CMB-CAL @ BICOCCA

4—8 November 2024

Planck calibration

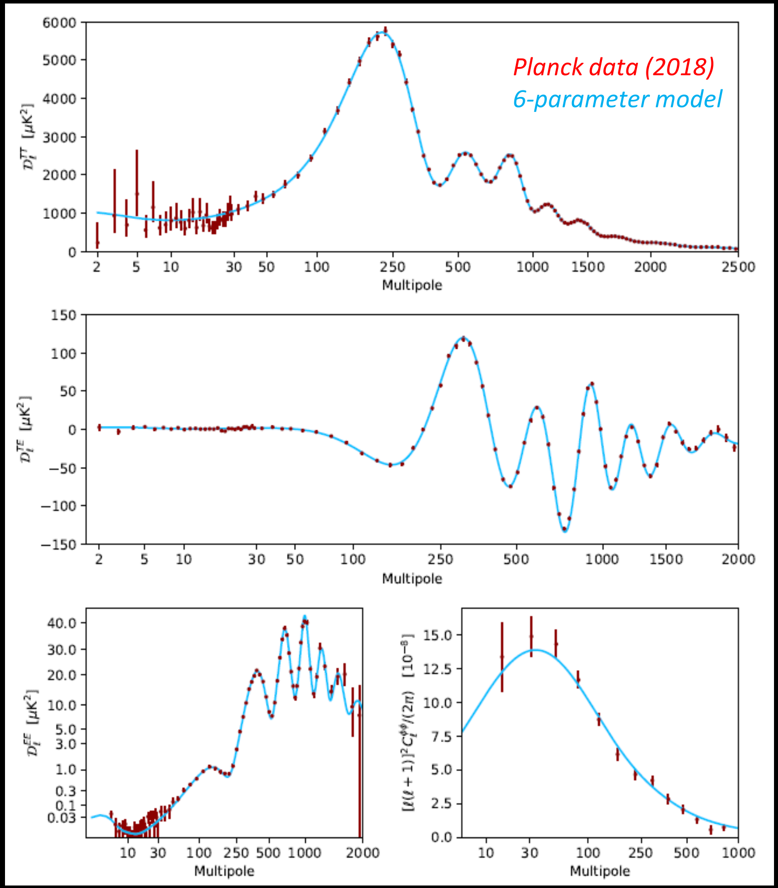
Lessons learned

Marco Bersanelli

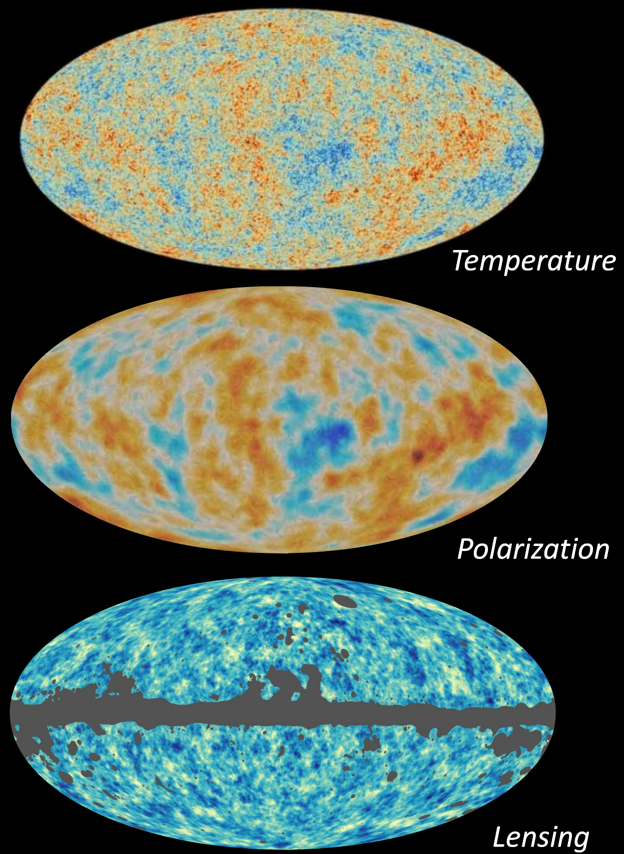
Physics Department, Università degli Studi di Milano

UNIVERSITÀ DEGLI STUDI DI MILANO · INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati · PLANCK

Planck Legacy Results

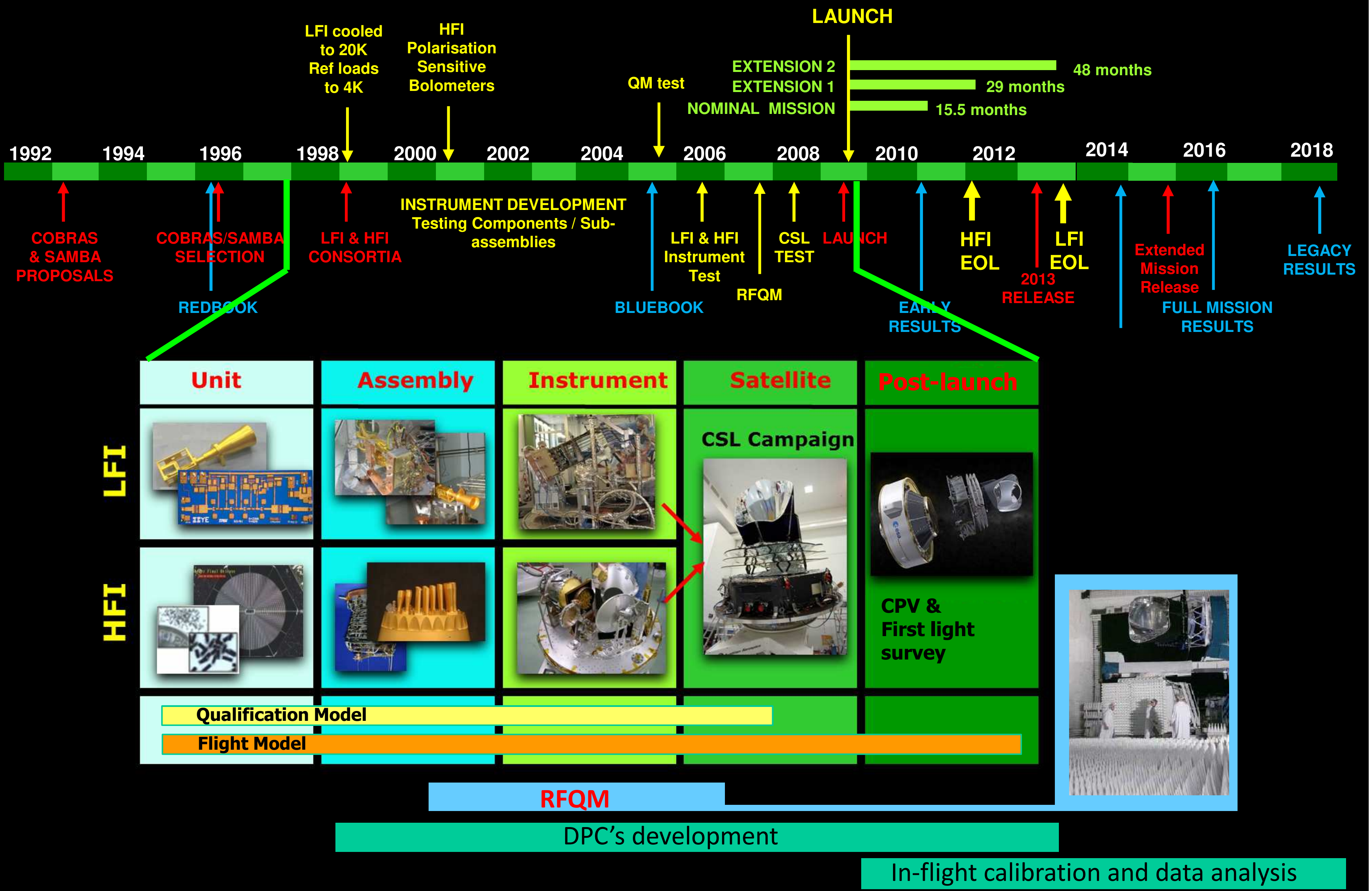


Planck Collaboration 2018

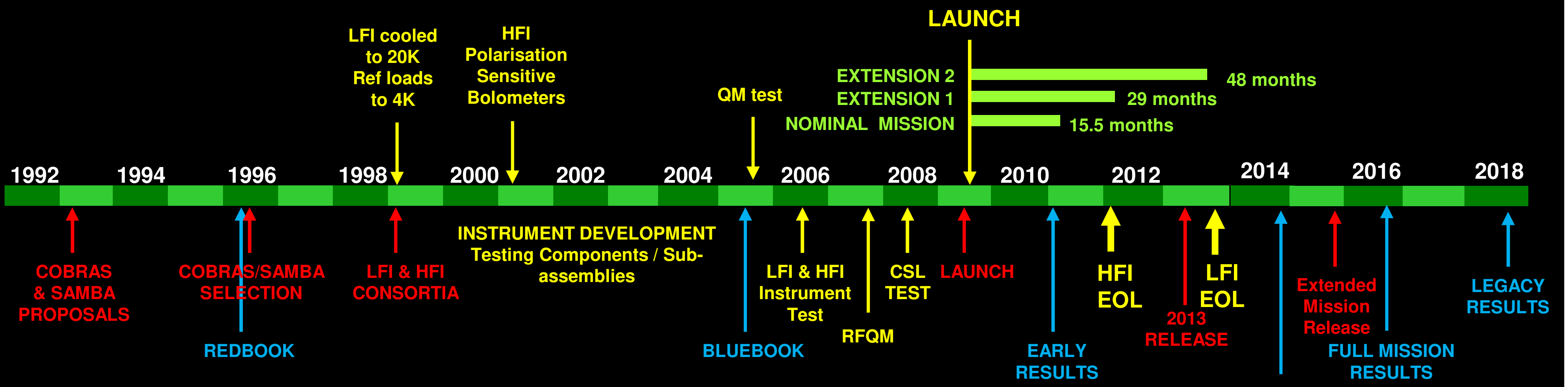


The success of Planck relied on a very demanding calibration effort throughout the project

Planck – Ground & in-flight calibration



Planck – Ground & in-flight calibration

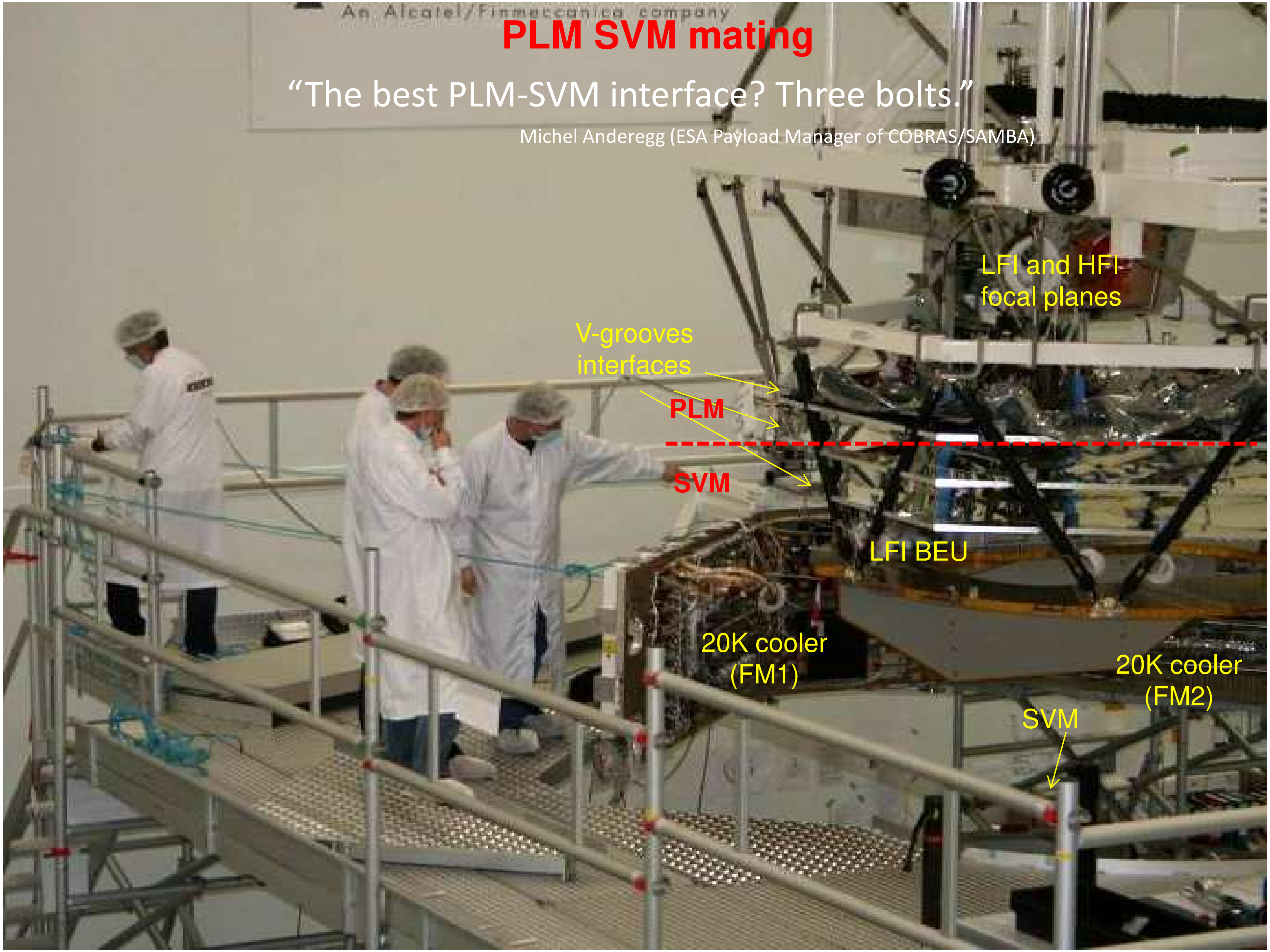


Many people (virtually all the Planck Collaboration) were involved

PLM SVM mating

"The best PLM-SVM interface? Three bolts."

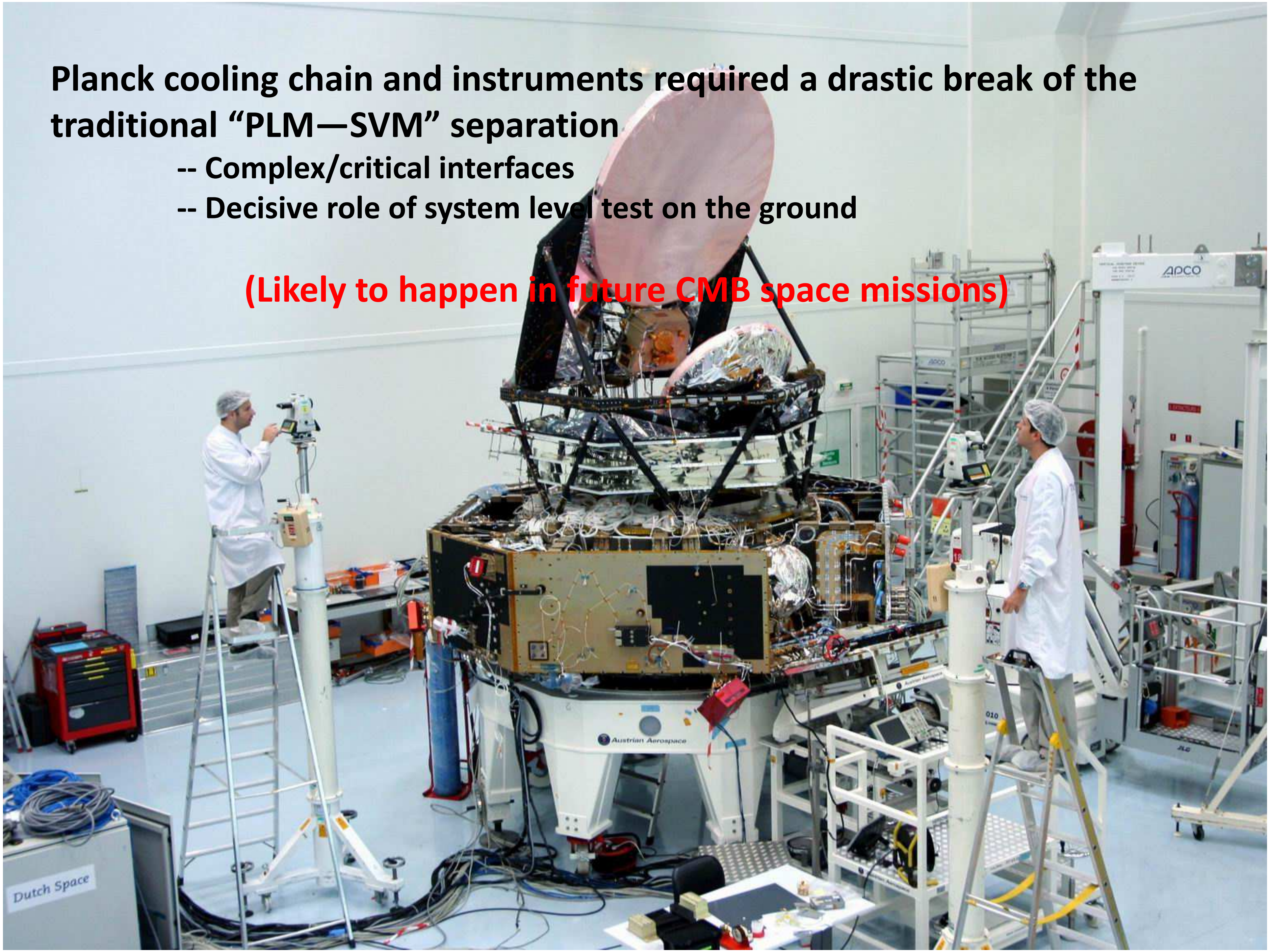
Michel Anderegg (ESA Payload Manager of COBRAS/SAMBA)



Planck cooling chain and instruments required a drastic break of the traditional “PLM—SVM” separation

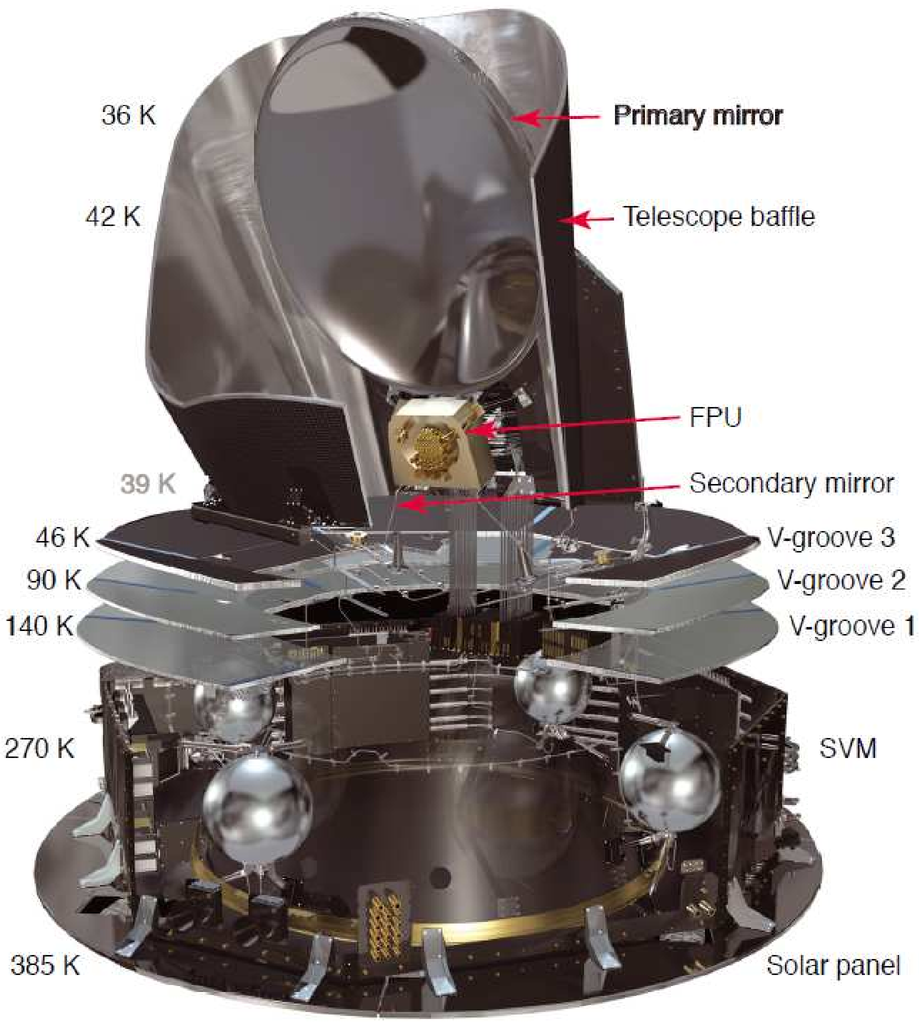
- **-- Complex/critical interfaces**
- **-- Decisive role of system level test on the ground**

(Likely to happen in future CMB space missions)



Planck Instruments, PPLM, SVM

Thermal requirements were key design driver of Planck payload and satellite

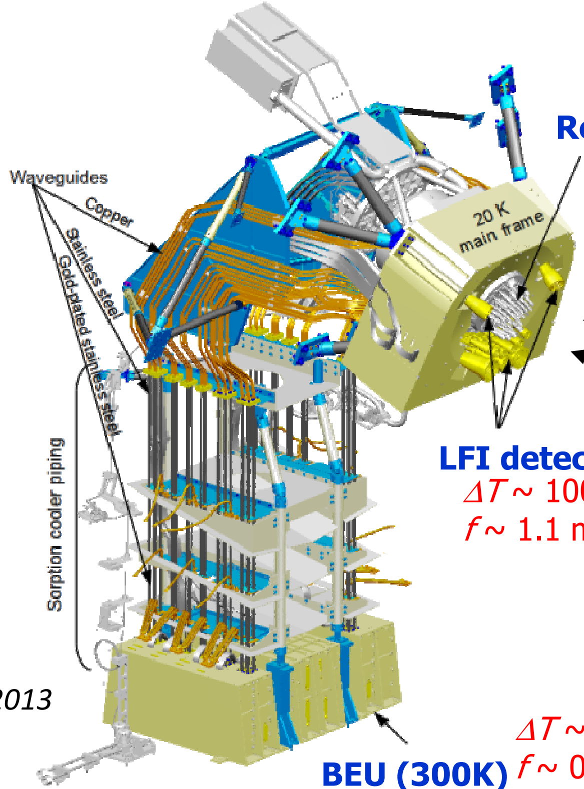


Planck Collaboration A&A 536, A2 (2011)

- Complex and critical interfaces between PPLM and SVM
  - The 3-stage cooling system (18-20K, 4K, 0.1K)
  - Instruments (LFI waveguides)
  - Passive cooling (3rd V-groove at <60K)
- Fully representative instrument configuration was obtained only at satellite integration level
  - Thermal oscillations when 1.6K stage was too cold (exceeding goal performance)
  - Margins management!
- The CSL facility supported instruments operation in nominal conditions (*not initially foreseen!)*
  - 4K blackbody calibrator
- CSL test was needed by both LFI and HFI to calibrate Instrument thermal model

Instrument model

Key thermal requirements: T and stability at 300, 20K, 4K, 0.1K



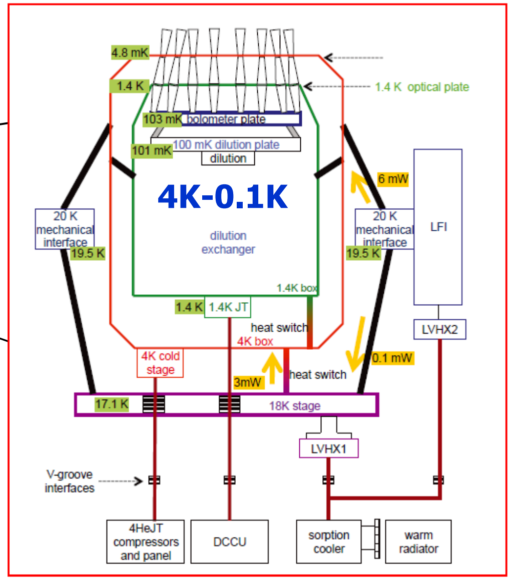
Ref Loads (4K)
$\Delta T \sim 0.9$ mK
$f \sim 1.1$ mHz (15min)
$f \sim 0.2$ mHz (90min)

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)

M.B. et al. 2009
Mennella et al. 2013

HFI detectors

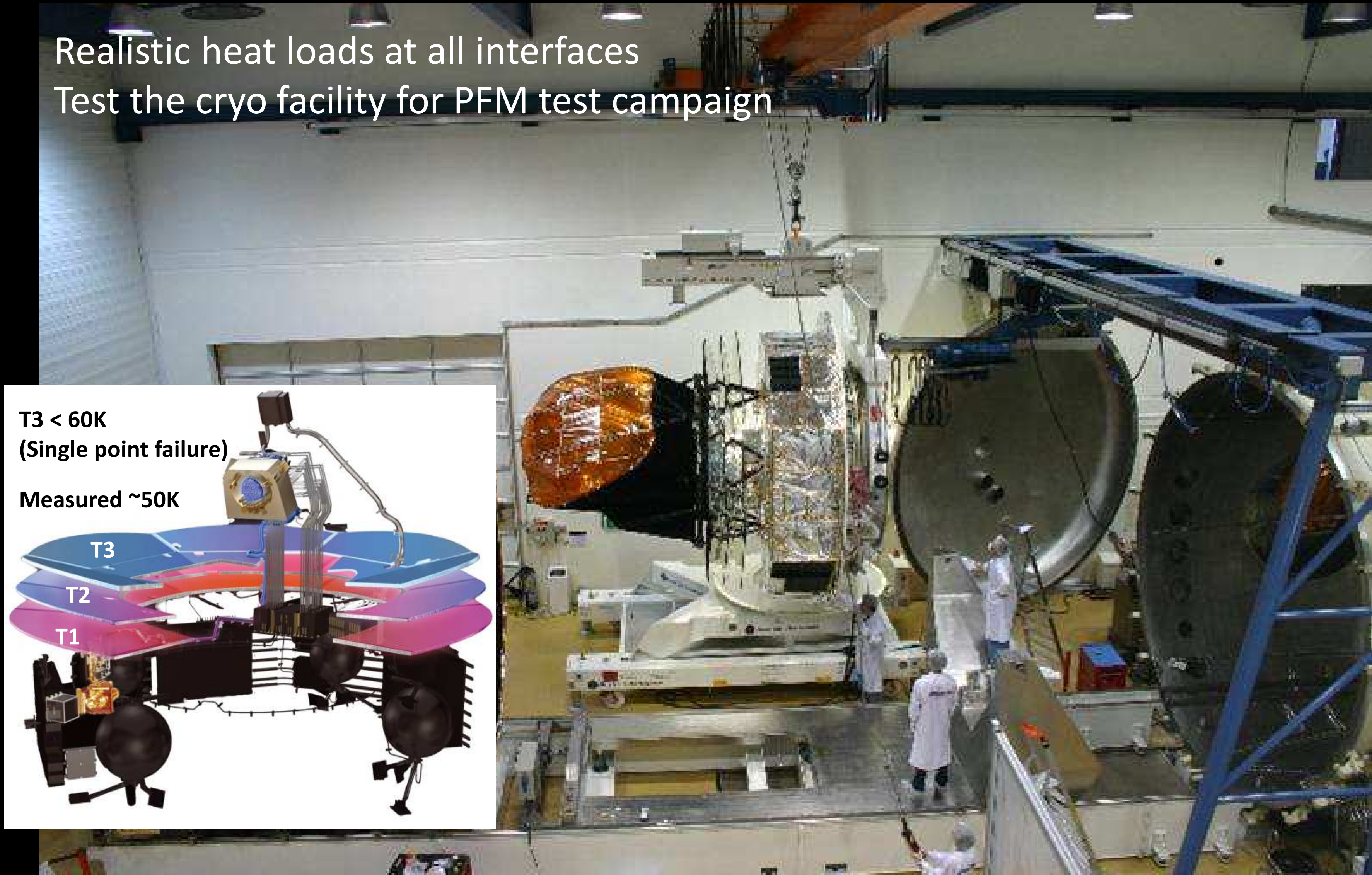


Lamarre et al. 2009

- Instrument model:
    - Thermal transfer functions
    - Radiometric transfer functions
    - Optical parameters
- Support ground calibration at increasing levels of integration (and QM, FM)
    - Finalize instrument design (*requirements, interfaces*)
    - Retrieve instrument status (*thermal, electrical*) from H/K info
    - Update and use for in-flight analysis

Planck CQM test campaign (CSL) – September 2005

Realistic heat loads at all interfaces
Test the cryo facility for PFM test campaign

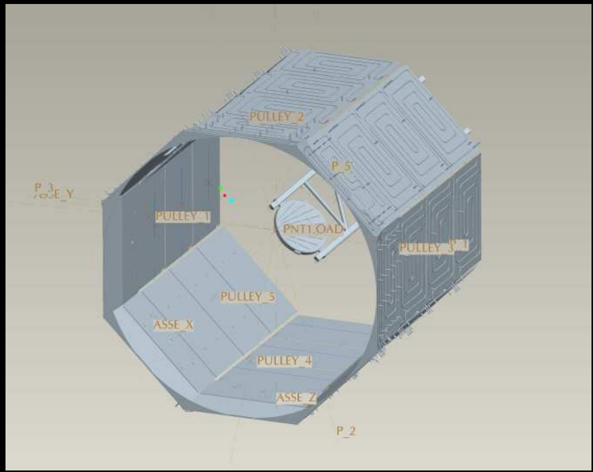


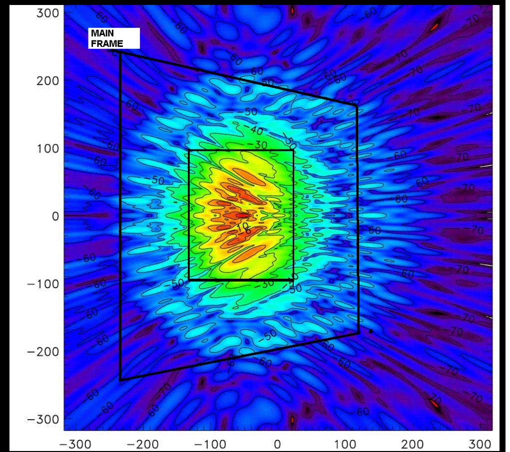
Demonstration of passive cooling of 3rd V-groove requirement (<60K), with margin (~50K)
Excellent agreement with model prediction
ESA implemented the solution -- *Planck was first satellite to adopt this technique*

Planck Flight Model test campaign (CSL) – July-August 2008

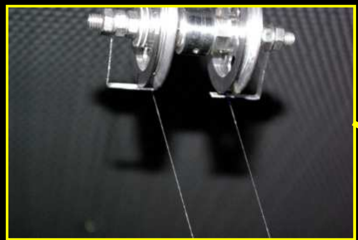
Fully integrated system (intrsuments, cryo-chain, Telescope, SVM)

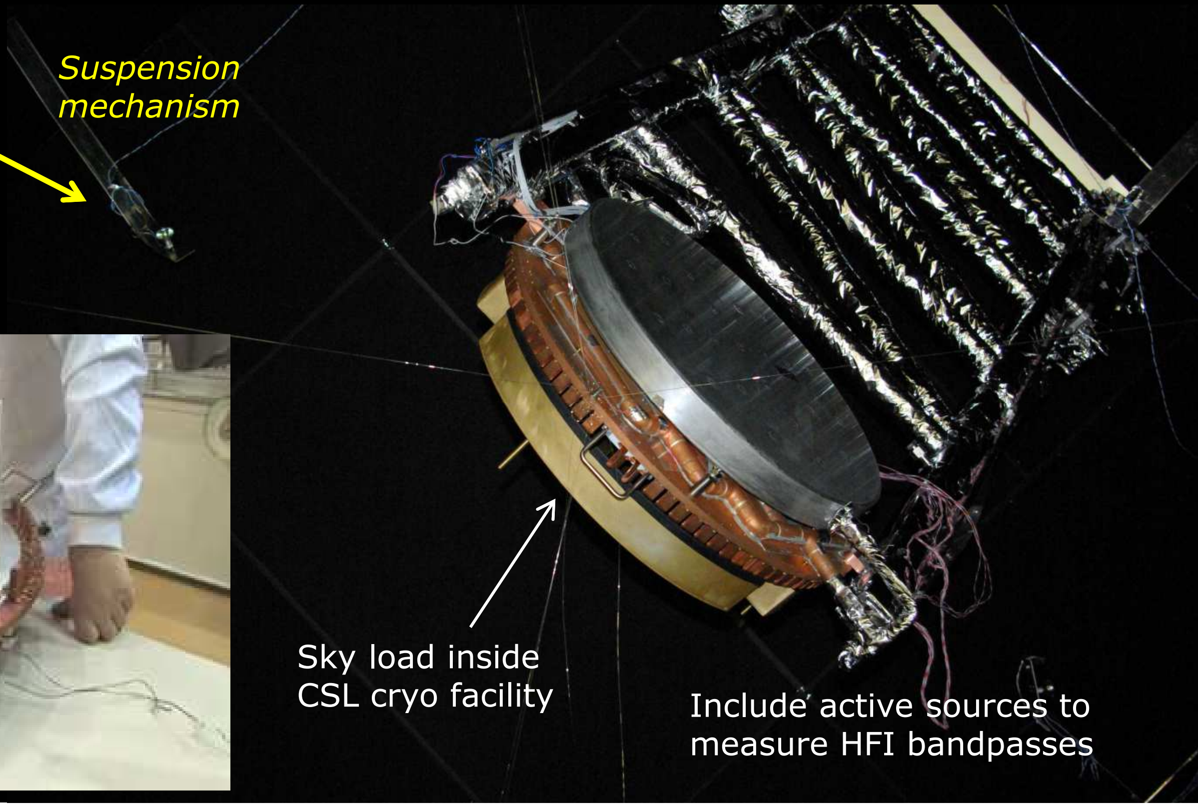
Calibrators: CSL 4K Sky Load



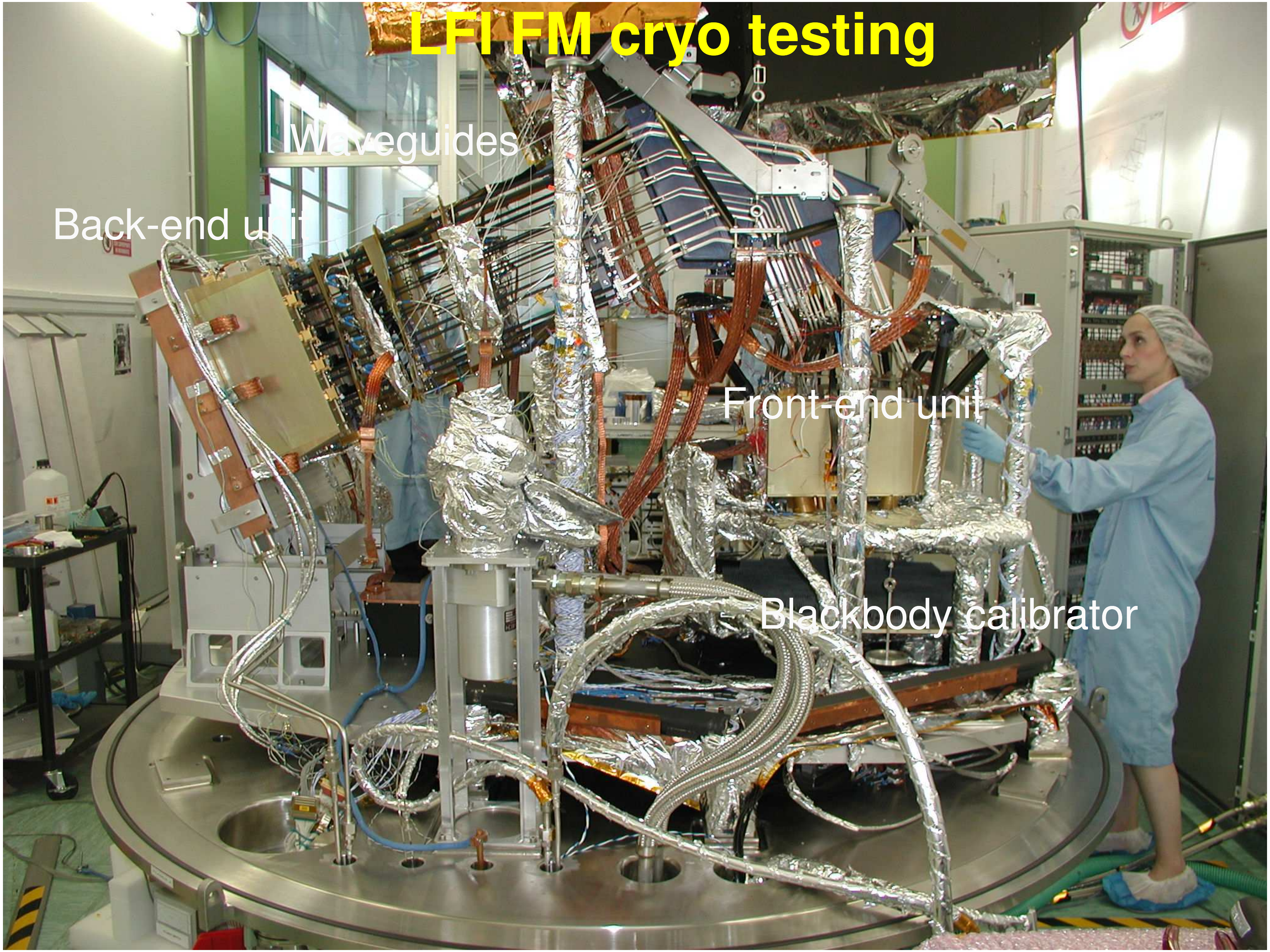


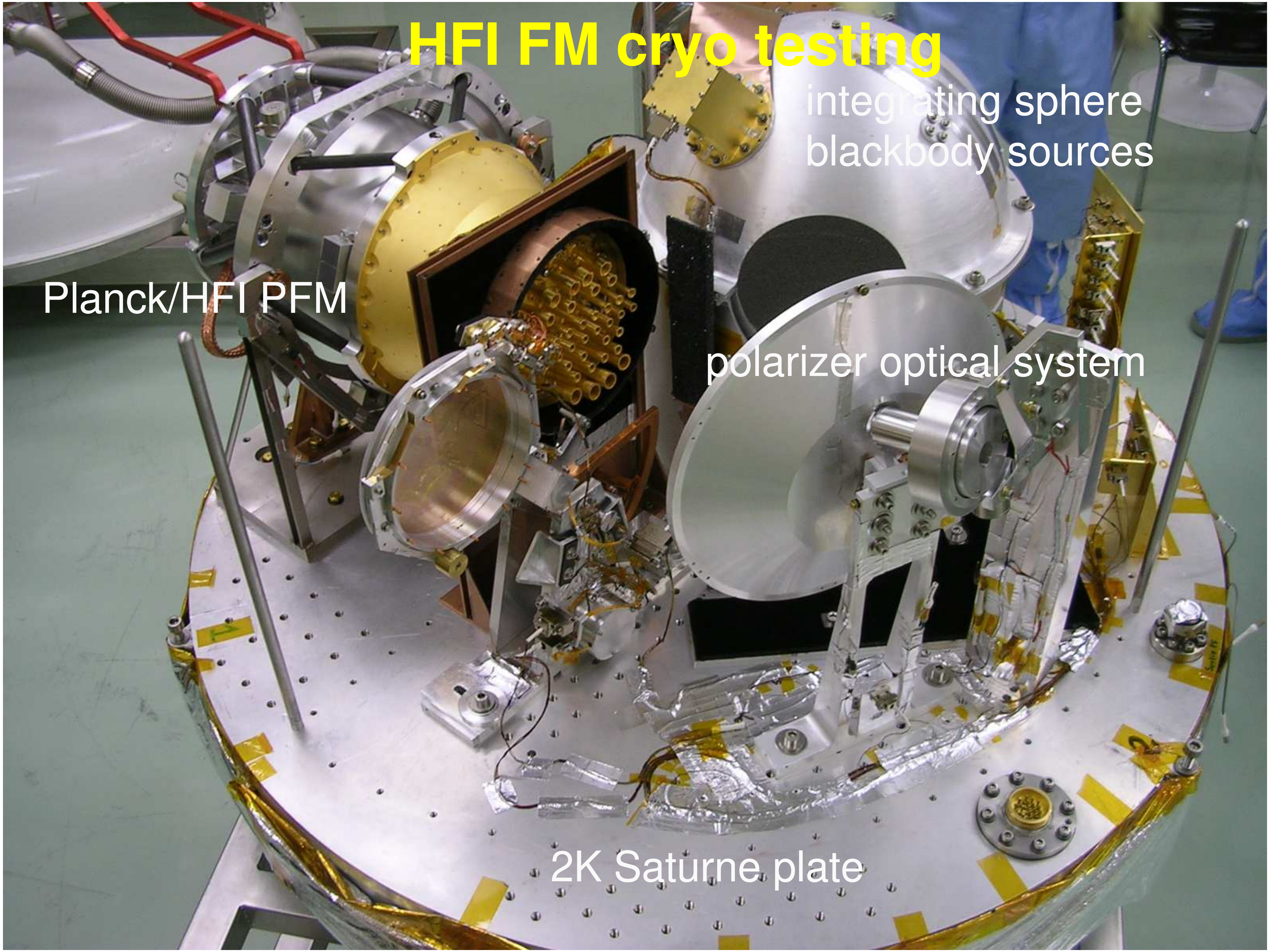
Beams footprints on target





LFI FM cryo testing



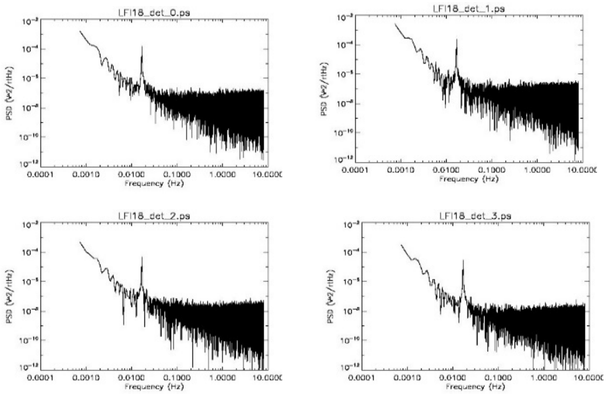

HFI FM cryo testing
integrating sphere
blackbody sources
Planck/HFI PFM
polarizer optical system
2K Saturne plate

Planck: “Single channel approach”

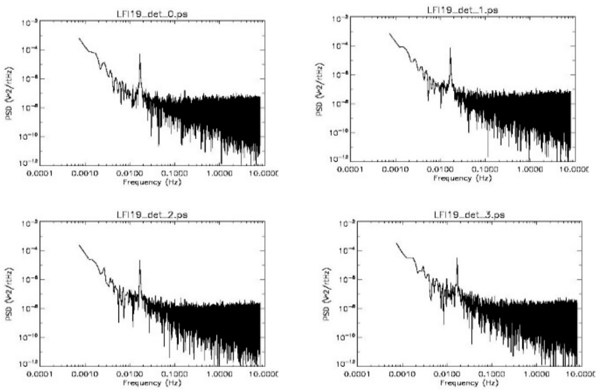
- Each of the LFI+HFI channels (~50 horns) was known “by name” and treated with care
- Huge amount of dedicated tuning, optimization, debugging, …
- Each noise spectrum/parameter was repeatedly measured on-ground at all levels
  (unit, RCA/assembly, instrument, system, in flight)

Example: 70GHz single diode spectra

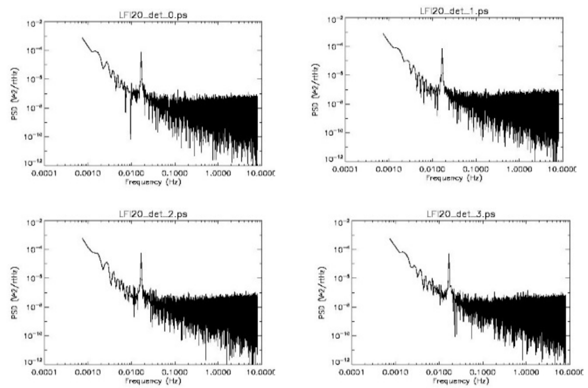
LFI-18



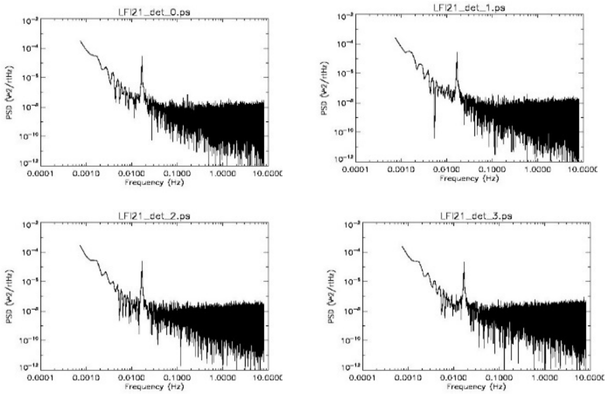
LFI-19



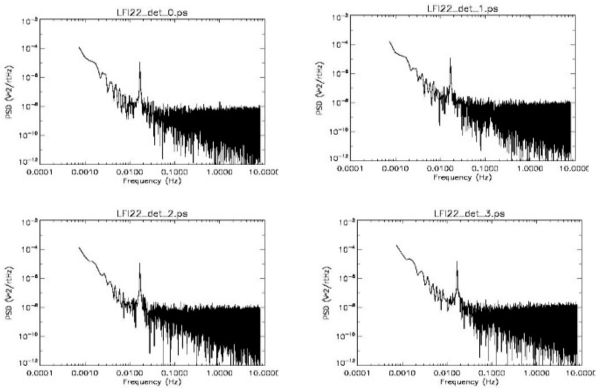
LFI-20



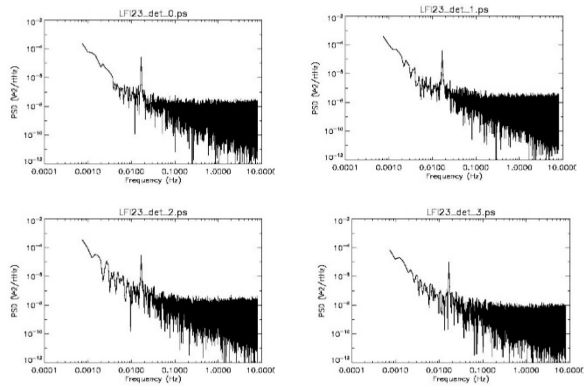
LFI-21



LFI-22



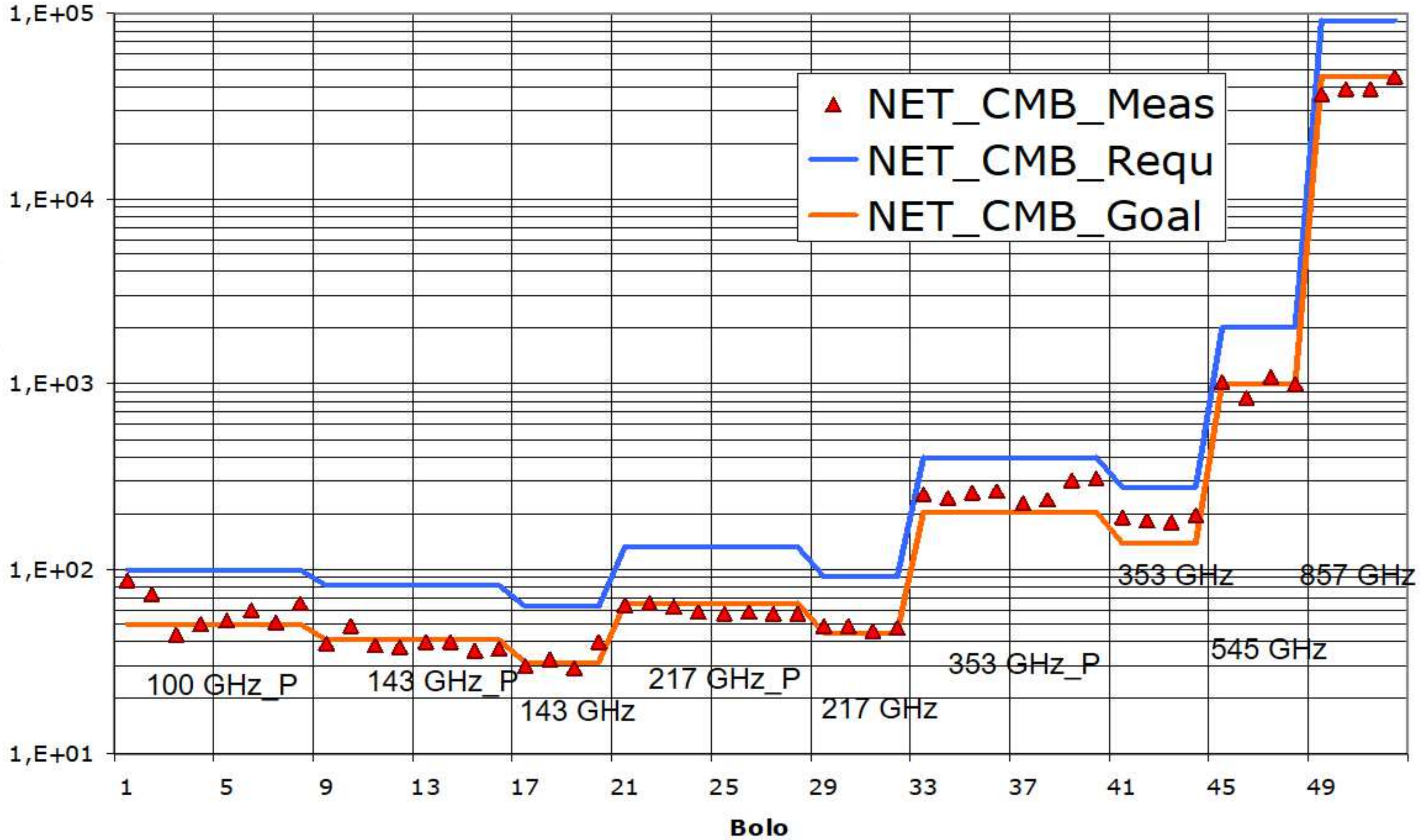
LFI-23



Planck: "Single channel approach"

- Each of the LFI+HFI channels (~50 horns) was known "by name" and treated with care
- Huge amount of dedicated tuning, optimization, debugging, …
- Each noise spectrum/parameter was repeatedly measured on-ground at all levels
  (unit, RCA/assembly, instrument, system, in flight)

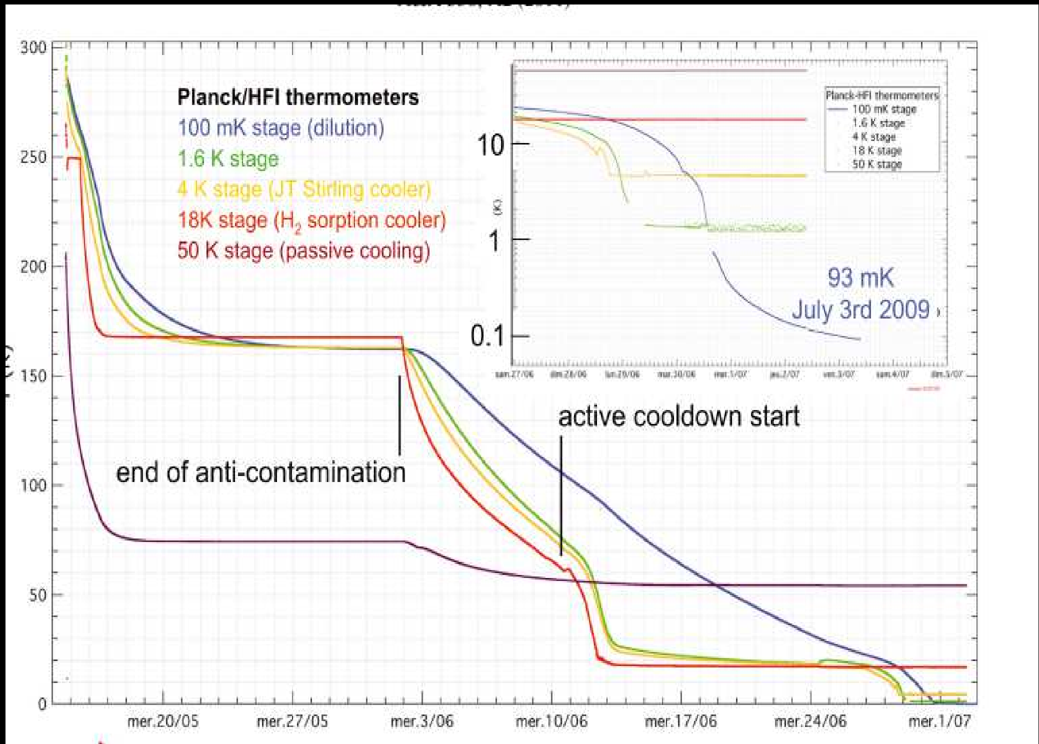
Example: HFI Bolometers measured Noise Equivalent Temperature

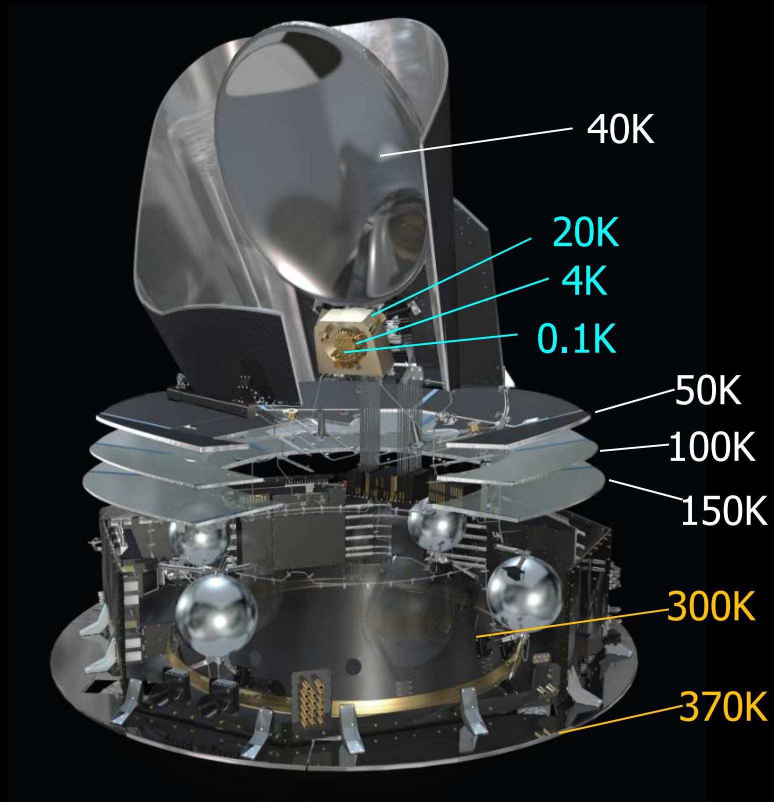


In-flight cryo-chain performance & mission lifetime

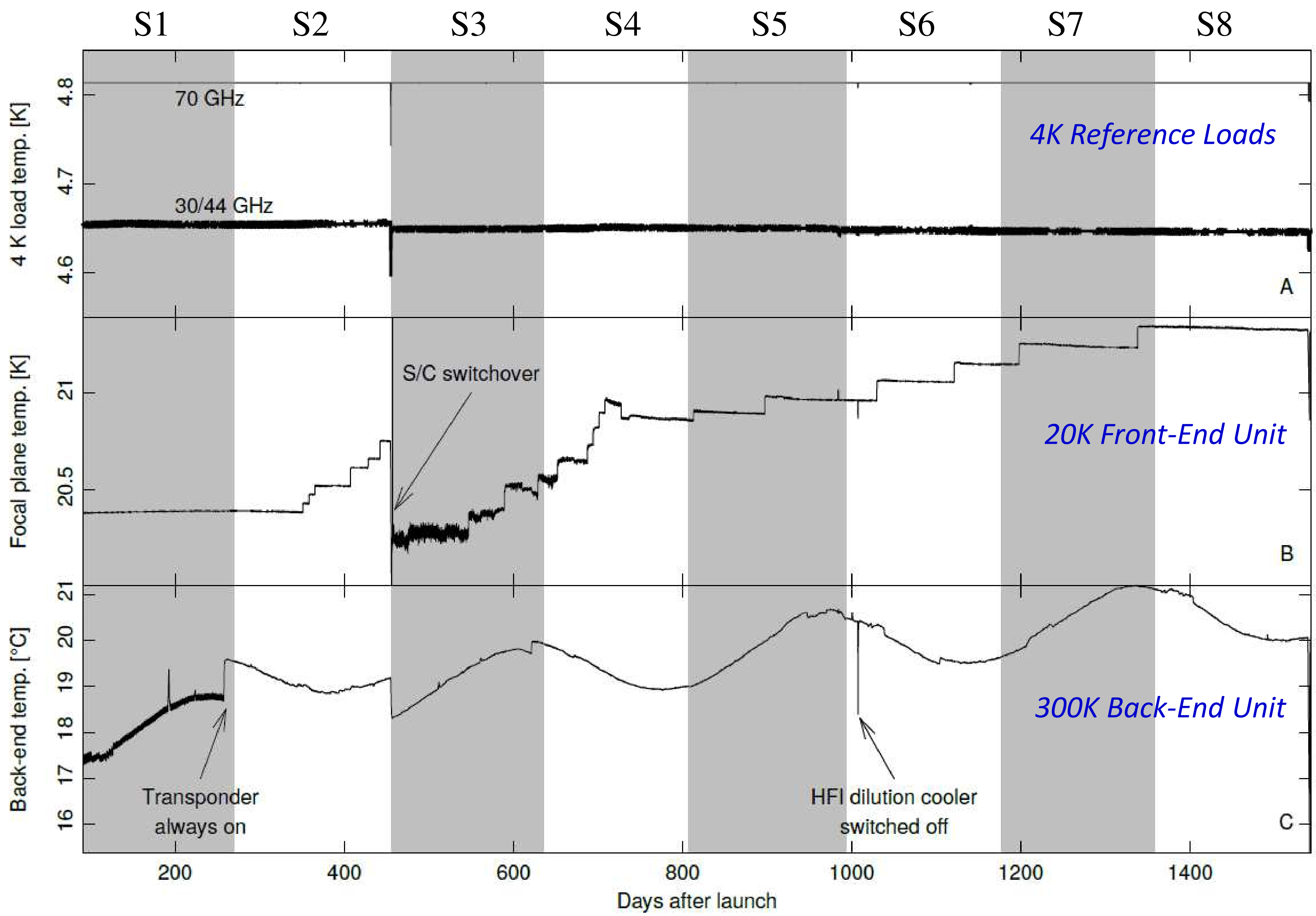
Excellent in-flight thermal performance

– Bolometer plate = 103mK
– LFI reference loads = 4.4-4.6 K
– LFI focal plane = 19.8–20.8 K
– Secondary mirror = 39.6 K
– Primary mirror = 36.5 K
– V-groove 3 (final radiative pre-cool) = 46 K





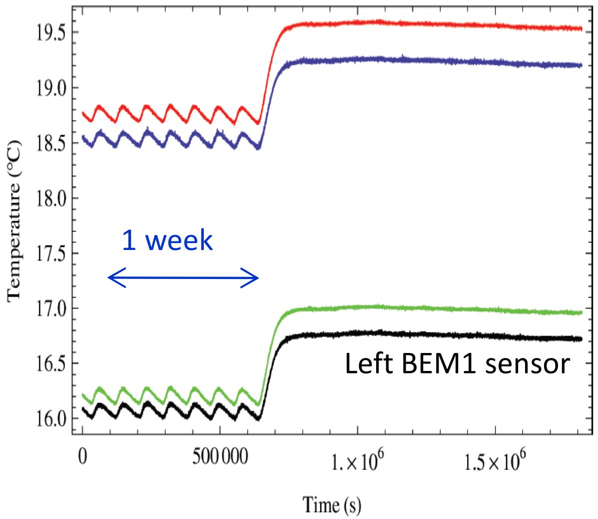
H/K data from Planck mission

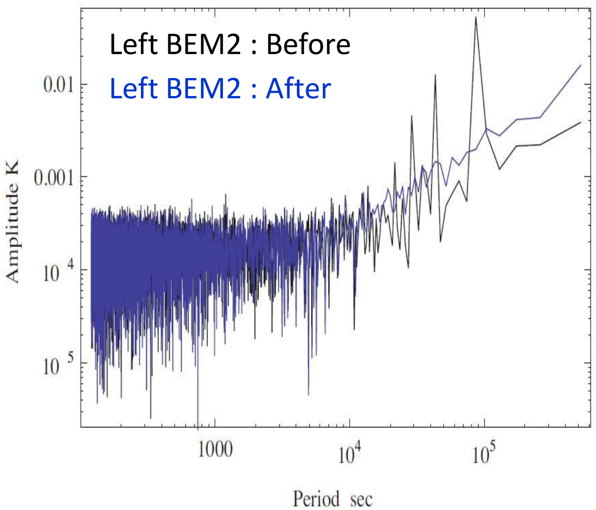


Flight H/K data

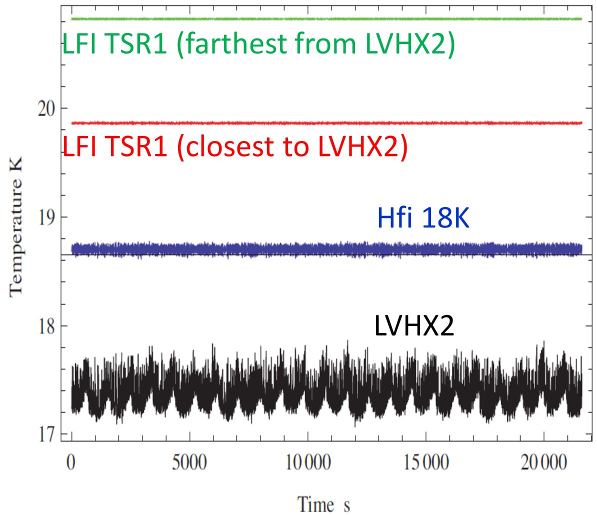
(Planck Collaboration 2011)

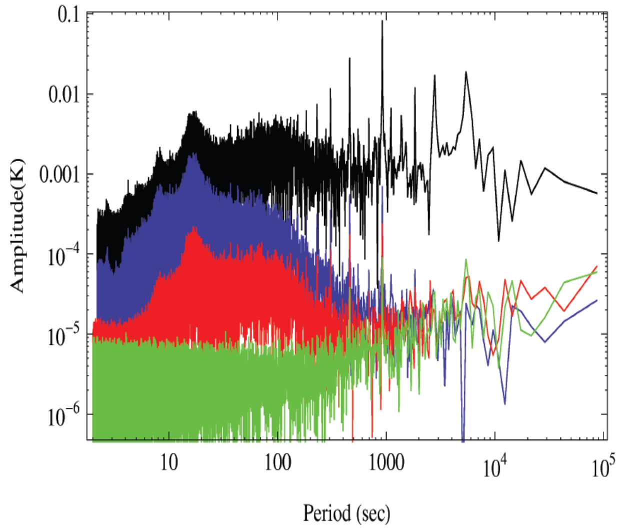
LFI back-end (300K)



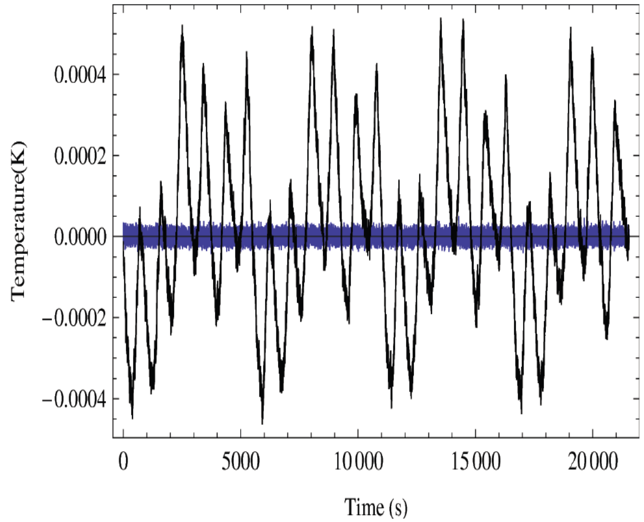


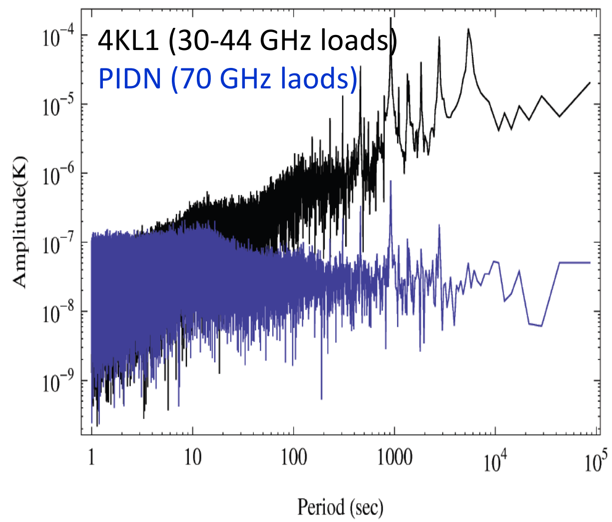
FPU (18-20K)





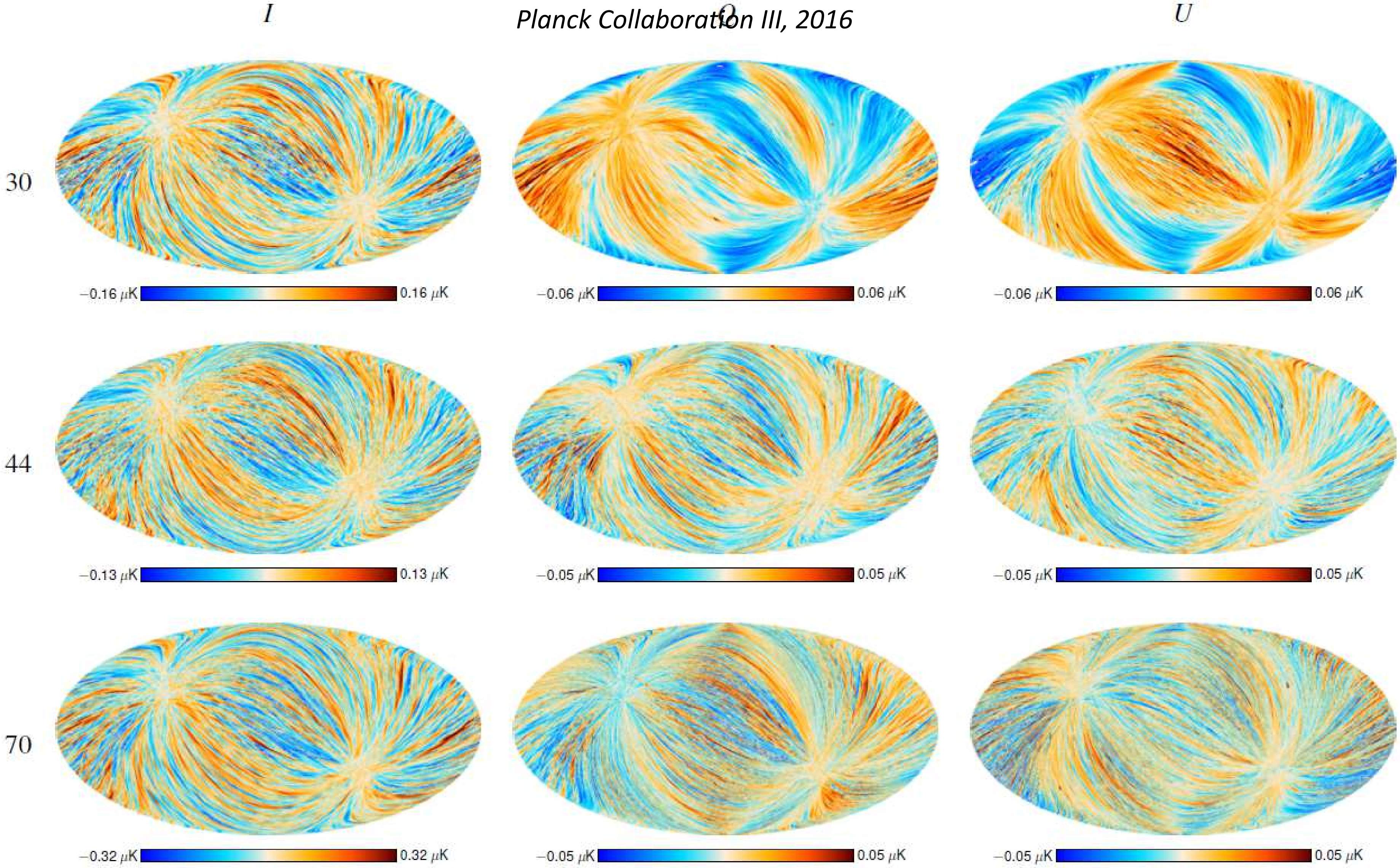
HFI box (4K)





Combined effect on LFI of flucturations at 300, 20 and 4K

Planck Collaboration III, 2016

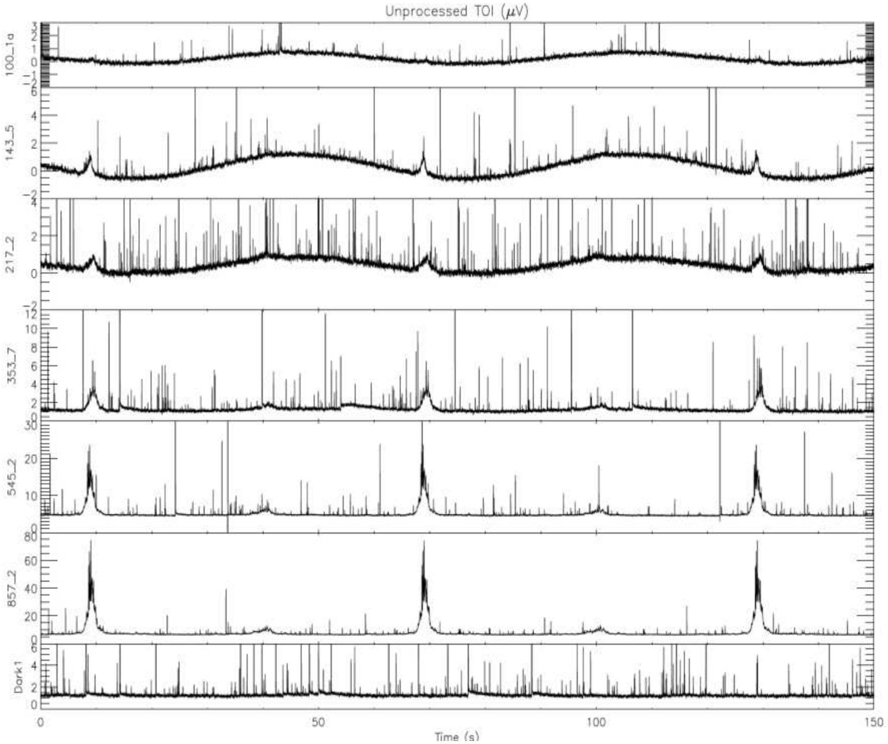


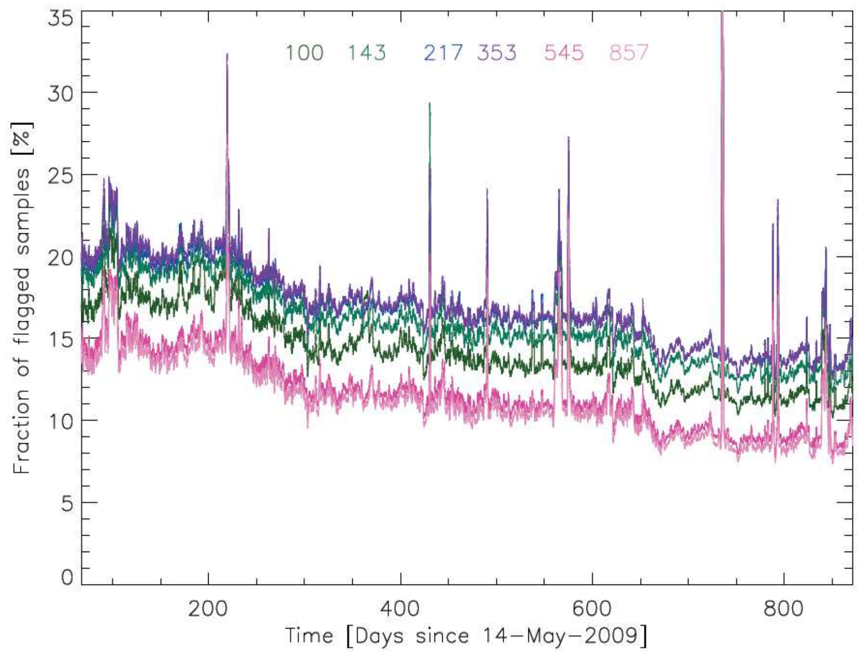
Thermal effects were controlled to beolw significance thanks to early definition of adequate requirements

Impact on HFI from Cosmic Rays

Bolometers were disigned with a grid absorber, efficient for photon absorption but offering a small cross section to particles

Effect is both glitches and thermal (limited the stability of 0.1K stage)

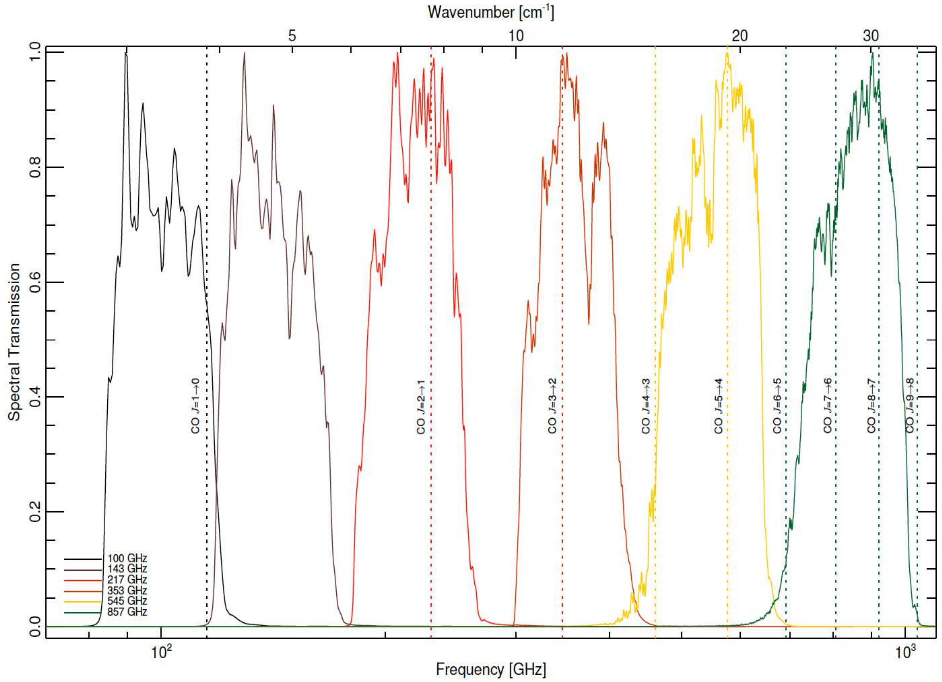


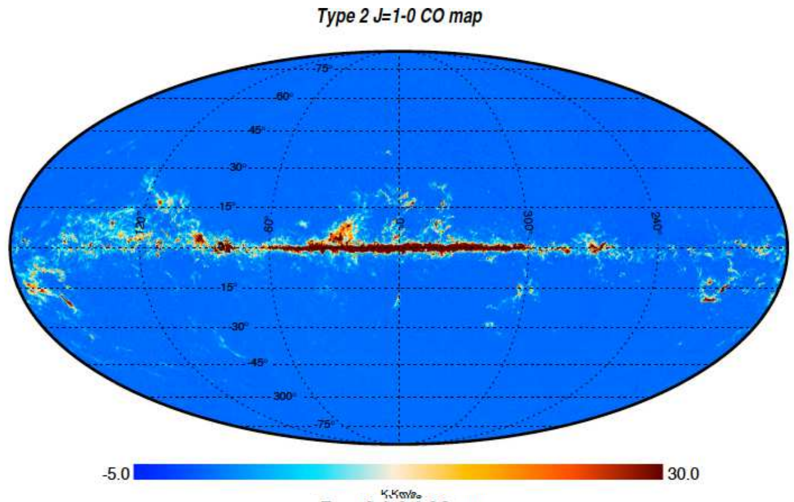


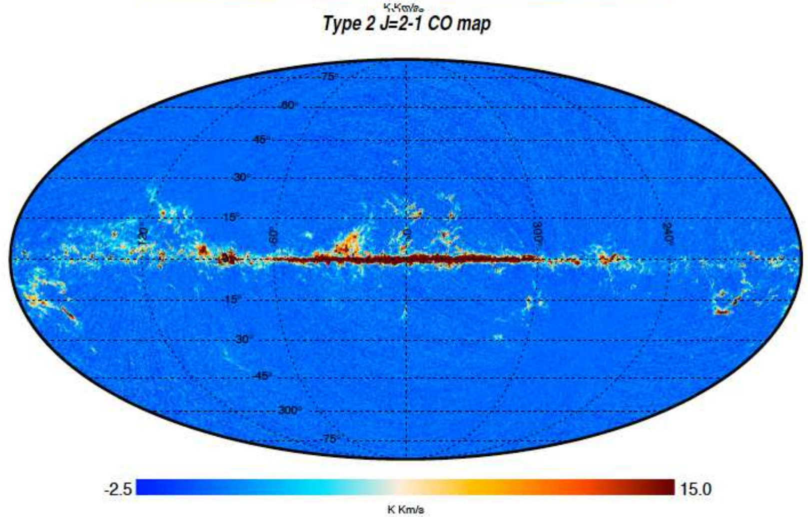
- Effect could have been predicted (SOHO data on solar CR modulation)
- "Bolometers (or any detector sensitive to particles) AND their environment have to be DESIGNED to minimize the effect of cosmic rays" (J.-M.Lamarre)
- Prepare for removing glitches and control residual systematics (as done in LiteBIRD)
- Early tests on the ground needed to verify glitch rate and test data analysis

CO lines
A probem turned into an achievement

- CO lines are strong and «contaminate» dust measurements: impact on HFI
- Accurate measurements of the HFI spectral response was crucial to produce CO maps
- An unexpected scientific outcome of Planck.





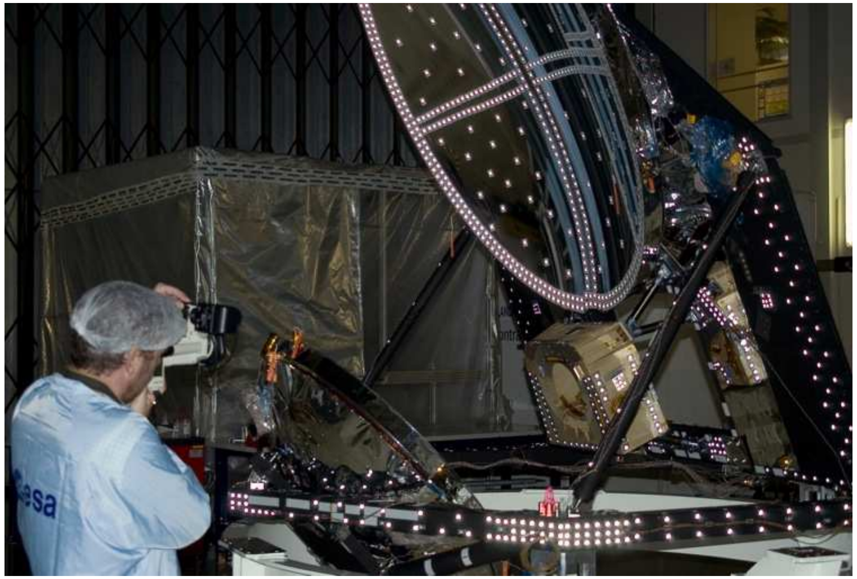


- Future missions should consider trade off between including lines and limit bandwidth

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*



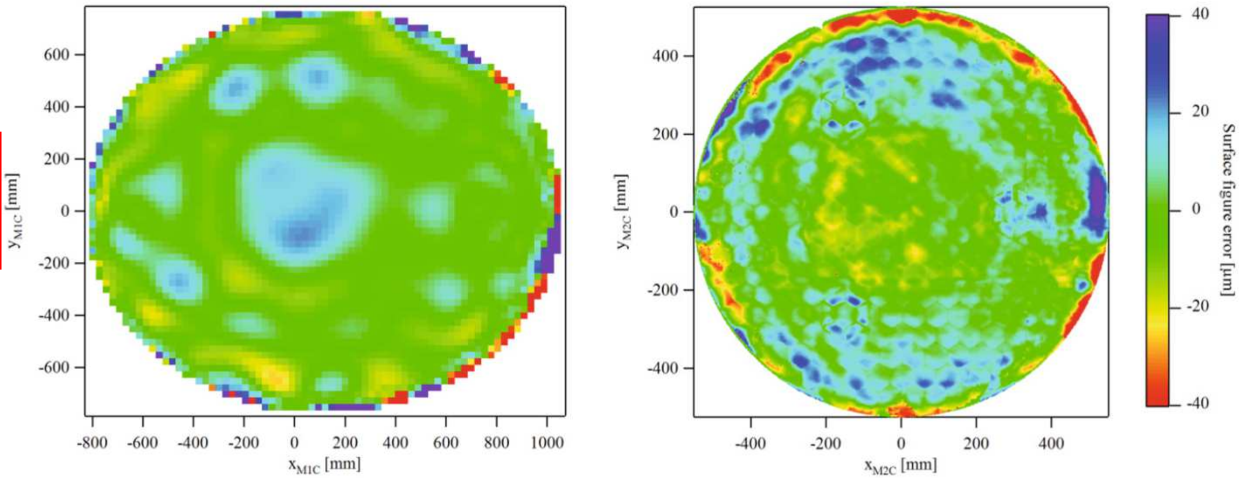
↓

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

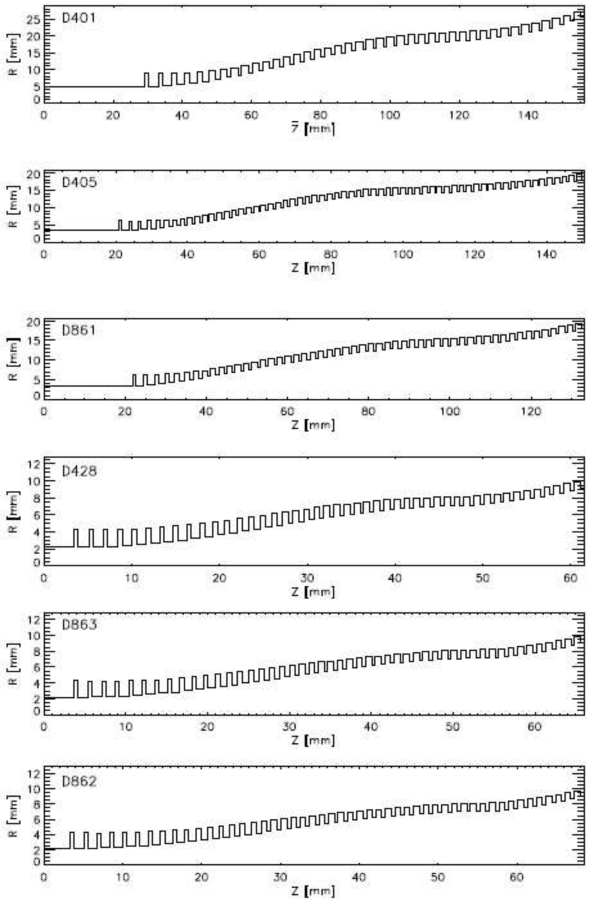
Corrugation profile (sin-squared + exponential) for compactness and high control of sidelobes

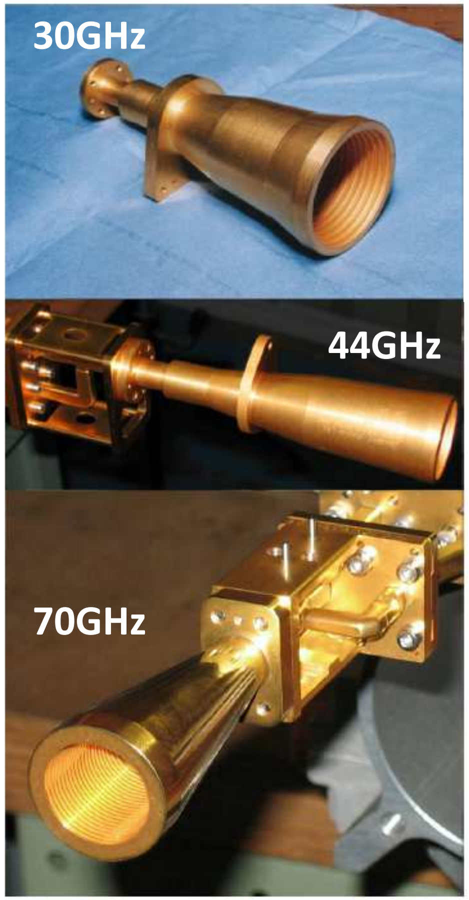
$$R(z) = R_{th} + (R_s - R_{th})\left[(1-A)\frac{z}{L_s} + A\sin^{\beta}\left(\frac{\pi}{2}\frac{z}{L_s}\right)\right]$$

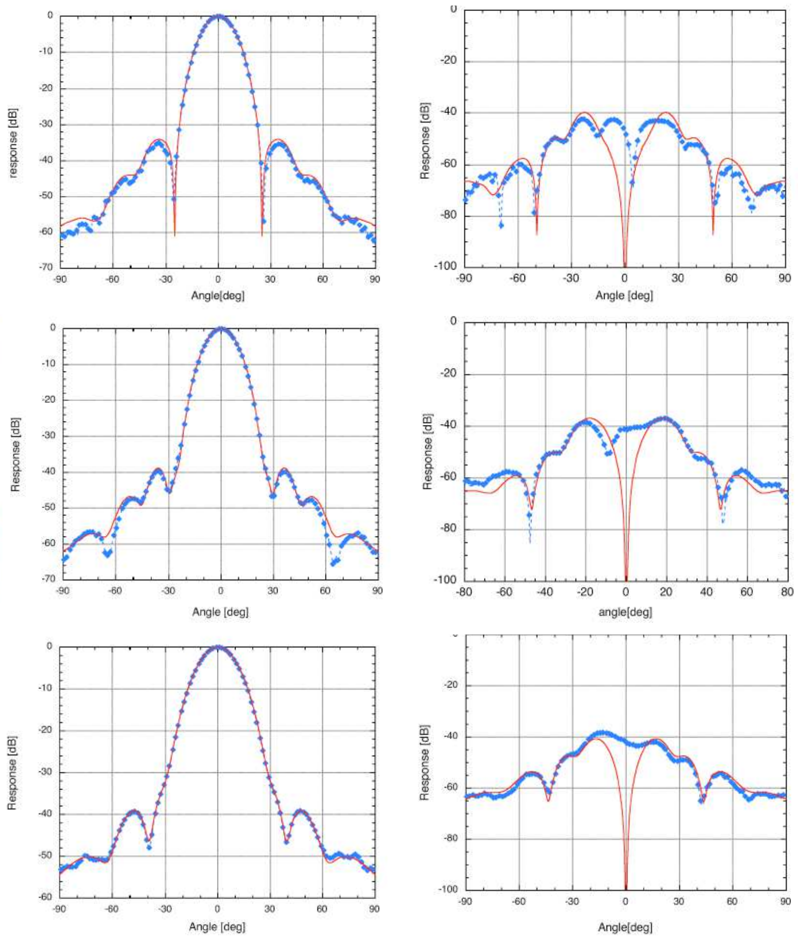
$$0 \le z \le L_s$$

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

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







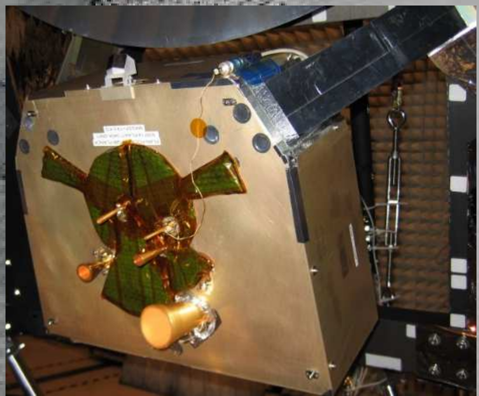
Co-pol accuracy <1dB above -40dB, Cross-pol <-35dB, RL < -30dB

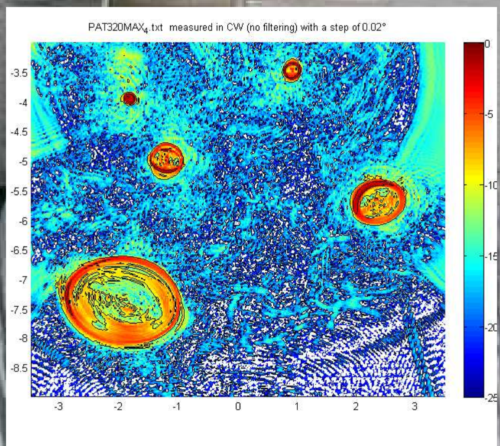
Several frequencies mesured across the-band

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)

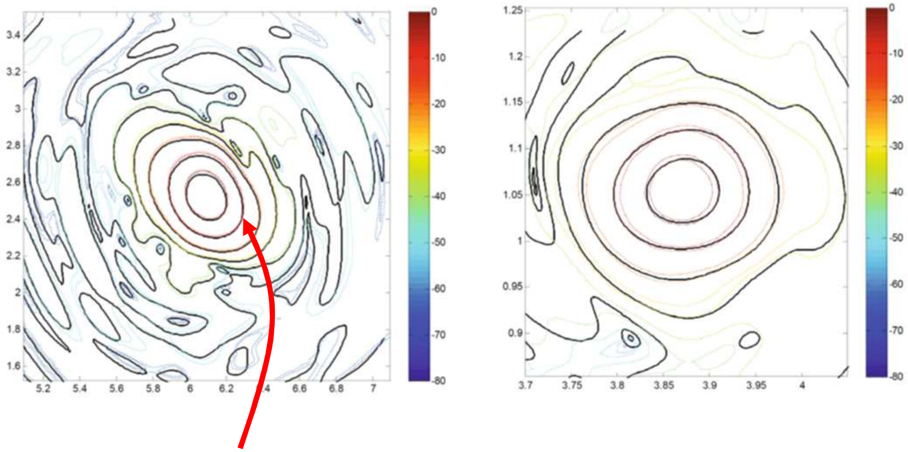




Comparing RFQM measurements and Optical model (at 300K)

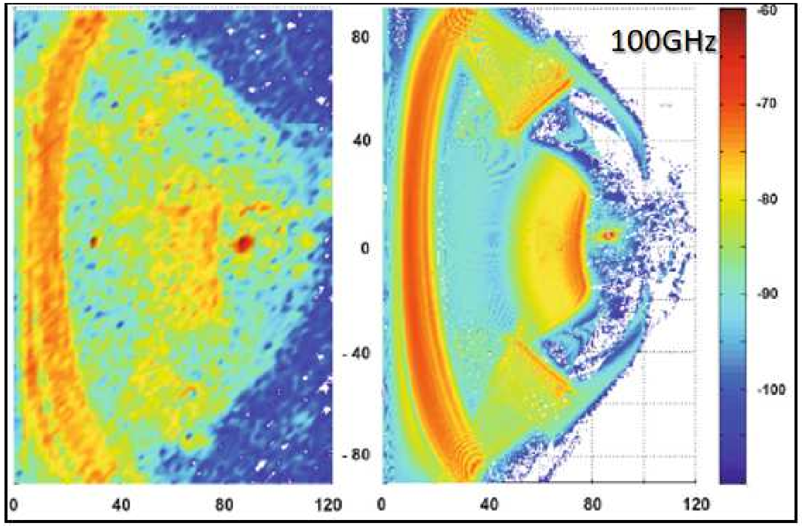
MAIN BEAMS

70 GHz   320 GHz

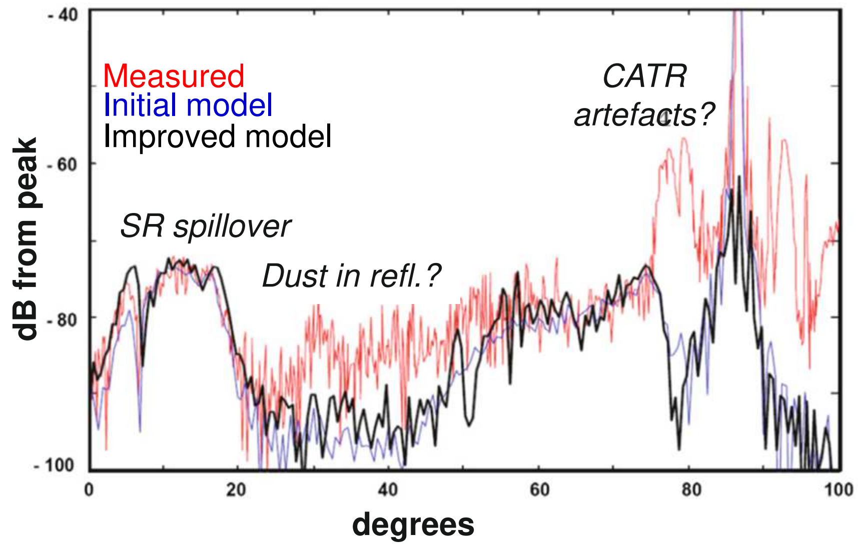


±1σ measurement error

SIDELOBES



100 GHz



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**

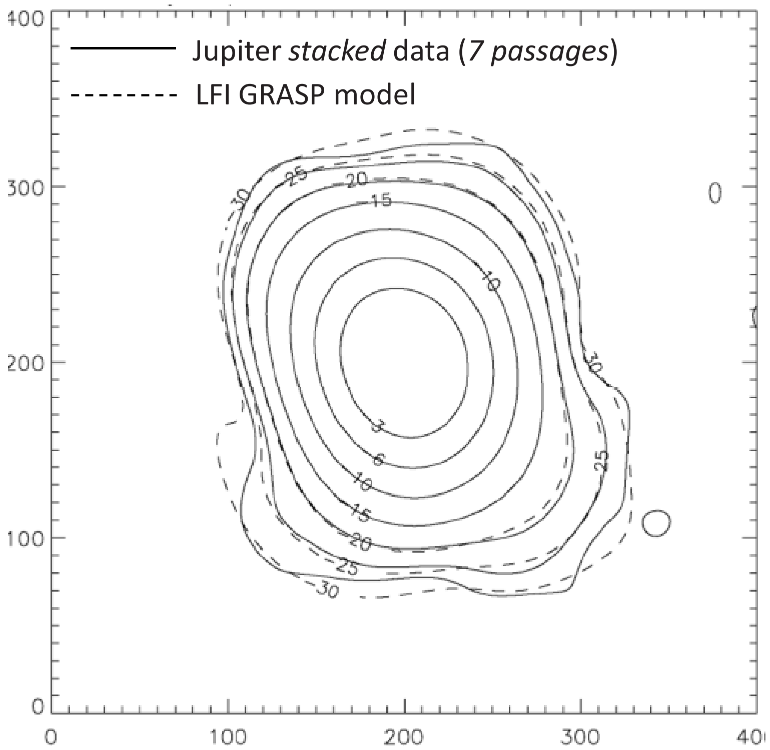
Tauber et al. (2019)

Mu-Lab @ UniMI
STILES/PNRR – C. Franceschet et al.
New CATR 2x2m up to 600GHz
New NF system up to 750GHz
Completion: September 2025

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

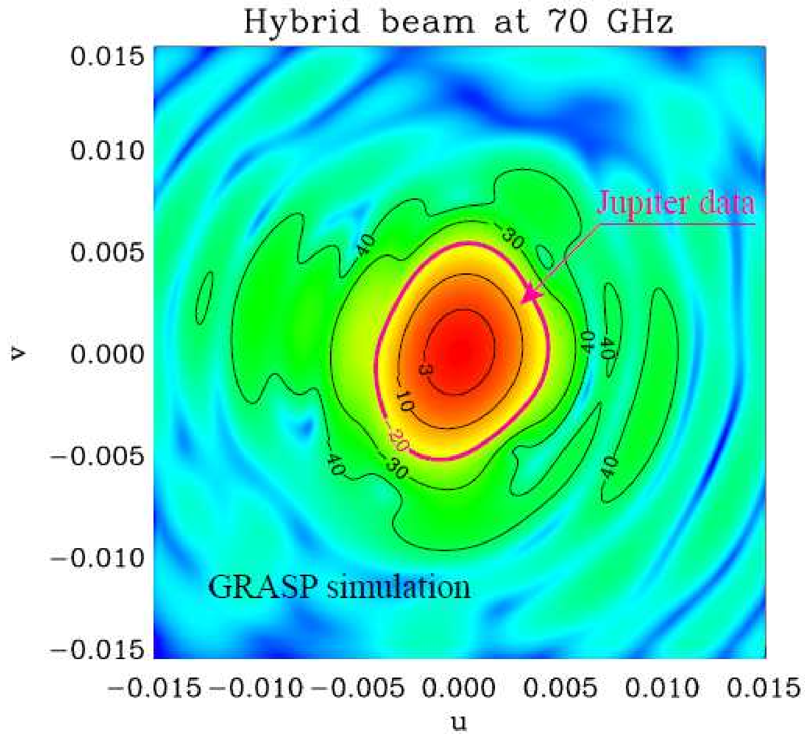


Final analysys: Hybrid «scanning beams»

– Cover time constant effect in HFI beams

-- Data from Jupiter above a S/N floor

– GRASP fiducial model below threshold

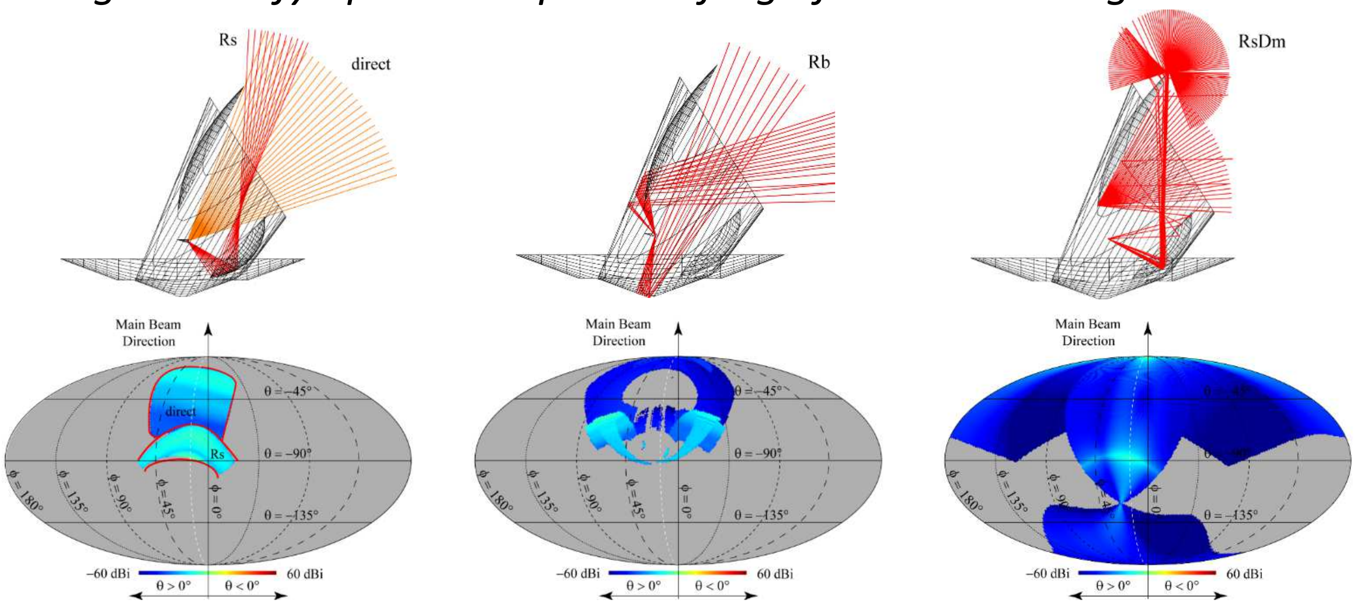


Sandri et al. 2010, Planck Collaboration IV 2014

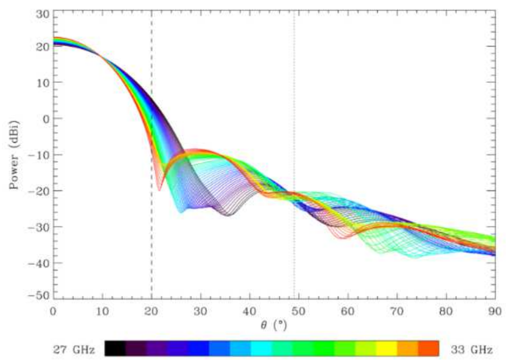
LFI far-sidelobes calculation: GRASP MrGTD

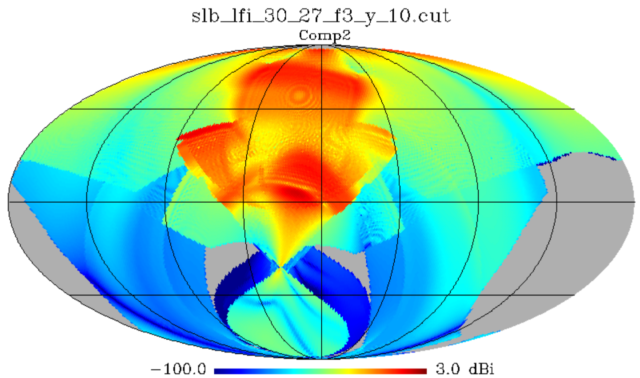
Compute scattered field (reflected or diffracted) from each element (backward ray tracing)

Challenge: Identify optimal sequence of significant scattering elements



Effect of beam pattern variation inside the detector bandwidth





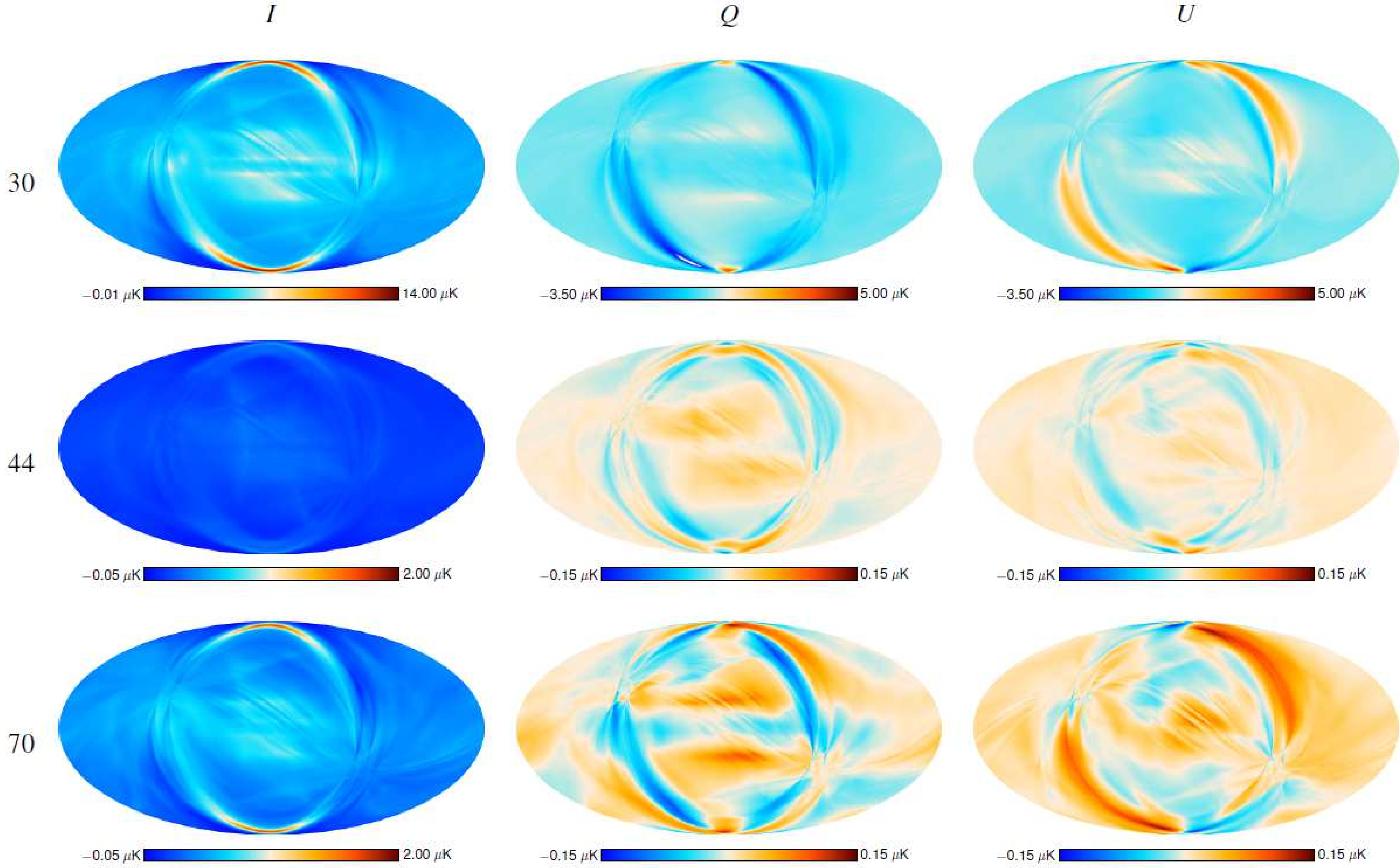
7 FSL frequency cuts within 30GHz band Co-Pol pattern

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

(No parallel computing with GRASP)

Effect from far sidelobes before subtraction

Planck Collaboration III, 2016



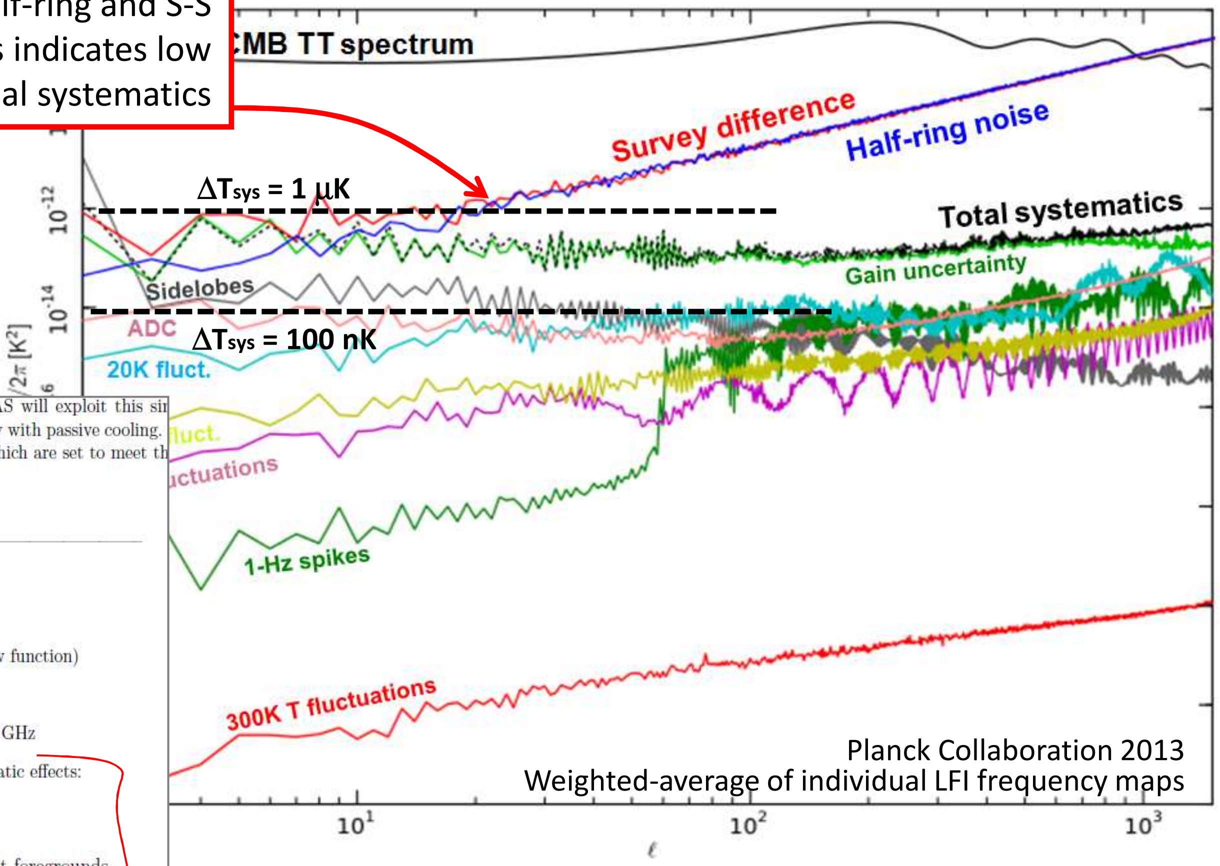
Effect removed in timelines

Calibration key objective: understanding systematics

“TOP DOWN”

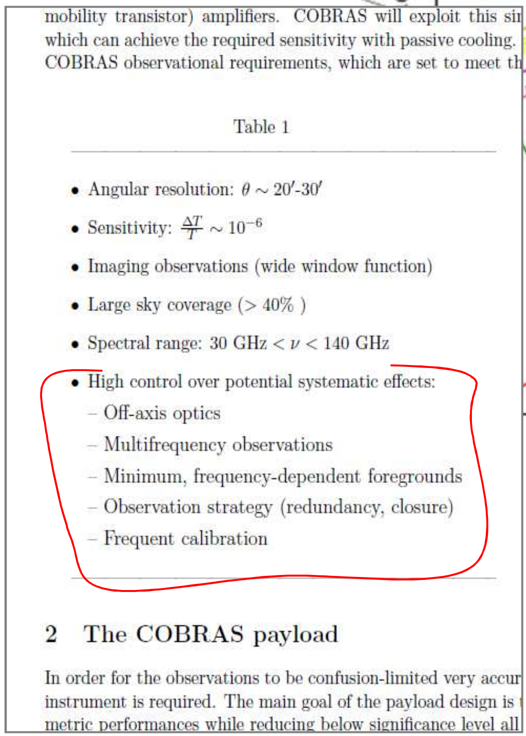
Match between half-ring and S-S differences indicates low residual systematics

2013



“BOTTOM UP”

1993



mobility transistor) amplifiers. COBRAS will exploit this si[...] which can achieve the required sensitivity with passive cooling. COBRAS observational requirements, which are set to meet th[...]

Table 1

- Angular resolution: $\theta \sim 20'$-$30'$
- Sensitivity: $\frac{\Delta T}{T} \sim 10^{-6}$
- Imaging observations (wide window function)
- Large sky coverage (> 40%)
- Spectral range: 30 GHz $< \nu <$ 140 GHz
- High control over potential systematic effects:
  - Off-axis optics
  - Multifrequency observations
  - Minimum, frequency-dependent foregrounds
  - Observation strategy (redundancy, closure)
  - Frequent calibration

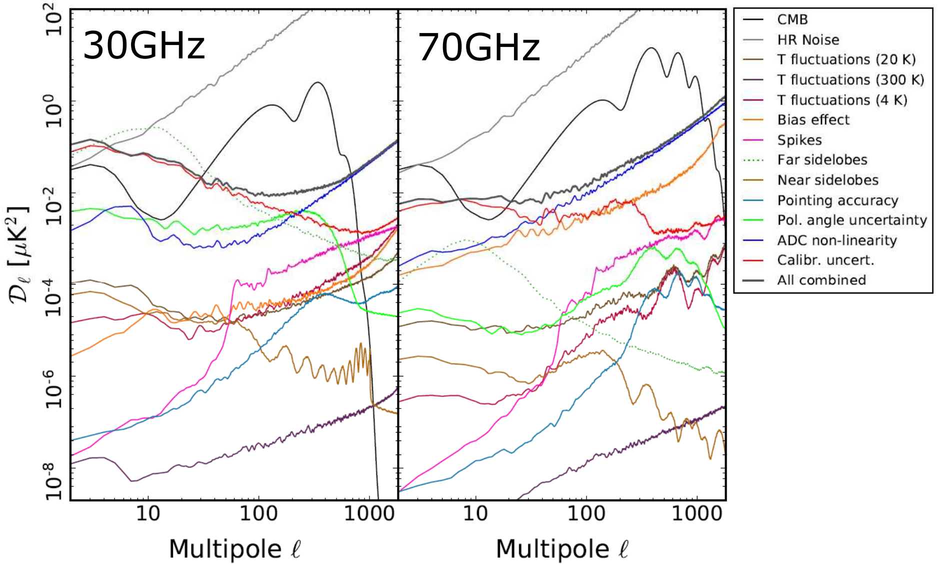
2 The COBRAS payload

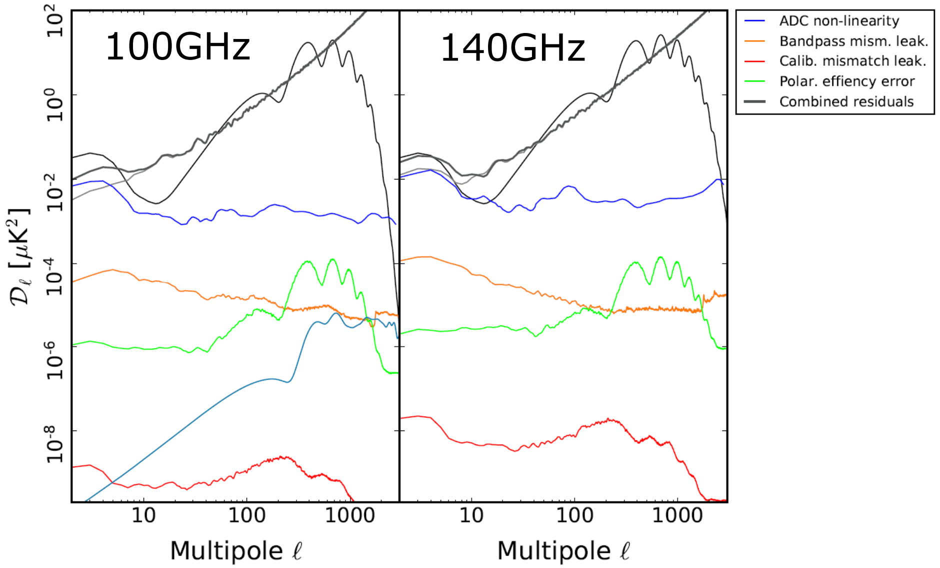
In order for the observations to be confusion-limited very accur[...] instrument is required. The main goal of the payload design is [...] metric performances while reducing below significance level all[...]

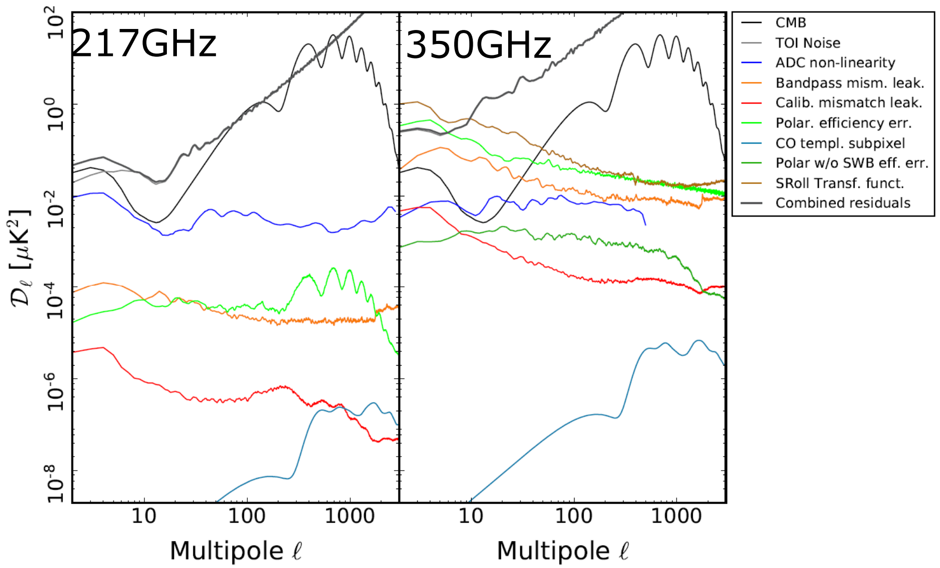
Systematics mitigation was recognized as a central objective since the very start of COBRAS and SAMBA

Calibration key objective: understanding systematics

Planck Collaboraiton 2018

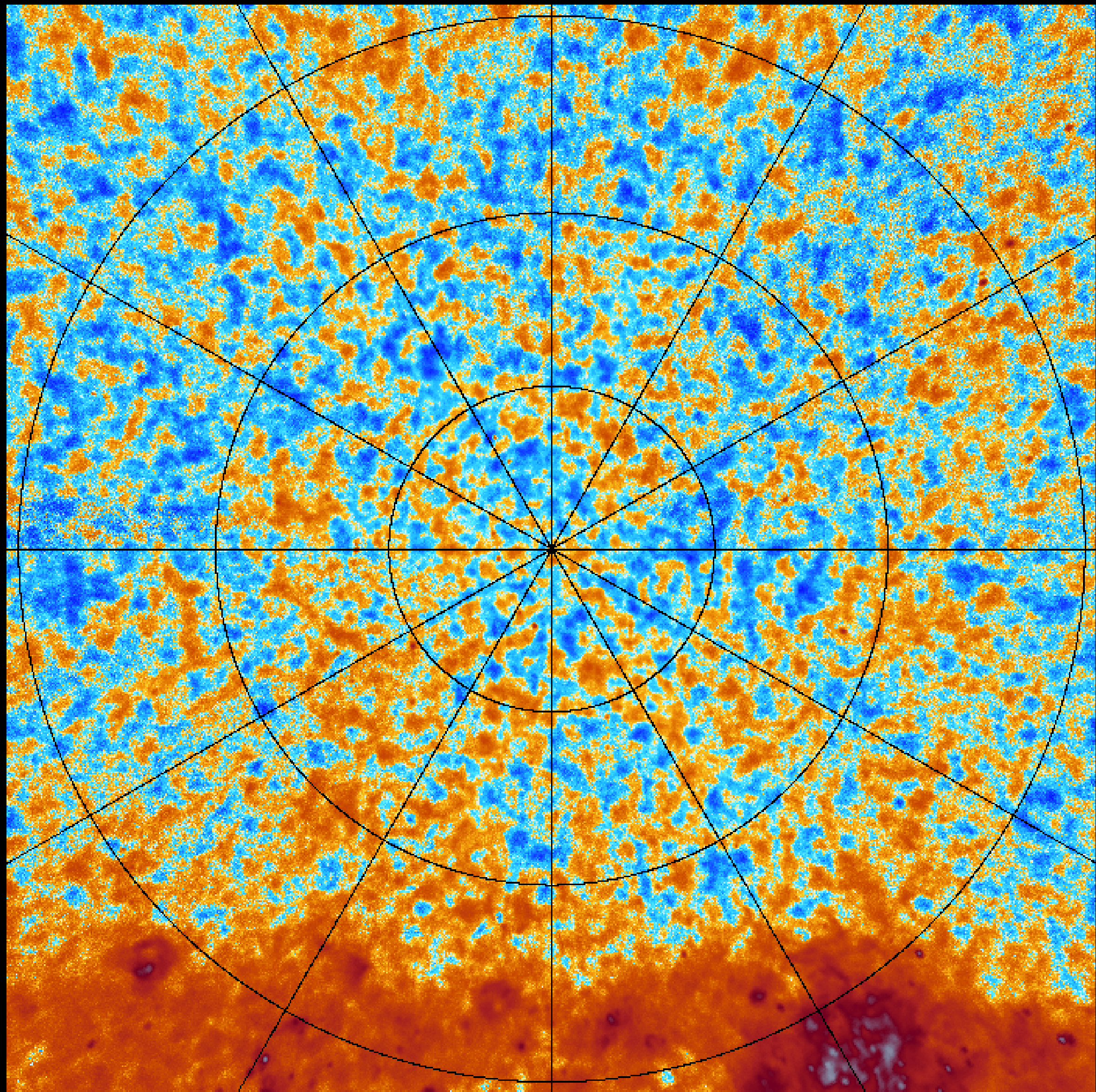






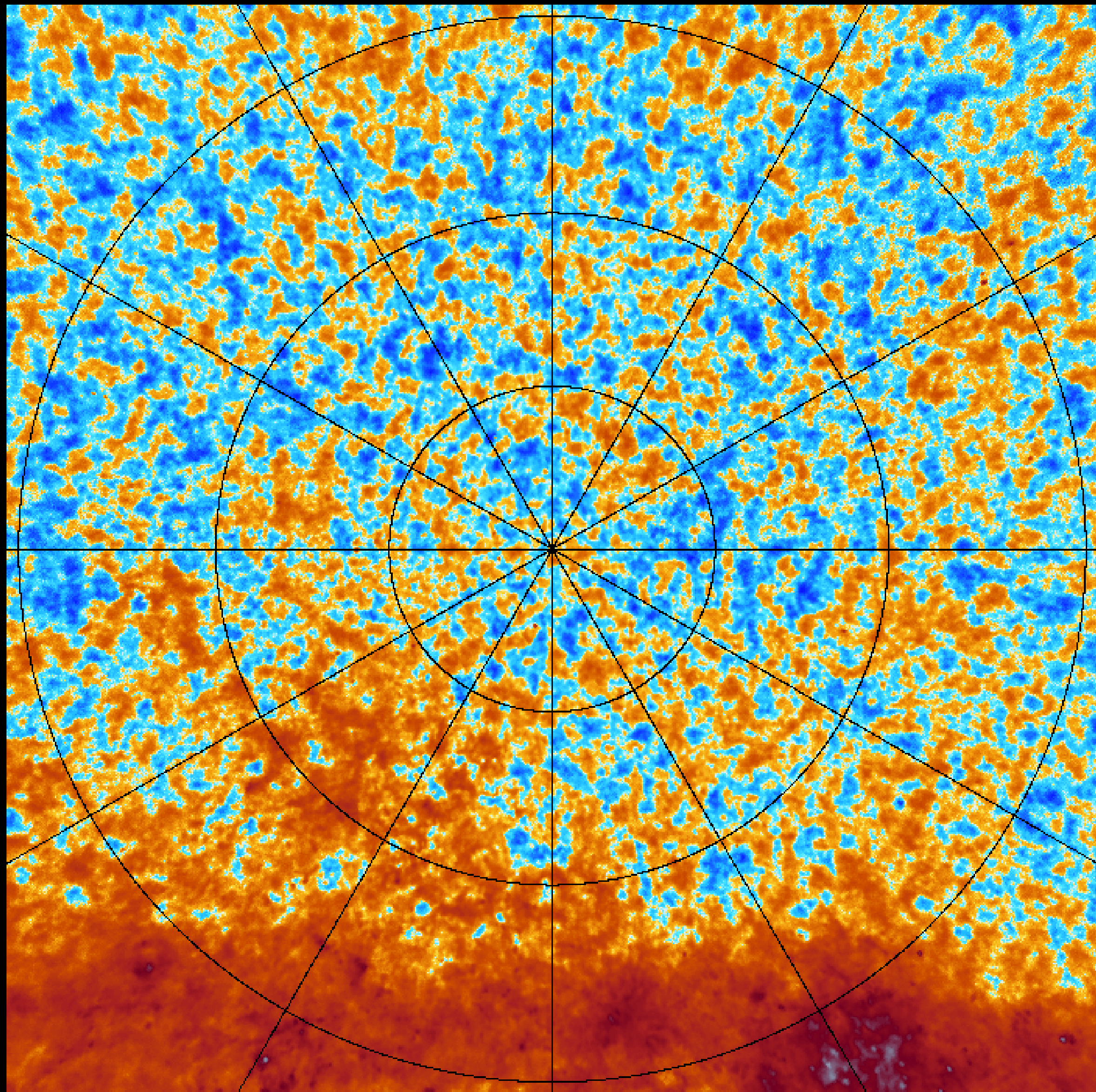
Planck 2015
North Ecliptic Pole region

LFI 70GHz



Planck 2015
North Ecliptic Pole region

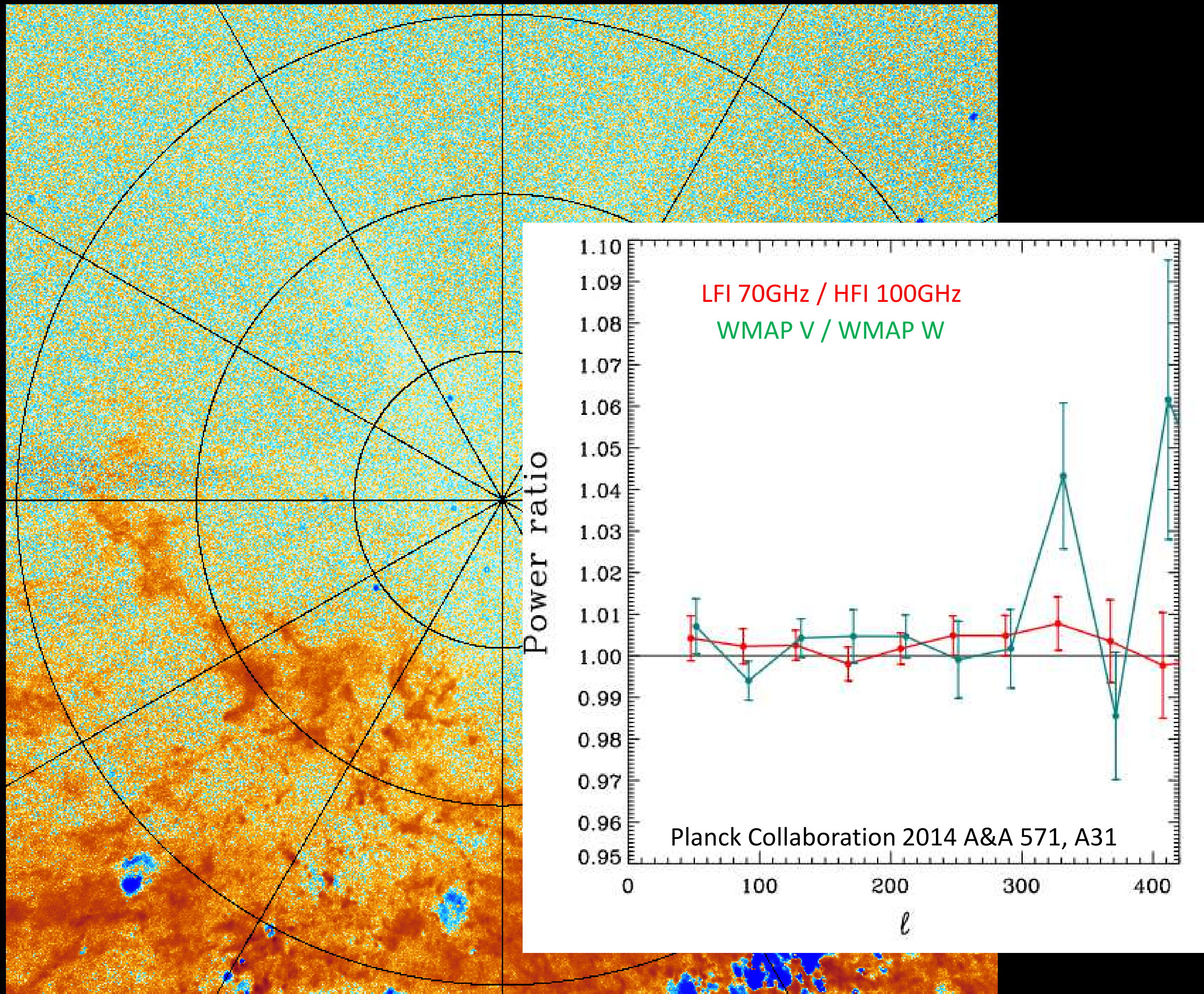
HFI 100GHz



Planck 2015

North Ecliptic Pole region

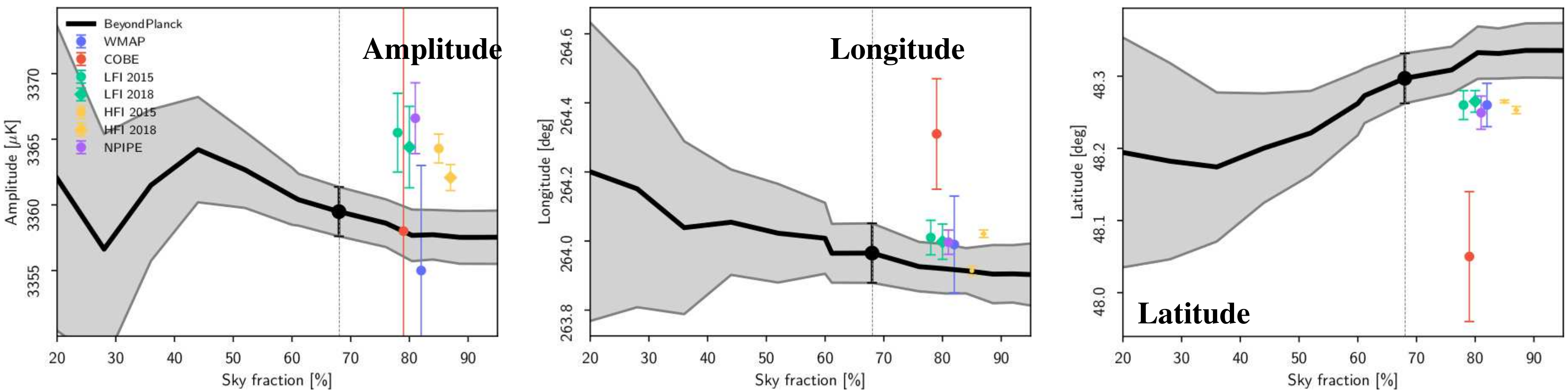
HFI100 – LFI70 diff



CMB: Solar dipole

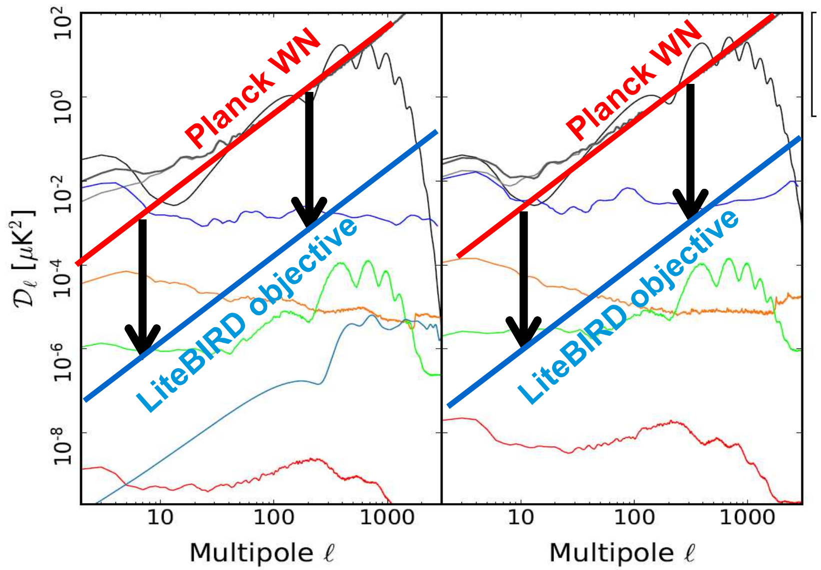
BeyondPlanck - Colombo et al. (2020)

		Galactic coordinates		
Experiment	Amplitude [μK_{CMB}]	l [deg]	b [deg]	Reference
COBE[a,b]	3358 ± 23	264.31 ± 0.16	48.05 ± 0.09	Lineweaver et al. (1996)
WMAP[c]	3355 ± 8	263.99 ± 0.14	48.26 ± 0.03	Hinshaw et al. (2009)
LFI 2015[b]	3365.5 ± 3.0	264.01 ± 0.05	48.26 ± 0.02	Planck Collaboration II (2016)
HFI 2015[d]	3364.29 ± 1.1	263.914 ± 0.013	48.265 ± 0.002	Planck Collaboration VIII (2016)
LFI 2018[b]	3364.4 ± 3.1	263.998 ± 0.051	48.265 ± 0.015	Planck Collaboration II (2020)
HFI 2018[d]	3362.08 ± 0.99	264.021 ± 0.011	48.253 ± 0.005	Planck Collaboration III (2020)
NPIPE[a,c]	3366.6 ± 2.6	263.986 ± 0.035	48.247 ± 0.023	Planck Collaboration (2020)
BeyondPlanck[e] . .	**3359.5 ± 1.9**	**263.97 ± 0.09**	**48.30 ± 0.03**	Section 9.5



Ready for next space mission: LiteBIRD

- Next exciting objectives:
  - *B-modes at r ~ 0.001*
  - *Cosmic-variance-limited measurement of τ*



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

- For LiteBIRD, a coordinated calibration plan (*including thermal, optical aspects*) is being developed

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

- Although less directly, it may be useful for ground-based experiments

- An important message from Planck:

  Very ambitious challenges can be successfully tackled!

Systematics and calibration (e.g. LFI)

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)