Planck-HFI lessons learned on systematics and calibration

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Lessons from Planck (1)

- The data analysis and cleaning was a long process and required many iterations
- The required precision of detector calibration was 10^{-4}!
- At the end, we reached the detector noise fundamental limit for cosmological channels
- Some effects were not expected at the level we found them in flight data
  - --> ADC non-linearities: T to P leakage
  - --> Long time constant
  - --> Response to cosmic rays
  - --> 1/f noise
  - --> Band-pass mismatch: T to P leakage
- Coupling between effects was problematic. Ex: 4K lines and ADC non-linearities

Last important systematics:

- ADC residuals
- BP mismtaches → improved in 2018
- Polarization efficiency → improved in 2018
- Beam mismatches → improved in 2018

Lessons from Planck (2)

- 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 and scanning strategy with more scanning angles will help.
- Importance of observation redundancies: different survey, different scanning angle (limited for Planck), different detectors, ~ 50 circles per ring, etc…
- The 353 GHz channel was harder to process but is a key channel.
- **Importance of the dipole** as a calibrator for systematic effects.
- Importance of housekeeping 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 → move towards joint analysis of systematics and component separation. End to end simulations are required!

Data reduction

Model of the raw data:

Additive effects such as glitches

Electronic response

4K lines (A_k, w_k, …)

$$d_i(t) = g_i \int R_i(t - t')W(t')\left[X_i(t') + \sum_j T_{ij}(t')\right]\mathrm{d}t' + Q_i(t) + n_{J\,i}(t) + \sum_c F_{ic}(t).$$

Gain

Transfer function (A, τ, …)

$$X_i(t') = \left[\int H_i(t' - t'')\left(\{B_{i;\psi_{it''}} * [S_i + o]\}(\vec{r_{t''}}) + n_{s\,i}(t'')\right)\mathrm{d}t''\right]$$

Lobes

Data are digitized, averaged over 40 samples, and compressed on board

ADC [d (t_n)]

Data processing: compression

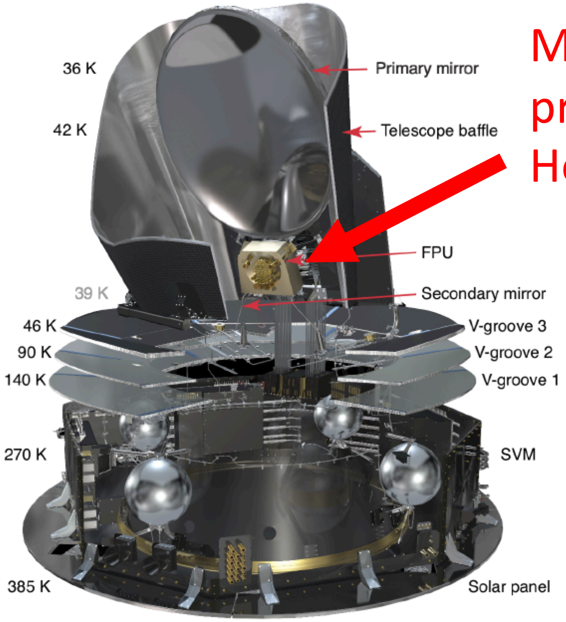
Goal to reach

$$d_i(t_p) = \{B_{\psi_{itp}} * [S_i + o]\}(\vec{r_{t_p}}) + n_{i;\mathrm{total}}(t_p).$$

Symmetrized lobe

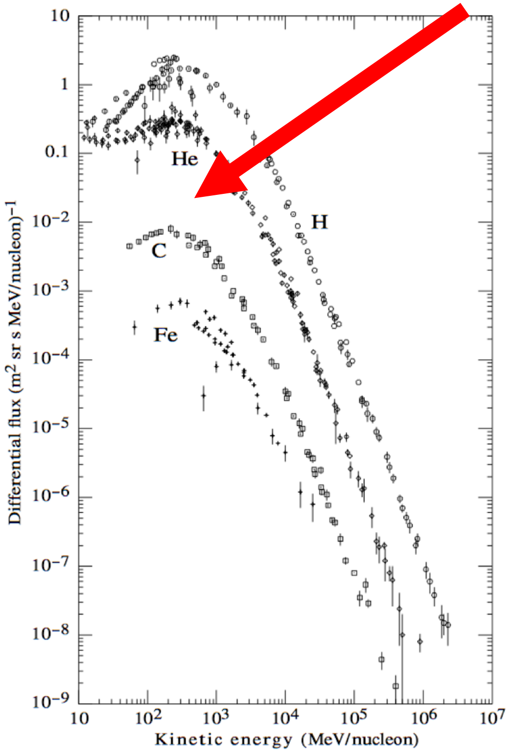
Many parameters are unknown and must be measured in flight

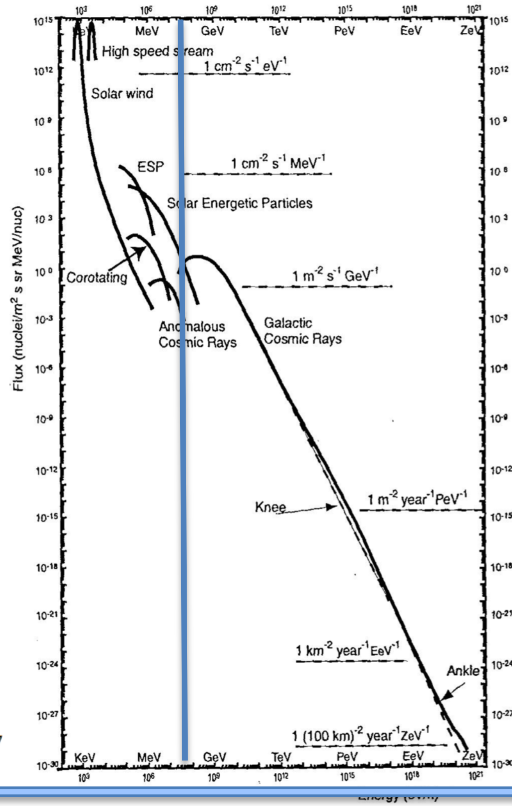
Cosmic rays at L2



Mainly galactic protons and Helium nuclei

CR of ~ 1 GeV dominate

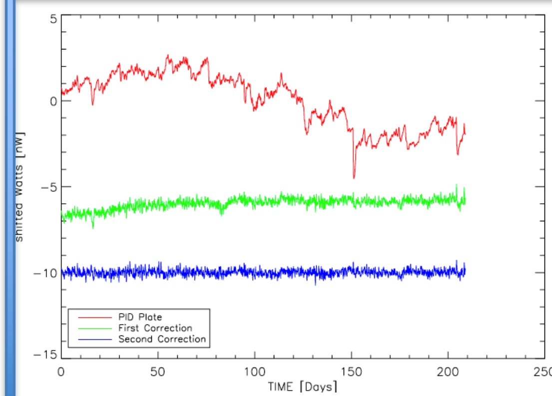




Cut off due to material around the detectors at ~ 50 MeV

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

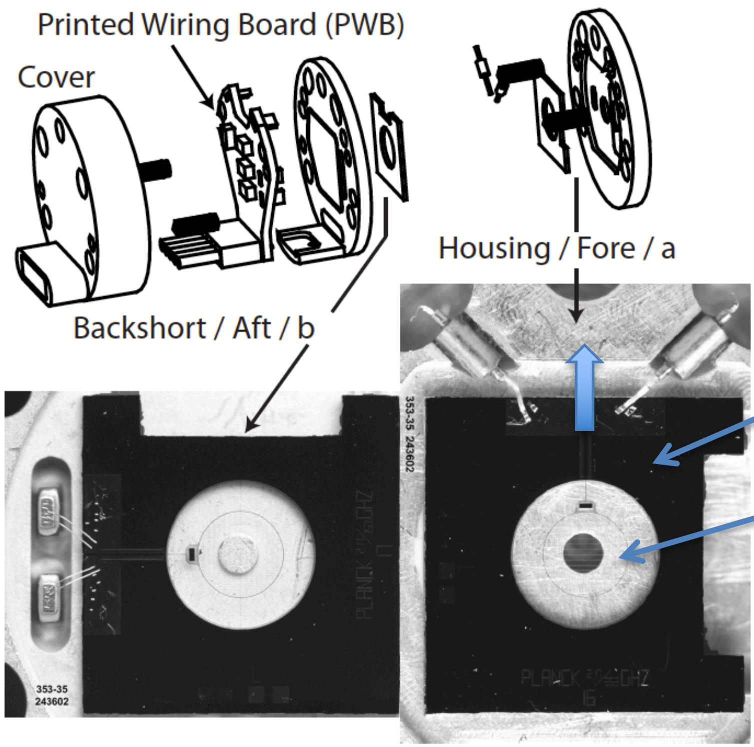
Amplitude of the spectrum at L2 is modulated by solar activity

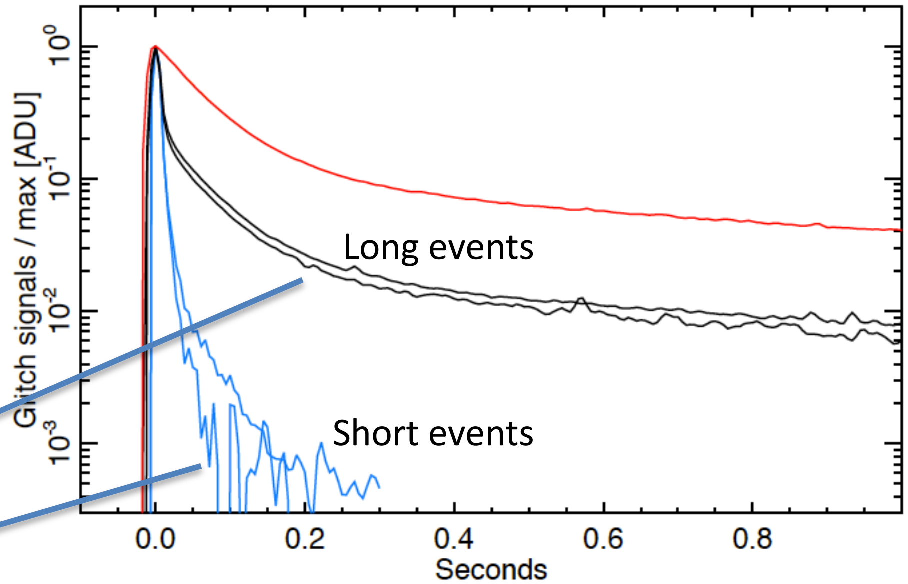


Thermal fluctuations of the focal plate are caused by CR:

Compensated by PIDs on time scales > 1h

CR interaction with HFI detectors





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

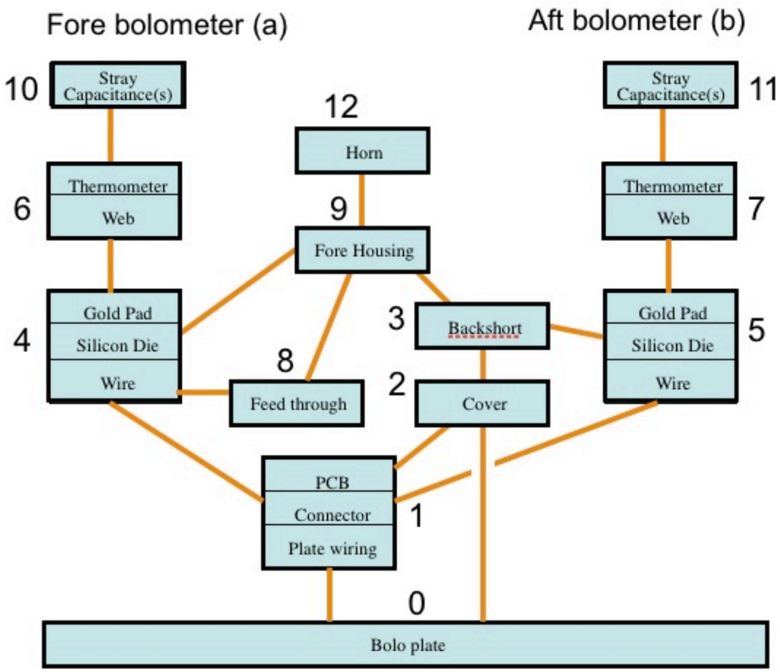
- Long glitches are direct impact of protons in the silicon wafer

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

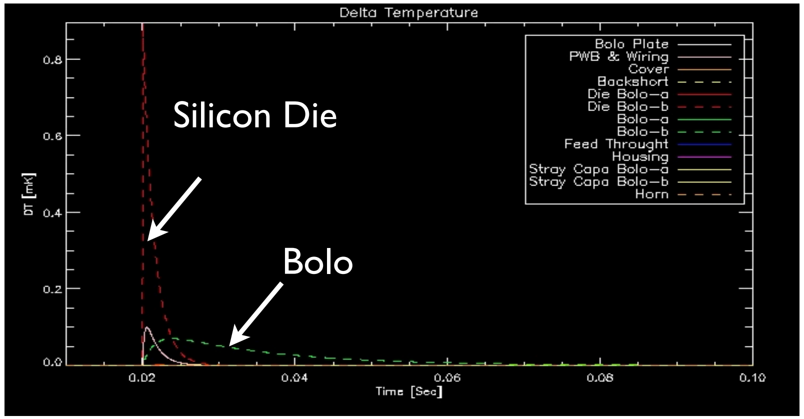
This was proved with the help of ground tests with alpha particles

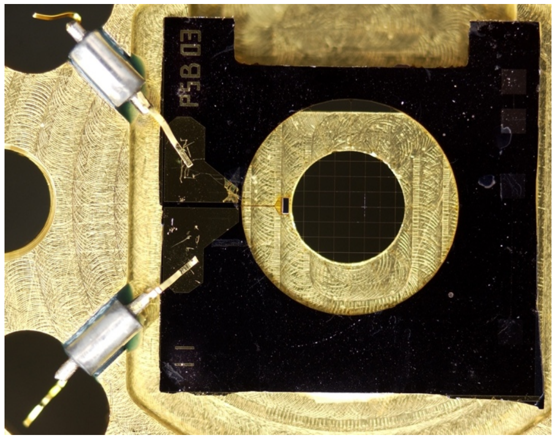
Ground tests and thermal modeling

Ground tests did not provide a definitive answer on the thermal path



Simulation of a 23MeV Proton in the silicon die





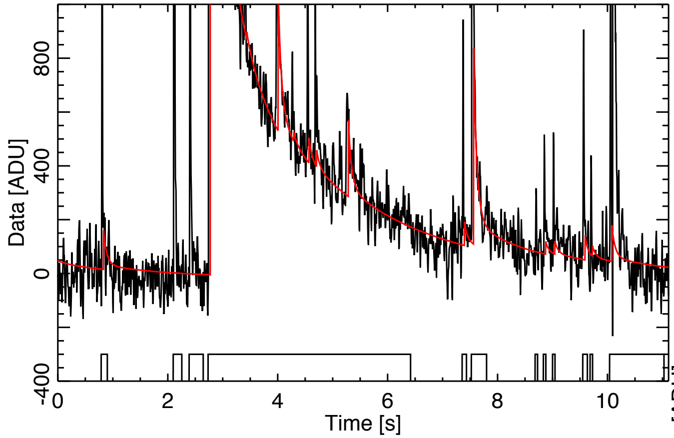
Basic Equation

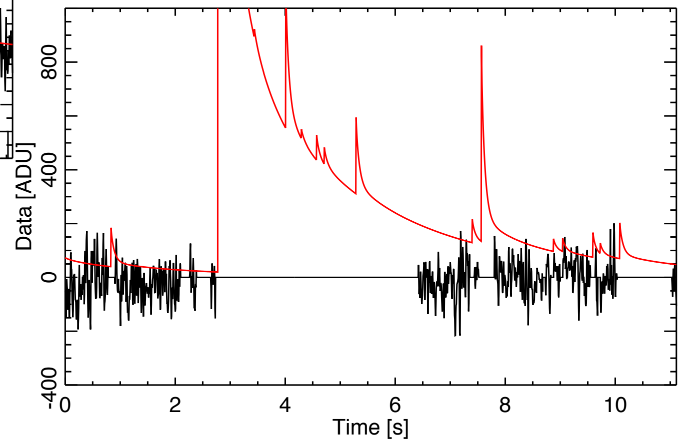
$$C_j \frac{dT_j}{dt} = \sum_{i=0}^{12} G_{ij}(T_i - T_j)$$

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

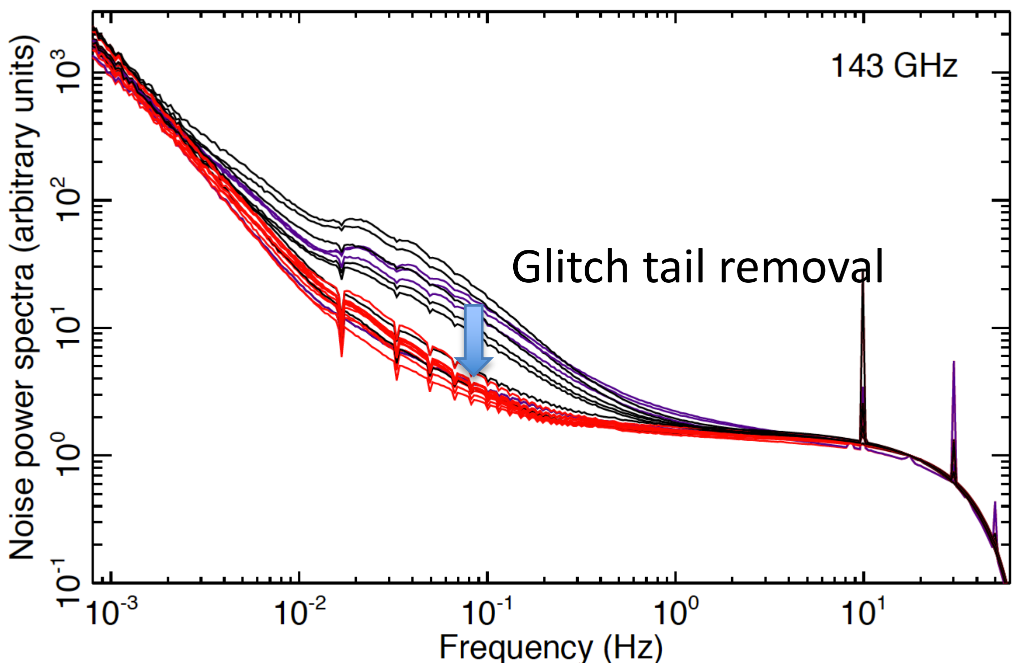




Analysis made difficult because of the high confusion of events

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



Noise in HFI time ordered data

Uncorrelated noise

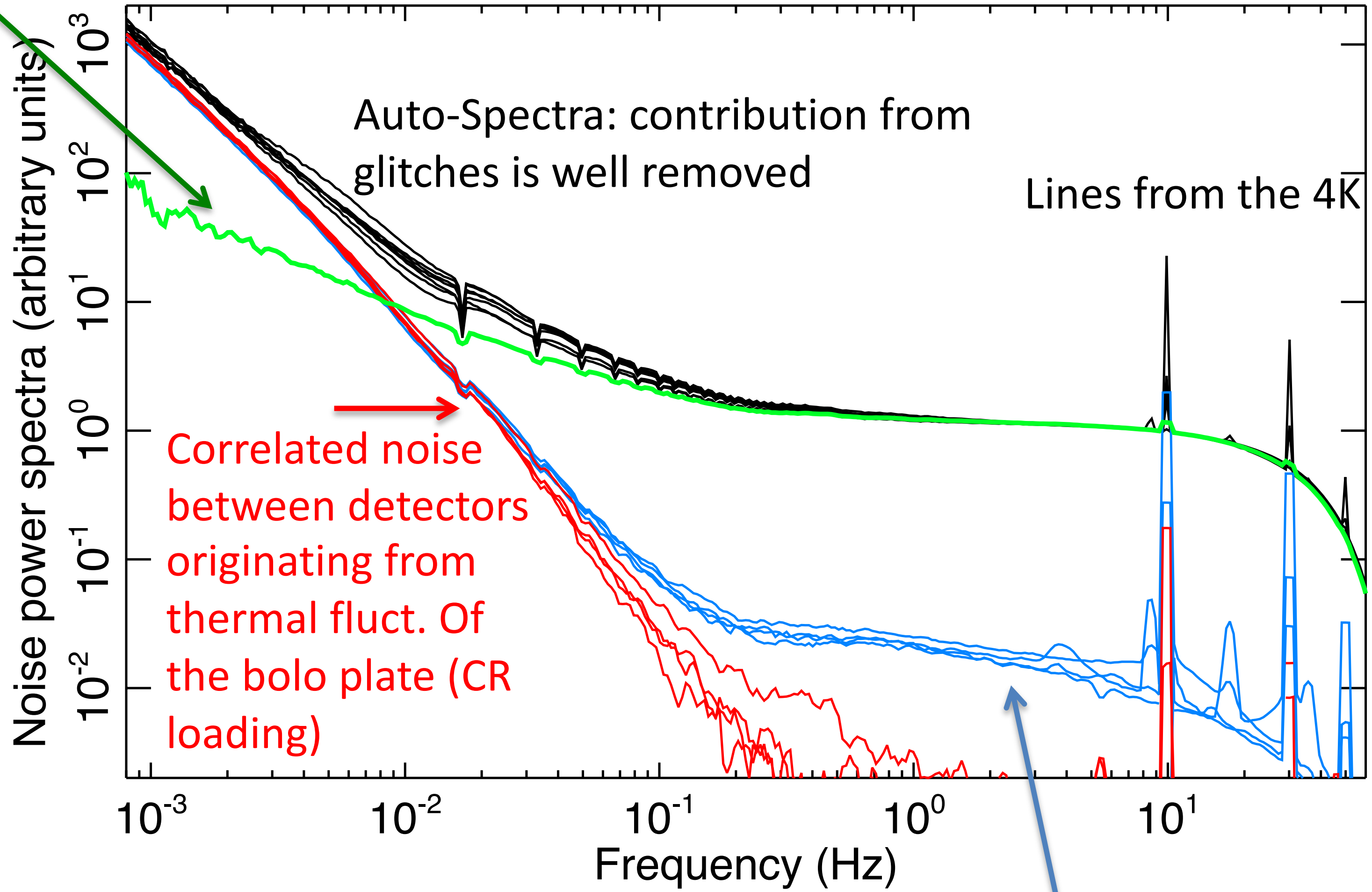
Not observed at that level on the ground

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

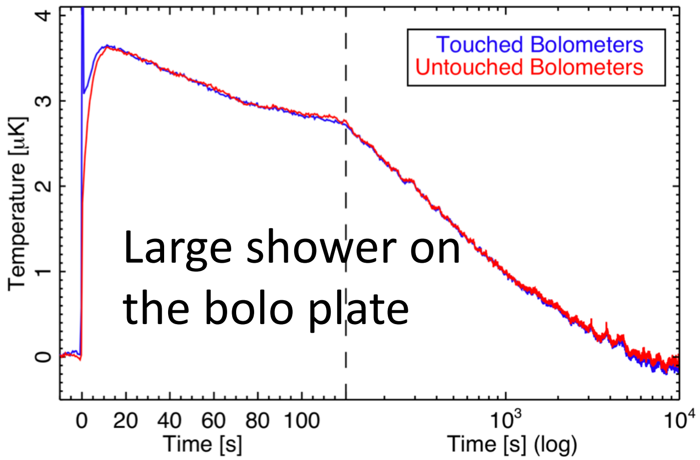


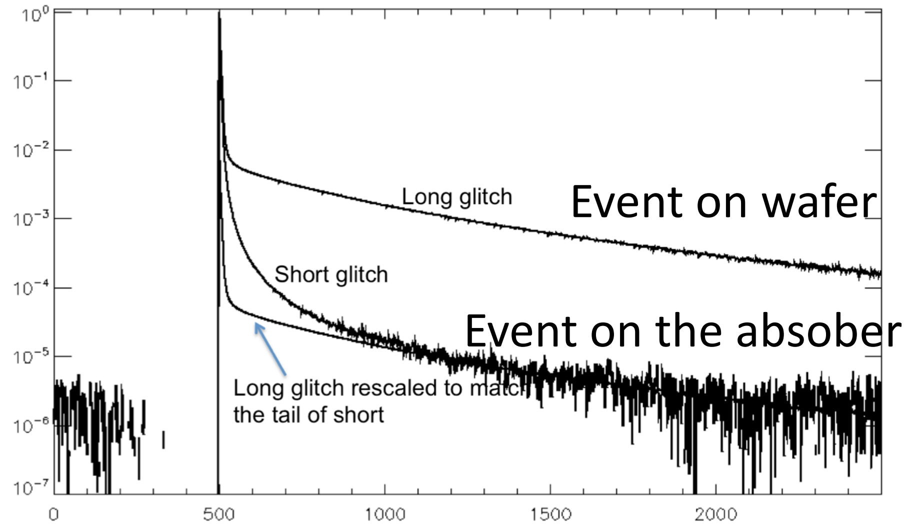
Glitches below the detection threshold common between PSB-a and PSB-b
Provide a limit on the level of remaining glitches in data

Lesson learned

CR signals were a rich probe of detector and focal plane parameters, allowing to constrain some systematic effects

- Thermal links in the focal plane





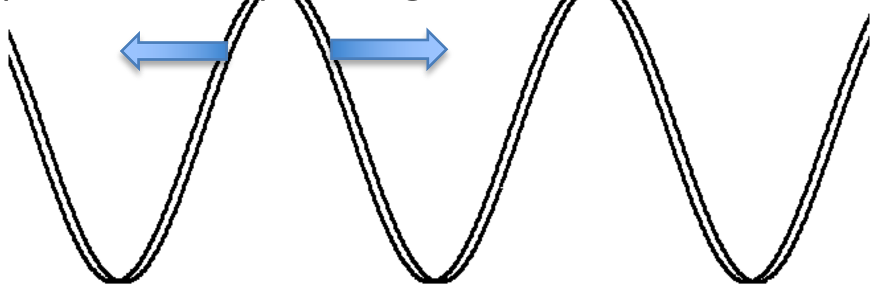
  - Coherent picture of the interaction: Balistic phonons + thermal propagation

- Origin of the low frequency noise, correlated among detectors

  ⇨ Events on the bolometer plate

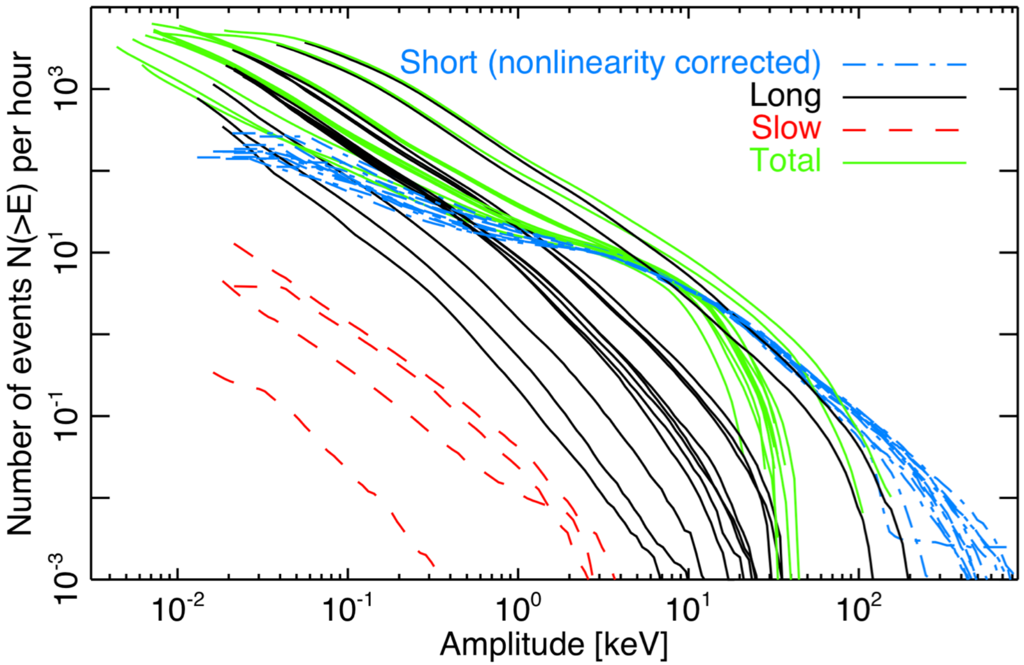
- Long time constants

Dipole shift depending on the scan direction

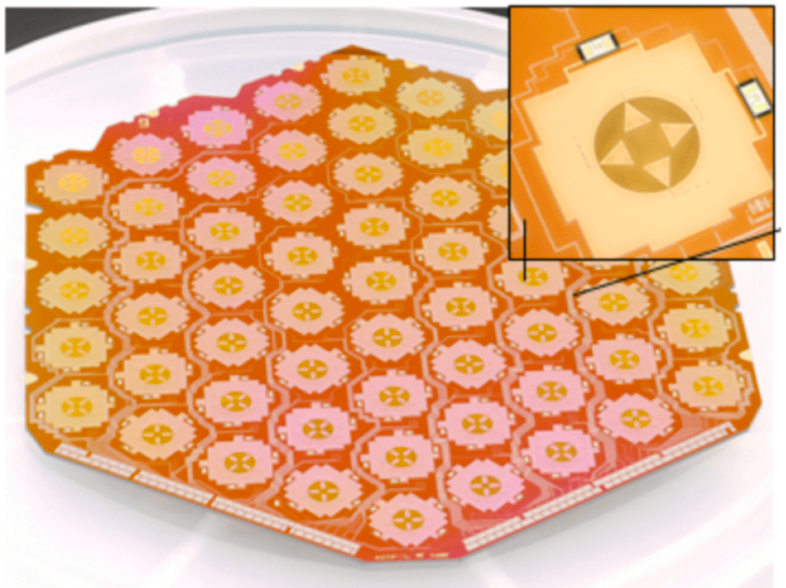


The 2-second TC induces a bias on the power spectrum of ~1-2% if uncorrected

Lessons for future experiments



- All events were detected in Planck!!
- Ballistic phonons helped the detection
- Could create corraleted noise with large wafers



Main systematic effects

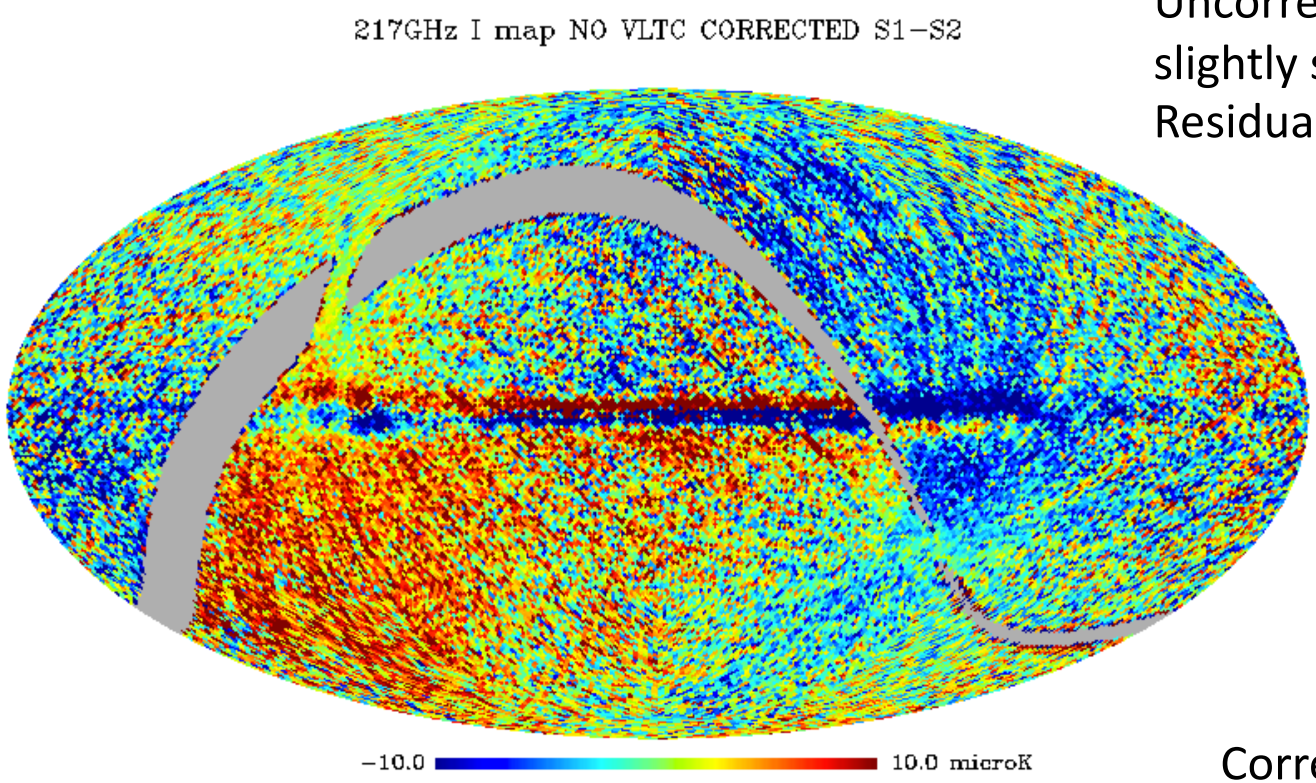
- Additive effects : Glitches, unexpected 1/f noise, microphonic noise
- Main effects I to P leakages, different detectors had to be combined to estimate Q and U Stokes parameters
  - ADC non-linearities
  - Band-pass mismatch
  - Long time constants
- Other systematics
  - Beam + time constants
  - Polar efficiencies

Many effects scale with <cos 2Ψ> and <sin 2Ψ>. The use of a HWP and better angle redondancies as planned for LiteBIRD help.

- Use of redundancies of observations and of the strong dipole signal to calibrate and correct the data : Surveys with opposite scanning directions allowed optimization of parameters and correction of many systematic effects.

Survey difference maps

Survey difference maps were useful to track and characterize systematic effect

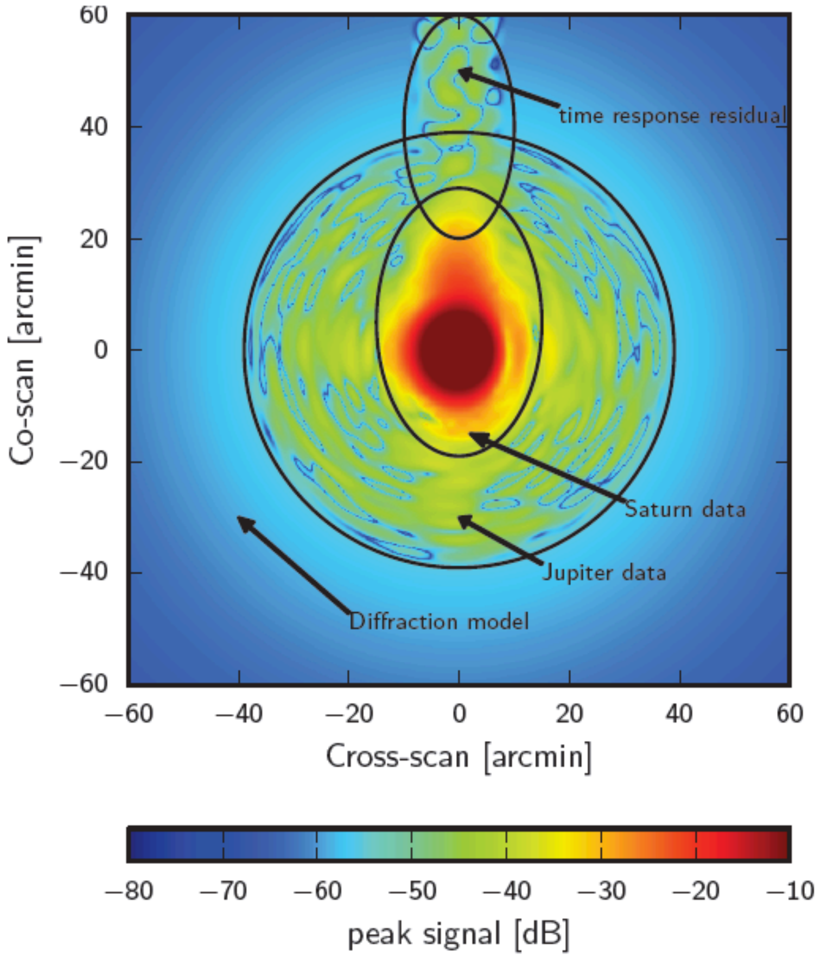


Uncorrected **long time constants** slightly shift the galaxy
Residual dipole seen in the difference

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



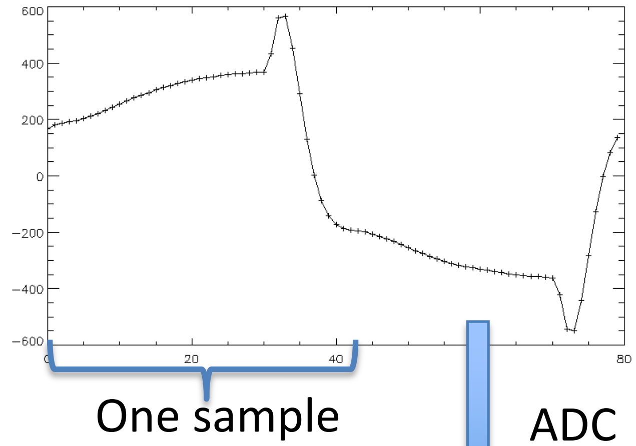
→ Corrections of the transfer function at the likelihood optimization stage

ADC non-linearities

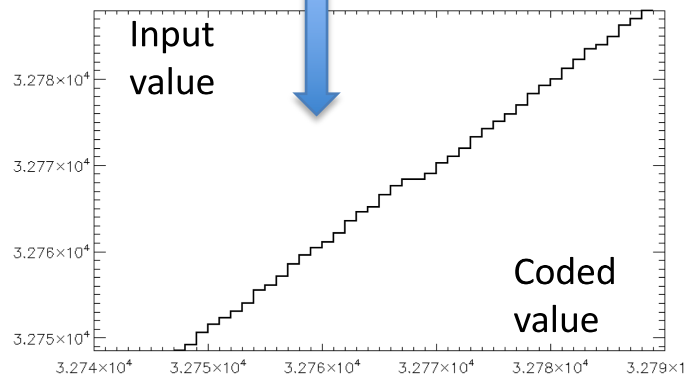
Analog to Digital convertor have some non-linearities

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

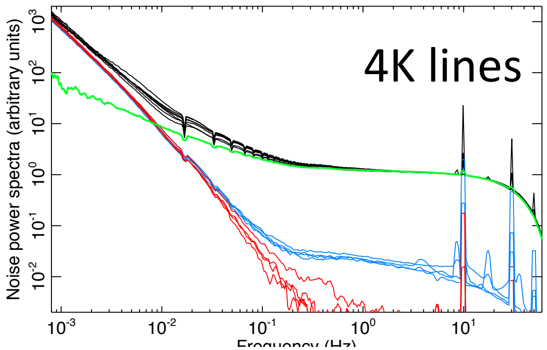
Electronic response



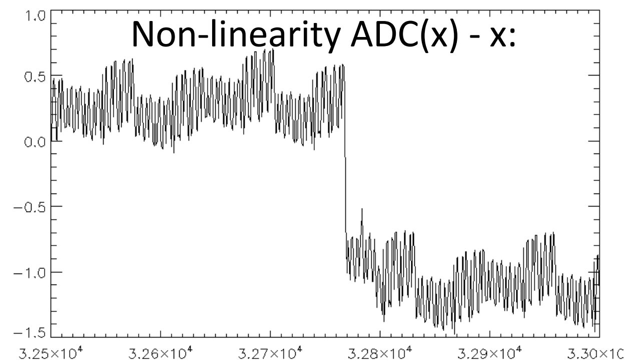
ADC



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



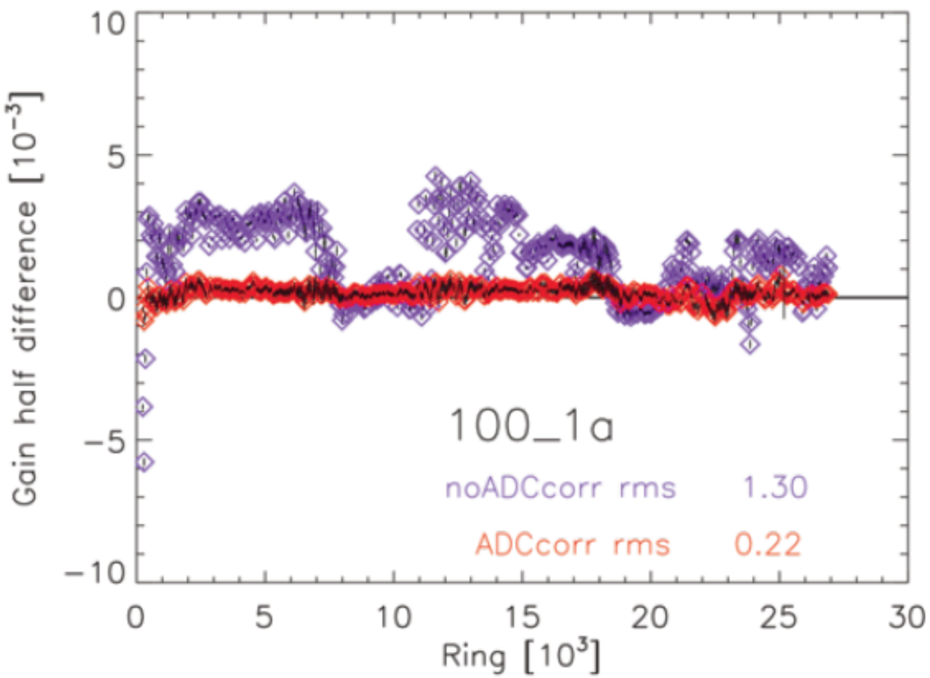
House-keeping data were essential!



ADC correction

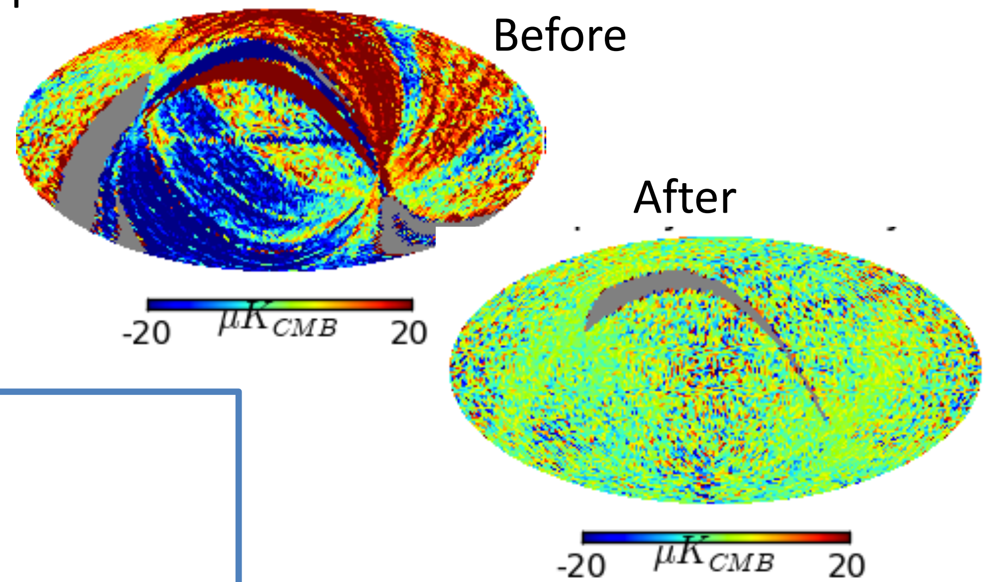
The correction is very effective but limited by the 4K line estimation.

Relative effective gain per pointing period



A second correction was performed at the map-making level

Jackknife : positive – negative parities

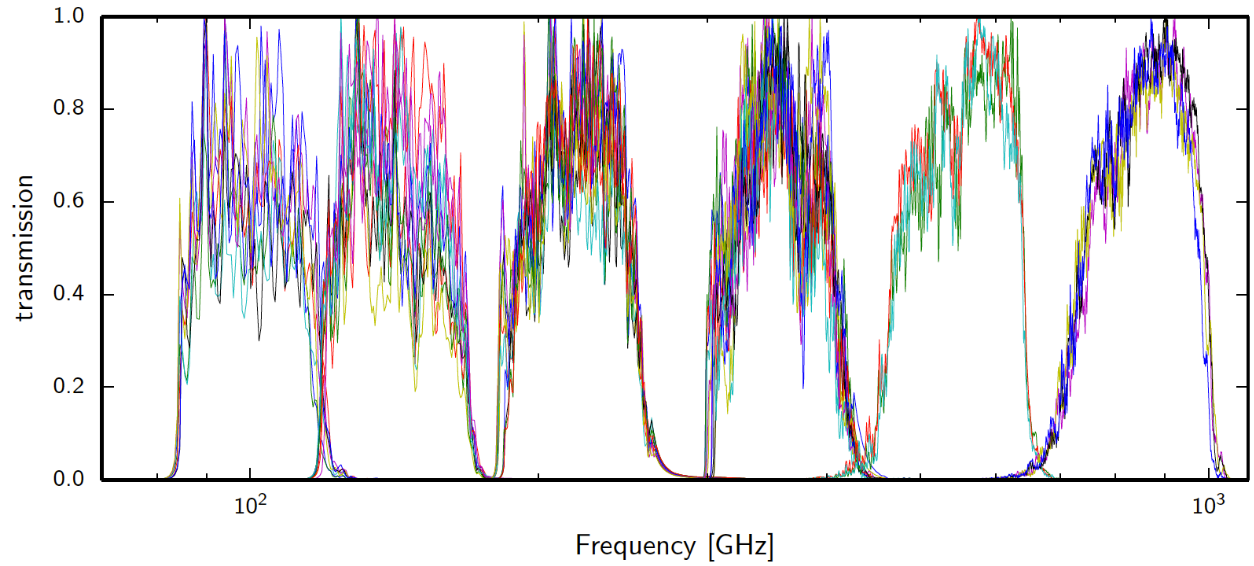


ADC is the limiting systematic effect in Planck for polarization measurement

No intrinsic detector gain variations have been detected

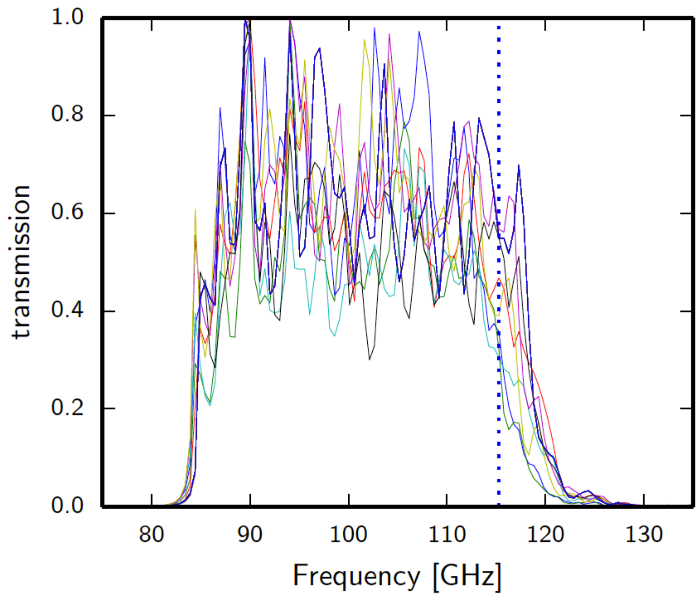
Band-pass mismatch

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



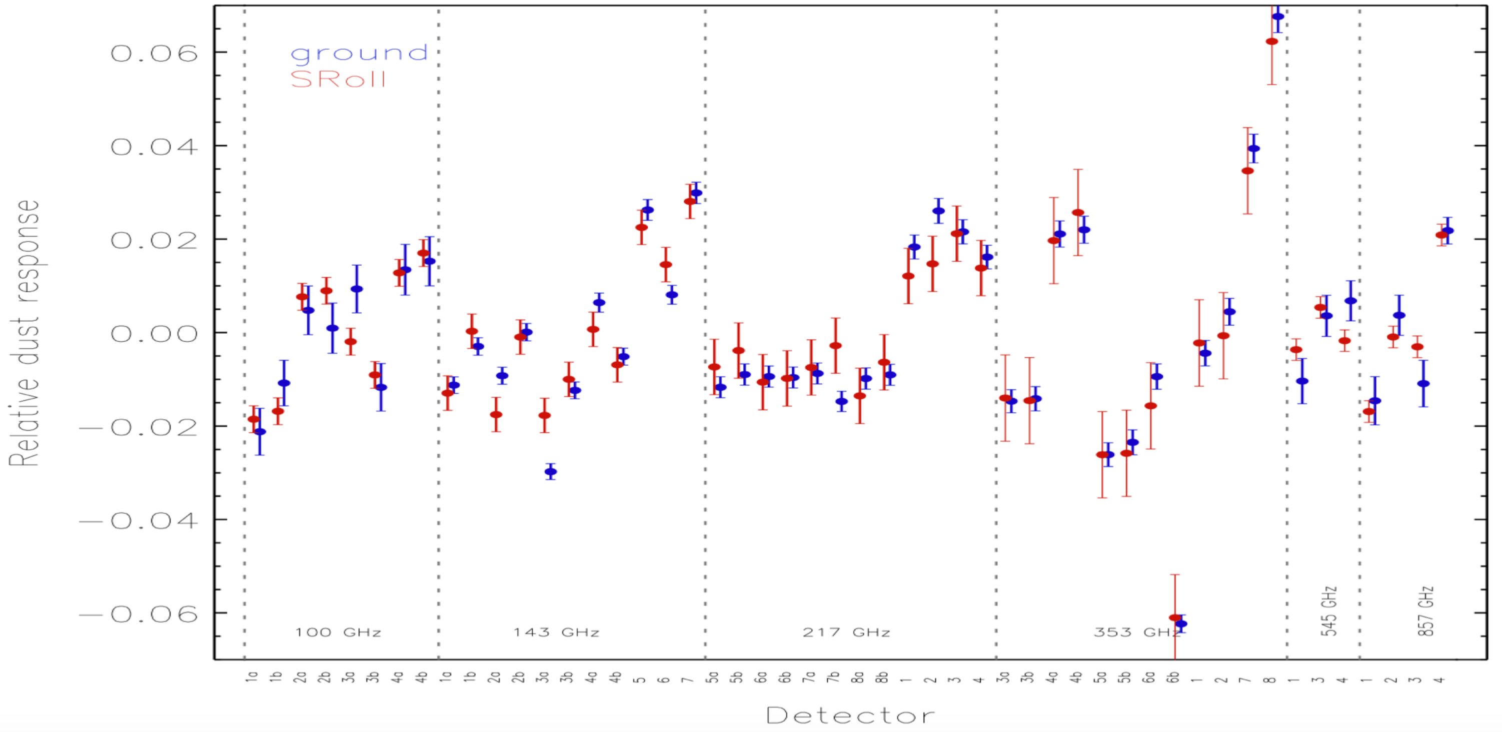
CO transition line 1-> 0 falls at the edge of the 100 Hz filters so the CO components has very different amplitude from detector to detector

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

Adressed for LiteBIRD in
- Hoang et al.
- Ghigna et al.

Summary of systematic effects (HFI)

- ADC is the dominant systematic effect
- Its contribution is at the level of the noise at low ells
- Other systematic effects are negligible after processing