Planck cosmological legacy highlights

The almost unreasonable effectiveness of the base LCDM model

François R. Bouchet

Institut d'Astrophysique de Paris (IAP), CNRS & Sorbonne Université

on behalf of the Planck Collaboration

Menu: from data to model…

- ~ 900 billion time samples in ~100 Timelines
- ~ 1 billion pixel values (7*{I,Q,U+2*I=23 maps of ~50million pixels) [+ all subsets; **the basic legacy w. relevant simulations**]
- ~ 100 million CMB pixel values (2 map of ~50 million pixels, I, E) [B]
- ˜10 million harmonic modes (2l+1 m-modes/l, TT+TE+EE+ΦΦ+B's)
- Fit with just 6 parameters! (of a base LCDM model)
- *··· With no significant evidence for a 7th*
- *···And still holding with the rest of cosmological probes*

6 parameters Base LCDM model

An incredibly minimal model, deceptively simple, since it relies on far reaching assumptions:

1) Physics is the same throughout the observable Universe.
2) General Relativity (GR) is an adequate description of gravity.
3) On large scales the Universe is statistically the same everywhere.
4) The Universe was once much hotter and denser and has been expanding since early times.
5) There are five basic cosmological constituents:
    a) *Dark energy that behaves just like the energy density of the vacuum.*
    b) *Dark matter that is pressureless (for the purposes of forming structure), stable and interacts with normal matter only gravitationally.*
    c) *Regular atomic matter that behaves just like it does on Earth.*
    d) *The photons we observe as the CMB.*
    e) *Neutrinos that are almost massless (again for structure formation) and stream like non-interacting, relativistic particles at the time of recombination.*
6) The curvature of space is very small, dynamically negligible.
7) Variations in density were laid down everywhere at early times, and are Gaussian, adiabatic, and nearly scale invariant (i.e., proportionally in all constituents and with similar amplitudes as a function of scale), as predicted by inflation.
8) The observable Universe has ``trivial'' topology (i.e., like R^3).

...Assumptions which Planck helps putting on quite firm ground...

MAPS LEGACY

Solar Dipole

Experiment	Amplitude [μK_{CMB}]	Galactic coordinates l [deg]	Galactic coordinates b [deg]
COBE [a]	3358 ± 24	264.31 ± 0.20	48.05 ± 0.11
WMAP [b]	3355 ± 8	263.99 ± 0.14	48.26 ± 0.03
Planck 2015 nominal [c]	3364.5 ± 2.0	264.00 ± 0.03	48.24 ± 0.02
LFI 2018 [d]	3364.4 ± 3.1	263.998 ± 0.051	48.265 ± 0.015
HFI 2018 [d]	3362.08 ± 0.99	264.021 ± 0.011	48.253 ± 0.005
***Planck* 2018 [e]**	**3362.08 ± 0.99**	**264.021 ± 0.011**	**48.253 ± 0.005**

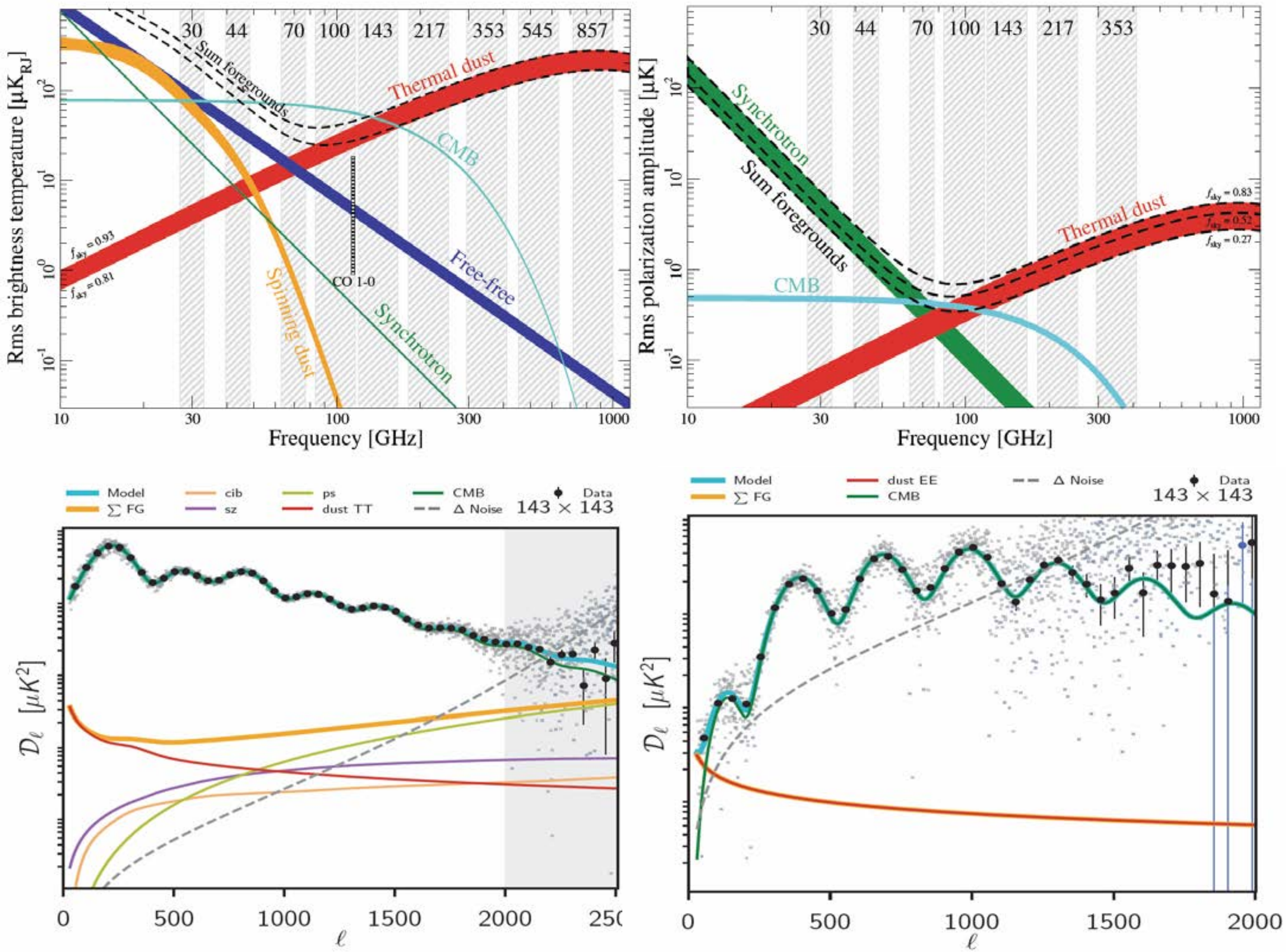
1. The new best-fit dipole amplitude is now known to about 0.025% (including systematic uncertainties), essentially the same precision as the monopole.
2. The dipole amplitude corresponds to v = (369.82 ± 0.11) km/s (towards Crater).

(Planck 2018 I)

CMB Foregrounds revelation

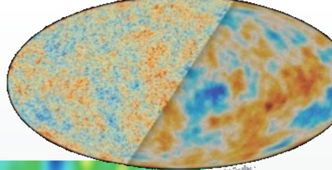
planck

Planck opened the window on the high-frequency side of the CMB peak (above 90 GHz)

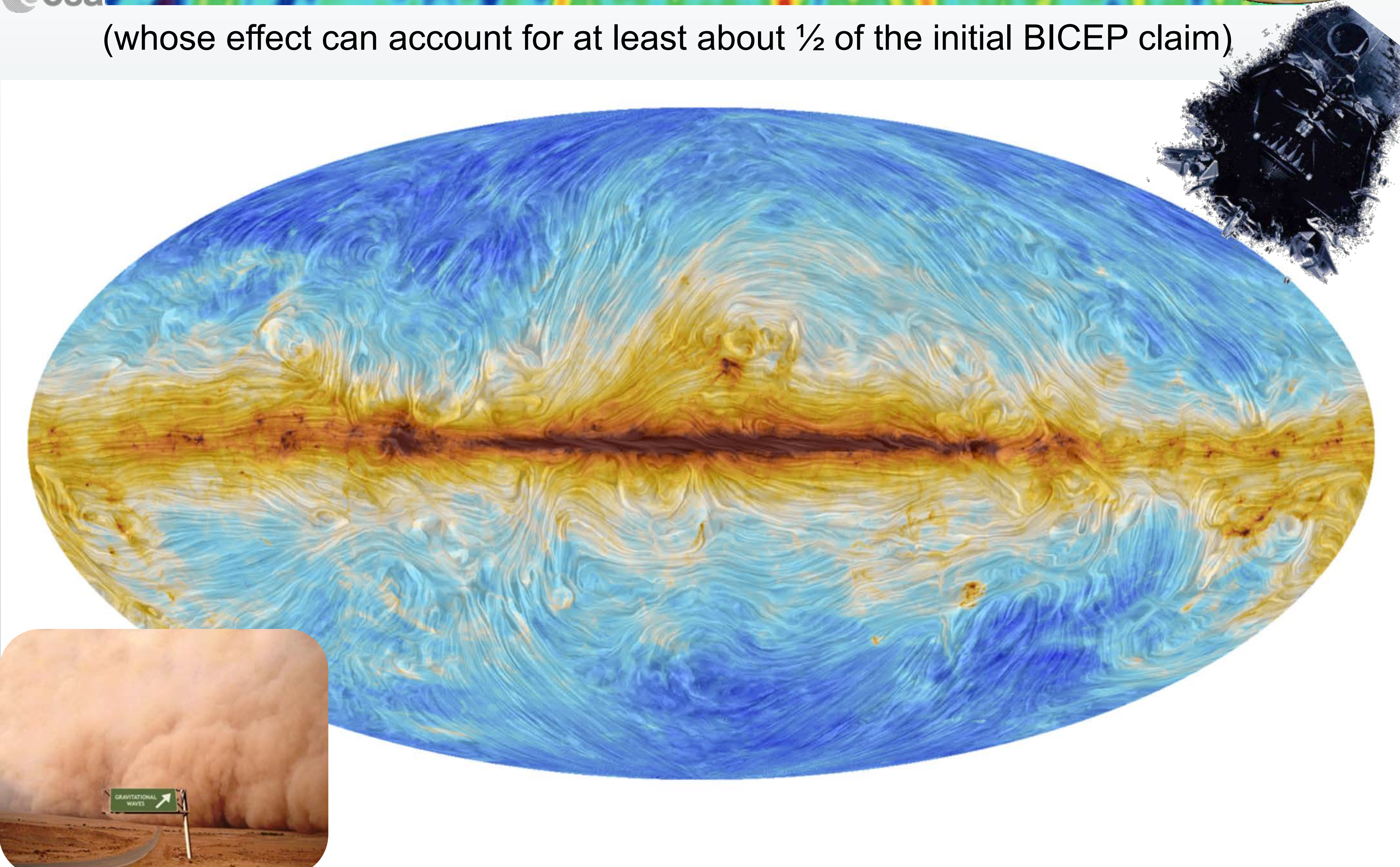


(Planck 2018 I)

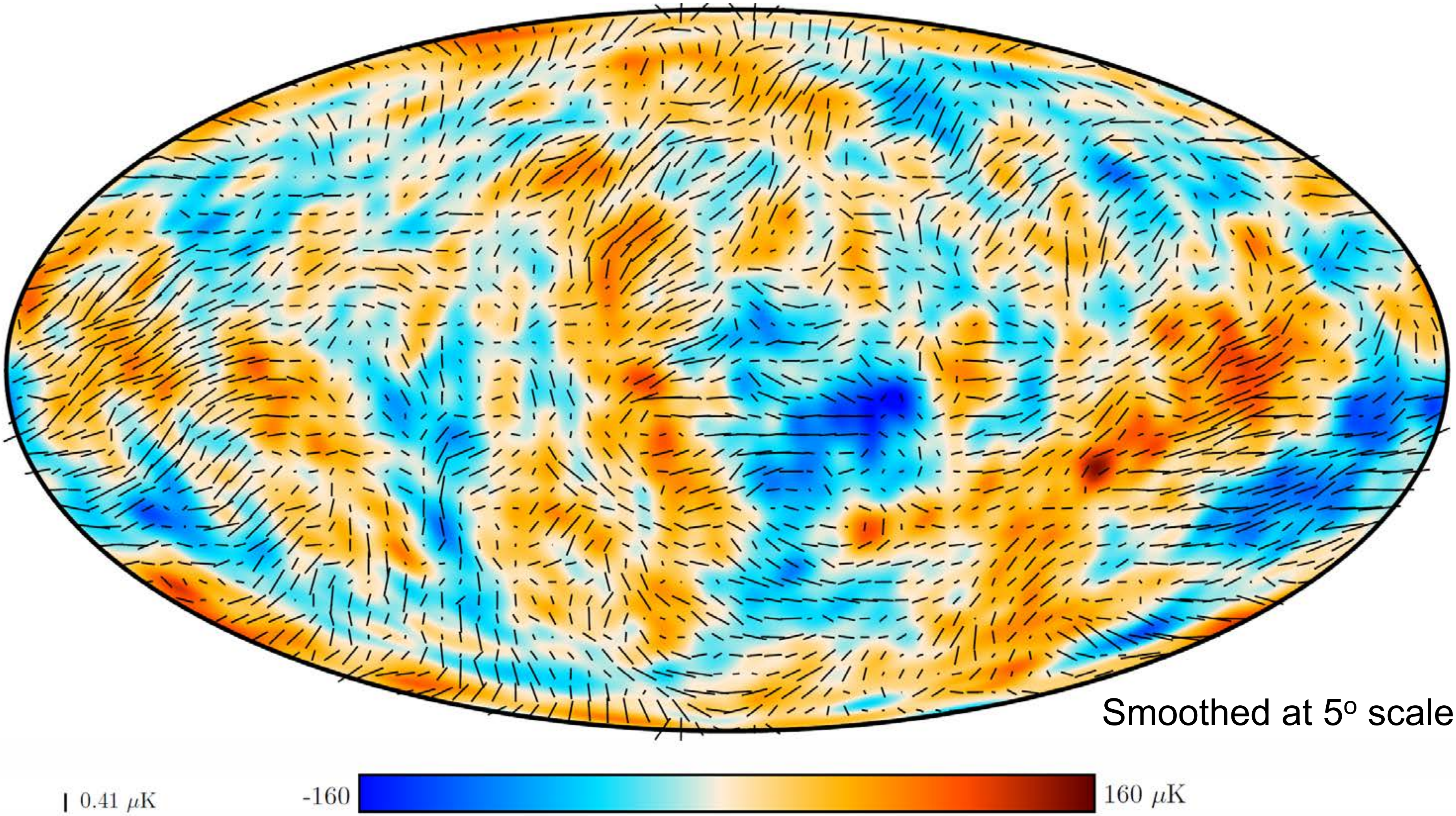
Planck 353GHz reveals the Galactic magnetic field



(whose effect can account for at least about ½ of the initial BICEP claim)



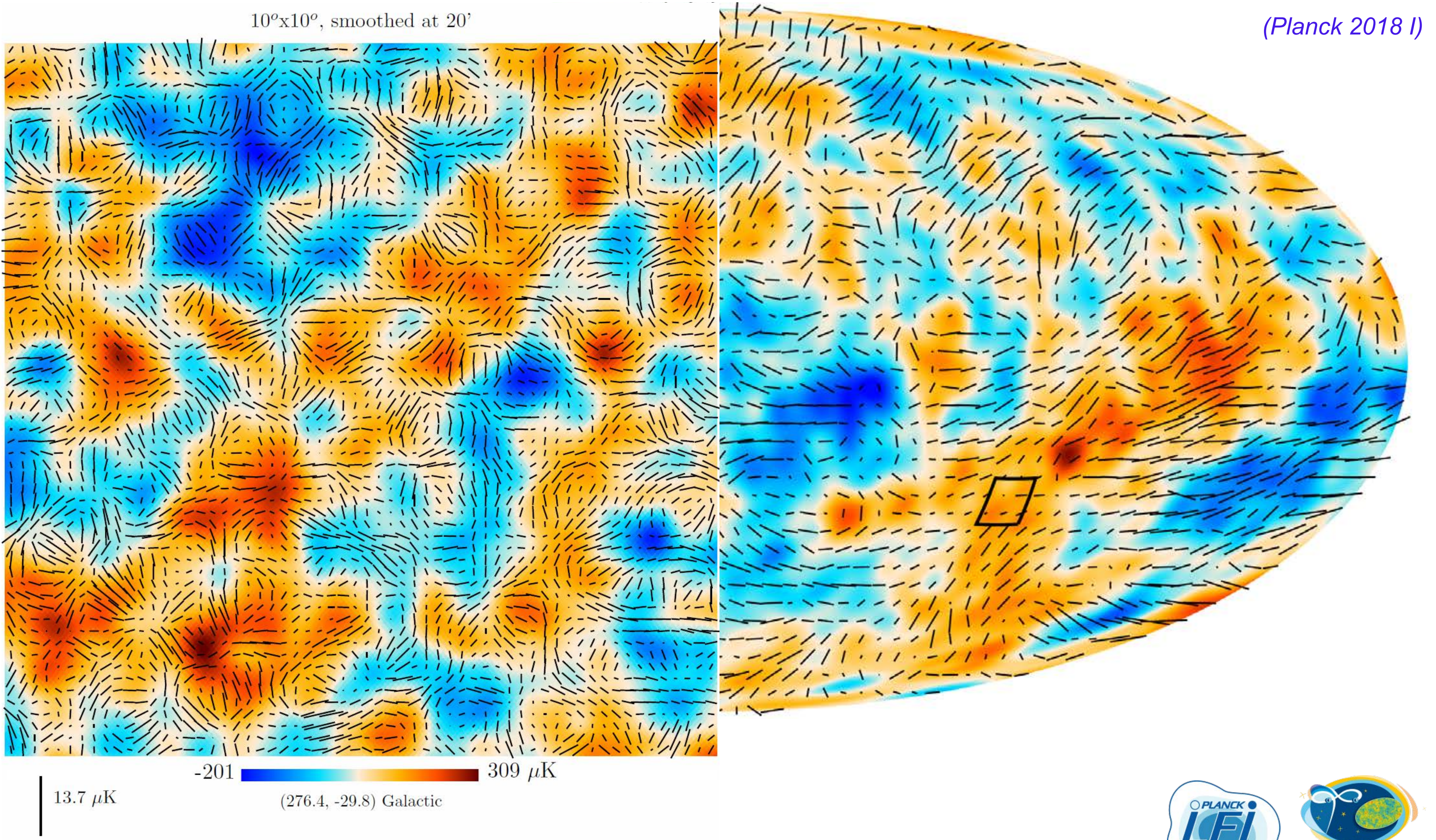
Planck Polarisation superimposed on T



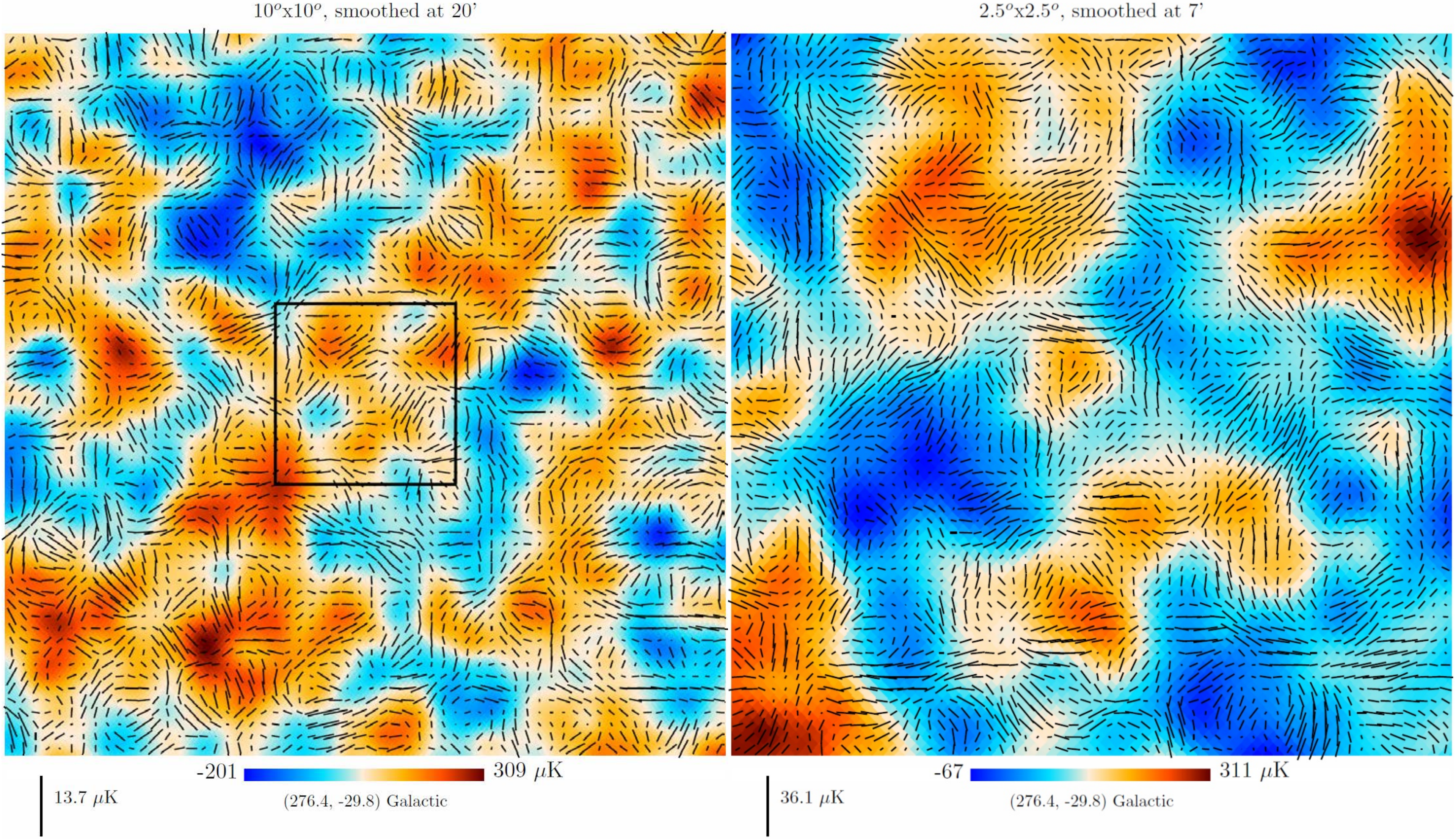
(Planck 2018 I)

Planck Polarisation superimposed on T

(Planck 2018 I)



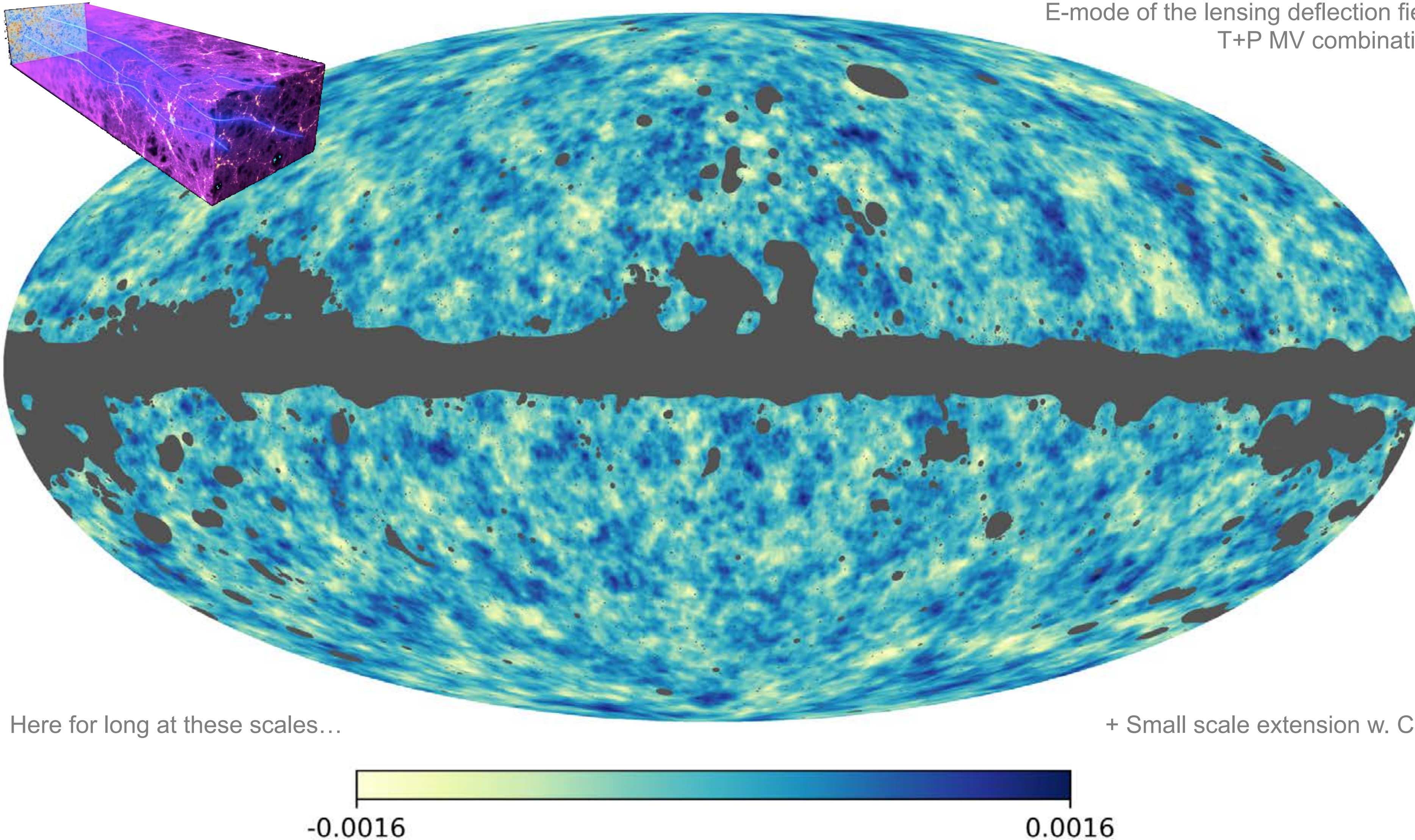
Planck Polarisation superimposed on T



Planck lensing map

(Planck 2018 VIII)

E-mode of the lensing deflection field
T+P MV combination

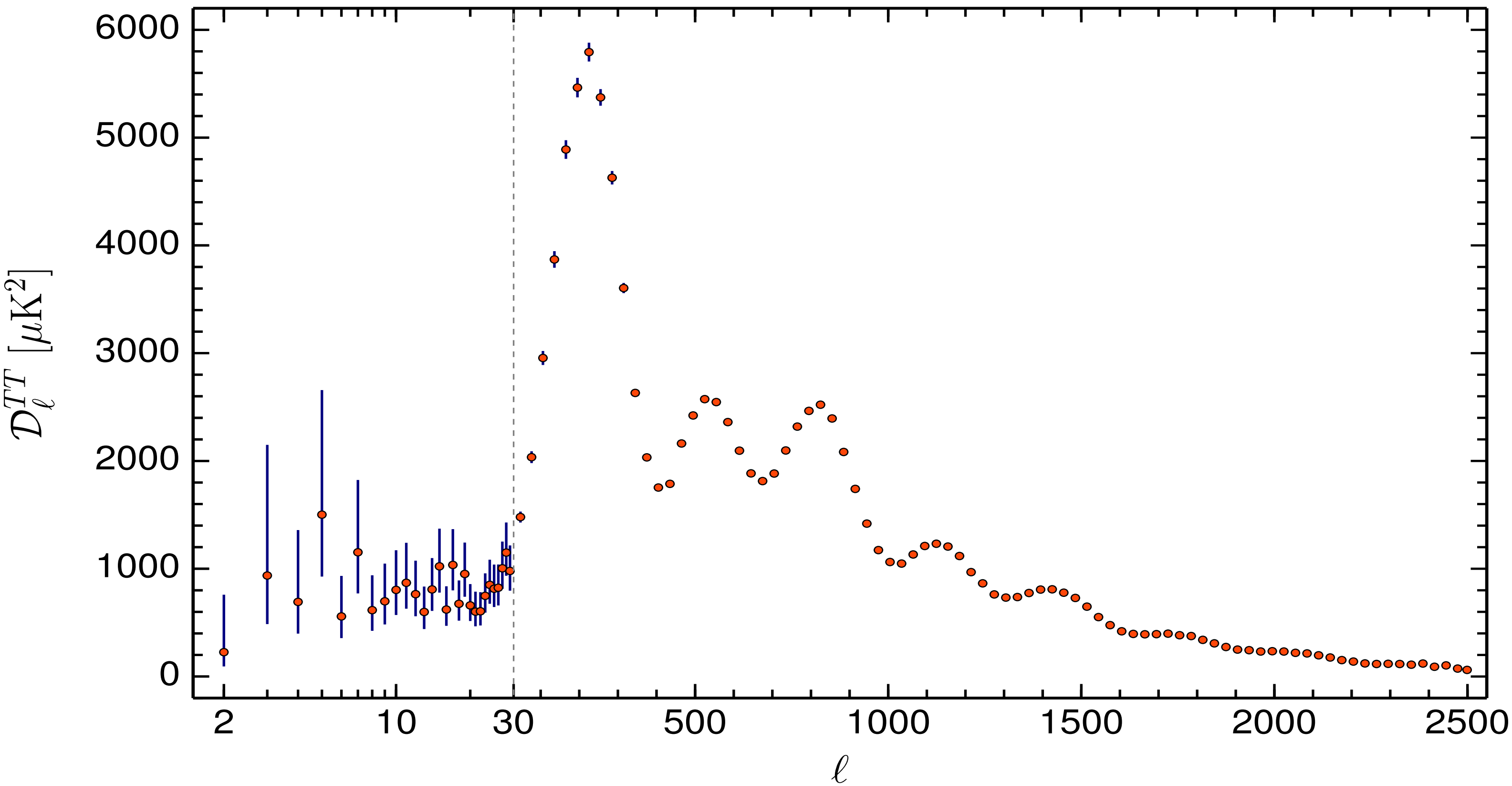


Here for long at these scales…

+ Small scale extension w. CIB

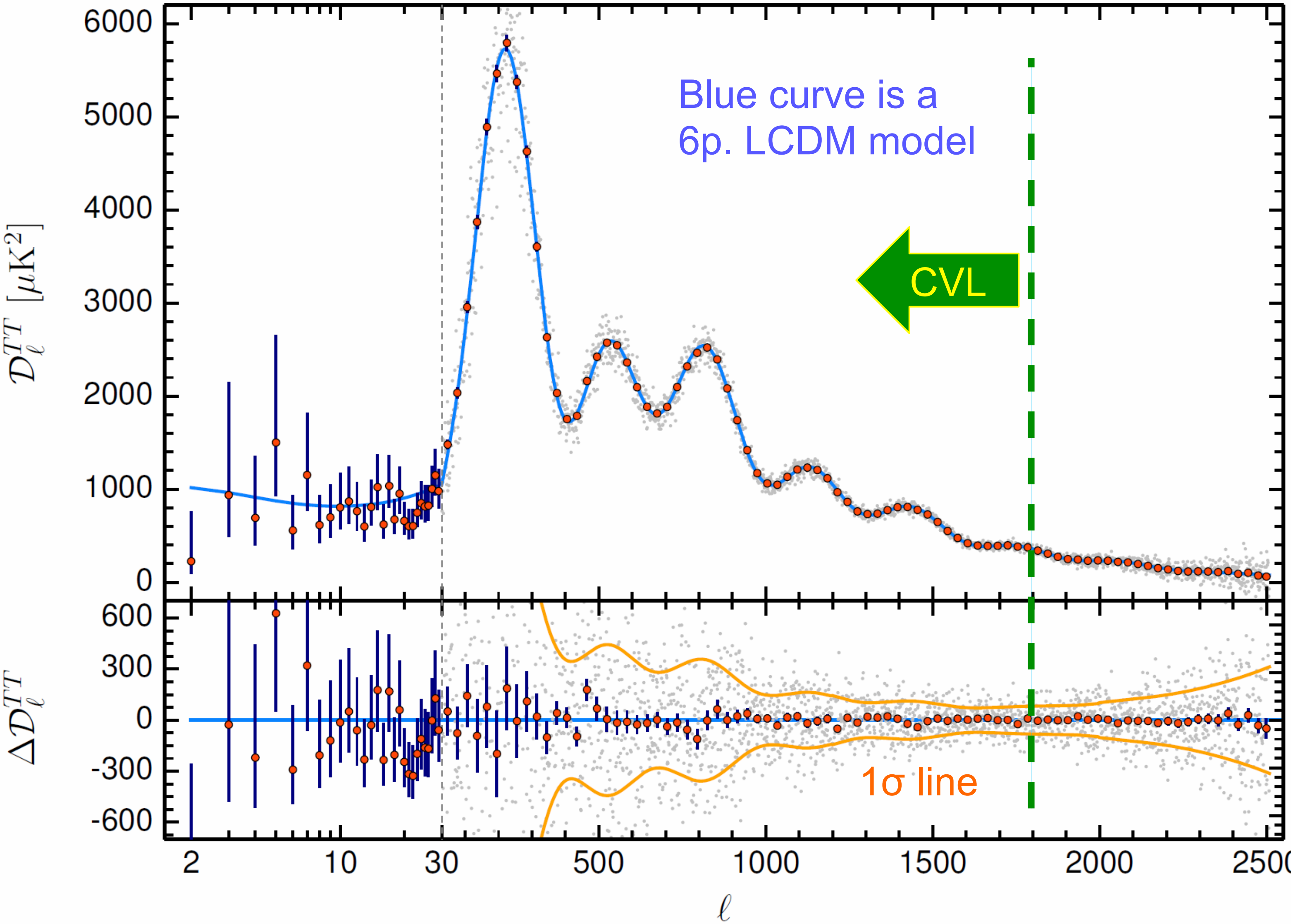
ANGULAR POWER SPECTRA

Planck 2018 TT spectrum



7 acoustic peaks well detected

Planck 2018 TT spectrum



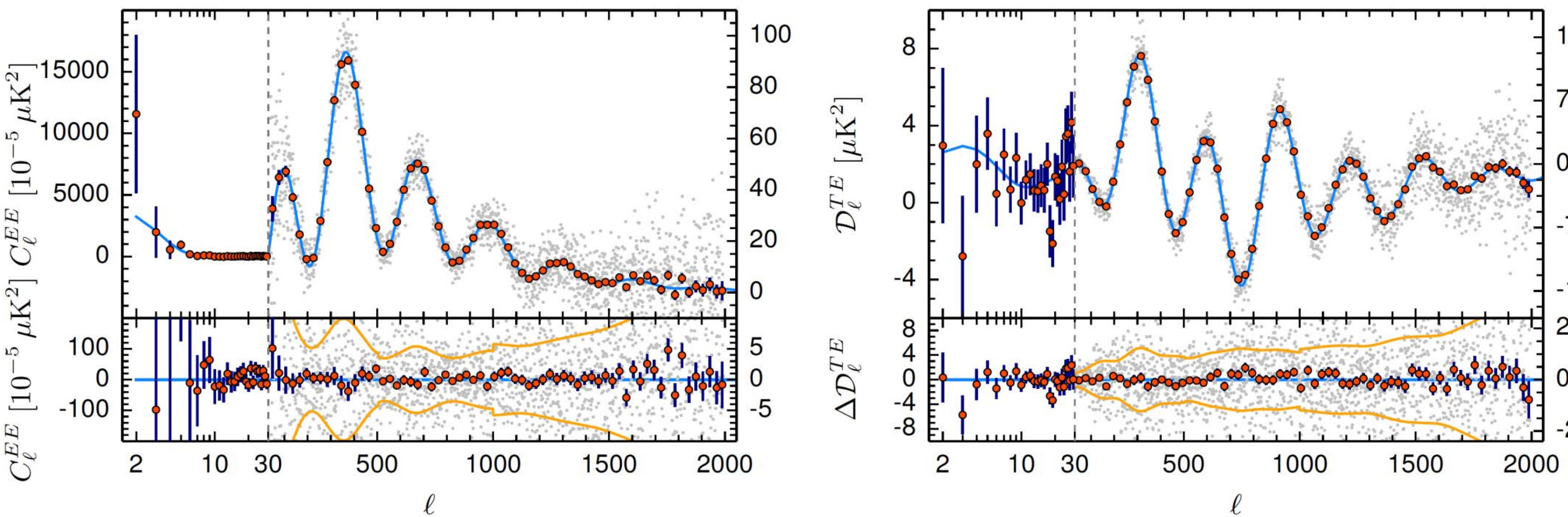
CVL till
l~1800

(l~1600 on
40-70% of
the sky for
subsets)

7 acoustic
peaks well
detected

Planck 2018 - EE & TE spectra

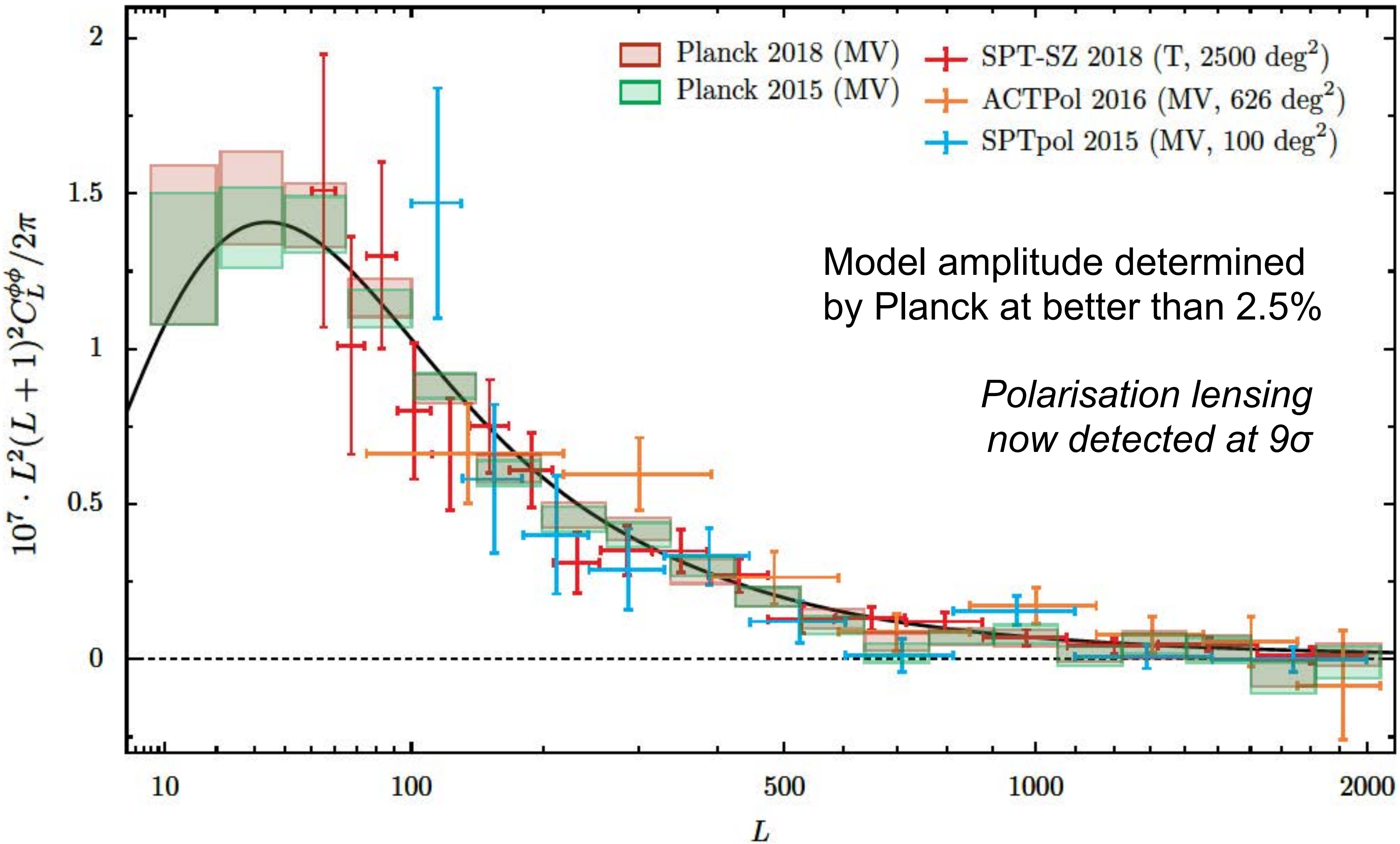
(Planck 2018 VI)



1. Top: Blue curve is the *prediction* based on the best fit TT in base ΛCDM. No adjustment.
2. Bottom: residuals wrt prediction, together with (in orange) the expected 1sigma dispersion

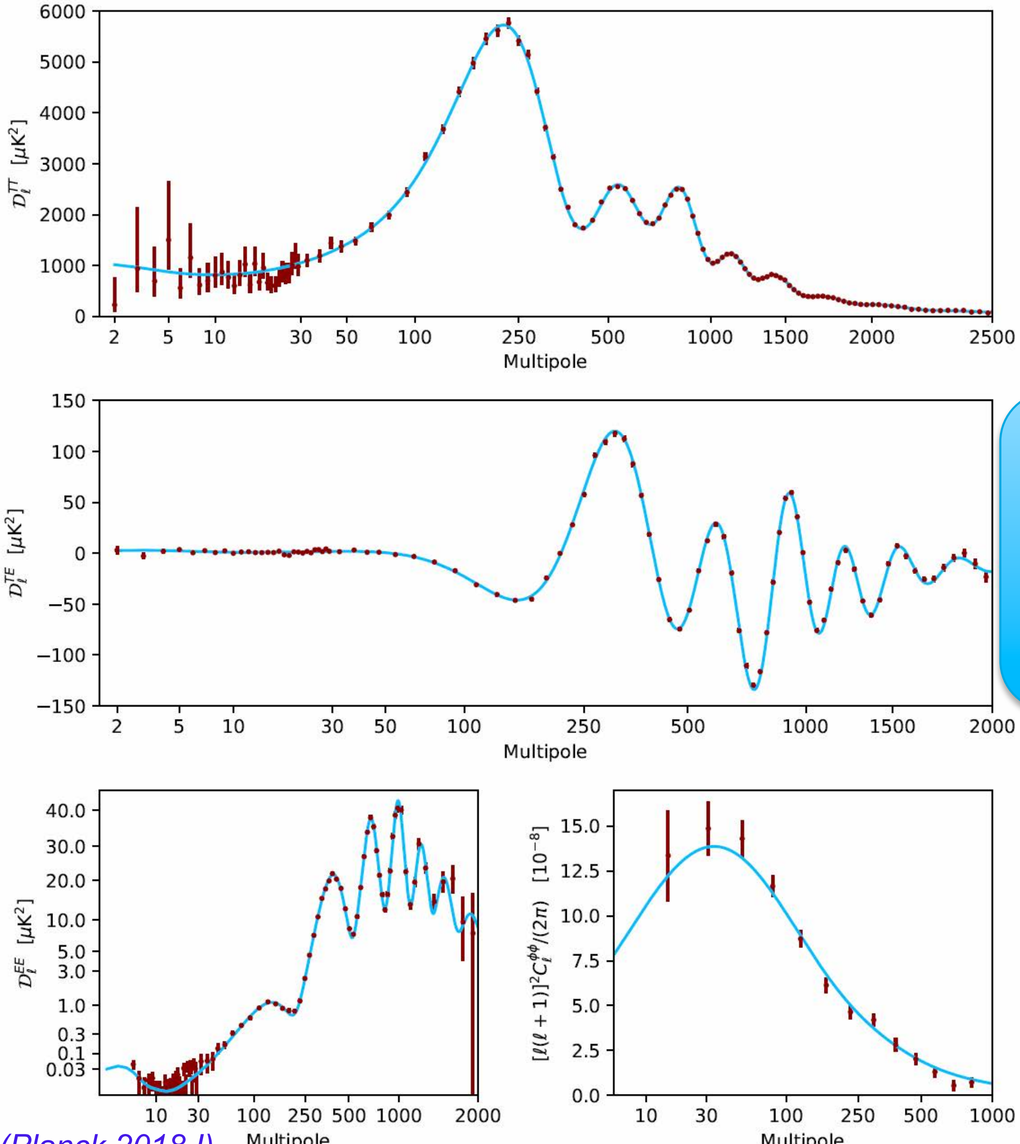
The grey dots indicate the individual measurements, and the red circles their binned value.

CMB Lensing power spectrum



Planck for the first time measured (in 2015) the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

Planck T+E data and Best-fit LCDM

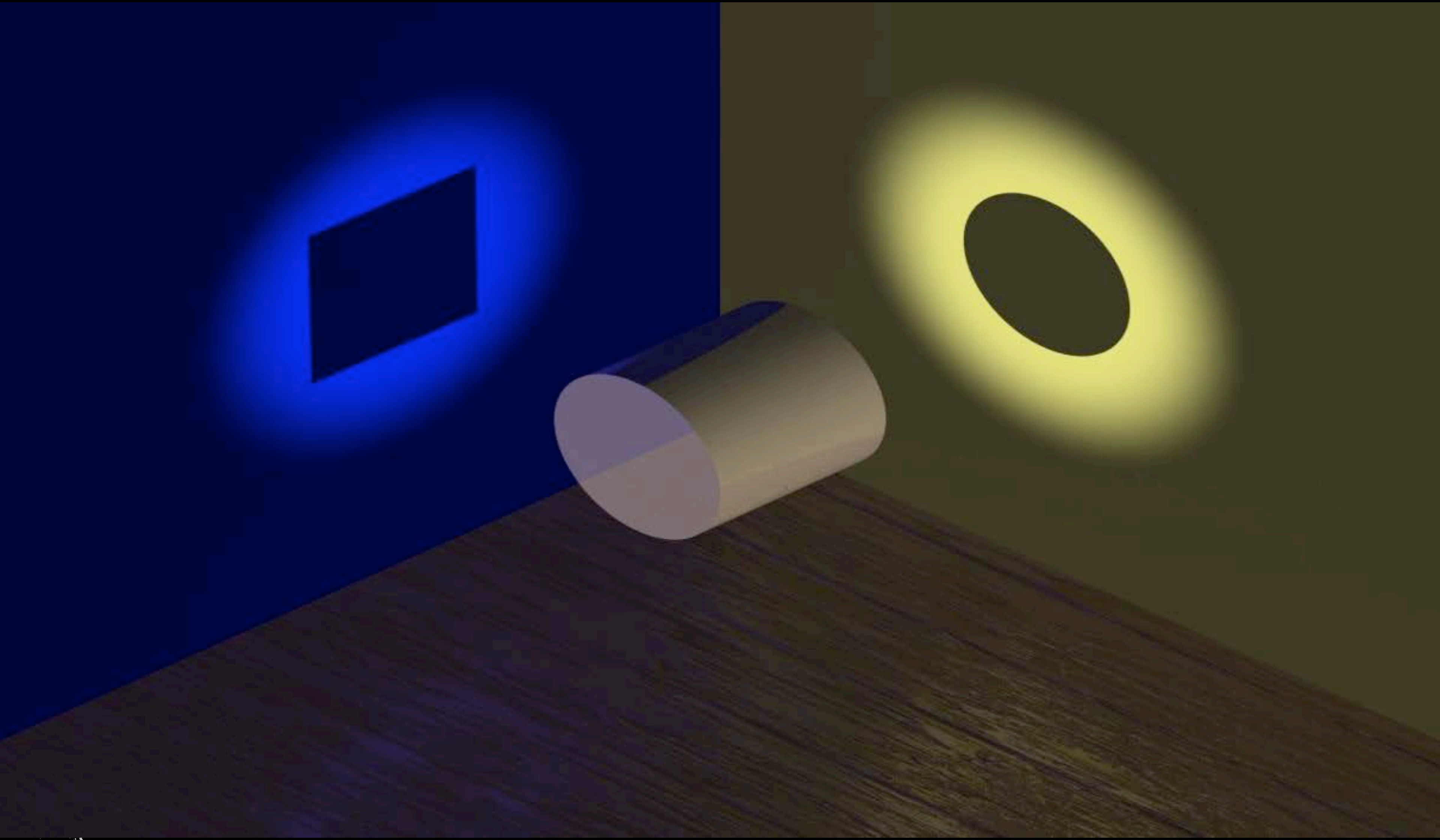


(Planck 2018 I)

Per cent accuracy on all base LCDM parameters, but tau

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_Λ	0.6847 ± 0.0073
Ω_m	0.3153 ± 0.0073
$\Omega_m h^2$	0.1430 ± 0.0011
$\Omega_m h^3$	0.09633 ± 0.00030
σ_8	0.8111 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013
z_{re}	7.67 ± 0.73
Age[Gyr]	13.797 ± 0.023
r_*[Mpc]	144.43 ± 0.26
$100\theta_*$	1.04110 ± 0.00031
r_{drag}[Mpc]	147.09 ± 0.26
z_{eq}	3402 ± 26
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081

Temp., Polar., Lensing are quite consistent within LCDM. It could have been otherwise!



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

LCDM MODEL EXTENSIONS

(Very) Much sought after extensions

Primordial physics

1. Detection of a tensor component, $r=A_T/A_s$
2. Detection of running ($dn_s/d\ln k$), or features
3. Detection of primordial non gaussianity, f_{NL}
4. Detection of an isocurvature component, α_1

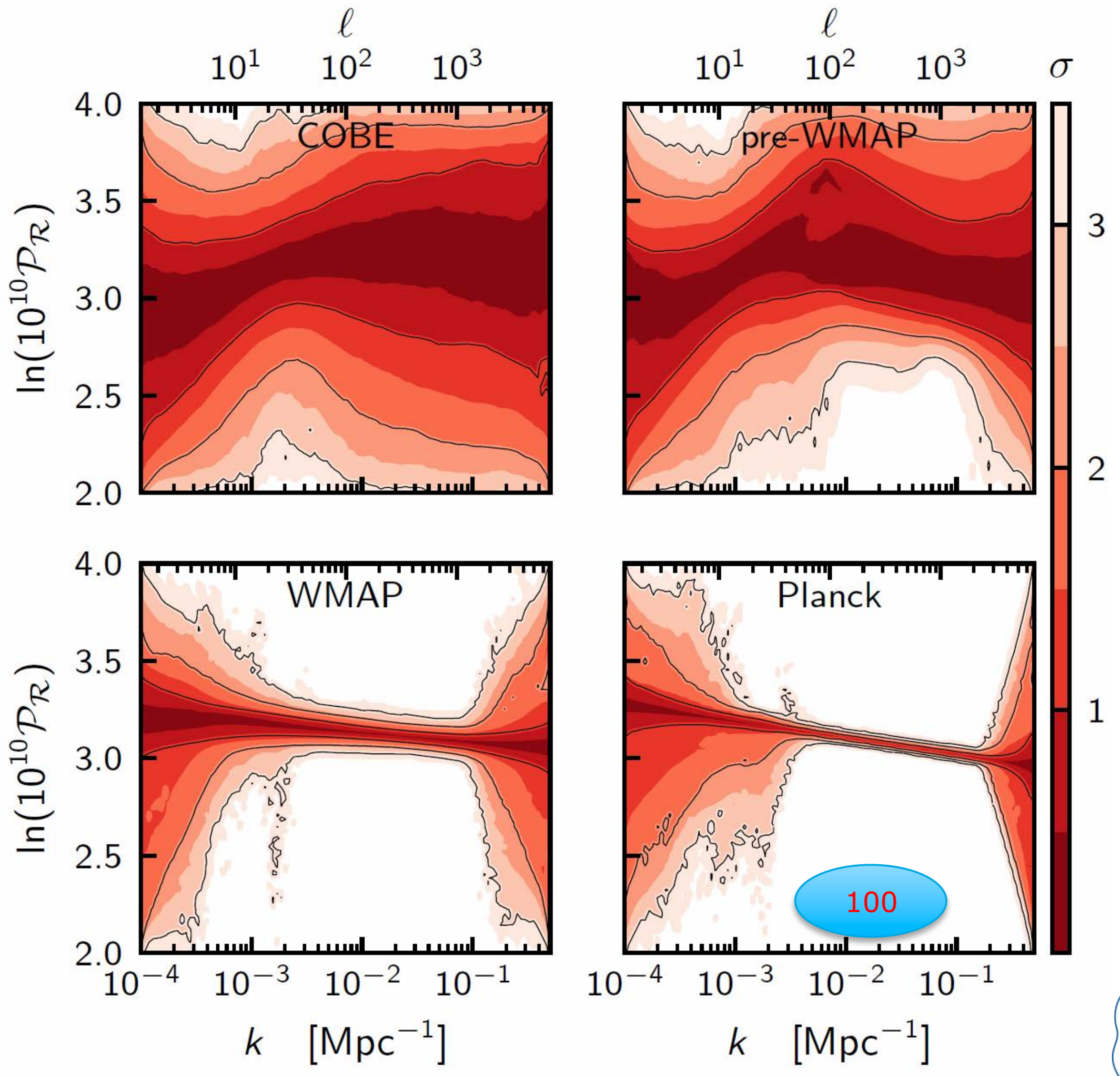
All adressed by Planck, often providing the best available constraints today

Checking bases

1. Departure from flat spatial hypersurfaces, $\Omega_k=1-\Omega_m-\Omega_\Lambda$
2. "Dark energy" equation of state, w
3. Neutrinos masses, $\Sigma\, m_\nu$
4. N_{eff} ($C^2_{eff}=C^2_{vis}=1/3$?)

5. And also: Defects, Fundamental constants, T_{CMB}, A2s→1s, deviations from GR….

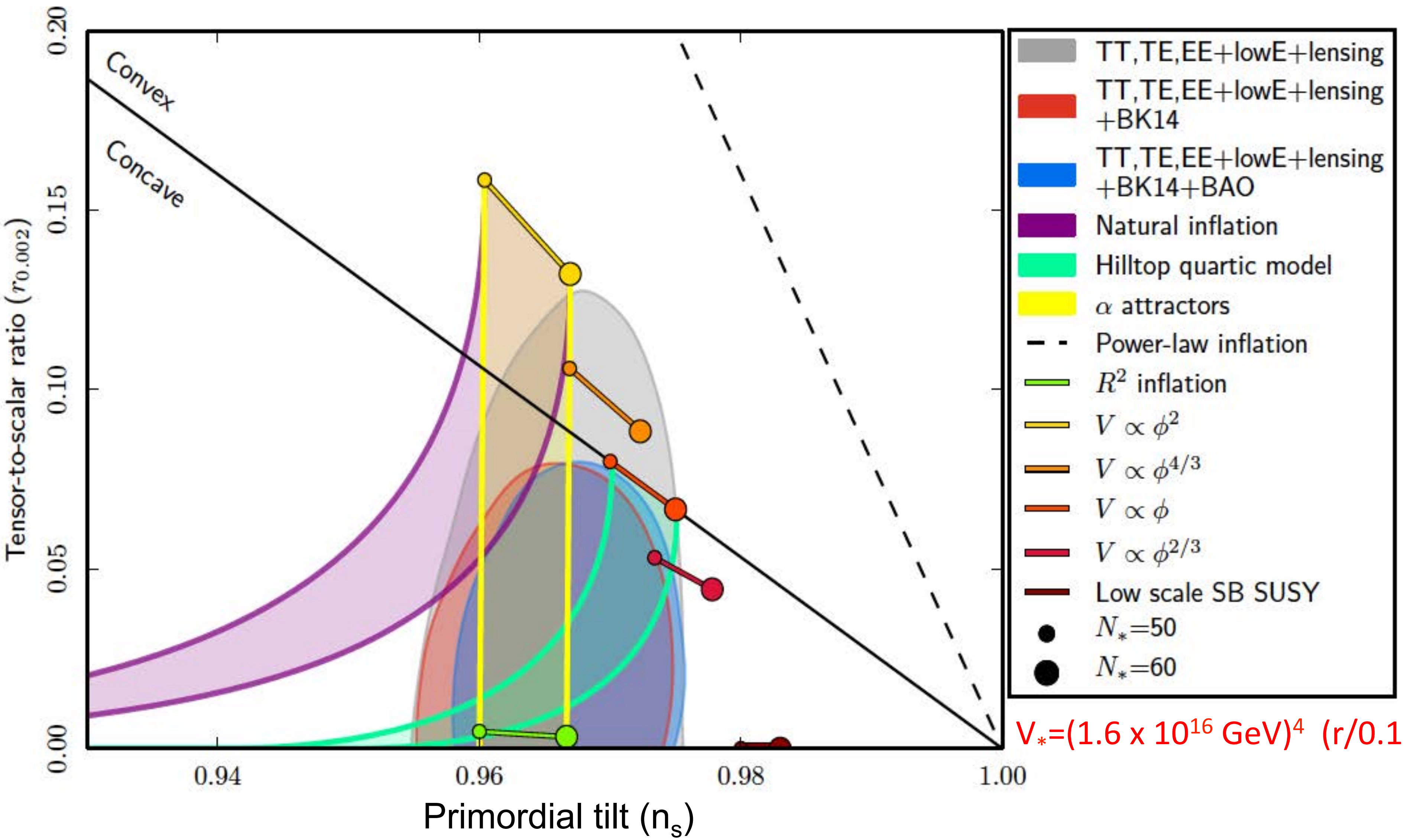
Primordial Power Spectrum reconstruction



$n_s \neq 1$ at 8σ

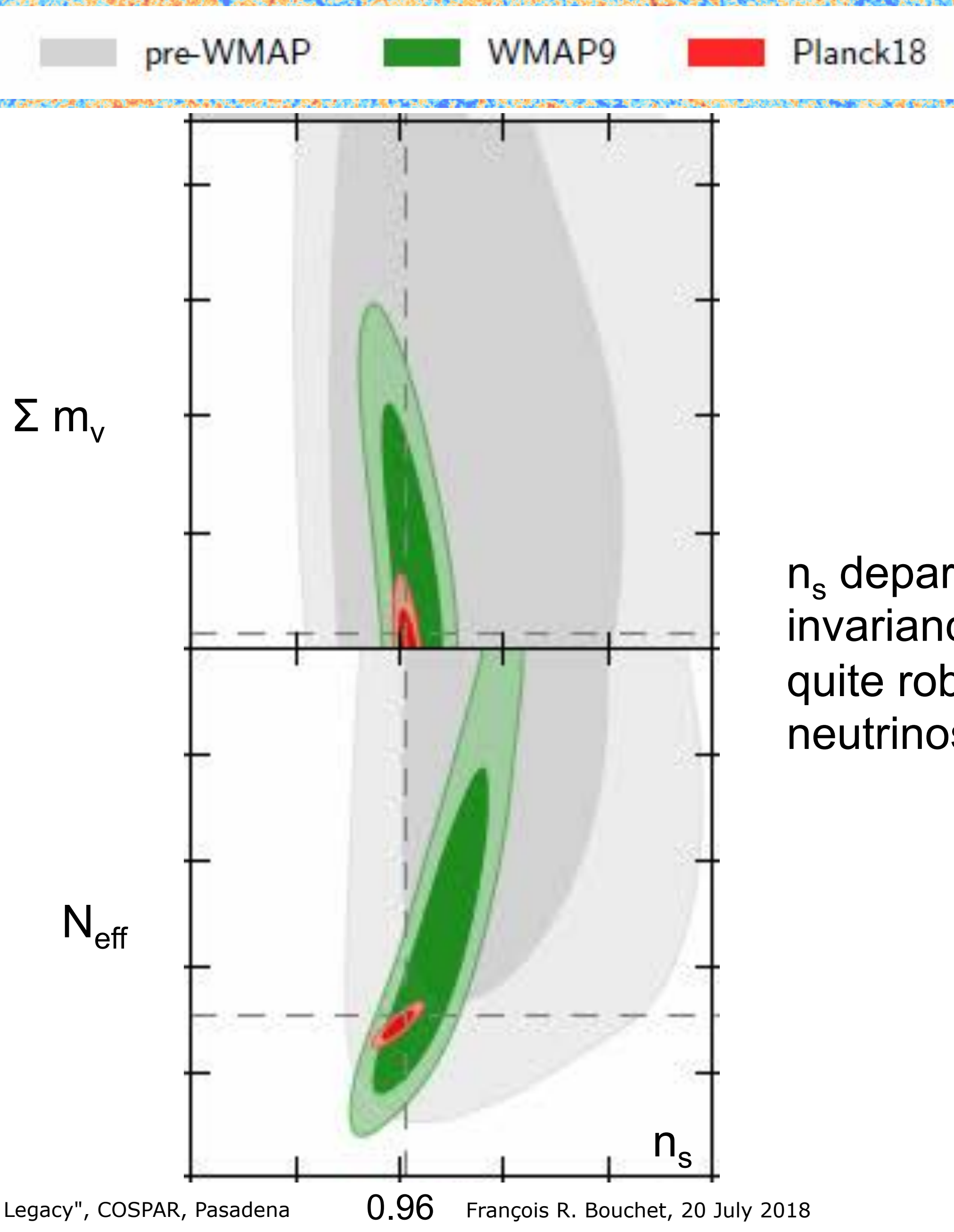
(Planck 2018 I)

95%CL Limits on tensor component



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

CMB zooming in LCDM...

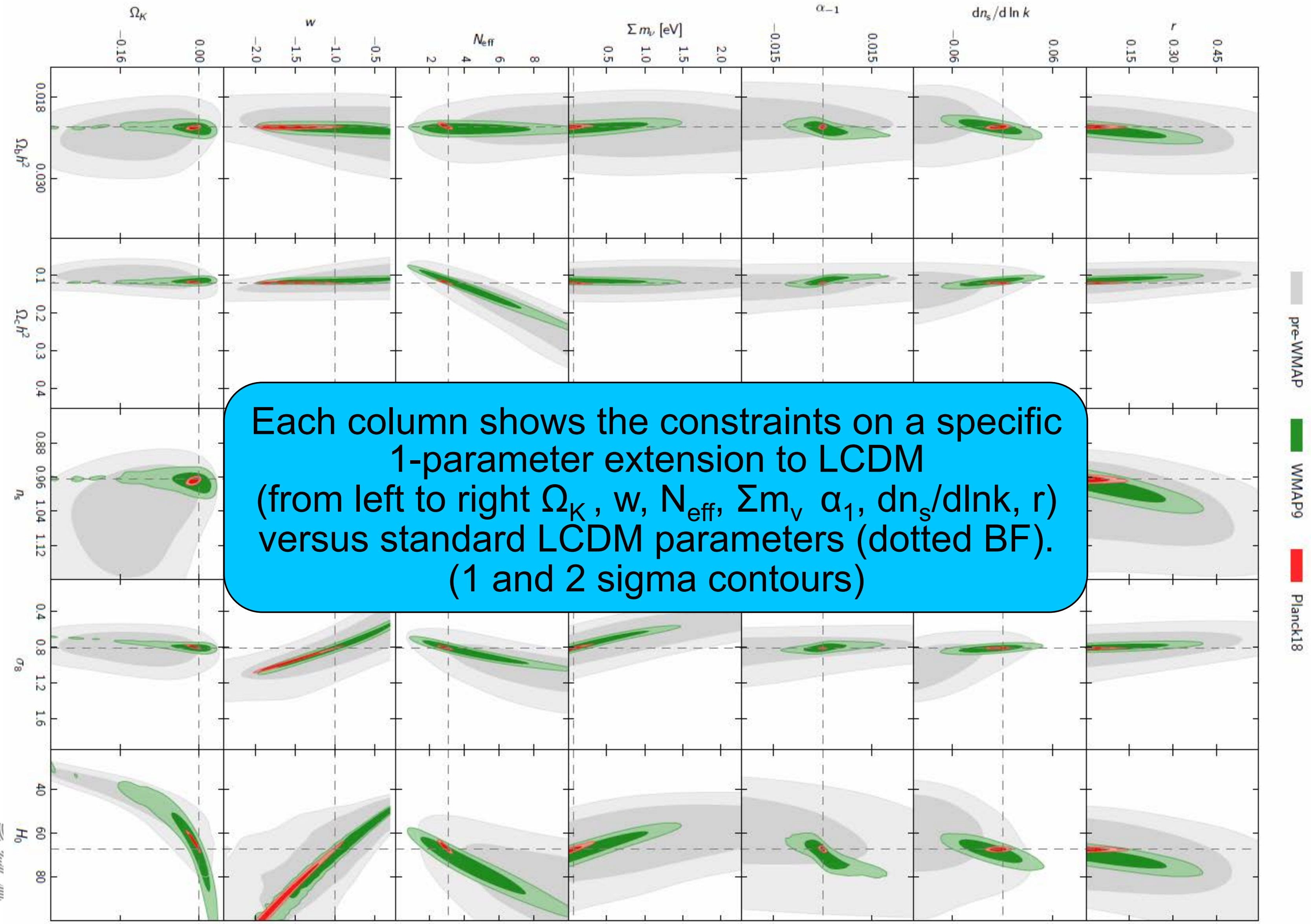


n_s departure from scale invariance (n_s < 1) is now quite robust against, e.g., neutrinos physics

(Planck 2018 I)

CMB zooming in LCDM...

(Planck 2018 I)



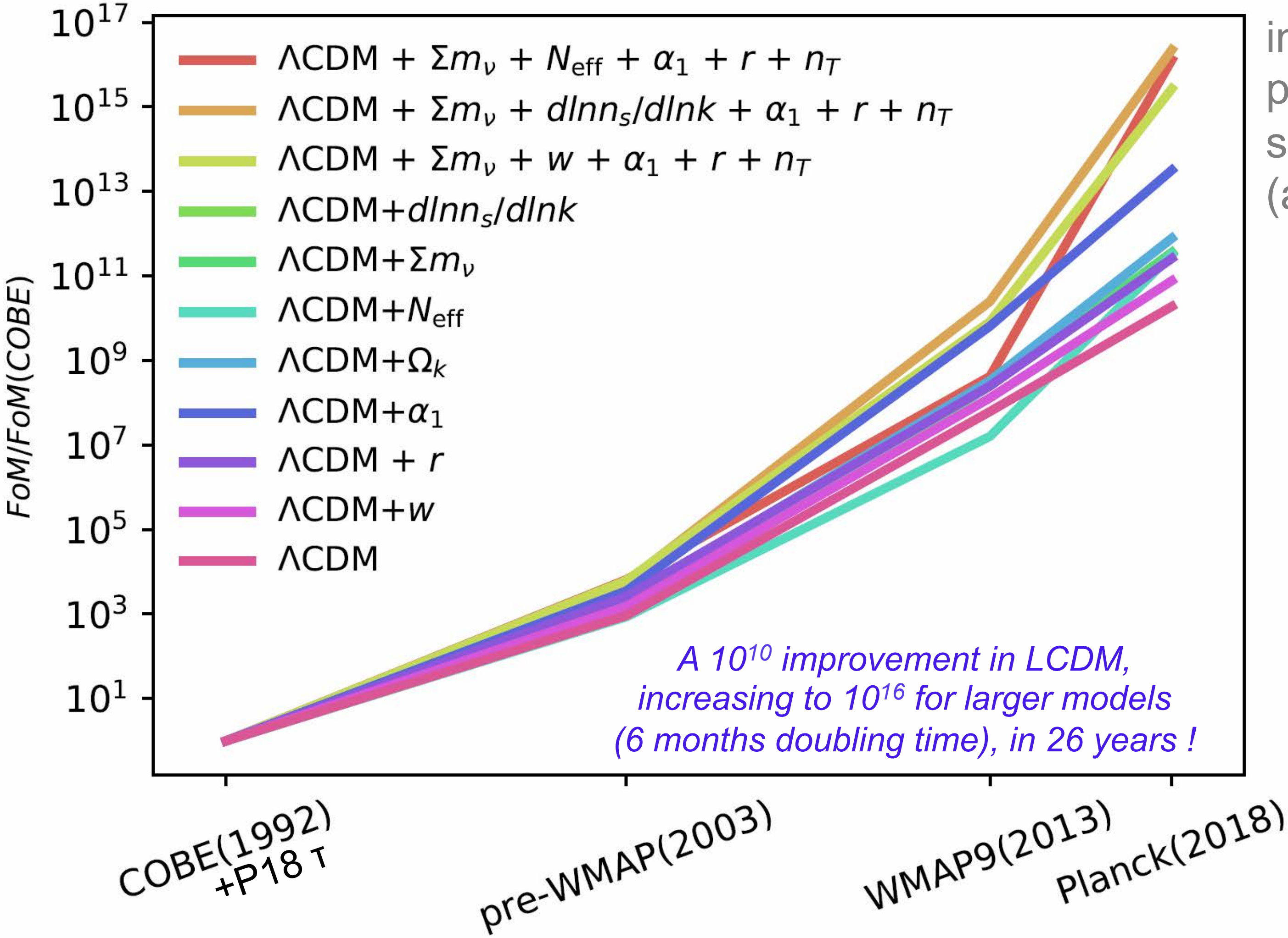
Each column shows the constraints on a specific 1-parameter extension to LCDM (from left to right Ω_K , w, N_{eff}, Σm_ν α_1, dn_s/dlnk, r) versus standard LCDM parameters (dotted BF). (1 and 2 sigma contours)

FOM / FOM_COBE

(Planck 2018 I)

$$\left\{\det\left[\mathrm{Cov}(\Omega_b h^2;\Omega_c h^2;\tau,A_s;n_s;\ldots)\right]\right\}^{-1/2}$$

This measures the decrease in the allowed parameter space volume (at 1σ)



 (Planck 2018 I)

Inflationary scorecard

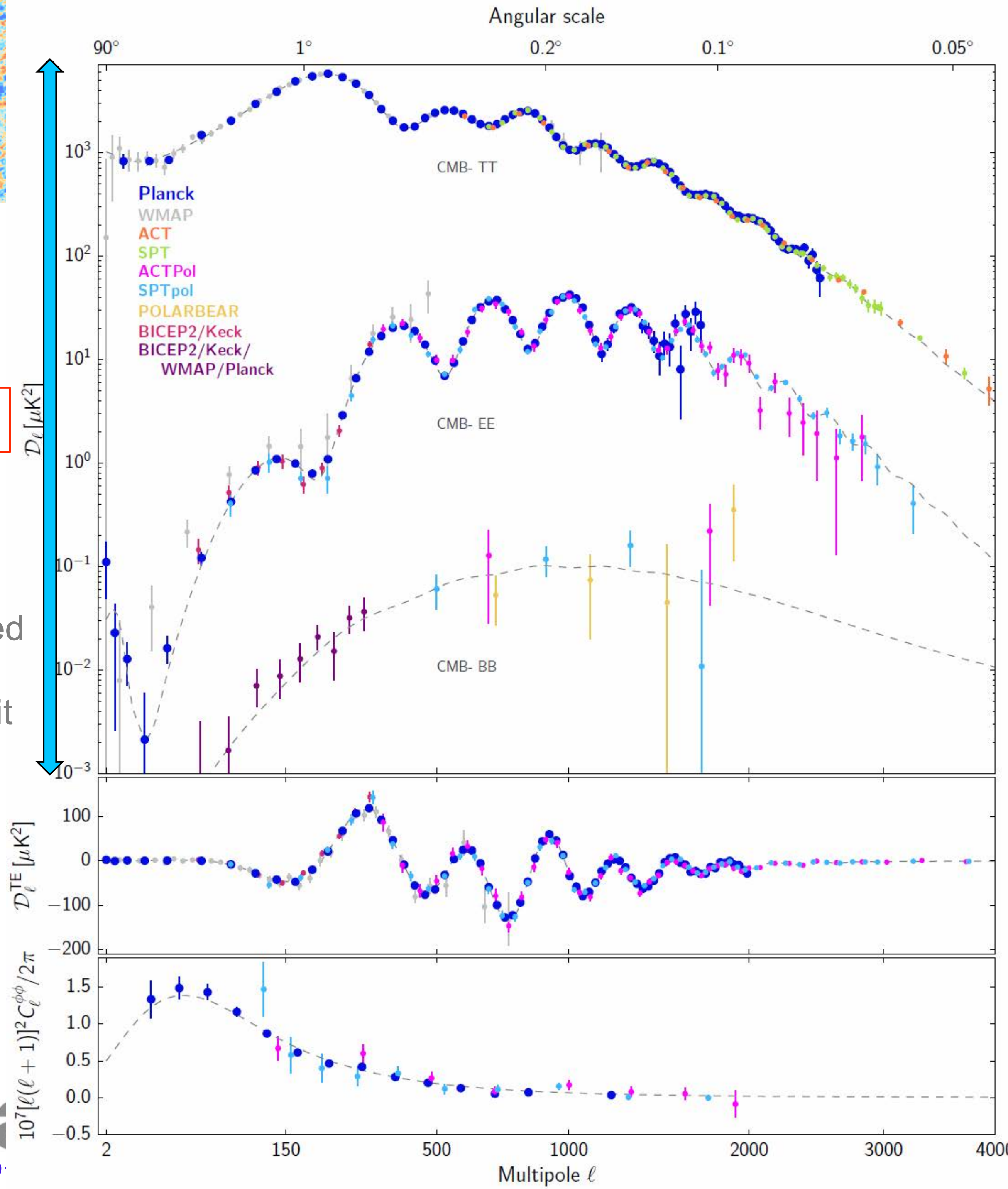
Prediction	Measurement	
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$	100
with a *nearly* scale-invariant (red)		
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$	100
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$	
dominated by scalar perturbations,	$r_{0.002} < 0.07$	
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$	100
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$	
with negligible topological defects	$f < 0.01$	

100 *This pictorial denotes a hundred fold improvement in precision since (at most) COBE*

(Planck 2018 I)

PLANCK VERSUS OTHER PROBES

CMB Landscape 07/2018



10^7

The grey dotted lines are for Planck Best Fit LCDM model

Planck 18:

1 430 000 Modes measured with TT,

64 000 with TE (not shown)

109 000 with EE

3000 with PP

… and 10's in BB

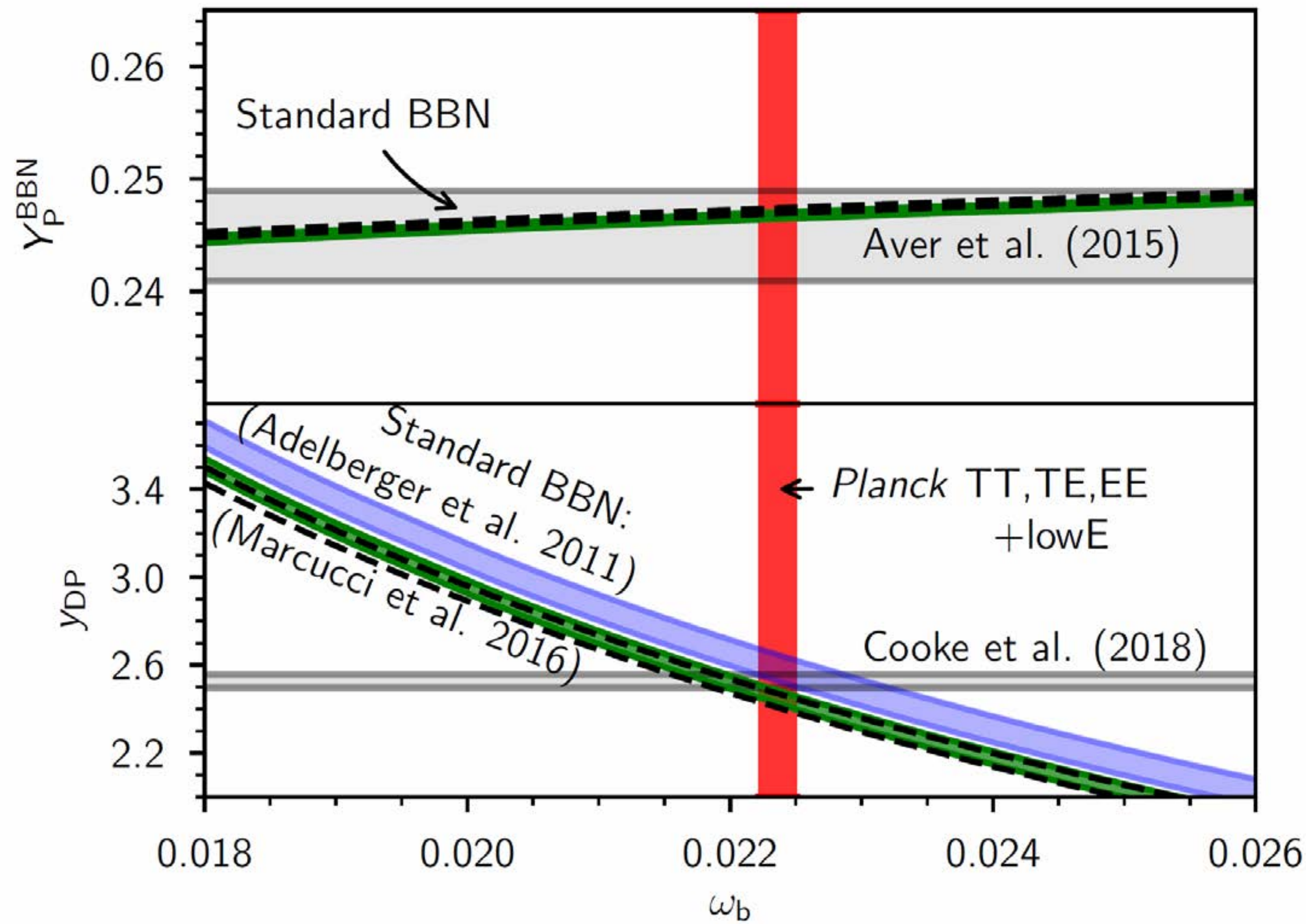
+ weak constraints with TB and EB

(Planck 20

Planck and BBN

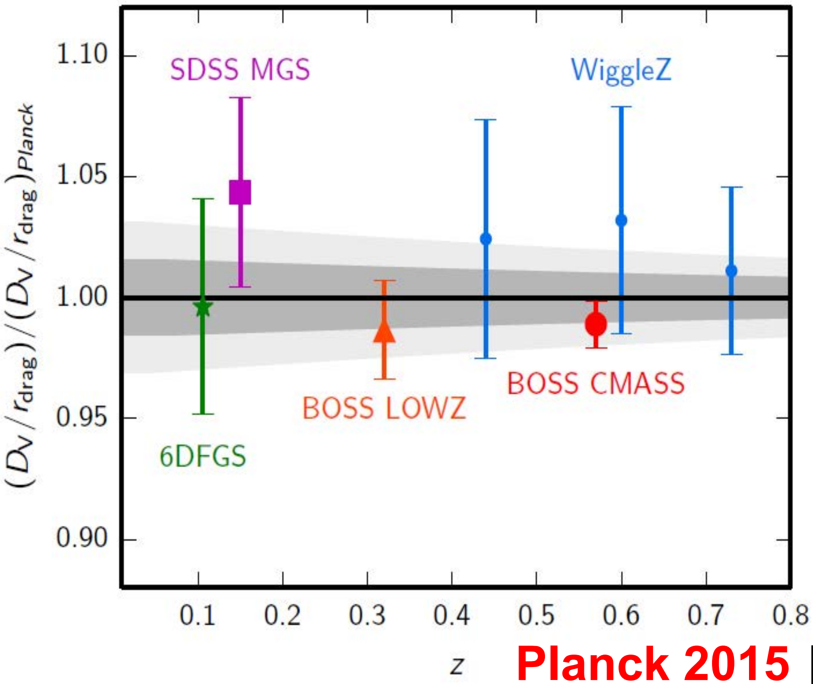
Primordial He

Primordial D

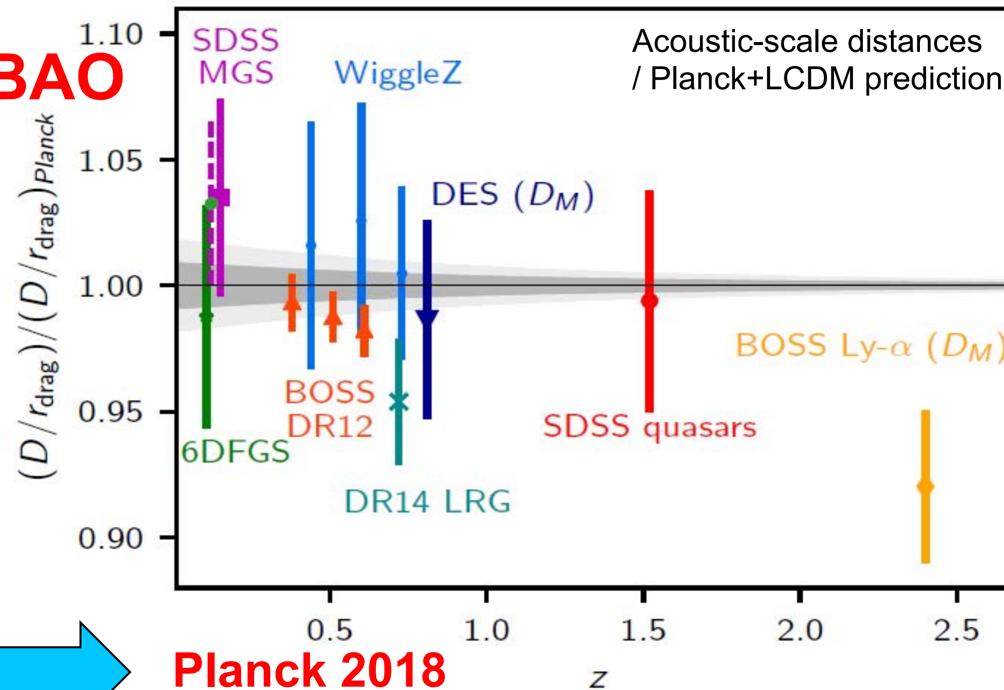


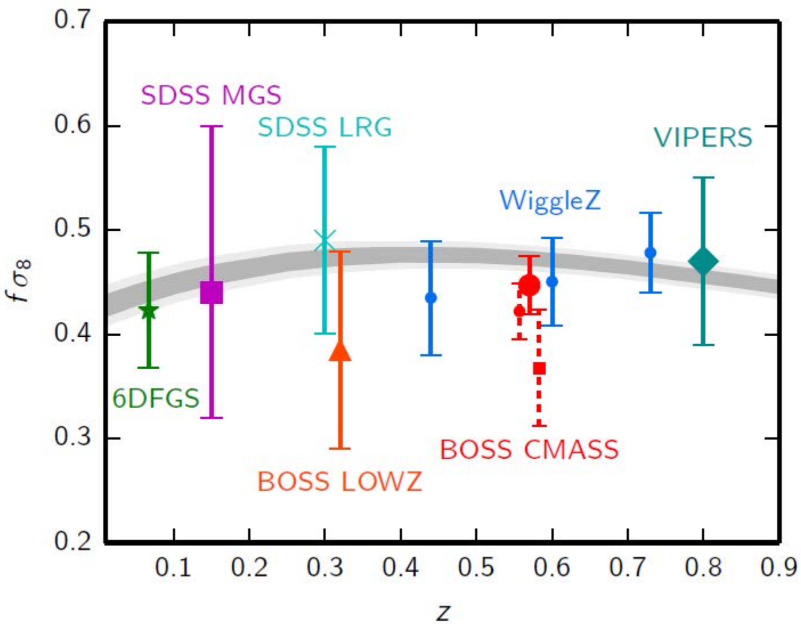
Standard matter abundance

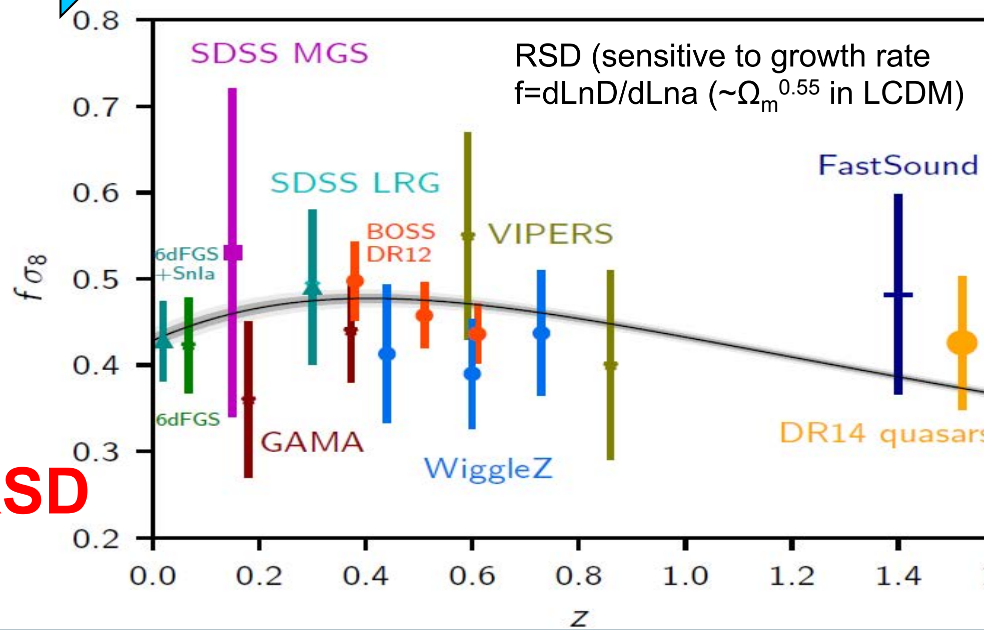
BAO



Planck 2015 → **Planck 2018**

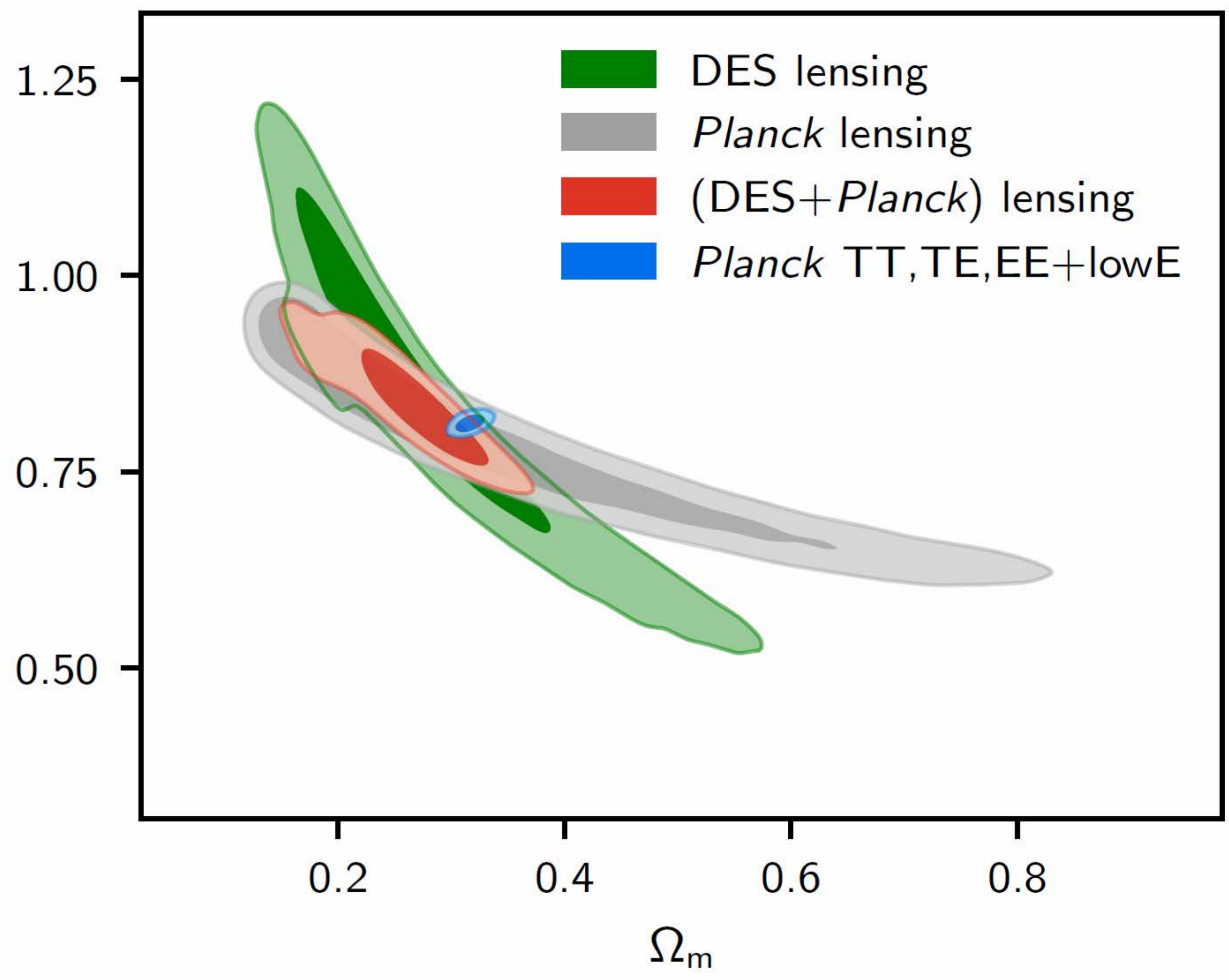






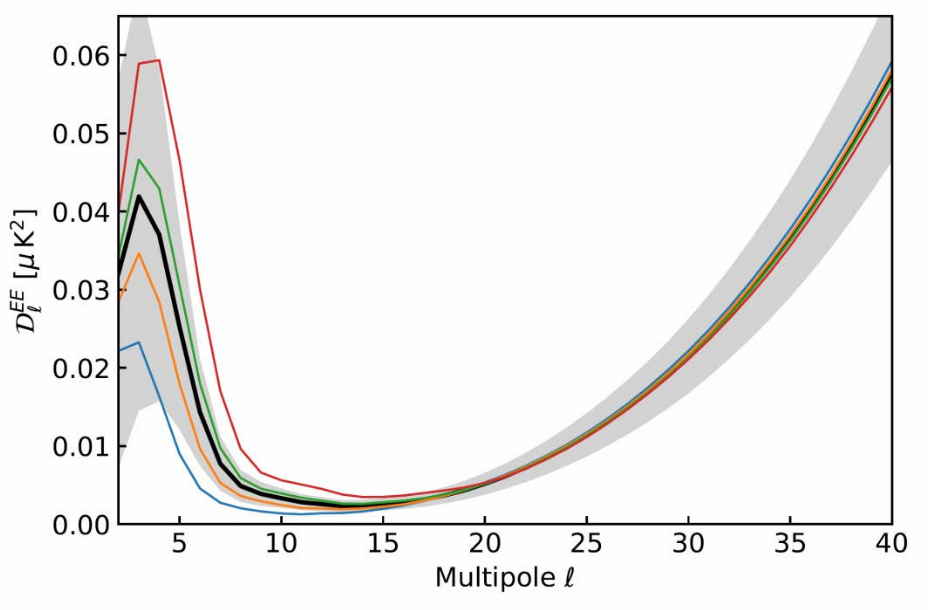
RSD

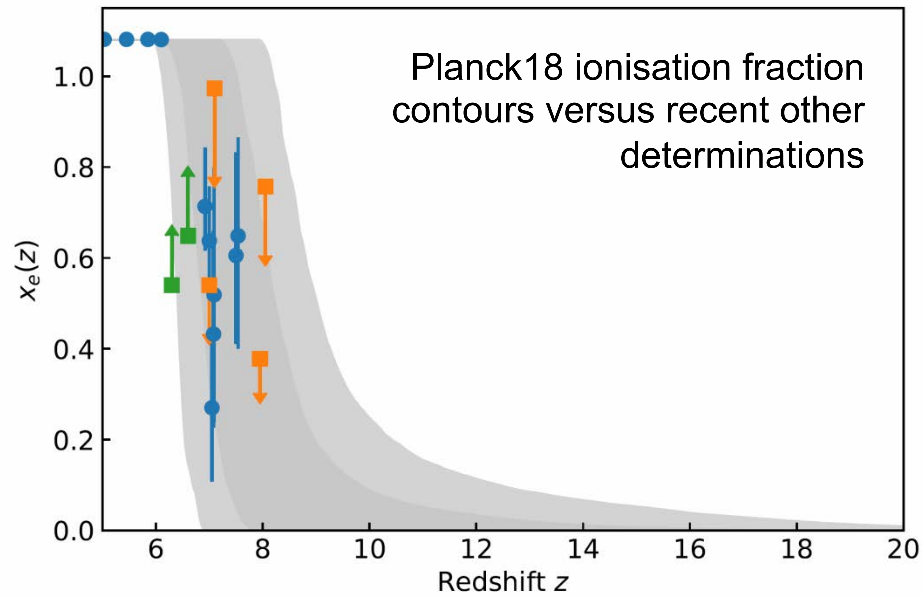
CMB Lensing



DES lensing
Planck lensing
(DES+*Planck*) lensing
Planck TT,TE,EE+lowE
1.25
1.00
0.75
0.50
σ_8
0.2
0.4
0.6
0.8
Ω_m

EE Spectrum & Reionisation

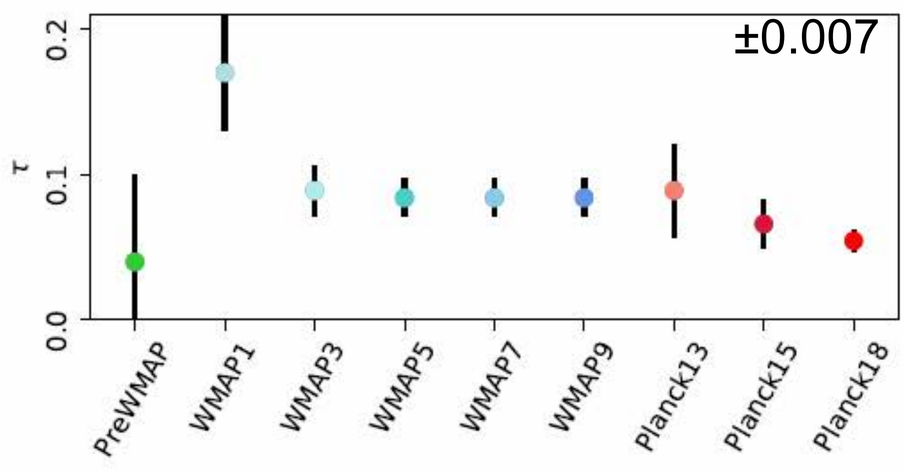




τ=0.04 − 0.07 *by step of* 0.01

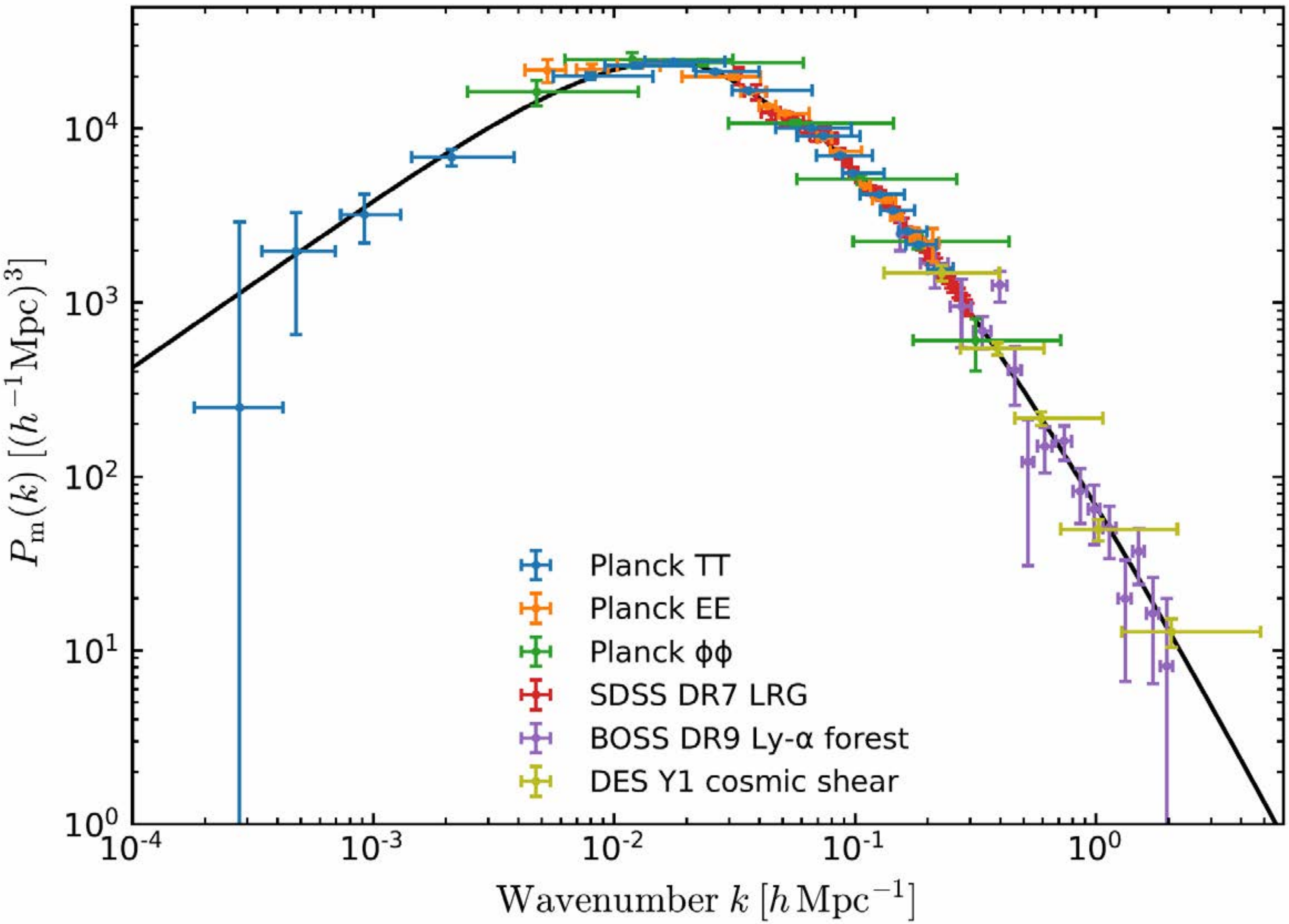
τ=0.056 shown with it $1\sigma_{CV}$−67%

(BF: τ = 0.0544 ±0.0073)



The (linear) matter power spectrum at z = 0

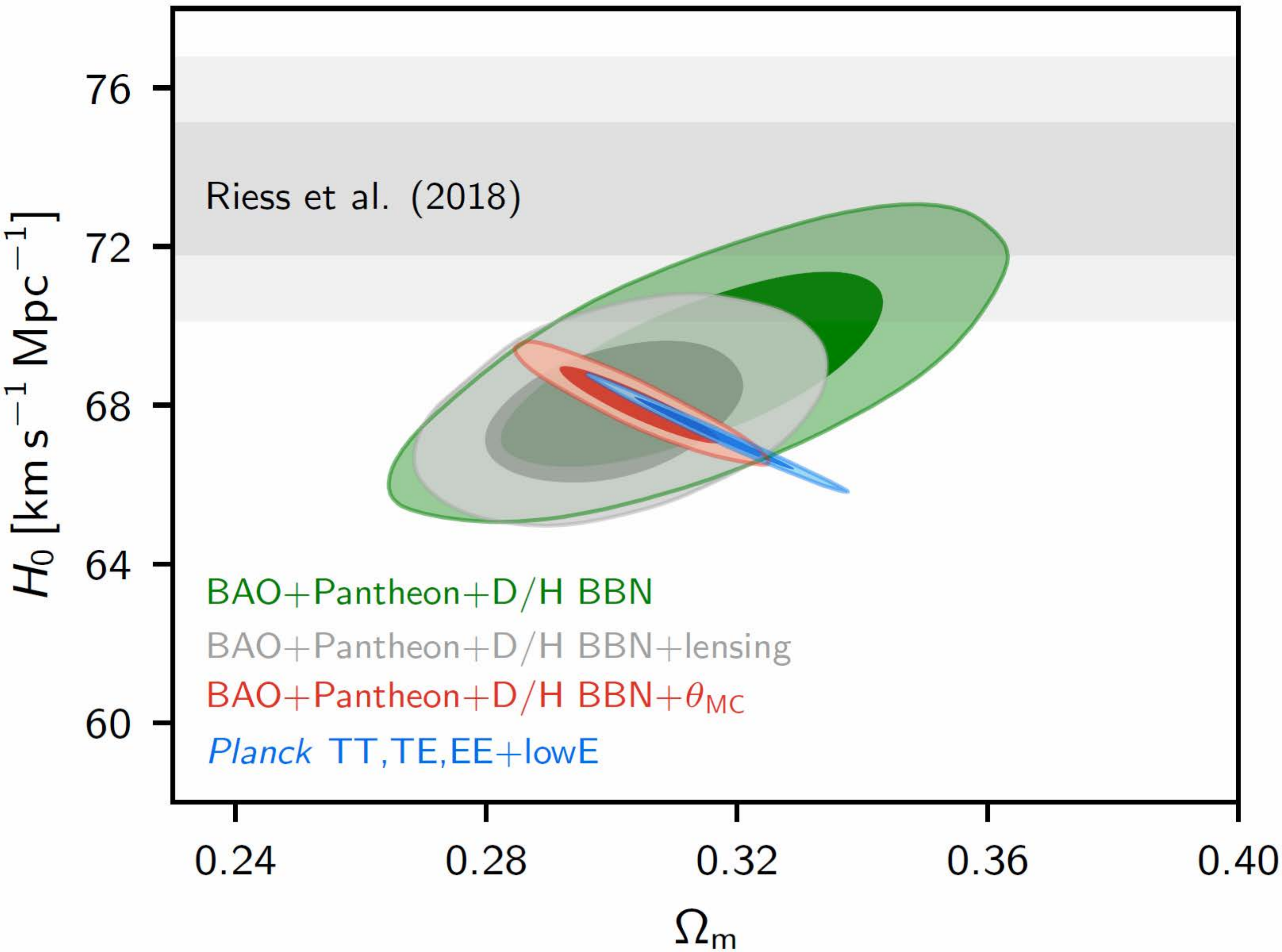
As deduced from different cosmological probes spanning 14Gyr in time and > 3 decades in scale



(Planck 2018 I)

The direct H_0 outlier

(Planck 2018 VI)



Assumptions underlying LCDM

A1: Physics is the same throughout the observable Universe. [rec., BBN!]

A2: General Relativity (GR) is an adequate description of gravity. [Many]

A3: On large scales the Universe is statistically the same everywhere. [CMB near isotropy].

A4: The Universe was once much hotter and denser and has been expanding since early times. [Hot plasma supporting acoustic oscillations]

A5: There are five basic cosmological constituents: [All needed for good fits, with the properties as stated]

A6: The curvature of space is very small, dynamically negligible. [Inflation scorecard]

A7: Variations in density were laid down everywhere at early times, and are Gaussian, adiabatic, and nearly scale invariant (i.e., proportionally in all constituents and with similar amplitudes as a function of scale) as predicted by inflation. [Inflation scorecard]

A8: The observable Universe has ``trivial'' topology (i.e., like R^3). In particular it is not periodic or multiply connected. [no matching circles, etc]

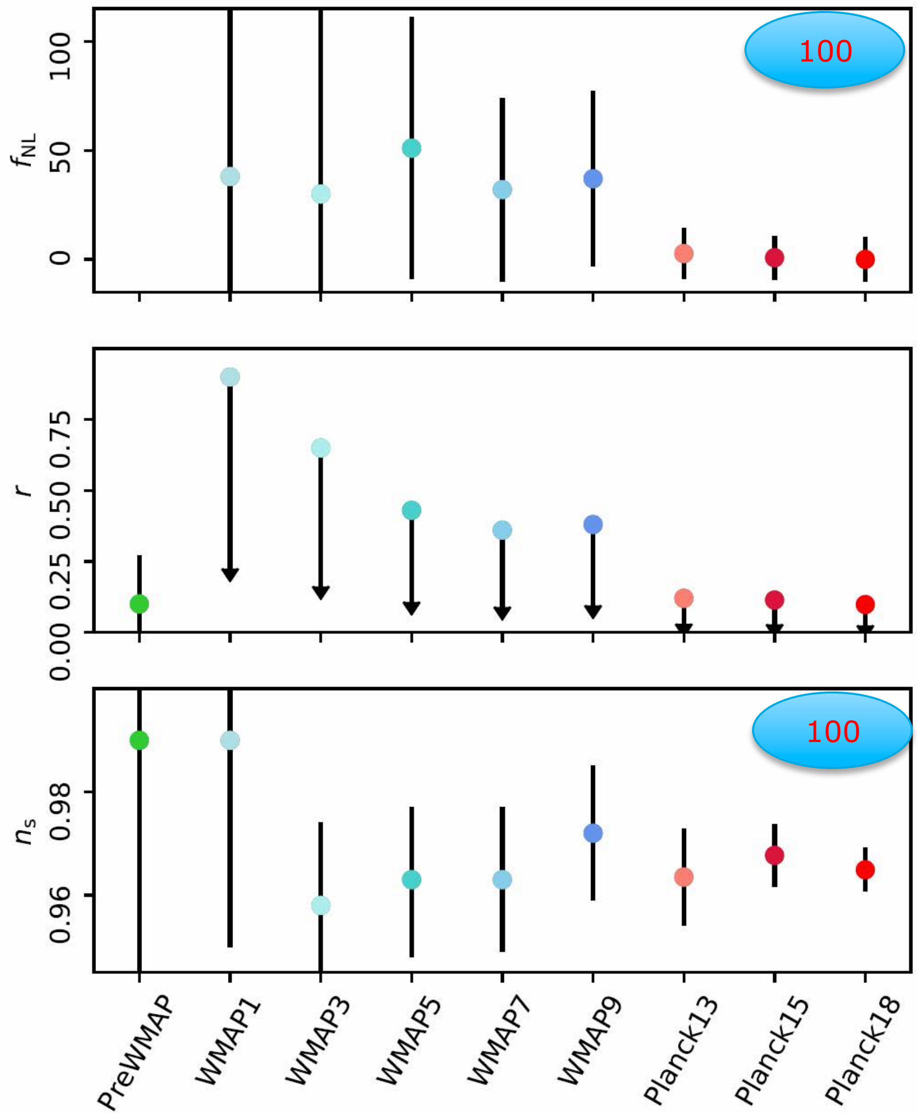
Cosmology post-Planck

1. The LCDM model fits all CMB data in T, E, B, φ (stable across releases).
   a. No need for any extension. Firm footing for the basic assumptions.
   b. Same model parameters, determined at the per cent level (but tau), also fit other data (BBN, BAO, SN1a…). Consistency on 14Gy, and >3 decades
   c. Some tensions (anomalies, SZ?, WL?, H0), whose meaning remains unclear as of now.
2. LCDM is a tilted model (n_s <1) and the inflationary phase models check all the generic boxes. Many specific models have been ruled out though.
3. T anisotropies information essentially exhausted (as we promised to ESA back in 1996), but much still to learn on foregrounds, e.g., from SZ. Polarisation promises a very rich harvest at all angular scales.
4. A new field, CMB lensing, has emerged (observationally), with a great scientific potential···

Planck: a robust stepping stone to the future

LCDM parameters versus time

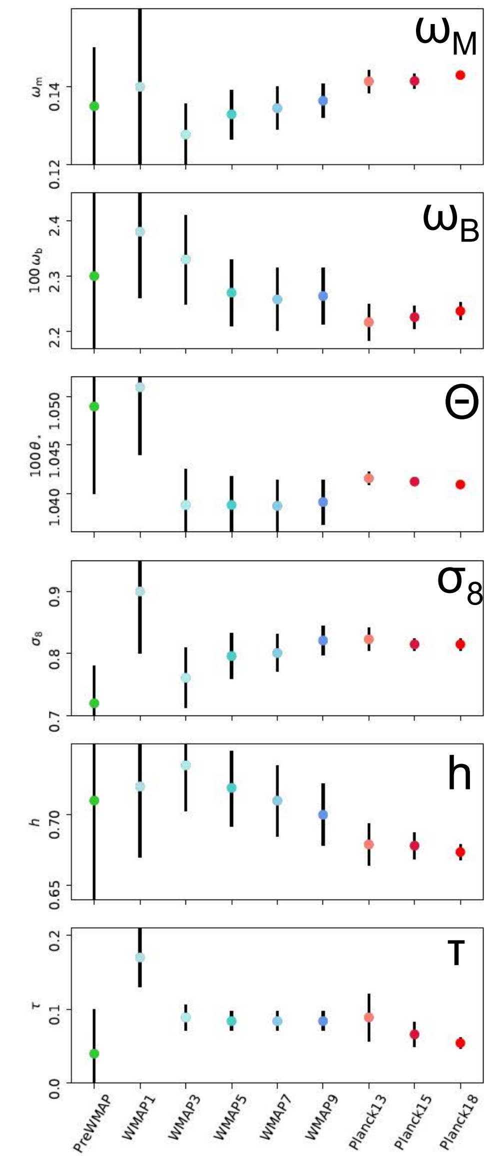
(Planck 2018 I)



Planck LCDM parameters remained quite consistent across analyses, and crossed a number of scientifically significant precision thresholds…

While data volume increased greatly (surveys, polarisation) and 5 years of analyses by a large and varied team allowed many more checks for instrumental effects, thanks to conservative analysis choices from start.

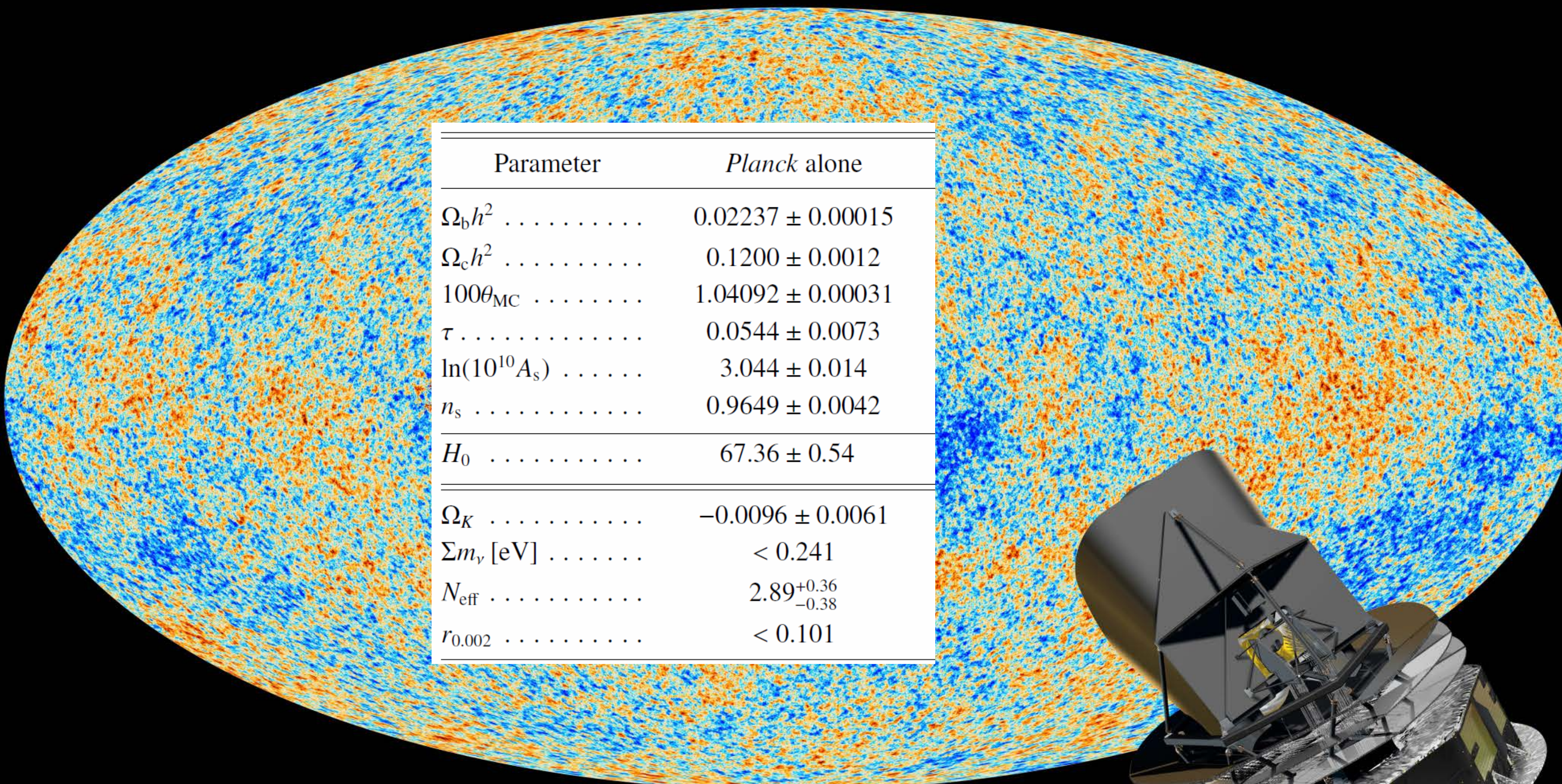
(despite quite a number of surprises, glitches, VLTC, ADC, fluke…)



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.

The Planck (cosmological) legacy



Parameter	*Planck* alone
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$\Omega_c h^2$	0.1200 ± 0.0012
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τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54
Ω_K	-0.0096 ± 0.0061
Σm_ν [eV]	< 0.241
N_{eff}	$2.89^{+0.36}_{-0.38}$
$r_{0.002}$	< 0.101

François R. Bouchet
Institut d'Astrophysique de Paris (IAP),
CNRS & Sorbonne Université

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 primordial fluctuations.
Flat spatial geometry.

1. $\Omega_b h^2$ Baryon density today - The amount of ordinary matter
2. $\Omega_c h^2$ Cold dark matter density today – only weakly interacting
3. Θ Sound horizon size when optical depth τ reaches unity
   (Distance travelled by a sound wave since inflation, when universe became transparent at recombination at t ~380 000 years)

4. 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

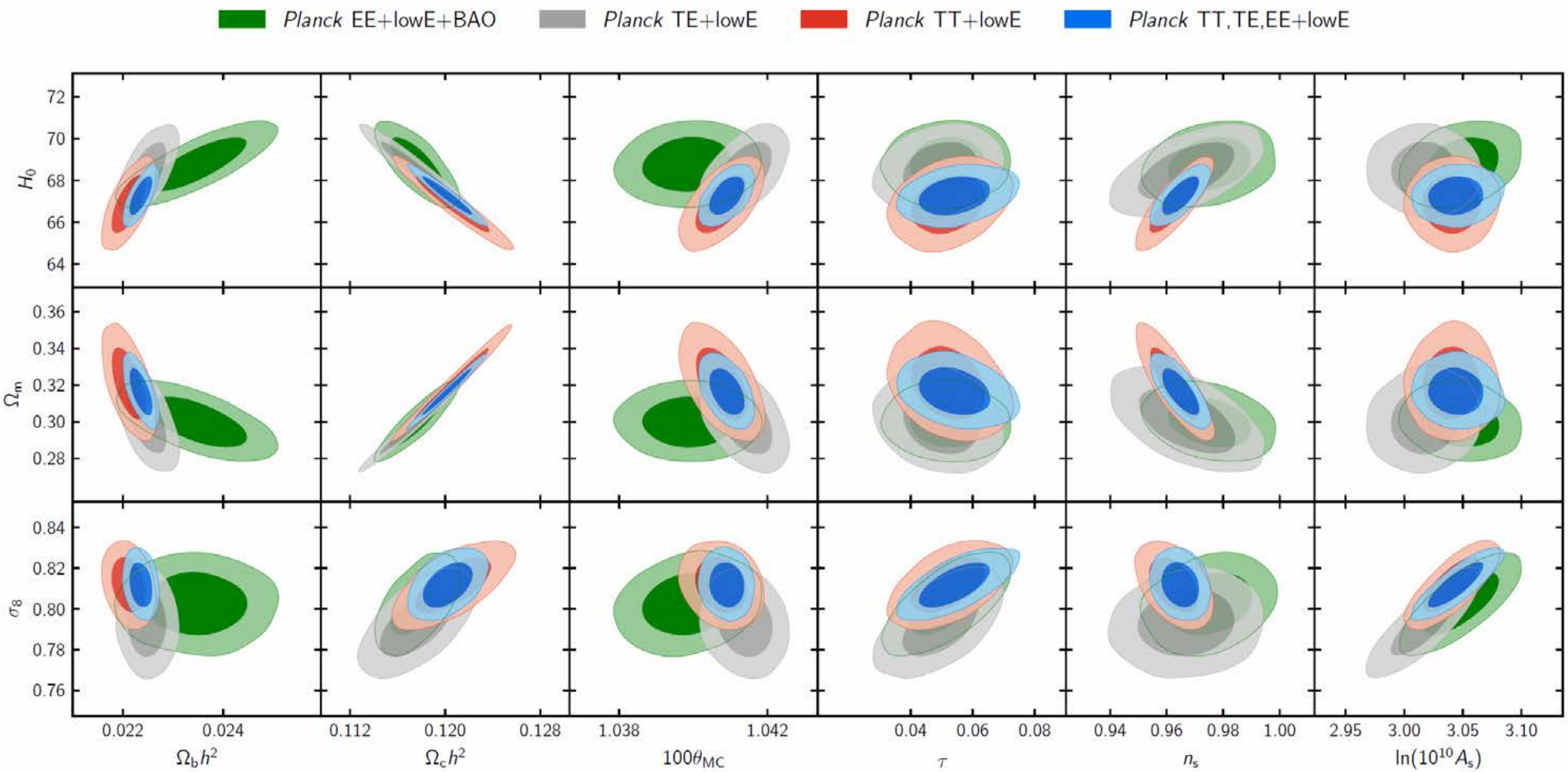
1. A_s Amplitude of the curvature power spectrum
   (Overall contrast of primordial fluctuations)
2. n_s Scalar power spectrum power law index
   (n_s-1 measures departure from scale invariance)

3. Others are *derived* parameters within the model, in particular
   a. Ω "Dark Energy" fraction of the critical density (derived only if assumed flat)
   b. H_0 the expansion rate today (in km/s per Mpc of separation)
   c. t_0 the age of the universe (in Gy)

Temperature and Polarisation agree

(Planck 2018 VI)

Within LCDM



Anomalies

1. Some large scale anomalies detected pre-Planck were confirmed and significance often increased (in particular since BF model is better determined)
    a. Power deficit at low-ell
    b. Power asymmetry between hemisphere
    c. Low multipoles alignment
    d. Dipolar modulation
    e. Low variance
    f. Cold spot
    g. Point parity and mirror-parity asymmetry
2. Planck provides high confidence in their existence due to two independent instruments, the quality of data, the unprecedented coverage of Foregrounds…
3. No compelling explanation yet:
    a. Statistical fluke in LCDM is quite possible (NB: A_lens)
    b. Secondary effect apparently too weak
    c. Foregrounds are well controlled (and systematics essentially ruled out)
    d. Then tantalising possibility of new physics; but CV limit, a posteriori statistics, etc.

[Planck 2015 XVI]