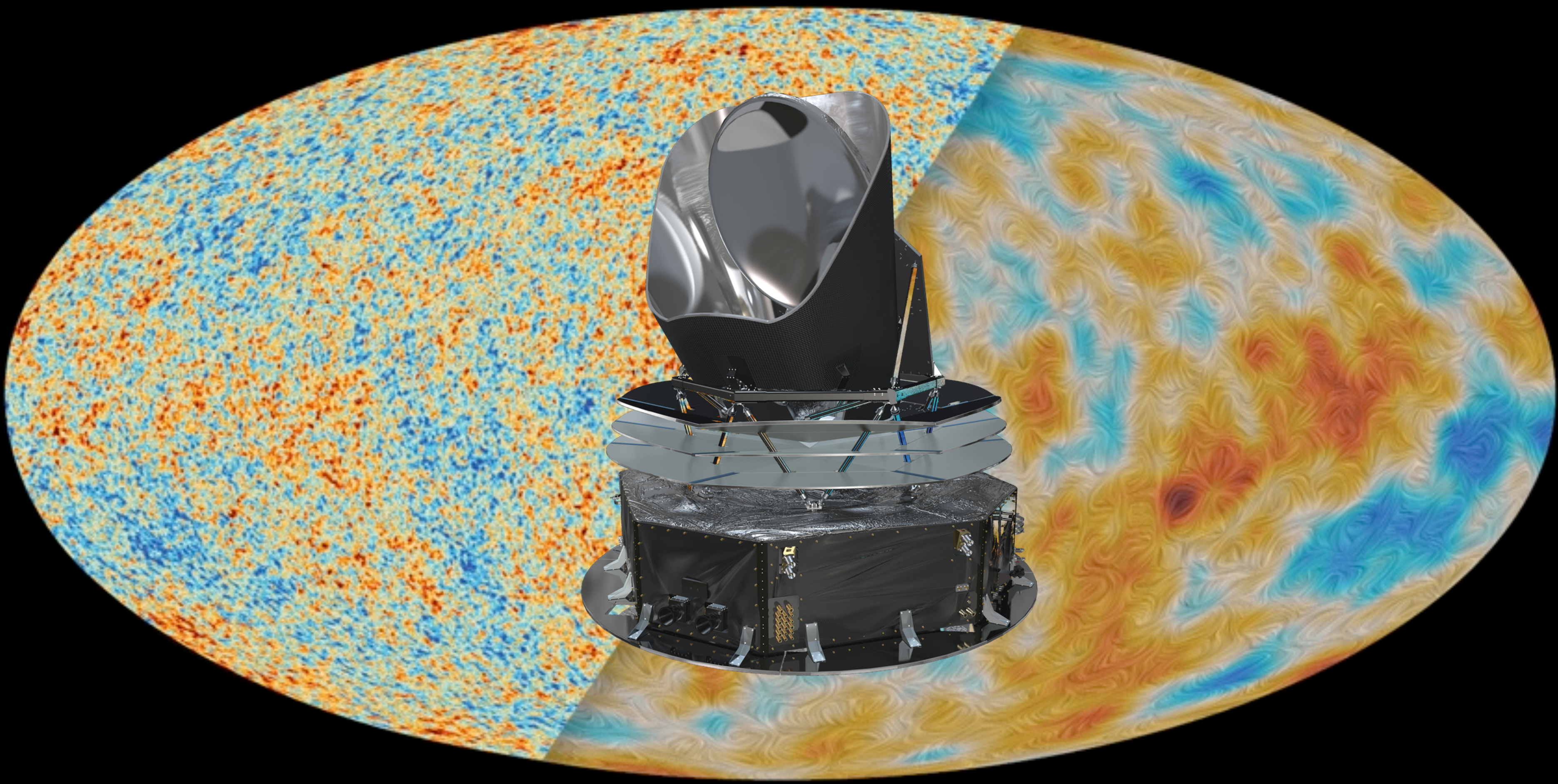
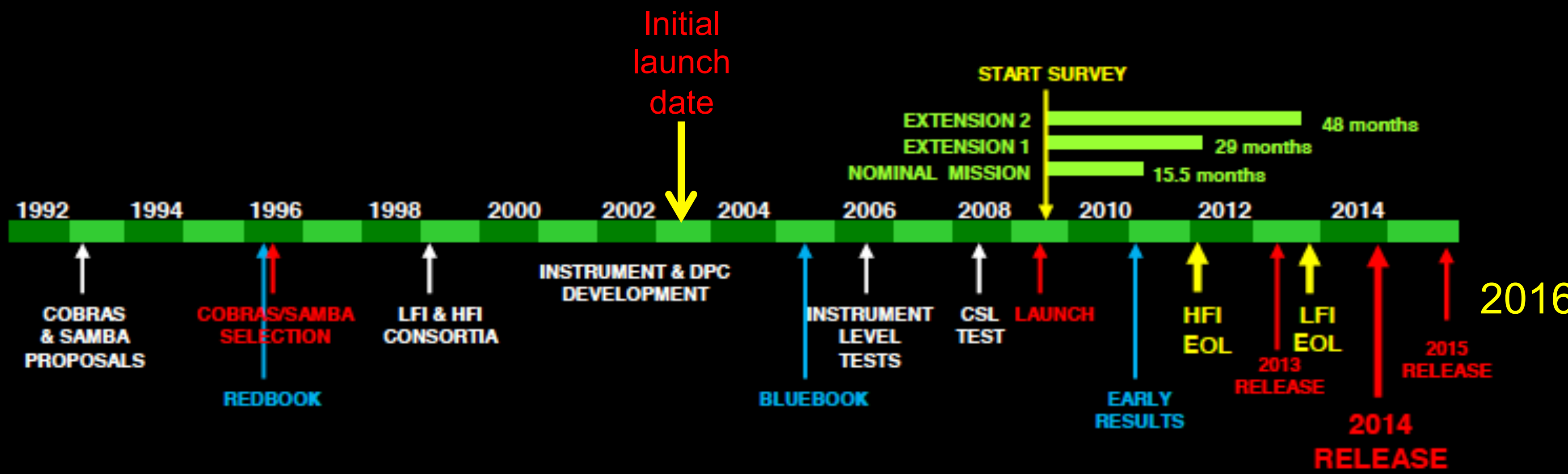
Legacy of PLANCK

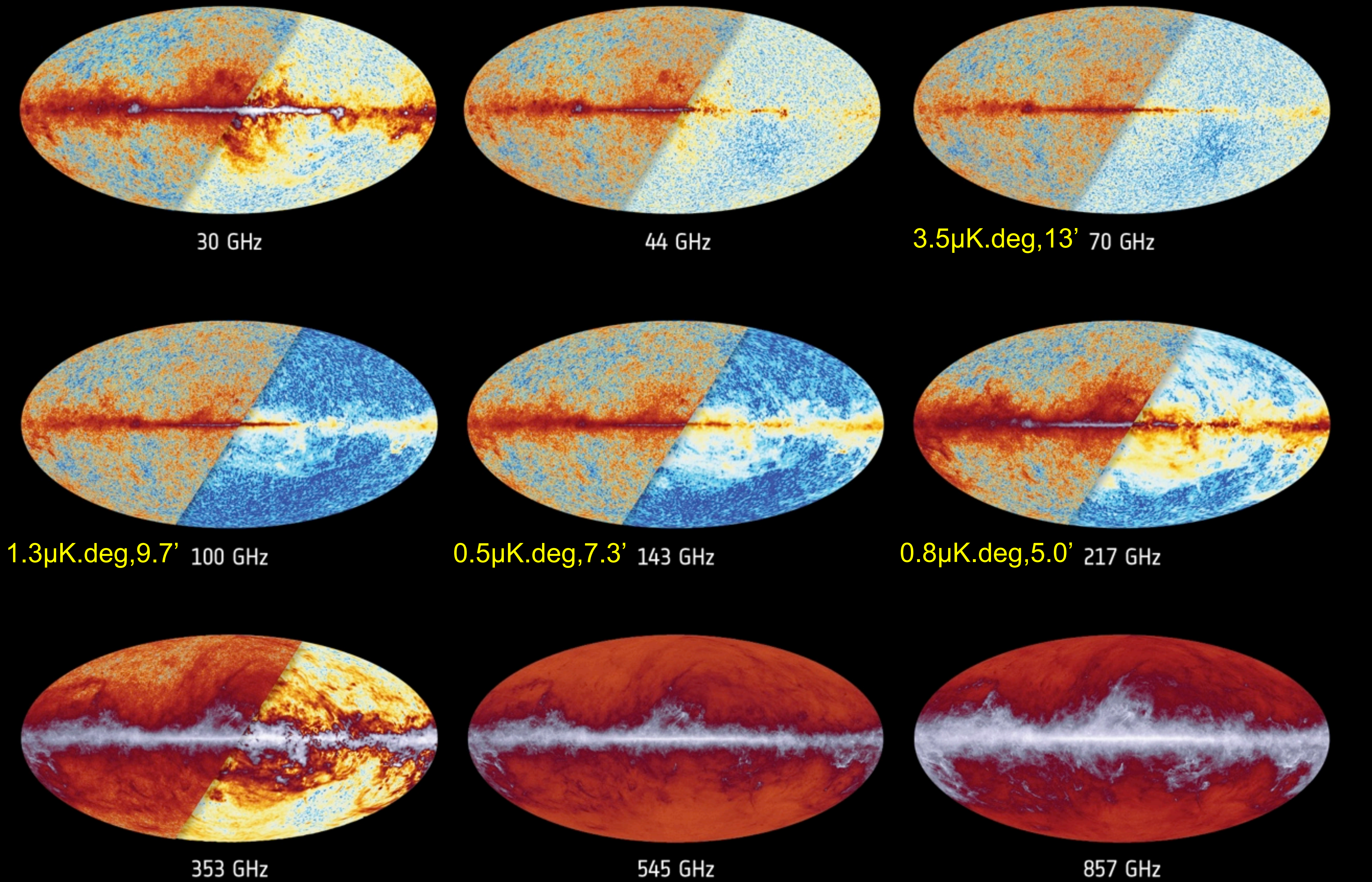


François R. Bouchet

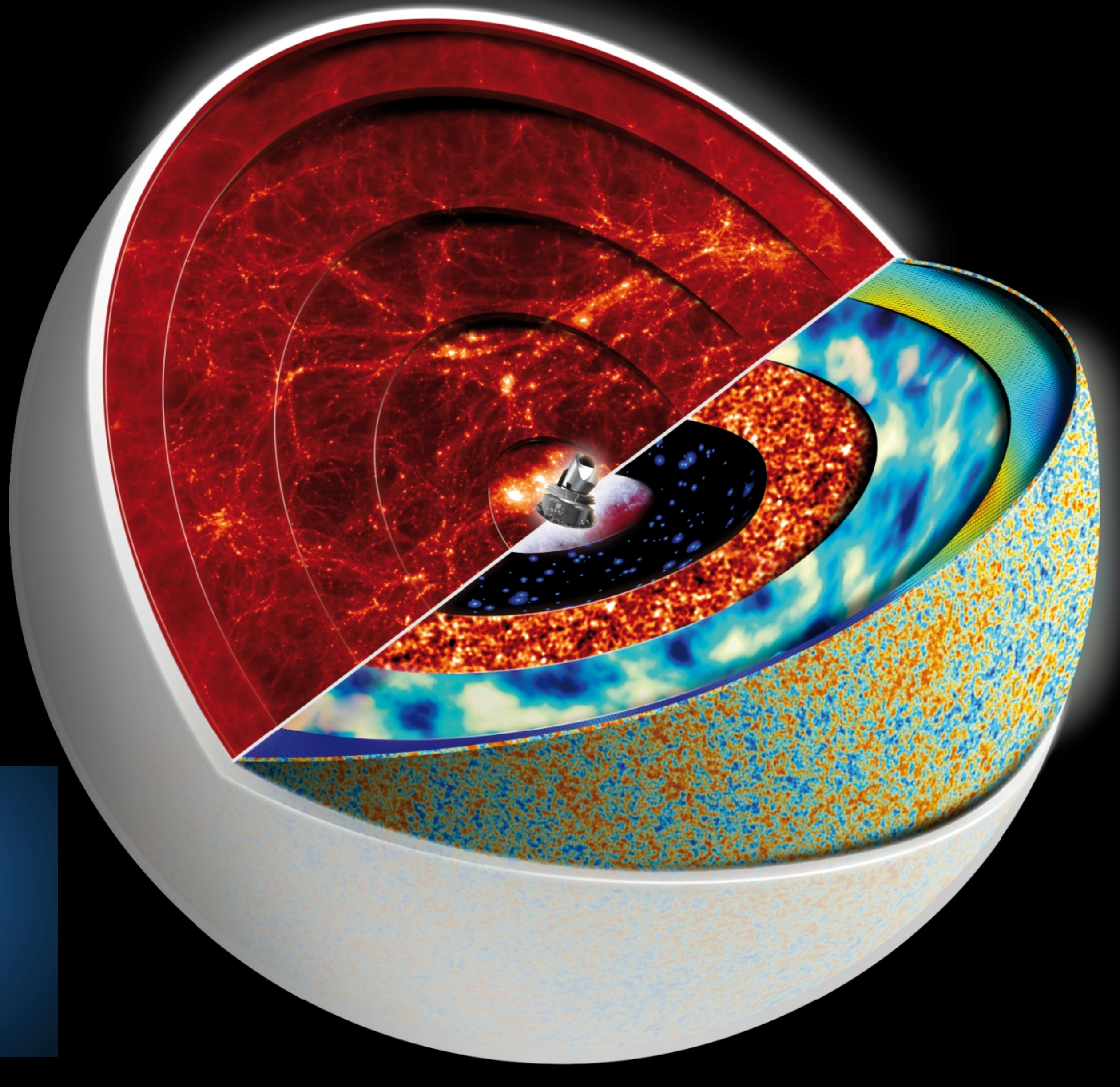
The Planck Collaboration

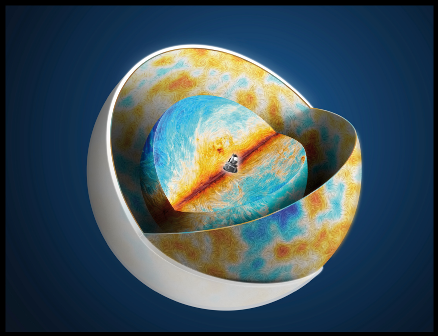


Now available in a store near you

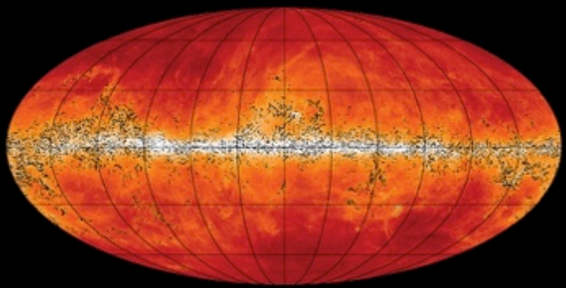


CMB, and much more

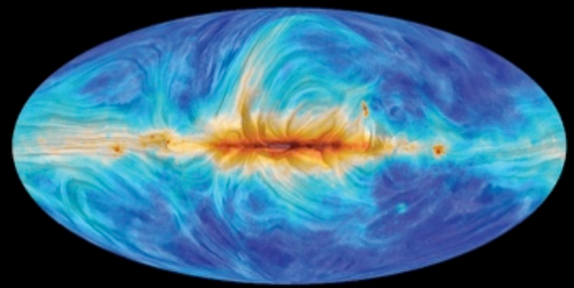




And a lot more…

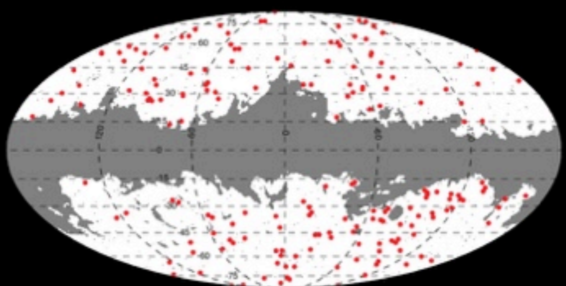


Galactic cold clumps

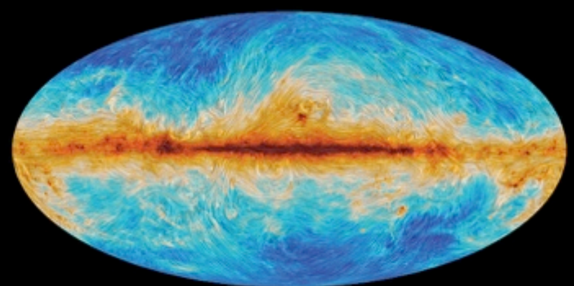


Magnetic field lines traced by synchrotron radiation at 30 GHz

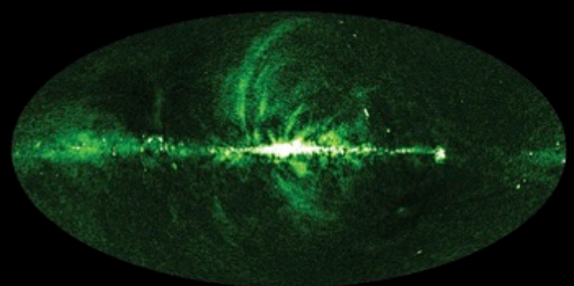
Polarised dust emission



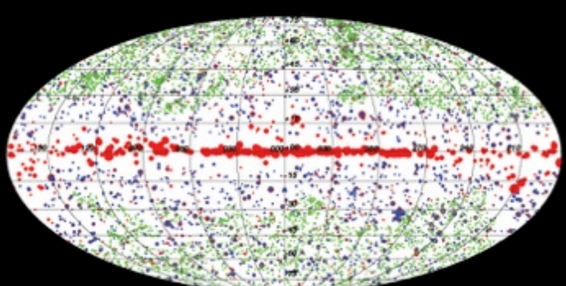
Galaxy clusters detected by the Sunyaev-Zeldovich effect



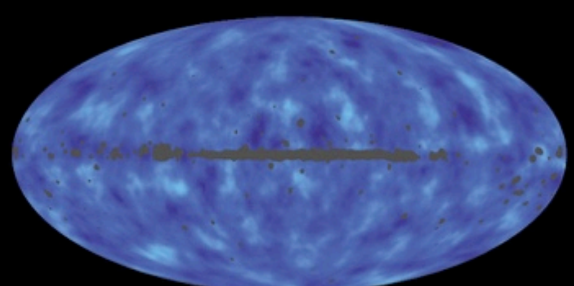
Magnetic field lines traced by dust emission at 353 GHz



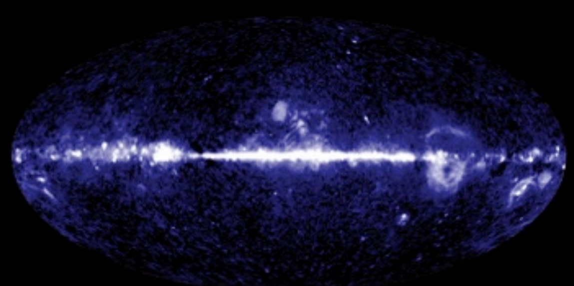
Polarised synchrotron emission



Compact sources



Gravitational-lensing potential — a tracer of dark matter structures



Line radiation from carbon monoxide gas

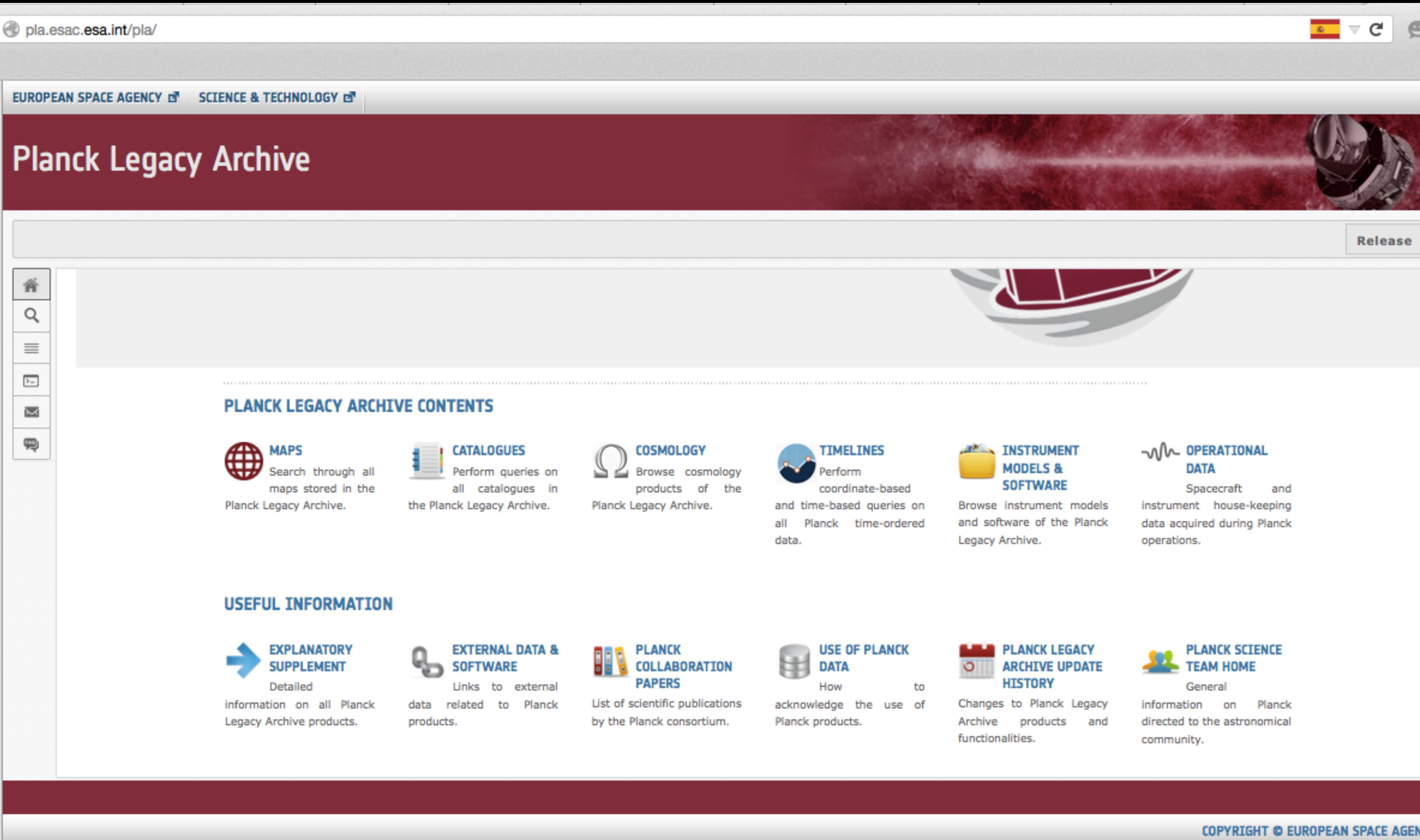
Including a competent community

2 AstroParticule et Cosmologie, Paris (F)
3 Laboratoire de Physique Subatomique et de Cosmologie, Grenoble (F)
3 Institut Louis Néel, Grenoble (F)
4 Centre d'Études Spatiales des Rayonnements, Toulouse (F)
5 Cardiff University, Cardiff (UK)
6 Rutherford Appleton Laboratory, Chilton (UK)
7 Institute of Astronomy, Cambridge (UK)
7 Mullard Radio Astronomy Observatory, Cambridge (UK)
8 Imperial College, London (UK)
9 National University of Ireland, Maynooth (IR)
10 Space Science Dpt of ESA, Noordwijk (NL)
11 Danish Space Research Institute, Copenhagen (DK)
12 Max-Planck-Institut fuer Astrophysik, Garching (D)
13 Université de Genève , Geneva (CH)
14 University La Sapienza, Rome (I)
15 Universidad de Granada, Granada (E)
16 California Institute of Technology, Pasadena (USA)
16 Jet Propulsion Laboratory, Pasadena (USA)
16 Stanford University, Stanford (USA)
17 Canadian Institute for Theoretical Astrophysics, Toronto (Canada)

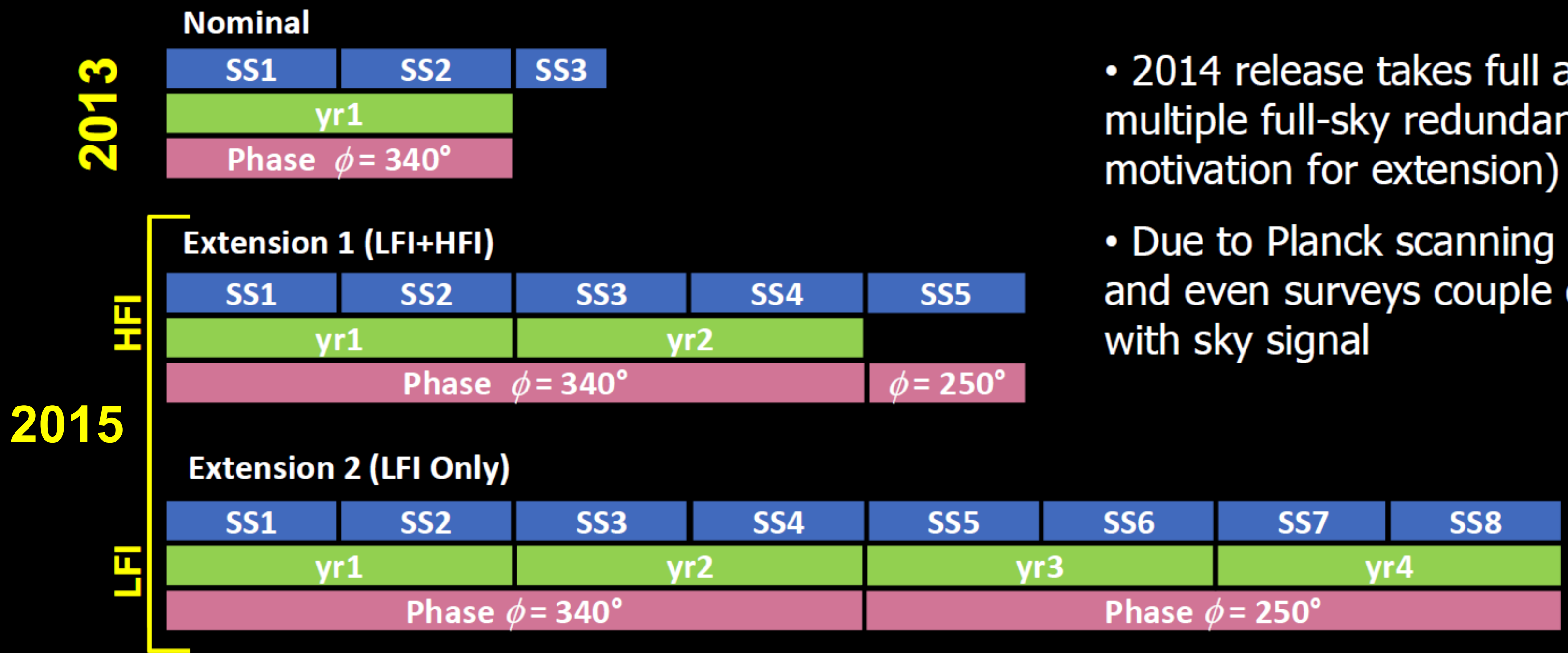
Research Laboratories in the LFI Collaboration

A Istituto Nazionale di Astrofisica Spaziale et Fisica Cosmica, Bologna (I)
B Istituto CAISMI, Firenze (I)
C Istituto IASF (CNR), Milano (I)
C Istituto di Fisica del Plasma IFP (CNR), Milano (I)
D Osservatorio Astronomico di Padova, Padova (I)
E Osservatorio Astronomico di Trieste, Trieste (I)
E SISSA, Trieste (I)
F Istituto IFSI, Roma (I)
F Universita Tor Vergata, Roma (I)
G Instituto de Fisica de Cantabria, Santander (E)
H Instituto de Astrofisica de Canarias, La Laguna (E)
I Jodrell Bank Observatory, Macclesfield (UK)
J Space Science Dpt of ESA , Noordwijk (NL)
K Danish Space Research Institute , Copenhagen (DK)
K Theoretical Astrophysics Center, Copenhagen (DK)
L University of Oslo, Oslo (N)
M Chalmers University of Technology, Goteborg (S)
N Millimetre Wave Laboratory, Espoo (FI)
O Max-Planck-Institut fuer Astrophysik, Garching (D)
P Université de Genève, Geneva (CH)
Q University of California (Berkeley), Berkeley (USA)
Q University of California (Santa Barbara), Santa Barbara (USA)
Q Jet Propulsion Laboratory, Pasadena (USA)

Mission accomplished !



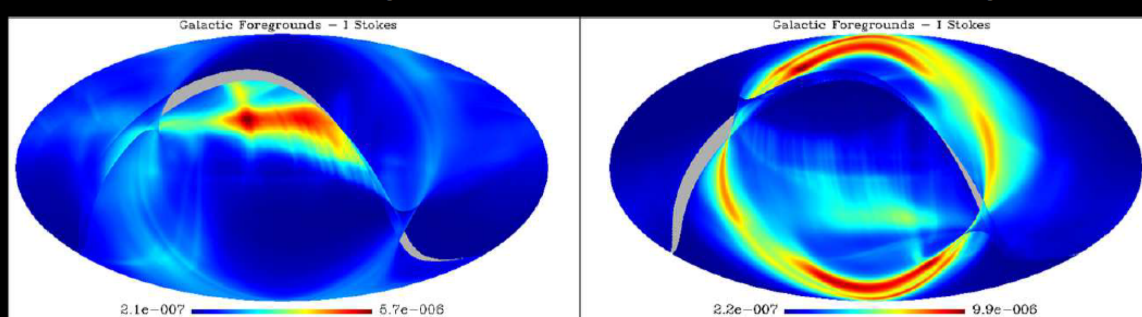
2015 release: Planck full mission data



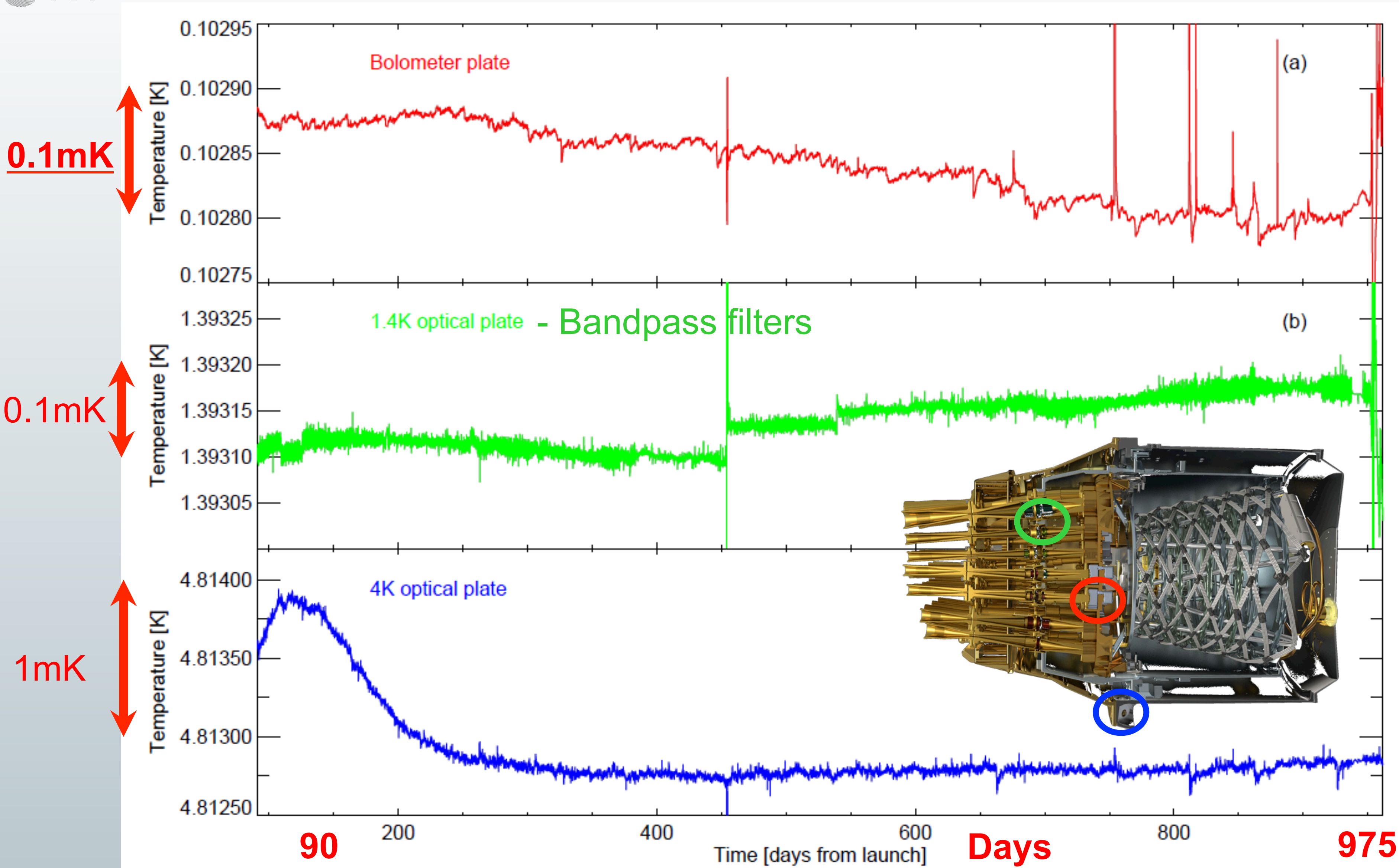
- 2014 release takes full advantage of multiple full-sky redundancies (main motivation for extension)
- Due to Planck scanning strategy, odd and even surveys couple differently with sky signal

Galactic straylight (simulation)

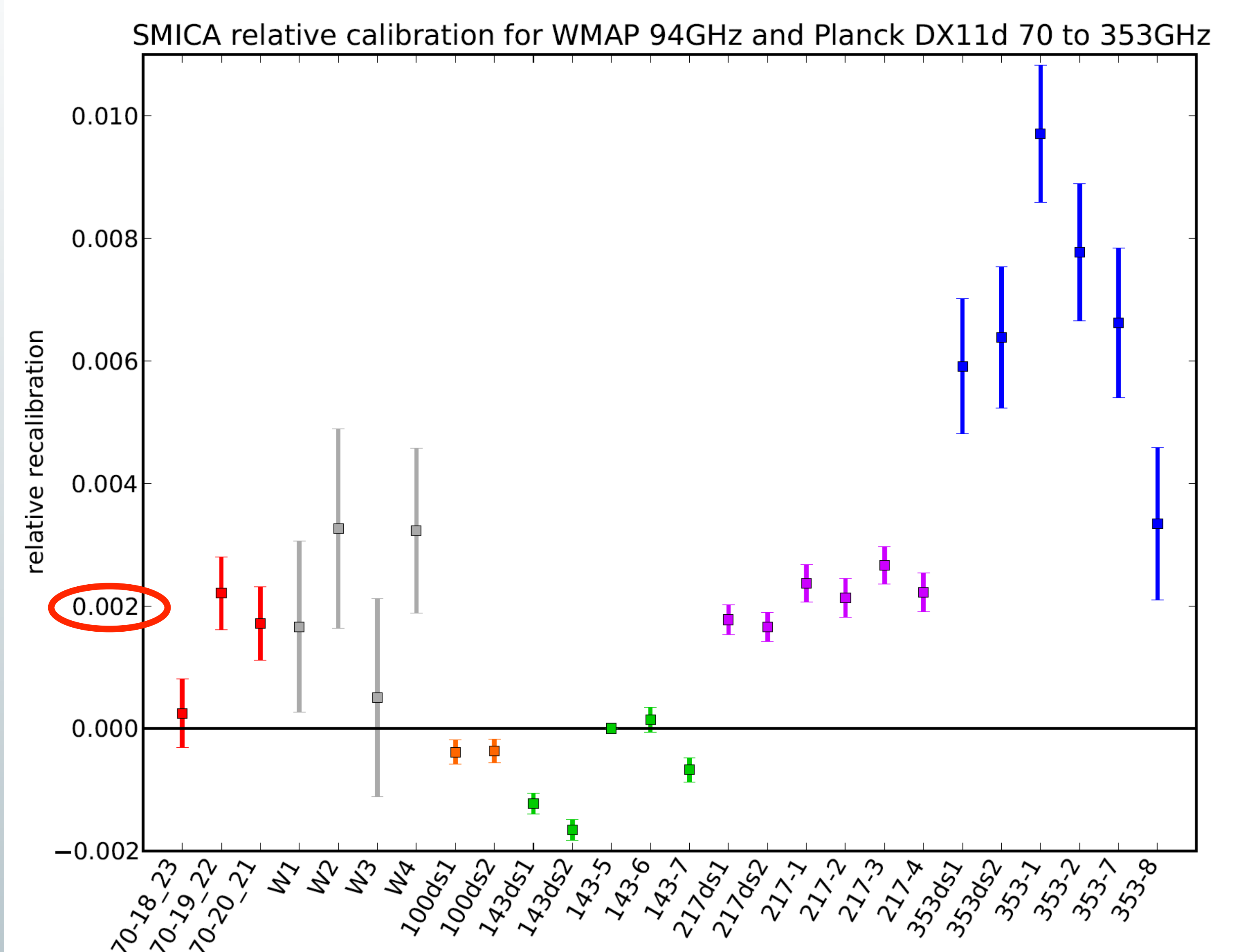
Odd survey Even survey



Quietly cool…

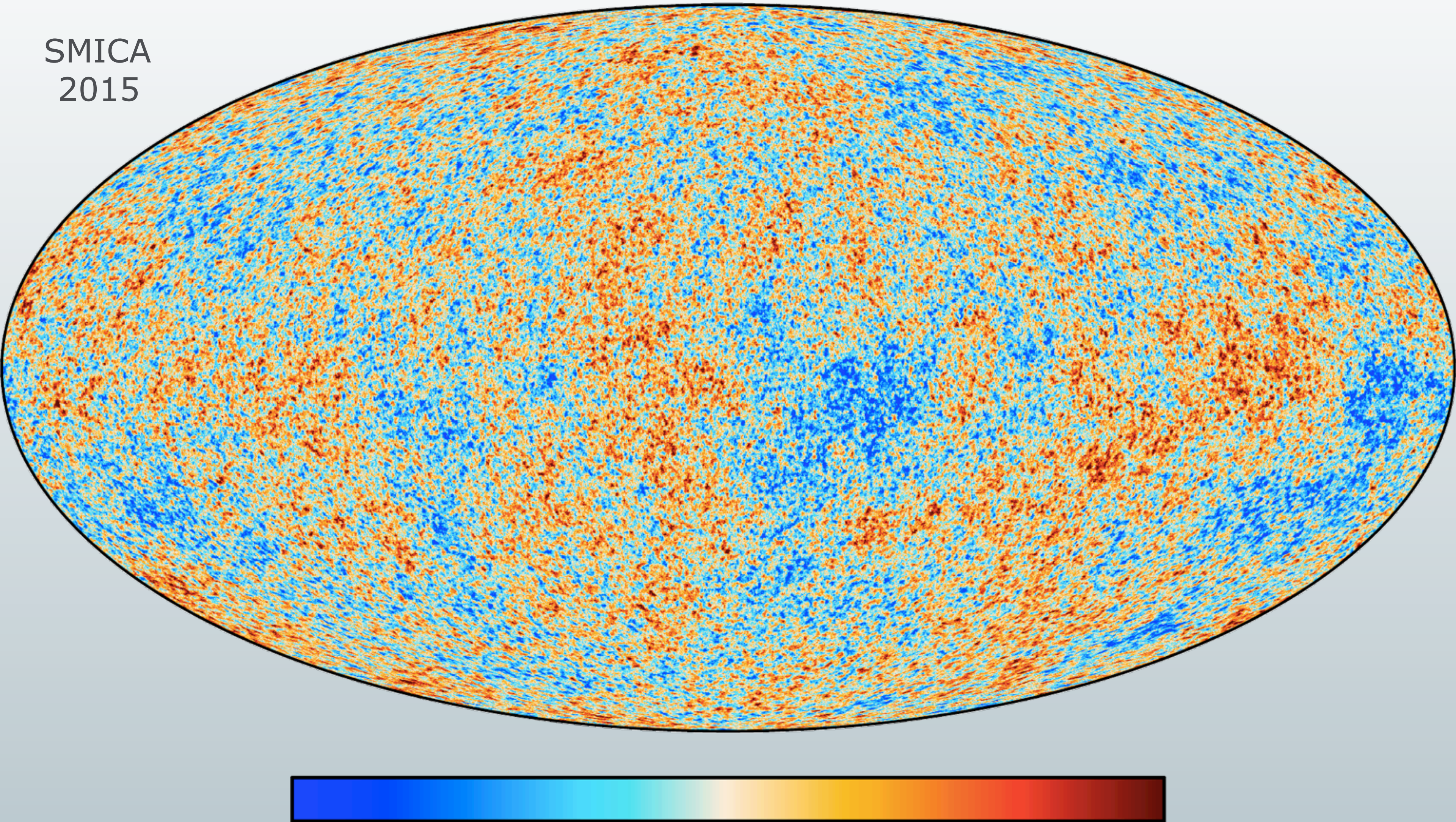


CMB Relative calibration over l=50-495 range

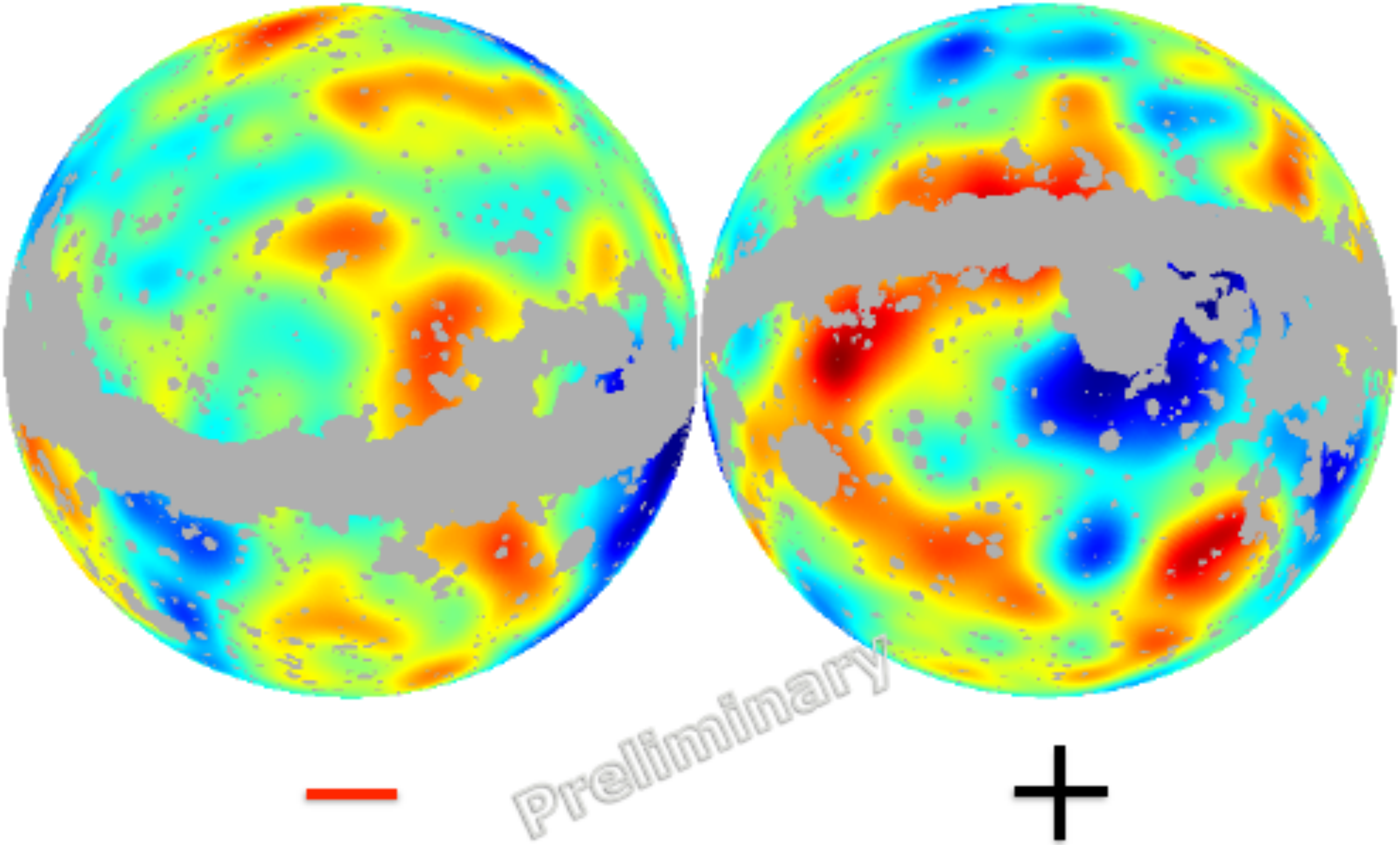


Planck 2015 T anisotropies map

SMICA
2015

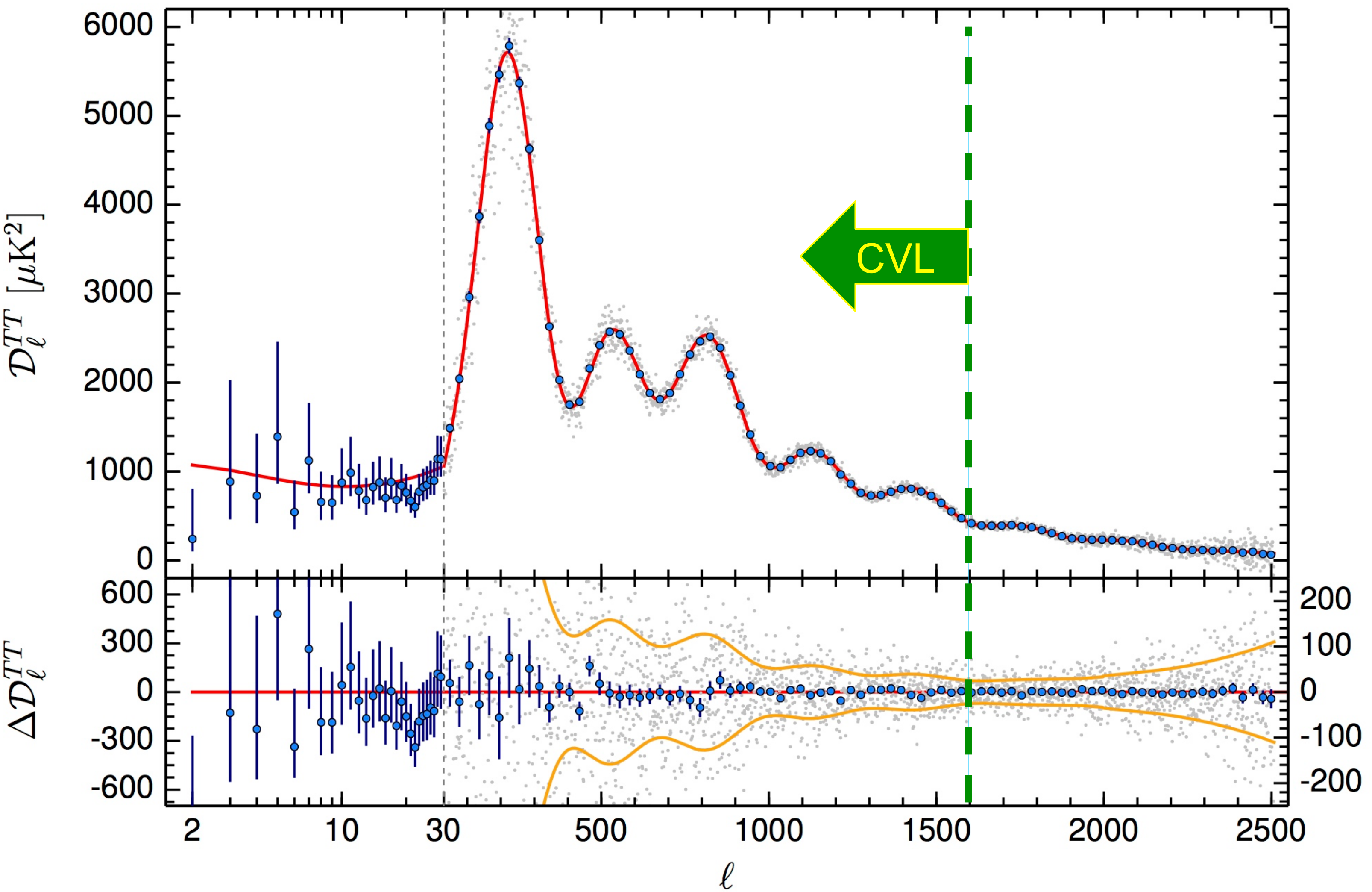


Power asymmetry in *Planck* 2014 full mission data



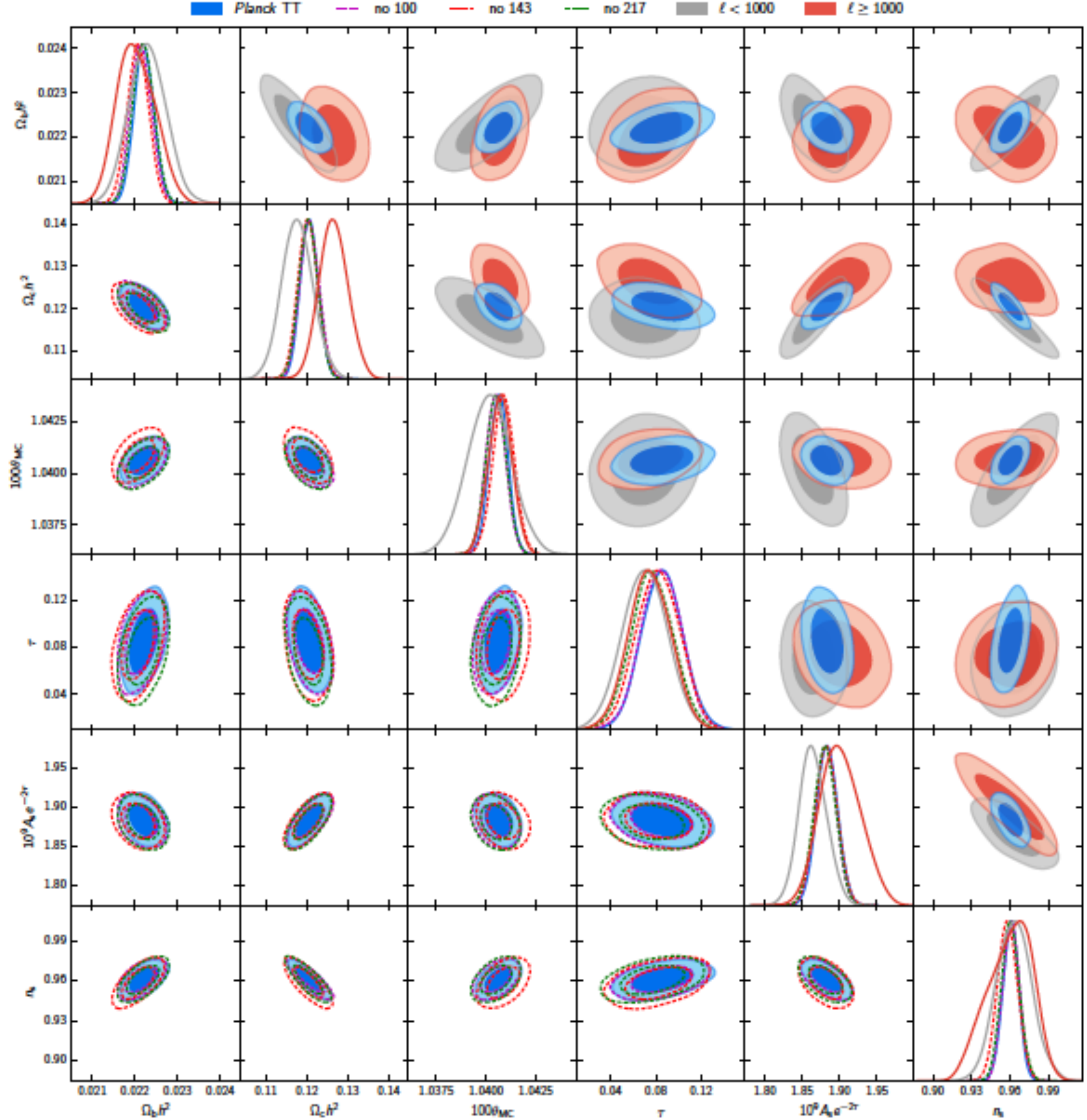
Features on 2014 full mission data are very similar to 2013 nominal mission data.

Planck 2015 TT spectrum



8 acoustic peaks well detected

CVL till l~1600 on 40-70% of the sky

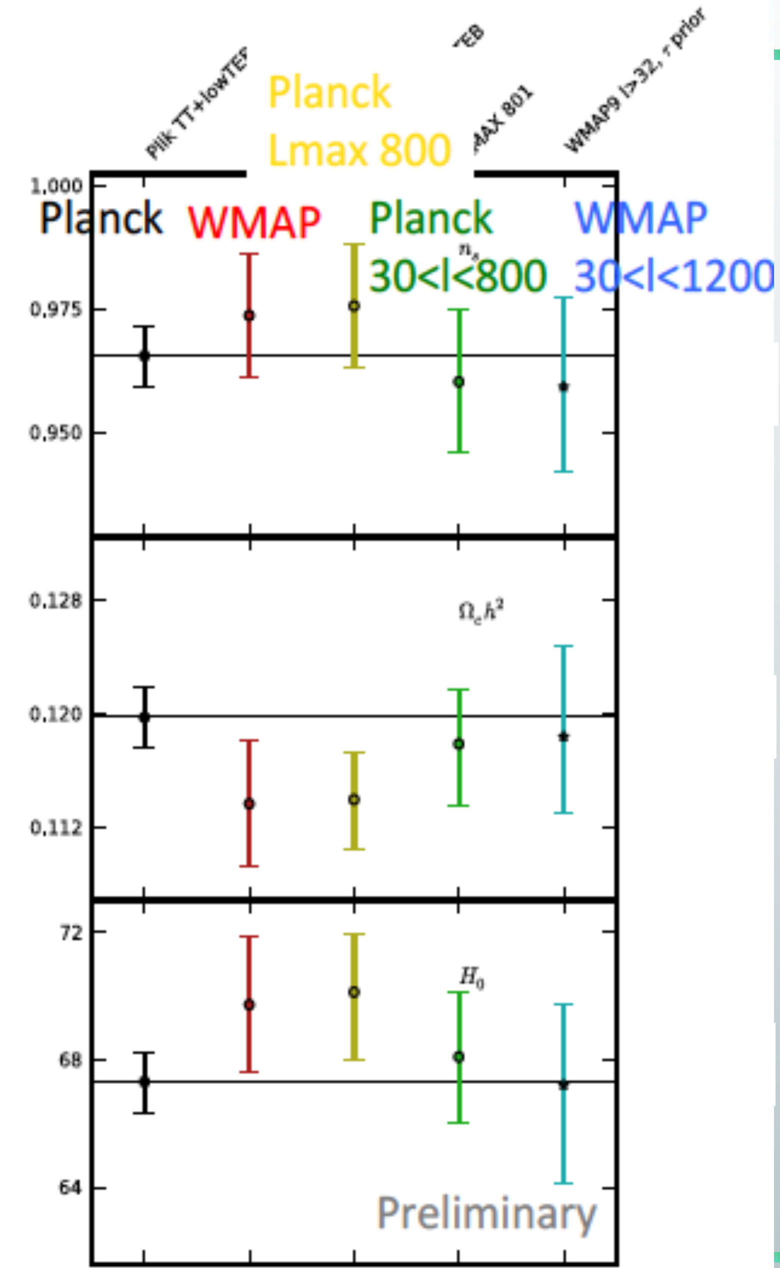


Parameters on jack-knife tests (removing channels or even l-range)

Planck restricted to lmax=800 is quite consistent with WMAP.

Cutting the TT l<30, one recovers the full Planck cosmology, both with Planck w. lmax=800 and with WMAP!

Planck is less affected than WMAP by the l~20 deficit (however it still has some impact on some parameters, e.g. N_{eff}, A_{lens}). More modes is better ☺

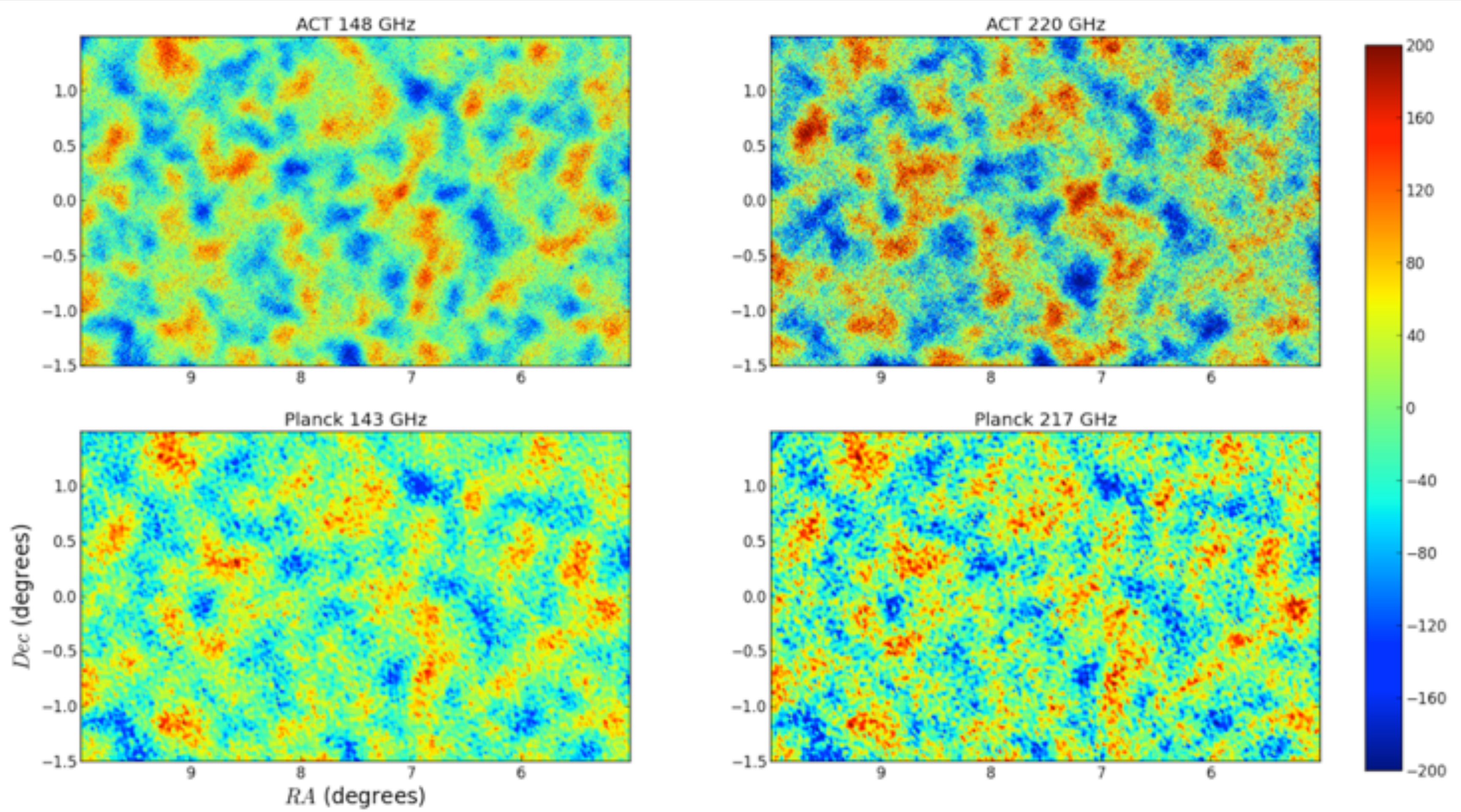


NB: with a relatively restricted number of modes, parameter degeneracies may be large.
n_s may then increase to reduce the low-ell power; but this also reduces the height of the first peak, which can be compensated by decreasing $O_c h^2$, requiring a larger H_0 to keep the position of the peak!

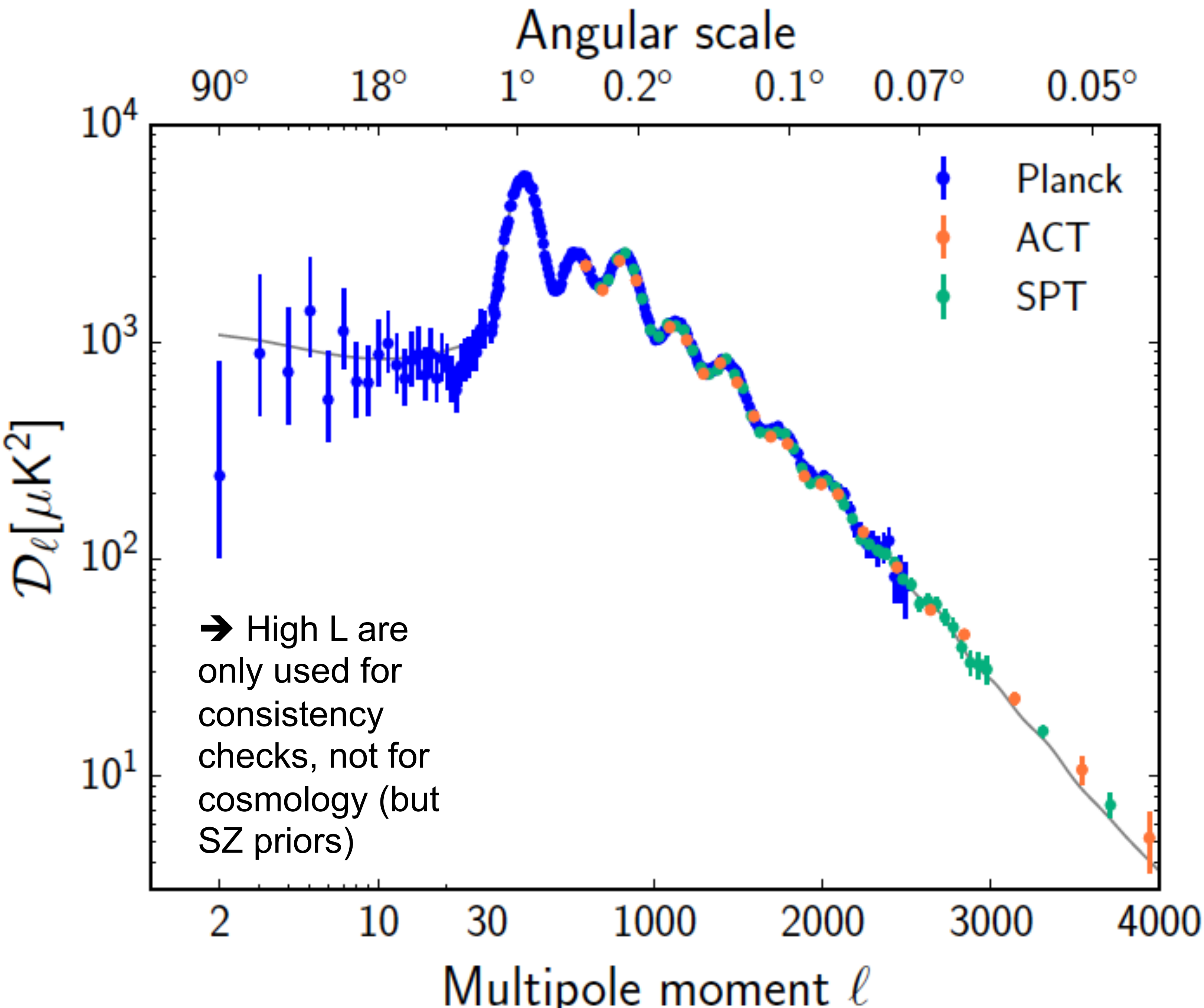
(we cut here both the TT and Pol data at low-l. We use a prior on tau to break degeneracies)

Planck & high-resolution experiments

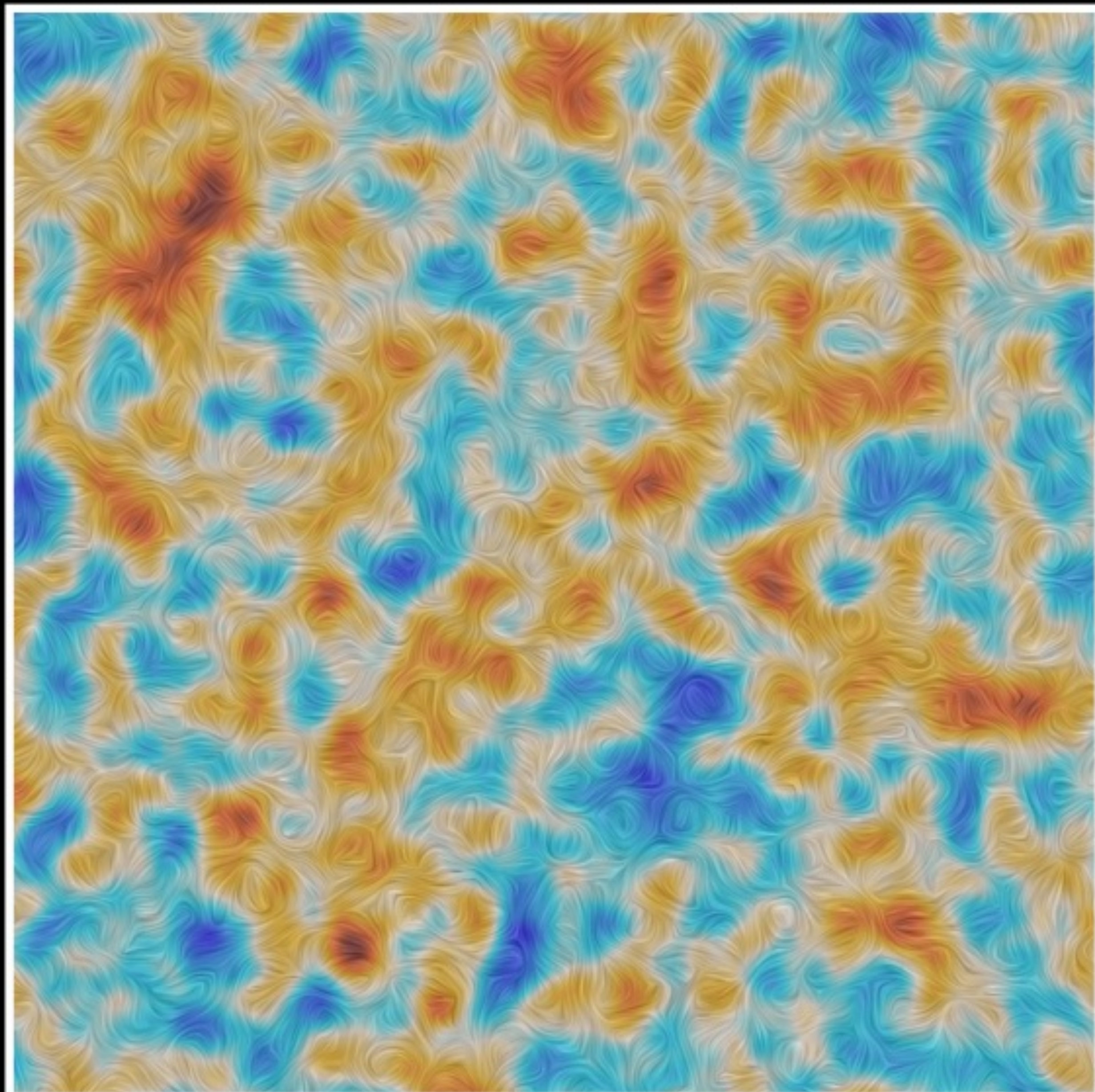
also see the same sky

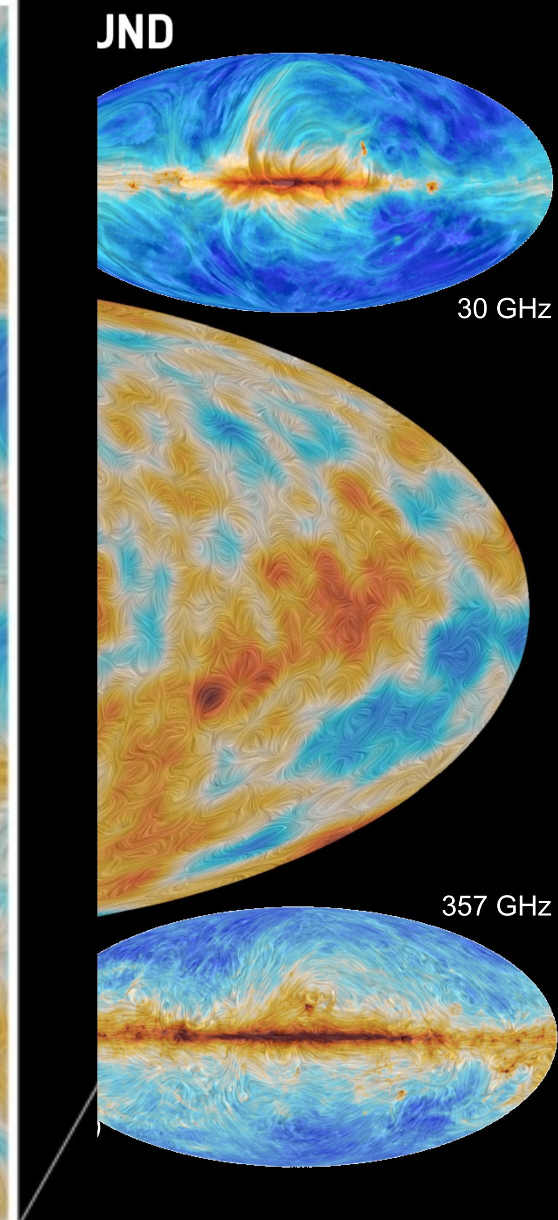


In the bands accessible from the ground. NB: Planck 2013 data



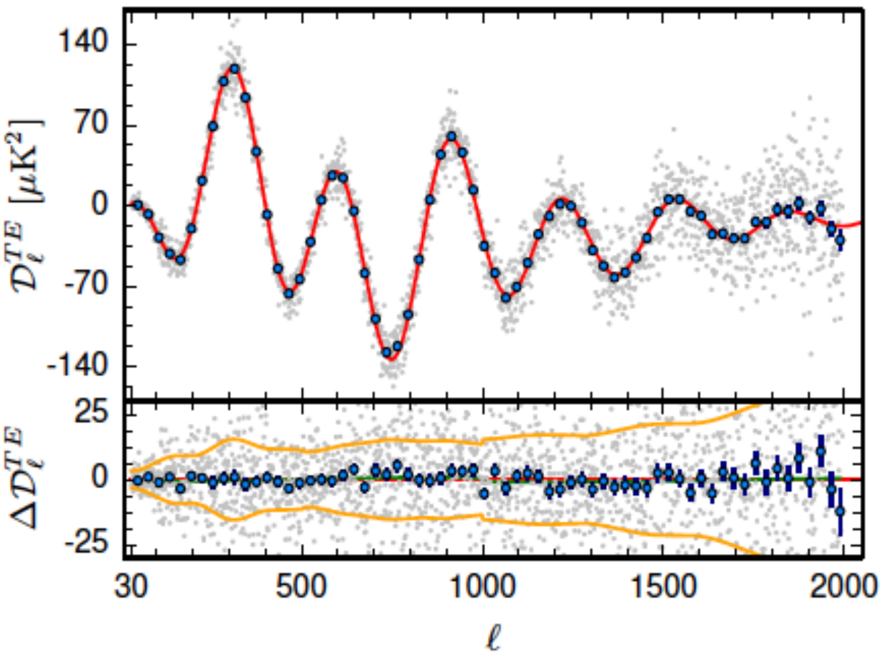
➔ High L are only used for consistency checks, not for cosmology (but SZ priors)

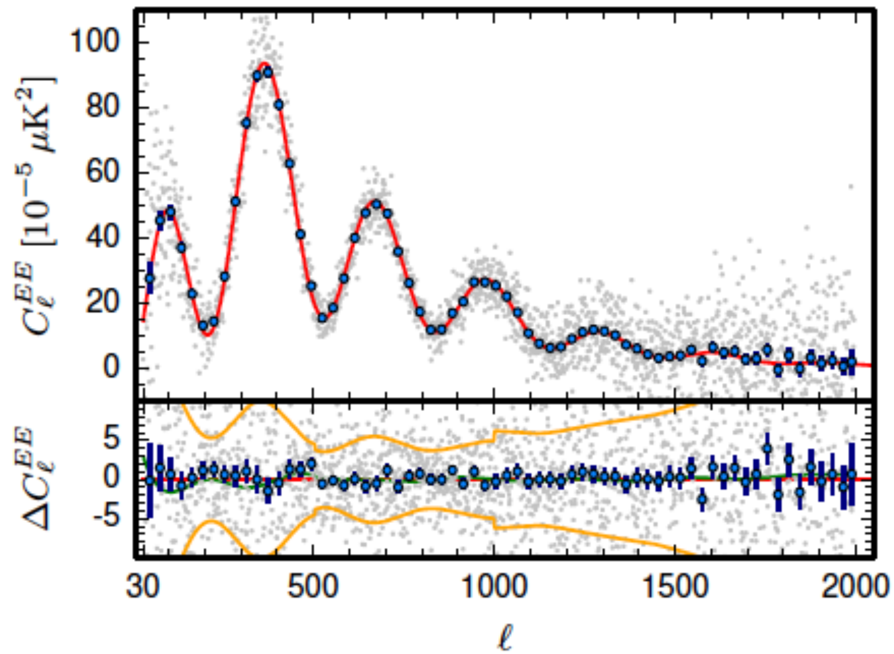




Filtered at 20 arcminutes

Planck 2015 - TE & EE spectra



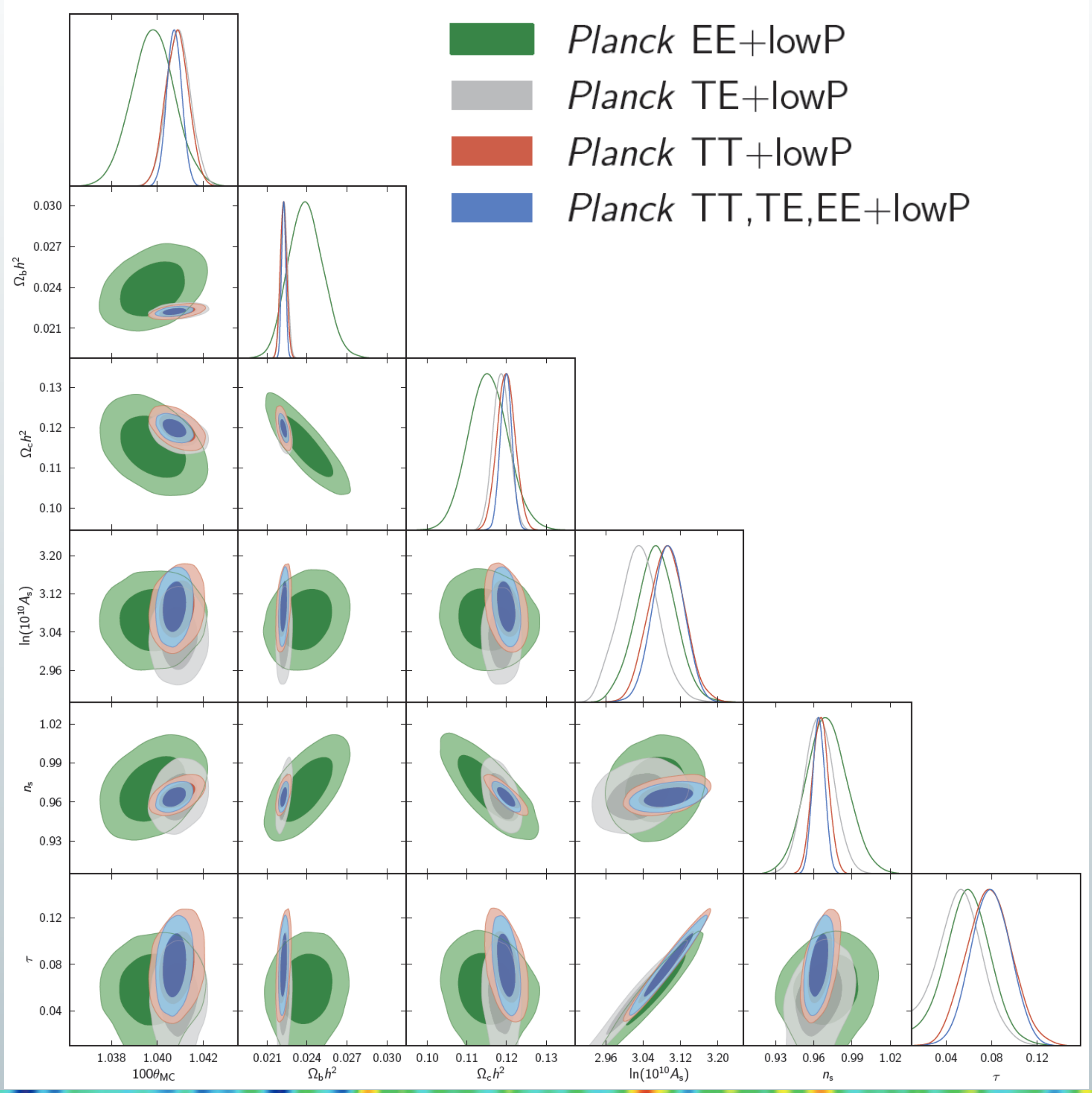


Frequency averaged spectrum reduced ^{2} = 1.04

Frequency averaged spectrum reduced ^{2} = 1.01

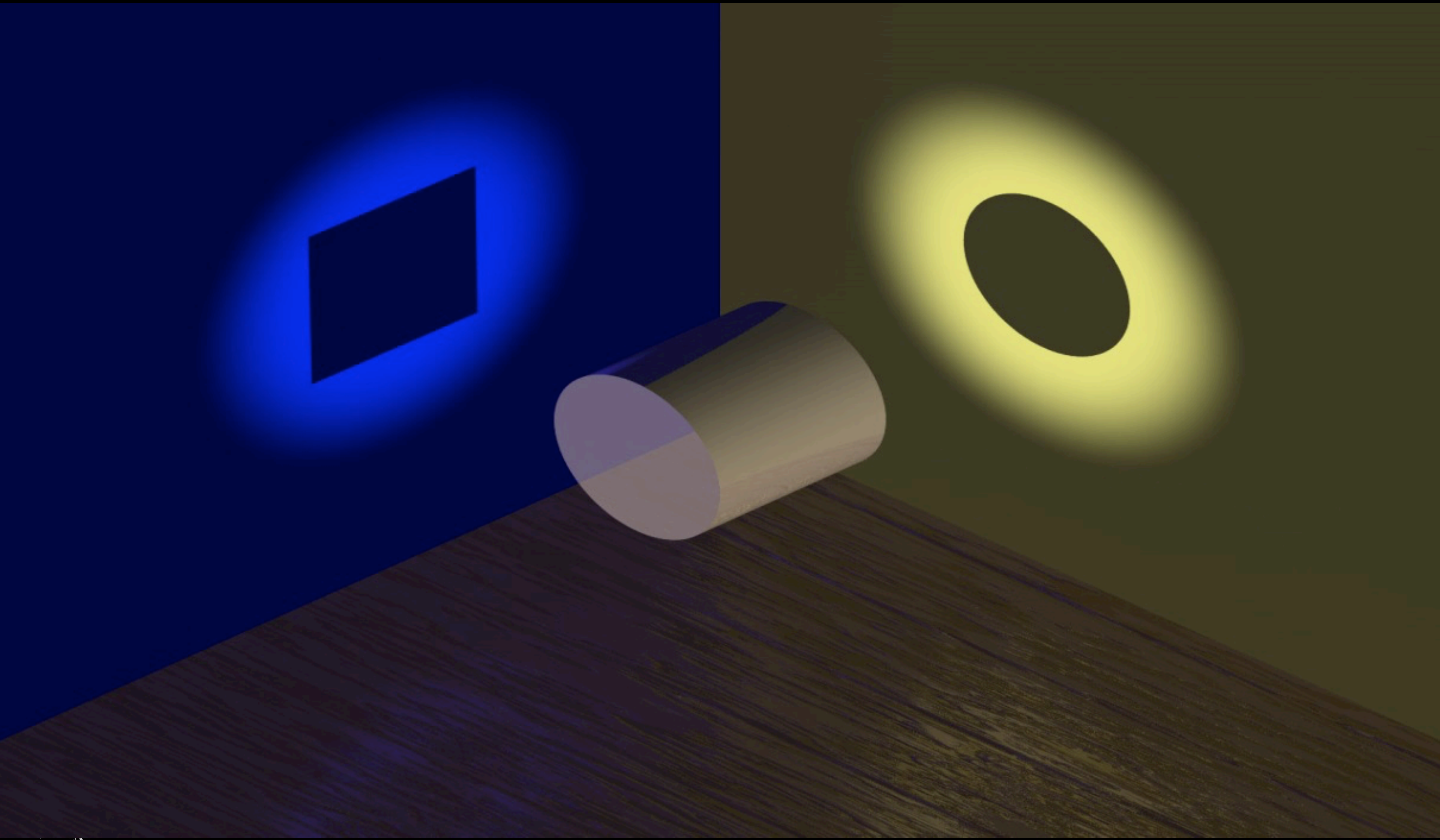
- Red curve is the prediction based on the best fit TT in base ΛCDM
- Albeit quite precise already, 2015 polarisation data and results are not final yet because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

T & E – LCDM parameters



Parameters from polarisation spectra are ***highly consistent*** *with those from TT spectra.*

This was not granted…

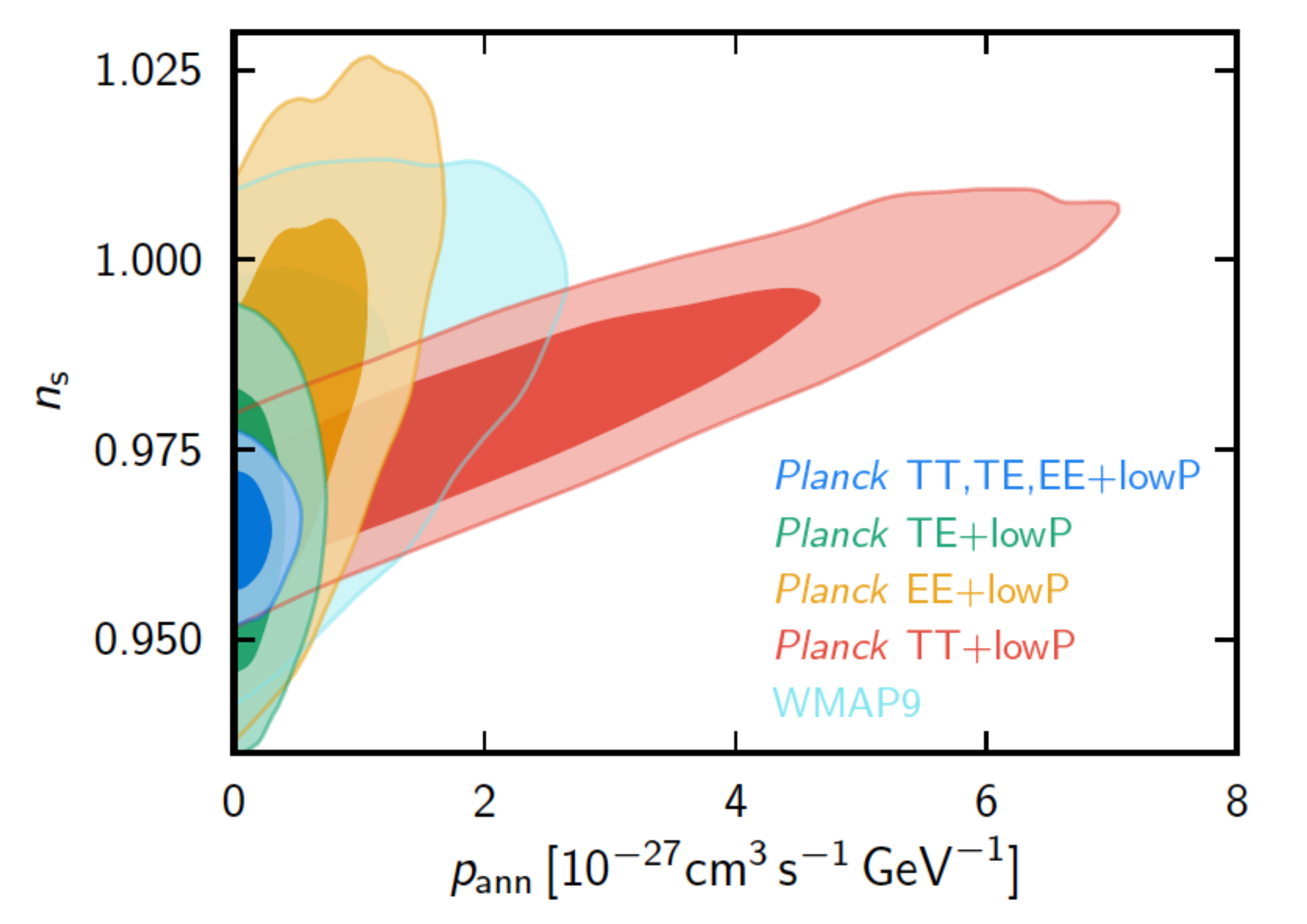


And it further constrains deviations from the base tilted LCDM model

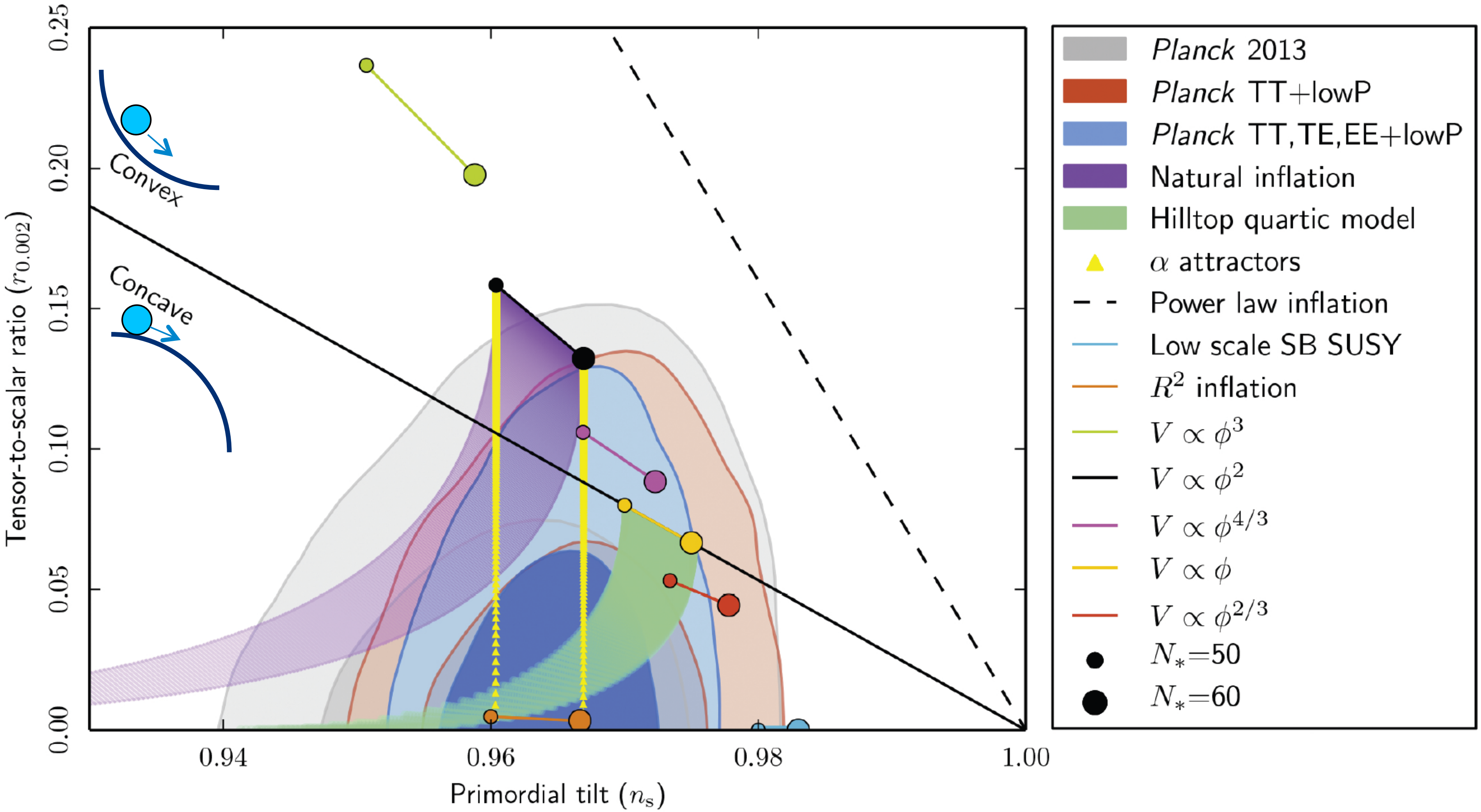
Dark matter annihilation?

Planck TTTEEE breaks degeneracies and already **sets a limit 5 times stronger than WMAP9+SPT**

$$p_{ann} = f_{eff} \frac{<\sigma v>}{m_\chi}$$

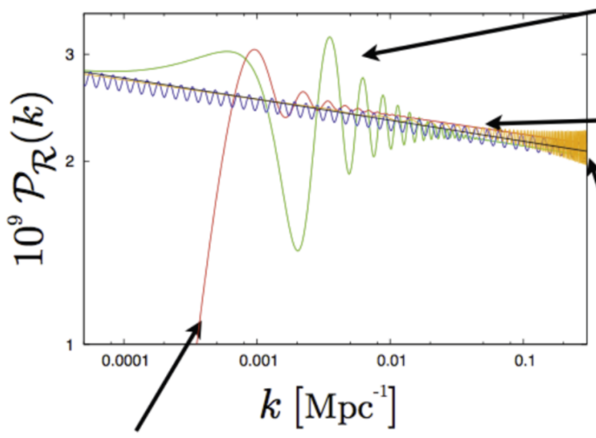


Planck 2015: n_s vs r



Similar (indirect) r constraint than with 2013 release ($r_{0.002} < 0.10$ @ 95% CL vs 0.11)

(Unsuccessful) Search for features



Feature in the potential:

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Non vacuum initial conditions/instanton effects in axion monodromy

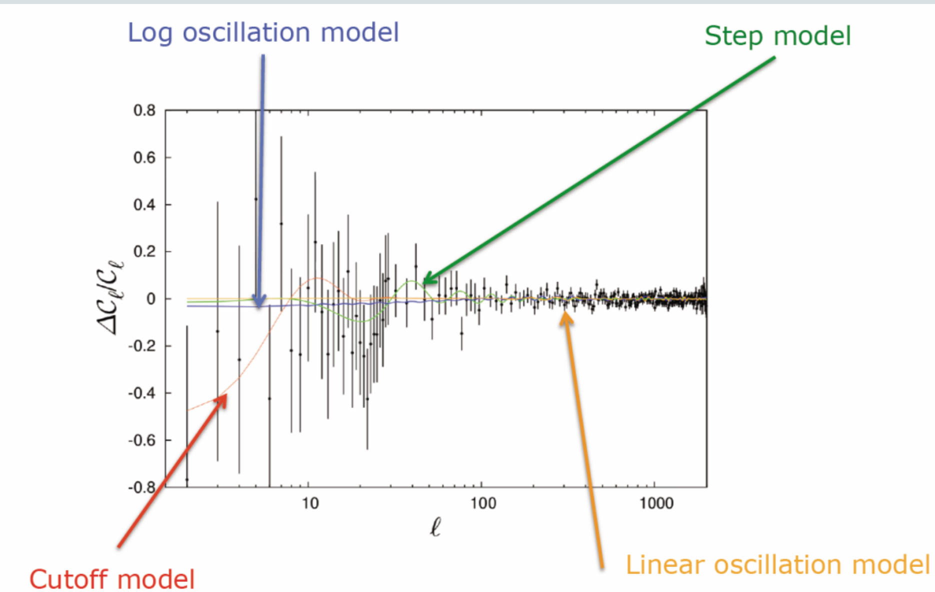
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

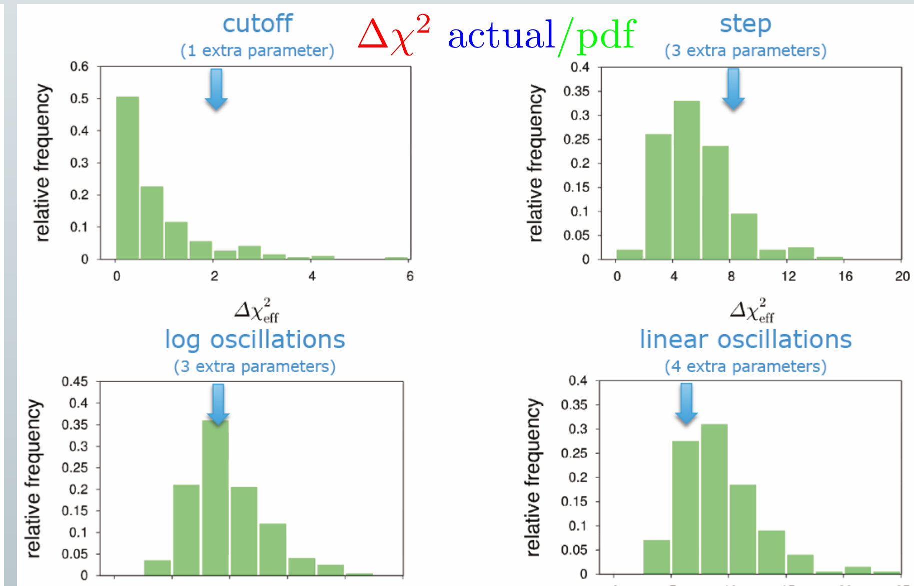
$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^{0}(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

$$\mathcal{P}_\mathcal{R}^{\mathrm{lin}}(k) = \mathcal{P}_\mathcal{R}^{0}(k)\left[1 + \mathcal{A}_{\mathrm{lin}}\left(\frac{k}{k_*}\right)^{n_{\mathrm{lin}}}\cos\left(\omega_{\mathrm{lin}}\frac{k}{k_*} + \varphi_{\mathrm{lin}}\right)\right]$$

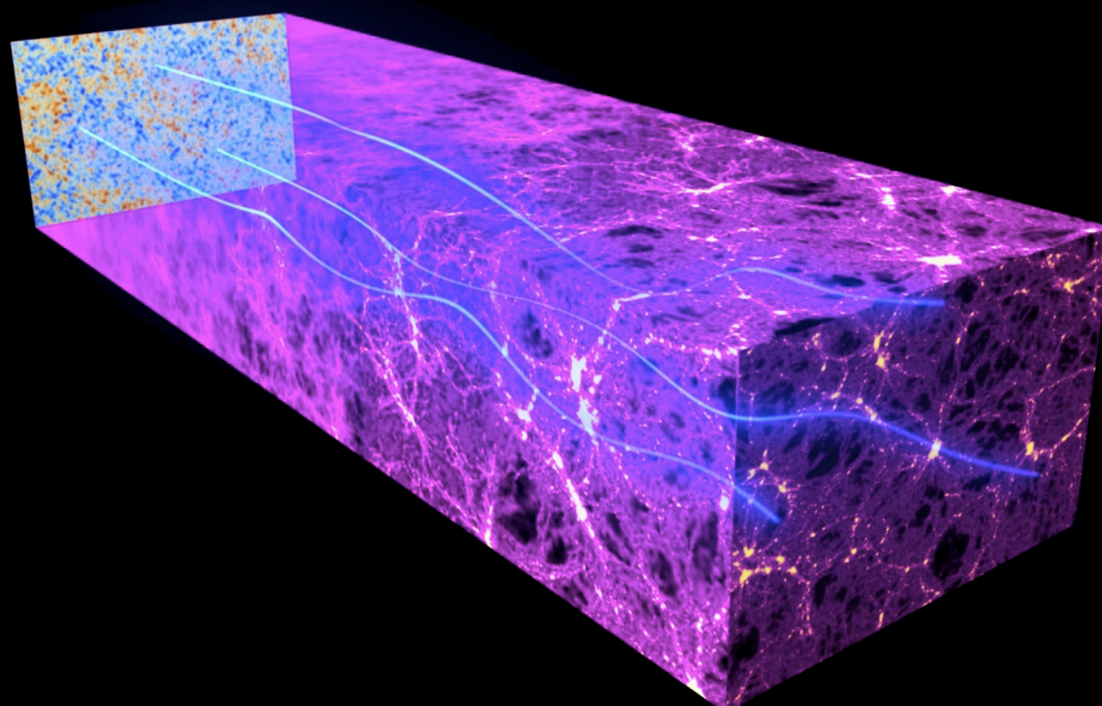
Just enough e-folds, i.e. inflation preceded by a kinetic stage





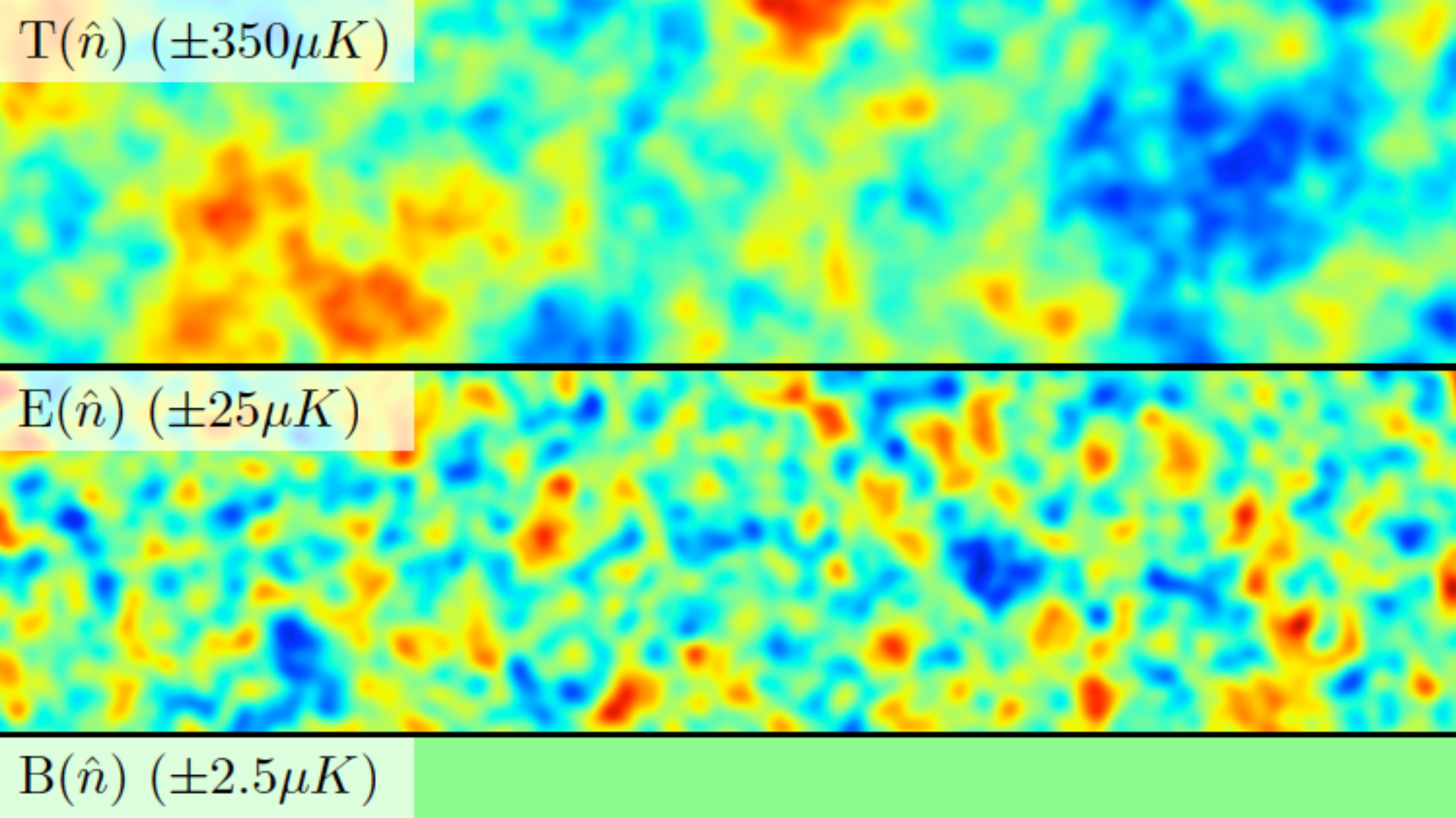
GRAVITATIONAL LENSING DISTORTS IMAGES

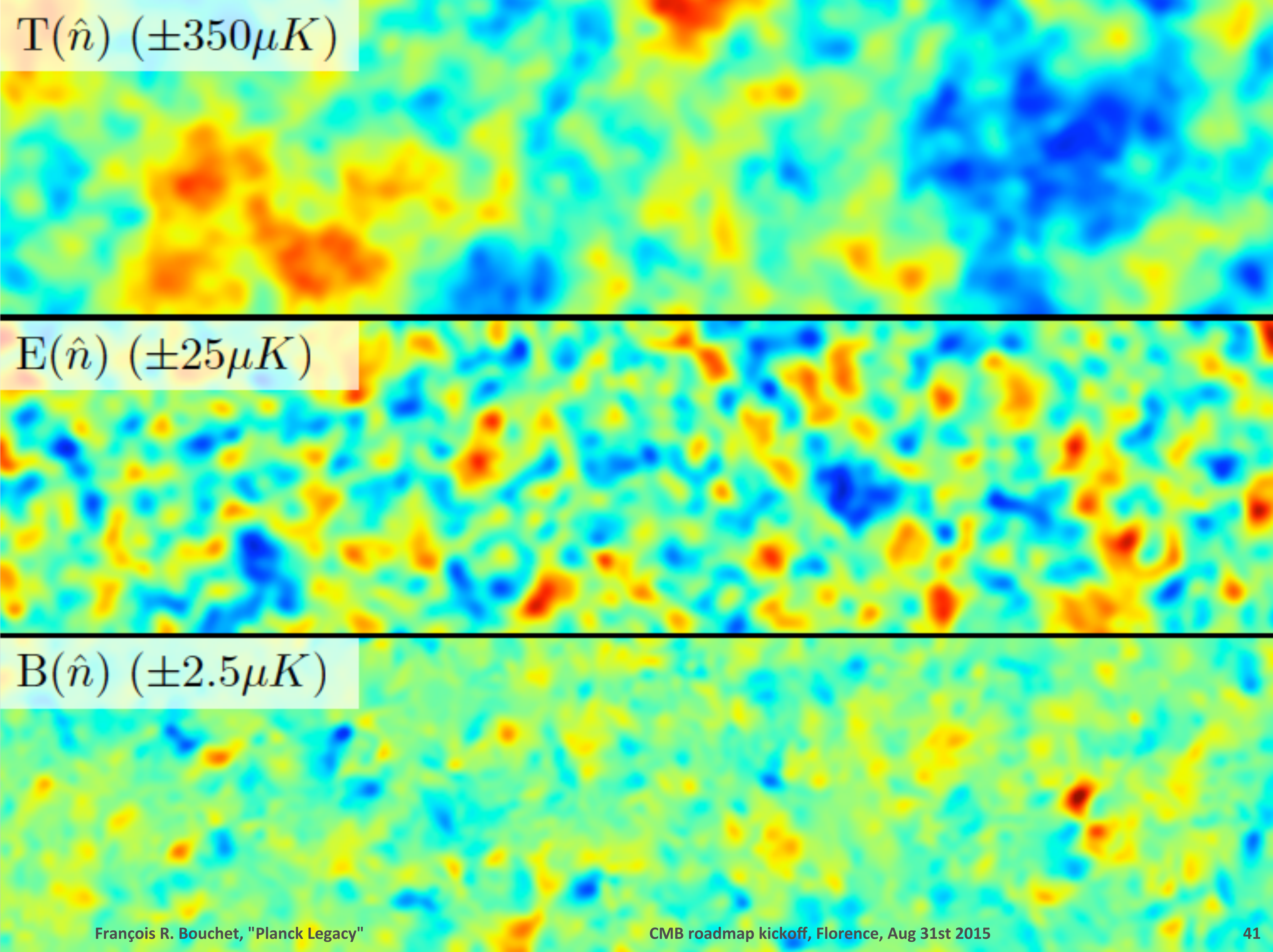
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



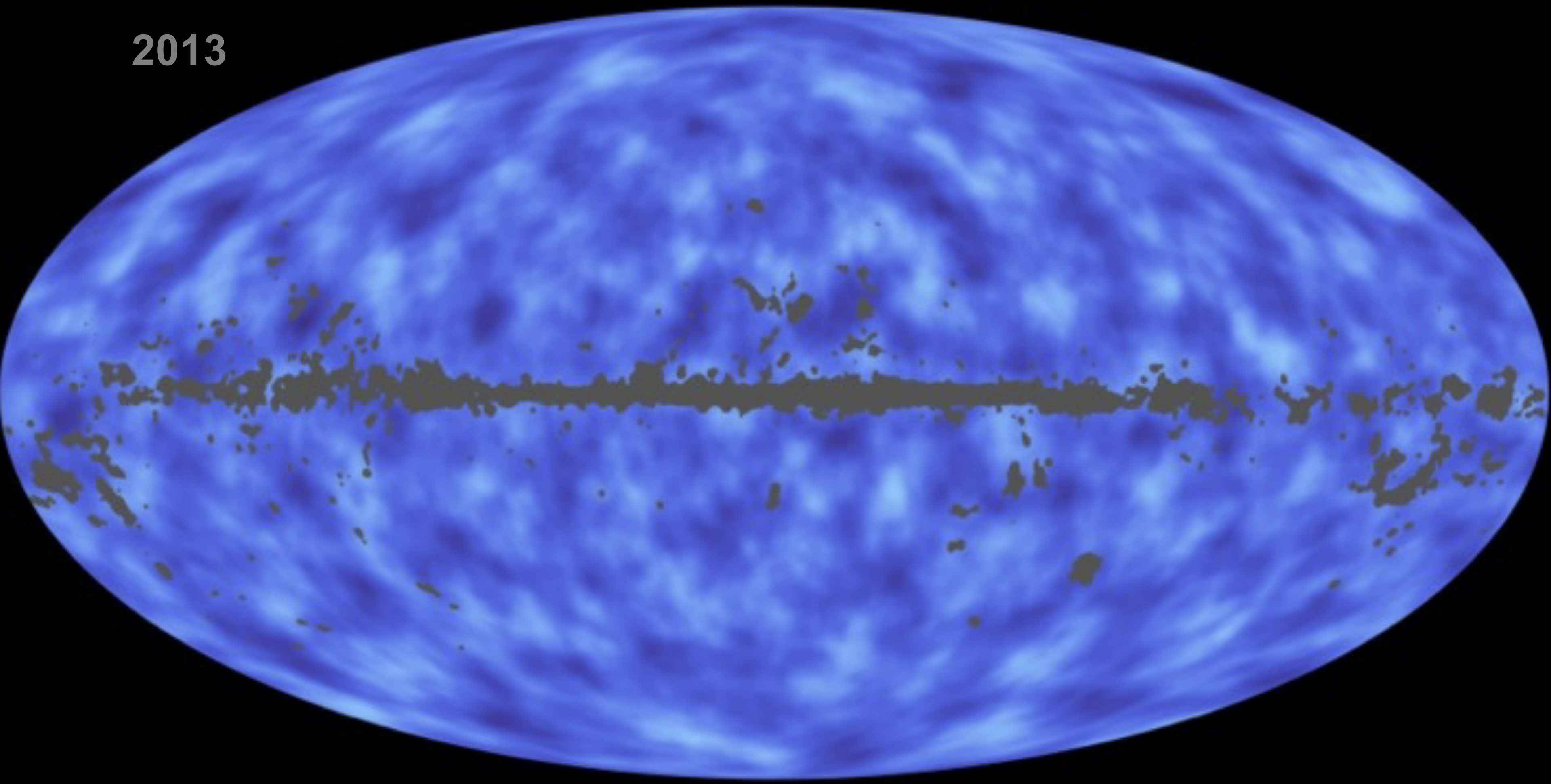
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$

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


$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$

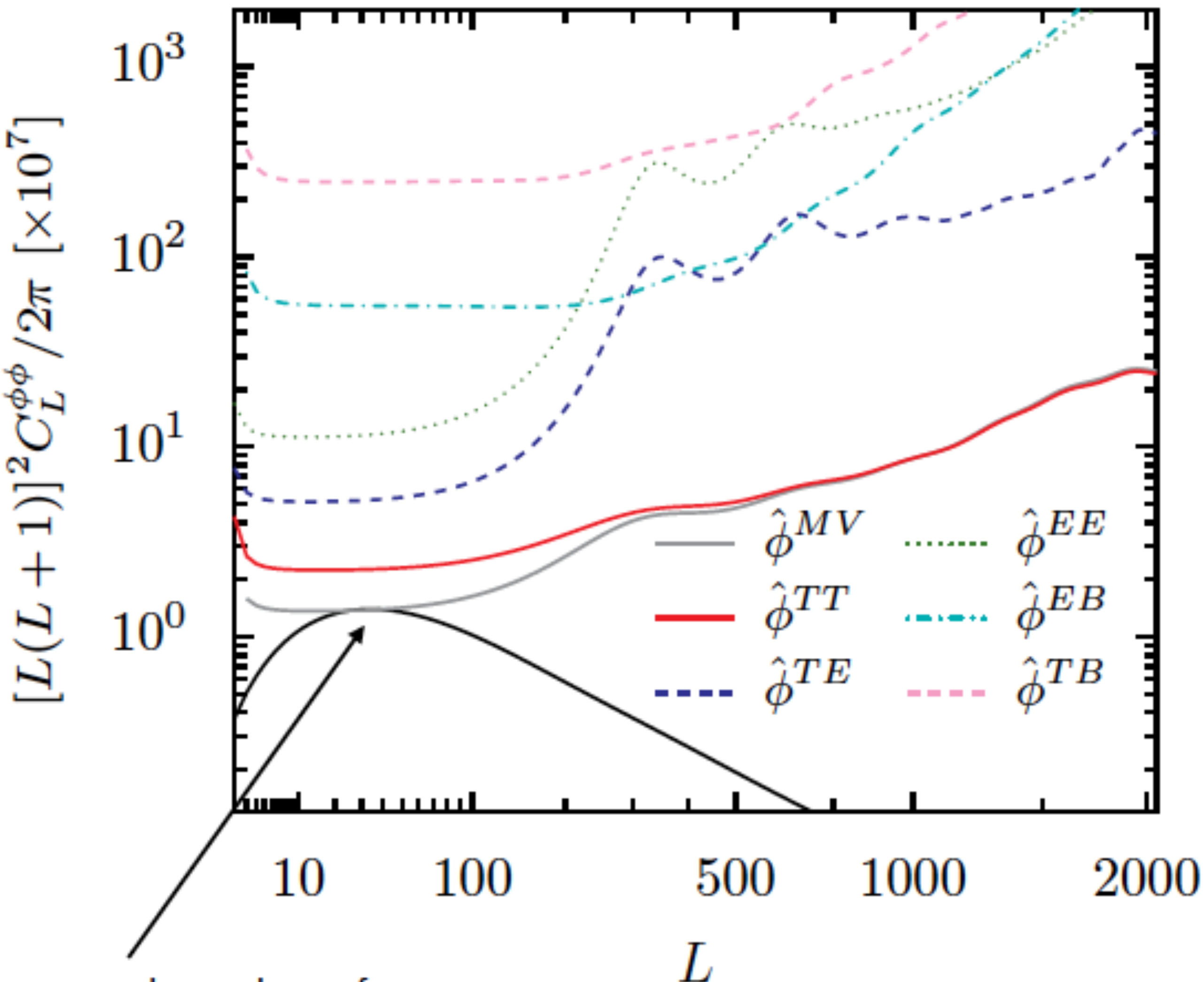

$T(\hat{n})$ ($\pm 350\mu K$)
$E(\hat{n})$ ($\pm 25\mu K$)
$B(\hat{n})$ ($\pm 2.5\mu K$)

Projected mass map



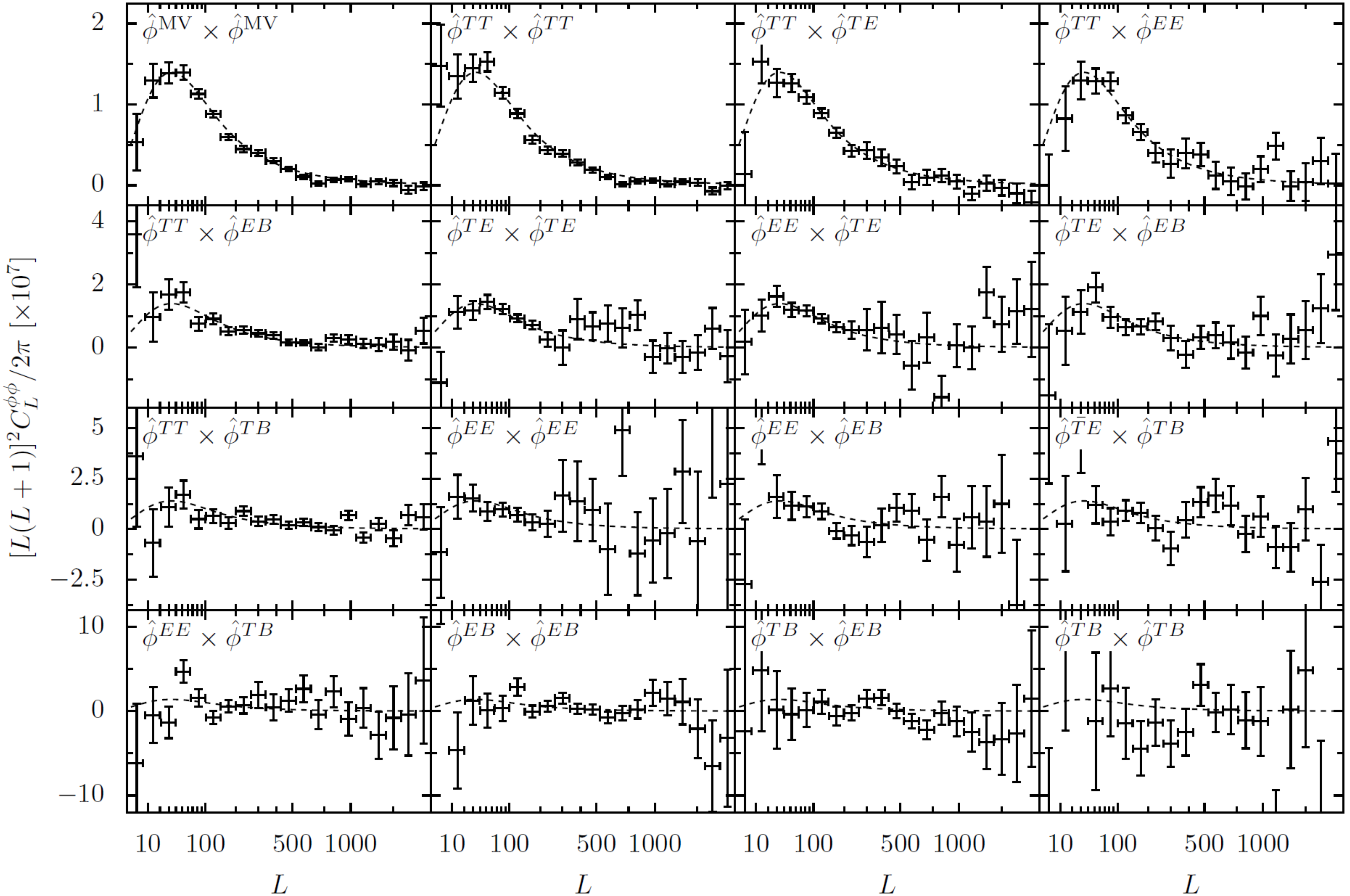
The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

Noise power spectra for lensing estimators

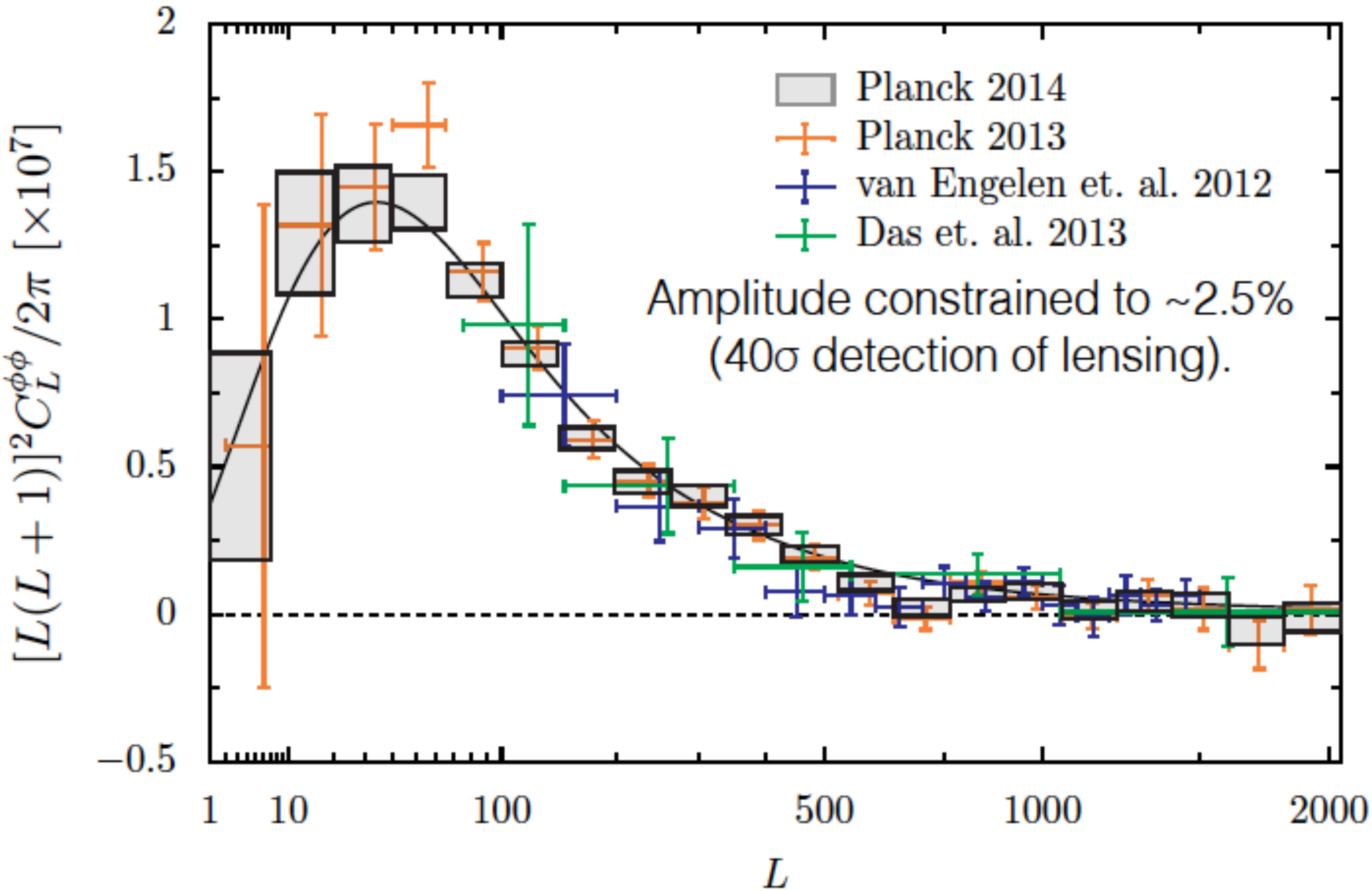


Best measured modes of
MV estimator have S/N=1.

Individual lensing cross-spectra



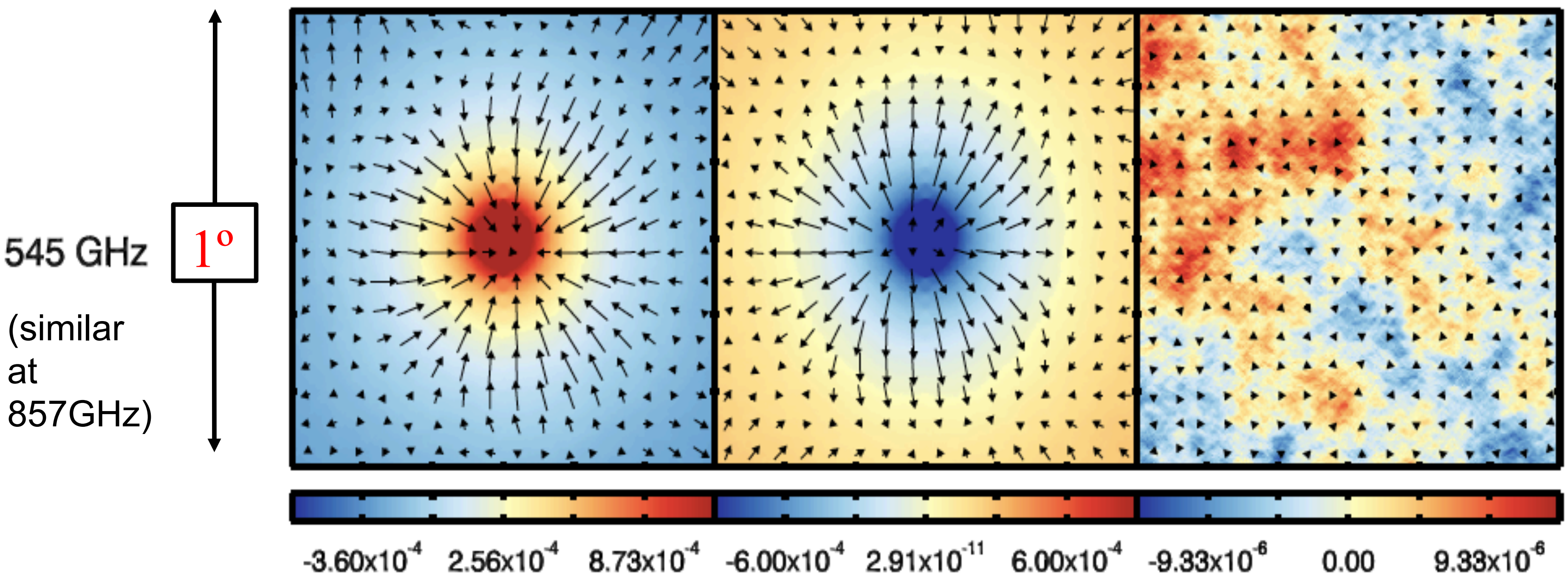
Lensing power spectrum



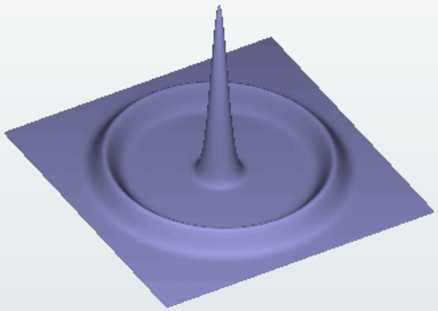
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

CIB PEAKS CORRESPOND TO MASS PEAKS

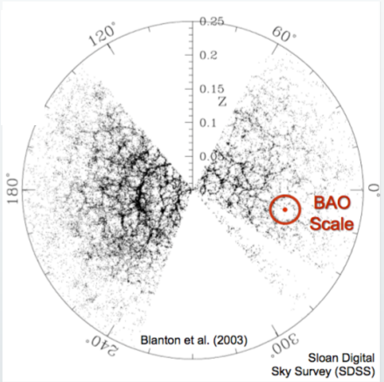
Stacking the Planck mass maps at the positions of peaks and troughs of Cosmic Infrared Background leads to a strong detection of the mass associated with these distant star forming galaxies.

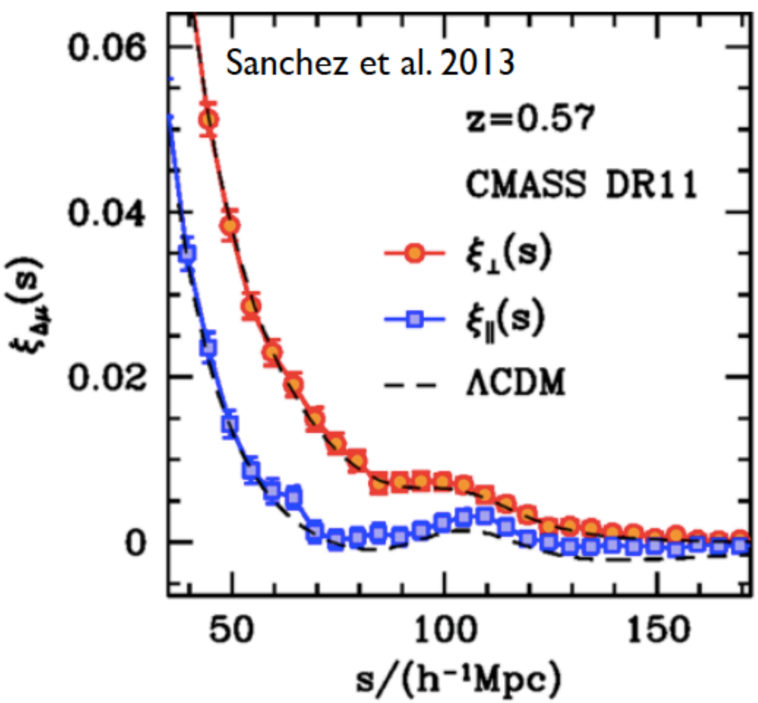


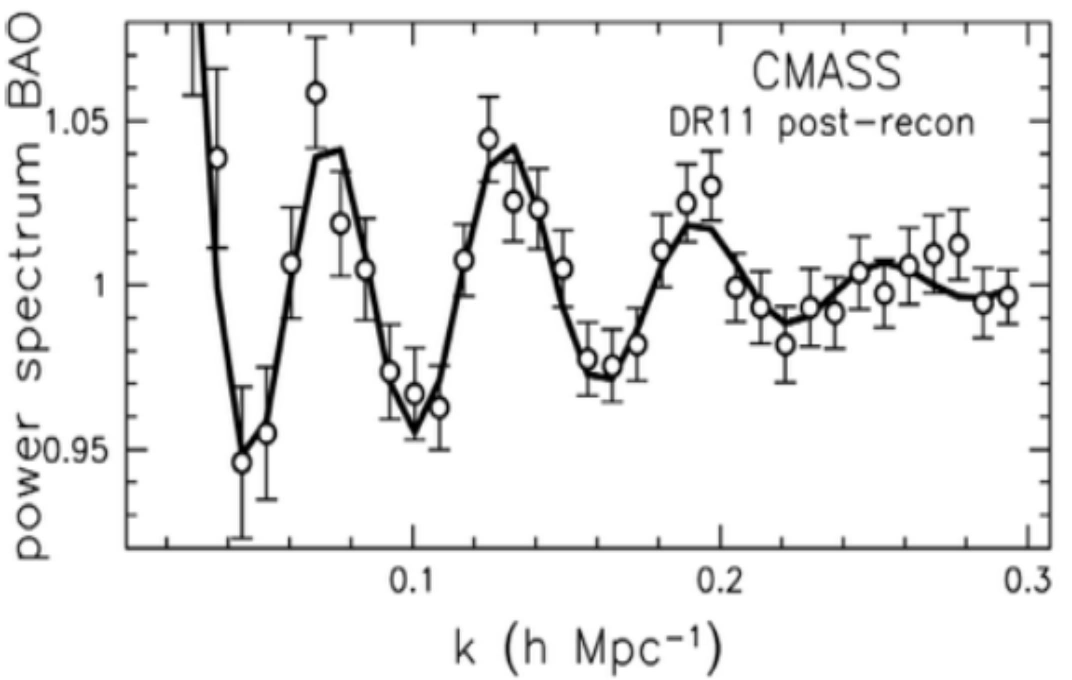
[Planck Collaboration XVIII 2013]



The spherical sound wave from an initial overpressure stalls after decoupling at a distance estimated by Planck of 147.5 ± 0.6 Mpc

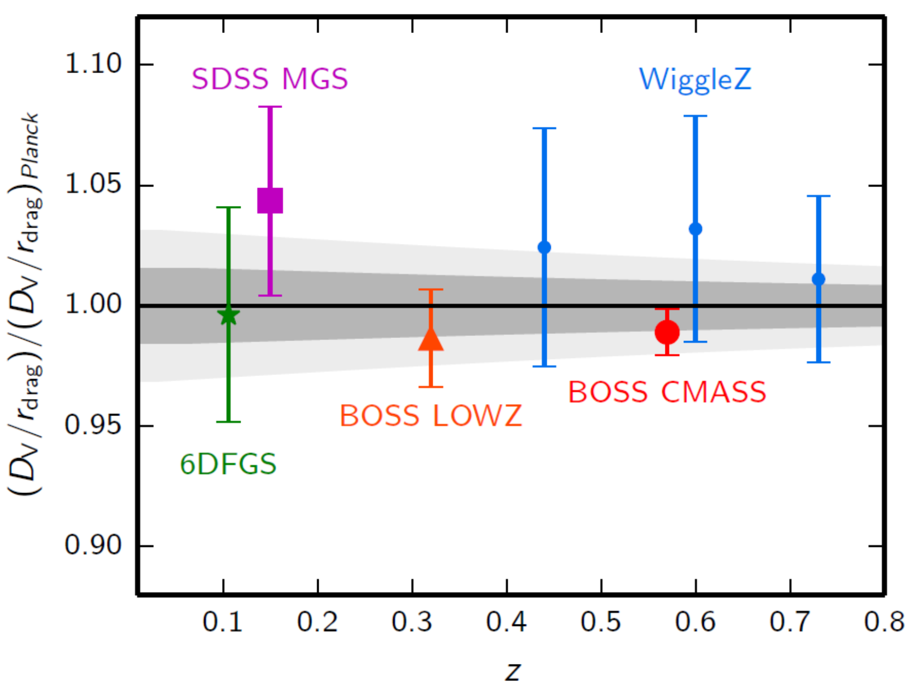


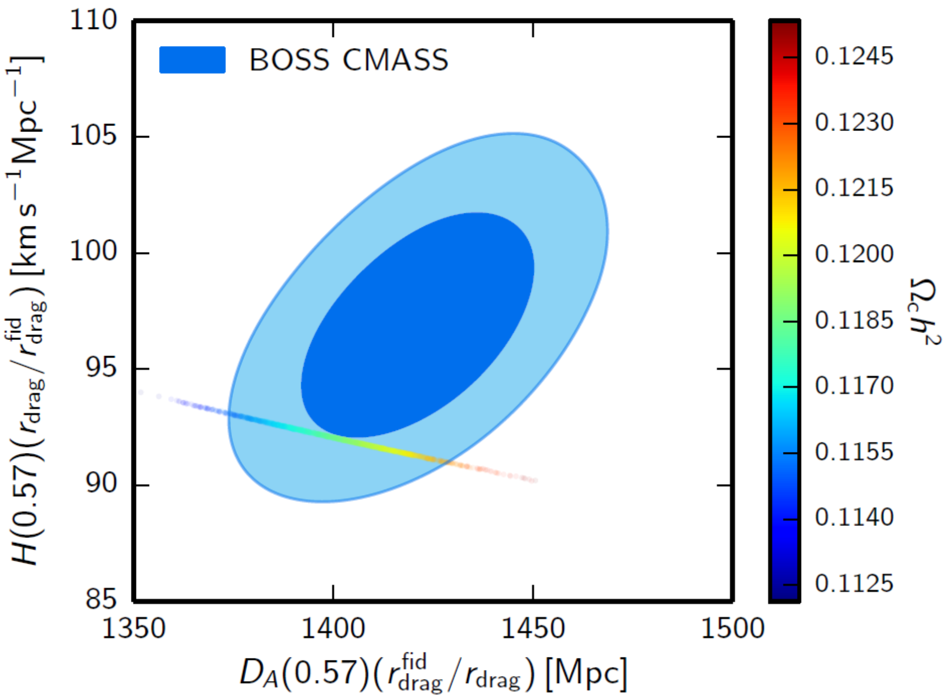




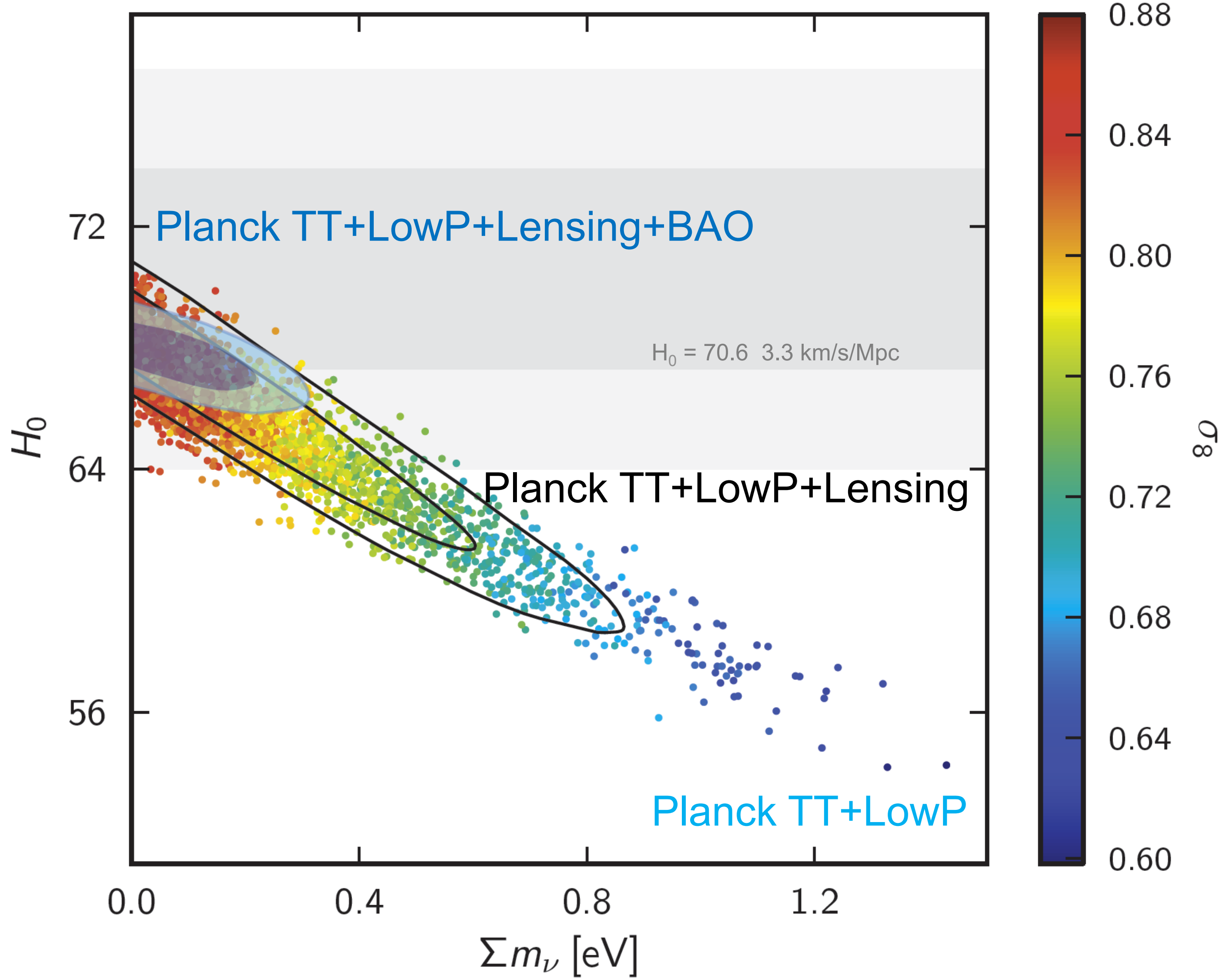
BAO

Grey band is Planck TT+LowP 1(2) sigma range





Neutrino masses $\sum m_\nu < 0.23\,\mathrm{eV}$ (95%CL)



assuming three species of degenerate massive neutrinos

0.23 eV comes from TT+lowP +lensing +ext (BAO +JLA +H_0)

$\Omega_\nu h^2 < 0.0025$

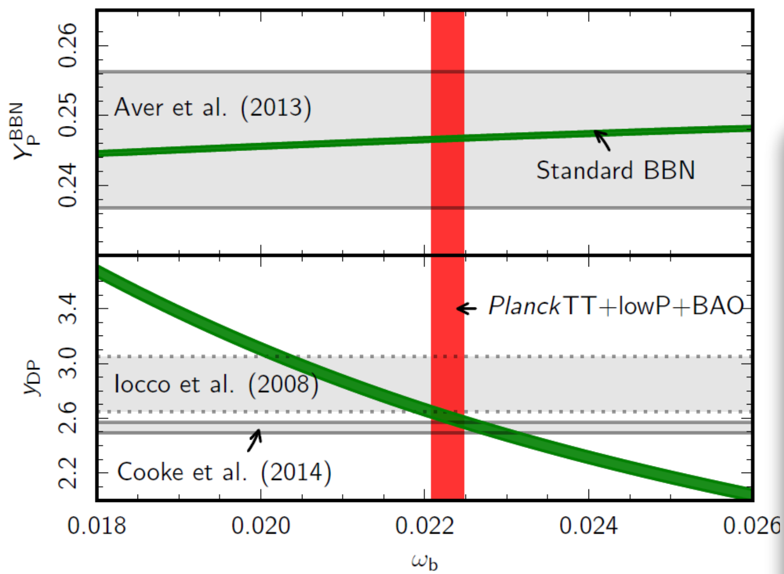
With slight tightening with TE & EE

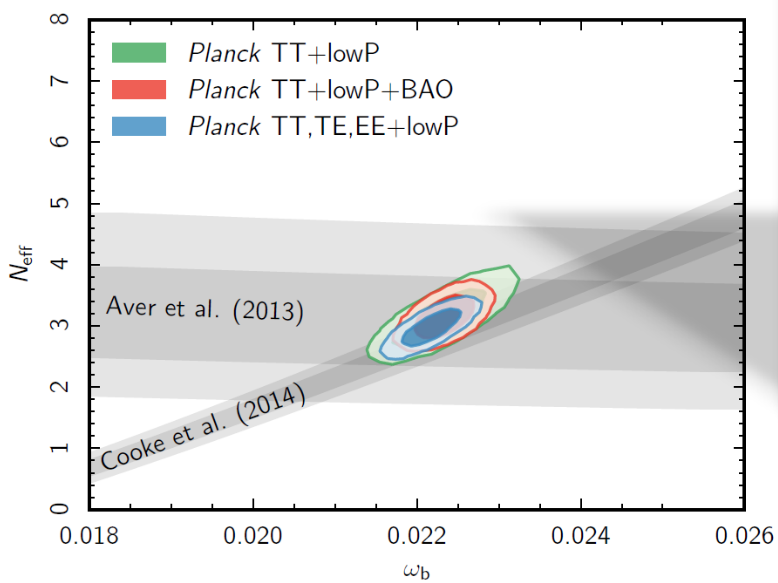
Neutrino masses constraints

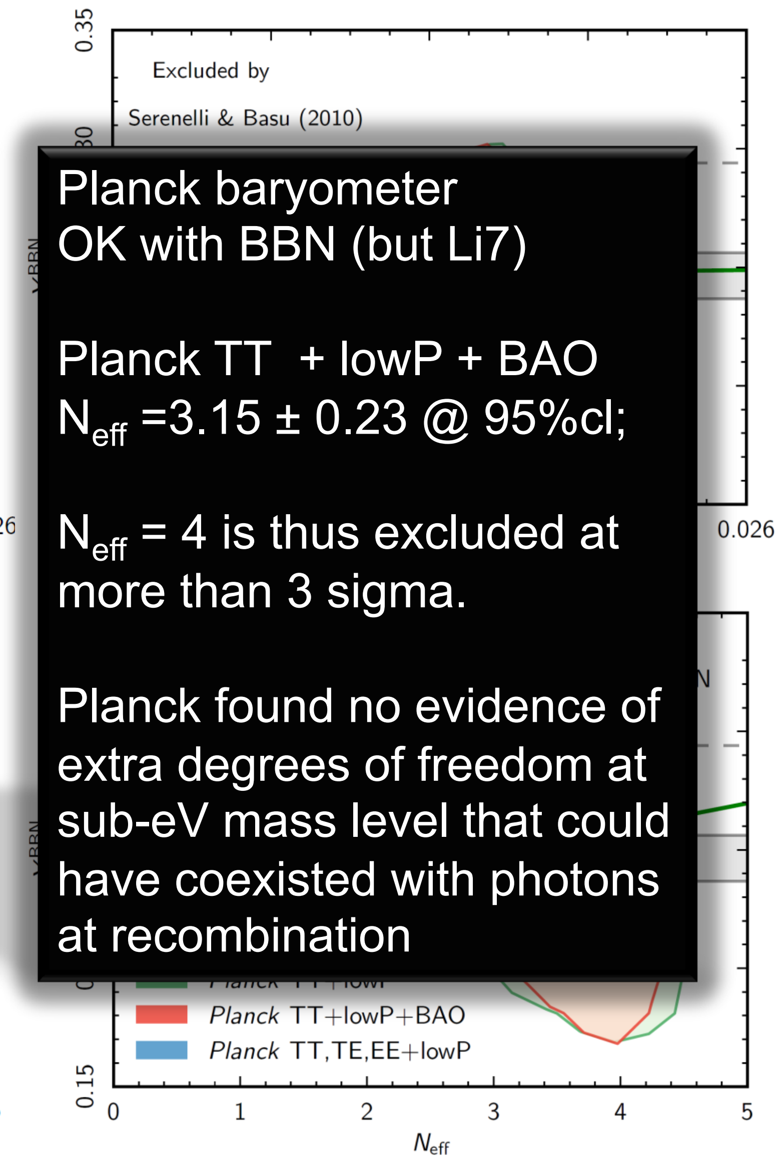
Σm_ν (95% CL) [eV]	**2013**	**2015**	**2015 +TE,EE**
PlanckTT+lowP	<0.93	<0.72 (23%)	<0.49 (48%)
PlanckTT+lowP +lensing	<1.1	<0.70 (36%)	<0.58 (47%)
PlanckTT+lowP +lensing+ Ext		**<0.23**	<0.19

For 2013, lowP is WMAP polarization
Assumption: 3 degenerate massive neutrinos

BBN – N_{eff}, Y_p







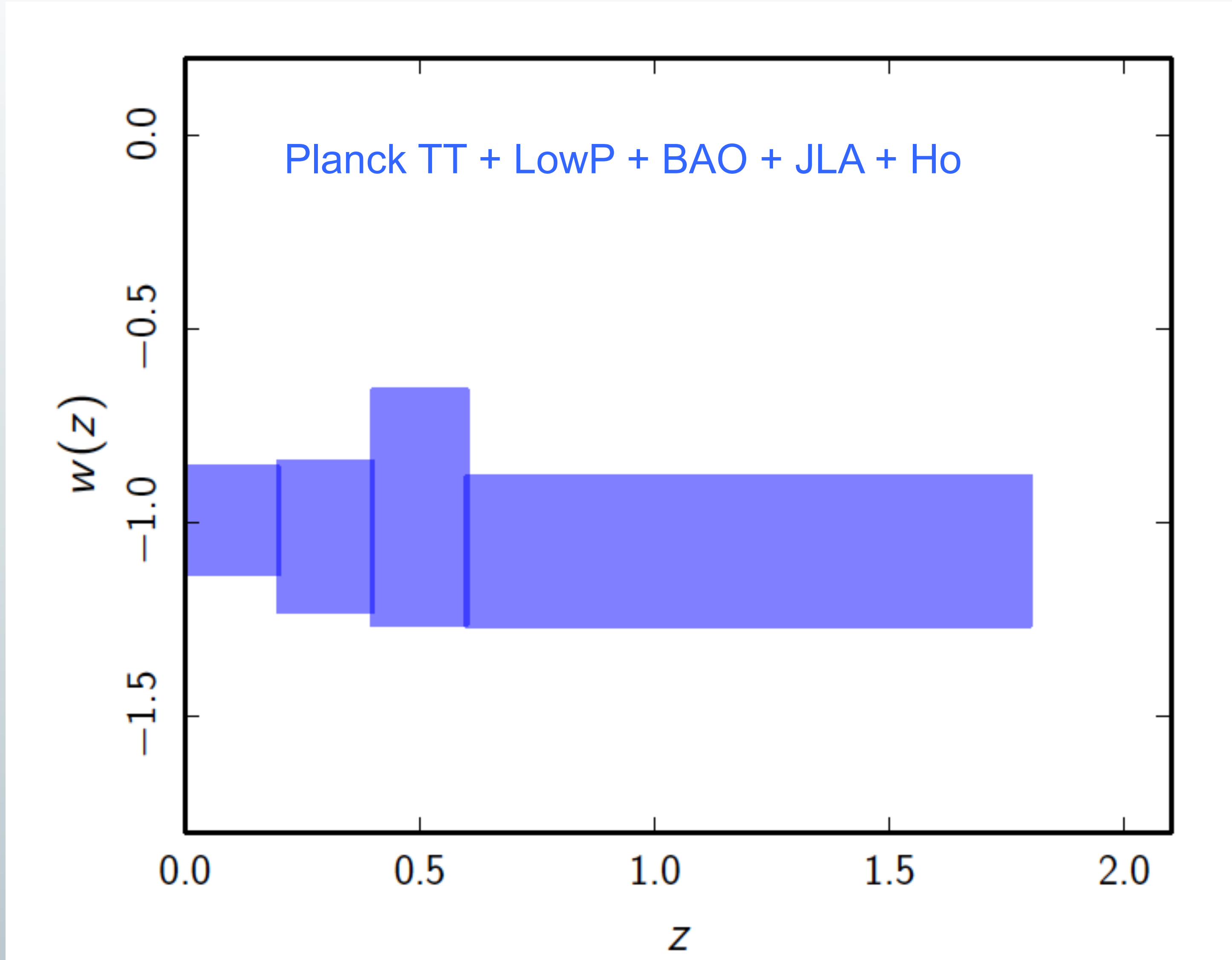
Planck baryometer
OK with BBN (but Li7)

Planck TT + lowP + BAO
N_{eff} =3.15 ± 0.23 @ 95%cl;

N_{eff} = 4 is thus excluded at more than 3 sigma.

Planck found no evidence of extra degrees of freedom at sub-eV mass level that could have coexisted with photons at recombination

PCA of w(z)

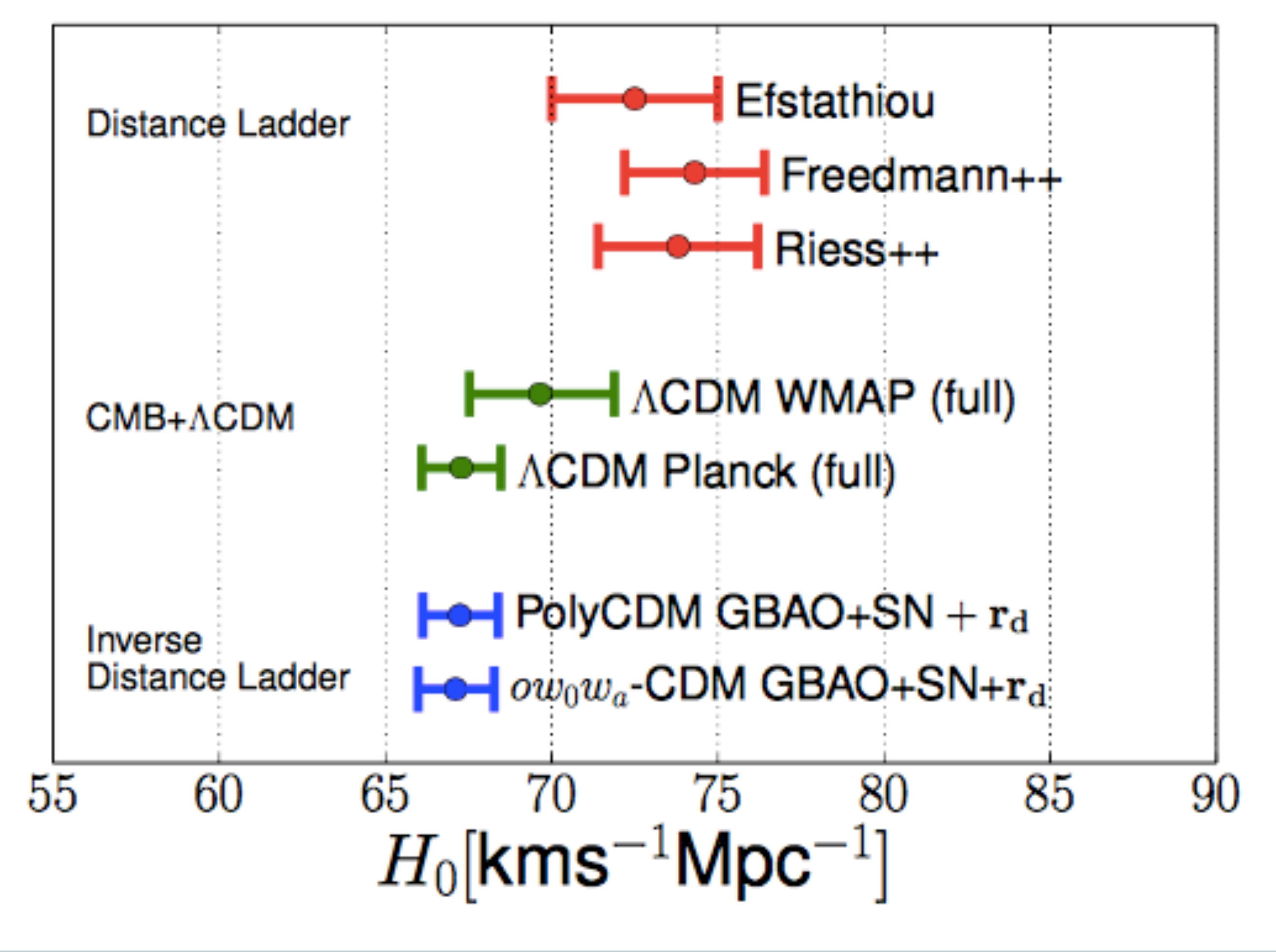


Standard cosmological model - LCDM

- Thus the CMB TT, TE, EE, Φ-Φ, as well as BBN (but Li7), BAO and SN1a measurements are all consistent, among themselves and across experiments, within LCDM.
- This network of tests is done with per cent level precision.
- The consistency allows many different checks of the robustness of this base LCDM model and some of its extensions, including τ constrained two-ways thanks to CMB lensing, flatness at 5×10^{-3} level, neutrinos masses and number, DM annihilation limits, w(z), details of the recombination history ($A_{2s\rightarrow 1}$, T_0, and also fundamental constants variation, or any energy input).

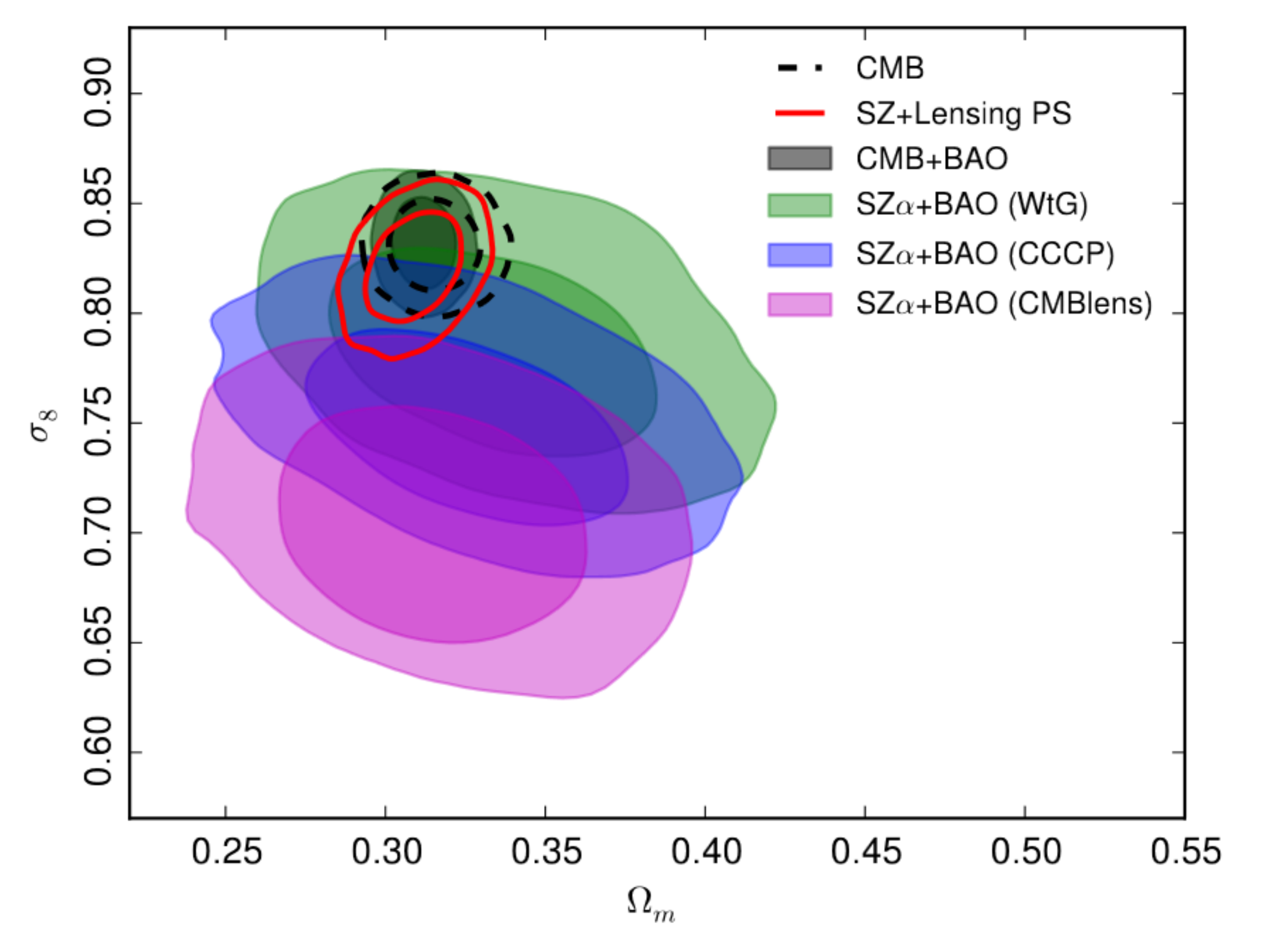
Comparison of H_0

- Inverse distance ladder is in perfect agreement with Planck CMB (this uses the absolute calibration from BAO to calibrate SN1a in the overlapping region at z=0.57 to bring it down to z=0.)
- Some discrepancy with direct distance ladder



arXiv:1411.1074v2

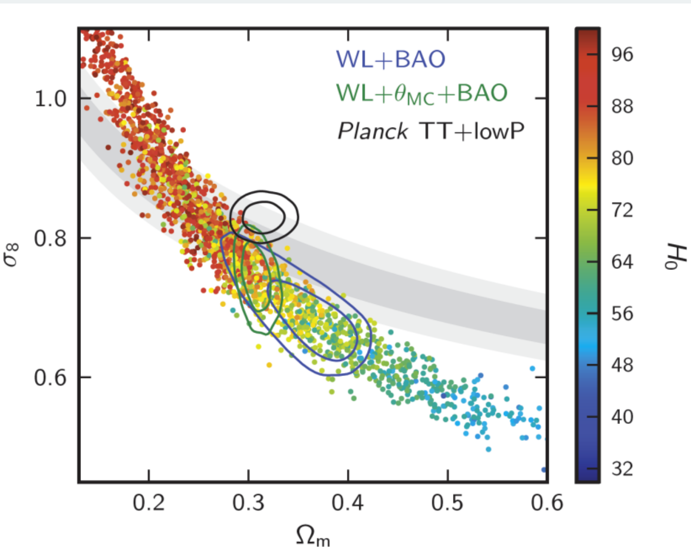
Number counts of SZ clusters



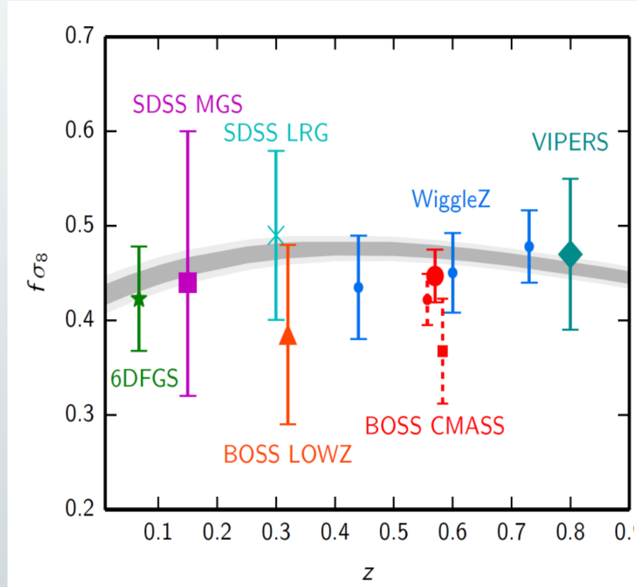
2013 tension only remains with **some** mass proxy calibration

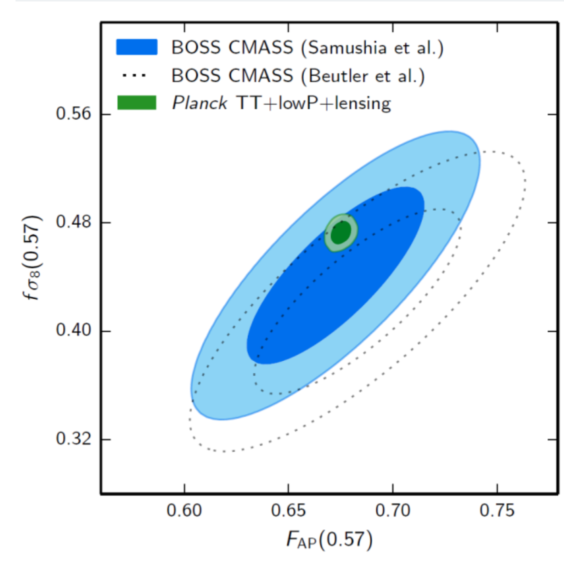
Some tensions

Weak Lensing from CFHTLens



Growth rate of fluctuations from redshift space distortions



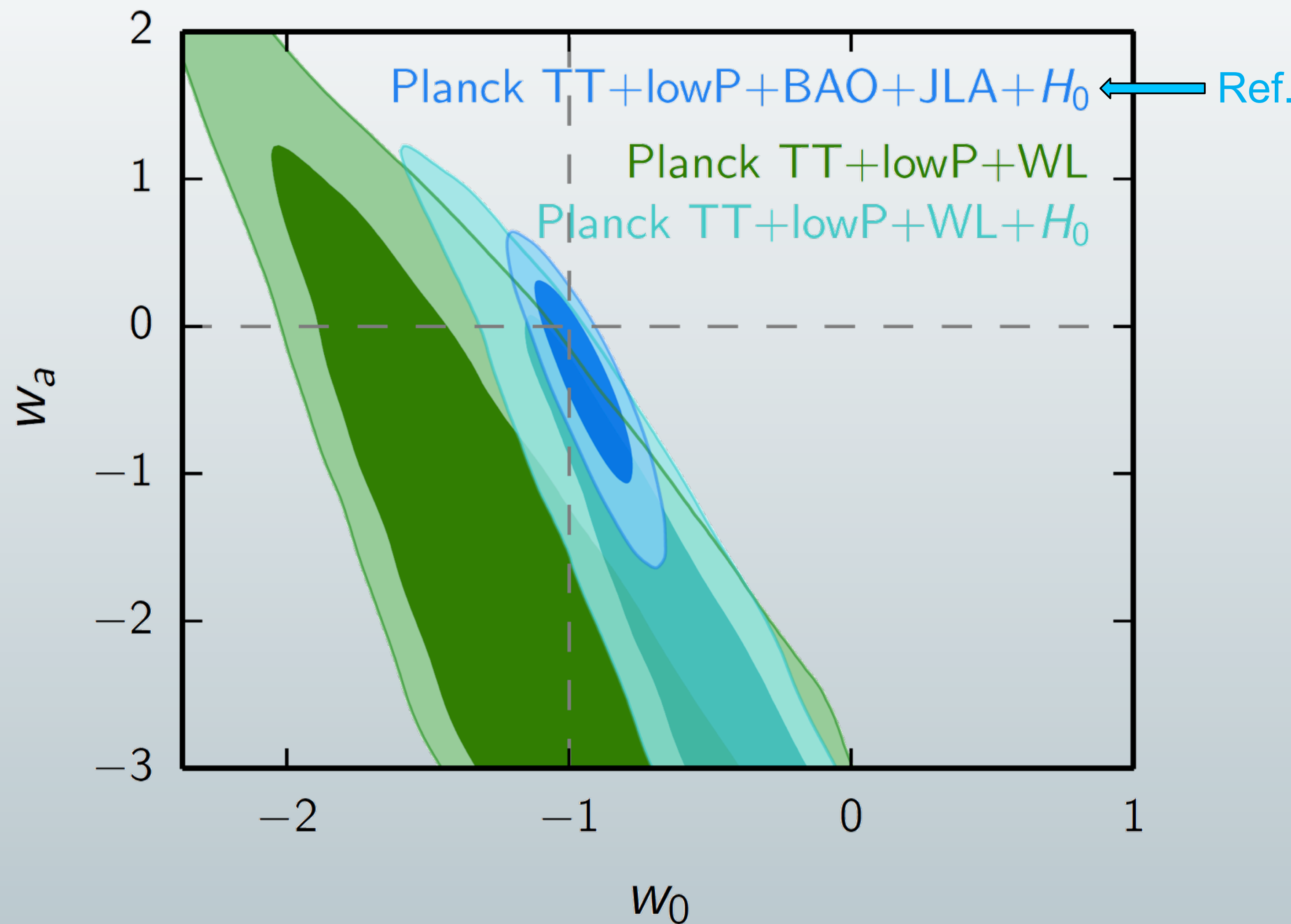


i.e. some tensions with astrophysical measurements of the amplitude of matter fluctuations at low z.

NB: Ly BAO measurements at high redshift are discrepant at 2.7sig, and it is quite difficult to find physical explanation not disrupting BAO consistency elsewhere, see eg Aubourg etal. 2015

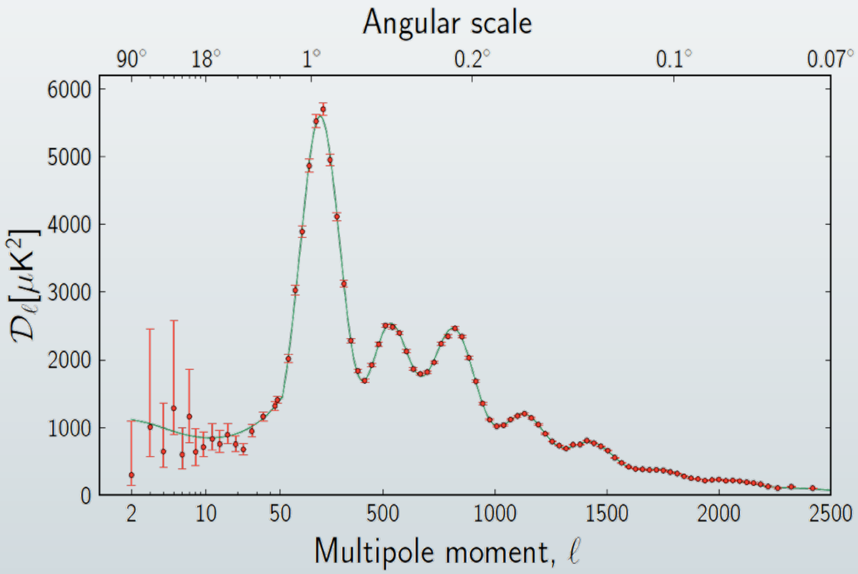
What these tensions can do…

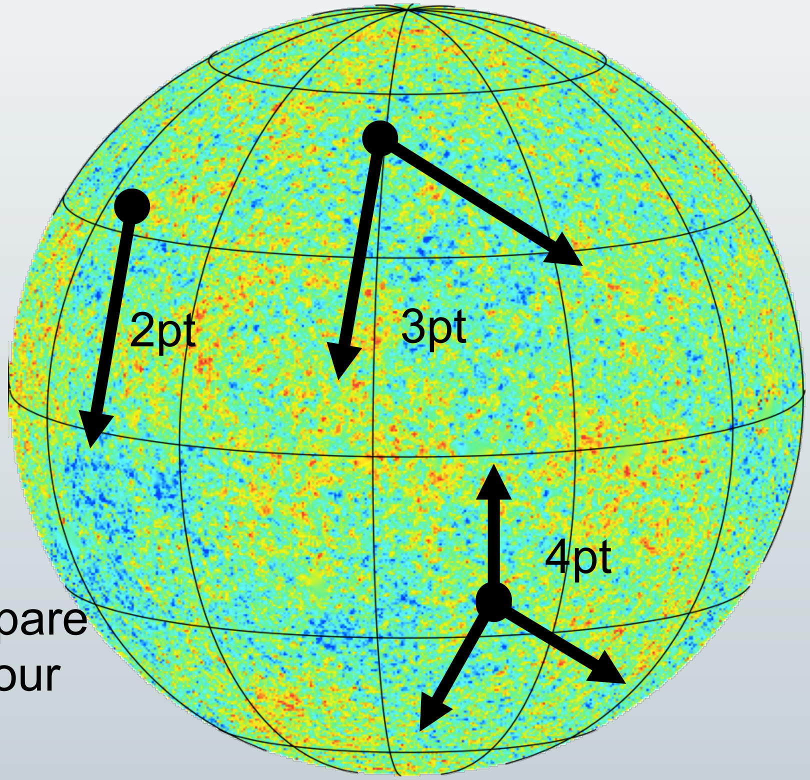
$W(a) = w_0 + (1\text{-}a)\, w_a$



Random field characterisation

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



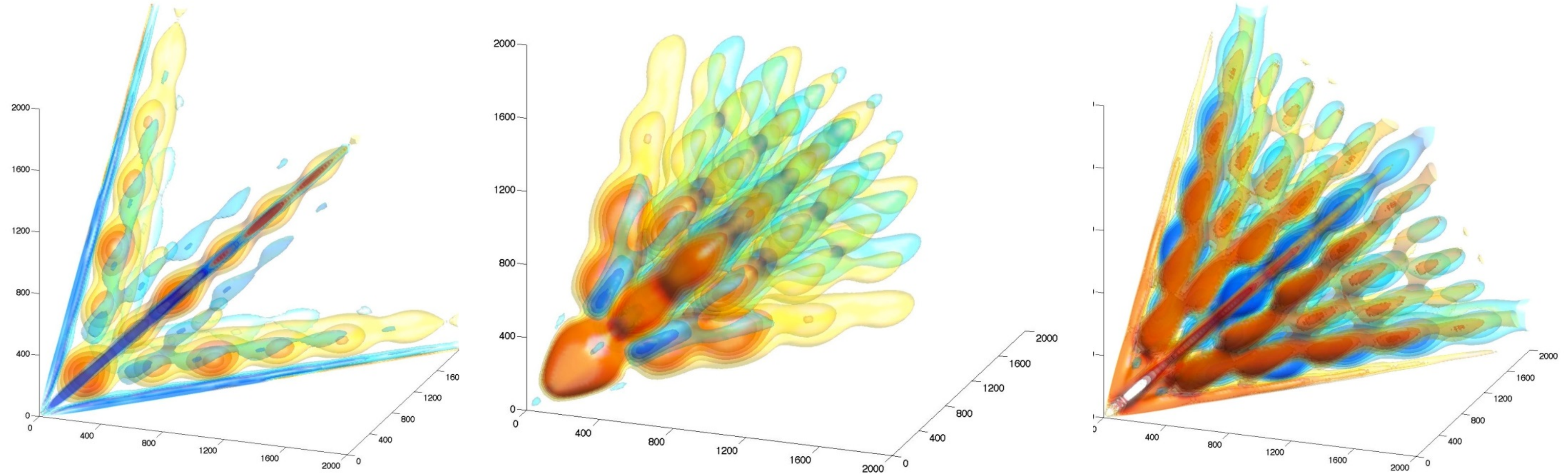


To assess non Gaussianity, one must compare fluctuations in three points (bi-spectrum), four point (tri-spectrum), etc.

Need **three** numbers to characterize a triangle

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

LEO (Local, Equilateral, Orthogonal) are common outputs



NG of ***local*** type (k_1 $k_2 \sim k_3$):
- 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 constraints w. full mission data

Planck 2015

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	
Equilateral	−8.9 ± 44	
Orthogonal	−35 ± 22	

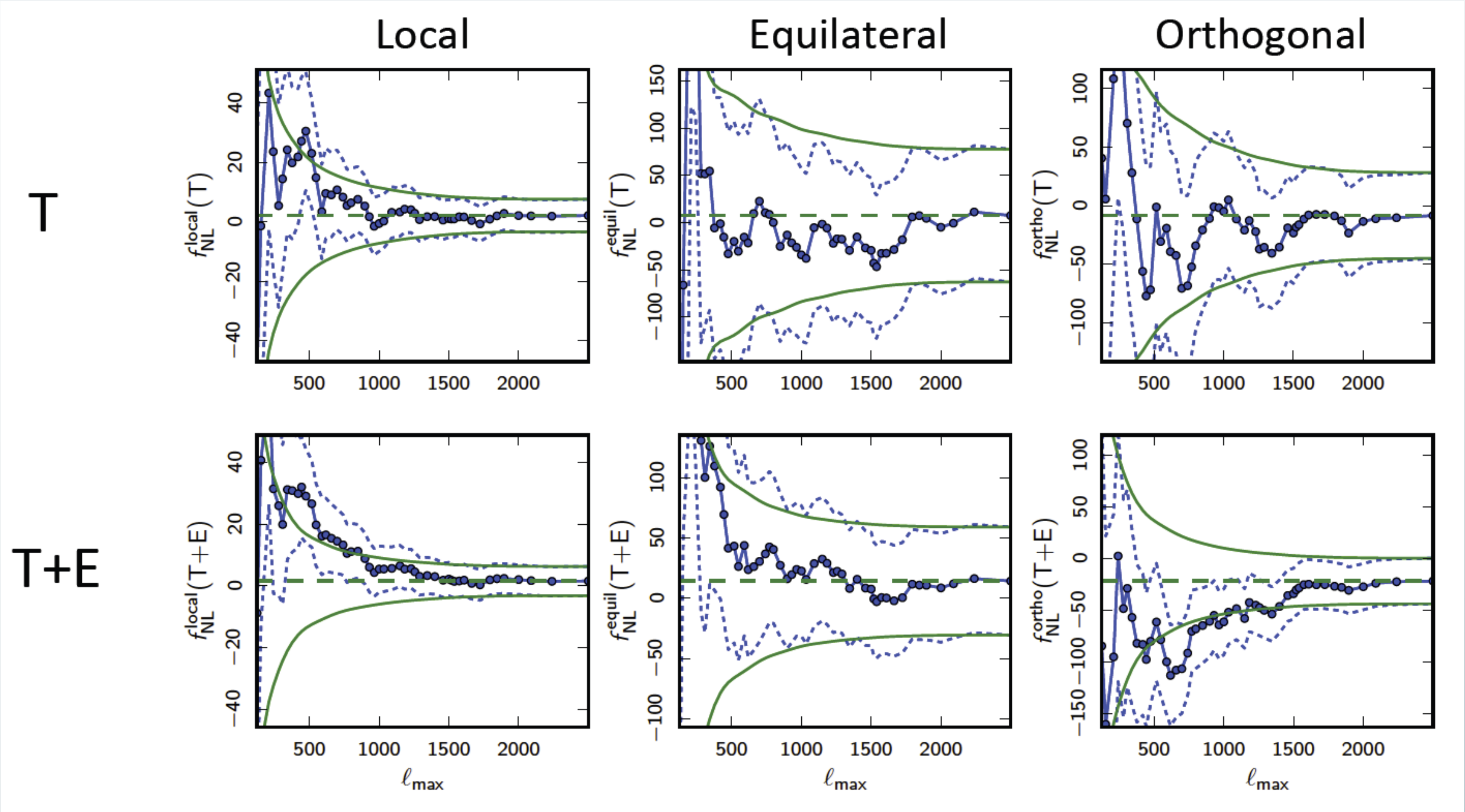
f^{local}_{NL} = 0.8 ± 5.0
f^{equil}_{NL} = - 4 ± 43
f^{ortho}_{NL} =-26 ± 21

Planck 2013

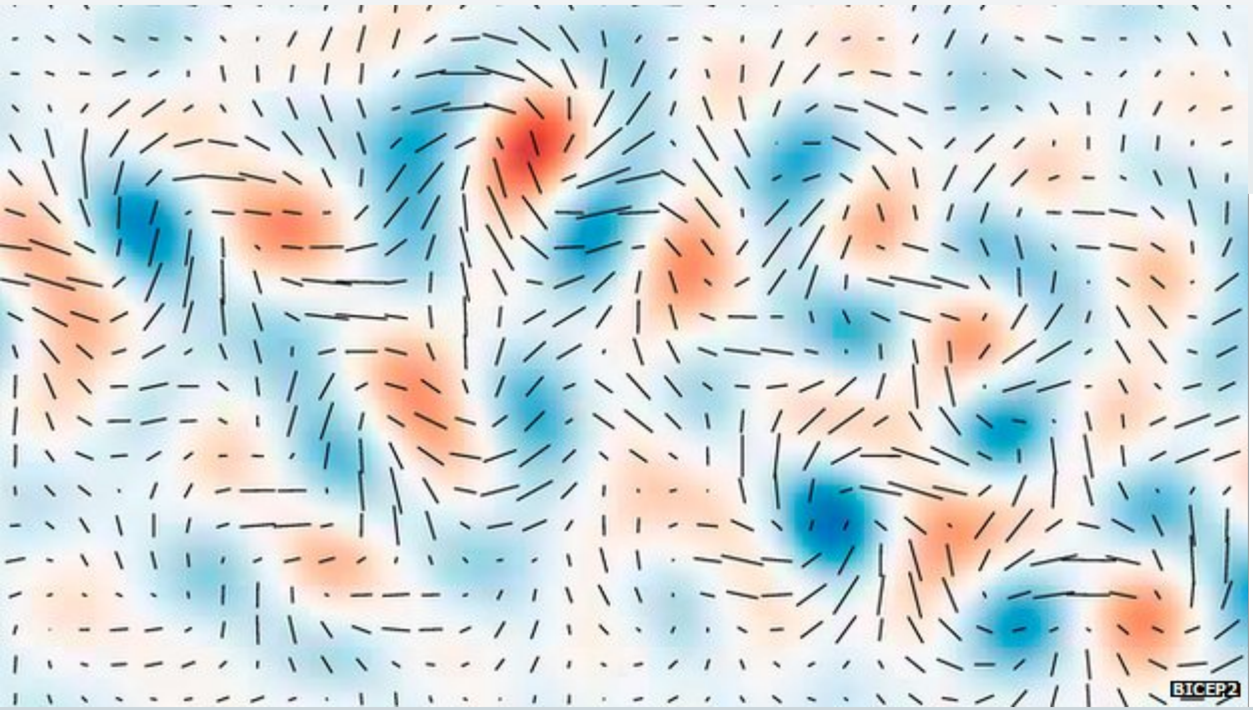
ISW-lensing subtracted KSW	ISW-lensing subtracted Binned	ISW-lensing subtracted Modal
2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
−42 ± 75	−25 ± 73	−20 ± 77
−25 ± 39	−17 ± 41	−14 ± 42

Constraint volume in LEO space shrunk by factor of 3.

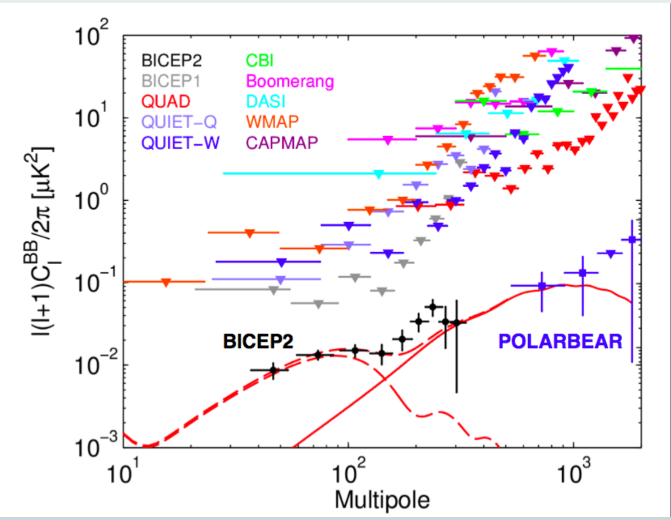
Results are stable when l_{max} increases



BICEP2



March 17th 2014



The world of physics is taken aback by an extraordinary result from a beautiful experiment:

The search for primordial gravitationnal waves is over.

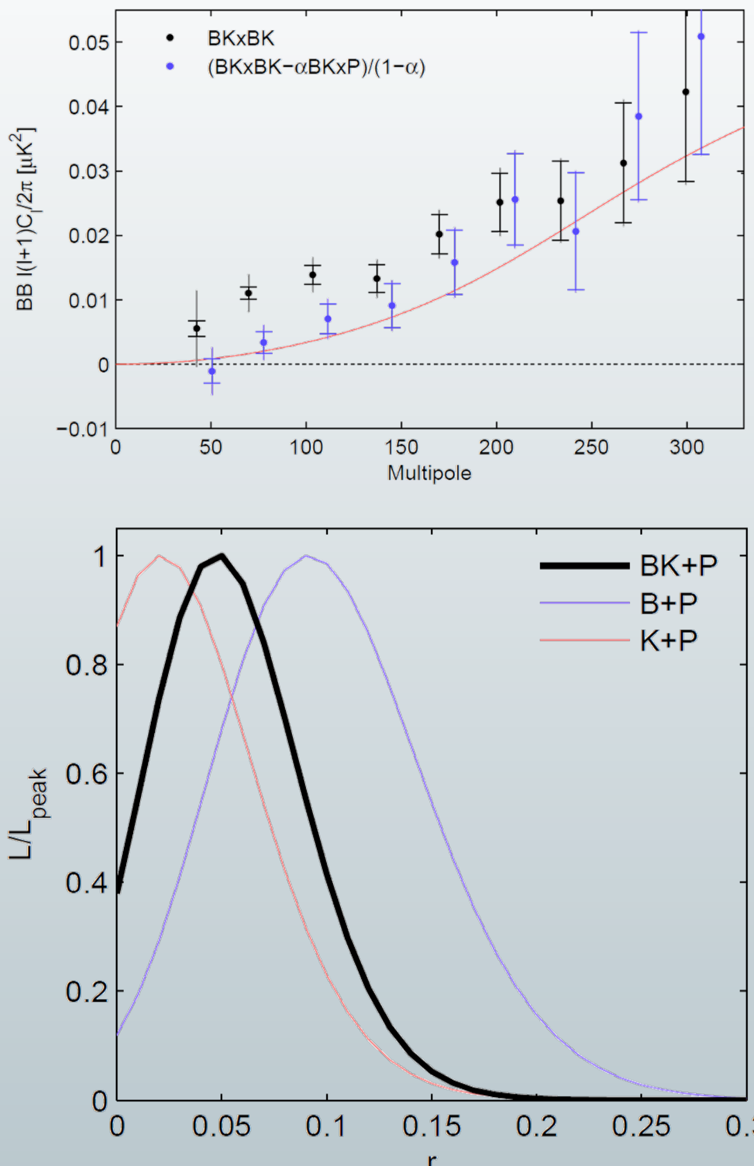
It is r=0.2 and it is 5 sigma!

Planck X (Bicep2 & Keck)

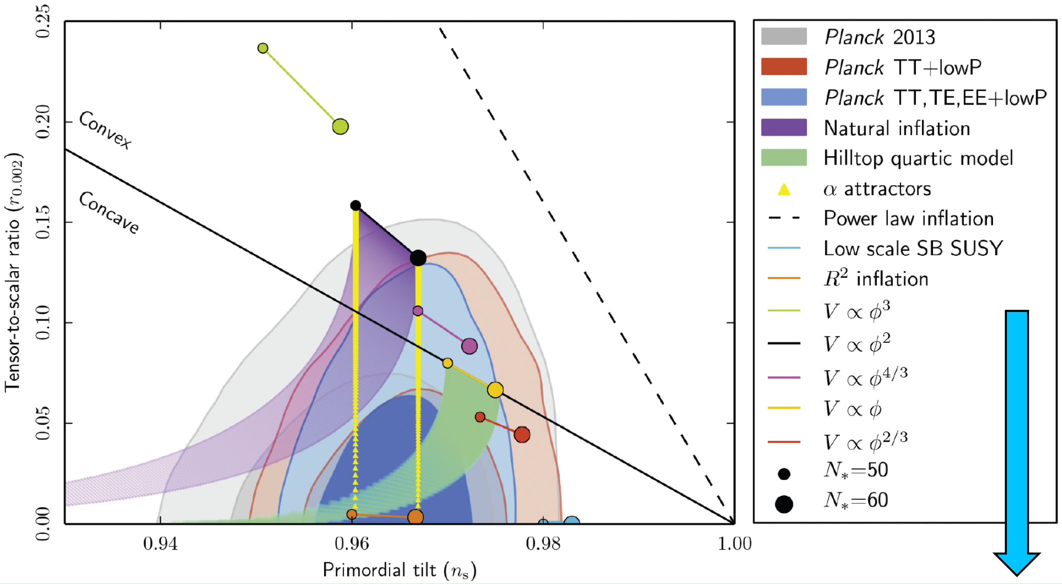
- Since January 30th 2015, the **direct** constraints on r (Planck X Bicep2 & Keck) have reached the level of the previous best **indirect constraints** (from Planck alone T), i.e.

- r < 0.11 @ 95%CL
  (r =A_s/A_T à, e.g., k=0.05Mpc^{-1})

- A new era began…

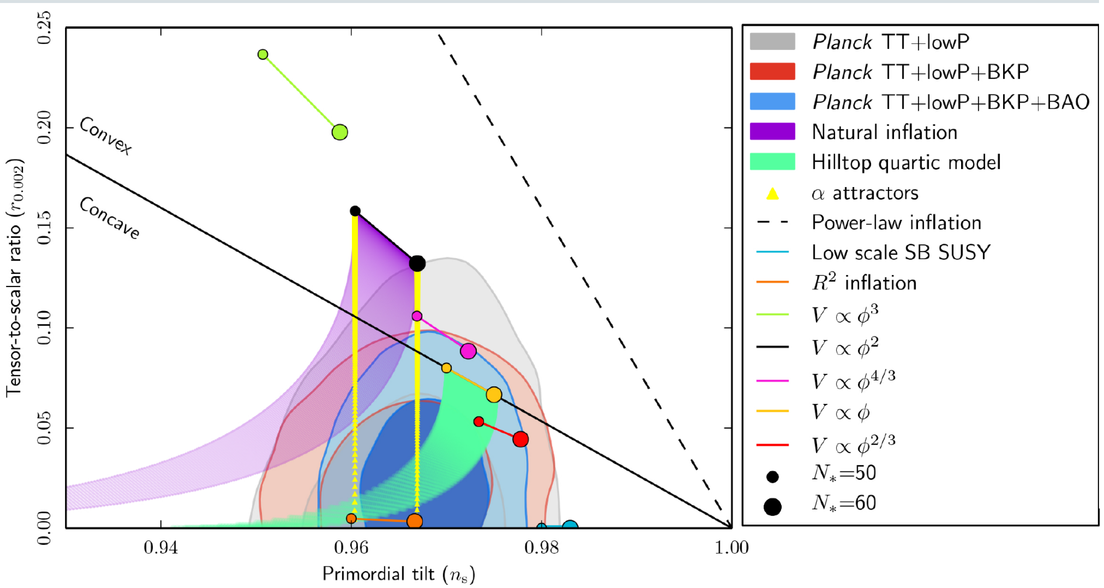


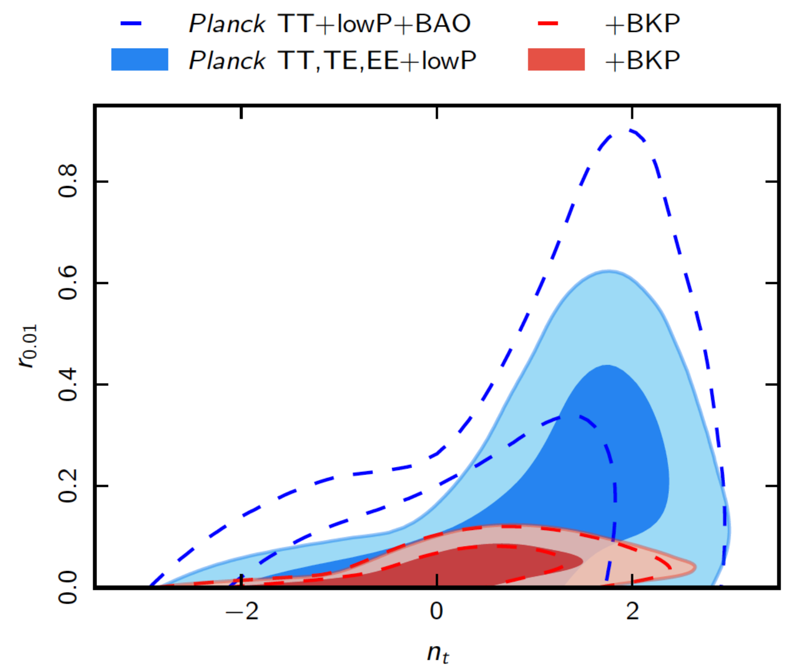
Planck + BK X Planck



Planck 2013: $r_{0.002}$ < 0.11 @95%cl
Planck 2015: $r_{0.002}$ < 0.10 @95%cl
BKP : $r_{0.002}$ < 0.12 @95%cl

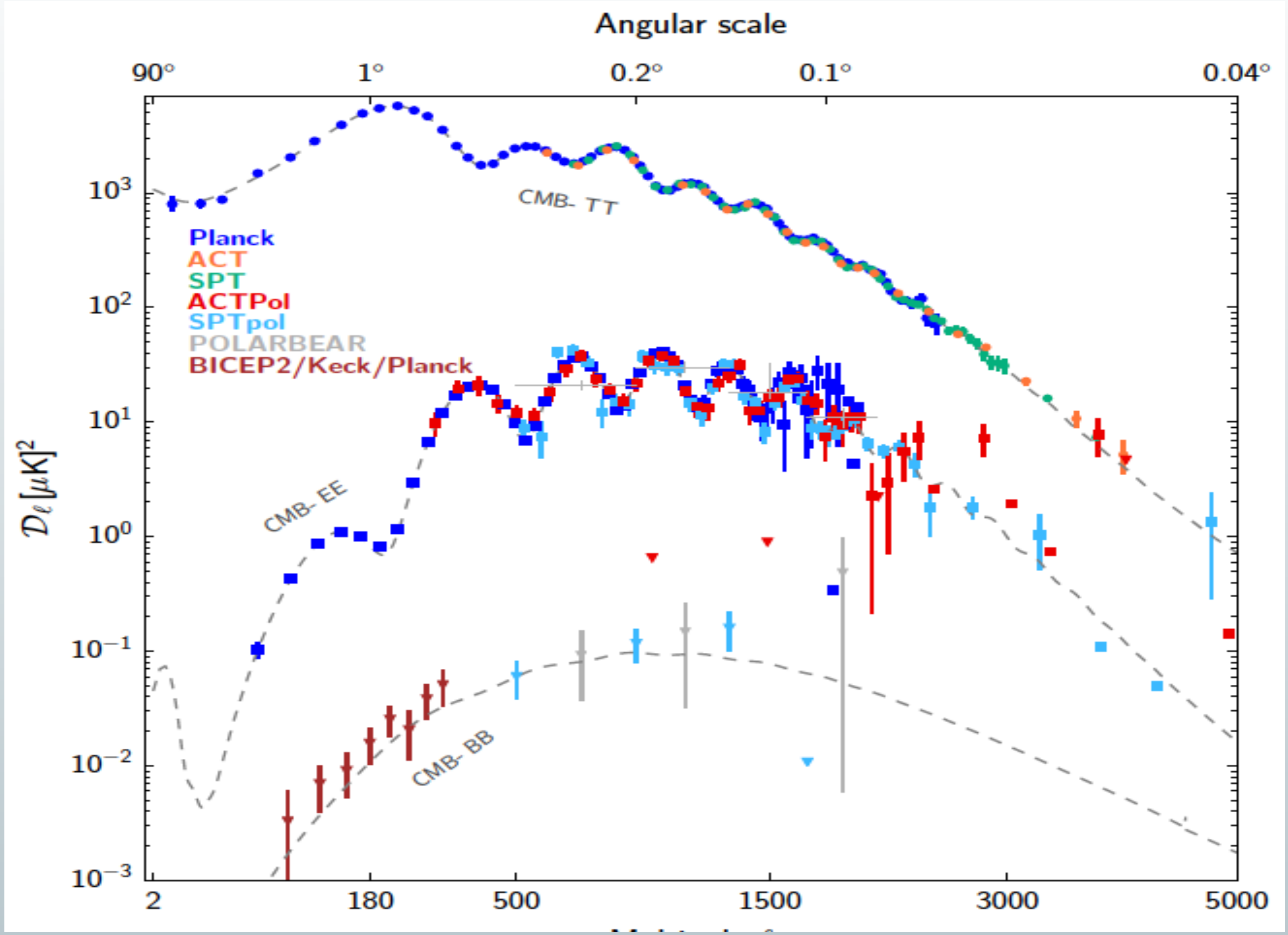
Planck+BKP: $r_{0.002}$ < 0.08 @95%cl





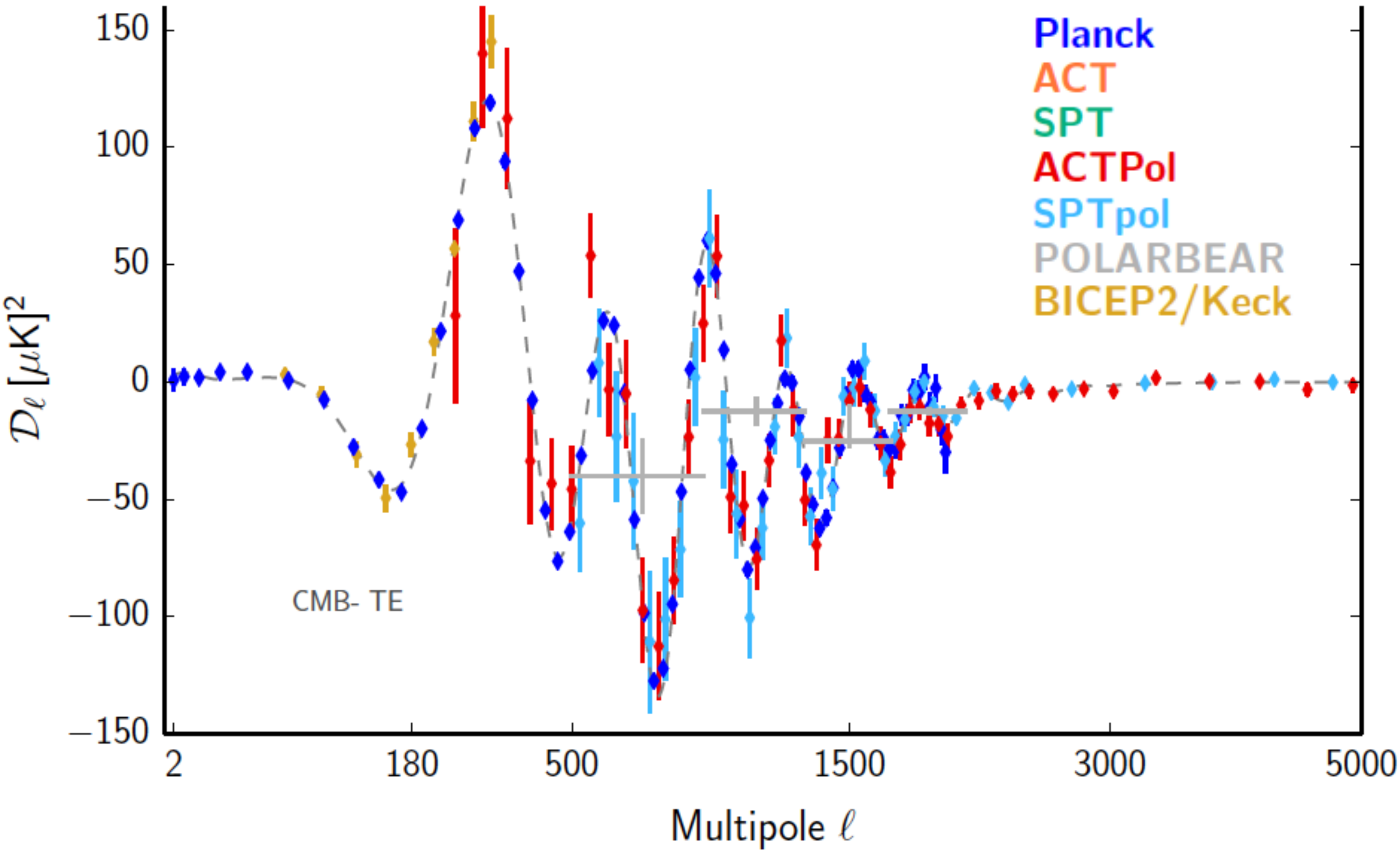
(using n_T and $r_{0.002}$ as primary parameters)

TT, EE, BB – mid 2015 status



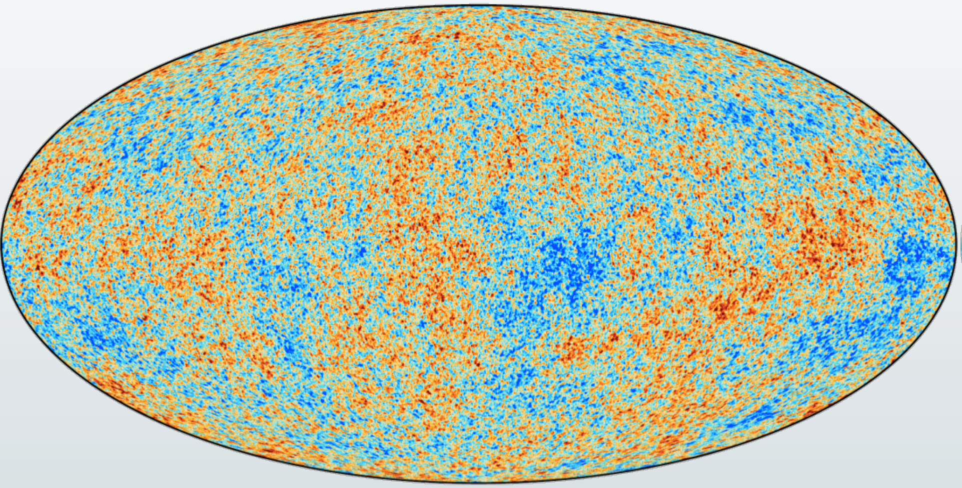
Only keeping points w. sufficiently small error bars

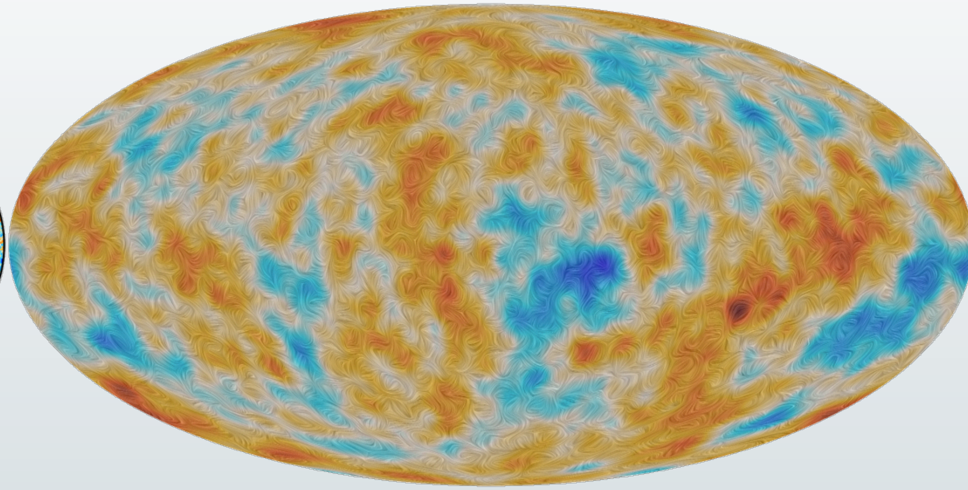
Not forgetting mighty TE !



Conclusions

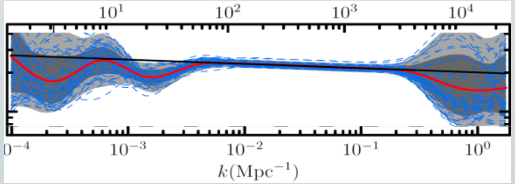
➔ base ΛCDM continues to be a good fit to the Planck data, *including polarisation*.

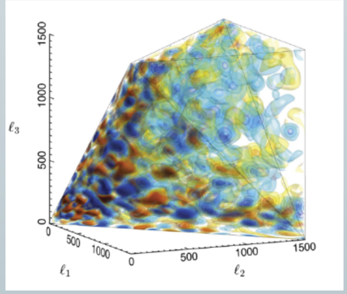




➔powerful evidence in favour of simple inflationary models, that match Planck data to very high precision.

Parameter	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.882 ± 0.012





@95%cl

Parameter	TT, TE, EE+lensing+ext
Ω_K	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV] . .	< 0.194
$N_{\rm eff}$	$3.04^{+0.33}_{-0.33}$
Y_P	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$ . .	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.113
w	$-1.019^{+0.075}_{-0.080}$

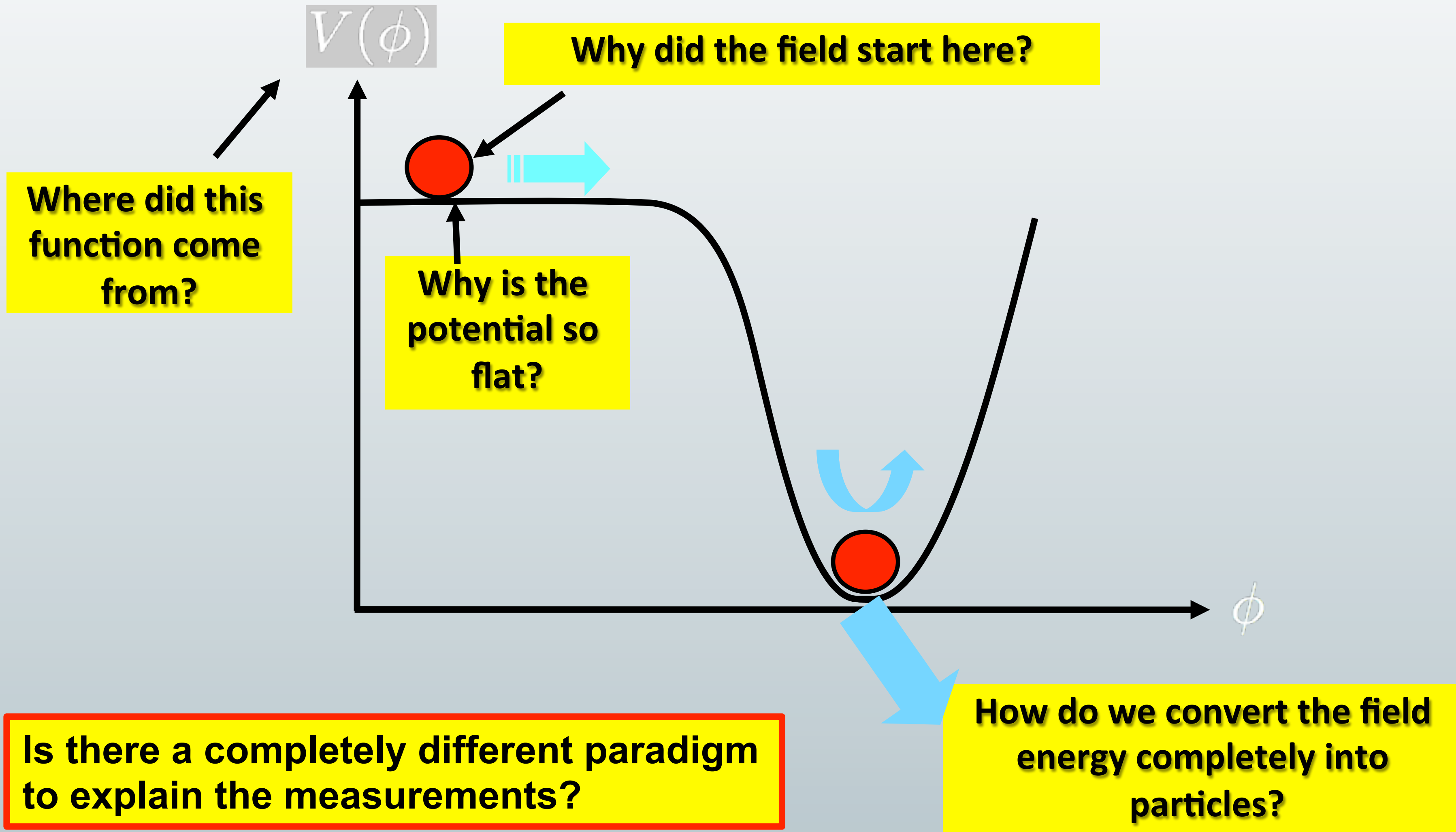
$f^{local}_{NL} = 0.8 \pm 5.0$
$f^{equil}_{NL} = -4 \pm 43$
$f^{ortho}_{NL} = -26 \pm 21$

α_{iso}
P_{ann}
…

Defect	$G\mu/c^2$
NG . .	$< 1.3 \times 10^{-7}$
AH . .	$< 2.4 \times 10^{-7}$
SL . .	$< 8.5 \times 10^{-7}$
TX . .	$< 8.6 \times 10^{-7}$

➔If there is new physics beyond base ΛCDM, its observational signatures in the CMB are weak & difficult to detect.

But what is the physics of inflation?



Is there a completely different paradigm to explain the measurements?

To conclude

- There is something to be said in favour of measuring all the primary CMB modes which nature made available to us and which have an unmatched record of direct interpretation on fundamental physics, and in so doing on a large part of astrophysics, with great synergies with other probes.
- It was great that ESA deciding to try achieve that in Temperature with HFI, despite the daunting challenge at the time of that technology and its requirements.
- In less than a year, Planck legacy release will have been delivered and the community is at a crossroad.

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.


Thank you
X, Ferrara, Dec 2014