Controlling systematics for future CMB experiments: lessons from Planck and beyond

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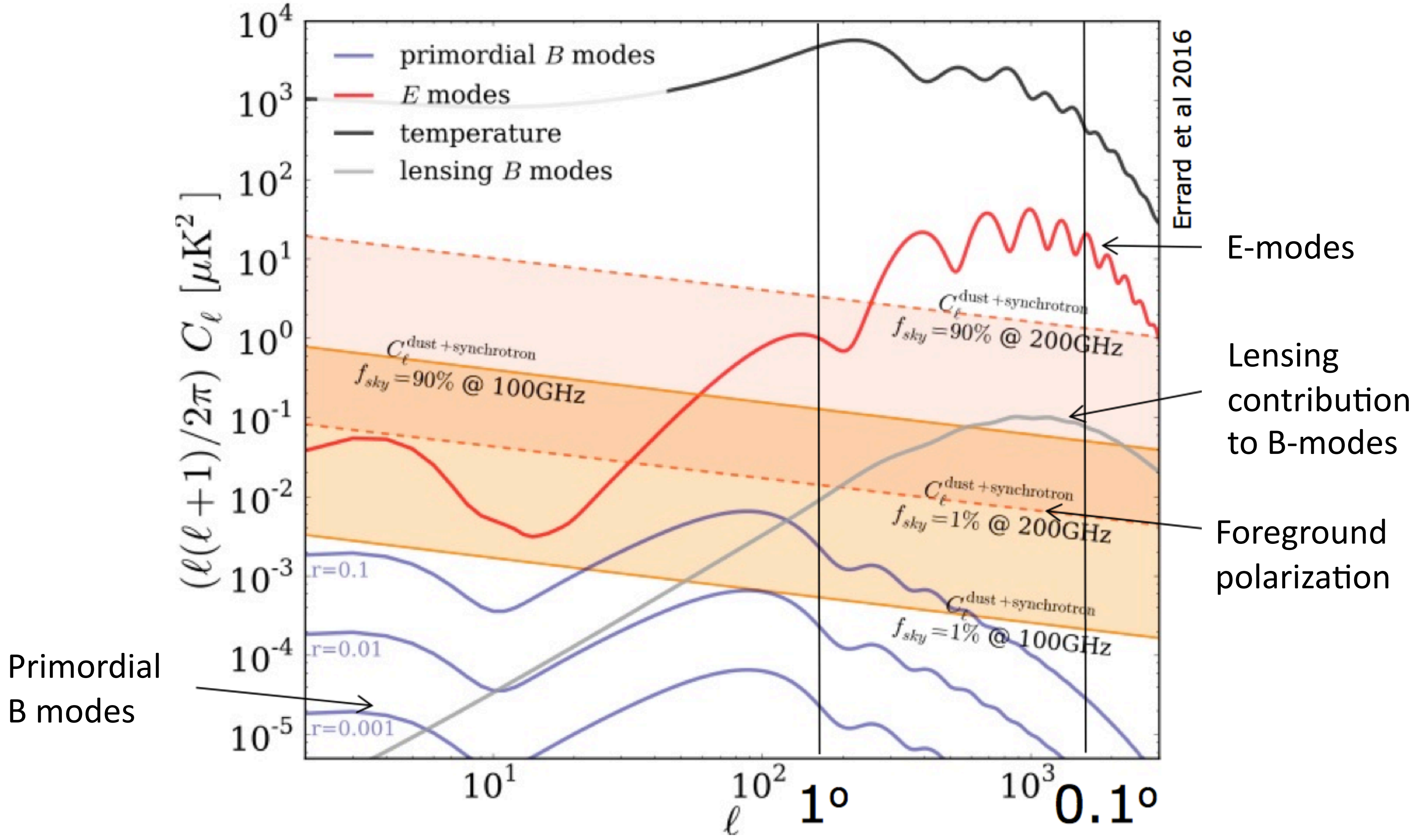
E/B spectra

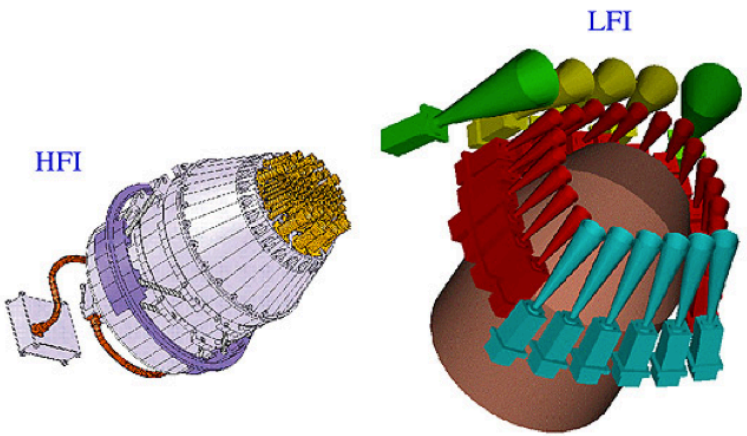


primordial B modes
E modes
temperature
lensing B modes
Errard et al 2016
$C_\ell^{\text{dust+synchrotron}}$ $f_{sky}=90\%$ @ 200GHz
$C_\ell^{\text{dust+synchrotron}}$ $f_{sky}=90\%$ @ 100GHz
$C_\ell^{\text{dust+synchrotron}}$ $f_{sky}=1\%$ @ 200GHz
$C_\ell^{\text{dust+synchrotron}}$ $f_{sky}=1\%$ @ 100GHz
r=0.1
r=0.01
r=0.001
$(\ell(\ell+1)/2\pi)\ C_\ell\ [\mu K^2]$
ℓ
1°
0.1°
E-modes
Lensing contribution to B-modes
Foreground polarization
Primordial B modes

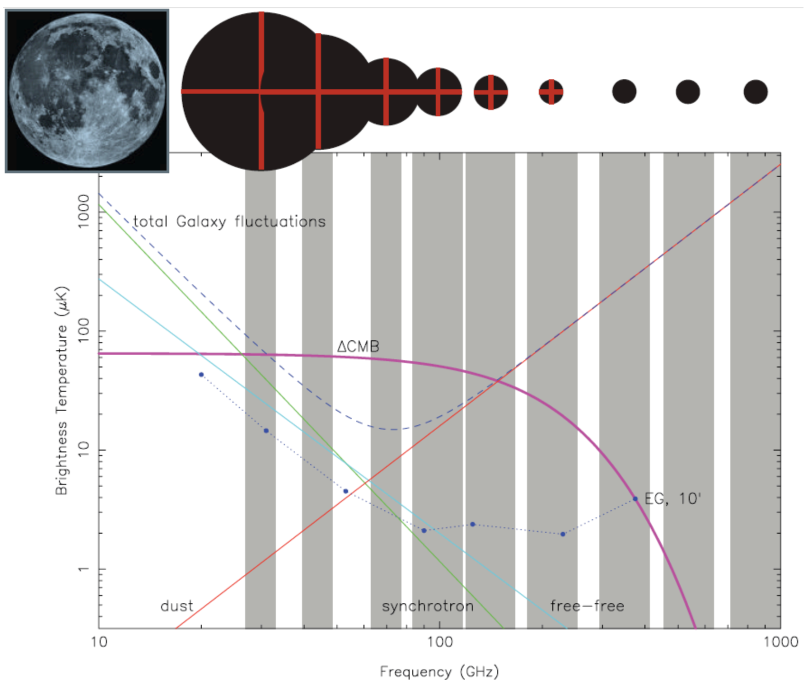
Planck

- 1.5 m off-axis Gregorian telescope
- 2 instruments:
- LFI (20K)
- HFI (0.1K)
- Angular resolution : 30’ to 5’
- 650 M€, 600 scientists, 29 laboratories, 14 countries (Europe, USA, Canada)

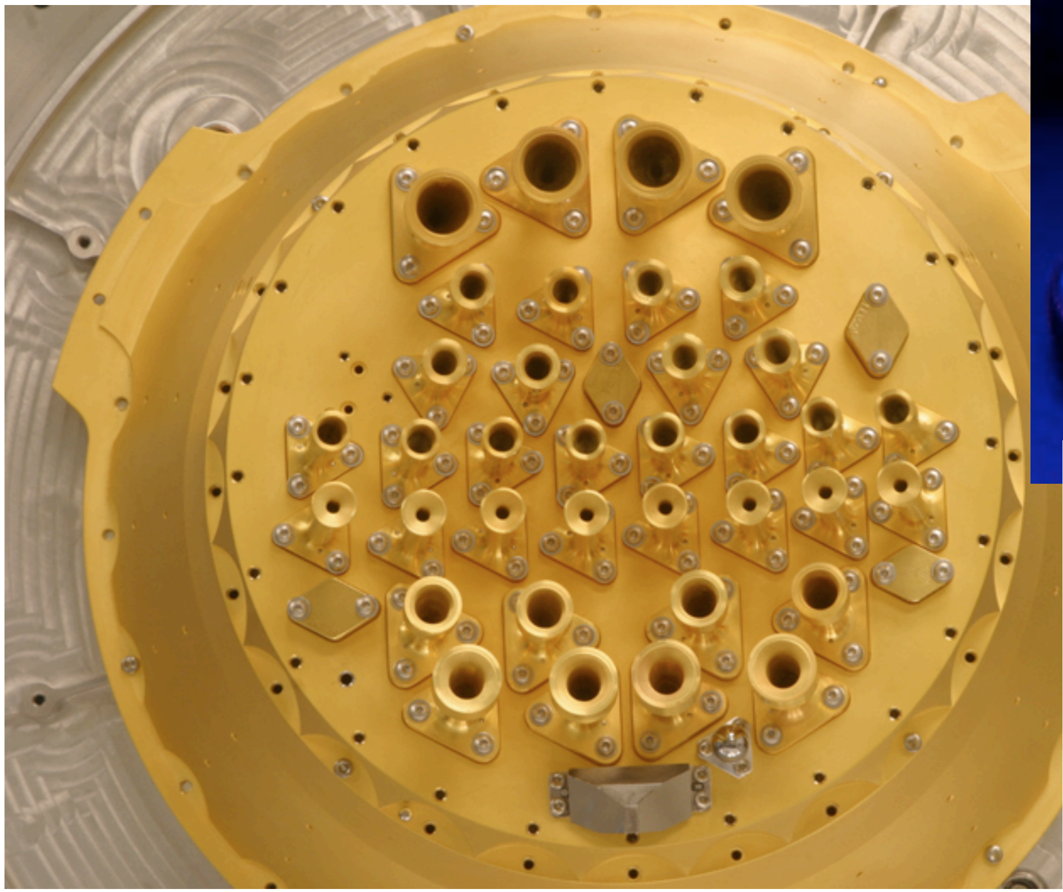
The Planck instruments

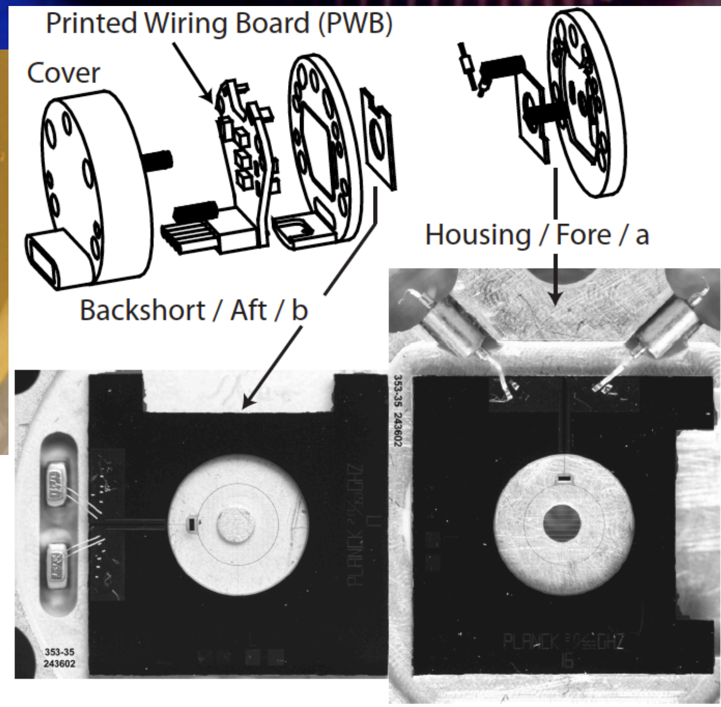


- LFI instrument: HEMT antennas, 3 bands between 33 and 70 GHz
- HFI instrument: bolometers cooled down to 100 mK, 6 bands between 100 and 857 GHz



HFI focal plane





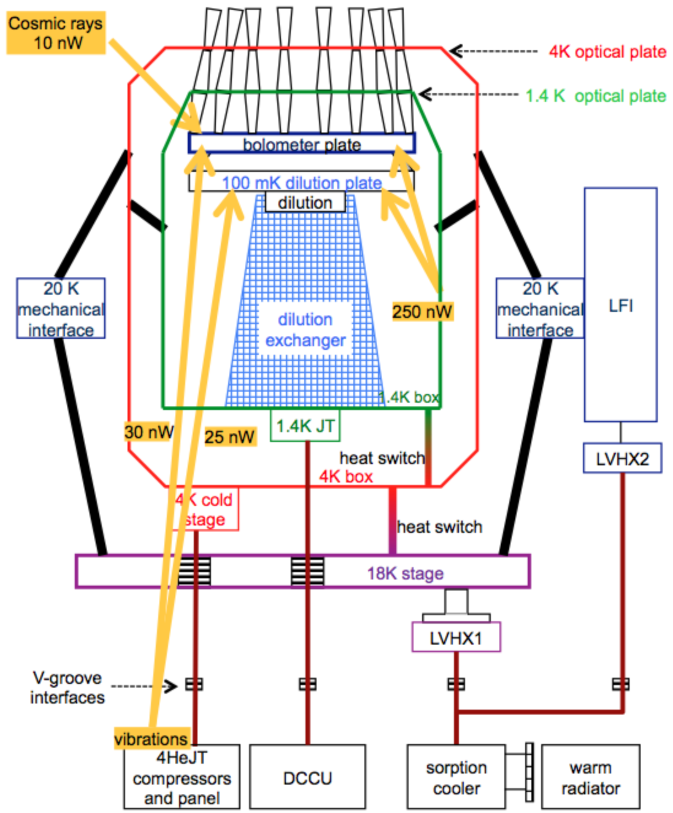
Thermal stability

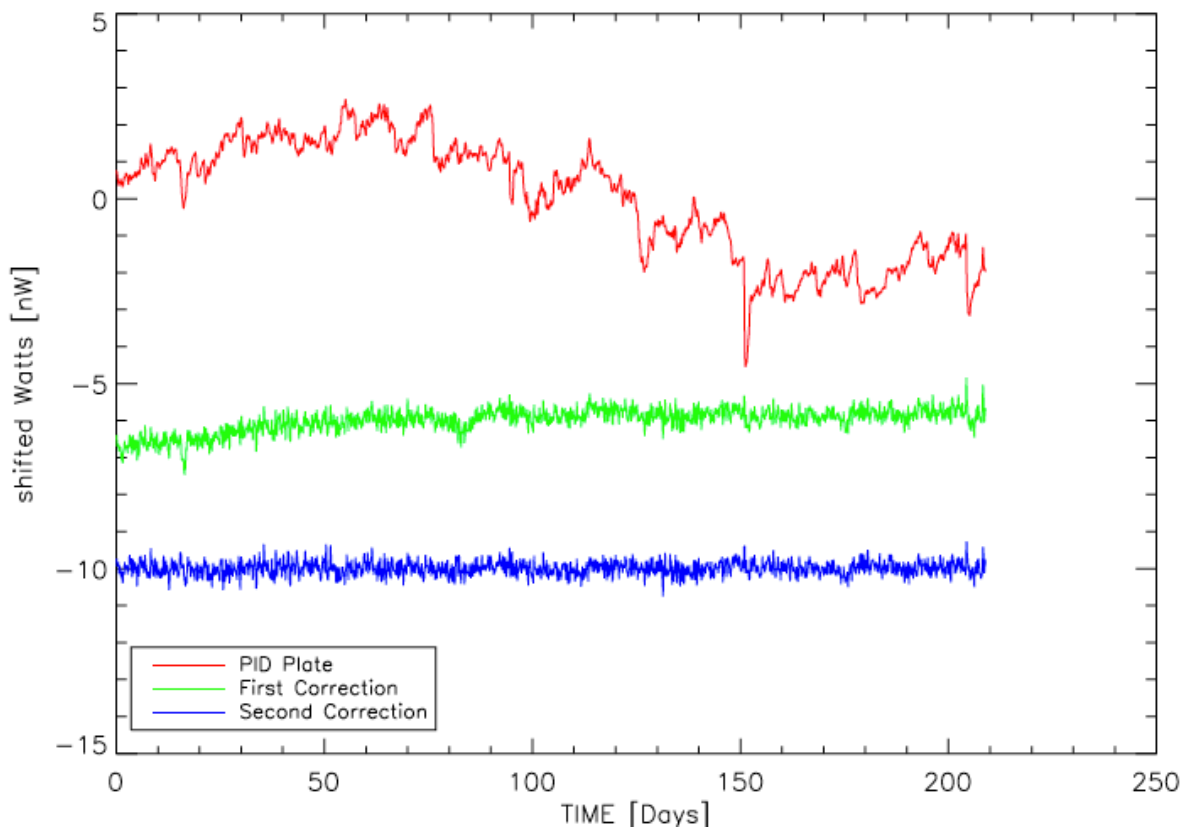
Temperature fluctuations induced by cosmic ray hit fluctuations!!

Corrected by PID at time scales larger than the hour

Second correction from the dilution plate PID

Great thermal stability of detectors

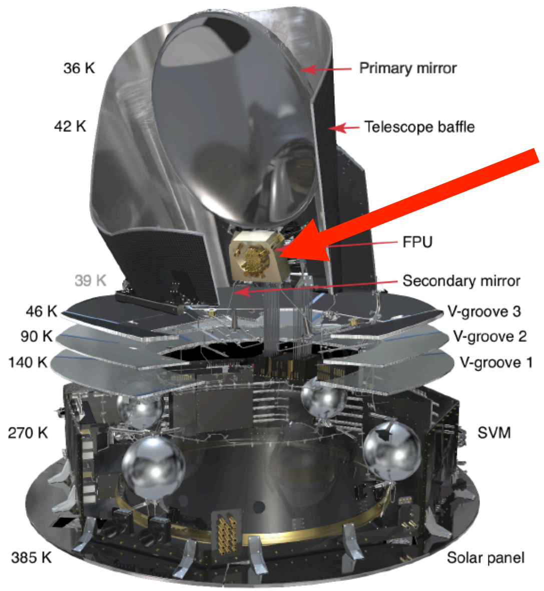




Additive systematic effects

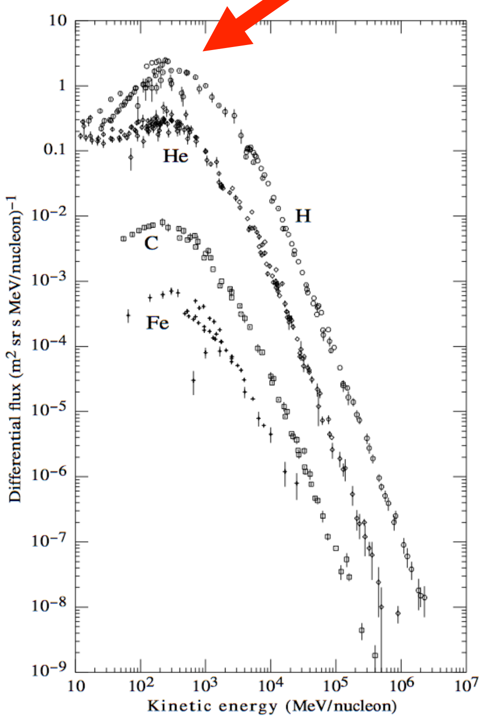
- Cosmic rays
- 1/f noise
- Thermal fluctuations
- Microphonics from the coolers
- Scan synchronous effects

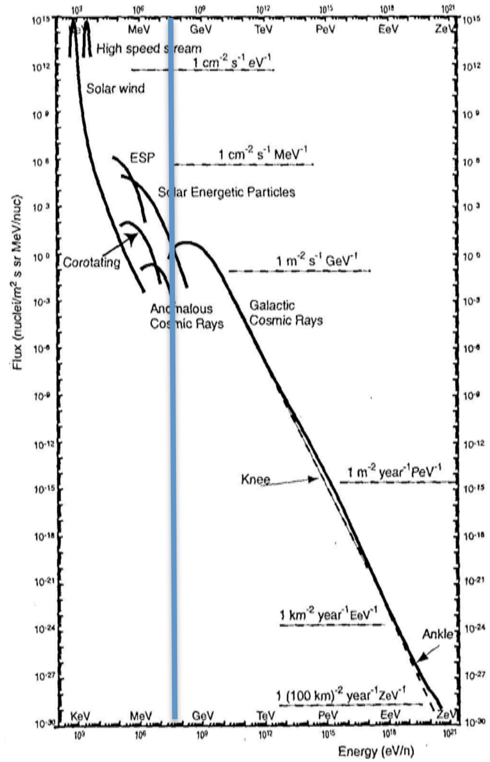
Cosmic rays



Mainly galactic protons and Helium nuclei

CR of ~ 1 GeV dominate





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

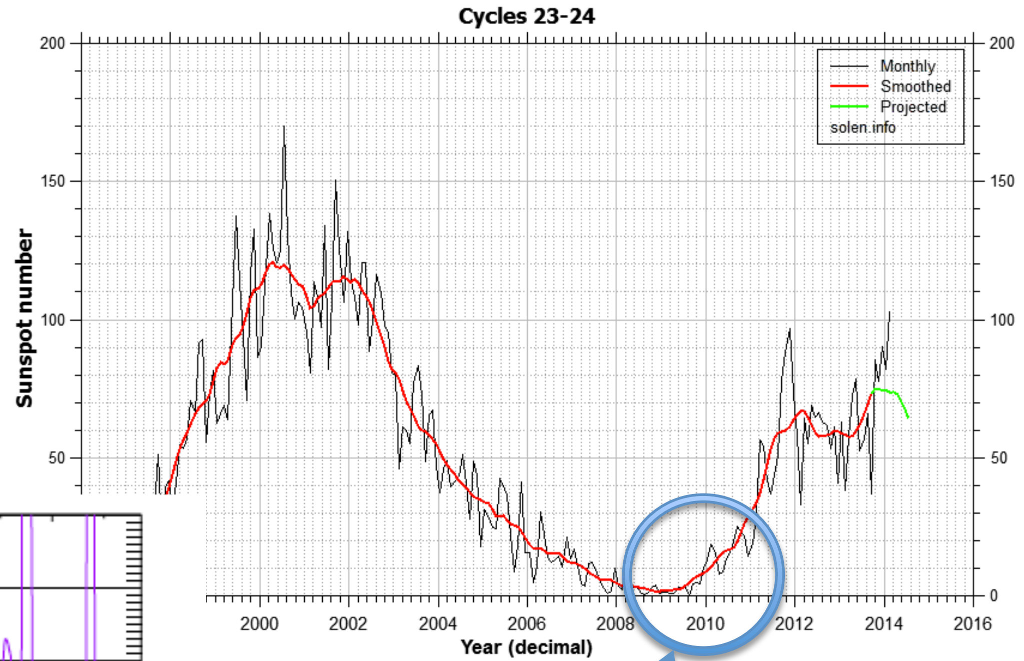
No contribution from solar particles which can not reach the detectors, except during flares

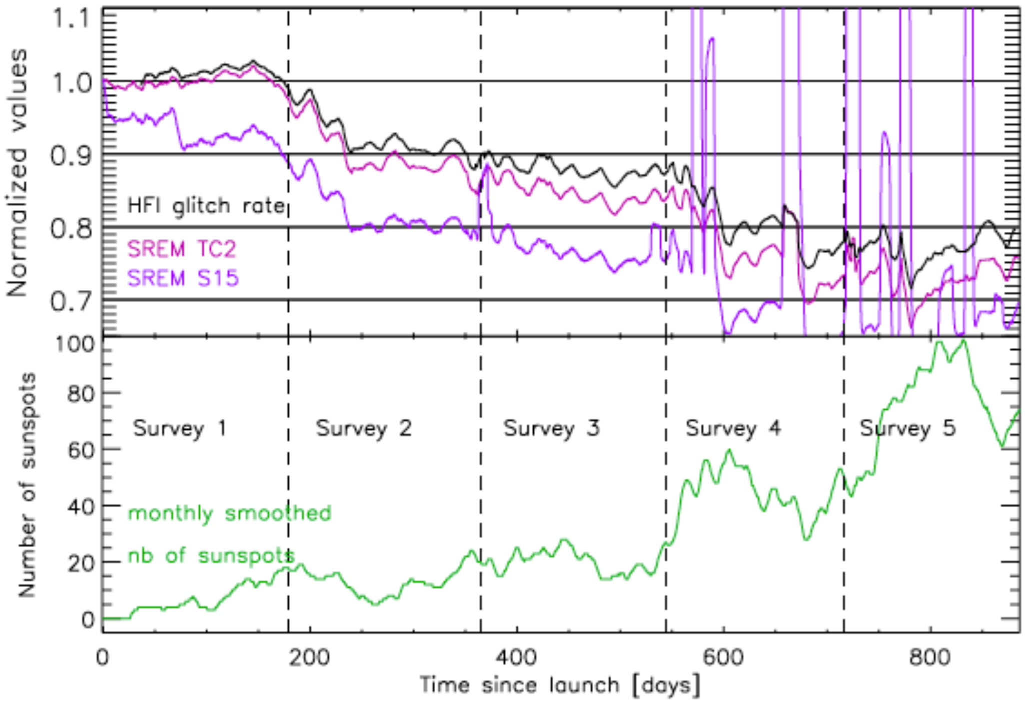
Amplitude of the spectrum at L2 is modulated by solar activity

Solar activity and Planck hit rate

Planck was launched at the minimum of solar activity

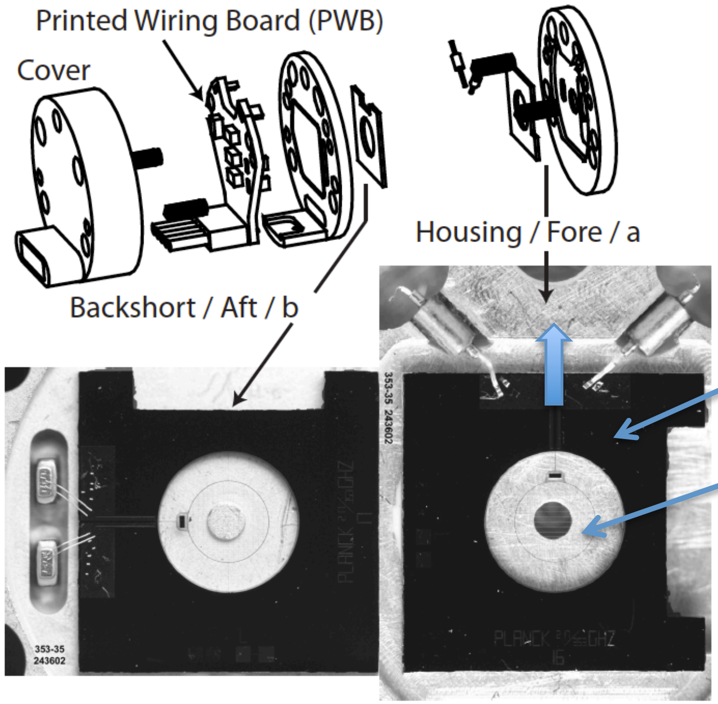
→ High cosmic ray rate

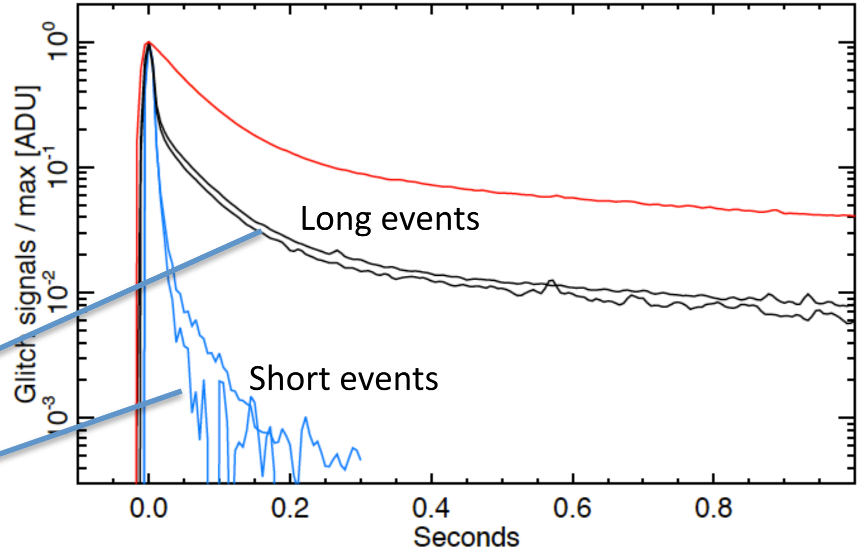




Glitch rate decreased as solar activity increased during the mission

CR interaction with detectors





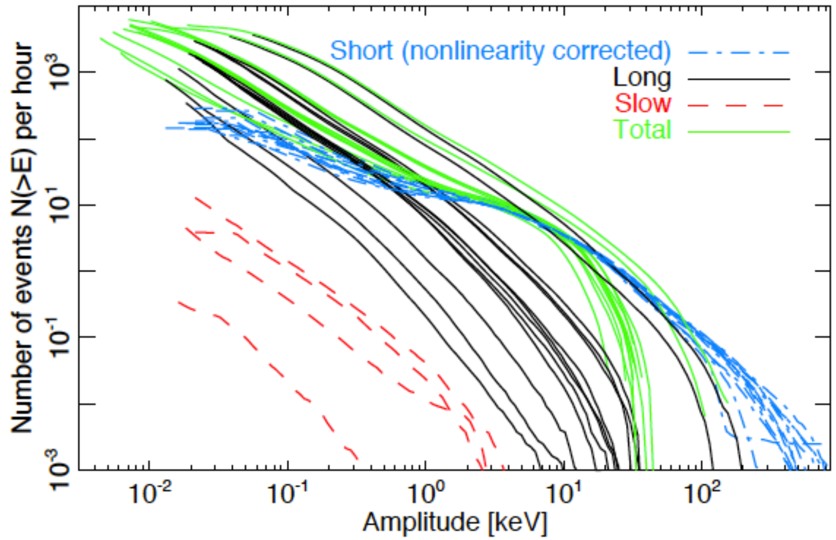
- Only 3 families of glitches

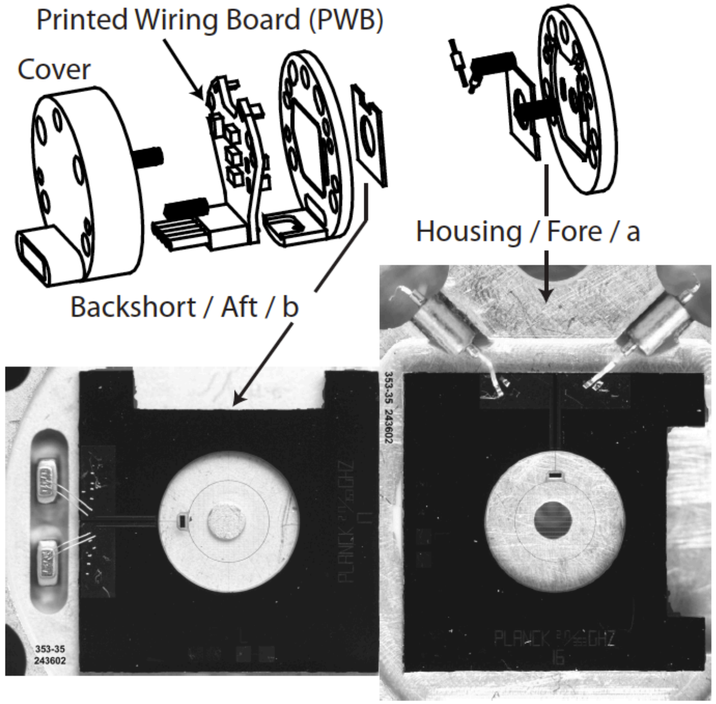
- Long glitches are direct impact of protons in the silicon wafer

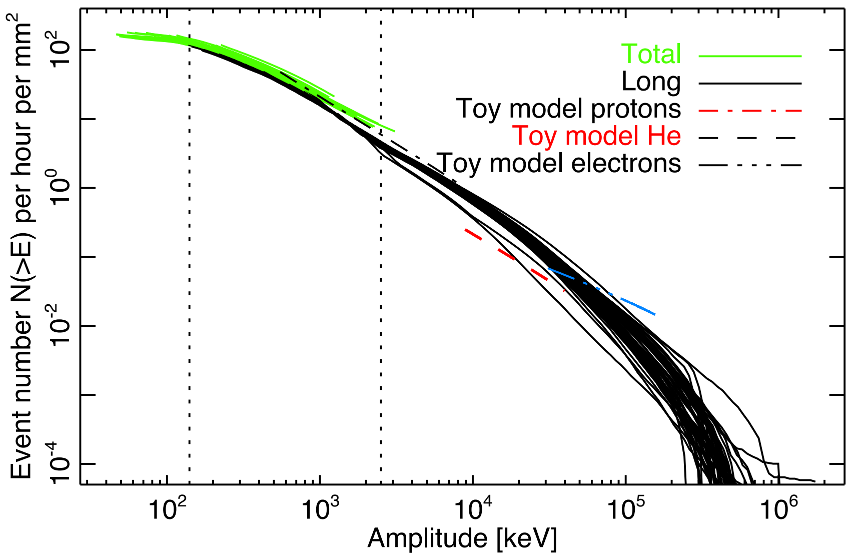
- short glitches are direct impact of protons in the grid/crystal. Should be representative of response to photons.

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

CR populations







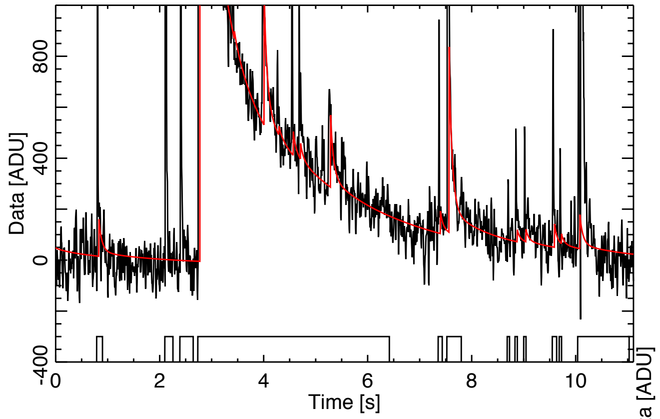
- Almost all depositing energy on the wafer are glitches detected !
Partly because of ballistic phonon

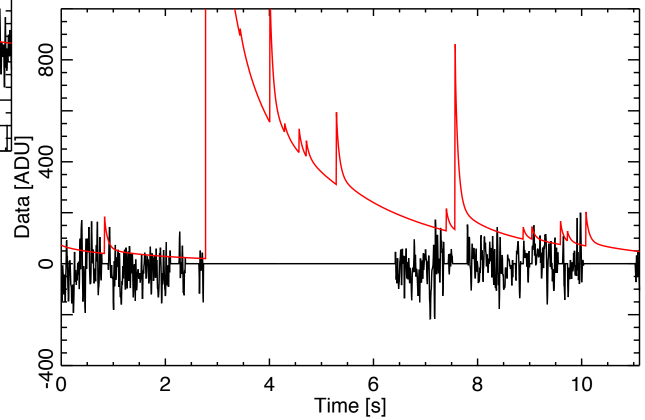
- Long events mostly correlated between PSB a/b

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

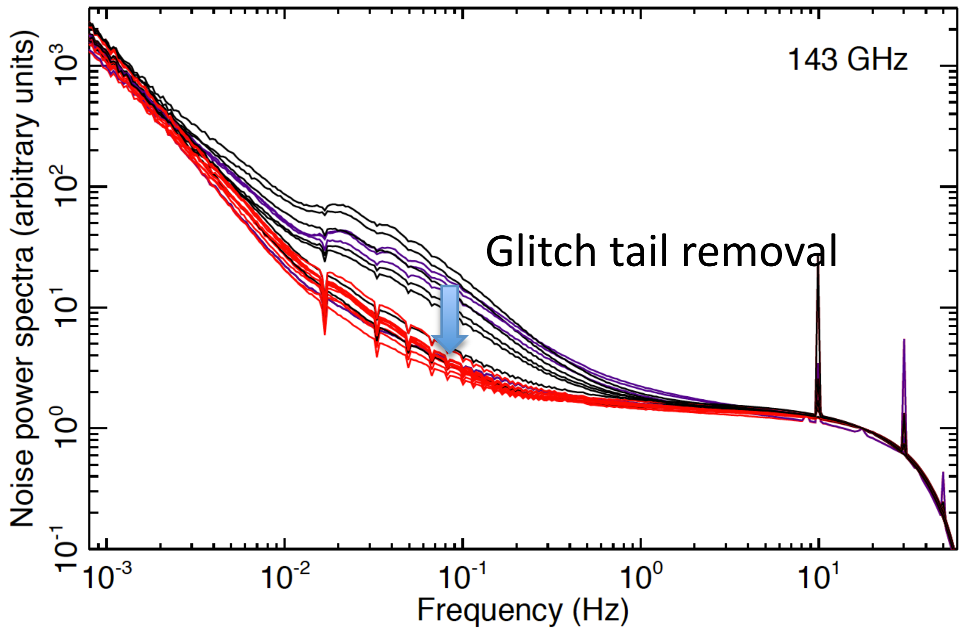




Analysis made difficult because of the high confusion of events

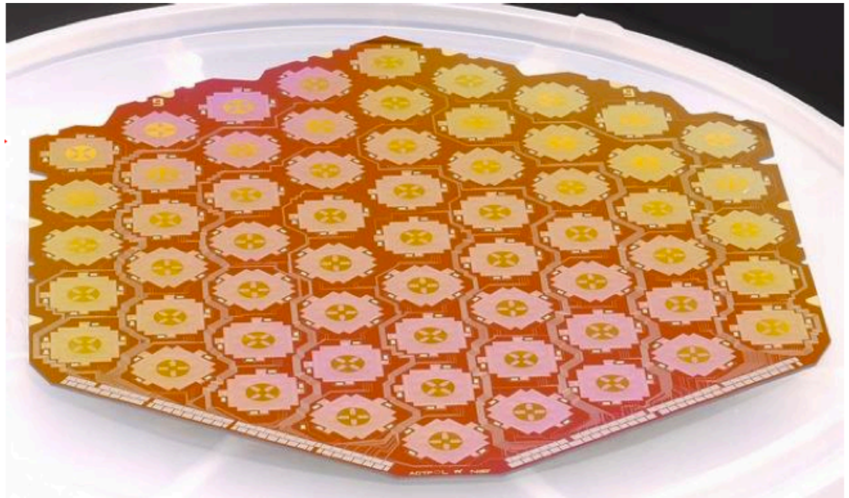
Residual at the level of noise for the worst channels at low frequencies < 0.2 Hz

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



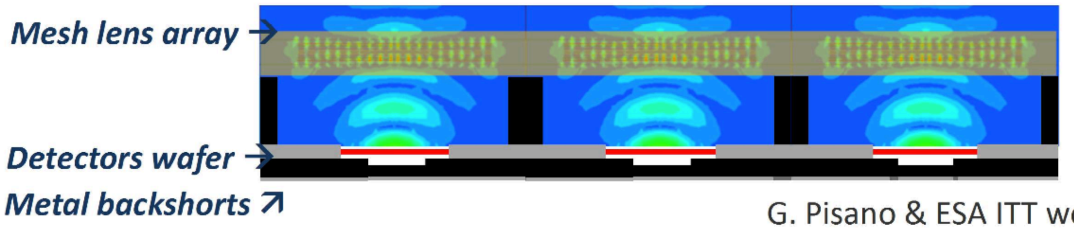
Next generation experiments

Example TES detectors

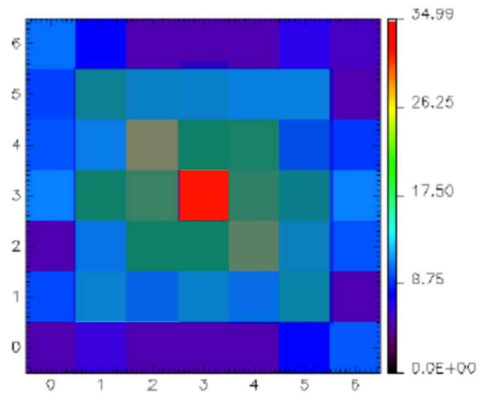


Impact of cosmic rays on detector arrays for future satellite missions have to be studied carefully

KIDS



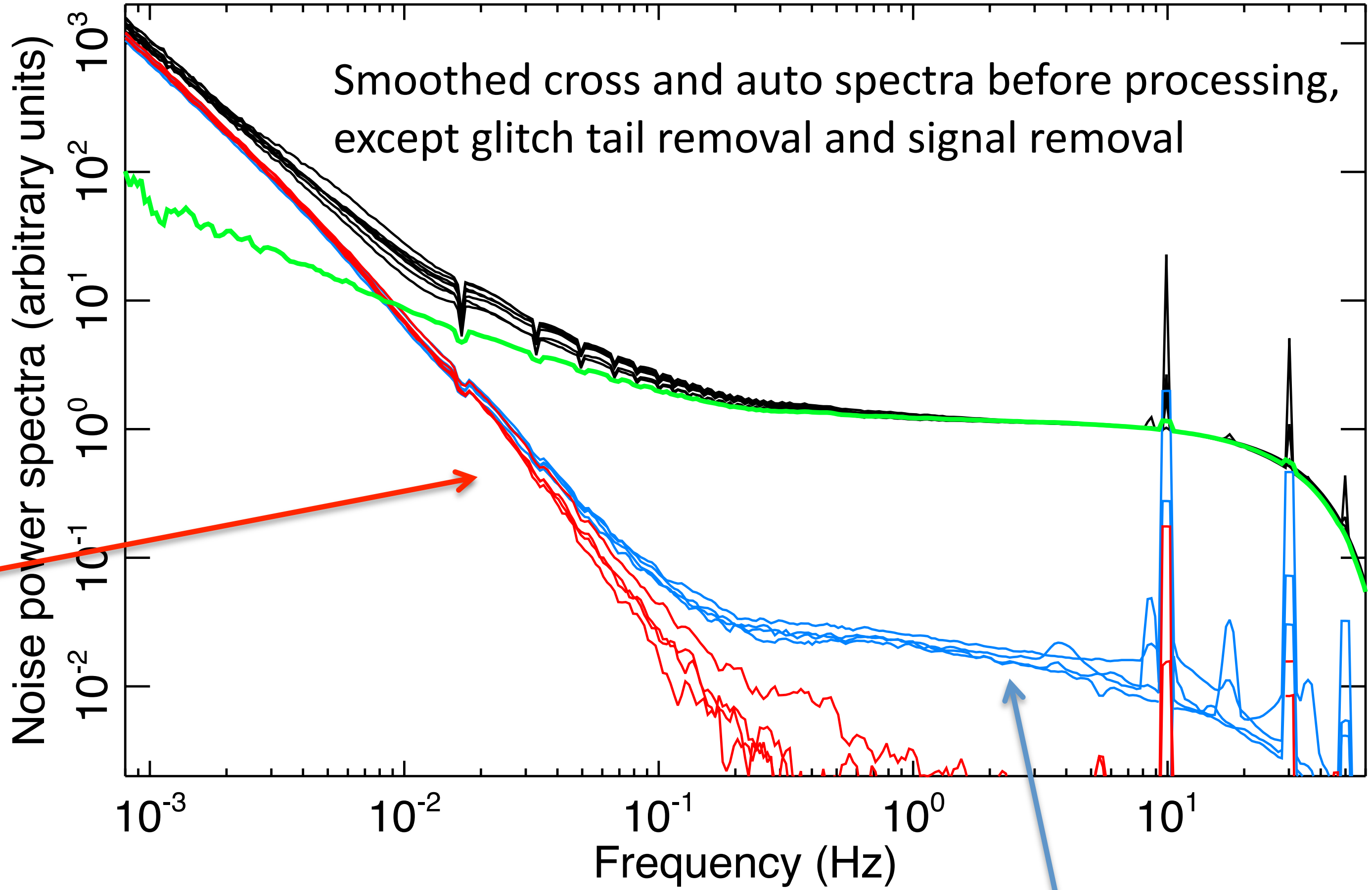
G. Pisano & ESA ITT workgroup



Cosmic ray tests (A. Catalano)

Noise spectra on Planck-HFI TOIs

Correlated noise between detectors. Related to thermal fluctuation of the plate due to CR hits



Glitches below the detection threshold common between PSB-a and PSB-b
Provide a limit on the level of remaining glitches in data ~ 5% contribution

Uncorrelated noise

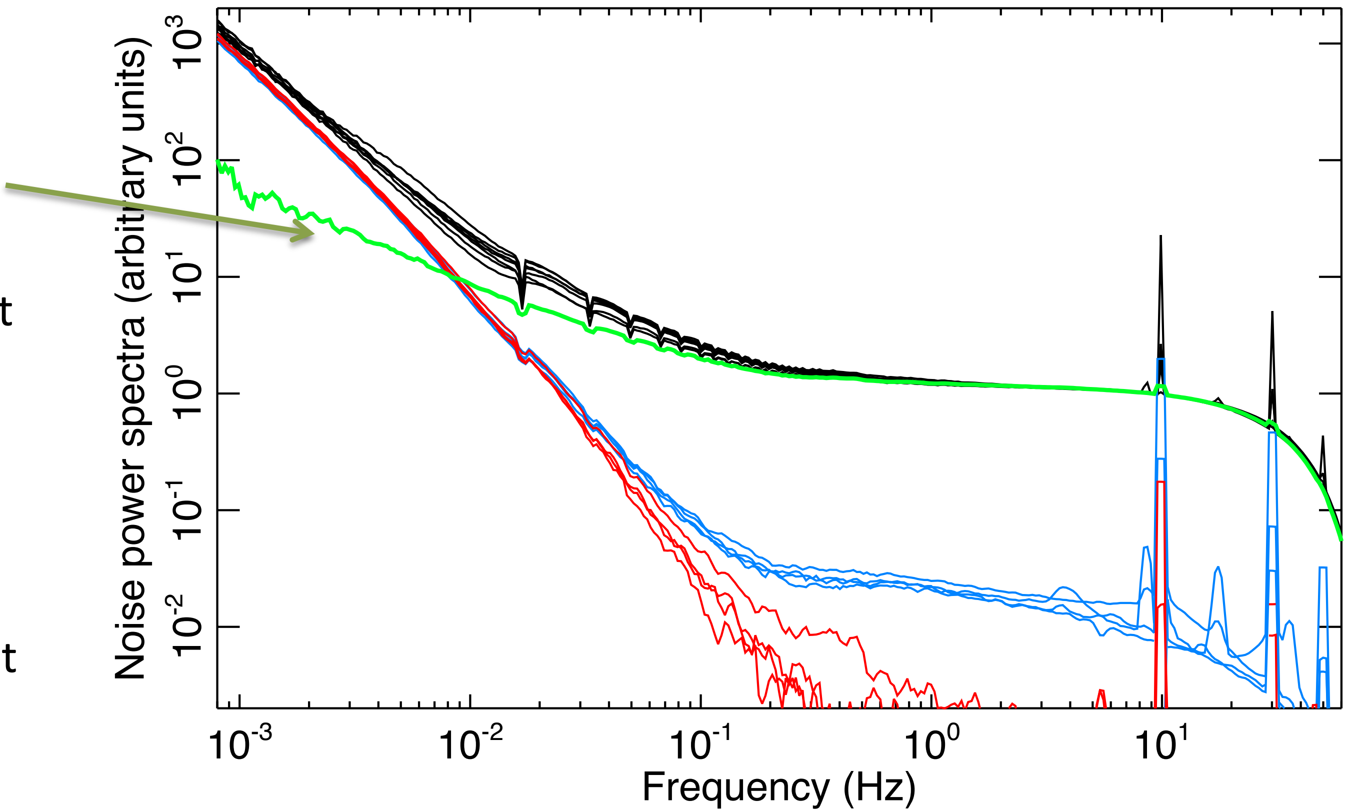
Uncorrelated component seen in all detector time-streams.

- Not observed while measuring intrinsic detector noise
- Observed to some extent after plug in to the electronic box

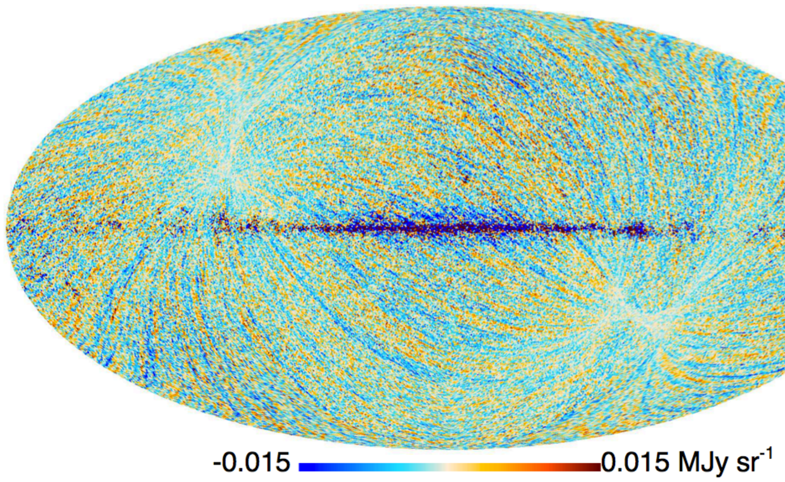
f_{knee}~ 0.15 Hz

No clear explanation, can't be due to CRs since not modulated as glitch rate

Gives the fundamental limit after removal of systematics



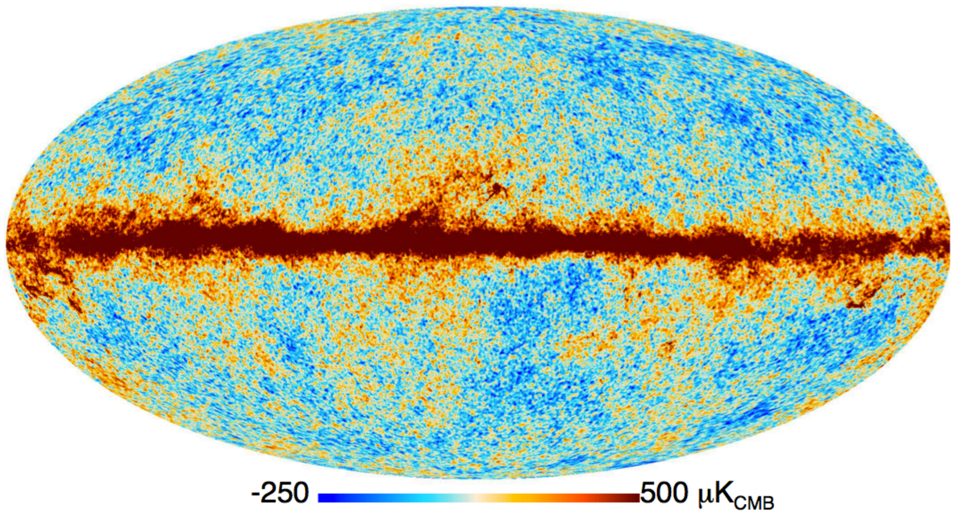
Map-Making



Low frequency noise produces stripes in the maps if not accounted properly.

Map-making techniques are based on maximum likelihood approaches to solve for the I, Q, U signals in the maps.

High redundancy of observations allows to reduce the low frequency noise in maps

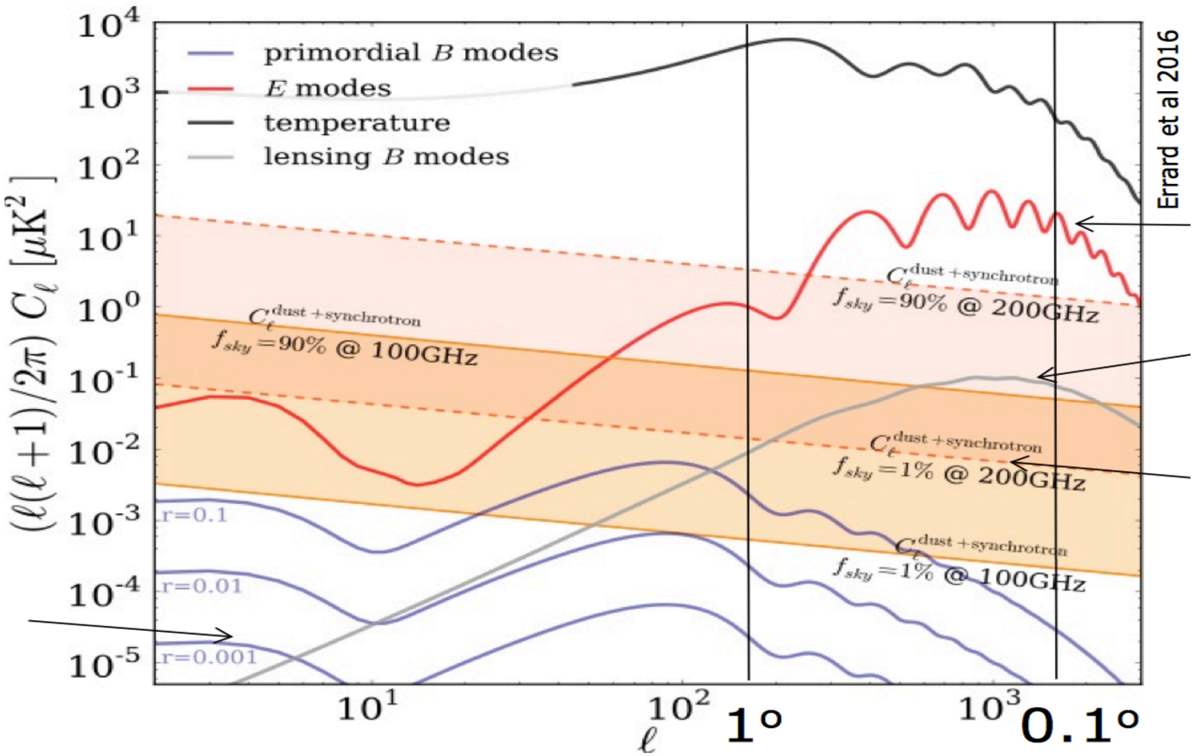


Intensity to polarization leakages

Polarization parameters Q and U are obtained by differencing different detector measurements or measurements obtained at different time.

Ex: linear combination of Q and U can be obtained by: $S_A - S_B$

In that case unpolarized intensity vanishes

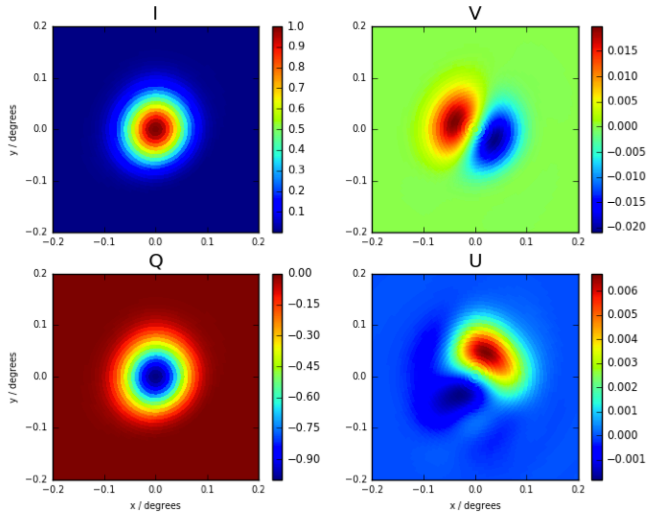


Intensity to polarization leakages

Any mismatch between detectors create intensity to polarization leakages :

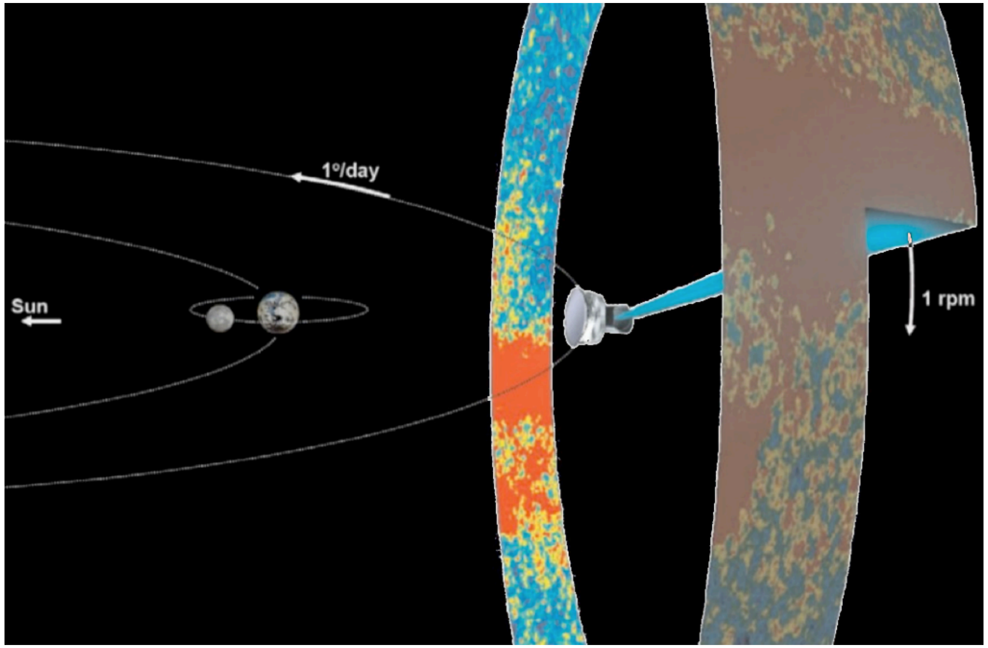
- Relative gain errors: small enough thanks to accurate dipole calibration
- Beam mismatch: well taken care in Planck data
- Band-Pass mismatches :
- ADC non-linearities: main limiting systematic effect in Planck.

Example: Beam mismatch



Leakages strongly dependent on the scanning strategy.

Planck scanning strategy



Pointing 85 degrees from the spin axis
7 degree precession angle

Same regions in the sky are observed every 6 month

Time varying effects are hardly constrained

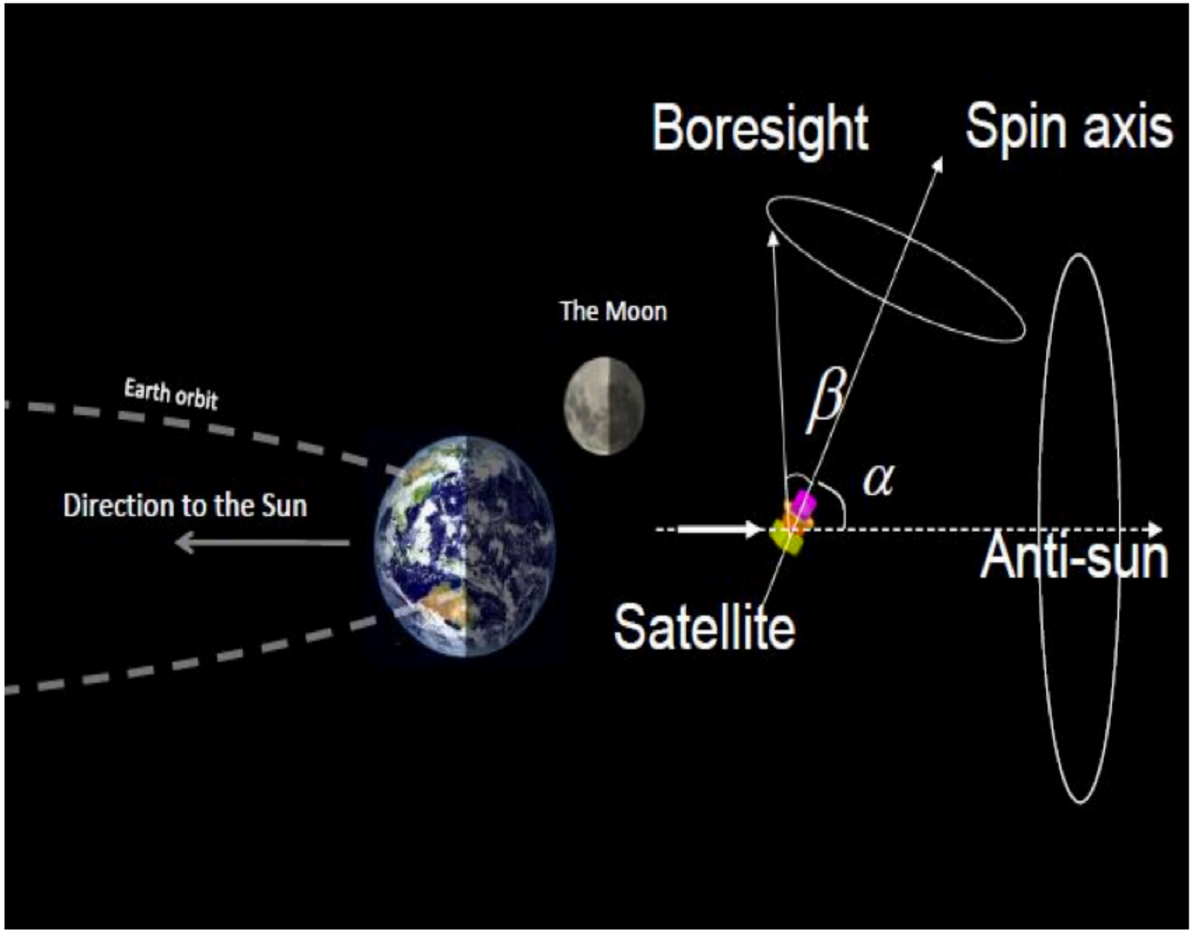
Small angle difference :

Polarization estimation requires differencing different detectors

Detector mismatch have an impact on final results

Future experiments

Example: LiteBird scanning strategy

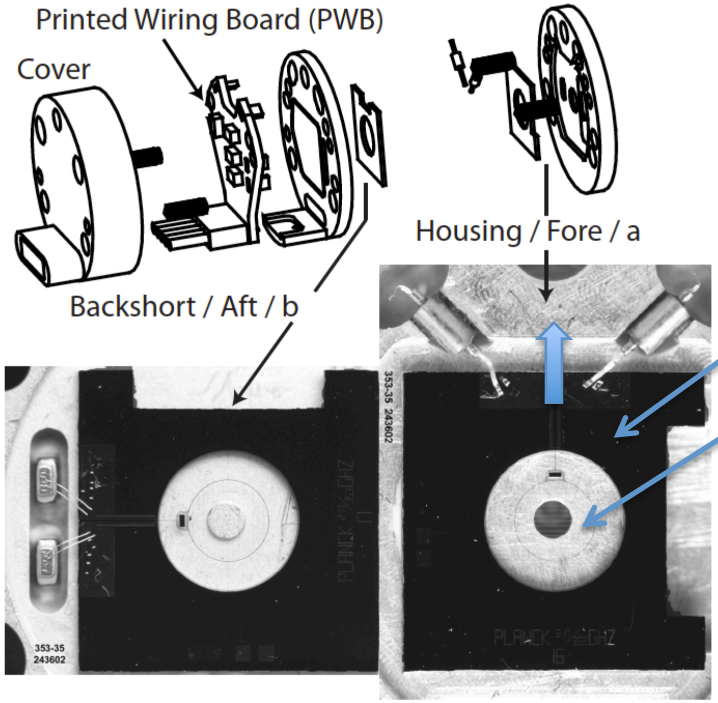


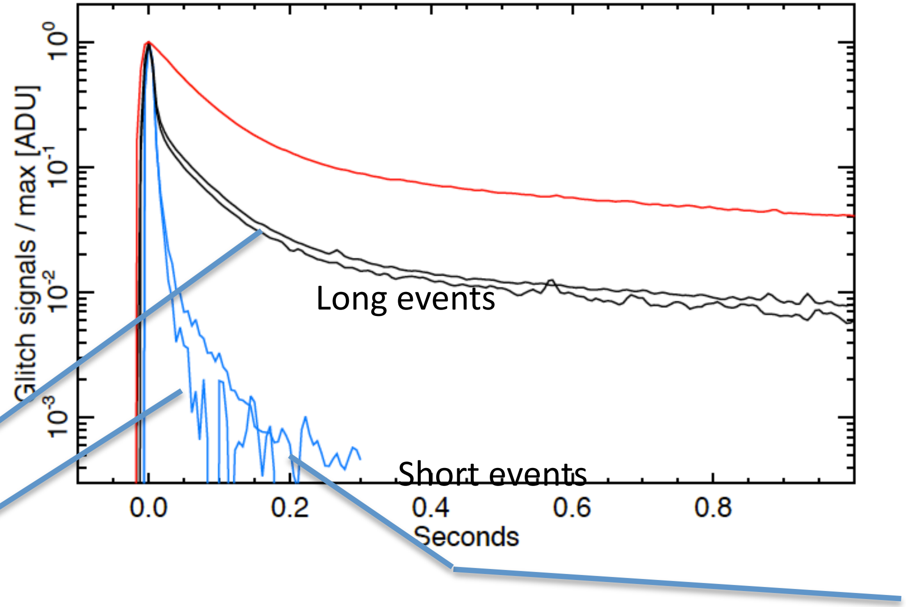
More uniform coverage

Many polarizer angle from the same detector

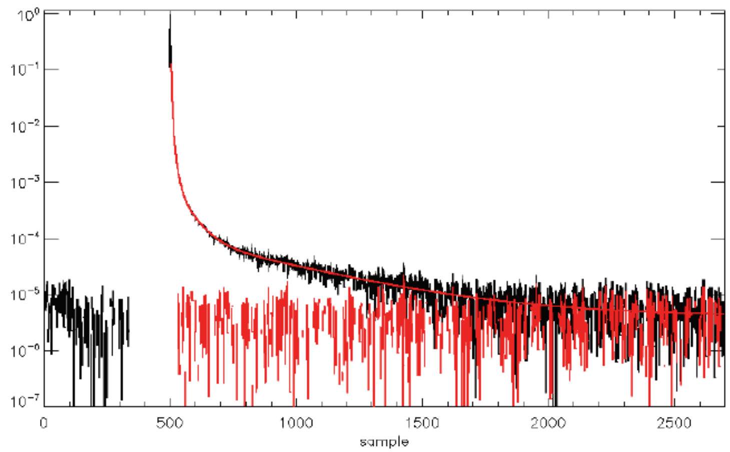
⇨ Allows single detector polarization maps

Gain calibration and long time constants





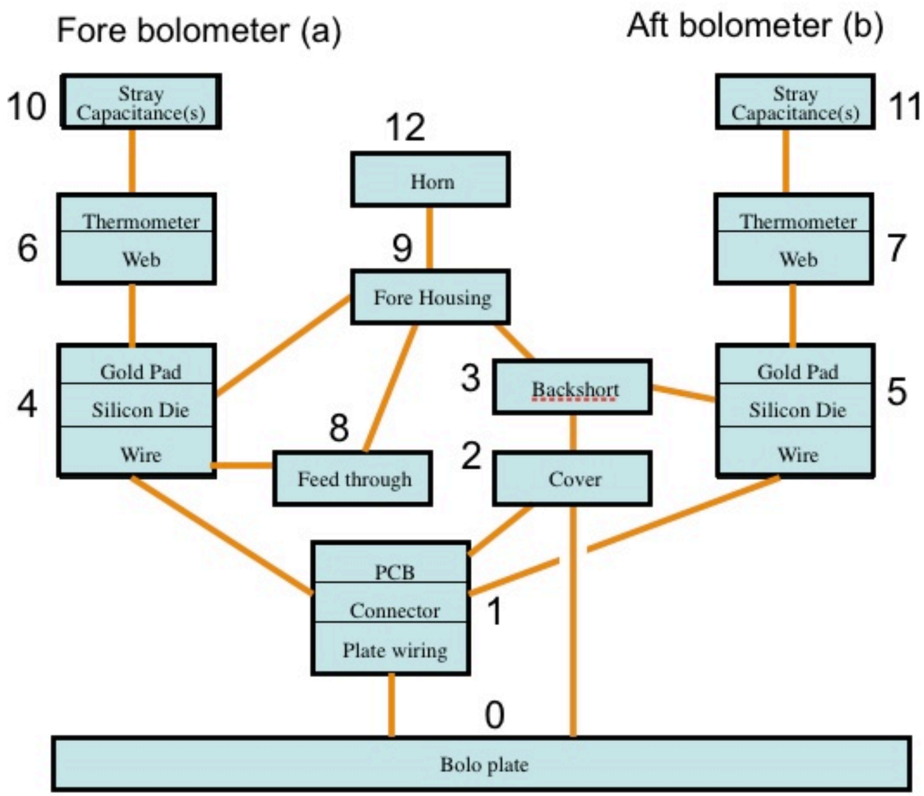
Long time constants seen by stacking all events related to CR hitting on the wafer



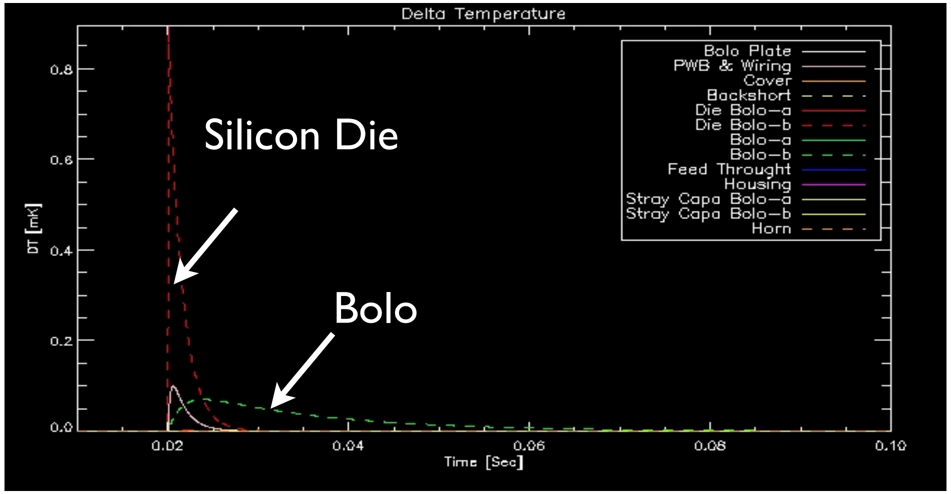
Thermal modeling is important. Long time constants might come from the links between the wafer and the detector housing and are seen on both categories of glitches

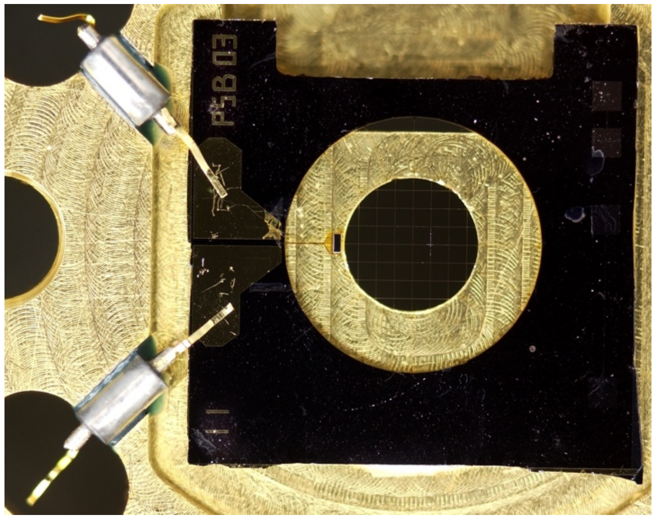
Bolo Thermal Model

PSB "simplified" thermal model



Simulation of a 23MeV Proton in the silicon die





Basic Equation

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

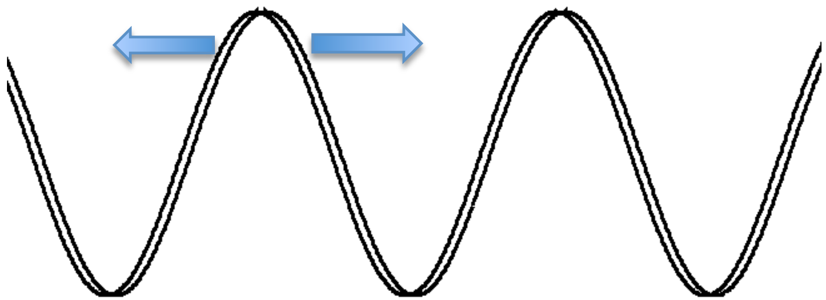
Impact of long time constants on data

• 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



• Induce percent effect in the calibration if not properly corrected as it affects the highest and lowest multipoles in a different way

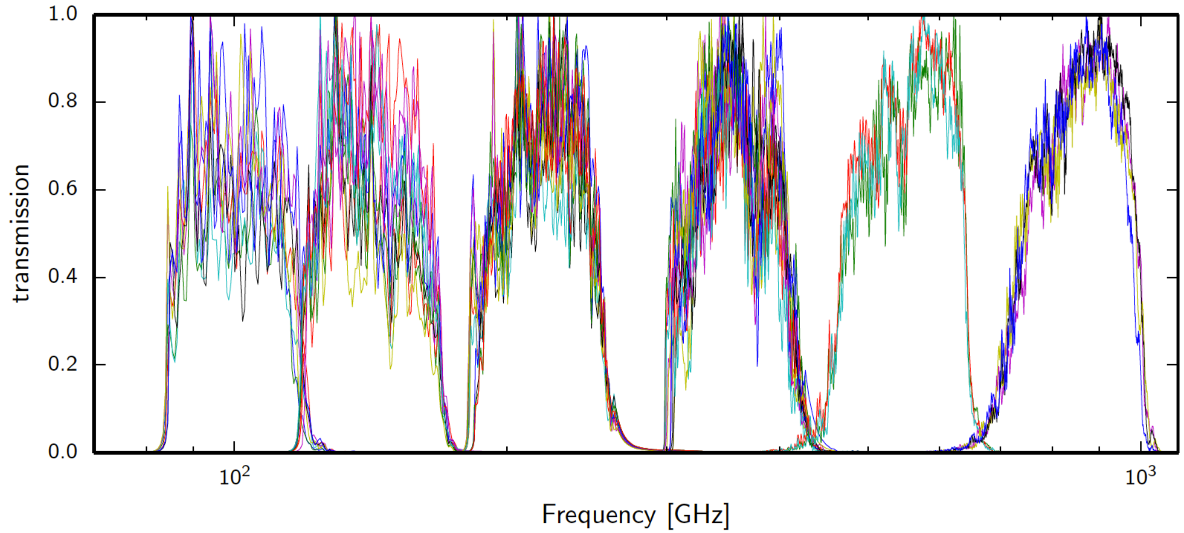
• Time constants are variable from detector to detector

• Having different survey with nearly opposite scan directions helped to constrain and correct the longest time constants

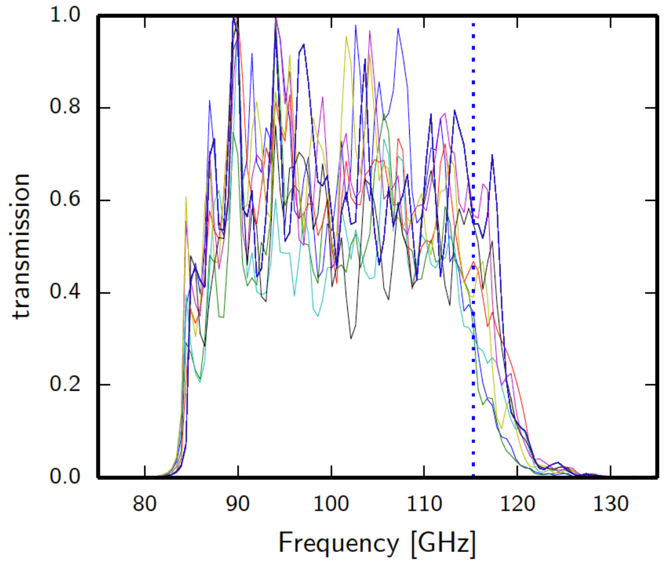
• Solved at the map-making stage by template fitting (largest multipole shifts)

Band-pass mismatch

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



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

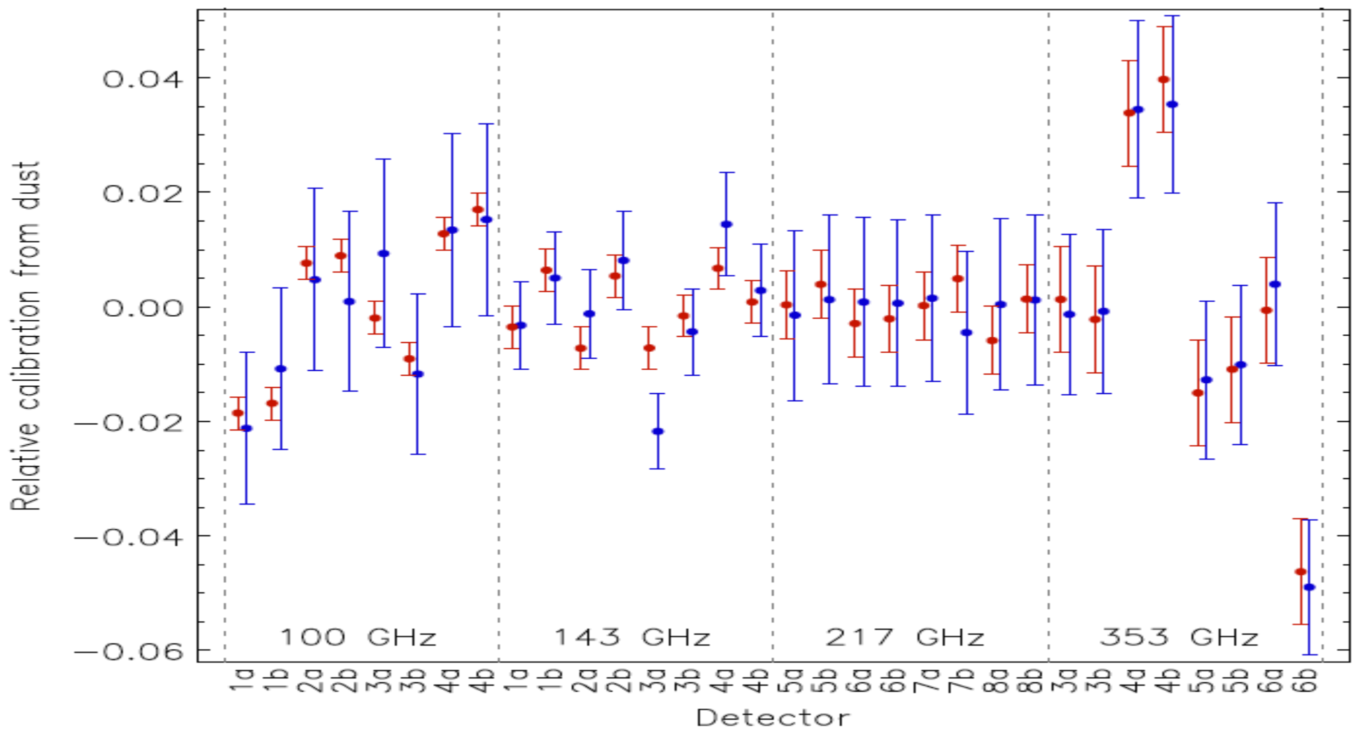


CO transition line 1-> 0 falls at the edge of the 100 Hz filters so the CO components has very different amplitude from detector to detector

Band-pass mismatch correction

-Band passes were measured from the ground. The precision is not accurate enough to remove the dust intensity to polarization leakage with the predicted coefficients

- Joint estimation of CO and dust leakages at the map-making level in Planck. Naturally minimizes the survey difference contamination

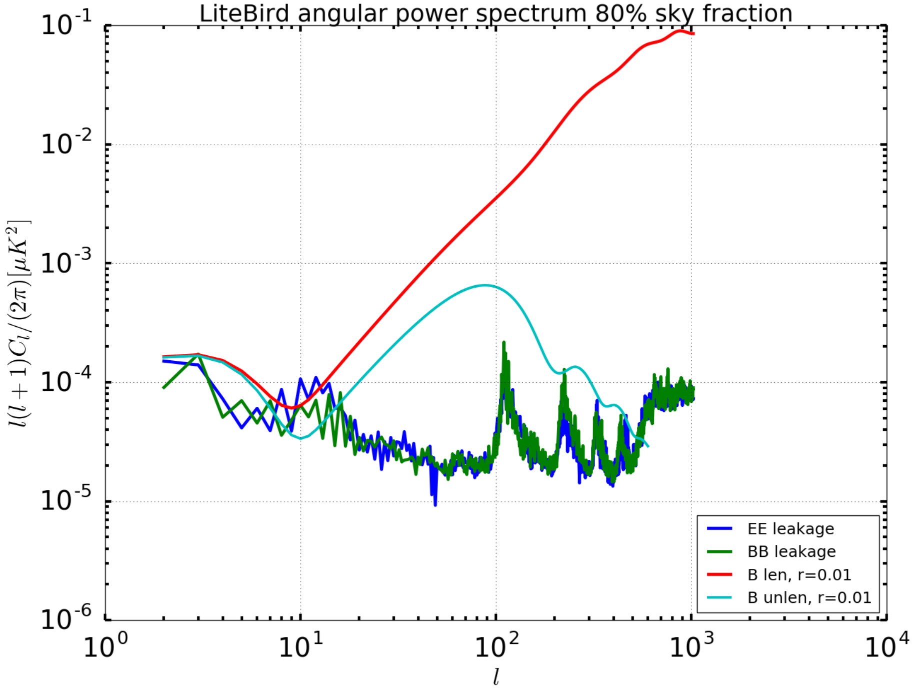


Effect mostly removed at the end, given the level of accuracy of Planck

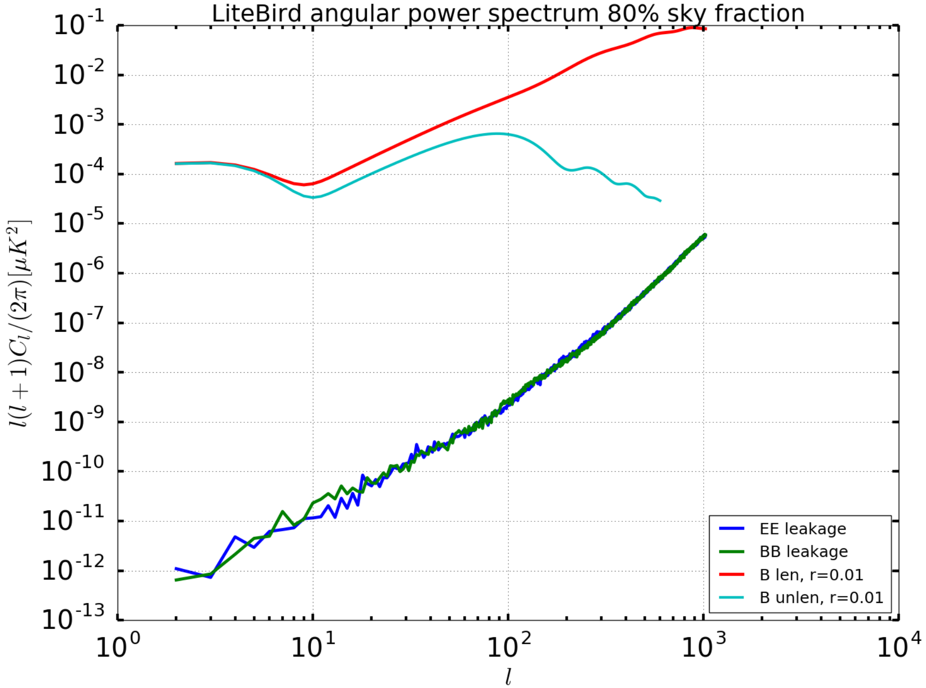
Future missions

- Future missions will avoid CO lines in frequency bands

- Effect should be reduced as compared to Planck but treatment will probably be required



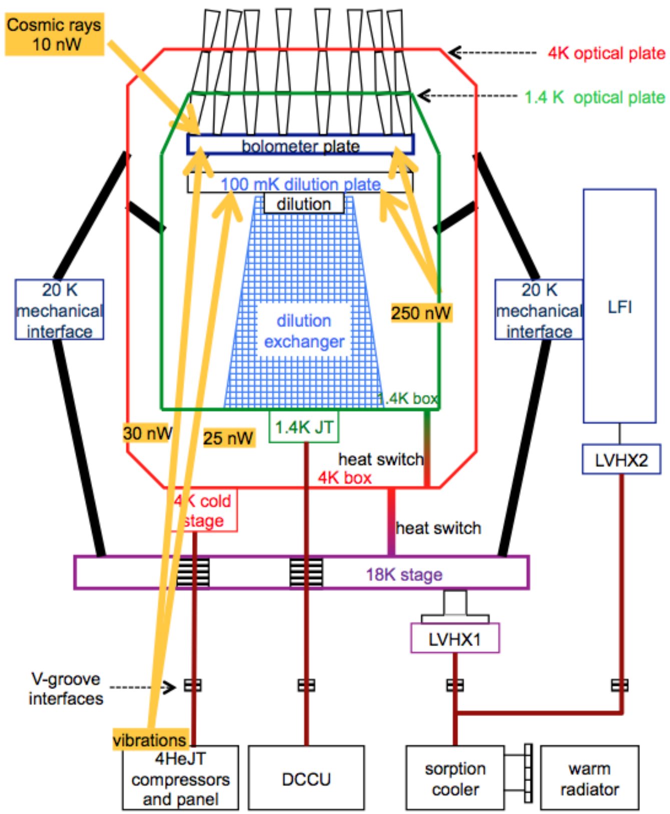
With perfect HWP:

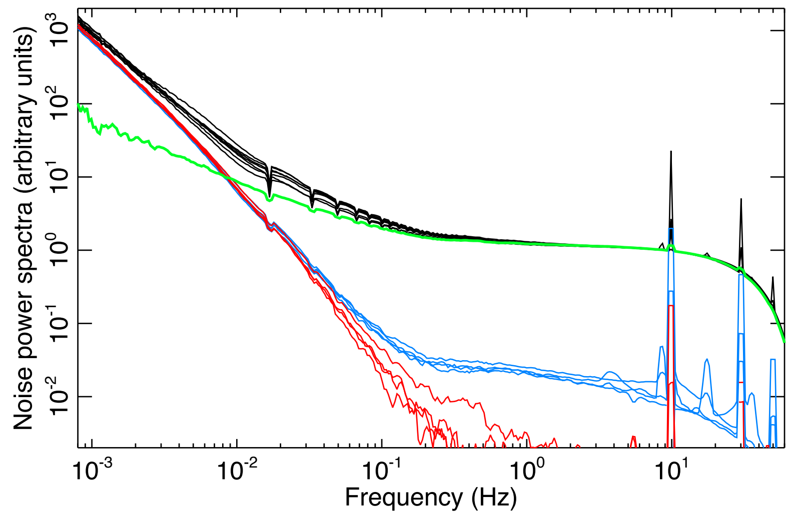


Credit: Hoang Đuc Thuong

Lines induced by the 4K compressors

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

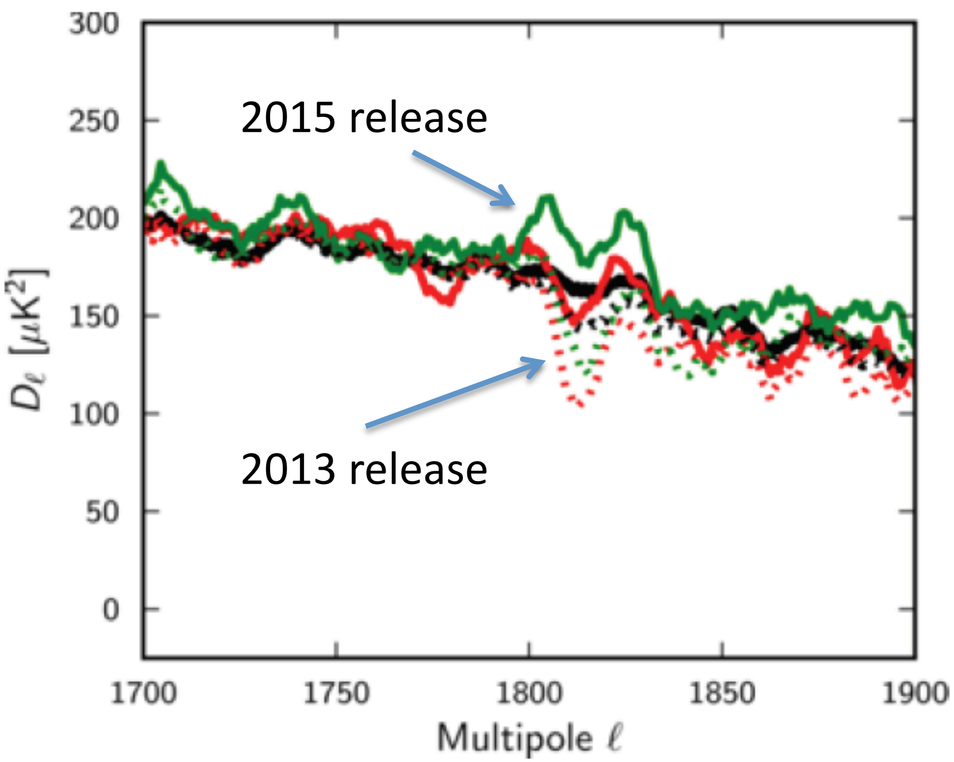




Data acquisition locked on the 4K cooler compressor: fixed line frequencies, multiple of 20 Hz (before demodulation)

Amplitudes vary across 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

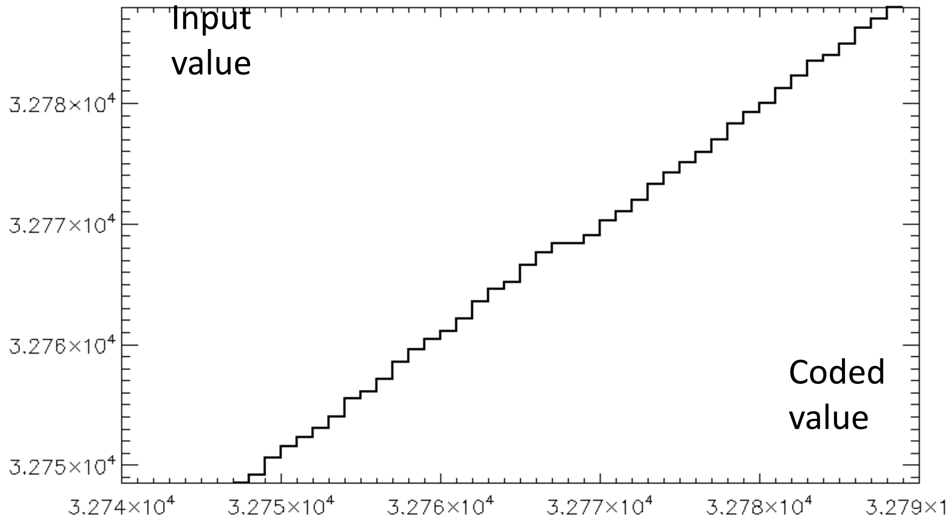
Better rejection for 2015 results correcting an artifact affecting cosmology in 2013 data.

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

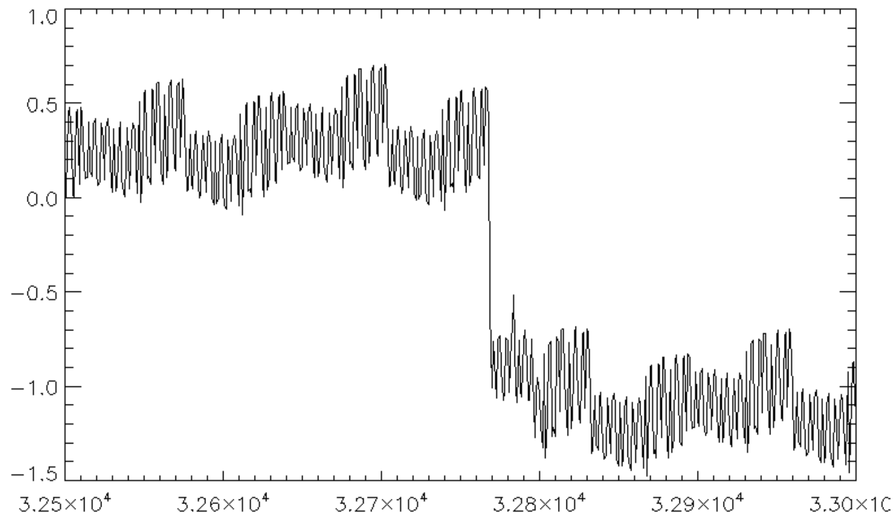
ADC non-linearities

Analog to Digital convertor have some non-linearities

This problem was not considered before flight.



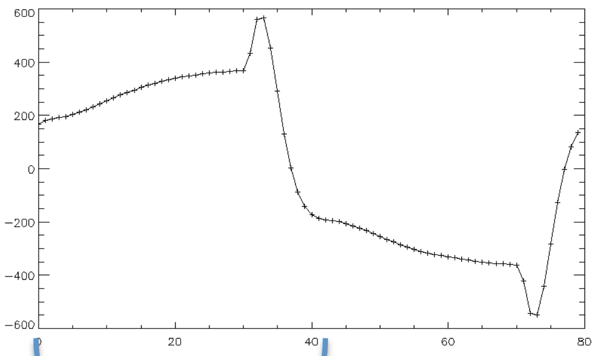
Non-linearity ADC(x) - x:



Planck data are for the very large majority sampling -300 to +300 ADUs around the central value, where the non-linearity is larger!

Data model

Fast sample data (40*180 Hz):



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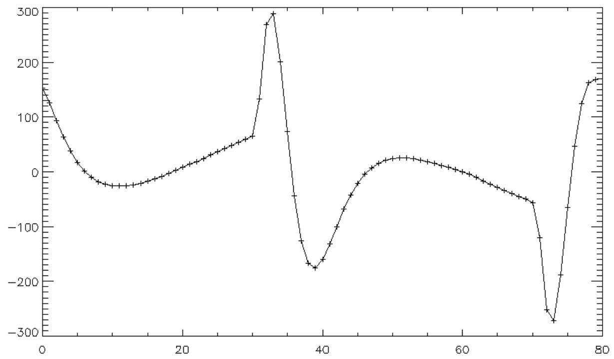
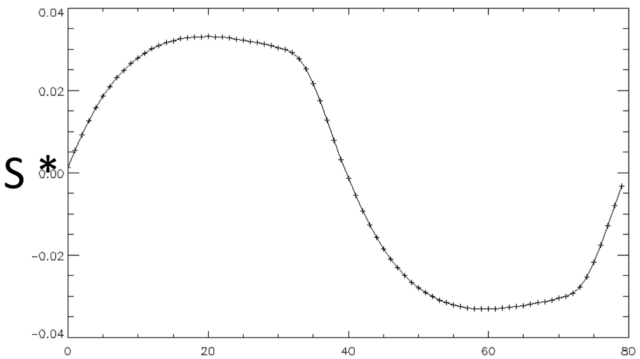


+ S *



One sample

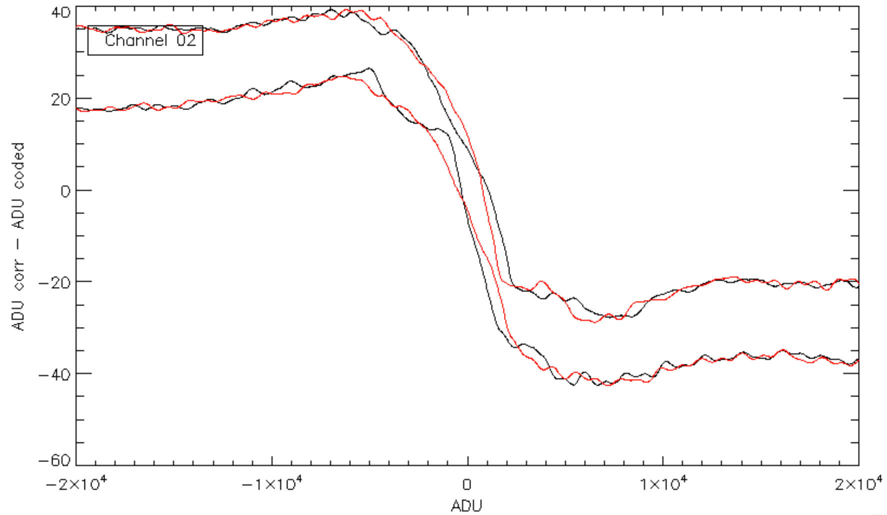
(+ d4K(t))

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

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

Non-linearity function :

$$\langle m \rangle = F(S)$$



F is a non-linear function

Correction is straightforward with the knowledge of F.

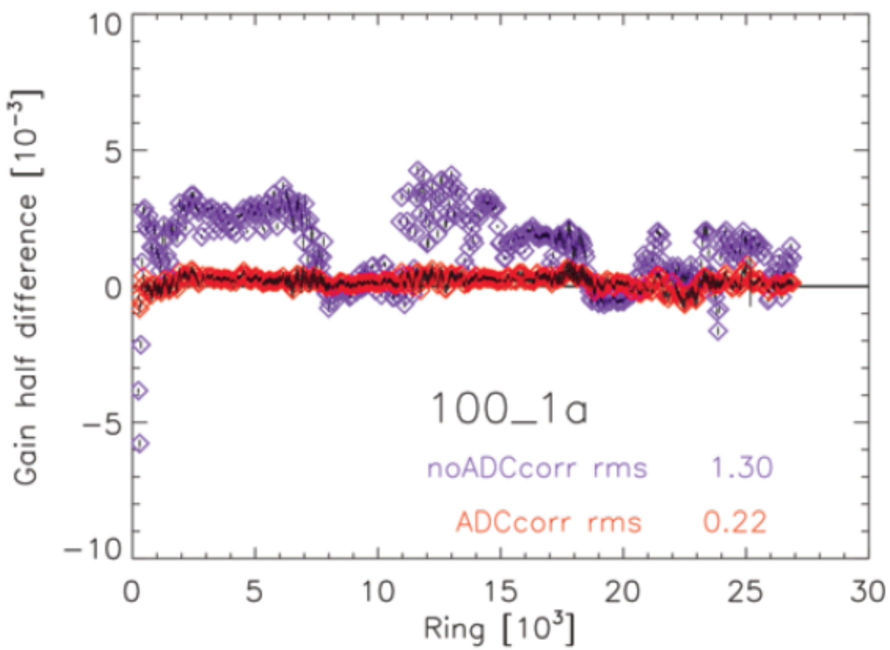
F depends on elect. response and ADC shape

ADC correction

1st order correction with time dependant gain is not accurate enough.

The non-linearity function is estimated for each ring using a maximum likelihood approach.

- The ADC shape is estimated using warm data taken at the end of the mission
- The electronic response is measured every 100 seconds for each detector



Data Jackknives are very efficient to test the quality of the ADC correction

Correction allows to reduce the systematics level by 1 to 2 orders of magnitude!!

Limited by 4K line knowledge

2nd correction performed at the map-making stage.

ADC correction

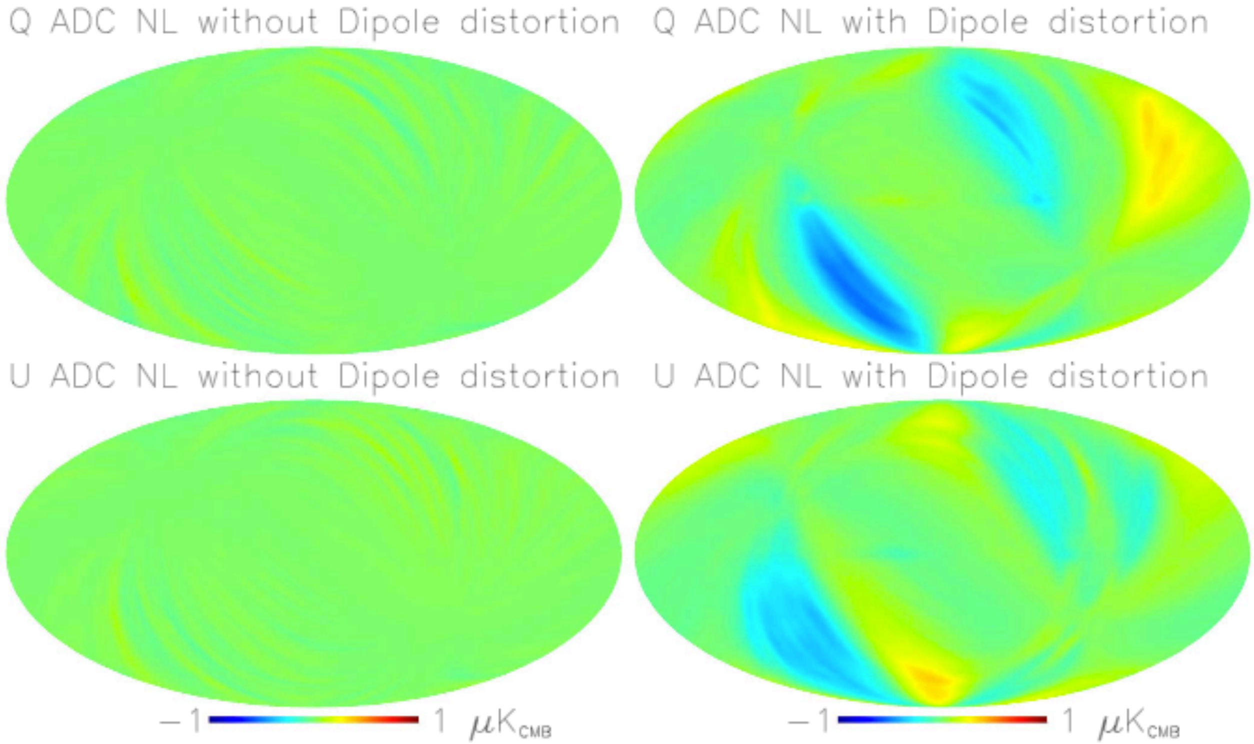
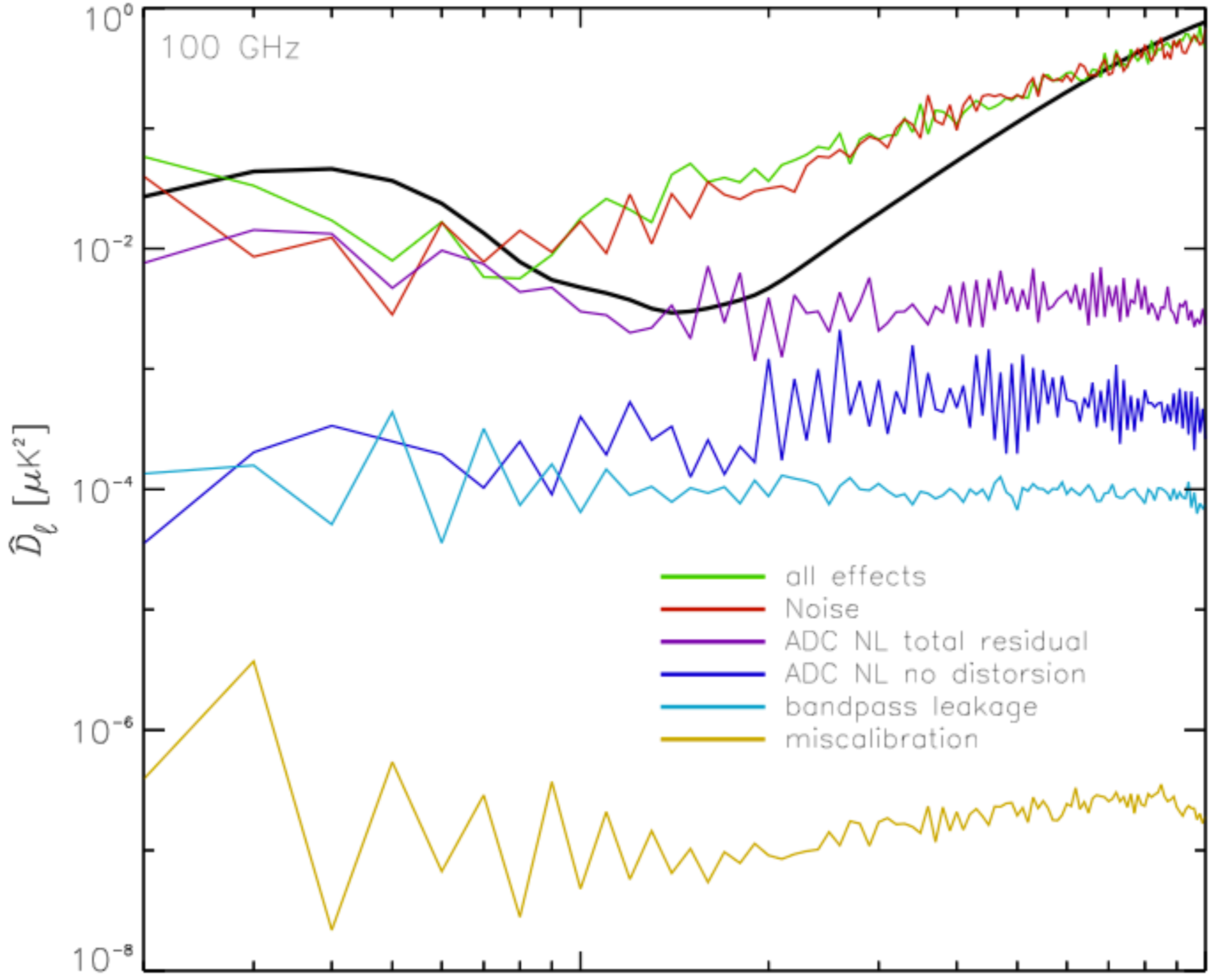


Fig. B.13. Simulation of residual polarization (*Q* on the top row and *U* on the bottom row) maps at 100 GHz. Maps in the left column are obtained by using a constant gain per ring, while maps in the right column are obtained when the simulations are run with the ADC NL model.

Estimated contributions to the polarization spectra

- High ell dominated by detector noise
- Low ells have systematics at the level of noise. The ADC non-linearity is dominant effect even after correction



Conclusions

- Main systematics in Planck HFI data affecting the low multipoles:
  - ADC non-linearities/ 4K lines
  - CR glitches
  - Band-pass mismatches
  - Long time constants
  - Far side-lobes

- Some of the systematics could have been avoided or reduced with dedicated measurement on the ground. In particular ADC and glitches

- Dedicated methods removed efficiently most of the effects in Planck. Many effects are removed at the map-making stage.

- Most of the residuals are below the HFI Planck noise after correction
  Dominant effects residual ADC non-linearities at the level of noise for $l < 10$

- Future satellite experiments will have to deal with all those effects carefully, given the precision required for r
  Large number of detectors and scanning strategies with large precession angle will help.