# Systematic effects in Planck: Evaluation, Processing and lesson learned

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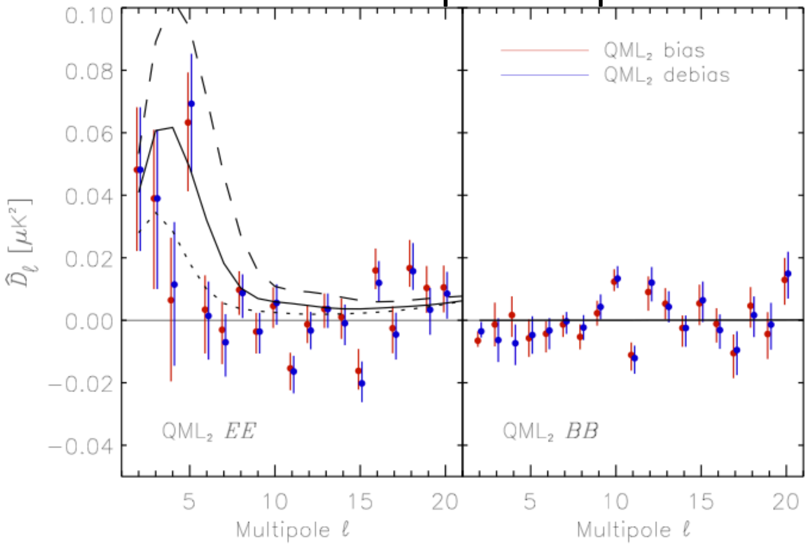
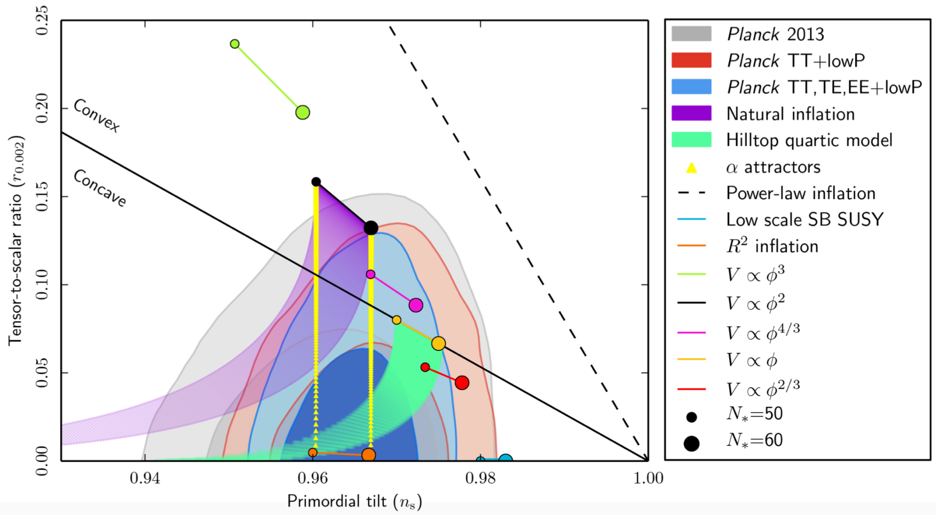
B-mode from Space, Berkeley, Dec. 17

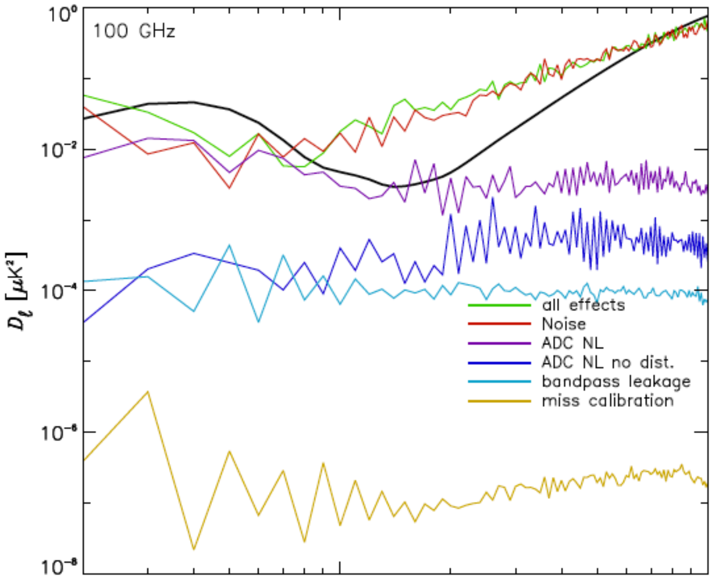
# Planck low ell constraints

Polarization power spectra





Limits on systematics (2015)



Planck reached its objectives at all multipoles

At low ell: $\tau = 0.055 \pm 0.009$

# Lessons from Planck

- ☐ The data analysis and cleaning was a long process and required many iterations
- ☐ At the end, we reached the detector fundamental limit for cosmological channels
- ☐ Some effects were not expected at the level we found them in flight data
    - --> ADC non-linearities
    - --> Long time constants
    - --> Response to cosmic rays
    - --> 1/f noise
    - --> Band-pass mismatch
- ☐ Coupling between effects was problematic. Ex: 4K lines and ADC non-linearities
- ☐ but for future experiment targeting $\sigma_r < 10^{-3}$, systematic effects must be controlled to a higher precision, although many effects will probably scale as 1/Ndet.
- ☐ Importance of observation redundancies: different survey, different scanning angle (limited for Planck), different detectors etc…, **importance of the dipole**, 353 GHz is harder to process
- ☐ Importance of house keeping data. E.g: fully sampled raw data for the ADC correction.
- ☐ Many affect as band-pass mismatch, polarization efficiency, calibration are coupled and need to be corrected at the map-making level, with the help of the dipole

# Noise in HFI time ordered data

Uncorrelated noise

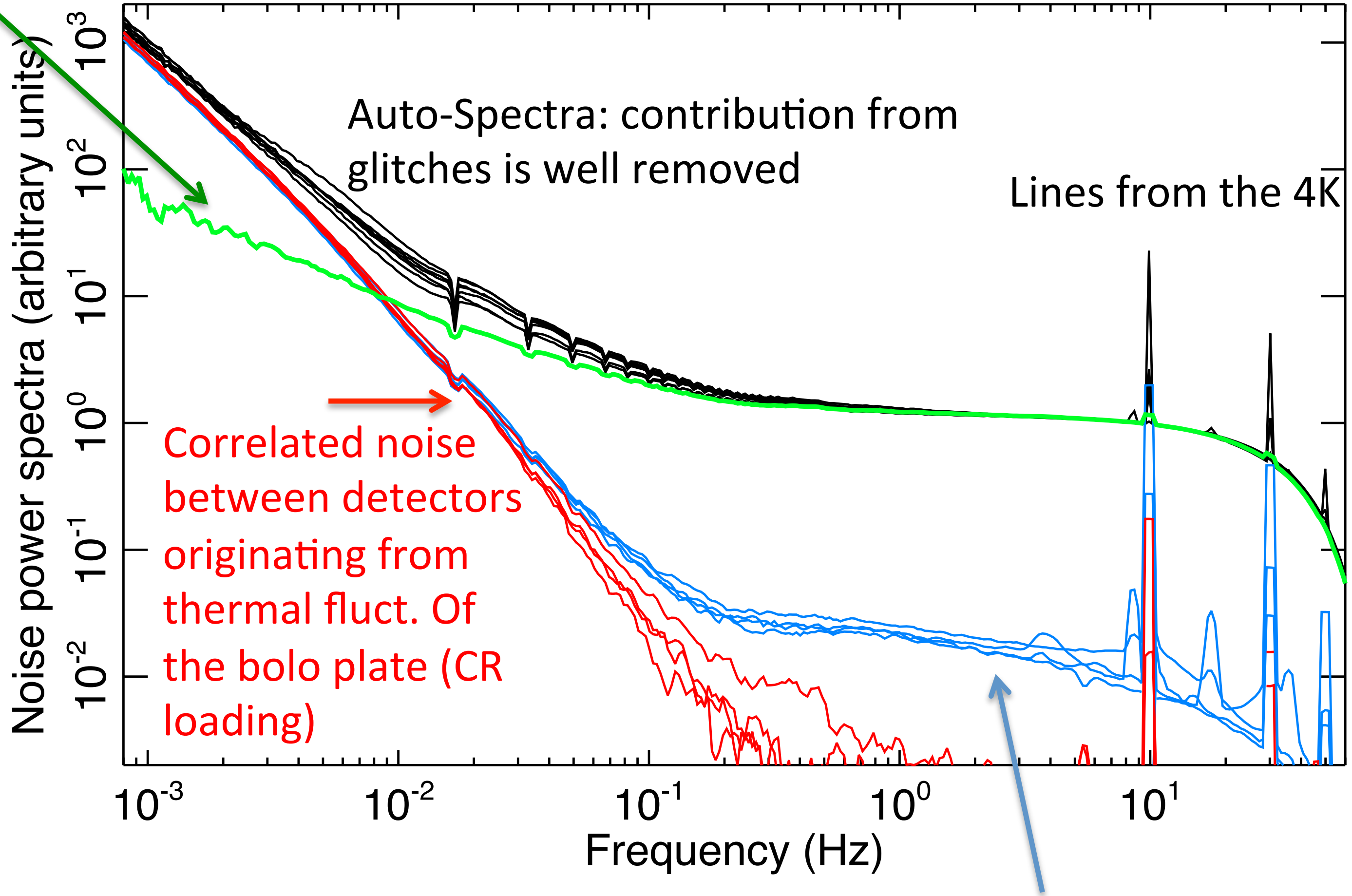
Not observed at that level on the ground

$f_{knee}$~ 0.15 Hz

No clear explanation, probably not due to CRs since not modulated as glitch rate

Fundamental limit after removal of systematics

Auto and cross power spectra



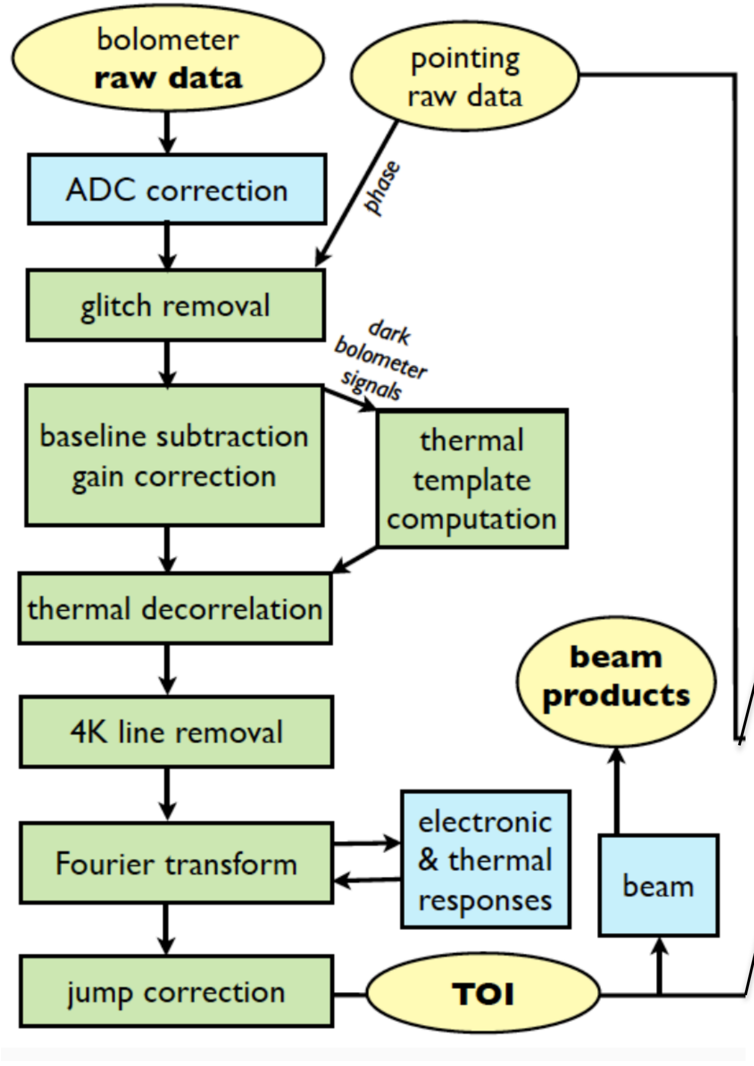
Auto-Spectra: contribution from glitches is well removed

Lines from the 4K

Correlated noise between detectors originating from thermal fluct. Of the bolo plate (CR loading)

Glitches below the detection threshold common between PSB-a and PSB-b
Provide a limit on the level of remaining glitches in data

# HFI processing pipeline overview



Map-making code (destriper)

Calibration

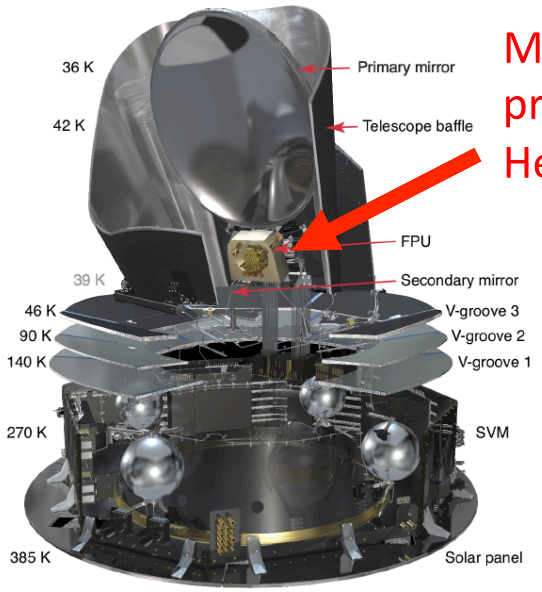
Map-making is complex and required the correction of other effects:

- 1/f noise
- long time constants
- BP mismatch
- FSL correction,
- 2nd order ADC correction

in an iterative way, using templates if available.

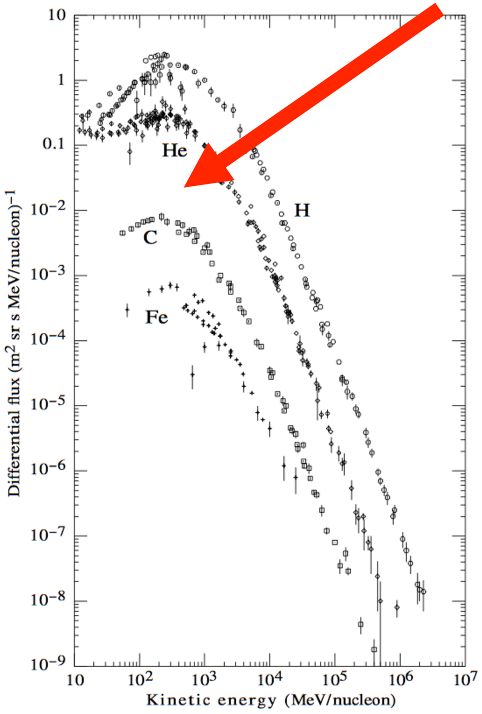
**As the processing evolves, more and more effects are treated at the map-making level**

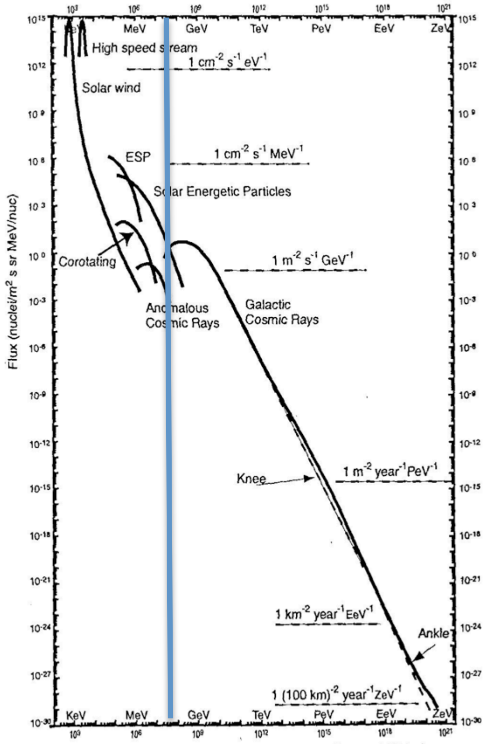
# Cosmic rays at L2



Mainly galactic protons and Helium nuclei

CR of ~ 1 GeV dominate

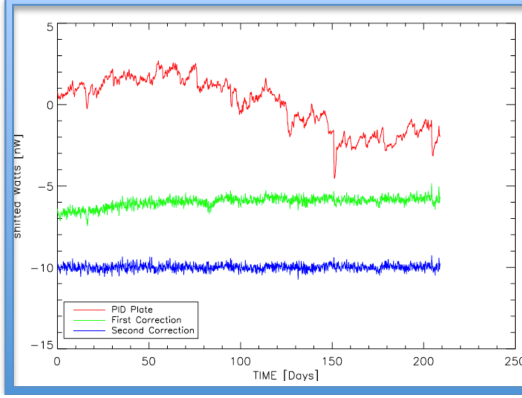




Cut off due to material around the detectors at ~ 50 MeV

No contribution from solar particles which can not reach the detectors, except during flares

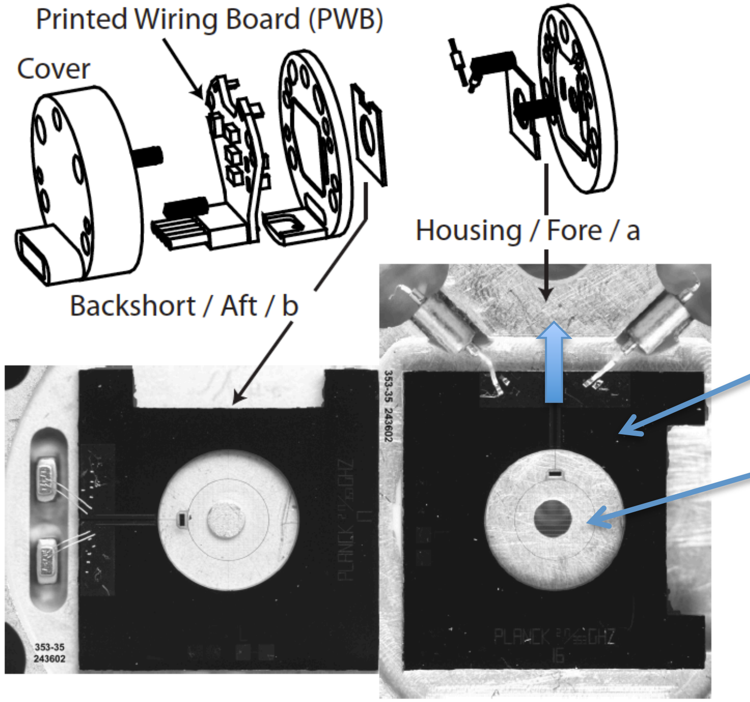
Amplitude of the spectrum at L2 is modulated by solar activity

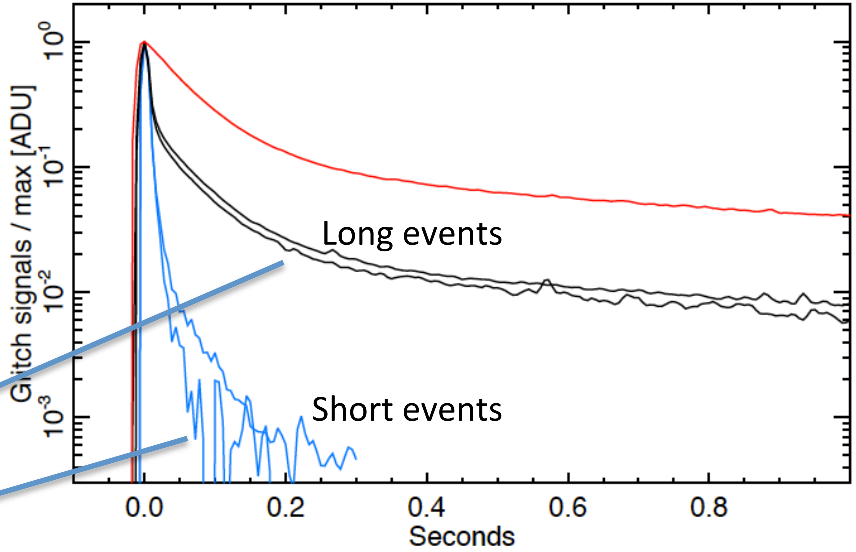


Thermal fluctuations of the focal plate are caused by CR:

Compensated by PIDs on time scales > 1h

# CR interaction with HFI detectors





- Long glitches are direct impact of protons in the silicon wafer

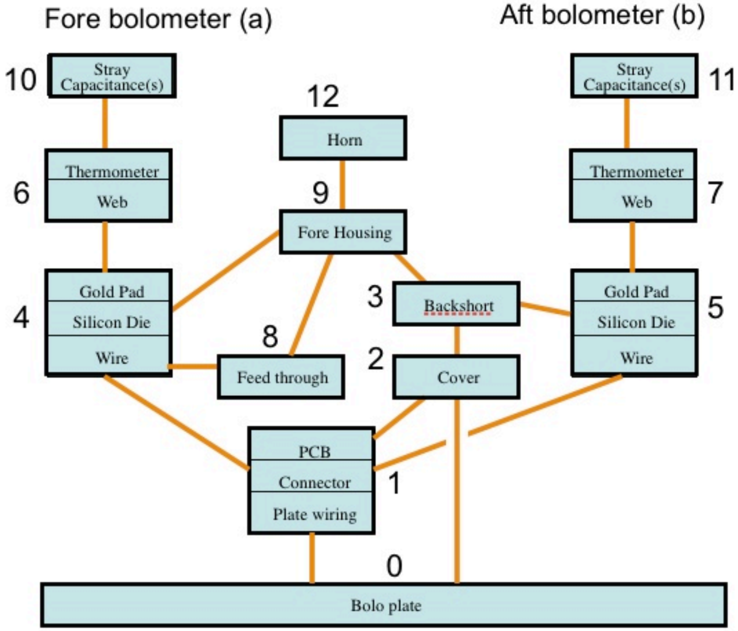
- short glitches are direct impact of protons in the grid/thermistor. Should be representative of response to photons.

This was proved with the help of ground tests with alpha particles

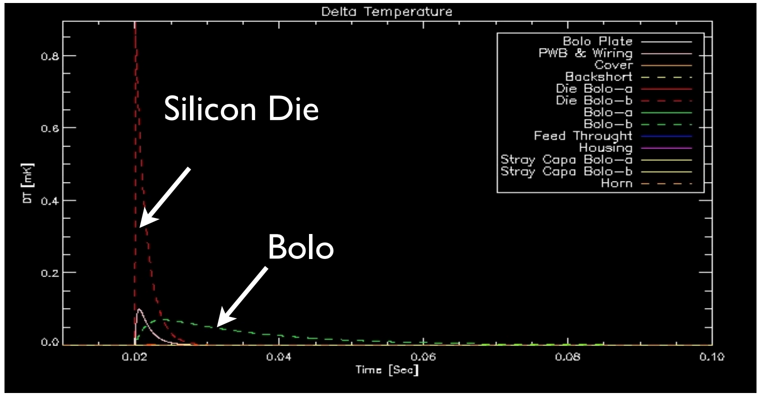
Thermal modeling is important. Long time constants come from the links between the wafer and the detector housing

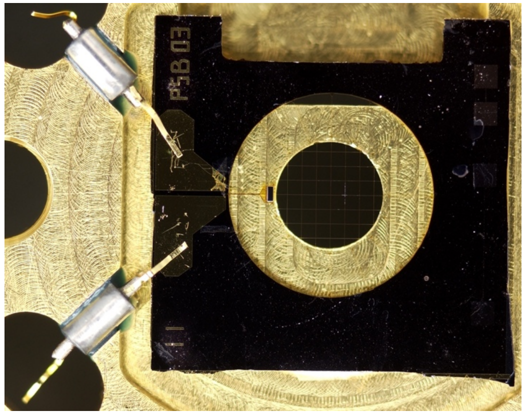
# Ground tests and thermal modeling

Ground tests were not performed to a sufficient accuracy to provide a definitive answer on the thermal path



Simulation of a 23MeV Proton in the silicon die





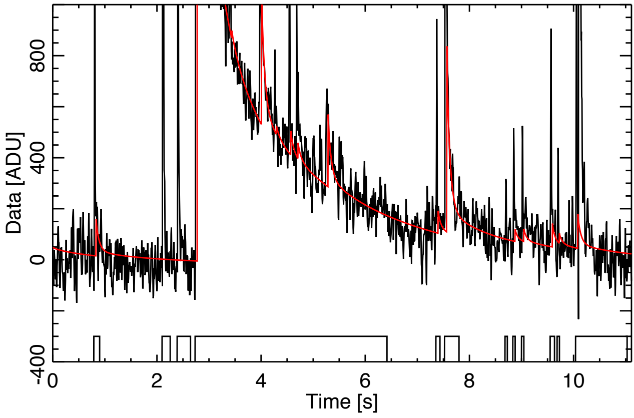
Basic Equation

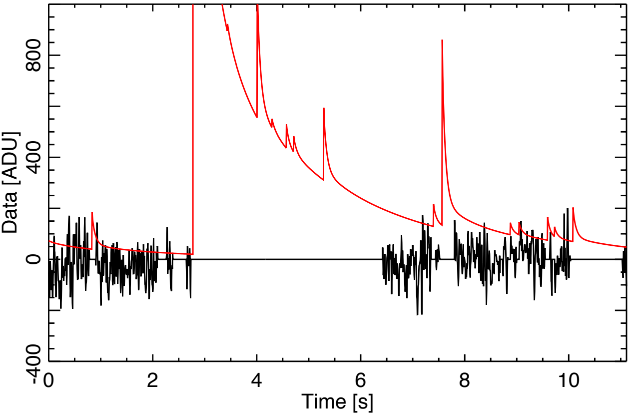
$$C_j \frac{dT_j}{dt} = \sum_{i=0}^{12} G_{ij}(T_i - T_j)$$

# Cosmic ray removal

Joint fit of templates for each detected event.

- Removal of long glicth tails
- Flagging 10 to 25 % of data depending on the detector

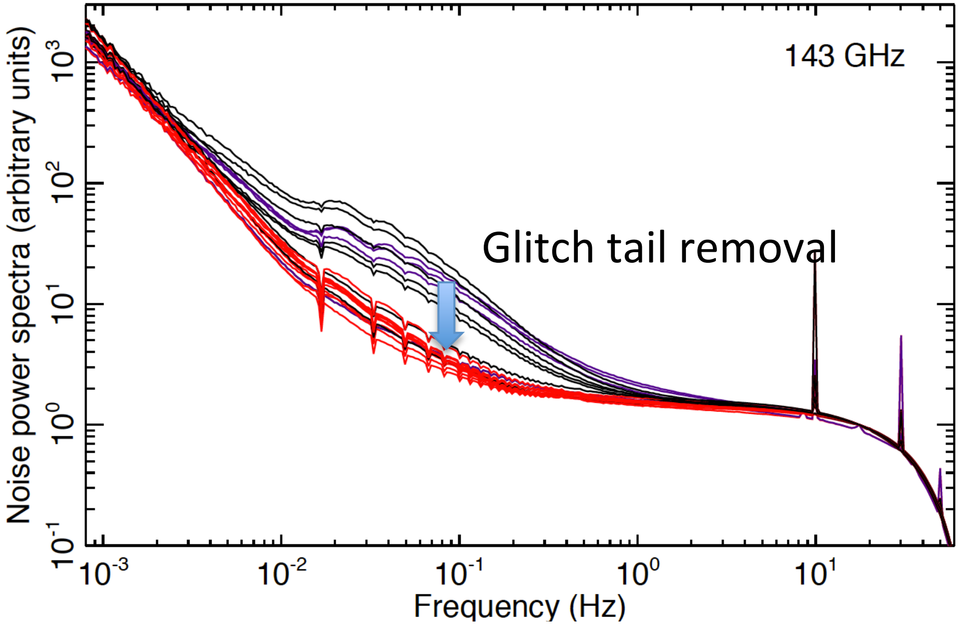




Analysis made difficult because of the high confusion of events

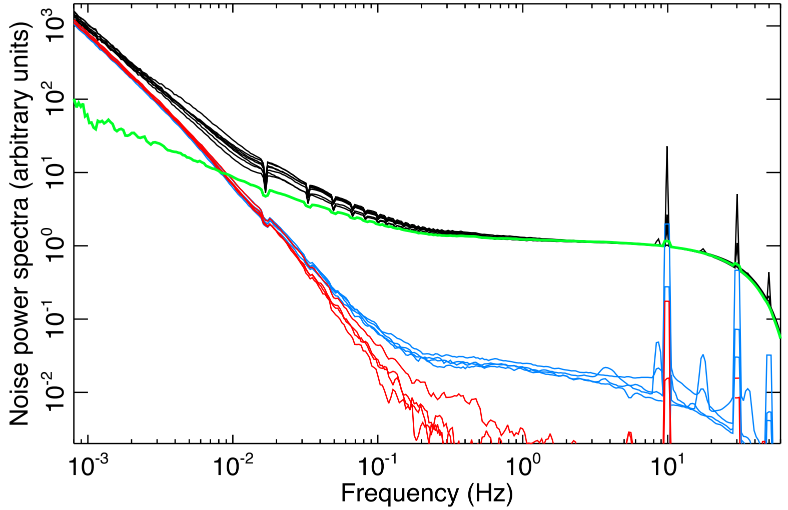
Residual at the level of noise for the worst channels at low frequencies < 0.2 Hz

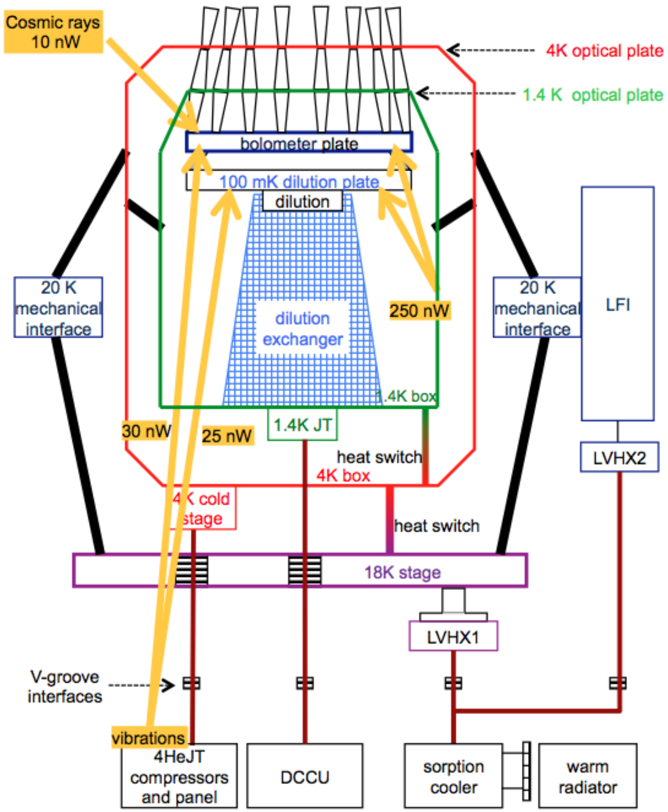
At the end, the glitch contribution to the noise on the maps is significant only for ell < 10, still smaller than detector noise


Glitch tail removal

# Lines induced by the 4K compressors

4He – JT cooler induced sharp lines in the data, due to electromagnetic and microphonics interference with the detector wires

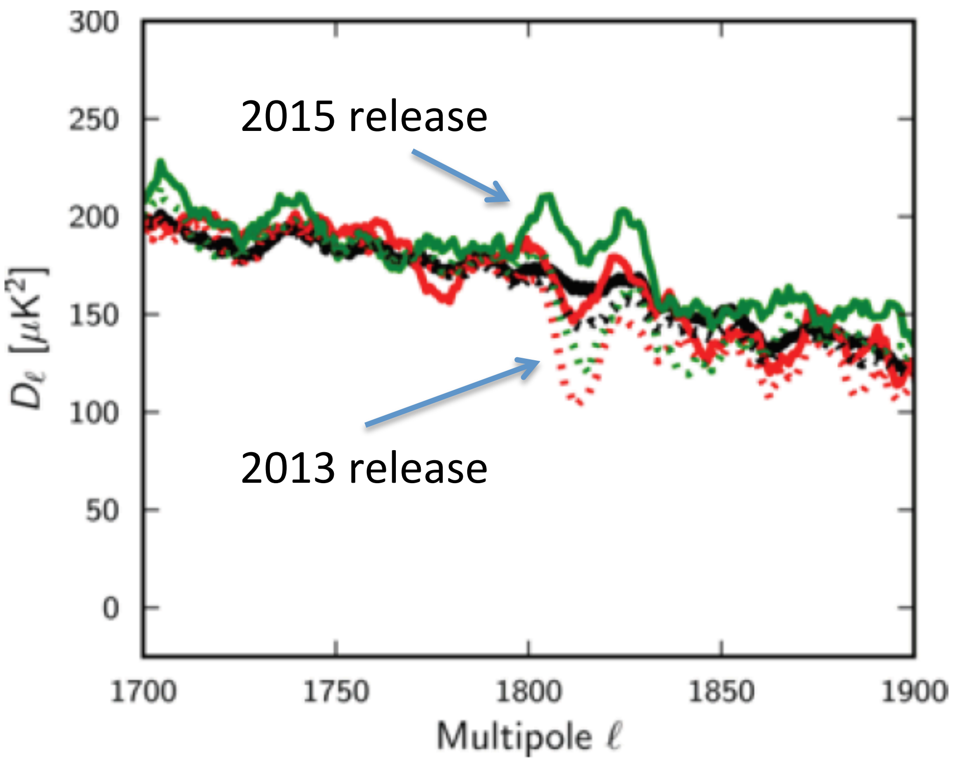




Data acquisition locked on the 4K cooler compressor: fixed line frequencies, multiple of 20 Hz (before demodulation)

Amplitudes vary during the mission

# 4 K line processing



Removed by notch filters, ring by ring

Resonant rings, for which harmonics of the signal are close to the 4K line frequencies are removed

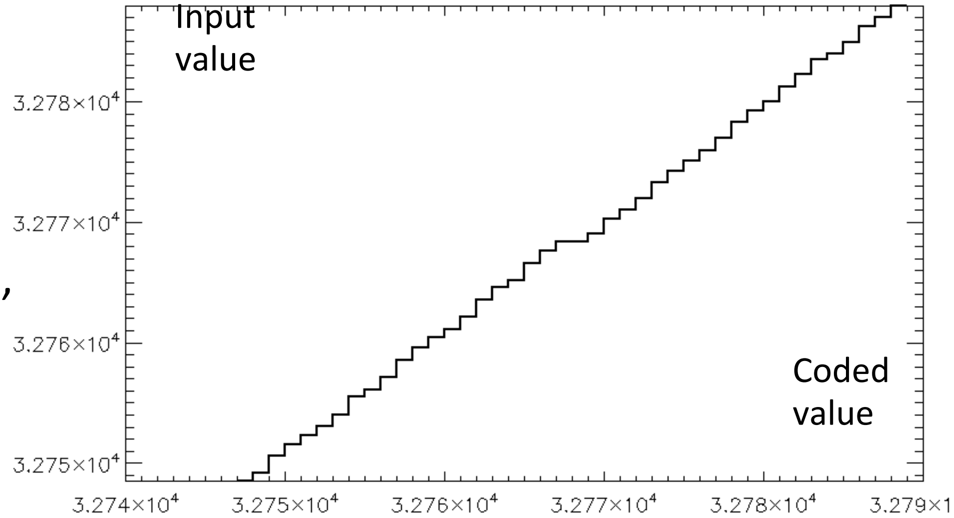
Better rejection for 2015 results correcting an artifact affecting cosmology in 2013 data.

→ Biggest problem is that 4K lines affect the ADC non-linearities!

# ADC non-linearities

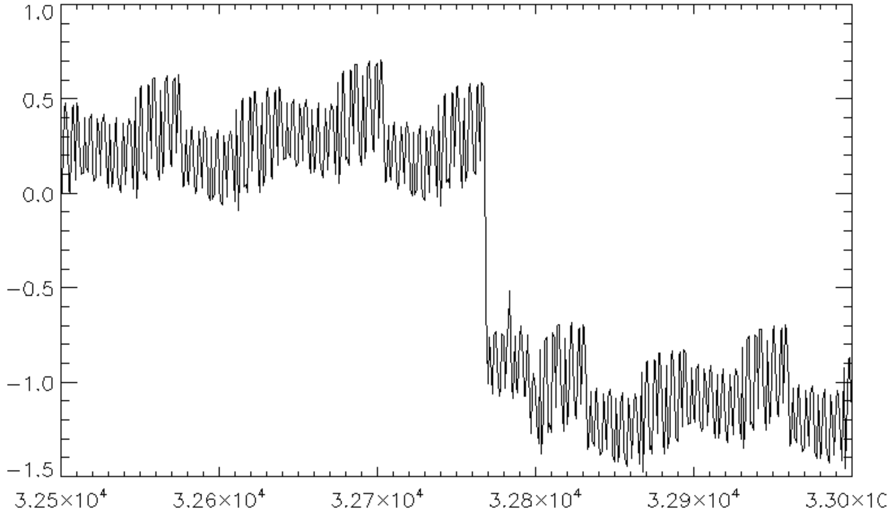
Analog to Digital convertor have some non-linearities

This problem was not considered before flight, the ADC response had to be guessed from flight data!



Cosmological data Planck data are sampling -300 to +300 ADUs near the code 32768, that's where the non-linearity is larger!

Non-linearity ADC(x) - x:



Variations of the baseline of the data + signal (dipole) induced non-linearities of ~ 1%

# Model and correction

**The Electronics response** estimated from:

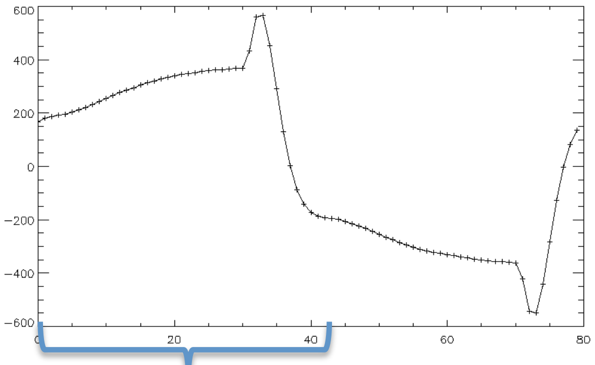
- CPV data
- Raw data every 100 seconds (same 4K phase)

**The ADC** is estimated from

- The raw data measurement

at 4K (end of the mission)

Fast sample data (40*180 Hz):



One sample

Including **4K lines**:
20, 80, 160, 200 Hz

- CPV data
- Science data

Model:

Digitization: $d_{\text{int}}(t) = ADC[d(t)]$

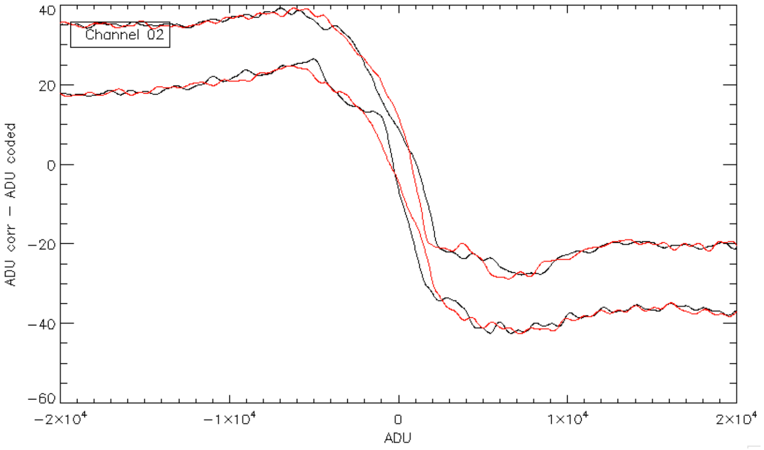
Data sample: $$m_i = \sum_{t_i}^{t_i+40} ADC(d(t))$$

Non-linearity function : $\langle m \rangle = F(S)$

Correction is straightforward with the knowledge of F.

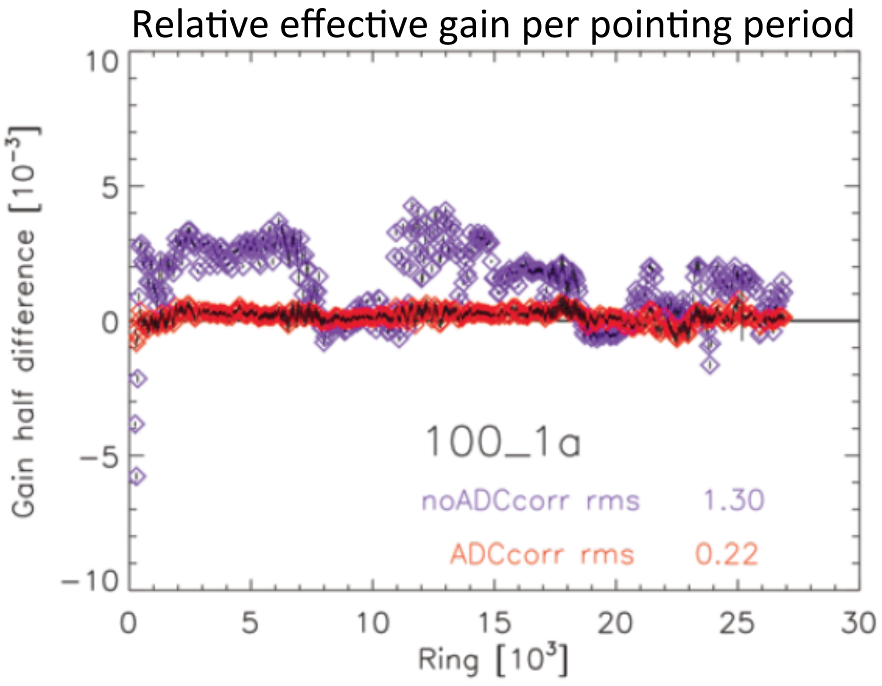
F is calculated from an estimation of the electronic and the ADC responses, and 4K lines

**Uncertainties in the 4K line freqs.** → **Main systematic effect in Planck for polar.**



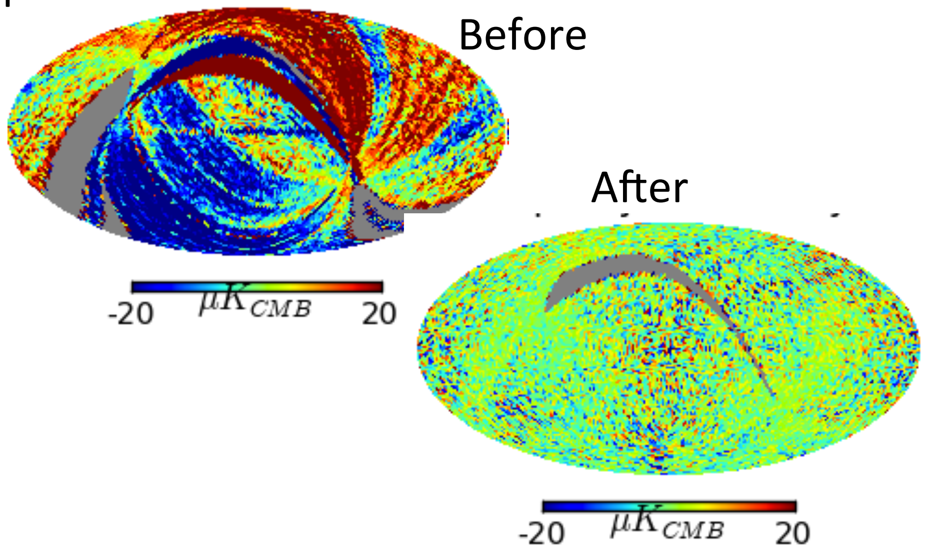
# ADC correction

**The correction is very effective but limited by the 4K line estimation.**

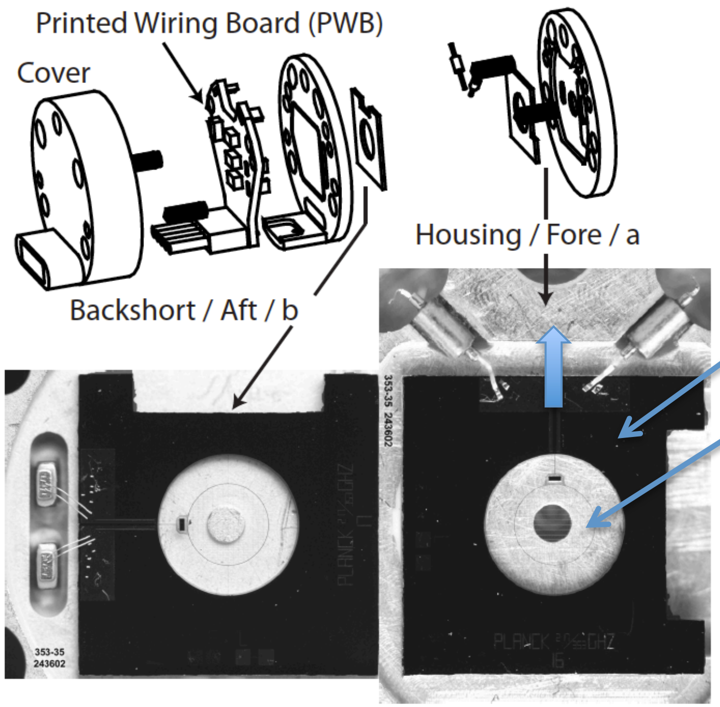

Relative effective gain per pointing period

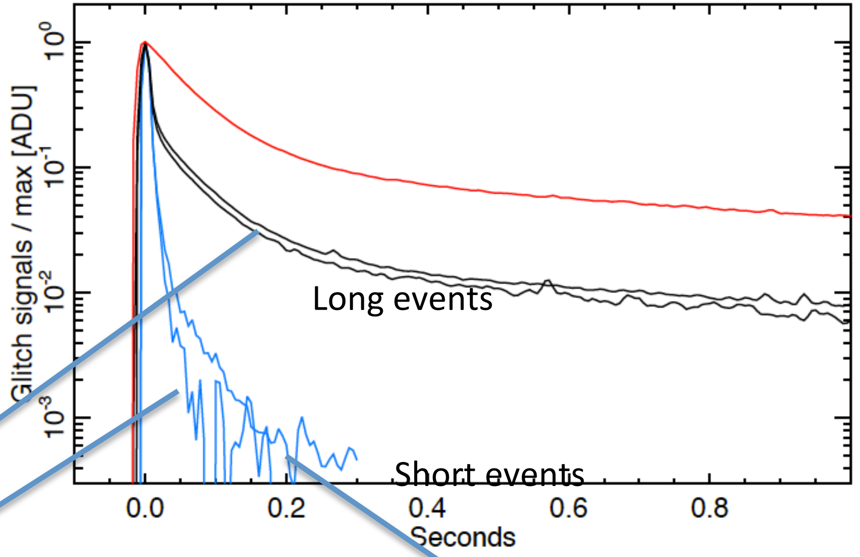
**A second correction was performed at the map-making level**

Jackknife : positive – negative parities

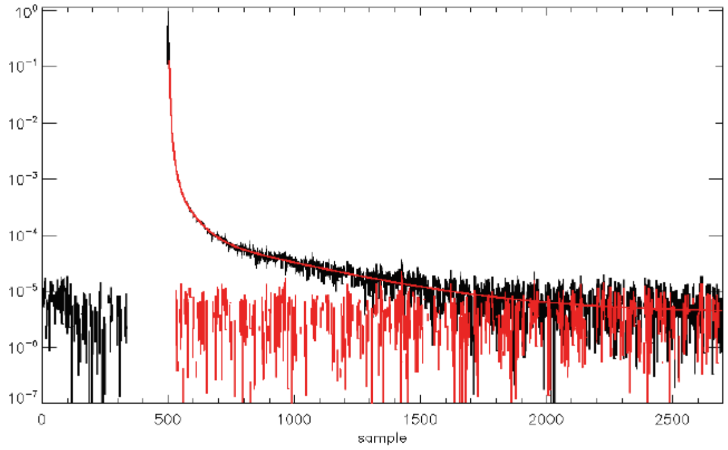


# Gain calibration and long time constants





Long time constants seen by stacking all events related to CR hitting on the wafer



Thermal modeling is important. Long time constants might come from the links between the wafer and the detector housing and are seen on both categories of glitches

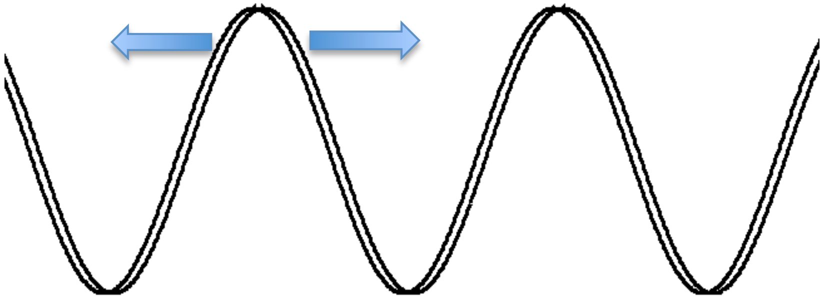
# Impact of long time constants on data

- Long time constants are observed in data ~ 2 s for the longest

  seen in the tail of short glitches

  seen on planet maps

  **induces a shift of the dipole**



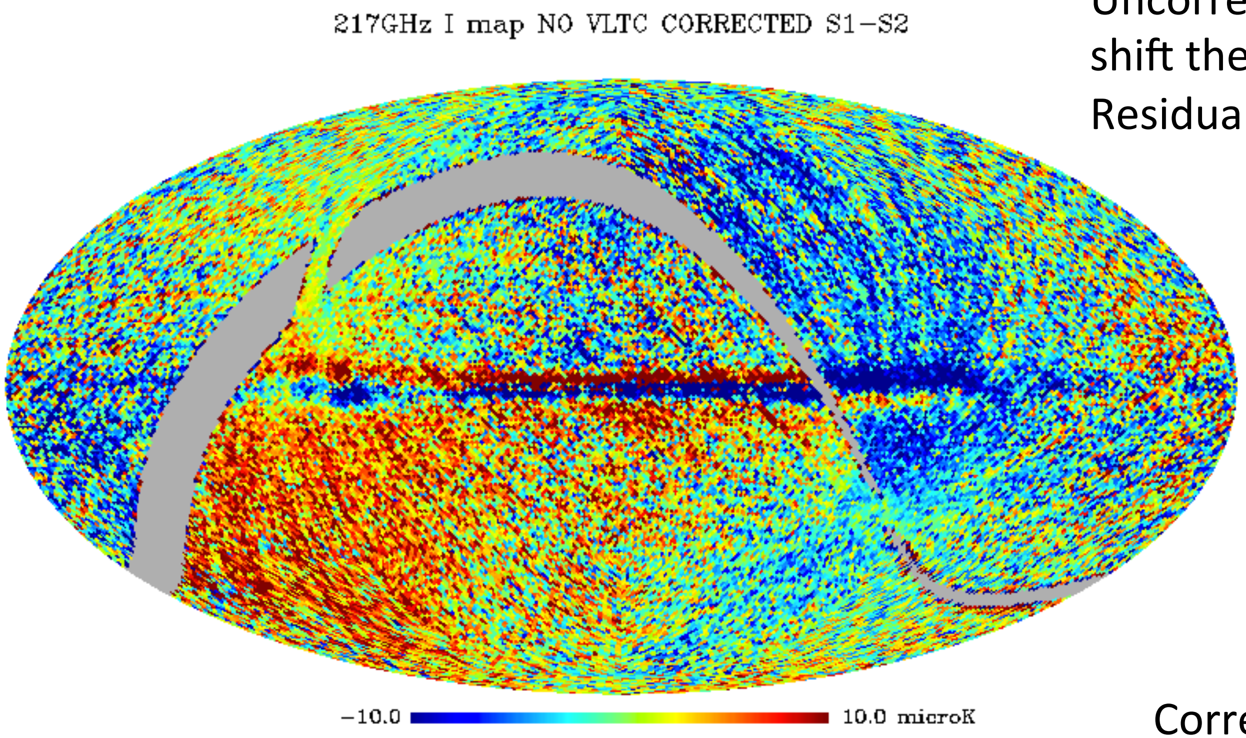
→ **1-2 % effect in the calibration if not properly corrected: affect l >~ 20**

→ variable from detector to detector

→ Different survey with nearly opposite scan directions helped to constrain and correct the longest time constants

# Survey difference maps

**Survey difference maps were useful to track and characterize systematic effect**



Uncorrected time constants slightly shift the galaxy

Residual dipole seen in the difference

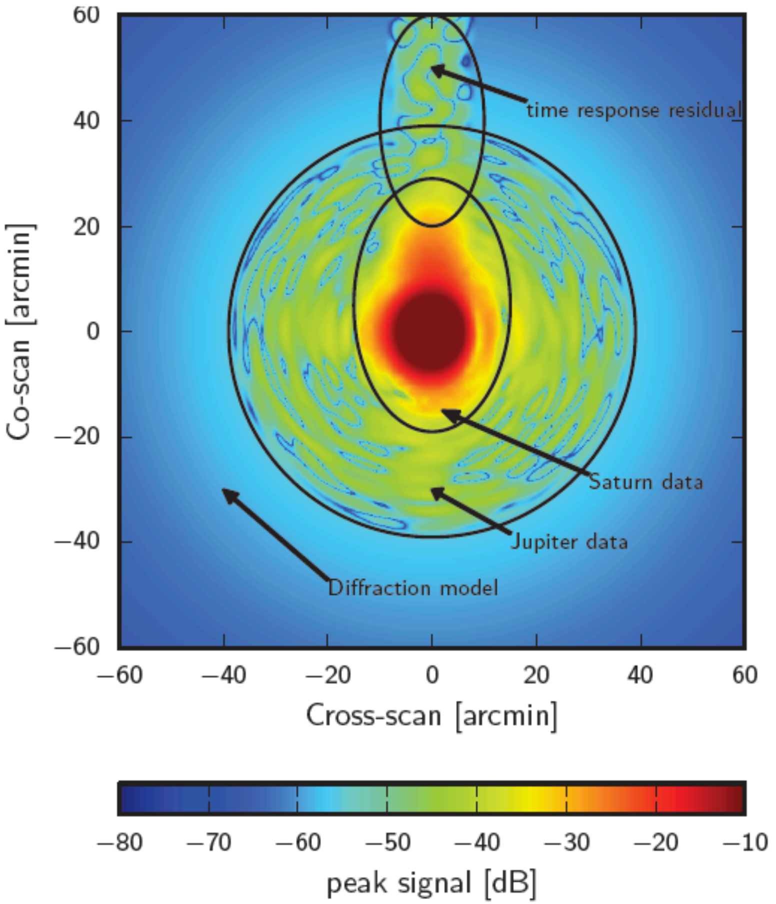
Corrected after optimization at the map-making level by template fitting

# Beam and transfer function estimation

- Time response is degenerate with the beam response

- The time response and beam shapes are estimated using a combination of planet scans (by symmetrizing the beam shape), galaxy crossings, bias steps (CPV phase) and glitch data.

- The pointing uncertainties (~ 3 arcsec) and glitch is the main source of errors in the main lobe estimation



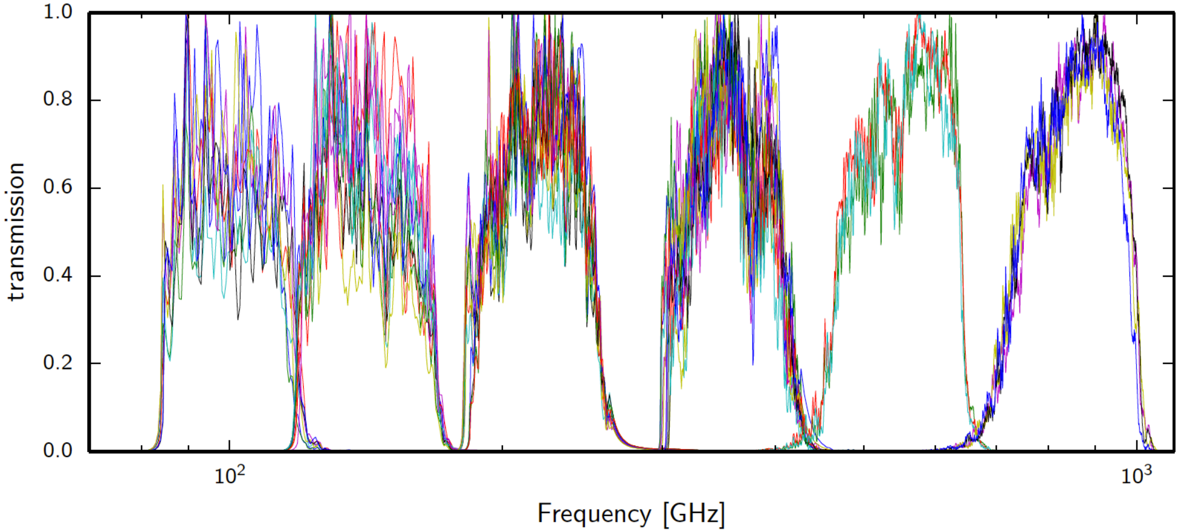
# High redundancies help

- Surveys with opposite scanning directions allowed optimization of parameters and correction of many systematic effects.

- Limited single detector cross-linking in Planck data : many effects on polarization as I -> P scale with <cos $2\Psi$> and <sin $2\Psi$>. Larger precession angle provides higher cross-linking params.

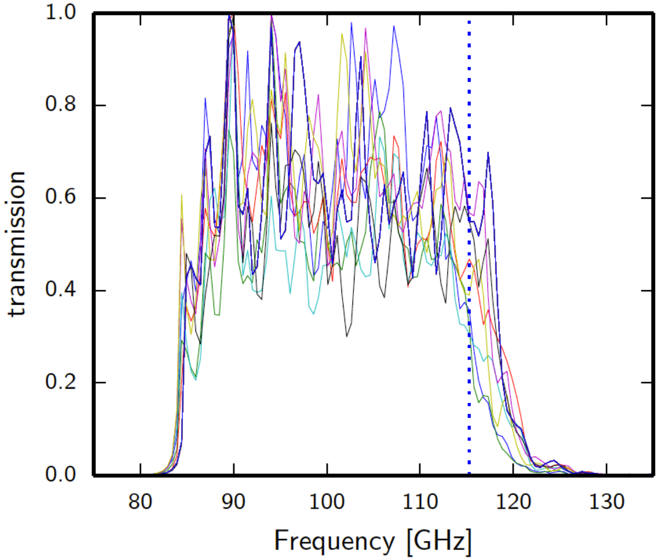
# Band-pass mismatch

Differences in the band shapes from detector to detector induced intensity to polarization of galactic components when calibrating on CMB



After integrating the dust spectrum:

A few percent effects for the amplitude of the dust from detector to detector



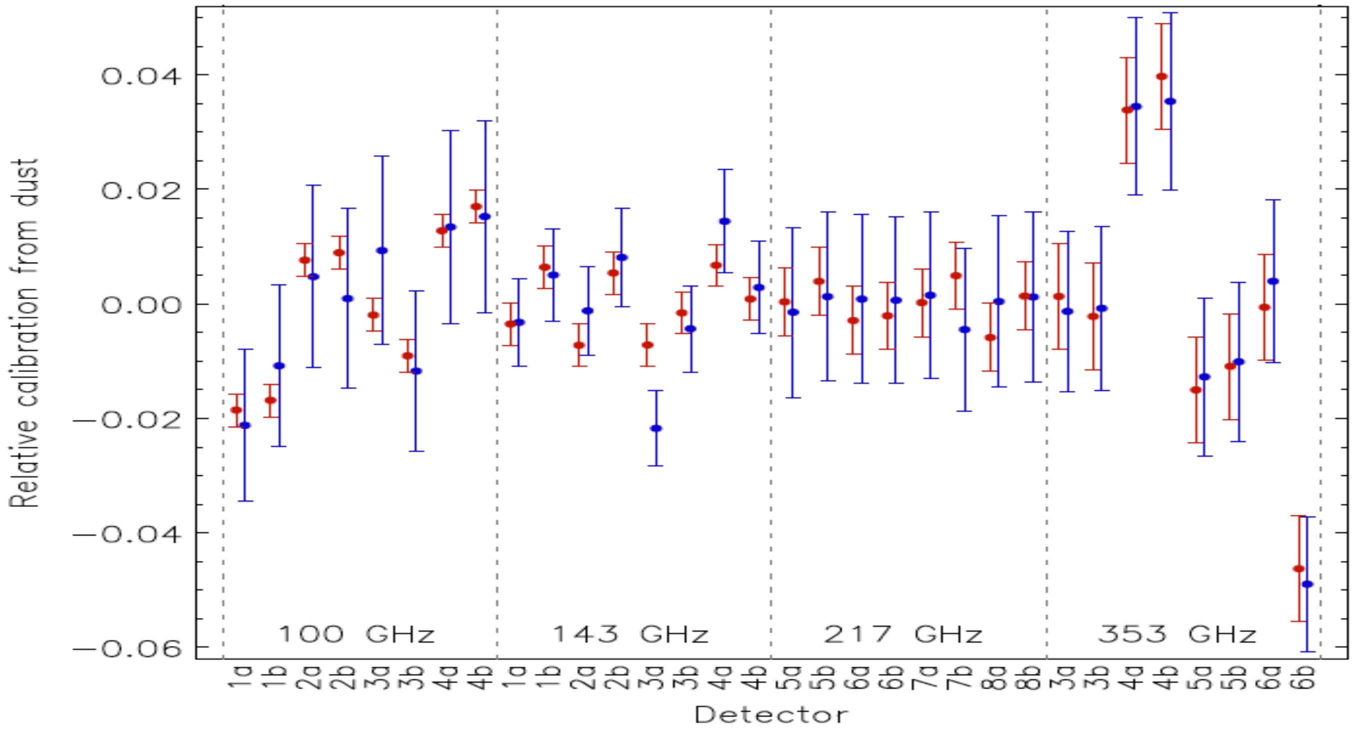
CO transition line 1-> 0 falls at the edge of the 100 Hz filters so the CO components has very different amplitude from detector to detector

# Band-pass mismatch correction

-Band passes were measured from the ground, but leakage coefficients have to be estimated from flight data

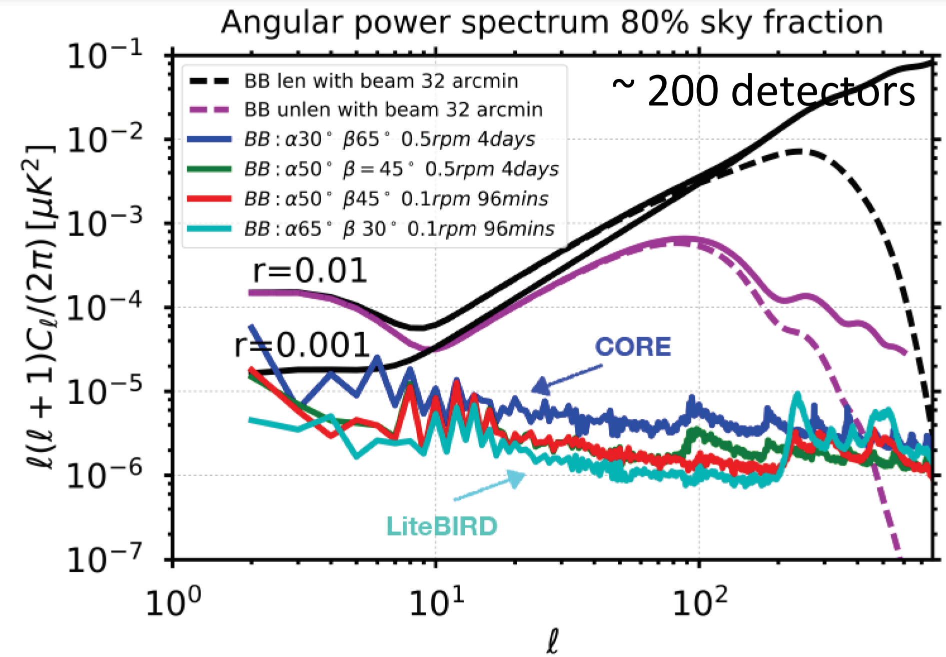
$$m = T_{Sky} + (\gamma_{Dust} - 1)T_{Dust} + (\gamma_{CO} - 1)T_{CO} + \ldots$$

- Joint estimation of CO and dust leakages at the map-making level. Naturally minimizes the survey difference contamination. Coupled with many effects.



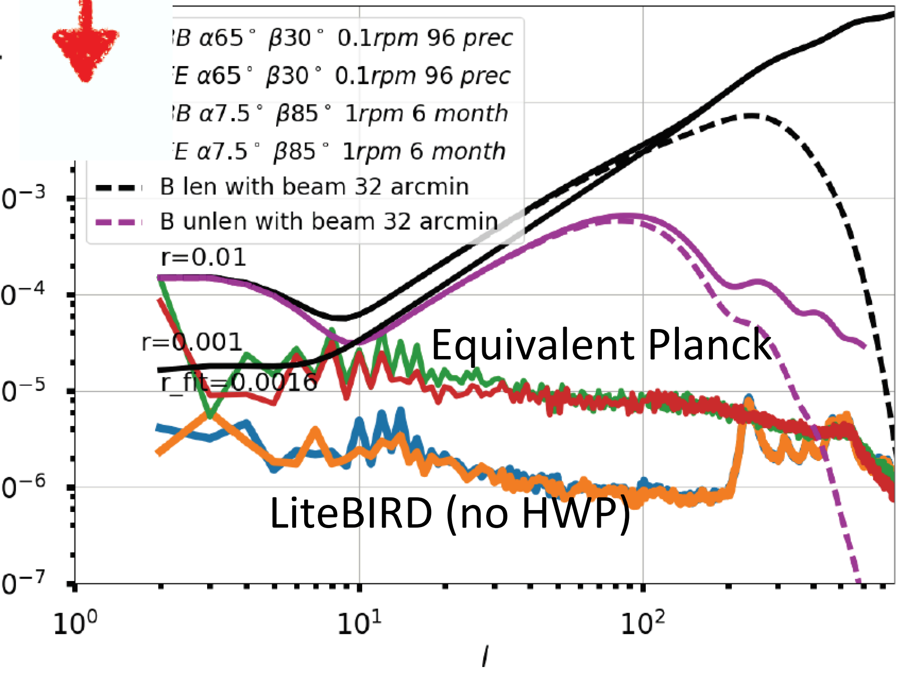
Effect mostly removed at the end

# Band-pass mismatch error prediction



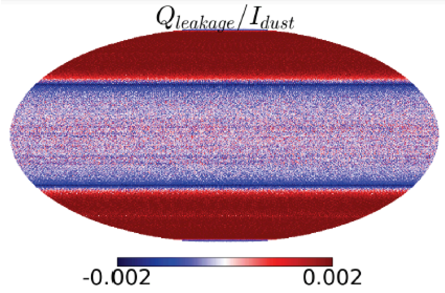
**Hoang et al.**

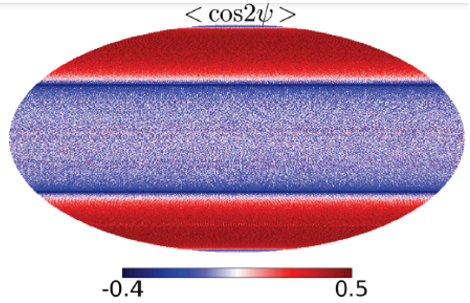
Precession angle



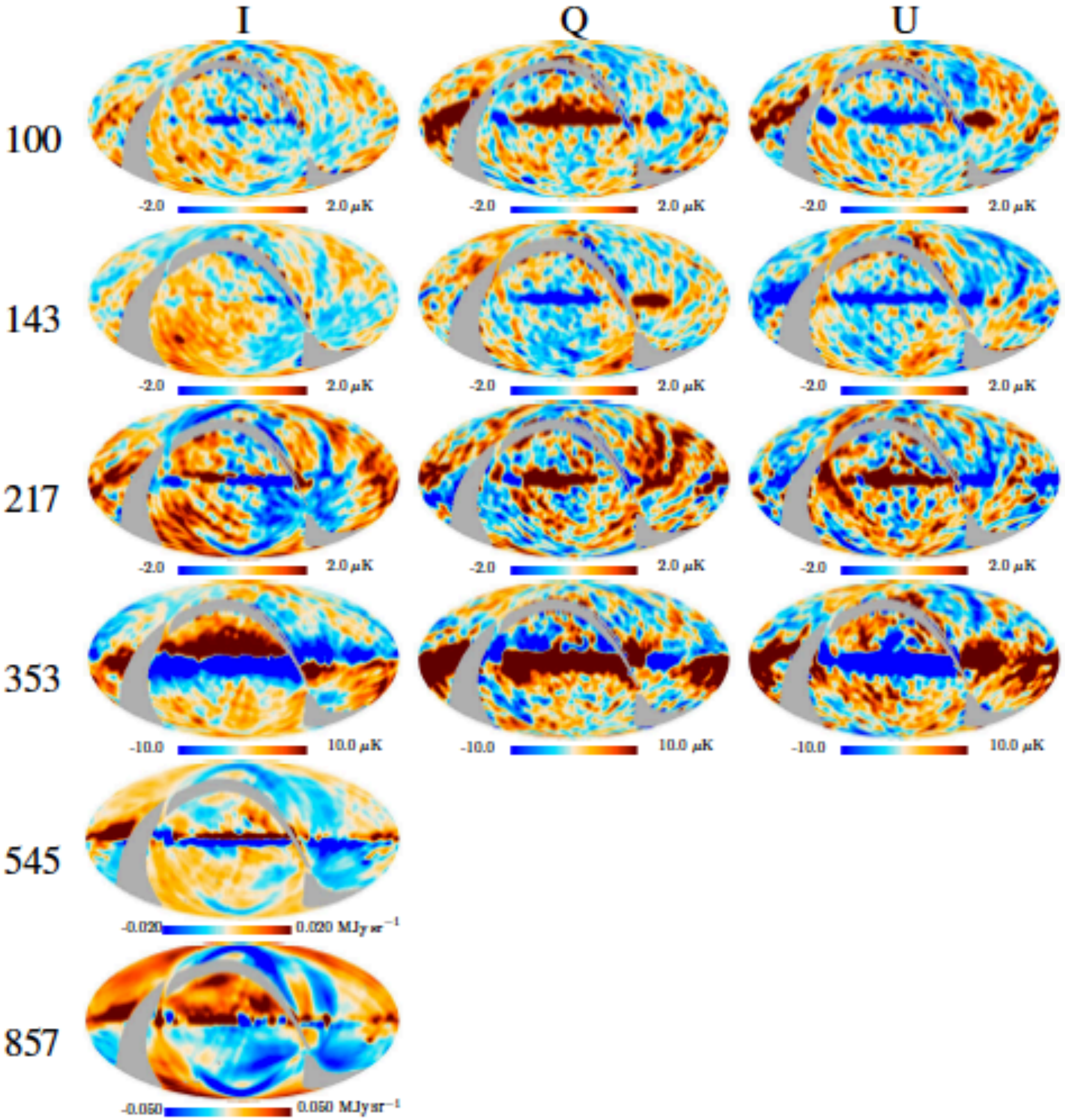
Equivalent Planck

LiteBIRD (no HWP)

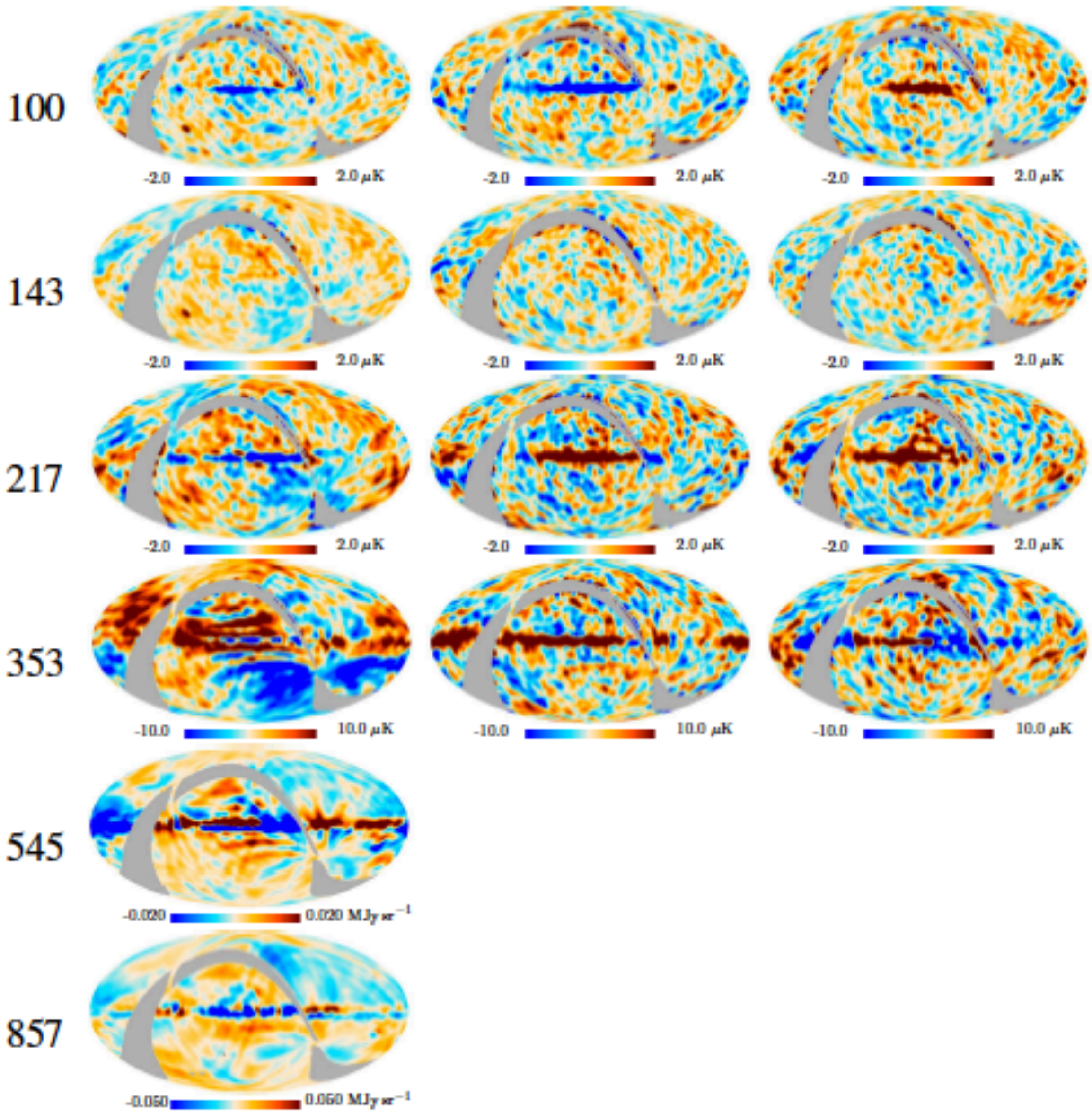




# Odd even rings, null test 2015



# Odd even rings, null test 2017



# Summary of systematic effects (HFI)