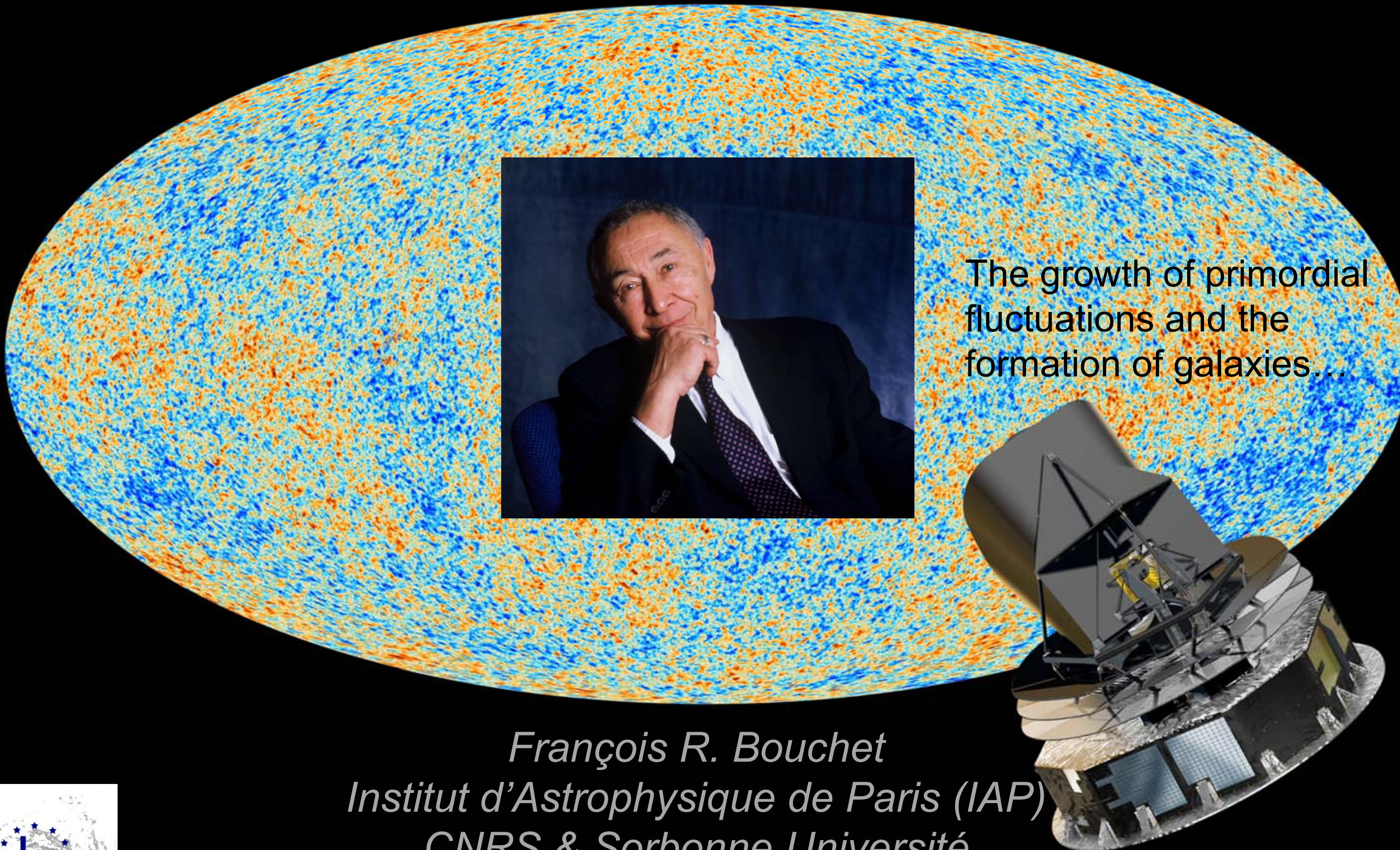
The Planck (cosmological) legacy

The almost unreasonable effectiveness of the standard cosmological (LCDM) model



The growth of primordial fluctuations and the formation of galaxies…

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

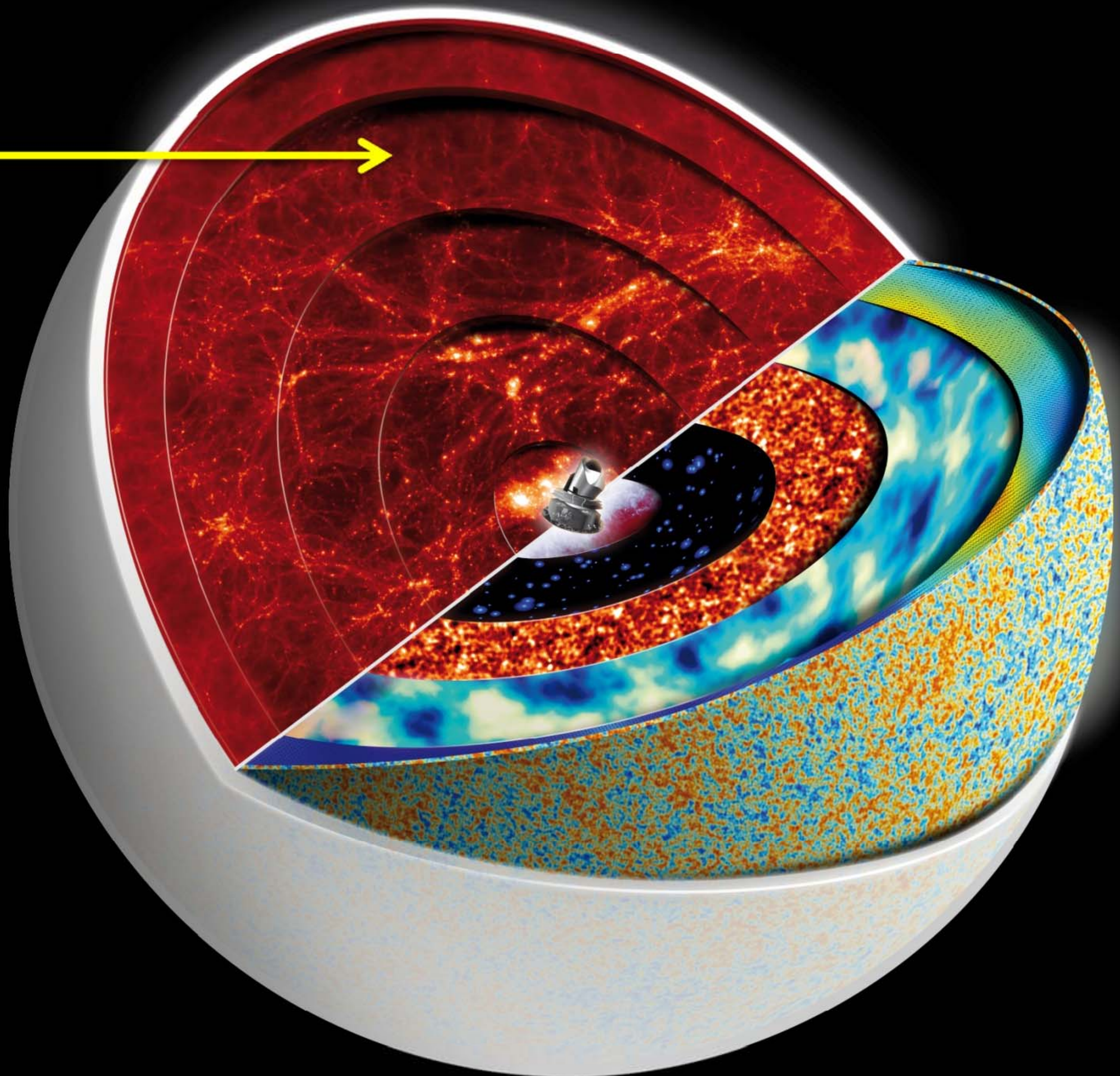
@ CPHT 1981-1984, PhD with R. Pellat

The observable Universe in a nutshell

Dark Matter Distribution.

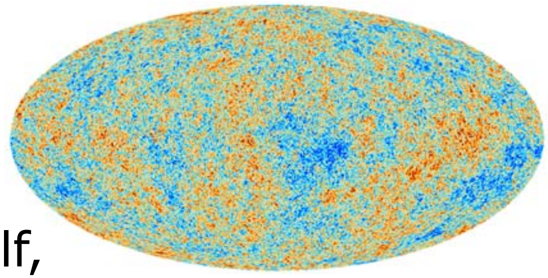
Simulated w. a treecode builind on Experience From a PIC plasma code

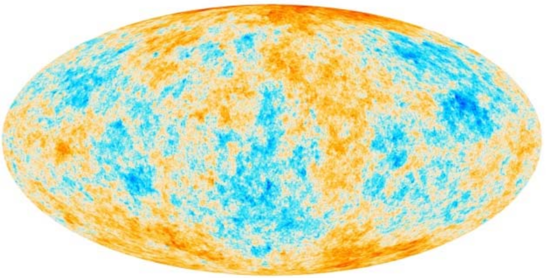
And the kind nurturing from J.-C. Adam & A. Gourdin-S.



From the cosmic sponge back to quantum foam

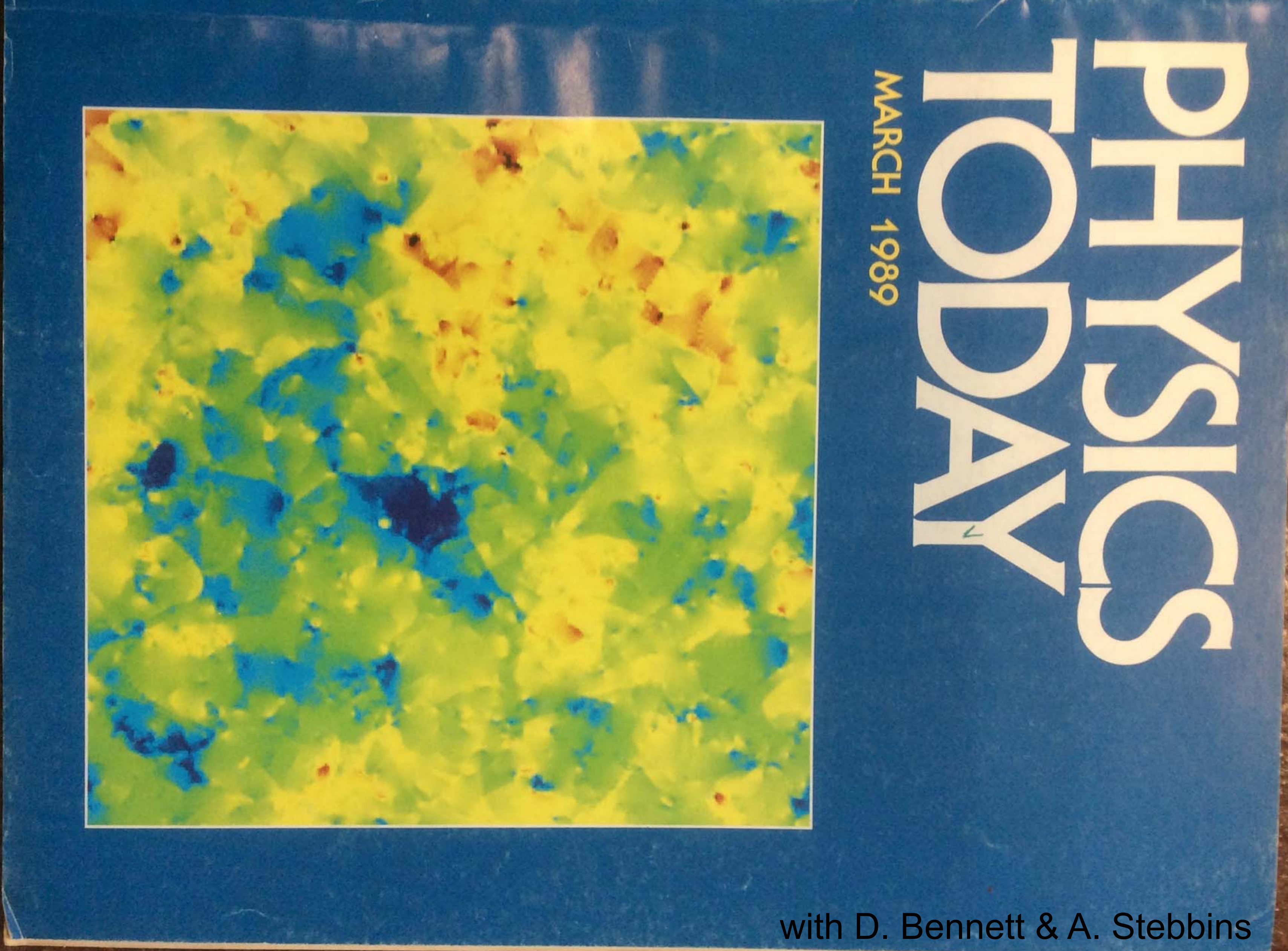
Theorists precomputed possible imprints in various scenarii





Gamow, Peebles, Yu, Sachs & Wolf, Sunyaev, Zeldovich, Silk, Vittorio, Wilson, Mukhanov, Chibisov, Bardeen, Linde, Bond, Efstathiou, Bouchet, Bennett, Gott, Kaiser, Stebbins, Allen, Shellard, Seljack, Zaldariaga, Kamionkowski, Hu, Sugyama…

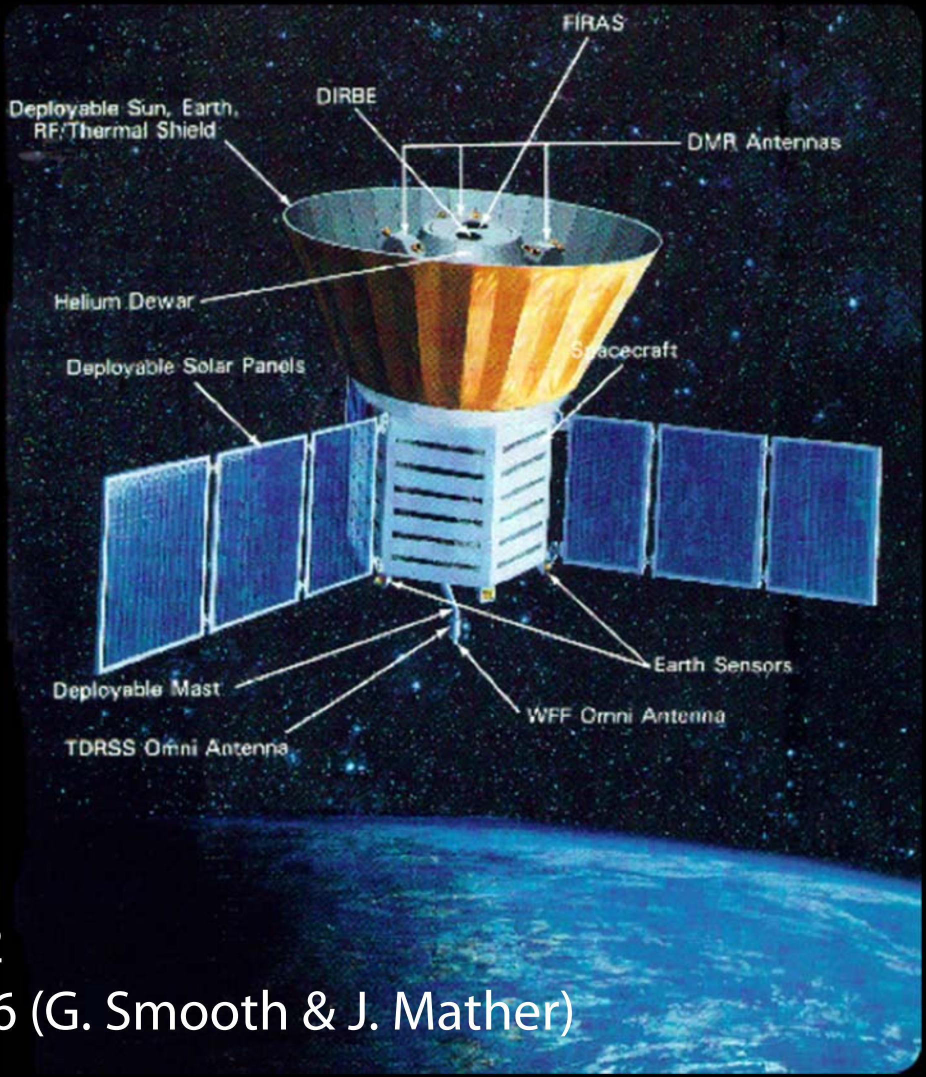
For different models and their *cosmological* parameters, which turn out to encode the content and determine the dynamics of the Universe and the origin of its large scale structures!



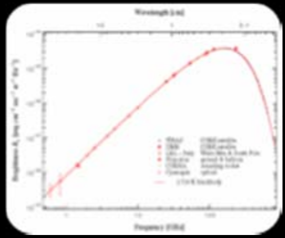
with D. Bennett & A. Stebbins

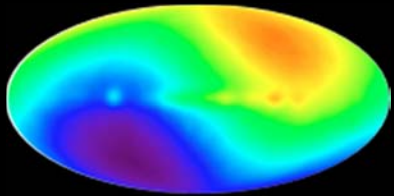
Cosmic Strings imprint on CMB, again using experience I gathered @ CPHT

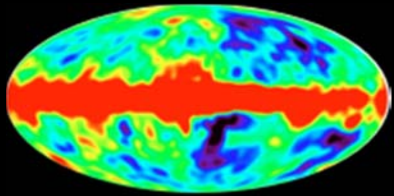
PLANCK IN THE MAKING



COBE 1992
Nobel 2006 (G. Smooth & J. Mather)







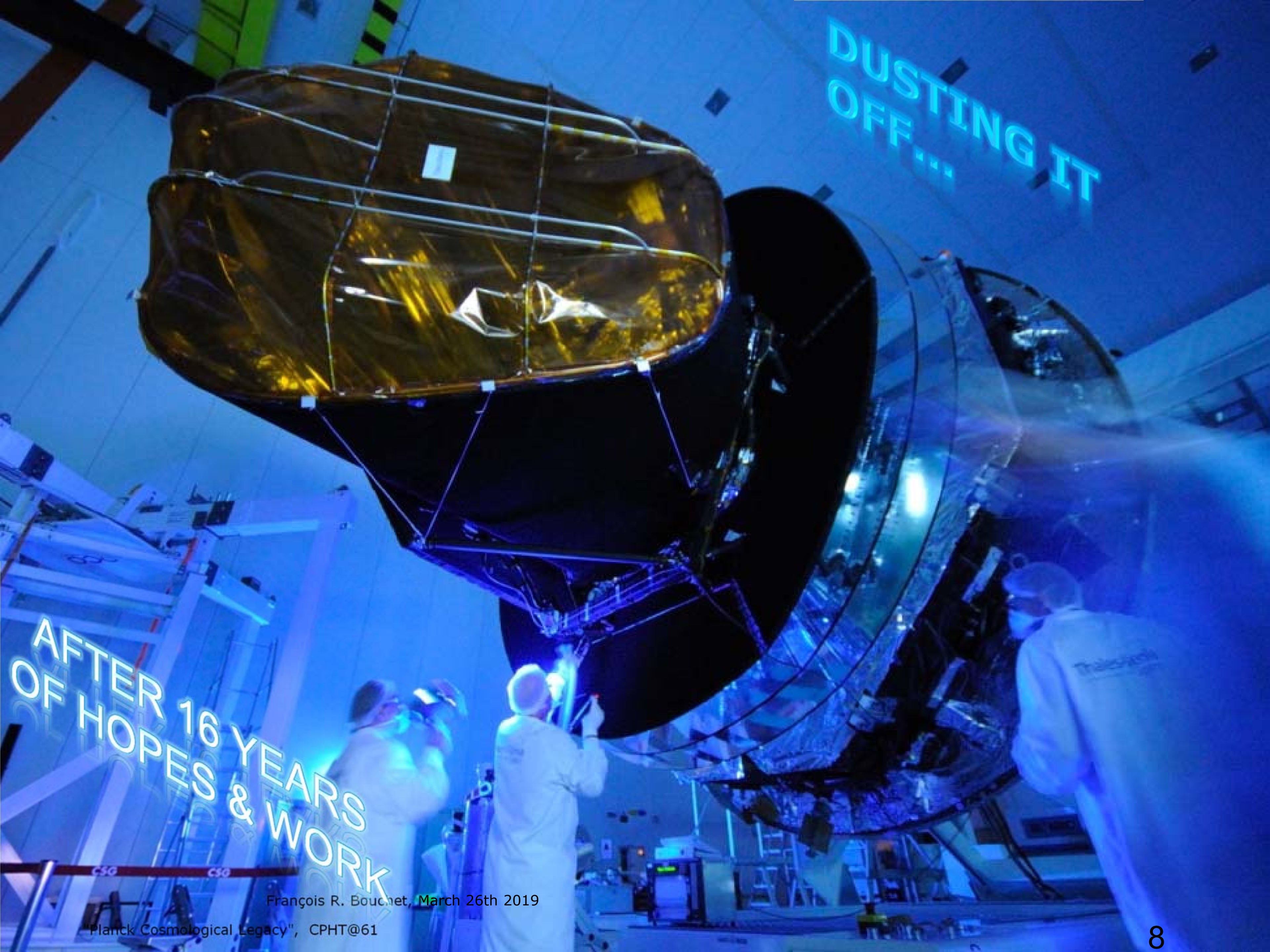
The Planck mission concept/challenge

- 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)

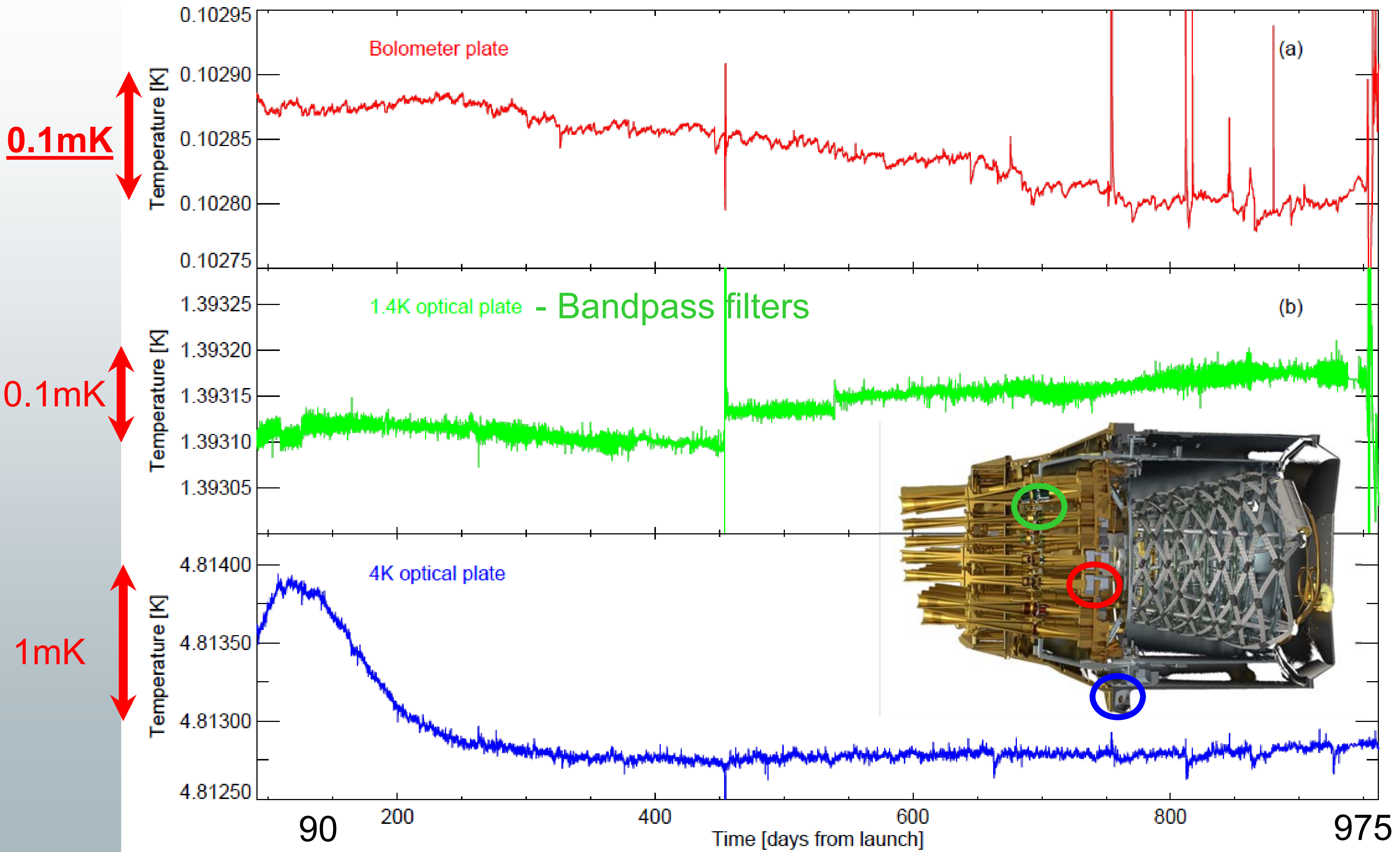
NB1: This required a number of technological breakthroughs.

NB2: with the Ariane-501 failure delaying us by several years (2003 → 2007) 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
ThalesAlenia


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

Very cold, very stable, for very long…



French cellars don't only have great wine

+ CC/CINECA/ Darwin/NERSC…

To process ~1000 billion time samples (after 2013)

Planck data/cosmology in a nutshell

- ~ 1000 billion time samples in ~100 Timelines
- ~ **1 billion pixel values** (7*{I,Q,U+2*I=23 maps of ~50million pixels) [+ IMO & Simulations & subsets; **the data legacy**]
- ~ 100 million CMB pixel values (2 maps of ~50 million pixels, I, E) [B]
- ~ 10 million harmonic modes (2l+1 m-modes/l, TT+TE+EE+ΦΦ+B's)
- ~ 10 thousand power spectra bins
- All fit with just **6** parameters of a **base LCDM cosmological model**!
- *… With no significant evidence for a **7th***
- *…And still holding together with **most** other cosmological probes*

6 parameters Base LCDM model

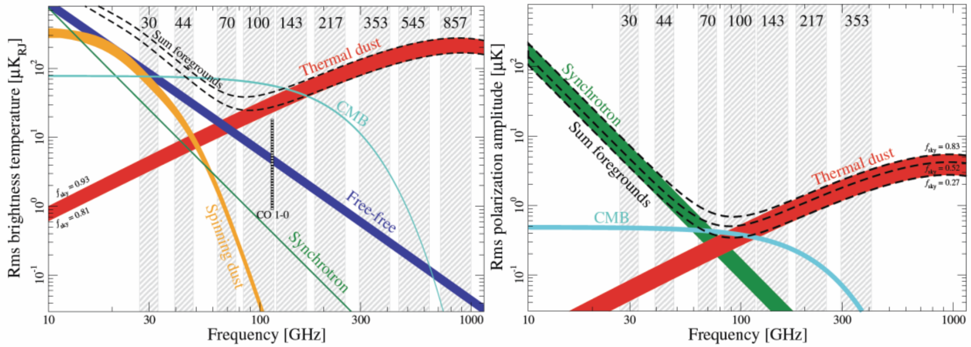
An amazingly minimal model, deceptively simple, since it relies on **far reaching assumptions**:

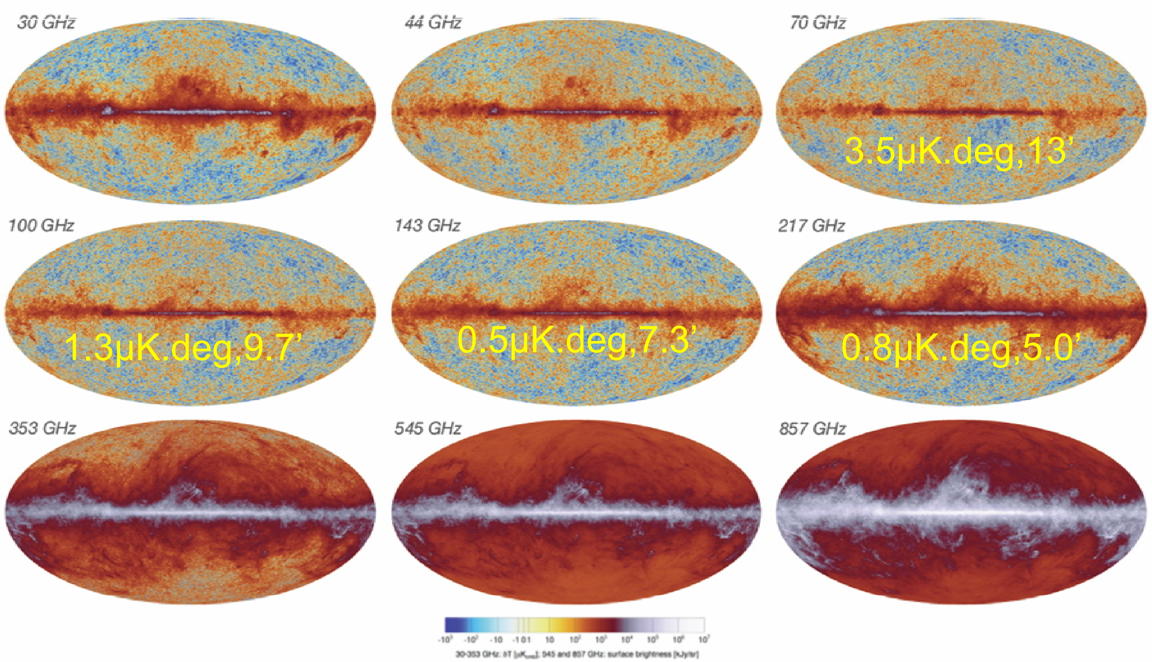
1) Physics is the same throughout the observable Universe.
2) General Relativity (GR) is an adequate description of gravity.
3) On large scales the Universe is statistically the same everywhere.
4) The Universe was once much hotter and denser and has been expanding since early times.
5) There are five 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).

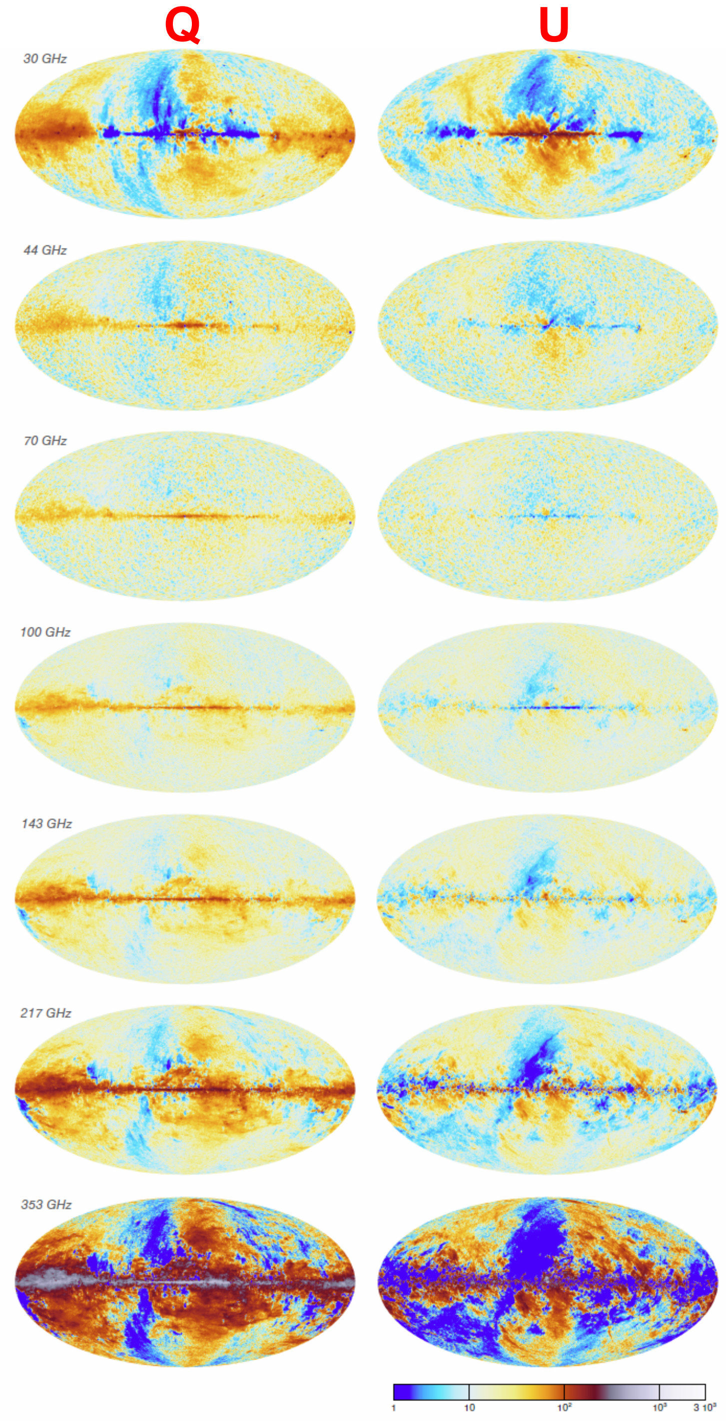
...**Assumptions which Planck helps putting on quite firm ground**...

MAPS LEGACY

Planck 2018 Intensity I & Stockes parameters Q&U maps







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

esa

Francois F

Solar Dipole

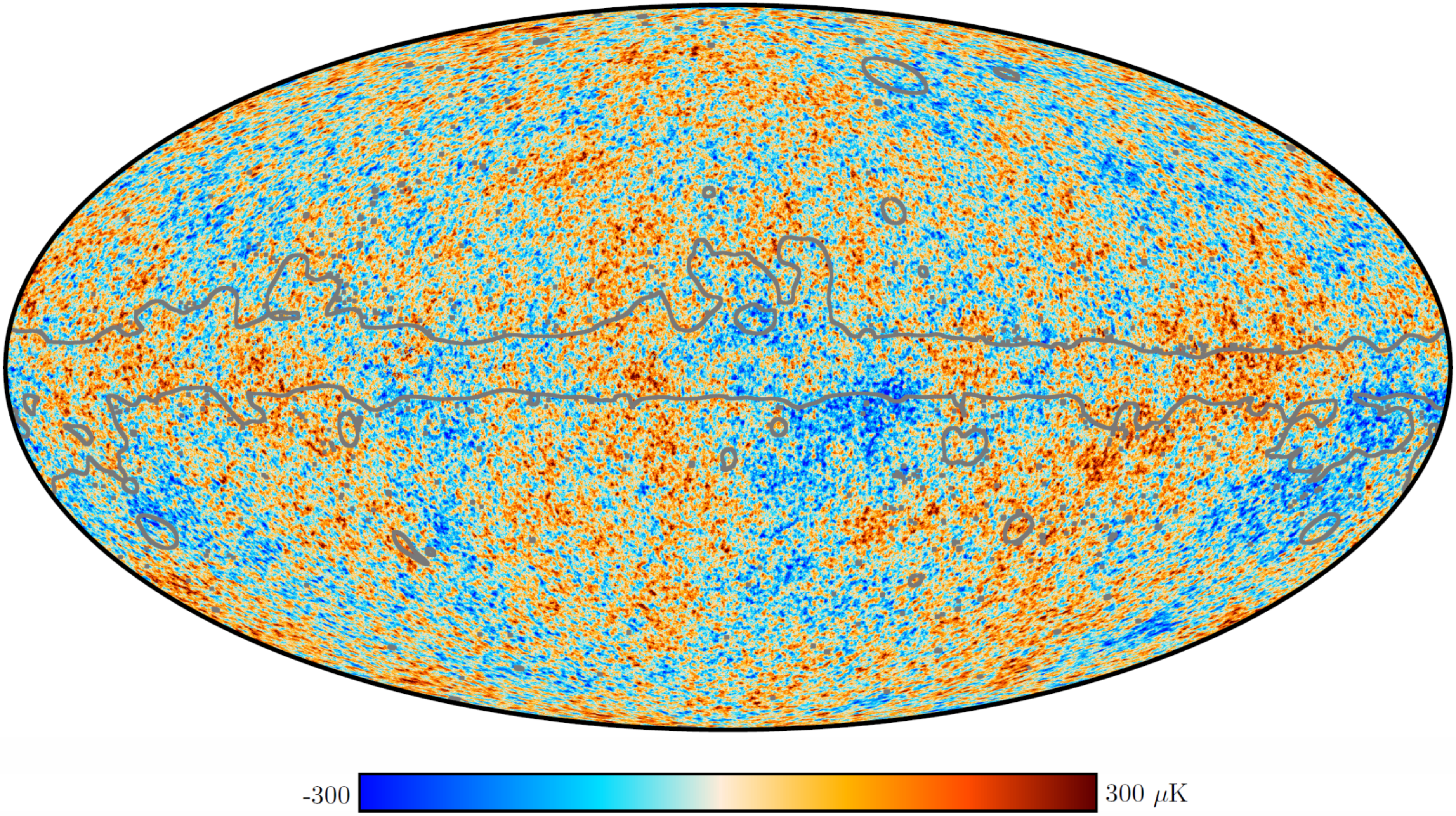
Experiment	Amplitude [μK_{CMB}]	Galactic coordinates l [deg]	Galactic coordinates b [deg]
COBE [a]	3358 ± 24	264.31 ± 0.20	48.05 ± 0.11
WMAP [b]	3355 ± 8	263.99 ± 0.14	48.26 ± 0.03
Planck 2015 nominal [c]	3364.5 ± 2.0	264.00 ± 0.03	48.24 ± 0.02
LFI 2018 [d]	3364.4 ± 3.1	263.998 ± 0.051	48.265 ± 0.015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

Planck CMB anisotropies map & mask

Final, released 2018/07/17 (but visually indistinguishable from 2013 version)



(Planck 2018 I)

COLLECTION LE MONDE EST MATHÉMATIQUE

Le Monde

physicsworld TOP 10 BREAKTHROUGH 2013

CRISE CHYPRIOTE : L'ULTIMATUM DE FRANCFORT

En Tunisie, le drame des disparus de la révolution

Vendredi 22 mars 2013 - 69e année - N° 21204 - 1,80 € - France métropolitaine - www.lemonde.fr

Moins d'impôts et plus d'austérité, Londres persiste

- Le Royaume-Uni fait cavalier seul en matière fiscale et décide 13 milliards d'euros de coupes budgétaires
- En panne de croissance comme le reste de l'Europe, Londres mise toujours plus sur la Banque d'Angleterre
- L'efficacité des politiques d'austérité en question

C'ÉTAIT L'UNIVERS IL Y A 13,8 MILLIARDS D'ANNÉES

Des images inédites du satellite européen Planck dévoilent l'enfance du monde. Ni étoile ni galaxie, mais des particules microscopiques, des électrons et des protons LIRE PAGES 2-3

Image du rayonnement primordial de l'Univers prise par le satellite européen Planck.

LE MONDE DES LIVRES

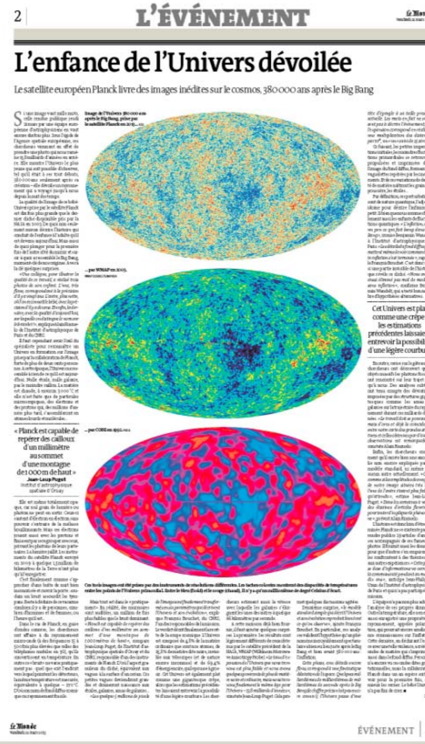
Spécial Salon du livre de Paris

- Barcelone ville invitée, Roumanie à l'honneur
- Quelle littérature enseignée au collège et au lycée ? Regards d'auteurs et d'enseignants
- Le livre numérique peine à décoller

Le pari de Cameron : politique de l'offre contre récession

AUJOURD'HUI

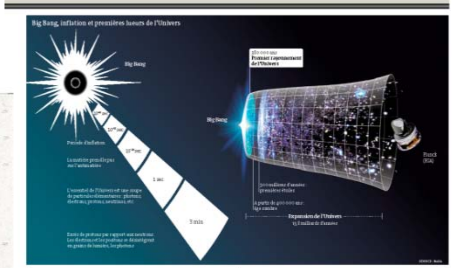
ÉDITORIAL



L'ÉVÉNEMENT

L'enfance de l'Univers dévoilée

Le satellite européen Planck livre des images inédites sur le cosmos, 380 000 ans après le Big Bang

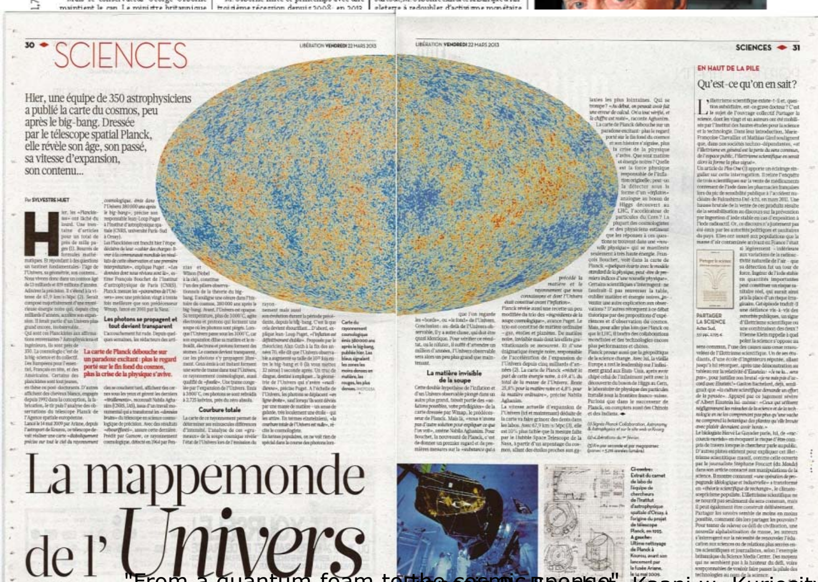


« Les découvertes ne s'arrêtent jamais... Tout ça grâce à un rayonnement micro-onde ! »

Des fientes de pigeon au « visage de Dieu »

Les indégivrables

Avec l'Internet des objets, le web sort du bocal

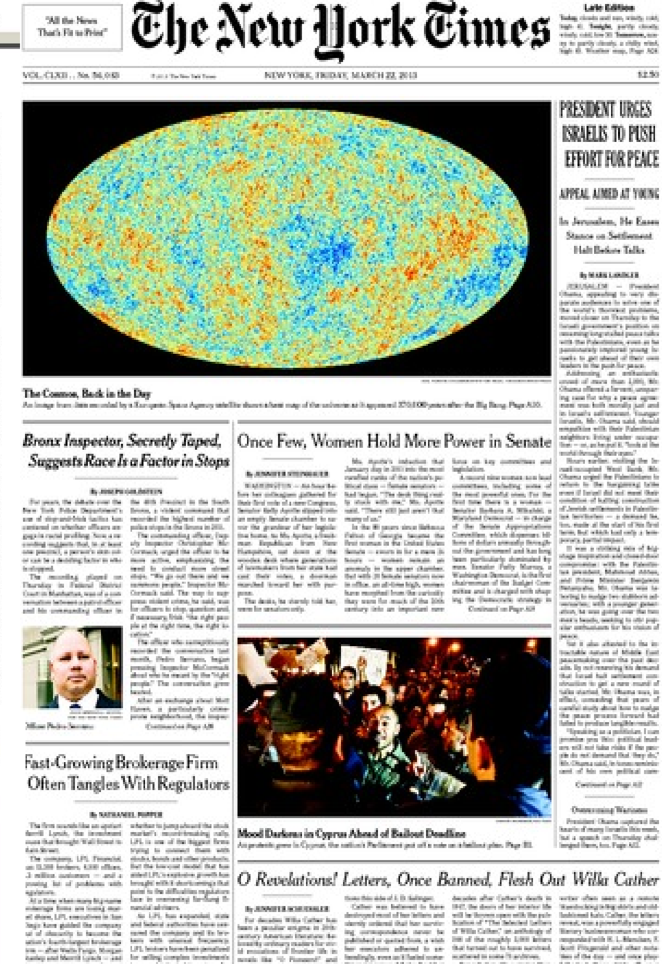


SCIENCES

Hier, une équipe de 350 astrophysiciens a publié la carte du cosmos, peu après le big-bang. Dressée par le télescope spatial Planck, elle révèle son âge, son passé, sa vitesse d'expansion, son contenu...

La mappemonde de l'Univers

Qu'est-ce qu'on en sait ?



The New York Times

NEW YORK, FRIDAY, MARCH 22, 2013

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

The Cosmos, Back in the Day

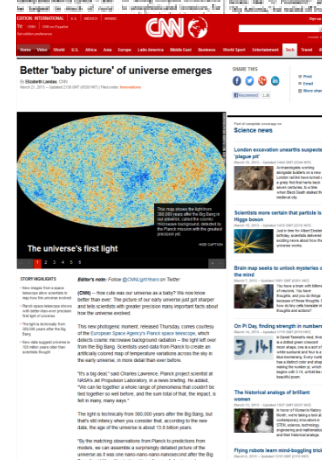
Bronx Inspector, Secretly Taped, Suggests Race Is a Factor in Stops

Once Few, Women Hold More Power in Senate

Fast-Growing Brokerage Firm Often Tangles With Regulators

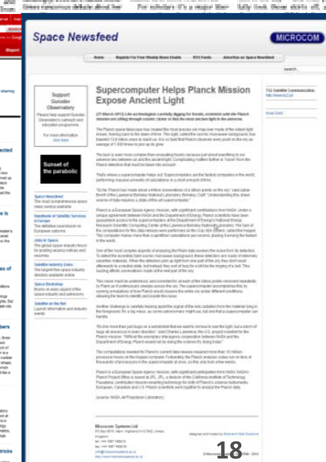
Mood Darkens in Cyprus Ahead of Bailout Deadline

O Revelations! Letters, Once Banned, Flesh Out Willa Cather



Better 'baby picture' of universe emerges

The universe's first light



Space Newsfeed

Supercomputer Helps Planck Mission Expose Ancient Light

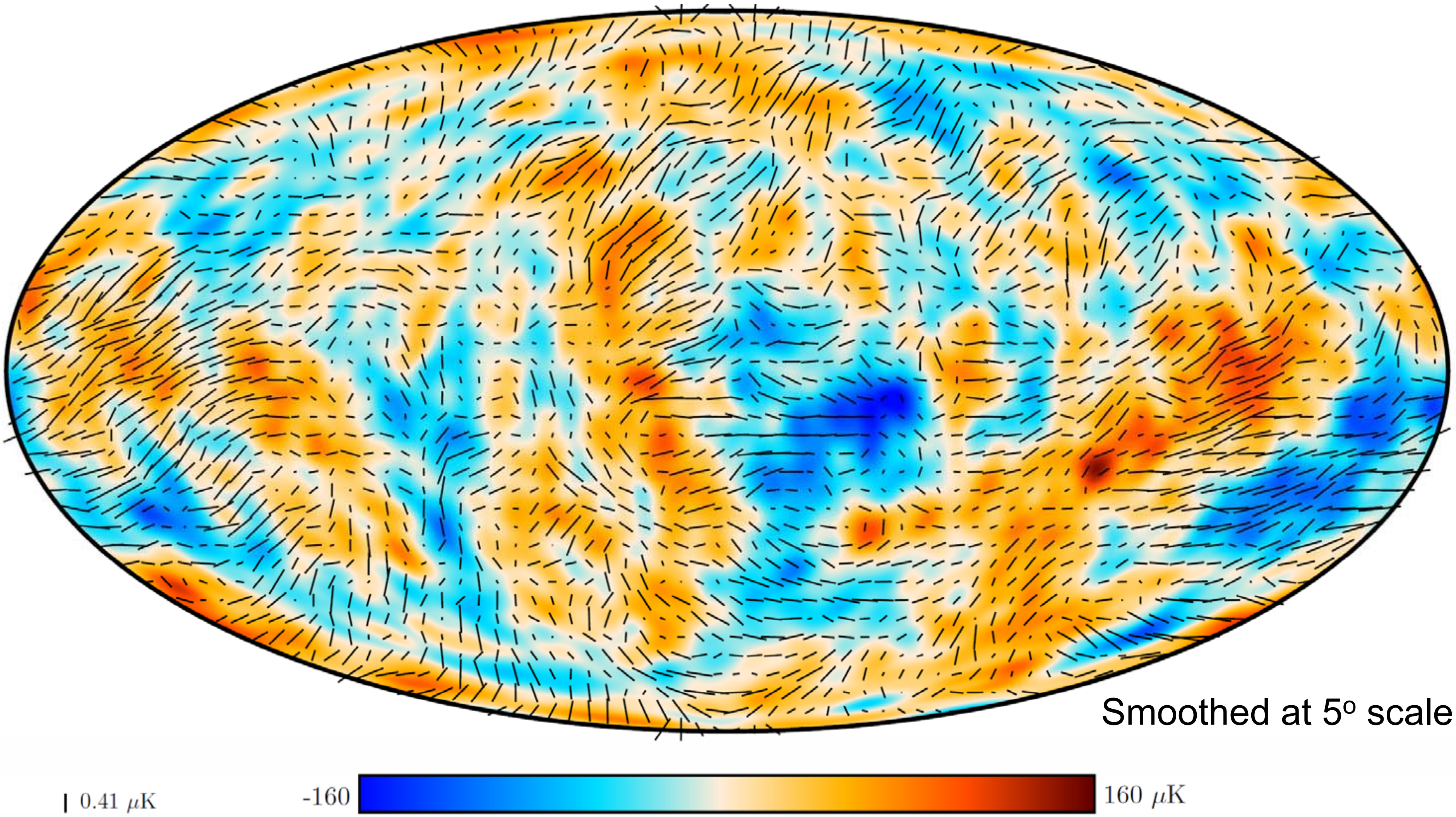
"From a quantum foam to the cosmic sourse", François R. Bouchet, Kaapi w. Kuriosity, Jan 20th 2019

Rose interest in broad circles ☺

Entrevue papale du 12 mai 2017

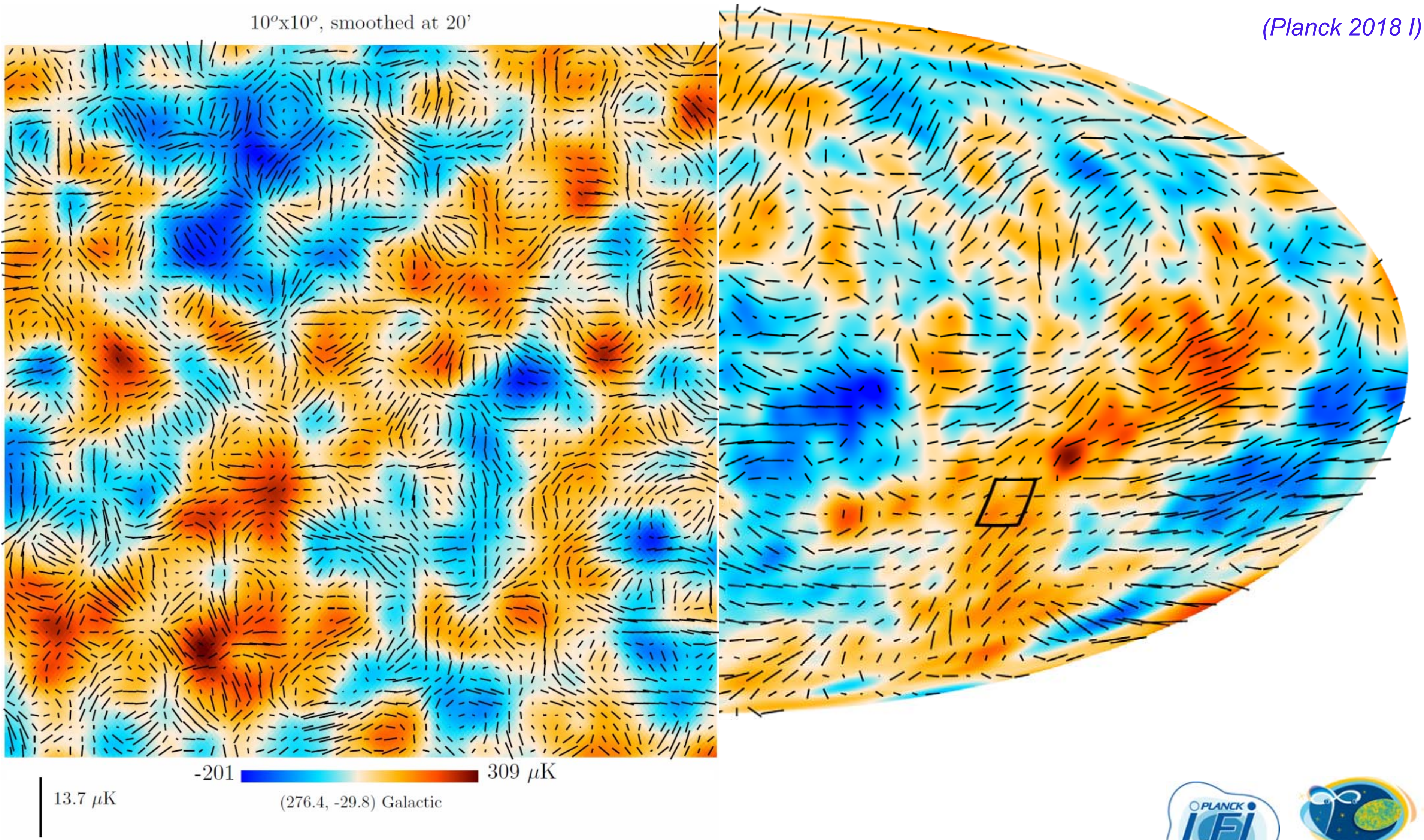
Lemaitre Conference @ Castel Gandolfo

Planck Polarisation superimposed on T

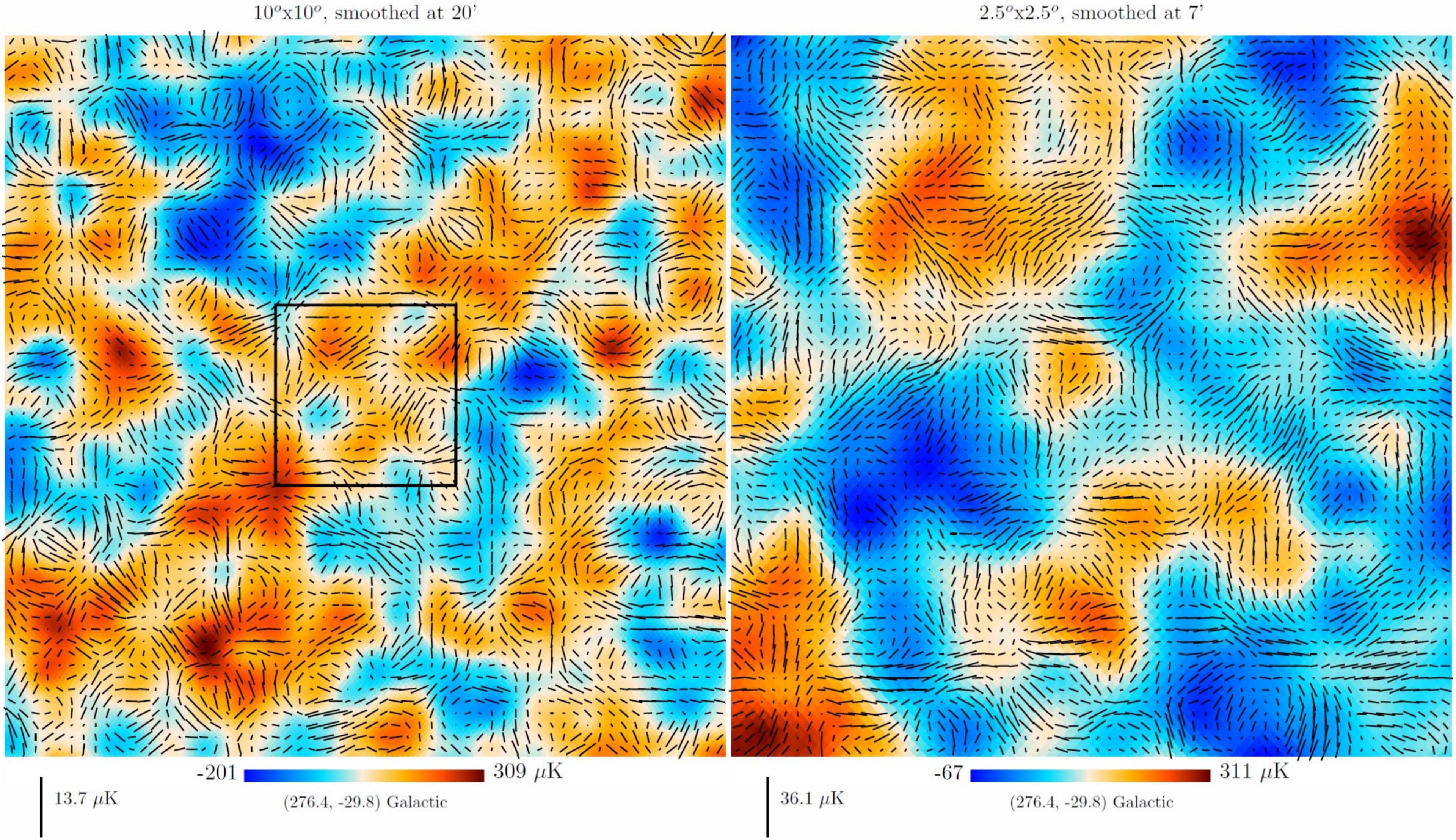


Planck Polarisation superimposed on T

(Planck 2018 I)

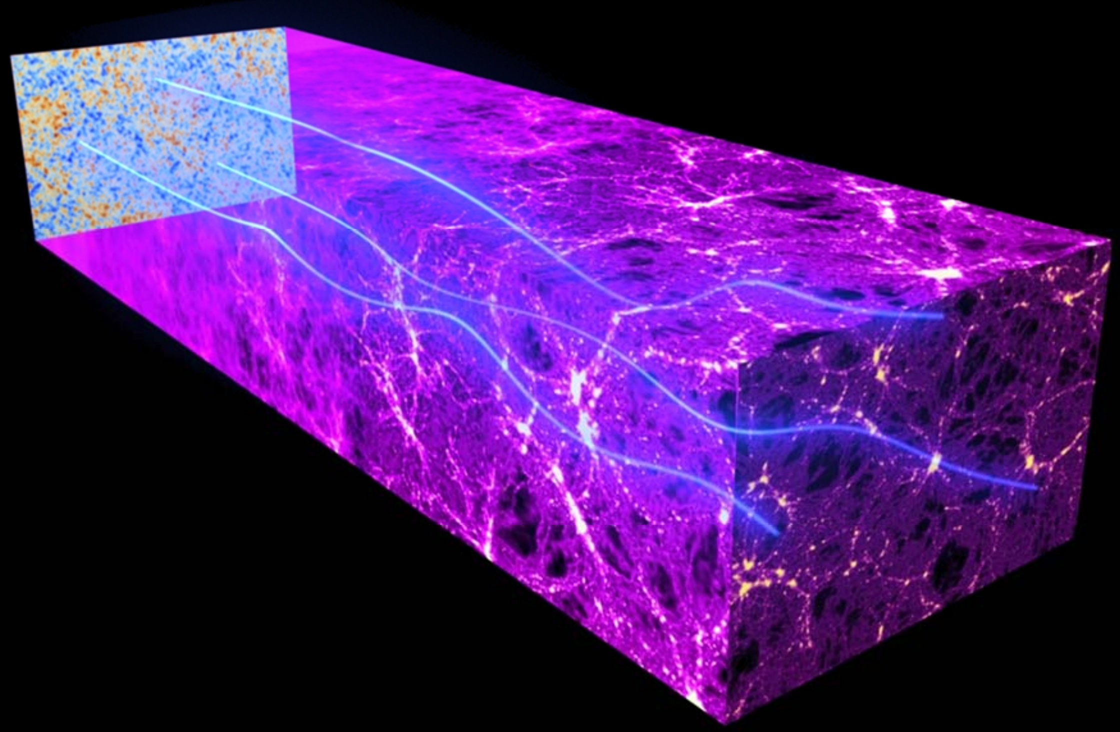


Planck Polarisation superimposed on T



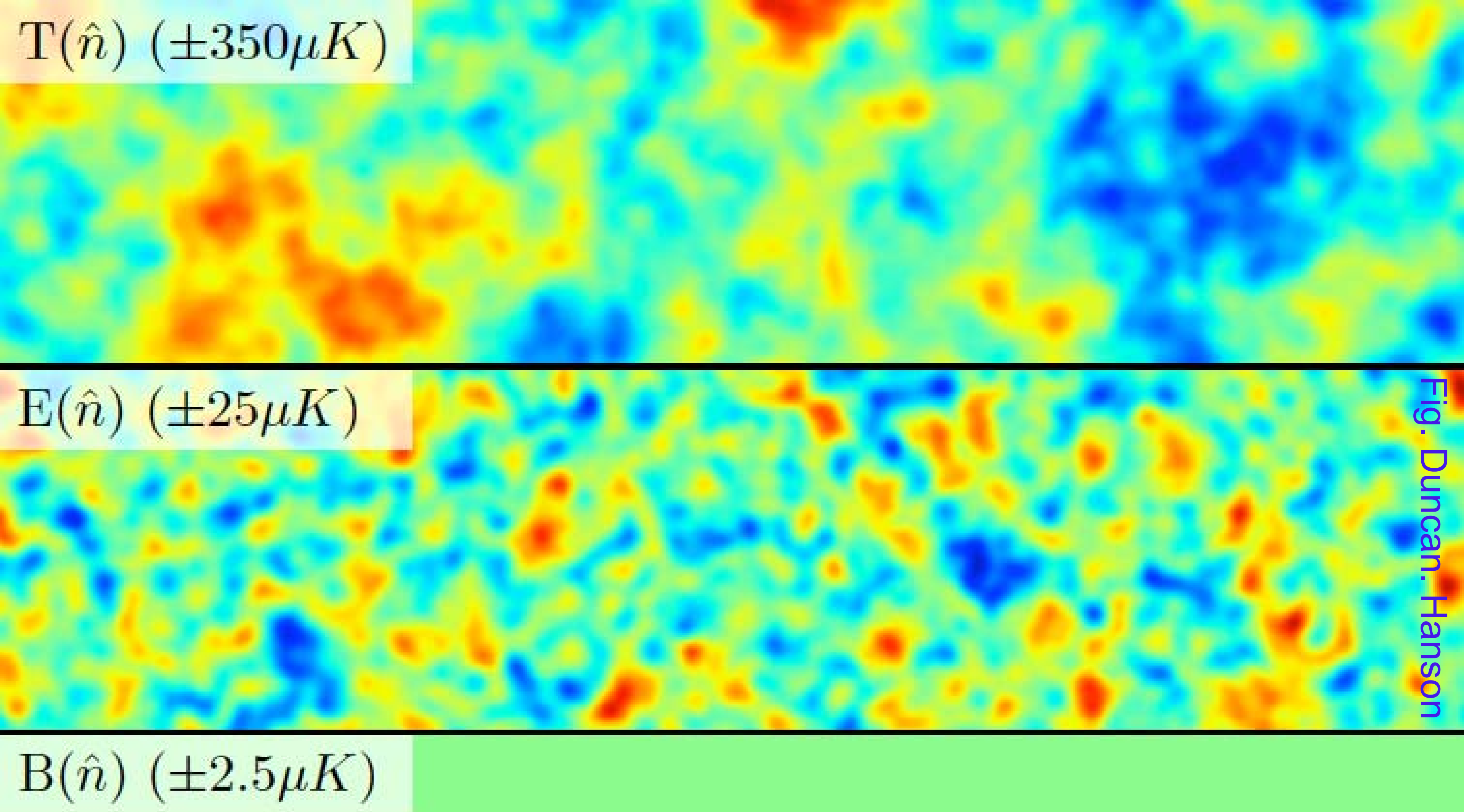
GRAVITATIONAL LENSING DISTORTS BACKGROUND IMAGES

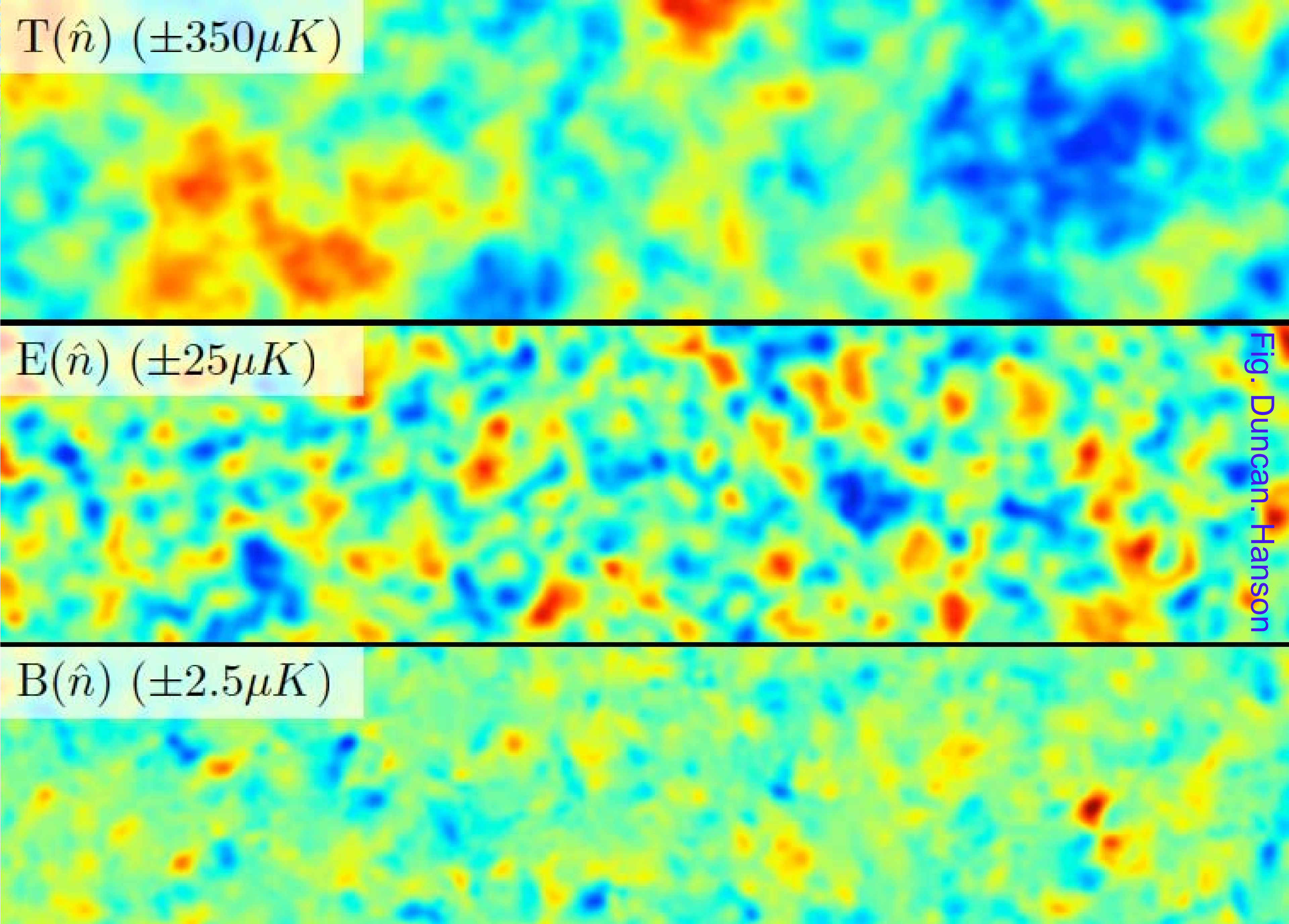
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



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

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

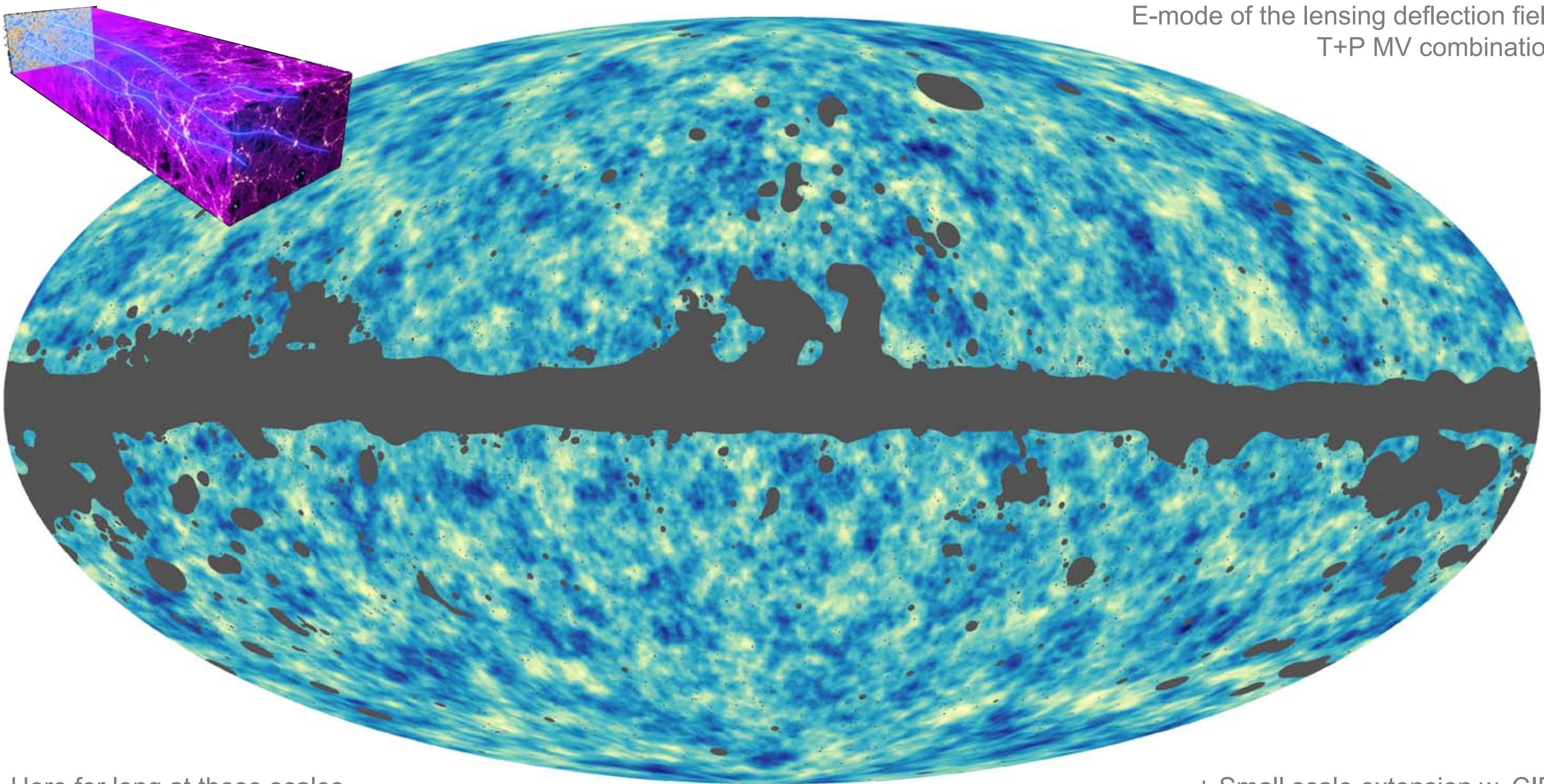

$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Fig. Duncan Hanson


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

Planck lensing map

(Planck 2018 VIII)

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

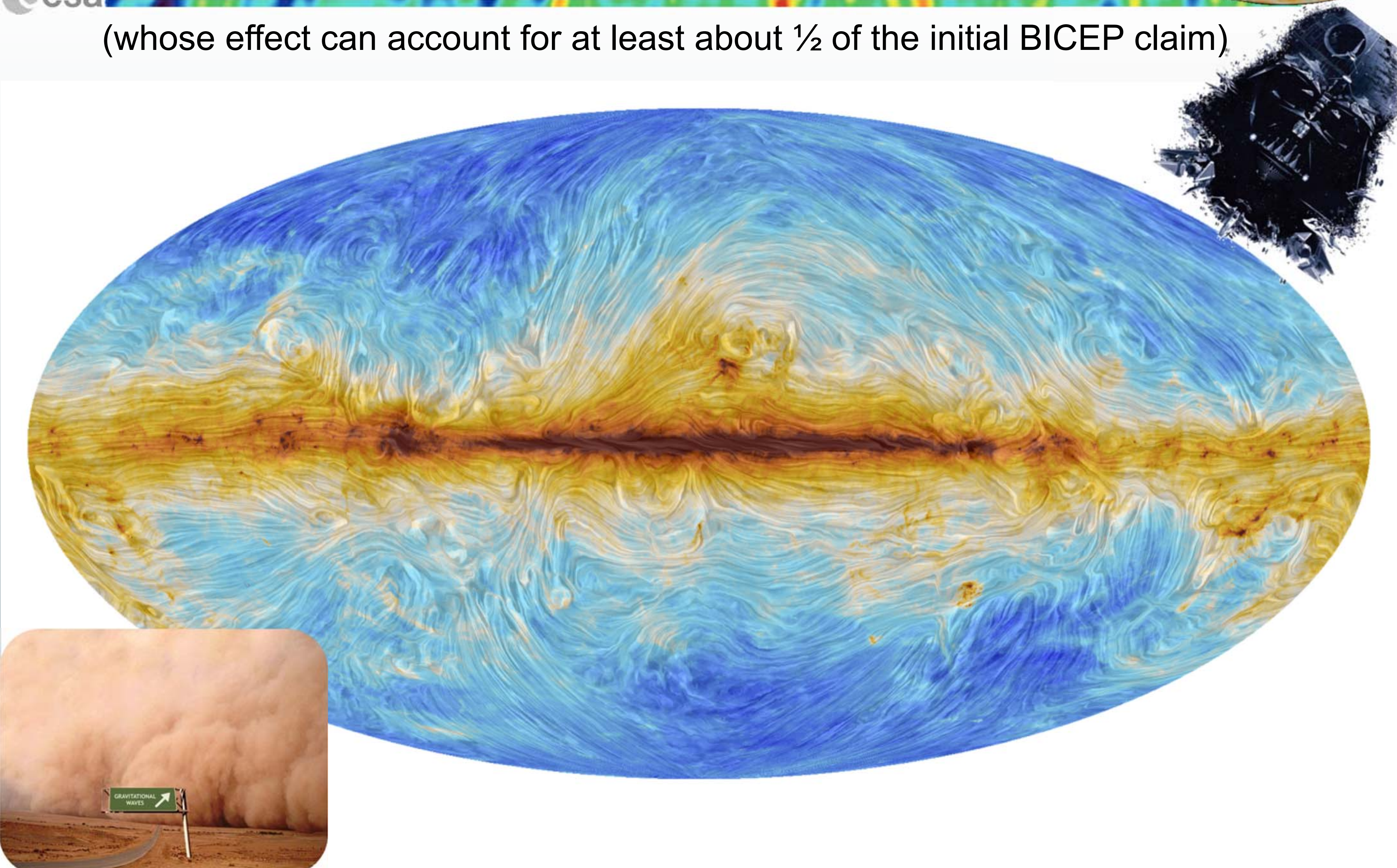


Here for long at these scales…

+ Small scale extension w. CIB

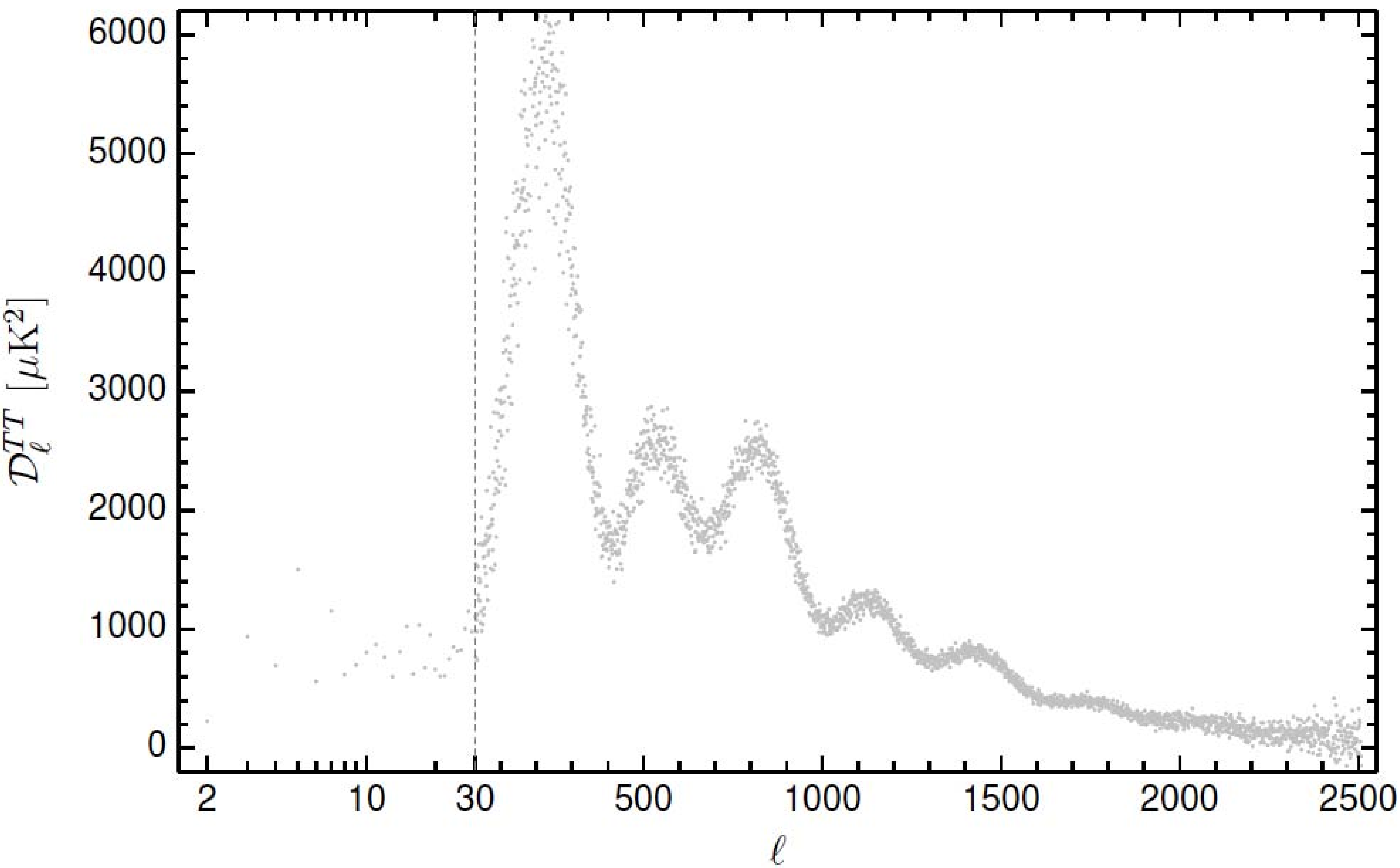
Planck 353GHz reveals the Galactic magnetic field

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

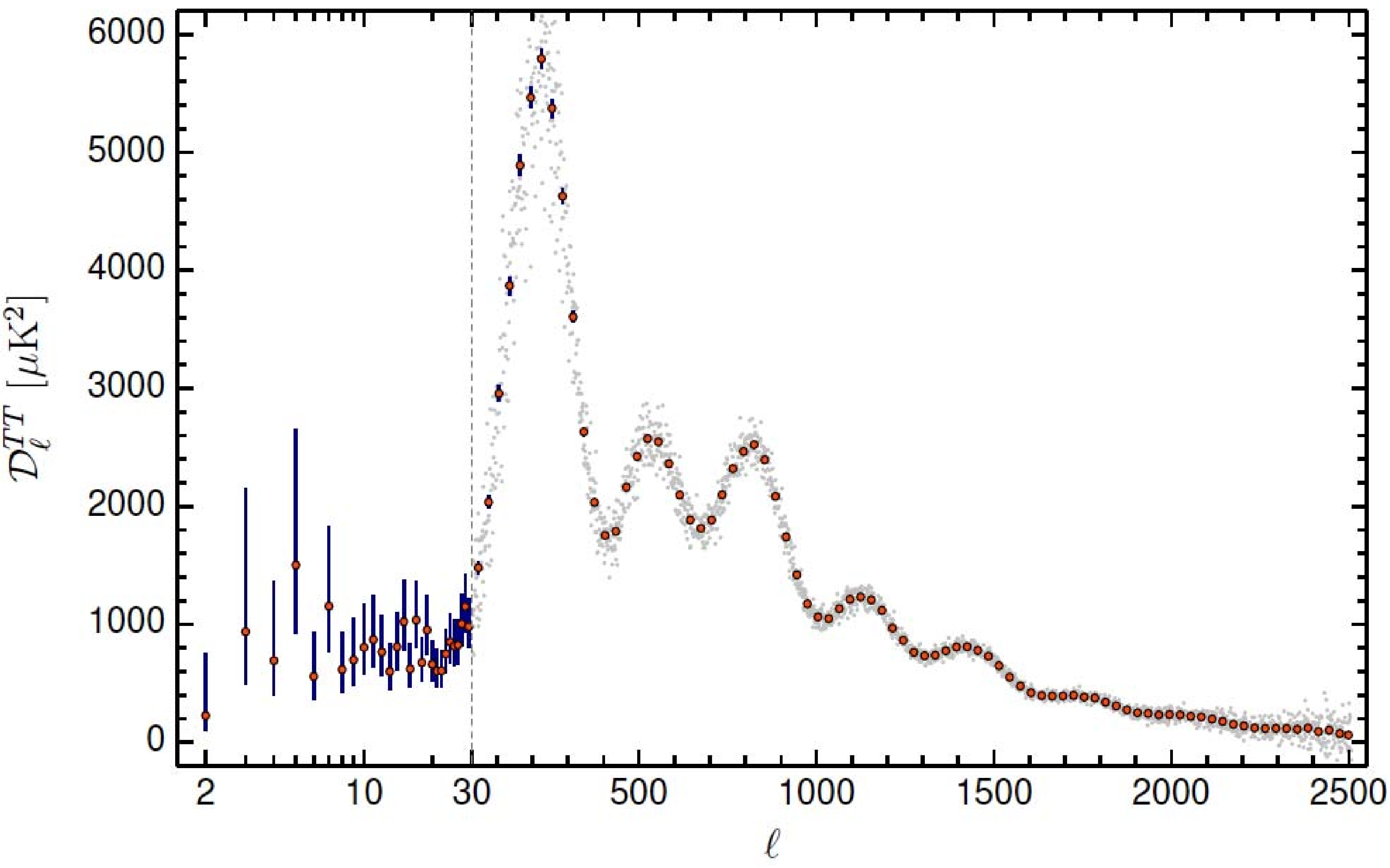


ANGULAR POWER SPECTRA

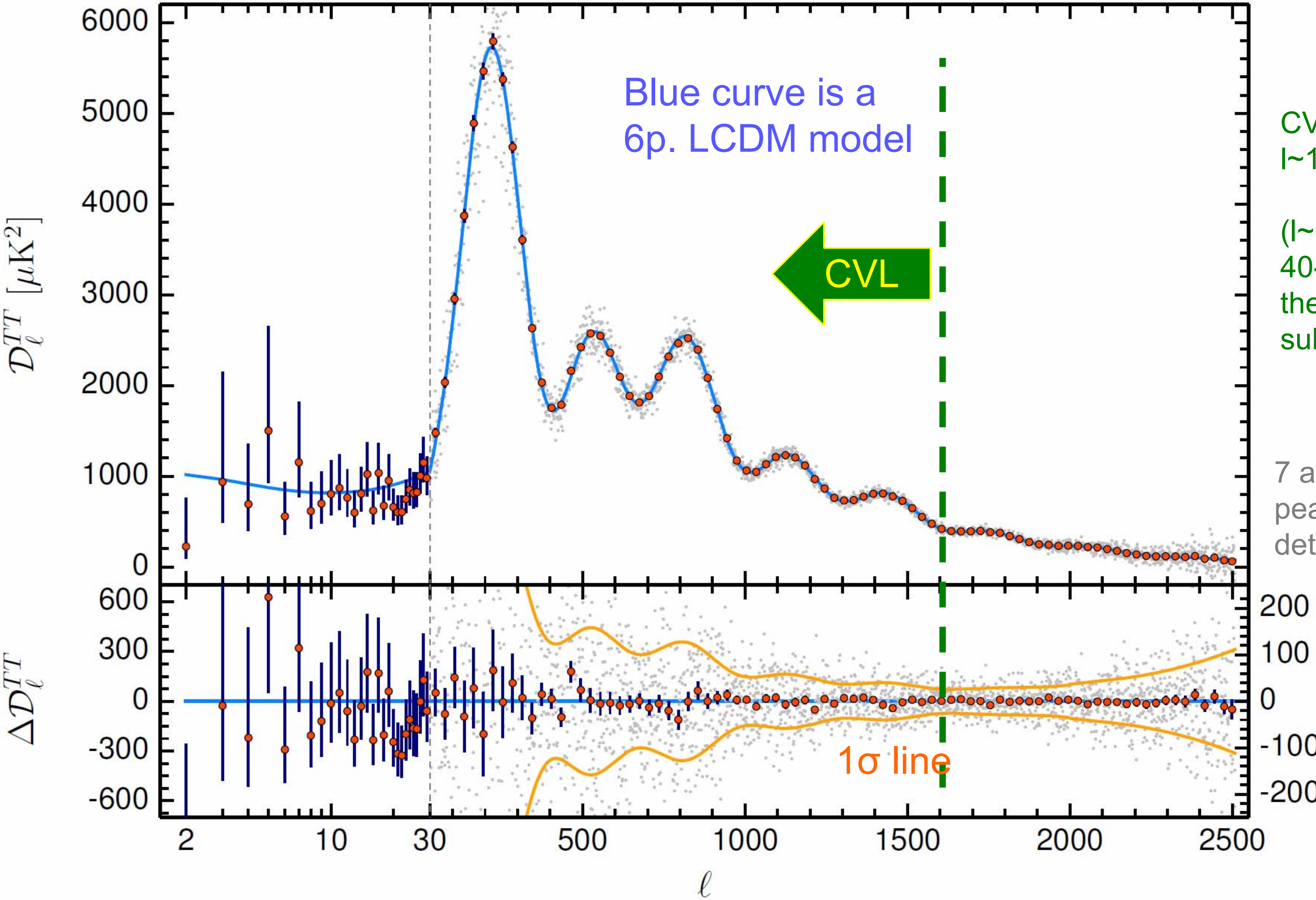
Planck 2018 TT spectrum



Planck 2018 TT spectrum, binned



Planck 2018 TT spectrum



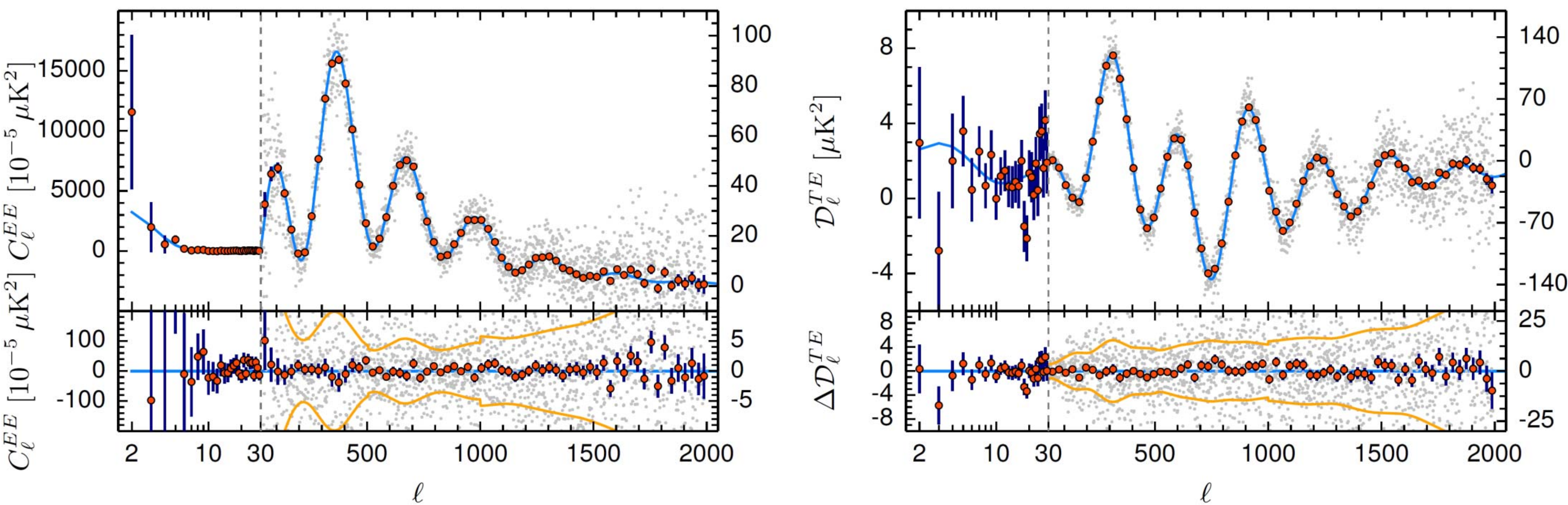
CVL till l~1600

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

7 acoustic peaks well detected

Planck 2018 - EE & TE spectra

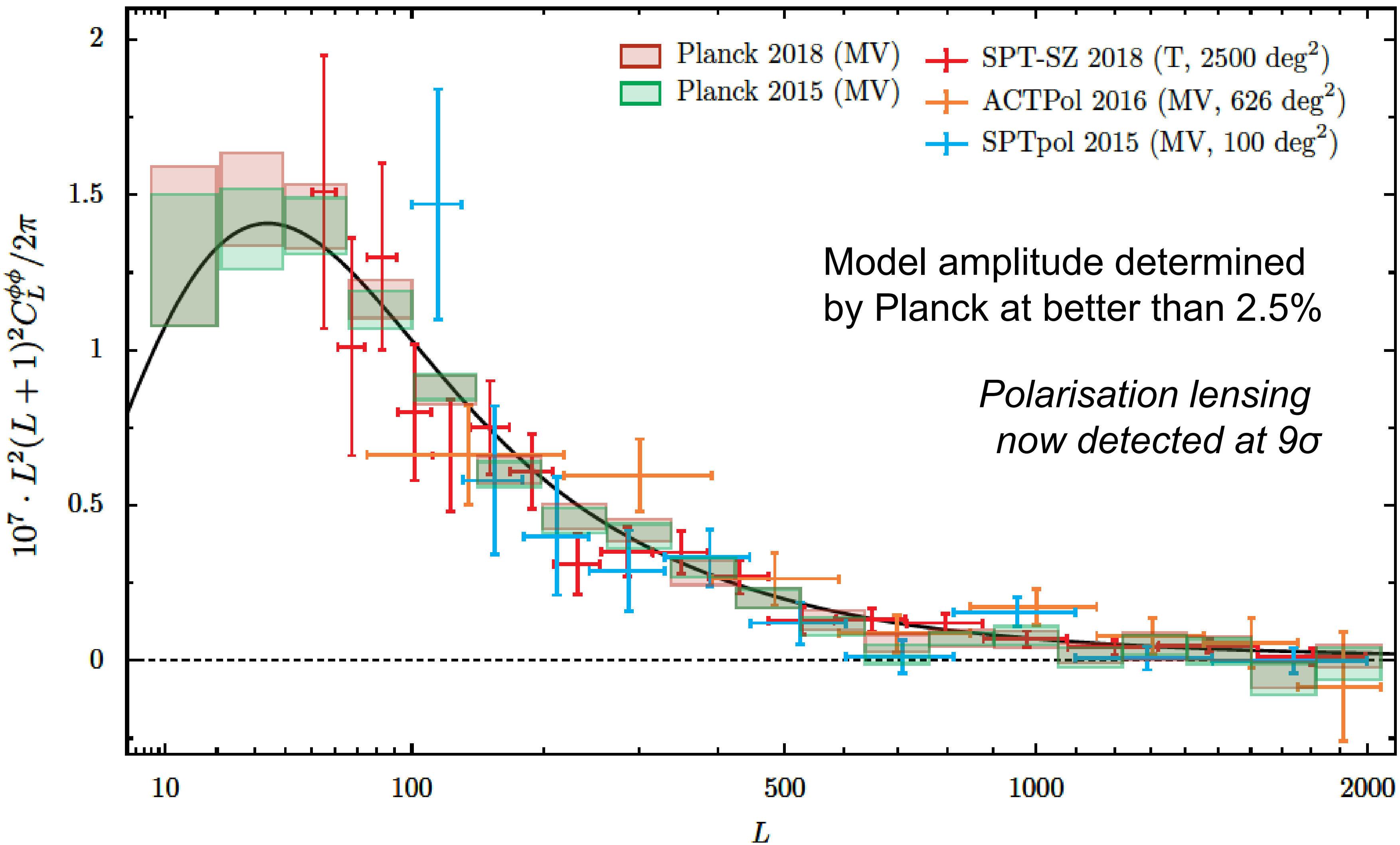
(Planck 2018 VI)



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

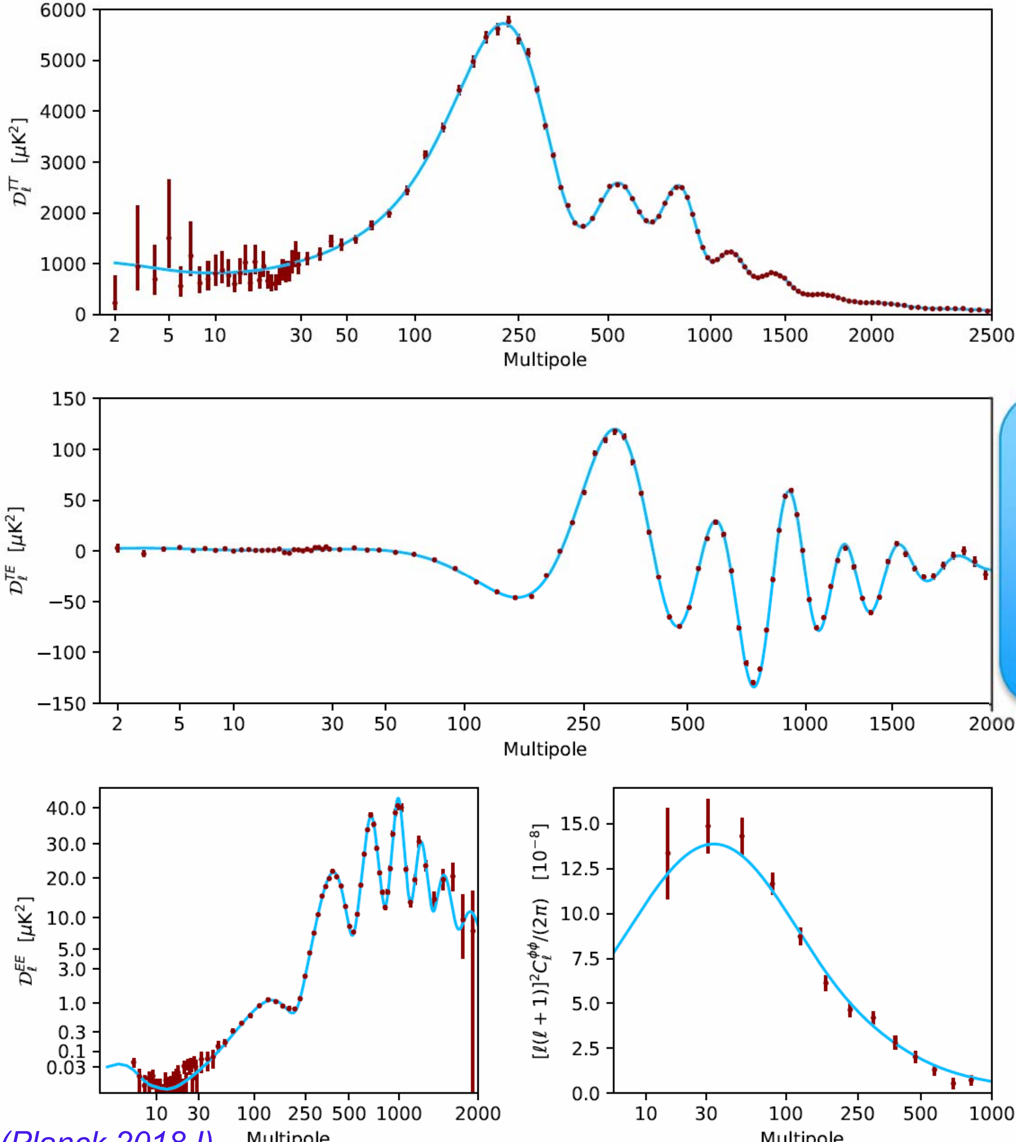


Model amplitude determined by Planck at better than 2.5%

Polarisation lensing now detected at 9σ

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

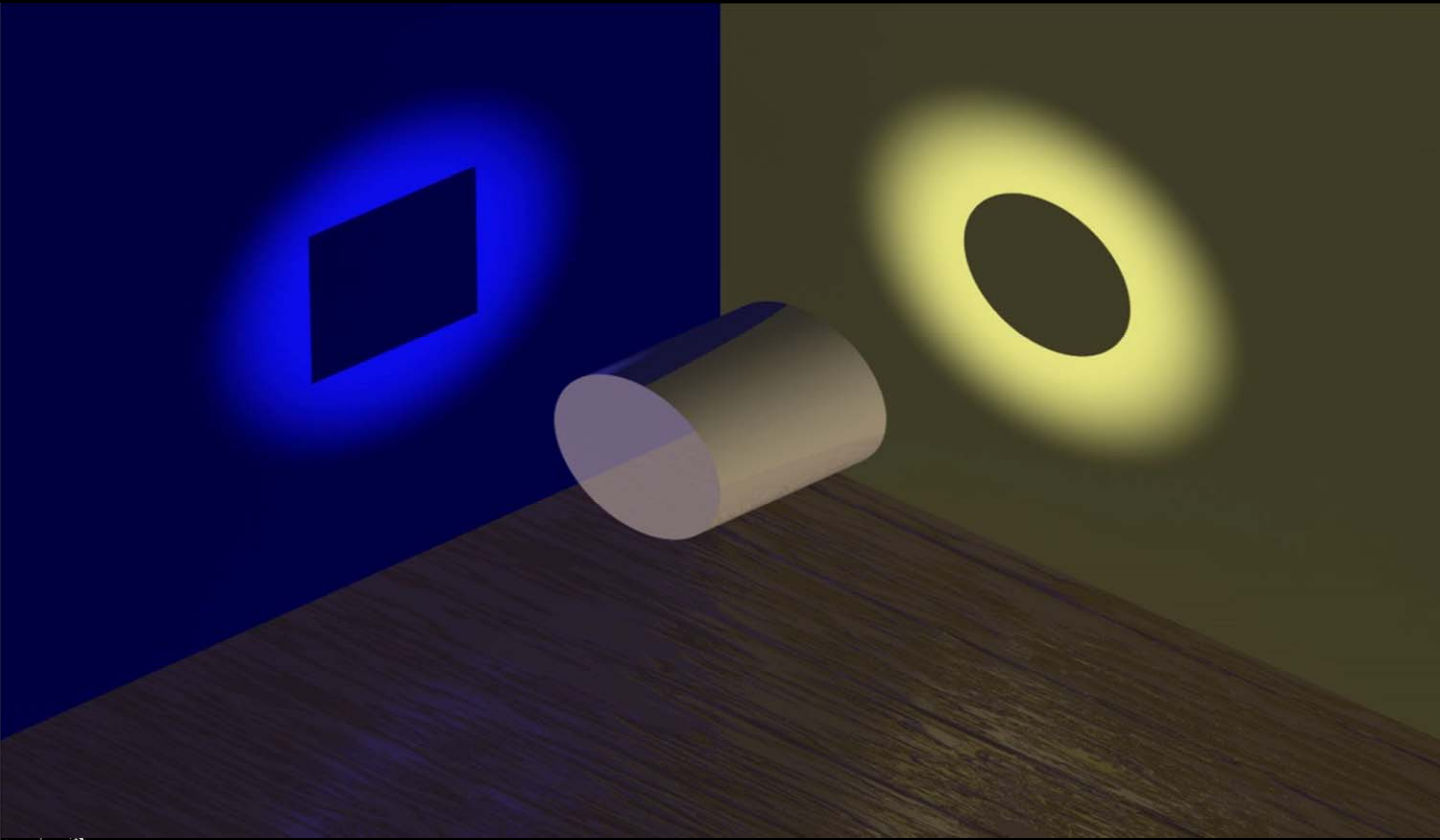


(Planck 2018 I)

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
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081

Per cent accuracy on all base LCDM parameters, but tau

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

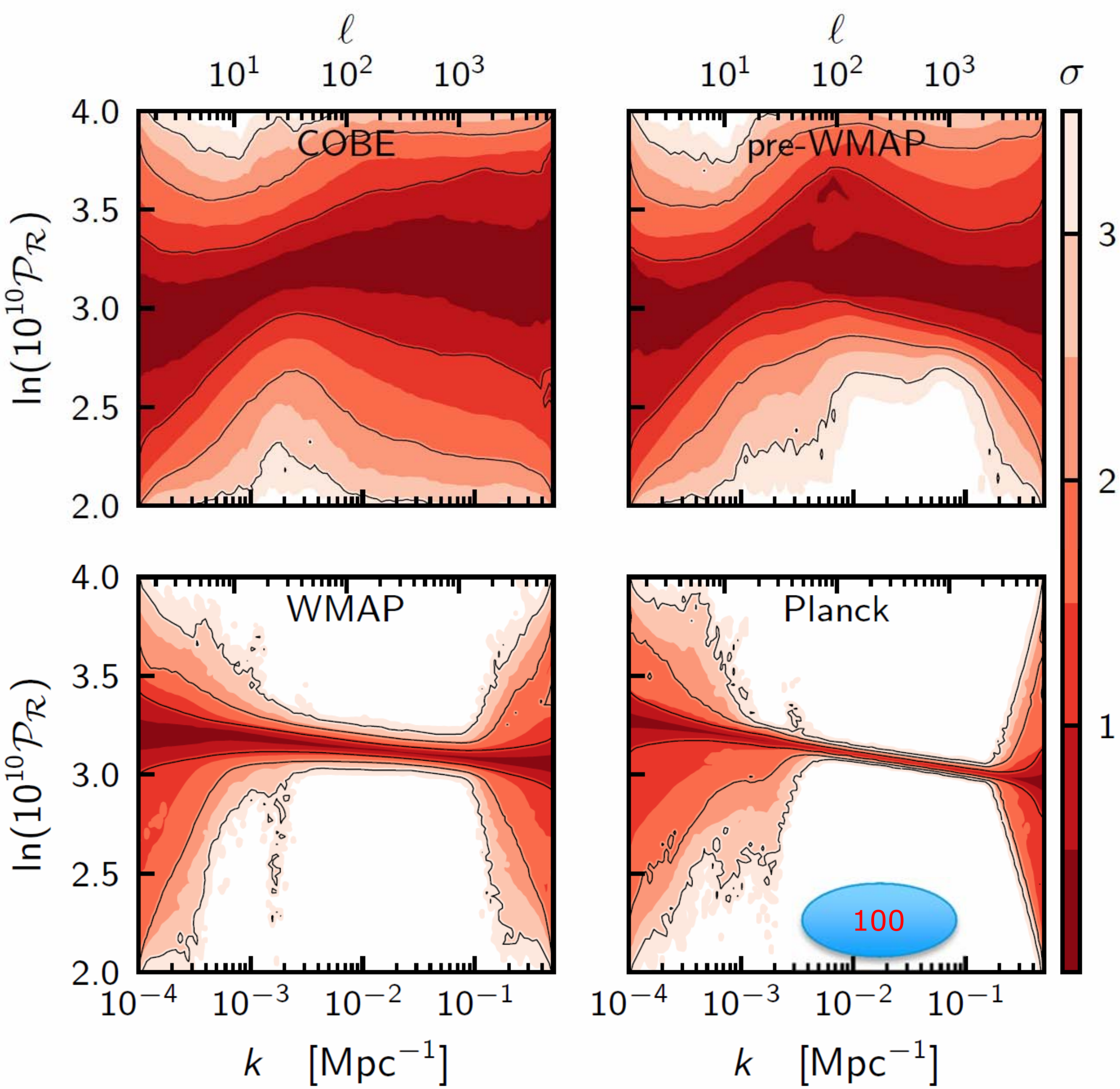
All adressed by Planck, often providing the best available constraints today

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: Combination of extensions, Defects, variation of Fundamental constants, T_{CMB}, A2s→1s, deviations from GR…

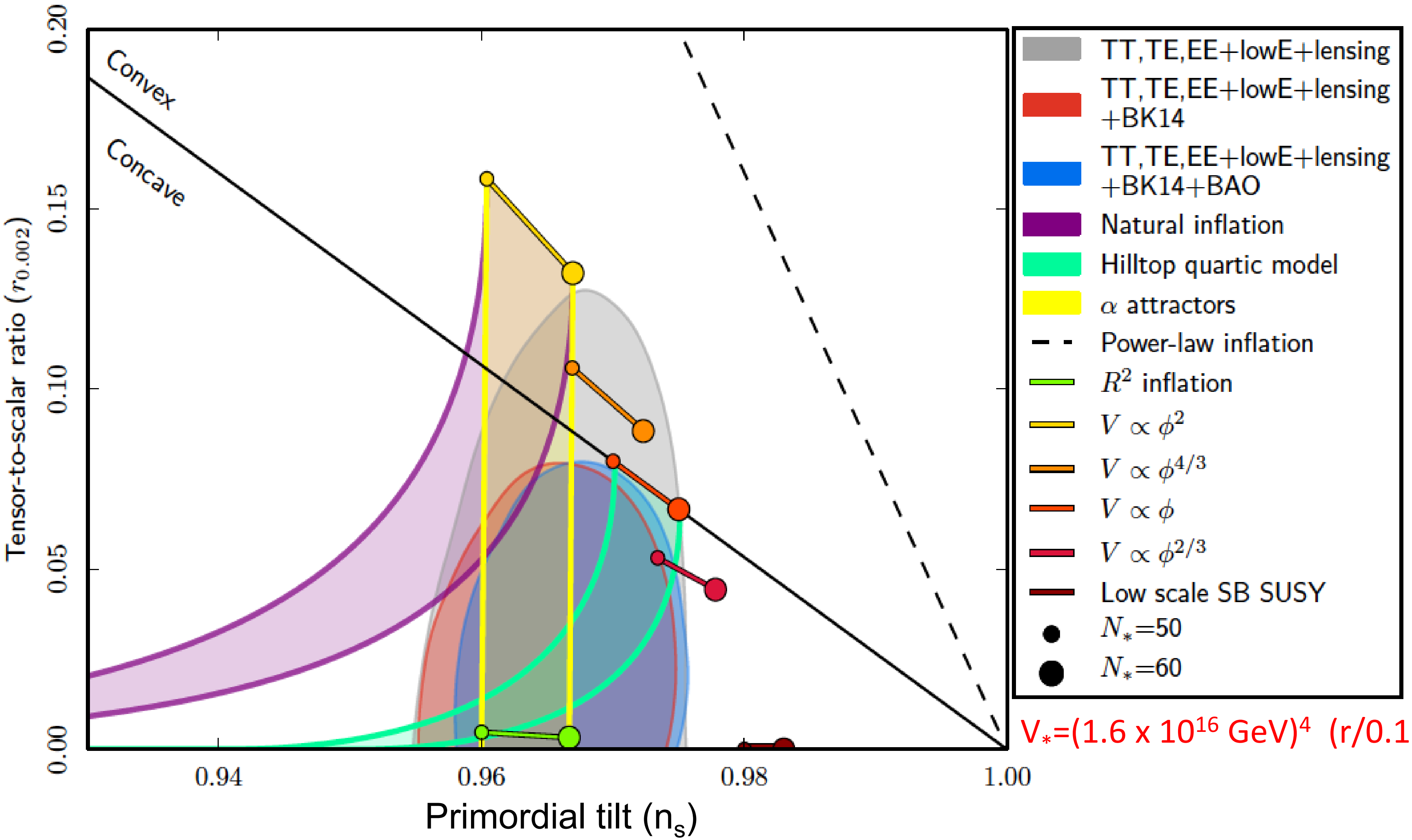
Primordial Power Spectrum reconstruction



$n_s \neq 1$ at 8σ

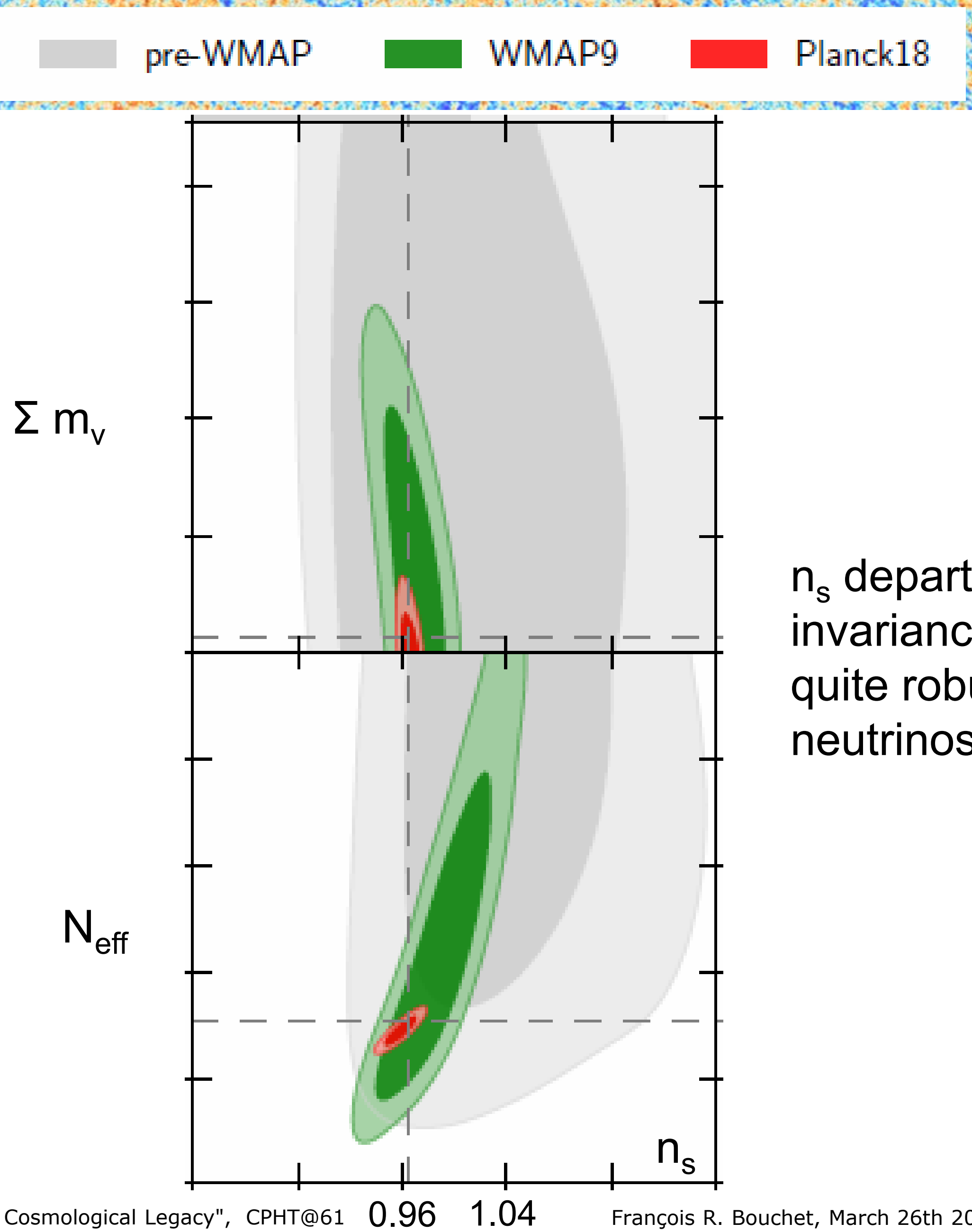
(Planck 2018 I)

95%CL Limits on tensor component



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

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...

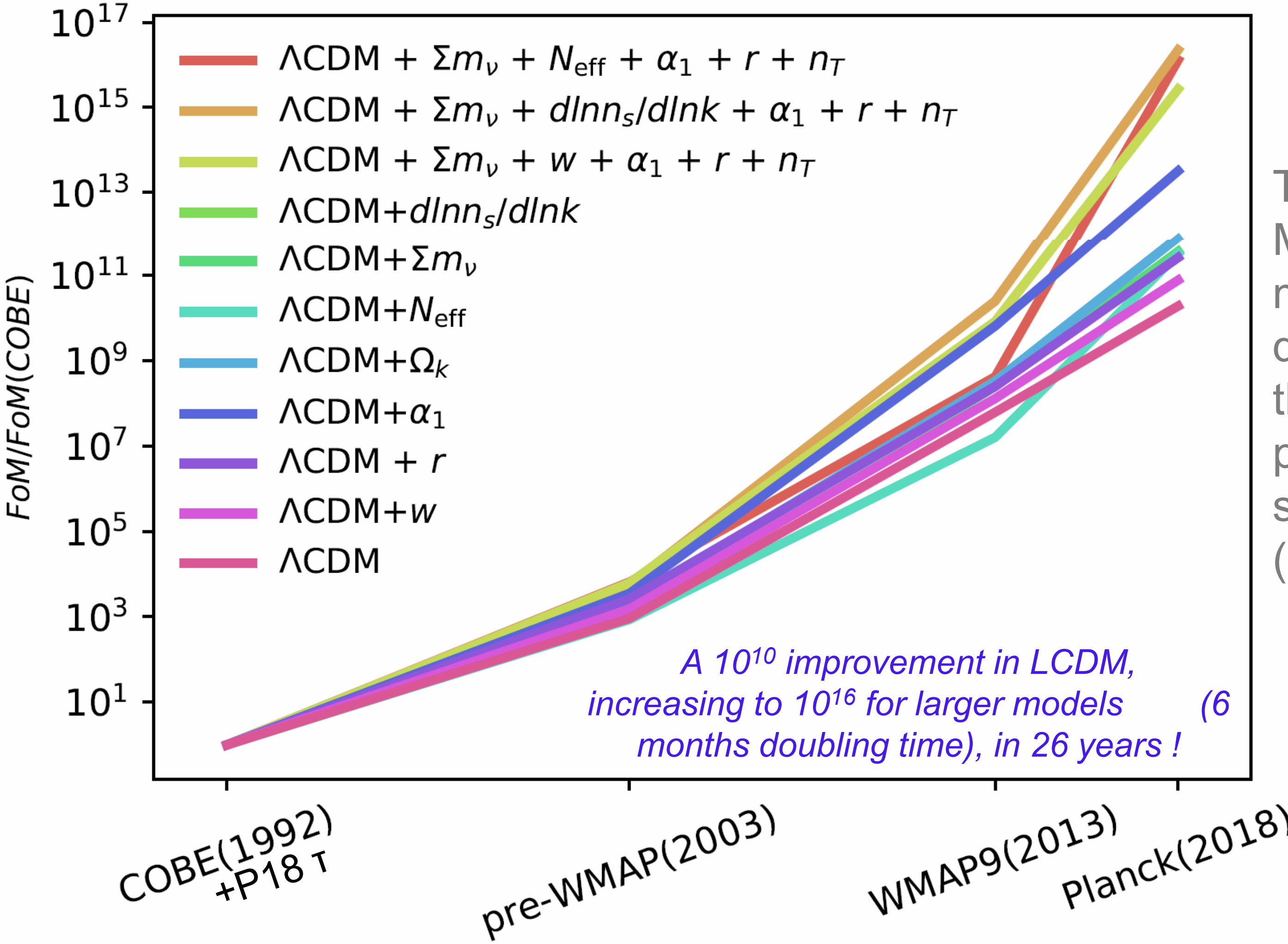
(Planck 2018 I)

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, $dn_s/d\ln k$, r) versus standard LCDM parameters (dotted BF). (1 and 2 sigma contours)

FOM / FOM_COBE

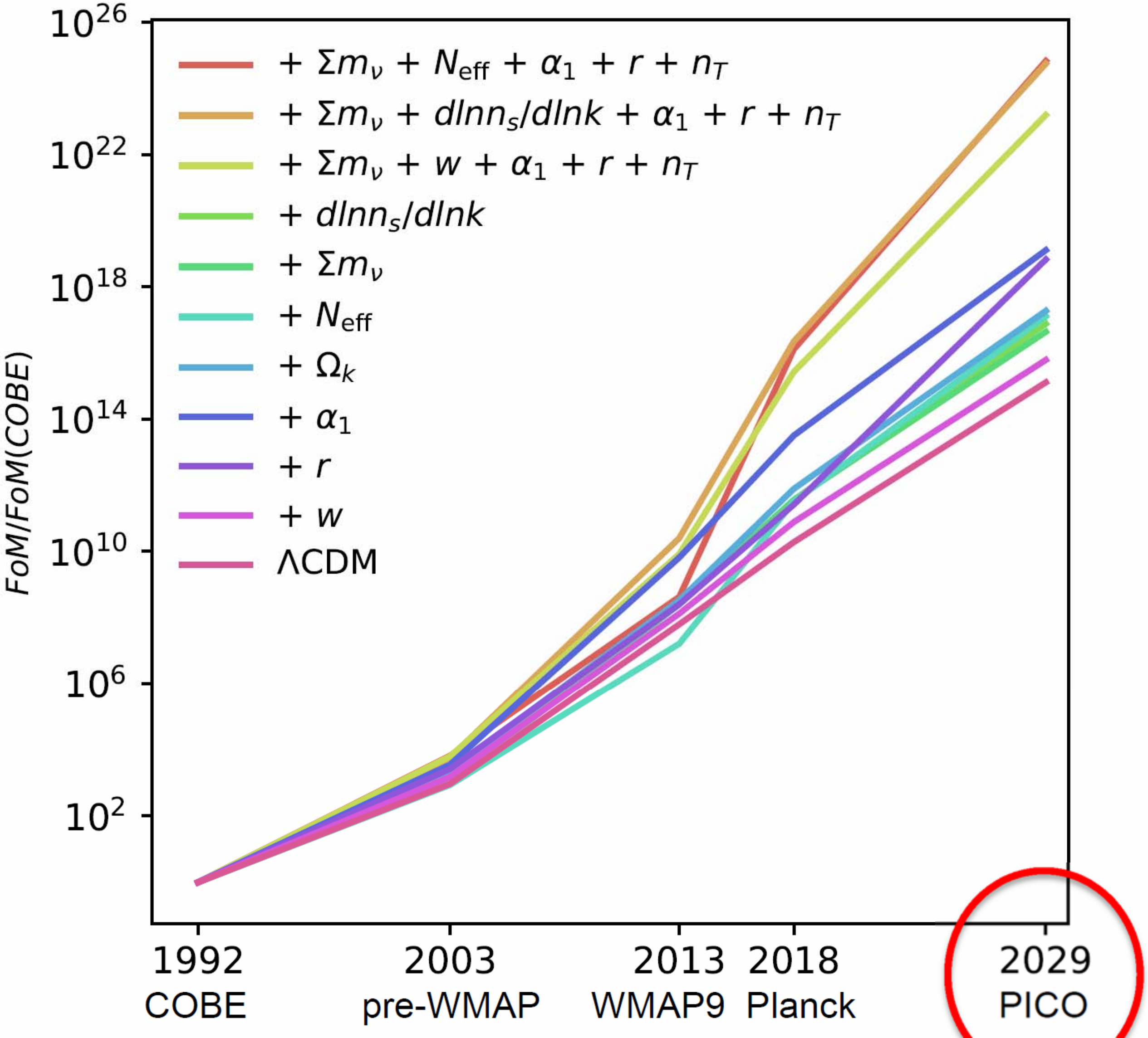
(Planck 2018 I)

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



This Figure Of Merit (FOM) measures the decrease in the allowed parameter space volume (at 1σ)

With much more to come (hopefully)!



Inflationary scorecard

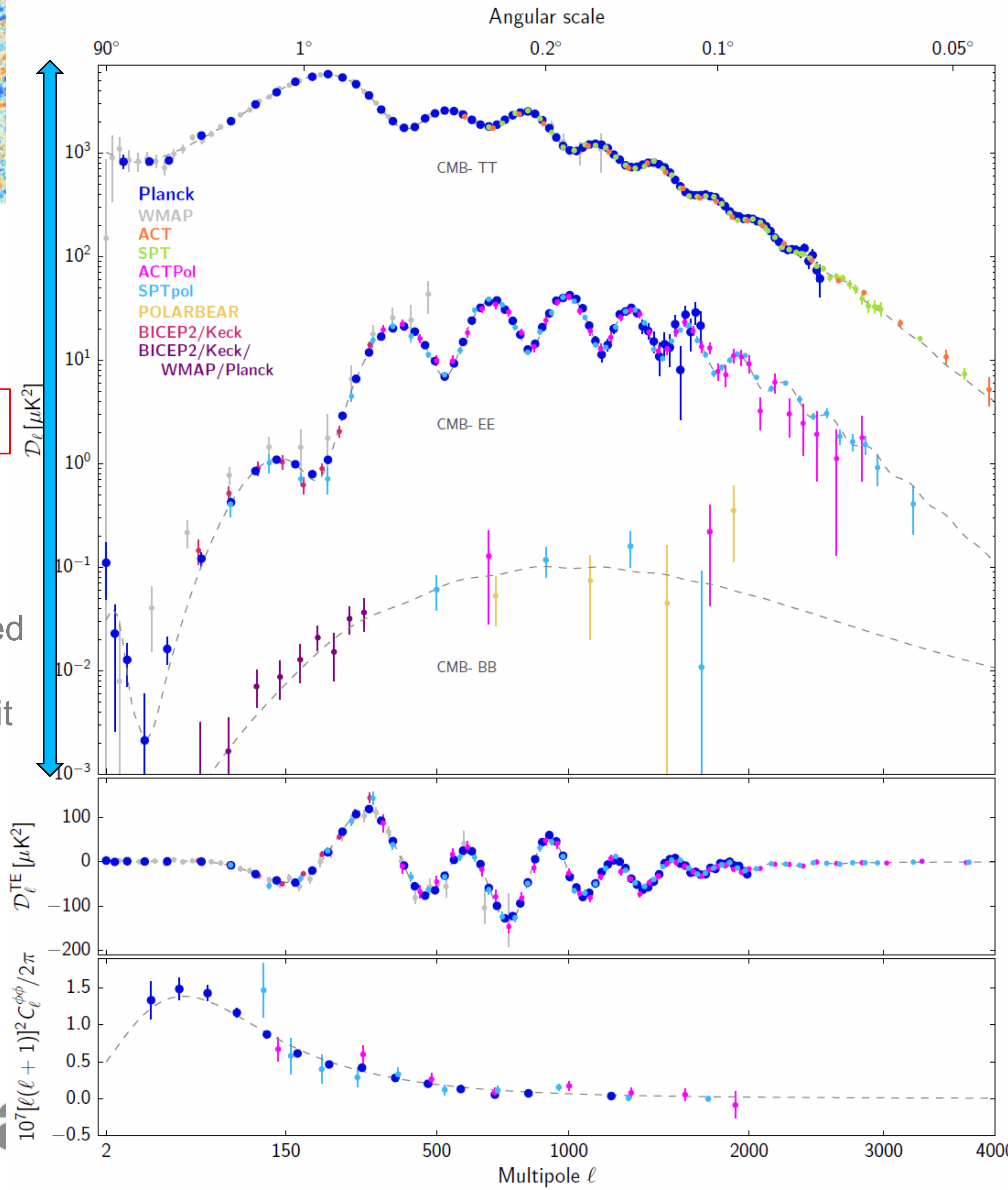
Prediction	Measurement	
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$	100
with a *nearly* scale-invariant (red)		
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$	100
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$	
dominated by scalar perturbations,	$r_{0.002} < 0.07$	
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



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

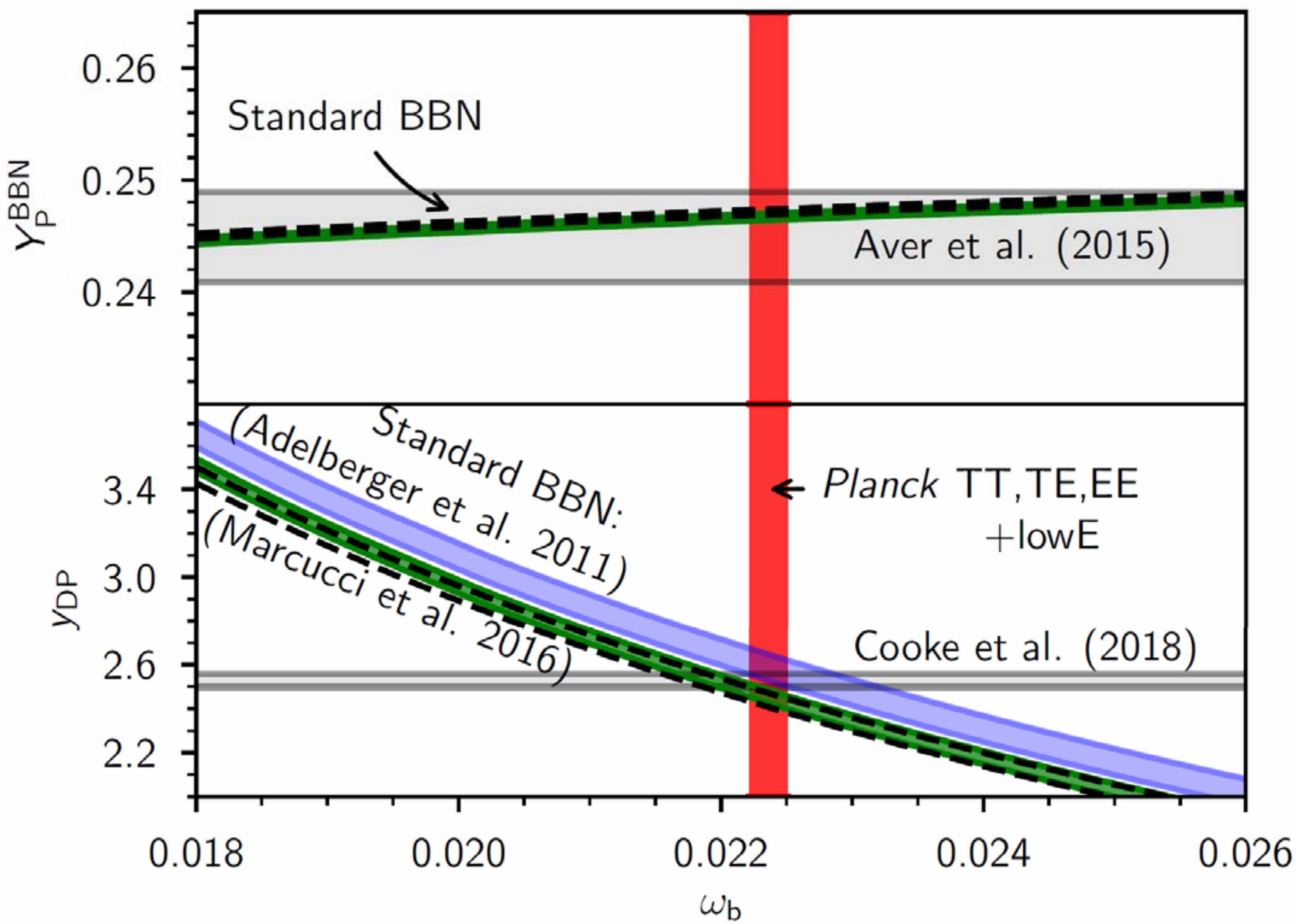
+ weak constraints with TB and EB

(Planck 2018 I)

Planck and BBN

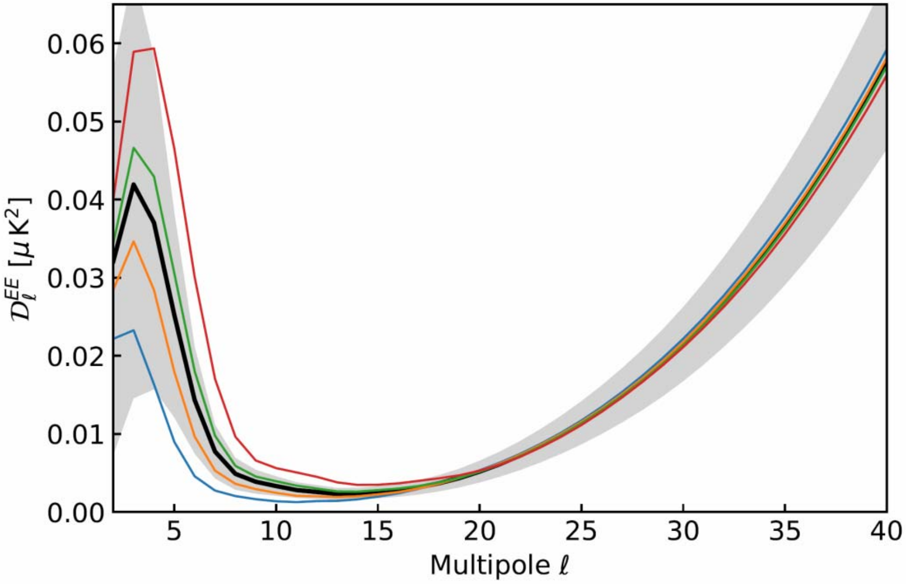
Primordial He

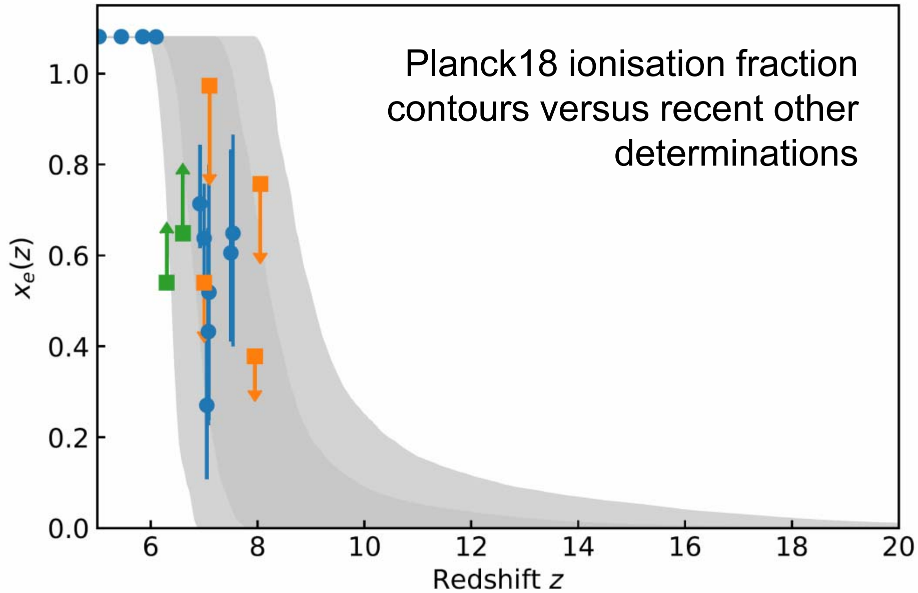
Primordial D



Standard matter abundance

EE Spectrum & Reionisation

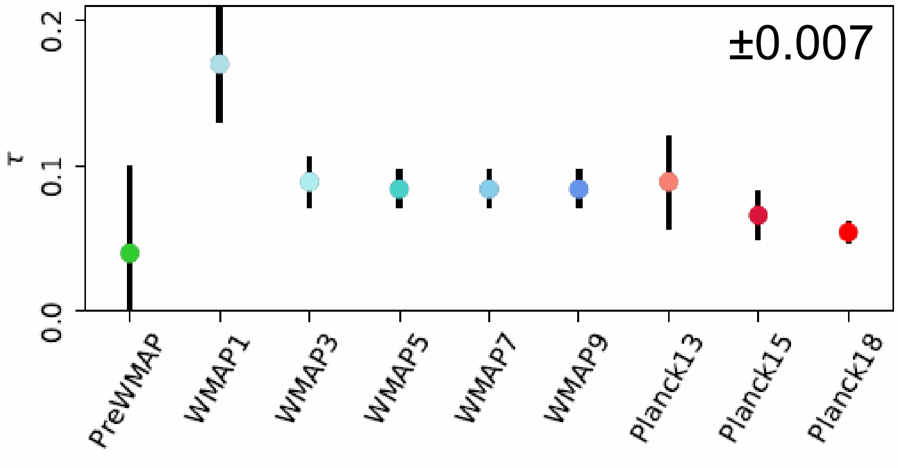




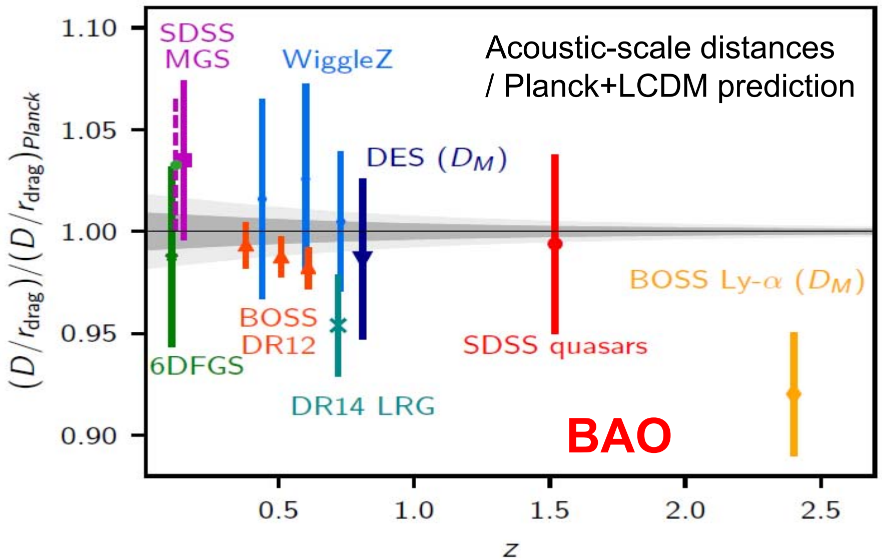
$\tau = 0.04 - 0.07$ *by step of* 0.01

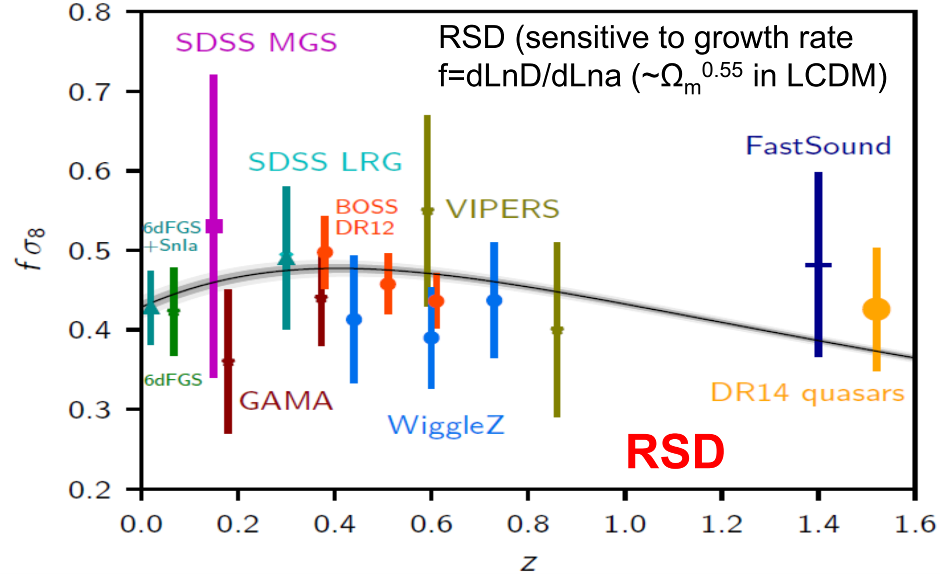
$\tau = 0.056$ shown with it $1\sigma_{CV\_67\%}$

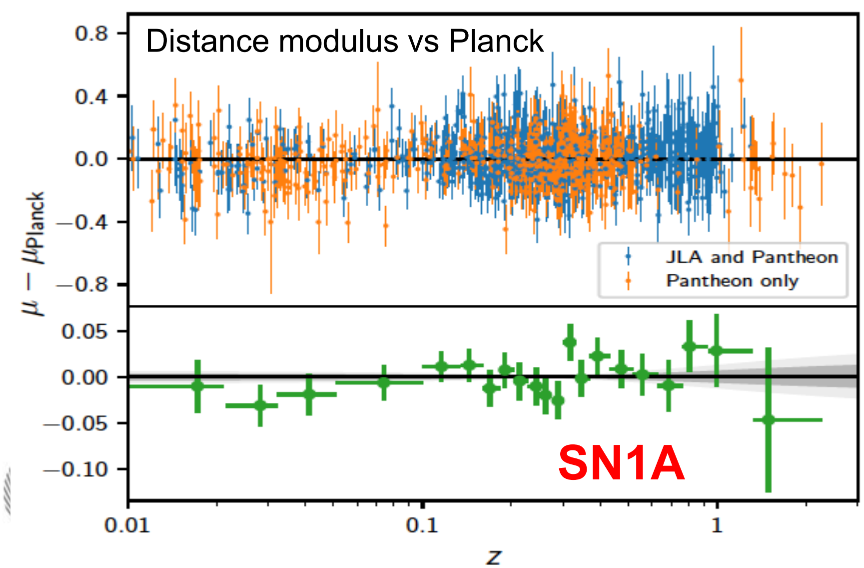
(BF: τ = 0.0544 ±0.0073)

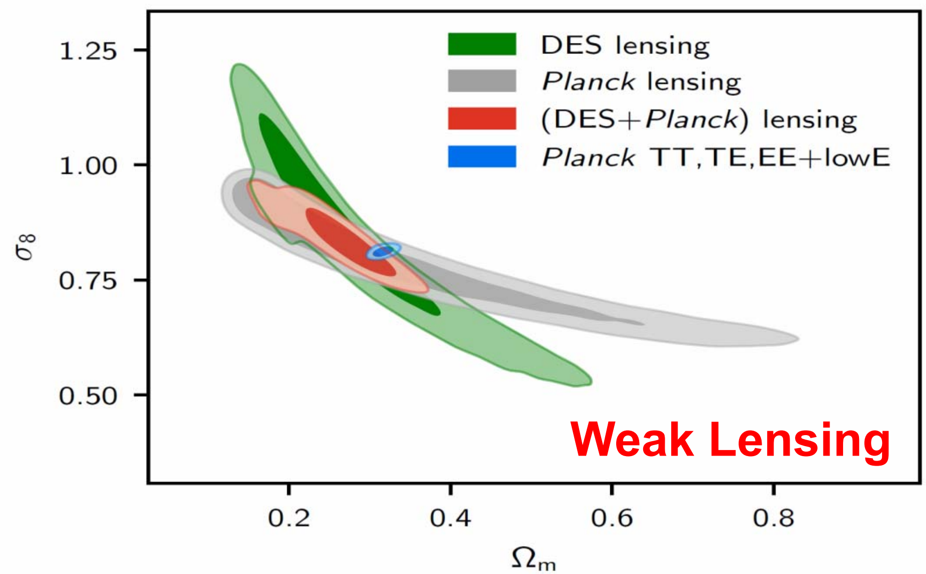


Good consistency with BAO, RSD, SNIa, WL



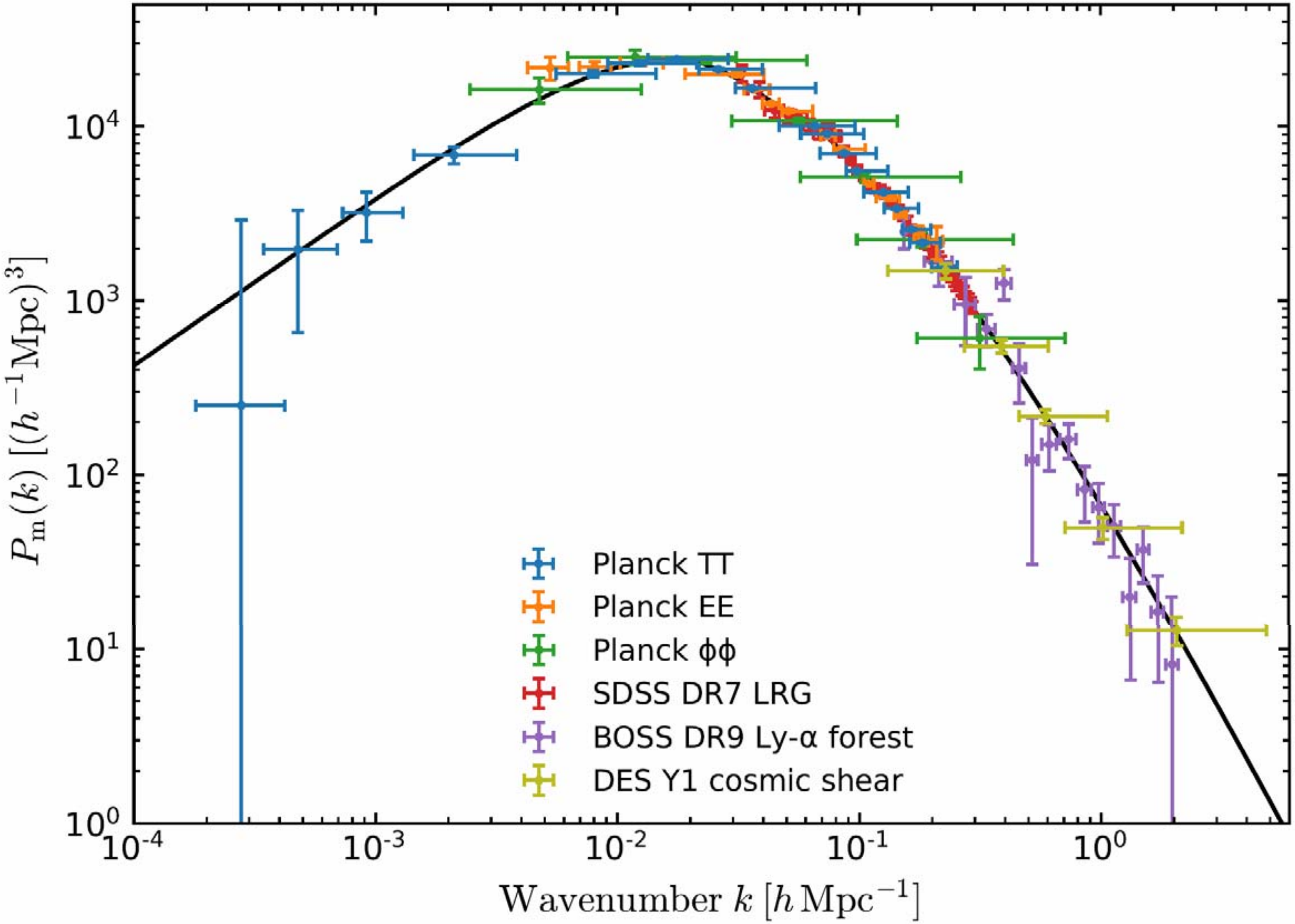






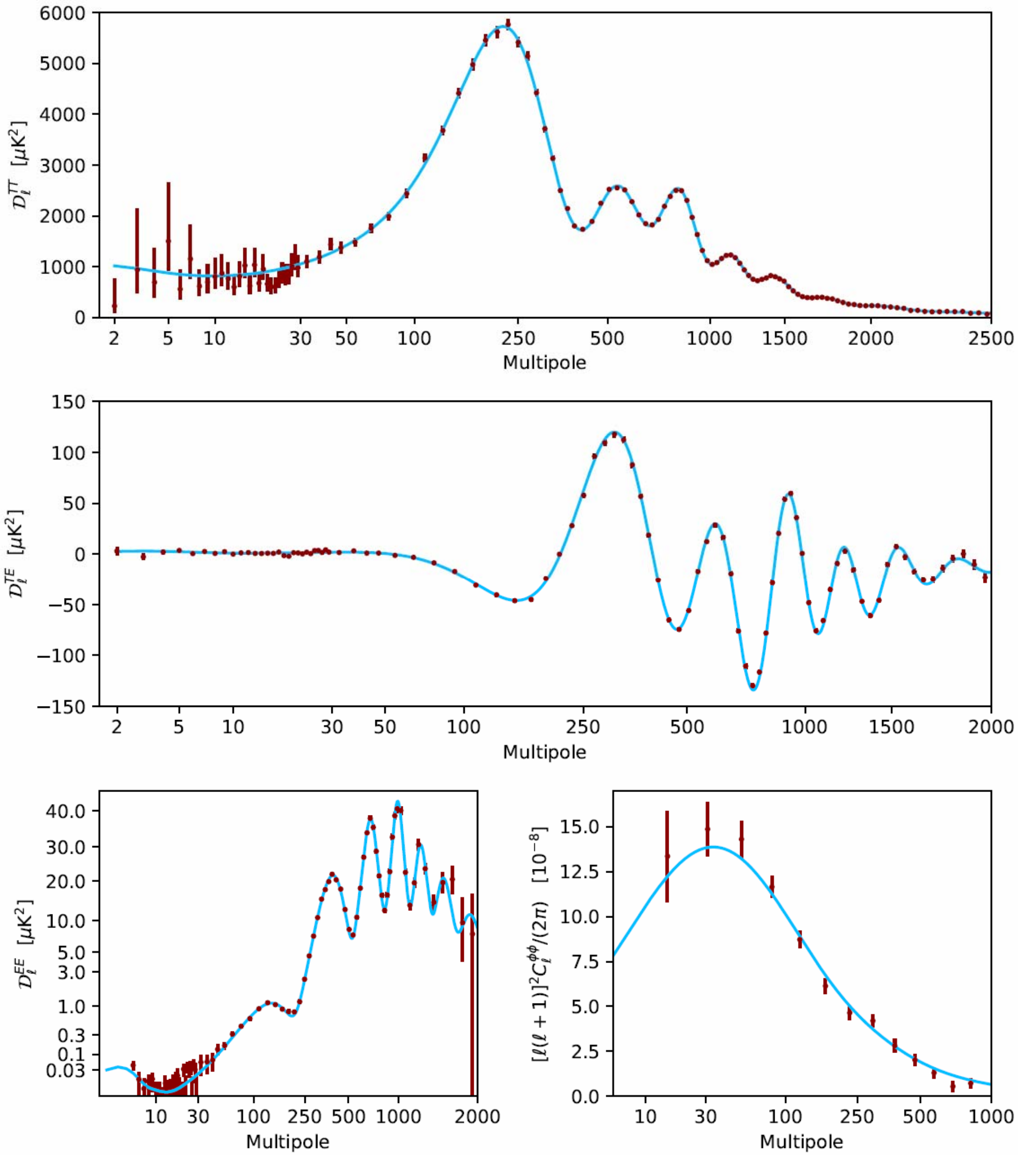
The (linear) matter power spectrum at z = 0

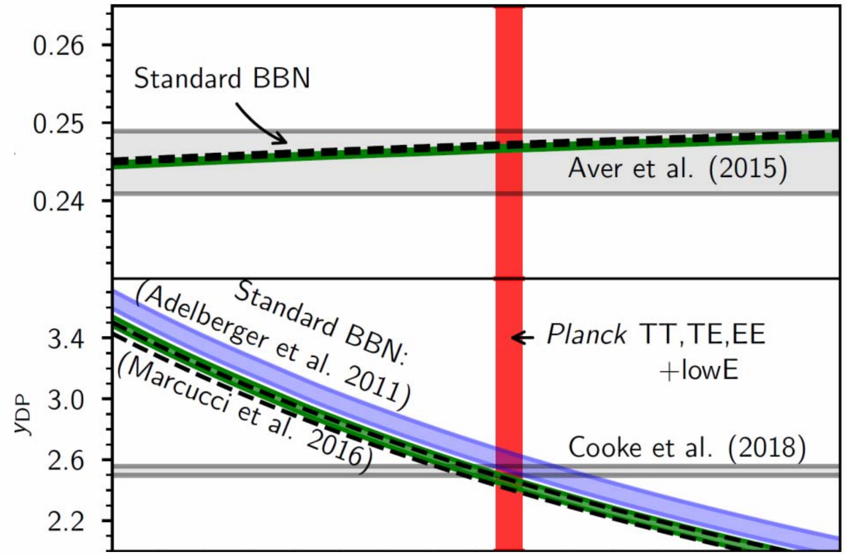
As deduced from different cosmological probes spanning 14Gyr in time and > 3 decades in scale

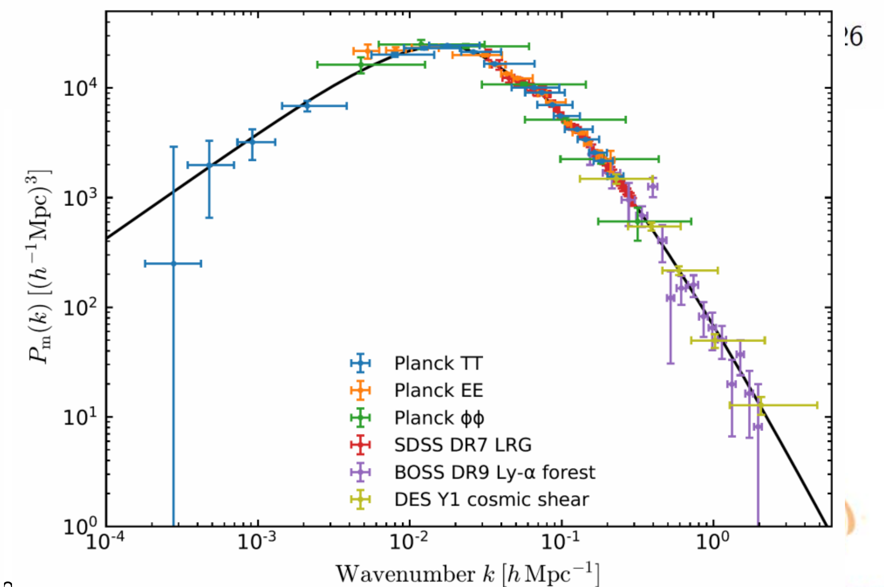


(Planck 2018 I)

Cosmological Consistency 2019







A perfect (-ly boring) Universe?

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

(NB: 2015 constraints)

+ all others obtained by the community!
(Specific theories, specific data combinations, new data…)

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

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

α_{ISO}
α (Fine structure constant)
P_{ann}
C_s (for MG)
$c^2_{eff} = c^2_{vis} = 1/3$ for nu's
$A_{2s\to1s}$
…

Curiosities (?)

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]

Mild tension with weak lensing surveys

planck

- Acceptable agreement with DES lensing alone, mild tension with *joint* DES lensing+galaxy-galaxy lensing+clustering.

- DES joint (DES priors)

$$S_8 \equiv 0.792 \pm 0.024 \qquad S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$$

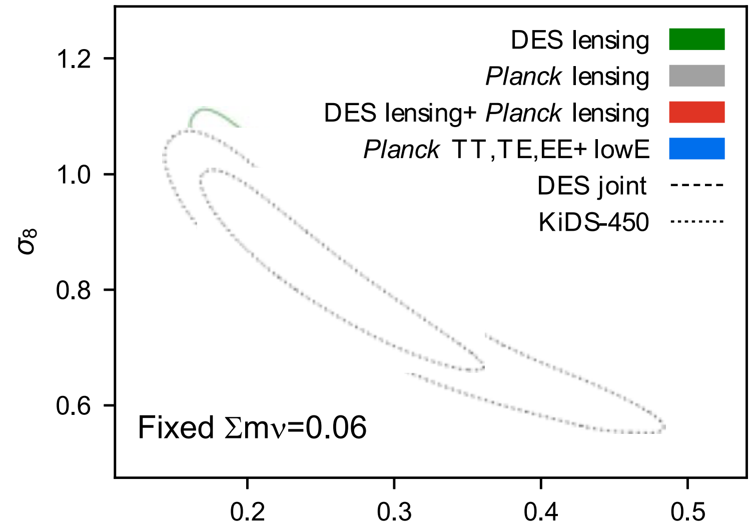
$$\Omega_m = 0.257^{+0.023}_{-0.031}$$

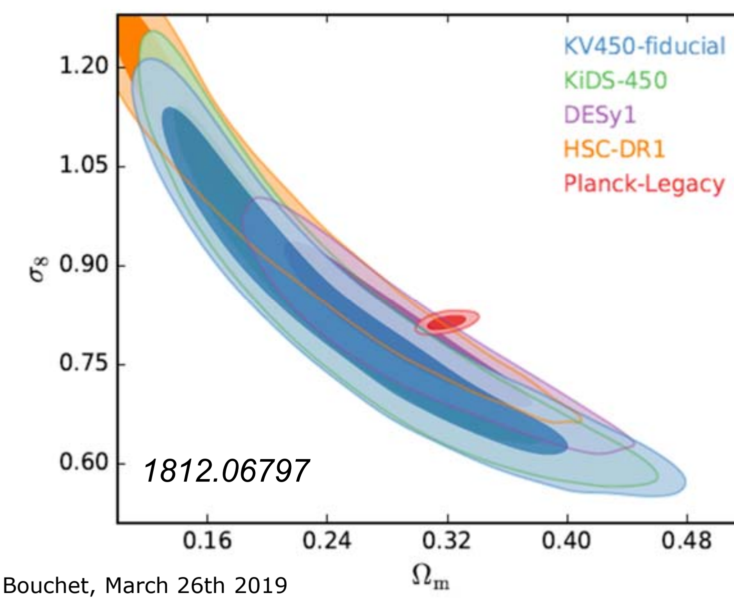
- Planck TT,TE,EE+lowE+lensing

$$S_8 = 0.832 \pm 0.013$$
$$\Omega_m = 0.315 \pm 0.007$$

- Kids450+Viking in Hildebrandt etal 1812.06797:
  S_8=0.737±0.04 (2.3σ /Planck)

- DES: joint DES results discrepant at the ~1%level w.r.t. Planck





esa

Strong tension with direct measurements. Agreement with inverse distance ladder.

planck

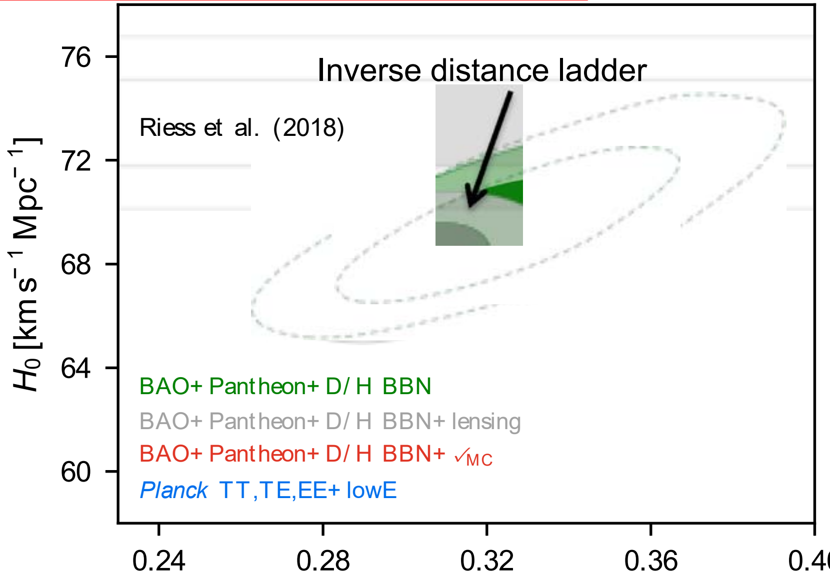
H_0= 67.36±0.54 km/s/Mpc Planck ΛCDM
H_0= 73.5 ±1.6 km/s/Mpc SH0ES (Riess+ 18)

3.6σ tension

Inverse distance ladder:
H_0= 67.9 ± 1.3 km/s/Mpc galBAO+D/H+CMB lensing(or LyαBAO or DES lensing)

Time delay multiply-imaged quasars
$H_0=72.5^{+2.1}_{-2.3}$ km/s/Mpc H0LiCOW (Birrer+ 2018)

- Tension with direct measurement (SnIa+cepheids+anchors)
- H_0 can be measured independently from CMB (but indirectly) by using inverse distance ladder.
- BAO galaxy+CMB lensing (or BAO Ly-alpha or DES)+baryon density from (BBN+deuterium measurements) gives low H_0.
- Time delay from multiply-imaged quasars give H_0 on the high side.



(see also Aubourg+15, Addison+ 17, DES collaboration+ 17)

The H_0 tension

- Despite quite a bit of scrutiny, no (single?) systematics effect unearthed/agreed so far to explain the discrepancy within LCDM (but environmental effects, Rigault).
- Much work is ongoing to further decrease the final uncertainty of local H_0 measurements.
- New gravity wave probes will not come to bear in the immediate future.
- It is by no means easy to find theoretical explanations without ruining (at least part of) the agreement between theory and rather solid data.
- So, interacting dark matter or neutrinos, a new phase of early accelerated expansion (if not at $z<.1$), or ???

A new little dark cloud? Lots of ongoing discussions…

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

Assumptions underlying LCDM

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

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

A3: On large scales the Universe is statistically the same everywhere. [I&S].

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 very precise fits, with the properties as stated, e.g., neutrinos]

A6: The curvature of space is very small, dynamically negligible. [CMB+BAO]

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]

Open questions (some)

1. What is the mechanism for the generation of fluctuations in the early Universe?
2. If it is inflation, as we suspect, what is the inflaton, what determines the initial state, and how does inflation end?
3. How did baryo
4. What is the da
5. Are there add
6. What is causi e today?
7. How did the Universe reionize?
8. How do astrophysical objects form and evolve in the cosmic web?

CMB Study is guaranteed to remain one of the most exciting area of all science for decades to come!

9. What is the origin of the tension with some low-z probes?
10. Are any of the curiosities a clue to physics beyond LCDM?

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.

Planck publications and products

2003-2015: Planck technical results	≈ 47 publications describing work performed by the Instrument Teams, DPCs and WGs.
2010: Planck pre-launch papers	13 publications describing the technical capabilities of Planck's instruments
2011: Planck Early papers	26+1 publications coming with the 1st delivered product: The Early Release Compact Source Catalogue
2012-2018: Planck intermediate results	55 publications mainly on galactic and extragalactic astrophysics
2013: Planck 2013 results	32 publications on cosmology science from CMB temperature data (first year data). Maps, C_l's and likelihoods delivered
2015: Planck 2015 results	28 publications mainly on cosmology science from CMB temperature and polarization data (full mission)
2018: Planck 2018 results	12 papers expected. Updated products and legacy results

Planck products can be found at: http://pla.esac.esa.int/pla/


Thank you
CPHT
X, Ferrara, Dec 2014