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PLANCK
Looking back to the dawn of time
European Space Agency
Agence spatiale européenne
More information can be found on:
http://www.esa.int/science/planck

The Planck mission and the measurements with LFI instrument

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Italian Space Agency (ASI)
on behalf of LFI Planck collaboration

A dream 16 years old

1992- two space-based CMB experiments (COBRAS and SAMBA) were proposed to ESA.
1996- ESA selected a combined mission renamed PLANCK as the third Medium-Sized Mission of the Horizon 2000 SP

1997- ESA released an Announcement of Opportunity for *Planck* instruments.

1999 - Two proposals were received and accepted:

- **Low Frequency Instrument** (LFI, an array of receivers based on HEMT amplifiers, covering the frequency range 30–100 GHz, and operated at a temperature of 20 K), led by N. Mandolesi (INAF,Bo)
- **High Frequency Instrument** (HFI, an array of receivers based on bolometers covering the frequency range 100–857 GHz, and operated at a temperature of 0.1 K), led by J.L.Puget (IAS, Orsay).

- 14.05.2009 PLANCK launch

The current status

18.05 ok orbit

21.05 focal lane at 170k

27.05 on board computer ok, TM/TC ok

2.06 satellite ok

3.06 sorption cooler turn on

PLANCK:
the third generation CMB satellite

1992 – COBE team announced the detection of intrinsic temperature fluctuations in the CMB on angular scales larger than *about* 7◦, at a level $\Delta T/T$ *of* 10^{-5}.

Since this detection the main objective is to measure the fluctuations of the CMB with an accuracy set by fundamental astrophysical limits.

2003 – WMAP team announced results on scales of about 15’ with similar sensitivity

>>> strongly support inflationary Big Bang models and confirms Standard Model but CMB measurements with high angular resolution and sensitivity are required to determine the initial conditions for structure evolution, the origin of primordial fluctuations, the existence of topological defects, and the nature and amount of dark matter.

Planck **will image the the whole sky with an unprecedented combination of sensitivity (**$\Delta T/T \sim 2 \times 10^{-6}$**), angular resolution (to 5'), and frequency coverage (30–857 GHz).**

The collaboration

Planck is being developed in a partnership with the European scientific community:

-Two Consortia of scientific institutes, each led by a PI, supported by national agencies, have delivered to ESA Instruments.

-The instruments sit at the focus of a telescope whose mirrors are being developed in a collaborative effort between ESA and a Danish Consortium of Institutes led by H. U. Norgaard Nielsen (DSRI, Copenhagen).

-ESA manages the project, develops and procures the spacecraft, integrates the instruments into the spacecraft, and will launch and operate it.

-Each of the two instrument Consortia will operate their respective Instrument and process all the data into usable scientific products.

At the end of the mission (approximately in December of 2012), the Consortia will deliver the final products to ESA, who will archive them and distribute them to the wide community. **Up to that time, the three scientific institutes will have exclusive access to the data for scientific exploitation.**

The LFI team, a great international collaboration: **about 300 people contributing to the instrument and the data processing development**

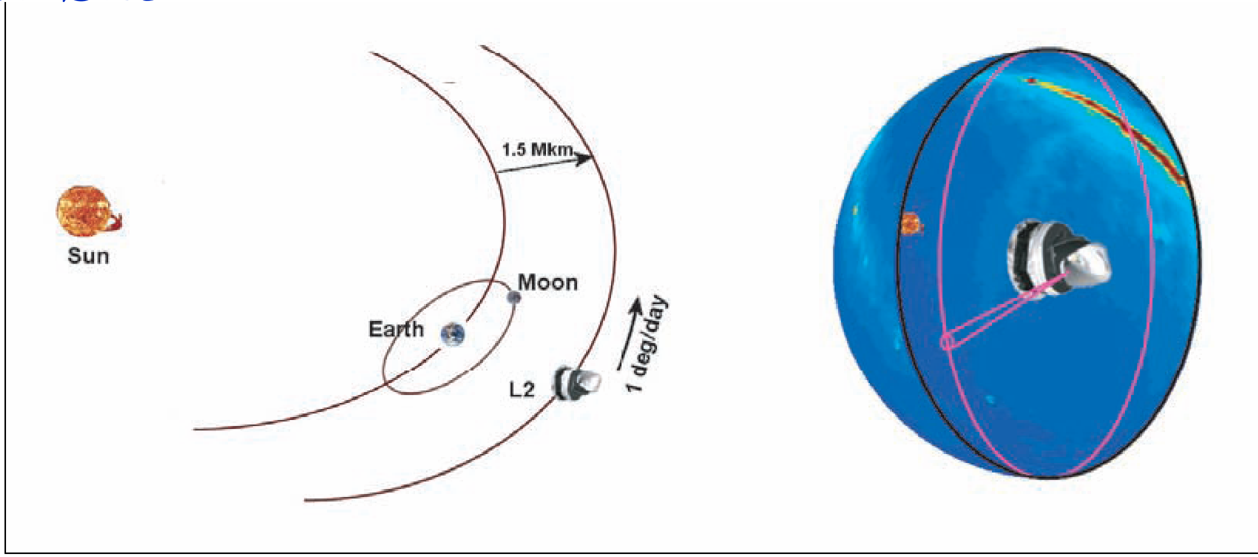
It is crucial to limit at μK level the residual instrumental systematic errors specially those that are synchronous with spacecraft spin period.
Spin-synchronous signals are virtually indistinguishable from any *true sky* signal and can affect permanently the final maps

>>>Need of a stable enviroment to minimize thermal and radioactive systematics effects:

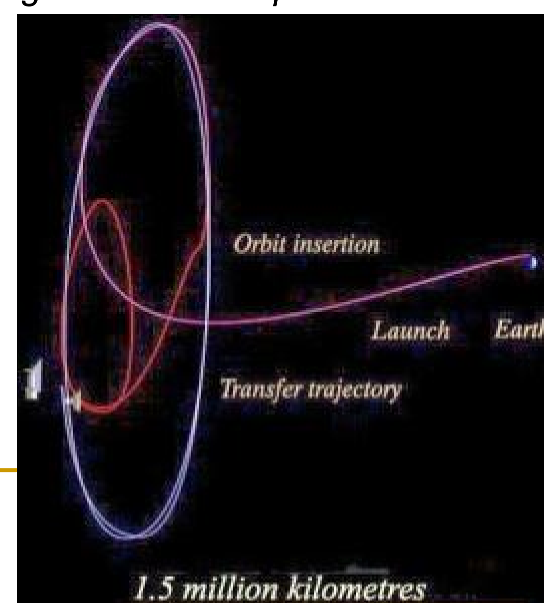
- L2 orbit
- scanning strategy

spin axis in anti-solar dir., field of view scan circles in the sky at 85° from the spin axis
Not sufficiently "cross-linked" to suppress the effects of correlated (e.g., 1/*f*) noise
Polarization angle coverage is not uniform enough

Launch and orbit



Planck orbit at the 2nd Lagrangian point of the Earth-Sun system (L2). The spin axis is pointed near the Sun, with the solar panel shading the payload, and the telescope sweeps the sky in large circles at 1 rpm.



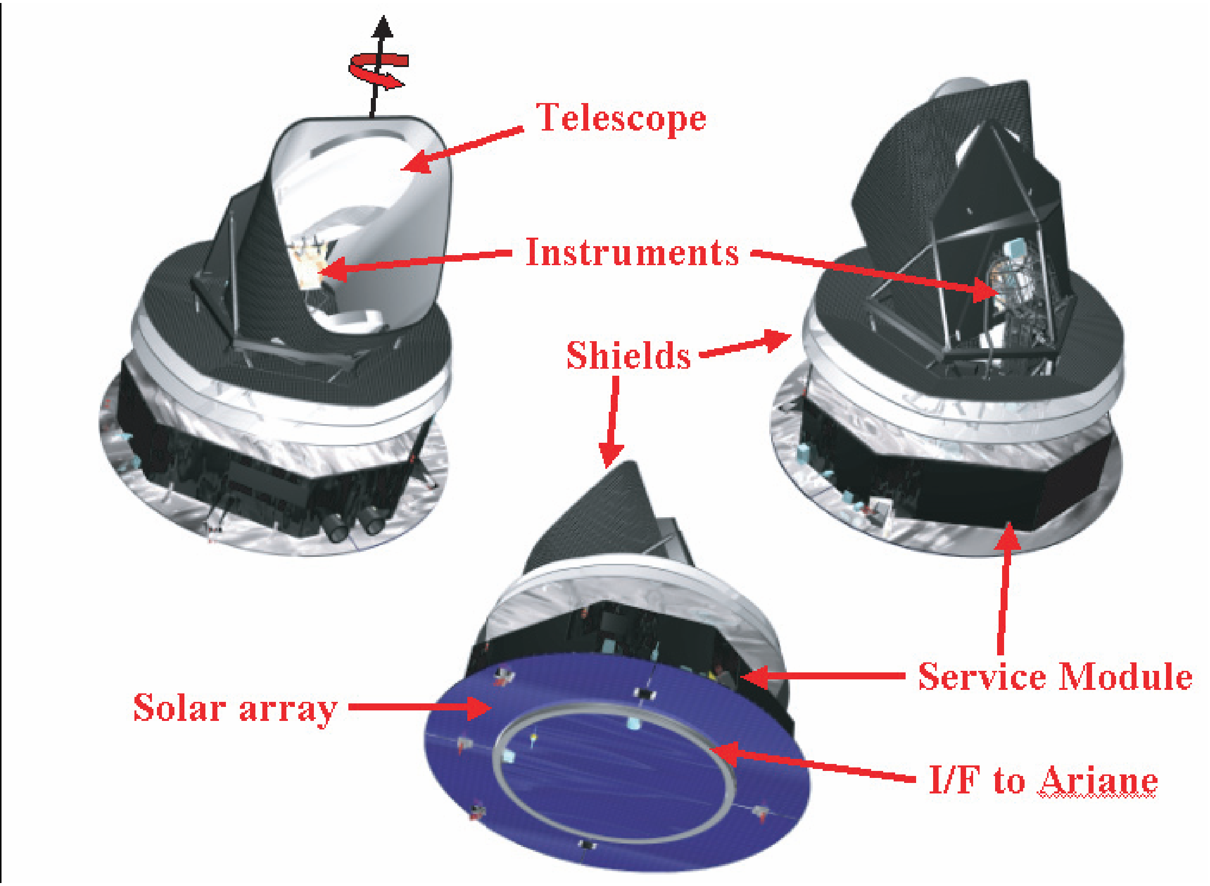
LIFETIME

- Planck nominal lifetime is 15 months
- 2 surveys of the sky set to allow to compare two independent sets of observations
- Planck total lifetime is limited by the presence of on-board active coolers required to operate the Planck detectors, in particular:

  - A dilution refrigerator using ^{3}He and ^{4}He, which cools the Planck bolometers to 0.1 K

  - A hydrogen sorption refrigerator, which cools the Planck radiometers to 20 K and provides a first pre-cooling stage for the bolometer system.

The main components of *Planck*



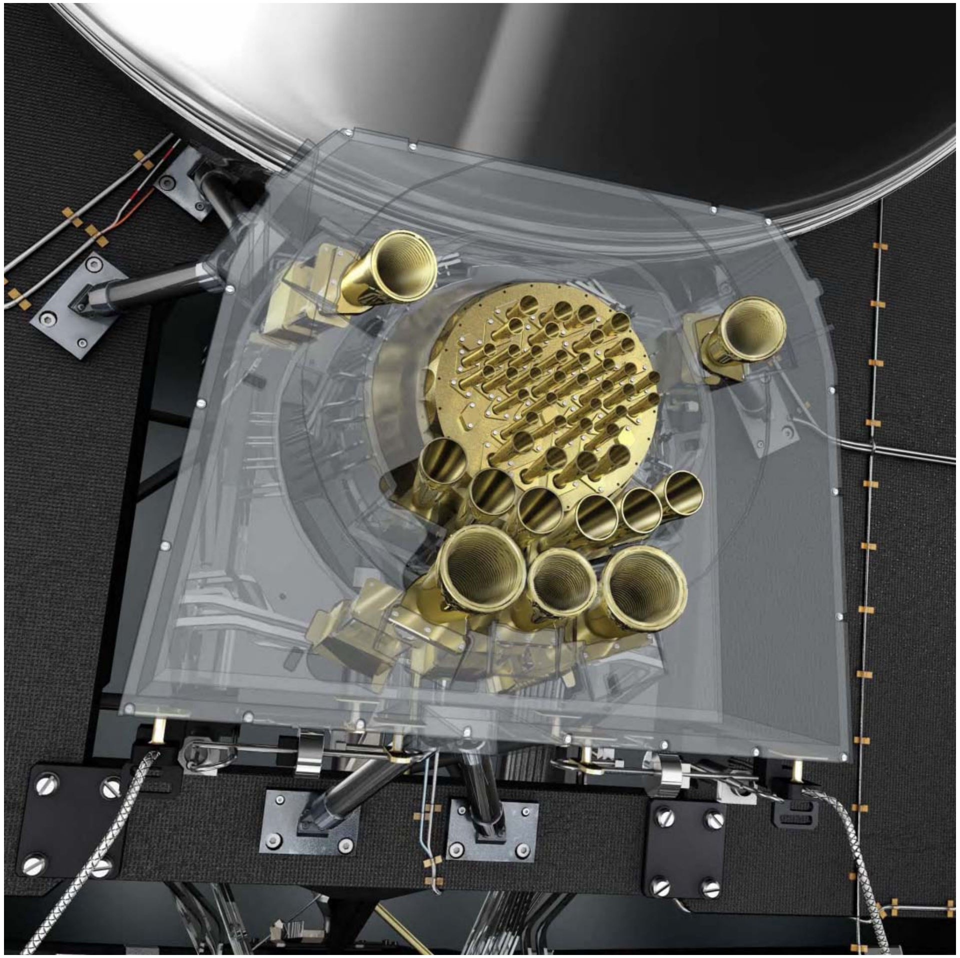
•an off-axis telescope with a projected diameter of 1.5 m;
•a telescope baffle that simultaneously provides straylight shielding and radiative cooling
•two state-of-the-art cryogenic instruments, operating at 20K and 0.1 K;
•three conical "V-groove" baffles tha provide thermal isolation between the warm
•spacecraft and the cold telescope and instruments;
•the service module
•the solar panel

In flight, the solar panel faces the Sun; everything else is always in shadow. The cryogenic temperatures required by the instruments are achieved through a combination of passive radiative cooling and three active refrigerators. The cooling provided by the passive system leads to a temperature of ~ 50K for the telescope and baffle. The active cryocoolers further reduce the temperature to 20K and 0.1K for the instruments.

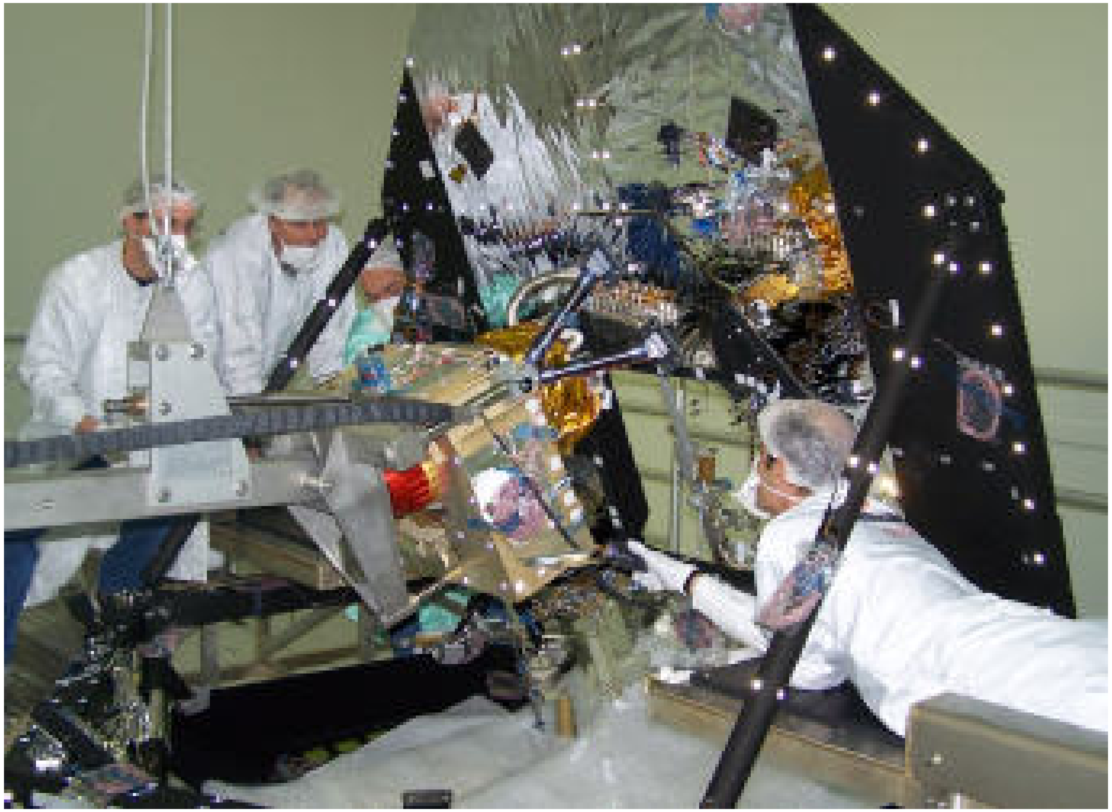
PLANCK INSTRUMENT CHARACTERISTICS

	LFI			HFI					
Detector Technology	.HEMT arrays			Bolometer arrays					
Center Frequency [GHz] . . .	30	44	70	100	143	217	353	545	857
Bandwidth (Δv/v)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
*ΔT/T p.p. (Stokes I)**	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
*ΔT/T p.p. (Stokes Q &U)**	2.8	3.9	6.7	4.0	4.2	9.8	29.8	. . . . . .	

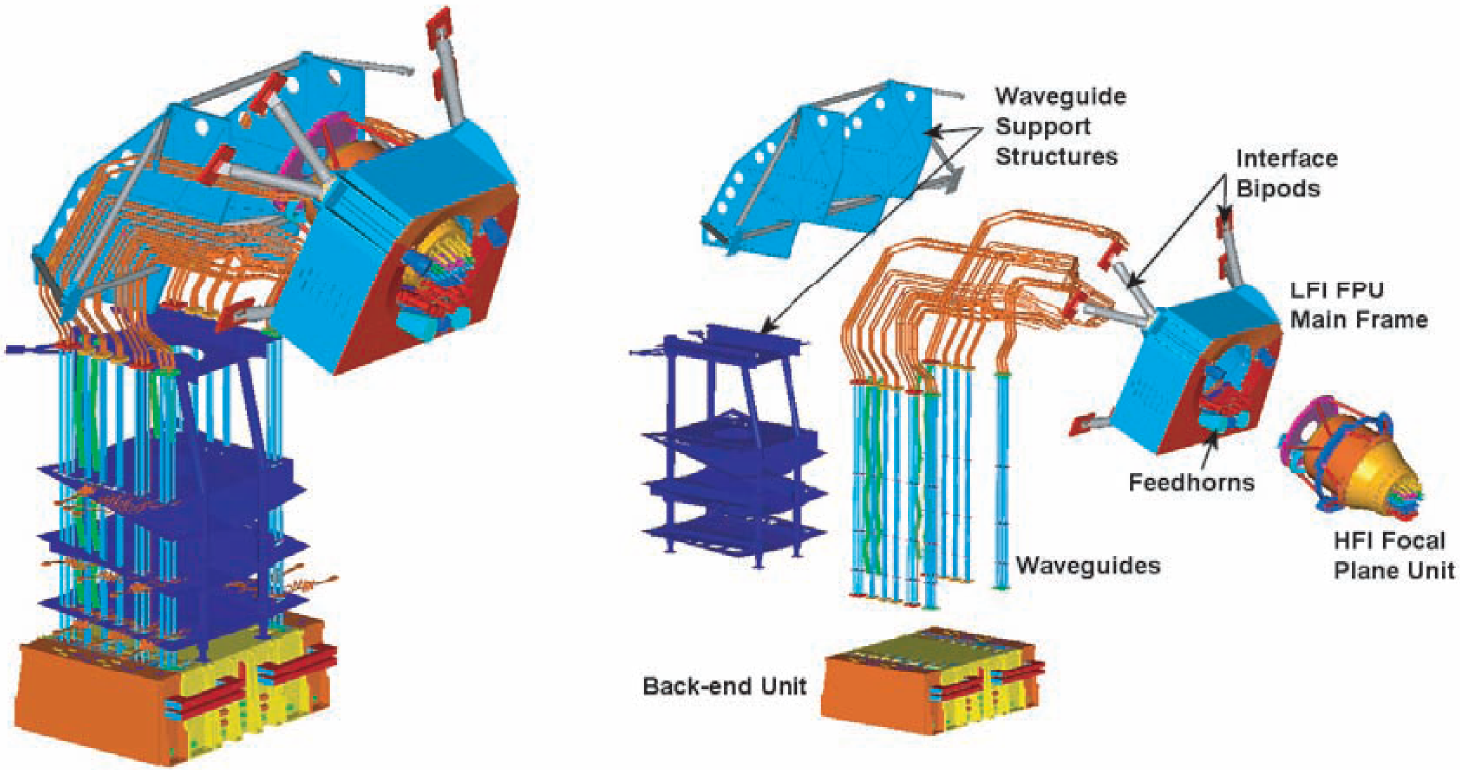
* Goal (in *μ*K/K) for 14 months integration, 1*σ*, for square pixels whose sides are given in the row "Angular Resolution".



HFI and LFI FPU on spacecraft



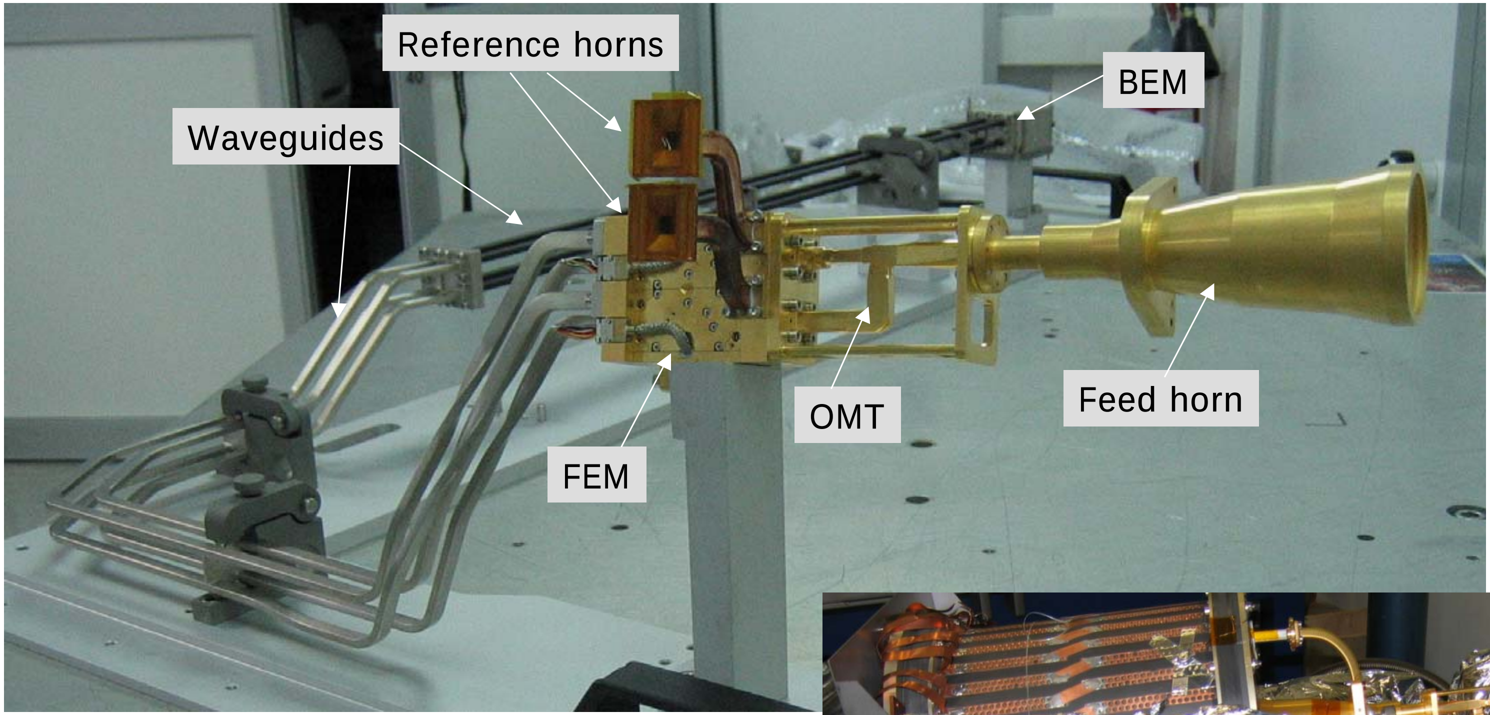
The Planck LFI Instrument



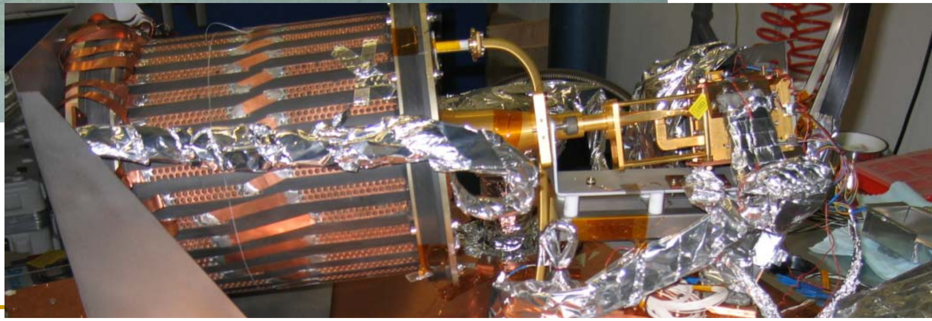
The LFI radiometer array assembly .
The front-ends are based on wide-band low-noise amplifiers, fed by corrugated feedhorns which collect the radiation from the telescope. The waveguides transport the amplified signals from the front-end (at 20 K) to the back-end (at 300 K). They are designed to meet simultaneously radiometric, thermal, and mechanical requirements, and are thermally linked to the three V-groove thermal shields of the *Planck* payload module. The back-end unit, located on top of the *Planck* service module, contains additional amplification as well as the detectors, and is interfaced to the data acquisition electronics. The HFI is inserted into and attached to the frame of the LFI focal-plane unit.

- LFI take advantage of transistor amplifier technology particularly for low noise performance and reliability of criogenically cooled indium phosphide (InP) high-electon-mobility transistors (HEMTs).
- HEMTs exhibit the best noise performance in the LFI frequency range.

LFI contains 11 feed horns and 22 radiometers



30 GHz Radiometer chain



Systematics effects

- Main Beam distortion
- Istrument Intrinsic
- External Straylight (dominates at high galactic latitude, crucial for polarization measurements)
- Thermal effects (due to ext. & int.source, crucial out of 1’- 60’ range)
- Pointing (affects recovery of beam resolution & angular resolution>>> accuracy 1’ at 2σ level)

4K Load

4K Load

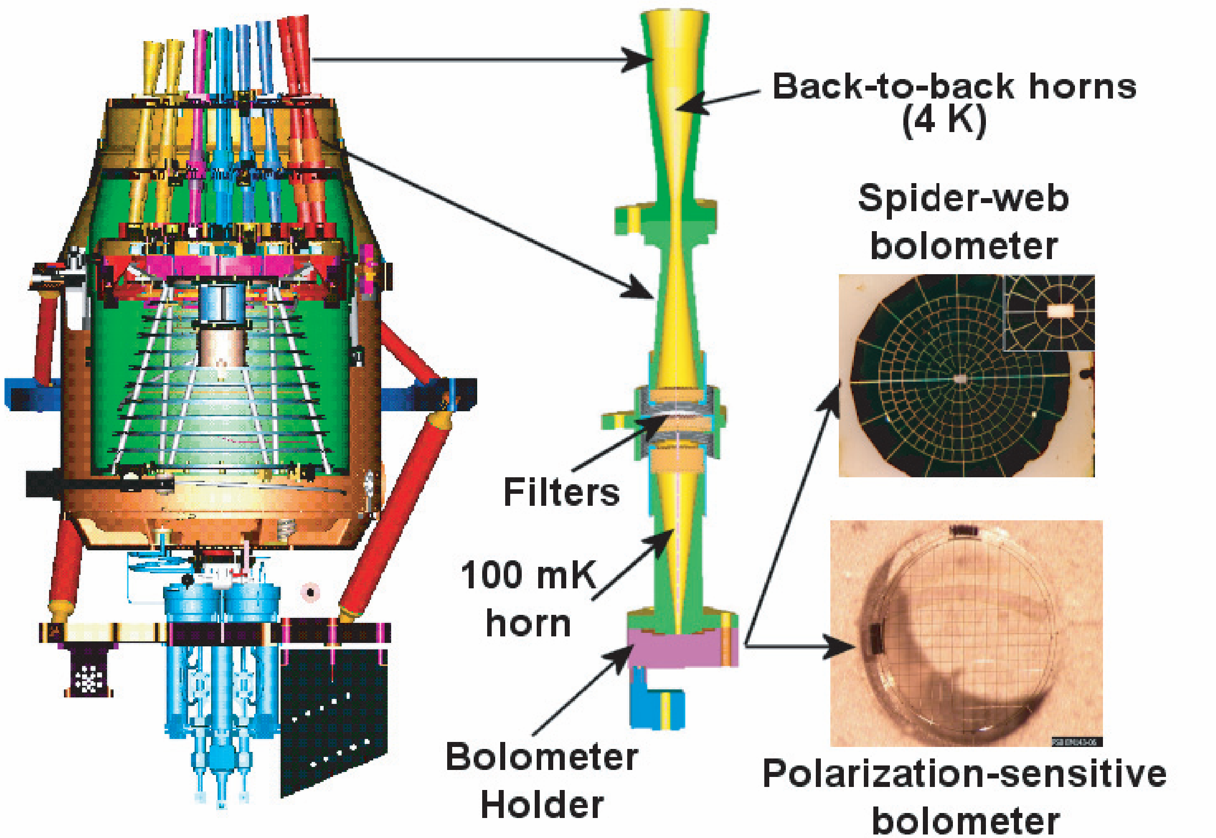
- It a critical part of LFI
- The 54 receivers of LFI follow a correlation scheme observing continuosly the sky and the stable reference load a T~4K
- 4K Load is made of 54 absorbing targets mechanically and thermally connected to HFI cryostat.

LFI PERFORMANCE GOALS

INSTRUMENT CHARACTERISTIC	CENTER FREQUENCY [GHz] 30	44	70
InP HEMT Detector technology	MIC		MMIC
Detector temperature		20K	
Cooling system		H2 Sorption Cooler	
Number of feeds	2	3	6
Angular resolution [arcminutes FWHM]	33	24	14
Effective bandwidth [GHz]	6	8.8	14
Sensitivity [mK $Hz^{-1/2}$]	0.17	0.20	0.27
System temperature [K]	7.5	12	21.5
Noise per 30 reference pixel [μK]	6	6	6
$\Delta T/T$ Intensity b [10^{-6} μK/K]	2.0	2.7	4.7
($\Delta T/T$) Polarisation (Q and U) b [μK/K]	2.8	3.9	6.7
Maximum systematic error per pixel [μK]	< 3	< 3	< 3

All subsystems are designed to reach or exceed the performances of this table.
Average 1σ sensitivity per pixel (a square whose side is the FWHM extent of the beam),
In thermodynamic temperature units, achievable after 2 full sky surveys (14 months).

The Planck HFI Instrument

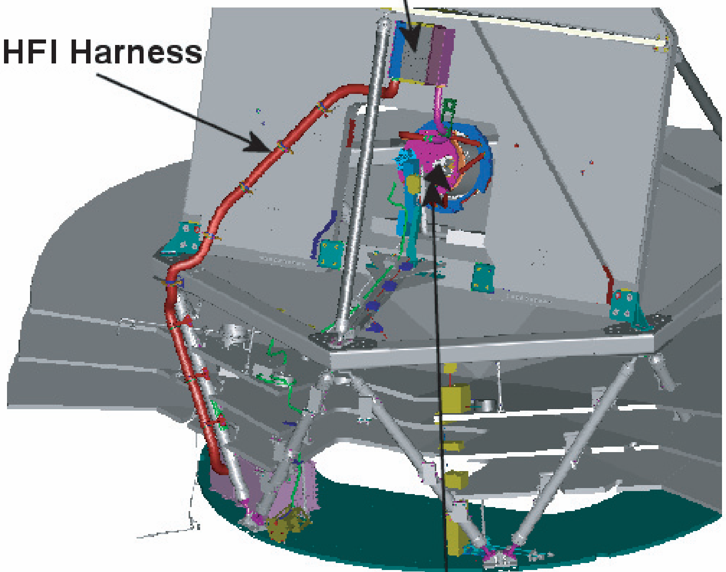


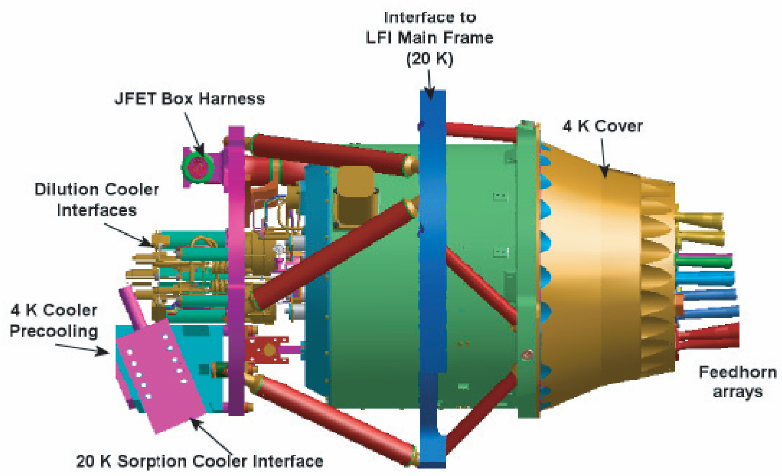
HFI performances

-HFI covers the frequency range between 100 and 1000GHz at 5' in 6 spectral bands.

-The detectors are bolometer cooled down to 100mK

-Its sensitivity will be limited, in CMB channels, by the statistical fluctuations of the CMB itself



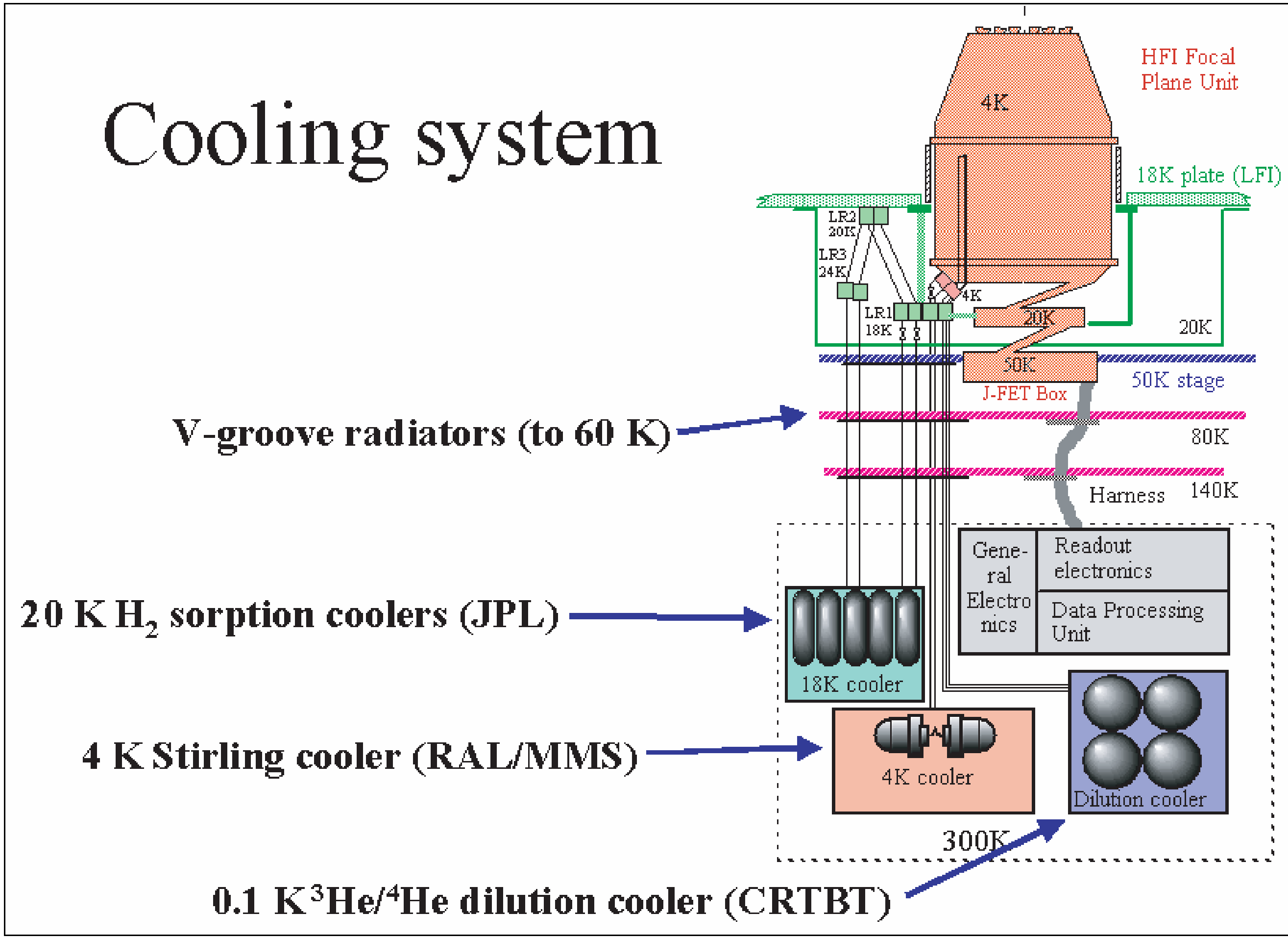


The HFI focal plane unit. The telescope focuses radiation at the entrance of the corrugated horns. This flux is then filtered and detected by the low temperature (0.1 K) bolometers. The attachment points for the 20 K, 4K, and 0.1K coolers are shown, as well as the entrance point of the harness. The harness is shielded by a flexible bellows, and leads the bolometer signals to JFET-based circuits mounted in a box on the frame of the telescope.
A second harness leads the signals to room-temperature electronics in the service module.

The Cryostat

4 K 4He JT cooler:

– Cools overall HFI structure to ~ 4 K; precools gas for dilution cooler;
- Cools LFI cold loads
 0.1 K 3He–4He dilution cooler
– Cools bolometers to 100 mK; JT expansion cools feeds, etc., to 1.6 K

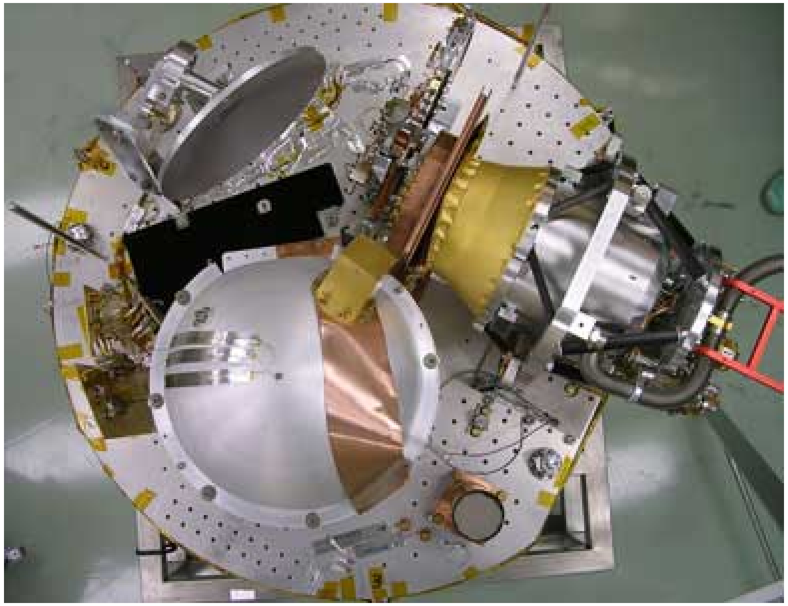


HFI PERFORMANCE GOALS

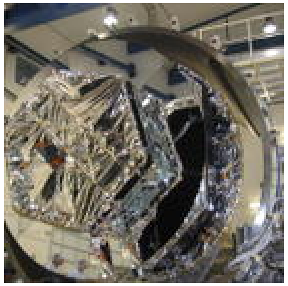
INSTRUMENT CHARACTERISTIC	CENTER FREQUENCY [GHz] 100	143	217	353	545	857
Spectral resolution $\nu/\Delta\nu$	3	3	3	3	3	3
Detector technology	Spider-web and polarisation-sensitive bolometers					
Detector temperature	0.1K					
Cooling system	20K Sorption Cooler + 4K J-T + 0.1K Dilution					
Number of spider-web bolometers	0	4	4	4	4	4
Number of polarisation-sensitive bolometers	8	8	8	8	0	0
Angular resolution [FWHM arcminutes]	9.5	7.1	5.0	5.0	5.0	5.0
Detector Noise-Equivalent Temperature [$\mu K s0.5$]	50	62	91	277	1998	91000
$\Delta T/T$ Intensity b [10−6μK/K]	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ Polarisation (U and Q)b [10−6μK/K]	4.0	4.2	9.8	29.8		
Sensitivity to unresolved sources [mJy]	12.0	10.2	14.3	27	43	49
ySZ per FOV [10−6]	1.6	2.1	615	6.5	26	605

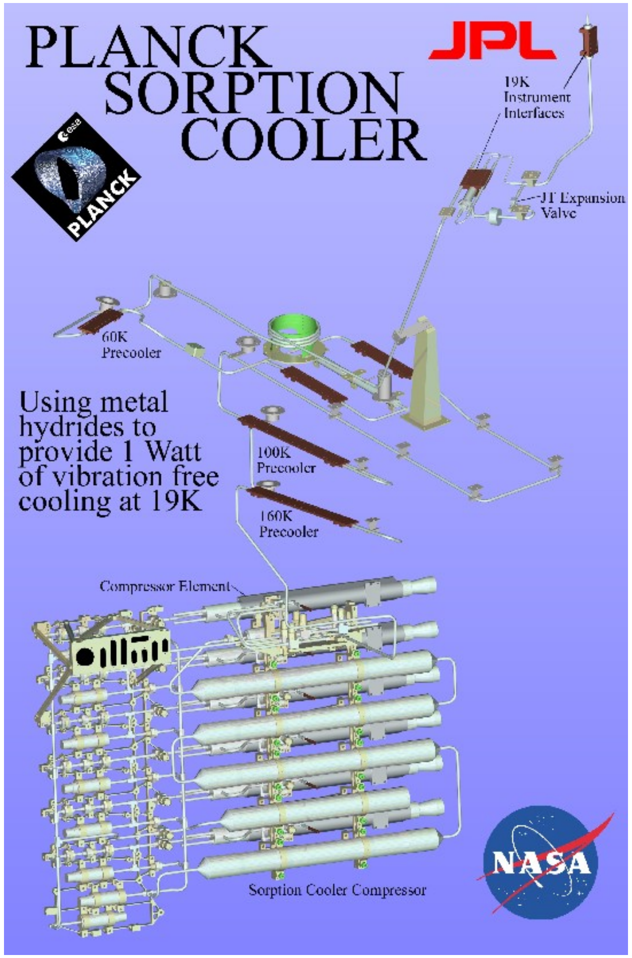
All subsystems have been designed to reach or exceed the performances of this table, which are expected to be achieved in orbit. Sensitivity requirements are a factor of two worse, and would still Achieve the core scientific objectives of the mission.
Average 1σ sensitivity per pixel (a square whose side is the FWHM extent of the beam), in Thermodynamic temperature units, achievable after 2 full sky surveys (14 months).

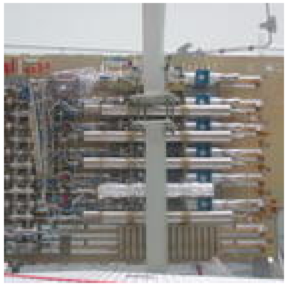
HFI



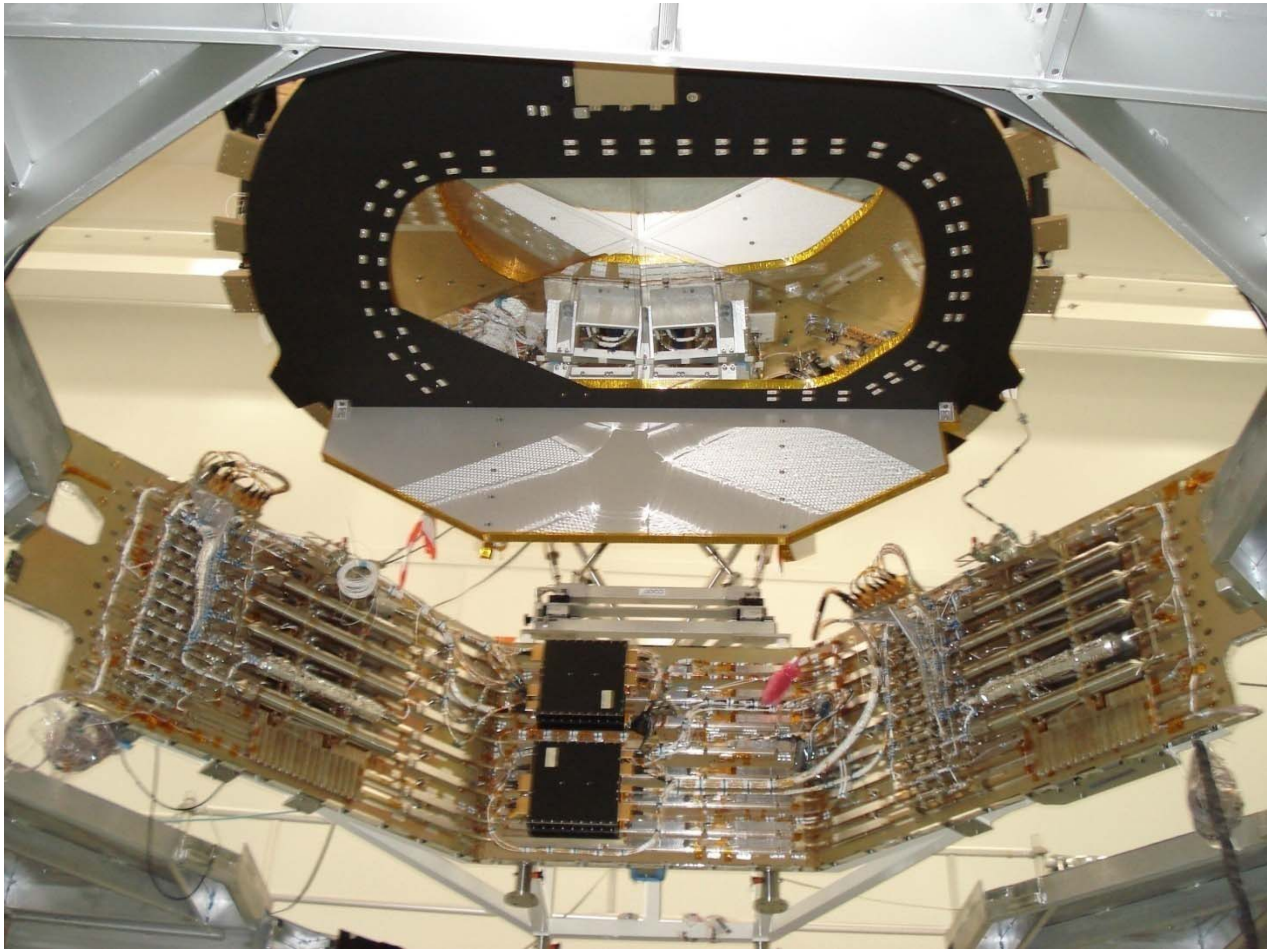
Planck Sorption Coolers on SVM Radiator Panels





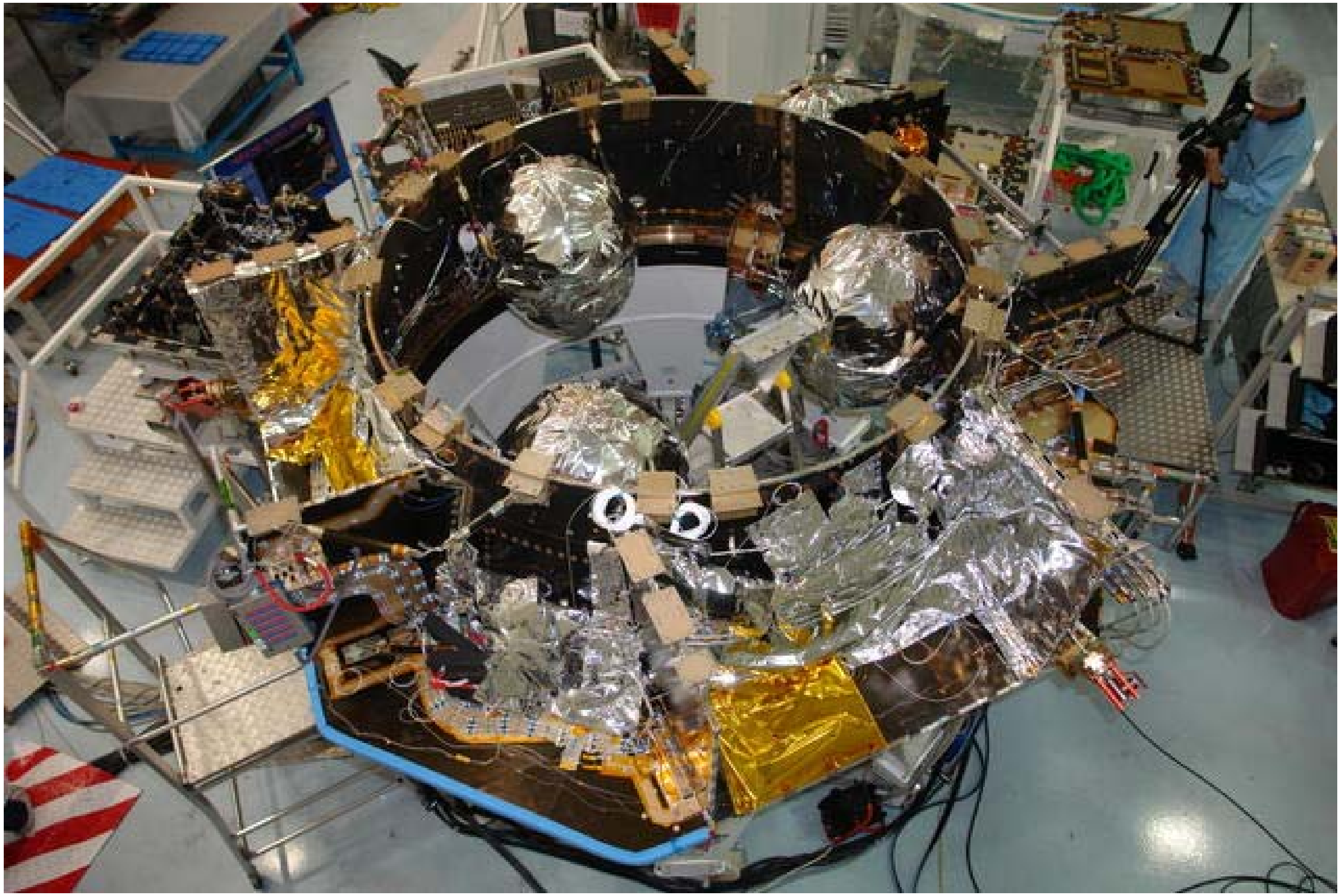


Sorption Cooler

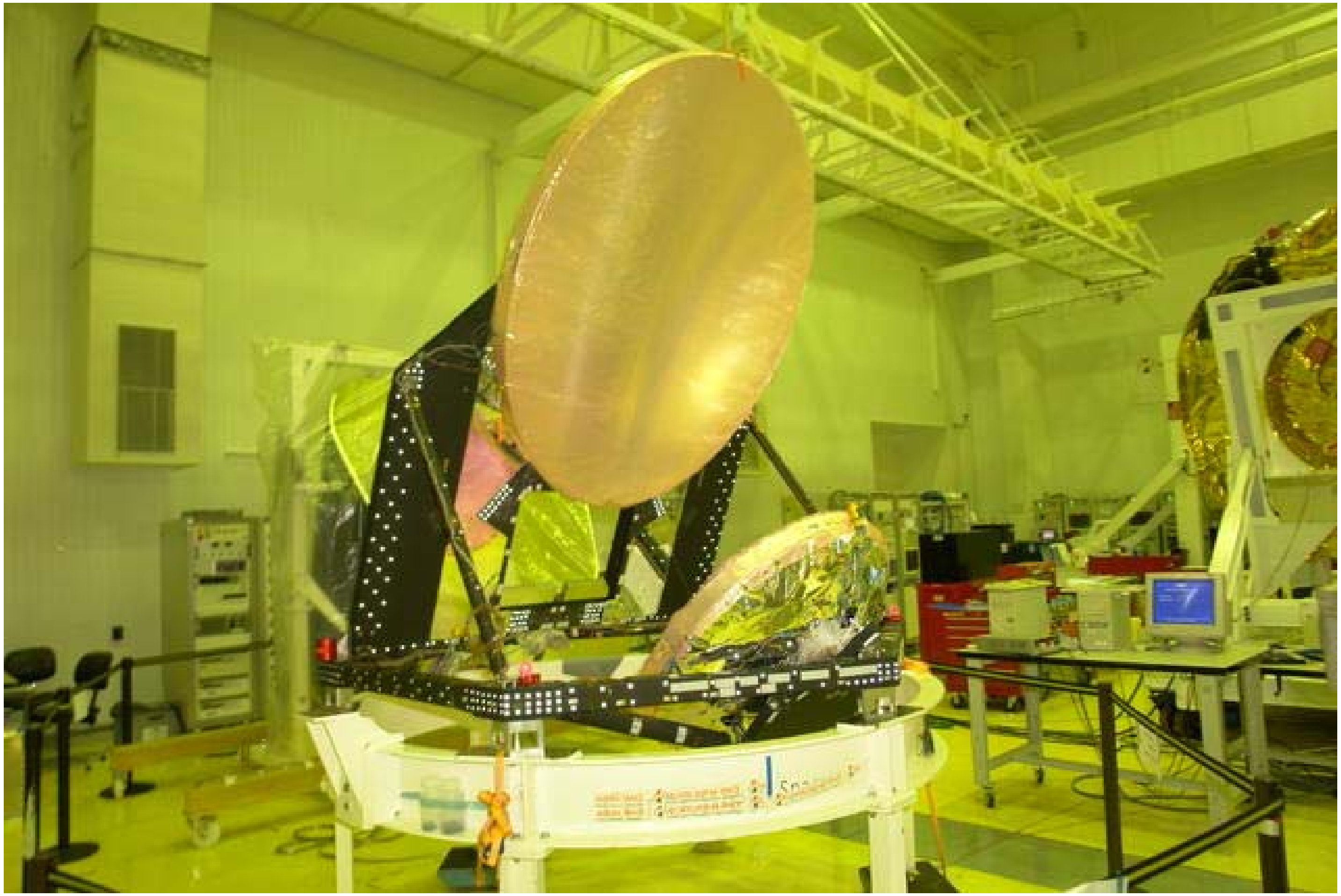


Planck principal cryogenic cooler system, a very new development of JPL (NASA) offering a new baseline for active high cooling power in cryogenic space missions

20 K hydrogen sorption cooler (fully redundant)
– Cools LFI to≤20 K
– Provides precooling to HFI at ~18 K



The telescope

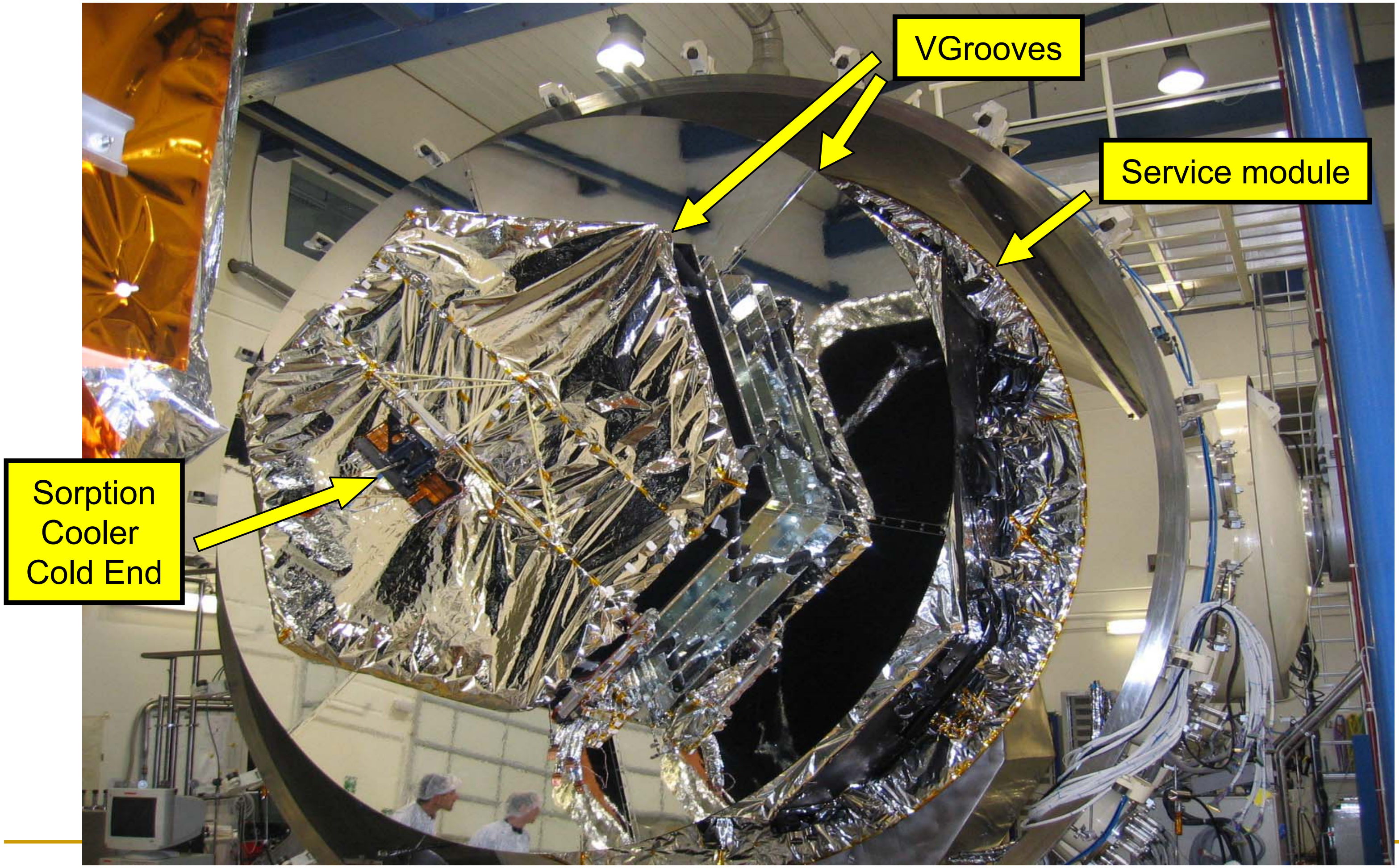


The telescope

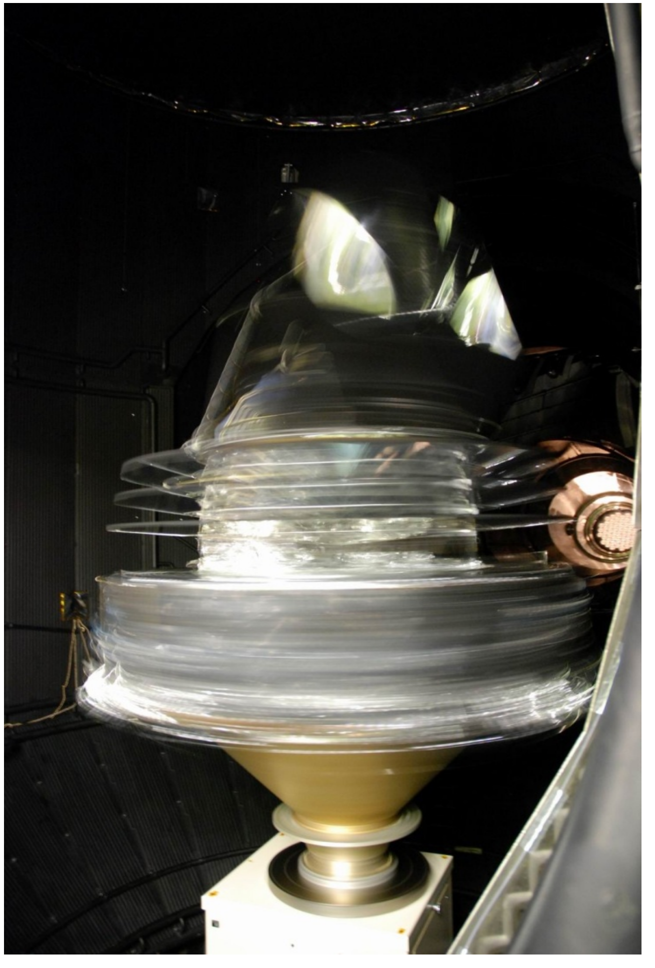
- It represents a challenge both for telescope technology and optical design
- It will operates at ~50 K (passively cooled)
- Electromagnetic models, verified in clean room, still need an infligh validation

- **Design**: Aplanatic optimized Gregorian
- **Frequency**: 25 – 1000 GHz
- **Temperature**: 50 K
- **Totale mass**: < 120 Kg
- **Lifetime**: 6 years on the ground + 2 years in space

Planck Spacecraft ready for Cryogenic Test (at CSL)



Fine balancing test at LSS (ESA)

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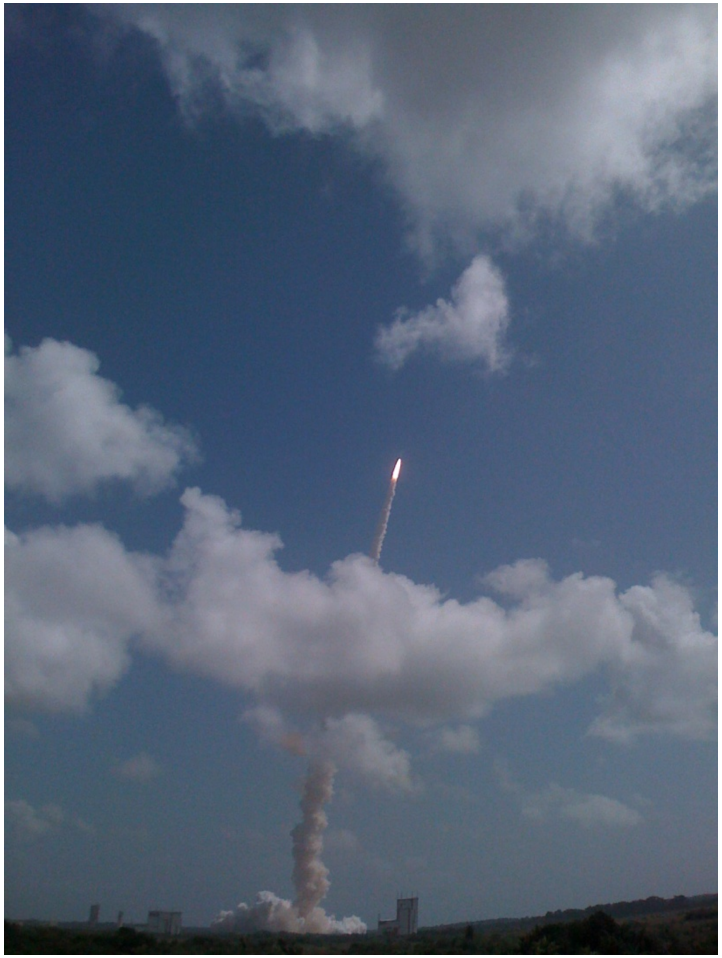
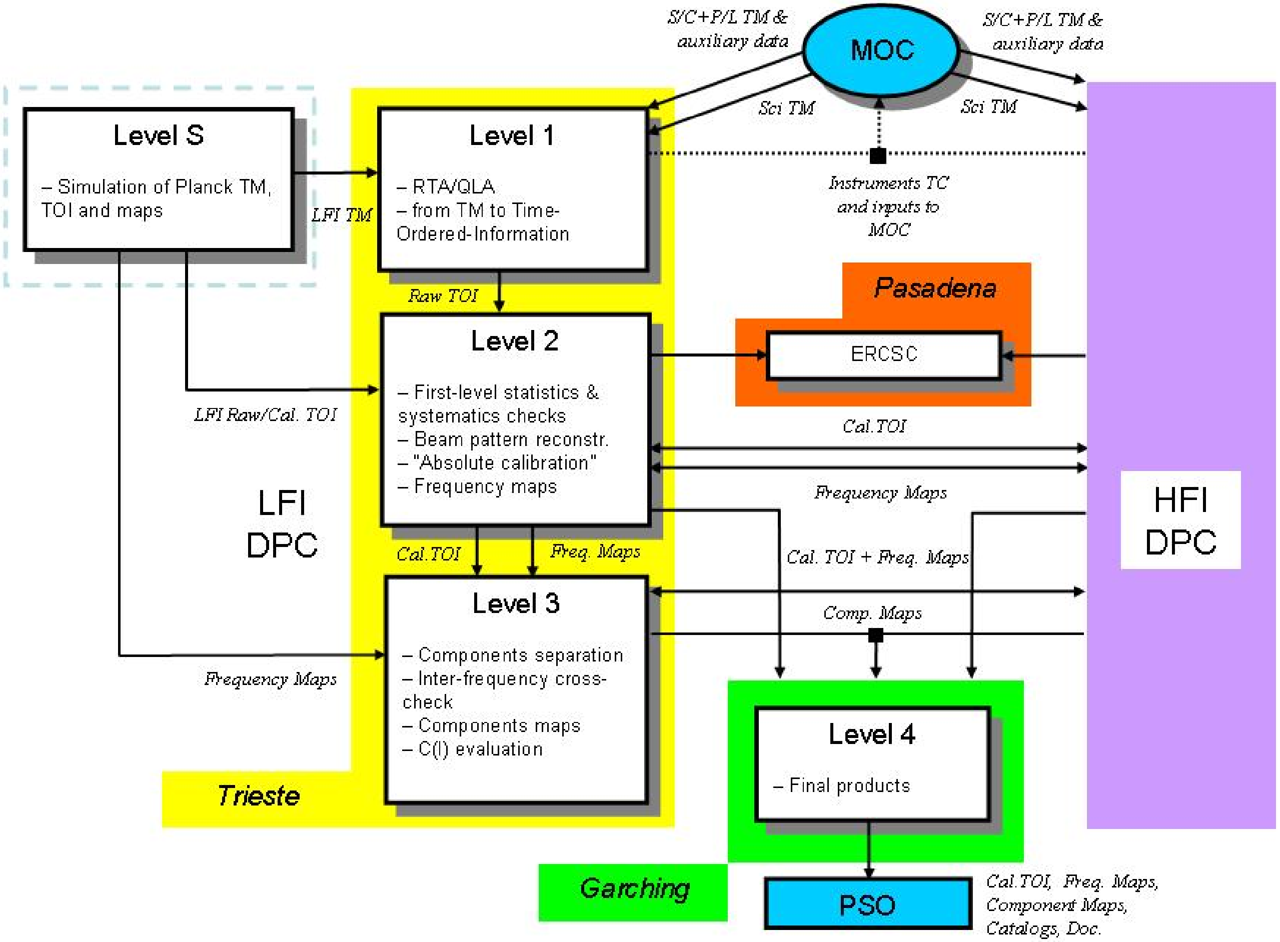


Data Processing Center

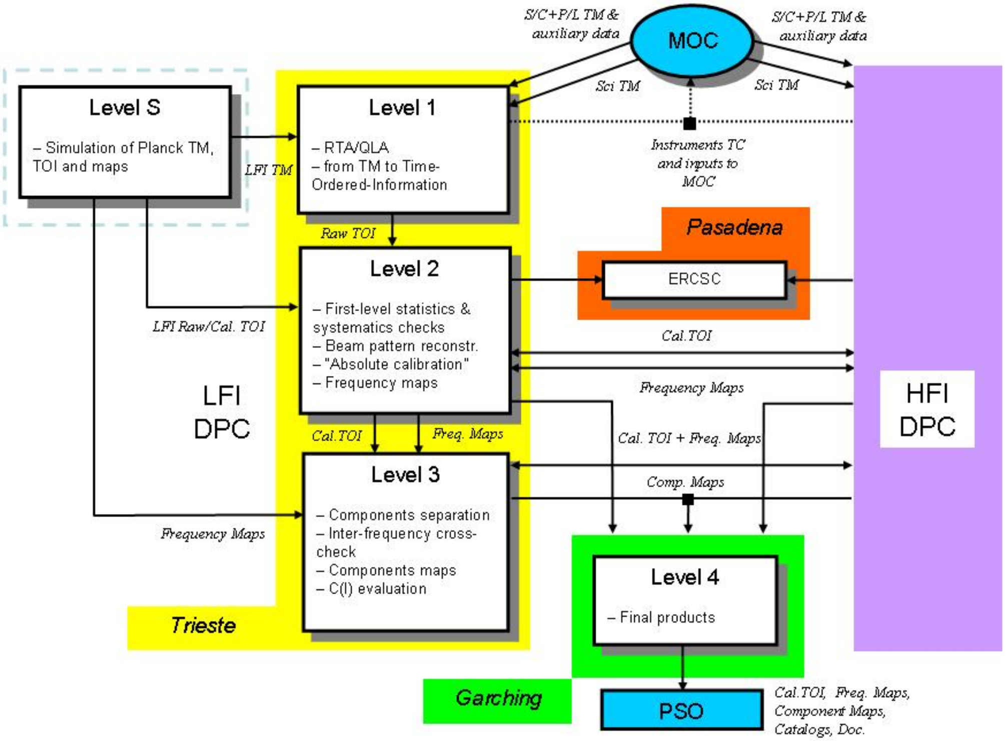
Scientific data will be sent daily from the MOC to Data Processing Centres (DPCs) Developed and operated by the Instrument Consortia. The DPCs are responsible for all levels of processing of the *Planck* data, from raw telemetry to deliverable scientific products.

- The success of the mission depends on the combination of measurements from both instruments.

Data Processing



The Data Processing Centre will transform the telemetry received from the satellite into the scientific results of the mission, using massive parallel computation.
The LFI and HFI DPCs share data and resources to achieve these ambitious goals

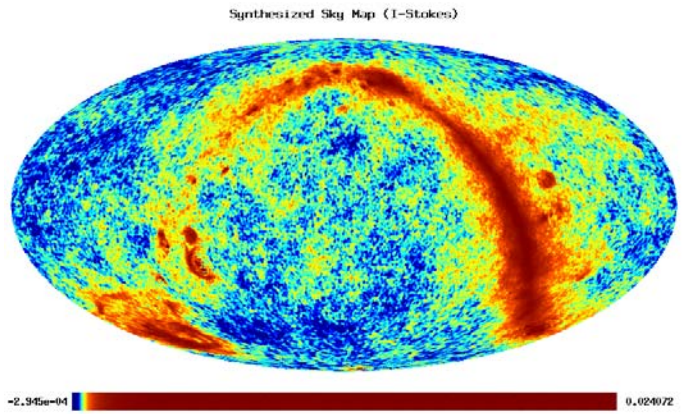


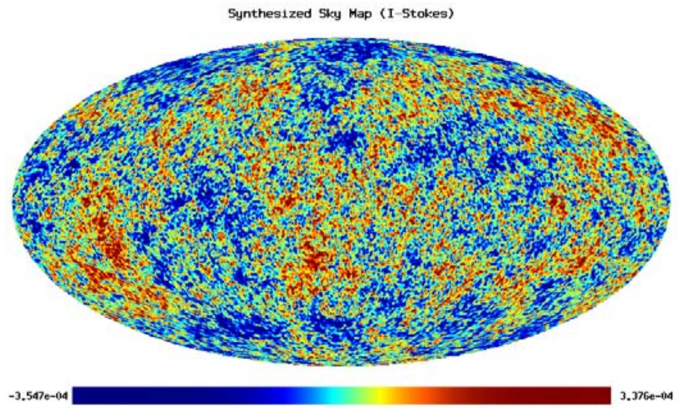
Level 1: telemetry processing and instrument control (no scientific processing of the data) direct interface with the ESA Mission Operations Centre (MOC) in Darmstadt;

- Level 2: data reduction and calibration (requires detailed instrument knowledge);
- Level 3: component separation and optimization (requires joint analysis of HFI and LFI data);
- Level 4: generation of final products (reception, archiving, preparation of public release material, operated by MPA, Garching);
- Level S: simulation of data acquired from the *Planck* mission on the basis of a software system agreed upon across Consortia , operated by MPA, Garching

LFI operations are centralized in Trieste, where they are run jointly by the OAT and SISSA. The HFI DPC is a more distributed system, with Levels 1 and 2 distributed among several institutes, mostly located in the Paris area, but with some contributions from the UK. HFI Level 3 processing is concentrated in the UK at Cambridge University. Levels 4 and S are shared with the LFI.

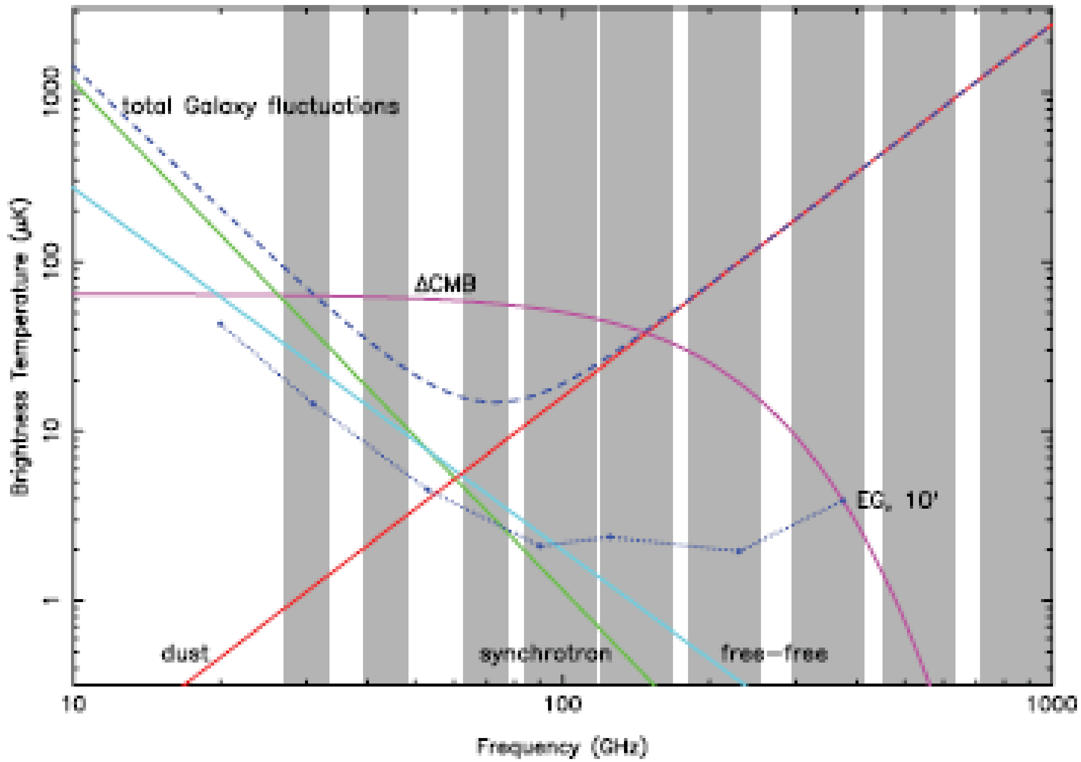
Although the primary goal of Planck is cosmology, it will provide data valuable for a broad range of astrophysics.





Main scientific goals

- Highly precise determination of fundamental cosmological parameters: age of the Universe, balance of different cosmological components (baryons, Dark Matter, Dark Energy), ‘re-ionization’ epoch, cosmological constant
- Understanding of the origin of the Universe: inflationary parameters, origin of primordial perturbations, detection of potential ‘non-gaussian’ features...
- Studing of gravitational lensing, reionization, galaxy clusters, clustering of dark energy, massive neutrinos, etc.
- Non CMB science:Galactic properties, extragalactic sources



Spectrum of the CMB, and the frequency coverage of the *Planck* channels. Also indicated are the spectra of other sources of fluctuations in the microwave sky. Dust, synchrotron, and free-free temperature fluctuation (i.e., unpolarized) levels correspond to the *WMAP* Kp2 levels (85% of the sky; Bennett et al. 2003). The CMB and Galactic fluctuation levels depend on angular scale, and are shown for ~1◦. On small angular scales, extragalactic sources dominate. The minimum in diffuse foregrounds and the clearest window on CMB fluctuations occurs near 70 GHz. The highest HFI frequencies are primarily sensitive to dust.

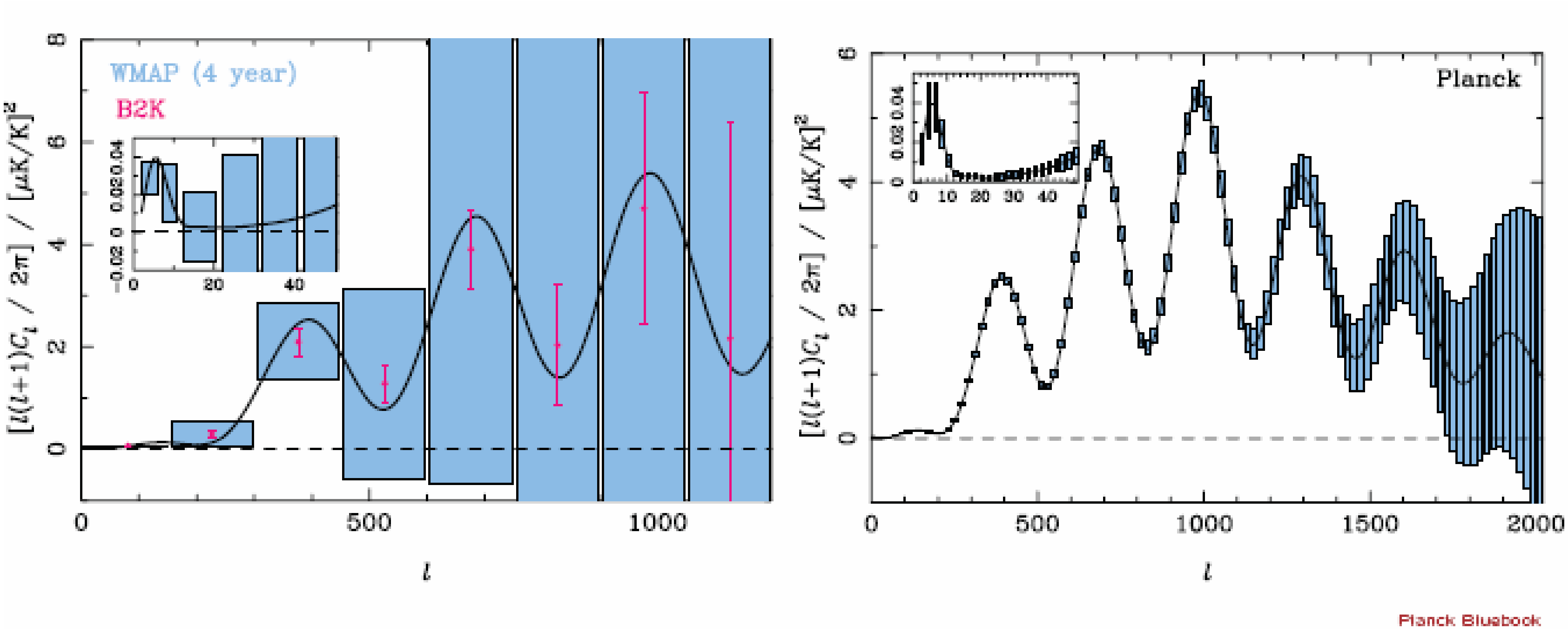
Polarization measurements

Planck will measure polarization about as well as WMAP measures temperature

All of the LFI channels, and four of the HFI channels, can measure Linear Polarization as well as intensity.

By combining the signals measured by several detectors, whose planes of Polarisation are rotated with respect to each other in multiples of 45°, the linear polarization of the incoming radiation can be determined fully. The horn location and orientation are chosen to optimise these measurements. Circular polarisation is not detectable by *Planck*.

Forecast on E-mode polarization spectrum



In plots above (WMAP 4 years; Planck 1 year), WMAP is averaged over $\Delta\ell = 100$. Planck is averaged over $\Delta\ell = 20$ in main plot, over $\Delta\ell = 2$ in inset.

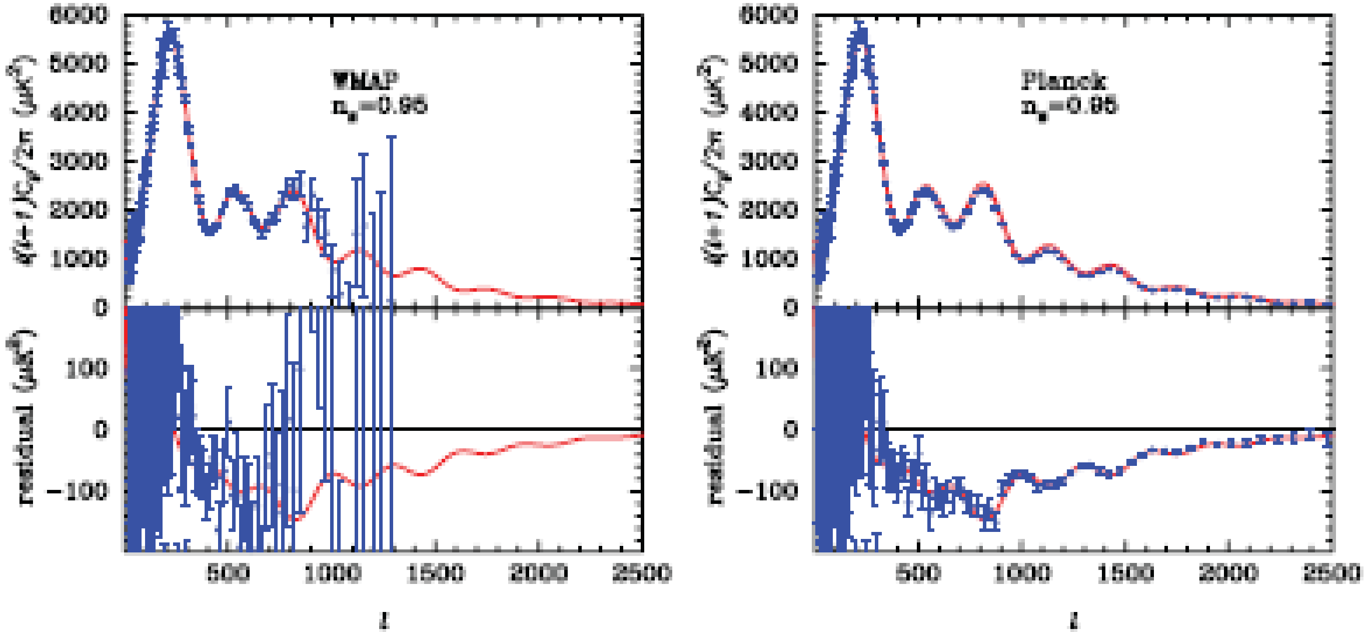


FIG. 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals between the points and the $n_S = 1$ model, and the solid lines show the theoretical expectation for these residuals. The left and right plots show simulations for *WMAP* and *Planck*, respectively.

LIFETIME

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- 2 surveys of the sky set to allow to compare two independent sets of observations
- Planck total lifetime is limited by the presence of on-board active coolers required to operate the Planck detectors, in particular:

- A dilution refrigerator using ^{3}He and ^{4}He, which cools the Planck bolometers to 0.1 K

- A hydrogen sorption refrigerator, which cools the Planck radiometers to 20 K and provides a first pre-cooling stage for the bolometer system.

The cooling system provides the potential for an increase in the lifetime of Planck of one year above its nominal one:

4 surveys of the sky!!!

The improvement in the scientific return due to this increase is considerable, particularly for measurements of the polarization of the CMB

The mission estension

- The main objective of the Planck mission is to measure temperature anisotropies in the CMB radiation with an accuracy set by fundamental astrophysical limits.
- Polarisation measurements were *not* part of the original goals

- the importance of high sensitivity polarization measurements of the CMB, especially of B-mode, are now widely recognized

- Now these measurements are considered as part of the core scientific objectives and of the data product deliverables.

THE FORESEEN IMPACT OF AN EXTENSION ON THE PLANCK MISSION

The additional 2 full sky surveys will:

- provide the additional redundancy required to enhance significantly the confidence and legacy value in the polarisation products, not only for CMB-related science, but also for a wide variety of astrophysical areas.
- allow Planck to reach the benchmark sensitivity of $r \sim 0.01$ in the quest for CMB B-mode detection, making it competitive with and complementary to other ground-based and sub-orbital experiments. The combination of Planck and other ongoing experiments offers the opportunity to measure the B mode spectrum over a wide multipole range.
- provide the basic understanding of polarised foregrounds on which to base the design of the next-generation B-mode satellite.

Deliverables

Deliverables will be produced by the two DPCs jointly, and will be made publicly available two years after completion of mission operations:

- 1 year to reduce the survey data into scientifically usable products
- 1 year of proprietary exploitation by the *Planck* Consortia.

Two years after termination of survey operations, the *Planck* data will be put into the public domain.

The major deliverables of the *Planck* mission

- Calibrated time-ordered data
- All-sky maps at each frequency
- All-sky component maps, including the CMB itself, plus Galactic synchrotron, free-free, and dust emission, etc.
- A final compact-source catalog, including galactic and extra galactic objects. This catalog will also include galactic clusters detected through the Sunyaev-Zeldovich effect.

Data Exploitation

The principal objective of *Planck* is to produce an all-sky map of the CMB.

As a byproduct of the extraction of the CMB, *Planck* will also yield all-sky maps of all the majorsources of microwave to far-infrared emission:

- the physics of dust at long wavelengths and the relative distribution of interstellar matter (neutral and ionized) and magnetic fields will be investigated using dust, free-free, and synchrotron maps
- a systematic search of the sky for dense, cold condensations which are the first stage in the star formation process (i.e. SZ effect).

The *Planck* all-sky surveys of foreground emission will constitute a rich astrophysical resource comparable to the IRAS and COBE-DIRBE maps at shorter wavelengths.

The goal of *Planck* is to obtain a photometric calibration of better than 1% across all frequency channels where the CMB is strong

The first data release

Based on two sky surveys (~100 paper):

- Calibrated data
- Frequency maps
- Component maps (CMB, synchrotron, dust, etc.)
- Source catalog
- Likelihood function

The Early Release Compact Source Catalog will be released 9 months after completion of the first all sky survey, i.e., approximately 16 months after the start of routine operations.

SCHEDULE

- Launch 14.05.2009

Cruise, cooldown, checkout	about 70 days
Mini Survey (14 day, last part of commissioning)	late July 2009
First sky survey	6 months up to Jan. 2010
Second sky survey	6 months up to July 2010
Extended mission	11-14 additional months (up to 2011, tbc)
ERCSC (based on first sky survey)	Dec 2010
Analyze first year data	24 months
Release results based on first year	Summer 2012

Conclusions

- Planck can be considered a kind of ultimate experiment in CMB

- Planck will also open to a new survey era : with such a great increase in capability over previous CMB missions we can also anticipate completely new Science. As well as several thousands of galaxies, of young stellar objects, of clustes of galaxies will be observed in a new way.

- PLANCK lifetime extension is fundamental not only for polarization data but for trhe whole users community