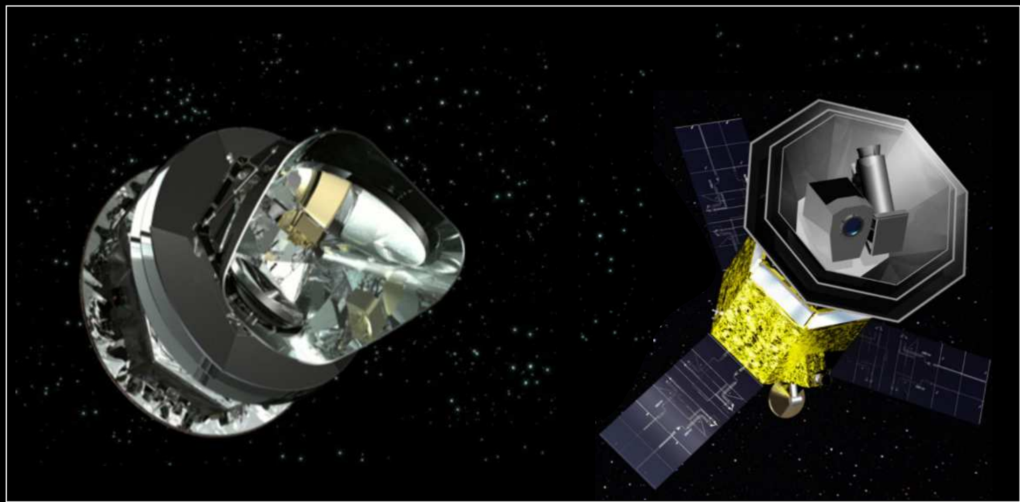
From Planck to LiteBIRD

Instrument and calibration

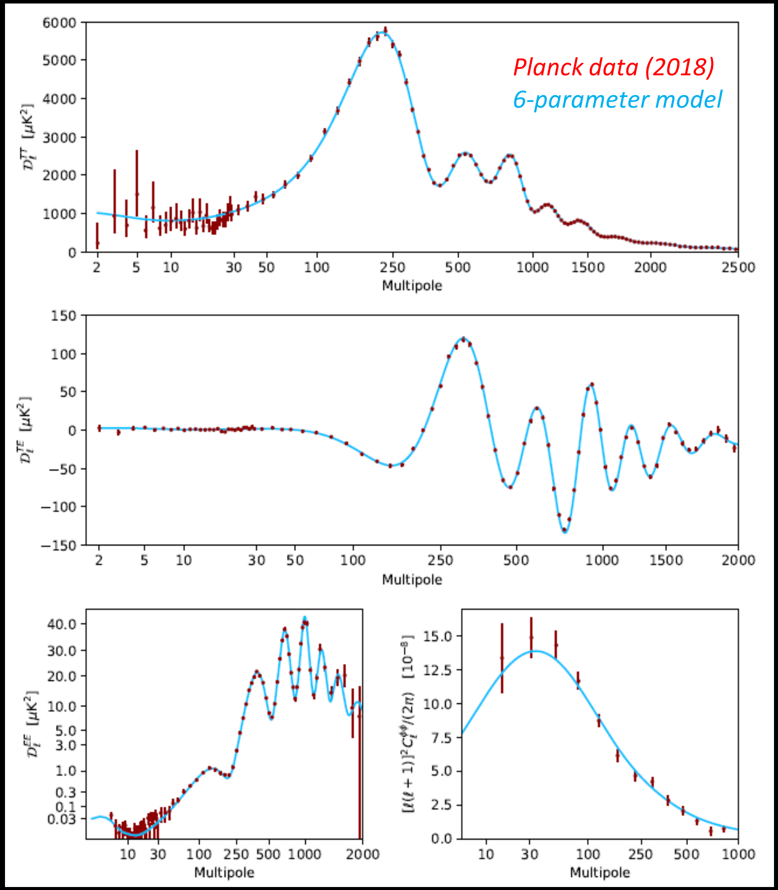


Marco Bersanelli

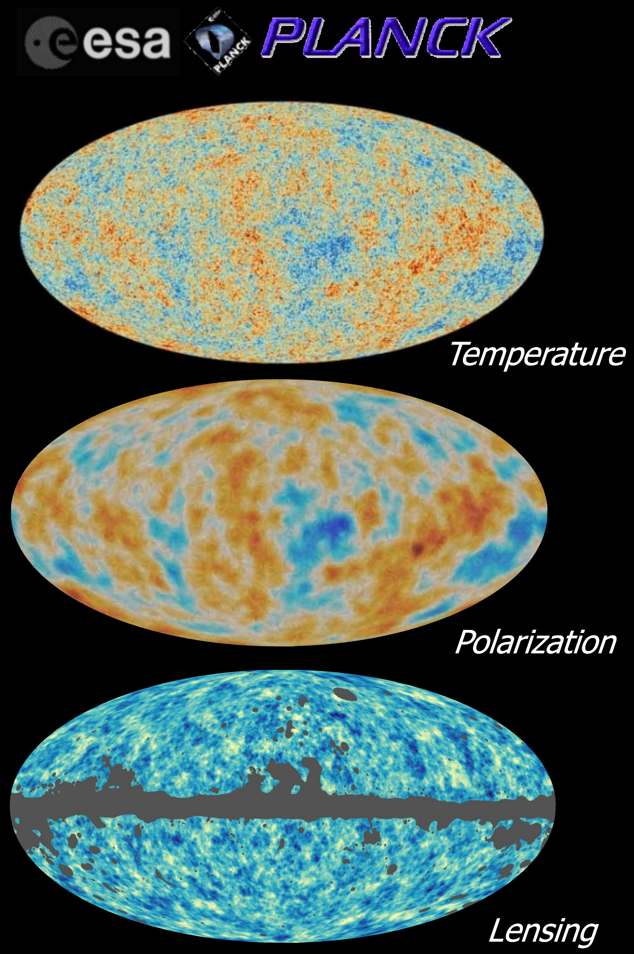
(University of Milano, INFN, INAF)

and The Planck Collaboration

The success of Planck relied on a very demanding calibration effort throughout the project

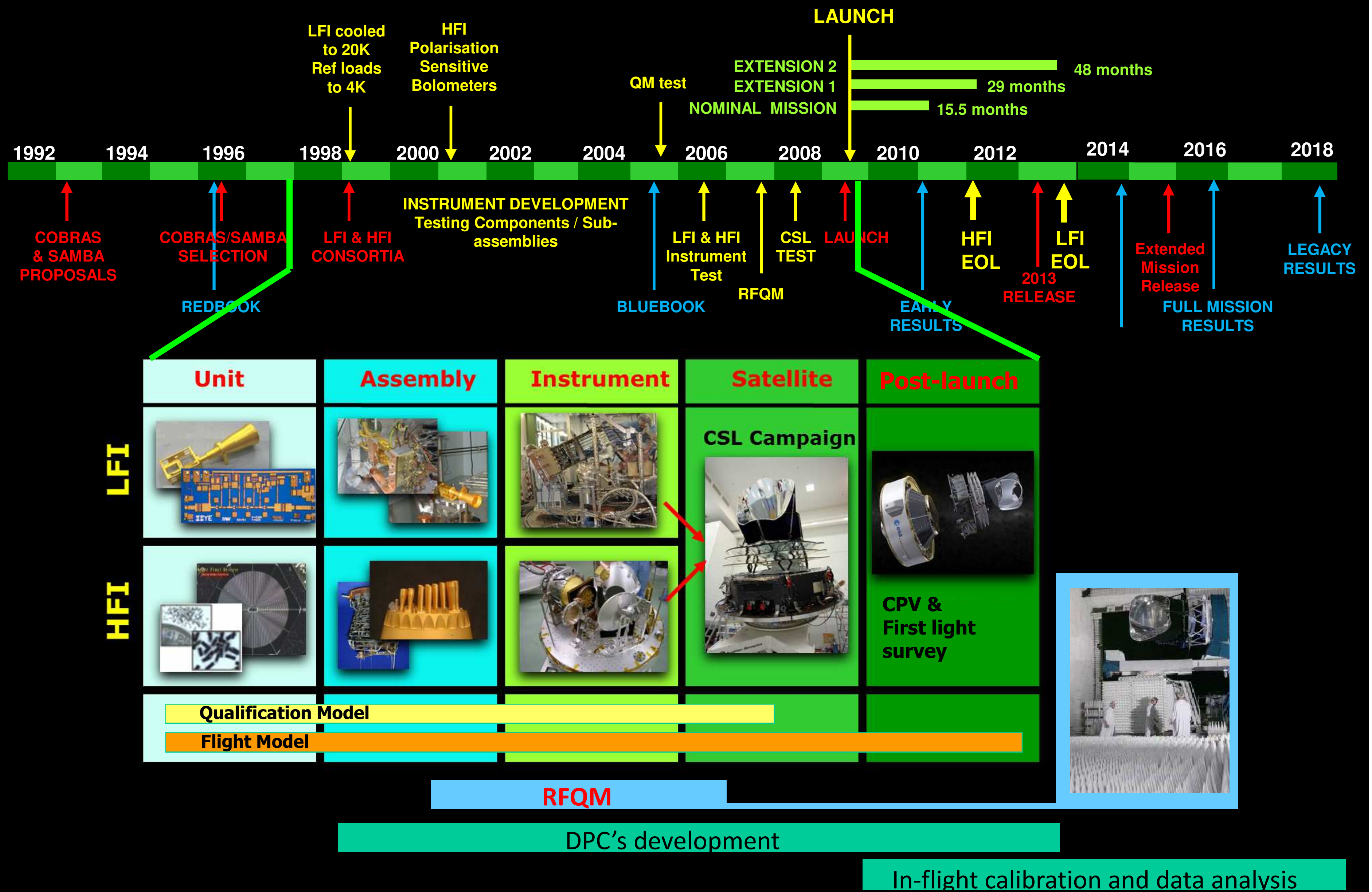


Planck Collaboration 2018

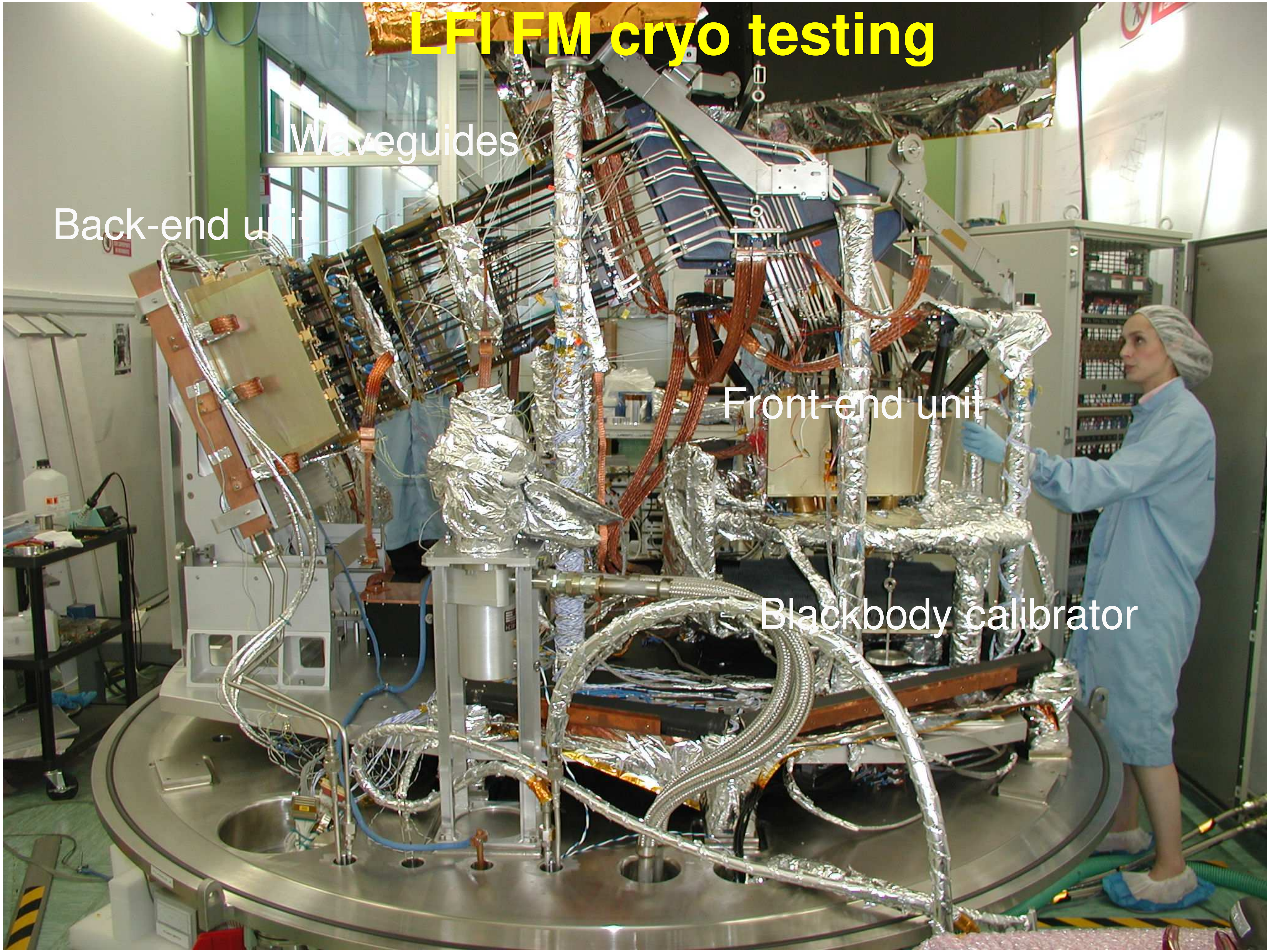


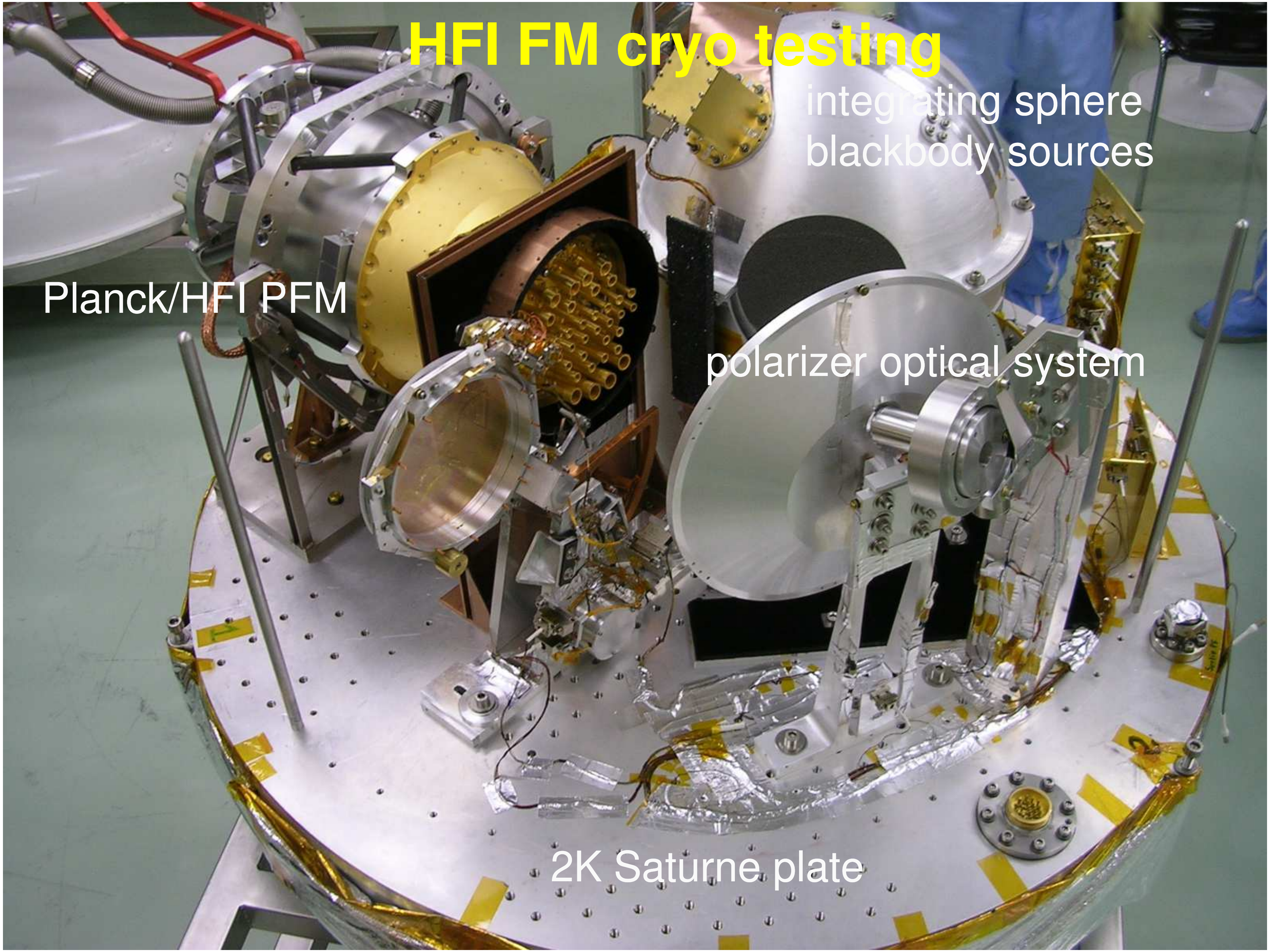
Many people (virtually all the Planck Collaboration) were involved

Planck – Ground & in-flight calibration



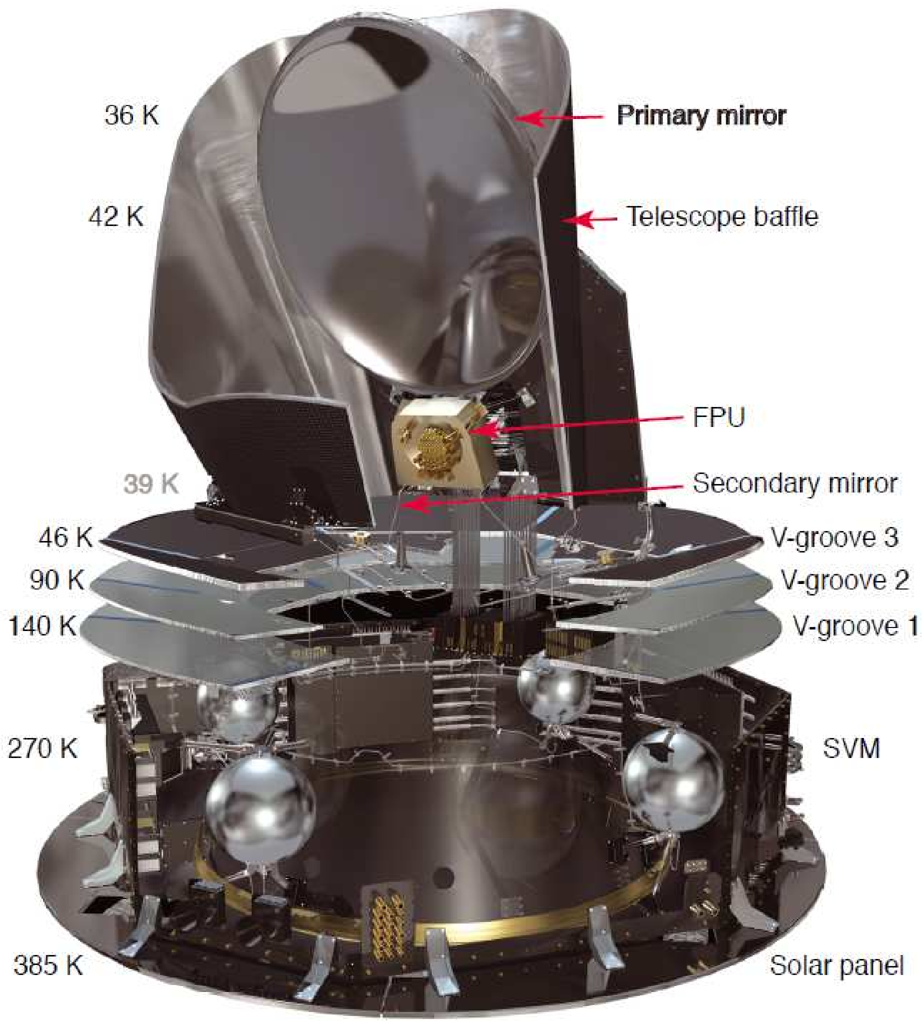
LFI FM cryo testing




HFI FM cryo testing
integrating sphere
blackbody sources
Planck/HFI PFM
polarizer optical system
2K Saturne plate

Planck Instruments, PPLM, SVM

Thermal requirements were key design driver of Planck payload and satellite



Planck Collaboration A&A 536, A2 (2011)

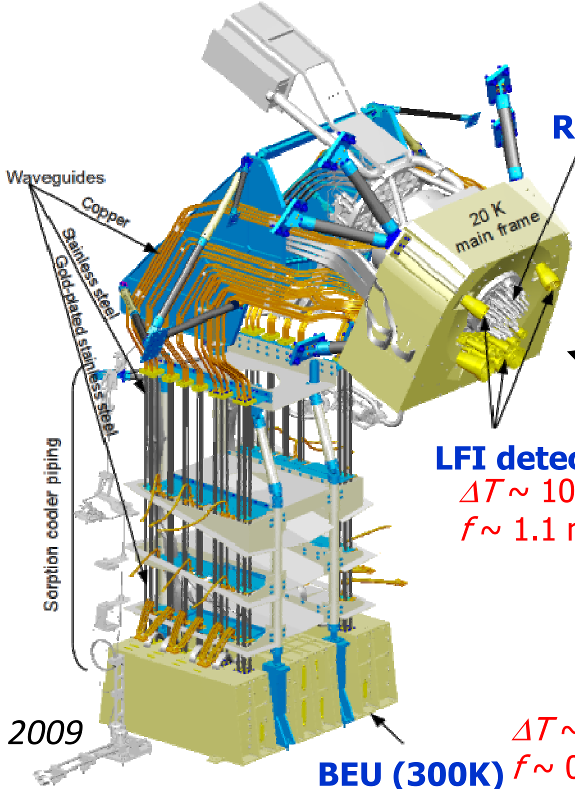
- Very complex interfaces between PPLM and SVM
- In particular:
  - The 3-stage cooling system (18-20K sorption cooler)
  - Instruments (LFI waveguides)
  - Passive cooling (3rd V-groove at 50K)
- Fully representative instrument configuration was obtained only at satellite integration level
- The CSL cryo facility supported instruments operation in nominal conditions.
  - 4K blackbody calibrator
- CSL test was needed by both LFI and HFI to calibrate Instrument thermal model

Satellite-level cryo-calibration

Beams footprints on target

Thermal model

LFI key thermal requirements: T and stability at 300, 20 and 4K



M.B. et al. 2009

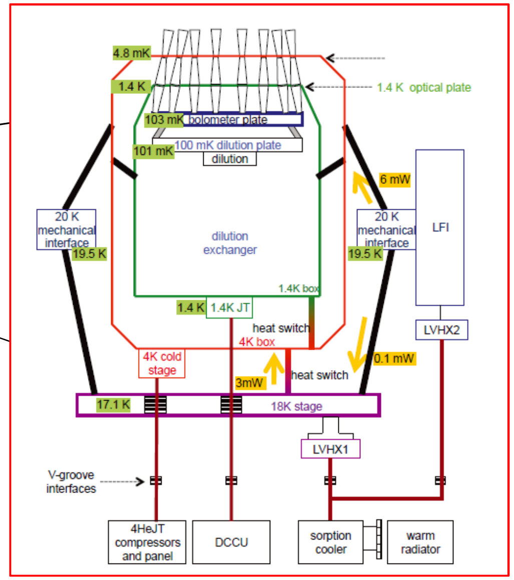
Ref Loads (4K)
$\Delta T \sim$ 0.9 mK
$f \sim$ 1.1 mHz (15min)
$f \sim$ 0.2 mHz (90min)

LFI detectors (20K)
$\Delta T \sim$ 100 mK
$f \sim$ 1.1 mHz (15min)

BEU (300K)
$\Delta T \sim$ 0.2 K
$f \sim$ 0.012 mHz (24h)
(up to OD 258)

J.-L Puget's talk

HFI box (4K-0.1K)



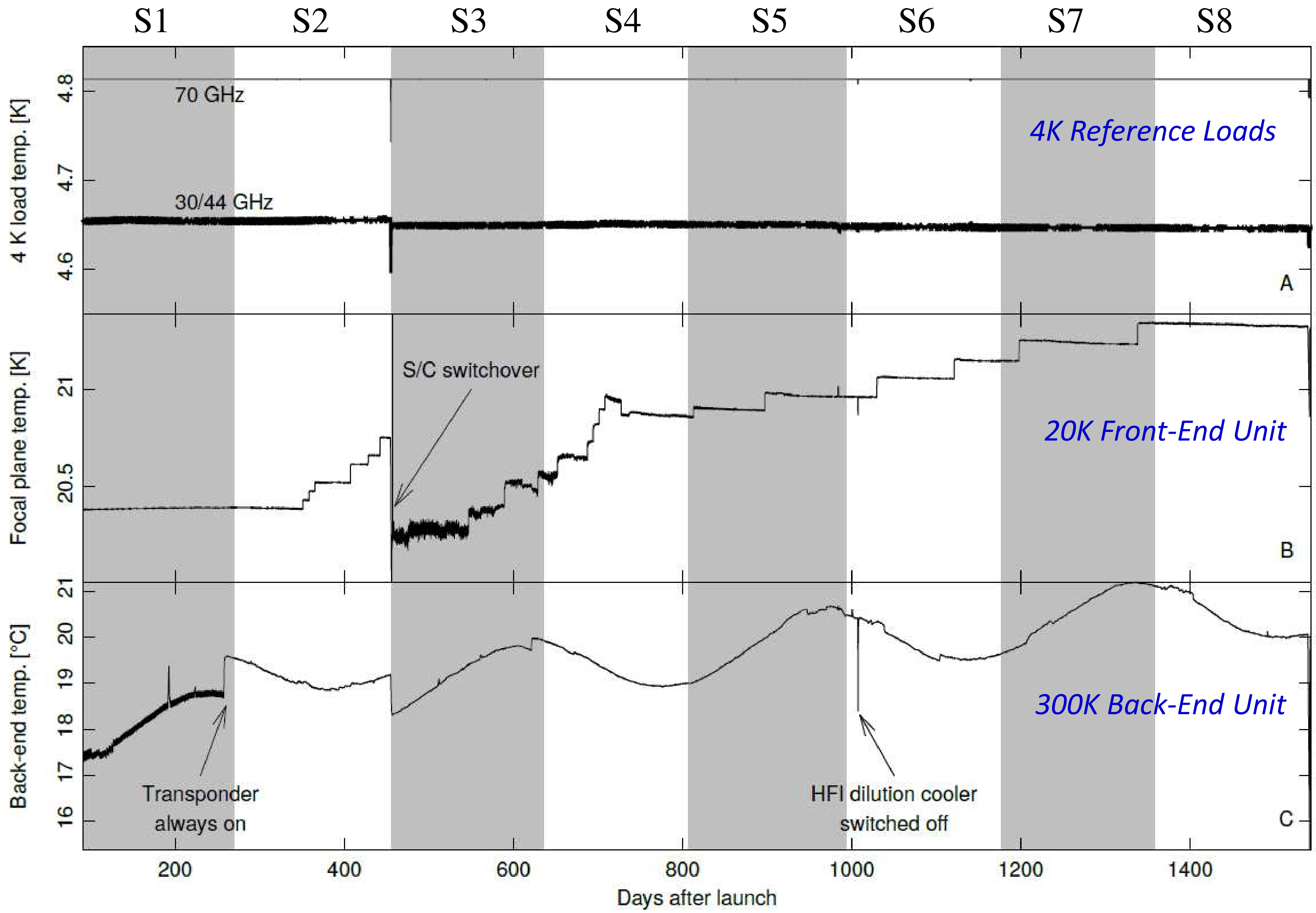
Lamarre et al. 2009

- Instrument model:
  - *Thermal transfer functions*
  - *Radiometric transfer functions*

(Tomasi et al. 2010, Terenzi et al. 2010)

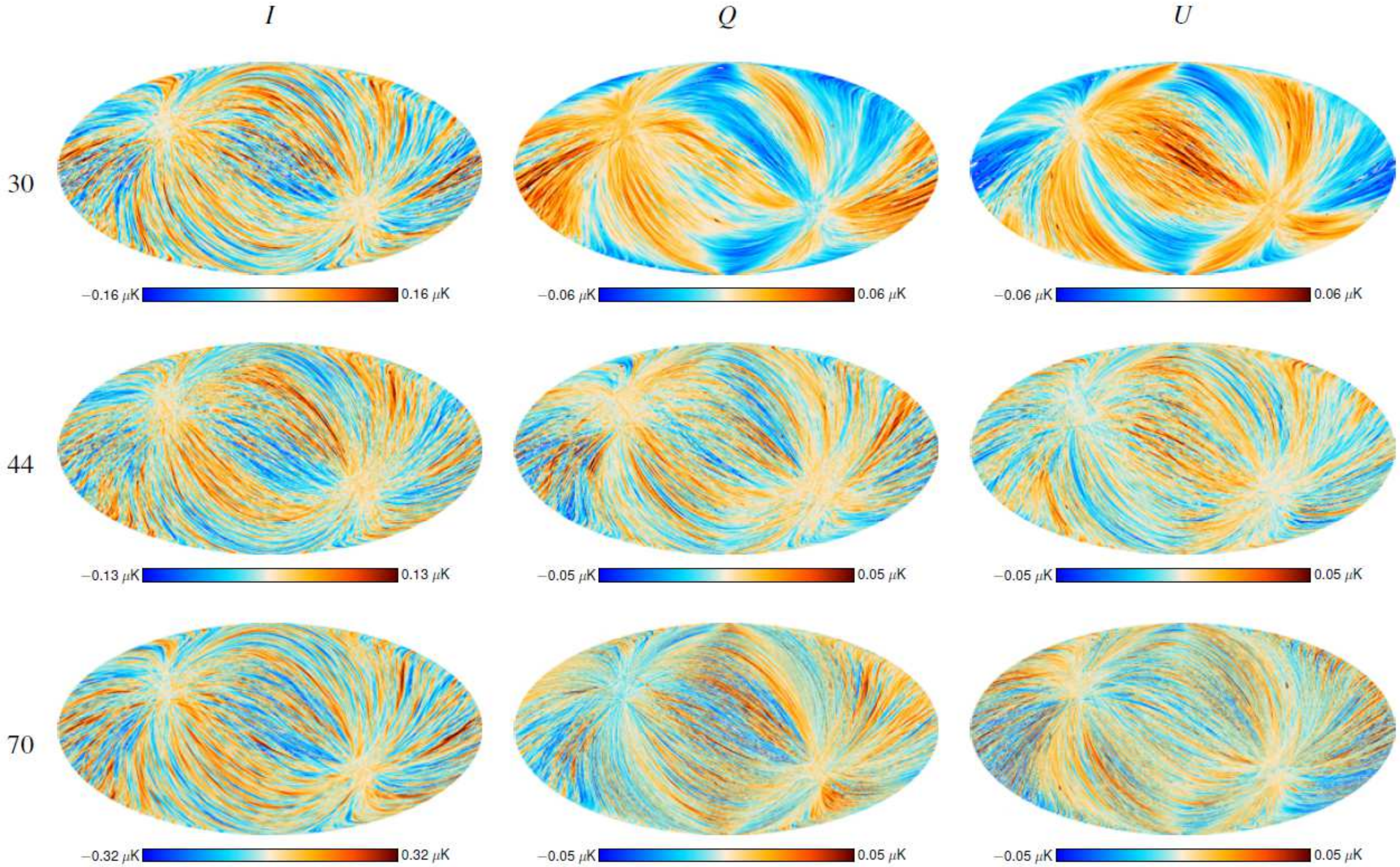
- Ground calibration at increasing levels of integration (and QM, FM)
- Finalize instrument design (→ *stringent constraints on 18-20K sorption cooler stability*)
- Temperature sensors
- Prepare for in-flight analysis

H/K data from Planck mission



Combined effect of flucturations at 300, 20 and 4K

Planck Collaboration III, 2016



Thermal effects were controlled to beolw significance thanks to early definition of adequate requirements

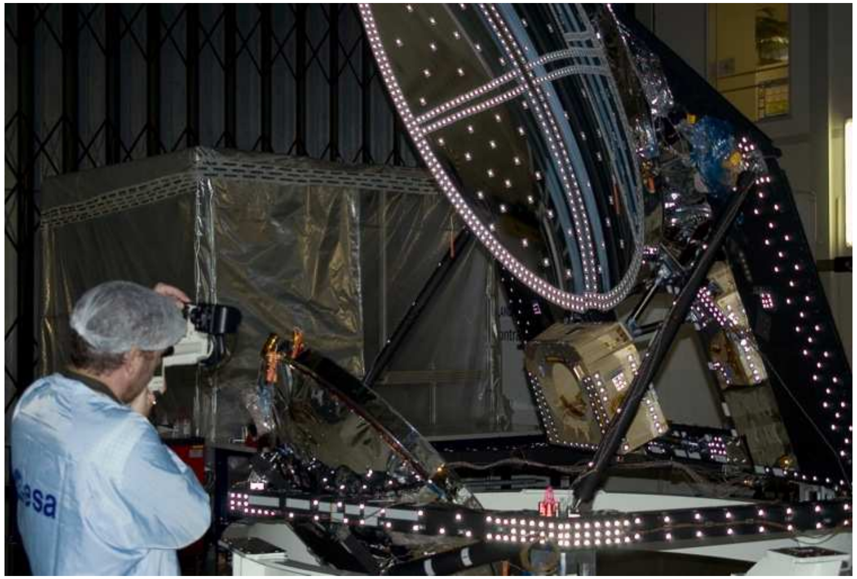
LFI potential effects and calibration strategy

Effect	Source	Control/Removal	Reference
Effects independent of the sky signal (temperature and polarization)			
White noise correlation	Phase switch imbalance	Diode weighting	Planck Collaboration III (2014)
$1/f$ noise	RF amplifiers	Pseudo-correlation and destriping	Planck Collaboration III (2014)
Bias fluctuations	RF amplifiers, back-end electronics	Pseudo-correlation and destriping	3.2.5 Planck Collaboration III (2016)
Thermal fluctuations	4-K, 20-K and 300-K thermal stages	Calibration, destriping	3.2.4 Planck Collaboration III (2016)
1-Hz spikes	Back-end electronics	Template fitting and removal	3.2.6 Planck Collaboration III (2016)
Effects dependent on the sky signal (temperature and polarization)			
Main beam ellipticity	Main beams	Accounted for in window function	Planck Collaboration III (2016)
Near sidelobe pickup	Optical response at angles $< 5°$ from the main beam	Masking of Galaxy and point sources	Planck Collaboration II (2016), 2.1.2, 3.2.1 Planck Collaboration III (2016)
Far sidelobe pickup	Main and sub-reflector spillover	Model sidelobes removed from timelines	2.1.1, 3.2.1 Planck Collaboration III (2016)
Analogue-to-digital converter nonlinearity	Back-end analogue-to-digital converter	Template fitting and removal	3.2.3 Planck Collaboration III (2016)
Imperfect photometric calibration	Sidelobe pickup, radiometer noise temperature changes, and other non-idealities	Adaptive smoothing algorithm using 4π beam, 4-K reference load voltage output, temperature sensor data	Planck Collaboration II (2016), 2.2, 3.2.2 Planck Collaboration III (2016)
Pointing	Uncertainties in pointing reconstruction, thermal changes affecting focal plane geometry	Negligible impact on anisotropy measurements	2.1, 3.2.1 Planck Collaboration III (2016)
Effects specifically impacting polarization			
Bandpass asymmetries	Differential orthomode transducer and receiver bandpass response	Spurious polarization removal	2.3 Planck Collaboration III (2016)
Polarization angle uncertainty	Uncertainty in the polarization angle in-flight measurement	Negligible impact	2.1.3, 3.2.1 Planck Collaboration III (2016)
Orthomode transducer cross-polarization	Imperfect polarization separation	Negligible impact	Leahy et al. (2010)

Planck Telescope testing

Tauber et al. A&A 520, A2 (2010)

- Photogrammetry of Primary and Secondary Reflectors from 300K to ~95 K
  - *Measure curvature R, conic constant k, large-scale deformations*
- Interferometry at λ=10 μm of SR between 300K and ~40 K
  - *Trace small-scale deformations ("dimples")*
- Photogrammetry of telescope structure between 300K and ~95 K
  - *Thermoelastic deformations*

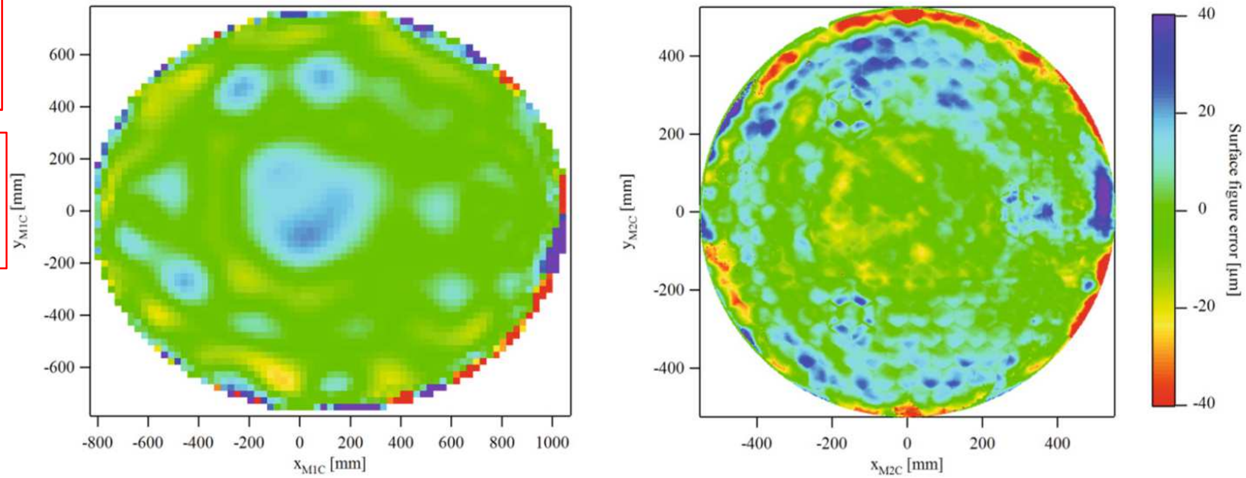


Extrapolate Telescope geometry to 40K

Generate GRASP models at 300K (for testing) and 40K

(Feedhorns beams precisely measured at instrument and unit level)

Estimated surface deformation at 40K



LFI feedhorns design and measurements

Villa et al. JINST 2009

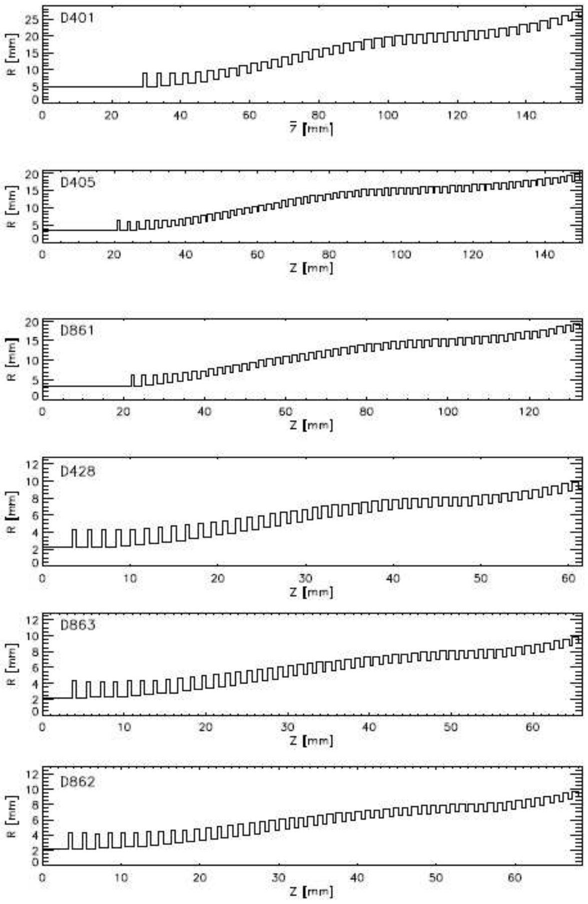
Corrugation profile (sin-squared + exponential) for compactness and high control of sidelobes

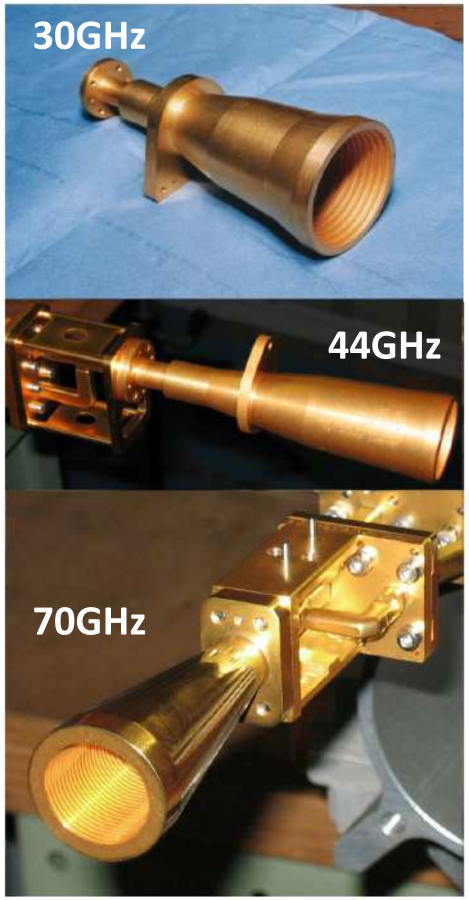
$$R(z) = R_{th} + (R_s - R_{th})\left[(1-A)\frac{z}{L_s} + A\sin^{\beta}\left(\frac{\pi}{2}\frac{z}{L_s}\right)\right]$$

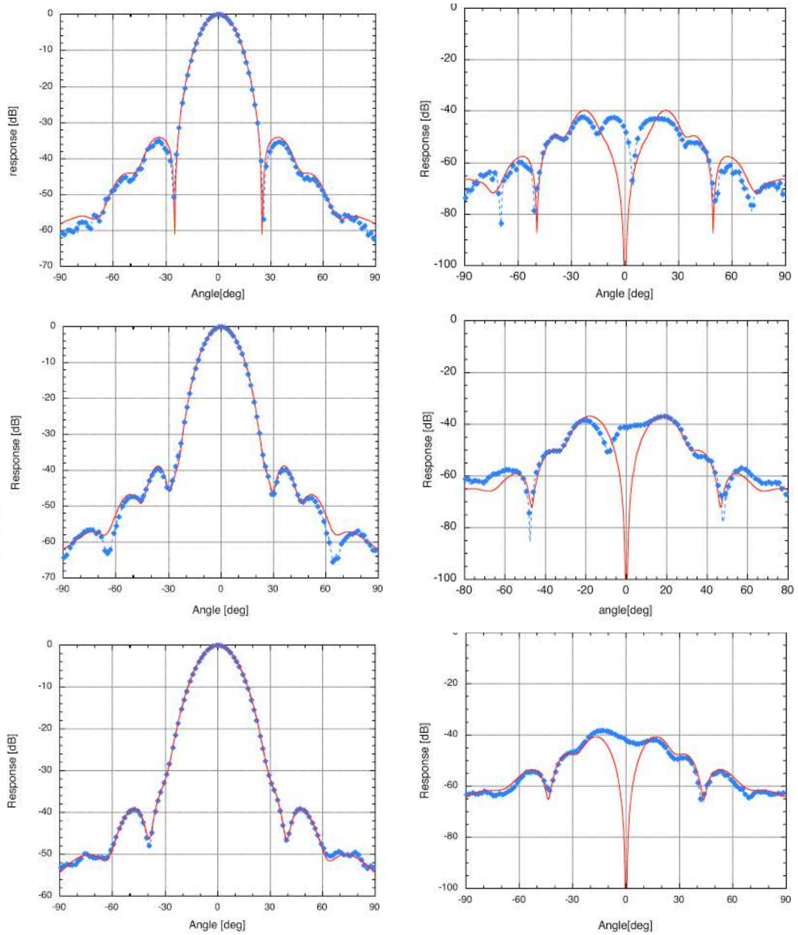
$$0 \le z \le L_s$$

$$R(z) = R_s + e^{\alpha(z-L_s)} - 1; \alpha = \frac{1}{L_e} ln(R_{ap} - R_s)$$

$$L_s \le z \le L_e + L_s$$







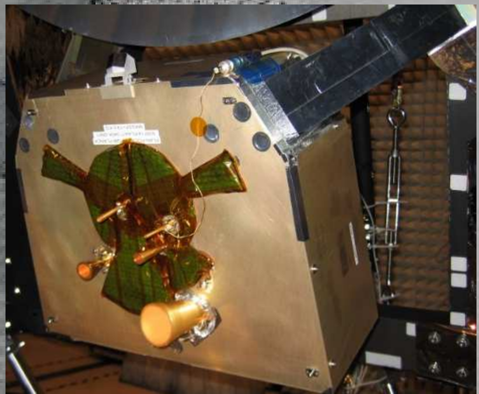
Co-pol accuracy <1dB above -40dB, Cross-pol <-35dB, RL < -30dB

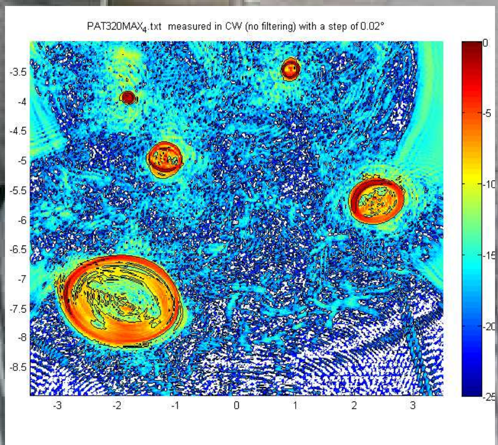
Several frequencies mesured across the-band

Planck RF verification

RFQM:

- Planck QM telescope
- Representative focal plane structure
- All relevant payload elements (e.g. baffle, V-groove)
- Test system: CATR at 300K (*Thales, Cannes*)
- Measure 4π beams of flight-like horns at 30-320 GHz (incl. 2 orthogonal polarizations)

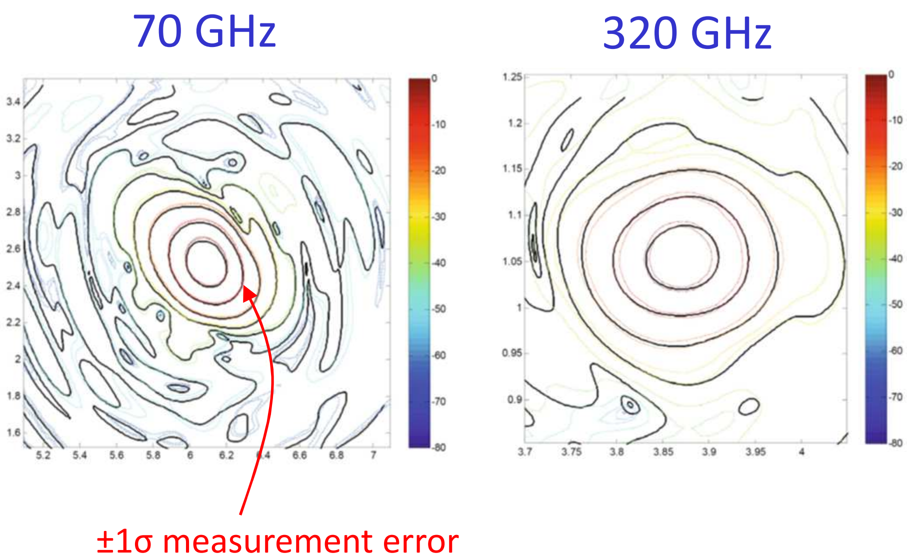




Comparing RFQM measurements and Optical model (at 300K)

Tauber et al. A&A 520, A2 (2010)

MAIN BEAMS



Model: GRASP physical optics (PO)

Consistency with measurements:

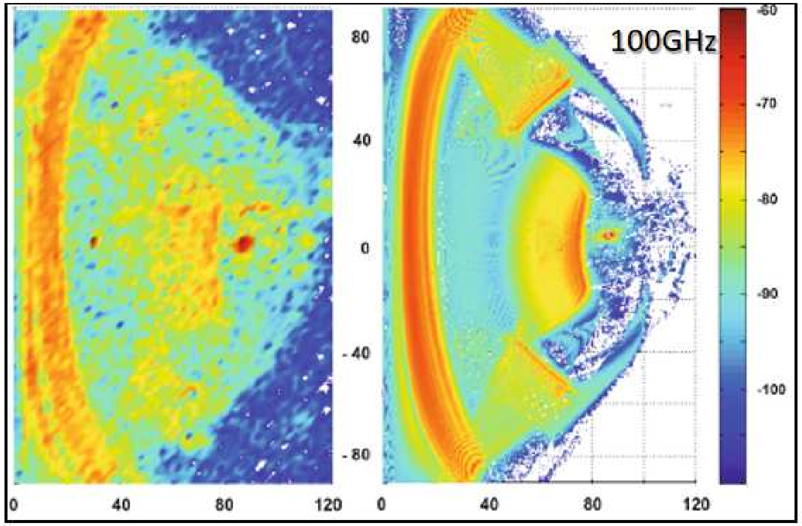
- Co-pol: <1% (low freq), 6-7% (high freq)
- Cross-pol: several percent below -40dB

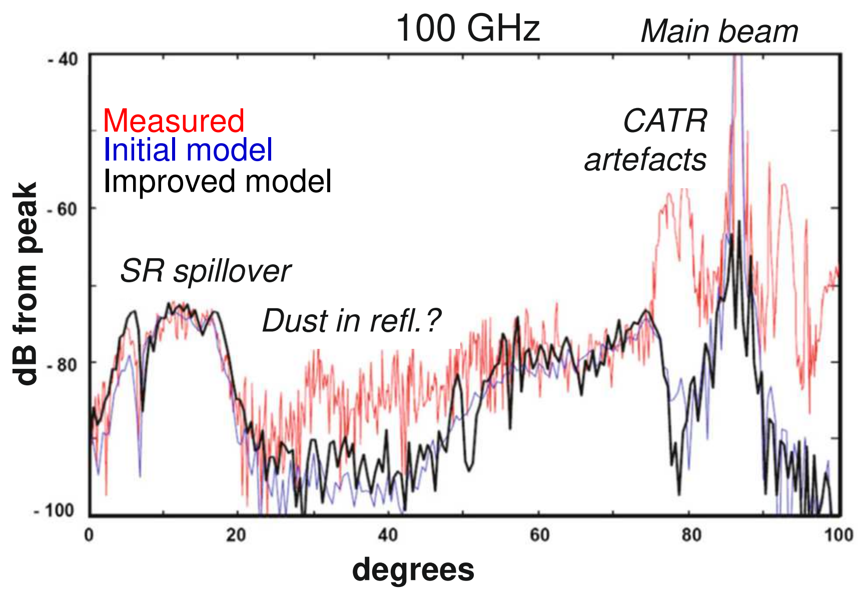
Discrepancies attributed to measurement errors and CATR-induced systematics

→ **Need to rely on in-flight Planets measurements**

Tauber et al. (2019)

SIDELOBES

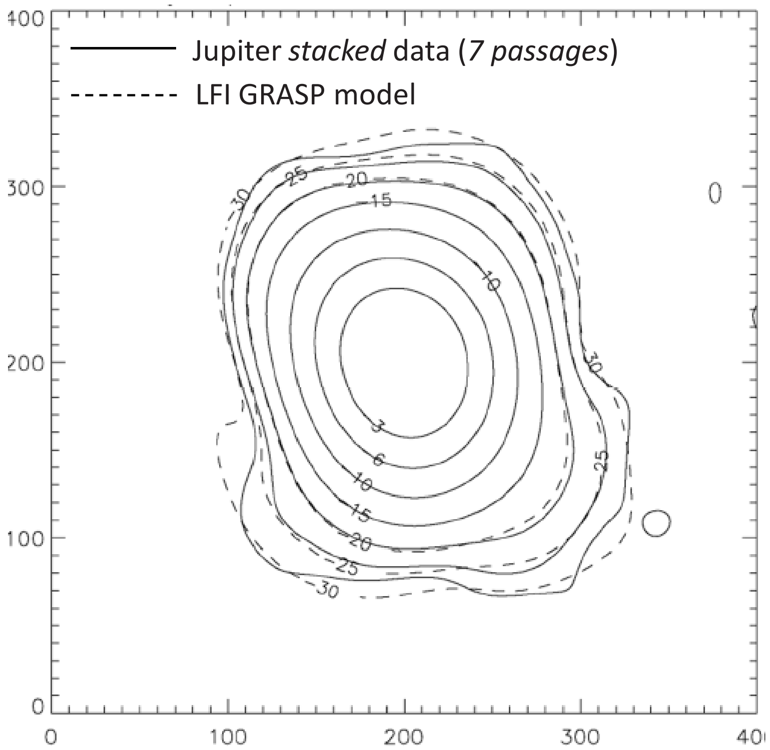




LFI beams: GRASP model and in-flight measurement

- Thermo-elastic model to translate 300K best model to flight conditions (40K reflectors, structure)
- Compute bandpass-averaged beams (25 cuts/beam)
- Include effect of OMT cross-pol,
- "Tuned model": fit telescope model parameters (*R, k,* alignment) to in-flight data within measurements errors

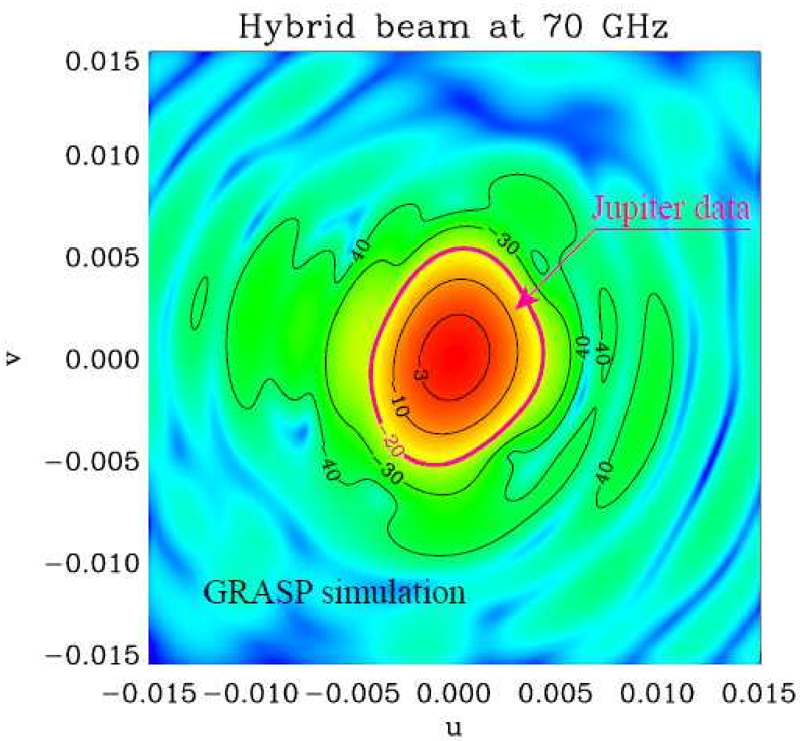
Typical accuracy for all LFI beams at all 3 frequencies



Final analysys: Hybrid scanning beams

– *Data from Jupiter above a S/N floor*

– *GRASP fiducial model below threshold*

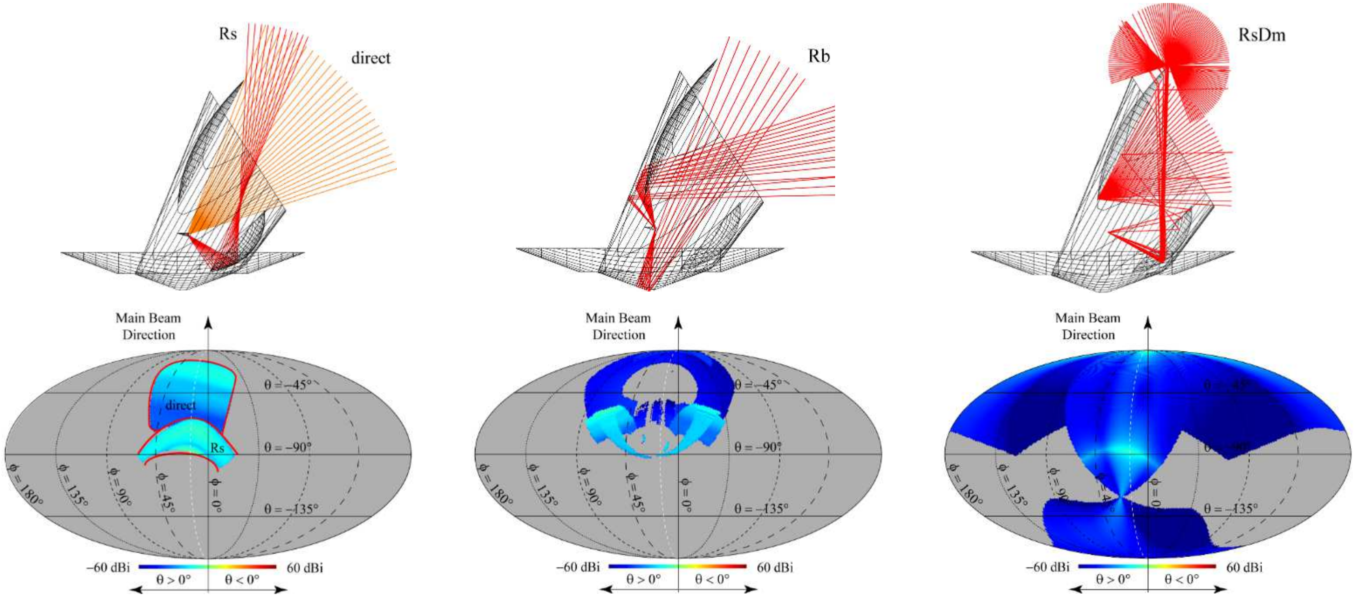


Sandri et al. 2010, Planck Collaboration IV 2014

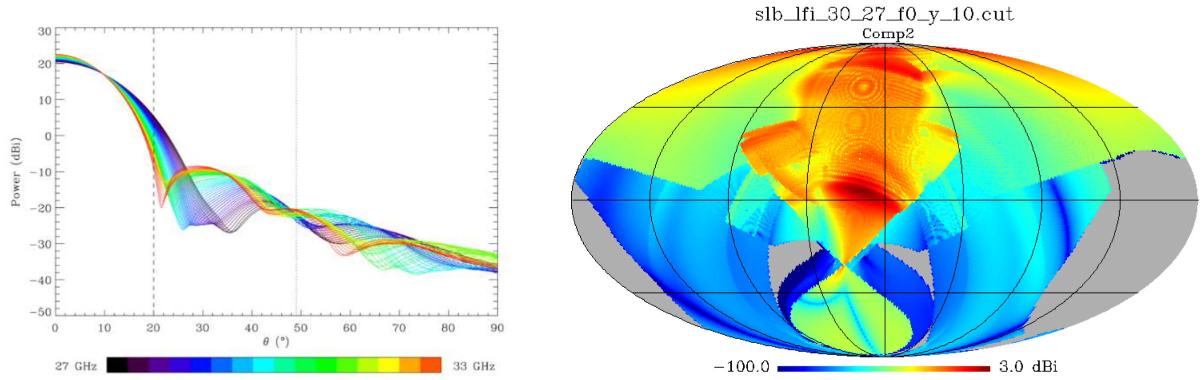
LFI far-sidelobes calculation: GRASP MrGTD

Compute scattered field (reflected or diffracted) from each element (backward ray tracing)

Challenge: Identify optimal sequence of significant scattering elements



Effect of beam pattern variation inside the detector bandwidth

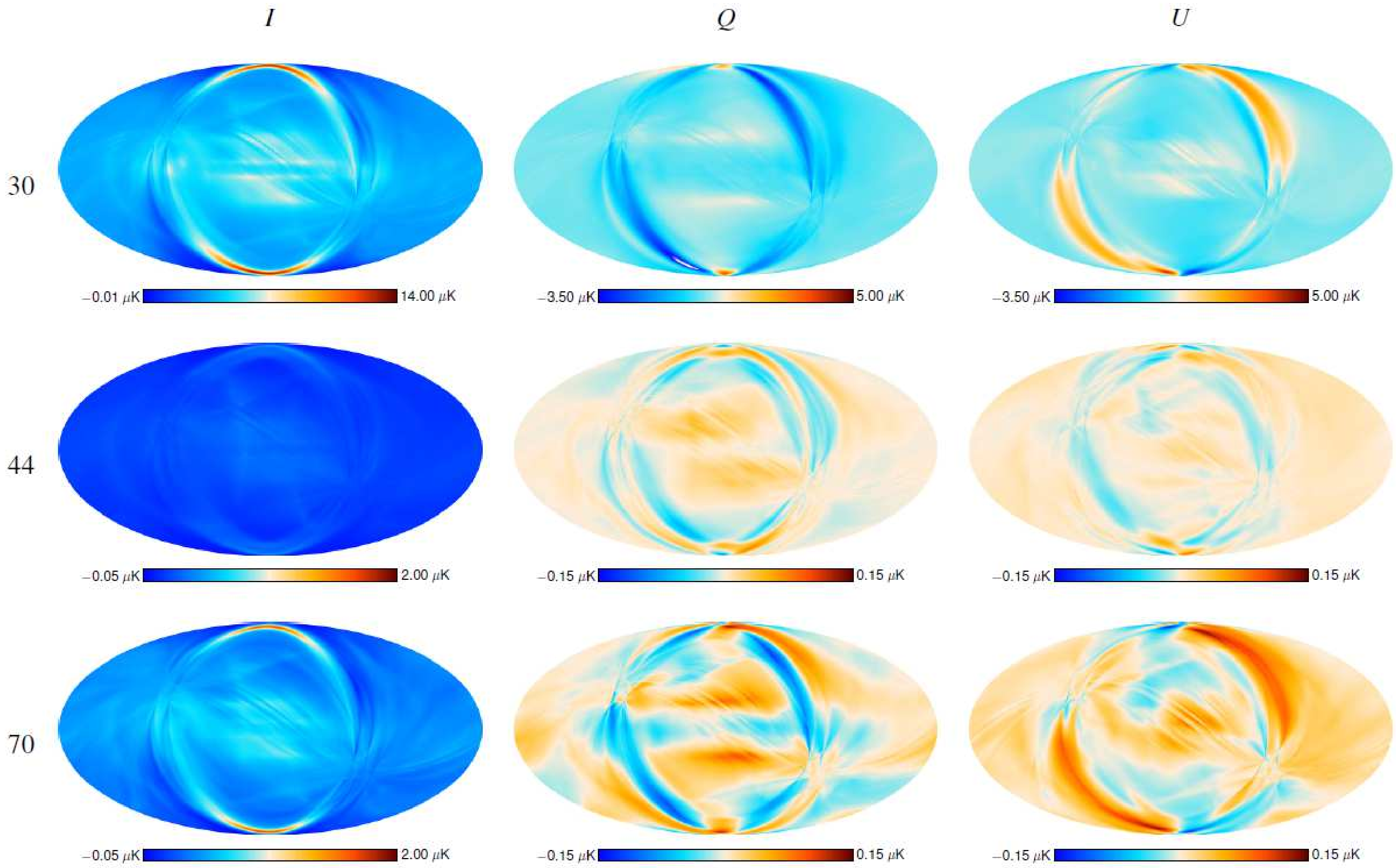


7 frequency cuts within 30GHz band Co-Pol pattern

For 11 LFI horns: ~40K beams were computed… How many for LiteBIRD?

Effect from far sidelobes before subtraction

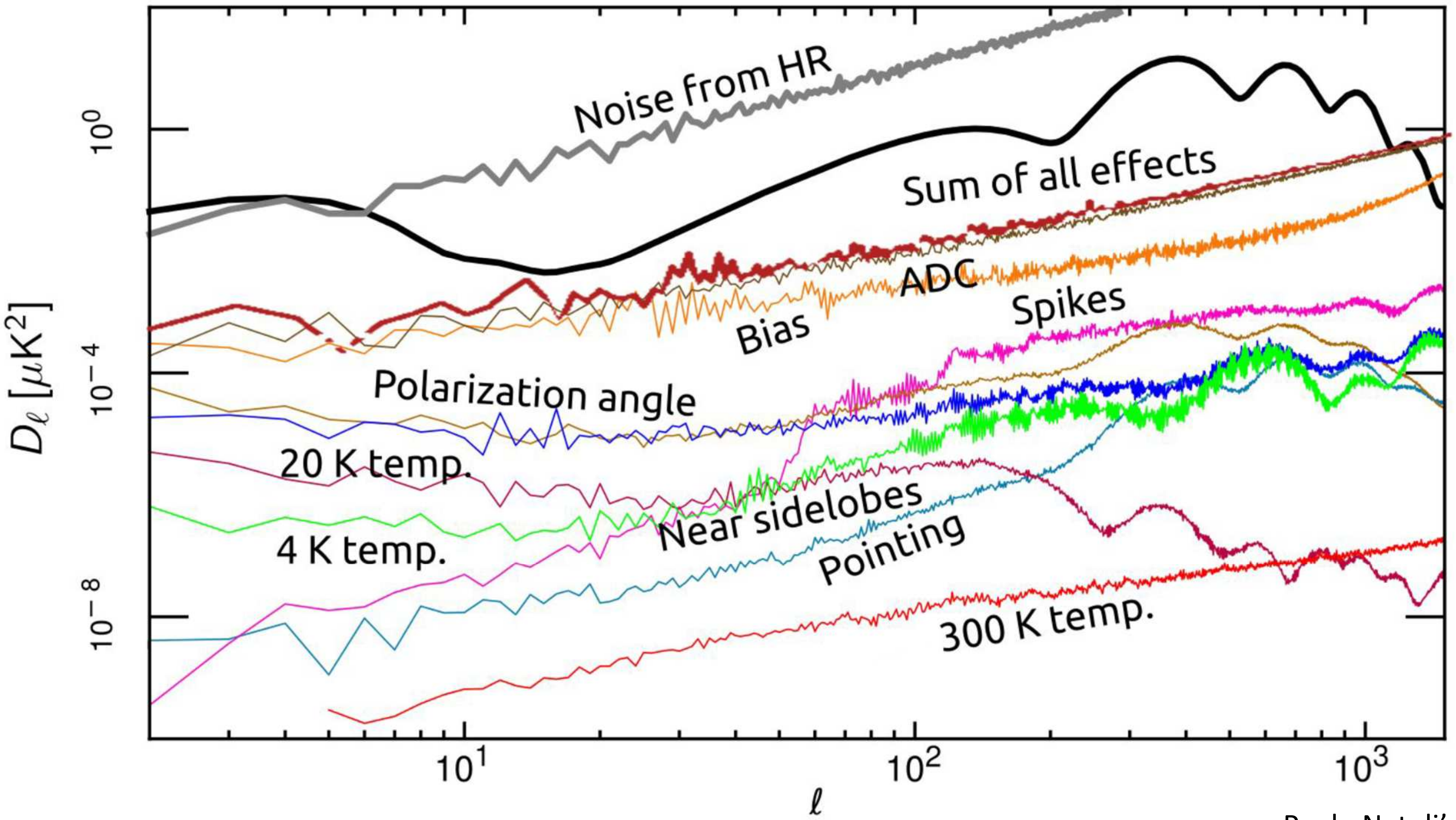
Planck Collaboration III, 2016



Effect removed in timelines

Systematic effects - LFI

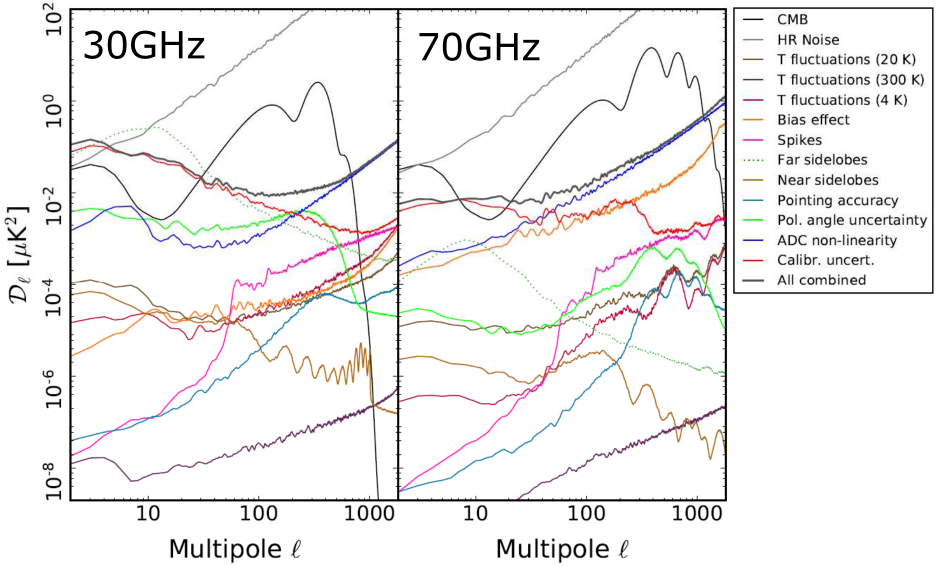
Planck 70 GHz systematic effects

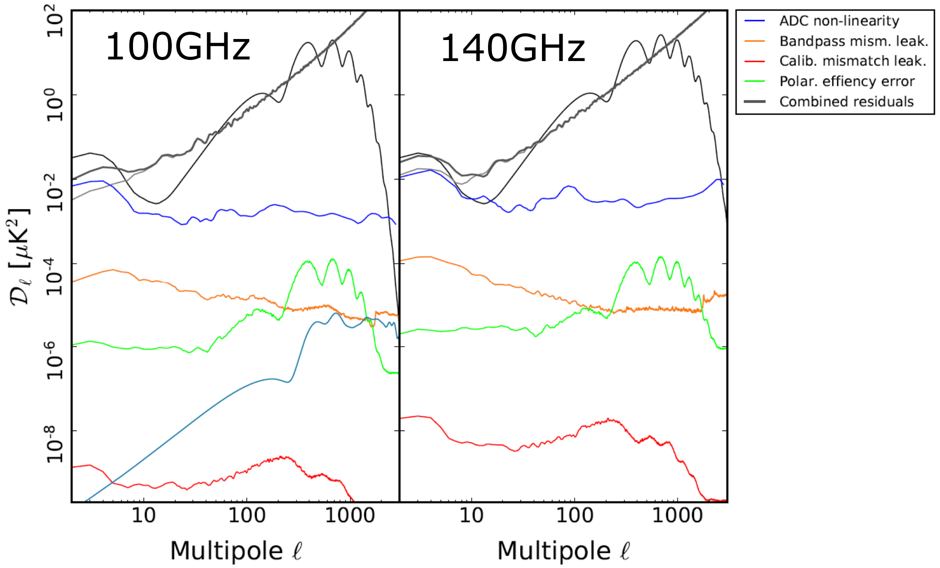


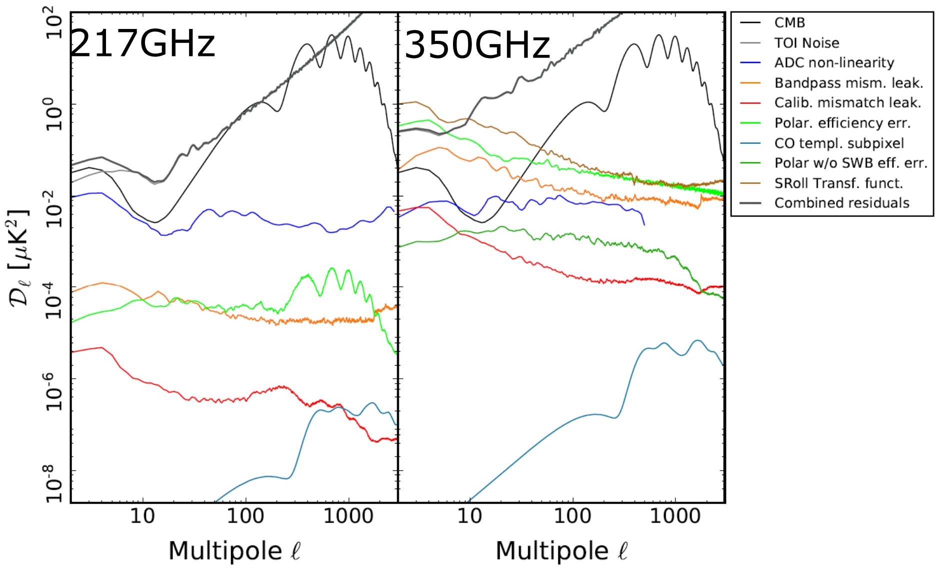
Paolo Natoli's talk

Angular power spectra of residual systematics in polarization

Planck Collaboraiton 2018



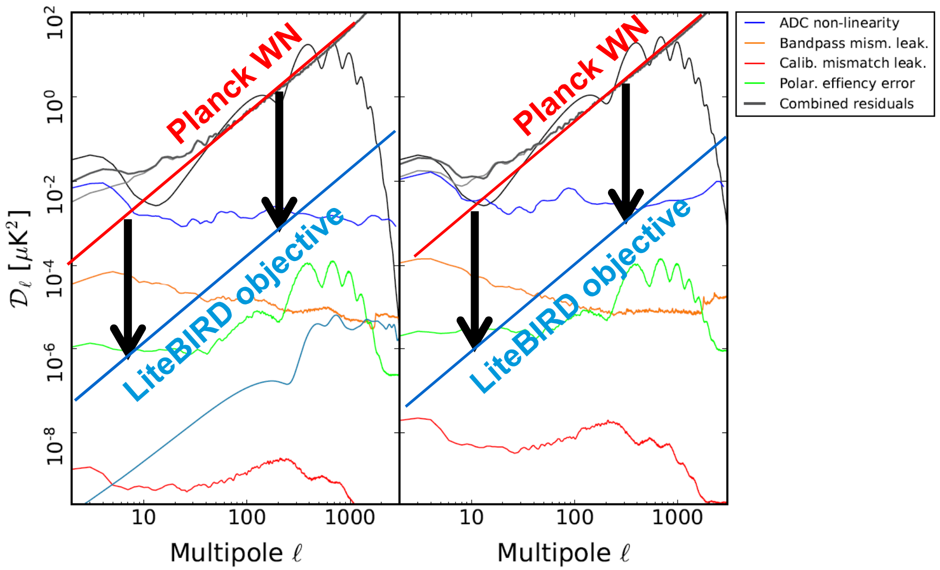




Ready for LiteBIRD !

- LiteBIRD's new exciting objectives:
  - *B-modes at r ~ 0.001*
  - *Cosmic-variance-limited measurement of τ*

- Instrument design and testing
  (x 100 detectors, …)
  will be pushed well beyond that achieved by Planck



- The LiteBIRD Team has excellent expertise and motivation
- For LiteBIRD, a coordinated calibration plan (*including thermal, optical aspects*) is already being developed

- Much of the experience gained in Planck will be inherited by LiteBIRD *(through papers & reports, technology, especially people)*

- An important message from Planck:

Very ambitious challenges can be successfully tackled!

LFI Radiometric Transfer function at 20K

$$T_f^{FEM} = \left(\frac{L_{fh-OMT}}{(G_{F1}+G_{F2})\cdot(1-r)+2\cdot\sqrt{G_{F1}\cdot G_{F2}}\cdot(1+r)}\right)\cdot\left[\left(\frac{\partial G_{F1}}{\partial T_{phys}^{FEM}}\right)\cdot\left((T_{sky}+T_{4K}+2\cdot T_{nF1})\cdot(1-r)+\sqrt{\frac{G_{F2}}{G_{F1}}}\cdot(1+r)\right)+\right.$$

$$\left(\frac{\partial G_{F2}}{\partial T_{phys}^{FEM}}\right)\cdot\left((T_{sky}+T_{4K}+2\cdot T_{nF2})+\cdot(1-r)+\sqrt{\frac{G_{F1}}{G_{F2}}}\cdot(1+r)\right)+\left(\frac{\partial T_{nF1}}{\partial T_{phys}^{FEM}}\right)\cdot(2\cdot G_{F1}\cdot(1-r))+\left(\frac{\partial T_{nF2}}{\partial T_{phys}^{FEM}}\right)\cdot(2\cdot G_{F2}\cdot(1-r))+$$

$$\left.\left(1-\frac{1}{L_{fh-OMT}}\right)\cdot\left((G_{F1}+G_{F2})\cdot(1-r)+2\cdot\sqrt{G_{F1}\cdot G_{F2}}\cdot(1+r)\right)+\left(1-\frac{1}{L_{4K}}\right)\cdot\left((G_{F1}+G_{F2})\cdot(1-r)-2\cdot\sqrt{G_{F1}\cdot G_{F2}}\cdot(1+r)\right)\right]$$

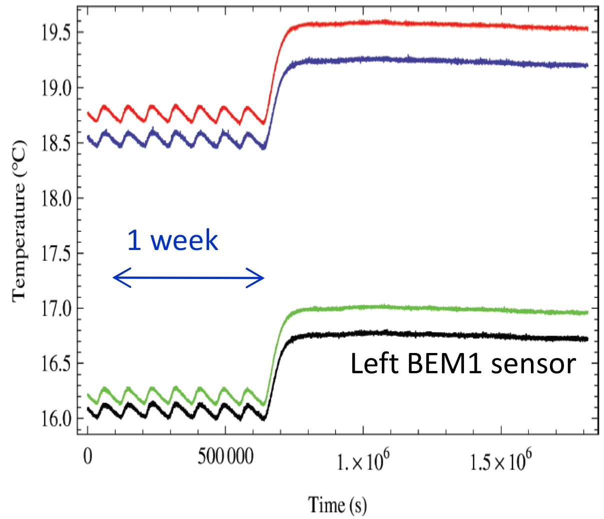
where:

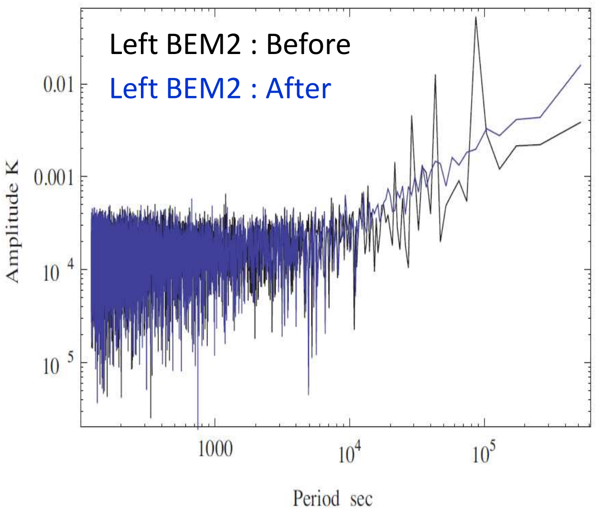
- L_i are insertion losses either for the feed horn–OMT system or for the 4K horn antenna; in our analysis we assume their values estimated from measurements at room temperature;
- r is the *gain modulation factor* used to balance the sky and reference output signals; its value is evaluated from the ratio of sky to reference channel mean voltage values;
- G_{Fi} are the front end amplifier gains, whose typical value is about 35 dB
- T_{nFi} are the front end amplifier noise temperatures, evaluated from dedicated tests

Flight H/K data

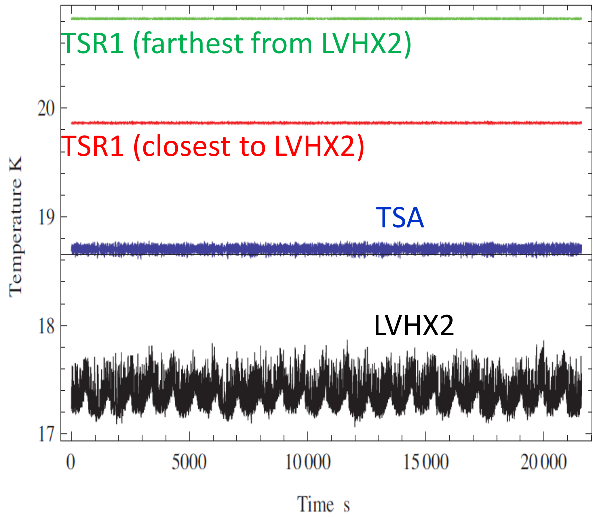
(Planck Collaboration 2011)

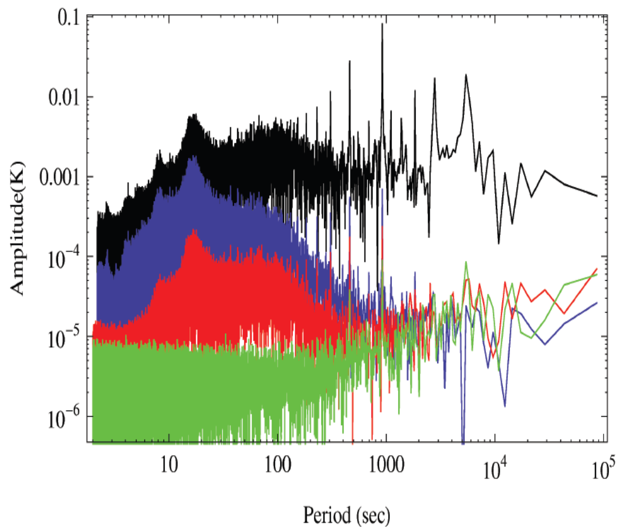
LFI back-end (300K)



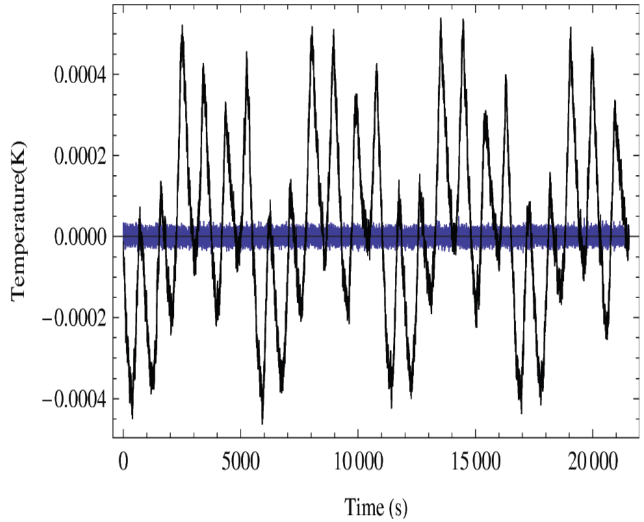


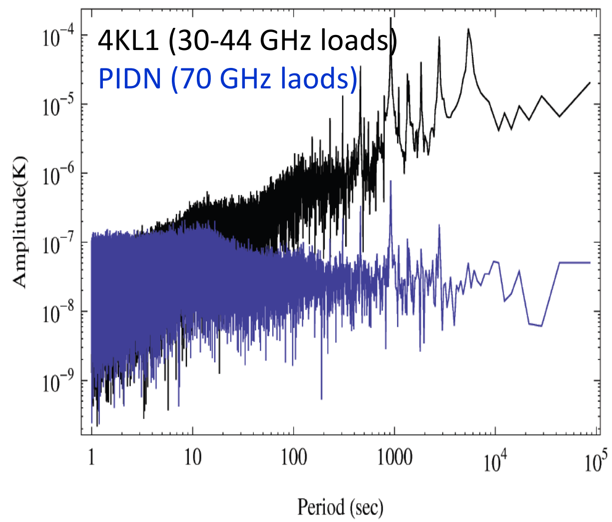
LFI focal plane (20K)





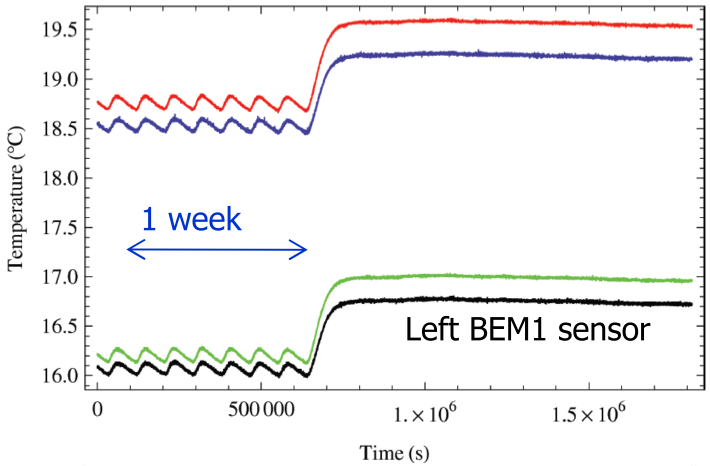
Reference loads (4K)

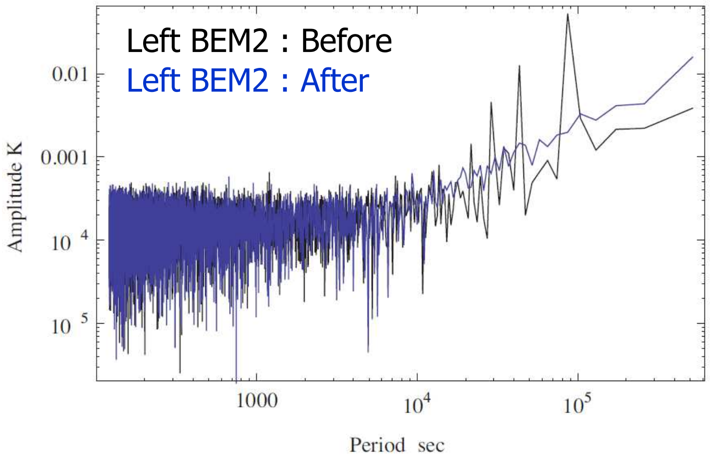




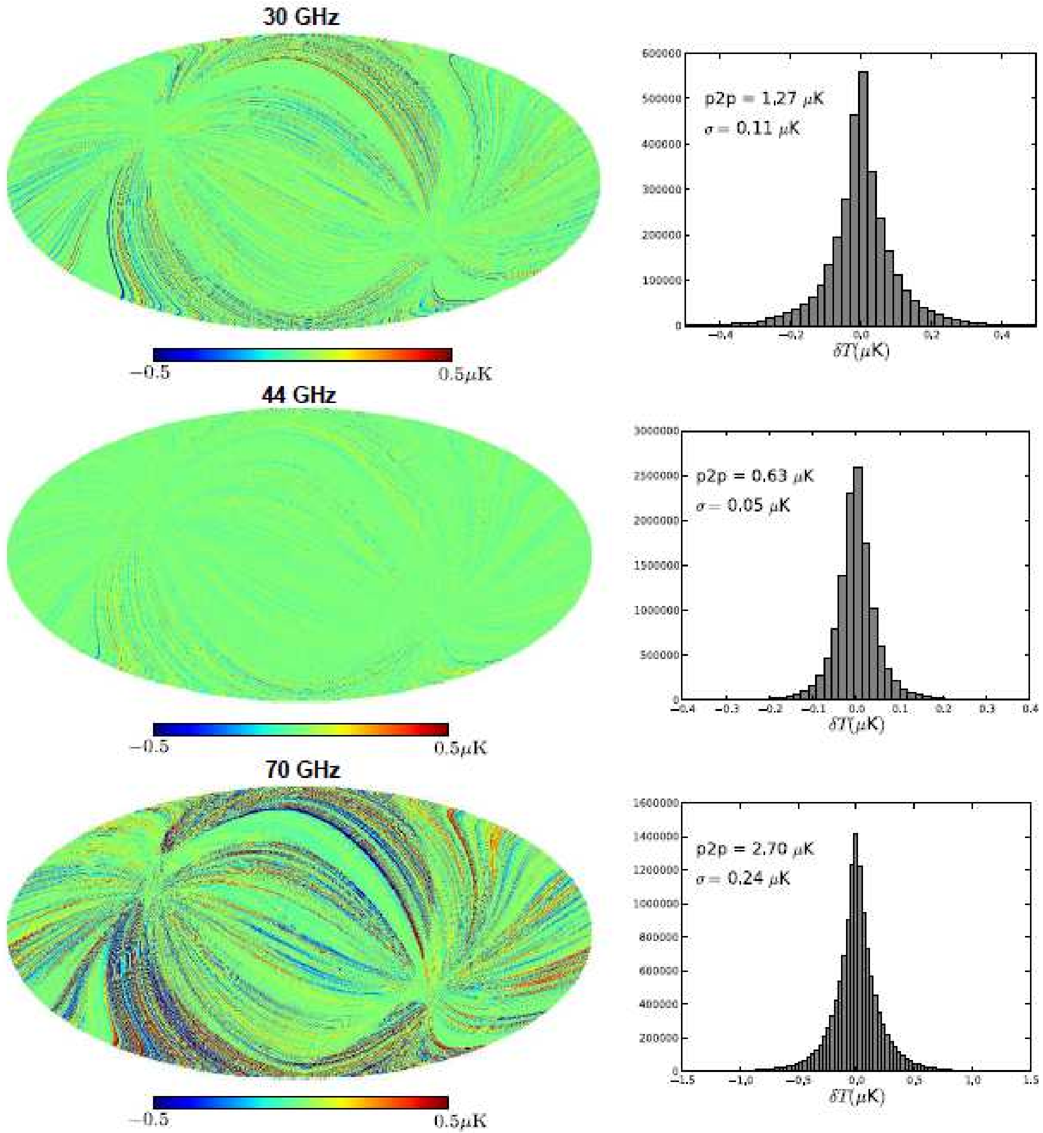
LFI Back-end fluctuations (300K)

LFI back-end
Flight Temperature Sensors data
(around OD258)





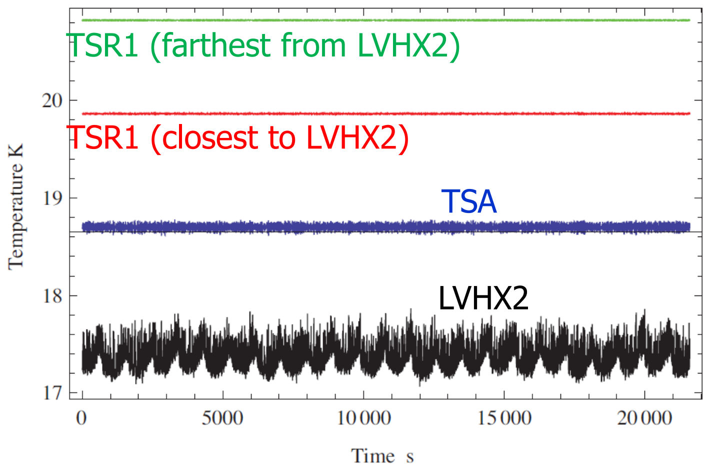
(Planck Collaboration 2011)

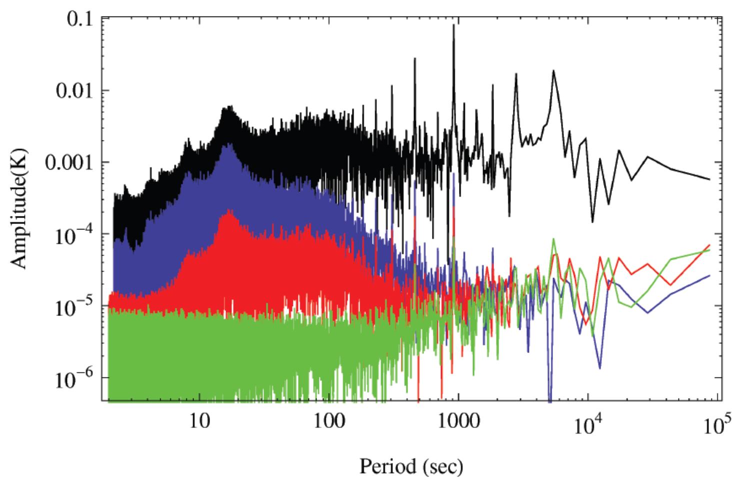


(Mennella et al. 2011)

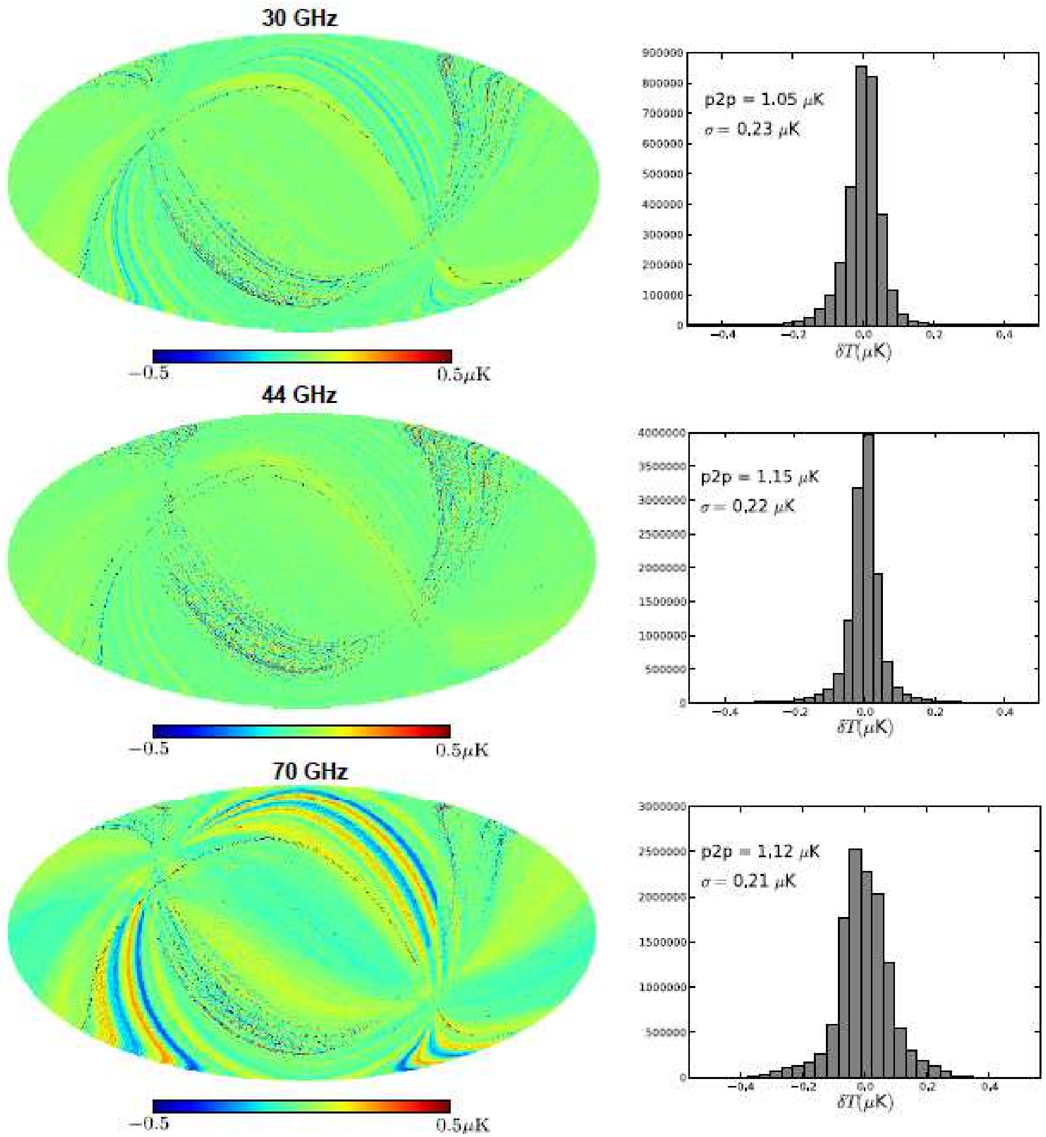
LFI Front-end fluctuations (20K)

LFI focal plane
Flight Temperature Sensors data
(24h, Oct 09)





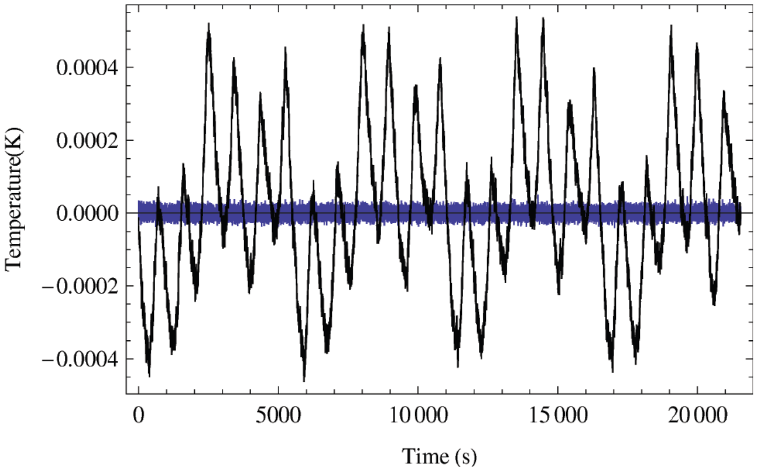
(Planck Collaboration 2011)

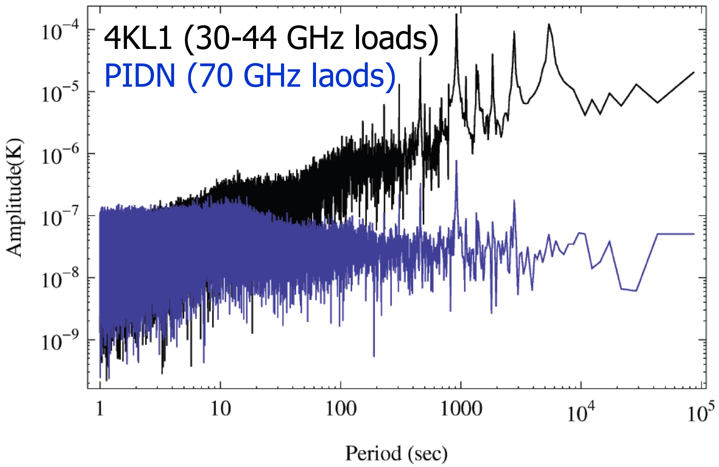


(Mennella et al. 2011)

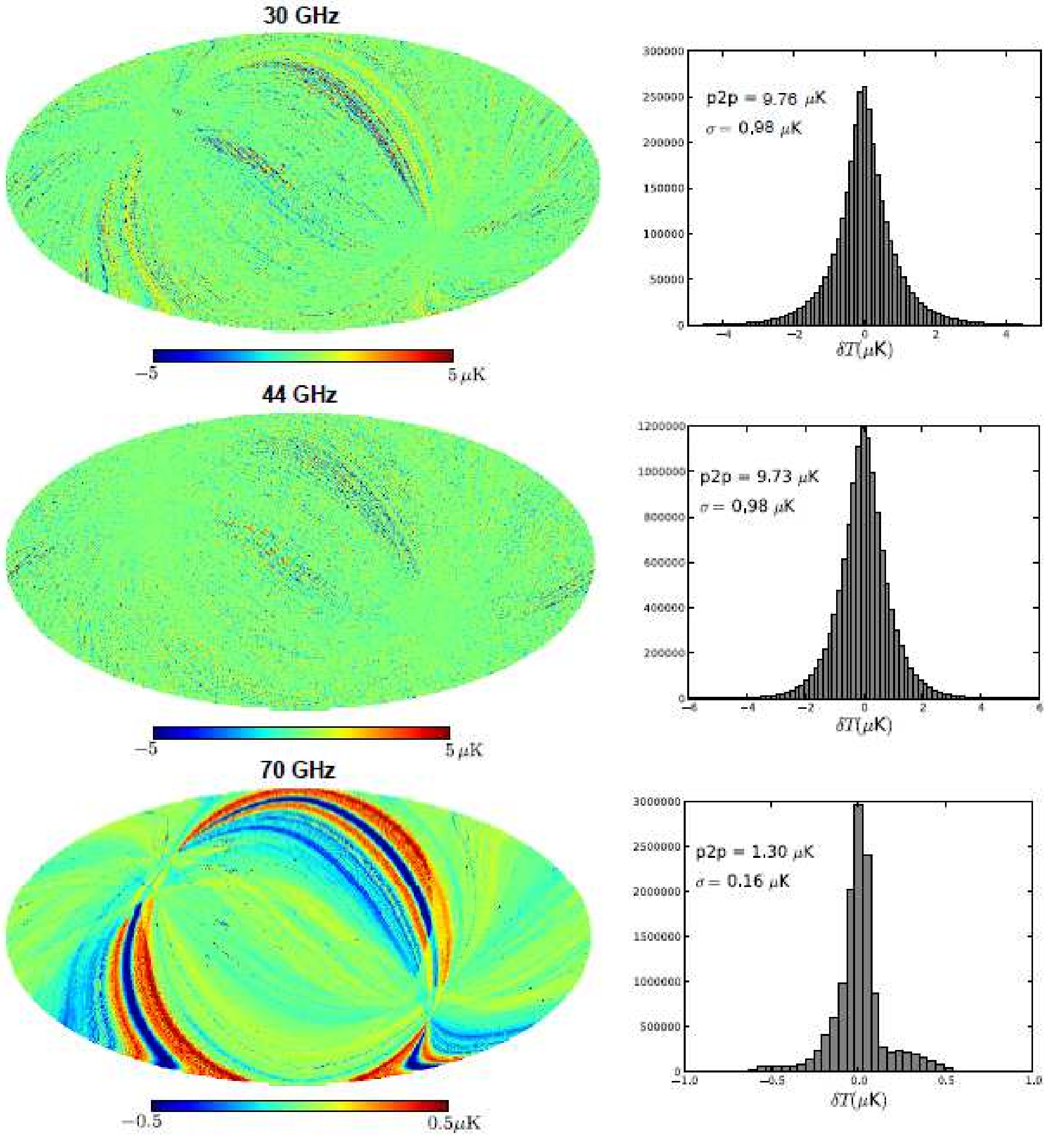
LFI Reference load fluctuations (4K)

HFI outer shield
Flight Temperature Sensors data
(24h, Oct 09)





(Planck Collaboration 2011)



(Mennella et al. 2011)