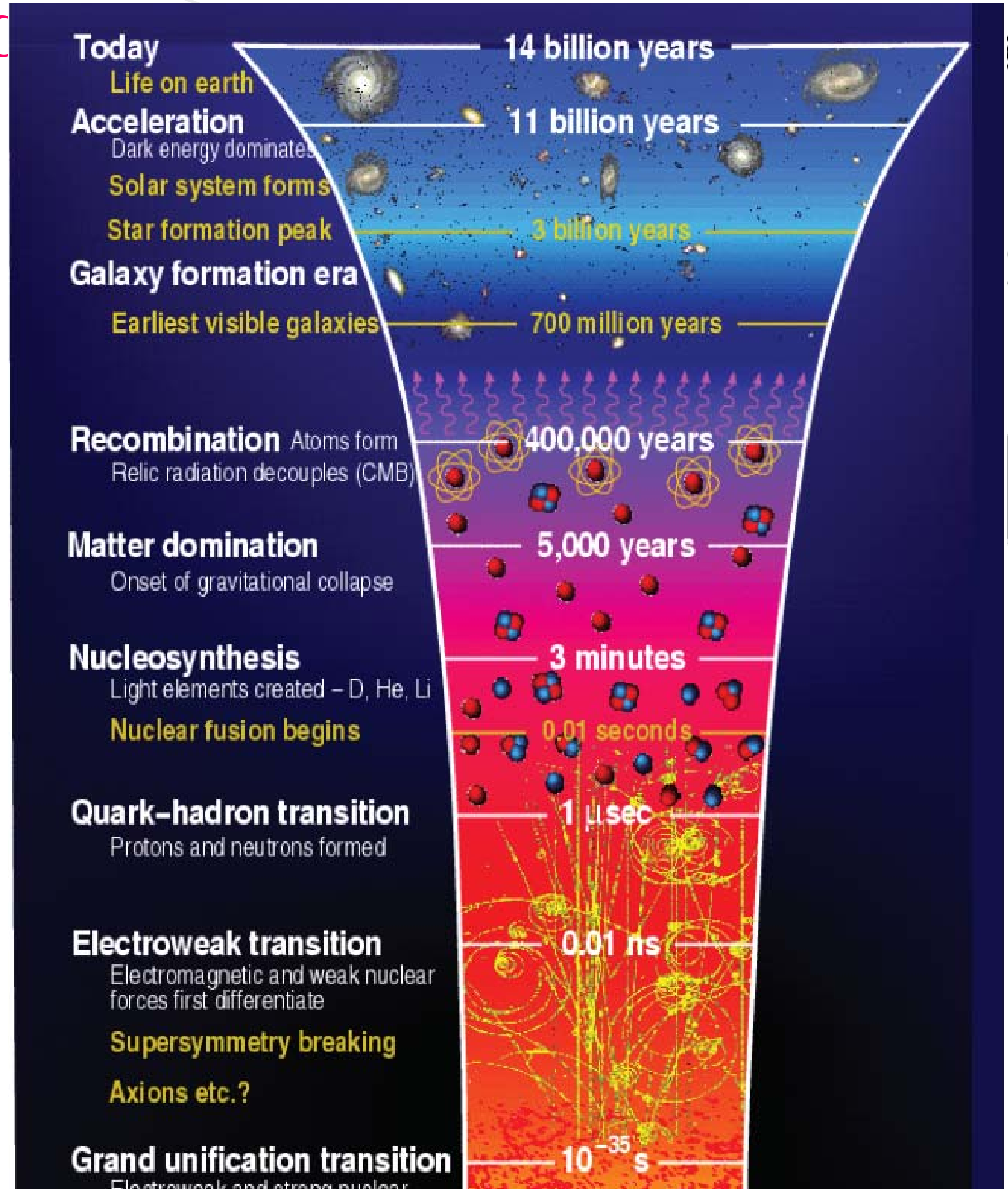
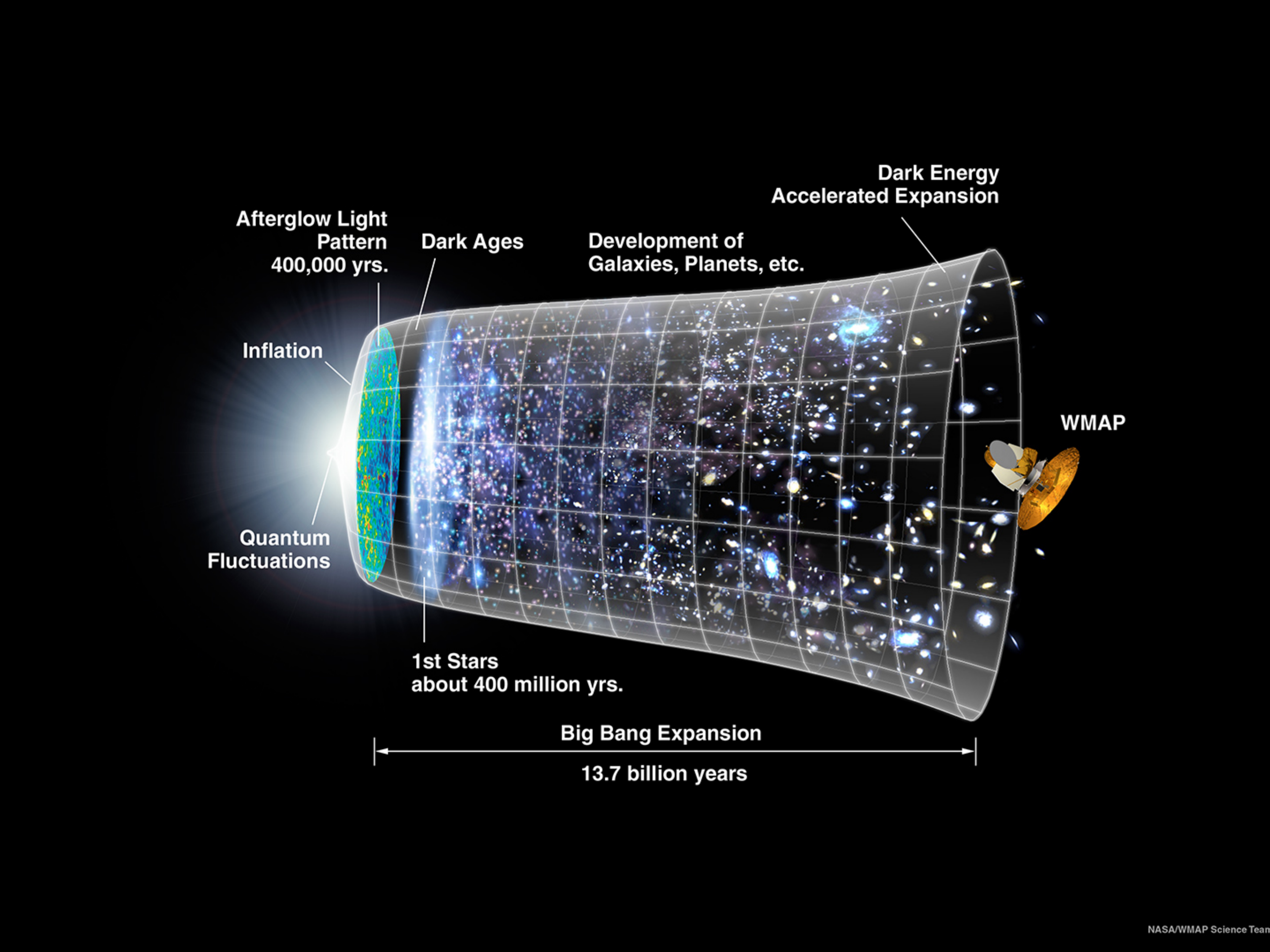
Penzias and Wilson Nobel Price in Physics 1978

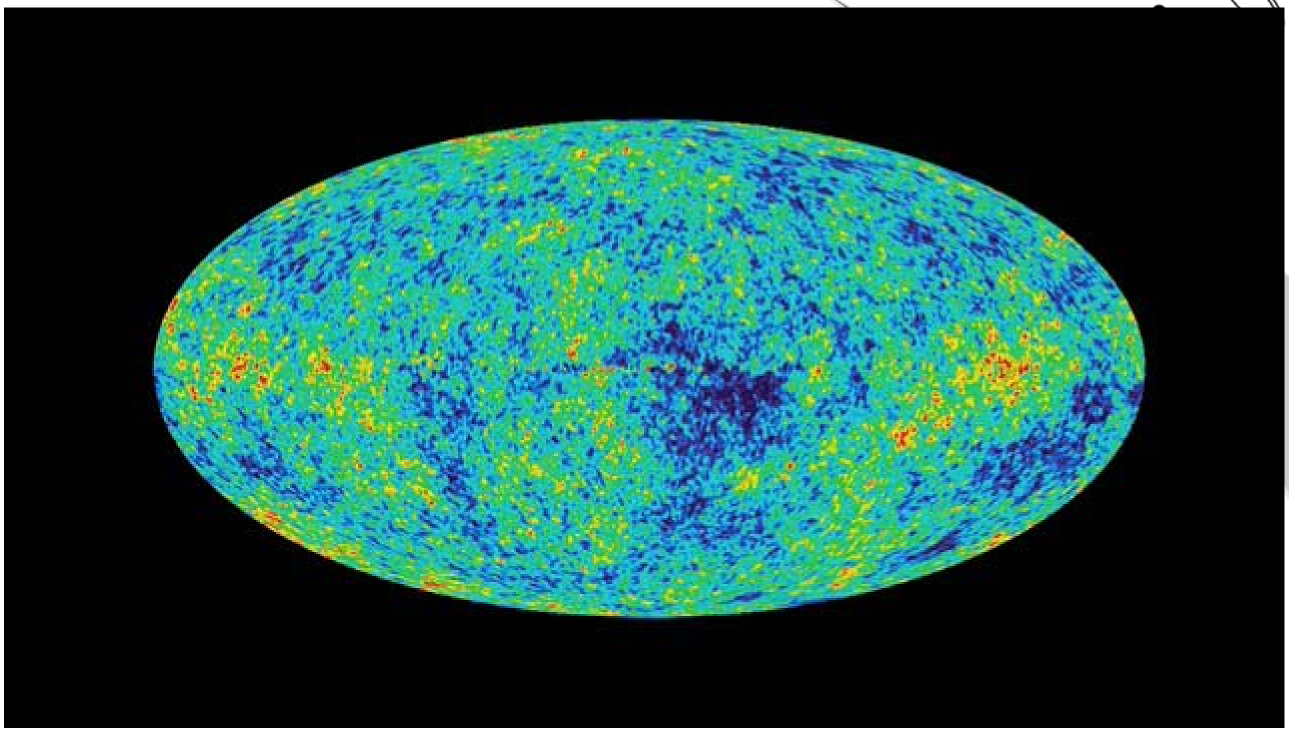
PLANC



Today
Life on earth
14 billion years
Acceleration
Dark energy dominates
11 billion years
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation decouples (CMB)
400,000 years
Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
Protons and neutrons formed
1 µsec
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
0.01 ns
Supersymmetry breaking
Axions etc.?
Grand unification transition
10^{-35} s

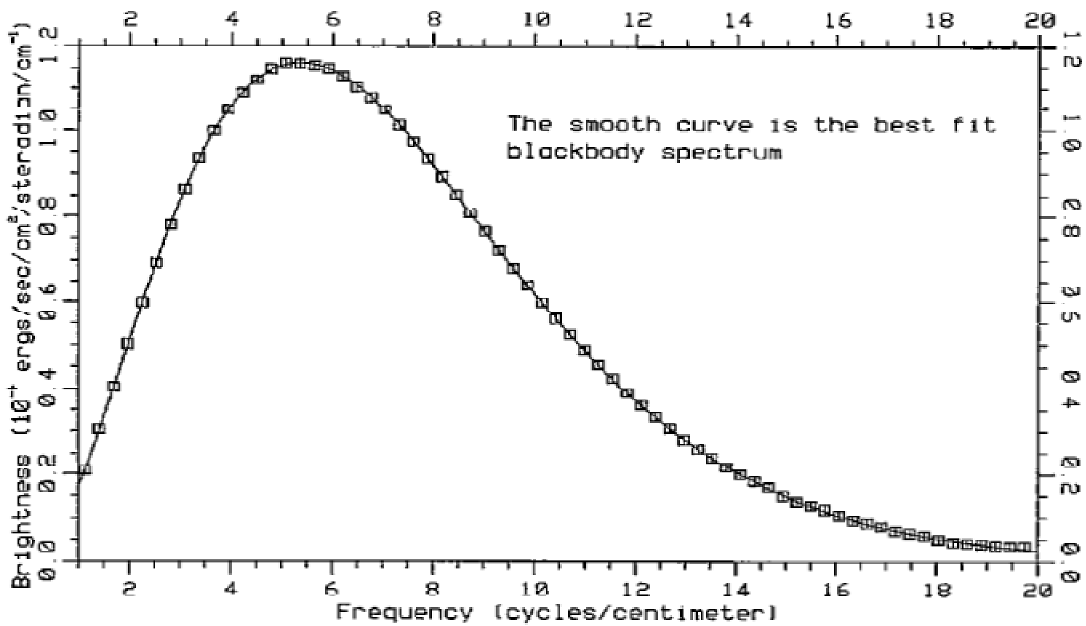

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

PLANCK Reflector Programme



PLANCK Reflector Programme

Figure 7 shows the deviations from a blackbody spectrum with a temperature of 2.726 ± 0.010 K published 1994 (Mather et al. 1994). After careful studies of errors caused by the FIRAS calibrator (figure 4), the CMB temperature was finally given as 2.725 ± 0.002 K (Mather et al. 1999) with deviations from a blackbody spectrum less than 1 part in 10^5.



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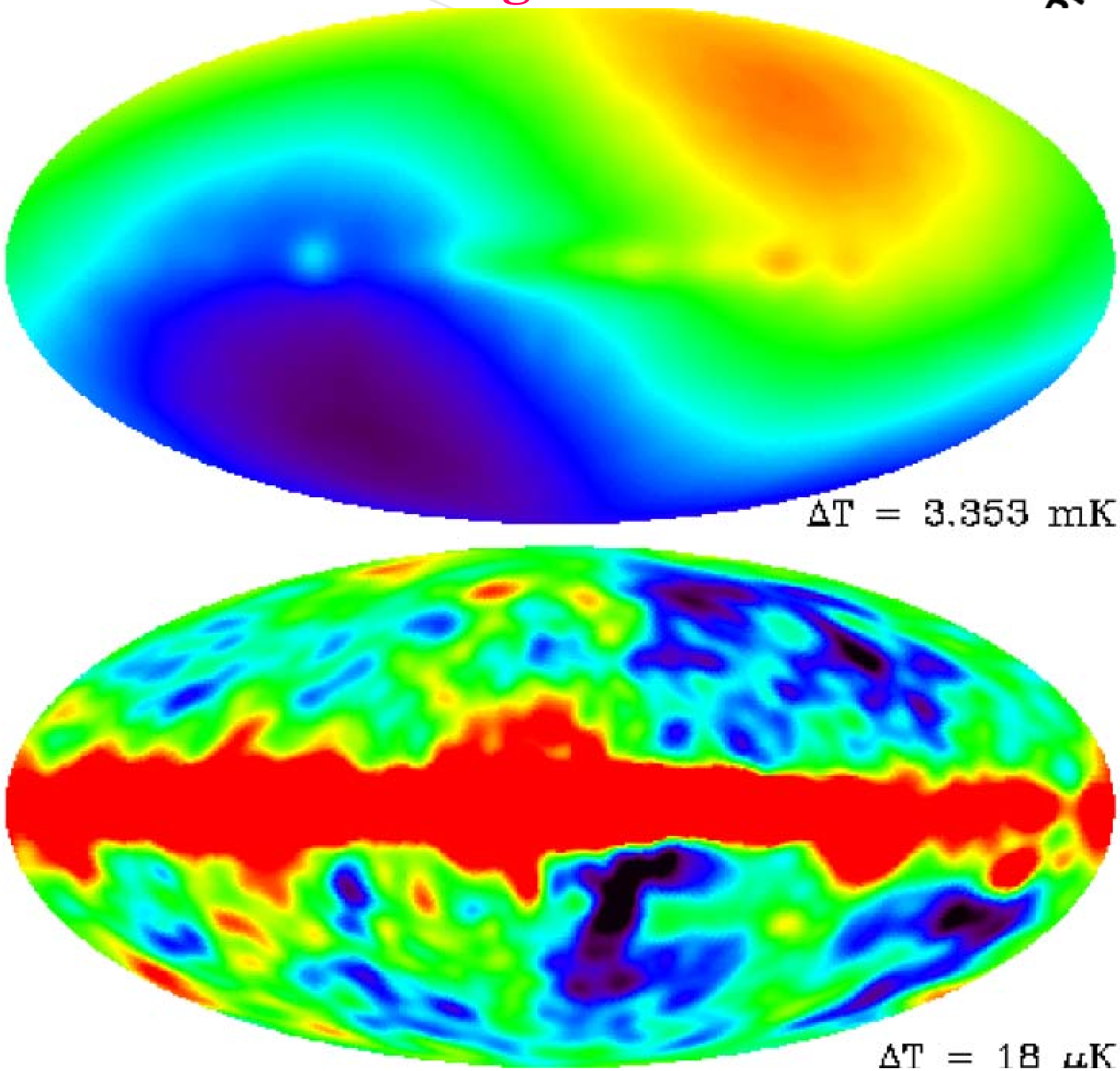
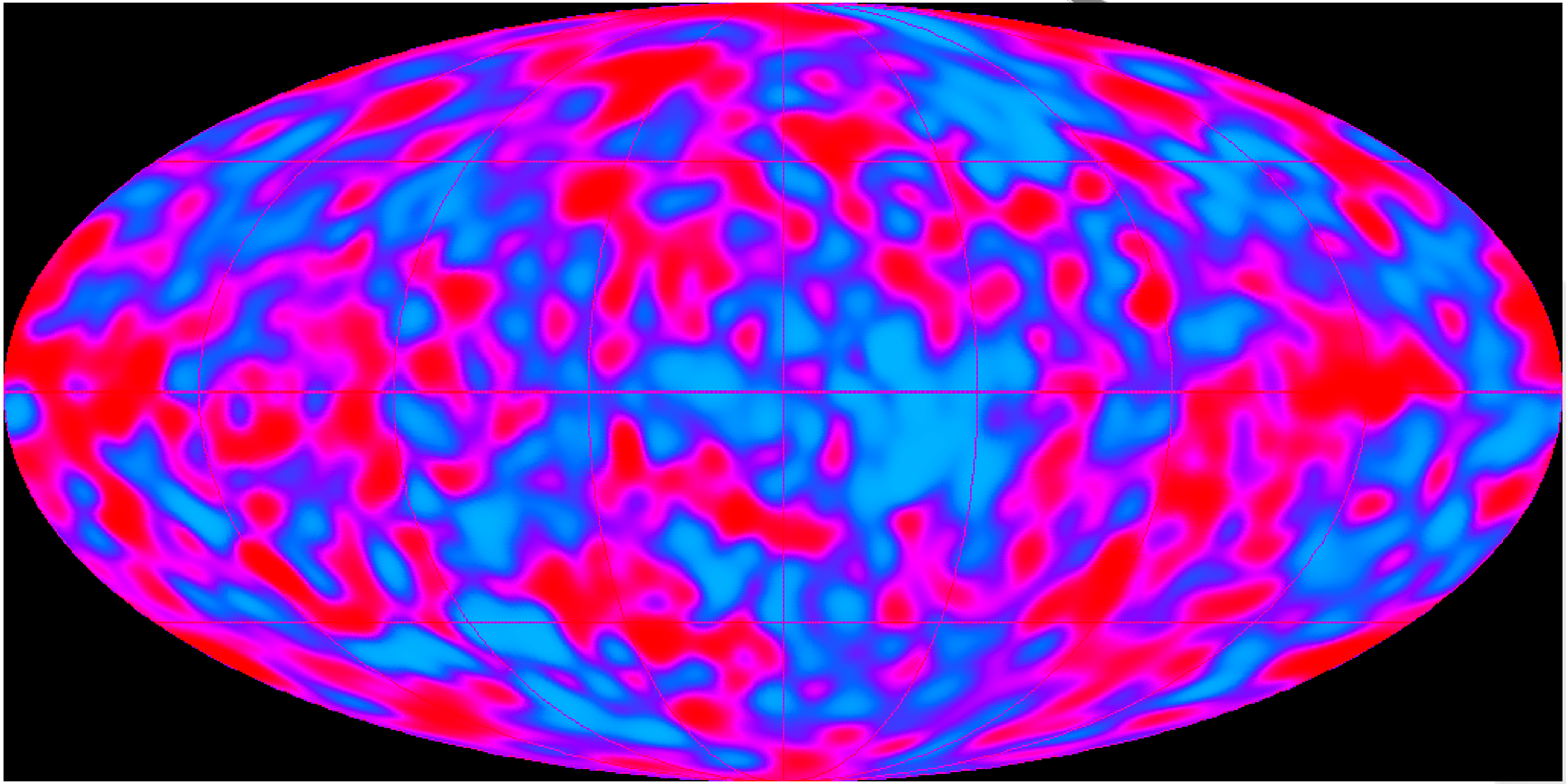


PLANCK Reflector Programme



PLANCK Reflector Programme

The Nobel Prize in Physics 2006

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

Photo: NASA

John C. Mather

1/2 of the prize

USA

NASA Goddard Space Flight Center
Greenbelt, MD, USA

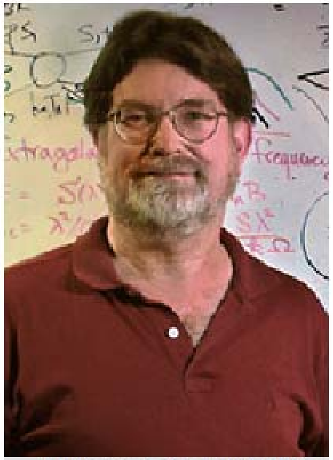


Photo: R. Kaltschmidt/LBNL

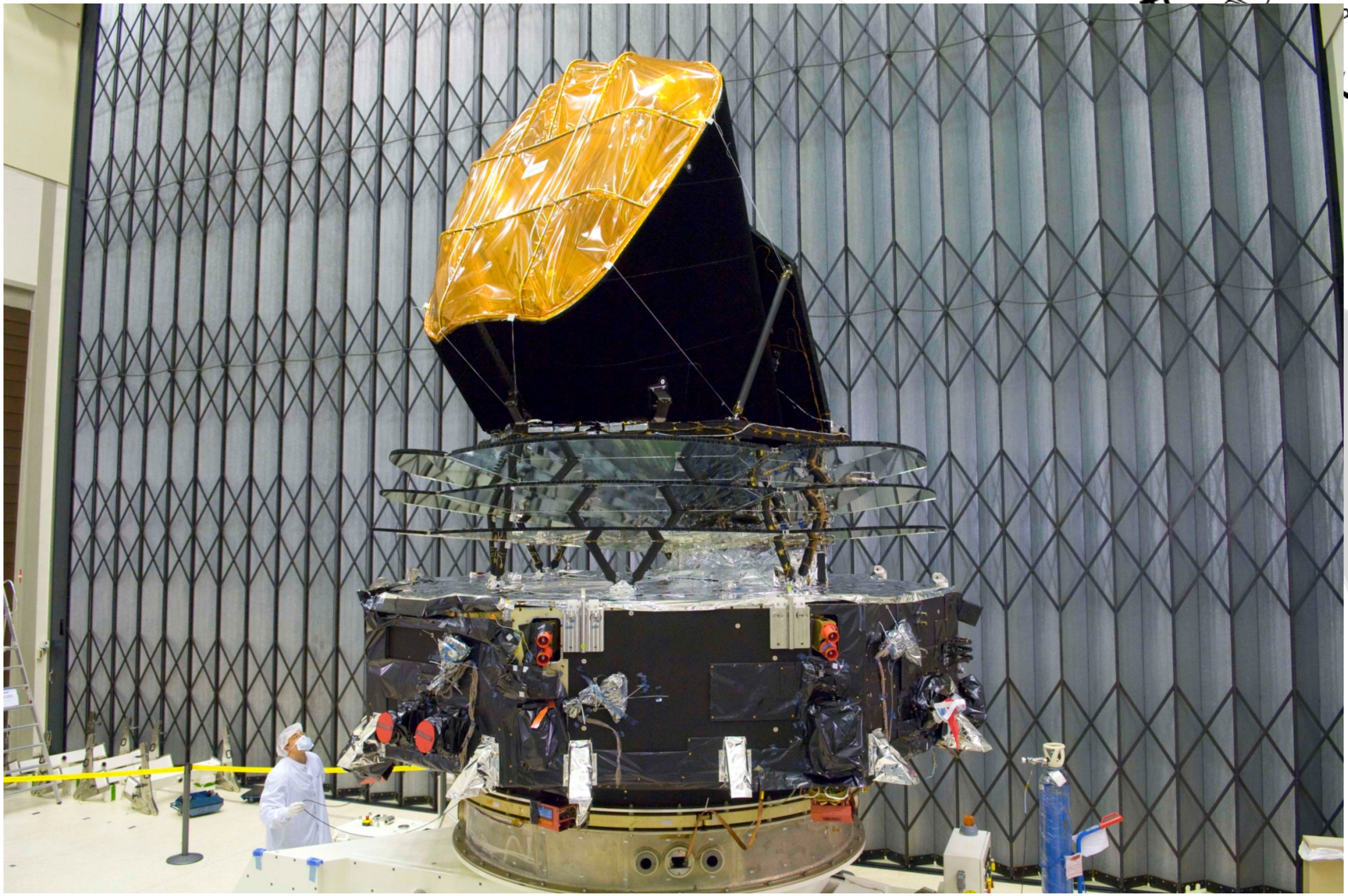
George F. Smoot

1/2 of the prize

USA

University of California
Berkeley, CA, USA

PLANCK Reflector Programme



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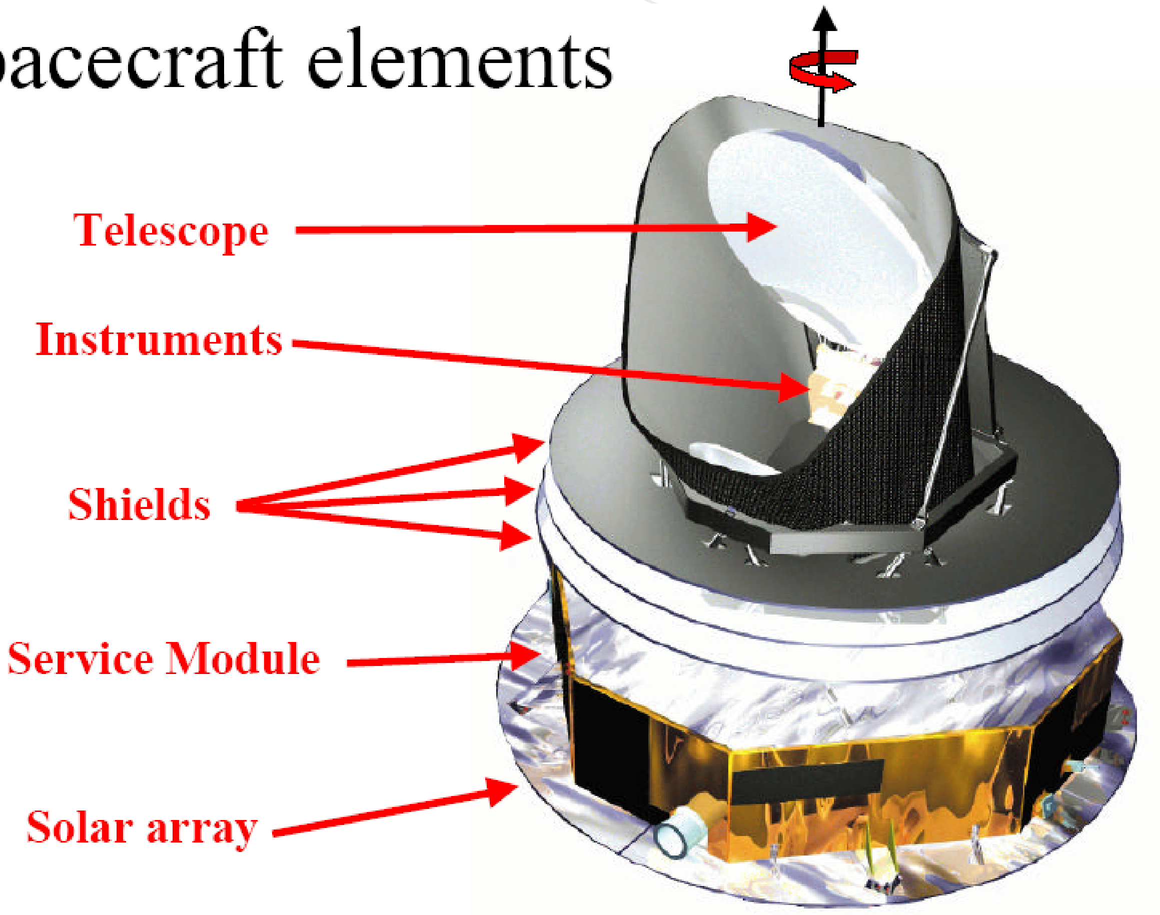
Spacecraft elements

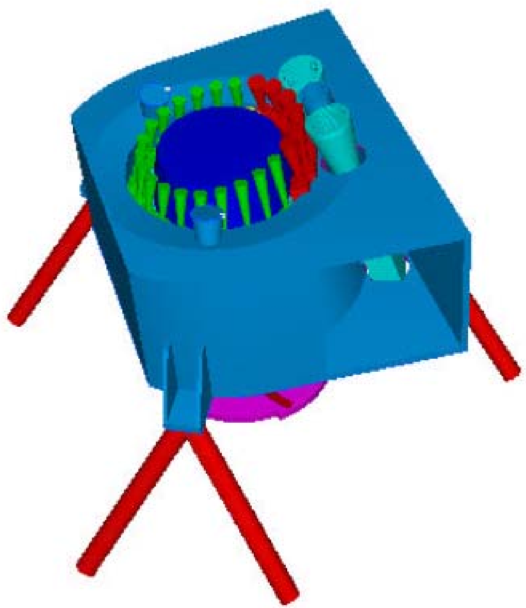


PLANCK Reflector Programme

Planck Reflectors
DSRI • ESA • DK-PLANCK

Low Frequency Instrument

- Freq.: 30 -100 GHz
- Techn.: HEMT correlation receivers (56)
- Temp.: 20 K (Front-end), 300 K (Back-end)
- Ang. res.: 10' (100 GHz) to 33' (30 GHz)
- Temp. sens. (@100 GHz): ~12 μK
- PI: N. Mandolesi (CNR - Bologna)



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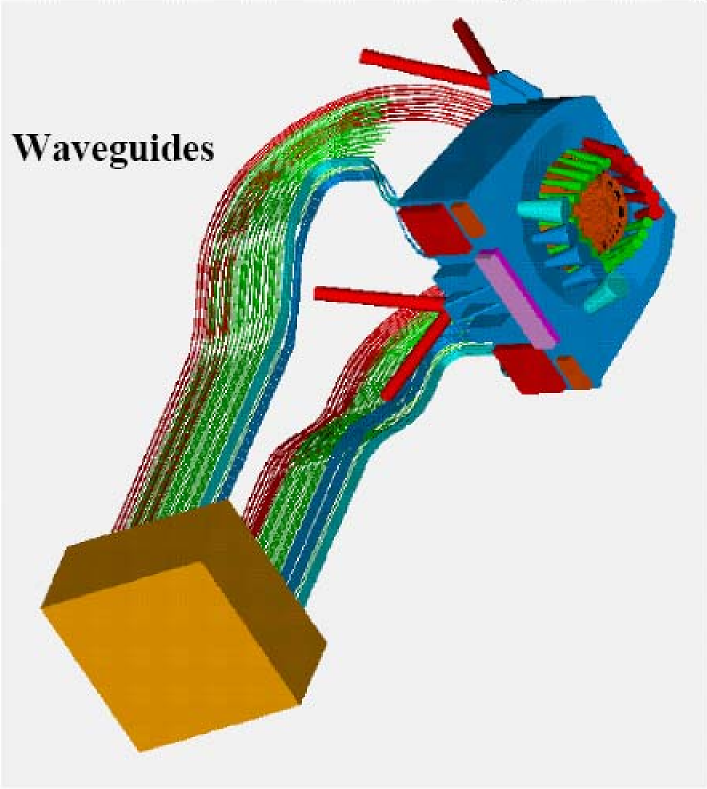
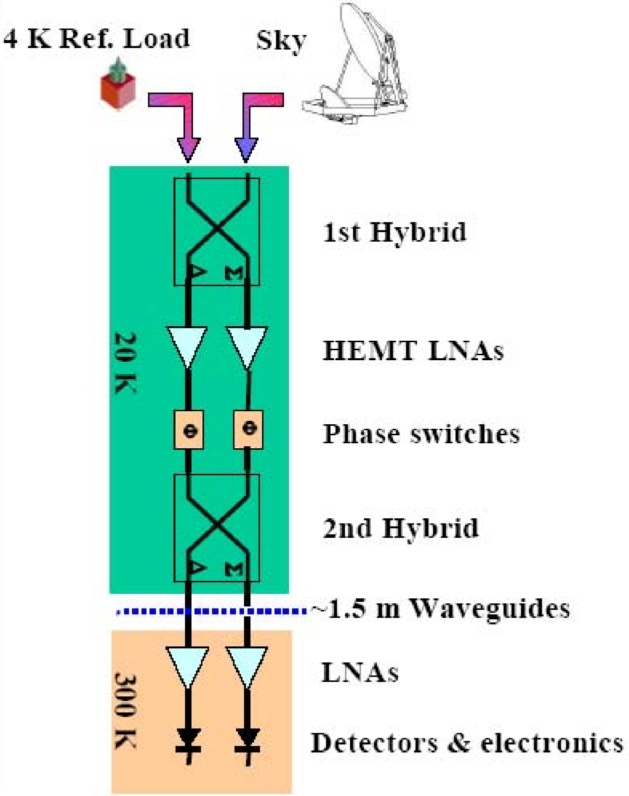
PLANCK Reflector Programme

Low Frequency Instrument





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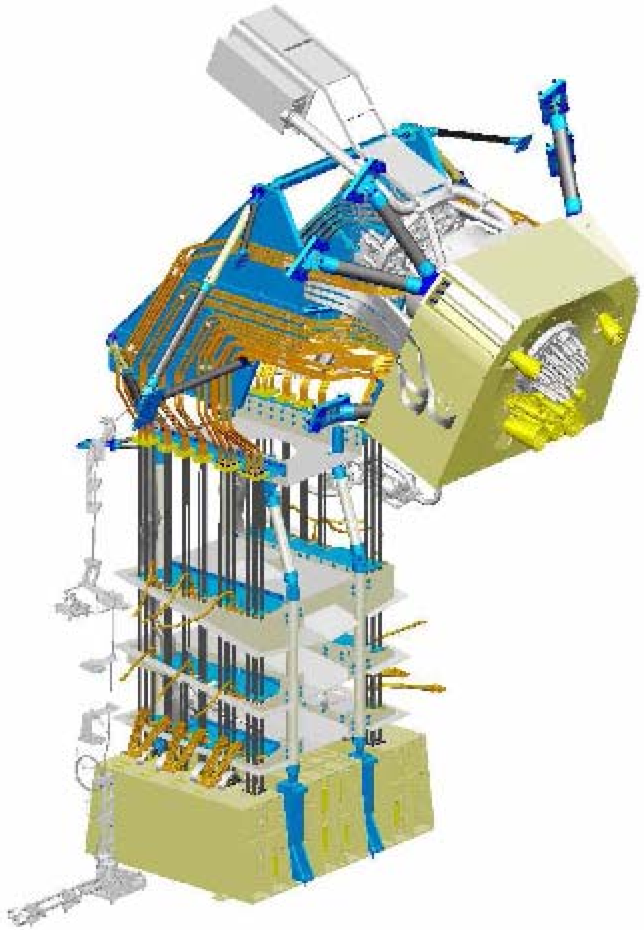
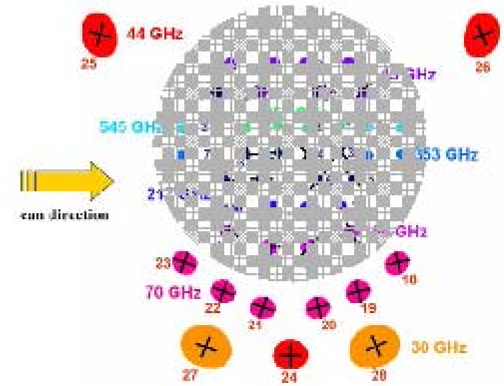
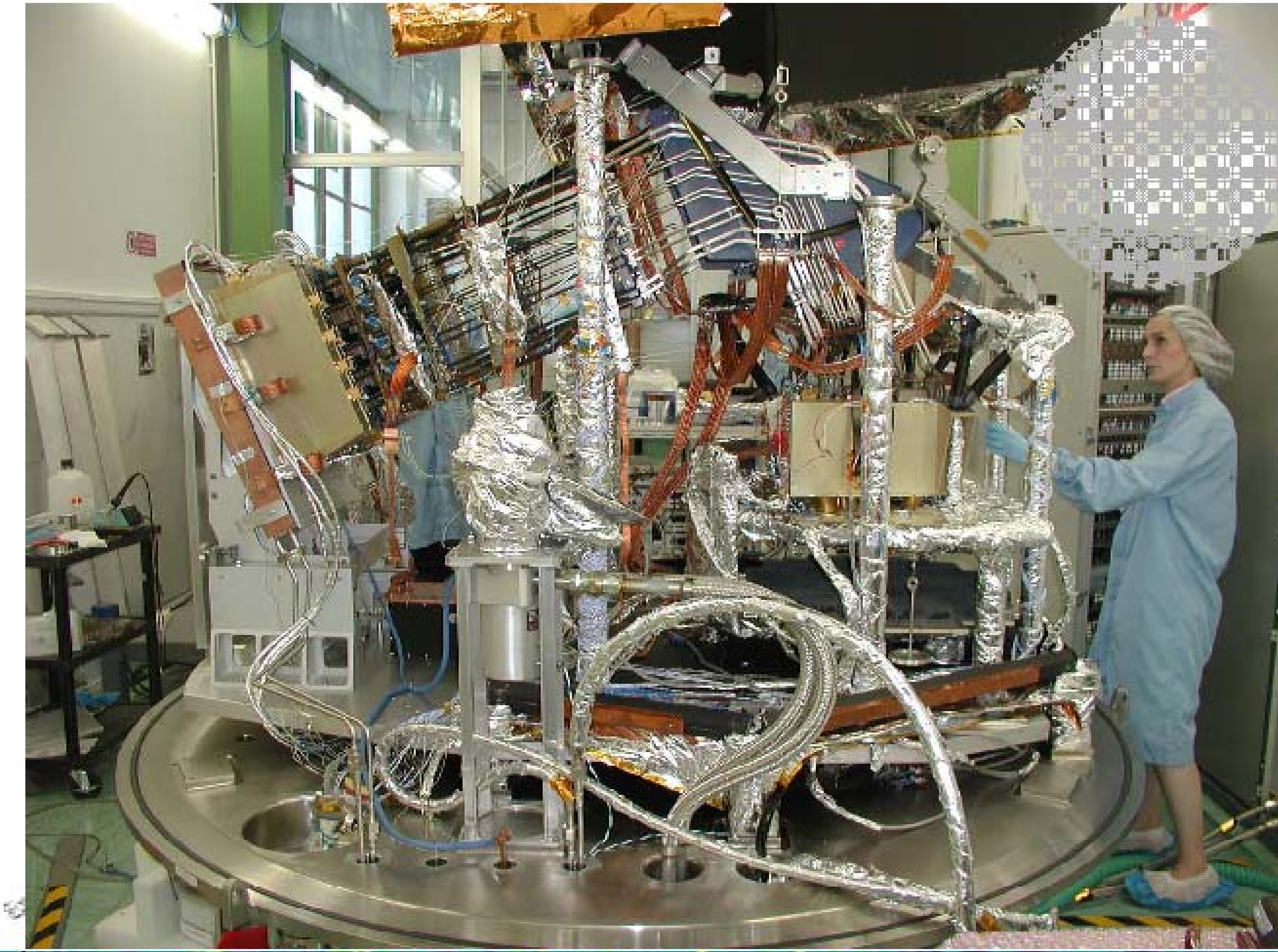




LFI: Low Frequency Instrument

- 22 pseudo-correlation radiometers, based on HEMT LNAs operated at 20 K
- 3 bands, 30 – 70 GHz, linearly polarised

LFI PI: N. Mandolesi, IASF Bologna

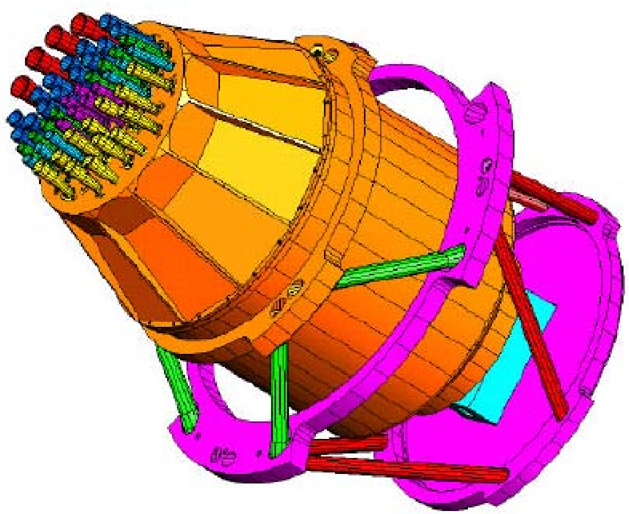


LFI PI: N. Mandolesi, IASF Bologna

PLANCK Reflector Programme

High Frequency Instrument

- Freq.: 100 -850 GHz
- Techn.: spider-web bolometers (50)
- Temp.: 0.1 K
- Ang. res.: 9.2' (100 GHz) t 5' (850 GHz)
- Temp. sens. (@100 GHz): ~5 μK
- PI: J.L. Puget (IAS - Orsay)



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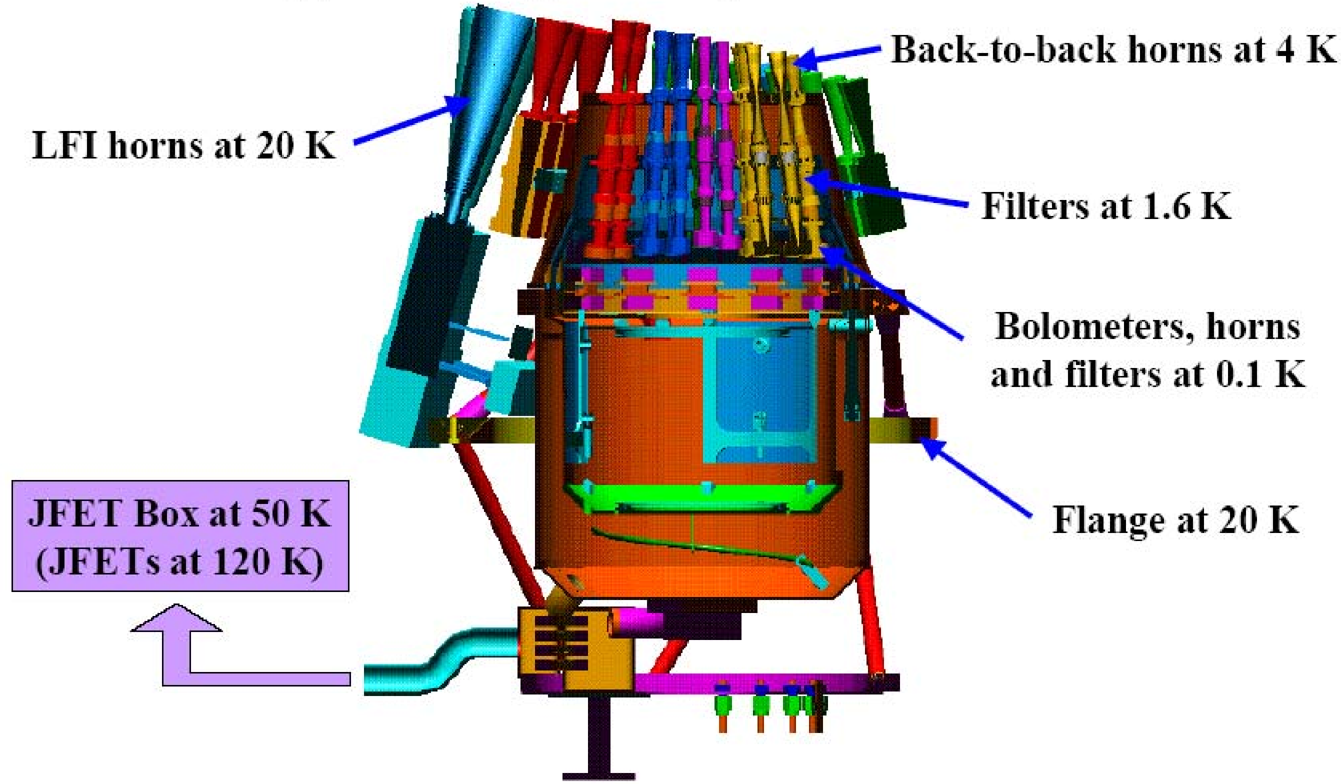
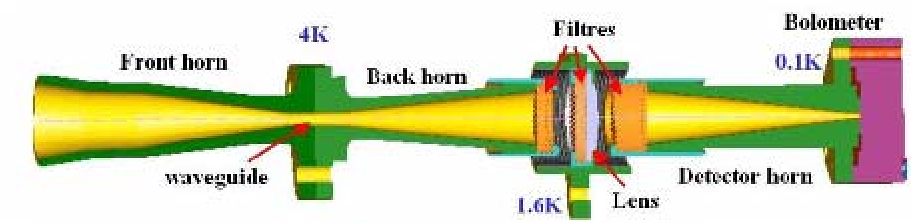
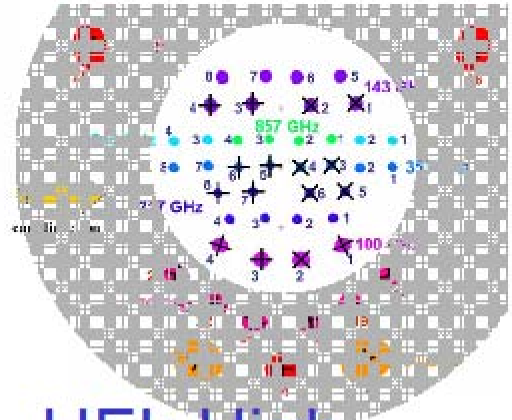
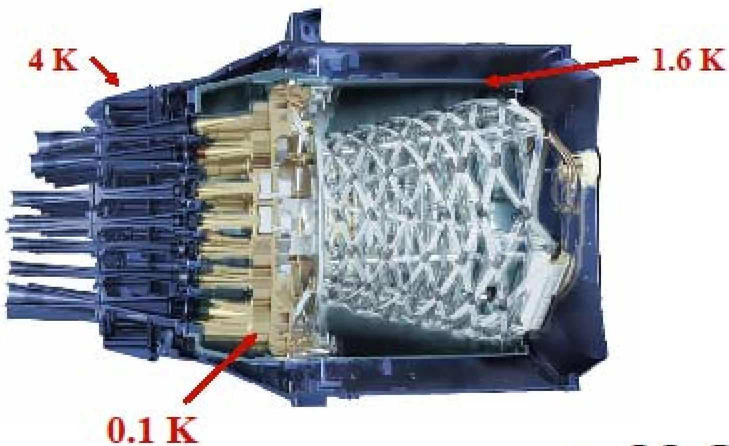
High Frequency Instrument

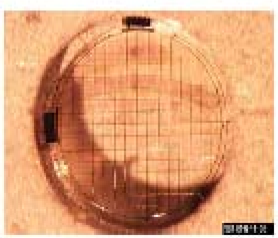


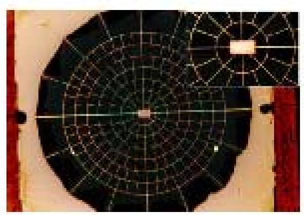






HFI: High Frequency Instrument



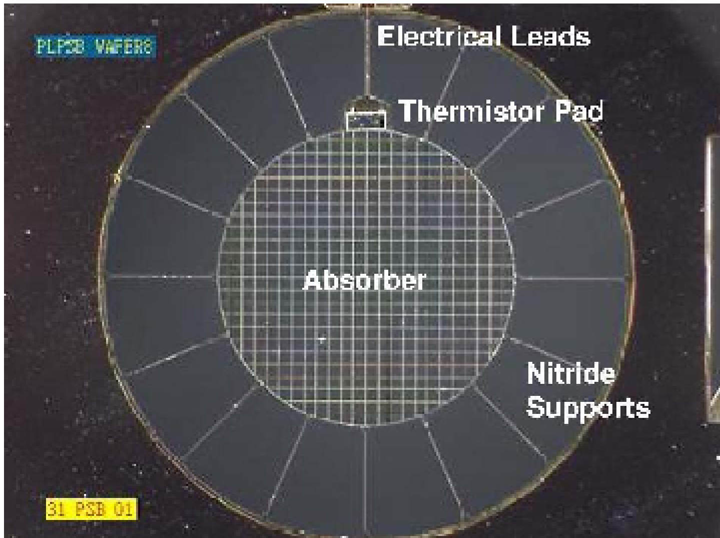


- 20 Spider-web bolometers, and 16 pairs of Polarisation-sensitive bolometers, cooled to 0.1 K
- 6 bands, 100 – 857 GHz

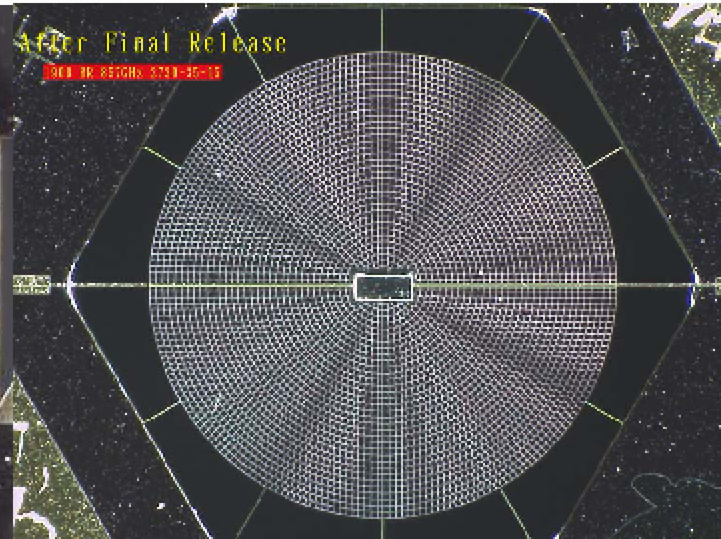
HFI PI: J.L. Puget, IAS Orsay

PLANCK Reflector Programme

Spider Web Bolometers & PSBs



145 GHz PolarSensitiveBolometers

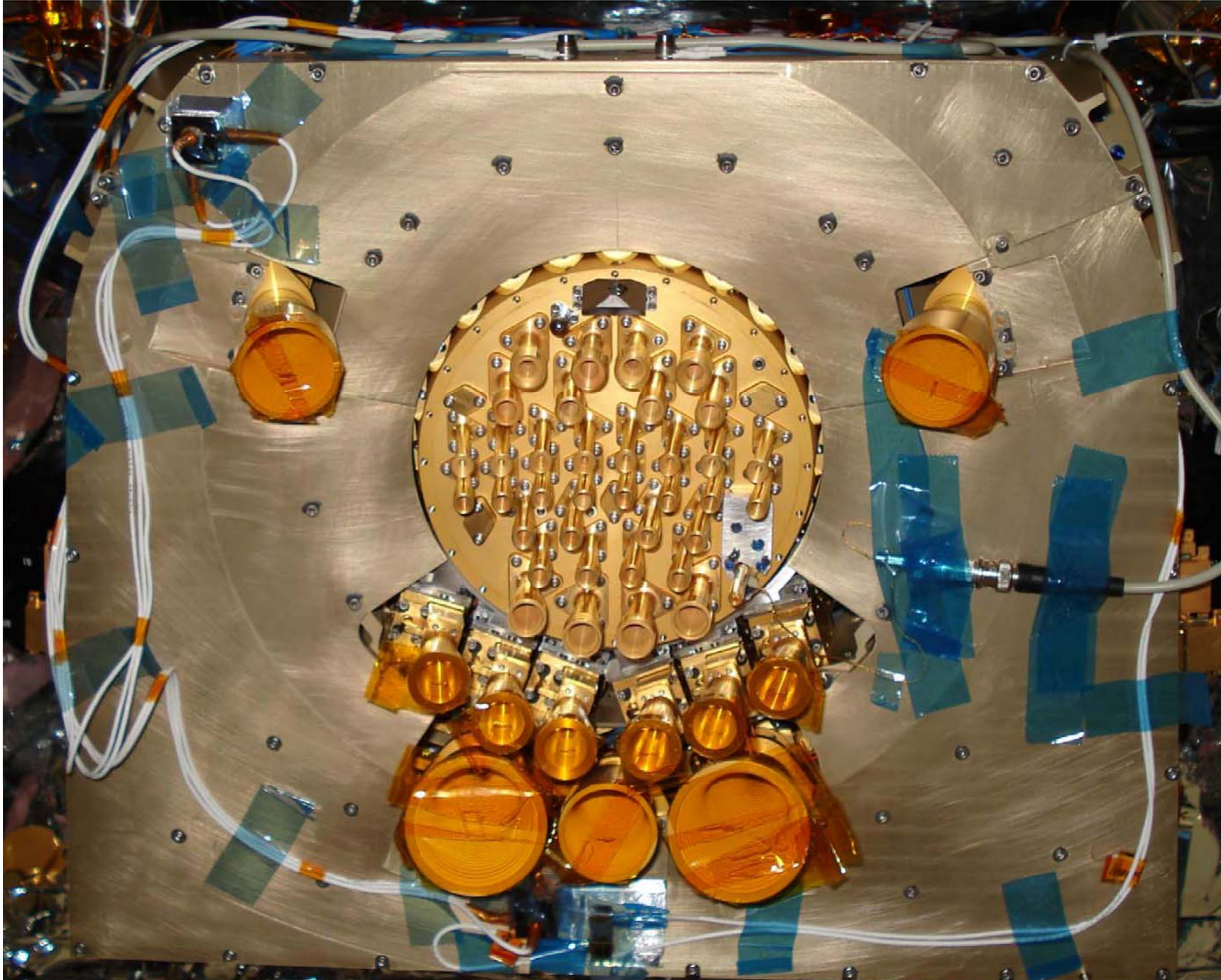


857 GHz SpiderWeb Bolometer

All HFI flight bolometers have been built by Caltech/JPL, integrated into pixels and tested in Cardiff, integrated into HFI – notably. JFET (Rome) + REU (CESR) and then tested at instrument level @ IAS, Orsay.

NB: Flight Model includes 4 PSB pairs @ 100 GHz

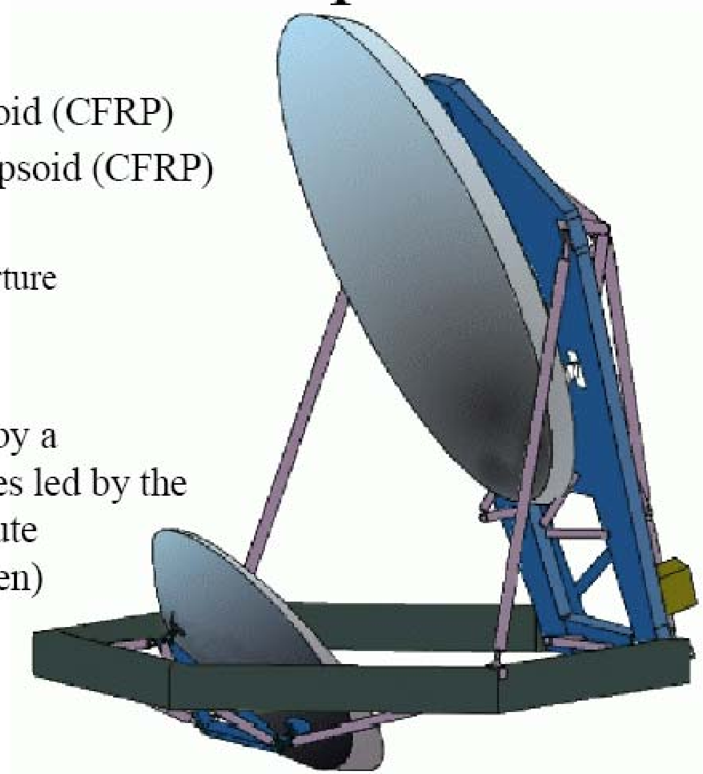
(following the descoping of the 100 GHz receivers from the LFI)



PLANCK Reflector Programme

Planck Telescope

- Primary: 1.50 x 1.89 m ellipsoid (CFRP)
- Secondary: 1.02 x 1.04 m ellipsoid (CFRP)
- System:
  - 1.5 m circular projected aperture
  - Total MWFE<40 μm rms
  - Total ε <0.01
- Reflectors will be developed by a Consortium of danish institutes led by the Danish Space Research Institute (PI: Dr. H.U. Norgaard-Nielsen)



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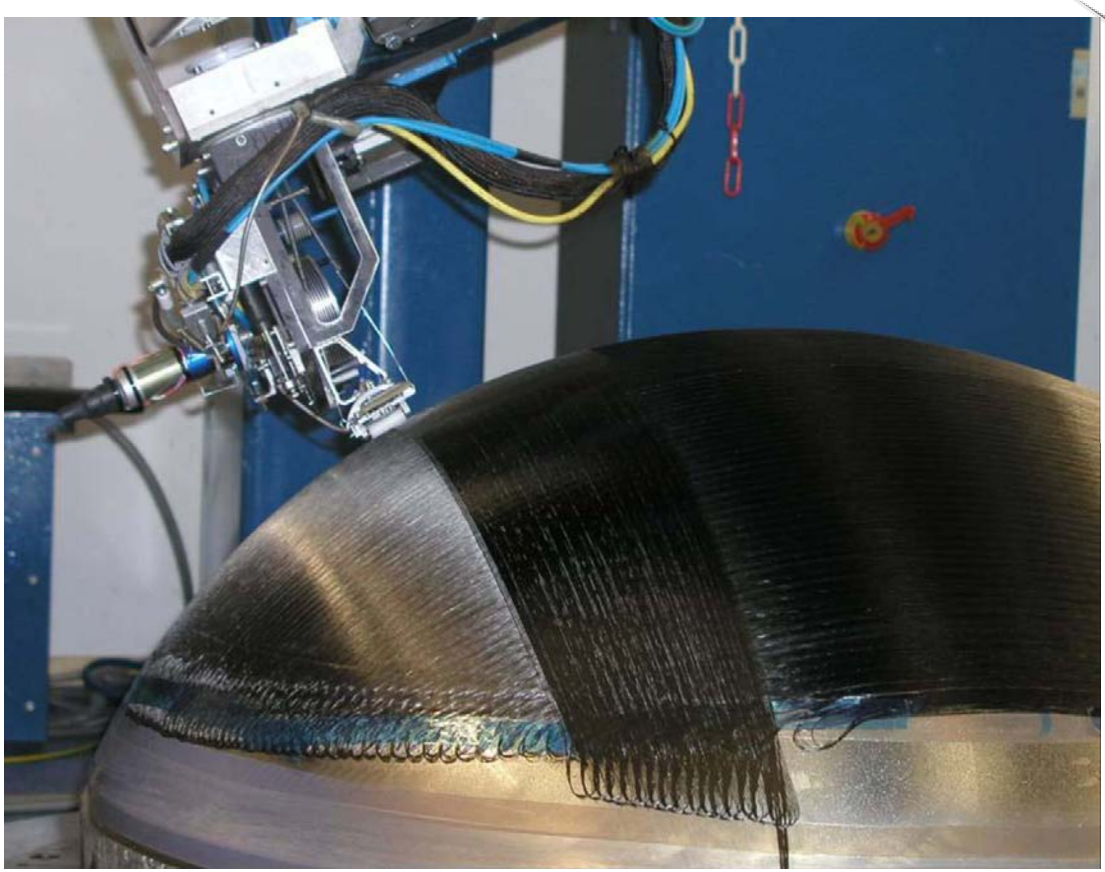
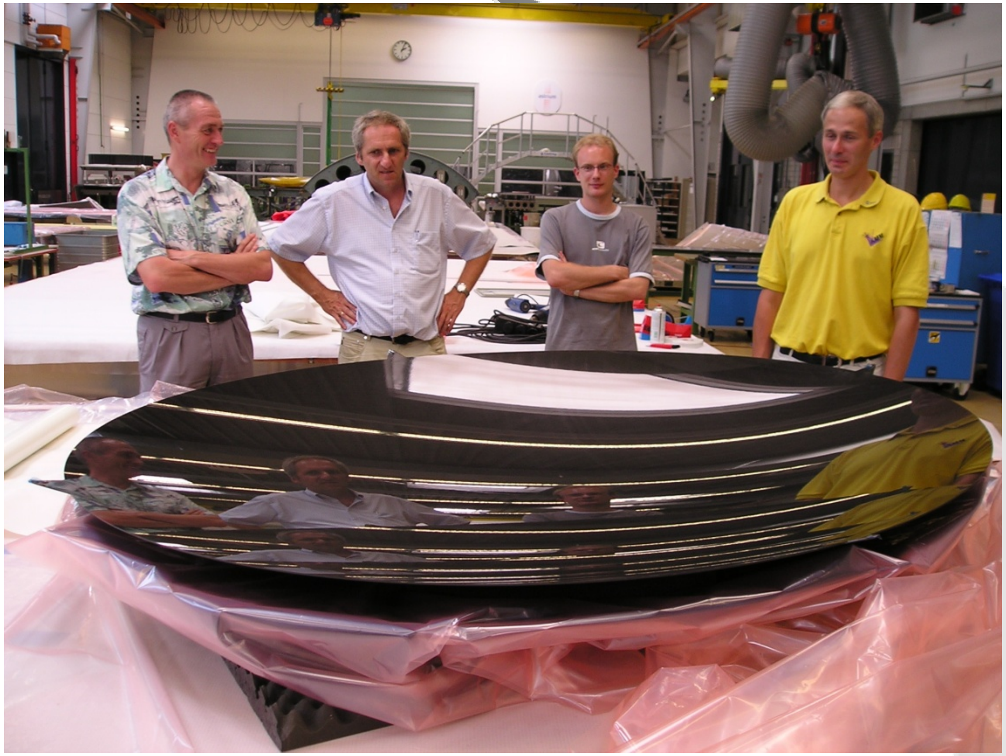
PLANCK Reflector Programme

True angle lay up af Sekundær spejlets skin



Planck
CFRP-mirrors

Mould for Primary Reflector

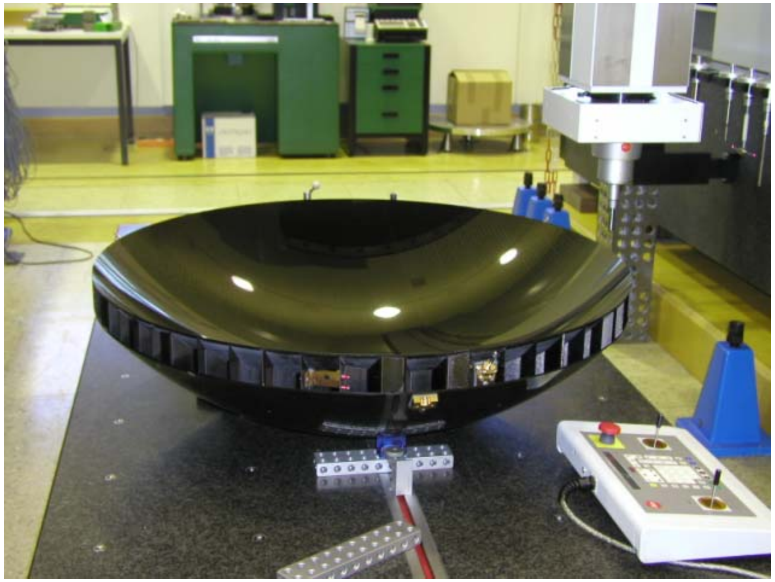


Face sheet of Primary Reflector

Planck
CFRP-mirrors

Bonding core to face sheet

Planck
CFRP-mirrors



QM Secondary Reflector in 3D measurement machine

Dimensions 1051 x 1104

FM Primary Reflector coated with aluminum. Shown in aluminizing plant.

Dimensions 1556 x 1887

Planck
CFRP-mirrors

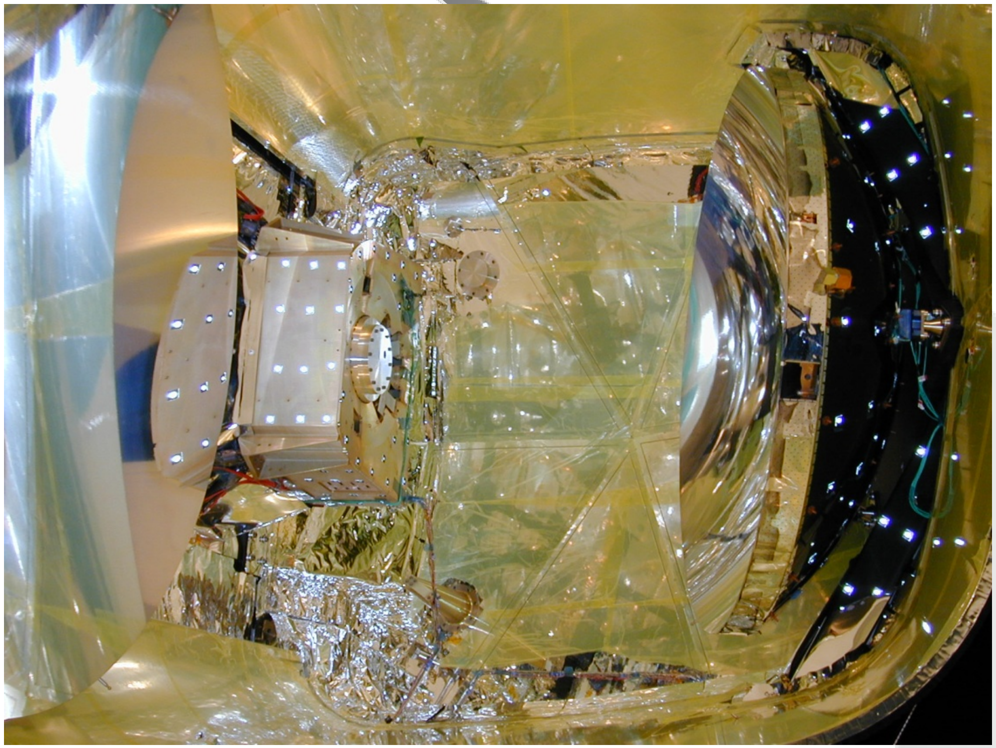
Tests incl.

Vibration tests to 37 g

Measurements of optical performance at 41K in Vacuum.

Planck
CFRP-mirrors

QM Satellite



Reflectors in place

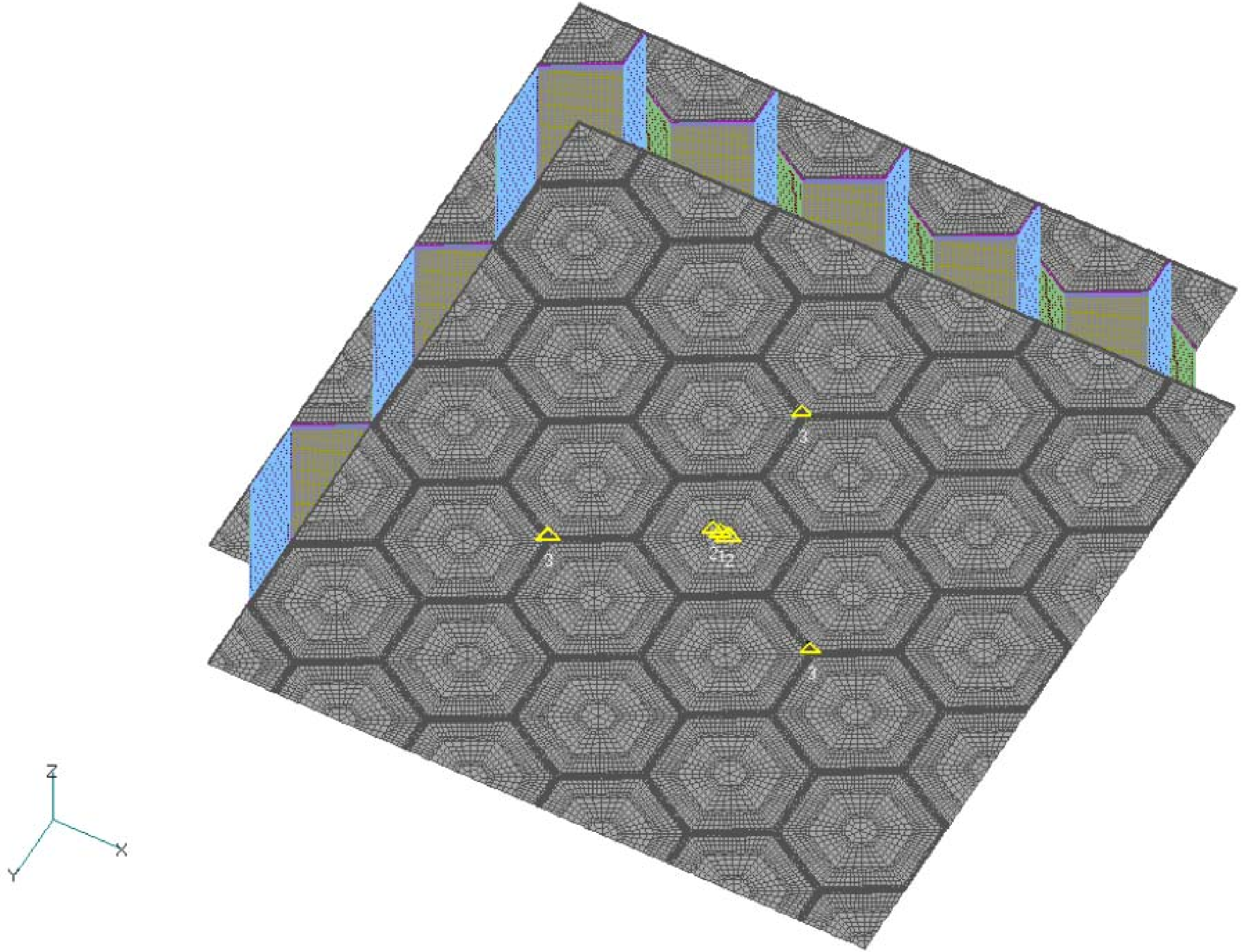


Fig. 3.0.1 FE-model of the sandwich. The yellow triangles refer to the nodes where the sandwich is supported.

PLANCK Reflector Programme

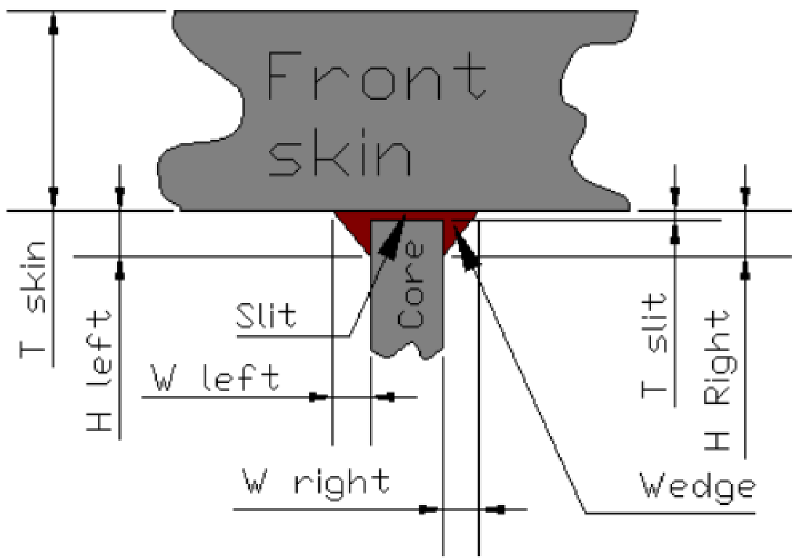


Fig. 5.0.1 Main dimension for the bonding

PLANCK Reflector Programme

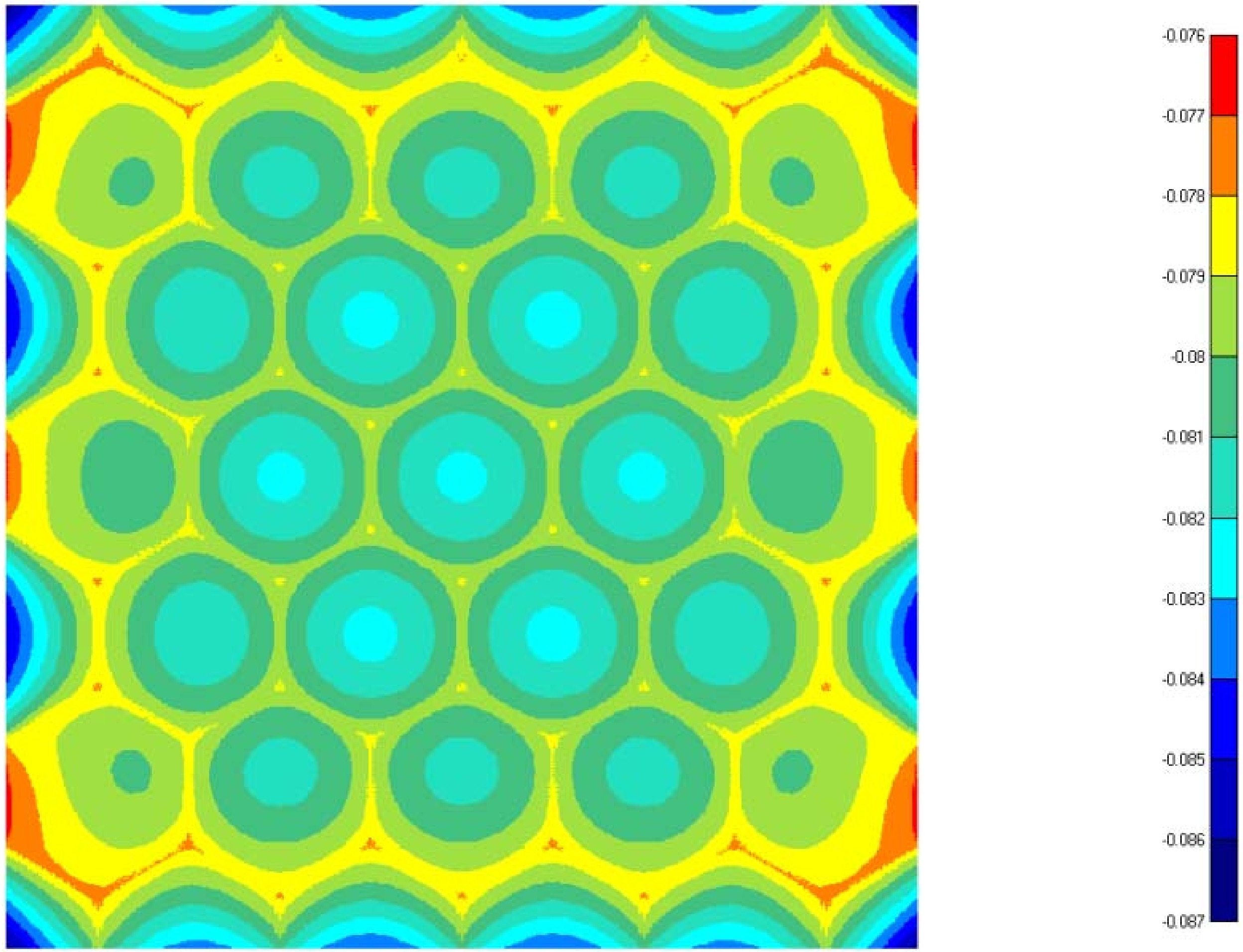


Fig. 5.1.3 Thickness of face sheets was increased to 2.1 mm

Case 3

PLANCK Reflector Programme

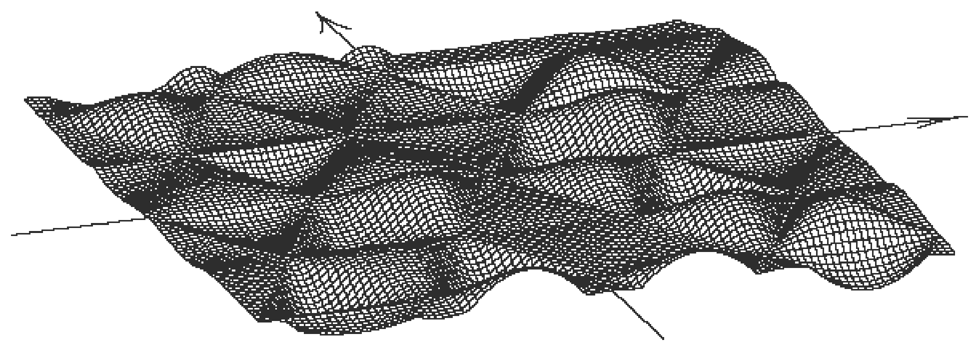


Figure 1 Random core-print-through surface distortion.

PLANCK Reflector Programme

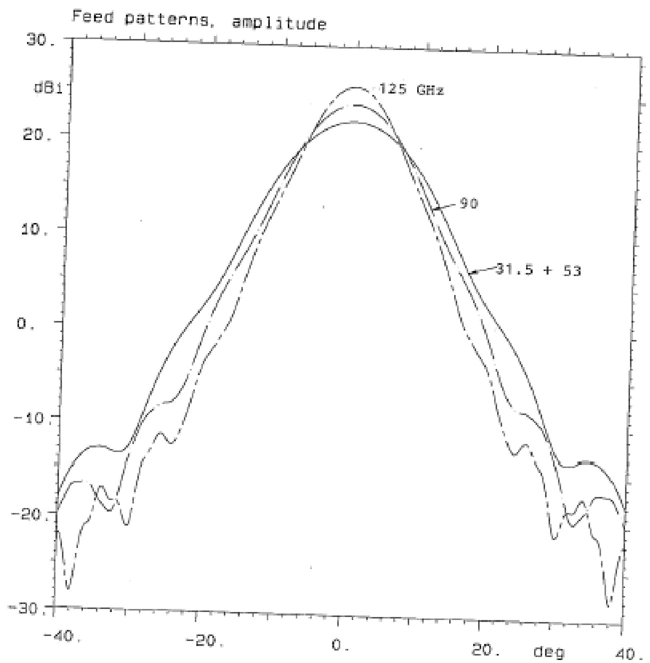
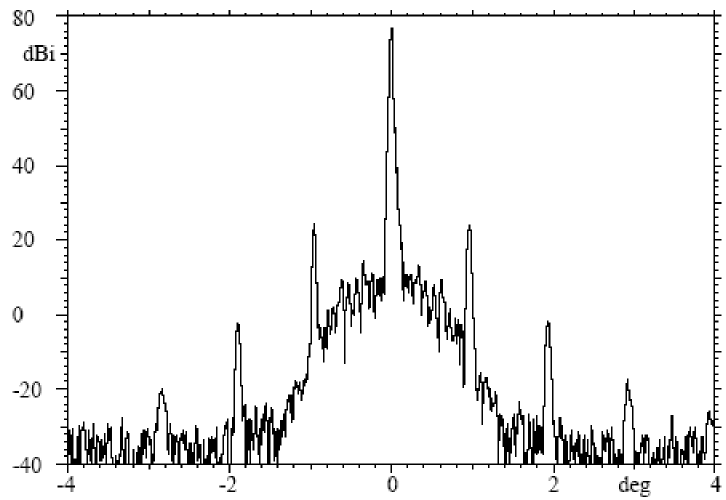


Figure 3.1 LFI feed patterns, amplitude

PLANCK Reflector Programme



c) bulge peaks in the interval [0, 4μ]

Figure 2 Far field from core print-through on primary mirror, $\phi = 0°$.

PLANCK Reflector Programme

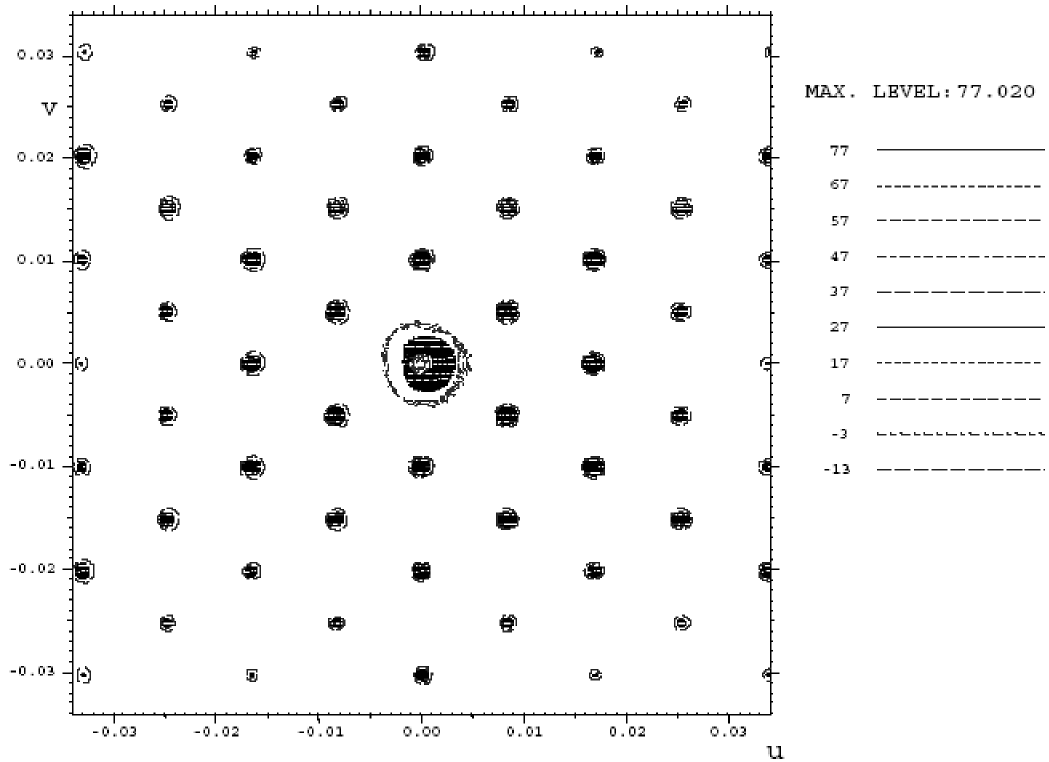
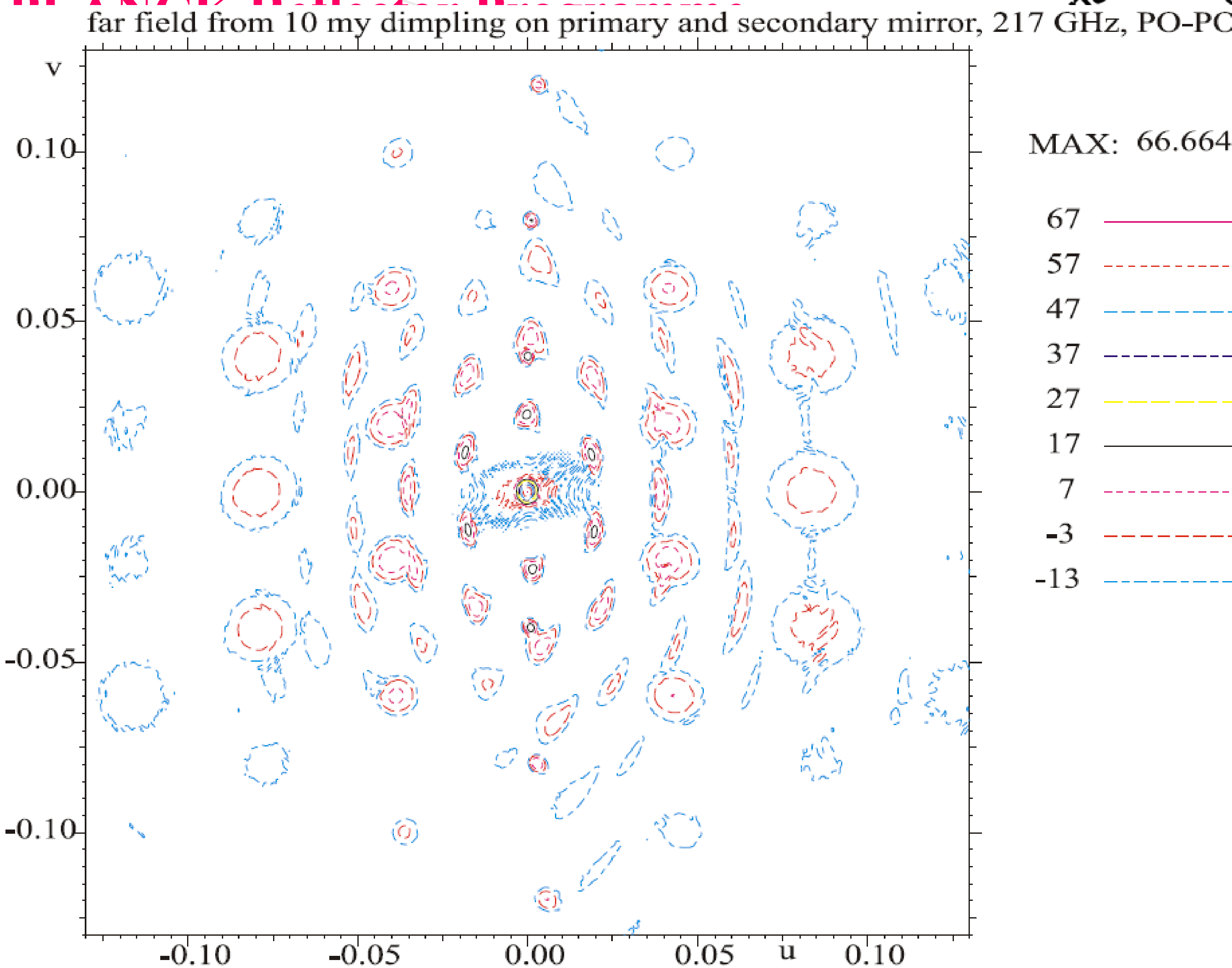


Figure 5 Far field from 2μ core print-through on primary mirror.

PLANCK Reflector Programme



a) uv pattern

PERF-040 *The coating shall comply with the durability requirements defined in AD-3. The coating shall be conductive.*

5.2.3 Periodic Structure and Sensitivity to Micro-Cracks

PERF-045 *The surfaces of the PR and the SR shall not present medium frequencies periodic or quasi periodic structures (typical example: core print-through) with an amplitude larger than ± 2µm.*

PERF-050 *The density of the micro-cracks interrupting the conductivity of the coating on the optical surface of the PR and the SR shall be less than one crack per 200 cm² (spec) with a goal of zero crack and the maximal length of the micro-cracks shall be less than one cm (spec). Micro-crack width shall be less than 100 microns.*

5.3 Physical Requirements

5.3.1 Dimensions and Design

PHYS-005 *The dimensions for the primary reflector and the secondary reflector are defined in section 5.2. The tolerances on the size of both reflectors at operational temperature shall be (+0; -2.5mm).*

PHYS-010 *The location of the interface points and the fixation points of the Primary and the Secondary Reflectors are given in section 5.9.*

PHYS-015 *The thickness of the PR reflector shall not exceed 9.5 cm (including 1.5 cm for thermal H/W).*

The thickness of the SR shall not exceed 8 cm (including 1.5 cm for thermal H/W).

PHYS-020 *Both reflectors shall have sharp edges on their circumferential rims.*

5.3.2 Mass Properties

PHYS-025 *The total mass of the reflectors including 10% margins shall not exceed (with the thermal H/W, the isostatic mounts and the alignment devices):*

- *30.6 kg for the Primary Reflector*
- *14.5 kg for the Secondary Reflector*

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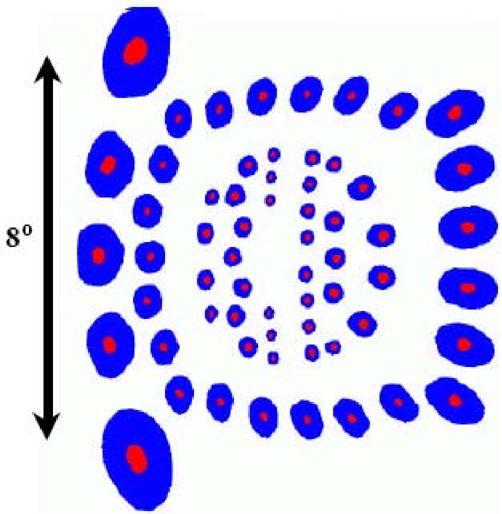
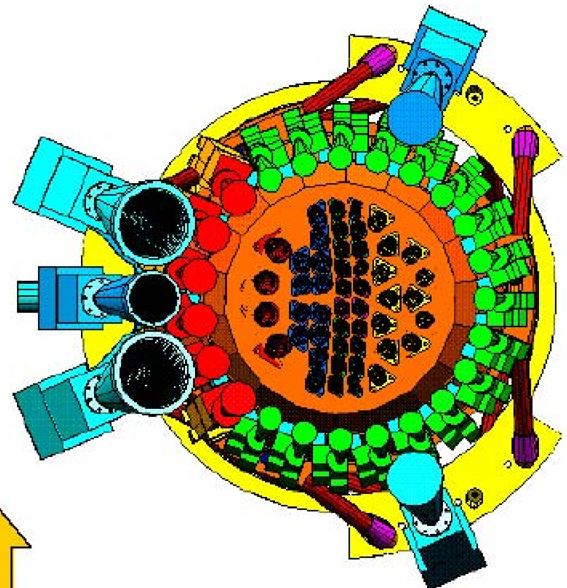
Optical configuration





On the sky

In the focal plane

Scan direction

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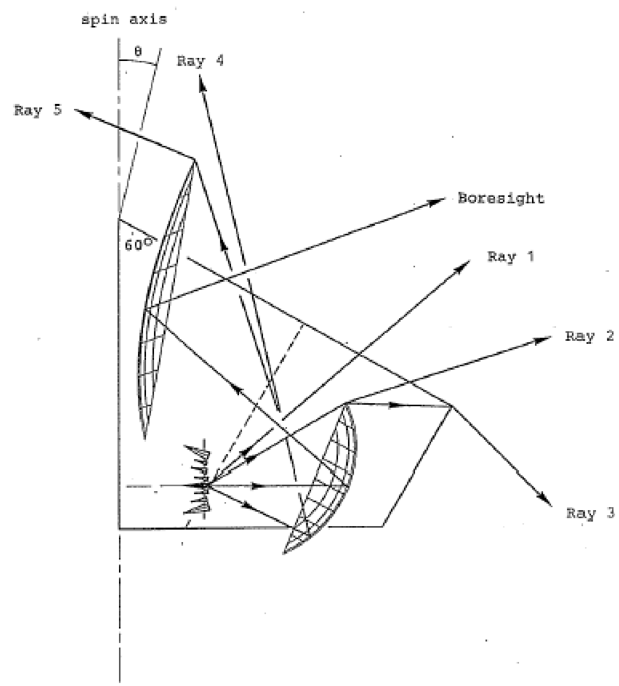

Figure 5.5 Rays used for telescope with shield

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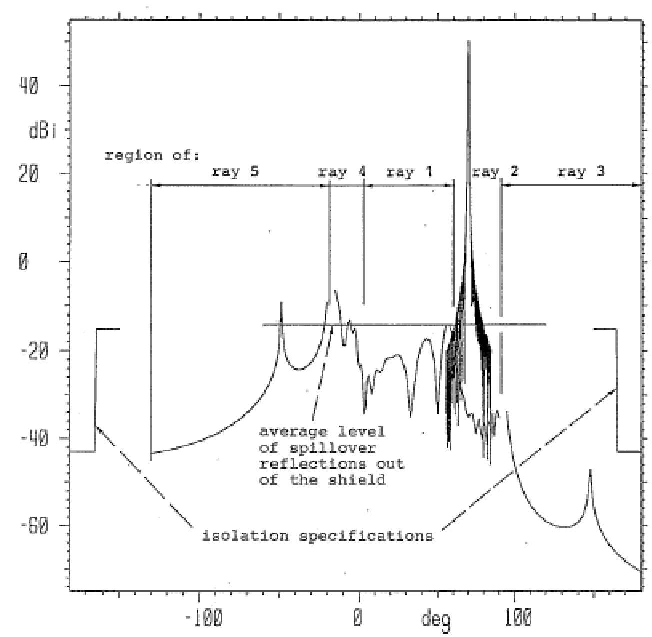

Figure 5.6 Radiation patterns showing the desired main reflector field as well as the direct contribution from the rays identified in Figure 5.5. The figure also shows the average level of -14 dBi of the unpredictable field not hitting the main reflector

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Planck Reflectors
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$$G(\theta) = G_o(\theta)e^{-\overline{\delta^2}} + \left(\frac{2\pi c}{\lambda}\right)^2 e^{-\overline{\delta^2}} \sum_{n=1}^{\infty} \frac{\overline{\delta^2}^n}{n \cdot n!} e^{-(\pi c \sin\theta/\lambda)^2/n} \quad (1.1)$$

where 2c is the correlation distance and

$\overline{\delta^2}$ is the mean square phase error in radians given by

$$\overline{\delta^2} = \frac{\iint_{surface} f(r,\phi)\delta^2(r,\phi) r\,dr\,d\phi}{\iint_{surface} f(r,\phi) r\,dr\,d\phi} \quad (1.2)$$

where $f(r,\phi)$ is the illumination function in the aperture coordinates r, ϕ. For small errors of $\delta_{rms} < 0.05\lambda$ the series of (1.1) can be approximated by its first term and one obtains the following simple expression

$$G(\theta) = G_0(\theta)e^{-(k\delta_{rms})^2} + (kc)^2 e^{-(k\delta_{rms})^2} \cdot (k\delta_{rms})^2 e^{-\left(\frac{1}{2}kc\sin\theta\right)^2} \quad (1.3)$$

where k is the wave number, $k = 2\pi/\lambda$, and δ_{rms} is the root mean square error in the aperture. For random distortions the mean surface error is, in general, zero.

The first term gives the peak gain reduction by the factor

$$e^{-(k\delta_{rms})^2} \quad (1.4)$$

The second term of (1.3) gives a power envelope of the error field pattern in the sidelobe regions. The pattern for different values of the correlation length, $2c = 4\lambda$, 8λ, 16λ, 32λ and 64λ, but for constant rms error $\delta_{rms} = 0.05\lambda$ is shown in Figure 4.6.3.

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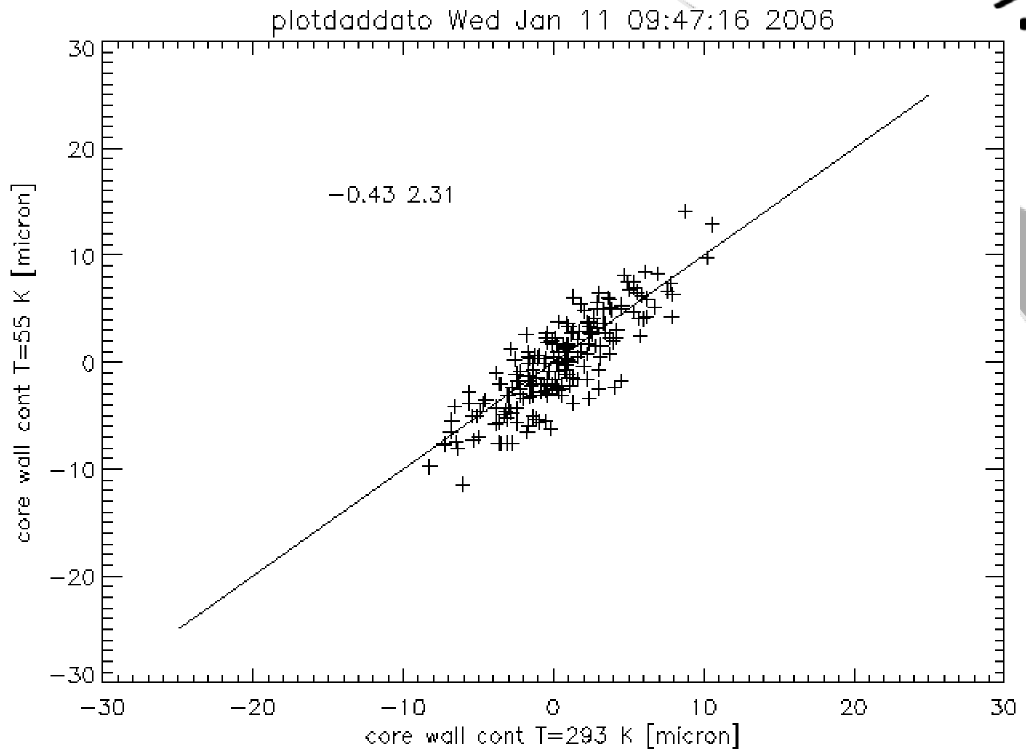

PLANCK Reflector Programme

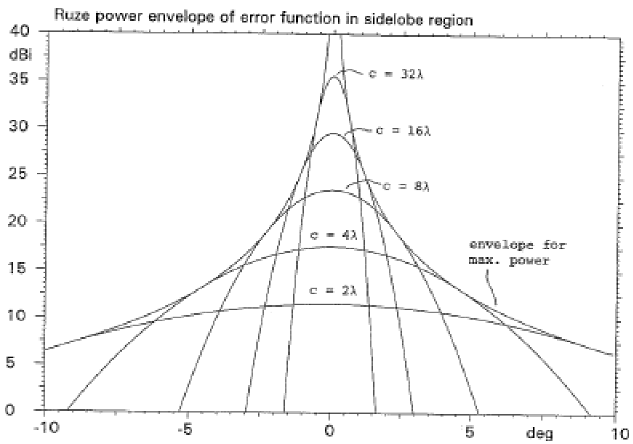

Figure 4.6.3 Power envelope pattern due to random surface errors with $\delta_{rms} = 0.05\lambda$.

It must be noticed that these envelope patterns are not valid in the main beam region and only valid for correlation lengths less than the illuminated aperture diameter, $2c \ll D$. The aperture illumination function only has influence on the calculation of the δ_{rms} value but for rapidly varying random distortions the rms value will remain unchanged giving the same power envelope patterns for different illumination functions, especially for different tapered illuminations.

The maximum envelope error power for a given θ angle is given by

$$G_{max} = \left(\frac{2k\delta_{rms}}{\sin\theta}\right)^2 \Big/ e \qquad (1.5)$$

where the θ angle corresponds to a correlation length of

$$k\,c = 2/\sin\theta \qquad (1.6)$$

PERF-010 *The aperture of the reflectors shall be:*

PR	Elliptical contour	1555.98mm x 1886.79mm
SR	Elliptical contour	1050.96mm x 1104.39mm

Remark: The real needed size (optical surface size) of the SR is 1018x1043.23mm^2. The larger size requested takes into account margins for telescope alignment and manufacturing inaccuracies.

PERF-012 *The Offset distance between the centre of the reflectors and the major axis are:*

PR	1,038.85 mm
SR	-309.52 mm

The Mechanical Surface Error (MSE) shall be measured perpendicular to the optical surface relative to the Best Fit Ellipsoid (defined in 5.9.3).

The major and the minor axis of the ellipsoid are given by r/ (1 + K) and r/sqrt(1 + K), respectively.

PERF-015 *The variation of MSE is allowed to vary from the center to the reflector edge according to the following table, where the reflector is subdivided in five aperture rings: one elliptical centre area (aperture referenced 1) and four elliptical rings around it, (referenced 2, 3, 4, 5) all having the same radius or width.*

Aperture ring	Goal Rms (µm)	Spec Rms (µm)
1	5	7.5
2	8	12
3	13	20
4	22	33
5	33	50

The mentioned errors shall be maintained within the operational temperature range (45K +/- 10K). These errors shall include the in-orbit residual e.g. (hystesis due to thermal cycling, aging…) deformations defined below:

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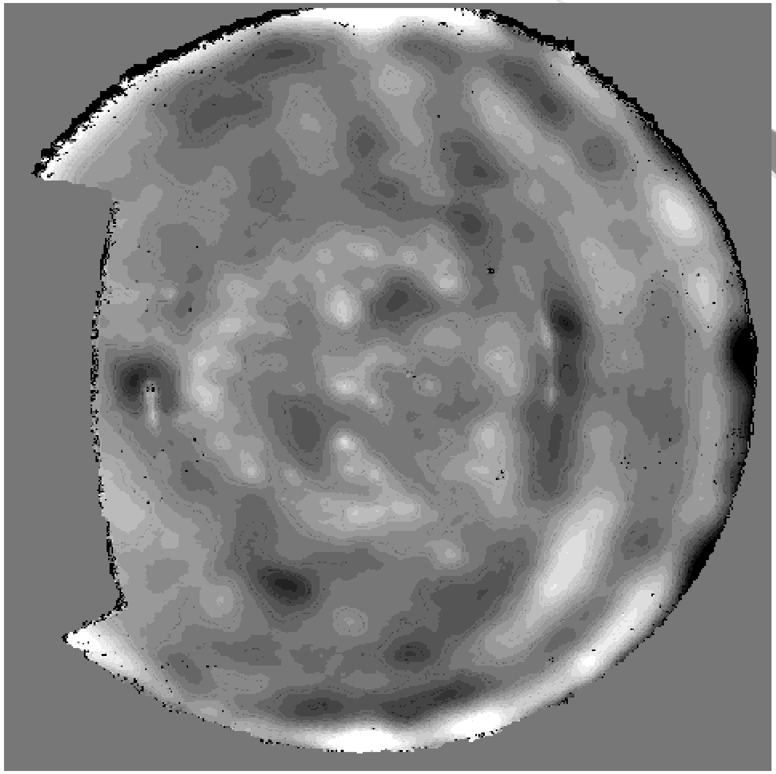
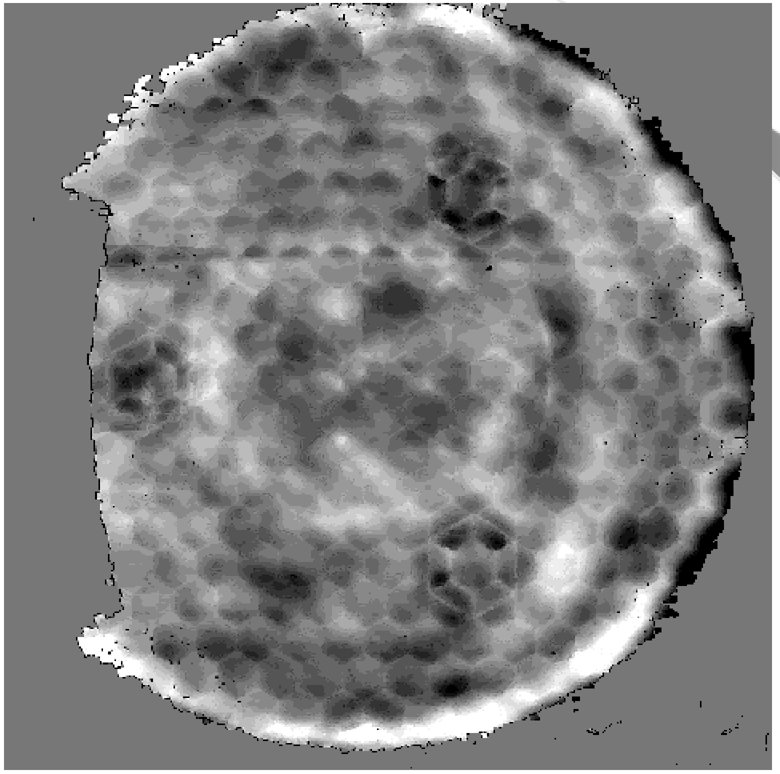


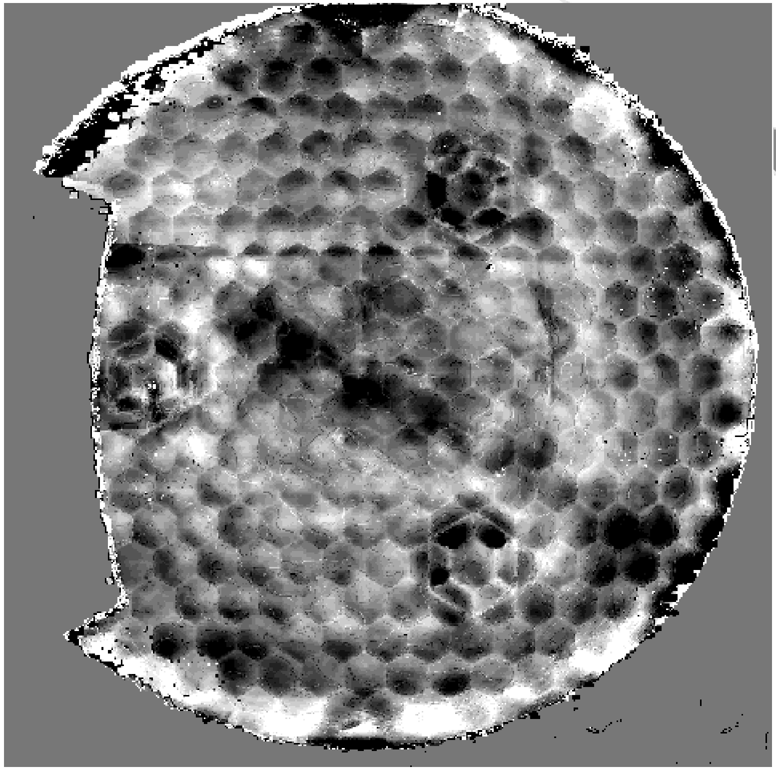
Interferometer data SRFM Room Temperature [-25 µm : +25 µm]

PLANCK Reflector Programme



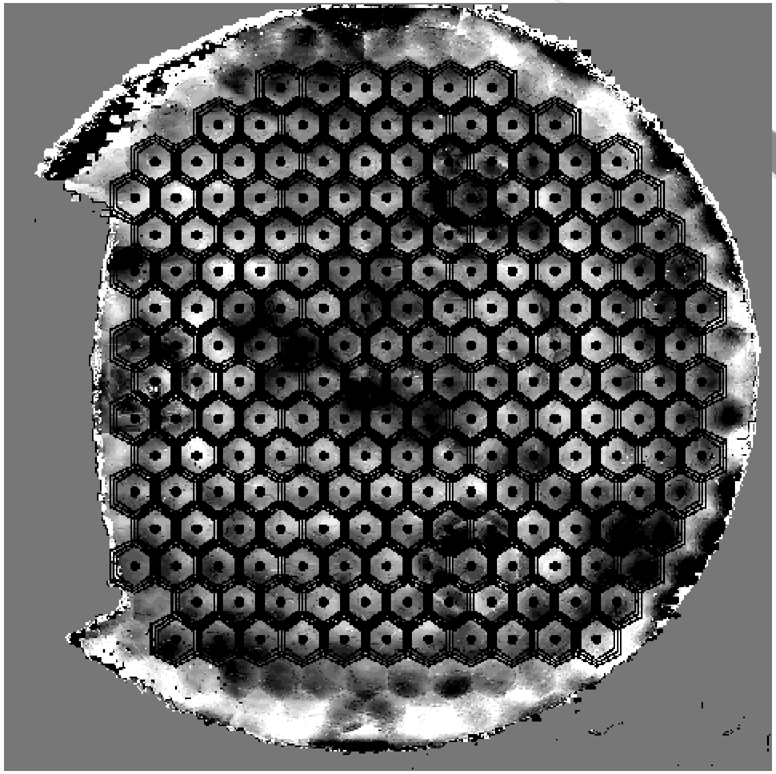
Interferometer data SRFM at 55 K
[-25 µm : +25 µm]

PLANCK Reflector Programme



Difference 293 K – 55 K

PLANCK Reflector Programme



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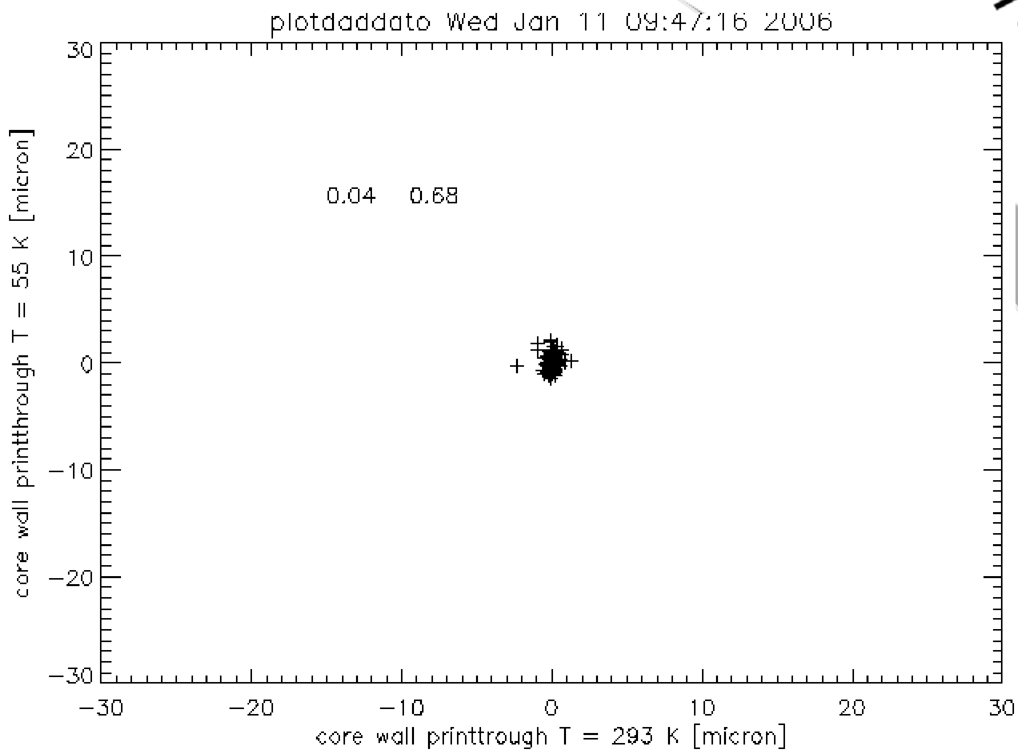

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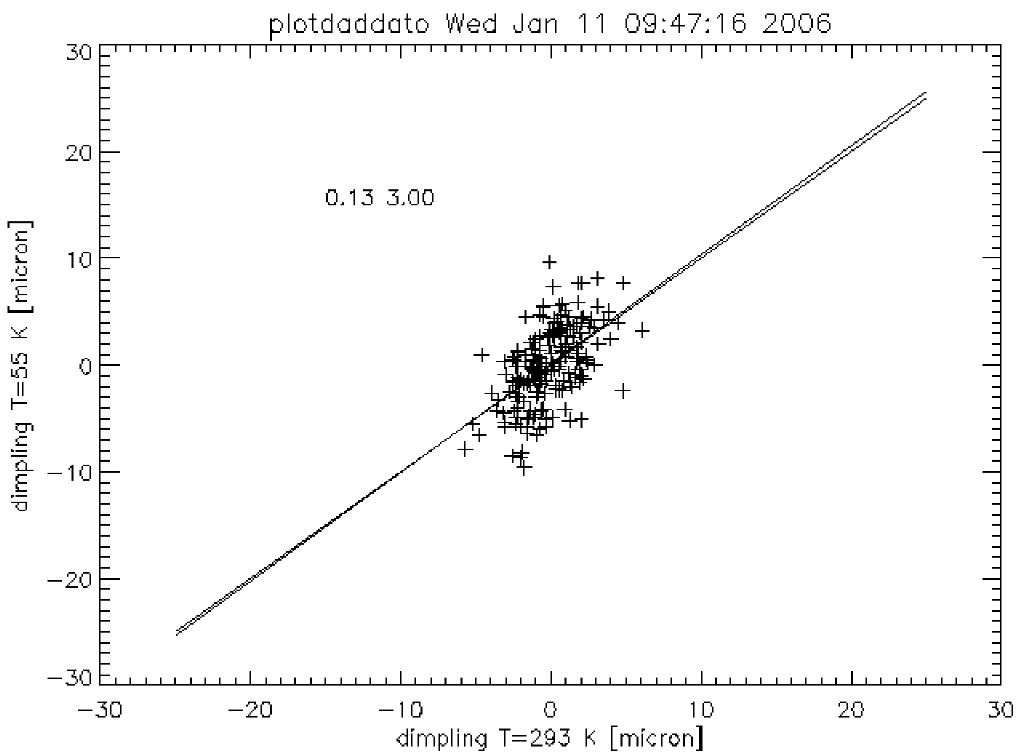
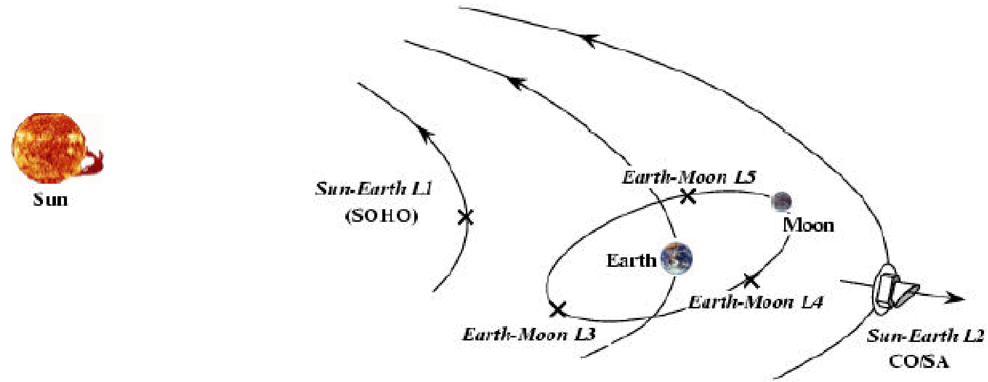
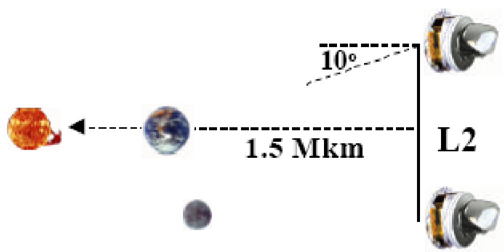
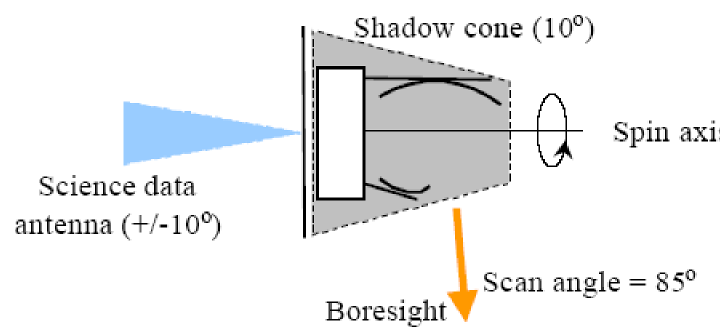


PLANCK Reflector Programme

Choice of orbit



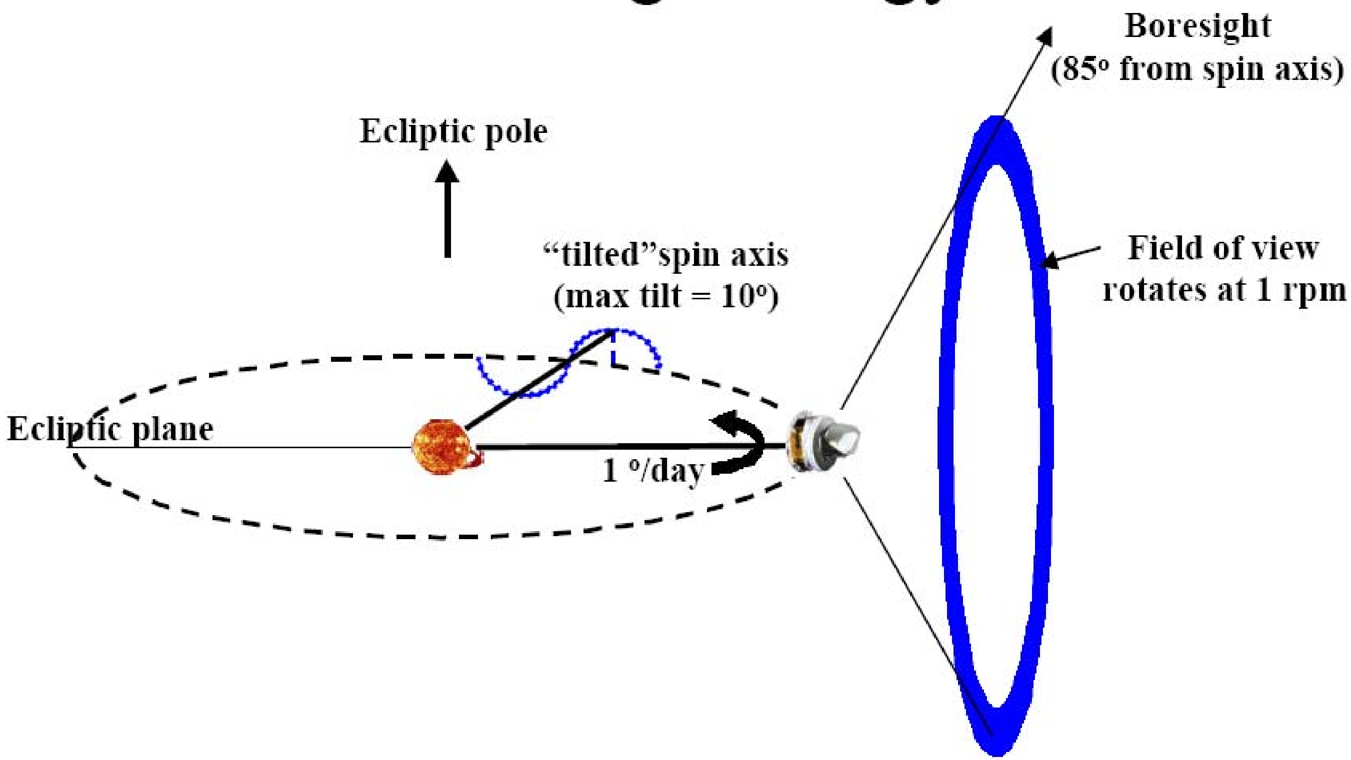




PLANCK

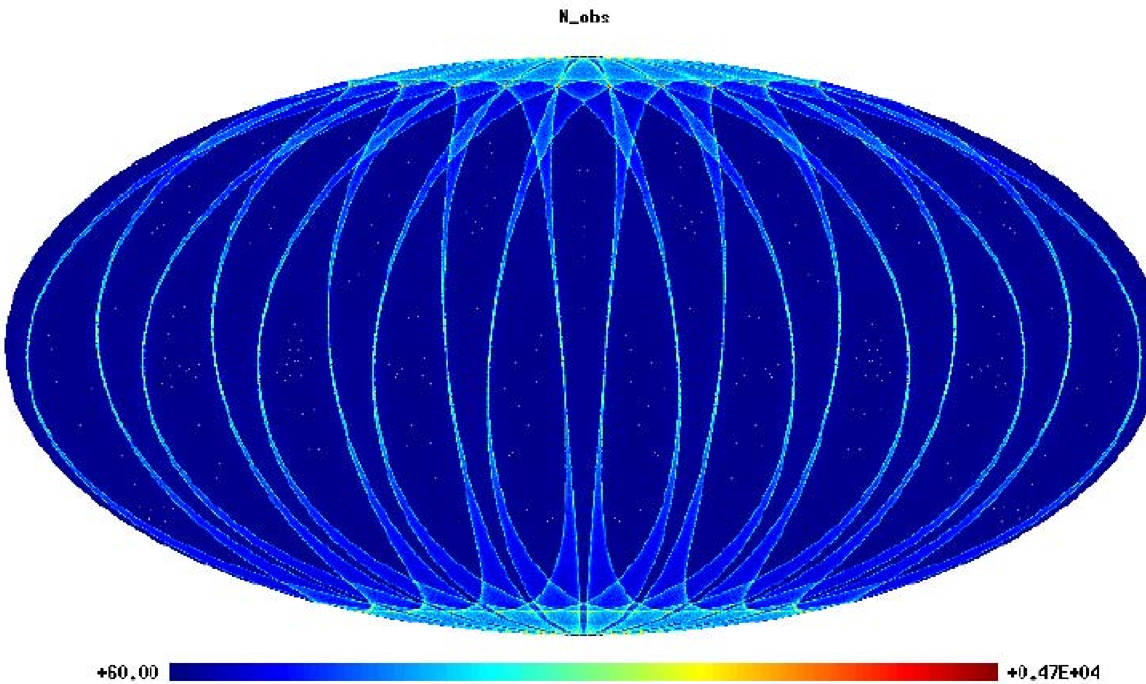
esa ASTROPHYSICS

Observing strategy



PLANCK Reflector Programme

(Possible) distribution of integration time



PLANCK

esa ASTROPHYSICS

PLANCK Reflector Programme

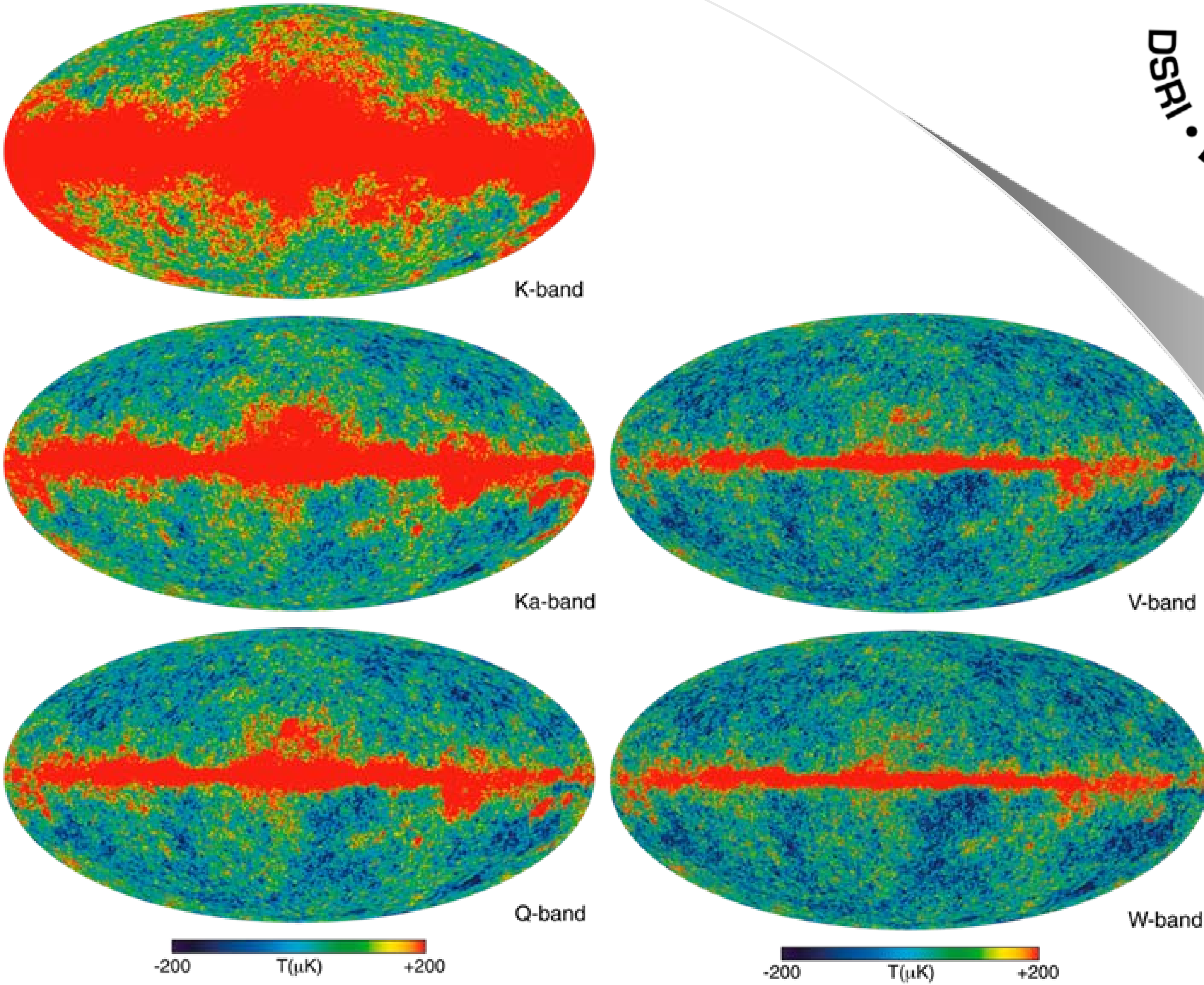
TABLE 1.1

SUMMARY OF PLANCK INSTRUMENT CHARACTERISTICS

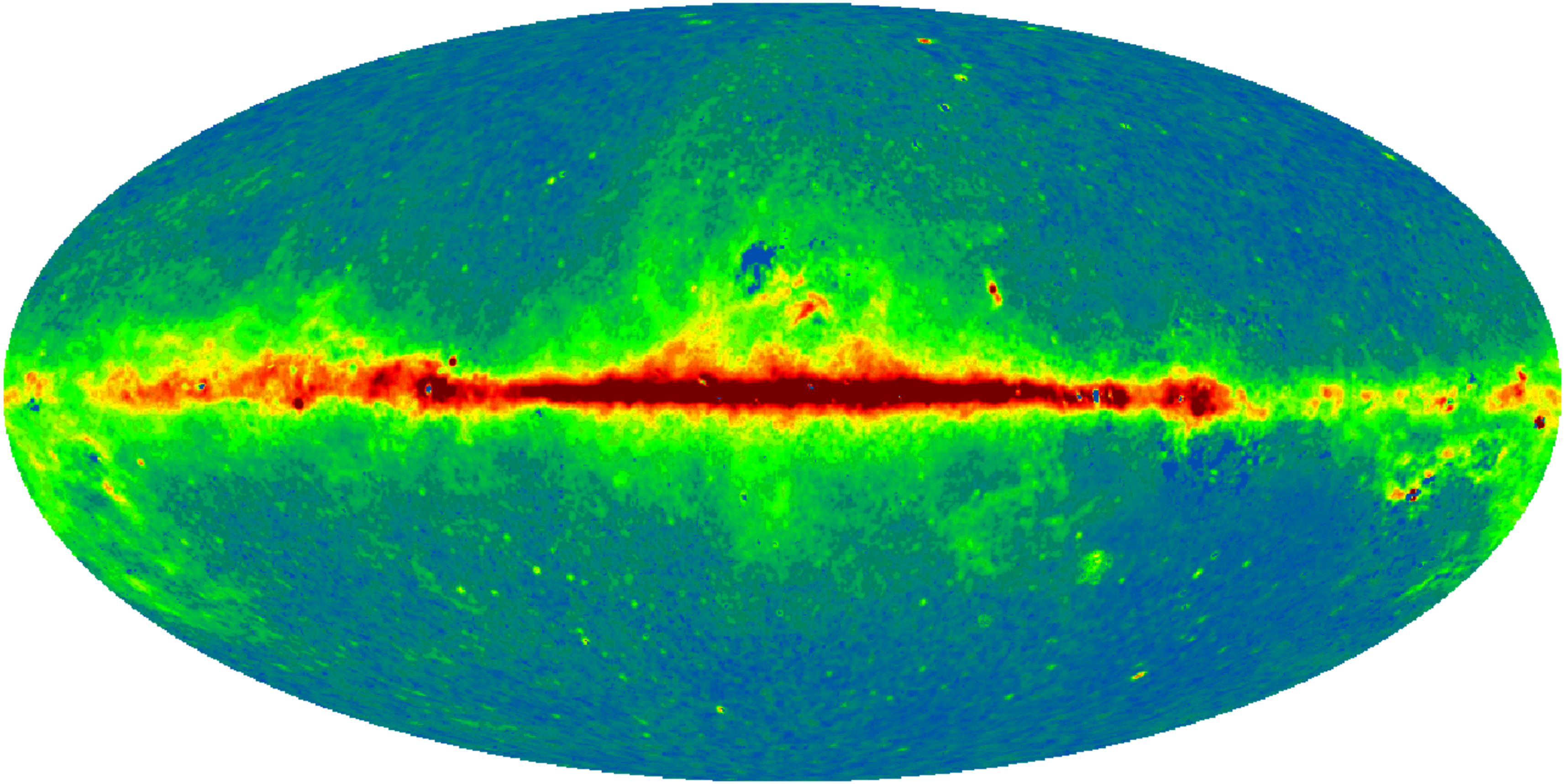
INSTRUMENT CHARACTERISTIC	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)^a	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q &U)^a	2.8	3.9	6.7	4.0	4.2	9.8	29.8	...	...

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

PLANCK Reflector Programme

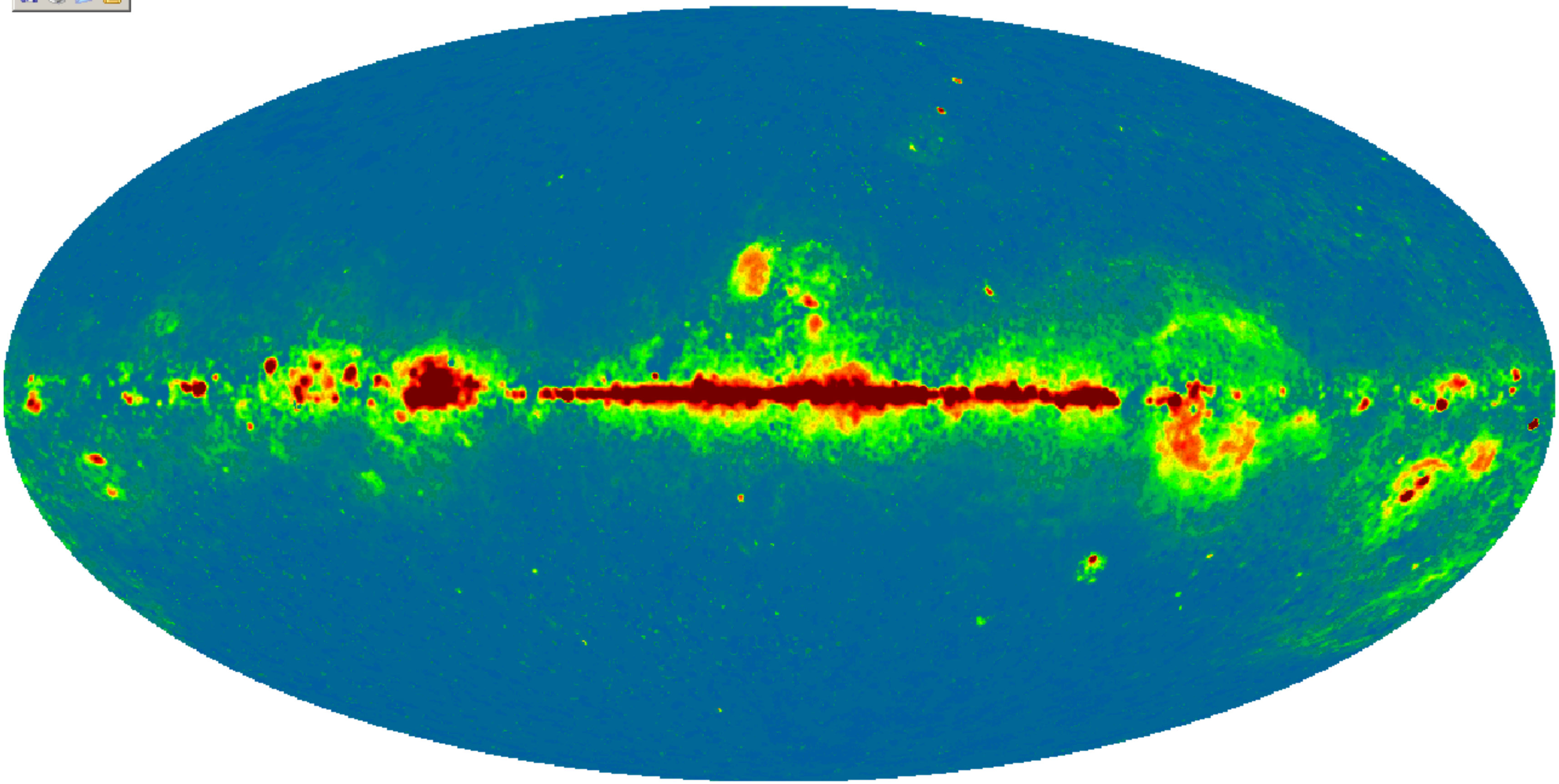


PLANCK Reflector Programme



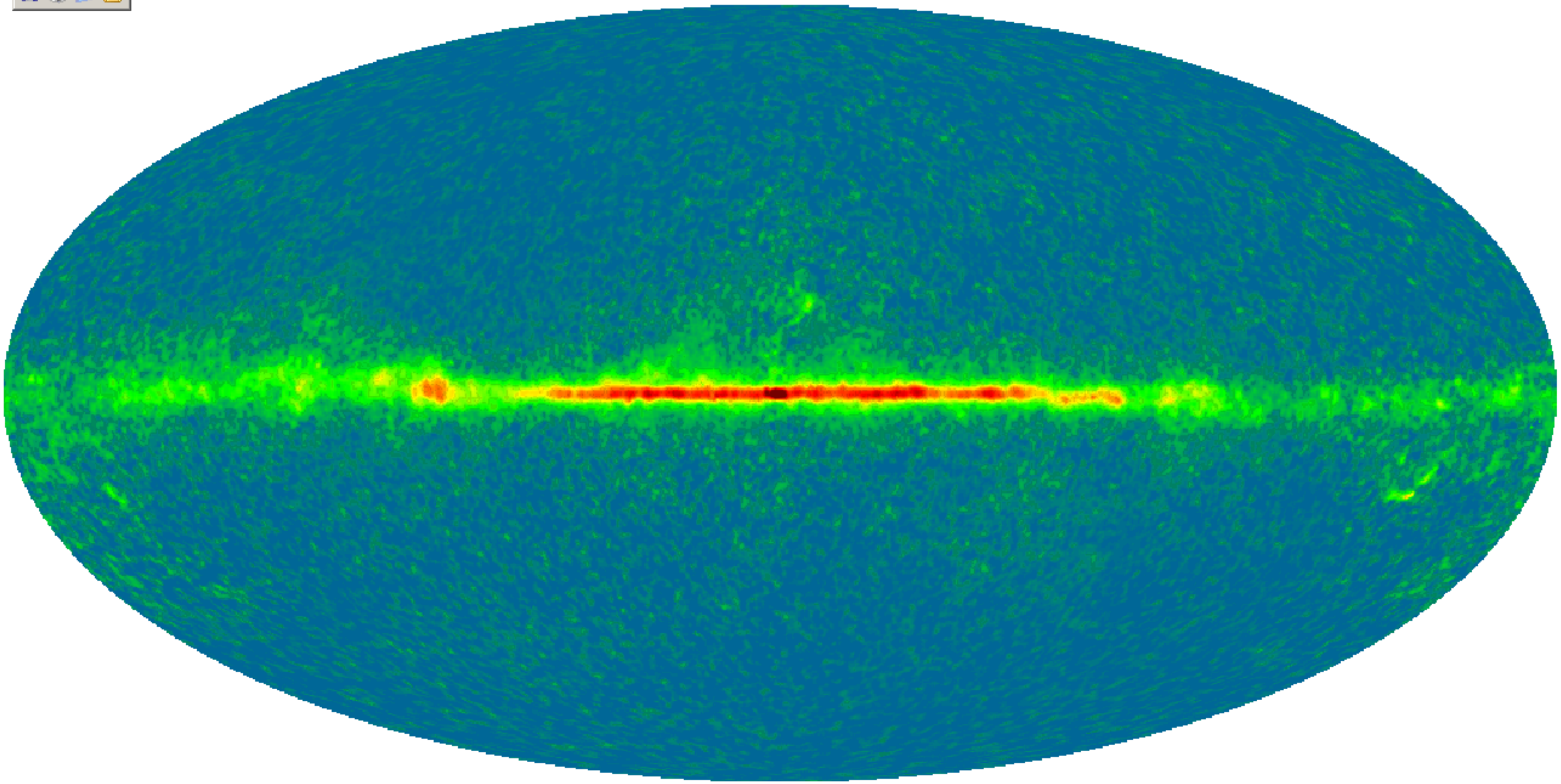
WMAP Synchrotron Map K band (23 GHz)

PLANCK Reflector Programme



WMAP Free – Free Map K band (23 GHz)

PLANCK Reflector Programme



WMAP Dust Map W band (94 GHz)

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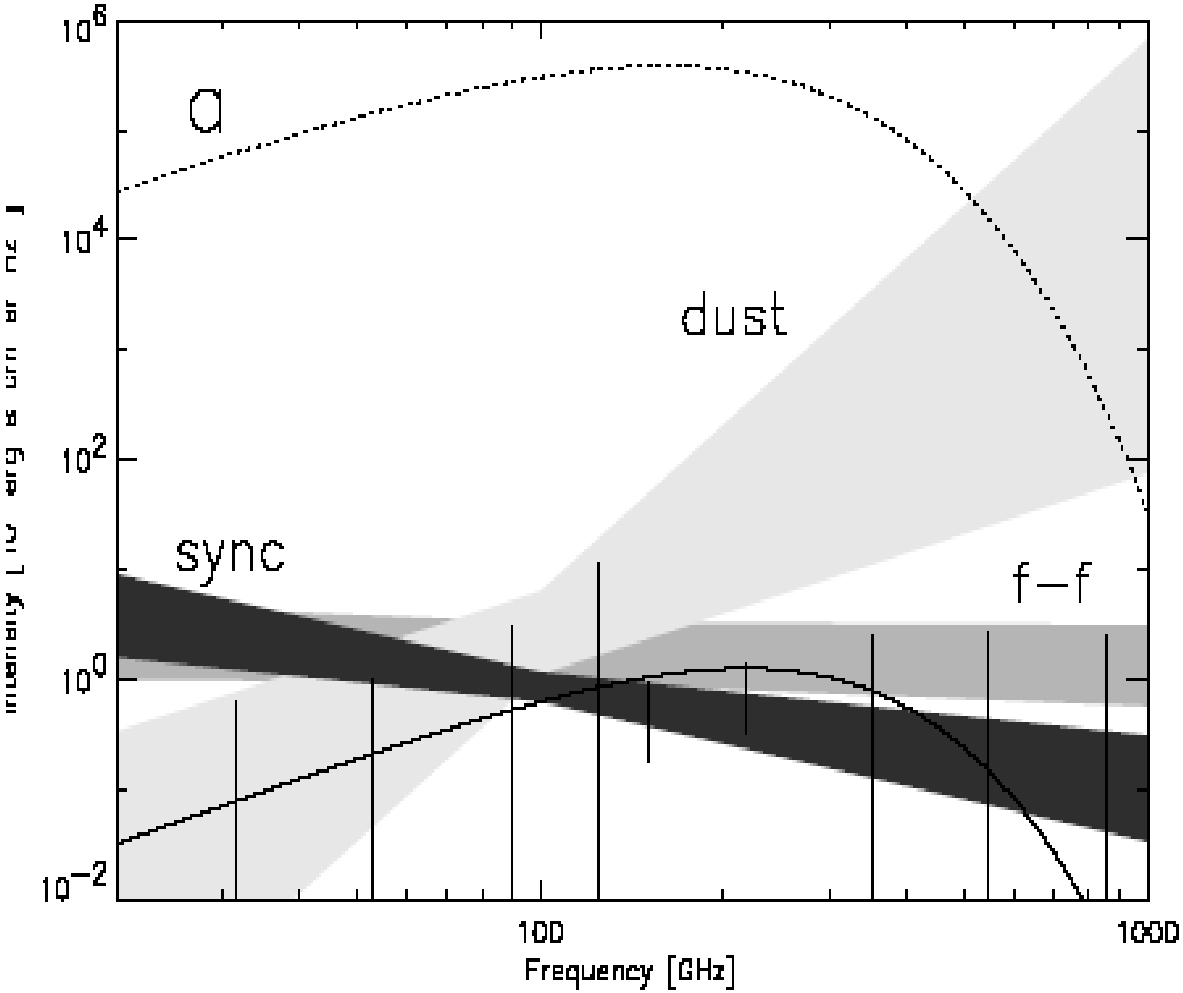
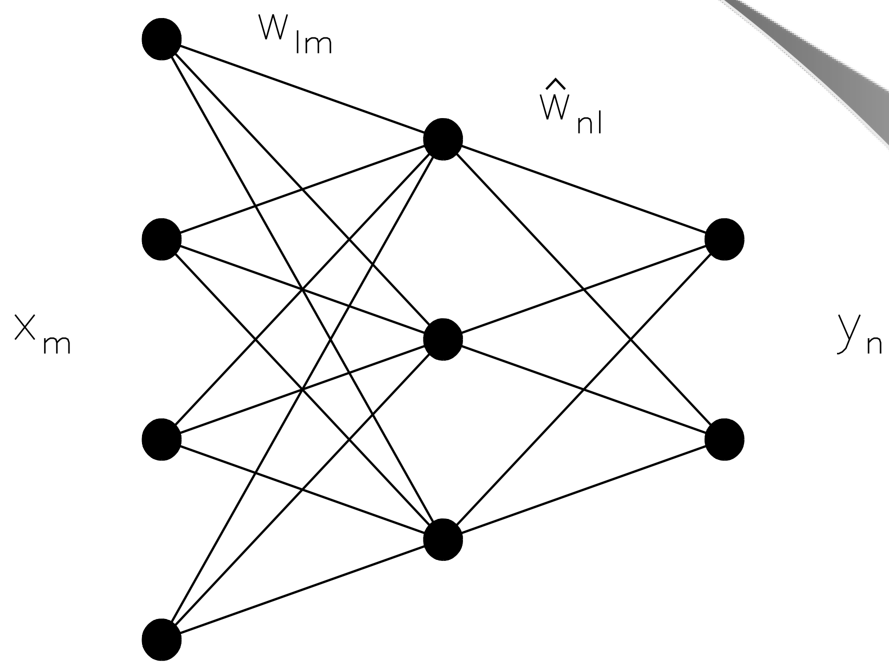
Planck Reflectors DSRI • ESA • DK-PLANCK

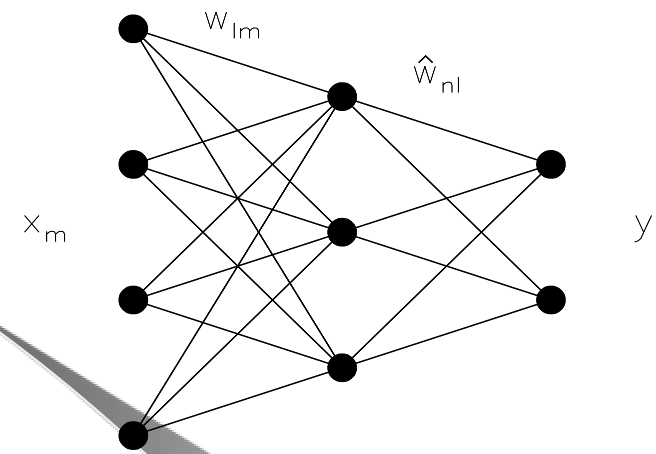


Simple Neural Network: Multilayer Perceptron (MLP)

exp



Straight forward to generalise to more hidden layers and more nodes per layer (2 hidden layers (12 and 3 nodes) used)



$$z_l = F\left(\sum_{m=1}^{M} w_{lm} x_m + \Theta_l\right) \quad (l = 1, ..., L),$$

where Θ_l is an offset (or threshold). We

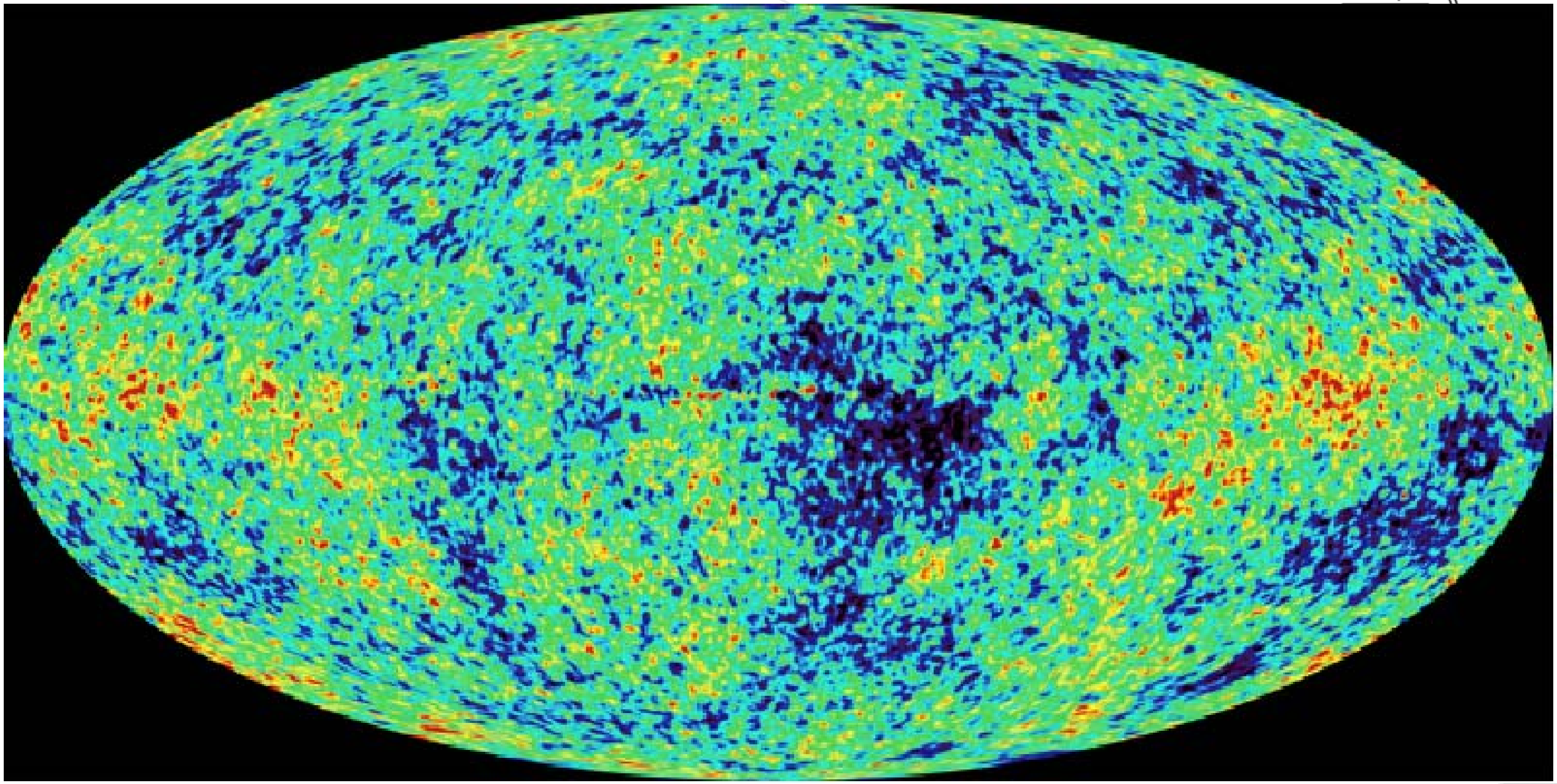
$$tansig(x) = \frac{2}{1 + exp(-2\,x)} - 1,$$

It is seen that values of *tansig* fall within the interval [−1; 1].

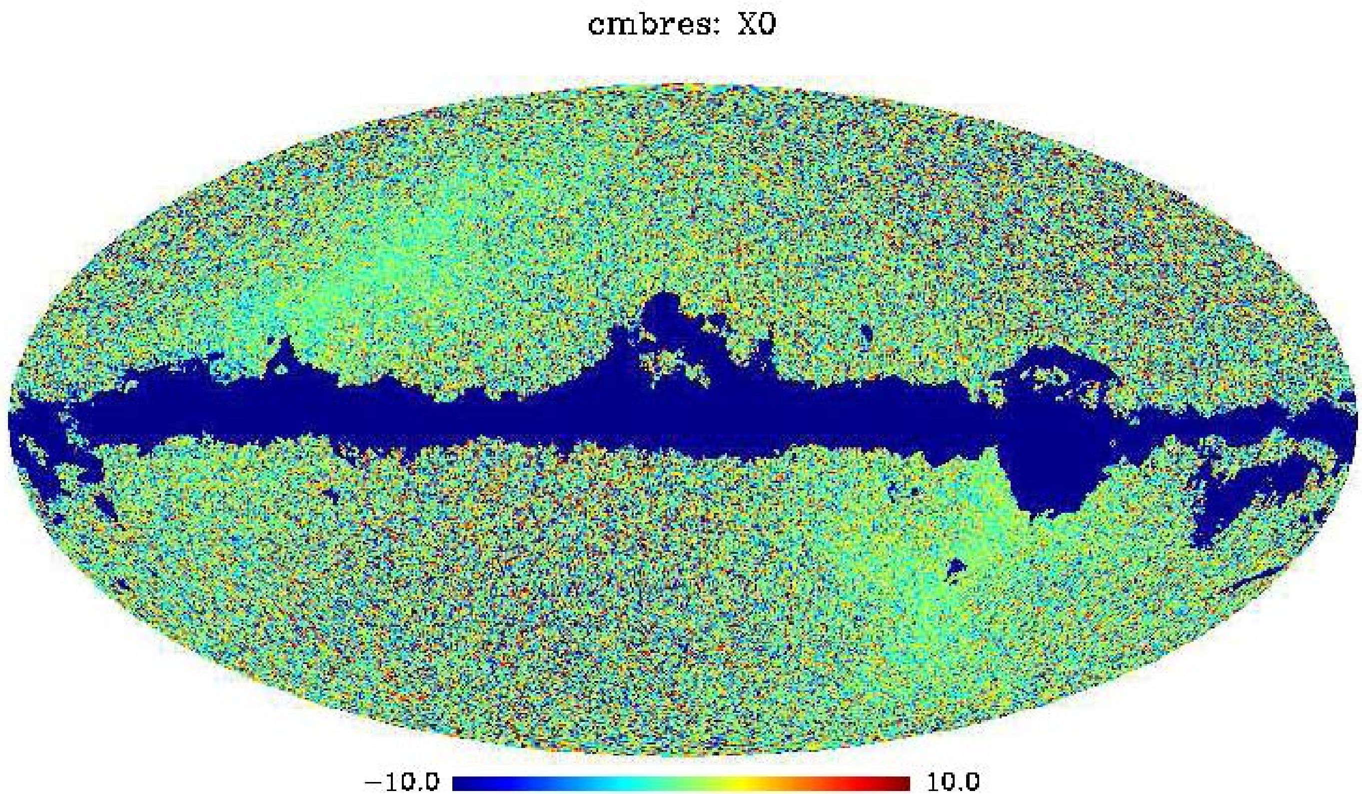
$$y_n(x_1, ..., x_M) = \sum_{l=1}^{L} \widehat{w}_{nl}\, F\left(\sum_{m=1}^{M} w_{lm} x_m + \Theta_l\right) + \widehat{\Theta}_n,$$

$$E_{net} = \sum_{p=1}^{P} \sum_{n=1}^{N} [y_n(x^p) - y_n^p]^2,$$

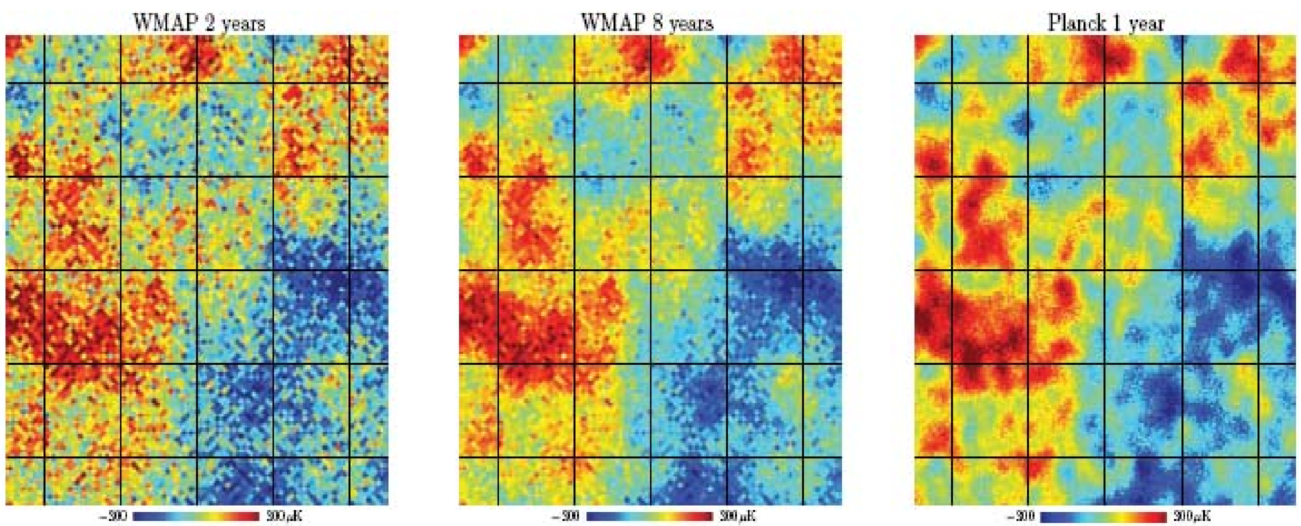
PLANCK Reflector Programme



WMAP Internal Linear Combination Map (± 200 μK)


cmbres: X0
−10.0
10.0

PLANCK Reflector Programme



PLANCK Refl

Jungman et al. (1996)

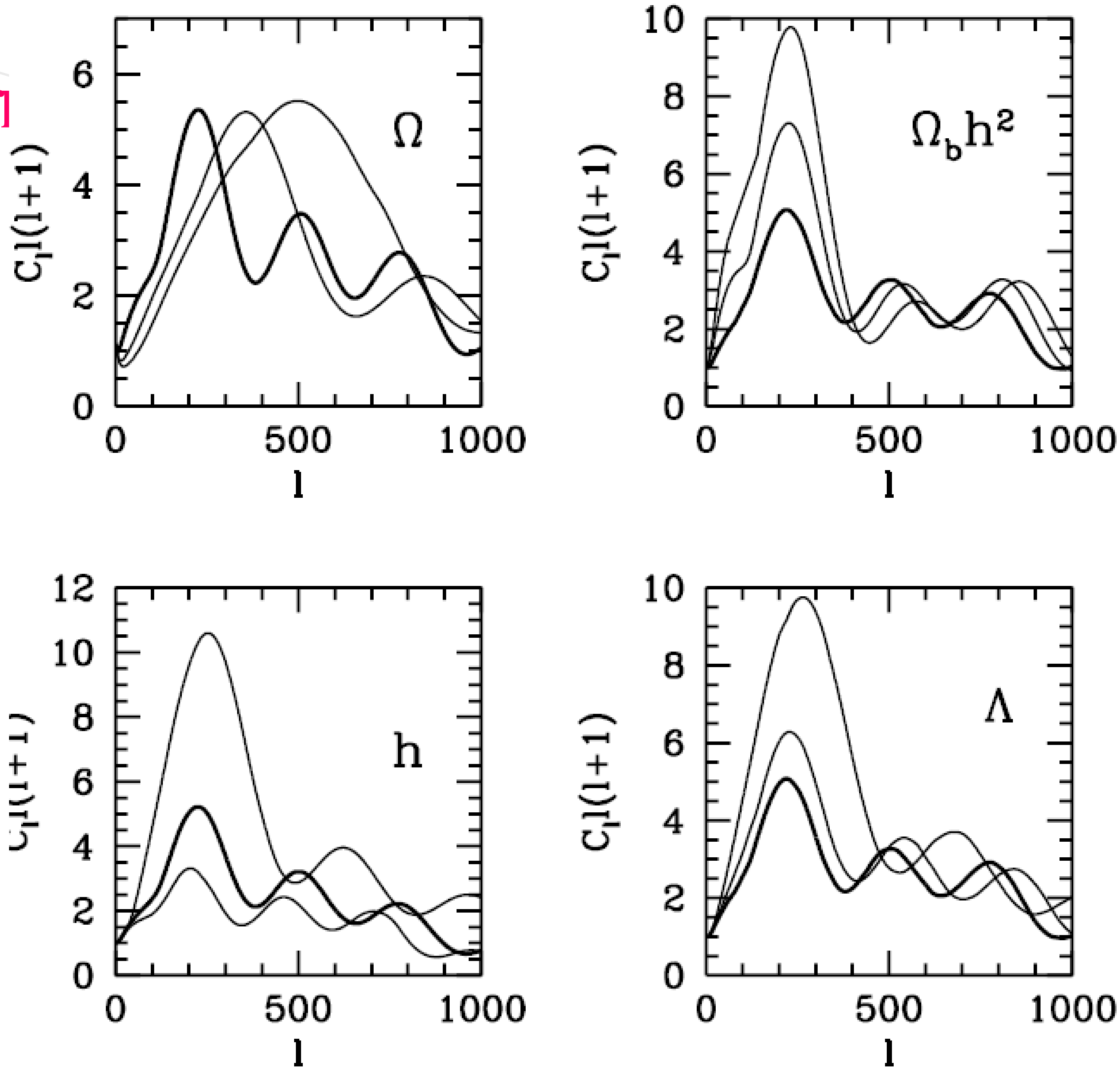


FIG. 1. Predicted multipole moments for standard CDM and variants. The heavy curves in each graph are for a model with primordial adiabatic perturbations with $\Omega = 1$, $\Lambda = 0$, $n_S = 1$, $\Omega_b h^2 = 0.01$, $h = 0.5$, $\alpha = 0$, and no tensor modes. The graphs show the effects of varying Ω, Λ, h, $\tau_{\rm reion} = 0$, and $\Omega_b h^2$ while holding all other parameters fixed. In the Ω panel, from left to right, the solid curves are for $\Omega = 1$, $\Omega = 0.5$, and $\Omega = 0.3$. The curves in the $\Omega_b h^2$ panel are (from lower to upper) for $\Omega_b h^2 = 0.01$, $\Omega_b h^2 = 0.03$, and $\Omega_b h^2 = 0.05$. In the h panel, the heavy curves is for $h = 0.5$, while the other two curves are for $h = 0.3$ (the upper light curve) and $h = 0.7$ (the lower light curve). The curves in the Λ panel are for (from lower to upper) $\Lambda = 0$, $\Lambda = 0.3$, and $\Lambda = 0.7$.

PLANCK Reflector Programme

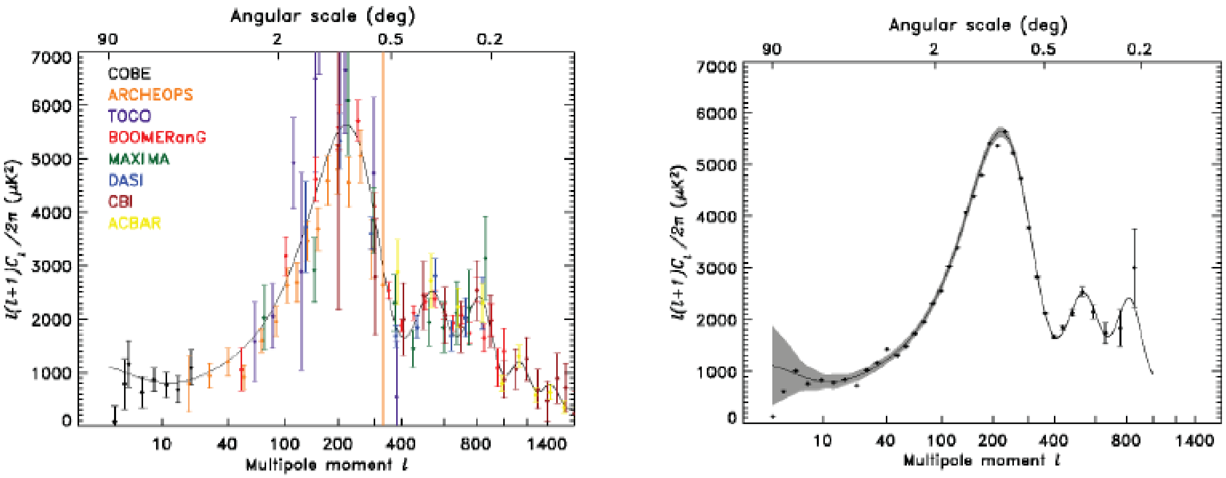


FIG 2.2.— The left panel (courtesy of the *WMAP* Science Team) shows a summary of CMB anisotropy measurements from various experiments prior to the release of the first year results from *WMAP*. The references to the experimental data are as follows: *COBE* (Tegmark 1996), Archeops (Benoit et al. 2003), TOCO (Miller et al. 2002), Boomerang (Ruhl et al. 2003), Maxima (Lee et al. 2001), DASI (Halverson et al. 2002), CBI (Pearson et al. 2003) and ACBAR (Kuo et al. 2004). The right panel shows results from the first year of *WMAP* data.

PLANCK Reflector Programme

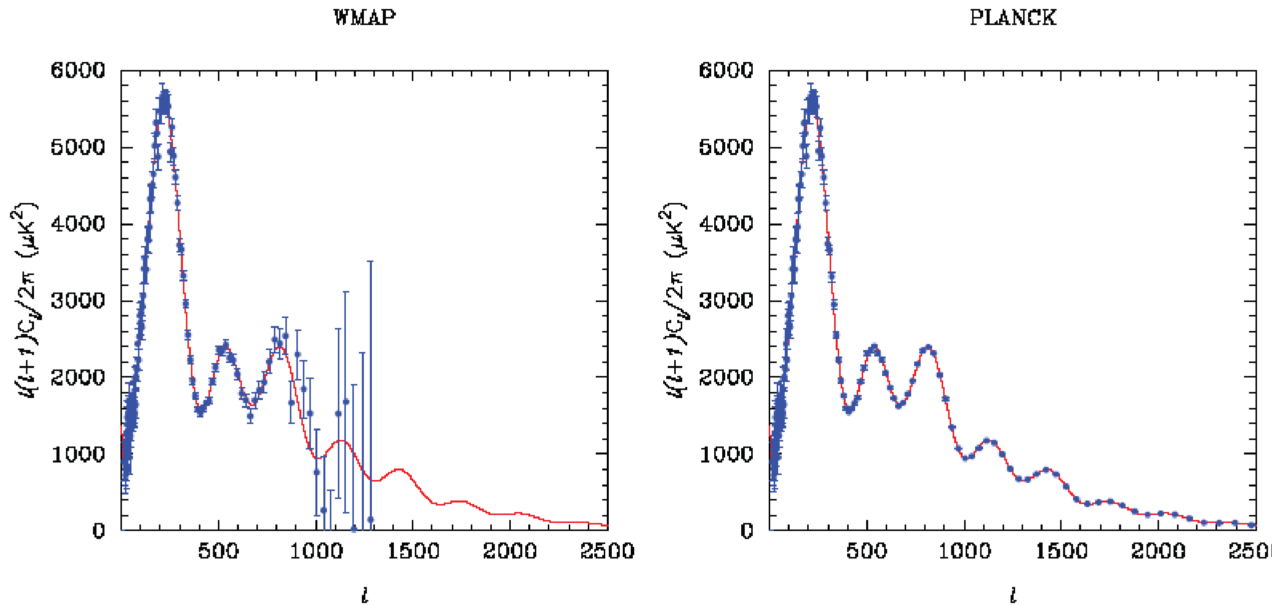


FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

PLA

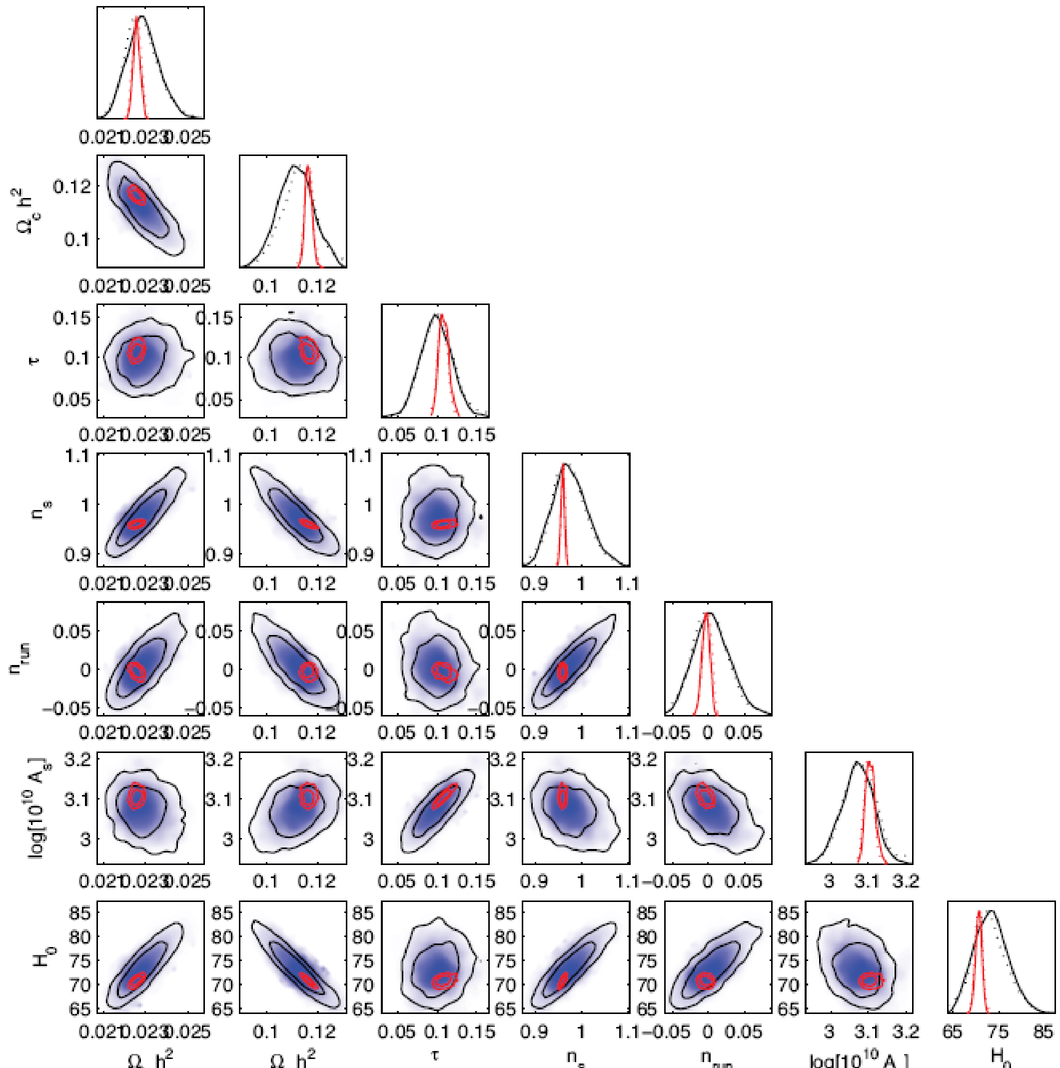


FIG 2.18.—Forecasts of 1 and 2σ contour regions for various cosmological parameters when the spectral index is allowed to run. Blue contours show forecasts for *WMAP* after 4 years of observation and red contours show results for *Planck* after 1 year of observations. The curves show marginalized posterior distributions for each parameter.

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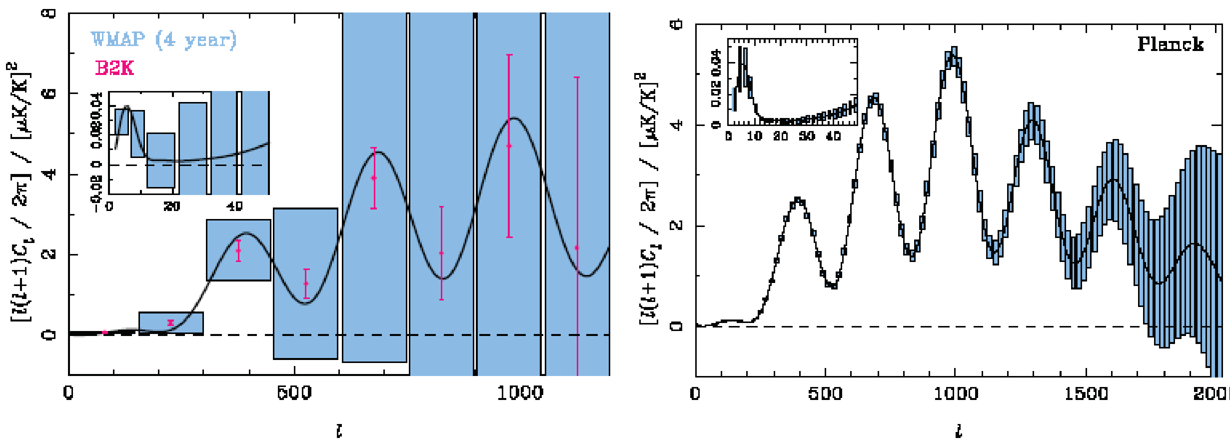

FIG 2.14.—Forecasts for the $\pm 1\sigma$ errors on the E-mode polarization power spectrum C_ℓ^E from *WMAP* and B2K (left) and *Planck* (right). The cosmological model, and the assumptions about instrument characteristics, are the same as in Figure 2.13. For *WMAP* and B2K, flat band powers are estimated with $\Delta\ell = 150$ (with finer resolution on large scales for *WMAP* in the inset). For *Planck* we have used the same ℓ-resolution as in Figure 2.13.

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2.3 Cosmological Parameters from Planck 41

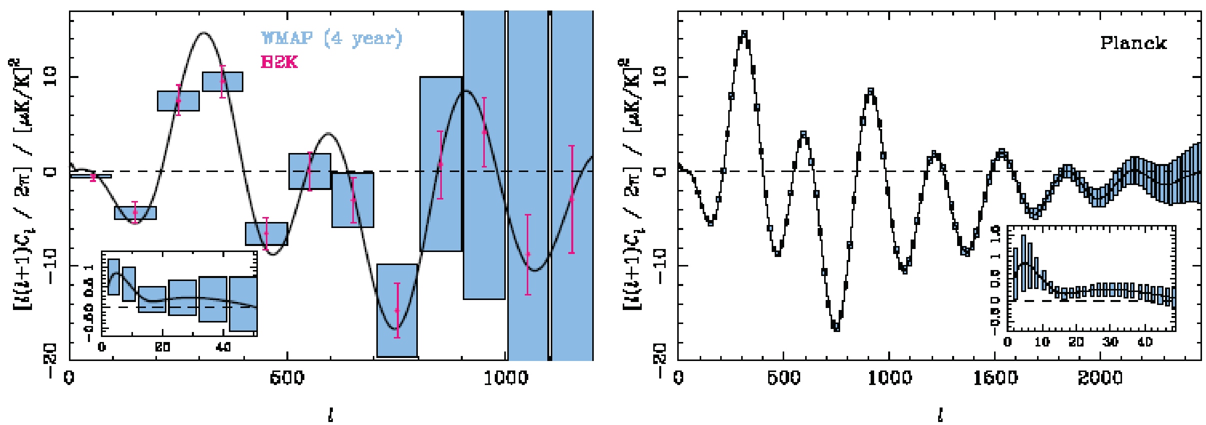
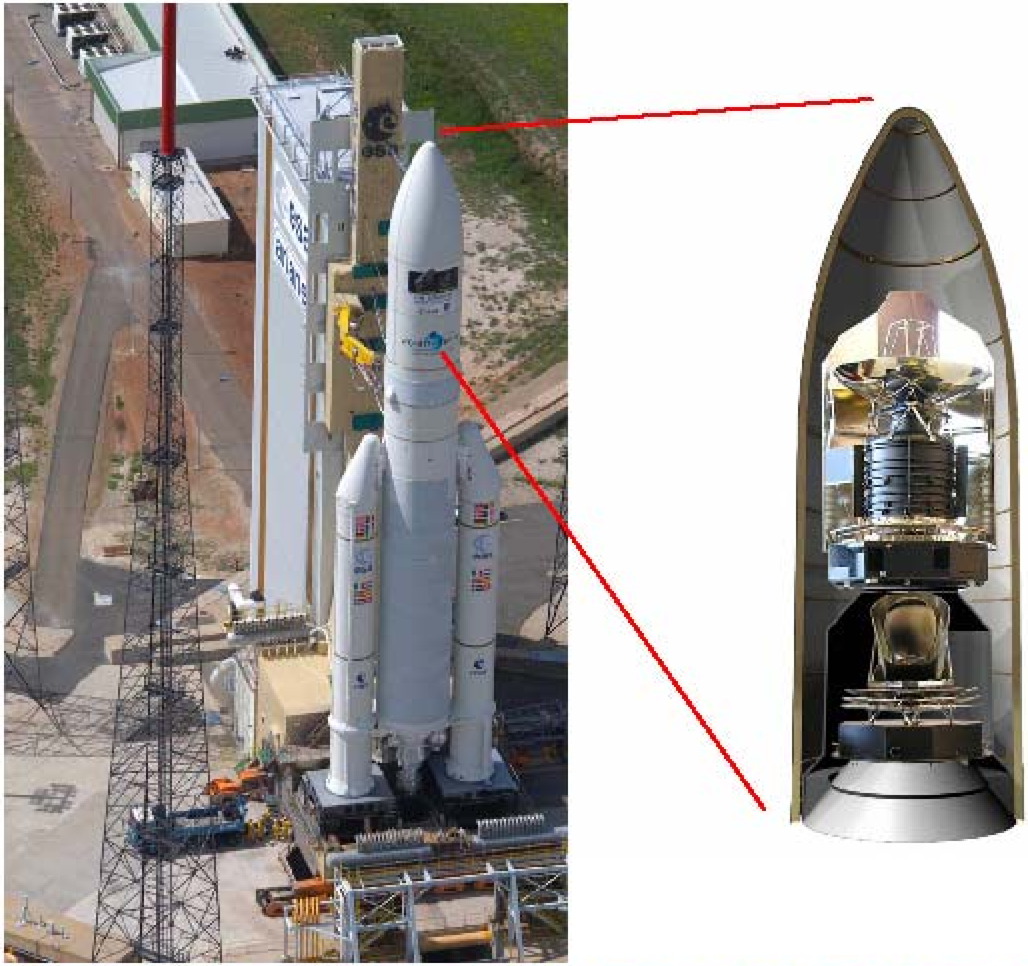


FIG 2.13.—Forecasts for the $\pm1\sigma$ errors on the temperature-polarization cross-correlation power spectrum C_ℓ^{TE} in a ΛCDM model (with $r = 0.1$ and $\tau = 0.17$) from *WMAP* (4 years of observation) and BOOMERanG2K (left) and *Planck* (right). In the left-hand plot, flat band powers are estimated with $\Delta\ell = 100$ for both experiments for ease of comparison. The inset shows the *WMAP* forecasts on large angular scales with a finer $\Delta\ell$ resolution. For *Planck*, flat band powers are estimated with $\Delta\ell = 20$ in the main plot, but with $\Delta\ell = 2$ in the inset on large scales.

14 May 2009


HERSCHEL SPACE OBSERVATORY
PLANCK

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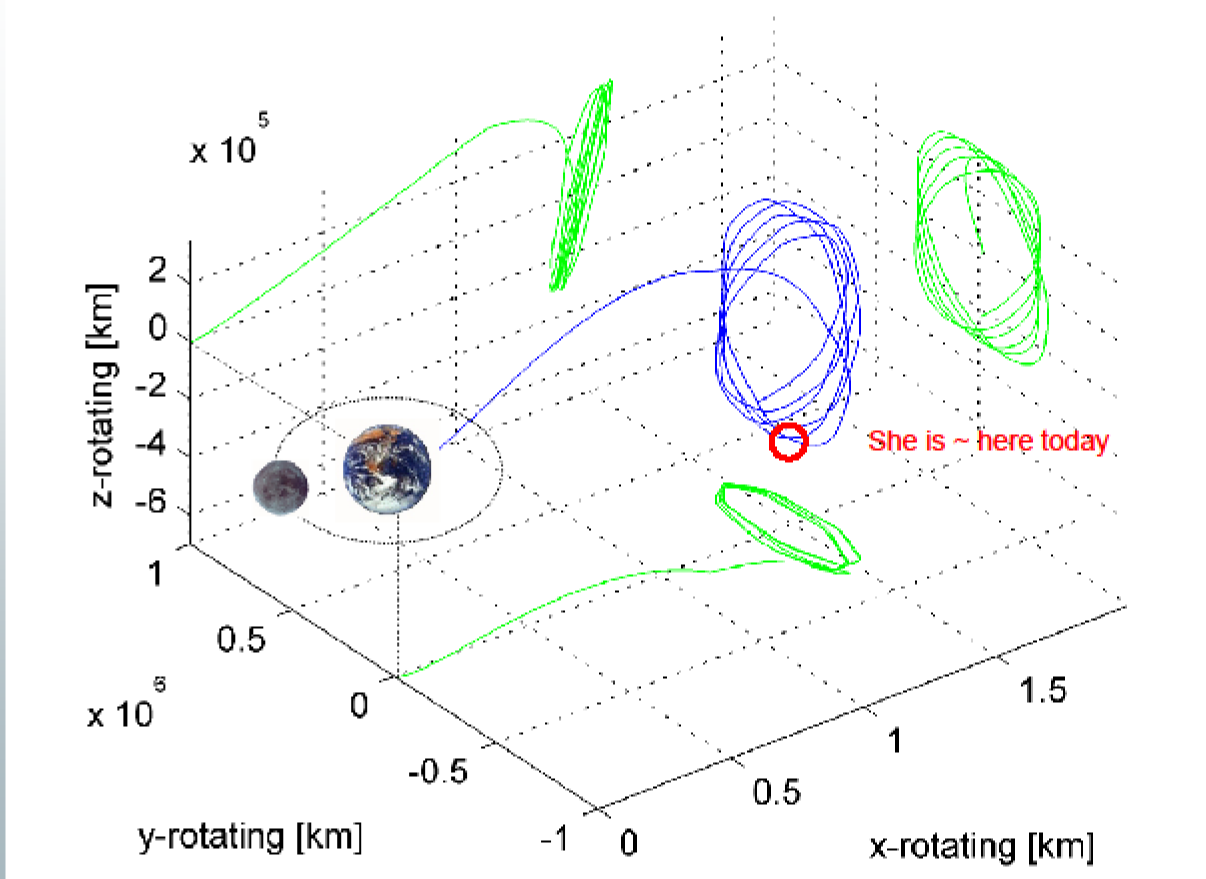
Planck is in L2 orbit since July



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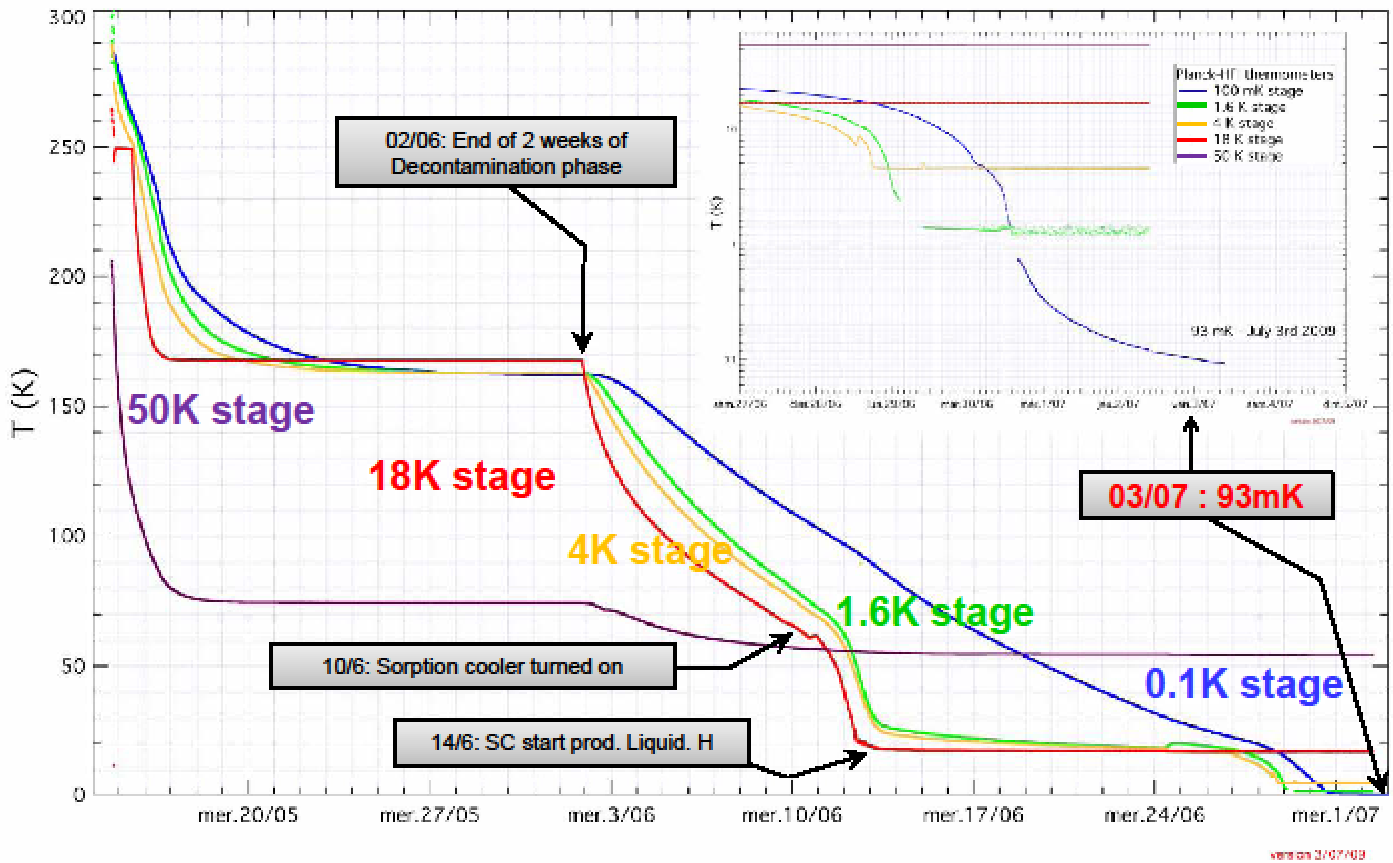
Planck is cool...



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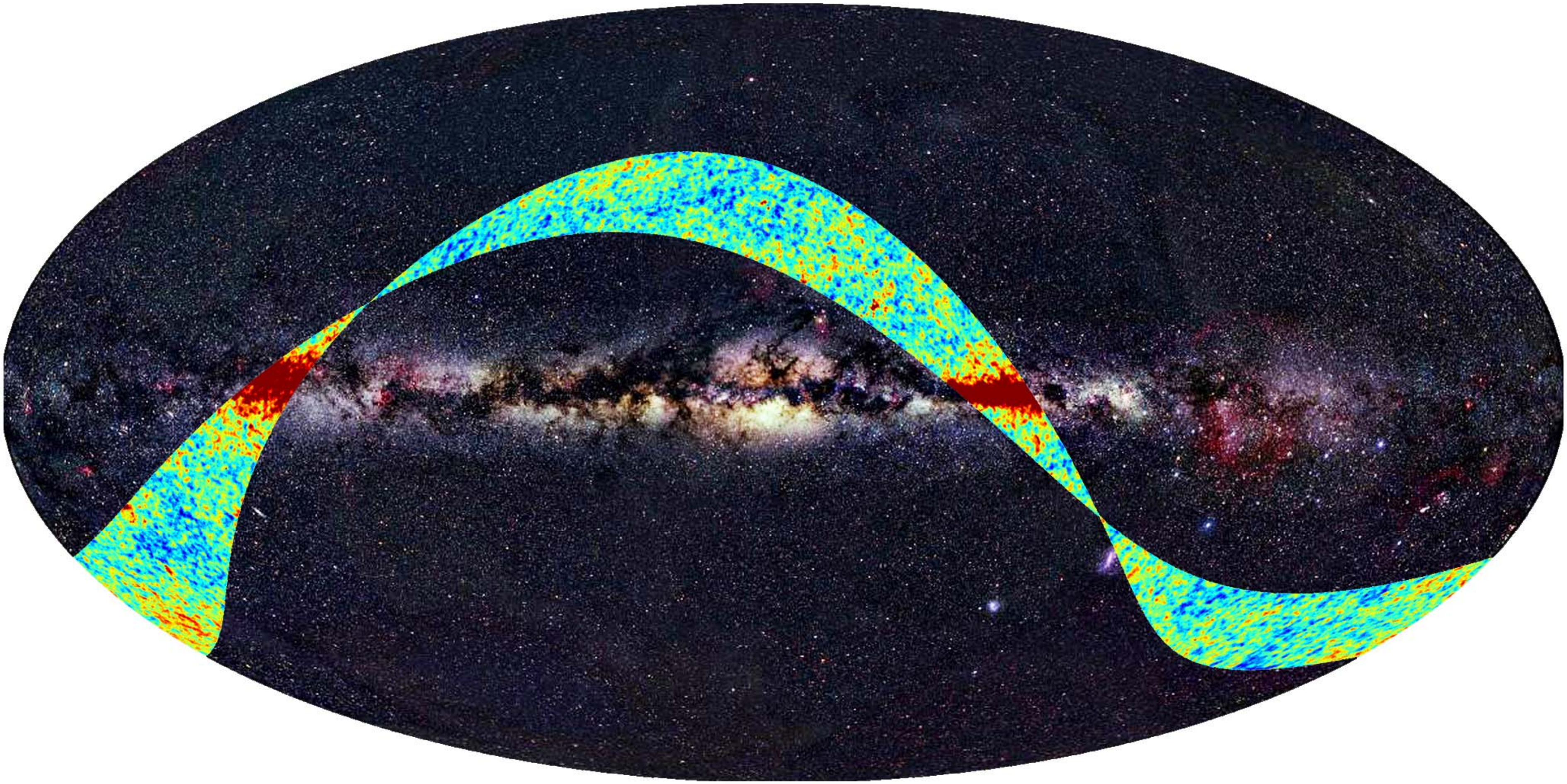
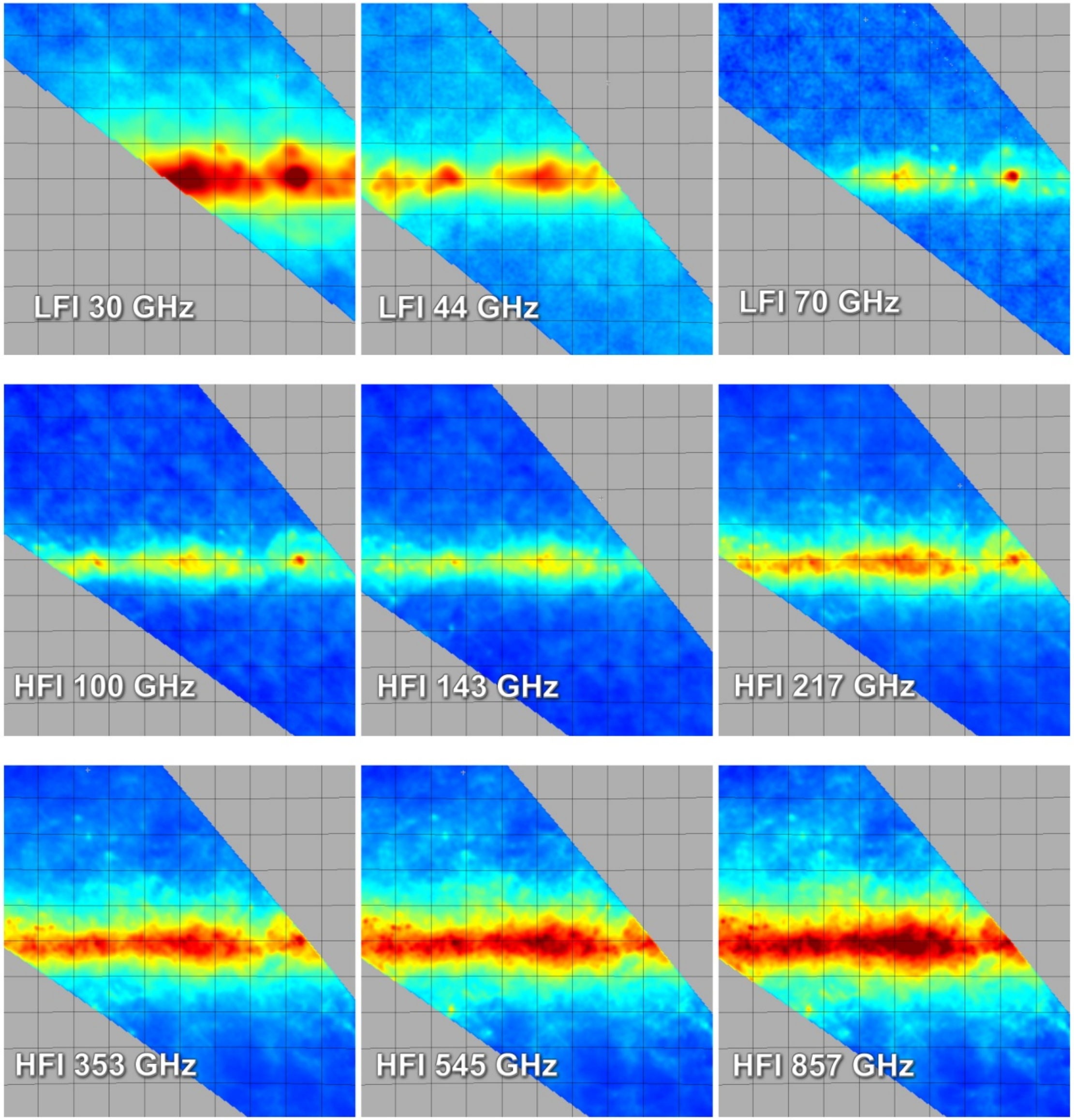


PLanck First Light Survey

PLANCK Reflector Programme



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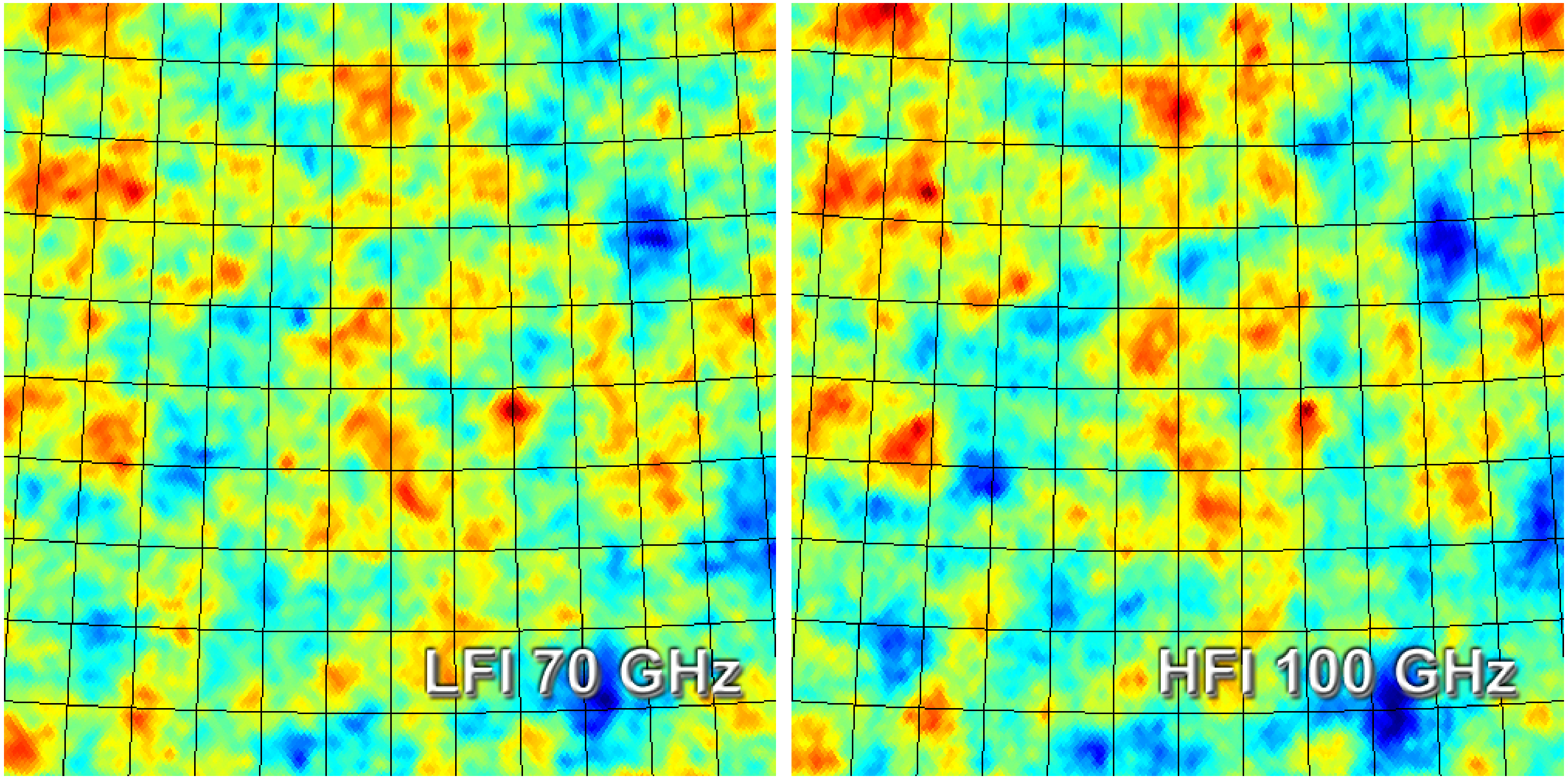

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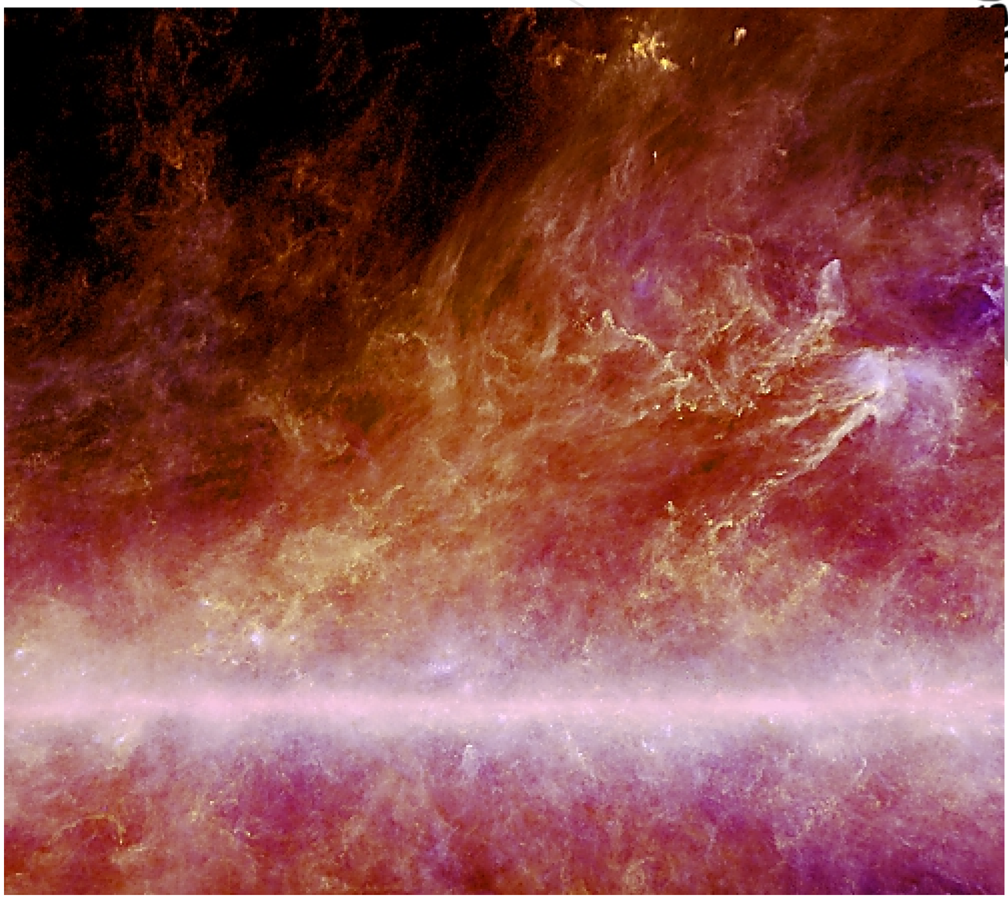

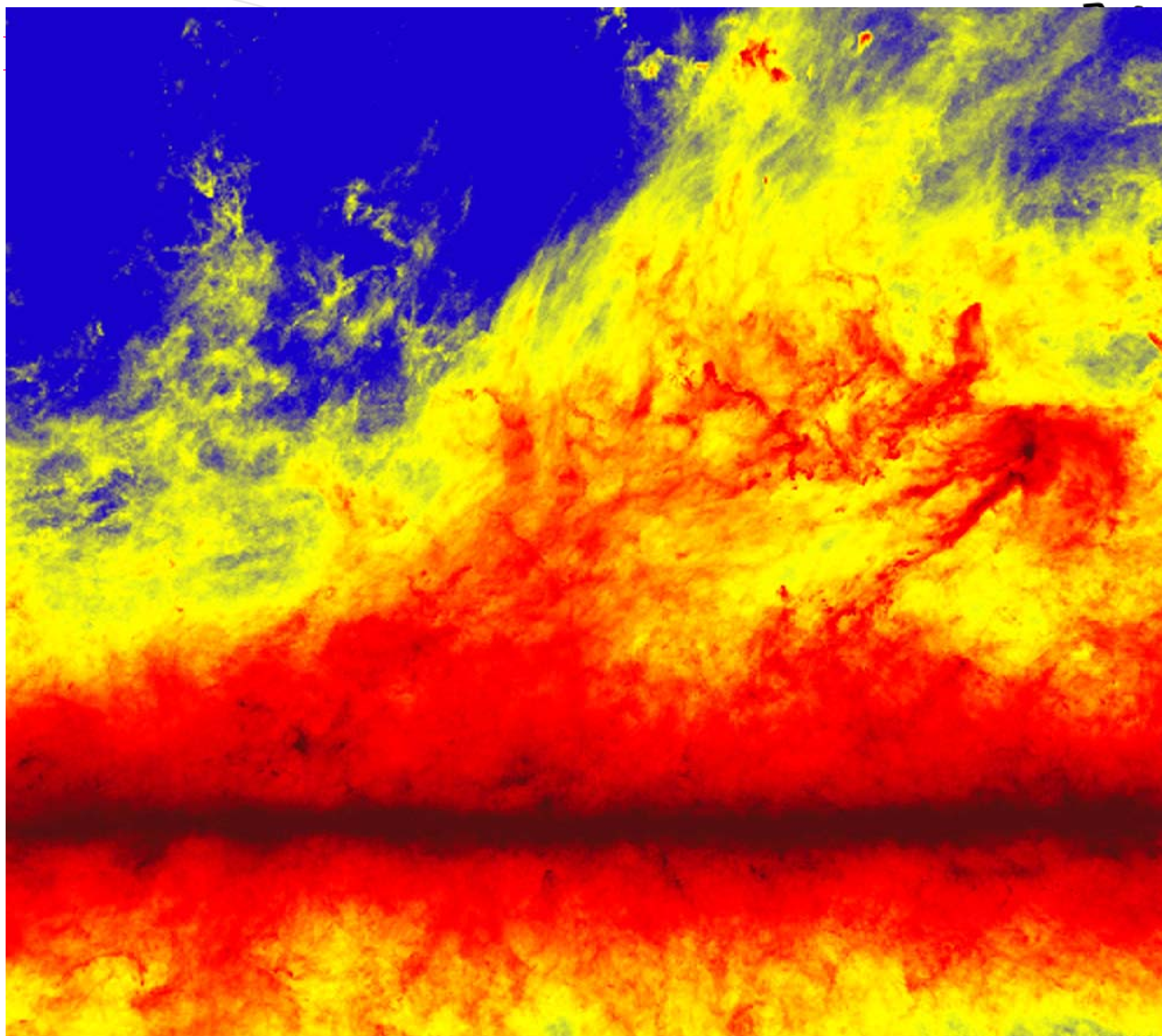

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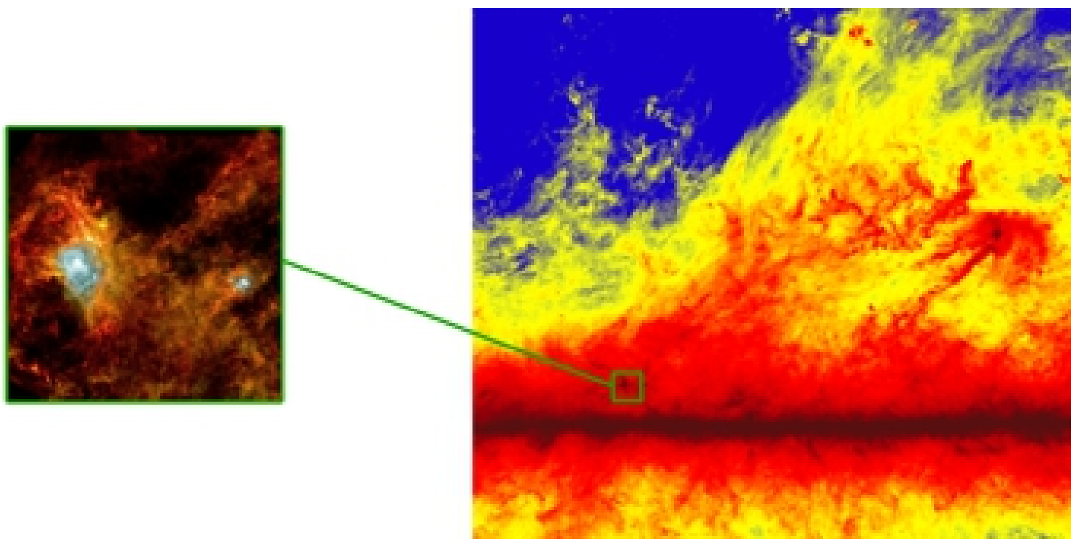

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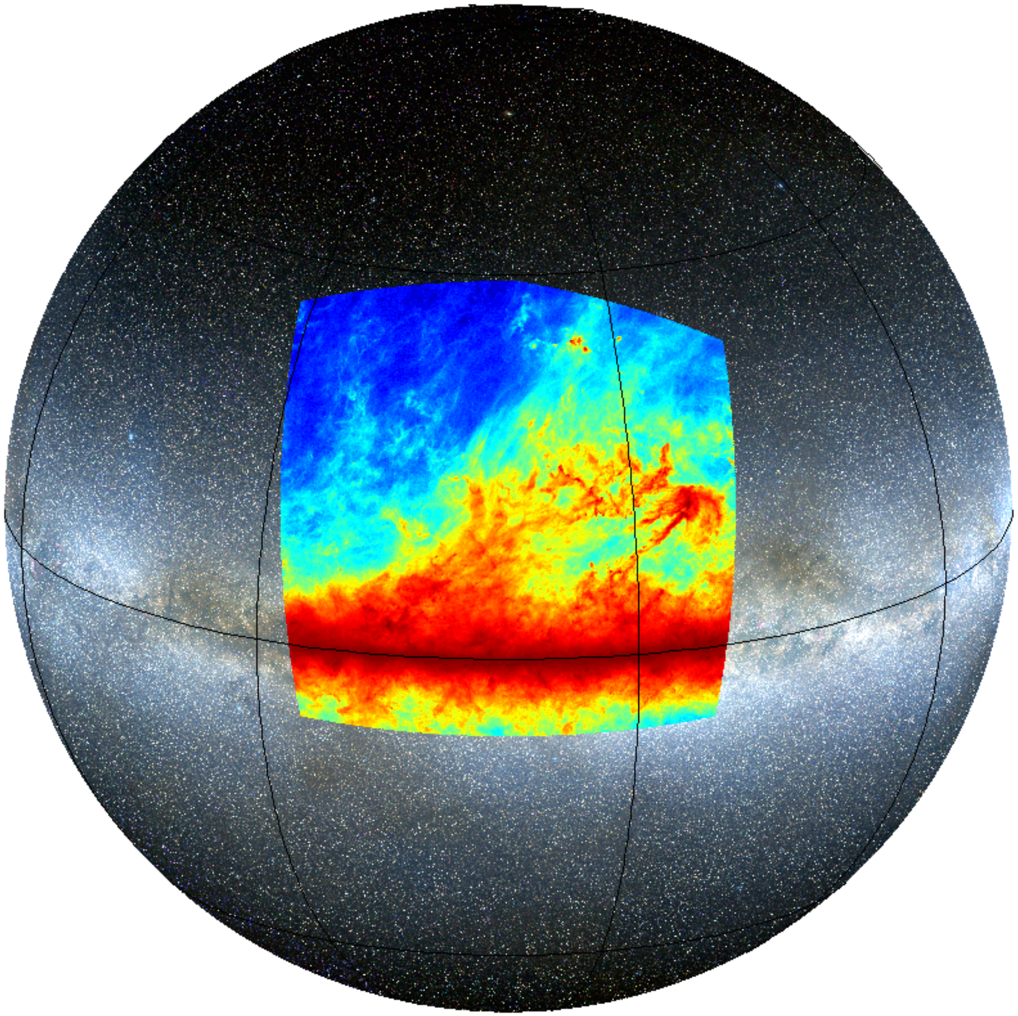

PLANCK Reflector Programme

PLANCK Reflector Programme

Planck Reflectors
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PLANCK Reflector Programme

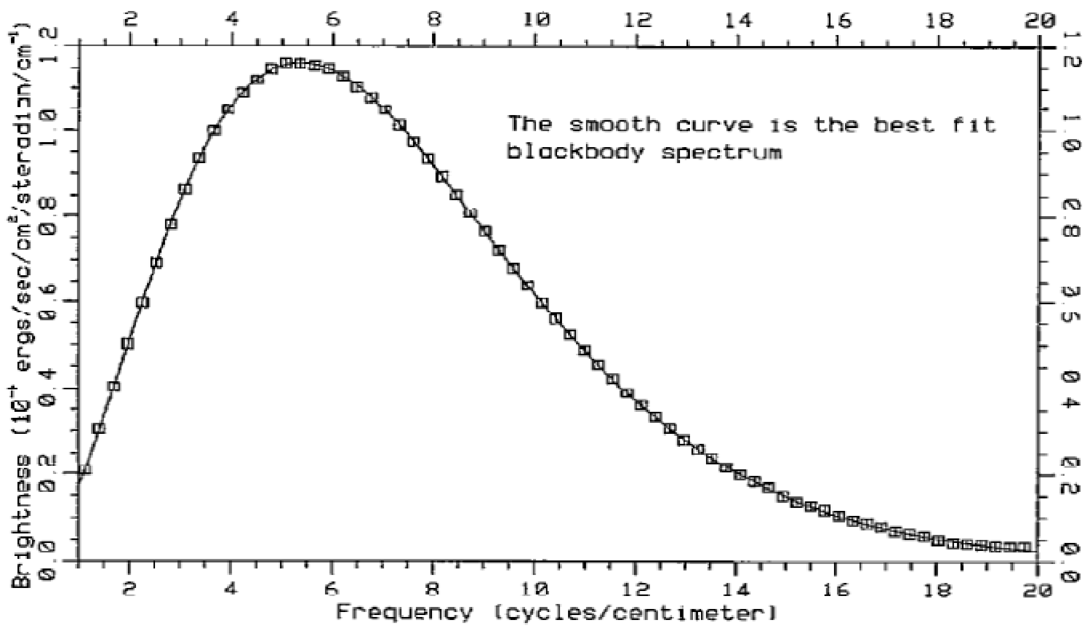
PLANCK Reflector Programme

$$tansig(x) = \frac{2}{1 + exp(-2\,x)} - 1,$$

It is seen that values of *tansig* fall within the interval [−1; 1].

PLANCK Reflector Programme

Figure 7 shows the deviations from a blackbody spectrum with a temperature of 2.726 ± 0.010 K published 1994 (Mather et al. 1994). After careful studies of errors caused by the FIRAS calibrator (figure 4), the CMB temperature was finally given as 2.725 ± 0.002 K (Mather et al. 1999) with deviations from a blackbody spectrum less than 1 part in 10^5.



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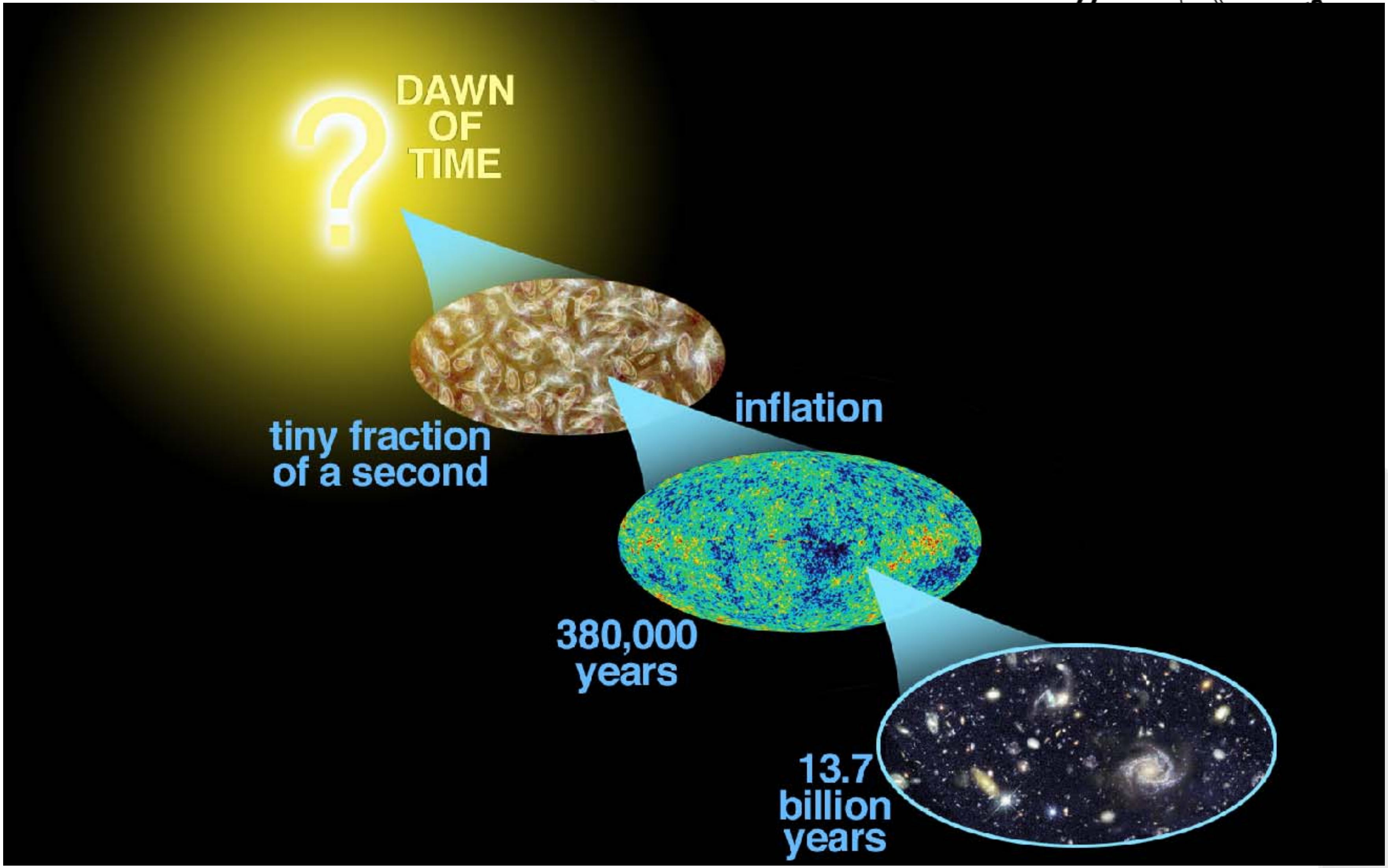
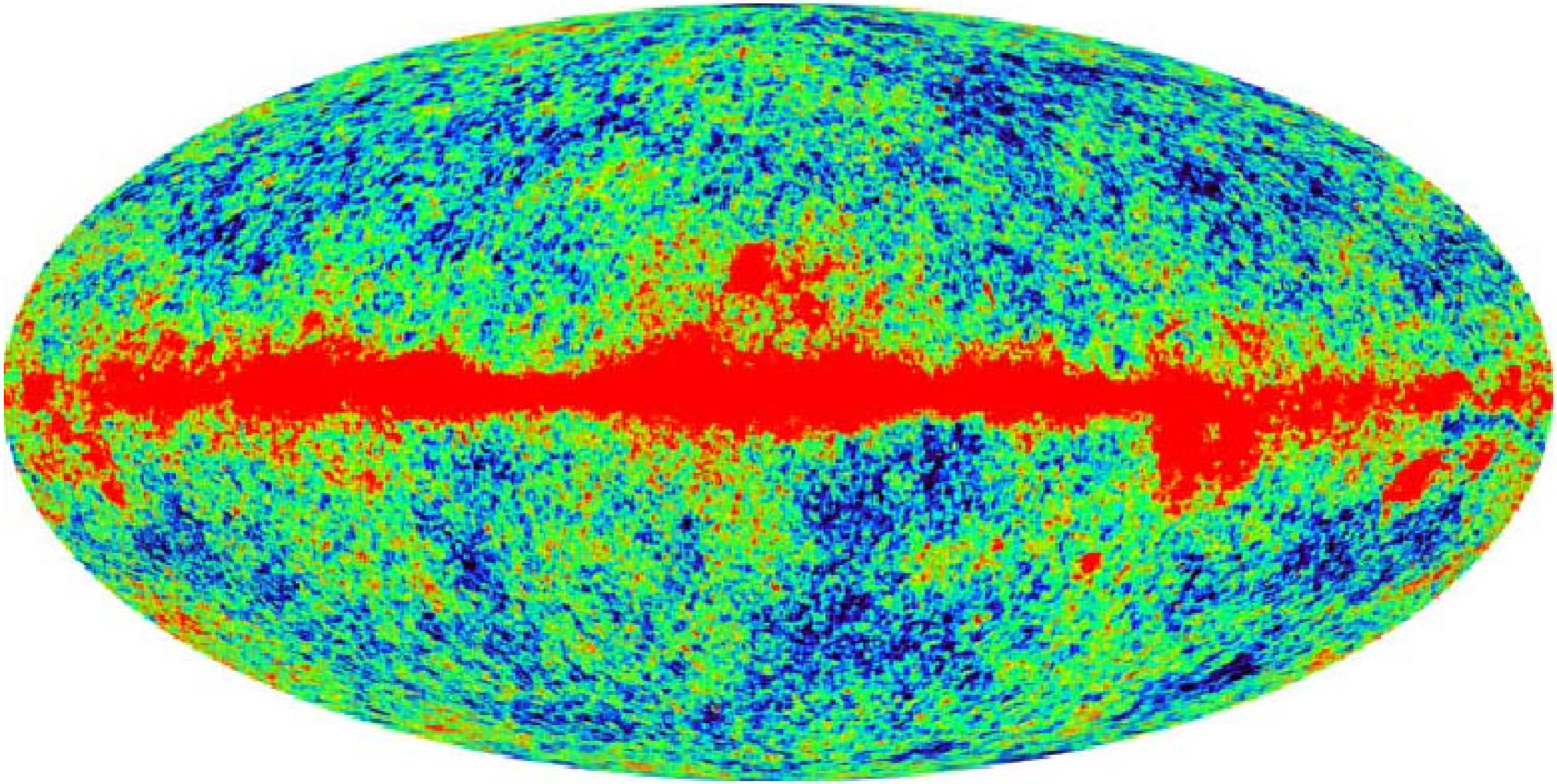


PLANCK Reflector Programme



WMAP Q band (41 GHz)

PLANCK Reflector Programme

PLANCK Reflector Programme

Table 2. Summary of the Planck instrument characterization taken from the 'Blue Book' (ESA-SCI(2005)1). The 1σ flux sensitivity is derived for a common beam with a 30 arcmin diameter (unit: $10^{-20} erg s^{-1} cm^{-2} Hz^{-1} sr^{-1}$)

	LFI	LFI	LFI	HFI	HFI	HFI	HFI	HFI	HFI
Center frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	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	5	5	5	5
1σ sensitivity	0.22	0.38	0.90	0.58	0.61	1.19	2.25	4.34	5.22

Due to the Planck scanning strategy the errors scales with the same factor