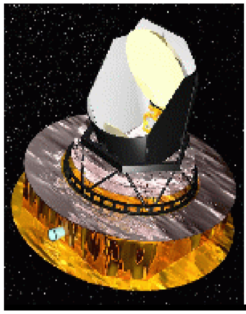
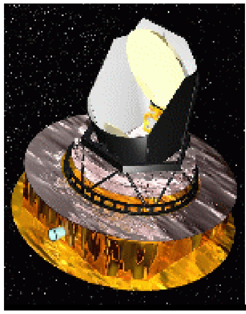


Planck in-flight photometric calibration

G. Lagache

and

J.-P. Bernard, M. Douspis, L. Montier, M. Piat, O. Perdereau, J.-L. Puget, C. Rosset



Planck photometric calibration

PLANCK HFI

Planck

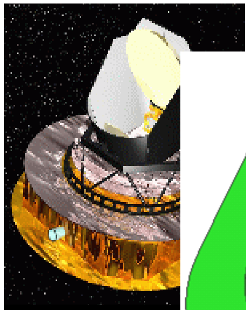
- Third generation of space CMB satellites (after COBE and WMAP)
- Launch date: Oct., 31srt - Nominal life time >21 months (>2 surveys)
- Sensitivity limited mainly by CMB photon noise
- Polarisation (from 353 to 100 GHz (HFI) and 30-44-70 GHz)

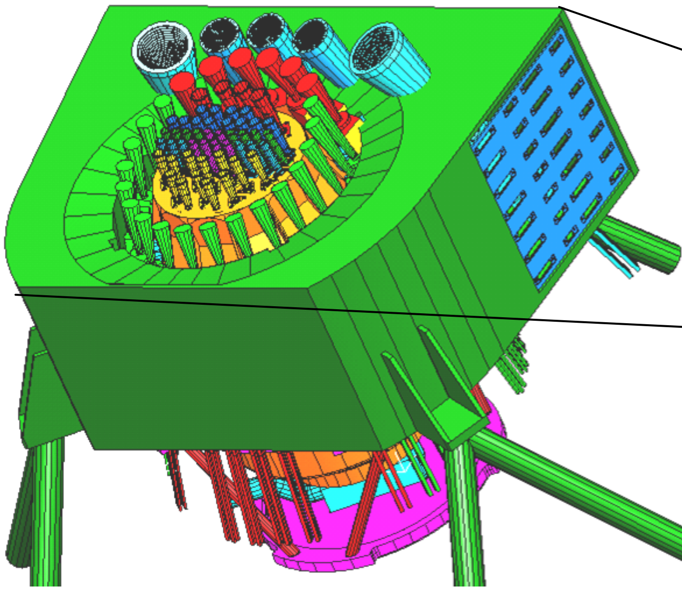
HFI:

Central Frequency (ν)	Ghz	100	143	217	353	545	857
Central wavelength	mm	3.0	2.1	1.38	0.85	0.55	0.35
Bandwidth	λ/Ęλ	3	3	3	3	3	3
Angular resolution	arc min	9.2	7.1	5.0	5.0	5.0	5.0

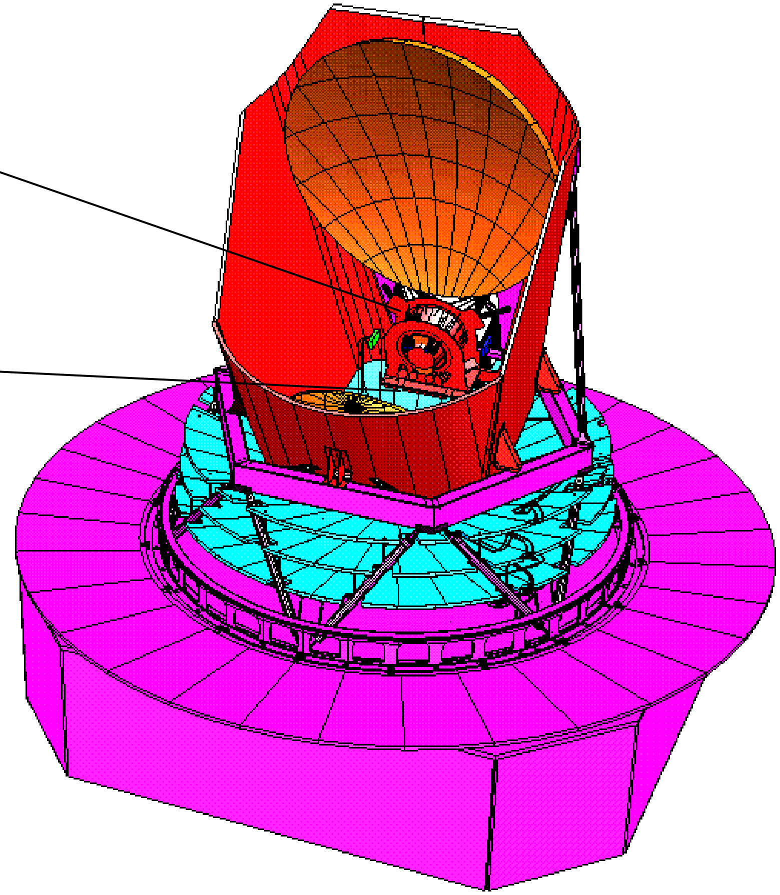
LFI:

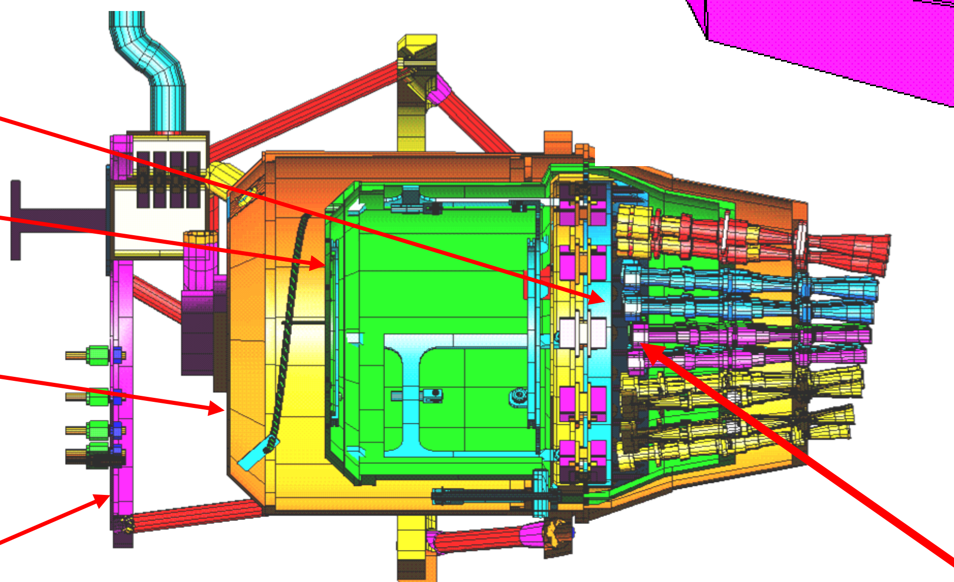
Central Frequency (ν)	Ghz	30	44	70
Angular resolution	arcmin	33	24	14

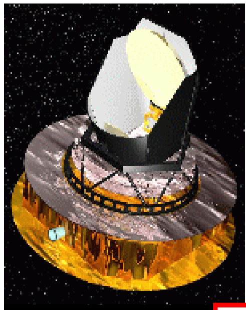




PLANCK Focal plane

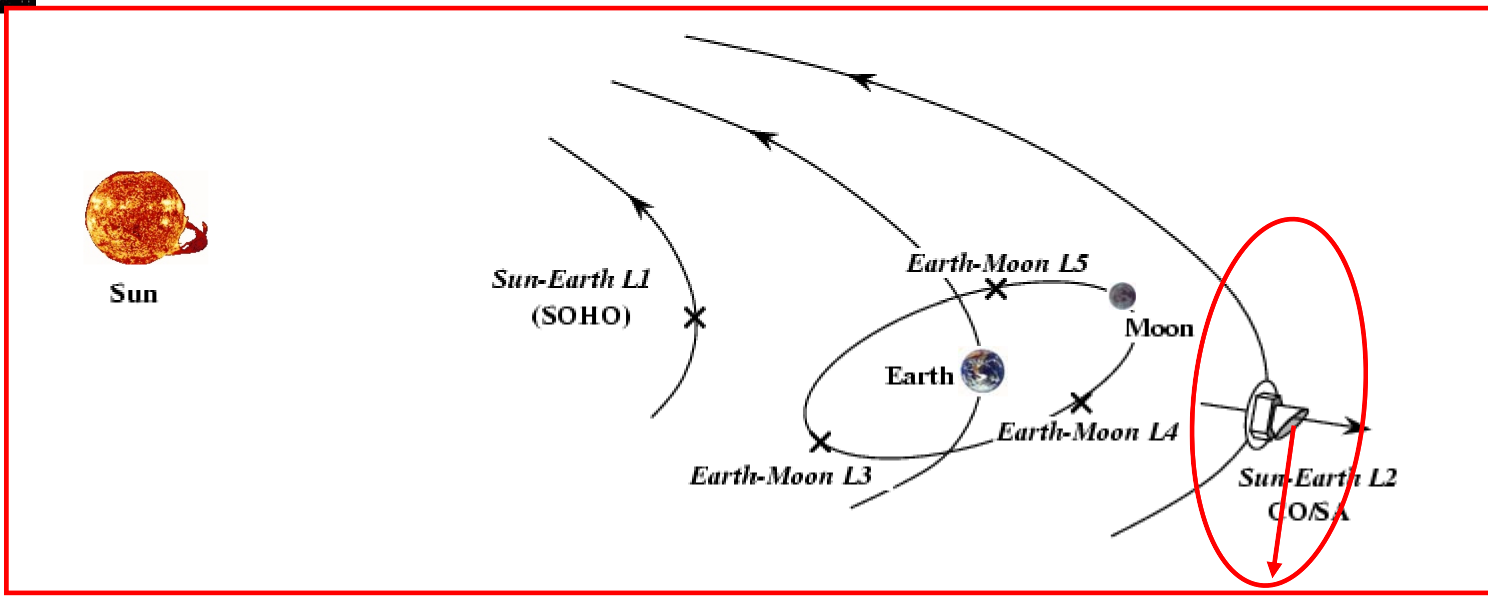


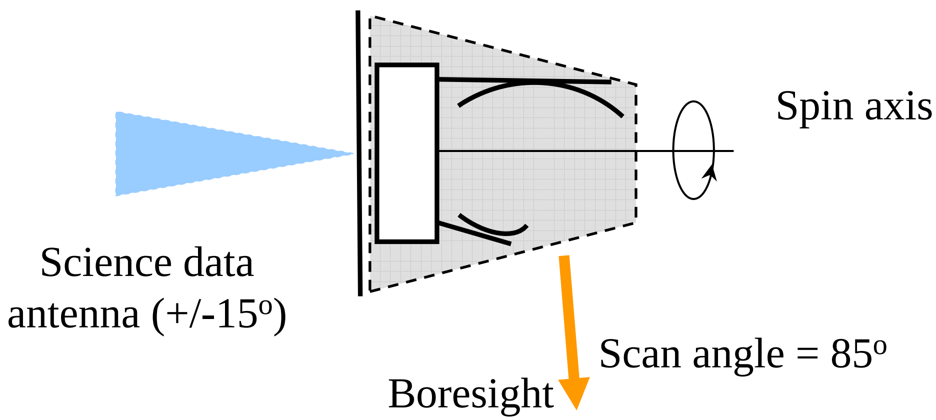




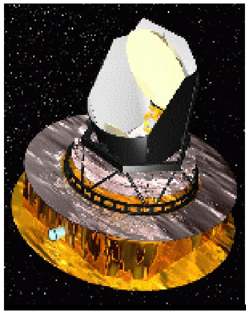
Planck photometric calibration

Planck





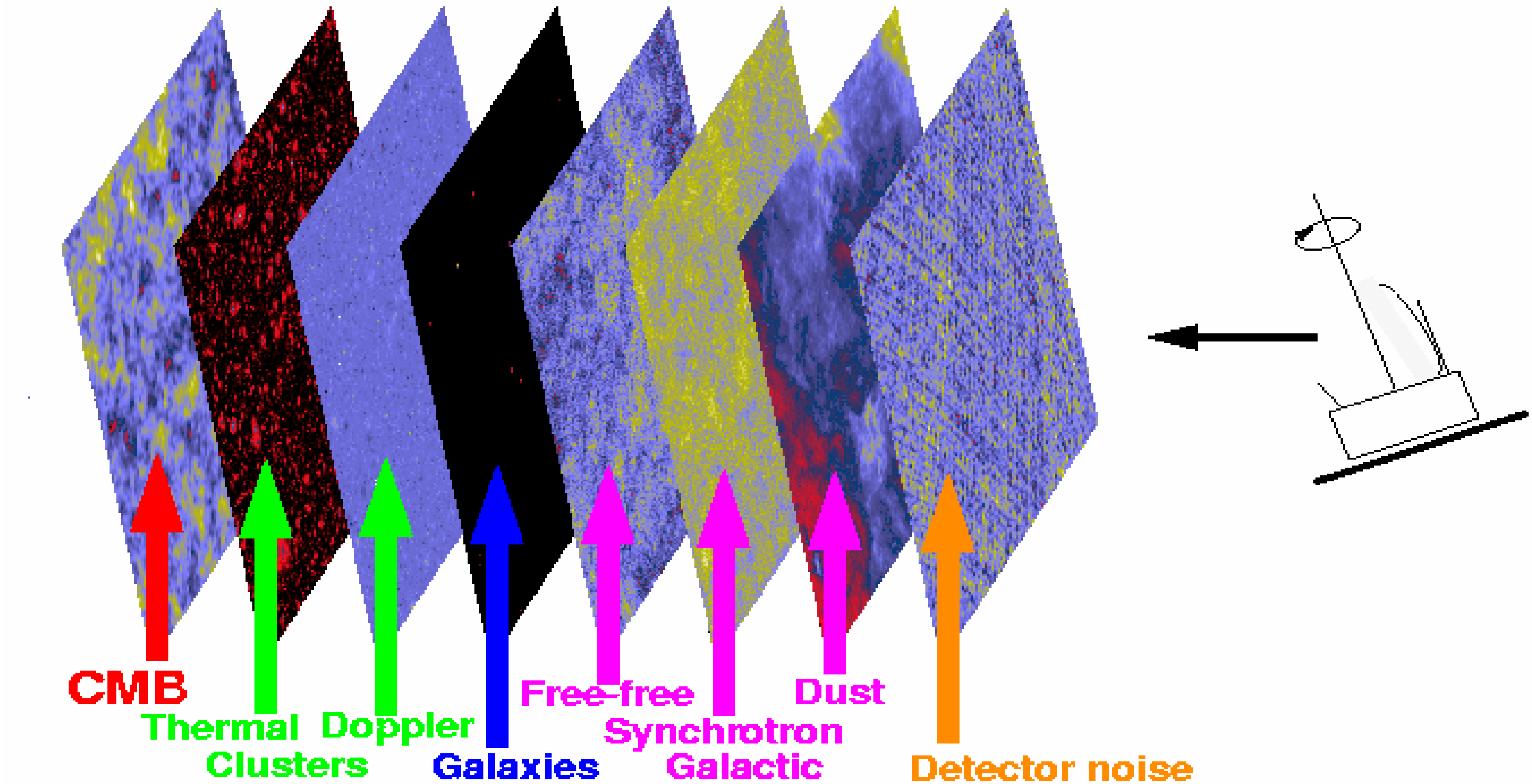
- 1 RPM (sampling 2')
- Repointing every ~60mn by 2' steps
- Full sky in ~6 months

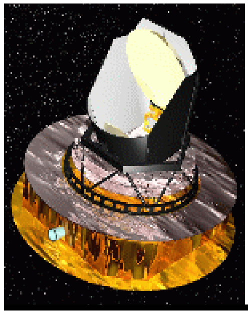


Planck photometric calibration

PLANCK HFI

Planck

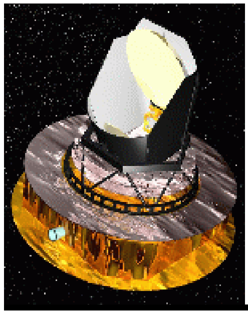




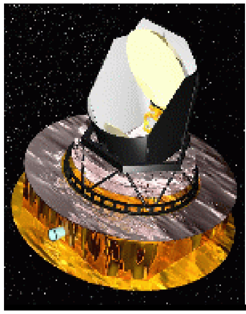
OUTLINE

- More infos on Planck: "Blue book": http://www.rssd.esa.int/Planck

- Absolute calibration
  - Overview of the procedure
  - Dipole
  - Galaxy
- Relative calibration
  - Relative calibration of rings on the dipoles
  - Cross calibration (between bolos) using Galactic profiles
- Knowing the beam…
- Point source calibration
- Conclusion



Absolute photometric calibration



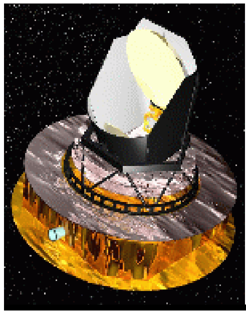
Calibration procedure overview

- Primary calibration: **extended source calibration**

- Point source calibration: generated from the extended source calibration knowing the main beam and the spectral transmission for each detectors

- Direct point source calibration will be done on planets

- Comparison will provide check on calibration and throughput per detectors (integrated beam)



PLANCK HFI

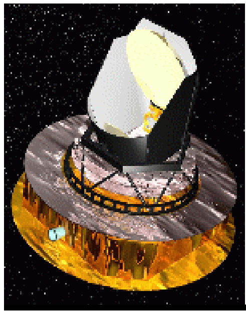
Calibration procedure overview

- Extended **absolute** calibration: established globally
  - Orbital dipole for the low frequencies
  - Galaxy for the high frequencies

- **Relative** calibrations will be done as precisely as possible between individual circles and rings **before** establishing an **absolute** calibration

  i.e. The absolute calibration is done as the last step of the reduction
  - **No Error propagations**
  - **Minimal loss of information from the original data**

- Iterative method
  - Benefits from increasing knowledge of the instrument



Planck photometric calibration

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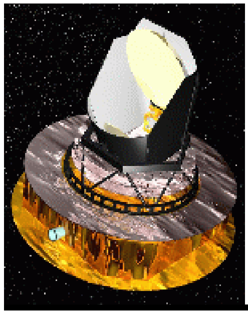
HFI

Dipole absolute calibration

- A very well calibrated source: the CMB temperature is known with accuracy better than 2.10^{-3} (Fixsen, 1996)
- Plank cannot measure accurately the monopole because many sources contribute (telescope, horns, filters,…)
- Our peculiar motion in a cosmological frame is well known and measured by COBE. This makes an absolute extended source of 3.36±0.024 mK (lineweaver et al, 1996) modulated at 1 period per minute by the satellite rotation
- It can be measured accurately by all HFI channels (<600 GHz)

- Photometric calibration on the Doppler effect induced on CMB by the earth orbital movement (known with the accuracy of the CMB itself i.e. better than $2.\ 10^{-3}$).
- Orbital dipole: Perfectly known in amplitude (~10% of the CMB dipole) and direction.



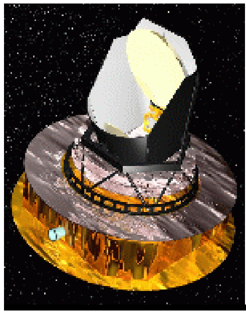
Absolute calibration on the orbital dipole: processing

♦ On all rings:

- Fit simultaneously the absolute calibration factor, CMB dipole amplitude and direction:

$$\text{Signal}(l,b) = F \times \left(\text{CMBdip}_{(A0,\, l0,\, b0)}(l,b) + \text{ORBdip}(l,b) + \text{Gal}(l,b) + \text{CMBA}(l,b) \right)$$

- Assume intercalibrated rings
- Mask the Galaxy (or remove it at first order)



Planck photometric calibration

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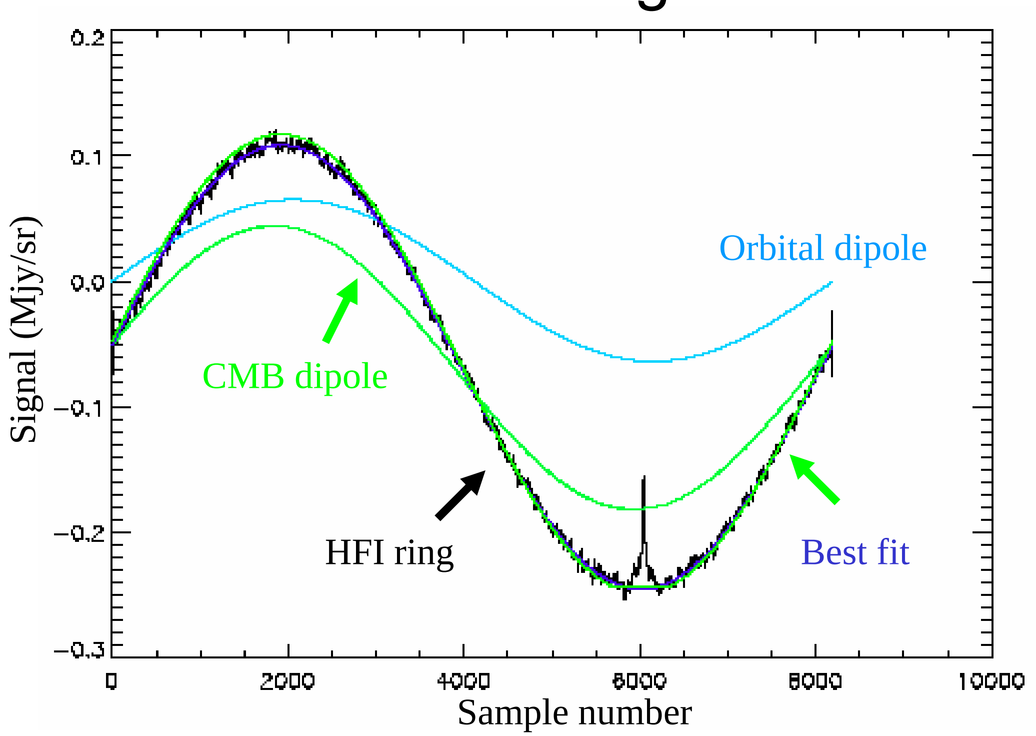
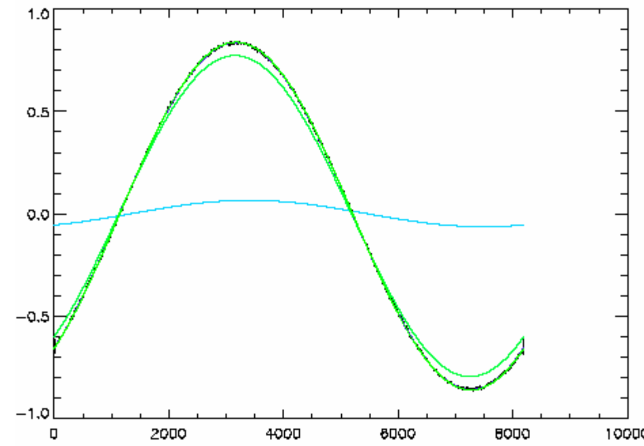
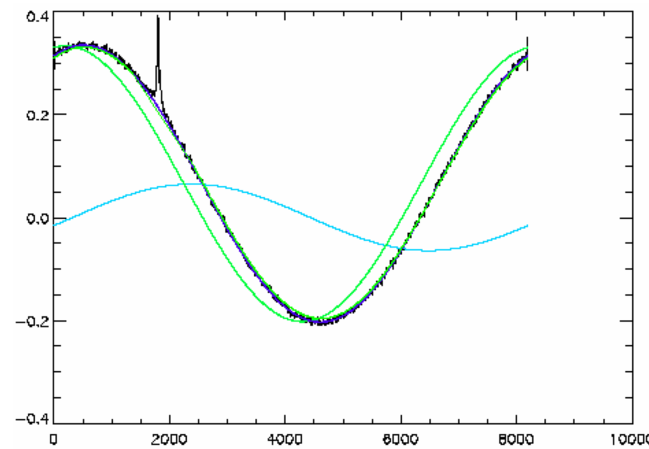
A ring

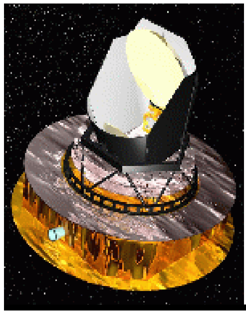
- A 100 GHz HFI ring:







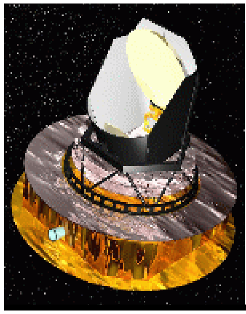
➯ Orbital dipole mostly in phase or in opposition phase wrt CMB dipole



Dipole absolute calibration : results

- CMB Dipole direction recovered at better than ~2’
- CMB Dipole amplitude recovered at better than ~0.5%

- **Absolute calibration:**
  - **better than ~0.5% at 100, 143, 217 GHz**
  - **~1 % at 353 GHz**



Absolute calibration using the Galaxy

- Compare HFI and FIRAS (7^{o} resolution) Galactic disc data (generate profiles or small maps per detector)

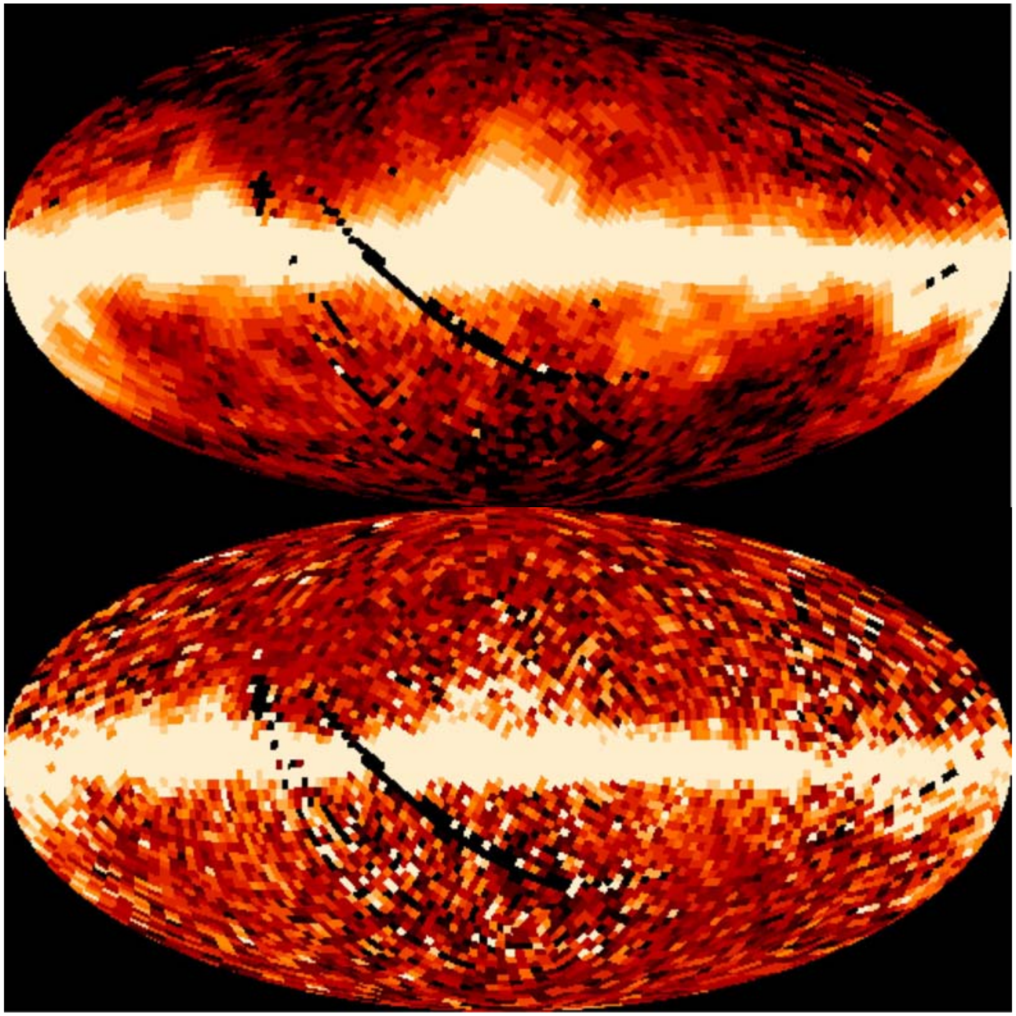
- HFI SNR in the FIRAS beam at 100 GHz on the Galactic Plane (including all detectors)

  - $l=0^{o}$, B=93 MJy/sr, S/N=2.6 10^{6}
  - $l=20^{o}$, B=69 MJy/sr, S/N=1.9 10^{6}
  - $l= 164^{o}$, B=4.7 MJy/sr, S/N=1.3 10^{5}

=> Main limitation = FIRAS noise

Planck photometric calibration

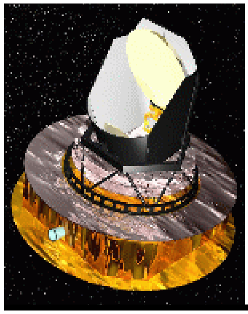
FIRAS data



200 μm

900 μm

Gain uncertainty < 3% …
but very noisy



FIRAS: spectra & fit

- FIRAS data: One spectrum per pixel

- Projection: COBE Quadrilateralized Spherical Cube (CSC)

- Fit of FIRAS spectra:

$$S_\nu = \tau \left(\frac{\nu}{\nu_0}\right)^\beta P(\nu, T_{dust})$$

- Color corrections:

$$I_{\nu_0}(actual) = I_{\nu_0}(quoted)/cc \qquad cc = \frac{\int (I_\nu / I_{\nu_0})_{actual} R_\nu d\nu}{\int (\nu_0/\nu) R_\nu d\nu}$$

Planck photometric calibration

FIRAS spectra and fit: example for three pixels

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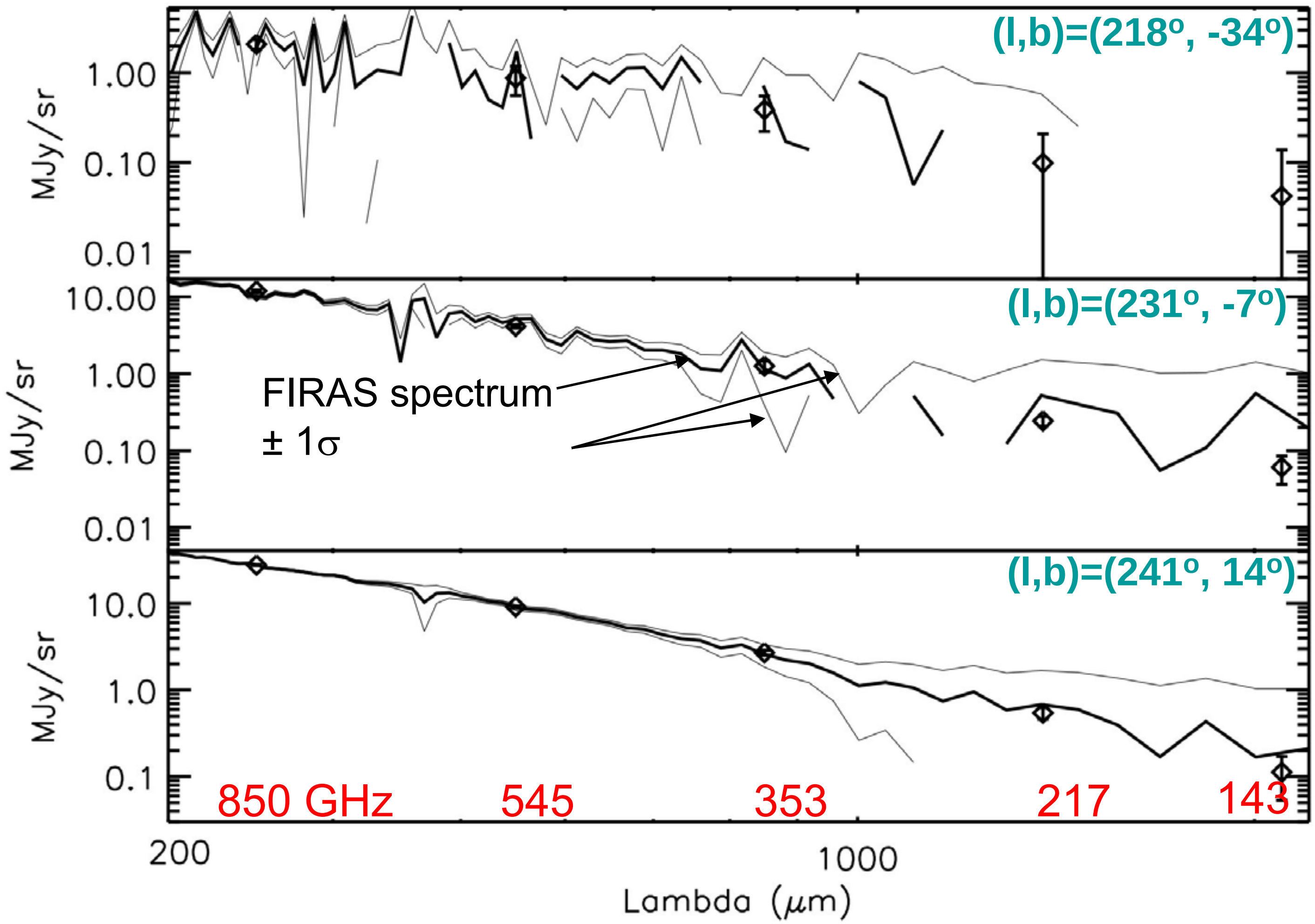
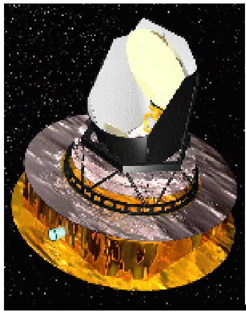
HFI





Planck photometric calibration

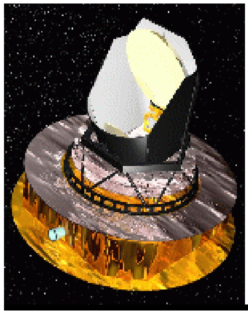
PLANCK
HFI

Calibration on the Galaxy

-The galactic calibration pipeline (at each ν):

- Put the HFI data in the DIRBE-CSC (DIRBE=1^{o})
- Convolve the DIRBE-CSC map with the FIRAS beam
- Decimate the HFI DIRBE-CSC pixels and create an HFI FIRAS-CSC map
- Compute the corresponding FIRAS brightness map using fits of FIRAS spectra and derive the color correction for each pixel
- Derive a FIRAS brightness map (with the convention νI_{ν}=cst)
- Compare galactic plane data (of FIRAS brightness maps and HFI FIRAS-CSC maps) to derive the calibration factor

- Test the galactic calibration on Archeops data: galactic profiles



Planck photometric calibration

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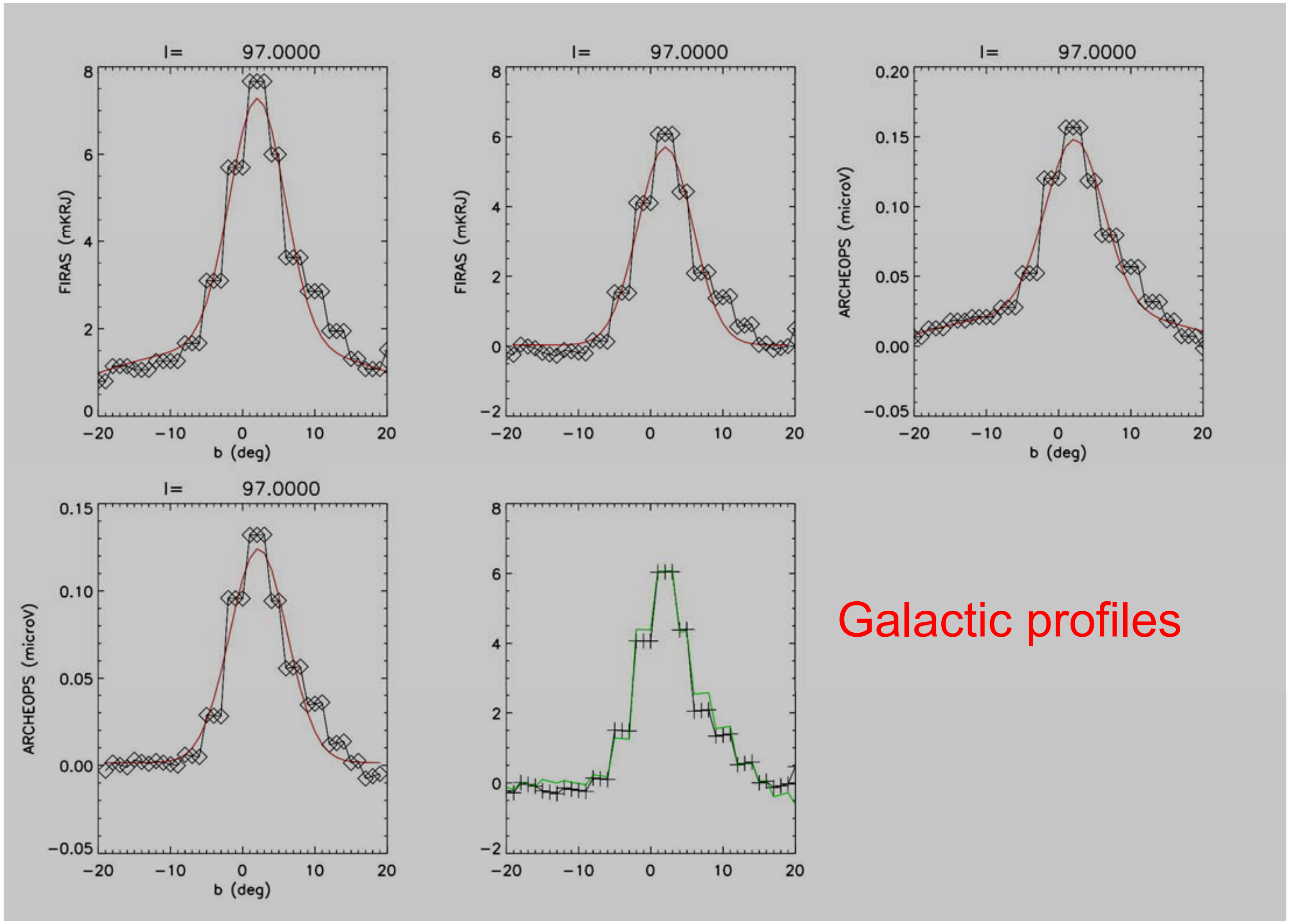
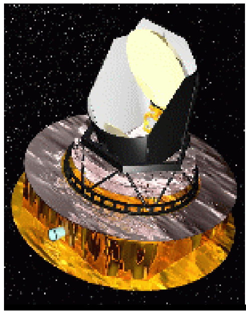
Archeops data: Calibration on the Galaxy





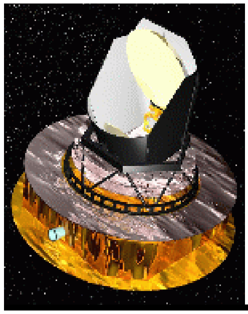
Planck photometric calibration

Calibration on the Galaxy

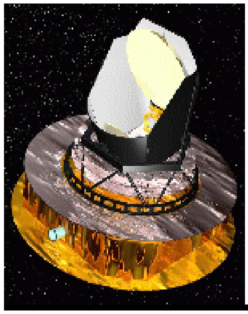
- Archeops calibration factors:
  - Intrinsic errors from 25% to 5%
  - Include the FIRAS noise (statistical noise, error in the gain, error in the parameters of the spectral fits)
  - Include Archeops statistical noise
  - On coadded Archeops maps:
    - => Errors 8, 4.4, 3% @ 143, 217, 353 GHz (5-6 bolometers)

- Archeops Dipole/Galaxy: <10% (143 and 217 GHz)

- Conclusion:
  - In the inner galactic disc**:** Very good absolute calibration on the Galaxy even for the CMB channels!



Relative calibration



Planck photometric calibration

PLANCK HFI

Relative calibration: rings

- **Time scale > 1 hour:**

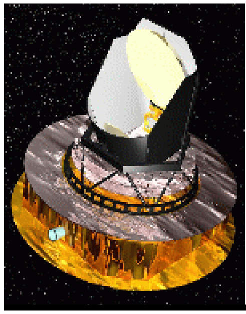
Long-term response variations + 1/f noise (if any…)

↳ $S_{sky} = R P_{sky} + A$

↳ Destriping for A (and R) + map-making for R.

↳ Of course:

Low frequency chanels: relative dipole calibration to monitor the variation of the response on long periods

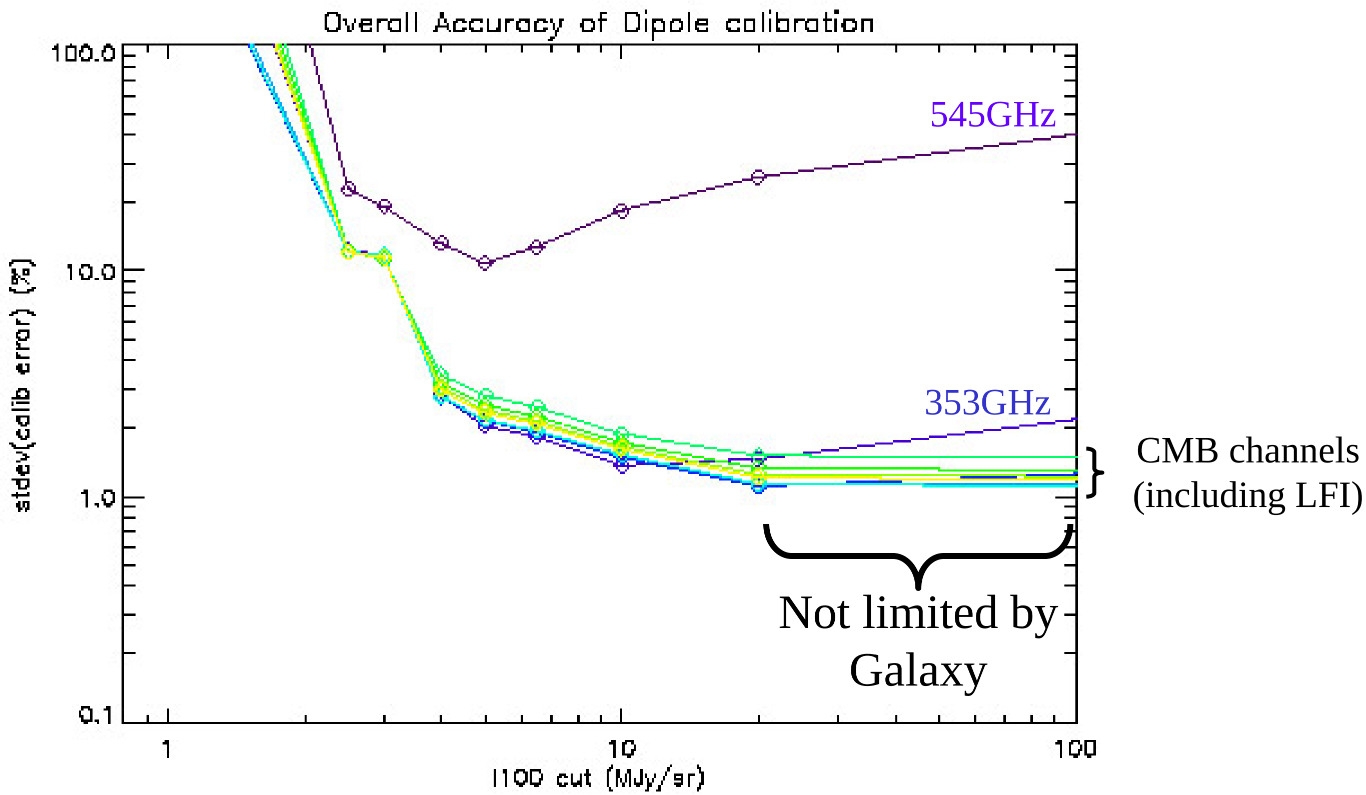


Planck photometric calibration

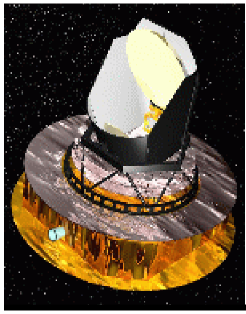
PLANCK HFI

Dipole relative calibration: accuracy

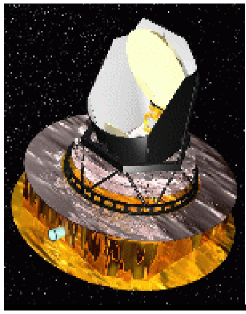
- RMS fluctuations of calibration factor on **rings**:



- < 2% achievable on CMB channels
- About 10% at 545GHz



Relative calibration:
Between bolometers (for one ν)

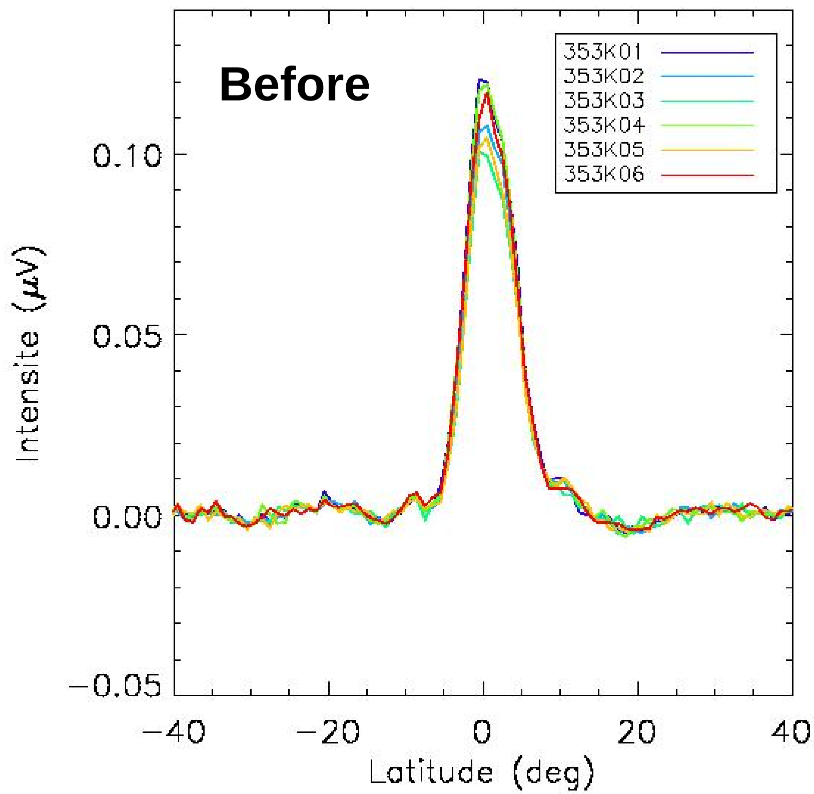


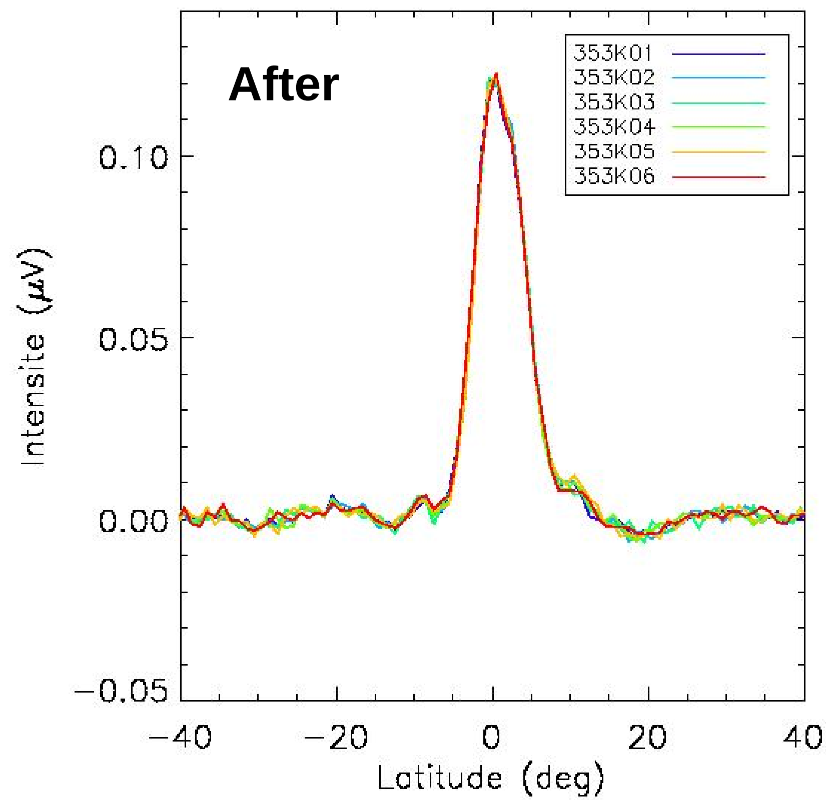
Planck photometric calibration

Xcalibration between bolometers

PLANCK HFI

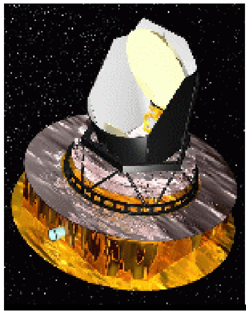
Exemple at 353 GHz, Archeops: Error = 2%





C. Rosset, PhD thesis

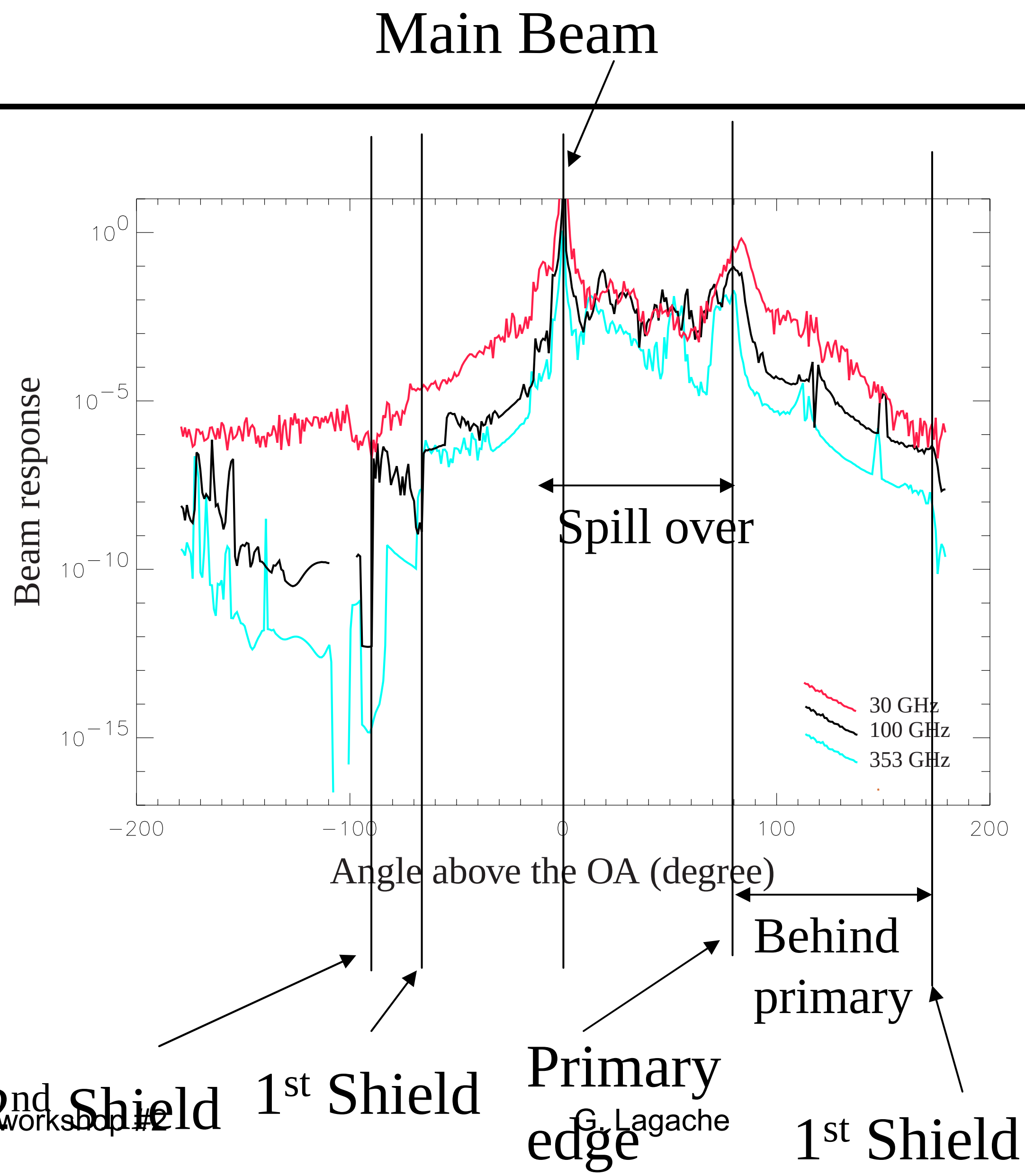
➥ And/or optimal map-making

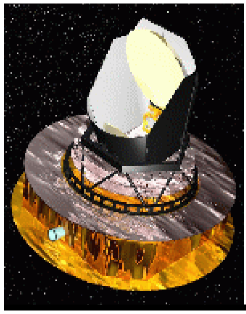


Knowing the beam….

Accurate calibration of the beam shape is mandatory for interpretation of CMB maps

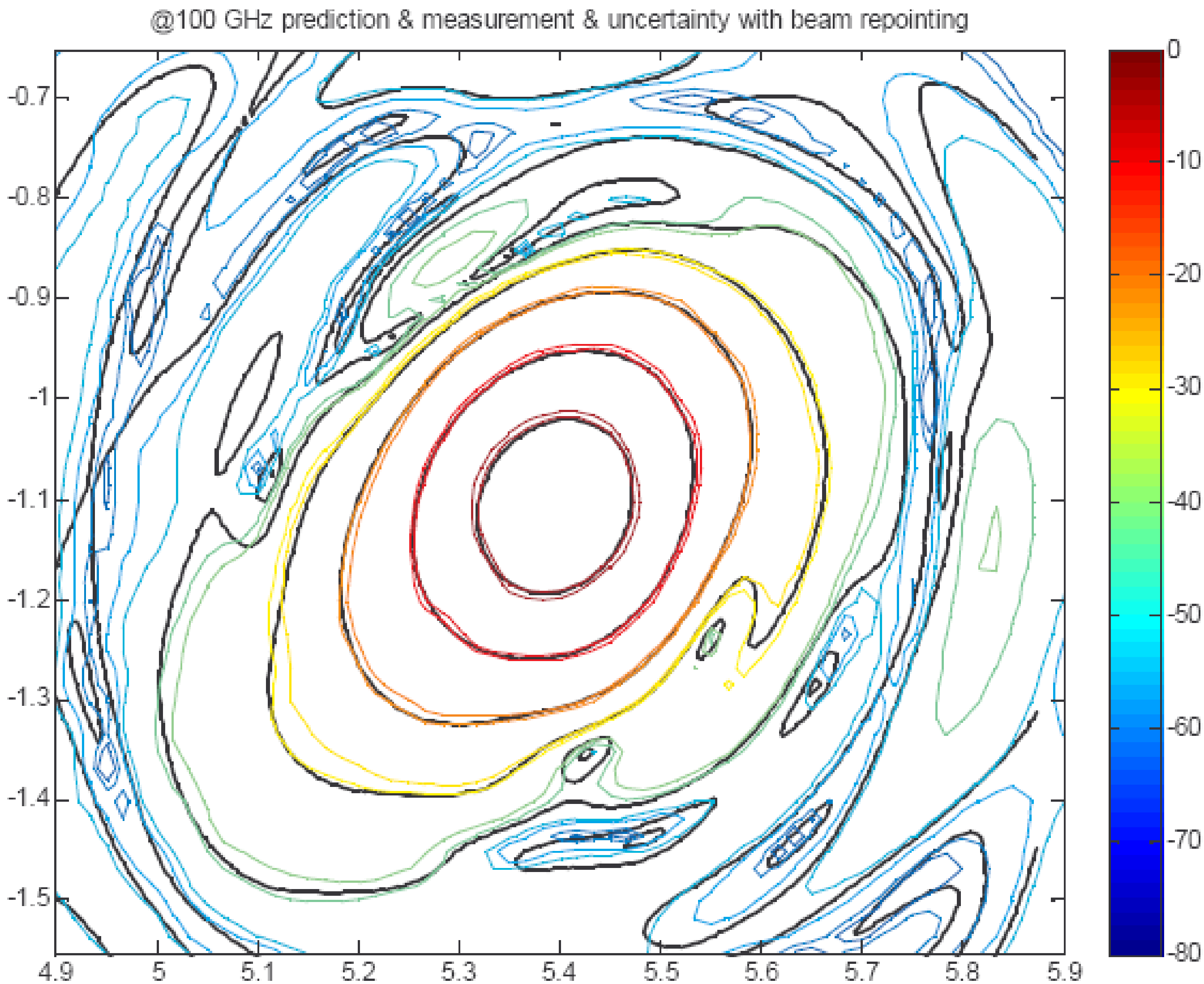
Planck photometric calibration

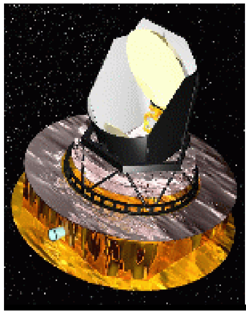




Planck photometric calibration

PLANCK
HFI



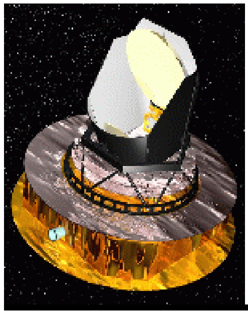


Planck photometric calibration

PLANCK HFI

Sources	Frequency GHz	Flux Jy	Peak brightness MJy/sr	S/N for beam mapping (2arcmin)
Mars 8"	143 217 857	190 440 $6.9\ 10^{3}$	21 99 $1.6\ 10^{3}$	732 $1.8\ 10^{3}$ $7.5\ 10^{3}$
Jupiter 38"	143 217 857	$2.9\ 10^{3}$ $6.8\ 10^{3}$ $1.1\ 10^{5}$	323 $1.53\ 10^{3}$ $2.5\ 10^{4}$	$1.1\ 10^{4}$ $2.7\ 10^{4}$ $1.2\ 10^{5}$

Jupiter: Non-linearity problems but useful for the near main beam reconstruction

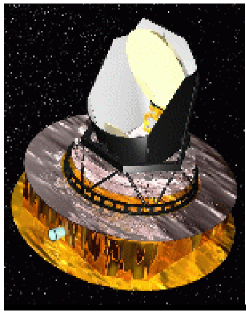


Planck photometric calibration

PLANCK
HFI

In-flight beam pattern measurements

- The main beam (30 arcmin) of a given bolometer is mapped with that bolometer with:
  - a time resolution corresponding to 2 arc minutes
  - a cross scan sampling of 2 arc minutes
- The main beam pattern can be measured with Mars (Saturn, Uranus, Neptune)+ Jupiter down to
  - 40 (50) dB (full resolution) at 217 (resp 857 GHz)
  - 50 (60) dB (16 arc minutes resolution)
- The part of the far side lobes inside the main baffle can be measured using the galactic center (and the galactic ridge) by comparing observations of the same sky point about 6 months apart (galactic center inside or behind the main bafle)
- The presence of sharp edges at high frequencies of known positions can be checked using Jupiter by summing a large number of crossing of these edges



Planck photometric calibration

PLANCK
HFI

Point source calibration

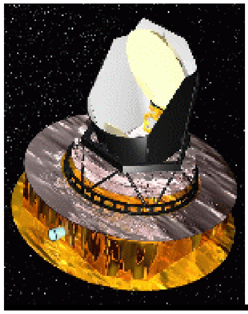
- Ω_{beam} will be known at <1%

  => Point source calibration not better than <1%

- **Direct point source calibration:**
  - Based on timelines around planet position
  - Small maps from combined scans / Flux integration
  - Comparison with the best models (convolved with the Planck spectral response)

-When compared with direct point source calibration, uncertainties on the models dominate

- The calibration of the ERCSC will be done using the first extended emission calibration and the beam measured on planets: ~20% accuracy



Planck photometric calibration

PLANCK HFI

Conclusions

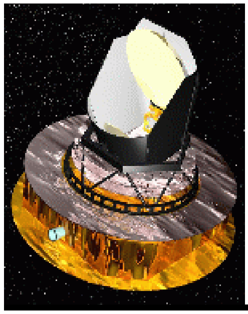
- Absolute in-flight calibration:
  - Better than 0.5% and 1% for 100, 143, 217 and 353 GHz resp.
  - 3% for high-ν channels (857, 545 GHz)

- Beam:
  - Accurate calibration of the beam shape is mandatory for interpretation of CMB maps
  - Huge effort in the Planck collaboration
  - Agreement between models and measurements is amazing!
  - Ω_{beam} known at <1%

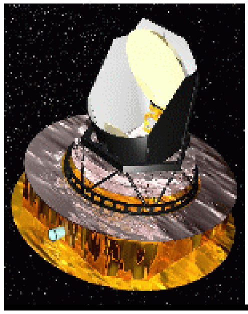
- Point source calibration ~1% for CMB channels 3-4% for high-ν

- Cross calibration with SPIRE (one cousin chanel and one sister channel)

EXTRA



2) The impact of the near main beam knowledge

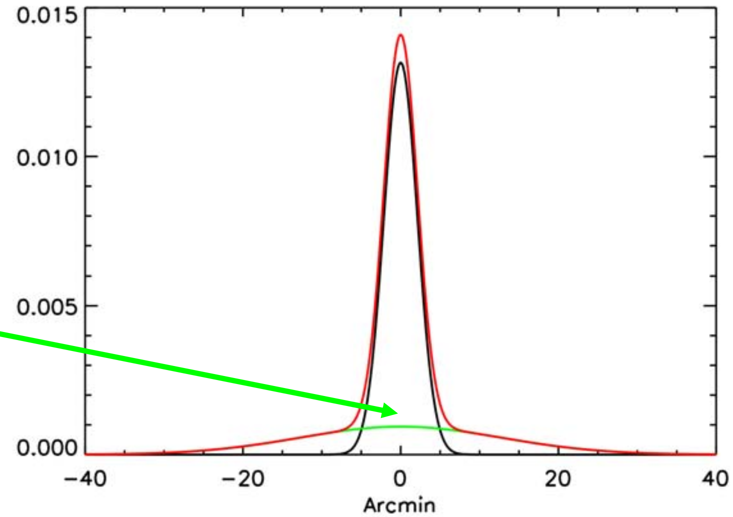


Planck photometric calibration

PLANCK HFI

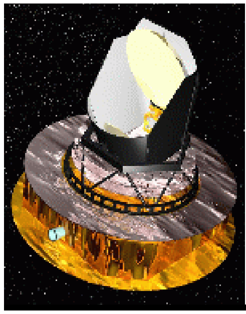
Absolute Calibration on the Galaxy: 545 GHz

- Nominal map, 5' resolution
- « Errors » in the beam:
  - 30% in a 30' gaussian beam
  - 5% in a 30' gaussian beam



- Calibration pipeline:
  Errors on the calibration factor
  → 0.07% for 30%
  → <0.02% for 5%

- Negligeable impact! (note that the 30% is completely non realistic!)

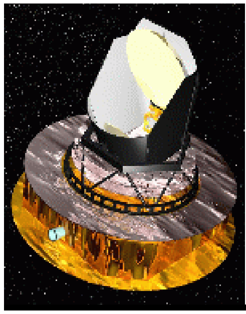


Absolute calibration on the orbital dipole at 44GHz and 100 GHz

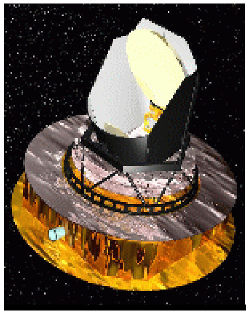
- Simulations as for the Galaxy
- Include only orbital dipole
- Fractional powers in main beam “wings”: 5 and 30%
- Calibration pipeline

Frequency	Nominal resolution	30 arcmin	60 arcmin	Error (%)
44 GHz (24’)	0.70		0.3	$1.4\ 10^{-3}$
	0.95		0.05	$2.3\ 10^{-4}$
100 GHz (9.2’)	0.70	0.30		$3.8\ 10^{-4}$
	0.95	0.05		$6.2\ 10^{-5}$
	0.70		0.30	$1.6\ 10^{-3}$
	0.95		0.05	$2.7\ 10^{-4}$

- Conclusion: **Completely negligible** (also for the relative calibration of rings on CMB+earth dipole)



3) Spillover lobes and far sidelobes

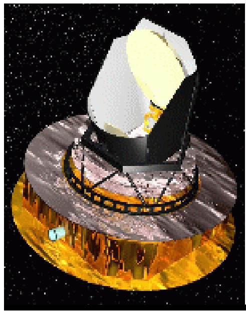


Planck photometric calibration

PLANCK HFI

Absolute calibration on the Galaxy: 545 GHz

- Hypothesis: main spillover at 85^{o} of the main beam ; fwhm=8^{o}
- Absolute calibration on only two profiles:
  - One at l=85^{o}, with the galactic center in the spillover
  - One at l=275^{o}, with the galactic center in the spillover
- Fractional power (wrt main beam) =0.003 => df/f=1%
- Fractional power (wrt main beam) =0.001 => df/f=0.4%
- A small effect (but needs to be checked using accurate simulations: not possible yet)



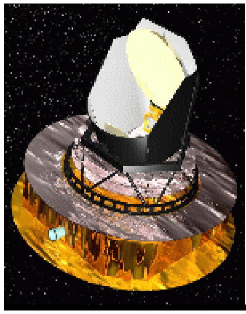
Planck photometric calibration

PLANCK HFI

Absolute calibration on the orbital dipole

Burigana et al. 2006 (+ Burigana et al. 2004)

- In the cosmological channels:
  - Dipole Straylight Contamination >Galactic Straylight Contamination
- « Spurious » dipole that contaminates the real one and then the calibration:
  - p = fractional integrated response within the main spillover (that represents the major fsl contribution)
  - p=0.001, p2p= ± 0.6 μK
  - p=0.003, p2p= ± 1.8 μK
- Orbital dipole: p2p= ± 0.3 mK
- **Effect of 0.6% if p=0.003**
- **Effect of 0.2% if p=0.001**
- **Goal: reach p<=0.001**
  - If p=0.003 and known to 30%, effective p of about 0.001
- Need accurate simulations with the calibration pipeline to determine the final error



Planck photometric calibration

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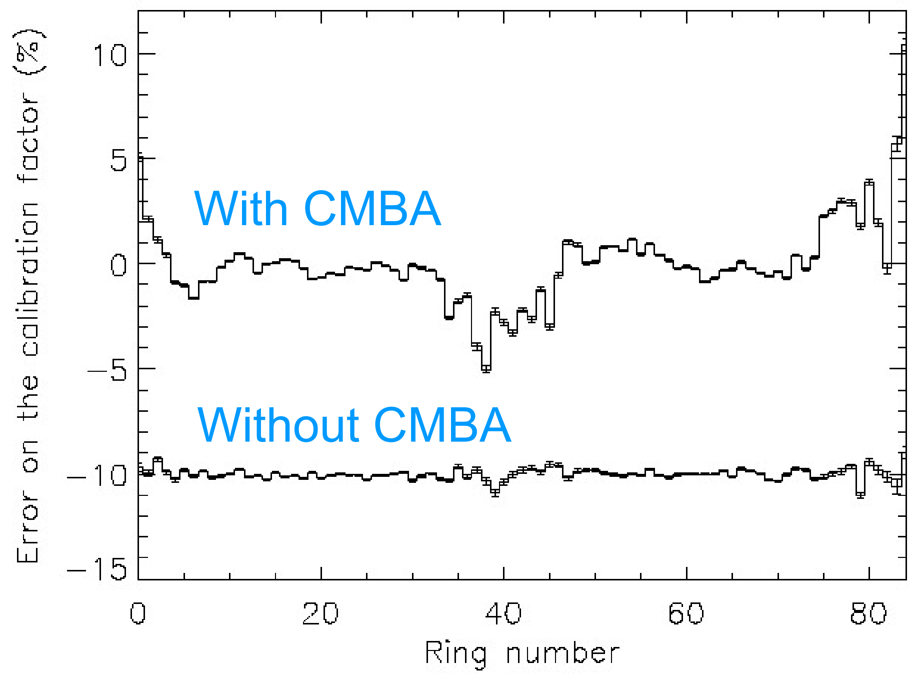
Relative dipole calibration : results

- Orbital dipole useful when low CMB dipole signal
- CMB Anisotropies limit the relative calibration accuracy



(Piat et al. 2002; Cappellini et al. 2003)

Planck photometric calibration

PLANCK HFI

Planck HFI focal plane geometry

MAP OF LINES OF SIGHTS