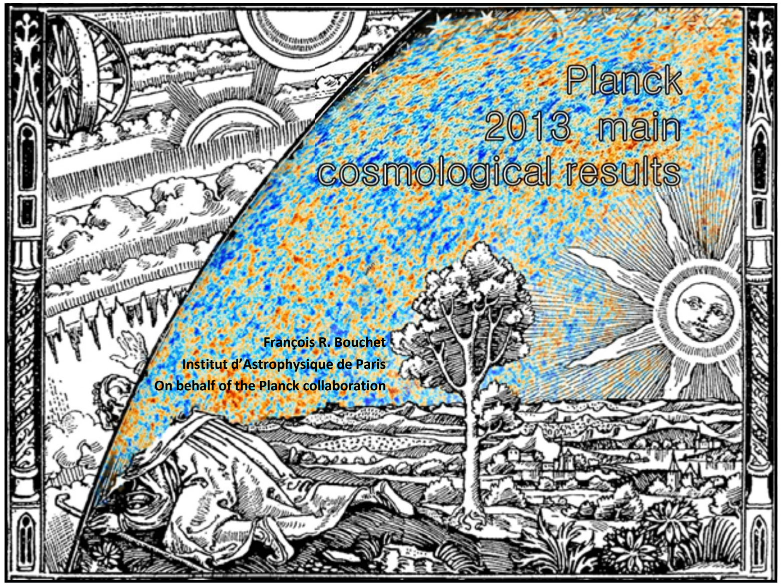
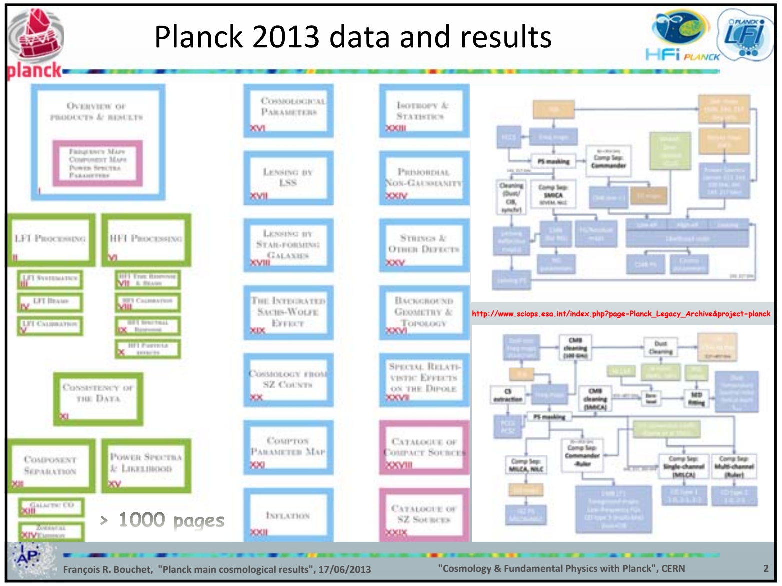
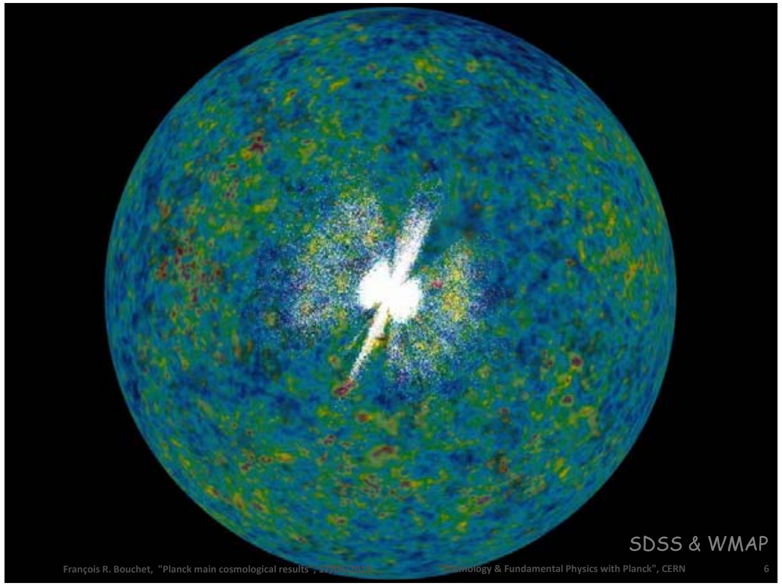


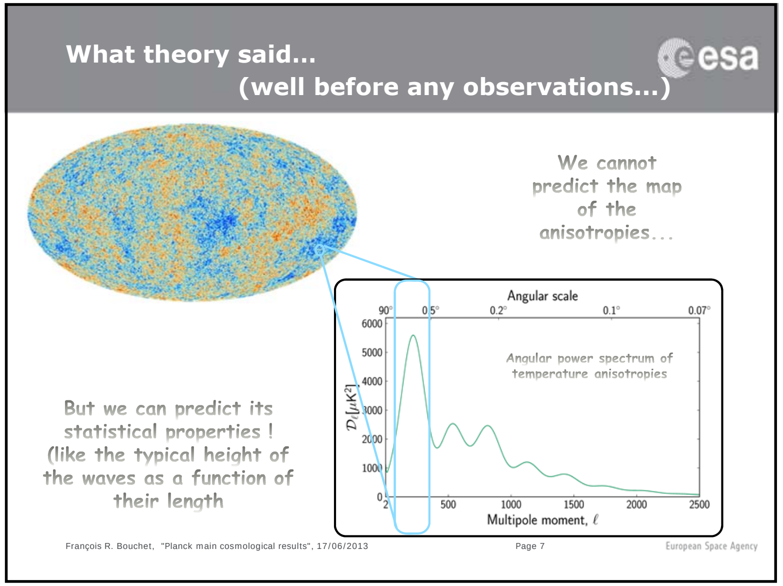
Planck
2013 main
cosmological results
François R. Bouchet
Institut d'Astrophysique de Paris
On behalf of the Planck collaboration



planck
Planck 2013 data and results
HFI PLANCK
LFI
Overview of products & results
LFI Processing
HFI Processing
Consistency of the Data
Component Separation
Power Spectra & Likelihood
Cosmological Parameters
Lensing by LSS
Lensing by Star-forming Galaxies
The Integrated Sachs-Wolfe Effect
Cosmology from SZ Counts
Compton Parameter Map
Inflation
Isotropy & Statistics
Primordial Non-Gaussianity
Strings & Other Defects
Background Geometry & Topology
Special Relativistic Effects on the Dipole
Catalogue of Compact Sources
Catalogue of SZ Sources
> 1000 pages
http://www.sciops.esa.int/index.php?page=Planck_Legacy_Archive&project=planck
François R. Bouchet, "Planck main cosmological results", 17/06/2013
"Cosmology & Fundamental Physics with Planck", CERN
2



SDSS & WMAP



What theory said…
(well before any observations…)
esa
We cannot predict the map of the anisotropies…
But we can predict its statistical properties ! (like the typical height of the waves as a function of their length
Angular scale
90°
0.5°
0.2°
0.1°
0.07°
Angular power spectrum of temperature anisotropies
$\mathcal{D}_\ell\,[\mu K^2]$
6000
5000
4000
3000
2000
1000
0
2
500
1000
1500
2000
2500
Multipole moment, ℓ
François R. Bouchet, "Planck main cosmological results", 17/06/2013
Page 7
European Space Agency

The Planck concept/challenge

- to perform the "ultimate" measurement of the Cosmic Microwave Background (CMB) temperature anisotropies:
  - *full sky coverage & angular resolution / to survey all scales at which the CMB primary anisotropies contain information (~5')*
  - *sensitivity / essentially limited by ability to remove the astrophysical foregrounds*

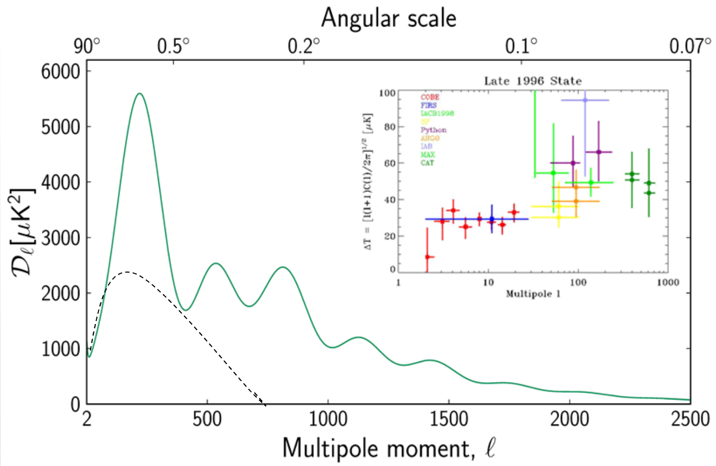
  $\Rightarrow$ *enough sensitivity within large frequency range [30 GHz, 1 THz] (~CMB photon noise limited for ~1yr in CMB primary window)*

- get the best performances possible on the polarization with the technology available

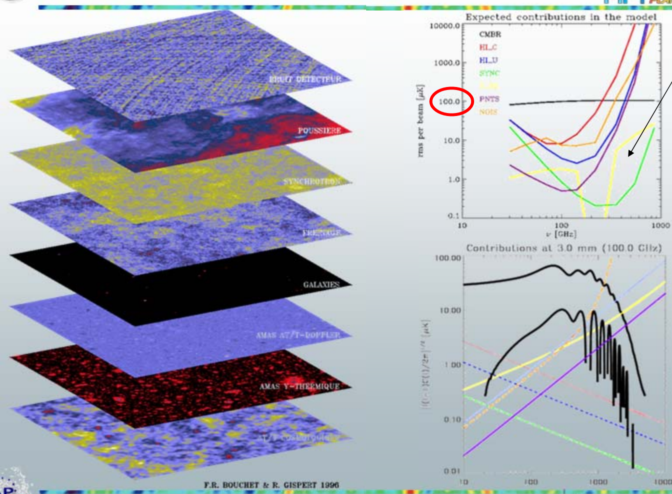
$\Rightarrow$ ESA selection in 1996 (after ~ 3 year study)

NB: with the Ariane 501 failure delaying us by several years (03 → 07) and WMAP then flying well before us, polarization measurements became more and more a major goal

Visualising the target



Foregrounds !!!



ΔH_0 =2%

Planck performance goals summary

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	545	857
Detector Technology	HEMT LNA arrays			Bolometer arrays					
Detector Temperature	~20 K			0.1 K					
Cooling Requirements	H_2 sorption cooler			H_2 sorption + 4 K J-T stage + Dilution cooler					
Number of Unpol. Detectors	0	0	0	0	4	4	4	4	4
Number of Linearly Polarised Detectors	4	6	12	8	8	8	8	0	0
Angular Resolution (FWHM, arcmin)	33	24	14	9.5	7.1	5	5	5	5
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Average $\Delta T/T_I$* 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 ($\times 10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

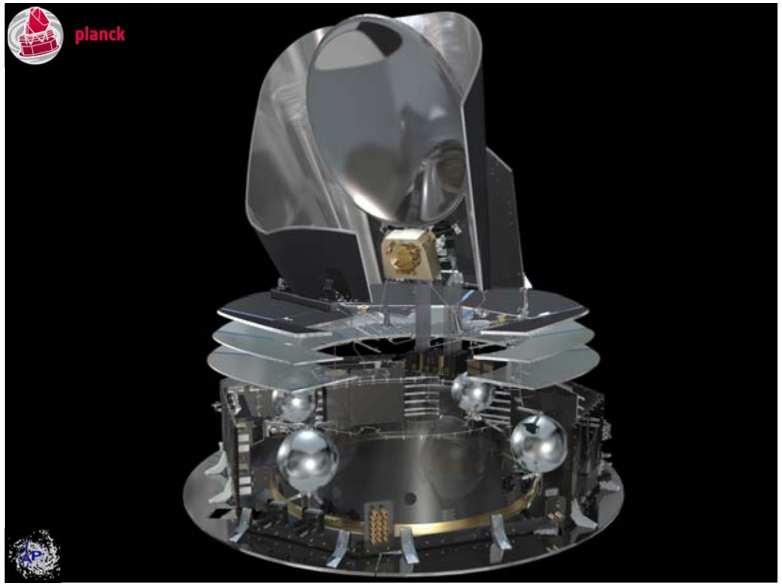
\# A pixel is a square whose side is the FWHM extent of the beam.

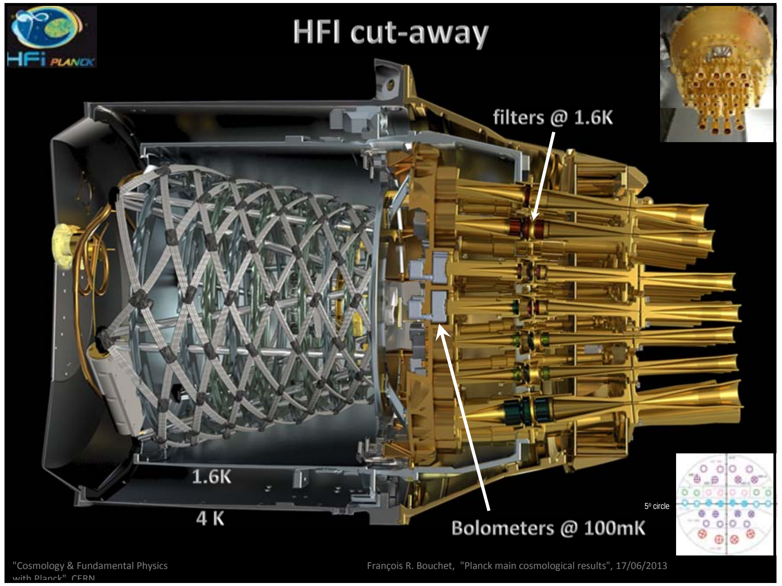
* Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($\times 10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

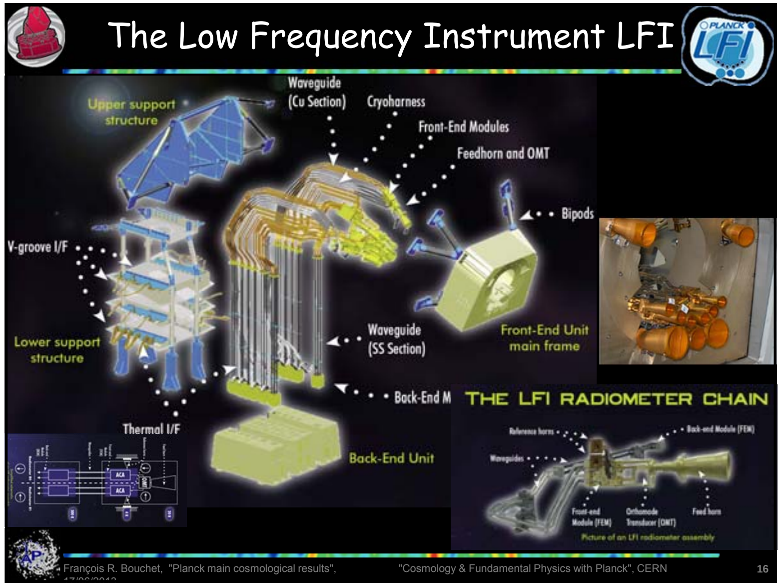
Planck needed breakthroughs

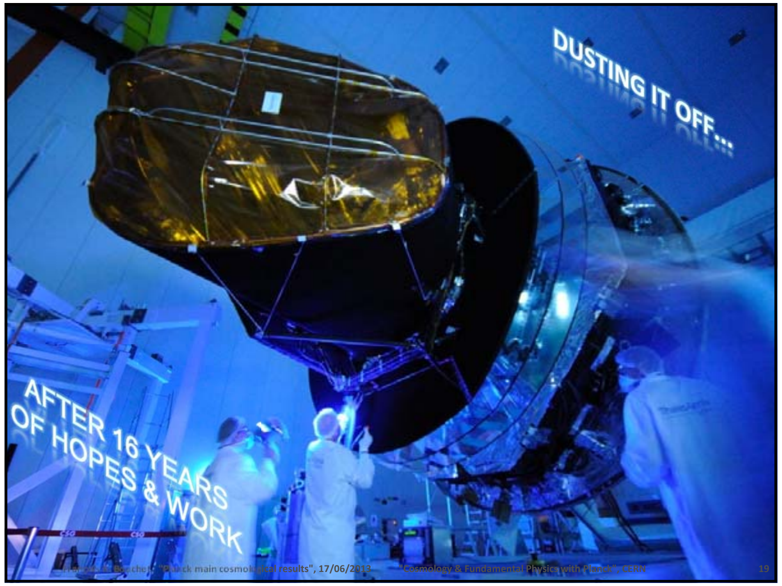
- The performance goals of Planck required several technological performances never achieved in space before
  - *Sensitive & fast bolometers with*
    - NEP< 2 10^{-17} W/$Hz^{1/2}$ & time constants typically < 5 msec
      (thus cooling them to 100 mK, very low heat capacity & charged particles sensitivity)
  - *total power read out electronics with very low noise*
    - < 6nV/$Hz^{1/2}$ from 10 mHz to 100 Hz
  - *Excellent temperature stability, from 10 mHz (1 rpm) to 100 Hz (cf. Lamarre et al. 04)*
    - < 10 μK/$Hz^{1/2}$ for 4K box (30% emissivity)
    - < 30 μK/$Hz^{1/2}$ on 1.6K filter plate (20% emissivity)
    - < 20 nK/$Hz^{1/2}$ for detector plate (~5000 damping factor needed)
  - *low noise HEMT amplifiers (⇒ cooled to 20K) & very stable cold reference loads (4K)*
- Additionally:
  - *low emissivity, very low side lobes, telescope (strongly under-illuminated)*
  - *no windows, minimum warm surfaces between detectors and telescope*
  - *Complex cryogenic cooling chain: 50K (passive)+20K+4K+0.1K active coolers*
    - 20K for LFI with large cooling power K (0.7W)
    - 4K, 1.6K and 100mK for HFI
    - Thermal architecture optimised to damp thermal fluctuations (active+passive)
  - *NB: 100mK cooling by dilution cooler does not tolerate micro-vibrations at sub-mg level or 7.10^{10} He atoms accumulated on dilution heat exchanger (typically He pressure 1.10^{-10} mb)*

⇒ *Integration of 3 intertwined complex chains - optical, electronic, cryogenic*





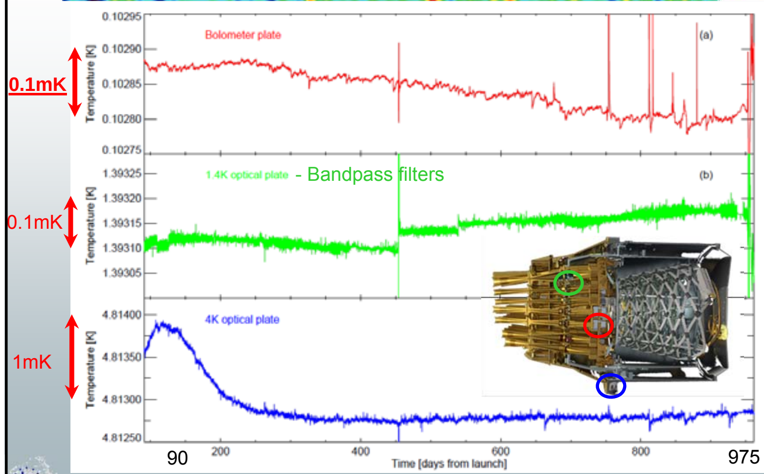




Log Book (``a bit'' abridged)

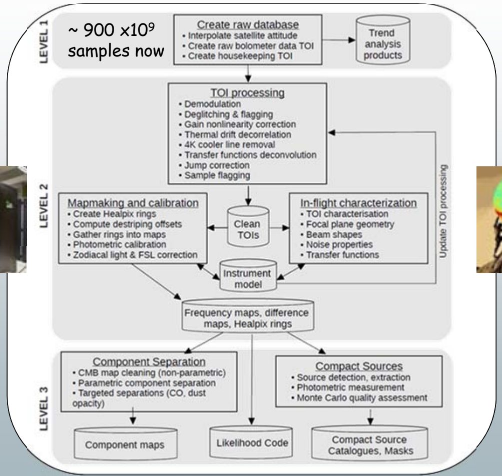
- August 13th 2009 : beginning of survey: Instruments very stable, continuously mapping the sky
- Essentially no hiccups since, till the end of HFI: Details in 16 monthly reports to MOC, 13 bi-monthly to PSO (150 p. each), 138 « operation » teleconf. minutes, 169 weekly reports to MOC, 91 « cryo » teleconf., 8 coordination meetings, 978 daily quality reports & 127 HFI weekly health reports (97 800 plots), 1278 pages wiki écrites ou co-écrites …:
- *Expectations on sensitivities confirmed in flight: HFI reaches or exceeds its goals.*
- June 2010 : first complete coverage of the sky by all detectors obtained with the first nearly 10 months of survey data. ERCSC release & batch of 25 papers on "Planck early results" submitted **in Jan 2011**;
- November 27th 2010 : Nominal mission completed, having collected about 15.5 months of survey data insuring that all the sky at been seen at least twice by each detector:
  - *12 "Planck Intermediate results" papers on CMB foregrounds results submitted **in 2012**.*
  - *public data delivery on **March 21st 2013**, together with 28 "Planck 2013 results" papers*
- **Jan 14th 2012:** all HFI survey data acquired! 885 days of survey, 900 billion samples, 5 surveys, twice the nominal duration. With some additional LFI data (~3 months) will be the basis of our next data delivery (DD2) in **mid-2014.** (including polarization)

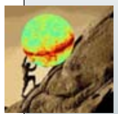
When I say very stable…



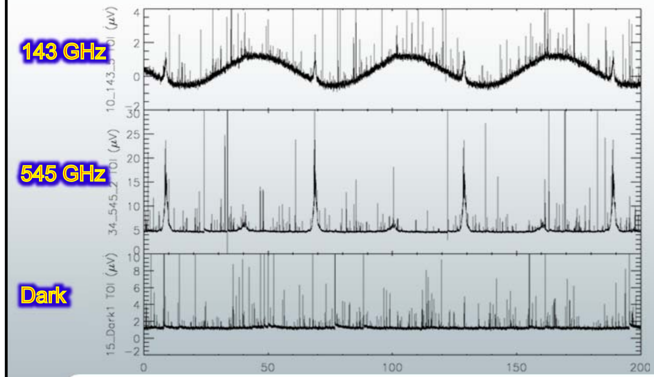
HFI Data Processing Centre flow


IAP cellar




Sisyphus

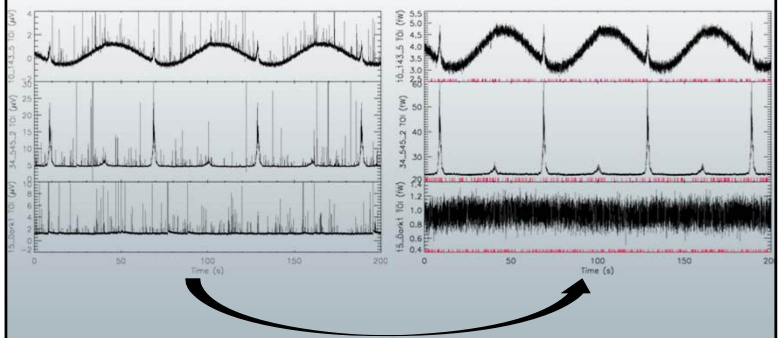
HFI Raw Detector TOI (Time Ordered Information)



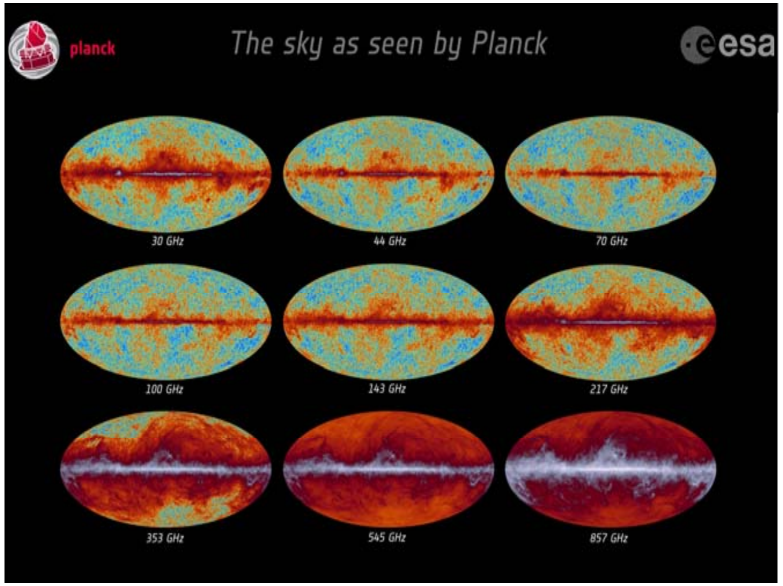
3 minutes of quasi 'raw" data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky signal, but displays a similar population of glitches from cosmic rays.

One surprise (of very few)

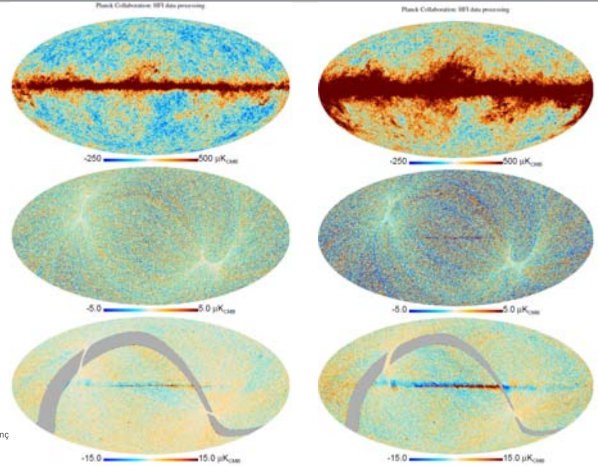
Many more glitches than anticipated. Need to update the pre-flight processing pipeline (Deglitching, T decorrelation, nonlinearity corrections, 4Klines, TF deconvolution, RTS)



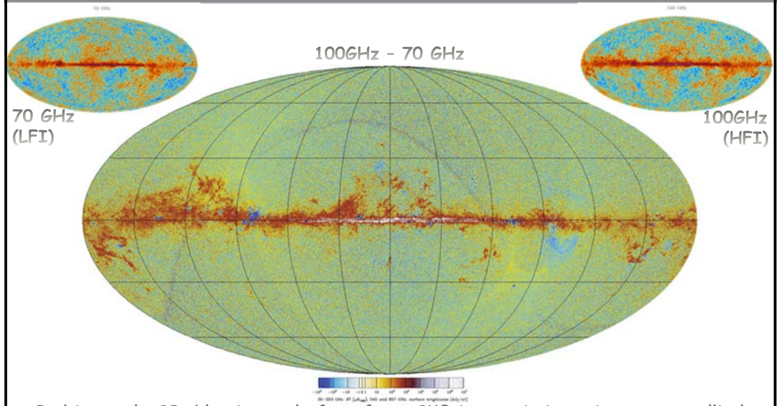
From µV to femto-Watts



143 GHz & 217 GHz maps

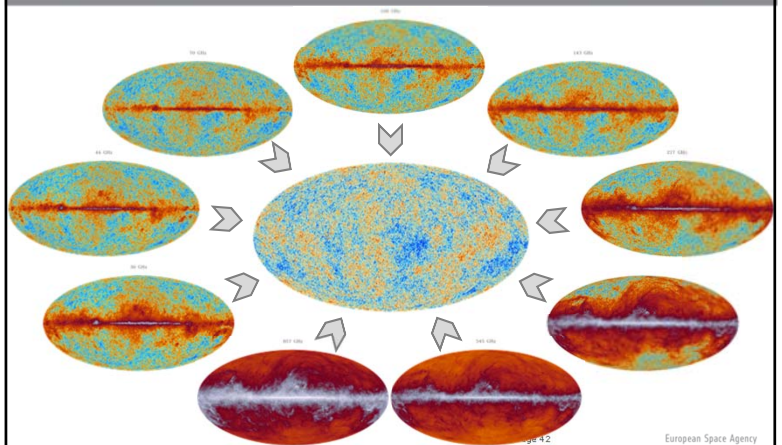


LFI-HFI consistency



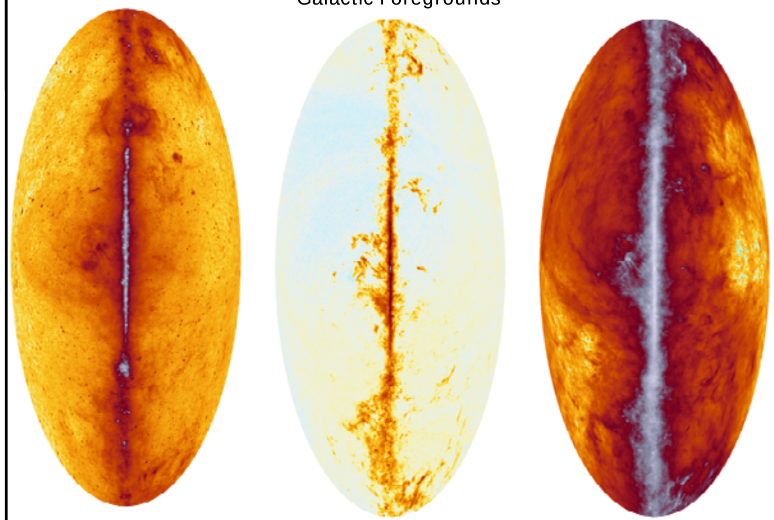
Red is mostly CO, blue is mostly free-free. CMB is gone in inter-instrument nulling!

Cleaning the background from its 7 veils



3% of the CMB sky replaced by a Gaussian Random realisation

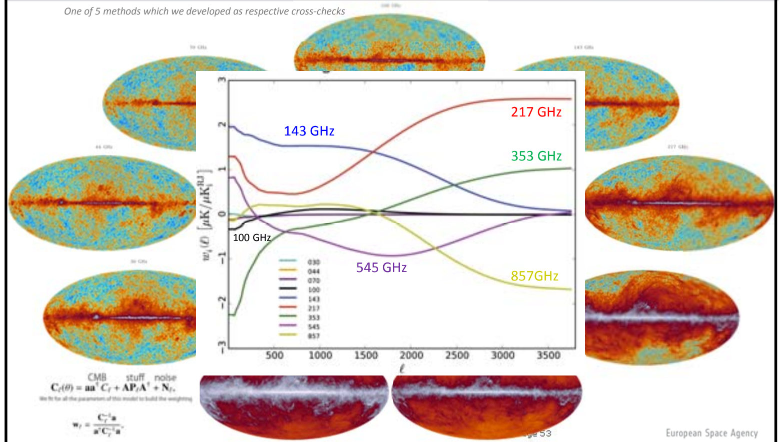
Galactic Foregrounds



Low frequency emission CO "discovery" map Dust emission amplitu

Cleaning the background with an l-dependent linear combination

One of 5 methods which we developed as respective cross-checks



CMB stuff noise

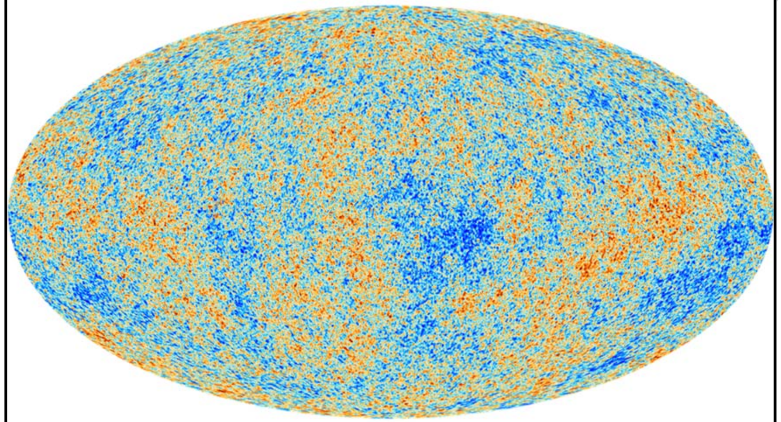
$$C_\ell(\theta) = \mathbf{a}\mathbf{a}^\dagger C_\ell + \mathbf{A}\mathbf{P}_\ell\mathbf{A}^\dagger + \mathbf{N}_\ell,$$

We fit for all the parameters of this model to build the weighting

$$\mathbf{w}_\ell = \frac{\mathbf{C}_\ell^{-1}\mathbf{a}}{\mathbf{a}^\dagger\mathbf{C}_\ell^{-1}\mathbf{a}},$$

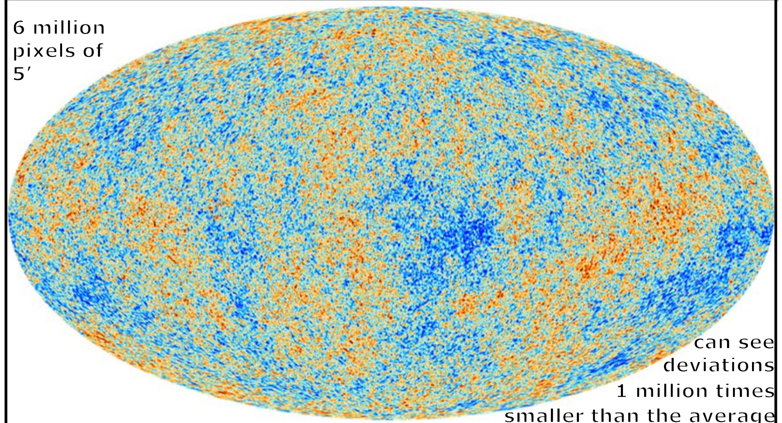
3% of the CMB sky replaced by a Gaussian Random realisation

The cosmic microwave background Temperature anisotropies



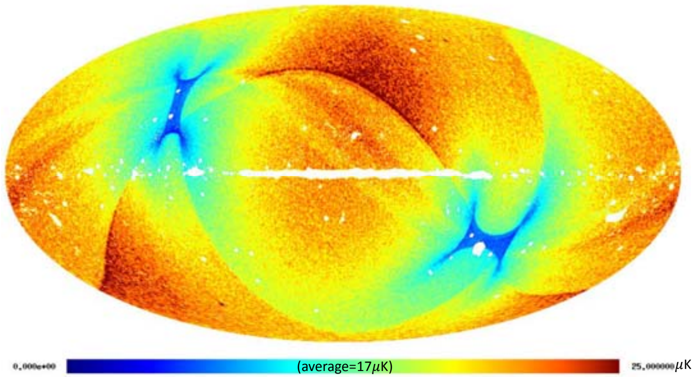
The cosmic microwave background Temperature anisotropies

6 million pixels of 5′



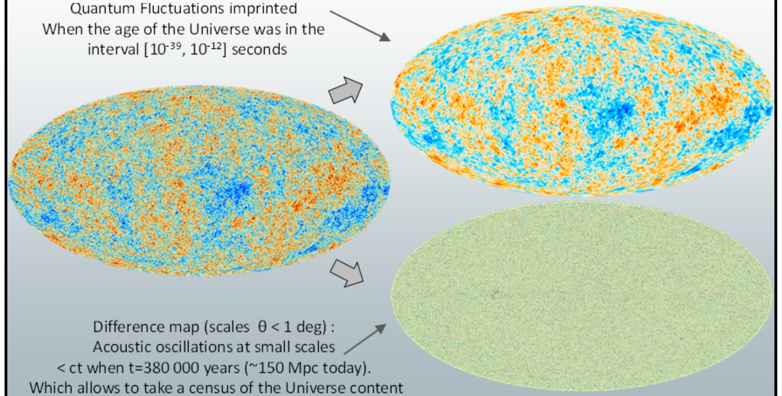
can see deviations 1 million times smaller than the average

Noise distribution

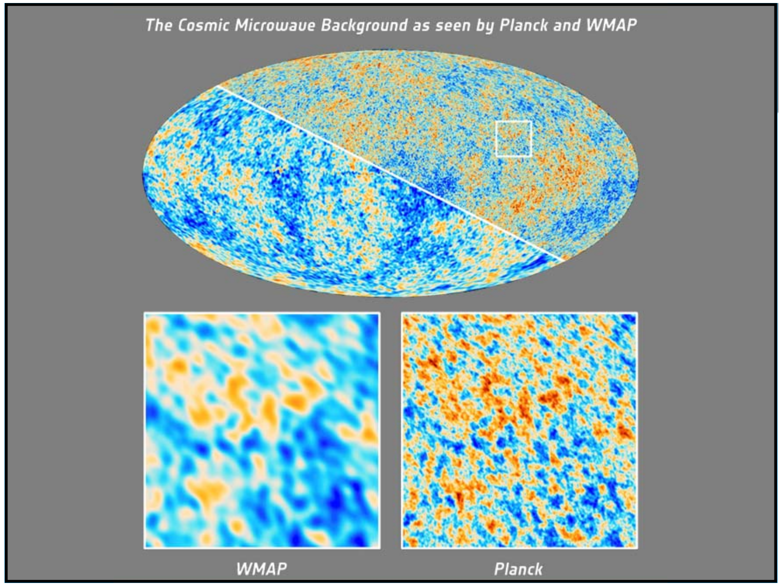


Our window

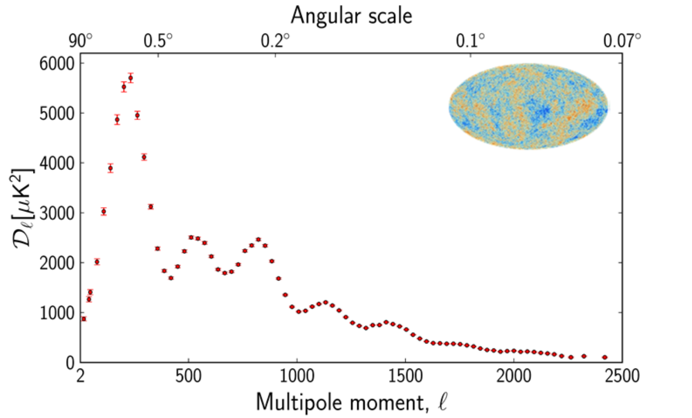
Smoothed map (suppressing scales θ < 1 deg) :
Quantum Fluctuations imprinted
When the age of the Universe was in the interval [10^{-39}, 10^{-12}] seconds



Difference map (scales θ < 1 deg) :
Acoustic oscillations at small scales
< ct when t=380 000 years (~150 Mpc today).
Which allows to take a census of the Universe content



The Planck spectrum of Temperature anisotropies



The straight pixel based approach

$\mathbf{m} = \mathbf{s} + \mathbf{n}$. m is the deduced CMB map, s it the true CMB map, and n the noise

Gaussian approximation for the s and n:

$$\mathcal{L}(C_\ell) = P(\mathbf{m}|C_\ell) = \frac{1}{2\pi^{n/2}|\mathbf{M}|^{1/2}} \exp\left(-\frac{1}{2}\mathbf{m}^t \mathbf{M}^{-1}\mathbf{m}\right)$$

Where, the data covariance matrix is an N X N matrix, for a map with N pixel. And

$\mathbf{M}(C_\ell) = \mathbf{C}(C_\ell) + \mathbf{N}$ The noise Cov mat. N is supposed given by the exp.

And the CMB covariance matrix in pixel space is

$$\langle T_{i_1} T_{i_2} \rangle = \sum_{\ell=2}^{\ell_{max}} \frac{2\ell+1}{4\pi} \hat{C}_\ell P_\ell(\theta_{i_1 i_2}) + \mathbf{N}_{i_1 i_2} \quad \hat{C}_\ell = C_\ell^{th} b_\ell^2 w_\ell^2$$

Where b stands for the beam and w for the pixel window function.
➔ Trivial (under these assumptions)

BUT… computing this Cl likelihood requires O(N^3) operation

➔ Can only be done at $\ell \lesssim 30$

Note on Gibbs sampling & Cramer-Rao

$\mathbf{d}_\nu = \mathbf{s} + \sum_i \mathbf{f}^i_\nu + \mathbf{n}_\nu$ generalises the sky model to include I foregrounds and n maps

Let's map out the posterior distribution $P(\mathbf{s}, \mathbf{f}^i, C_\ell | \mathbf{d})$ by Gibbs sampling:

$\mathbf{s} \leftarrow P(\mathbf{s}|\mathbf{f}, C_\ell, \mathbf{d})$ A multivariate Gaussian conditional distribution

$\mathbf{f} \leftarrow P(\mathbf{f}|\mathbf{s}, C_\ell, \mathbf{d})$ This conditional can be obtained numerically

$C_\ell \leftarrow P(C_\ell|\mathbf{s}, \mathbf{f}^i, \mathbf{d})$ Inverse gamma distribution

which generates realisation, s_k. of the CMB sky, for each of which we can compute

$$\mathcal{L}^k(C_\ell) \propto \frac{\sigma_{\ell,k}^{\frac{2\ell-1}{2}}}{C_\ell^{\frac{2\ell+1}{2}}} e^{-\frac{2\ell+1}{2}\frac{\sigma_{\ell,k}}{C_\ell}} \quad \text{with} \quad \sigma_{\ell,k} \equiv \frac{1}{2\ell+1} \sum_{\ell=-m}^{m} |a^k_{\ell m}|^2$$

Any one gives the likelihood in the absence of noise, FG, and sky mask.
Which are accounted for by the Blackwell-Rao estimate:

$\mathcal{L}(C_\ell) \propto \sum_{k=1}^{N_{\rm samp}} \mathcal{L}^k(C_\ell)$ *, which can be implemented as likelihood till l ~60…*

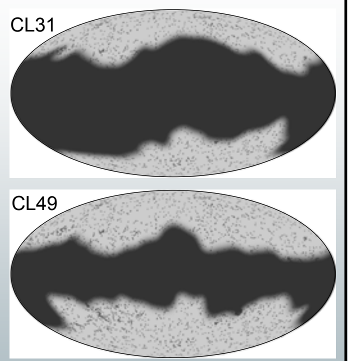
Likelihood Methodology

- Need to provide P(C$^{\rm theory}$(l) | Planck data)
- Hybrid multi-frequency likelihood approach
  - *Large scales (LL): Gaussian likelihood on maps*
  - *Small scales (HL): Gaussian likelihood approx. on spectra*
- Foregrounds:
  - *LL: Parametrised at the map level, Gibbs marginalisation*
  - *HL: Parametrised at the spectral level*
- Validation:
  - *Data selection & technical choices*
  - *Null tests*
  - *Simulations*
  - *Foreground cleaned CMB maps, LFI 70 GHz (HL)*

Planck HL: conservative data selection

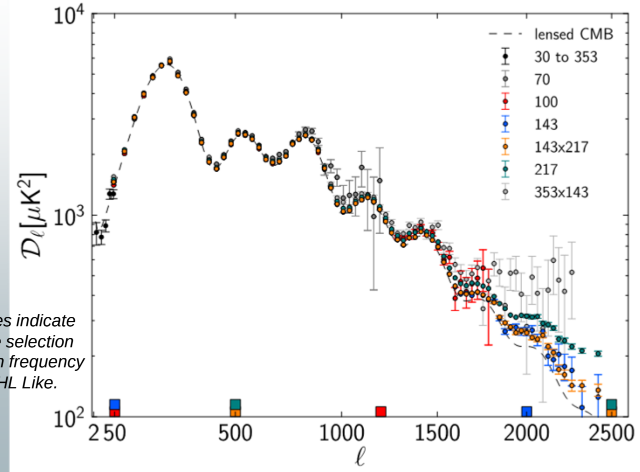
- Minimise foreground impact
  - *Spatially*
  - *In multipole space*
  - *Keeping low cosmic variance*
- Galaxy: 353 GHz thresholding
- Sources: 100-353 GHz catalog
- Maps: keep the easiest to model & most informative ones

Spectrum	Multipole range	Mask
100 × 100	50 – 1200	CL49
143 × 143	50 – 2000	CL31
143 × 217	500 – 2500	CL31
217 × 217	500 – 2500	CL31
Combined	50 – 2500	CL31/49



Galactic and sources apodised masks

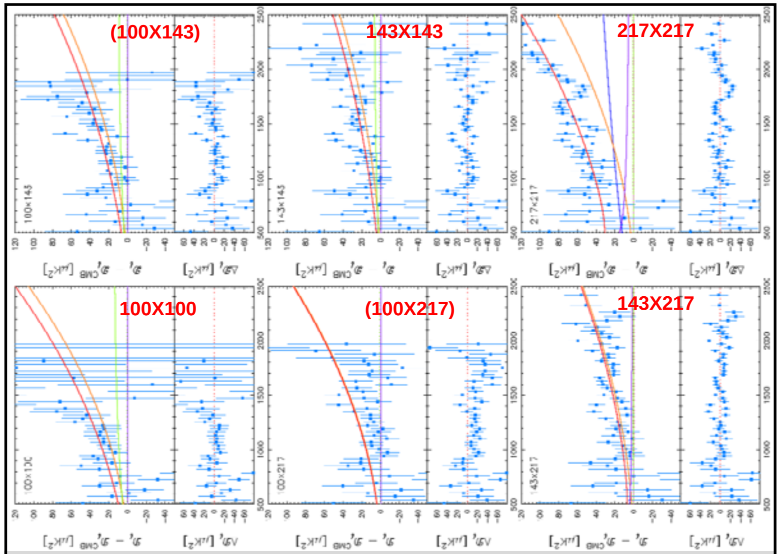
Planck angular power spectra



Squares indicate l-range selection at each frequency of the HL Like.

Spectral Foregrounds modeling

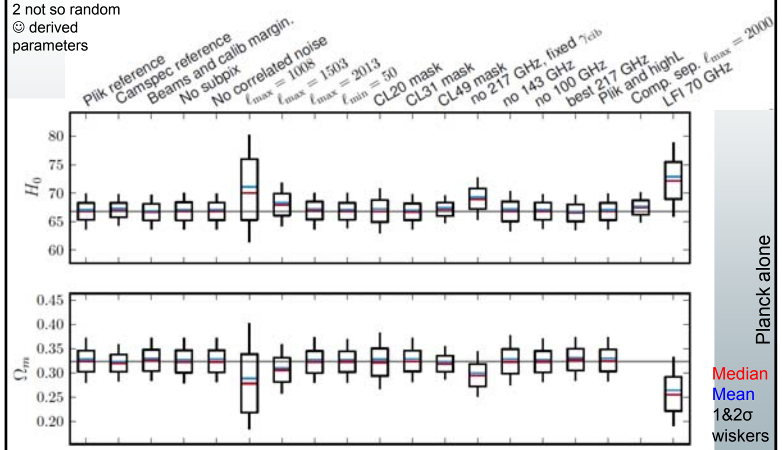
- Even after selection of *frequencies*, of cleanest *regions* through masking and tailoring *l-ranges*, residuals need to be modeled and part of error budget
- We include PS templates for
  - *Poisson Point sources (arbitrary level per frequency, A_υ^{PS})*
  - *Clustered Infrared sources (CIB) ($A_\upsilon^{CIB}\ l^\gamma$, $r_{\upsilon\upsilon'}^{CIB}$)*
  - *SZ clusters (A^{tSZ}, A^{kSZ} *ksz-l-template)*
  - *tSZ X CIB correlation ($\xi^{tSZ\ X\ cib}$)*
  - *(Dust residual in some configurations – PLIK)*
- And we include calibration and (correlated) beam uncertainties



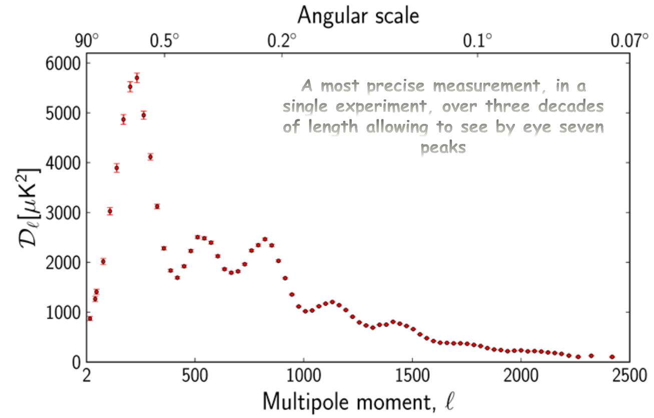
ML fit to Foreground contaminants (for these masks); model / compatible w. ACT & SPT

Verification and robustness tests

2 not so random
☺ derived
parameters

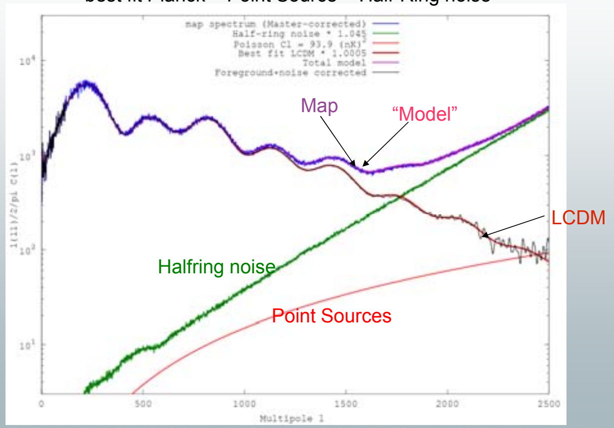


The Planck spectrum of Temperature anisotropies

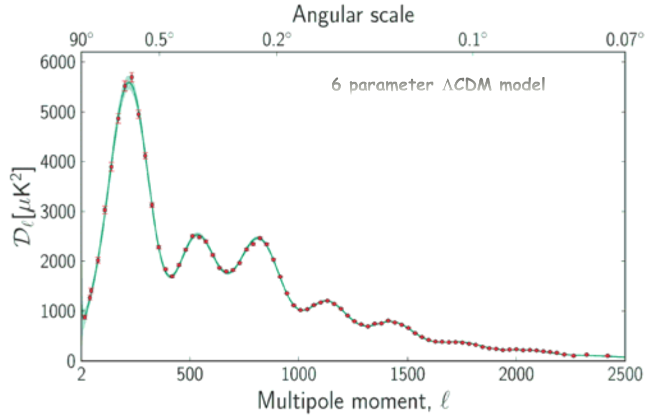


Checking consistency of the CMB PS/map

Over 89% of the sky, explain the map spectrum with:
best fit Planck + Point Source + Half-Ring noise



Theory confronts data



Base ΛCDM model 6 parameters

Planck alone

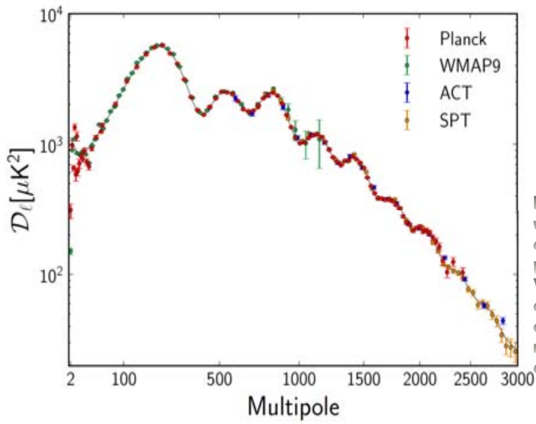
	Planck (CMB+lensing)	
Parameter	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

The sound horizon, θ, determined by the positions of the peaks (7), is now determined with 0.07% precision
(links together $\Omega_b h^2$, $\Omega_c h^2$, H_0 - here as $\Omega_m h^3$)

Exact scale invariance of the primordial fluctuations is ruled out, *at ~4σ*
(as predicted by base inflation models)

$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724° \pm 0.00038°$

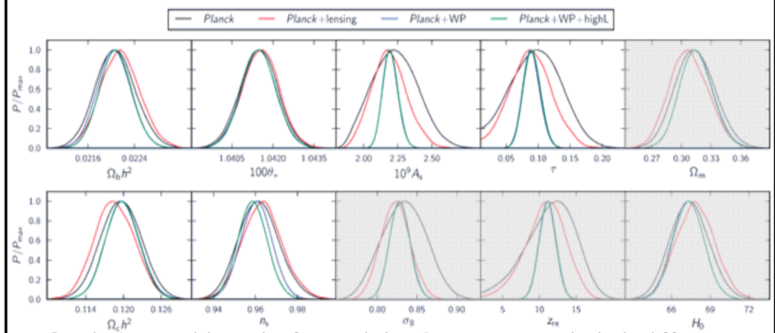
The 2013 CMB temperature landscape



NB: on-going work for consistency paper (incl. WMAP ~2.5% difference over large l-range to be explained

Base tilted ΛCDM model - 6 parameters

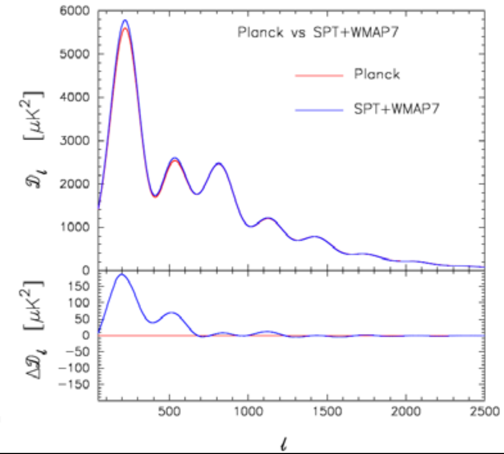
esa



For the base model, results from High-l CMB experiments make little difference
High-l CMB experiments = ACT + SPT (600 & 2540 deg², 2 & 3 freq.)

Planck vs pre-Planck

esa

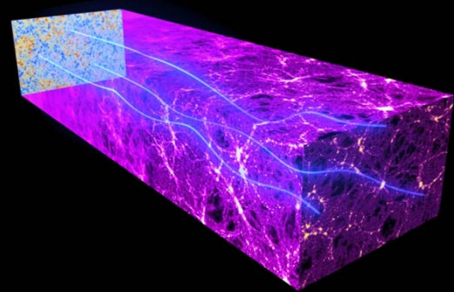


Conparisons with other "observables"

GRAVITATIONAL LENSING DISTORTS IMAGES

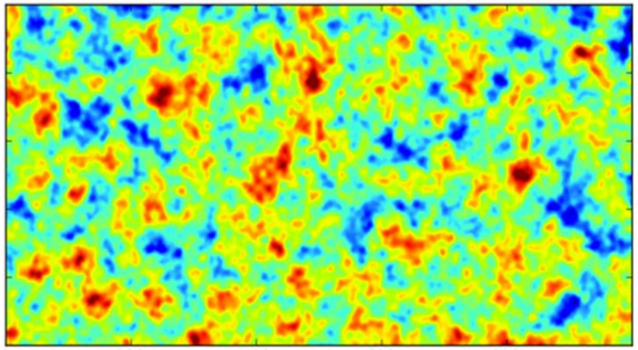
esa

The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB



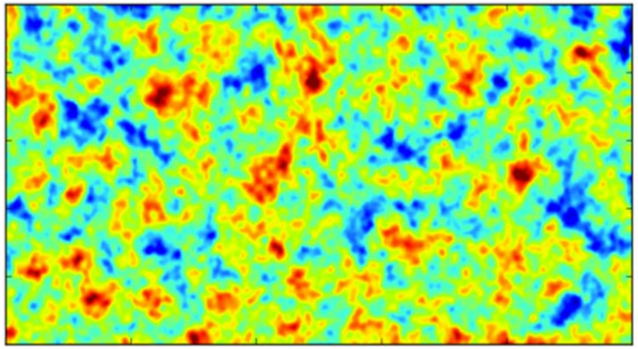
GRAVITATIONAL LENSING OF THE CMB

A simulated patch of CMB sky – **before lensing**



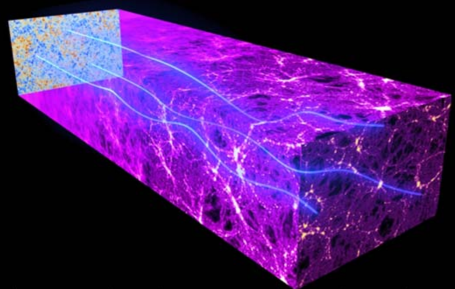
GRAVITATIONAL LENSING OF THE CMB

A simulated patch of CMB sky – **after lensing**



GRAVITATIONAL LENSING DISTORTS IMAGES

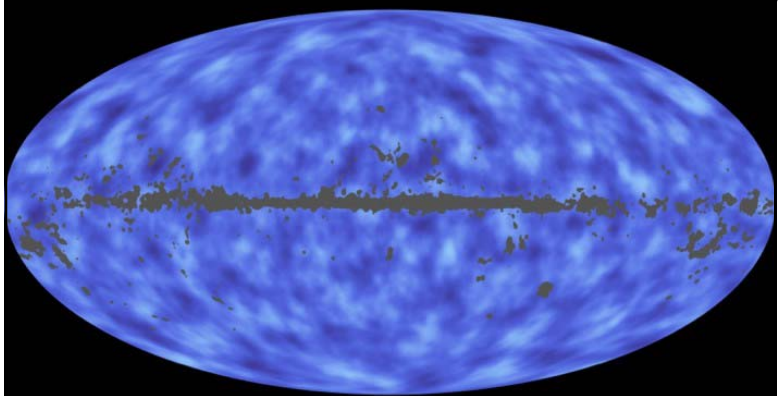
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



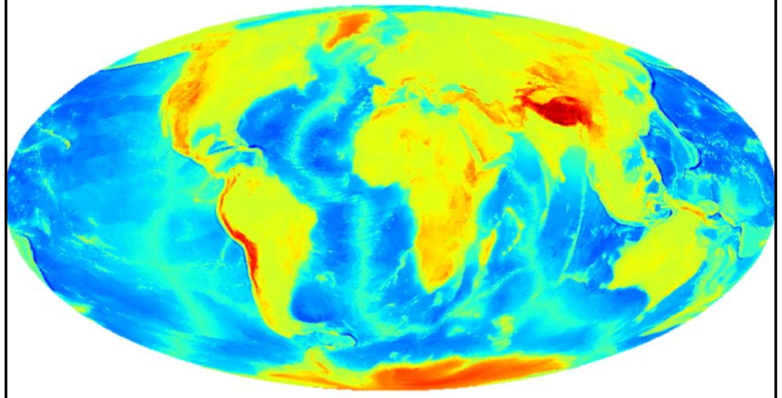
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$

$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\, \vec{\nabla}(C^{-1}T)]$$

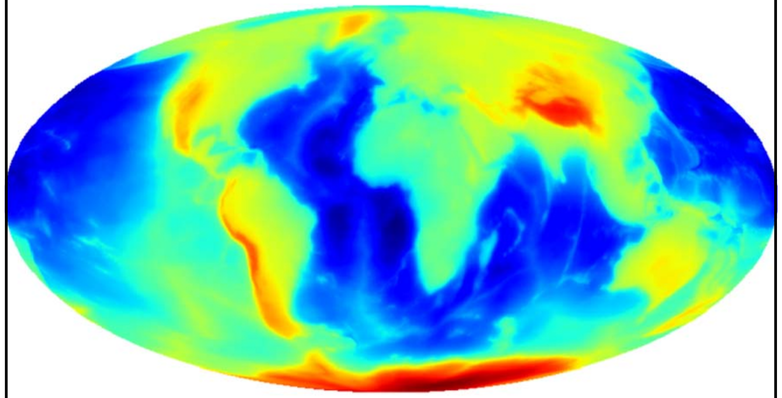
Projected mass map



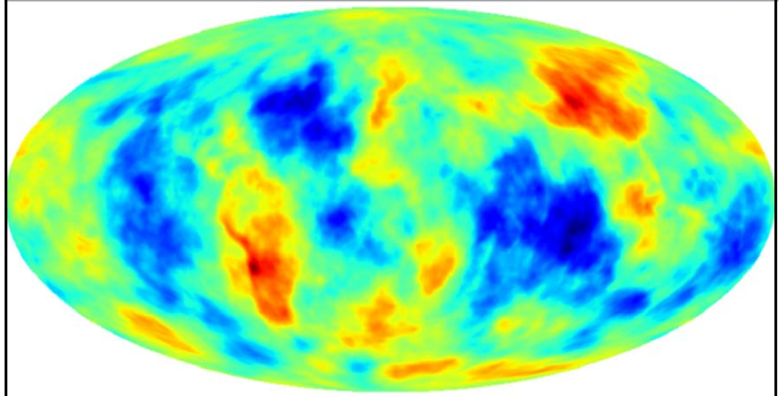
Another full sphere distribution



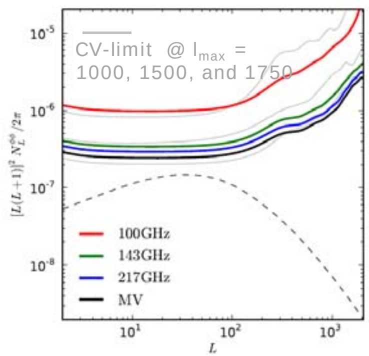
at our angular resolution...



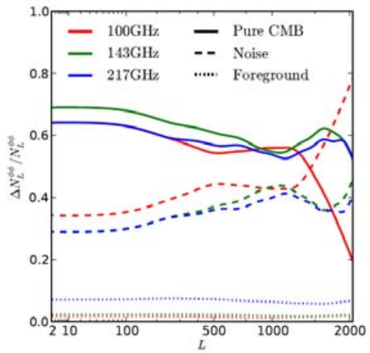
and noise level!



The lensing challenge

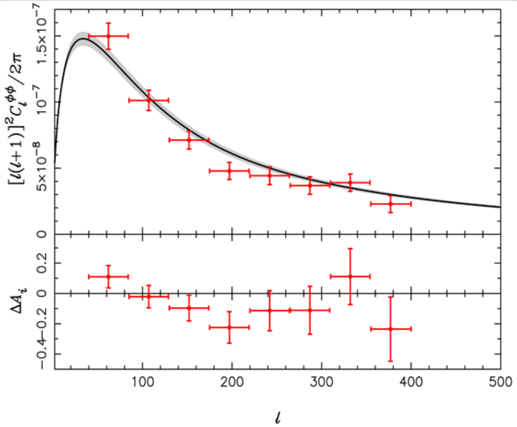


Sky-averaged lens reconstruction noise levels



Relative contributions of CMB, instrumental noise, and foreground power terms to the lens reconstruction variance

The lensing potential spectrum

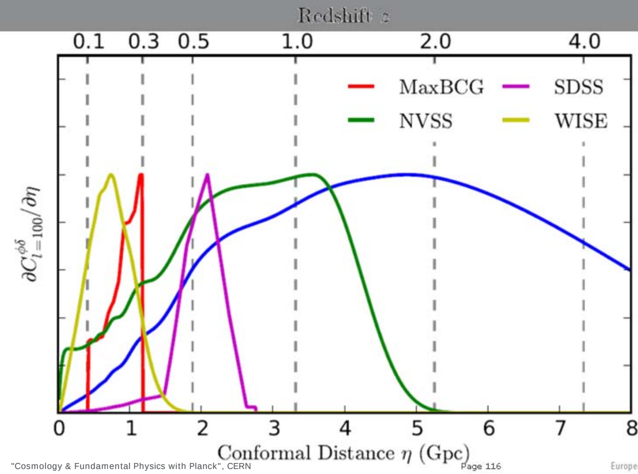


(26σ detection)

➔ Agrees well with the prediction from T alone

François R. Bouchet, "Planck main cosmological results", 17/06/2013 Page 111 European Space Agency

Redshift distribution

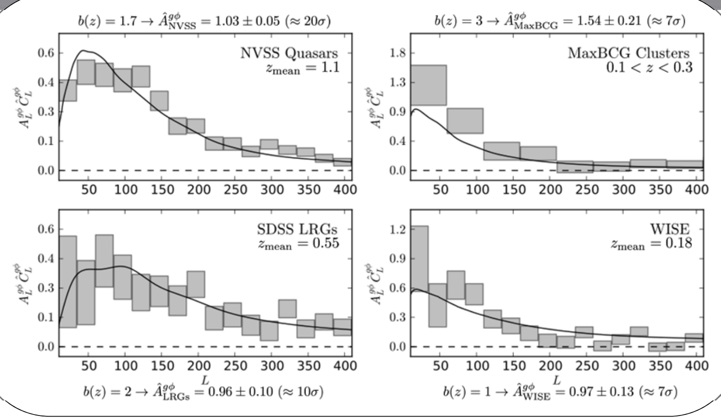


"Cosmology & Fundamental Physics with Planck", CERN Page 116 European Space Agency

François R. Bouchet, "Planck main cosmological results", 17/06/2013

116

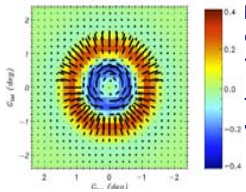
Lensing potential versus distribution of external tracers



"Cosmology & Fundamental Physics with Planck", CERN / François R. Bouchet, "Planck main cosmological results", 17/06/2013 Page 117 European Space Agency

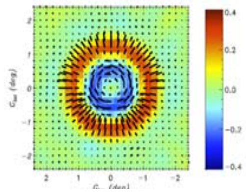
117

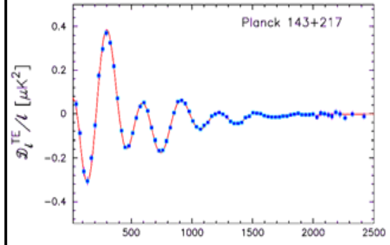
Polarisation around hot spots

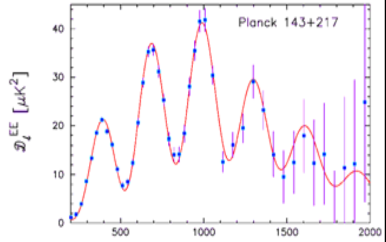


Planck "sees" precisely the dynamics of fluctuations, at ~380 000 years:

T-based expectation (left) versus Planck data (right)

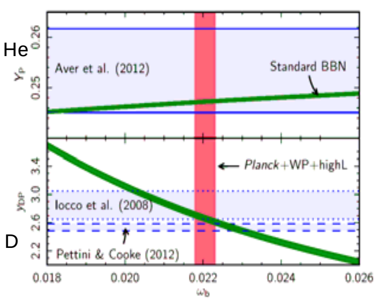




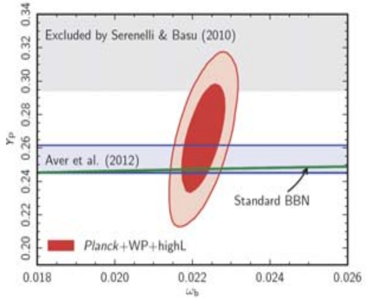


Red is prediction in base model from fitting T alone

Primordial nucleosynthesis

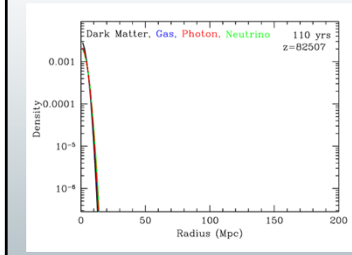


Y_P as a *derived* quantity:
$Y_p = 0.2477 \pm 0.0001$

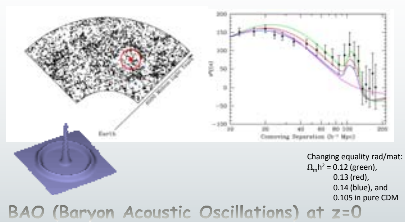


Y_P as an extra parameter

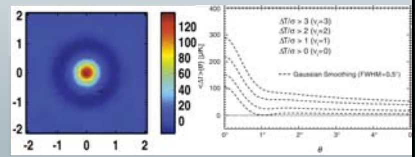
Echos of the primordial drum…



Watch baryon/Photon at z ~1100 decoupling

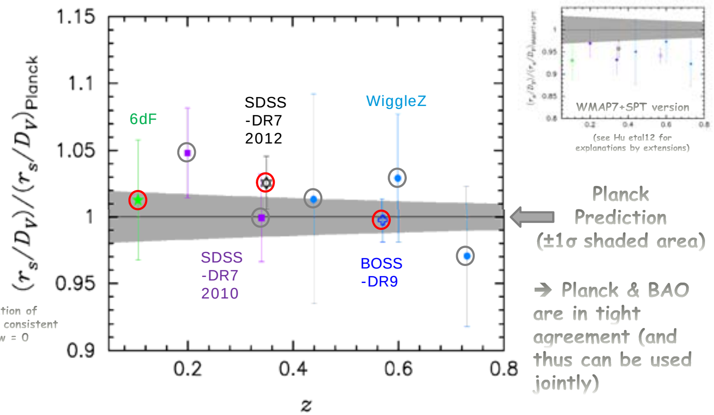


BAO (Baryon Acoustic Oscillations) at z=0



BAO (Baryon Acoustic Oscillations) at z=1100

BAO acoustic-scale distance ratio



DE equation of state is consistent with 1+w = 0

Planck Prediction (±1σ shaded area)

→ Planck & BAO are in tight agreement (and thus can be used jointly)

Base ΛCDM model 6 parameters

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025

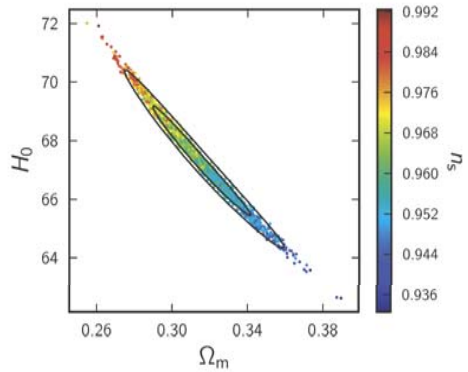
The sound horizon, θ, determined by the positions of the peaks (7), is now determined with 0.05% precision
(links together $\Omega_b h^2$, $\Omega_c h^2$, H_0 - here as $\Omega_m h^3$)

Exact scale invariance of the primordial fluctuations is ruled out, *at more than 7σ*

(as predicted by base inflation models)

$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724° \pm 0.00038°$

Sound Horizon



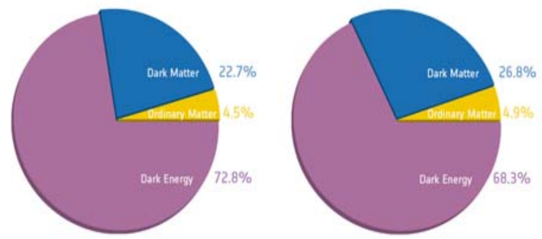
Samples are for Planck only.

Tighter contours along the degeneracy direction are from Planck +lensing+WP

r_s is constrained transversally

r_s constrains $\Omega_m h^3$ very well in LCDM

The basic content of the Universe



Before Planck After Planck

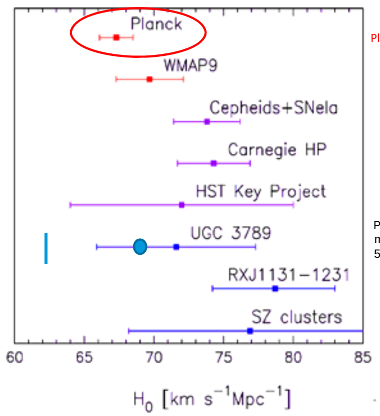
...has changed!

The rate of expansion

Riess et al. (2011)

Freedman et al. (2012),

Freedman et al. (2001)

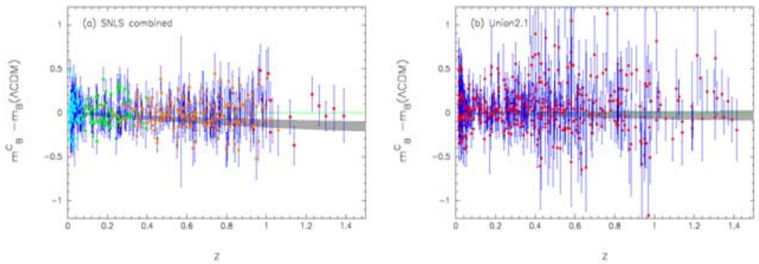


Planck H_0 is 67.95 ± 1.5 km/s/Mpc

Pap IV replacement on water maser UGC 3789: it is now at ~ 50 Mpc: H_0=68.9±7.1km/s/Mpc

... has changed also

Tension with SNLS result...



Data, BF model and Planck Prediction (±1σ shaded area)

Fig. 18. Magnitude residuals relative to the base ΛCDM model that best fits the SNLS combined sample (left) and the Union2.1 sample (right). The error bars show the 1σ (diagonal) errors on m_B. The filled grey regions show the residuals between the expected magnitudes and the best-fit to the SNe sample as Ω_m varies across the ±2σ range allowed by *Planck*+WP+highL in the base ΛCDM cosmology. The colour coding of the SNLS samples are as follows: low redshift (blue points); SDSS (green points); SNLS three-year sample (orange points); and *HST* high redshift (red points).

The total matter density

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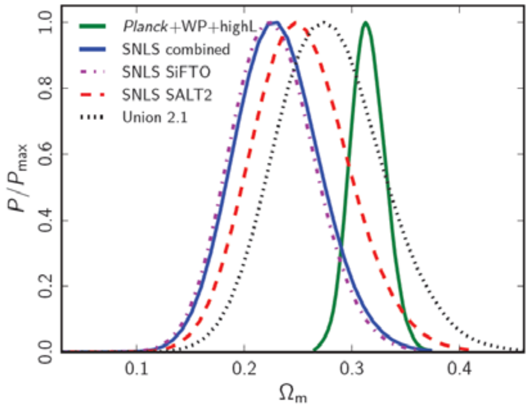
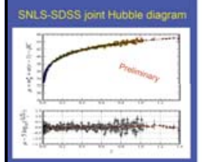
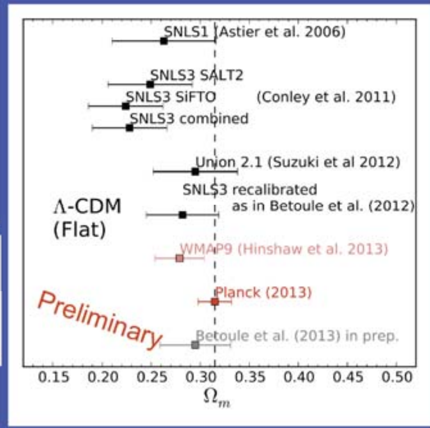


Comparison with Planck results





Apr 3, 2013 ESLAB Planck 30

(R. Pain)

Beyond the standard model

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We tested many extension to the simplest, base, 6 parameters, LCDM model:

- Curved space, Ω_k $(\neq 0\ ?)$
- Dynamical dark energy, w $(\neq -1\ ?)$
- Non-standard abundance of primordial Helium fraction, Y_p $(\neq 0.2477\ ?)$
- Neutrino properties, i.e. how many and how massive (N_{eff}, $\Sigma m_\nu \neq 3.046,\ 0.06$?)
- Curvature of the power spectrum of primordial fluctuations (running $dn_s/d\ln k \neq 0$?)
- Existence of primordial gravitational waves, $r_{0.002}$ $(\neq 0\ ?)$

➔ no compelling evidence for any of them ↓

Parameter	*Planck*+WP Best fit	*Planck*+WP 95% limits	*Planck*+WP+BAO Best fit	*Planck*+WP+BAO 95% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 95% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 95% limits
Ω_K	−0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	−0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
N_{eff}	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
Y_P	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_s/d\ln k$	−0.0090	$-0.013^{+0.018}_{-0.018}$	−0.0102	$-0.013^{+0.018}_{-0.018}$	−0.0106	$-0.015^{+0.017}_{-0.017}$	−0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	−1.20	$-1.49^{+0.65}_{-0.57}$	−1.076	$-1.13^{+0.24}_{-0.25}$	−1.20	$-1.51^{+0.62}_{-0.53}$	−1.109	$-1.13^{+0.23}_{-0.25}$

NB: no compelling evidence either for:

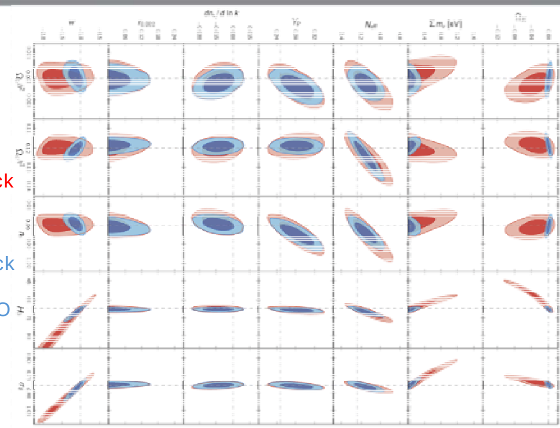
- Existence of an "isocurvature" part in the primordial fluctuations
- Existence of cosmic strings ($G\mu/c^2 < 1.3\ 10^{-7}$)
- Non-Gaussian signatures of non-minimal inflation (**f^{local}=2.7±5.8, f^{equil}=-42±75, f^{ortho}=-25±39 68%CL**)
- Evolution of the fine structure constant, dark matter annihilation, primordial magnetic fields…

Full grid of results available on line

esa

Planck
+WP

Planck
+WP
+BAO

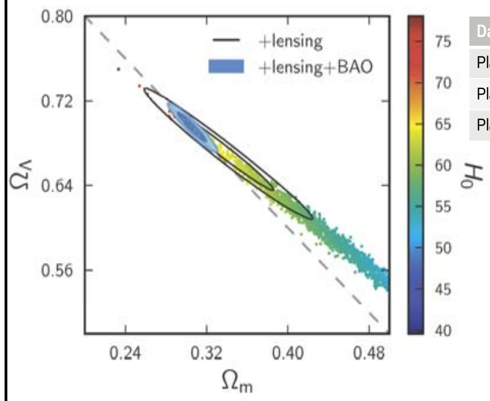


Vertical lines indicates the fixed baseline model parameter value

Horizontal lines shows the mean posterior value in the baseline model

➔ no compelling evidence for deviations from the baseline model

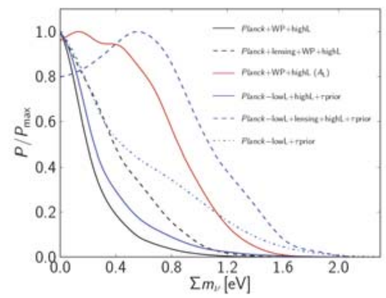
Geometry



Data	100 Ω_K
Planck+WP+HL	-4.2 ± 4.5
Planck+WP+HL+lensing	-0.69 ± 1.0
Planck+WP+HL+lensing+BAO	-0.07 ± 0.33

→ *a precisely* flat spatial geometry

Neutrinos



by l=1000 the lensing potential is suppressed by ~10% in power for Σm_ν=0.66eV.

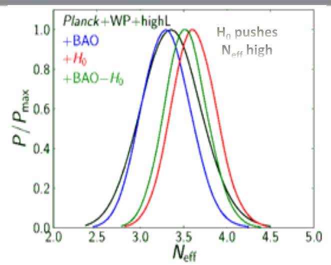
Planck constrains neutrino masses mostly through their effect via lensing: removing that constraint (marginalising over A_l) weakens considerably the limit:
Σm_ν< 0.66eV (95CL PT+WP+HL)
becomes
Σm_ν< 1.08eV (95CL PT+WP+HL)

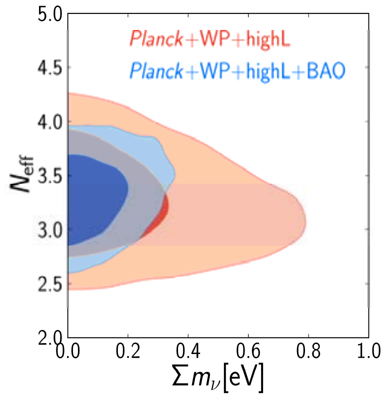
NB: the (4-pt based) lensing likelihood would prefer higher values for Σm_ν (i.e. it weakens the constraints): time will tell

With BAO
Σm_ν < 0.23eV (95CL PT+WP+HL)

Case of 3 active nus of mass $m_\nu=\Sigma m_\nu/3$ > 0.06eV; N_{eff} =3.046 (i.e. no additional ν-like relativistic particles)

Number of neutrinos





→No evidence for additional neutrino-like relativistic particles beyond the three families of neutrinos in the standard model

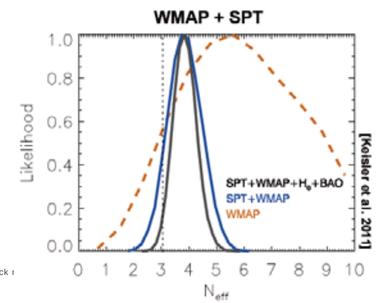
(N_{eff} = 3.3±0.27;Σm_ν<0.23 eV)

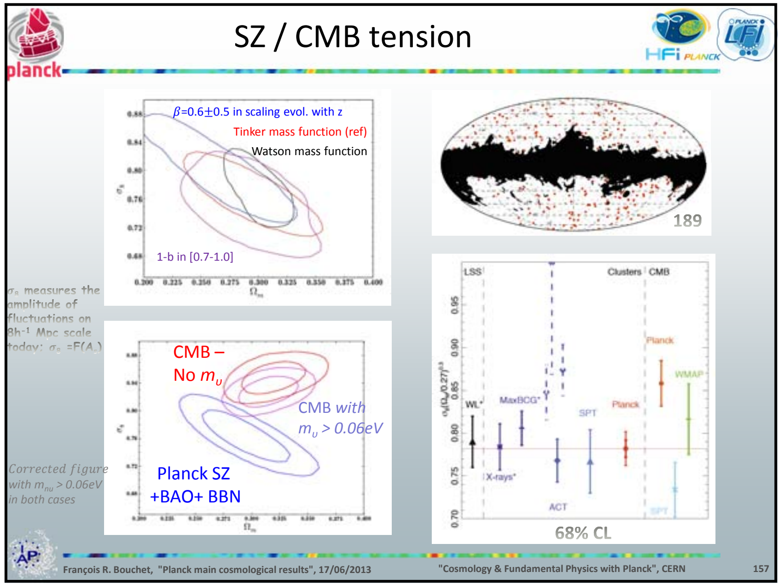
Case of 3 active nus of mass $m_\nu=\Sigma m_\nu/3$; ΔN_{eff} = N_{eff} -3.046 for possible extra massless relics (if >0)

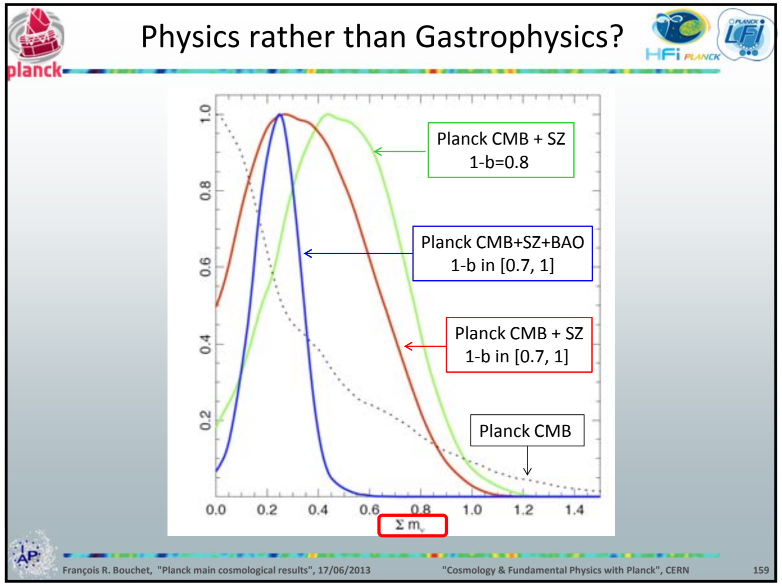
The end of a confusing situation?

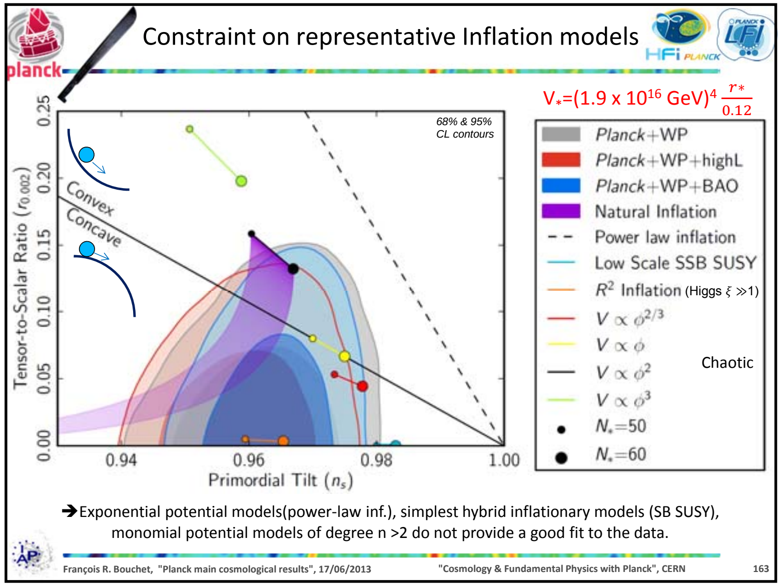
Parameter	*WMAP* 9	+eCMB	+eCMB+BAO	+eCMB+BAO+H_0
Number of relativistic species[b]				
N_{eff}	> 1.7 (95% CL)	3.89 ± 0.67	3.55 ± 0.60	3.84 ± 0.40

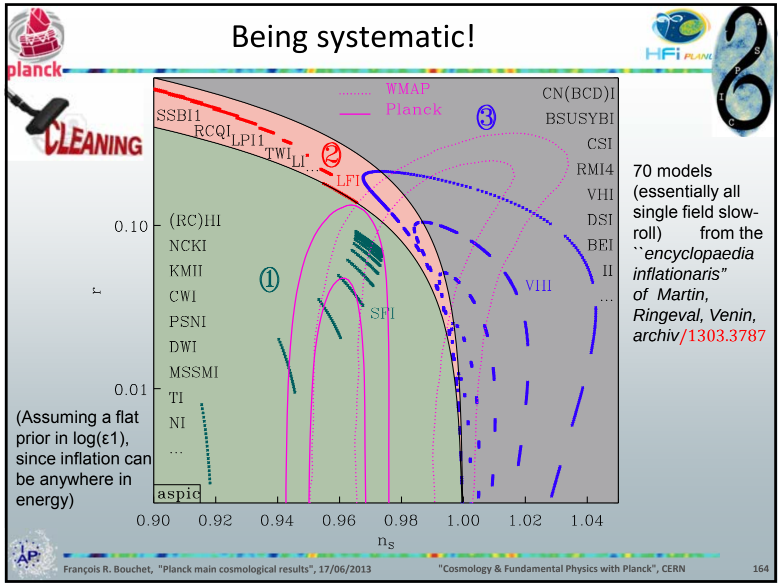
3 neutrinos excluded at more than 2 sigma (W9-Bennett et al. 2013, v2)




SZ / CMB tension
planck
β=0.6±0.5 in scaling evol. with z
Tinker mass function (ref)
Watson mass function
1-b in [0.7-1.0]
σ_8 measures the amplitude of fluctuations on 8h-1 Mpc scale today: σ_8 =F(A_s)
CMB – No m_ν
CMB with m_ν > 0.06eV
Planck SZ +BAO+ BBN
Corrected figure with m_ν > 0.06eV in both cases
189
LSS
Clusters
CMB
WL
MaxBCG
X-rays
SPT
ACT
Planck
WMAP
68% CL
François R. Bouchet, "Planck main cosmological results", 17/06/2013
"Cosmology & Fundamental Physics with Planck", CERN
157


Physics rather than Gastrophysics?
planck
Planck CMB + SZ
1-b=0.8
Planck CMB+SZ+BAO
1-b in [0.7, 1]
Planck CMB + SZ
1-b in [0.7, 1]
Planck CMB
Σm_ν
François R. Bouchet, "Planck main cosmological results", 17/06/2013
"Cosmology & Fundamental Physics with Planck", CERN
159


Constraint on representative Inflation models
planck
$V_*=(1.9 \times 10^{16}\ \mathrm{GeV})^4 \frac{r*}{0.12}$
68% & 95% CL contours
Convex
Concave
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation (Higgs $\xi \gg 1$)
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
N_*=50
N_*=60
Chaotic
➔Exponential potential models(power-law inf.), simplest hybrid inflationary models (SB SUSY), monomial potential models of degree n >2 do not provide a good fit to the data.
François R. Bouchet, "Planck main cosmological results", 17/06/2013
"Cosmology & Fundamental Physics with Planck", CERN
163


Being systematic!
planck
CLEANING
WMAP
Planck
SSBI1
RCQI
LPI1
TWI
LI
LFI
SFI
VHI
(RC)HI
NCKI
KMII
CWI
PSNI
DWI
MSSMI
TI
NI
...
aspic
CN(BCD)I
BSUSYBI
CSI
RMI4
VHI
DSI
BEI
II
...
r
n_s
(Assuming a flat prior in log(ε1), since inflation can be anywhere in energy)
70 models (essentially all single field slow-roll) from the ``encyclopaedia inflationaris" of Martin, Ringeval, Venin, archiv/1303.3787
François R. Bouchet, "Planck main cosmological results", 17/06/2013
"Cosmology & Fundamental Physics with Planck", CERN
164