Half-Wave Plate Systematics

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LiteBIRD Italia, LNF, 23 May 2023

Based on: Giardiello, Gerbino, Pagano, Errard, Gruppuso, Ishino, Lattanzi, Natoli, Patanchon, Piacentini, Pisano,
A&A 658 (2022) A15, A&A 671 (2023) C1 (erratum), 2106.08031 [astro-ph.CO];
Raffuzzi+, in prep.; LiteBIRD Project Paper Out-of-band rejection requirements for LiteBIRD Medium and High Frequency Telescopes

The Half-Wave Plate

180deg phase retarder due to different propagation of EM wave components

Mueller formalism

$$\begin{pmatrix} I^{out} \\ Q^{out} \\ U^{out} \\ V^{out} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} I^{in} \\ Q^{in} \\ U^{in} \\ V^{in} \end{pmatrix}$$

Jones formalism

$$\begin{pmatrix} E_X^{out} \\ E_Y^{out} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} E_X^{in} \\ E_Y^{in} \end{pmatrix}$$

Could be made of: birefringent material (e.g., sapphire); Metal-mesh (e.g., lumped CL circuits); Meta-material (e.g., artificial dielectrics).
Note: design is frequency-specific

The Half-Wave Plate

In CMB context: rotating HWP -> it modulates the polarisation signal to efficiently isolate it while reducing 1/f noise contamination and avoiding systematic effects of alternative methods (e.g., pair differencing)

$$d_{pol} = M_{pol} M_{rot}^{T} M_{HWP} M_{rot} M_{instr} S$$

For a polariser along X-direction

$$d_X = \frac{1}{2}[I + \cos(4\theta)Q + \sin(4\theta)U]$$

If we account for HWP non-idealities:

$$d_X = \frac{1}{2}[M^{TT} I + M^{TQ} Q + M^{TU} U + M^{TV} V]$$

Non-ideal HWP

Top-down modelling: start from physical effects and propagate down to measurements (Focus on BB power spectrum predictions)

$$J_{\mathrm{HWP}}^{\mathrm{ideal}} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \Rightarrow J_{\mathrm{HWP}}^{\mathrm{real}} = \begin{pmatrix} 1+h_1 & \zeta_1 \\ \zeta_2 & (1+h_2)e^{i\beta} \end{pmatrix}$$

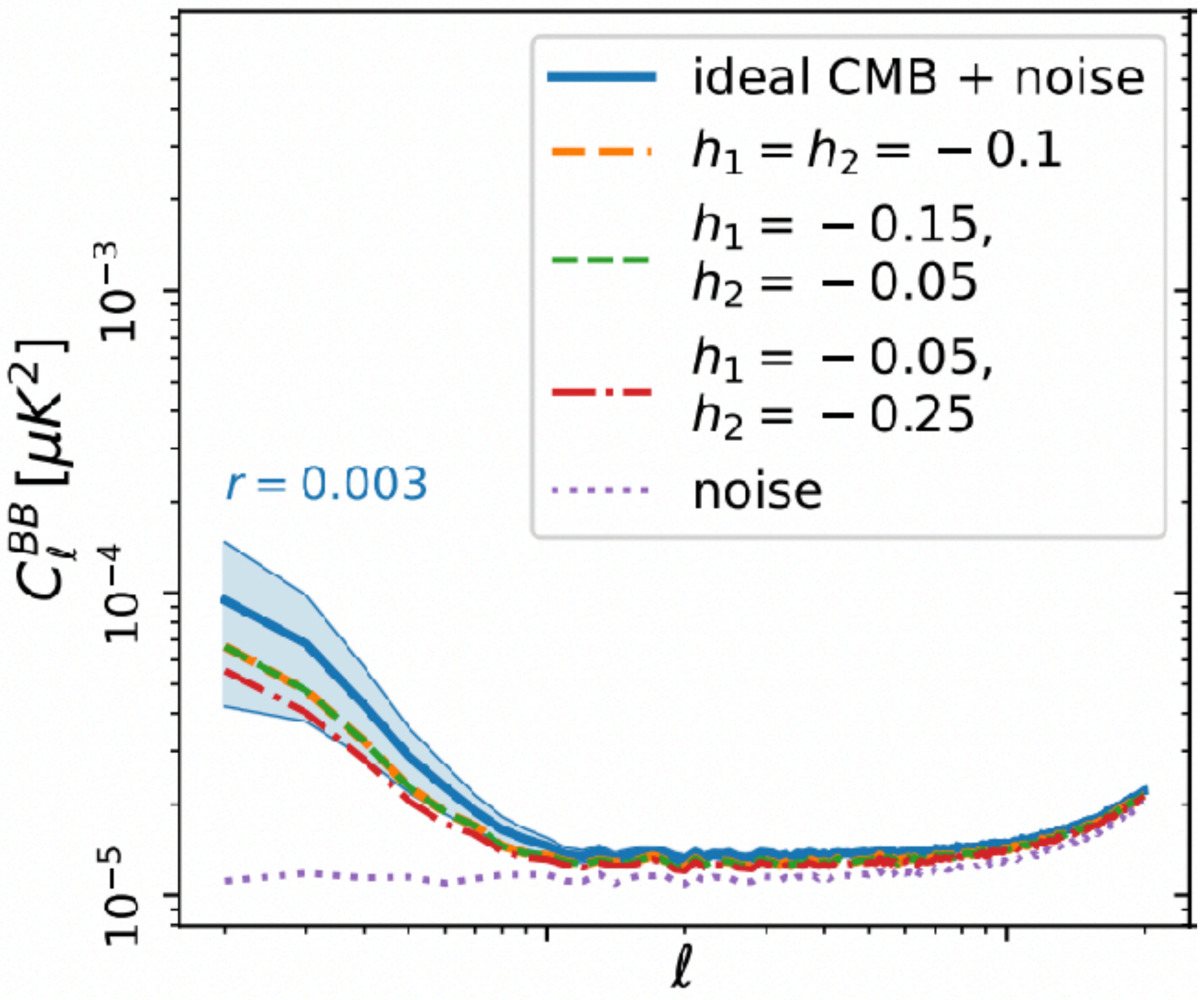
Frequency-dependent parameters: non-trivial effects when considering coupling with foreground emissions and bandpass filtering

Non-ideal HWP - transmission

Top-down modelling: start from physical effects and propagate down to measurements

$$J_{\mathrm{HWP}}^{\mathrm{ideal}} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \Rightarrow J_{\mathrm{HWP}}^{\mathrm{real}} = \begin{pmatrix} 1 + h_1 & \zeta_1 \\ \zeta_2 & (1 + h_2)e^{i\beta} \end{pmatrix}$$

h1, h2 < 0
Reduced power transmission ->
BB power spectrum suppression

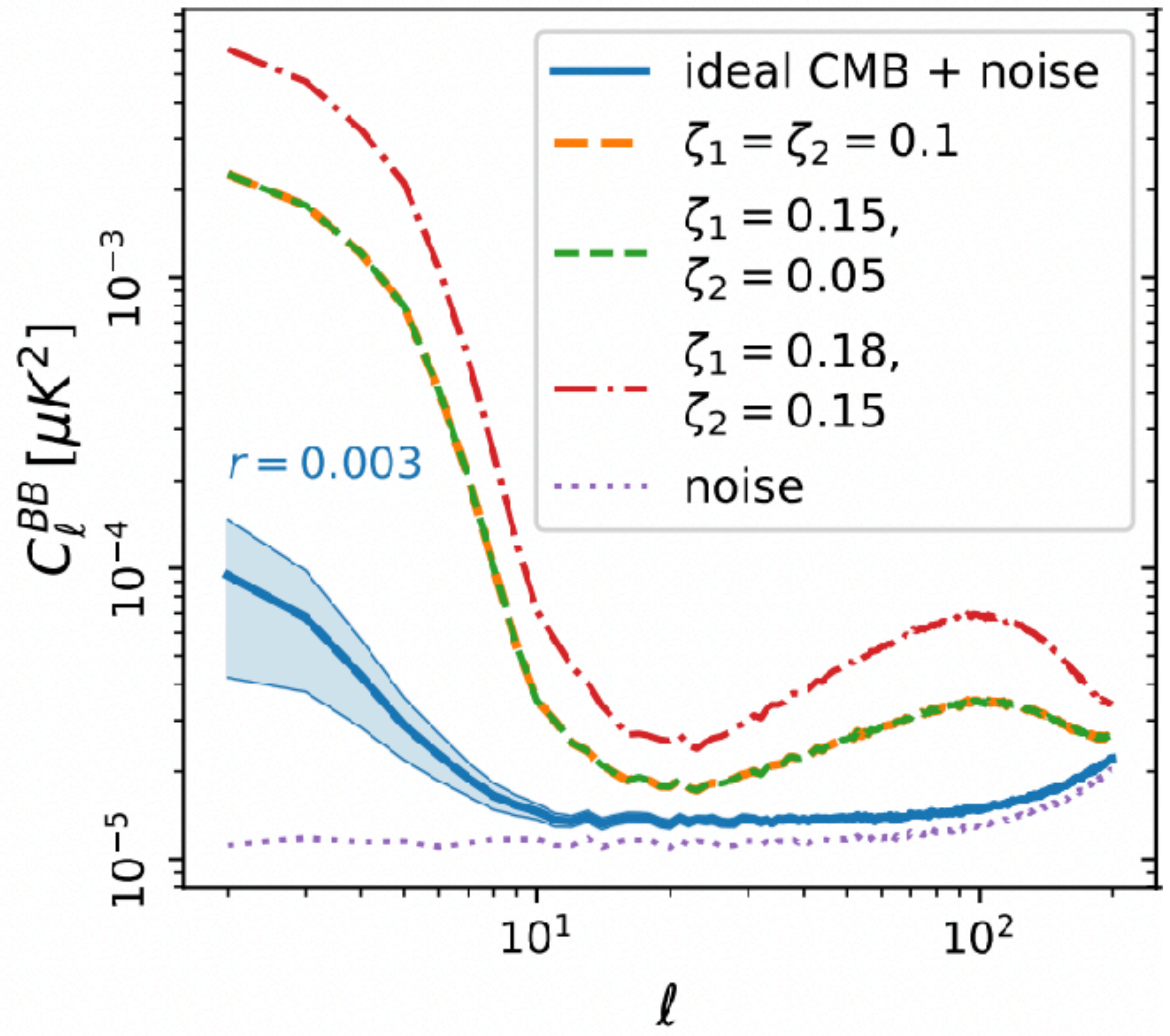


Non-ideal HWP - cross-pol

Top-down modelling: start from physical effects and propagate down to measurements

$$J_{\mathrm{HWP}}^{\mathrm{ideal}} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \Rightarrow J_{\mathrm{HWP}}^{\mathrm{real}} = \begin{pmatrix} 1+h_1 & \zeta_1 \\ \zeta_2 & (1+h_2)e^{i\beta} \end{pmatrix}$$

Cross-polarization ->
E-to-B power spectrum leakage



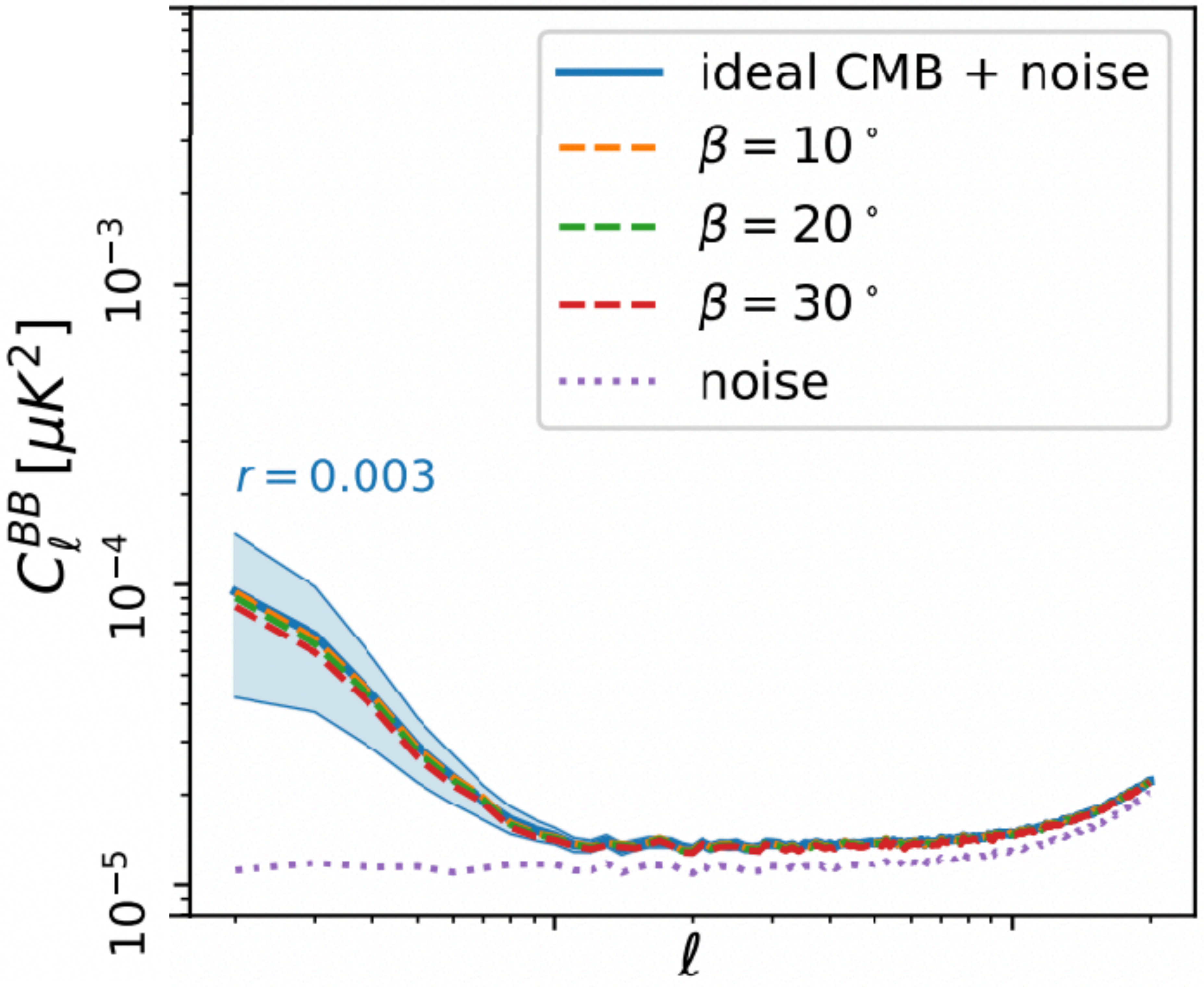
Non-ideal HWP - phase shift

Top-down modelling: start from physical effects and propagate down to measurements

$$J_{\mathrm{HWP}}^{\mathrm{ideal}} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \Rightarrow J_{\mathrm{HWP}}^{\mathrm{real}} = \begin{pmatrix} 1+h_1 & \zeta_1 \\ \zeta_2 & (1+h_2)e^{i\beta} \end{pmatrix}$$

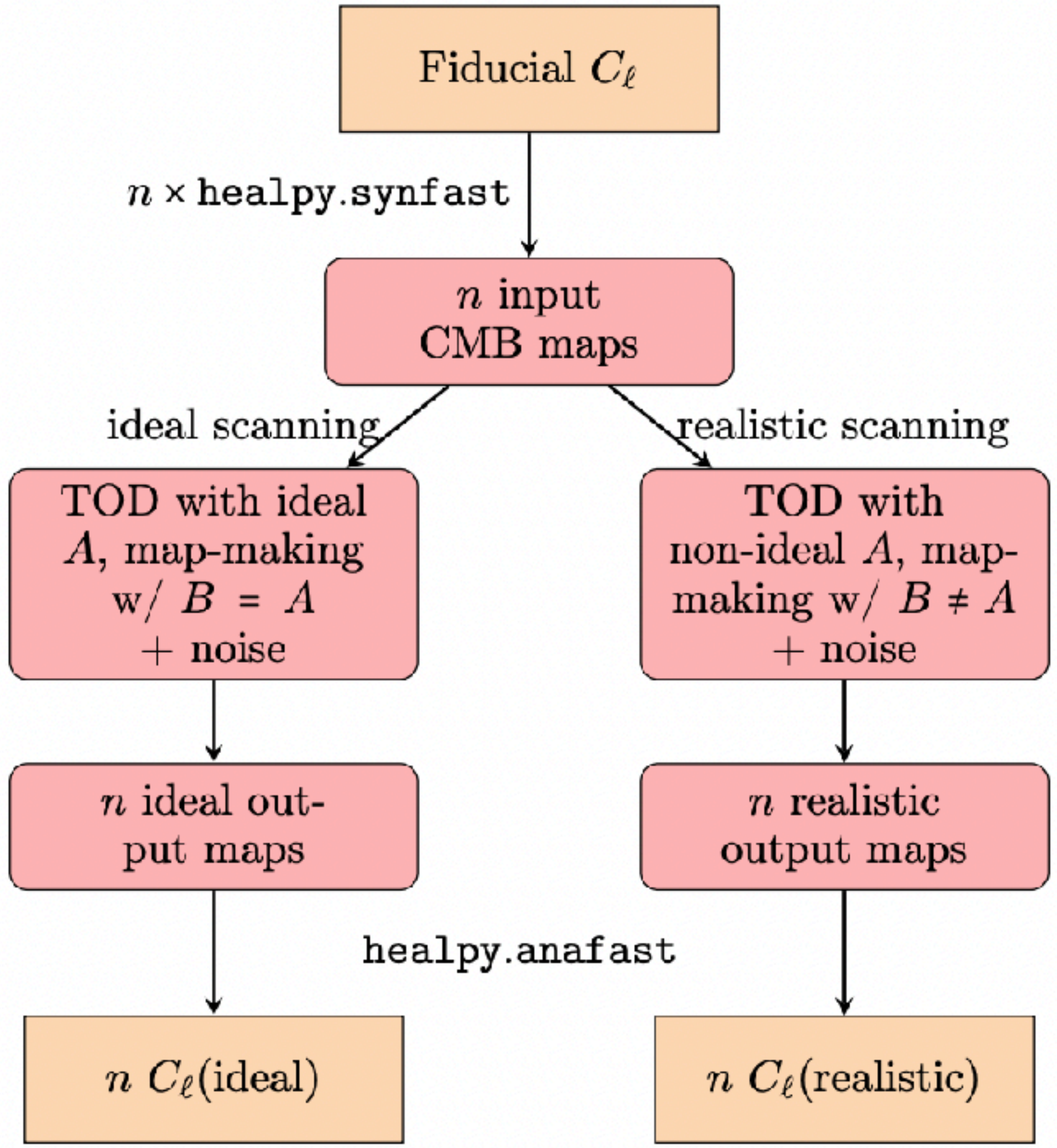
$\beta \neq \pi$

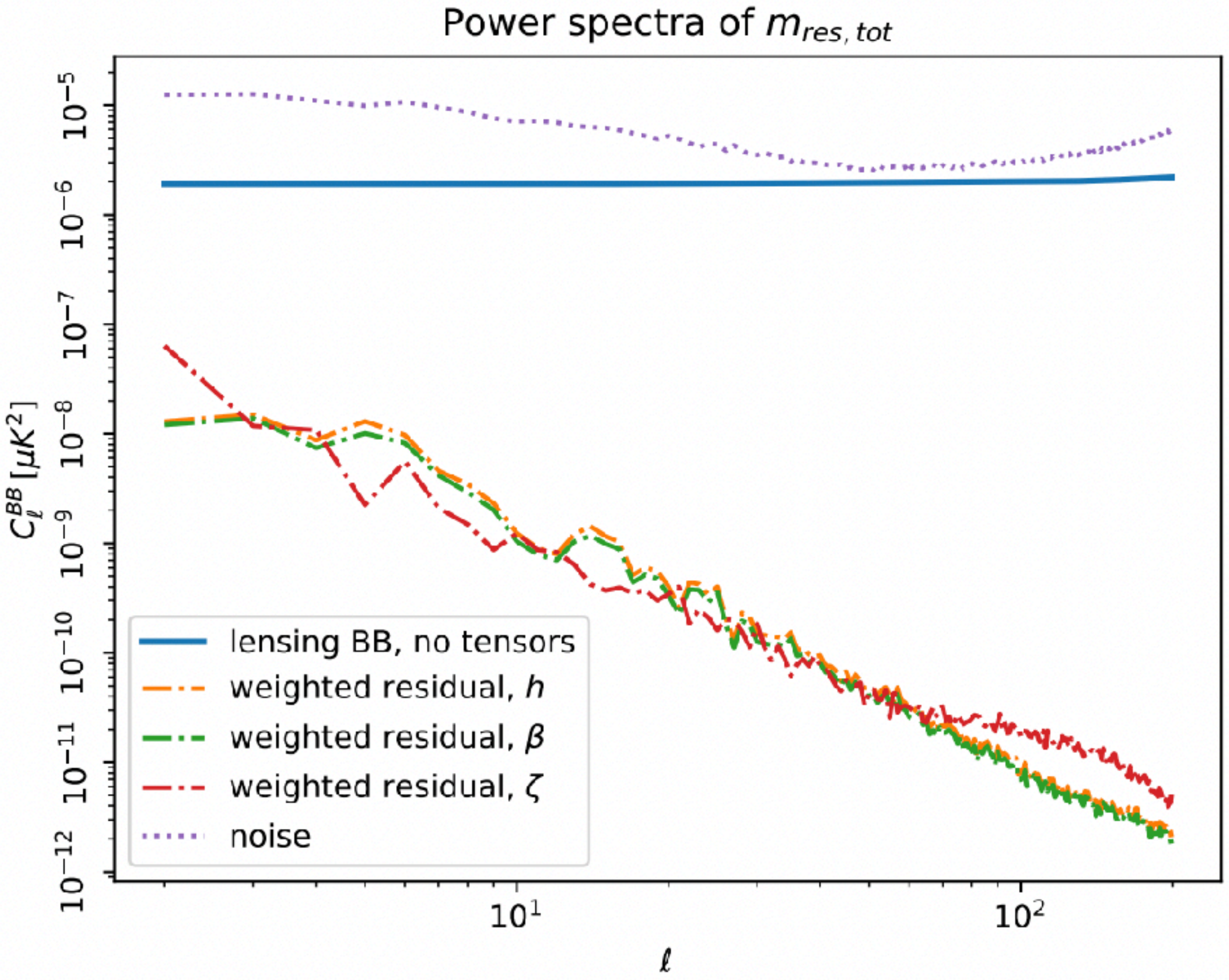
Phase shift ->
BB power spectrum suppression



Non-ideal HWP - BB residual

Top-down modelling: start from physical effects and propagate down to measurements

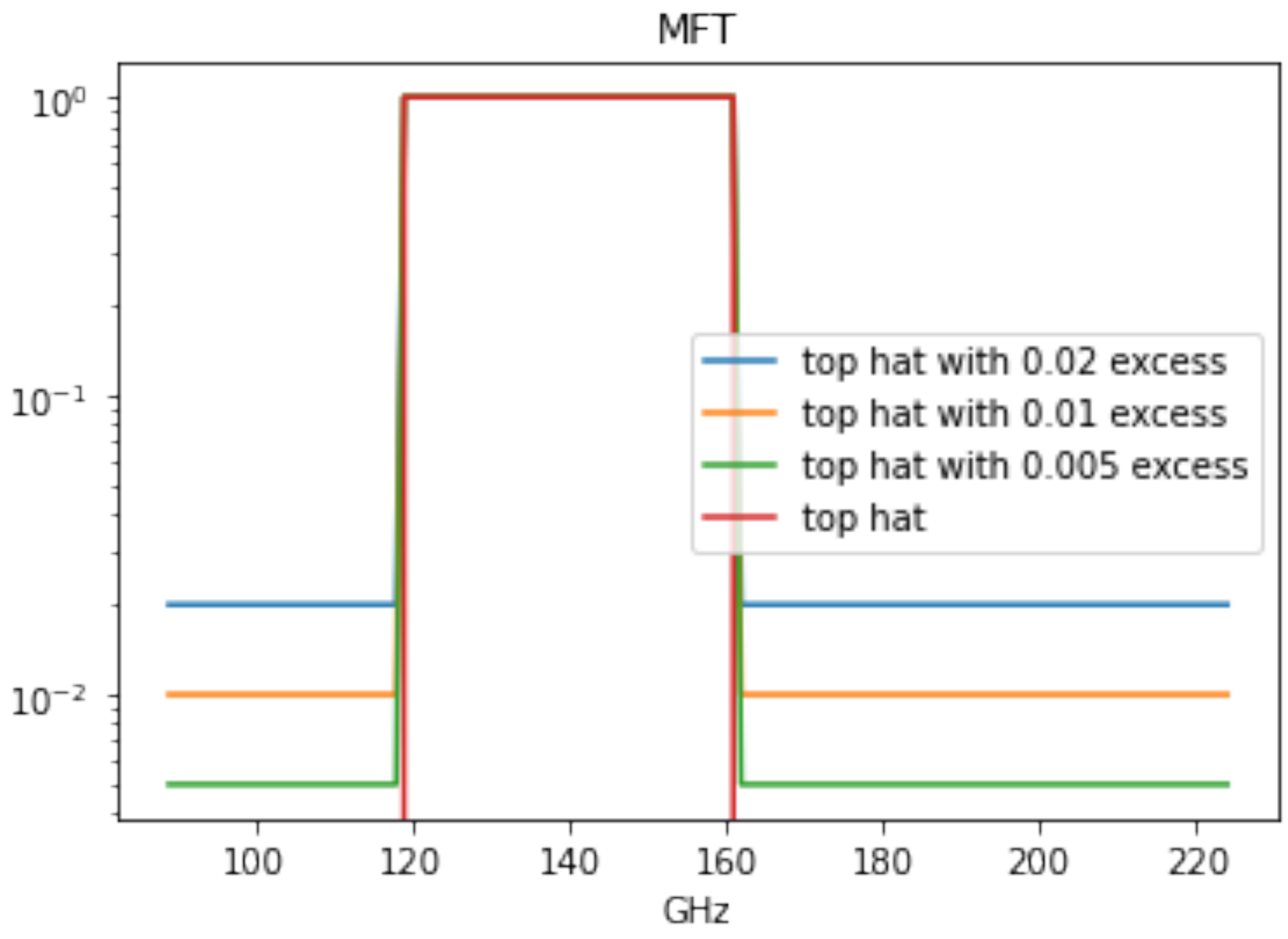


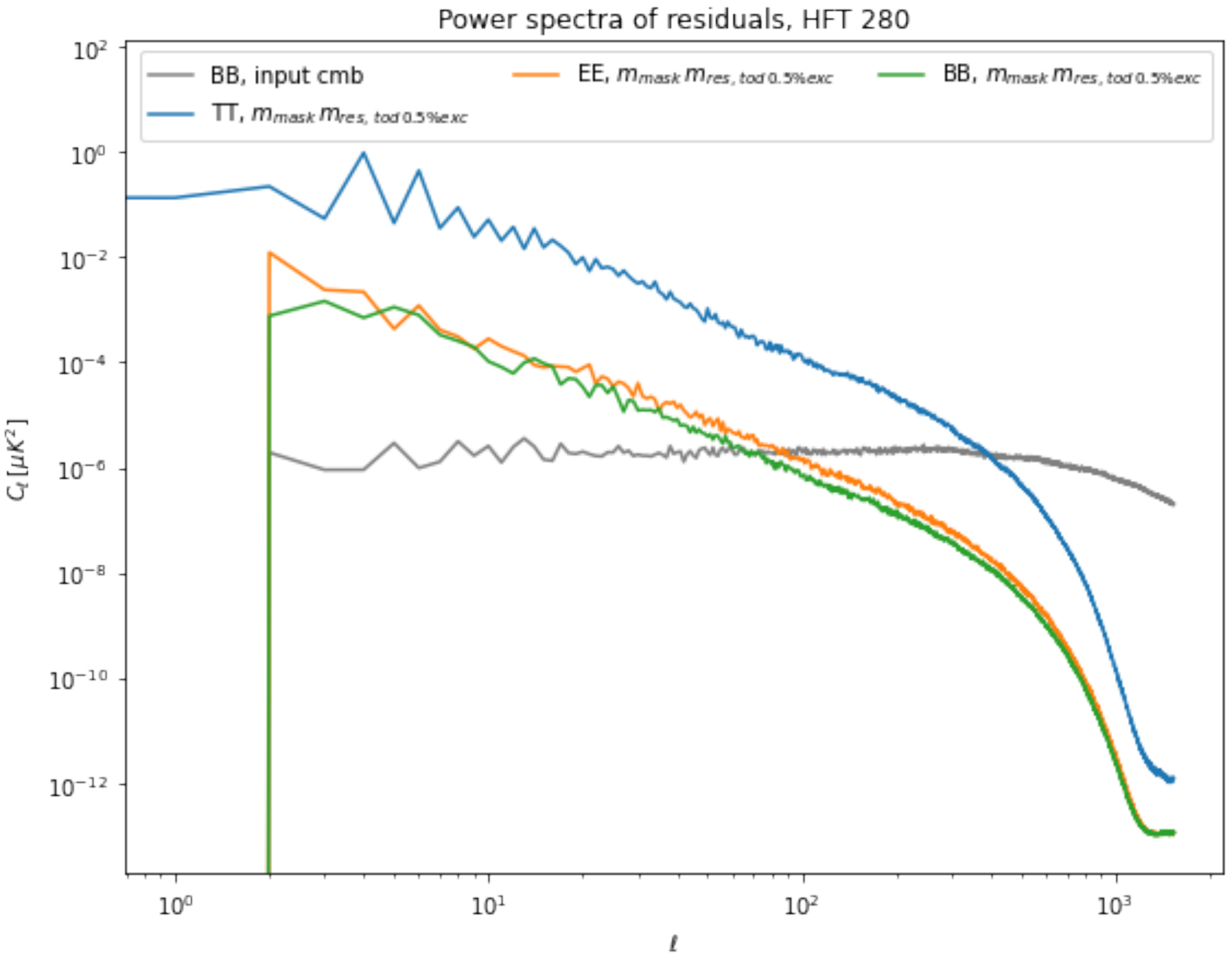


Compute residuals, add to the (instrumental) noise budget, run analysis, obtain requirements (also used in PTEP; module avail in LiteBIRD sim)

Extensions of the work - out-of-band

Non-ideal bandpass transmission coupled to HWP systematic effects. LB Project Paper: Out-of-band rejection requirements for LiteBIRD Medium and High Frequency Telescopes



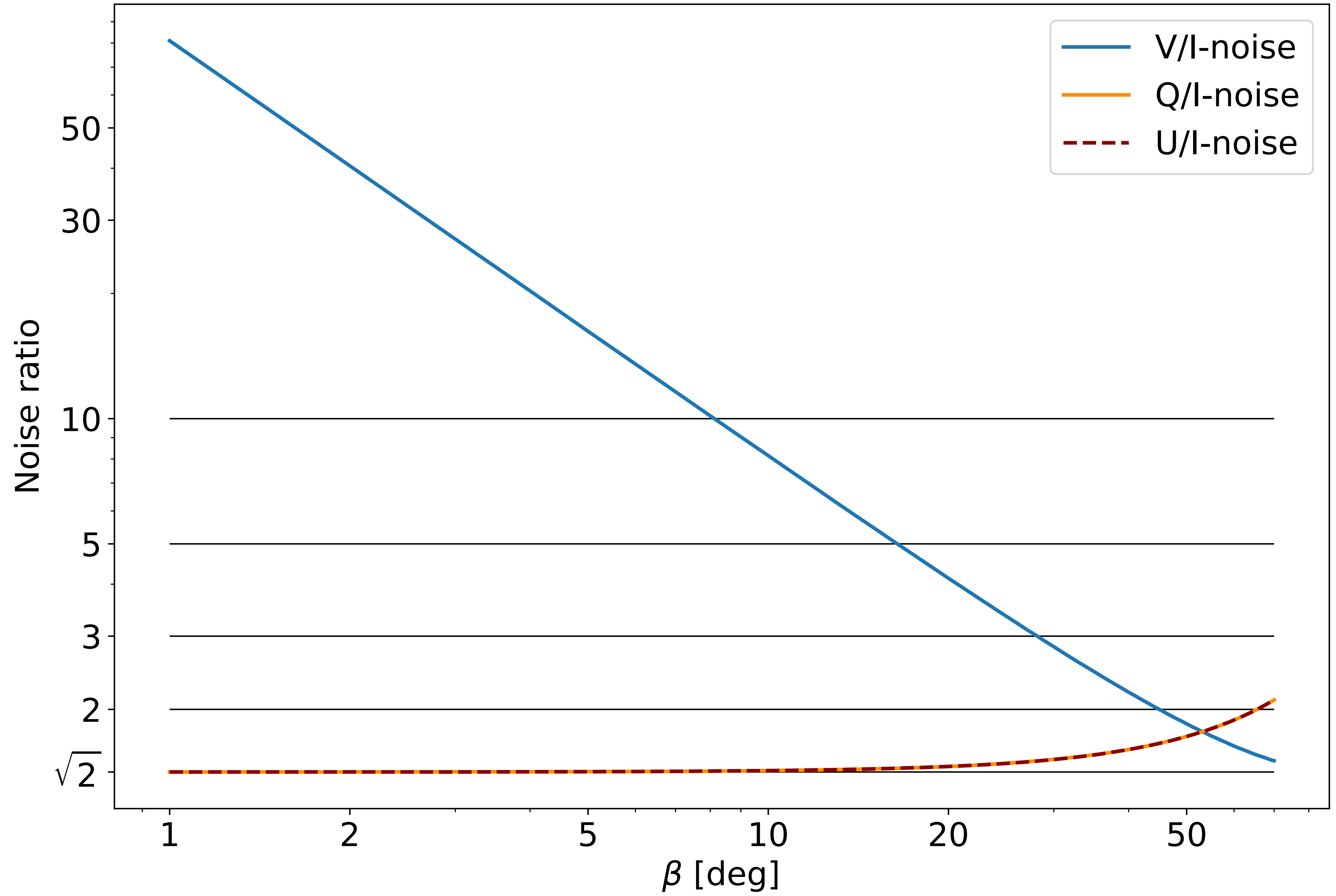


Preliminary figures, credit: S. Giardiello

Extension of the work - Bounds on V-modes

Use HWP non-idealities as a tool to constrain fundamental physics: search for V modes
Raffuzzi master thesis, Raffuzzi+, in prep. (See also works by CLASS and SPIDER collab.)

$$d_{\rm obs} = M^{TT}T + M^{TQ}Q + M^{TU}U + M^{TV}V, \quad M^{TV} = -\frac{1}{2}\sin\beta$$



Several BSM scenarios predict non-vanishing V modes (BSM EM, BSM photon scattering, ...)

Extensions of the work - Bottom-up approach

Top-down approach in Giardiello+ -> Pros: clear definition of physical effects and their individual impact on science products. Cons: hard to match with in-lab measurements of HWP performance; fail to catch some classes of physical effects (e.g., 4f I-to-P, odd harmonics contaminations)

$$J_{\mathrm{HWP}}^{\mathrm{real}} = \begin{pmatrix} 1+h_1 & \zeta_1 \\ \zeta_2 & (1+h_2)e^{i\beta} \end{pmatrix}$$

Propagate to →

$$d_X = \frac{1}{2}[M^{TT}I + M^{TQ}Q + M^{TU}U + M^{TV}V]$$

Adopt a complementary approach. Bottom-up: start from measured (combinations of) HWP (Mueller/Jones) matrix elements and inject them in the pipeline. Pros: clear connection to observations. Cons: physical origin of each term in the HWP matrix harder to infer.

$$d_{lab} = \sum_n a_n \cos(n\theta + \phi_n)$$

Propagate to →

$$d_X = \sum_n a_n \cos(n\theta + phi_n)$$

Work in progress in litebird_sim