Impact of HWP systematics on the measurement of cosmic birefringence from CMB polarization

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Marta Monelli

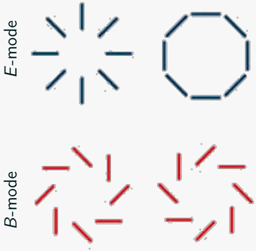
Max Planck Institut für Astrophysik

Garching (Germany)

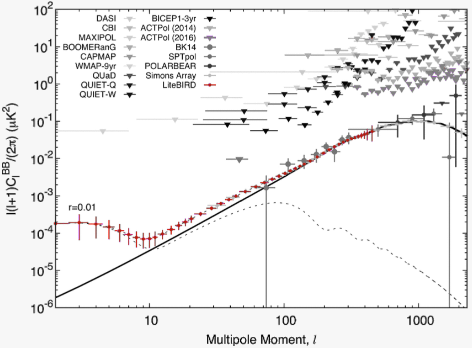
September 15th, 2022

searching for B-modes from inflation

Expectation: inflation-sourced perturbations leave traces on the CMB polarization.



B-modes can probe inflation.



Unprecedented sensitivity requirements!

image credit: Hazumi et al (2019)

a side effect: measuring cosmic birefringence

CMB might also carry information about parity-violating new physics: **cosmic birefringence**.

(time-dependent parity-violating pseudoscalar field)

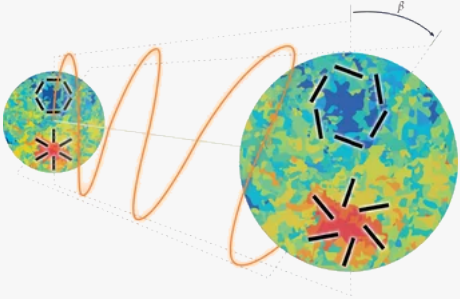


image credit: Yuto Minami;

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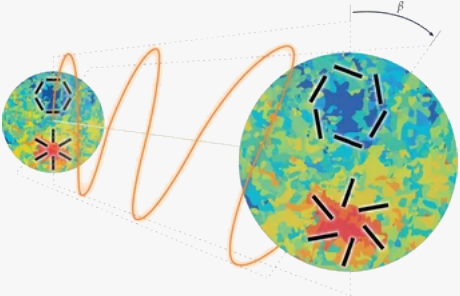

$$a^E_{\ell m,\mathrm{obs}} = a^E_{\ell m} \cos 2\beta - a^B_{\ell m} \sin 2\beta,$$
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$$C^{EB}_{\ell,\mathrm{obs}} = (C^{EE}_\ell - C^{BB}_\ell) \sin 4\beta/2 + C^{EB}_\ell \cos 4\beta.$$

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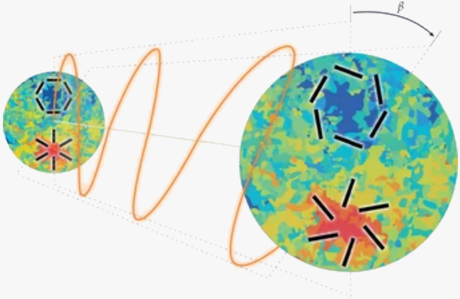

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From *Planck* data:

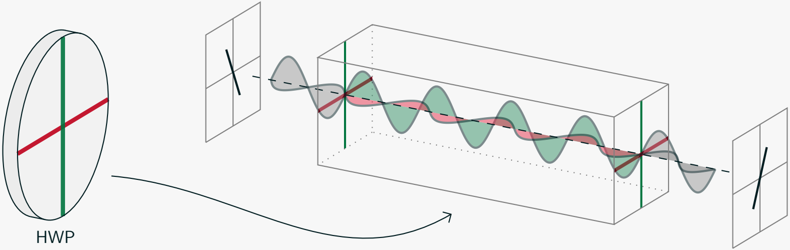
$\beta = 0.35 \pm 0.14^\circ$ at 68% C.L.

↓

Constraint expected to **improve**.

image credit: Yuto Minami; Minami and Komatsu (2020) Phys. Rev. Lett. 125

the HWP: reducing systematics



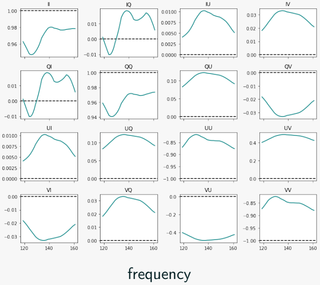
A **rotating** HWP as first optical element:

- modulates the signal to $4f_{\mathrm{HWP}}$, allowing to "escape" $1/f$ noise;
- makes possible for a single detector to measure polarization, reducing pair-differencing systematics.

the HWP: inducing systematics

Mueller calculus: radiation described as $S = (I, Q, U, V)$ and HWP effects parametrized by $\mathcal{M}_{\mathrm{HWP}}$, so that $\mathrm{S}' = \mathcal{M}_{\mathrm{HWP}}\mathrm{S}$.

$$\mathcal{M}_{\mathrm{ideal}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad \mathcal{M}_{\mathrm{HWP}} = \left(\vphantom{\begin{matrix}a\\a\\a\\a\end{matrix}} \right.$$



$$\left. \vphantom{\begin{matrix}a\\a\\a\\a\end{matrix}} \right).$$

Giardiello et al. (2022) A&A 658

outline of the talk

- framework of the simulations and their output;
- non-idealities' impact on the C_ℓs (simulated and analytic approx);
- impact on cosmic birefringence.

simulations

simulation input

- I, Q and U **input maps** ($n_{\text{side}} = 512$) from best-fit 2018 Planck power spectra;
- 1 year of LiteBIRD-like **scanning strategy** (mimicking `pyScan`).
- **Instrument specifics**: 160 detectors from the 140 GHz channel of LiteBIRD's MFT.
- Non-ideal **HWP**: Mueller matrix elements from Giardiello et al. (2022) A&A 658.

specs.	values
f_{samp}	19 Hz
HWP rpm	39
FWHM	30.8 arcmin
offset quats.	[...]

ideal vs non-ideal output spectra

ideal and non-ideal TODs, both processed with **ideal** map-maker.

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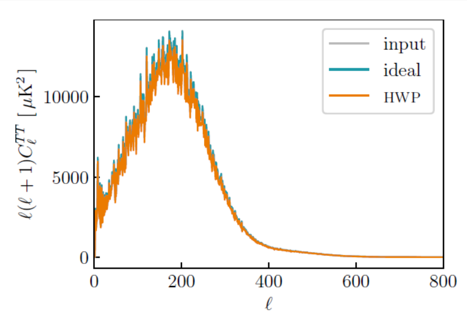

(beam transfer function not deconvolved)

- *TT* slightly affected

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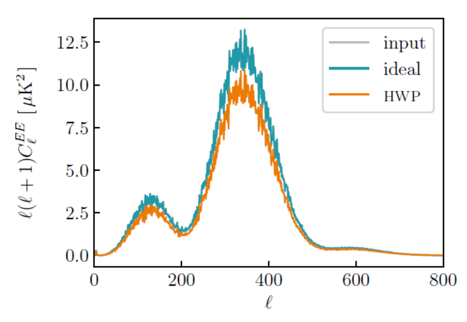

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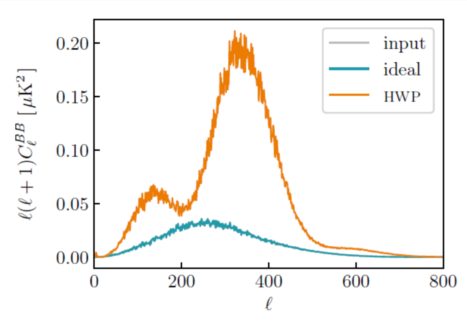

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- *BB* much larger (*EE* shape)

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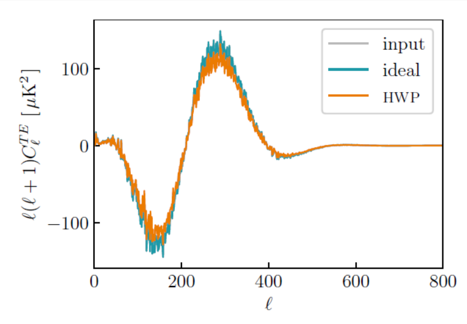

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- *TE* slightly affected

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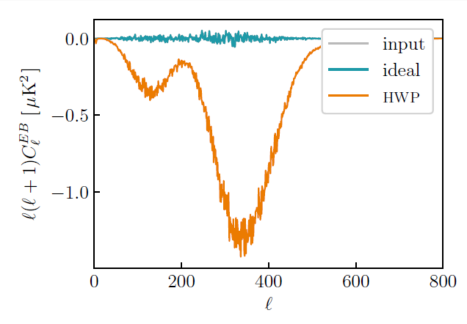

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- *EB* non-zero!

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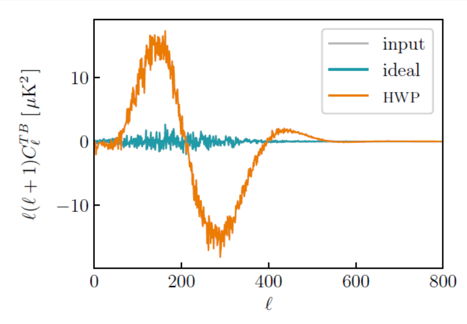


(beam transfer function not deconvolved)

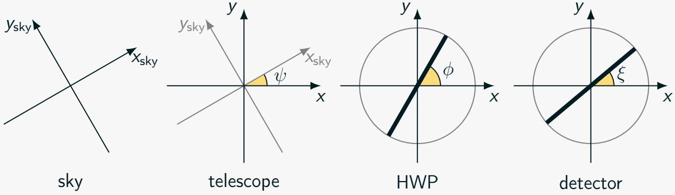
- *TT* slightly affected
- *EE* lost power
- *BB* much larger (*EE* shape)
- *TE* slightly affected
- *EB* non-zero!
- *TB* non-zero!

how can we understand this?

the idea

TOD: signal detected by 4 detectors looking at the same pixel;

Detected signal modeled as $d = (1\ 0\ 0) \cdot \mathcal{M}_{\text{det}} \mathcal{R}_{\xi-\phi} \mathcal{M}_{\text{HWP}} \mathcal{R}_{\phi+\psi} \cdot \text{S}$;



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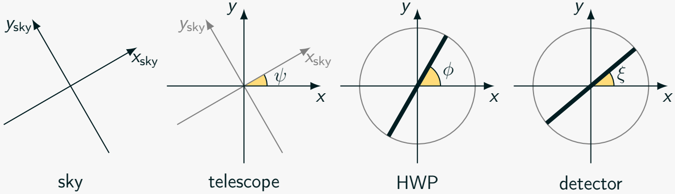


Apply a bin-averaging (ideal) map-maker to those 4 measurements.

$$\widehat{\text{S}} \simeq \begin{pmatrix} m_{ii} I_{\text{in}} \\ [(m_{qq} - m_{uu}) Q_{\text{in}} + (m_{qu} + m_{uq}) U_{\text{in}}]/2 \\ [-(m_{qu} + m_{uq}) Q_{\text{in}} + (m_{qq} - m_{uu}) U_{\text{in}}]/2 \end{pmatrix}.$$

equations for the $\widehat{C}_\ell$s (new result!)

Expanding $\widehat{S}$ in spherical harmonics:

$$\widehat{C}_\ell^{TT} \simeq m_{ii}^2 C_{\ell,\mathrm{in}}^{TT},$$

$$\widehat{C}_\ell^{EE} \simeq \frac{(m_{qq}-m_{uu})^2}{4} C_{\ell,\mathrm{in}}^{EE} + \frac{(m_{qu}+m_{uq})^2}{4} C_{\ell,\mathrm{in}}^{BB} + \frac{(m_{qq}-m_{uu})(m_{qu}+m_{uq})}{4} C_{\ell,\mathrm{in}}^{EB},$$

$$\widehat{C}_\ell^{BB} \simeq \frac{(m_{qq}-m_{uu})^2}{4} C_{\ell,\mathrm{in}}^{BB} + \frac{(m_{qu}+m_{uq})^2}{4} C_{\ell,\mathrm{in}}^{EE} - \frac{(m_{qq}-m_{uu})(m_{qu}+m_{uq})}{4} C_{\ell,\mathrm{in}}^{EB},$$

$$\widehat{C}_\ell^{TE} \simeq \frac{m_{ii}(m_{qq}-m_{uu})}{2} C_{\ell,\mathrm{in}}^{TE} + \frac{m_{ii}(m_{qu}+m_{uq})}{2} C_{\ell,\mathrm{in}}^{TB},$$

$$\widehat{C}_\ell^{EB} \simeq \frac{(m_{qq}-m_{uu})^2-(m_{qu}+m_{uq})^2}{4} C_{\ell,\mathrm{in}}^{EB} - \frac{(m_{qq}-m_{uu})(m_{qu}+m_{uq})}{4} (C_{\ell,\mathrm{in}}^{EE} - C_{\ell,\mathrm{in}}^{BB}),$$

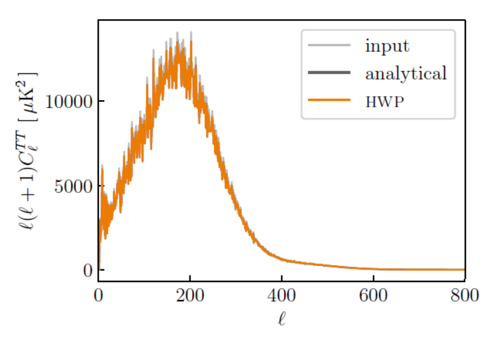
$$\widehat{C}_\ell^{TB} \simeq \frac{m_{ii}(m_{qq}-m_{uu})}{2} C_{\ell,\mathrm{in}}^{TB} - \frac{m_{ii}(m_{qu}+m_{uq})}{2} C_{\ell,\mathrm{in}}^{TE}.$$

...Let's see if this makes sense!

analytical vs non-ideal output spectra

the analytical and the output spectra almost perfectly overlap!

(the black line is behind the orange one)



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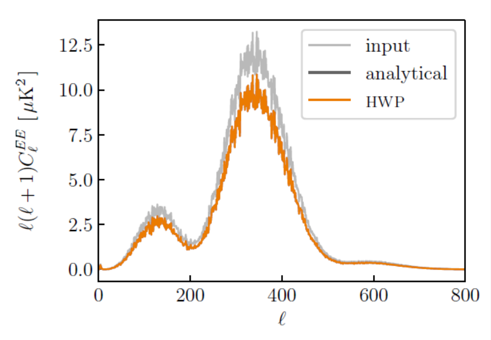

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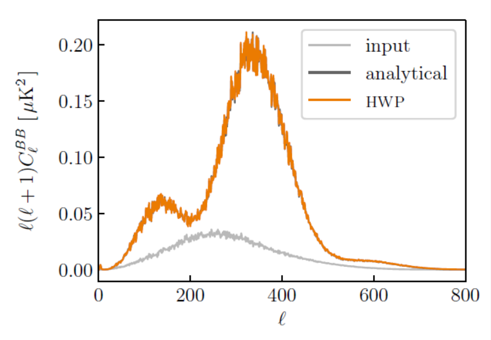

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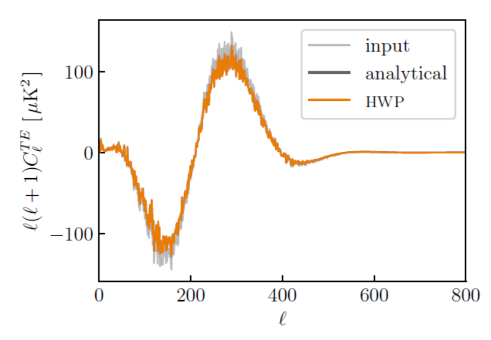

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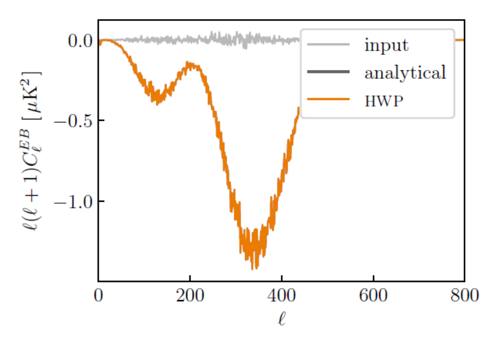

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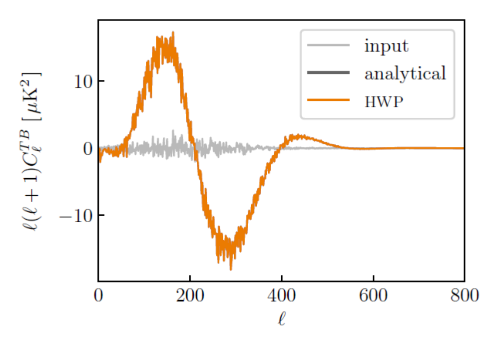


impact on cosmic birefringence

HWP-induced miscalibration

Analytic $\widehat{C}_\ell$s satisfy the relations:

$$\begin{cases} \widehat{C}_\ell^{EB} \simeq \tan(4\widehat{\theta})/2 \left[\widehat{C}_\ell^{EE} - \widehat{C}_\ell^{BB}\right] \\ \widehat{C}_\ell^{TB} \simeq \tan(2\widehat{\theta})\,\widehat{C}_\ell^{TE} \end{cases}$$

our formulae suggest

$$\widehat{\theta} \equiv -\frac{1}{2}\arctan\frac{m_{qu} + m_{uq}}{m_{qq} - m_{uu}}$$

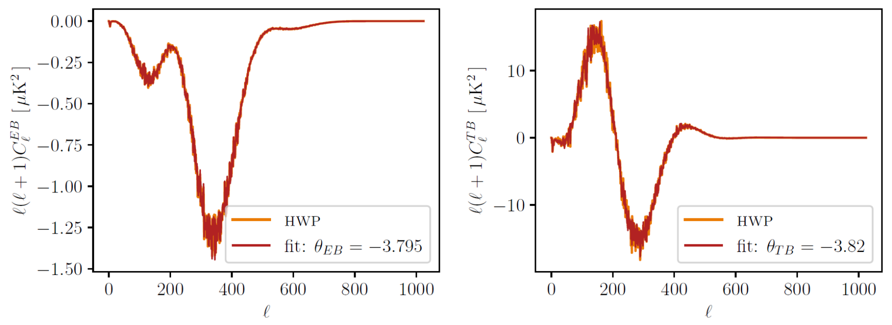
Degeneracy with cosmic birefringence and polarization angle miscalibration!

In first approximation, HWP induces an additional miscalibration.

θ_{EB}, θ_{TB} and $\widehat{\theta}$

analytical expectation: $\widehat{\theta} \sim -3.8°$.

compatible with best fit estimates!



the importance of calibration

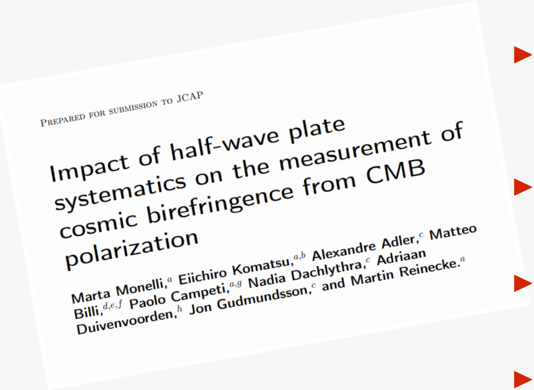
$$3.8^\circ \sim |\widehat{\theta}| \gg |\beta| \simeq 0.35^\circ.$$

Does this mean that the HWP will keep us from measuring β?

No: this effect is understood and can be calibrated.

However, it shows how important it is to carefully calibrate $\mathcal{M}_{\mathsf{HWP}}$.

conclusions and outlook



PREPARED FOR SUBMISSION TO JCAP

Impact of half-wave plate systematics on the measurement of cosmic birefringence from CMB polarization

Marta Monelli,[a] Eiichiro Komatsu,[a,b] Alexandre Adler,[c] Matteo Billi,[d,e,f] Paolo Campeti,[a,g] Nadia Dachlythra,[c] Adriaan Duivenvoorden,[h] Jon Gudmundsson,[c] and Martin Reinecke.[a]

- determine requirements on non-idealities so that systematics on β below 0.1°;
- study impact of non-idealities on EB angle calibration;
- study impact of non-idealities on Q/U maps of Tau A;
- include frequency dependence.