Systematic effects

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many figures in this presentation are taken from:

Planck **intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth**

arXiv:1605.02985

- Detector noise in Planck-HFI near the peak of the CMB (143 GHz) is dominated by the background photon noise
  - the white noise propagated to polar maps and power spectra is <2 10^{-4} μK^2
  - Planck HFI CMB observations released so far have not been fully detector noise limited for lowest ell polarization because of systematic effects (for the 2013 release we were around 1 μK^2 at l=2) although the 2015 released could use polar PS for l>100
  - It took 3 years to identify fully the systematics and remove most of them
- for future missions: the instrumental + scanning strategy choices lead to different systematic effects
  - if instrumental choices can avoid some of the main the systematics they should be a high priority
  - the increased sensitivity of the future CMB experiments aiming at B modes will probably reveal some mor systematic effects
  -

testing systematics: Simulations vs null tests

- Null tests provides an estimate of the noise and systematics residuals
- end to end simulations needs to be carried out including :
  - no syste,
  - all syste
  - any useful sub combination of syste
- The coherence of both sets of tests is the way to show that there is no obvious unknwon systematics (but not full proof !)

origin and removal of systematics

- Concentrate on low ell polarisation
  - polarisation extraction
    - combining different detectors
    - several observations with a single detector
    - single observation with fast rotating halfwave plate (I,Q,U in a single pointing)
- Mission level
  - redundancies
  - scanning strategies
  - thermal stability
  - telescope
    - induced polarisation
    - FSL
- Instrumental effects
  - polar parameter knowledge
  - sensitivity to thermal drifts
  - sensitivity to cosmic rays
- Data analysis
  - leakages (I→P, E→B)
    - spectral band pass knowledge
    - detector inter-calibration
  - global analysis
    - measuring instrumental parameters in ground tests
    - extraction of parameters from the sky data
  - Higher order terms (B_ν-T and V/c)

Systematics leading to intensity to polar leakages

- TES detectors are sensitive to:
  - temperature drifts
  - CR hits but with short time constants makes them less sensitive than the Planck bolomoters
- leakages E to B due to
  - broad bandpass mismatch lead
  - calibration mismatch
- KIDS detectors insensitive to T and even faster than TES thus very low losses due to Cosmic rays

- use of HWP provides I,Q,U measurement on each pixel if spin rate high enough
- Planck has shown that leakage parameters and other systematics corrections can be extracted from the sky if enough redundancies are present in the survey

negligible vs significant systematic effects

- zodi removal
- baseline removal f < sin frequency)
- Far Side Lobes removal
- glitch removal
- 4K cooler EMC pick up at low ell
- Instrumental polar
- detector cross talk

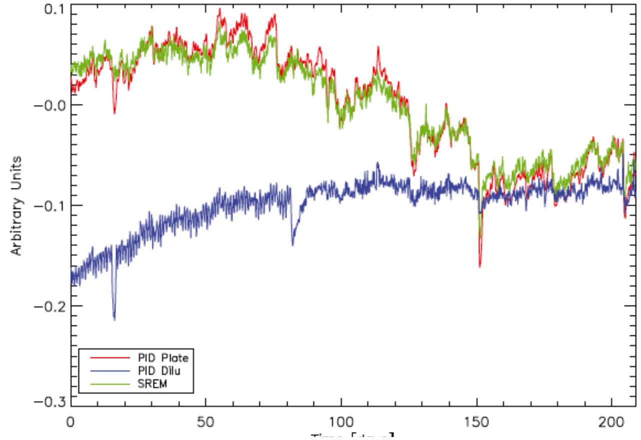
- extracted in the mapmaking (generalised destriper)
  – intercalibration
  – ADC non linearity
  – leakages due to mismatch between det

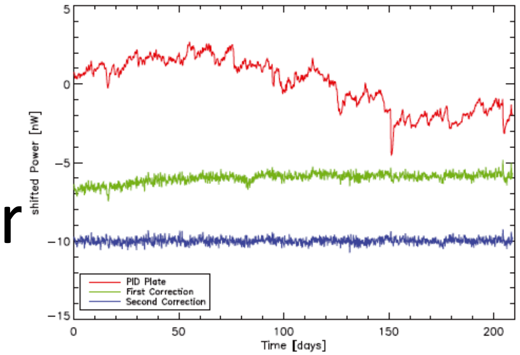
Thermal drift

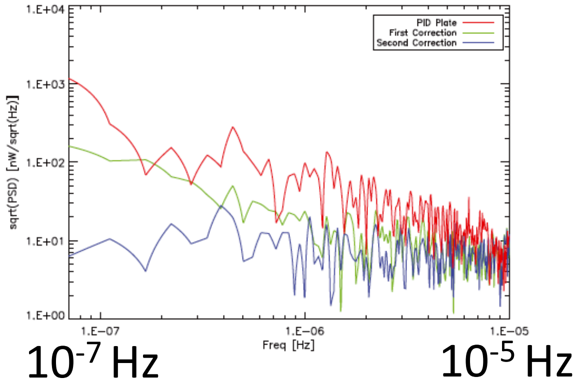
- Bolometers are equally sensitive to heat from the radiation from the telescope and changes in temperature of their common cryogenic reference plate
- thermal fluctuations in Planck needed to be <40 nK/rt Hz in the range 2 10^{-2} - 100 Hz
- reached on the ground but regulation was limited to ver low frequencies because of thermal drifts

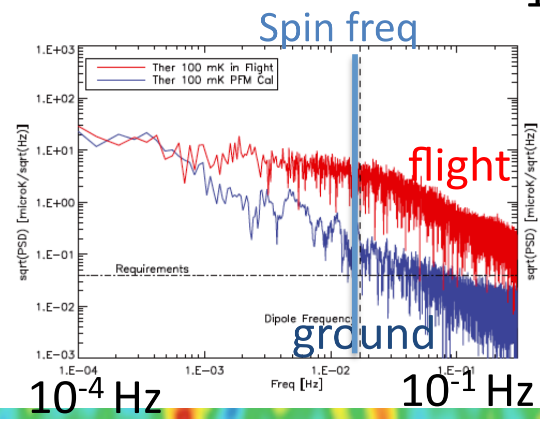
Thermal behaviour of the 100 mK stage

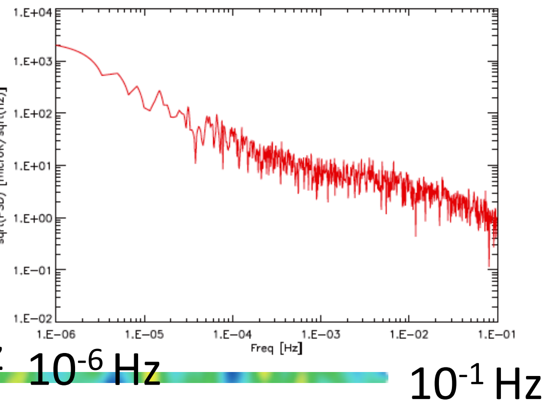
- long term follows cosmic ray rate (SREM)
- taking out SREM pattern and dilution drift correct FULLY the long term thermal behaviour (days to year
-





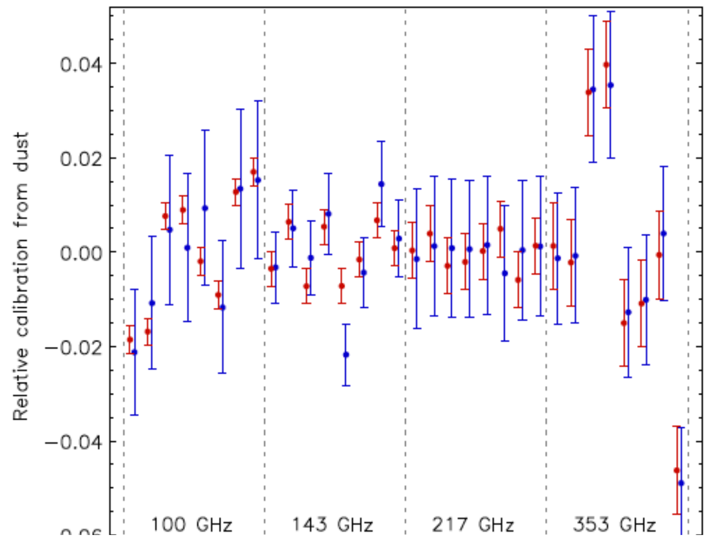


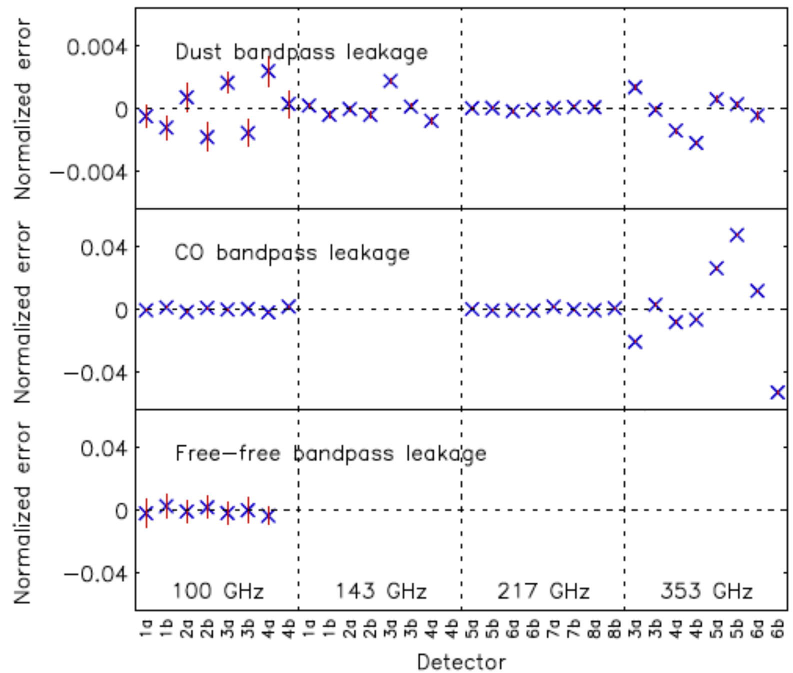




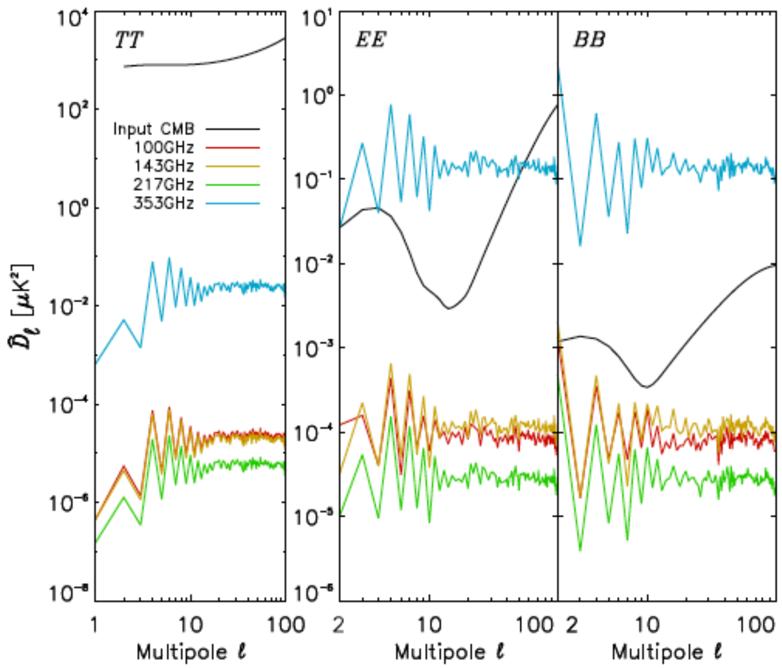
leakages: bandpass mismatch

- leakages can be measured from the sky data if we have a good template
- this can be done ultimately by iterarting mak making and component separation
- at the sensitivity of Post Planck experiments if several detectors are used to measure Q and U component separation should be integrated with map making

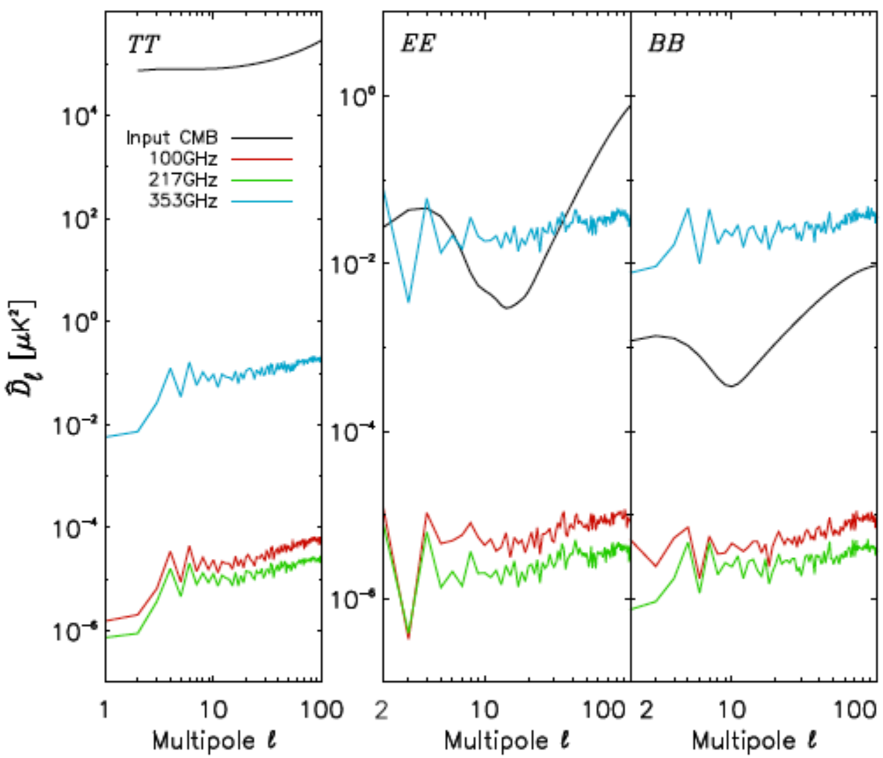




leakages: bandpass mismatch residuals



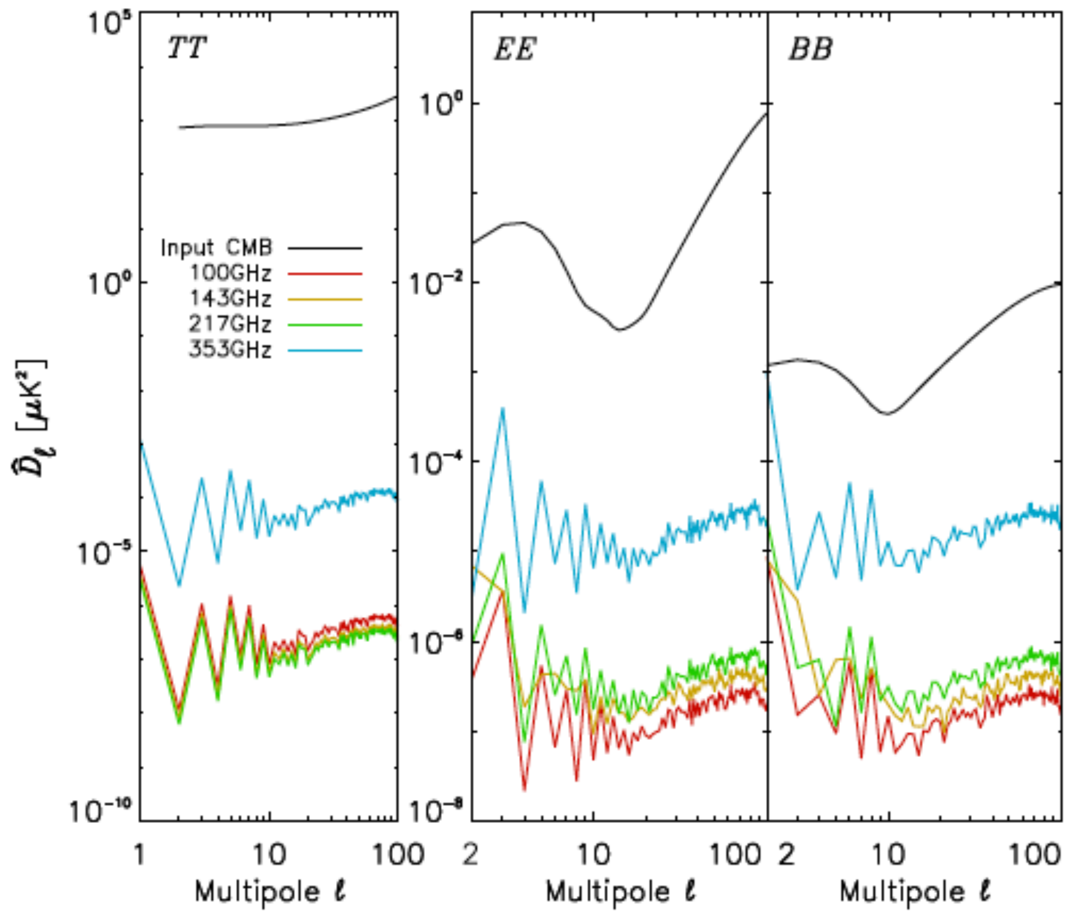
- Dust bandpass mismatch residuals

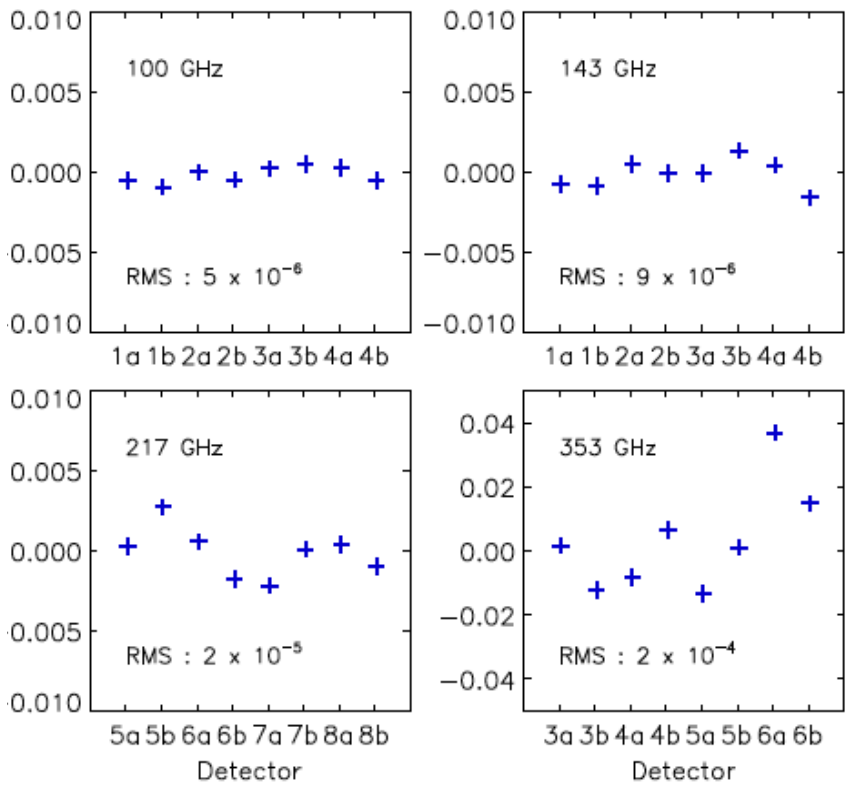


- CO bandpass mismatch residuals
-

leakages: inter-calibration

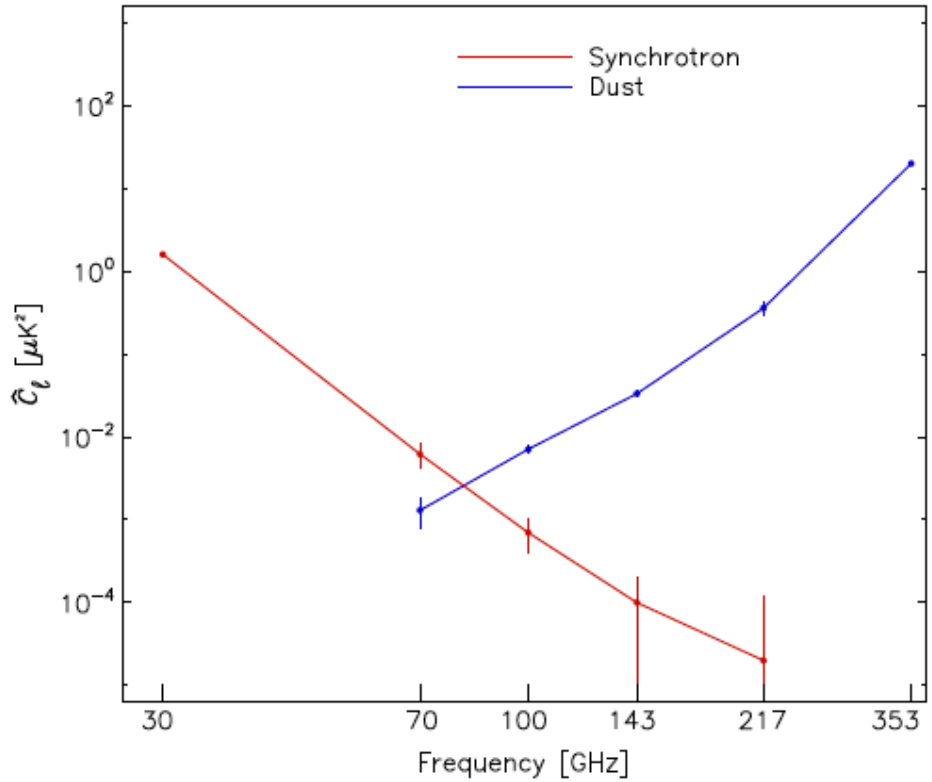
- calibration mismatch residuals





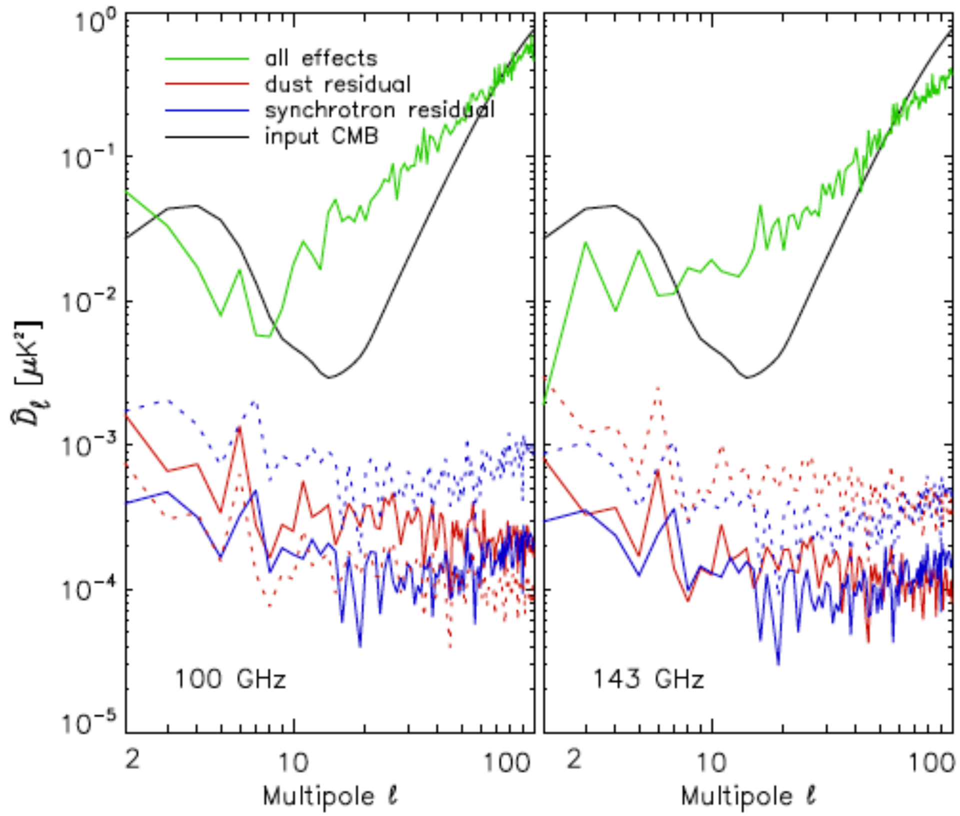
Polar foregrounds

- At frequencies >= 143 GHz, only one dominant foreground: dust
- estimates of uncertainty on the projection coef
- uncertainties (including l bining):
  - 100GHz 3. 10^{-4} μK^2
  - 143 GHz 5. 10^{-4} μK^2



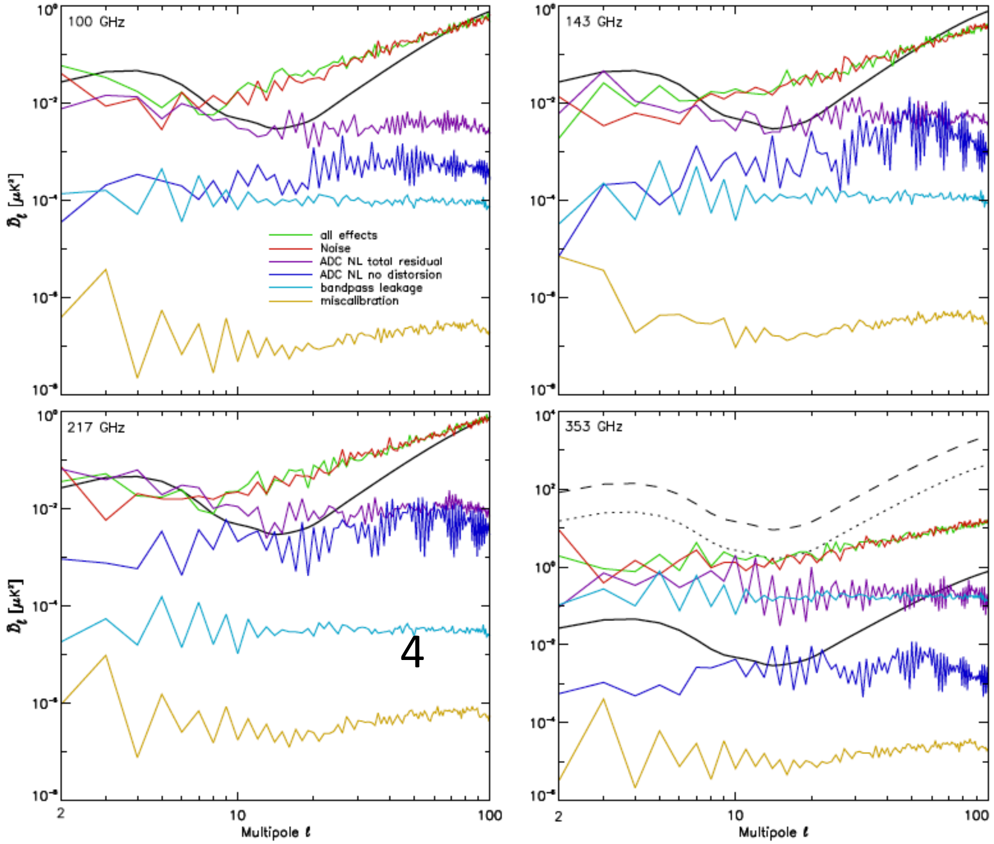
Component separation residuals

- direct component separation residuals
- band pass mismatch require forground spatial templates
- the mapmaking not independent of map making
- there are also indirect effect of component separation: foreground templates are needed in mapmaking



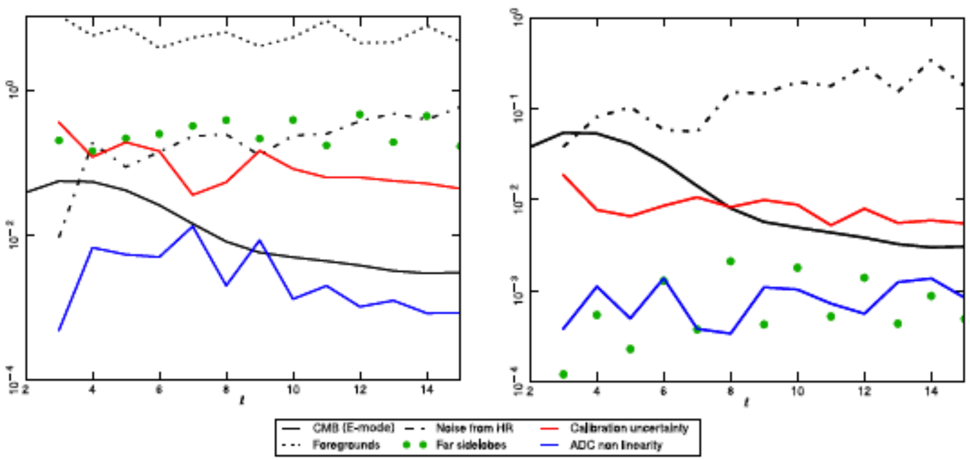
End to end simulations of systematics in HFI and LFI

- systematic effects propagated to EE power spectra
- LFI was more noise dominated than HFI
- notice that the main systematics are close to the fiducial EE PS at low ell

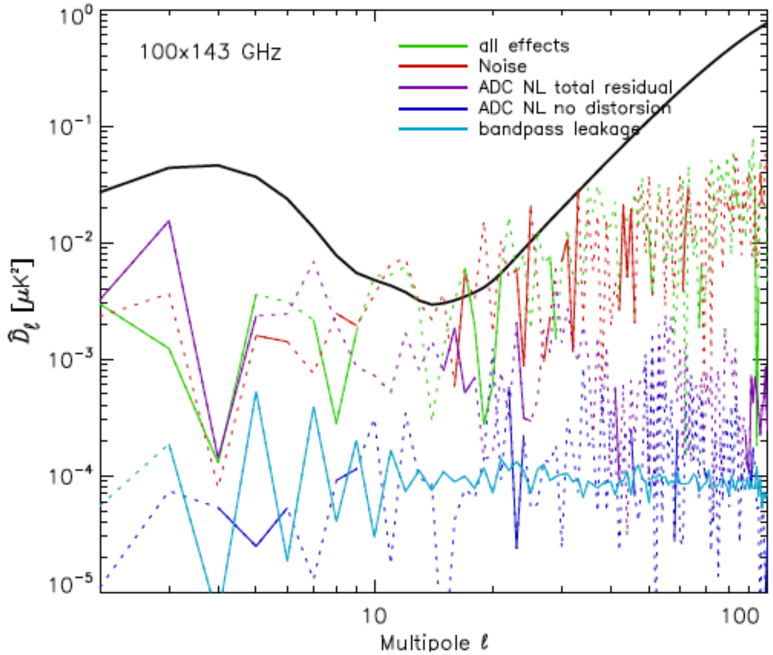


HFI

LFI



- Cross spectra between frequencies or instrument remove part of the systematic effects
- need nevertheless to get the noise much lower than the the single mode one
- noise in cross spectra is the noise variance + averaging in l bands



results on reionisation param Tau

- use of cross spectra in Planck (100x143 and between LFI and HFI 70X100 and 70x143 remove substantially the main systematics residuals

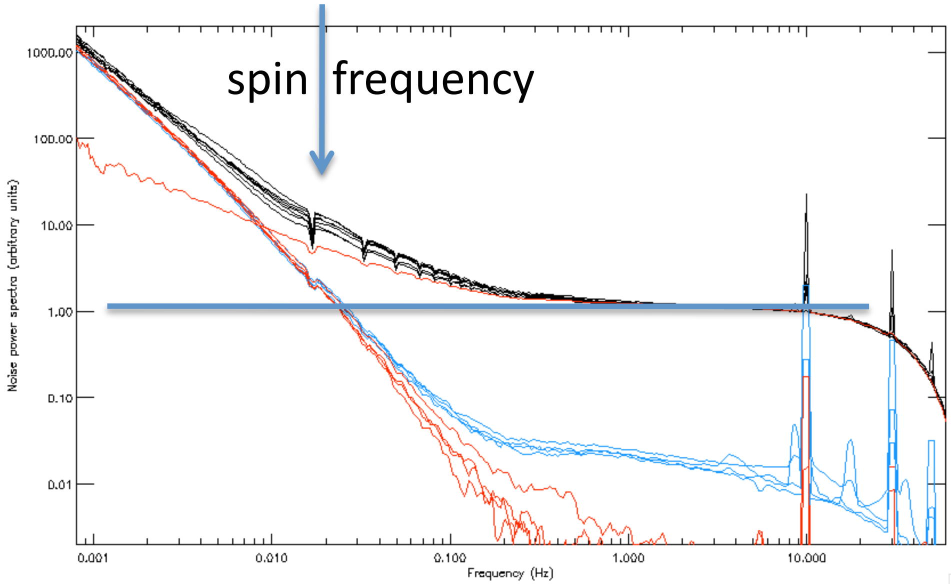
100x143 GHz cross spectra	PCL		QML	
Method	peak $\pm 1\sigma$	peak $+2\sigma$	peak $\pm 1\sigma$	peak $+2\sigma$
`Lollipop` . . .	$0.053^{+0.011}_{-0.016}$	0.075	. . .	. . .
`SimBaL1`	$0.052^{+0.011}_{-0.014}$	0.076	$0.055^{+0.009}_{-0.009}$	0.073
`SimBaL2`	. . .	. . .	$0.055^{+0.008}_{-0.008}$	0.071
`SimBaL3`	. . .	. . .	$0.055^{+0.009}_{-0.008}$	0.073

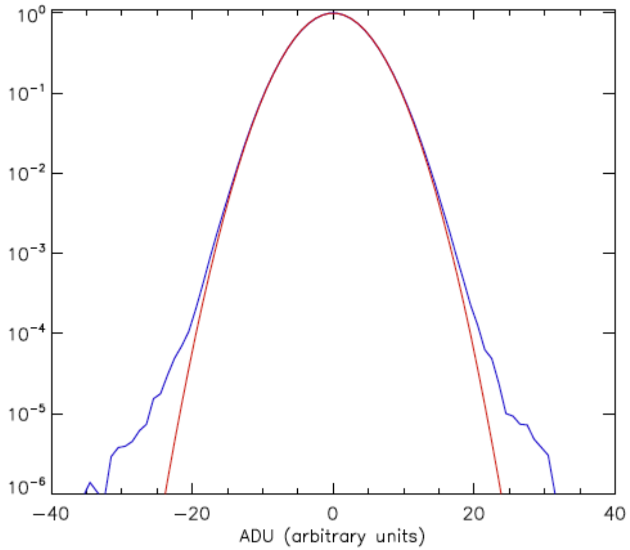
$$\tau = 0.049^{+0.015}_{-0.019} \text{ for the } 70\times100 \text{ cross-spectra,}$$

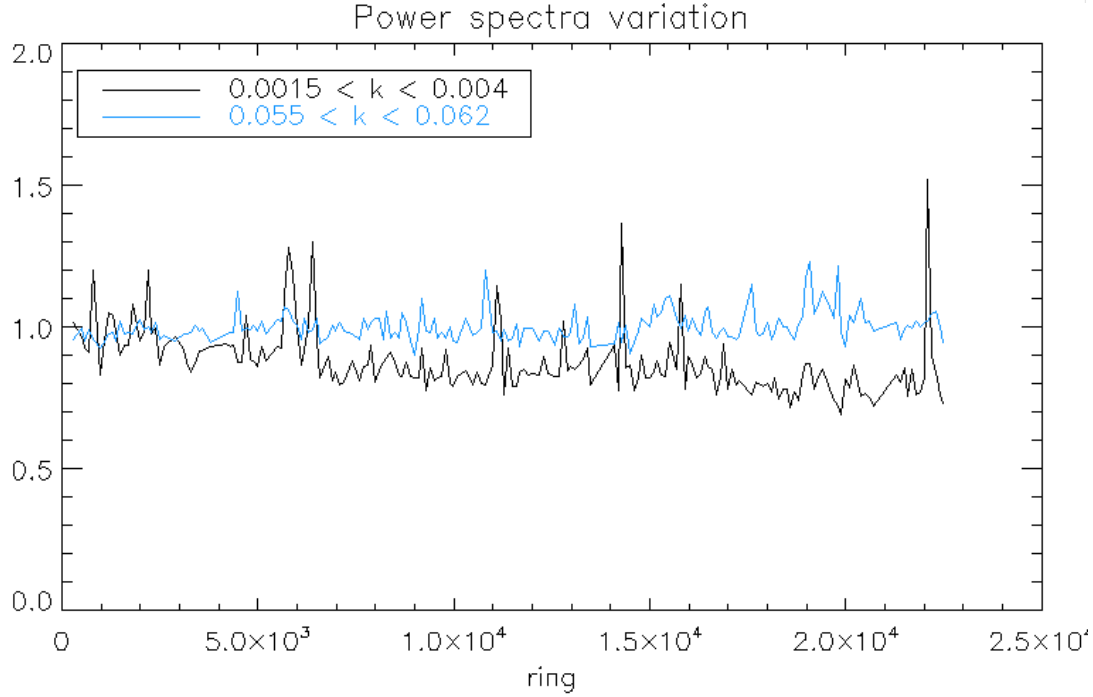
$$\tau = 0.053^{+0.012}_{-0.016} \text{ for the } 70\times143 \text{ cross-spectra.}$$

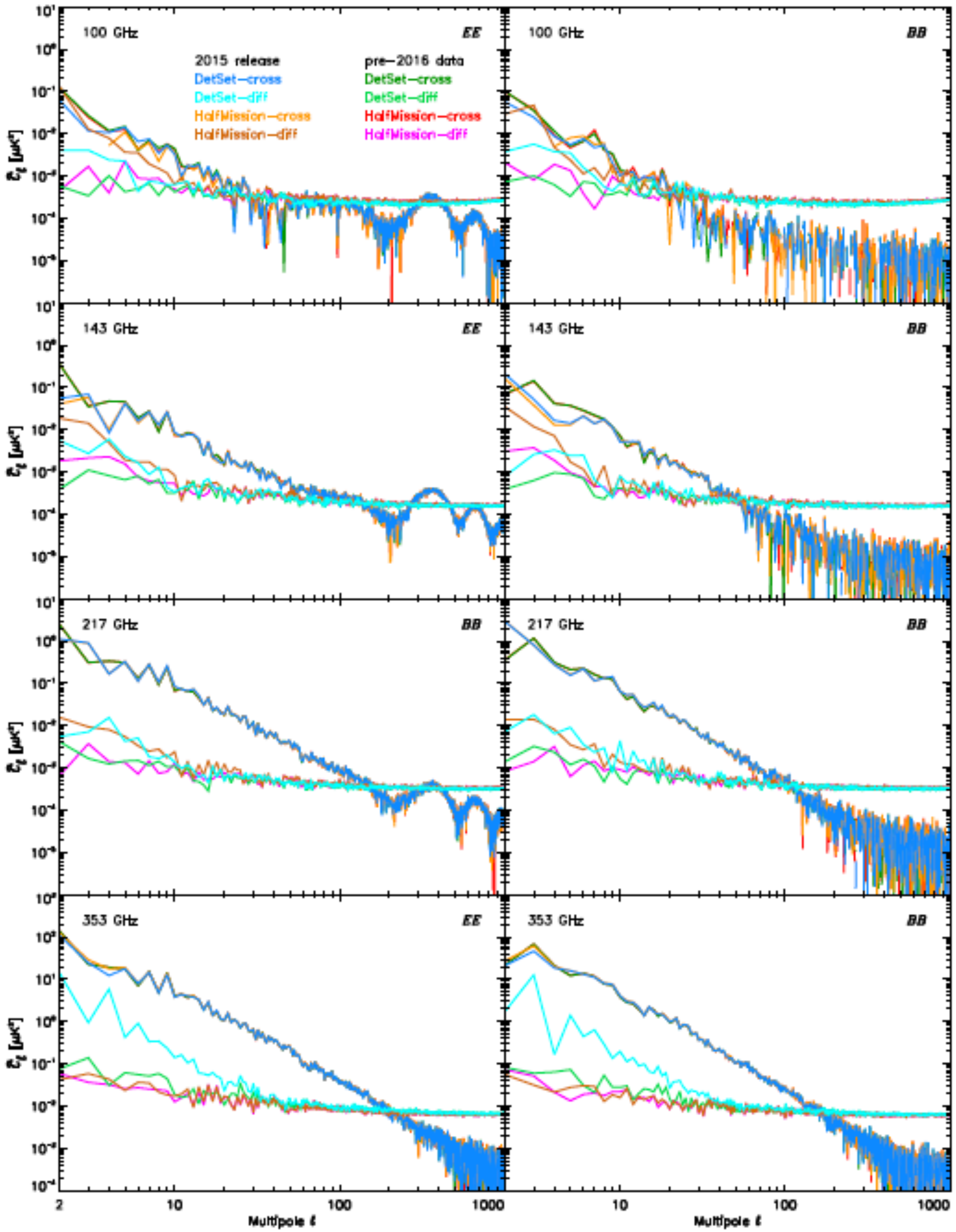
Noise (white and 1/f)- Cosmic Rays Glitches

- noise 1/f vs $1/f^2$









2. 10^{-4} μK^2

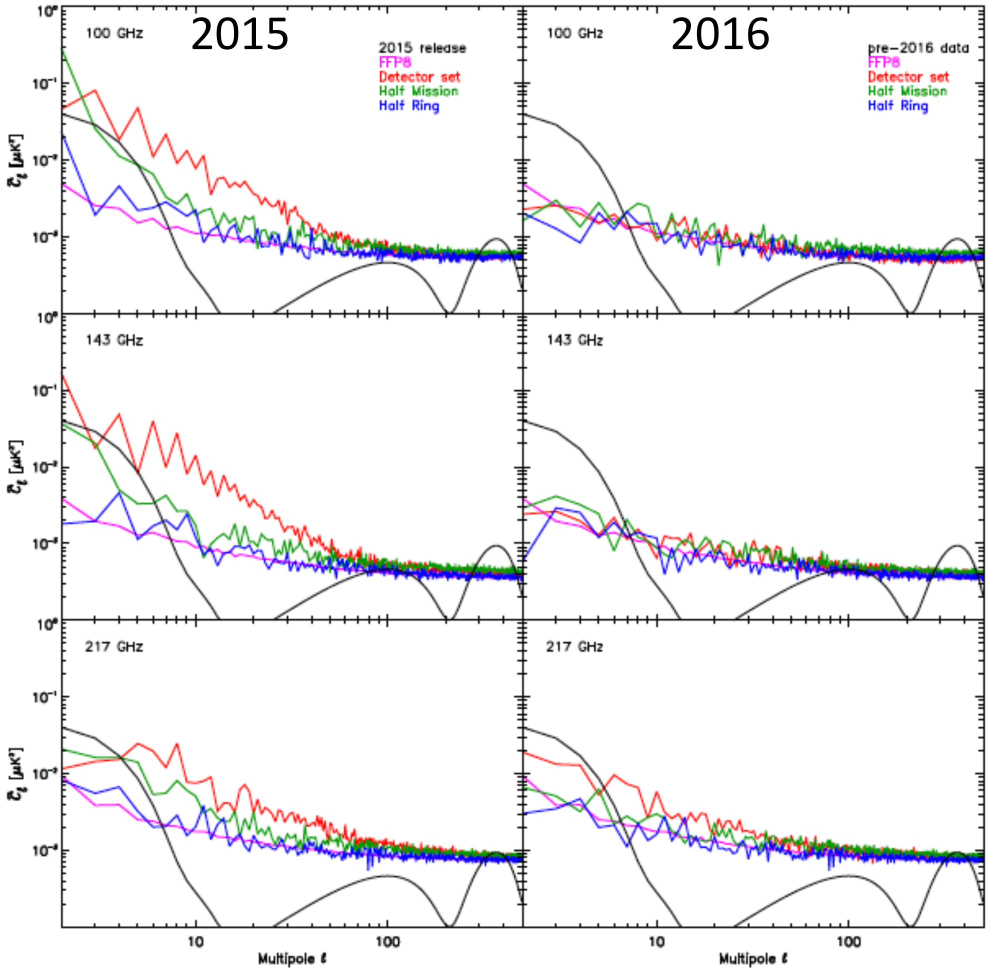
1.4 10^{-4} μK^2

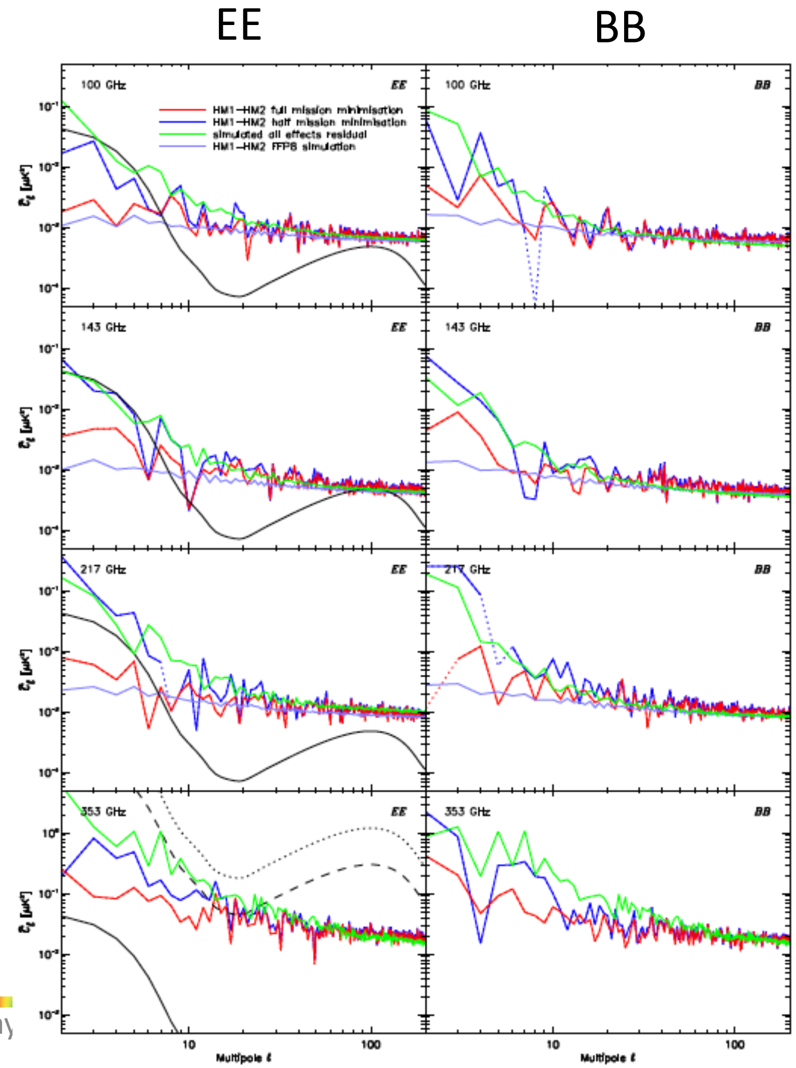
- Null tests
  - Det Sets
  - Half mission
  - half ring
  - these are respectively sensitive to
    - detector properties errors
    - long term drifts
    - very close to detector noise

Null tests – 2015 vs 2016 release

- Comparison 2015v vs 2016 release
  - Detector sets
  - Half mission
  - Half ring

For Half Mission null test:
minimization done independantly in each half mission reveales the ADC dipole distortion (blue curve) in agreement with the simulation of all systematics (green curve)
but not seen in the full mission minimization (red curve)

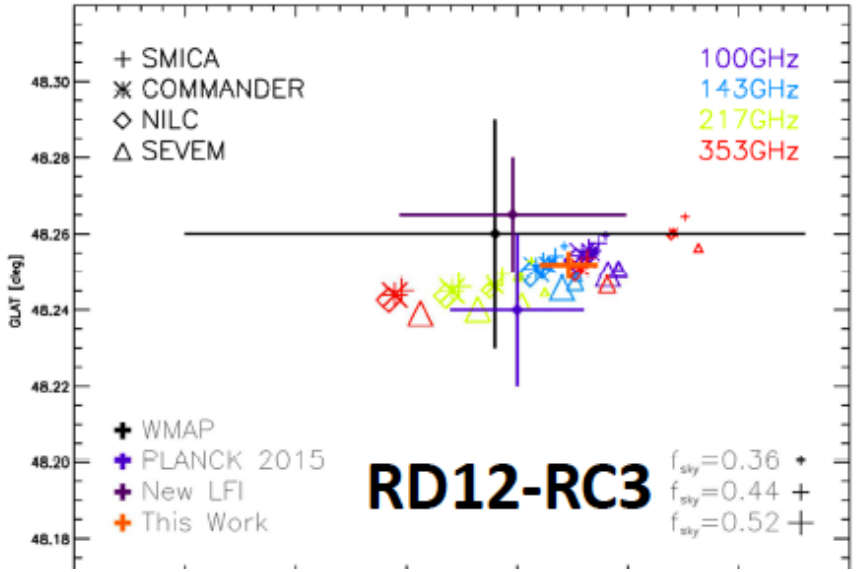




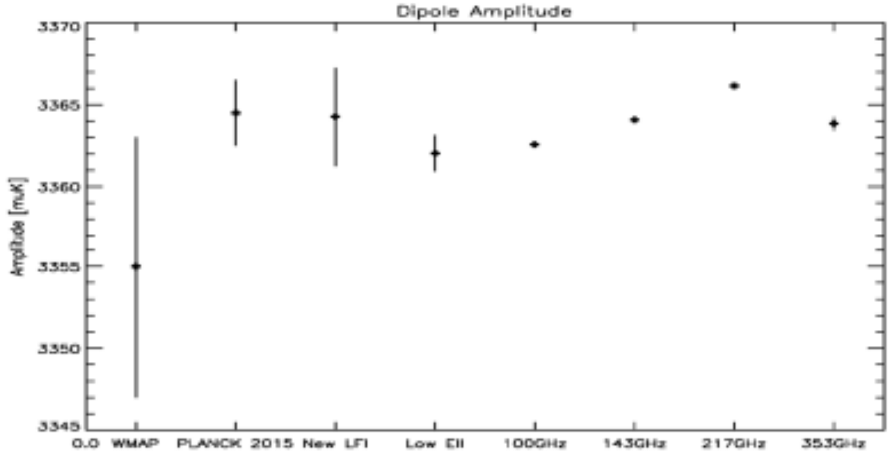
calibration
removal of dipoles and dipoles

- calibration uses the orbital dipole (and solar dipole at 545 GHz)
- the direction and amplitude of the solar dipole are VERY consistent between Planck frequency channels (in the two instruments)
- the kinetic dipoles and quadrupoles must be removed from the sky maps because they induce spurious low ell component through masking
- higher order terms should be computed and removed (see the end of this presentation)
- note that inter-calibration errors are below 0.1 %

RD12ll vs RD12-RC3



Conclusions on RD12-RC3



Average on 100&143:

Higher order terms leading to kinetic dipole and quadrupoles affecting calibration and their removal from the maps

- the relation between dB_ν and dT to second order

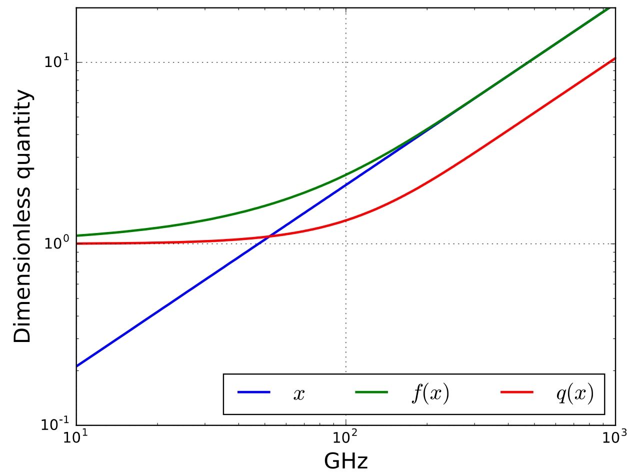
$$\frac{\delta B}{B} \simeq \frac{B(T(\hat{\mathbf{n}})) - B(T_0)}{B(T_0)} = f(x)\frac{\Delta T}{T_0} + f(x)\,(q(x) - 1)\left(\frac{\Delta T}{T_0}\right)^2$$

- the first order kinetic boost dipole beyond the Planckian CMB :
  - spectral distortions and CIB for both orbital and solar velocity
  - galactic foreground monopoles for solar velocity
- the second order terms in v/c

- these introduce extra dipoles and quadrupoles which either projects on the sky maps or on the rings (orbital dipole) or a mix for the cross term
- this affect the calibration and add more terms to be removed from the sky map beyond the solar non distorted CMB dipole
- we have introduced these terms in the Planck end to end simulations
- this allow to estimate for the Planck case their importance

Orbital Dipole Foregrounds Boost

Doppler boost of the foreground field



Considering the isotropic part of the foreground radiation field of Intensity I(ν), a motion with velocity β leads to an observed intensity:

$$I'(\nu) = \frac{I(\nu\,\gamma(1-\boldsymbol{\beta}\cdot\hat{\mathbf{n}}))}{(\gamma(1-\boldsymbol{\beta}\cdot\hat{\mathbf{n}}))^3}$$

At the first order in β

$$I'(\nu) = I(\nu) + I(\nu)\left(3 - \frac{d\log I(\nu)}{d\log\nu}\right)(\boldsymbol{\beta}\cdot\hat{\mathbf{n}})$$

Applied to the CIB and Dust fields, ignoring the aberration effect but not the boosting:

- CIB monopole (values from the mapmaking paper 2015)
- Dust emission monopole (depends on the mask) (Commander solution 2015)

Cross Term (solar x orbital)

Coupling between orbital and solar dipole

Boosting an isotropic sky component velocity β leads to and observed field:

$$T(\hat{\mathbf{n}}) = \frac{T_0}{\gamma(1-\boldsymbol{\beta}\cdot\hat{\mathbf{n}})}$$

At the second order in β:

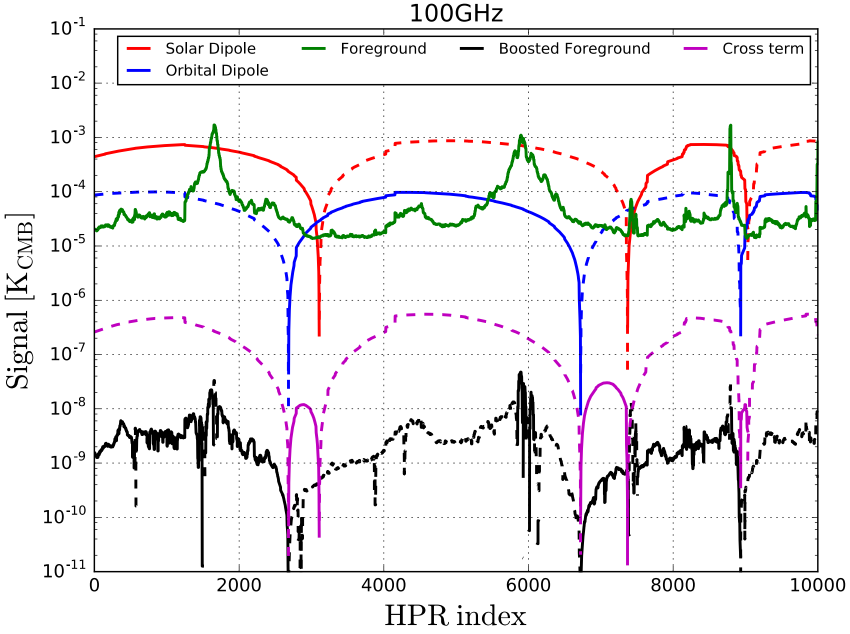
$$T(\hat{\mathbf{n}}) = T_0(1 + \boldsymbol{\beta}\cdot\hat{\mathbf{n}} + (\boldsymbol{\beta}\cdot\hat{\mathbf{n}})^2 - \frac{\beta^2}{2} + \mathcal{O}(\boldsymbol{\beta}^3))$$

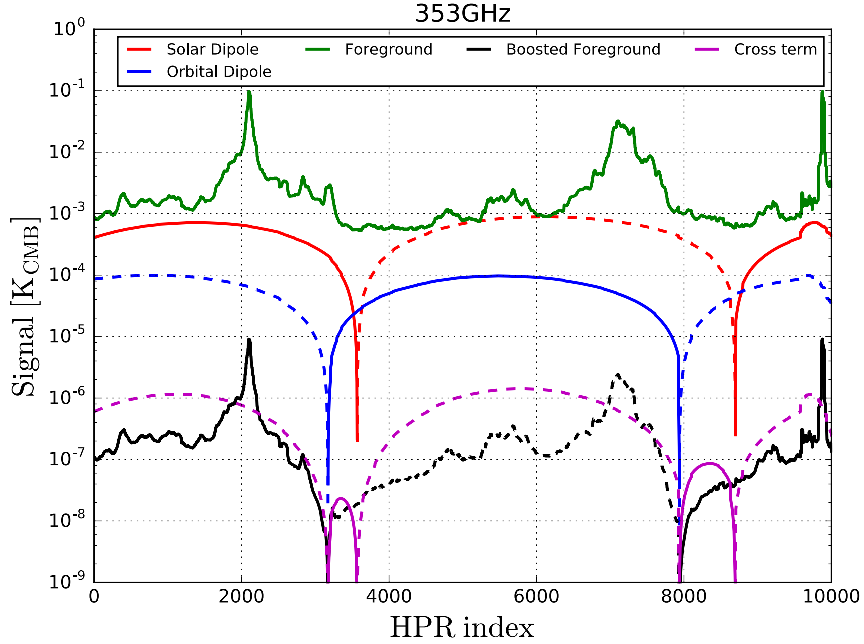
The following temperature contrast is:

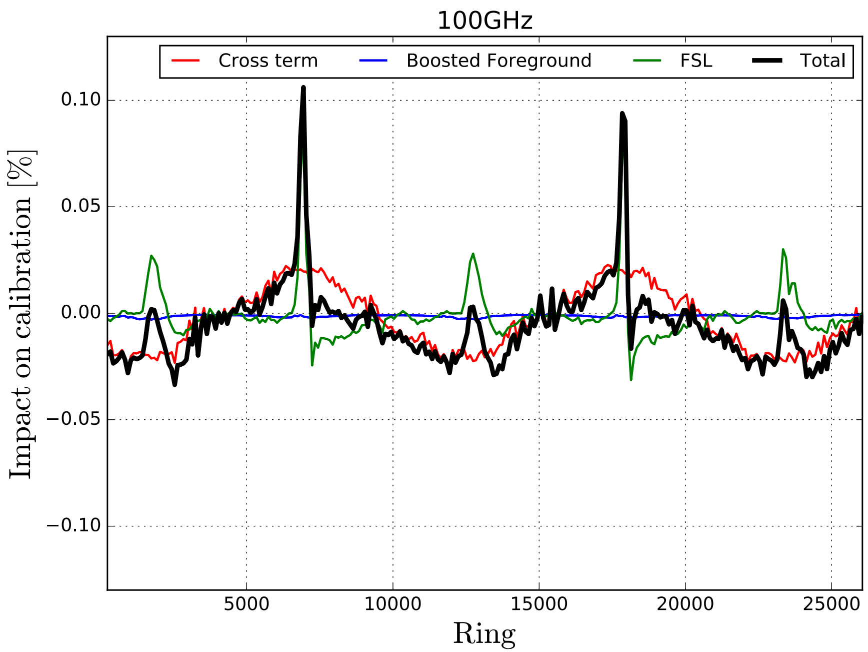
$$\frac{\Delta T}{T_0} = \boldsymbol{\beta}_{\mathbf{S}}\cdot\hat{\mathbf{n}} + \boldsymbol{\beta}_{\mathbf{O}}\cdot\hat{\mathbf{n}} + q(x)\left(\boldsymbol{\beta}_{\mathbf{S}}\cdot\hat{\mathbf{n}}\right)^2 + q(x)\left(\boldsymbol{\beta}_{\mathbf{O}}\cdot\hat{\mathbf{n}}\right)^2 + \underline{2q(x)\left(\boldsymbol{\beta}_{\mathbf{S}}\cdot\hat{\mathbf{n}}\right)\left(\boldsymbol{\beta}_{\mathbf{O}}\cdot\hat{\mathbf{n}}\right)} + \mathcal{O}(\beta^2)$$

With $q(x) = \frac{x}{2}\coth\left(\frac{x}{2}\right) = \frac{x}{2}\frac{e^x+1}{e^x-1}.$

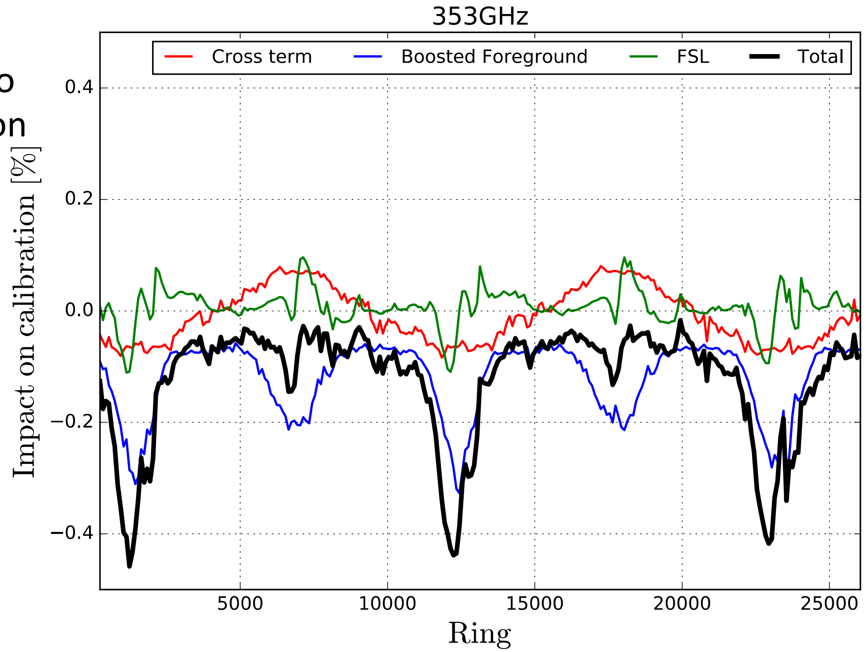
examples of spurious terms: level and impact on calibration







impact on calibration comparable to intercalibration errors shown earlier



Conclusions

- there is NO WAY to prove that you are fully noise dominated
- when you have reasonably identified what could be all systematics, you might still be unable to remove all of them in map properly
- coherence between
  - ground tests (system and system tests)
  - sky null tests (limit is the amount of redundancy in the data)
  - end to end simulations

  is critical
- then, and only then, you can usefully run 10^4 simulations with pure Gaussian noise and CMB and foregrounds (not Gaussian)
- many figures are taken from the paper