Mitigation of systematics for CORE

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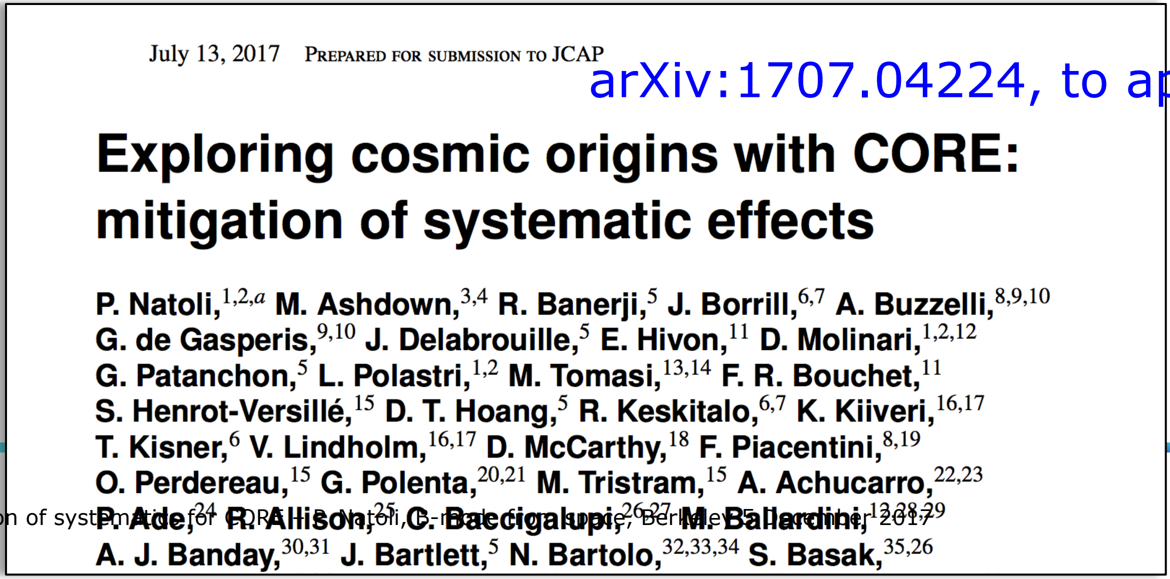
on behalf of the CORE WG on systematics mitigation, with straightforward contributions from M. Ashdown, R. Banerji, A. Buzzelli, J. Borrill, G. de Gasperis, J. Delabrouille, E. Hivon, D.T. Hoang, D. McCarthy, R. Keskitalo, K. Kiiveri, T. Kisner, V. Lindholm, D. Molinari, G. Patanchon, F. Piacentini, L. Polastri, M. Tomasi – Paper review effort by S. Henrot-Versillè, M. Tristram, O. Perderau and G. Polenta

B-Mode from Space Workshop, Berkeley, 4-6 Dec. 2017

(Talk material largely based on arXiv:1707.04224)

The CORE experience

1. The CORE experience has produced 10 ECO (= Exploring Cosmic Origins) papers, to support its bet to the M5 call (was not selected)
    a. Topics: Survey requirements, Cosmological parameters, Lensing, B mode component separation, Extragalactic sources, Inflation, Instrument, Peculiar motion, Cluster science and Systematics
2. The systematics paper ("Mitigation of systematic effects") deals more closely with Data Analysis, focusing on validating/optimizing mission design.



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Exploring cosmic origins with CORE: mitigation of systematic effects

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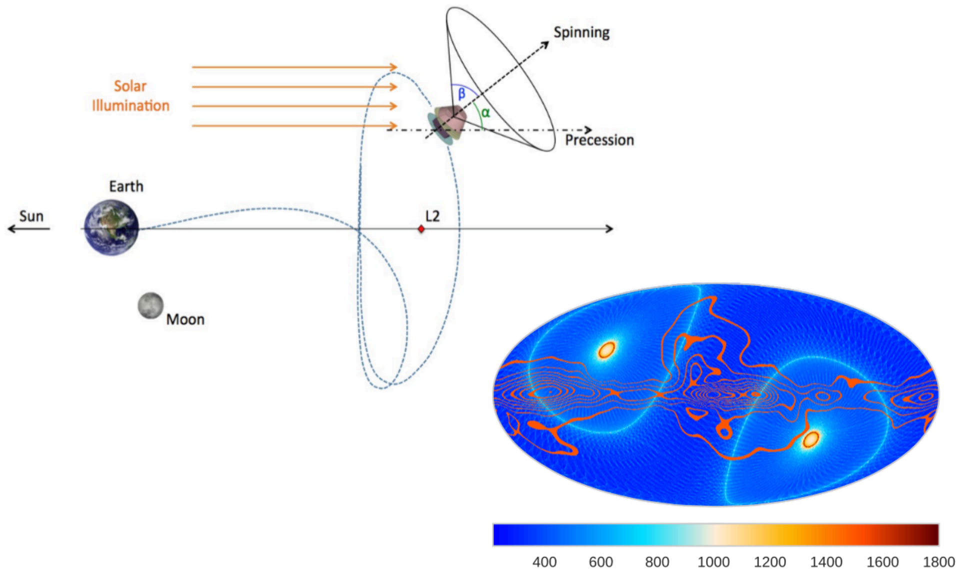
arXiv:1707.04224, to appear in JCAP

The CORE experience

1. Work was carried out within a group comprising several collaborators (plus internal reviewers) from France, Italy, UK, US, Finland, …, lead by PN and M. Ashdown (Cambridge)
2. Basic idea: support the CORE proposal, showing that
    a. The CORE scanning strategy is robust enough to cleanly resolve polarization, produce high quality Stokes maps and leave adequate margin/redundancy to implement correction for non idealities.
    b. We are able to assess the impact of the most relevant systematics expected to affect the data
    c. When appropriate, we can rely on effective and affordable mitigation techniques
3. Choice: consider each effect in isolation
    a. Advantages: analyze simulations in a "controlled" environment, disentangle "single source" contribution
    b. Disadvantage: miss potential interactions between different effects (no "end-to-end" simulations)
4. Choice: cannot afford to consider full focal plane simulations (off-scale exercise). But not necessary for the exercise. Considerer "representative" sub-unit, e.g. 2 or 4 detector system, vary position in the focal plane.

Infrastructure

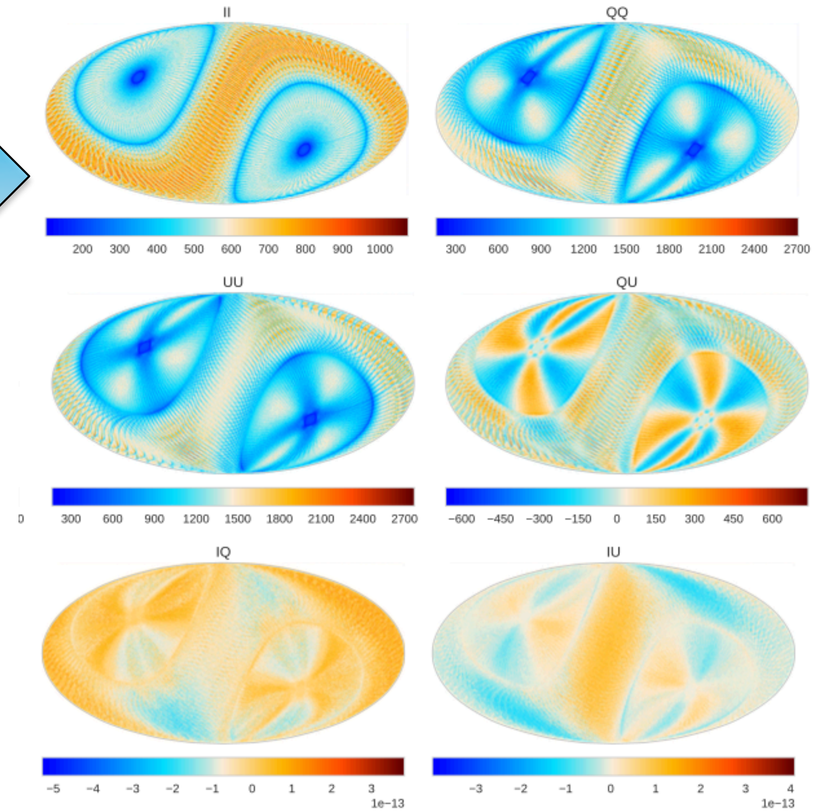


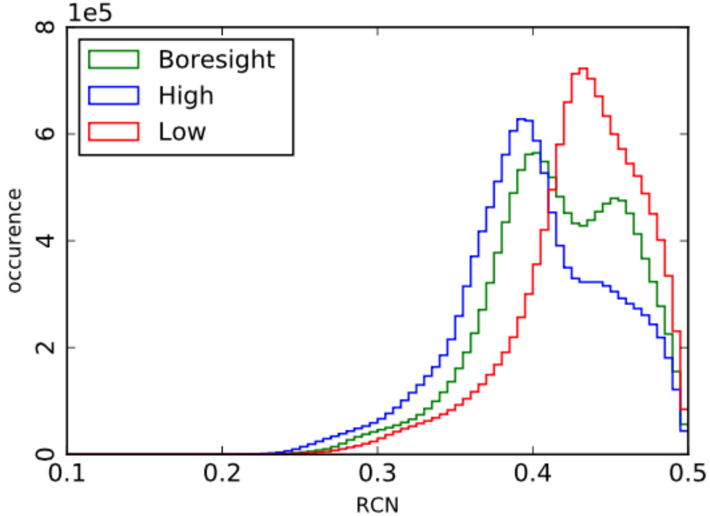
Parameter		Value
Precession angle [°]		30
Spin angle [°]		65
Precession period [days]		4
Spin period [s]		120
Hours of observation per day [h]		24
Length of a single chunk of data [h]		24
Observation duration [days]		366
Number of detectors		2
Frequency [GHz]		145
FWHM [arcmin]		7.68
Sampling rate [Hz]		84.97
Polarization orientation detector 1 [°]		-22.5
Polarization orientation detector 2 [°]		67.5
Knee frequency f_k [mHz]		0, 10, 20, 50
Noise slope α		1.0
NET [$\mu K\sqrt{s}$]		52.3
Deviation from boresight [°]	‘high’	+4.7
	‘low’	-4.7
N_{side}		1024
Offset length (with noise prior) [s]		1.0

1. Simulations based on the public TOAST package (T. Kisner, J. Borrill et al.,http://github.com/hpc4cmb/toast)
2. Makes use of fast, high performance tools:
    a. libconviqt for fast sky convolutions, libmadam for “optimal” and flexible map-making
3. Several ad-hoc tools, developed or recycled/readapted:
    a. Cross-correlation map-making
    b. Real and harmonic space deconvolution tools
    c. Band-pass mitigation machinery
    d. Ad-hoc calibration scheme

Noise performance

IQU covariance matrix elements show that CORE can resolve polarization for a minimal two-detector system just relying on the scanning strategy. Single detector maps are possible but challenging. This can be directly compared to different approaches, e.g. based on rotating HWP. Note weakness of TP couplings

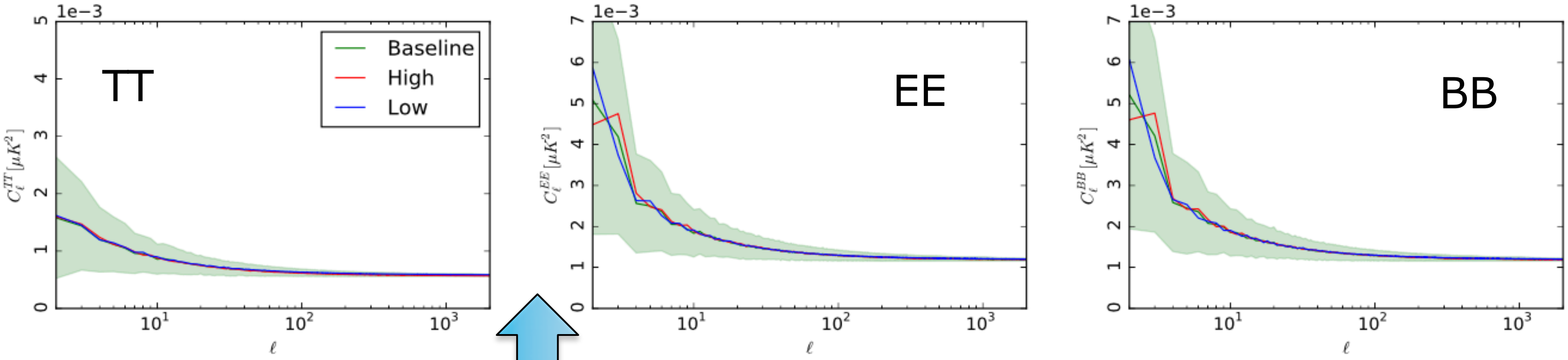




Distribution of RCN of IQU matrices across the map, for three positions in the focal plane (0.5 is ideal, 0 is singular).

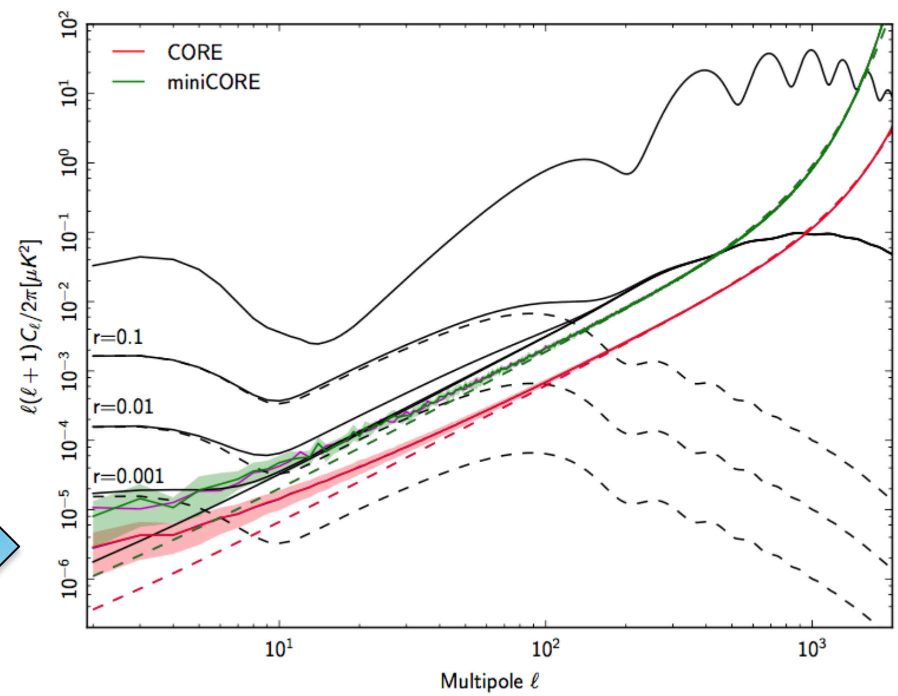
D. Molinari, L. Polastri, P.N.

Correlated noise and science performance



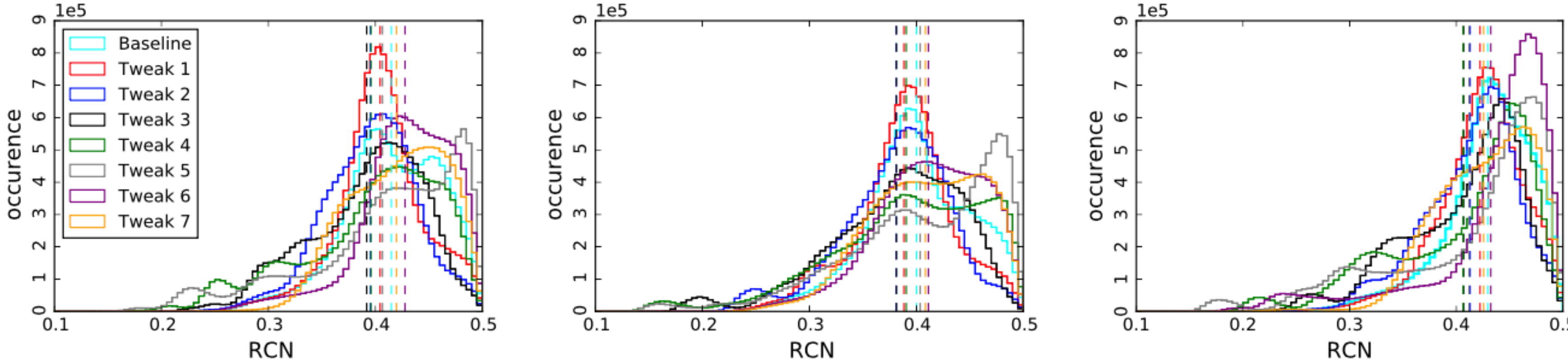
Noise excess at large scales in angular power spectra, and 1 σ spread from Monte Carlo. Evident tail even after optimal map-making (expected). Good power equalization, does not depend on FP position

Effect of realistic correlated noise on low ell BB power spectra. Heavily relies on Monte Carlo timeline-to-map simulations

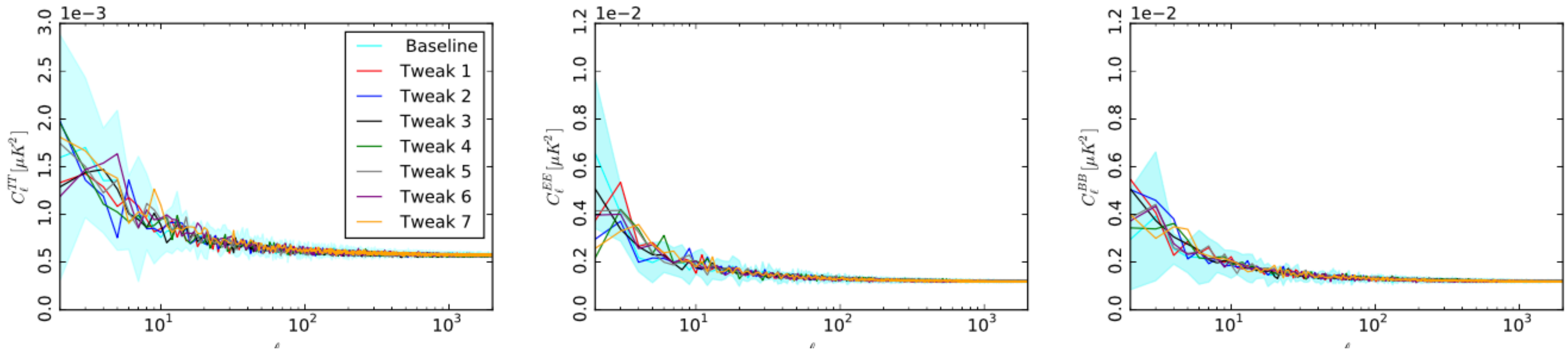


D. Molinari, L. Polastri, P.N.

Scan strategy optimization?



Parameter	Baseline	Tweak 1	Tweak 2	Tweak 3	Tweak 4	Tweak 5	Tweak 6	Tweak 7
Precession angle [°]	30	32	34	36	38	40	45	50
Spin angle [°]	65	63	61	59	57	55	50	45



Cross-correlation map-making (4 detector exercise)

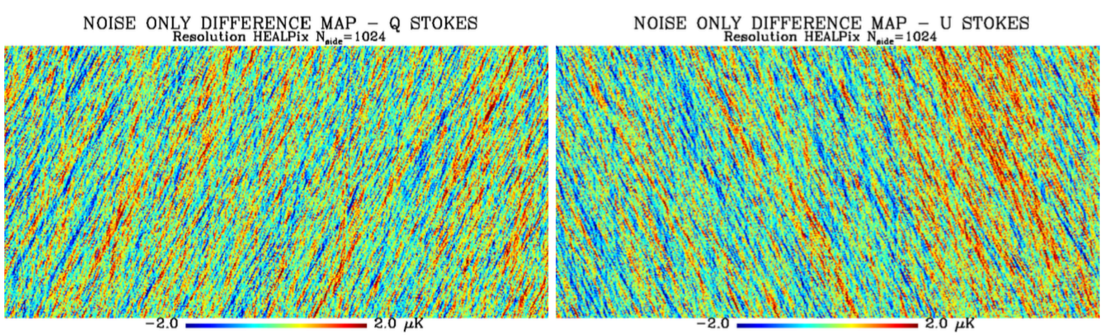
$$n_i = \tilde{n}_i + n_c$$

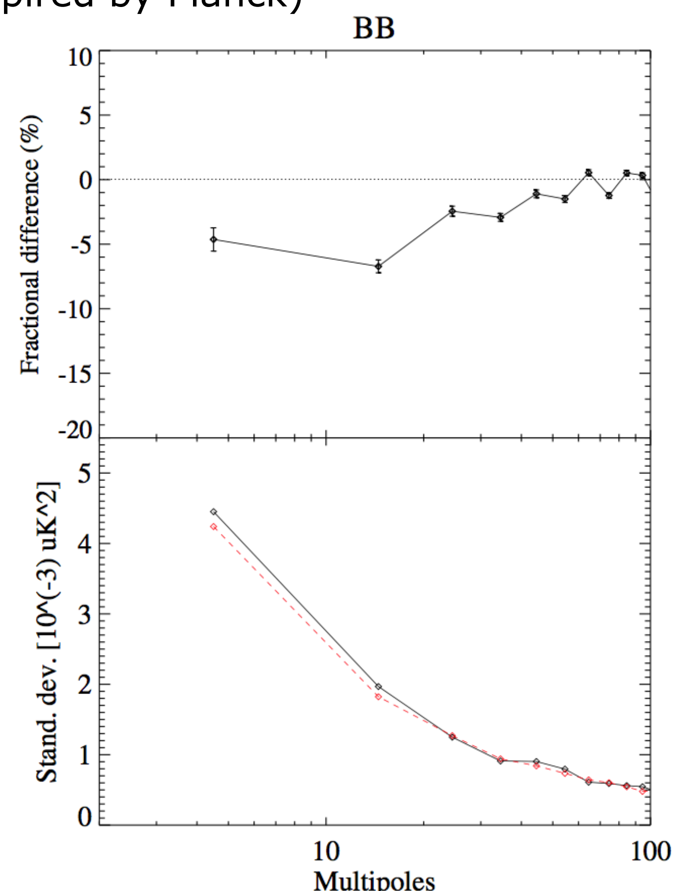
$$P_i(f) \equiv \langle \tilde{n}_i \tilde{n}_i \rangle = A\left[\left(\frac{f_k}{f}\right) + 1\right]$$

$$P_{ij}(f) \equiv \left\langle n_i n_j \right\rangle = \langle n_c n_c \rangle = A\left[\left(\frac{f_1}{f}\right)^2 + C\right] \text{for } i \neq j$$

$$\mathbf{N} \equiv \langle \mathbf{n}_t \mathbf{n}_{t'} \rangle = \begin{pmatrix} \left\langle n_t^{(1)} n_{t'}^{(1)} \right\rangle & \cdots & \left\langle n_t^{(1)} n_{t'}^{(k)} \right\rangle \\ \vdots & \ddots & \vdots \\ \left\langle n_t^{(k)} n_{t'}^{(1)} \right\rangle & \cdots & \left\langle n_t^{(k)} n_{t'}^{(k)} \right\rangle \end{pmatrix}$$

(Noise model inspired by Planck)





A. Buzzelli, G. de Gasperis et al.
ROMA optimal map-making code

Bandpass mismatch

R. Banerji, D.T. Hoang, G. Patanchon

1. Model the flux per unit solid angle and calibrate on CMB

$$\frac{dF}{d\Omega} = \int \sum_c g(\nu) f_c(\nu, p) d\nu, \qquad I(\nu_0) = I_{\rm CMB}(\nu_0) + \sum_{c \neq {\rm CMB}} \gamma_c(p) I_c(\nu_0),$$

2. Problem arises when considering more than one detector:

$$\gamma_c^{(i)} = \overline{\gamma}_c + \delta\gamma_c^{(i)}$$

$$\mathbf{d}^{(i)} = \sum_c \overline{\gamma}_c \left[\mathbf{I}_c + \mathbf{Q}_c \cos(2\psi) + \mathbf{U}_c \sin(2\psi)\right] + \sum_{c \neq {\rm CMB}} \delta\gamma_c^{(i)} \left[\mathbf{I}_c + \mathbf{Q}_c \cos(2\psi) + \mathbf{U}_c \sin(2\psi)\right] + \mathbf{n}.$$

3. as it will lead to leakage, e.g.

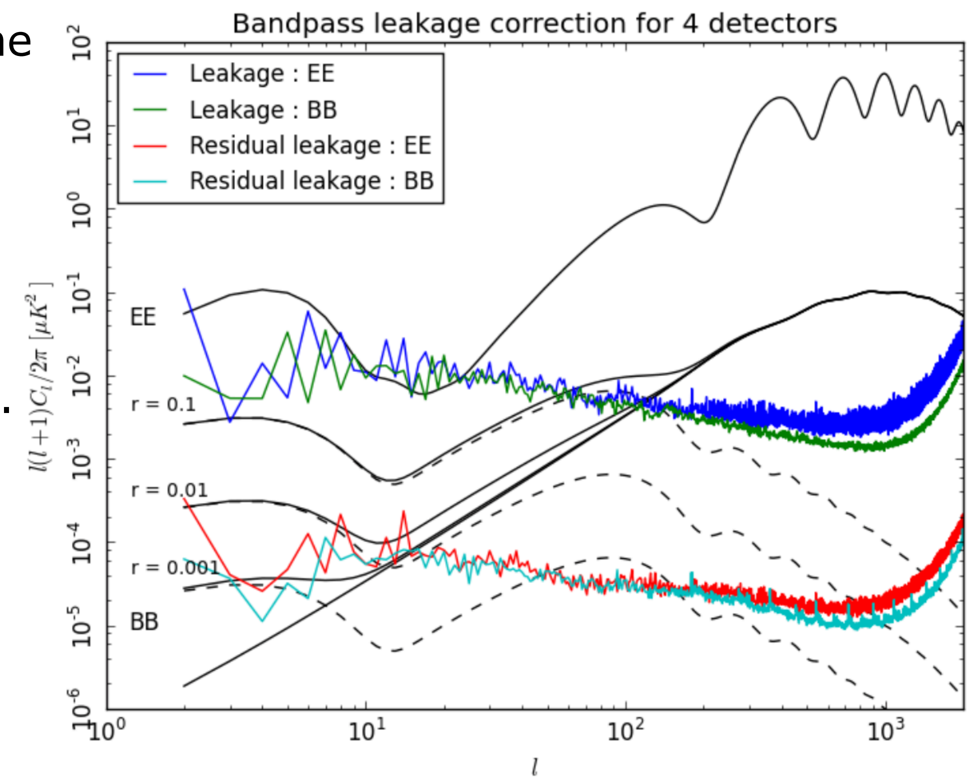
$$\begin{aligned}
\mathbf{d} &= \frac{1}{2}\left(\mathbf{d}^{(a)} - \mathbf{d}^{(b)}\right) \\
&= \sum_c \overline{\gamma}_c \left[\mathbf{Q}_c \cos(2\psi) + \mathbf{U}_c \sin(2\psi)\right] + \frac{1}{2}\left[\sum_{c \neq {\rm CMB}} \left(\delta\gamma_c^{(a)} - \delta\gamma_c^{(b)}\right) \mathbf{I}_c\right] + \left(\mathbf{n}^{(a)} - \mathbf{n}^{(b)}\right) \\
&= \mathbf{Q}\cos(2\psi) + \mathbf{U}\sin(2\psi) + \sum_{c \neq {\rm CMB}} y_c \mathbf{I}_c + \mathbf{n},
\end{aligned}$$

Bandpass mismatch

R. Banerji, D.T. Hoang, G. Patanchon

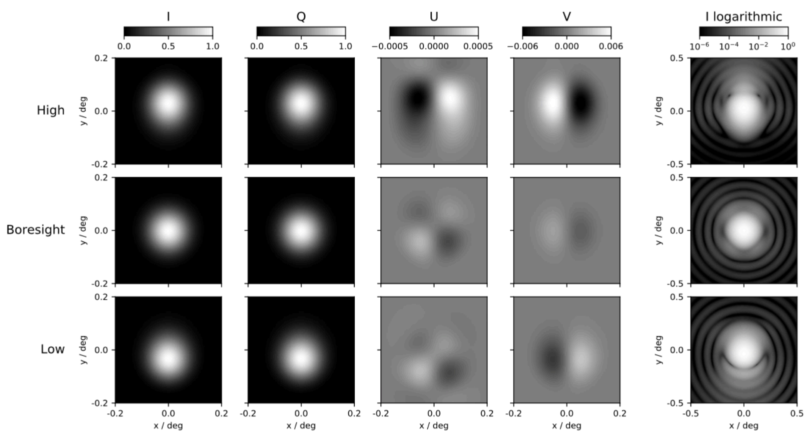
A map-making based correction scheme was implemented. Works iteratively, assuming imperfect knowledge of the band profiles and of foreground templates.

Results shown are for first order, could be extended to second order if needed. Also, residuals scales down as the number of detectors assuming joint multidetector map-making



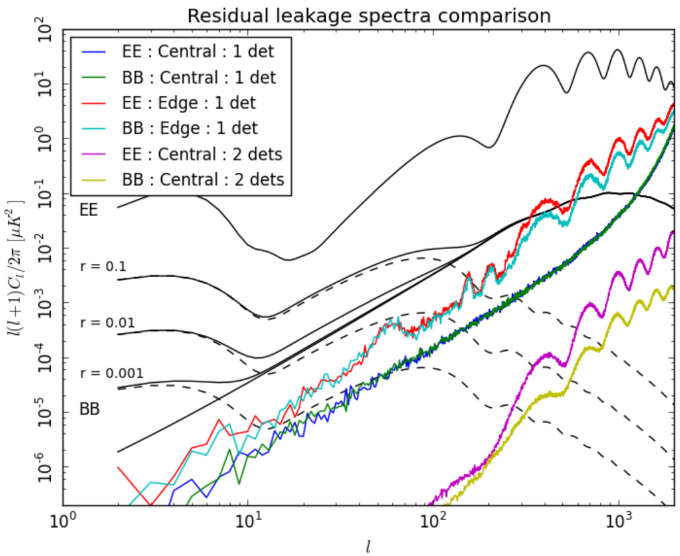
Asymmetric beam correction

1. This is a potential problem for a CORE-like strategy without a fast polarization modulator (i.e., no HWP). Effect is dominated by I -> P leakage (given magnitude of I signal)
2. Both a real space and an harmonic space method were implemented
3. Assumptions are based on physical optics models for the CORE focal plane, assuming three "representative" positions (boresight and edges) in the focal plane



D. McCarthy, M. Ashdown

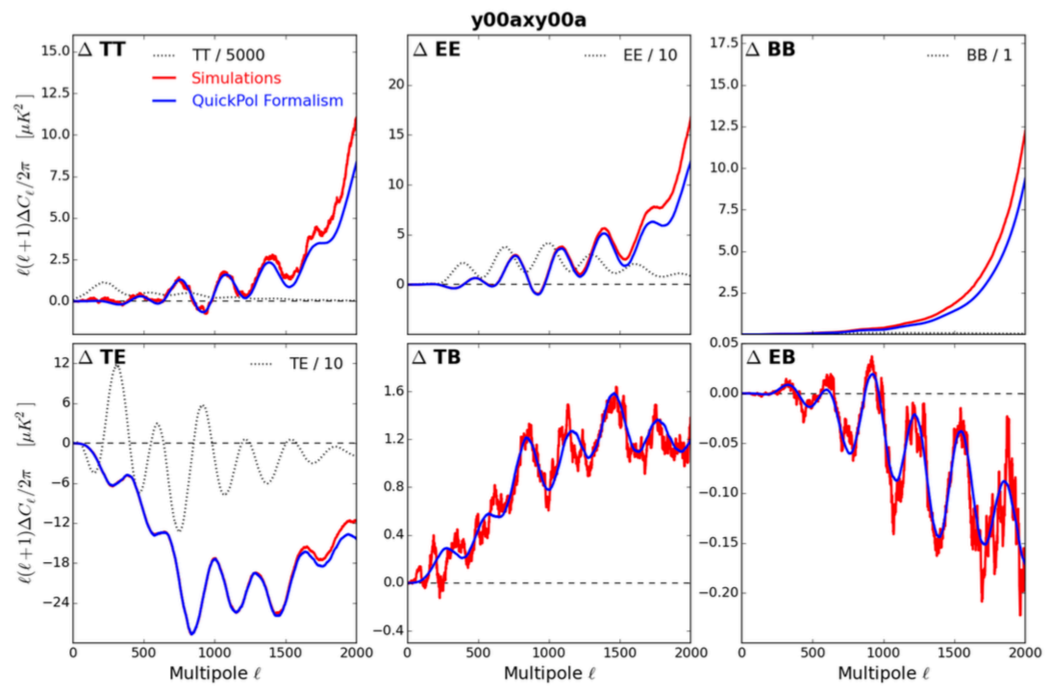
Asymmetric beam correction



Residual leakage from real-space, convolution based mitigation. Mitigates T -> P leakage by re-scanning observed T map, after deconvolving “best” symmetric beam.
R. Banerji and J. Delabrouille

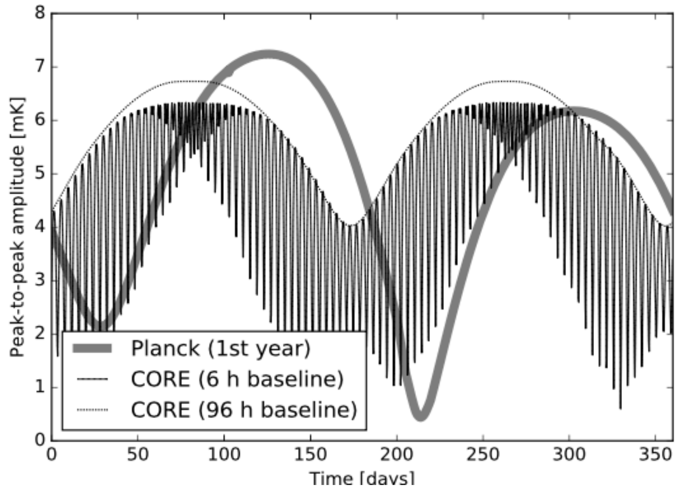
QuickPol formalism (E. Hivon et al). Fast prediction of beam induced leakages, compared to simulations (match well!)

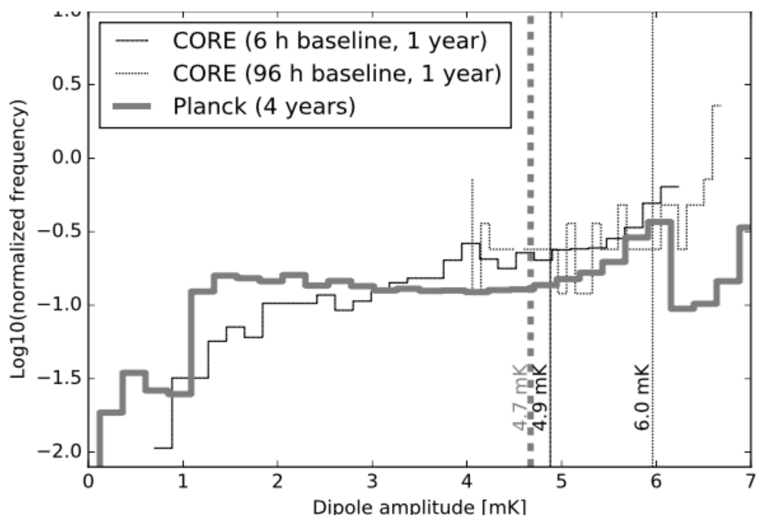
$$\widetilde{C}_\ell^{XY} = \sum_{X'Y'} W_\ell^{XY,\,X'Y'} C_\ell^{X'Y'},$$



Prototype calibration for CORE

1. Exercise based on Planck LFI heritage, adapted to CORE
2. Goal was to have machinery ready to test robustness to systematics (e.g., Galactic contamination)

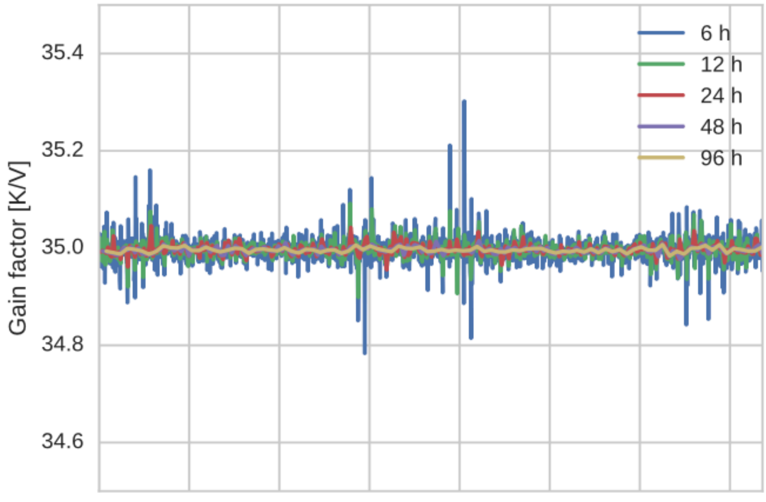


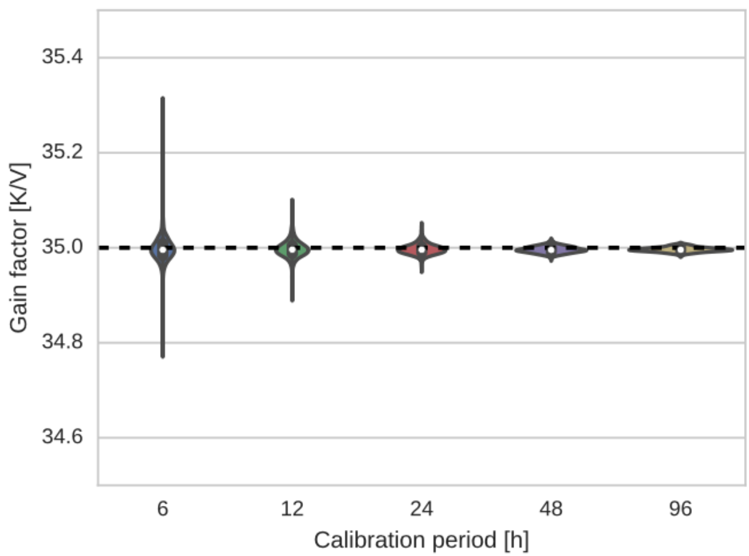


M. Tomasi

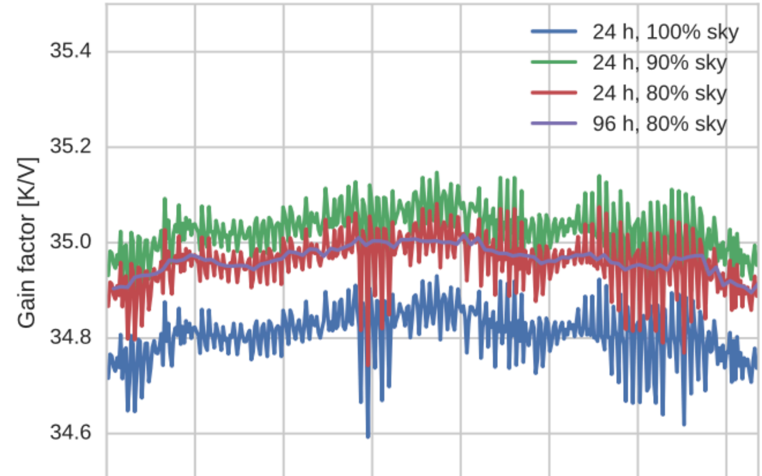
Prototype calibration for CORE

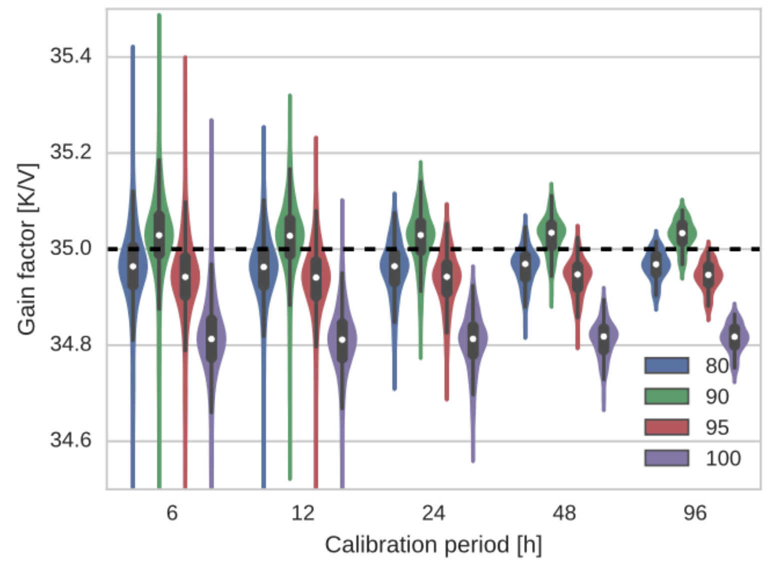
No Galactic contamination





Untreated Galactic contamination





M. Tomasi

Improvements

1. The very early stage of the CORE design did not allow us to take end-to-end simulations into account
2. Typical way to do this is to propagate complex data down to science (e.g. through the CMB likelihood to cosmological/nuisance parameters)
3. That would be more a phase-A kind of thing
4. Next slide shows an example from the Planck low ell likelihood pipeline

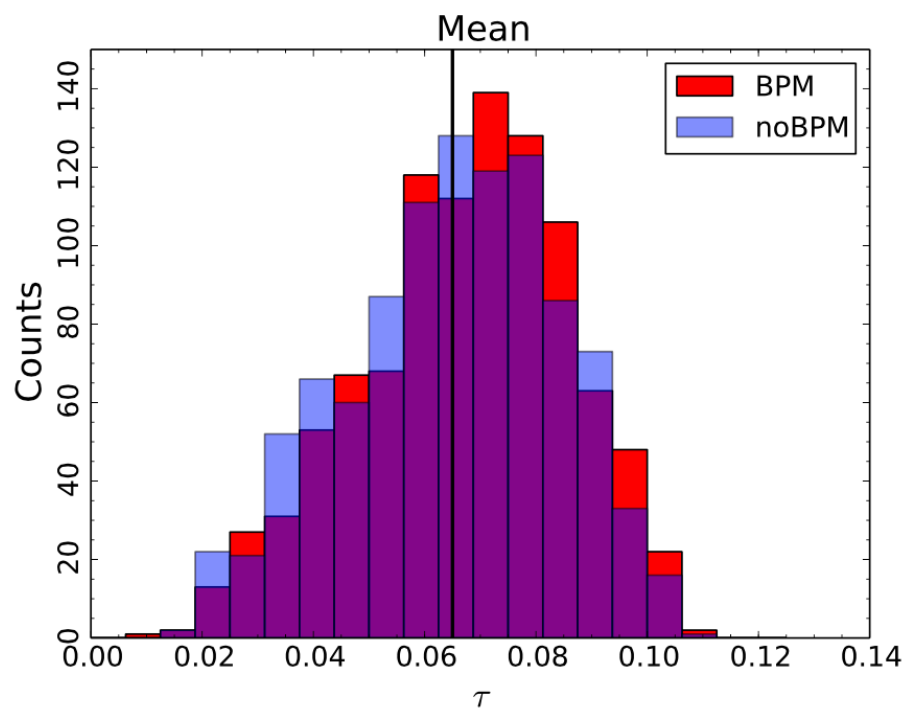
Example of integration of systematics, CS and low ell likelihood: full end to end validation for Planck

Table 4. Statistics for the empirical distribution of estimated cosmological parameters from the FFP8 simulations.[a]

	Cosmomc best-fit			Cosmomc mean			Standard deviation	
Parameter	mean	σ	Δ	mean	σ	Δ	mean	σ
τ	0.0641 ± 0.0007	0.0227	−4.1%	0.0650 ± 0.0006	0.0190	−0.1%	0.0186 ± 0.0001	0.0030
τ^*	0.0665 ± 0.0007	0.0226	+6.4%	0.0672 ± 0.0006	0.0189	+11.0%	0.0185 ± 0.0001	0.0031
$\log[10^{10}A_s]$	3.035 ± 0.002	0.059	−9.4%	3.036 ± 0.002	0.055	−8.0%	0.0535 ± 0.0001	0.0032
$\log[10^{10}A_s^*]$	3.039 ± 0.002	0.059	−1.7%	3.040 ± 0.002	0.056	−0.3%	0.0533 ± 0.0001	0.0033

Full end-to-end validation includes map-making, propagation of systematics, polarized component separation, CMB likelihood and parameter estimation.

This was used to validate the Planck 2015 likelihood in the presence of systematics (band pass mismatch)



Conclusions and remarks

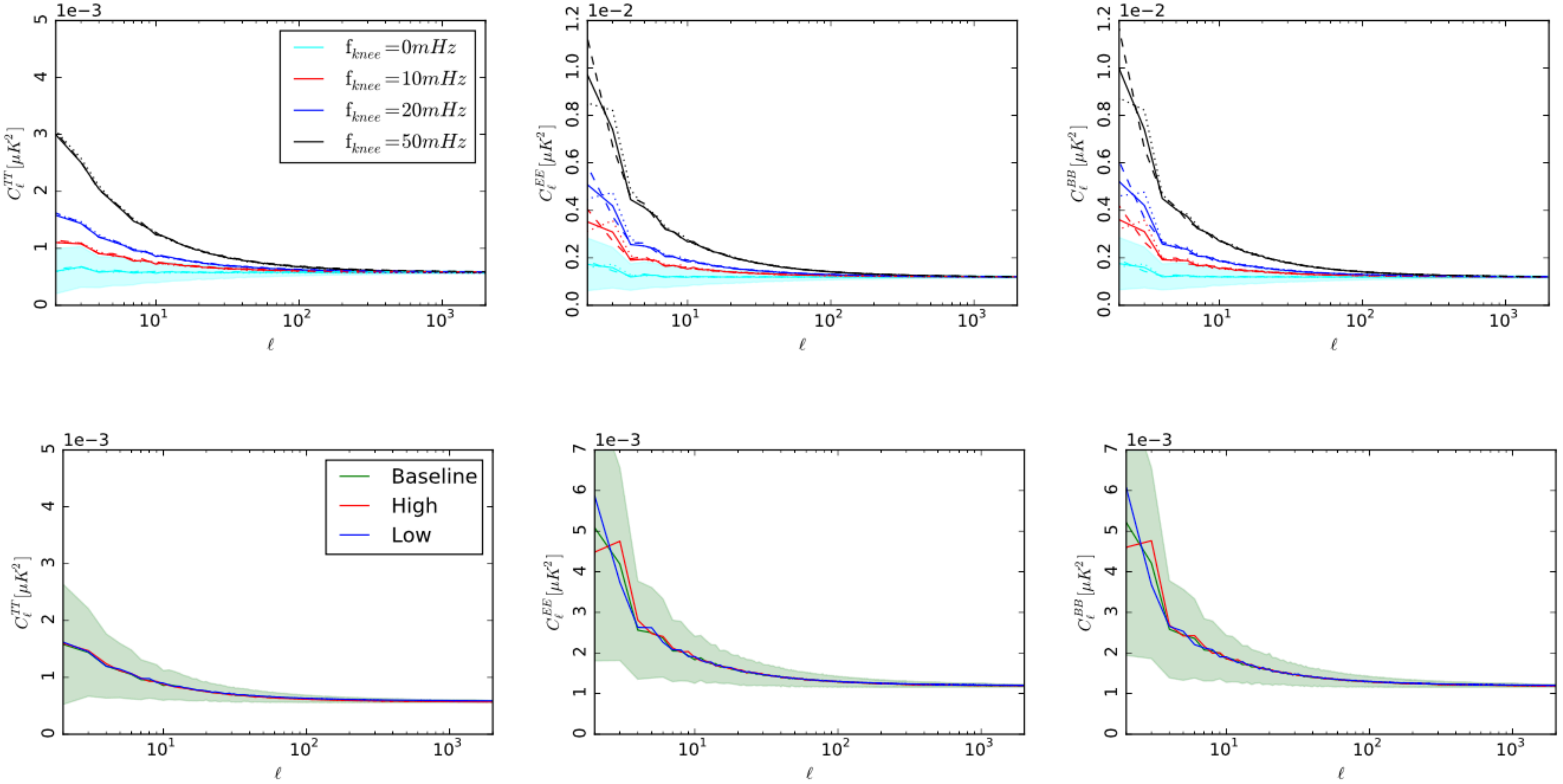
1. The exercise consisted in an assessment of the robustness of the CORE scanning strategy to potential contaminations and a one-at-a-time assessment/correction of specific effects.

    a. Purity of Stokes parameters
    b. Robustness to low frequency drifts
    c. Bandpass mismatch
    d. Beam induced leakages
    e. Robustness of calibration

2. Mutual interaction of effects as well as systematic residuals from the foreground cleaning pipeline have been ignored on purpose and deferred to later studies.
3. The next logical step would be to produce full end-to-end simulations. A finer knowledge of the instrument and the processing pipeline is necessary for this to be meaningful
4. The Planck experience/legacy can provide some insights concerning such an exercise

BACKUP SLIDES

1/f noise performance



Pointing inaccuracies

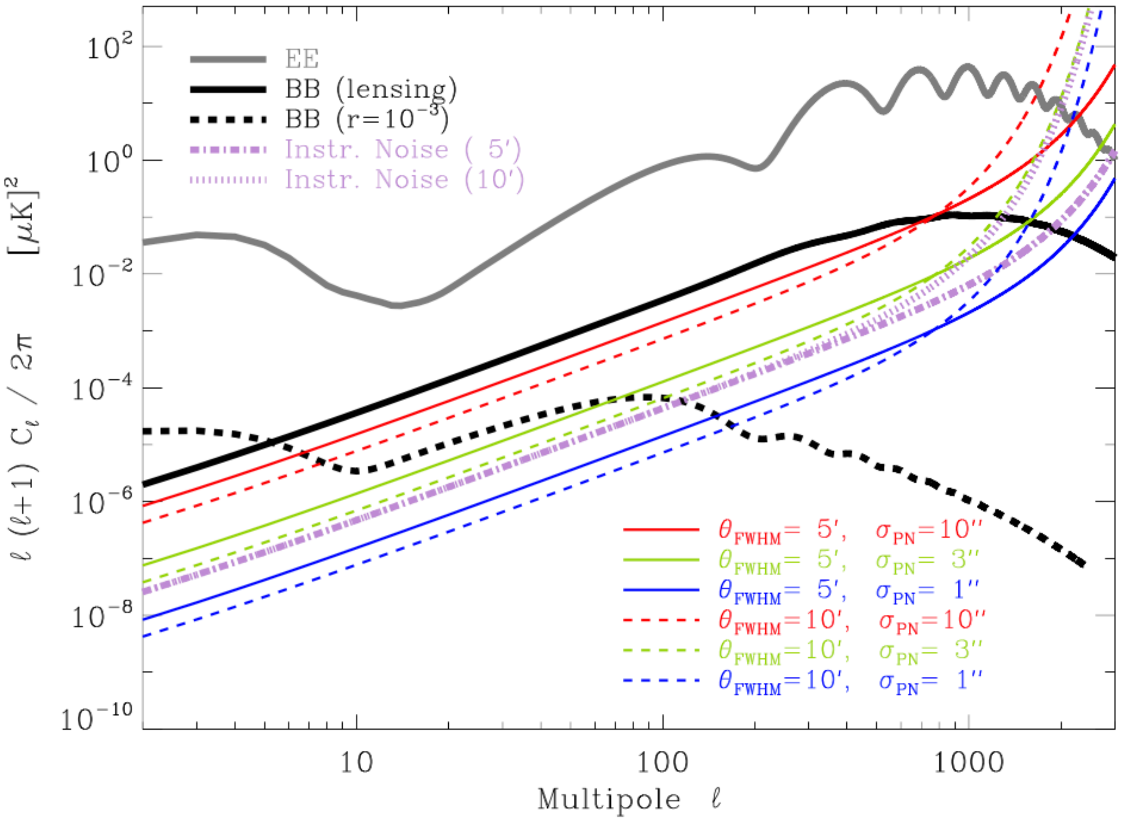


Figure 26. Angular power spectrum of the noise induced by pointing inaccuracy (red, green and blue curves), after correction of the beam window functions, compared to the *EE* and *BB* (either pure lensing or primordial with $r = 10^{-3}$) spectra (grey and black curves). The instrumental noise (purple curves) is assumed to be 2μK·arcmin, the expected *CORE* sensitivity to CMB polarization.