# Simultaneous determination of miscalibrated polarization angles and cosmic birefringence from *Planck* PR4

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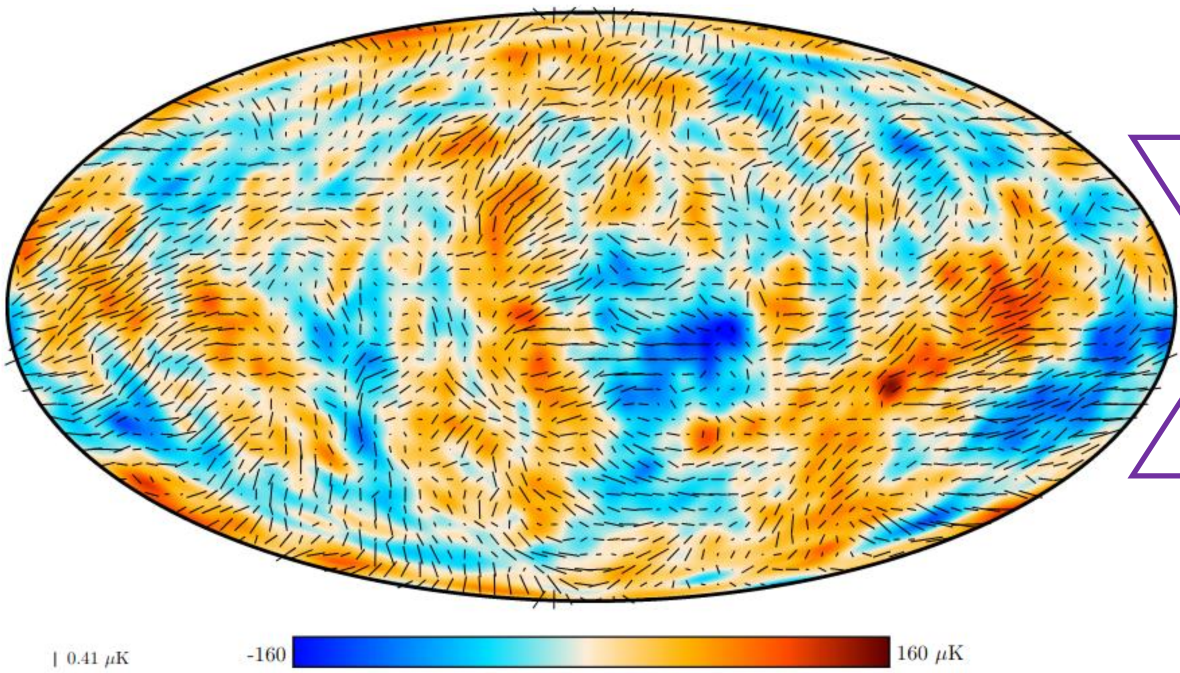
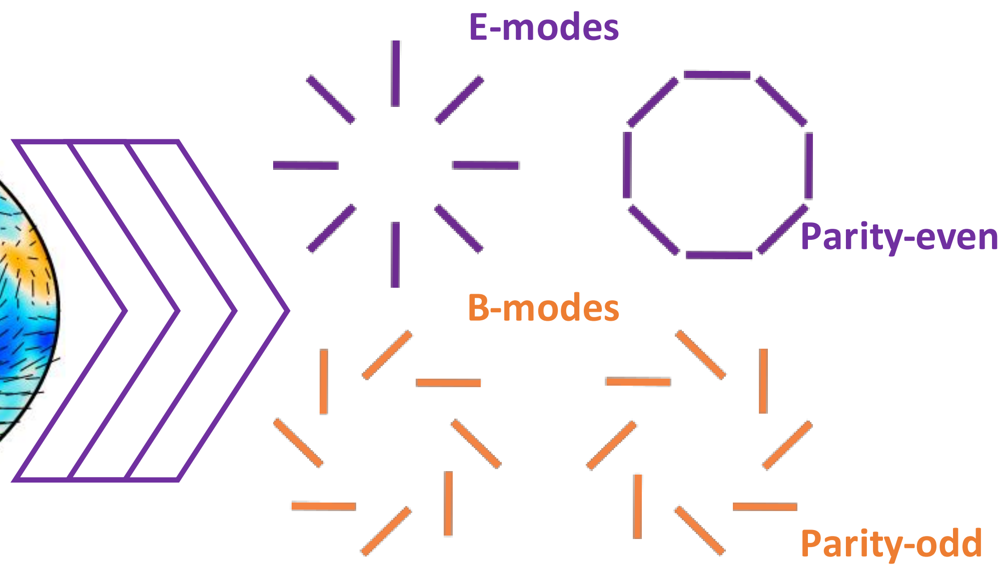
IFCA · EXCELENCIA MARÍA DE MAEZTU · CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS · UC UNIVERSIDAD DE CANTABRIA

# Based on

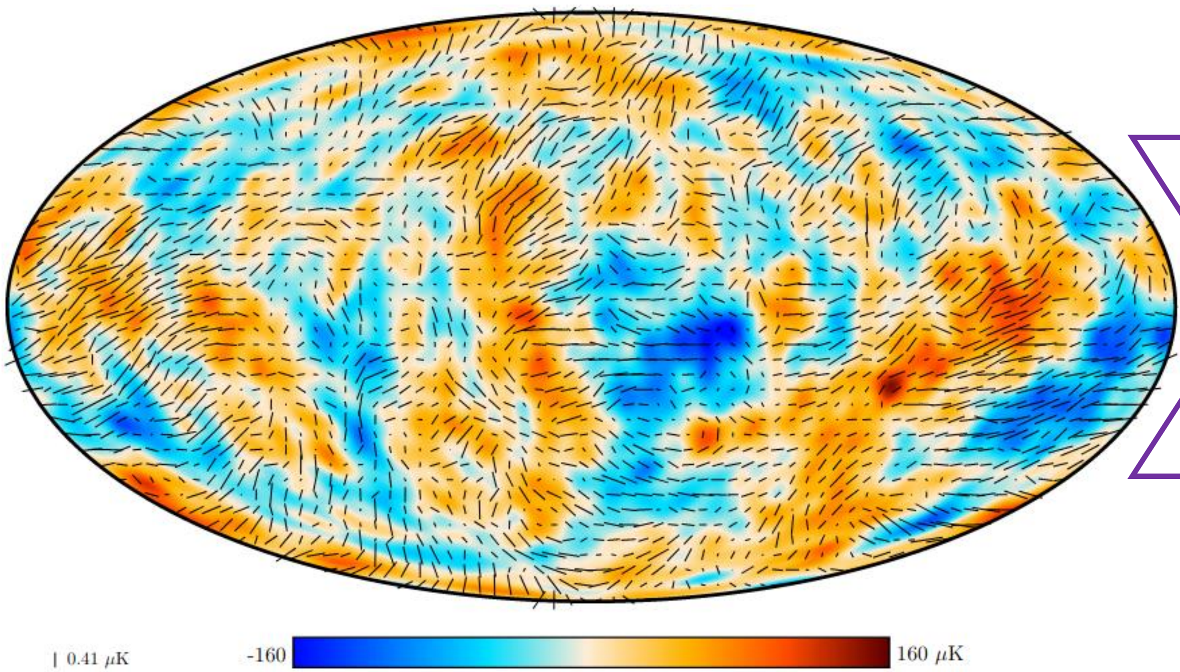
| | |
|---|---|
| Minami et al 2019, PTEP, 083E02 | The original presentation of the methodology |
| Minami 2020, PTEP, 063E01 | Extension to partial-sky observations |
| Minami & Komatsu 2020, PTEP, 103E02 | Extension to frequency cross-spectra |
| Minami & Komatsu 2020, PRL, 125, 221301 | Application to Planck HFI PR3<br>Without foreground modeling |
| PDP, Eskilt et al 2022, PRL, 128, 091302 | Application to Planck HFI PR4<br>With foreground modeling |
| Eskilt 2022, A&A, 662, A10 | Application to Planck LFI & HFI PR4<br>Analysis of the frequency dependence of birefringence |
| Eskilt & Komatsu 2022 [arXiv:2205.13962] | Joint analysis of Planck LFI & HFI PR4 and WMAP 9-year |
| PDP et al 2022 in prep | Alternative implementation: analytical maximum likelihood solution<br>Simulation study and assessment of the impact of systematics |




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




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

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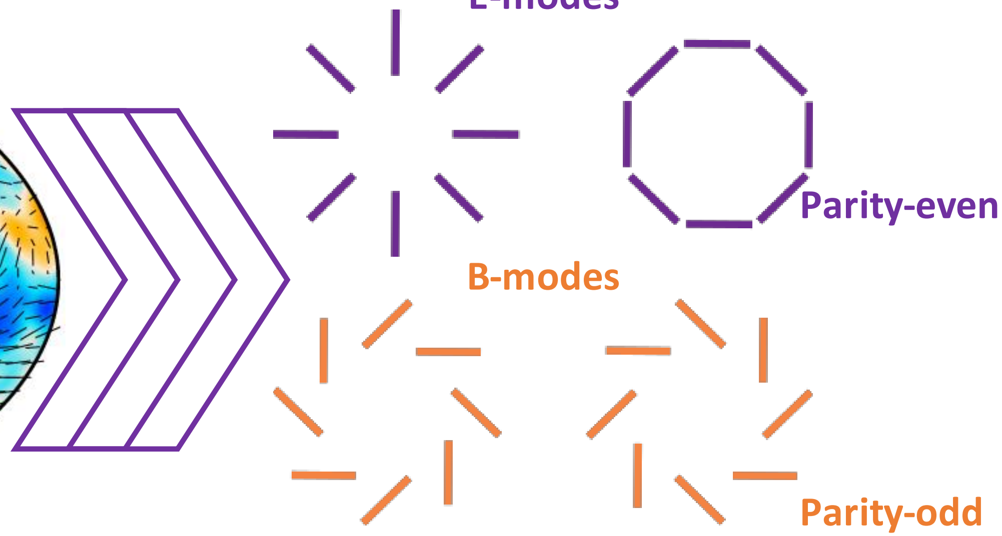


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**Analyzing CMB polarization in terms of spherical harmonics**

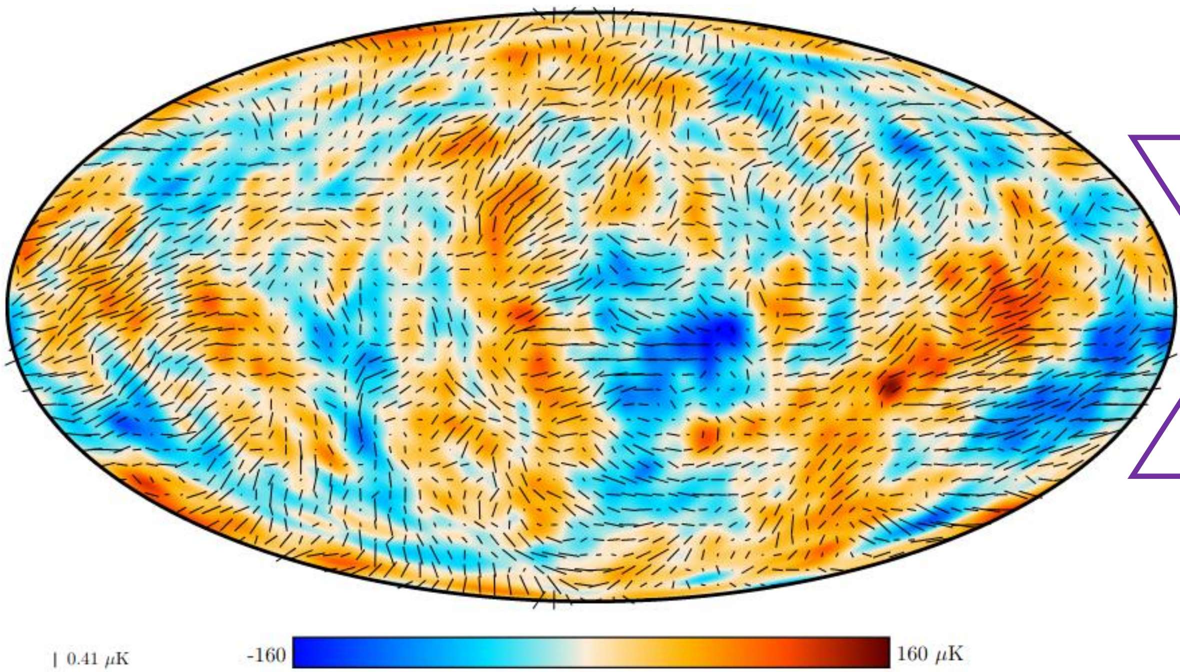
$$\langle E_{\ell m} E^*_{\ell' m'} \rangle = \delta_{mm'} \delta_{\ell\ell'} C_\ell^{EE}$$

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

} **Parity-even**

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

**Parity-odd**

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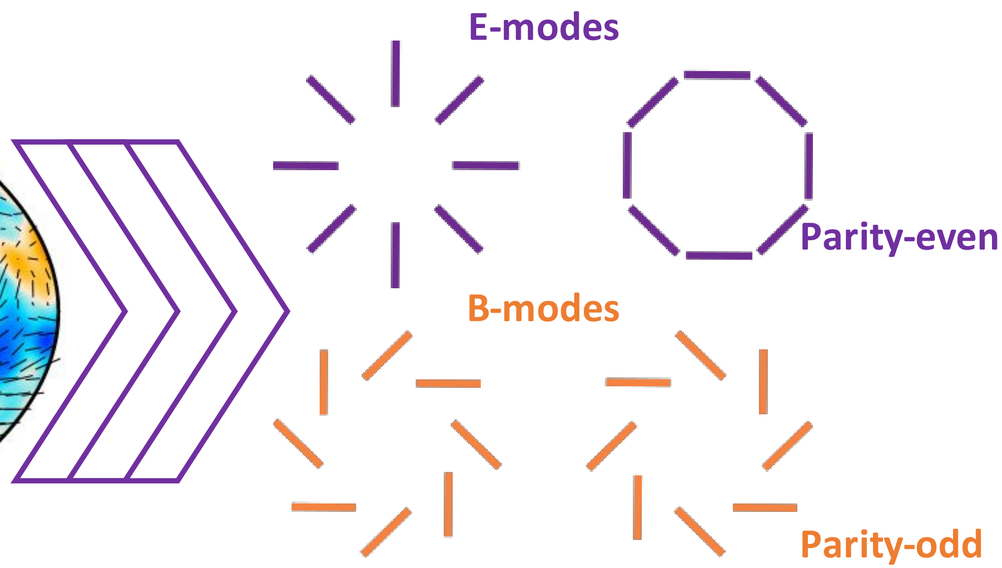


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**ΛCDM**

**The Universe has no preferred direction so the statistics of CMB anisotropies must be invariant under parity transformation**

EB≠0 evidence of parity-violating physics

Lue et al 1999, PRL, 83, 1506

DM/DE could be a parity-violating pseudoscalar field $\phi(-\vec{n}) = -\phi(\vec{n})$

Chern-Simons coupling to EM $\frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}_{\mu\nu}$


Carroll at al 1990, PRD, 41, 1231

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rotation of the plane of linear polarization clockwise on the sky by an angle

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

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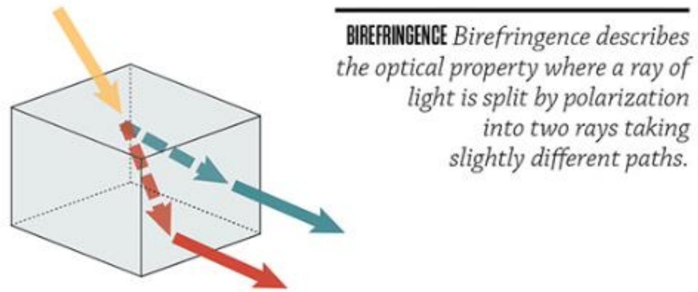
**Cosmic birefringence**



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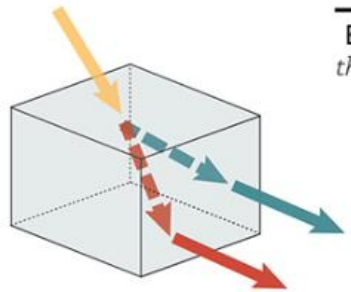

**BIREFRINGENCE** *Birefringence describes the optical property where a ray of light is split by polarization into two rays taking slightly different paths.*

**Cosmic birefringence rotates the CMB signal**

$$\begin{pmatrix} E^{\rm o}_{\ell m} \\ B^{\rm o}_{\ell m} \end{pmatrix} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E^{\rm cmb}_{\ell m} \\ B^{\rm cmb}_{\ell m} \end{pmatrix}$$

**so the observed angular power spectrum becomes**

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

**Any signal resembling EE found in EB could be attributed to cosmic birefringence**

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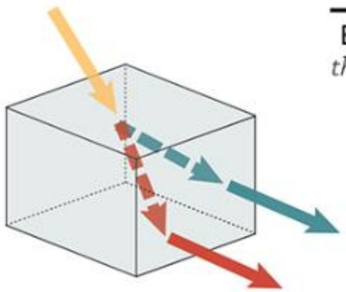


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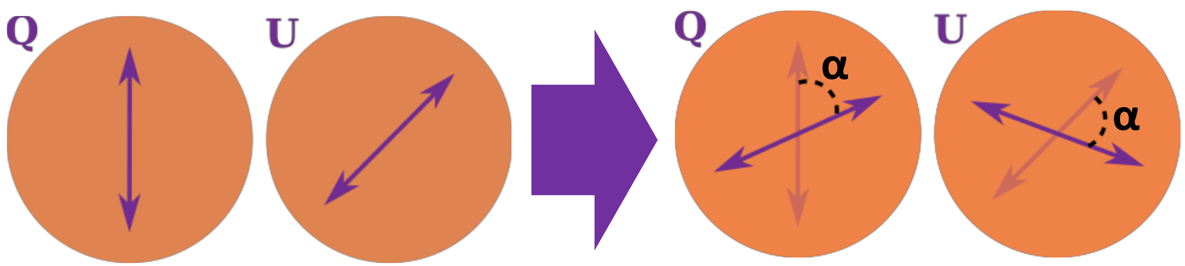
Base of most of the harmonic-space methodologies applied in the past

# Miscalibration of the detector's polarization angle

Krachmalnicoff et al 2022, JCAP, 01, 039

**Polarization-sensitive detector**




**Unknown α miscalibration**

**Completely degenerate with the birefringence**

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

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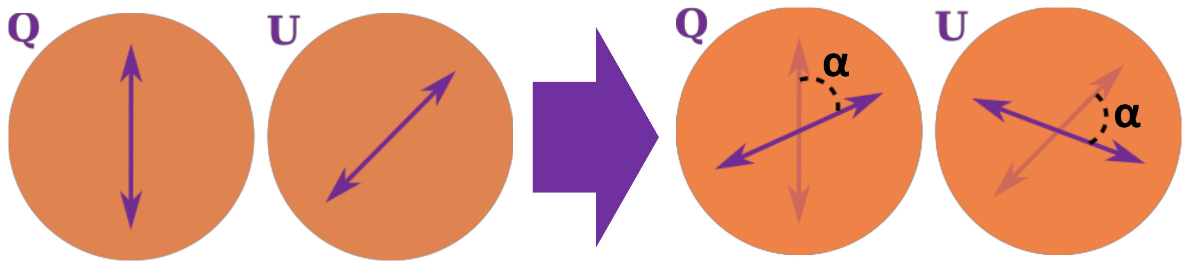


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**Spurious TB and EB correlations can also be produced by**

- **intensity-to-polarization leakage**
- **beam leakage**
- **cross-polarization effects**

Miller et al 2009, PRD, 79, 103002

# Past measurements

| | | |
|---|---|---|
| early WMAP & BOOMERANG | $\alpha+\beta = -6.0°$ ± 4.0° (stat) ± ?? (sys) | Feng et al 2006, PRL, 96, 221302 |
| QUaD | $\alpha+\beta = 0.55°$ ± 0.82° (stat) ± 0.5° (sys) | Wu et al 2009, PRL, 102, 161302 |
| WMAP 9-year | $\alpha+\beta = -0.36°$ ± 1.24° (stat) ± 1.5° (sys) | Hinshaw et al 2013, ApJS, 208, 19 |
| *Planck* 2015 | $\alpha+\beta = 0.31°$ ± 0.05° (stat) ± 0.28° (sys) | *Planck* Collaboration XLIX. 2016, A&A, 596, A110 |

⋮

Often dominated by systematic uncertainties

Calibration strategies set a ≈ 0.5° - 1° limit

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Birefringence depends on the propagation length of photons

Use Galactic foreground emission as our calibrator

Minami et al 2019, PTEP, 083E02

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Minami 2020, PTEP, 063E01
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**Observed signal is a rotation of the CMB and Galactic foreground emissions**

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

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Experimental constraints

*Planck* Collaboration XI. 2020, A&A, 641, A11
Martire et al 2022, JCAP, 04, 003

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

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0

**Build a Gaussian likelihood to simultaneously determine both angles**

$$-2\ln\mathcal{L} = \sum_{b=1}^{N_{\rm bins}} \left(\mathbf{A}\bar{C}_b^{\rm o} - \mathbf{B}\bar{C}_b^{\rm cmb}\right)^T \mathbf{M}_b^{-1} \left(\mathbf{A}\bar{C}_b^{\rm o} - \mathbf{B}\bar{C}_b^{\rm cmb}\right) + \sum_{b=1}^{N_{\rm bins}} \ln|\mathbf{M}_b|$$

**Cross-correlation of frequency bands of any CMB experiment**

$$\bar{C}_b^{\rm o} = \left(C_b^{E_iE_j,{\rm o}}\ C_b^{B_iB_j,{\rm o}}\ C_b^{E_iB_j,{\rm o}}\right)^T$$

**Theoretical prediction for CMB angular power spectra**

$$\bar{C}_b^{\rm cmb} = \left(C_b^{EE,{\rm cmb}} b_b^i b_b^j \omega_{b,{\rm pix}}^2\ C_b^{BB,{\rm cmb}} b_b^i b_b^j \omega_{b,{\rm pix}}^2\right)^T$$

**Covariance matrix**

$$\mathbf{M}_\ell = \mathbf{A}{\rm Cov}\left(\bar{C}_\ell^{\rm o}, \bar{C}_\ell^{{\rm o}T}\right)\mathbf{A}^T$$

**Rotation matrices**

$$\mathbf{A}(\alpha_i,\alpha_j) = \left(\frac{-\sin(4\alpha_j)}{\cos(4\alpha_i)+\cos(4\alpha_j)}\ \ \frac{\sin(4\alpha_i)}{\cos(4\alpha_i)+\cos(4\alpha_j)}\ \ 1\right)$$

$$\mathbf{B}(\alpha_i,\alpha_j,\beta) = \frac{\sin(4\beta)}{2\cos(2\alpha_i+2\alpha_j)}\left(1\ \ -1\right)$$

## *Planck* PR4 (NPIPE reprocessing)

Reprocessing of raw LFI and HFI *Planck* data
Scale-dependent reduction of total uncertainty due to
- Addition of data acquired during repointing maneuvers
- Improved modeling of instrumental noise and systematics

*Planck* Collaboration 2020, A&A, 643, A42

- NPIPE 100, 143, 217, 353 GHz data
- Focus on high-$\ell$ data to target the birefringence angle from recombination → bin $C_\ell/M_\ell$ from $\ell_{min}$=51 to $\ell_{max}$=1490 with $\Delta\ell$ = 20 spacing
- A/B detector splits → $\beta$, $\alpha_i$ (i=1,…,8)
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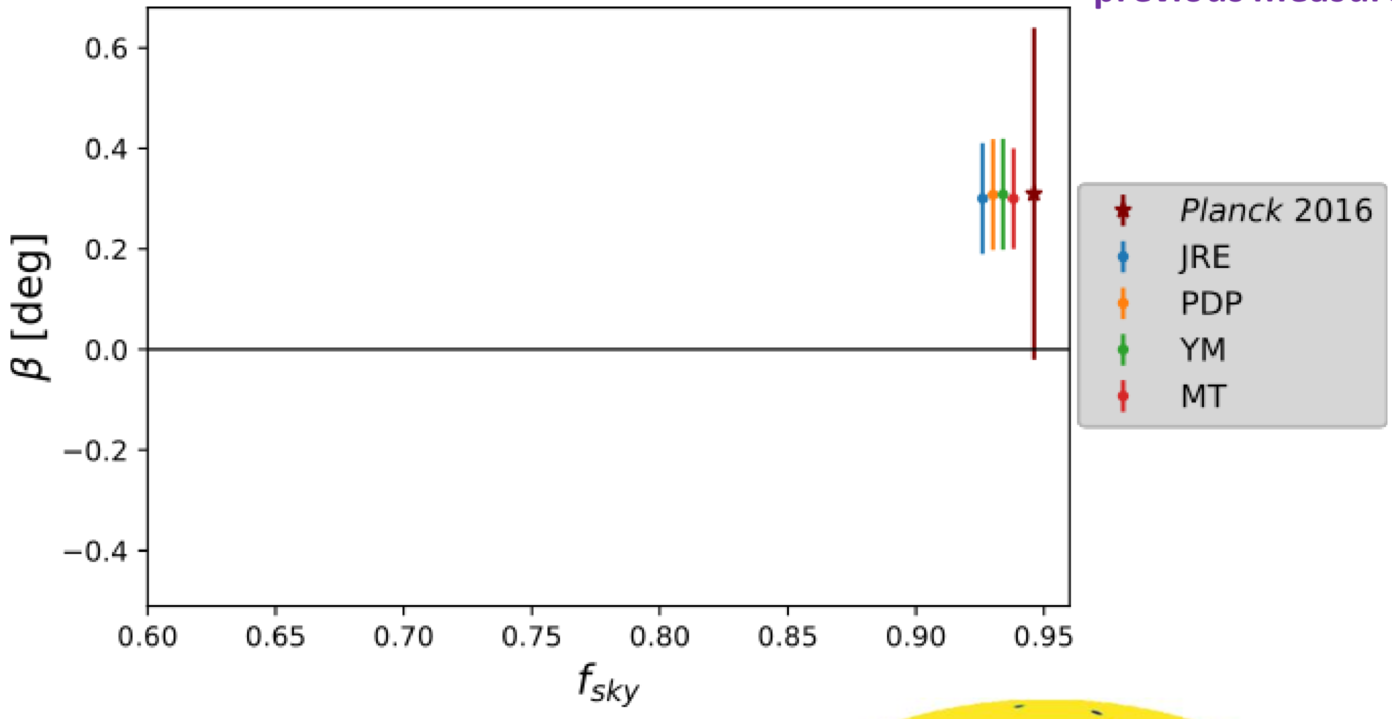
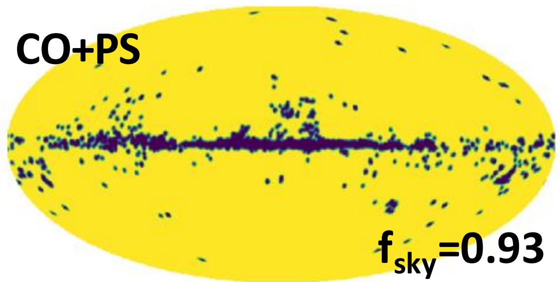
Consistent results across 4 independent pipelines

| Pipeline | Implementation | Pseudo-$C_\ell$ |
|---|---|---|
| JRE | Posterior distribution via MCMC | PolSpice |
| MT | | Xpol |
| YM | | NaMaster |
| PDP | Analytical minimization | |

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



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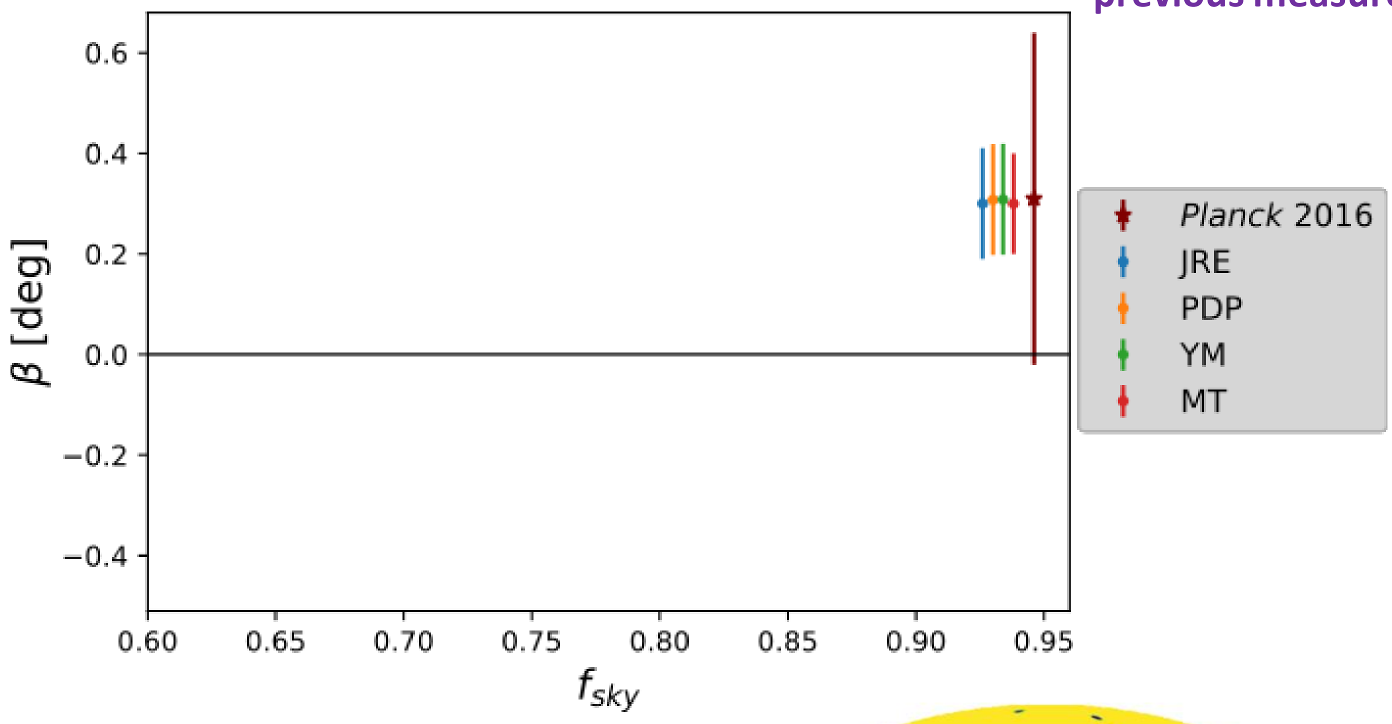
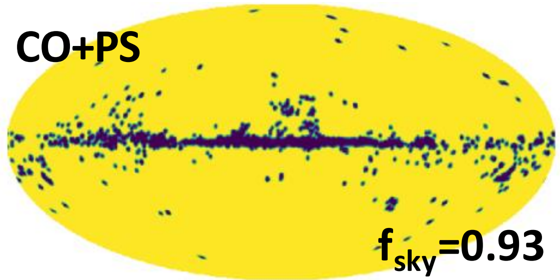
α & β are an isotropic rotation of the whole sky

We expect compatible angles from all regions of the sky



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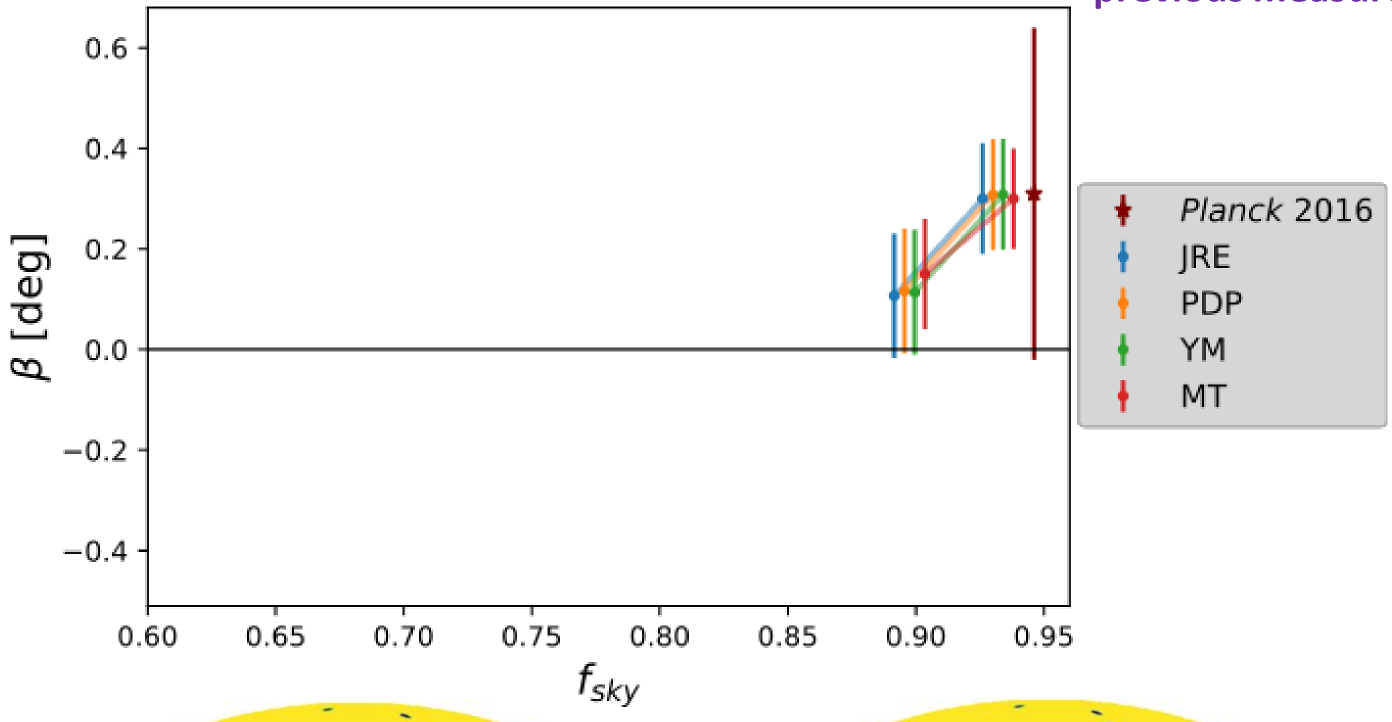


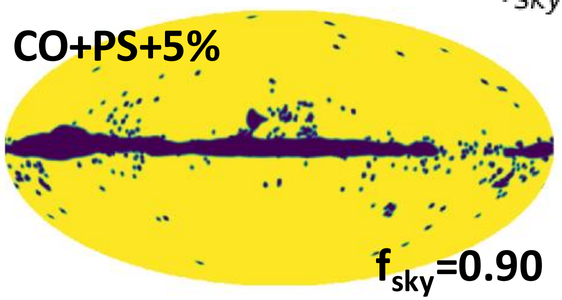


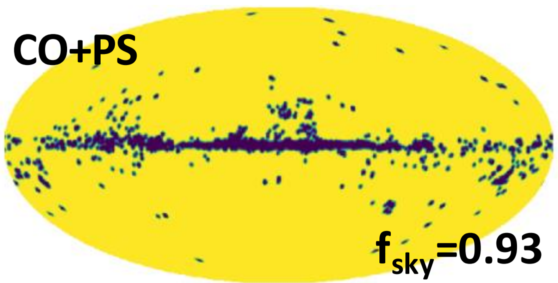

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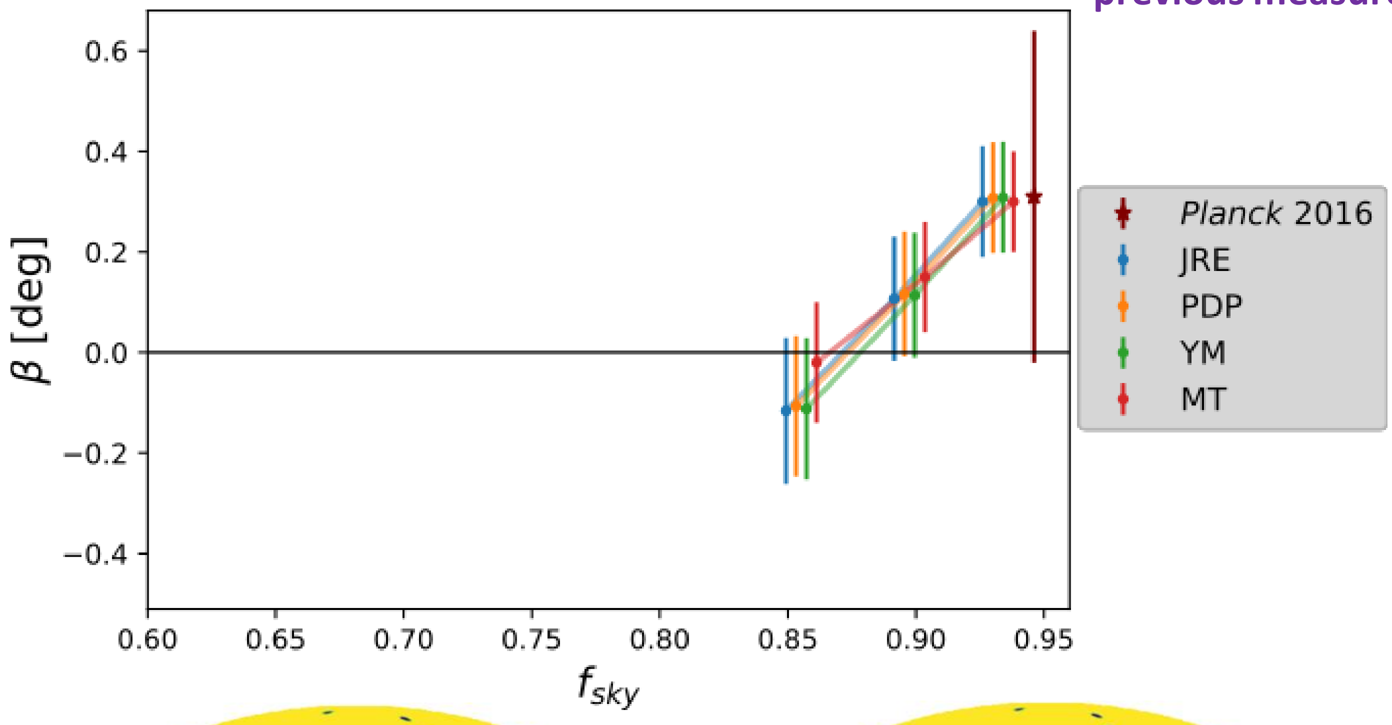
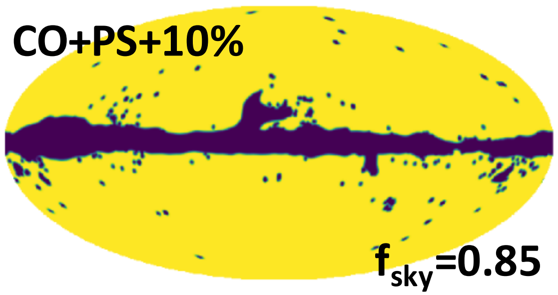
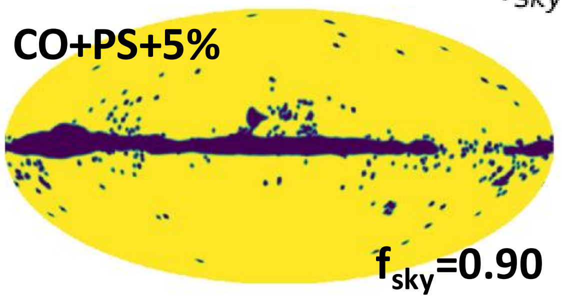
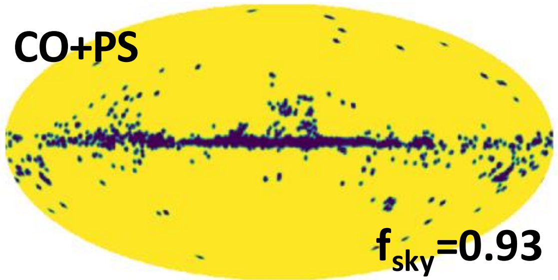


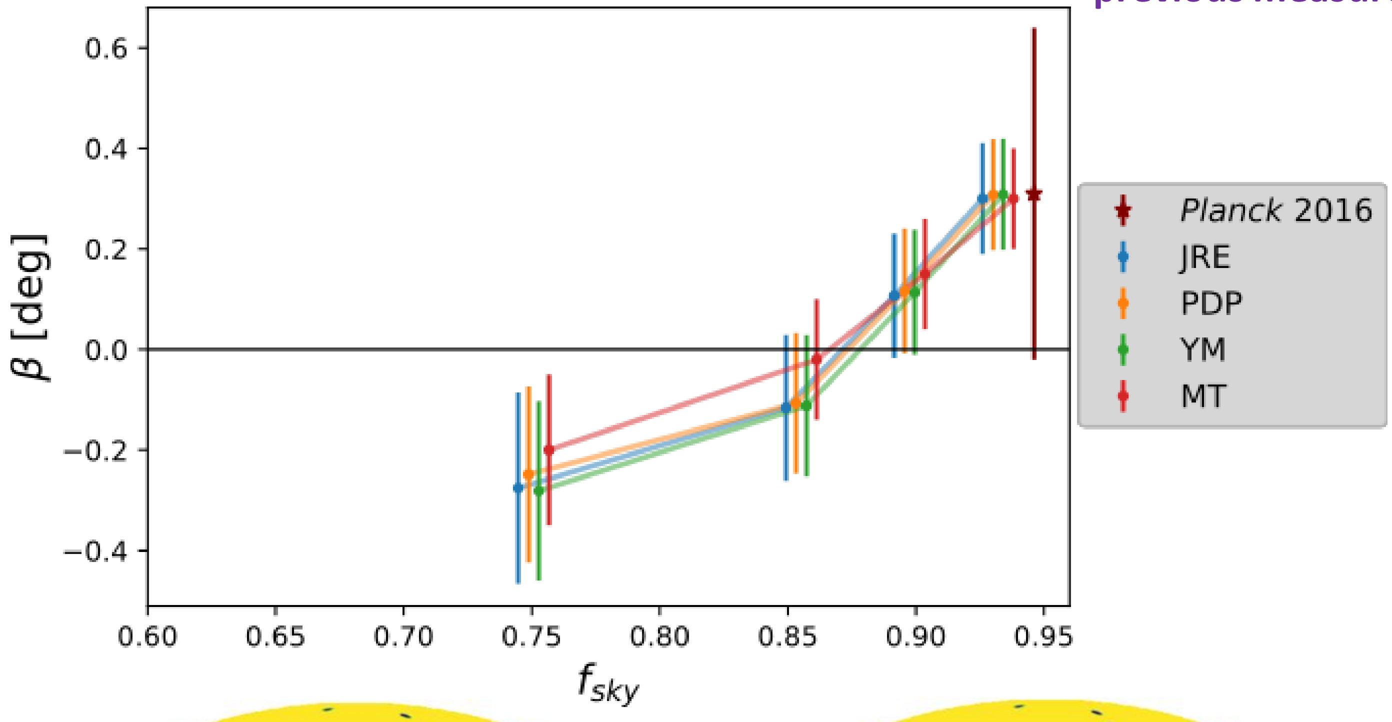



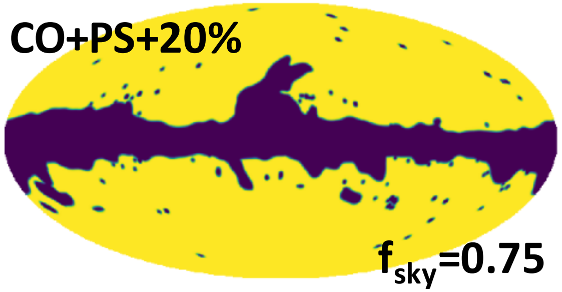



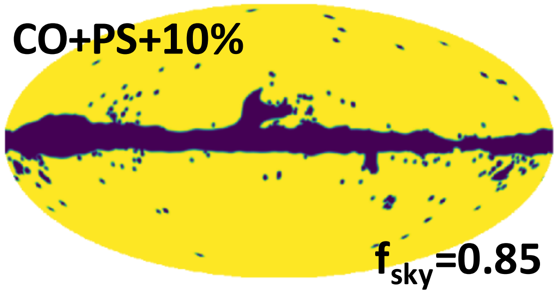
**For nearly full-sky: β = 0.30° ± 0.11° (2.7σ) → Consistent with and more precise than previous measurements!**

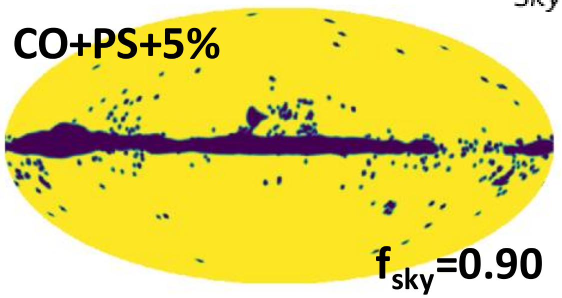
**α & β are an isotropic rotation of the whole sky**

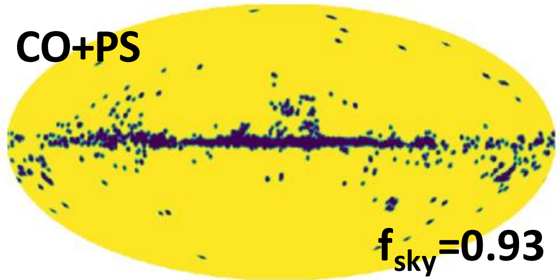
**We expect compatible angles from all regions of the sky**



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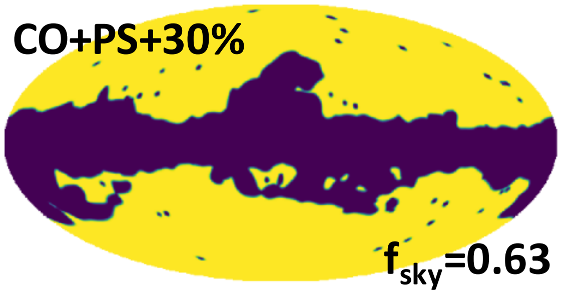
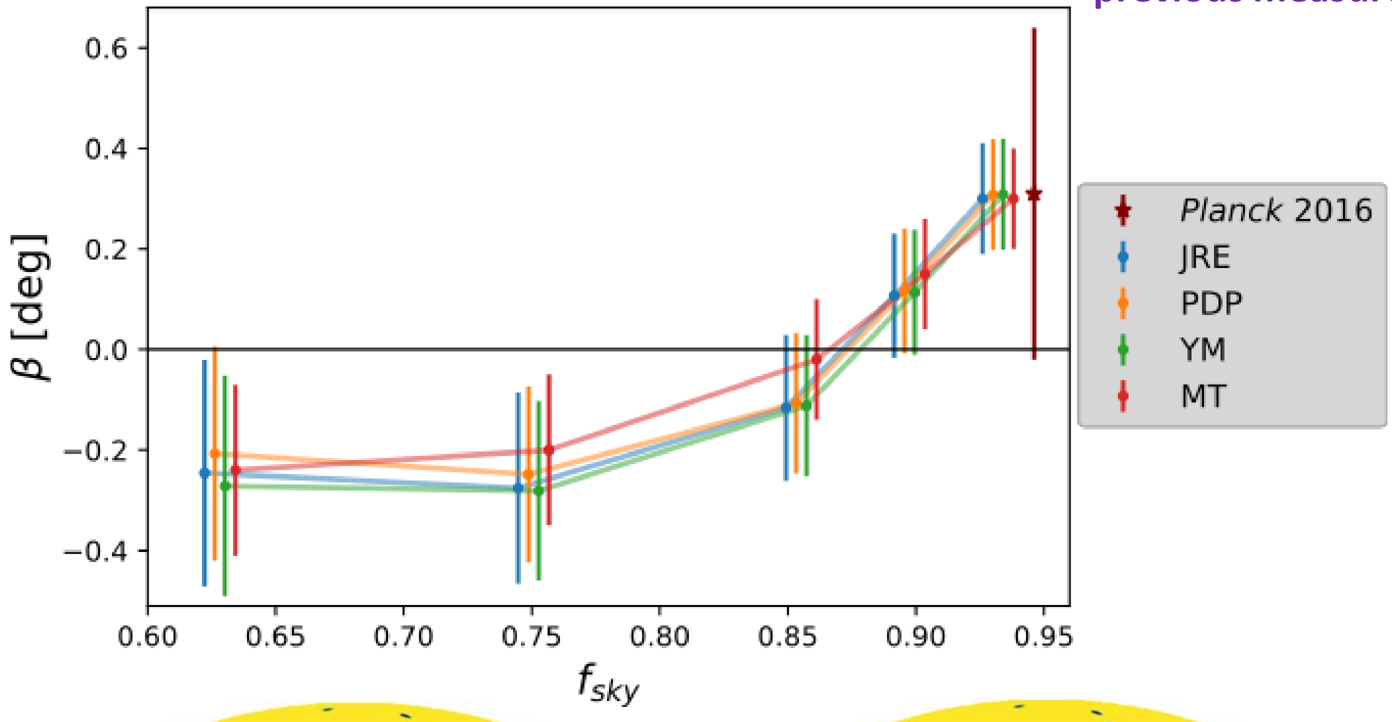
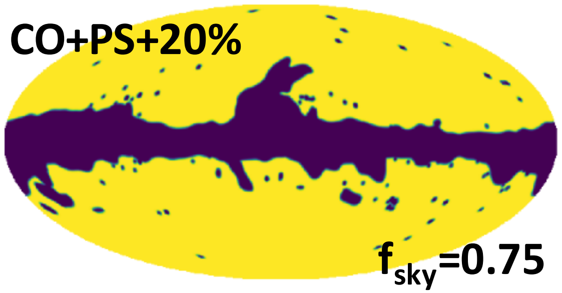
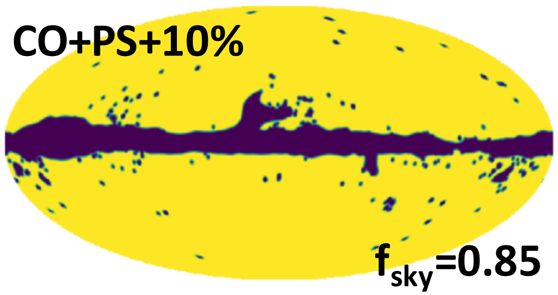
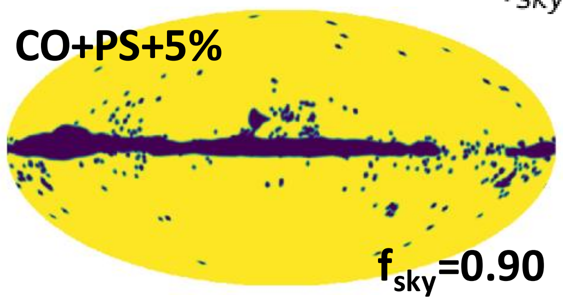
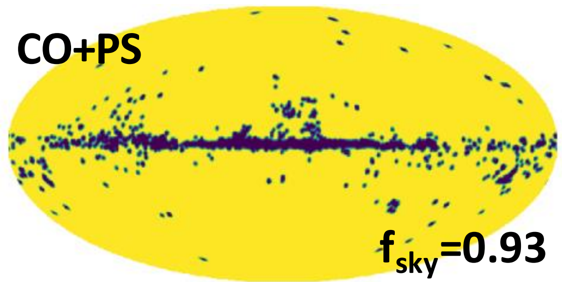


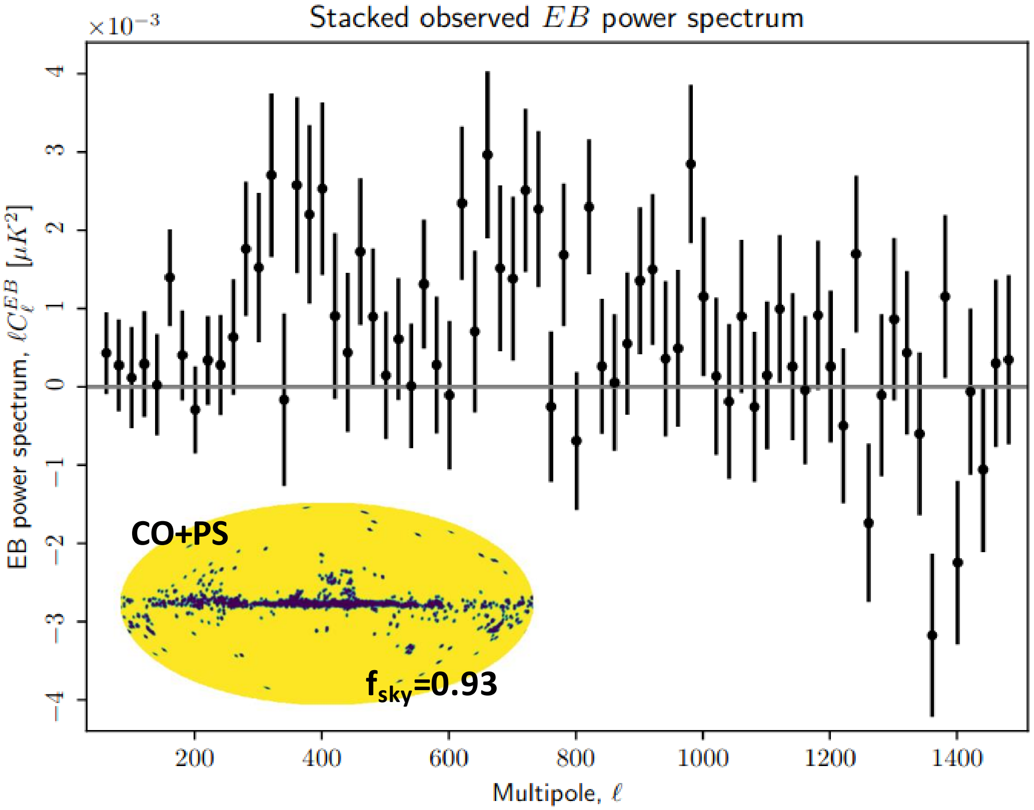



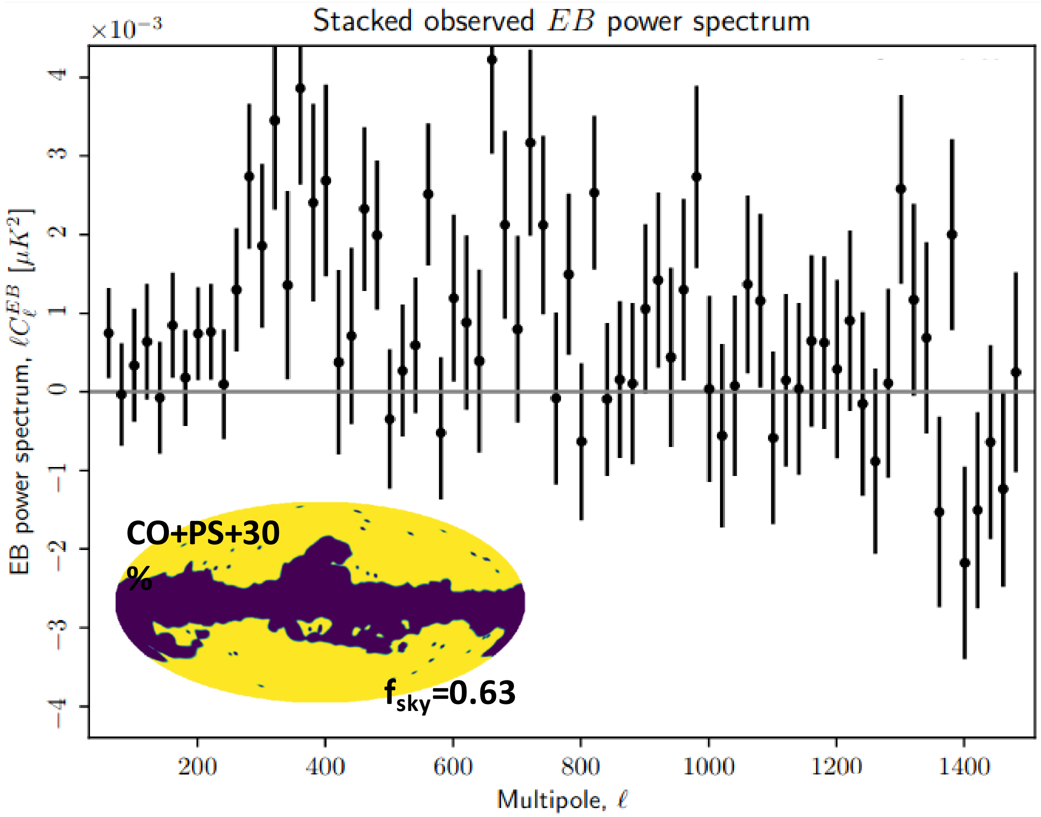



## The EB signal created by birefringence exists regardless of the Galactic mask ...

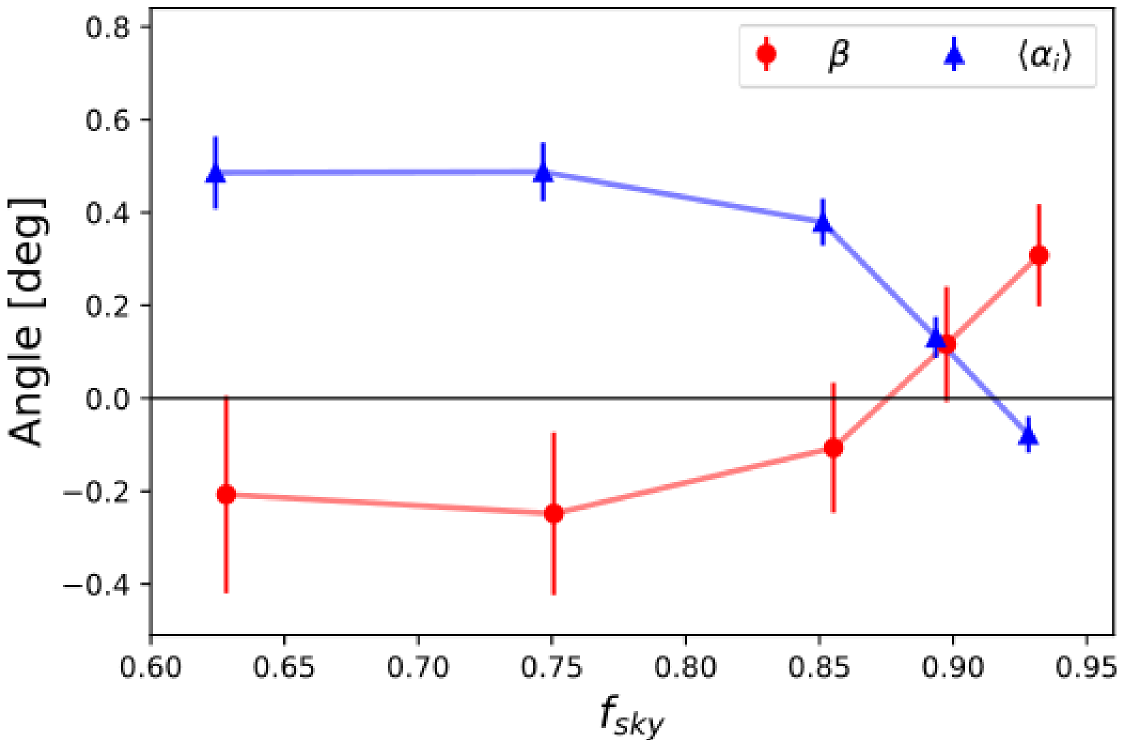



Eskilt & Komatsu 2022 [arXiv:2205.13962]

## … but our inferred value of α depends on Galactic dust

The existence of a non-accounted for dust EB correlation can bias our estimation of $\alpha_i$ angles, dragging with them the measurement of β



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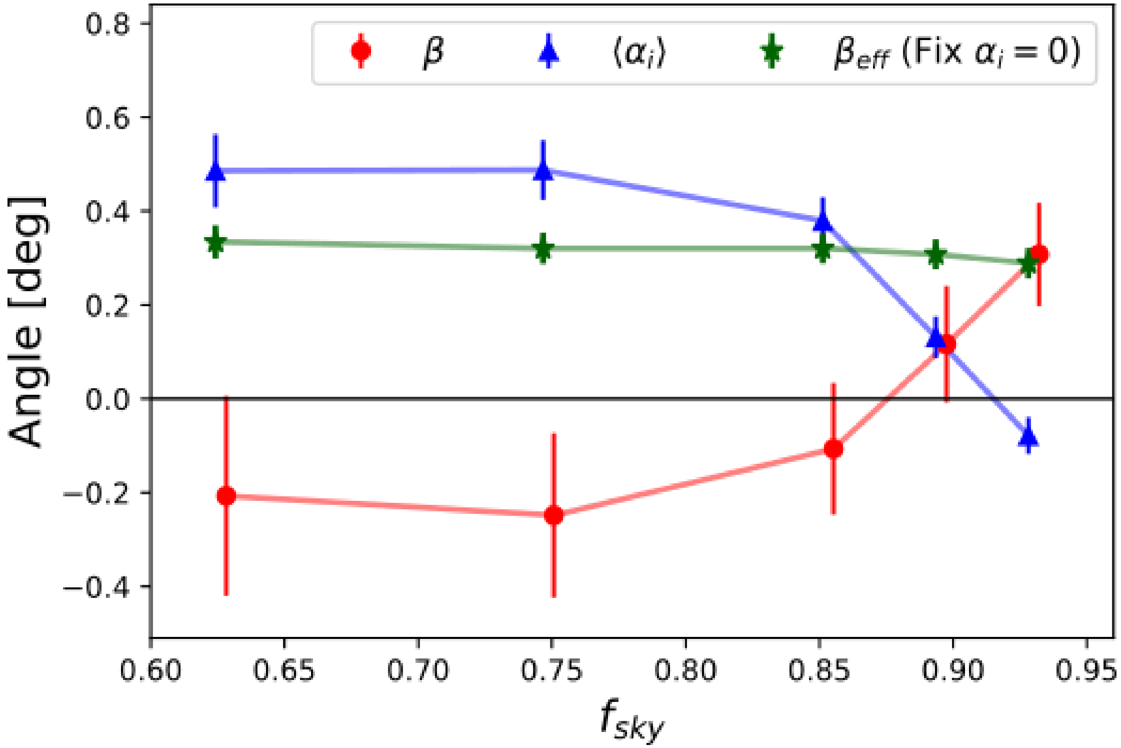


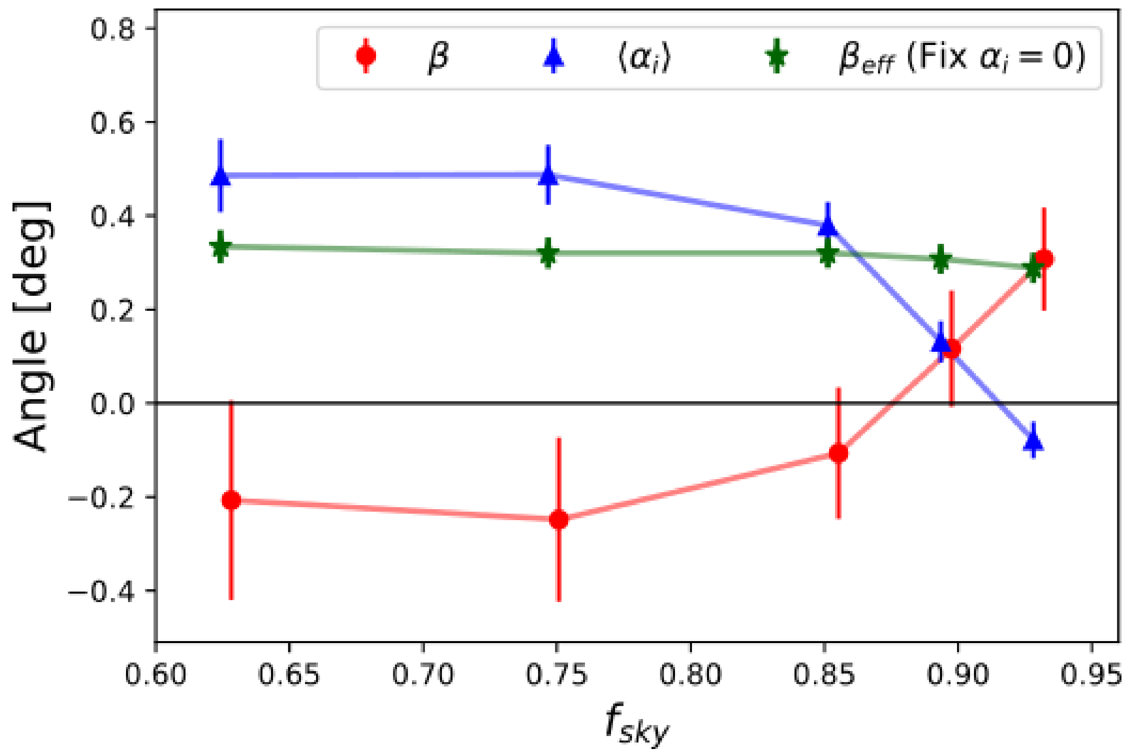

**By fixing $\alpha_i$=0 we are effectively measuring β+ᾱ**

## … but our inferred value of α depends on Galactic dust

By fixing $\alpha_i$=0 we are effectively measuring $\beta+\bar{\alpha}$

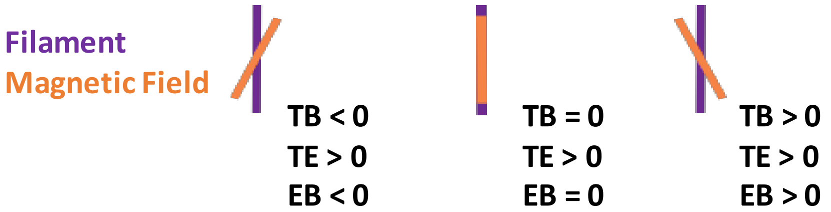
**The existence of a non-accounted for dust EB correlation can bias our estimation of $\alpha_i$ angles, dragging with them the measurement of β**

**We need to correct for dust EB to obtain an unbiased measurement of birefringence**



Clark et al 2021, ApJ, 919, 53

**Misalignment between the filamentary dust structures of the ISM and the plane-of-sky orientation of the Galactic magnetic field**




**Sign and magnitude of EB can be predicted from EE, TE, and TB**

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

**Take dust $C_\ell$ to be that of NPIPE @ 353GHz**

$A_\ell$ **free amplitude parameter**

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

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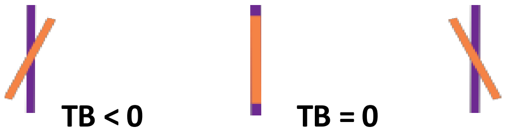
Filament
Magnetic Field



| | | |
|---|---|---|
| TB < 0 | TB = 0 | TB > 0 |
| TE > 0 | TE > 0 | TE > 0 |
| EB < 0 | EB = 0 | EB > 0 |

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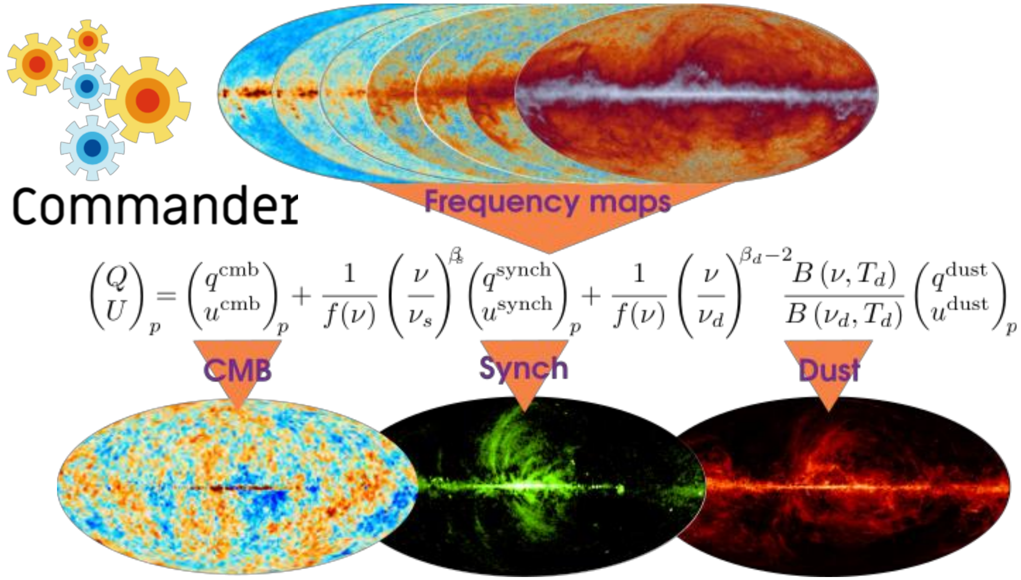
**Take the Commander sky model as our foreground model**



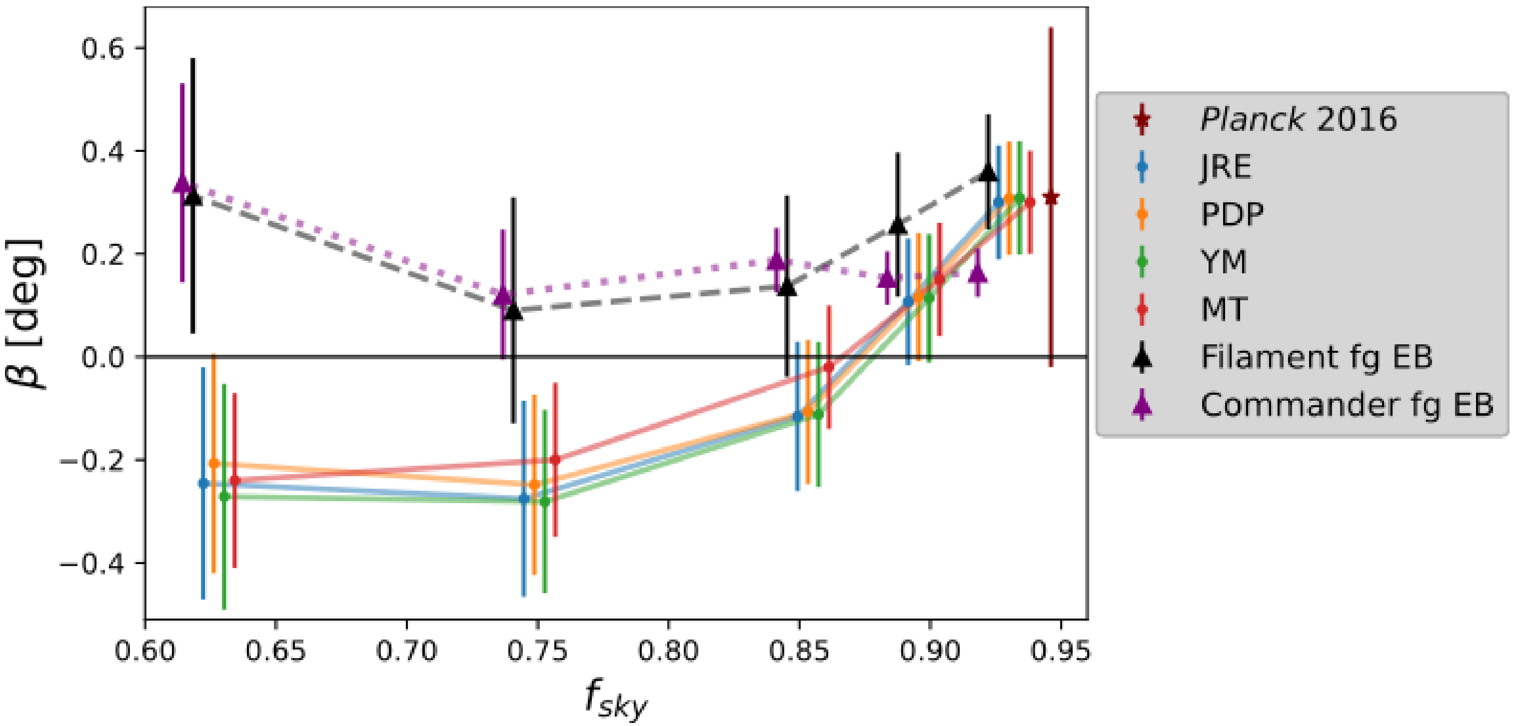

$$\begin{pmatrix} Q \\ U \end{pmatrix}_p = \begin{pmatrix} q^{\mathrm{cmb}} \\ u^{\mathrm{cmb}} \end{pmatrix}_p + \frac{1}{f(\nu)} \left(\frac{\nu}{\nu_s}\right)^{\beta_s} \begin{pmatrix} q^{\mathrm{synch}} \\ u^{\mathrm{synch}} \end{pmatrix}_p + \frac{1}{f(\nu)} \left(\frac{\nu}{\nu_d}\right)^{\beta_d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

*Planck* Collaboration IV. 2020, A&A, 641, A4

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

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

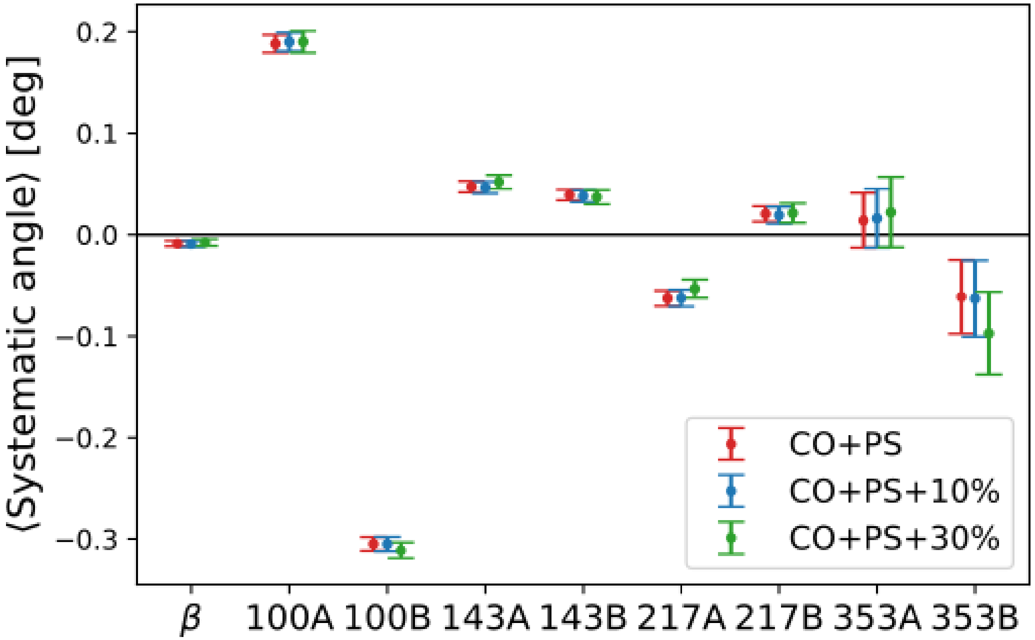
## $\beta>0$ for all $f_{sky}$, confirming that the decline was caused by dust EB




Good agreement except at $f_{sky}$=0.93 → complexity of dust emission near the Galactic plane not fully captured by Commander sky model

# Quantifying systematics using NPIPE end-to-end simulations

## Simulations of CMB + Noise + Systematics

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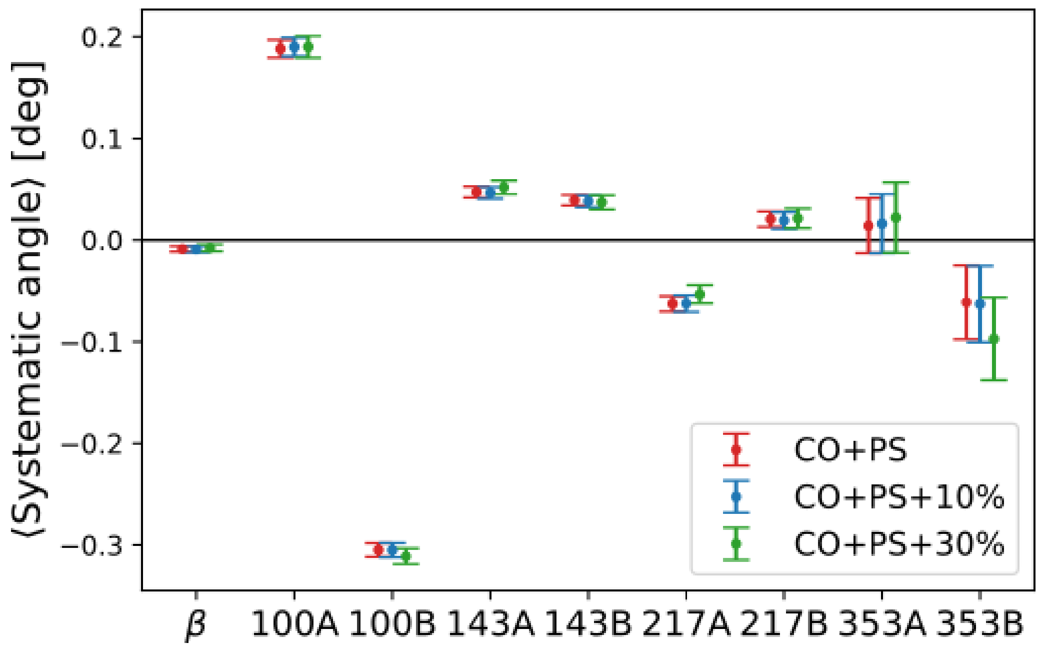


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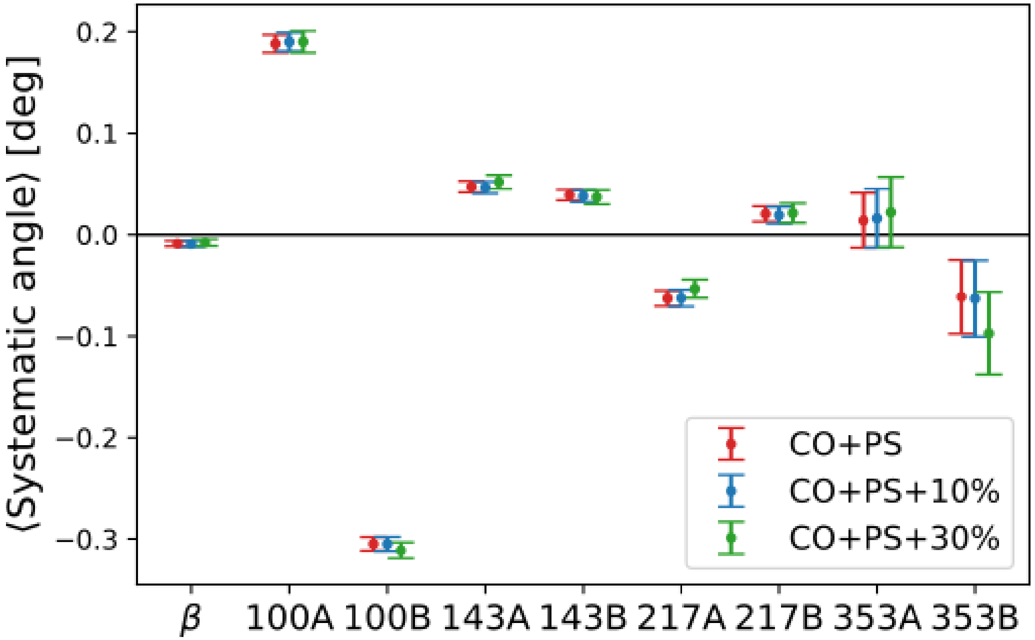


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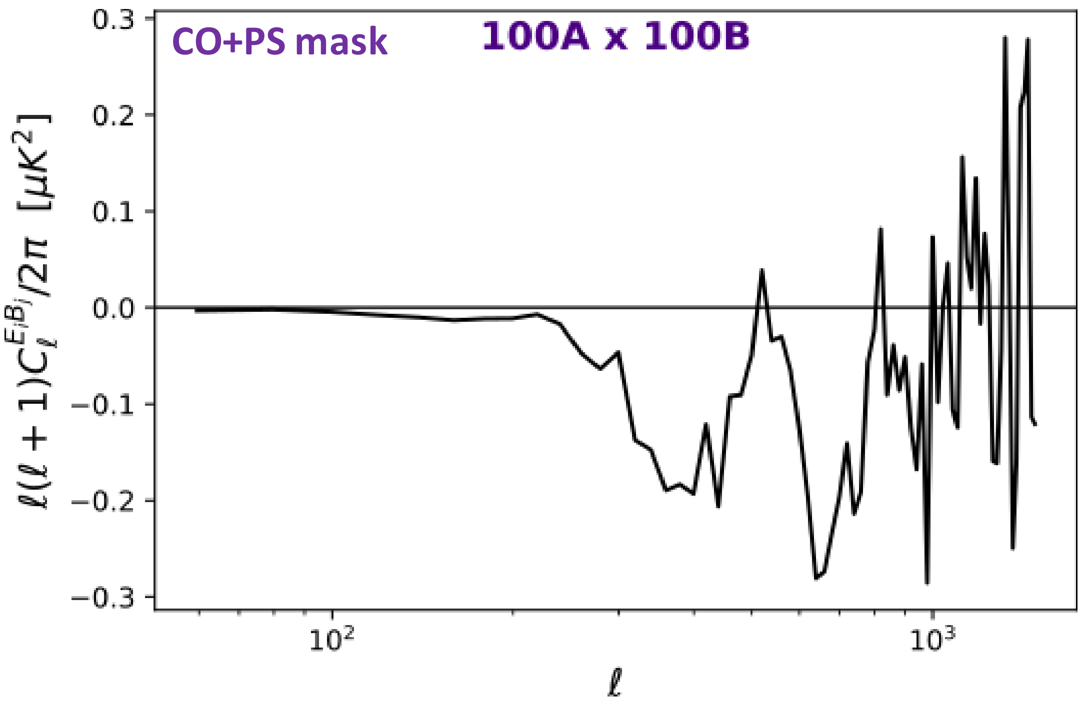
PDP et al 2022 in prep



**Intensity-to-polarization leakage** → $C_\ell^{EB} \propto C_\ell^{TT}$

**Cross-polarization effect** → $C_\ell^{EB} \propto C_\ell^{EE}$

**A combination of both** → $C_\ell^{EB} \propto C_\ell^{TE}$

**Beam leakage**

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

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

**QuickPol's polarization matrices**

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

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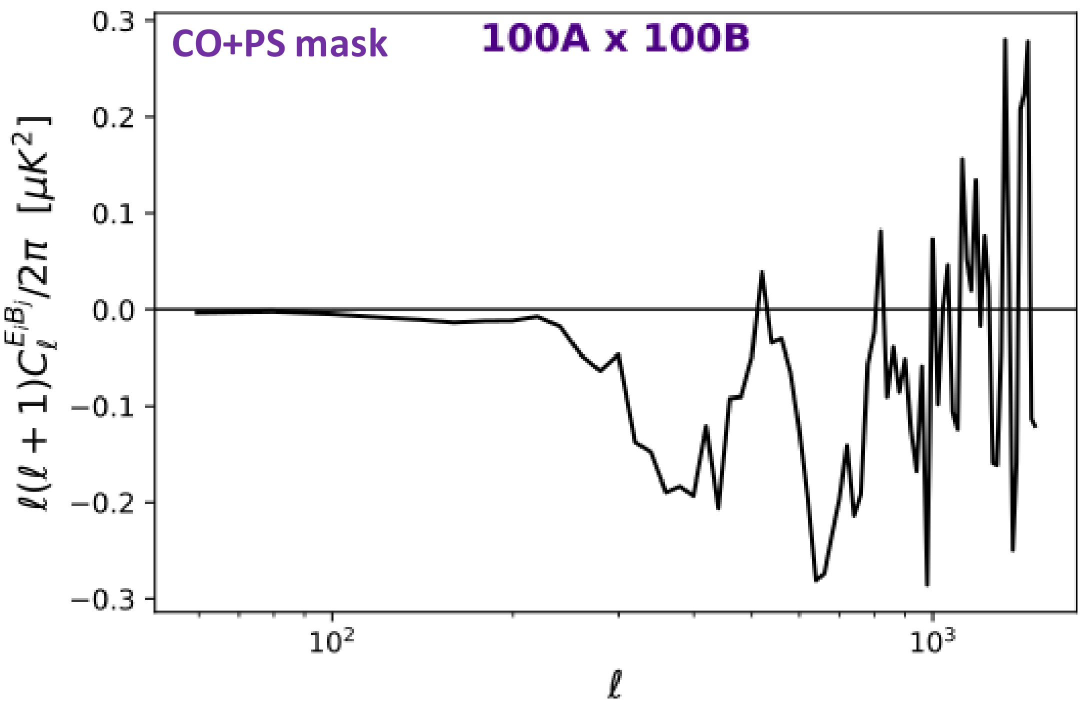

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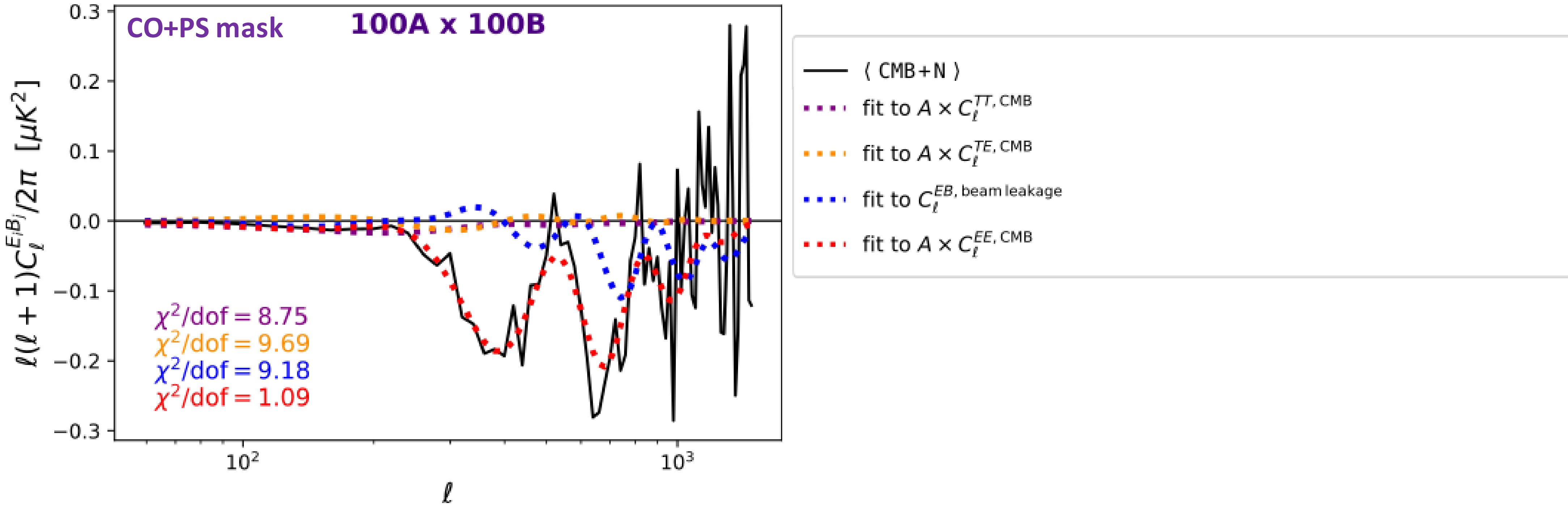

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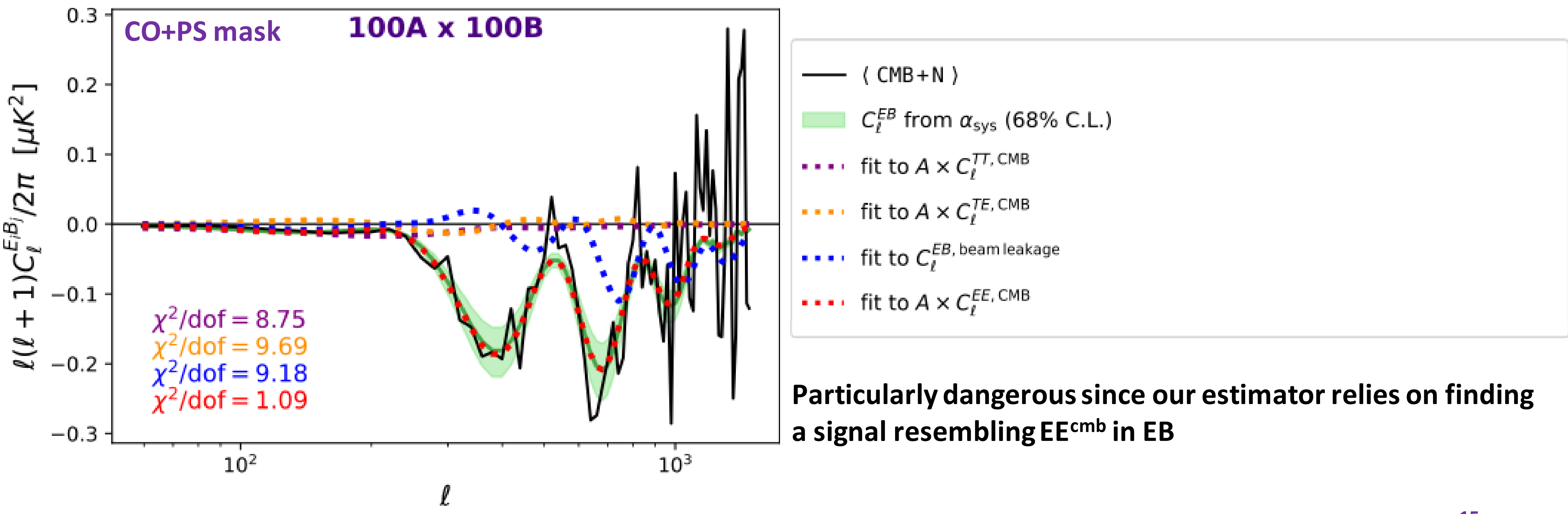


**Particularly dangerous since our estimator relies on finding a signal resembling $EE^{cmb}$ in EB**

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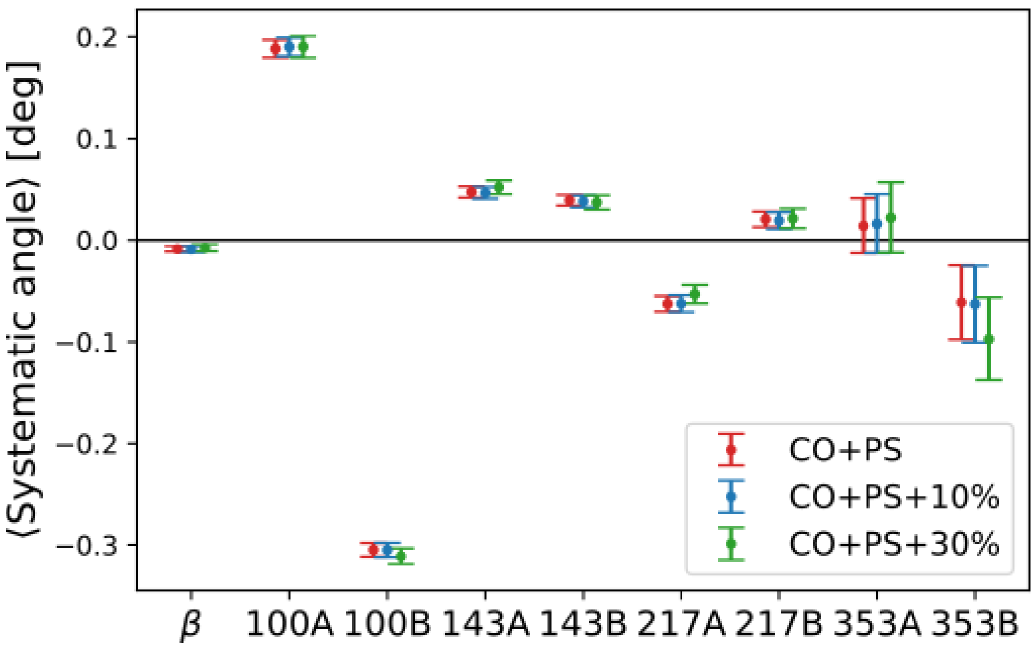


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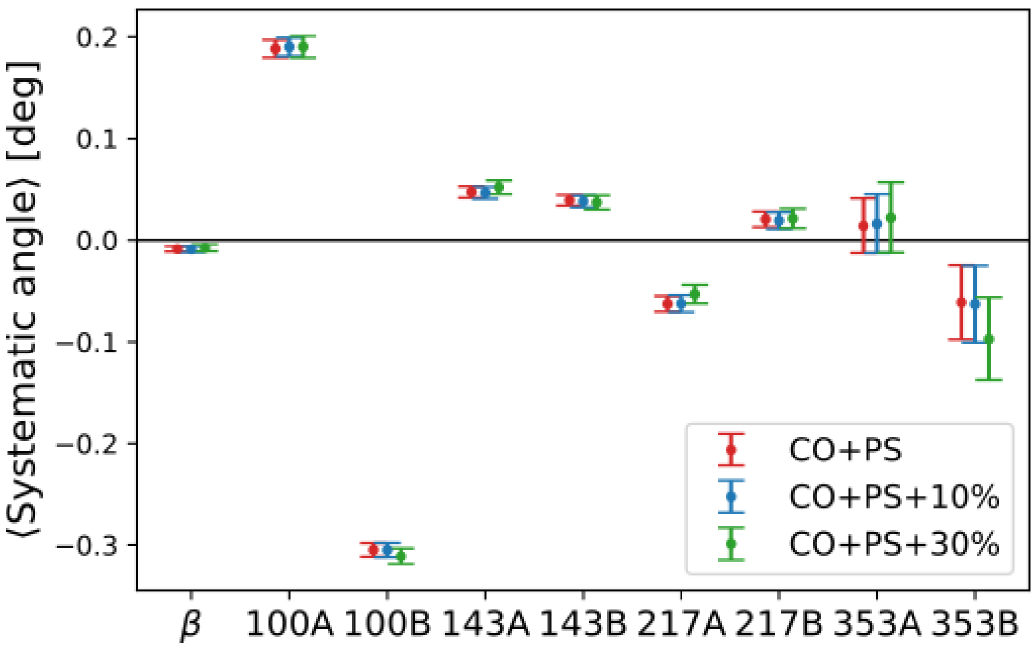


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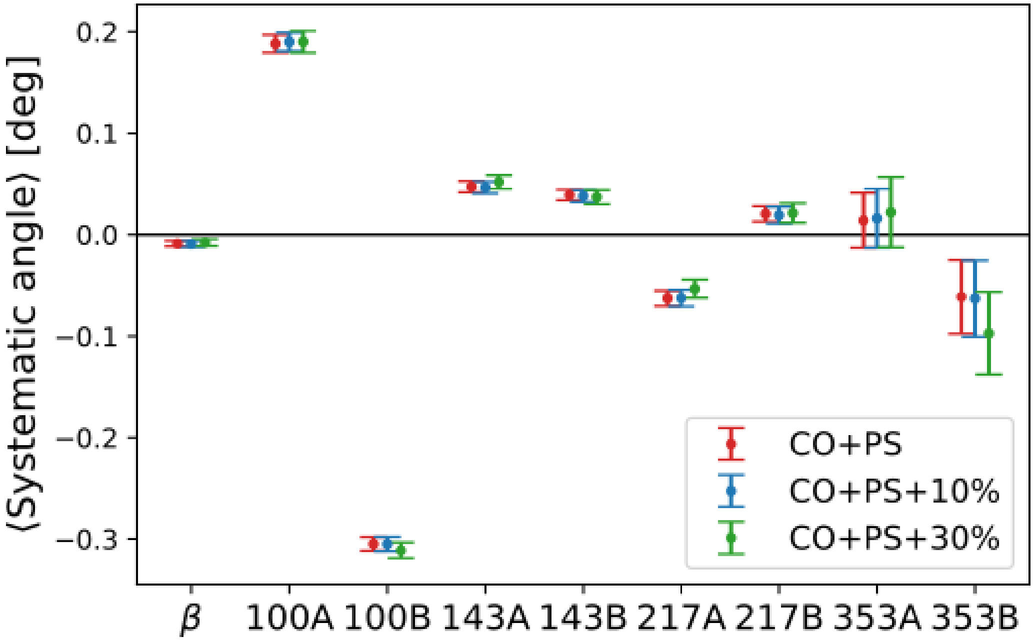


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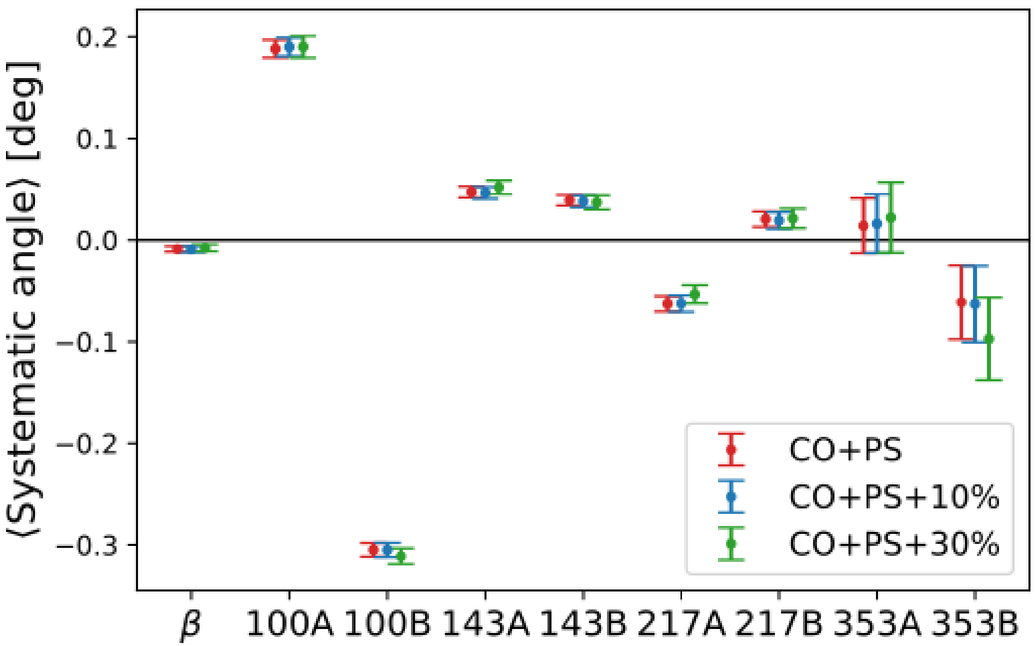


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**Negligible impact on β**

| | From simulations | $\sigma_{stat}$ in fit to data |
|---|---|---|
| $\langle\beta_{sys}\rangle$ = | - 0.009° ± 0.003° | 0.11° |

# Conclusions

**Our methodology provides a systematic-free measurement of birefringence...**

**β = 0.30° ± 0.11° (stat) ± 0.009° (sys) for nearly full-sky data (2.7σ)**

**vs previous harmonic-space methods β = 0.31° ± 0.05° (stat) ± 0.28° (sys)**

***Planck* Collaboration XLIX. 2016, A&A, 596, A110**

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To be confirmed as a cosmological signal ...

- Search for β in independent datasets, especially full-sky missions such as LiteBIRD
- Impulse on EB science for current/future CMB experiments

Importance of high-fidelity end-to-end simulations