# COrE calibration and testing

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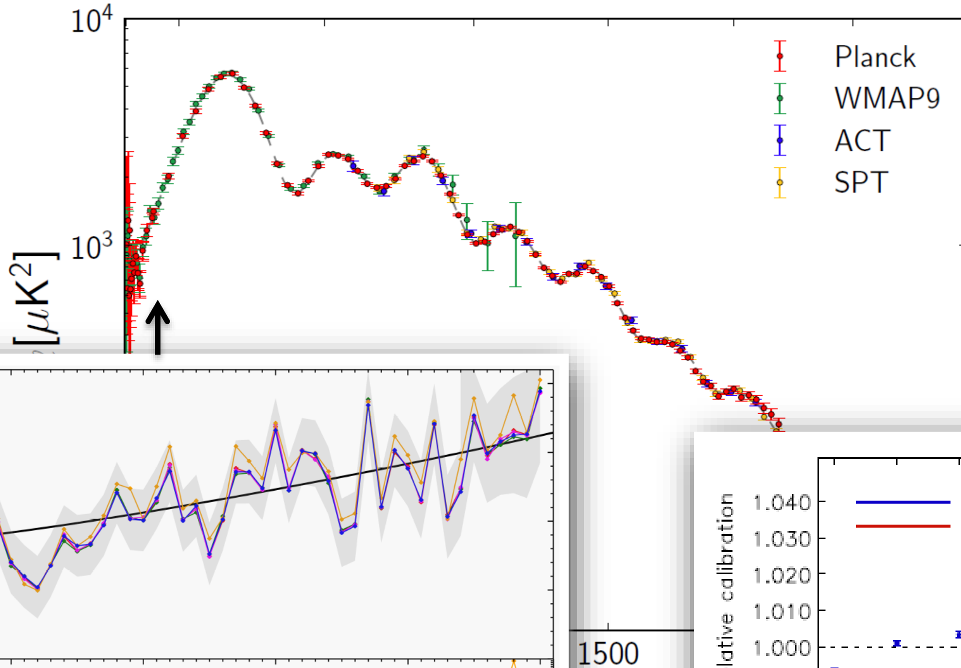
*University of Milano, Italy*

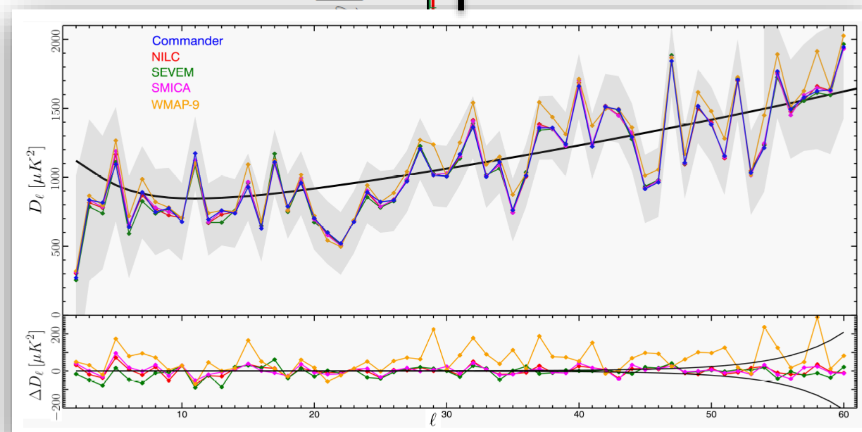
*CERN, Geneva, 17-20 May 2016*
*“Towards a next space probe for CMB observations and cosmic origins exploration”*

# CMB: High precision *and* High accuracy




Planck CMB Dipole calibration 0.2%

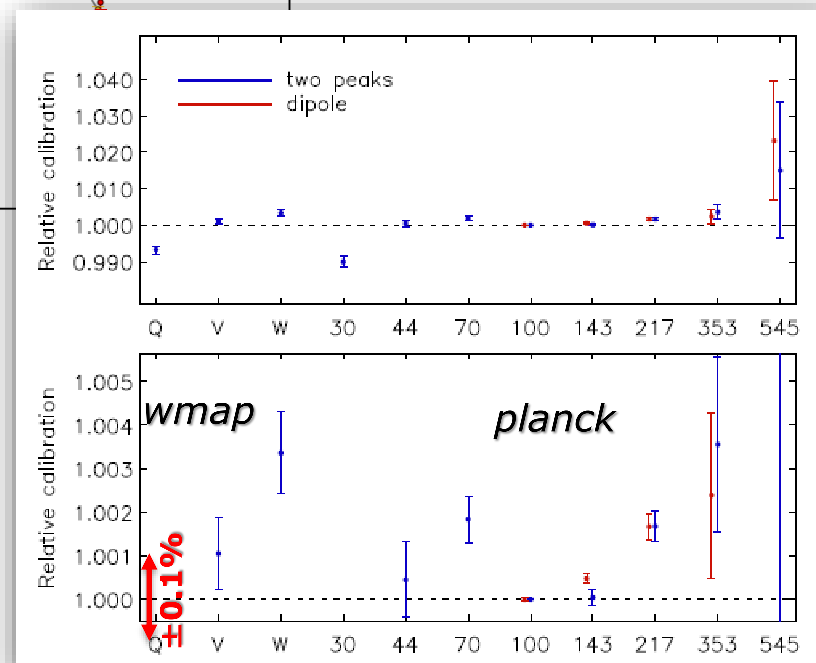
*Extend to radio (e.g. VLA) and sub-mm (e.g. Herschel)*




*Low multipoles:*
*Planck vs WMAP*

*~1% calibration discrepancy*

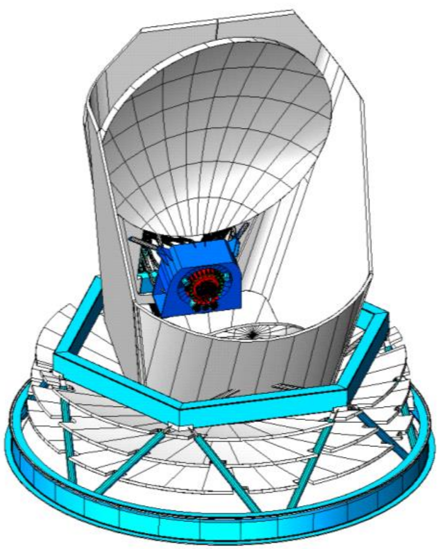
*Now completely solved!*

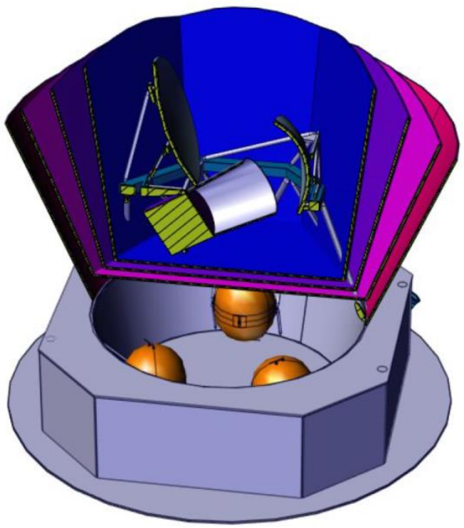



*Planck Collaboration 2016*

# Planck dipole: high quality calibrator for COrE

# From Planck to COrE





Telescope: 1.5m;
Frequency coverage 30–850 GHz
Number of detectors ~ few 10's
Cryogenically cooled to 0.1K
Detectors: rediometers, bolometers
Orbit: Sun-Earth L2

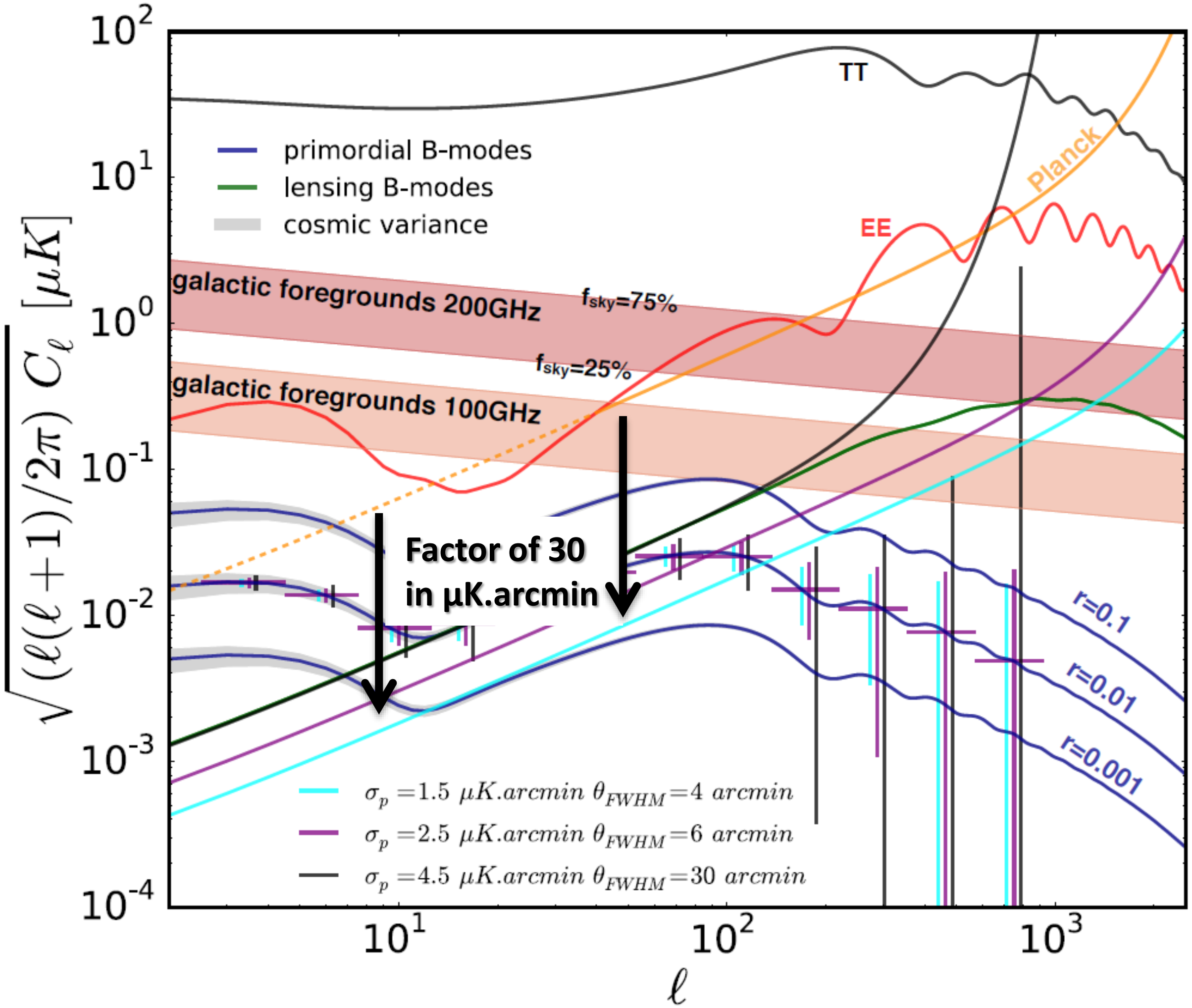
Telescope: ~1.2-1.5m;
Frequency coverage ~ 60–600 GHz
Number of detectors ~ few 1000's
Cryogenically cooled to ~0.1K
Detectors: KIDs, TES, …
Orbit: Sun-Earth L2

→ *Scan strategy optimized for polarization*
→ *Exploit where possible Planck heritage;*

**Replace few 10's detectors with few 1000's**
→ Improve map sensitivity by a factor of 30: *From 50 μK.arcmin to 1.5 μK.arcmin*
*Three orders of magnitude in power*

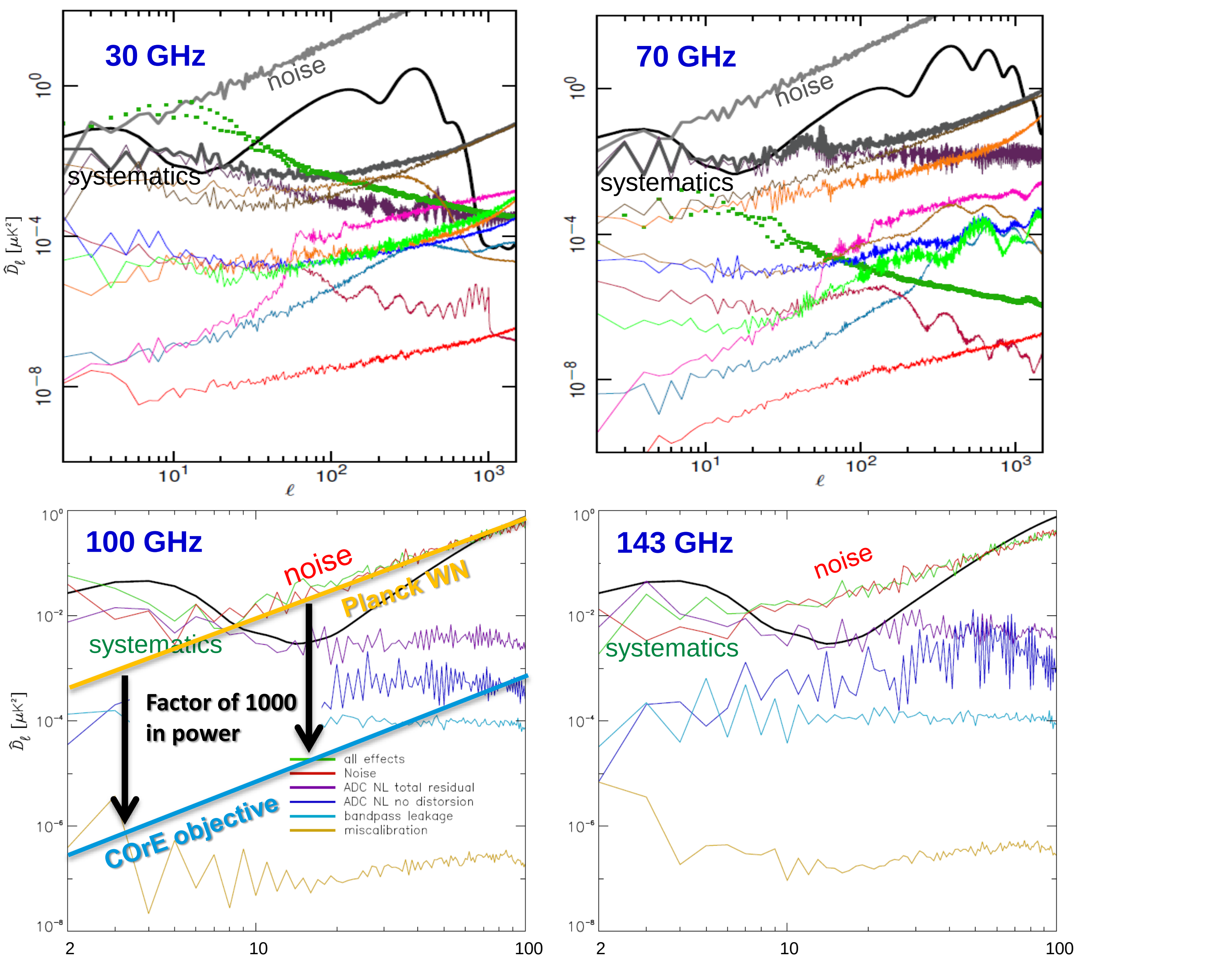
**Calibration challenge: ~ 100 times more channels, ~30 times deeper**

# COrE calibration requirements




- For COrE it is crucial to measure the re-ionization bump
- At large scales foregrounds and systematics are most difficult

# Planck: polarizaiton systematics at large scales (after removal)




Planck 2015 results. III.

***(D. Mennella's talk tomorrow)***

Planck 2016 intermediate results. XLVI.

# COrE calibration requirements

**The ultimate data quality of COrE (as for Planck) is likely to be limited not by white noise, but by residual systematic effects.**

- *WMAP and Planck were (essentially) noise-limited*
- *For Planck, this would not be the case if sensitivity was a factor 5-10 better*

**In spite of major efforts, Planck *<u>ground calibration was a limiting factor</u>***

The main Planck residual systematics:

*HFI: ADC non-linearity, cosmic rays*

*LFI: gain uncertainty, bandpass*

could have been mitigated with deeper ground testing

CORE sensitivity is a factor of 30 better than Planck

↓

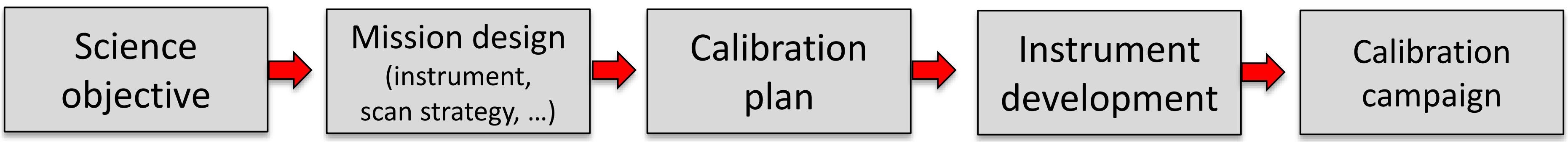
A similar improvement in calibration accuracy is required

# COrE Calibration

***It is crucial to plan calibration in early phase of instrument/mission design***

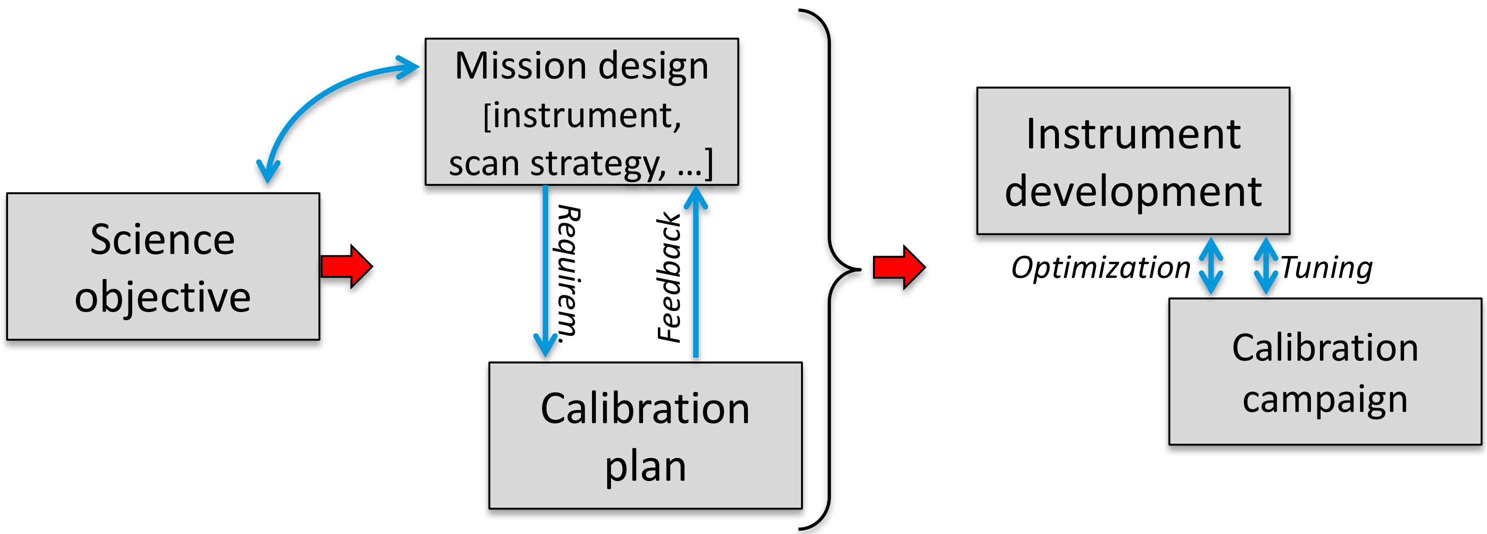
In principle a detailed calibration plan requires a fully developed instrument and payload design, as well as scanning strategy.

**Ideal sequence:**




In practice, calibration plan and mission design will evolve together, with increasing levels of refinement.

**Real-life sequence:**




***Significant impact on mission SCHEDULE and COST***

# COrE Calibration

***(Discussion for tomorrow)***

## Classes of instrument parameters

1. **Photometric calibration:** Conversion of telemetry units to physical units (KCMB). Gain factors fwill be measured on the ground at several stages. The final calibration will be performed in-flight.

2. **Relative calibration:** stability of the gain, 1/f noise, noise spectra, zero-level stability. The redundancy of the scanning strategy will help on this.

3. **Thermal effects:** systematics induced by thermal fluctuations in the 0.1 K, 1.7 K, 4 K, 20 K, and 300 K stages; cooler induced microphonics. Thermal susceptibility of detector response. Verify that temperature sensors H/K provide sufficient monitoring of instrument thermal configuration and stability.

4. **Detector chain non-idealities:** detector (TES ot KIDs) characterization, detector time-response; non-linearity of the detector response; nonlinearity of ADC converters; impact of cosmic rays; sensitivity to microphonics, temperature susceptibility, cross-talk.

5. **Spectral calibration:** filter characterization (module level), detailed bandpass measurements. These measurements will be done on the ground, as no sweeping sources is planned on the satellite. In-flight verification of the measured bandpasses will be possible through observation of diffuse and point sources with steep spectra.

6. **Optical calibration:** main beam determination, near side-lobes, far side-lobes (both total intensity and polarization). Direct measurements of the main beams and near lobes in-flight from planets and strong polarization sources. Cross-polarization, reflection. Alignmant. Pointing.

7. **Polarization-specific calibration:** polarization efficiency and polarization angle of each detector; These will be measured both on-ground and in-flight.

8. **Noise characterization:** detailed measurements of the noise properties (noise power spectrum, 1/f noise, possible non-gaussianity) and their time evolution.

# CORE Calibration

**"Calibration" :**

***Measurement of all the instrument/payload/SC parameters that are necessary to support in-flight operation and data analysis.***

**Global requirement:**

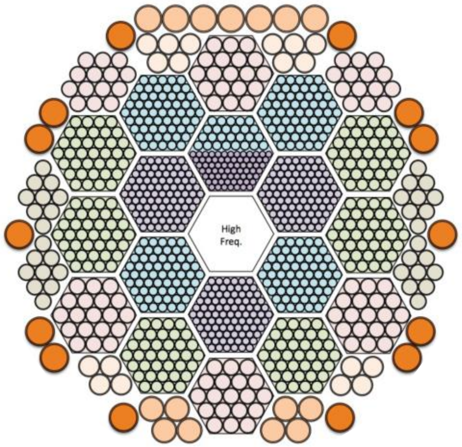
***The uncertainties in the measurements of all the instrument and payload parameters that have an effect on the data corresponds to a level of systematic effects that has negligible impact on the mission main science products.***

Many of these parameters to be measured repeatedly at various stages of integration.

**1) Ground test levels (*CDF study baseline*):**

***Detector, Module, Instrument (FPA),***
***SM, AVM, RFQM, CQM, PFM***

**2) In-flight measurements using astronomical sources**



*(COrE M4 FPA)*

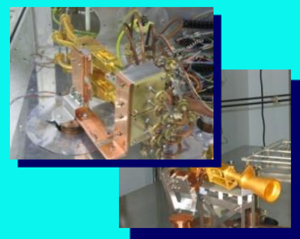
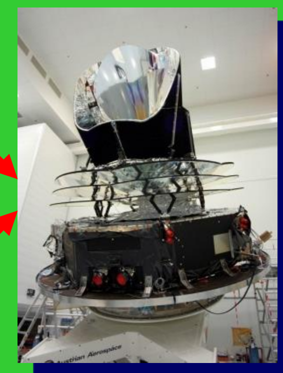
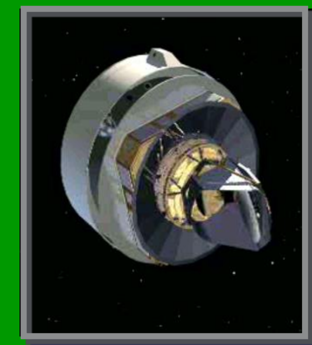
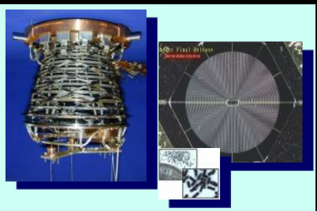
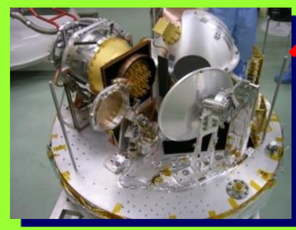
Identify key parameters of instrument, P/L, S/C

Set clear requirements (value and accuracy) on each parameter

*Processing removal should be included only for very solid correction algorithm*

*Correlation with other effects?*

# Planck Instrument Calibration Plan

| | Unit | Assembly | Instrument | Satellite | In-flight |
|---|---|---|---|---|---|
| LFI |  |  |  | CSL Campaign  |  CPV & FLS |
| HFI |  |  |  | | |

**Qualification Model (QM)**

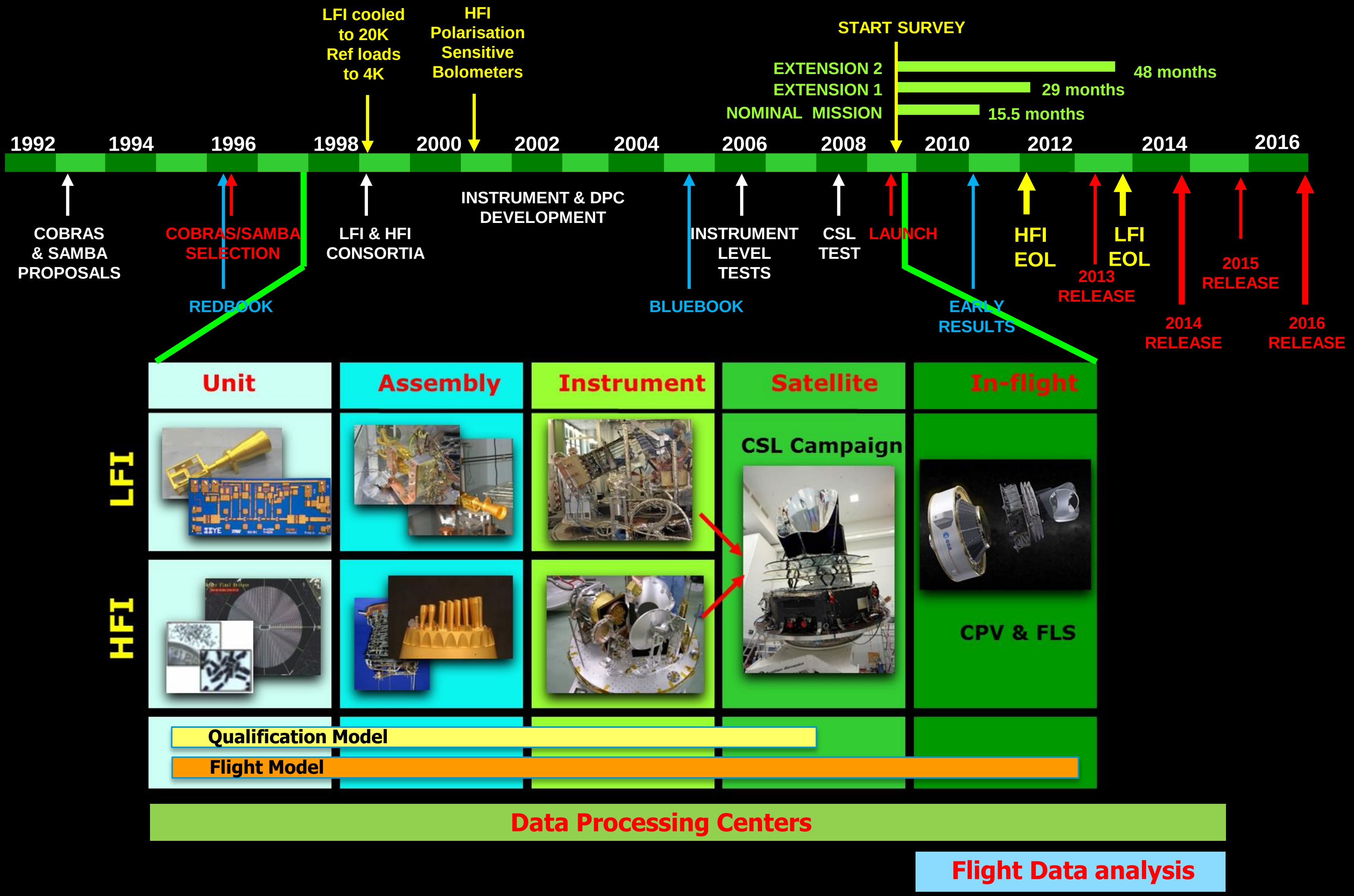
| Unit | Assembly | Instrument | Satellite | In-flight |
|---|---|---|---|---|
| *Completed* | *Completed* | *Completed* | *Completed* | |

**Flight Model (FM)**

| Unit | Assembly | Instrument | Satellite | In-flight |
|---|---|---|---|---|
| *Completed* | *Completed* | *Completed* | *Completed* | *Completed* |

Supported by Data Processing Centers

# Planck Ground & in-flight Calibration



# >80 pages of calibraiton table



| | | | | | |
|---|---|---|---|---|---|
| **RCA_SPR**<br>**RF Spectral Response**<br><br>***Estimated data taking time:***<br>***3 hours***<br>***(Note that this test requires warmup-cooldown of facility – NOT included)*** | Measure the radiometer spectral response within the operational band. The shape of the band is needed, i.e. only a *relative* measurement is performed. | The spectral response is measured at RCA level by injecting a calibrated RF monochromatic source into the sky horn sweeping through the band.<br>It is planned to perform this test at RCA level only, in cryogenic setup with the source coupled to the feedhorn aperture. The frequency of the input RF source is swept over the band of interest and the measured radiometer DC outputs are correlated with the input frequency to produce the RF frequency response. This test is done using the nominal operating mode and difference data. | ALL QM<br>ALL FM | *Radiometer band shape (relative) as a function of frequency*<br>$B(\nu)$ | |
| **RCA_THF**<br>**Sensitivity to thermal variations of the FEM**<br><br>***Estimated data taking time:***<br>***4 hours*** | Measure the radiometer | Both sky and load targets are at 4K, stable. The radiometer is working in normal switching mode. The radiometer characteristics (output voltage level, gain, noise temperature, offset) are monitored while perturbing by controlled amounts the physical temperatures of the FEM.<br>The RCA gain and noise temperatures are measured according to RCA_TNG, the output voltage and offset variations are recorded from the output signal.<br>The measurements are performed at a minimum of 3 temperatures (nominal 20K, higher and lower) to determine the first order dependence.<br><br>For a subset of RCAs hysteresis effects will be checked by repeating the test with the opposite sign of the temperature change.<br><br>Testing a sorption cooler-like perturbation to the 20K stage will be considered. | All QM<br><br>A subset (TBD) of FM<br><br>A subset (TBD) of QM for hysteresis effects. | *Sensitivity to FEM temperature:*<br>$V_{out}(T_{FEM})$<br>$\Delta T_{offset,out}(T_{FEM})$<br>$g_{TOT}(T_{FEM})$<br>$T_N(T_{FEM})$ | |
| **RCA_THB**<br>**Sensitivity to thermal** | Measure the radiometer susceptibility to temperature changes | Both sky and load targets are at 4K, stable. The radiometer is working in normal switching mode. The radiometer | QM: all RCAs<br><br>FM:one | *Sensitivity to BEM temperature:* | |





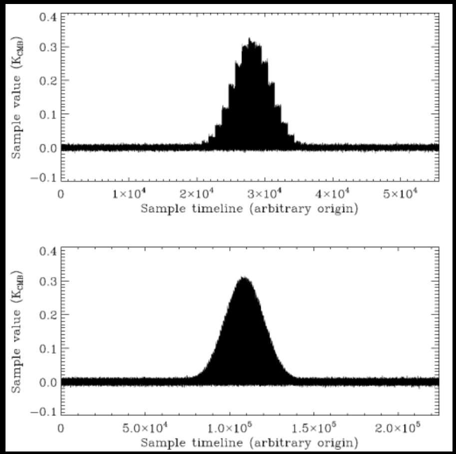
| | | | | | |
|---|---|---|---|---|---|
| **variations of the BEM**<br><br>***Estimated data taking time:***<br>***3 hours*** | in the BEM. | characteristics (output voltage level, gain, noise temperature, offset) are monitored while perturbing by controlled amounts the physical temperatures of the BEM.<br>The RCA gain and noise temperatures are measured according to RCA_TNG, the output voltage and offset variations are recorded from the output signal.<br>The measurements are performed at a minimum of 3 temperatures (nominal 300K, higher and lower) to determine the first order dependence.<br><br>For a subset of RCAs hysteresis effects will be checked by repeating the test with the opposite sign of the temperature change. | RCA per frequency<br><br>A subset (TBD) of QM for hysteresis effects. | $V_{out}(T_{BEM})$<br>$g_{TOT}(T_{BEM})$<br>$T_N(T_{BEM})$<br>$\Delta T_{offset,out}(T_{BEM})$ | |
| **RCA_THV**<br>**Sensitivity to thermal variations of the V-grooves**<br><br>***Estimated data taking time:***<br>***4 hours*** | Measure the radiometer susceptibility to temperature changes in the interface temperatures of the V-grooves. | Both sky and load targets are at 4K, stable. The radiometer is working in normal switching mode. The radiometer output voltage level is monitored while perturbing by controlled amounts the physical temperatures of the three V-grooved interfaces.<br>To determine the first order dependence, the measurements are performed at a minimum of 3 temperatures for each V-groove: nominal temperature (150K, 100K, 50K), and higher and lower values by about 10-20%. | QM: all RCAs<br><br>FM:one RCA per frequency | *Sensitivity to V-grooves interface temperatures:*<br>$V_{out}(T_{VG1})$<br>$V_{out}(T_{VG2})$<br>$V_{out}(T_{VG3})$ | |
| **RCA_THR**<br>**Sensitivity to variations of Reference load temperature**<br><br>***Estimated data taking time:***<br>***2 hours*** | Measure radiometer sensitivity to variations of Reference load temperature. | The RCA output is monitored (signal level and of spectral noise) while the 4K reference load is varied by TBD K (or perturbed with a controlled sine wave) to test sensitivity. Normal RCA operations and fully differenced data are used for this test. | QM: all RCAs<br><br>FM: all RCAs | *Sensitivity to 4K reference load temperature:*<br>$V_{out}(T_{Load})$ | |

# COrE Optical calibration

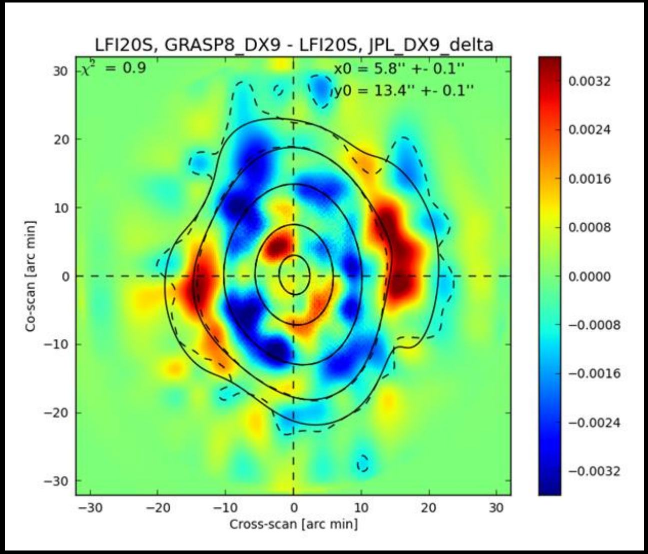
| Objective of test/ measurement | Requirements | On-ground (at what stage) | In-flight | Instrument model verification |
|---|---|---|---|---|
| **Optical coupling at FPA** | *FWHM (Edge taper): 30dB*<br>*Losses < 0.1dB*<br>*Reflections: VSWR > 40dB*<br>*Cross-polarization: <30dB* | *- Single detector*<br>*- Module*<br>*- Instrument* | *N/A* | *Compare to GRASP simulations*<br><br>*Feeds/lenses prototypes* |
| **Main beam determination**<br><br>*Both total intensity and polarization* | *FWHM per freq (value spread)*<br><br>*Ellipticity <* ***1.1*** | *- Single detector*<br>*- Module*<br><br>*RFQM (With telescope)* | *Direct measurements of main beam exploiting signals from ALL external planets*<br><br>*Strong polarization sources: polarized beams* | *Compare to GRASP simulations*<br><br>*Beam variation in-band* |
| **Sidelobe determination**<br><br>*- near side-lobes,*<br>*- far side-lobes*<br><br>*Both total intensity and polarization* | *Rejection needed for: Galaxy,*<br>*Sun, Earth, Moon*<br><br>***20dB lower than Planck*** | *RFQM (With telescope)* | *Intermediate sidelobes down to -35 dB to -40 dB with Jupiter will be possible in-flight* | ***Trade off edge taper with angular resolution***<br><br>*Compare to GRASP simulations*<br><br>*Beam variation in-band* |
| **Internal straylight** | *Limit background on detectors from*<br>*- FPA environment*<br>*- P/L environment*<br>*- Baffle* | *- Single detector*<br>*- Module*<br>*- Instrument*<br>*- CQM*<br>*- PFM (at CSL)* | *May be able to test during cooldown* | *Thermal model*<br>*Emissivity*<br>*Baffle* |
| **Filter characterization** | *- Band definition (from comp sep)*<br>*- Bandwidth (sensitivity)*<br>*- Consider CO lines (and other moloecules)* | *- Unit/Module level*<br>*- CQM (cryo conditions)* | *N/A* | *Filter models*<br><br>*Filters prototypes* |

# Planck RFQM & Optical Calibration

## Main beam




Flight data on Jupiter

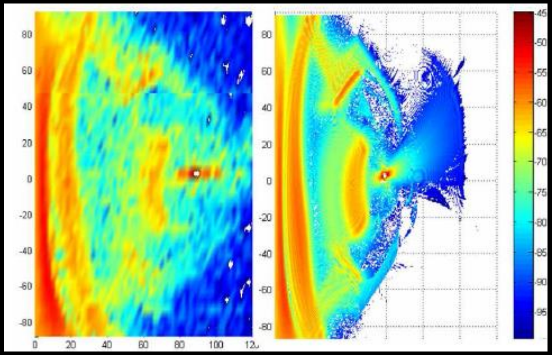



<1% between in-flight data and GRASP (<0.3% in the 70 GHz)

## Sidelobes

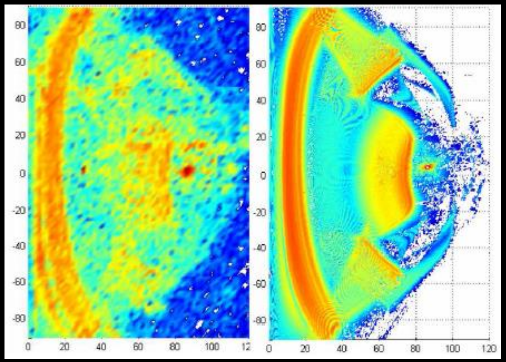
**LFI 30 GHz**

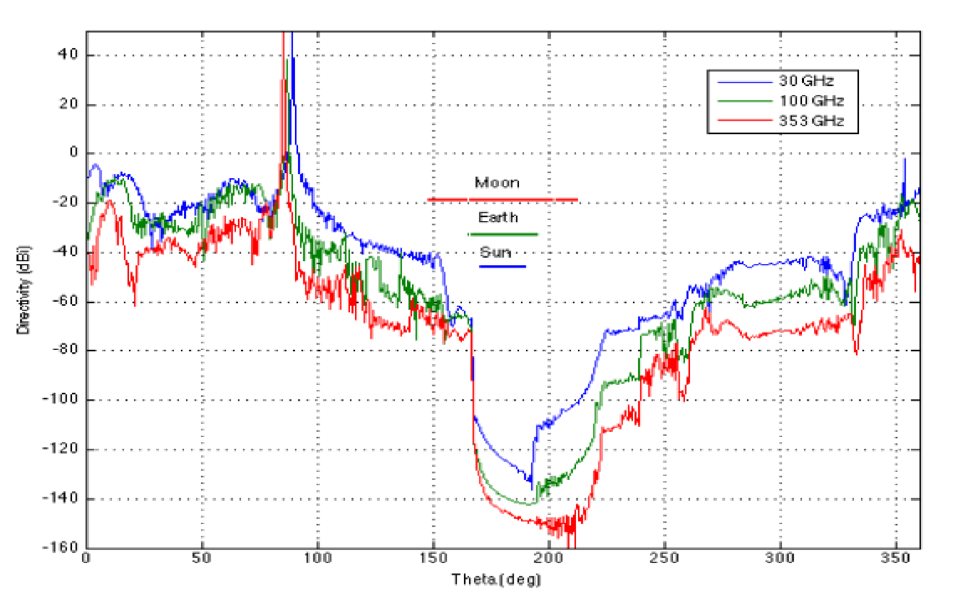
Predicted Measured



**HFI 100 GHz**

Predicted Measured



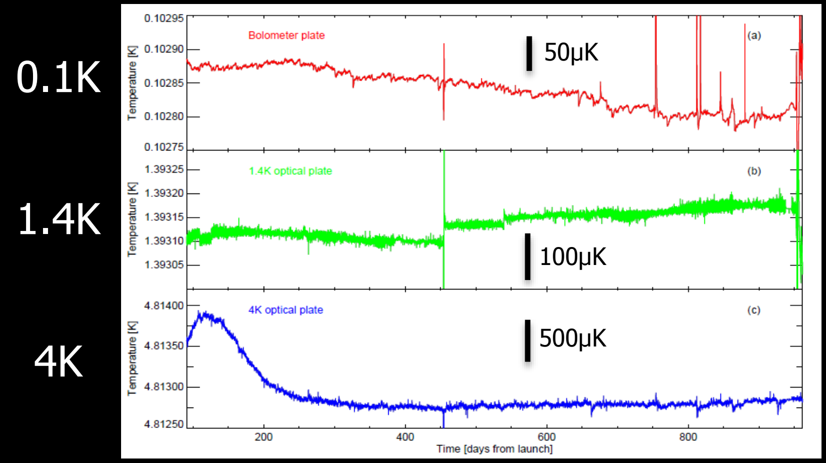


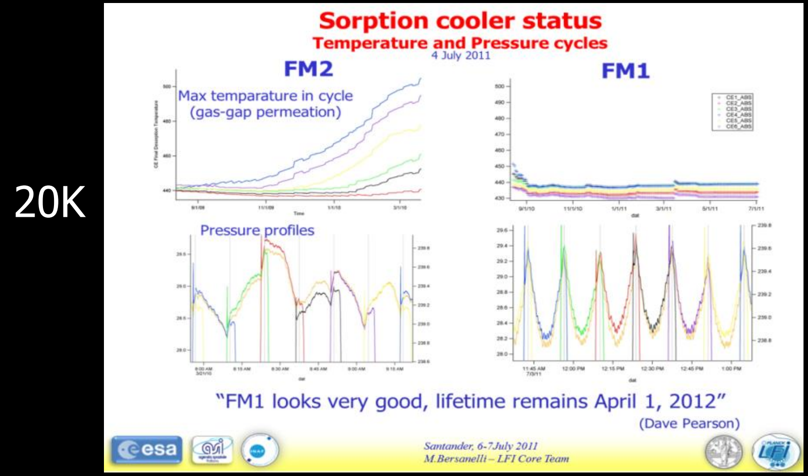

*(Maffei, Sandri talks tomorrow)*

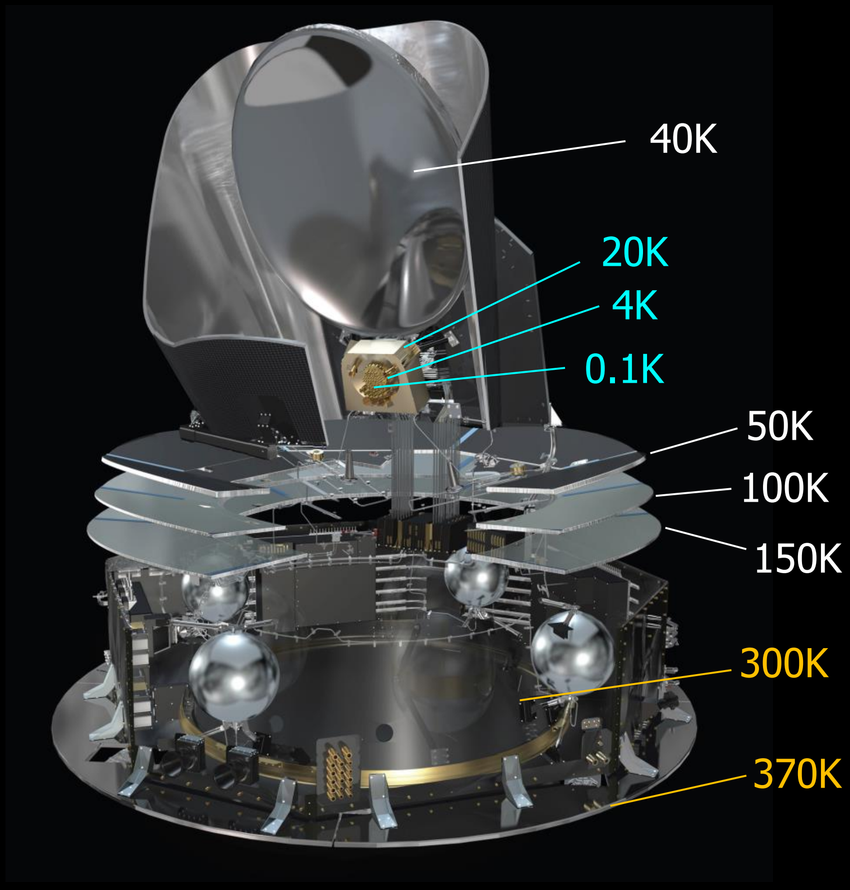
# Planck thermal calibration and thermal model

COrE temperature requirements expected to be similar to Planck led to stable conditions

Thermal stability




Planck: thermal model crucial to optimize lifetime & extended mission

# Instrument level campaign



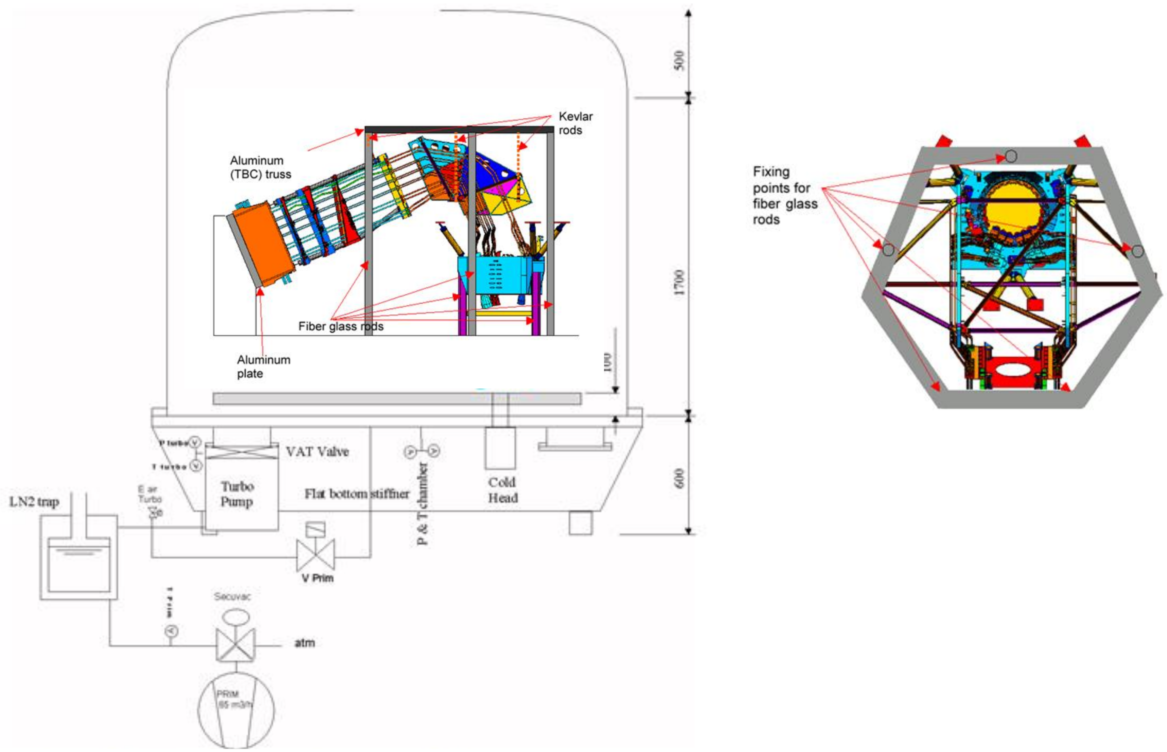


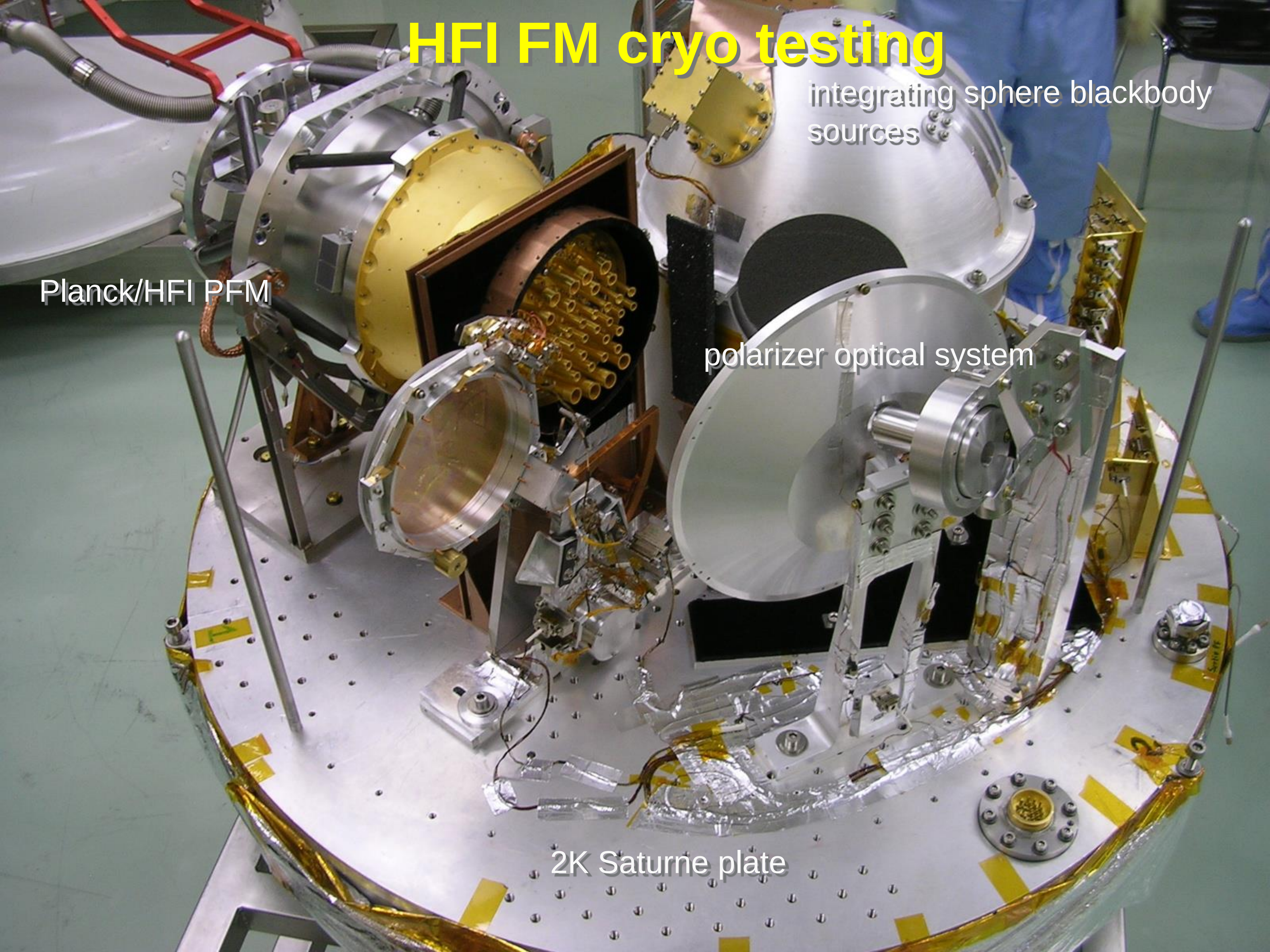

*Figure 6.3-1 – A Schematic Diagram of the RAA test setup (Laben)*

Figure 6.3-1 shows a schematic representation of the the RAA test facility showing the position of the LFI inside the cryo-chamber. The approximate size of the cryo-chamber is given as well as the additional equipment needed to acheive a stable RAA temperature of 20K and a vacuum of TBD atm. As shown in the schematic diagram the RAA waveguides and DAE are integrated in the flight configuration with the

# LFI FM cryo testing

Milano, Thales-I,
August 2006

# HFI FM cryo testing



# System level campaign

- System level test is normally conceived as a functionality test
- **In the case of COrE (as for Planck) is critical for calibration and performance verification**

### 6.5.2 System-level Cryofacility and MGSE

The cryo facility will support the instrument in its nominal cryogenic conditions. Cryo-testing of the PPLM will be carried out with the CSL cryo-facility with requirements given in RD25. In particular, the cryofacility will include an intermediate cooling stage at liquid Nitrogen temperature and it will incorporate a 20K shroud surrounding the entire PPLM during cryogenic tests and a target that can be cooled down to 4K in front of the Planck FPU.

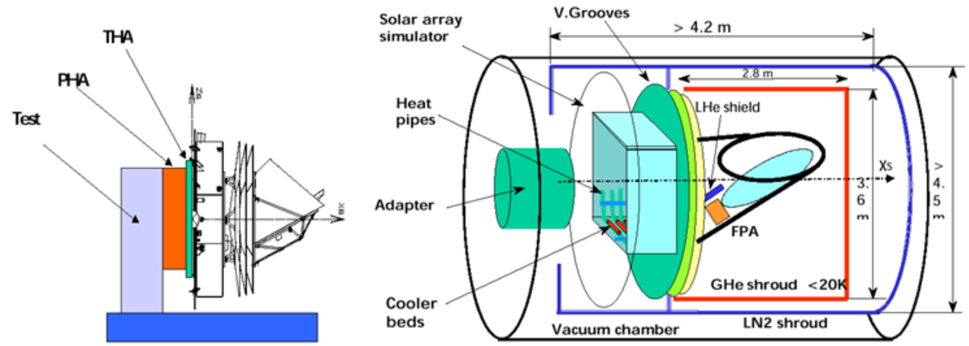



*Figure 6.5.1/1 – Thermal and cryogenic test configuration of the Planck PPLM. Left: support and test adapters (THA: Transport Handling Adapter; PHA: Planck Hosting Adapter). Right: a schematic of the system level test cryo chambe (From RD 25).*

**CSL facility, chamber and (possibly) shroud could be re-used for COrE**

Fine tuning of facility needed

New shrouds to be developed (Helium/Nitrogen?)

CSL, Liege,
July-August 2008

CSL, Liege, July-August 2008

CSL, Liege, July-August 2008

# Conclusions

- Calibration must be planned starting in the very early stages of instrument/mission design & development
- It will be one of the main drivers of COrE schedule and cost
- Planck experience (ground and in-flight) showed the criticality of calibration down to the science exploitation
- A great deal of experience gained in Planck calibraiton process will be inherited by COrE