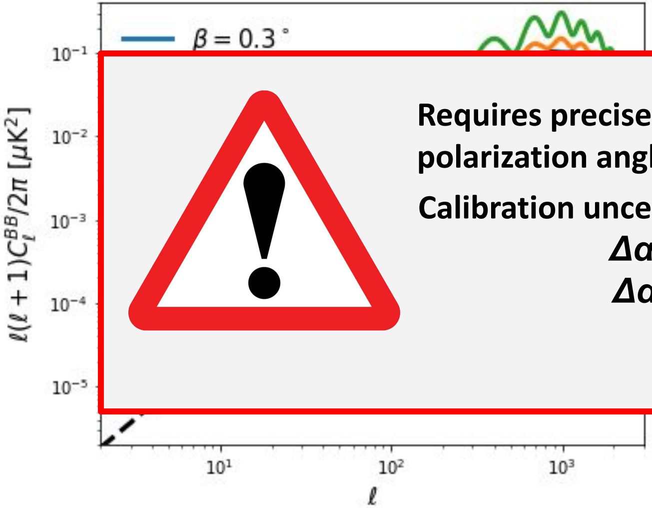


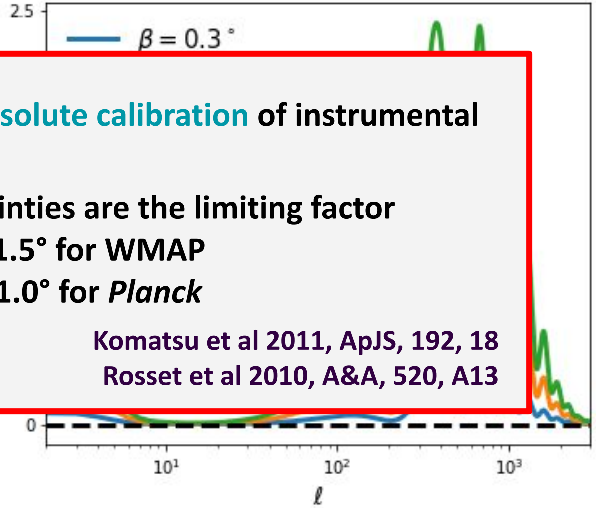
The observed signal is actually

$$\begin{pmatrix} E_{\ell m}^{\mathrm{obs}} \\ B_{\ell m}^{\mathrm{obs}} \end{pmatrix} = \begin{pmatrix} \cos(2\alpha+2\beta) & -\sin(2\alpha+2\beta) \\ \sin(2\alpha+2\beta) & \cos(2\alpha+2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m}^{\Lambda\mathrm{CDM}} \\ B_{\ell m}^{\Lambda\mathrm{CDM}} \end{pmatrix}$$

making observed spectra sensitive to ***α+β***

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





Requires precise absolute calibration of instrumental polarization angles

Calibration uncertainties are the limiting factor

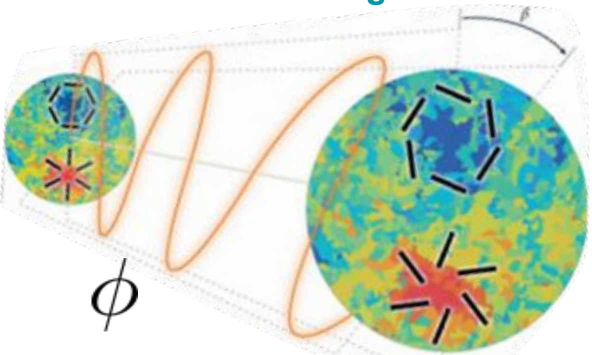
Δα **= 1.5° for WMAP**

Δα **= 1.0° for *Planck***

Komatsu et al 2011, ApJS, 192, 18

Rosset et al 2010, A&A, 520, A13

Cosmic birefringence



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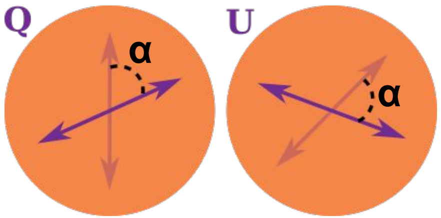
OR

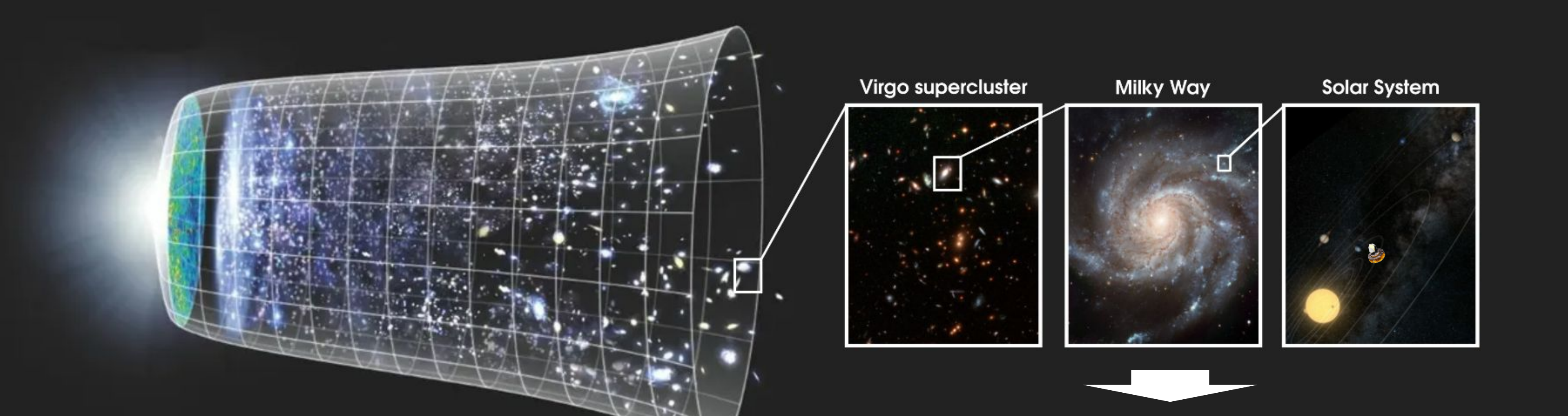
Miscalibration of the detector's polarization angle



Unknown *α* miscalibration

Degenerate with birefringence

Miller et al 2009, PRD 79, 103002



Milky Way emission in microwaves

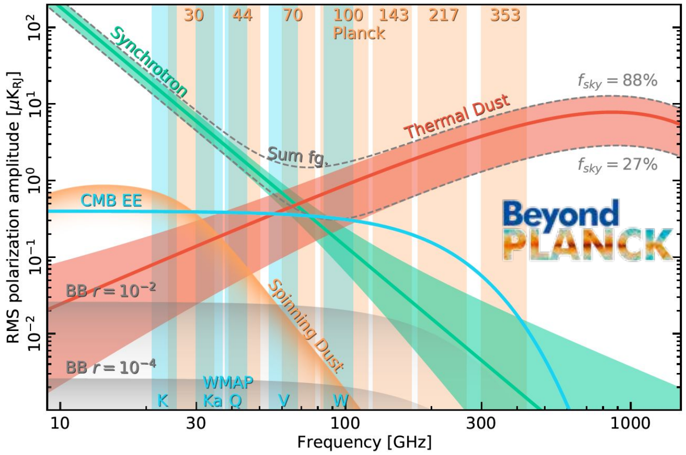
$$\beta = -\frac{1}{2} g_{\phi\gamma} \int \frac{\partial \phi}{\partial t} dt$$

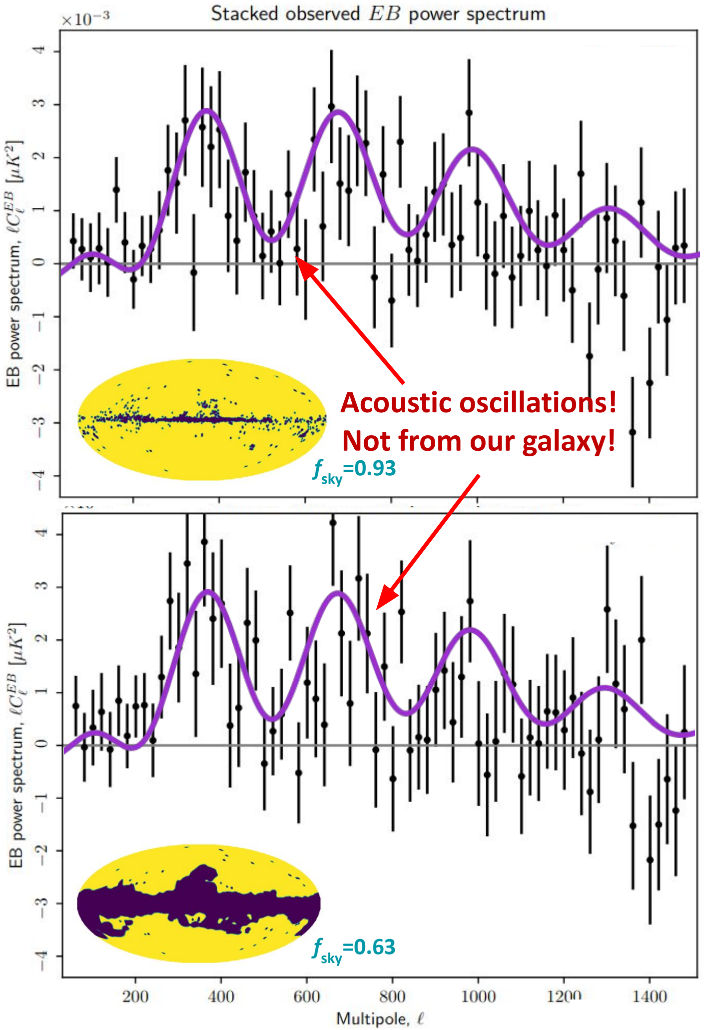
Birefringence depends on the propagation length of photons

Galactic emission will only be affected by instrumental miscalibrations

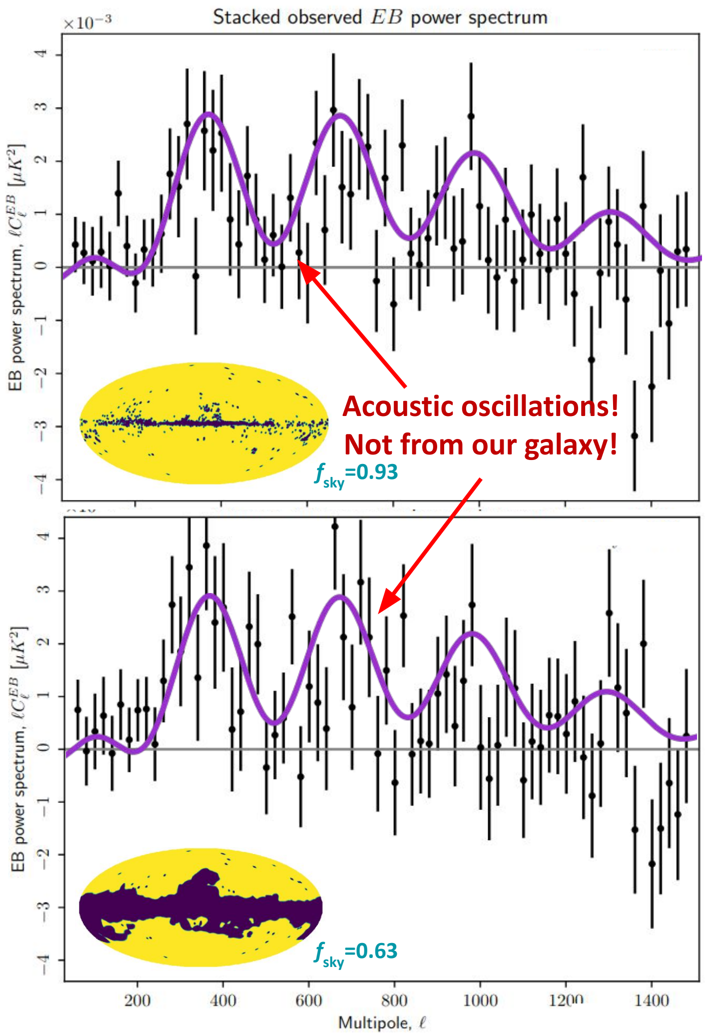
Use foregrounds as our calibrator

Minami et al 2019, PTEP, 083E02





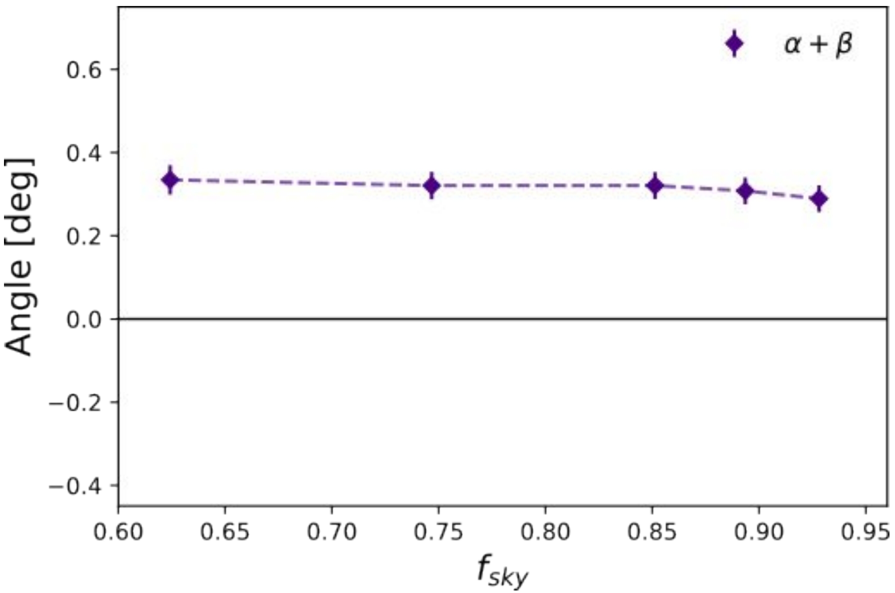
Eskilt & Komatsu 2022, PRD, 106, 063503



Eskilt & Komatsu 2022, PRD, 106, 063503

Fitting an effective *α+β* rotation

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



Isotropic rotation across the sky

Careful modeling of polarized Galactic emission!

Galactic foregrounds introduce an effective rotation

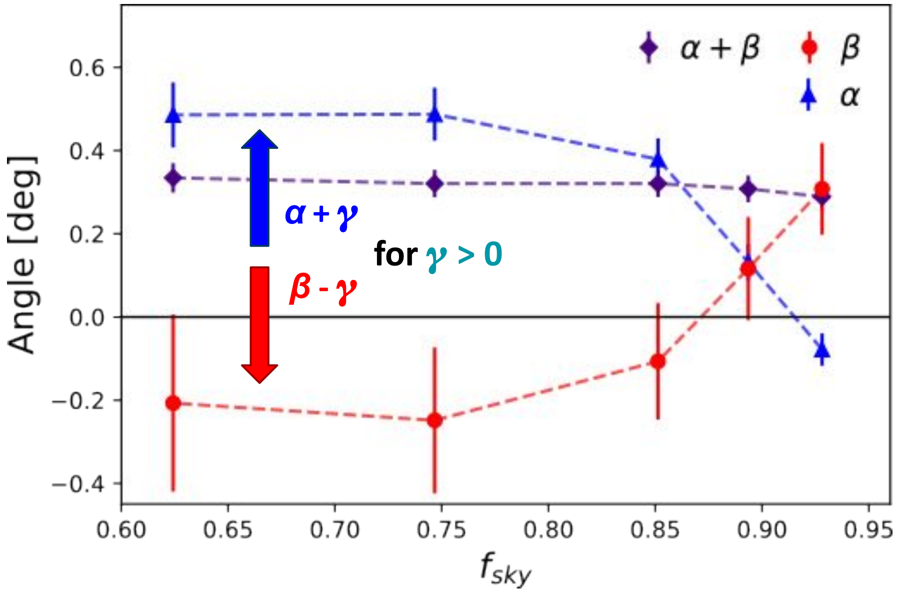
$$\gamma_\ell \approx \frac{C_\ell^{EB,\mathrm{Fg}}}{C_\ell^{EE,\mathrm{Fg}} - C_\ell^{BB,\mathrm{Fg}}}$$

leading to biased measurements of

$$\alpha \rightarrow \alpha + \langle \gamma_\ell \rangle$$
$$\beta \rightarrow \beta - \langle \gamma_\ell \rangle$$

Separating α and β rotations

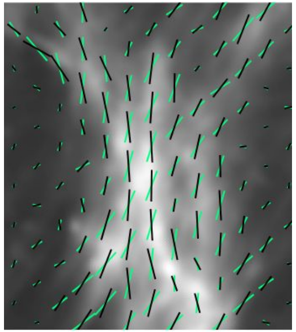
$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right) + \boxed{\frac{1}{\cos(4\alpha)} C_\ell^{EB,\mathrm{Fg}}} + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\Lambda\mathrm{CDM}} - C_\ell^{BB,\Lambda\mathrm{CDM}}\right)$$



Indirect detection of small dust $EB > 0$

PDP et al 2022, PRL, 128, 091302

Two independent dust models

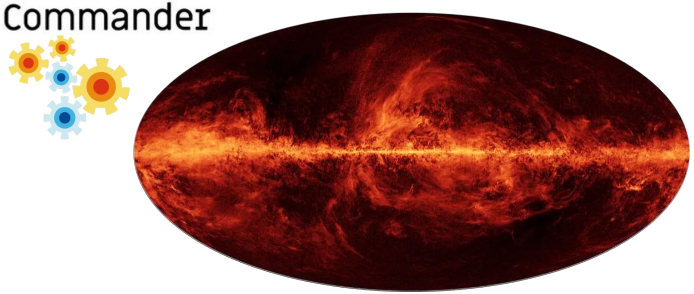


Magnetic misalignment

Huffenberger et al 2020, ApJ, 919, 53
Clark et al 2021, ApJ, 919, 53
Cukierman et al 2023, ApJ, 946, 106

Dust emission templates

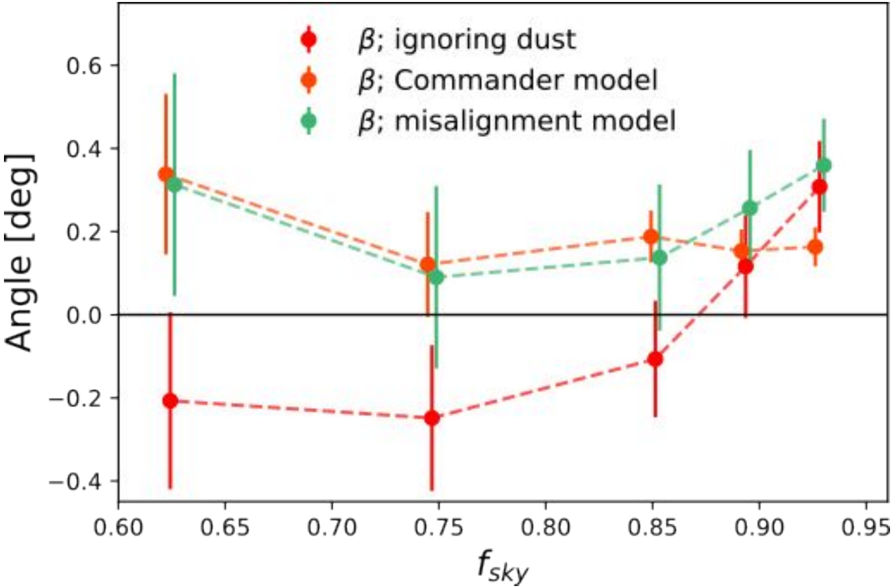
Commander



Planck IV 2020, A&A 641 A4

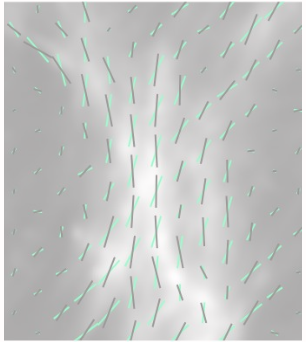
Separating α and β rotations

$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right) + \boxed{\frac{1}{\cos(4\alpha)}C_\ell^{EB,\mathrm{Fg}}} + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\Lambda\mathrm{CDM}} - C_\ell^{BB,\Lambda\mathrm{CDM}}\right)$$



PDP et al 2022, PRL, 128, 091302

Two independent dust models

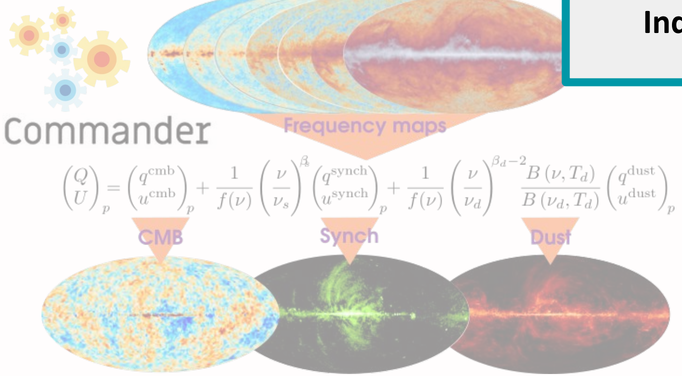


Magnetic misalignment

$$C_\ell^{EB,\mathrm{dust}} \approx A_\ell C_\ell^{EE,\mathrm{dust}} C_\ell^{TB,\mathrm{dust}}$$

Huffenberger et al 2020, ...
Clark et al 2021, ApJ, 919 ...
Cukierman et al 2023, Ap...

Parametric dust templates

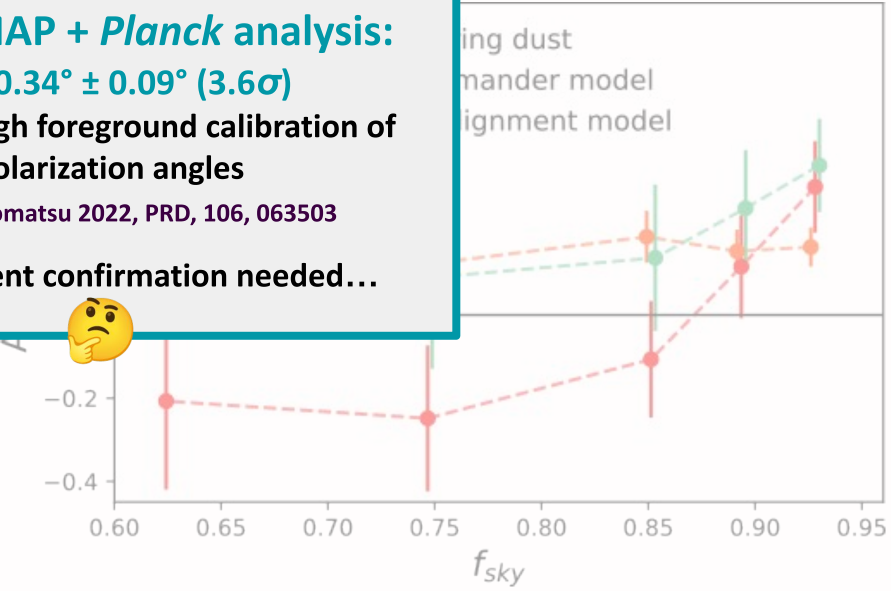


$$\begin{pmatrix} Q \\ U \end{pmatrix}_p = \begin{pmatrix} q^{\mathrm{cmb}} \\ u^{\mathrm{cmb}} \end{pmatrix}_p + \frac{1}{f(\nu)}\left(\frac{\nu}{\nu_s}\right)^{\beta_s}\begin{pmatrix} q^{\mathrm{synch}} \\ u^{\mathrm{synch}} \end{pmatrix}_p + \frac{1}{f(\nu)}\left(\frac{\nu}{\nu_d}\right)^{\beta_d-2}\frac{B(\nu, T_d)}{B(\nu_d, T_d)}\begin{pmatrix} q^{\mathrm{dust}} \\ u^{\mathrm{dust}} \end{pmatrix}_p$$

Planck IV 2020, A&A 641 A4

Separating α and β rotations

$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right) + \boxed{\frac{1}{\cos(4\alpha)}C_\ell^{EB,\mathrm{Fg}}} + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\Lambda\mathrm{CDM}} - C_\ell^{BB,\Lambda\mathrm{CDM}}\right)$$



PDP et al 2022, PRL, 128, 091302

Joint WMAP + *Planck* analysis:

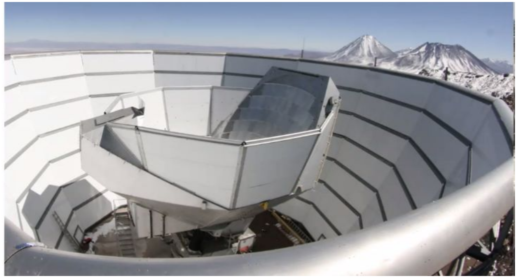
$\beta = 0.34° \pm 0.09°$ (3.6σ)

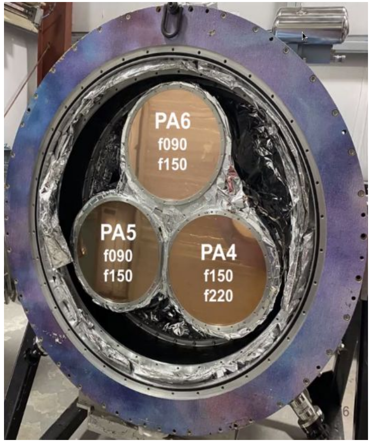
found through foreground calibration of polarization angles

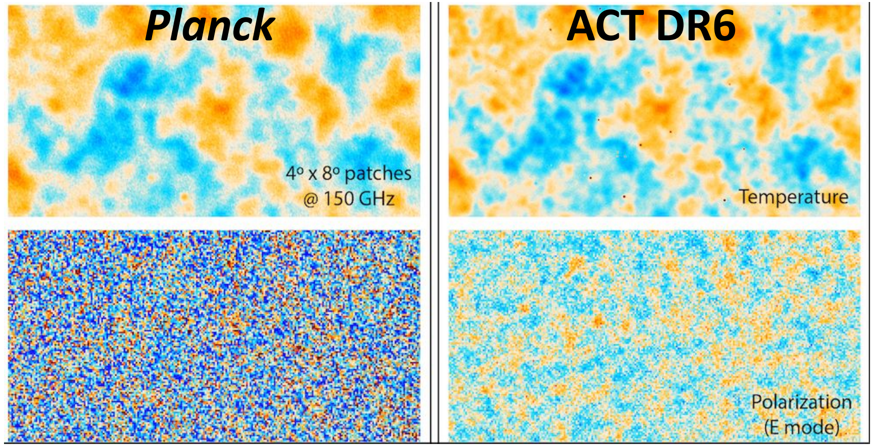
Eskilt & Komatsu 2022, PRD, 106, 063503

Independent confirmation needed… 🤔

Atacama Cosmology Telescope data release 6 (ACT DR6)







Compared to *Planck*

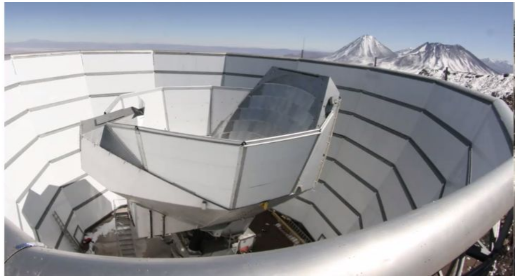
≈ 3 times lower polarization noise

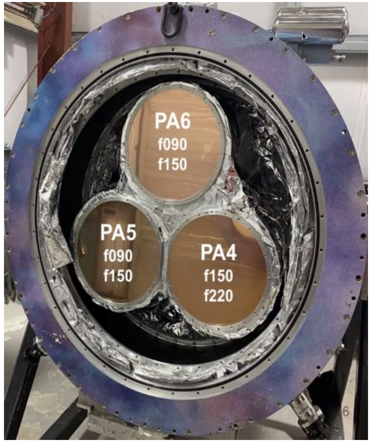
≈ 5 times better angular resolution

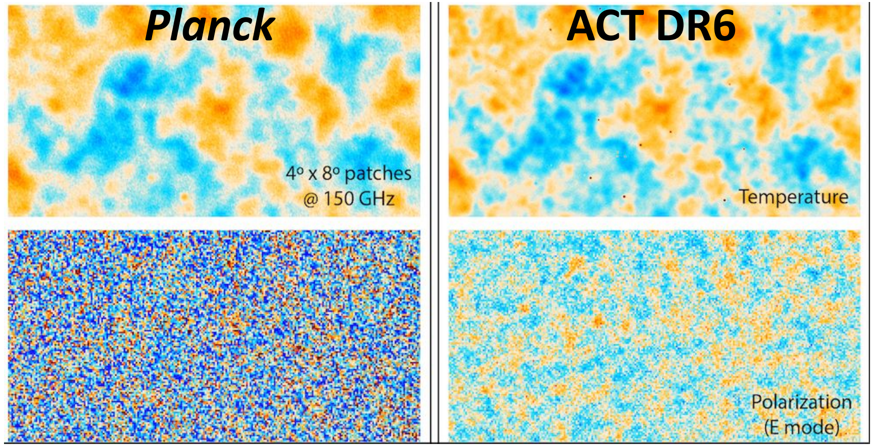
Næss et al 2025, JCAP, 11, 061

Louis et al 2025, JCAP, 11, 062

Atacama Cosmology Telescope data release 6 **(ACT DR6)**





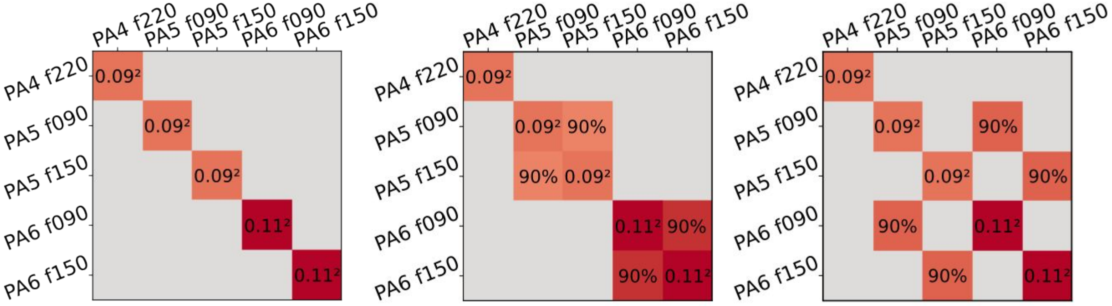


Compared to *Planck*
≈ 3 times lower polarization noise
≈ 5 times better angular resolution

Næss et al 2025, JCAP, 11, 061
Louis et al 2025, JCAP, 11, 062

Avoid dust contamination
&
Incorporate systematic uncertainties through priors derived from the optics model

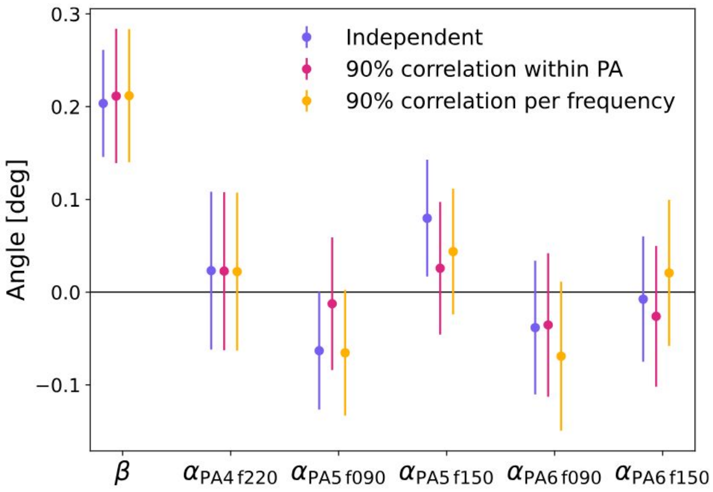
Murphy et al 2024, Appl Opt, 63, 5079

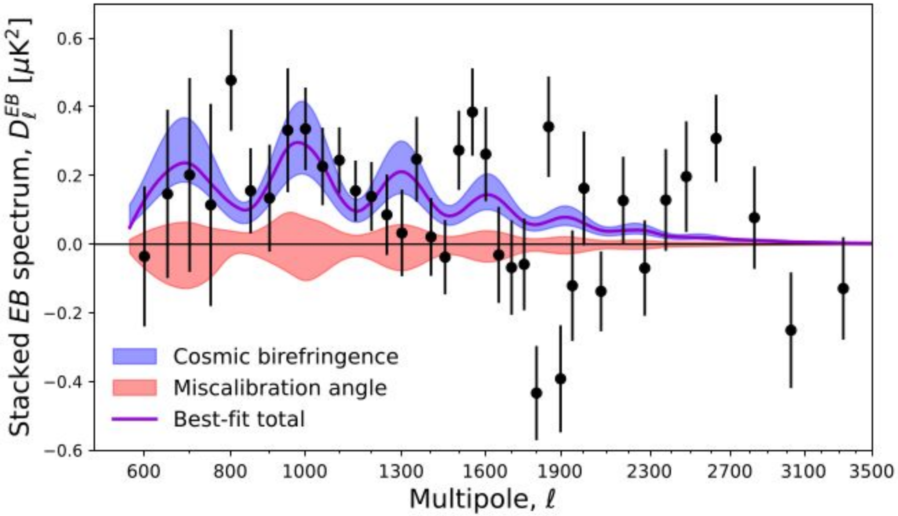


Independent, Π^{ind}

Correlated within PA, Π^{PA}

Correlated per frequency, Π^{ν}





Consistent $\beta \approx 0.20°$ and $\alpha_i \approx 0°$ across all priors, with very stable χ^2 ($\Delta\chi^2$=3 for 1984 d.o.f.)

ACT DR6 analysis:

$\beta = 0.21° \pm 0.07°$ (2.9σ)

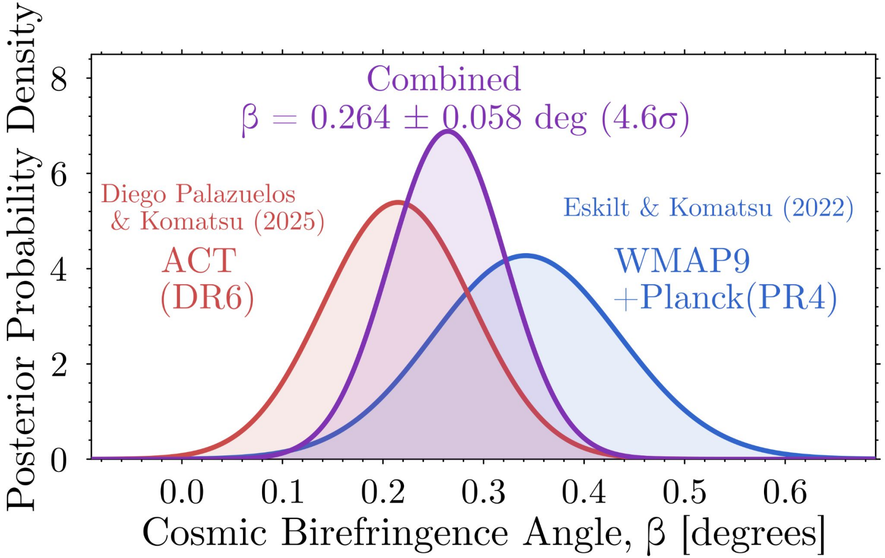
constraining polarization angles with the optics model

PDP & Komatsu 2025 [arXiv:2509.13654]

First independent confirmation!

Present and future outlook

Measurement		Calibration
WMAP + *Planck*	β= 0.34°±0.09°	Galactic emission
		Eskilt & Komatsu 2022, PRD 106 063503
ACT DR6	β= 0.21°±0.07°	Optical model
		PDP & Komatsu 2025 [arXiv:2509.13654]



Present and future outlook

Measurement		Calibration
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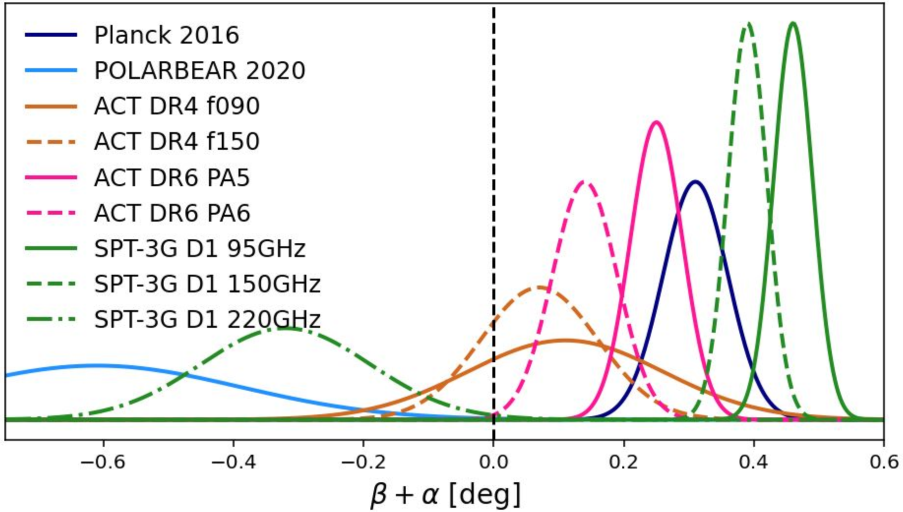
ACT DR6	β= 0.21°±0.07°	Optical model PDP & Komatsu 2025 [arXiv:2509.13654]

Mounting evidence for β>0 across experiments

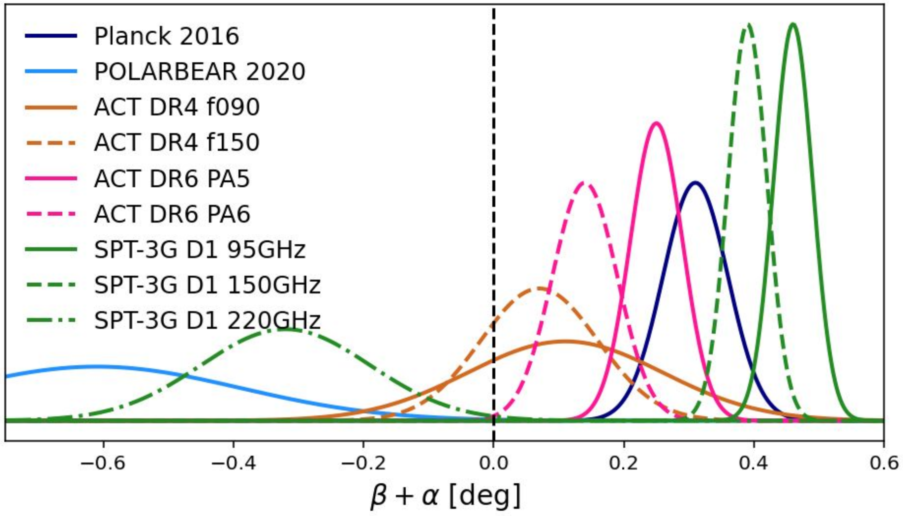
We are still lacking an absolute calibration to confirm the cosmological origin of the signal



POLARBEAR 2020, ApJ, 897, 55
Planck XLIX 2016, A&A, 596, 110
Louis et al 2025, JCAP, 11, 062
Quan et al 2026 [arXiv:2603.20163]

Present and future outlook

Measurement		Calibration
WMAP + *Planck*	β= 0.34°±0.09°	Galactic emission
		Eskilt & Komatsu 2022, PRD 106 063503
ACT DR6	β= 0.21°±0.07°	Optical model
		PDP & Komatsu 2025 [arXiv:2509.13654]



POLARBEAR 2020, ApJ, 897, 55
Planck XLIX 2016, A&A, 596, 110
Louis et al 2025, JCAP, 11, 062
Quan et al 2026 [arXiv:2603.20163]

Mounting evidence for β>0 across experiments

We are still lacking an absolute calibration to confirm the cosmological origin of the signal

Confirmation might come from:

South Pole **BICEP3:** rotating polarized source (exp. $\sigma_\alpha \approx$ 0.03°)
BICEP/Keck XVIII 2025, PRD, 111, 063505

Atacama **Simons Observatory:** rotating sparse wire grid (exp. $\sigma_\alpha \approx$ 0.08°), drone (exp. $\sigma_\alpha \approx$0.045°), satellites
Murata et al 2023, Rev. Sci. Instrum., 94, 124502; Coppi et al 2025, ApJS, 279, 30; Casas et al 2021, Sensors 21, 3361;
Ritacco et al 2024, PASP, 136, 115001

If confirmed, cosmic birefringence…

… will change our understanding of the fundamental symmetries of nature

… could be the first evidence for axionlike particles

If dark energy like, $m_\phi \lesssim 10^{-33}$eV

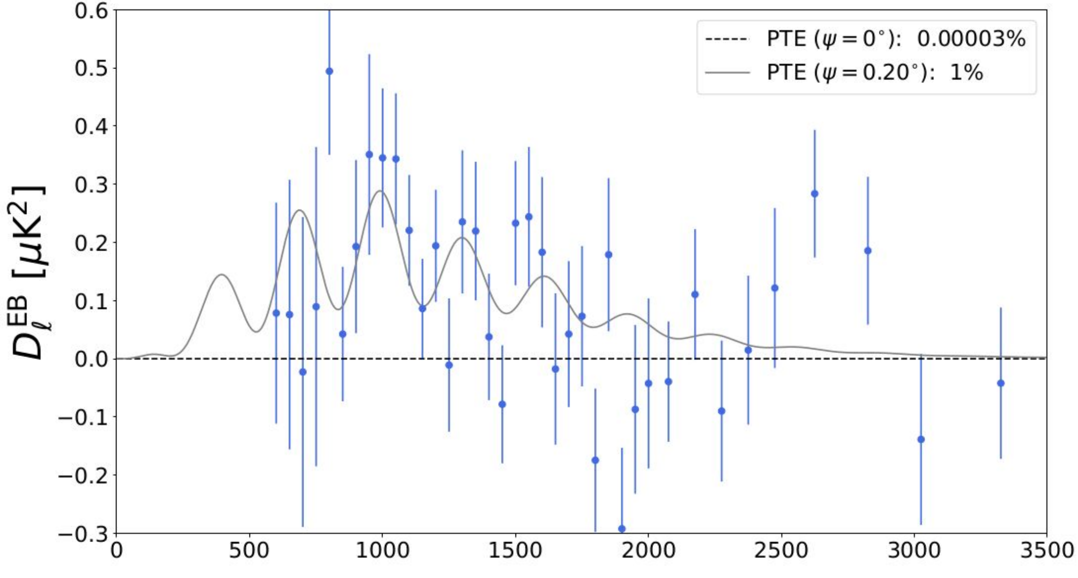
Rules out the cosmological constant

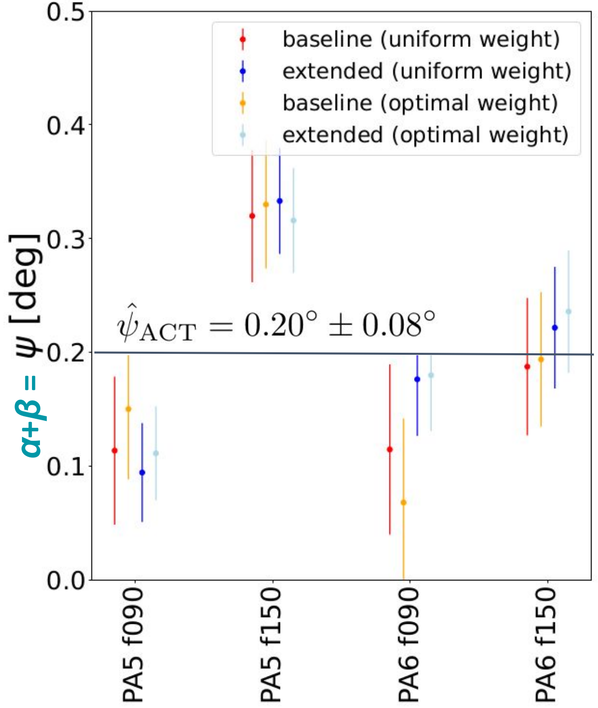
If dark matter like, $m_\phi \gtrsim 10^{-33}$eV

Shows that at least a fraction of dark matter violates parity

Motivates other laboratory experimental searches for axions

Backup slides





While the EB and TB spectra are consistent with an angle miscalibration, we do not exclude non-zero cosmic birefringence. We also note the following:

- Although the extended cuts are not used for any cosmological results, and while our result for $\hat{\psi}_{\rm ACT}$ does not depend on the choice of cut, we note that $\psi_{\rm PA5\ f150}$ and $\psi_{\rm PA5\ f090}$ are in statistical disagreement ($> 3\sigma$) in the extended cut case. This is unexpected given that these arrays are in the same optics tube, so at present we lack an instrument-based model to explain this discrepancy.
- The preference for a nonzero $\hat{\psi}_{\rm ACT}$ is primarily driven by our 150 GHz data, with only weak evidence for a non-zero angle in the 90 GHz data. This could point to frequency-dependent instrumental effects.

Text and figures from Louis et al 2025 [arXiv:2503.14452]

Differences with official ACT analysis

ACT

Louis et al 2025 [arXiv:2503.14452]

Frequentist statistics, adding systematic uncertainties in quadrature

Fitting a rotation angle per array-band, $\psi_i = \beta + \alpha_i$

Neglecting PA4 f220 and *TB* due to limited signal-to-noise

Us

PDP & Komatsu 2025[arXiv:2509.13654]

Bayesian statistics, adding systematic uncertainties through the use of priors

Using the knowledge of the instrument to separate rotations into cosmological β and small α_i miscalibration per array-band

Including PA4 f220 and *TB* to prove the consistency of β

ACT optical modeling of systematic uncertainties

Murphy et al 2024, Appl Opt, 63, 5079

Models the relative orientation and rotation of polarization angles across the focal plane using polarization-sensitive ray tracing software

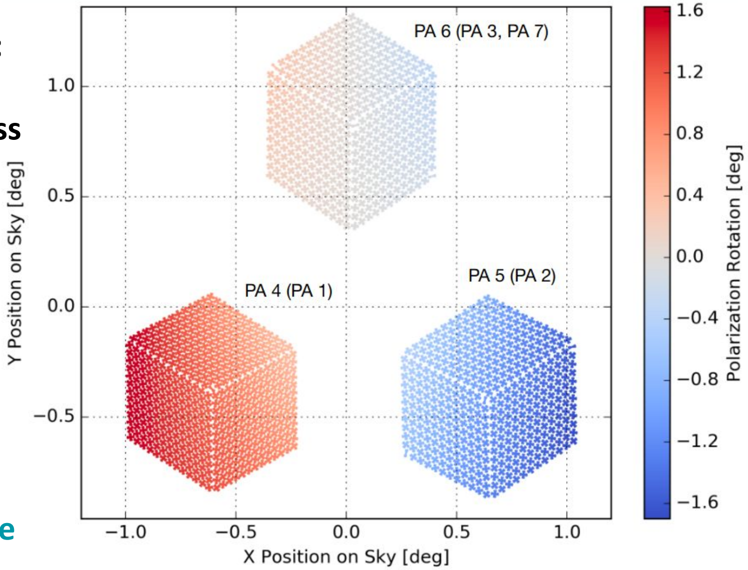
Accounts for uncertainties on lenses':

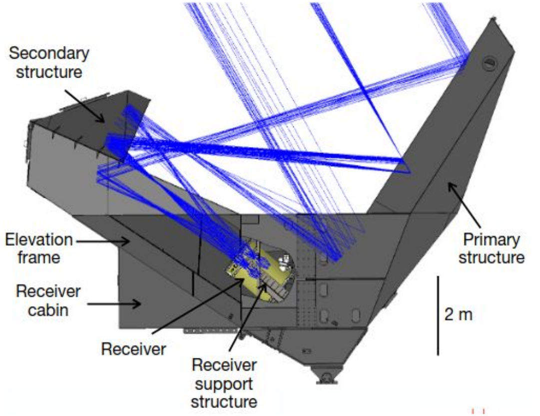
- **position and orientation**
- **anti-reflection coating thickness**
- **refractive index**

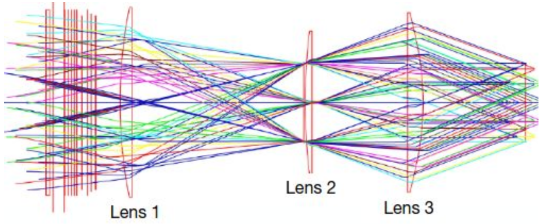
Standard deviation of systematic uncertainties per PA

- $\sigma_{PA4} = 0.09°$
- $\sigma_{PA5} = 0.09°$
- $\sigma_{PA6} = 0.11°$

Warning: model that does not capture any subsequent data processing







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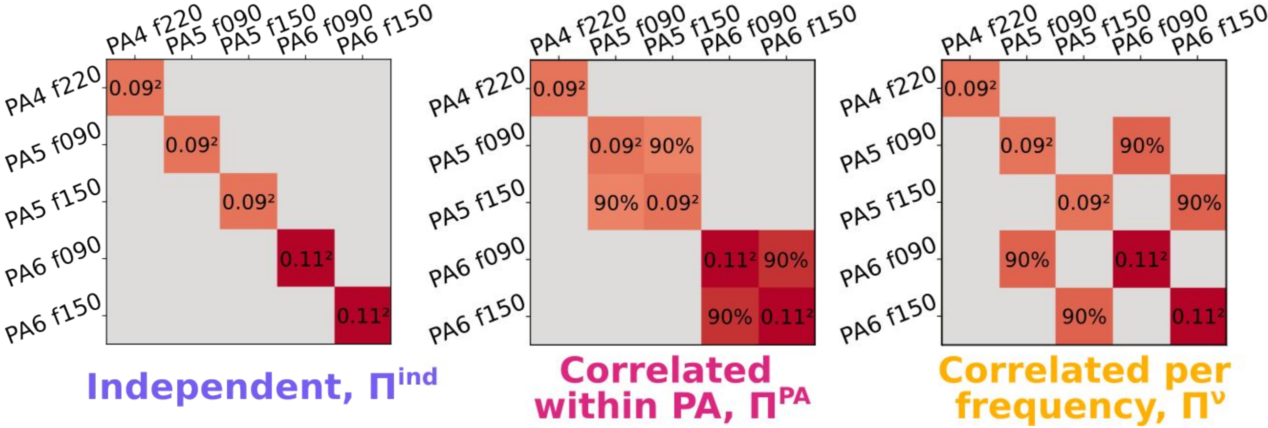
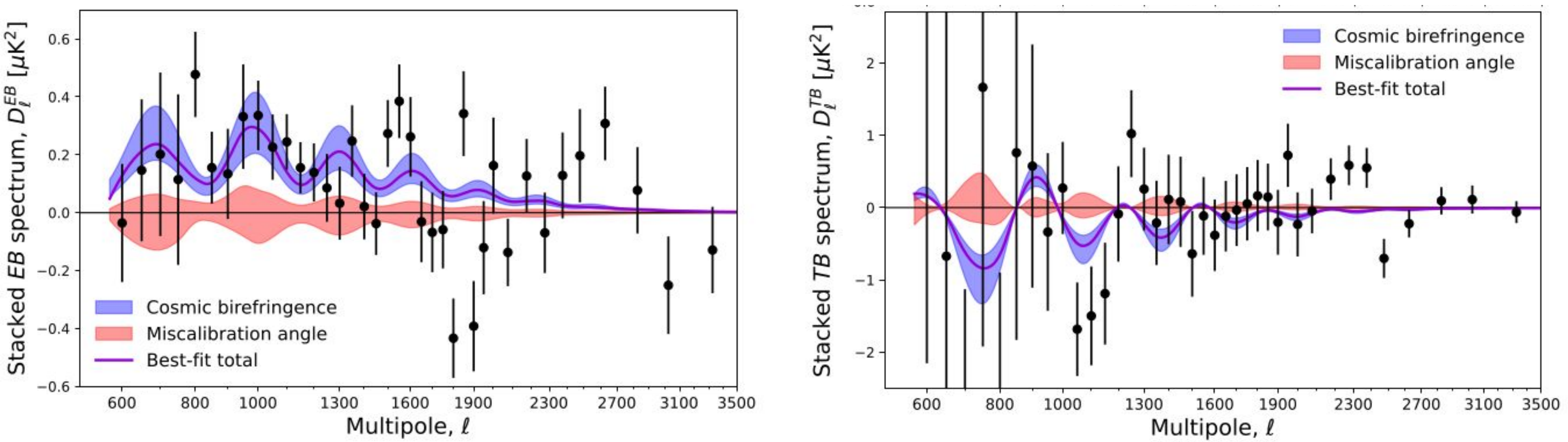


Incorporate systematic uncertainties through Gaussian priors with zero mean

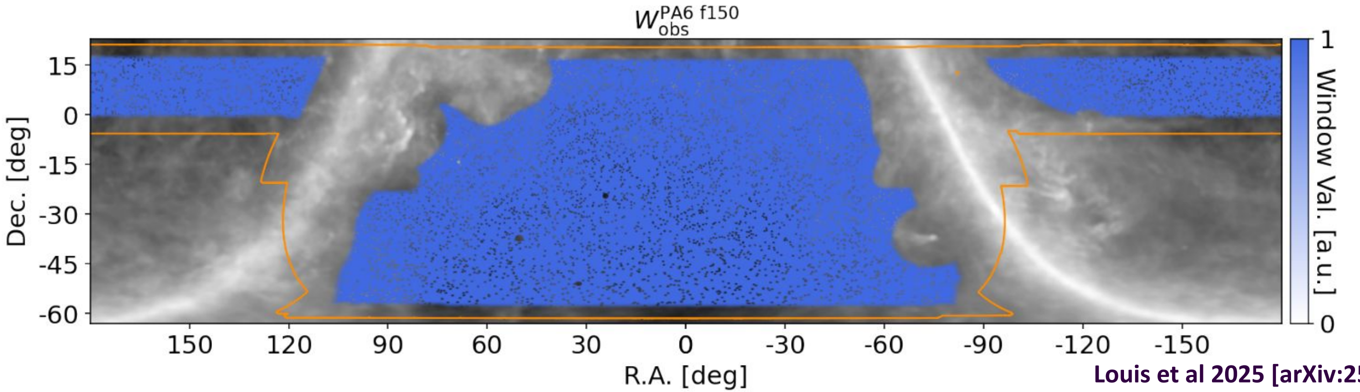


Stacked EB spectrum, D_ℓ^{EB} [μK^2]
Multipole, ℓ
Cosmic birefringence
Miscalibration angle
Best-fit total
Stacked TB spectrum, D_ℓ^{TB} [μK^2]
Multipole, ℓ
Cosmic birefringence
Miscalibration angle
Best-fit total

Differences with WMAP + *Planck* analyses

ACT power spectra:

- **contain the cleanest 25% fraction of the sky after excluding the brightest dust regions**
- **exclude the large angular scales (ℓ<600), where diffuse Galactic emission dominates, to avoid contamination from atmosferic *1/f***



Louis et al 2025 [arXiv:2503.14452]

Not much access to dust in f090 and f150, perhaps a subdominant contribution in f220

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

Calibrate against optical model instead!

Impact of residual *I*⟶*P* leakage

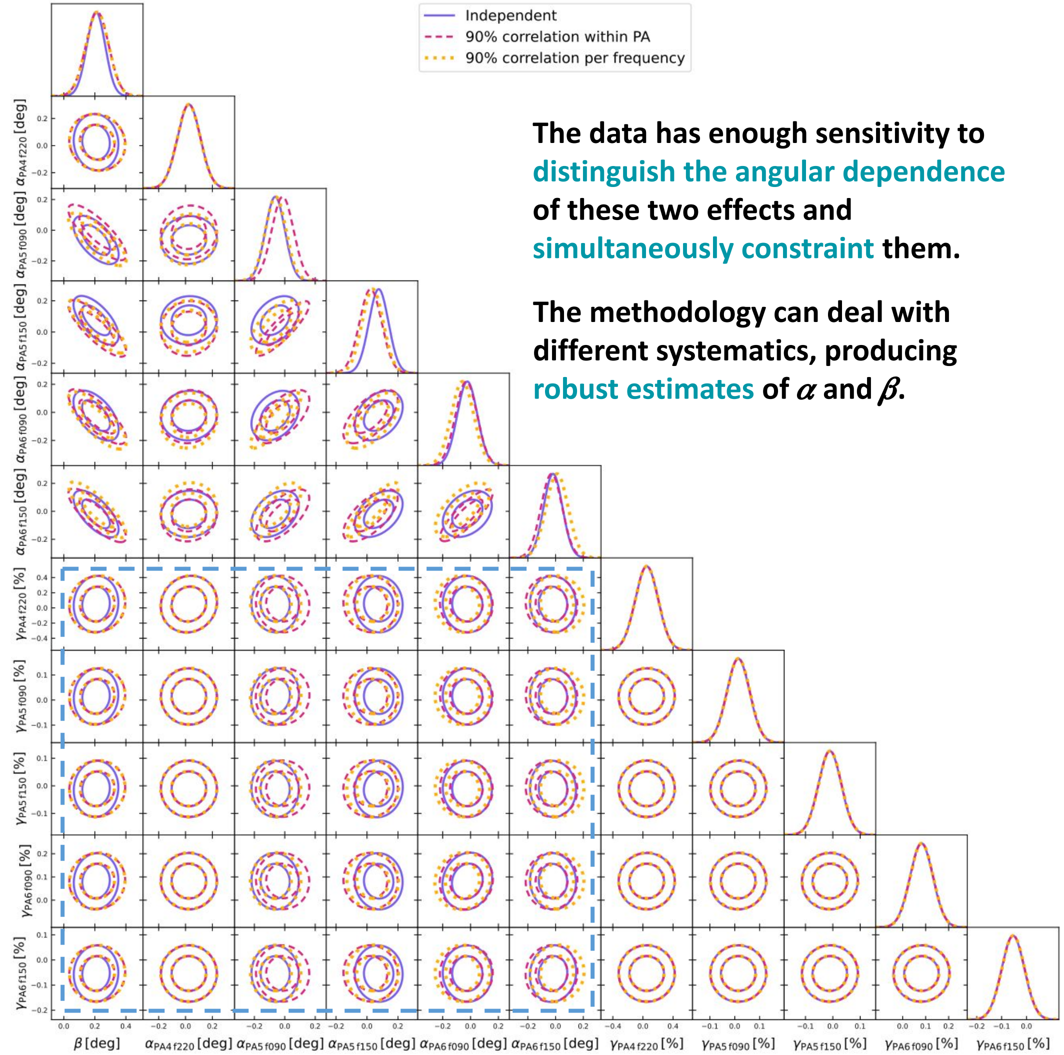
Extended model for the multi-frequency data, including I⟶P leakage

$$\begin{pmatrix} T_{\ell m}^{i,\mathrm{obs}} \\ E_{\ell m}^{i,\mathrm{obs}} \\ B_{\ell m}^{i,\mathrm{obs}} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ \gamma_i & \cos(2\alpha_i + 2\beta) & -\sin(2\alpha_i + 2\beta) \\ \gamma_i & \sin(2\alpha_i + 2\beta) & \cos(2\alpha_i + 2\beta) \end{pmatrix} \begin{pmatrix} T_{\ell m}^{\Lambda\mathrm{CDM}} \\ E_{\ell m}^{\Lambda\mathrm{CDM}} \\ B_{\ell m}^{\Lambda\mathrm{CDM}} \end{pmatrix}$$

After a Taylor series expansion to leading order ($|\alpha|, |\beta|, |\gamma| \ll 1$), fitting equations can simultaneously marginalize over polarization angle miscalibration and *I*⟶*P* leakage

$$C_\ell^{E_i B_j,\mathrm{obs}} \approx 2\alpha_j C_\ell^{E_i E_j,\mathrm{obs}} - 2\alpha_i C_\ell^{B_i B_j,\mathrm{obs}} + 2\beta \left(C_\ell^{EE,\Lambda\mathrm{CDM}} - C_\ell^{BB,\Lambda\mathrm{CDM}} \right) + \gamma_j C_\ell^{TE,\Lambda\mathrm{CDM}}$$

$$C_\ell^{T_i B_j,\mathrm{obs}} \approx 2\alpha_j C_\ell^{T_i E_j,\mathrm{obs}} + 2\beta C_\ell^{TE,\Lambda\mathrm{CDM}} + \gamma_j C_\ell^{TT,\Lambda\mathrm{CDM}}$$



The data has enough sensitivity to distinguish the angular dependence of these two effects and simultaneously constraint them.

The methodology can deal with different systematics, producing robust estimates of α and β.

Prior	Independent	90% correlation within PA	90% correlation per frequency
β	0.208 ± 0.059	0.215 ± 0.074	0.216 ± 0.073
$\alpha_{\mathrm{PA4\,f220}}$	0.025 ± 0.085	0.025 ± 0.085	0.024 ± 0.085
$\alpha_{\mathrm{PA5\,f090}}$	-0.063 ± 0.064	-0.014 ± 0.072	-0.059 ± 0.068
$\alpha_{\mathrm{PA5\,f150}}$	0.075 ± 0.063	0.023 ± 0.072	0.037 ± 0.068
$\alpha_{\mathrm{PA6\,f090}}$	-0.023 ± 0.072	-0.030 ± 0.077	-0.058 ± 0.080
$\alpha_{\mathrm{PA6\,f150}}$	-0.018 ± 0.068	-0.029 ± 0.076	0.011 ± 0.079
$10^2\gamma_{\mathrm{PA4\,f220}}$	0.050 ± 0.152	0.051 ± 0.152	0.051 ± 0.152
$10^2\gamma_{\mathrm{PA5\,f090}}$	0.014 ± 0.046	0.015 ± 0.046	0.015 ± 0.046
$10^2\gamma_{\mathrm{PA5\,f150}}$	-0.011 ± 0.042	-0.010 ± 0.042	-0.010 ± 0.042
$10^2\gamma_{\mathrm{PA6\,f090}}$	0.081 ± 0.050	0.083 ± 0.050	0.083 ± 0.050
$10^2\gamma_{\mathrm{PA6\,f150}}$	-0.054 ± 0.046	-0.053 ± 0.046	-0.053 ± 0.046
χ^2	2027	2030	2029
PTE	22.1 %	20.7 %	21.4 %

The χ^2 has 1979 degrees of freedom.

I→P **leakage has no significant impact on our results, producing only <0.21σ and <0.07σ shifts in our α and β posteriors**

$$\beta = -\frac{1}{2} g_{\phi\gamma} \int \frac{\partial \phi}{\partial t} dt$$

Galactic foregrounds not significantly affected by birefringence

Use foregrounds as our calibrator

Minami et al 2019, PTEP 083E02
Minami & Komatsu 2020, PTEP 103E02

The observed *EB* angular power spectrum of frequency maps becomes

$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right) + \boxed{\frac{1}{\cos(4\alpha)} C_\ell^{EB,\mathrm{Fg}}} + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\Lambda\mathrm{CDM}} - C_\ell^{BB,\Lambda\mathrm{CDM}}\right)$$

Synchrotron

No significant global *EB* to date

Martire et al 2022, JCAP ,04, 003; QUIJOTE 2023, MNRAS, 519, 3383

Thermal dust

***TB* and *EB* from the misalignment between dust filaments and the Galatic magnefic field**

Clark et al 2021, ApJ, 919, 53; Cukierman et al 2023, ApJ, 946, 106

Joint WMAP + *Planck* analysis:

β = 0.34° ± 0.09° (3.6σ)

found through foreground calibration of polarization angles

Eskilt & Komatsu 2022, PRD, 106, 063503

Waiting for confirmation form independent experiments

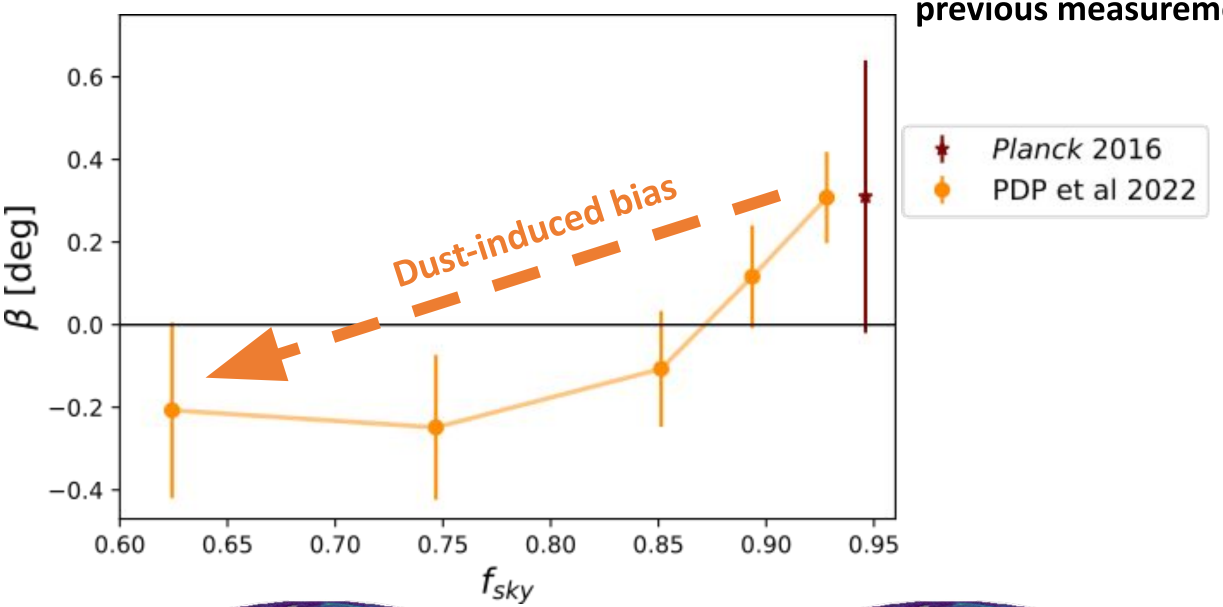
Further tests

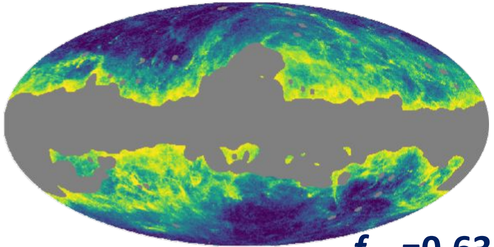
- **First detection of the impact of dust *EB***
  PDP et al 2022, PRL, 128, 091302
- **Robustness of measured β against dust modeling**
  Hervías-Caimapo et al 2025, PRD, 111, 083532
- **β > 0 found in synchrotron-dominated bands**
- **β > 0 independently seen across WMAP, LFI, HFI**
- **WMAP and *Planck* instrumental systematics have no significant impact on measured β**
  Eskilt et al 2023, A&A, 679, 144
  PDP et al 2023, JCAP, 01, 044
- **Frequency-independence of measured β**
  Eskilt 2022, A&A ,662, A10

PDP et al 2022, PRL, 128, 091302

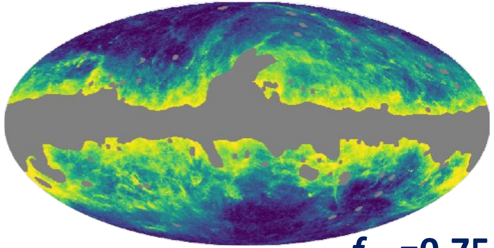
Detecting the impact of dust *EB* in NPIPE 100, 143, 217, 353GHz data

For nearly full-sky: β = 0.30° ± 0.11° (2.7σ) → Consistent with and more precise than previous measurements!

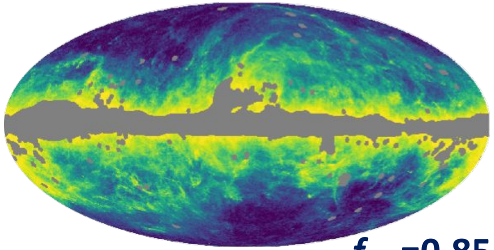




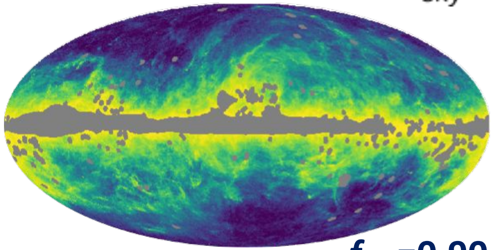
f_{sky}=0.63



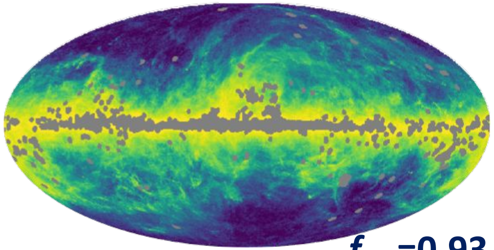
f_{sky}=0.75



f_{sky}=0.85



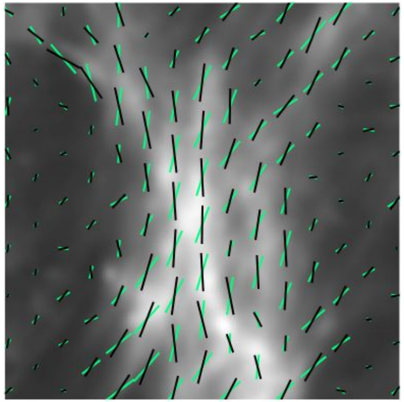
f_{sky}=0.90



f_{sky}=0.93

Huffenberger et al 2020, ApJ, 919, 53
Clark et al 2021, ApJ, 919, 53
Cukierman et al 2023, ApJ, 946, 106

Misalignment between dust filaments and the Galactic magnetic field



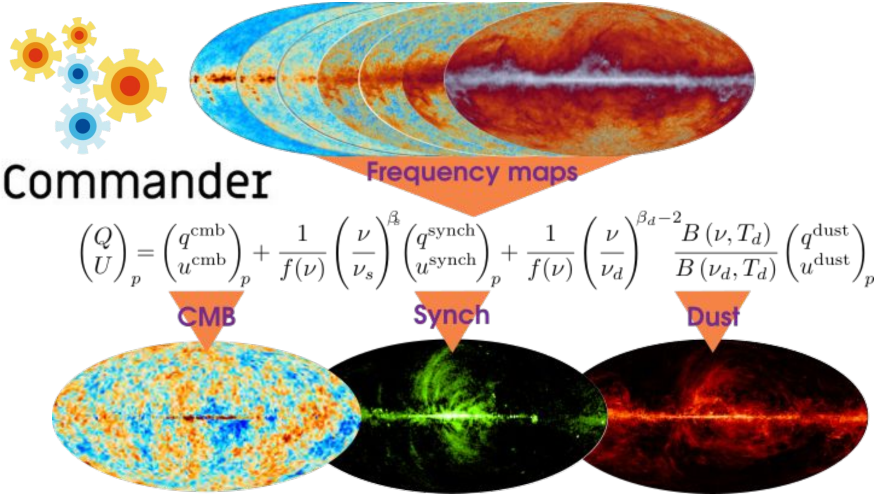
$$C_\ell^{EB,\mathrm{dust}} \approx A_\ell C_\ell^{EE,\mathrm{dust}} \frac{C_\ell^{TB,\mathrm{dust}}}{C_\ell^{TE,\mathrm{dust}}}$$

Take dust C_ℓ to be that of NPIPE @ 353GHz

A_ℓ **free amplitude parameter**

$$0 \leq A_\ell \ll 1$$

Take the Commander sky model as our foreground model



$$\begin{pmatrix} Q \\ U \end{pmatrix}_p = \begin{pmatrix} q^{\mathrm{cmb}} \\ u^{\mathrm{cmb}} \end{pmatrix}_p + \frac{1}{f(\nu)} \left(\frac{\nu}{\nu_s}\right)^{\beta_s} \begin{pmatrix} q^{\mathrm{synch}} \\ u^{\mathrm{synch}} \end{pmatrix}_p + \frac{1}{f(\nu)} \left(\frac{\nu}{\nu_d}\right)^{\beta_d - 2} \frac{B(\nu, T_d)}{B(\nu_d, T_d)} \begin{pmatrix} q^{\mathrm{dust}} \\ u^{\mathrm{dust}} \end{pmatrix}_p$$

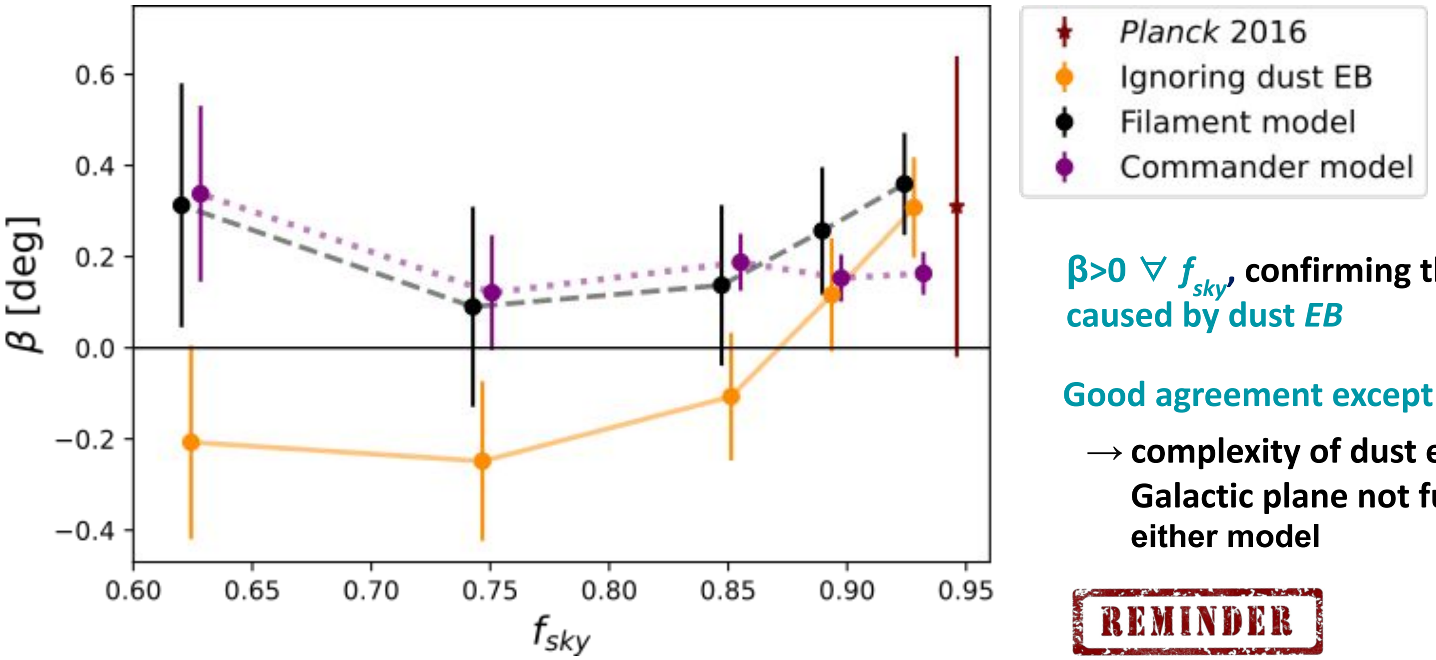
Planck IV 2020, A&A 641 A4

$$C_\ell^{EB,\mathrm{dust}} \approx \mathcal{D} C_\ell^{EB,\mathtt{Commander}}$$

$\mathcal{D}$ **free amplitude parameter**

PDP et al 2022, PRL, 128, 091302

After correcting for dust *EB* in NPIPE 100, 143, 217, 353GHz data



$\beta>0\ \forall\ f_{sky}$, confirming that the decline was caused by dust *EB*

Good agreement except at f_{sky}=0.93

→ complexity of dust emission near the Galactic plane not fully captured by either model

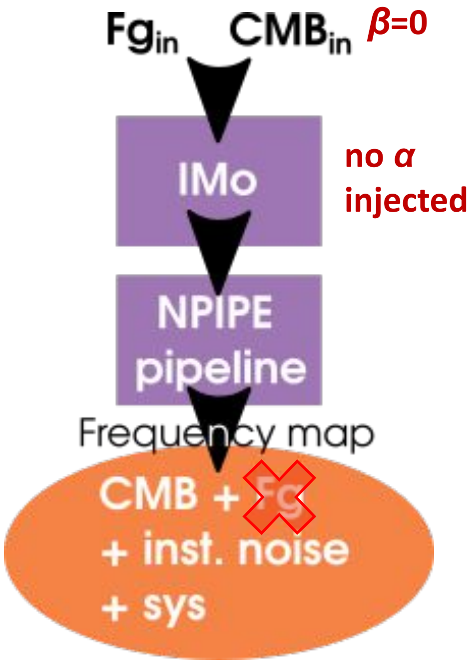
REMINDER

Questioning dust as an instrument calibrator not as the origin of the observed *EB* signal

Planck LVII 2020, A&A, 643, A42

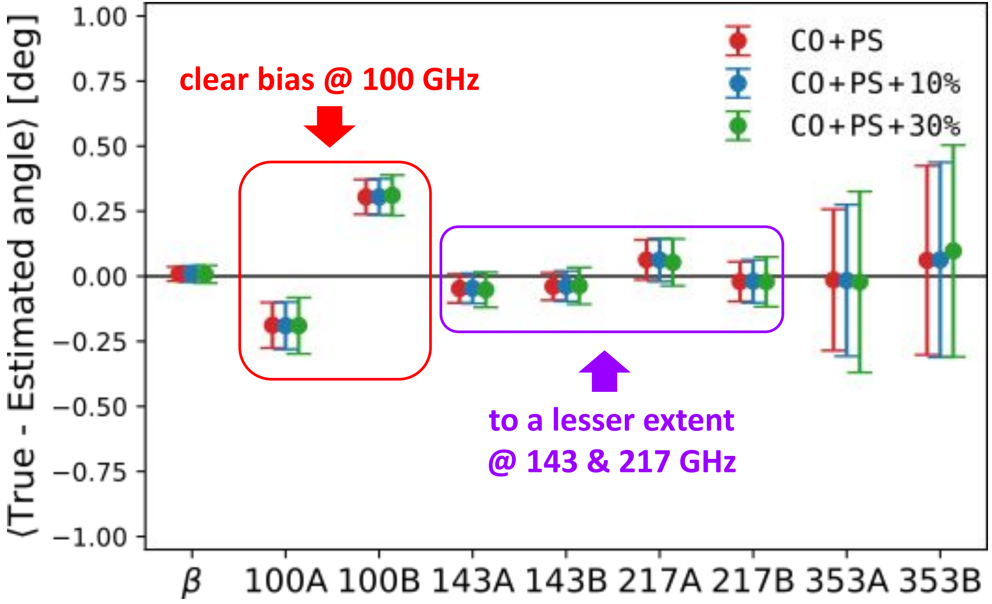
PDP et al 2023, JCAP, 01, 044

NPIPE end-to-end simulations



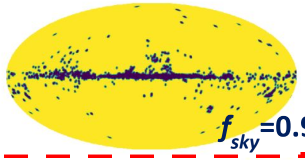
Null test by removing foregrounds

Sims of CMB + Noise + Systematics

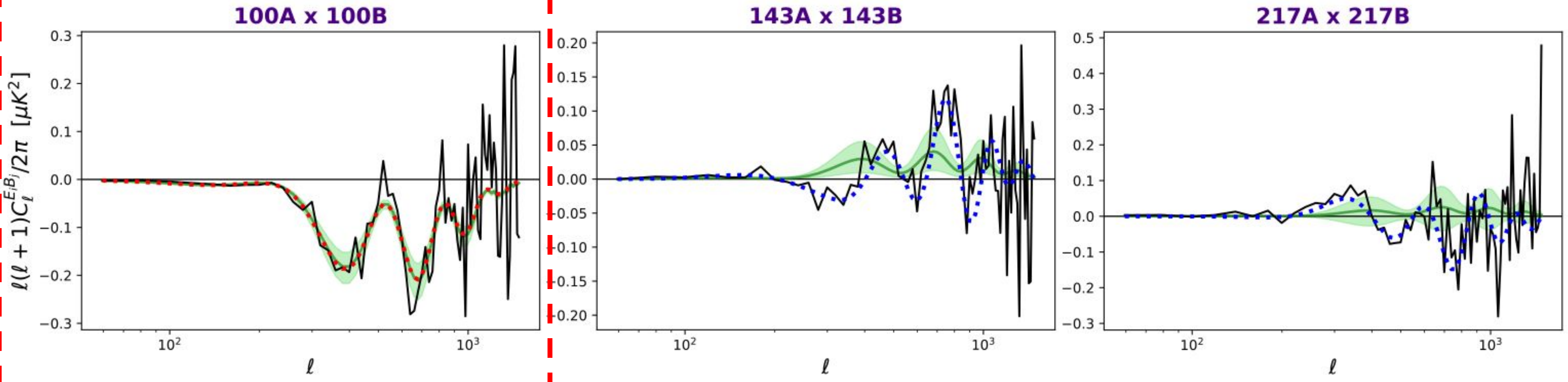


Average over 100 simulations

Error bar = simulations dispersion



PDP et al 2023, JCAP, 01, 044



Cross-polarization effect @ 100 GHz

$$C_\ell^{EB} \propto C_\ell^{EE}$$

Most harmful as is degenerate with α

Beam leakage @ 143 and 217 GHz

$$C_\ell^{EB} = \omega^2_{\ell,\mathrm{pix}} \sum_{XY} W_\ell^{EB,XY} C_\ell^{XY,\mathrm{cmb}}$$

$$XY \in \{TT, EE, BB, TE\}$$

QuickPol's polarization matrices

Hivon et al 2017, A&A, 598, A25

Distinct angular dependence partially confused with α

Planck LVII 2020, A&A, 643, A42

PDP et al 2023, JCAP, 01, 044

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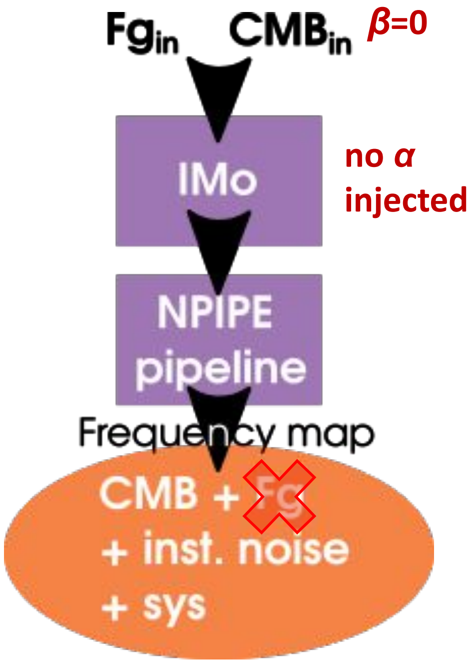

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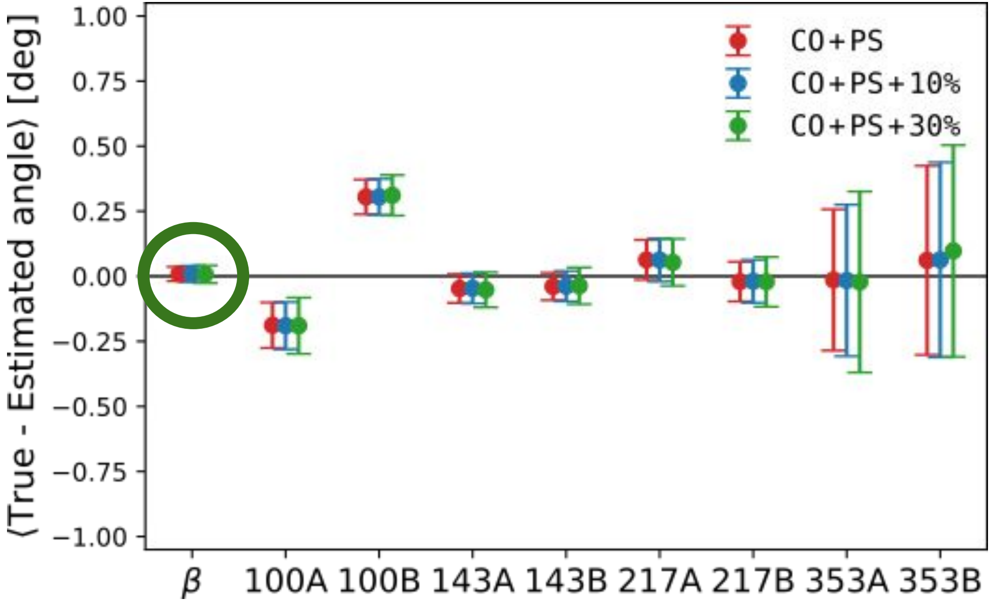
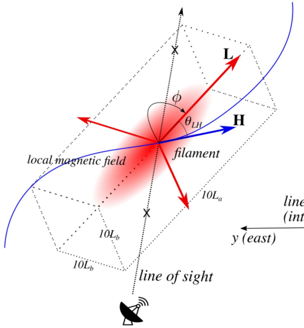


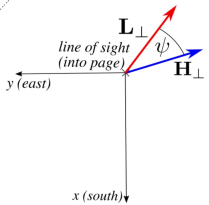
Negligible impact on β

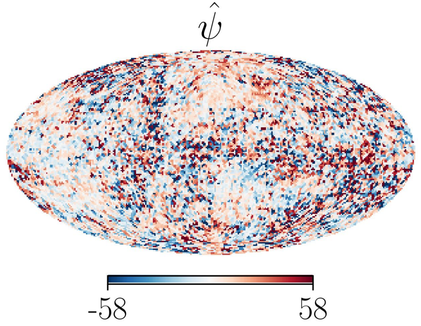
$$\langle\beta_{sys}\rangle = 0.009° \pm 0.003° \text{ vs } \sigma_{stat} = 0.11°$$

Cukierman et al 2023, ApJ, 946, 106
BICEP/Keck XVI 2023, ApJ, 945, 72

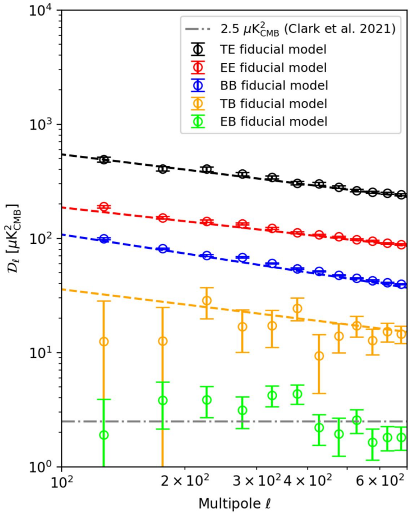
Different misalignment estimators and tracers







Filament-based model calibrated to reproduce **filaments' (21-cm HI) and magnetic field (*Planck* polarization)** orientation that **predicts *EB* of few μK^2**



Hervías-Caimapo et al 2025, PRD, 111, 083532

Alternative analyses of *Planck* PR4 that do not rely on foreground modeling

Real-space measurement via **stacking of anisotropy peaks**

β = 0.46° ± 0.04° (stat) ± 0.28° (syst) for SEVEM
β = 0.48° ± 0.04° (stat) ± 0.28° (syst) for Commander

Sullivan et al 2025, JCAP, 06, 025

Field-level constraints via **hybrid ILC disentangling the (un)correlated E and B components**

β = 0.32° ± 0.12°

Remazeilles 2025 [arXiv:2507.22109]

Joint WMAP + *Planck* analysis, both in frequentist and Bayesian frameworks

- Increase in total significance,
  β = 0.34° ± 0.09° (3.6σ)
- β > 0 in synchrotron-dominated bands
- β > 0 independently across WMAP, LFI, HFI

Cosmoglobe
Beyond PLANCK

Eskilt & Komatsu 2022, PRD, 106, 063503
Eskilt et al 2023, A&A, 679, 144