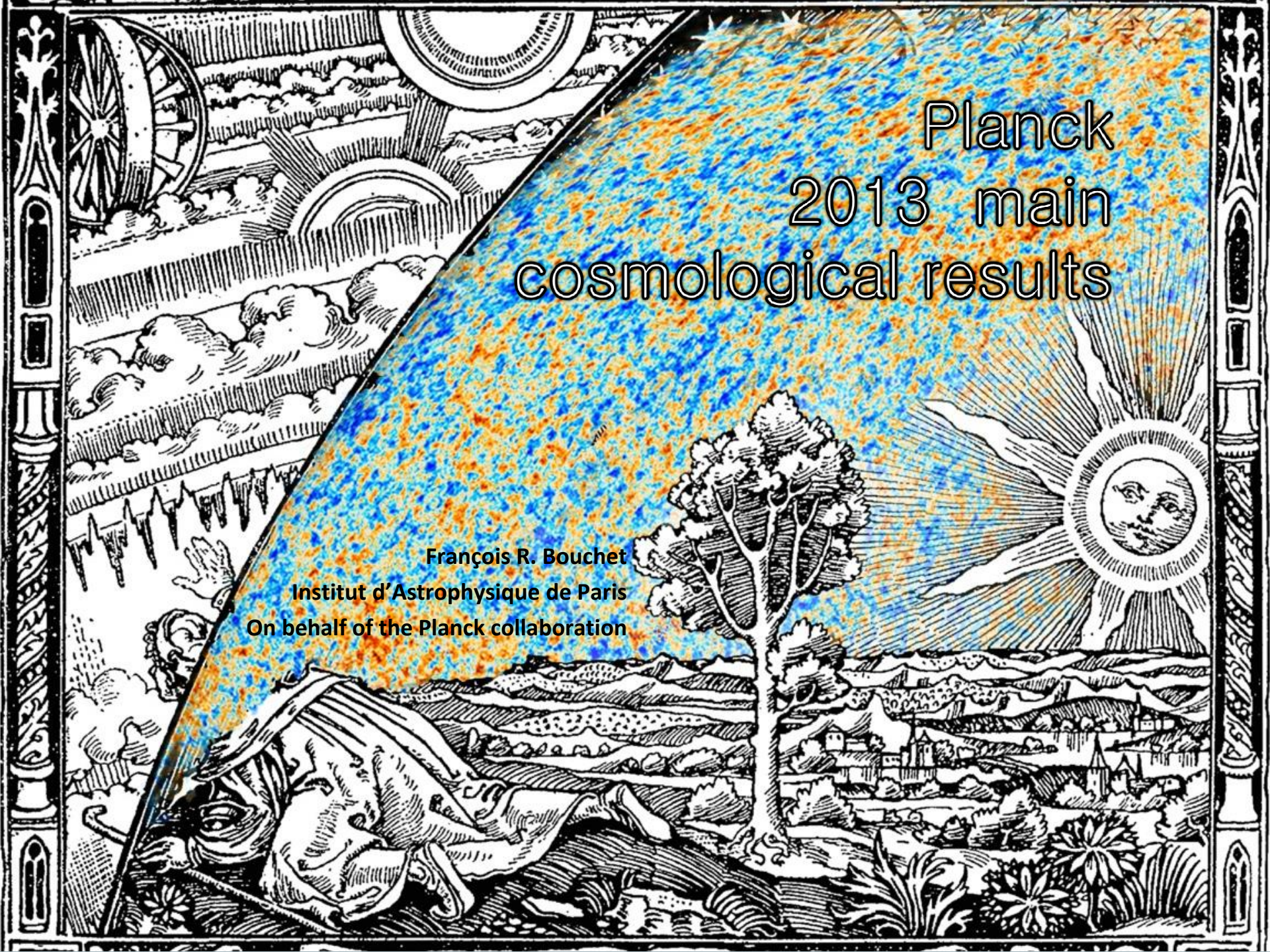


Planck 2013 main cosmological results

François R. Bouchet

Institut d'Astrophysique de Paris

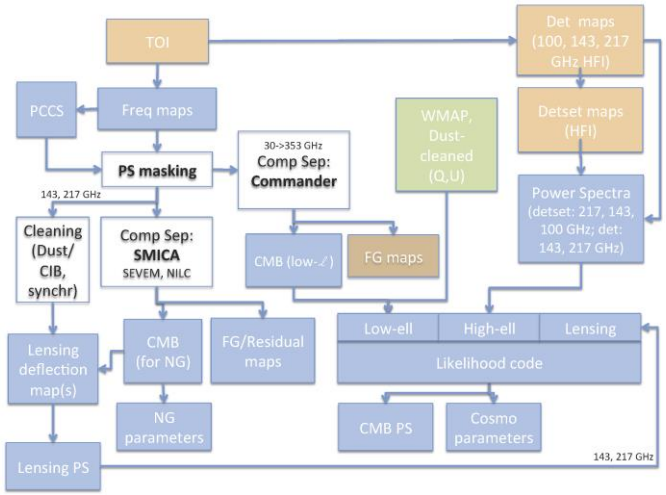
On behalf of the Planck collaboration

Planck 2013 data and results

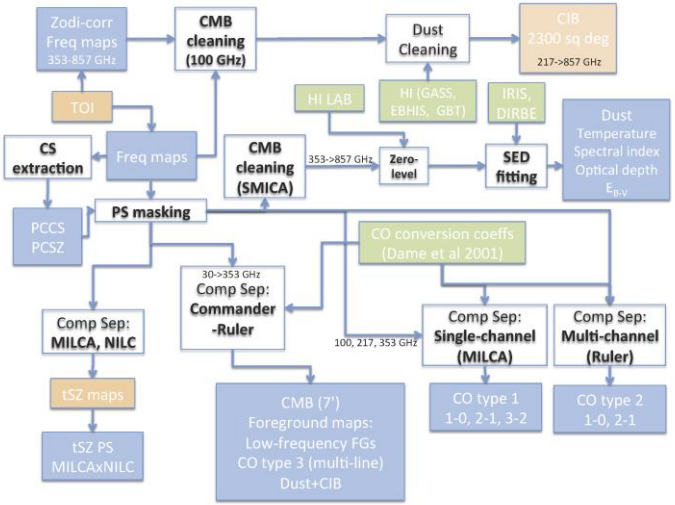
- Overview of products & results (I)
  - Frequency Maps, Component Maps, Power Spectra, Parameters
- LFI Processing (II)
  - LFI Systematics (III)
  - LFI Beams (IV)
  - LFI Calibration (V)
- HFI Processing (VI)
  - HFI Time Response & Beams (VII)
  - HFI Calibration (VIII)
  - HFI Spectral Response (IX)
  - HFI Particle effects (X)
- Consistency of the Data (XI)
- Component Separation (XII)
  - Galactic CO (XIII)
  - Zodiacal Emission (XIV)
- Power Spectra & Likelihood (XV)

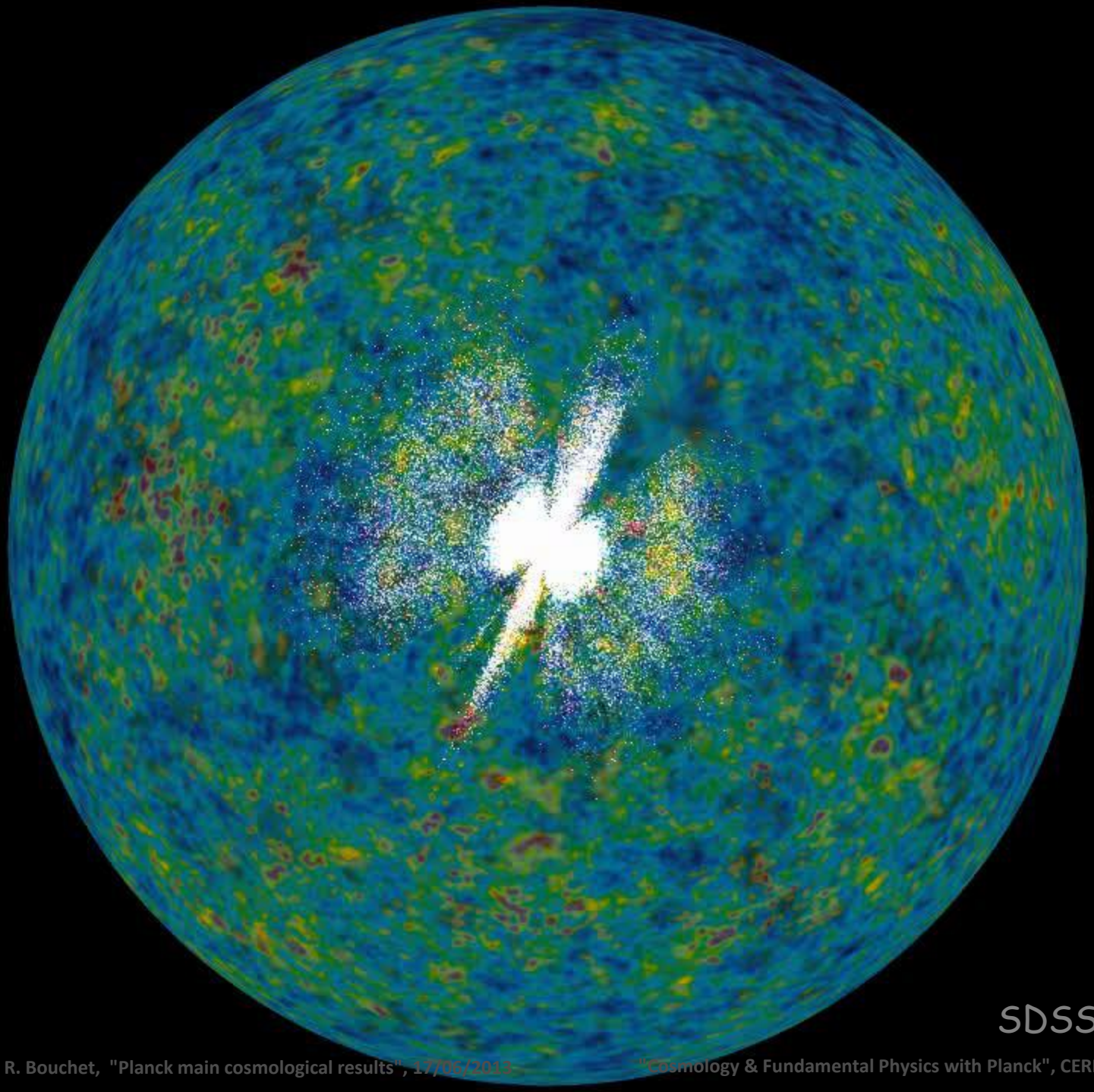
> 1000 pages

- 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





SDSS & WMAP

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*

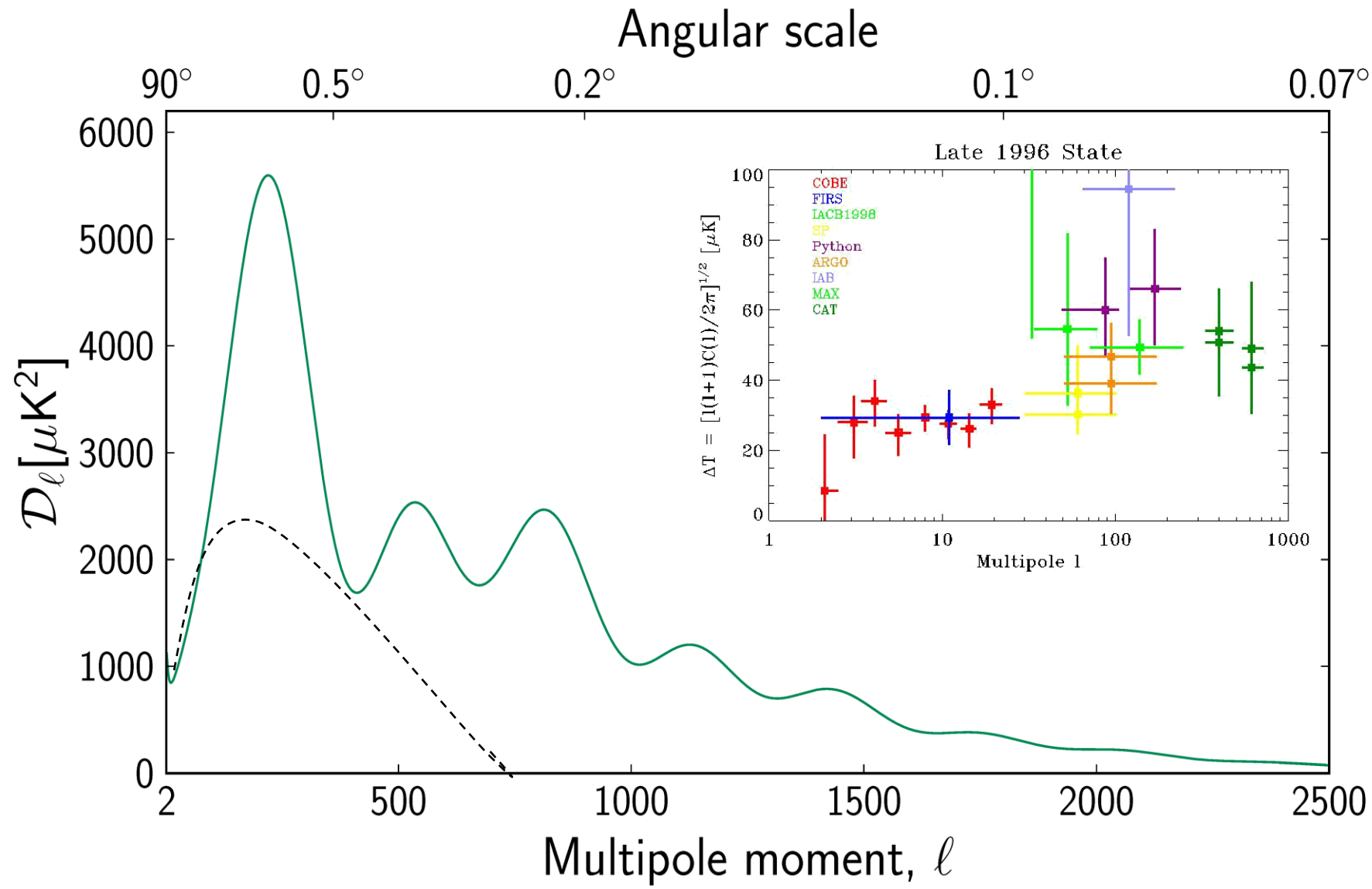
  ⇒ *enough sensitivity within large frequency range [30 GHz, 1 THz] (~CMB photon noise limited for ~1yr in CMB primary window)*

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

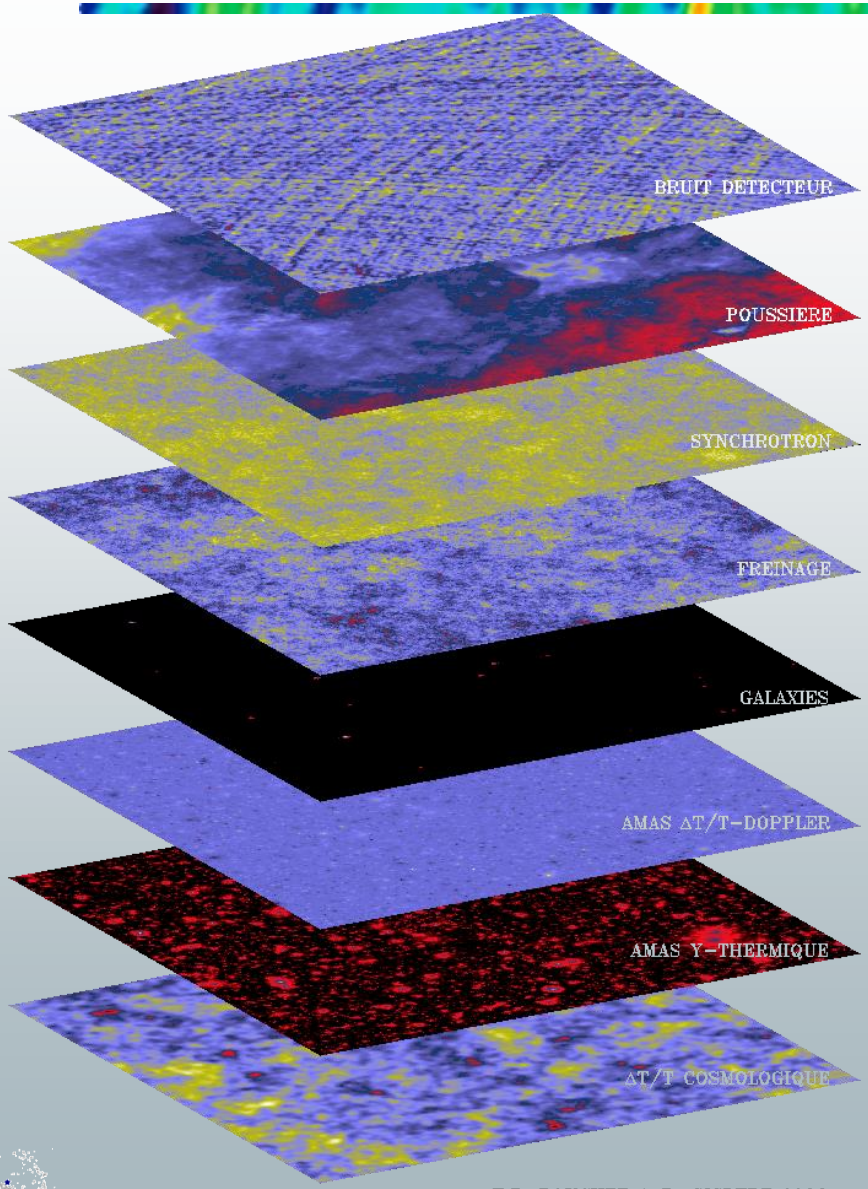
⇒ ESA selection in 1996 (after ~ 3 year study)

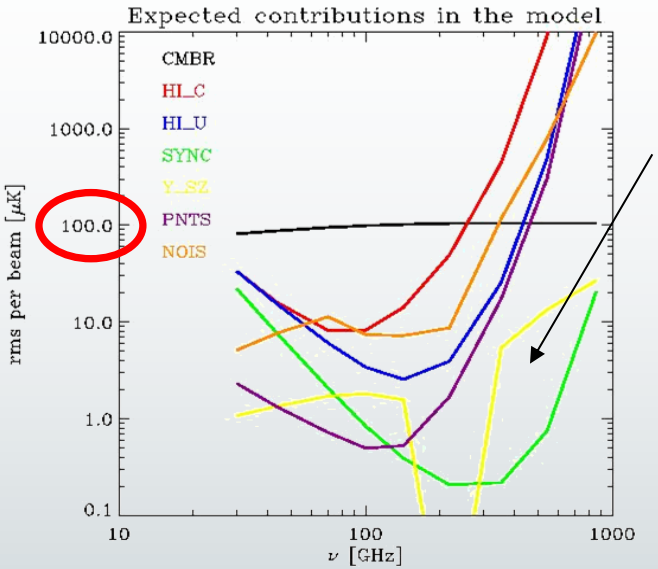
NB: with the Ariane 501 failure delaying us by several years (03 → 07) and WMAP then flying well before us, polarization measurements became more and more a major goal

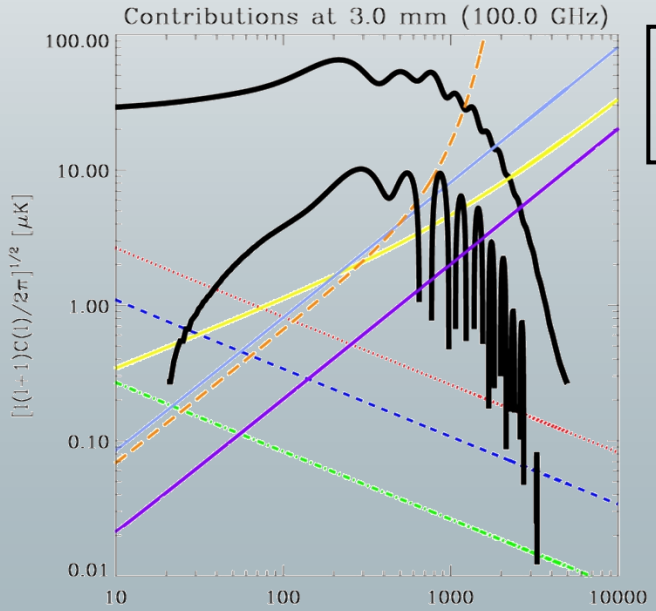
Visualising the target



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 ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

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

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

Planck needed breakthroughs

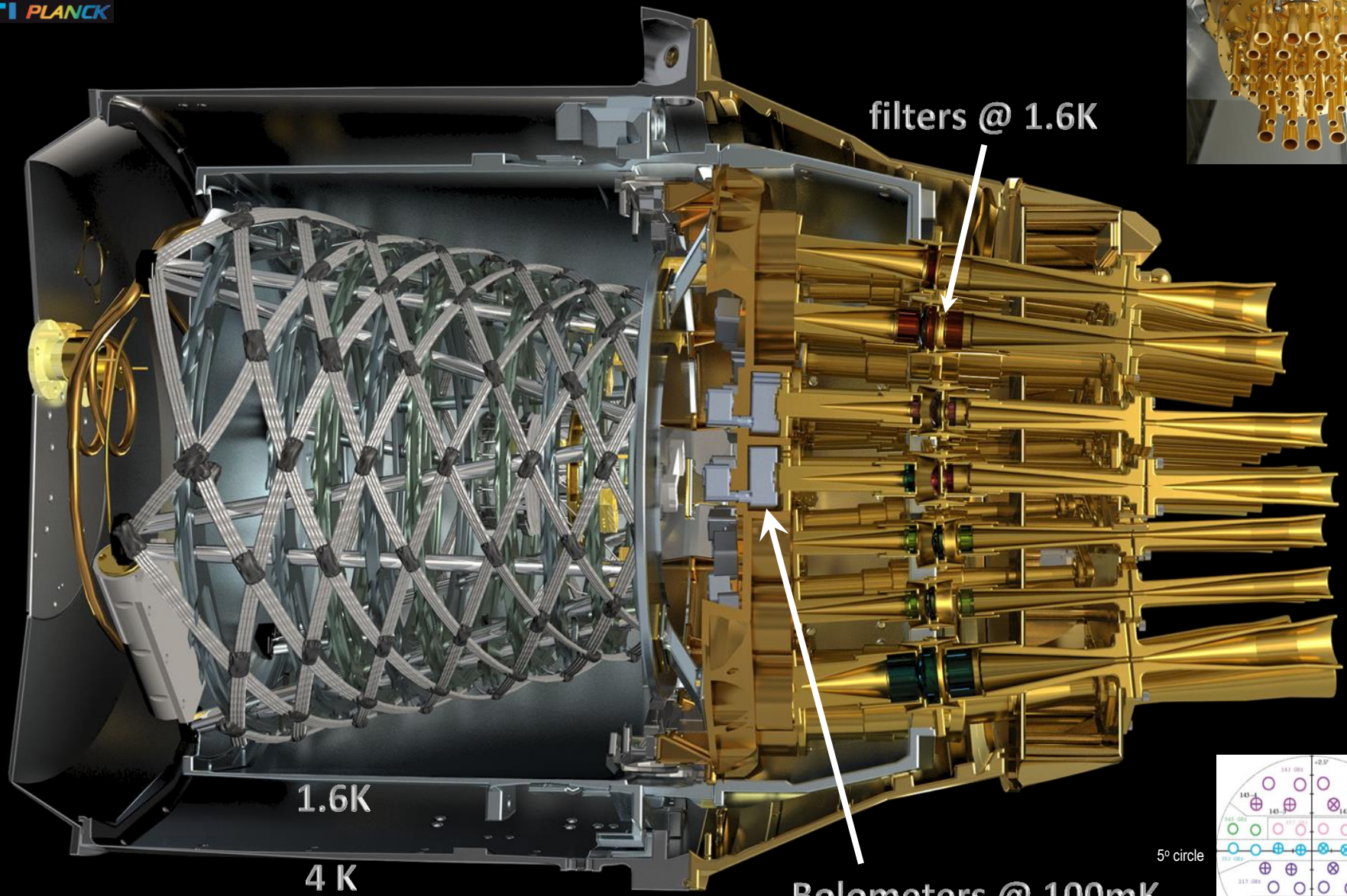
- The performance goals of Planck required several technological performances never achieved in space before
  - *Sensitive & fast bolometers with*
    - NEP< 2 10^{-17} W/Hz$^{1/2}$ & time constants typically < 5 msec

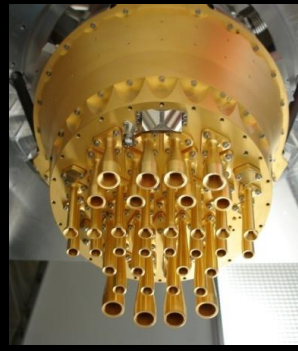
      (thus cooling them to 100 mK, very low heat capacity & charged particles sensitivity)
  - *total power read out electronics with very low noise*
    - < 6nV/Hz$^{1/2}$ from 10 mHz to 100 Hz
  - *Excellent temperature stability, from 10 mHz (1 rpm) to 100 Hz (cf. Lamarre et al. 04)*
    - < 10 µK/Hz$^{1/2}$ 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)*

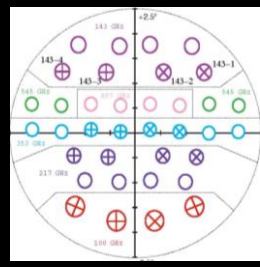
⇒ *Integration of 3 intertwined complex chains - optical, electronic, cryogenic*

planck

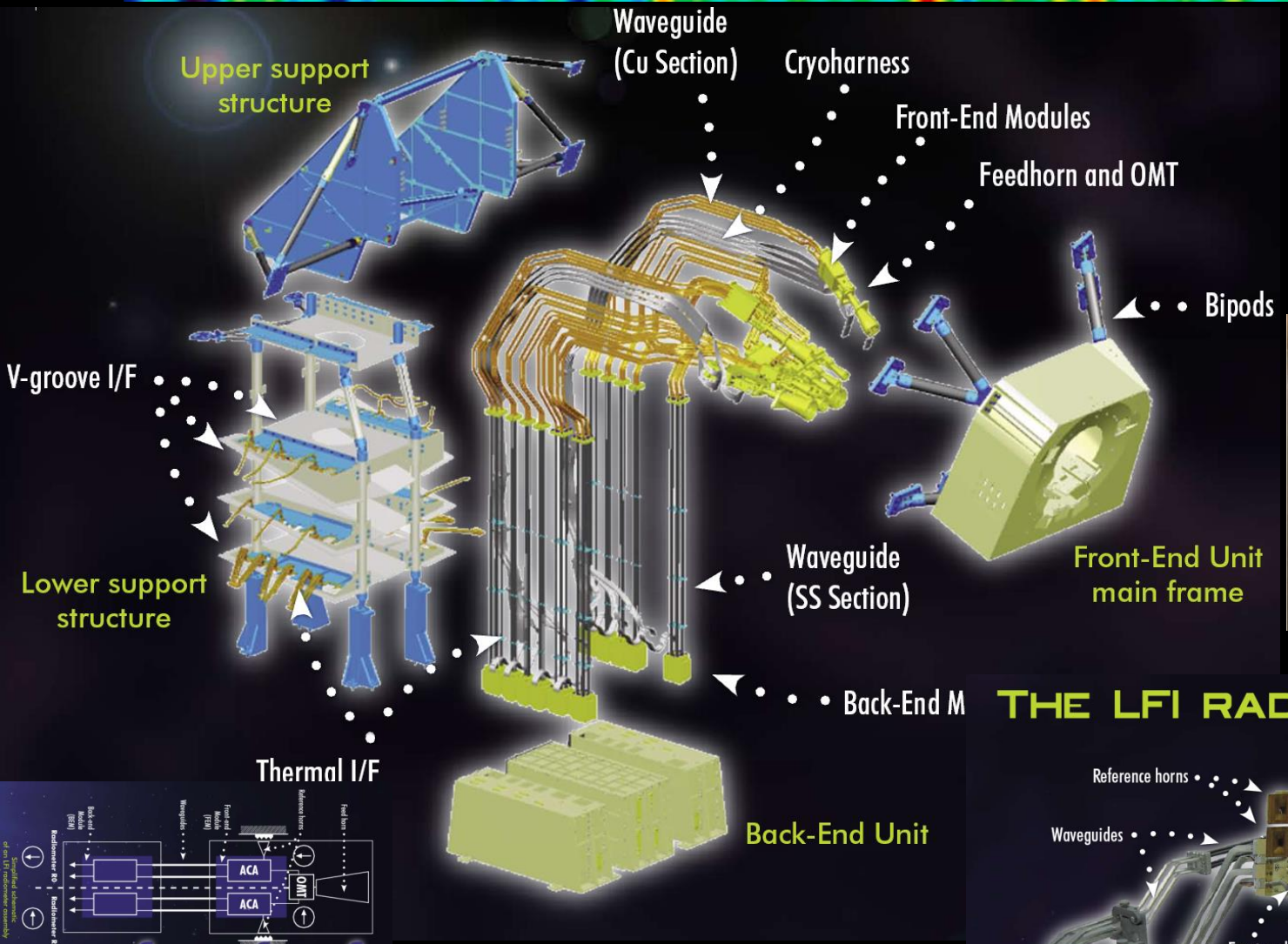
HFI cut-away

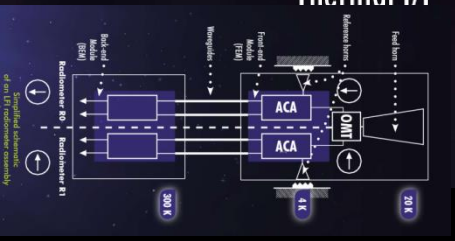


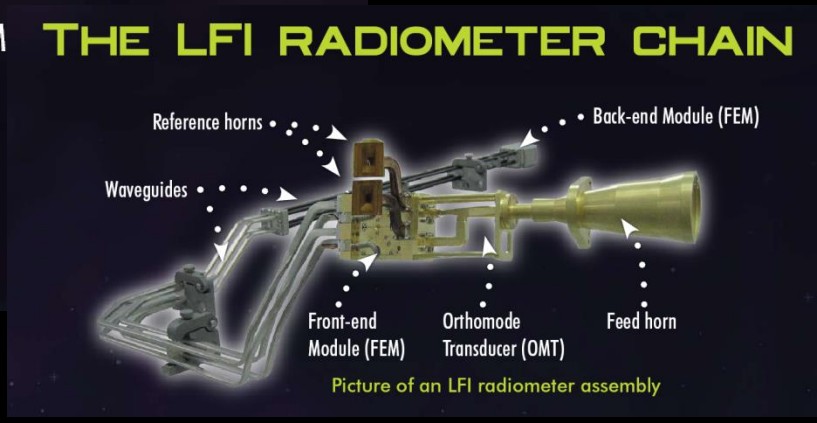




The Low Frequency Instrument LFI







DUSTING IT OFF…
AFTER 16 YEARS
OF HOPES & WORK

Ariane 5 ECA Launch • HERSCHEL – PLANCK - May 14, 2009

Log Book (``a bit'' abridged)

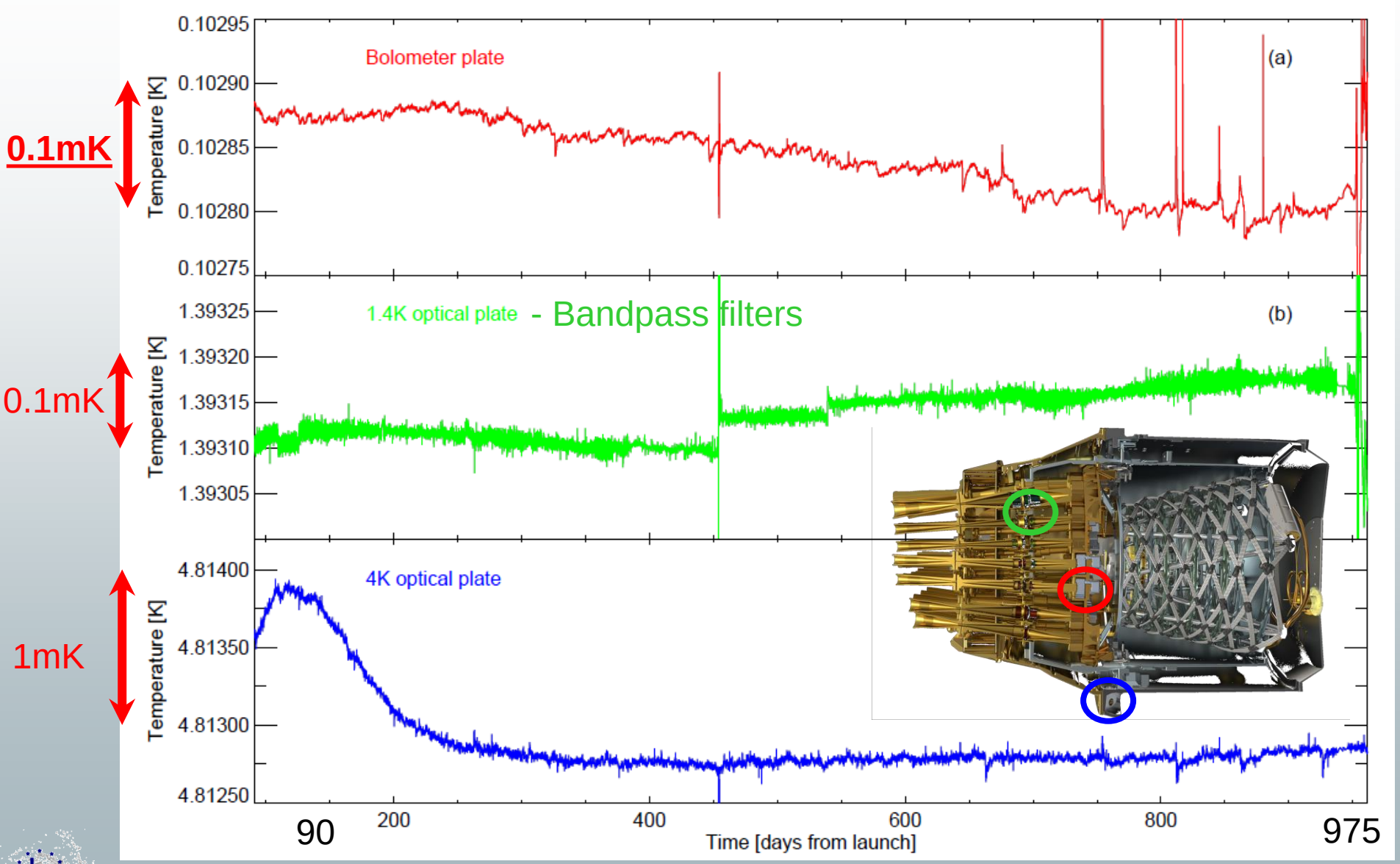
- August 13th 2009 : beginning of survey: Instruments very stable, continuously mapping the sky
- Essentially no hiccups since, till the end of HFI: Details in 16 monthly reports to MOC, 13 bi-monthly to PSO (150 p. each), 138 « operation » teleconf. minutes, 169 weekly reports to MOC, 91 « cryo » teleconf., 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**;

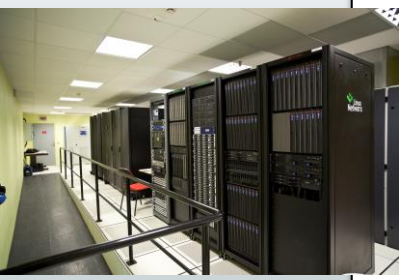
- November 27th 2010 : Nominal mission completed, having collected about 15.5 months of survey data insuring that all the sky at been seen at least twice by each detector:
  - *12 "Planck Intermediate results" papers on CMB foregrounds results submitted **in 2012**.*
  - *public data delivery on **March 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…

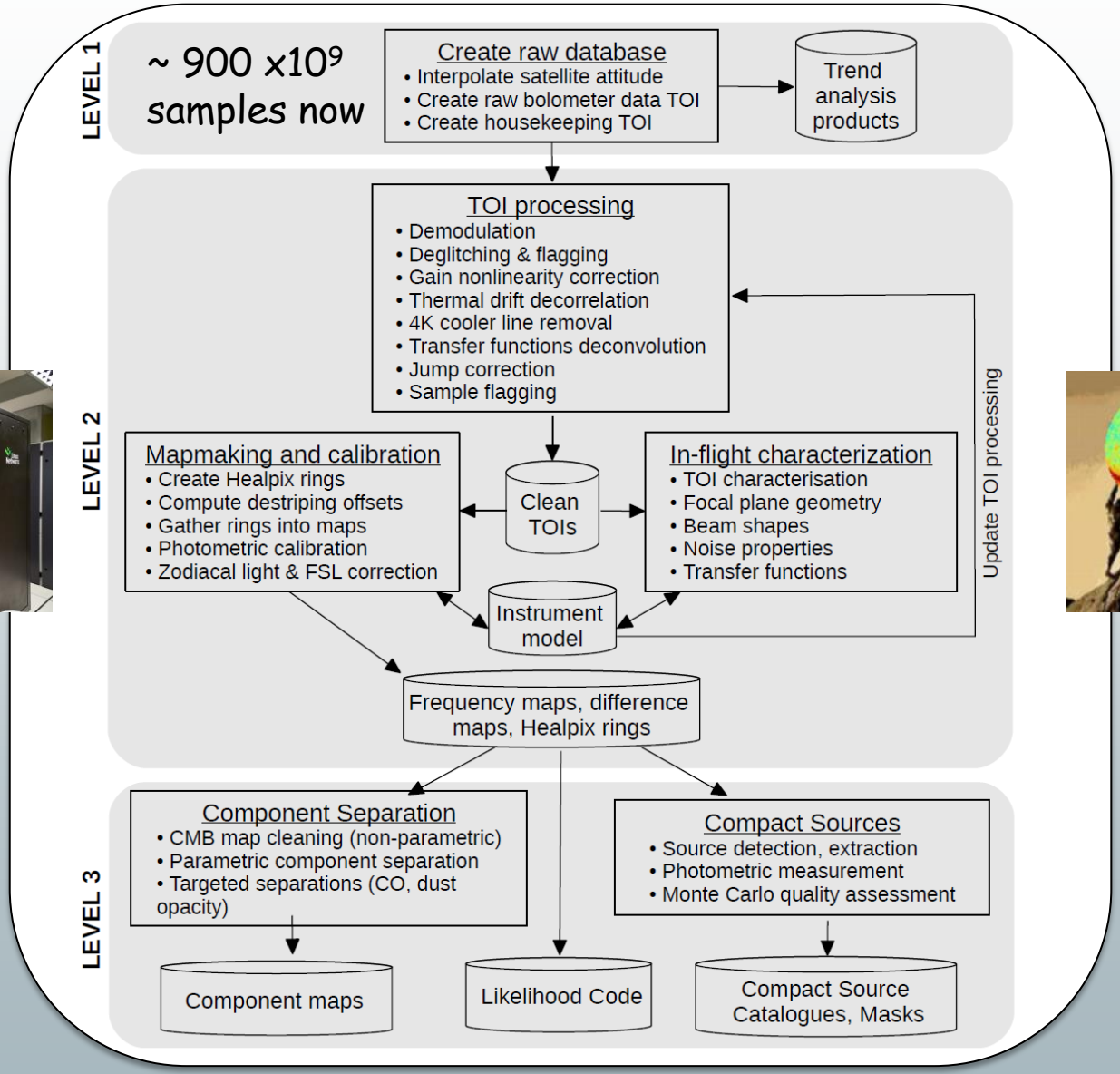


HFI Data Processing Centre flow

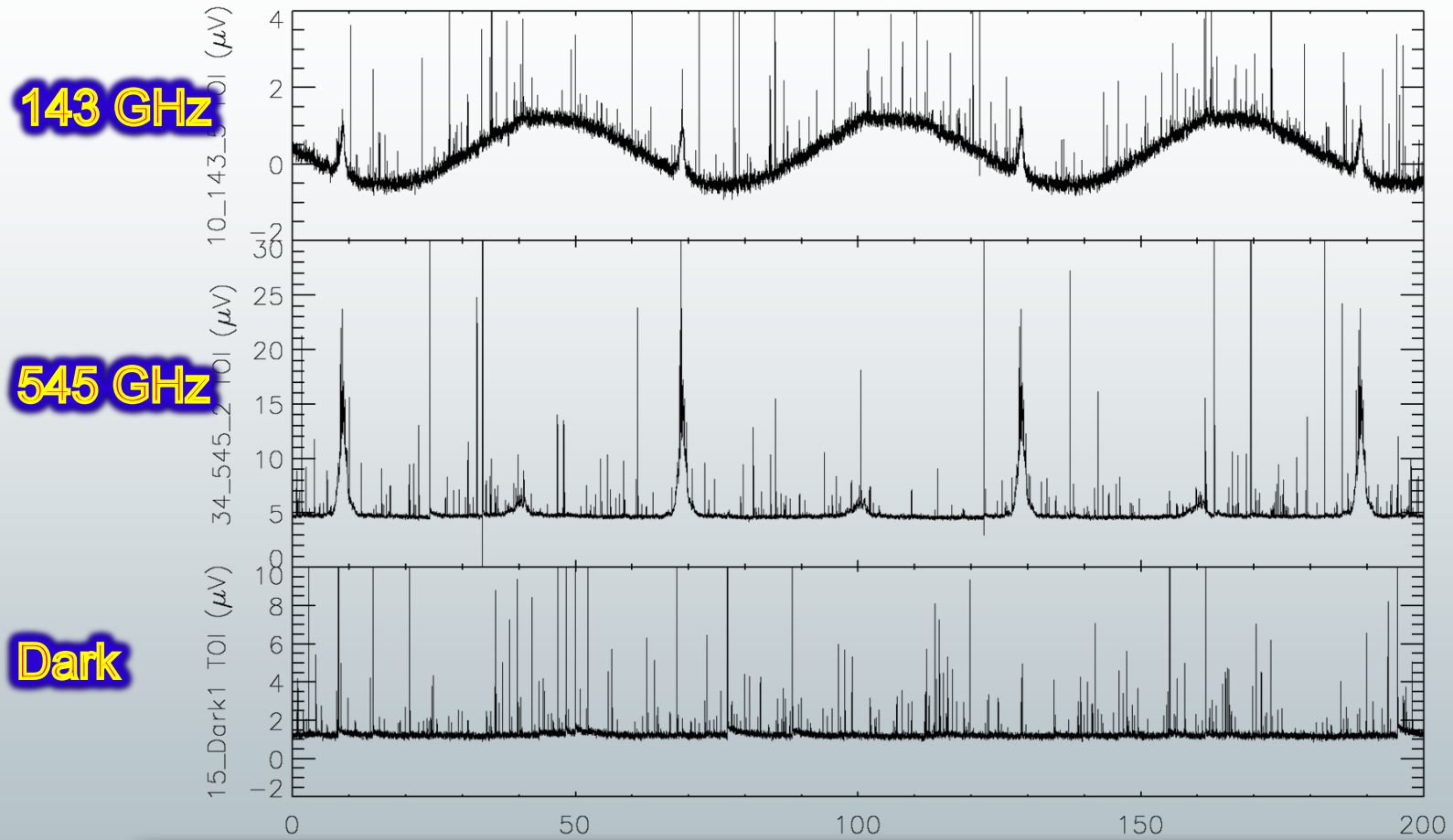


IAP cellar

Sisyphus



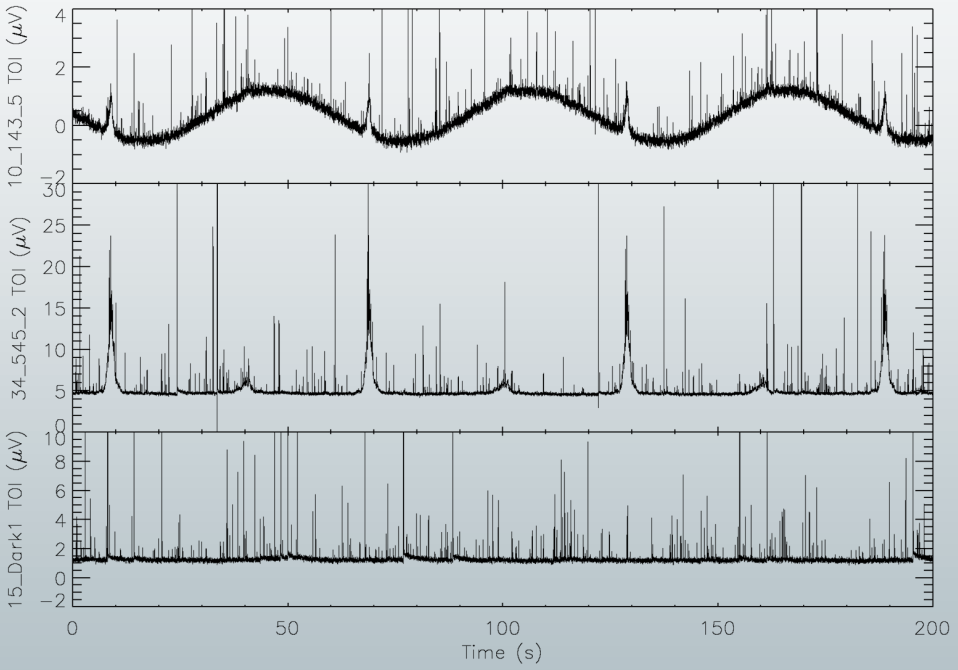
HFI Raw Detector TOI (Time Ordered Information)

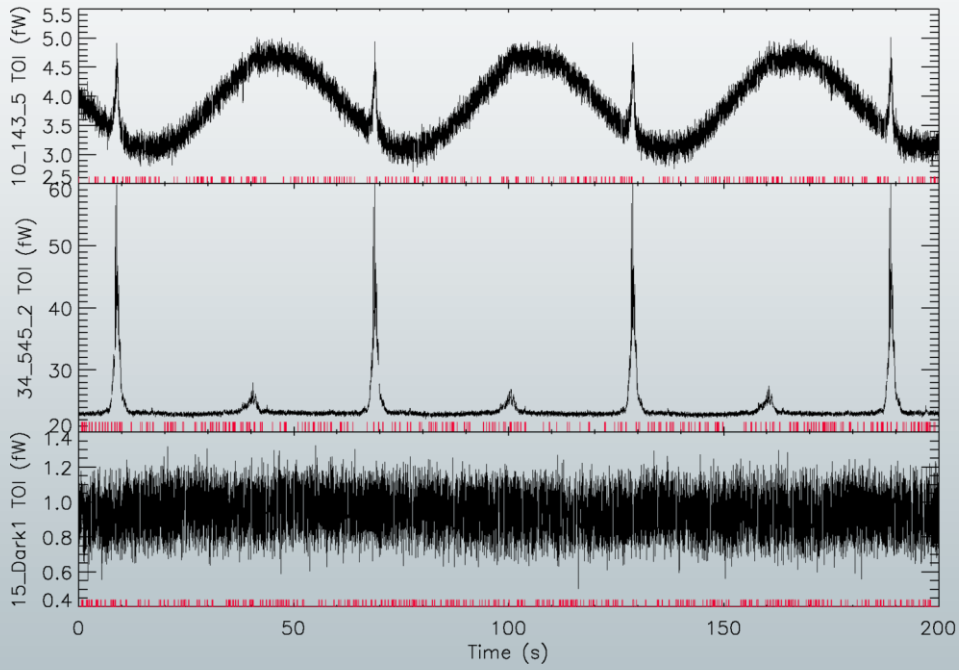


3 minutes of quasi 'raw" data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky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



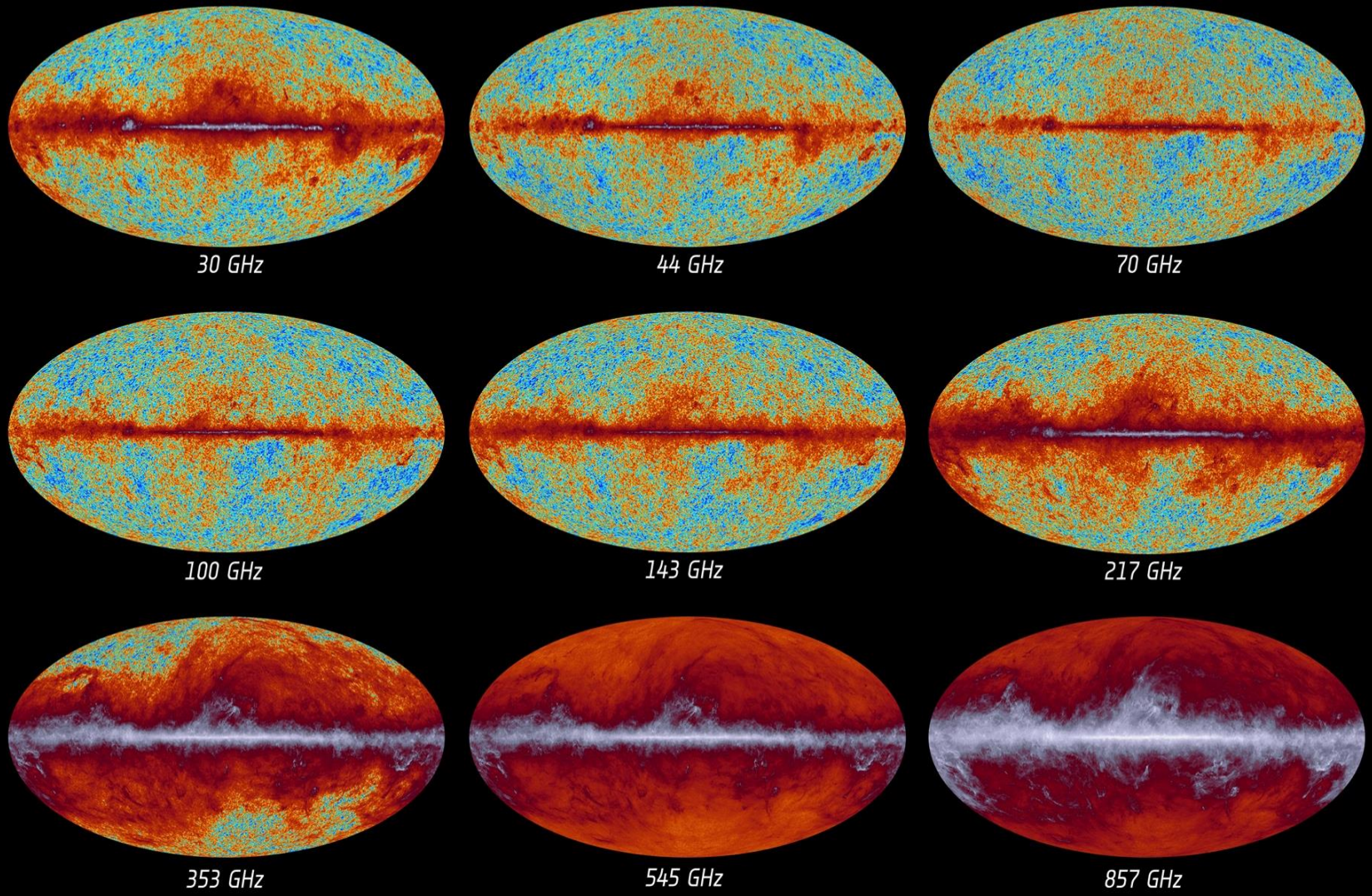


From μV to femto-Watts

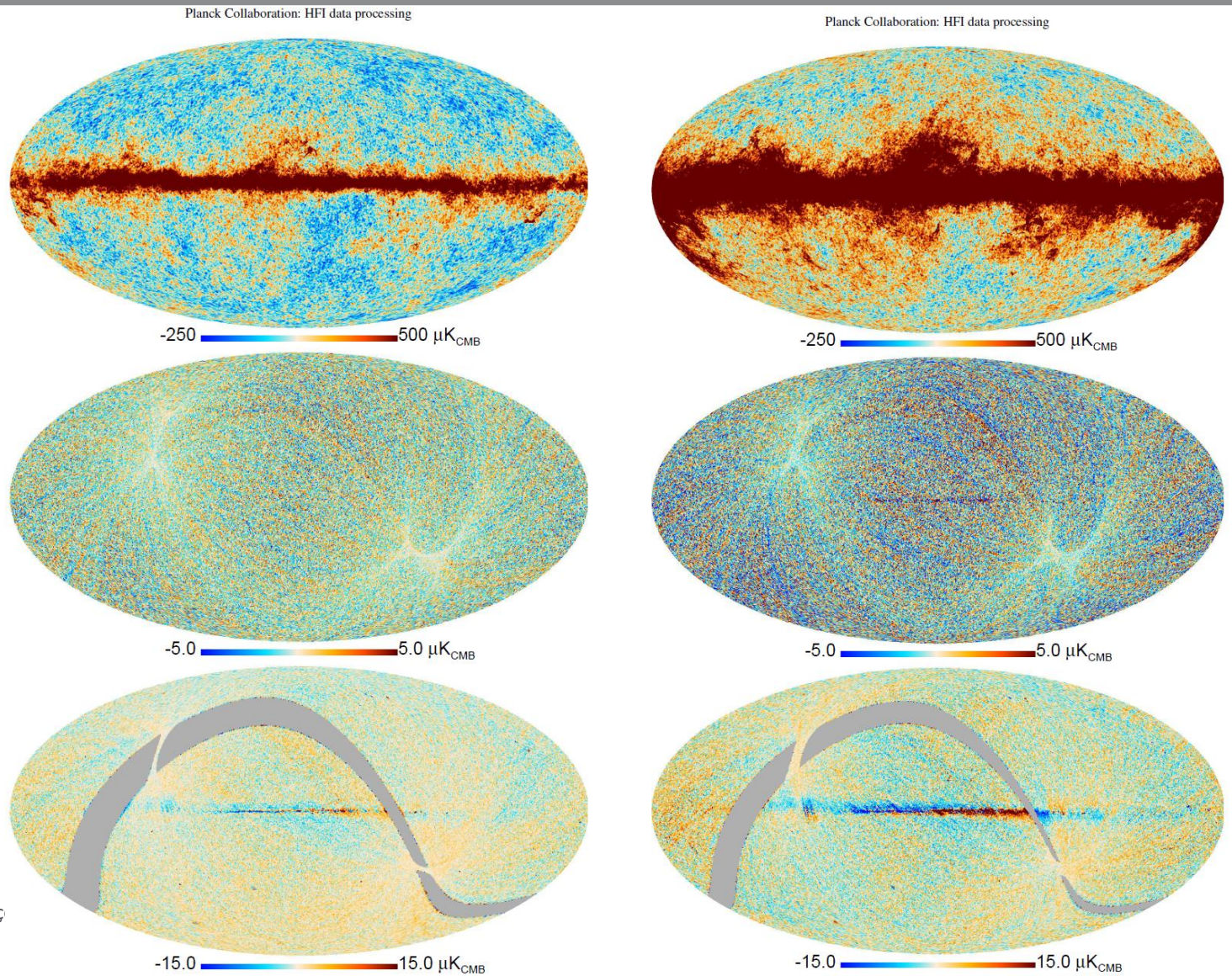
planck

The sky as seen by Planck

esa



143 GHz & 217 GHz maps

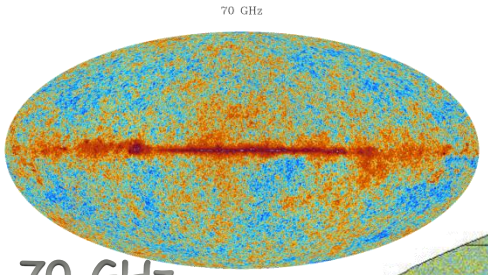


Intensity maps

Difference between Half-ring maps

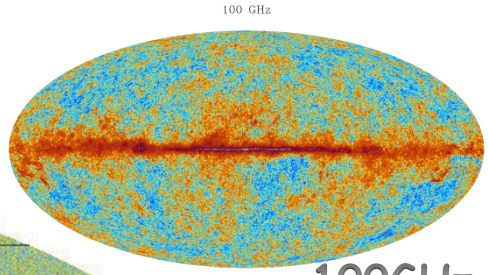
Difference between Survey 1 and Survey 2 maps

LFI-HFI consistency

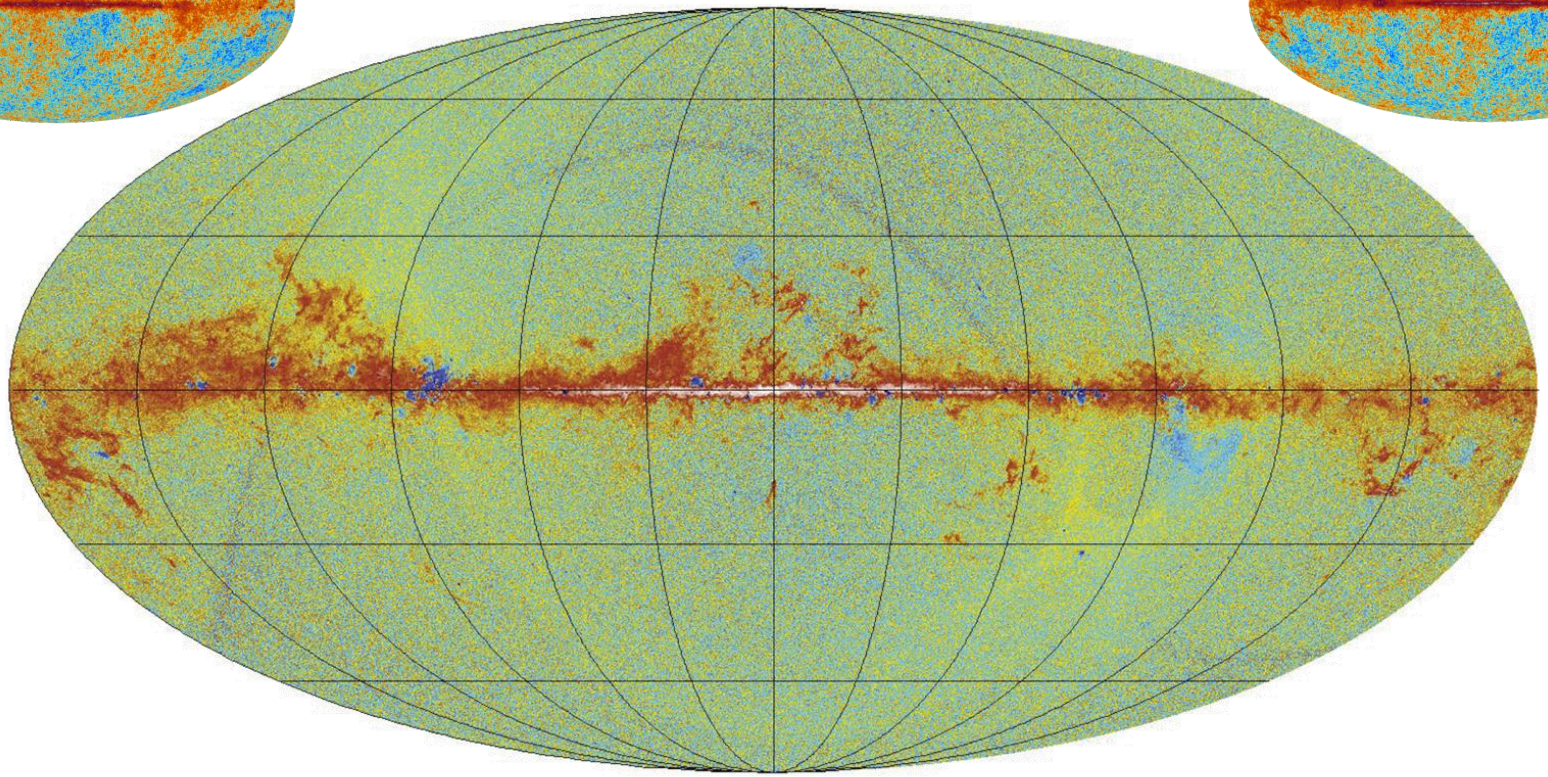


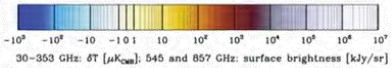
70 GHz
(LFI)

100GHz - 70 GHz



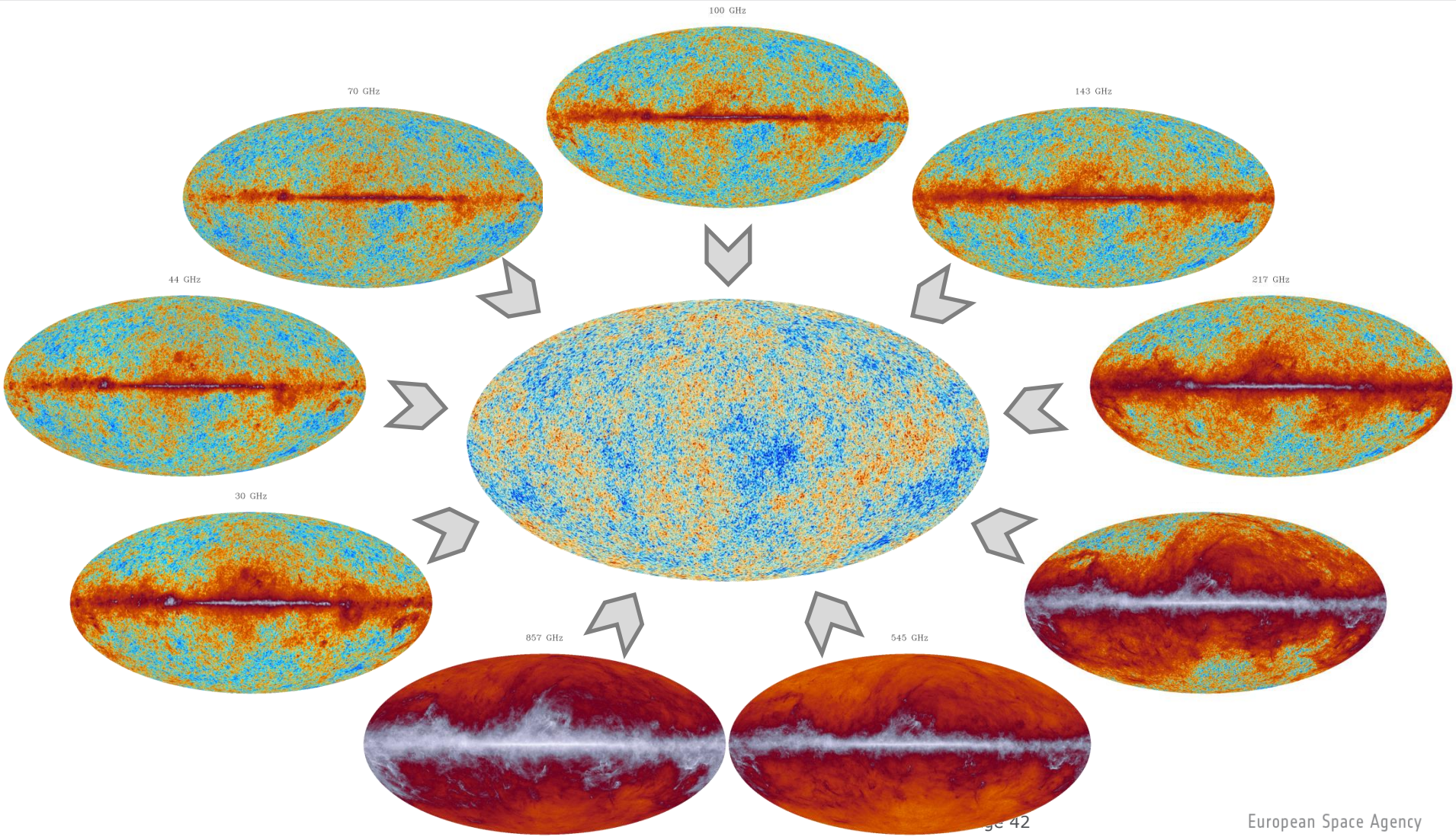
100GHz
(HFI)





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

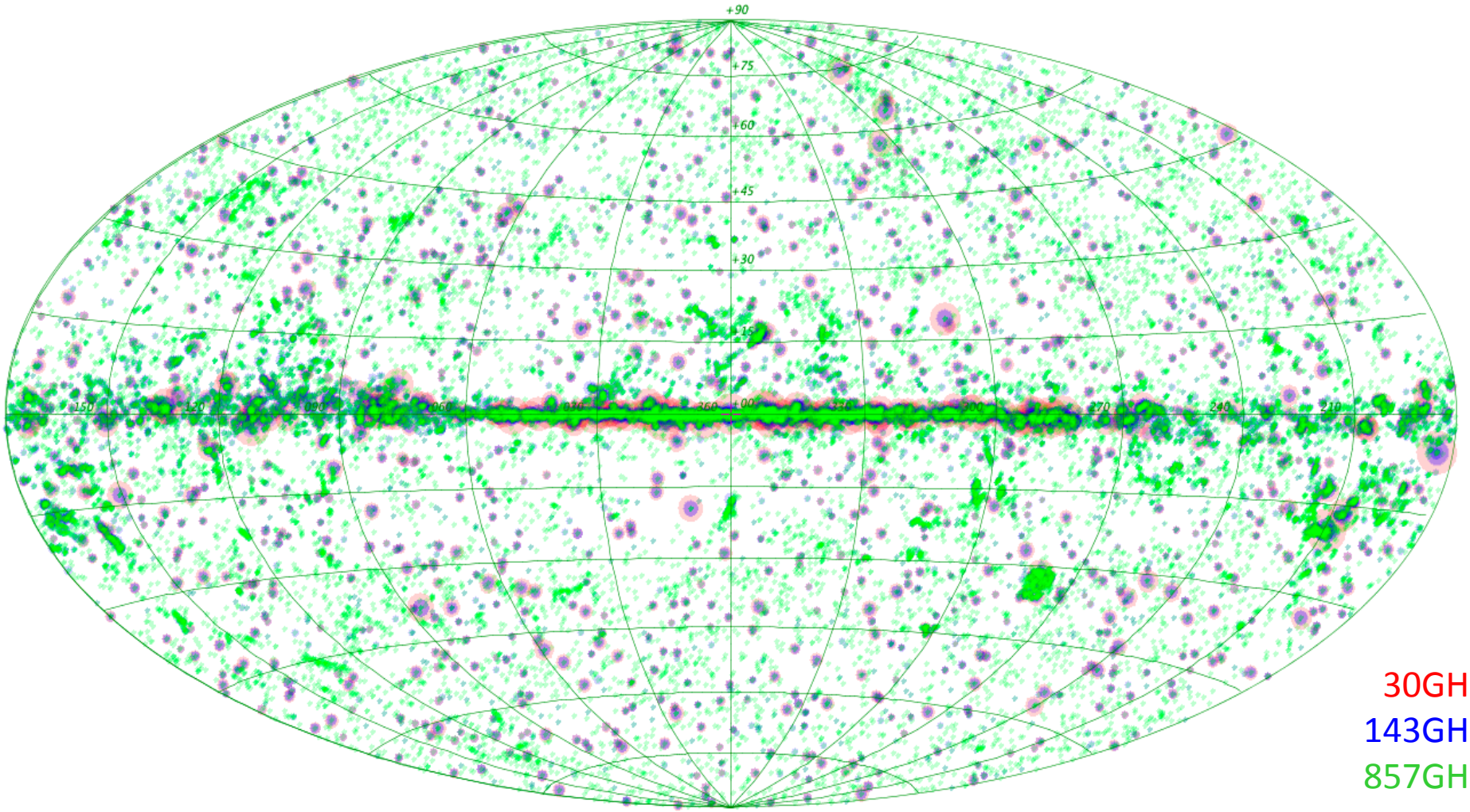
Cleaning the background from its 7 veils



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

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

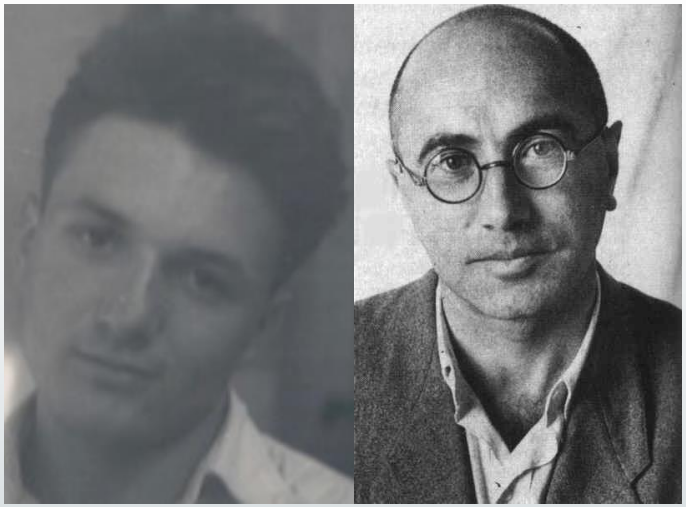
Compact galactic and extragalactic sources

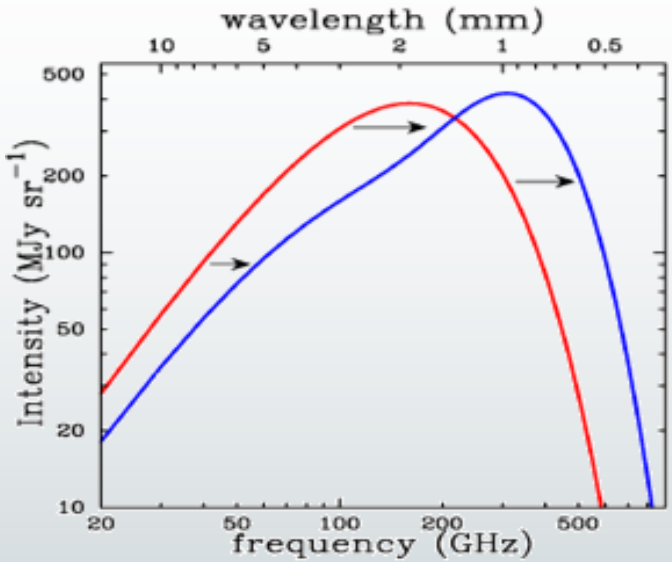


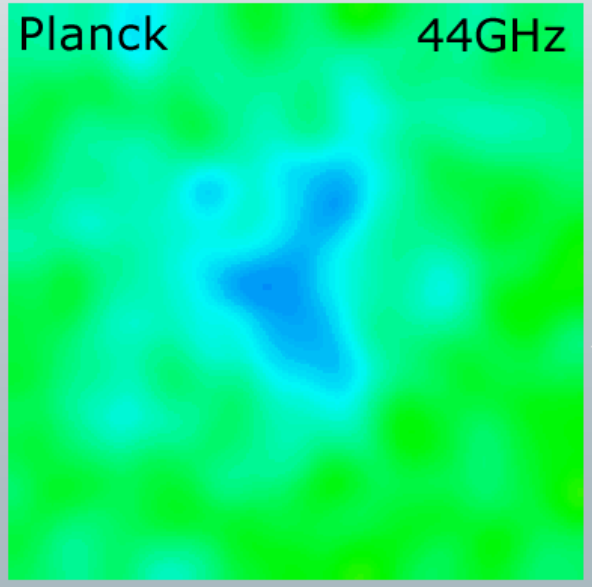
At 850GHz: ~25 000 sources, 90% completeness level at 658mJy flux density; uncertainties: 166 mJy, 0.4 arcmin

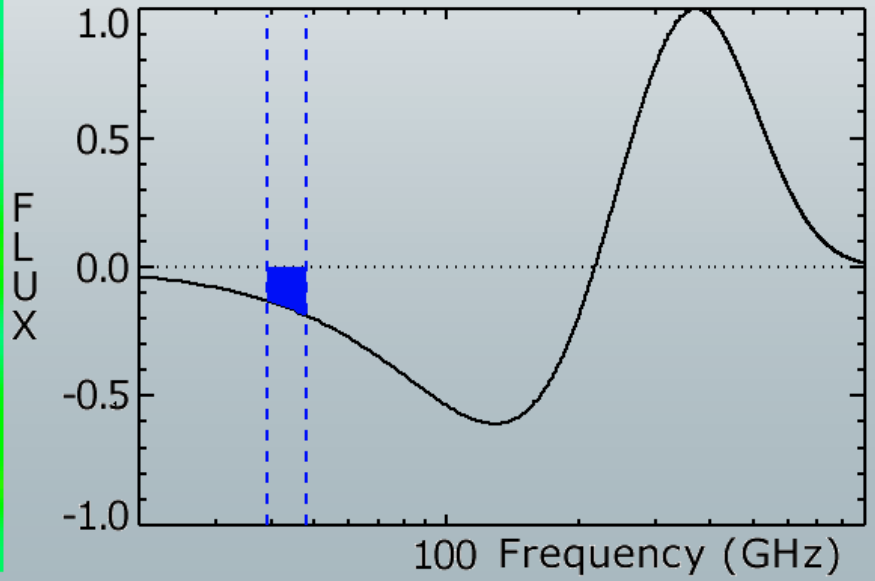
The Sunyaev-Zeldovich effect

Comments on Astrophysics and Space Physics 1972





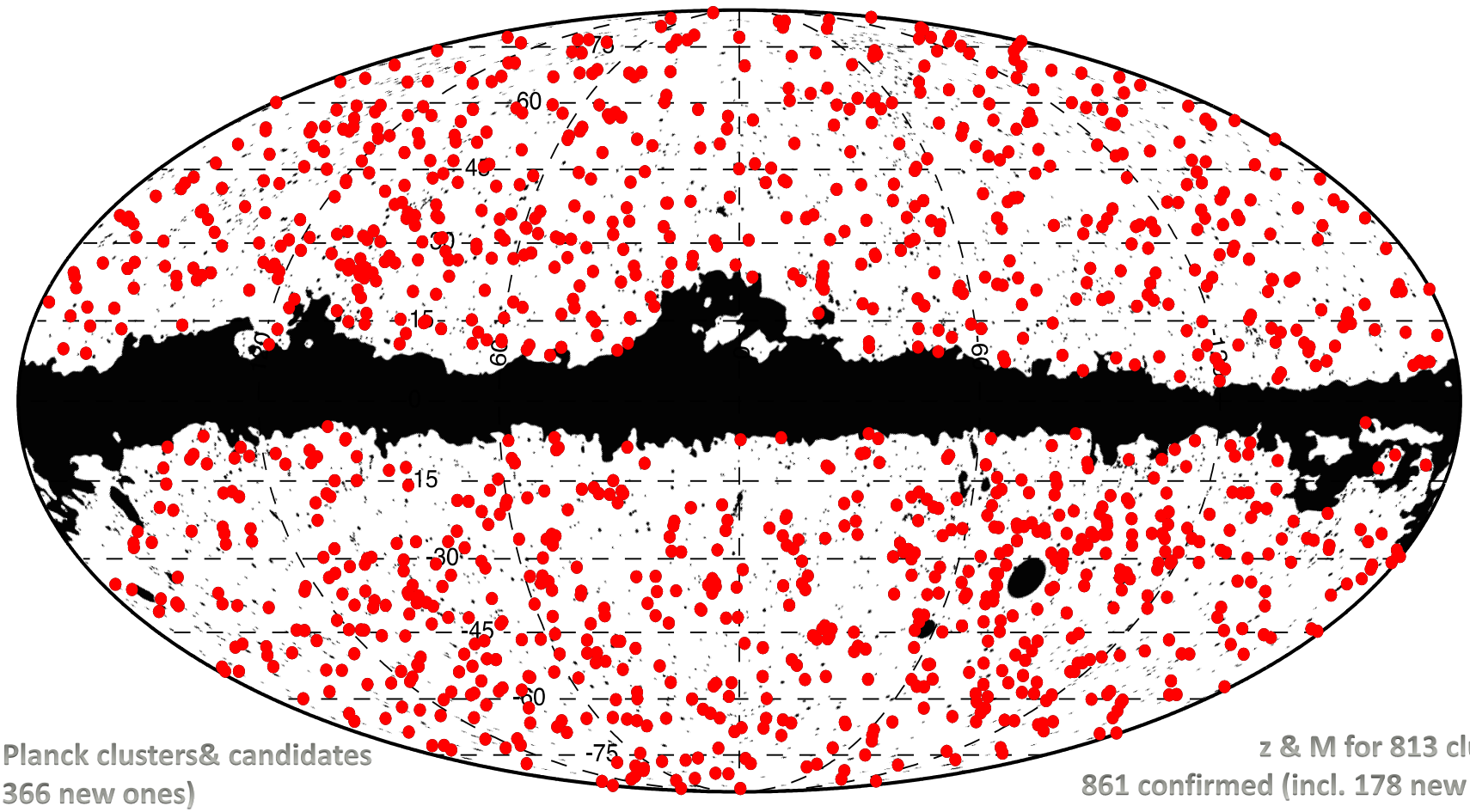




SZ
Planck measures the subtle distortions that clusters of galaxies induce on the Cosmic Microwave Background
(and tells us that they don’t quite behave as we thought)
Simulation Horizon, DM in red, Gas in blue

Clusters of galaxies

Planck SZ catalog

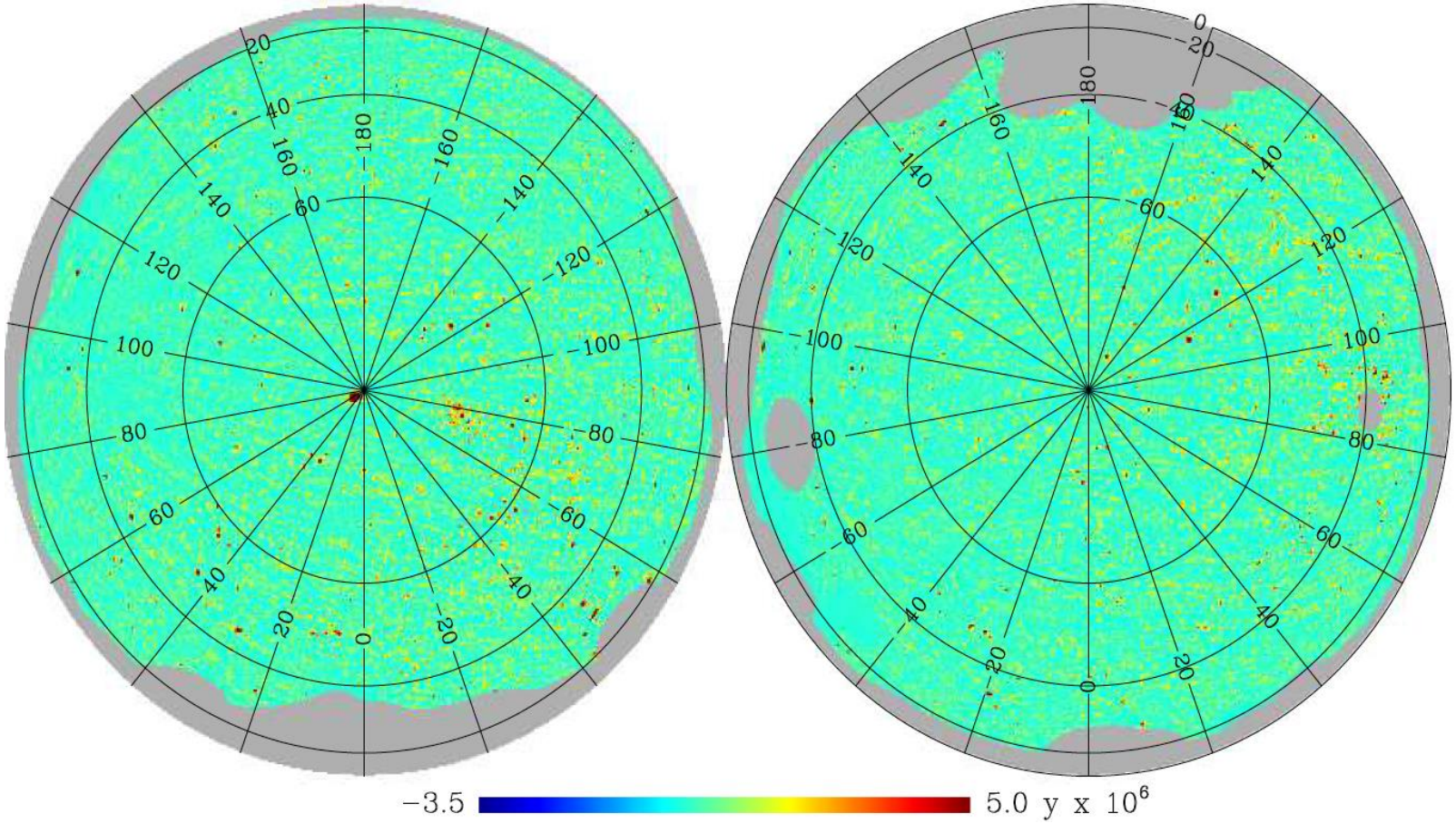


1227 Planck clusters& candidates
(incl. 366 new ones)

z & M for 813 clusters
861 confirmed (incl. 178 new ones)

MAP OF THE HOT GAS DISTRIBUTION

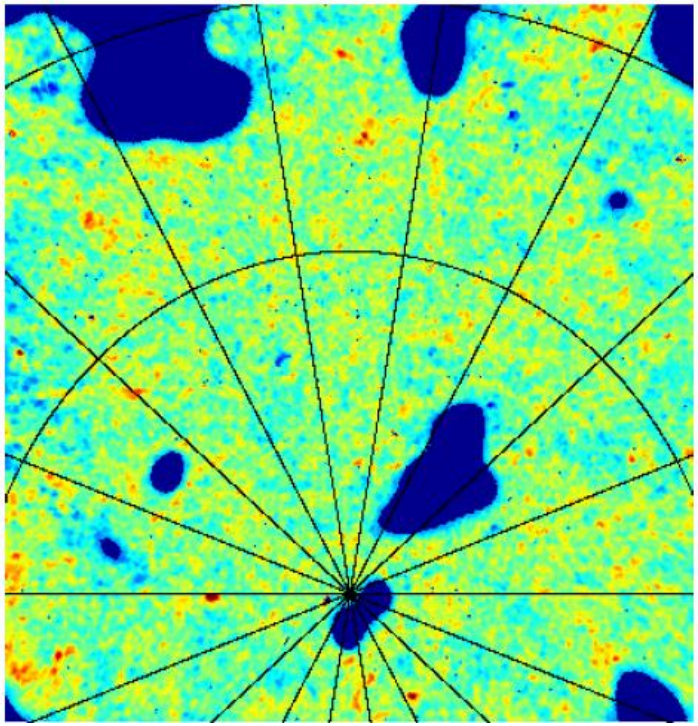
Planck imaged the gas (baryon) distribution in the low-redshift Universe using scattering of CMB photons off the electrons. This SZ effect causes a change in the shape of the CMB spectrum



THE COSMIC INFRARED BACKGROUND

Planck image of part of the sky with little Milky Way dust emission. What is there has been removed using Galactic hydrogen maps made by other telescopes.

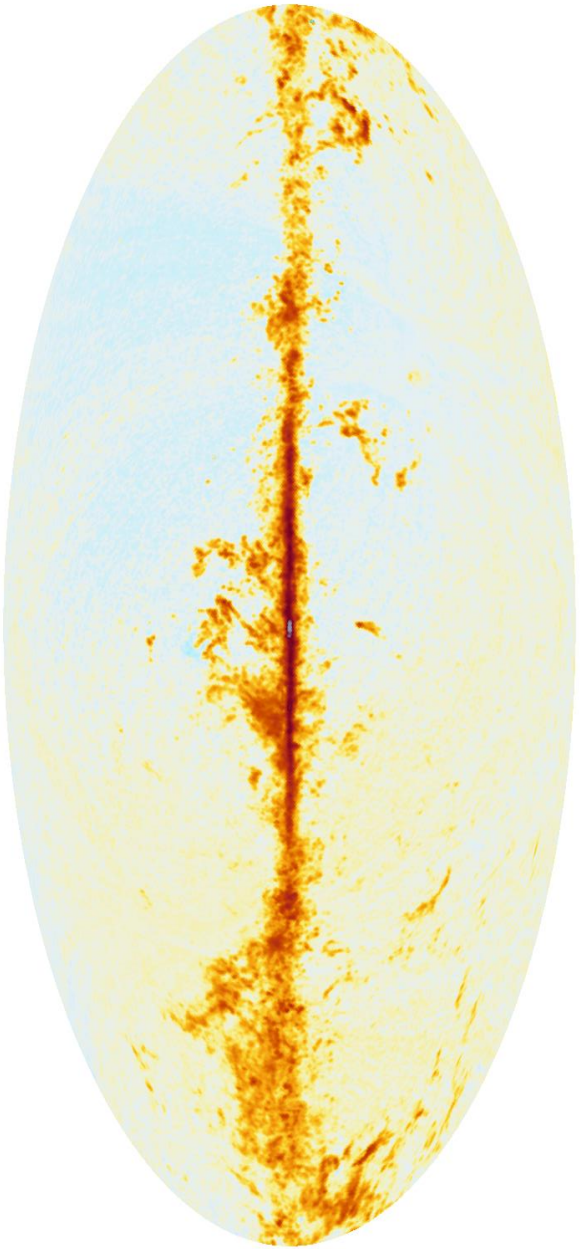
This map primarily shows the Cosmic Infrared Background, emission from warm dust in distant star-forming galaxies at redshifts between 1 and 3



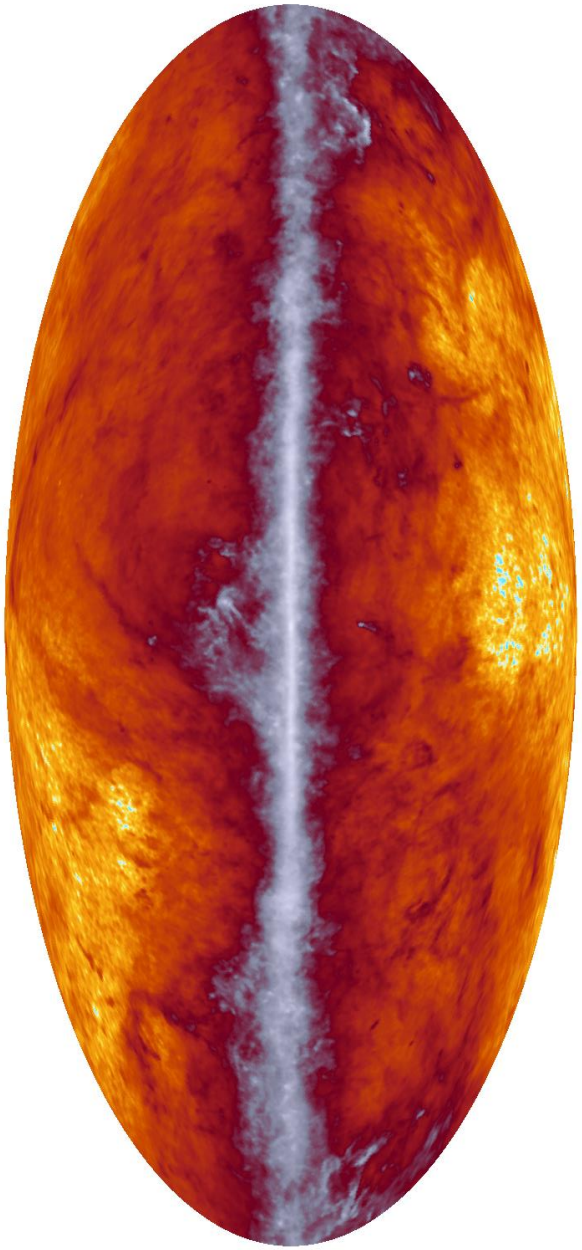
545 GHz

Galactic Foregrounds

Low frequency emission

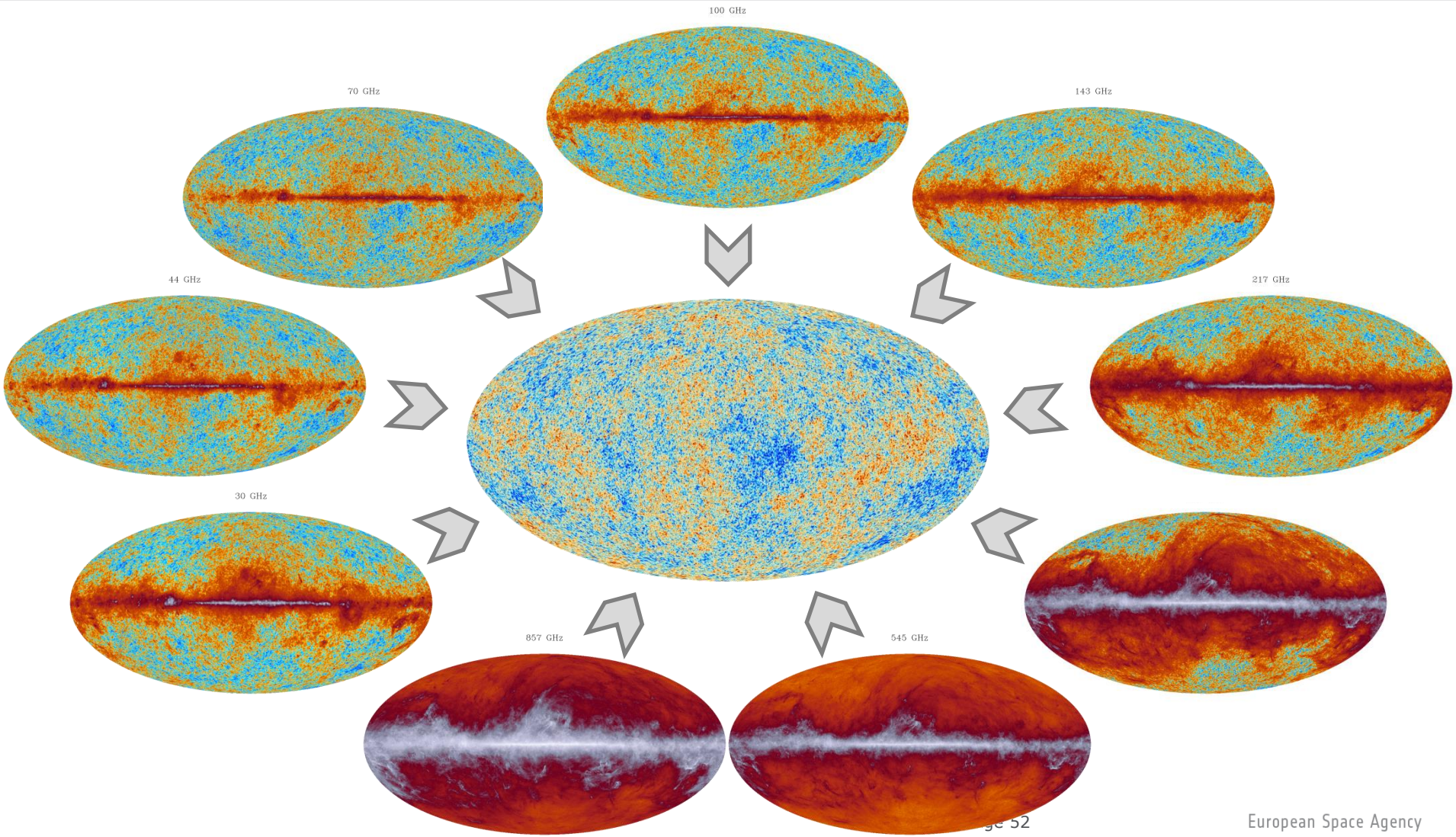


CO “discovery” map



Dust emission amplitud

Cleaning the background from its 7 veils

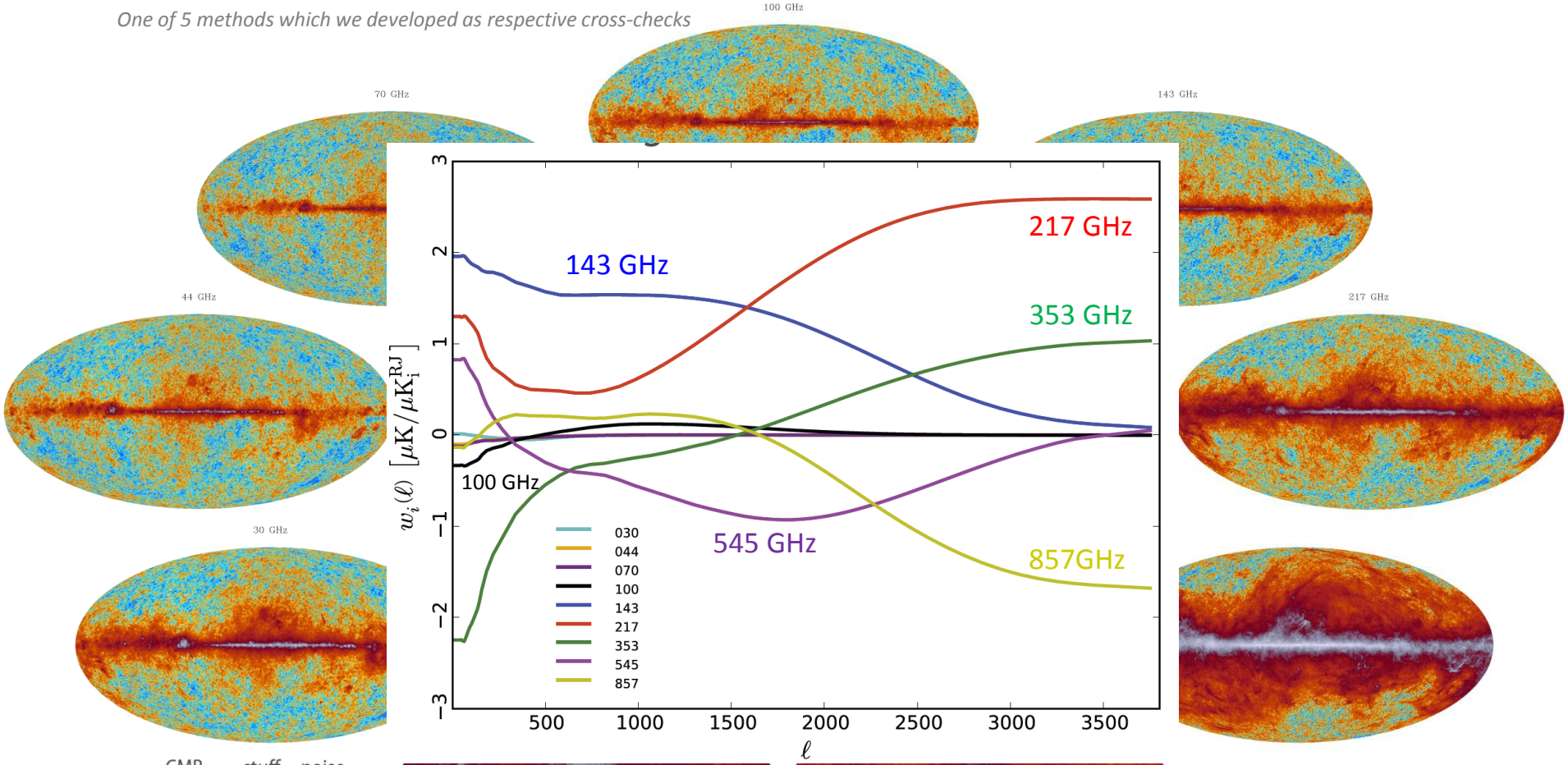


François R. Bouchet, "Planck main cosmological results", 17/06/2013

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

Cleaning the background with an l-dependent linear combination

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



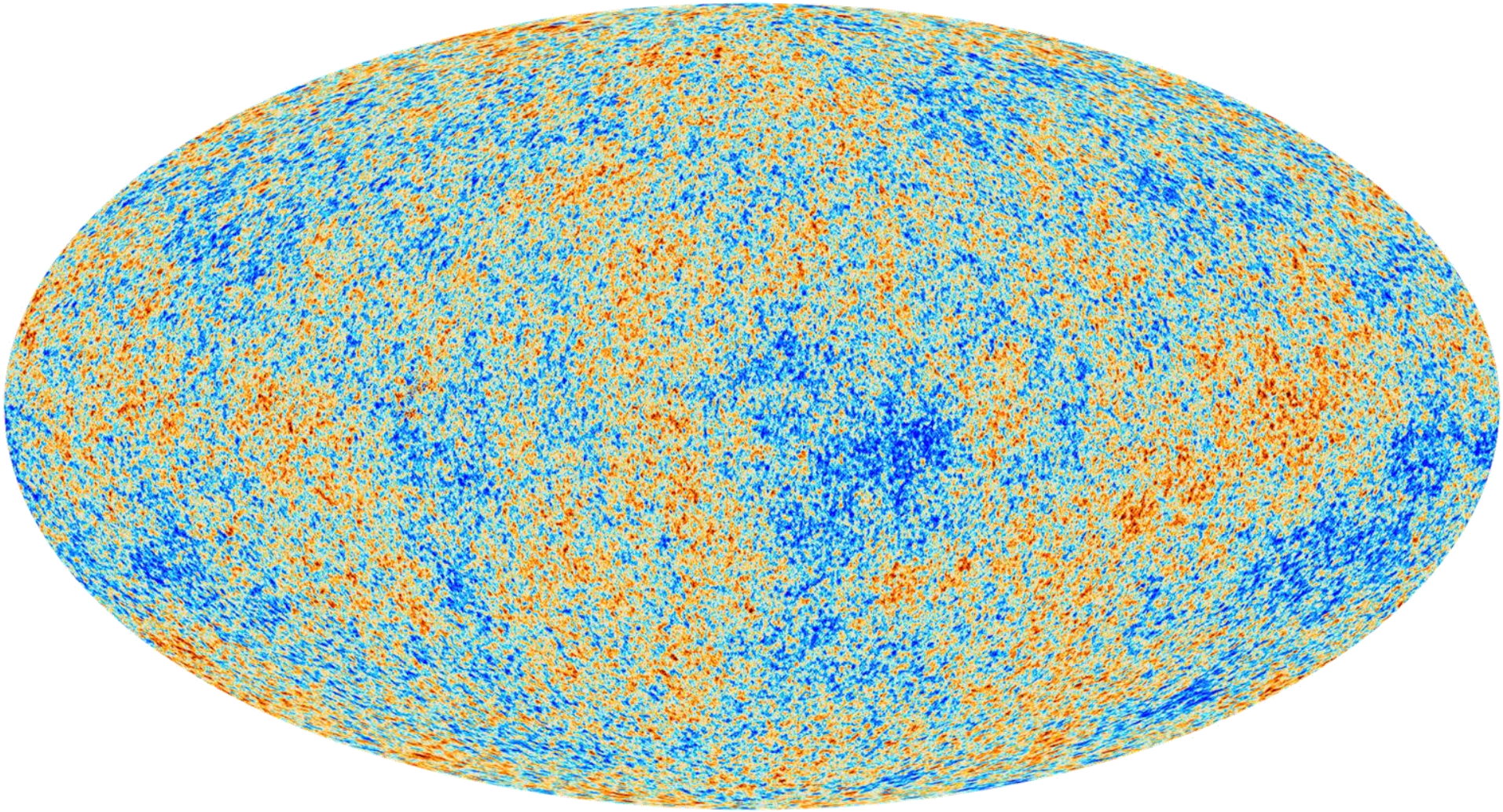
$$\mathbf{C}_\ell(\theta) = \overset{\text{CMB}}{\mathbf{a}\mathbf{a}^\dagger C_\ell} + \overset{\text{stuff}}{\mathbf{A}\mathbf{P}_\ell\mathbf{A}^\dagger} + \overset{\text{noise}}{\mathbf{N}_\ell},$$

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

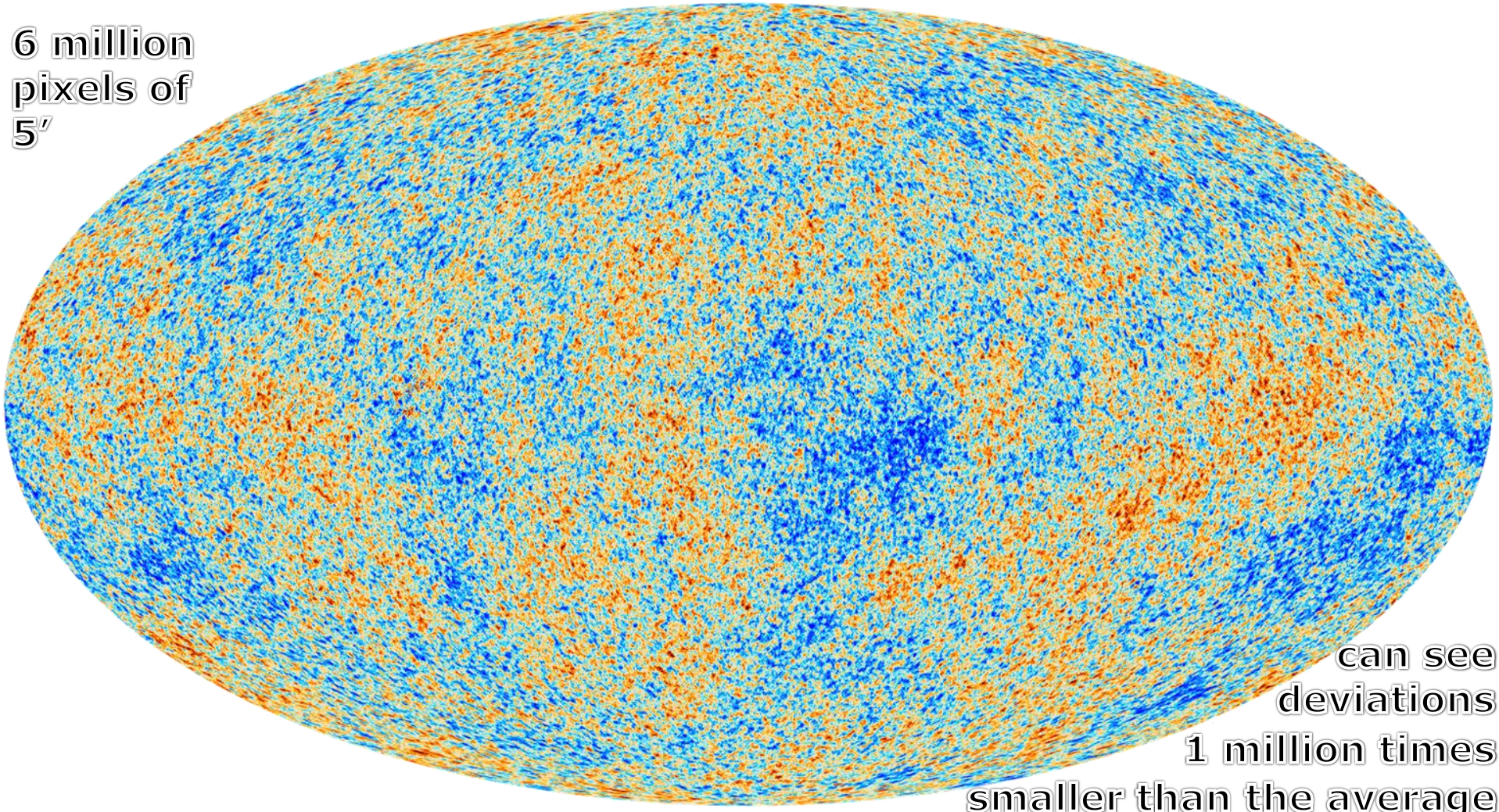
$$\mathbf{w}_\ell = \frac{\mathbf{C}_\ell^{-1}\mathbf{a}}{\mathbf{a}^\dagger\mathbf{C}_\ell^{-1}\mathbf{a}},$$

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

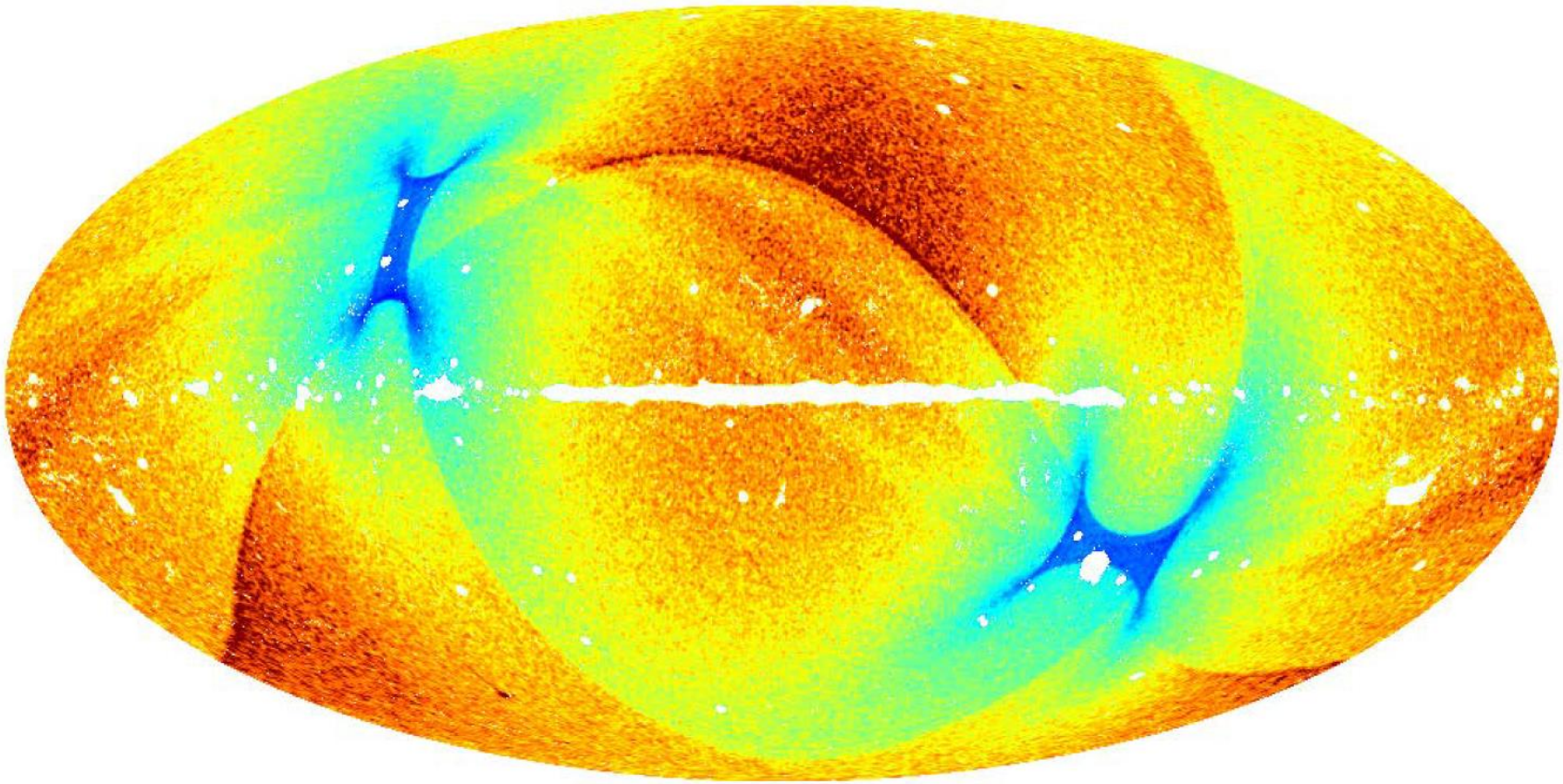
The cosmic microwave background
Temperature anisotropies



The cosmic microwave background
Temperature anisotropies



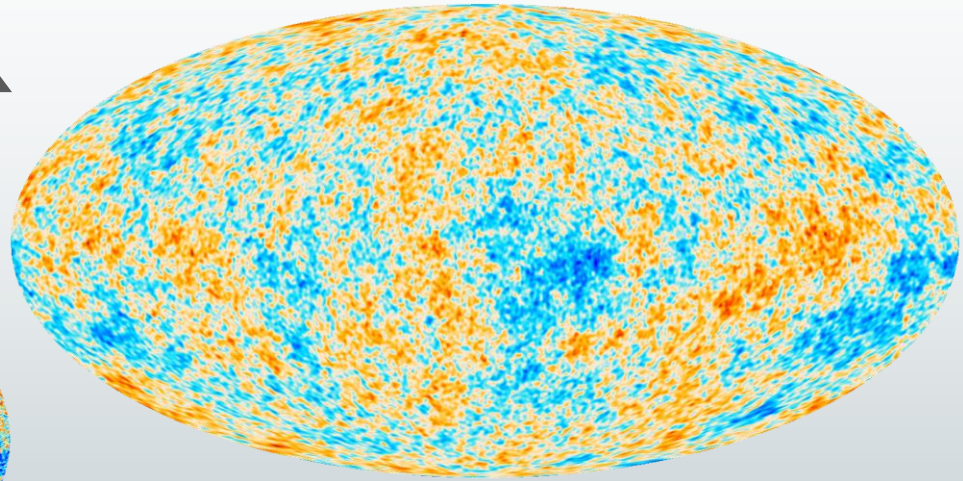
Noise distribution

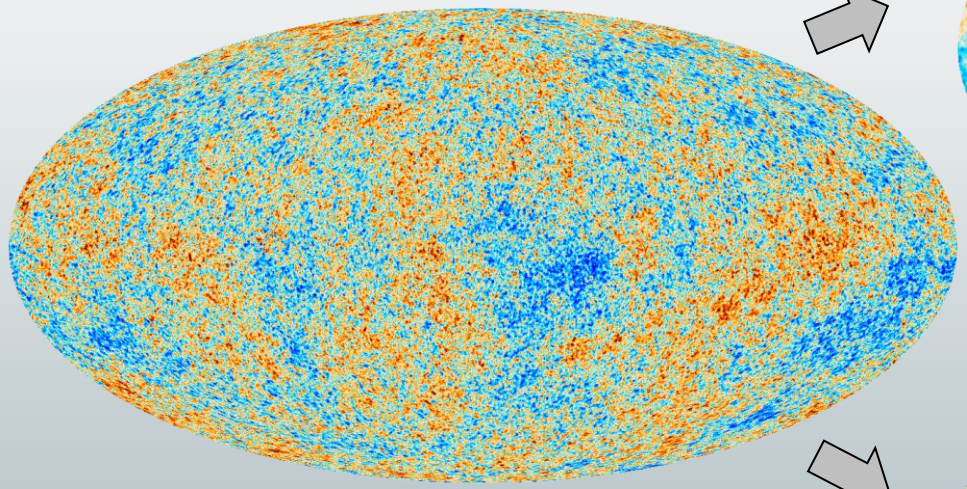


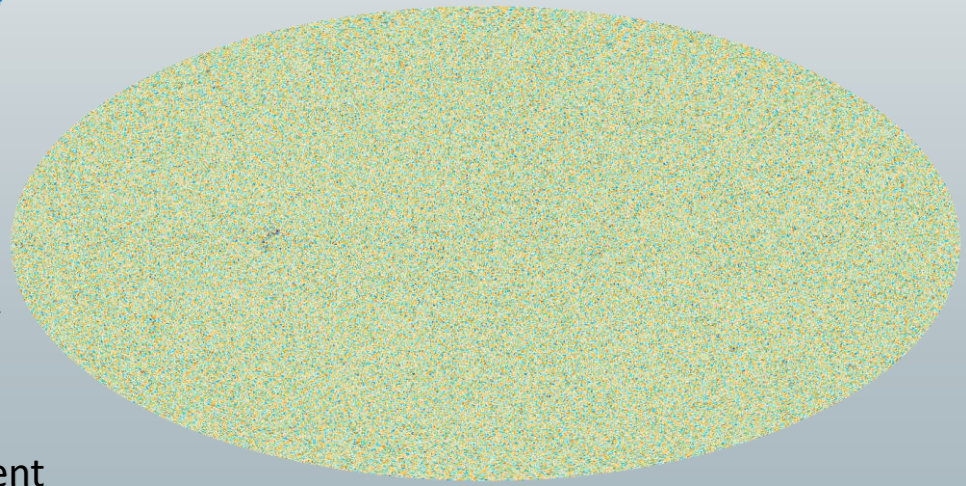
0.000e+00 (average=17μK) 25.000000μK

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

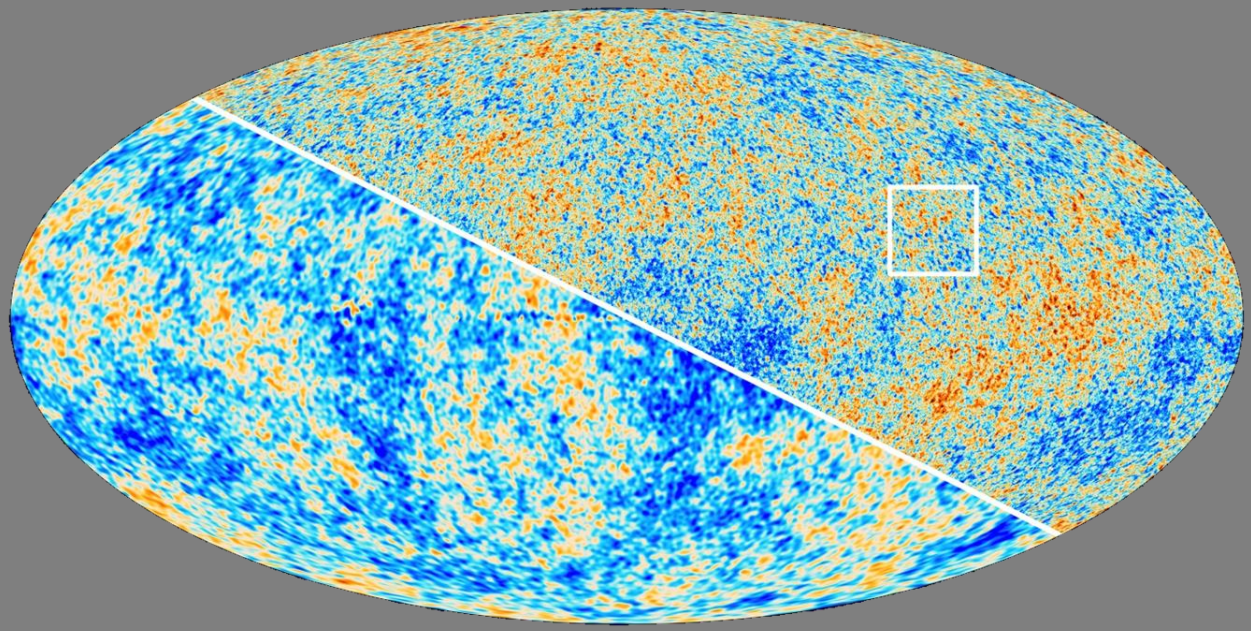


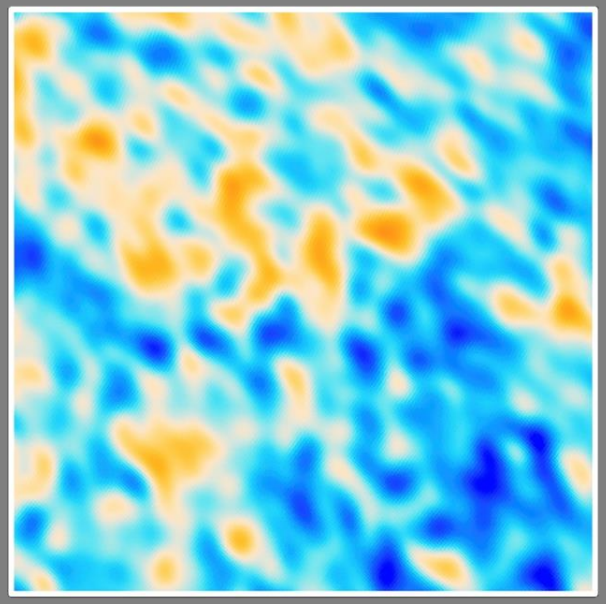




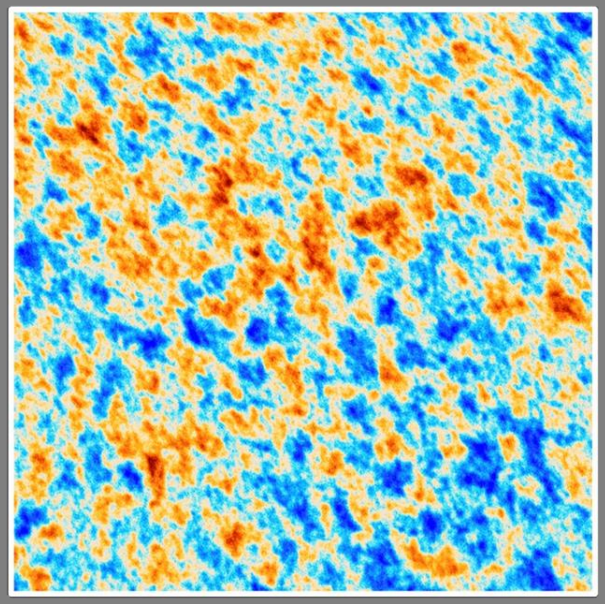
Difference map (scales θ < 1 deg) :
Acoustic oscillations at small scales
< ct when t=380 000 years (~150 Mpc today).
Which allows to take a census of the Universe content

The Cosmic Microwave Background as seen by Planck and WMAP



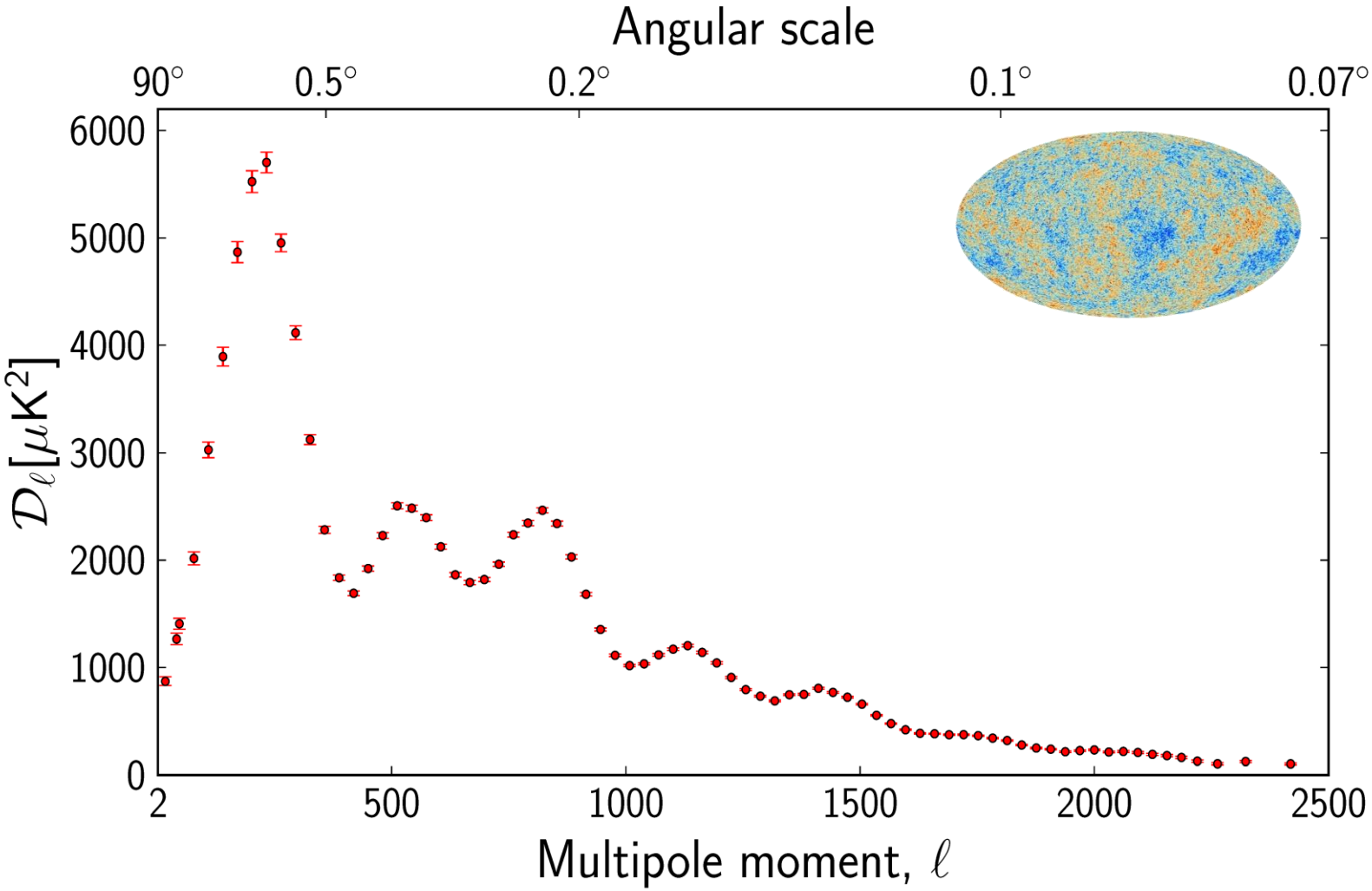


WMAP



Planck

The Planck spectrum of Temperature anisotropies



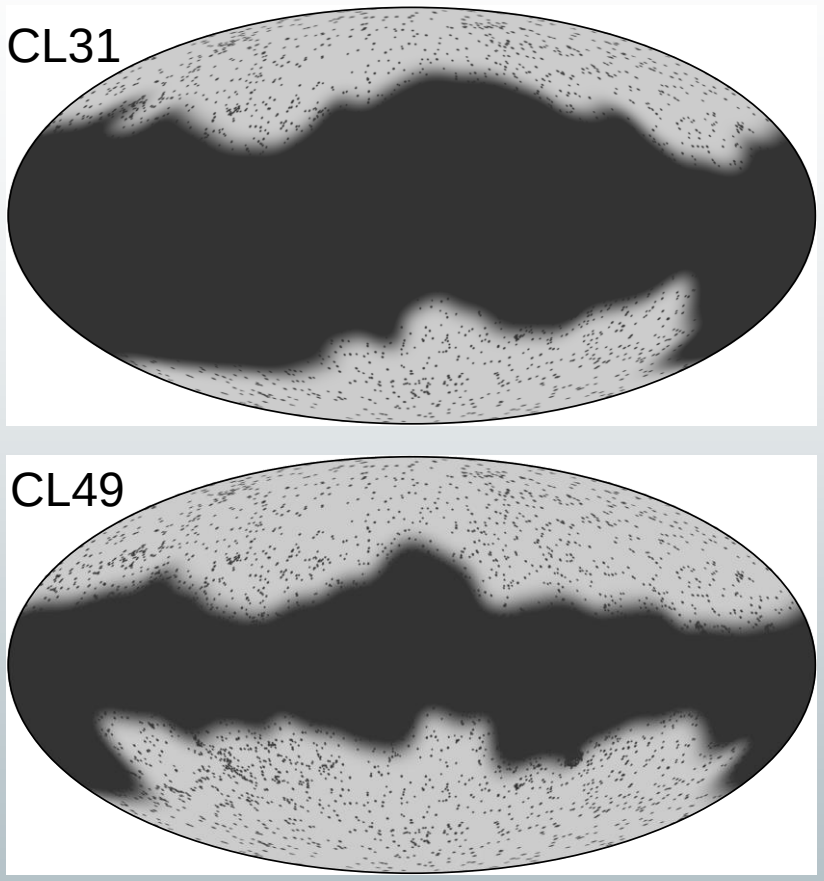
Likelihood Methodology

- Need to provide $P(C^{theory}(l) \mid \text{Planck data})$
- 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

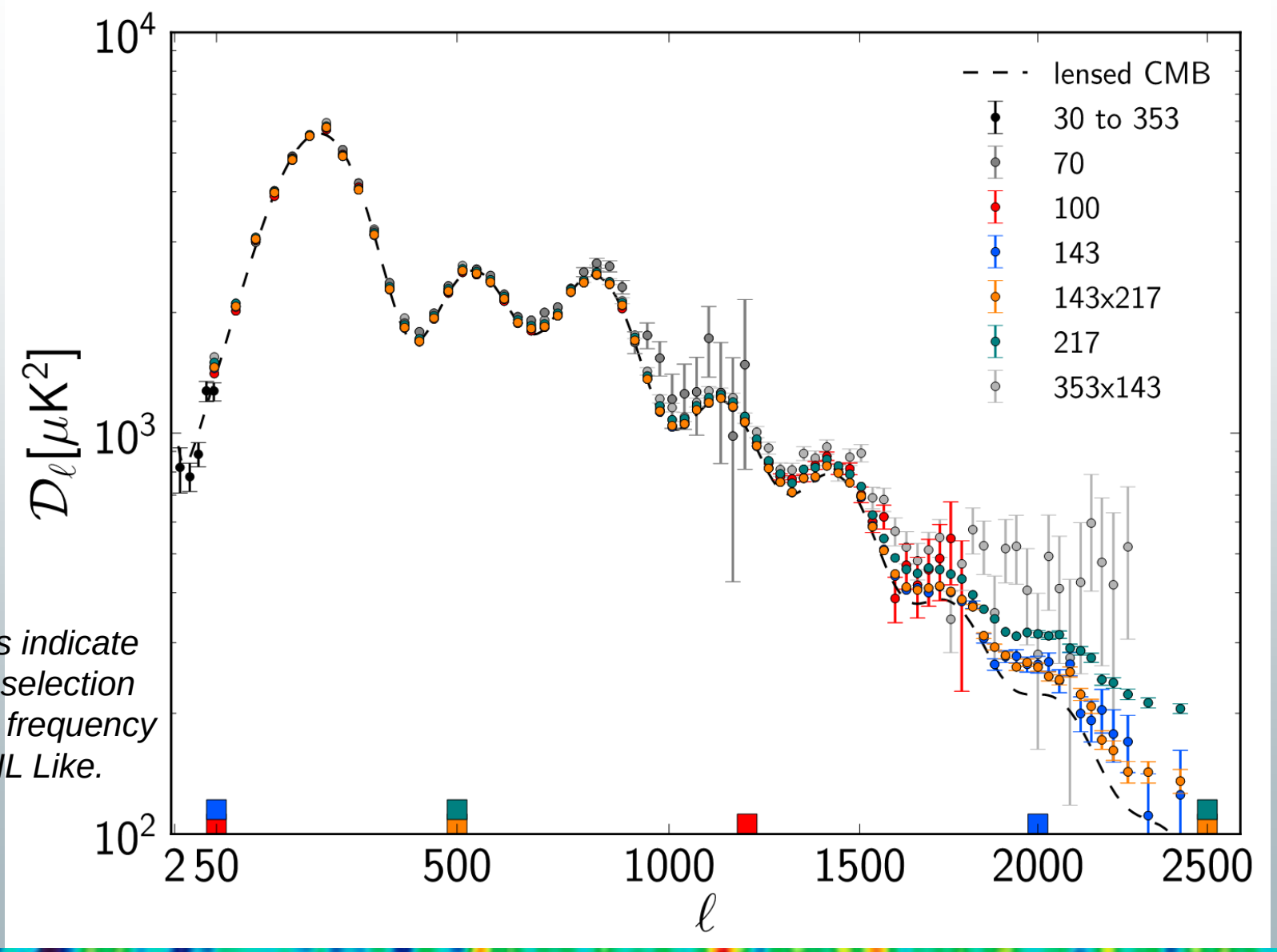
- Minimise foreground impact
  - *Spatially*
  - *In multipole space*
  - *Keeping low cosmic variance*
- Galaxy: 353 GHz thresholding
- Sources: 100-353 GHz catalog
- Maps: keep the easiest to model & most informative ones

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

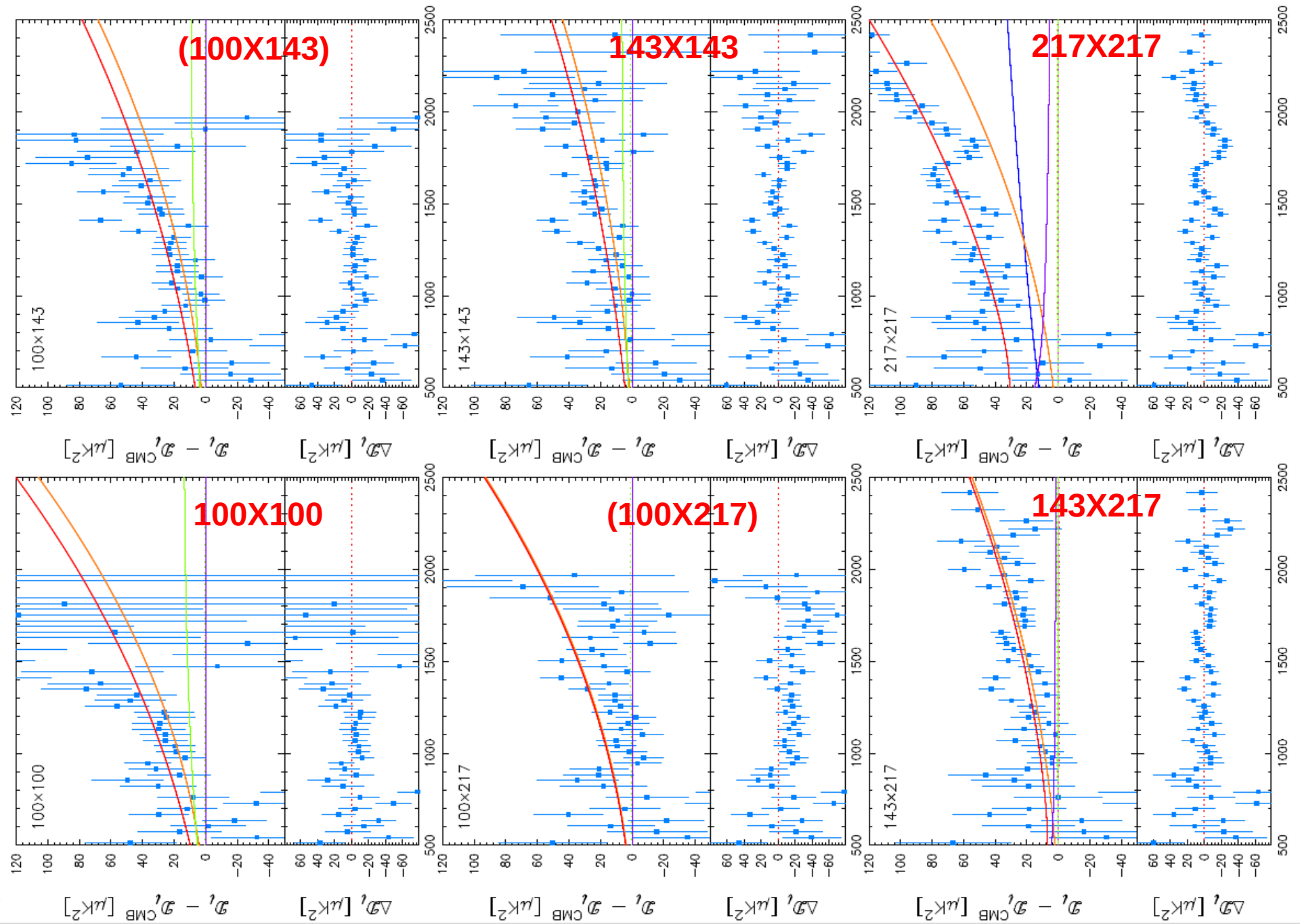
Planck angular power spectra



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

Spectral Foregrounds modeling

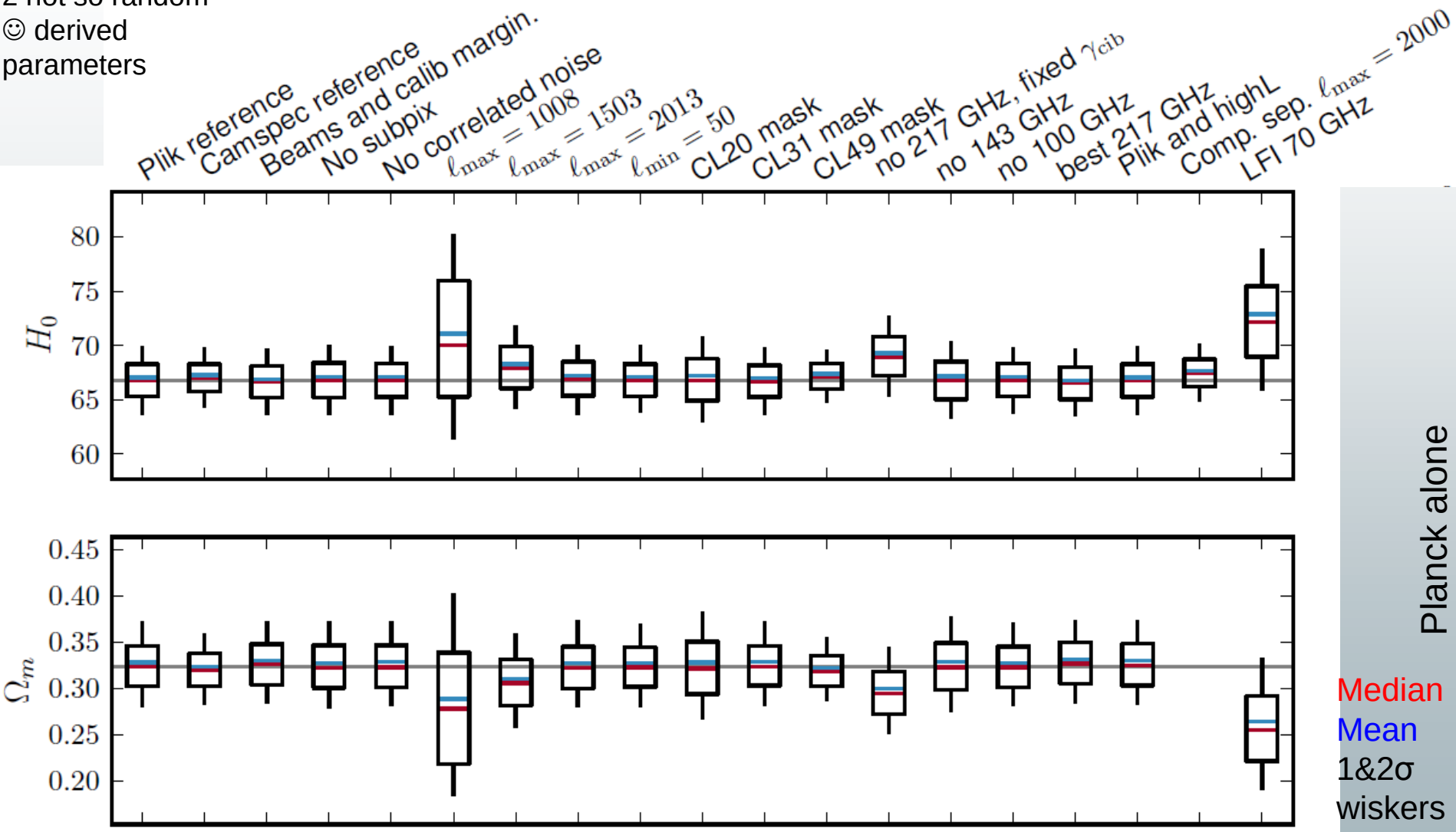
- Even after selection of *frequencies*, of cleanest *regions* through masking and tailoring *l-ranges*, residuals need to be modeled and part of error budget
- We include PS templates for
  - *Poisson Point sources (arbitrary level per frequency, A_ν^{PS})*
  - *Clustered Infrared sources (CIB) (A_ν^{CIB} I^γ, $r_{\nu\nu'}^{CIB}$)*
  - *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

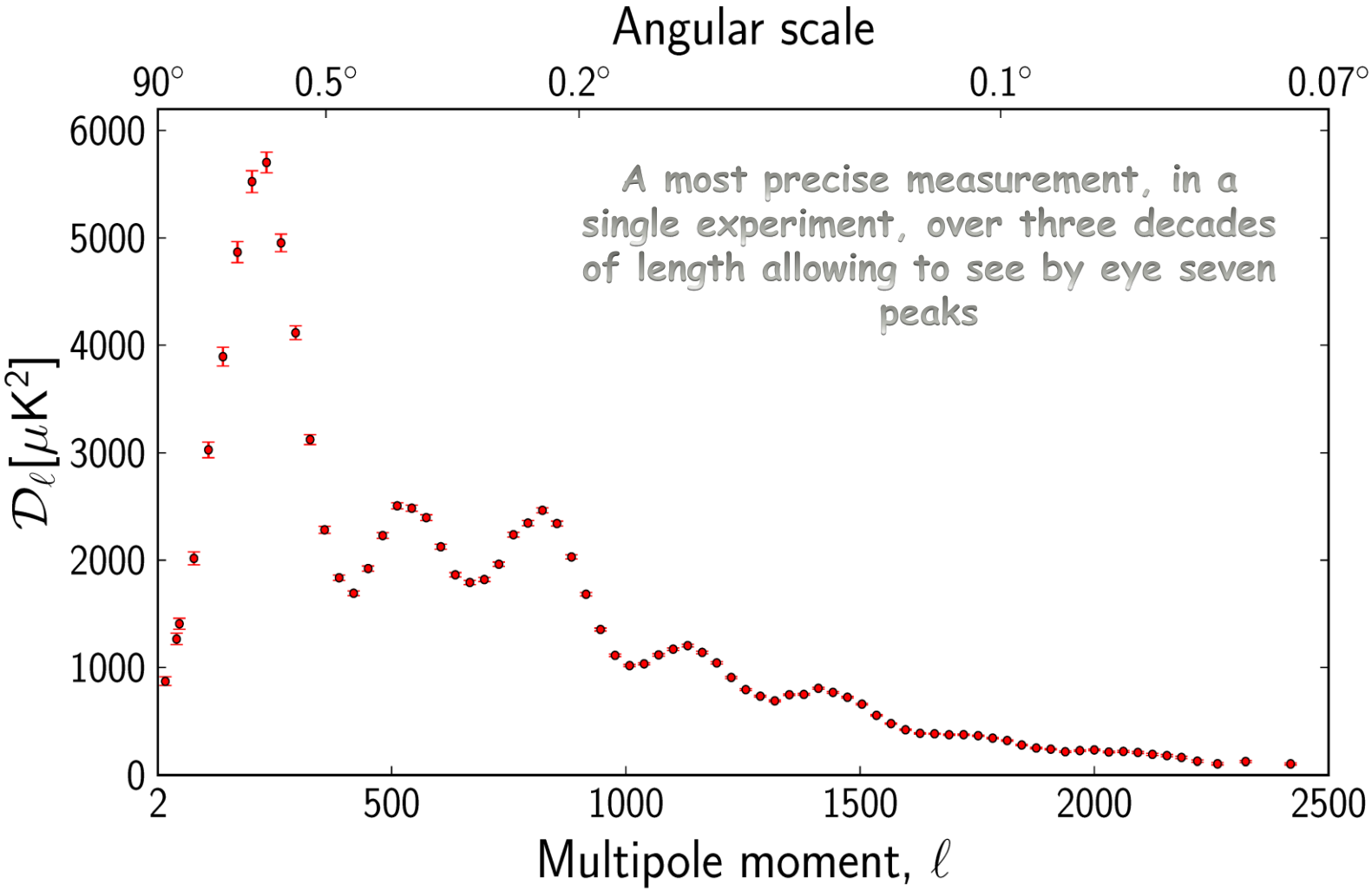
2 not so random
☺ derived
parameters



Planck alone

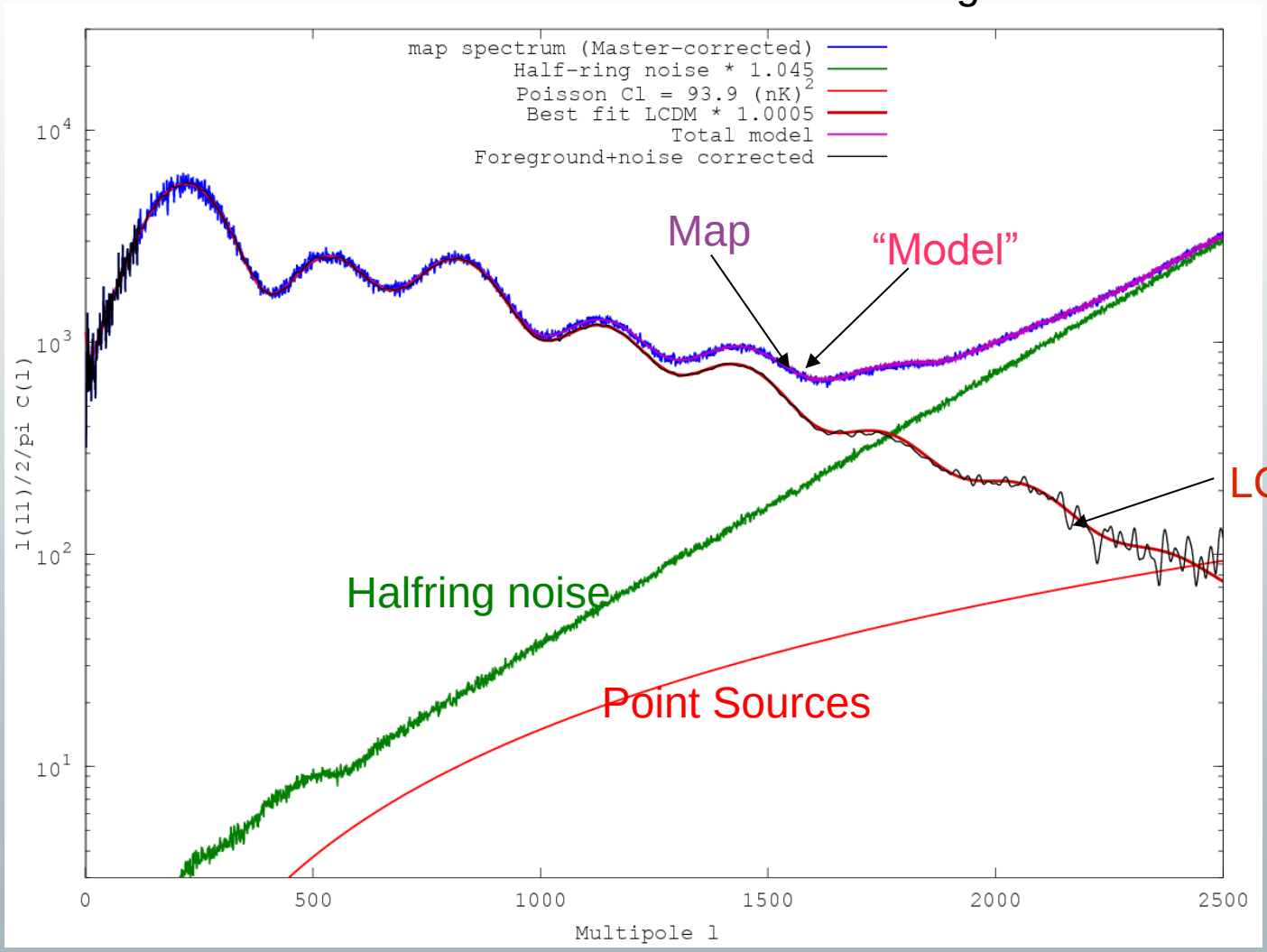
Median
Mean
1&2σ
wiskers

The Planck spectrum of Temperature anisotropies

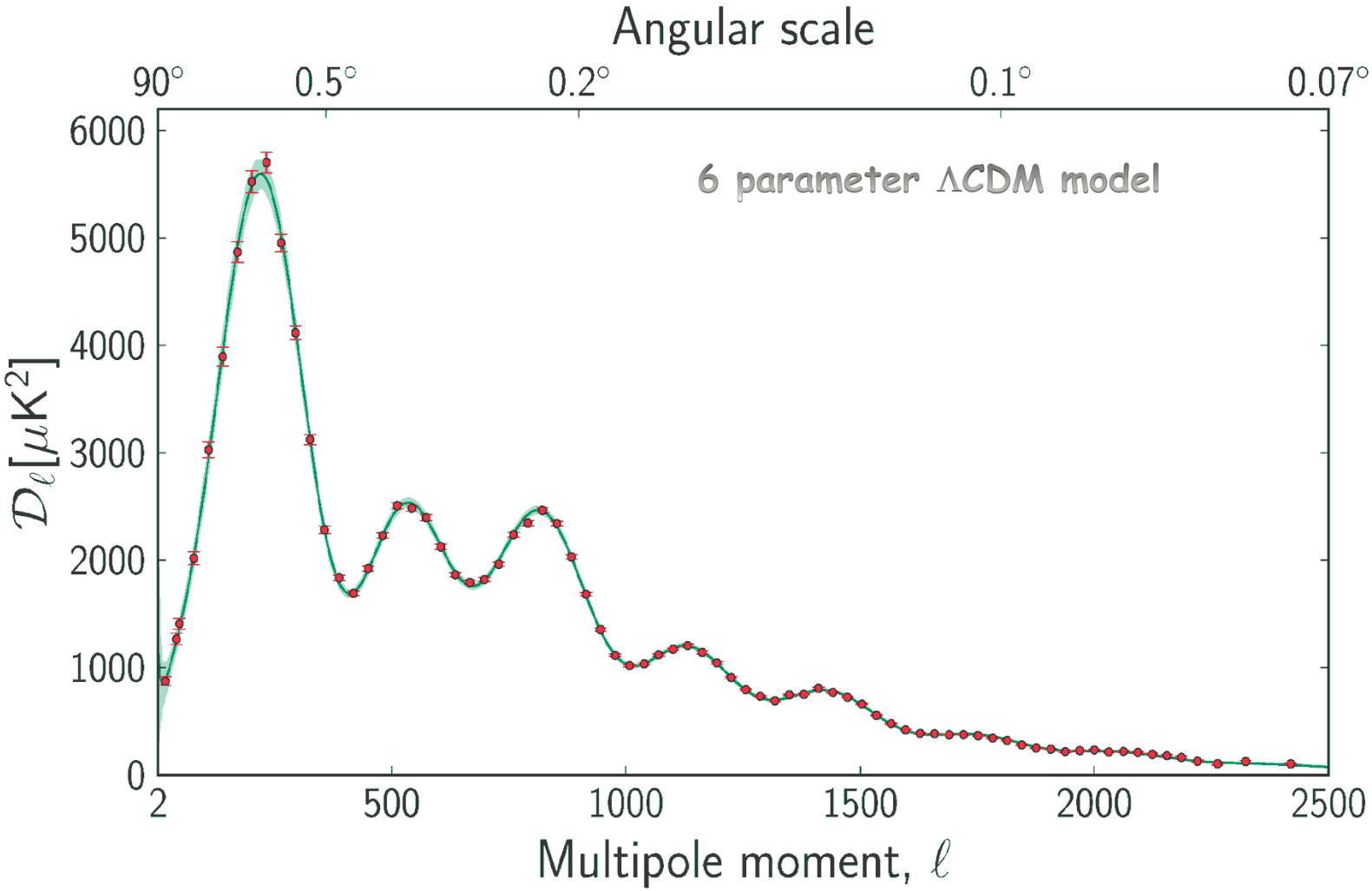


Checking consistency of the CMB PS/map

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

Parameter	*Planck* (CMB+lensing) 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)

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

Base ΛCDM model 6 parameters

Planck alone

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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 $\Omega_m h^3$)

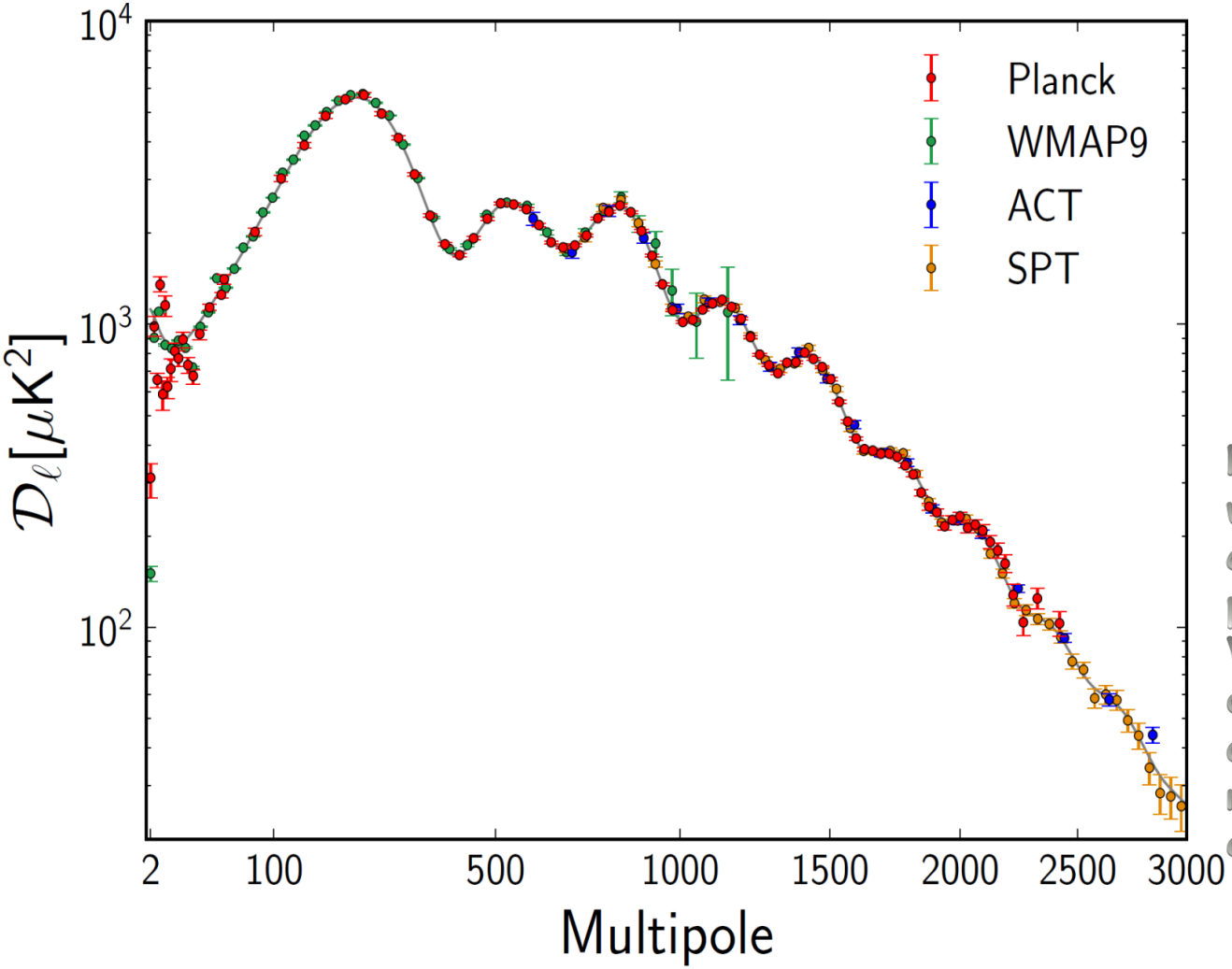
Goodness of fit:

$$\chi^2 = \sum_{\ell\ell'} (C_\ell^{\rm data} - C_\ell^{\rm CMB} - C_\ell^{\rm fg}) \mathcal{M}^{-1}_{\ell\ell'} (C_{\ell'}^{\rm data} - C_{\ell'}^{\rm CMB} - C_{\ell'}^{\rm fg})$$

Spectrum	$\ell_{\rm min}$	$\ell_{\rm max}$	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

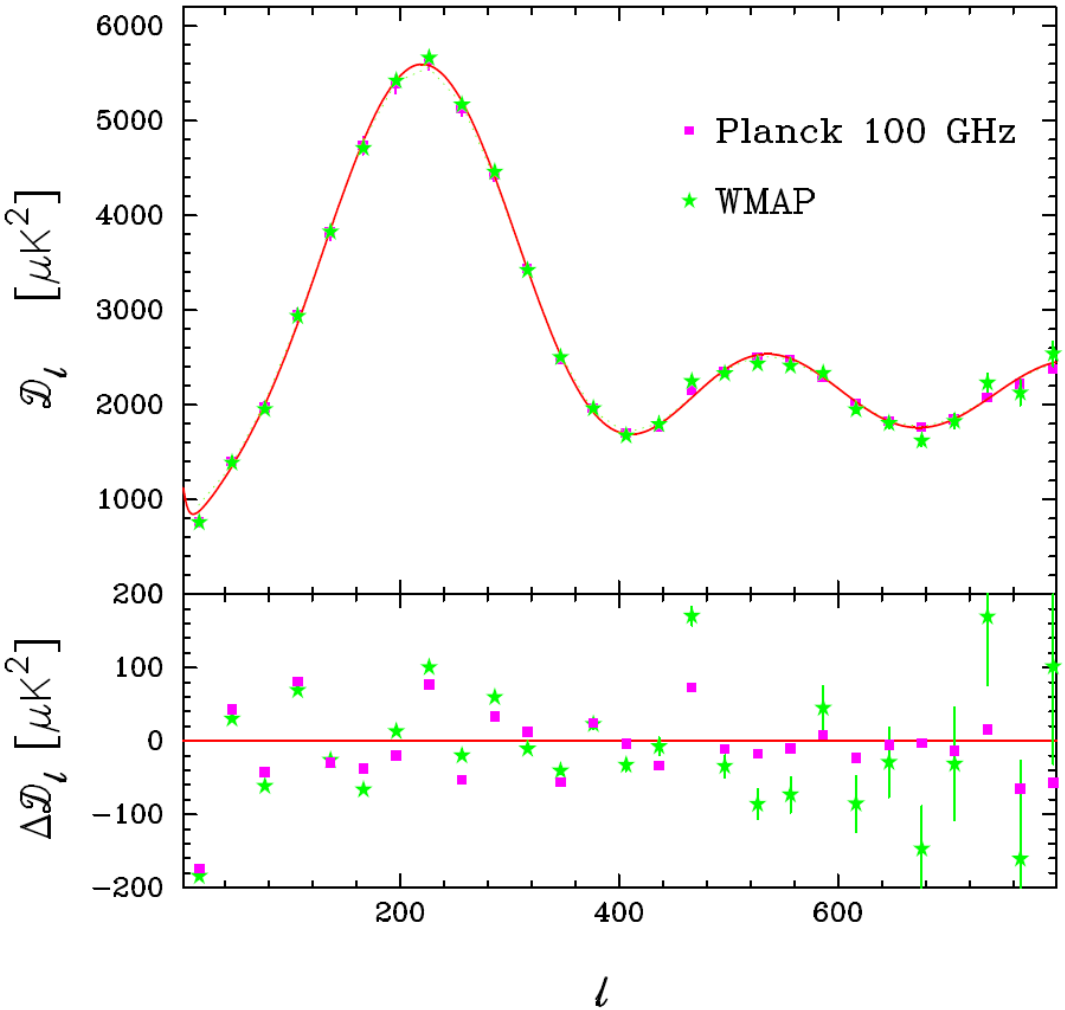
$$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724^\circ \pm 0.00038^\circ$$

The 2013 CMB temperature landscape



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

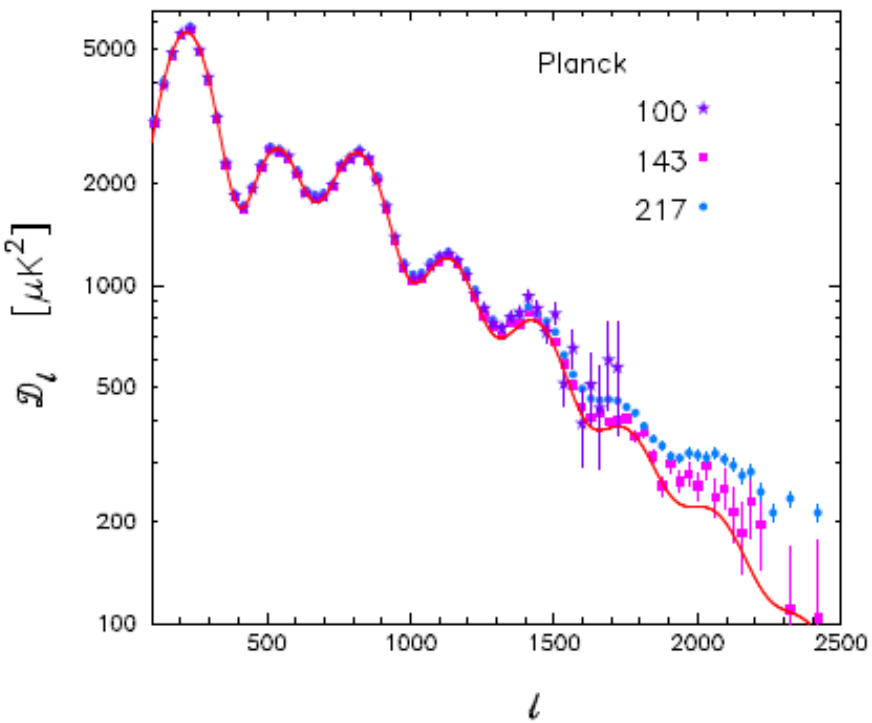
Planck vs WMAP

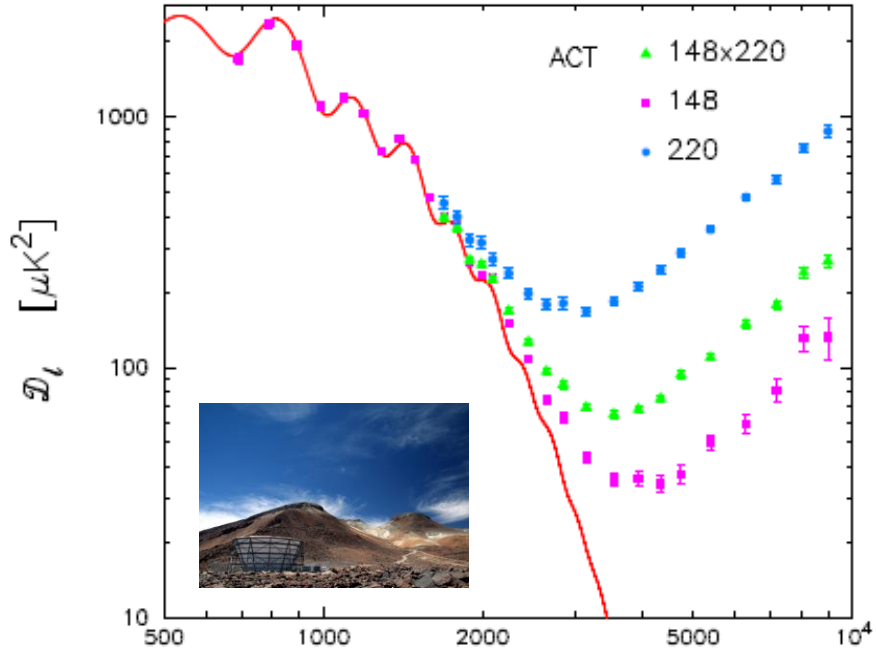


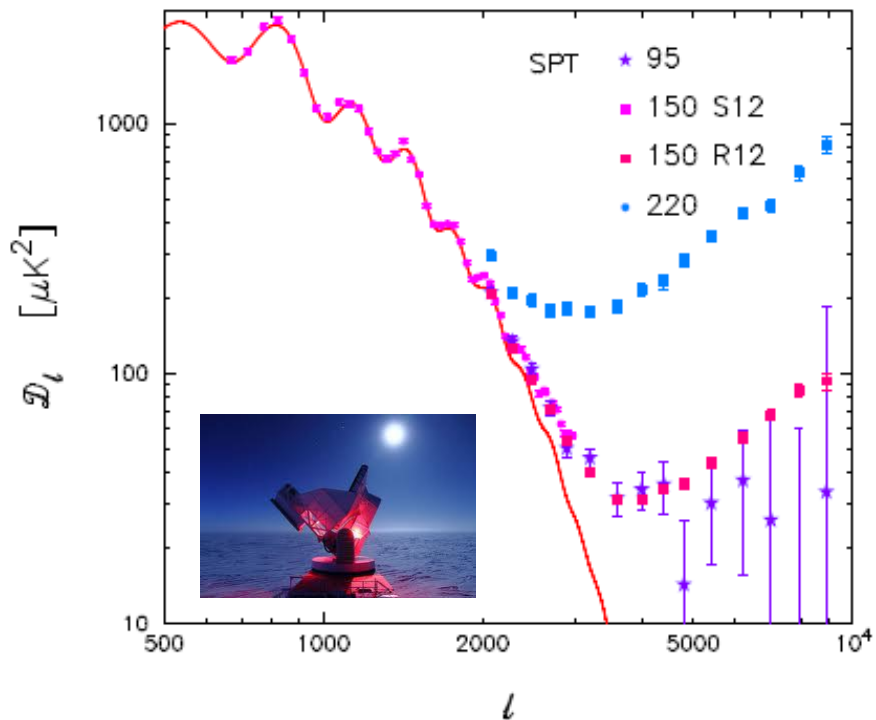
After rescaling WMAP by a factor 0.976 (akin to a recalibration by 1.2%, the origin of which is under investigation by both teams)

Planck & HL

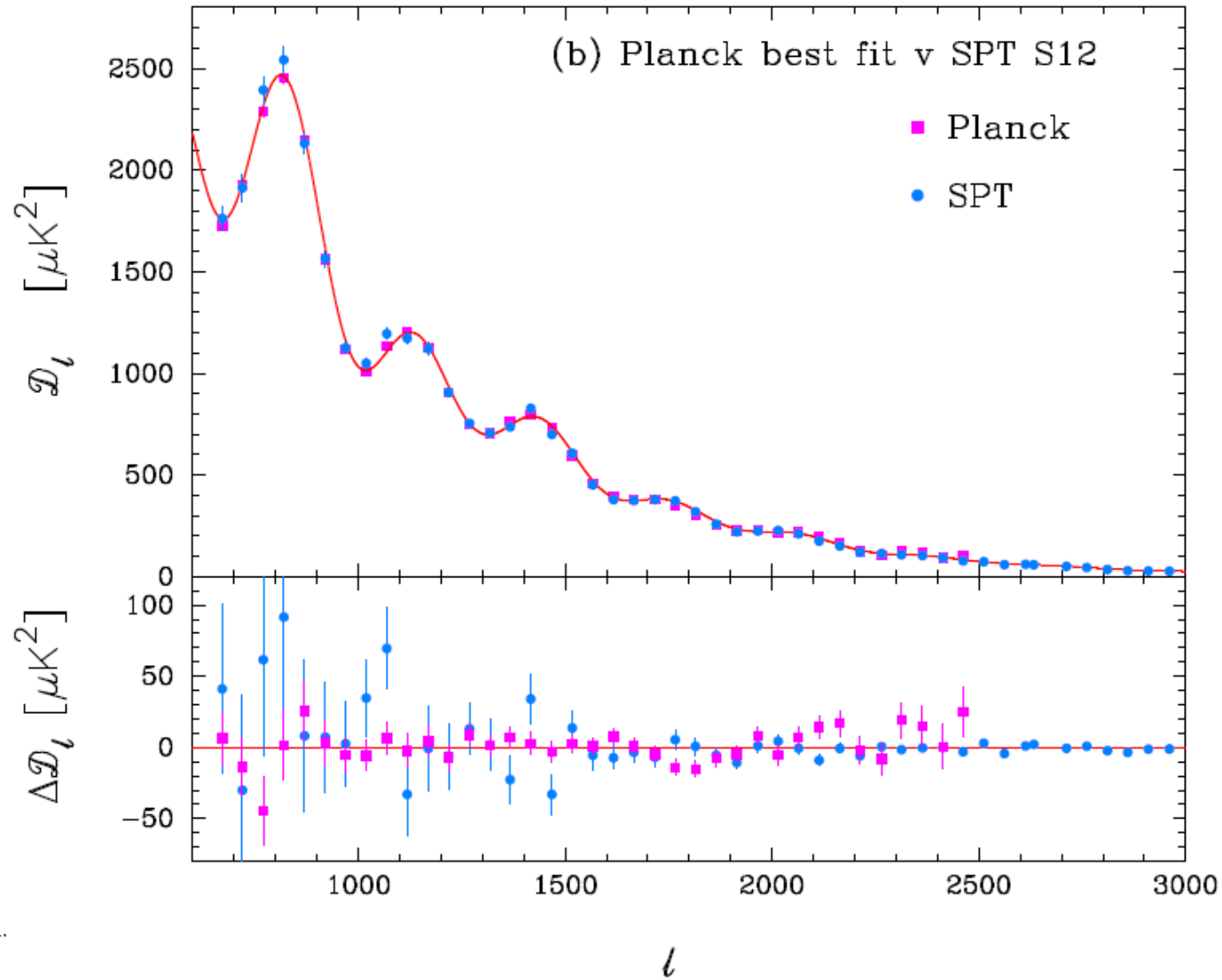
HL=high-l CMB = ACT + SPT





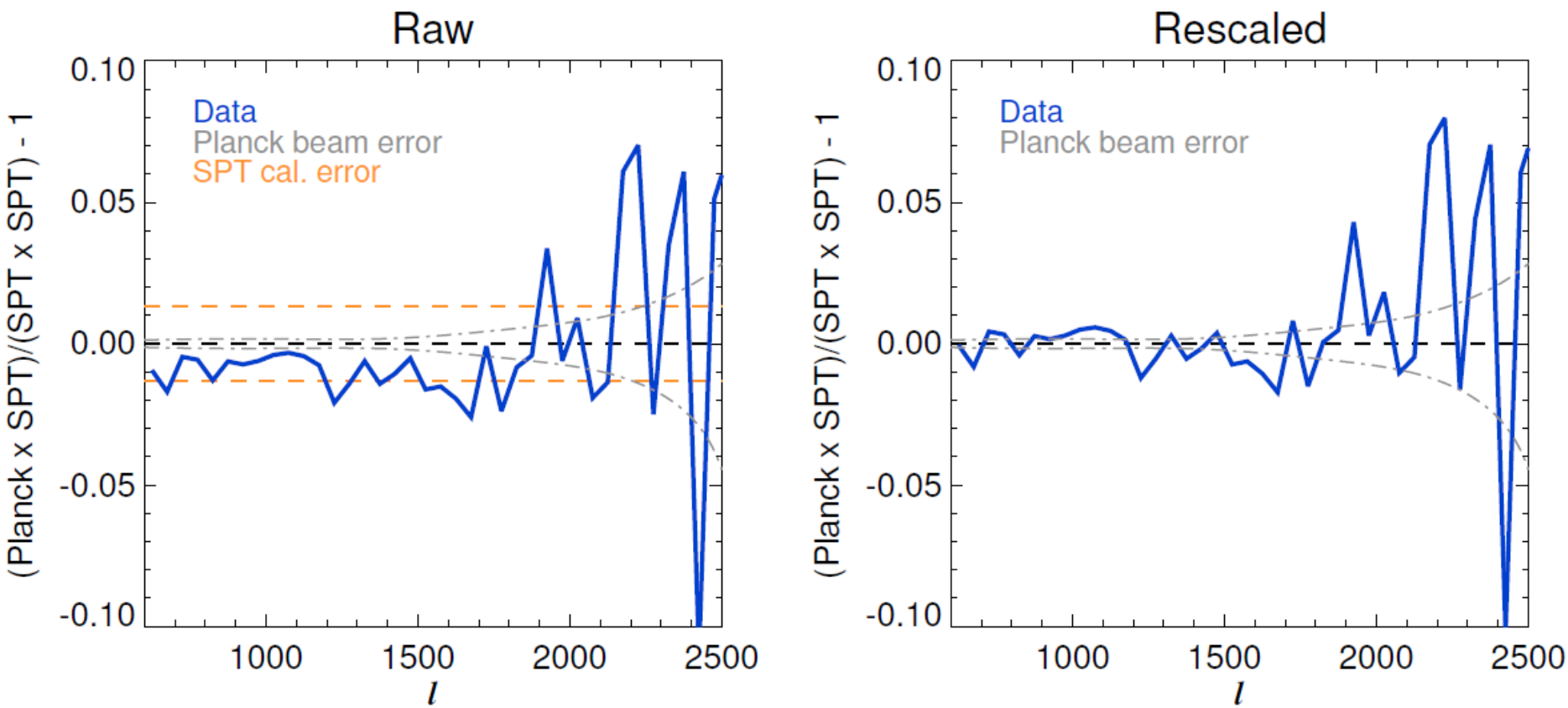


Planck / SPT consistency

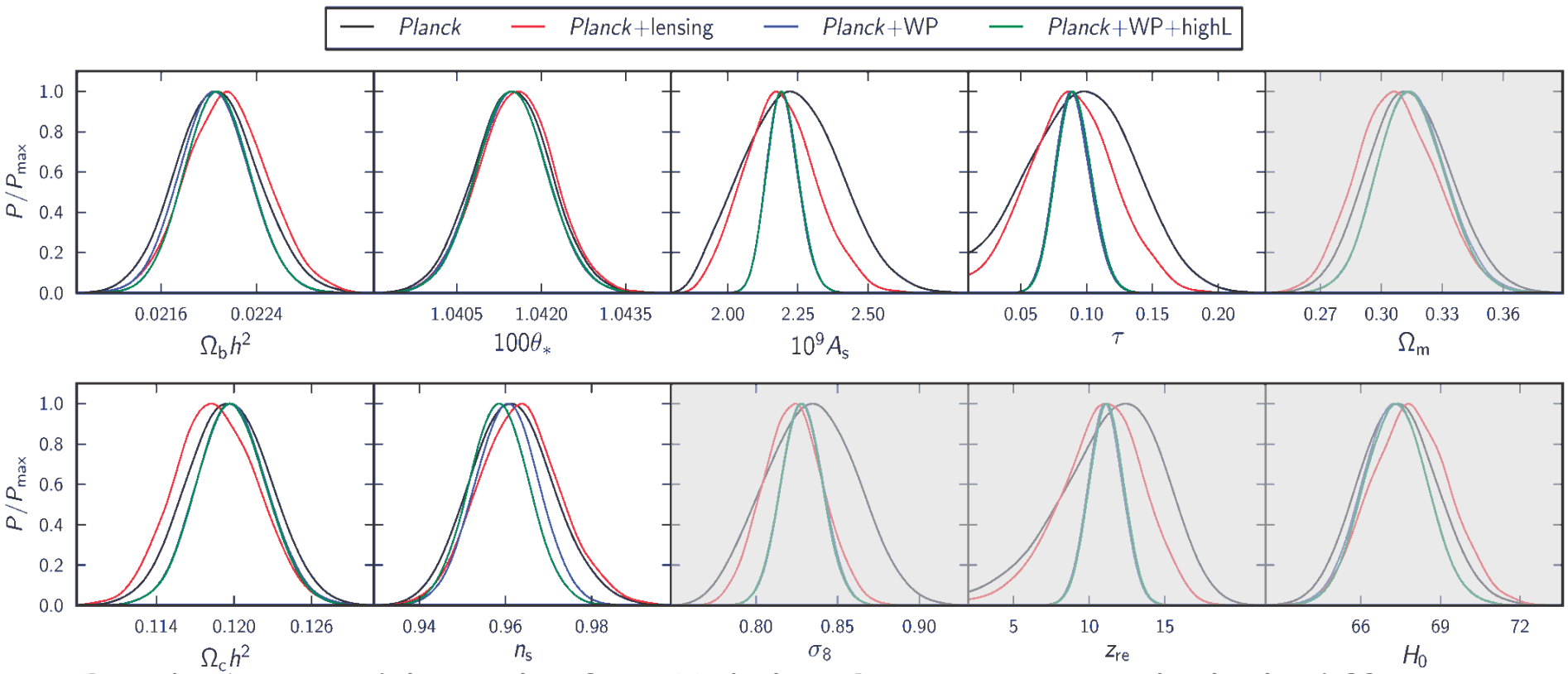


SPT points sit a little high at l<1100

Planck / SPT consistency



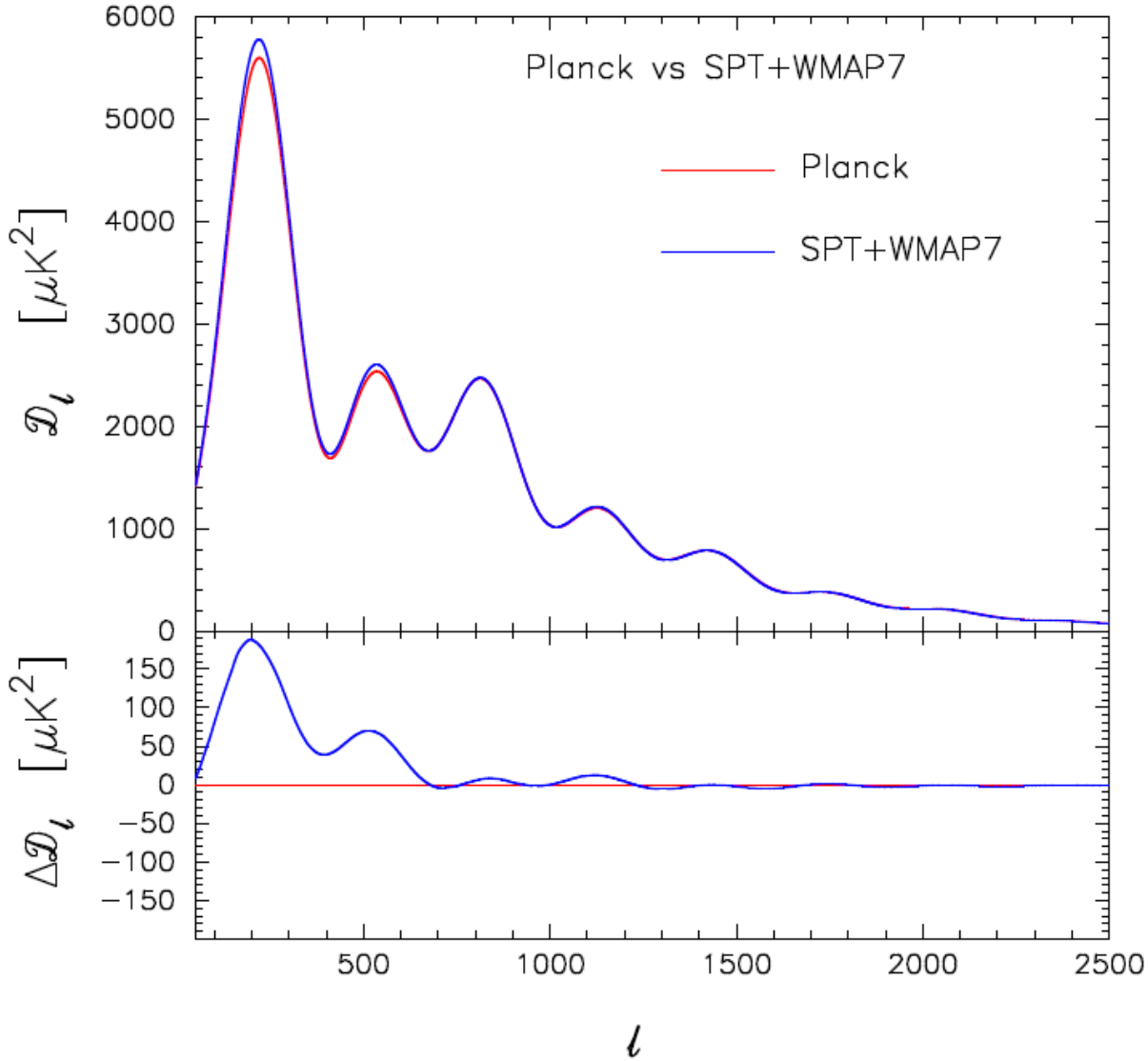
Base tilted ΛCDM model - 6 parameters



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

High-l CMB experiments = ACT + SPT (600 & 2540 deg², 2 & 3 freq.)

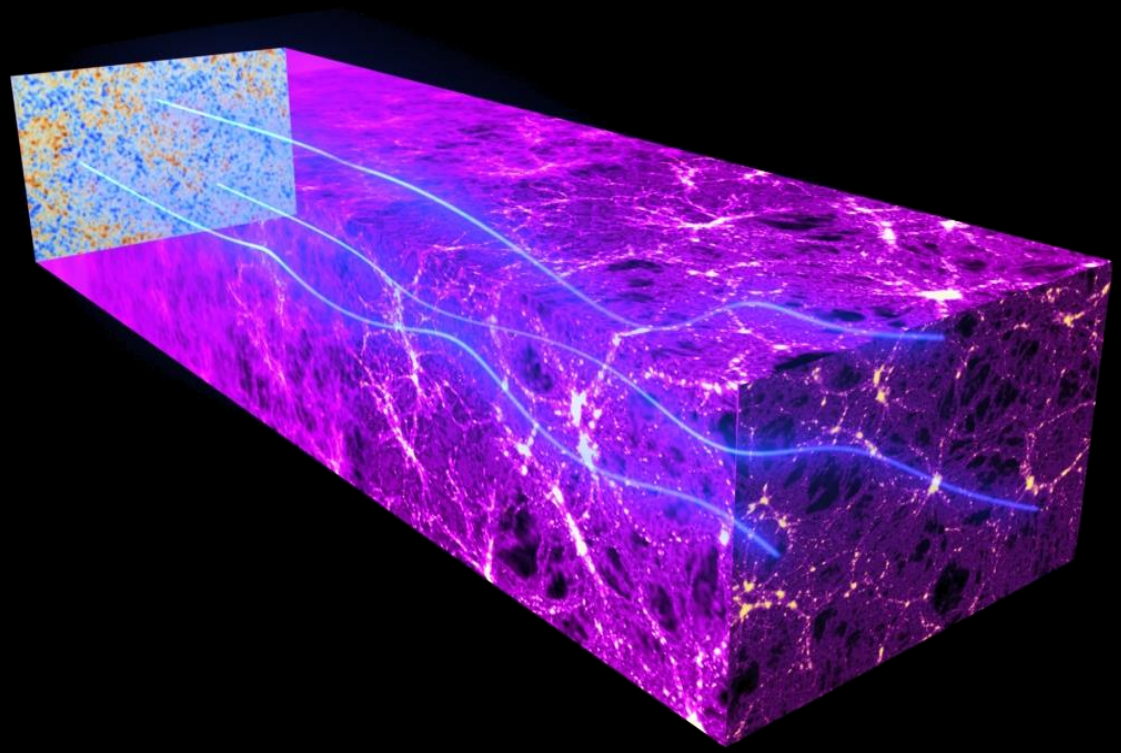
Planck vs pre-Planck



Conparisons with other “observables”

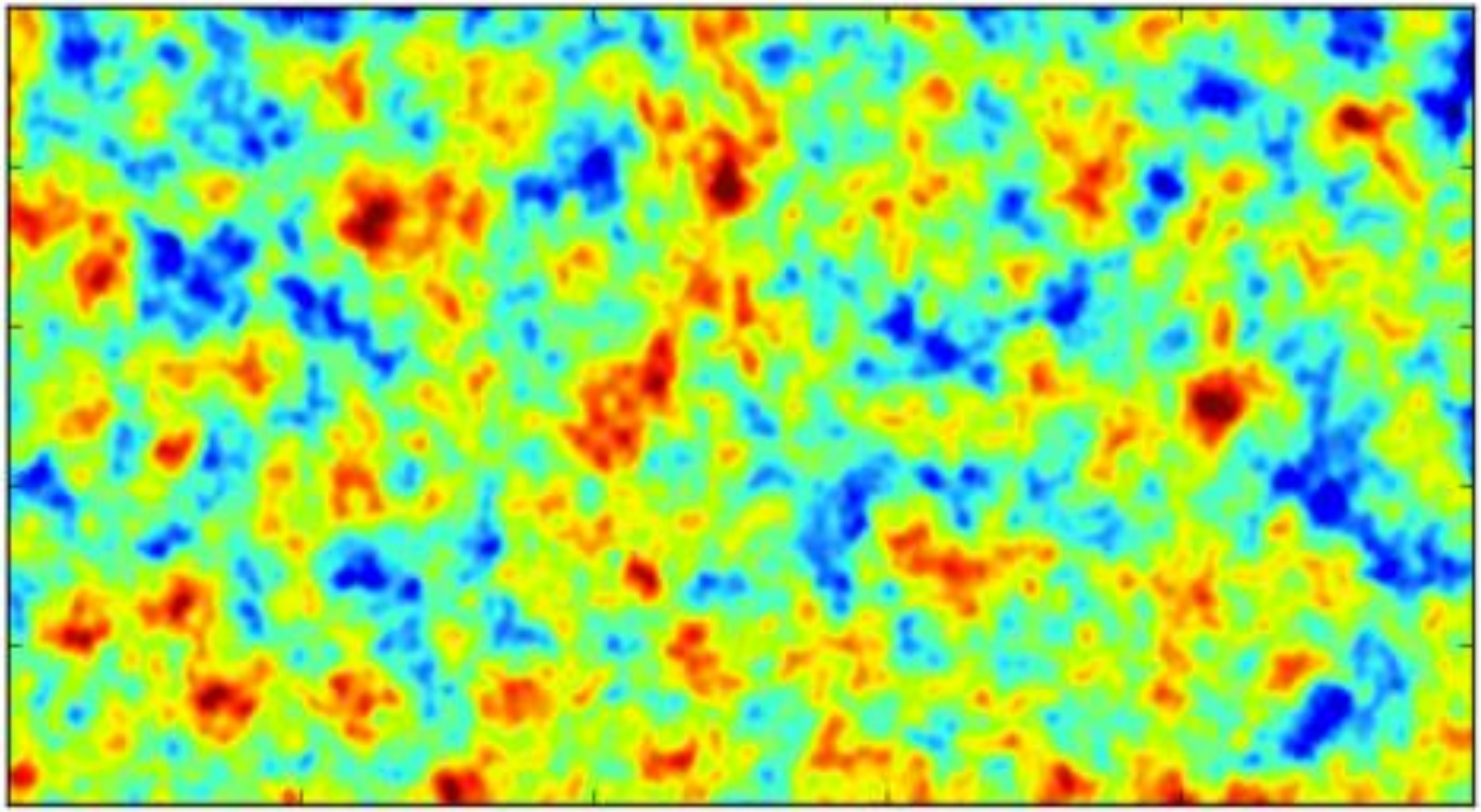
GRAVITATIONAL LENSING DISTORTS IMAGES

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



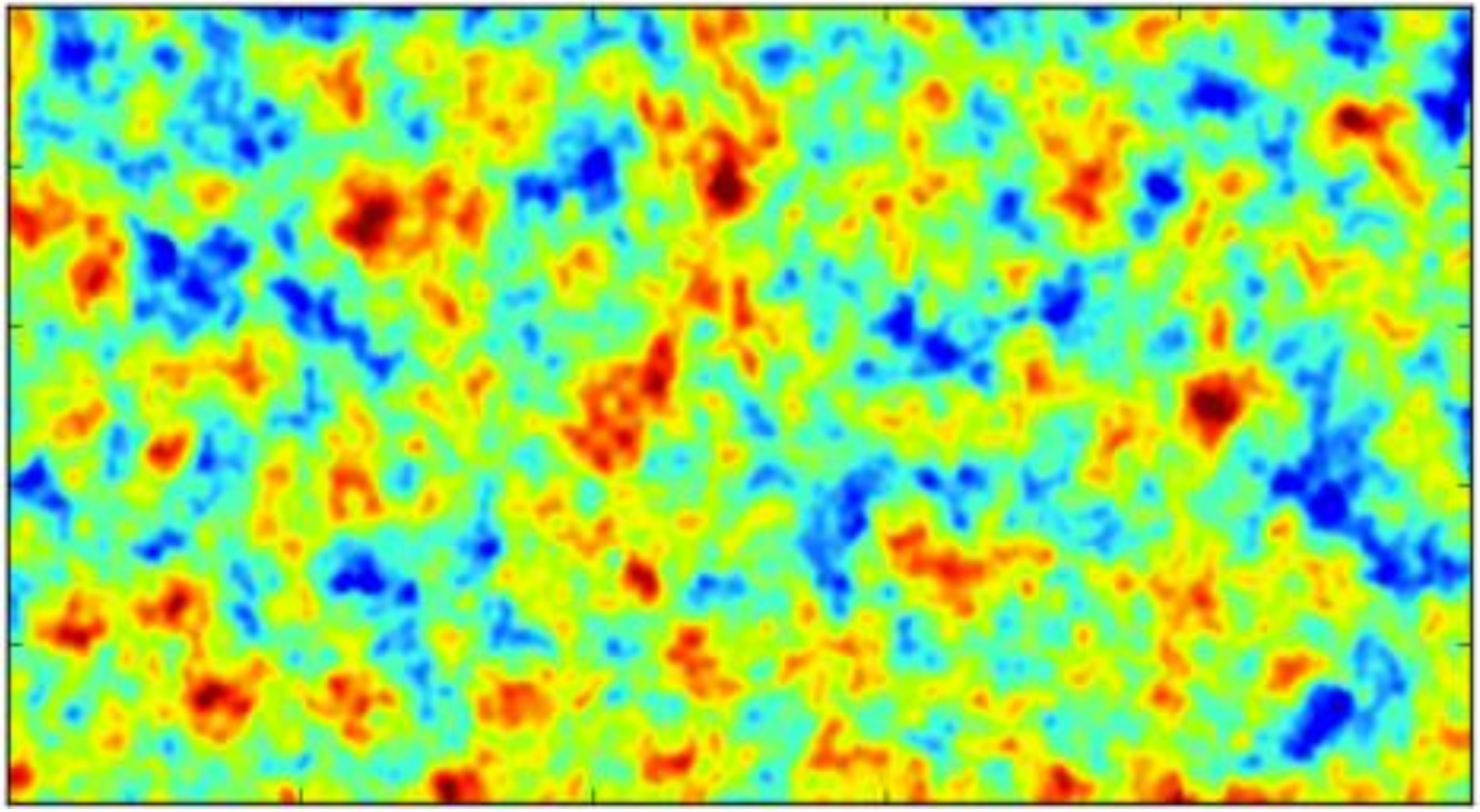
GRAVITATIONAL LENSING OF THE CMB

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



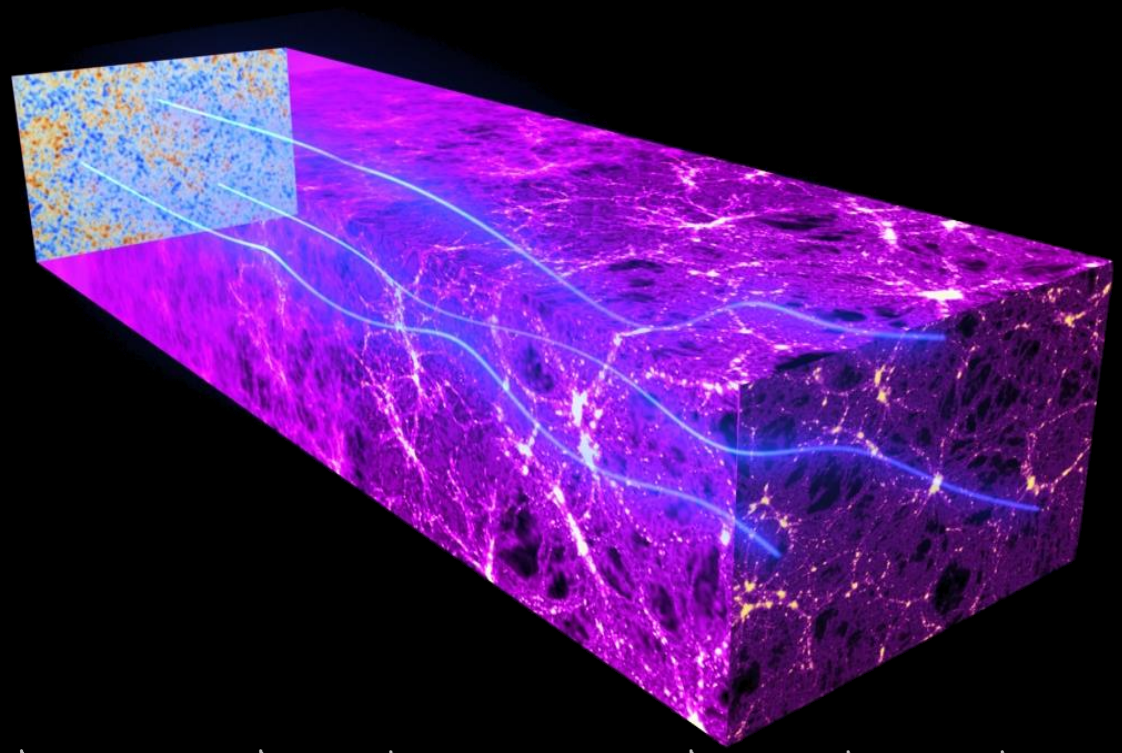
GRAVITATIONAL LENSING OF THE CMB

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



GRAVITATIONAL LENSING DISTORTS IMAGES

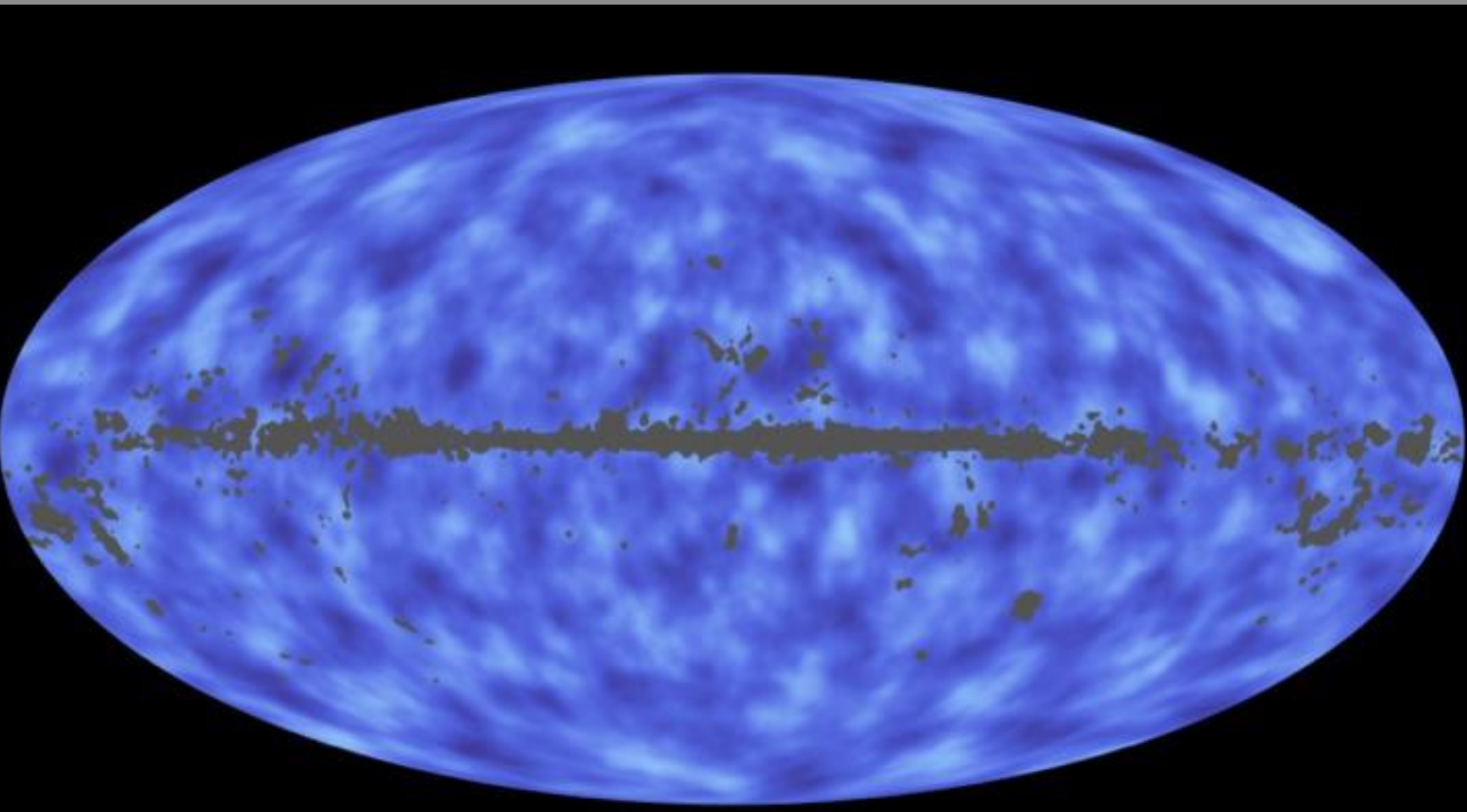
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



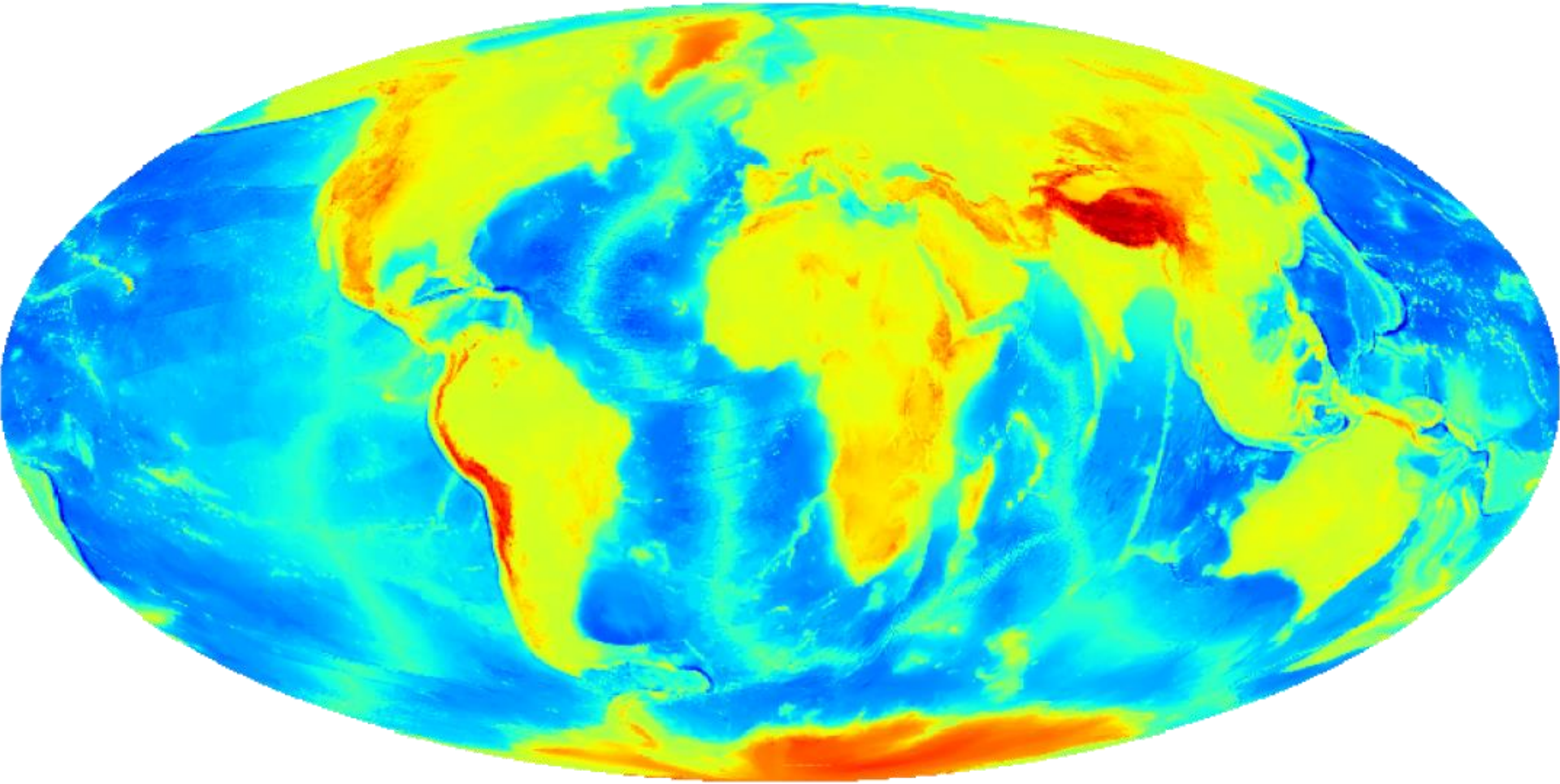
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$

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

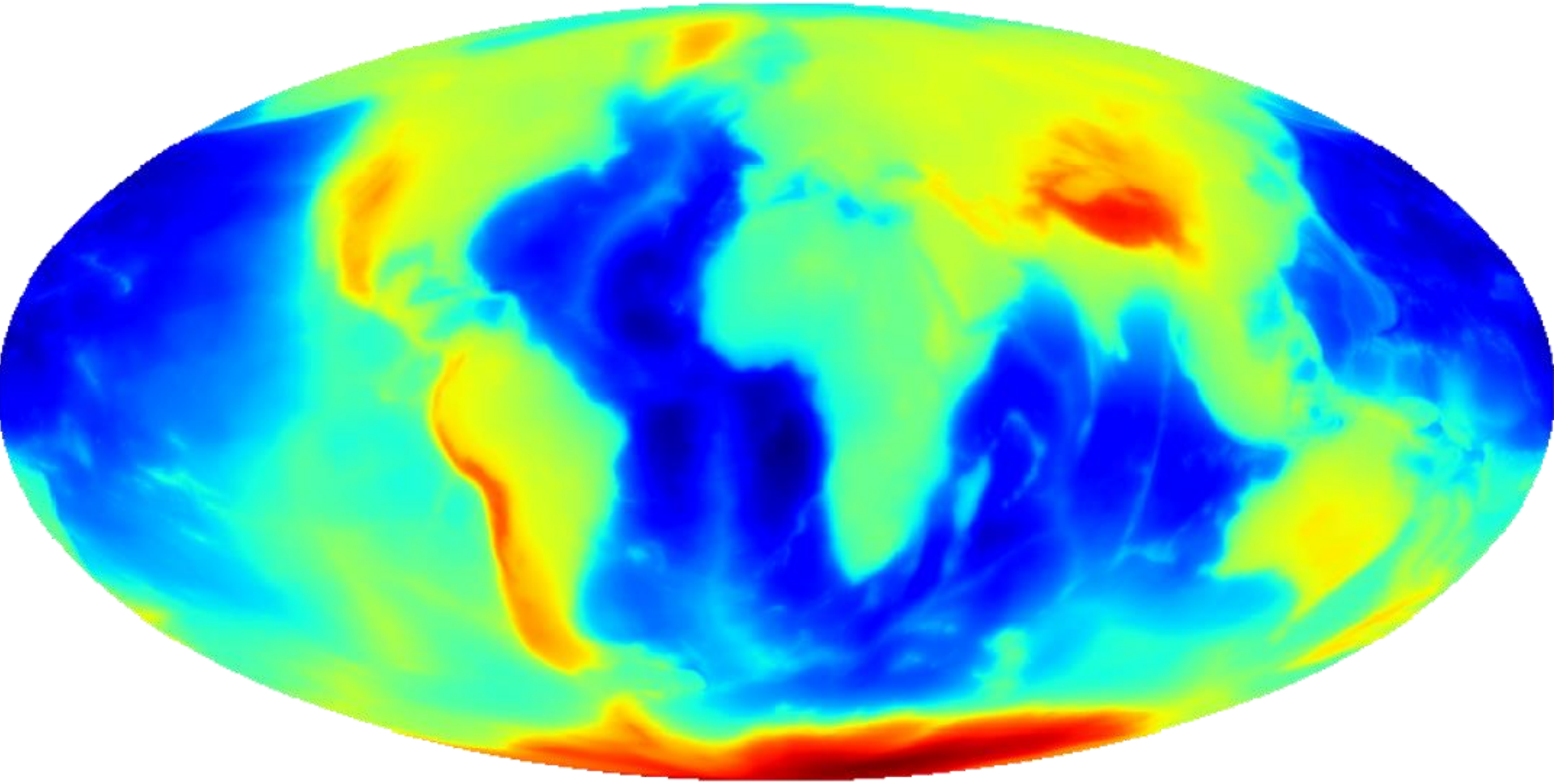
Projected mass map



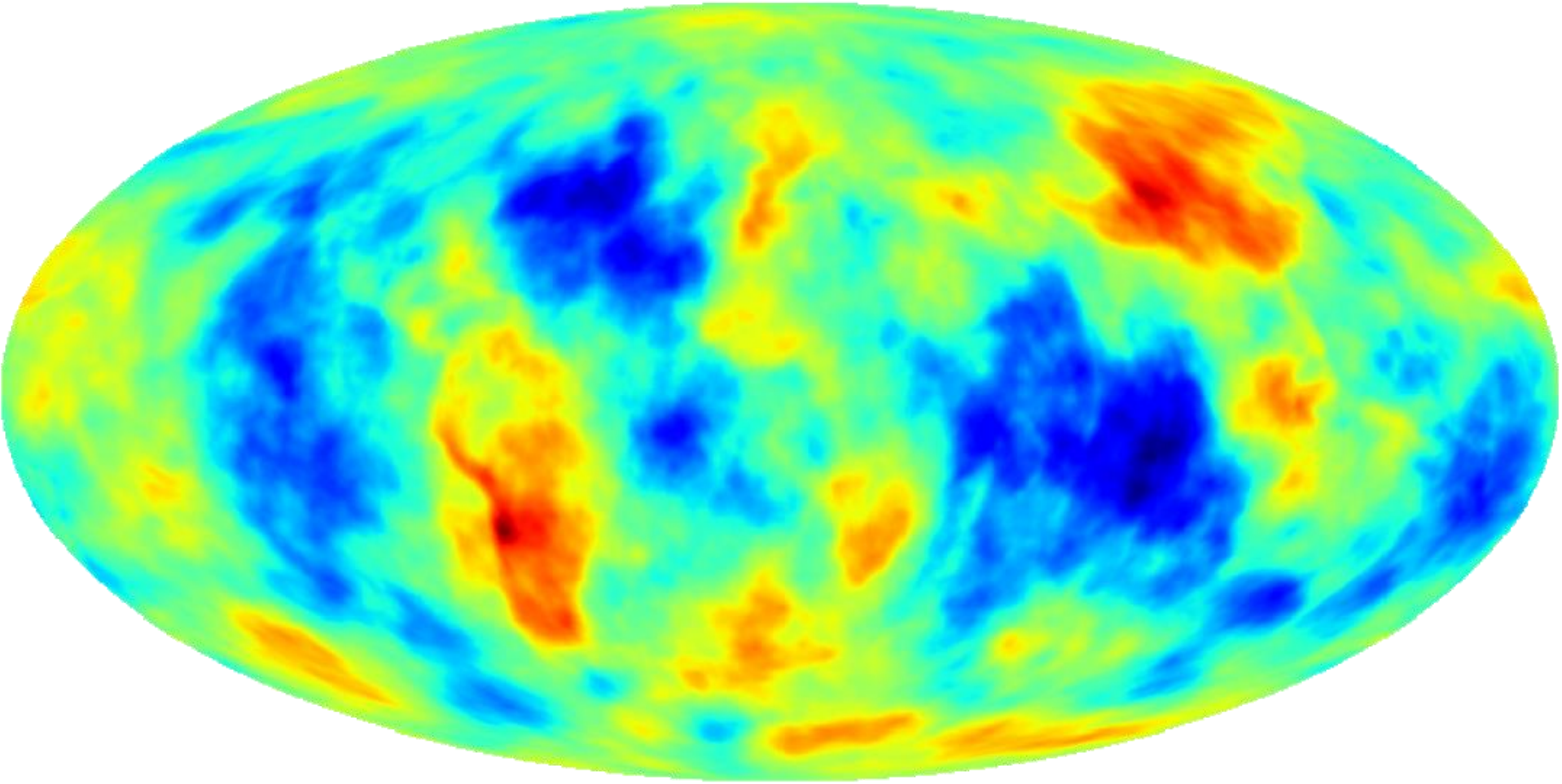
Another full sphere distribution



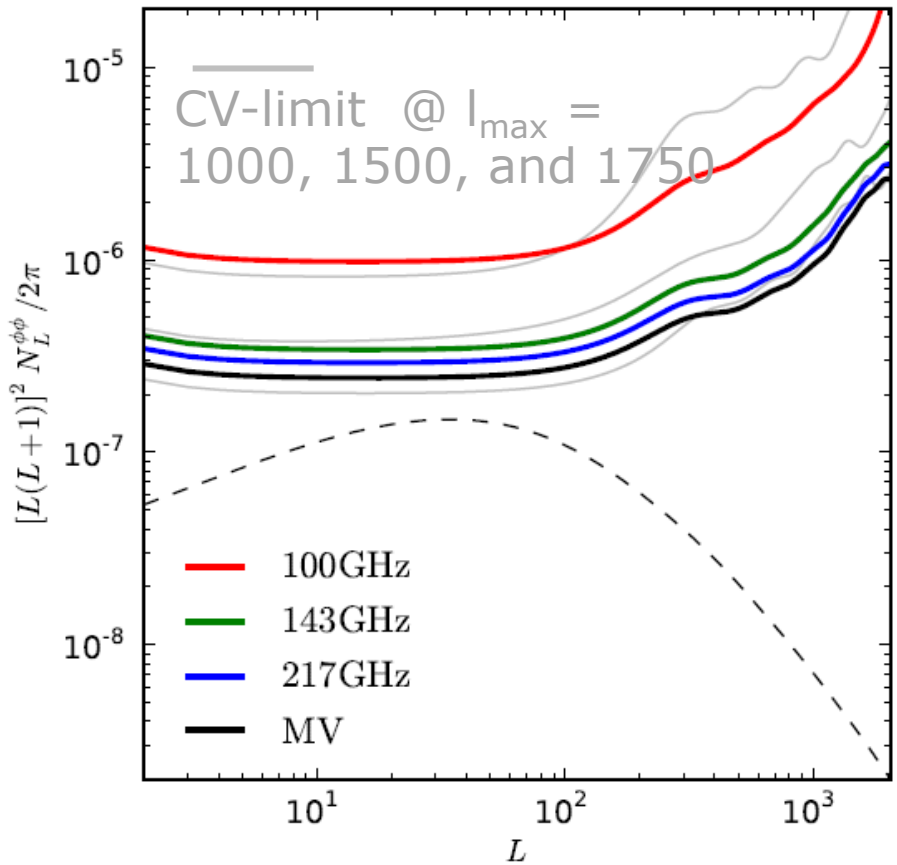
at our angular resolution…



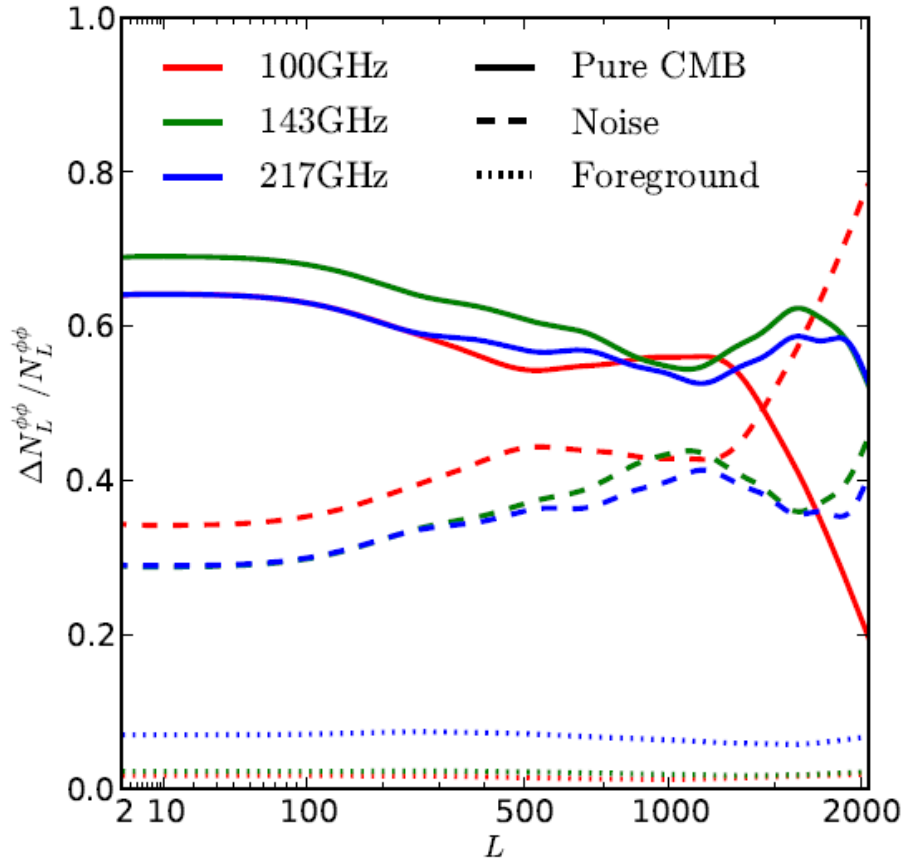
and noise level!



The lensing challenge

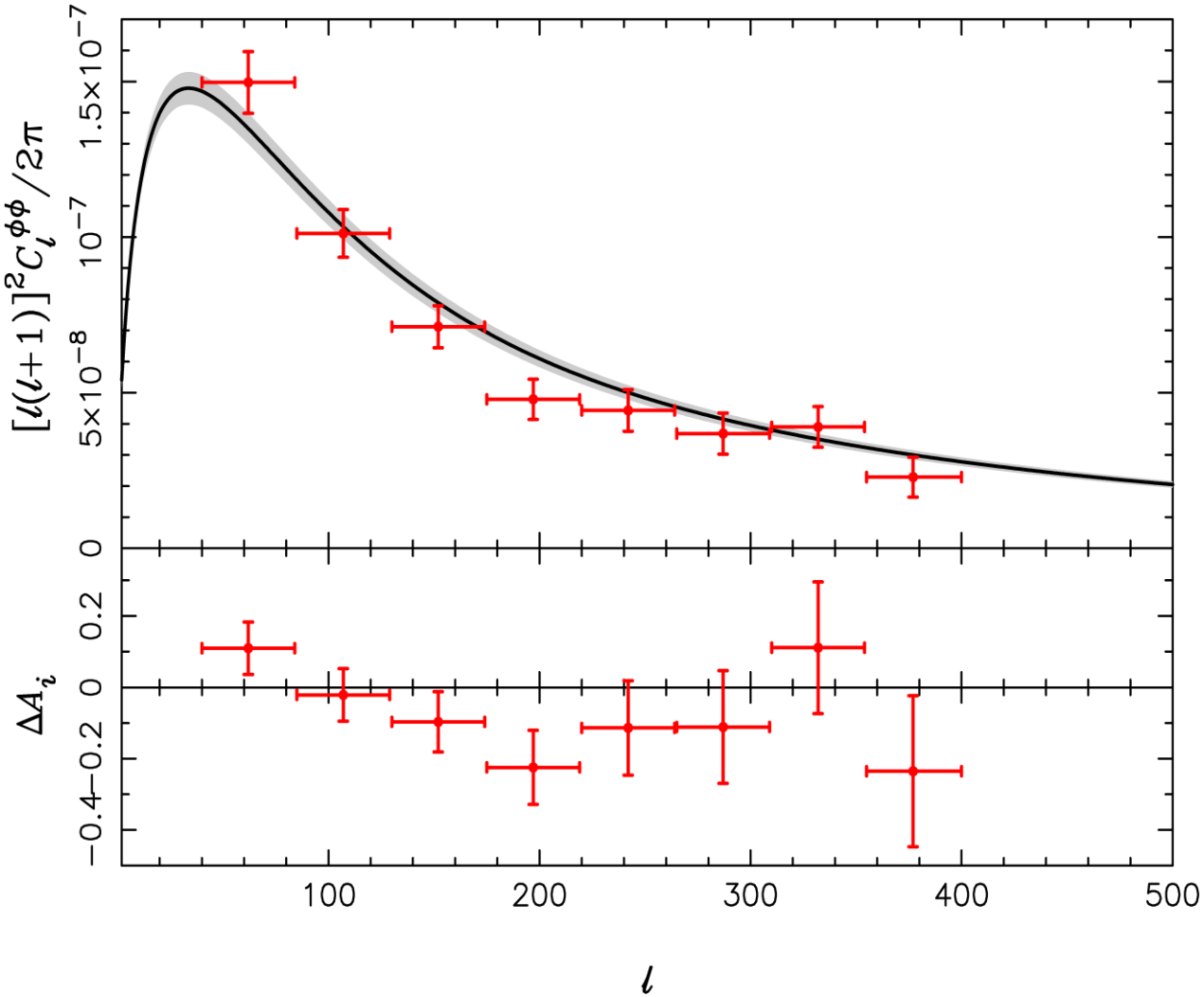


Sky-averaged lens reconstruction noise levels



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

The lensing potential spectrum

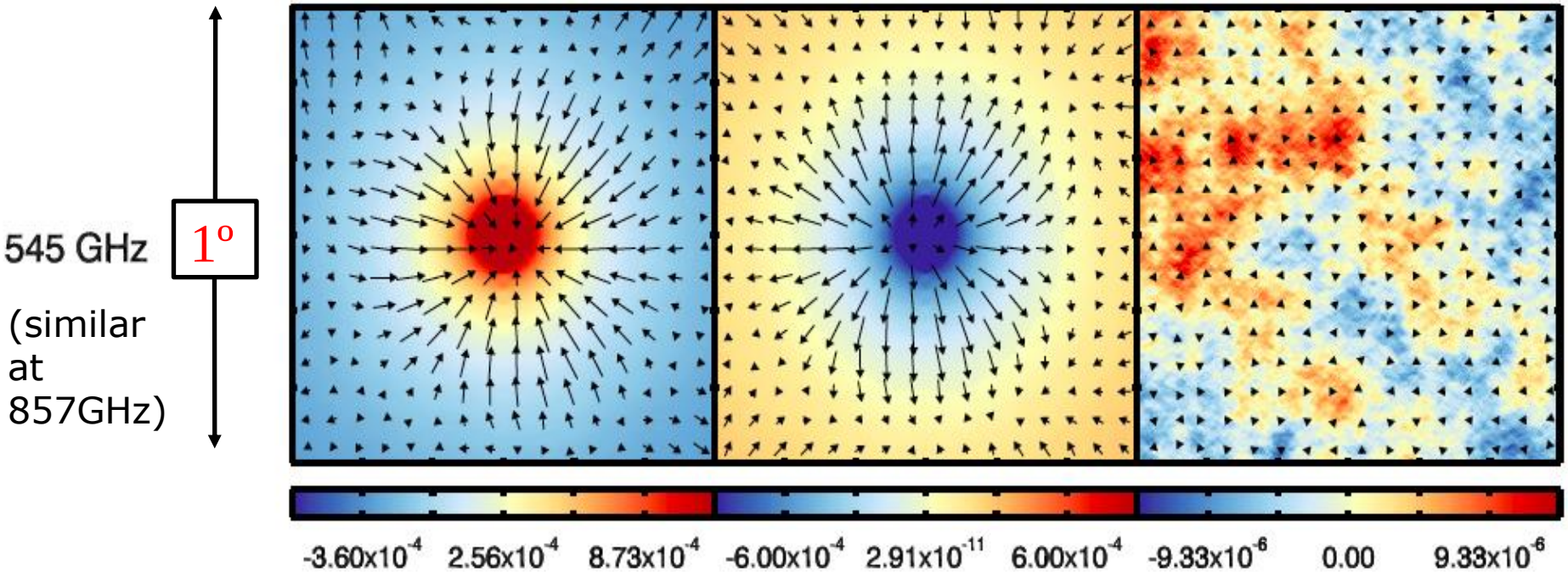


(26σ detection)

➔ Agrees well with the prediction from T alone

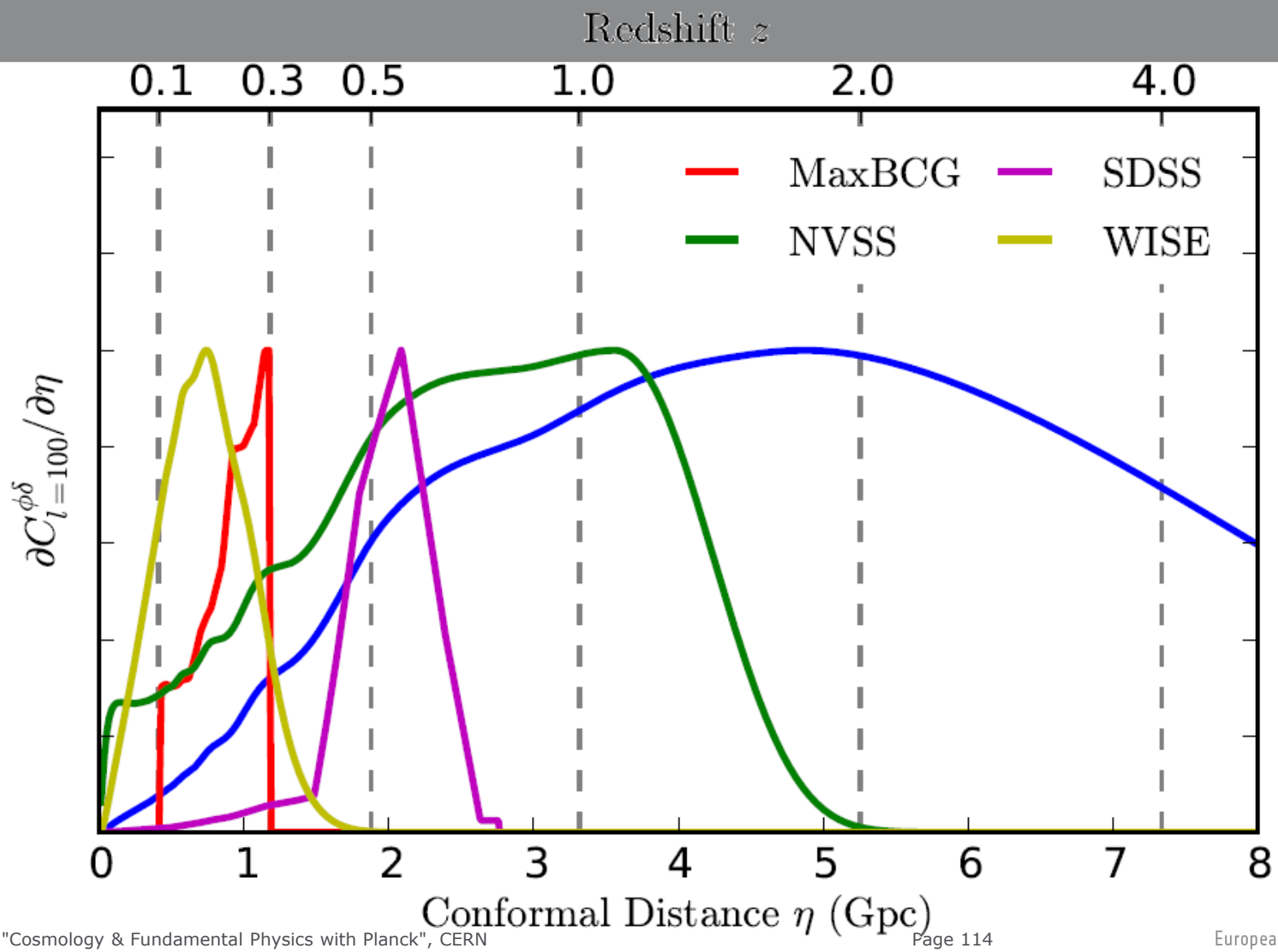
CIB PEAKS CORRESPOND TO MASS PEAKS

Stacking the Planck mass maps at the positions of peaks and troughs of Cosmic Infrared Background leads to a strong detection of the mass associated with these distant star forming galaxies.

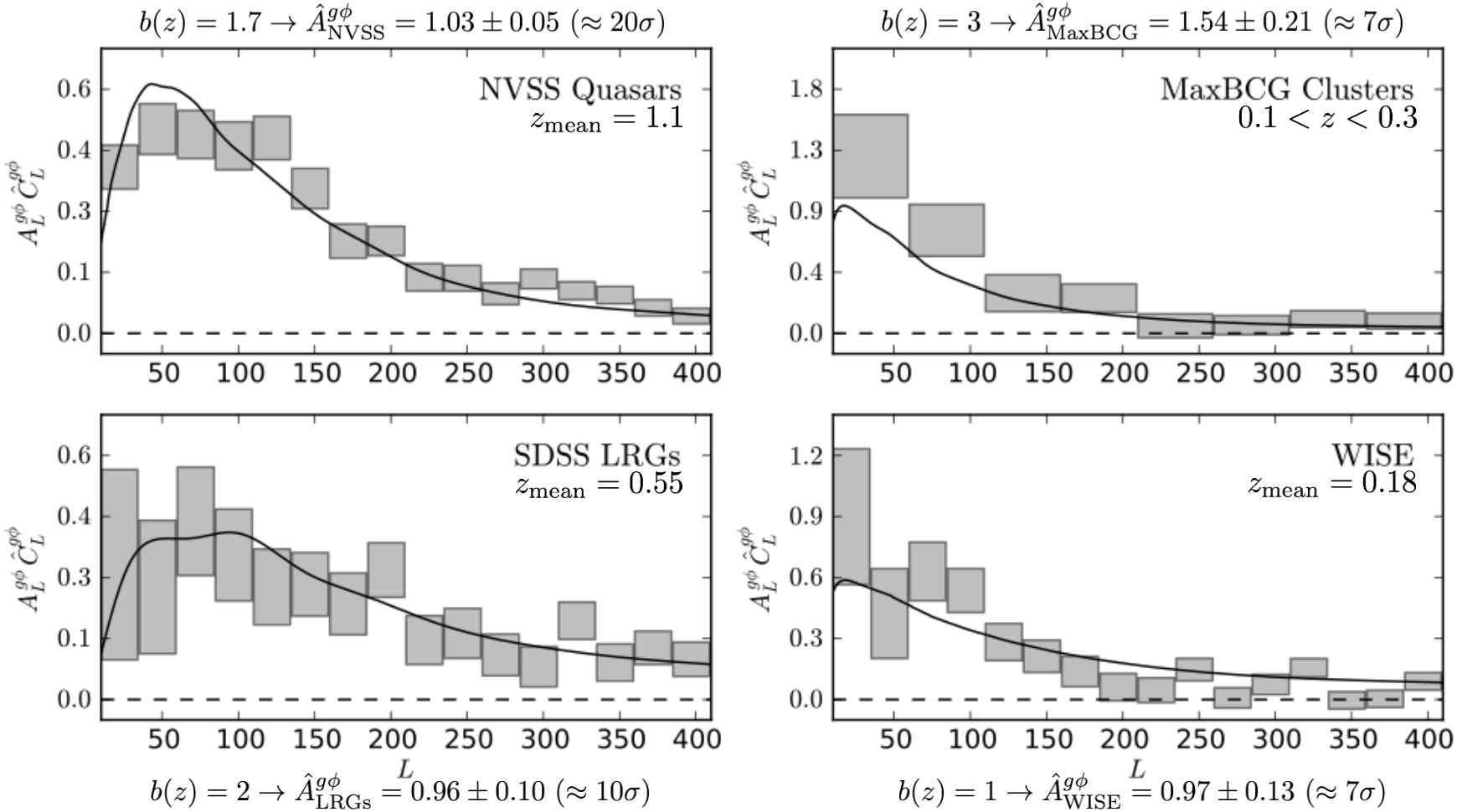


[Planck Collaboration XVIII

Redshift distribution

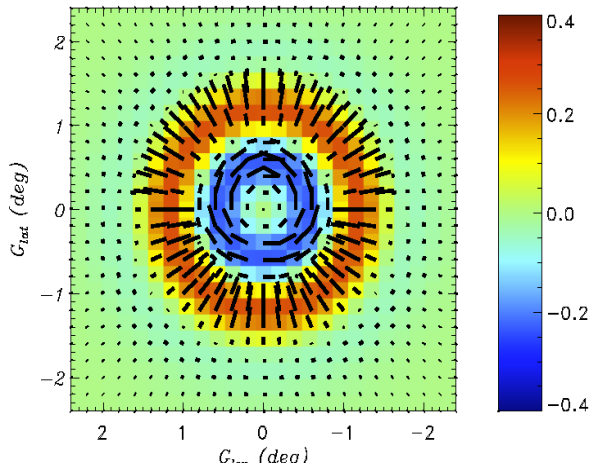


Lensing potential versus distribution of external tracers



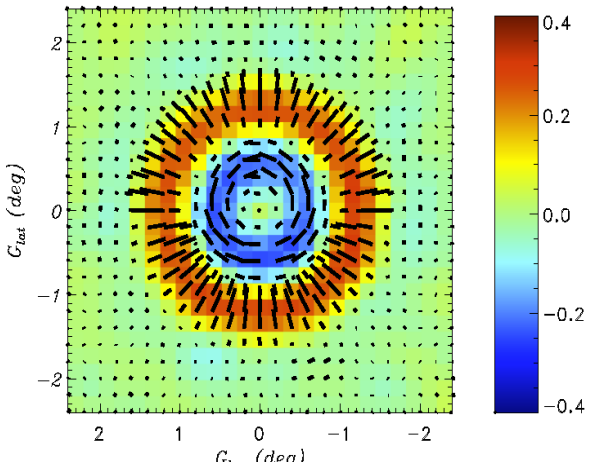
No particular effort here to optimize the model for the external survey

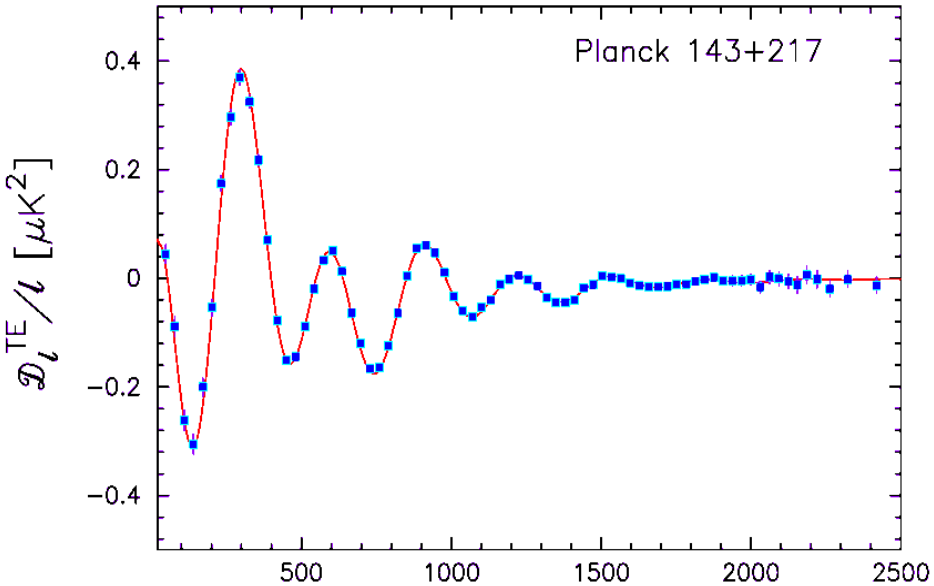
Polarisation around hot spots

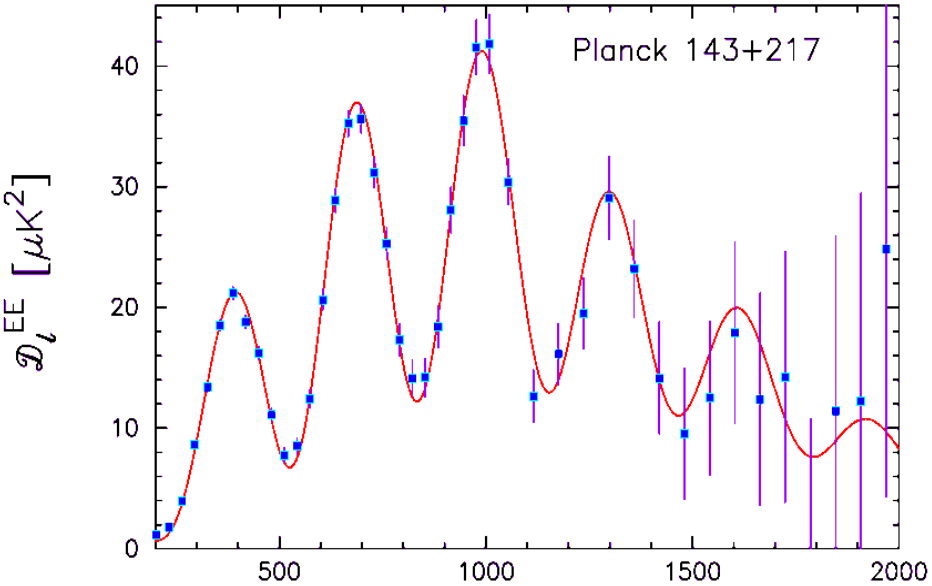


Planck "sees" precisely the dynamics of fluctuations, at ~380 000 years:

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

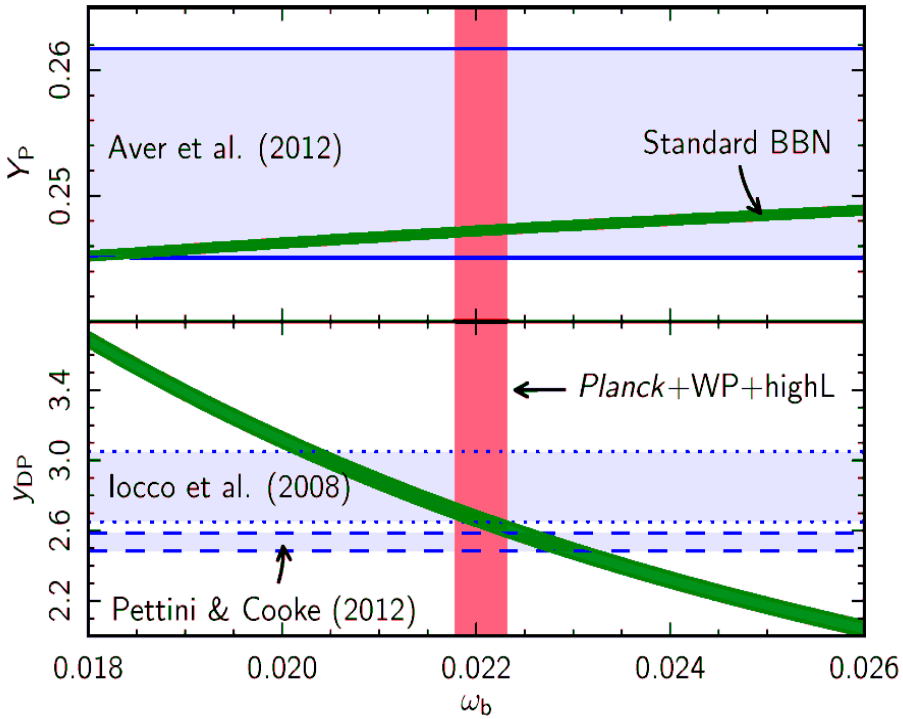




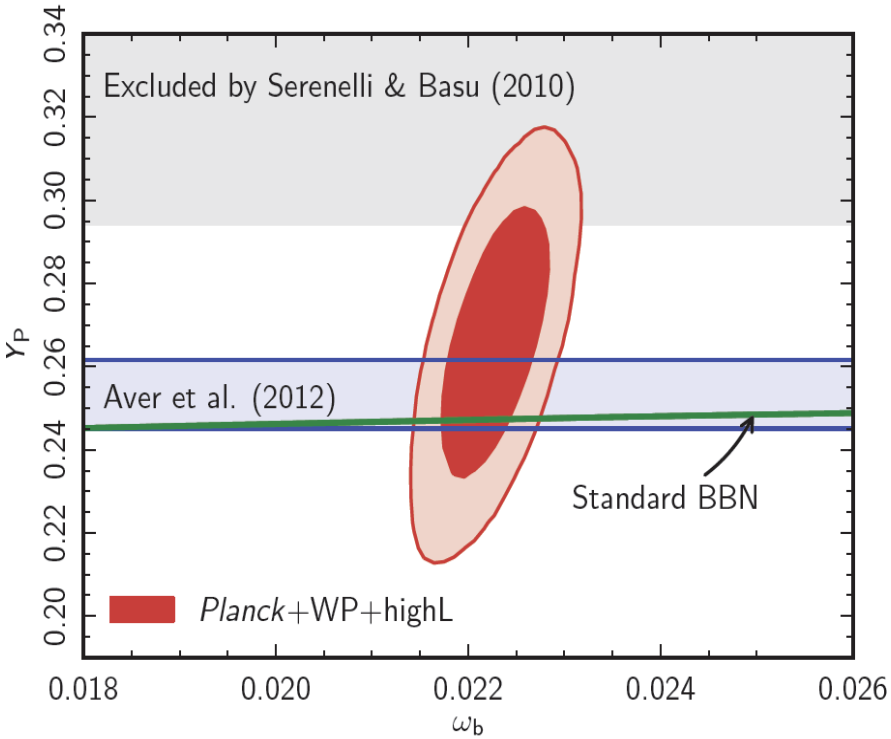


Red is prediction in base model from fitting T alone

Primordial nucleosynthesis

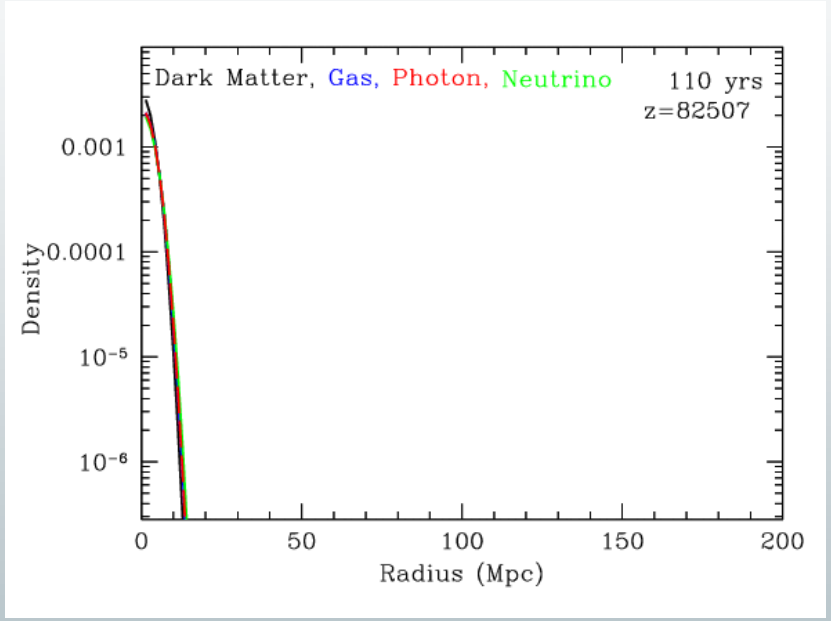


Y_P as a *derived* quantity:
$Y_p = 0.2477 \pm 0.0001$

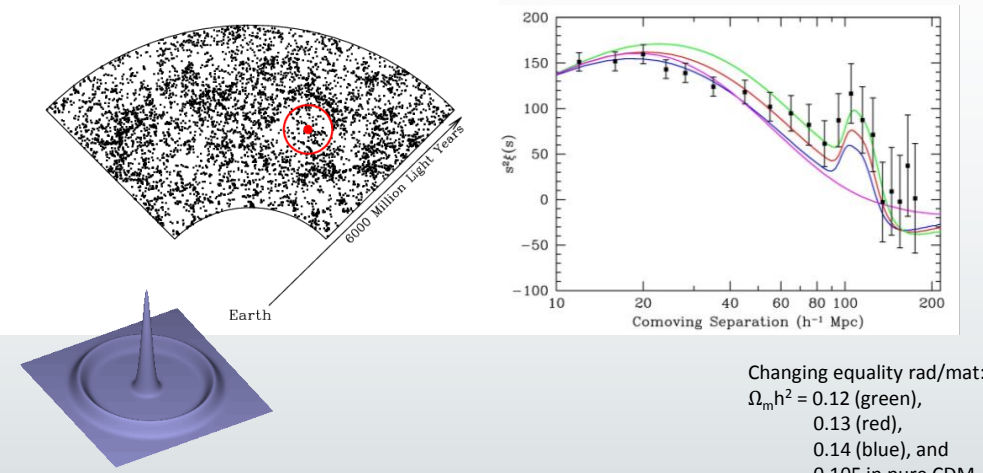


Y_P as an extra parameter

Echos of the primordial drum…

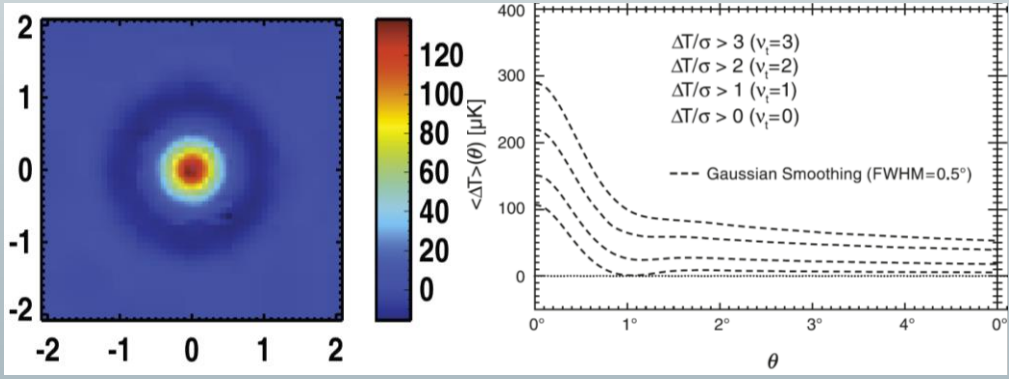


Watch baryon/Photon at z ~1100 decoupling



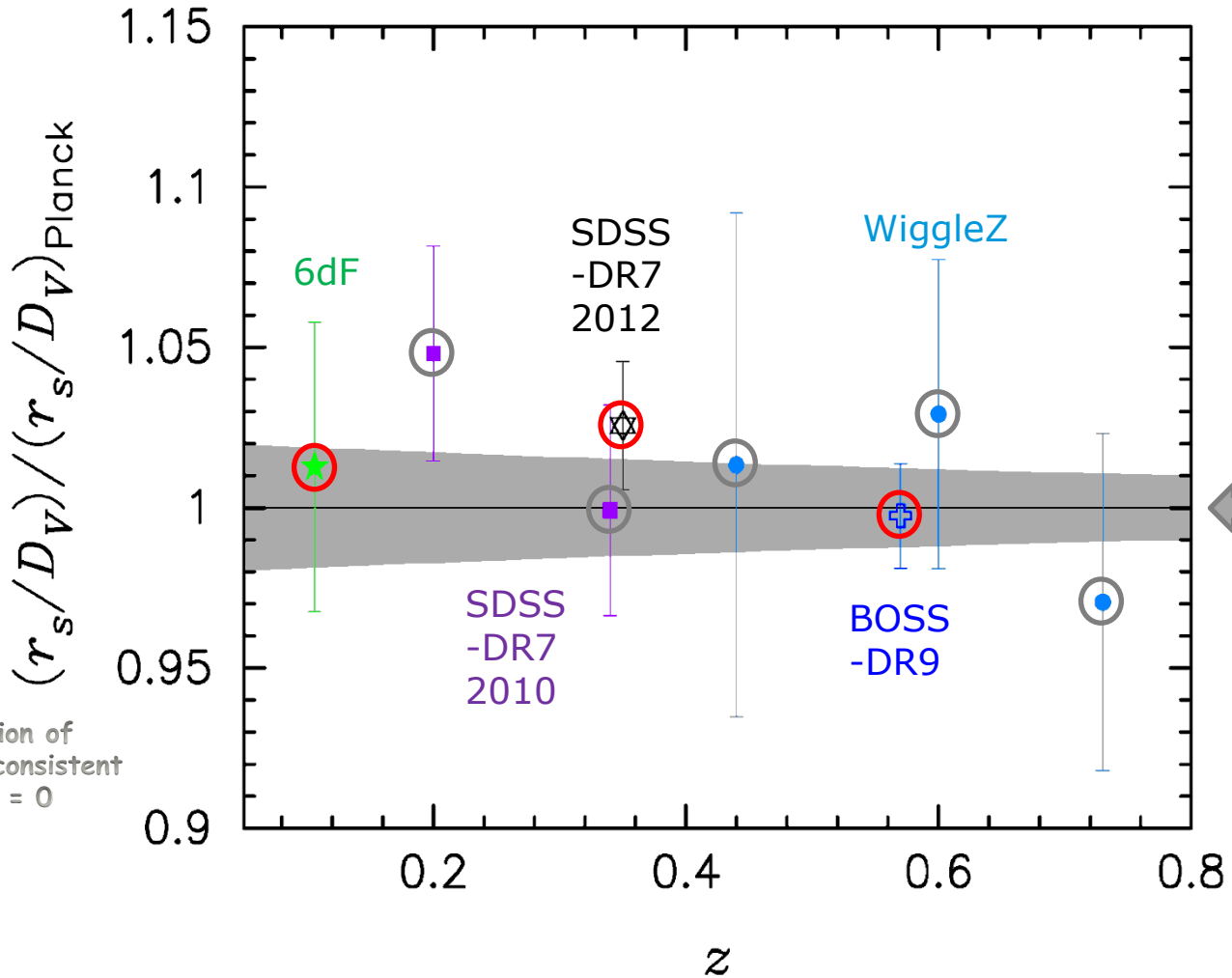
Changing equality rad/mat: $\Omega_m h^2$ = 0.12 (green), 0.13 (red), 0.14 (blue), and 0.105 in pure CDM

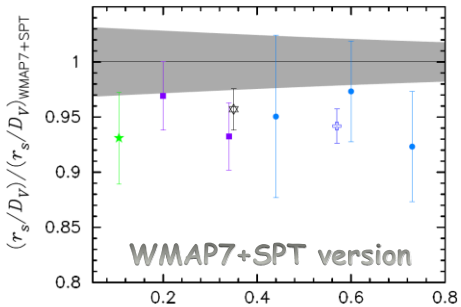
BAO (Baryon Acoustic Oscillations) at z=0



BAO (Baryon Acoustic Oscillations) at z=1100

BAO acoustic-scale distance ratio





(see Hu etal12 for explanations by extensions)

Planck Prediction (±1σ shaded area)

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

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

Base ΛCDM model 6 parameters

Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 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

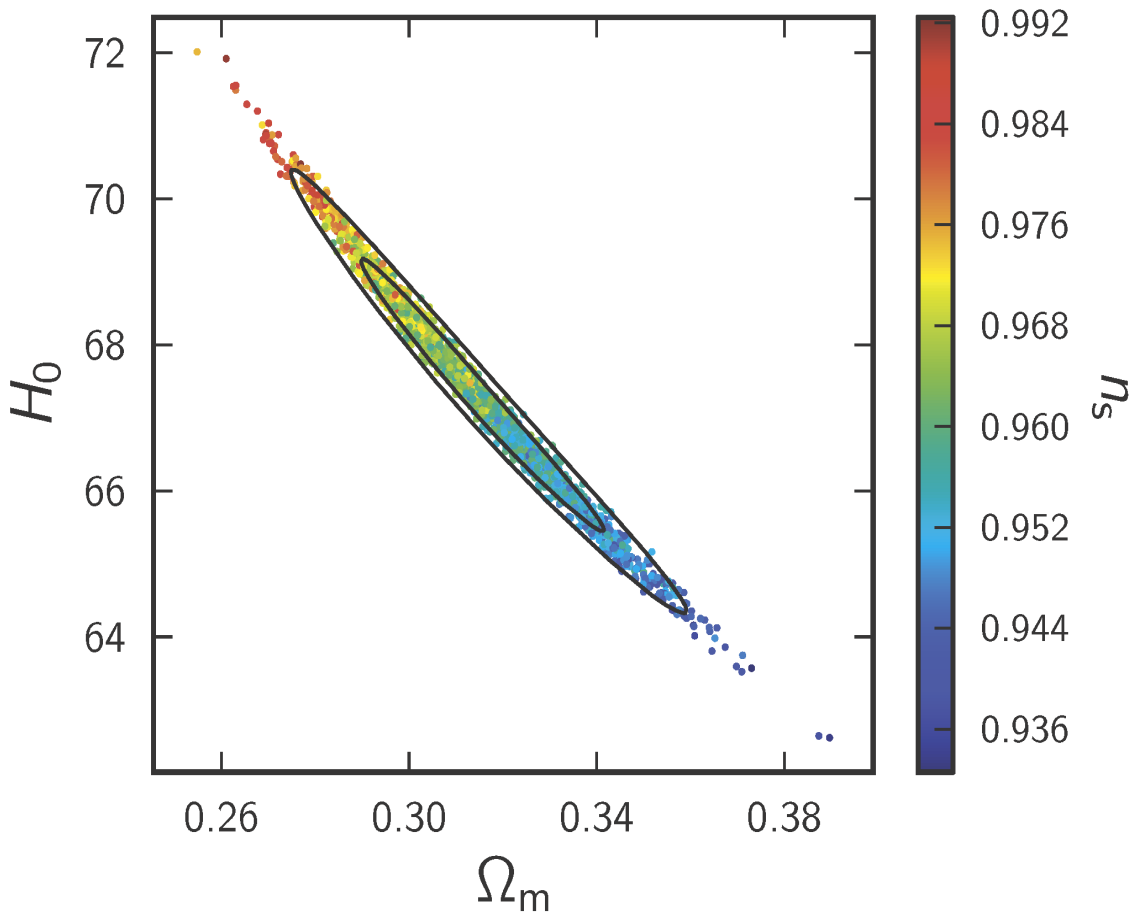
The sound horizon, θ, determined by the positions of the peaks (7), is now determined with 0.05% precision
(links together $\Omega_b h^2$, $\Omega_c h^2$, H_0 - here as $\Omega_m h^3$)

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

(as predicted by base inflation models)

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

Sound Horizon



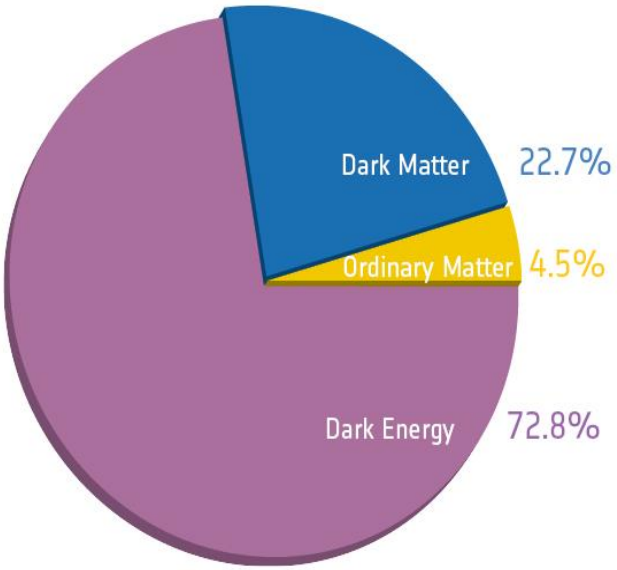
Samples are for Planck only.

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

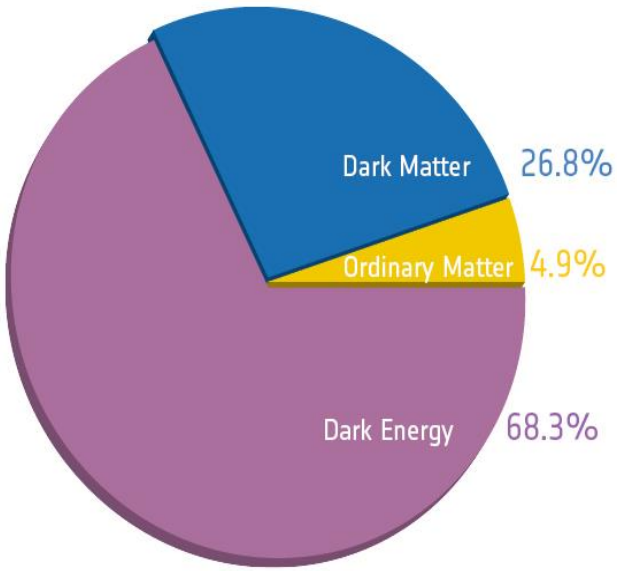
rs is constrained transversally

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

The basic content of the Universe



Before Planck



After Planck

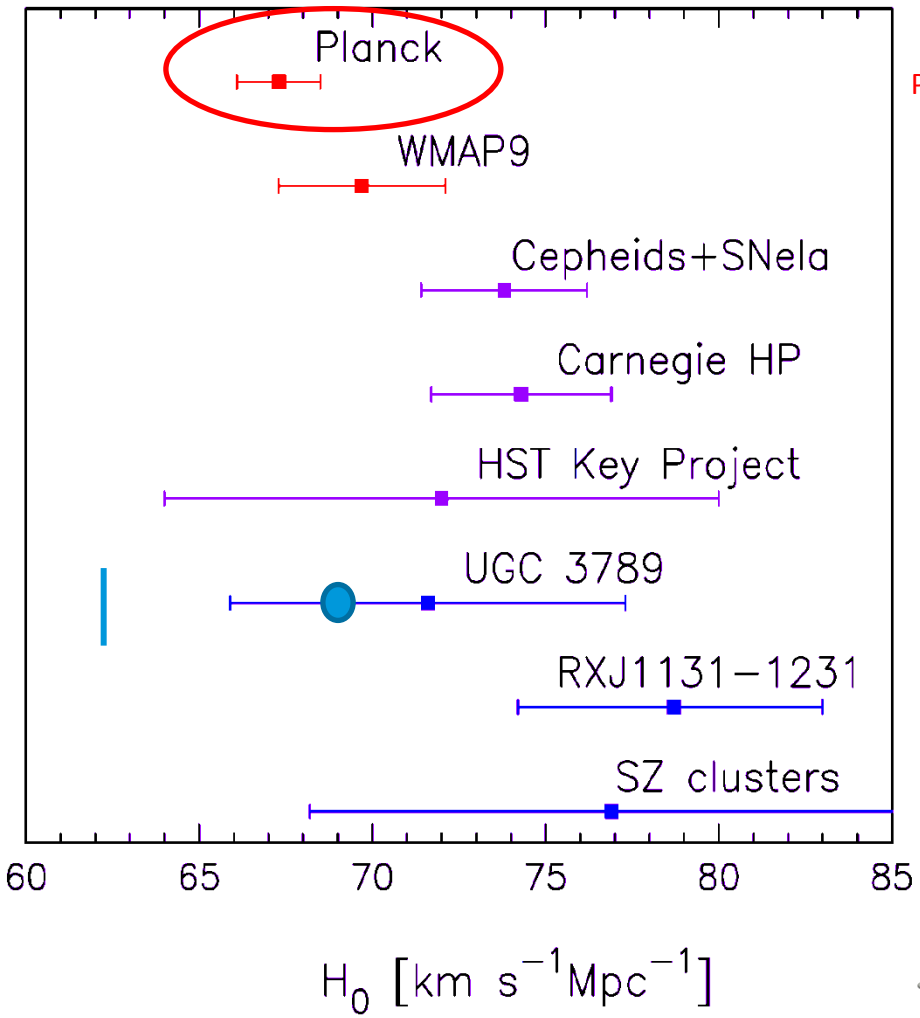
...has changed!

The rate of expansion

Riess et al. (2011)

Freedman et al. (2012),

Freedman et al. (2001)

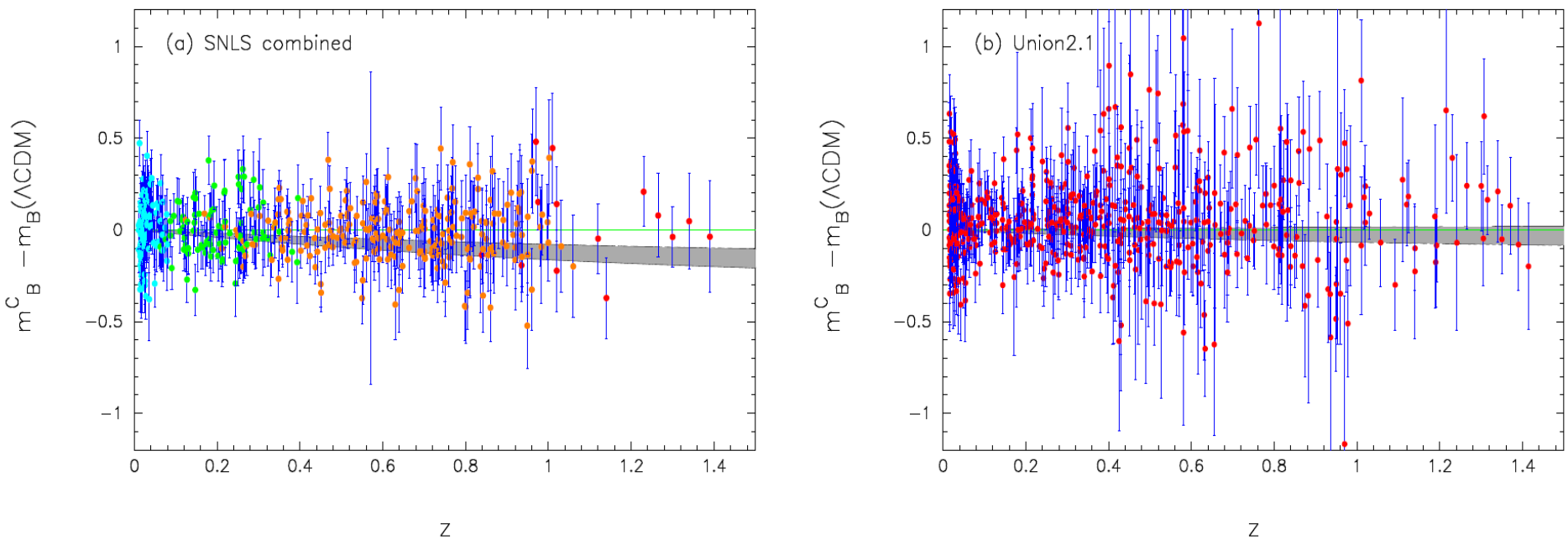


Planck H_0 is 67.95 ± 1.5 km/s/Mpc

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

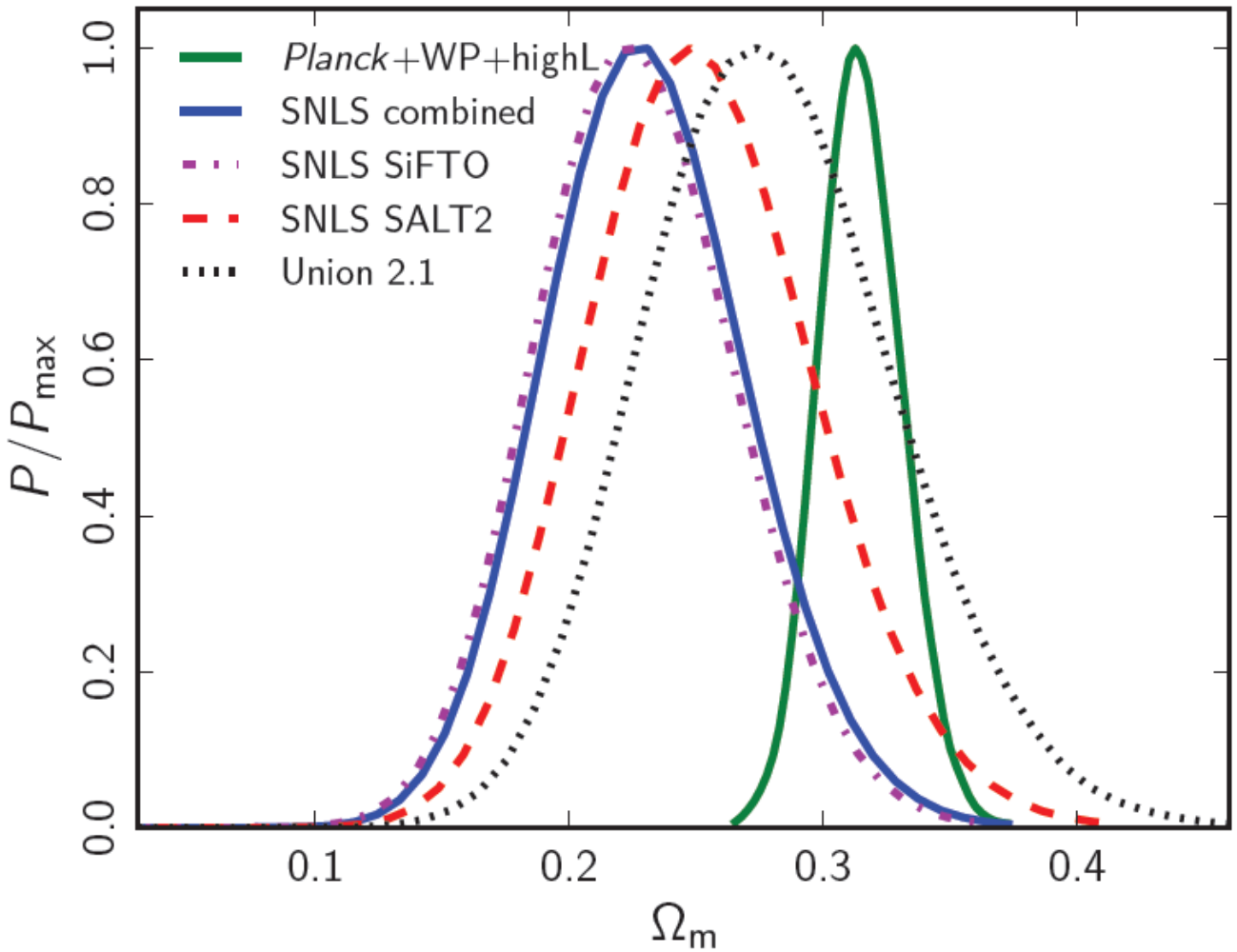
Tension with SNLS result…



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

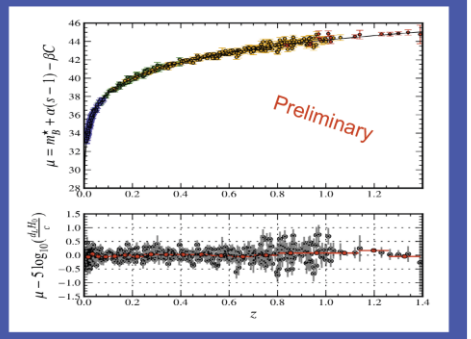
Fig. 18. Magnitude residuals relative to the base ΛCDM model that best fits the SNLS combined sample (left) and the Union2.1 sample (right). The error bars show the 1 σ (diagonal) errors on m_B. The filled grey regions show the residuals between the expected magnitudes and the best-fit to the SNe sample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

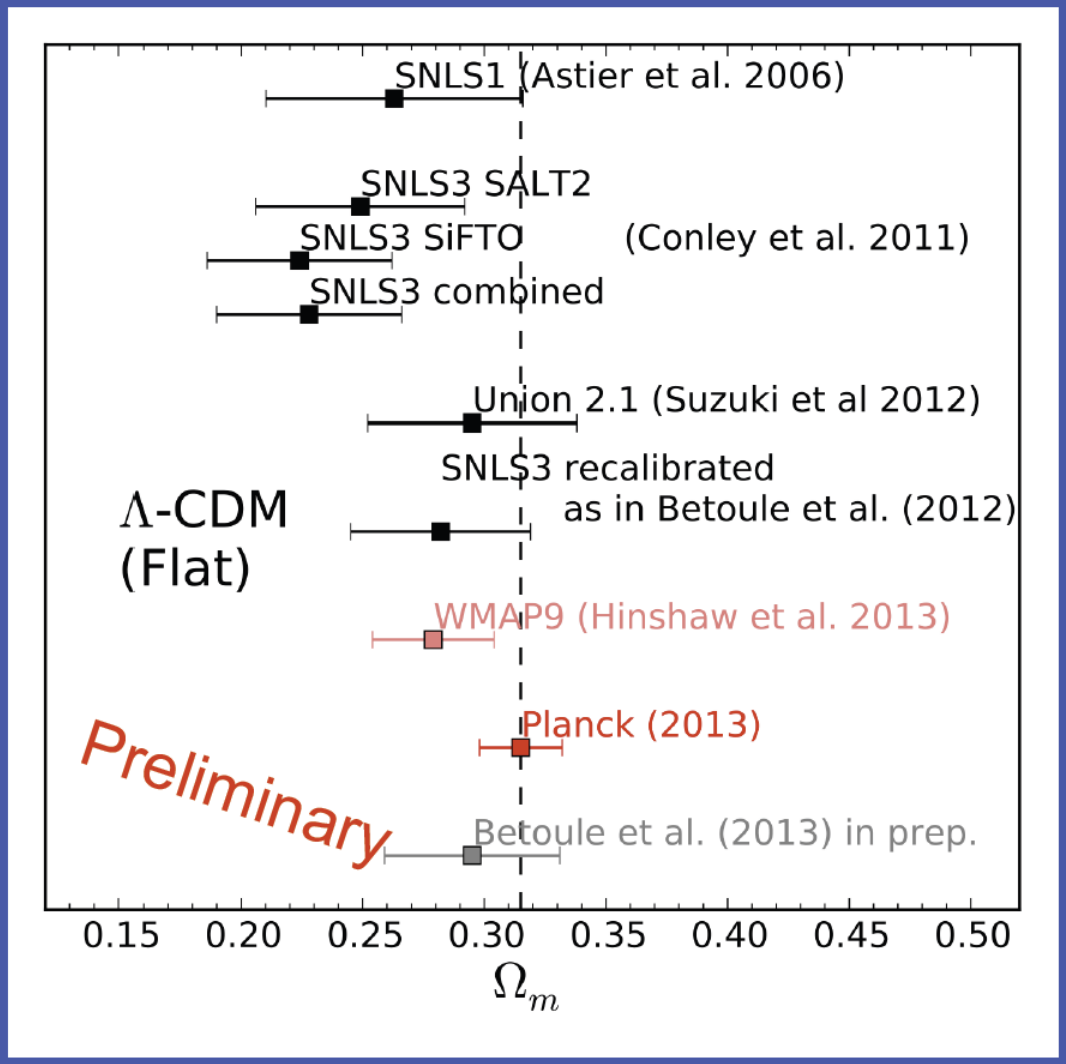
The total matter density



Comparison with Planck results

SNLS-SDSS joint Hubble diagram





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}, Σm_ν $\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 ?)

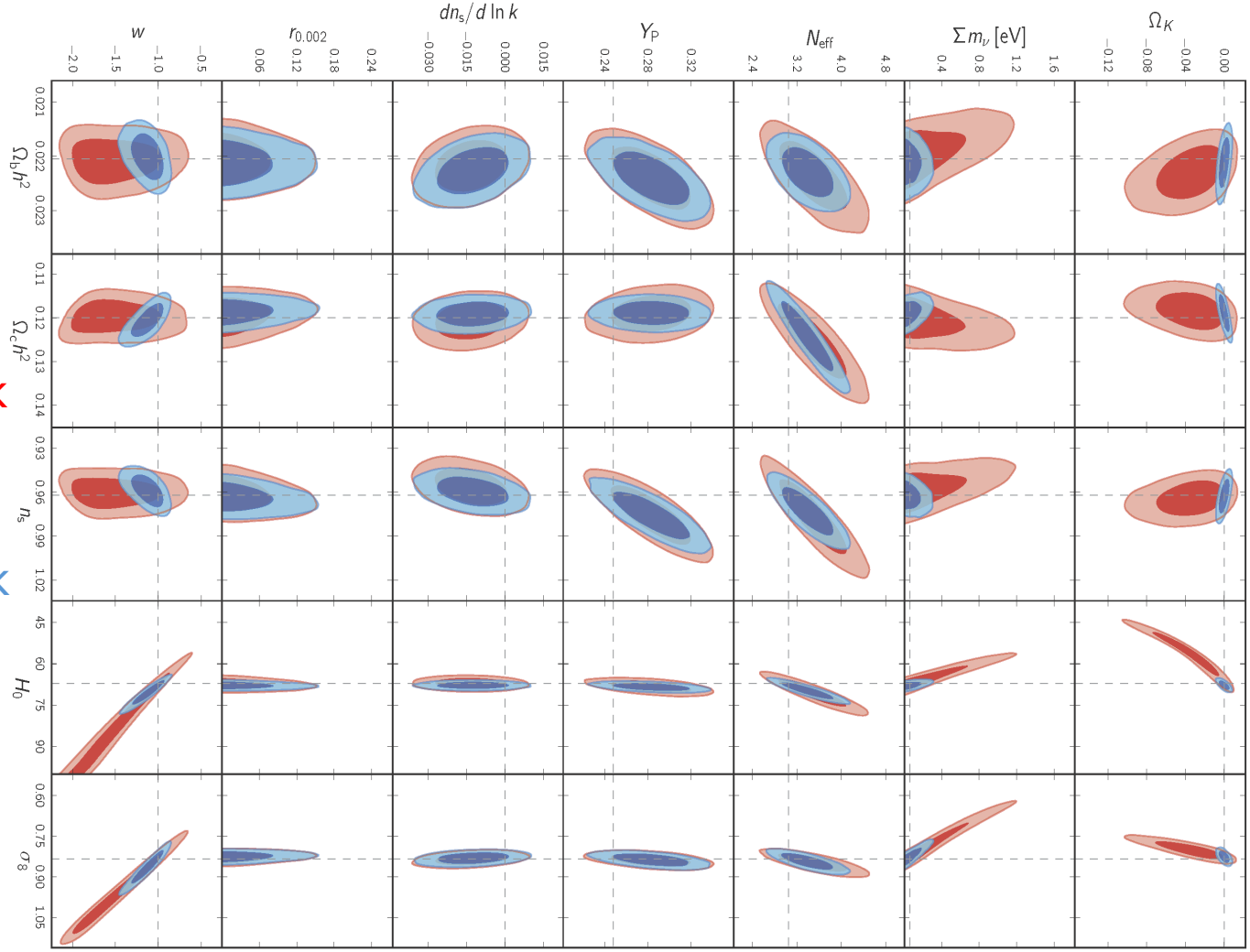
➔ no compelling evidence for any of them ⬇

	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…

Full grid of results available on line



Planck +WP

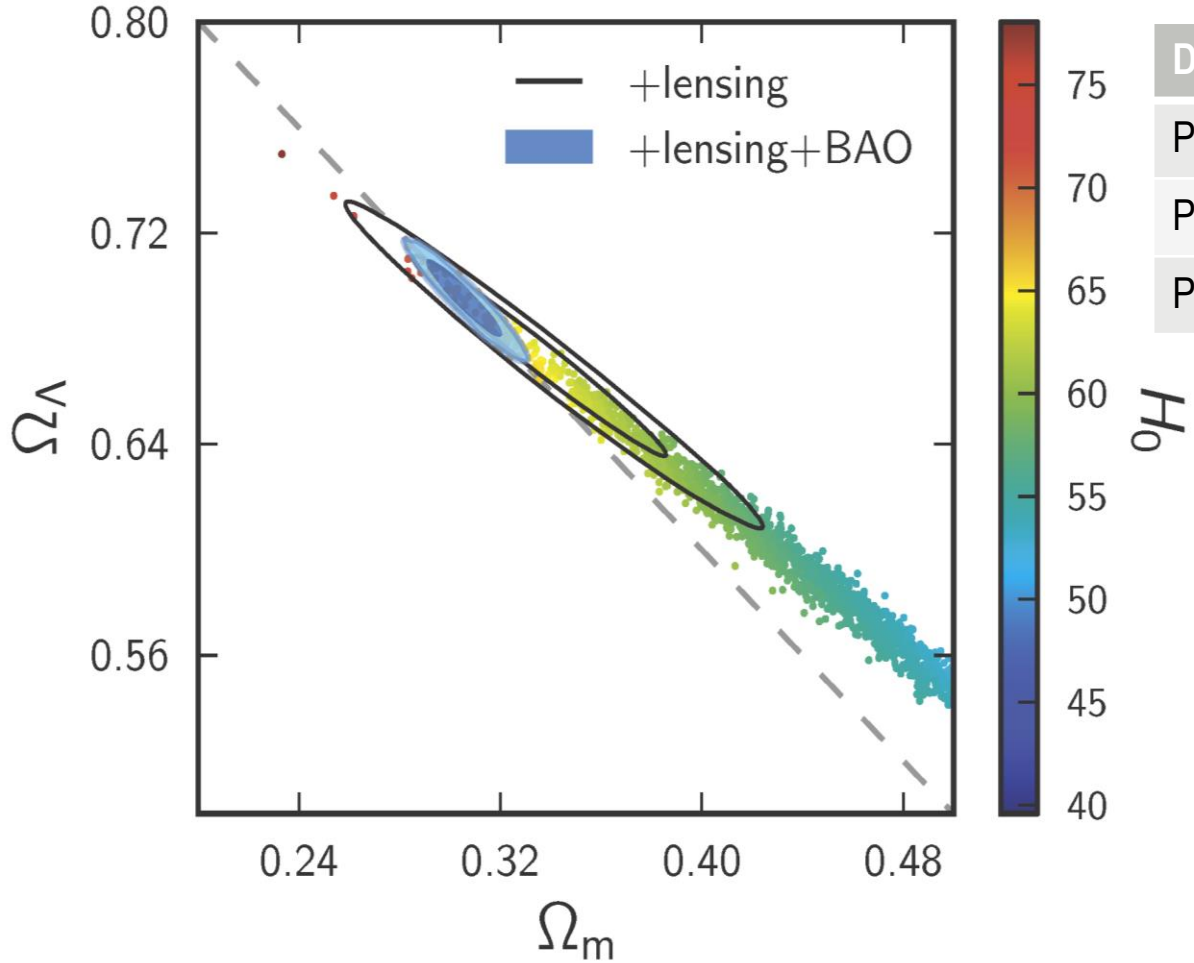
Planck +WP +BAO

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

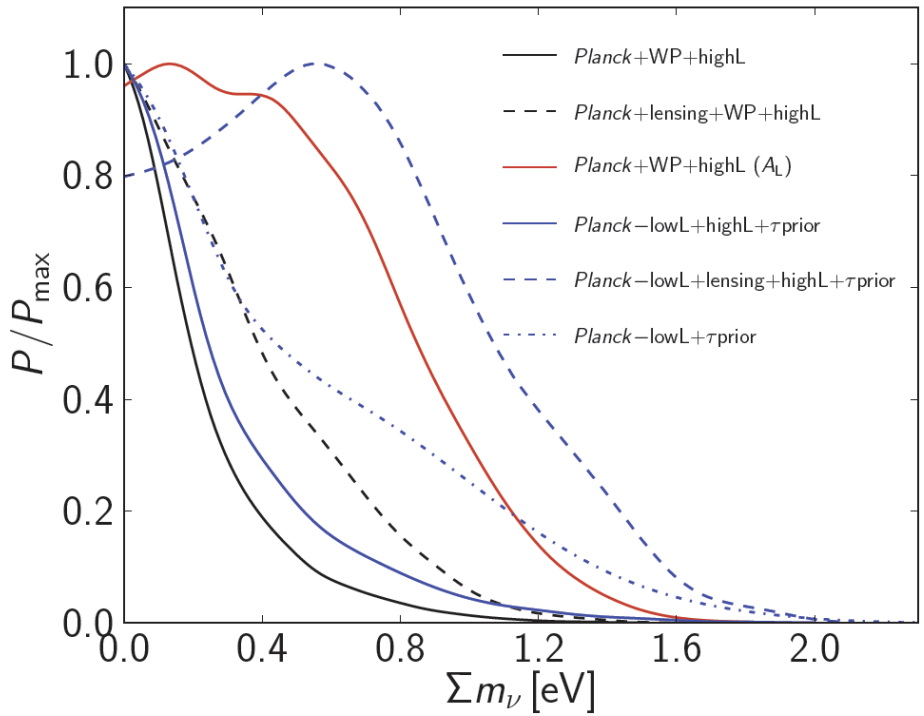
Geometry



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



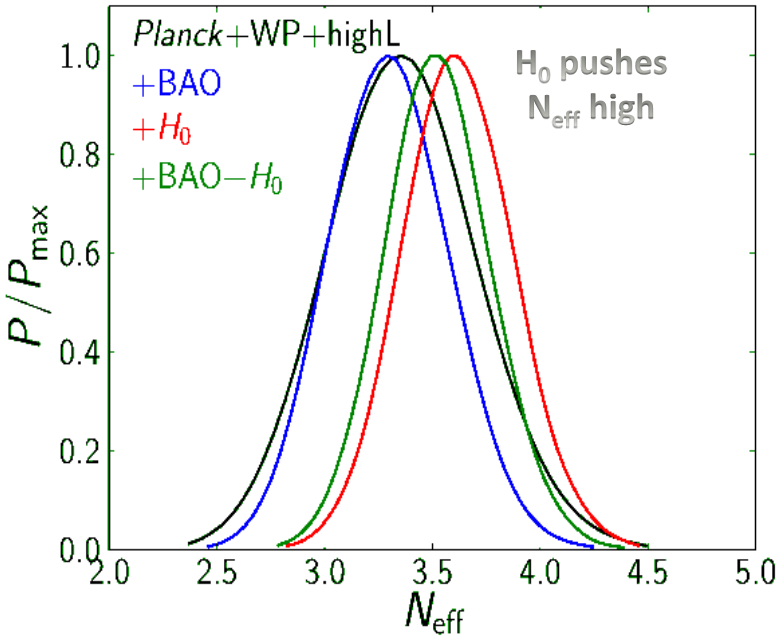
Planck constrains neutrino masses mostly through their effect via lensing:
removing that constraint (marginalising over A_L) weakens considerably the limit:
$\Sigma m_\nu < 0.23$eV (95CL PT+WP+HL)
becomes
$\Sigma m_\nu < 1.08$eV (95CL PT+WP+HL)

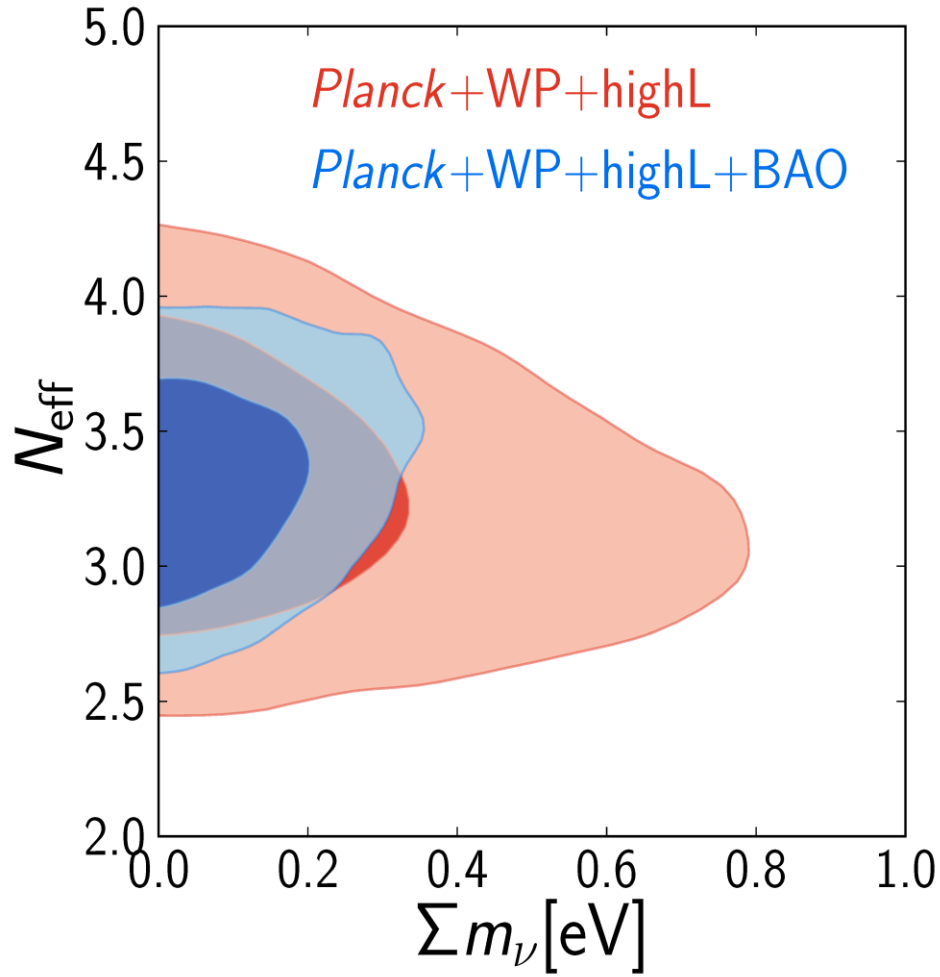
NB: the (4-pt based) lensing likelihood would prefer higher values for Σm_ν (i.e. it weakens the constraints): time will tell

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

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

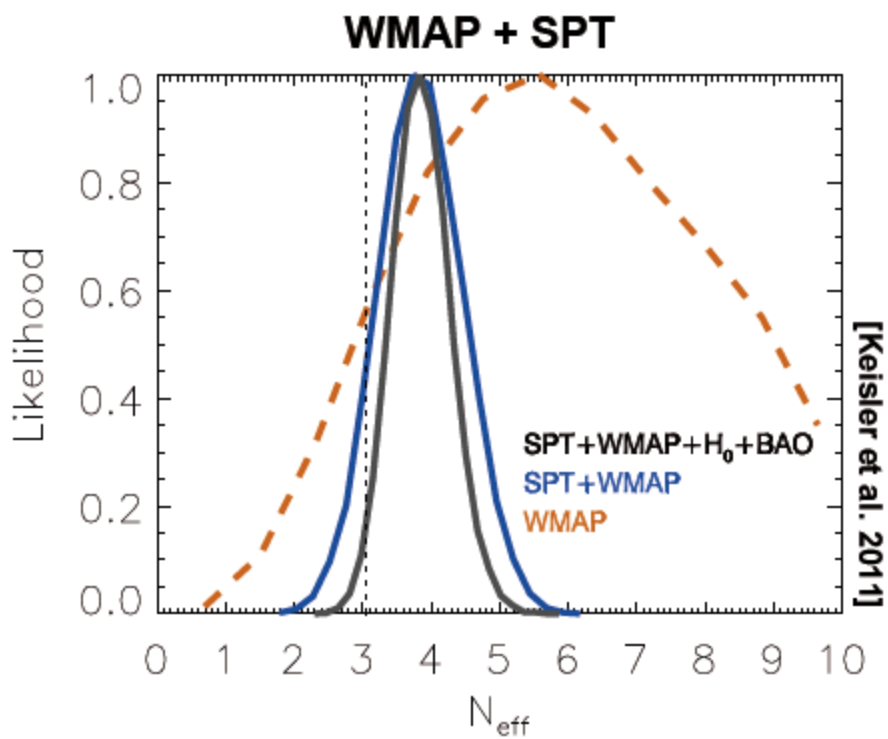
(N_{eff} = 3.3±0.27;Σm_ν<0.23 eV)

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)

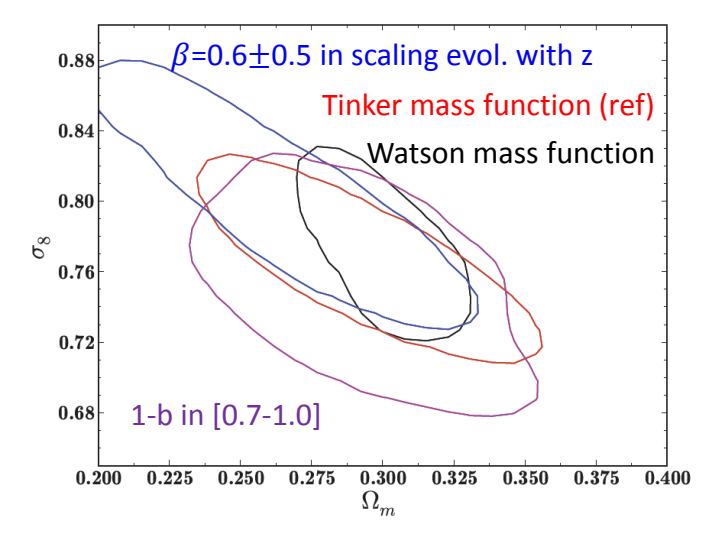
The end of a confusing situation?

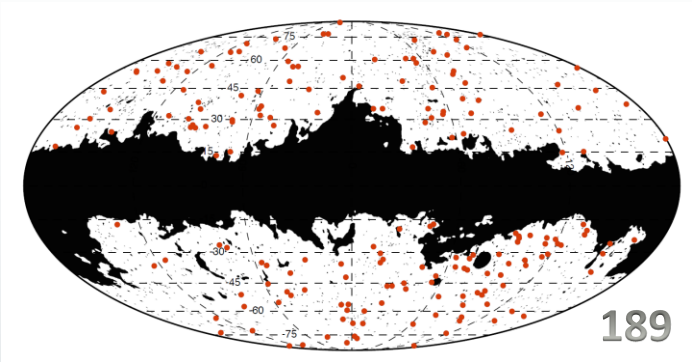
Parameter	*WMAP* 9	+eCMB	+eCMB+BAO	+eCMB+BAO+H_0
Number of relativistic species[b]				
$N_{\rm eff}$	> 1.7 (95% CL)	3.89 ± 0.67	3.55 ± 0.60	3.84 ± 0.40

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

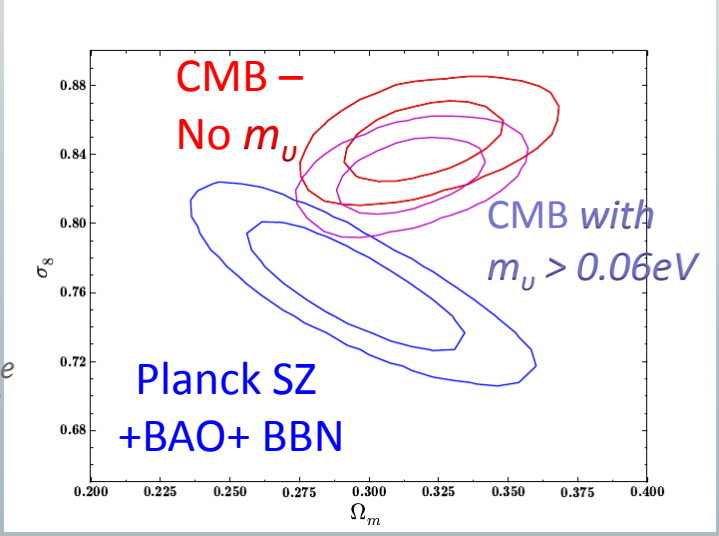


SZ / CMB tension

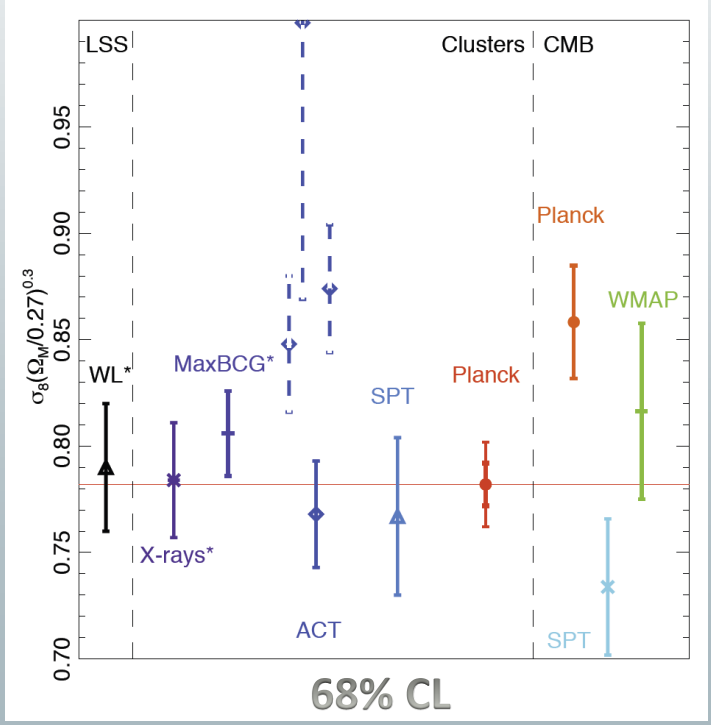




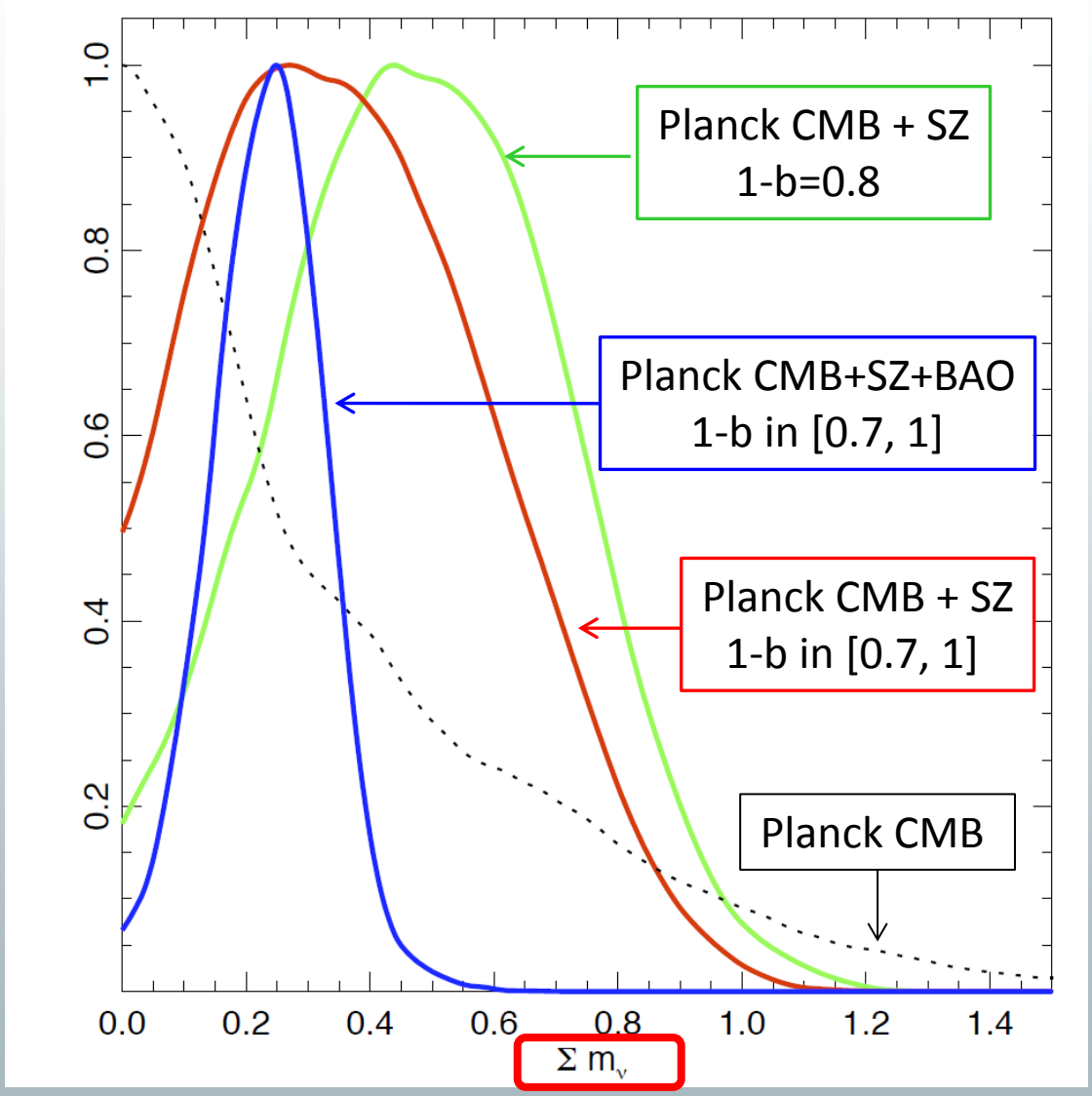
σ_8 measures the amplitude of fluctuations on $8h^{-1}$ Mpc scale today: $\sigma_8 = F(A_s)$



Corrected figure with $m_{nu} > 0.06$eV in both cases

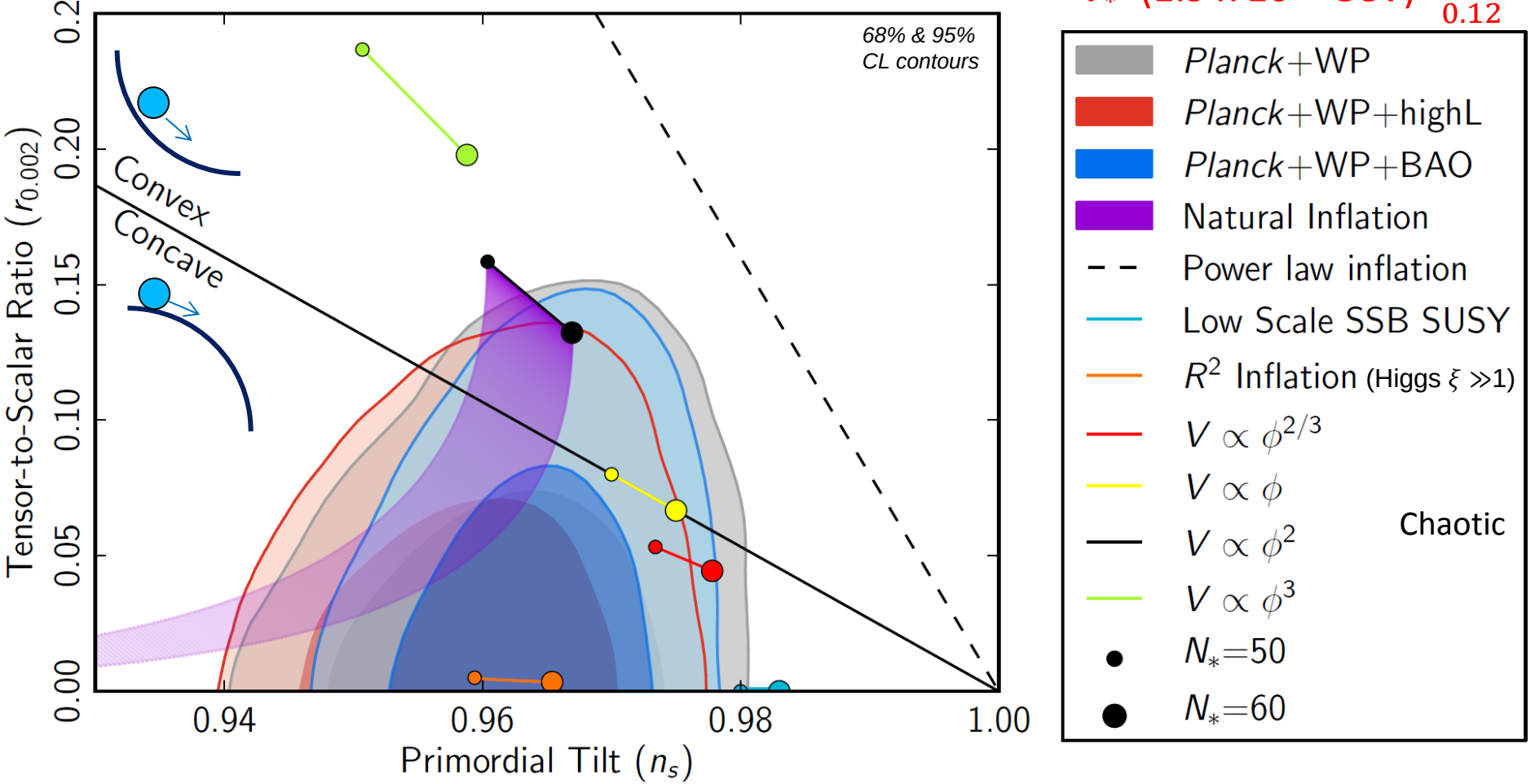


Physics rather than Gastrophysics?



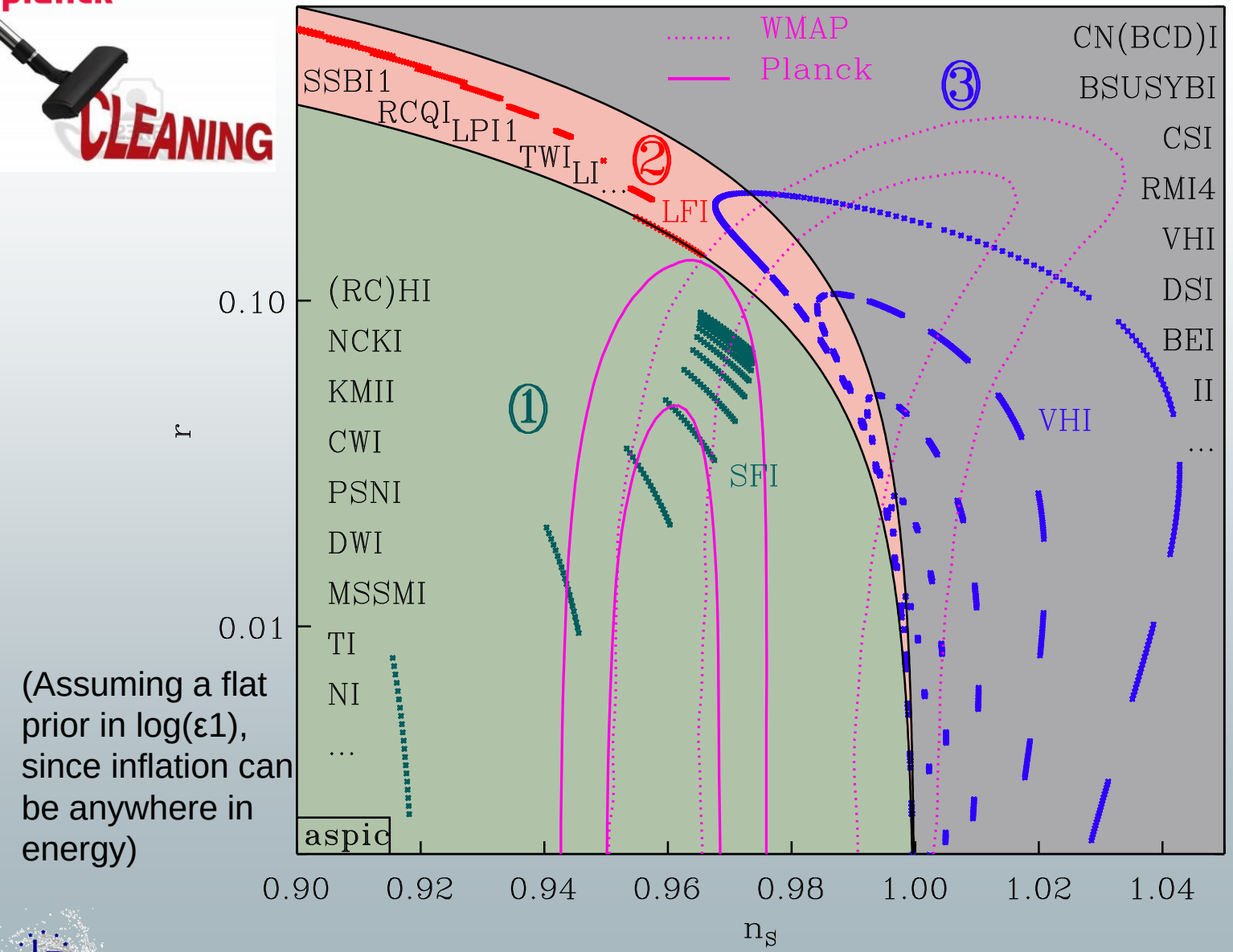
Constraint on representative Inflation models

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



➔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.

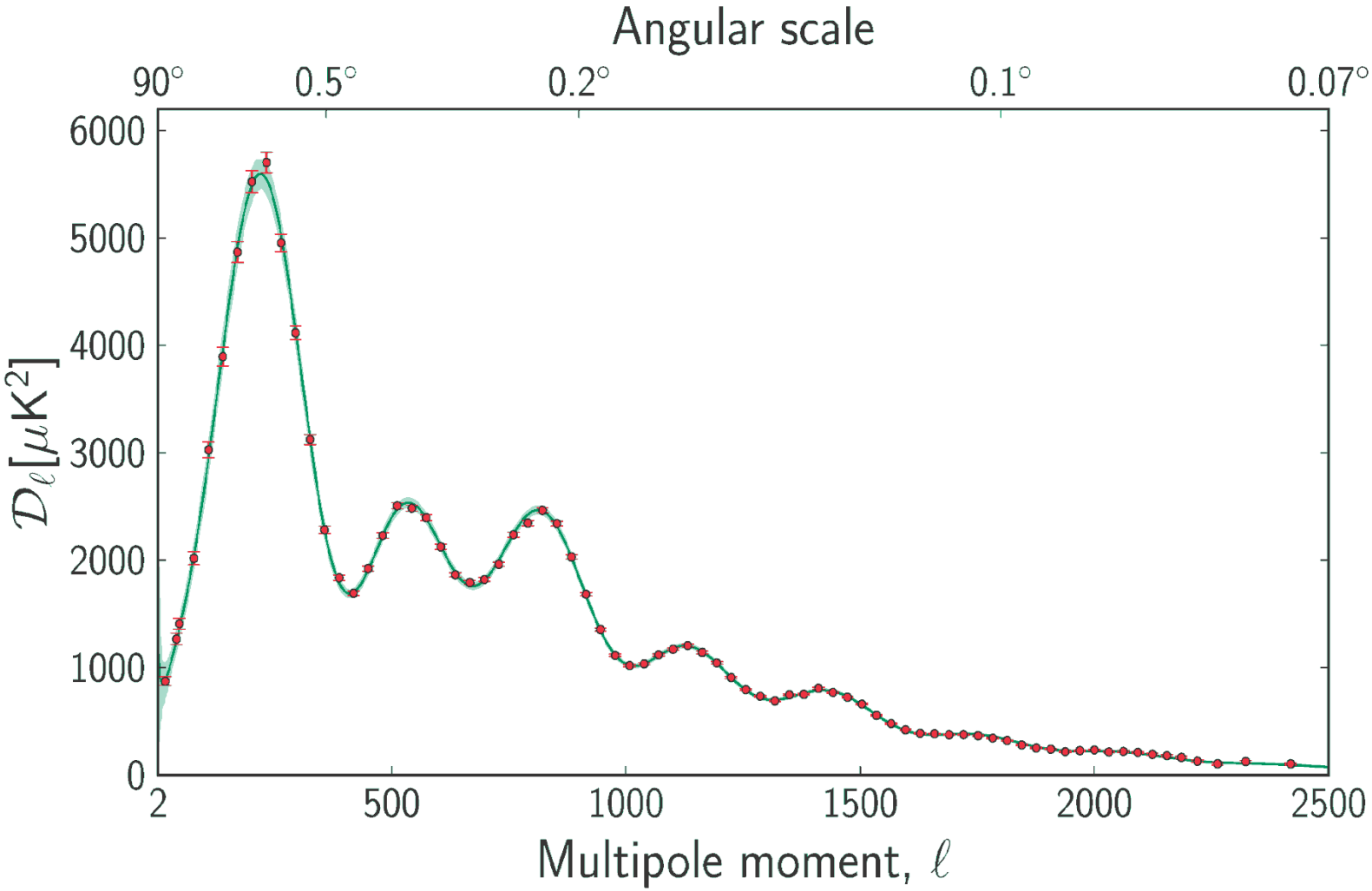
Being systematic!



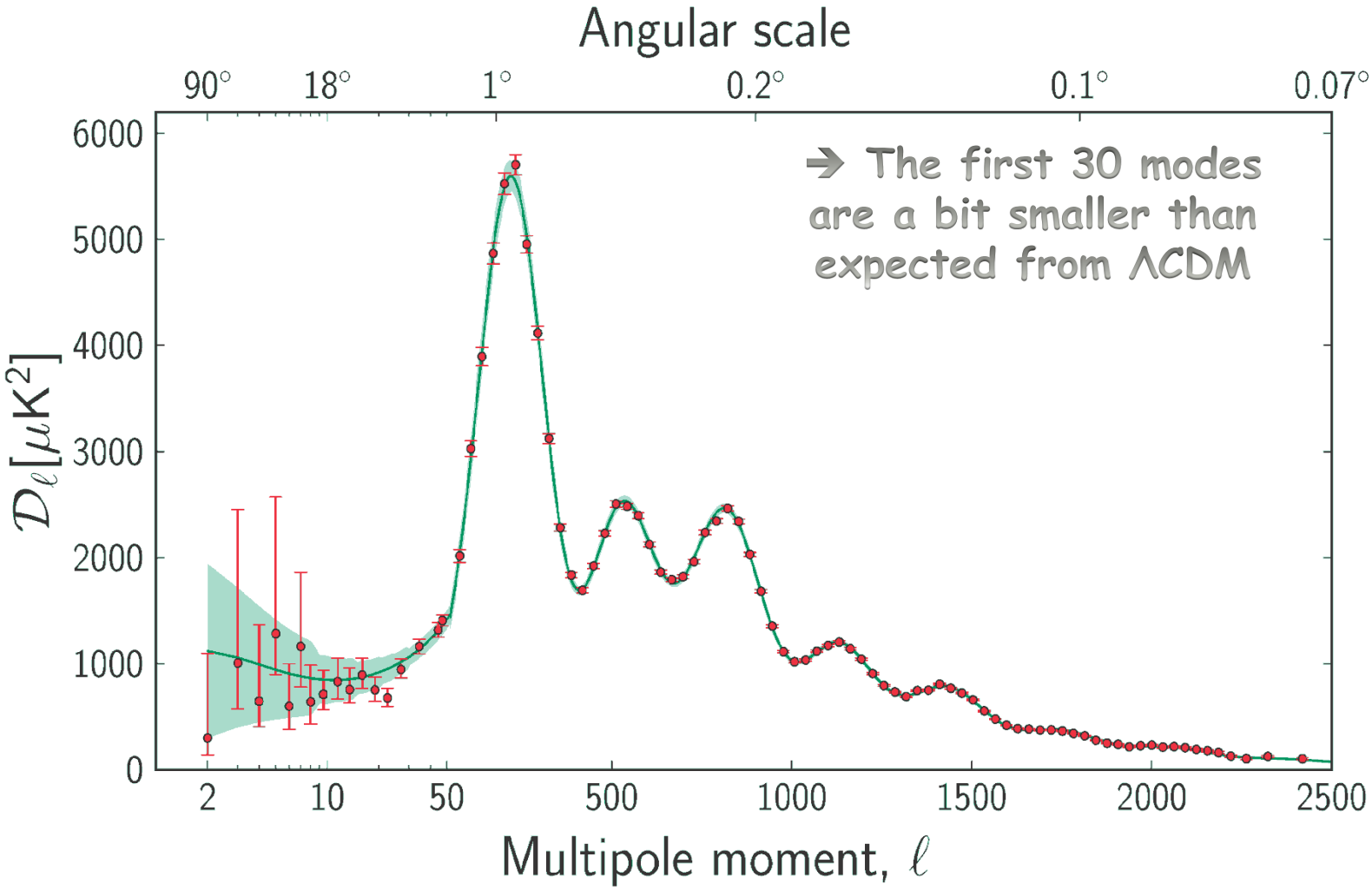
70 models (essentially all single field slow-roll) from the ``*encyclopaedia inflationaris*" of *Martin, Ringeval, Venin, archiv*/1303.3787

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

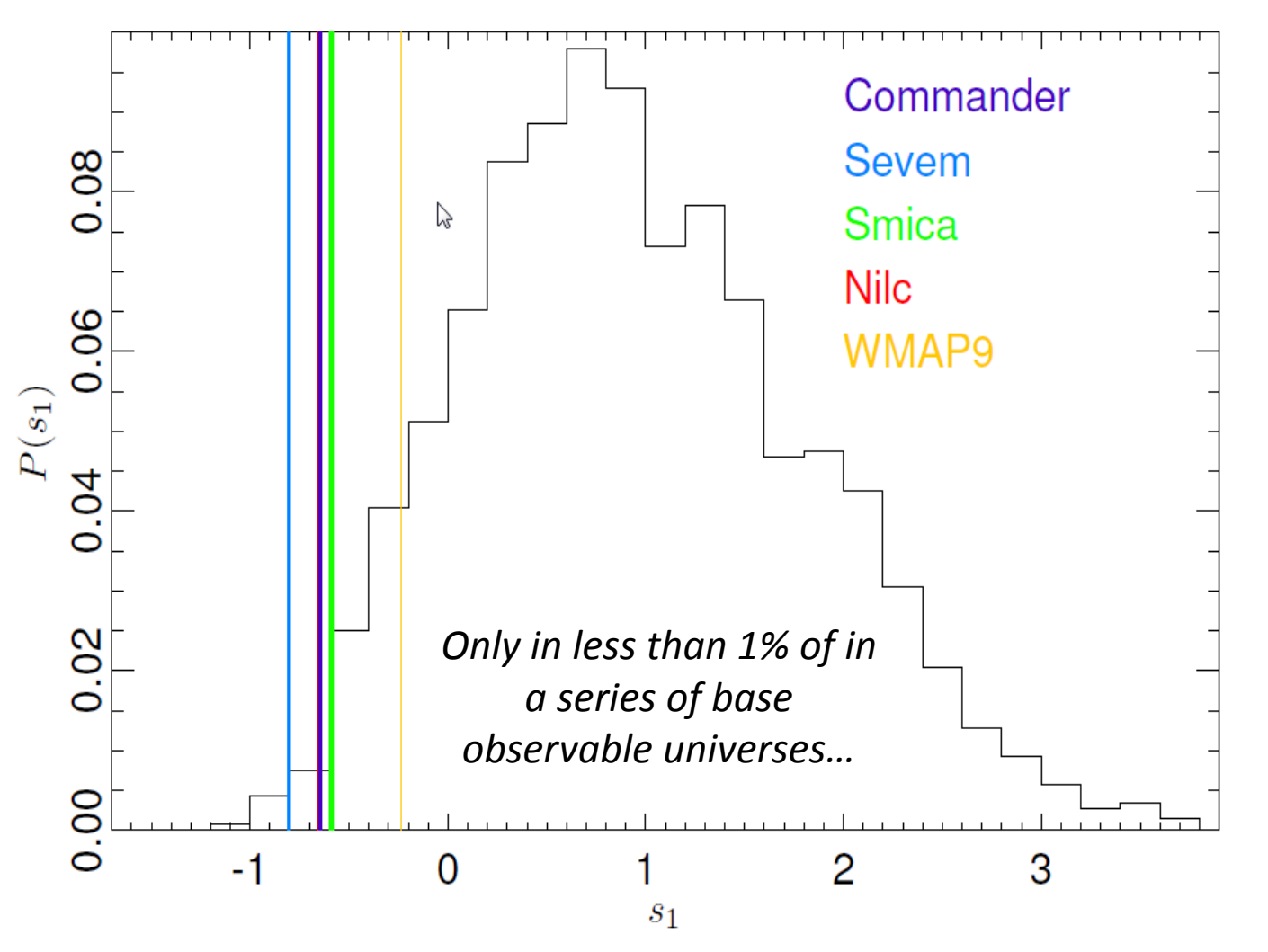
A theorist dream, or nightmare?



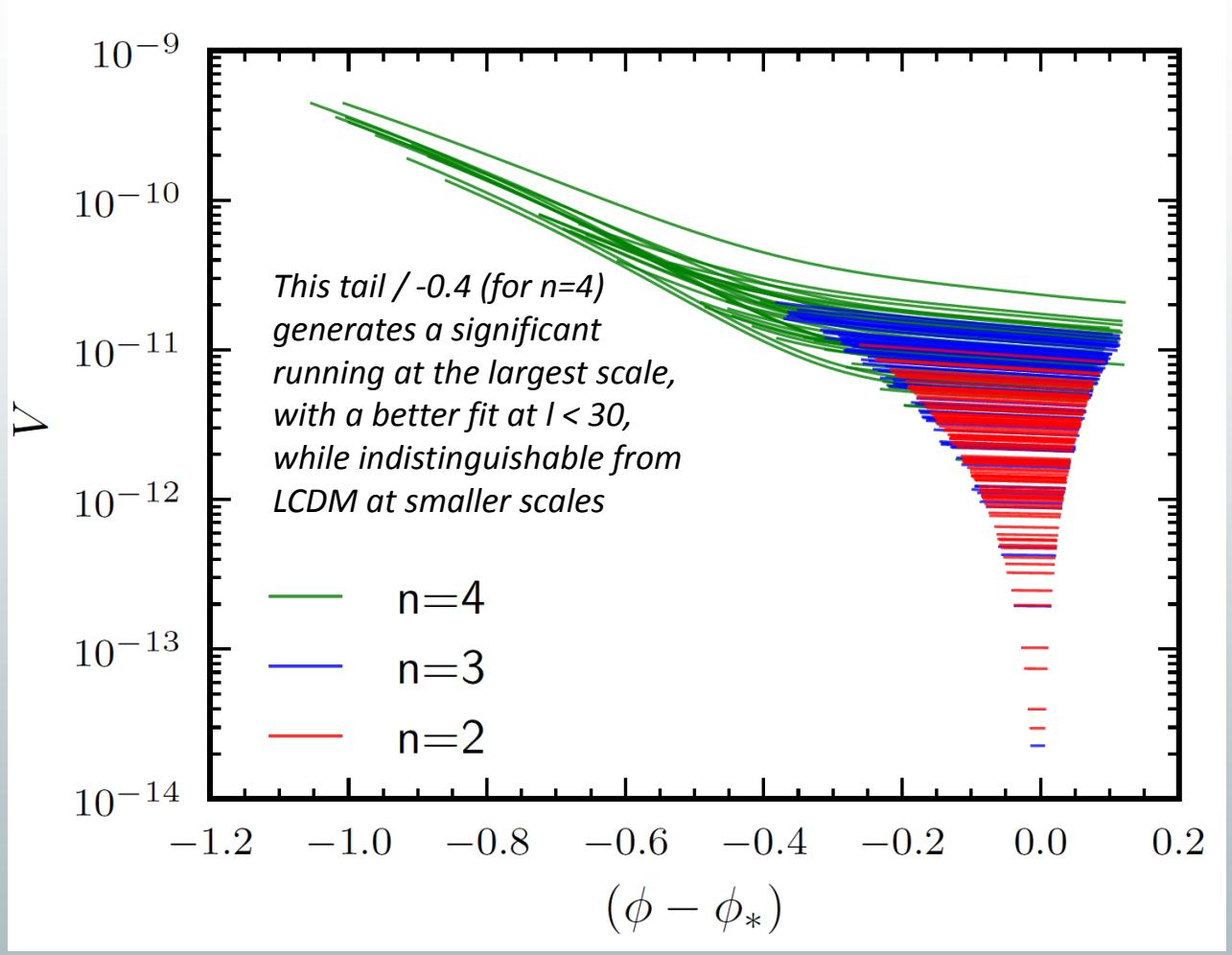
Zooming on the very largest scales, l<50…



How significant is this anomaly?



Inflaton potential reconstruction

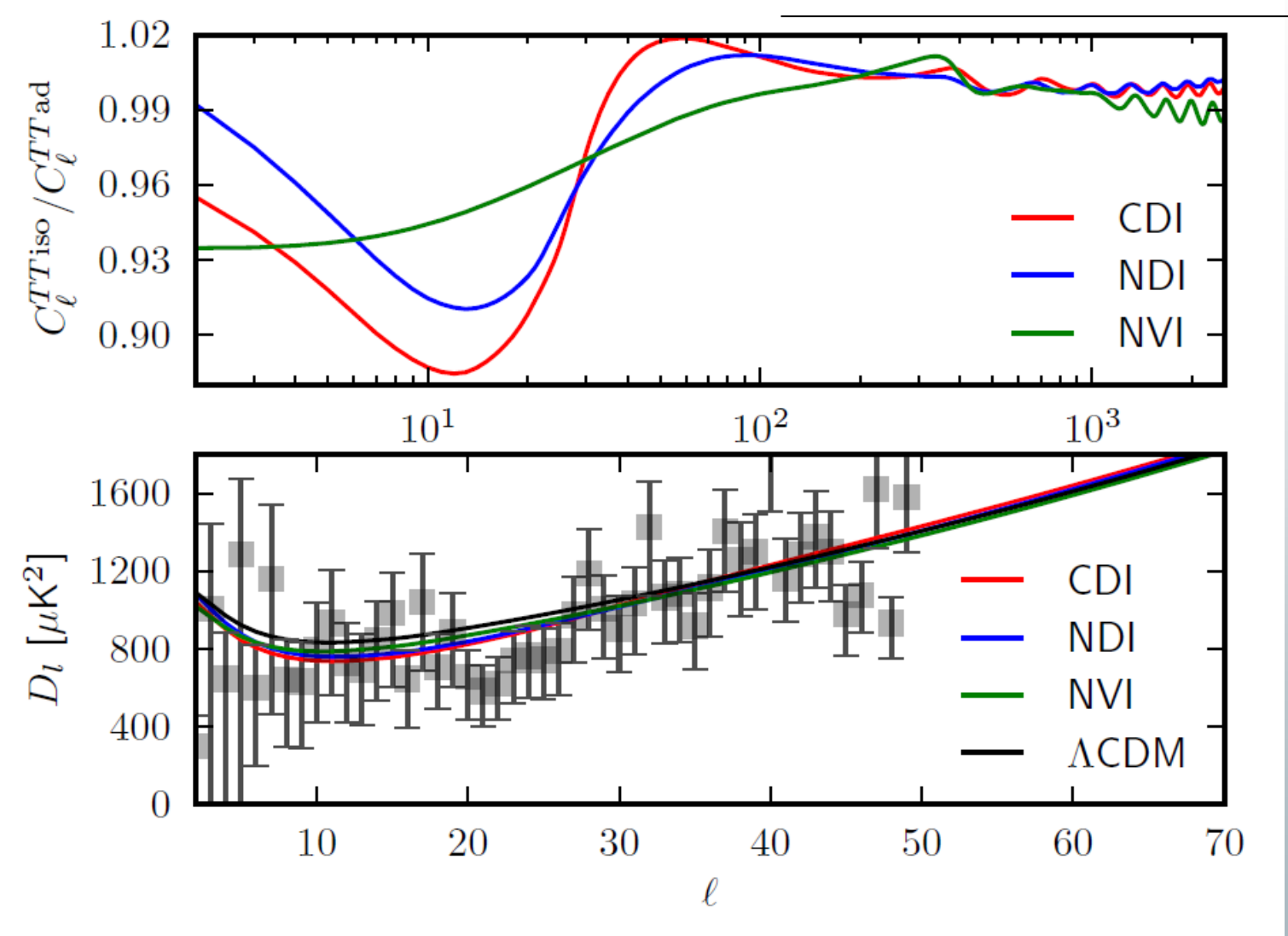


Best fitting potentials, when V(ϕ) is Taylor expanded at the n-th order around the pivot scale;
Planck-T+WP;
Flat priors on ε, η, ξ^2;

Φ_* in natural units / $(8\pi)^{1/2}$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	$0.961^{+0.015}_{-0.015}$	$0.958^{+0.017}_{-0.016}$	$0.954^{+0.018}_{-0.018}$
$100\,dn_s/d\ln k$	$-0.05^{+0.13}_{-0.14}$	$-2.2^{+2.2}_{-2.3}$	$-0.61^{+3.1}_{-3.1}$
$100\,d^2n_s/d\ln k^2$	$-0.01^{+0.73}_{-0.75}$	$-0.3^{+1.0}_{-1.2}$	$6.3^{+8.6}_{-7.8}$
r	< 0.12	< 0.22	< 0.35

Assuming a single isocurvature mode



… helps (somewhat) at low-l (again!)

Assuming a single isocurvature mode

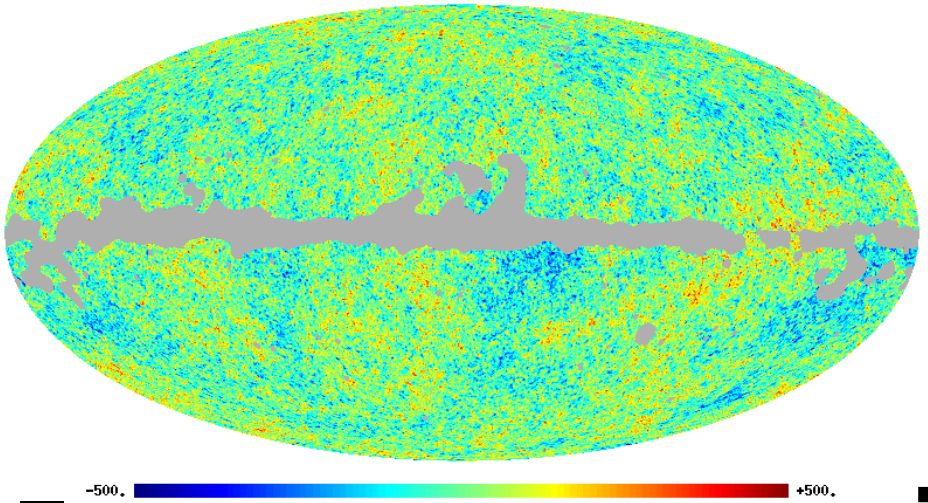
95% C.L. constraints and $\Delta\chi^2_{\rm eff} = \chi^2_{\rm eff,ISO,best} - \chi^2_{\rm eff,adiabatic,best}$

	Primordial isoc. fraction $\beta_{\rm iso}$ (k=0.002	0.050	0.100)	Isoc. frac. in **CMB** $\alpha_{\rm non-ad}$	$\Delta\chi^2_{\rm eff}$
CDI	<0.08	<0.39	<0.60	-7% . . . +2%	-4.6
NDI	<0.27	<0.27	<0.32	-9% . . . +1%	-4.2
NVI	<0.18	<0.14	<0.17	-5% . . . +4%	-2.5
Special CDI cases					Mostly Low-l
"axion"	<0.0360	<0.0390	<0.0400	<2%	0
"curvaton"	<**0.0025**	<0.0025	<0.0025	0% . . . +3%	0
anti-corr.	<0.0087	<0.0087	<0.0087	-6% . . . 0%	-1.3

The general cases IN COLOR have 4 extra parameters.
The special cases have **1 extra parameter** compared to the adiabatic model.

"axion" = no correlation ($\mathcal{P}_{\mathcal{RI}} = 0$), $n_{\rm iso} = 1$.
"curvaton" = +100% correlation ($\mathcal{P}_{\mathcal{RI}} = +\sqrt{\mathcal{P}_{\mathcal{RR}}\mathcal{P}_{\mathcal{II}}}$), $n_{\rm iso} = n_{\rm ad}$.
anti-corr. = -100% correlation ($\mathcal{P}_{\mathcal{RI}} = -\sqrt{\mathcal{P}_{\mathcal{RR}}\mathcal{P}_{\mathcal{II}}}$), $n_{\rm iso} = n_{\rm ad}$.

The « Bianchi » anomaly



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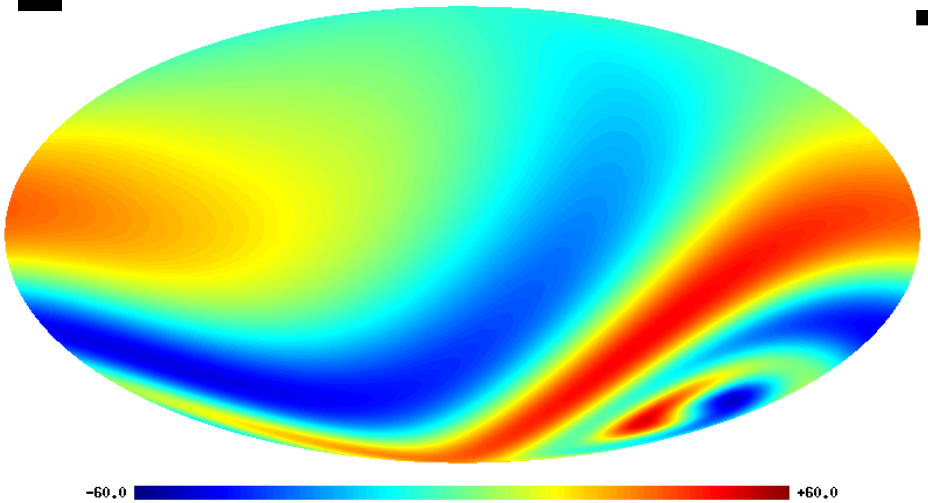

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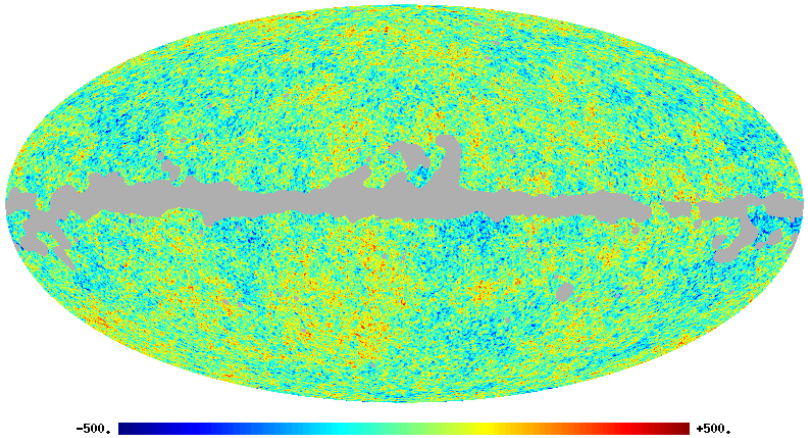
Removing a Bianchi VIIh leaves a manifestly more isotropic CMB sky



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

Detection of Doppler boosting

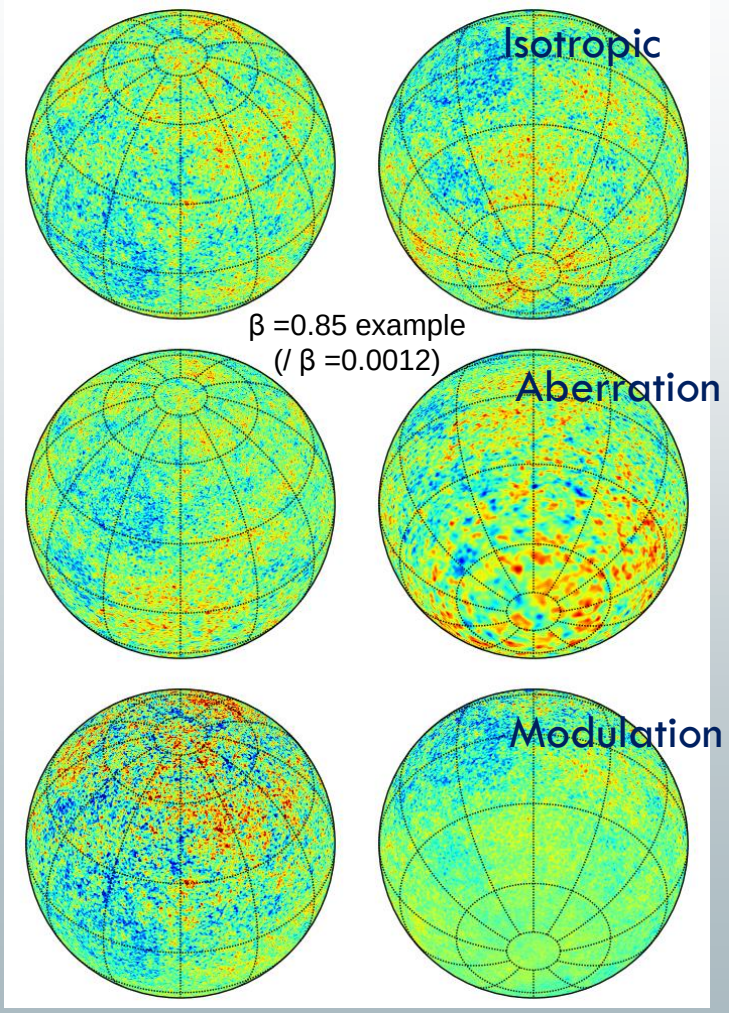
Eppur si muove

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

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

  (to compare to v_dipole = 368 $\pm$ 2 km s^{-1})

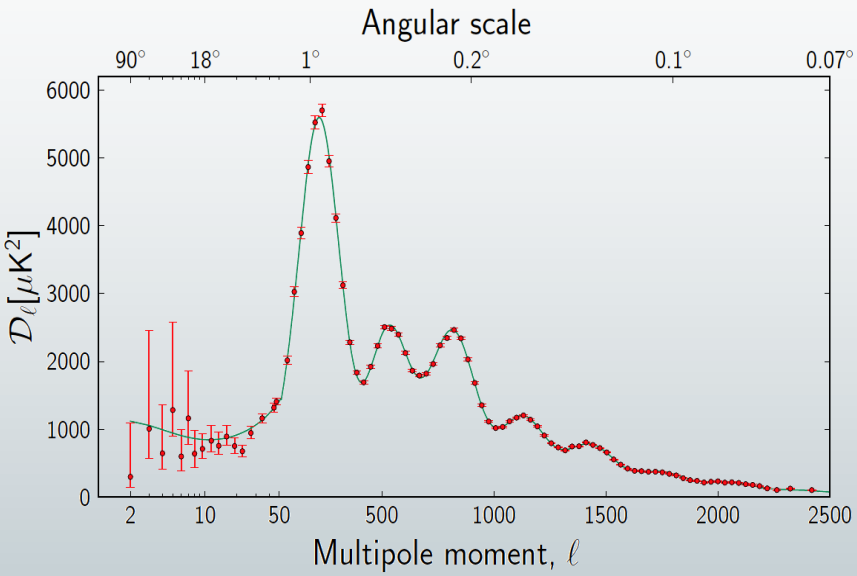
- **Modulation explains at least part of the high-*l* asymmetry.**

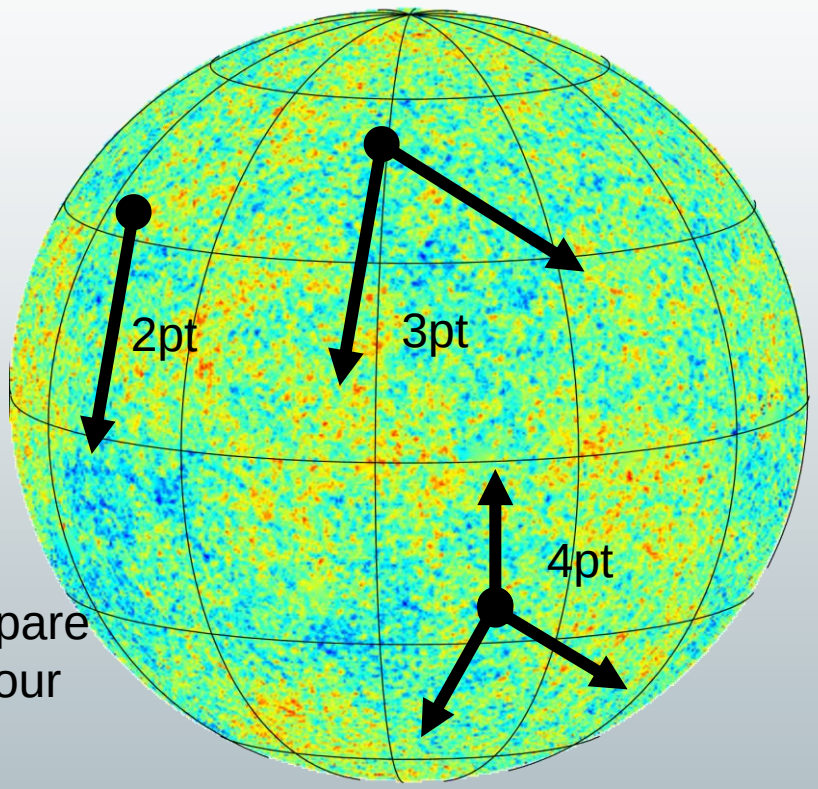


Planck 2013 XXVII

Random field characterisation

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





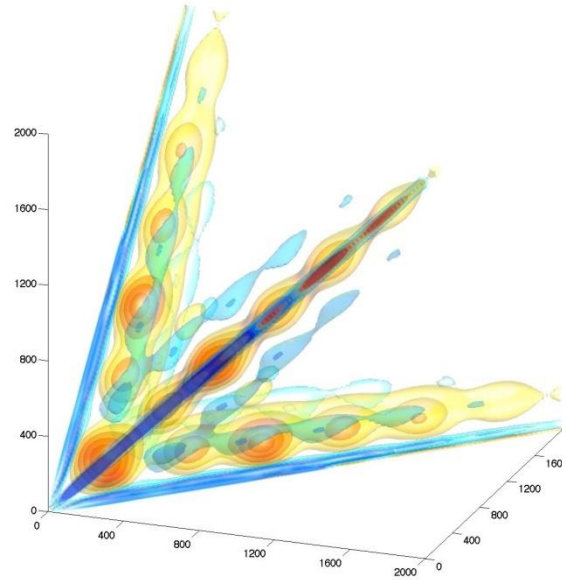
To assess non Gaussianity, one must compare fluctuations in three points (bi-spectrum), four point (tri-spectrum), etc.

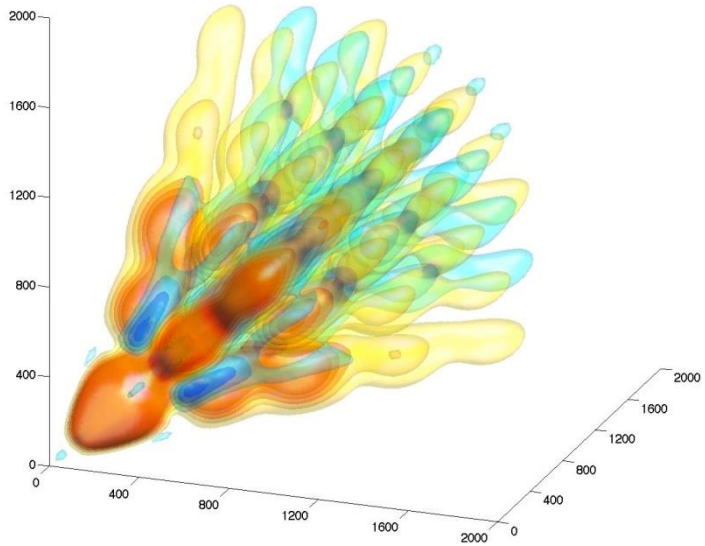
Need **three** numbers to characterize a triangle

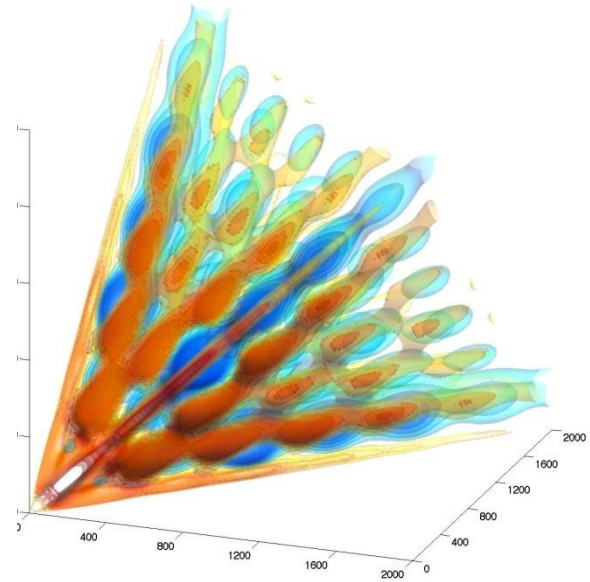
One origin of four point signal comes from lensing by Large Scale Structures.

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)

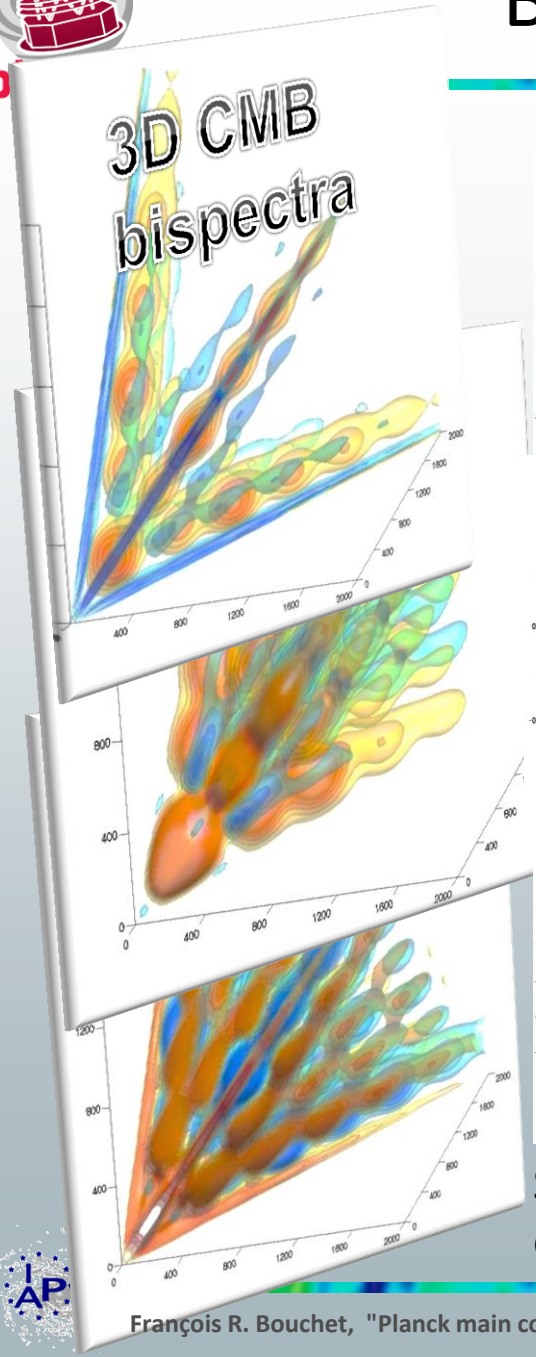
NG of ***equilateral*** type ($k_1 \sim k_2 \sim k_3$):

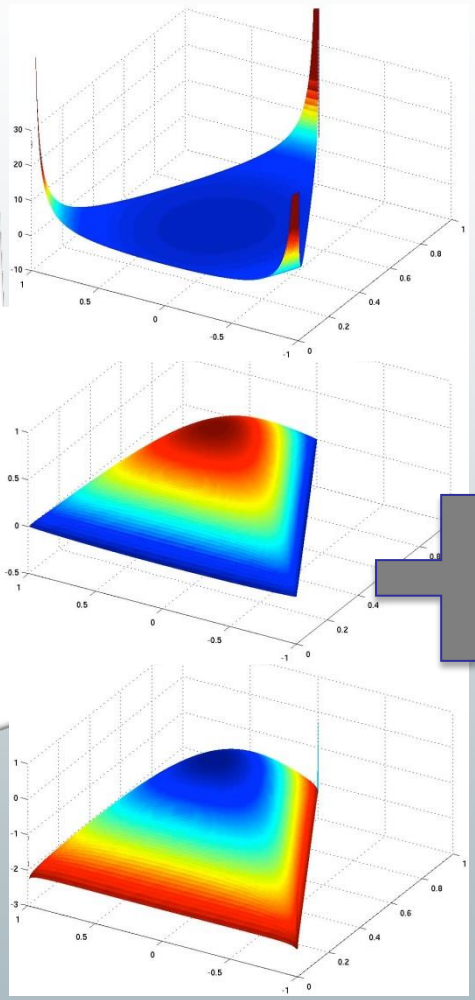
- Non-canonical kinetic term
  - K-inflation
  - DBI inflation
- Higher-derivate terms in Lagrangian
  - Ghost inflation
- Effective field theory

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

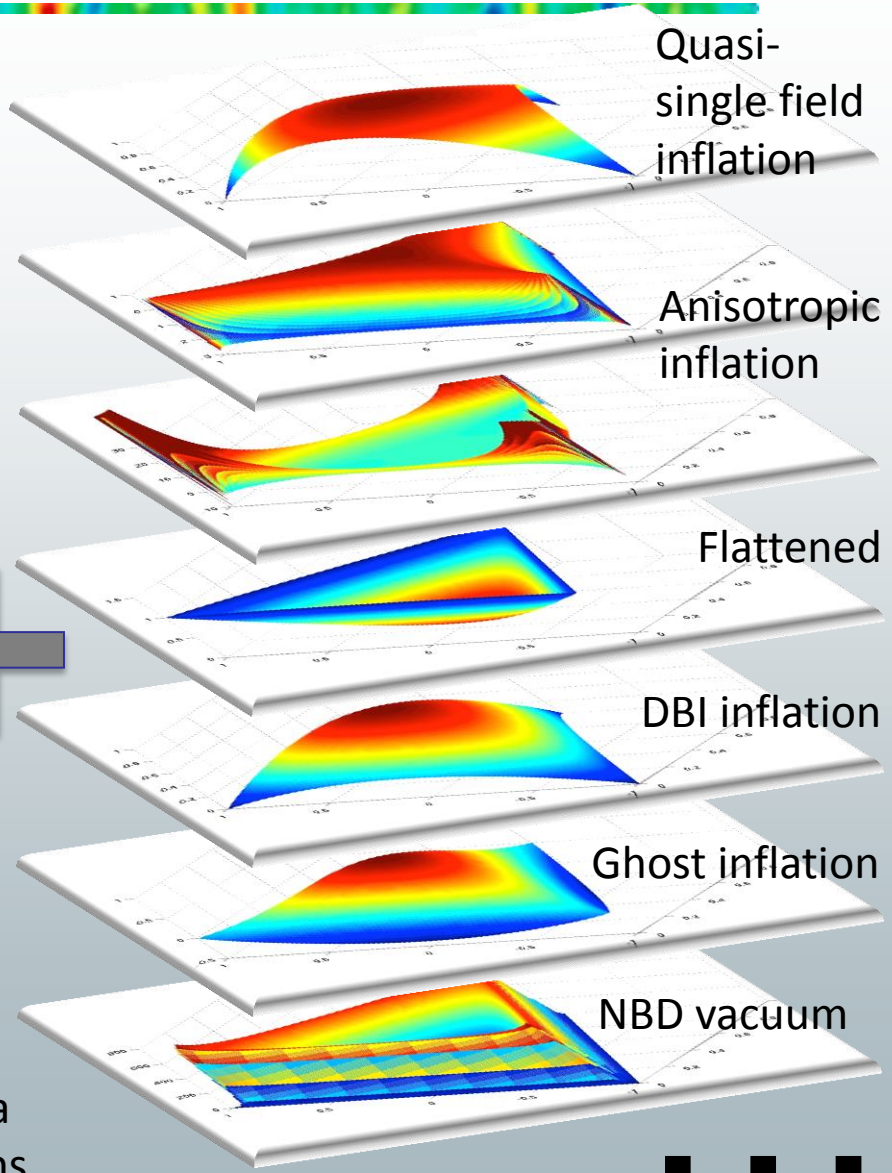
- Distinguishes between different variants of
  - Non-canonical kinetic term
  - Higher derivative interactions
- Galileon inflation

Bispectrum fingerprinting



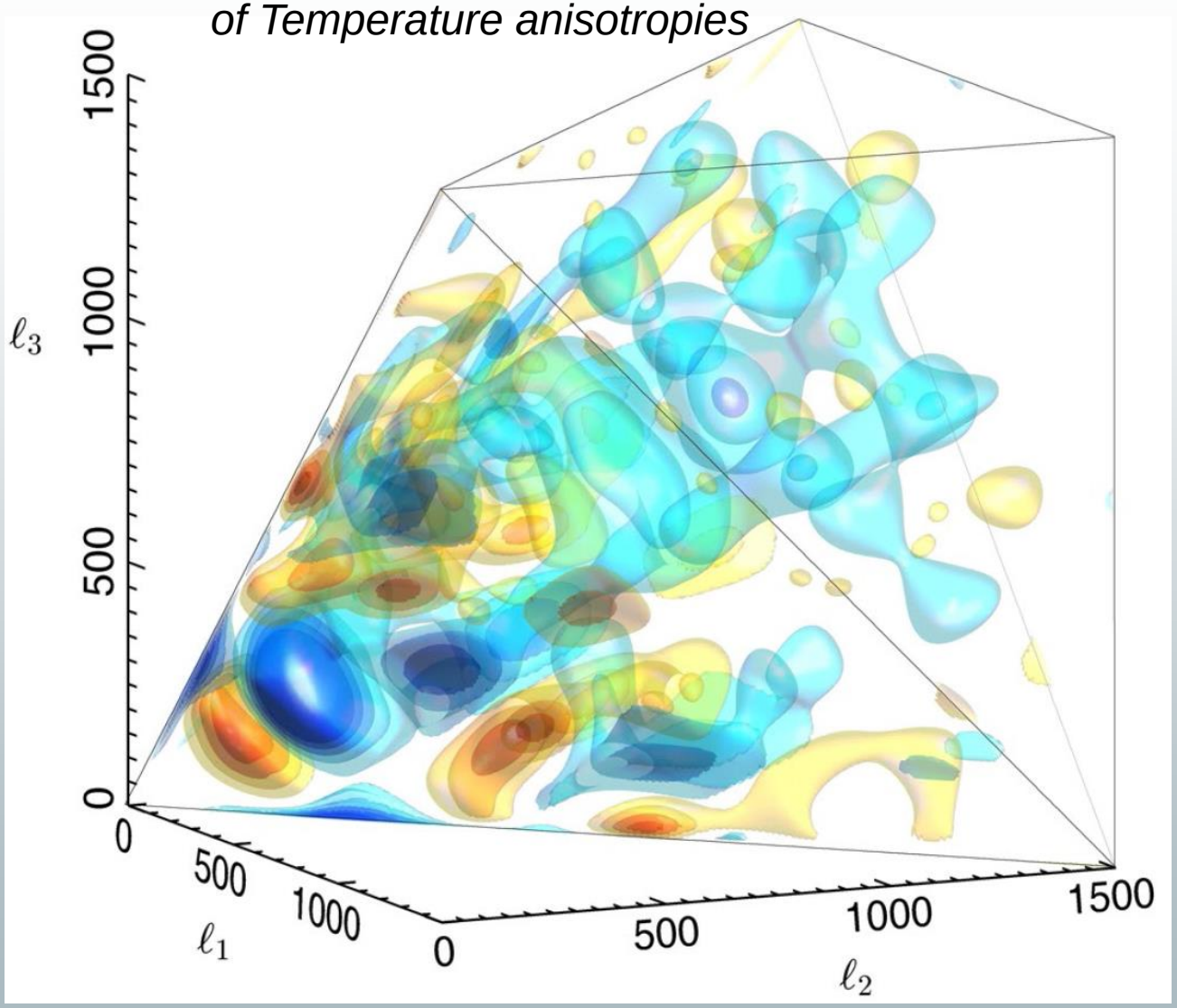


Slices through bi-spectra of primordial fluctuations



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...

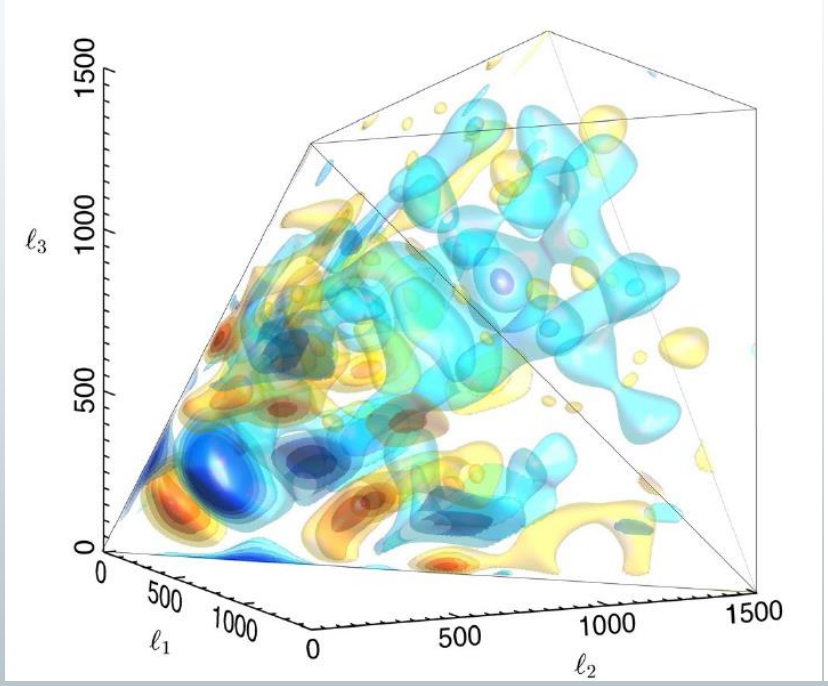
Flattened model (Eq. number)	Raw f_{NL}	Clean f_{NL}	Δf_{NL}	σ	Clean σ
Flat model (13)	70	37	77	0.9	0.5
Non-Bunch-Davies (NBD)	178	155	78	2.2	2.0
Single-field NBD1 flattened (14)	31	19	13	2.4	1.4
Single-field NBD2 squeezed (14)	0.8	0.2	0.4	1.8	0.5
Non-canonical NBD3 (15)	13	9.6	9.7	1.3	1.0
Vector model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

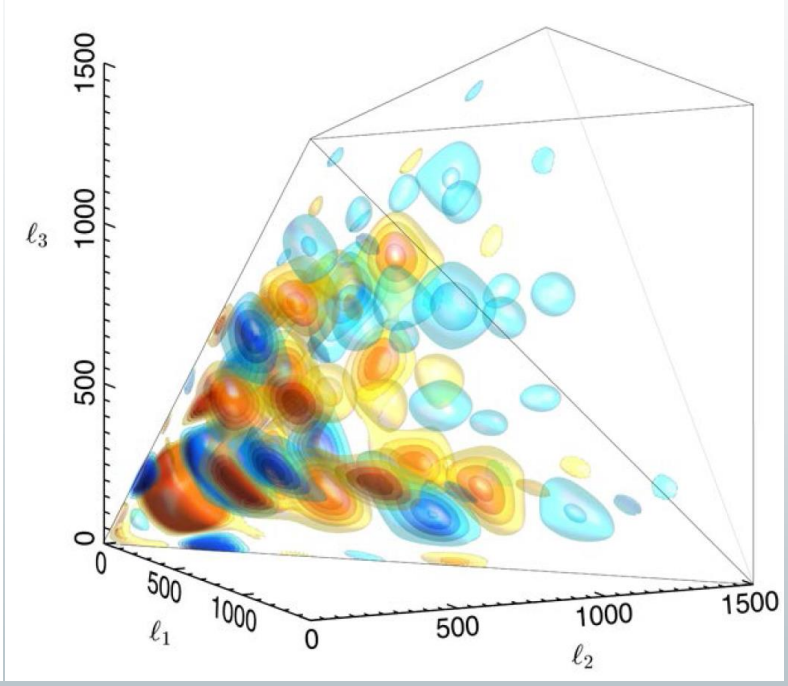
Width / Model	$\Delta k = 0.015$ $f_{NL} \pm \Delta f_{NL}$ (σ)	$\Delta k = 0.03$ $f_{NL} \pm \Delta f_{NL}$ (σ)	$\Delta k = 0.045$ $f_{NL} \pm \Delta f_{NL}$ (σ)	Full $f_{NL} \pm \Delta f_{NL}$ (σ)
$k_c = 0.01125$; $\phi = 0$	765 ± 275 (2.8)	703 ± 241 (2.9)	648 ± 218 (3.0)	434 ± 170 (2.6)
$k_c = 0.01750$; $\phi = 0$	−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.

Planck τ_{NL} constraint

- τ_{NL} can be understood as measuring the large-scale modulation of small-scale power.
- f_{NL} constraints show that such a modulation must be small **if** correlated with the temperature (as may be realized e.g. in multi-field inflation).

- The large-scale modes of ϕ can be measured from the modulation they induce in the small-scale power spectrum of the curvature perturbations ζ:

$$\zeta(\boldsymbol{x}) = \zeta_0(\boldsymbol{x})[1 + \phi(\boldsymbol{x})]$$

- Indeed, at scales much larger than the last-scattering surface, ϕ will modulate all small-scale perturbations , which translates directly into a large-scale modulation of the small-scale CMB temperature T_g

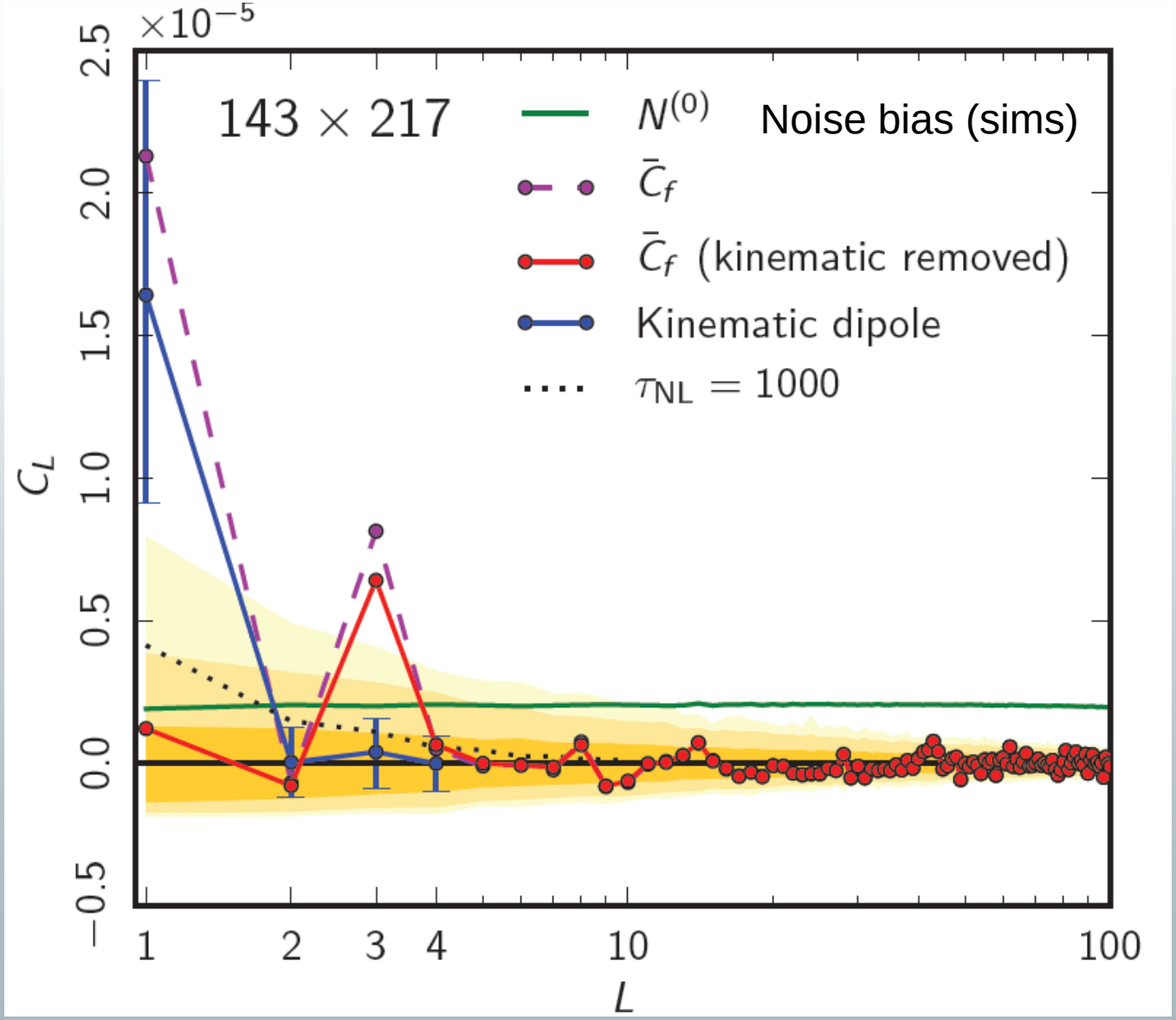
$$T(\hat{\boldsymbol{n}}) \approx T_{\rm g}(\hat{\boldsymbol{n}})[1 + \phi(\hat{\boldsymbol{n}}, r_*)] \equiv T_{\rm g}(\hat{\boldsymbol{n}})[1 + f(\hat{\boldsymbol{n}})]$$

- Hanson & Lewis (2009) developed a general quadratic estimator methodology for reconstructing f, as a quadratic function of the filtered data (~lensing); and

$$\tau_{\rm NL}(L) \equiv \frac{C_L^f}{C_L^{\zeta_\star}}$$

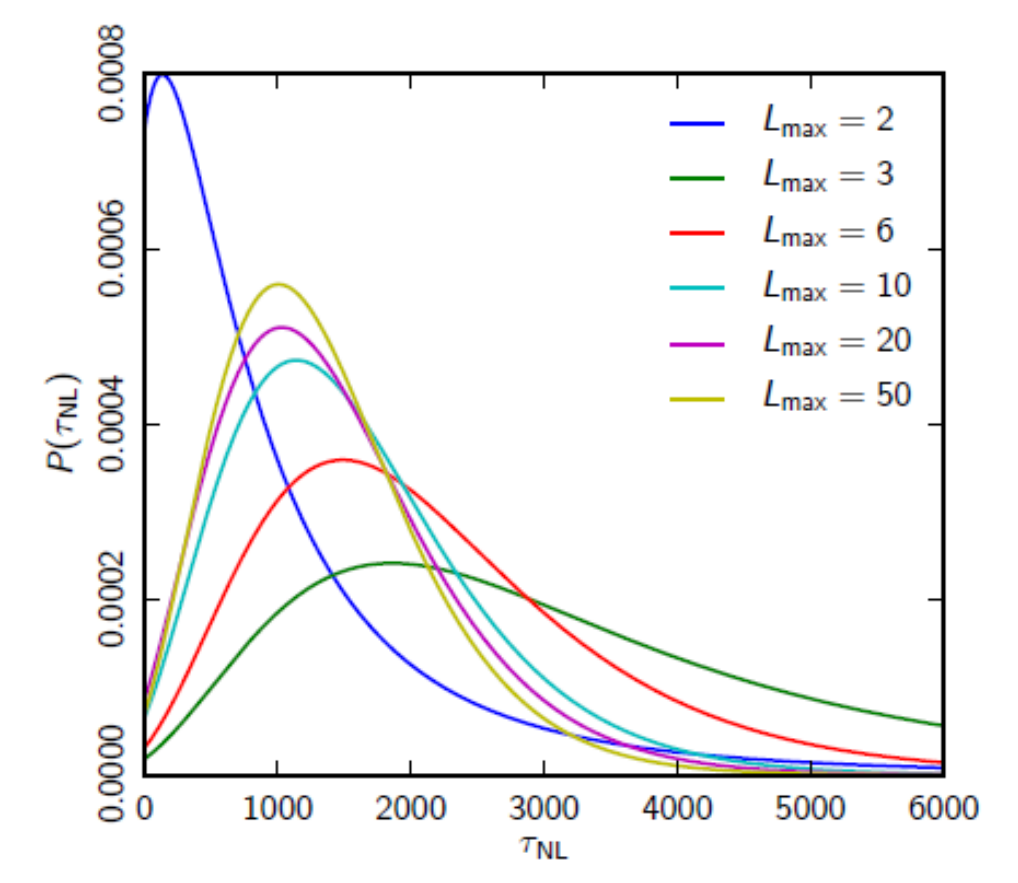
Power spectrum of modulating field f

- Dipole clearly detected as expected due to Doppler boost signature
- Octopole anomalously high at 143 x 217GHz (but varies across frequencies: unlikely to be physical)



Planck τ_{NL} constraint

- The high octopole is pulling the distributions up to higher τ_{NL} values, but increasing L_{max} reduces the high-L tail because very large τ_{NL} values are inconsistent with the low modulation power seen at L > 3.
- With L_{max} = 2 the posterior peaks near zero, but the distribution is then very broad because there are only about 8 modes, which therefore have large cosmic variance.
- For Lmax = 50 we find τ_{NL} < 2800 at 95% CL, which we took as our upper limit



Summary on primordial non-gaussianity

- Single field slow-roll inflation survived the most stringent test of Gaussianity performed to date; NG constraints severely limit alternatives.

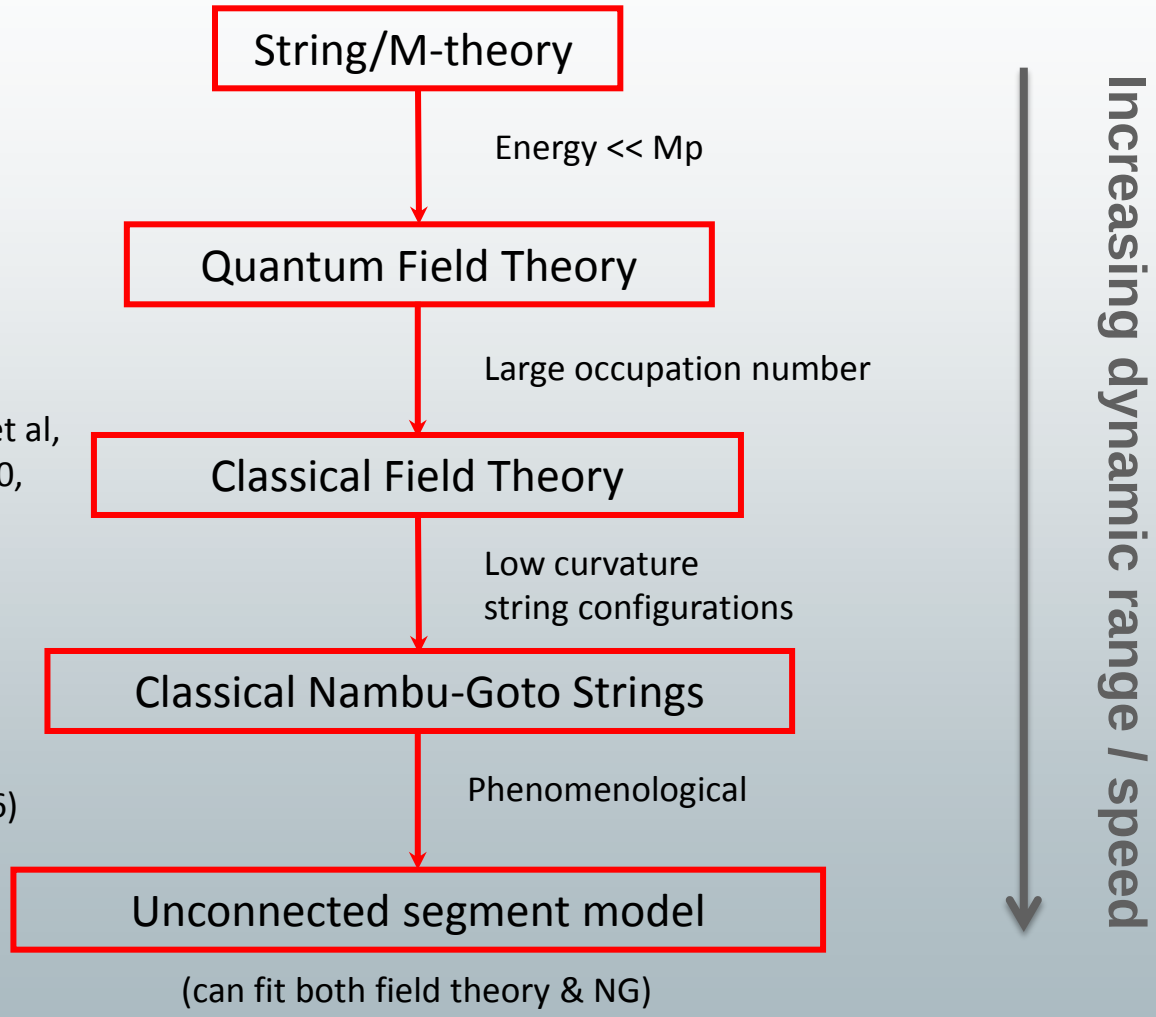
- The new LEO trio: $f_{NL}^{local} = 2.7 \pm 5.8$, $f_{NL}^{equi} = -42 \pm 75$, $f_{NL}^{orth} = -25 \pm 39$
- Model independent 3 dimensional reconstruction (modal&binned) → no new types (/LEO) at low-ell, but interesting hints a higher-l
- Constraints on signatures from key specific scenario, including
  - *General single field, including non-separable shapes*
  - *Excited initial states (Non-BD) – no indication*
  - *Directionally dependent vector model*
  - *Initial scout of scale dependent feature and resonant models*
- Limits on 4 points , $\tau_{NL} < 2800$ (95%CL) (ok / f_{NL}^2)

- Ekpyrotic/cyclic models are not favoured (predict local non-Gaussianity; either ruled out or under pressure)

Cosmic defects

- Cosmic defects are a generic outcome of symmetry-breaking phase transitions in the early Universe.
  - *Strings appear in a variety of supersymmetric and other grand unified theories, forming at the end of inflation.*
  - *Cosmic (super-)strings also emerge in higher-dimensional theories for LSS, as in brane inflation.*
  - *Comparable effects can also be caused by other types of cosmic defects, notably semi-local strings and global textures.*
- The discovery of any of these objects would identify GUT-scale symmetry breaking patterns, perhaps even providing direct evidence for extra dimensions. Conversely, their absence tightly constrains symmetry breaking schemes.
- The most stringent constraints on the string tension arise from predicted backgrounds of gravitational waves from decaying loops, thus rely on most uncertain part of string physics (loop production scale and nature of string radiation from cusps)
- CMB: defects affect both power spectrum and NG properties.

Levels of approximations

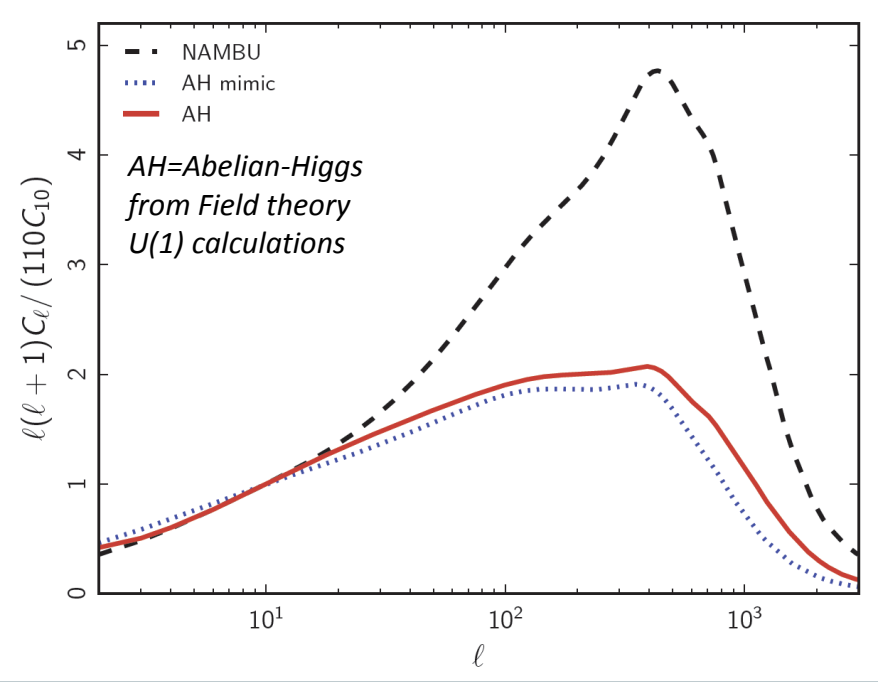


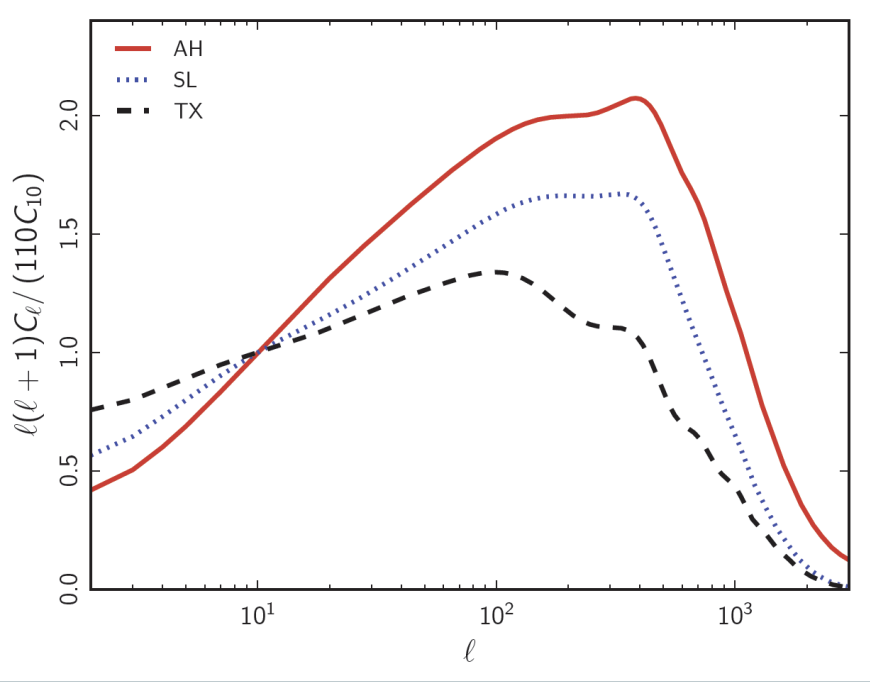
Bevis, Hindmarsh, Urrestilla, MK et al, astro-ph:0605018 arXiv:0704.3800, arXiv:1005.2663

Allen (1997)
Contaldi et al (1998)
Landriau et al (2004)
Olum et al (2005)
Ringeval et al (2005)
Martins & Shellard (2006)

Perivolaropoulos (1995)
Albrecht et al (1997)
Wyman et al (2005,2006)
Pogosian et al (1999, 2006)

Spectra used in this analysis





Cosmic strings, normalised to equal power at l=10 (around 2 10^{-6} with W7 ➔ less than 3% of overall spectrum

Comparison between global texture (black dashed) and semilocal (blue dotted) string power spectra and the AH field theory strings (red solid)

Cosmic strings: none in sight (yet?)

From power spectrum analysis: (other parameters, inc. n_s, unaffected)

Defect type	*Planck*+WP		*Planck*+WP+highL	
	f_{10}	$G\mu/c^2$	f_{10}	$G\mu/c^2$
NAMBU	0.015	1.5×10^{-7}	0.010	1.3×10^{-7}
AH-mimic	0.033	3.6×10^{-7}	0.034	3.7×10^{-7}
AH	0.028	3.2×10^{-7}	0.024	3.0×10^{-7}
SL Semilocal	0.043	11.0×10^{-7}	0.041	10.7×10^{-7}
TX Global texture	0.055	10.6×10^{-7}	0.054	10.5×10^{-7}

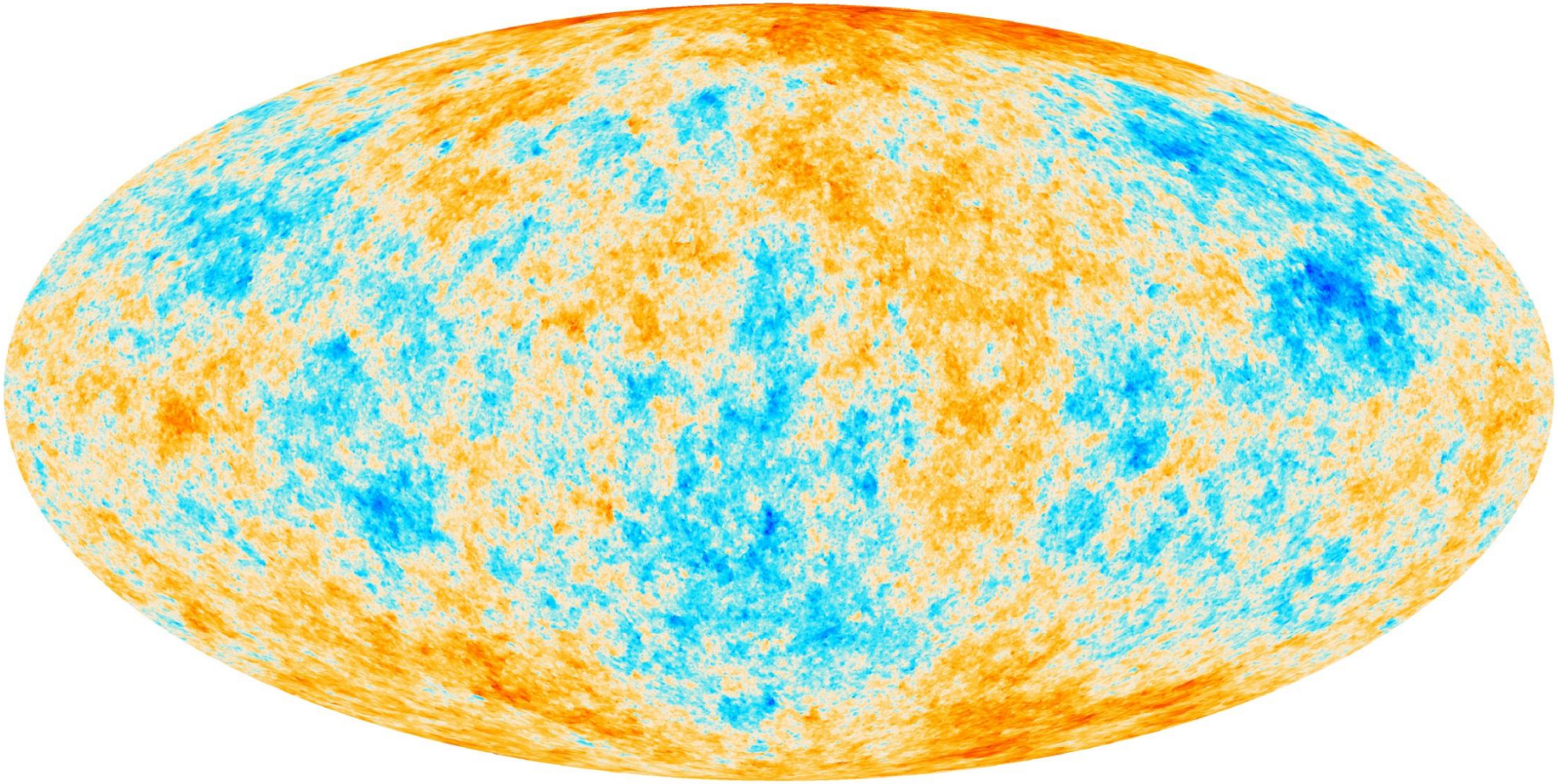
Cosmological parameters are unaffected

f_{10} = fractional contribution at l=10

Mass per unit length, $G\mu/c^2 = (\eta/m_p)^2$, η = energy scale of symmetry breaking

(ie $\eta < 4.7 \times 10^{15}$ GeV for Nambu-Goto strings)

The late CMB imprint from strings

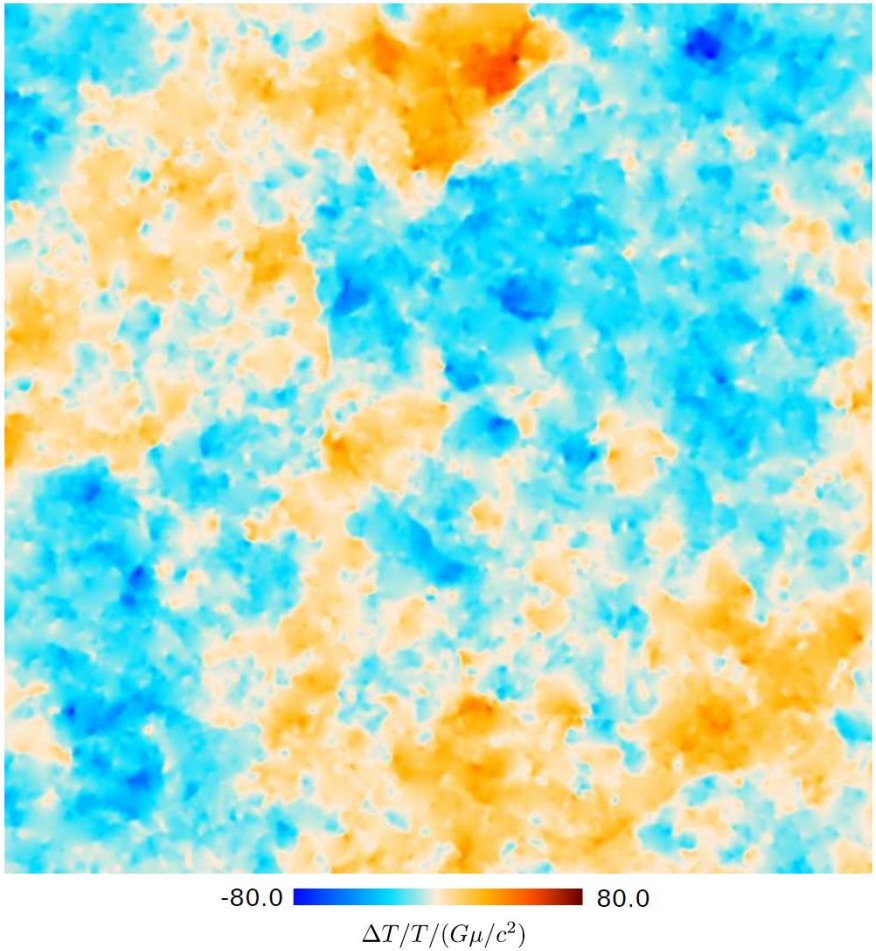


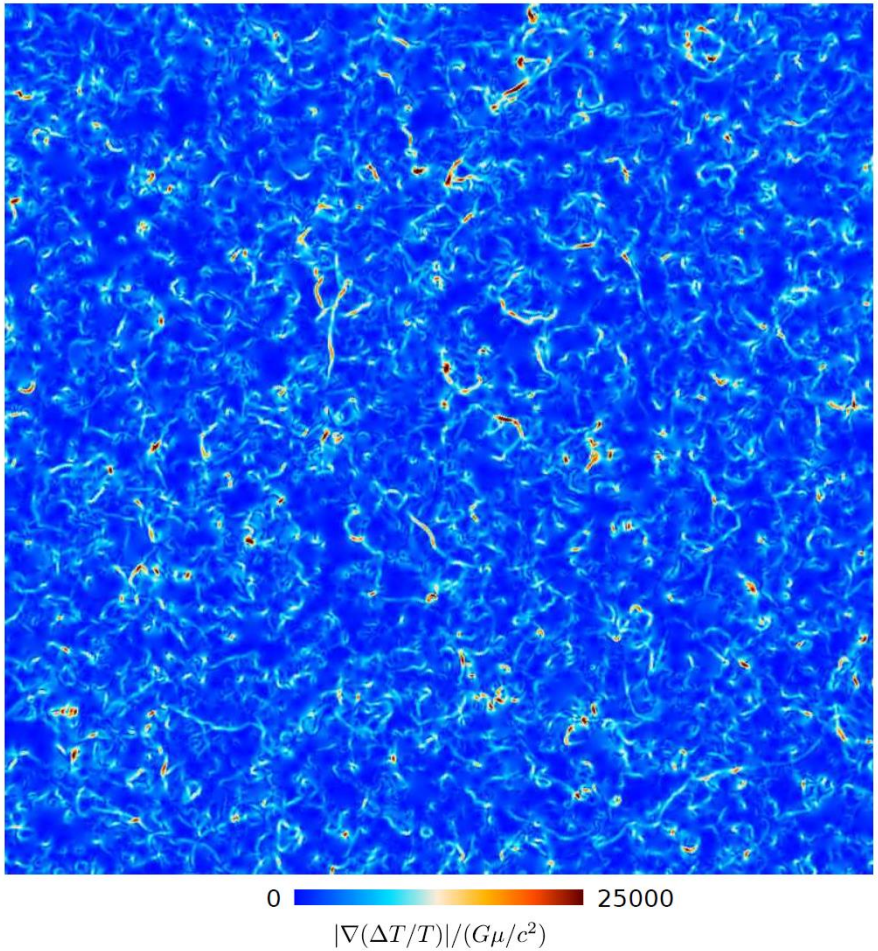
-100.0 100.0

1st high-res full (stringy) sky prediction $\Delta T/T/(G\mu/c^2)$ Ringeval & Bouchet, 2012, PRD86, 023513

Zooming in reveals the NG aspect

A zoom on a 20 degree patch extracted from a full sky simulated makes temperature steps visible. Applying the spherical gradient magnitude operator enhances the steps, and thus the string locations.





→ Modal bispectrum: $G\mu/c^2 < 8.8 \times 10^{-7}$ (95%CL); Minkowski functionals : $G\mu/c^2 < 7.8 \times 10^{-7}$ (95%CL); (post rec)

Conclusions 1/3

- The Planck hardware and scanning strategy afford a wide array of consistency tests.
- Planck's performance on these tests gives confidence that its unprecedented sensitivity is being realized, and that its scientific results are robust.
- A number of corrections and improved calibration and analysis procedures are known and will be implemented for the 2014 release. Everything we known suggests that these will only improve the consistency of the data, and bring HFI and LFI into even closer agreement.

Conclusions 2/2

- Ω_K=-0.006±0.018 at 95%CL from Planck-T+Planck-L (PT+PL).
- f_{NL}^{LEO} (and others) is 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).

- n_s=0.963 ±0.006 from PT+WP+BAO; HZ robustly excluded (even N_{eff} or Y_p worse by $\Delta\chi^2_{eff}$ = 4.6 or 8).
- No evidence for running (nor running of running).
- $r_{0.002} < 0.12$ (PT+WP) → inflation energy scale < 1.9×10^{16} GeV (or $H_* < 3.7 \times 10^{-5} M_p$) at 95%CL.
- Concave potentials preferred.
  - *Exponential potential, monomial with p>2, hybrid driven by quadratic term are all disfavored at more than 95% confidence. Simple Quadratic large field at the edge…*
- Strong constraints on parameters values of specific inflationary scenario (e.g. on scale parameter of natural inflation)
- Planck limits possibilities for unknown physics between end of inflation and the beginning of the radiation era (w_{int}).
- 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).
- Penalized Likelihood reconstruction of primordial spectrum hints at features;
  - *parameterized models (as motivated by NBD, axion monodromy or step in the potential) improve $\Delta\chi^2_{eff}$ by ~10, but no strong Bayesian evidence. Polarization will help .*
- No strong evidence for non-decaying isocurvature modes;
  - *(one at a time, but arbitrarily correlated to adiabatic mode). Axion and curvaton scenario (either uncorrelated or fully correlated) are not favored. But arbitrary correlation help lowering the low-l part of the spectrum ($\Delta\chi^2_{eff}$ >4).*

- ***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?)***

Conclusions 3/3

- 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"

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

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The journey
Just began!