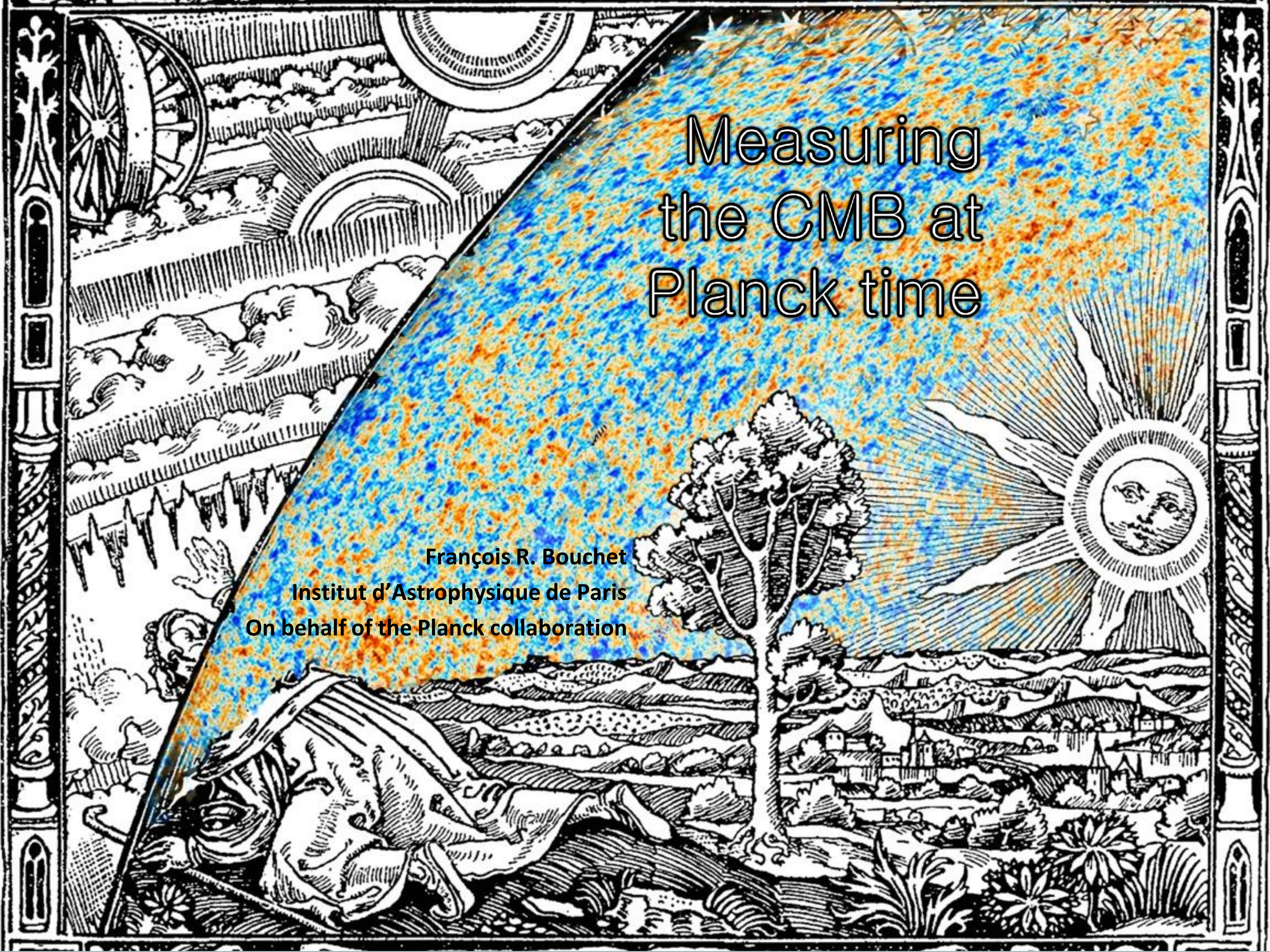
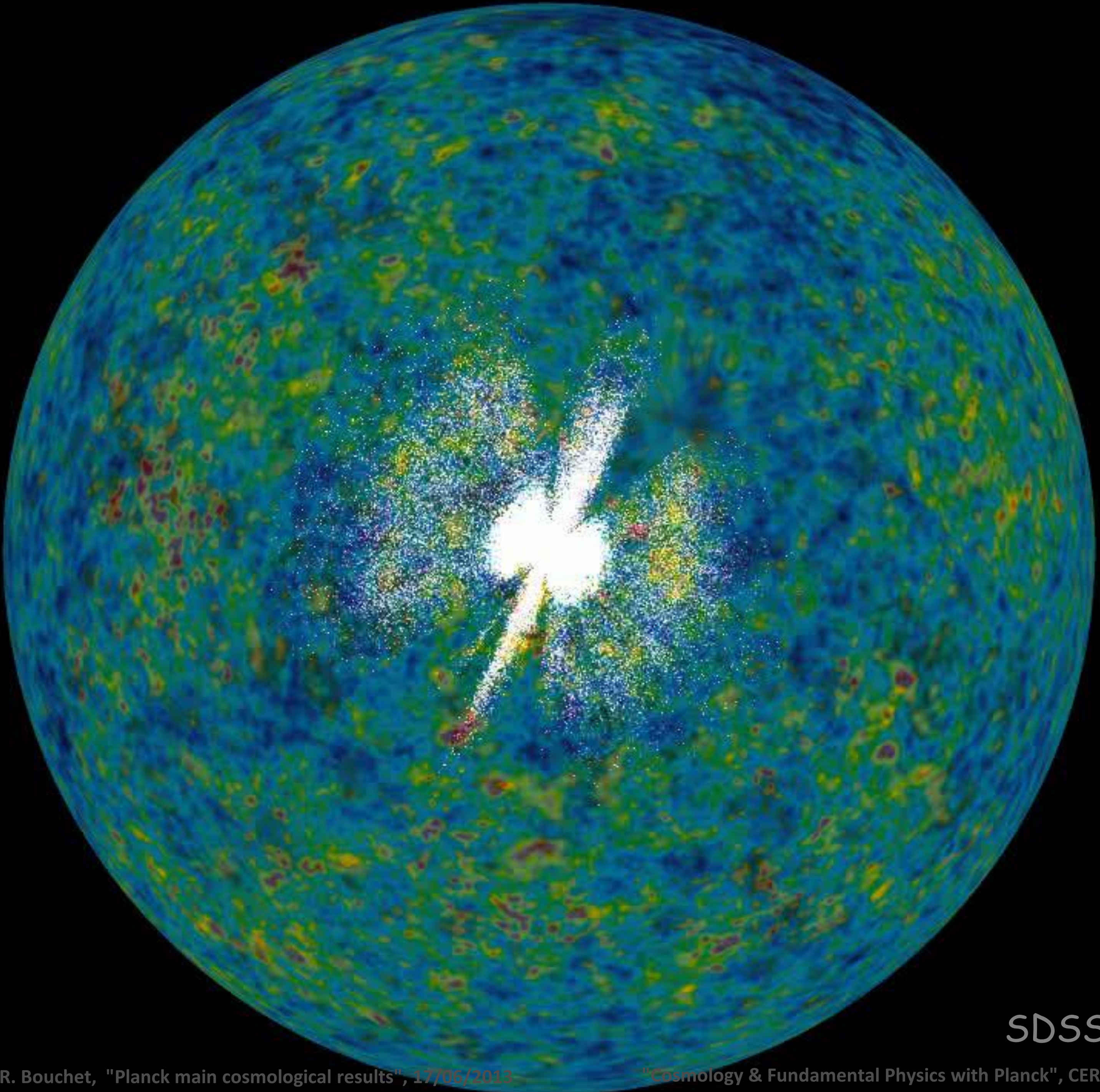


Measuring the CMB at Planck time

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



SDSS & WMAP

DUSTING IT OFF…

AFTER 16 YEARS
OF HOPES & WORK

Planck 2013 data and results

Overview of products & results I
- Frequency Maps
- Component Maps
- Power Spectra
- Parameters

LFI Processing II

HFI Processing VI

LFI Systematics III

LFI Beams IV

LFI Calibration V

HFI Time Response & Beams VII

HFI Calibration VIII

HFI Spectral Response IX

HFI Particle effects X

Consistency of the Data XI

Component Separation XII

Power Spectra & Likelihood XV

Galactic CO XIII

Zodiacal Emission XIV

> 1000 pages

Cosmological Parameters XVI

Lensing by LSS XVII

Lensing by Star-forming Galaxies XVIII

The Integrated Sachs-Wolfe Effect XIX

Cosmology from SZ Counts XX

Compton Parameter Map XXI

Inflation XXII

Isotropy & Statistics XXIII

Primordial Non-Gaussianity XXIV

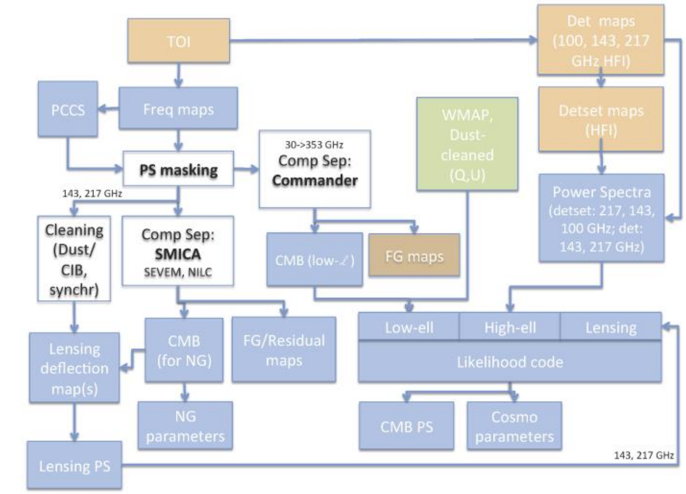
Strings & Other Defects XXV

Background Geometry & Topology XXVI

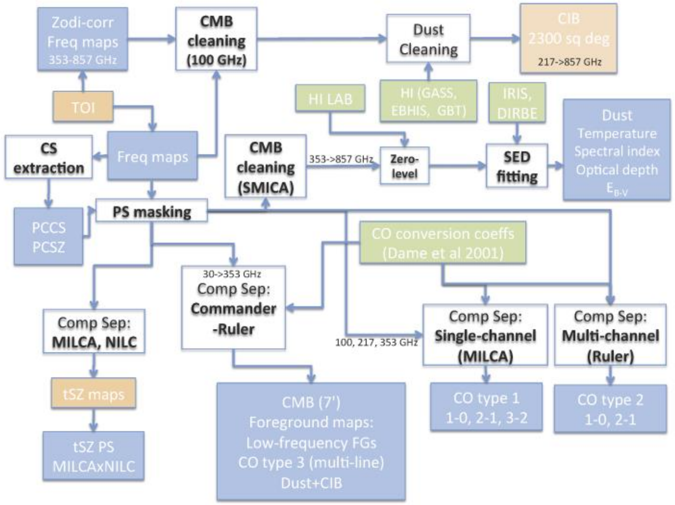
Special Relativistic Effects on the Dipole XXVII

Catalogue of Compact Sources XXVIII

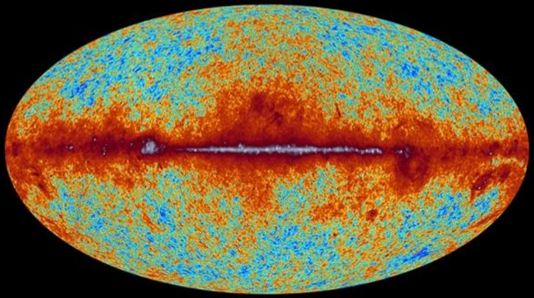
Catalogue of SZ Sources XXIX



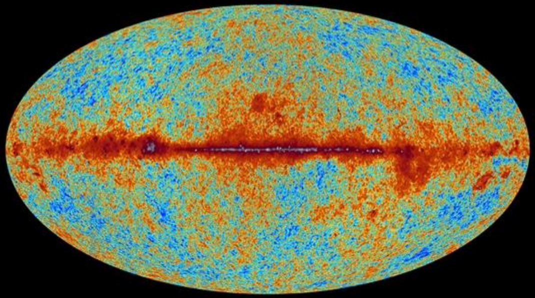
http://www.sciops.esa.int/index.php?page=Planck_Legacy_Archive&project=planck



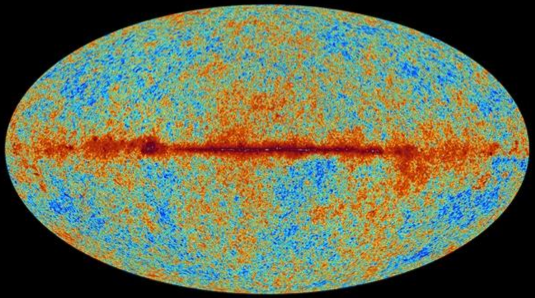
The sky as seen by Planck



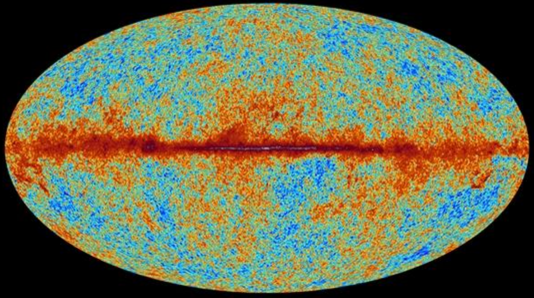
30 GHz



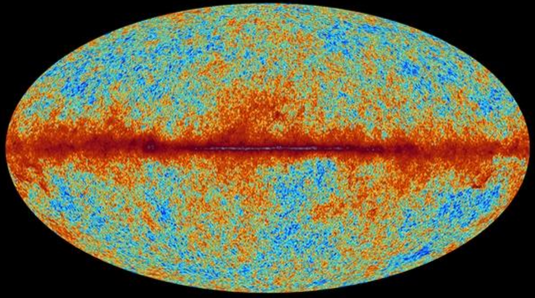
44 GHz



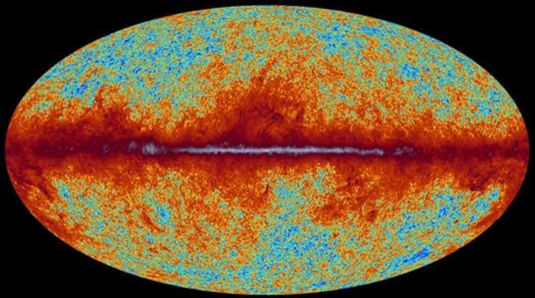
70 GHz



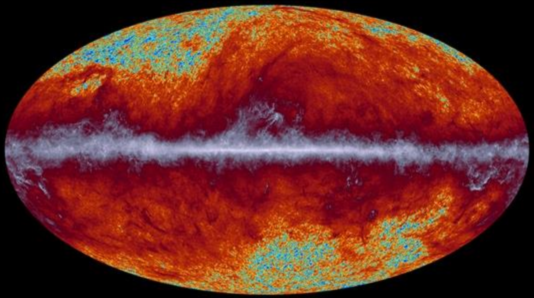
100 GHz



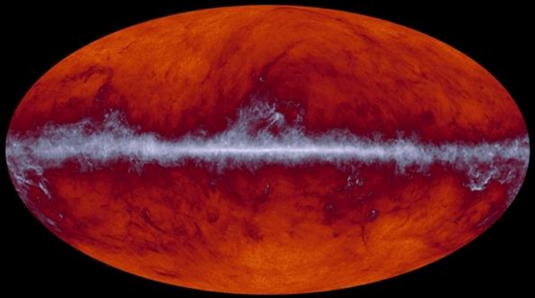
143 GHz



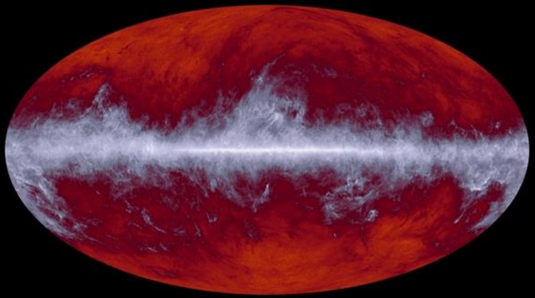
217 GHz



353 GHz



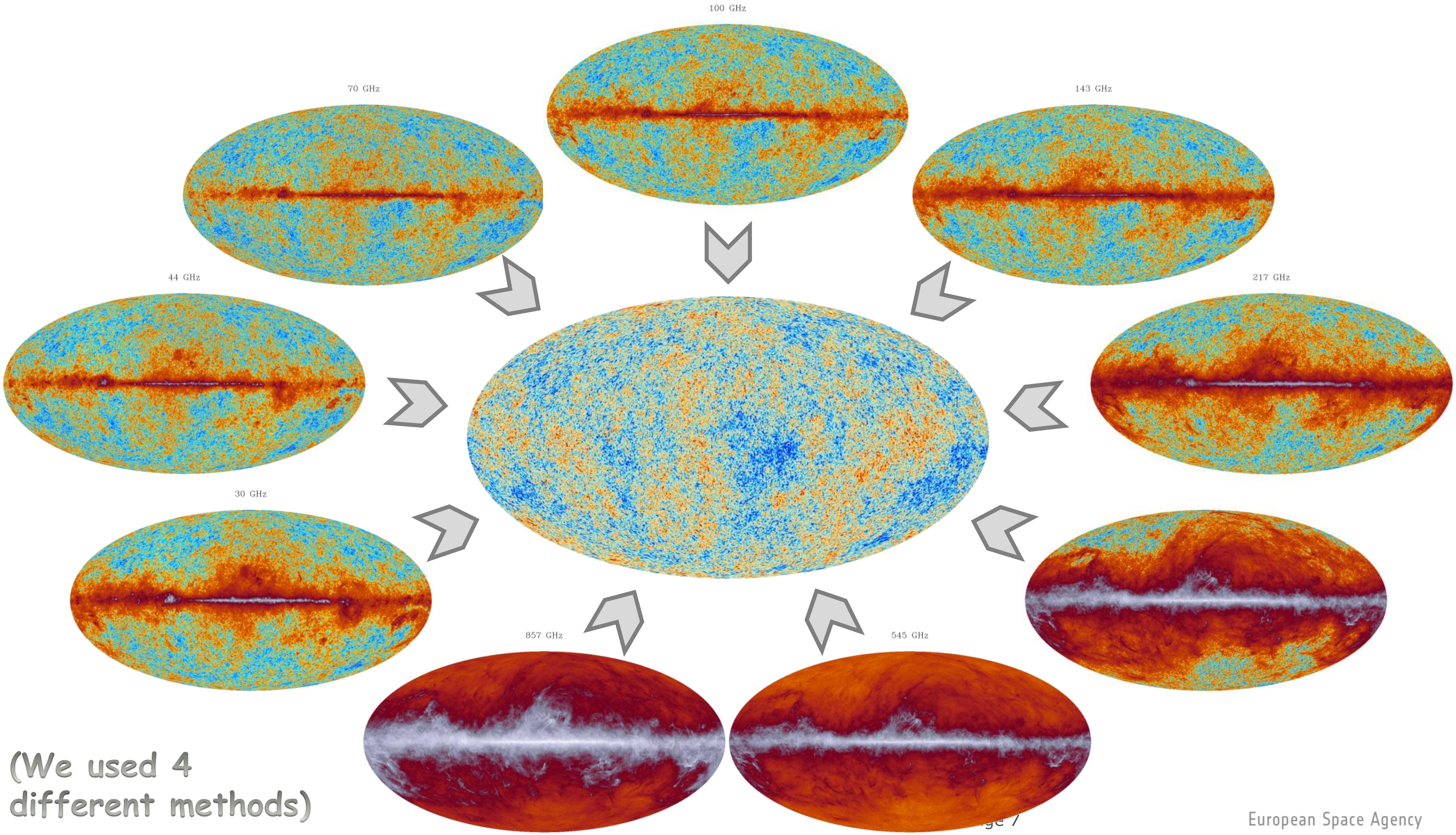
545 GHz



857 GHz

lanck coming out of March 21st 2013

Cleaning the background from its 7 veils

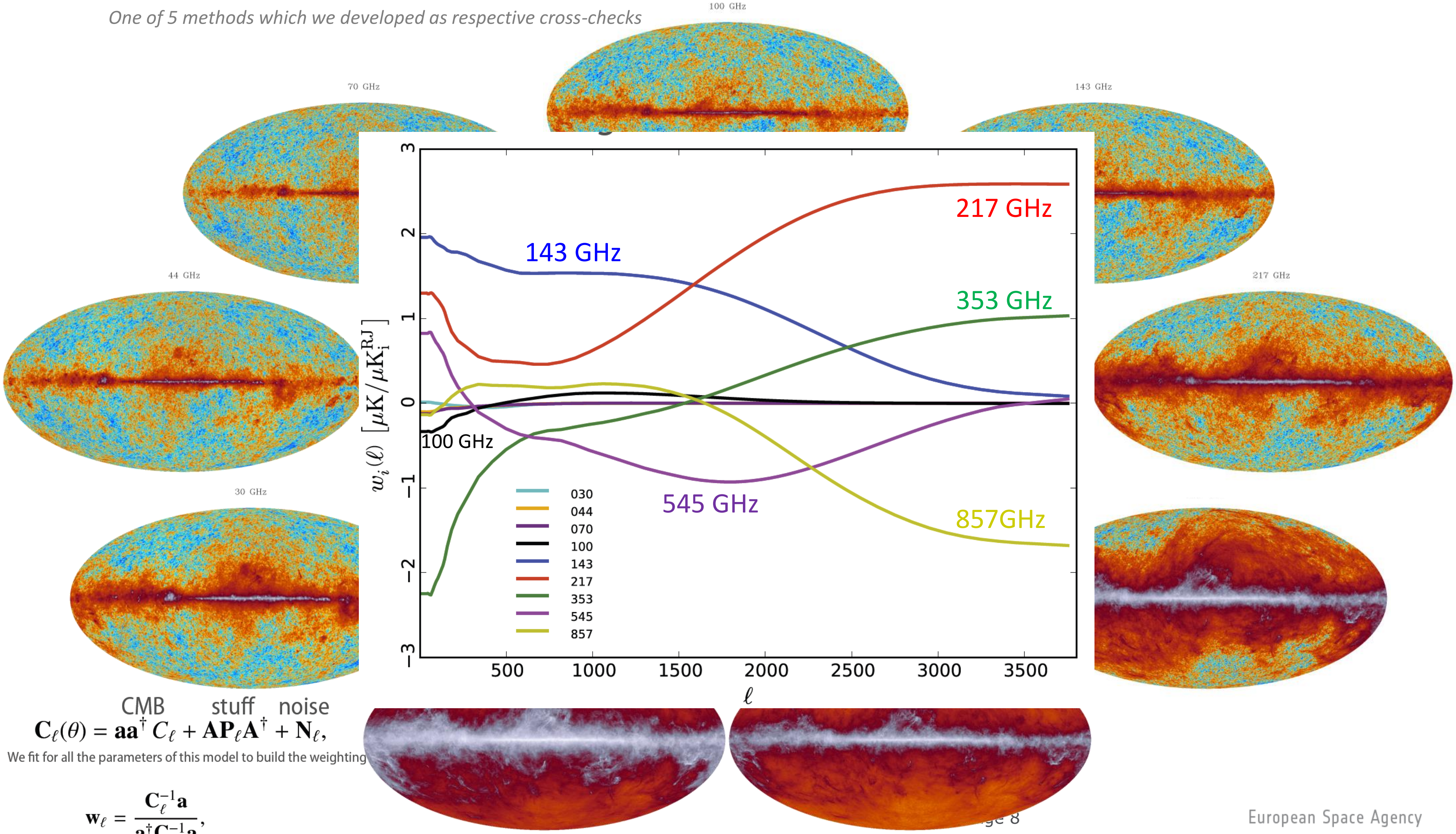


(We used 4 different methods)

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

Cleaning the background with a blind l-dependent linear combination

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



CMB stuff noise

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

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

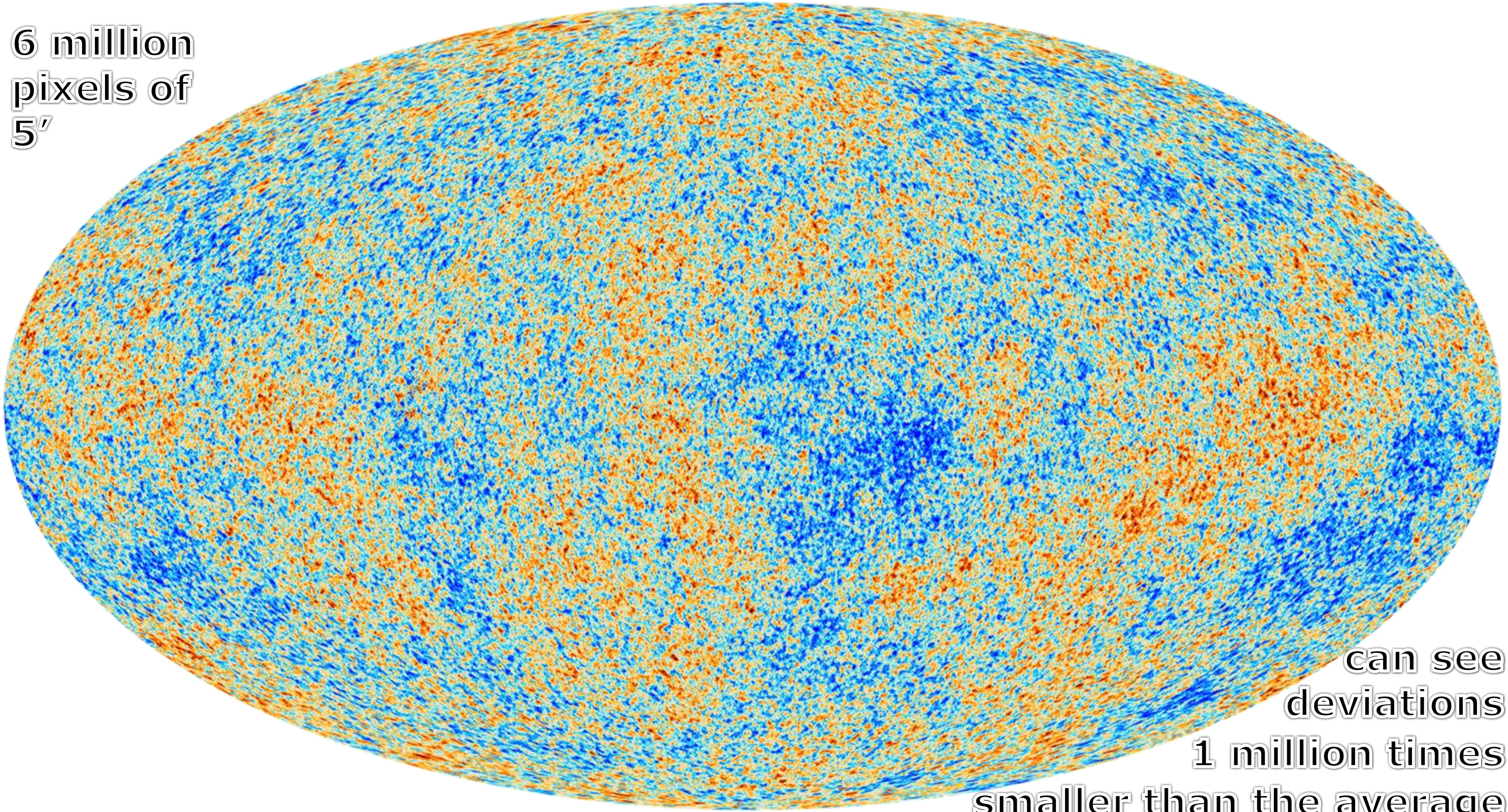
$$\mathbf{w}_\ell = \frac{\mathbf{C}_\ell^{-1}\mathbf{a}}{\mathbf{a}^\dagger\mathbf{C}_\ell^{-1}\mathbf{a}},$$

European Space Agency

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

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

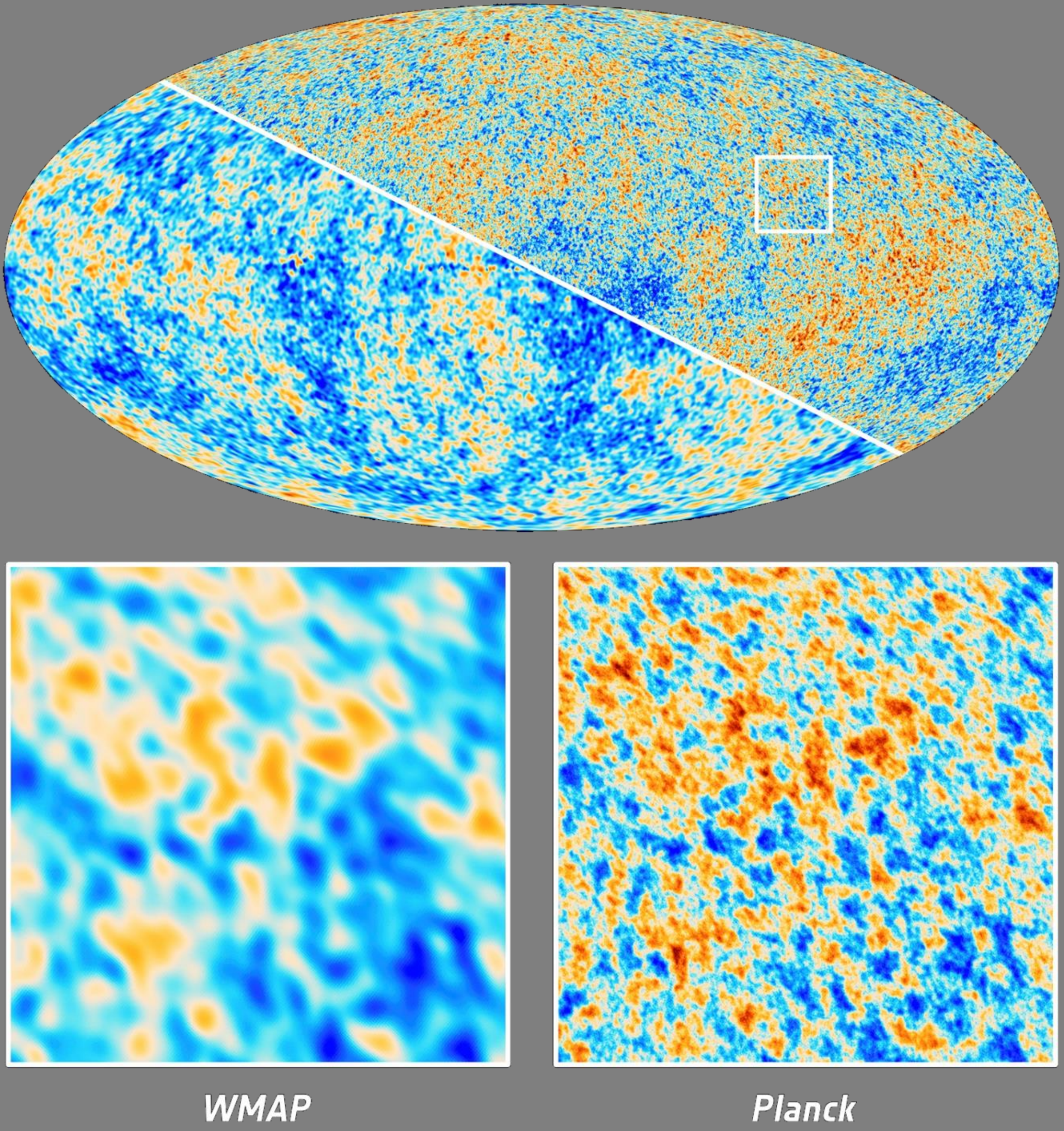
The cosmic microwave background Temperature anisotropies



6 million pixels of 5′

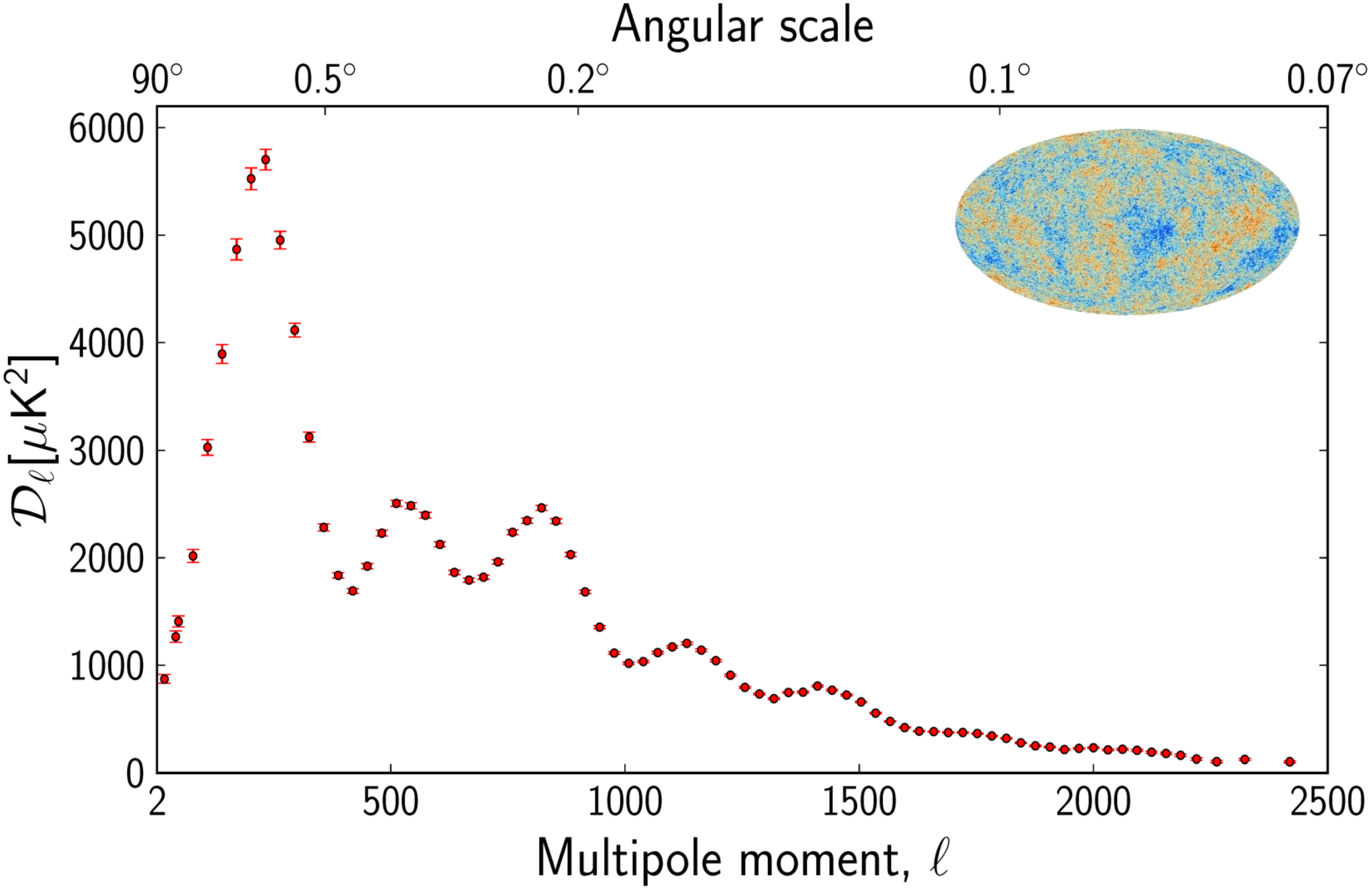
can see deviations 1 million times smaller than the average

The Cosmic Microwave Background as seen by Planck and WMAP

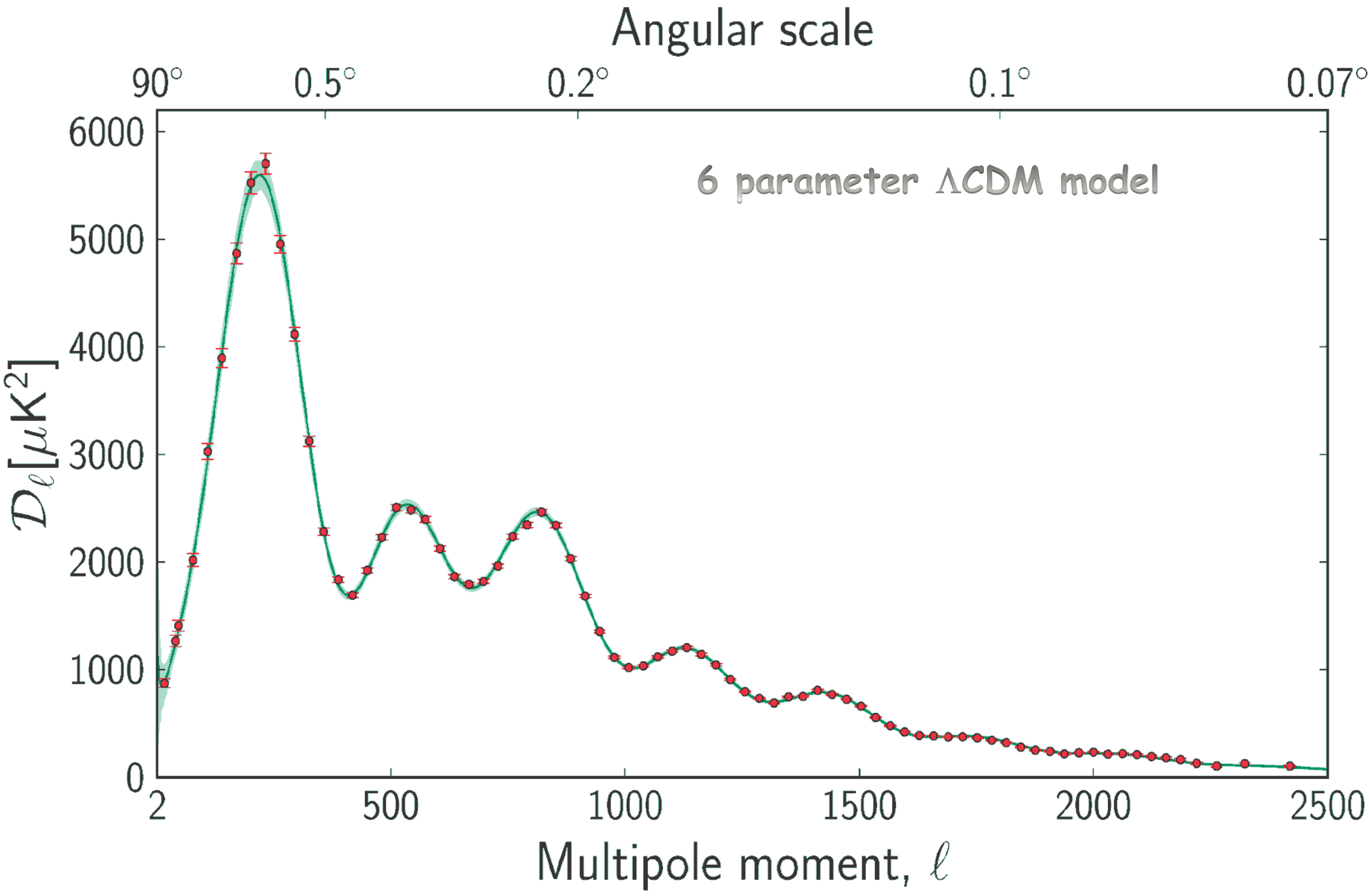


Excellent agreement once WMAP is cleaned a posteriori by subtracting a linear least squares fit to the dust traced by Planck/HFI @ 350GHz, see Lambda site

The Planck power spectrum of Temperature anisotropies

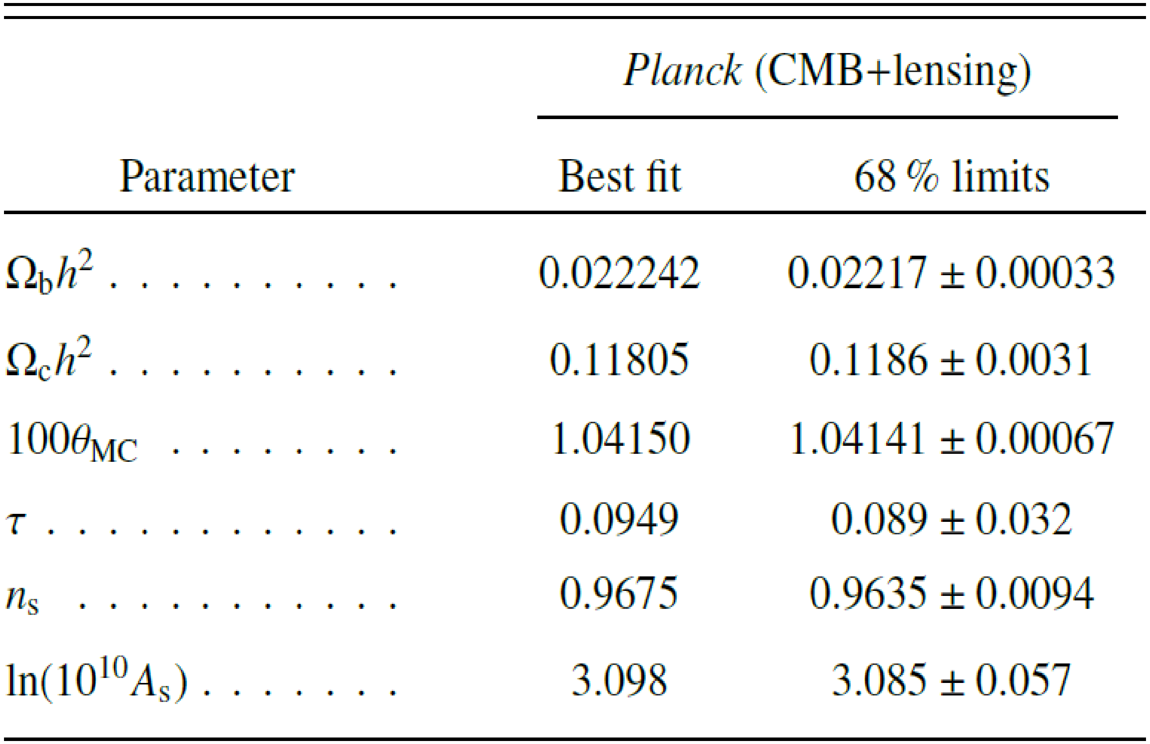


Theory confronts data



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

- $\Omega_b h^2$ Baryon density today
- $\Omega_c h^2$ Cold dark matter density today
- Θ Sound horizon size when optical depth τ reaches unity at t ~380 000y)
- τ Optical depth at reionisation, i.e. fraction of the CMB photons re-scattered during it
- A_s Amplitude of the curvature power spectrum
- n_s Scalar power spectrum power law index (n_s-1 measures departure from scale invariance)

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 $\Omega_m h^3$)

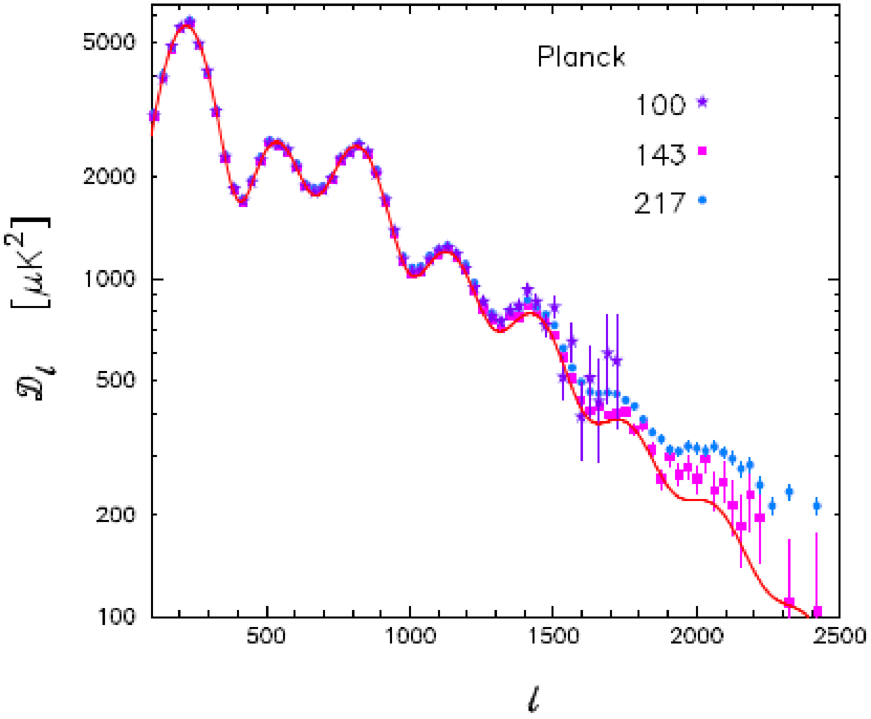
Exact scale invariance of the primordial fluctuations is ruled out, *at ~4σ*

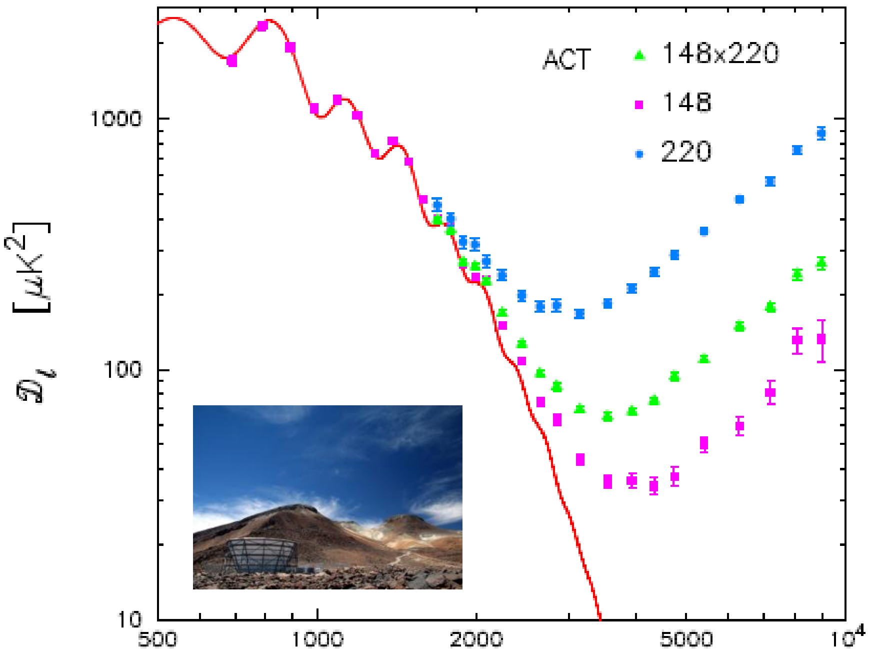
(as predicted by base inflation models)

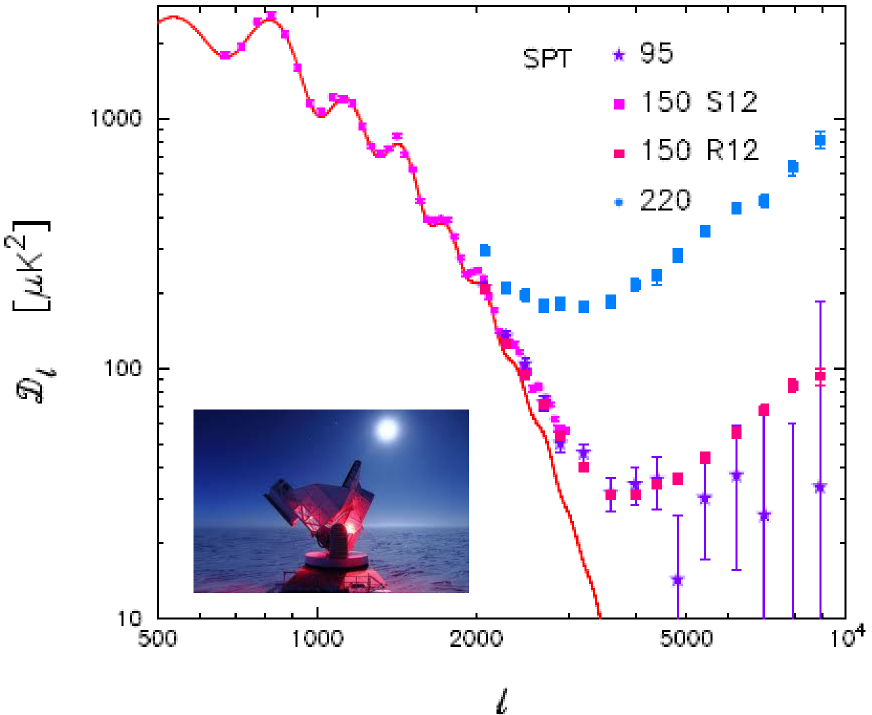
$$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724^\circ \pm 0.00038^\circ$$

Planck & HL

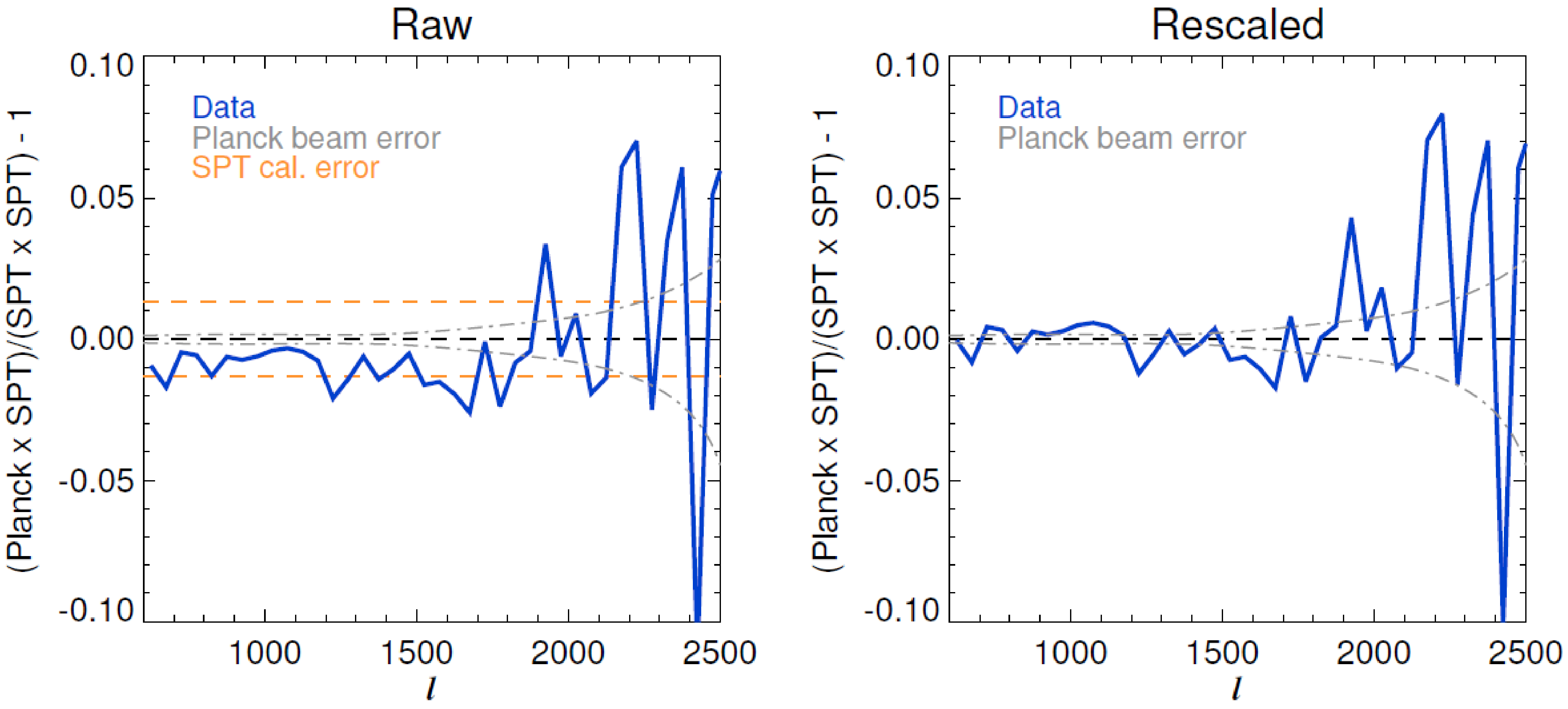
HL=high-l CMB = ACT + SPT



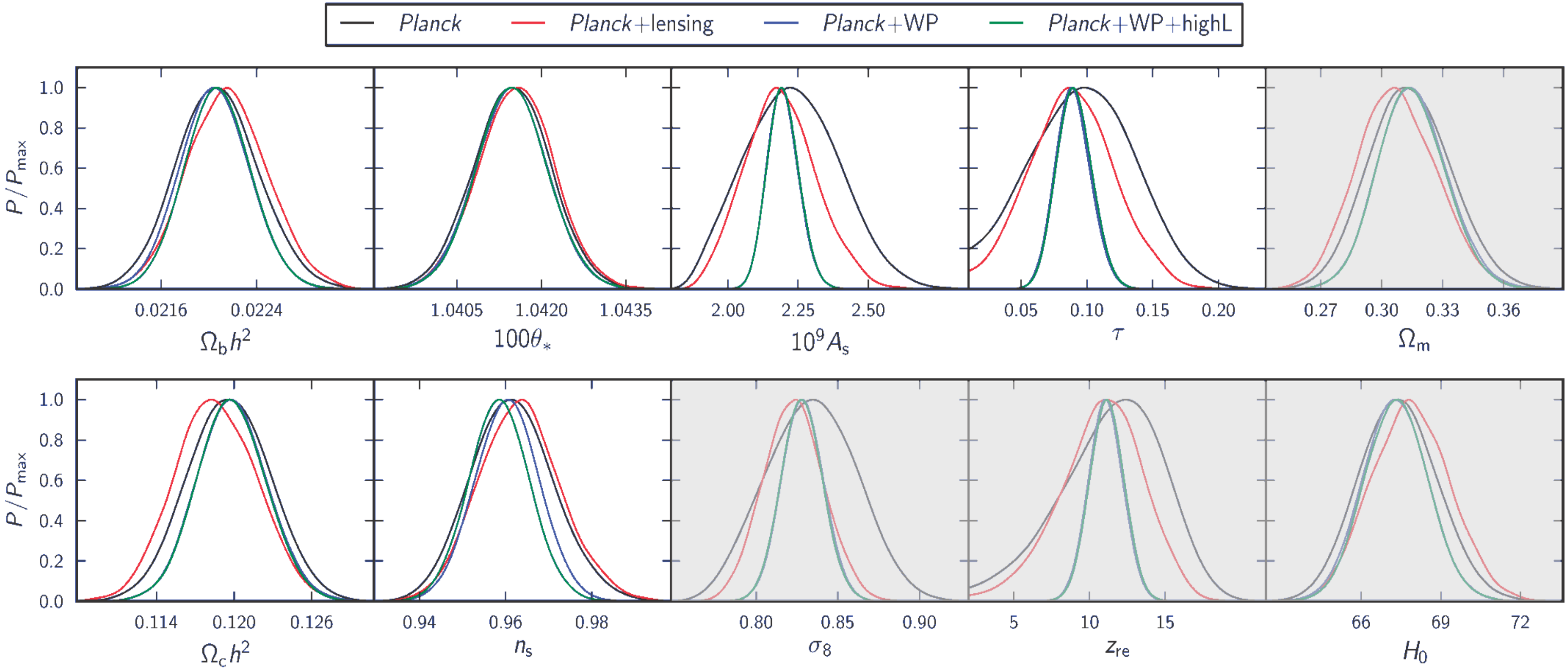




Planck / SPT consistency



Base tilted ΛCDM model - 6 parameters



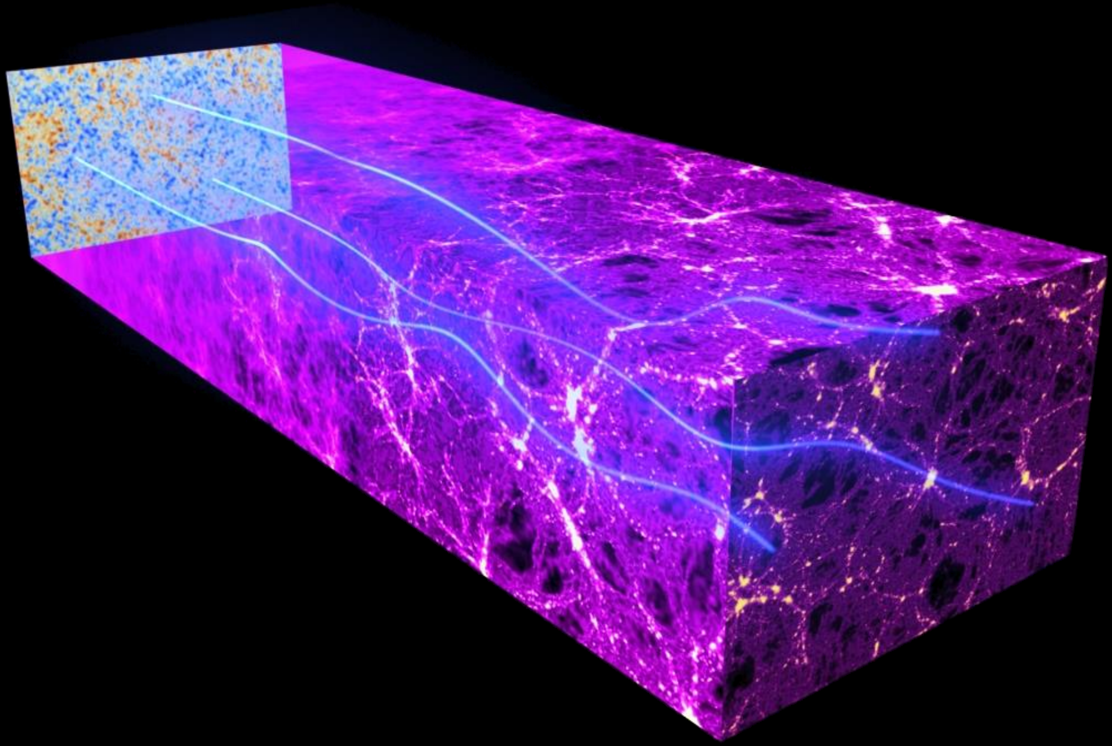
For the base model, results from High-l CMB experiments make little difference

High-l CMB experiments = ACT + SPT (600 & 2540 deg^2, 2 & 3 freq.)

Comparisons with other “observables”

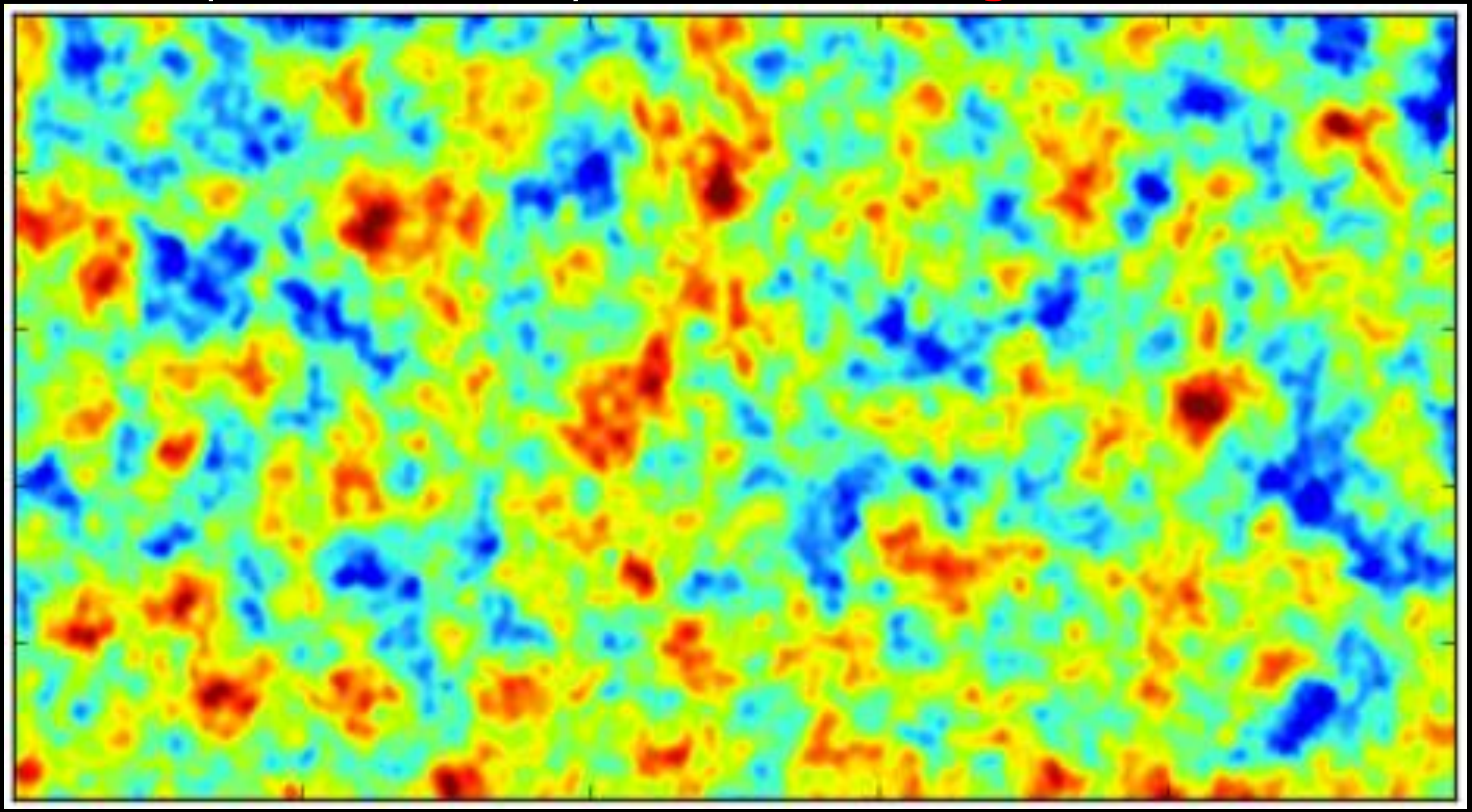
GRAVITATIONAL LENSING DISTORTS IMAGES

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



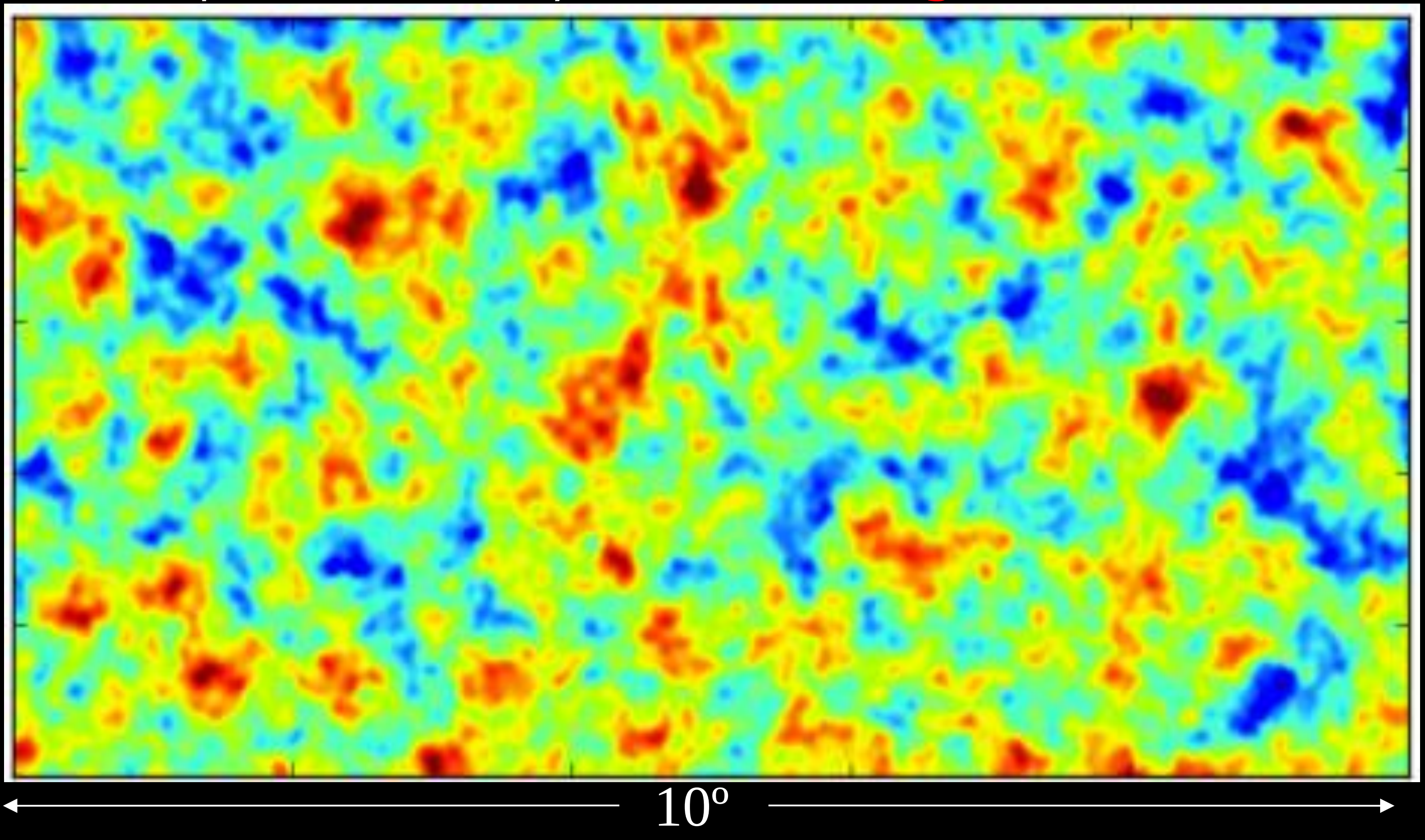
GRAVITATIONAL LENSING OF THE CMB

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



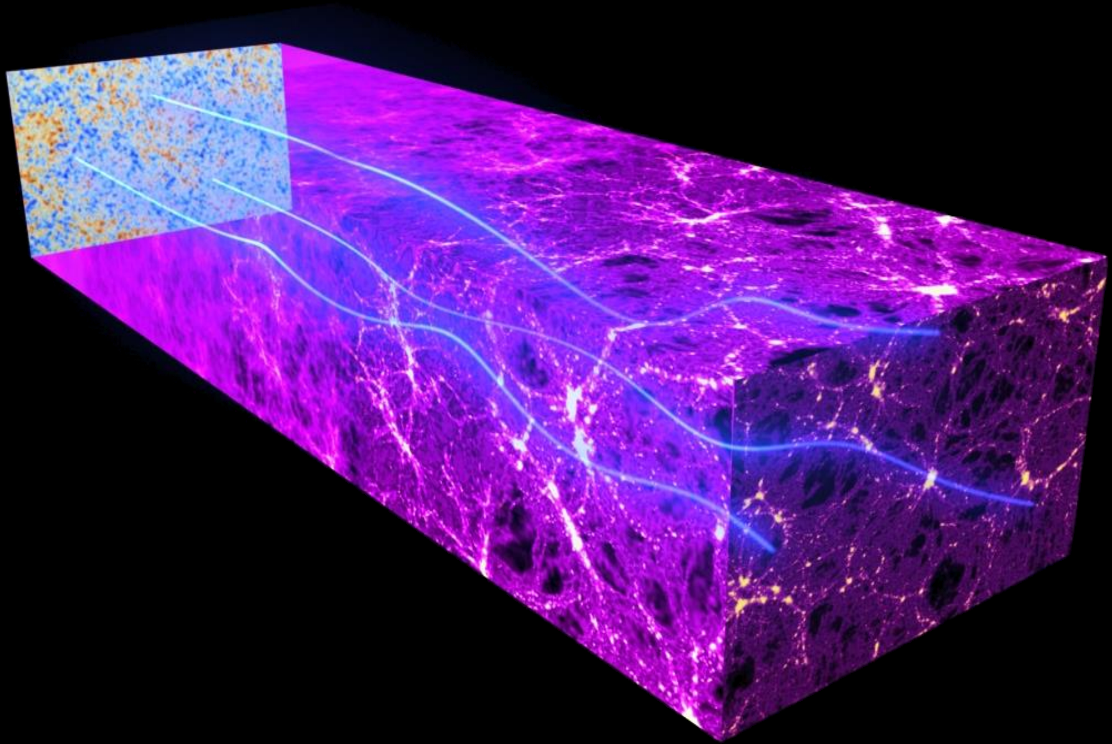
GRAVITATIONAL LENSING OF THE CMB

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



GRAVITATIONAL LENSING DISTORTS IMAGES

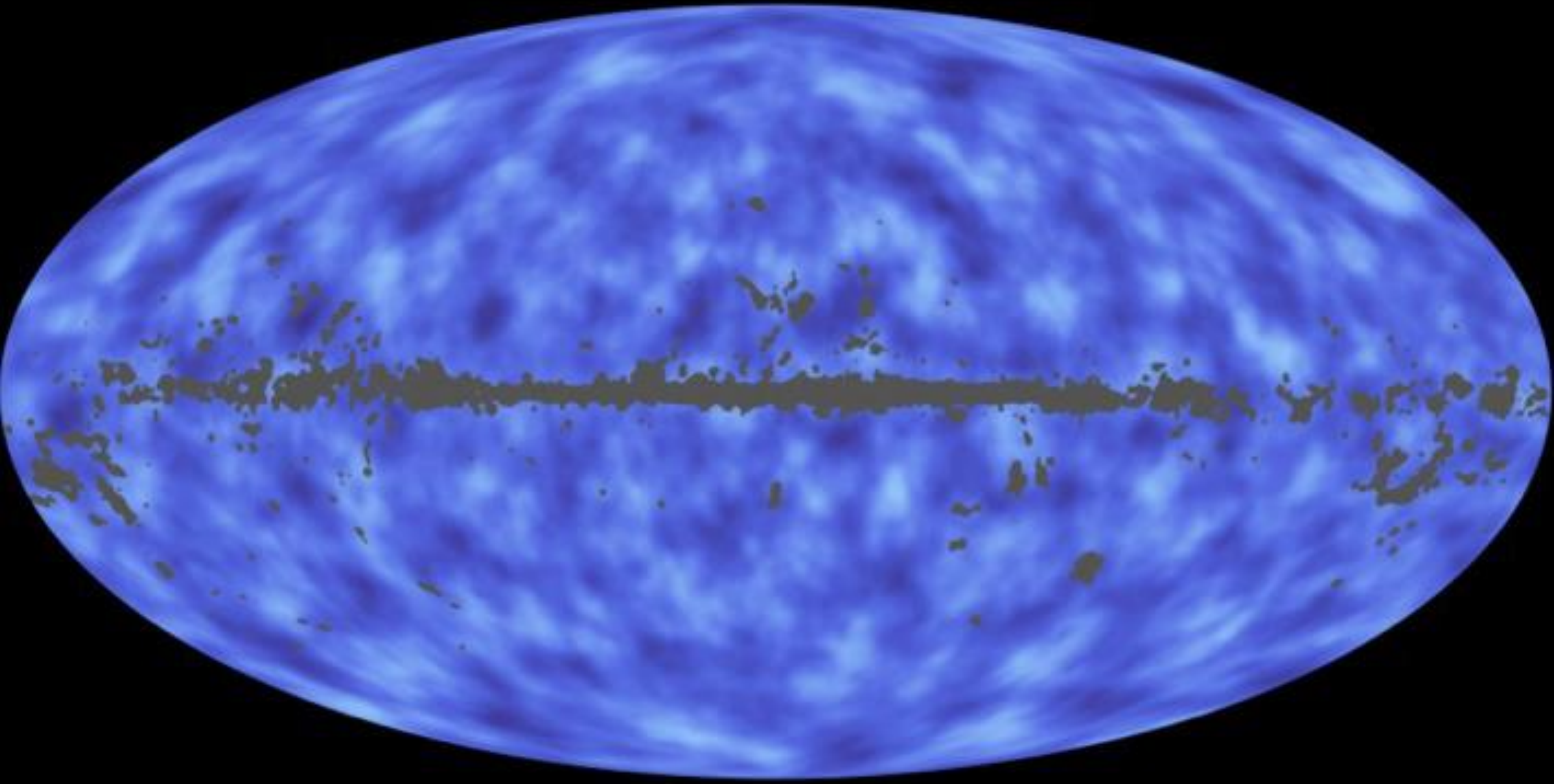
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



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

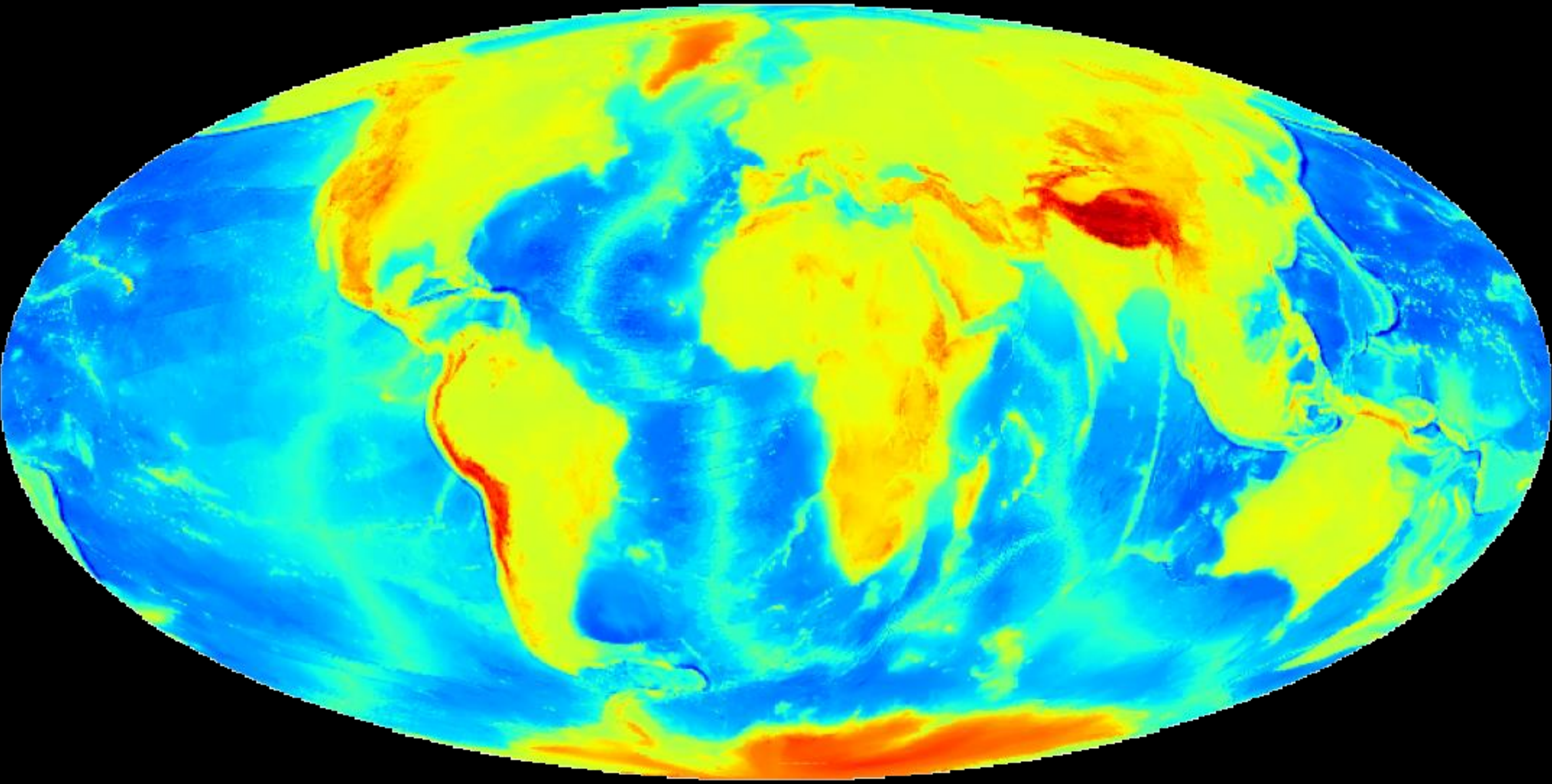
$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\,\vec{\nabla}(C^{-1}T)]$$

Projected mass map

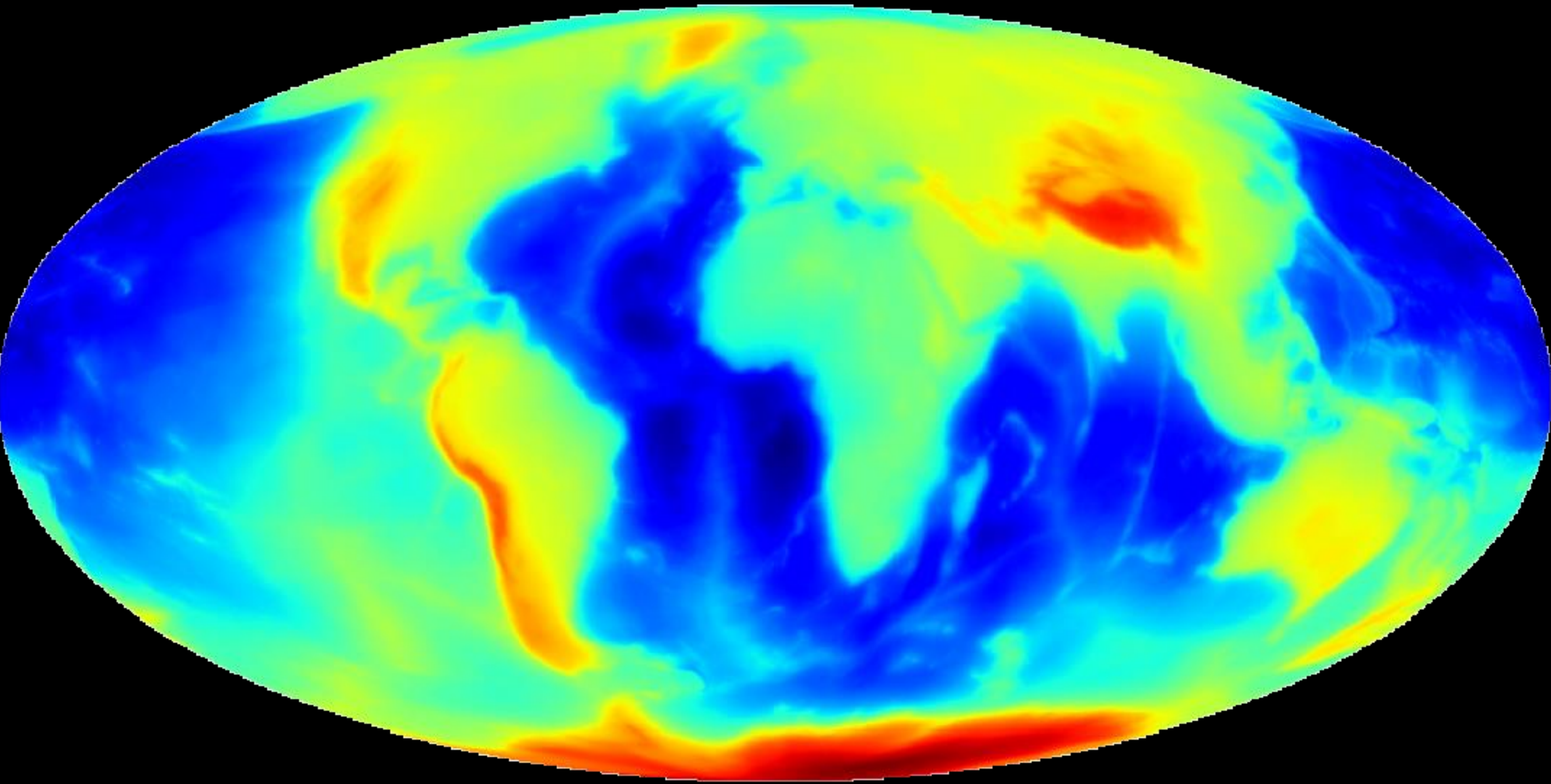


The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

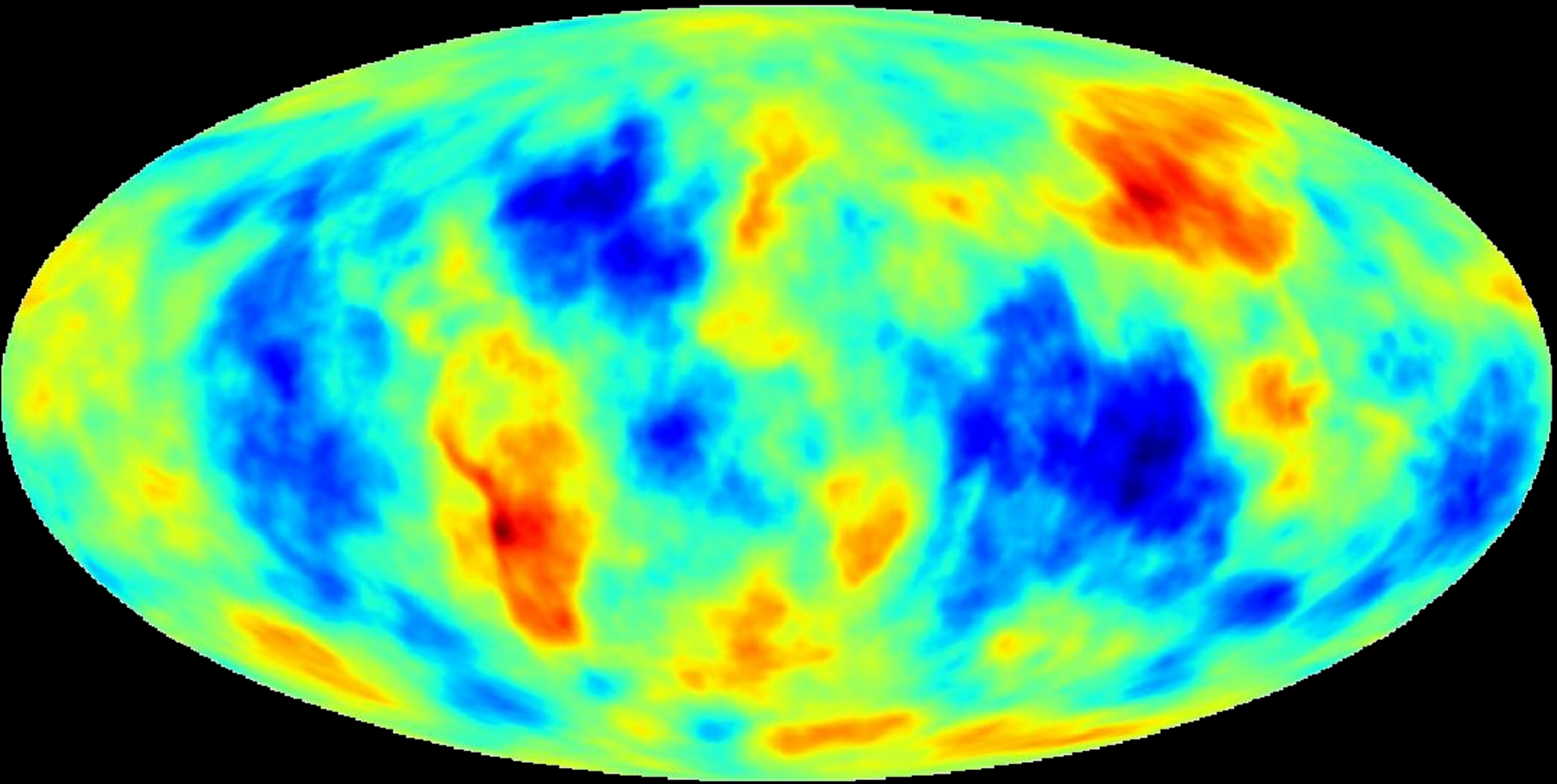
Another full sphere distribution



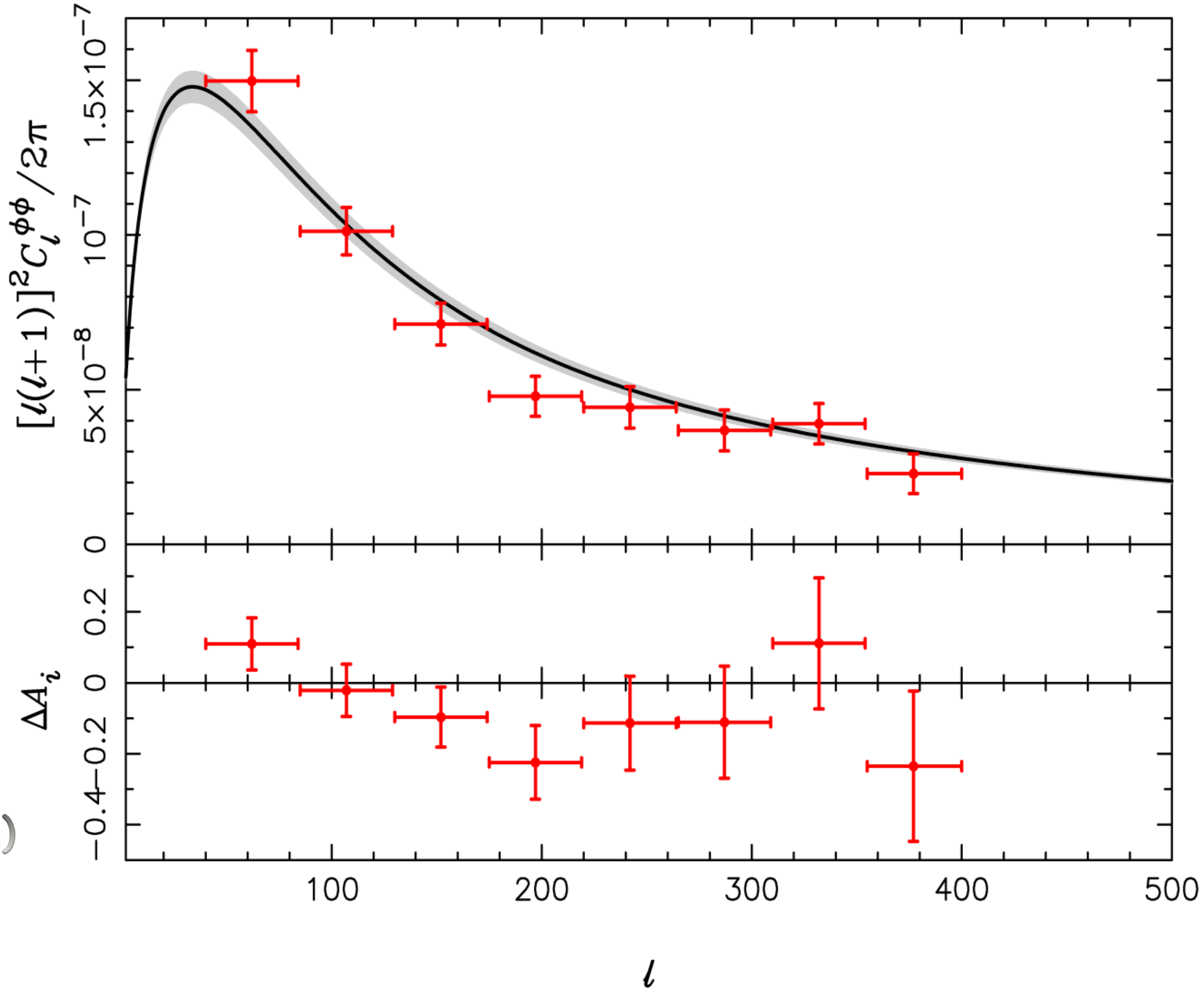
at our angular resolution…



and noise level!



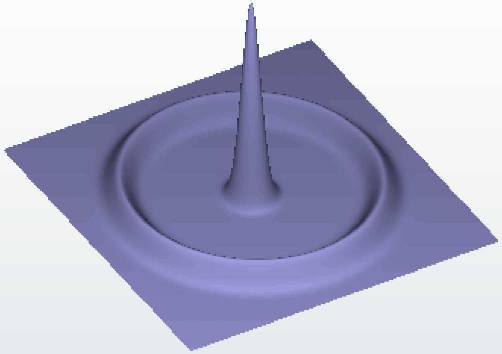
The lensing potential spectrum

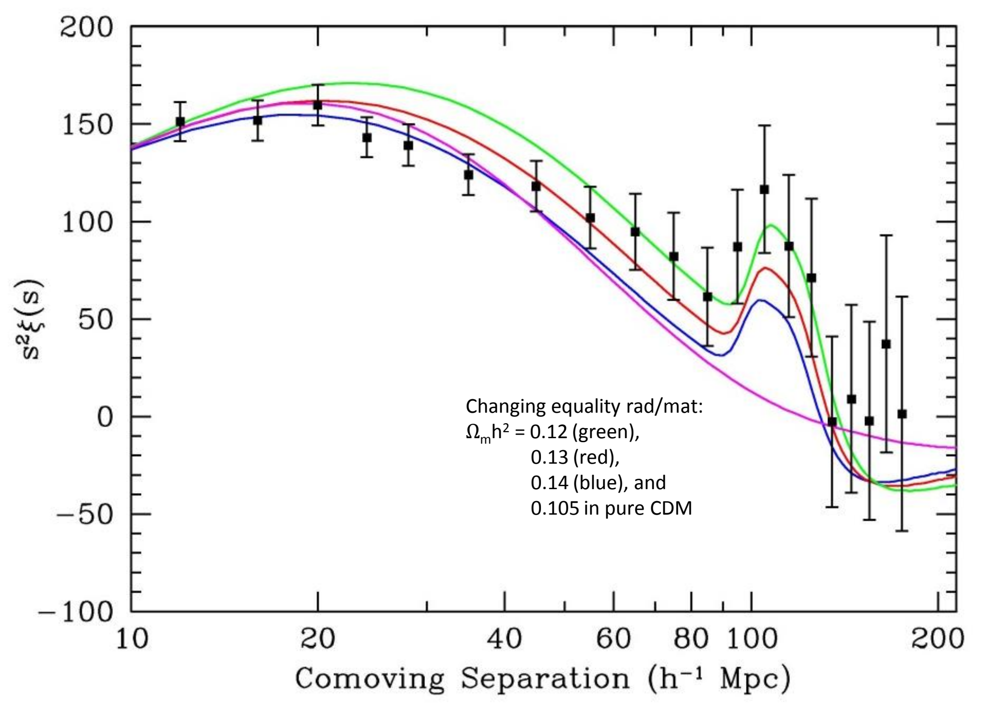


(26σ detection)

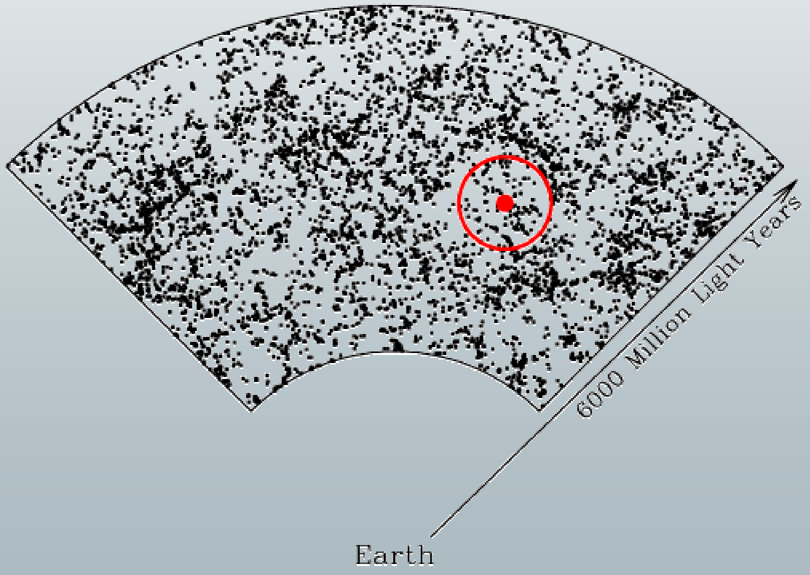
→ Agrees well with the prediction from T alone

Echos of the primordial drum…



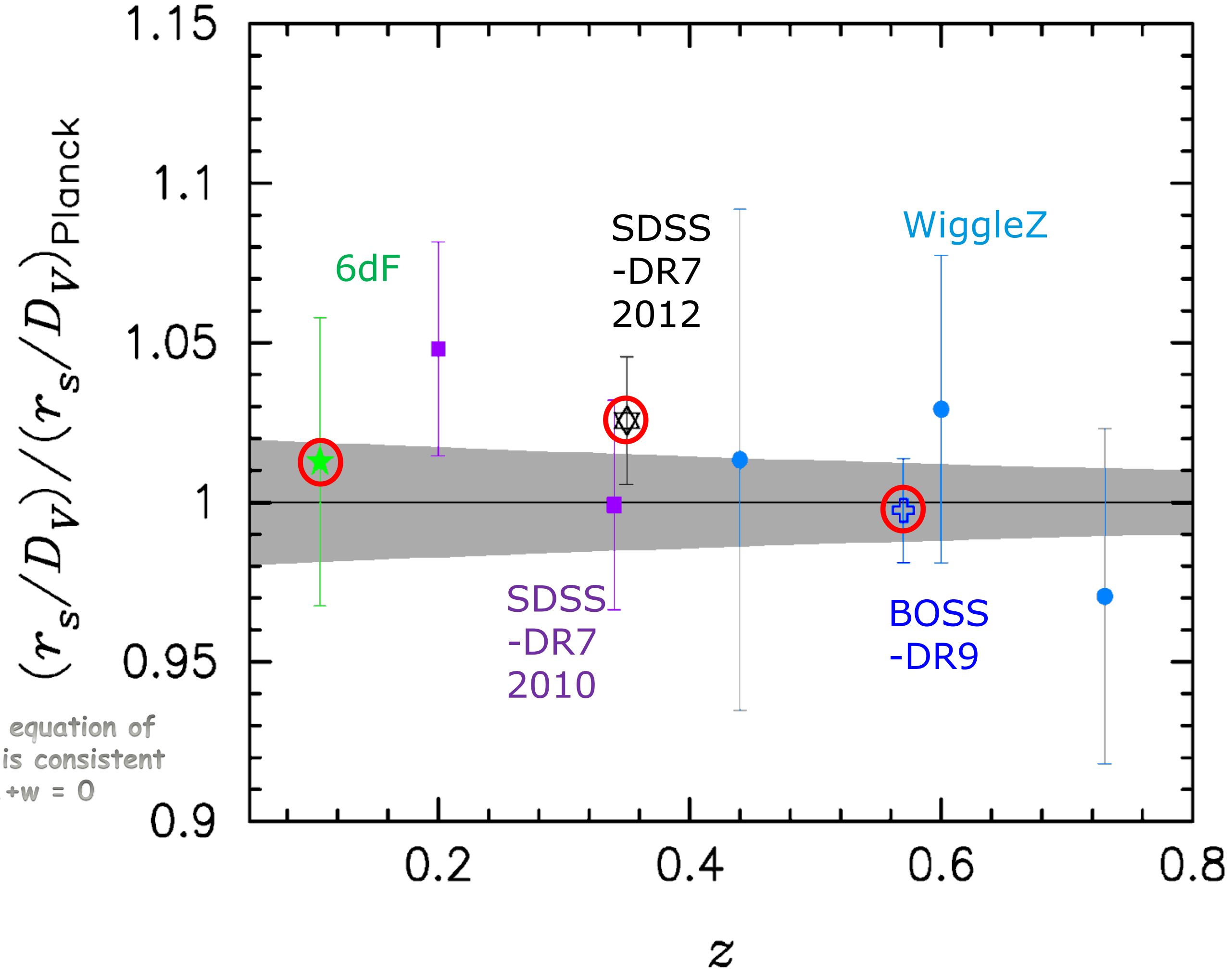


Changing equality rad/mat:
$\Omega_m h^2$ = 0.12 (green),
0.13 (red),
0.14 (blue), and
0.105 in pure CDM

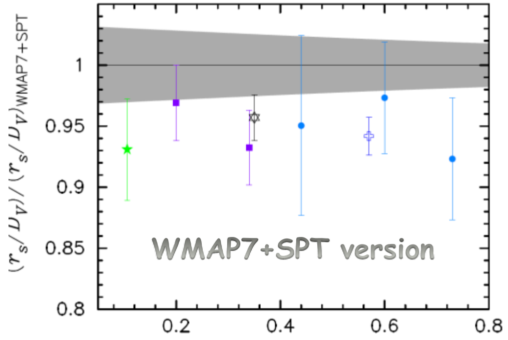


BAO (Baryon Acoustic Oscillations) probe the sound travel distance at z close to 0

BAO acoustic-scale distance ratio



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



(see Hu etal12 for explanations by extensions)

Planck Prediction (±1σ shaded area)

➔ Planck & BAO are all in quite tight agreement

Base ΛCDM model 6 parameters

CMB+LSS - 2013

	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	$\boxed{1.04147 \pm 0.00056}$
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	$\boxed{0.9608 \pm 0.0054}$
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025

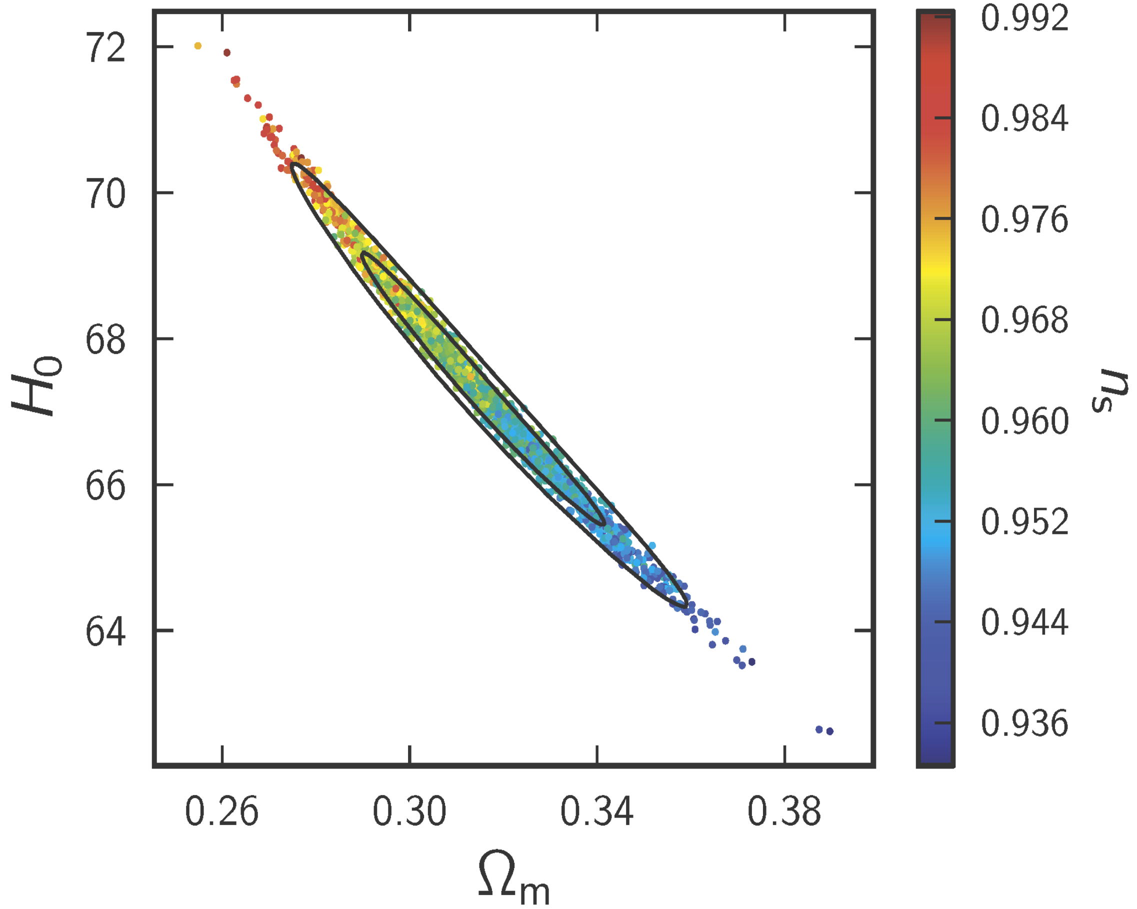
The sound horizon, θ, determined by the positions of the peaks (7), is now determined with 0.05% precision
(links together $\Omega_b h^2$, $\Omega_c h^2$, H_0 - here as $\Omega_m h^3$)

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

(as predicted by base inflation models)

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

Sound Horizon



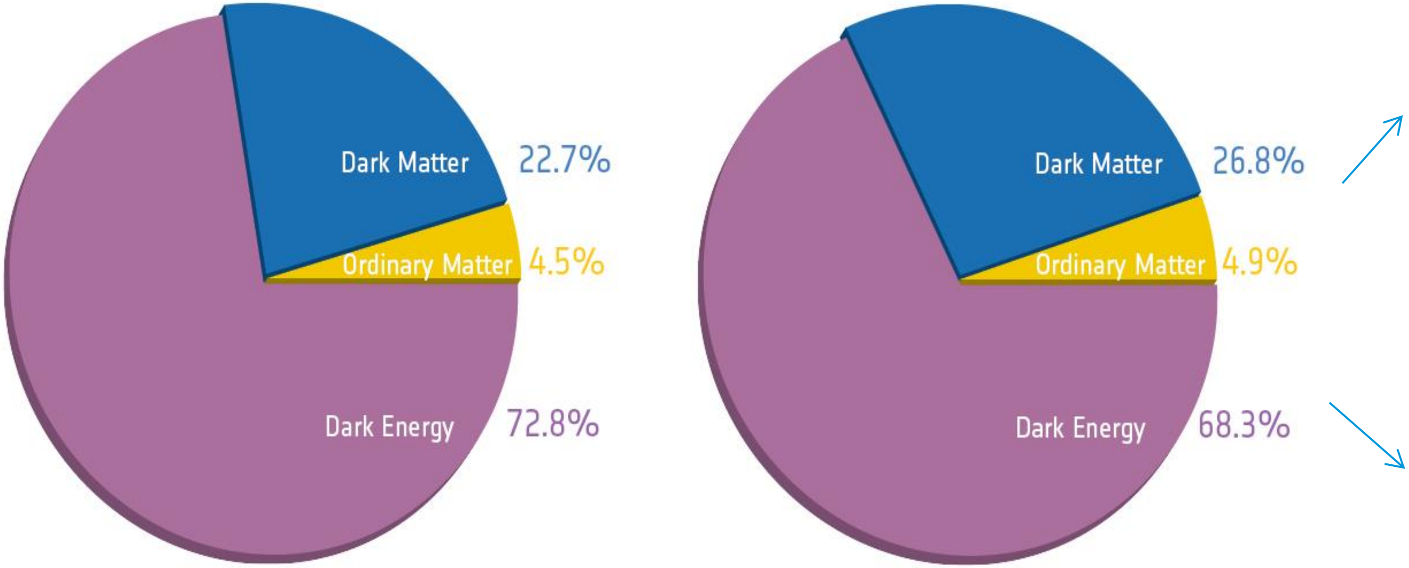
Samples are for Planck only.

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

r_s is constrained transversally

r_s constrains $\Omega_m h^3$ very tightly in LCDM; High Ω_m corresponds to low n_s and H_0

The basic content of the Universe



Before Planck

After Planck

...has changed!

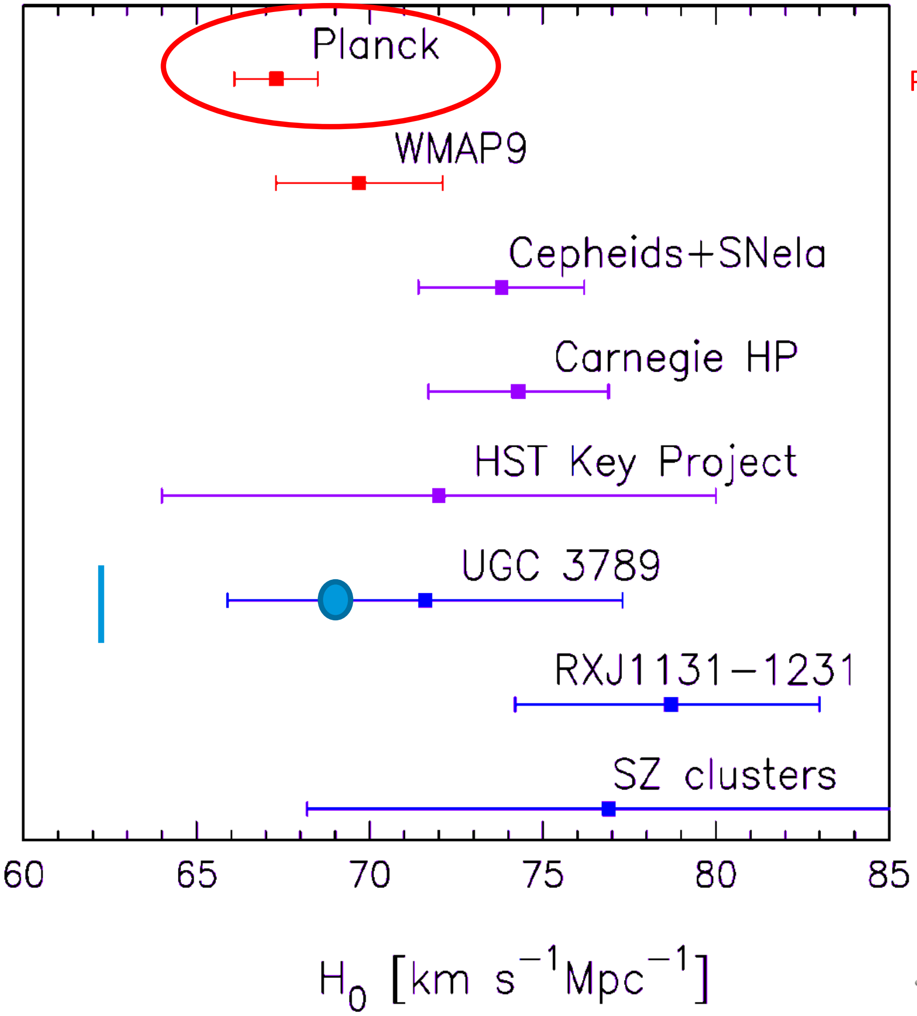
The rate of expansion

Direct determinations of the distance ladder:

Riess et al. (2011)

Freedman et al. (2012),

Freedman et al. (2001)

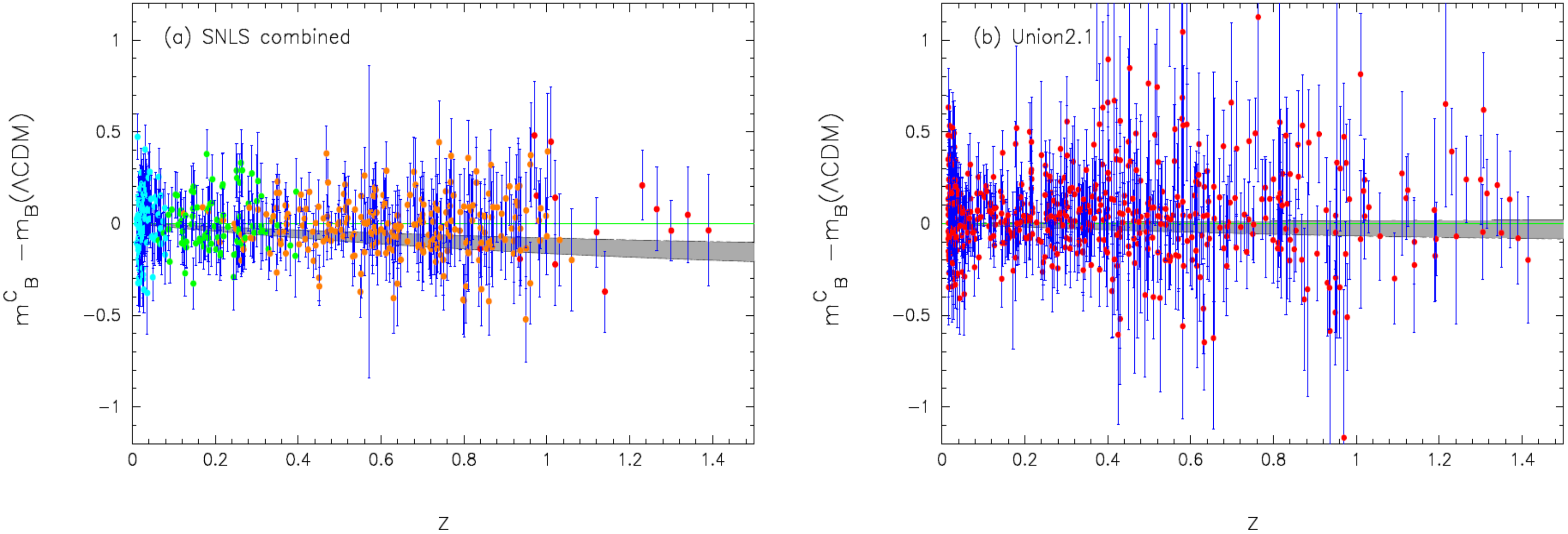


Planck H_0 is 67.95 ± 1.5 km/s/Mpc

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

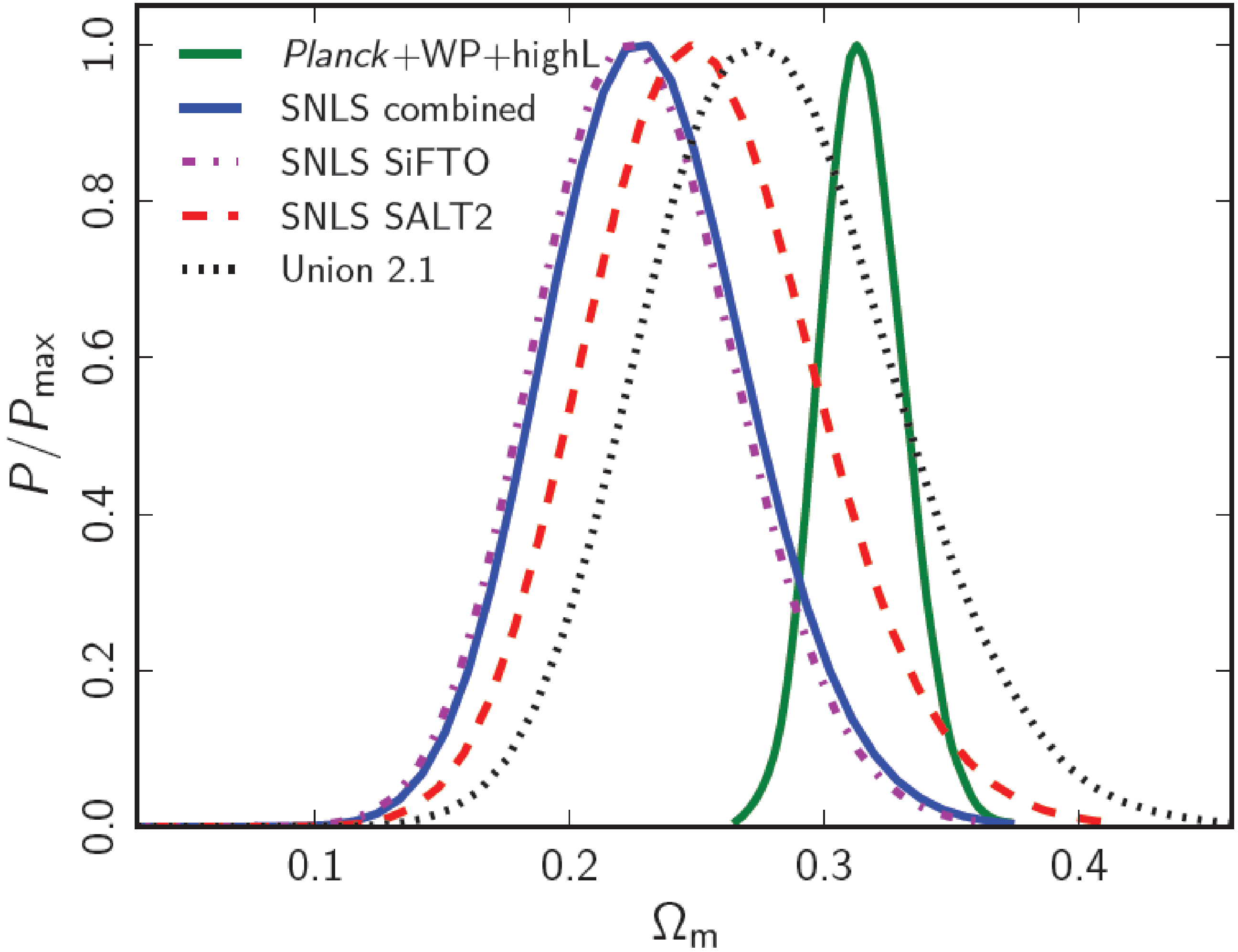
Tension with SNLS results…



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

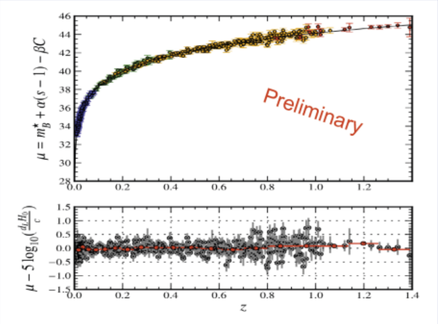
Fig. 18. Magnitude residuals relative to the base ΛCDM model that best fits the SNLS combined sample (left) and the Union2.1 sample (right). The error bars show the 1 σ (diagonal) errors on m_B. The filled grey regions show the residuals between the expected magnitudes and the best-fit to the SNe sample as Ω_m varies across the $\pm 2\,\sigma$ 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).

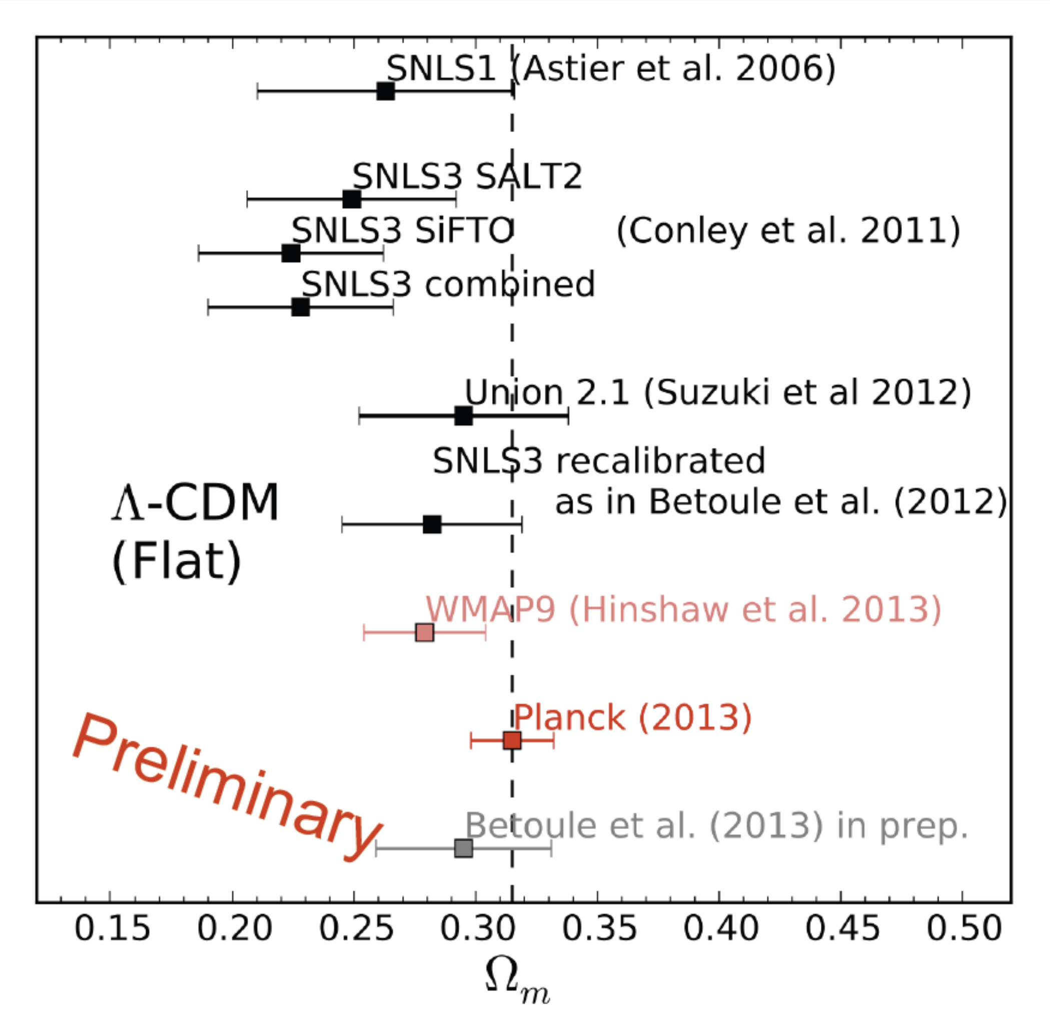
The total matter density



Comparison with Planck results

SNLS-SDSS joint Hubble diagram





(R. Pain)

Summary on base tilted LCDM

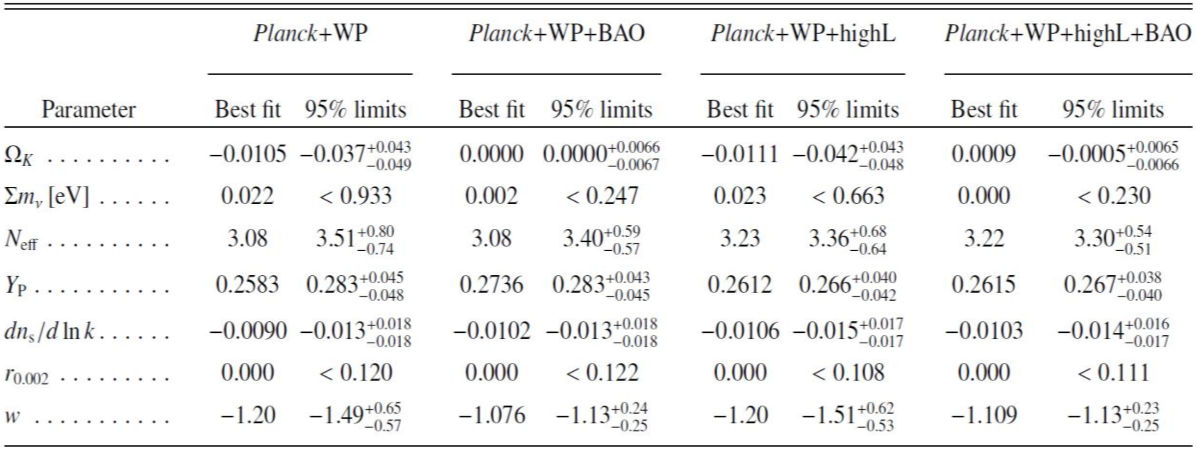
- Base LCDM is a very good fit to Planck T spectrum, with parameters (n_s, Ω_b, Ω_c, θ/H_0) accurately determined by Planck alone, with the exception of the (A_s, τ) degeneracy which can be broken by adding WP.
- The model is fully consistent with two other Planck observables, Lensing, and Polarisation spectra.
- This model is also fully consistent with BAO, and show some tension with direct H_0 determination. The situation regarding Ω_m from SN is promising.
- CMB+LSS now exclude scale invariance (n_s=1) at ~7σ

Beyond the standard model

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** ⬇

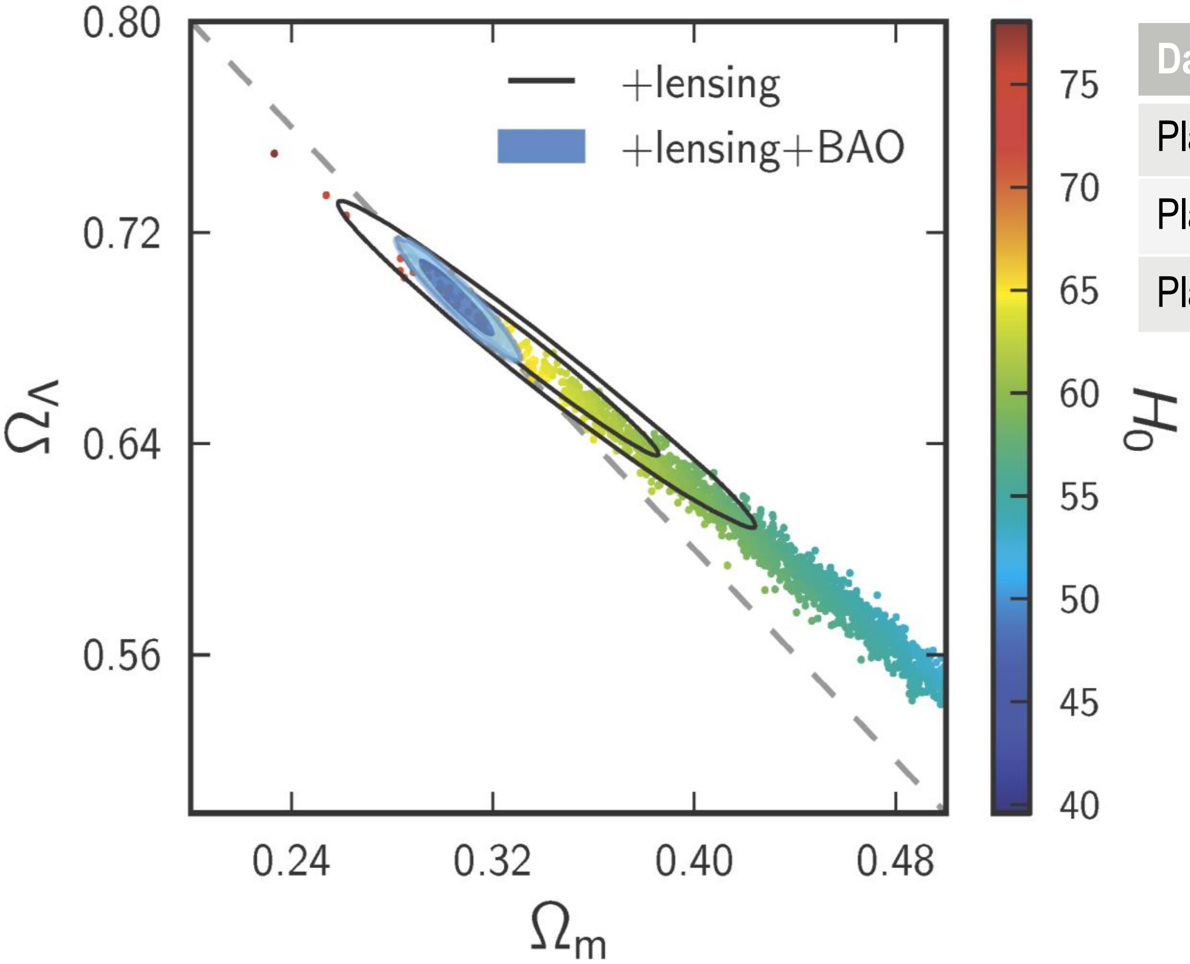


	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	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	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	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…

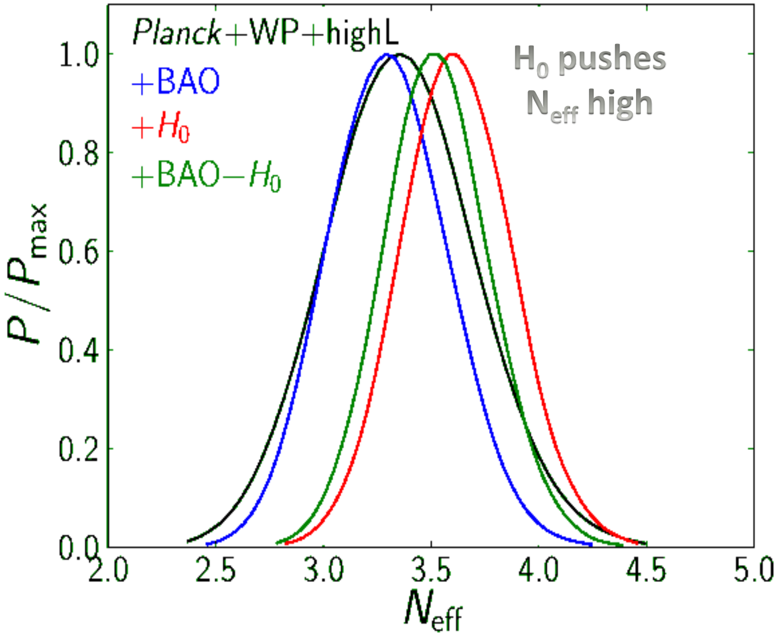
Geometry

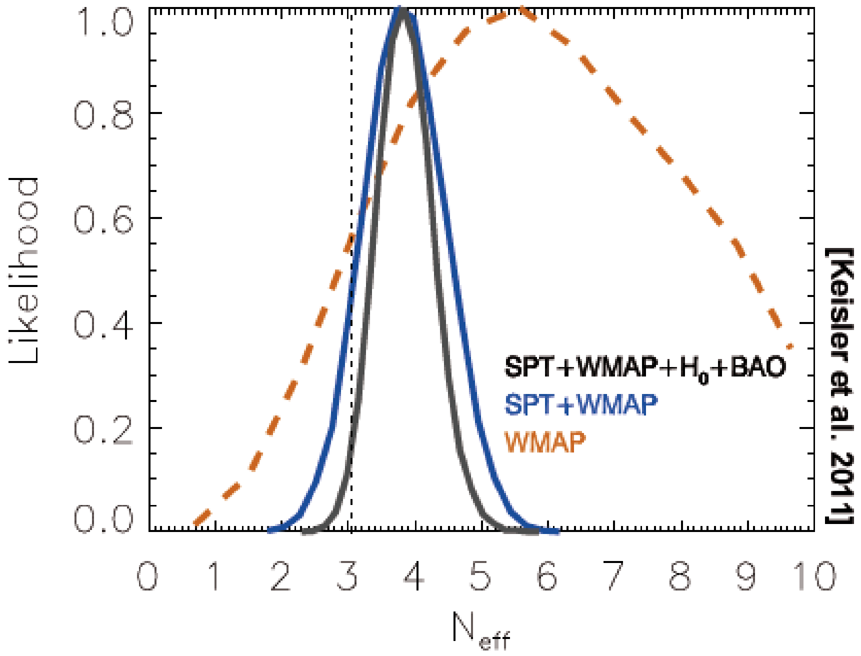


Data	100 Ω_k
Planck+WP+HL	-4.2 ± 4.5
Planck+WP+HL+lensing	-0.69 ± 1.0
Planck+WP+HL+lensing+BAO	-0.07 ± 0.33

➔ *a precisely* flat spatial geometry

Neutrinos number (relativistic dof at decoupling)



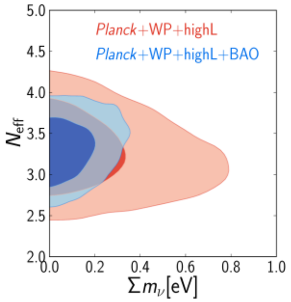


[Keisler et al. 2011]

→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)

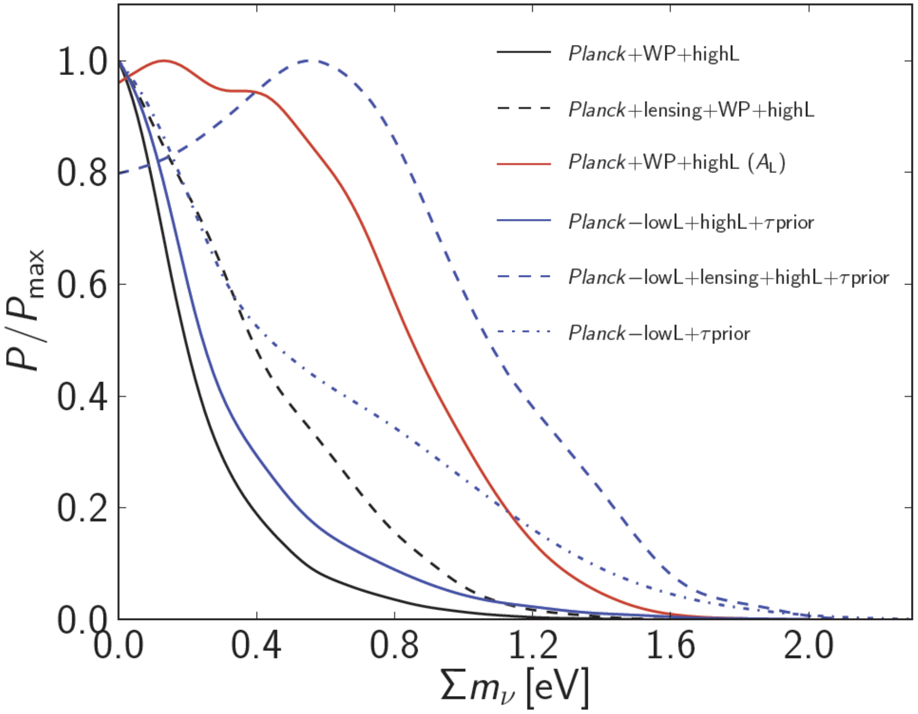
Parameter	*WMAP* 9	+eCMB	+eCMB+BAO	+eCMB+BAO+H_0
Number of relativistic species[b]				
N_{eff}	> 1.7 (95% CL)	3.89 ± 0.67	3.55 ± 0.60	3.84 ± 0.40



Wmap9+ excluded 3 neutrinos at more than 2σ (Bennett et al. 2013, v2)

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

Neutrinos masses



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

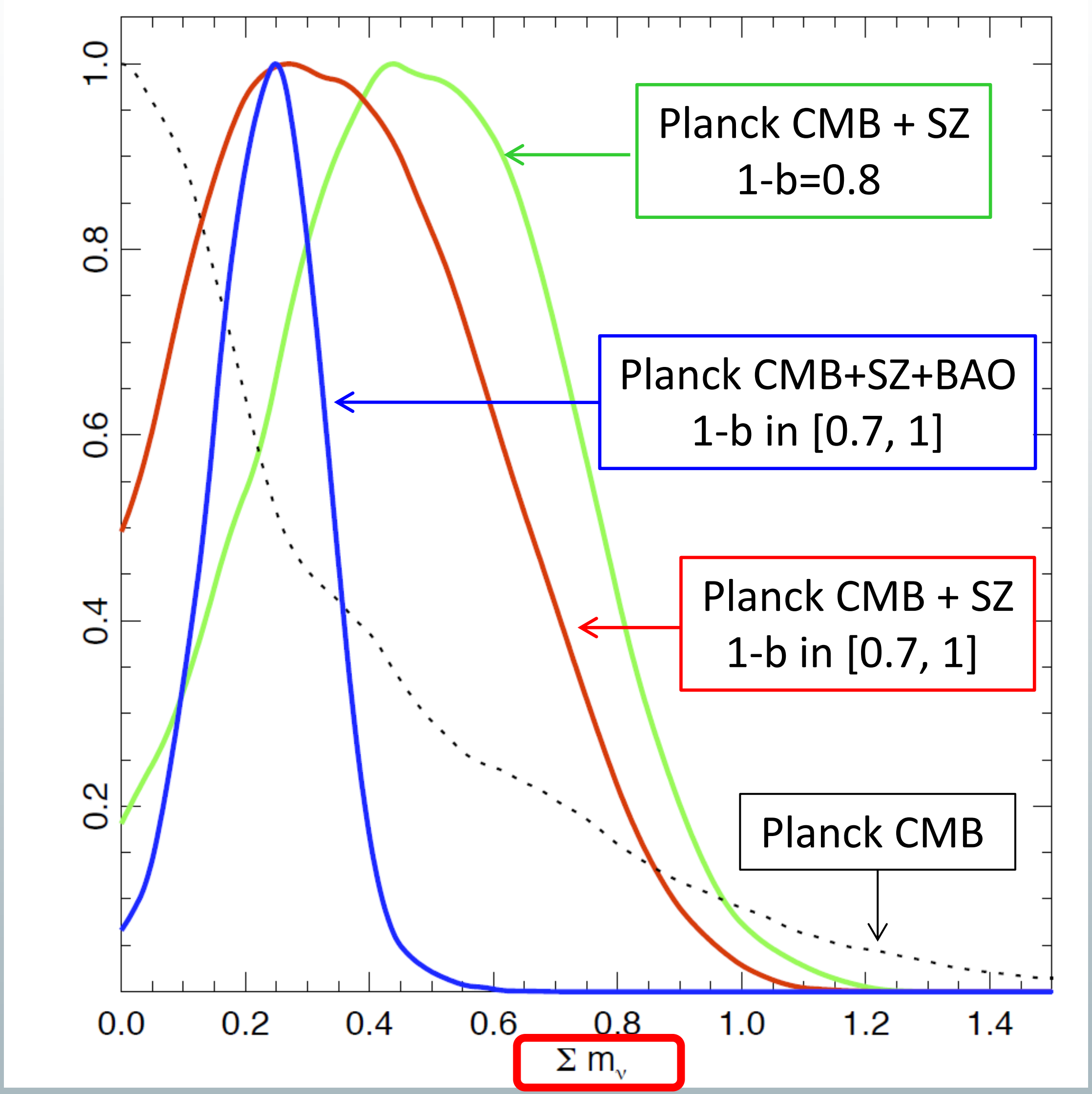
Planck constrains neutrino masses mostly through their effect via lensing:
removing that constraint (marginalising over A_L) weakens considerably the limit:
$\Sigma m_\nu <$ 0.66eV (95CL PT+WP+HL)
becomes
$\Sigma m_\nu <$ 1.08eV (95CL PT+WP+HL)

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:
$\Sigma m_\nu <$ 0.23eV (95CL CMB+BAO)

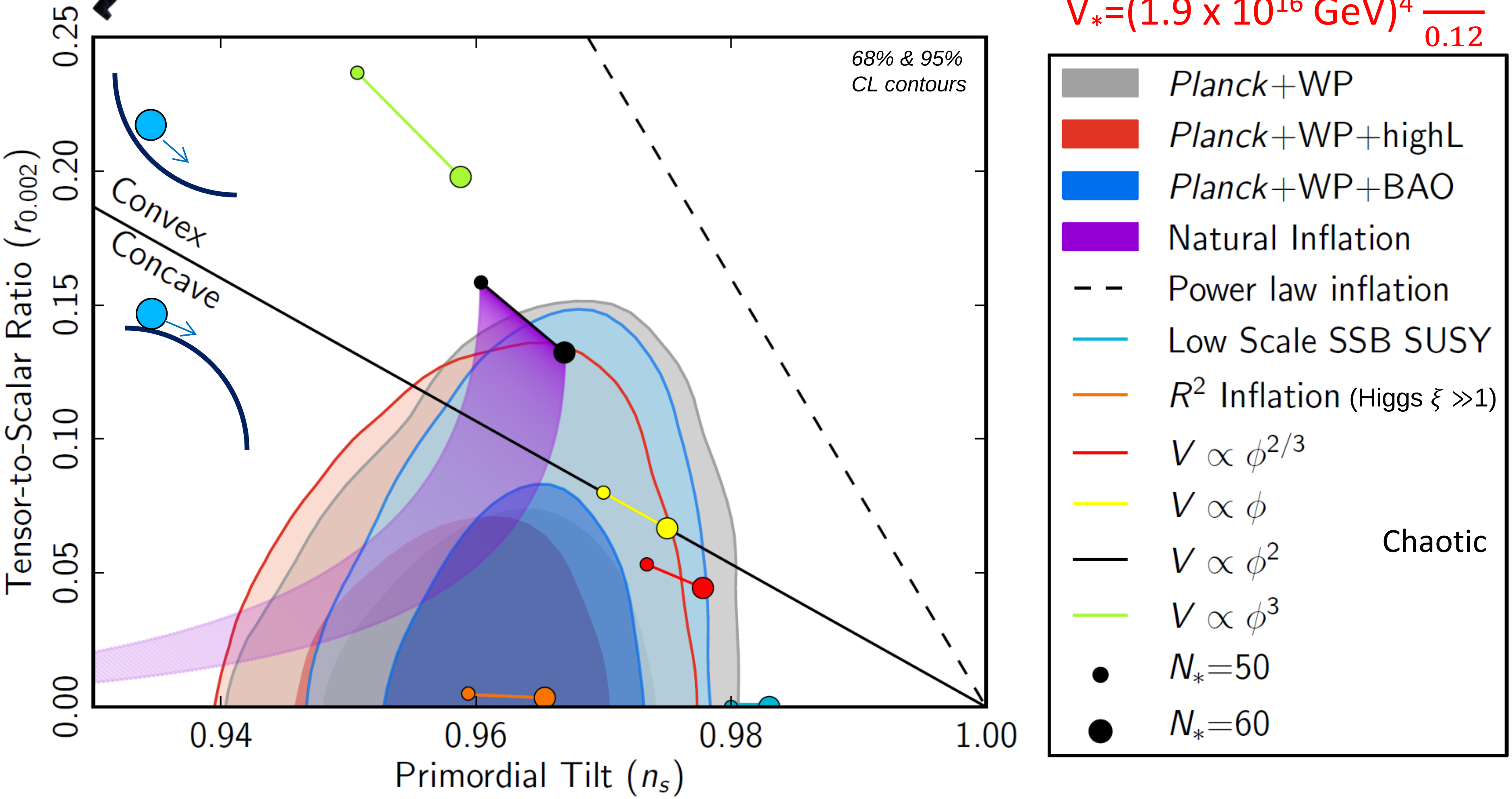
Case of 3 active nus of mass $m_\nu = \Sigma m_\nu/3 > 0.06$eV; N_{eff} =3.046 (i.e. no additional ν-like relativistic particles)

Physics or SZ Gastrophysics?



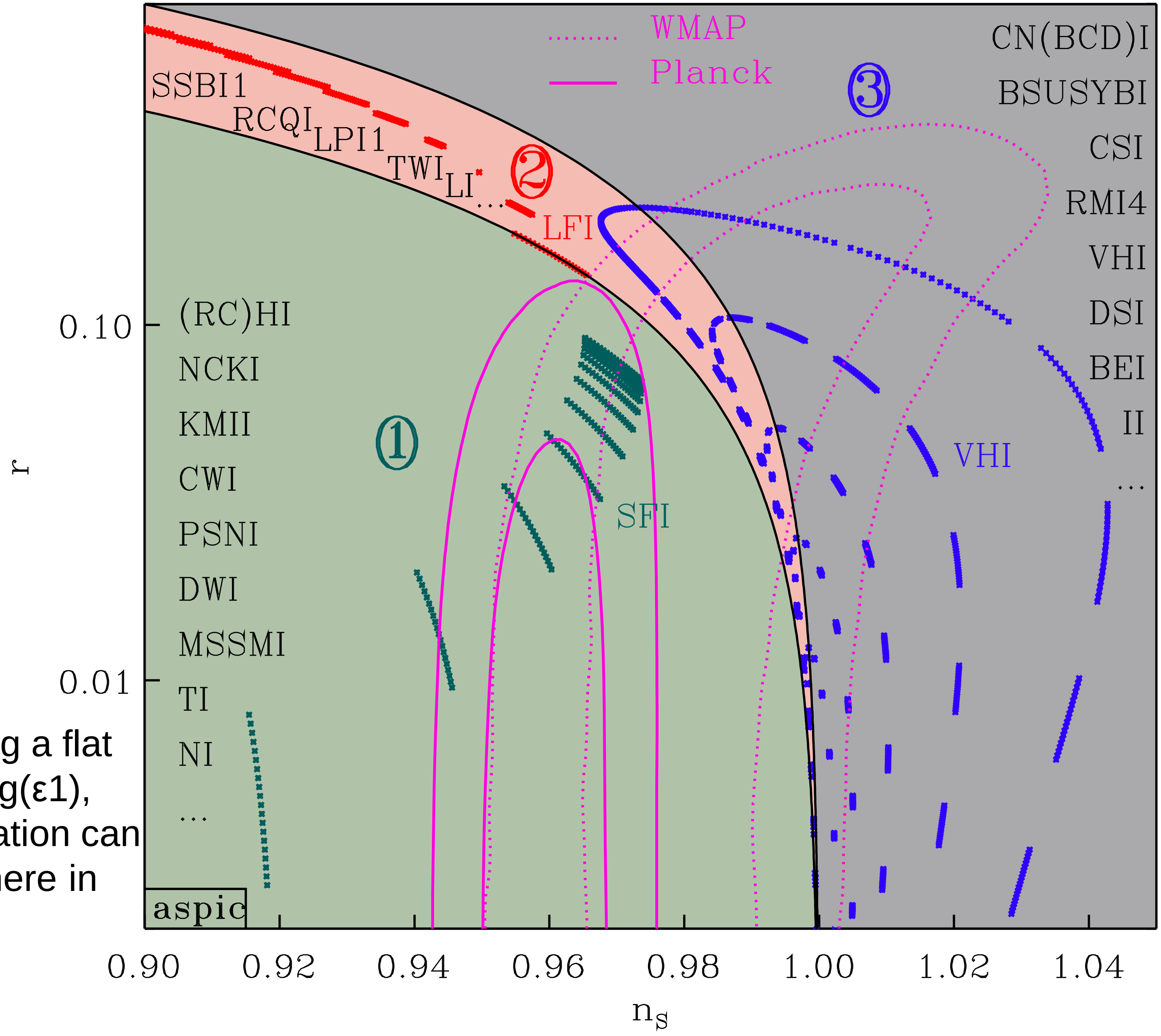
Constraint on representative Inflation models

$$V_* = (1.9 \times 10^{16}\ \mathrm{GeV})^4\,\frac{r_*}{0.12}$$



➔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.

Theory space

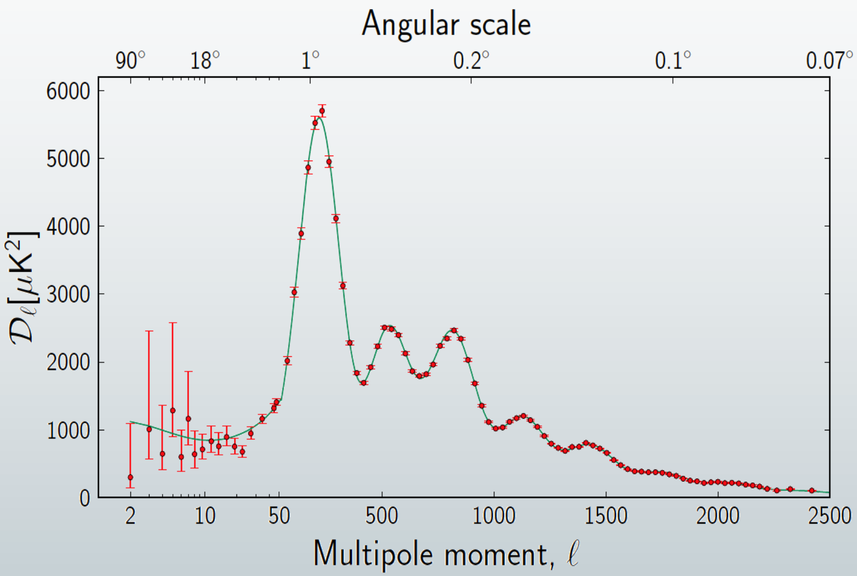


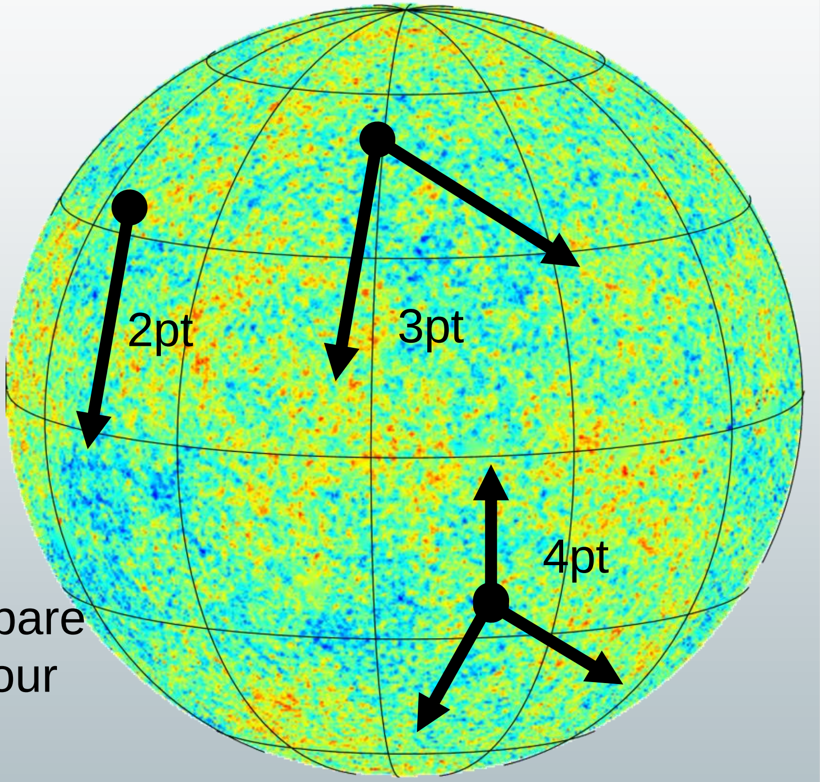
70 models (essentially all single field slow-roll) from the *``encyclopaedia inflationaris” of Martin, Ringeval, Venin, archiv*/1303.3787

(Assuming a flat prior in log(ε1), since inflation can be anywhere in energy)

Random field characterisation

The angular power spectrum compares two points separated by **one** angle





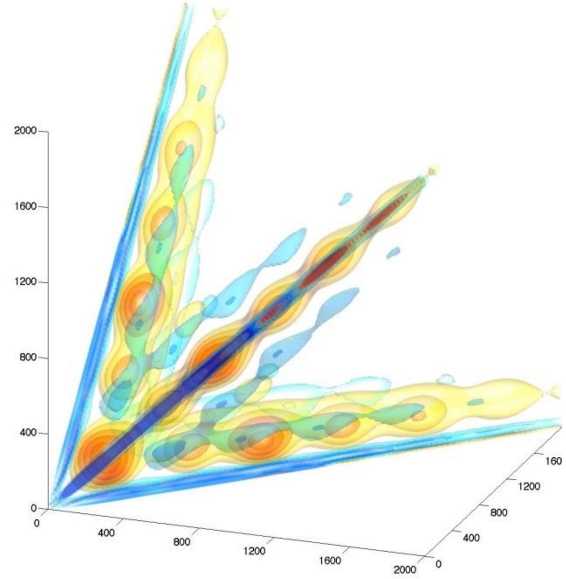
To assess non Gaussianity, one must compare fluctuations in three points (bi-spectrum), four point (tri-spectrum), etc.

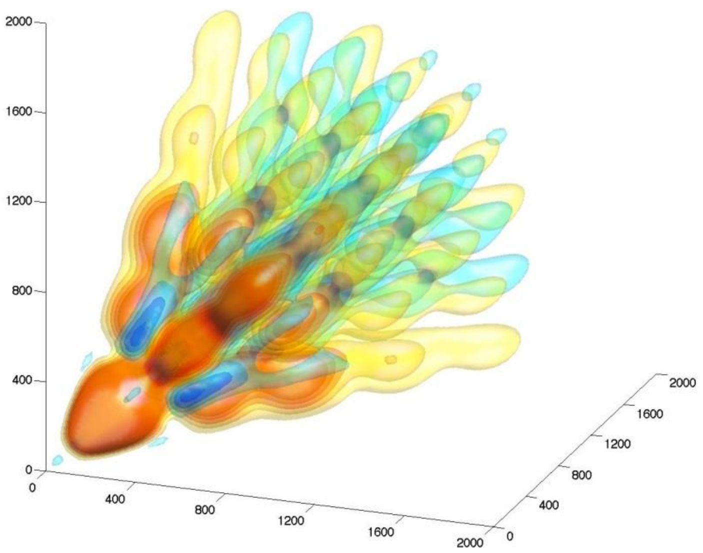
Need **three** numbers to characterize a triangle

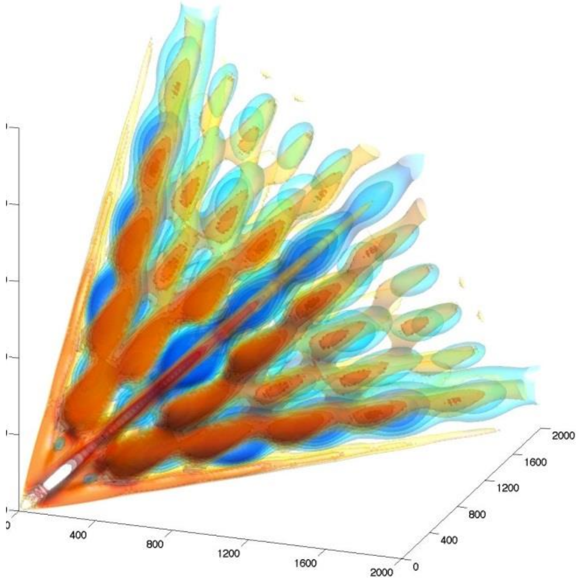
One origin of four point signal comes from lensing by Large Scale Structures.

CMB bispectrum fingerprinting with Planck

LEO (local, Equilateral, Orthogonal) are common outputs







NG of ***local*** type ($k_1 \gg k_2 \sim k_3$):

- Multi-field models
- Curvaton
- Ekpyrotic/cyclic models

(Also NG of **Folded** type

- Non Bunch-Davis
- Higher derivative)

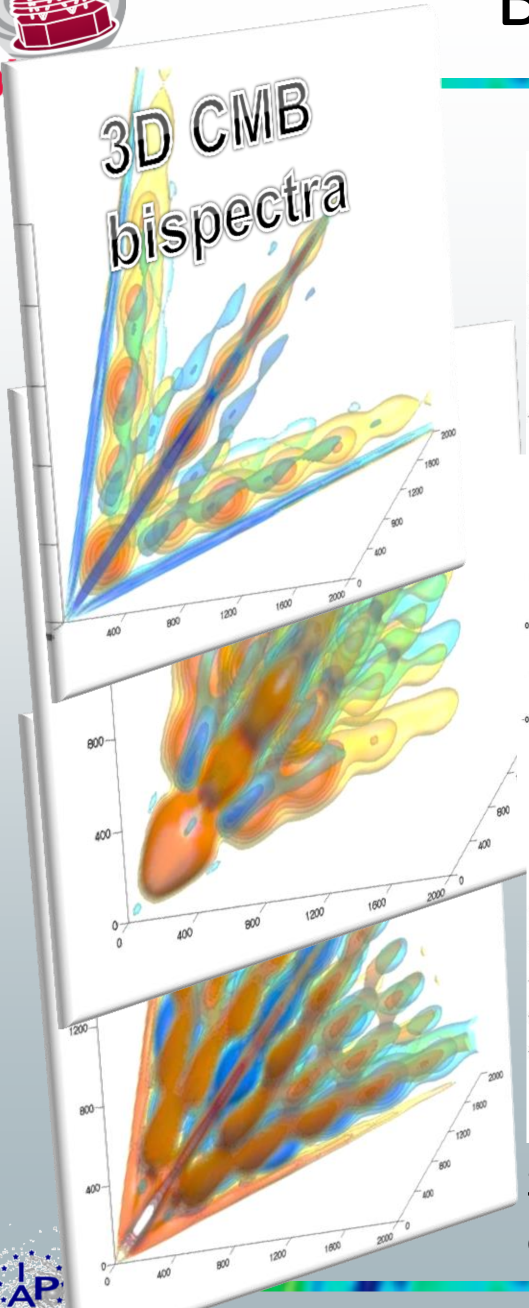
NG of ***equilateral*** type ($k_1 \sim k_2 \sim k_3$):

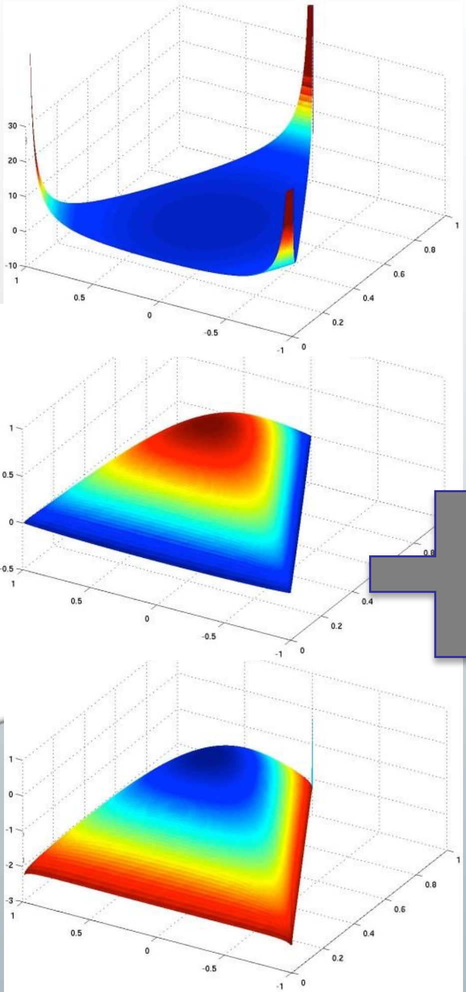
- Non-canonical kinetic term
  - K-inflation
  - DBI inflation
- Higher-derivate terms in Lagrangian
  - Ghost inflation
- Effective field theory

NG of ***orthogonal*** type ($k_1 \sim 2k_2 \sim 2k_3$) :

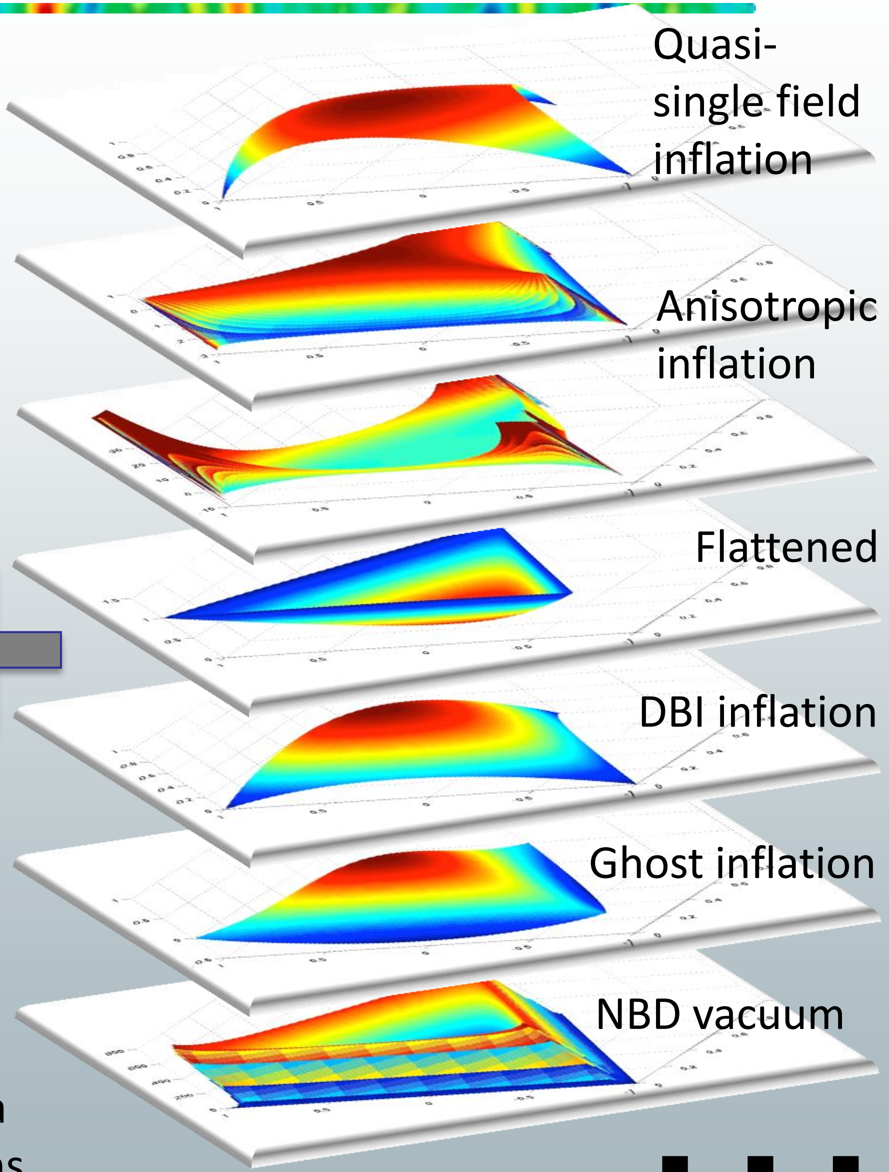
- Distinguishes between different variants of
  - Non-canonical kinetic term
  - Higher derivative interactions
- Galileon inflation

Bispectrum fingerprinting





Slices through bi-spectra of primordial fluctuations



Quasi-single field inflation

Anisotropic inflation

Flattened

DBI inflation

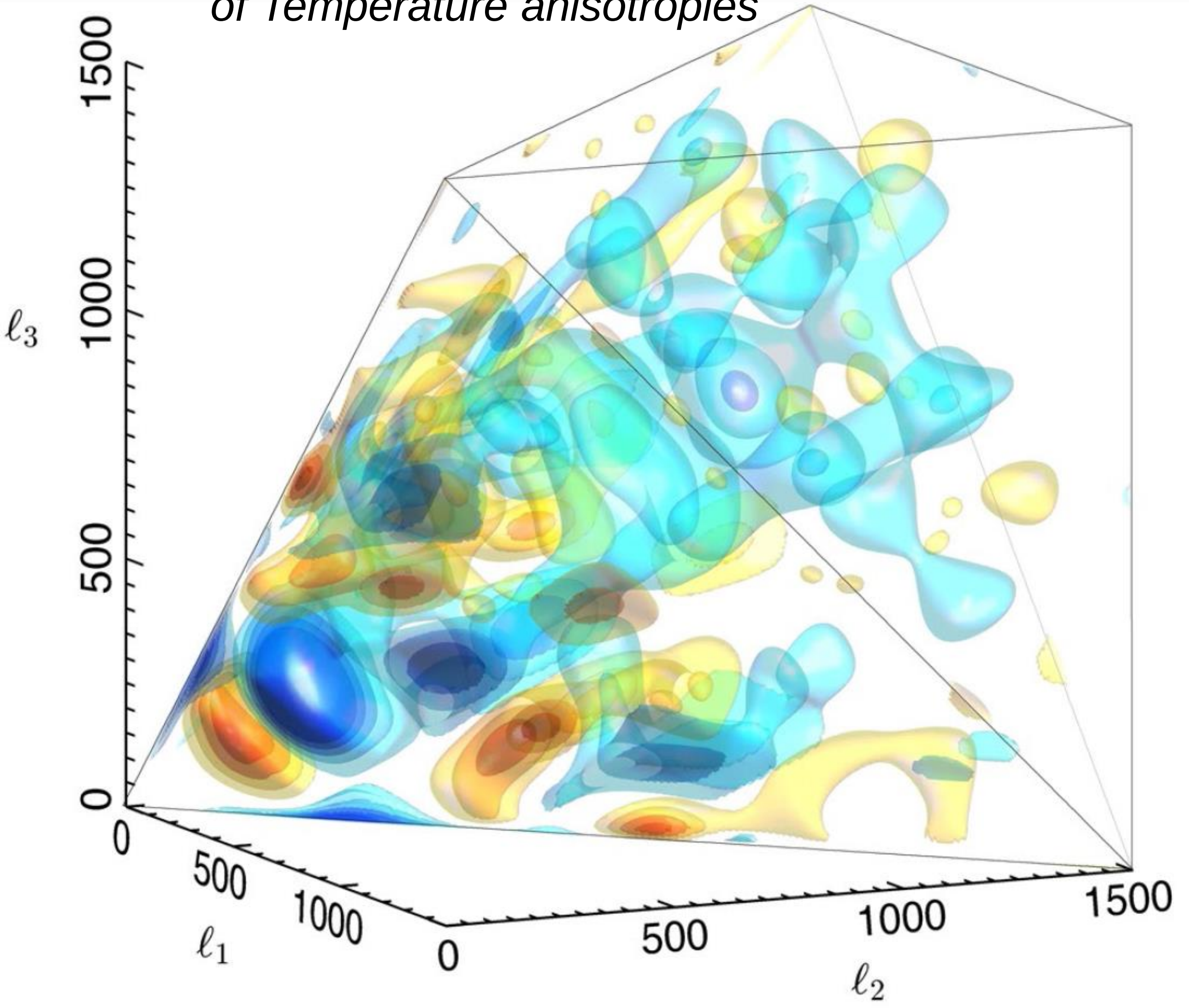
Ghost inflation

NBD vacuum

■ ■ ■

The Planck CMB bispectrum

of Temperature anisotropies



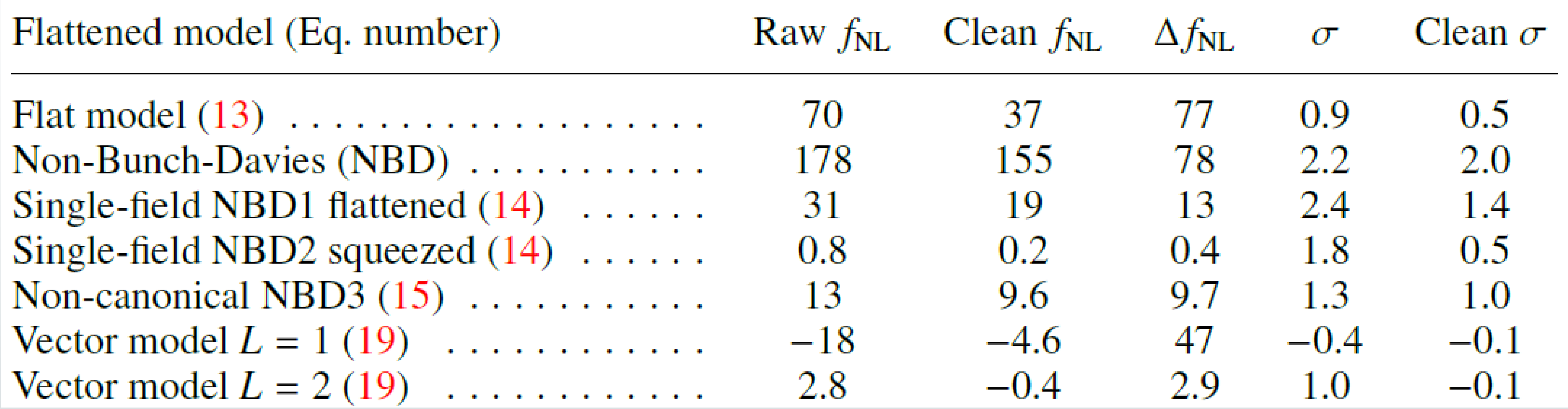
(modal decomposition on SMICA)

f^{local}= 2.7±5.8,
f^{equil} =-42±75,
f^{ortho}=-25±39
68%CL

WMAP-9 (68% CL)
f^{local}= 37± 20
f^{equil} =51±136,
f^{ortho}=-245±100,
(Non-joint)

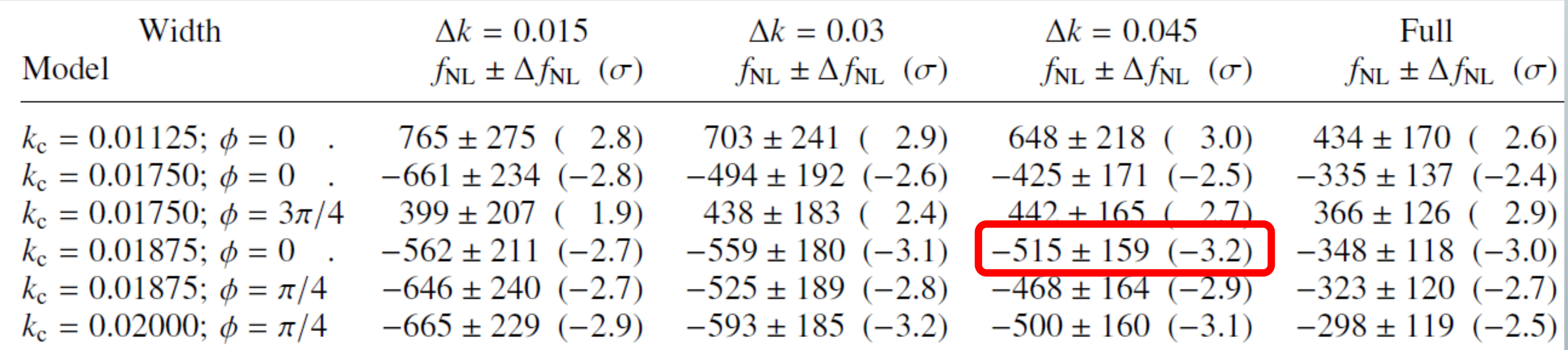
Searching specific shapes...

→ To no avail for flattened shapes...



Flattened model (Eq. number)	Raw $f_{\rm NL}$	Clean $f_{\rm NL}$	$\Delta f_{\rm NL}$	σ	Clean σ
Flat model (13)	70	37	77	0.9	0.5
Non-Bunch-Davies (NBD)	178	155	78	2.2	2.0
Single-field NBD1 flattened (14)	31	19	13	2.4	1.4
Single-field NBD2 squeezed (14)	0.8	0.2	0.4	1.8	0.5
Non-canonical NBD3 (15)	13	9.6	9.7	1.3	1.0
Vector model $L = 1$ (19)	−18	−4.6	47	−0.4	−0.1
Vector model $L = 2$ (19)	2.8	−0.4	2.9	1.0	−0.1

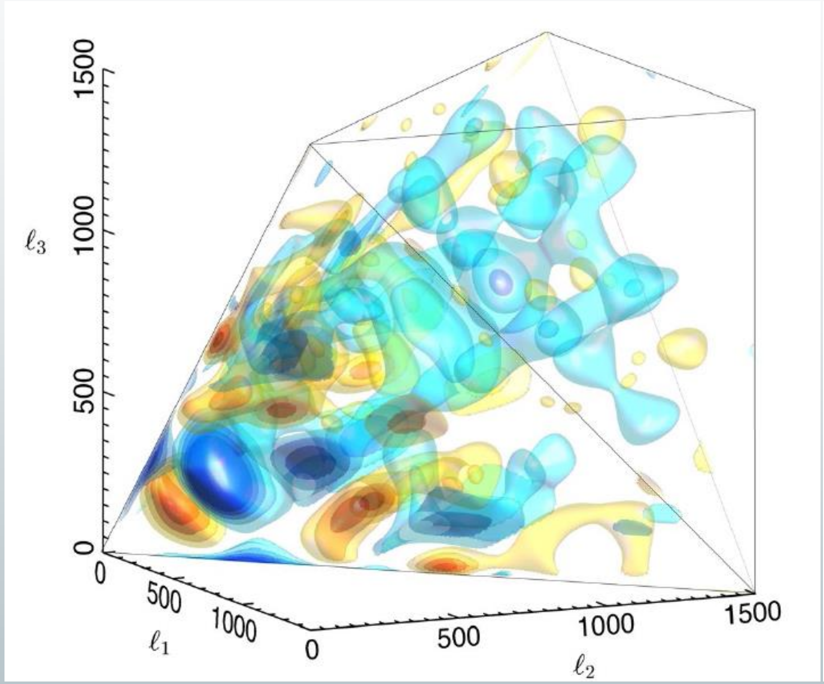
→ But with tantalising hints for some feature models...



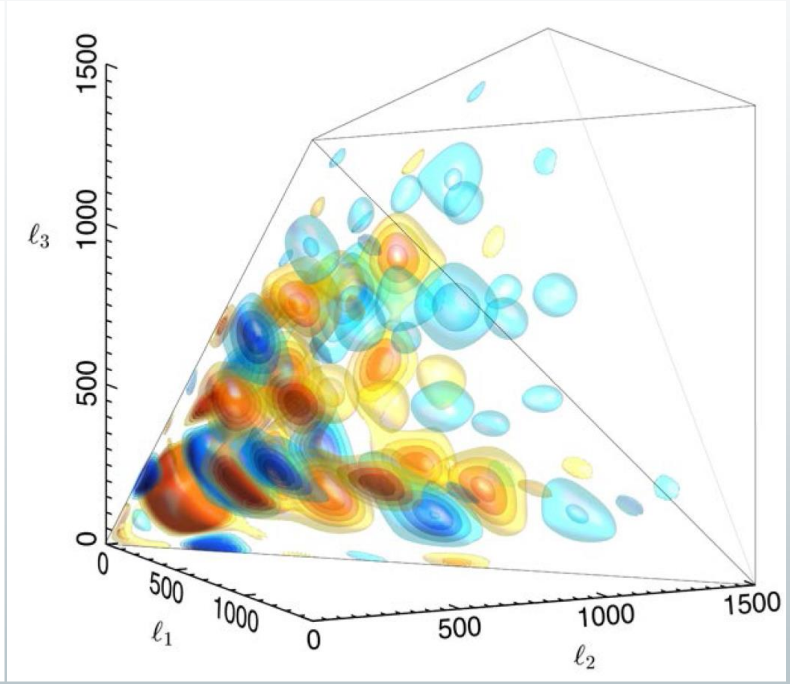
Width Model	$\Delta k = 0.015$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\Delta k = 0.03$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\Delta k = 0.045$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	Full $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)
$k_c = 0.01125;\ \phi = 0$.	765 ± 275 (2.8)	703 ± 241 (2.9)	648 ± 218 (3.0)	434 ± 170 (2.6)
$k_c = 0.01750;\ \phi = 0$.	−661 ± 234 (−2.8)	−494 ± 192 (−2.6)	−425 ± 171 (−2.5)	−335 ± 137 (−2.4)
$k_c = 0.01750;\ \phi = 3\pi/4$	399 ± 207 (1.9)	438 ± 183 (2.4)	442 ± 165 (2.7)	366 ± 126 (2.9)
$k_c = 0.01875;\ \phi = 0$.	−562 ± 211 (−2.7)	−559 ± 180 (−3.1)	−515 ± 159 (−3.2)	−348 ± 118 (−3.0)
$k_c = 0.01875;\ \phi = \pi/4$	−646 ± 240 (−2.7)	−525 ± 189 (−2.8)	−468 ± 164 (−2.9)	−323 ± 120 (−2.7)
$k_c = 0.02000;\ \phi = \pi/4$	−665 ± 229 (−2.9)	−593 ± 185 (−3.2)	−500 ± 160 (−3.1)	−298 ± 119 (−2.5)

3.2-sigma hint of oscillatory feature?

Data

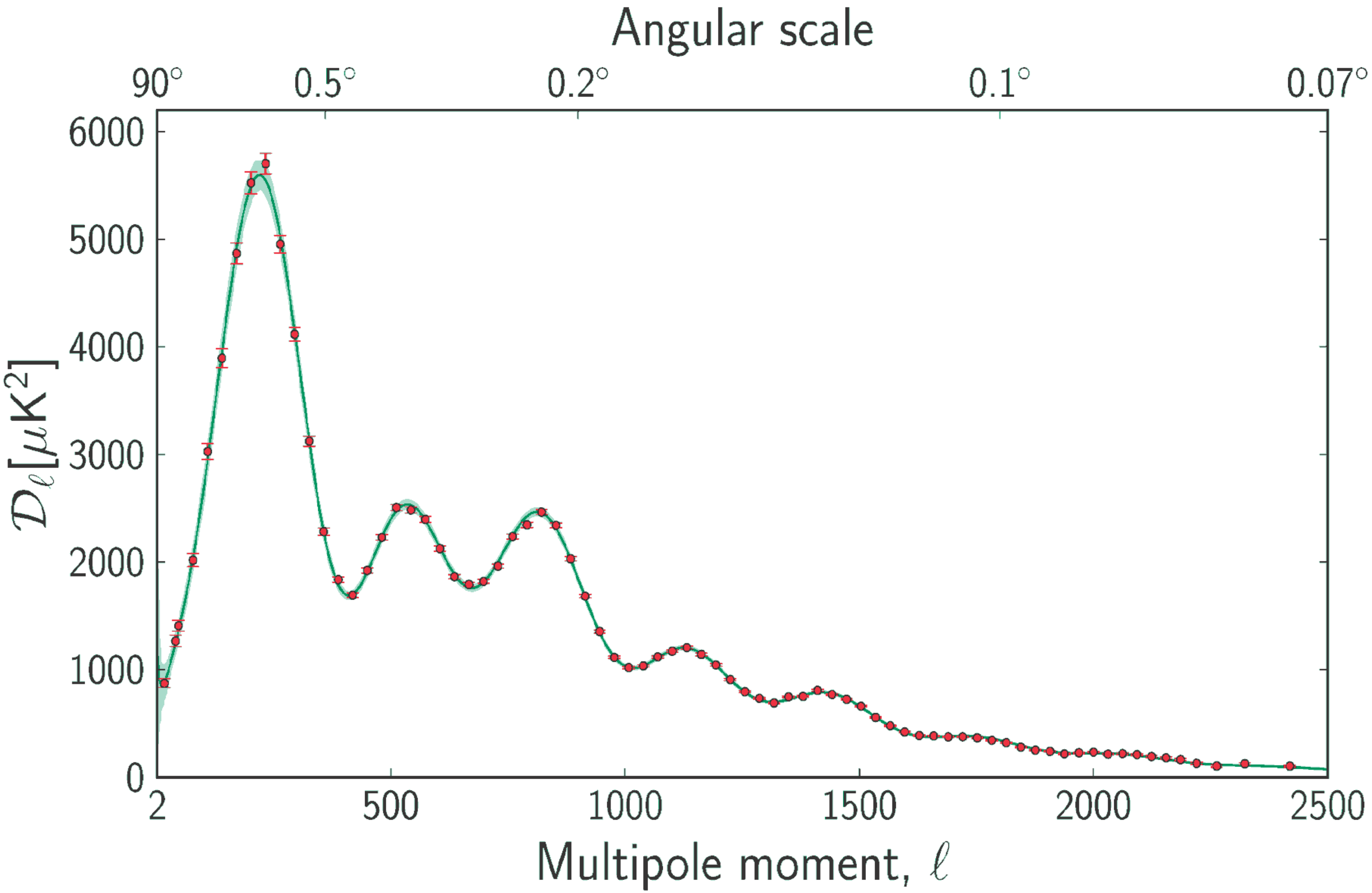


Best fit feature model bispectrum

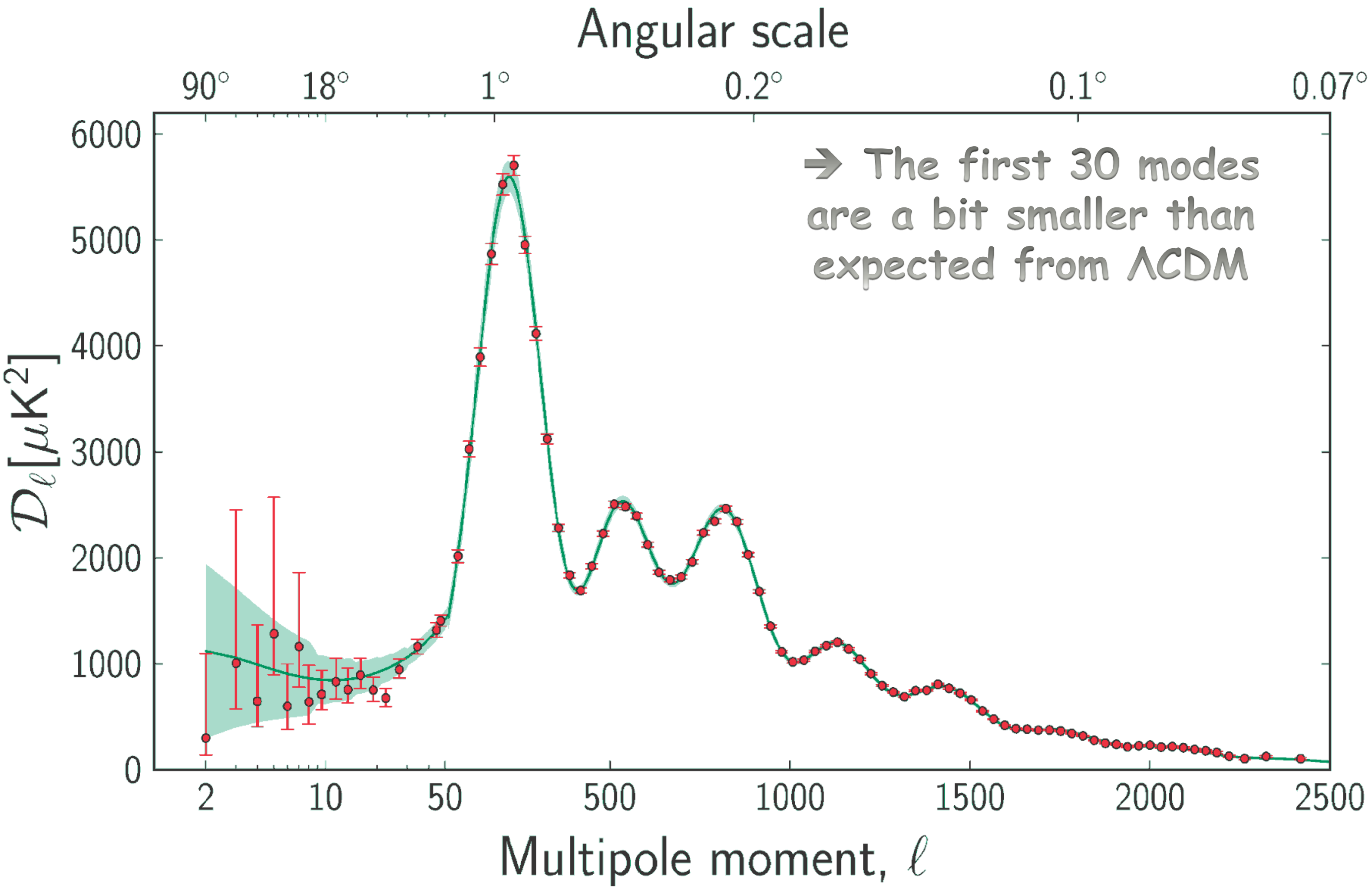


Not (yet?) highly significant if “look-elsewhere” effect is taken into account.
➔ Warrants further analysis.

A theorist dream, or nightmare?

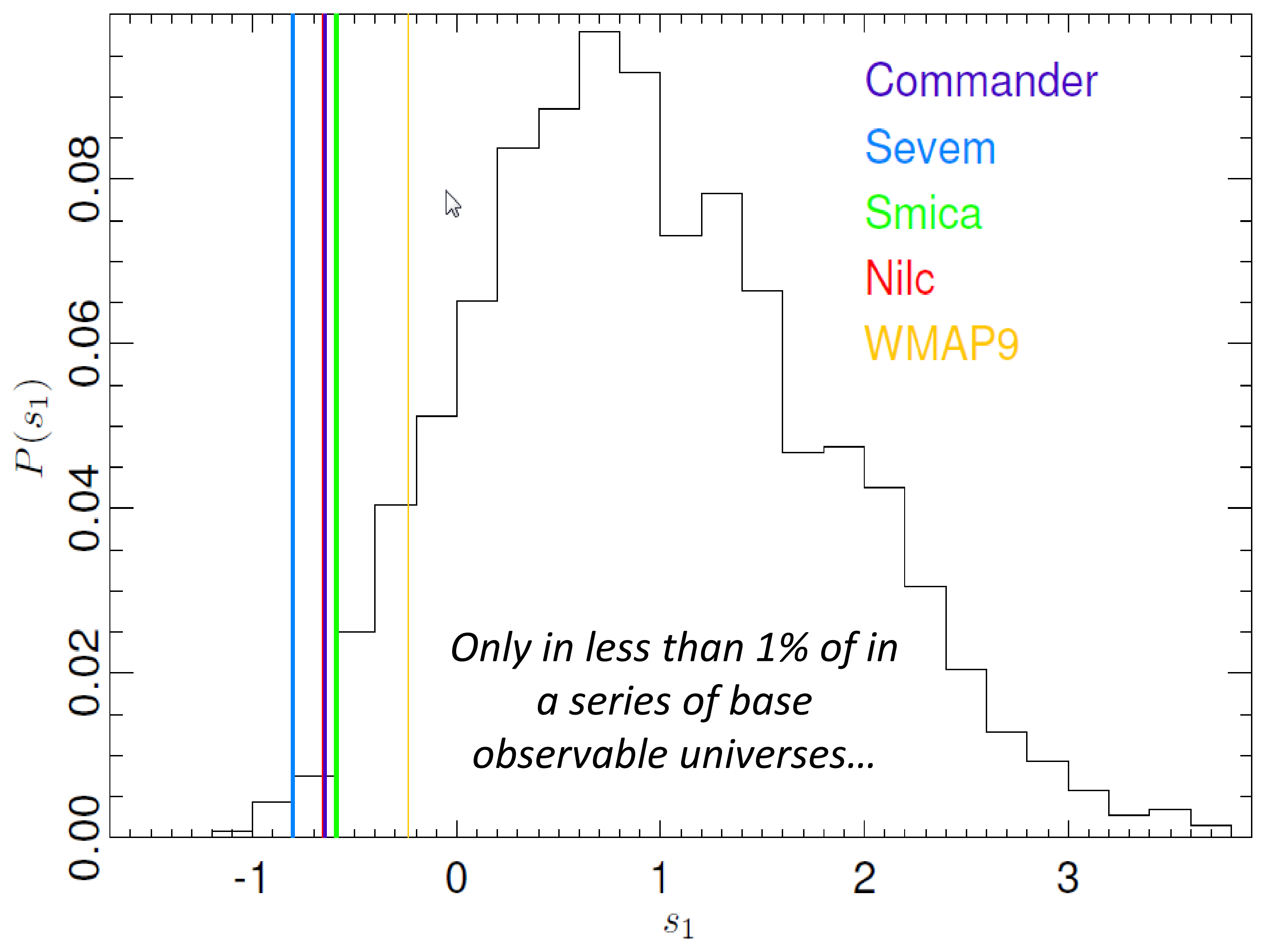


Zooming on the very largest scales, l<50…



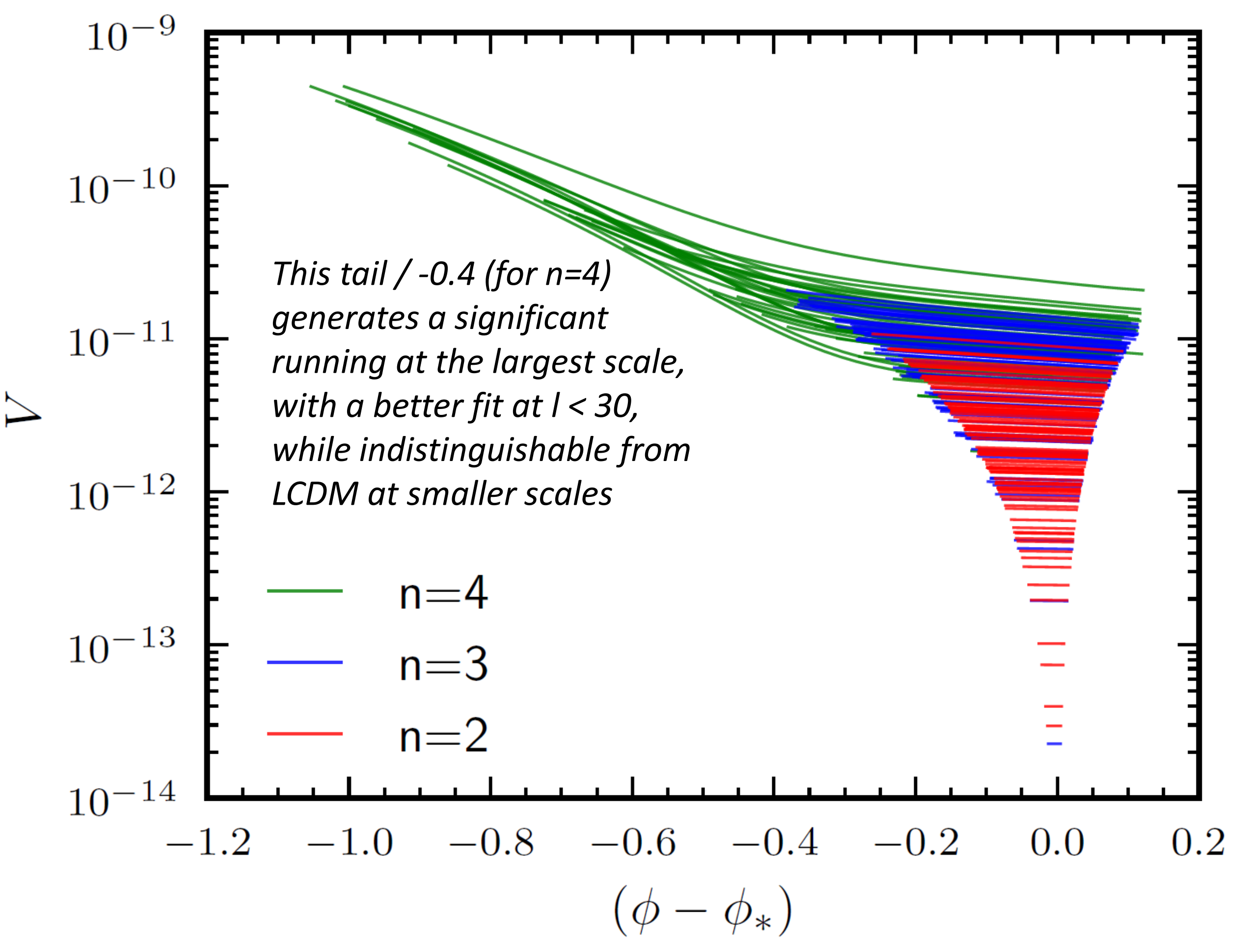
➔ The first 30 modes are a bit smaller than expected from ΛCDM

How significant is this anomaly?



Only in less than 1% of in a series of base observable universes…

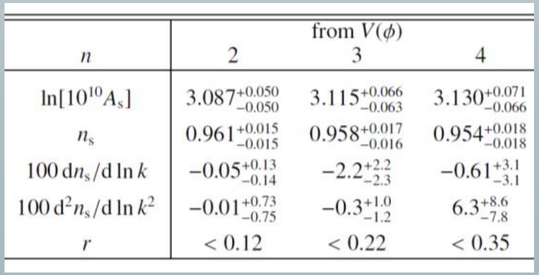
Inflaton potential reconstruction



This tail / -0.4 (for n=4) generates a significant running at the largest scale, with a better fit at l < 30, while indistinguishable from LCDM at smaller scales

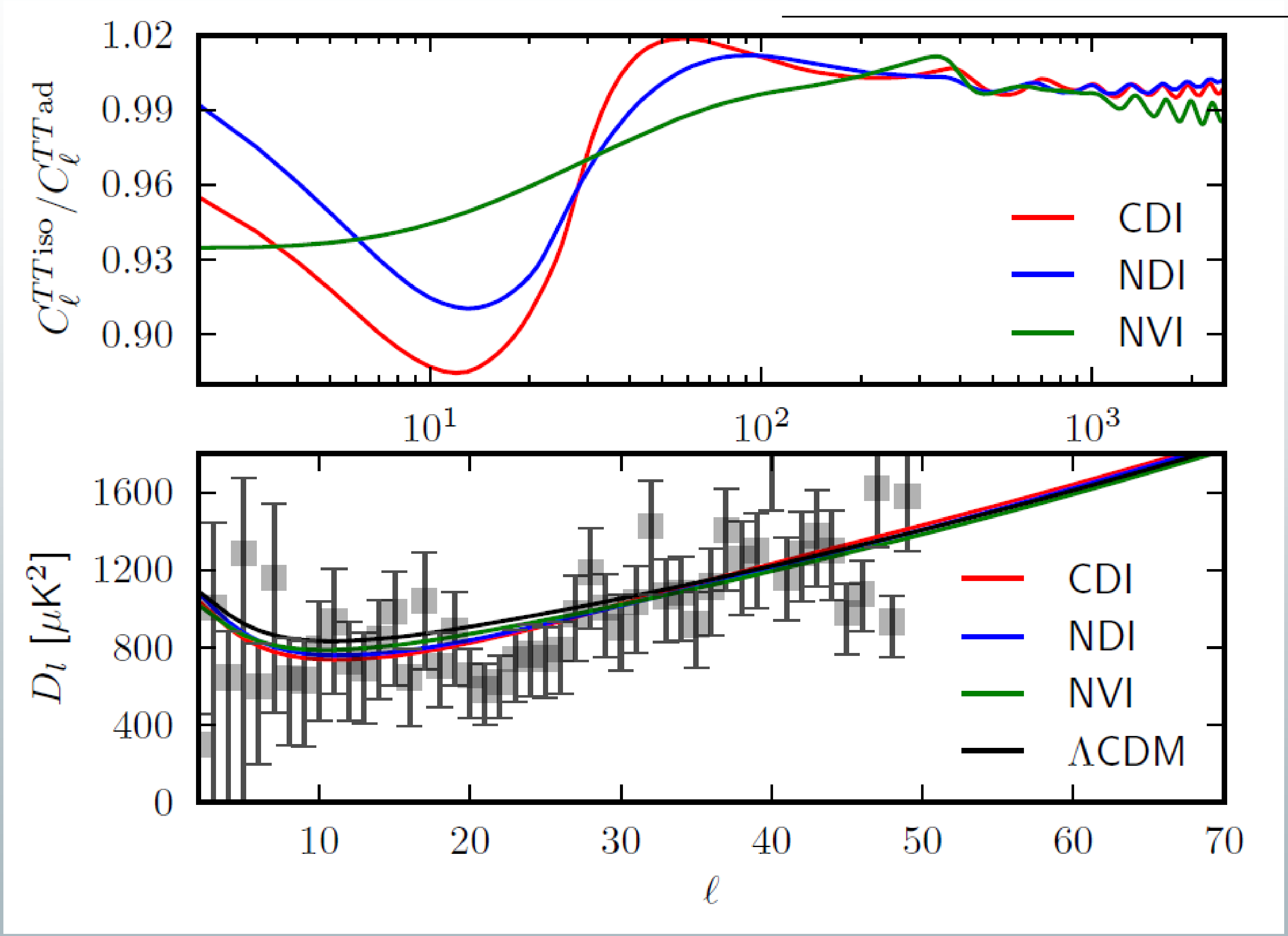
Best fitting potentials, when V(ϕ) is Taylor expanded at the n-th order around the pivot scale;
Planck-T+WP;
Flat priors on ε, η, ξ^2;

Φ$_*$ in natural units / (8π)$^{1/2}$Mp=1.



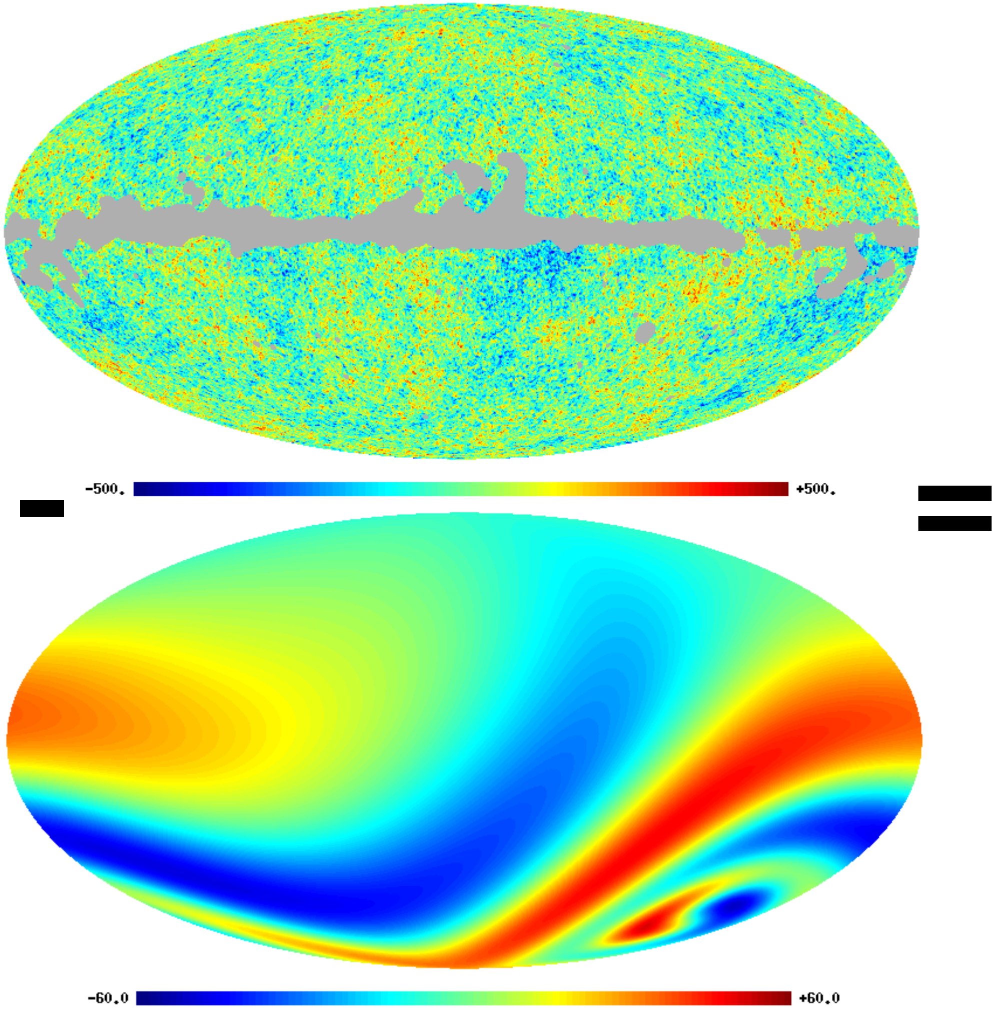
n	from $V(\phi)$ 2	 3	 4
$\ln[10^{10}A_s]$	$3.087^{+0.050}_{-0.050}$	$3.115^{+0.066}_{-0.063}$	$3.130^{+0.071}_{-0.066}$
n_s	$0.961^{+0.015}_{-0.015}$	$0.958^{+0.017}_{-0.016}$	$0.954^{+0.018}_{-0.018}$
$100\,\mathrm{d}n_s/\mathrm{d}\ln k$	$-0.05^{+0.13}_{-0.14}$	$-2.2^{+2.2}_{-2.3}$	$-0.61^{+3.1}_{-3.1}$
$100\,\mathrm{d}^2 n_s/\mathrm{d}\ln k^2$	$-0.01^{+0.73}_{-0.75}$	$-0.3^{+1.0}_{-1.2}$	$6.3^{+8.6}_{-7.8}$
r	< 0.12	< 0.22	< 0.35

Assuming a single isocurvature mode

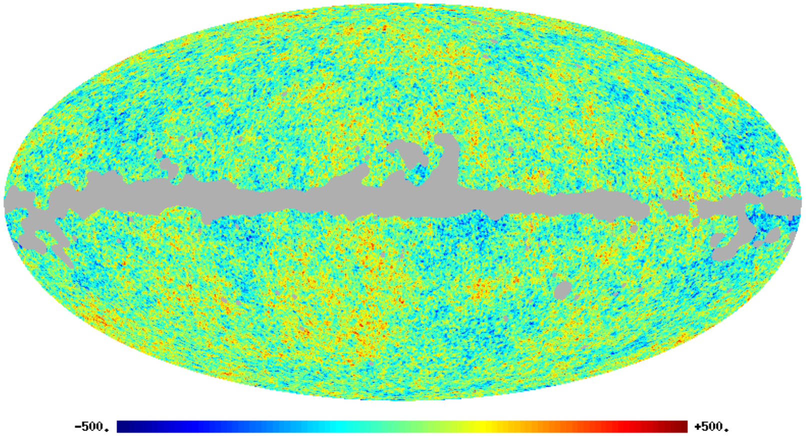


… helps (somewhat) at low-l (again!)

The « Bianchi » anomaly



Removing a Bianchi VIIh leaves a manifestly more isotropic CMB sky



NB: this Bianchi model needs to be open to fit the data…

Detection of Doppler boosting

- Planck's high sensitivity and angular resolution allows for the first direct detection of relativistic Doppler boosting in the CMB fluctuations

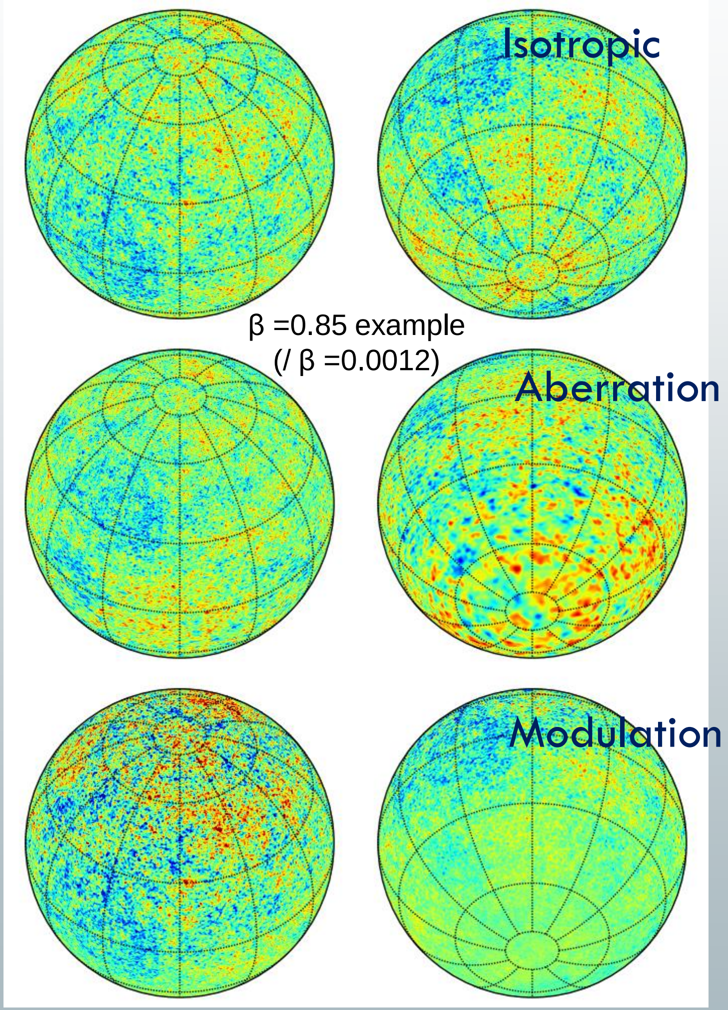
$$T(\hat{n}) = \frac{T'(\hat{n}')}{\gamma(1 - \hat{n} \cdot \beta)}$$

- Two different effects are relevant, both of which are frequency-dependent:
  - Aberration: Spots are smaller in the direction of Earth's motion
  - Dipole modulation: Features are enhanced in the direction of Earth's motion
- Planck uses these to measure the Earth's velocity ***independently*** of the CMB dipole

  v = 384 ± 78 (stat) ± 115 (syst) km s^{-1}

  (to compare to v_dipole = 368 ± 2 km s^{-1})
- **Modulation explains at least part of the high-*l* hemispherical asymmetry.**

Eppur si muove



Planck 2013 XXVII

Conclusions 1/2

- ***Excellent agreement between the Planck temperature spectrum at high l and the predictions of the tilted ΛCDM model using the simplest slow-roll inflationary models;***
- ***But with tantalizing hints both at low-l (<30) and high-l... (is there a model tying all Large Scale anomalies?)***

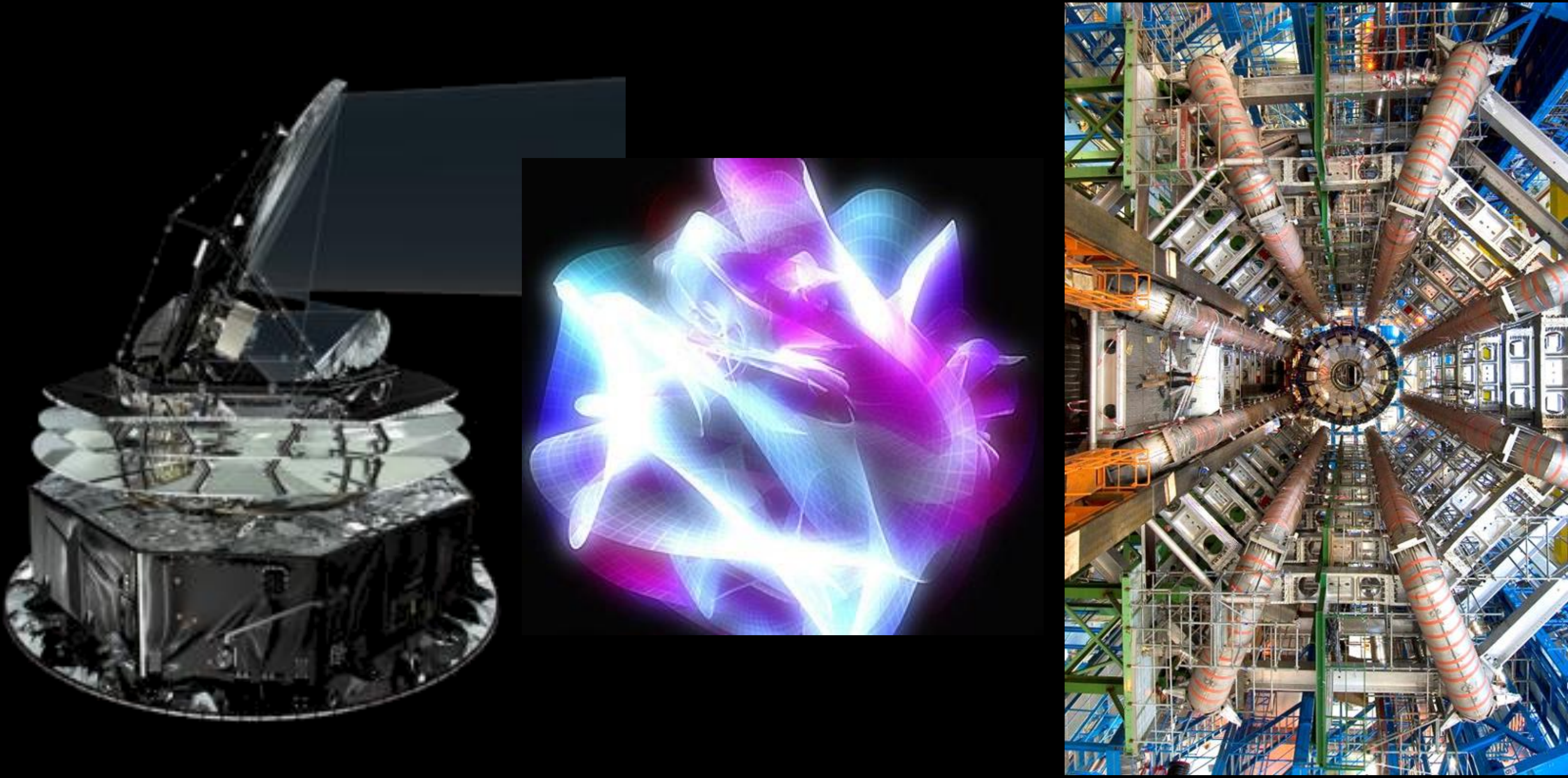
- n_s=0.963 ±0.006 from PT+WP+BAO; → HZ robustly excluded
- Ω_K=-0.006±0.018 at 95%CL from Planck-T+L → flat spatial geometry
- f_{NL}^{LEO} (and others) consistent with zero; → most stringent test of Gaussianity performed to date.
- No evidence for cosmic defects. Nambu-Goto strings have $G\mu/c^2 < 1.3 \times 10^{-7}$ ($\eta < 4.7 \times 10^{15}$ GeV).
- $r_{0.002} < 0.12$ (PT+WP alone) → inflation energy scale $< 1.9 \times 10^{16}$ GeV at 95%CL.
- Concave potentials preferred.
- Strong constraints on parameters values of specific inflationary scenario
- Potential reconstructed in observable window shows that allowing a fourth order leads to deviation to slow-roll, and allows a better fit to the low-l data (improvement of $\Delta\chi^2_{eff}$ ~4). Idem when allowing for CDI isocurvature.

Conclusions 2/2

- Planck data allows *much* additional exciting science (often in conjunction):
  - *Lensing science (cross-correlations with LSS probes)*
  - *SZ clusters science (the rarest ones, with X-ray, LSS, low-z lensing)*
  - *CIB science (high-redshift galaxies)*
  - *Galactic Interstellar Medium (CO, dark gaz, polarisation…)*
  - *All ESLAB slides at http://www.rssd.esa.int/index.php?project=PLANCK&page=47_ESLAB*

- Next Planck data release will be mid - 2014
  - *Twice as much data*
    - HFI, ~900 billions samples, complete since Jan 12th 2012, after 885 days of survey, 5 sky surveys
    - LFI is still in operation; in August 2013 it will reach 8 observed sky surveys.
  - *Less «conservative» temperature analyses, and further checks of tantalising hints/anomalies*
  - *Polarisation!*
  - *Expected results:*
    - Better Temperature science (more redundancy & checks, improved analyses...)
    - By measuring B modes polarisation, Planck may detect primordial gravitational waves
      - From B modes we can measure the energy scale of inflation and constrain the nature of the “inflaton”
    - Polarisation will help foray deeper into Non-Gaussianity analysis
    - Further handles to understand if the “deviations” are fundamental and if we need a “new physics”

Exciting times



Still Lie ahead

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: 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.

"Cosmology & Fundamental Physics with Planck", CERN