Title: Latest cosmological news from the Planck satelitte Project

Date: Jun 16, 2016 03:00 PM

URL: http://pirsa.org/16060021

Abstract: The Planck collaboration is working towards a "legacy release" by the end of 2016 which will mark the end of the formal collaboration we set up back in the previous century. To this end, we keep improving further our control on the potential level of residual systematics in the data and in accounting for these uncertainties in the final cosmological results to further enhance the robustness and precision of the constraints posed by Planck. For instance, we announced in May an improved likelihood analysis using detailed end-to-end simulation as well as an improved constraint on the reionisation optical depth by using for the first time the E-mode polarisation data from the HFI instrument. This determination fully reconciles the CMB results with other astrophysical measurements of reionization from sources at high redshift. It also gives constraints on the level of reionization at redshifts beyond that of the most distant sources ($z > 10$). I will further give some perspectives on what is coming next.

The Planck mission concept/challenge

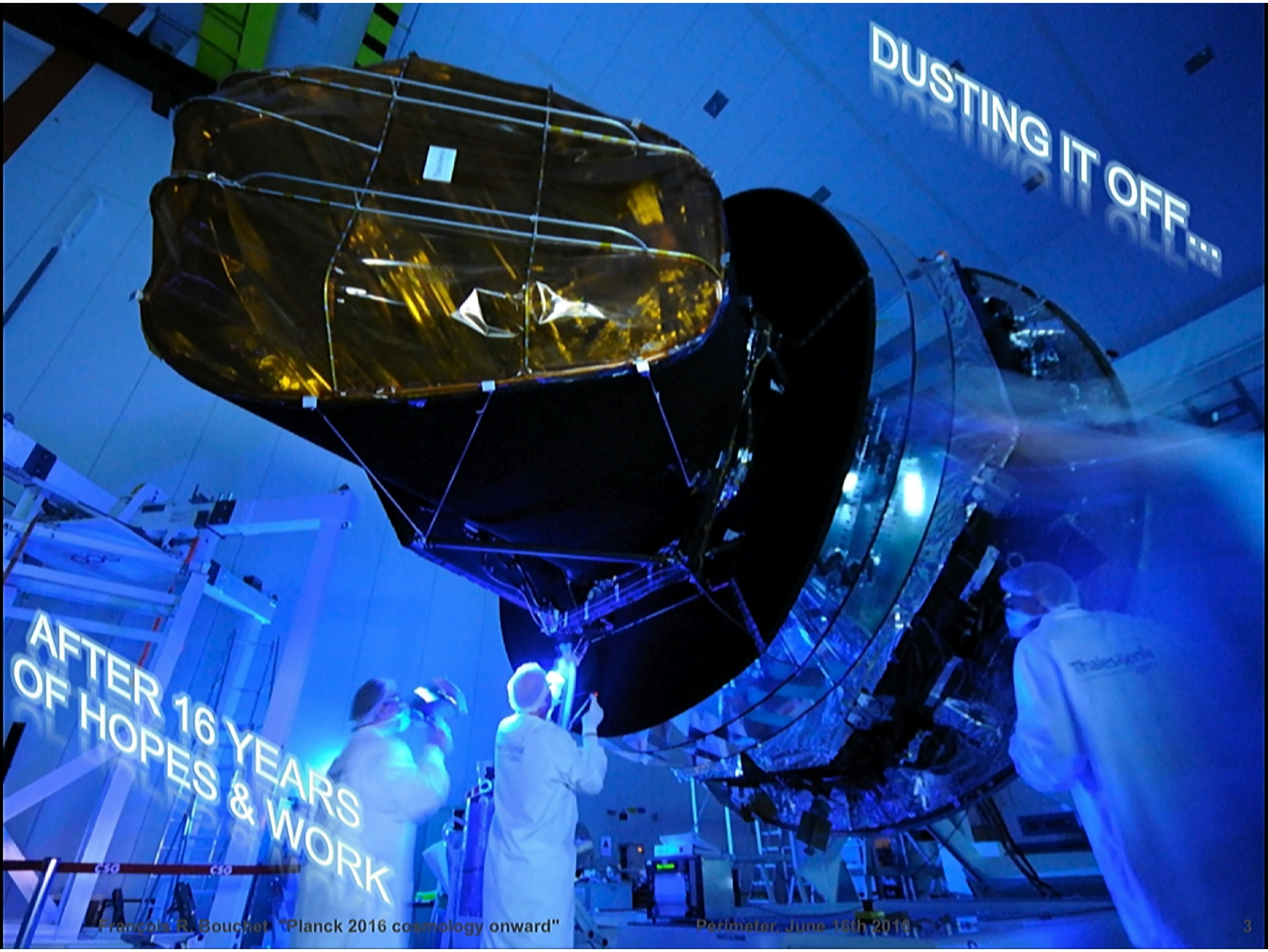
- ➢ to perform the “ultimate” measurement of the Cosmic Microwave Background (CMB) temperature anisotropies:
  - – *full sky coverage & angular resolution / to survey all scales at which the CMB primary anisotropies contain information (~5’)*
  - – *sensitivity / essentially limited by ability to remove the astrophysical foregrounds*
  - $\Rightarrow$ *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

$\Rightarrow$ ESA selection in 1996 (after ~ 3 year study)

NB: This required a number of technological breakthrough

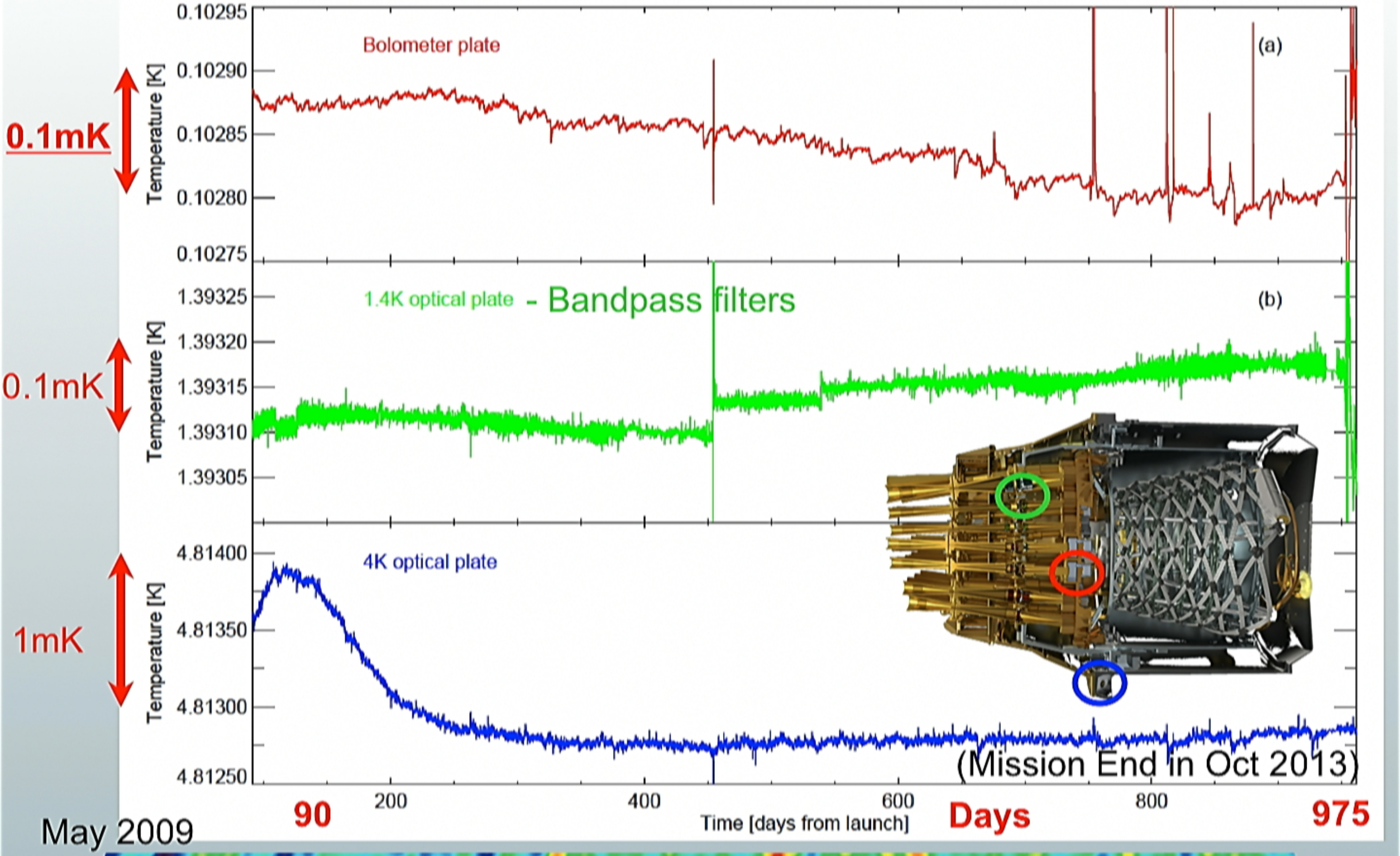
NB: with the Ariane 501 failure delaying us by several years (03 → 07) and WMAP then flying well before us, polarization measurements became more and more a major goal



DUSTING IT OFF...

AFTER 16 YEARS OF HOPES & WORK

Quietly cool…



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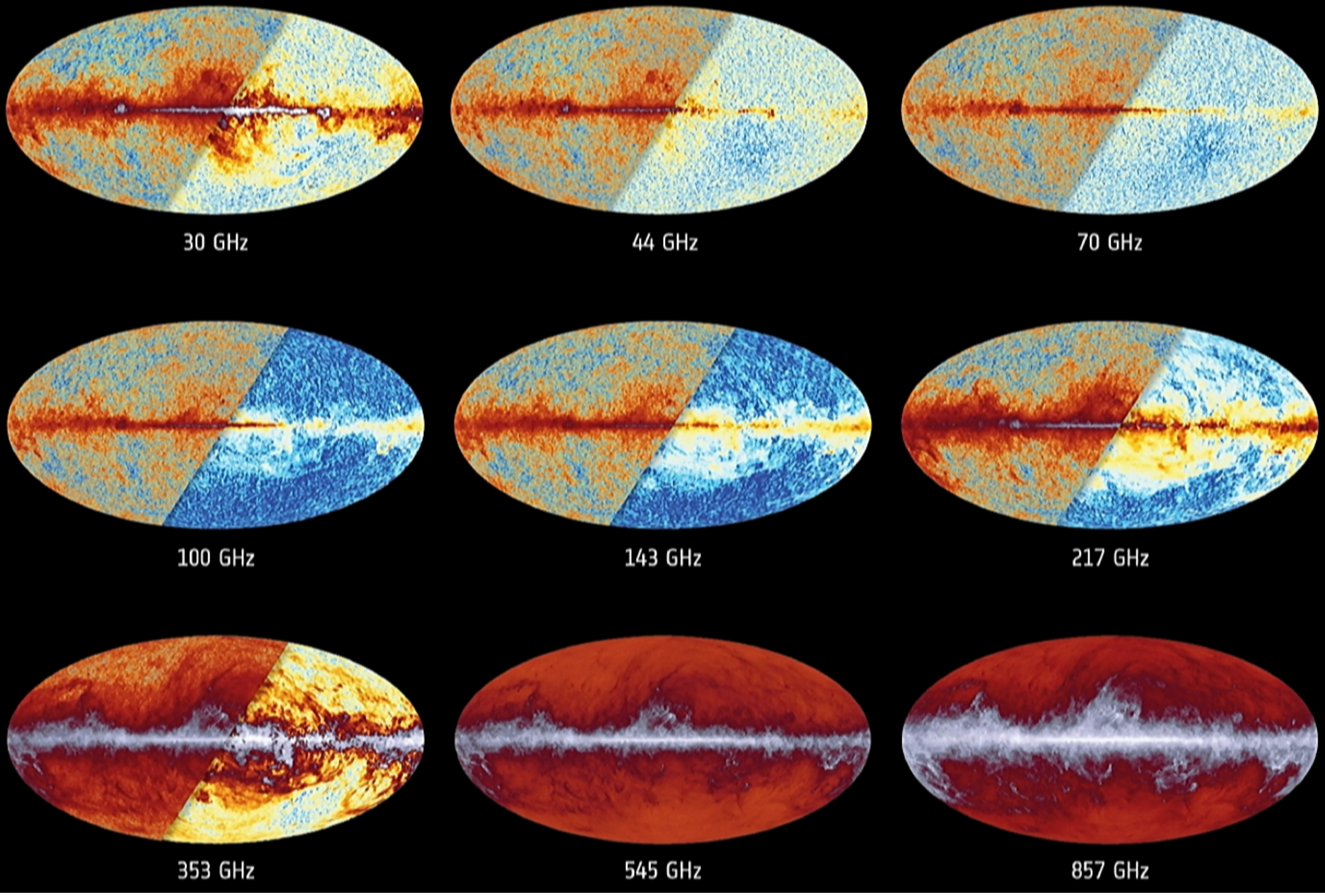

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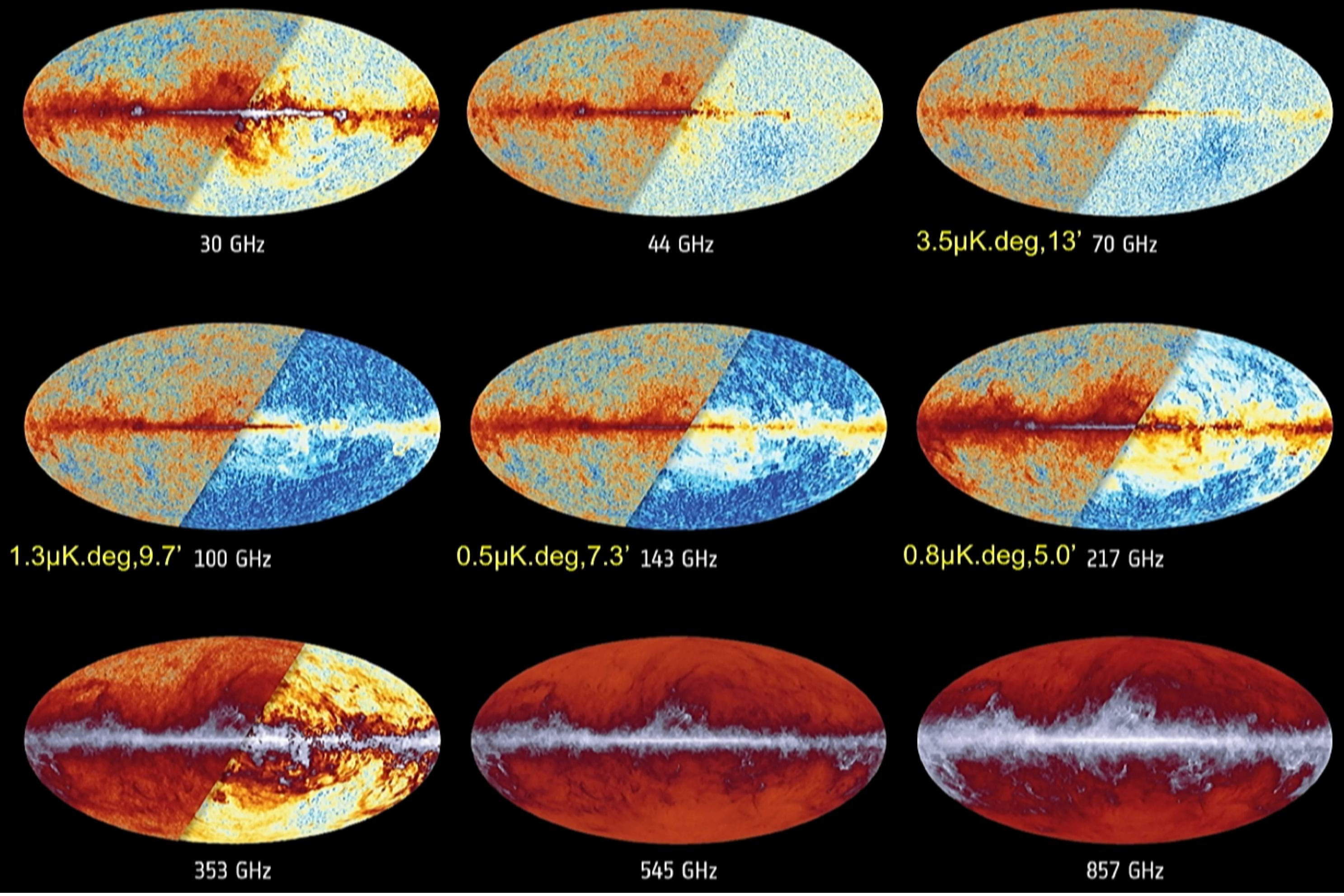
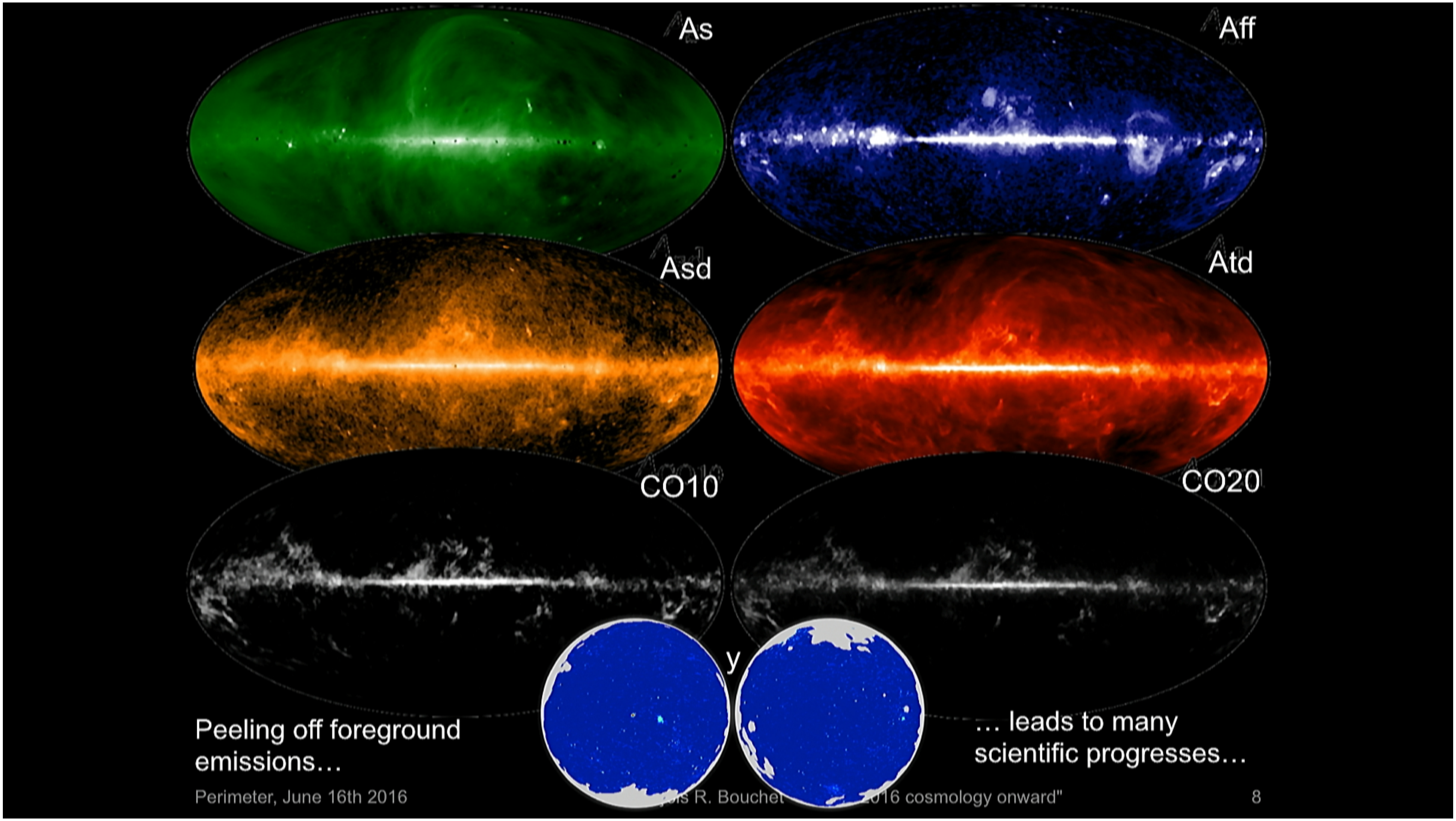
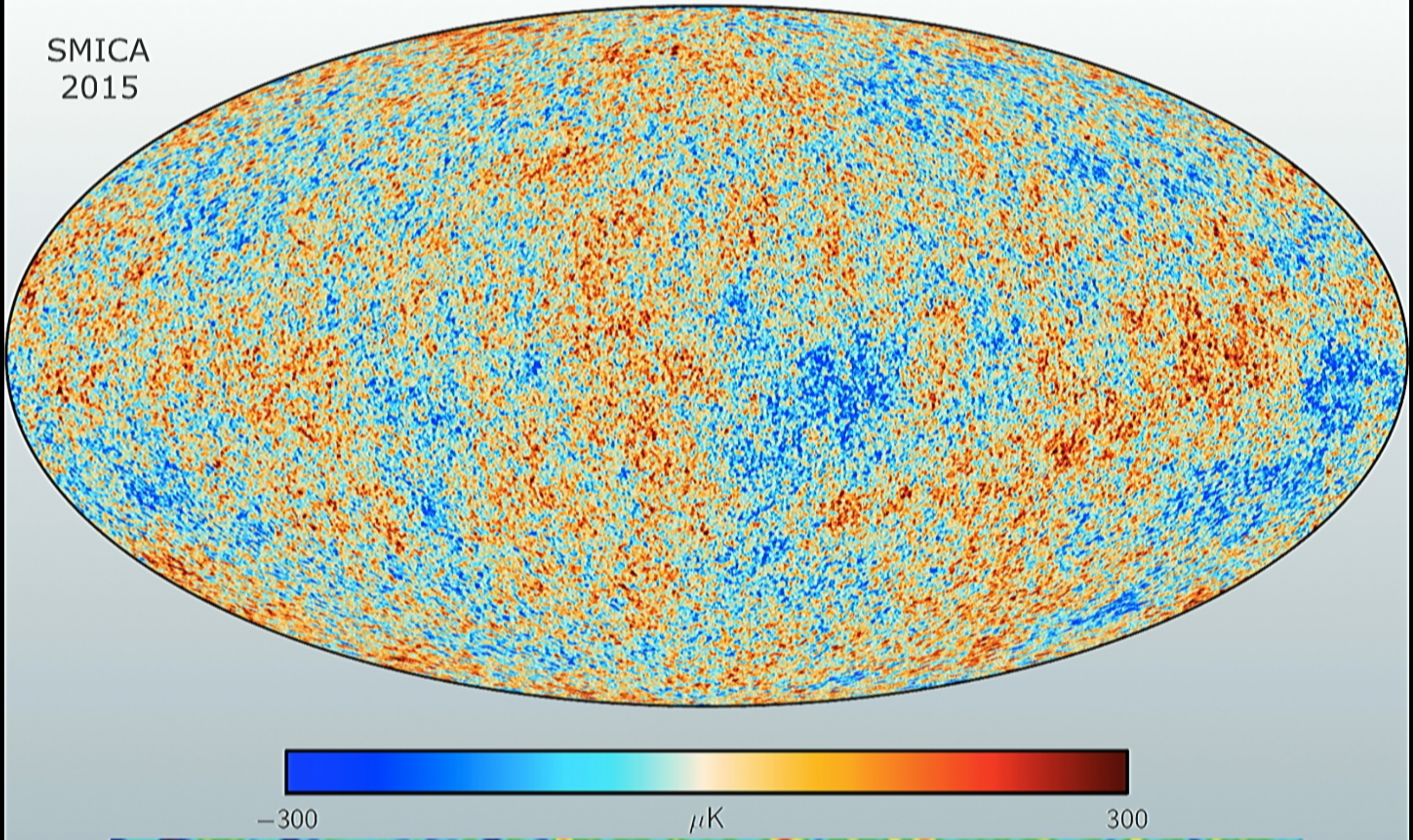




Peeling off foreground emissions…

… leads to many scientific progresses…

Planck 2015 T anisotropies map



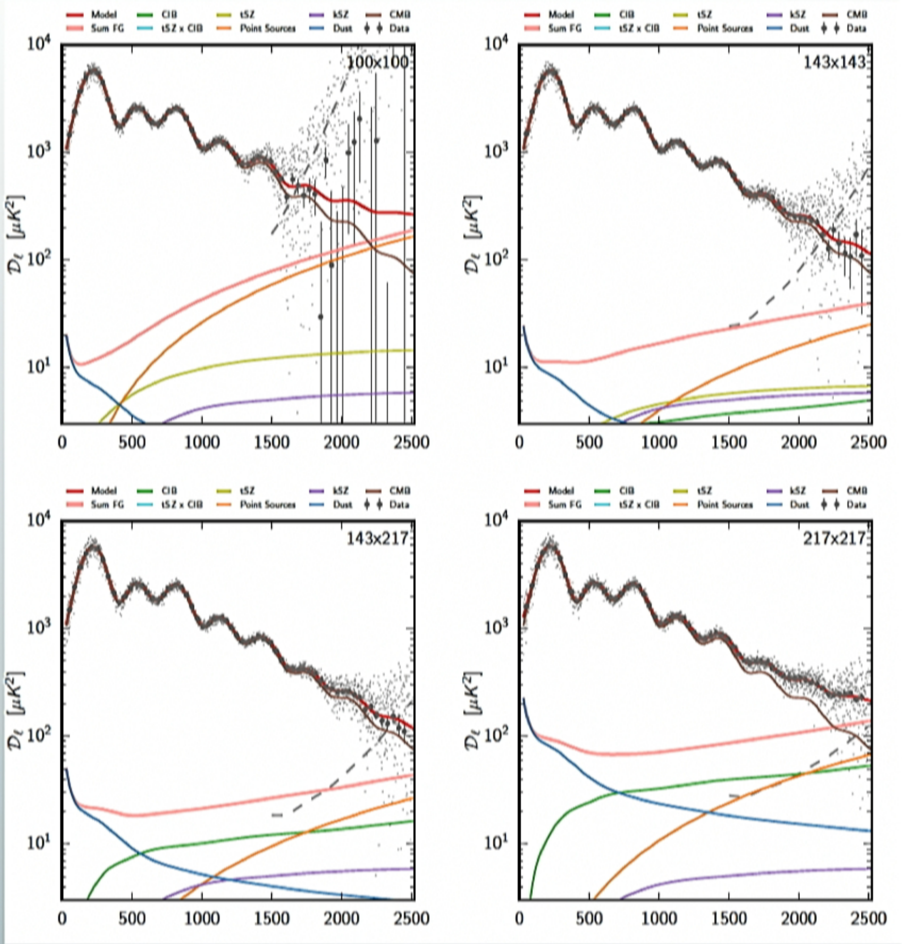
The high-ell likelihood (l>30)

We construct a Gaussian likelihood, using

- A parameterised foreground model to marginalise over (12 parameters)
- a covariance matrix which includes signal, noise, FG, masks… Full TT, TE, EE reduces to 2300^2 elements when binned (Cond Num~ $O(10^{11})$) [Instead of 23000^2]

- In practice, many detailed, intertwined choices, e.g., of masks, l-ranges, FG model, cross-spectra combination, etc.

- Test, test, test



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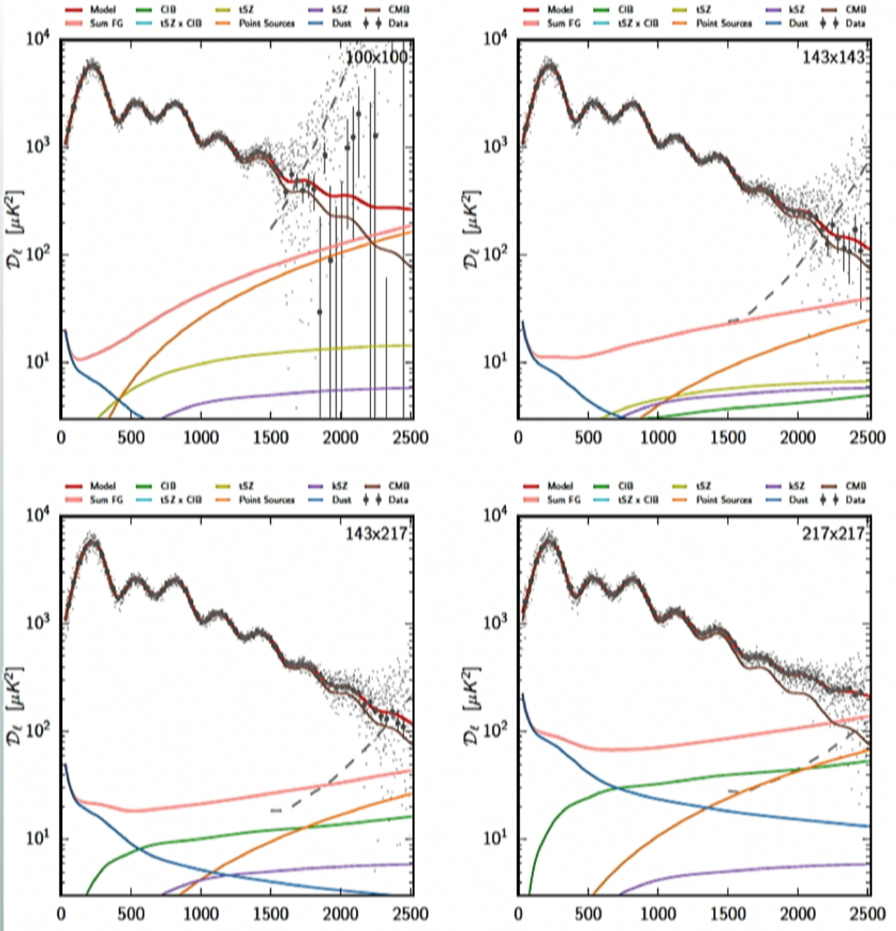
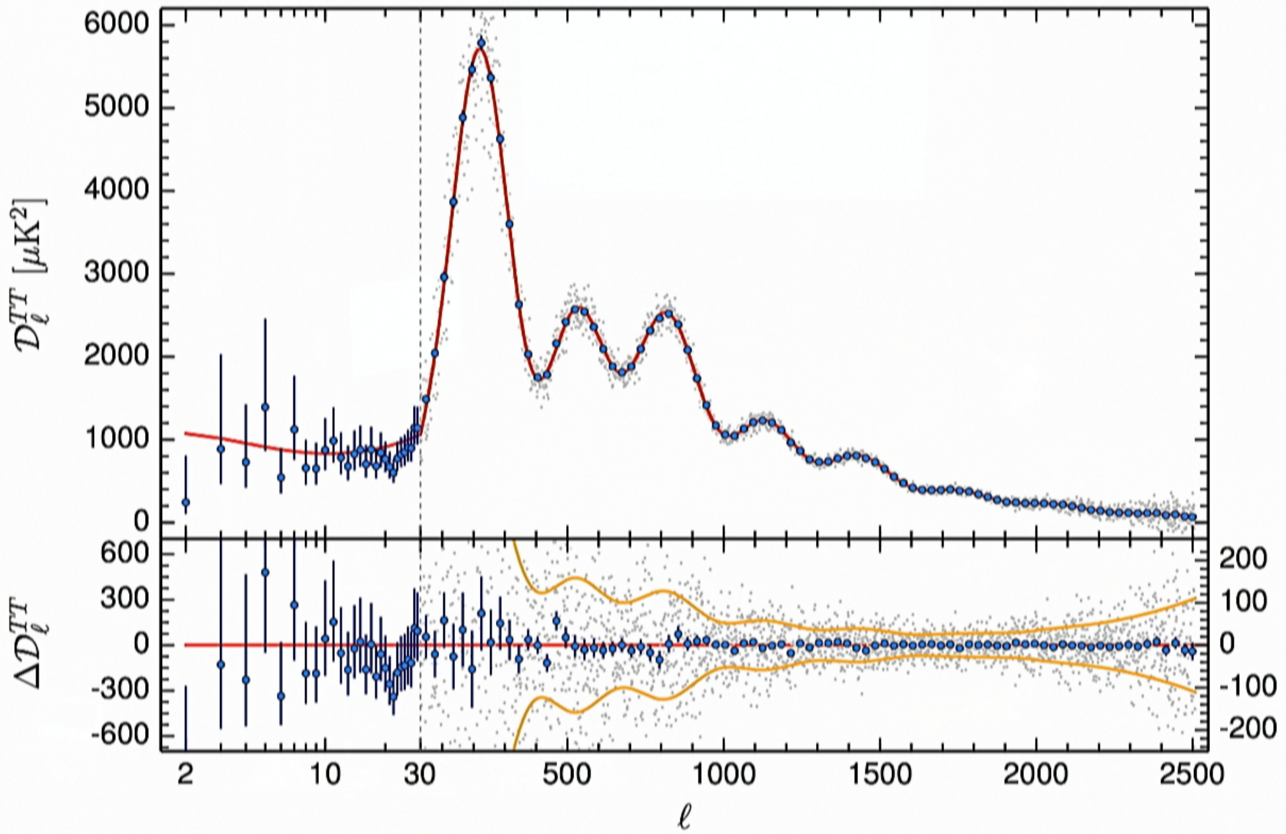
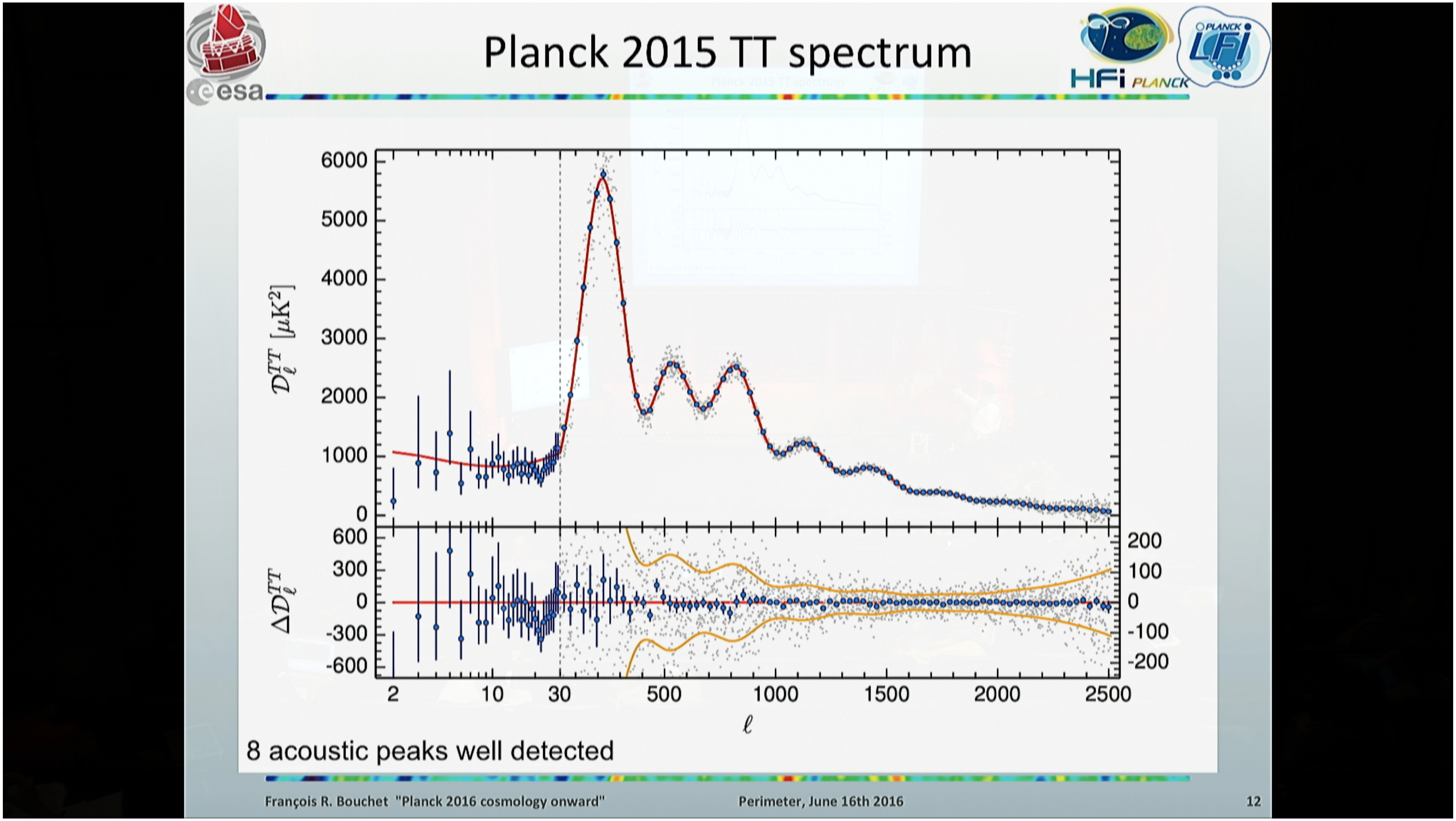


Planck 2015 TT spectrum



8 acoustic peaks well detected



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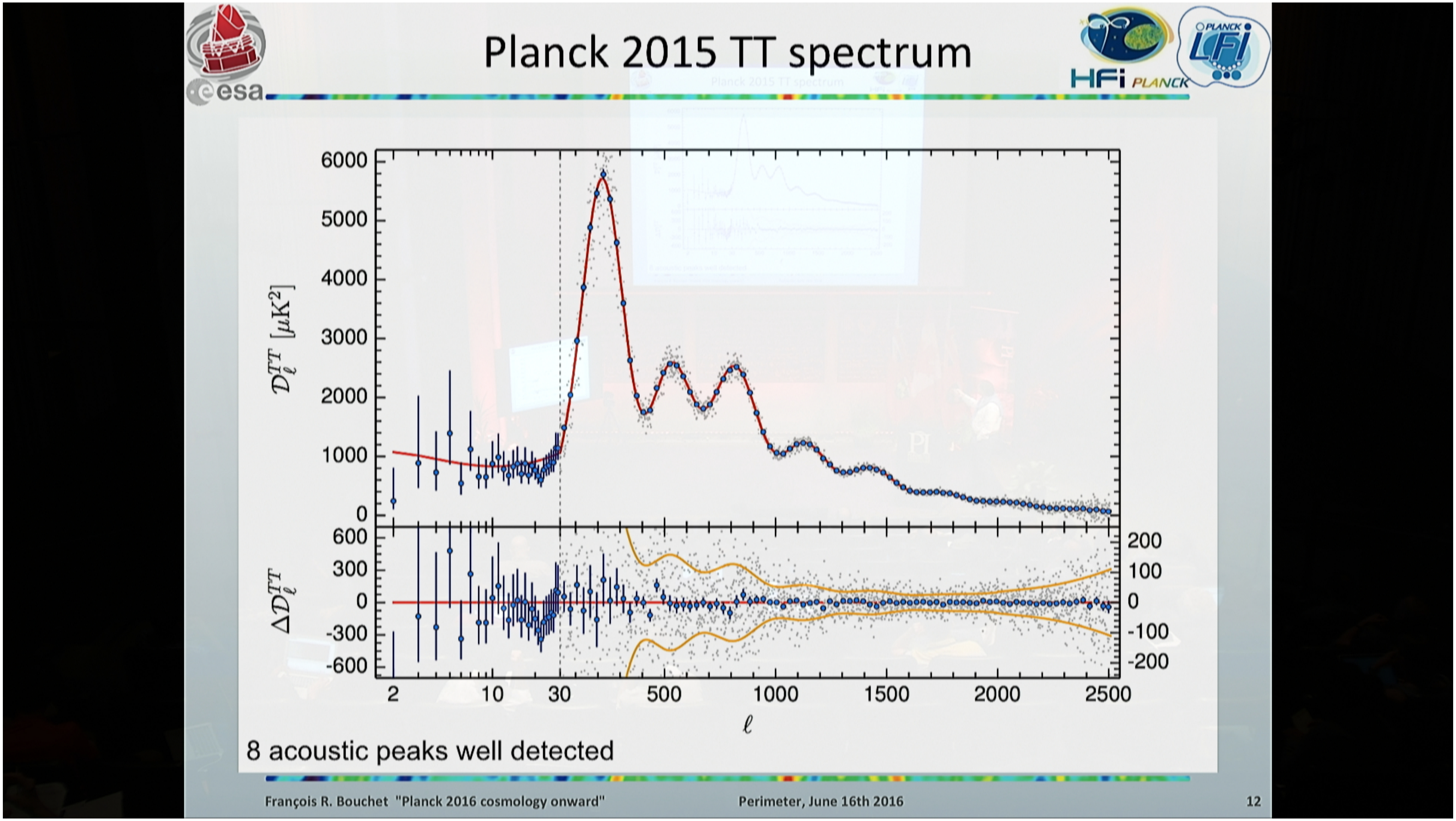
François R. Bouchet "Planck 2016 cosmology onward" Perimeter, June 16th 2016



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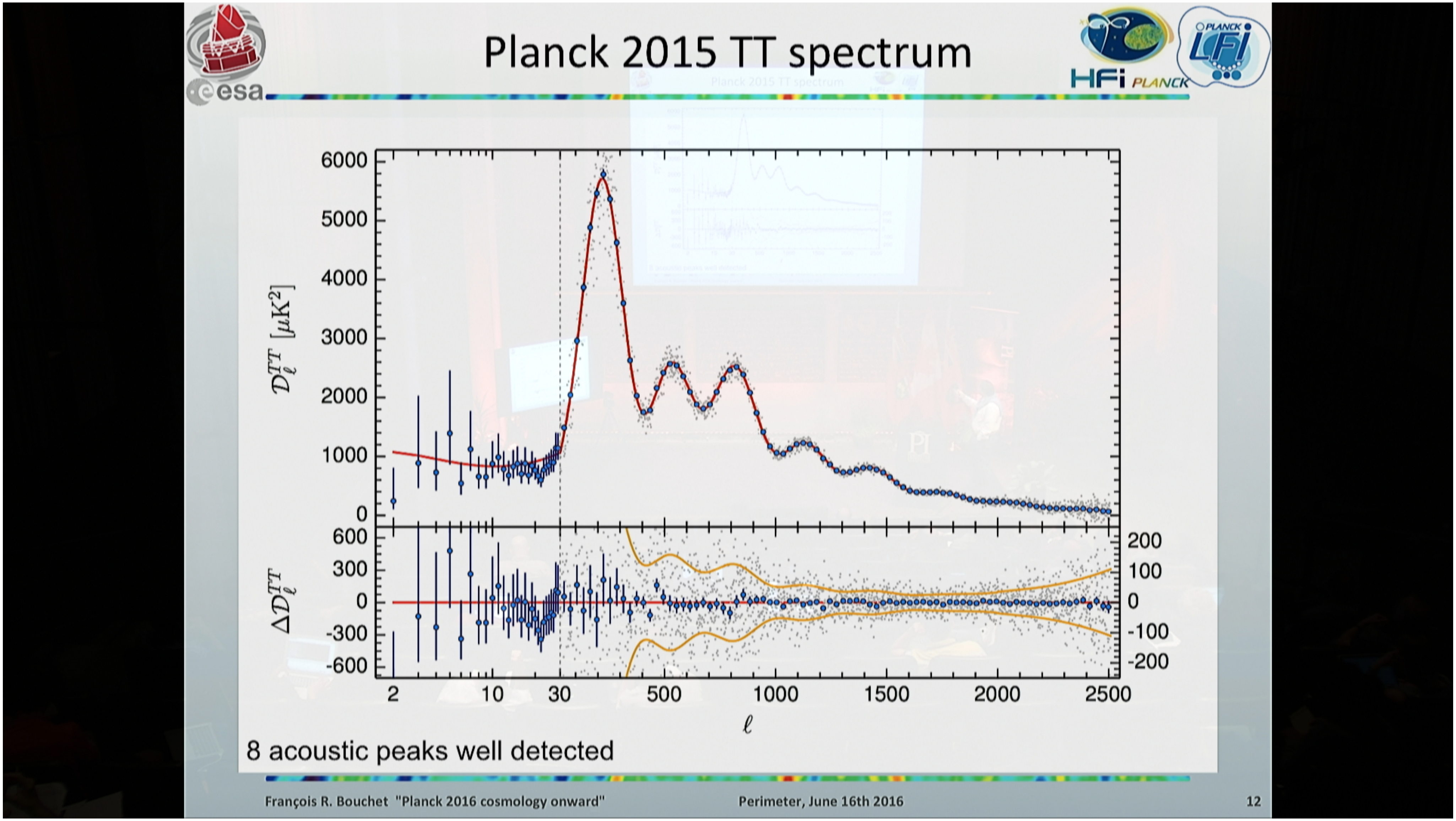

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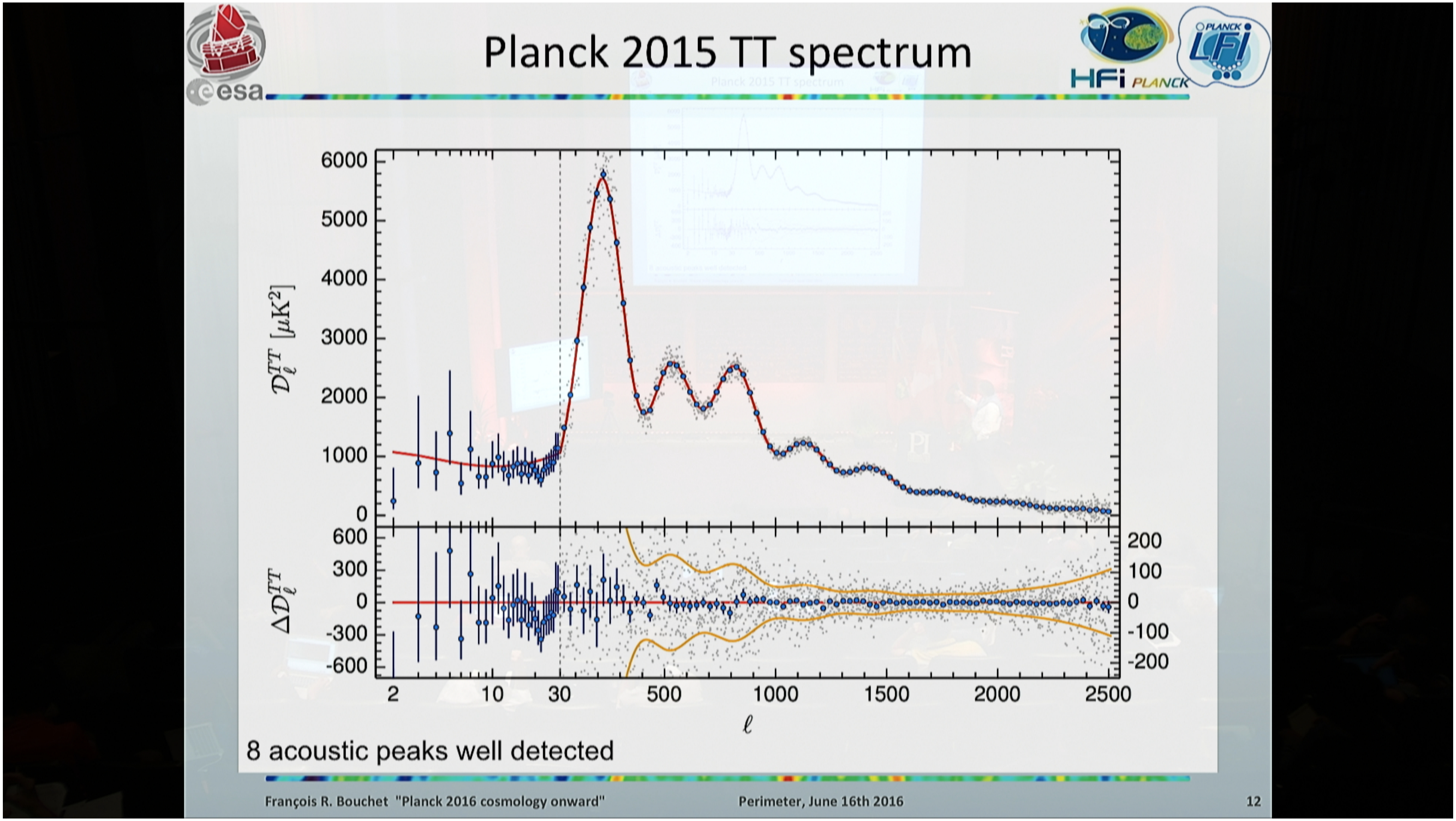

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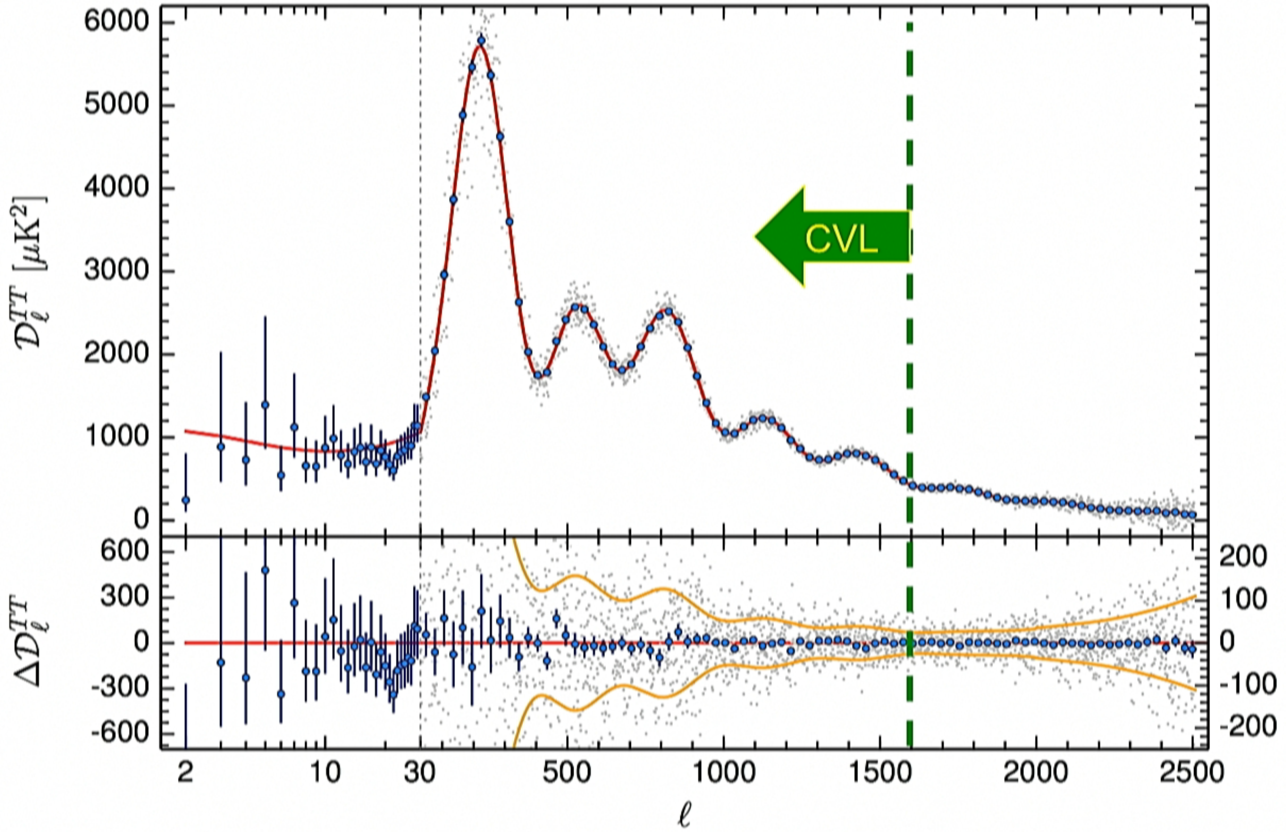

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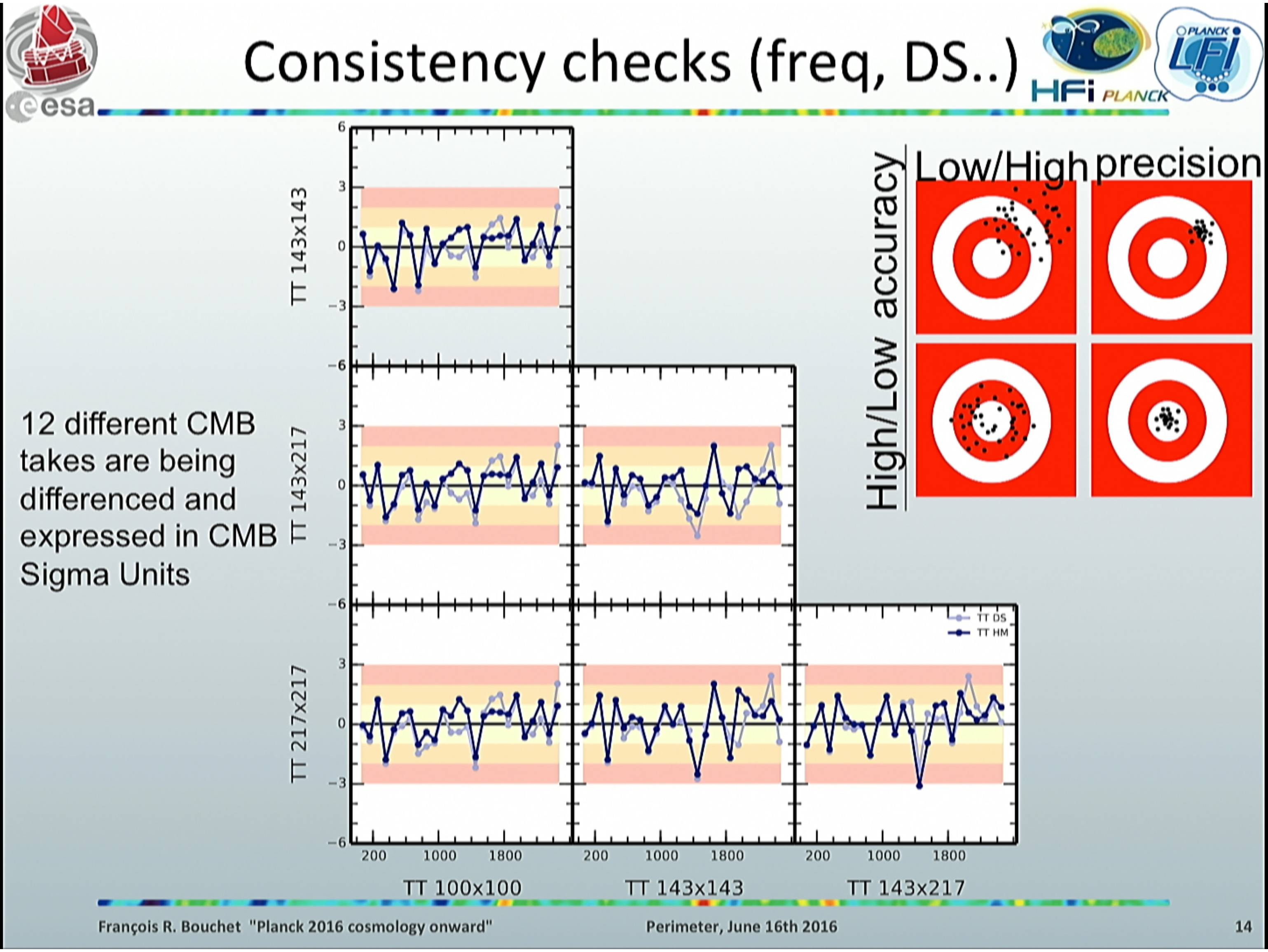
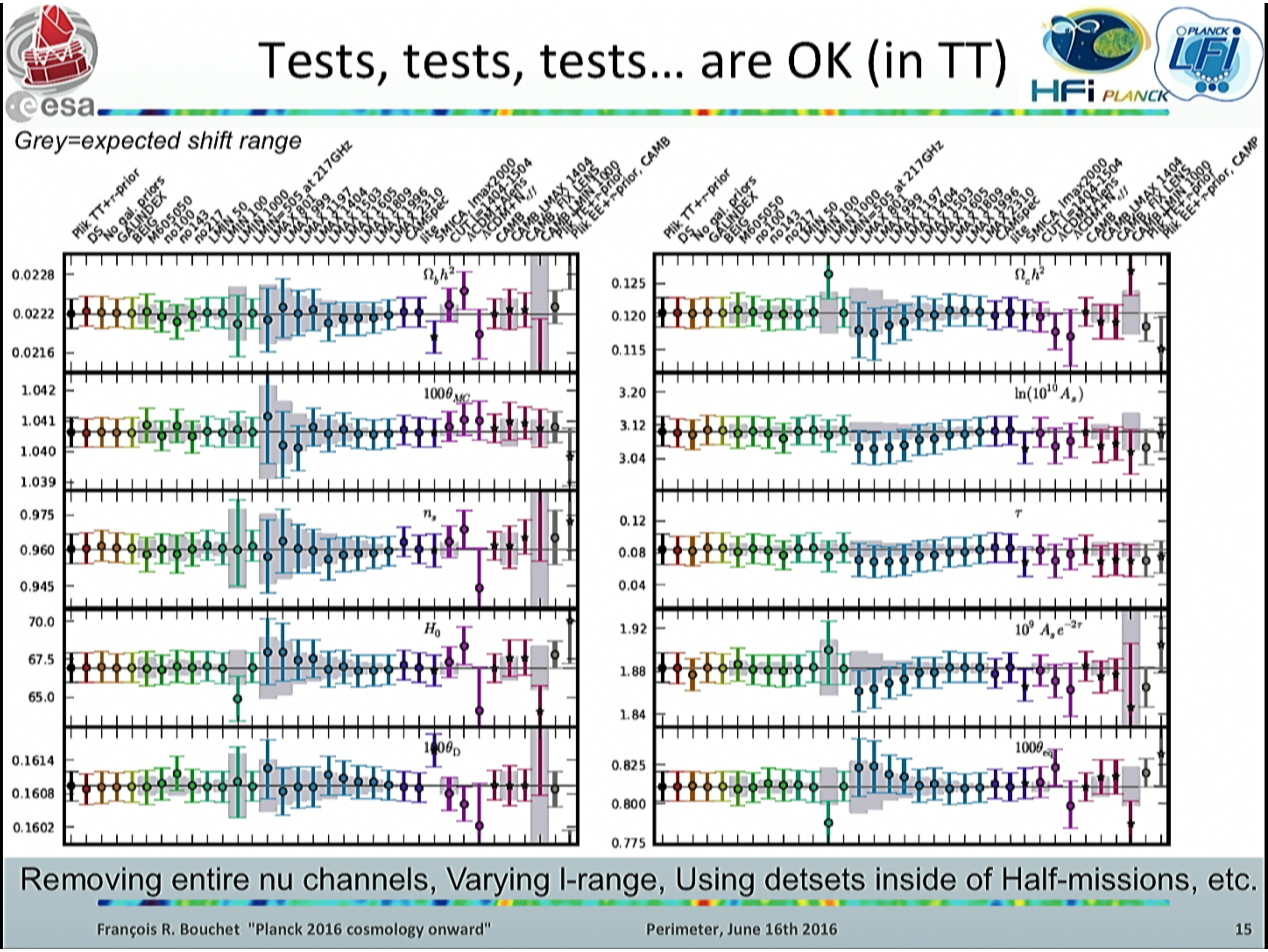
CVL till l~1600 on 40-70% of the sky



Consistency checks (freq, DS..)

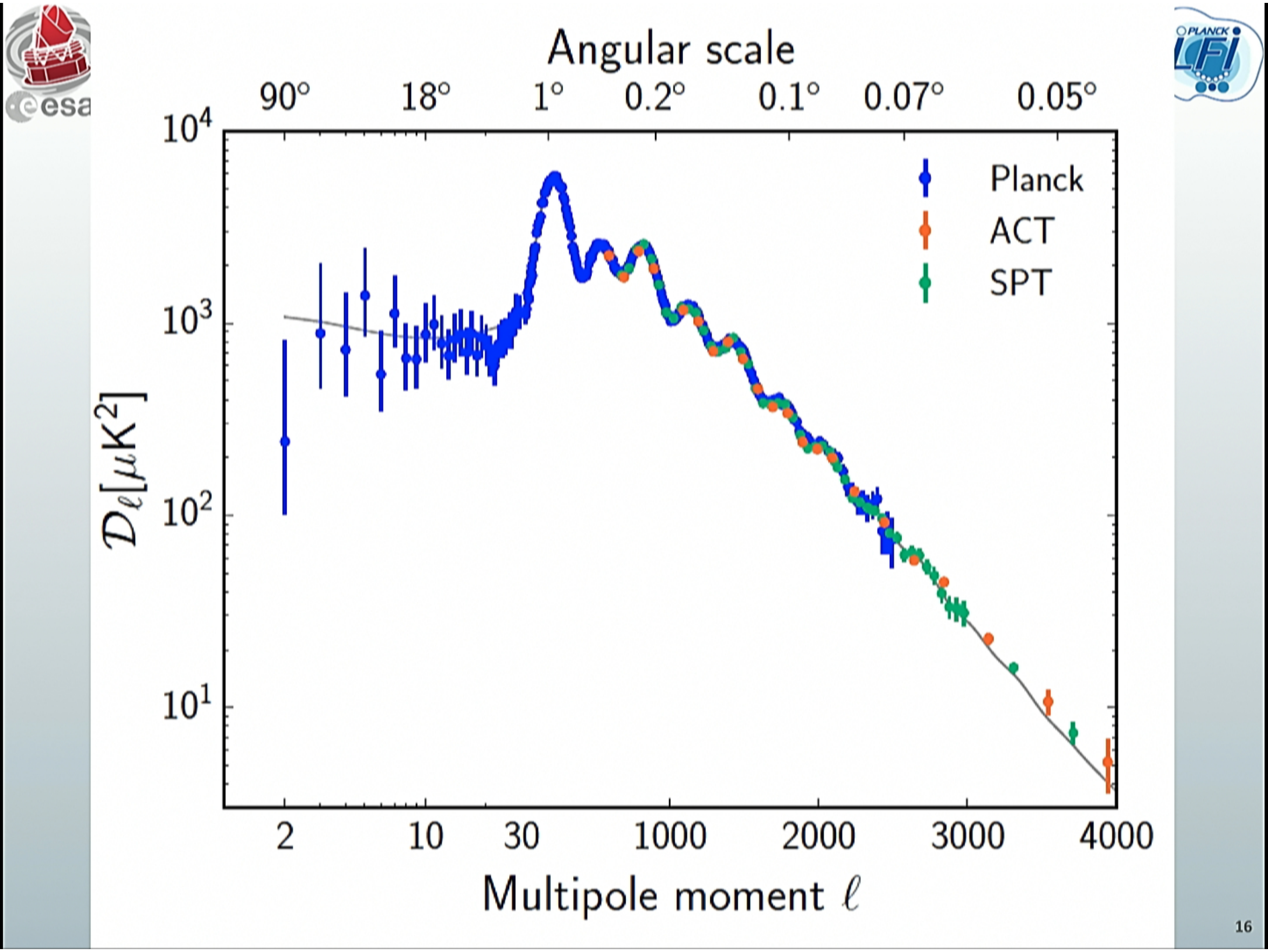
12 different CMB takes are being differenced and expressed in CMB Sigma Units

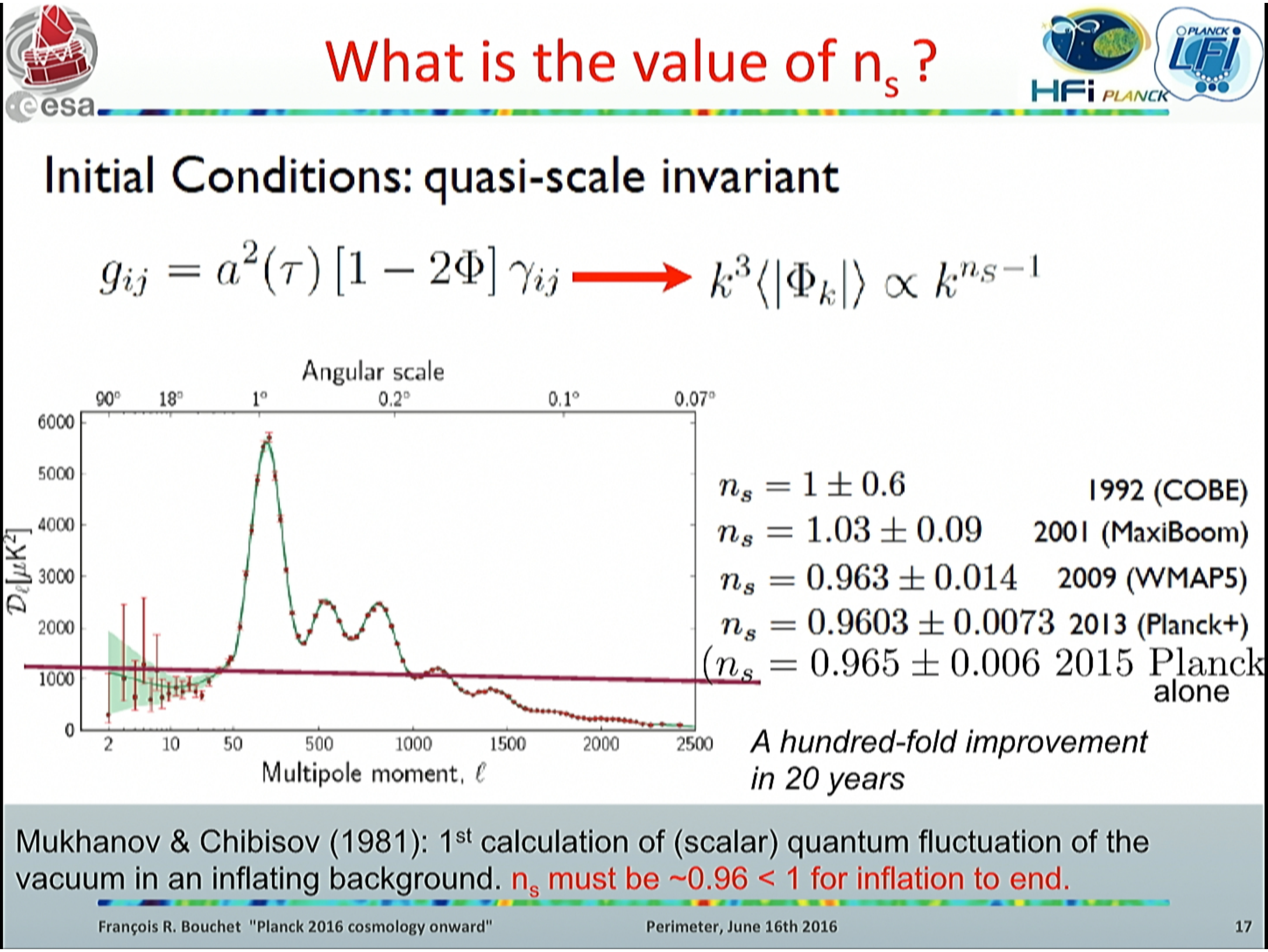


Tests, tests, tests... are OK (in TT)

Grey=expected shift range

Removing entire nu channels, Varying l-range, Using detsets inside of Half-missions, etc.


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
0.05°
10^4
10^3
10^2
10^1
$\mathcal{D}_\ell [\mu K^2]$
Planck
ACT
SPT
2
10
30
1000
2000
3000
4000
Multipole moment ℓ



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 alone

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.

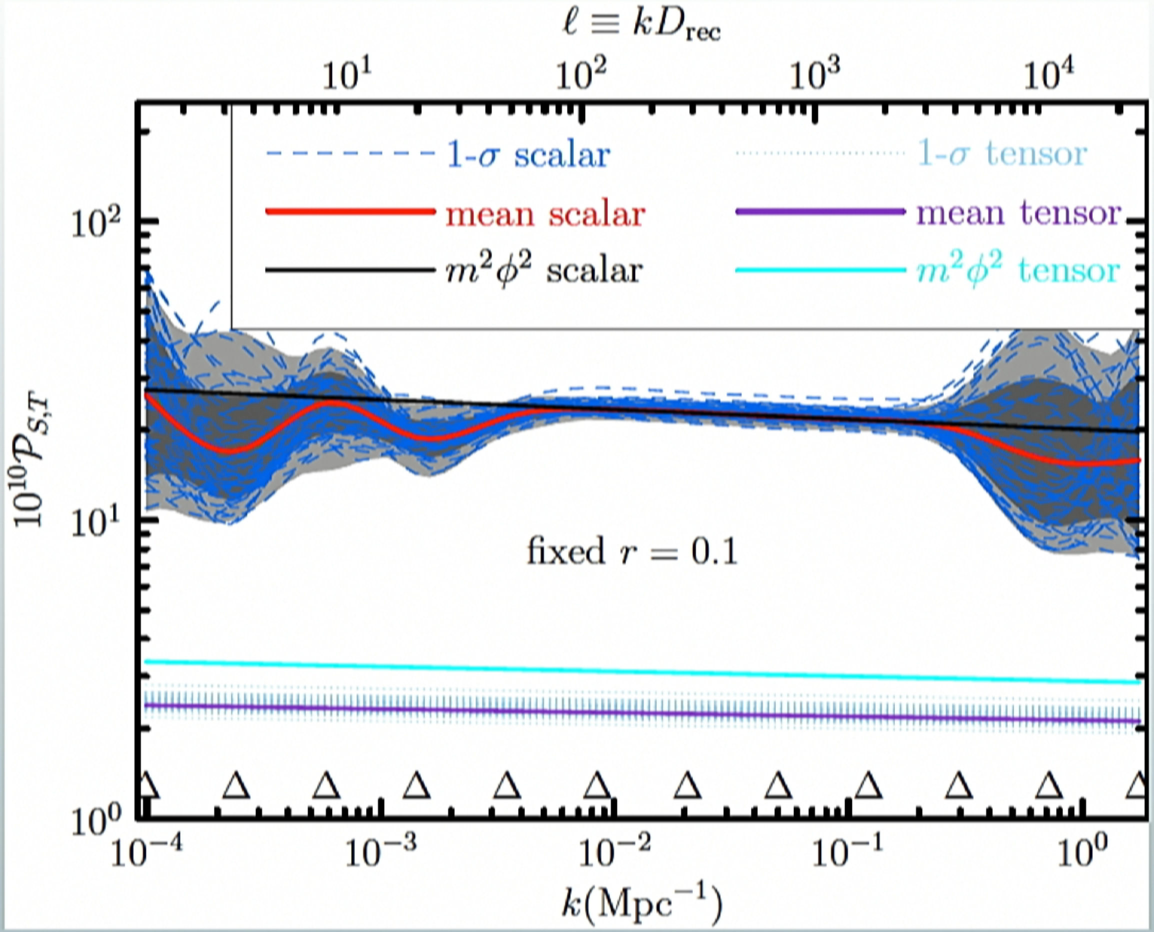
Power spectra reconstruction

2015

TT+lowP

+BAO+JLA

+Hlow



12-knots power spectra

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

Power spectra reconstruction

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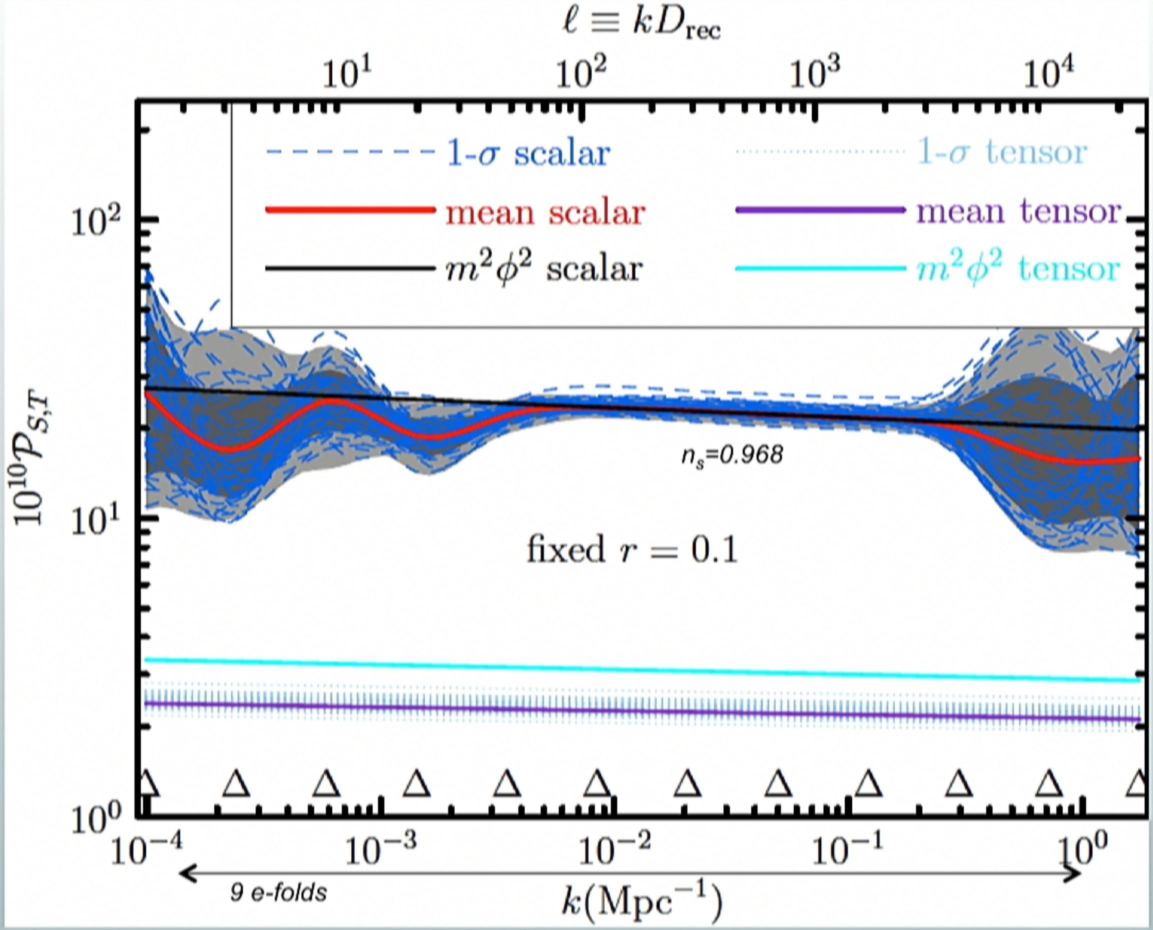

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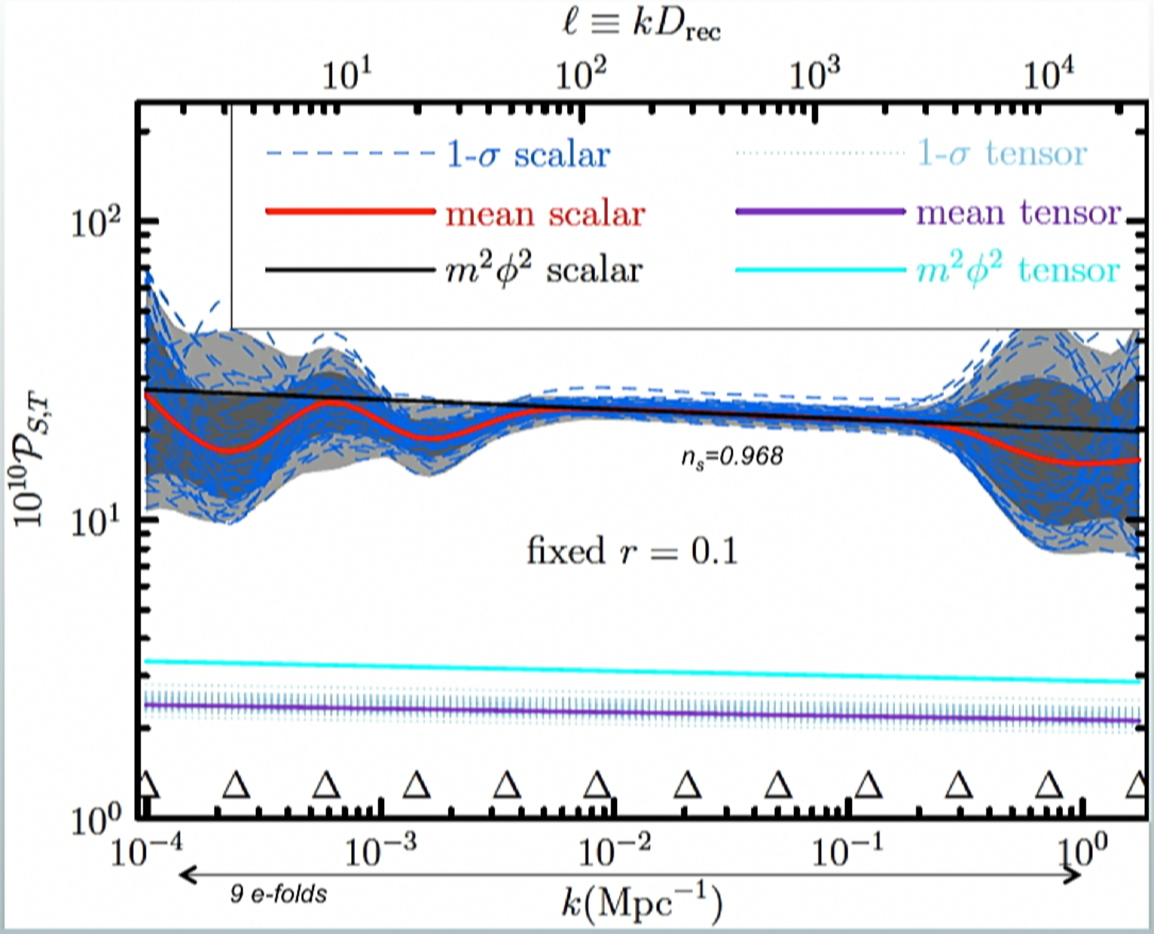


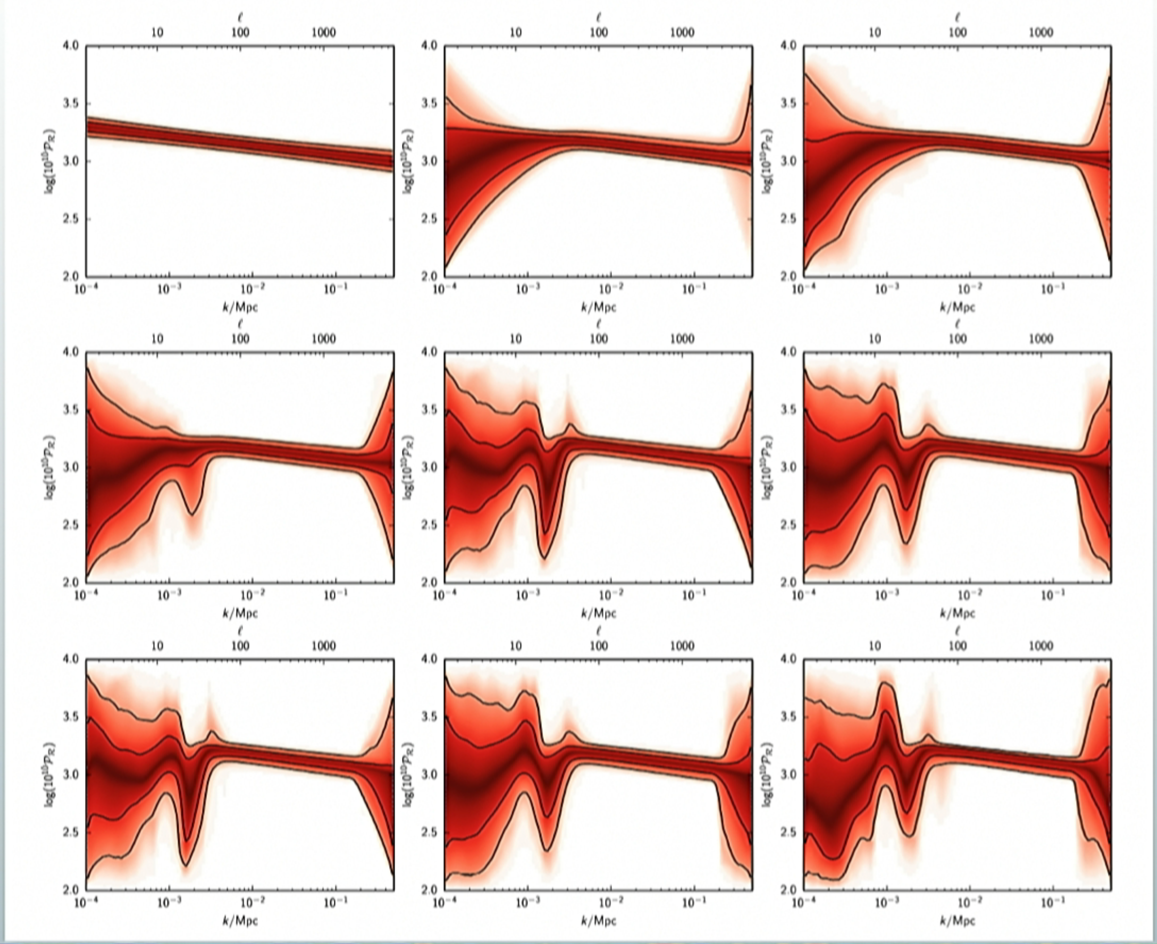
12-knots power spectra

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

Bayesian moveable knot PS reconstruction

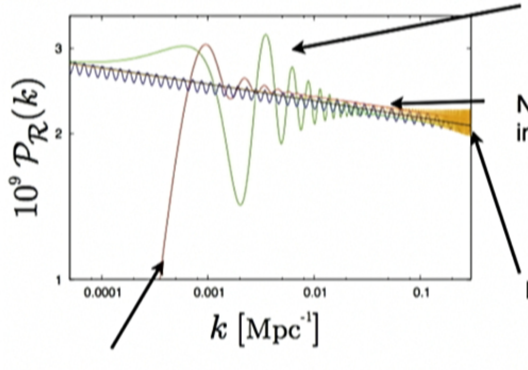
Adding
0 to 8
knots

(in addition to
minimum 2)



No truly
significant
deviation
found

(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

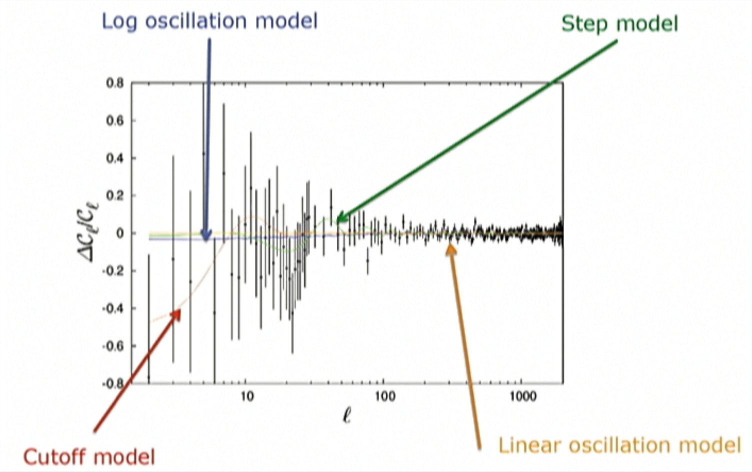
$$V(\phi)=\mu^3\phi+\Lambda^4\cos\left(\frac{\phi}{f}\right)$$

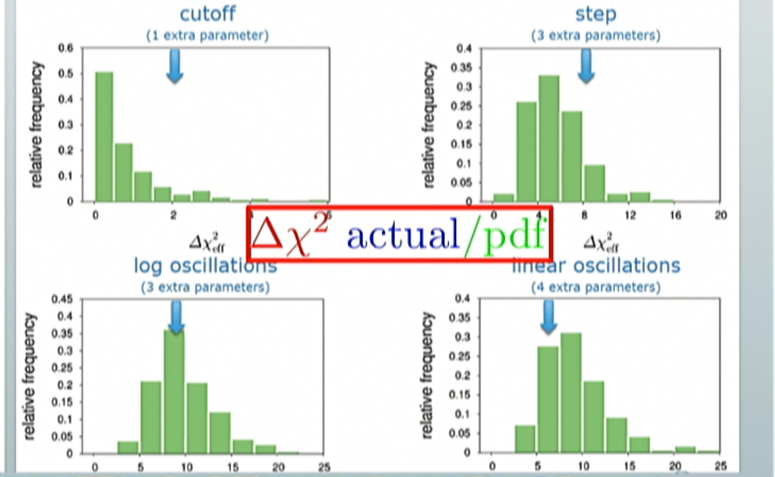
$$\mathcal{P}_\mathcal{R}^{\log}(k)=\mathcal{P}_\mathcal{R}^0(k)\left[1+\mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right)+\varphi_{\log}\right)\right].$$

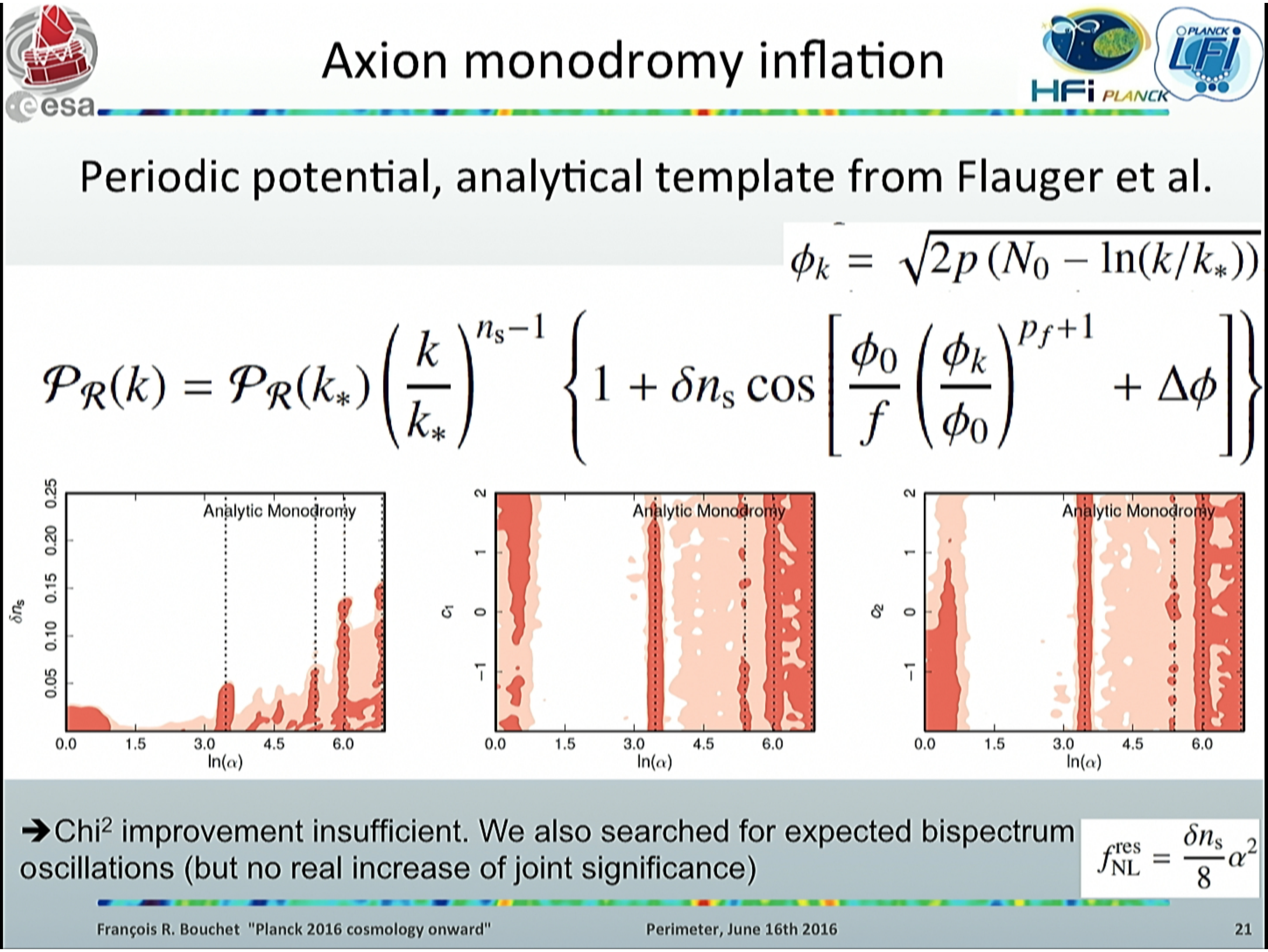
Linear oscillations as from Boundary EFT

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

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







Axion monodromy inflation

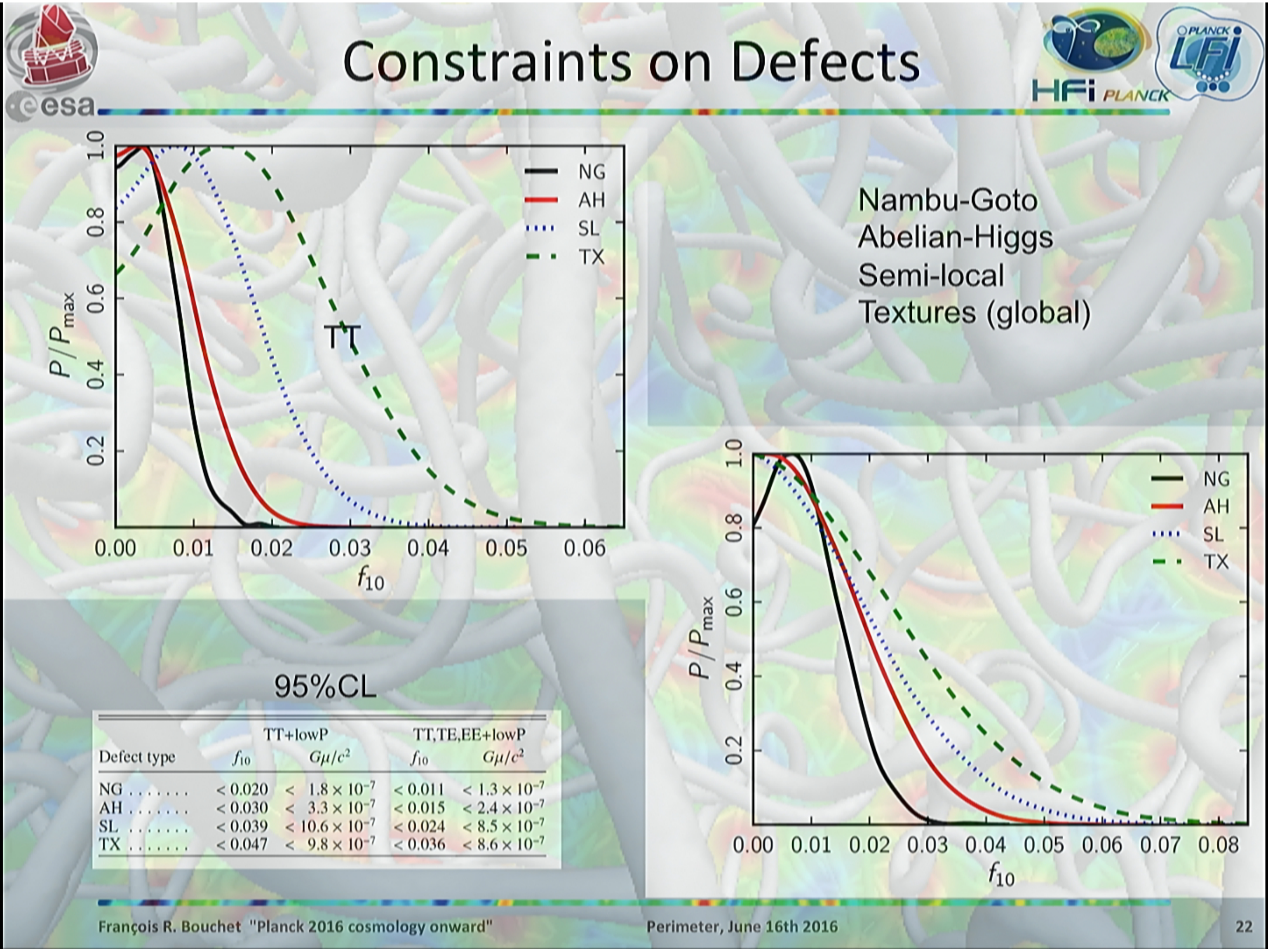
Periodic potential, analytical template from Flauger et al.

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

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

➔Chi^2 improvement insufficient. We also searched for expected bispectrum oscillations (but no real increase of joint significance)

$$f_{\rm NL}^{\rm res} = \frac{\delta n_s}{8}\alpha^2$$



Constraints on Defects

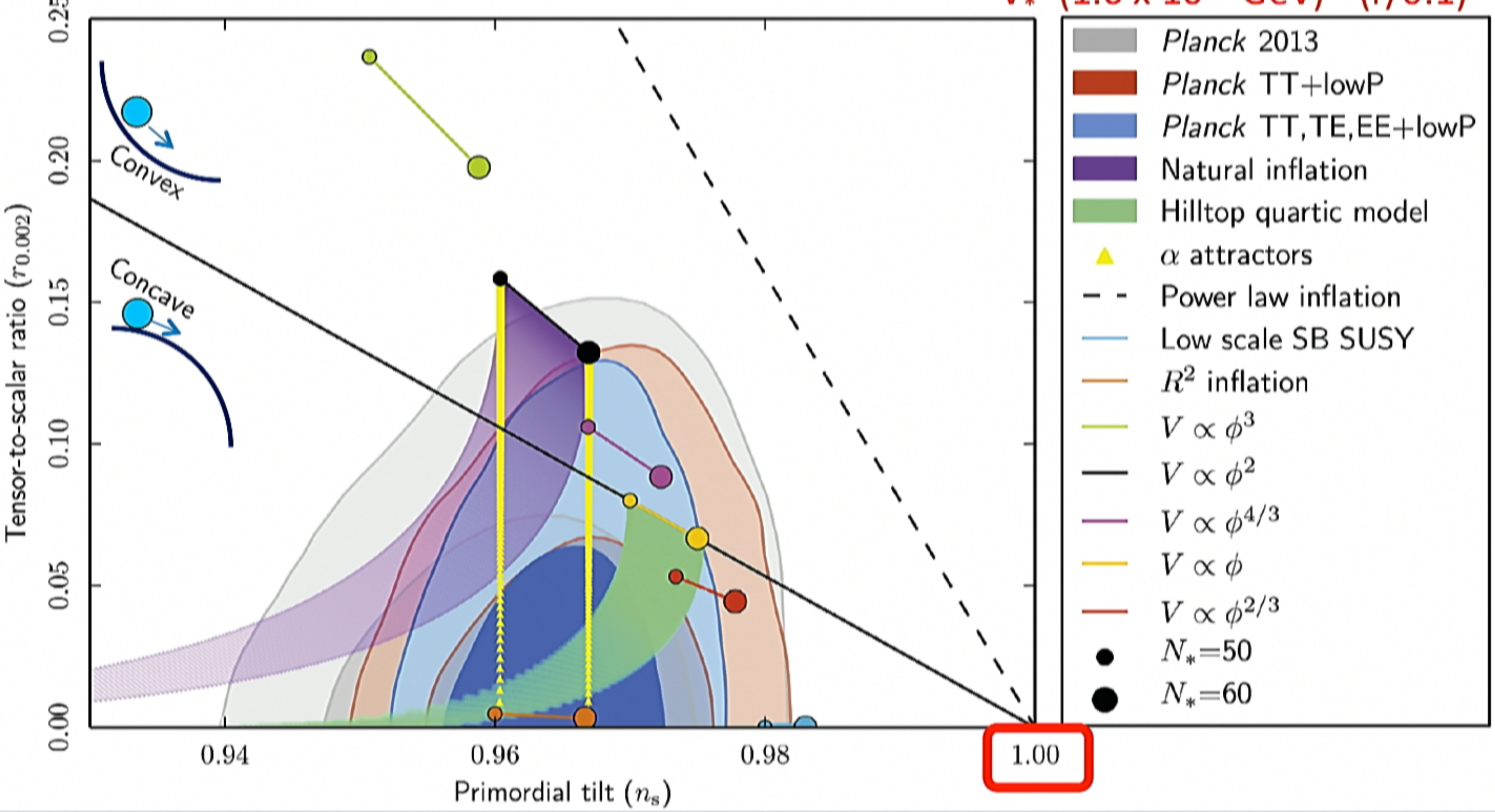
Nambu-Goto
Abelian-Higgs
Semi-local
Textures (global)

95%CL

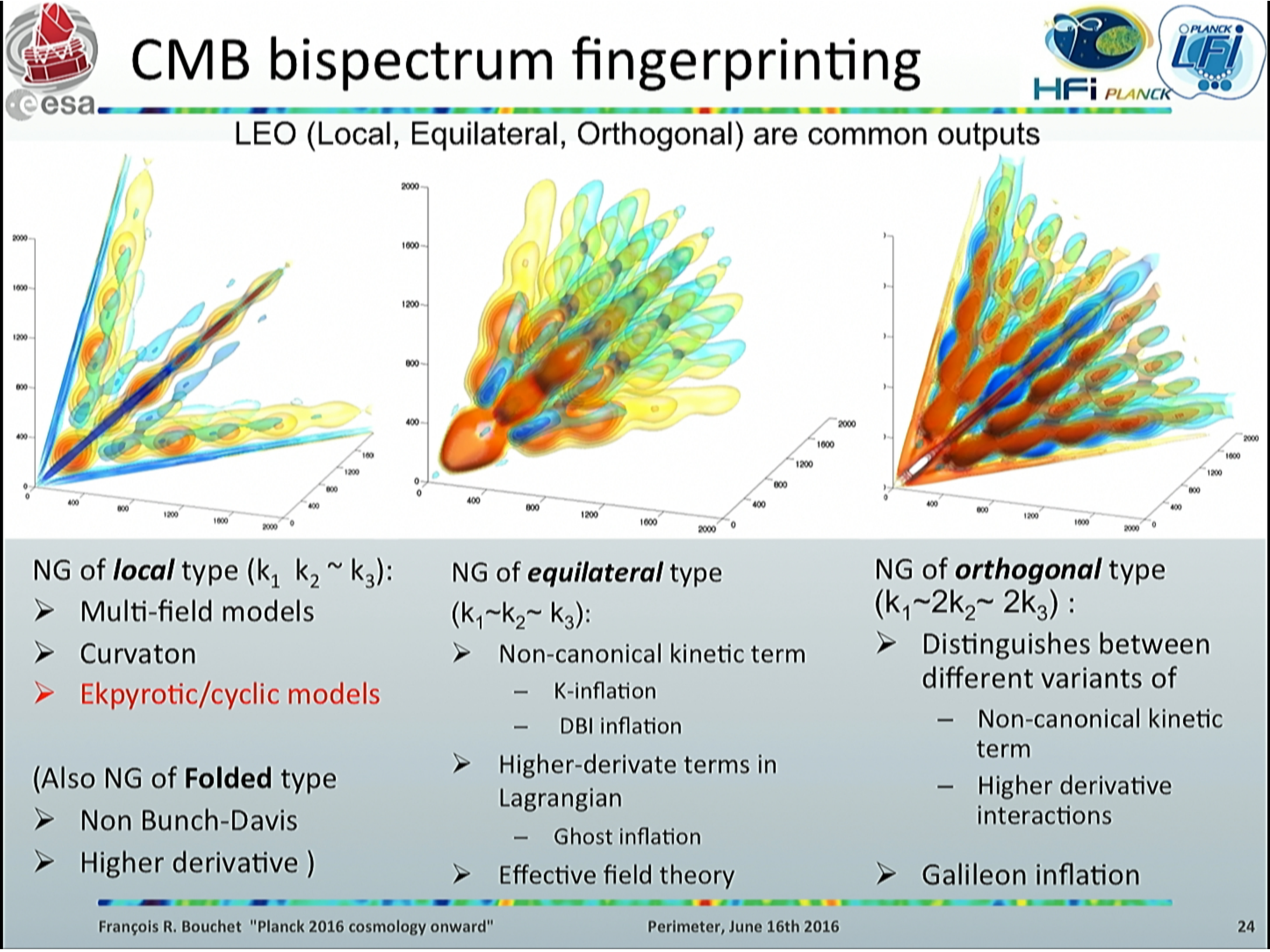
	TT+lowP		TT,TE,EE+lowP	
Defect type	f_{10}	$G\mu/c^2$	f_{10}	$G\mu/c^2$
NG	< 0.020	$< 1.8 \times 10^{-7}$	< 0.011	$< 1.3 \times 10^{-7}$
AH	< 0.030	$< 3.3 \times 10^{-7}$	< 0.015	$< 2.4 \times 10^{-7}$
SL	< 0.039	$< 10.6 \times 10^{-7}$	< 0.024	$< 8.5 \times 10^{-7}$
TX	< 0.047	$< 9.8 \times 10^{-7}$	< 0.036	$< 8.6 \times 10^{-7}$

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)



CMB bispectrum fingerprinting

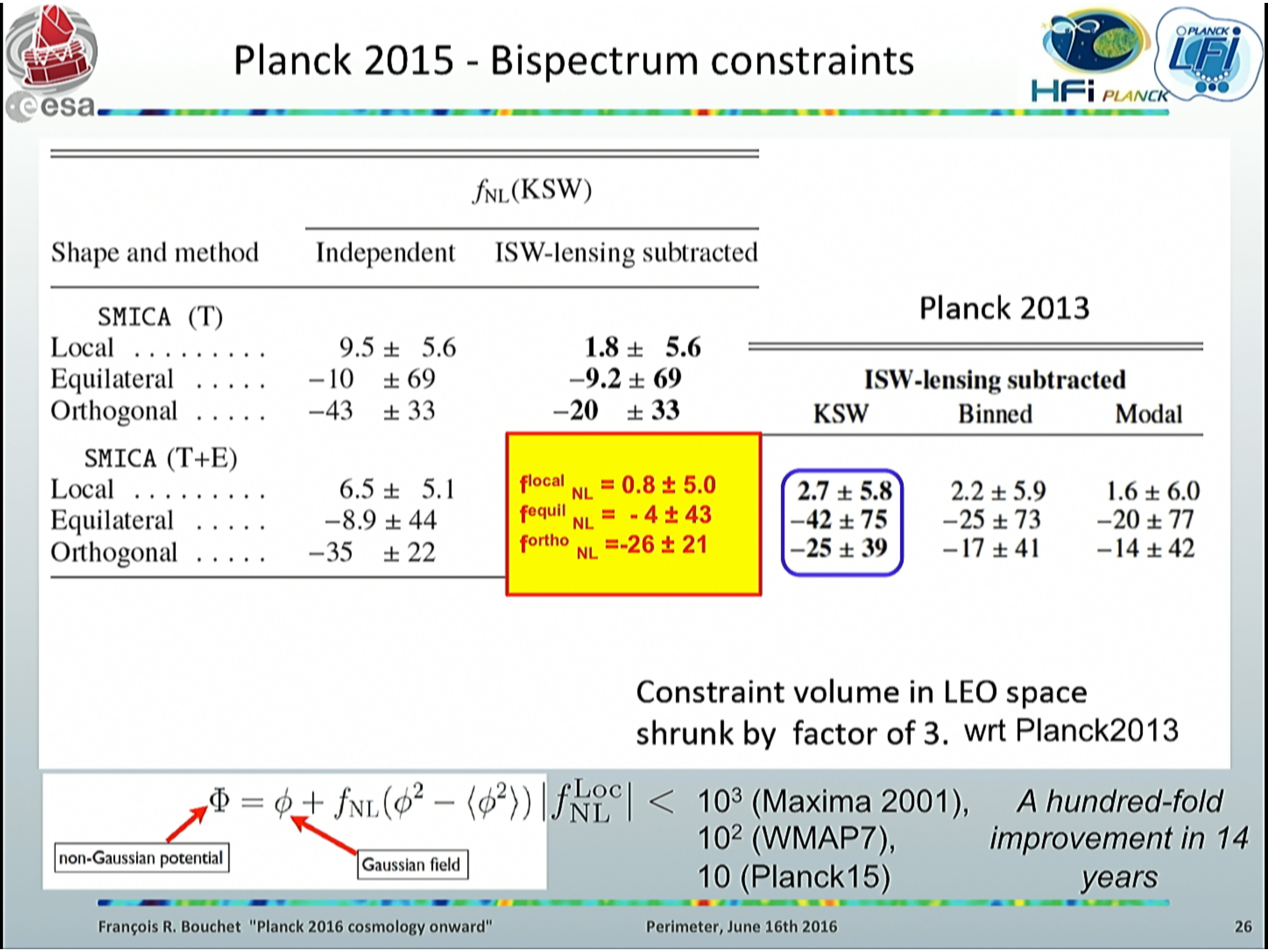
LEO (Local, Equilateral, Orthogonal) are common outputs

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 - Bispectrum constraints

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. wrt Planck2013

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

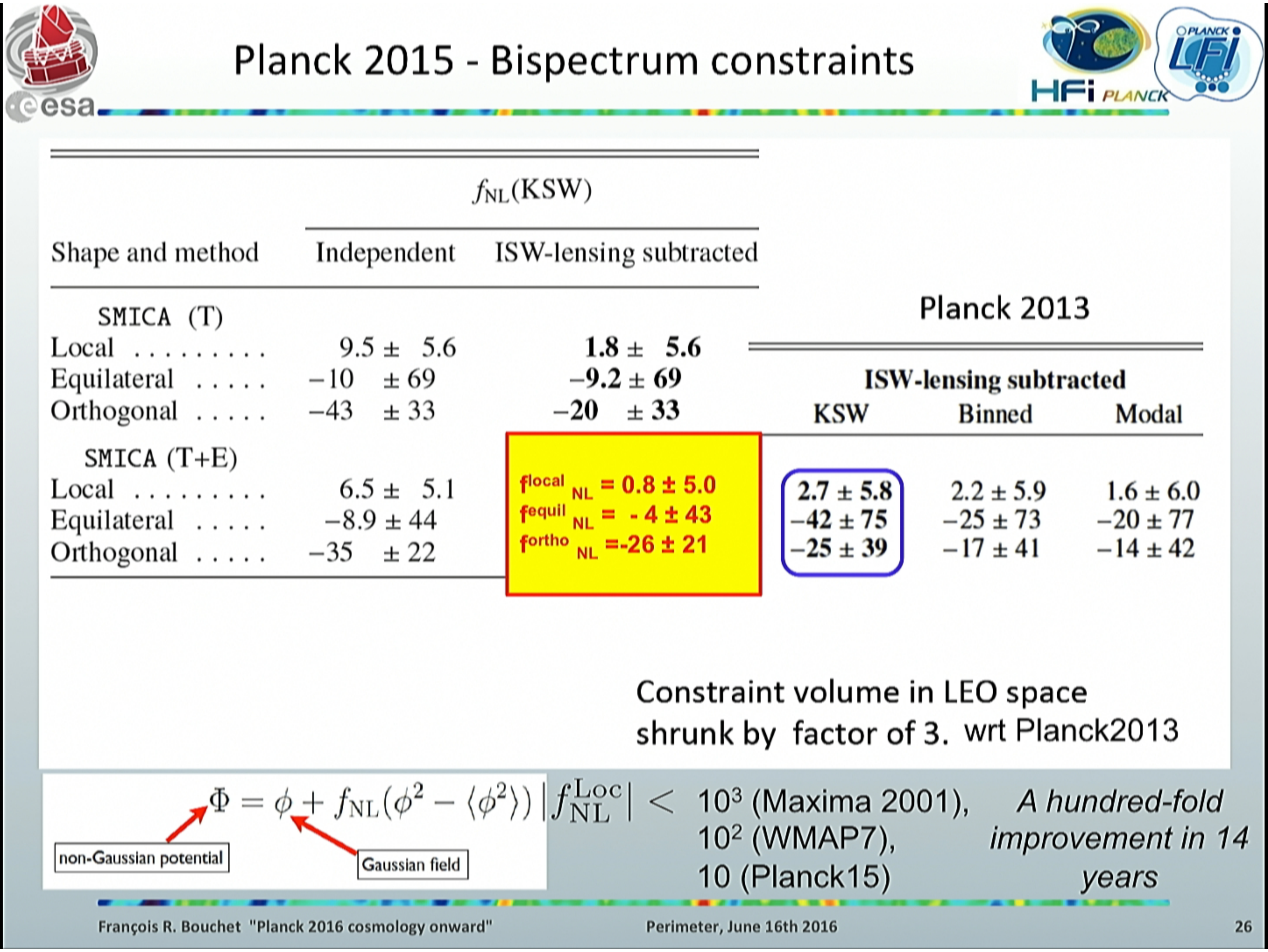
non-Gaussian potential

Gaussian field

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

A hundred-fold improvement in 14 years

François R. Bouchet "Planck 2016 cosmology onward" Perimeter, June 16th 2016 26



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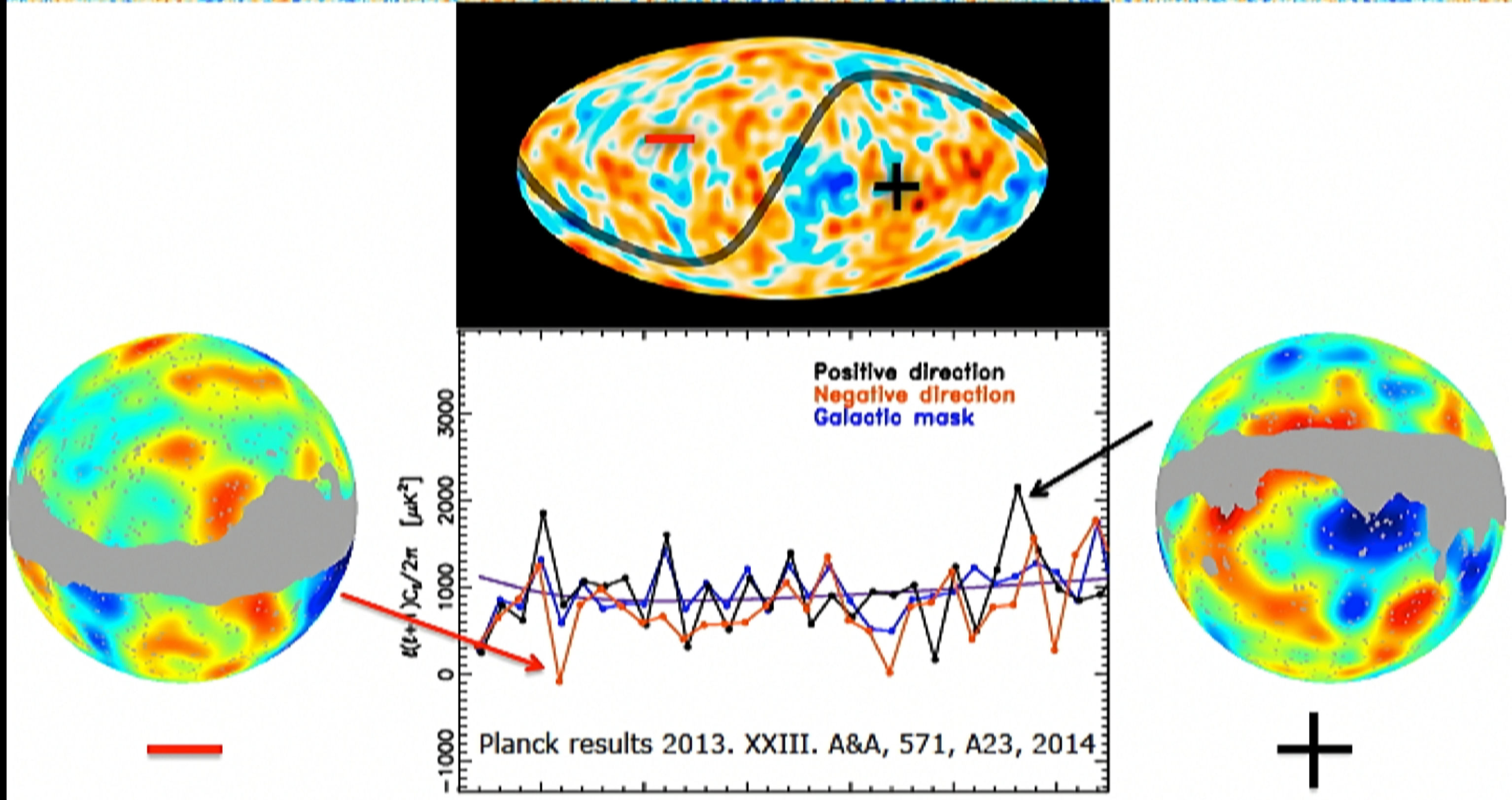
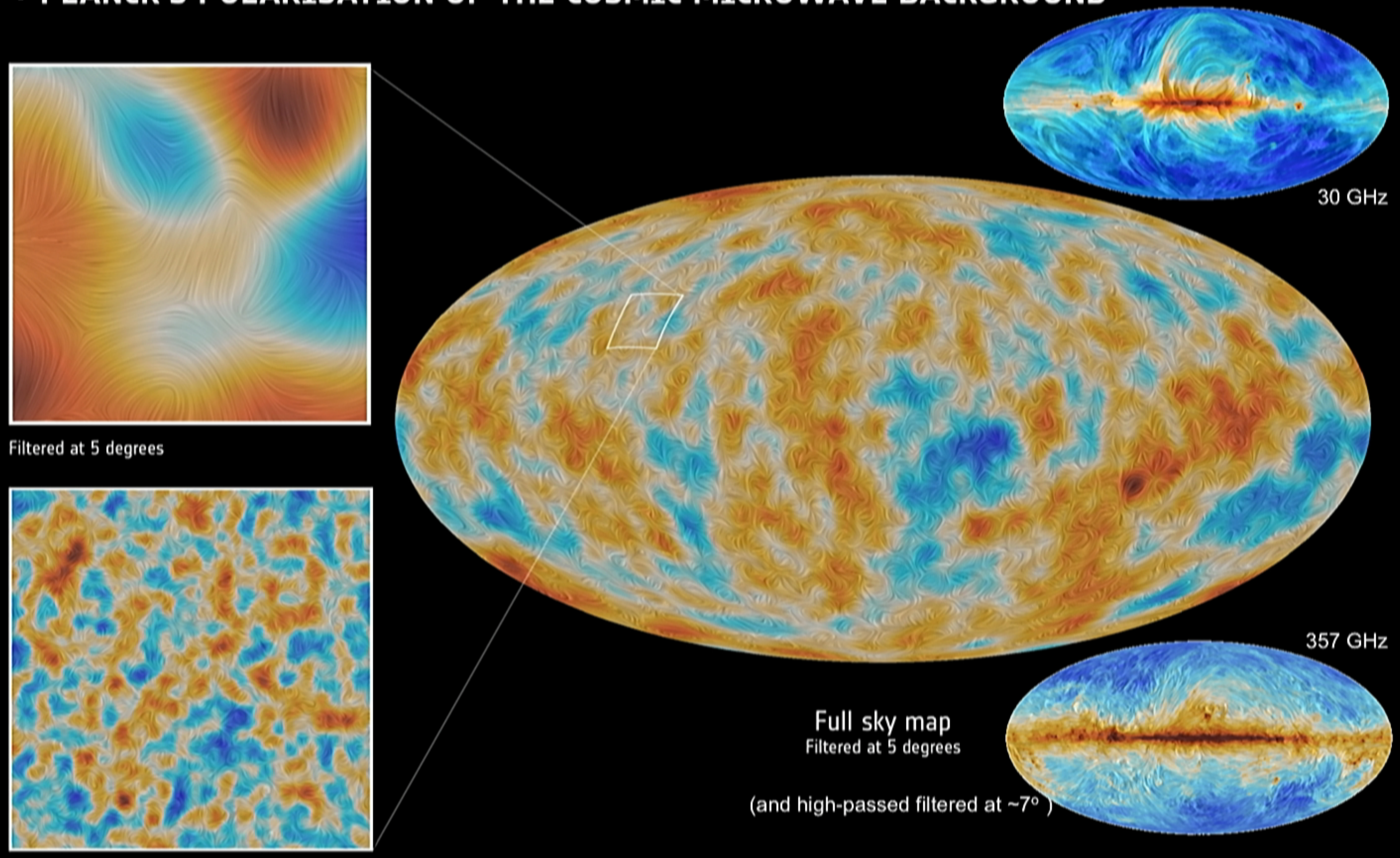
Power asymmetry in *Planck* 2013 nominal mission data



Planck results 2013. XXIII. A&A, 571, A23, 2014

Large scale feature in 2015 full mission data are very similar to those in 2013 nominal mission data

→ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND

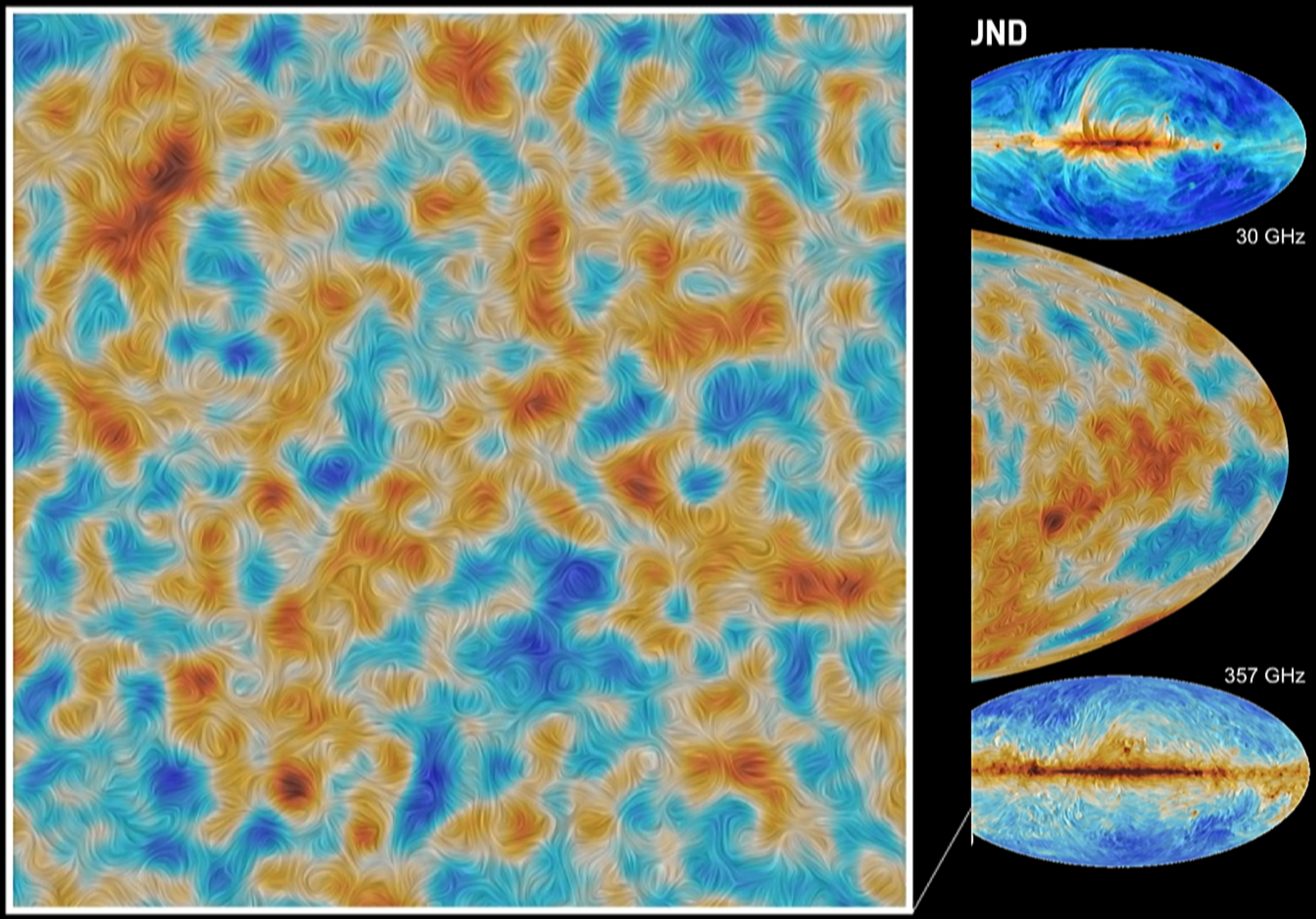


Filtered at 5 degrees

Filtered at 20 arcminutes

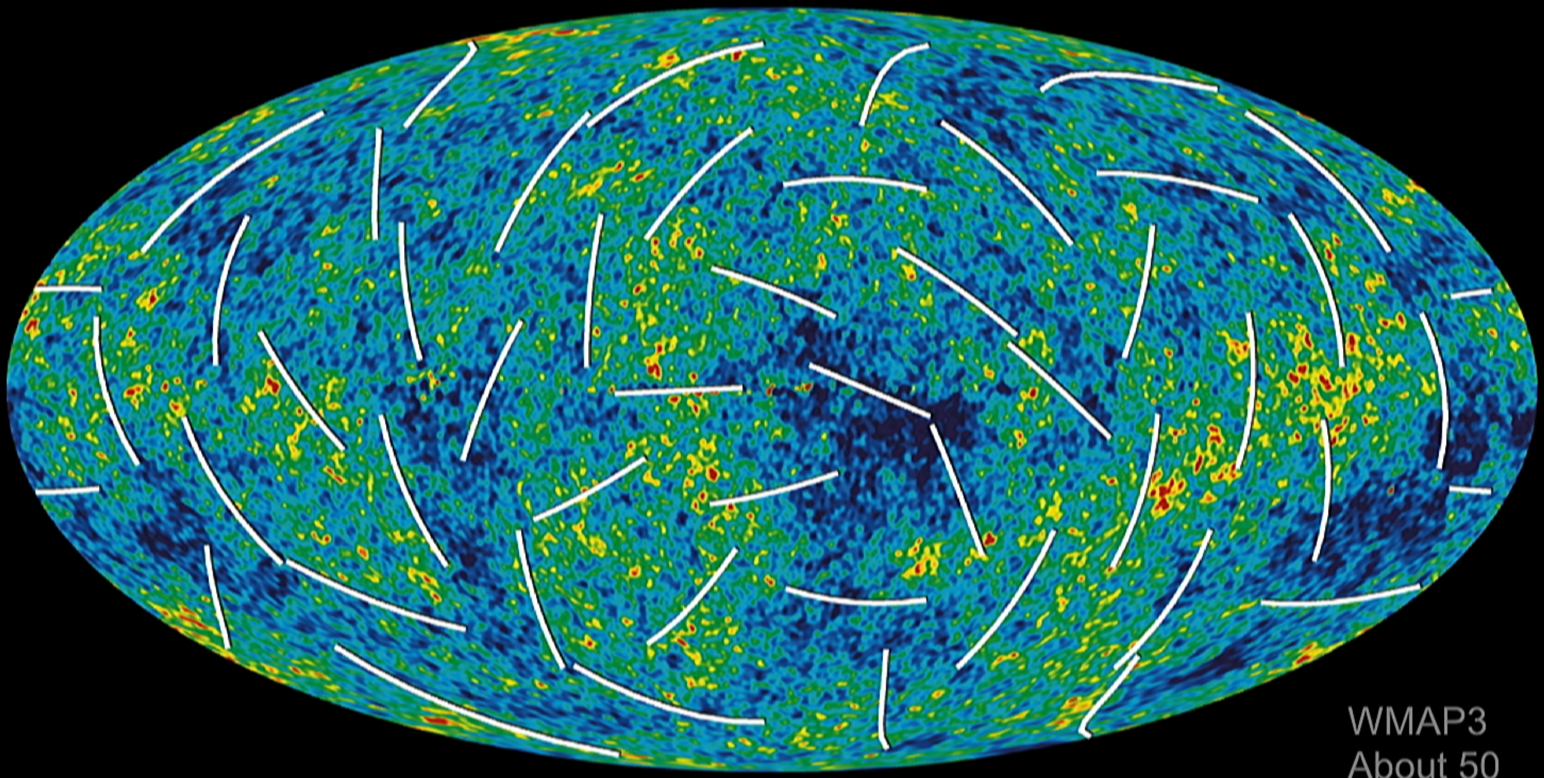
Full sky map
Filtered at 5 degrees

(and high-passed filtered at ~7°)



Filtered at 20 arcminutes

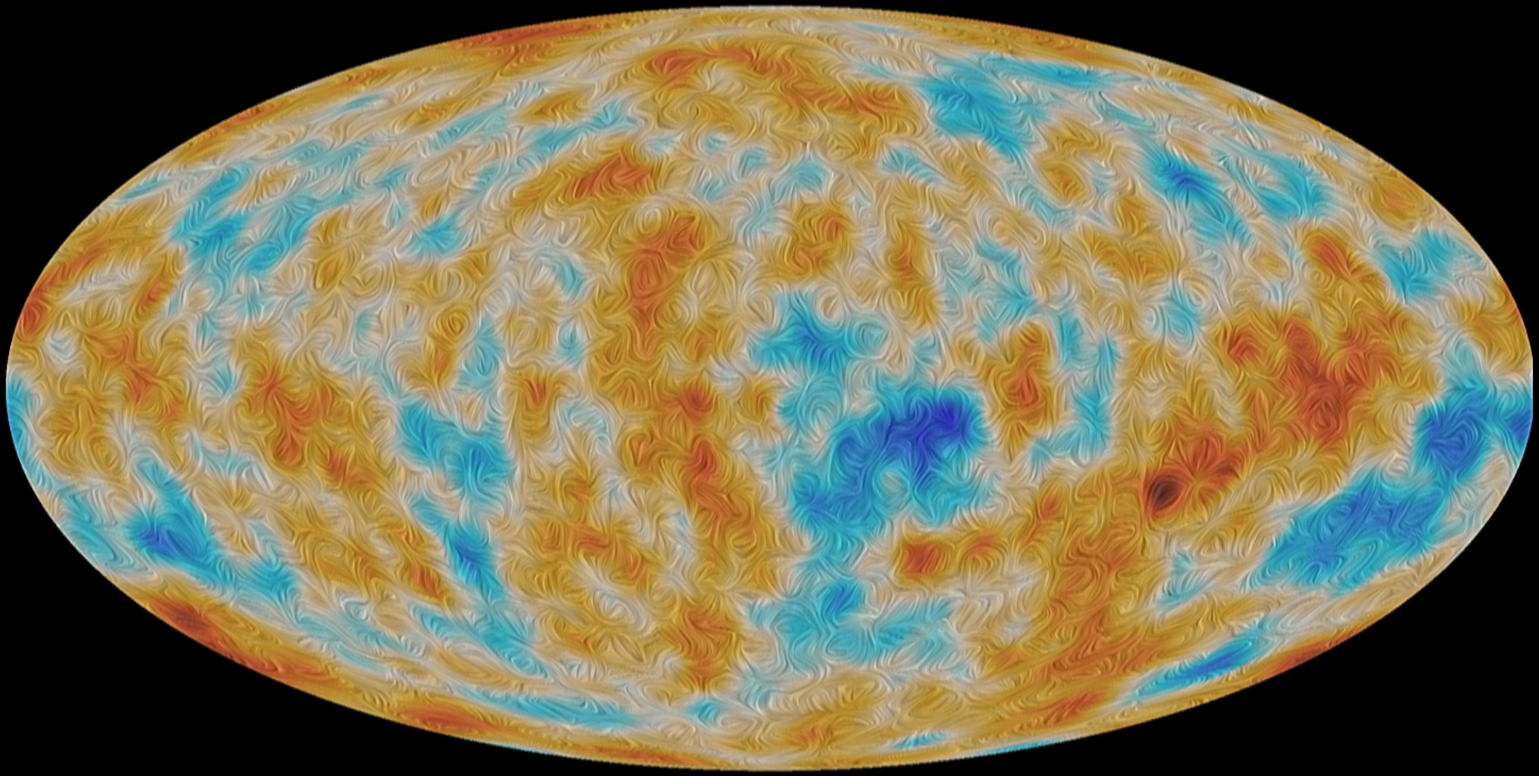
What we already knew



WMAP3
About 50
locations?

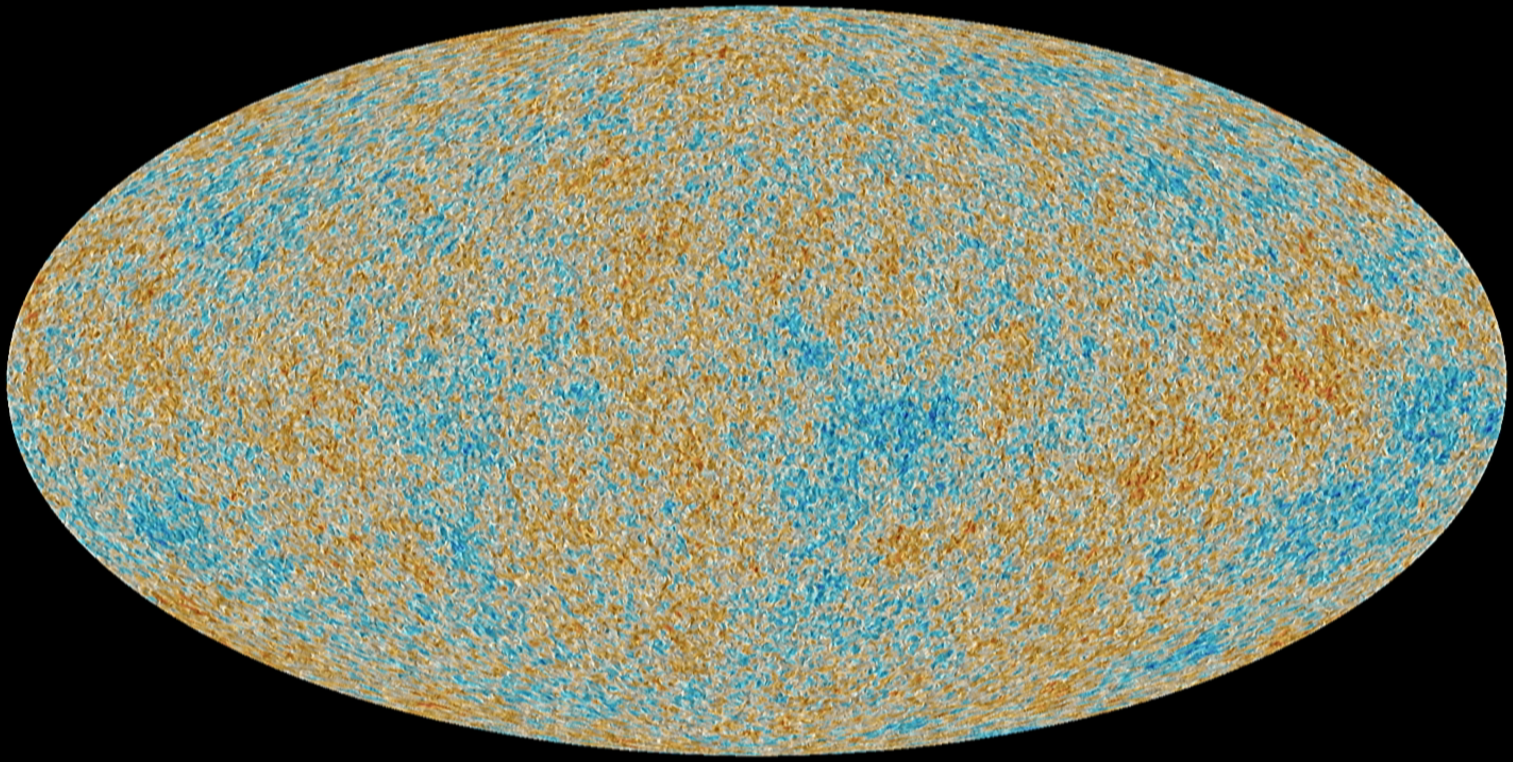
The Planck 2015 CMB polarisation sky

at 5 degree resolution



The Planck 2015 CMB polarisation sky

at 5 arc minute resolution



The Planck 2015 CMB polarisation sky

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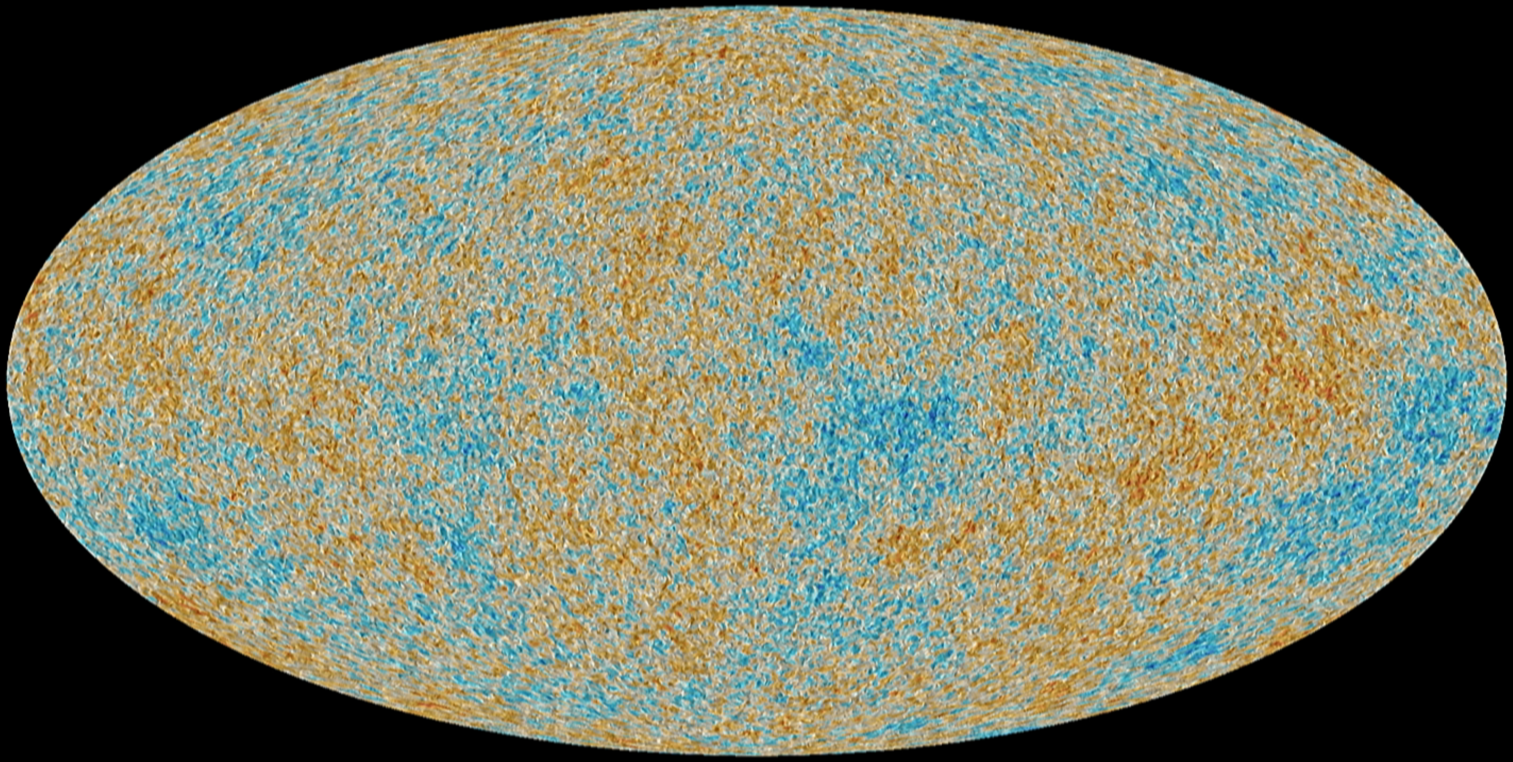
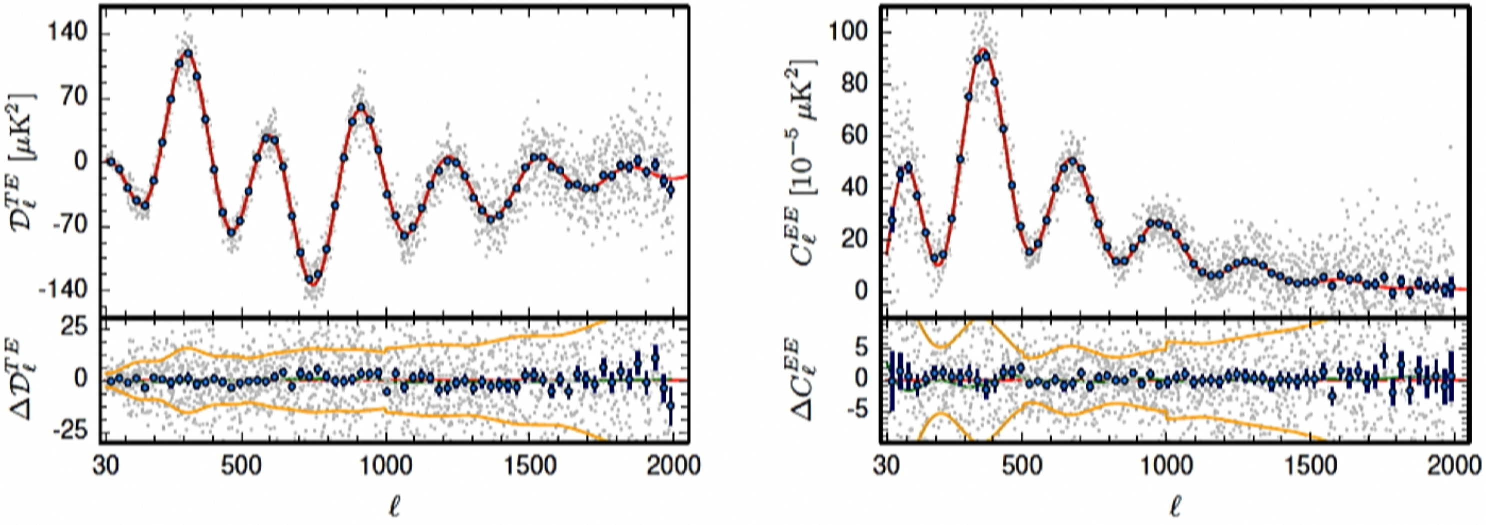
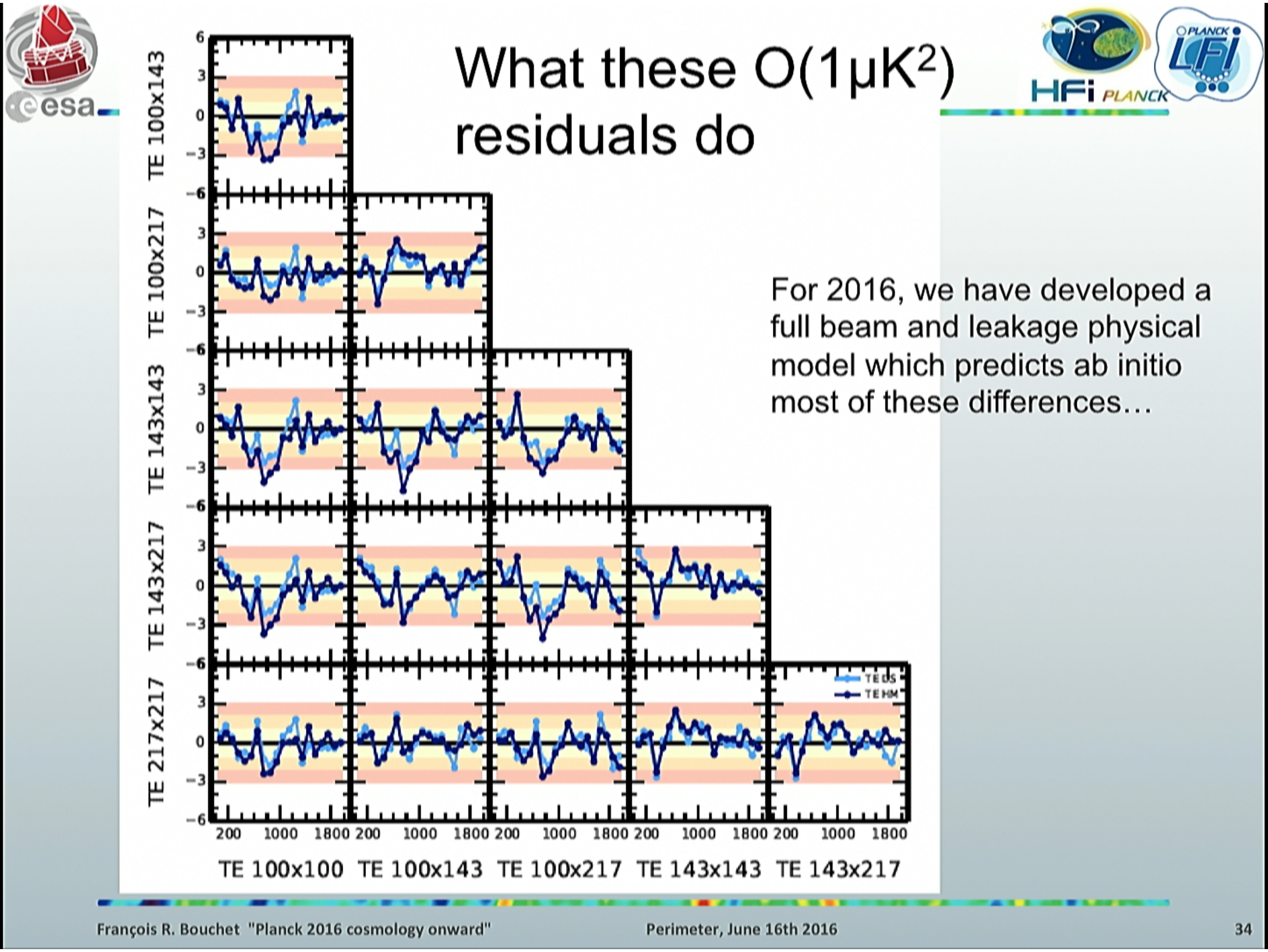


Planck 2015 - TE & EE spectra



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).



What these O(1μK^2) residuals do

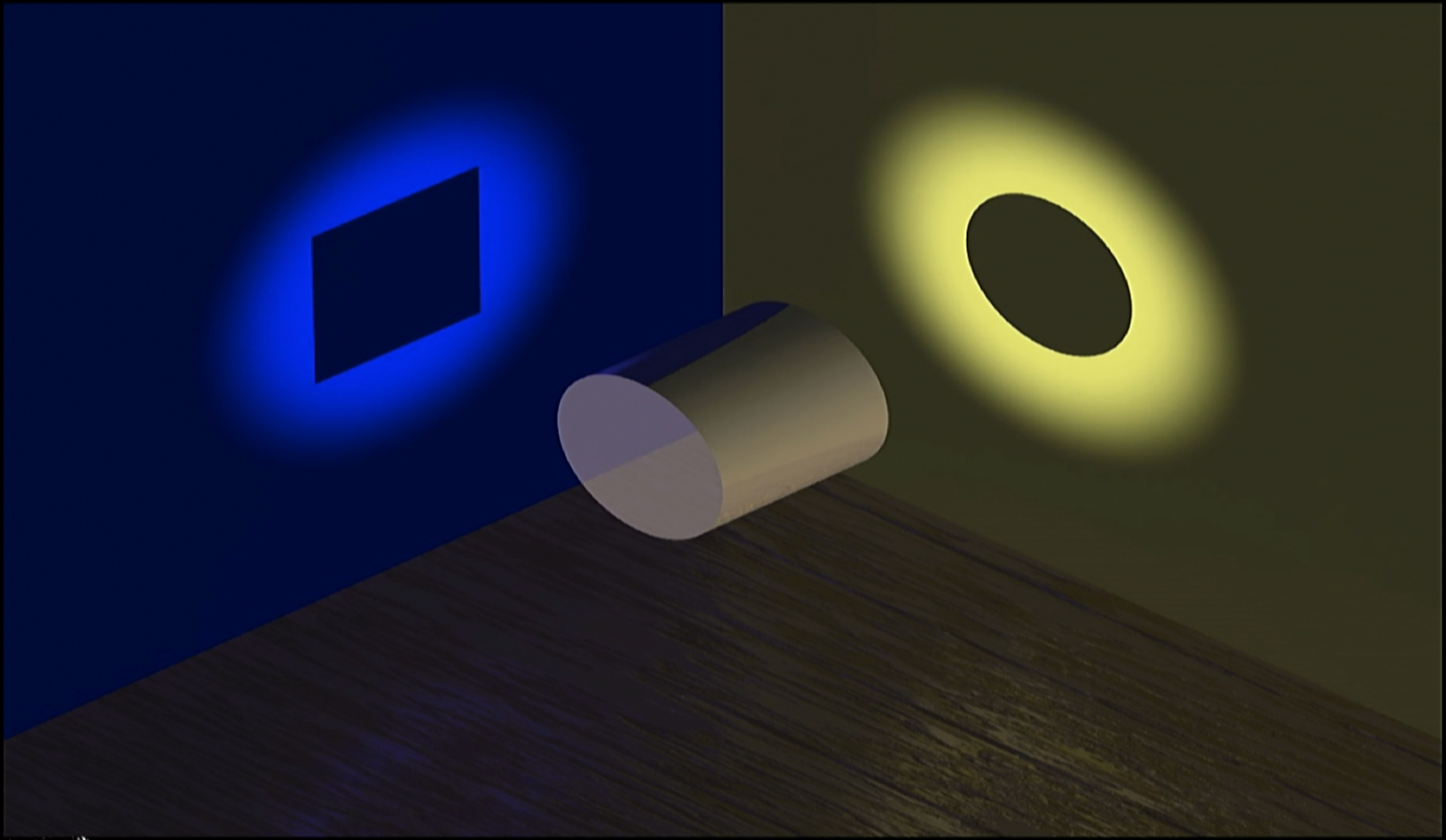
For 2016, we have developed a full beam and leakage physical model which predicts ab initio most of these differences…

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]

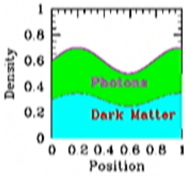
This was not granted!

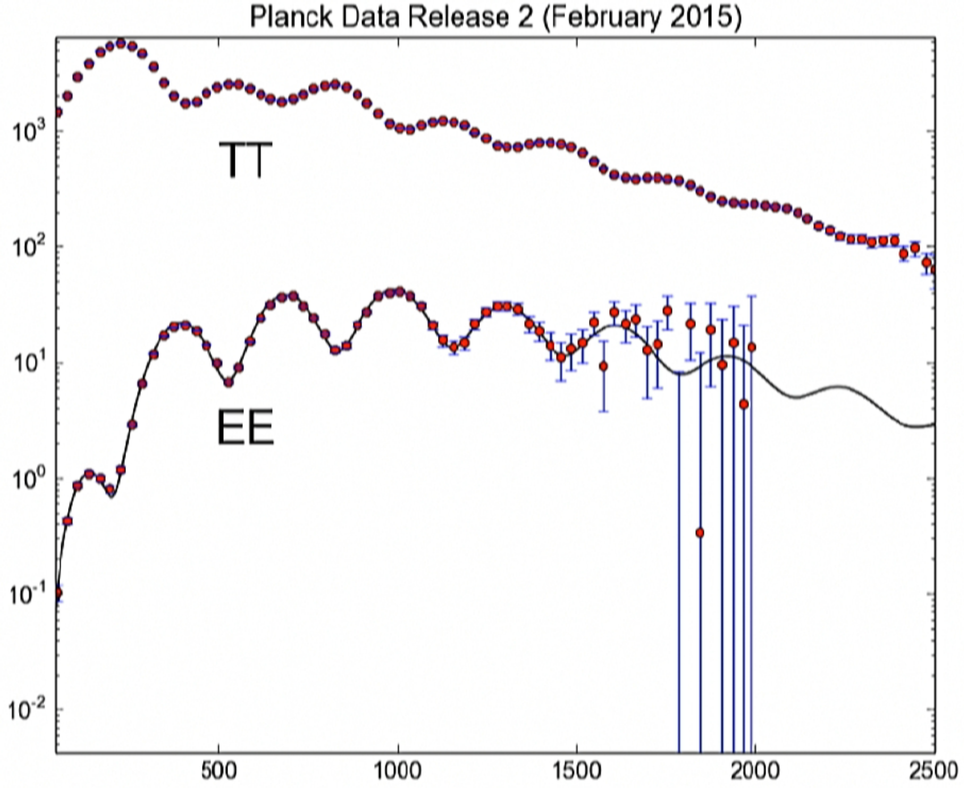


And it further constrains potential deviations from the base tilted LCDM model/physics

Adiabaticity ?

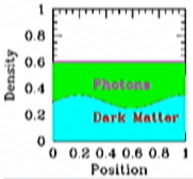
Adiabatic IC



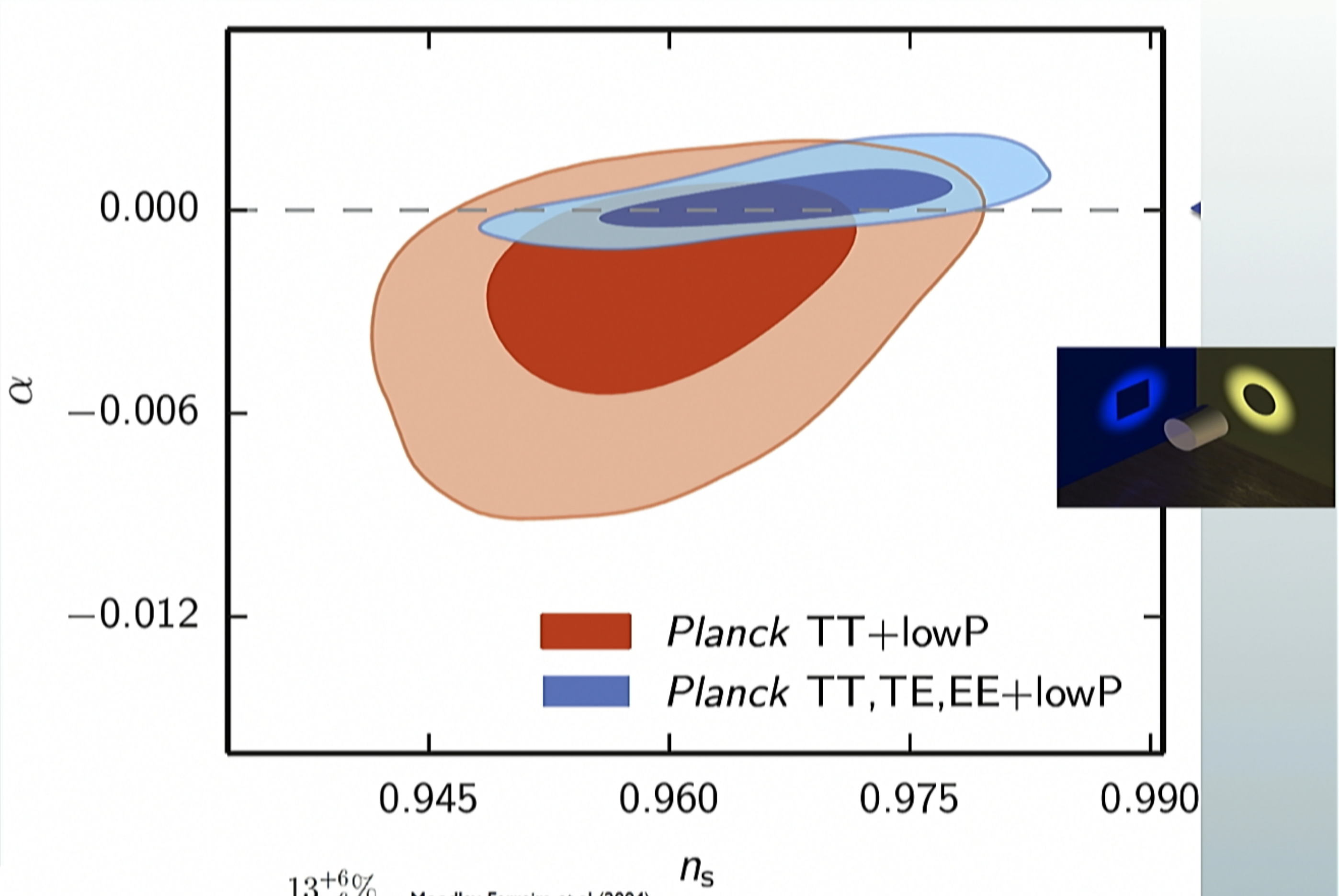


(Data: Planck Legacy Archive)

Isocurvature IC



Isocurvature modes fraction

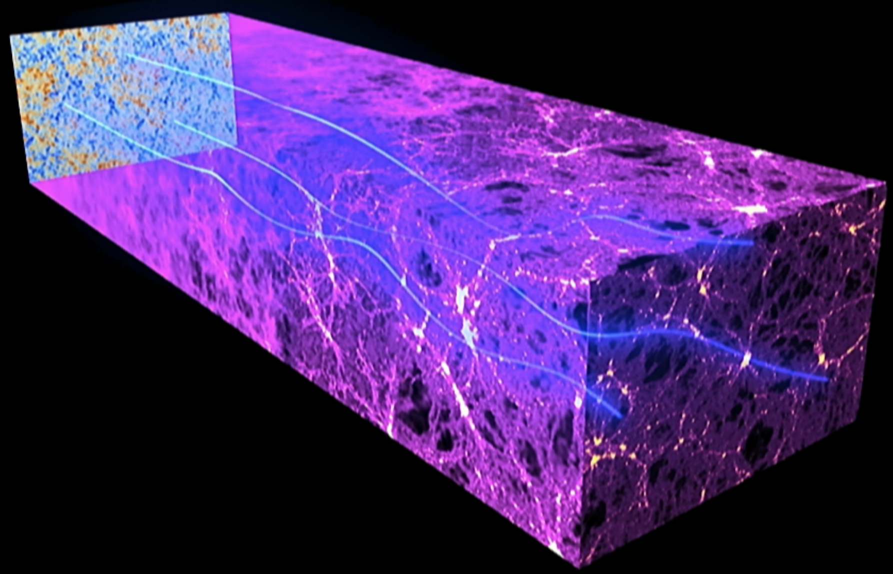


Percentage of isocurvature: $13^{+6}_{-6}\%$ Moodley, Ferreira et al (2004)

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

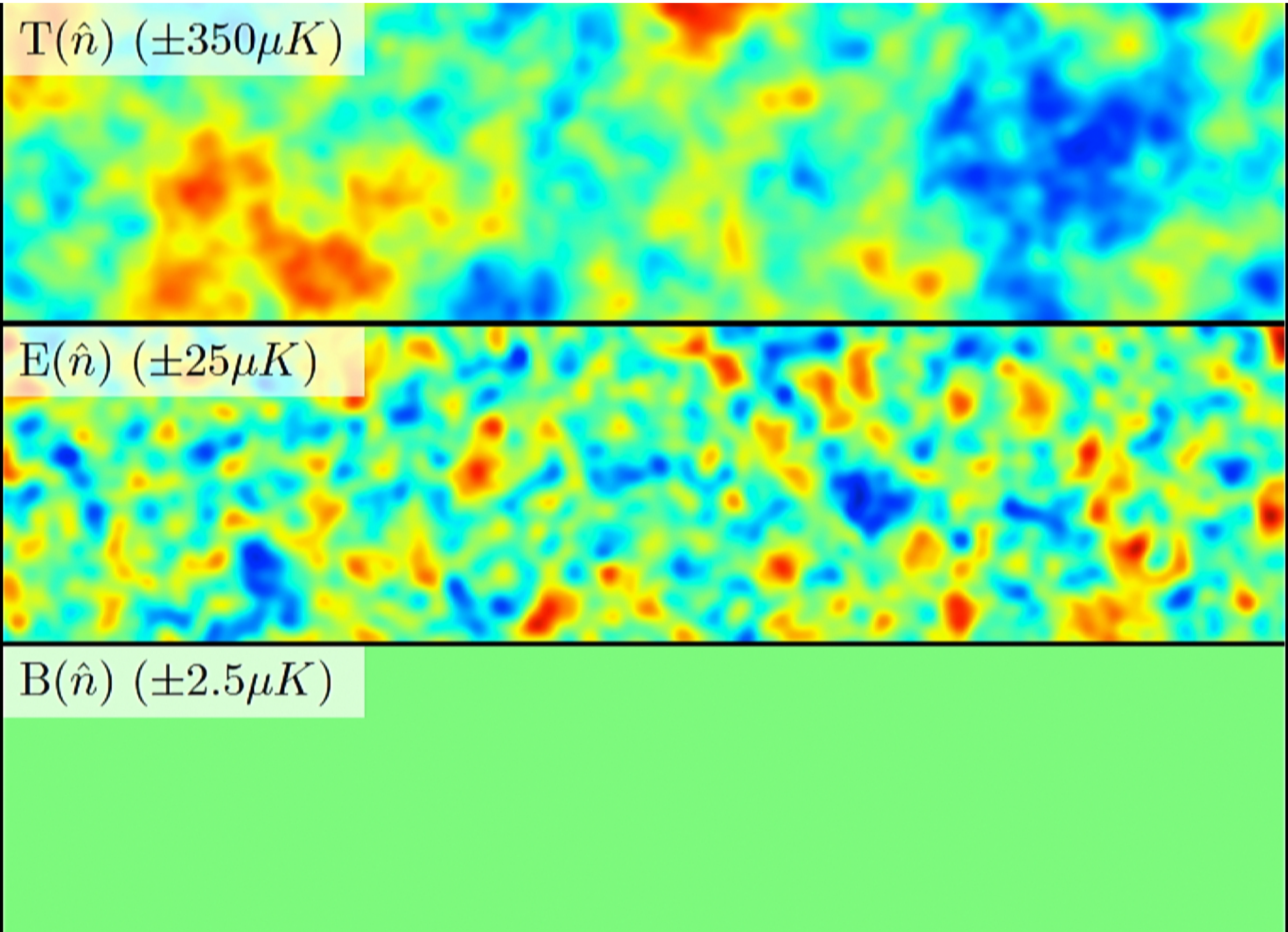
GRAVITATIONAL LENSING DISTORTS IMAGES

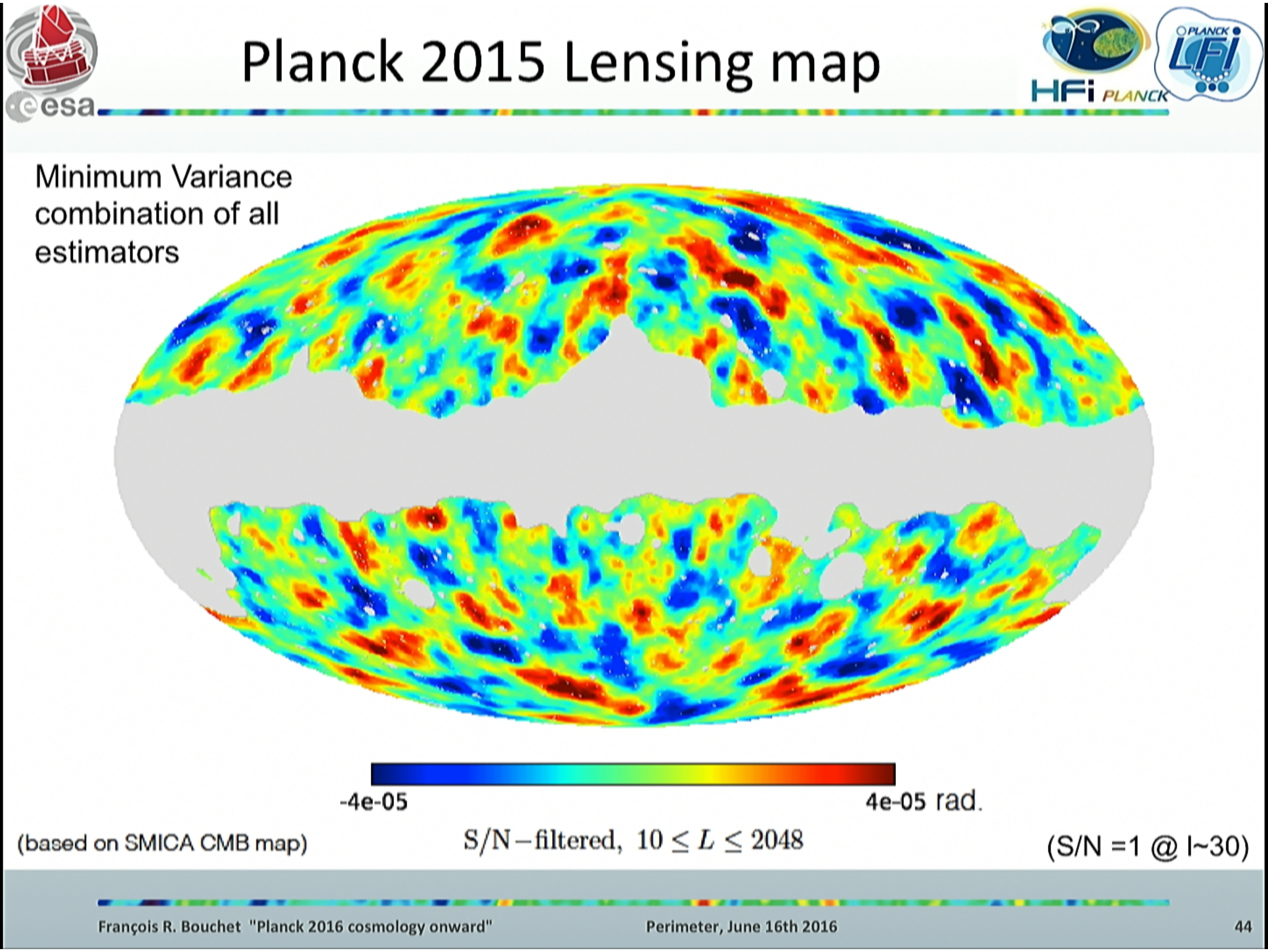
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



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

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


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



Planck 2015 Lensing map

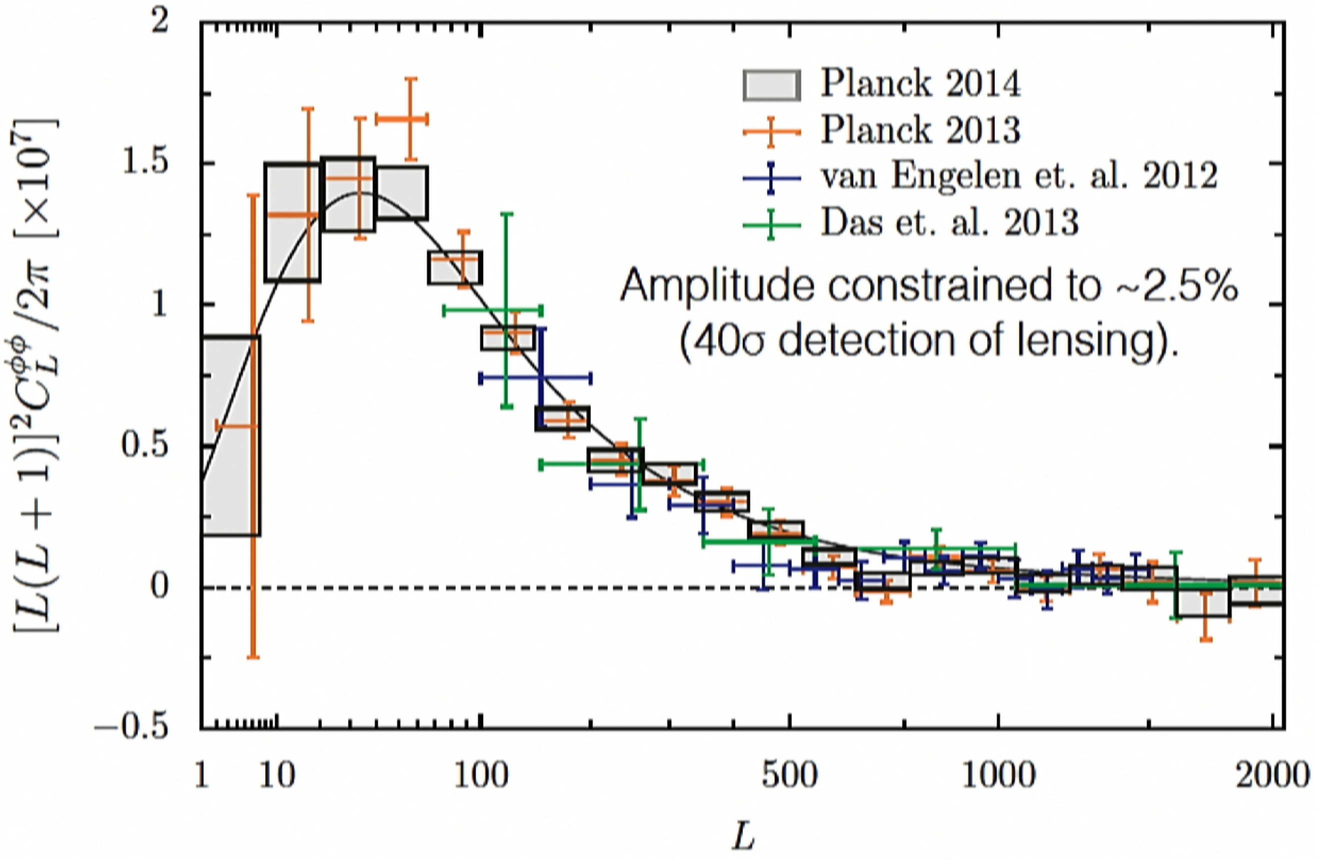
Minimum Variance combination of all estimators

(based on SMICA CMB map)

S/N−filtered, $10 \le L \le 2048$

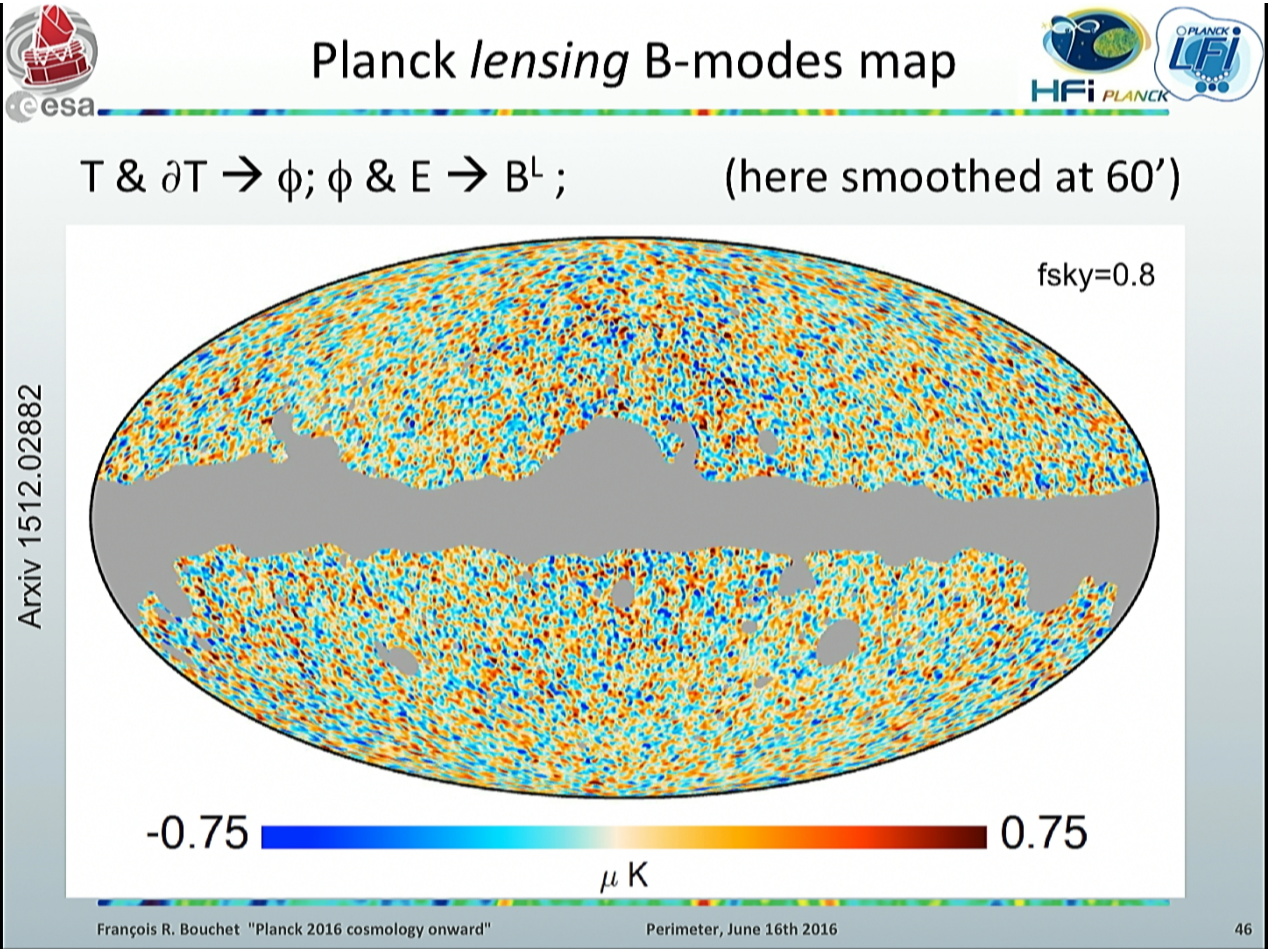
(S/N =1 @ l~30)

Lensing power spectrum



Amplitude constrained to ~2.5% (40σ detection of lensing).

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



Planck *lensing* B-modes map

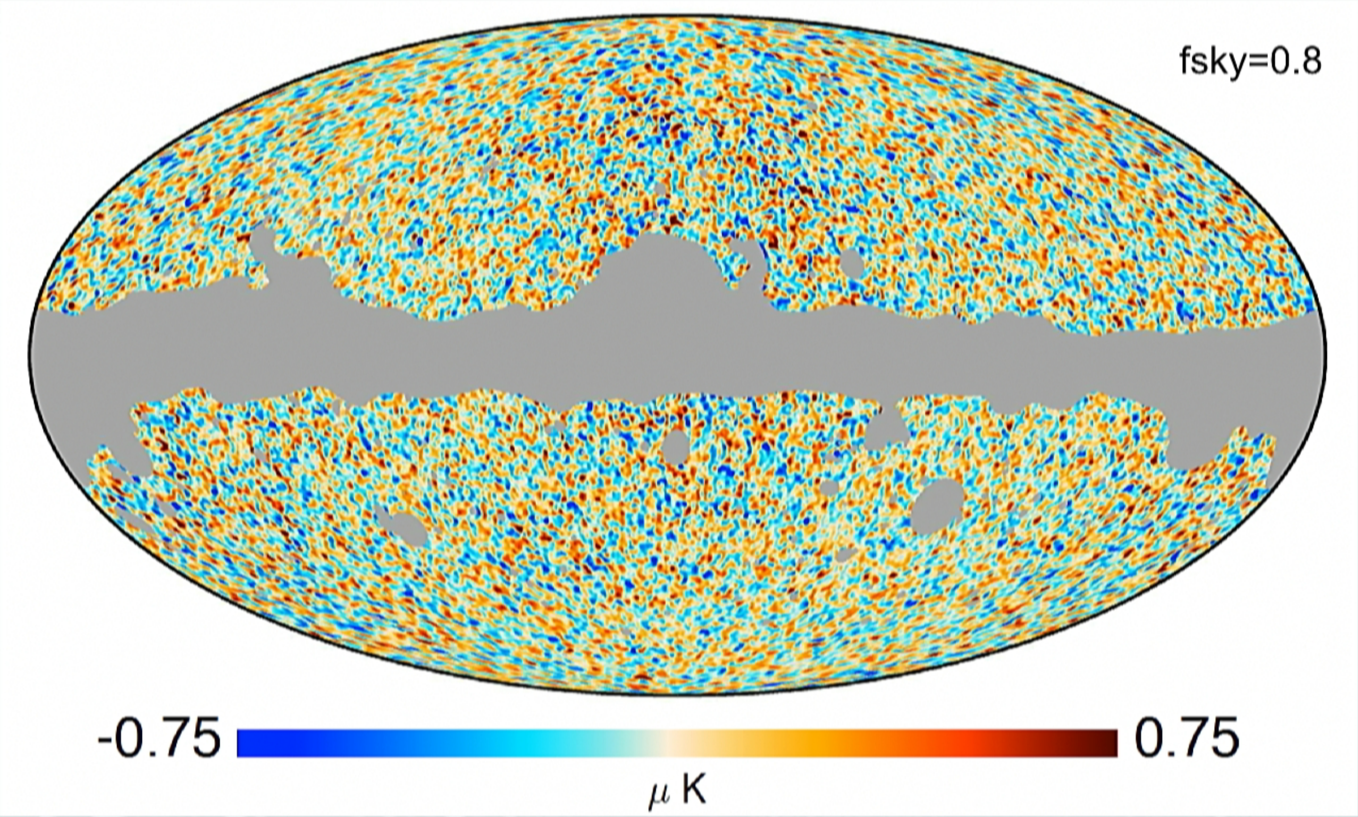
T & $\partial T \rightarrow \phi$; ϕ & $E \rightarrow B^L$; (here smoothed at 60')

Arxiv 1512.02882

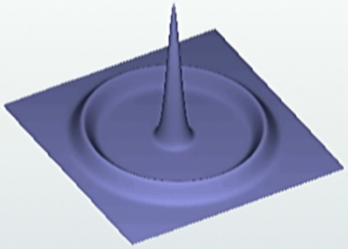
Planck *lensing* B-modes map

$T \;\&\; \partial T \rightarrow \phi;\ \phi \;\&\; E \rightarrow B^L$; (here smoothed at 60')

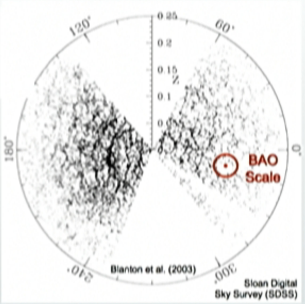
Arxiv 1512.02882

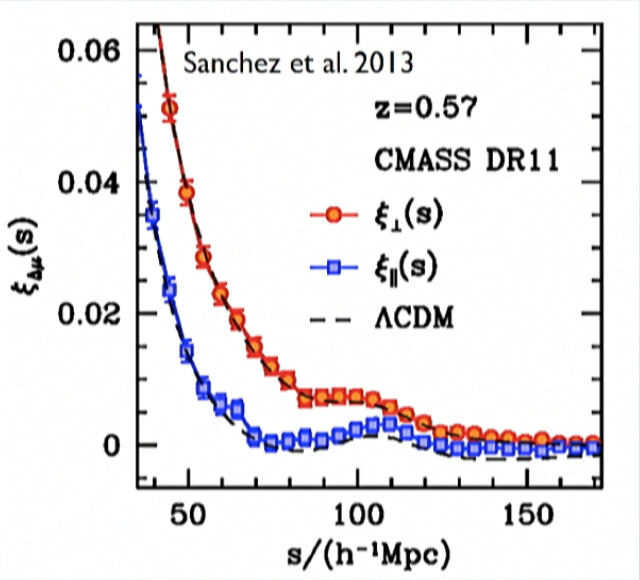


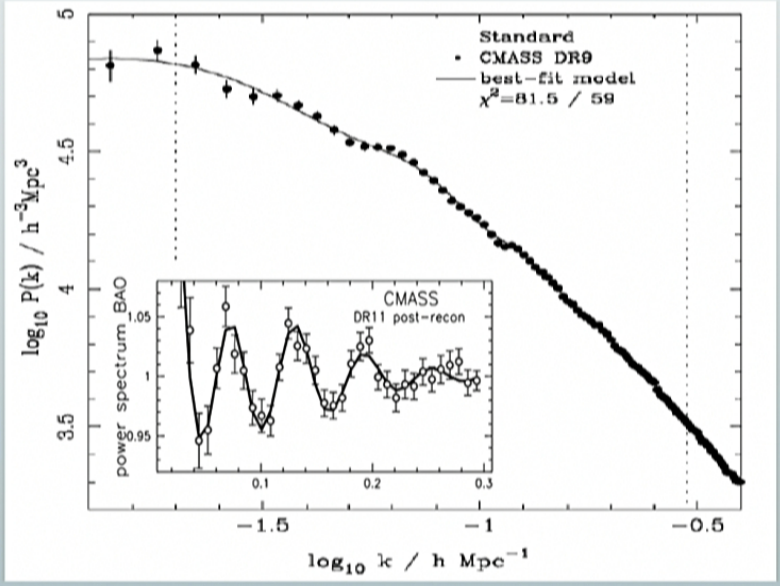
BAO: correlation function & power spectrum



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

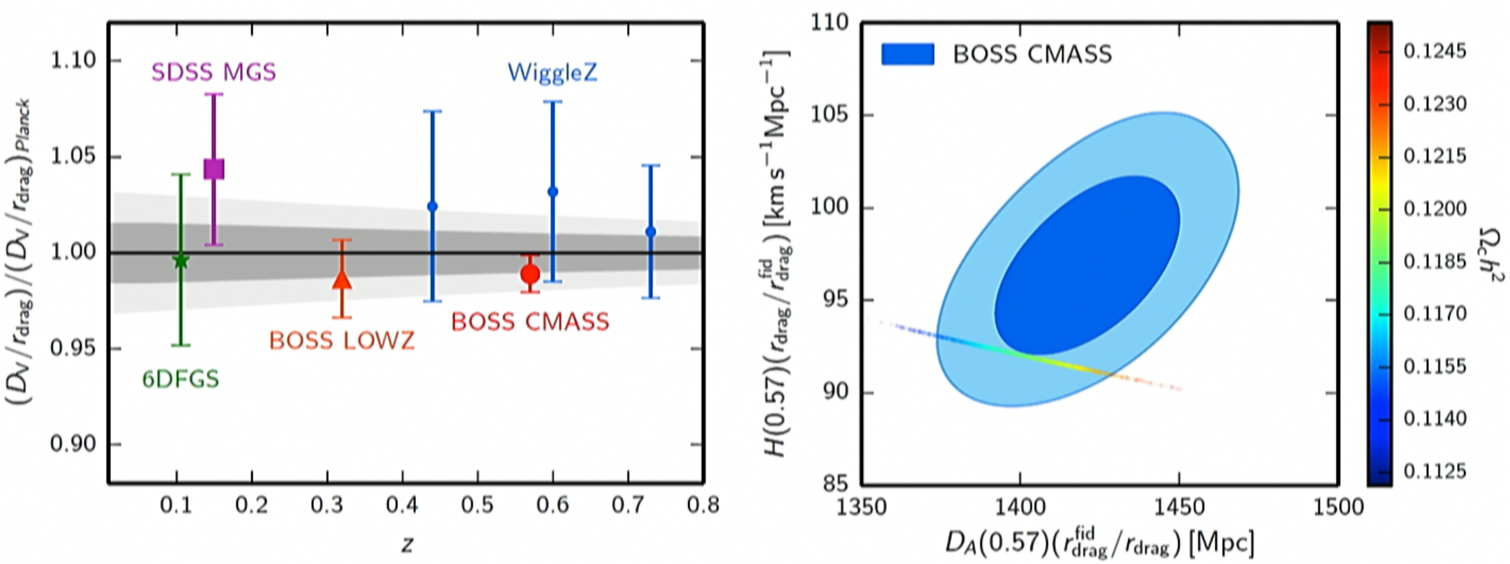






Baryonic Acoustic Oscillations / Planck

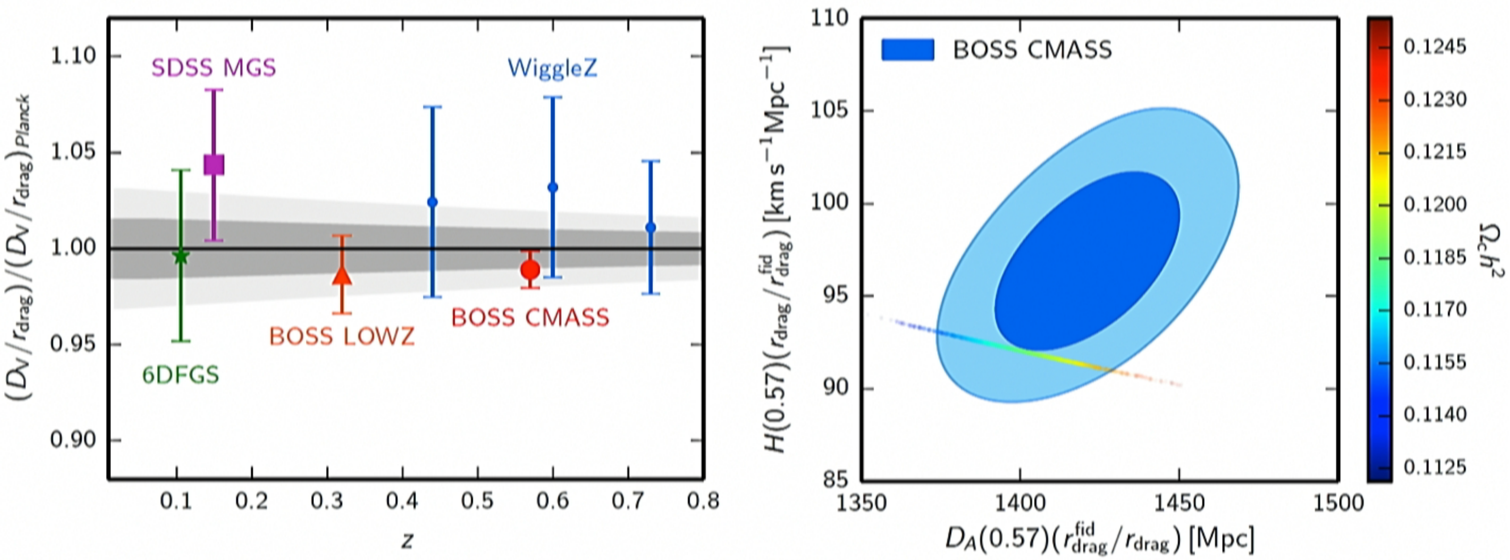
Grey band is Planck TT+LowP 1(2) sigma range



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

Baryonic Acoustic Oscillations / Planck

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



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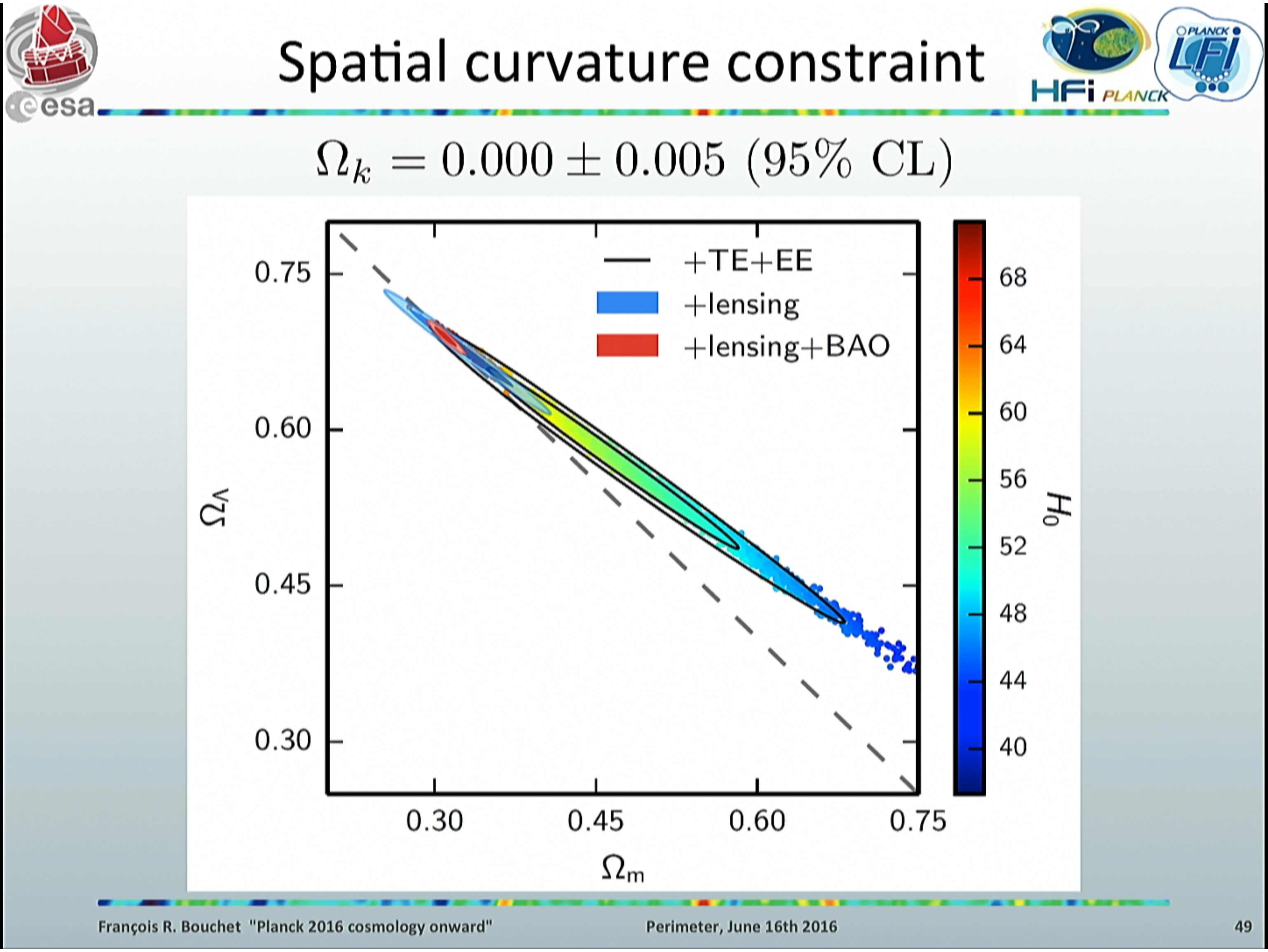
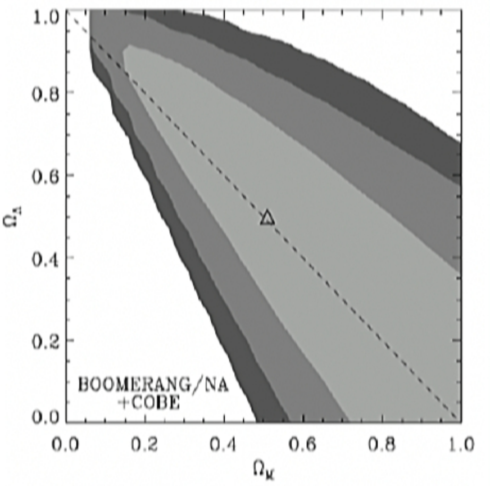


Spatial curvature constraint

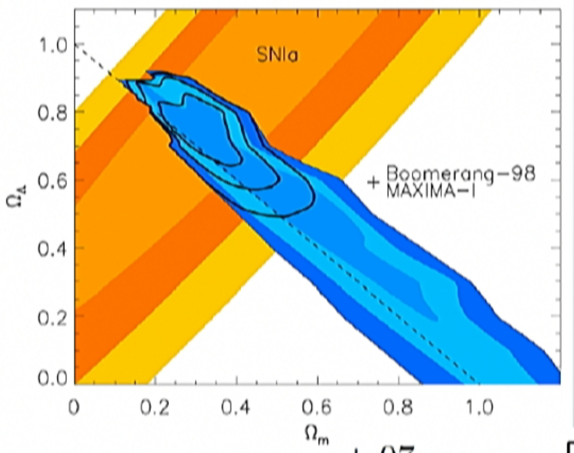
$$\Omega_k = 0.000 \pm 0.005 \ (95\% \ \mathrm{CL})$$

Spatial curvature constraint



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

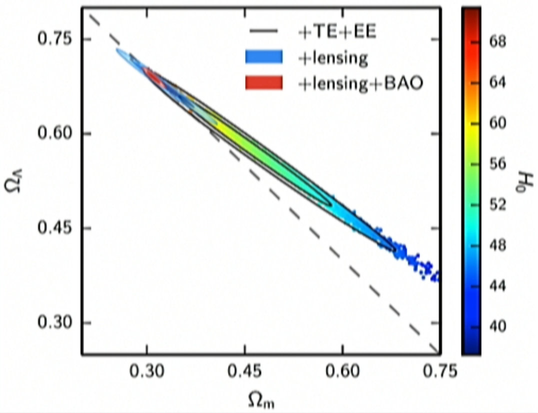
Melchiorri et al. 2000



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

Jaffe et al. 2001

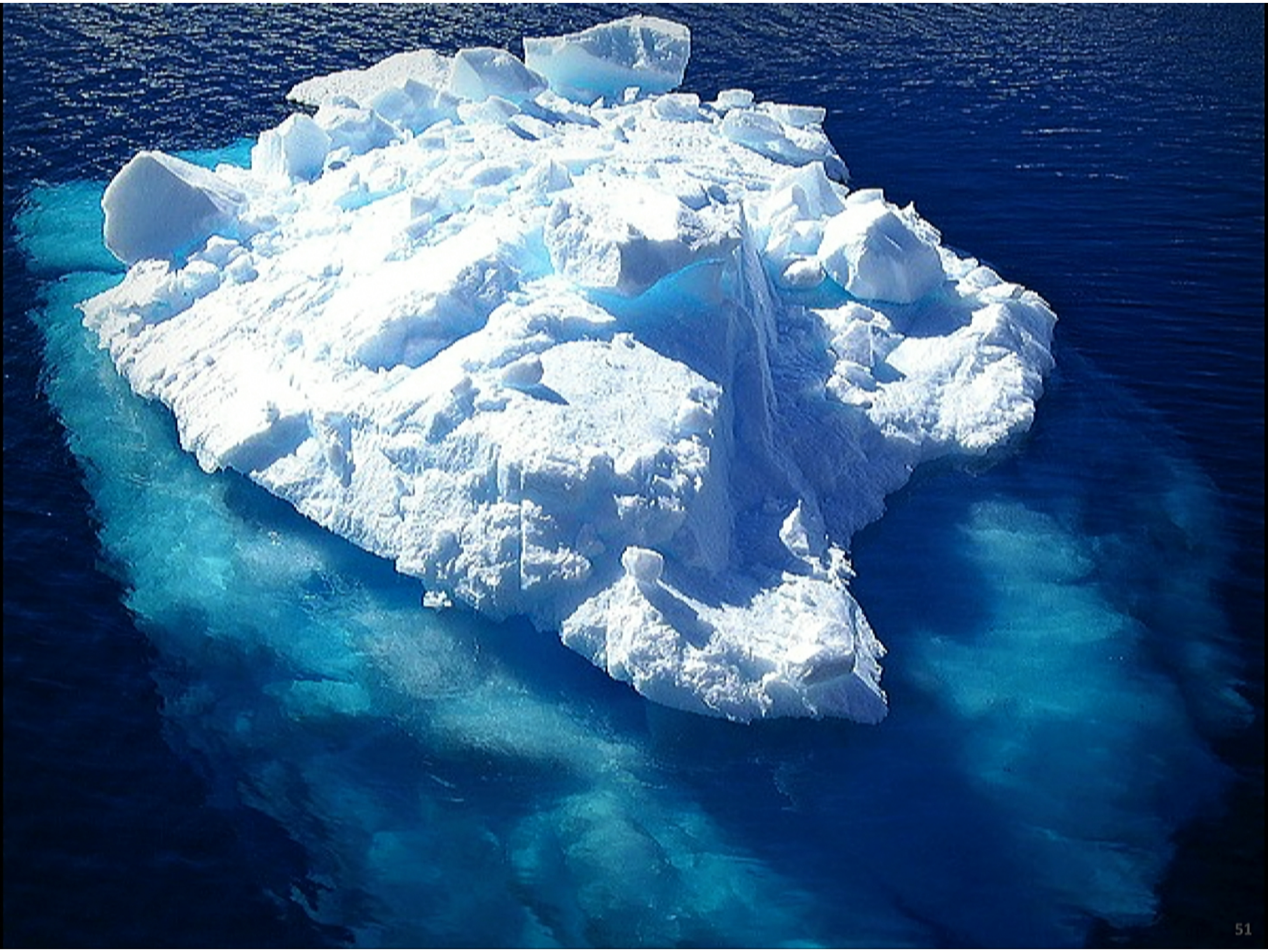
Note the change of axes
For Planck below



Planck 2015

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

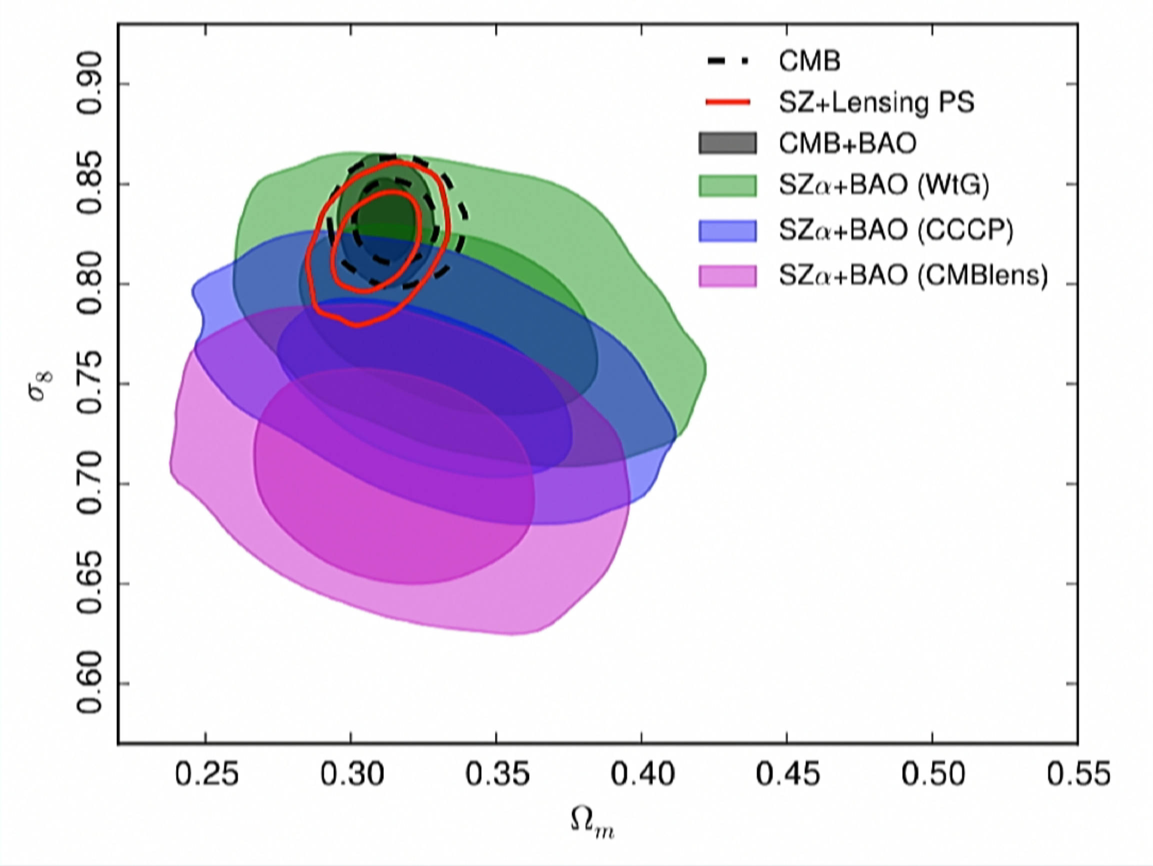
A hundred-fold improvement in 15 years



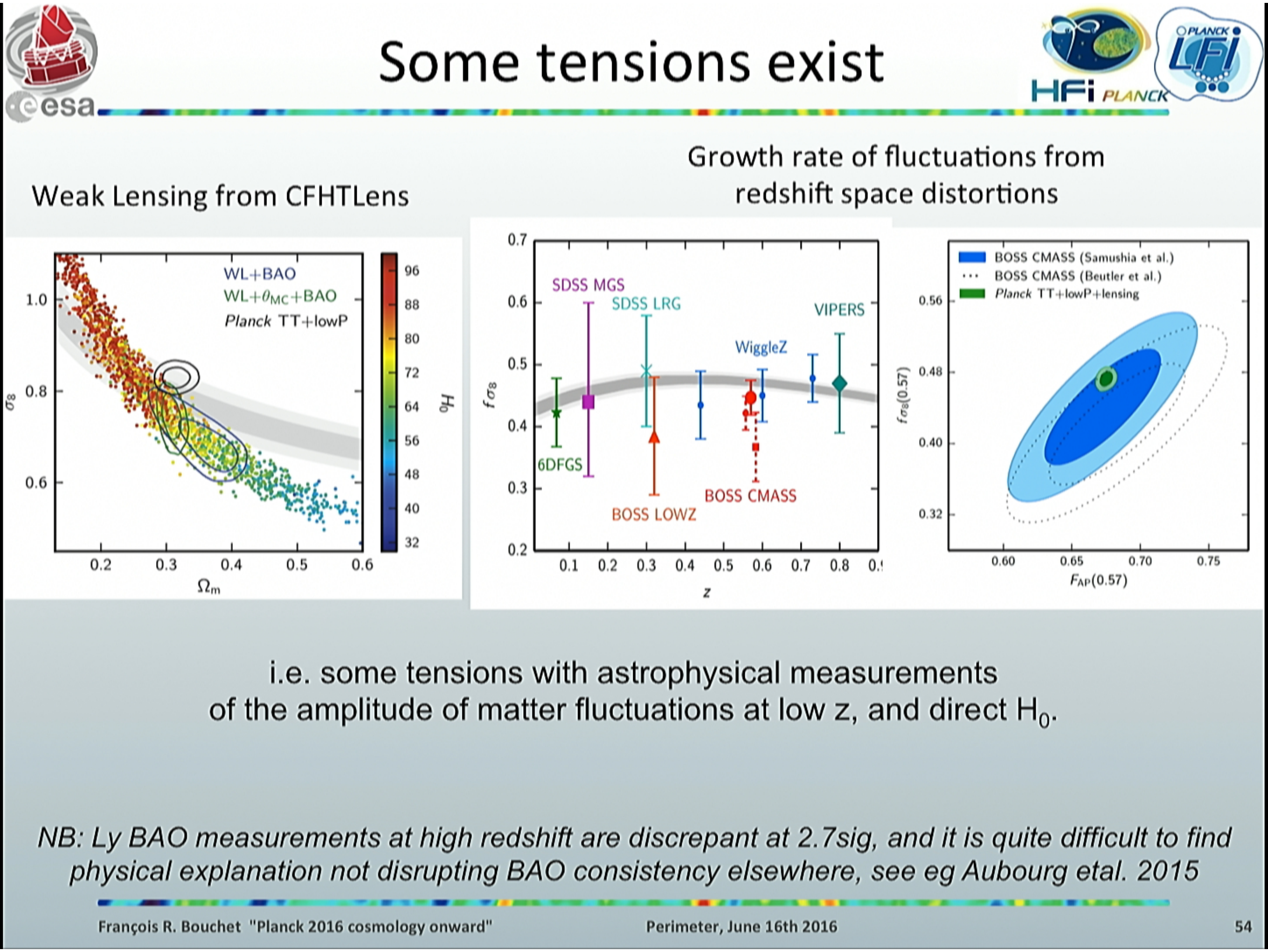
Standard cosmological model - LCDM

- 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 <u>many</u> 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 ($A_{2s \rightarrow 1}$, 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



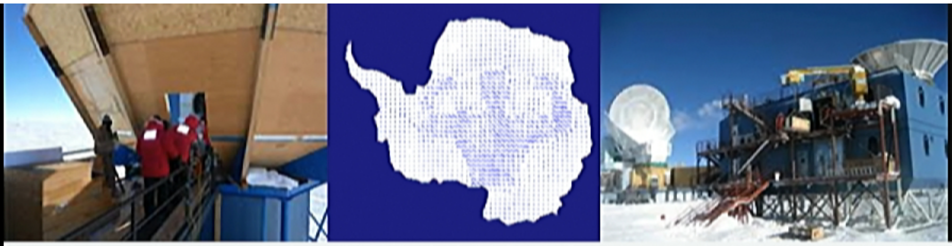
Some tensions exist

Weak Lensing from CFHTLens

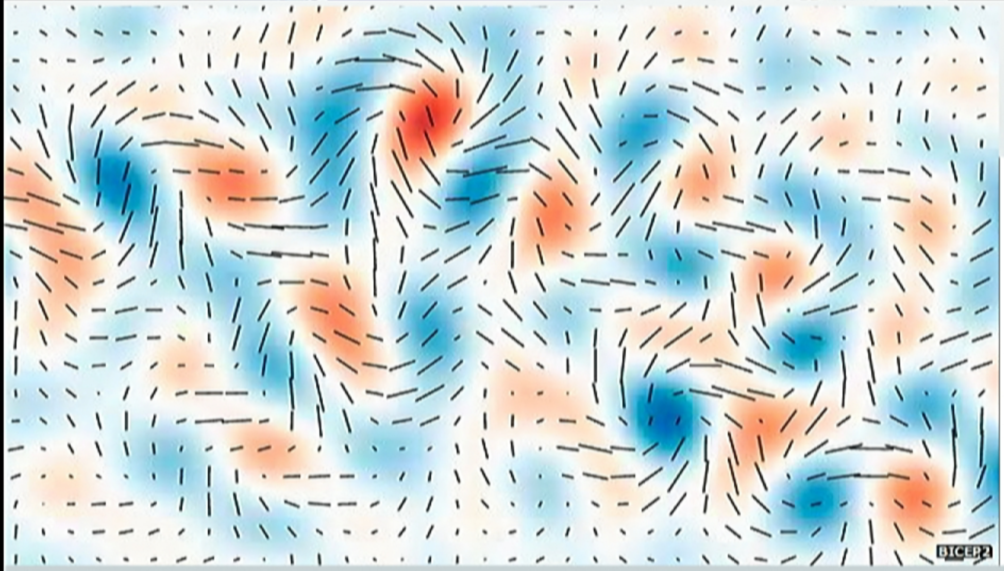
Growth rate of fluctuations from redshift space distortions

i.e. some tensions with astrophysical measurements of the amplitude of matter fluctuations at low z, and direct H_0.

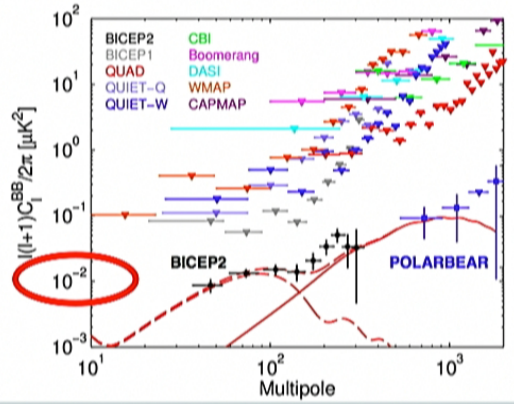
NB: Ly BAO measurements at high redshift are discrepant at 2.7sig, and it is quite difficult to find physical explanation not disrupting BAO consistency elsewhere, see eg Aubourg etal. 2015



BICEP2



March 17th 2014

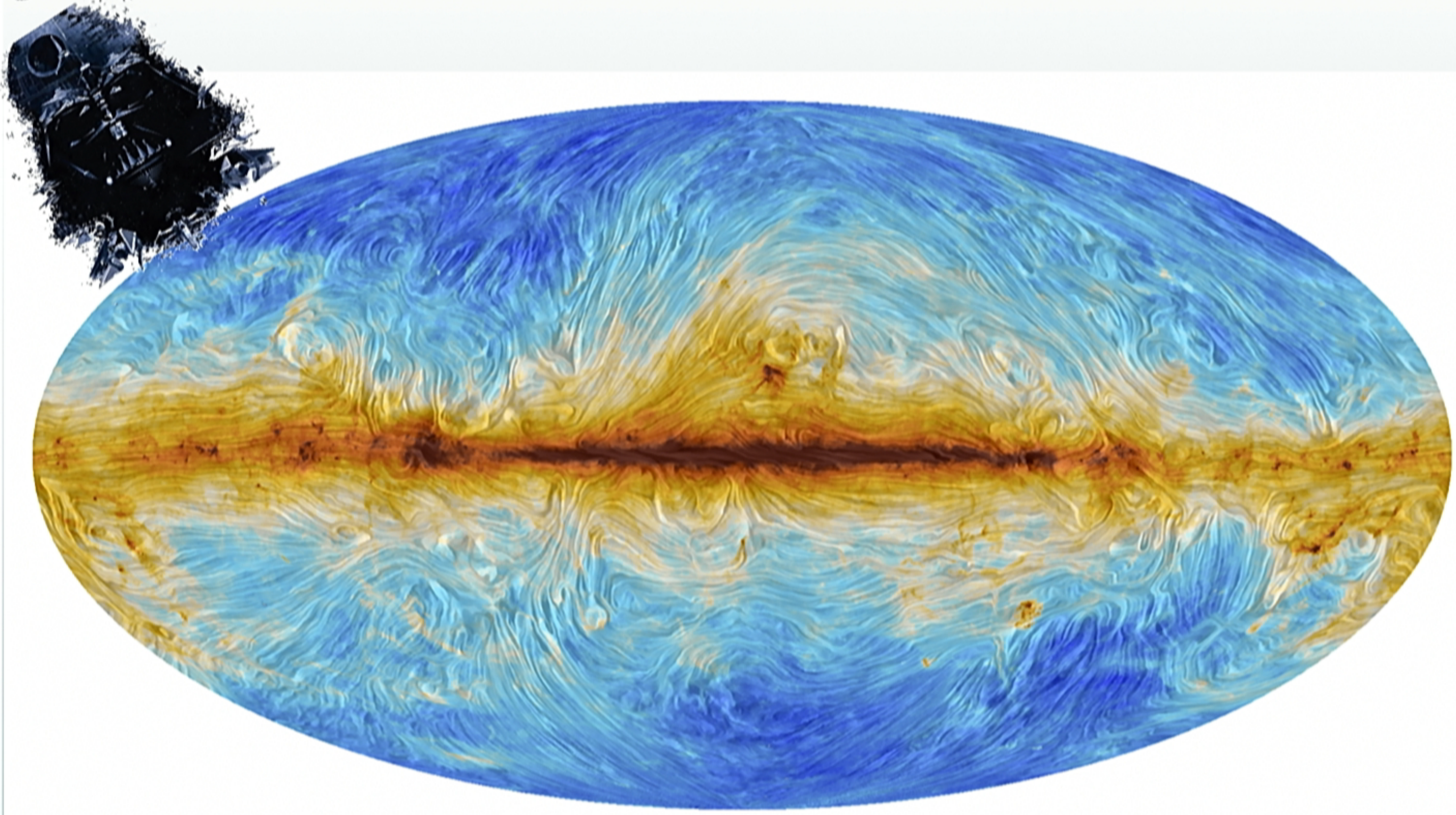


The world of physics is taken aback by an extraordinary result from a beautiful experiment:

The search for primordial gravitationnal waves is over.

It is r=0.2 and it is 5 sigma!

Planck 353GHz reveals the Galactic magnetic field

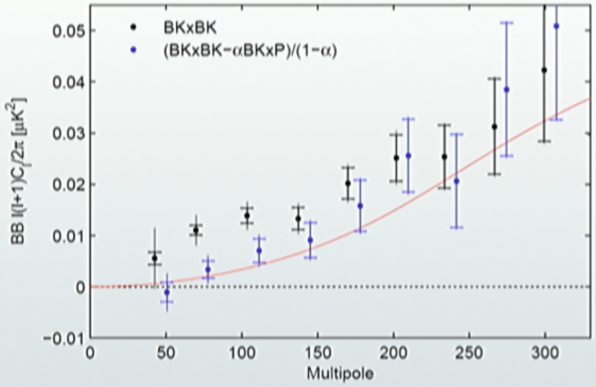


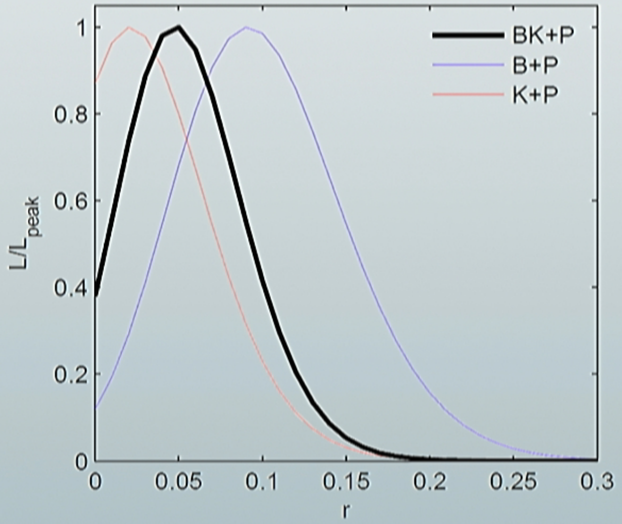
Planck X (Bicep2 & Keck)

- 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., $k=0.05\mathrm{Mpc}^{-1}$)
  (r <0.07 w. new BK2 data)

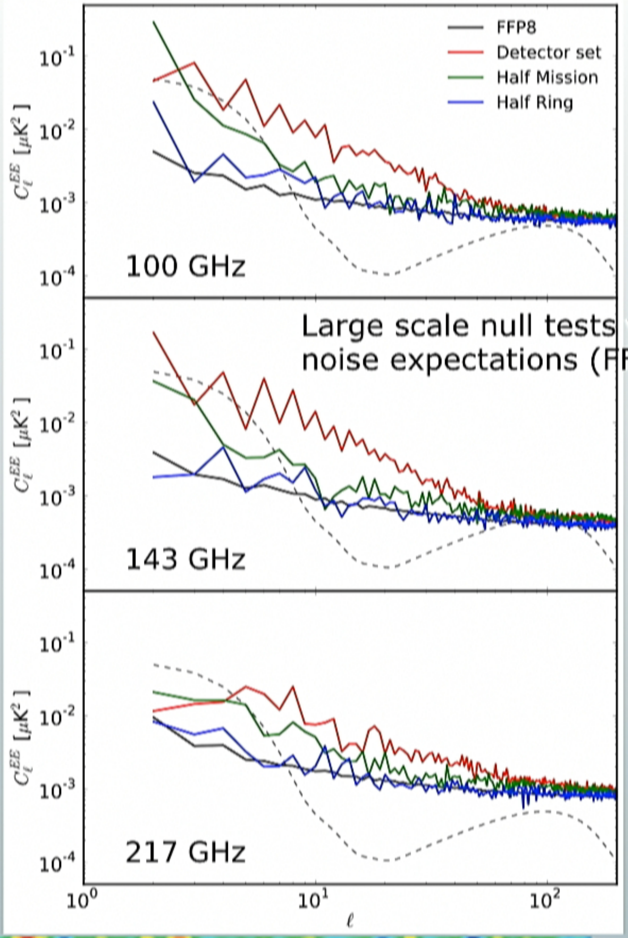
- A new era has begun…





Large scale polarization

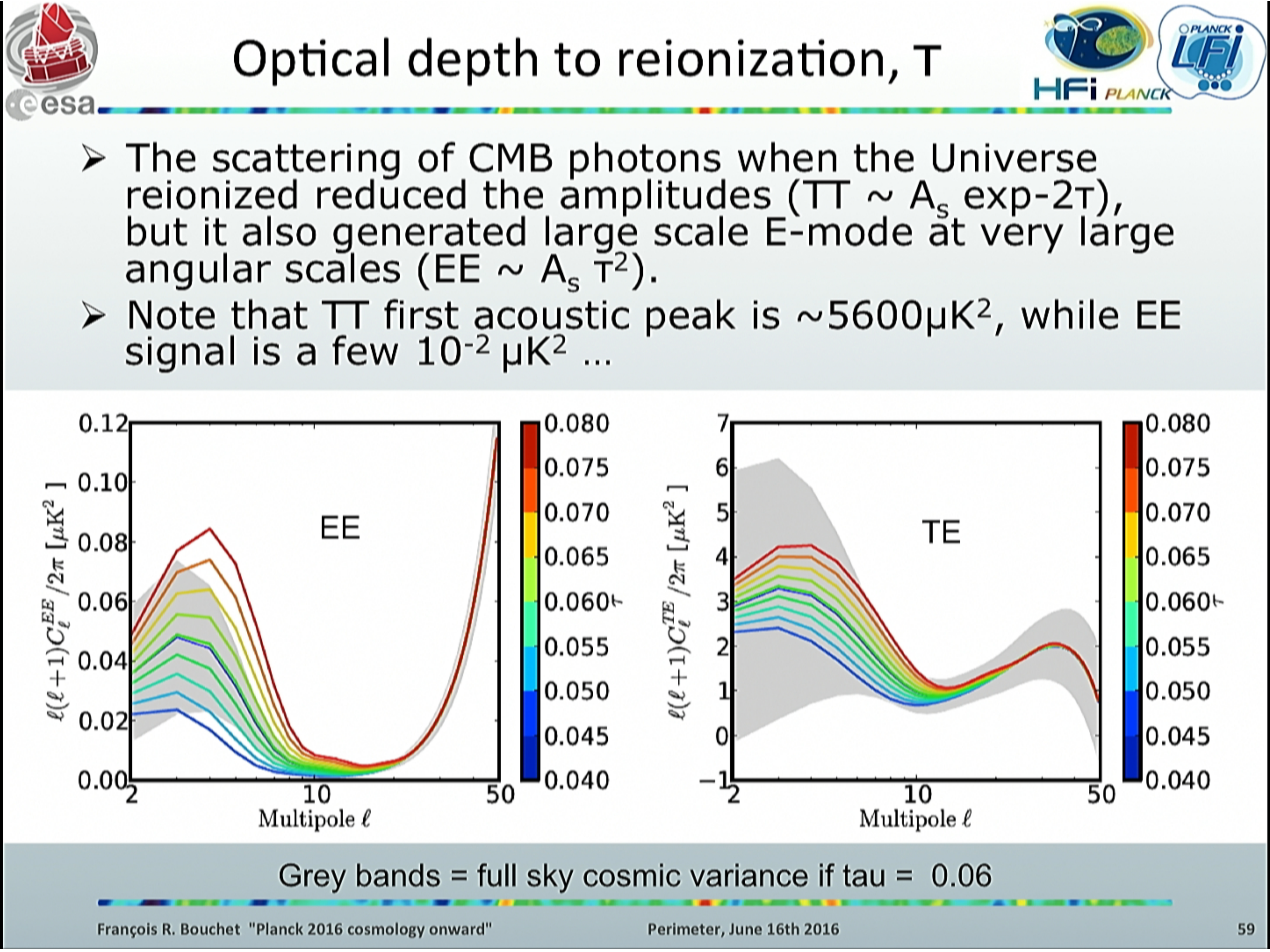
- The 2015 polarized maps of HFI still contain significant excess power at large angular scales
  - *Only the 70 GHz data was deemed safe enough for polarization-based science at large angular scales*
  - *CMB pol-map-based analysis uses high-pass filtering*



Large scale null tests vs noise expectations (FFP9)

Planck Collaboration VIII 2016

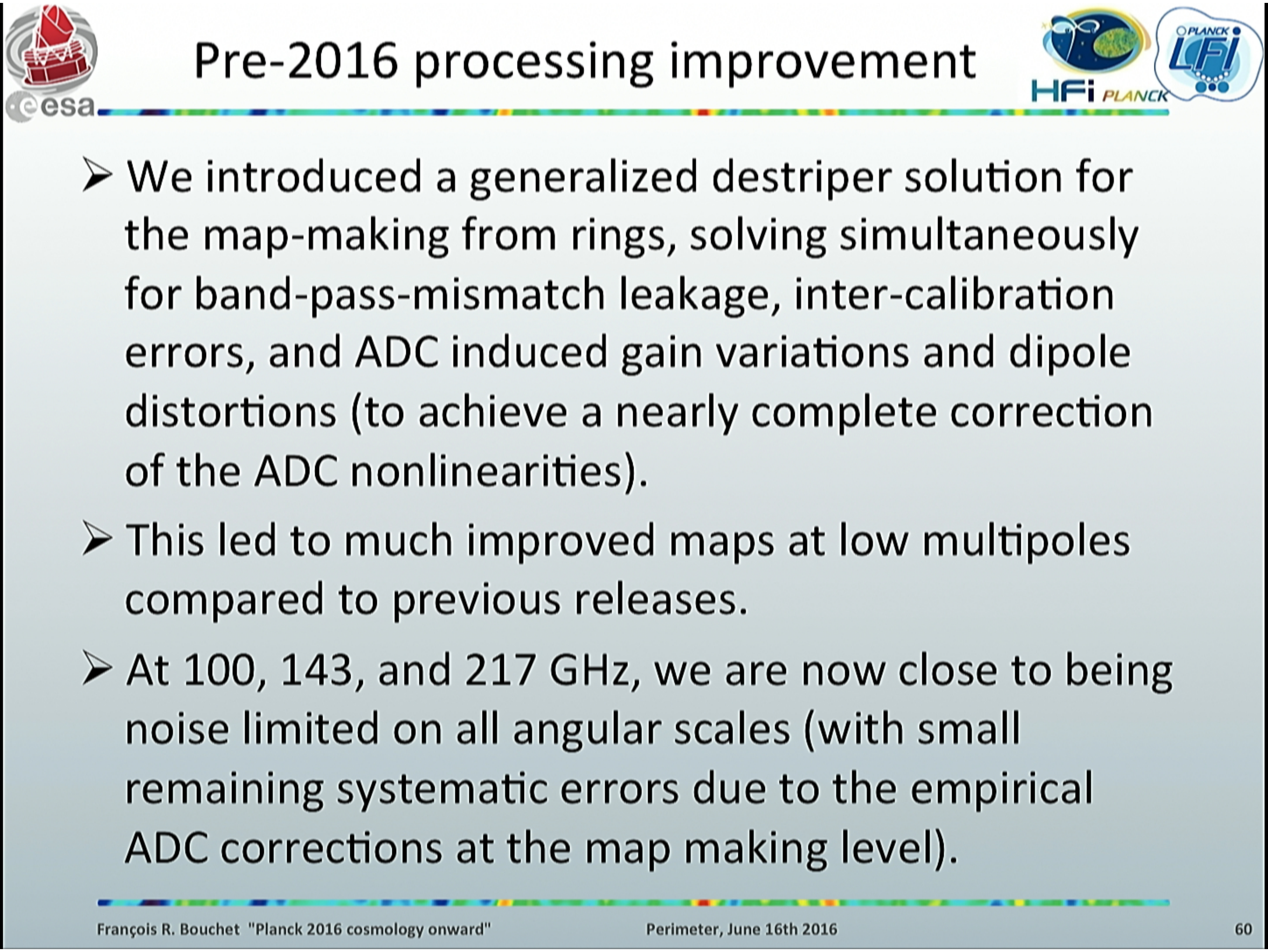
- Large scale polarization is particularly important for two cosmological parameters
  - τ *(optical depth to reionization)*
  - *r (amplitude of primordial gravitational*



Optical depth to reionization, τ

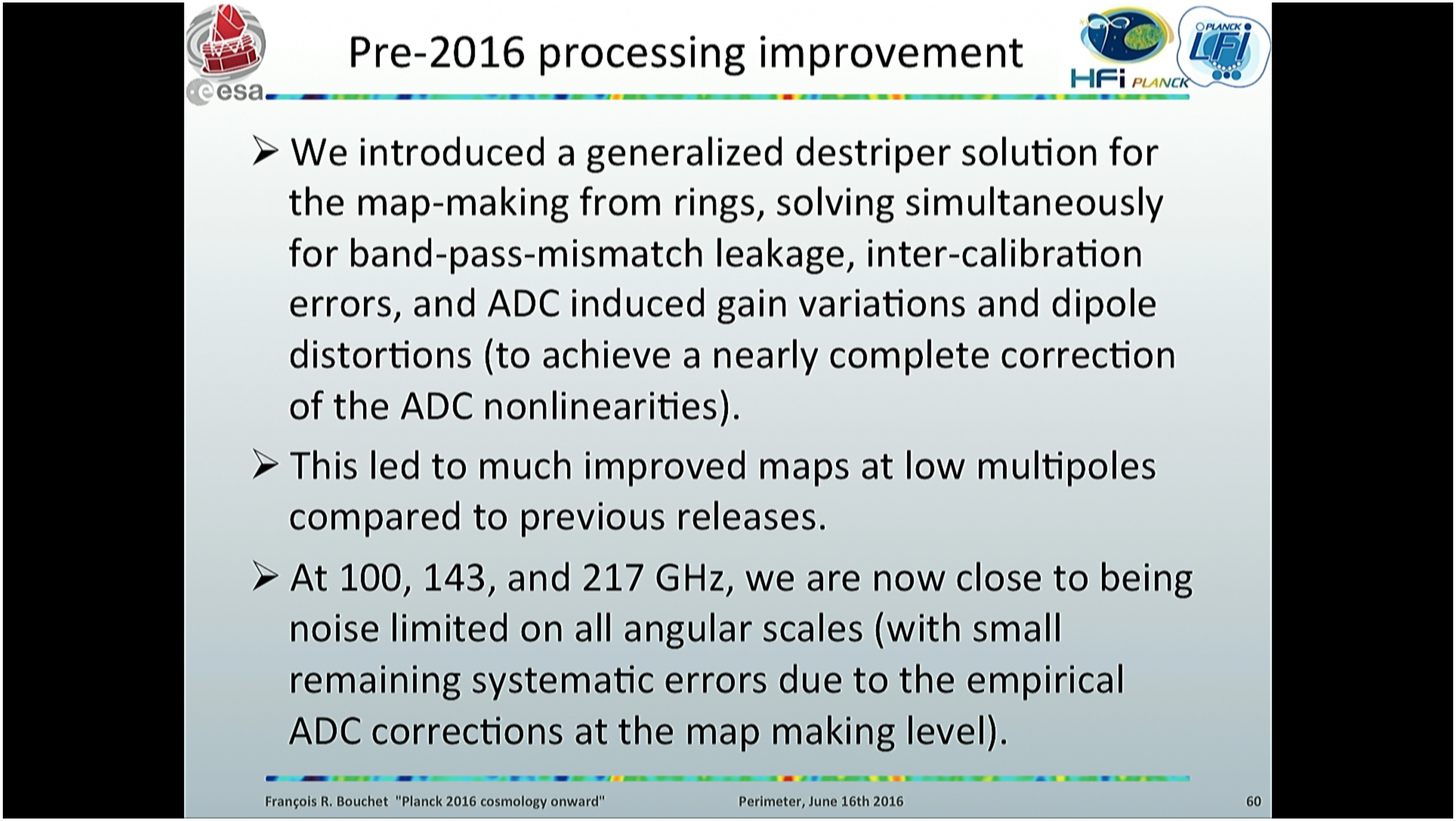
- The scattering of CMB photons when the Universe reionized reduced the amplitudes (TT ~ $A_s \exp{-2\tau}$), but it also generated large scale E-mode at very large angular scales (EE ~ $A_s \tau^2$).
- Note that TT first acoustic peak is ~5600μK^2, while EE signal is a few 10^{-2} μK^2 …

Grey bands = full sky cosmic variance if tau = 0.06



Pre-2016 processing improvement

- We introduced a generalized destriper solution for the map-making from rings, solving simultaneously for band-pass-mismatch leakage, inter-calibration errors, and ADC induced gain variations and dipole distortions (to achieve a nearly complete correction of the ADC nonlinearities).
- This led to much improved maps at low multipoles compared to previous releases.
- At 100, 143, and 217 GHz, we are now close to being noise limited on all angular scales (with small remaining systematic errors due to the empirical ADC corrections at the map making level).



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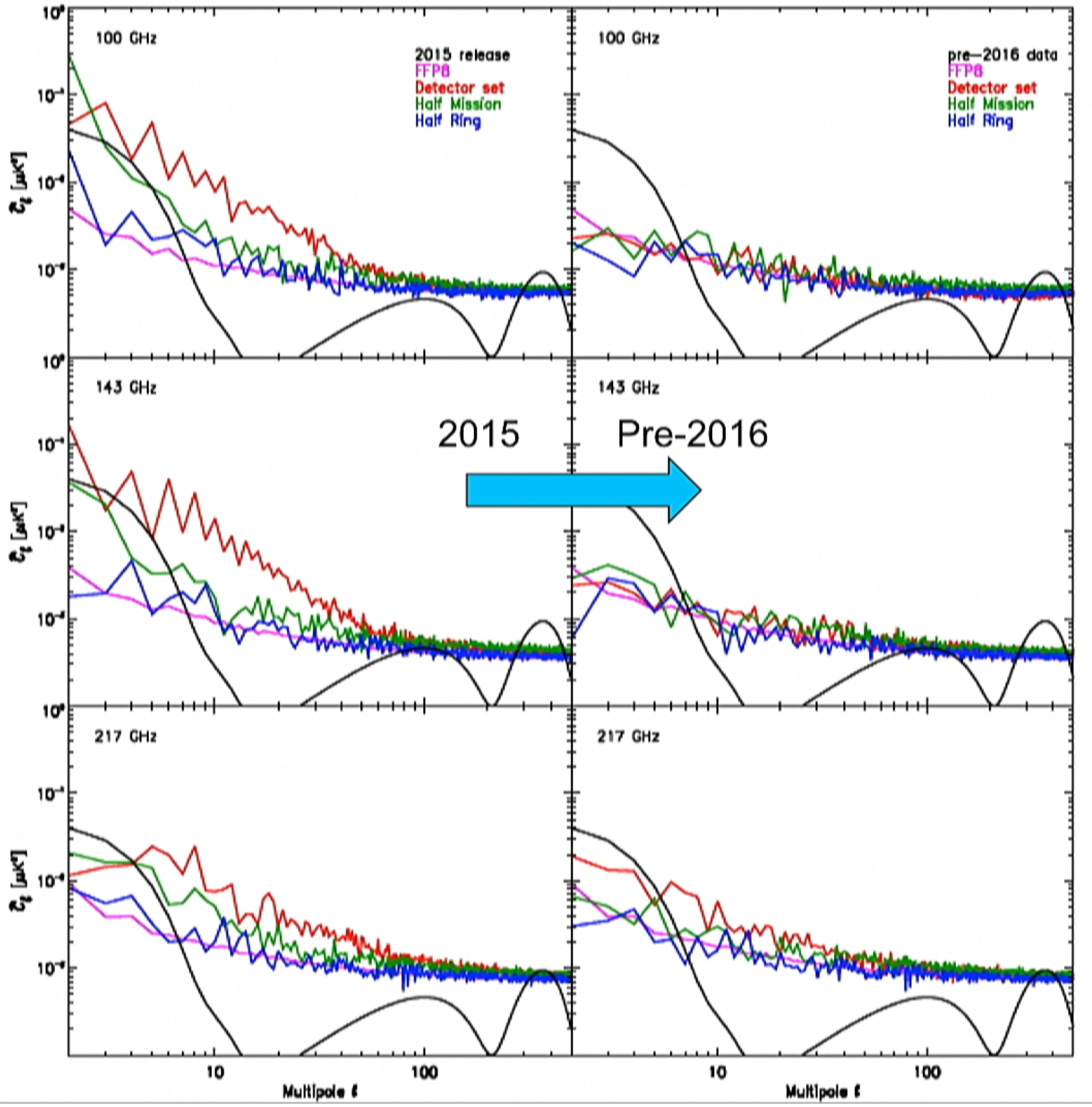
EE

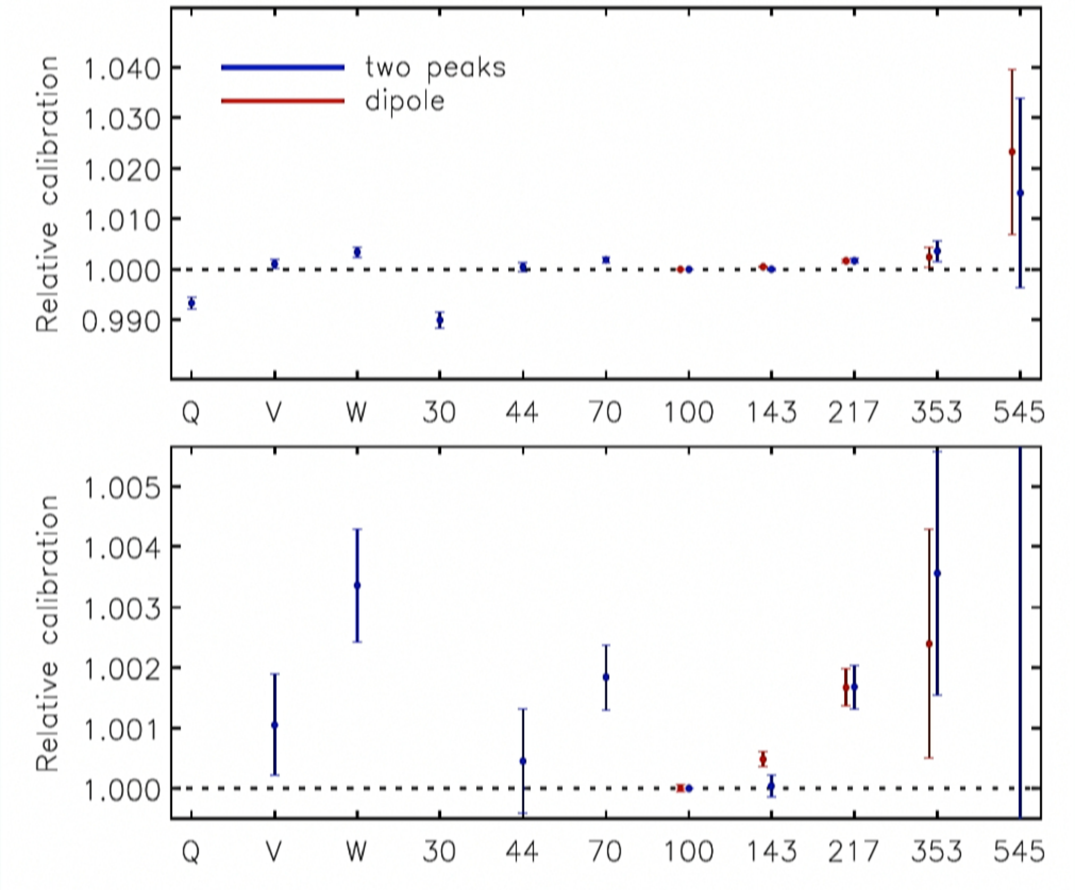


2015 → Pre-2016

Spectacular reduction of residual systematic effects at large scales (in pre-2016 vs 2015 polarisation maps)

Fiducial model in black, for tau=0.066

Frequency Intercalibration

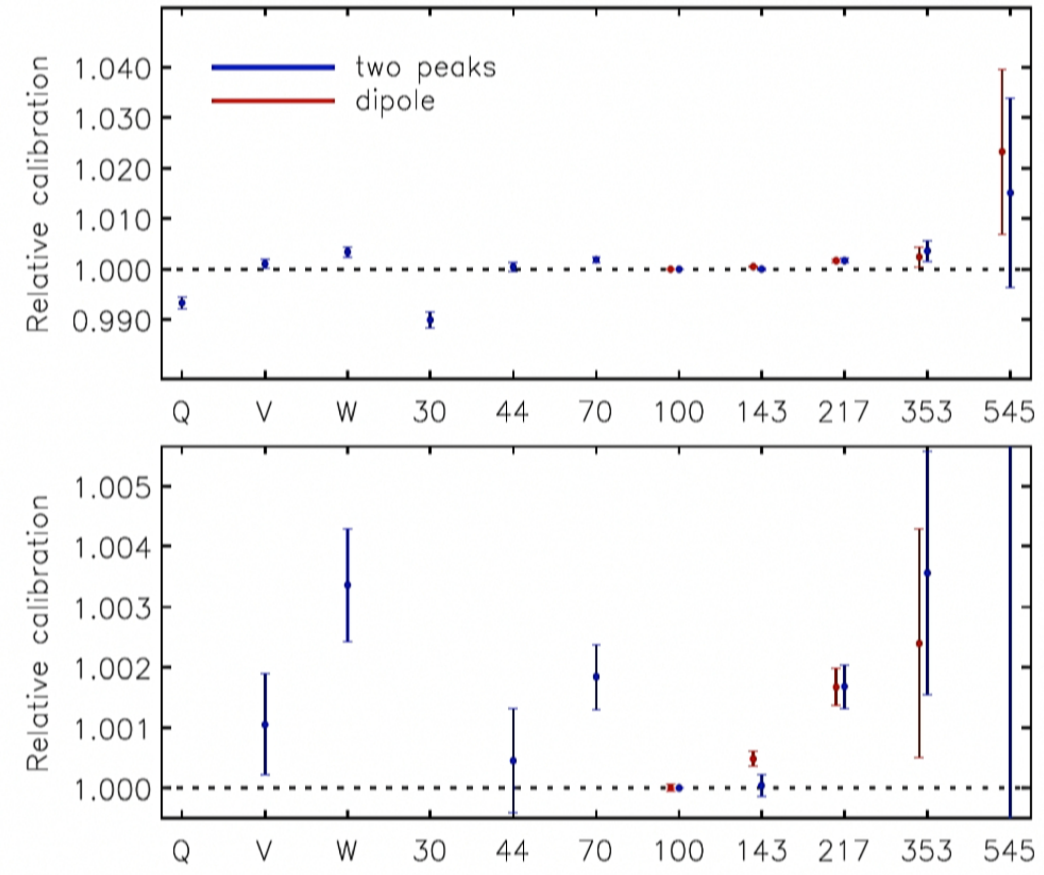


0.1% accuracy achieved over a broad frequency range

~0.01% accuracy at frequencies used for the tau analysis!

Note consistency of solar dipole versus 1st two acoustic peaks calibrations (a direct check on transfer function)

Frequency Intercalibration



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~0.01% accuracy at frequencies used for the tau analysis!

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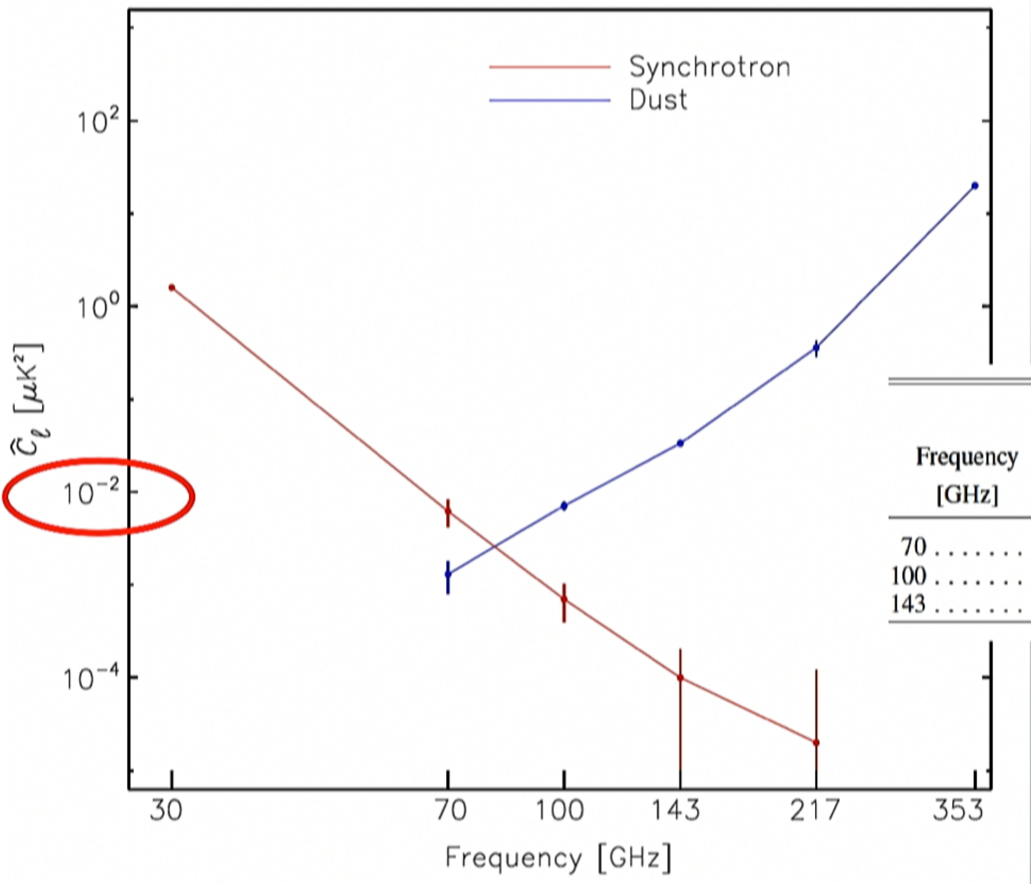
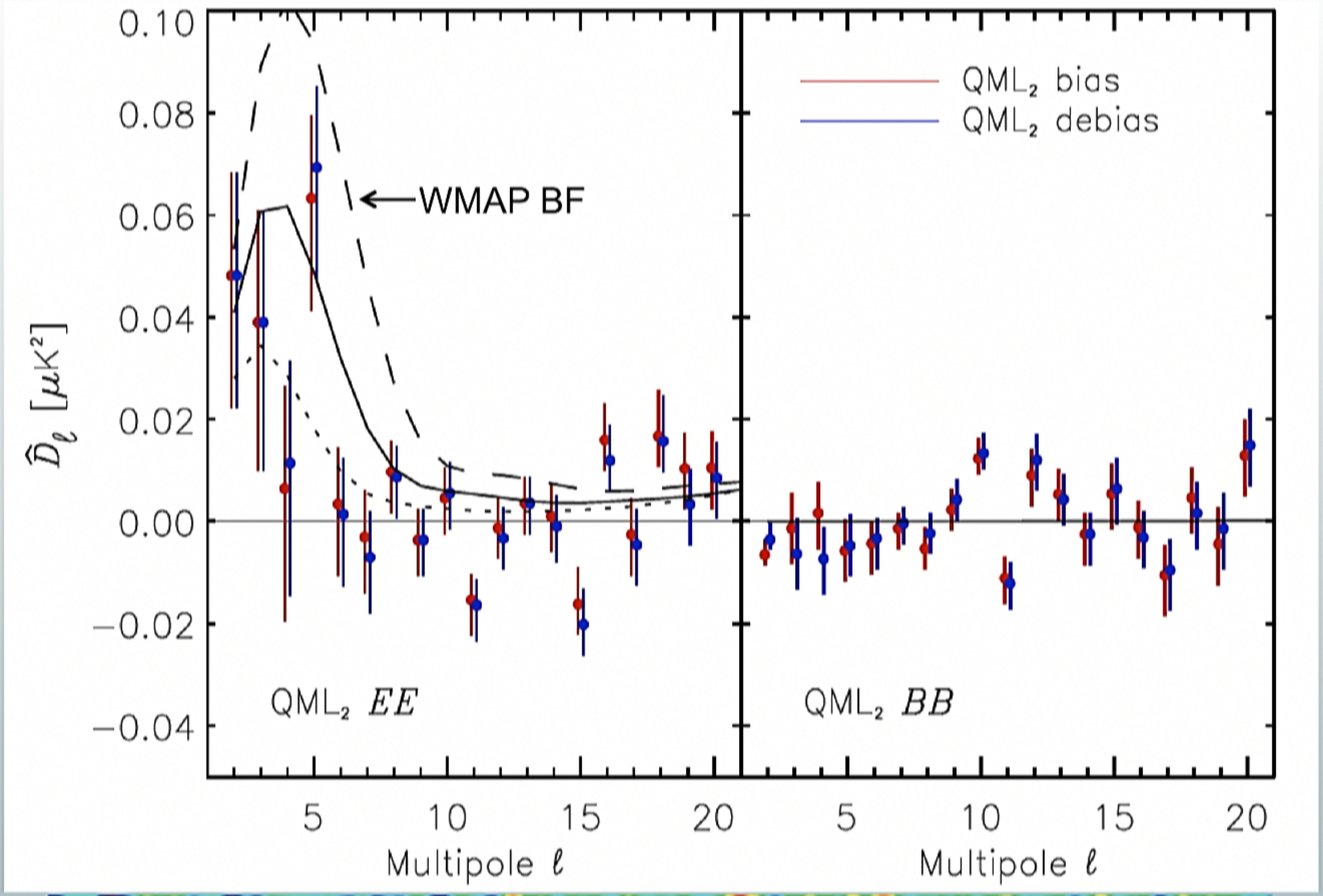
Polarised foregrounds corrections



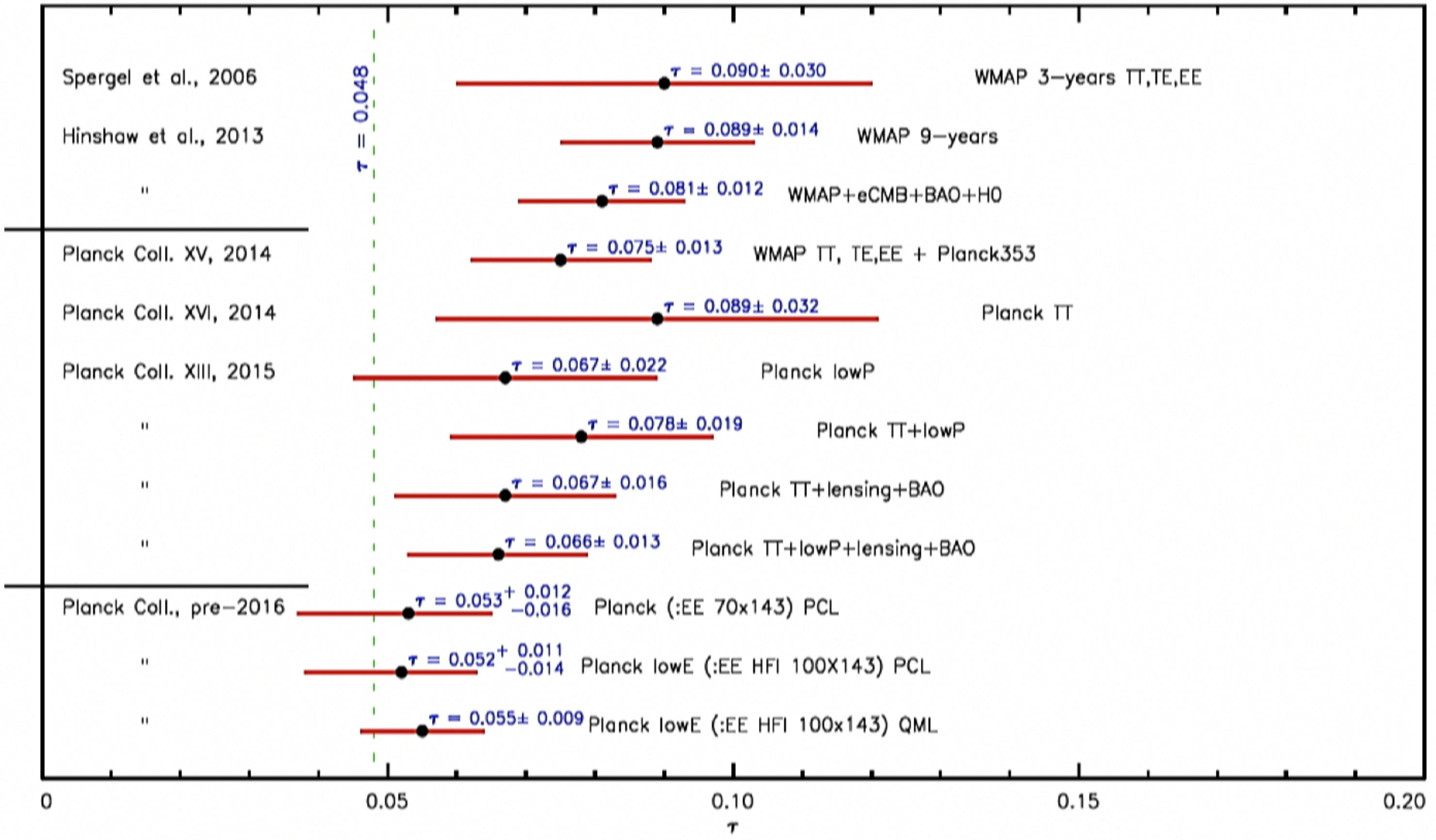
average value of the power spectrum removed
for each foreground at the peak of the EE reionization feature (l=4)

Frequency [GHz]	Dust Mean [μK^2]	Dust Uncertainty [μK^2]	Synchrotron Mean [μK^2]	Synchrotron Uncertainty [μK^2]
70	0.0041	0.0010	0.019	0.005
100	0.0227	0.0020	0.0036	0.0011
143	0.106	0.0052	0.0007	0.0004

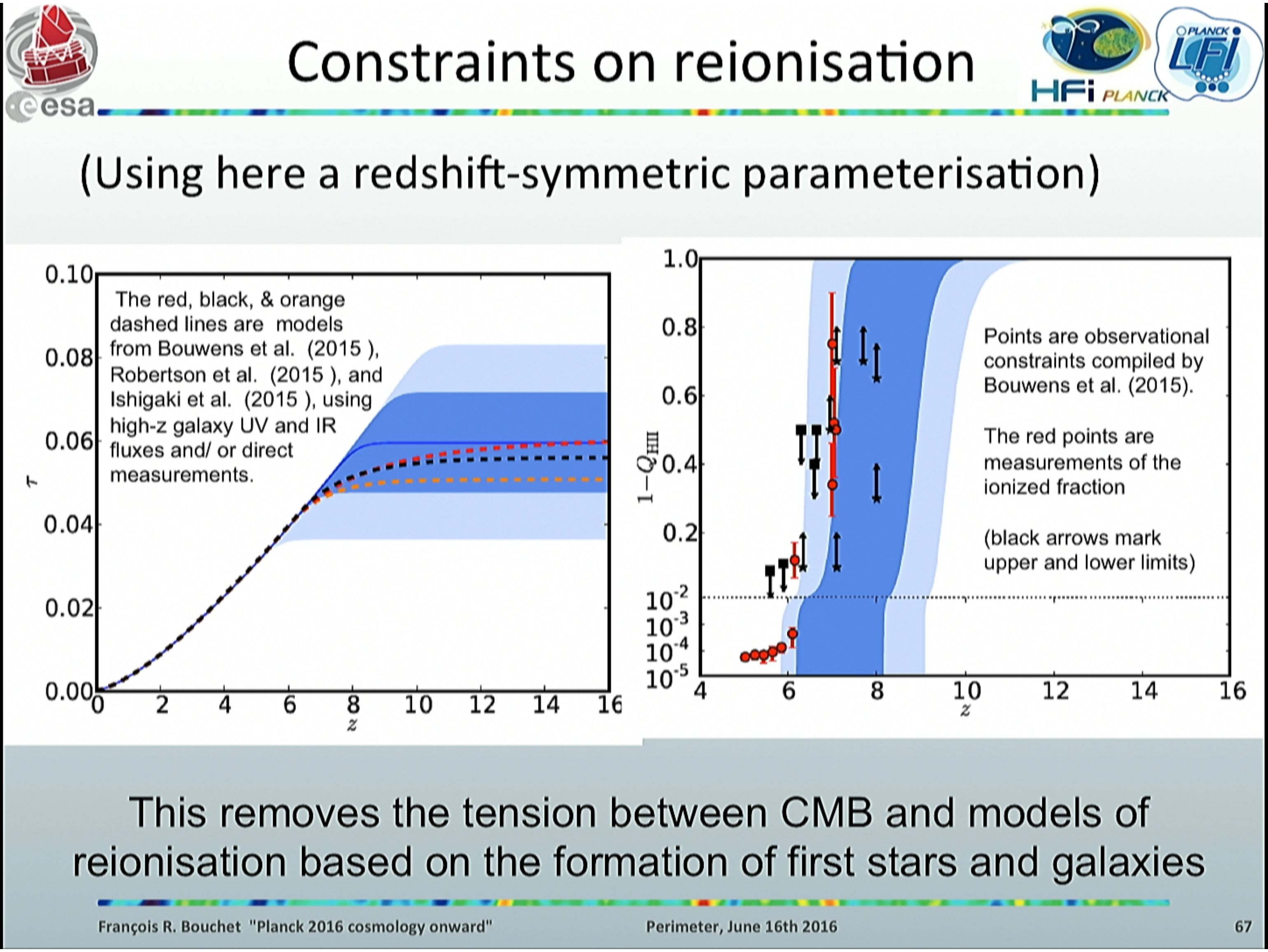
Data versus τ_{fid}=0.05, 0.07, 0.09



A short « history » of tau



(w. BAO, and sym hist, z_{re} = 8.5 +-1)



Constraints on reionisation

(Using here a redshift-symmetric parameterisation)

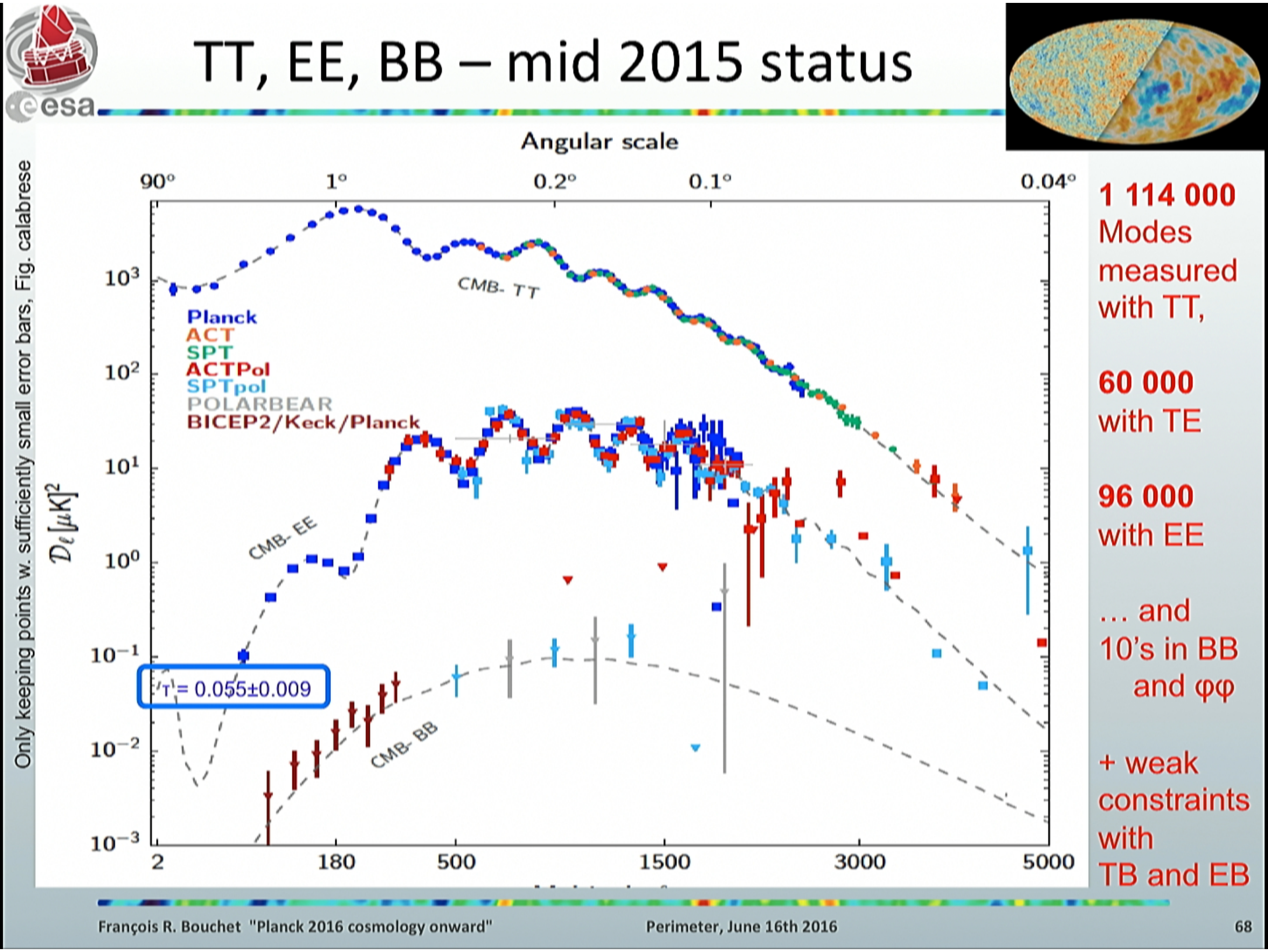
The red, black, & orange dashed lines are models from Bouwens et al. (2015), Robertson et al. (2015), and Ishigaki et al. (2015), using high-z galaxy UV and IR fluxes and/ or direct measurements.

Points are observational constraints compiled by Bouwens et al. (2015).

The red points are measurements of the ionized fraction

(black arrows mark upper and lower limits)

This removes the tension between CMB and models of reionisation based on the formation of first stars and galaxies



TT, EE, BB – mid 2015 status

Only keeping points w. sufficiently small error bars, Fig. calabrese

$\tau = 0.055 \pm 0.009$

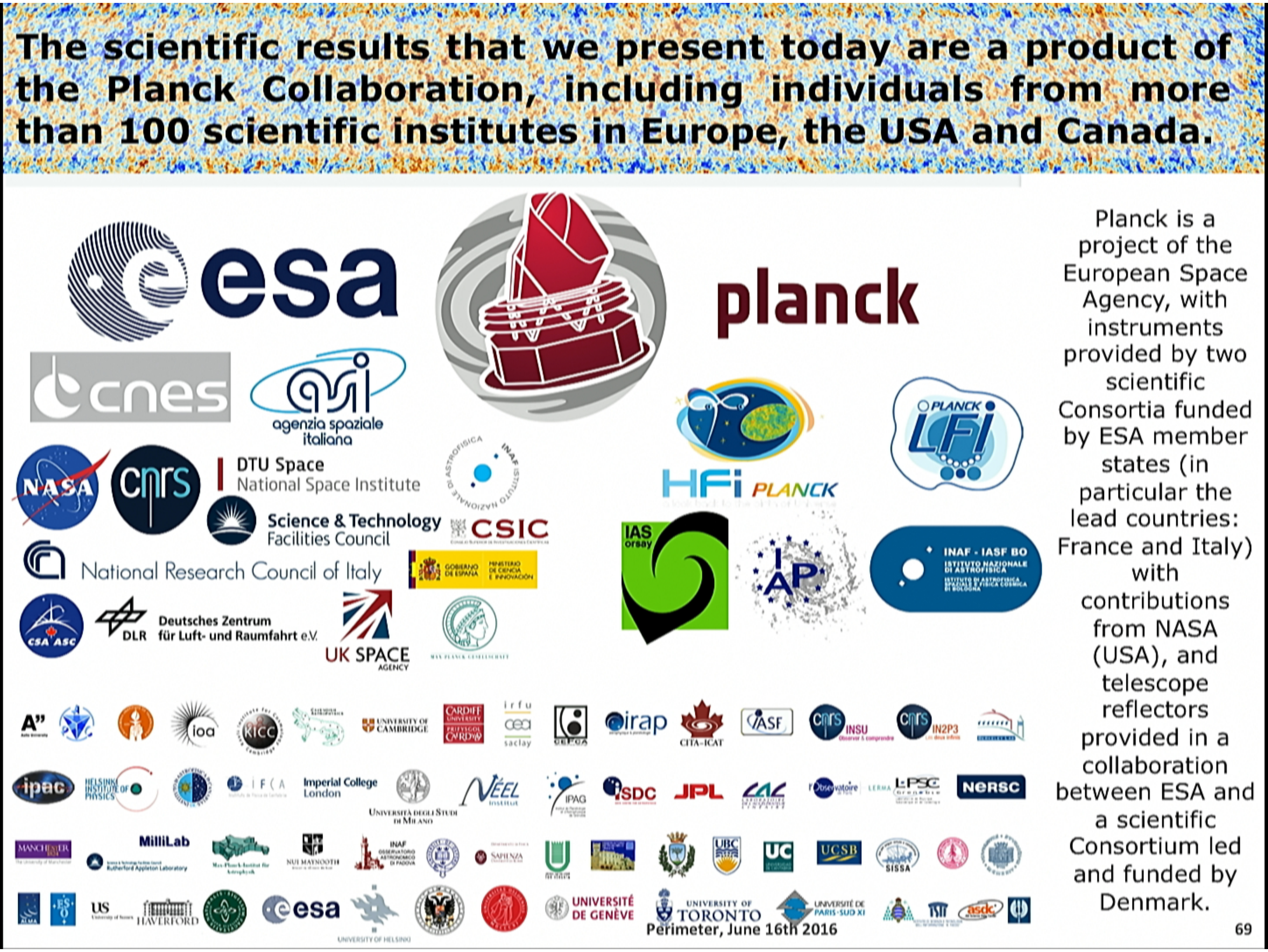
1 114 000 Modes measured with TT,

60 000 with TE

96 000 with EE

… and 10's in BB and φφ

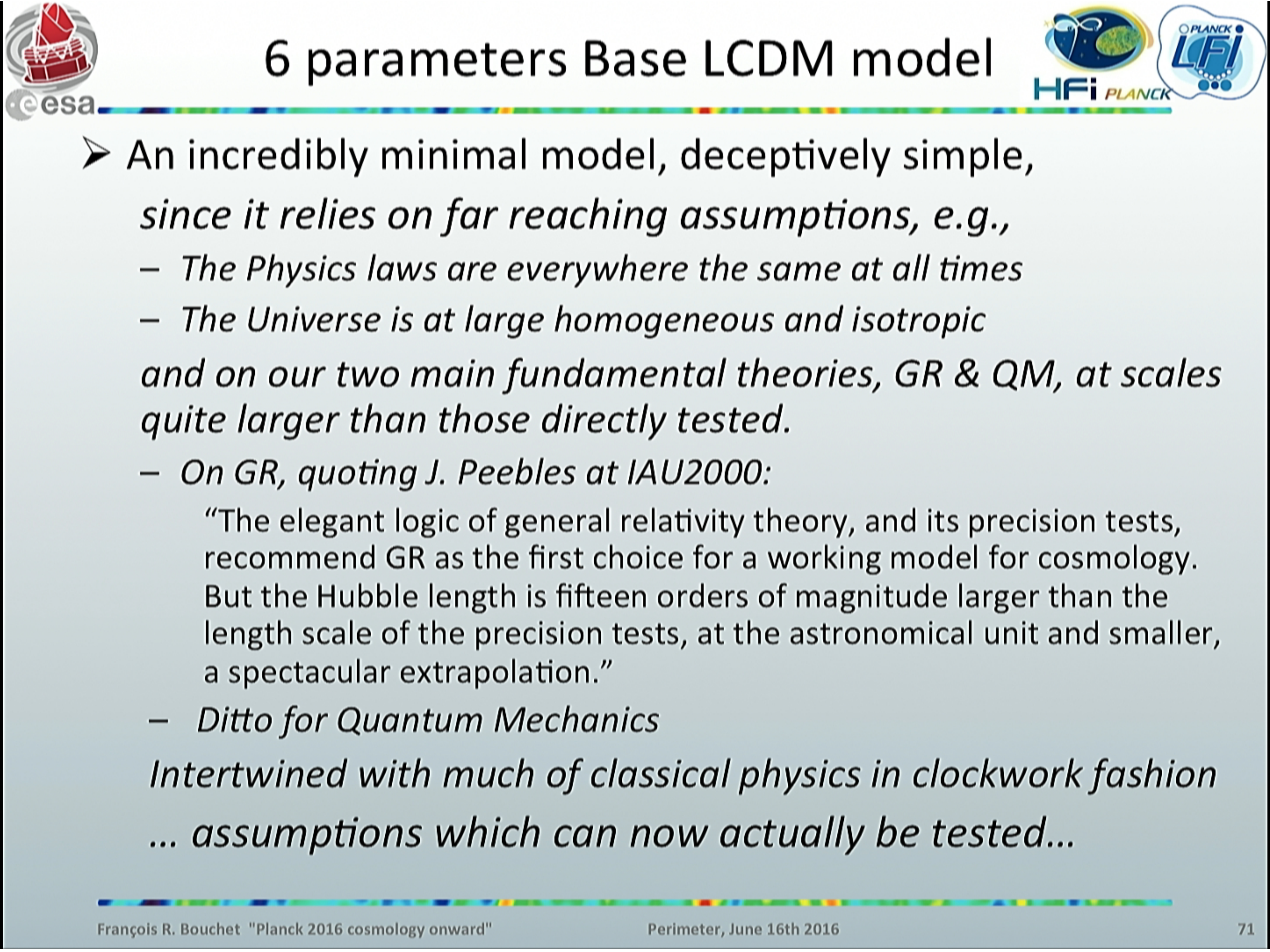
+ weak constraints with TB and EB



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.

Perimeter, June 16th 2016



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*

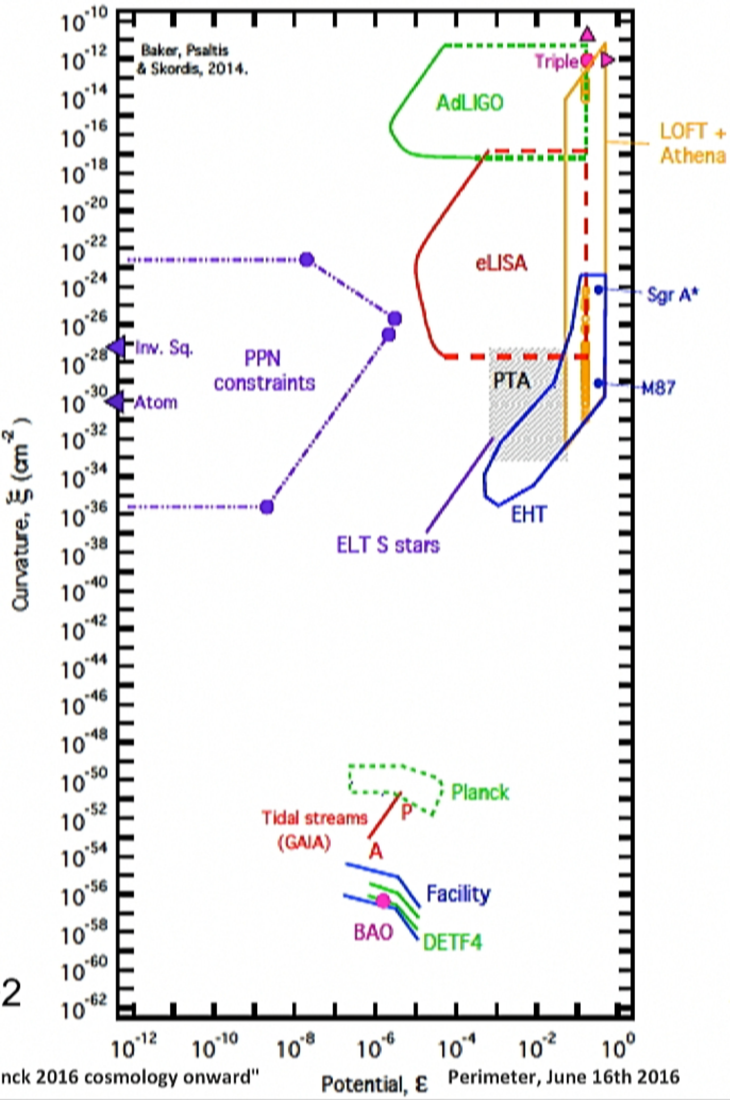
  and on our two main fundamental theories, GR & QM, at scales quite larger than those directly tested.
  - *On GR, quoting J. Peebles at IAU2000:*

    "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

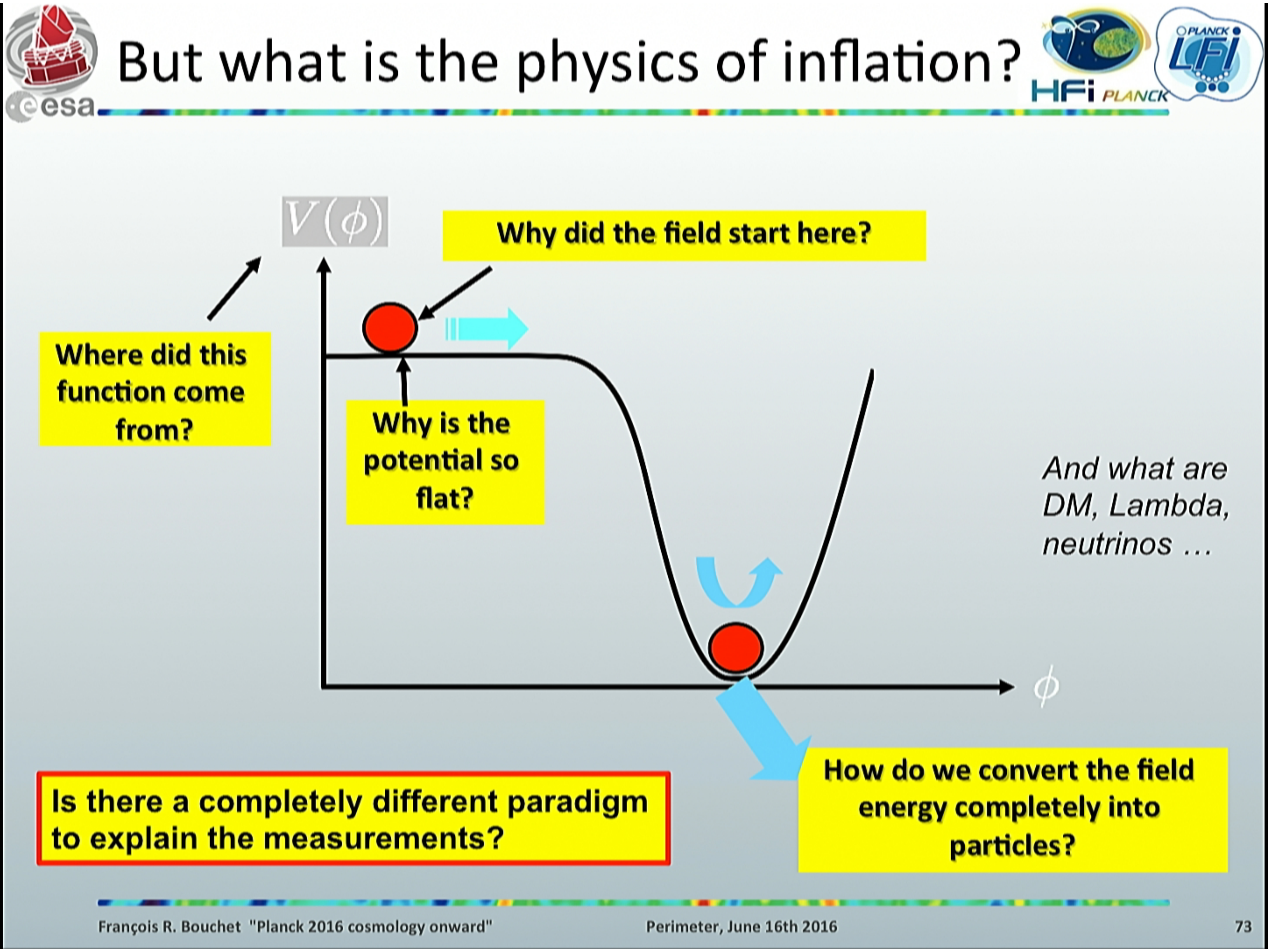
  … assumptions which can now actually be tested…

The metric curvature, Xi, is, for a Schwartschild metric Sqrt(48) GM/r^3 c^2



For a test particle Eps equiv GM/rc^2

Baker et al 2014 ArXiv:1412:3455



But what is the physics of inflation?

Where did this function come from?

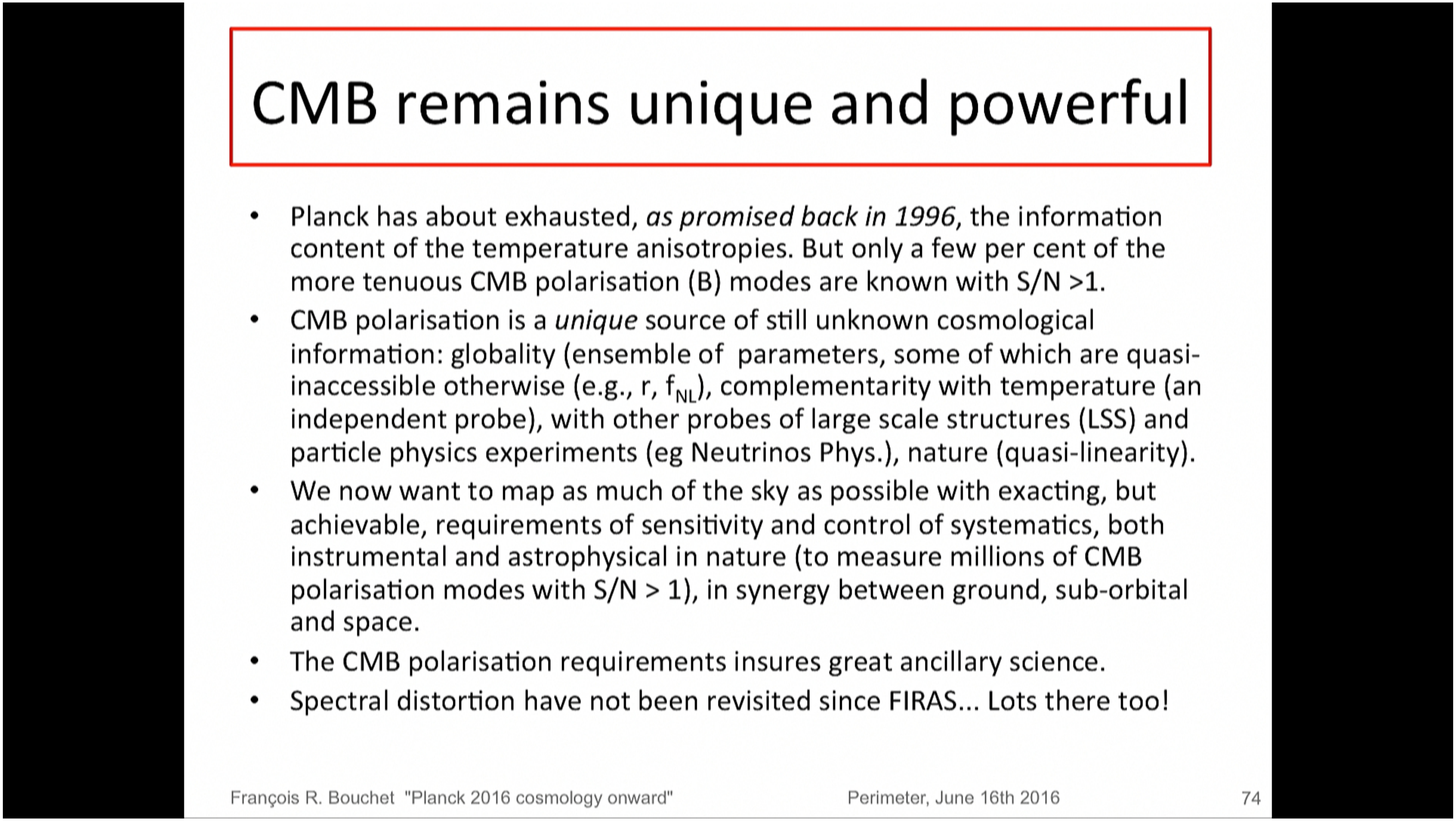
Why did the field start here?

Why is the potential so flat?

And what are DM, Lambda, neutrinos …

Is there a completely different paradigm to explain the measurements?

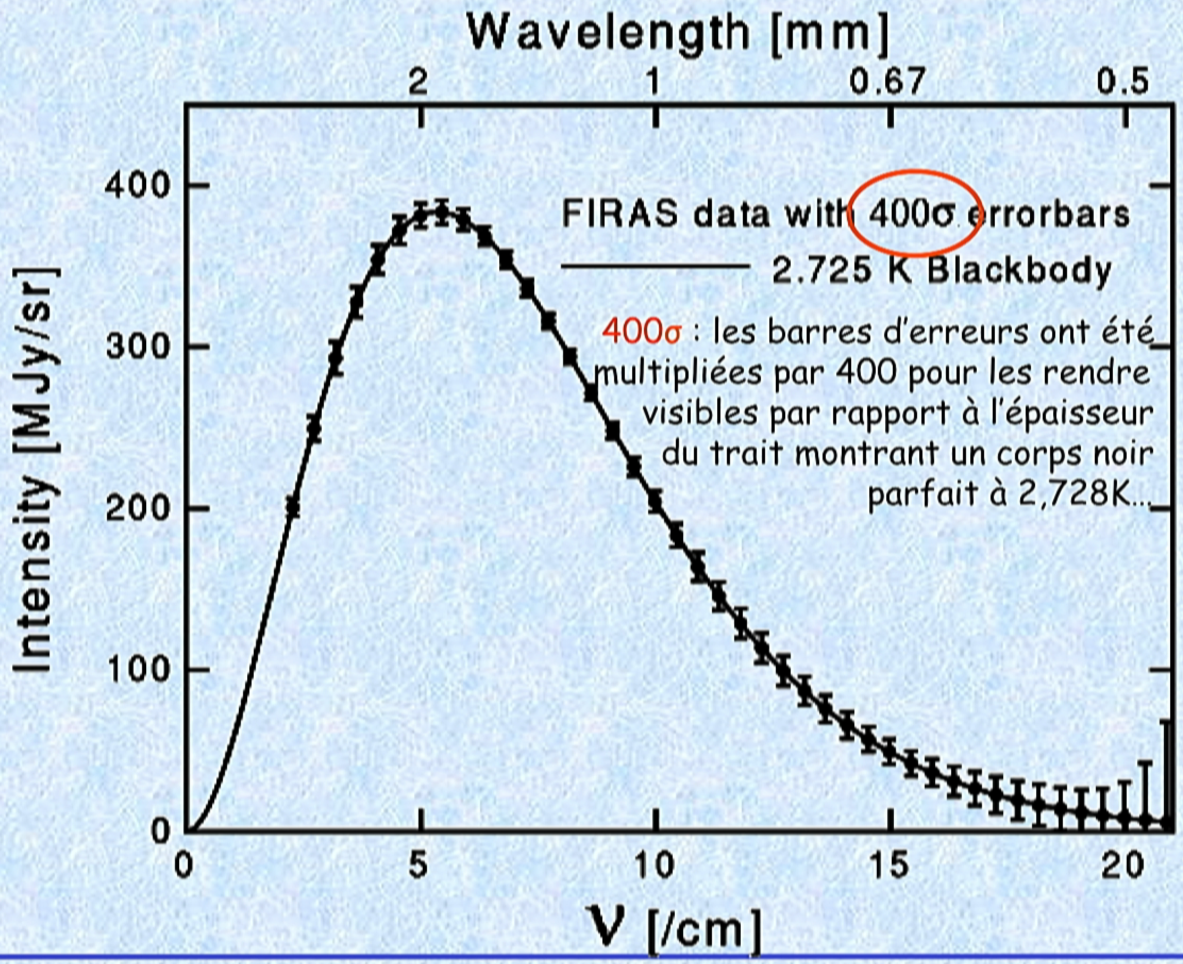
How do we convert the field energy completely into particles?



CMB remains unique and powerful

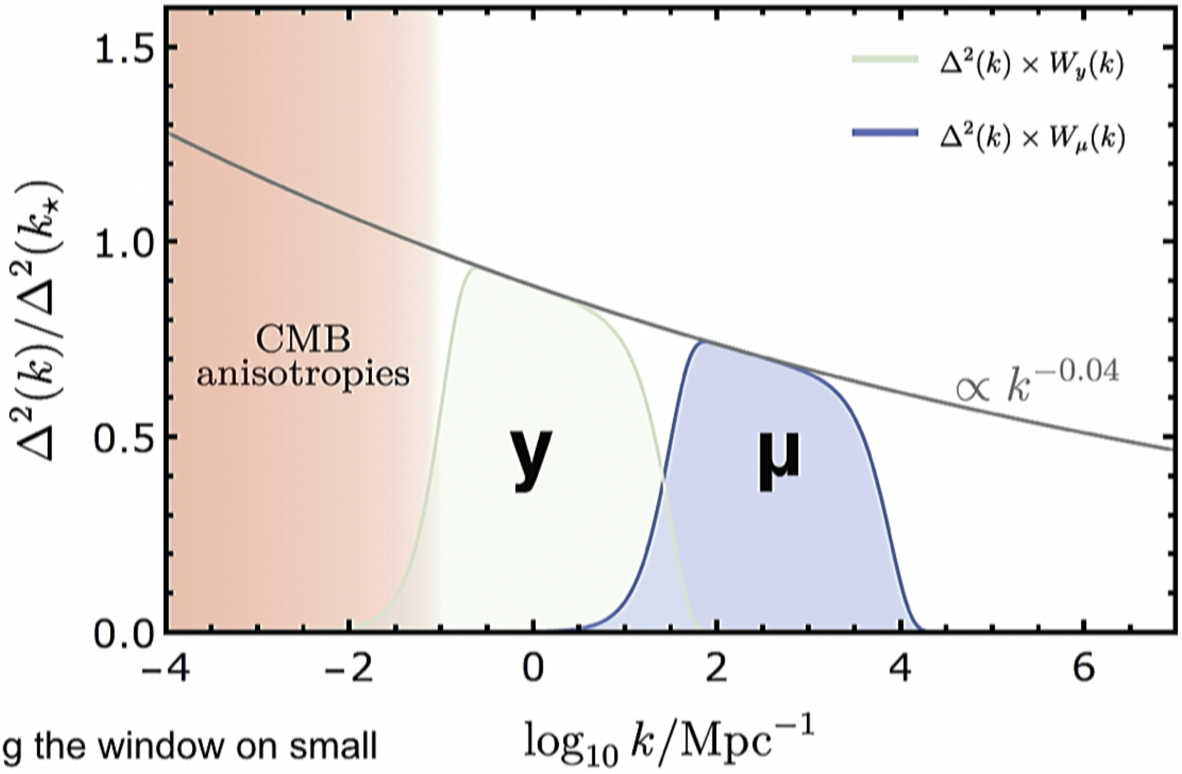
- Planck has about exhausted, *as promised back in 1996*, the information content of the temperature anisotropies. But only a few per cent of the more tenuous CMB polarisation (B) modes are known with S/N >1.
- CMB polarisation is a *unique* source of still unknown cosmological information: globality (ensemble of parameters, some of which are quasi-inaccessible otherwise (e.g., r, f_{NL}), complementarity with temperature (an independent probe), with other probes of large scale structures (LSS) and particle physics experiments (eg Neutrinos Phys.), nature (quasi-linearity).
- We now want to map as much of the sky as possible with exacting, but achievable, requirements of sensitivity and control of systematics, both instrumental and astrophysical in nature (to measure millions of CMB polarisation modes with S/N > 1), in synergy between ground, sub-orbital and space.
- The CMB polarisation requirements insures great ancillary science.
- Spectral distortion have not been revisited since FIRAS... Lots there too!

FINAL SPECTRUM



400σ : les barres d'erreurs ont été multipliées par 400 pour les rendre visibles par rapport à l'épaisseur du trait montrant un corps noir parfait à 2,728K…

y and mu distorsions from standard inflationary models of the CMB spectrum



Extending the window on small scale scalar primordial power spectrum (+9 e-folds)

Broad band windows.

Also sensitive to any energy input – exotic or astrophysics – a very extended net

Spectral distortions and foreground emission

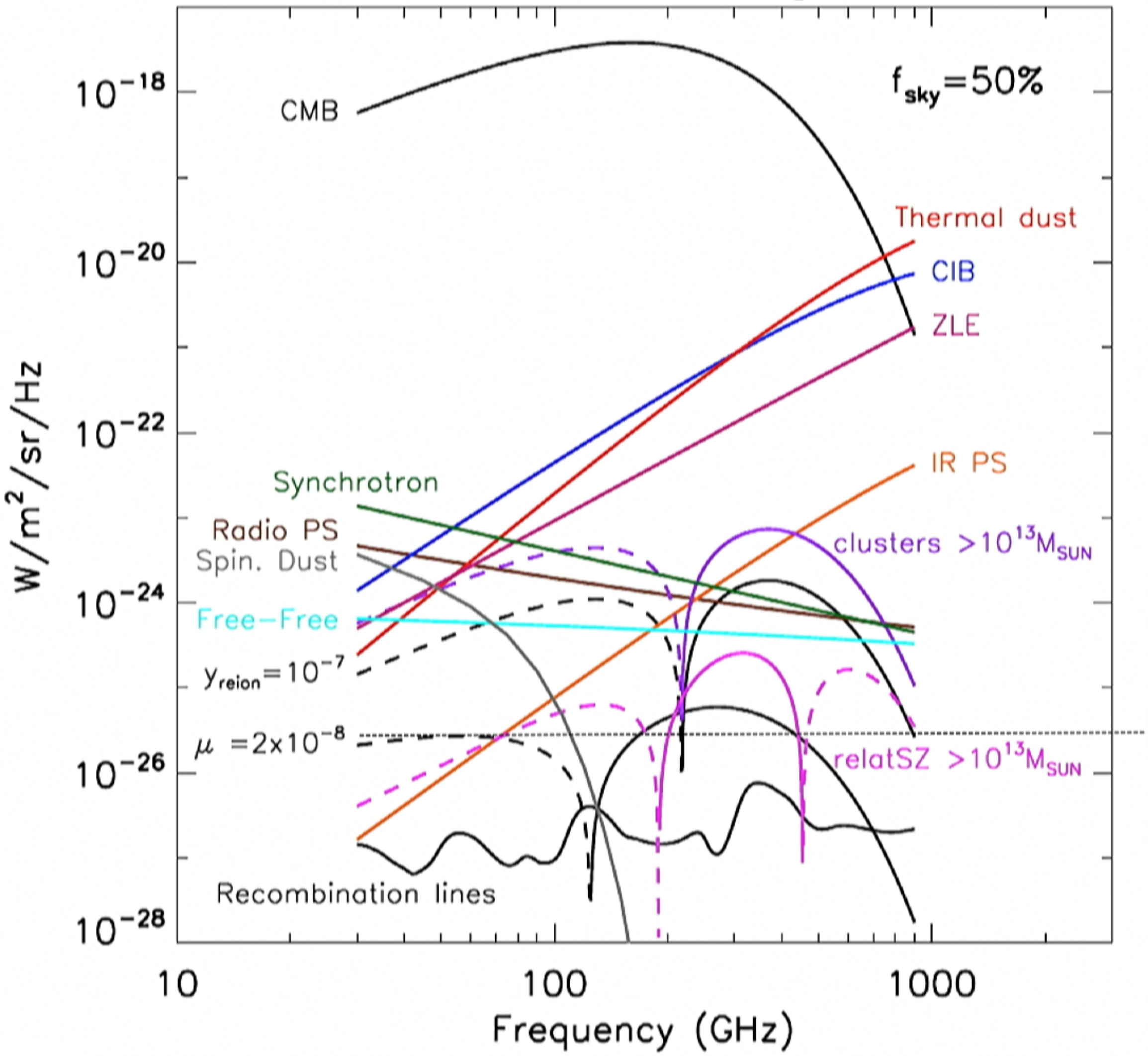
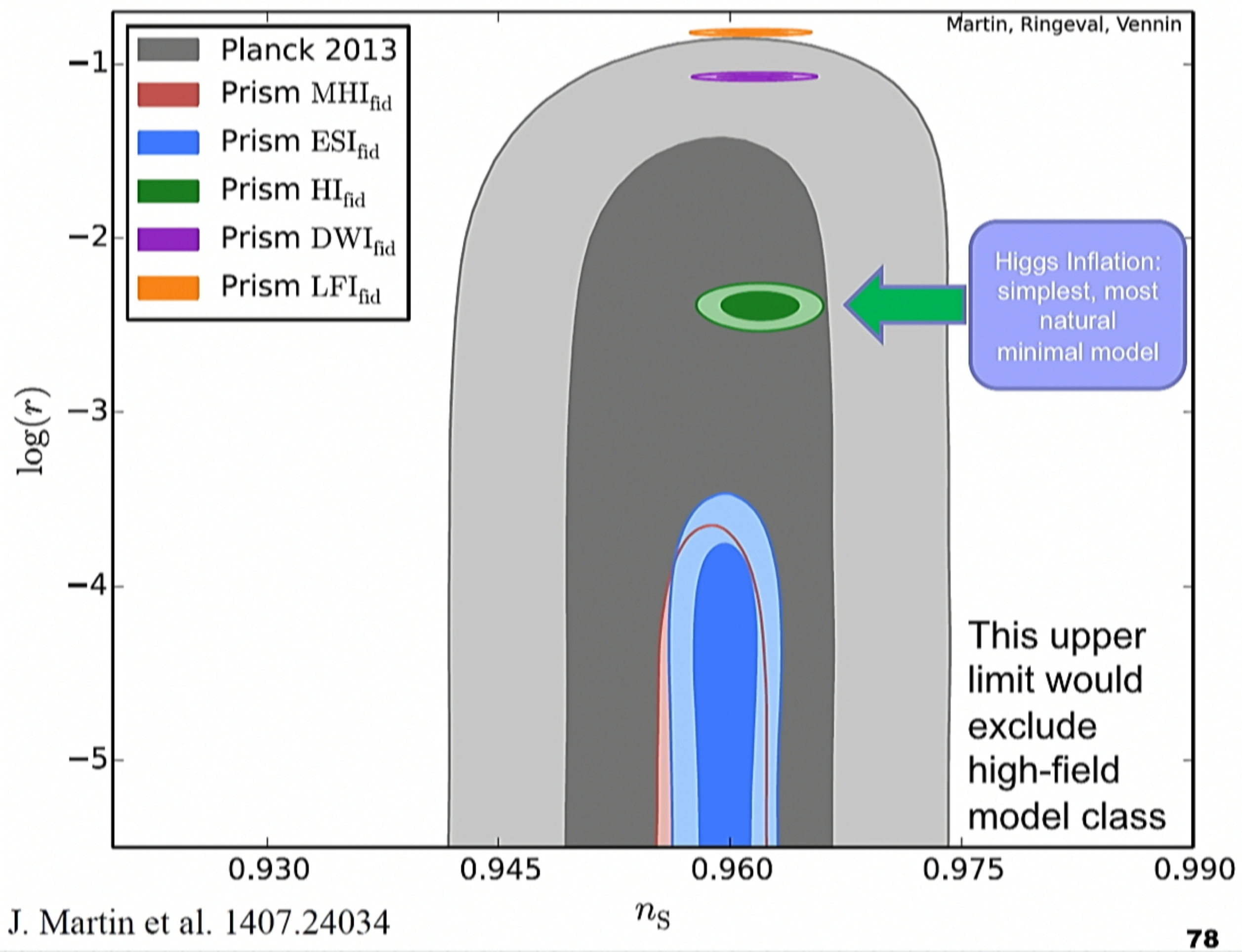


Fig. Delabrouille

Pixie 4 years
50% sky
To be proposed
to NASA explorer
Pgm In 12/2016
For 2023 launch
(with also r cap.)

Forecasts for PRISM

(with sigma(r) ~ few 10^{-4})



Higgs Inflation: simplest, most natural minimal model

This upper limit would exclude high-field model class

J. Martin et al. 1407.24034

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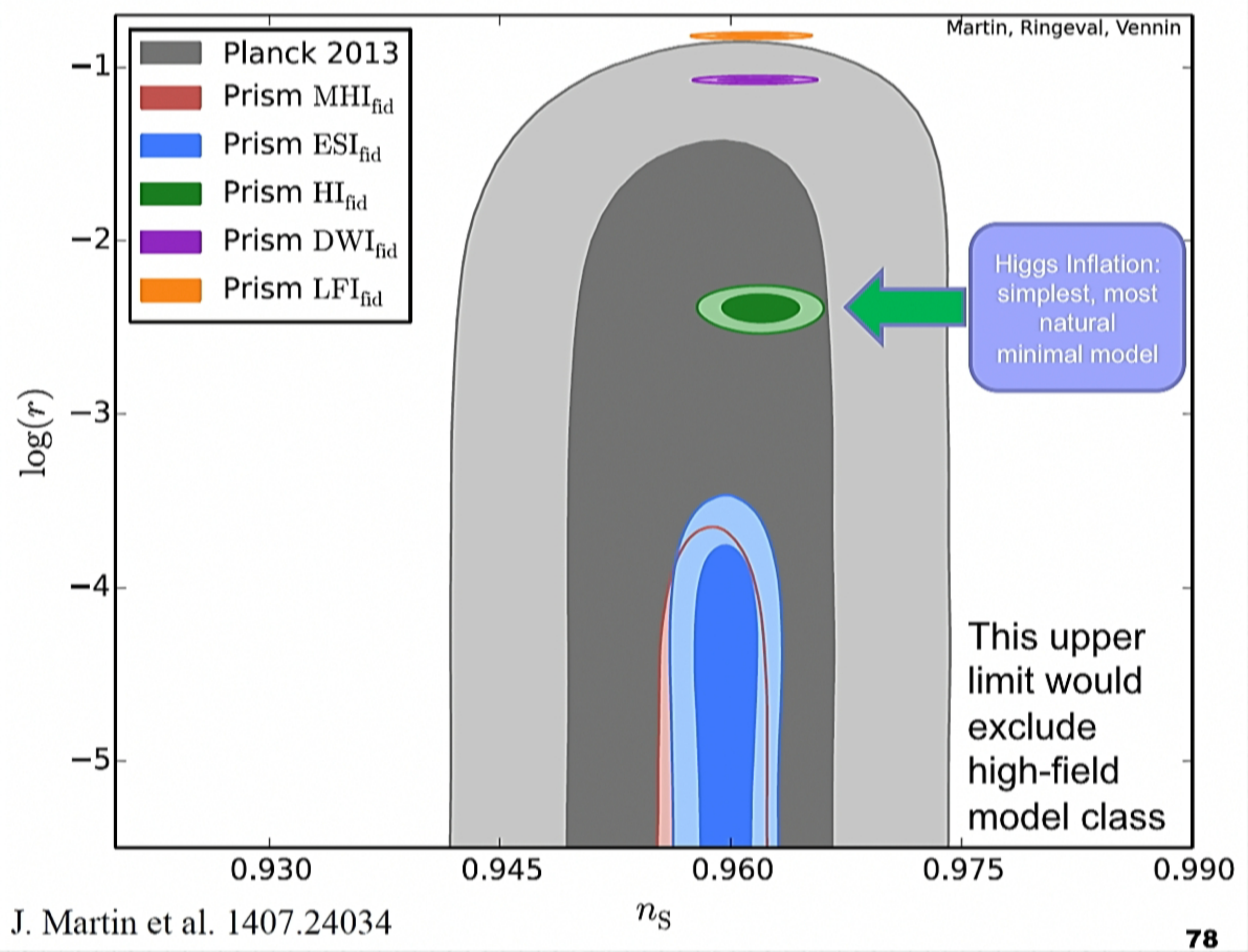

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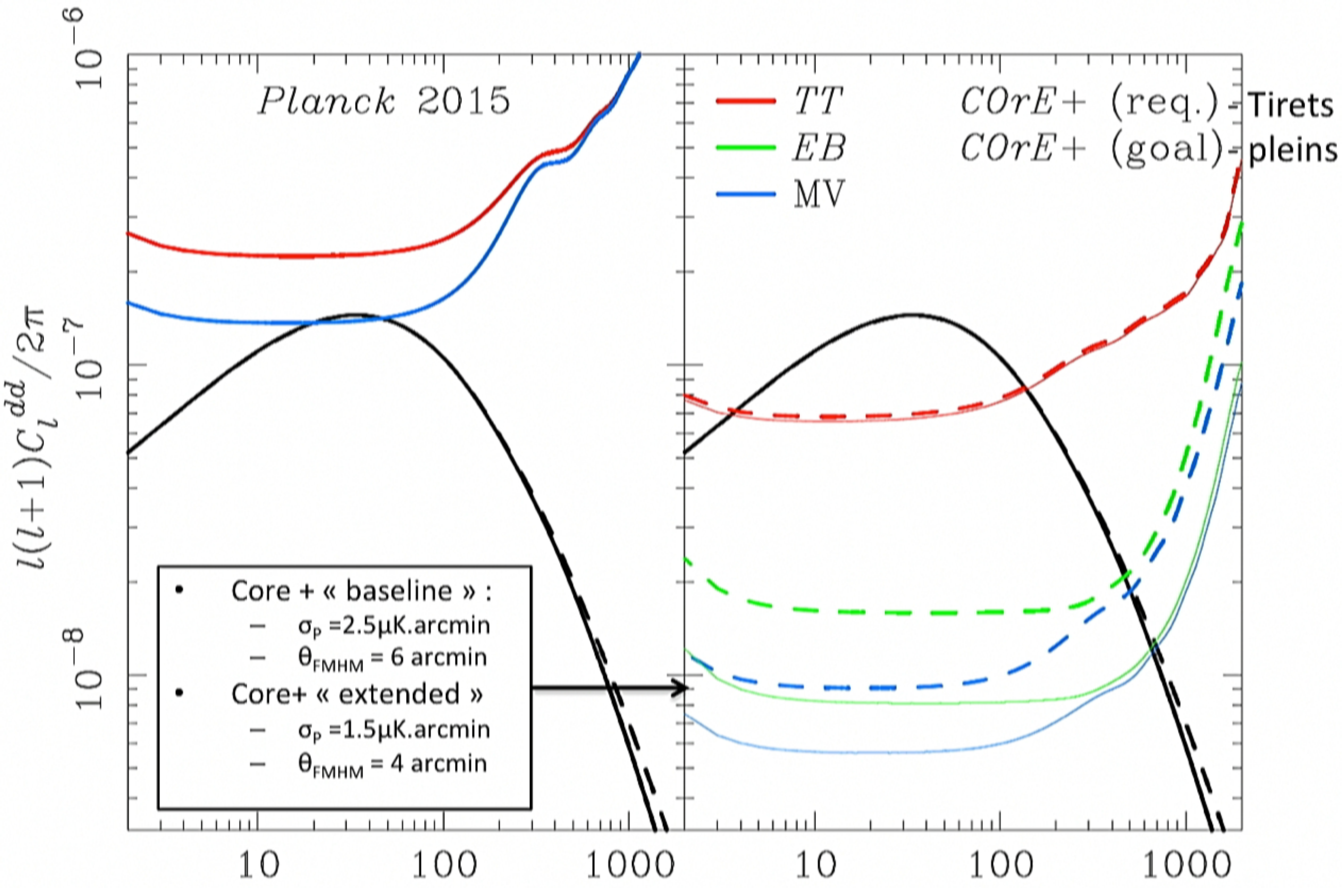
Core+ Lensing performance



- Core + « baseline » :
  - σ_p =2.5μK.arcmin
  - θ_{FMHM} = 6 arcmin
- Core+ « extended »
  - σ_p =1.5μK.arcmin
  - θ_{FMHM} = 4 arcmin

CMB B Modes

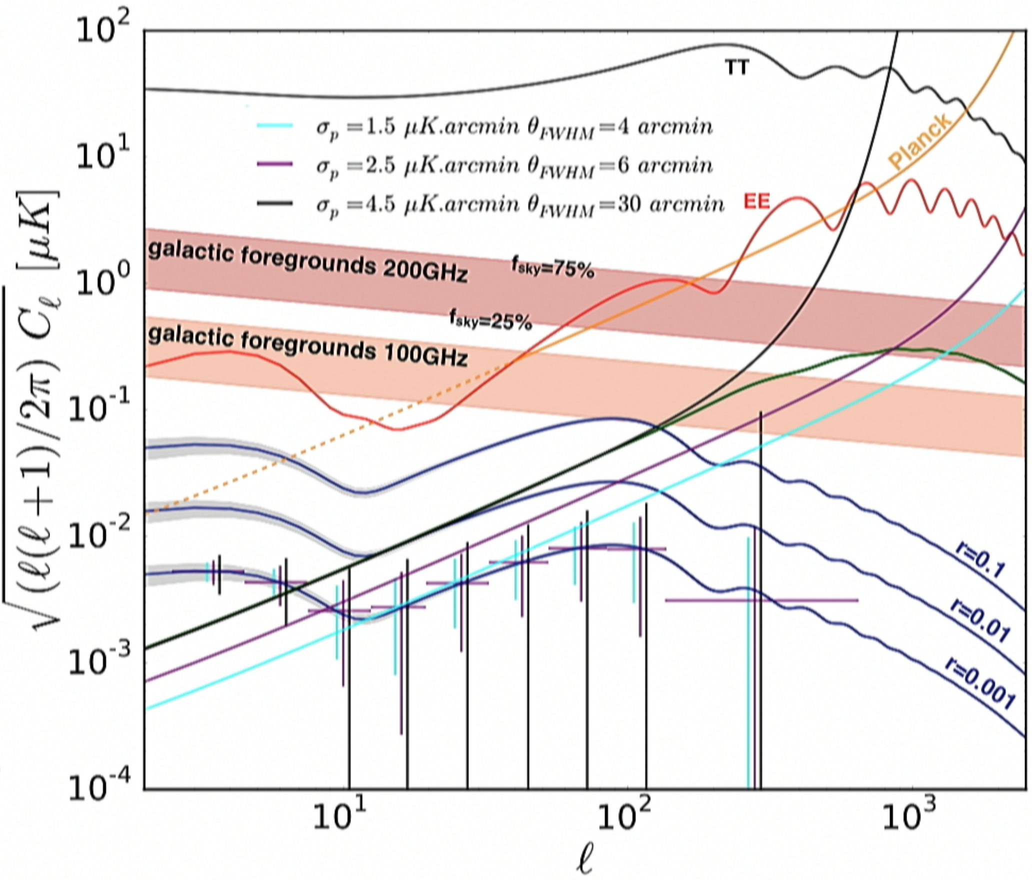


Figure by Josquin Errard

In the r=0.001 case, even with this plot broad binning, not a single bin detection at l>10 with 4.5μKarcmin and 30arcmin.

A "small" amount of delensing would allow measuring a spectrum! (n_T !)

NB: If space data would only be used for getting E and Phi, how to clean the (ground) B-modes from foregrounds?

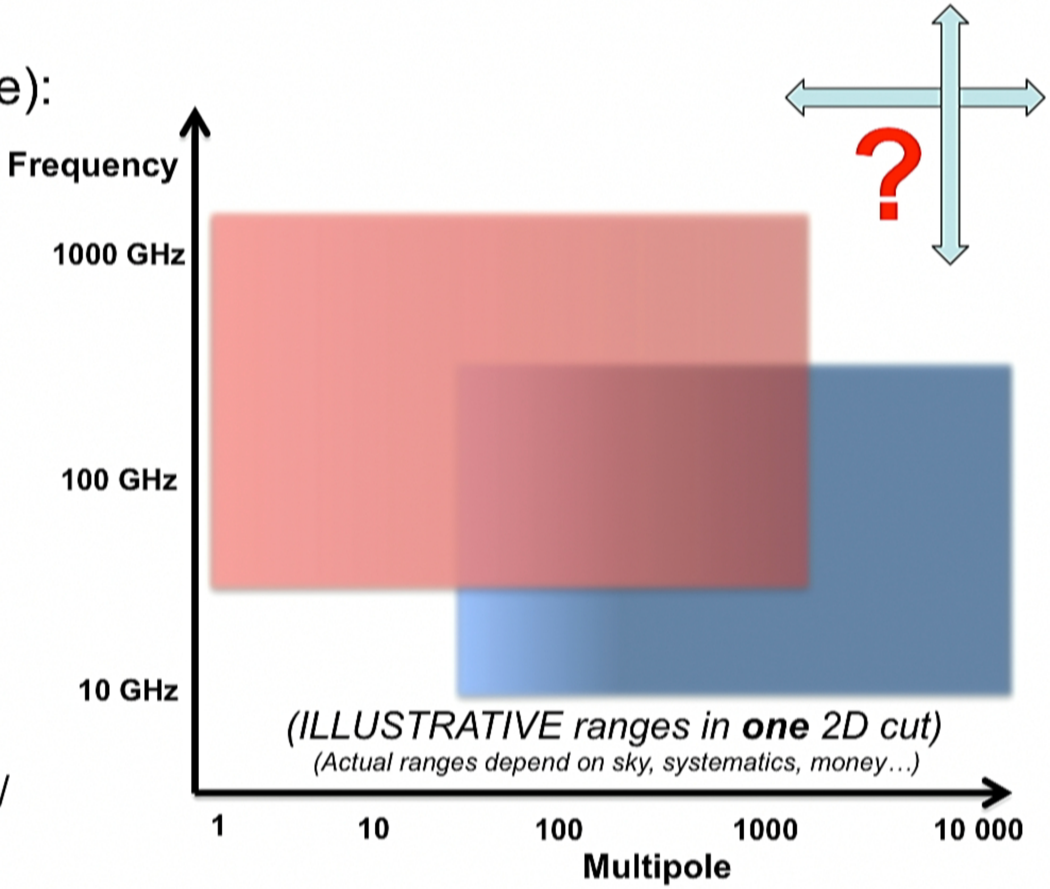
NB: Single iteration delensing

Required synergy of probes

Experimental Parameters (some):

- Frequency coverage
- Angular coverage
- Sky coverage [Xcorr, fnl…]
- Duration of stable conditions (HFI @0.1K0.1mK over 900 days)
- Sensitivity (per nu/ final)

\+ Cost/Timing/…



*(ILLUSTRATIVE ranges in **one** 2D cut)*

(Actual ranges depend on sky, systematics, money…)

(different science in different ranges)

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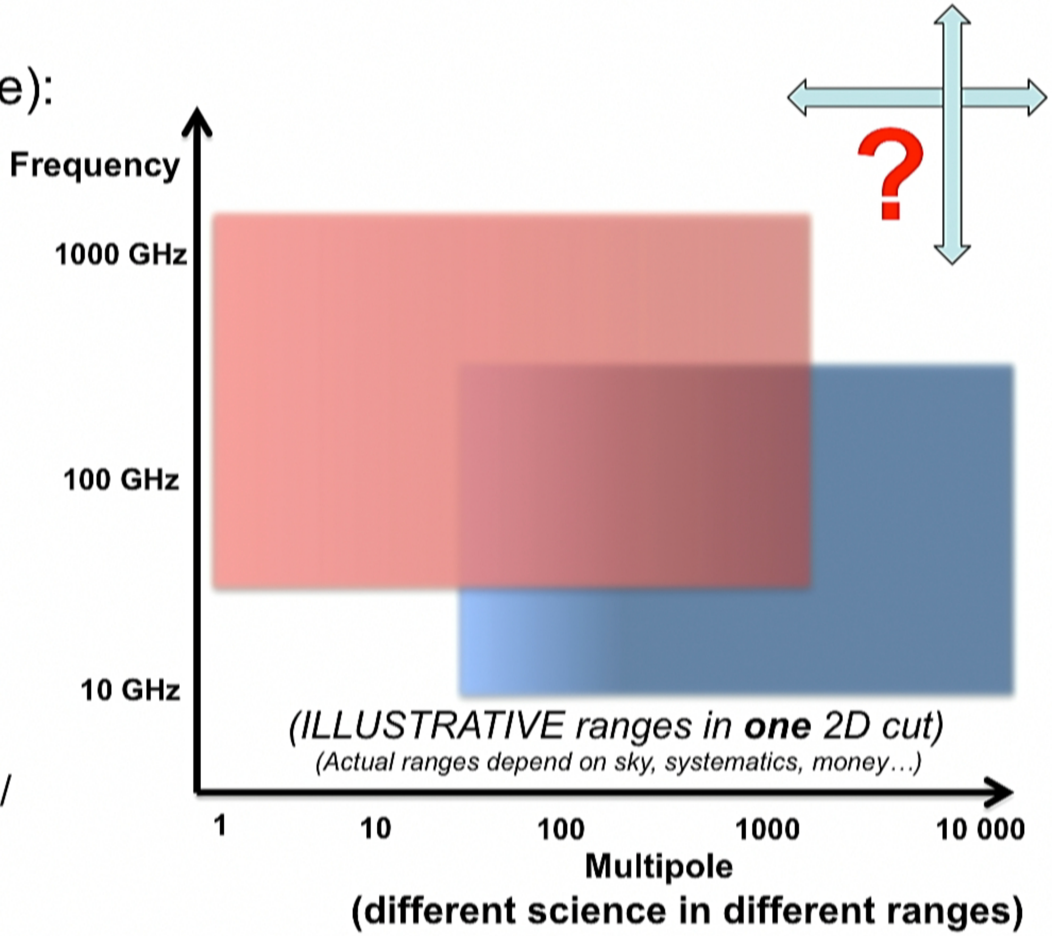

(*ILLUSTRATIVE ranges in* ***one*** *2D cut)*

(Actual ranges depend on sky, systematics, money…)

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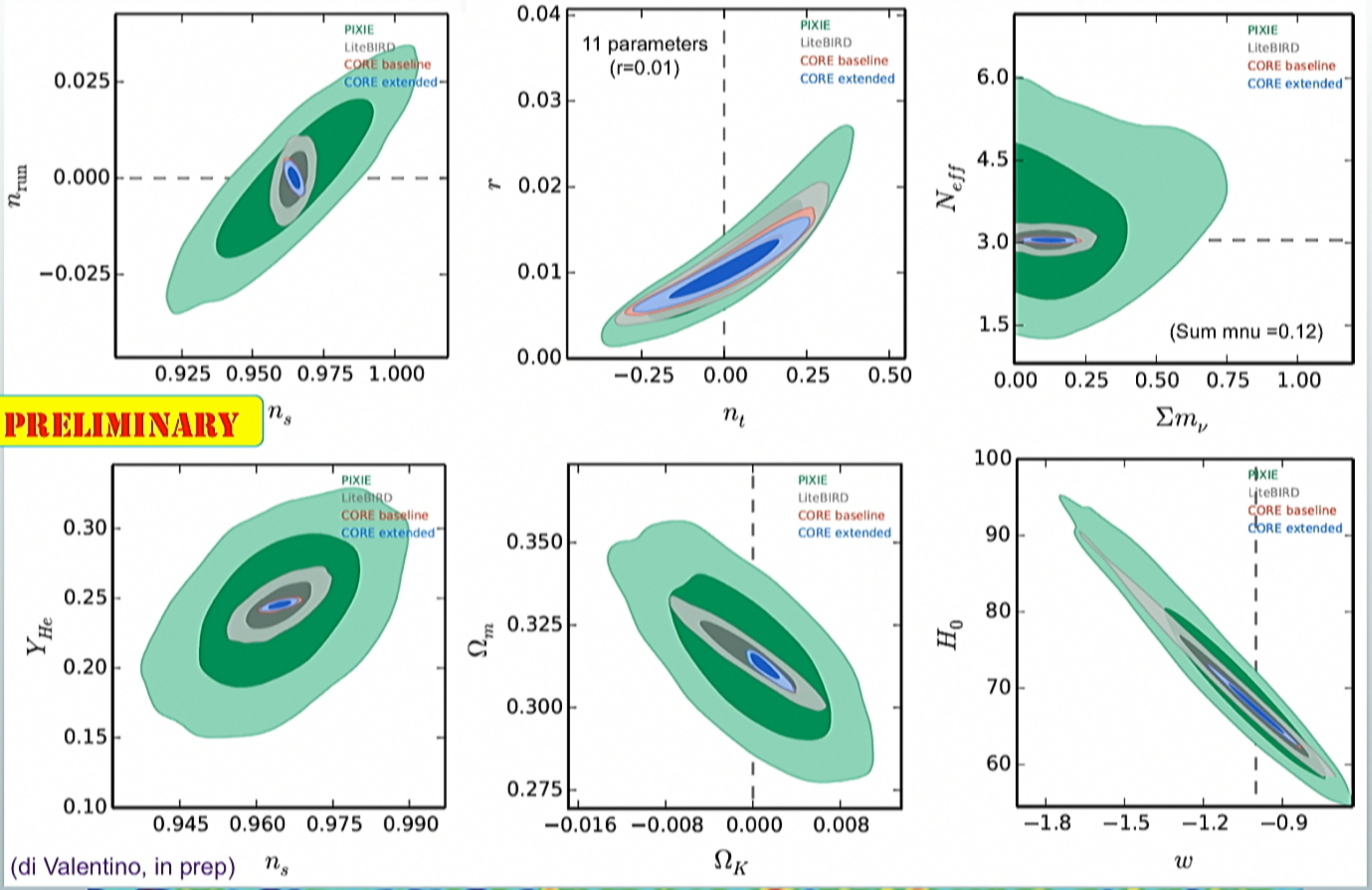
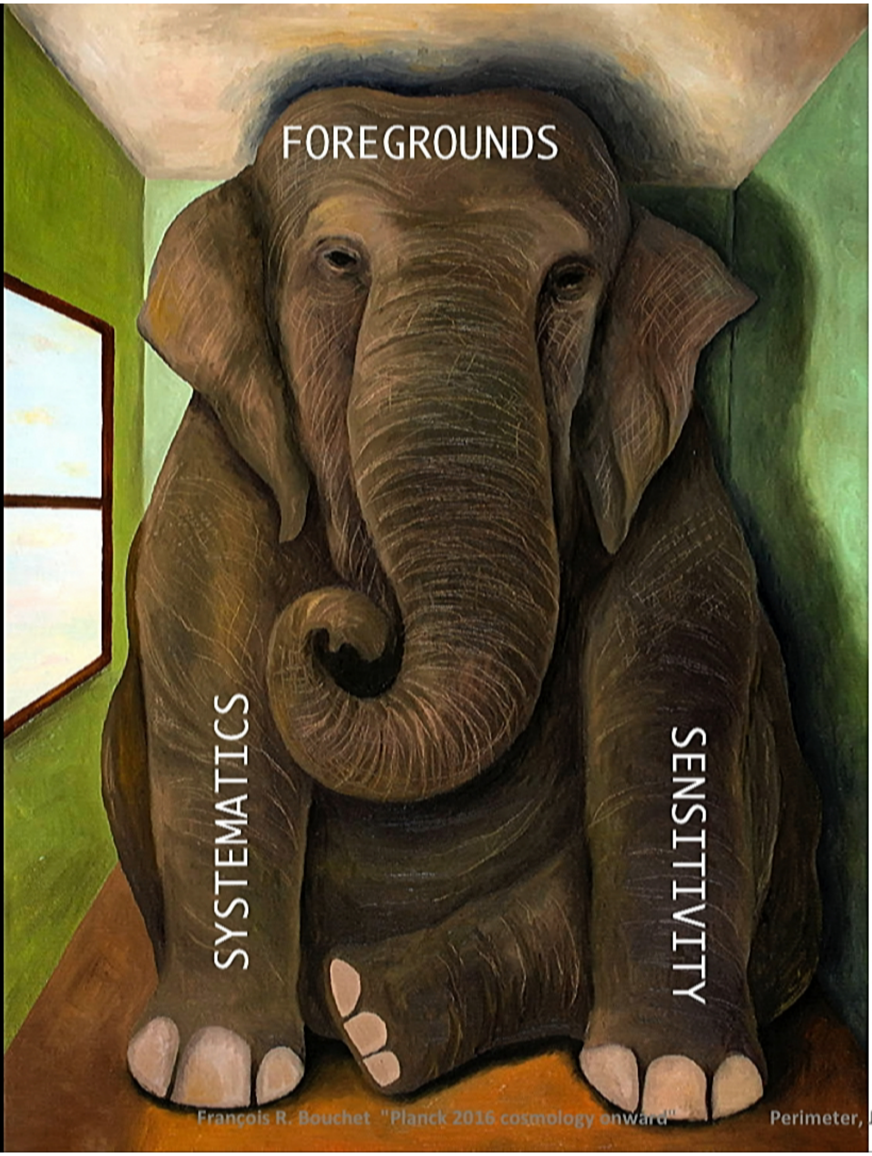
Sats alone (wo delensing)



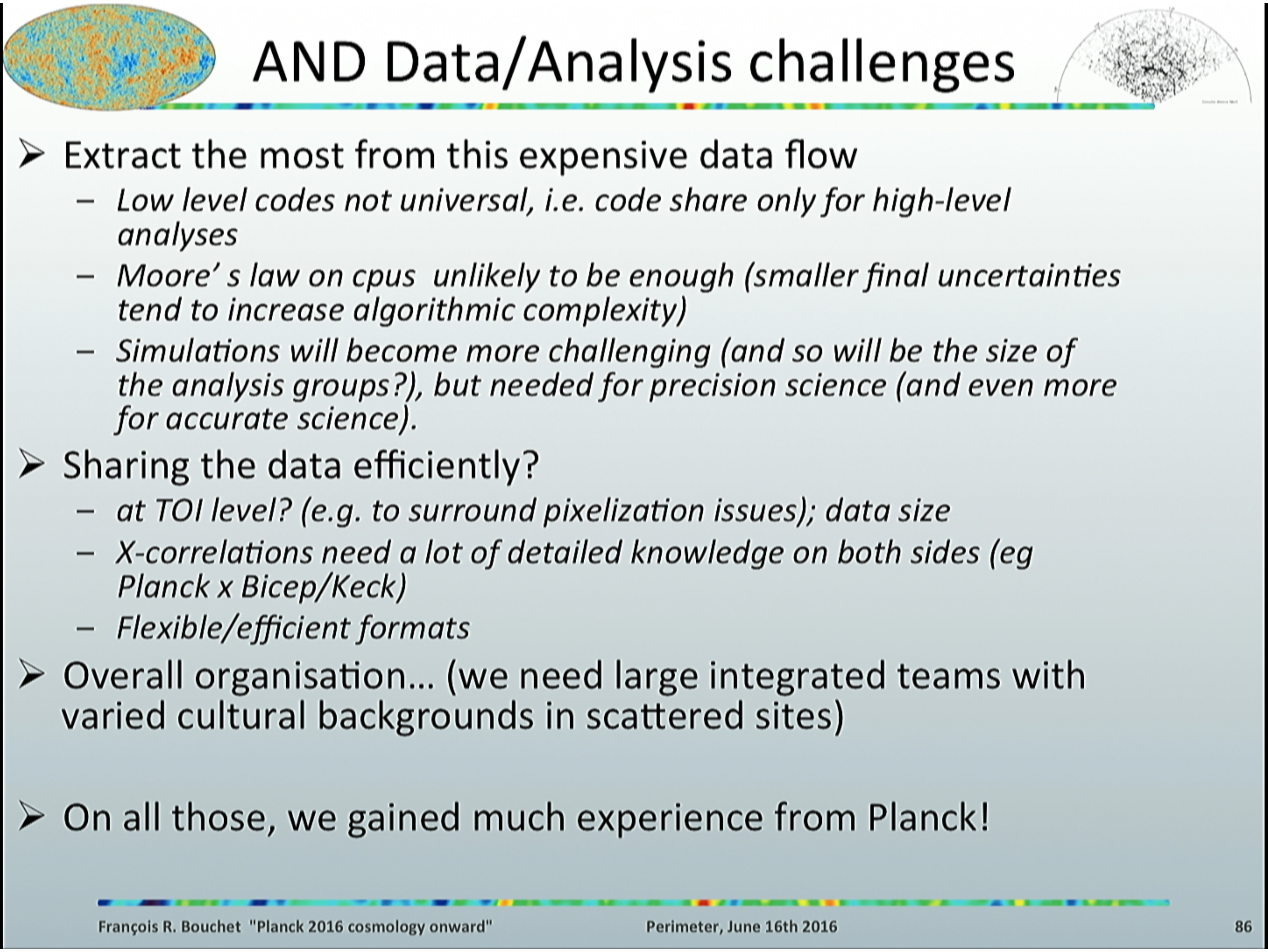
PRELIMINARY

(di Valentino, in prep)



CHALLENGES

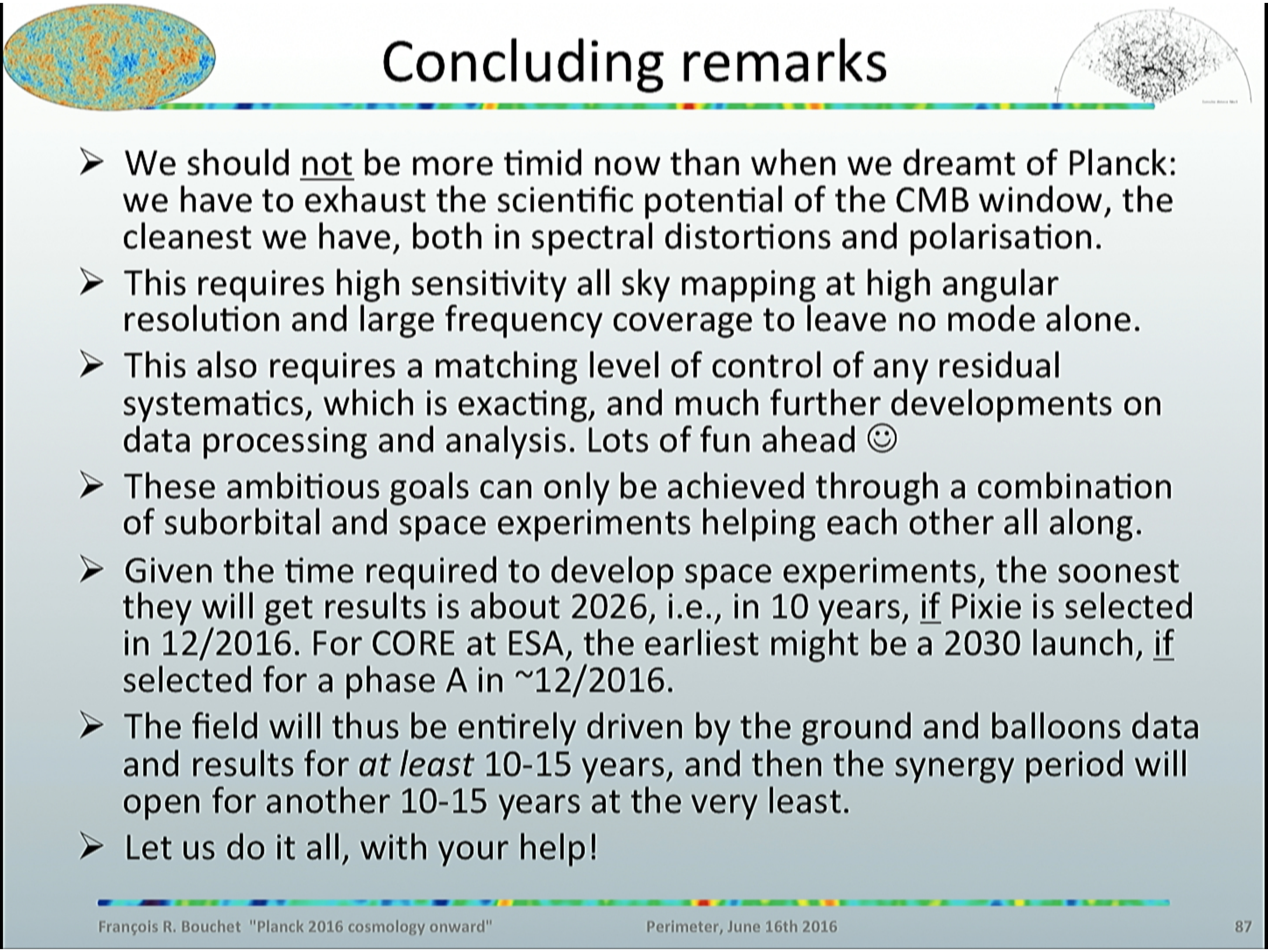
- **BEAMS**: in situ measurement of beams, esp. sidelobes (ν & polzn dependence, stability)
- **BANDPASSES:** in situ characterization, matching, polzn dependence, avoiding CO etc
- **GROUND PICKUP**: shielding, sufficient suppression of scan synchronous pickup, stability
- **I → Q/U LEAKAGE**: ν dependence, polarization dependence, stability, spatial dependence
- **SENSITIVITY**: low loading, high optical throughput
- **CALIBRATION**: stability, dynamic range, ν dependence, pointing jitter
- **POLARIZATION ANGLES**: in situ measurement, ν dependence
- **STRIPING**: minimize 1/f with fast modulation



AND Data/Analysis challenges

- Extract the most from this expensive data flow
  - *Low level codes not universal, i.e. code share only for high-level analyses*
  - *Moore' s law on cpus unlikely to be enough (smaller final uncertainties tend to increase algorithmic complexity)*
  - *Simulations will become more challenging (and so will be the size of the analysis groups?), but needed for precision science (and even more for accurate science).*
- Sharing the data efficiently?
  - *at TOI level? (e.g. to surround pixelization issues); data size*
  - *X-correlations need a lot of detailed knowledge on both sides (eg Planck x Bicep/Keck)*
  - *Flexible/efficient formats*
- Overall organisation… (we need large integrated teams with varied cultural backgrounds in scattered sites)

- On all those, we gained much experience from Planck!



Concluding remarks

- We should not be more timid now than when we dreamt of Planck: we have to exhaust the scientific potential of the CMB window, the cleanest we have, both in spectral distortions and polarisation.
- This requires high sensitivity all sky mapping at high angular resolution and large frequency coverage to leave no mode alone.
- This also requires a matching level of control of any residual systematics, which is exacting, and much further developments on data processing and analysis. Lots of fun ahead ☺
- These ambitious goals can only be achieved through a combination of suborbital and space experiments helping each other all along.
- Given the time required to develop space experiments, the soonest they will get results is about 2026, i.e., in 10 years, if Pixie is selected in 12/2016. For CORE at ESA, the earliest might be a 2030 launch, if selected for a phase A in ~12/2016.
- The field will thus be entirely driven by the ground and balloons data and results for *at least* 10-15 years, and then the synergy period will open for another 10-15 years at the very least.
- Let us do it all, with your help!