

Tokio, 1-2 July 2019 – LiteBIRD kick-off symposium

From Planck to LiteBIRD
Instrument and calibration



Marco Bersanelli
(University of Milano, INFN, INAF)
and The Planck Collaboration

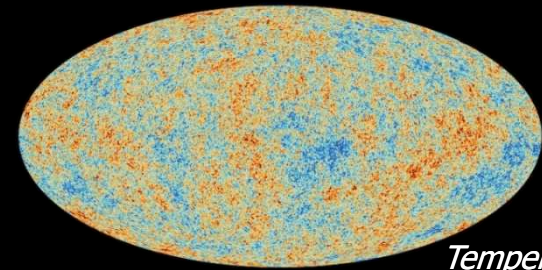
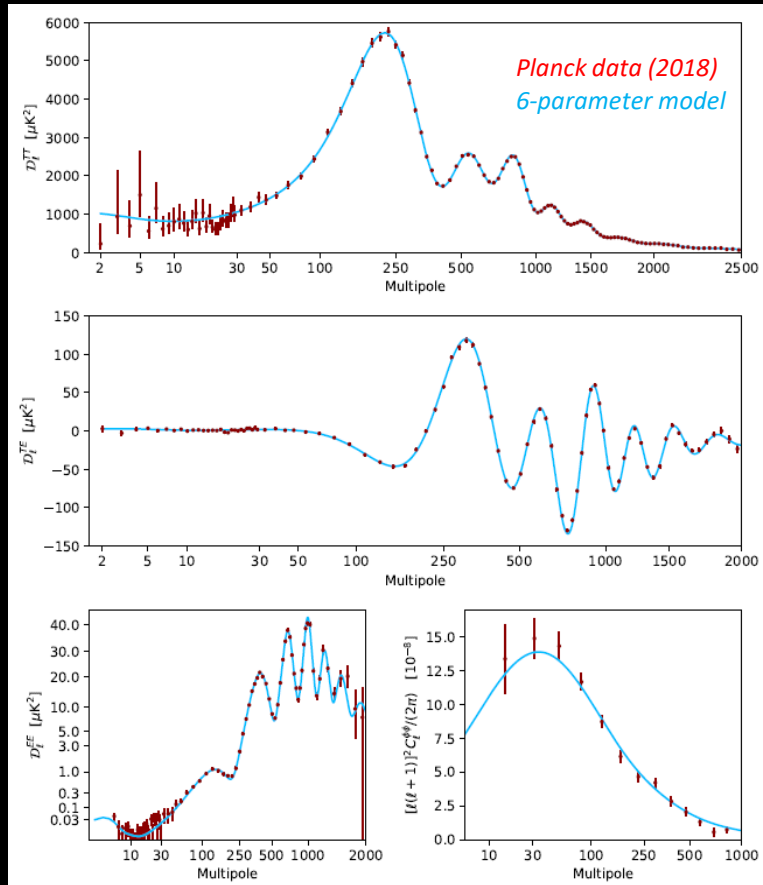


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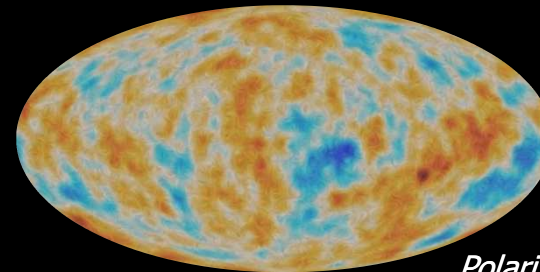
Tokio, 1-2 July 2019 – M. Bersanelli & Planck Collaboration
From Planck to LiteBIRD: instruments and calibration



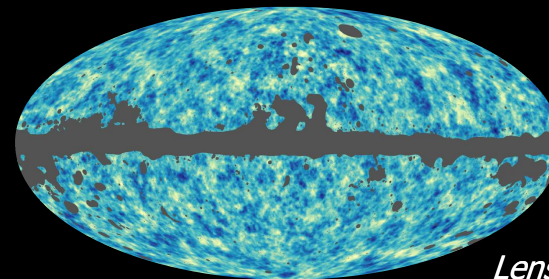
The success of Planck relied on a very demanding calibration effort throughout the project



Temperature



Polarization



Lensing

Planck Collaboration 2018

Many people (virtually all the Planck Collaboration) were involved

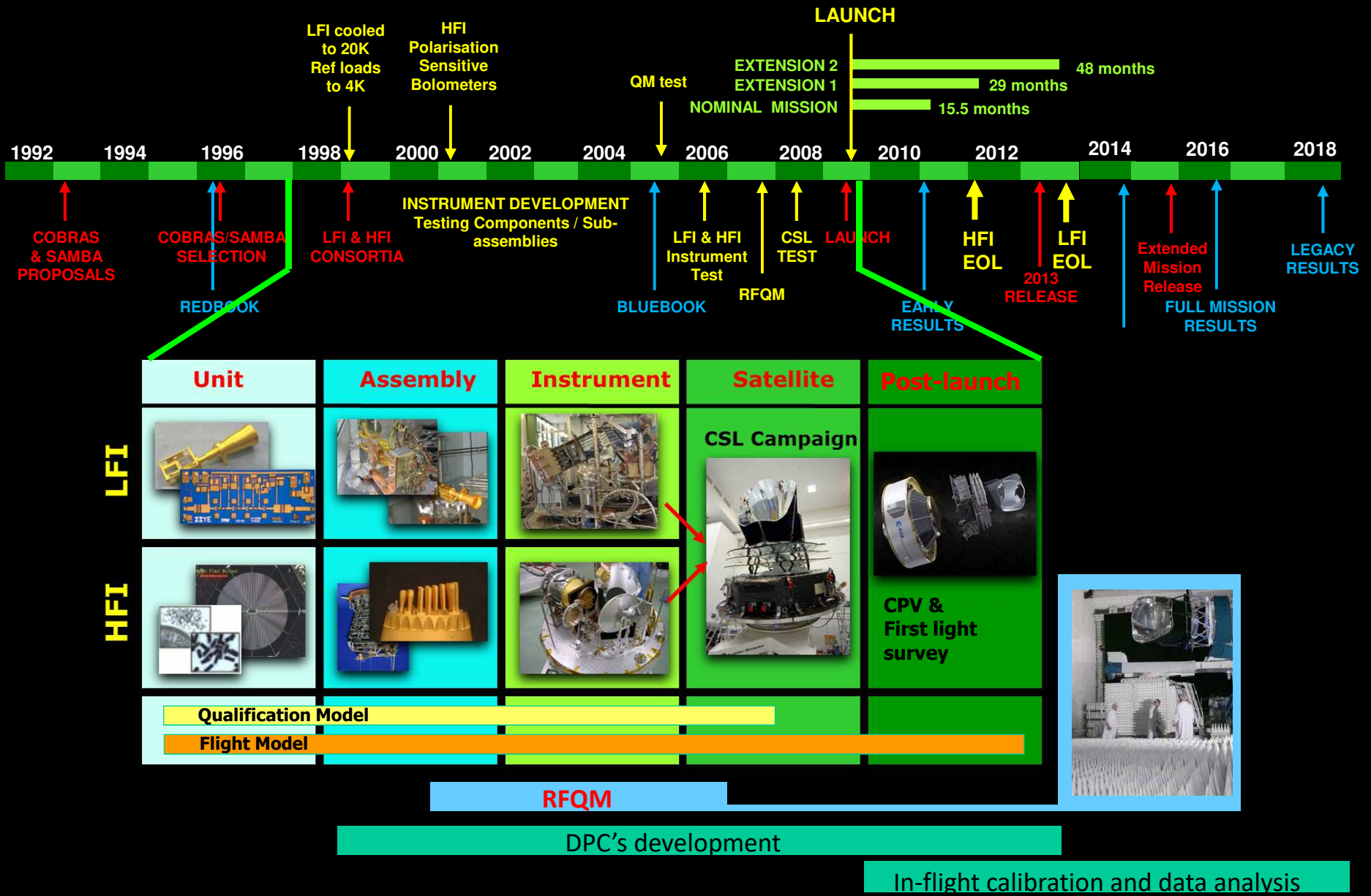


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Planck – Ground & in-flight calibration



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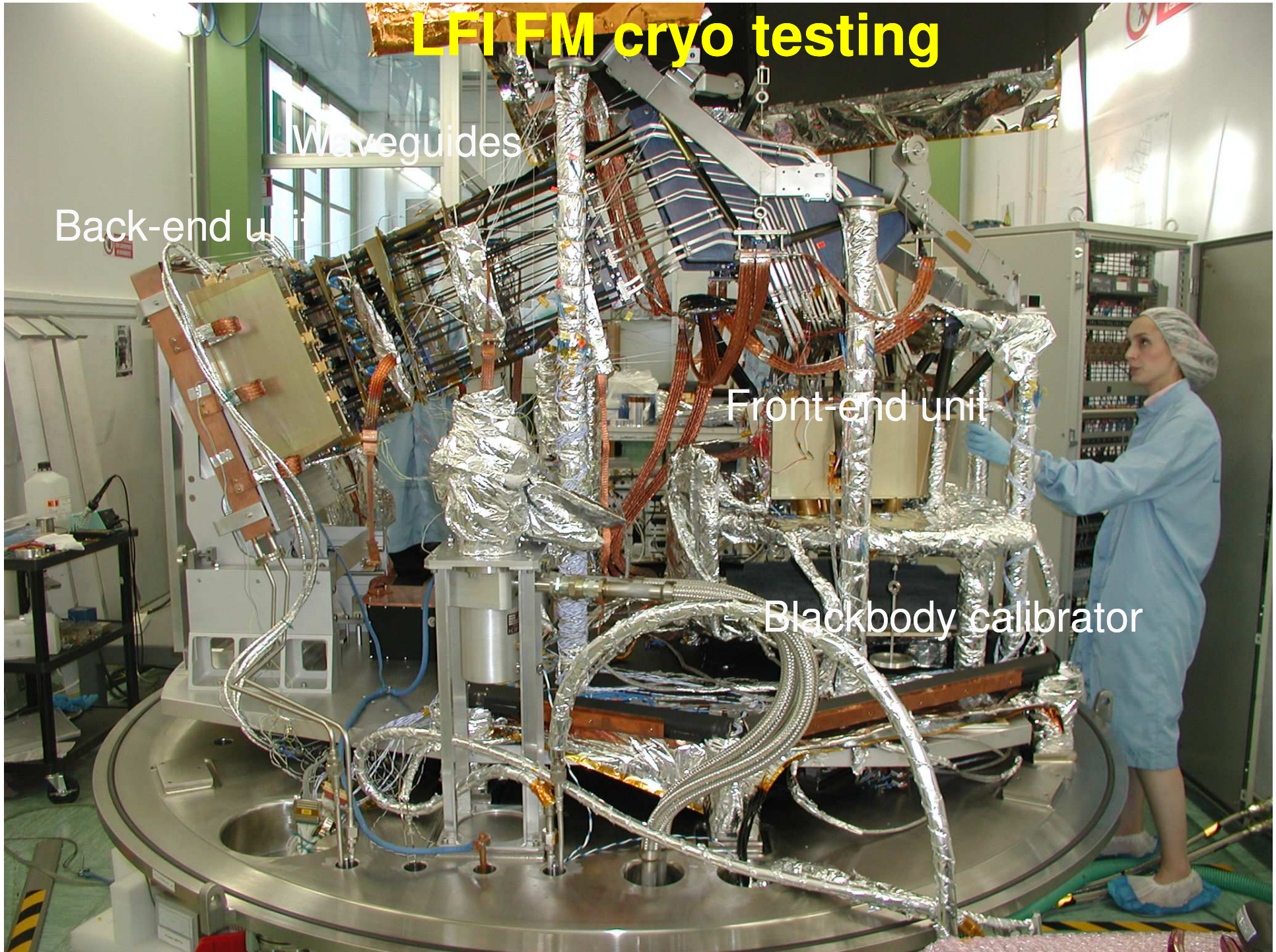
LFI FM cryo testing

Waveguides

Back-end unit

Front-end unit

Blackbody calibrator



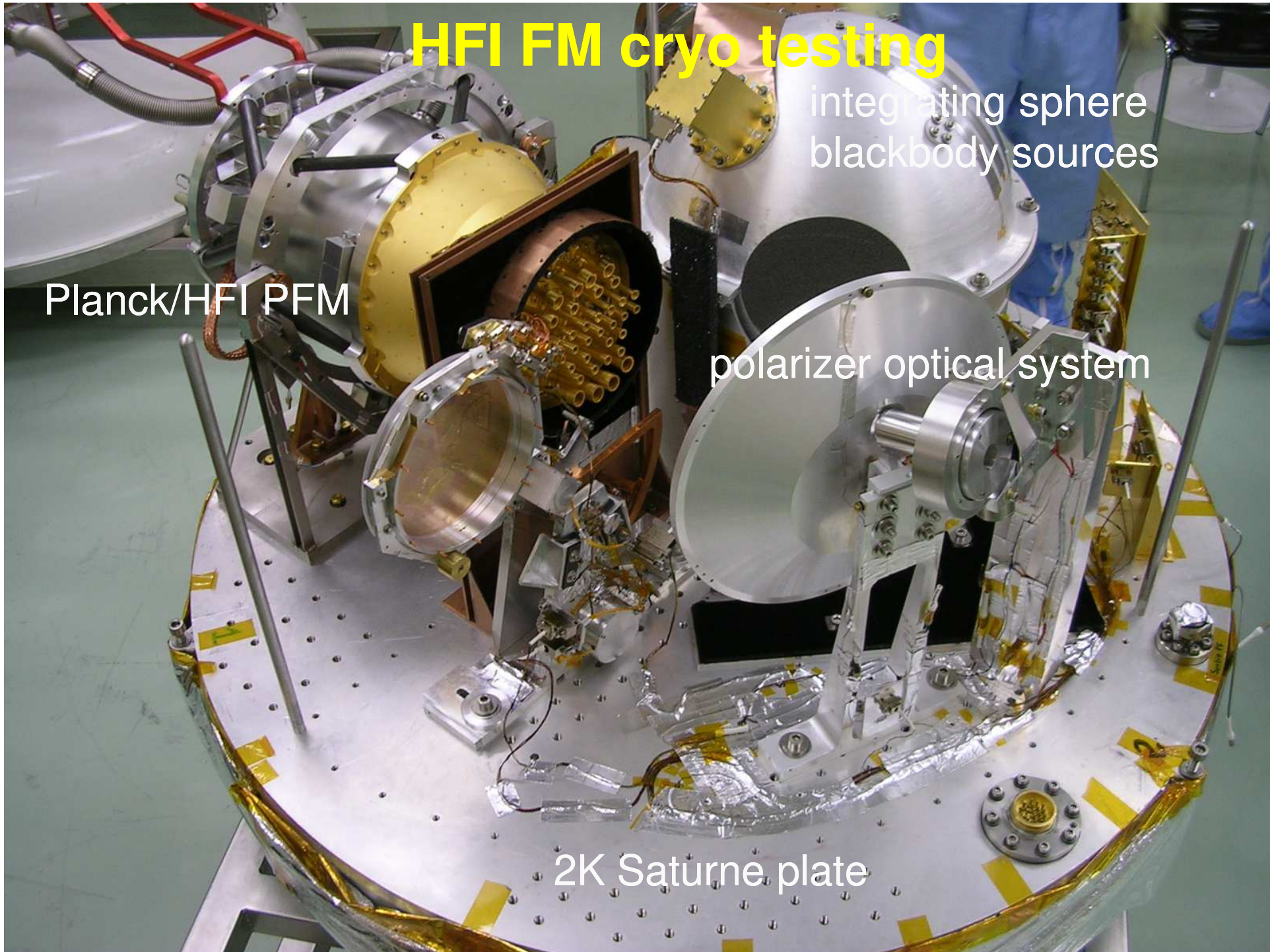
HFI FM cryo testing

integrating sphere
blackbody sources

Planck/HFI PFM

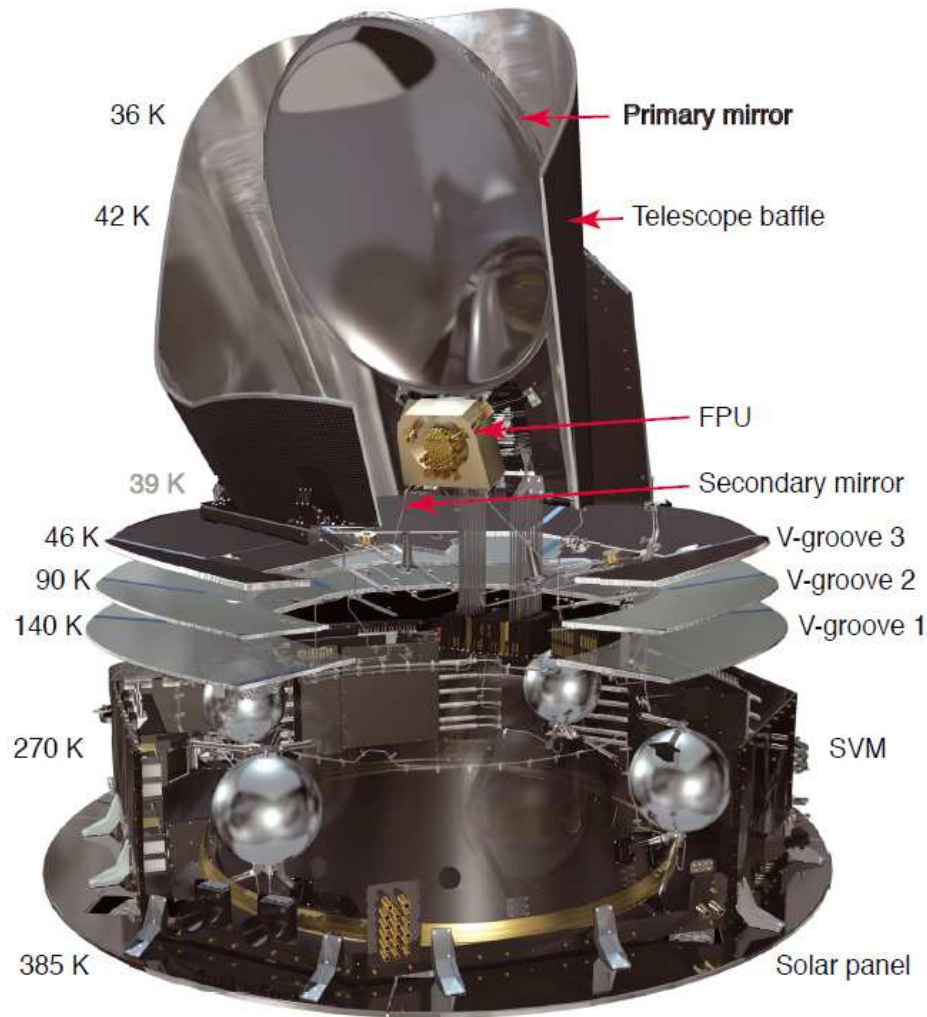
polarizer optical system

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

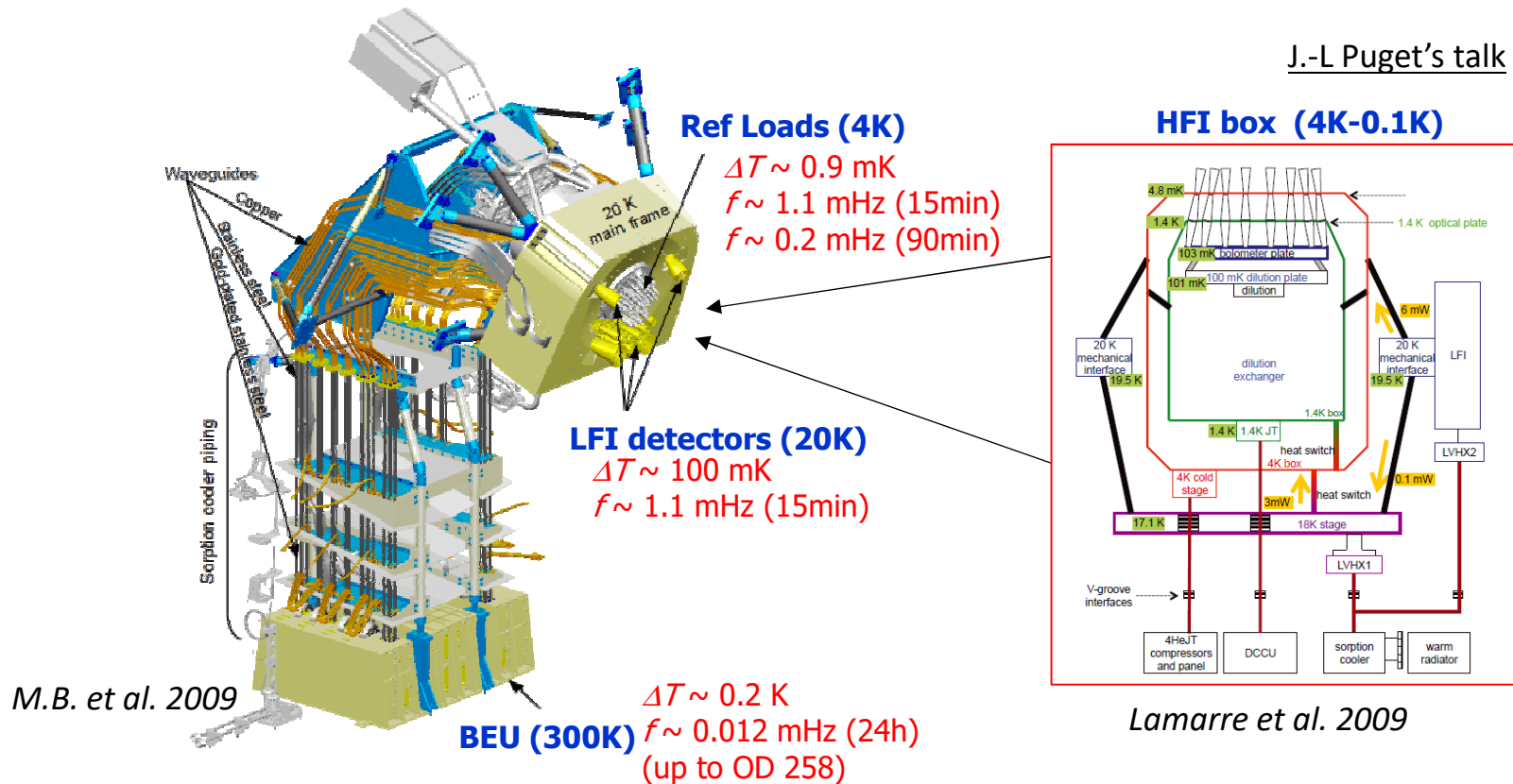
Beams footprints on target





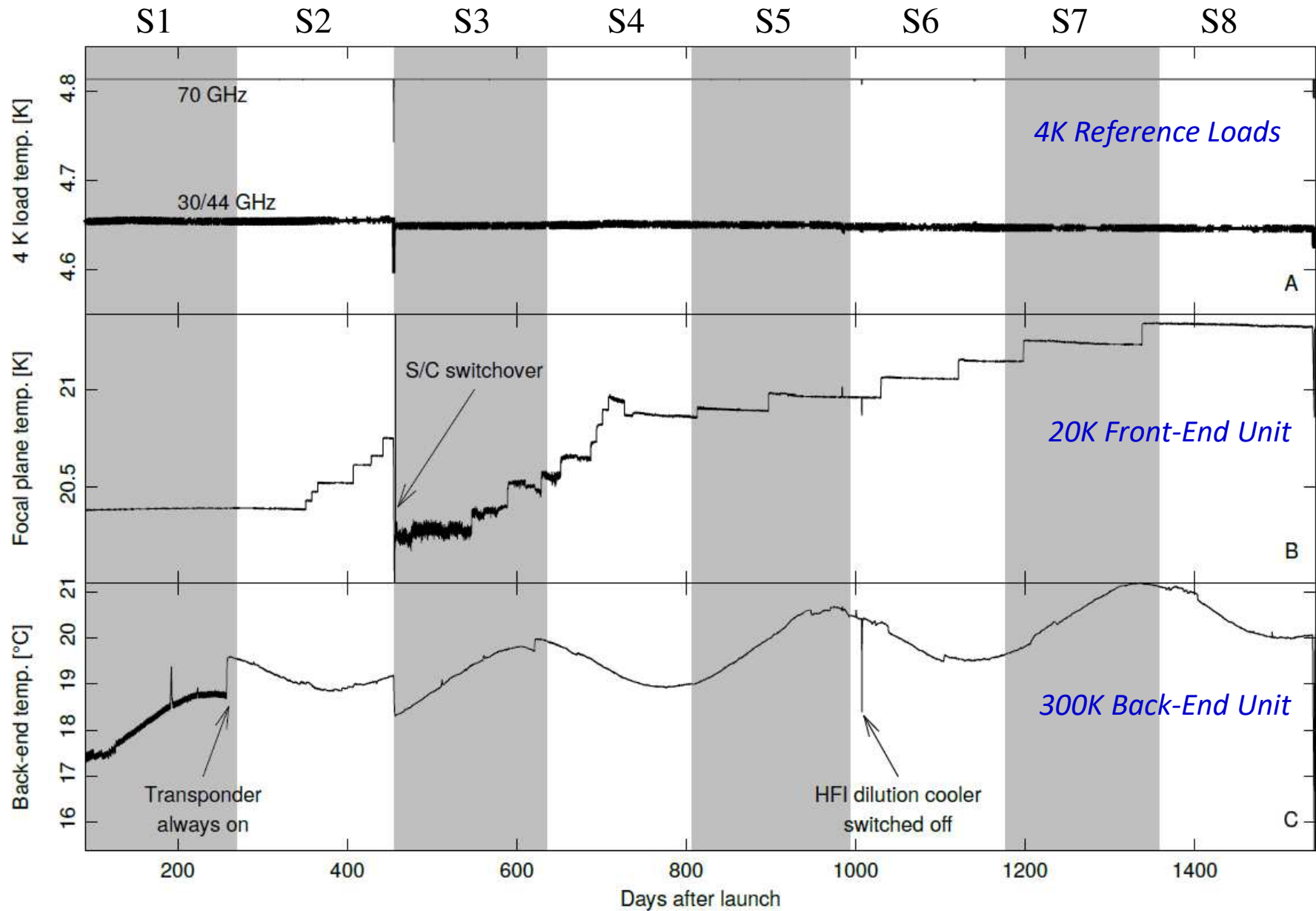
Thermal model

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



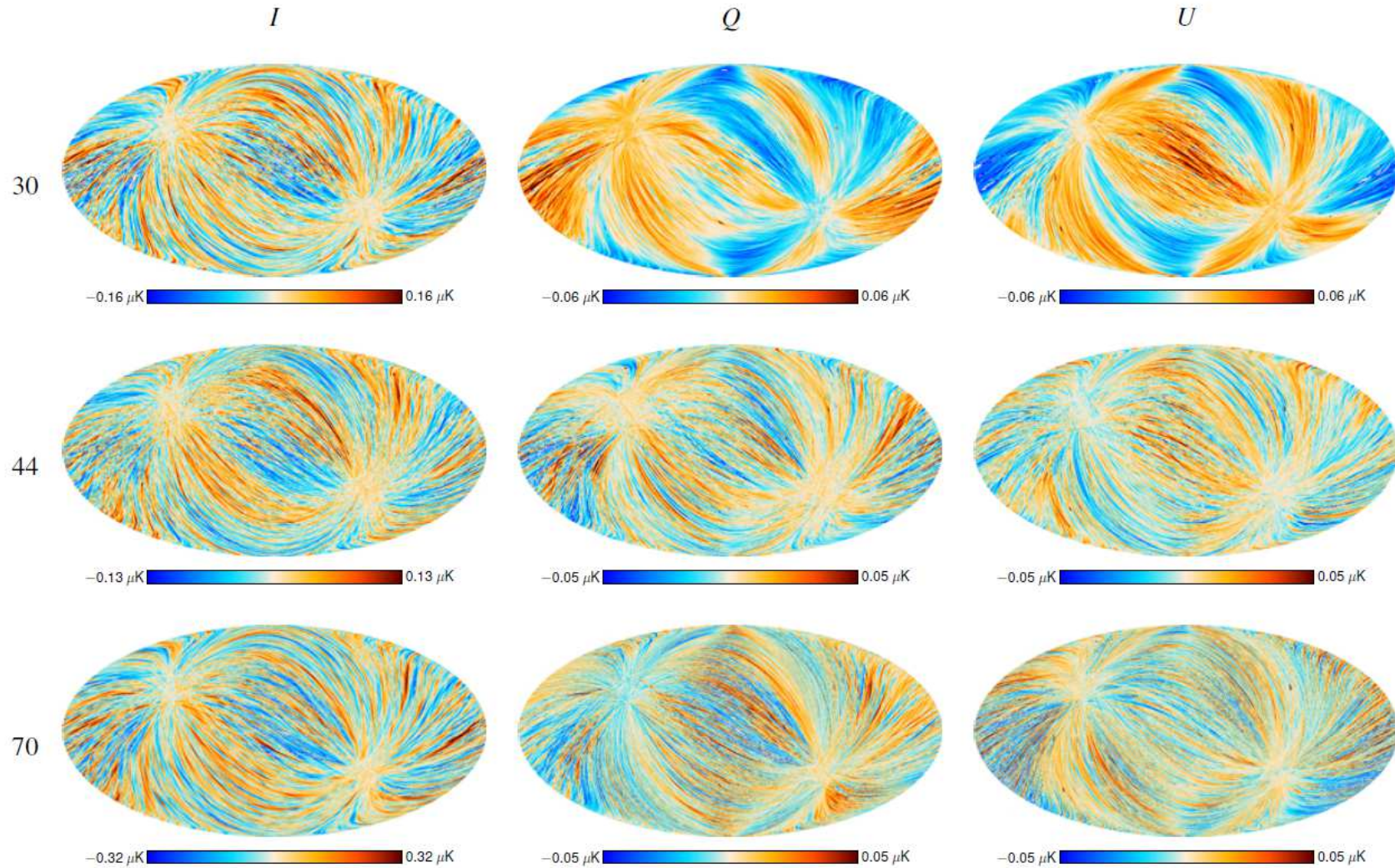
- Instrument model:
 - Thermal transfer functions
 - Radiometric transfer functions
 - Ground calibration at increasing levels of integration (and QM, FM)
 - Finalize instrument design (\rightarrow *stringent constraints on 18-20K sorption cooler stability*)
 - Temperature sensors
 - Prepare for in-flight analysis
- (Tomasi et al. 2010, Terenzi et al. 2010)

H/K data from Planck mission



Combined effect of fluctuations at 300, 20 and 4K

Planck Collaboration III, 2016



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

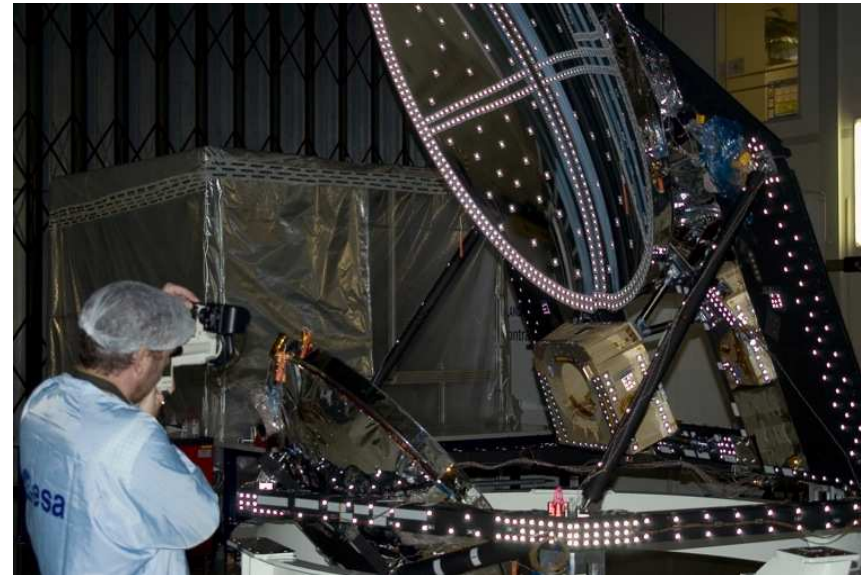
LFI potential effects and calibration strategy

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 4 π 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 $\lambda=10 \mu\text{m}$ of SR between 300K and ~ 40 K
 - Trace small-scale deformations (“dimples”)
- Photogrammetry of telescope structure between 300K and ~ 95 K
 - Thermoelastic deformations



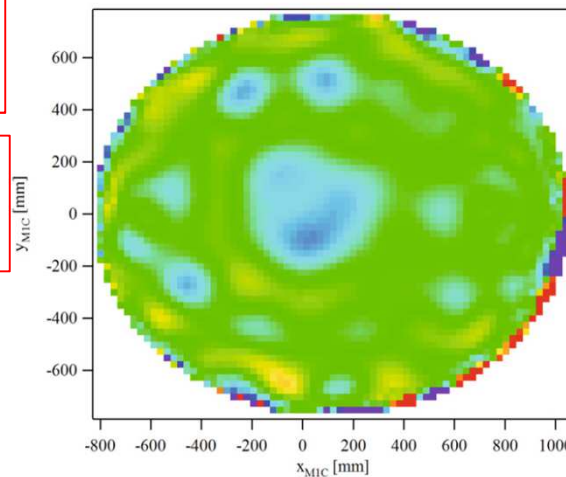
Extrapolate Telescope geometry to 40K

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

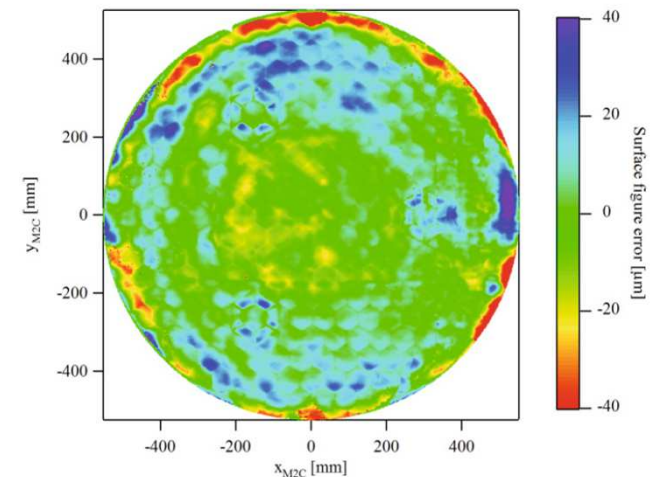
(Feedhorns beams precisely measured at instrument and unit level)

Estimated surface deformation at 40K

Primary



Secondary



LFI feedhorns design and measurements

Villa et al. JINST 2009

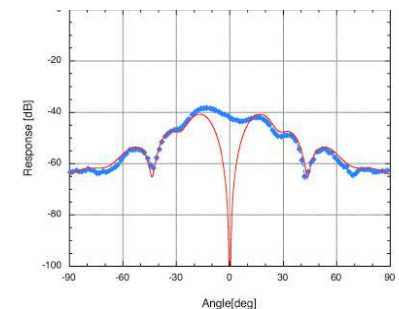
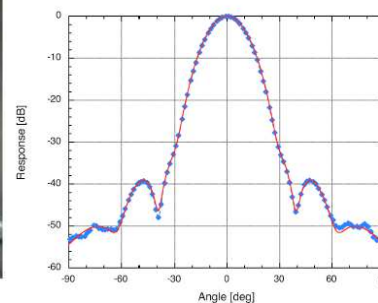
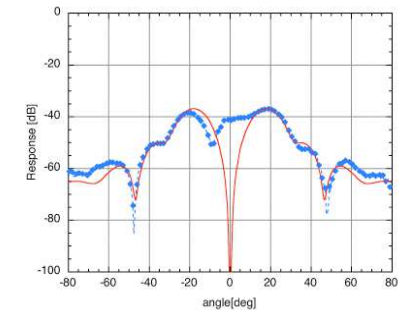
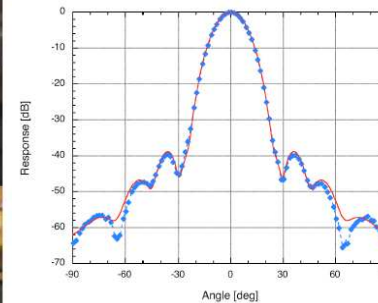
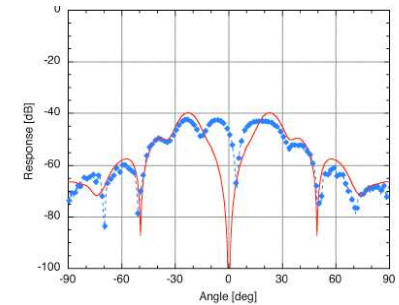
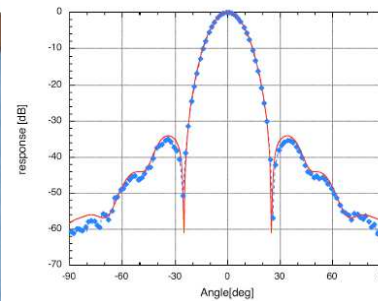
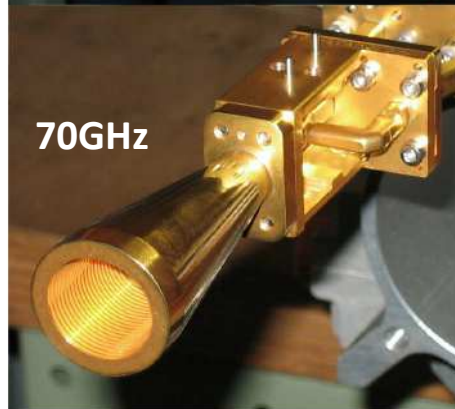
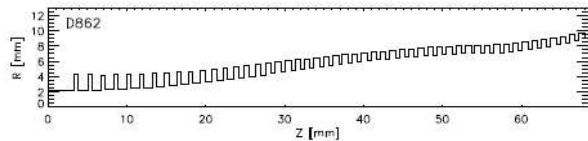
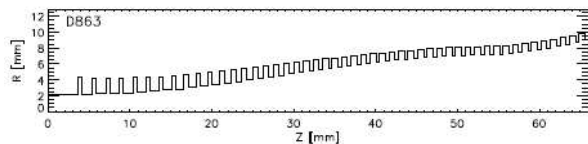
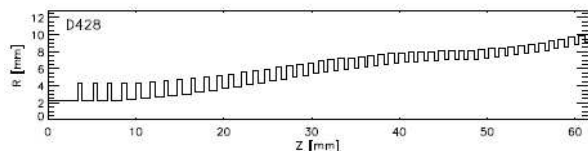
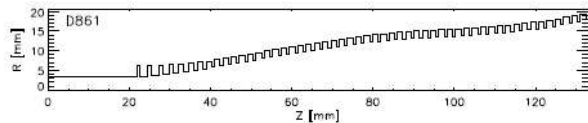
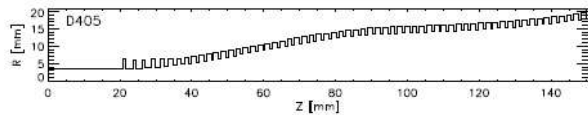
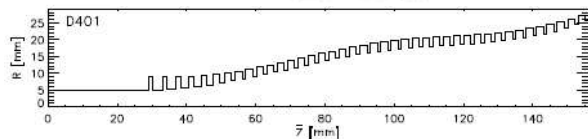
Corrugation profile (sin-squared + exponential) for compactness and high control of sidelobes

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

$$0 \leq z \leq L_s$$

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

$$L_s \leq z \leq L_e + L_s$$



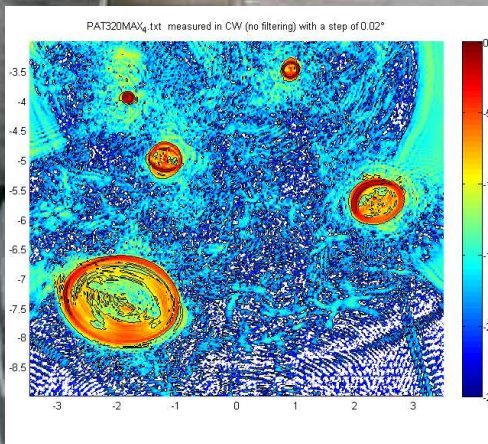
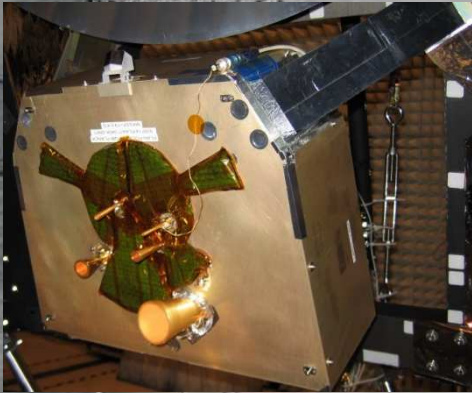
Co-pol accuracy <1dB above -40dB, Cross-pol <-35dB, RL < -30dB

Several frequencies measured across the-band

Planck RF verification

RFQM:

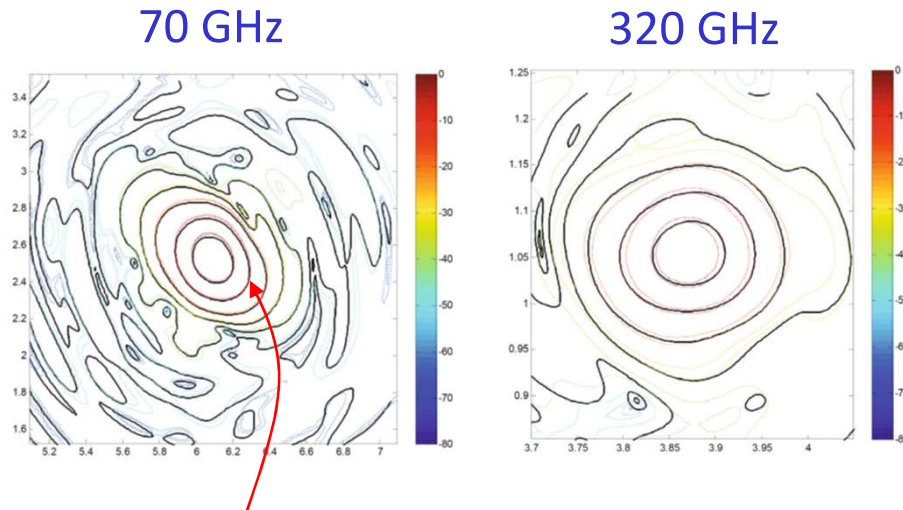
- Planck QM telescope
- Representative focal plane structure
- All relevant payload elements (e.g. baffle, V-groove)
- Test system: CATR at 300K (*Thales, Cannes*)
- Measure 4π beams of flight-like horns at 30-320 GHz (incl. 2 orthogonal polarizations)



Comparing RFQM measurements and Optical model (at 300K)

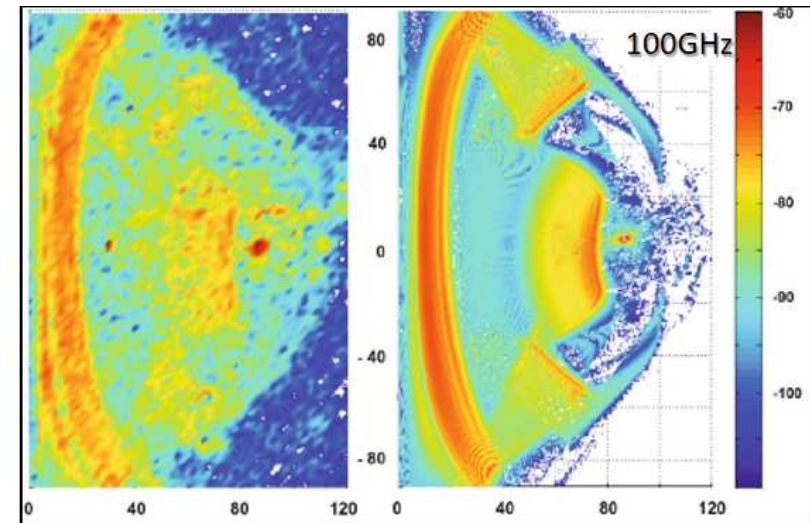
Tauber et al. A&A 520, A2 (2010)

MAIN BEAMS



$\pm 1\sigma$ measurement error

SIDELOBES



Model: GRASP physical optics (PO)

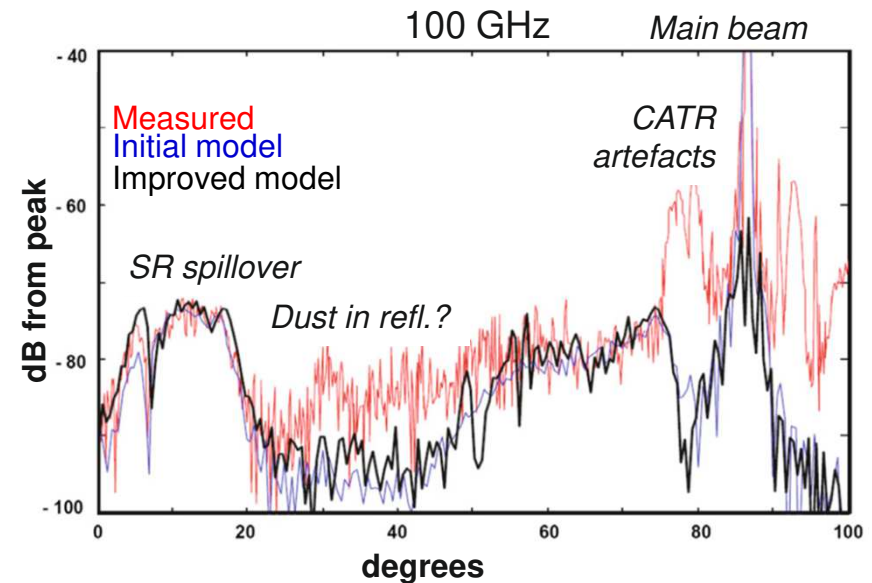
Consistency with measurements:

- 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**

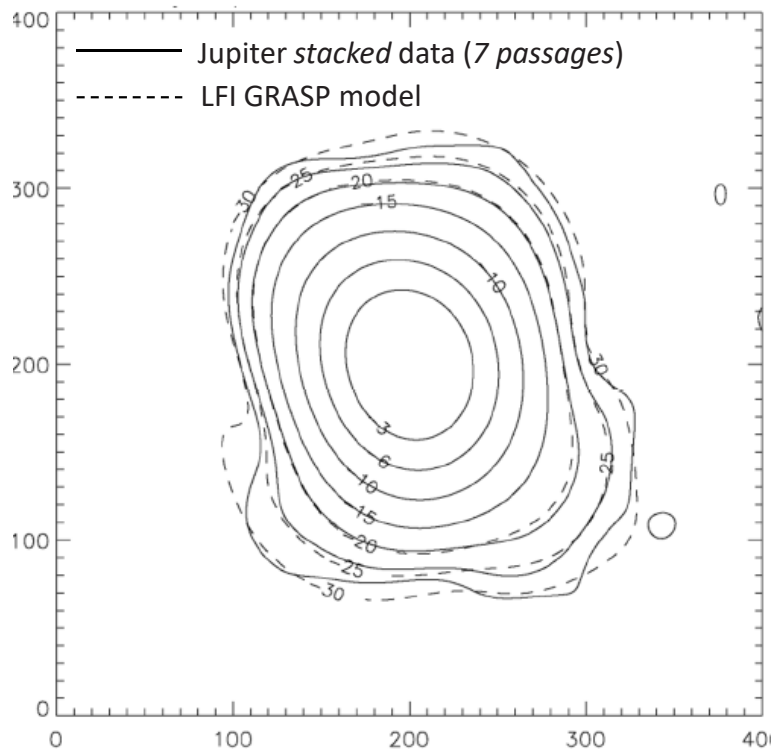
Tauber et al. (2019)



LFI beams: GRASP model and in-flight measurement

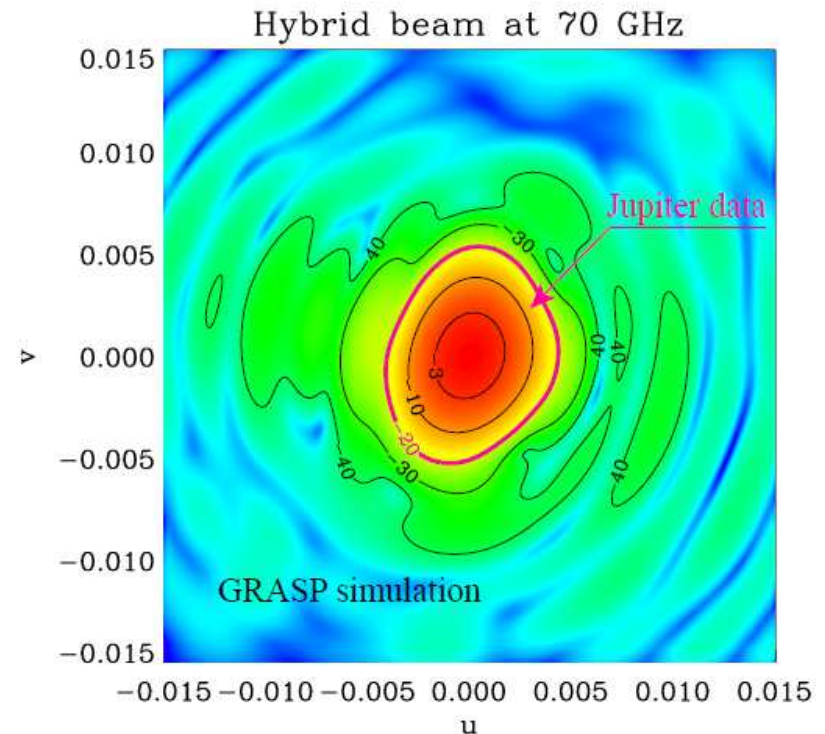
- Thermo-elastic model to translate 300K best model to flight conditions (40K reflectors, structure)
- Compute bandpass-averaged beams (25 cuts/beam)
- Include effect of OMT cross-pol,
- “Tuned model”: fit telescope model parameters (R , k , alignment) to in-flight data within measurements errors

*Typical accuracy for all LFI beams
at all 3 frequencies*



Final analysis: Hybrid scanning beams

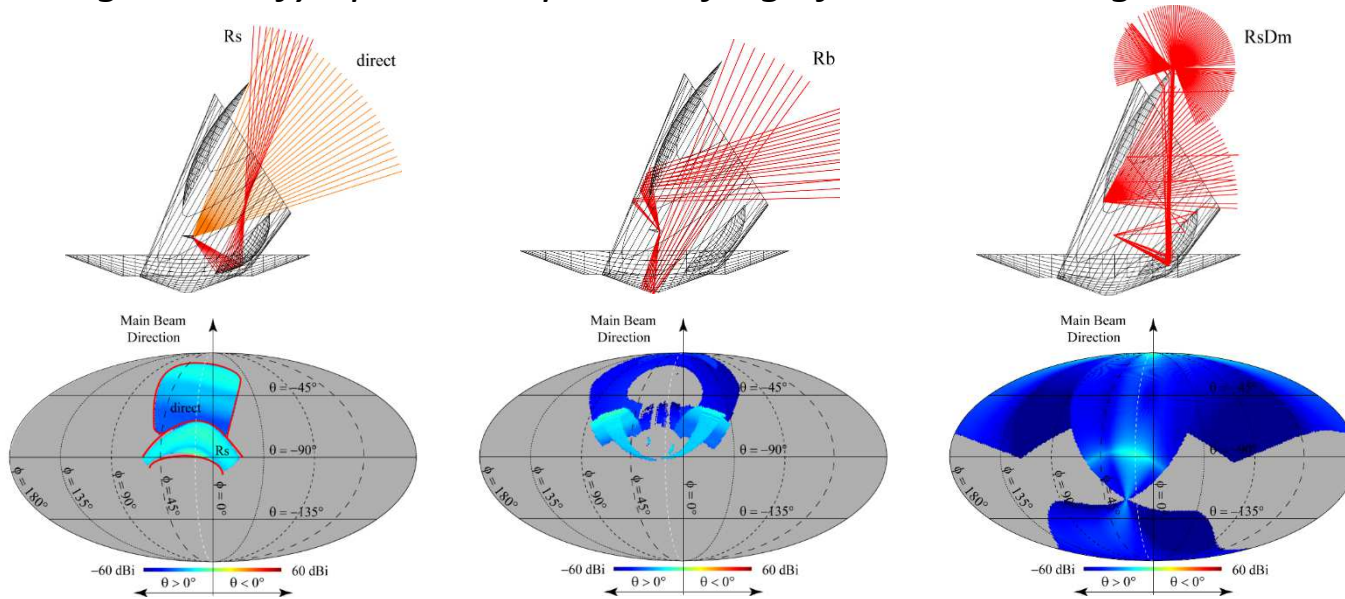
- Data from Jupiter above a S/N floor
- GRASP fiducial model below threshold



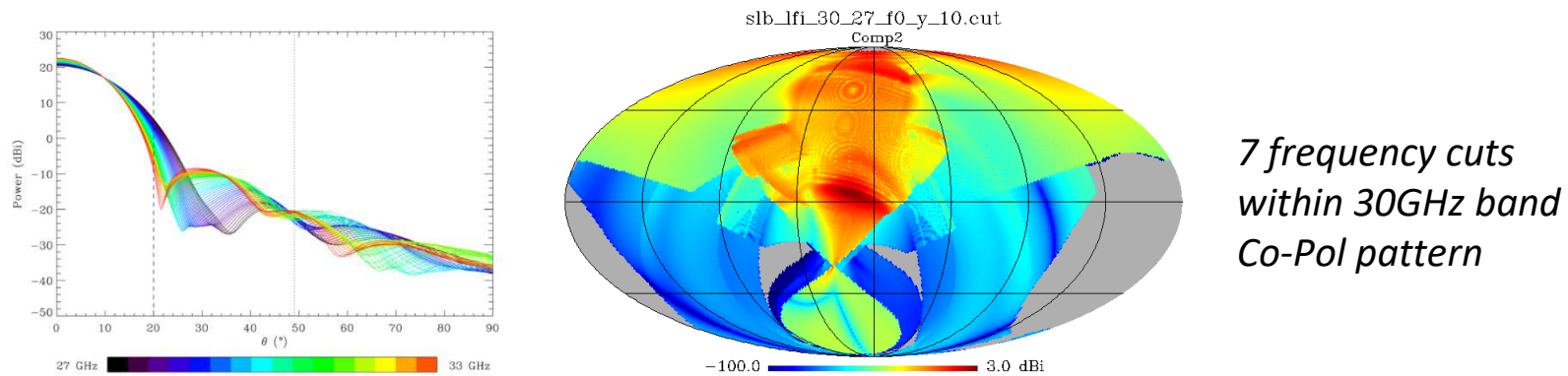
LFI far-sidelobes calculation: GRASP MrGTD

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

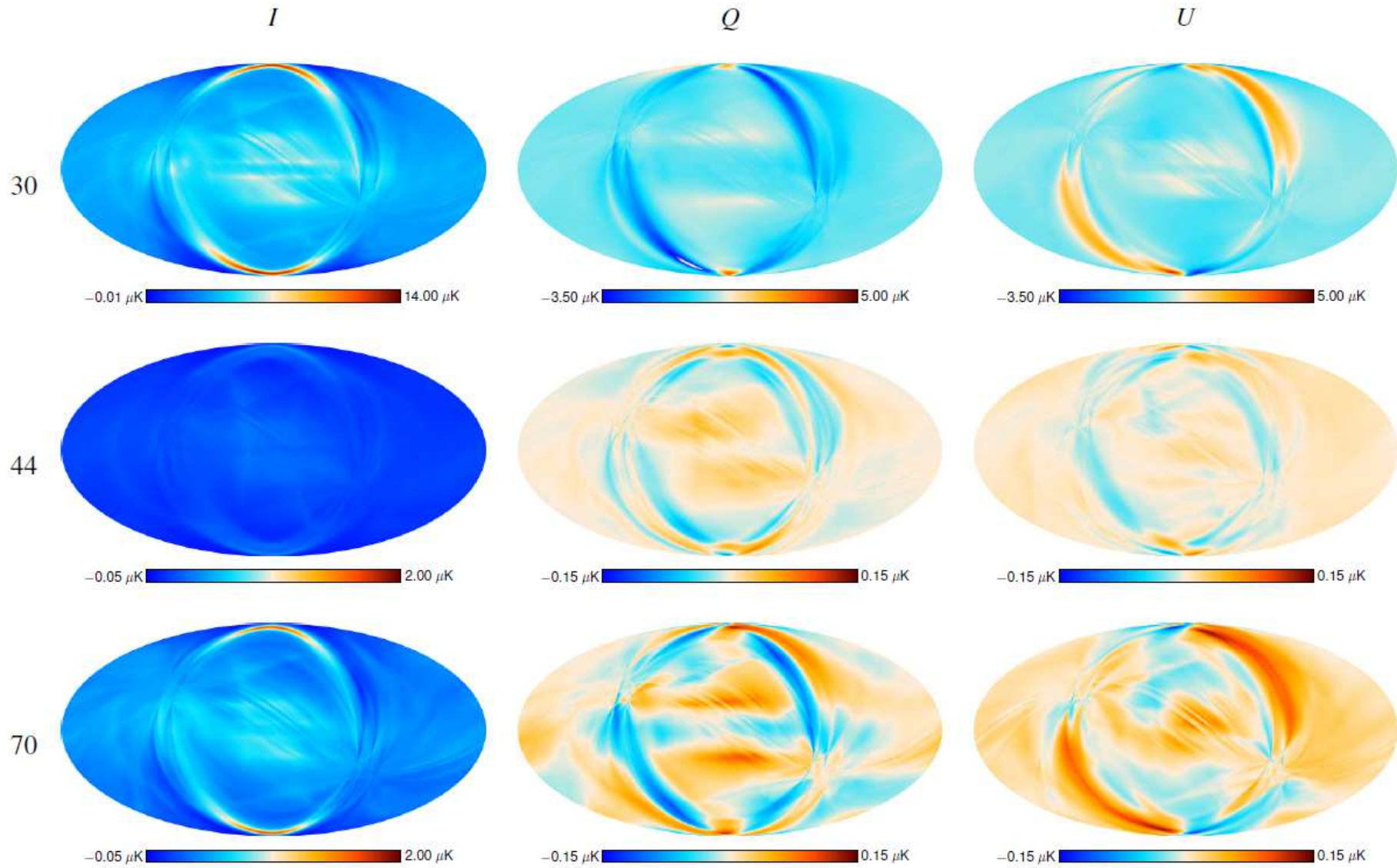


7 frequency cuts
within 30GHz band
Co-Pol pattern

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

Effect from far sidelobes before subtraction

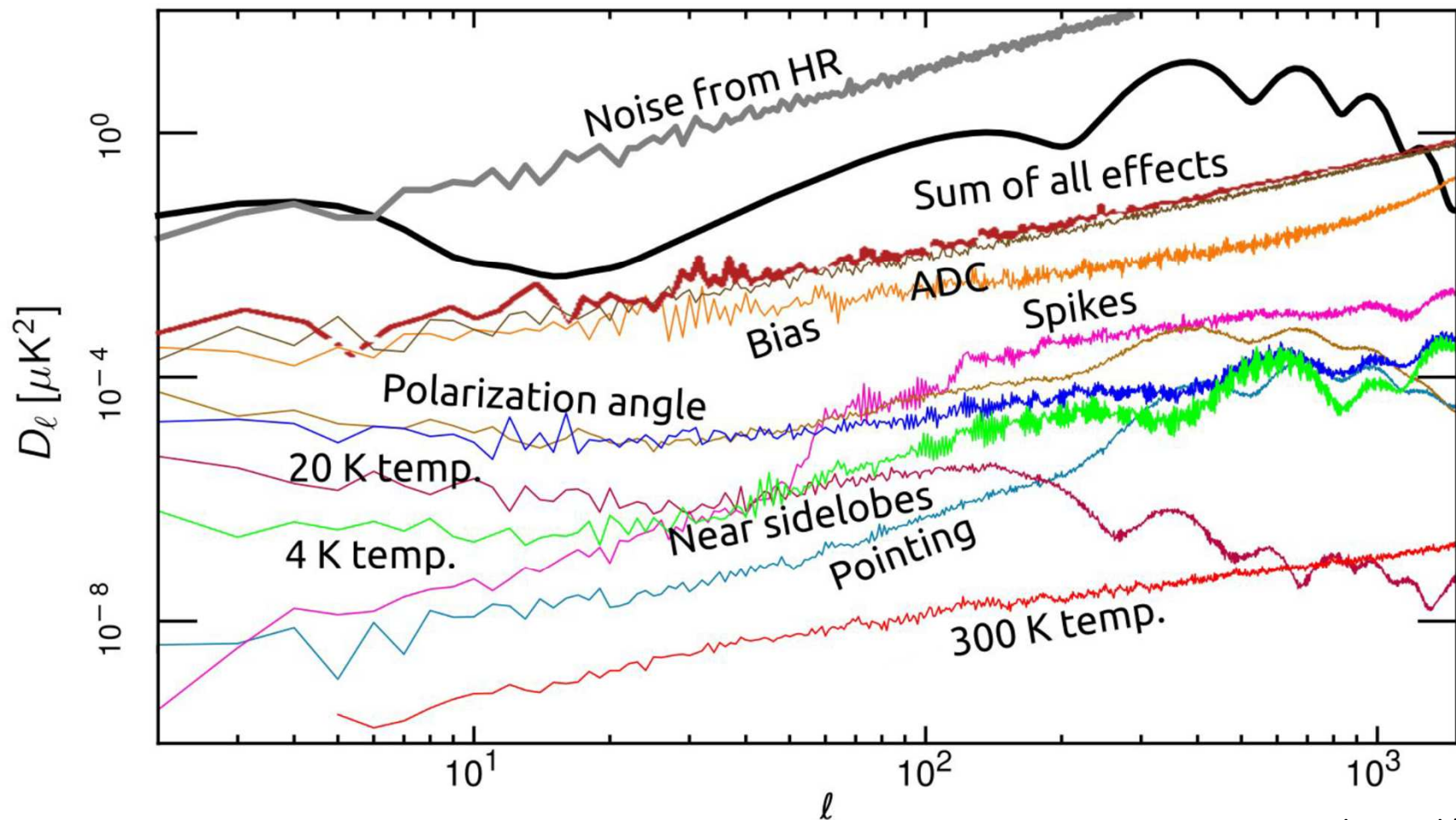
Planck Collaboration III, 2016



Effect removed in timelines

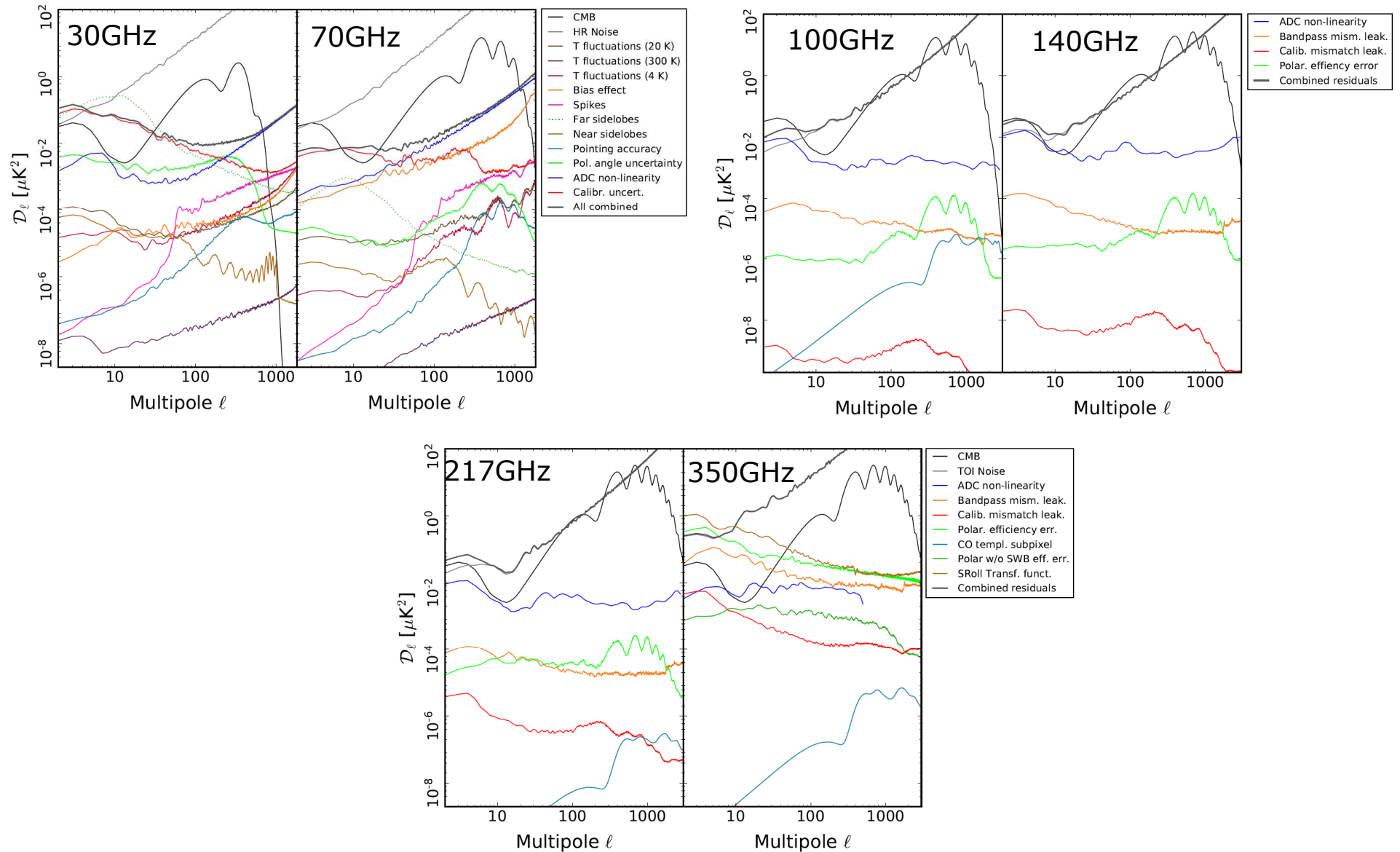
Systematic effects - LFI

Planck 70 GHz systematic effects



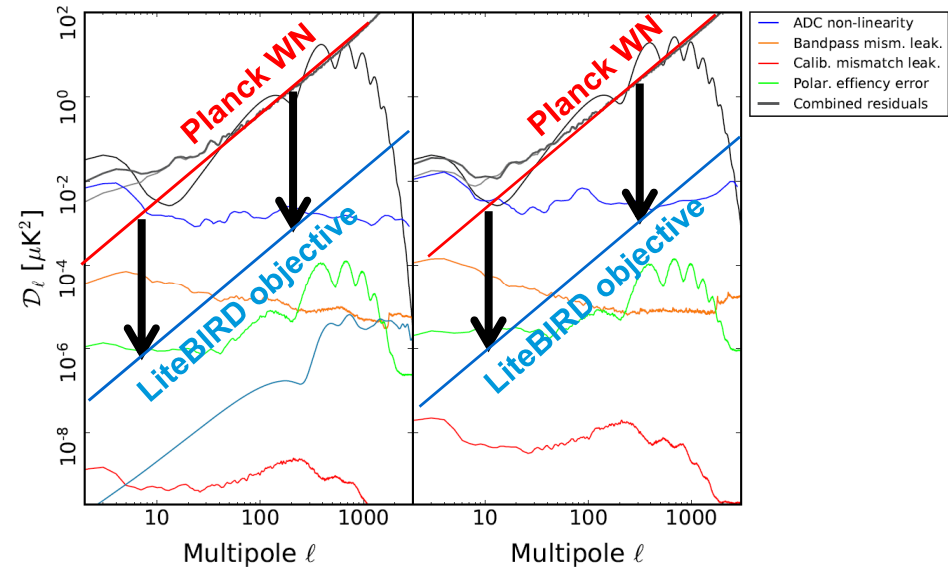
Angular power spectra of residual systematics in polarization

Planck Collaboraiton 2018



Ready for LiteBIRD !

- LiteBIRD's new exciting objectives:
 - *B-modes at $r \sim 0.001$*
 - *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!

the 1990s, the number of people in the UK who are employed in the public sector has increased from 10.5 million to 12.5 million, and the number of people in the public sector who are employed in health care has increased from 2.5 million to 3.5 million (Department of Health 2000).

There are a number of reasons why the public sector has become an important part of the UK economy. One of the main reasons is that the public sector provides a wide range of services that are essential for the well-being of the population. These services include health care, education, and social care. The public sector also provides a number of other services that are important for the economy, such as transport and housing.

Another reason why the public sector has become an important part of the UK economy is that it provides a source of employment for a large number of people. In 2000, the public sector employed 12.5 million people, which is 20% of the total UK workforce. This is a significant proportion of the workforce, and it shows that the public sector is an important source of employment for many people in the UK.

There are a number of challenges that the public sector faces in the future. One of the main challenges is that the population is ageing, and this is leading to an increase in the number of people who need health care and social care. This is putting a strain on the public sector, and it is likely to lead to an increase in public sector spending in the future.

Another challenge that the public sector faces is that there is a need to improve the efficiency of public sector services. This is because the public sector is often inefficient, and it is not always clear how to improve it. There are a number of ways in which the public sector can be made more efficient, such as by introducing competition and by improving the way in which public sector services are delivered.

There are a number of other challenges that the public sector faces, such as the need to improve the quality of public sector services and the need to ensure that public sector services are accessible to all people. These are all important challenges, and they need to be addressed if the public sector is to continue to provide the services that are essential for the well-being of the population.

In conclusion, the public sector is an important part of the UK economy, and it provides a wide range of services that are essential for the well-being of the population. The public sector also provides a source of employment for a large number of people in the UK. There are a number of challenges that the public sector faces in the future, and these need to be addressed if the public sector is to continue to provide the services that are essential for the well-being of the population.

LFI Radiometric Transfer function at 20K

$$\begin{aligned}
 T_f^{FEM} = & \left(\frac{L_{fh-OMT}}{(G_{F1} + G_{F2}) \cdot (1-r) + 2 \cdot \sqrt{G_{F1} \cdot G_{F2}} \cdot (1+r)} \right) \cdot \left[\left(\frac{\partial G_{F1}}{\partial T_{phys}^{FEM}} \right) \cdot \left((T_{sky} + T_{4K} + 2 \cdot T_{nF1}) \cdot (1-r) + \sqrt{\frac{G_{F2}}{G_{F1}}} \cdot (1+r) \right) + \right. \\
 & \left(\frac{\partial G_{F2}}{\partial T_{phys}^{FEM}} \right) \cdot \left((T_{sky} + T_{4K} + 2 \cdot T_{nF2}) \cdot (1-r) + \sqrt{\frac{G_{F1}}{G_{F2}}} \cdot (1+r) \right) + \left(\frac{\partial T_{nF1}}{\partial T_{phys}^{FEM}} \right) \cdot (2 \cdot G_{F1} \cdot (1-r)) + \left(\frac{\partial T_{nF2}}{\partial T_{phys}^{FEM}} \right) \cdot (2 \cdot G_{F2} \cdot (1-r)) + \\
 & \left. \left(1 - \frac{1}{L_{fh-OMT}} \right) \cdot \left((G_{F1} + G_{F2}) \cdot (1-r) + 2 \cdot \sqrt{G_{F1} \cdot G_{F2}} \cdot (1+r) \right) + \left(1 - \frac{1}{L_{4K}} \right) \cdot \left((G_{F1} + G_{F2}) \cdot (1-r) - 2 \cdot \sqrt{G_{F1} \cdot G_{F2}} \cdot (1+r) \right) \right]
 \end{aligned}$$

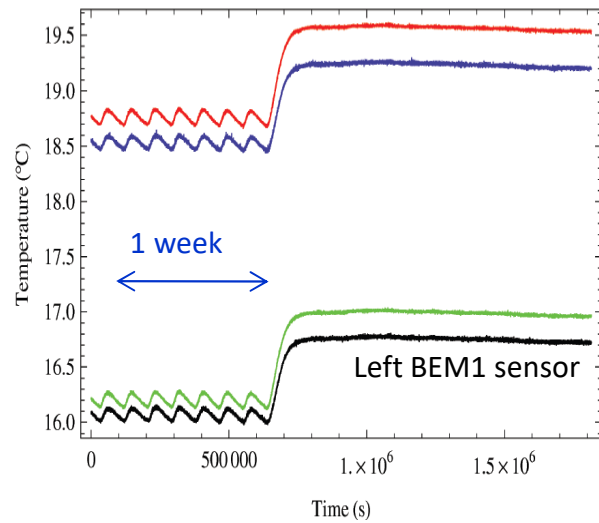
where:

- 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

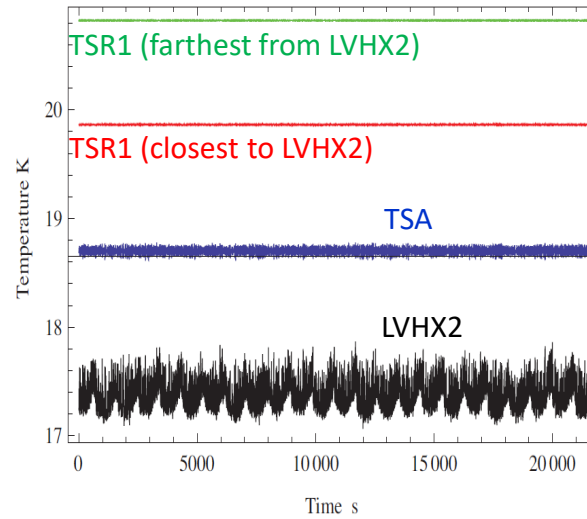
Flight H/K data

(Planck Collaboration 2011)

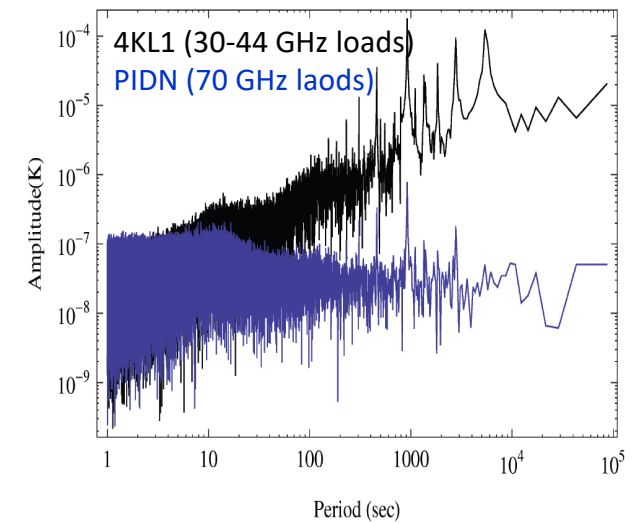
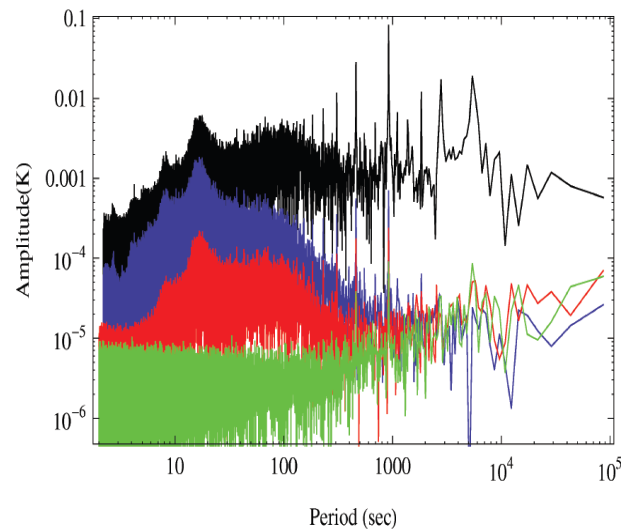
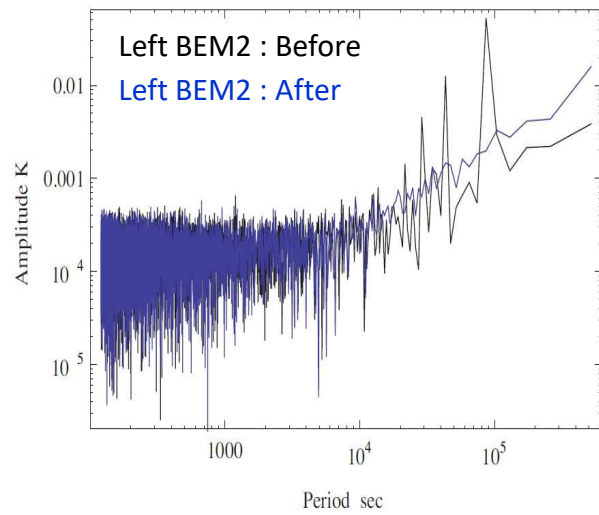
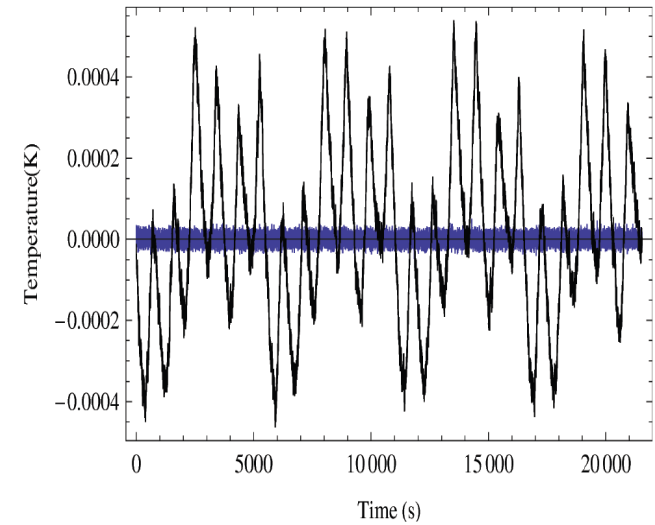
LFI back-end (300K)



LFI focal plane (20K)

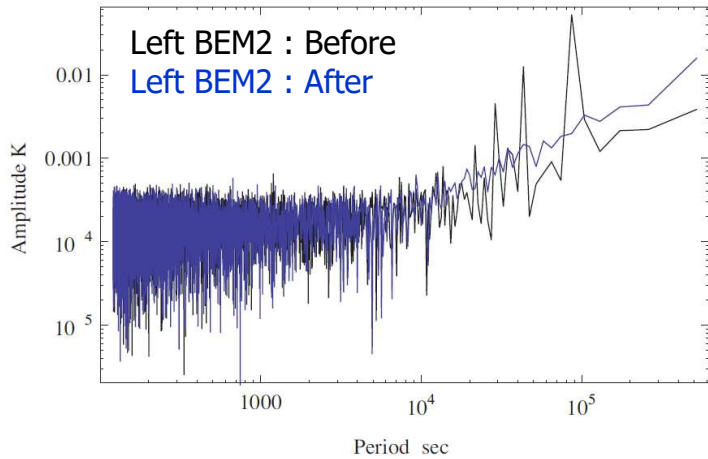
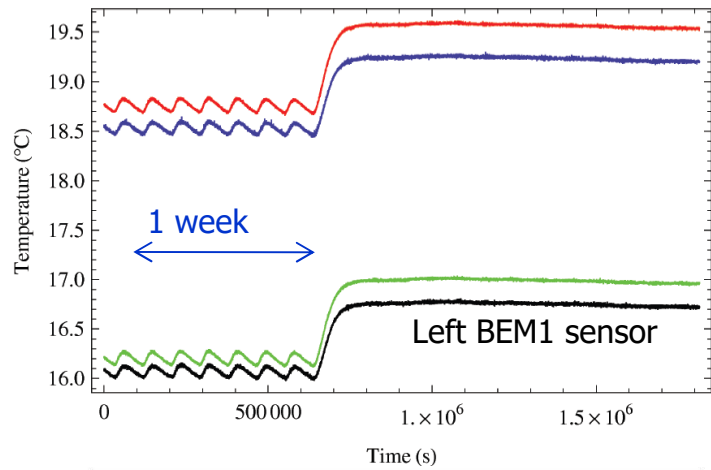


Reference loads (4K)

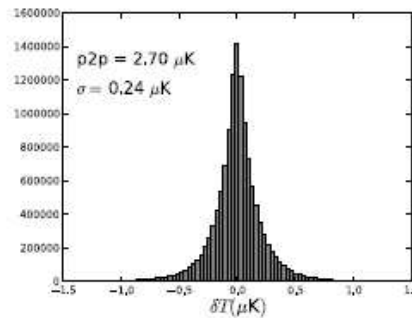
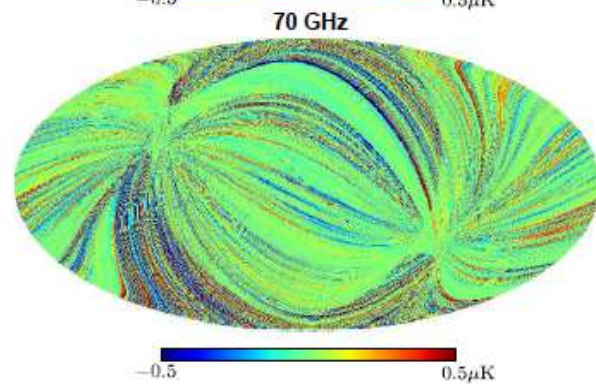
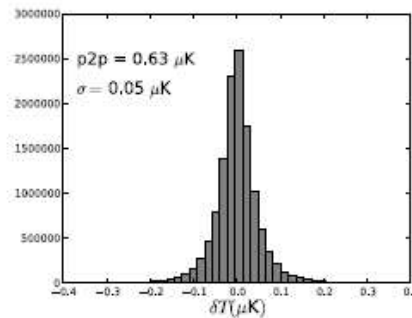
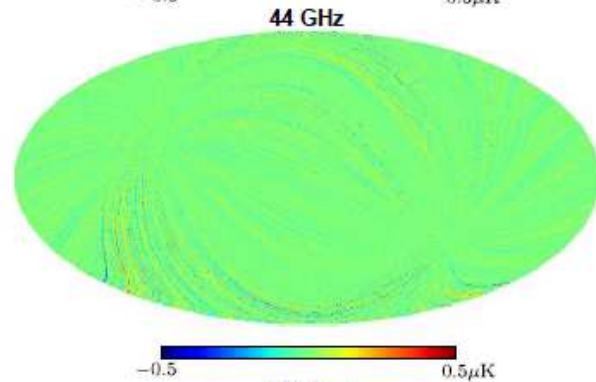
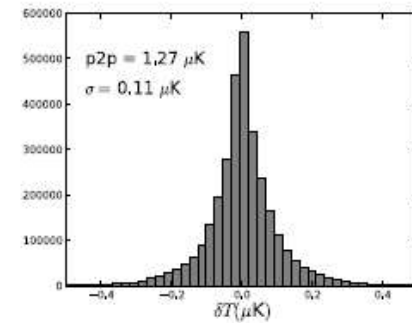
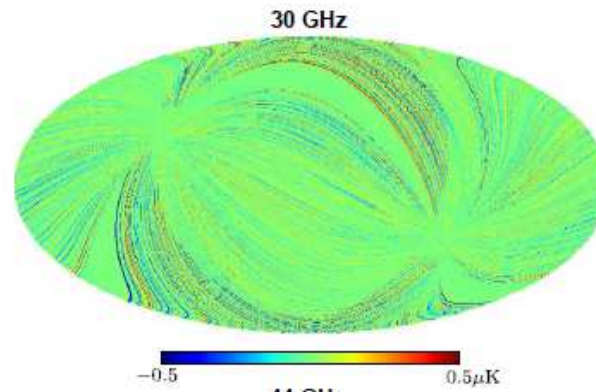


LFI Back-end fluctuations (300K)

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



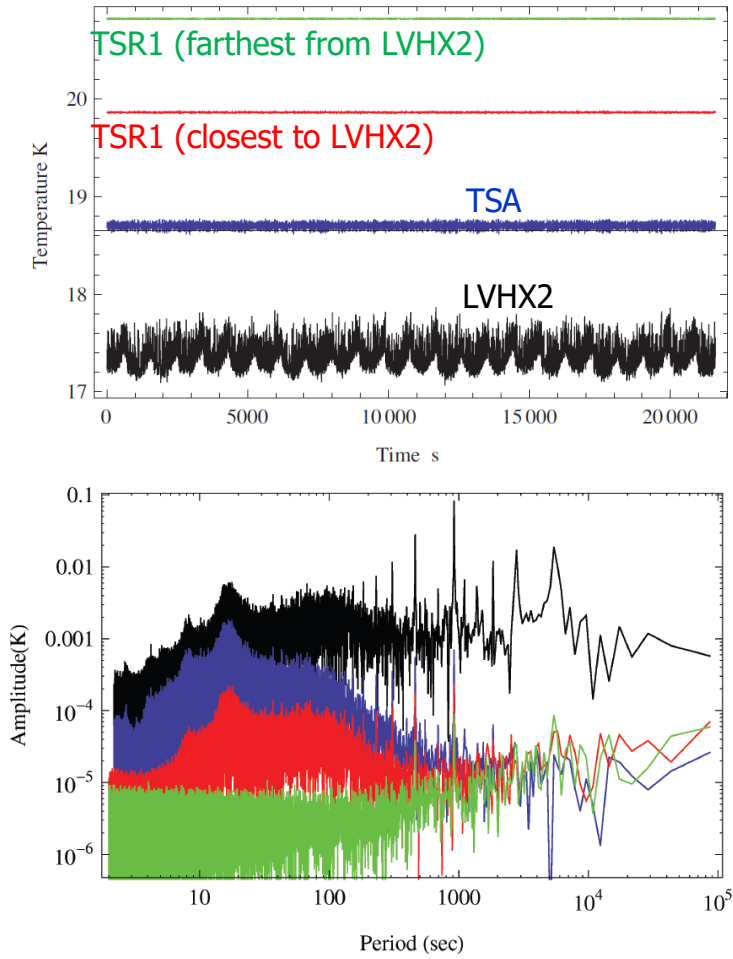
(Planck Collaboration 2011)



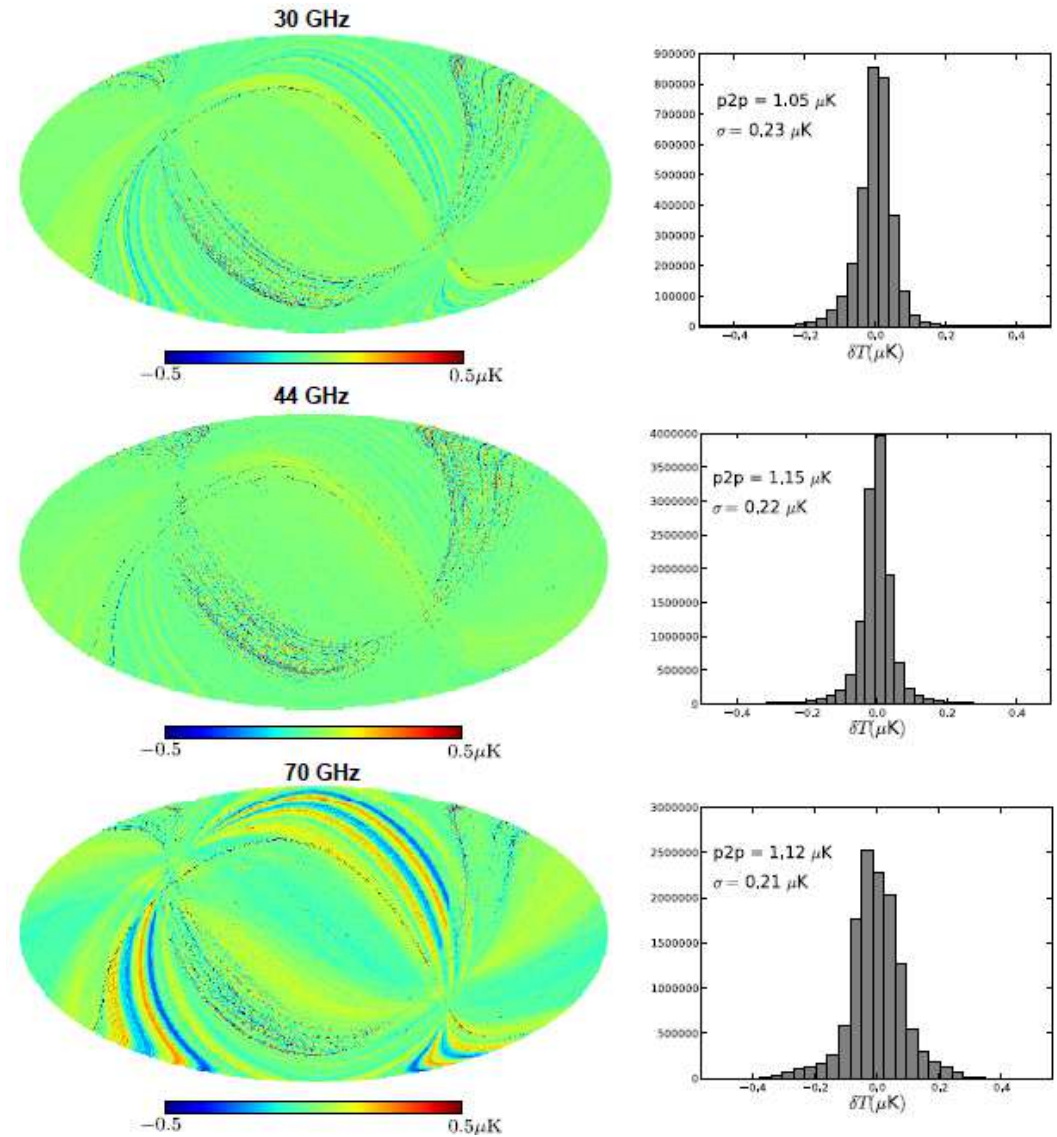
(Mennella et al. 2011)

LFI Front-end fluctuations (20K)

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



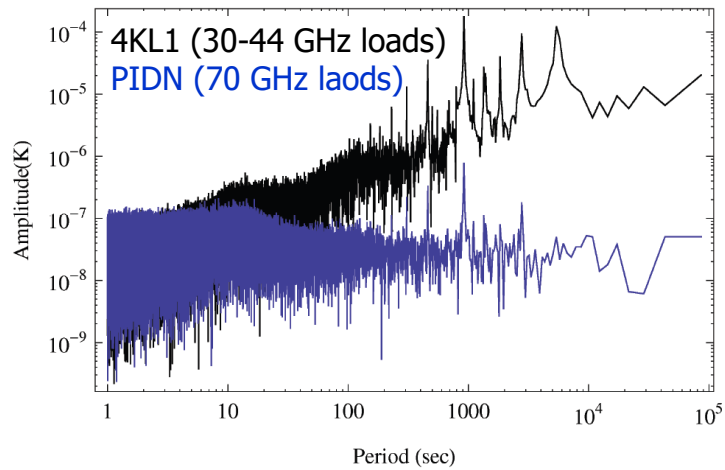
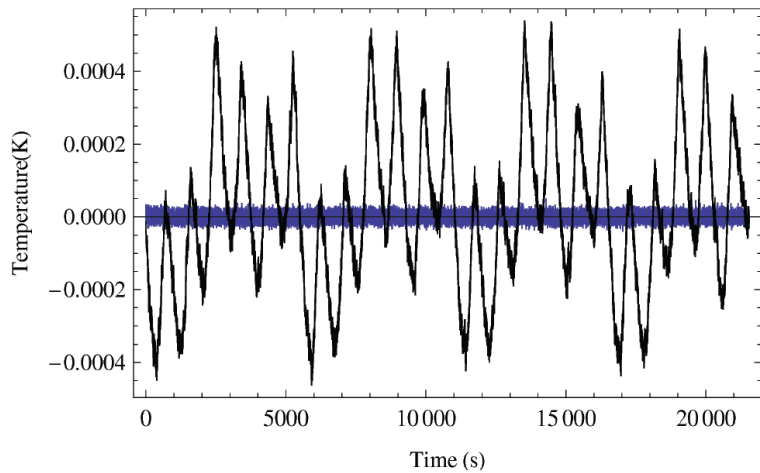
(Planck Collaboration 2011)



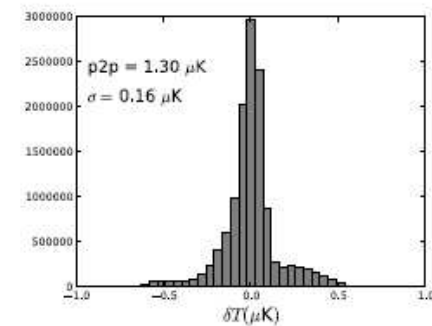
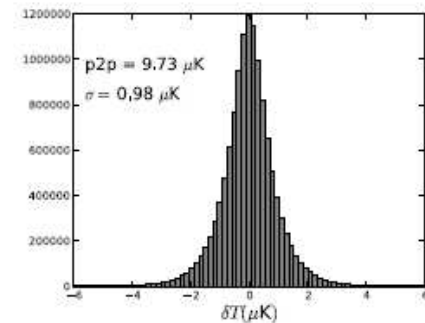
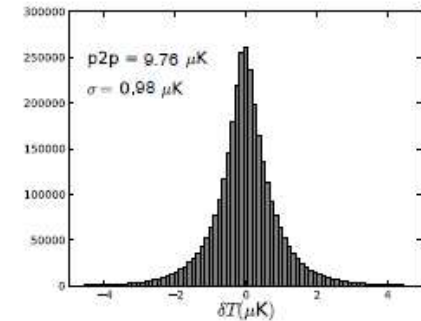
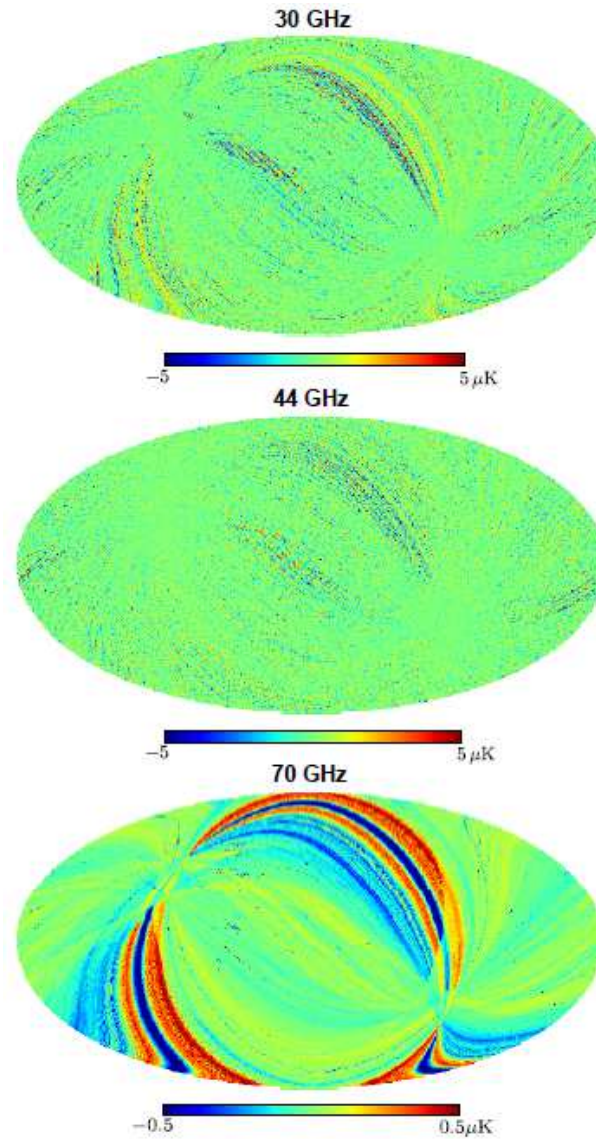
(Mennella et al. 2011)

LFI Reference load fluctuations (4K)

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



(Planck Collaboration 2011)



(Mennella et al. 2011)