LFI frequency maps: data analysis, results and future challenges

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New Light in Cosmology from the CMB
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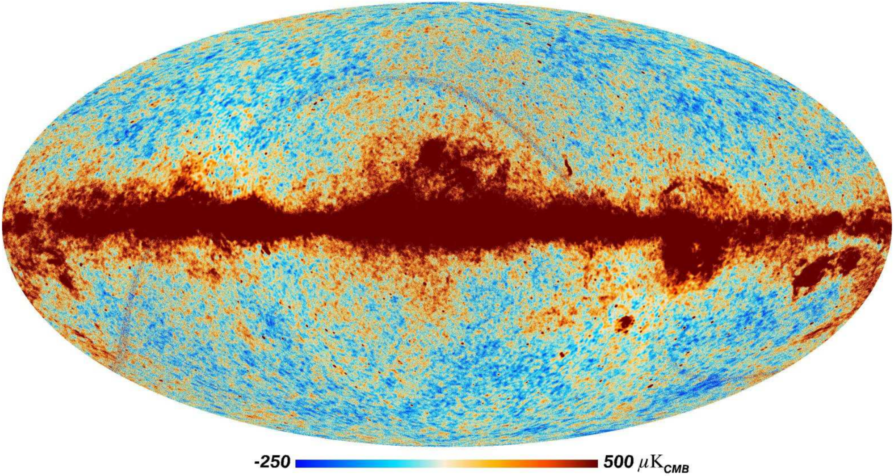
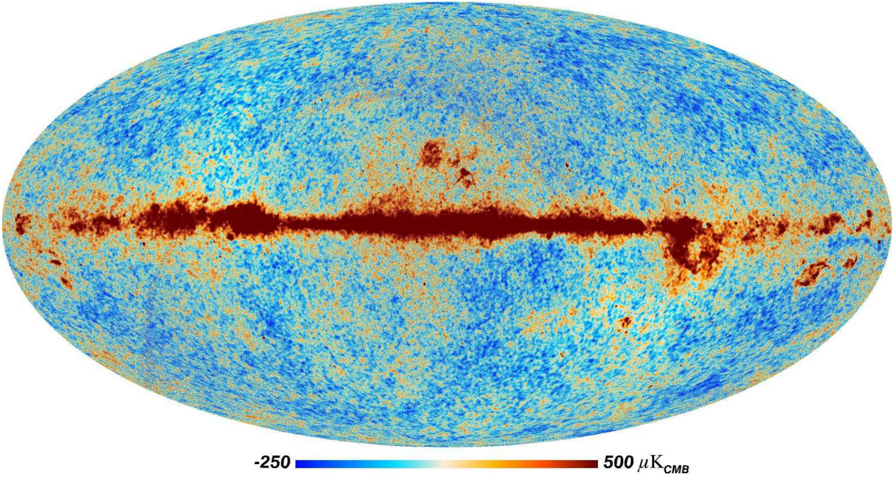
Outline

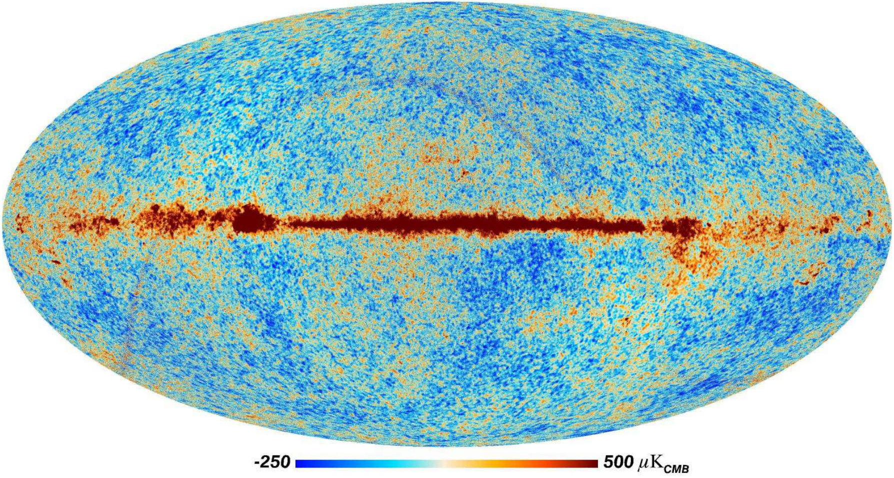
Planck-LFI 30 GHz



Planck-LFI 44 GHz



Planck-LFI 70 GHz



Operations

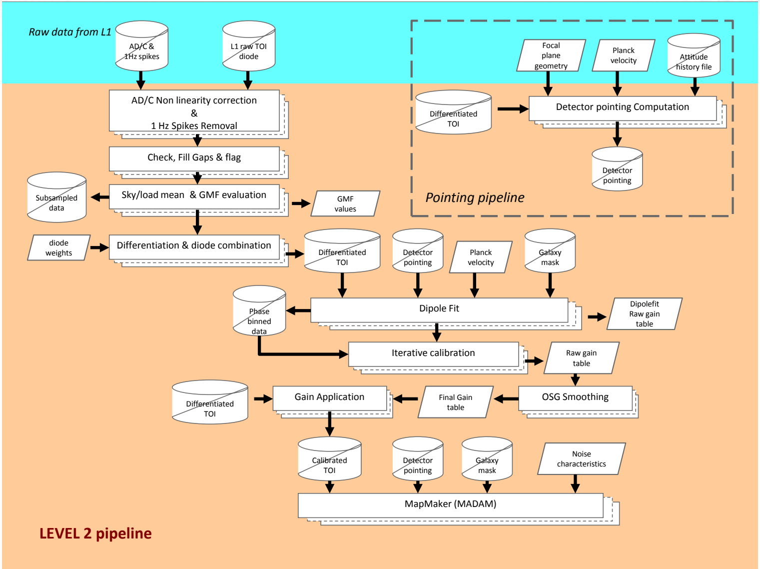
PLANCK

- *Planck* was launched on 14 May 2009 and the current data release includes temperature maps based on the first 15.5 months of observations
- *Planck* is still alive and LFI is currently taking data
  - HFI was switched off on January 2012, beyond the *nominal* period and now is supporting LFI providing essential H/K telemetry (e.g. 4K cooler)
  - LFI is expected to continue at least till September 2013
- Data are of incredible quality!

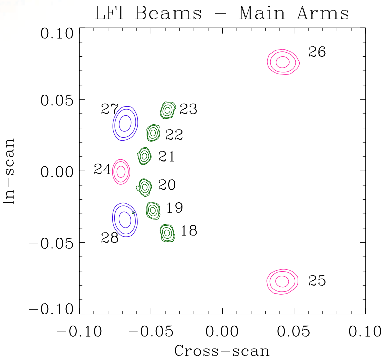
Data Processing Overview

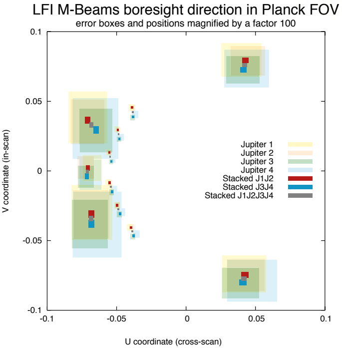
- DPC approaches data reduction with specific tasks aiming to estimate and correct instrumental systematic effects
- There are three main logical levels:
  - Level 1: H/K and Science telemetry from the satellite are transformed into raw timelines and stored into dedicated databases with the associated time information
  - Level 2: instrument information is gathered and ingested into the Instrument Model, removal of systematic effects, flag data of suspected quality, photometric calibration and creation of maps and ancillary products
  - Level 3: more science here with component separation, power spectra estimation and extraction of cosmological parameters
- Each step is internally validated (with dedicated sims) and most of the DPC work is spent cross-checking internally and between the two instruments

From raw data to maps



Beams reconstruction

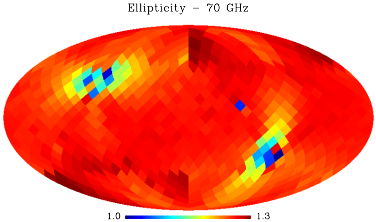




- Beams contours (-20dB/LFI) from planet transit
- Pointing reconstruction: error smaller that $0.5'$

Effective Beams

Band	FWHM [′]	e	Ω [arcmin^2]
30	32.239±0.013	1.320±0.031	1189.51±0.84
44	27.01±0.55	1.034±0.031	833±32
70	13.252±0.033	1.223±0.026	200.7±1.0



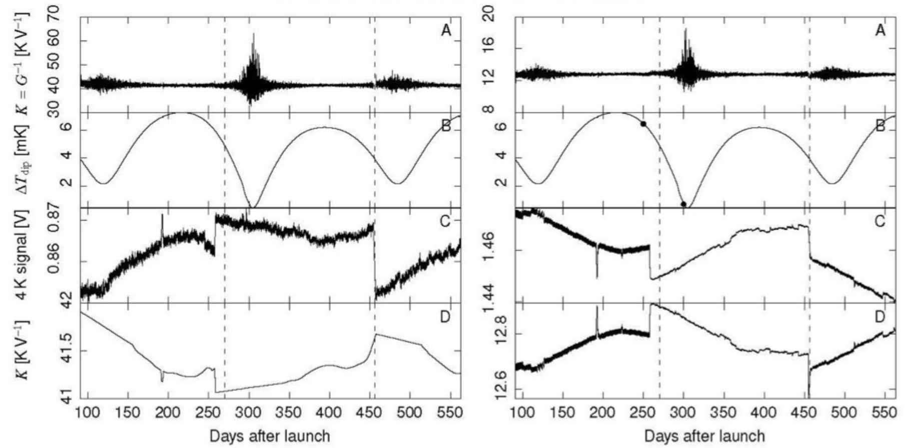
- Scanning beams are used to compute effective beams which gives pixel-by-pixel the beam shape projected in the sky when scanning strategy is accounted for. Fundamental point for source extractions and beam window function

Photometric Calibration

PLANCK

- This is the most important and critical aspect of data reduction pipeline. The LFI one works as follows
  - estimate dipole amplitude and alignment of dipole for any direction
  - create the expected level of the dipole signal accounting for the full-beam shape
  - fit real data with dipole with iterative approach (raw gains)
  - filter raw gains or use 4K to calibrate data

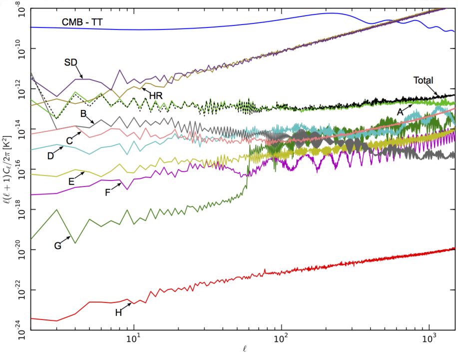
Photometric Calibration



Map-making

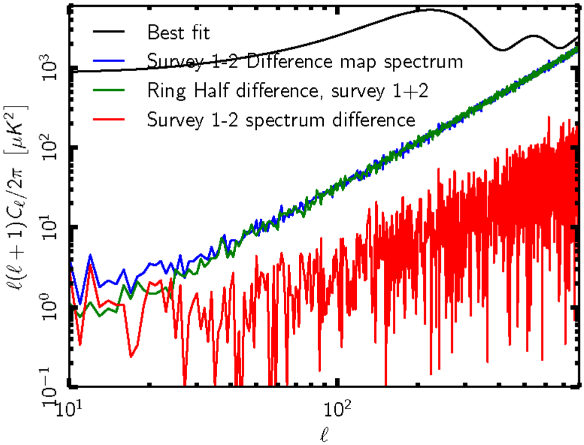
- Calibrated TOI for each radiometer are input of `madam` map-making code, together with pointing data
- The algorithm is a maximum-likelihood destriping and estimates in this fashion the amplitude of the $1/f$-noise baseline, subtract from the timelines and then simply bins the resulting TOI into a map
- Maps produced at different levels:
  - Frequency maps, HR maps and Survey maps
  - Low resolution maps used for the computation of the noise covariance matrix

Systematic effects



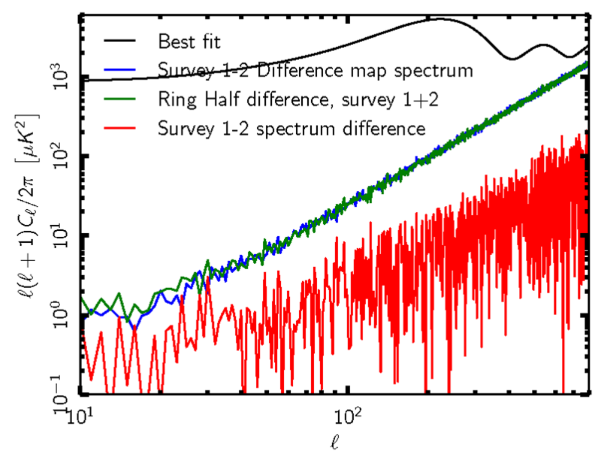
- Null tests: primary tool to see systematic effect residual w.r.t. white noise level
- Sims: Assess their impact on TOI using in-flight H/K data. This approach provides a powerful tool to check for systematics

44 GHz



Best fit
Survey 1-2 Difference map spectrum
Ring Half difference, survey 1+2
Survey 1-2 spectrum difference
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{1}
10^{2}
ℓ

70 GHz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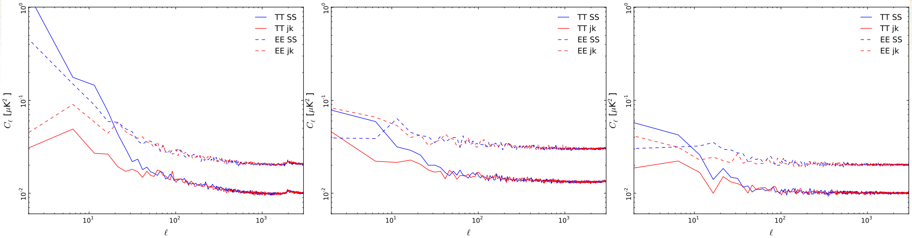
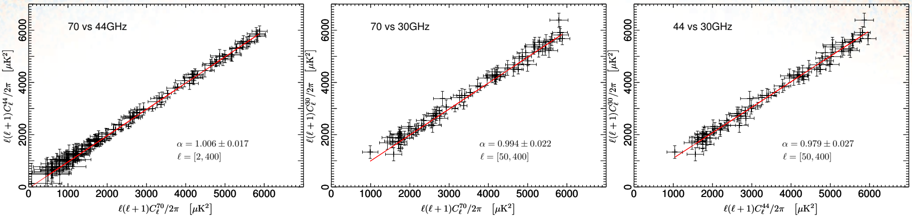
LFI Internal Validation - Null tests



- Quality of LFI maps is assessed and verified by a set of null-tests in an almost automatic way
- Several data combination (radiometer, horn-pairs, frequency) on different time-scales (1 hour, survey, full-mission): difference at horn level at even/odd surveys clearly reveals side lobe effect
- Null-test power spectra are used to check total level of system. effects to be compared w.r.t. white noise level and systematic effects analysis

LFI Internal Validation - Check Spectra



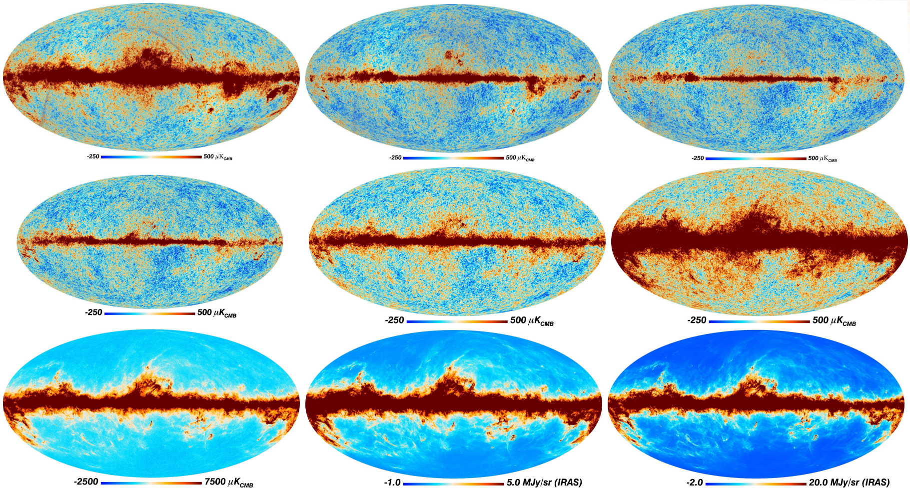
- Compute power spectra in multipole range around the first acoustic peak removing the unresolved point source contributions. Spectra are consistent within errors. 30 and 44/70 have different approaches to gain applied
- Hausman test assess consistency at 70 GHz showing no statistically significant problem
- Spectra from horn-pairs and from all 12 radiometers: χ^2 analysis shows compatibility with null-hypothesis

Maps Characteristics

Uncertainty	Applies to	Method
Gain calib	All sky	*WMAP* dipole
Zero level	All sky	Galactic Cosecant model
Beam	All sky	GRASP models via FeBecop
CC	non-CMB	ground/flight bandpass leakage
Resid. Sys	All sky	Null-tests

Property	30	44	70
Frequency [GHz]	28.4	44.1	70.4
Noise rms/pixel [μK_{CMB}]	9.2	12.5	23.2
Gain Uncert	0.82%	0.55%	0.62%
Zero Level Uncert [μK_{CMB}]	$\pm$2.23	$\pm$0.78	$\pm$0.64

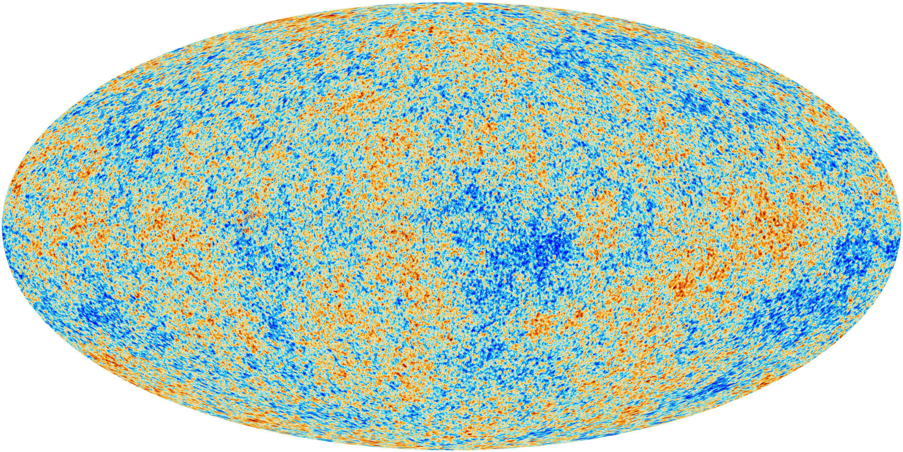
Component Separation



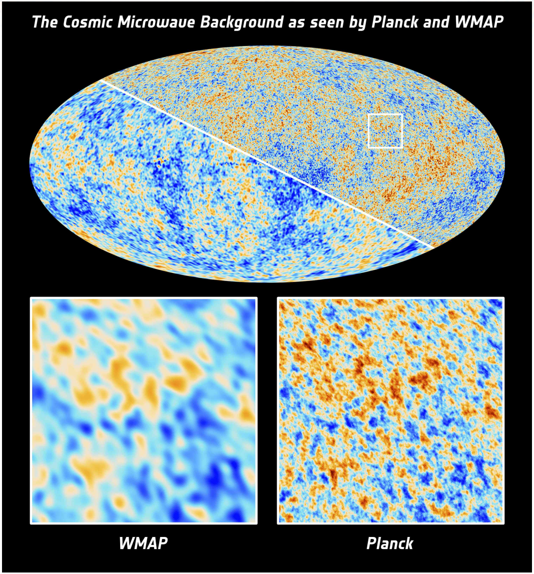
Component Separation

- Microwave emission is dominated by CMB from 70 to 143 GHz
- At low and high frequency foregrounds emissions dominates not only along the galactic plane: synchrotron, free-free, dust
- Forerground components have distinct spectral shapes different from CMB
- Multi-frequency observations are fundamental to separate such components

Planck CMB sky



Planck vs WMAP



From maps to Power Spectrum

- Given a map of CMB sky $\Delta T(\hat{n})$ decompose in spherical harmonics

$$a_{\ell m} = \int d\hat{n}\, \Delta T(\hat{n})\, Y^{\star}_{\ell m}(\hat{n})$$

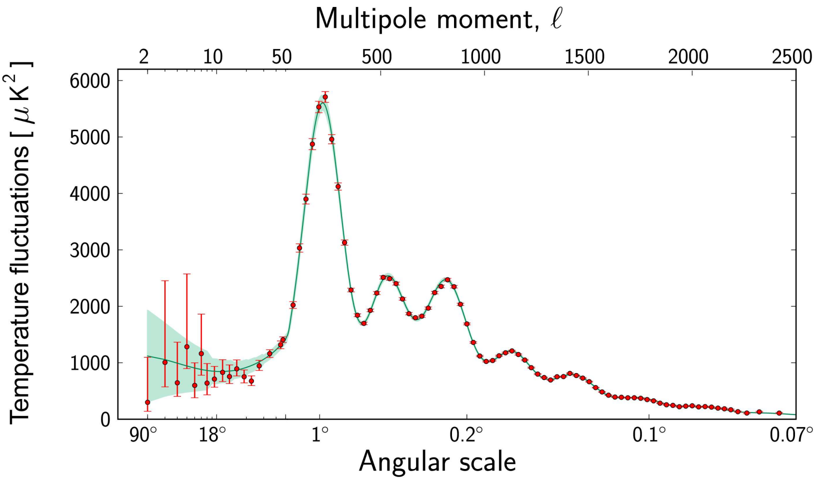
- Without instrumental noise power spectrum is given by

$$\mathcal{C}_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

- For real experiments, with finite beam size, noise and incomplete sky coverage

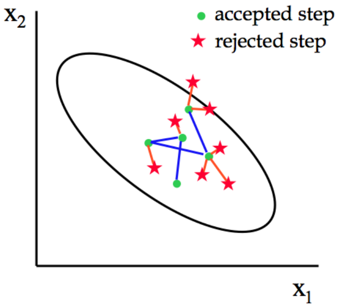
$$\tilde{\mathcal{C}}_\ell = \sum_{\ell'} M_{\ell\ell'} F_{\ell'} B^2_{\ell'} \mathcal{C}^{\rm th}_{\ell'} + \mathcal{N}_\ell$$

Planck TT Angular Power Spectrum

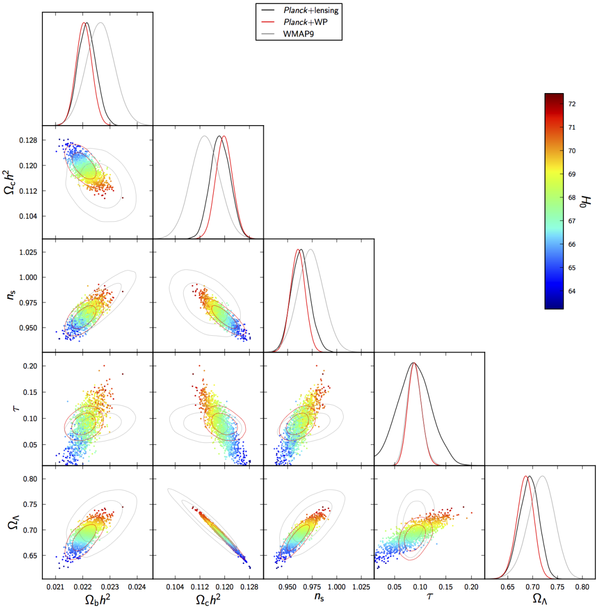


- *Planck* 2013 results. XVI. Cosmological Parameters

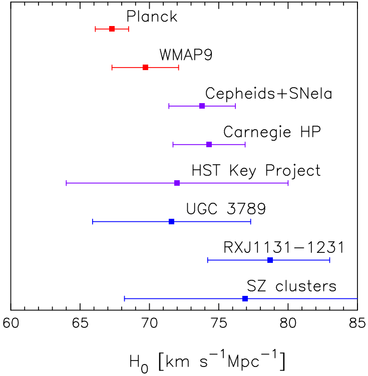
- Shape, positions and heights of peaks strongly depends on cosmological parameters
- Instead of comparing theory ($\mathcal{C}_\ell^{\rm th}$) with data on defined grid points in parameter space, a Monte Carlo Marchov Chain approach is used: random walk with Metropolis-Hasting chain samples



Planck Cosmological Parameters

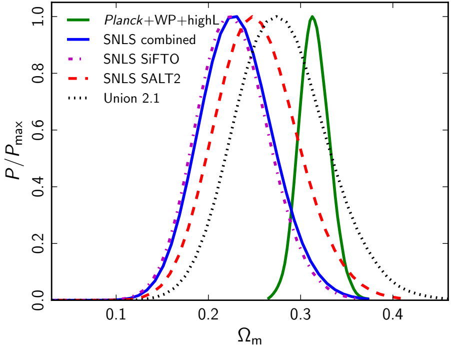


Hubble Constant H_0



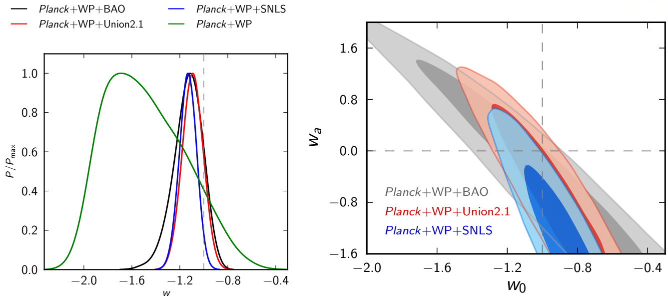
- $H_0 = (67.3 \pm 1.2)$km s^{-1} Mpc^{-1}. Lower than previous estimation based on astrophysical observations.
- Higher age of the Universe 13.817 ± 0.048 Gyr

Ω_m



- SN data are almost consistent within each other
- Union 2.1 is consistent with *Planck* and SNLS combined shows some tension
- Residual systematics?

Dark Energy

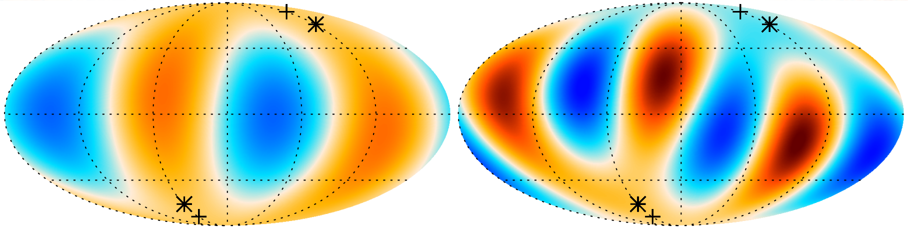


- $w = p/\rho = -1$ cosmological constant. All data-sets consistent with this but the inclusion of SNLS
- $w(a) = w_0 + w_a(1 - a)$: the $(w_0, w_a) = (-1, 0)$ is within 68% CL but for the inclusion of SNLS

Intriguing inconsistencies

- *WMAP* reported some “anomalies” on large angular scales:
    - Quadrupole/Octupole alignment
    - Low variance
    - Hemispherical asymmetry
    - Dipolar power modulation
    - Cold Spot
- *Planck* revises these “anomalies” and provides new robust results

Quadropole/Octupole alignment

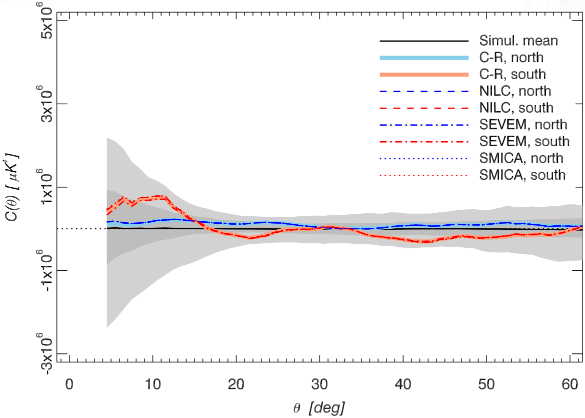


- Search for axis of maximum momentum dispersion independently for $\ell = 2$ and $\ell = 3$
- CMB map derived from different component separation methods
- Alignment varies between 9° and 13° (depending on comp. sep.) less significant (below 98%)

Hemispherical asymmetry

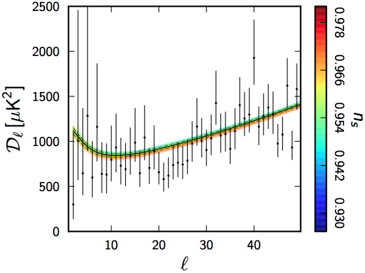
- Analysis of *WMAP* data reveal power spectrum asymmetry: power in hemisphere centred in $(\theta, \phi) = (110^\circ, 237^\circ)$ (close to ecliptic plane) is larger than in the opposite for $\ell = 2 - 40$
- Other methods (Minkowski functionals, $N-$point correlation functions) show similar evidence
- *Planck* reviews such evidences using different CMB component separated maps and $N-$point correlation functions

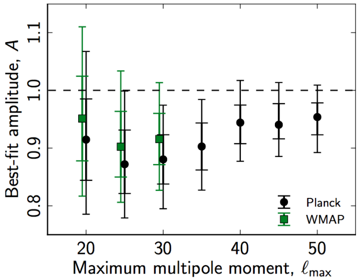
Hemispherical asymmetry



- North: almost 99.9% of simulations has larger structure of 4-pt correlation function
- South: in line (54-57%) with (Gaussian) simulations

Low-ℓ deficit





- ΛCDM is not a good fit for *Planck* data for $20 \lesssim \ell \lesssim 40$
- Already present in *WMAP* but with *Planck* at $2 - 2.5\,\sigma$ level

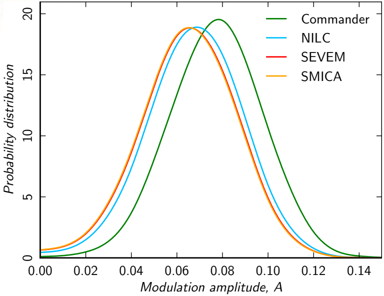
Dipole Modulation

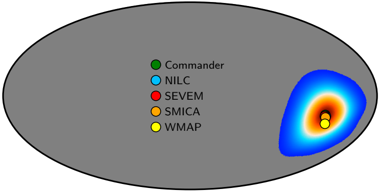
- Gordon et al. (2005) proposed a phenomenological model for large scale power in *WMAP* data described by a multiplicative dipole modulation

$$\mathbf{d} = (1 + A\mathbf{p} \cdot \mathbf{n})\mathbf{s}_{iso} + \mathbf{n}$$

- *WMAP*-5yr found $A = 0.072 \pm 0.022$ and $(l, b) = (224^\circ, -22^\circ)$ at $3.3\,\sigma$ level

Dipole Modulation





- Dipole amplitude consistent between different CMB maps with $A \in [0.065, 0.078] \pm 0.022$
- Dipole direction in agreement also with *WMAP* with significance $\sim 2.9 - 3.5\,\sigma$

Interpretations of "anomalies"

- Many features observers by *WMAP* are seen by *Planck*: inter-instrument consistency rules out intrinsic systematic effects
- Microwave sky is neither Gaussian nor isotropic but component separation is robust
- Possible local origin: removing ISW originated with a volume at $z < 0.3$ alleviates most of the "anomalies"
- Most interesting would be their cosmological origin:
  - candidates models with compact topology although no evidence is shown
  - anisotropic Bianchi VII_h model is a good template and when subtracted from the data many of the large-scale "anomalies" are no longer present but ...
  - ... Bianchi provides parameters incompatible with ΛCDM

Conclusions

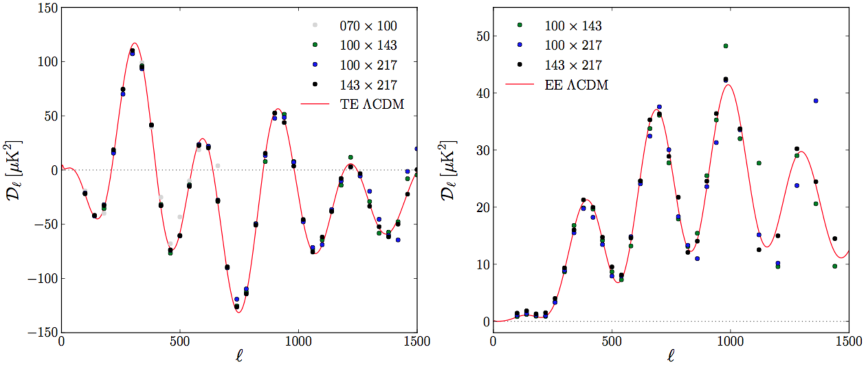
PLANCK

- Standard ΛCDM provides a good fit to data for $\ell \gtrsim 40$
- *Planck* provides a unique window on the early universe and shades light on content of the Universe: $\Omega_m, \Omega_\Lambda, \Omega_b$
- Possible new physics from "tension" on some parameters values (e.g. H_0)
- Spectrum shape $20 \lesssim \ell \lesssim 40$ is a real feature of CMB anisotropies. Not a decisive significance but is an "anomaly".

What's next?

- Polarisation data will open new possibilities: direct measure of τ, new hints on tensor modes, break some parameter degeneracies with temperature only data
- Foregrounds polarisation maps will provides informations on, e.g., emission mechanisms and structure of galactic magnetic field
- Challenging due to the tiny CMB polarisation signal but ...

What's next?



- Angular power spectra of TE (left) and EE (right) from *Planck* data combinations. $f_{sky} = 0.4$, no foreground cleaning, uniform weight of channels