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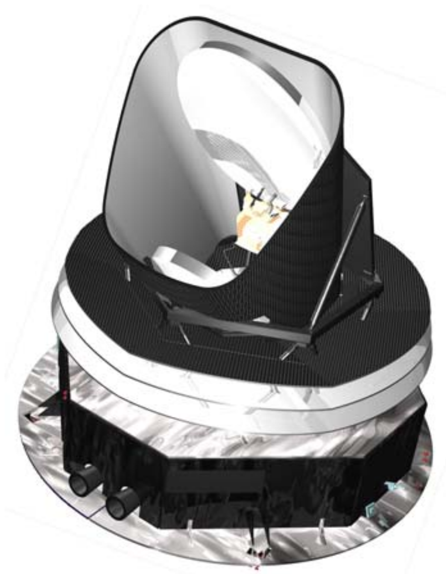

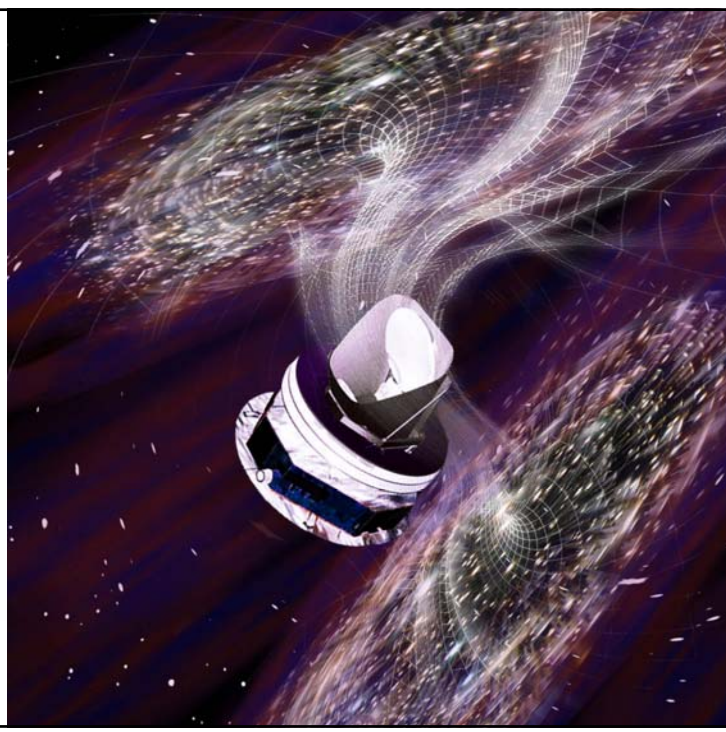

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The European mission to map the Cosmic Microwave Background

1. **Scientific objectives**
2. **Mission facts & status**

[+ following talk by Jean-Loup Puget]

J. Tauber, on behalf of the Planck Collaboration

See also *http://www.rssd.esa.int/Planck*, e.g. the "Bluebook

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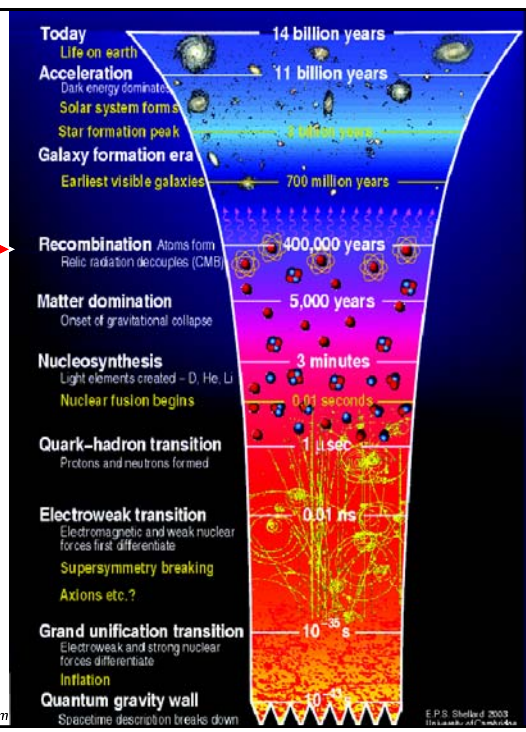
The Cosmic Microwave Background is generated here



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Main Observational Objective of PLANCK

To image the temperature anisotropies and polarisation of the Cosmic Microwave Background (CMB), over the whole sky, with an uncertainty on the temperature limited by “natural causes” (foreground fluctuations, cosmic variance) rather than intrinsic or systematic detector noises, and an angular resolution ~5 arcminutes.

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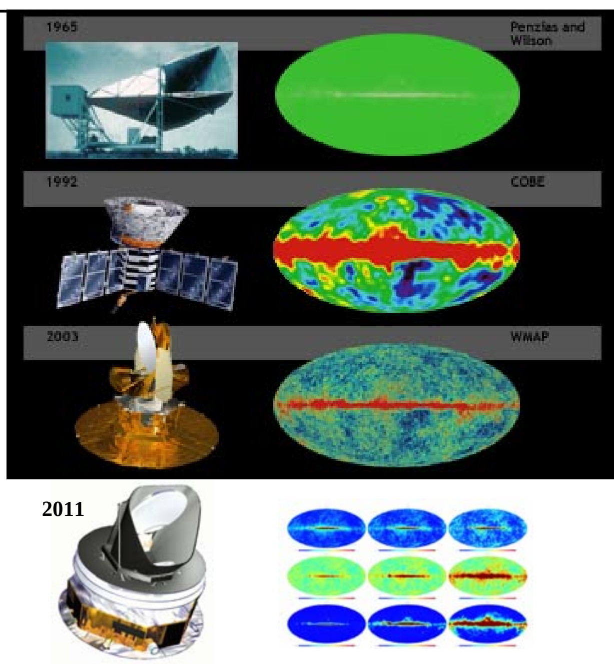

Planck:
3rd Generation
CMB space
experiment

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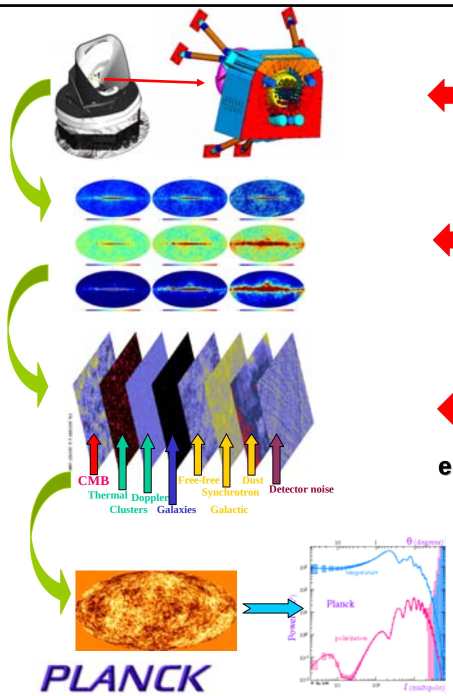

Acquiring and processing time-ordered information

Converting time-ordered data to maps of the sky emission at many frequencies

Converting frequency maps to component maps, e.g. the Cosmic Microwave Background

Estimating the CMB angular power spectrum and cosmological parameters

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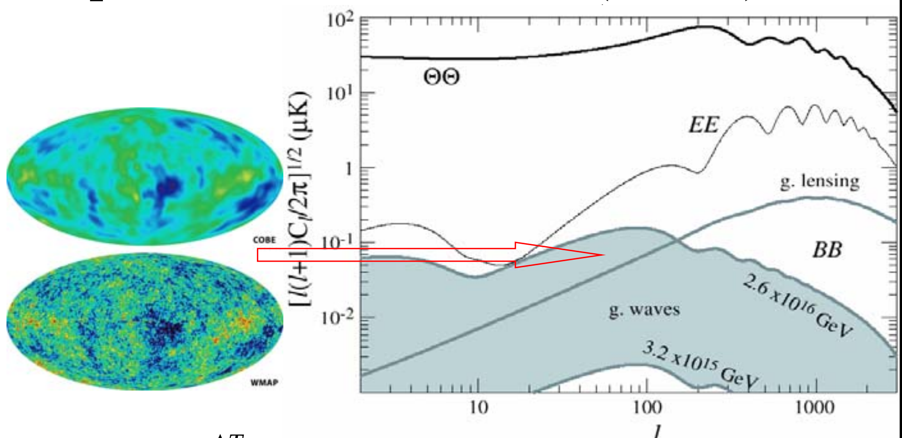
Theoretical angular power spectrum of the CMB (CDM)



$$\frac{\Delta T}{T} = \sum_{l,m} a_l^m Y_l^m(\theta,\varphi)$$

l (multipole)

$$C_l = \langle |a_l^m|^2 \rangle$$

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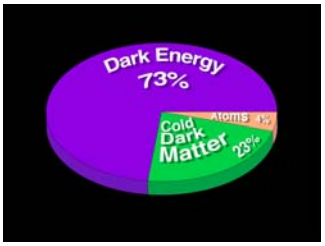
Parameter	Value[a]	Description	WMAP[b]
		Ten Global Parameters	
h	0.72 ± 0.07	Present expansion rate[c]	$0.71^{+0.04}_{-0.03}$
q_0	-0.67 ± 0.25	Deceleration parameter[d]	-0.66 ± 0.10[e]
t_0	13 ± 1.5 Gyr	Age of the Universe[f]	13.7 ± 0.2 Gyr
T_0	2.725 ± 0.001 K	CMB temperature[g]	
Ω_0	1.03 ± 0.03	Density parameter[h]	1.02 ± 0.02
Ω_B	0.039 ± 0.008	Baryon Density[i]	0.044 ± 0.004
Ω_{CDM}	0.29 ± 0.04	Cold Dark Matter Density[i]	0.23 ± 0.04
Ω_ν	$0.001 - 0.05$	Massive Neutrino Density[j]	
Ω_X	0.67 ± 0.06	Dark Energy Density[i]	0.73 ± 0.04
w	-1 ± 0.2	Dark Energy Equation of State[k]	< -0.8 (95% cl)
		Six Fluctuation Parameters	
$\sqrt{S}$	$5.6^{+1.5}_{-1.0} \times 10^{-6}$	Density Perturbation Amplitude[l]	
$\sqrt{T}$	$< \sqrt{S}$	Gravity Wave Amplitude[m]	$T < 0.71S$ (95%cl)
σ_8	0.9 ± 0.1	Mass fluctuations on 8 Mpc[n]	0.84 ± 0.04
n	1.05 ± 0.09	Scalar index[h]	0.93 ± 0.03
n_T	—	Tensor index	
$dn/d\ln k$	-0.02 ± 0.04	Running of scalar index[o]	-0.03 ± 0.02

[a]The 1-σ uncertainties quoted in this table represent our combined analysis of published data.
[b]Bennett *et al.*, 2003.
[c]Freedman *et al.*, 2001; note: $H_0 = 100h$ km sec^{-1} Mpc^{-1}.
[d]Supernovae results combined with measurements of the total matter density, $\Omega_M = \Omega_\nu + \Omega_B + \Omega_{CDM}$ and Ω_0, assuming $w = -1$ (Perlmutter *et al.*, 1999; Riess *et al.*, 1998).



Fundamental Parameters: the "Concordance Model"

From Freedman and Taylor 2004

Science with accurate cosmological parameters

- Determining cosmological parameters to high accuracy
  - Geometry of Universe
  - Age of Universe, H_o, Ω_o, Λ, …
  - Neutrino mass, …
- Testing inflation, constraining the inflaton potential
  - Finding signatures of primordial gravitational waves
- Finding non-gaussianities
  - Primordial
  - "local"
- physics beyond standard model, e.g. superstrings
- Evolution of structure and nature of dark matter
- epoch of reionisation
- …

WMAP 3-year TT spectrum
Spergel et al. 2006

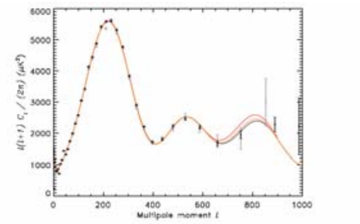
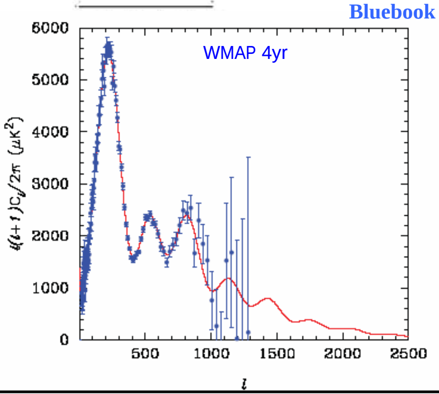
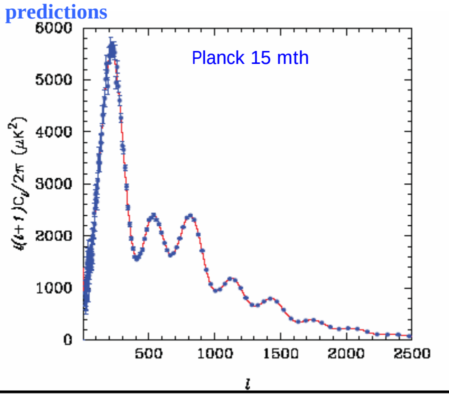


Fig. 2.— Comparison of the predictions of the different best fit models to the data. The *black* line is the angular power spectrum predicted for the best fit three-year WMAP only ΛCDM model. The *red* line is the best fit to the 1-year WMAP data. The *orange* line is the best fit to the combination of the 1-year WMAP data, CBI and ACBAR (WMAPext in Spergel et al. (2003)). The solid data points are for the 3 year data and the light gray data points are for the first year data.

Bluebook predictions





The need for accuracy

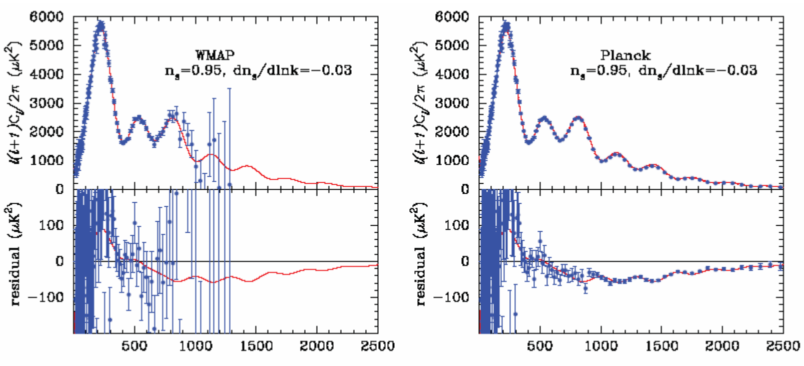


FIG 2.12.—Same as Figure 2.11, but now comparing the concordance ΛCDM model, having $n_S = 0.95$ and zero run (solid line), with a realisation of a model having with $n_S = 0.95$ (at a fiducial wavenumber of $k_0 = 0.05$ Mpc^{-1}) and a run of $dn_S/d\ln k = -0.03$.

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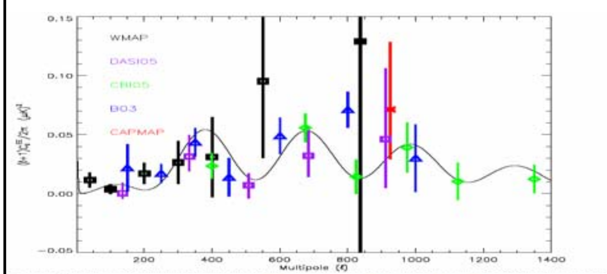
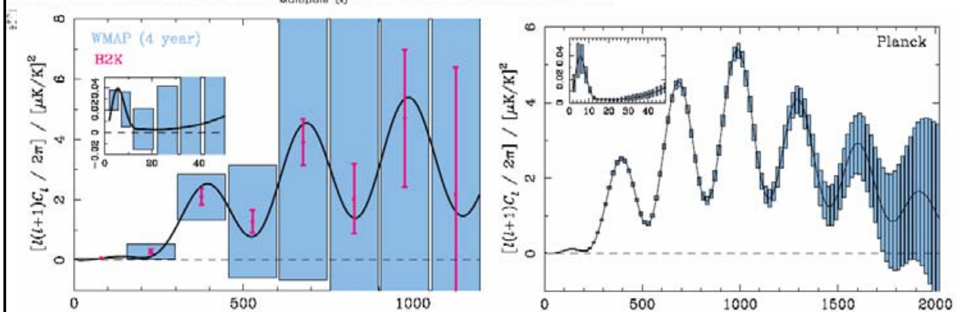


WMAP 3-year EE spectrum
Page et al. 2006



Bluebook predictions

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.

B-mode polarisation

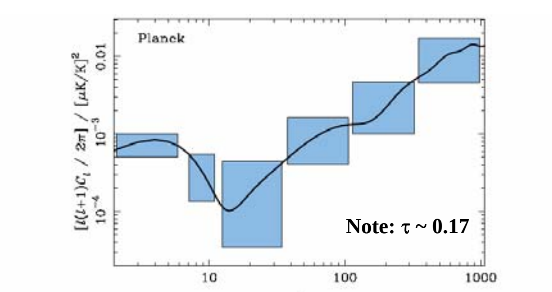


FIG 2.17.—Forecasts for the $\pm 1\sigma$ errors on the B-mode polarization power spectrum C_ℓ^B from *Planck* (for $r = 0.1$ and $\tau = 0.17$). Above $\ell \sim 150$ the primary spectrum is swamped by weak gravitational lensing of the E-polarization produced by the dominant scalar perturbations. The cosmological model, and the assumptions about instrument characteristics, are the same as in Figure 2.13.

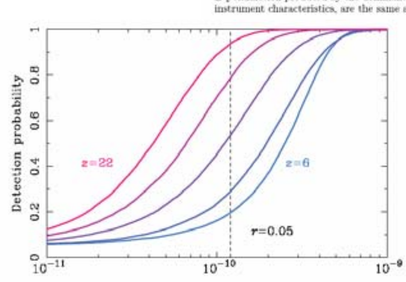


FIG 2.16.—The probability of detecting B-mode polarization at 95% confidence as a function of A_T, the amplitude of the primordial tensor power spectrum (assumed scale-invariant), for *Planck* observations using 65% of the sky. The curves correspond to different assumed epochs of (instantaneous) reionization: $z = 6, 10, 14, 18$ and 22. The dashed line corresponds to a tensor-to-scalar ratio $r = 0.05$ for the best-fit scalar normalisation, $A_S = 2.7 \times 10^{-9}$, from the one-year *WMAP* observations.

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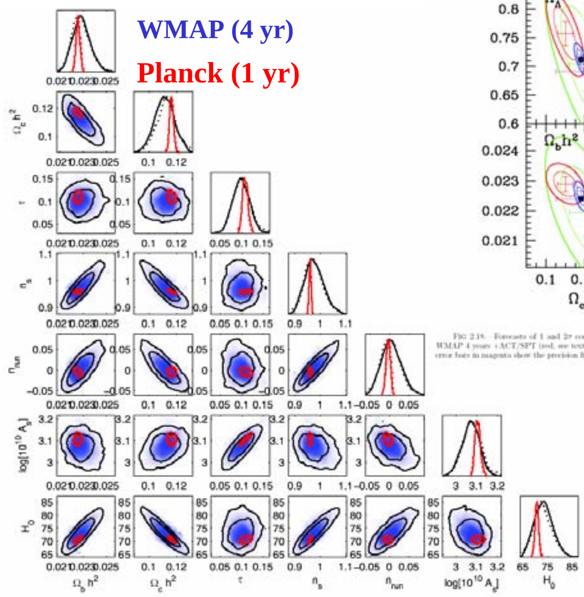
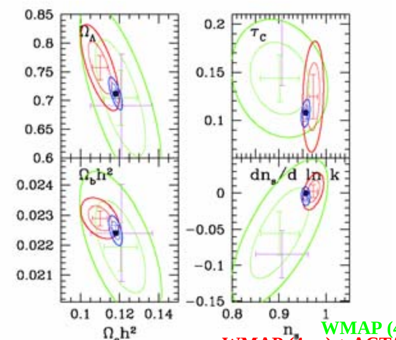


FIG 2.18.—Forecasts of 1 and 2σ contour regions for various cosmological parameters when the spectral index is allowed to run. Blue contours show forecasts for *WMAP* after 4 years of observation and red contours show results for *Planck* after 1 year of observations. The curves show marginalized posterior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

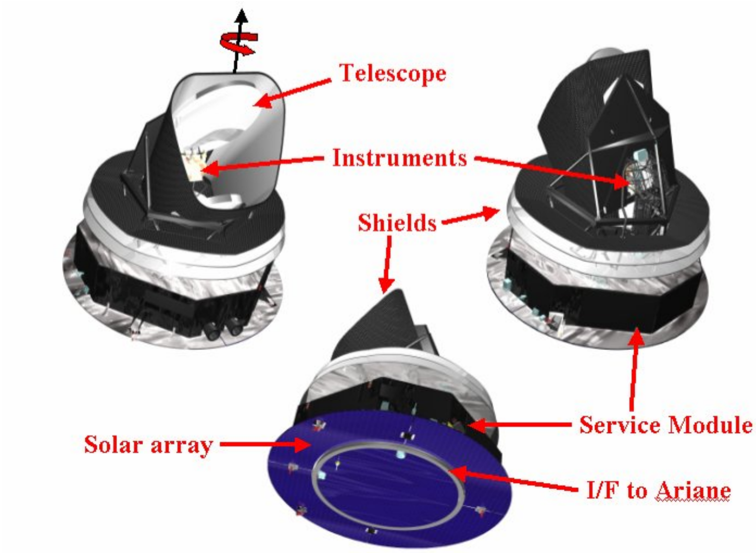


Recovery of cosmological parameters

Key Non-CMB Science with Planck

- Sunyaev-Zeldovich effect
  - Measurement of y in > 10^4 galaxy clusters
  - Cosmological evolution of clusters to z > 1
  - H_o and X-ray measurements, gas properties
  - Bulk velocities on scales > 300 Mpc
- Extragalactic sources and backgrounds
  - IR and radio galaxies
  - AGN's, QSO's, blazars
  - Evolution of galaxy counts to z > 1
  - Far-IR background fluctuations
- Maps of Galaxy at frequencies 30 - 1000 GHz
  - Dust properties, Cloud and cirrus morphology
  - Star forming regions, Cold molecular clouds
  - Cosmic ray distribution
  - Polarisation-based science, e.g. Galactic magnetic field

Spacecraft elements



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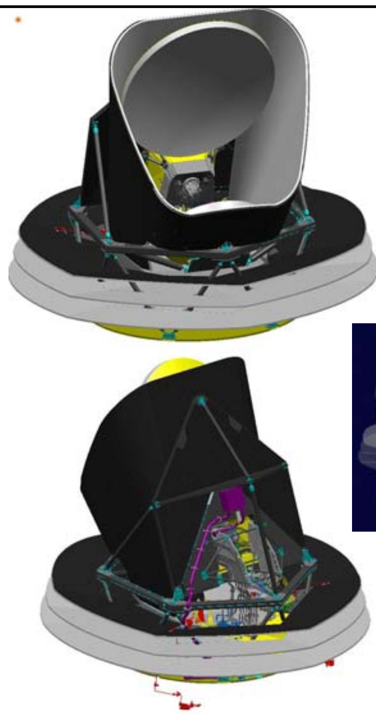
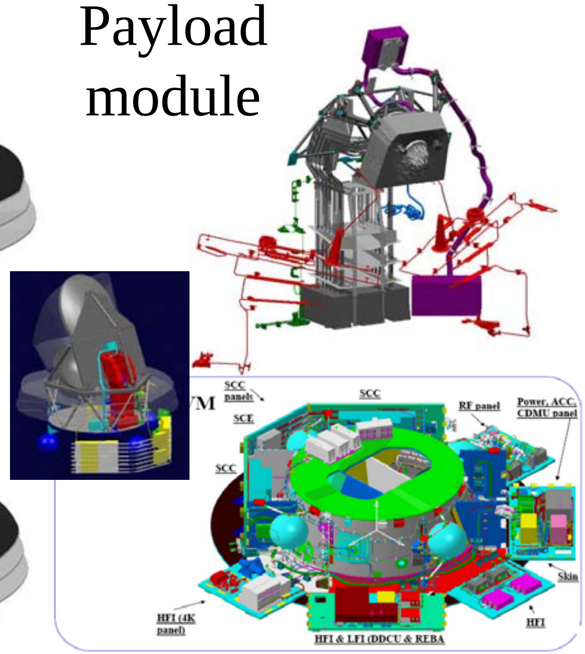
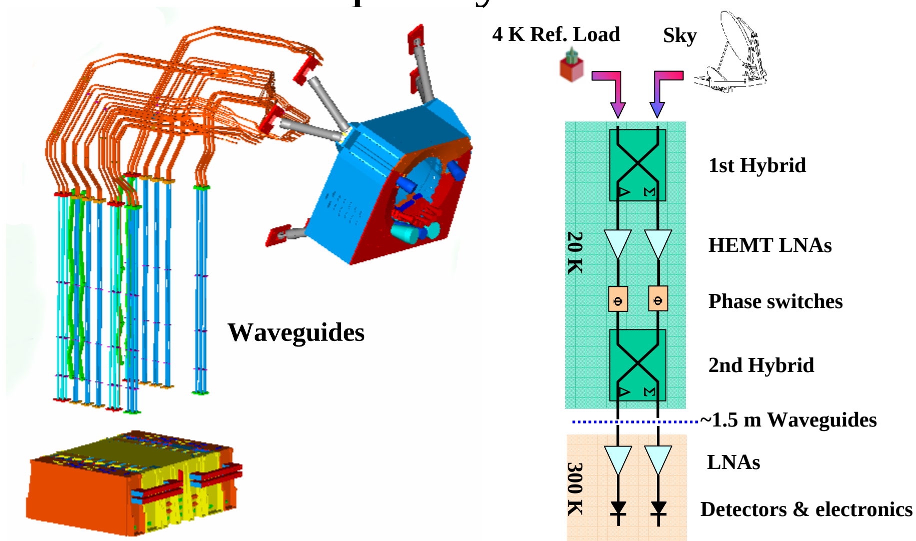
Payload module



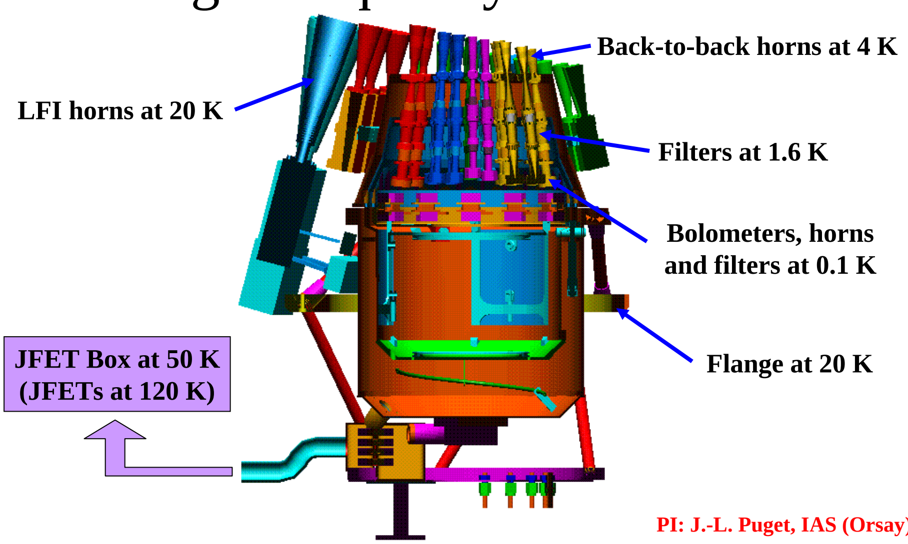


Low Frequency Instrument



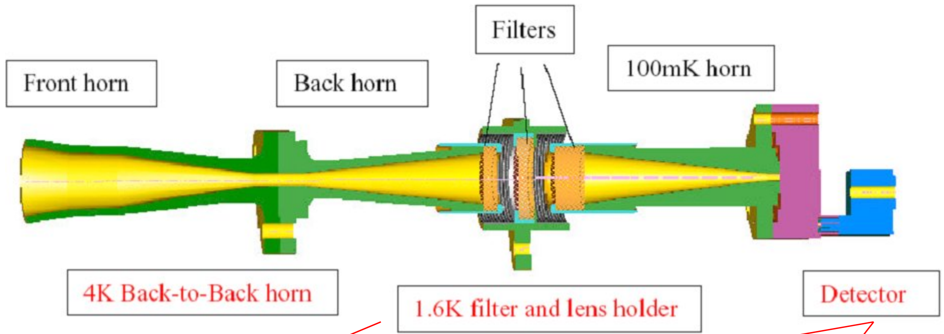
P.I.: R. Mandolesi, IASF (Bologna)

High Frequency Instrument

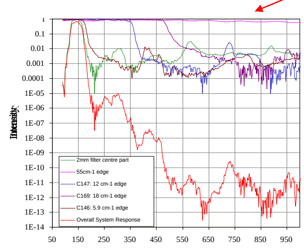


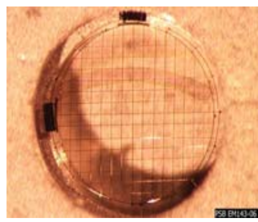
PI: J.-L. Puget, IAS (Orsay)

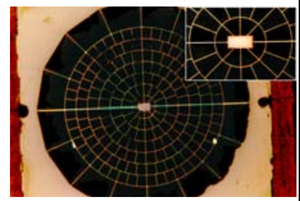
High Frequency Instrument



Filters (QMW)







Spider-web or polarisation-sensitive bolometers (CalTech/JPL

Paris Cosm

Estimated Instrument Performance Goals

Telescope	1.5 m (proj. aperture) aplanatic; shared focal plane; system emissivity 1% Viewing direction offset 85° from spin axis; Field of View 8°								
Instrument	LFI			HFI					
Center Freq. (GHz)	30	44	70	100	143	217	353	[illegible]	[illegible]
Detector Technology	HEMT LNA arrays			Bolomet[illegible]					
Detector Temperature	~20 K			[illegible]					
Cooling Requirements	H_2 sorption cooler			H_2 sorption [illegible] + Dilution cooler					
Number of Unpol. Detectors	0	0	0	0	[illegible]	[illegible]	4	4	4
Number of Linearly Polarised Detectors	4	6	[illegible]	[illegible]	8	8	8	0	0
Angular Resolution (FWHM, arcmin)	33	[illegible]	[illegible]	9.5	7.1	5	5	5	5
Bandwidth (GHz)	[illegible]	8.8	14	33	47	72	116	180	283
Average ΔT/T* per pixel#	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Average $\Delta T/T_{U,Q}$* per pixel#	2.8	3.9	6.7	4.0	4.2	9.8	29.8		

* Sensitivity (1σ) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

\# A pixel is a square whose side is the FWHM extent of the beam.

* Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

Required levels are being confirmed by calibration campaigns

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Table last updated Feb. 2004

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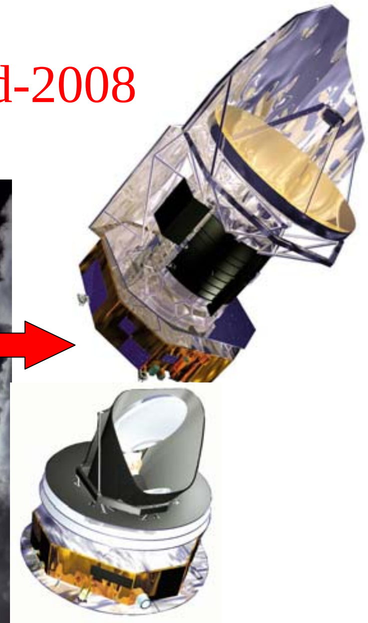
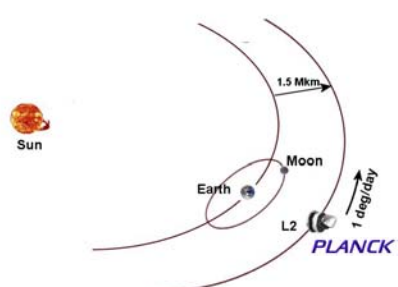
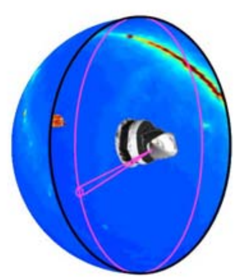
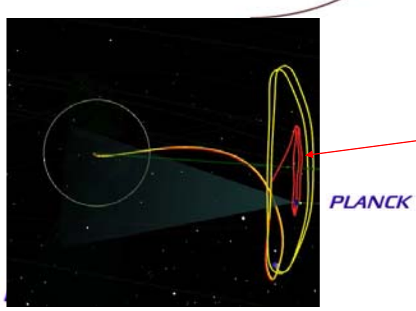
Launch in mid-2008



Orbit and Observing strategy







Transfer to orbit around L2

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Observational Strategy

- Temperature sensitivity (per pixel) of $\Delta T/T \sim 10^{-6}$ based on state-of-the-art detectors
- Ability to measure polarisation (Stokes I, Q, U) in the CMB bands, with good cross-polar characteristics
- 1.5 metre aperture telescope to provide ~5' resolution for the CMB
- Extreme attention to systematic effects:
  - wide frequency coverage (25 - 950 GHz for temperature and 25 - 400 GHz for polarisation)
  - Far-Earth orbit
  - Redundancy built in at many time-scales, from one minute to half-year

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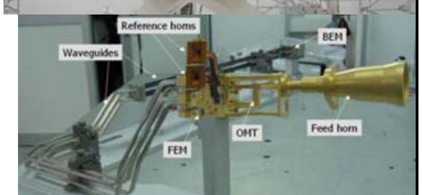
Planck status

- Spacecraft:
  - cryo-qualification tests at Centre Spatial de Liège successfully completed
  - Flight Service Model completed and delivered
- LFI:
  - FM testing completed (Sept 2006)
  - Delivered for integration October 2006
- HFI:
  - FM tested and delivered (August 2006)
  - Integration with LFI starting October 2006
- Telescope:
  - flight reflectors delivered to Alcatel
  - reflectors tested at cryo T
  - radio-freq model test campaign on-going



Next Major Milestone: Full flight satellite cryogenic test (October 2007)

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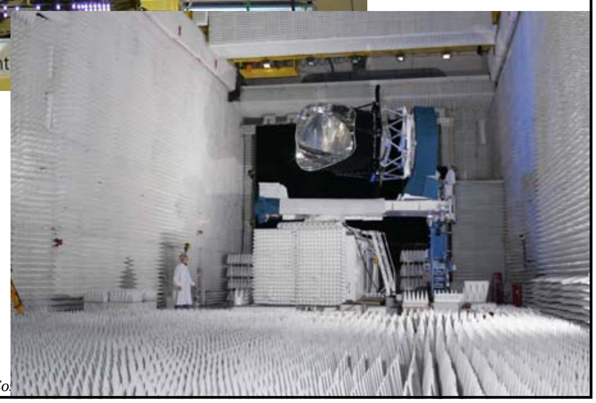

Telescope

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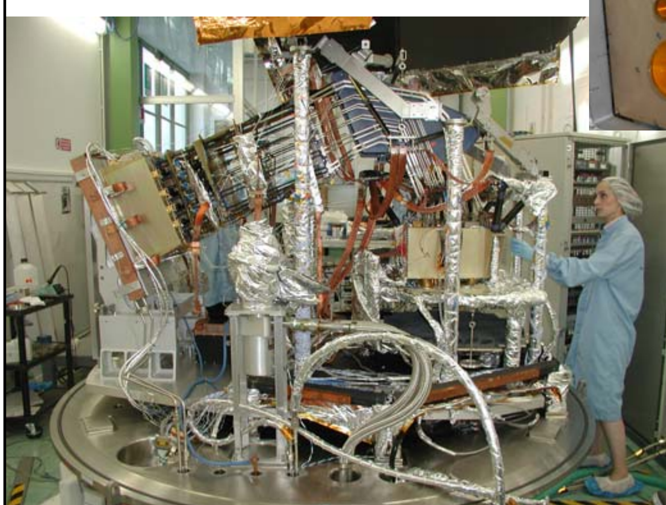
LFI



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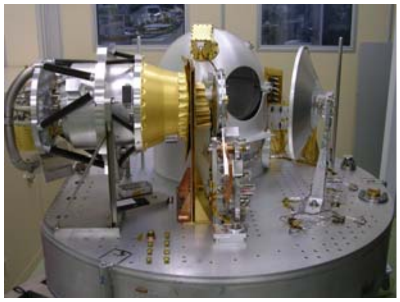
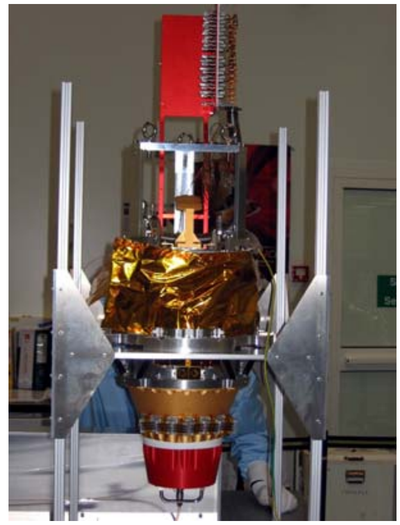
HFI





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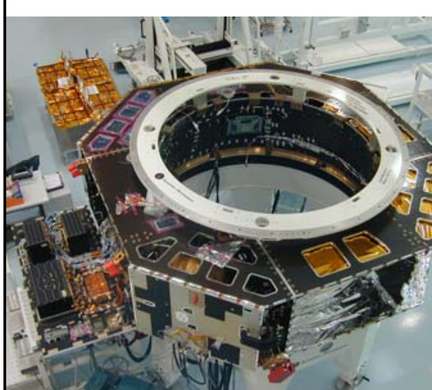
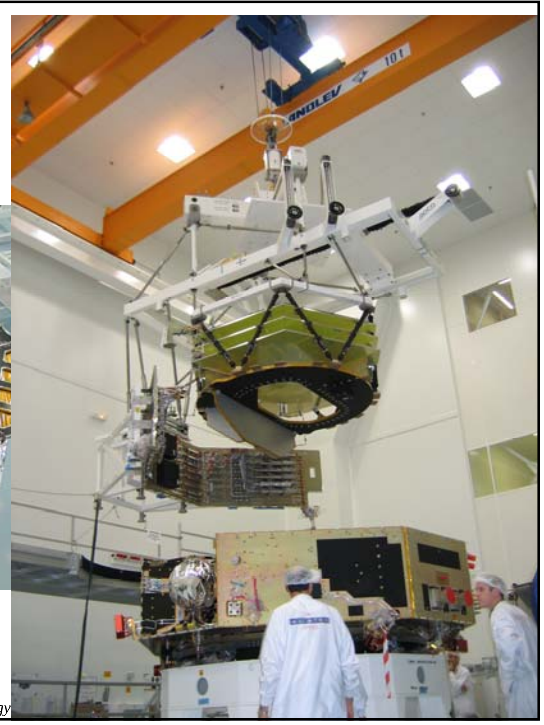
Satellite assembly





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Paris Cosmology

H+P

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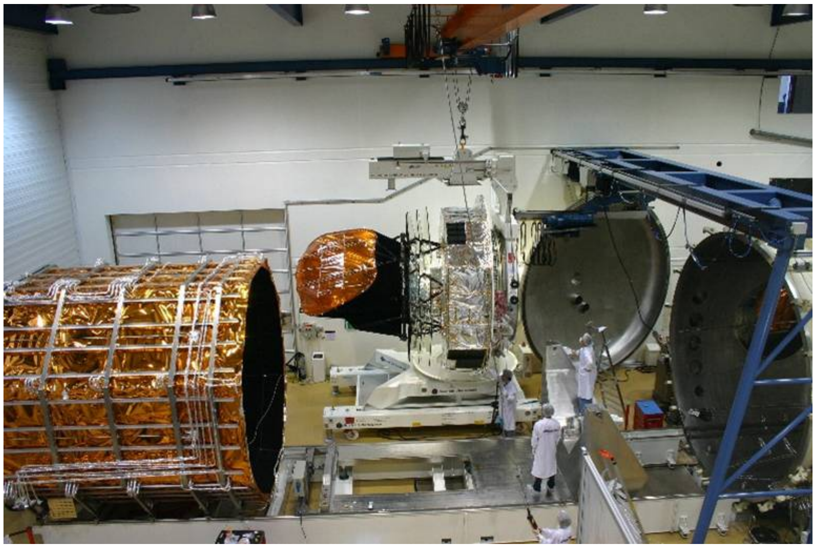

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Summary

- Planck is the next major milestone in space CMB research
- The development is on course for a launch in 2008
- The first results are expected to be published ~2011

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