Planck-HFI polarised beam window functions

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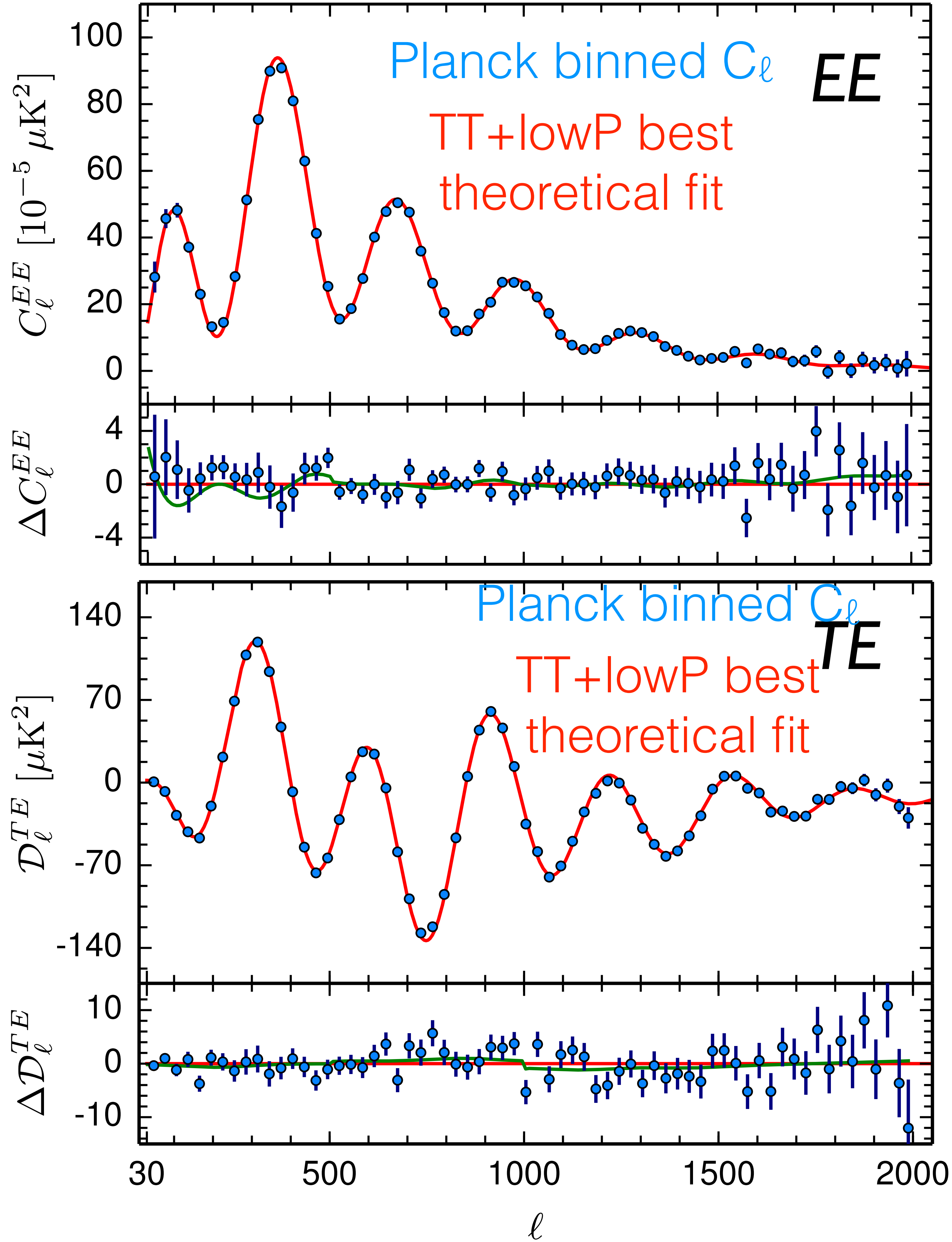
Polarised beam window functions

- **Why?**
- Possible Approches
- Validation on simulations
- Application to analysis of Planck observations (preliminary)
- Conclusions

A few μK^2 residuals seen in Planck EE and TE $\ell^2 C_\ell$ spectra !

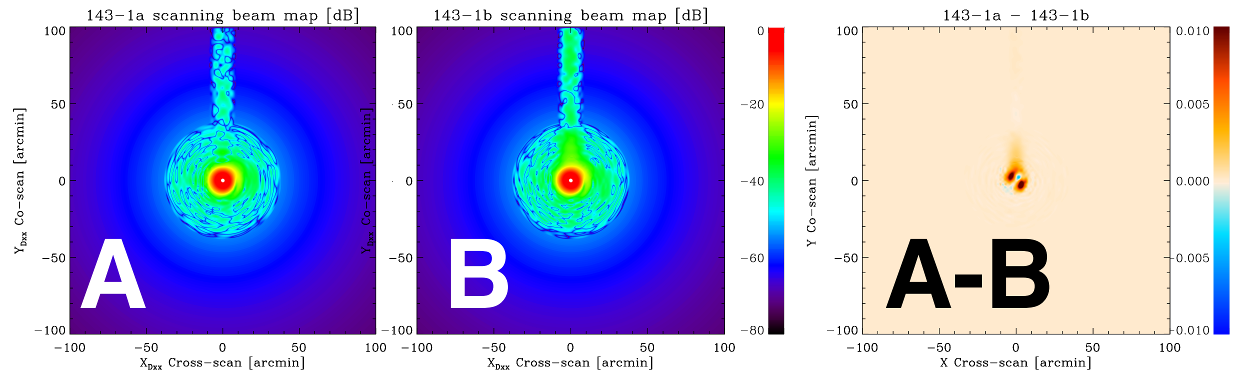
Could this be related to beams?

Planck 2015 Cosmological Parameters paper



Beam related power leakage

- Since polarisation measurement is differential, and no polarisation modulation (like HWP) in Planck beyond scanning
  - mismatches between *a* and *b* effective beams, (**<u>different in each sky pixel!</u>**) due to differences in



    - scanning beams
      = optics + TF - deconvolution,
      (see B. Crill presentation)
    - noise level
      (if individual 1/Noise weighting in map making:
      $0 < \Delta\sigma^{-2}/\sigma^{-2} < 80\%$), and
    - number of valid samples or valid rings
      ($0 < \Delta n/n < 20\%$),
  - coupling with scanning strategy <u>and</u> NGP map making
  - cause (small scale) Temperature-Polarisation cross talk
- intensely studied (mostly for requirements of B mode measurements)

Challinor++ (2000), Souradeep & Ratra (2001), Fosalba++ (2002),
Hu++ (2003), Mitra++ (2004), O'Dea++ (2007), Smith++ (2007), Shimon++ (2008), Miller++ (2009), Mitra++ (2009),
Hanson++(2010), Rosset++ (2010), Ramamonjisoa++ (2013)

Plan

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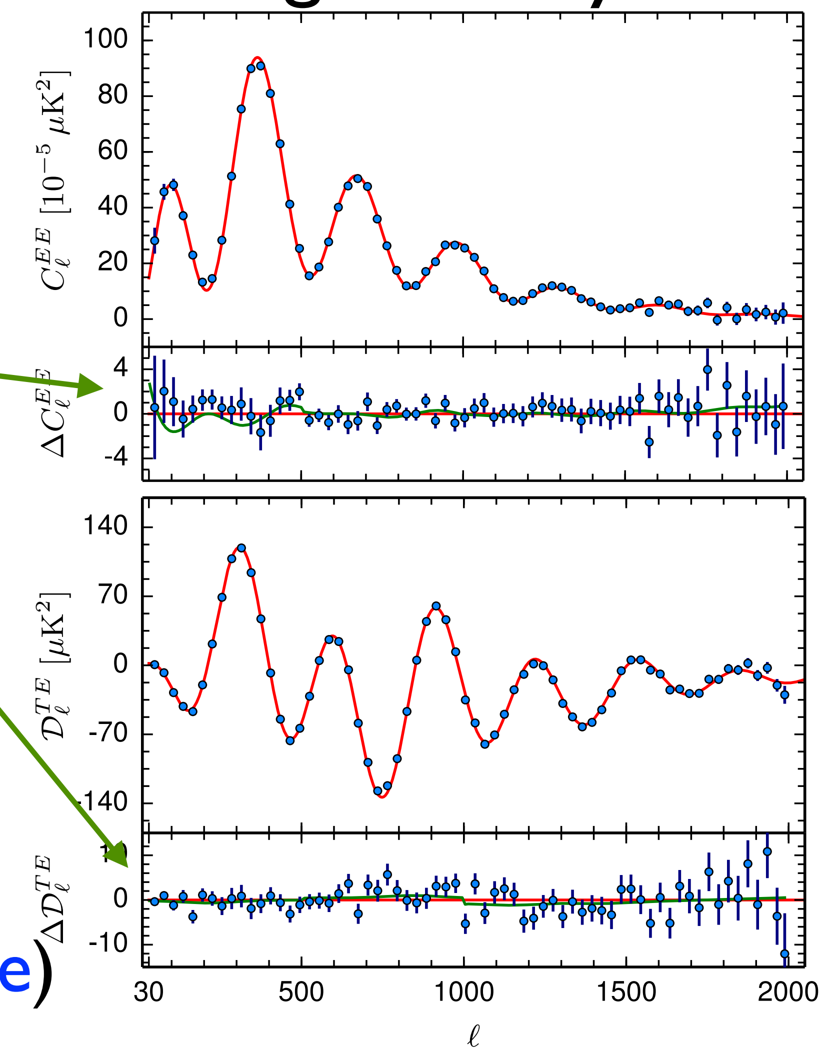
Different approaches to effect of beam mismatch on polarisation

- **Numerical approaches**
  - Map deconvolution: PreBeam (Armitage++ 2009), ArtDeco (Keihanen & Reinecke 2012),…
    - IN: Observed polarised maps
    - OUT: leakage free polarised maps
    - **ArtDeco used by LFI in 2015 analysis**
  - MC based description: FEBeCoP (Mitra++ 2011, extended to polarisation)
    - IN: MC simulated observations of fiducial sky with real beam and scanning
    - OUT: Effective TT, EE, (TE) beam window functions
    - **used in 2015 CMB-only map analysis**
- **Analytical approaches**
  - 1) Backward:
    - IN: rough modelling of leakage
    - OUT: templates (with priors) of leakage to be fitted in final EE and TE $C(\ell)$
    - **used in 2015 Likelihood**
  - 2) Forward: QuickPol
    - IN: precise calculation of leakage with real beam ($b_{\ell m}$) and scanning
    - OUT: full beam matrix coupling TT, EE, TE, BB, TB, EB, …
    - **this talk; will be used in 2016 Likelihood**

1) Beam leakage in Plik analysis of 2014/2015 maps (DR2)

- backward approach: look in polarised "final" *C(l)* for contamination templates and remove/marginalise them before cosmological analysis



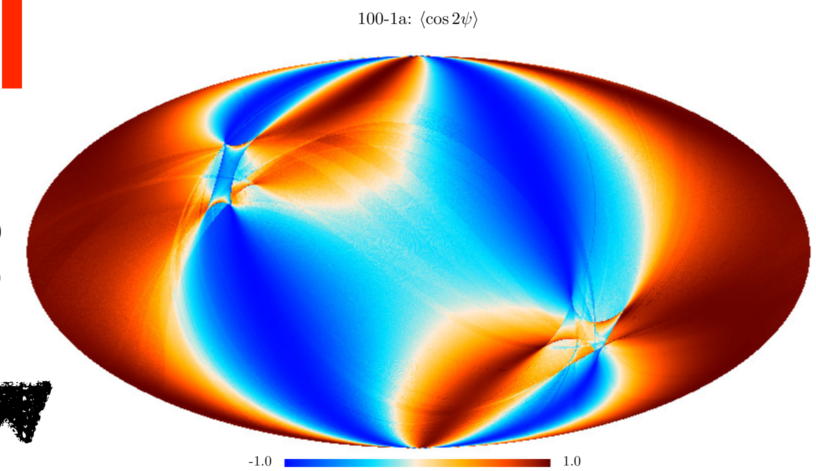
  - leakage model: $E_{\ell m} \longmapsto E_{\ell m} + \varepsilon(\ell)\, T_{\ell m}$
    - ★ $\Delta C_\ell^{TE} = \varepsilon(\ell)\ C_\ell^{TT}$
    - ★ $\Delta C_\ell^{EE} = \varepsilon(\ell)^2\, C_\ell^{TT} + 2\ \varepsilon(\ell)\, C_\ell^{TE}$
  - Templates used: $\varepsilon(\ell) = \varepsilon_0 + \varepsilon_2\, \ell^2 + \varepsilon_4\, \ell^4$
    - because of
      - ★ $b_{\ell m}\ \alpha\ \ (\theta_{FWHM}\, \ell)^m\ \ b_{\ell 0}$
        (the wider the beam, the worst the leakage)
      - ★ scanning strategy (reduces odd degree terms)
    - Gaussian priors of ε_m : mean = 0,
      $\sigma_0 = 1\text{x}10^{-5}$, $\sigma_2 = 1.25\text{x}10^{-8}$, $\sigma_4 = 2.7\text{x}10^{-15}$

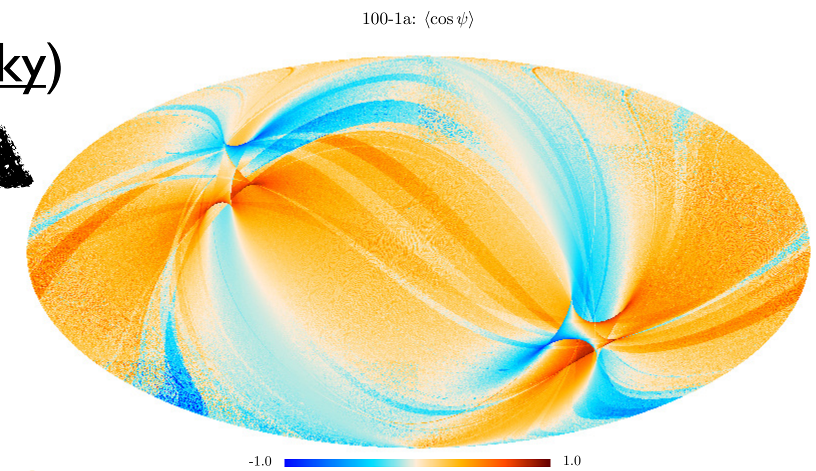
- See Likelihood2015 paper

2) QuickPol

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

$s=2$





$s=1$

- **Temperature + Polarisation QuickPol** (New!):
  - ✦ $\mathbf{C}'_{\ell} = \Sigma_{sij} \;\; \mathbf{\Omega}_{sij} \circledast \mathbf{B}^{*t}_{\ell si} \,.\, \mathbf{C}_{\ell} \,.\, \mathbf{B}_{\ell sj}$
    - **C** : 3x3 *C(l)* matrix
    - **B** : weighted scanning polarised beams in DetSet
    - **Ω** : encodes scanning strategy weighted by map-making IQU inverse covariance matrix
  - ✦ 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

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

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

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

TT column

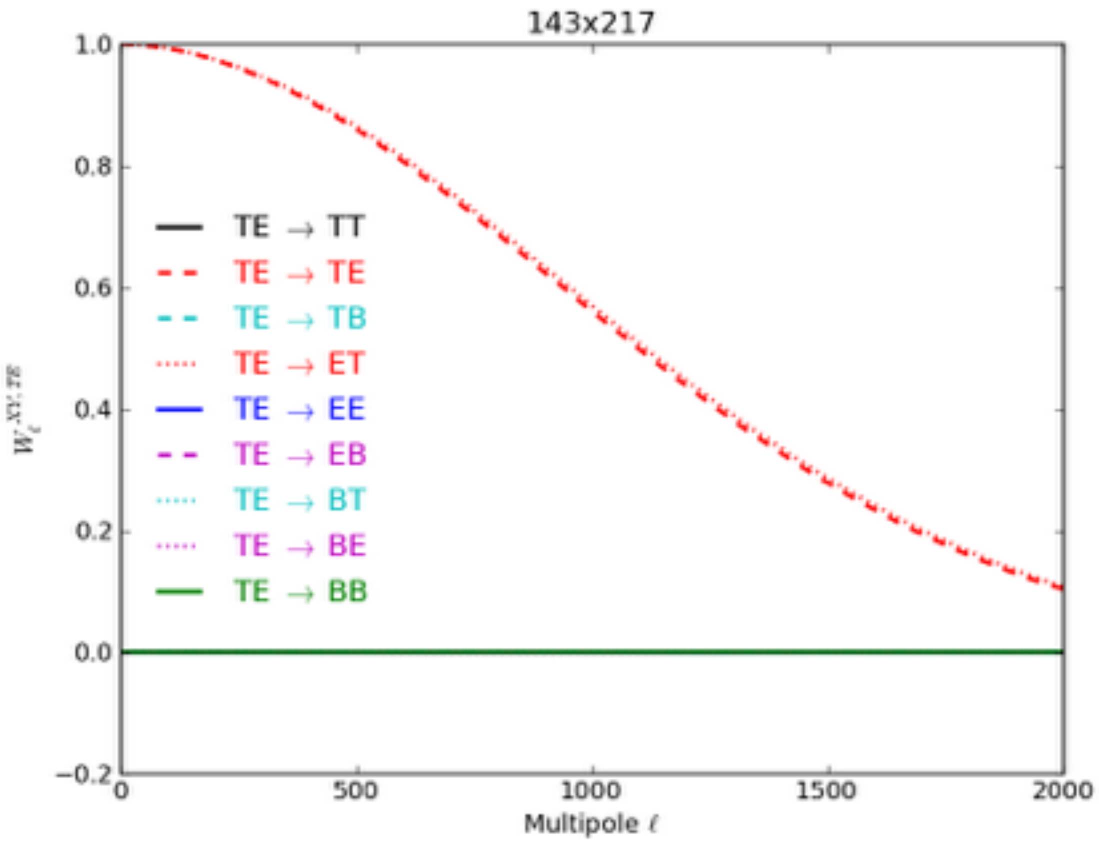
EE column

ρ': polar efficiency

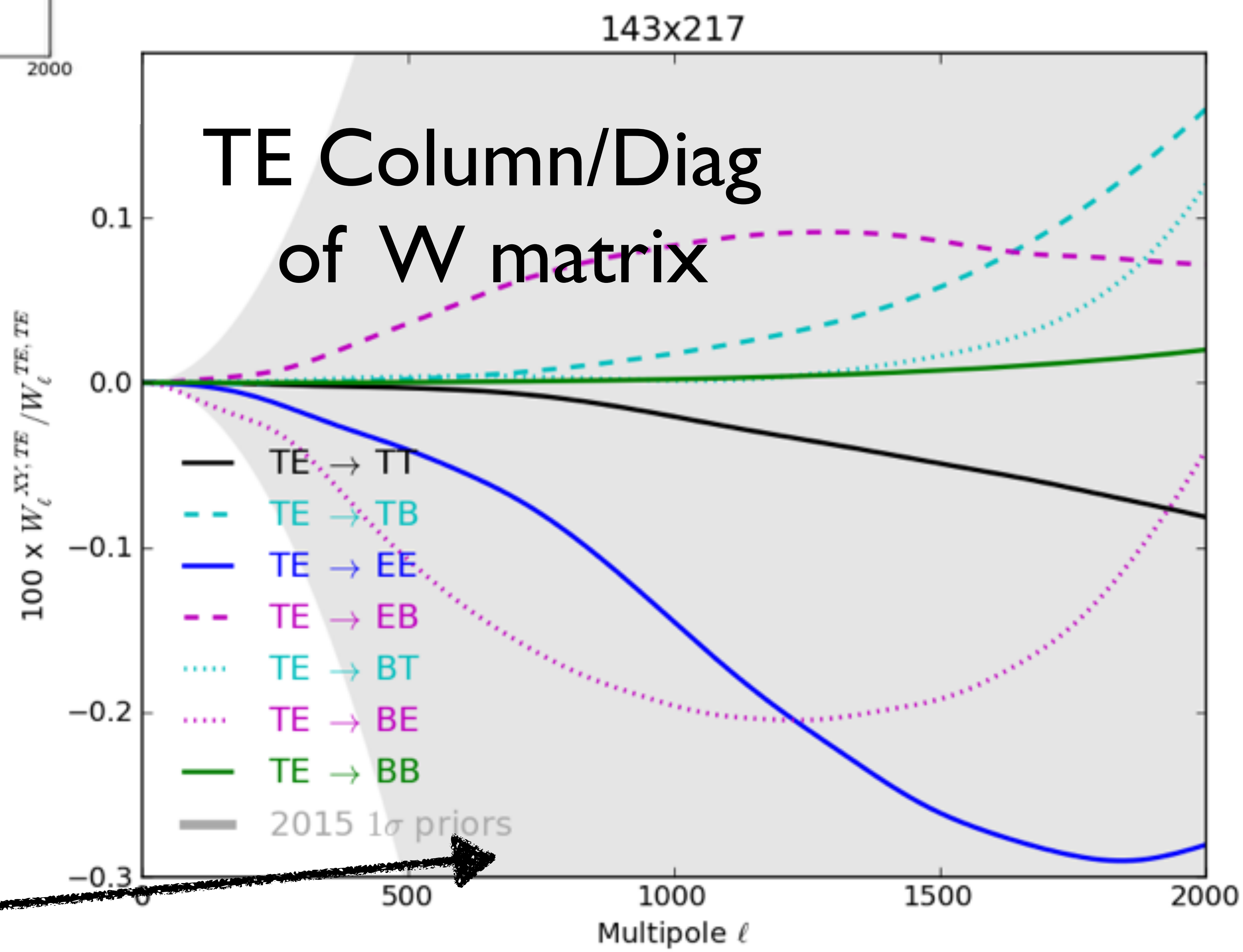
$$W_l^{XY,EE} = \sum_s \sum_{j_1 j_2} \frac{\rho'_{j_1} \rho'_{j_2}}{4} \begin{pmatrix} \hat{\Omega}^s_{00} \left(\hat{b}^{(j_1)*}_{l,s-2} + \hat{b}^{(j_1)*}_{l,s+2} \right) \left(\hat{b}^{(j_2)}_{l,s-2} + \hat{b}^{(j_2)}_{l,s+2} \right) \\ \hat{b}^{(j_1)*}_{l,s} \left[\hat{b}^{(j_2)}_{l,s} \left(\hat{\Omega}^s_{-2-2} + \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} \tag{95}$$

143x217

TE column
of W matrix



TE Column/Diag
of W matrix



The 2015 prior was
wide enough !

Plan

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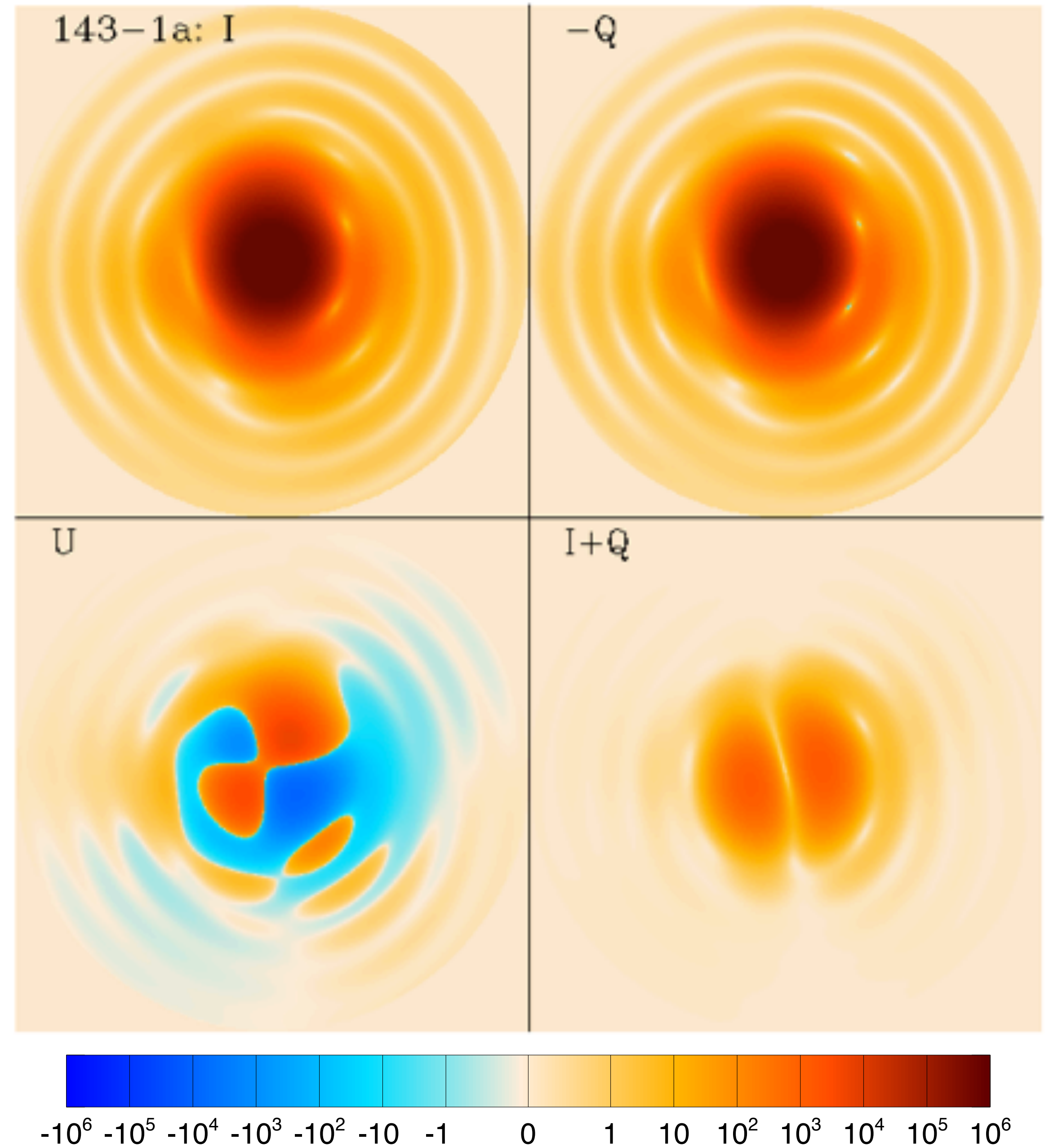
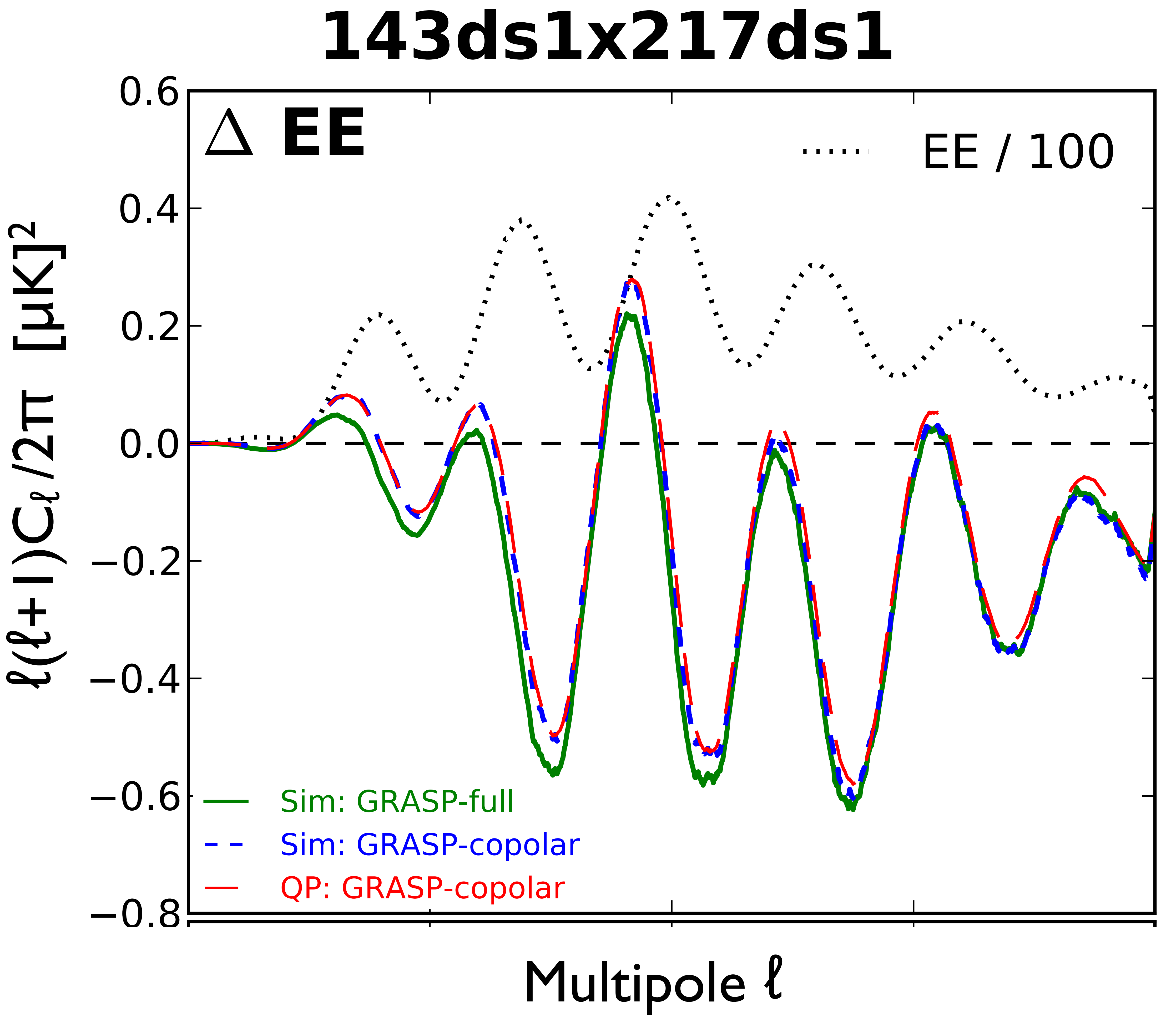
Comparison to simulations

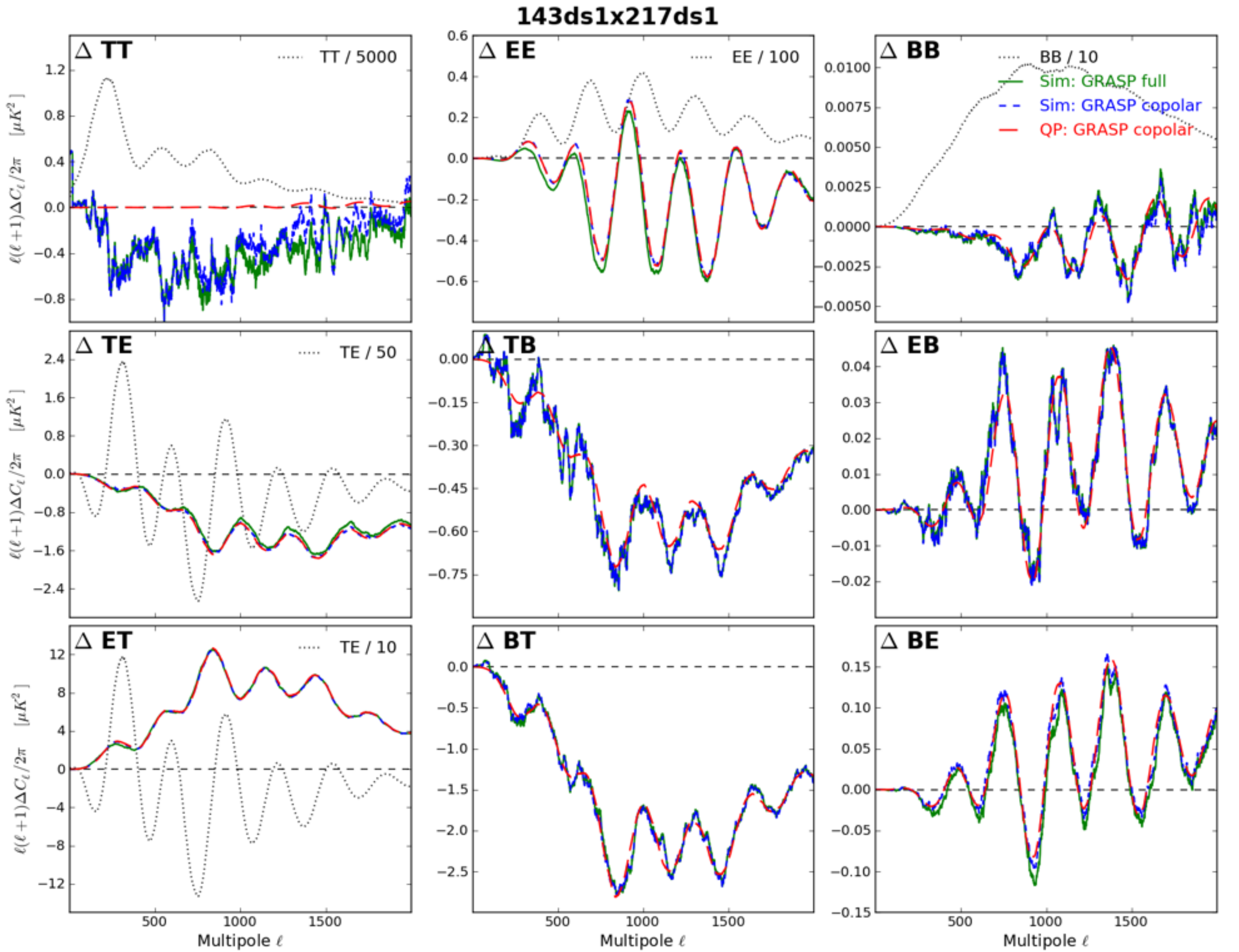
- Simulations using (some of) newly available HFI **End-to-End** simulation facility
  - ✦ CMB only
  - ✦ 100ds1, 143ds1, 217ds1
  - ✦ with GRASP 2007 beam maps:
    - *either* full IQU maps,
    - *or* I maps only, assumed perfectly co-polar (as for actual beams)



  - ✦ imperfect bolometer polar efficiencies (Rosset et al 2010, IMO based)
  - ✦ same flags and bad rings as DR2
  - ✦ TODs generated with LS convicQT + multimod
  - ✦ maps produced with TOI2HPR+Polkapix_projector (assuming perfect calibration)



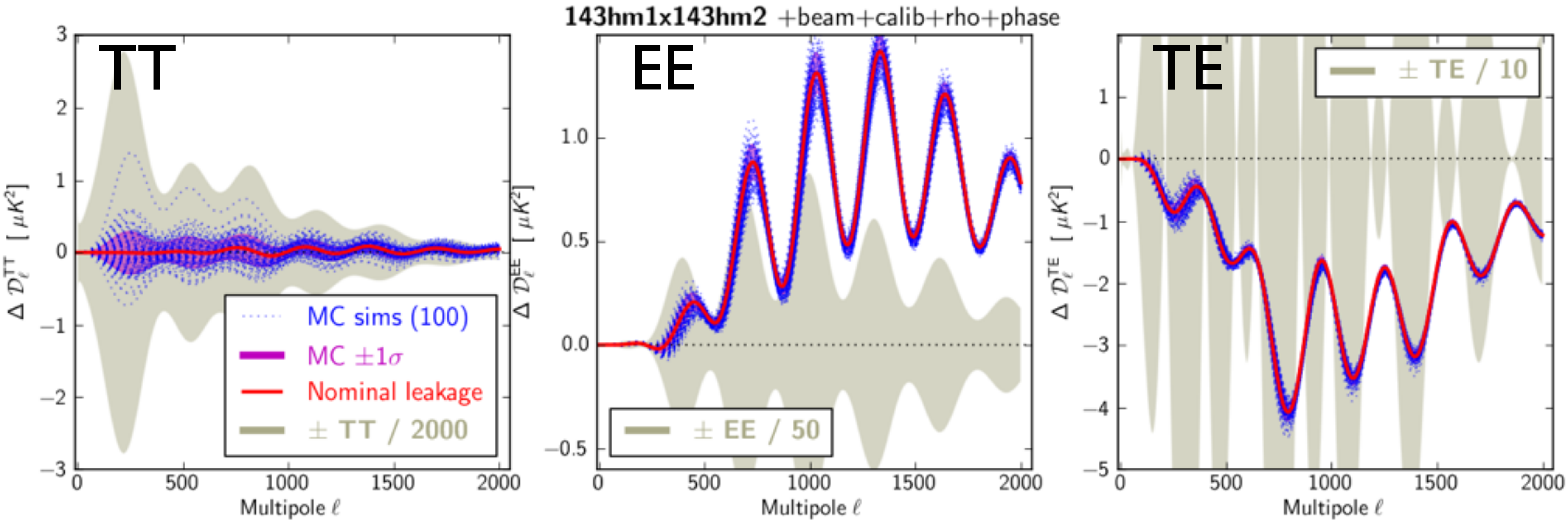
143ds1x217ds1
Δ EE
EE / 100
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
ℓ(ℓ+1)Cℓ/2π [μK]²
Sim: GRASP-full
Sim: GRASP-copolar
QP: GRASP-copolar
Multipole ℓ



143ds1x217ds1
Δ TT
TT / 5000
Δ EE
EE / 100
Δ BB
BB / 10
Sim: GRASP full
Sim: GRASP copolar
QP: GRASP copolar
Δ TE
TE / 50
Δ TB
Δ EB
Δ ET
TE / 10
Δ BT
Δ BE
$\ell(\ell+1)\Delta C_\ell/2\pi \quad [\mu K^2]$
Multipole ℓ

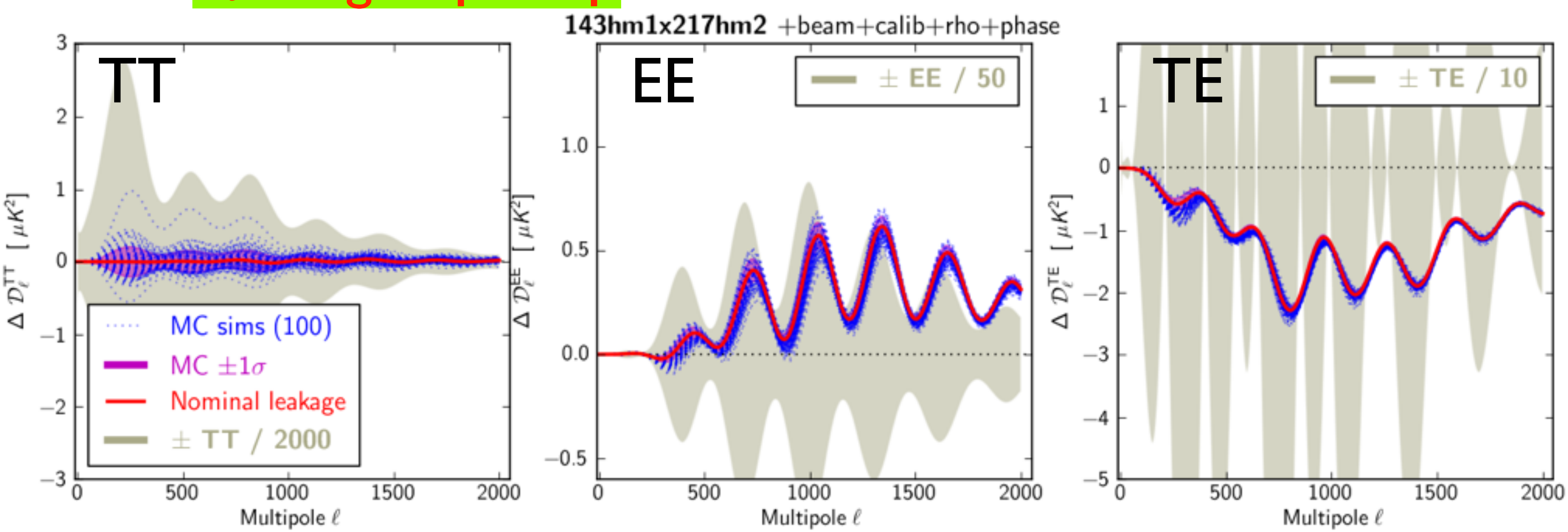
Error propagation

- 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!



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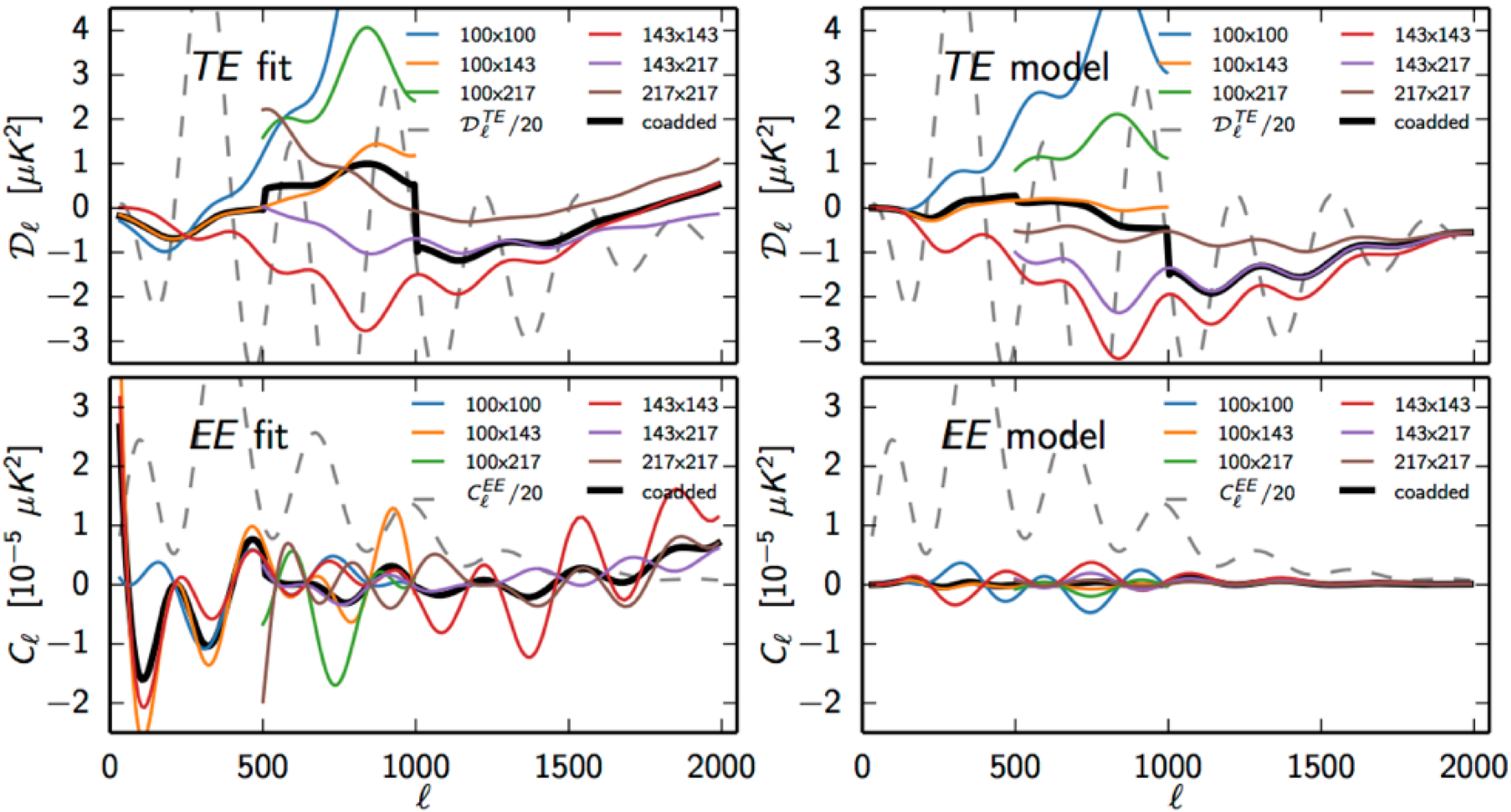
a posteriori fit
(2015 likelihood paper)

QuickPol
a priori model

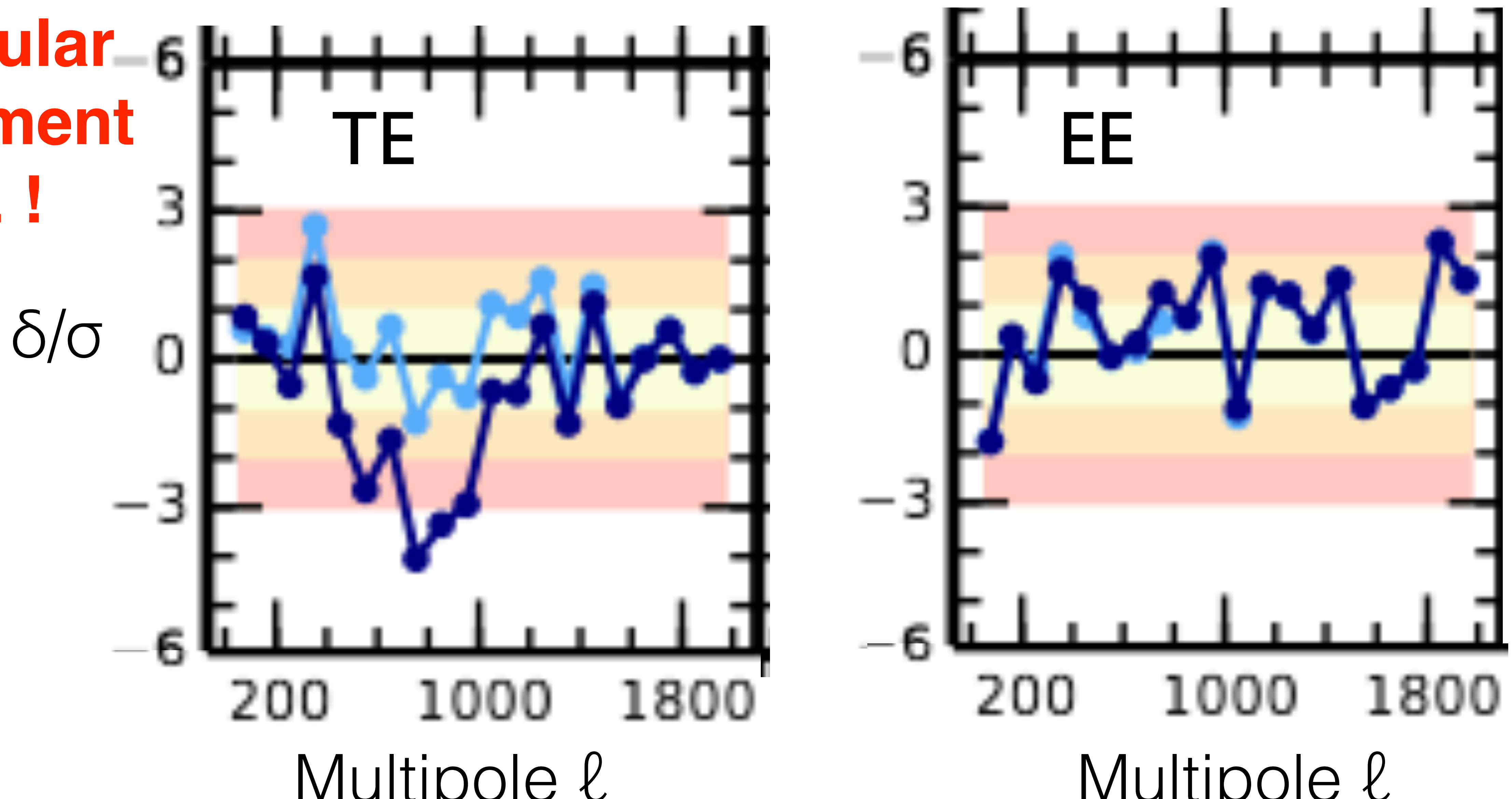


Inter-frequency consistency:
fg corrected C(l)
143x143 - 100x100

Preliminary!

Ignoring beam leakage (2015 analysis)
With beam leakage prediction+correction (2016 analysis)

Spectacular improvement for TE !



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Conclusions

- Make identical circular small beams,
  and modulate polarisation by other means than scanning only !
- Otherwise:
  - T→P leakage and P↔P cross-talk due to beam mismatch (and polar efficiency and inter calibration inaccuracy)
    can *not* be ignored (in Planck)
  - Analytical tool to model it fully now available,
    - validated with simulations,
    - allowing extensive error propagation (no need for full focal plane simulations),
    - which seems to greatly improve TE inter-frequency consistency in Planck-HFI data (preliminary).
  - Applicable to other problems ?
    - HPW specific systematic problems
    - data mosaicking (heterogeneous data processing)