Impact of HWP non-idealities on the observed CMB polarization

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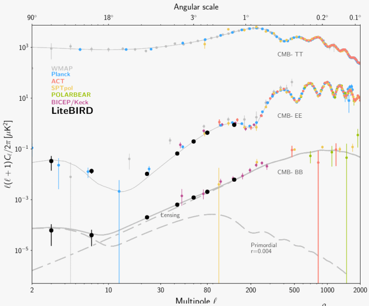
new physics from CMB polarization

- B modes are sensitive to primordial GWs ($C_\ell^{BB} = rC_\ell^{\rm GW} + C_\ell^{\rm lensing}$): they can be used to test/constrain **inflationary models**.



- CMB polarization is also sensitive to cosmic birefringence: probe of **parity-violating** physics.

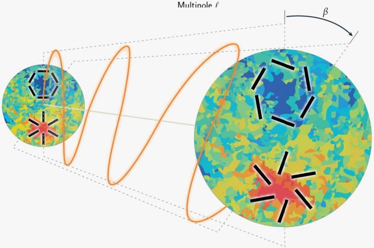


image credit: LiteBIRD Collaboration (2022) PTEP, Yuto Minami

how to get there

- LiteBIRD,
- Simons Observatory,
- South Pole Observatory,
- CMB-S4,
- ...

Mitigating systematics is key!

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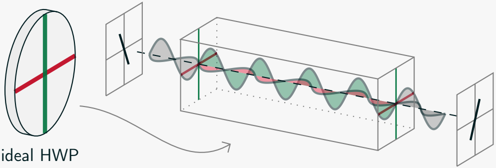
Mitigating systematics is key!

Some instruments will employ rotating **half-wave plates (HWPs)** as polarization modulators to mitigate $1/f$ noise and reduce $I \to P$ leakage.

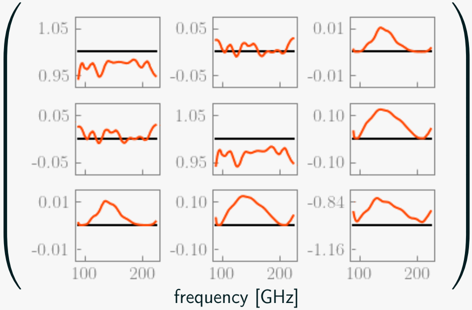


$$\mathcal{M}_{\text{ideal}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

beyond the ideal HWP

For a realistic HWP, $\mathcal{M}_{\text{HWP}} \neq \text{diag}(1, 1, -1)$. Instead

$\mathcal{M}_{\text{HWP}} =$



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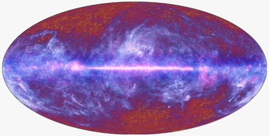
How does this affect the observed maps/spectra/...?

Giardiello et al. (2022) A&A 658

two complementary approaches



detection

time ordered data (TOD)

map-making

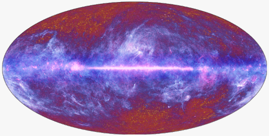
multi-frequency maps

foreground cleaning

CMB sky maps

image credit: *Planck* collaboration

two complementary approaches



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TOD simulations are key to study systematics: they can account for them in their (at least partial) complexity.

image credit: *Planck* collaboration

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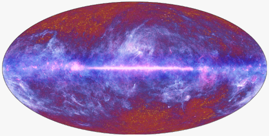

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Map-based simulations are approximate but extremely useful to gain some intuition about the problem at hand.

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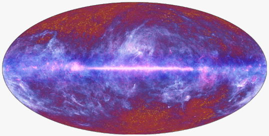

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modeling the observed maps

TOD: $\mathsf{d} = A\,\mathsf{m}_{\mathsf{in}}$

map-maker: $\mathsf{m}_{\mathsf{out}} = (\widehat{A}^T \widehat{A})^{-1} \widehat{A}^T \mathsf{d}$

modeling the observed maps

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recalling the structure of response matrices

explictly: $$m_{\text{out},p} = \left[\sum_{j't' \in \{jt\}_p} \widehat{\mathbb{S}}_{j't'} \widehat{\mathbb{S}}^T_{j't'} \right]^{-1} \left[\sum_{jt \in \{jt\}_p} \widehat{\mathbb{S}}_{jt} \mathbb{S}^T_{jt} \right] m_{\text{in},p}$$

$\mathbb{S}_{jt}$ encodes instrumental response relative to detector j at time t.

validation: toy model

$$m_{\text{out},p} = \left[\sum_{j't' \in \{jt\}_p} \widehat{\mathbb{S}}_{j't'} \widehat{\mathbb{S}}_{j't'}^T \right]^{-1} \left[\sum_{jt \in \{jt\}_p} \widehat{\mathbb{S}}_{jt} \mathbb{S}_{jt}^T \right] m_{\text{in},p}$$

- no noise,
- single frequency,
- CMB-only,
- ideal binning map-maker,
- neglecting non-linearities,
- simple beams,
- HWP aligned to the detector line of sight.

Monelli et al. (2023) JCAP 03

validation: toy model

$$I_{\text{out}} = m_{ii} I_{\text{in}} + (m_{iq} Q_{\text{in}} + m_{iu} U_{\text{in}}) \cos(2\alpha) + (m_{iq} U_{\text{in}} - m_{iu} Q_{\text{in}}) \sin(2\alpha)$$

$$\begin{aligned} Q_{\text{out}} = \frac{1}{2}\Big\{ & (m_{qq} - m_{uu}) Q_{\text{in}} + (m_{qu} + m_{uq}) U_{\text{in}} + 2 m_{qi} I_{\text{in}} \cos(2\alpha) + 2 m_{ui} I_{\text{in}} \sin(2\alpha) \\ & + \left[(m_{qq} + m_{uu}) Q_{\text{in}} + (m_{qu} - m_{uq}) U_{\text{in}}\right] \cos(4\alpha) \\ & + \left[-(m_{qu} - m_{uq}) Q_{\text{in}} + (m_{qq} + m_{uu}) U_{\text{in}}\right] \sin(4\alpha) \Big\} \end{aligned}$$

$$\begin{aligned} U_{\text{out}} = \frac{1}{2}\Big\{ & (m_{qq} - m_{uu}) U_{\text{in}} - (m_{qu} + m_{uq}) Q_{\text{in}} - 2 m_{ui} I_{\text{in}} \cos(2\alpha) + 2 m_{qi} I_{\text{in}} \sin(2\alpha) \\ & + \left[-(m_{qq} + m_{uu}) U_{\text{in}} + (m_{qu} - m_{uq}) Q_{\text{in}}\right] \cos(4\alpha) \\ & + \left[(m_{qu} - m_{uq}) U_{\text{in}} + (m_{qq} + m_{uu}) Q_{\text{in}}\right] \sin(4\alpha) \Big\} \qquad \text{where } \alpha \equiv \phi + \psi \end{aligned}$$

For **good** coverage and **rapidly spinning** HWP:

$$m_{\text{out},p} \simeq \begin{pmatrix} m_{ii} & 0 & 0 \\ 0 & (m_{qq} - m_{uu})/2 & (m_{qu} + m_{uq})/2 \\ 0 & -(m_{qu} + m_{uq})/2 & (m_{qq} - m_{uu})/2 \end{pmatrix} m_{\text{in},p}.$$

Monelli et al. (2023) JCAP 03

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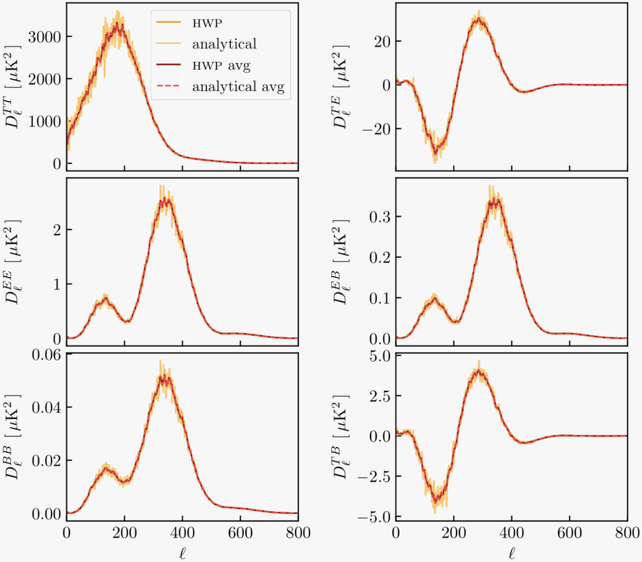

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relaxing some assumptions

$$m_{\mathrm{out},p} = \left[\sum_{j't' \in \{jt\}_p} \widehat{\mathbb{S}}_{j't'} \widehat{\mathbb{S}}^T_{j't'} \right]^{-1} \left[\sum_{jt \in \{jt\}_p} \widehat{\mathbb{S}}_{jt} \mathbb{S}^T_{jt} \right] m_{\mathrm{in},p}$$

- ~~no noise,~~
- ~~single frequency,~~
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- ideal binning map-maker,
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band-integrated maps

$$\textbf{with HWP:}\quad \mathsf{m}^i_{\text{out}} \simeq \sum_\lambda \begin{pmatrix} g^i_\lambda & 0 & 0 \\ 0 & \rho^i_\lambda & \eta^i_\lambda \\ 0 & -\eta^i_\lambda & \rho^i_\lambda \end{pmatrix} \overline{\mathsf{m}}^i_\lambda(\nu_*) + \mathsf{n}^i\,,$$

$$\text{where}\quad g^i_\lambda \equiv \int_{\nu^i_{\text{min}}}^{\nu^i_{\text{max}}} \frac{\mathrm{d}\nu}{\Delta\nu^i} a_\lambda(\nu) m_{\text{ii}}(\nu)\,,$$

$$\rho^i_\lambda \equiv \frac{1}{2}\int_{\nu^i_{\text{min}}}^{\nu^i_{\text{max}}} \frac{\mathrm{d}\nu}{\Delta\nu^i} a_\lambda(\nu)\left[m_{\text{qq}}(\nu) - m_{\text{uu}}(\nu)\right]\,,$$

$$\eta^i_\lambda \equiv \frac{1}{2}\int_{\nu^i_{\text{min}}}^{\nu^i_{\text{max}}} \frac{\mathrm{d}\nu}{\Delta\nu^i} a_\lambda(\nu)\left[m_{\text{qu}}(\nu) + m_{\text{uq}}(\nu)\right]\,.$$

How the HWP non-idealities affect gain, polarization-efficiency and cross-pol leakage, differ for each frequency channel and each component.

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an extra step: end-to-end model

sky model

↓

multifrequency maps $m^i_{\rm out} \simeq \sum_\lambda \begin{pmatrix} g^i_\lambda & 0 & 0 \\ 0 & \rho^i_\lambda & \eta^i_\lambda \\ 0 & -\eta^i_\lambda & \rho^i_\lambda \end{pmatrix} \overline{m}^i_\lambda(\nu_*) + n^i$

↓

reconstructed CMB spectra

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sky model CMB, dust, synchrotron; uniform SEDs

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HILC foreground removal

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HILC foreground removal

reconstructed CMB spectra **can be modeled analytically!**

$$C^{BB}_{\ell,\mathrm{HILC}} = \sum_{i,j=1}^{n_{\mathrm{chan}}} \frac{w^i_\ell w^j_\ell}{g^i_{\mathrm{CMB}} g^j_{\mathrm{CMB}}} \left\{ \sum_\lambda \left[\rho^i_\lambda \rho^j_\lambda C^{BB}_{\ell,\lambda} + \eta^i_\lambda \eta^j_\lambda C^{EE}_{\ell,\lambda} - \left(\rho^i_\lambda \eta^j_\lambda + \eta^i_\lambda \rho^j_\lambda \right) C^{EB}_{\ell,\lambda} \right] + \frac{\mathbb{N}^{BB,ij}_\ell}{B^i_\ell B^j_\ell} \right\}$$

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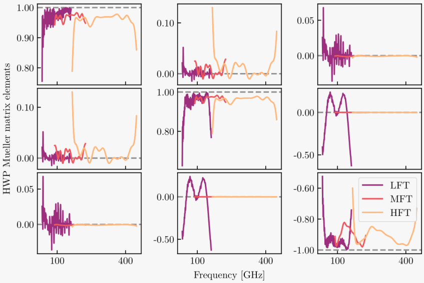
HILC solution



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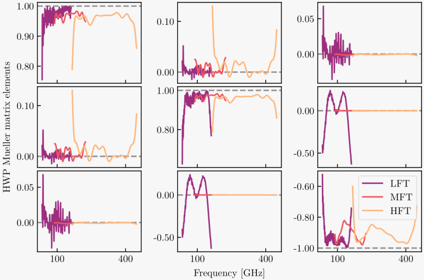
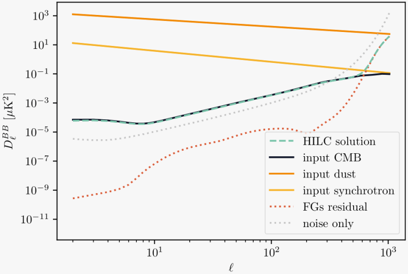


(power law $D_{\ell,\lambda}$)



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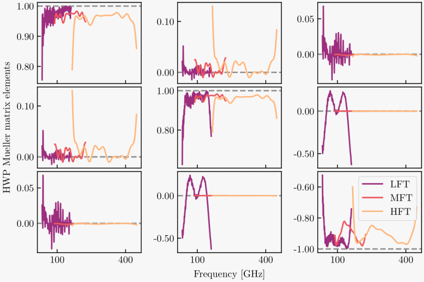

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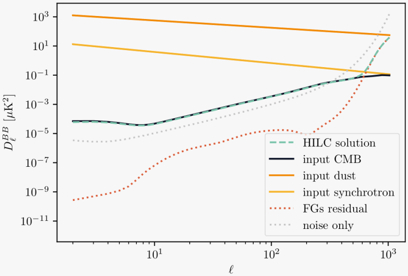

Blind component separation reduces the impact of the non-idealities.
We are left with a slight **underestimation** of r.

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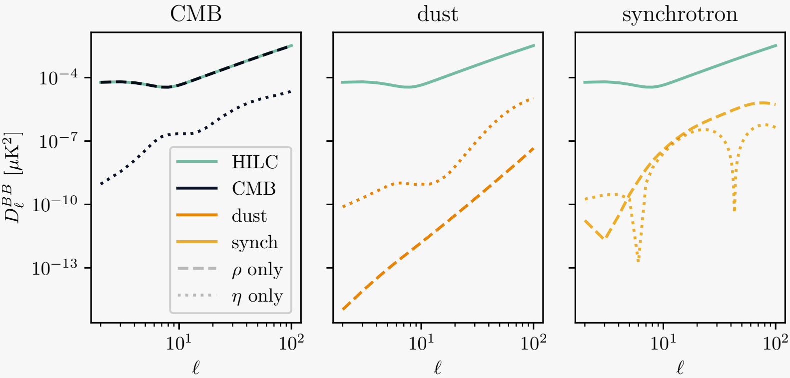
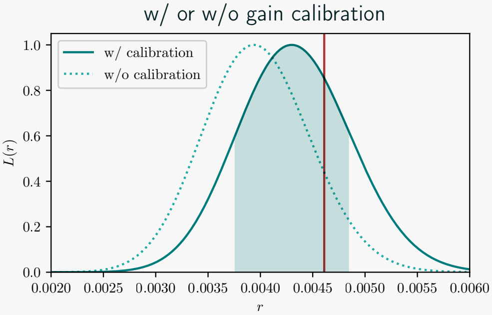
term by term



$$C^{BB}_{\ell,\mathsf{HILC}} = \sum_{i,j=1}^{n_{\mathsf{chan}}} \frac{w^i_\ell w^j_\ell}{g^i_{\mathsf{CMB}} g^j_{\mathsf{CMB}}} \left\{ \sum_\lambda \left[\rho^i_\lambda \rho^j_\lambda C^{BB}_{\ell,\lambda} + \eta^i_\lambda \eta^j_\lambda C^{EE}_{\ell,\lambda} - \left(\rho^i_\lambda \eta^j_\lambda + \eta^i_\lambda \rho^j_\lambda \right) C^{EB}_{\ell,\lambda} \right] + \frac{\mathbb{N}^{BB,ij}_\ell}{B^i_\ell B^j_\ell} \right\}$$

impact on r and design recommendations

To mitigate this effect, one can **design** the HWP to maximizes the benefits of gain calibration.



- ▷ Cross-polarization coupling should be small, $\zeta_{1,2} \lesssim 10^{-2}$, which can be achieved for both metal-mesh and multi-layer HWPs;
- ▷ The loss parameters should also be small, $h_{1,2} \lesssim 10^{-2}$, or, alternatively, $|h_1 - h_2| \lesssim 10^{-3}$;
- ▷ At least one of $h_1(\nu) + h_2(\nu)$ and $[1 + \cos\beta(\nu)]/2$ should be slowly varying within the band, so that $\rho^i_{\rm CMB} \simeq A^i g^i_{\rm CMB}$;
- ▷ Cross-polarization coupling can be kept under control by requiring $\zeta_{1,2}$ to be even smaller, or alternatively, by ensuring that $\eta^i_{\rm CMB}$ fluctuates around zero.

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conclusions

- CMB polarization is a promising probe of new physics, that can only be extracted if systematics are well under control,
- A rotating HWP can help, but it induces **additional systematics** which should be accounted for.
- Map-based simulations can help us gain intuition about the problem and develop mitigation strategies (design recommendations).
- Next steps: consider realistic sky models, together with a sophisticated foreground cleaning method: the multi-clustering needlet internal linear combination (MCNILC). Do the design recommendation change?