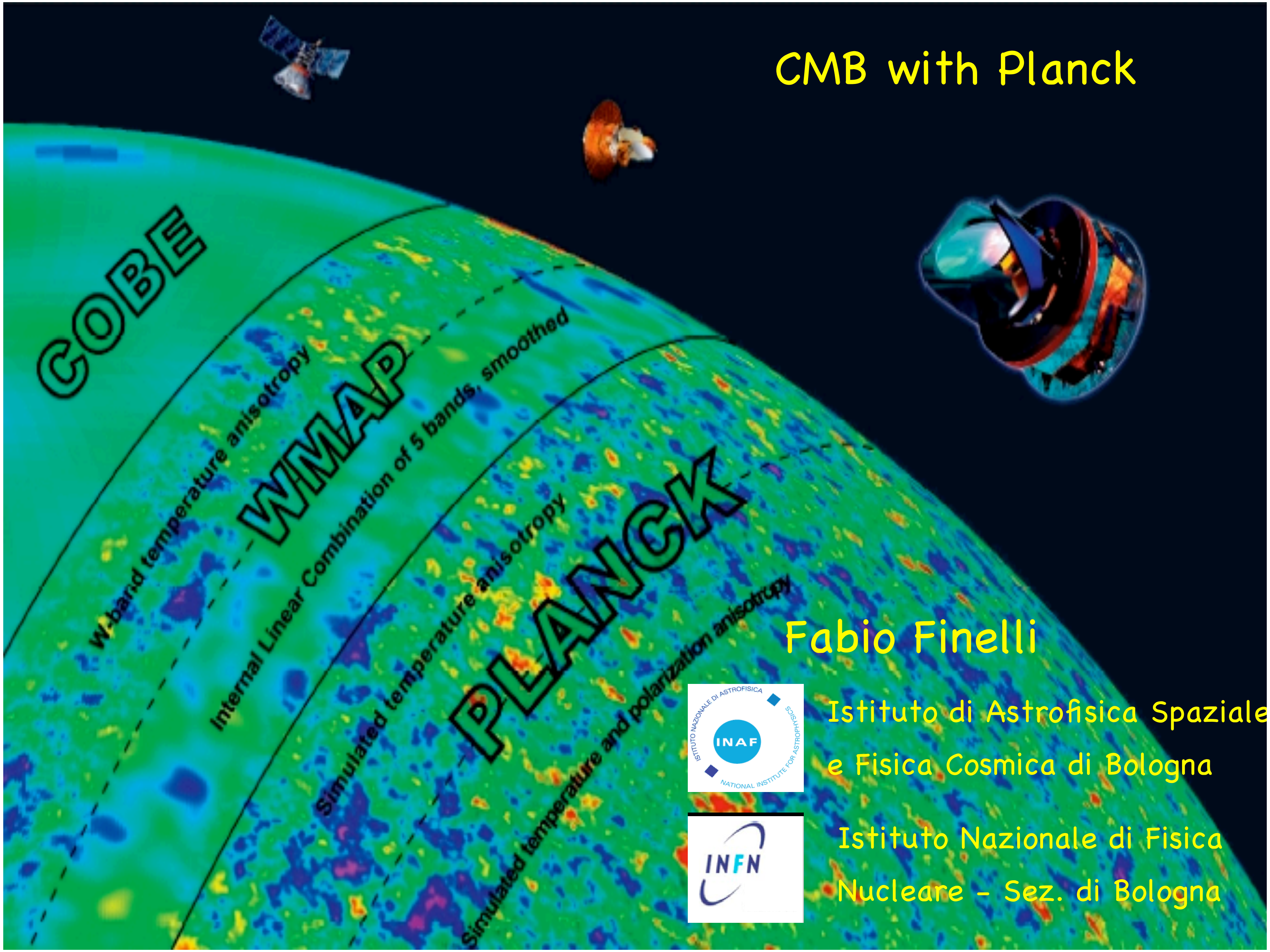
CMB with Planck



Fabio Finelli

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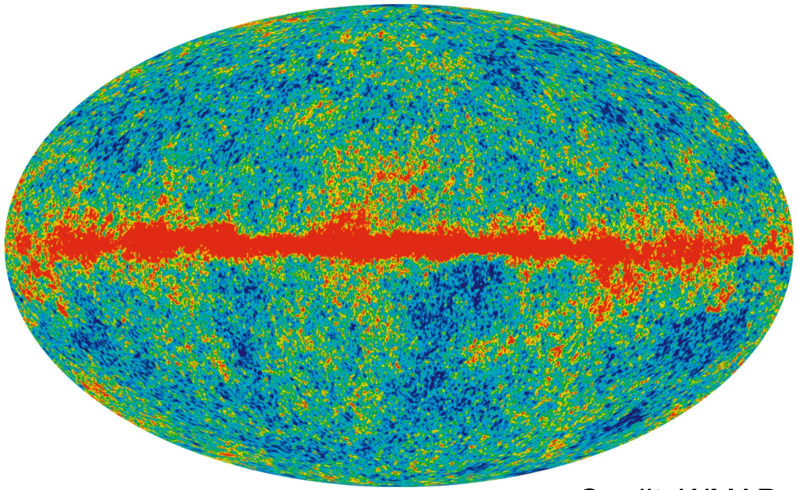
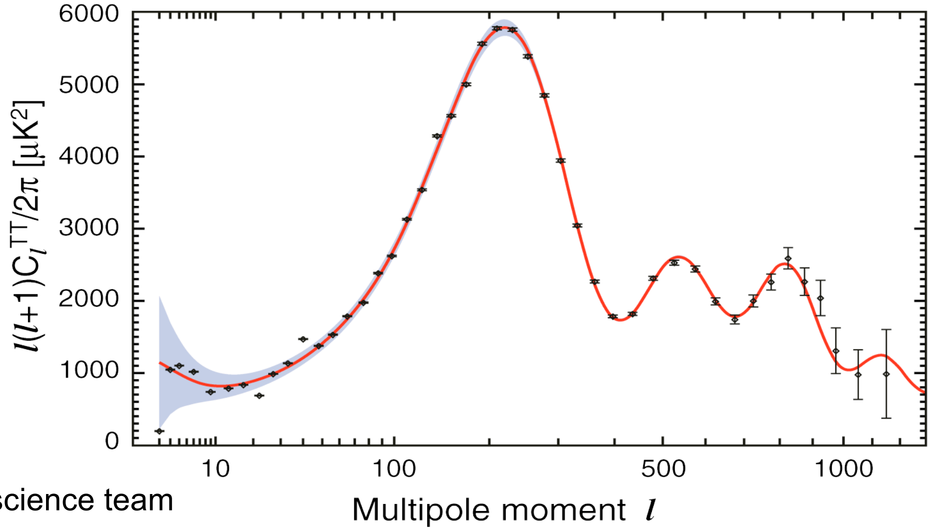
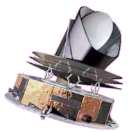
Istituto Nazionale di Fisica Nucleare - Sez. di Bologna

- During its expansion, the temperature of the Universe decreases allowing the cosmological combination of hydrogen around few eV from the free electron and ions of the primordial plasma.
- The Universe became transparent to light, and the relic radiation - CMB - can be observed in the microwaves in the cleanest window.
- This is the oldest snapshot of our Universe (around 13.7 Gyrs ago): anisotropies in the CMB map the density inhomogeinities which later led to clusters and galaxies by gravitational collapse.





Credit: WMAP science team



PLANCK

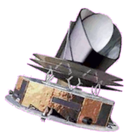
- *Planck* has been designed to perform the "final" measurement of the Cosmic Microwave Background (CMB) temperature fluctuations in the region where the primary contribution is dominant

  ➢ full sky coverage from space and angular resolution down to 5' (multipoles $l \sim 180/\text{deg}$ larger than 2000)

  ➢ high sensitivity enough to be essentially limited by the ability in removing astrophysical foregrounds

  ➢ wide frequency range: 9 frequency channels covering from 27 GHz to 1 THz

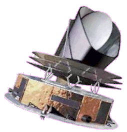
- *Planck* will perform the cleanest measurement of CMB anisotropies in polarization since most of the channels are sensitive to Q,U.



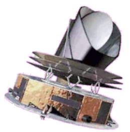
- *Planck* has been selected by ESA as a medium size mission (M3) of the Horizon 2000 Program in 1996 after 3 years of assessment study.

- *Planck* was the new name for COBRAS/SAMBA, i.e. the merging of the two original proposals (COBRAS, Cosmic Background Radiation Satellite *Mandolesi et al. 1994* and SAMBA, Satellite for Measurement of Background Anisotropies, *Tauber et al. 1994*) for CMB observations submitted to the Horizon 2000 Call.

- *Planck* (http://www.rssd.esa.int/Planck) is an ESA project with instruments funded by ESA member states (in particular the PI countries: France and Italy), and with special contributions from Denmark and NASA (USA).



Planck is a project of ESA with instruments provided by two scientific Consortia funded by member states (the lead countries: are France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.



LFI & HFI

- Two instruments on board

LFI - Low Frequency Instrument, based on high electron mobility transistor (HEMT) amplifiers

HFI - High Frequency Instrument, based on bolometers

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".

From Planck Bluebook

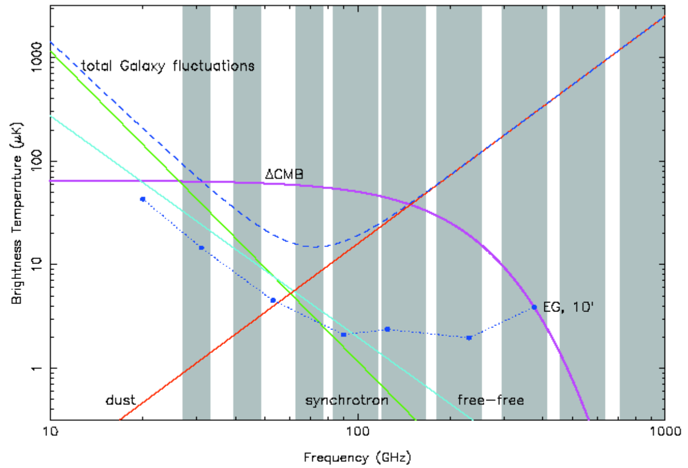
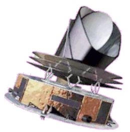


FIG 1.3.— Spectrum of the CMB, and the frequency coverage of the *Planck* channels. Also indicated are the spectra of other sources of fluctuations in the microwave sky. Dust, synchrotron, and free-free temperature fluctuation (i.e., unpolarized) levels correspond to the *WMAP* Kp2 levels (85% of the sky; Bennett et al. 2003). The CMB and Galactic fluctuation levels depend on angular scale, and are shown for $\sim 1°$. 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.

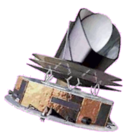


Comparison with WMAP

Planck center frequency [GHz]	30	44	70	100	143	217	353	535	857
Angular resolution (FWHM [arcmin]	33	24	14	10	7.1	5	5	5	5
Sensitivity in I [μK deg] nominal mission	2.7	2.6	2.6	1.0	0.6	1.0	2.9		

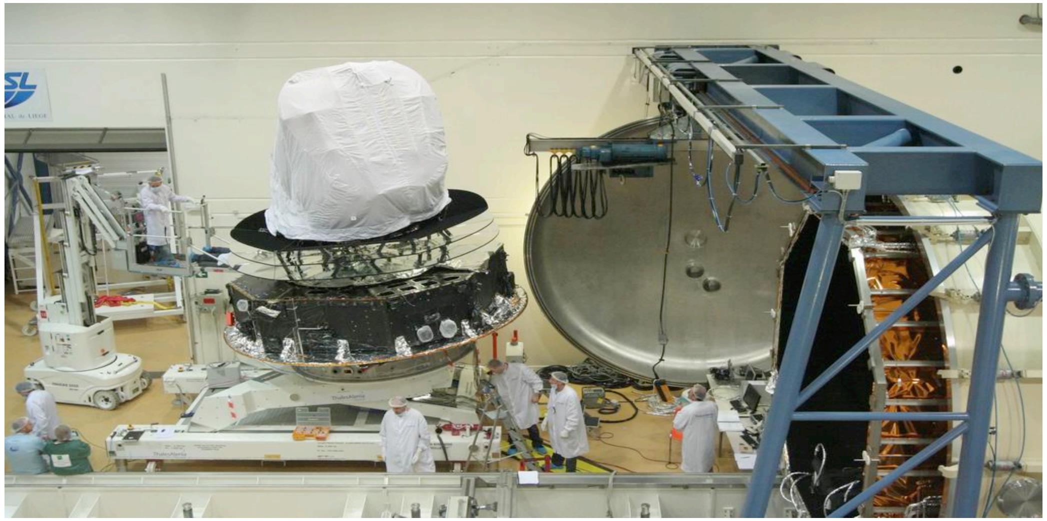
WMAP center frequency [GHz]	23	33	41	61	94
Angular resolution (FWHM [arcmin]	49	37	29	20	12.6
Sensitivity in I [μK deg] 1 yr (9 yrs)	12.6 (4.2)	12.9 (4.3)	13.3 (4.4)	15.6 (5.2)	15 (5.0)

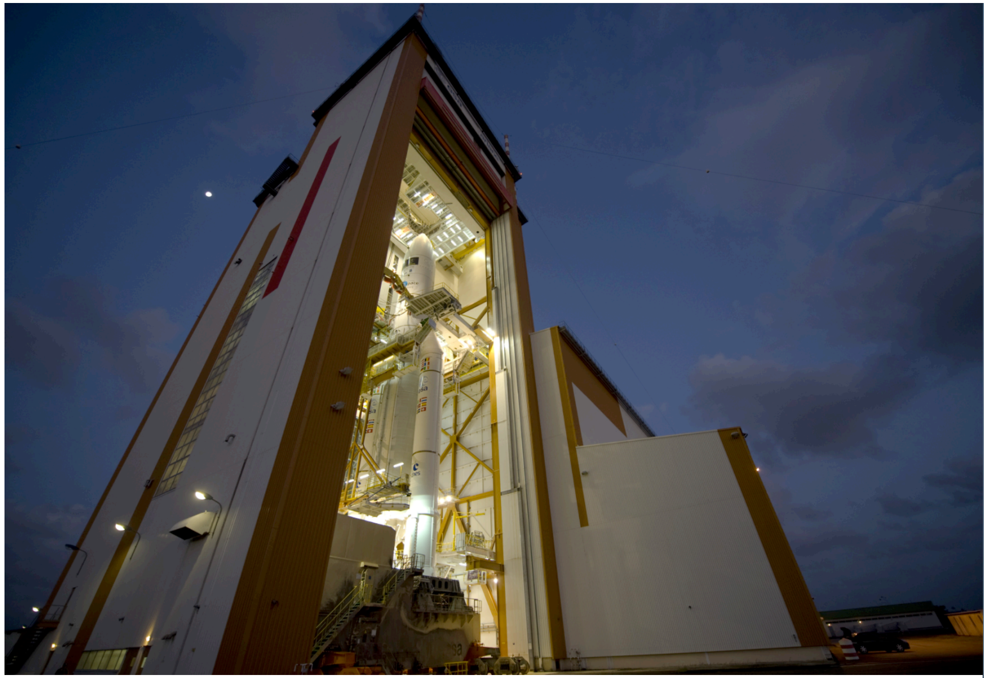
- *Planck* has around 3 x smaller angular resolution and a sensitivity per channel which can be even 10 x times better



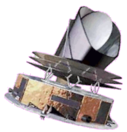
Planck required sensitivity → Technological performances never achieved in space before

- Sensitive and fast bolometers → Cooling at 100mK
- Complex cryogenic cooling chain: 50K (passive)+20K+4K+0.1K (active)
- 100mK by dilution cooler
- Excellent temperature stability

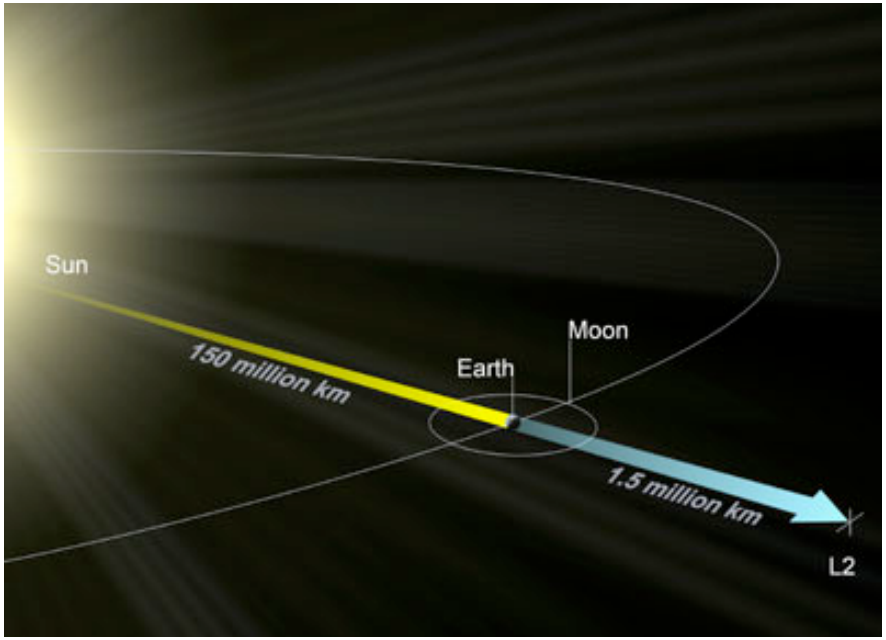




Successful launch of Planck - Herschel from Kourou (French Guyana) on May 14, 2009



The Universe seen from L2



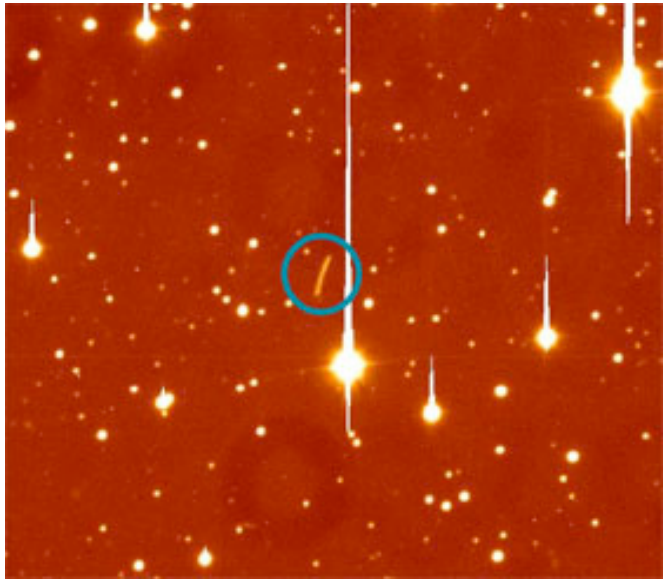
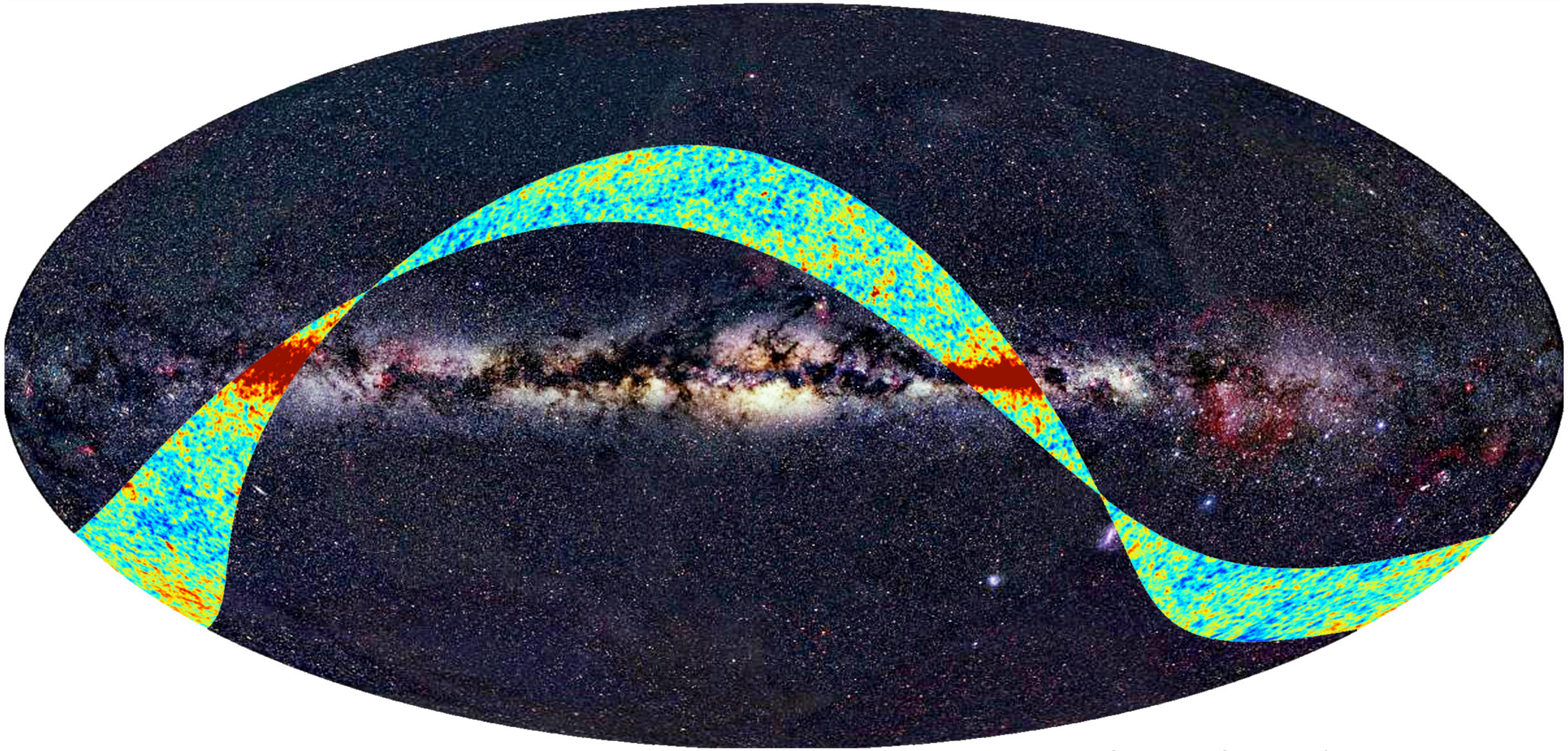


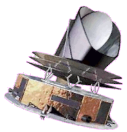
Image of Planck taken by Masetti & Majorano at the Observatory of Loiano (Bologna)

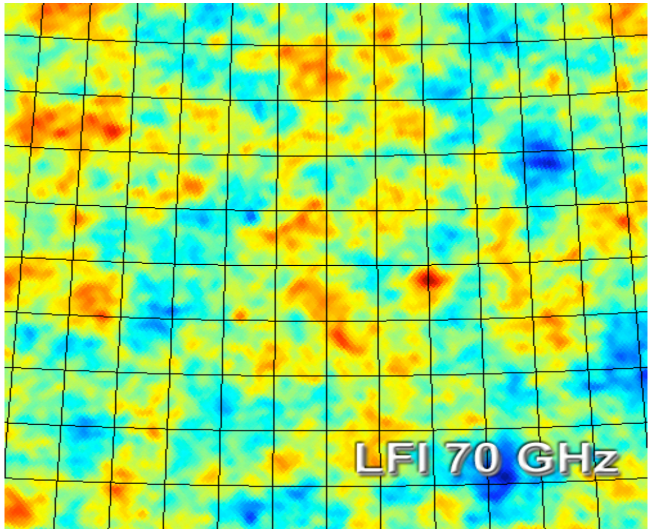
Postcard 1

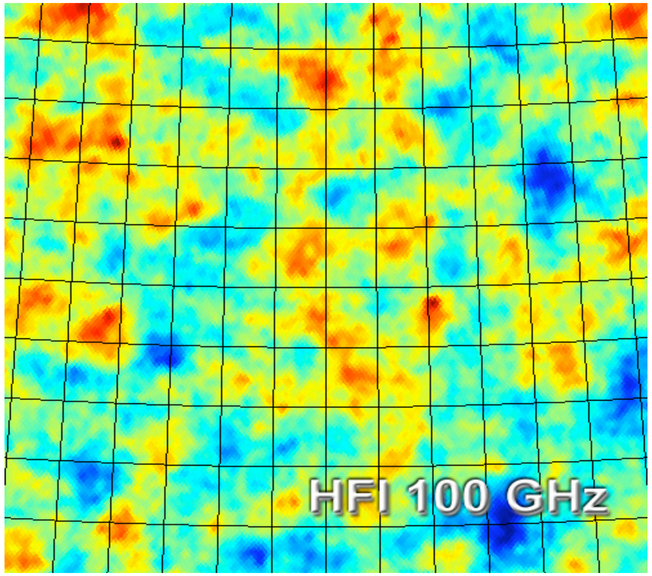


Credit: ESA,HFI & LFI consortia

~ 7.5 % of the sky observed during the First Light Survey!



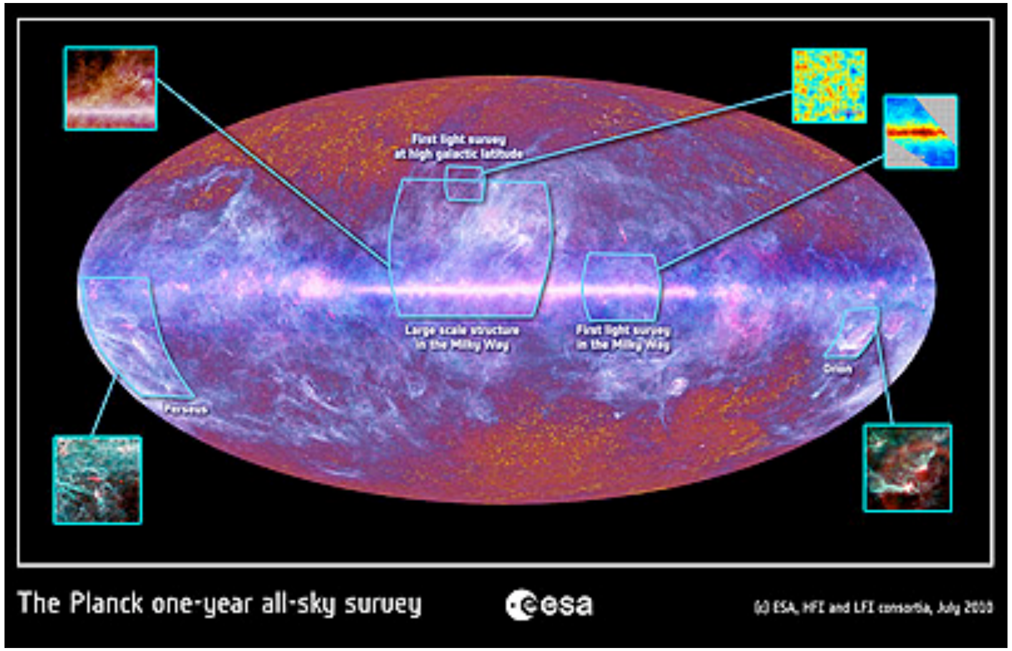




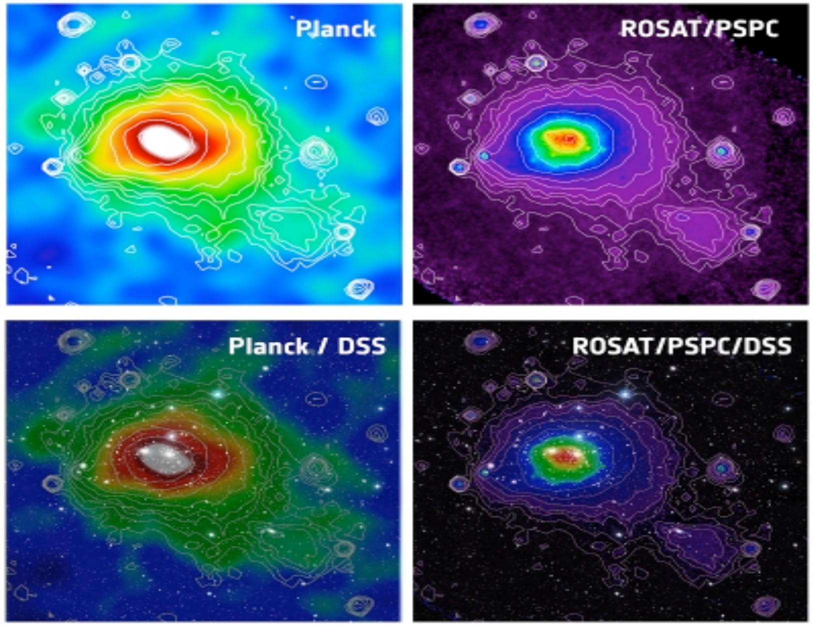
Postcards 2

Detailed Views of the Recombination Epoch
(z=1088, 13.7 Gyrs ago)

Credit: ESA,HFI & LFI consortia

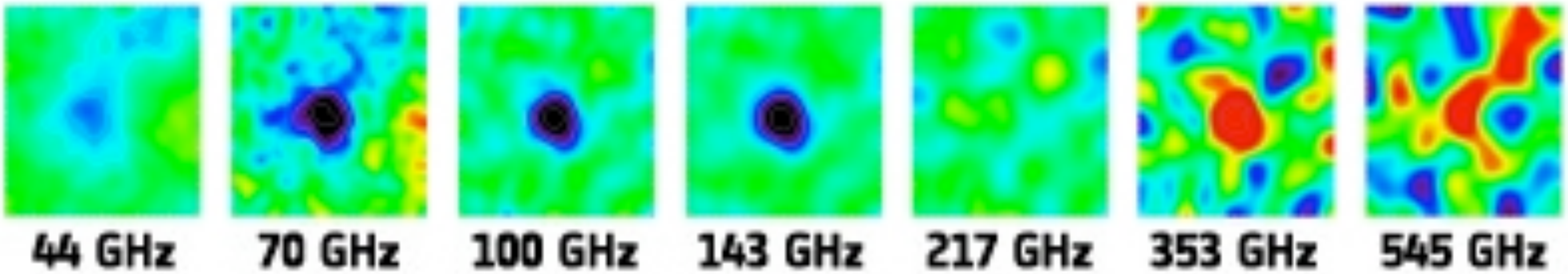


Postcards 3



Coma cluster:
Planck/X-ray/Digital Sky Survey

Galaxy cluster
Abell 2319 as seen in seven of the Planck frequencies



Credit: ESA,HFI & LFI consortia

Expected improvements on the angular power spectrum: 1

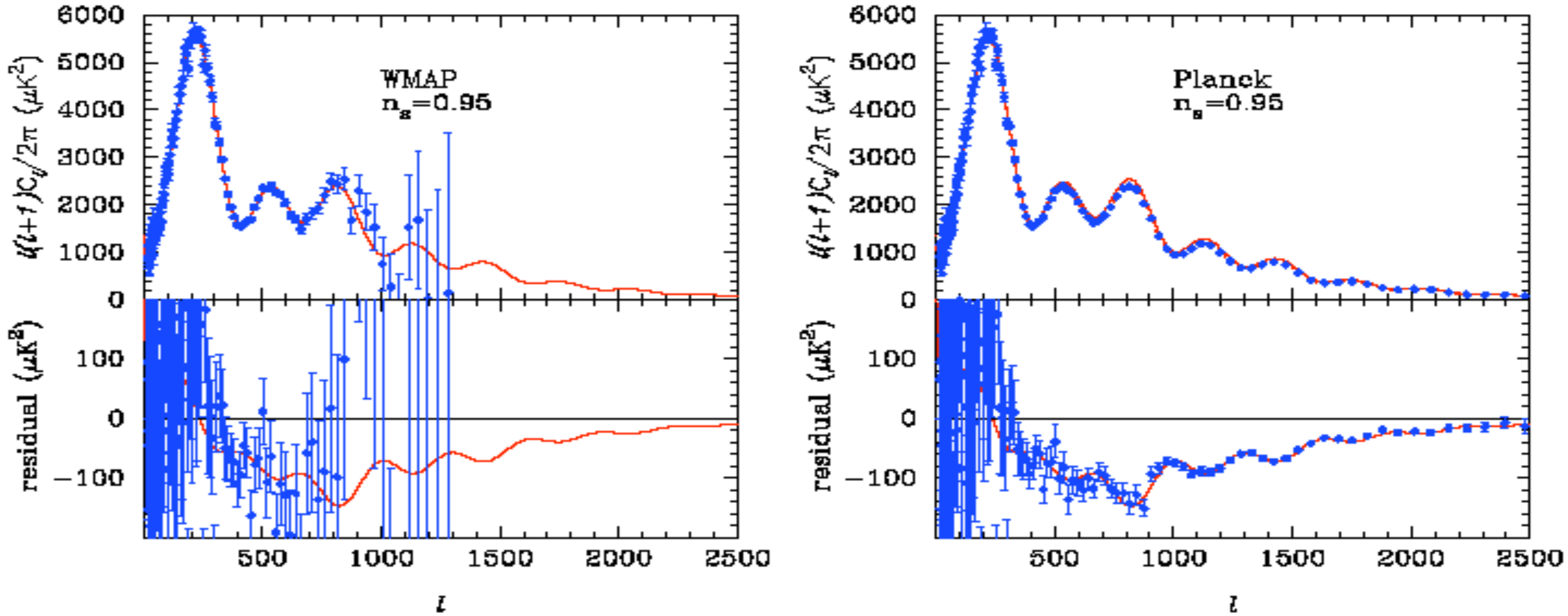
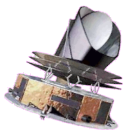


FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower 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.

From Planck Bluebook



Expected improvements on the angular power spectrum: 2

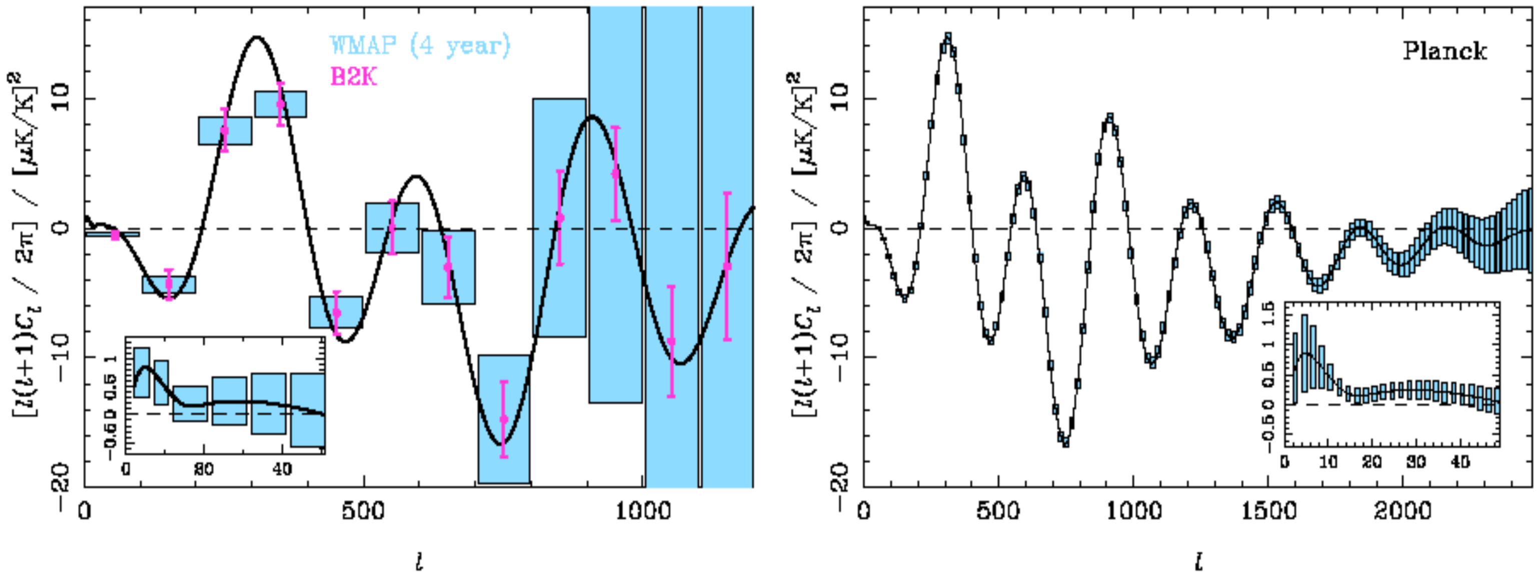
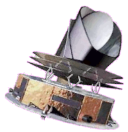


FIG 2.13.—Forecasts for the $\pm 1\sigma$ errors on the temperature-polarization cross-correlation power spectrum C_ℓ^{TE} in a ΛCDM model (with $r = 0.1$ and $\tau = 0.17$) from *WMAP* (4 years of observation) and BOOMERanG2K (left) and *Planck* (right). In the left-hand plot, flat band powers are estimated 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.

From Planck Bluebook



Expected improvements on the angular power spectrum: 3

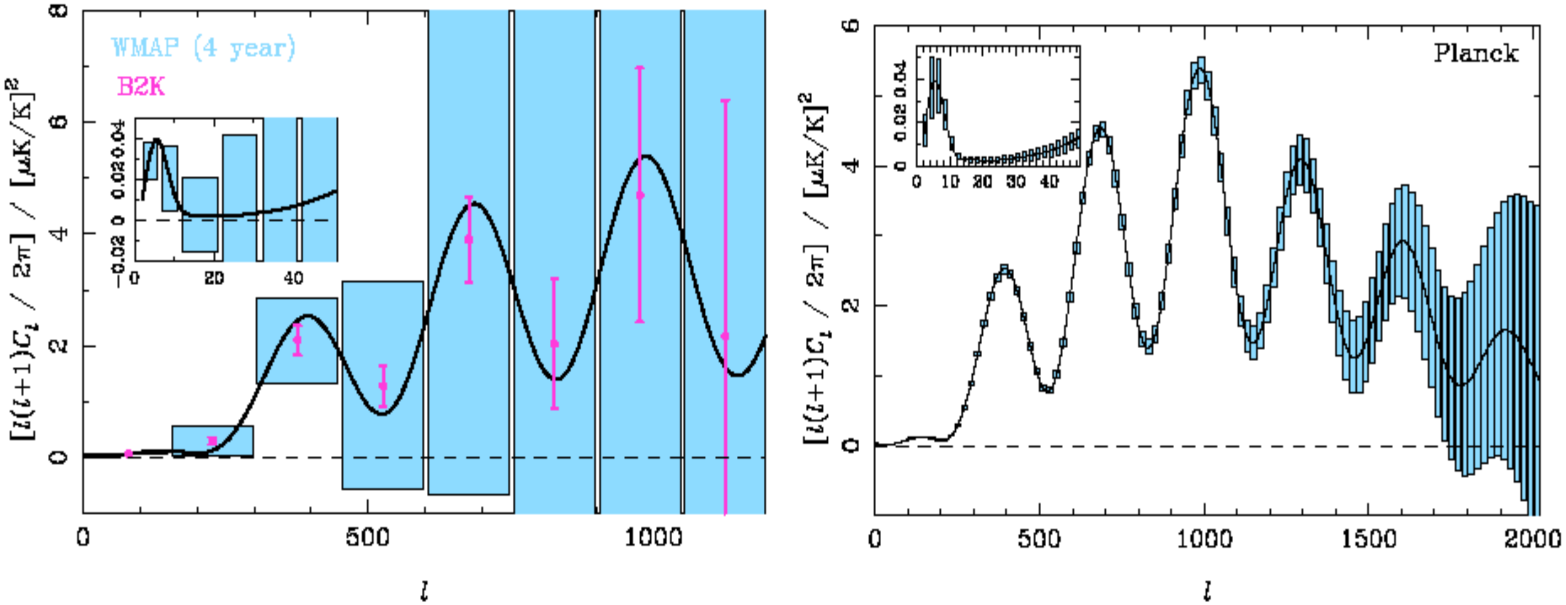
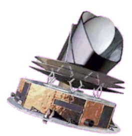


FIG 2.14.—Forecasts for the $\pm 1\sigma$ errors on the E-mode polarization power spectrum C_ℓ^E from *WMAP* and B2K (left) and *Planck* (right). The cosmological model, and the assumptions about instrument characteristics, are the same as in Figure 2.13. For *WMAP* and B2K, flat band powers are estimated 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.

From Planck Bluebook



Expected improvements on the angular power spectrum: 4

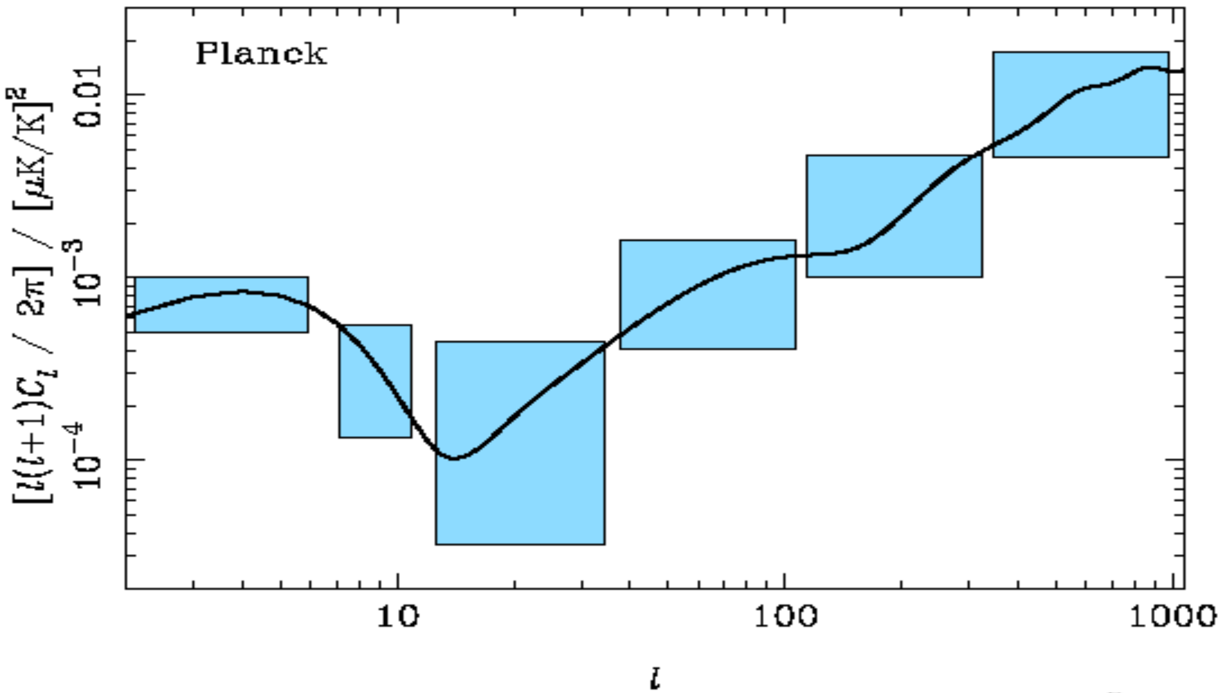
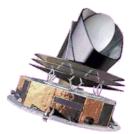
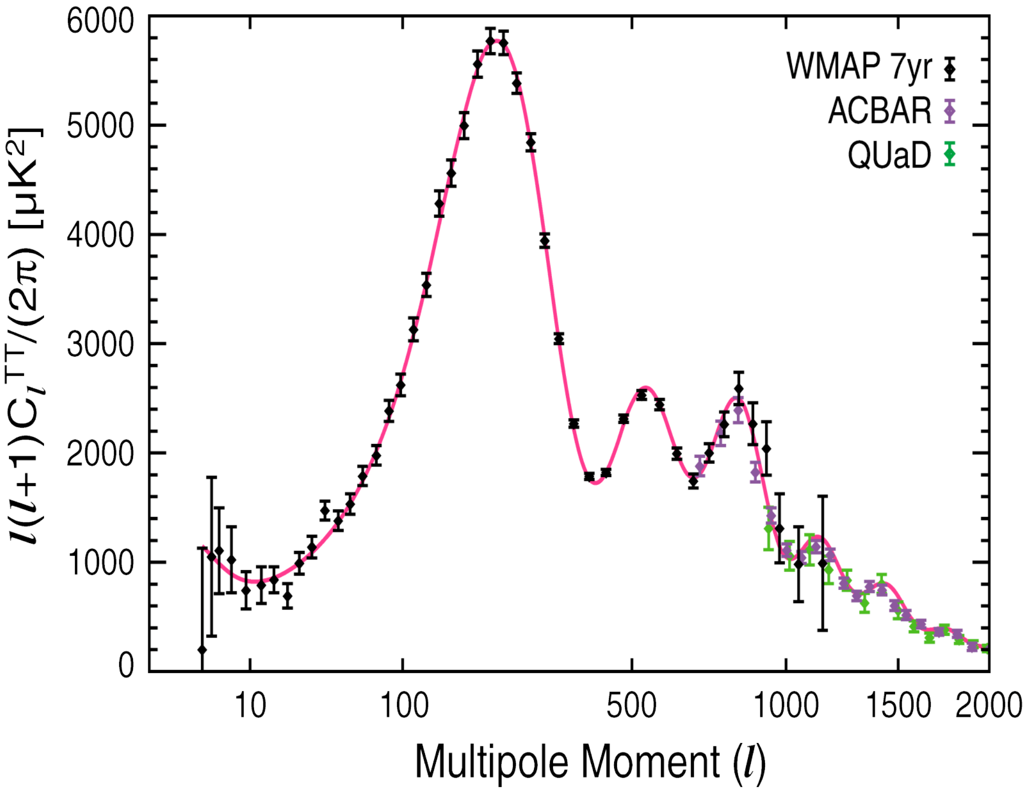


FIG 2.17.—Forecasts for the $\pm 1\sigma$ errors on the B-mode polarization power spectrum C_ℓ^B from *Planck* (for $r = 0.1$ and $\tau = 0.17$). Above $\ell \sim 150$ the primary spectrum is swamped by weak gravitational lensing of the E-polarization produced by the dominant scalar perturbations. The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

From Planck Bluebook



Expected improvements on the angular power spectrum: 5



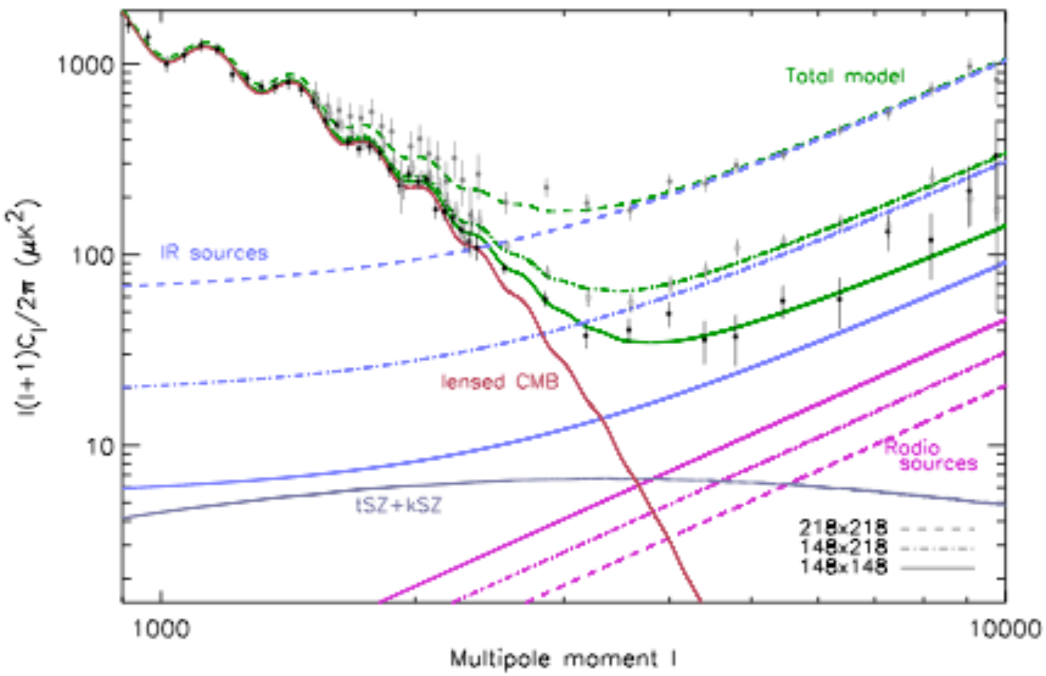
Komatsu et al., WMAP Team Collaboration 2010

CMB anisotropies observations is an extremely competitive area.

Planck vs WMAP

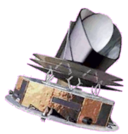
Ground and satellite observations target high *l* anisotropies which will be also seen by Planck. The combination of data set is obtained by calibrating with WMAP, but Planck will be free from this calibration uncertainty.

Expected improvements on the angular power spectrum: 6

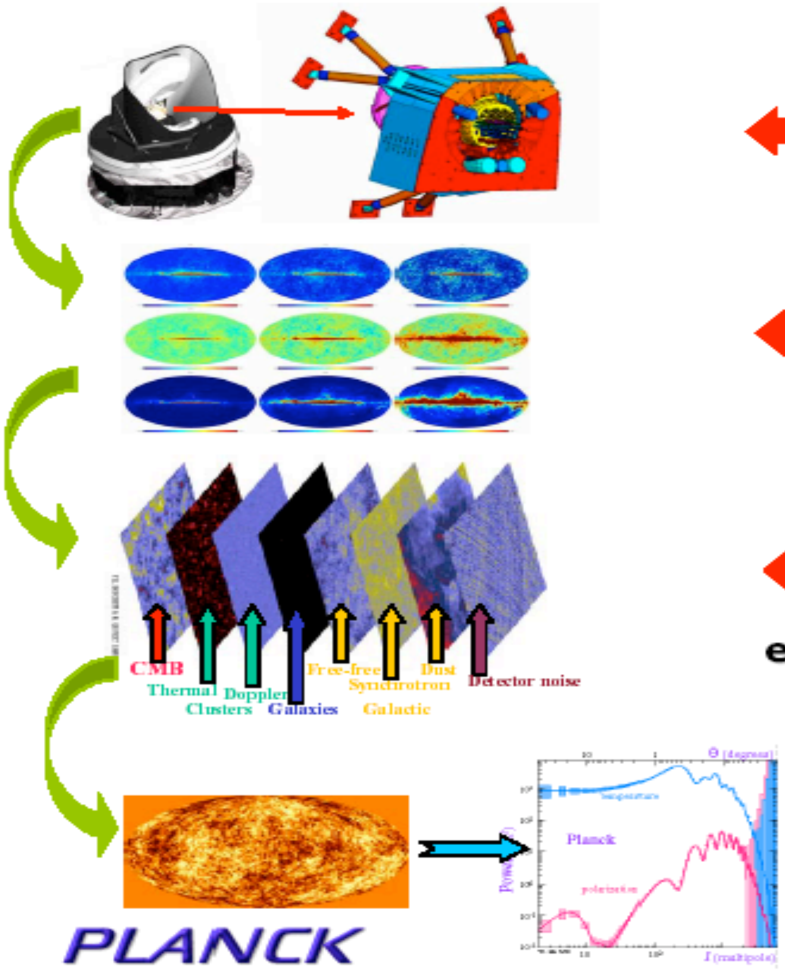


At the same time, measurements of CMB anisotropies in the damping tail (SPT and ACT) will help Planck in improving the comprehension of foreground uncertainties at high l which limits the ability in constraining cosmological parameters.

Dunkley et al. [ACT Collaboration], 2010



Data Processing



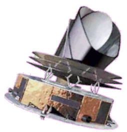
Acquiring and processing time-ordered information

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

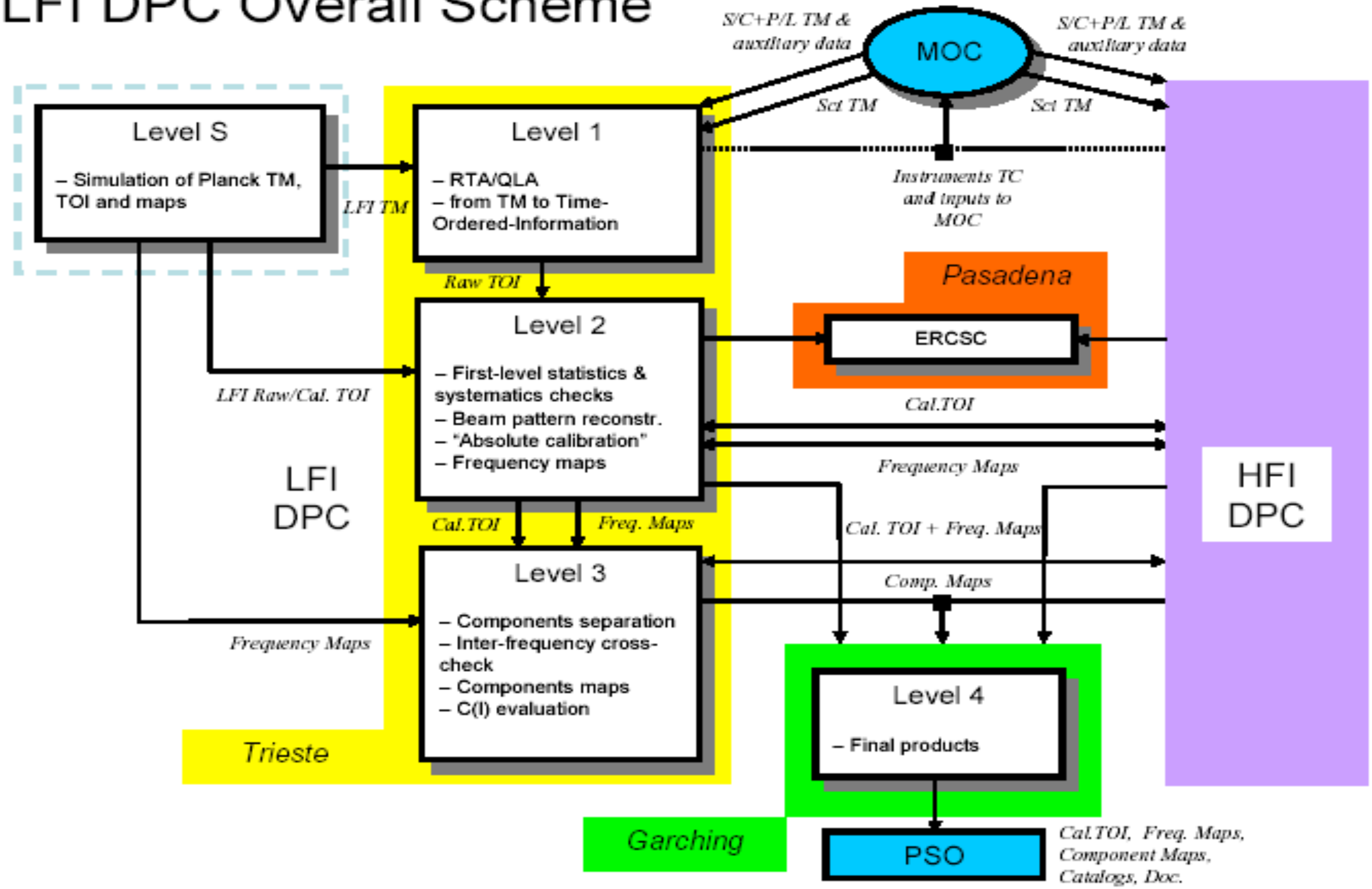
Converting frequency maps to component maps, e.g. the Cosmic Microwave Background

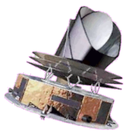
Estimating the CMB angular power spectrum and cosmological parameters

esa ASTROPHYSICS



LFI DPC Overall Scheme





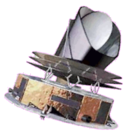
Planck needs improvements in theoretical predictions: recombination

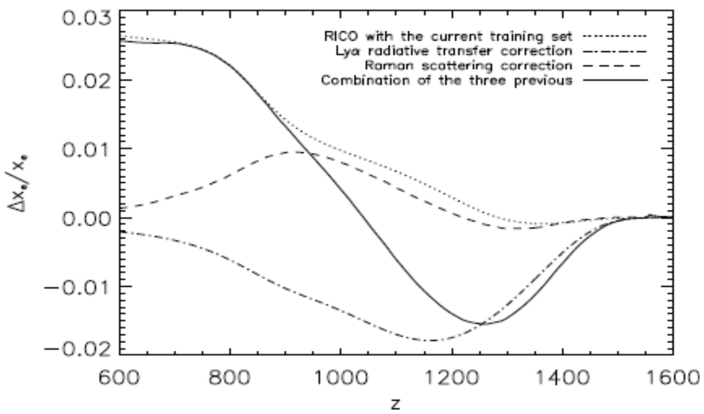
- Chluba-Sunyaev (2005) pointed out that two-photon transitions in primordial hydrogen recombination were missed in the recombination code widely used by Einstein-Boltzmann engines (RECFAST, *Seager, Sasselov and Scott 1999*)

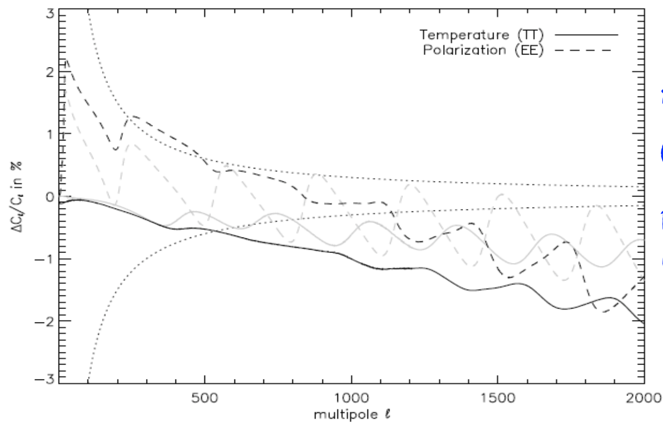
  See also following works by the same authors and/or in collaboration with Rubino-Martin). Hirata (2008) then showed that these and other corrections could lead to a 7 σ effect for Planck.

- Switzer-Hirata (2007) pointed out that several effects due to helium recombination were also missing in RECFAST (see also Rubino-Martin, Chluba & Sunyaev 2007).

- Connecting the Einstein-Boltzmann engines with codes computing the atomic processes with the associated transition rates was hopeless since the latter were way too slow.







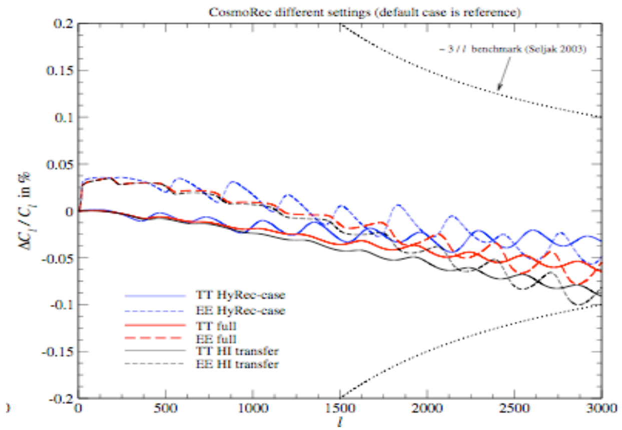
Rubino-Martin, Chluba, Fendt & Wandelt, 2009

- Several approaches in taking into account these corrections: fudge factors in subsequent version of RECFAST, alternative approaches as

RICO Rubino-Martin, Chluba, Fendt & Wandelt, 2009

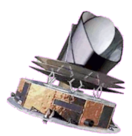
HyRec Ali-Haimoud & Hirata, 2010

CosmoREC, Chluba & Thomas, 2010

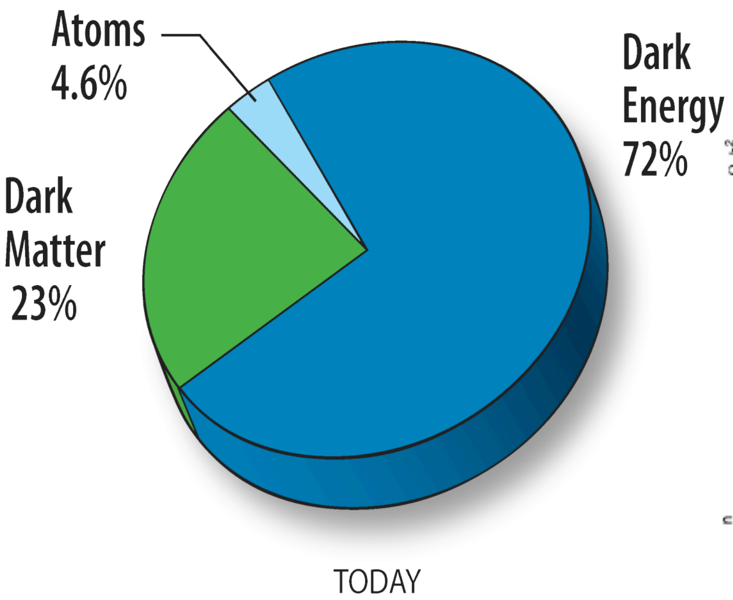


Shaw & Chluba, 2011

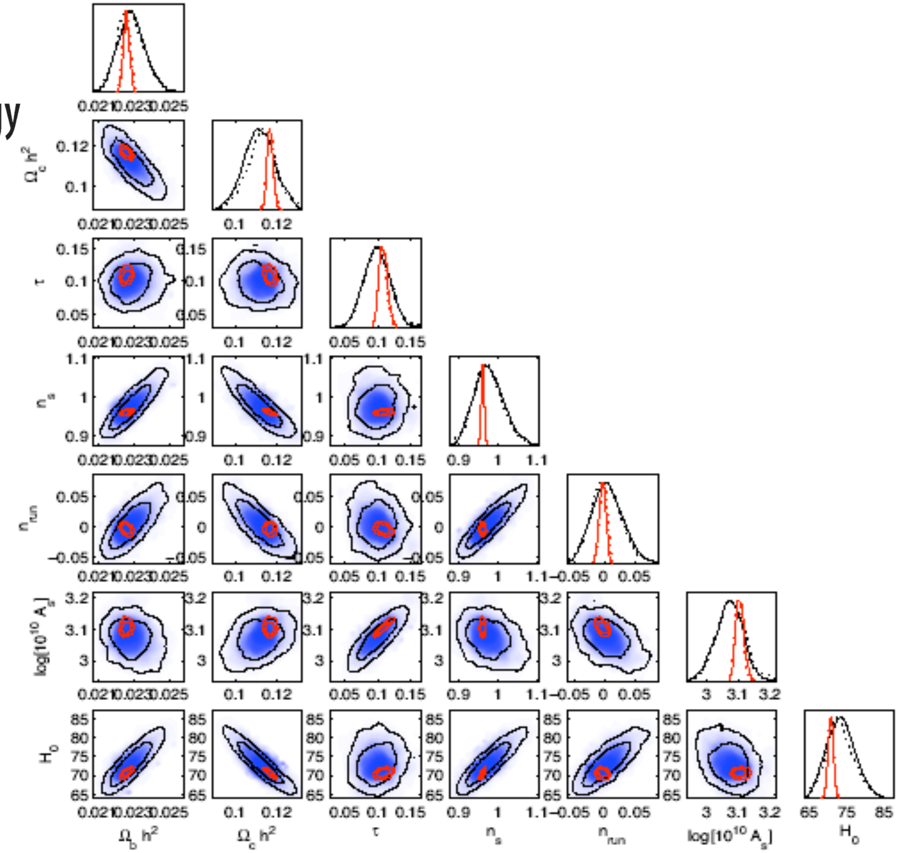
- Now ready for a precise computation of recombination for arbitrary Helium fraction and relativistic abundance, even for a cosmic variance experiment up to l=2000 (ACTPol and SPTpol)!



Cosmological Parameters

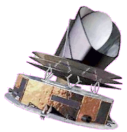


Credit: WMAP science team



From Planck Bluebook

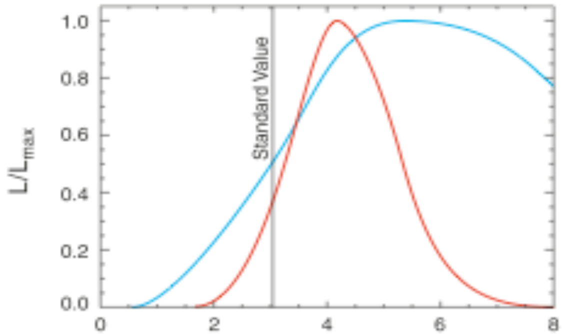
FIG 2.18.—Forecasts of 1 and 2σ contour regions for various cosmological parameters when the spectral index is allowed to run. Blue contours show forecasts for *WMAP* after 4 years of observation and red contours show results for *Planck* after 1 year of observations. The curves show marginalized posterior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



Cosmological Parameters: 2

Few examples:

Number of relativistic species



$$\Delta N_{\rm rel} \sim 0.26$$

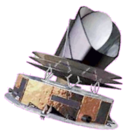
Absolute Neutrino mass

$$\sum m_\nu < 1.3\text{eV}$$

$$\sum m_\nu < 0.26\text{eV}$$

Komatsu et al., WMAP Team Collaboration 2010

Planck alone nominal mission forecast



Cosmological Parameters: 3

Dark Energy

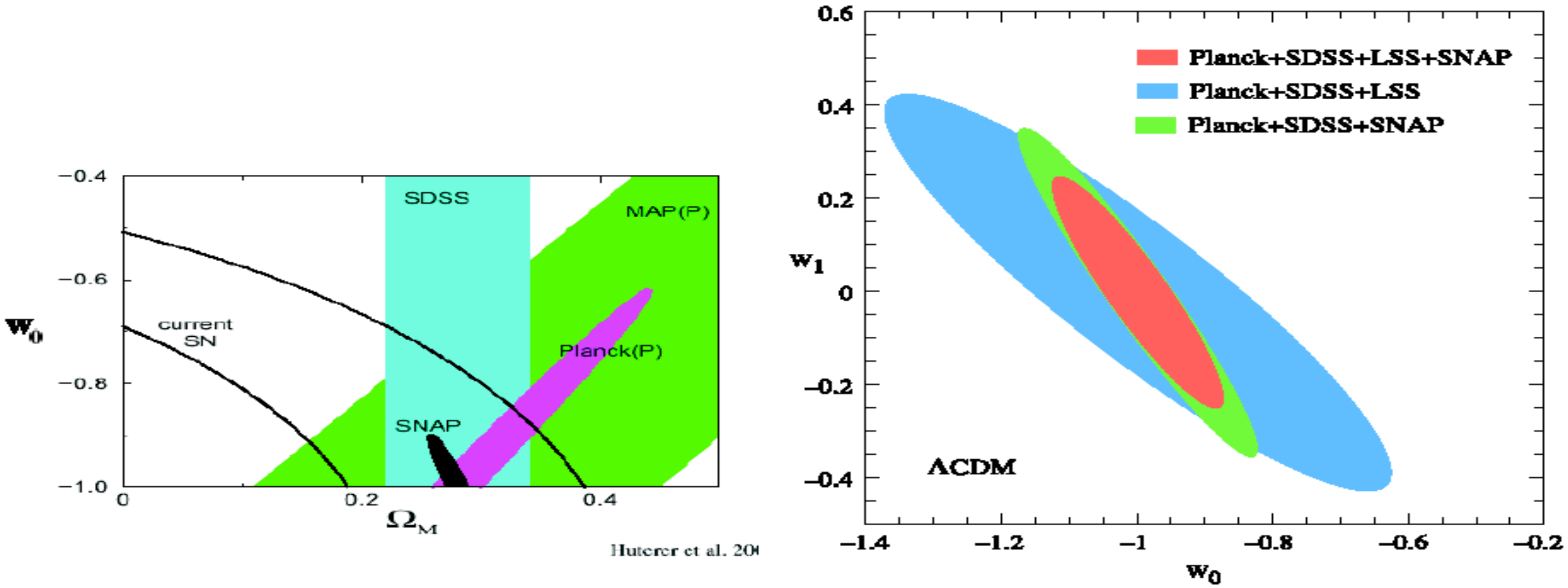


FIG 2.22.—The left panel (from Huterer & Turner 2001) shows forecasts of constraints on the dark energy equation of state parameter w and Ω_m for various experiments including *Planck*. The right panel (from Seo & Eisenstein 2003) shows forecasts of constraints on the time evolution of w, parameterised through $w \equiv w_0 + w_1 z$, for *Planck* combined with various redshift surveys and SNe observations from SNAP (see text for details).

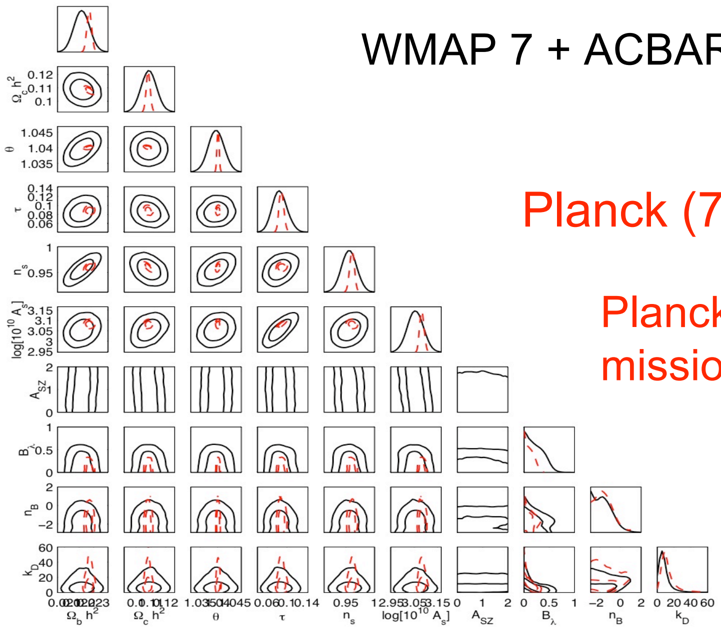
Cosmological Parameters: 4

Primordial Magnetic Fields (see talks by Durrer, Hollenstein, Ruchayskiy)

Stochastic Background

$$\langle B_i(\mathbf{k}) B_j^*(\mathbf{k}') \rangle = (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}')(\delta_{ij} - \hat{k}_i \hat{k}_j) \frac{P_B(k)}{2}$$

$$P_B(k) = A\, k^{n_B}\,, \quad n_B > -3$$



WMAP 7 + ACBAR + QUAD + BICEP

$B_{1\mathrm{Mpc}} < 5.0\,\mathrm{nG}$ at 95% CL

$n_B < -0.12$ at 95% CL

Planck (70+100+143 GHz)

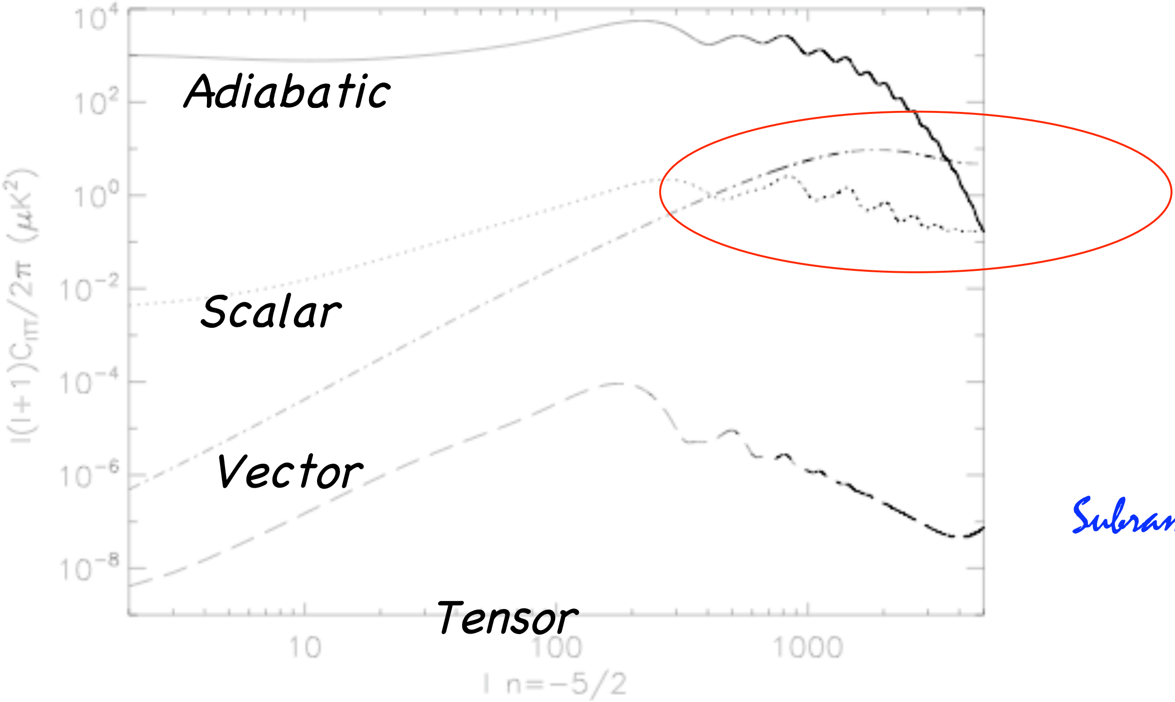
$B_{1\mathrm{Mpc}} < 2.7\,\mathrm{nG}$ at 95% CL

$n_B < -0.05$ at 95% CL

Planck alone extended mission forecast

Causal mechanisms with n_B even ≥ 2 not favoured by data

Paoletti & Finelli 2010



Constraints from present and Planck data mainly derive from the high l vector contribution

Subramanian & Barrow 1998

Paoletti, Finelli & Paci 2009

- Remind that $C_{\ell\,\mathrm{MAG}} \sim B_\lambda^4$

  An improvement of a factor 2 in the constraints in B_λ derives from an improvement of a factor 16 in C_l
- Additional constraints from non-Gaussianities, Faraday rotation, …

  Seshadri & Subramanian, 2009; Caprini, Finelli, Paoletti, Riotto 2009; …

Inflation

- Low scale inflation (negligible gravitational waves) assuming power-law spectra

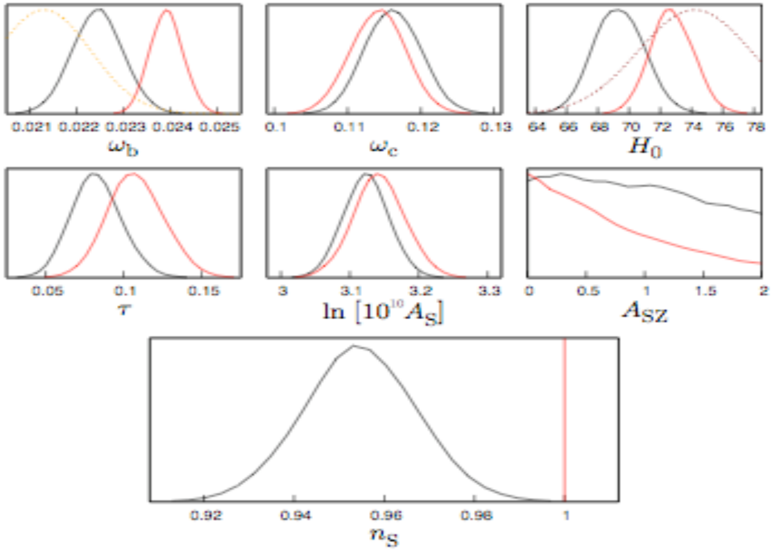


Figure 1: Posterior probabilities of the parameters of the HZ model (red) and the tilted model (black). The dotted orange line denotes constraints on ω_b from BBN and the dotted maroon line represents the HST prior on H_0.

Finelli, Hamann, Leach, Lesgourgues 2009

CMB+SDSS LRG DR 7

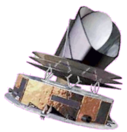
WMAP 5 + ACBAR + QUAD + BICEP

$$n_S = 0.955^{+0.012}_{-0.013}$$

Results confirmed by WMAP 7 yrs data, *Komatsu et al. 2010*

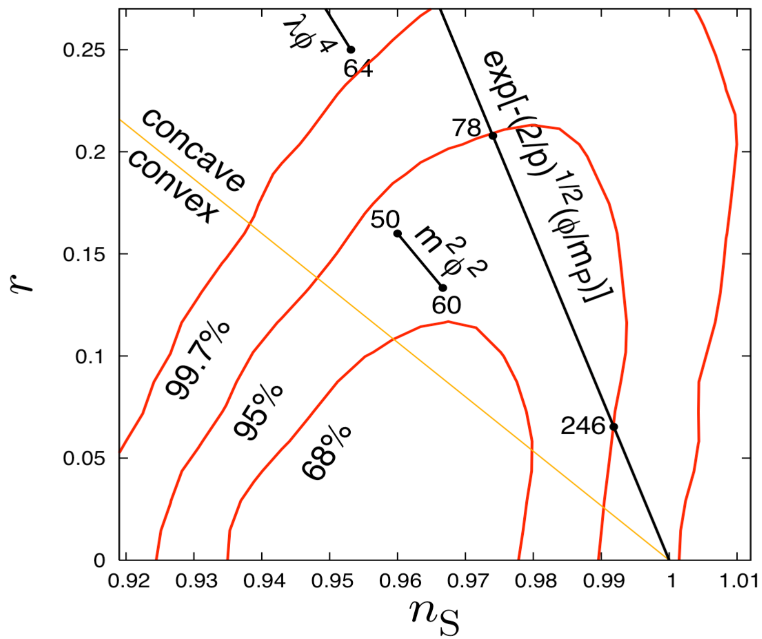
Planck alone nominal mission Bluebook forecast

$$\Delta n_S = 0.0045$$



Inflation

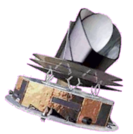
- Non negligible gravitational waves with power-law spectra



$$r < 0.17 \quad \text{at} \quad 95\%\text{CL}$$

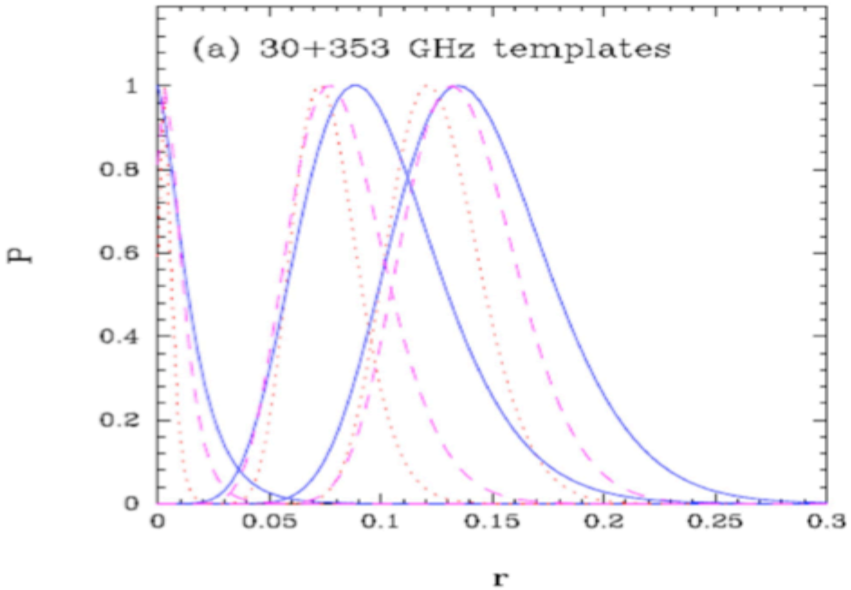
$$V_*^{1/4} < 2.1 \times 10^{16} \text{GeV}$$

Finelli, Hamann, Leach, Lesgourgues 2009



Inflation

- Planck capabilities in measuring the tensor-to-scalar ratio are strongly dependent on the ability of subtract diffuse (mainly galactic) foregrounds



Efstathiou, Gratton & Paci 2009

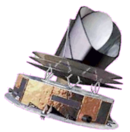
Efstathiou & Gratton 2009

Use of 70,100,143 and 217 GHz channels plus 30 and 353 channels as templates with extended mission.

Even low values as r ~ 0.05 can be detected

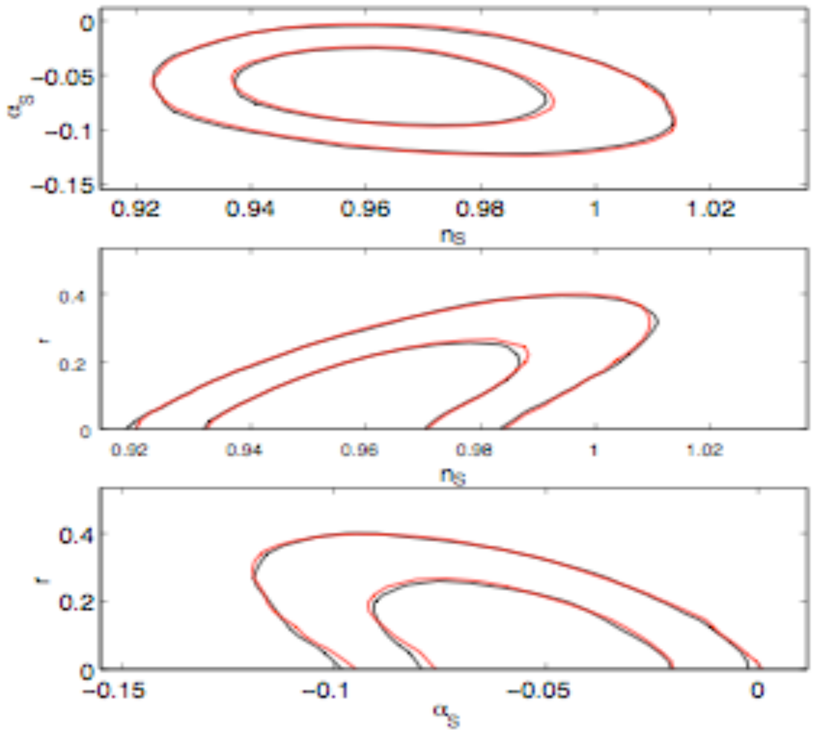
If r low then a 95 % CL constraint 0.03 can be reached

Bonaldi & Ricciardi 2011



Inflation

- Allowing deviations from power-law spectra of scalar and tensor fluctuations

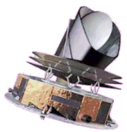


Finelli, Hamann, Leach, Lesgourgues 2009

$$\frac{dn_S}{d\ln k} = -0.063^{+0.061}_{-0.049} \quad \text{at} \quad 95\%\text{CL}$$

Planck 1 year Bluebook forecast

$$\Delta \frac{dn_S}{d\ln k} = 0.005$$



Non-Gaussianities

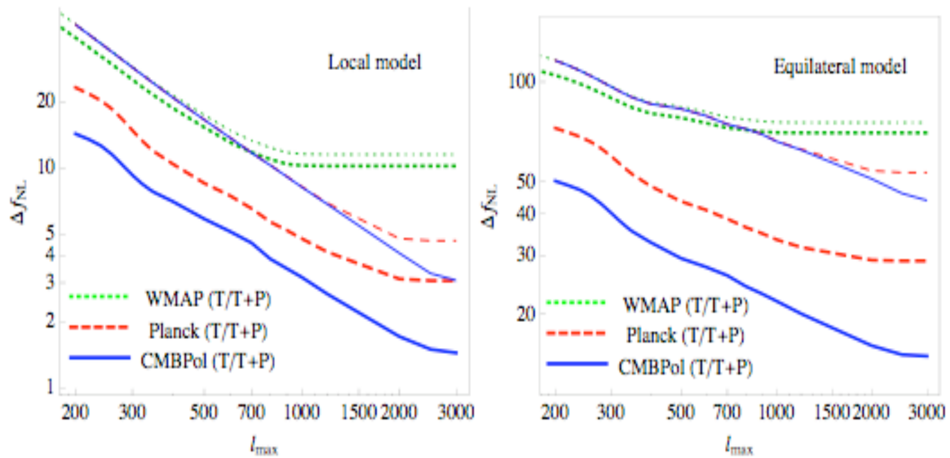
- Planck will perform extensive tests of the isotropy and the statistics of CMB fluctuations

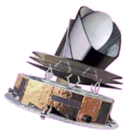
- Planck will search non-gaussianities in cosmological models with
  - second-order general relativistic effects
  - non-standard inflationary models
  - topological defects (cosmic strings, …)
  - non trivial topologies
  - primordial magnetic fields

  ….

$$\Phi(\mathbf{x}) = \Phi_L(\mathbf{x}) + \Phi_{NL}(\mathbf{x})$$
$$= \Phi_L(\mathbf{x}) + f_{NL}[\Phi_L^2(\mathbf{x}) - \langle\Phi_L^2(\mathbf{x})\rangle]$$

Liguori, Sefusatti, Fergusson & Shellard 2010





Departures from Isotropy

- Despite the several observational confirmations of one pillar of cosmology such as homogeneity and isotropy, there are several puzzling anomalies in the CMB pattern at large scales

a. striking alignment between the harmonic quadrupole and octupole modes in the temperature anisotropies.

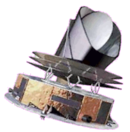
b. an asymmetric distribution of CMB power between two hemispheres. — Hansen et al. 2004, Eriksen at al. 2004

c. the low power of the quadrupole

d. the lack of power of the temperature correlation function on large angular scales

e. the presence of a cold spot in the southern galactic emisphere

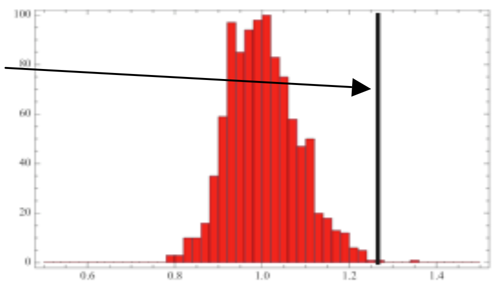
f. a breaking of parity symmetry of the CMB pattern, either at large angular scales and at intermediate scales. — Kim & Naselsky 2010



- With an optimal and minimum variance estimator we have searched for anomalies in CMB polarization corrisponding to those in intensity: for hemispherical asymmetry (*Paci et al. 2010*) and (point) parity symmetry (*Gruppuso et al. 2010*). No anomalies at significant statistical level could be claimed at WMAP 5 yr and 7yr sensitivities, but Planck will provide a better probe of polarization on large scales.

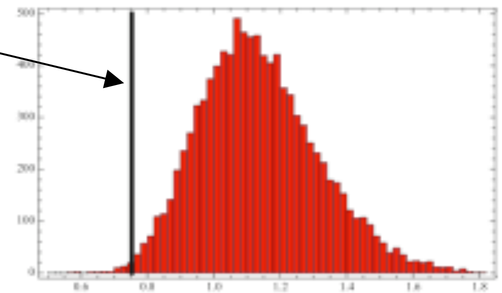
WMAP 5 yr value

$\Delta(TT_S/TT_N)$



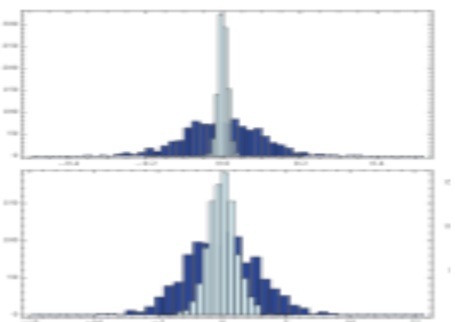
WMAP 7 yr value

$\Delta(TT_+/TT_-)$



$\Delta(EE_S - EE_N)$

$\Delta(TE_S - TE_N)$



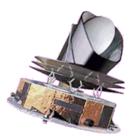
Planck 143 GHz noise

WMAP 5 noise

With Planck 143 GHz from a factor 2 (TE) to a factor 20 (BB, EB) better than WMAP 7!

Paci et al. 2010

Gruppuso et al. 2010



Planck Early Results

Planck's early results = 25 articles (19 science articles) on 10 months of data in less than 6 months of analysis

Interstellar physics studies (spinning dust particles, large scale ISM emission, ...)

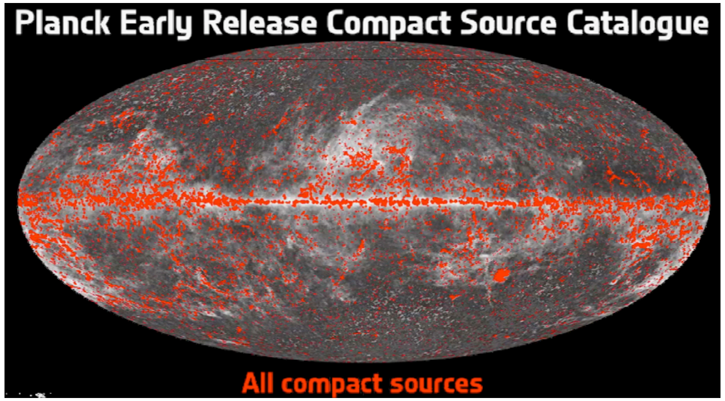
Cosmic Infrared Background anisotropies measured (217 to 857GHz, to 10arcmin)

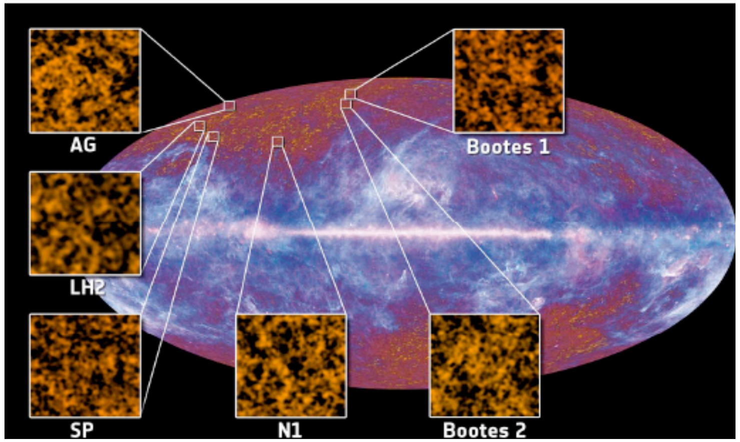
Radio galaxy spectra steeper than expected

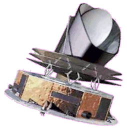
Planck's first product delivered to the community (ERCSC)

- ~15000 sources (from 30 to 857GHz)
- ~10000 Cold Core (pre-stellar cores & molecular clouds)
- 199 SZ clusters in total (30 new)

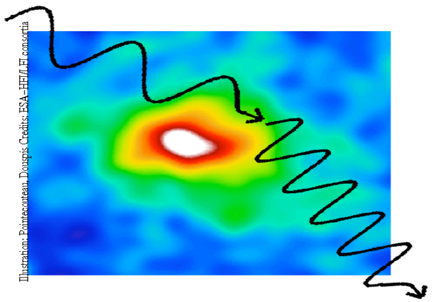
Material from Nabila Aghanim

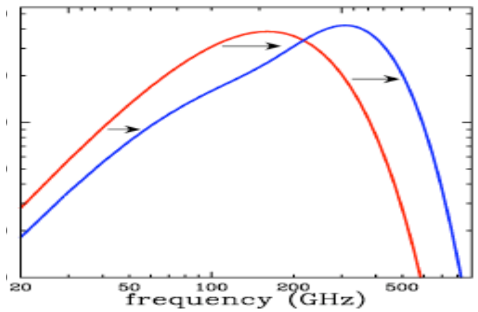






Highlights from Early Results: ESZ





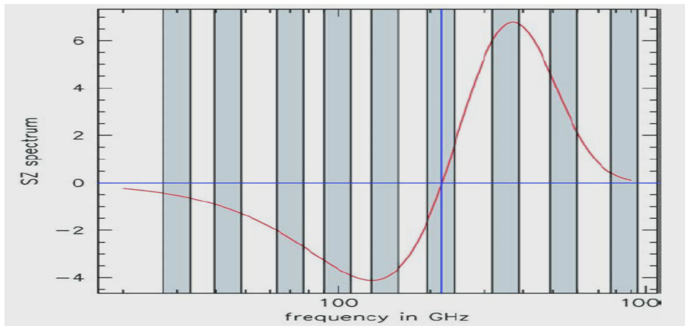
- Planck is unique for SZ detection

  for frequency coverage

  all sky survey

  can detect rarest and most

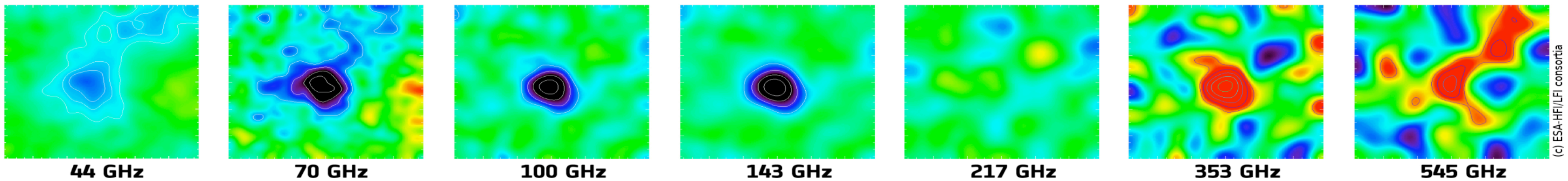
  massive clusters over the whole sky

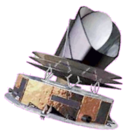


Credit: ESA,HFI & LFI consortia

Galaxy cluster

Abell 2319 as seen in seven of the Planck frequencies



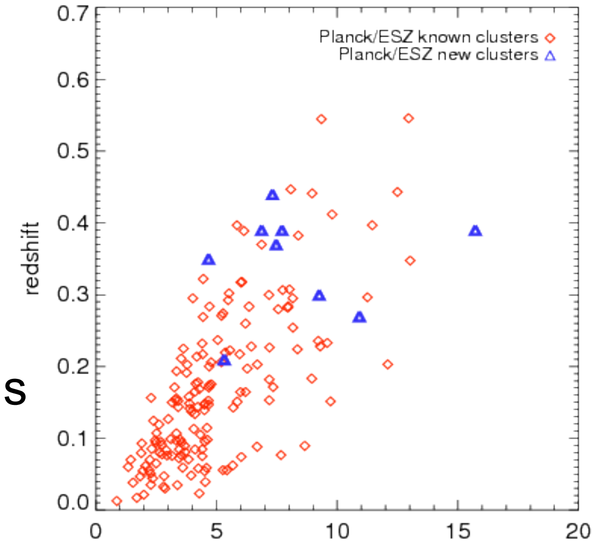


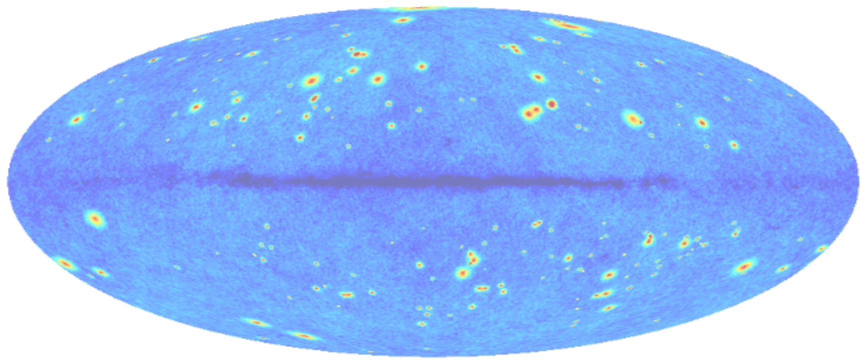
The all-sky Early SZ (ESZ) cluster sample =

189 candidates (S/N from 6 to 29 & |b| >14deg)

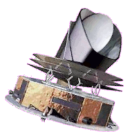
- 169 identified with known clusters
- 20 candidates or new clusters
  - 11 confirmed with XMM-*Newton* (z, M), 1 with AMI
  - 8 candidates (6 confirmed by SPT & AMI teams independently from Planck collaboration)

Further 10 new clusters (S/N <6) from the XMM-*Newton* follow-u





Material from Nabila Aghanim



First all-sky S/N selected sample of SZ clusters detected blindly

Only all-sky cluster survey since ~1992 (ROSAT)

First **SZ measure for ~80% of the known clusters** in the ESZ

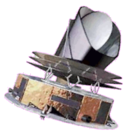
Detection of the rarest and **most massive clusters over the whole sky**

Discovery of new clusters (low luminosity, disturbed morphology) 30 published to date → A non-negligible population of **massive dynamically perturbed systems**, under-represented in X-ray surveys?

More details can be found in

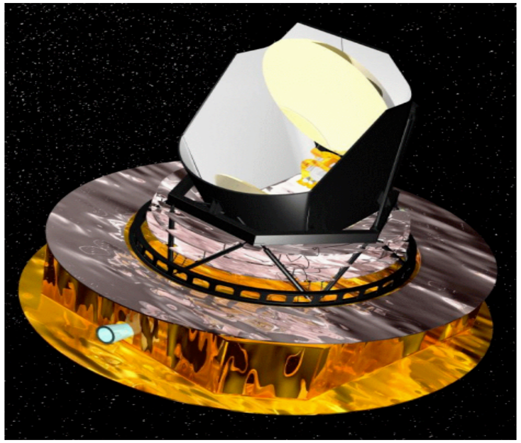
Planck collaboration arXv1101.2024,.2025,2026,2043

Material from Nabila Aghanim



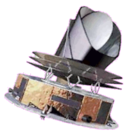
Conclusions

- *Planck* is completing the third survey, performances are as expected.
- *Planck* will bring us in a new era of precision cosmology.
- E*arly Planck release* in January 2011, more in 2012 and 2013.



The Planck early scientific results are a product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of ESA with instruments provided by two scientific Consortia funded by member states (the lead countries: are France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

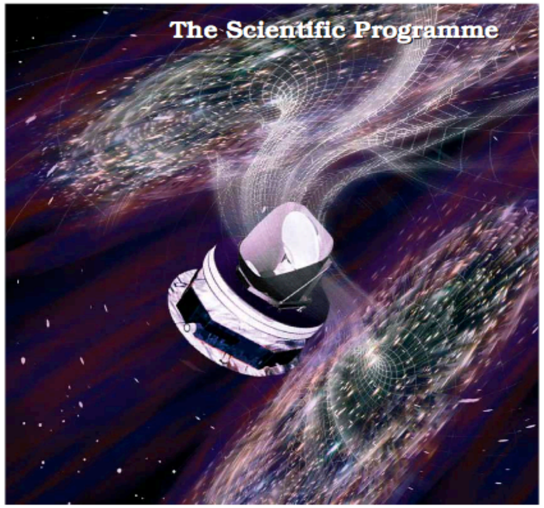


Sources

ESA-SCI(2005)1

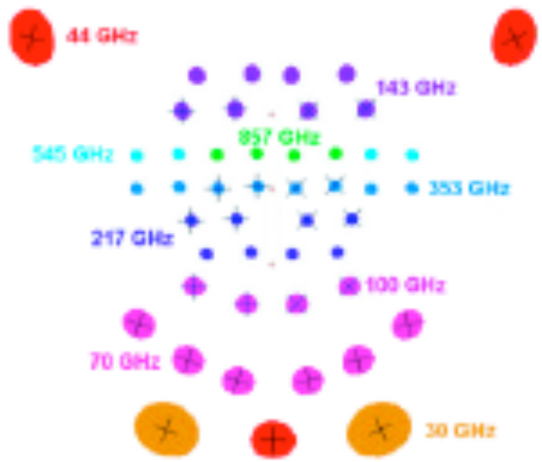
esa

PLANCK



European Space Agency
Agence spatiale européenne

astro-ph/0604069



Observing strategy