Self-calibration of instrumental polarisation angles in the case of *LiteBIRD*

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MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

Framework of our discussion today

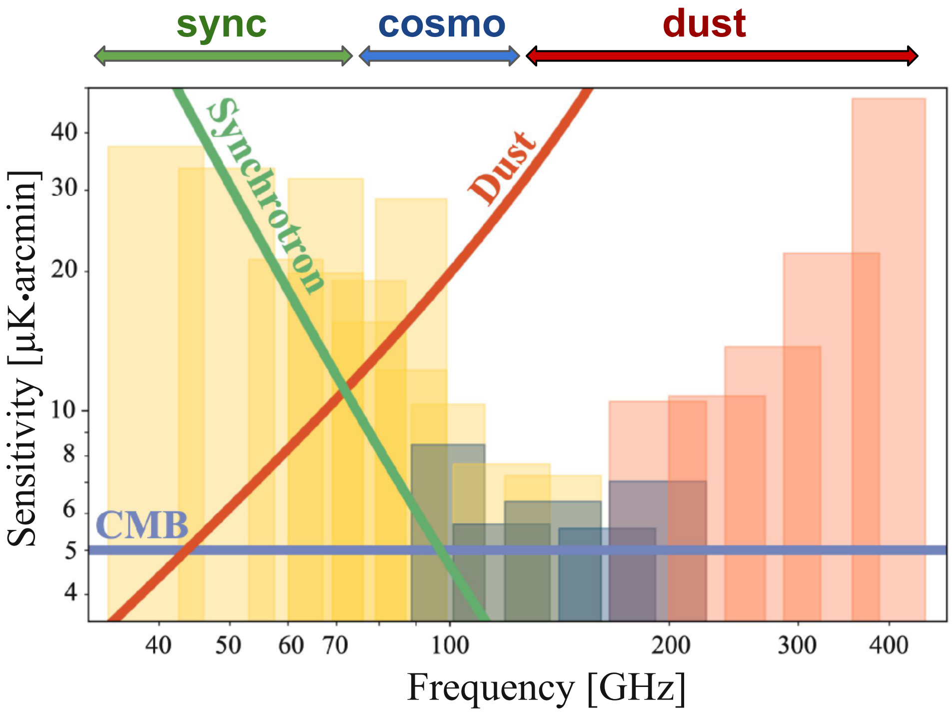
Simulations based on ***LiteBIRD* PTEP 2023**

- Lensed CMB, s1d1 foregrounds, end-to-end noise (ideal HWP, top-hat bandpasses)

General discussion in terms of the **frequency coverage**, **angular resolution** and **sensitivity**, and **sky coverage** applicable to any CMB experiment

Target precision:

- **6 arcmin (0.1°)**, standard benchmark for stage IV experiments
- **3.5 arcmin (0.06°)**, to confirm cosmic birefringence hints
  Eskilt & Komatsu PRD 2022
- **≲1 arcmin (0.017°)** for certain frequency bands, depending on the experiment
  Vielva+ JCAP 2022



***LiteBIRD* PTEP 2023**

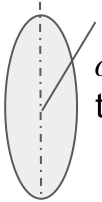
Pol. angle calibration through *EB* nulling

Keating+ ApJL 2013

Polarised sky signal

CMB* + sync + dust

Instrument model



α miscalibration of the detector

Null the observed *EB*

$C_\ell^{EB,\mathrm{obs}} = f(C_\ell^{EE,\mathrm{obs}}, C_\ell^{BB,\mathrm{obs}}, \ldots)$

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

Master Eq. describing this sky + instrument model*

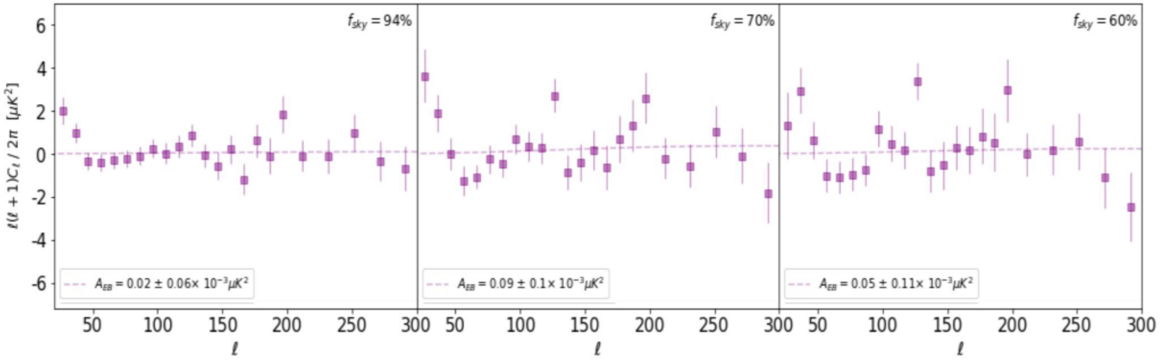
$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right) + \frac{1}{\cos(4\alpha)}\left[C_\ell^{EB,\mathrm{sync}} + C_\ell^{E_{\mathrm{sync}}B_{\mathrm{dust}}} + C_\ell^{B_{\mathrm{sync}}E_{\mathrm{dust}}} + C_\ell^{EB,\mathrm{dust}}\right]$$

Often assumed to be zero… but are they?

*Assuming no birefringence. $\beta \neq 0$ would be absorbed as a global offset, biasing individual estimates to $\alpha+\beta$ and making re-calibrated maps not sensitive to isotropic birefringence

*Showing auto-spectrum Eq. for simplicity but the estimator is built from frequency cross-spectra.

Global sync *EB* statistically compatible with null



Fitting $C_\ell^{EB,sync}=A^{EB}$ to *Planck*+WMAP

Martire+ JCAP 2022

QUIJOTE 10-20 GHz:

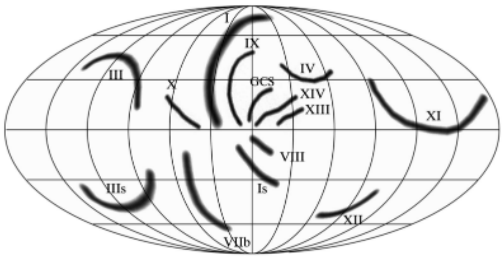
$C_\ell^{EB,sync}\approx 0$ for $30\lesssim\ell\lesssim 150$

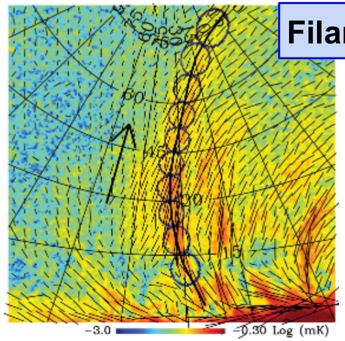
Rubiño-Martín+ MNRAS 2023

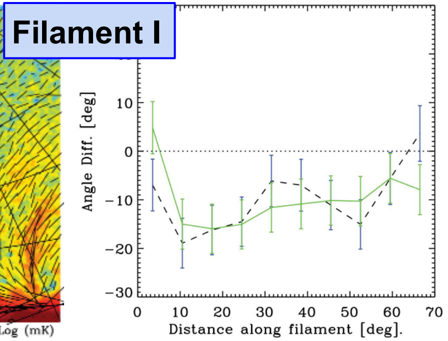
Negligible impact in birefringence studies

Eskilt A&A 2022

Although…

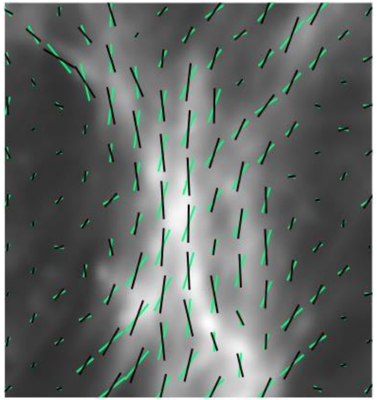






Evidence for **local misalignments** between filament direction and pol. angle

Vidal+ MNRAS 2015



Magnetic misalignment between dust filaments and the plane-of-sky orientation of the **Galactic magnetic field** creates ***TB* and *EB*** correlations

Huffenberger+ ApJ 2020, Clark+ ApJ 2021

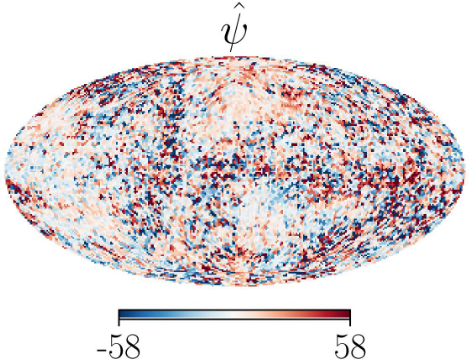
Planck data reports **$C_\ell^{TB,\mathrm{dust}}>0$** and **a hint of $C_\ell^{EB,\mathrm{dust}}>0$**

***Planck* XI A&A 2020**

Impact of dust *EB* detected in birefringence studies

Diego-Palazuelos+ PRL 2022

Different magnetic misalignment estimators and tracers



Cukierman+ ApJ 2023, Halal+ ApJ 2024

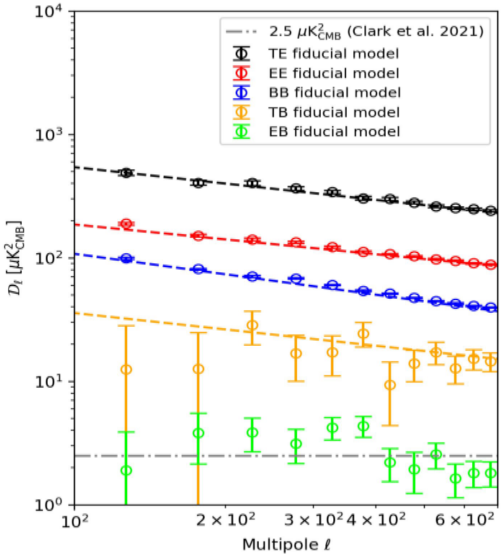
Filament-based model calibrated to reproduce **filaments' (21-cm HI)** and **magnetic field (*Planck* polarization)** orientations

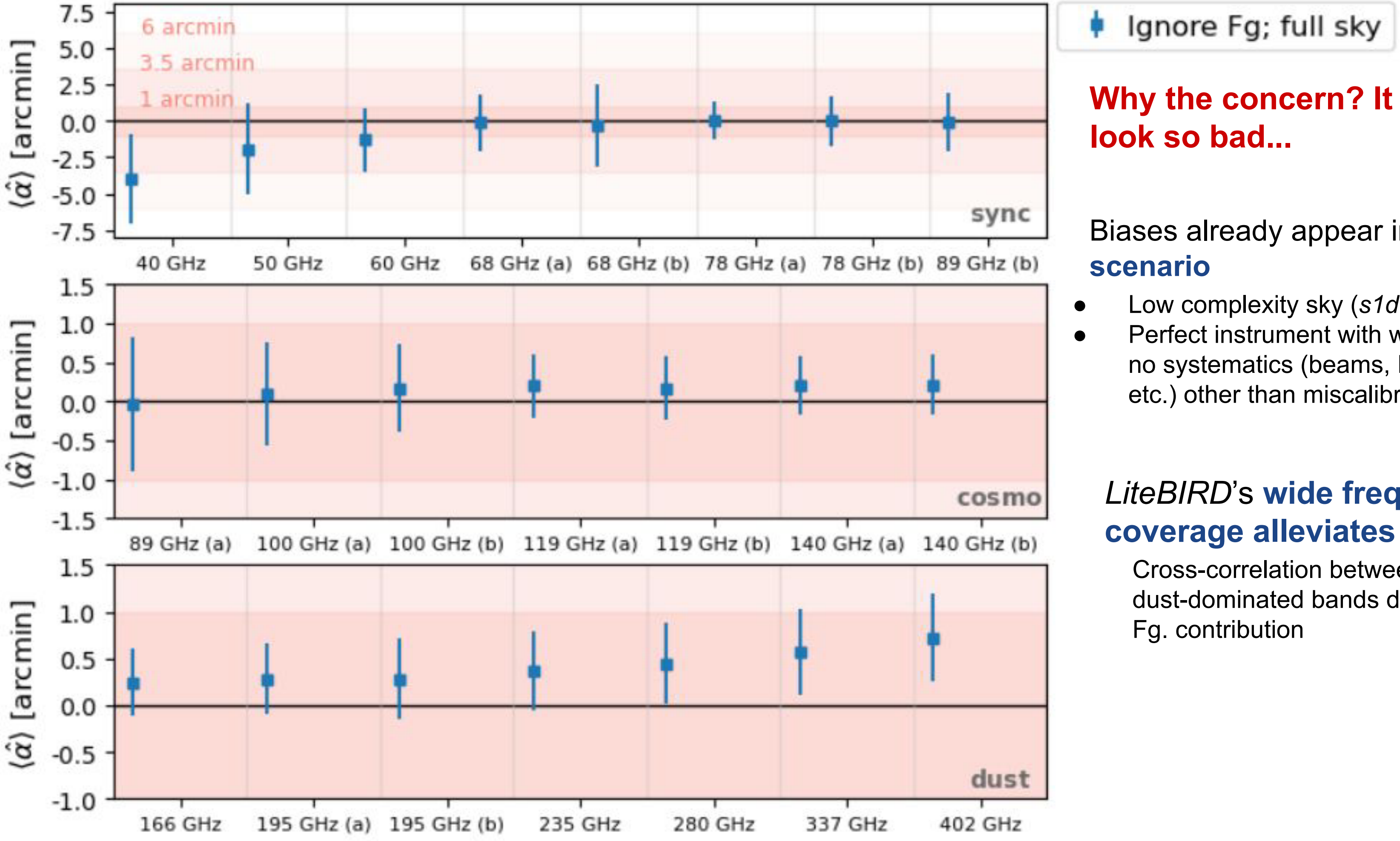
Hervías-Caimapo & Huffenberger ApJ 2022

It predicts

- 6-12% preference for right-handed misalignments
- **$C_\ell^{EB,\mathrm{dust}}$~few $\mu K^2 \times \ell^{-2}$**

Hervías-Caimapo+ [arXiv:2408.06214]





Why the concern? It doesn't look so bad...

Biases already appear in the **ideal scenario**

- Low complexity sky (*s1d1*)
- Perfect instrument with white noise and no systematics (beams, HWP, pointing, etc.) other than miscalibrated pol. angles

LiteBIRD's **wide frequency coverage alleviates Fg. *EB* bias**

Cross-correlation between sync- and dust-dominated bands downweights the Fg. contribution

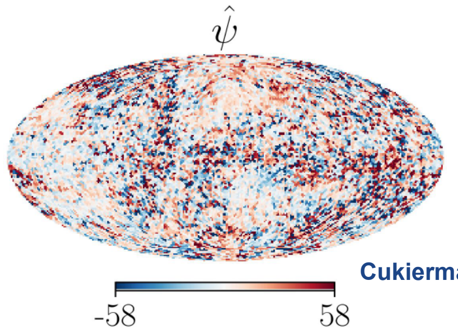
Model-independent approach

Sufficiently reduce Fg. *EB* through **masking**

Focus on dust. Due to the spatial correlation between sync and dust emission, masking bright dust regions is enough to suppress the worst of the sync contribution.

Optimal masking Target the regions known to source dust *EB*

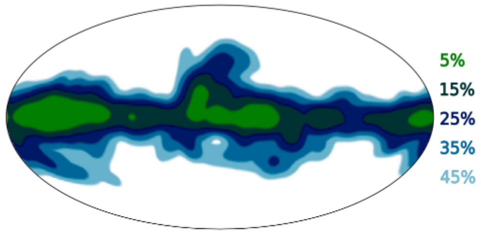
Testing this approach requires more realistic sky models than *s1d1* **Hervías-Caimapo+ [arXiv:2408.06214]**

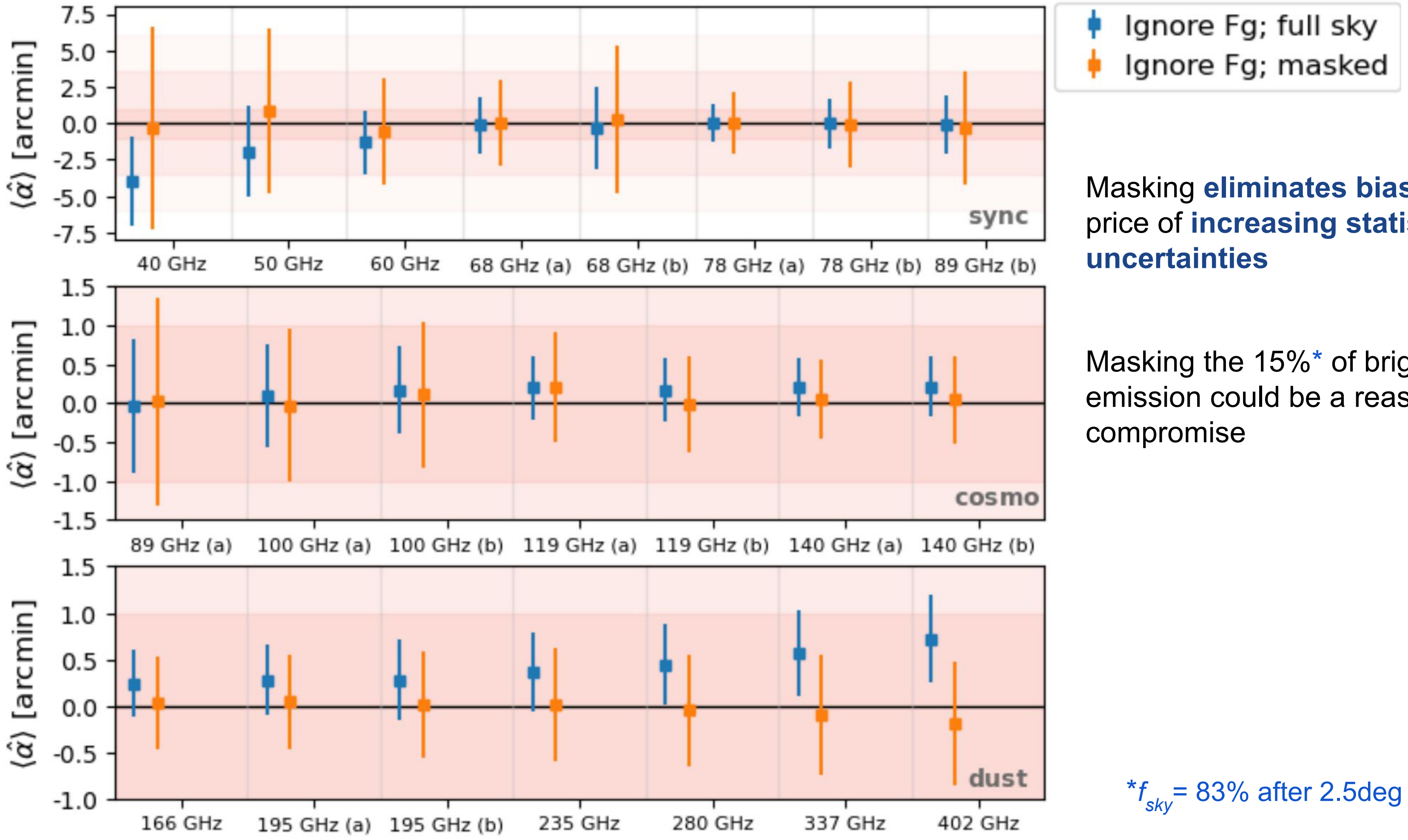


Cukierman+ ApJ 2023

***P* threshold masking** Target the regions of brightest dust emission

Mask *X*% fraction of a smoothed map of dust polarisation intensity ($P=\sqrt{Q^2+U^2}$)





Masking **eliminates biases** at the price of **increasing statistical uncertainties**

Masking the 15%* of brightest dust emission could be a reasonable compromise

*f_{sky}= 83% after 2.5deg apodisation

Model-dependent approach

Provide a **model** for the Fg. ***EE, BB, EB*** multi-frequency angular power spectra

$$\chi^2 = \sum[C_\ell^{EB,obs} - f(C_\ell^{EE,obs}, C_\ell^{BB,obs}, C_\ell^{EB,fg})]^2/\mathrm{Cov}[C_\ell^{EB,obs} - f(C_\ell^{EE,obs}, C_\ell^{BB,obs}, \mathbf{C_\ell^{EB,fg}})]$$

$$\mathrm{Cov}[C_\ell^{EB,fg}] = \mathbf{C_\ell^{EE,fg} C_\ell^{BB,fg}} + (C_\ell^{EB,fg})^2$$

Fg. *EE*, *BB* are the main contribution at low ℓ

Embedded in component separation Fully propagate the uncertainties in Fg. modeling at the map level

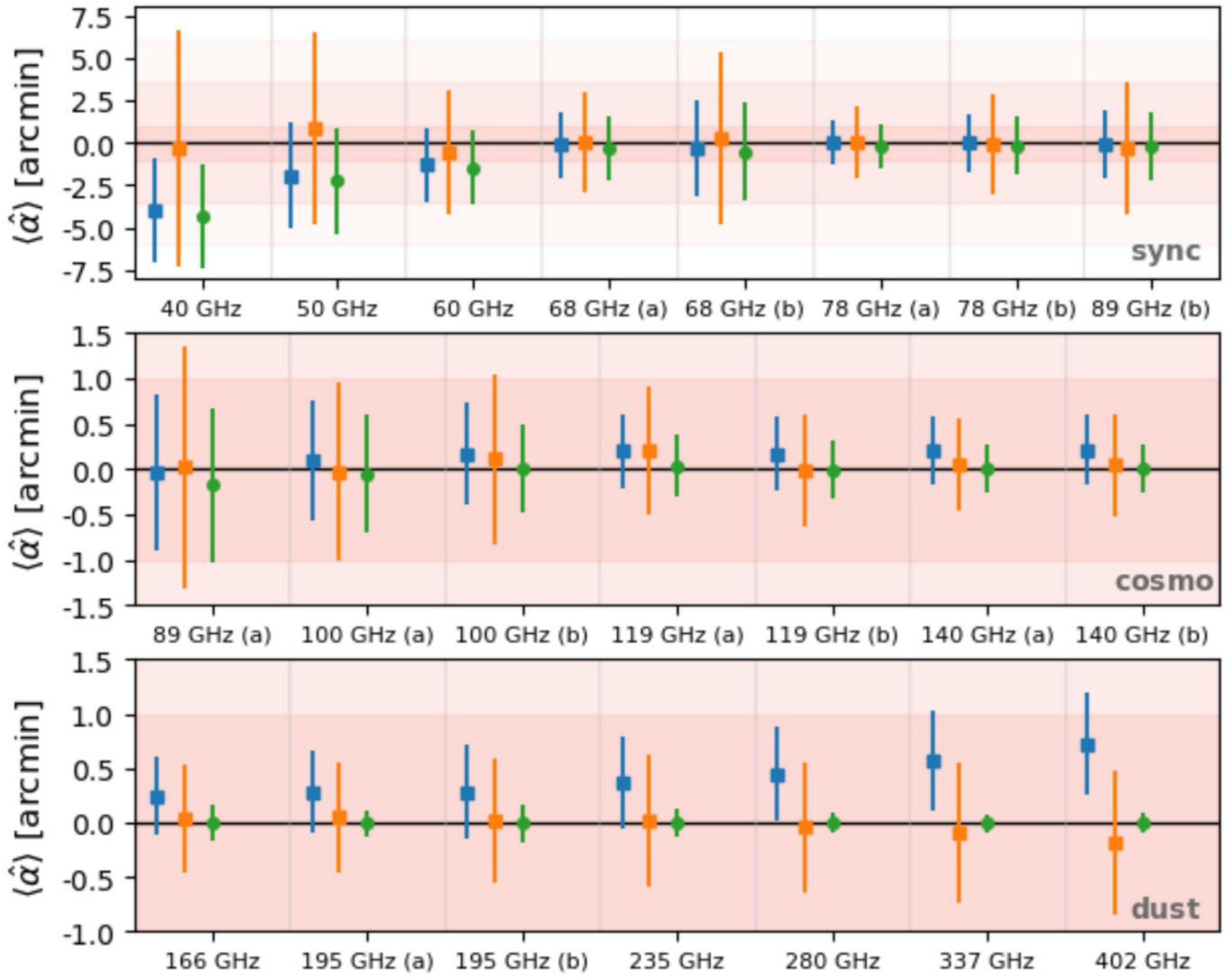
$$\begin{pmatrix} Q(\nu) \\ U(\nu) \end{pmatrix}_p = \begin{pmatrix} \cos(2\alpha_\nu) & -\sin(2\alpha_\nu) \\ \sin(2\alpha_\nu) & \cos(2\alpha_\nu) \end{pmatrix} \left[\begin{pmatrix} c^Q \\ c^U \end{pmatrix}_p + \frac{1}{u(\nu)} \left(\frac{\nu}{\nu_\mathrm{s}}\right)^{\beta_\mathrm{s}} \begin{pmatrix} s^Q \\ s^U \end{pmatrix}_p + \frac{1}{u(\nu)} \left(\frac{\nu}{\nu_\mathrm{d}}\right)^{\beta_\mathrm{d}-2} \frac{B(\nu, T_\mathrm{d})}{B(\nu_\mathrm{d}, T_\mathrm{d})} \begin{pmatrix} d^Q \\ d^U \end{pmatrix}_p \right]$$

de la Hoz+ JCAP 2022, Jost+ PRD 2023

Fg. template Marginalise over a previously known Fg. model

$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right) + \frac{1}{\cos(4\alpha)}\left[\mathcal{A}_\mathrm{s} C_\ell^{EB,\mathrm{sync}} + \mathcal{A}_\mathrm{sd}\left(C_\ell^{E_\mathrm{sync}B_\mathrm{dust}} + C_\ell^{B_\mathrm{sync}E_\mathrm{dust}}\right) + \mathcal{A}_\mathrm{d} C_\ell^{EB,\mathrm{dust}}\right]$$

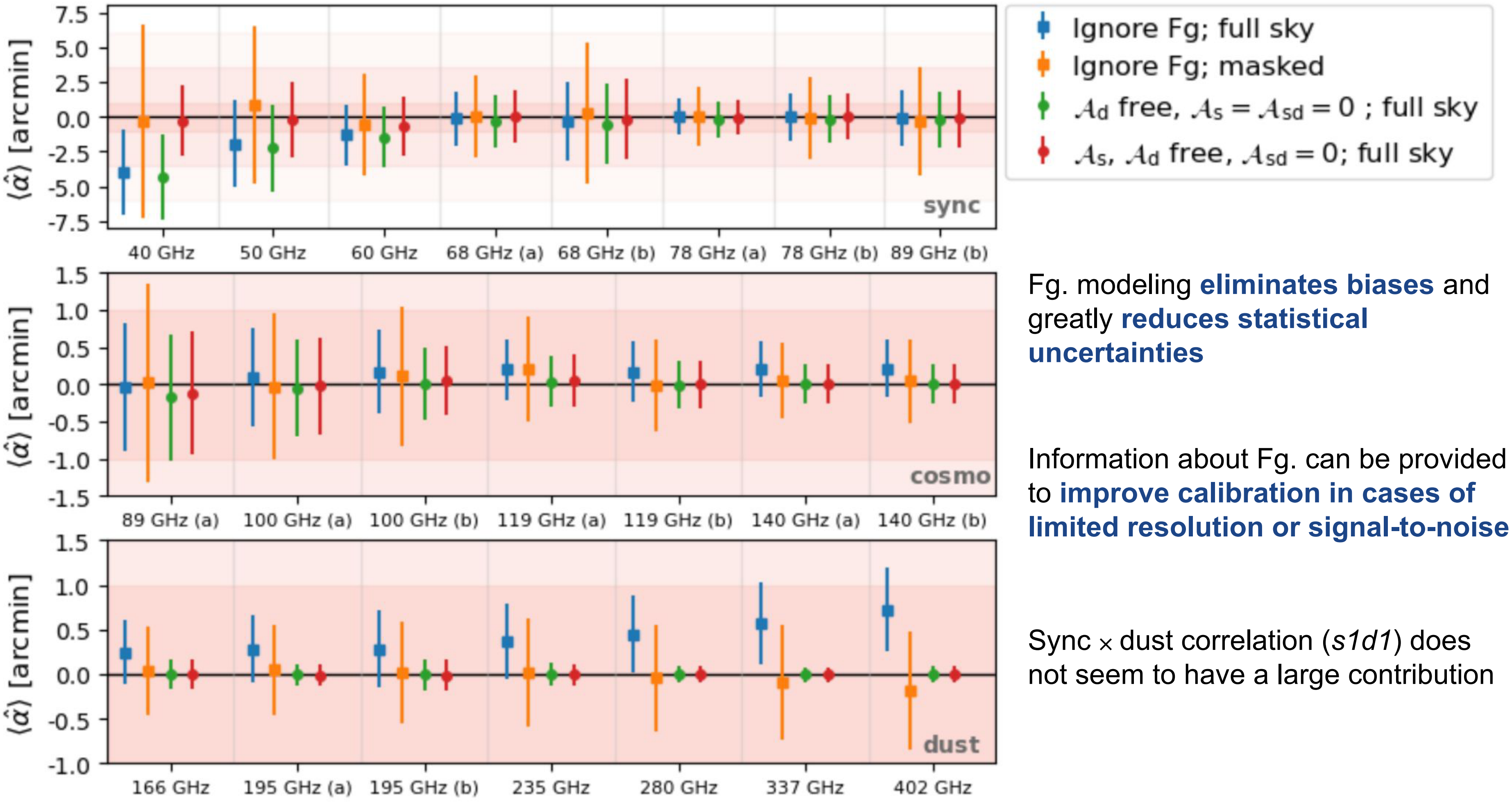
Diego-Palazuelos+ JCAP 2023



Fg. modeling **eliminates biases** and greatly **reduces statistical uncertainties**

Information about Fg. can be provided to **improve calibration in cases of limited resolution or signal-to-noise**

Sync × dust correlation (*s1d1*) does not seem to have a large contribution



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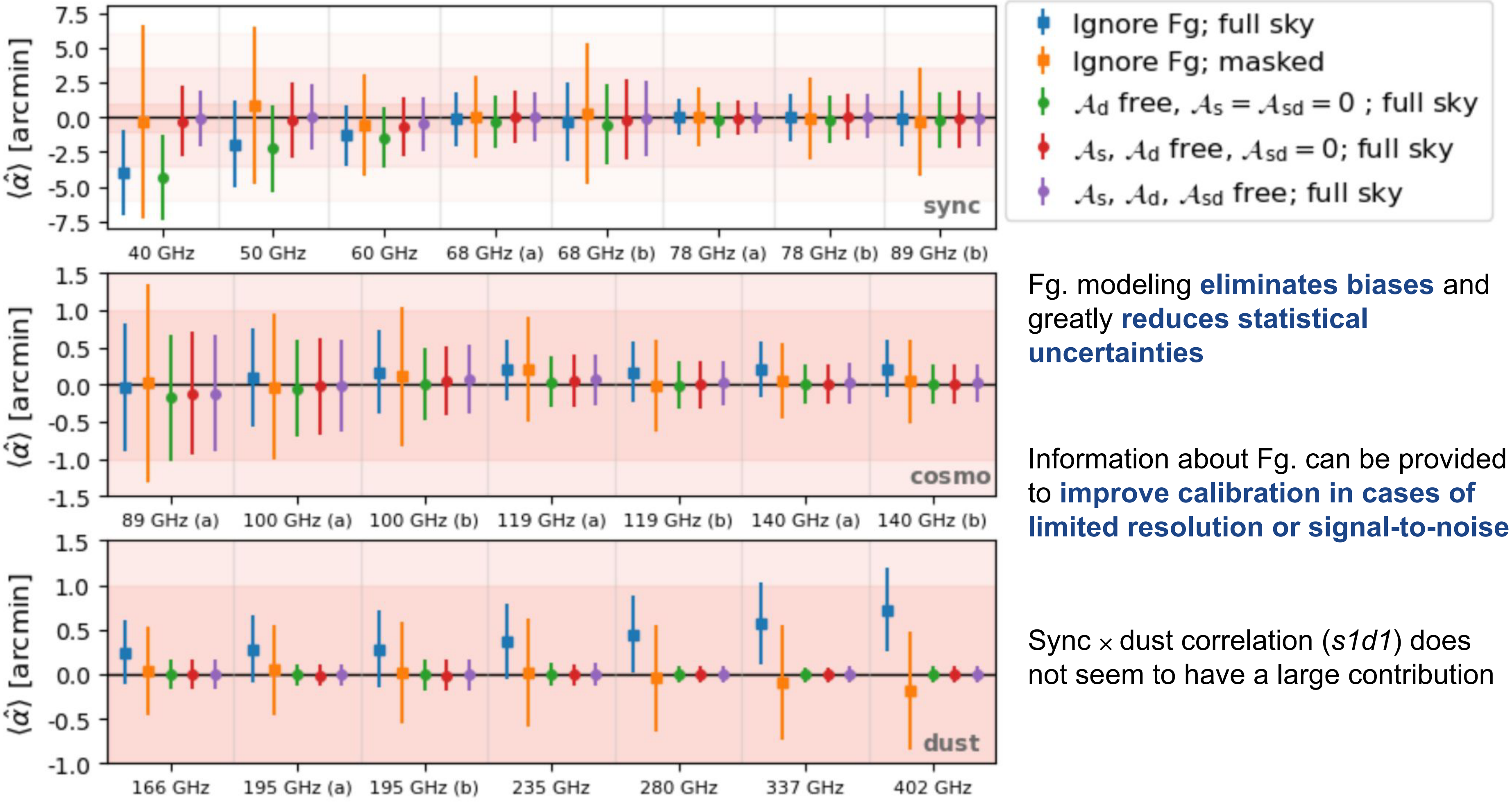

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Calibration of realistic instruments

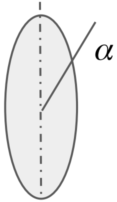
Sky signal
(not only polarised)

CMB + sync + dust
+ free-free + AME + CO

Instrument model

HWP
Beam
Pointing
…

+



α miscalibration

Null the observed *EB*

$C_\ell^{EB\text{,obs}} = f(C_\ell^{EE\text{,obs}}, C_\ell^{BB\text{,obs}}, \ldots)$

$$\begin{pmatrix} T_{\ell m}^{\text{obs}} \\ E_{\ell m}^{\text{obs}} \\ B_{\ell m}^{\text{obs}} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(2\alpha) & -\sin(2\alpha) \\ 0 & \sin(2\alpha) & \cos(2\alpha) \end{pmatrix} \mathcal{M}(\nu, \ell, \ldots) \begin{pmatrix} T_{\ell m}^{\text{sky}} \\ E_{\ell m}^{\text{sky}} \\ B_{\ell m}^{\text{sky}} \end{pmatrix}$$

Master Eq. describing this sky + instrument model

$$\begin{aligned} C_\ell^{EB,\text{obs}} = &\frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\text{obs}} - C_\ell^{BB,\text{obs}}\right) \\ &+ f_1\left(\nu, \ell, \alpha, \ldots, C_\ell^{TT,\text{CMB}}, C_\ell^{EE,\text{CMB}}, C_\ell^{BB,\text{CMB}}\right) \\ &+ f_2\left(\nu, \ell, \alpha, \ldots, \boxed{C_\ell^{TT,\text{sync}}, C_\ell^{EE,\text{sync}}, C_\ell^{BB,\text{sync}}}, C_\ell^{EB,\text{sync}}\right) \\ &+ f_3\left(\nu, \ell, \alpha, \ldots, \boxed{C_\ell^{TT,\text{dust}}, C_\ell^{EE,\text{dust}}, C_\ell^{BB,\text{dust}}}, C_\ell^{EB,\text{dust}}\right) \\ &+ f_4\left(\nu, \ell, \alpha, \ldots, \boxed{C_\ell^{T_\text{sync}T_\text{dust}}, C_\ell^{E_\text{sync}E_\text{dust}}, C_\ell^{B_\text{sync}B_\text{dust}}}, C_\ell^{E_\text{sync}B_\text{dust}}, C_\ell^{B_\text{sync}E_\text{dust}}\right) \end{aligned}$$

I cannot mask these terms away

In realistic settings, **calibration will not be independent of Fg. modeling**

Take home message

EB-nulling can provide a **high-precision self-calibration** of polarisation angles…

… but it is **not (completely) independent of foreground modeling**

Foregrounds are not (always) our enemy as they provide…

… **extra constraining power** in cases of limited angular resolution and/or signal-to-noise

… leverage to **model more complex instruments**

... a reference signal to break the degeneracy between instrument systematics and **cosmic birefringence**