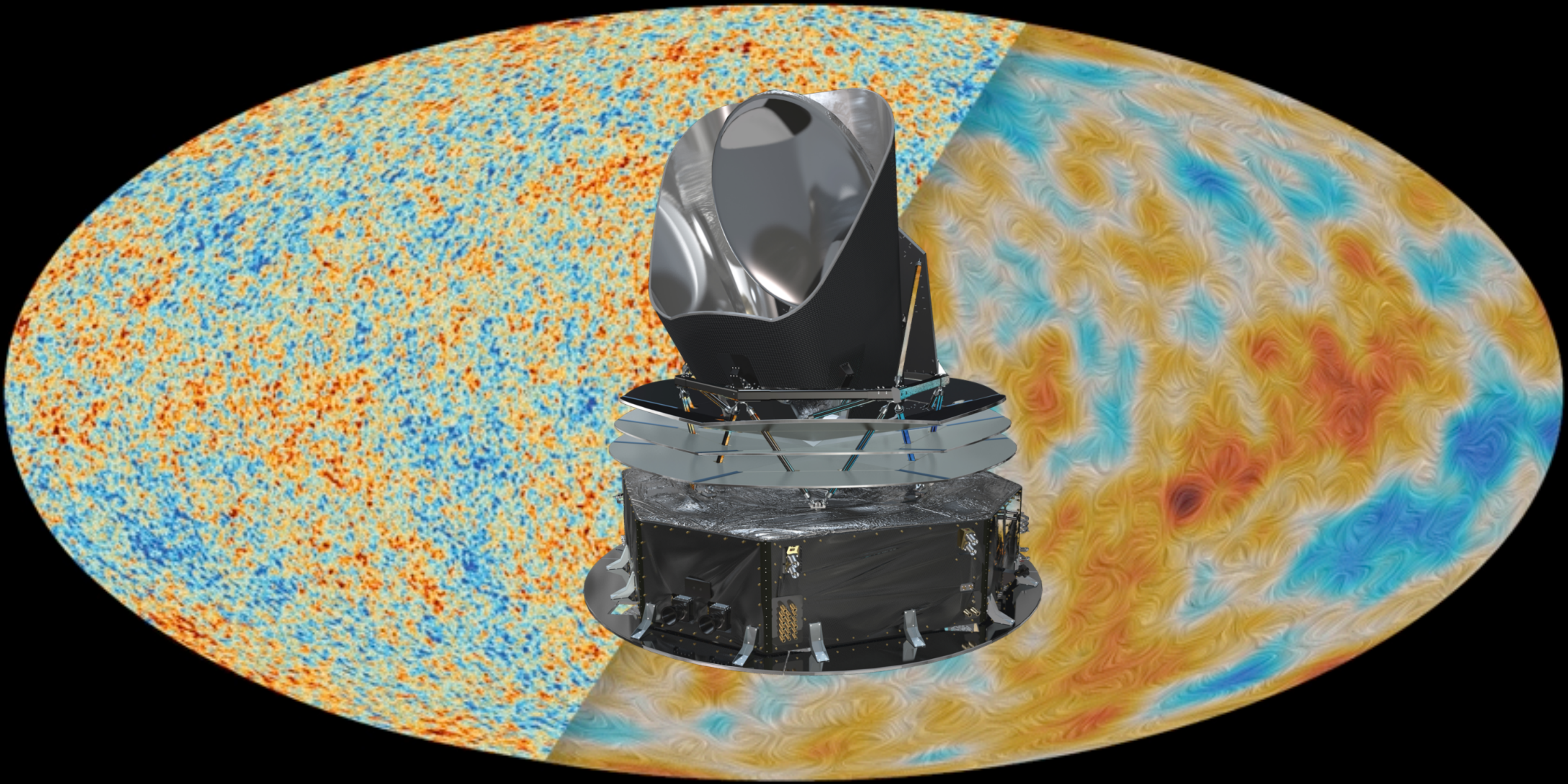
PLANCK 2015 COSMOLOGY



François R. Bouchet on behalf of the Planck Collaboration

The Planck mission 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: This required a number of technological breakthrough

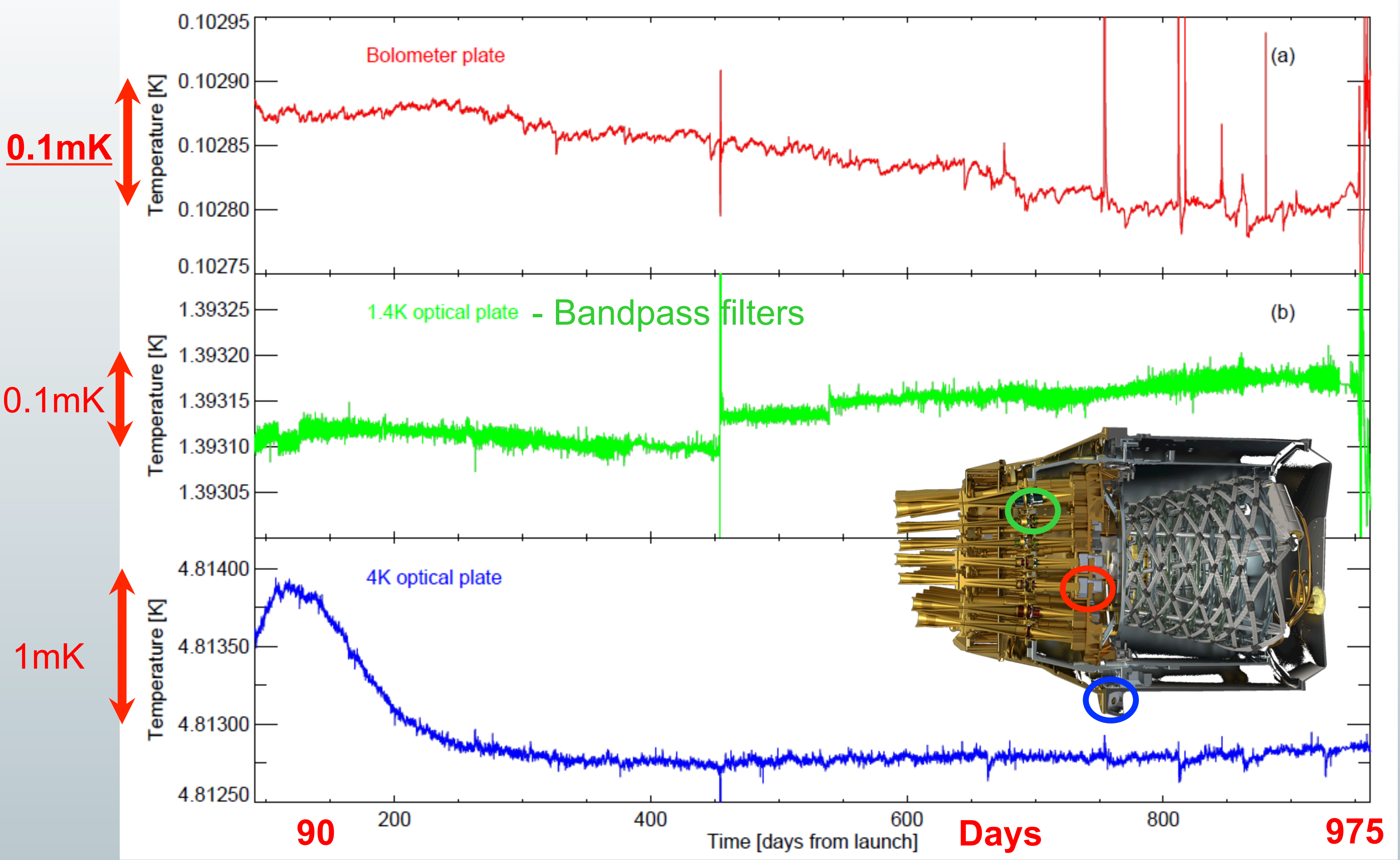
NB: with the Ariane 501 failure delaying us by several years (03 → 07) and WMAP then flying well before us, polarization measurements became more and more a major goal

DUSTING IT OFF...

AFTER 16 YEARS
OF HOPES & WORK

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

Quietly cool…



0.1mK

0.1mK

1mK

- Bandpass filters

90

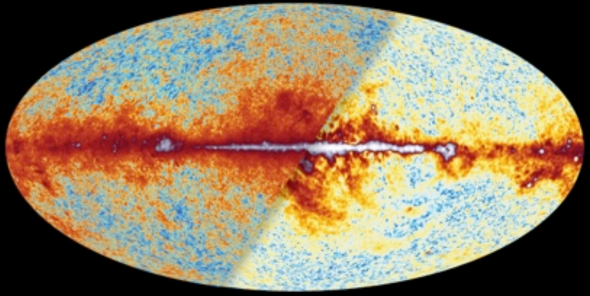
Days

975

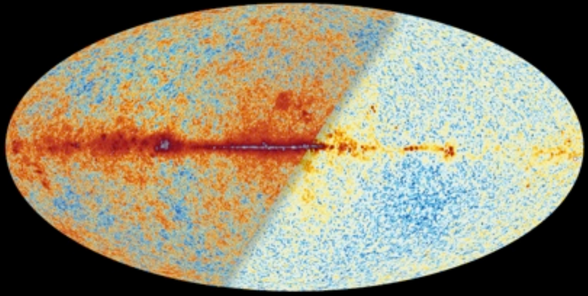
The IAP Cellar...

+ CC/CINECA/ Darwin/NERSC...

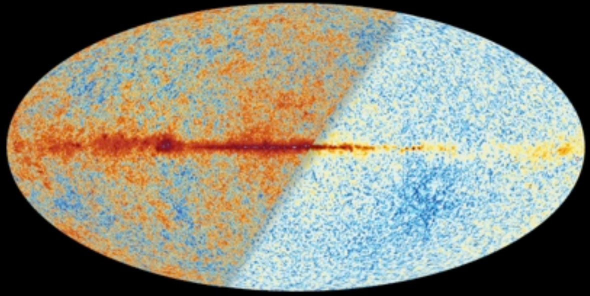
Now available in a store near you



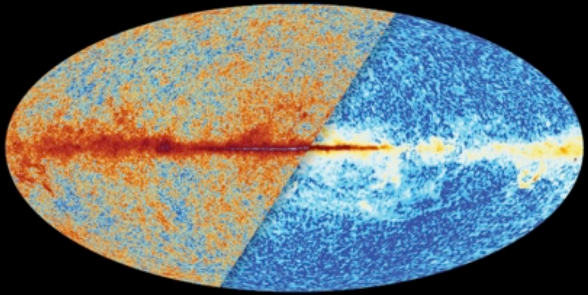
30 GHz



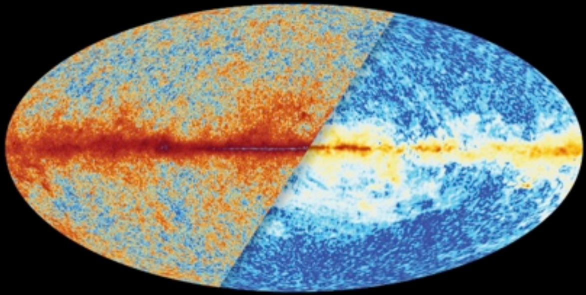
44 GHz



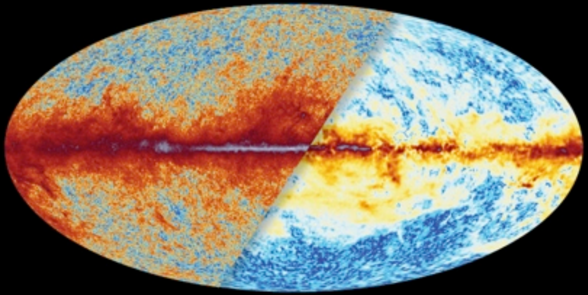
3.5μK.deg,13’ 70 GHz



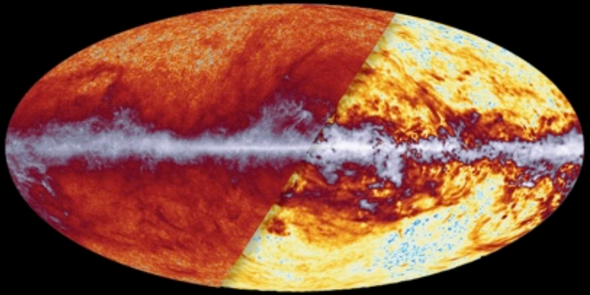
1.3μK.deg,9.7’ 100 GHz



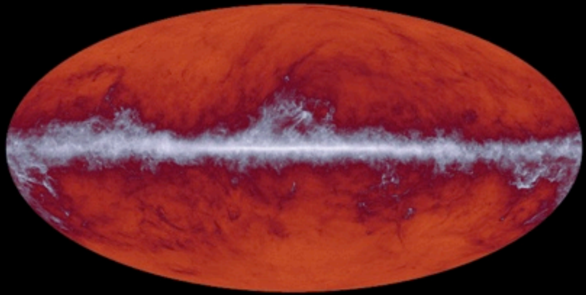
0.5μK.deg,7.3’ 143 GHz



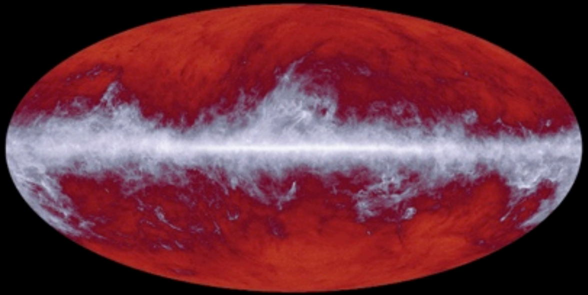
0.8μK.deg,5.0’ 217 GHz



353 GHz



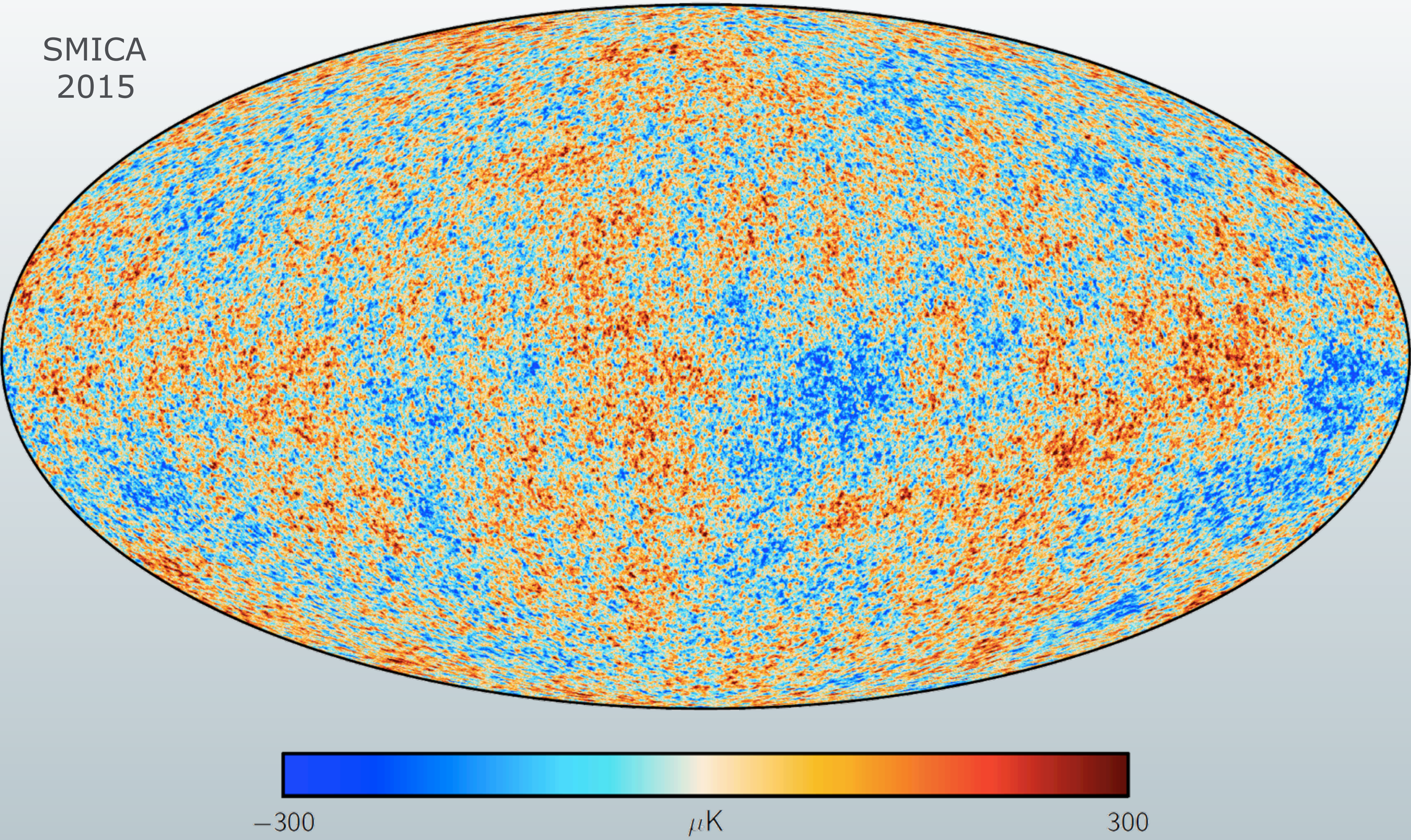
545 GHz



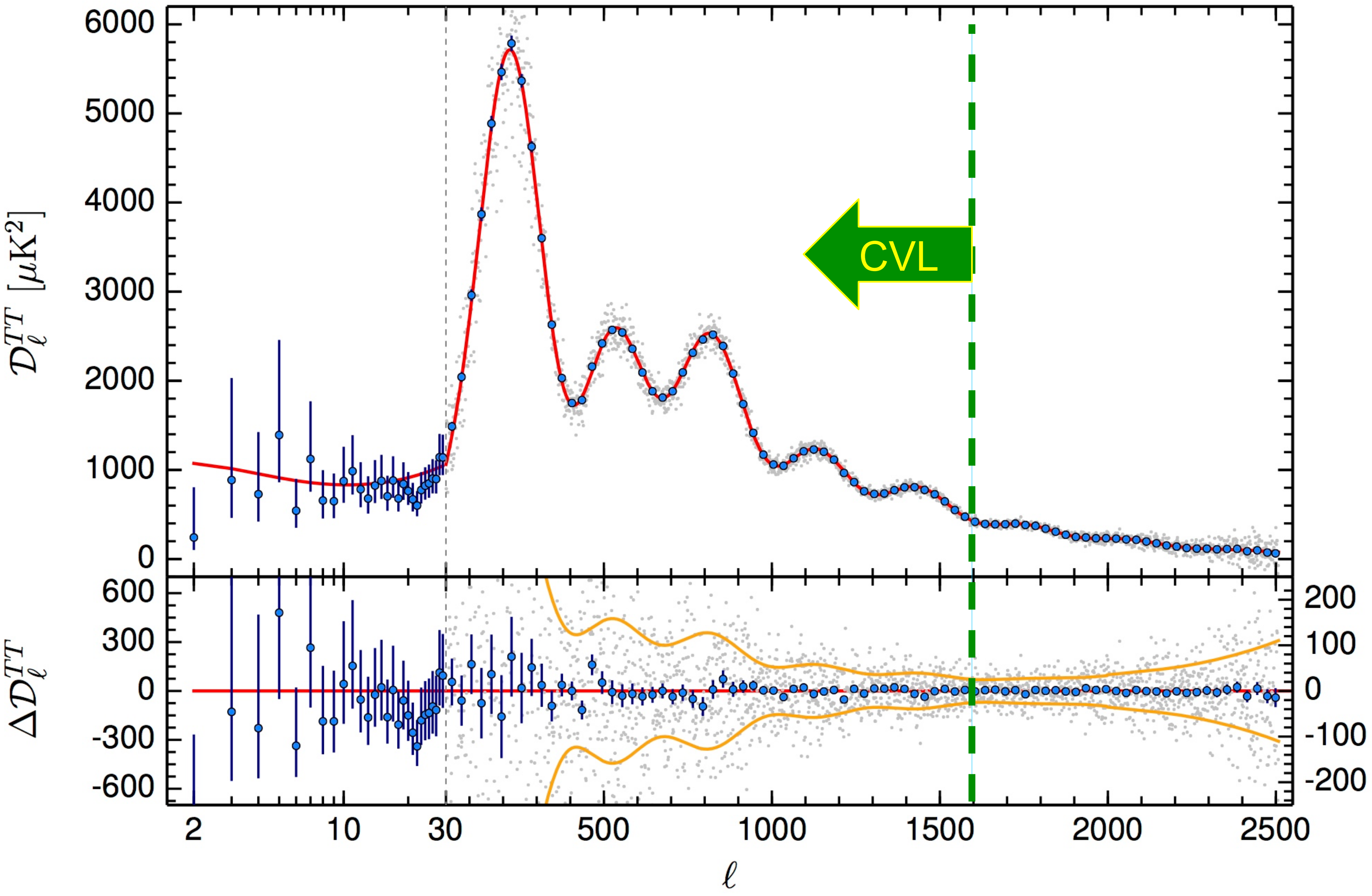
857 GHz

Planck 2015 T anisotropies map

SMICA
2015



Planck 2015 TT spectrum



8 acoustic peaks well detected

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

Base ΛCDM model with 6 parameters

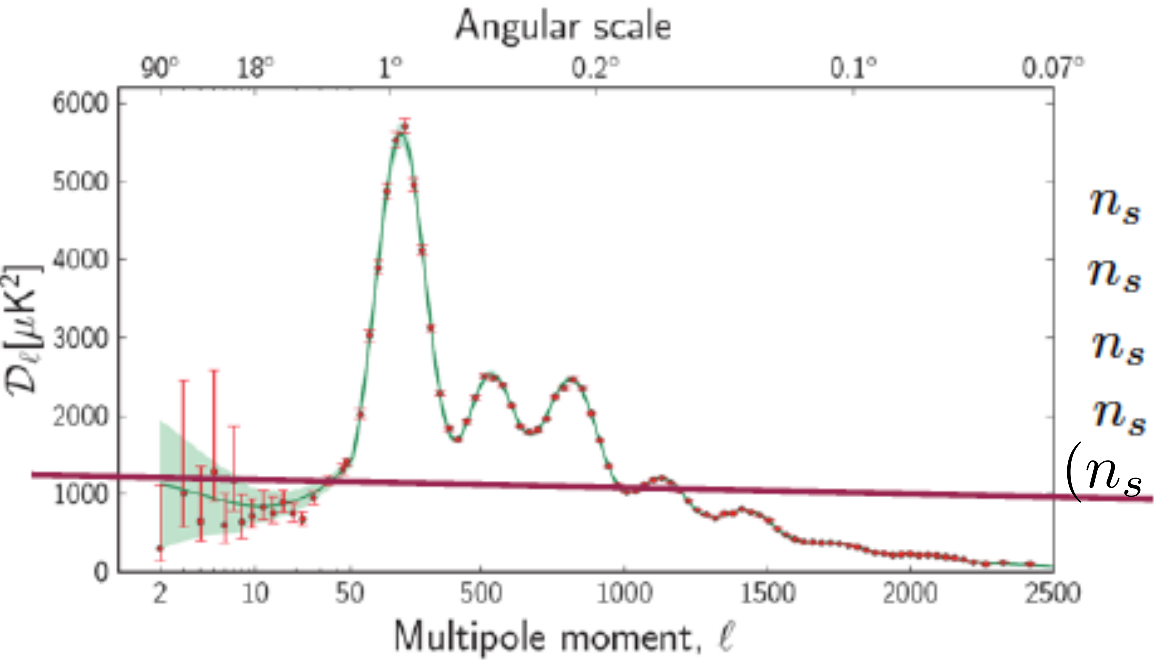
3 parameters to set (though General Relativity) the dynamics of the Universe,
1 parameter to capture the effect of reionisation (end of the dark ages),
2 parameters to describe the characteristics of primordial fluctuations.
Flat spatial geometry assumed.

- $\Omega_b h^2$ Baryon density today - The amount of ordinary matter
- $\Omega_c h^2$ Cold dark matter density today – only weakly interacting
- Θ Sound horizon size when optical depth τ reaches unity
  (Distance traveled by a sound wave since inflation, when universe became transparent at recombination at t ~380 000 years)
- τ Optical depth at reionisation (due to Thomson scattering of photons on e^-), i.e. fraction of the CMB photons re-scattered during that process
- A_s Amplitude of the curvature power spectrum
  (Overall contrast of primordial fluctuations)
- **n_s** Scalar power spectrum power law index
  (n_s-1 measures departure from scale invariance)
- Others are *derived* parameters within the model, in particular
  - *Ω "Dark Energy" fraction of the critical density (derived only if assumed flat)*
  - *H_0 the expansion rate today (in km/s per Mpc of separation)*
  - *t_0 the age of the universe (in Gy)*

What is the value of n_s ?

Initial Conditions: quasi-scale invariant

$$g_{ij} = a^2(\tau)\,[1-2\Phi]\,\gamma_{ij} \longrightarrow k^3\langle|\Phi_k|\rangle \propto k^{n_S-1}$$

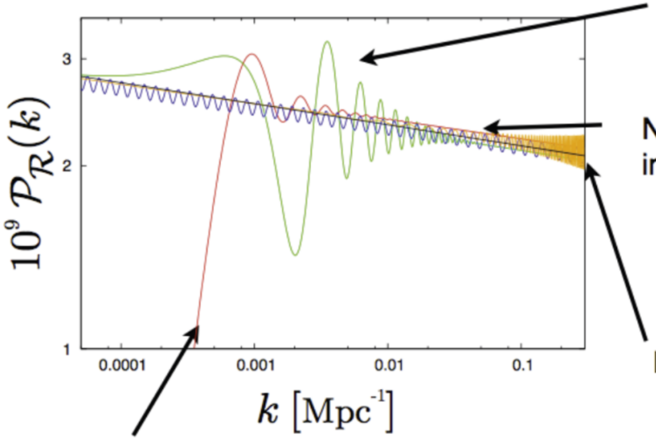


$n_s = 1 \pm 0.6$ 1992 (COBE)
$n_s = 1.03 \pm 0.09$ 2001 (MaxiBoom)
$n_s = 0.963 \pm 0.014$ 2009 (WMAP5)
$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)
$(n_s = 0.965 \pm 0.006$ 2015 Planck

A hundred-fold improvement in 20 years

Mukhanov & Chibisov (1981): 1st calculation of (scalar) quantum fluctuation of the vacuum in an inflating background. n_s must be ~0.96 < 1 for inflation to end.

(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

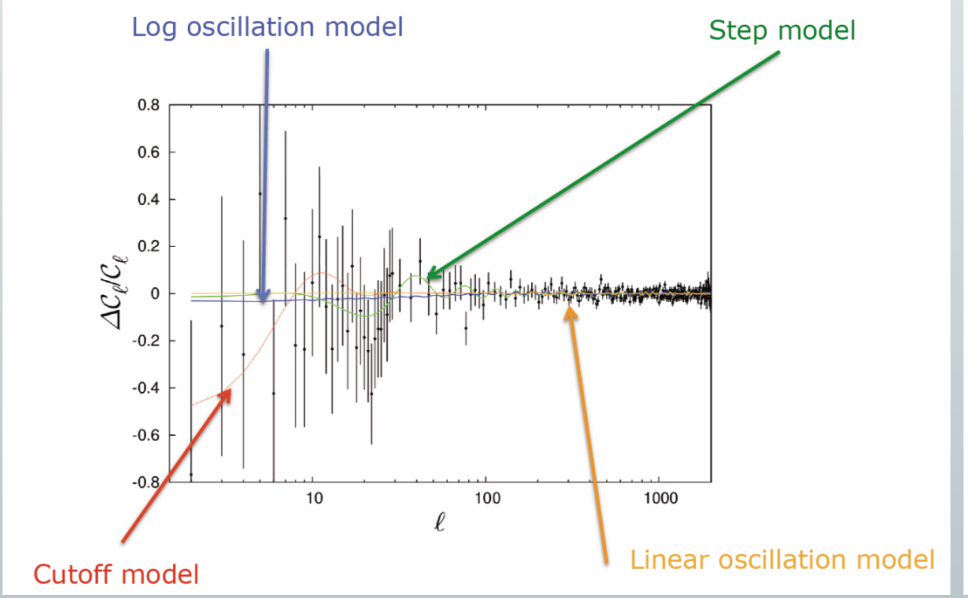
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

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

Linear oscillations as from Boundary EFT

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

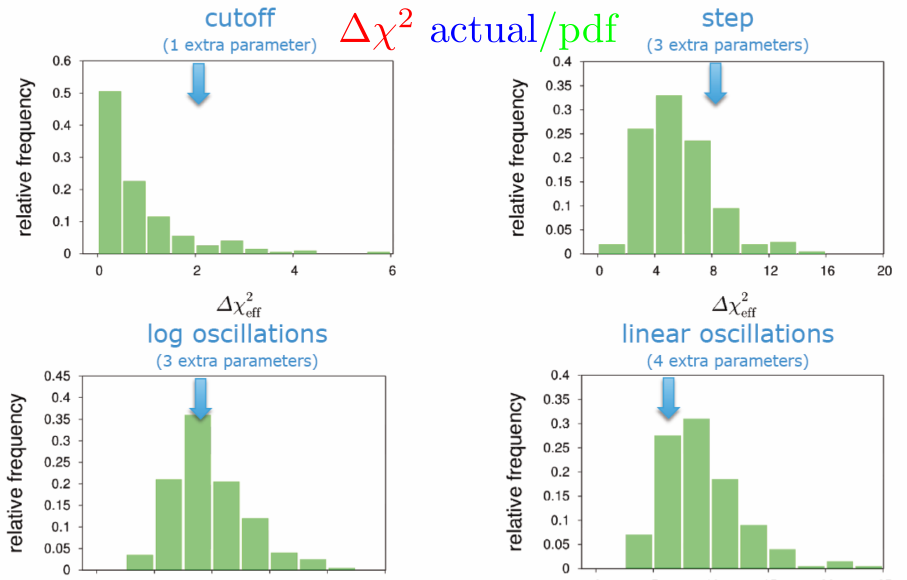
Just enough e-folds, i.e. inflation preceded by a kinetic stage


Log oscillation model

Step model

Cutoff model

Linear oscillation model


$\Delta\chi^2$ actual/pdf

cutoff (1 extra parameter)

step (3 extra parameters)

log oscillations (3 extra parameters)

linear oscillations (4 extra parameters)

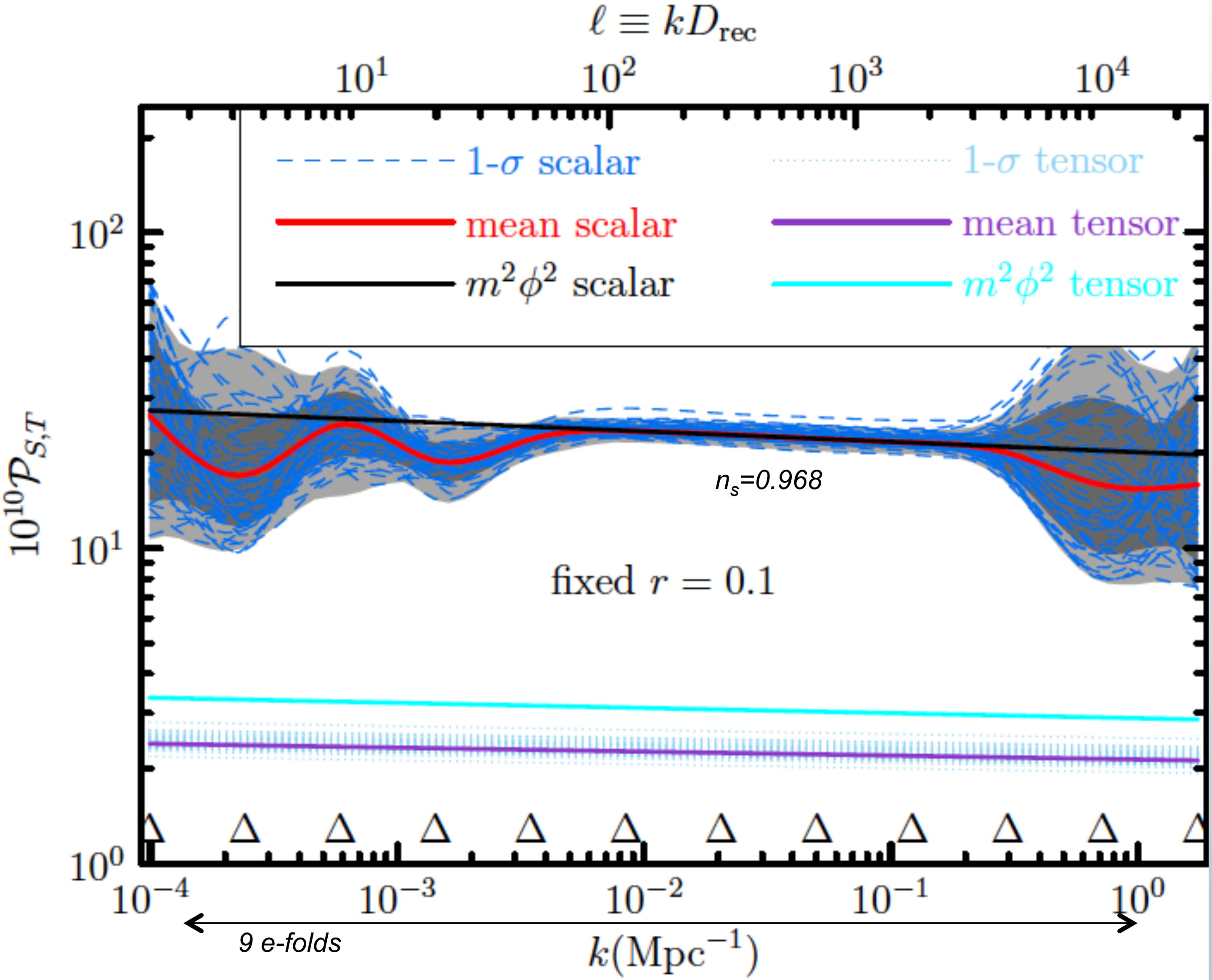
Power spectra reconstruction

2015

TT+lowP

+BAO+JLA

+Hlow

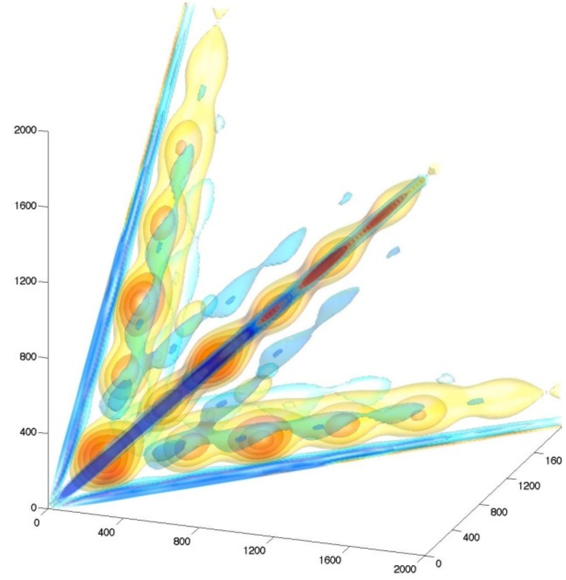


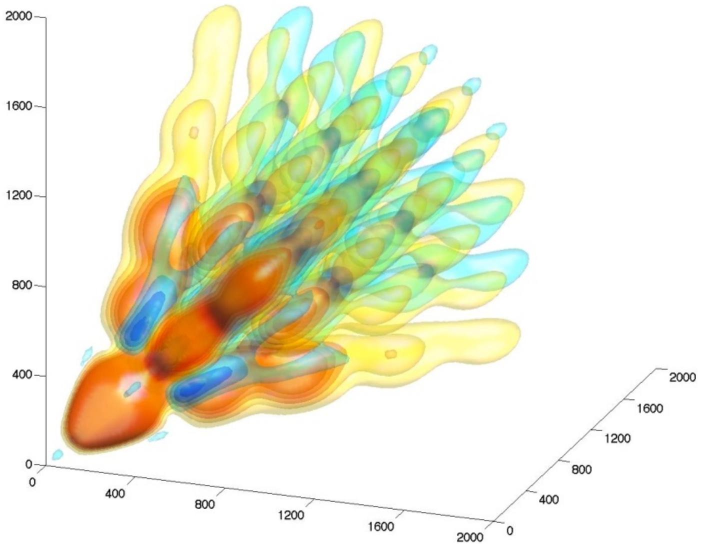
12-knots power spectra

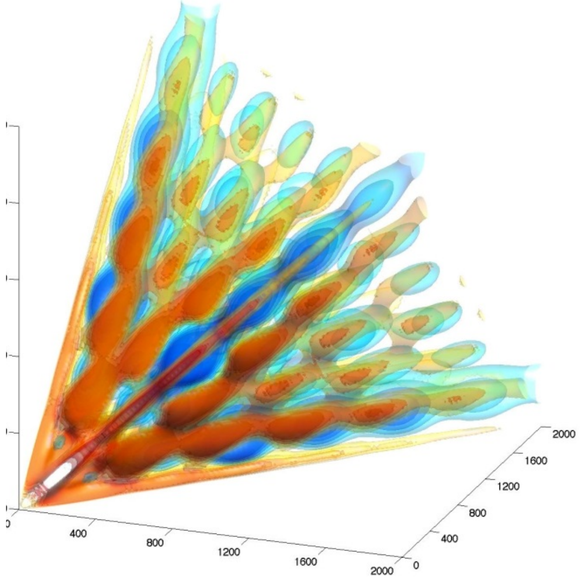
(actually used 3 different methods, all with similar results)

CMB bispectrum fingerprinting with Planck

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)

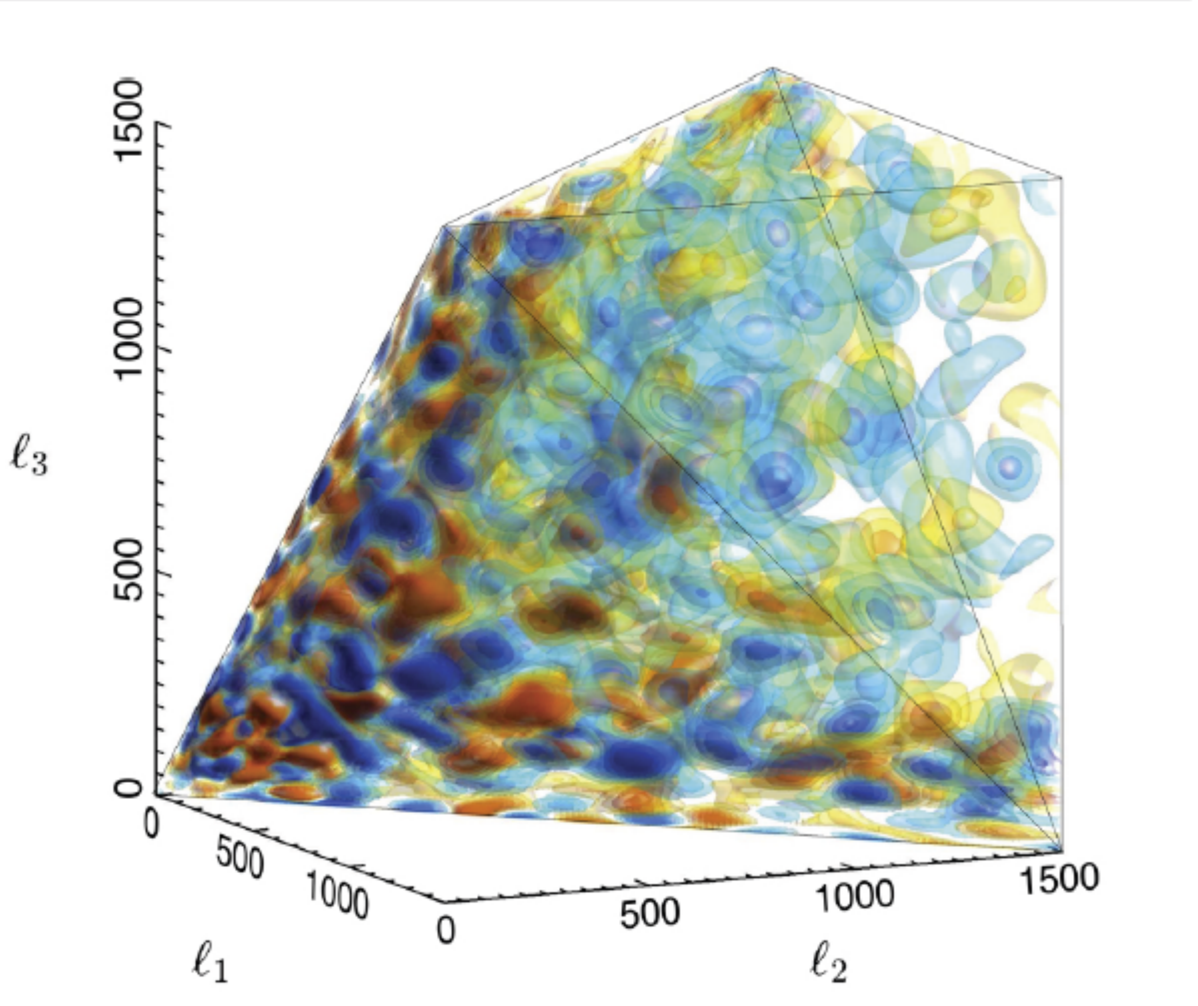
NG of ***equilateral*** type ($k_1 \sim k_2 \sim k_3$):

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

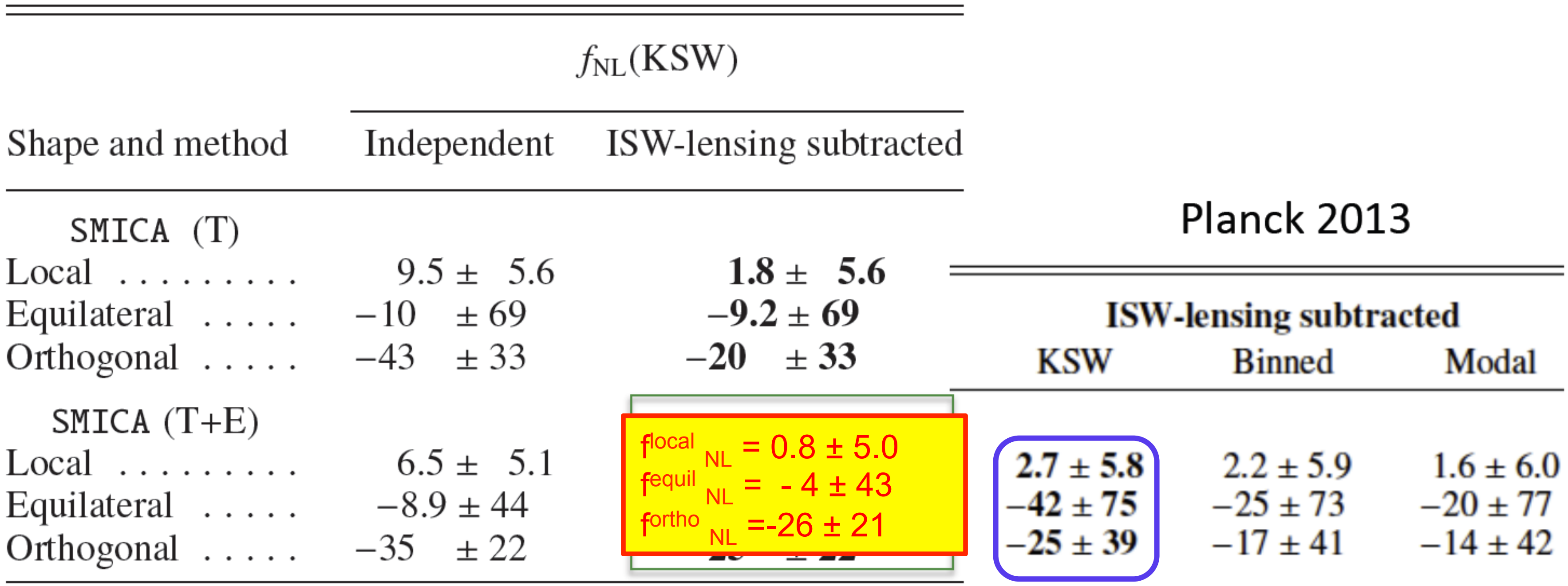
NG of ***orthogonal*** type ($k_1 \sim 2k_2 \sim 2k_3$) :

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

Planck 2015 TTT – 2001 modes



New bispectrum constraints w. full mission data



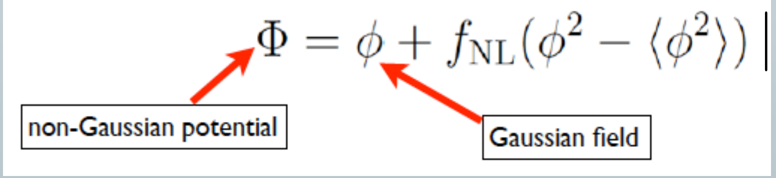
Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	
Equilateral	−8.9 ± 44	
Orthogonal	−35 ± 22	

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

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. wrt Planck2013

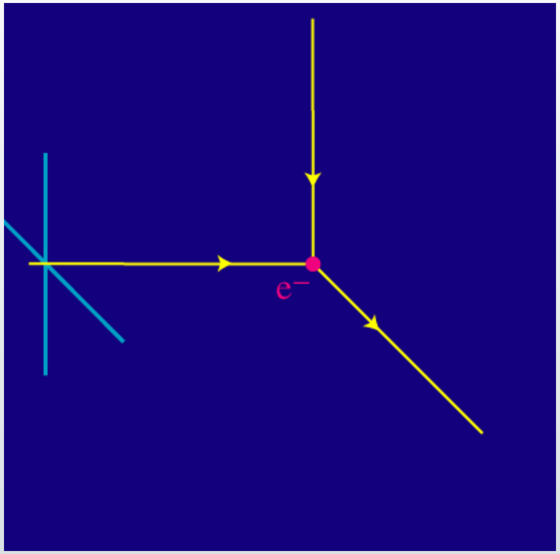


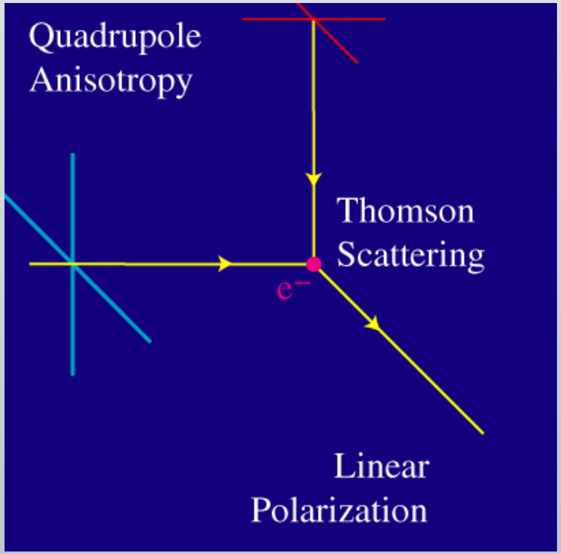
$$\Phi = \phi + f_{\rm NL}(\phi^2 - \langle\phi^2\rangle)$$

$|f_{\rm NL}^{\rm Loc}| <$ 10^3 (Maxima 2001), 10^2 (WMAP7), 10 (Planck15)

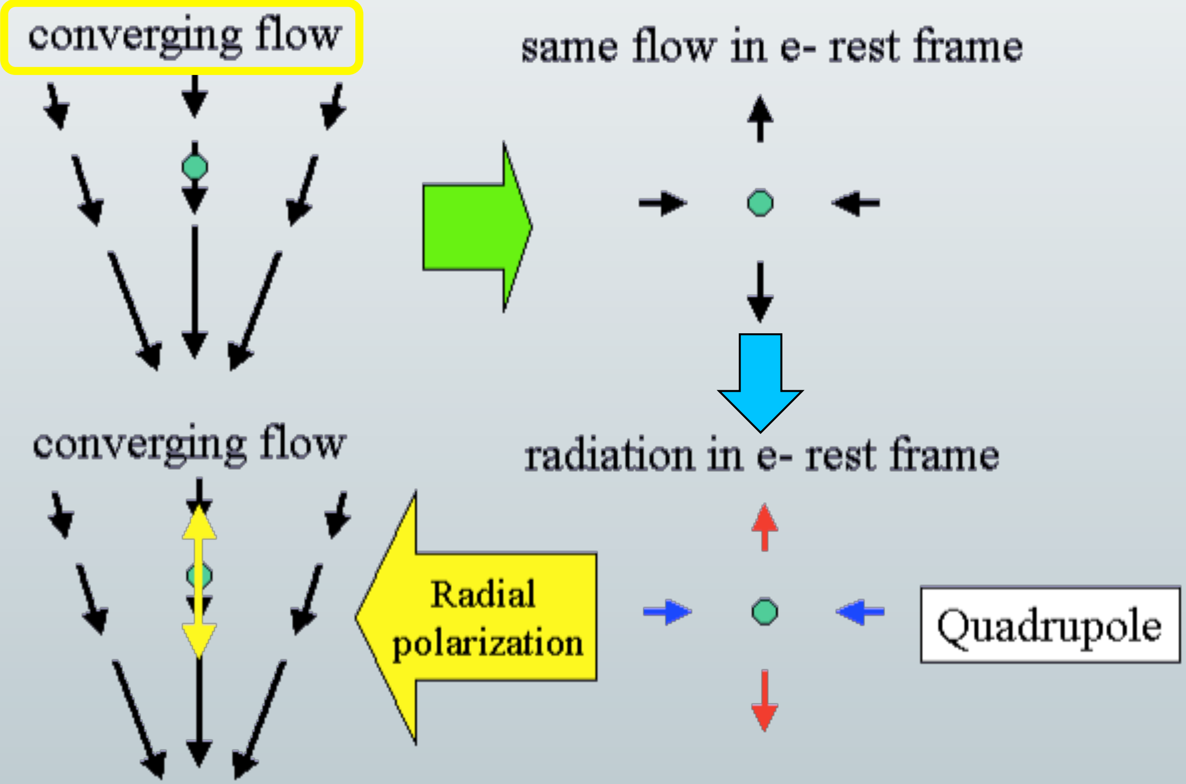
A hundred-fold improvement in 14 years

Thomson scatterings are polarised



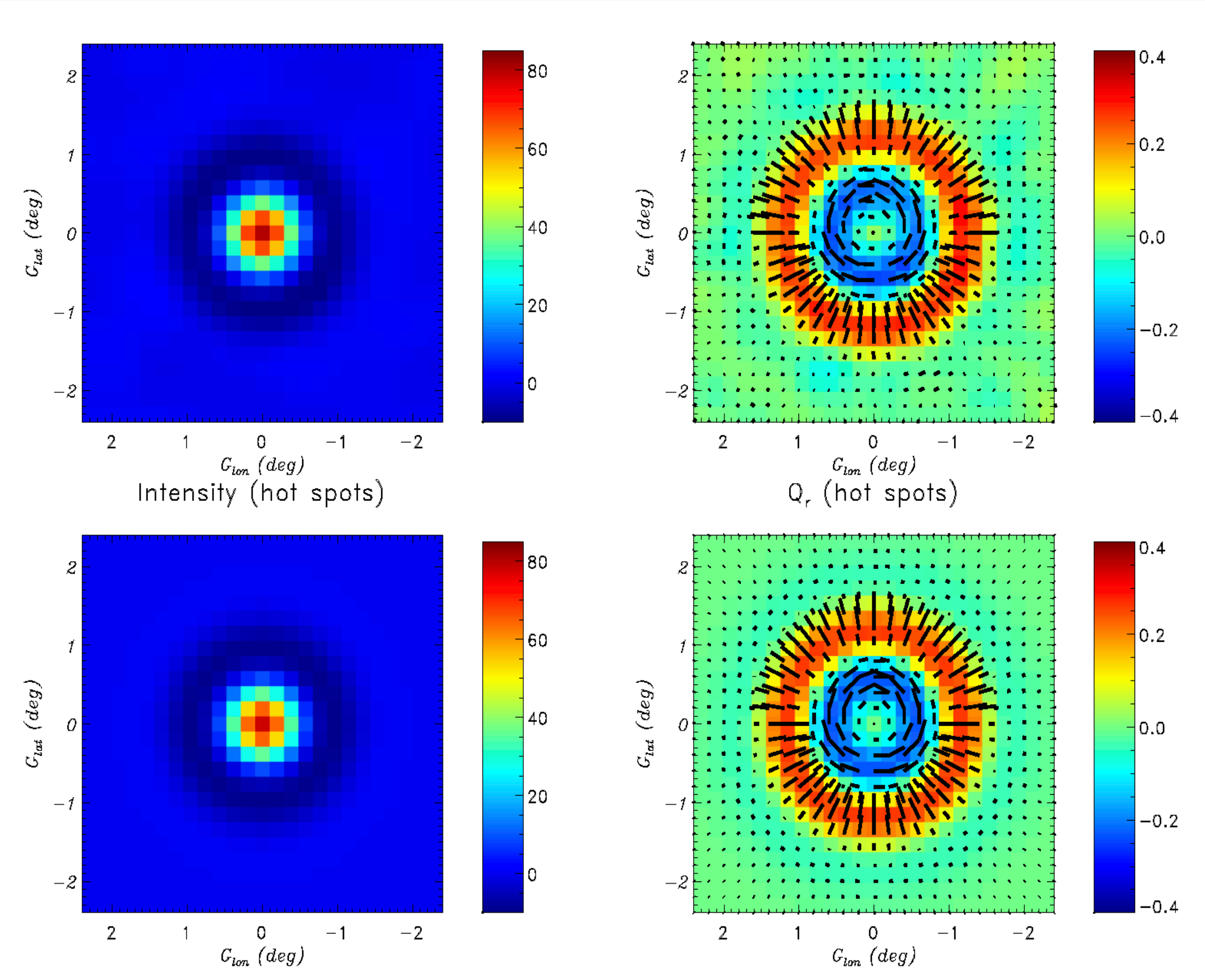


- Before recombination, successive scatterings destroy polarization and the radiation arrives at recombination unpolarized.
- During recombination, Gradients in the velocity field can produce a quadrupole in the rest frame of the scattering electron.



- A *diverging* flow leads to a *tangential* pattern of polarization

Polarisation around hot spots



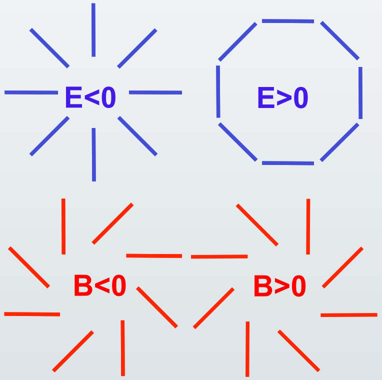
Data (top) versus expectation (bottom)

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

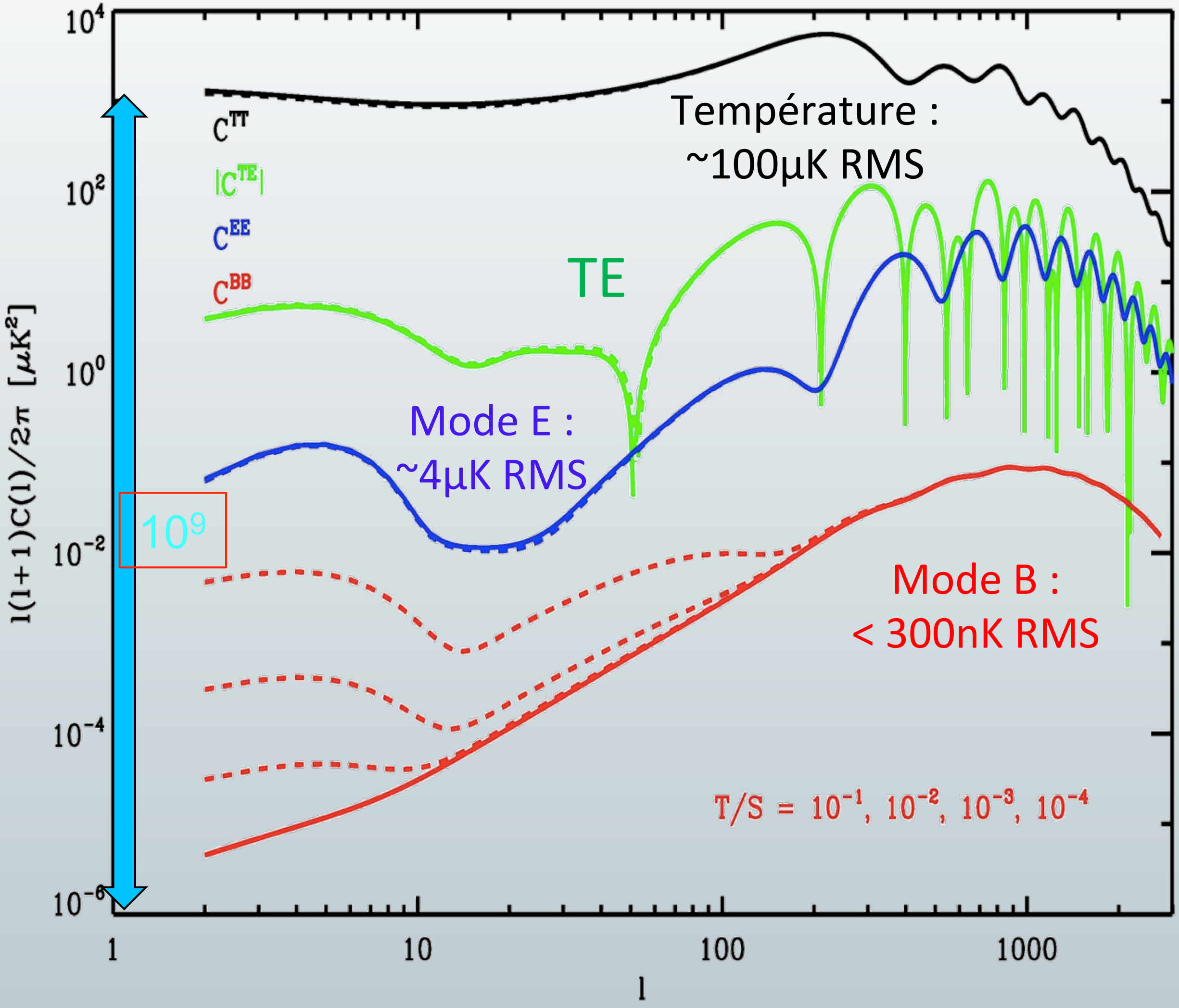
➔ It would be different with a different content

CMB angular power spectra

- 3 observables : T, E, B



- B Modes:
  - **Not** generated by scalar modes
  - "Smoking gun" of tensorial perturbations
  - At best 300 times weaker than T fluctuations
  - case T/S = r = 0.1 (cf. fig),
  - E_{inf}=1.6 x 10^{16} GeV (~GUT).
- B mode Spectrum peaks at l < 200, i.e. θ > 1 deg

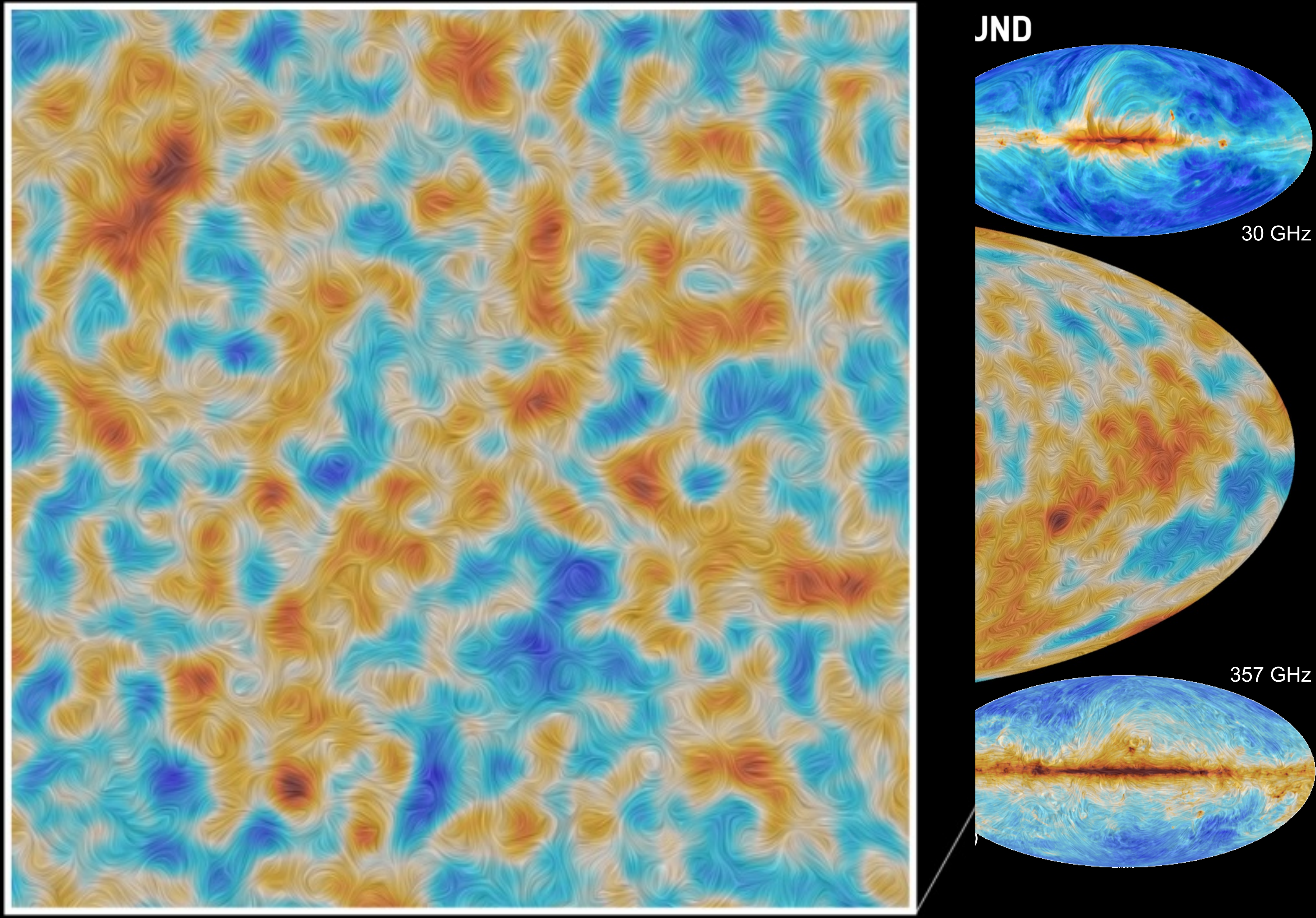


Température : ~100µK RMS

Mode E : ~4µK RMS

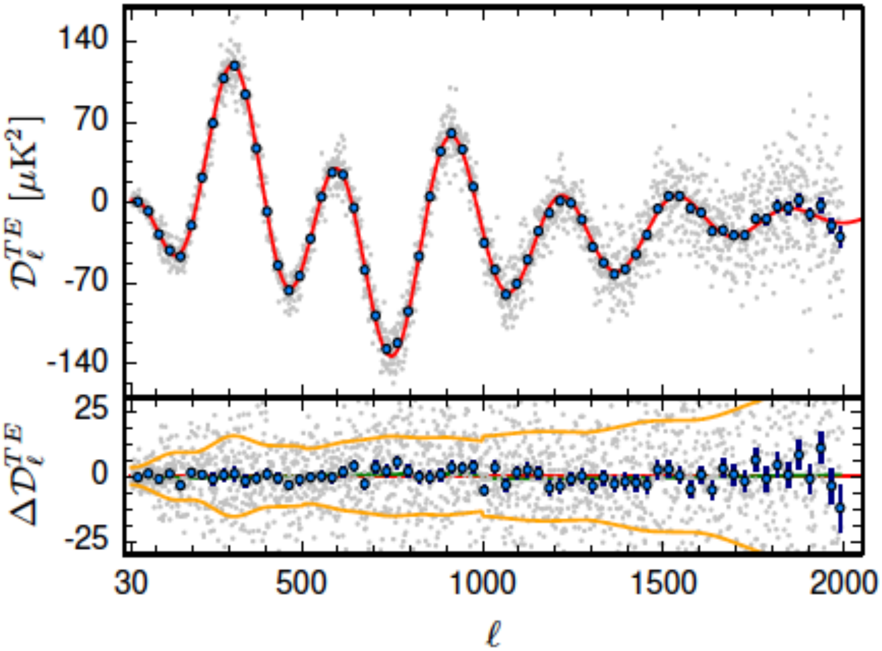
Mode B : < 300nK RMS

($\theta \approx 180 / l$)

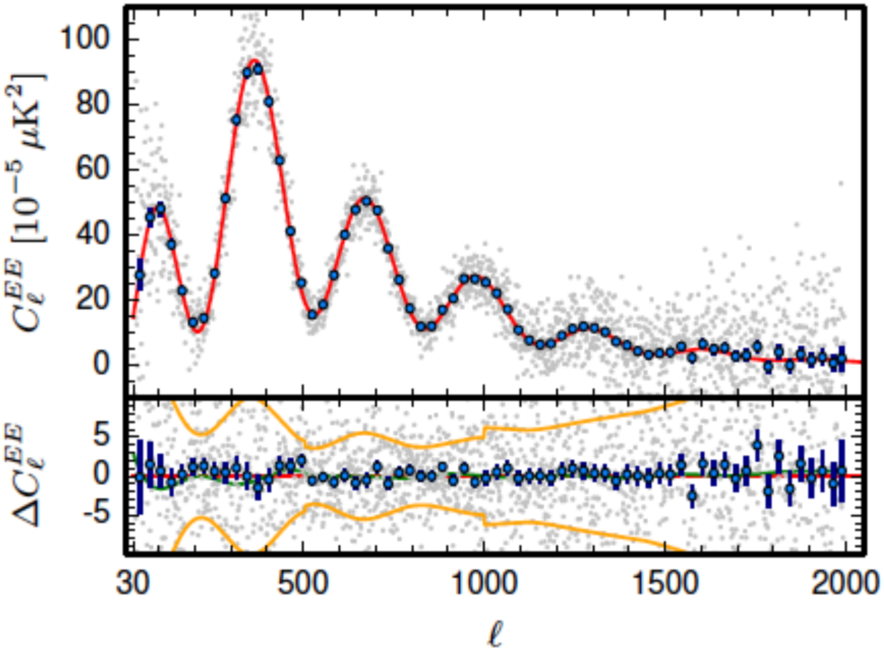


Filtered at 20 arcminutes

Planck 2015 - TE & EE spectra



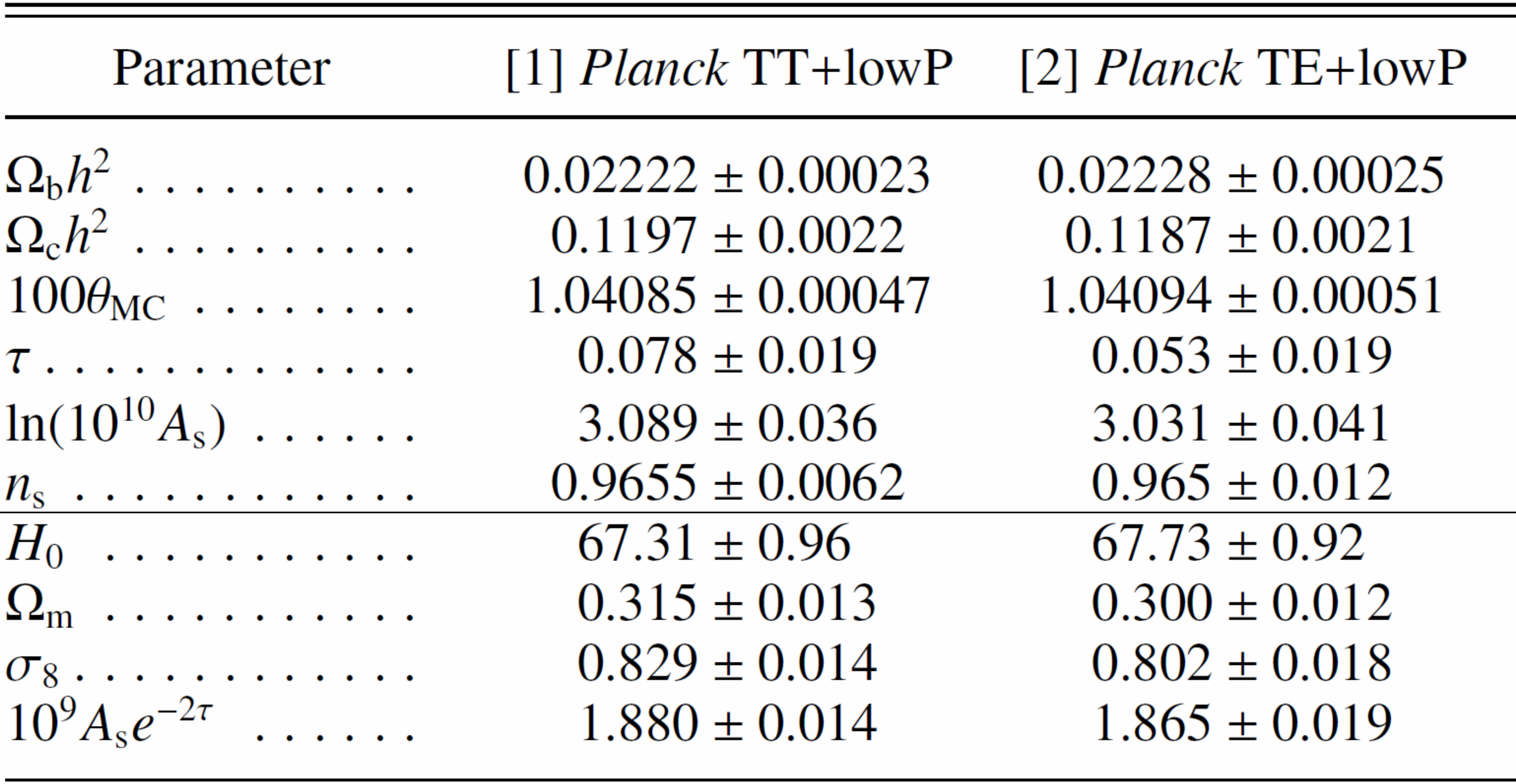
Frequency averaged spectrum reduced ^{2} = 1.04



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).

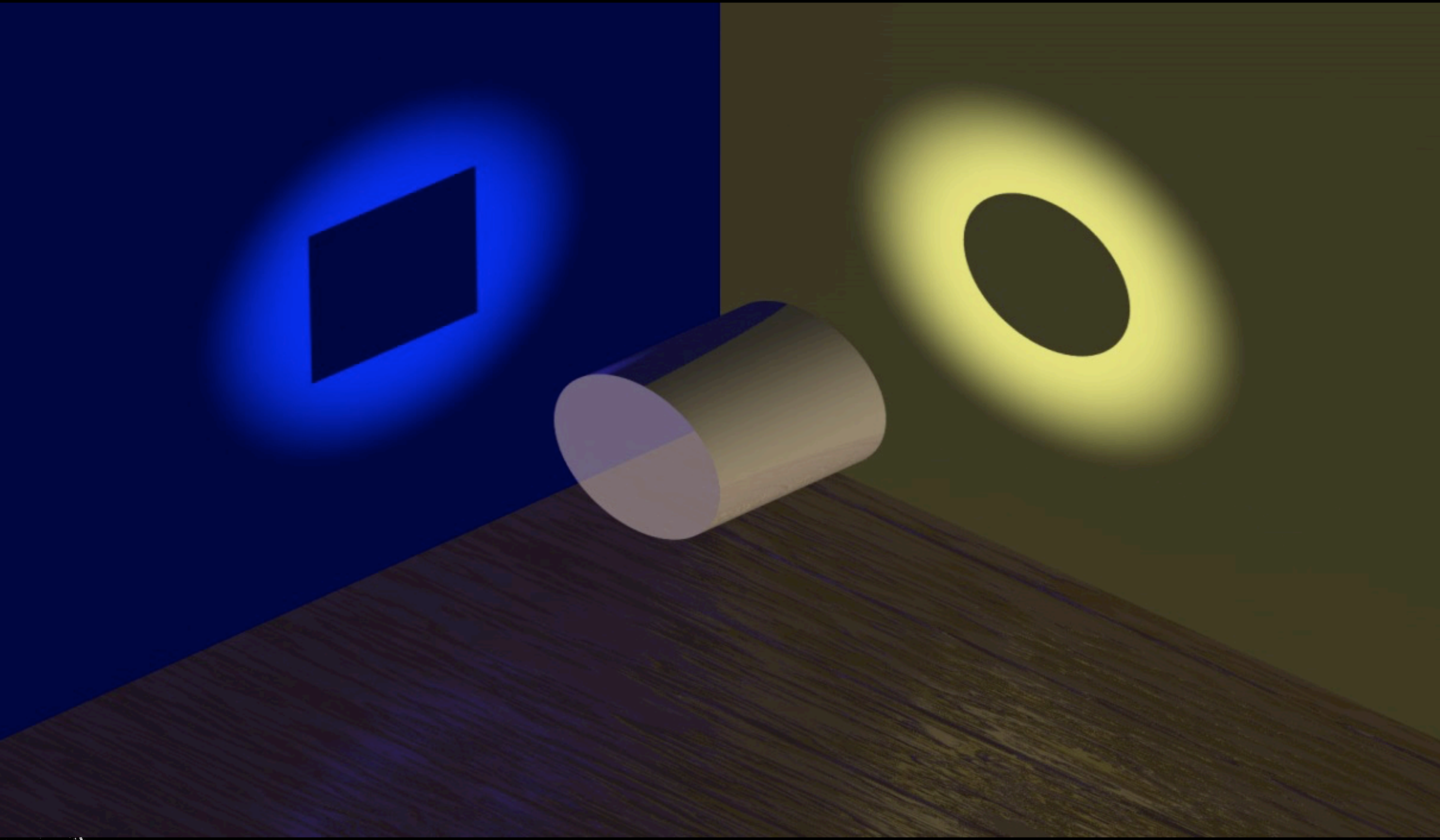
Base ΛCDM model



Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051
τ	0.078 ± 0.019	0.053 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041
n_s	0.9655 ± 0.0062	0.965 ± 0.012
H_0	67.31 ± 0.96	67.73 ± 0.92
Ω_m	0.315 ± 0.013	0.300 ± 0.012
σ_8	0.829 ± 0.014	0.802 ± 0.018
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019

TT & TE have quite similar uncertainties (but for n_s),
but beware that they are still some low level systematics in the polarisation data

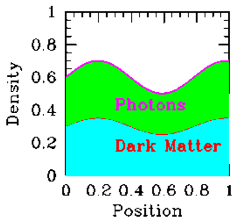
This was not granted!

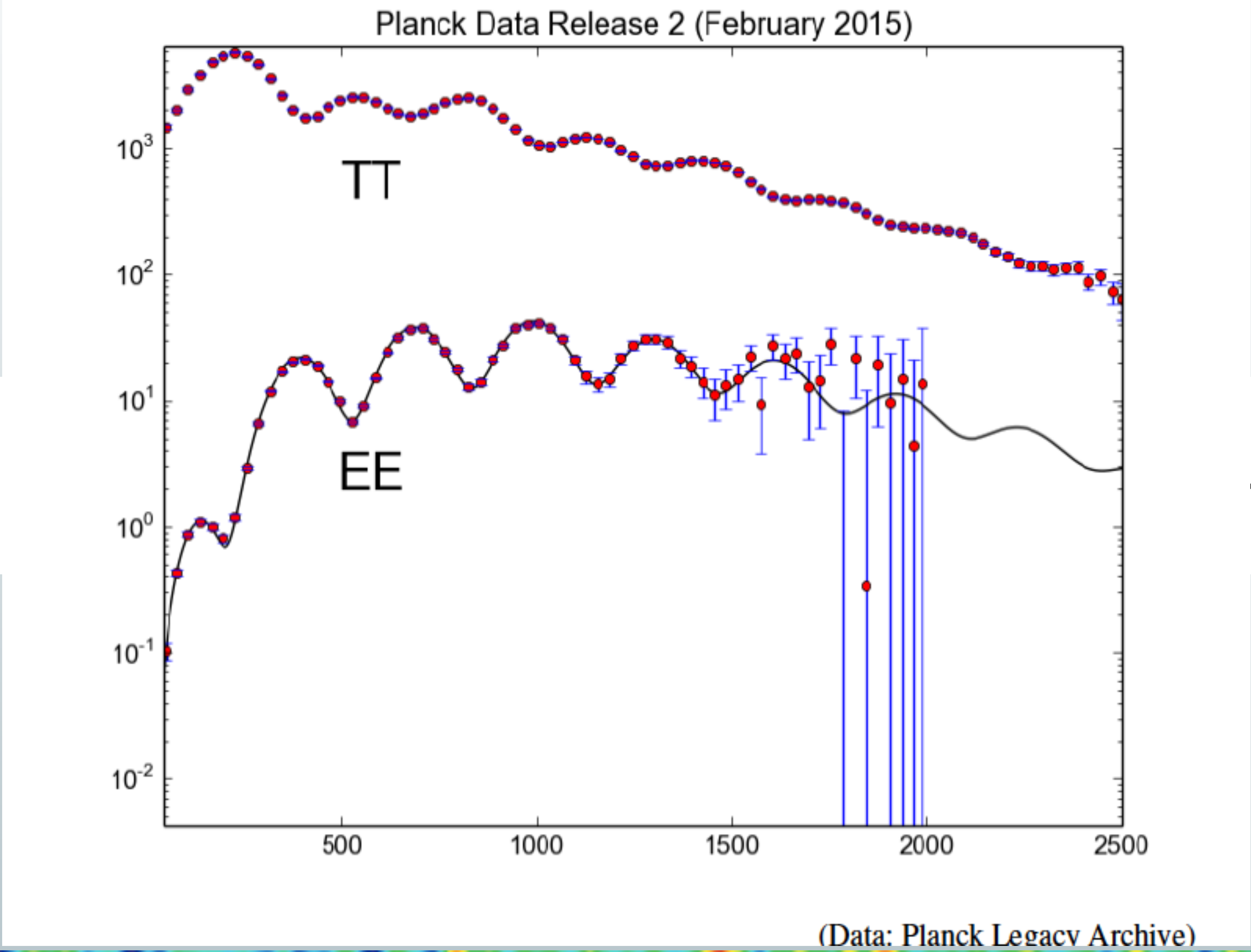


And it further constrains potential deviations from the base tilted LCDM model/physics

Adiabaticity ?

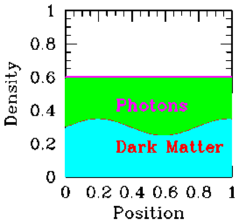
Adiabatic IC





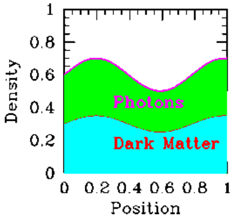
(Data: Planck Legacy Archive)

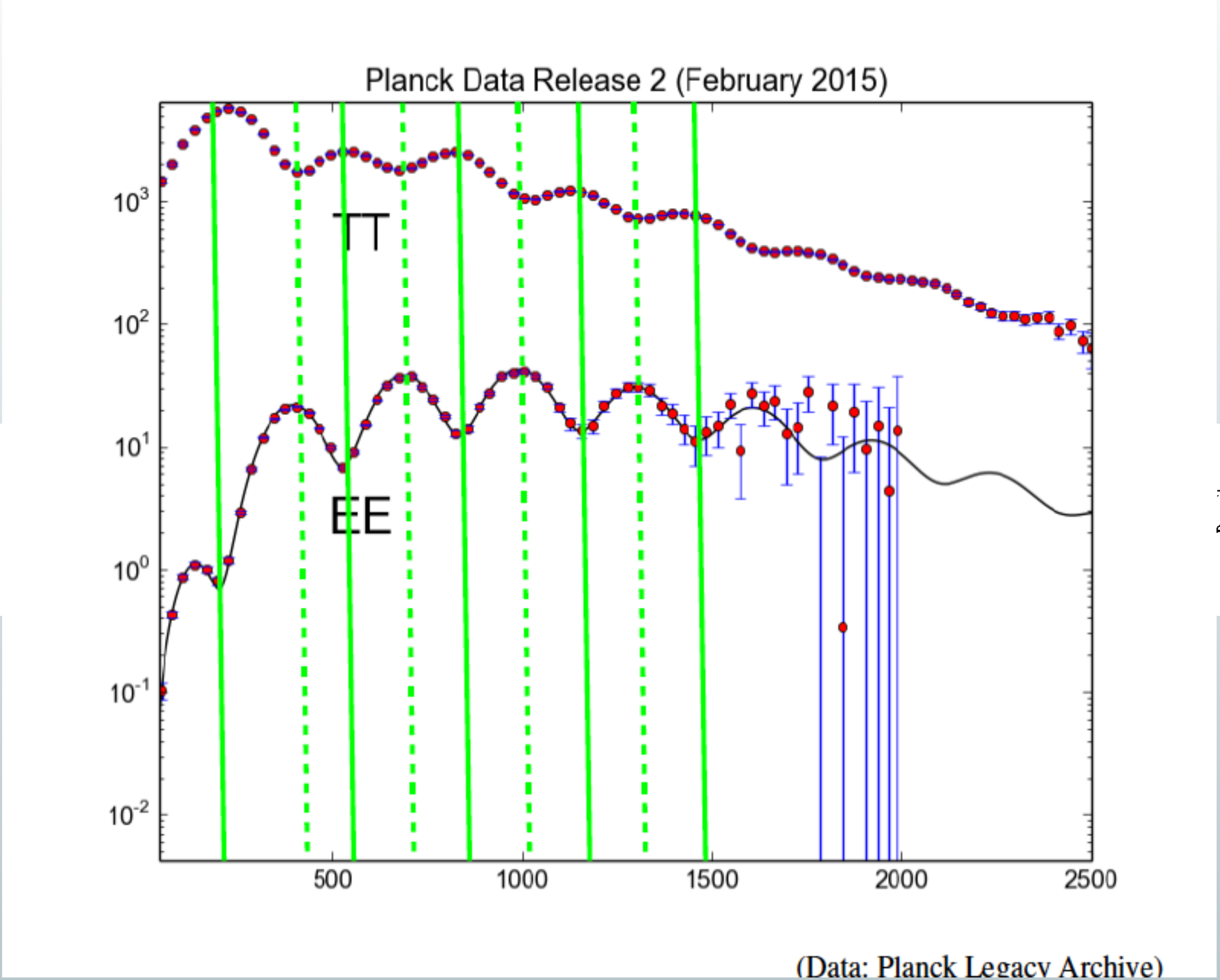
Isocurvature IC



Adiabaticity ✔

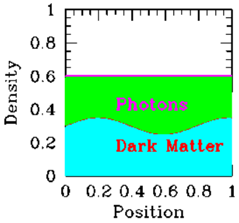
Adiabatic IC





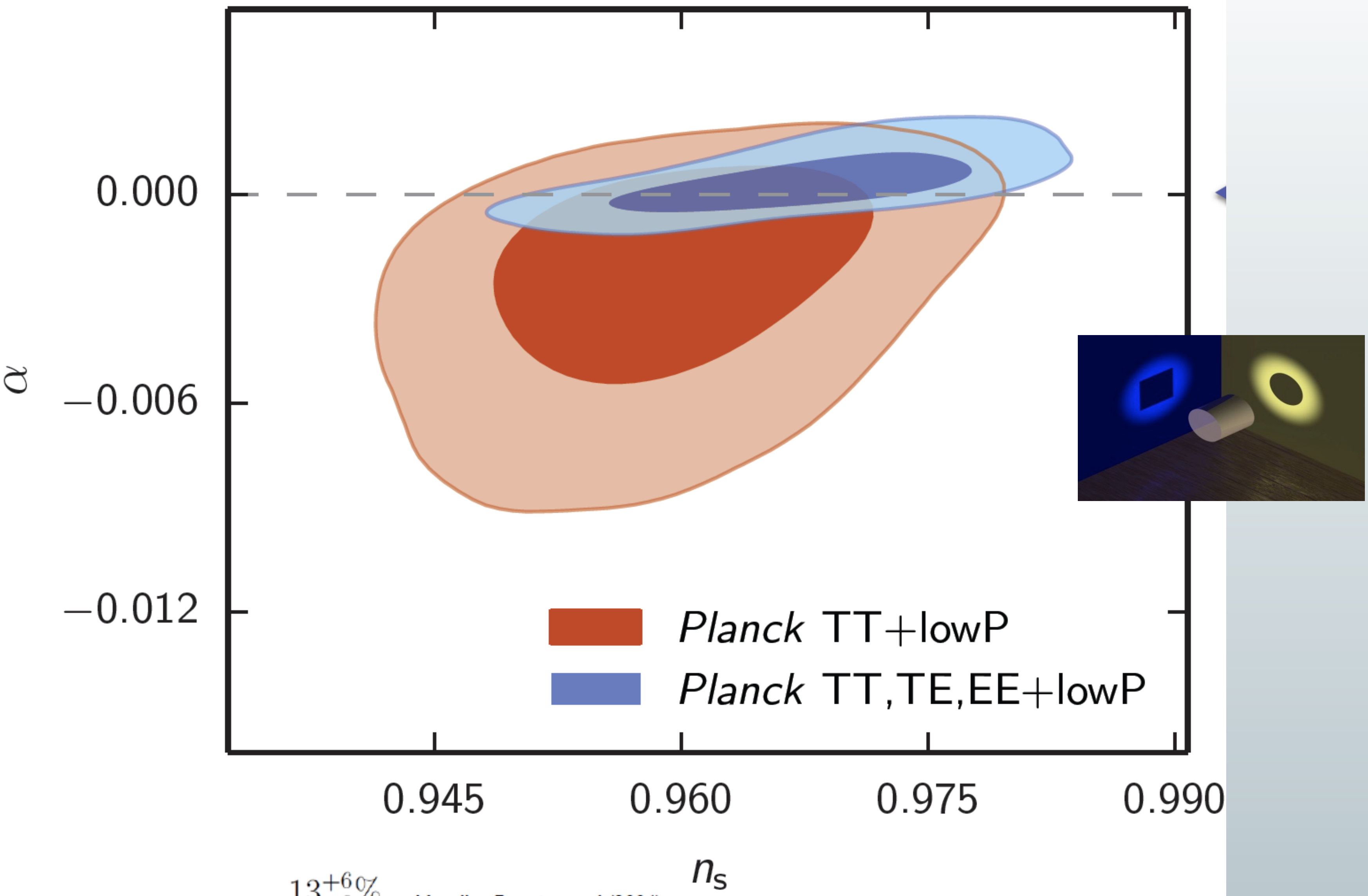
(Data: Planck Legacy Archive)

Isocurvature IC



Kinney

Isocurvature modes fraction

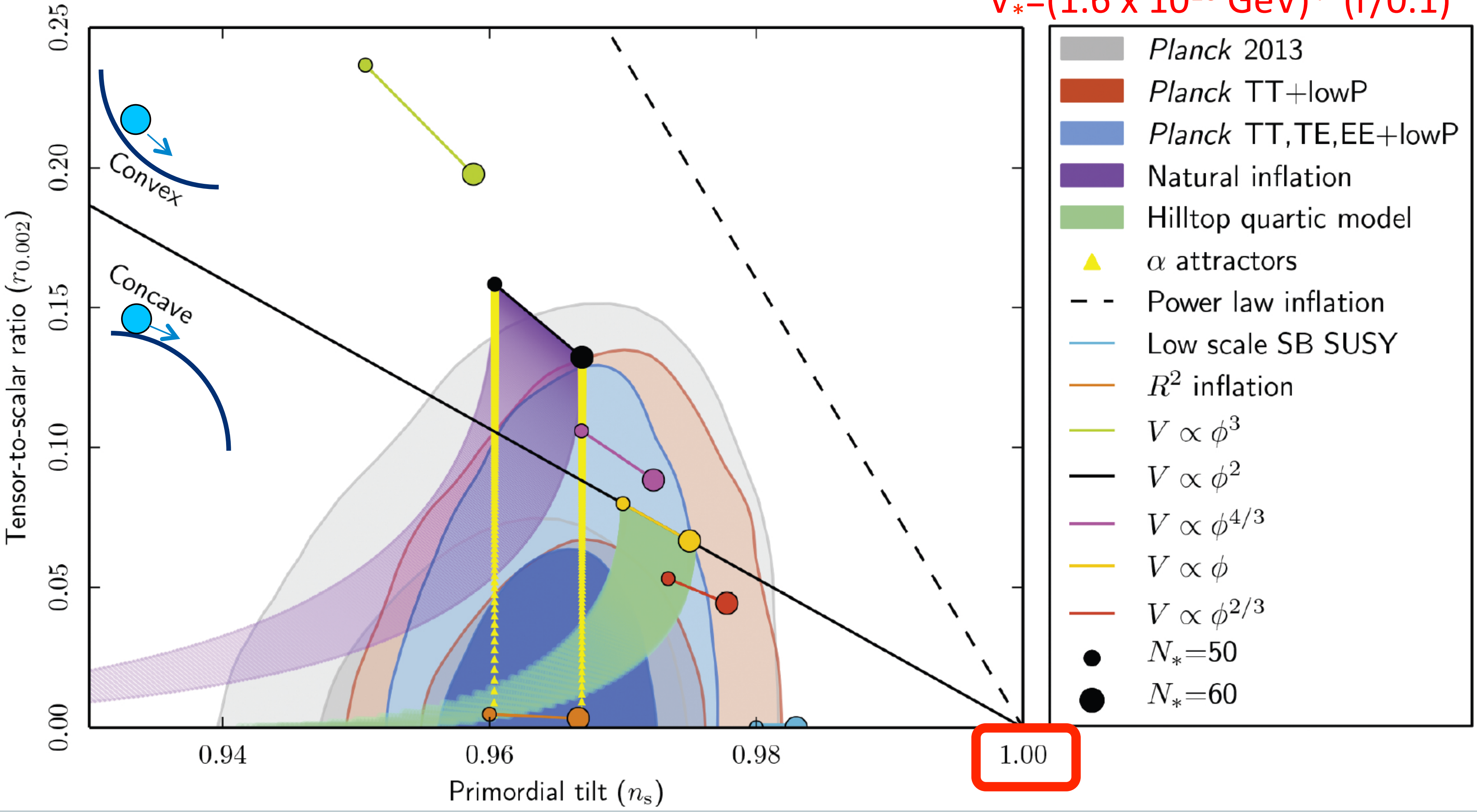


Percentage of isocurvature: $13^{+6}_{-6}\%$ Moodley, Ferreira et al (2004)

$1^{+0.5}_{-0.9}\%$ Planck (2015) (conservative)

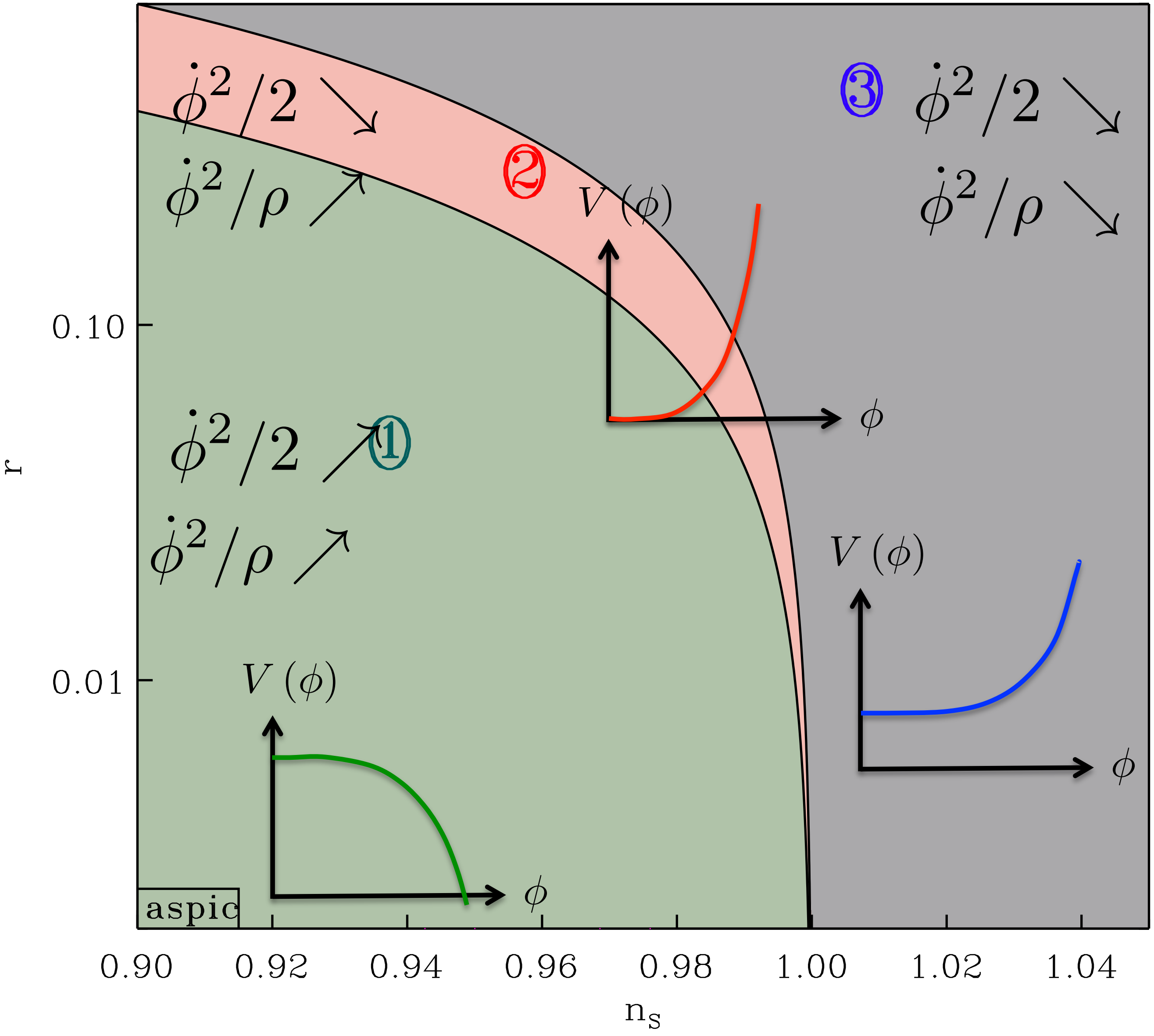
Planck 2015: n_s vs r

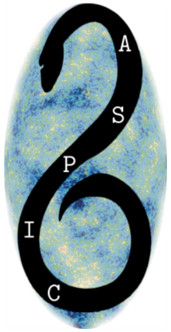
$V_* = (1.6 \times 10^{16}\ \mathrm{GeV})^4\ (r/0.1)$



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

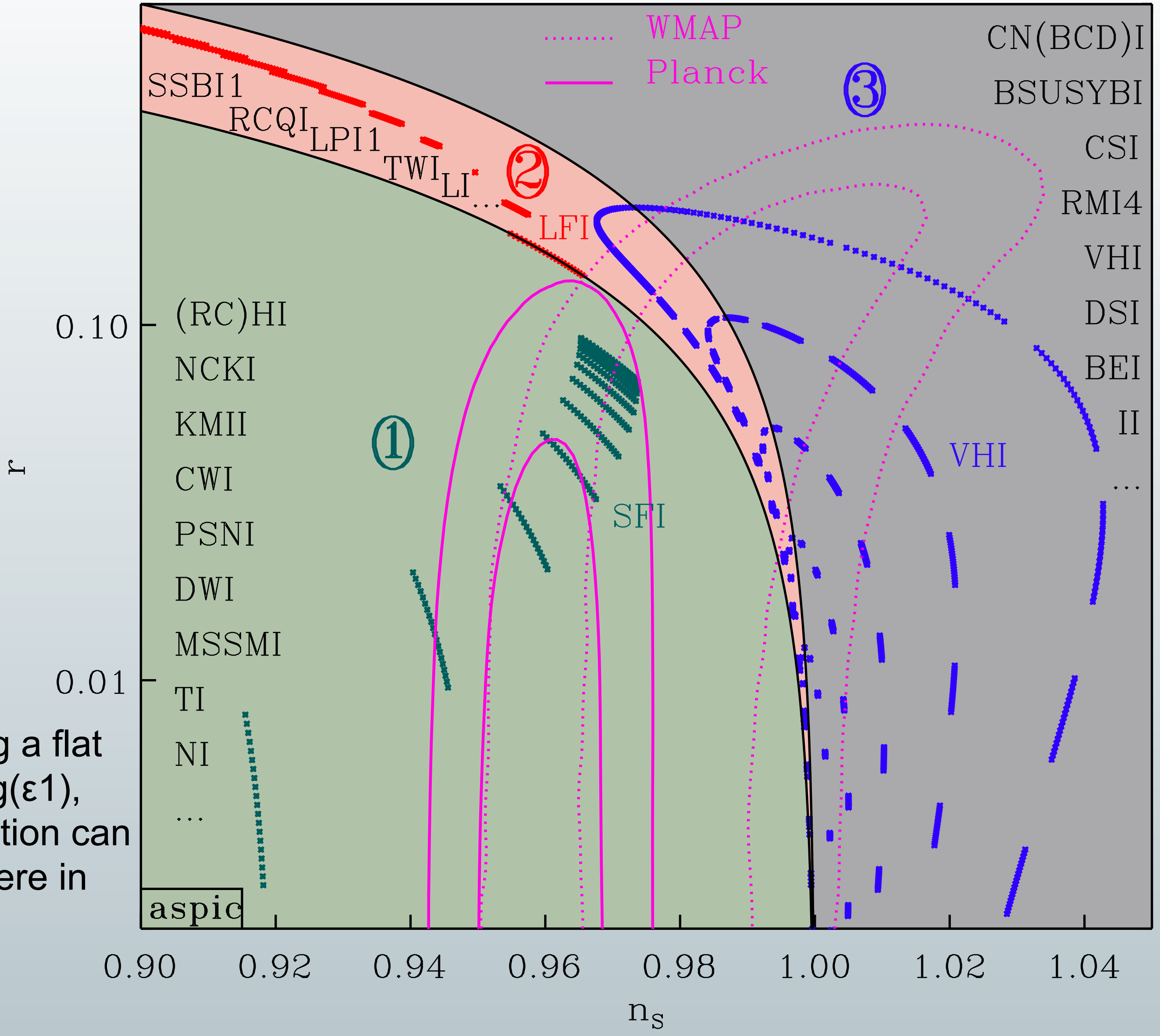
Typological classification





(single field, slow-roll)

Theory space



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

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

NB: This illustration is for Planck 2013

6 parameters Base LCDM model

- An incredibly minimal model, deceptively simple,

  since it relies on far reaching assumptions, e.g.,

  - *The Physics laws are everywhere the same at all times*
  - *The Universe is at large homogeneous and isotropic*

  and on our two main fundamental theories, GR & QM, at scales quite larger than those directly tested.

  - *On GR, quoting J. Peebles at IAU2000:*

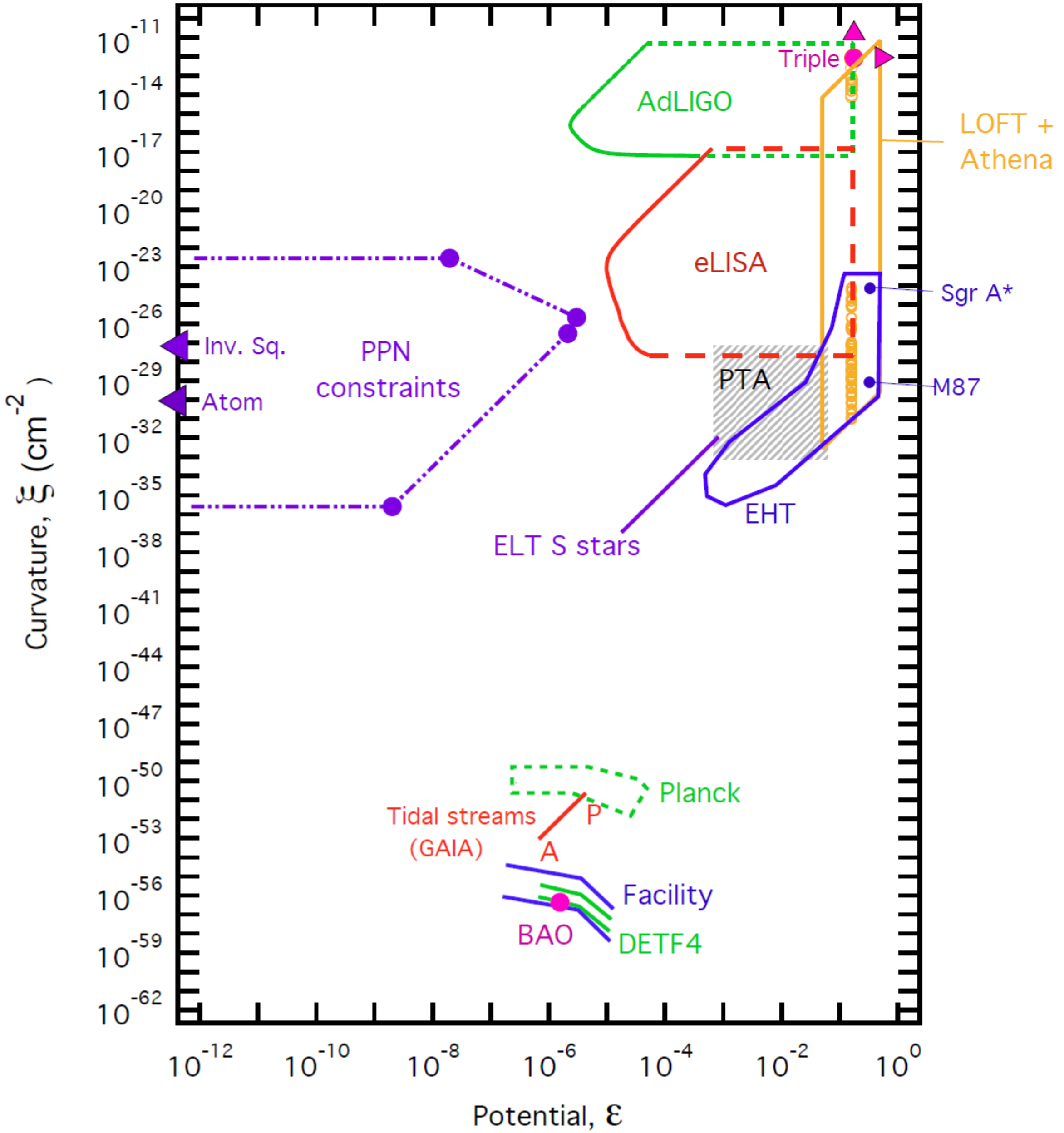
    "The elegant logic of general relativity theory, and its precision tests, recommend GR as the first choice for a working model for cosmology. But the Hubble length is fifteen orders of magnitude larger than the length scale of the precision tests, at the astronomical unit and smaller, a spectacular extrapolation."

  - *Ditto for Quantum Mechanics*

  Intertwined with much of classical physics in clockwork fashion

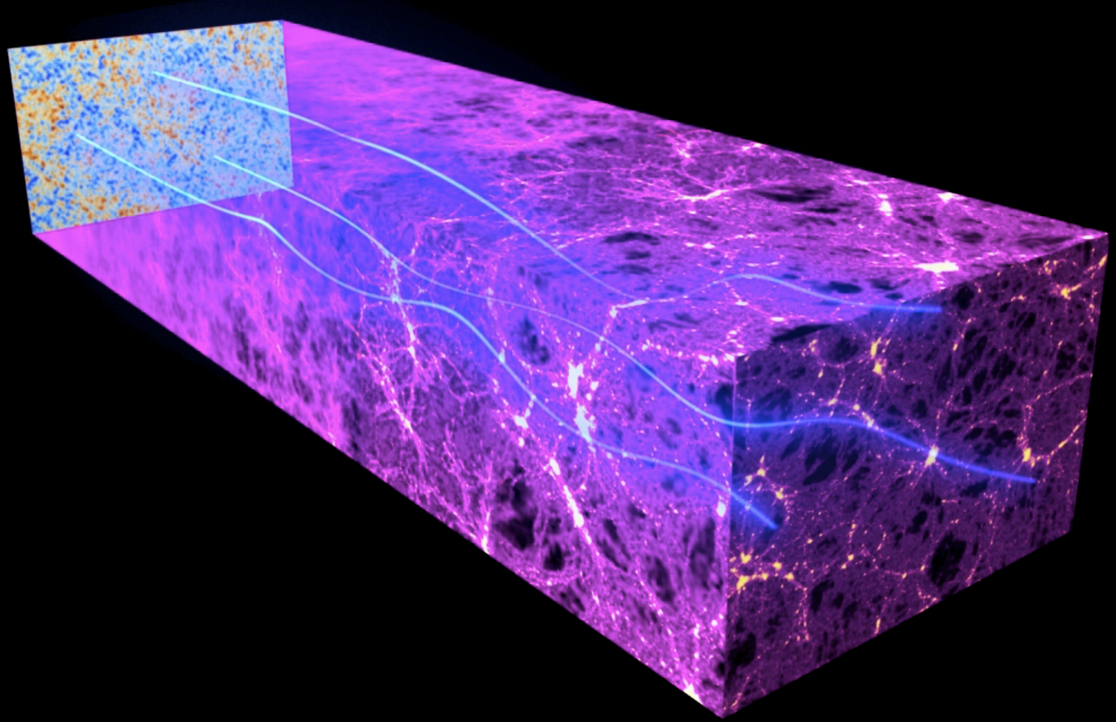
  … assumptions which can now actually be tested…

Baker et al. ArXiv:1412.3455



GRAVITATIONAL LENSING DISTORTS IMAGES

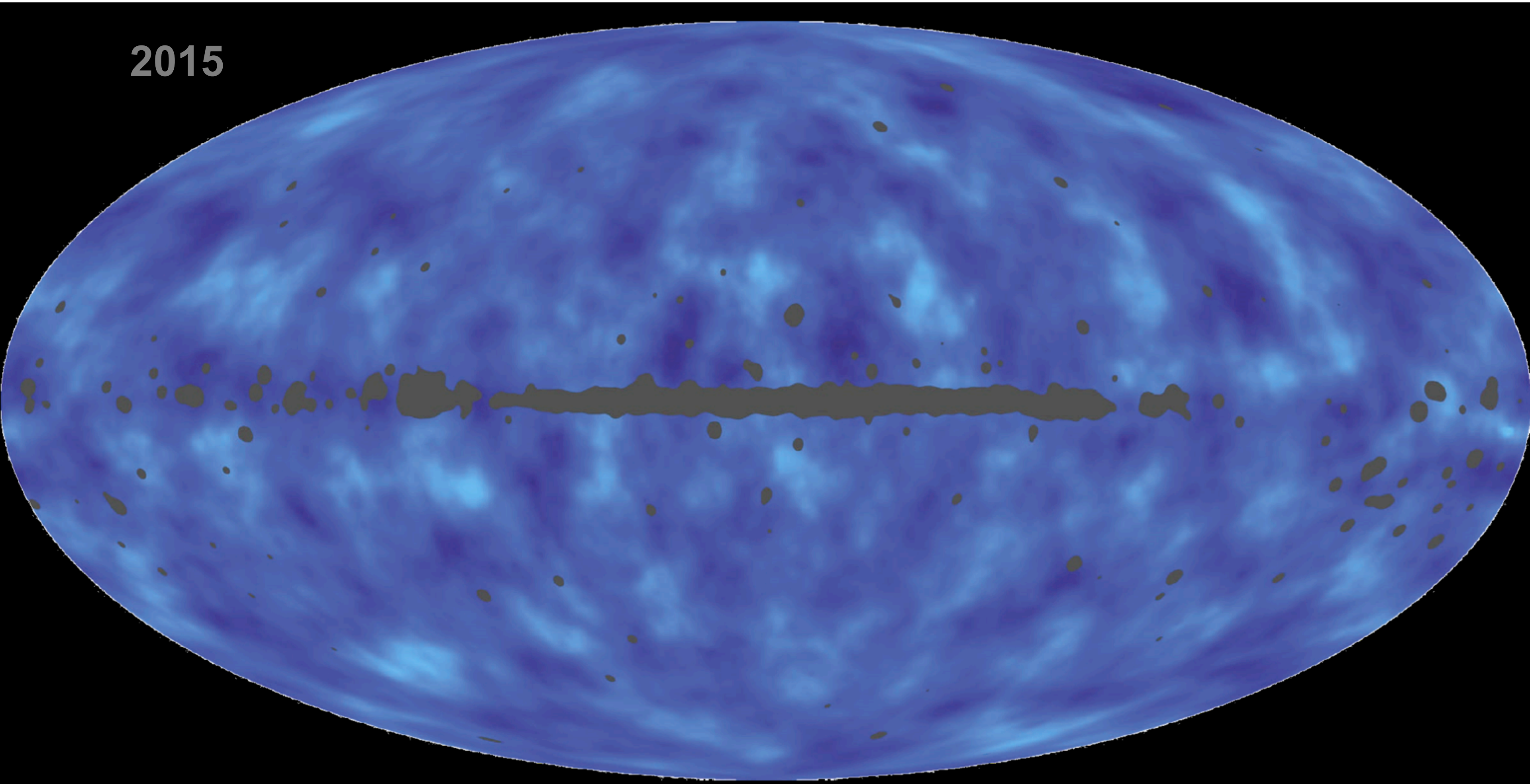
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



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

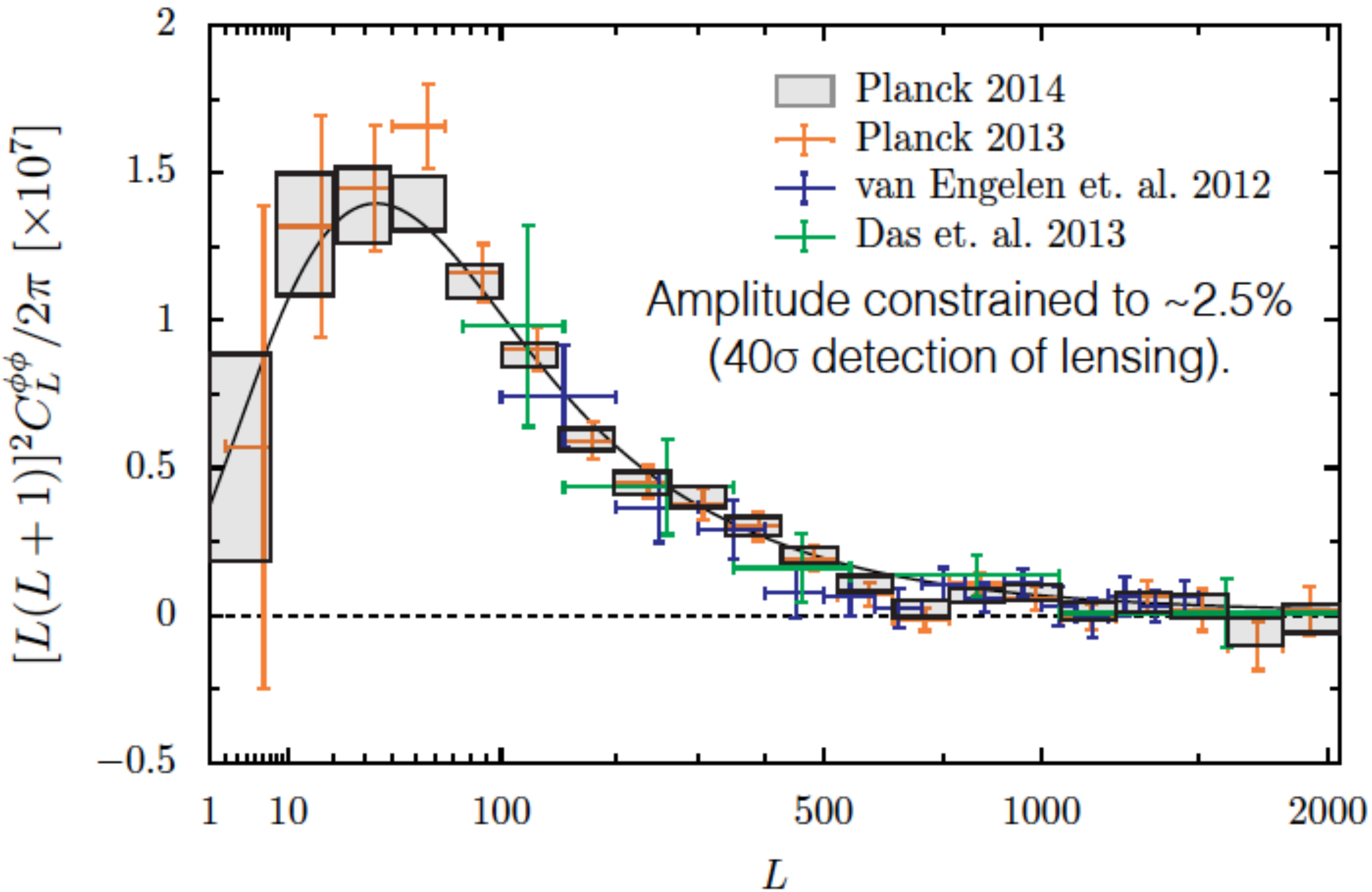
$$\bar{\phi} = \Delta^{-1}\vec{\nabla}\cdot[C^{-1}T\,\vec{\nabla}(C^{-1}T)]$$

Projected mass map



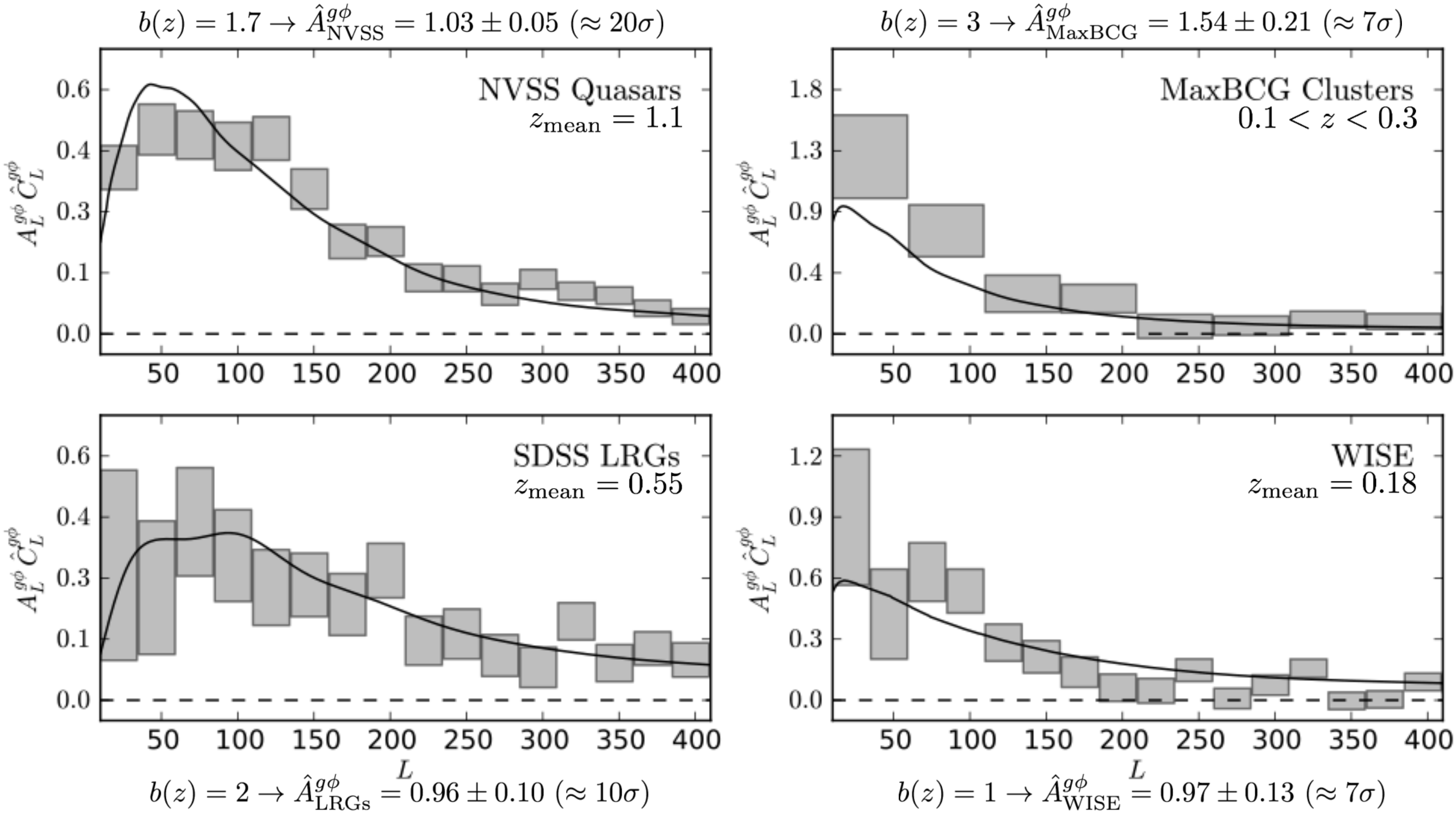
The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

Lensing power spectrum



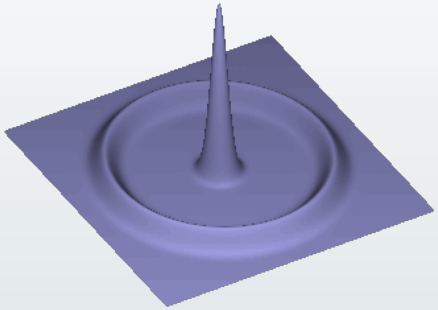
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

Lensing potential versus distribution of external tracers

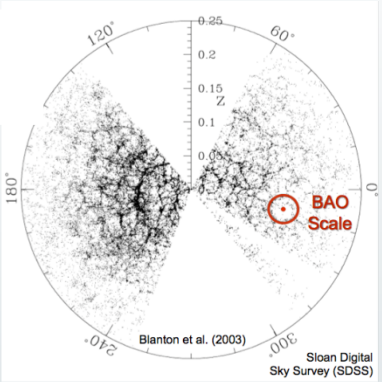


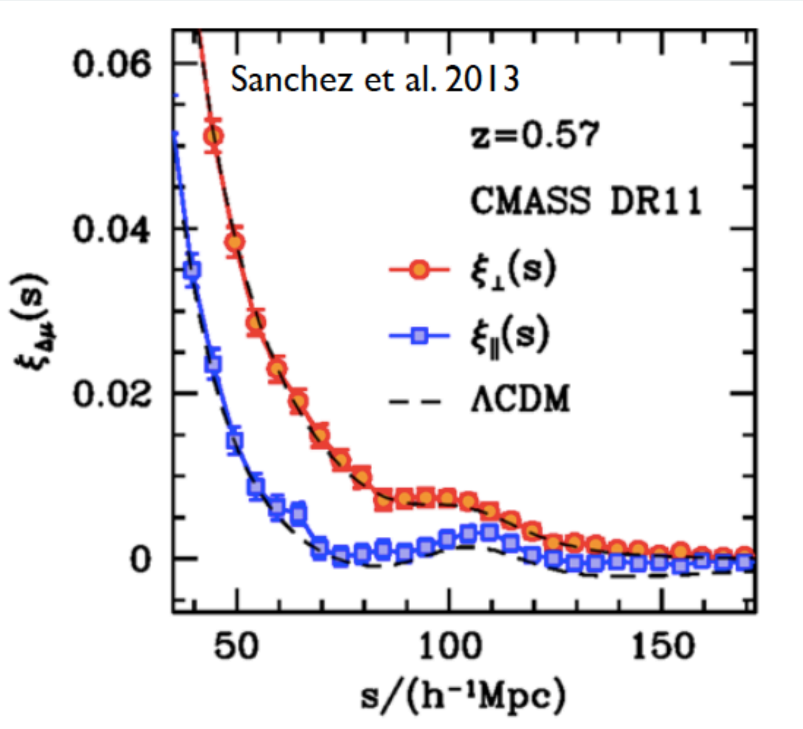
No particular effort here to optimize the model for the external survey

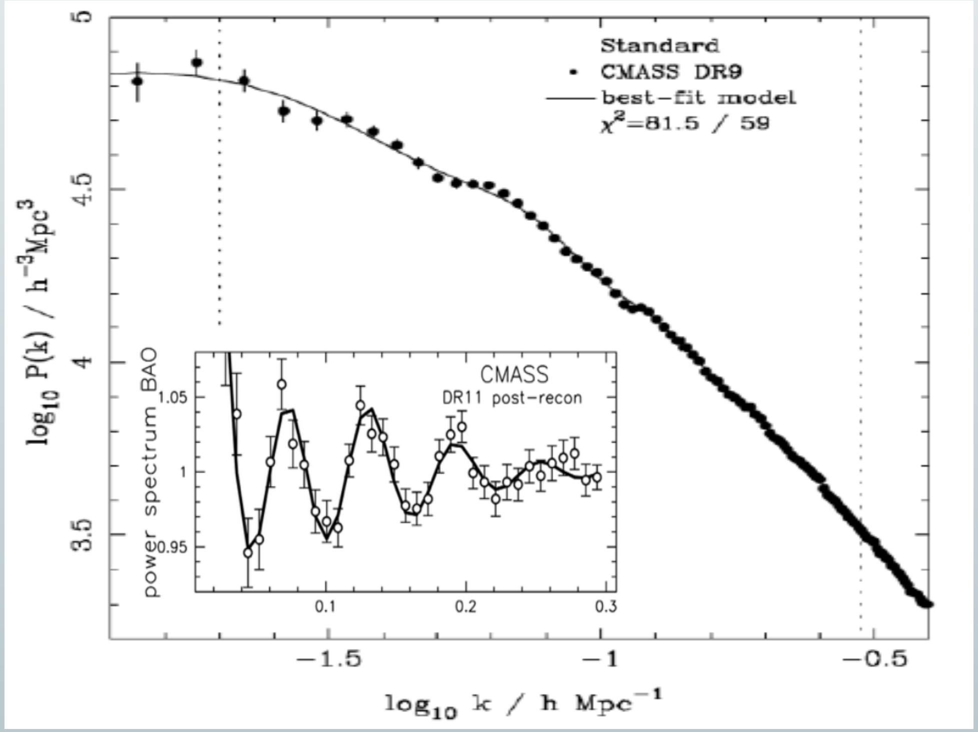
BAO: correlation function & power spectrum



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

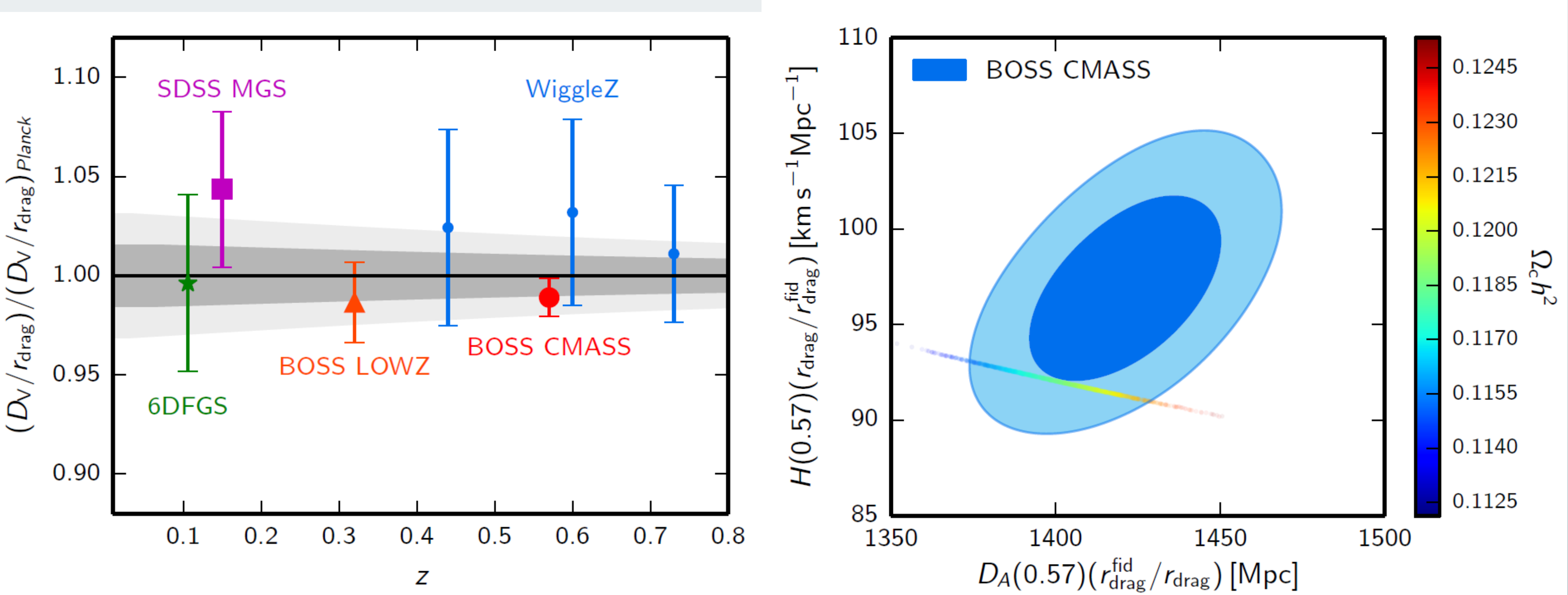






Baryonic Acoustic Oscillations (BAO)

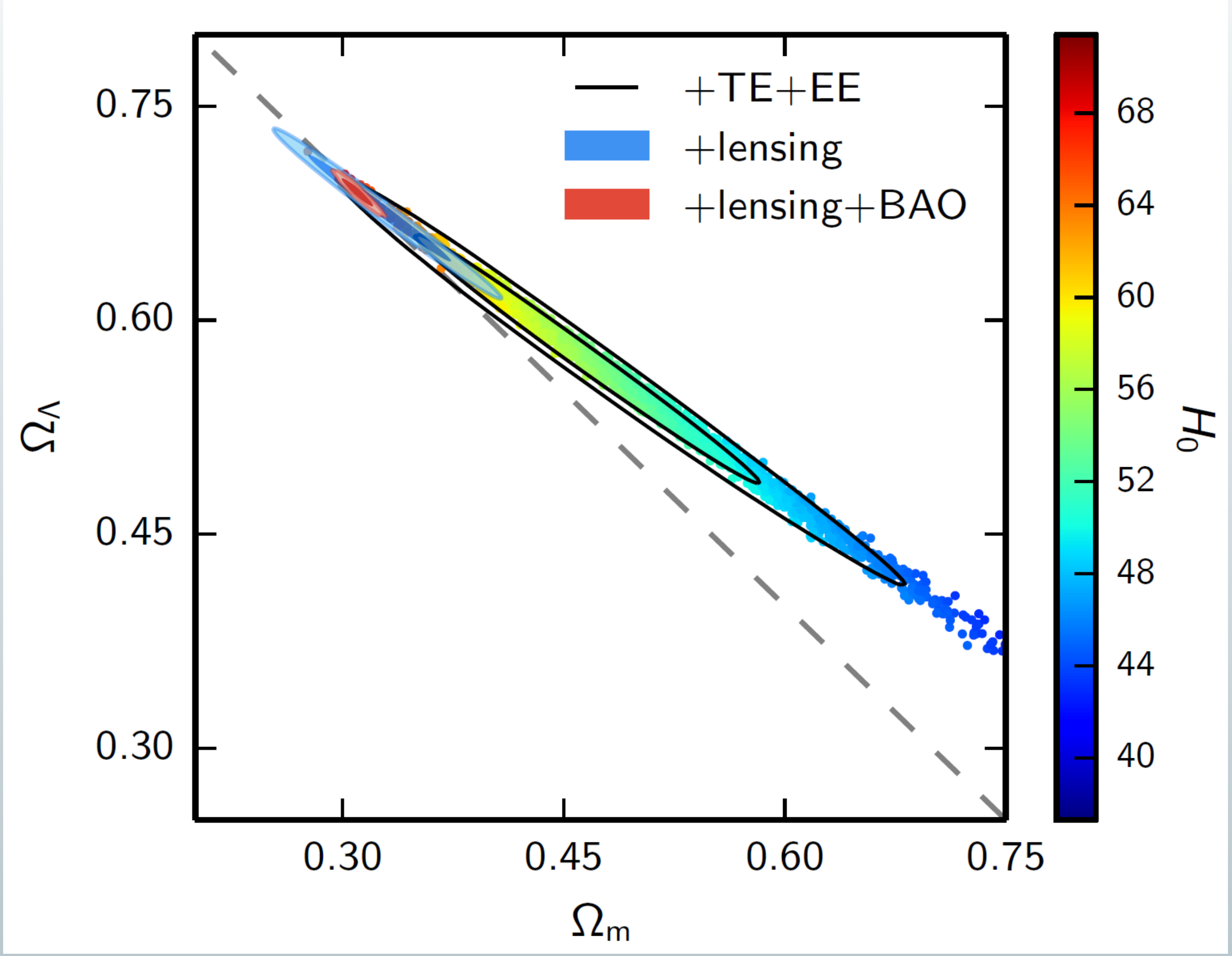
Grey band is Planck TT+LowP 1(2) sigma range



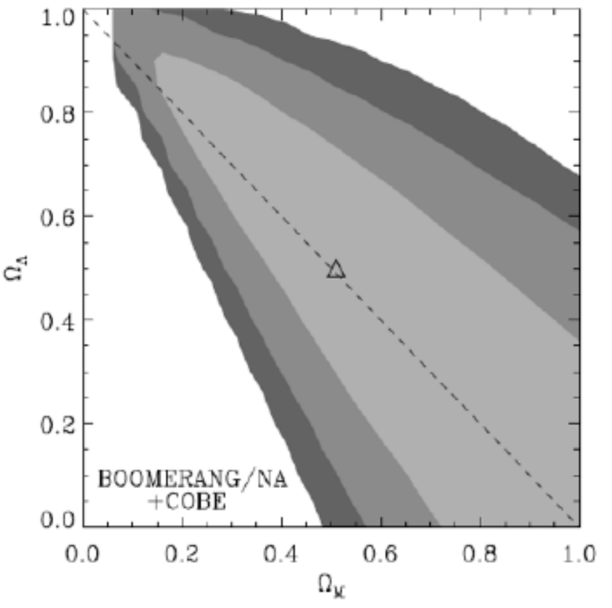
Acoustic-scale distance ratio, $D_V(z)/r_s$, divided by the distance ratio of the Planck TT base model.

Spatial curvature constraint

$$\Omega_k = 0.000 \pm 0.005 \ (95\% \ \mathrm{CL})$$

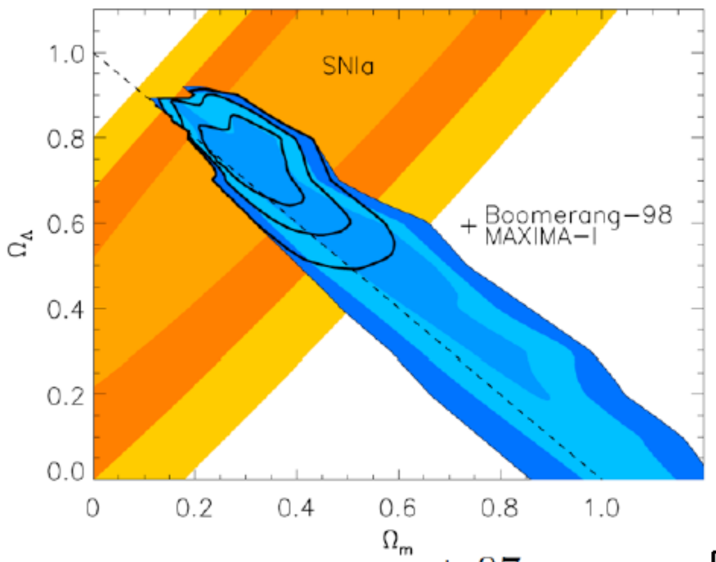


Spatial curvature constraint



$$\Omega_K = -0.05^{+.40}_{-.40}$$

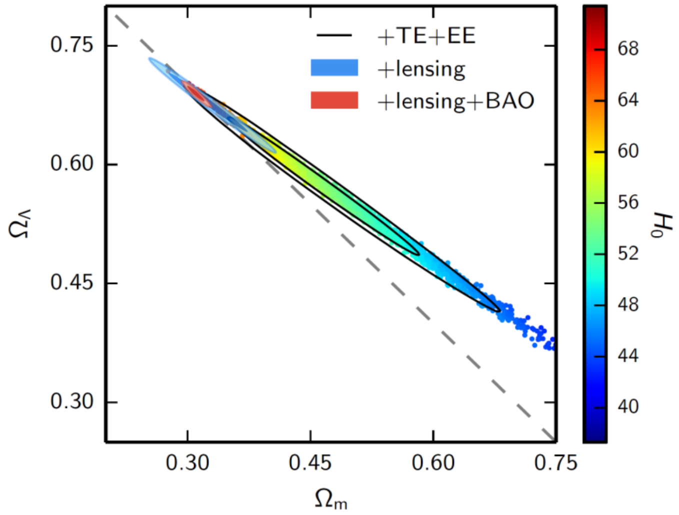
Melchiorri et al. 2000



$$\Omega_K = -0.11^{+.07}_{-.07}$$

Jaffe et al. 2001

Note the change of axes
For Planck below

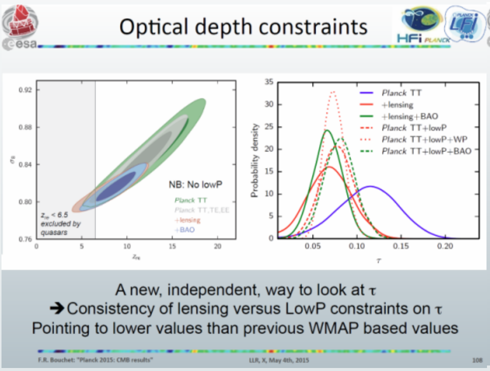


Planck 2015

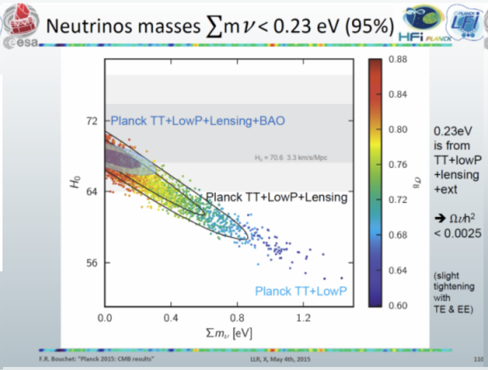
$$\Omega_k = 0.000 \pm 0.005 \ (95\% \ \mathrm{CL})$$

A hundred-fold improvement in 15 years

We can test & constrain a lot more…


Optical depth constraints

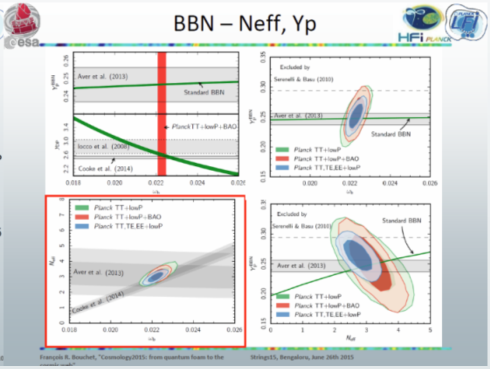
A new, independent, way to look at τ
➔Consistency of lensing versus LowP constraints on τ
Pointing to lower values than previous WMAP based values

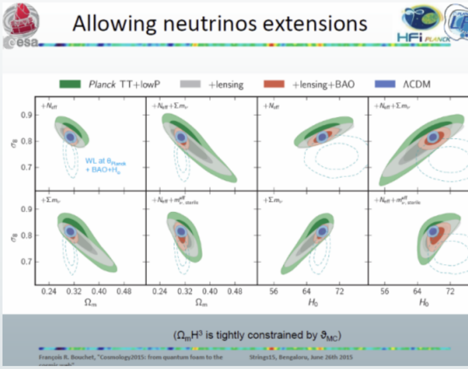

Neutrinos masses $\sum m_\nu < 0.23$ eV (95%)

0.23eV is from TT+lowP +lensing +ext

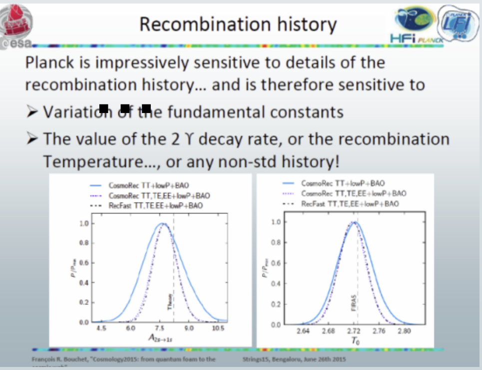
➔ $\Omega_\nu h^2 < 0.0025$

(slight tightening with TE & EE)

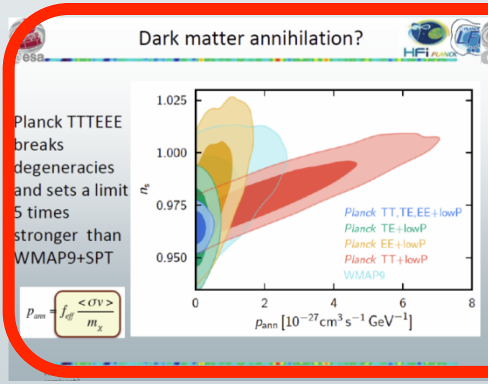

BBN – Neff, Yp


Allowing neutrinos extensions

($\Omega_m H^3$ is tightly constrained by ϑ_{MC})

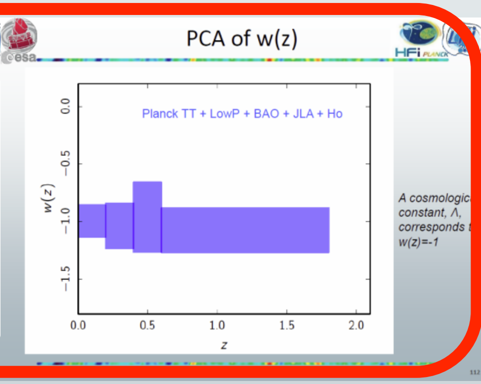

Recombination history

Planck is impressively sensitive to details of the recombination history… and is therefore sensitive to
- Variation of the fundamental constants
- The value of the 2 Υ decay rate, or the recombination Temperature…, or any non-std history!

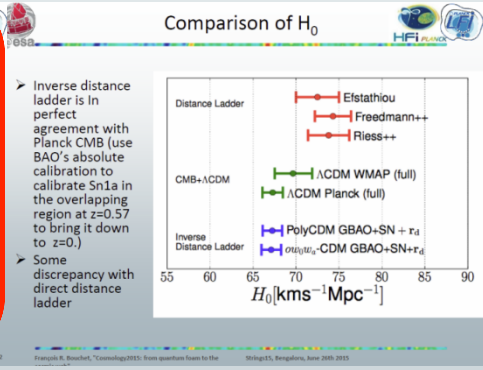

Dark matter annihilation?

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

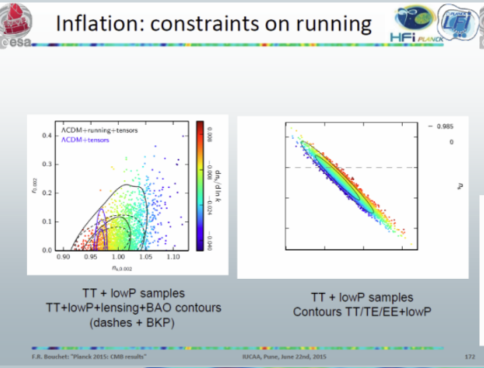
$$p_{ann} = f_{eff}\,\frac{<\sigma v>}{m_\chi}$$


PCA of w(z)

A cosmological constant, Λ, corresponds to w(z)=-1

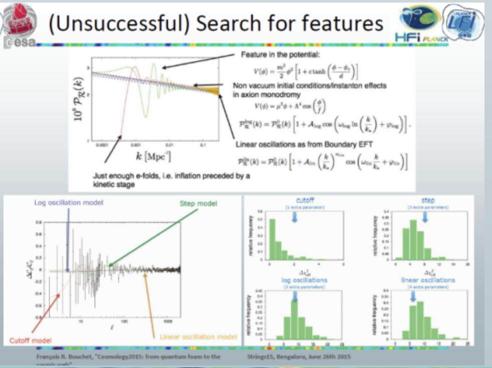

Comparison of H_0

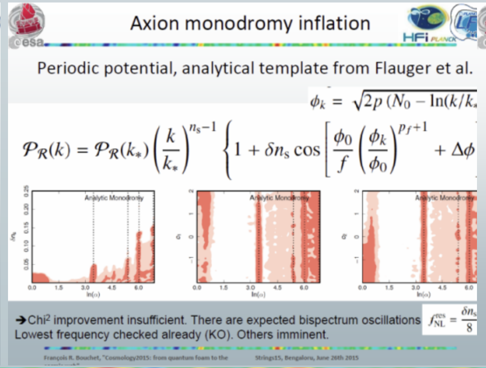
- Inverse distance ladder is In perfect agreement with Planck CMB (use BAO's absolute calibration to calibrate Sn1a in the overlapping region at z=0.57 to bring it down to z=0.)
- Some discrepancy with direct distance ladder


Inflation: constraints on running

TT + lowP samples
TT+lowP+lensing+BAO contours
(dashes + BKP)

TT + lowP samples
Contours TT/TE/EE+lowP


(Unsuccessful) Search for features

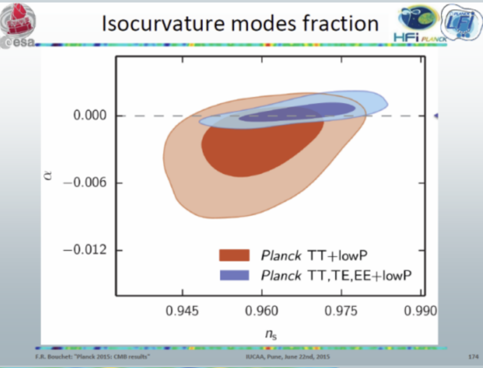

Axion monodromy inflation

Periodic potential, analytical template from Flauger et al.

$$\phi_k = \sqrt{2p\,(N_0 - \ln(k/k_*$$

$$\mathcal{P}_\mathcal{R}(k) = \mathcal{P}_\mathcal{R}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left\{1 + \delta n_s \cos\left[\frac{\phi_0}{f}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1} + \Delta\phi\right.\right.$$

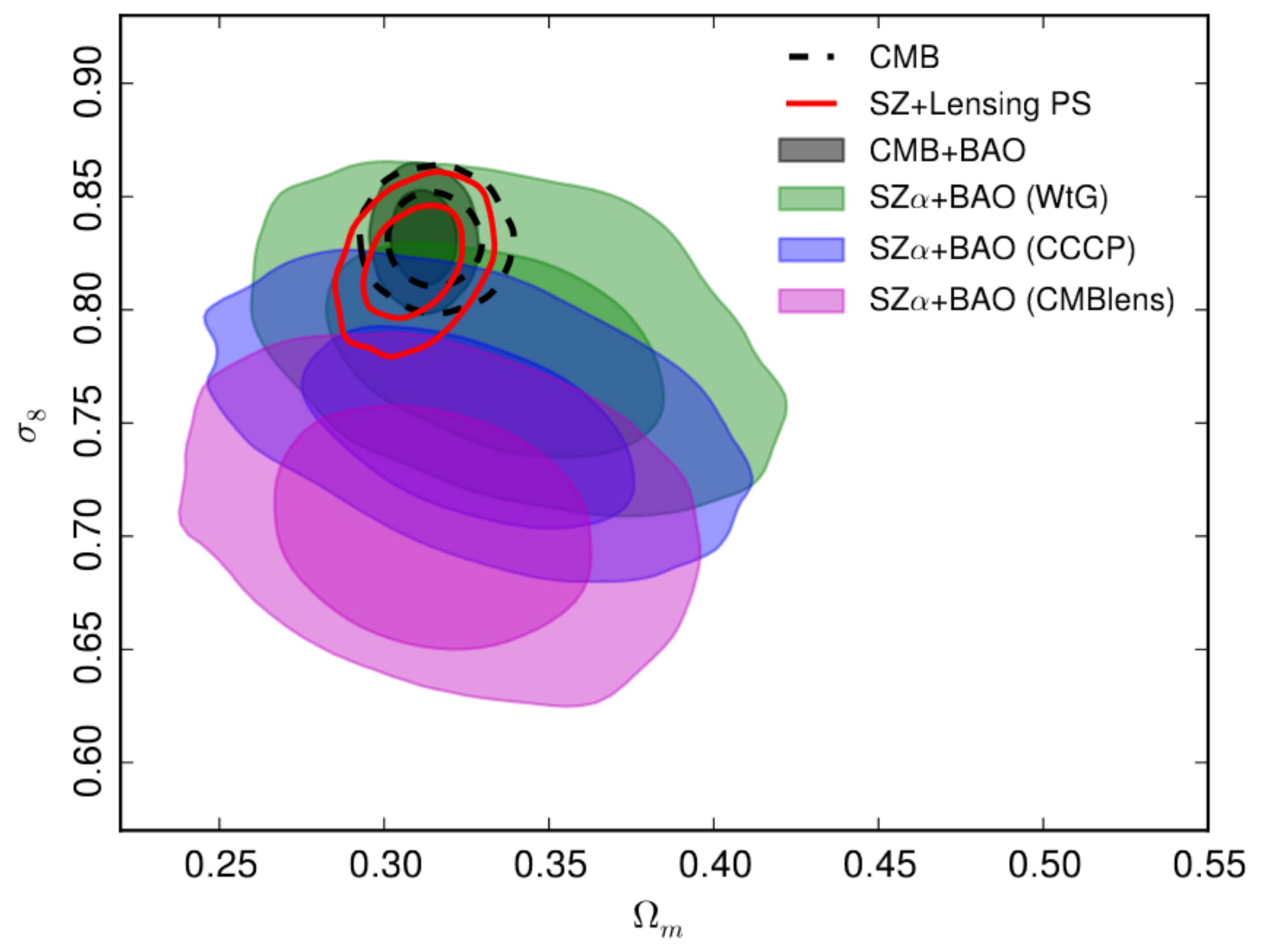
➔Chi² improvement insufficient. There are expected bispectrum oscillations $f_{NL}^{res} = \frac{\delta n_s}{8}$
Lowest frequency checked already (KO). Others imminent.


Isocurvature modes fraction

Standard cosmological model - LCDM

- The CMB TT, TE, EE, Φ-Φ, as well as BAO, BBN (but Li7), and SN1a measurements are all consistent, among themselves and across experiments, within LCDM.
- This network of consistency tests is passed **with per cent level precision.**
- These tests allow many different checks of the robustness of this base LCDM model and of some of its extensions, including τ constrained two-ways thanks to CMB lensing, flatness at 5 x 10^{-3} level, neutrinos masses and number, DM annihilation limits, w(z), details of the recombination history ($A_{2s\rightarrow1}$, T_0, and also fundamental constants variation, or any energy input…).

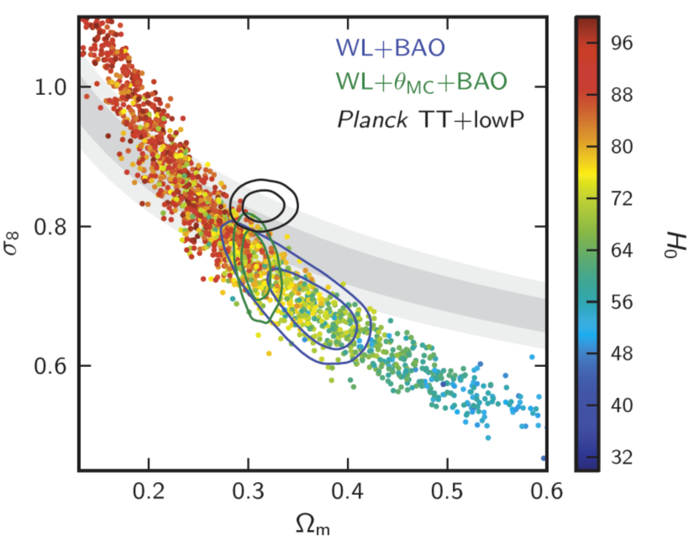
Number counts of SZ clusters



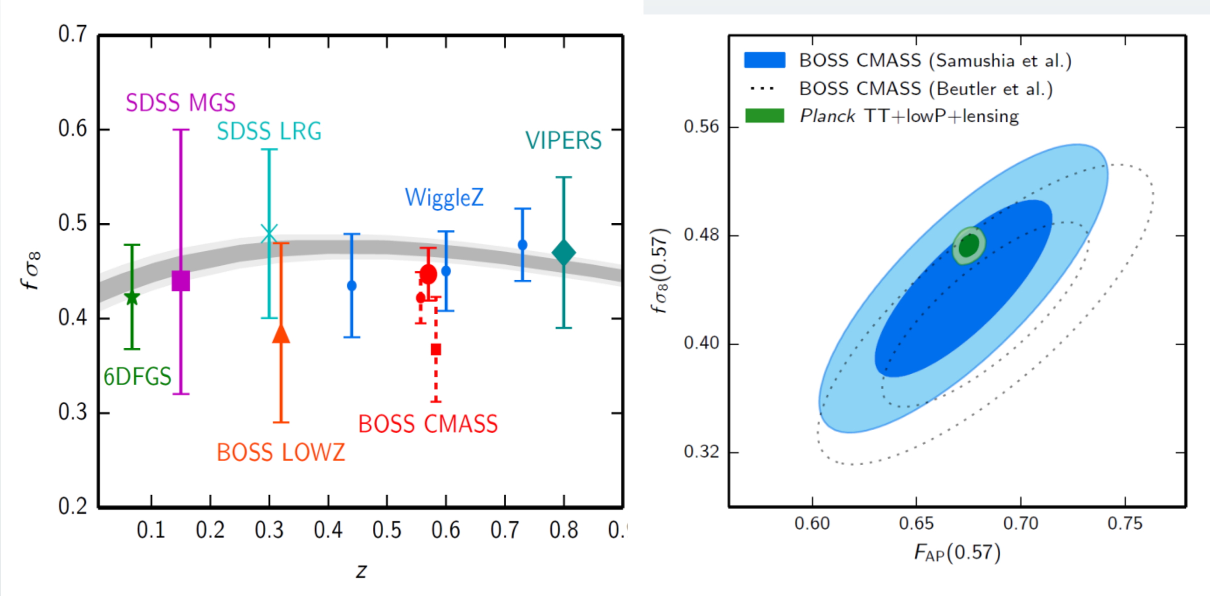
2013 tension only remains with **some** mass proxy calibration

Some tensions exist

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

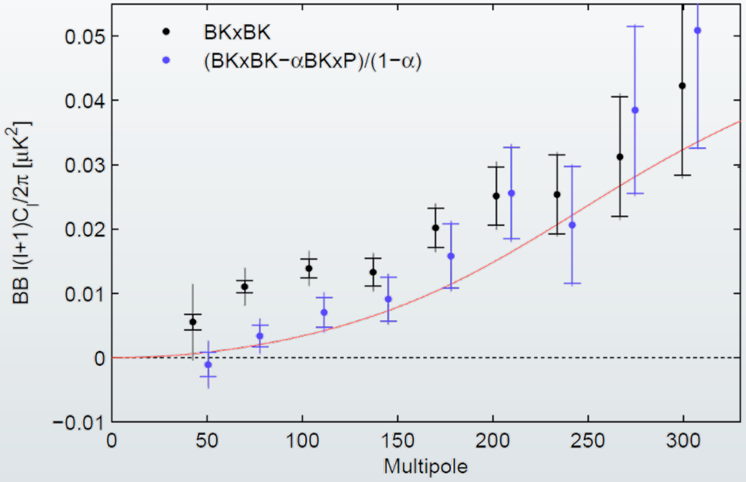
Planck X (Bicep2 & Keck)

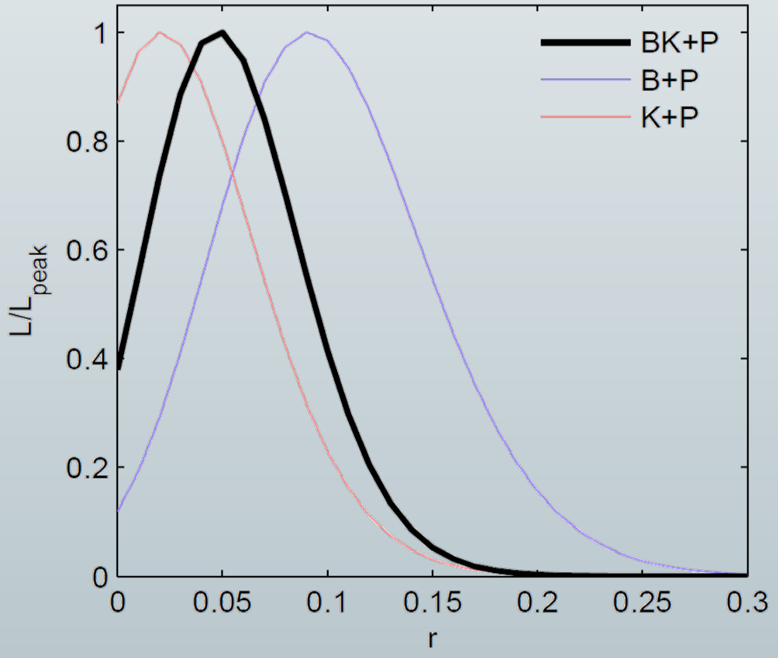
- ➢ Since January 30th 2015, the **direct** constraints on r (Planck X Bicep2 & Keck) have reached the level of the previous best **indirect constraints** (from Planck alone T), i.e.,

- ➢ $r < 0.11$ @ 95%CL

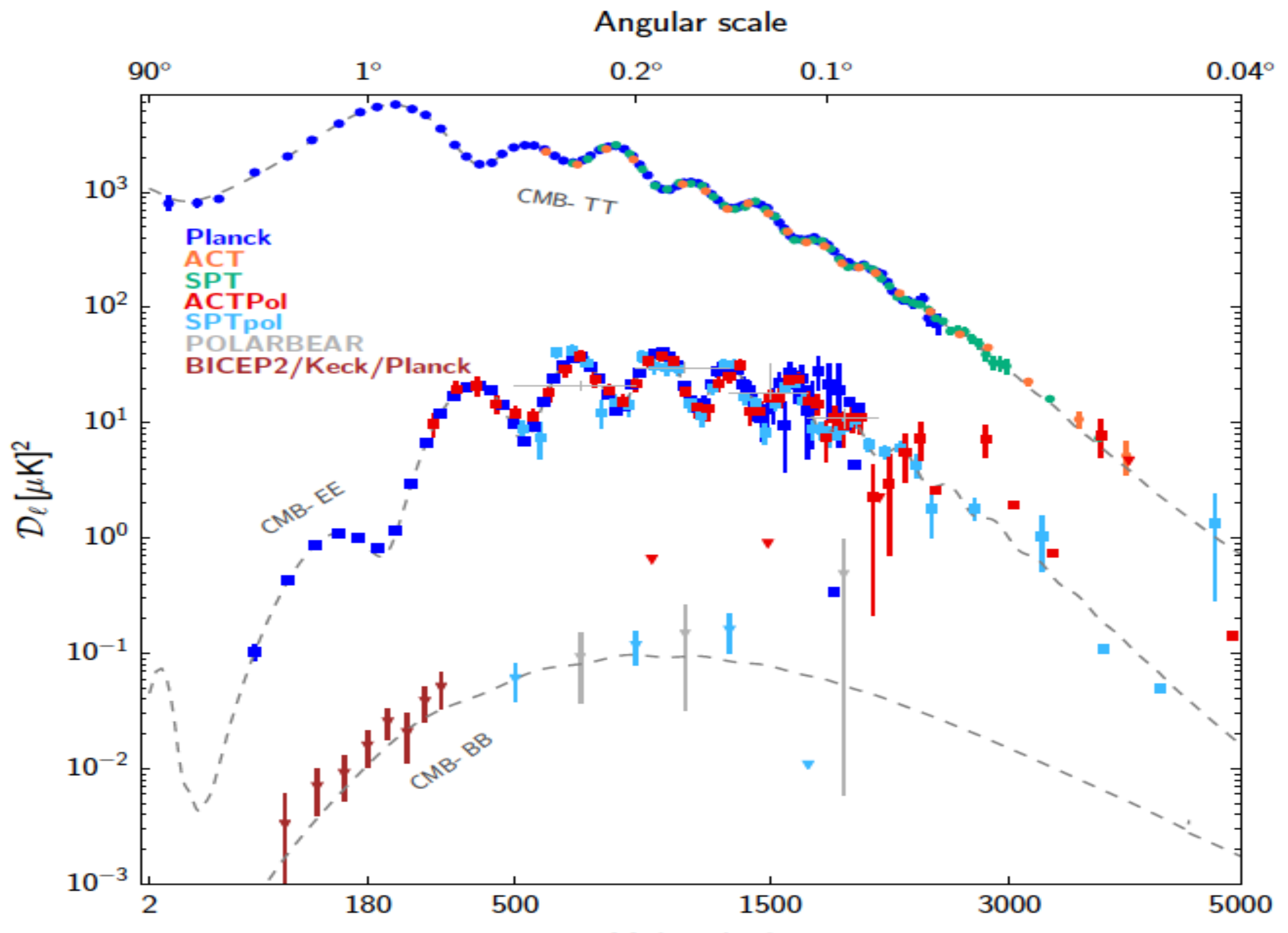
  ($r = A_s/A_T$ at, e.g., $k = 0.05 \mathrm{Mpc}^{-1}$)

- ➢ A new era has begun…



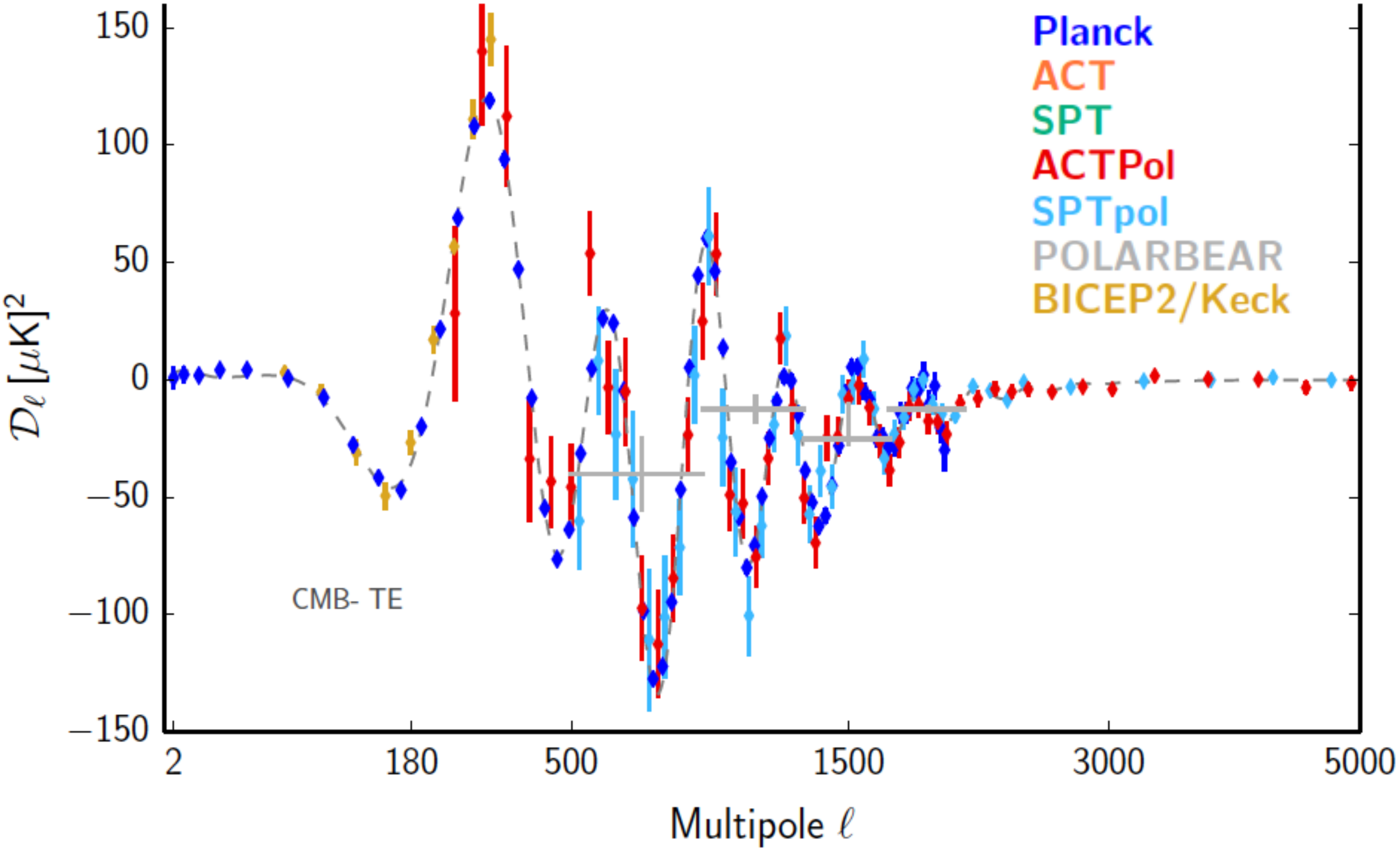


TT, EE, BB – mid 2015 status



Only keeping points w. sufficiently small error bars

Not forgetting mighty TE !



Facts/Numerology

Which is the effective number of a_{lm} modes that have been measured?

- This is equivalent to estimating 2 times the square of the total S/N in the power spectra, a measure that contains all the available cosmological information if we assume that the anisotropies are purely Gaussian (and hence ignore all non-Gaussian information coming from lensing, the CIB, cross-correlations with other probes, etc.).
-
- Carrying out this procedure for the Planck 2013 TT power spectrum yields the number **826 000** (which includes the effects of instrumental noise, cosmic variance and masking).
- The 2015 TT data have increased this value to **1 114 000**, with TE and EE adding a further **60 000** and **96 000** modes, respectively.
- From this perspective the 2015 Planck data constrain approximately 55% more modes than in the 2013 release.
- Of course this is not the whole story, since some pieces of information are more valuable than others, and in fact Planck is able to place considerably tighter constraints on particular parameters (e.g., reionization optical depth, LCDM extensions).

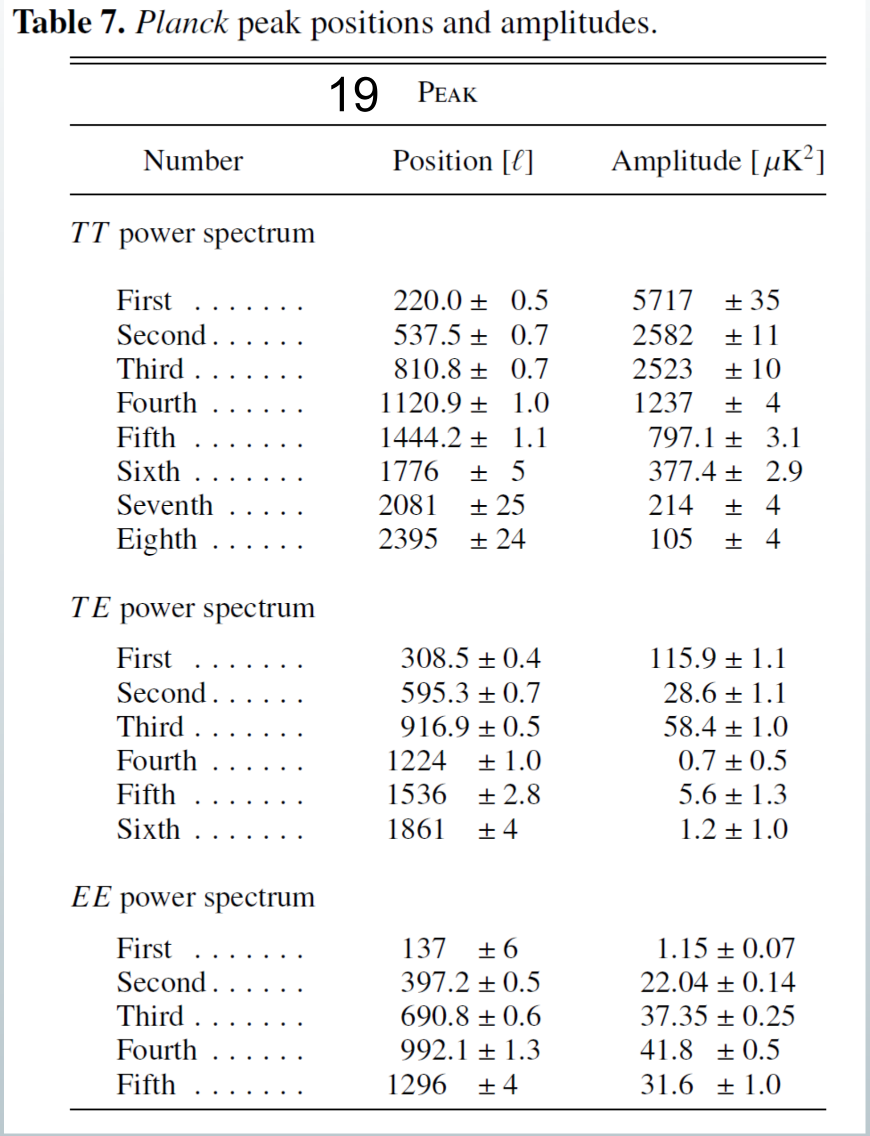
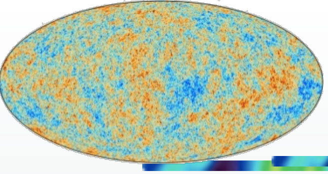


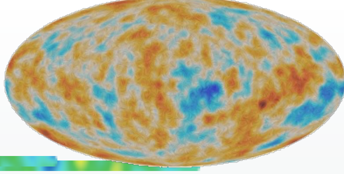
Table 7. *Planck* peak positions and amplitudes.

19 PEAK

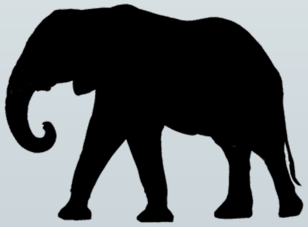
Number	Position [ℓ]	Amplitude [μK^2]
TT power spectrum		
First	220.0 ± 0.5	5717 ± 35
Second	537.5 ± 0.7	2582 ± 11
Third	810.8 ± 0.7	2523 ± 10
Fourth	1120.9 ± 1.0	1237 ± 4
Fifth	1444.2 ± 1.1	797.1 ± 3.1
Sixth	1776 ± 5	377.4 ± 2.9
Seventh	2081 ± 25	214 ± 4
Eighth	2395 ± 24	105 ± 4
TE power spectrum		
First	308.5 ± 0.4	115.9 ± 1.1
Second	595.3 ± 0.7	28.6 ± 1.1
Third	916.9 ± 0.5	58.4 ± 1.0
Fourth	1224 ± 1.0	0.7 ± 0.5
Fifth	1536 ± 2.8	5.6 ± 1.3
Sixth	1861 ± 4	1.2 ± 1.0
EE power spectrum		
First	137 ± 6	1.15 ± 0.07
Second	397.2 ± 0.5	22.04 ± 0.14
Third	690.8 ± 0.6	37.35 ± 0.25
Fourth	992.1 ± 1.3	41.8 ± 0.5
Fifth	1296 ± 4	31.6 ± 1.0



Summary: Basic ΛCDM fits

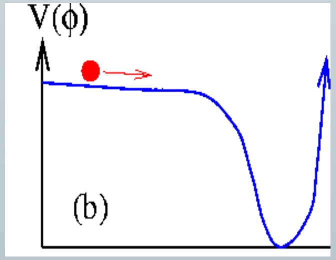


- CMB + LSS provide a consistent picture within LCDM. Content known with percent accuracy.
- Primordial fluctuations are, to a very good approximation:
  - *Isotropic*
  - *Gaussian*
  - *Adiabatic* *(fluctuations in pressure α to the density)*
  - *Coherent* *(fluctuations start @same time, harm. osc)*
  - *Close to Scale invariant*
  - *but not exactly* *(n_s =1 is excluded at more than 5σ)*
- With minimal cosmological content,
  - *Flat spatial geometry* *(is a very good approximation)*
  - *Matter is mostly dark* *(and cold)*
  - *"Dark energy" consistent with Λ* *(w=-1)*
  - *Small fraction of baryon, consistent with BBN*
- No gravitational waves (10 percent level)
- Large scale power, with TT versus TE anti-correlation ($5^{o} > \vartheta > 1^{o}$):
  - *apparently a-causal physics, calling for a period of accelerated expansion*



➔ I.e. all consistent within the generic inflationary framework, completing the standard model of cosmology (w. Hot Big Bang phase).

➔ "Anomalies" are present at tantalizing levels, but at large scales.



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.

esa

planck

cnes

agenzia spaziale italiana

NASA

CNRS

DTU Space
National Space Institute

Science & Technology Facilities Council

ISTITUTO NAZIONALE DI ASTROFISICA INAF

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK
a look back to the birth of Universe

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

Aalto University

ioa

KICC
Kavli Institute for Cosmology Cambridge

CAVENDISH ASTROPHYSICS

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

irfu
cea
saclay

CEFCA

irap

CITA–ICAT

ASF

CNRS INSU

CNRS IN2P3

BERKELEY LAB

ipac

HELSINKI INSTITUTE OF PHYSICS

IFCA

Imperial College London

UNIVERSITÀ DEGLI STUDI DI MILANO

NÉEL institut

IPAG

ISDC

JPL

LAL

l'Observatoire de Paris

LERMA

LPSC Grenoble

NERSC

MANCHESTER 1824
The University of Manchester

Rutherford Appleton Laboratory

MilliLab

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF OSSERVATORIO ASTRONOMICO DI PADOVA

UNIVERSITY OF OXFORD

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI ROMA TOR VERGATA

OSSERVATORIO ASTRONOMICO TRIESTE

UBC

UC
UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

ALMA

ESO

US
University of Sussex

HAVERFORD

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

UNIVERSITÉ DE PARIS-SUD XI

asdc
ASI Science Data Center

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