Simulating beam related systematic effects with QuickPol

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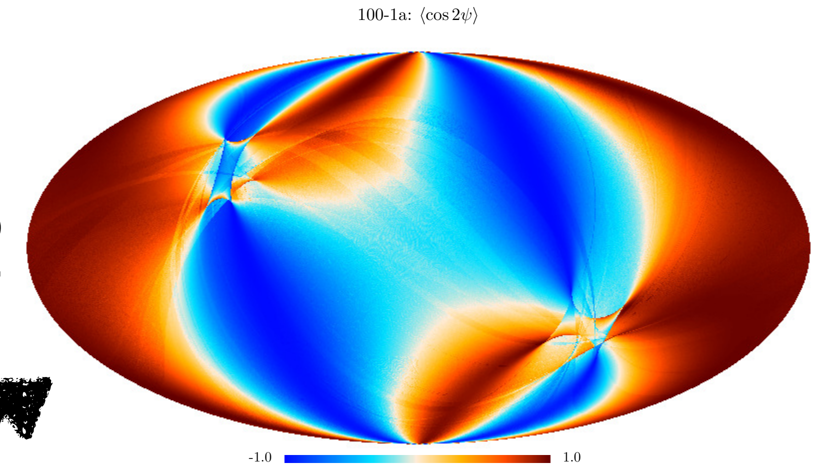
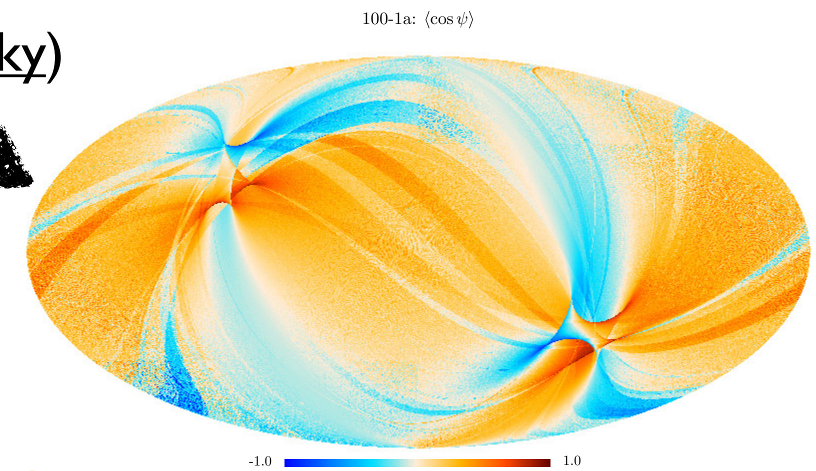
QuickPol

- **Temperature QuickBeam** (used in Planck DR1 and DR2):
  - ✦ $C'^{TT}_\ell = \Sigma_s\, \omega_s^2 \;\; b_{\ell s}^* \;\; b_{\ell s} \quad C_\ell^{TT}$
    - $b_{\ell s}$: weighted combination of scanning beams in DetSet,
    - ω_s^2: encodes scanning strategy (<u>assumed to vary slowly across the sky</u>)

$s=2$





$s=1$

- **Temperature + Polarisation QuickPol** (New in DR3!):
  - ✦ $\mathbf{C}'_\ell = \Sigma_{sij} \;\; \mathbf{\Omega}_{sij} \;\; \circledast \;\; \mathbf{B}_{\ell si}^{*t} \,.\, \mathbf{C}_\ell \,.\, \mathbf{B}_{\ell sj}$
    - **C** : 3x3 *C(l)* matrix
    - **B** : weighted scanning polarised beams in DetSet
    - **Ω** : encodes scanning strategy weighted by map-making IQU inverse covariance matrix
      can be based on a subset of pixels !
  - ✦ provides effective beam window matrix $\mathbf{W}_\ell$ describing C_ℓ coupling
  - ✦ has be extended to gain and polar efficiency uncertainty
  - ✦ Backward *C(l)* fitting can then still be used as a rain check to detect/catch remaining systematics

Map(s) Power Spectra

Sky Power Spectra

$$\begin{pmatrix} \tilde{C}_\ell^{TT} \\ \tilde{C}_\ell^{EE} \\ \tilde{C}_\ell^{BB} \\ \tilde{C}_\ell^{TE} \\ \tilde{C}_\ell^{TB} \\ \tilde{C}_\ell^{EB} \\ \tilde{C}_\ell^{ET} \\ \tilde{C}_\ell^{BT} \\ \tilde{C}_\ell^{BE} \end{pmatrix} = \mathbf{W}_\ell \cdot \begin{pmatrix} C_\ell^{TT} \\ C_\ell^{EE} \\ C_\ell^{BB} \\ C_\ell^{TE} \\ C_\ell^{TB} \\ C_\ell^{EB} \end{pmatrix}$$

For each ℓ,
$\mathbf{W}_\ell$ is a 9x6
(diagonal dominated)
matrix

Hivon, Mottet & Ponthieu, 2017

$$
W_l^{XY,TT} = \sum_s \sum_{j_1 j_2} \begin{pmatrix}
\hat{\Omega}^s_{00} \hat{b}^{(j_1)*}_{l,s} \hat{b}^{(j_2)}_{l,s} \\
\hat{b}^{(j_1)*}_{l,s+2} \left(\hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+2} + \hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-2} \right) + \hat{b}^{(j_1)*}_{l,s-2} \left(\hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+2} + \hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-2} \right) \\
\hat{b}^{(j_1)*}_{l,s+2} \left(\hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+2} - \hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-2} \right) + \hat{b}^{(j_1)*}_{l,s-2} \left(\hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-2} - \hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+2} \right) \\
-\hat{b}^{(j_1)*}_{l,s} \left(\hat{\Omega}^s_{0-2} \hat{b}^{(j_2)}_{l,s+2} + \hat{\Omega}^s_{02} \hat{b}^{(j_2)}_{l,s-2} \right) \\
-i\hat{b}^{(j_1)*}_{l,s} \left(\hat{\Omega}^s_{02} \hat{b}^{(j_2)}_{l,s-2} - \hat{\Omega}^s_{0-2} \hat{b}^{(j_2)}_{l,s+2} \right) \\
i\hat{b}^{(j_1)*}_{l,s+2} \left(\hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-2} - \hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+2} \right) + i\hat{b}^{(j_1)*}_{l,s-2} \left(\hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-2} - \hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+2} \right) \\
-\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-20} \hat{b}^{(j_1)*}_{l,s+2} + \hat{\Omega}^s_{20} \hat{b}^{(j_1)*}_{l,s-2} \right) \\
-i\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-20} \hat{b}^{(j_1)*}_{l,s+2} - \hat{\Omega}^s_{20} \hat{b}^{(j_1)*}_{l,s-2} \right) \\
i\hat{b}^{(j_1)*}_{l,s+2} \left(\hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+2} + \hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-2} \right) - i\hat{b}^{(j_1)*}_{l,s-2} \left(\hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+2} + \hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-2} \right)
\end{pmatrix}
$$

TT column of beam window matrix

EE column

ρ': polar efficiency

$$
W_l^{XY,EE} = \sum_s \sum_{j_1 j_2} \frac{\rho'_{j_1} \rho'_{j_2}}{4} \begin{pmatrix}
\hat{\Omega}^s_{00} \left(\hat{b}^{(j_1)*}_{l,s-2} + \hat{b}^{(j_1)*}_{l,s+2} \right) \left(\hat{b}^{(j_2)}_{l,s-2} + \hat{b}^{(j_2)}_{l,s+2} \right) \\
\hat{b}^{(j_1)*}_{l,s} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-2-2} + \hat{\Omega}^s_{-22} + \hat{\Omega}^s_{2-2} + \hat{\Omega}^s_{22} \right) + \hat{b}^{(j_2)}_{l,s+4} \left(\hat{\Omega}^s_{-2-2} + \hat{\Omega}^s_{2-2} \right) + \hat{b}^{(j_2)}_{l,s-4} \left(\hat{\Omega}^s_{-22} + \hat{\Omega}^s_{22} \right) \right] \\
\quad + \hat{b}^{(j_1)*}_{l,s+4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-2-2} + \hat{\Omega}^s_{-22} \right) + \hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-4} \right] \\
\quad + \hat{b}^{(j_1)*}_{l,s-4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{2-2} + \hat{\Omega}^s_{22} \right) + \hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-4} \right] \\
\hat{b}^{(j_1)*}_{l,s} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-2-2} - \hat{\Omega}^s_{-22} - \hat{\Omega}^s_{2-2} + \hat{\Omega}^s_{22} \right) + \hat{b}^{(j_2)}_{l,s+4} \left(\hat{\Omega}^s_{-2-2} - \hat{\Omega}^s_{2-2} \right) + \hat{b}^{(j_2)}_{l,s-4} \left(\hat{\Omega}^s_{22} - \hat{\Omega}^s_{-22} \right) \right] \\
\quad + \hat{b}^{(j_1)*}_{l,s+4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-2-2} - \hat{\Omega}^s_{-22} \right) + \hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+4} - \hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-4} \right] \\
\quad + \hat{b}^{(j_1)*}_{l,s-4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{22} - \hat{\Omega}^s_{2-2} \right) - \hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-4} \right] \\
-\left(\hat{b}^{(j_1)*}_{l,s-2} + \hat{b}^{(j_1)*}_{l,s+2} \right) \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{0-2} + \hat{\Omega}^s_{02} \right) + \hat{\Omega}^s_{0-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{02} \hat{b}^{(j_2)}_{l,s-4} \right] \\
-i \left(\hat{b}^{(j_1)*}_{l,s-2} + \hat{b}^{(j_1)*}_{l,s+2} \right) \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{02} - \hat{\Omega}^s_{0-2} \right) - \hat{\Omega}^s_{0-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{02} \hat{b}^{(j_2)}_{l,s-4} \right] \\
i\hat{b}^{(j_1)*}_{l,s} \left[\hat{b}^{(j_2)}_{l,s} \left(-\hat{\Omega}^s_{-2-2} + \hat{\Omega}^s_{-22} - \hat{\Omega}^s_{2-2} + \hat{\Omega}^s_{22} \right) - \hat{b}^{(j_2)}_{l,s+4} \left(\hat{\Omega}^s_{-2-2} + \hat{\Omega}^s_{2-2} \right) + \hat{b}^{(j_2)}_{l,s-4} \left(\hat{\Omega}^s_{-22} + \hat{\Omega}^s_{22} \right) \right] \\
\quad + i\hat{b}^{(j_1)*}_{l,s+4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-22} - \hat{\Omega}^s_{-2-2} \right) - \hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-4} \right] \\
\quad + i\hat{b}^{(j_1)*}_{l,s-4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{22} - \hat{\Omega}^s_{2-2} \right) - \hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-4} \right] \\
-\left(\hat{b}^{(j_2)}_{l,s-2} + \hat{b}^{(j_2)}_{l,s+2} \right) \left[\left(\hat{\Omega}^s_{-20} + \hat{\Omega}^s_{20} \right) \hat{b}^{(j_1)*}_{l,s} + \hat{\Omega}^s_{-20} \hat{b}^{(j_1)*}_{l,s+4} + \hat{\Omega}^s_{20} \hat{b}^{(j_1)*}_{l,s-4} \right] \\
i \left(\hat{b}^{(j_2)}_{l,s-2} + \hat{b}^{(j_2)}_{l,s+2} \right) \left[\left(\hat{\Omega}^s_{20} - \hat{\Omega}^s_{-20} \right) \hat{b}^{(j_1)*}_{l,s} - \hat{\Omega}^s_{-20} \hat{b}^{(j_1)*}_{l,s+4} + \hat{\Omega}^s_{20} \hat{b}^{(j_1)*}_{l,s-4} \right] \\
i\hat{b}^{(j_1)*}_{l,s} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-2-2} + \hat{\Omega}^s_{-22} - \hat{\Omega}^s_{2-2} - \hat{\Omega}^s_{22} \right) + \hat{b}^{(j_2)}_{l,s+4} \left(\hat{\Omega}^s_{-2-2} - \hat{\Omega}^s_{2-2} \right) + \hat{b}^{(j_2)}_{l,s-4} \left(\hat{\Omega}^s_{-22} - \hat{\Omega}^s_{22} \right) \right] \\
\quad + i\hat{b}^{(j_1)*}_{l,s+4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-2-2} + \hat{\Omega}^s_{-22} \right) + \hat{\Omega}^s_{-2-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{-22} \hat{b}^{(j_2)}_{l,s-4} \right] \\
\quad - i\hat{b}^{(j_1)*}_{l,s-4} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{2-2} + \hat{\Omega}^s_{22} \right) + \hat{\Omega}^s_{2-2} \hat{b}^{(j_2)}_{l,s+4} + \hat{\Omega}^s_{22} \hat{b}^{(j_2)}_{l,s-4} \right]
\end{pmatrix}
$$

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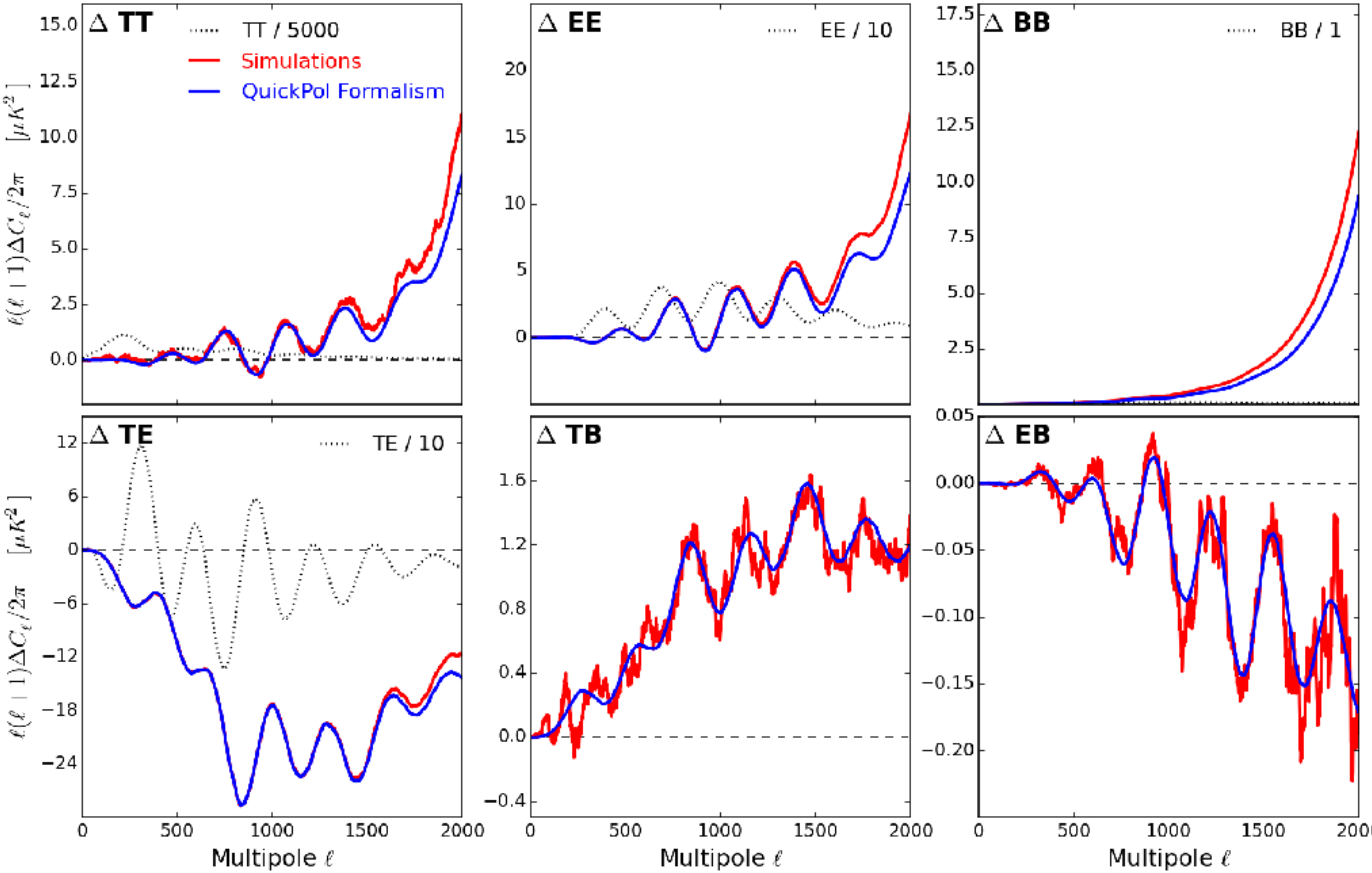

Simulation for CORE/M5 proposal: single detector
Natoli et al, 2018

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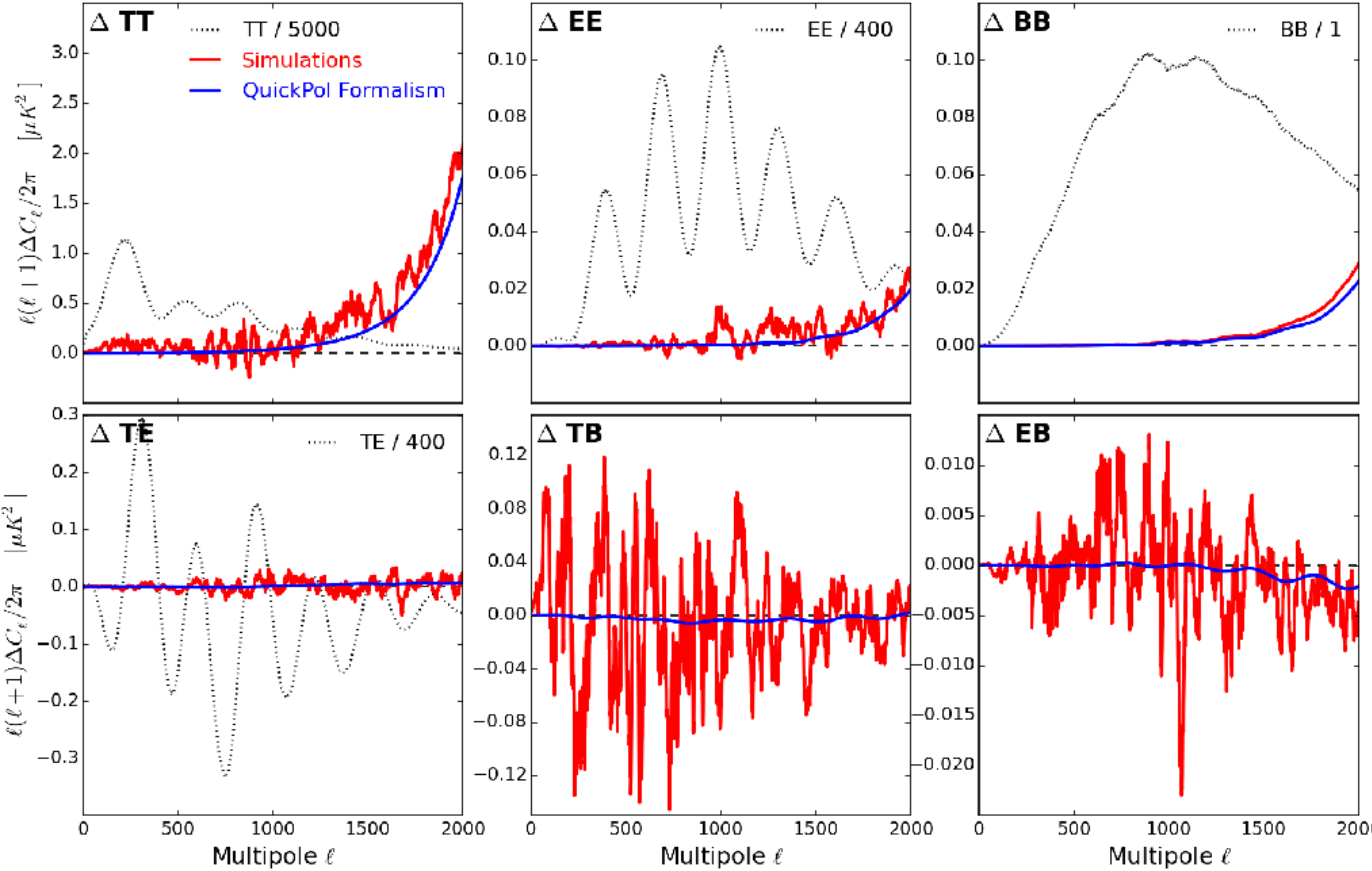
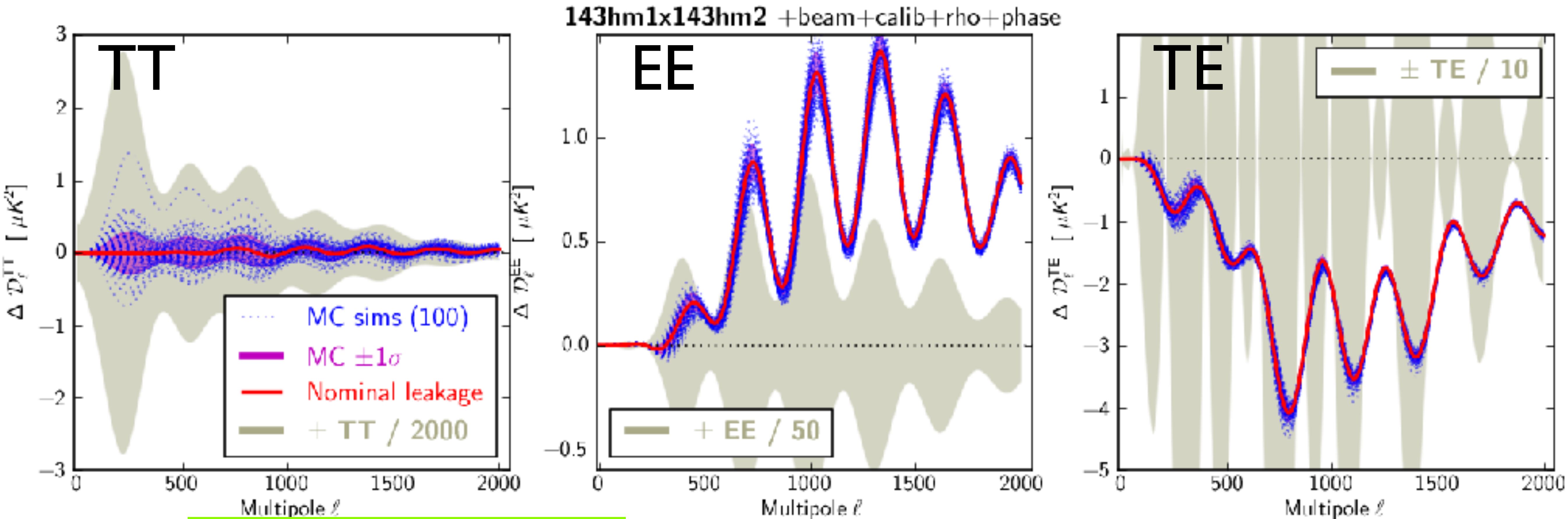


Simulation for CORE/M5 proposal: detectors pair
Natoli et al, 2018

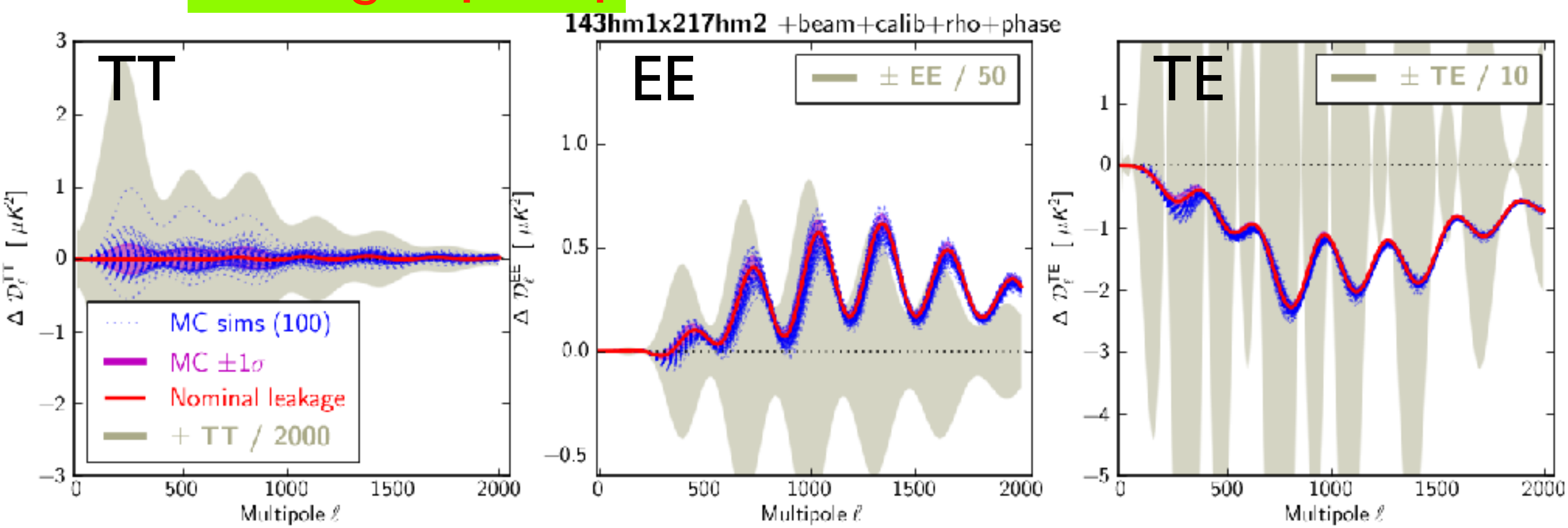
Error propagation in Planck-HFI

- MonteCarlo simulations of QuickPol are run quickly with the following uncertainties on each detector
  - **beam measurements:**
    - ★ detector scanning $b_{\ell m}$ from MC observation of planets,
  - **gain calibration (g):**
    - ★ Gaussian distributed (GD) around nominal value (1.0),
    - ★ $\delta g = 0.1\%$ @ 100-217GHz,
  - **polar efficiency (ρ), $0 < \rho_{SWB} < \rho_{PSB} < 1$**
    - ★ GD around IMO value,
    - ★ $\delta\rho$ = a few 0.1% (read from Rosset+2010),
  - **polarisation orientation (ψ):**
    - ★ GD around IMO value,
    - ★ $\delta\psi$ = 1deg for PSB, 5deg for SWB (adapted from Rosset+2010).



$b_{\ell m}+\delta g+\delta\rho+\delta\psi$

2 CPU.min per realisation!



Conclusion

- Facility to quickly simulate systematics effects induced by
  - beam elongation and mismatch +
  - calibration (g), polarisation angles (ψ), polarisation efficiency (ρ)
- No need for full TOD simulations
- Need:
  - ⋆ detailed pointing information (hits + orientation in a sub-set of pixels) of un-flagged samples,
  - ⋆ beam map or $b_{\ell m} + \delta b_{\ell m}$,
  - ⋆ $g + \delta g$,
  - ⋆ $\psi + \delta\psi$,
  - ⋆ $\rho + \delta\rho$