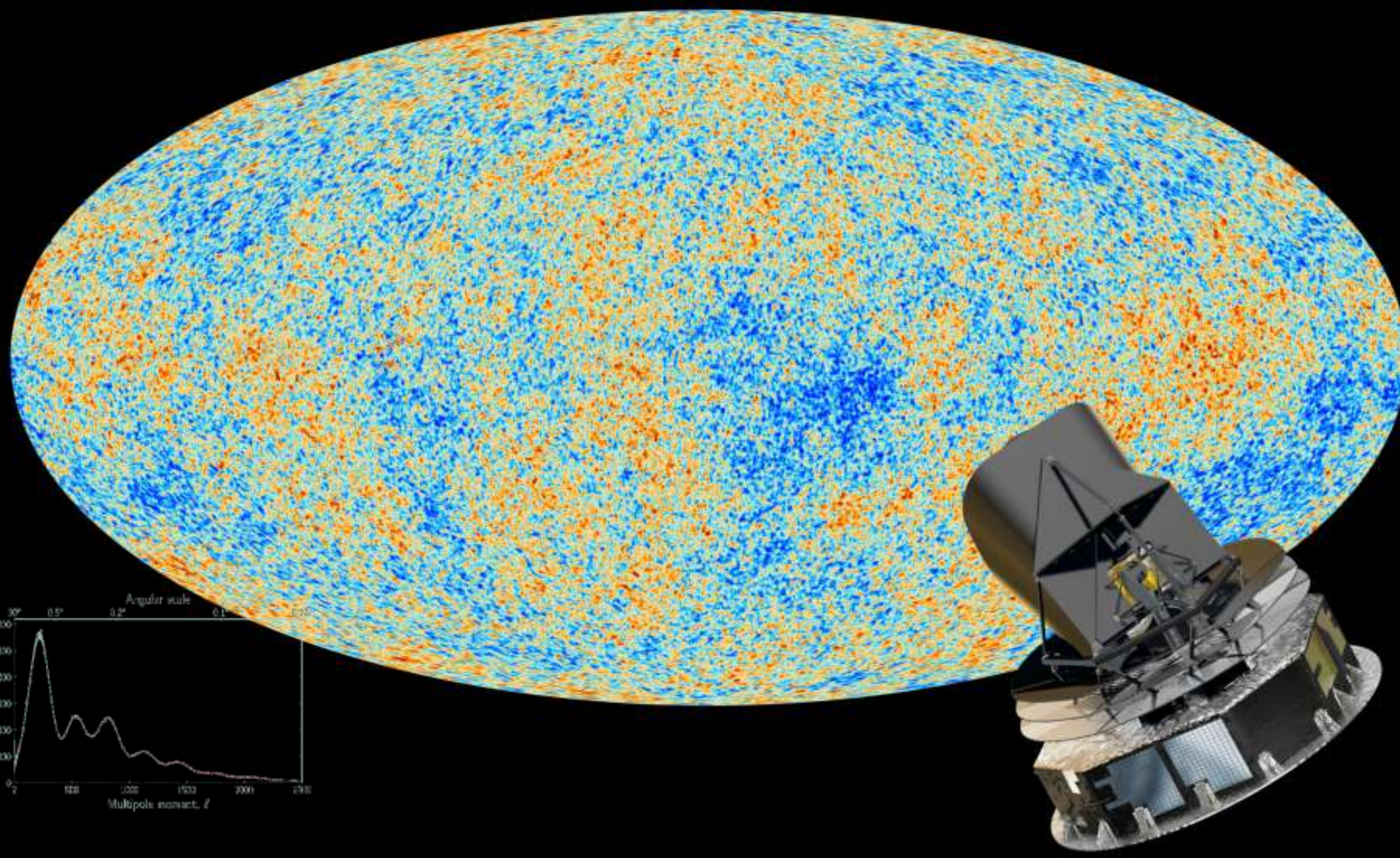
Un bilan de Planck



François R. Bouchet, Institut d'Astrophysique de Paris

The Planck mission concept/challenge

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

  ⇒ *enough sensitivity within large frequency range [30 GHz, 1 THz]*
  (~CMB photon noise limited for ~1yr in CMB primary window)

- get the best performances possible on the polarization with the technology available

⇒ ESA selection in 1996 (after ~ 3 year study)

NB: This required a number of technological breakthrough

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

Planck Milestones

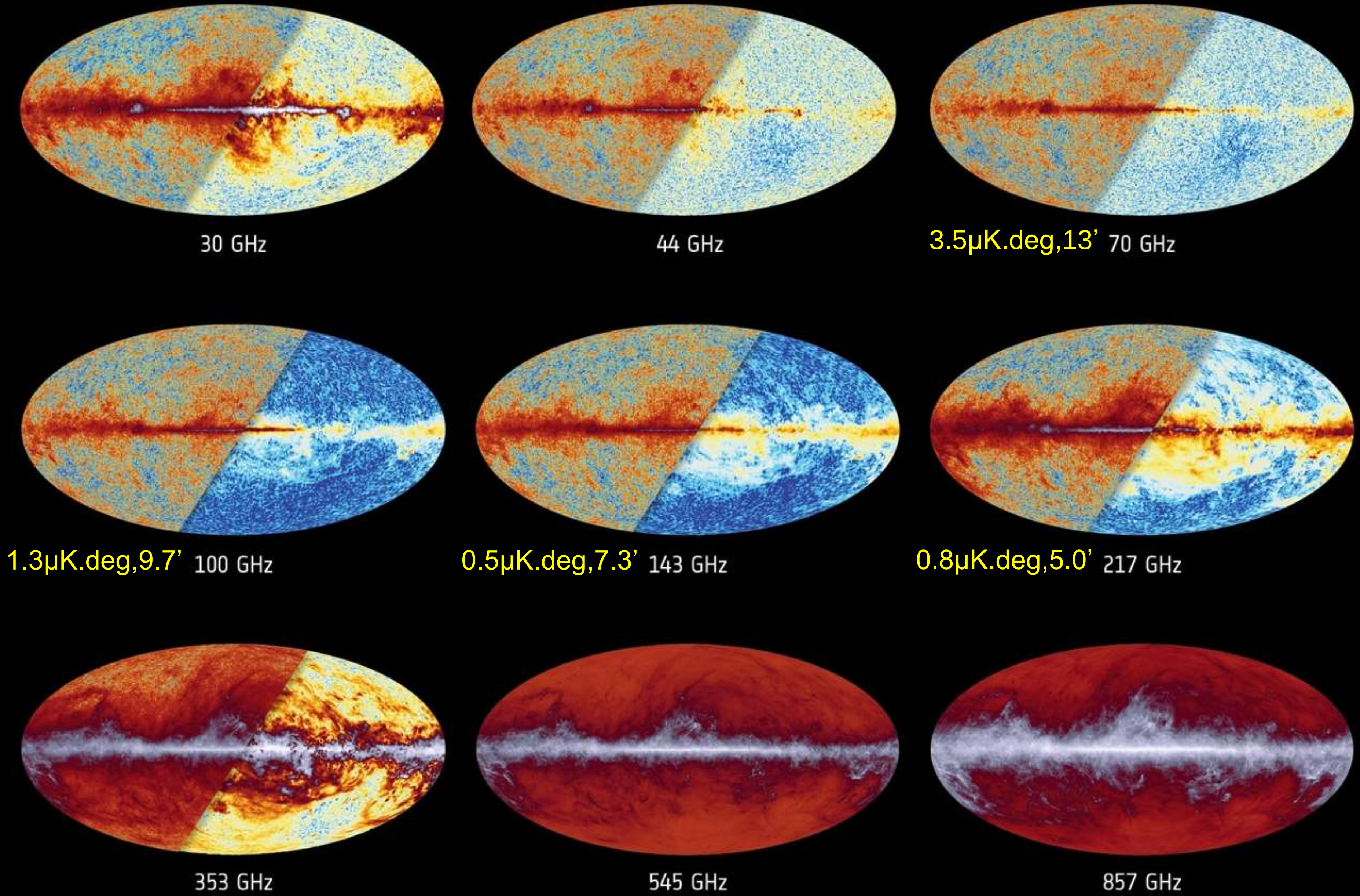
- 1993: CNES & ESA (accepted) proposals, followed by a 3 years phase A study with ESA
- 1996 Selection by ESA (for a 2003 launch)
- …. (industry in, consortia in, design & tests…)
- 2009 May 14th : Launch from Kourou, French Guyana.

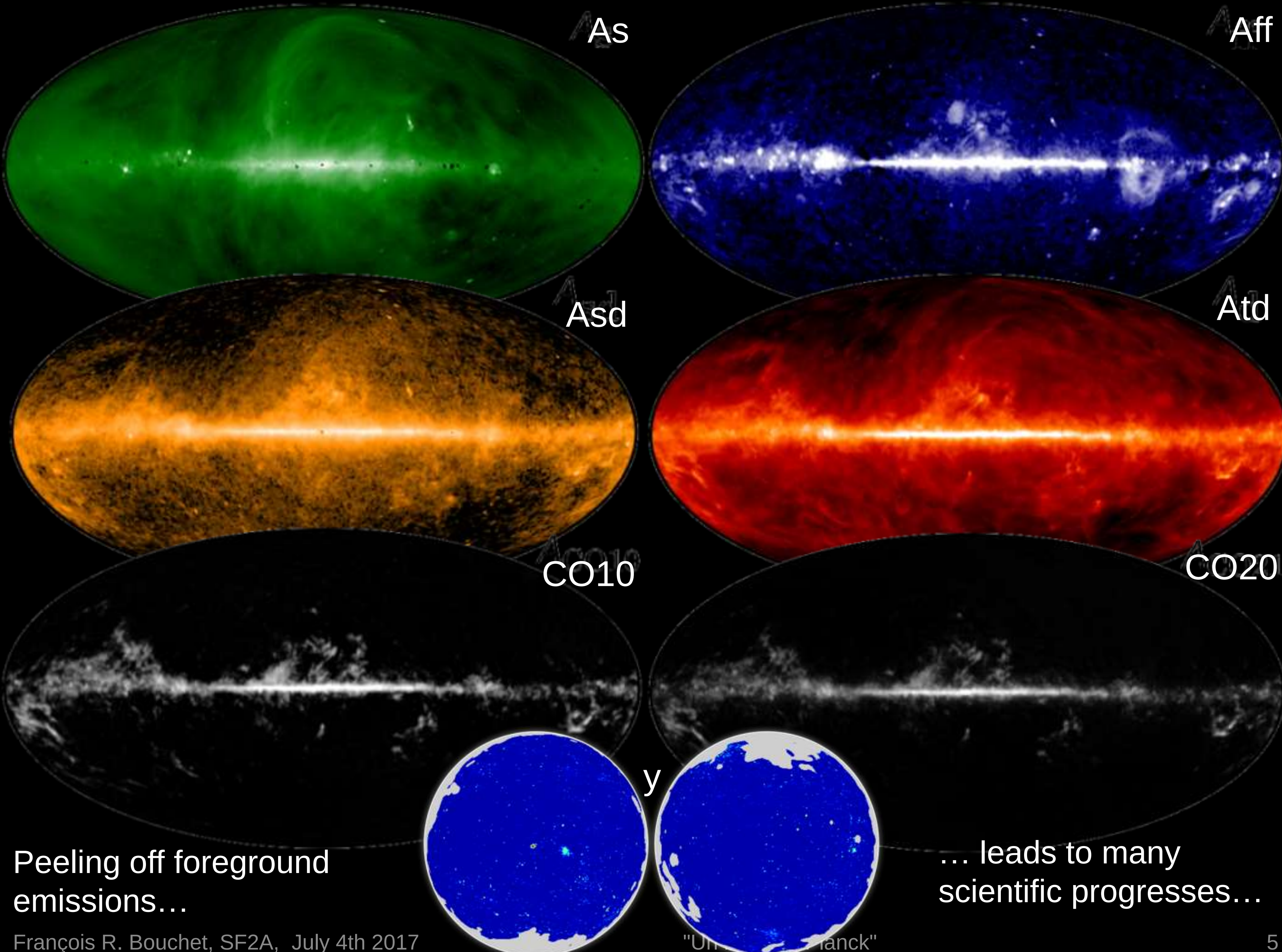
- 2009 August 13th : beginning of survey: Instruments very stable; Essentially no hiccups since, till the end of HFI: Details in 16 monthly reports to MOC, 13 bi-monthly to PSO (150 p. each), 138 « operation » teleconf. minutes, 169 weekly reports to MOC, 91 « cryo » teleconf., 8 coordination meetings, 978 daily quality reports & 127 HFI weekly health reports (97 800 plots), 1278 pages wiki écrites ou co-écrites …:

- 2010 June : first complete coverage of the sky by all detectors obtained with the first nearly 10 months of survey data.
- → 2011 January: ERCSC release & 25 "Planck early results" papers;
- 2010 November 27th : Nominal mission completed, having collected about 15.5 months of survey data insuring that all the sky at been seen at least twice by each detector:
  - *22 "Planck Intermediate results" papers on CMB foregrounds submitted in 2012-14*
- → 2013 March: First Cosmology release (T only), with 32 "Planck 2013 results" papers;
- 2012 Jan 14th**:** all HFI survey data acquired! 885 days of acquisition, 900 billion samples, 5 surveys, ~30 months, full mission = twice the nominal duration. LFI continues to 8th survey followed by warm tests → 2013 Oct 23rd: last command (off!) to the spacecraft from Darmstadt control room…
- → 2015 February: Second Cosmology release, based on data from the entire Planck mission, including both temperature and polarization (preliminary), along with 28 "Planck 2015 results" papers.

- → 2017 fall: "legacy release" with ~10 papers. (NB: about 33 more papers published between releases)

Disponible maintenant, chez vous!



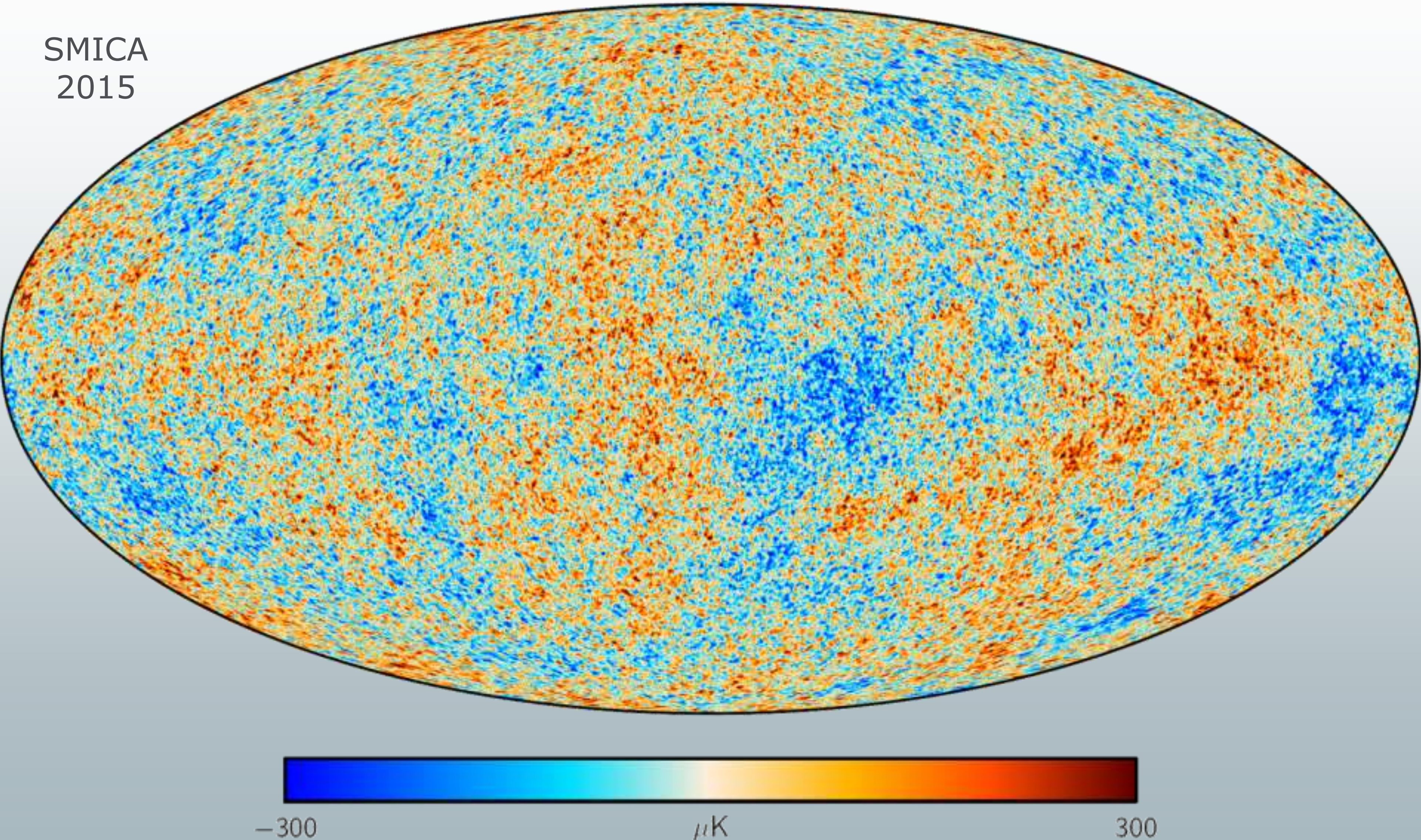


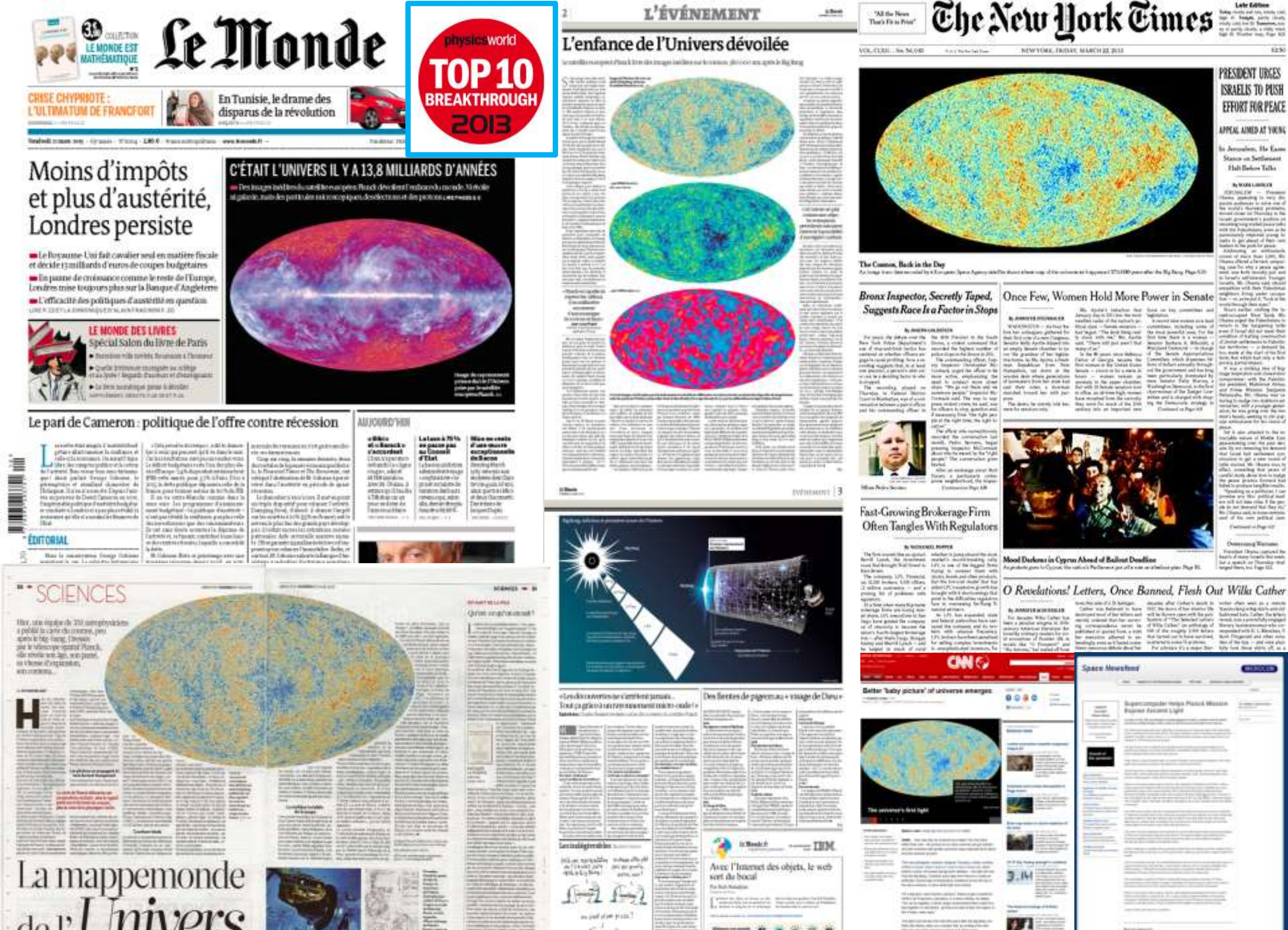
Peeling off foreground emissions…

… leads to many scientific progresses…

Planck 2015 T anisotropies map

SMICA
2015



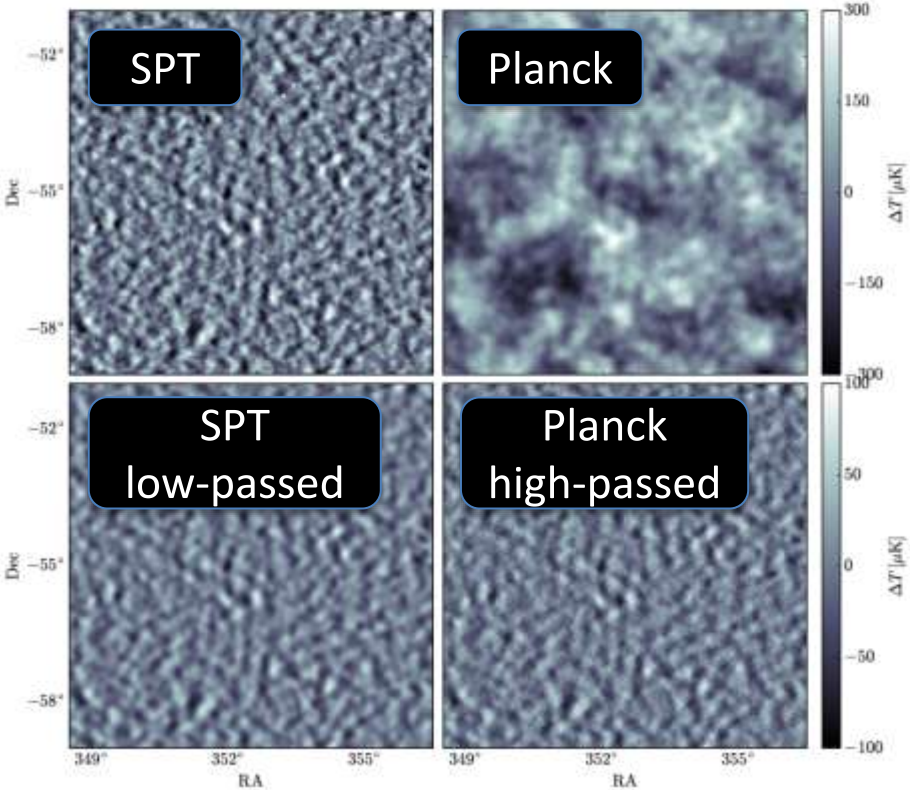

Le Monde
physicsworld
TOP 10 BREAKTHROUGH 2013
CRISE CHYPRIOTE : L'ULTIMATUM DE FRANCFORT
En Tunisie, le drame des disparus de la révolution
Moins d'impôts et plus d'austérité, Londres persiste
C'ÉTAIT L'UNIVERS IL Y A 13,8 MILLIARDS D'ANNÉES
LE MONDE DES LIVRES
Spécial Salon du livre de Paris
Le pari de Cameron : politique de l'offre contre récession
AUJOURD'HUI
ÉDITORIAL
L'ÉVÉNEMENT
L'enfance de l'Univers dévoilée
The New York Times
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
SCIENCES
La mappemonde de l'Univers
Des fientes de pigeon au « visage de Dieu »
Avec l'Internet des objets, le web sort du bocal
CNN
Better 'baby picture' of universe emerges
The universe's first light
Space Newsfeed
Supercomputer Helps Planck Mission Expose Ancient Light

SPT@150GHz vs planck@143GHz

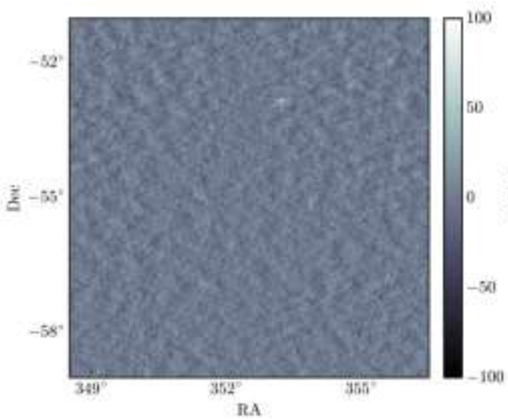
Hou+ arXiv:1704.00884v1

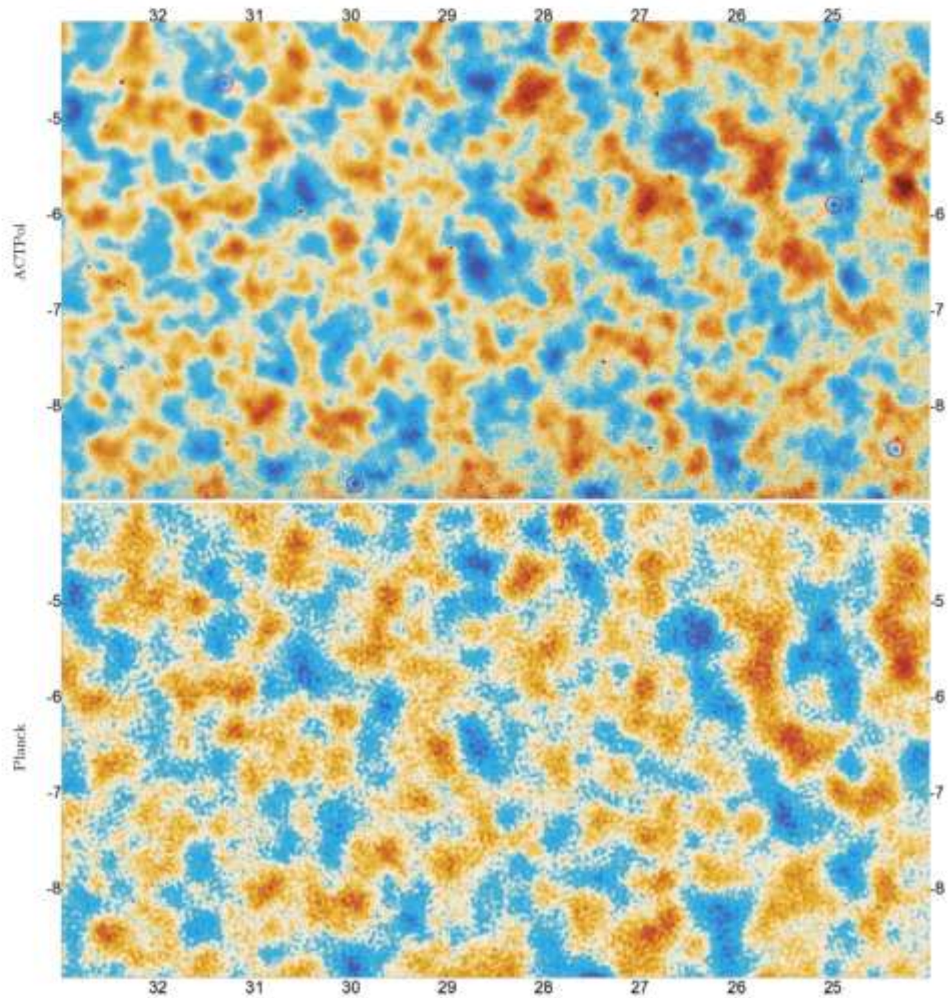
ACT@150GHz vs planck@143GHz

Louis+ arXiv:1610.02360v1



Little residual in SPT-low minus Planck-high
But a variable source





A theories-measurements contact

The harmonic modes

$$a_{lm} = \int d^2\hat{n}\, T(\hat{n})\, Y^*_{lm}(\hat{n}) \quad ,$$

obey, for a statistically isotropic field,

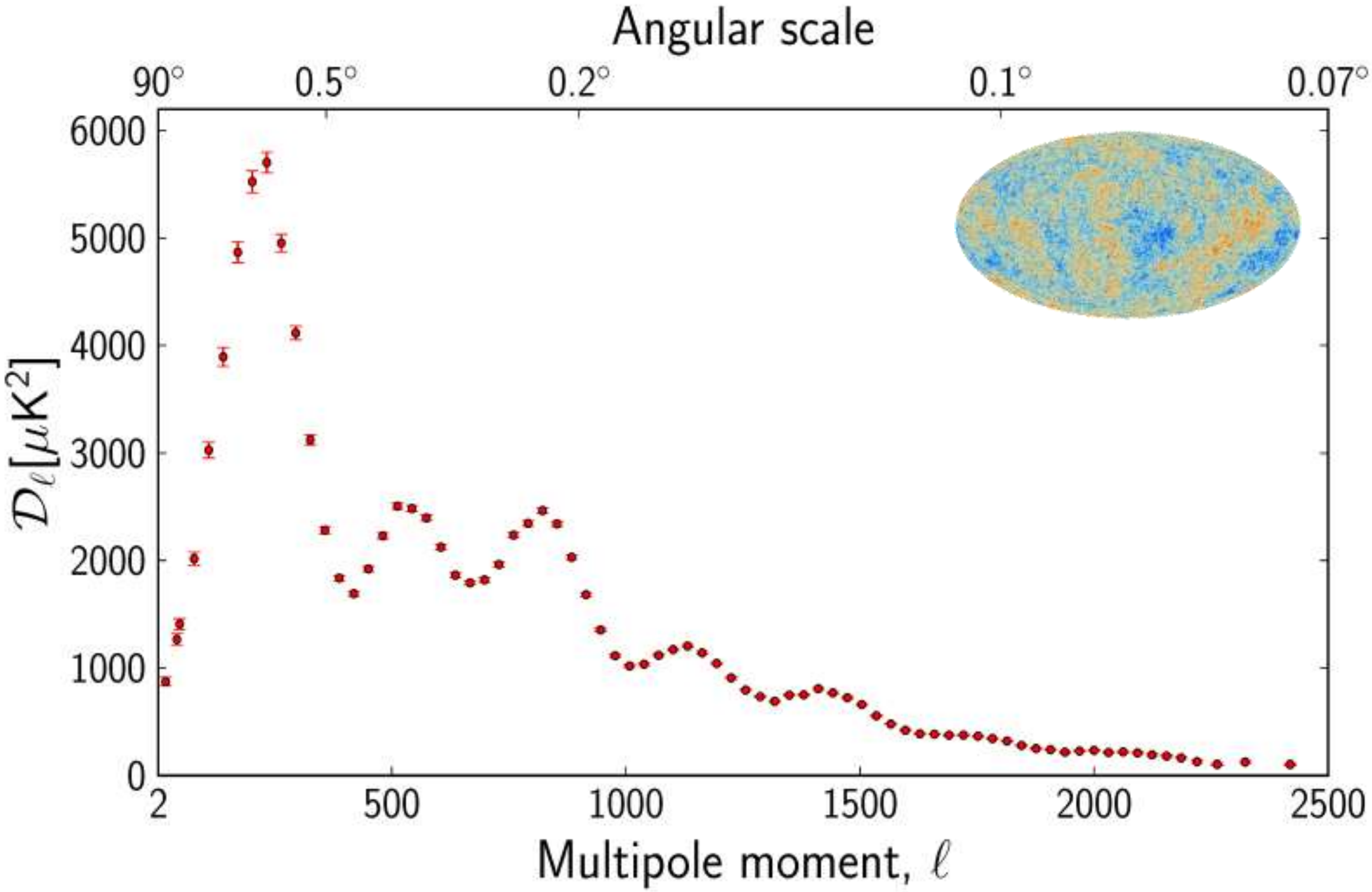
$$< a_{\ell m}\, a_{\ell' m'} > = C_\ell\, \delta_{\ell\ell'}\, \delta_{mm'}$$

The temperature angular **power spectrum** is estimated in practice by

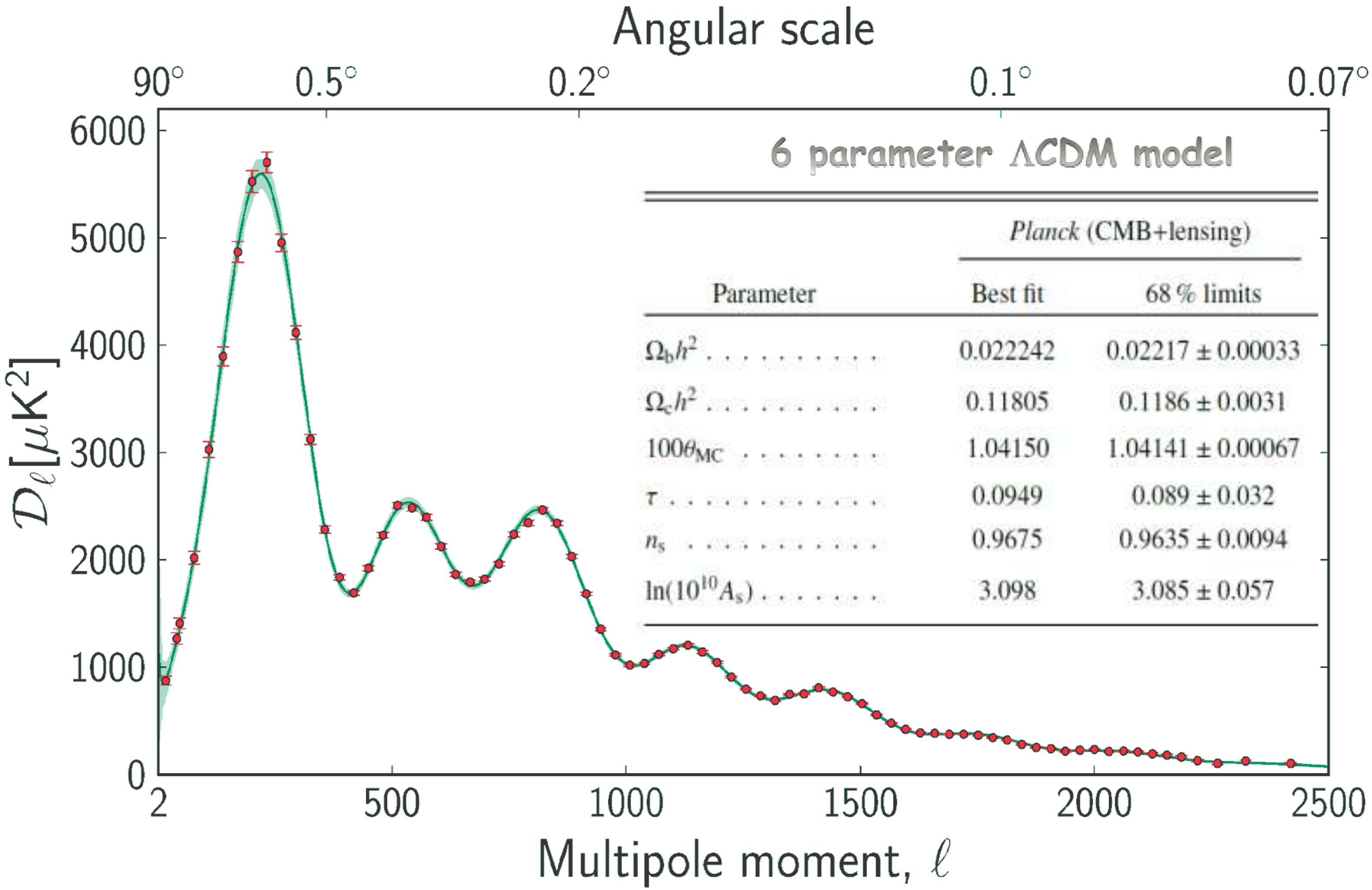
$$\widehat{C_\ell} = \sum_m \frac{|a_{\ell m}|^2}{2\ell + 1}$$

The bi- and tri-spectra may be used to test for NG, NB: biposh coeff.

The Planck power spectrum of Temperature anisotropies



Theory confronts data



Parameter	*Planck* (CMB+lensing) Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067
τ	0.0949	0.089 ± 0.032
n_s	0.9675	0.9635 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057

Le modèle ΛCDM minimal à 6 paramètres

3 paramètres pour déterminer (via la Relativité générale) la dynamique de l'Univers,
1 paramètre pour rendre compte de la réionisation (la fin des âges sombres),
2 paramètres pour décrire les fluctuations primordiales.
Une géométrie spatiale plate.

- $\Omega_b h^2$ Densité baryonique aujourd'hui – La quantité de matière ordinaire
- $\Omega_c h^2$ Densité de matière sombre froide – n'interagit que faiblement
- Θ Taille de l'horizon sonore quand la profondeur optique τ atteint l 'unité
  (Distance parcourue par une onde sonore depuis l'inception, quand l'Univers est devenu transparent, à la recombinaison vers t ~380 000 ans)

- τ Profondeur optique à la réionisation (due aux diffusion Thomson photons sur e^-),i.e. fraction des photons du CMB photons diffusés entre la réionisation et nous

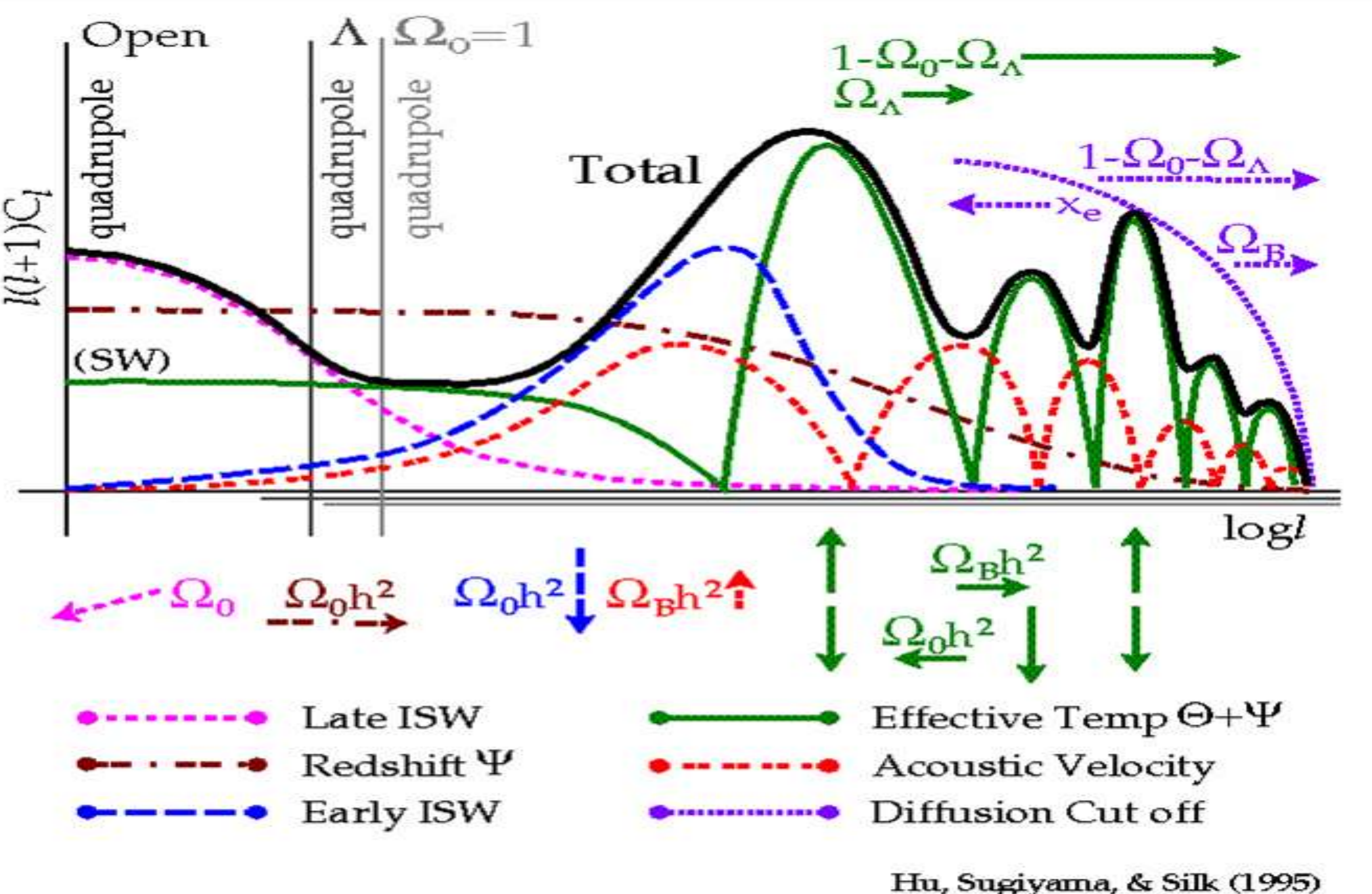
- A_s Amplitude du spectre de puissance de la courbure
  (Contraste global des fluctuations primordiales)
- n_s Exposant de la loi de puissance du spectre Scalaire
  (n_s-1 mesure l'écart à l'invariance d'échelle)

- Les autres paramètres sont *dérivés* au sein du modèle, en particulier
  - *Ω La fraction d'"Energie sombre" (dérivée seulement en supposant la platitude)*
  - *H_0 le taux d'expansion aujourd'hui (en km/s par Mpc de séparation)*
  - *t_0 l'âge de l'univers (en Gans)*

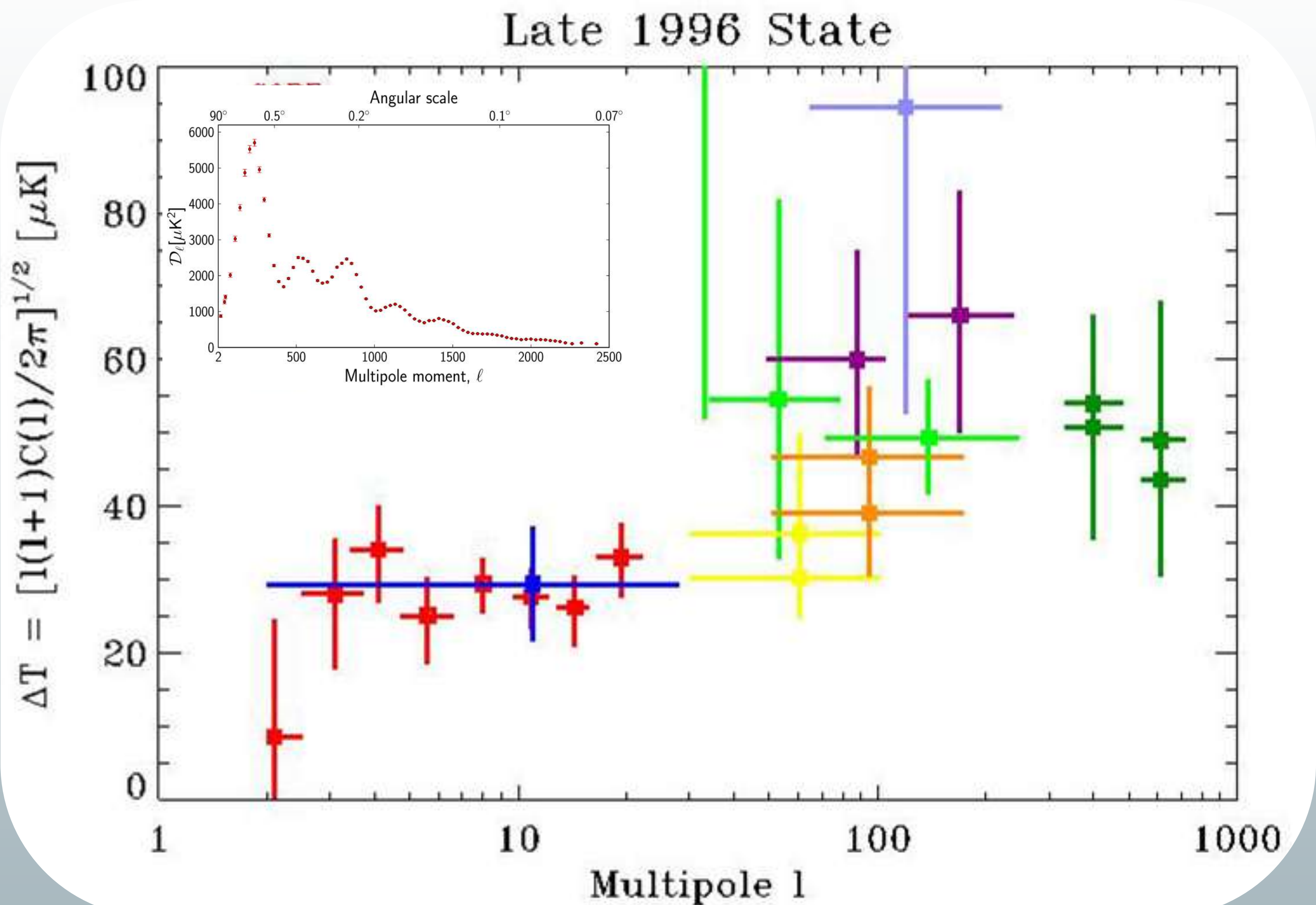
“Ave les mains”

- Normalisation du P(k)← Amplitude bas-ell
- Pente log du P(k) ← rapport bas/haut-ell
- Horizon acoustique ← localisation du 1er pic   (H_0)
- Densité de matière totale ←contraste entre les pics
- Densité baryonique ← rapport d’amplitudes des pics pairs/impairs
- Profondeur optique à la réionisation: bosse en EE (surtout)
- Etc..
- Il existe des dégénérescences (levées plus ou moins avec une précision croissante)

Power spectrum shape and cosmological parameters



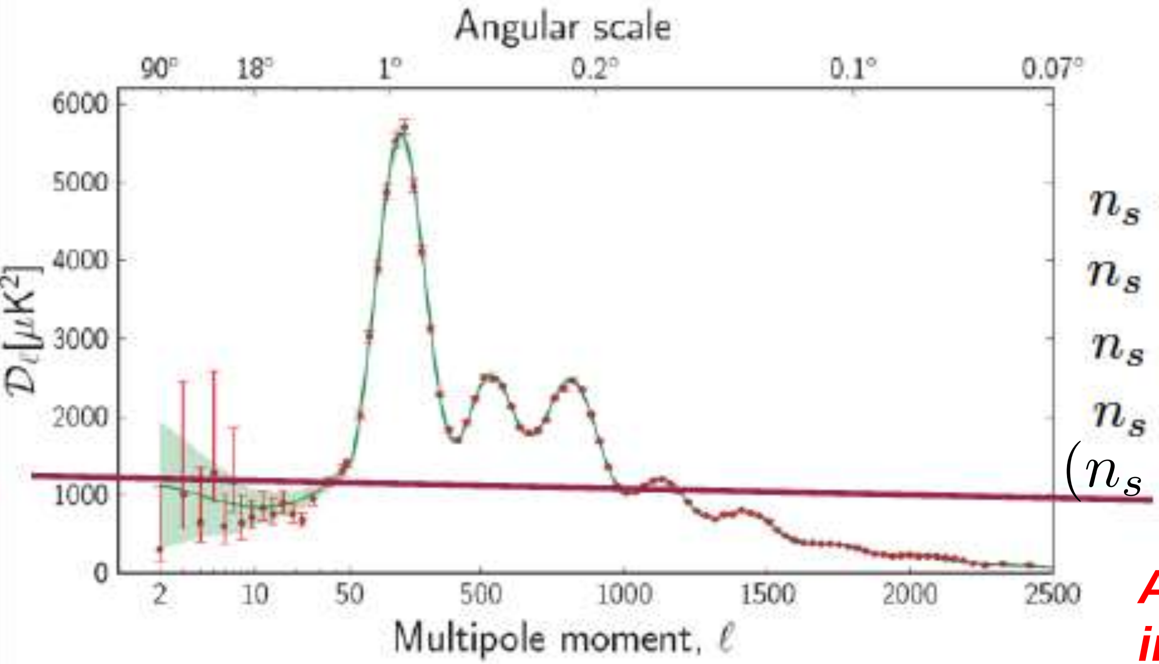
When Planck (& WMAP) were selected



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)

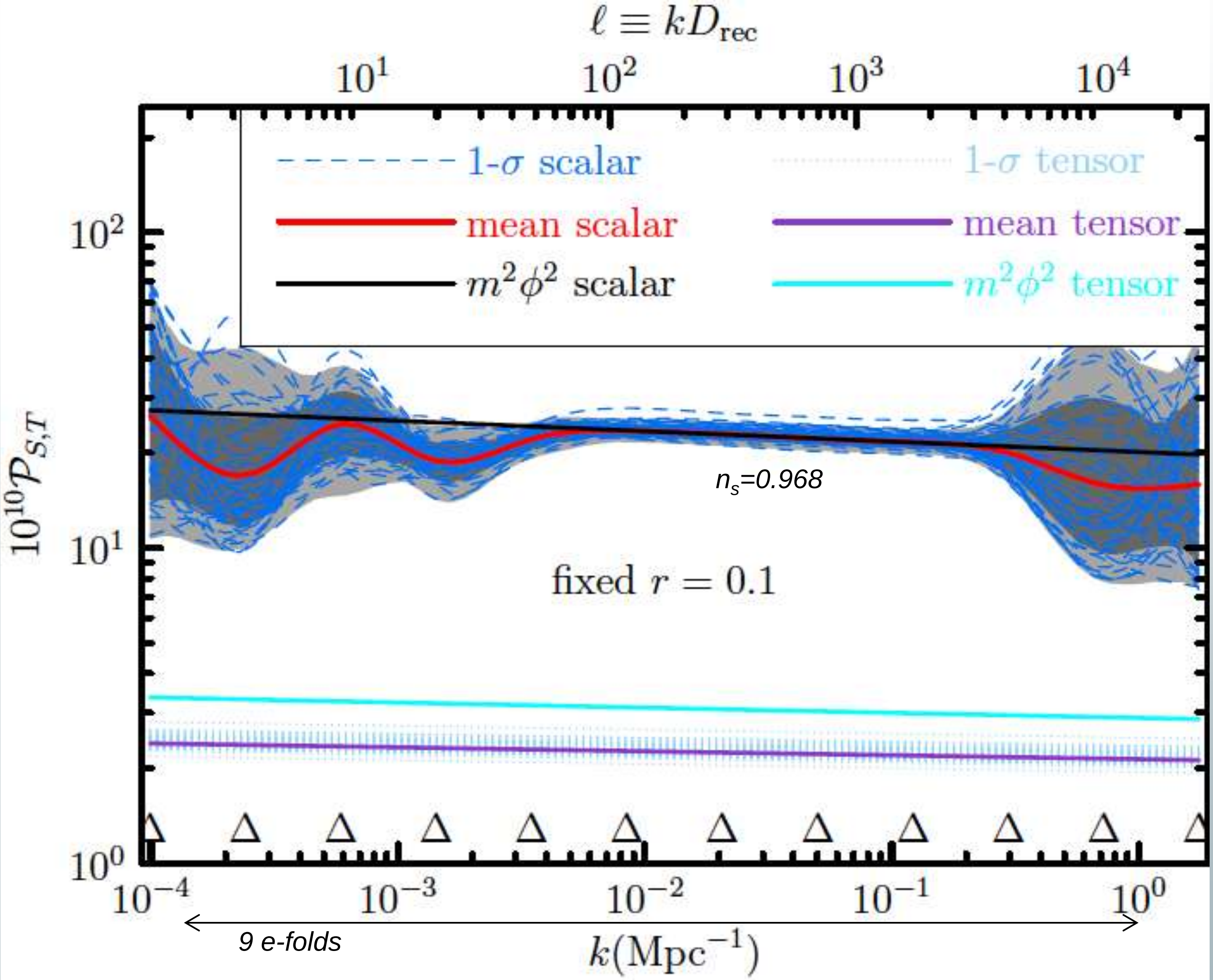
$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)

($n_s = 0.965 \pm 0.006$ 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

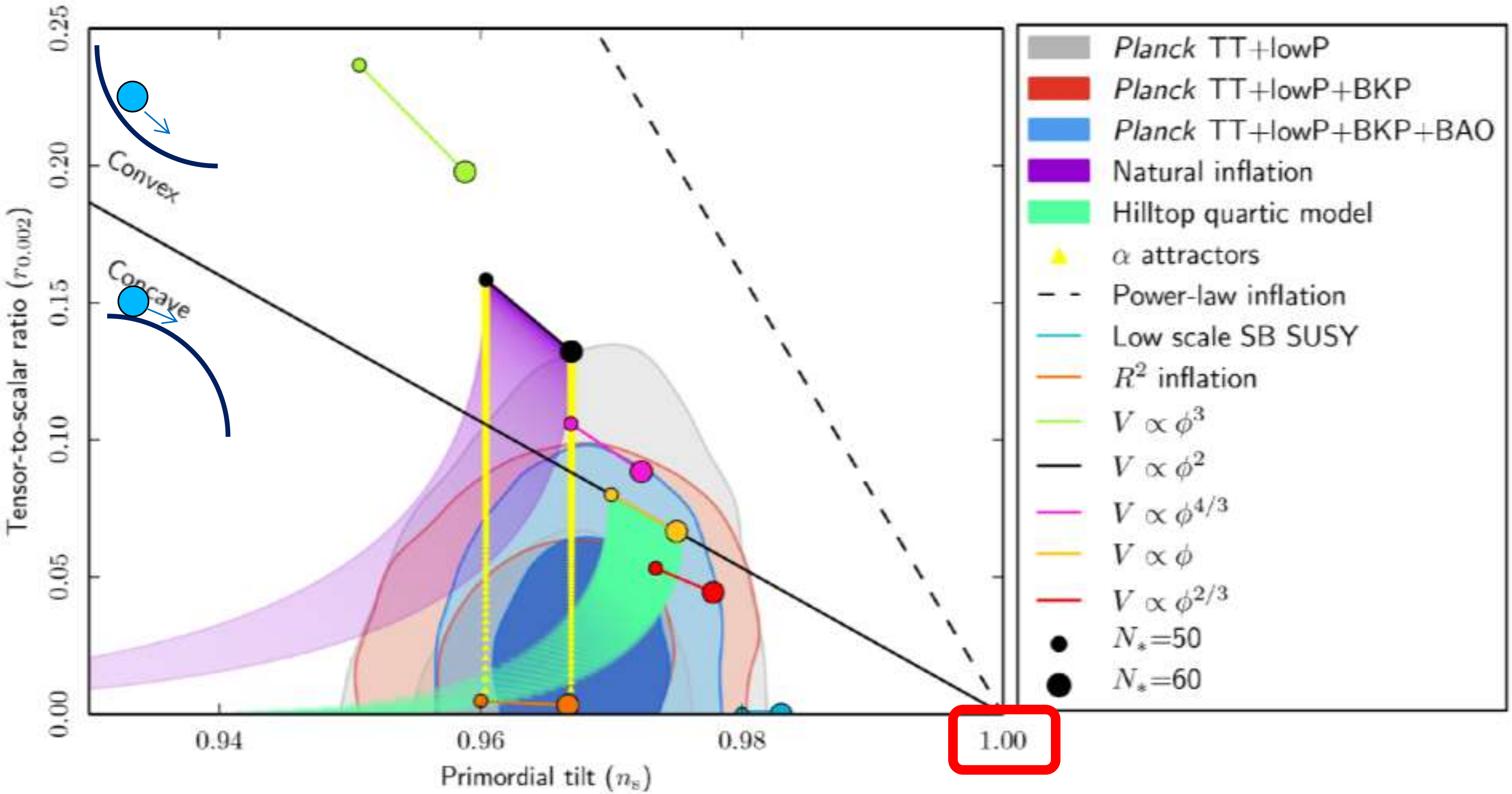
+Hlow

12-knots power spectra

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

Planck 2015: n_s vs r

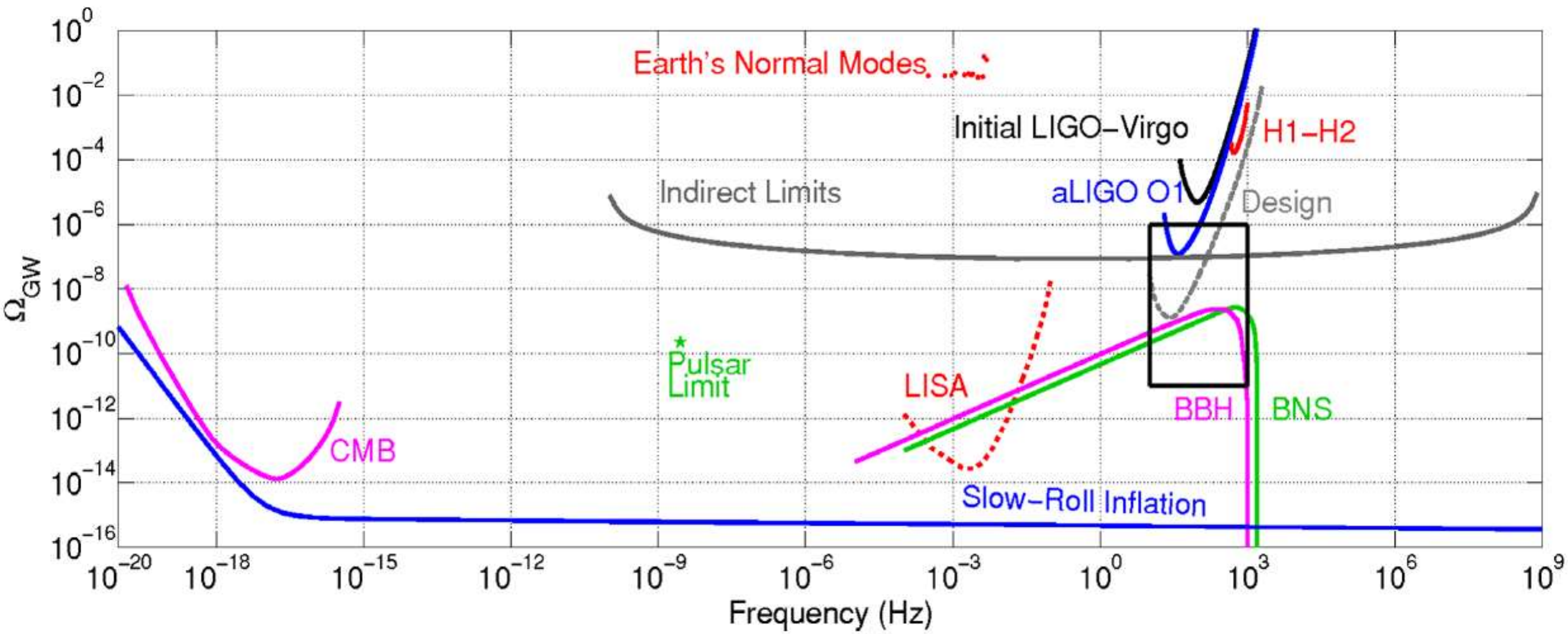
$V_* = (1.9 \times 10^{16}\ \text{GeV})^4\ (r/0.12)$



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

CMB versus other GW detectors

2017) March 27 PHYSICAL REVIEW LETTERS

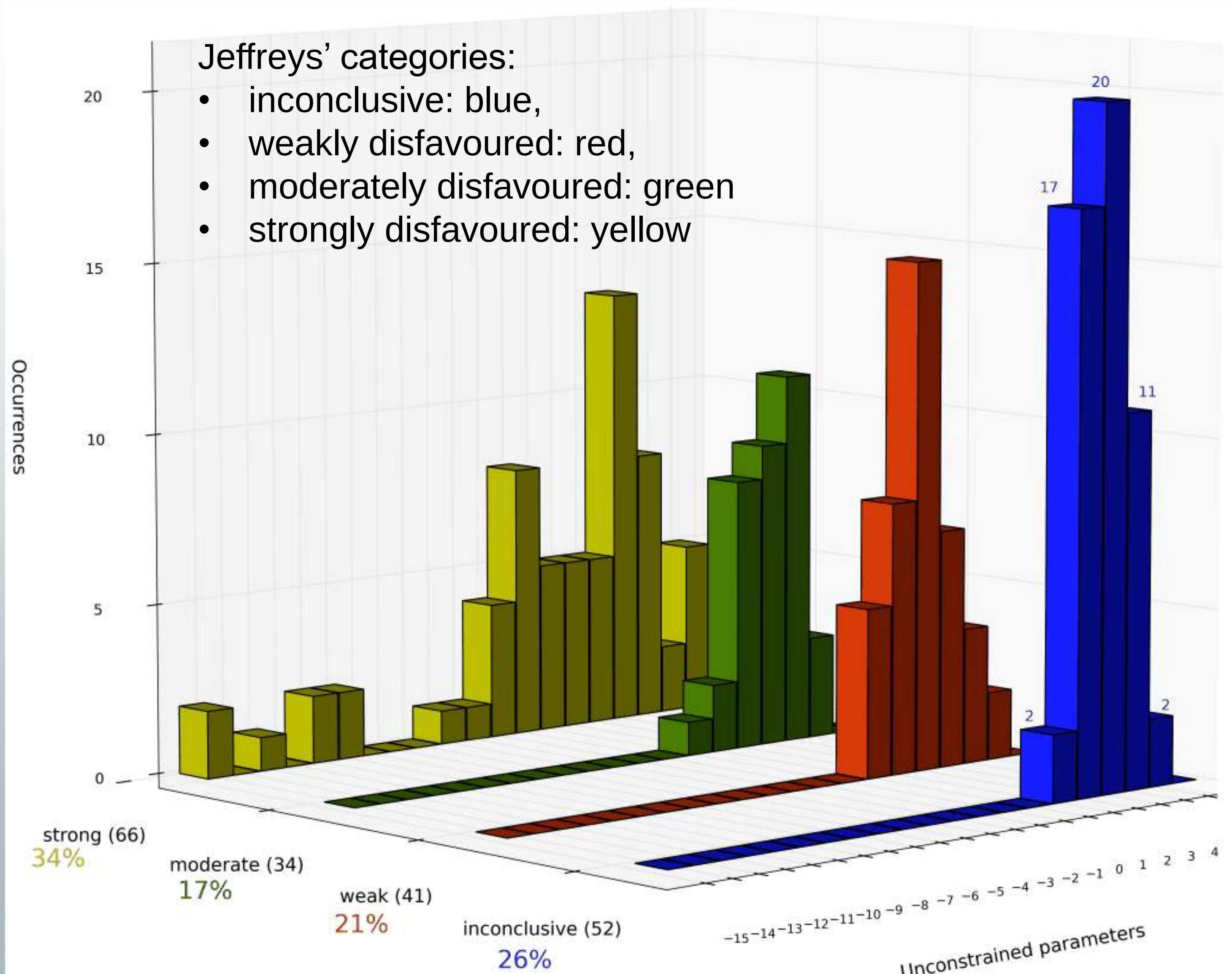


For the not-too-distant future, direct local detections can only constrain non-scale invariant primordial GW backgrounds

➔ Dedicated CMB experiments might soon (or not) yield a detection

Single field slow-roll models

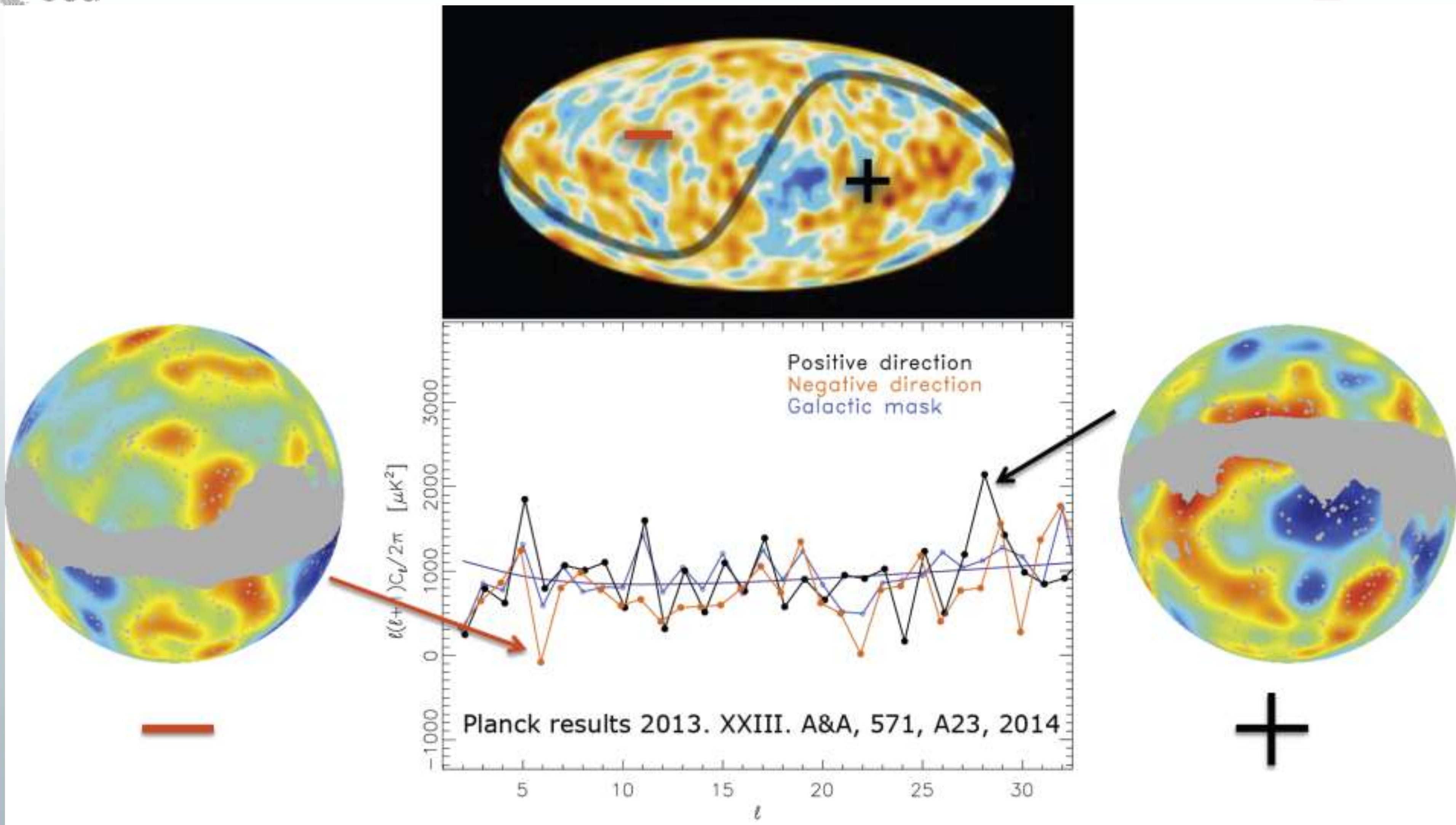
Jeffreys' categories:
- inconclusive: blue,
- weakly disfavoured: red,
- moderately disfavoured: green
- strongly disfavoured: yellow



archiv/1303.3787

"models" include different priors

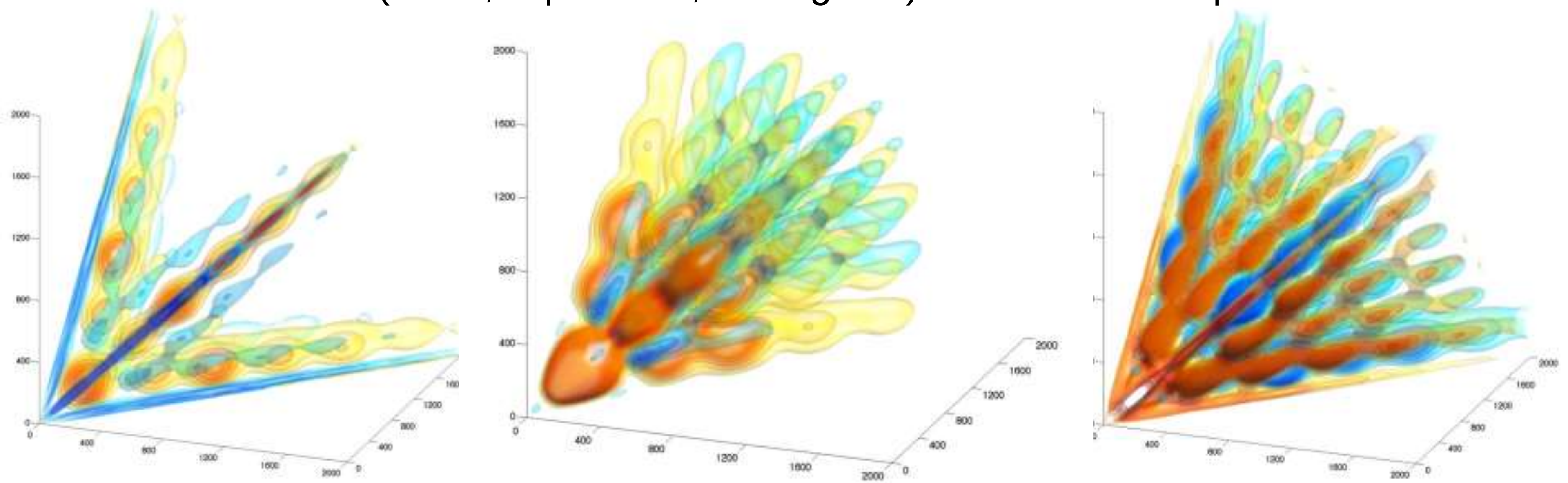
Power asymmetry



Mais pas de non gaussianité à petite échelle (fnl, gnl…)

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

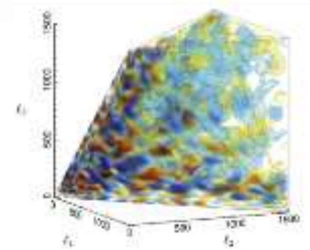
NG of ***orthogonal*** type ($k_1 \sim 2k_2 \sim 2k_3$) :

- 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	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	Binned	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

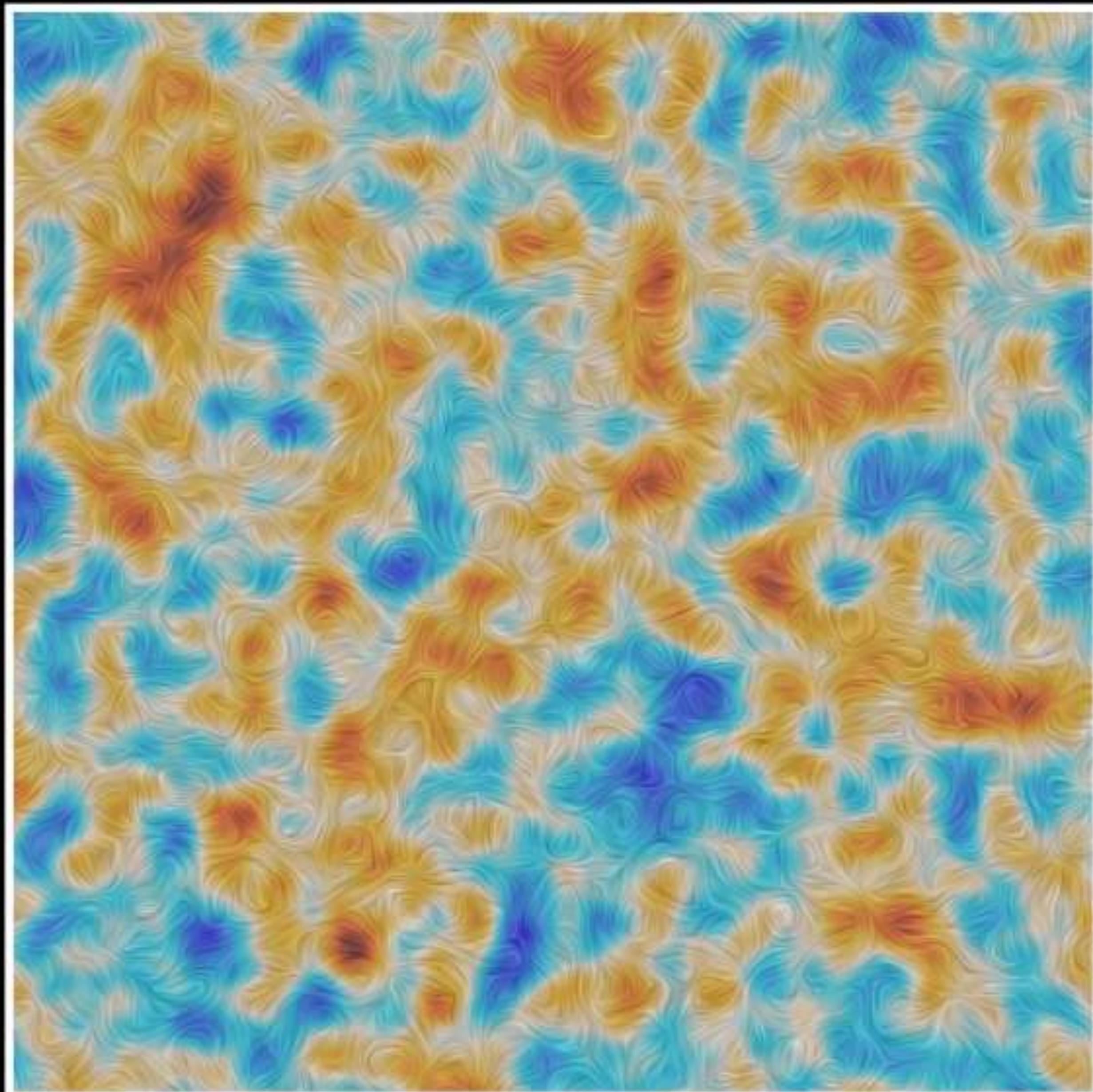
$$\Phi = \phi + f_{\rm NL}(\phi^2 - \langle\phi^2\rangle)$$

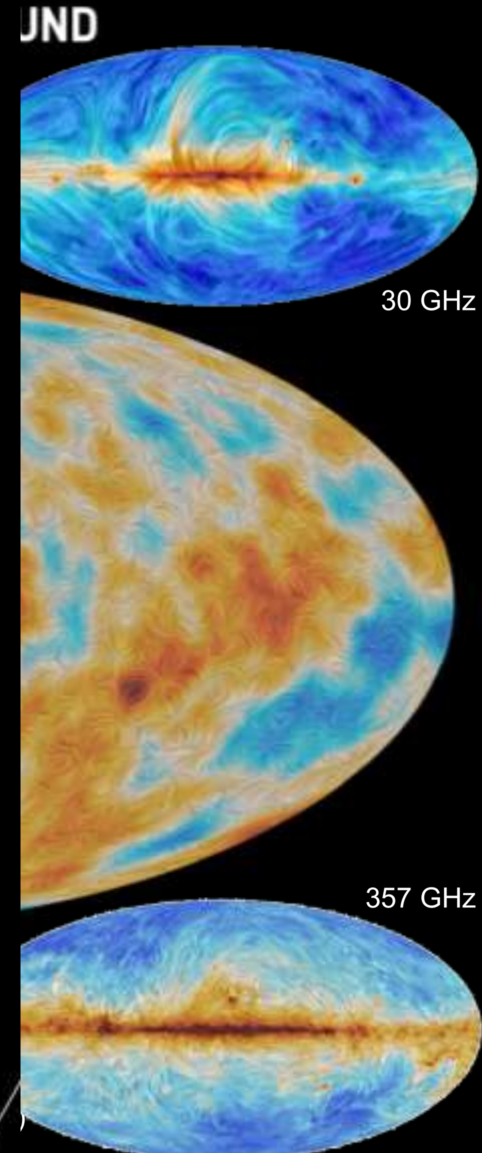
non-Gaussian potential

Gaussian field

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

A hundred-fold improvement in 14 years

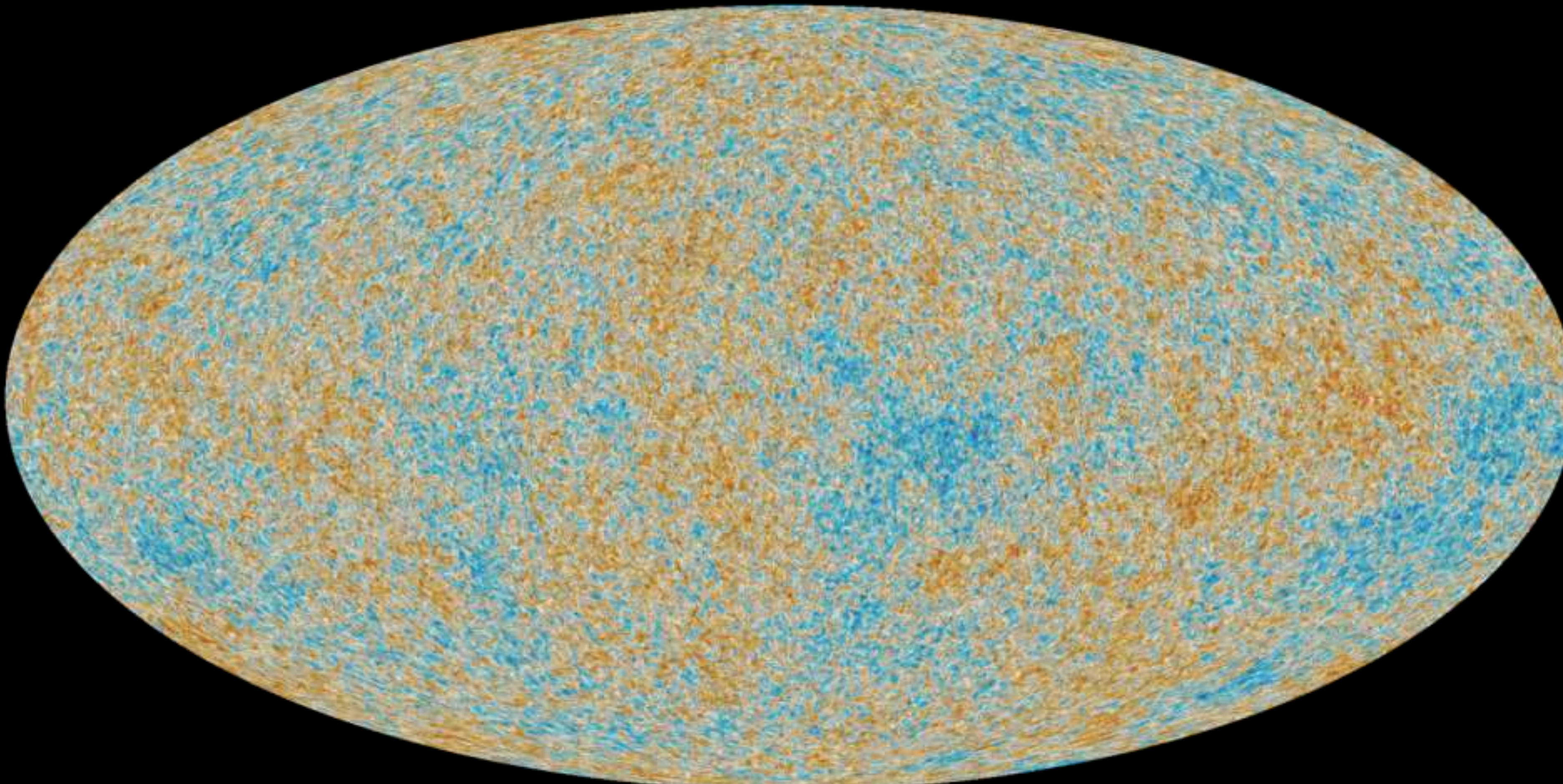




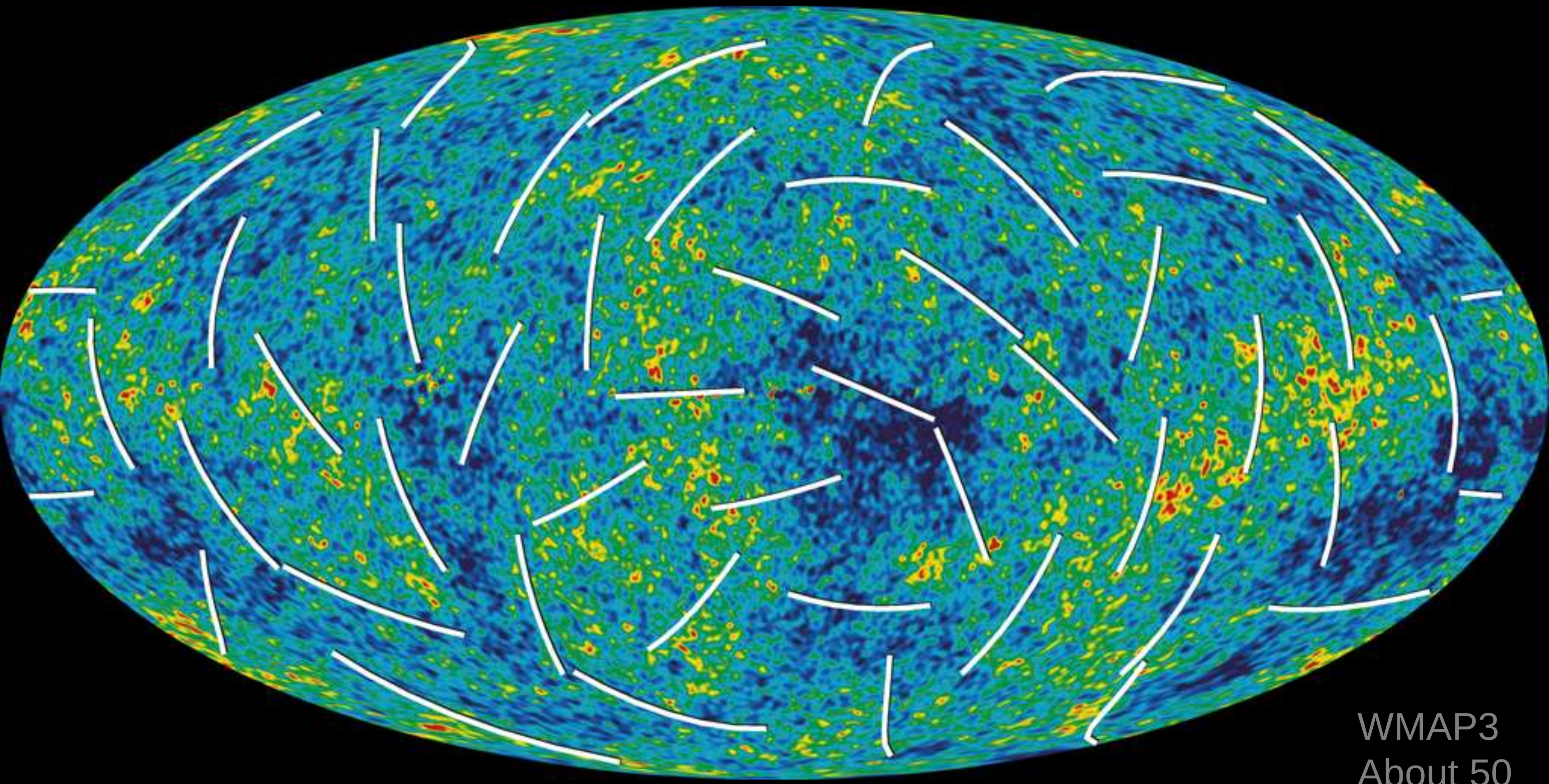
Filtered at 20 arcminutes

The Planck 2015 CMB polarisation sky

at 5 arc minute resolution

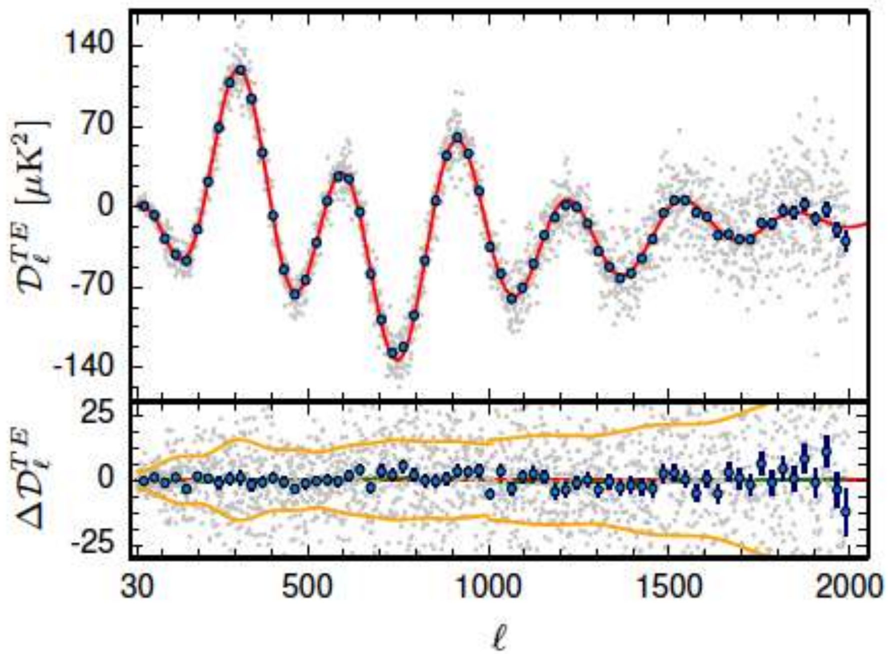


What we already knew

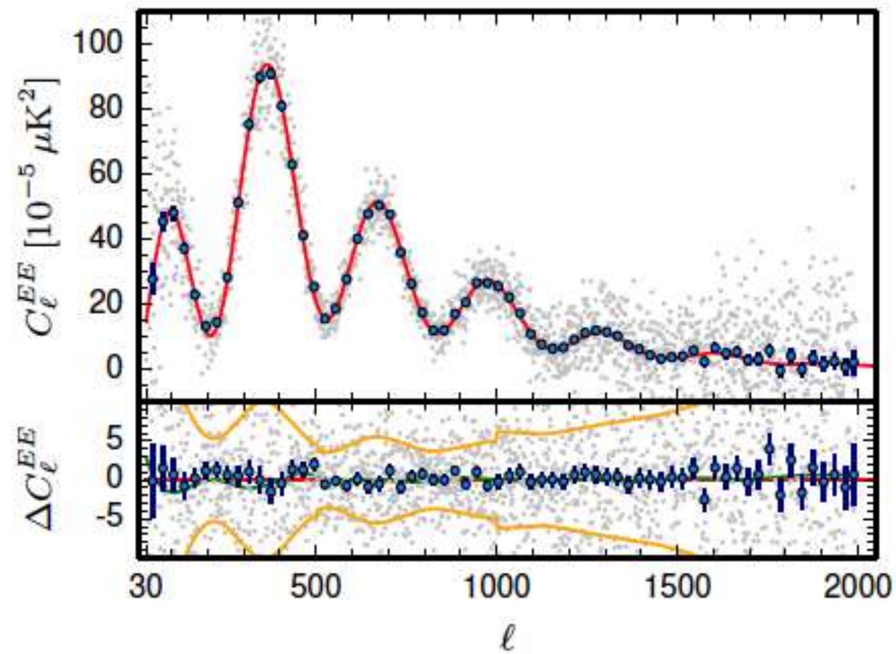


WMAP3
About 50
locations?

Planck 2015 - TE & EE spectra



Frequency averaged spectrum reduced ^{2} = 1.04



Frequency averaged spectrum reduced ^{2} = 1.01

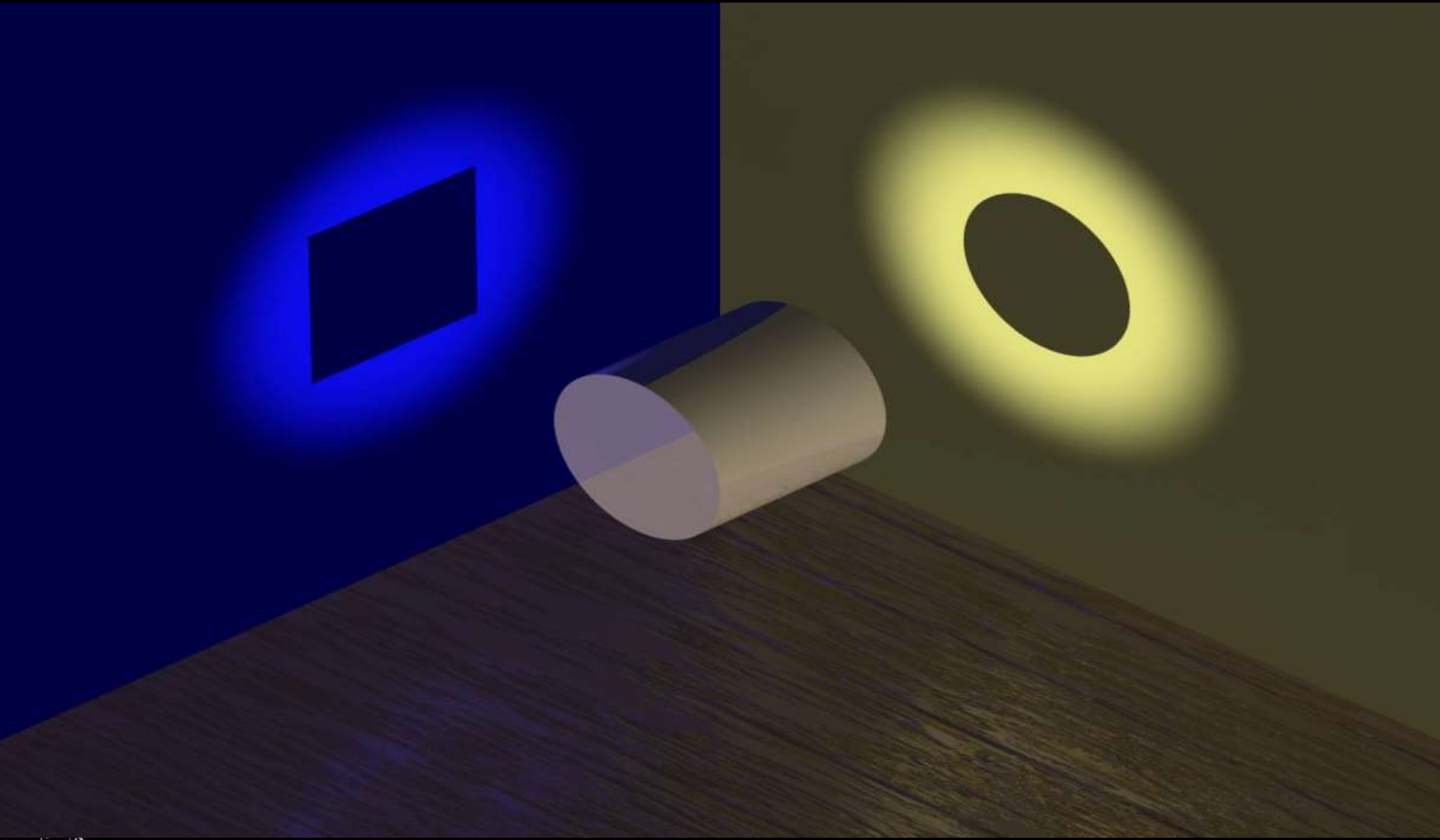
- Red curve is the *prediction* based on the best fit TT in base ΛCDM
- Albeit *magnificent*, 2015 polarisation data and results are *preliminary* because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

Base ΛCDM model

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

Note that parameters from TT & TE have *similar uncertainties*,
but beware that they are still some low level systematics in the polarisation data

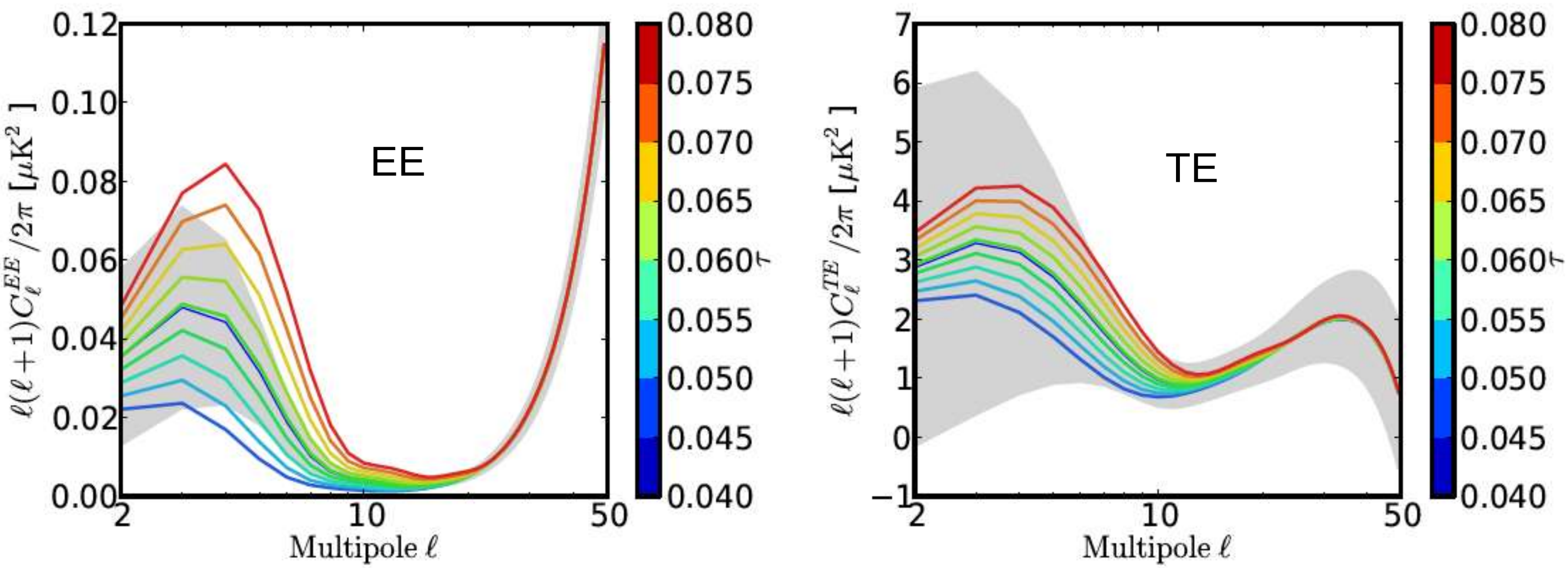
It could have been otherwise!



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

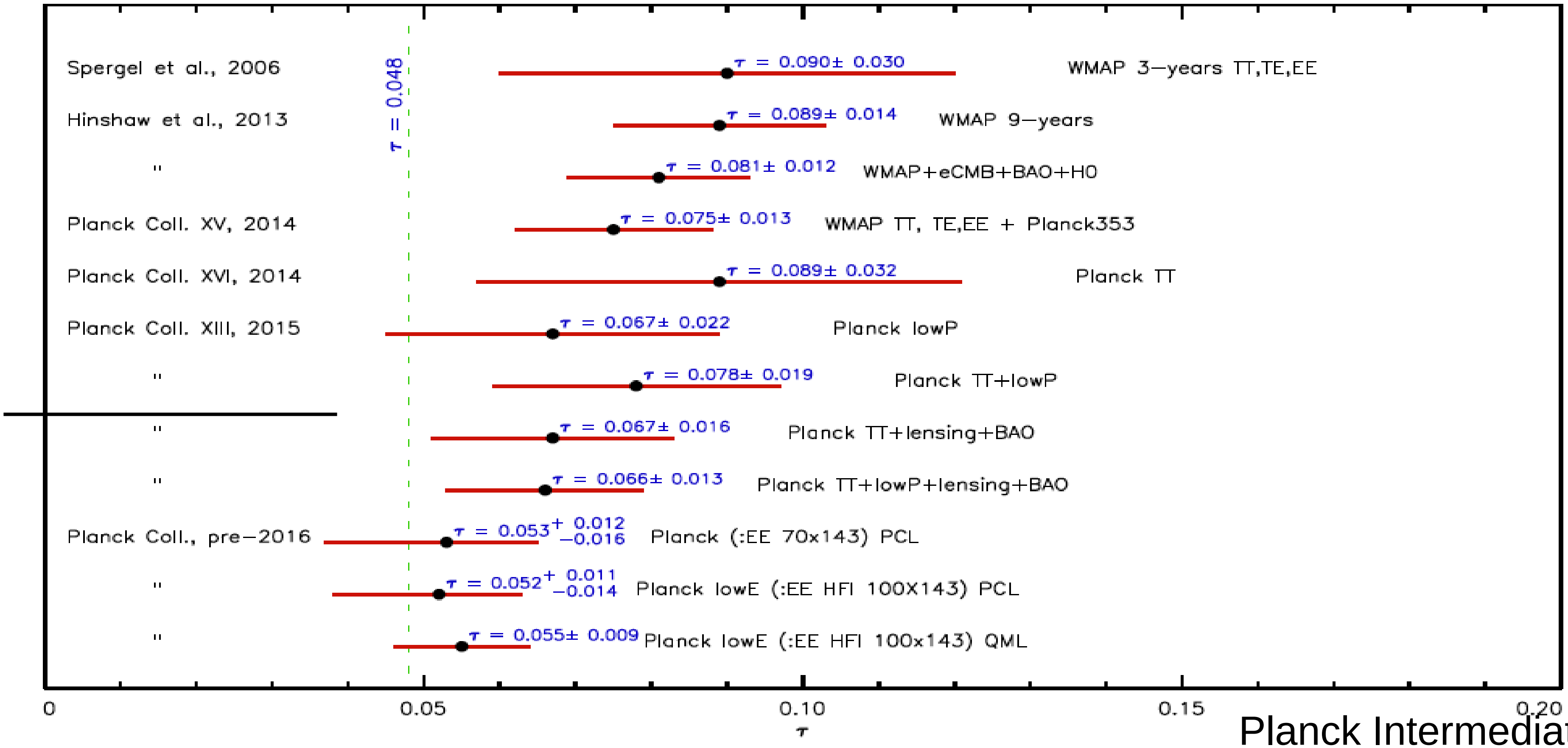
Optical depth to reionization, τ

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

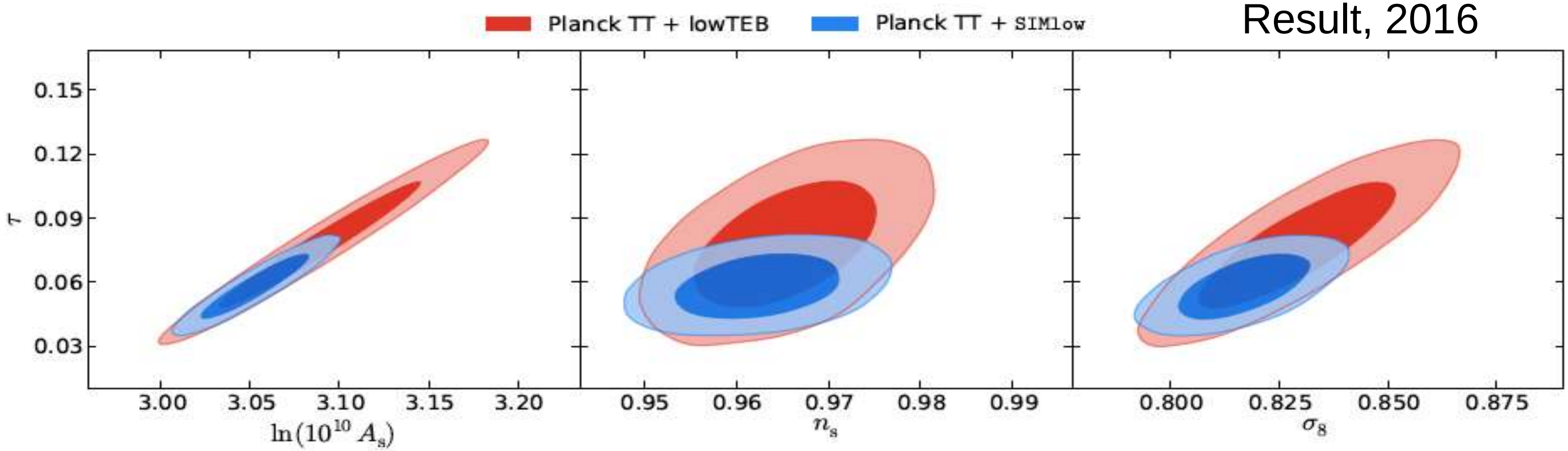


Grey bands = full sky cosmic variance if tau = 0.06

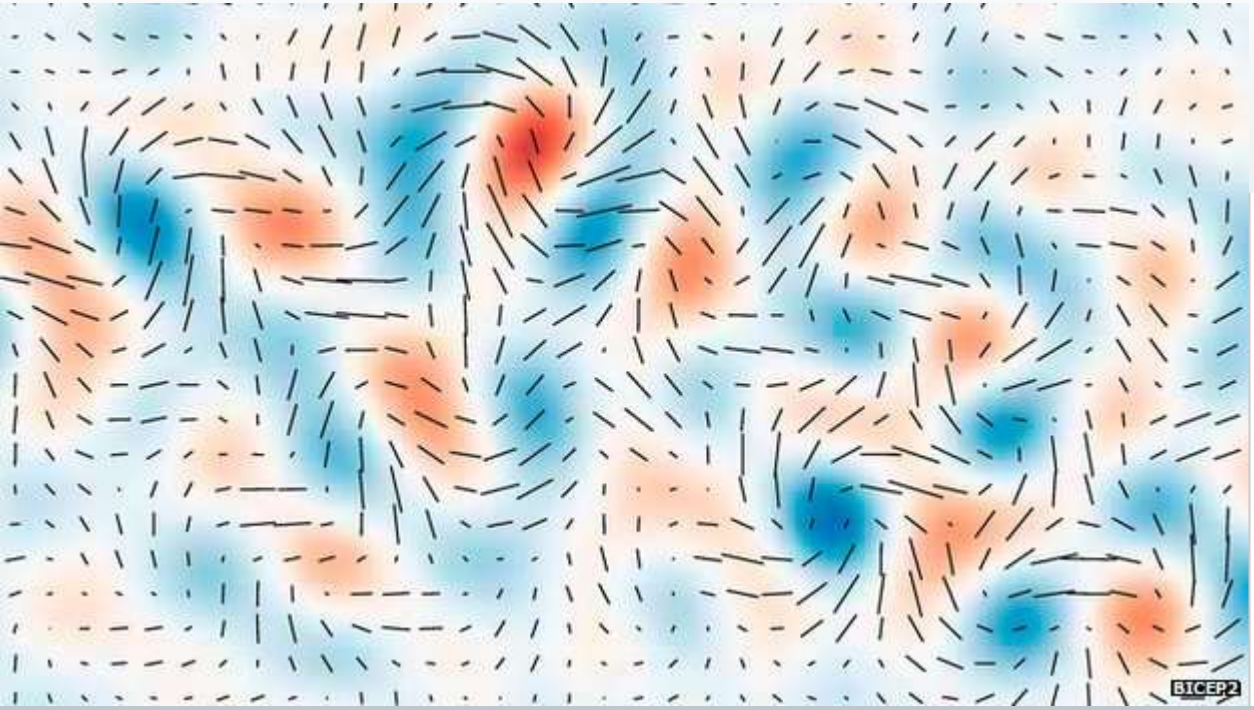
Planck Collaboration 2016



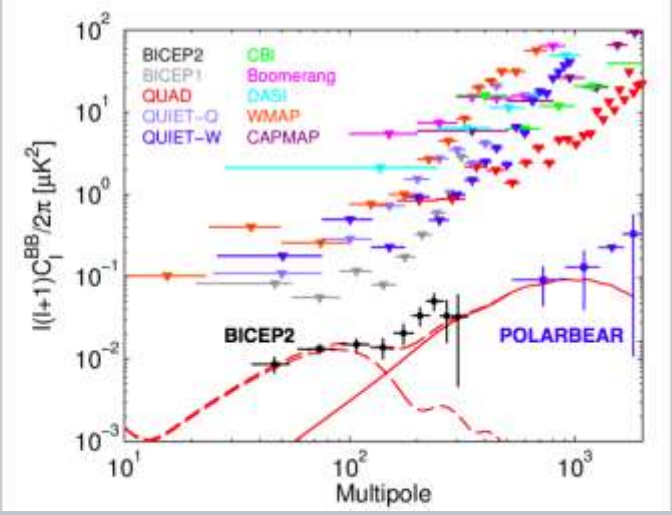
Planck Intermediate Result, 2016



BICEP2



March 17th 2014

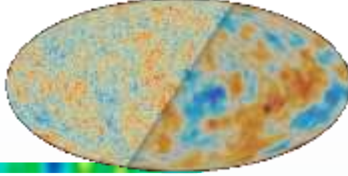


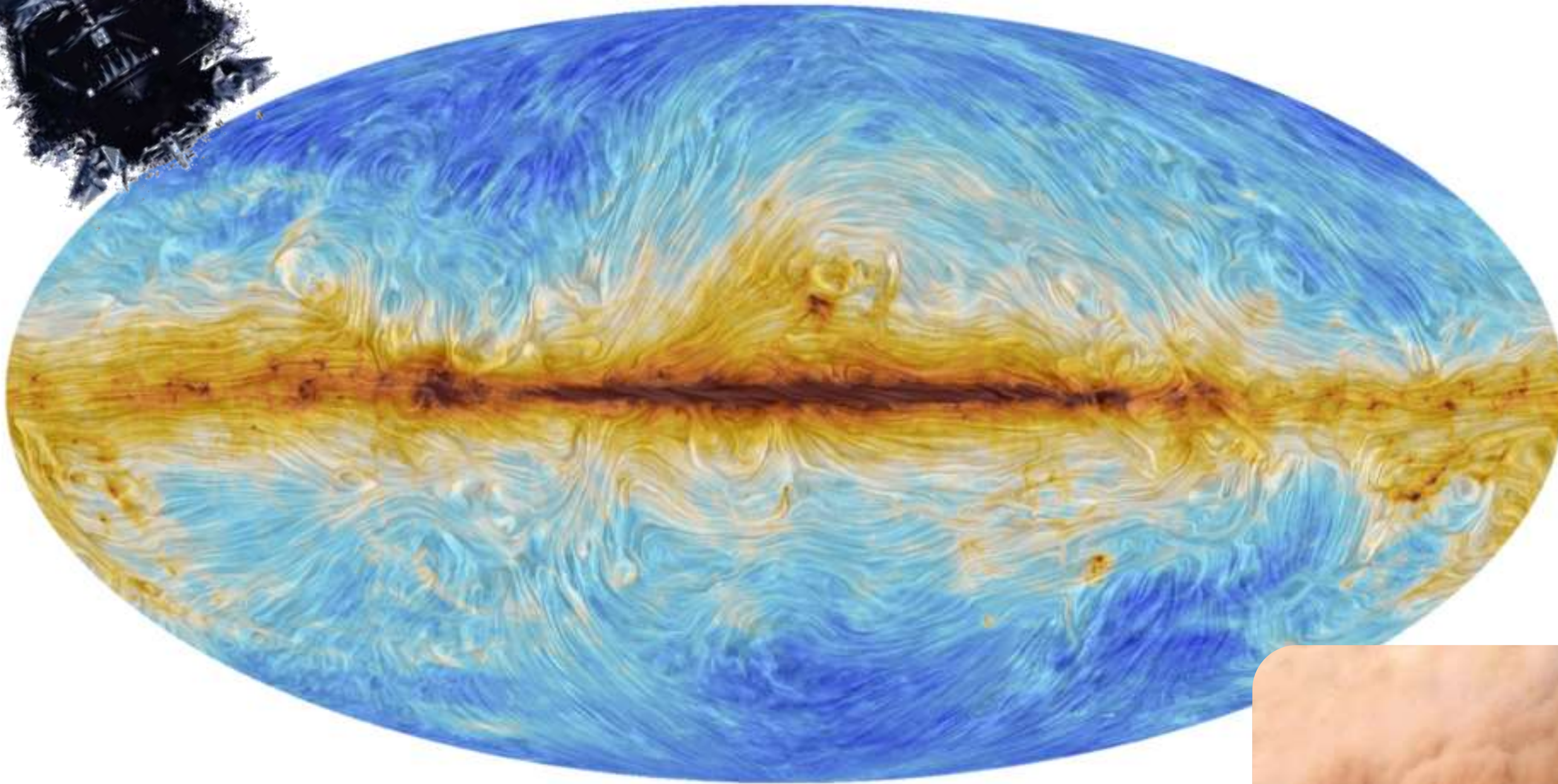
The world of physics is taken aback:

« The search for primordial gravitationnal waves is over »

« Andrei, it is r=0.2 and it is 5 sigma! »

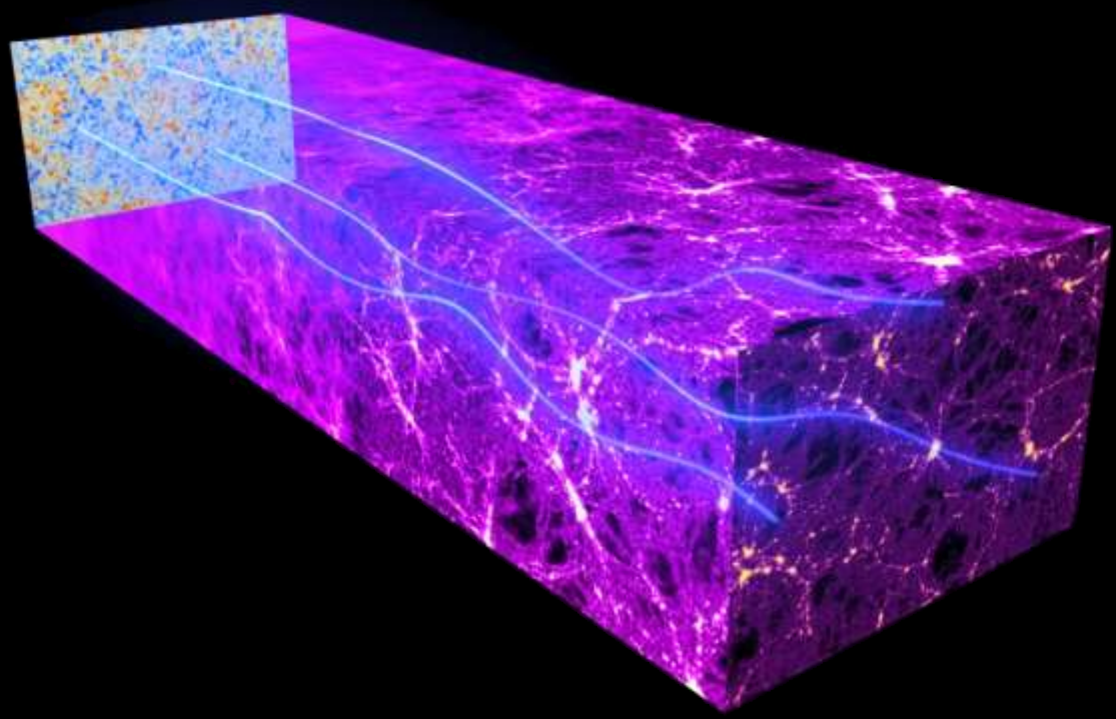
Planck 353GHz reveals the Galactic magnetic field





GRAVITATIONAL LENSING DISTORTS IMAGES

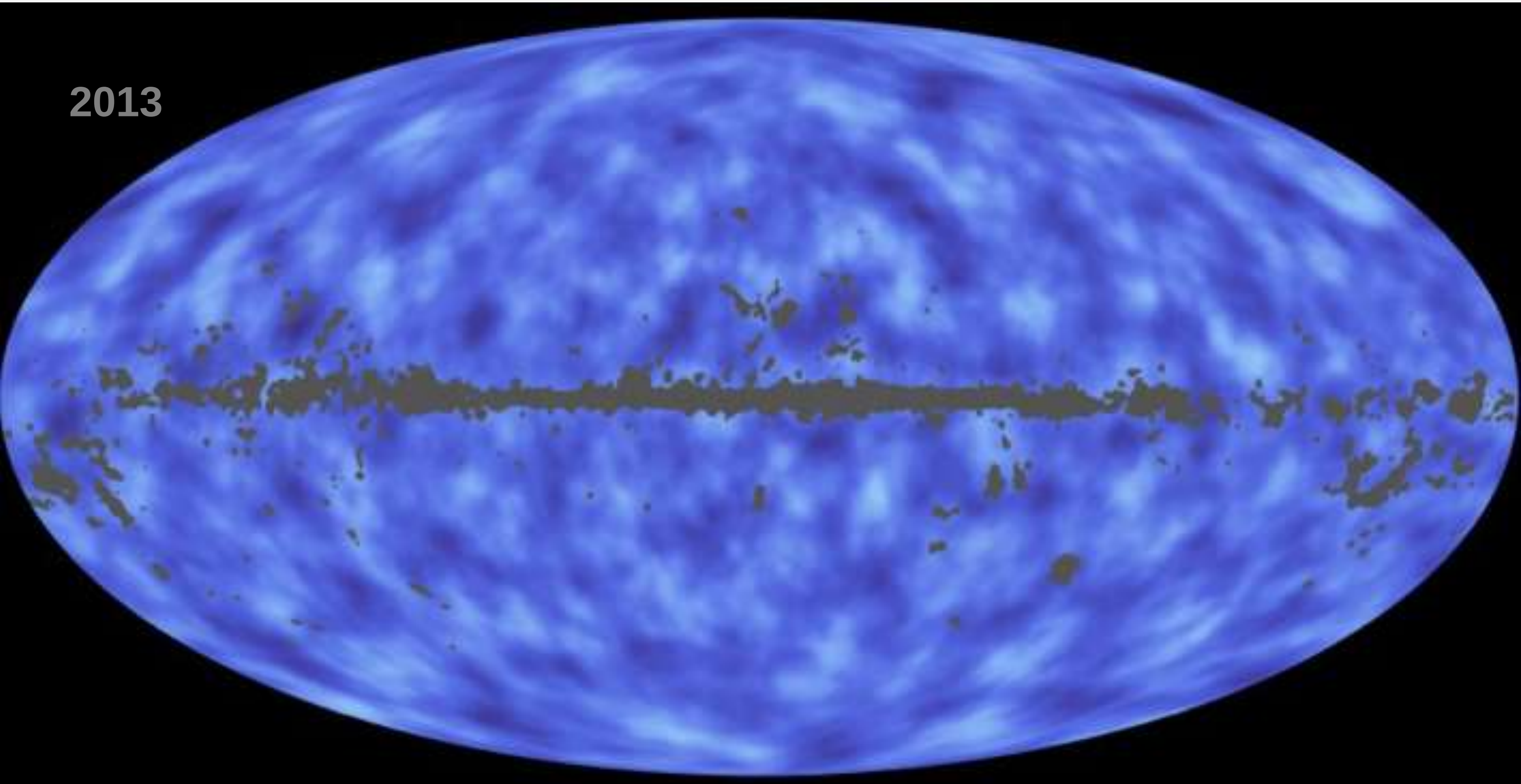
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



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

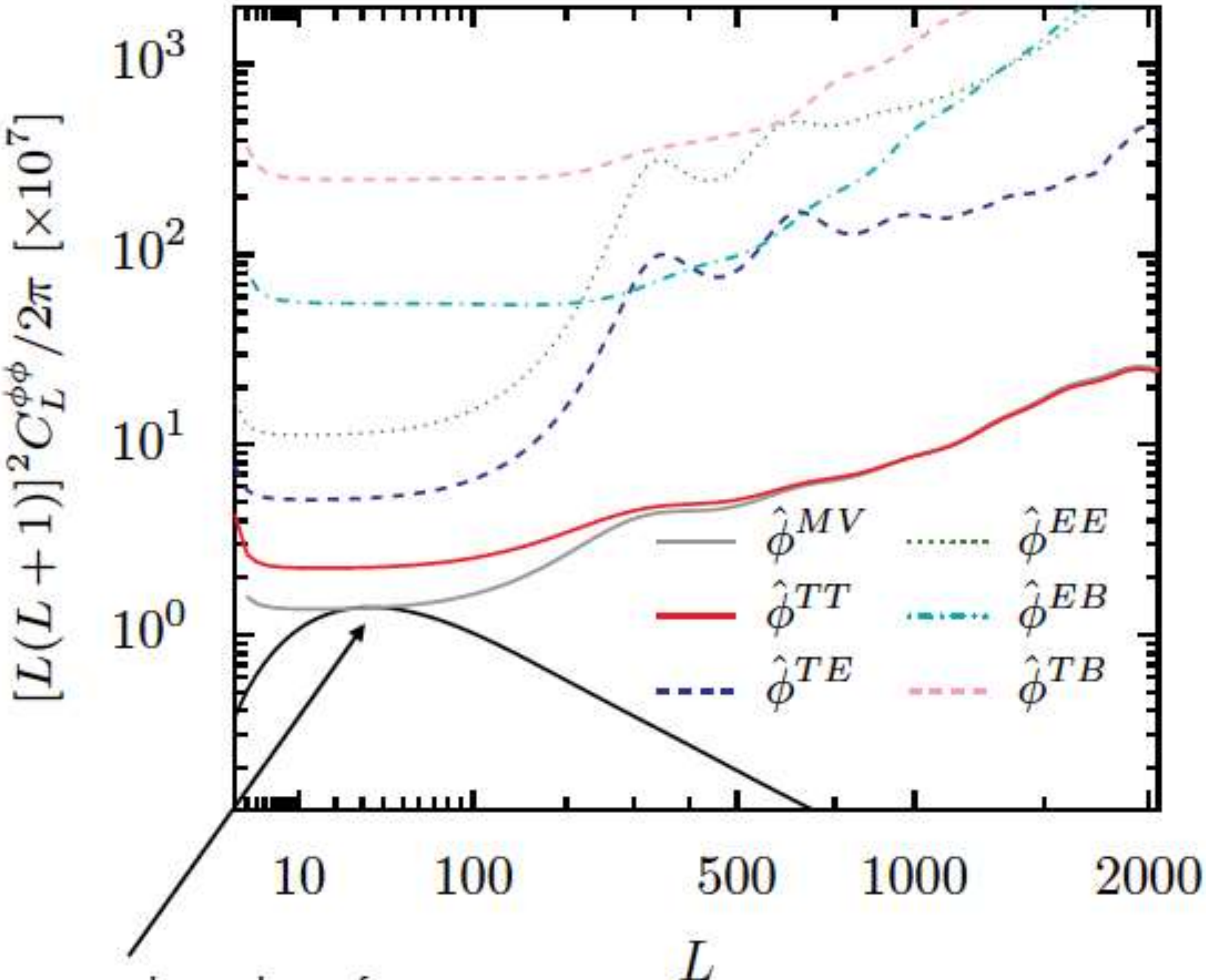
$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\, \vec{\nabla}(C^{-1}T)]$$

Projected mass map



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

Noise power spectra for lensing estimators



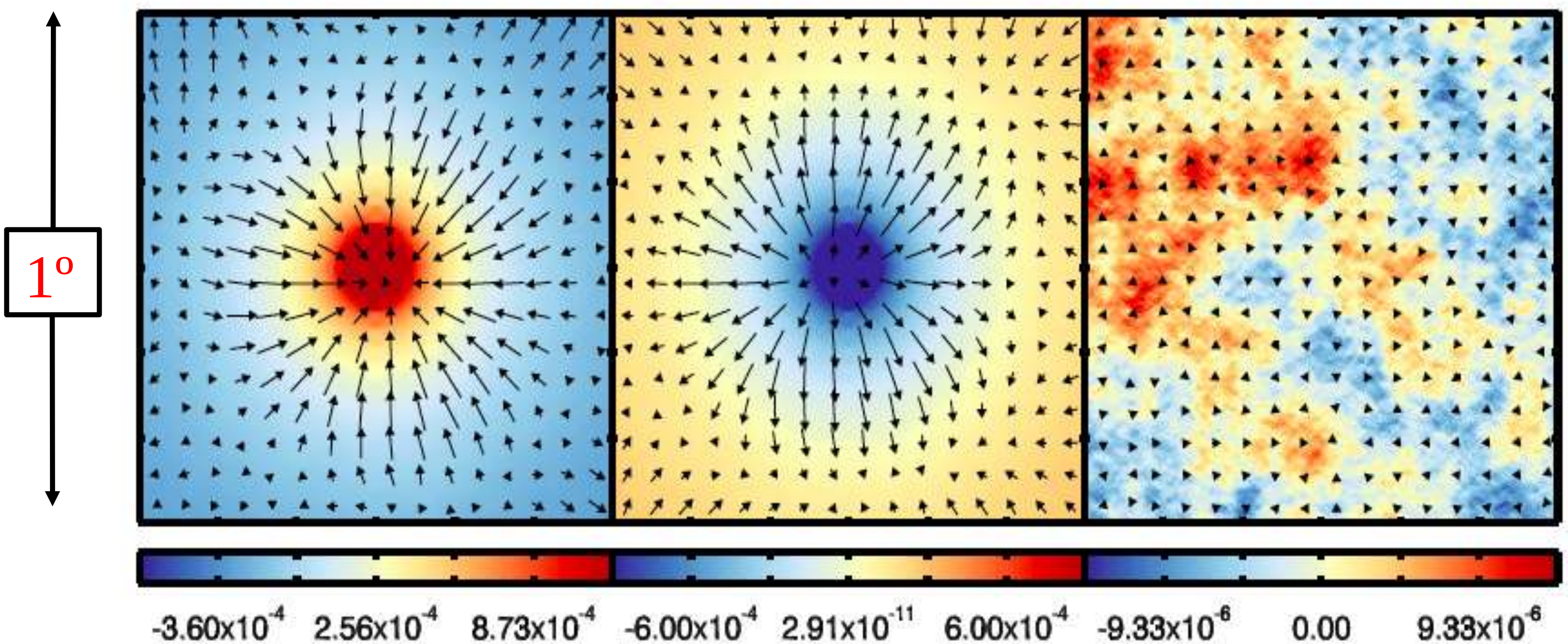
Best measured modes of MV estimator have S/N=1.

CIB PEAKS CORRESPOND TO MASS PEAKS

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

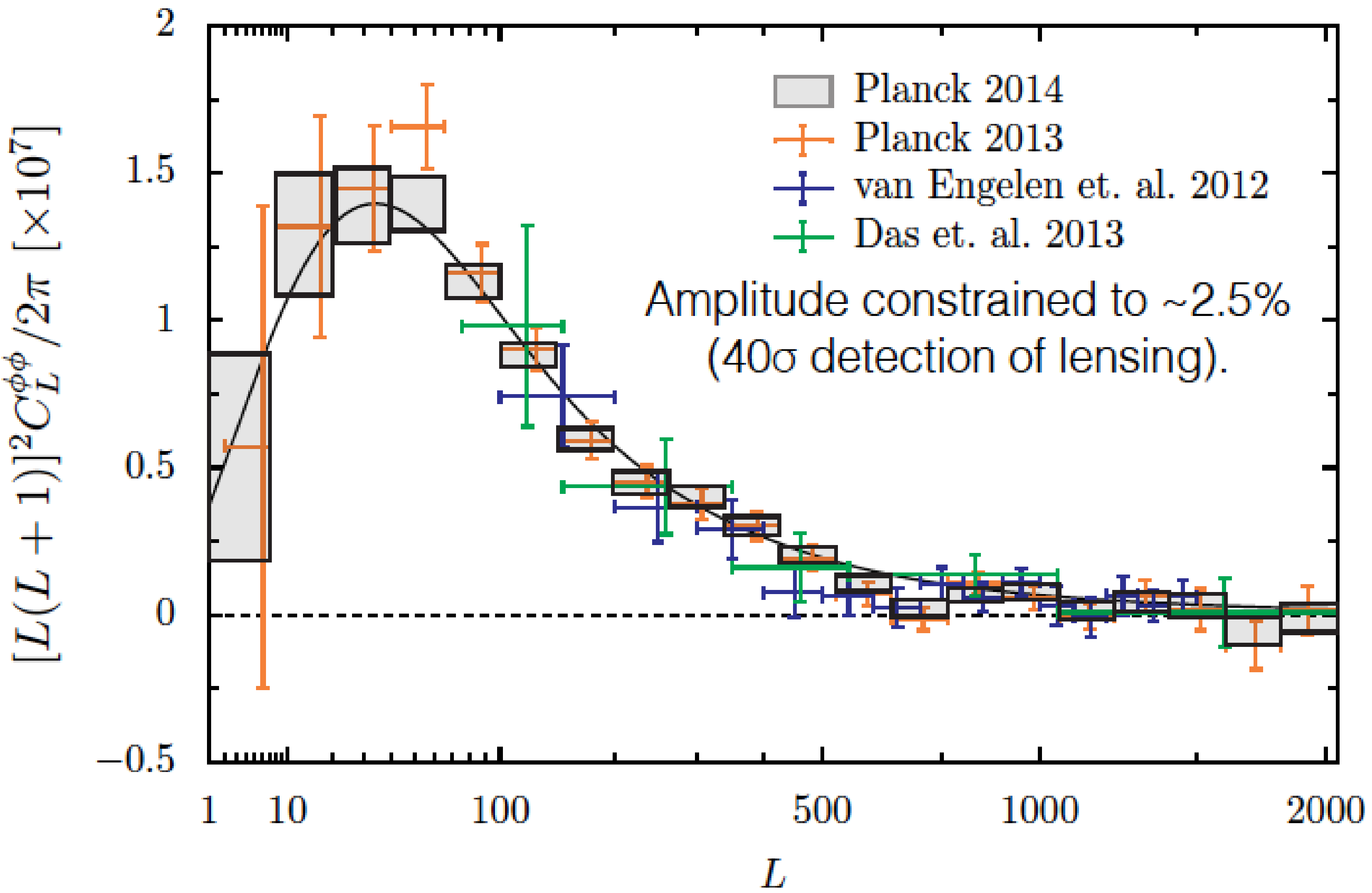
545 GHz

(similar at 857GHz)



[Planck Collaboration XVIII 2013]

Lensing power spectrum



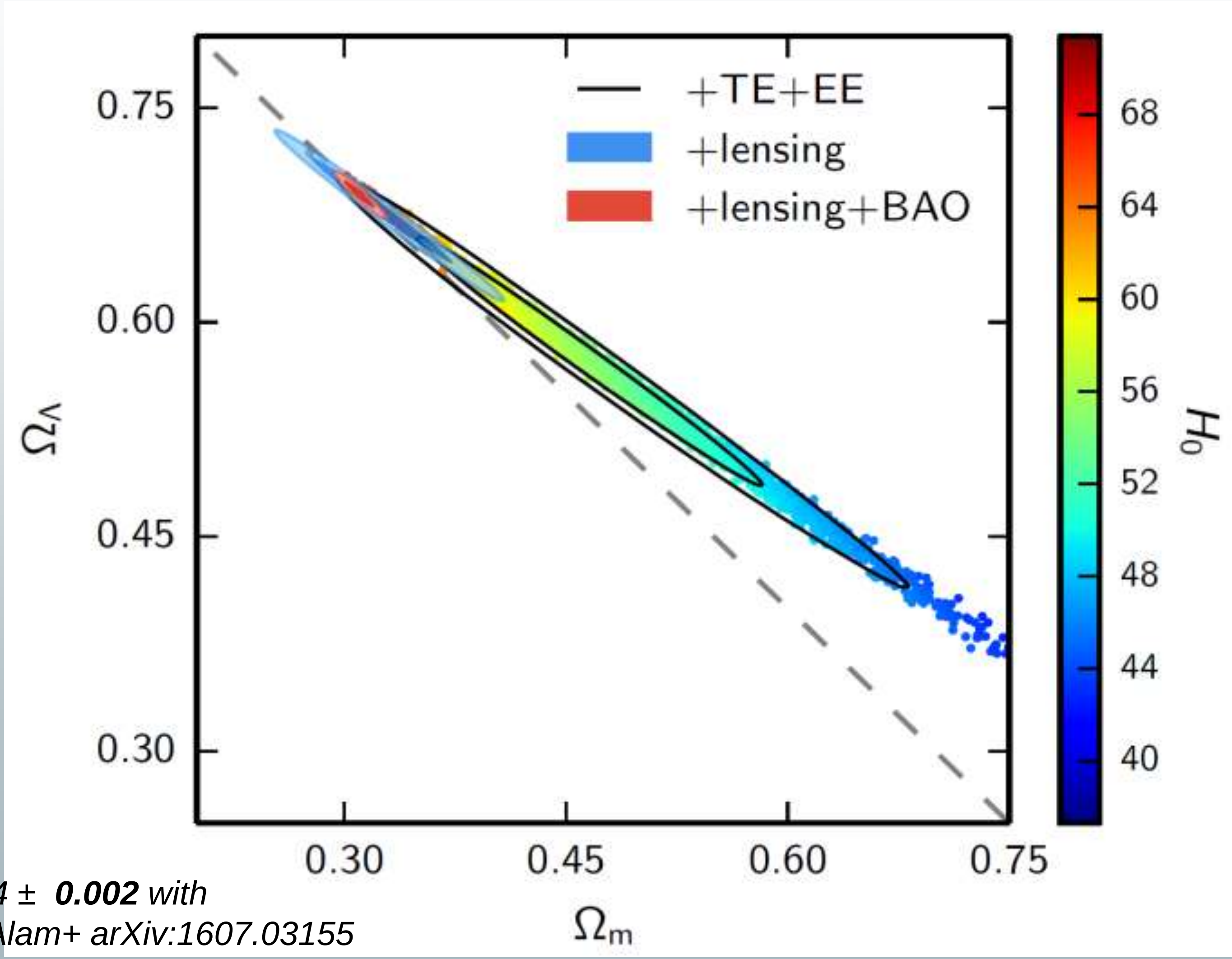
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

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. Idem for most parameters.**
- 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…).

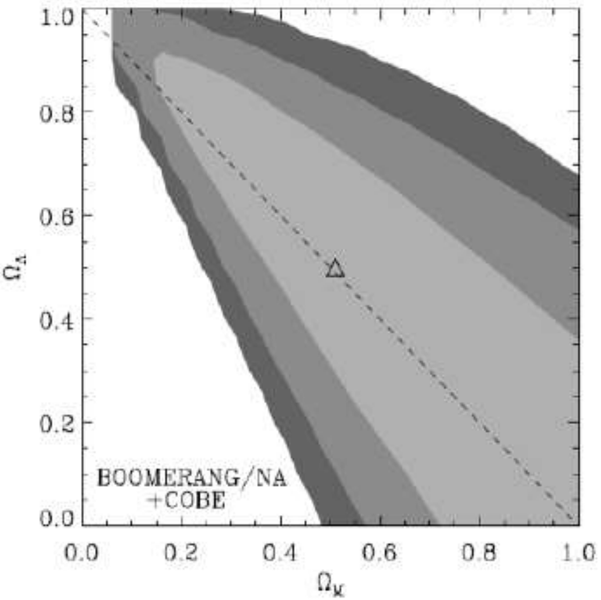
Spatial curvature constraint

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



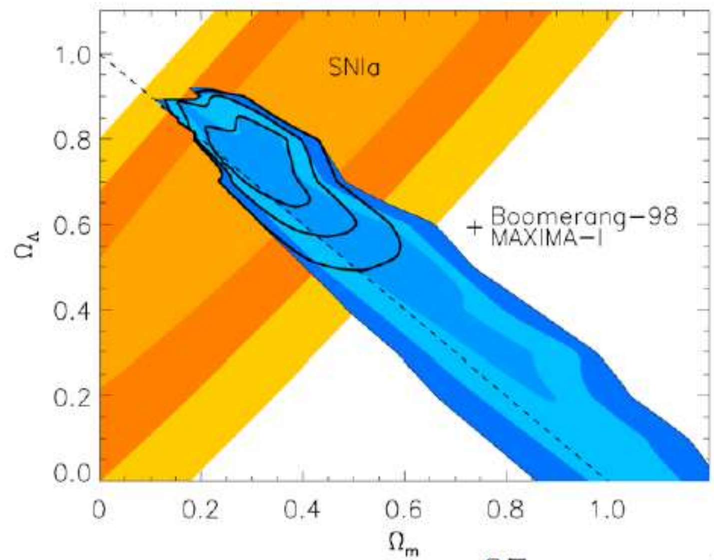
*NB: Ωk =0.0004 ± **0.002** with SDSS3-DR12 Alam+ arXiv:1607.03155*

Spatial curvature constraint



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

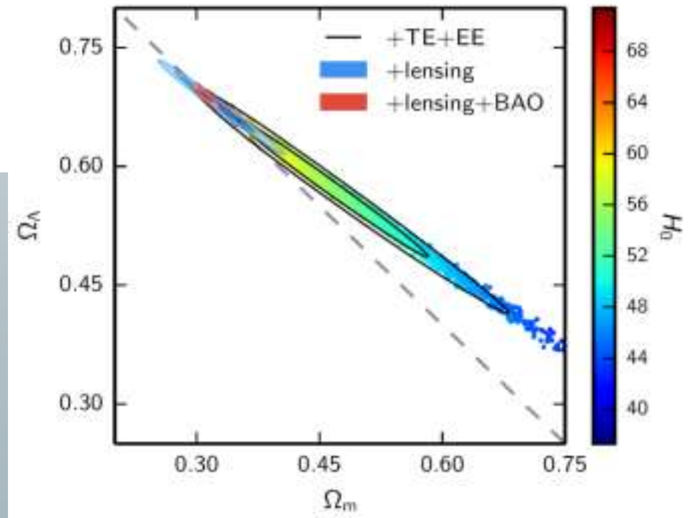
Melchiorri et al. 2000



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

Jaffe et al. 2001

Note the change of axes
For Planck below



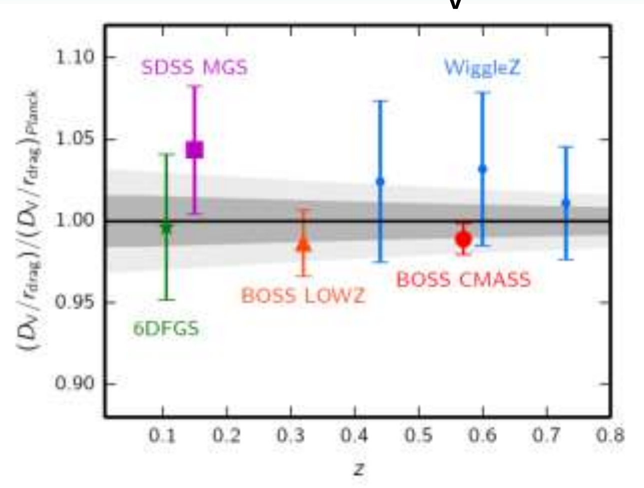
Planck 2015

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

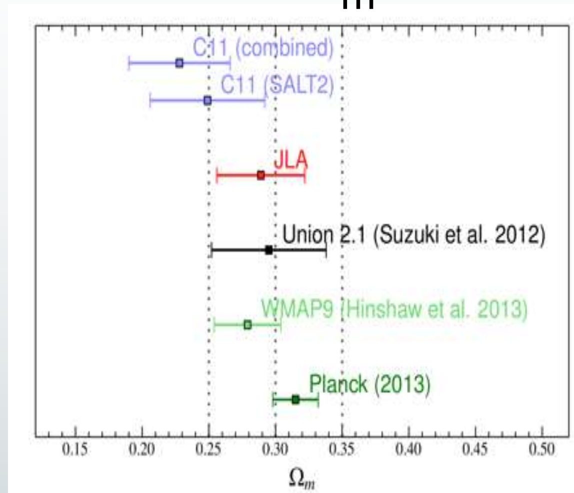
A hundred-fold improvement in 15 years

The good, the ?, the ??

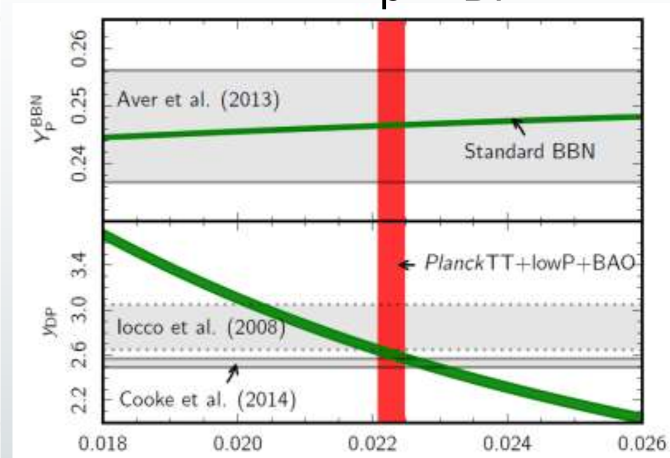
BAO D_v



SN Ω_m

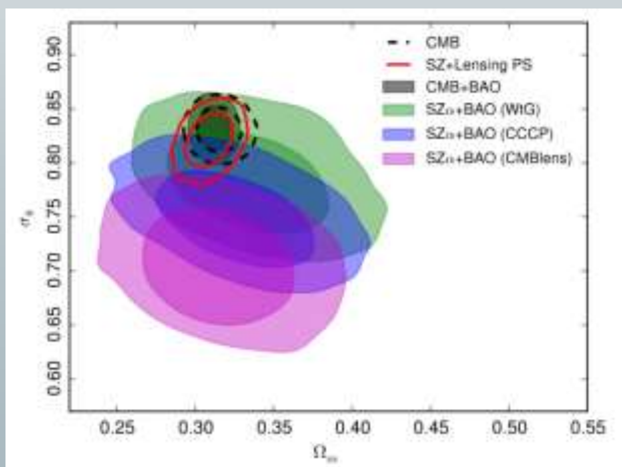


BBN Y_p Y_{DP}

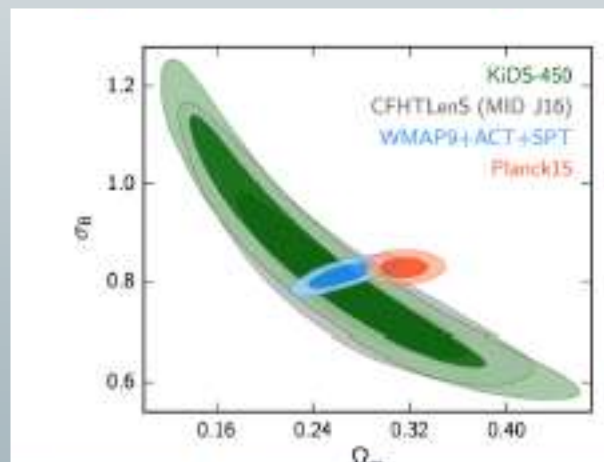


(but 2.3 sig w. latest Y_{DP})

SZ

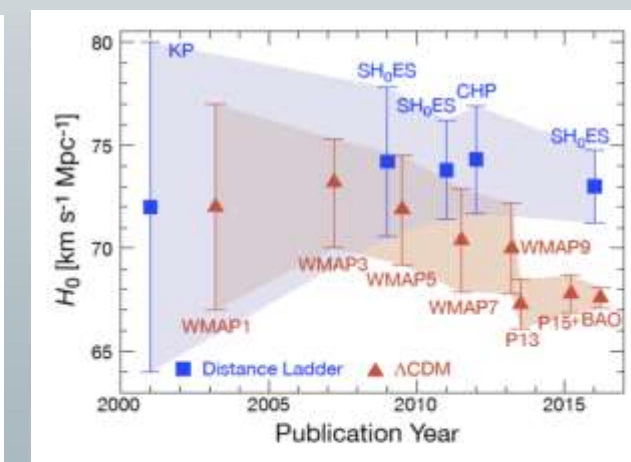


WL



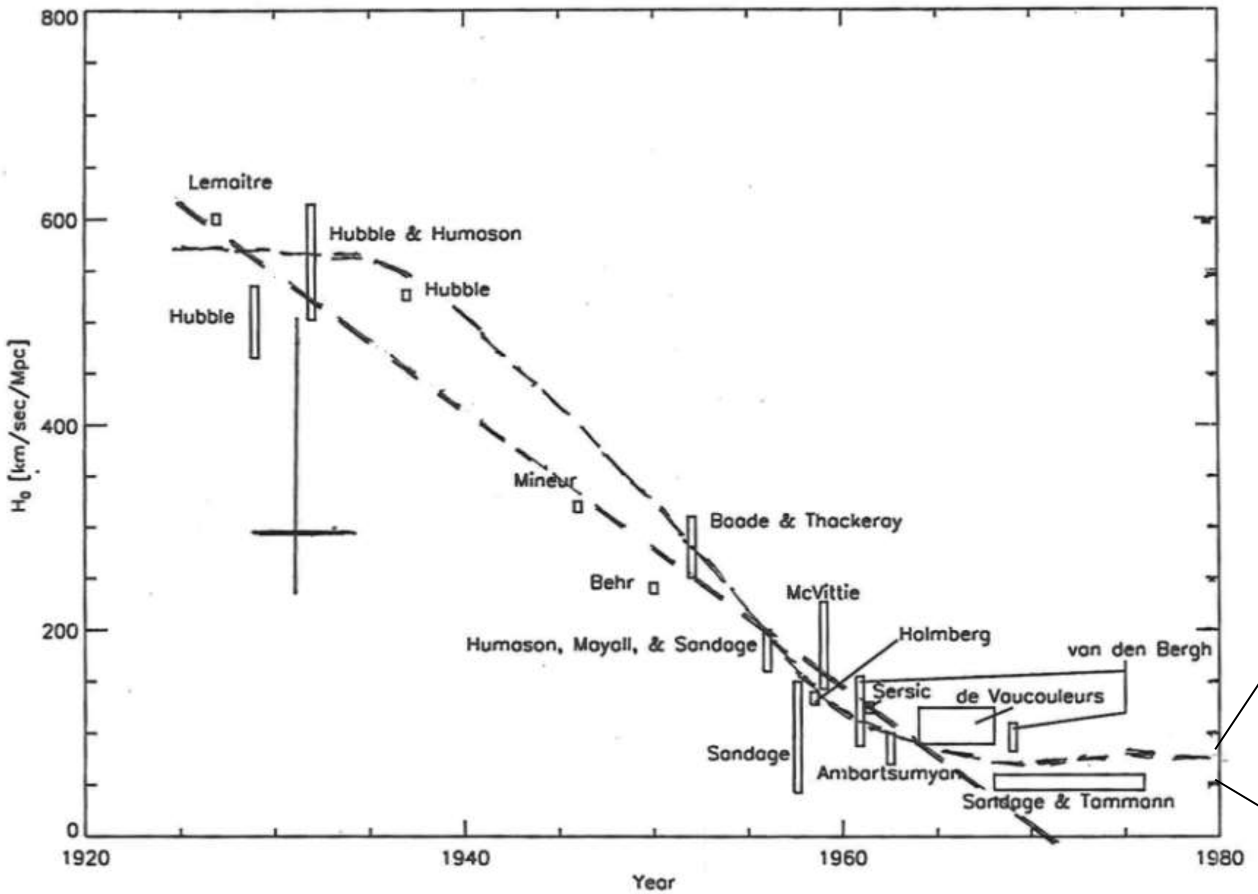
Hildebrandt+ 16

H0

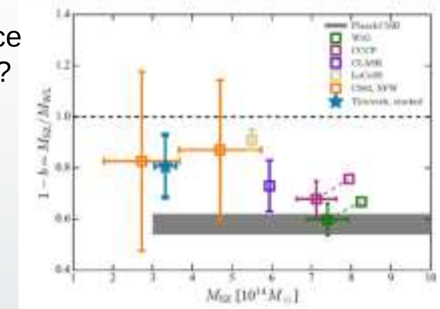


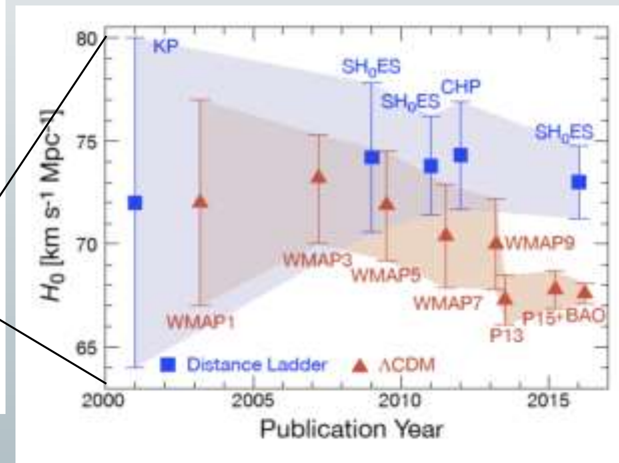
Freedman, arxiv/1706.02739

No-luck, Systematics, or new physics?



a cluster mass dependence of the bias?





Planck 2017 "Legacy" Release

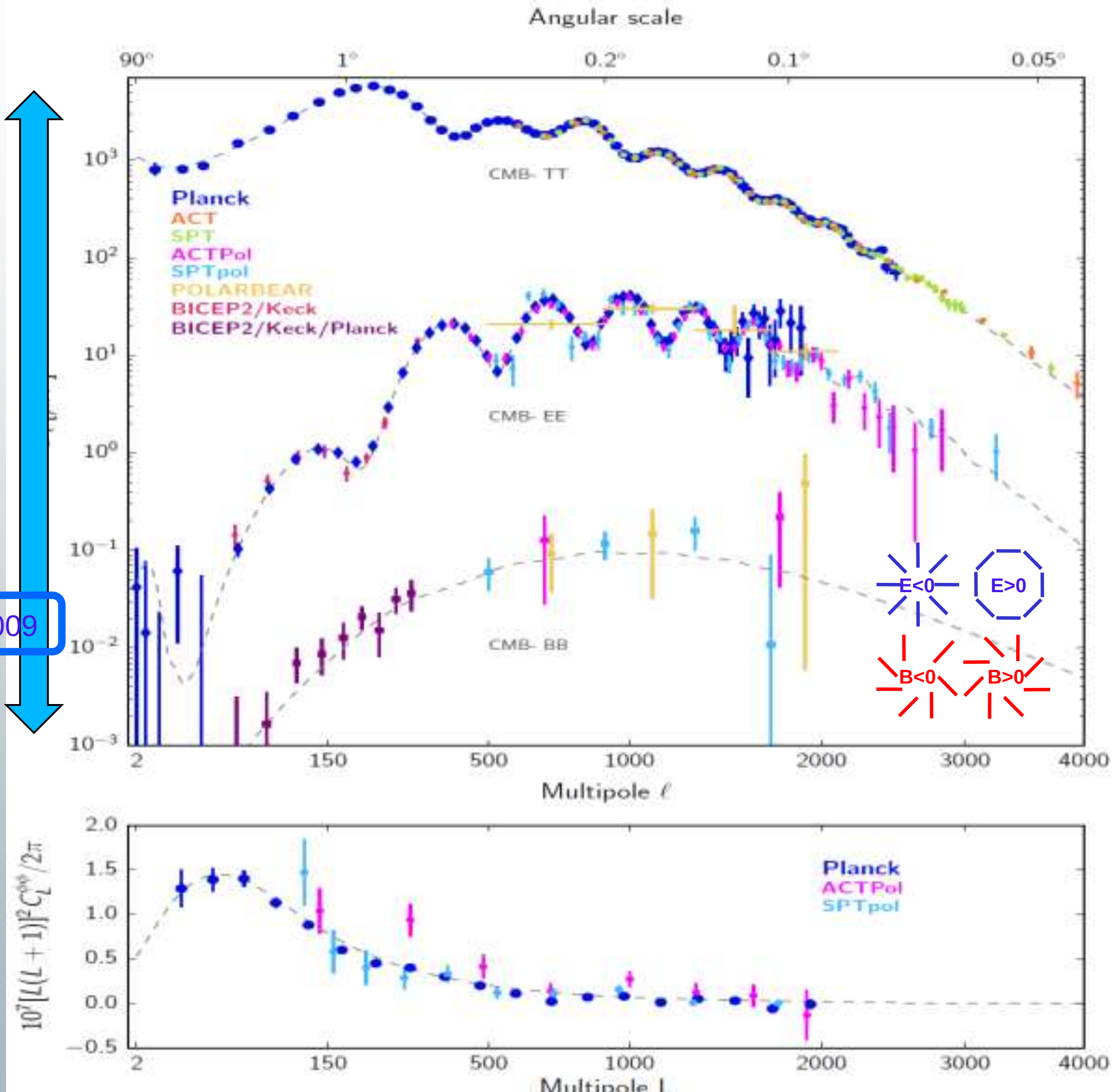
- Expected after the summer.
- New set of maps with notably the processing improvements introduced for the HFI low-ell EE analysis (i.e., same TOIs, different HPR & data model)
- A new set of simulations with fidelity enhanced to much lower levels (for instrumental systematics, e.g., ADC NL, BP leakage, etc.)
- A new round of analyses (which is currently ongoing) with updated CMB likelihoods (in development), chains and parameters, component maps, NG analysis, etc.

TT, EE, BB, ΦΦ – mid 2017 status

Only keeping points w. sufficiently small error bars, Fig. E Calabrese

10^7

τ = 0.055±0.009



1 114 000 Modes measured with TT,

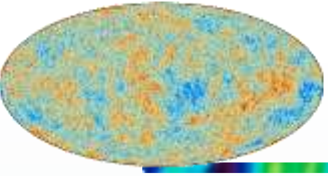
60 000 with TE (not shown)

96 000 with EE

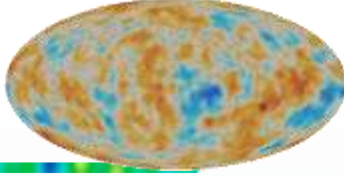
… and 10's in BB and φφ

+ weak constraints with TB and EB

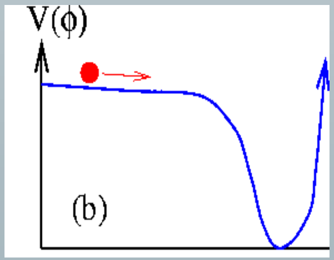
And statistically isotropic…



Summary: Basic ΛCDM fits



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



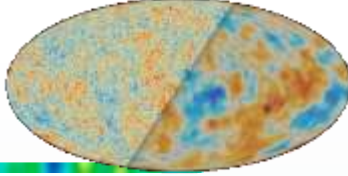
➔ I.e. all consistent within the generic inflationary framework, completing the standard model of cosmology.

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

➔ Tensions? (And Beware of DUST!)


Attention: j'ai laissé de
coté des tas de trucs
Intéressants – SZ, CIB,
ISM…(even strings)

Numerology



- A collaboration of ~500 scientists,
  - *115 French)*
- An HFI Core team of ~150 people
  - *> 50 PhD in France*
- About 150 papers only!
- About ½ of the papers are non CMB.
- ADS, most cited papers since the 2013 Planck first cosmology release), in all of Physics+Astrophysics:
  - *Planck has #1 and #3 (parameters)*
  - *#2 is from particle physics data group, #4 & 10 is WMAP, #5 is GW, #9 is Bicep2 (which Planck corrected)…*
  - *Planck has also #7, 13, 14, 25, 76, 101…*
- And many more papers USING Planck

SAO/NASA Astrophysics Data System (ADS)

Query Results from the ADS Database

Retrieved 500 abstracts, starting with number 1. Total number selected: 1604141. Total citations: 4033274

#	Bibcode / Authors	Cites / Title	Date	List of Links / Access Control Help
1	2014A&A...571A..16P Planck Collaboration; Ade, P. A. R.; Aghanim, N.; Armitage-Caplan, C.; Arnaud, M.; Ashdown, M.; Atrio-Barandela, F.; Aumont, J.; Baccigalupi, C.; Banday, A. J.; and 235 coauthors	5197.000 Planck 2013 results. XVI. Cosmological parameters	11/2014	A E E X
2	2014ChPhC..38i0001O Olive, K. A.; Particle Data Group	3699.000 Review of Particle Physics	08/2014	A E
3	2016A&A...594A..13P Planck Collaboration; Ade, P. A. R.; Aghanim, N.; Arnaud, M.; Ashdown, M.; Aumont, J.; Baccigalupi, C.; Banday, A. J.; Barreiro, R. B.; Bartlett, J. G.; and 252 coauthors	3195.000 Planck 2015 results. XIII. Cosmological parameters	09/2016	A E E X
4	2013ApJS..208...19H Hinshaw, G.; Larson, D.; Komatsu, E.; Spergel, D. N.; Bennett, C. L.; Dunkley, J.; Nolta, M. R.; Halpern, M.; Hill, R. S.; Odegard, N.; and 11 coauthors	2579.000 Nine-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations	10/2013	A E E X
5	2016PhRvL.116f1102A Abbott, B. P.; Abbott, R.; Abbott, T. D.; Abernathy, M. R.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T.; Addesso, P.; Adhikari, R. X.; and 1003 coauthors	1558.000 Observation of Gravitational Waves from a Binary Black Hole Merger	02/2016	A E X
6	2014JHEP...07..079A Alwall, J.; Frederix, R.; Frixione, S.; Hirschi, V.; Maltoni, F.; Mattelaer, O.; Shao, H.-S.; Stelzer, T.; Torrielli, P.; Zaro, M.	1557.000 The automated computation of tree-level and next-to-leading order differen	07/2014	A E X
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8	2014PhRvL.112i1303A Akerib, D. S.; Araújo, H. M.; Bai, X.; Bailey, A. J.; Balajthy, J.; Bedikian, S.; Bernard, E.; Bernstein, A.; Bolozdynya, A.; Bradley, A.; and 93 coauthors	1342.000 First Results from the LUX Dark Matter Experiment at the Sanford Underg	03/2014	A E X
9	2014PhRvL.112x1101B BICEP2 Collaboration; Ade, P. A. R.; Aikin, R. W.; Barkats, D.; Benton, S. J.; Bischoff, C. A.; Bock, J. J.; Brevik, J. A.; Buder, I.; Bullock, E.; and 38 coauthors	1289.000 Detection of B-Mode Polarization at Degree Angular Scales by BICEP2	06/2014	A E X
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11	2013PASP..125..306F Foreman-Mackey, Daniel; Hogg, David W.; Lang, Dustin; Goodman, Jonathan	1122.000 emcee: The MCMC Hammer	03/2013	A E E X
12	2014RvMP...86.1391A Aspelmeyer, Markus; Kippenberg, Tobias J.; Marquardt, Florian	1103.000 Cavity optomechanics	10/2014	A E X
13	2014A&A...571A...1P Planck Collaboration; Ade, P. A. R.; Aghanim, N.; Alves, M. I. R.; Armitage-Caplan, C.; Arnaud, M.; Ashdown, M.; Atrio-Barandela, F.; Aumont, J.; Aussel, H.; and 301 coauthors	1010.000 Planck 2013 results. I. Overview of products and scientific results	11/2014	A E E X
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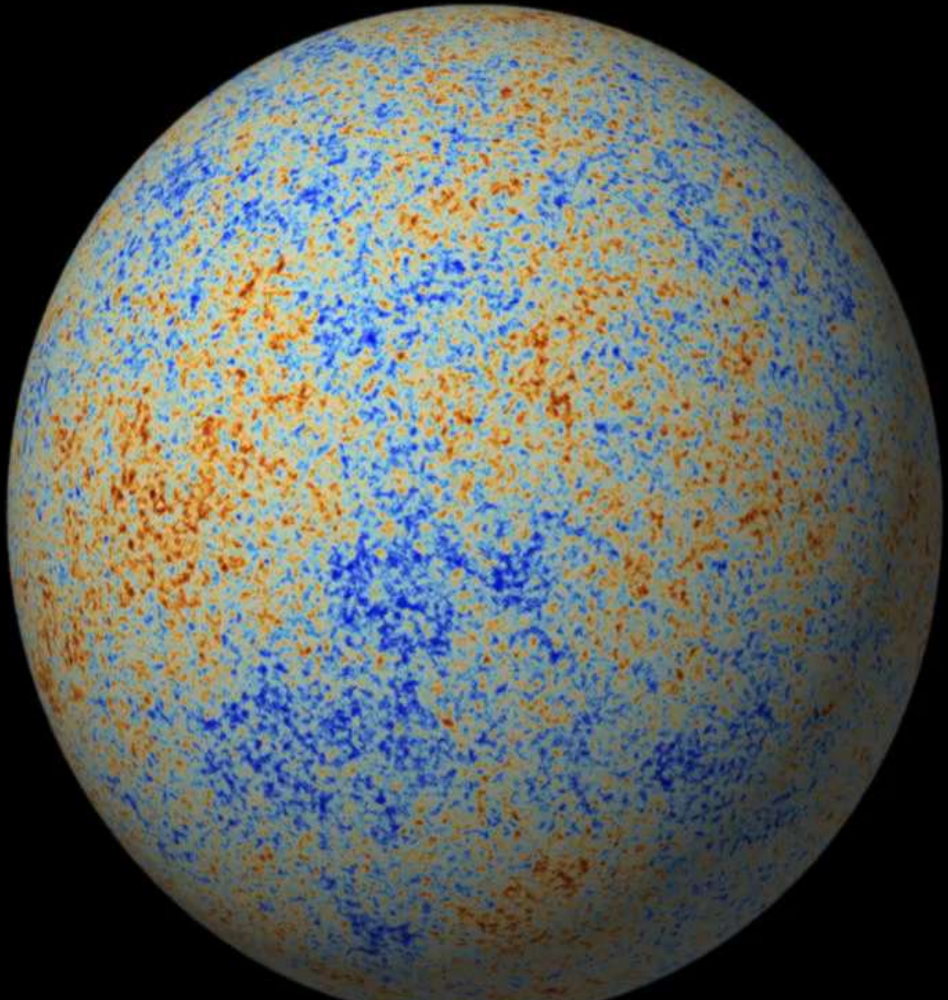
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

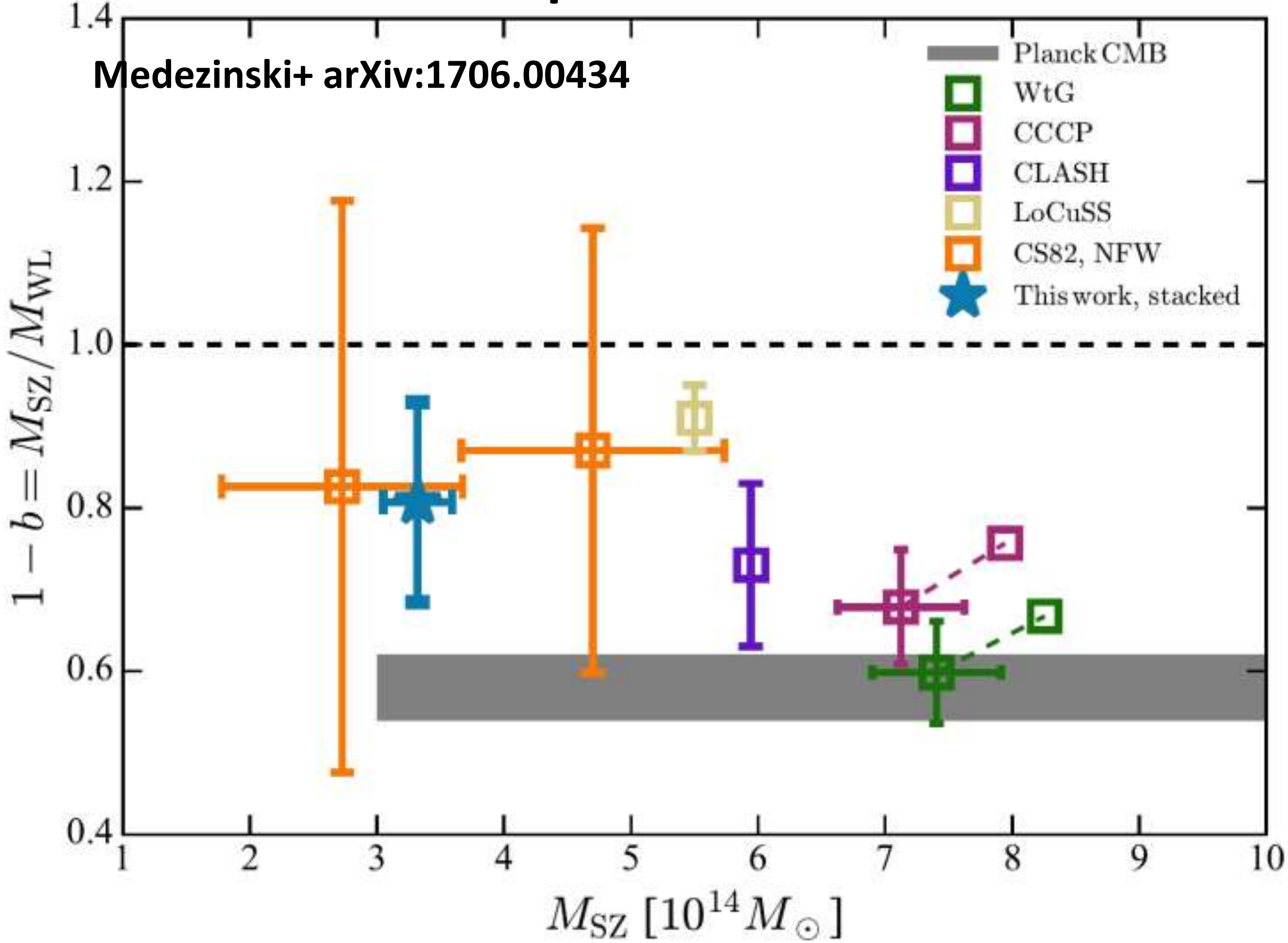
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.



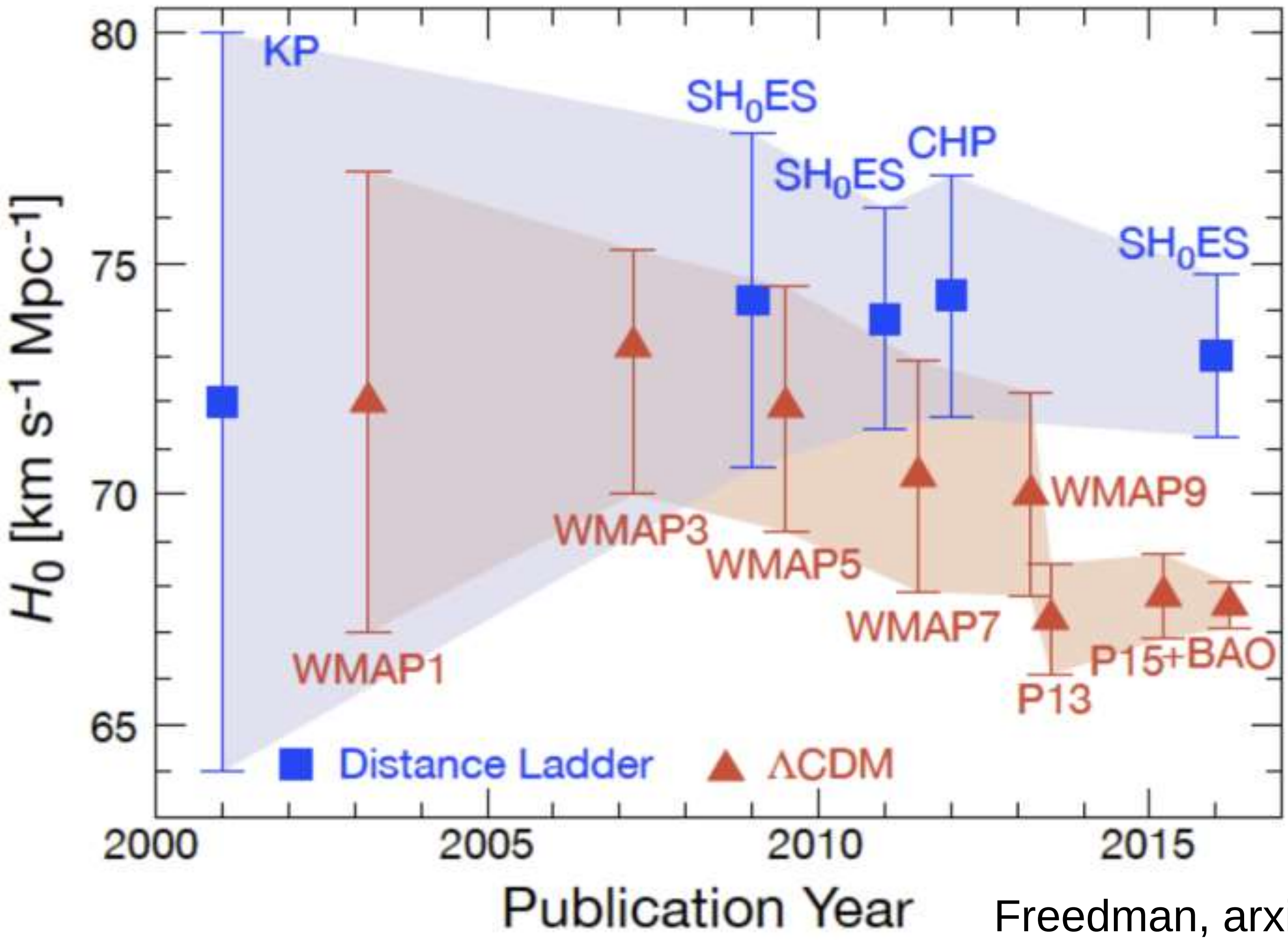
Laboratory	Main institute	Area	CMB projects	Nb of COrE (M4)	Nb HFI_Ass &CoI in Planck
APC	IN2P3	IdF	S, Q, E, P, C	10	21
IAP	INSU	IdF	N, B, P, C	9	23
IAS	INSU	IdF	N, B, P, C	6	30
LAL	IN2P3	IdF	Q, E, P, C	4	10
SAp-AIM	IRFU	IdF	N, C	4	3
SPP	IRFU	IdF	C	1	2
I. Néel	I. physique	Grenoble	N, B, P, C	3	1
IPAG	INSU	Grenoble	N, B, C	2	3
LPSC	IN2P3	Grenoble	N, B, C	4	8
IRAP	INSU	Toulouse	N, Q, B, P, C	5	13
LAM	INSU	Marseille	N, P, C	1	1

S = PolarBEAR (Simmons Array), N = NIKA2, Q = QUBIC, B = Bside, E = EBEX-IDS, P = PIXIE, C = COrE
~ 50 French people in the M4 proposition, 115 French scientists in Planck-HFI (includes PhD students & post-docs)

Following up Planck clusters: a cluster mass dependence of the bias?



The H0 "tension": no-luck, Systematics, new physics?



Freedman, arxiv/1706.0273

More numerology

ADS, most cited papers since 2013, i.e., since the first Planck release, in all of Physics+Astrophysics :

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- ➢ #2 is particle physics data group, #4 & 10 is WMAP, #5 is GW, #9 is Bicep2…
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14	2016A&A...594A..20P Planck Collaboration; Ade, P. A. R.; Aghanim, N.; Arnaud, M.;	1007.000 Planck 2015 results. XX. Constraints on inflation	09/2016	A E F X R C S O U

Parameter		Current results	*CORE* expected uncertainties
Ω_k	Curvature	$\Omega_k = -0.005^{+0.009}_{-0.008}$ (68 % CL) [30]	$\sigma(\Omega_k) = \mathbf{0.0018}$
$dn_s/d\ln k$	Running index	$dn_s/d\ln k = -0.003 \pm 0.007$ (68 % CL) [30]	$\sigma(dn_s/d\ln k) = \mathbf{0.0023}$
f_{NL}	Non-Gaussianity	$f_{NL}^{local} = 0.8 \pm 5.0$ (68 % CL) [13]	$\sigma(f_{NL}^{local}) = \mathbf{2.1}$
		$f_{NL}^{equil} = -3.7 \pm 43$ (68 % CL) [13]	$\sigma(f_{NL}^{equil}) = \mathbf{21}$
		$f_{NL}^{ortho} = -26 \pm 21$ (68 % CL) [13]	$\sigma(f_{NL}^{ortho}) = \mathbf{9.6}$
β_{iso}	Non-adiabaticity	$\beta_{iso} < 0.0013$ (95 % CL) [11]	$\beta_{iso} < \mathbf{0.00026}$ (95 % CL)
$G\mu$	Cosmic strings	$G\mu < 2.0 \times 10^{-7}$ (95 % CL) [31]	$G\mu < \mathbf{2.1 \times 10^{-8}}$ (95 % CL)

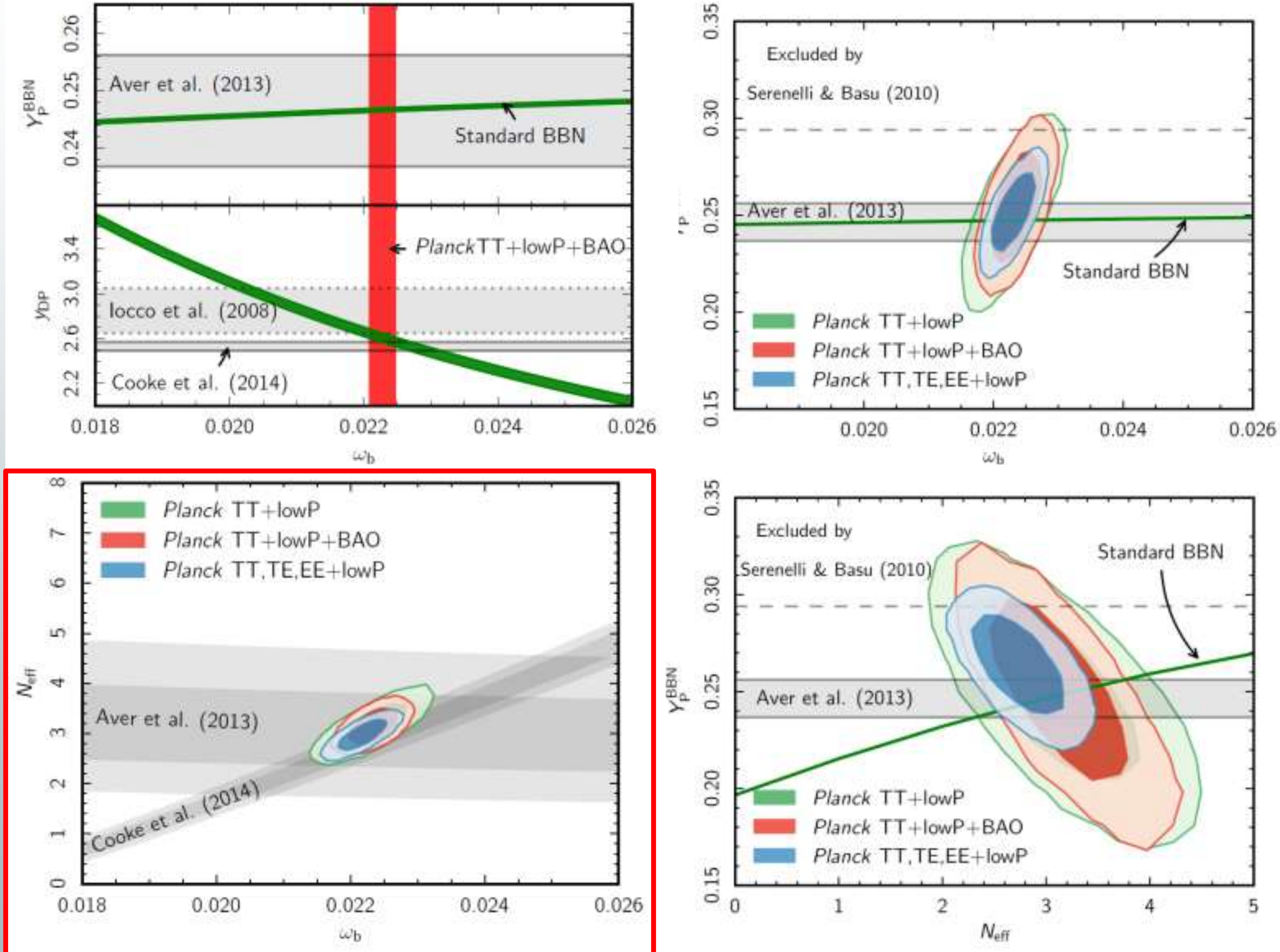
Table 1: Current limits and *CORE* uncertainty forecasts. The 3-point function measurements of non-Gaussianity will shrink the allowed volume in local-equilateral-orthogonal f_{NL}-parameter space by a factor of approximately 20.

For reference, expectation for CORE

Model	*Planck*15+BAO	*CORE*	*CORE*+BAO
ΛCDM	3.3	2.3×10^3	2.3×10^3
$\Lambda\text{CDM} + \sum m_\nu$	11	8.9×10^3	2.0×10^4
$\Lambda\text{CDM} + w$	24	5.4×10^3	2.2×10^4
$\Lambda\text{CDM} + \sum m_\nu + N_{eff}$	15	4.7×10^4	1.0×10^5
$\Lambda\text{CDM} + w_0 + w_a$	42	4.7×10^3	1.3×10^5
$\Lambda\text{CDM} + Y_P + \sum m_\nu + N_{eff}$	13	2.5×10^5	5.0×10^5
$\Lambda\text{CDM} + r + dn_s/d\ln k + \sum m_\nu + N_{eff}$	12	5.8×10^5	1.2×10^6
$\Lambda\text{CDM} + w + Y_P + \sum m_\nu + N_{eff}$	140	5.2×10^5	9.1×10^6
$\Lambda\text{CDM} + w + r + \sum m_\nu + N_{eff}$	110	3.9×10^5	7.6×10^6

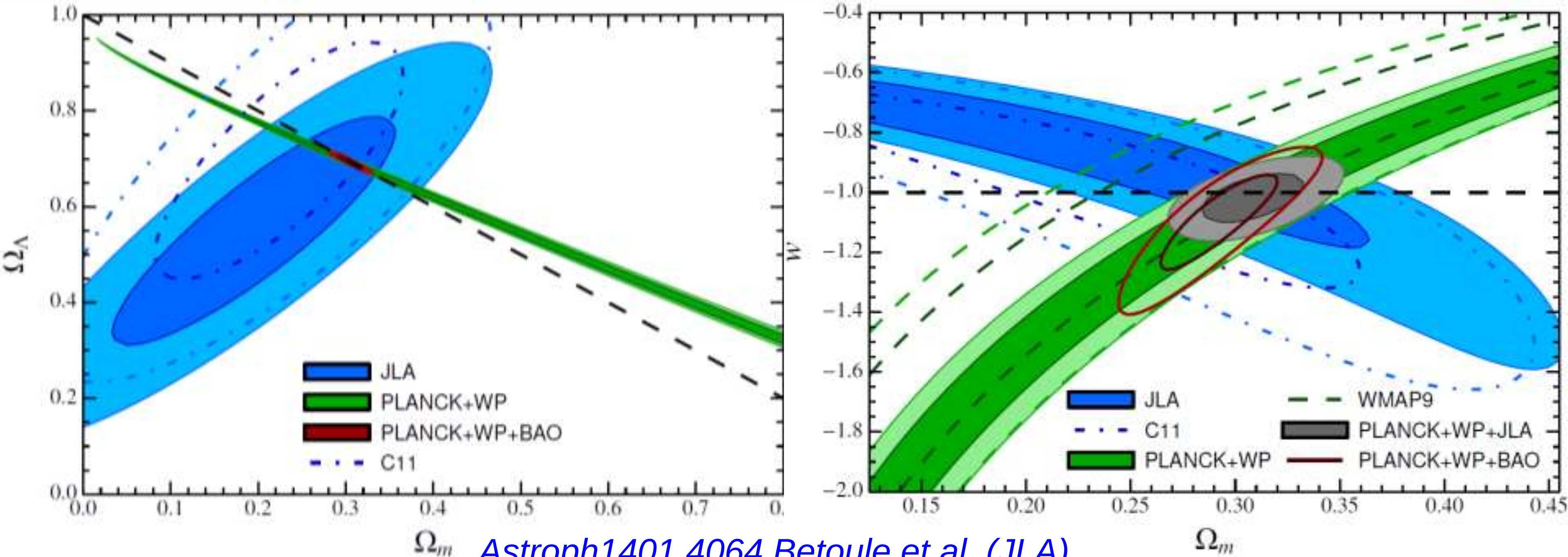
Table 2: Improvement with respect to *Planck*15 of the global figure of merit (see text) in the different cosmological scenarios specified in the first column for various data combinations involving *CORE* and future BAO measurements.

BBN



Aver et al. (2013)
Standard BBN
Y_P^{BBN}
Planck TT+lowP+BAO
Iocco et al. (2008)
Cooke et al. (2014)
y_{DP}
ω_b
Excluded by
Serenelli & Basu (2010)
Planck TT+lowP
Planck TT+lowP+BAO
Planck TT,TE,EE+lowP
N_{eff}

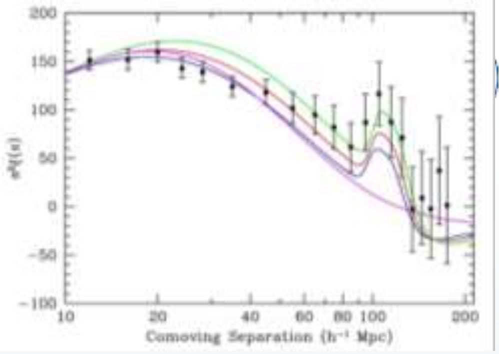
Planck versus JLA (SNLS +SDSS)



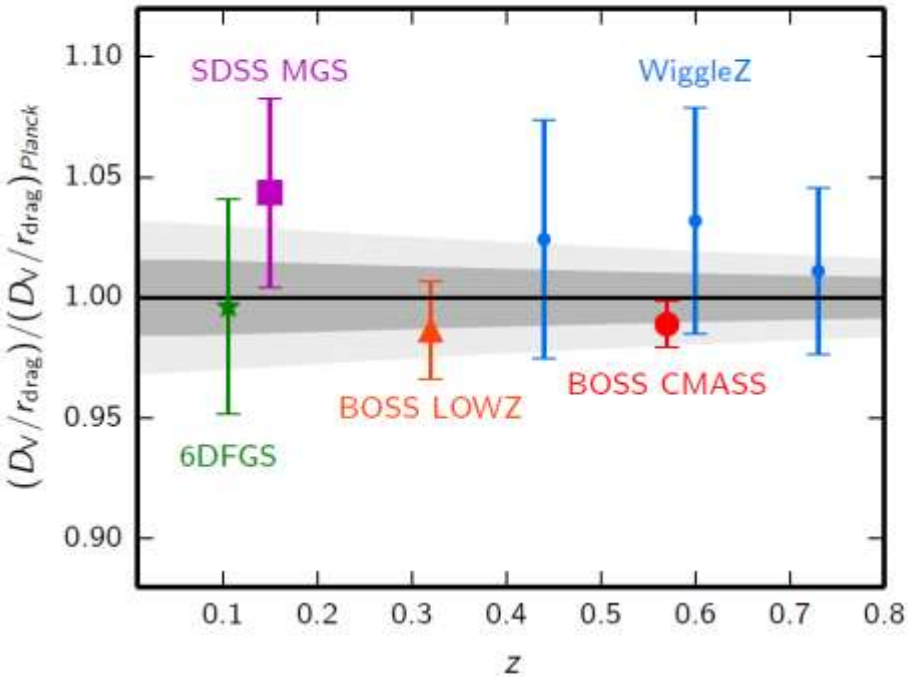
Astroph1401.4064 Betoule et al. (JLA)

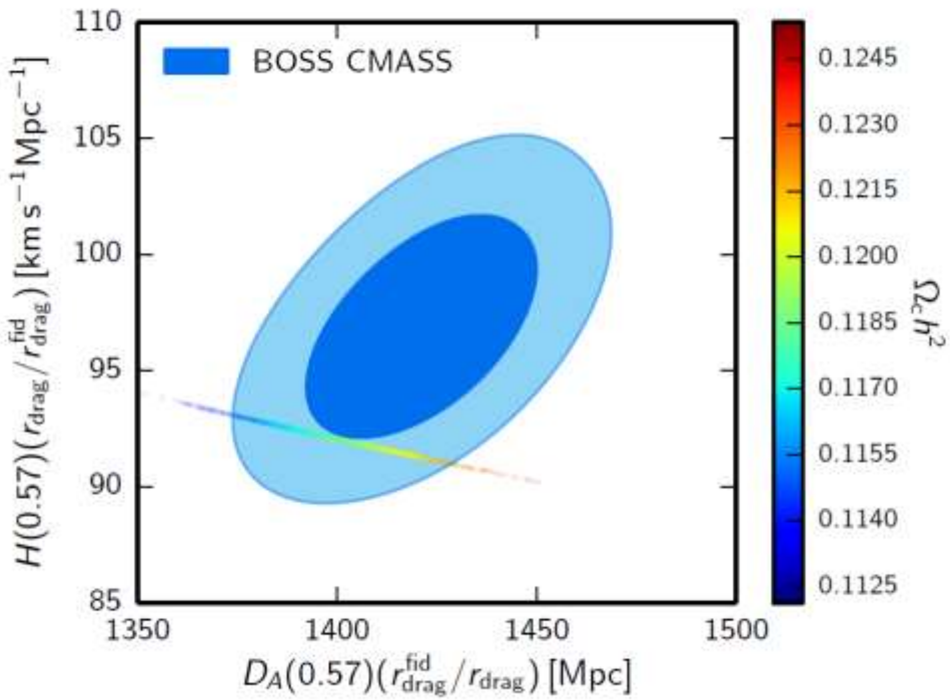
	Ω_m	w	H_0	$\Omega_b h^2$
Planck+WP+BAO+JLA	0.303 ± 0.012	-1.027 ± 0.055	68.50 ± 1.27	0.0221 ± 0.0003
Planck+WP+BAO	0.295 ± 0.020	-1.075 ± 0.109	69.57 ± 2.54	0.0220 ± 0.0003
Planck+WP+SDSS	0.341 ± 0.039	-0.906 ± 0.123	64.68 ± 3.56	0.0221 ± 0.0003
Planck+WP+SDSS+SNLS	0.314 ± 0.020	-0.994 ± 0.069	67.32 ± 1.98	0.0221 ± 0.0003
Planck+WP+JLA	0.307 ± 0.017	-1.018 ± 0.057	68.07 ± 1.63	0.0221 ± 0.0003
WMAP9+JLA+BAO	0.296 ± 0.012	-0.979 ± 0.063	68.19 ± 1.33	0.0224 ± 0.0005
Planck+WP+C11	0.288 ± 0.021	-1.093 ± 0.078	70.33 ± 2.34	0.0221 ± 0.0003

BAO



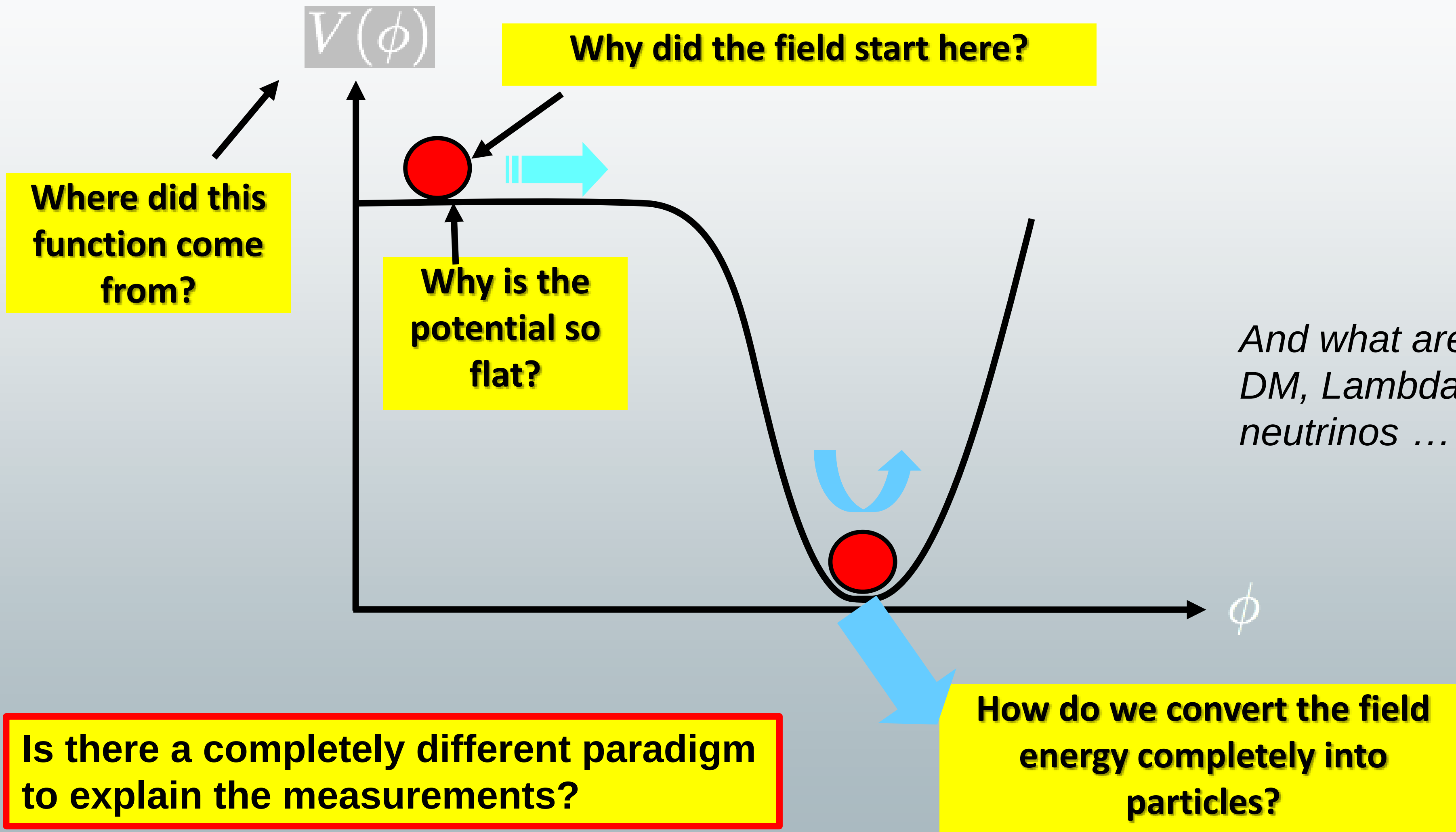
Grey band is Planck TT+LowP 1(2) sigma range






GRAVITATIONAL
WAVES

But what is the physics of inflation?



And what are DM, Lambda, neutrinos …

Is there a completely different paradigm to explain the measurements?

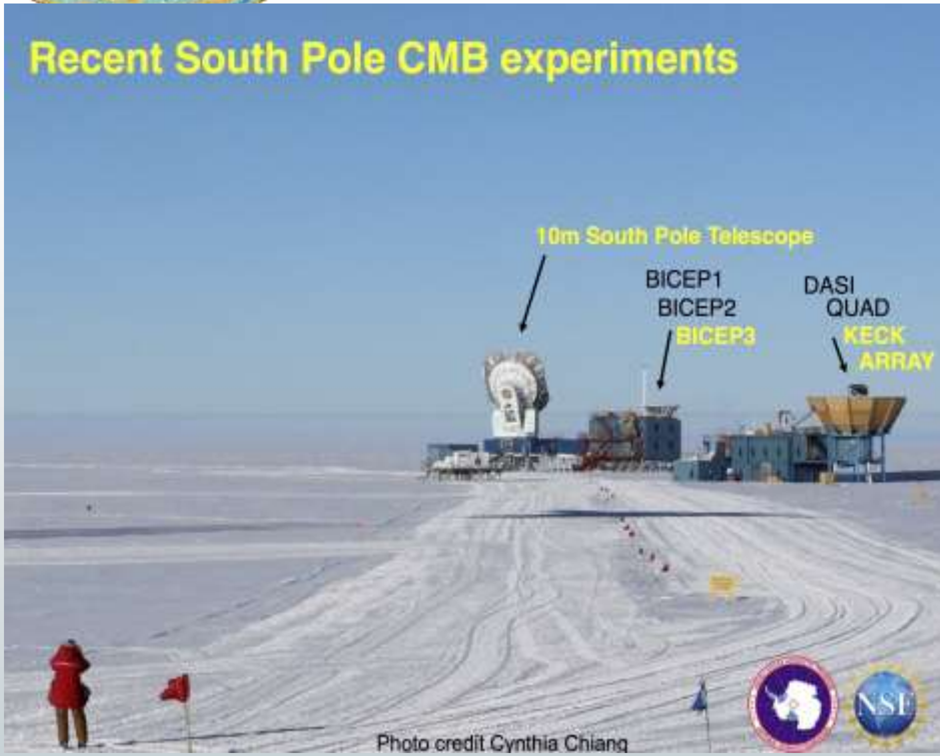

The
journey
continues!

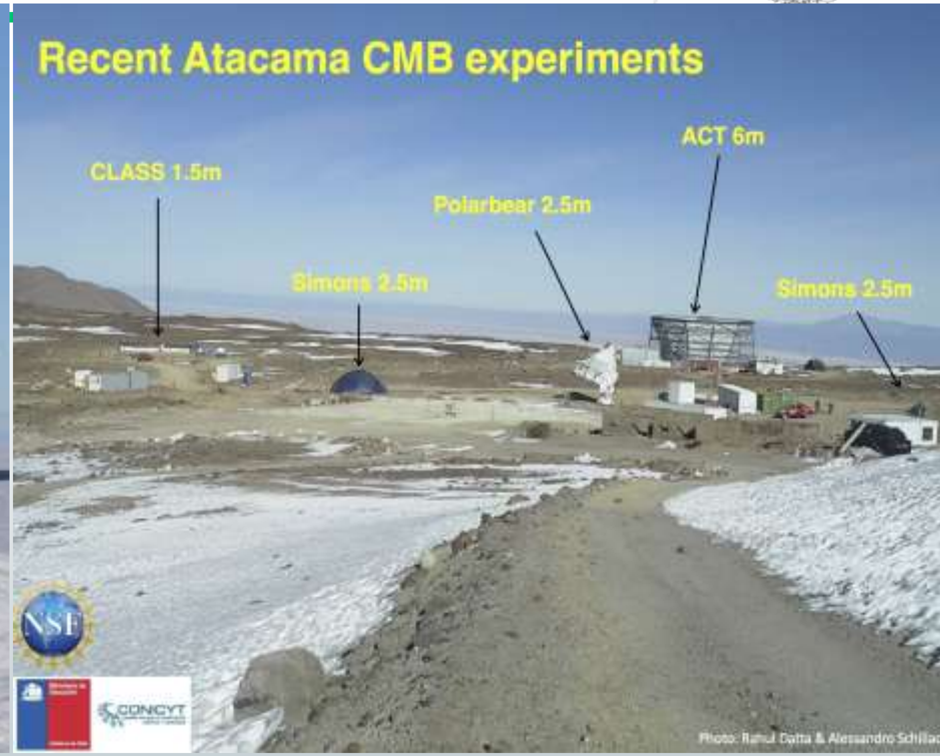
CMB remains unique and powerful

- 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!

- Let's do it and check the unknown, with your support!

Primary Ground-Based Locations





- Most of the ground-based "weight" in the CMB is at two sites – either (the Chilean) Atacama Desert, or the South Pole.

- There is also
  - QUBIC, NIKA from France
  - QUIJOTE, C-BASS from Europe
  - GroundBird, AMIBA from Asia
  - Mustang2 in the US

Comp to SPT (params)

Aylor+ arXiv:1706.10286v1

30 juin

2540 deg2 SPT-SZ

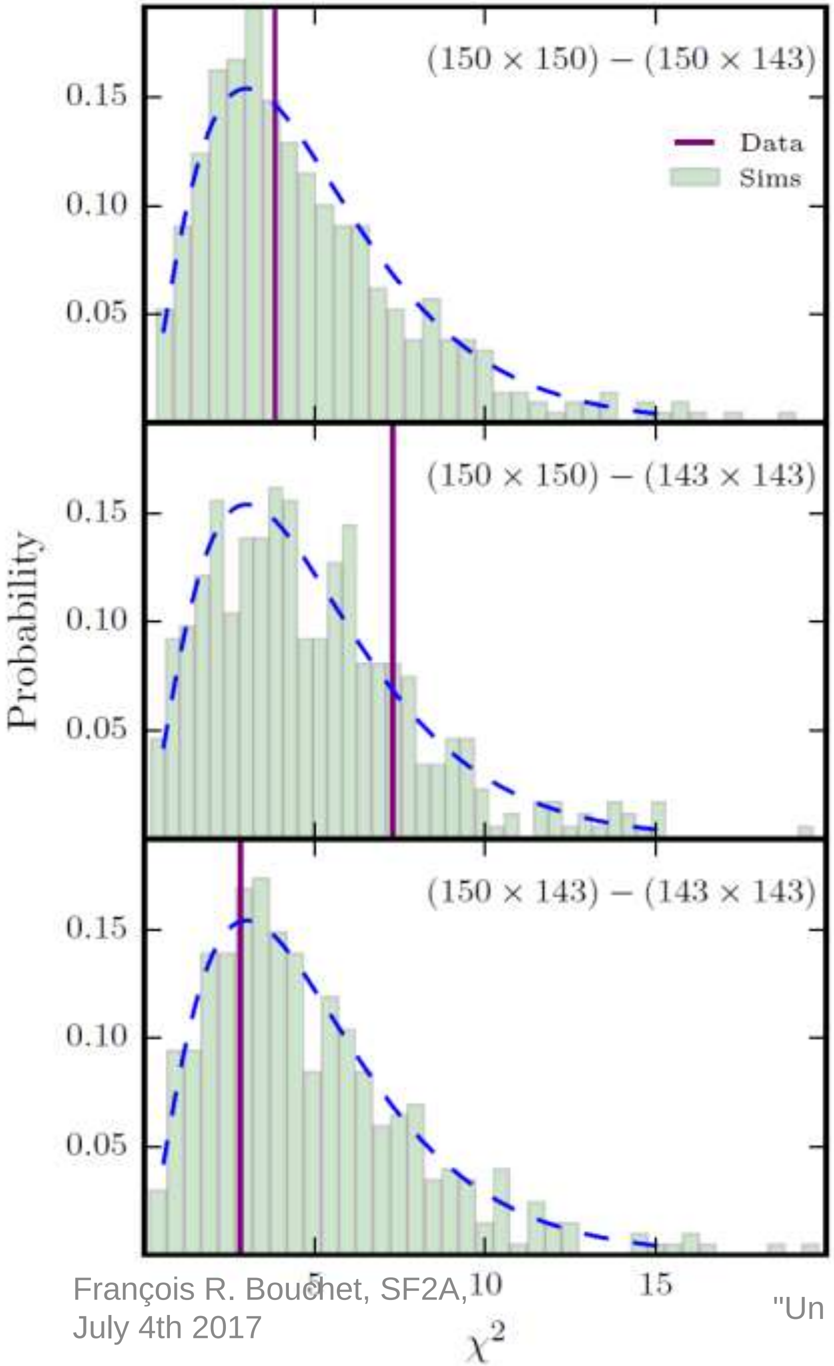


TABLE 1
PTEs Between Parameters in SPT Sky Patch.

	ℓ_{max}		
	2000	2500	3000
150 × 150 − 150 × 143	0.74	0.66	0.57
150 × 150 − 143 × 143	0.32	0.38	0.20
150 × 143 − 143 × 143	0.62	0.73	

Planck and SPT LCDM parameters fully
Consistent WITHIN the SPY sky patch

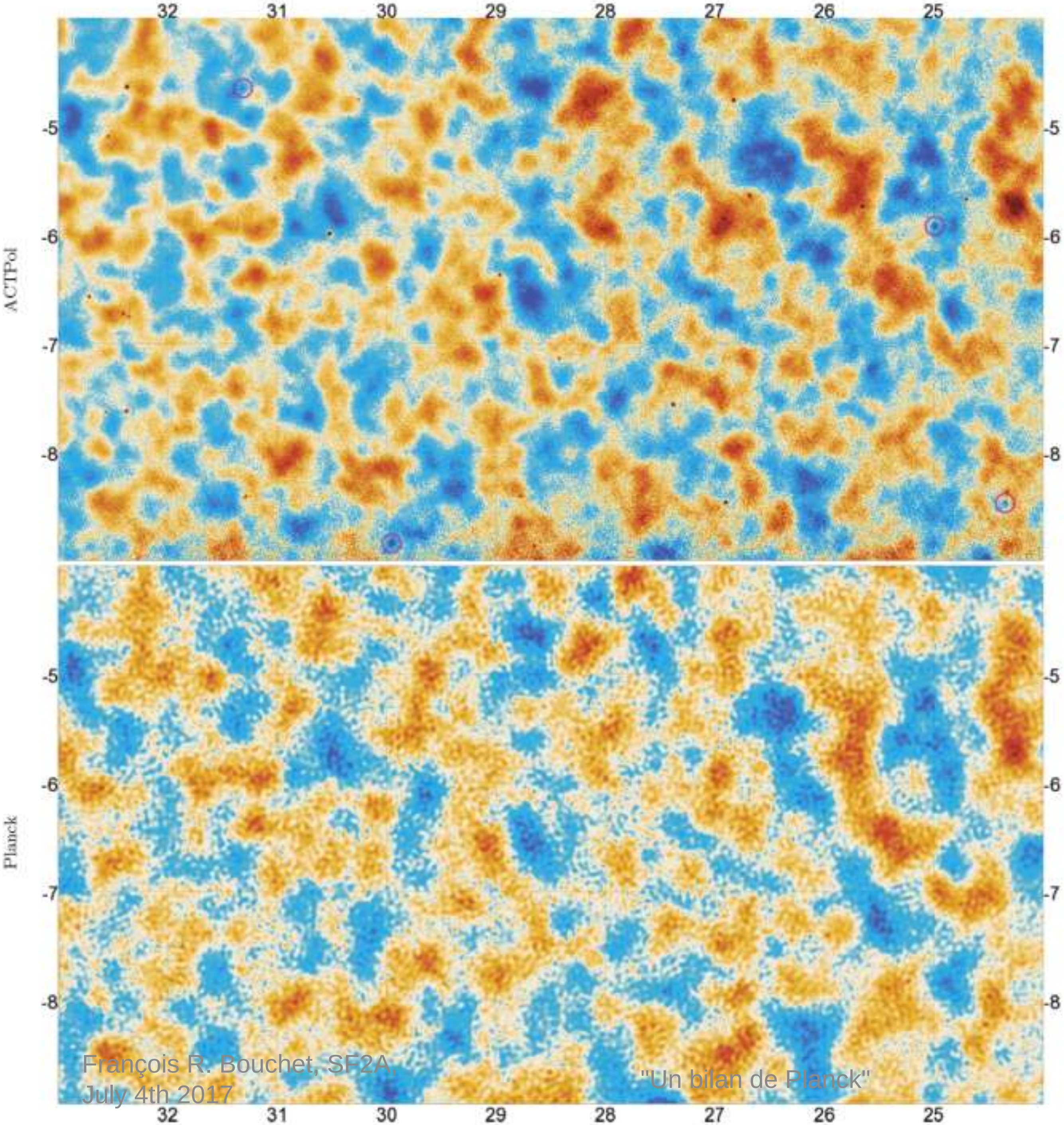
TABLE 2
PTEs Between PlanckFS and In-patch Parameters.

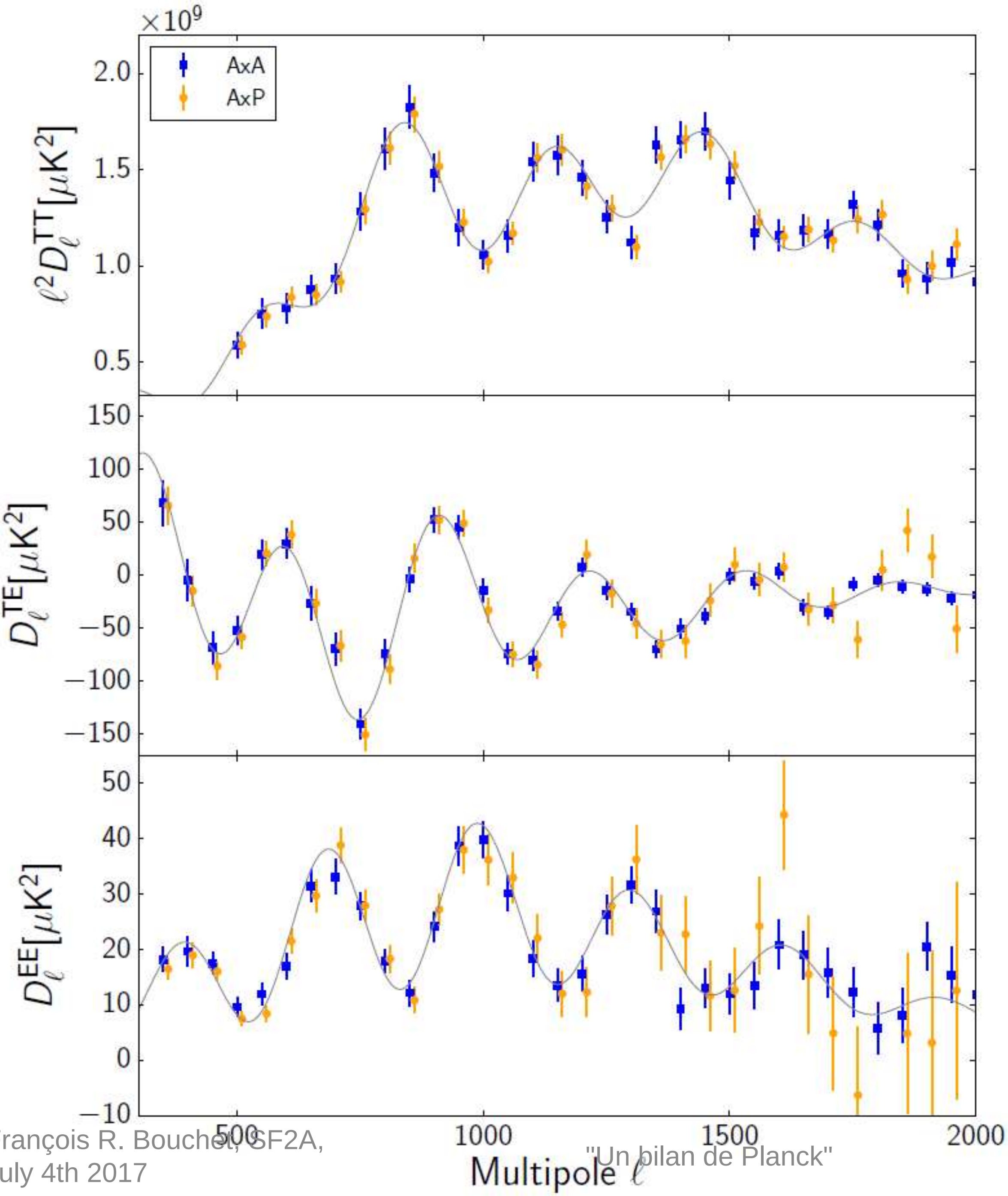
	ℓ_{max}		
	2000	2500	3000
150 × 150	0.24	0.094	0.032
150 × 143	0.19	0.18	
143 × 143	0.29	0.31	

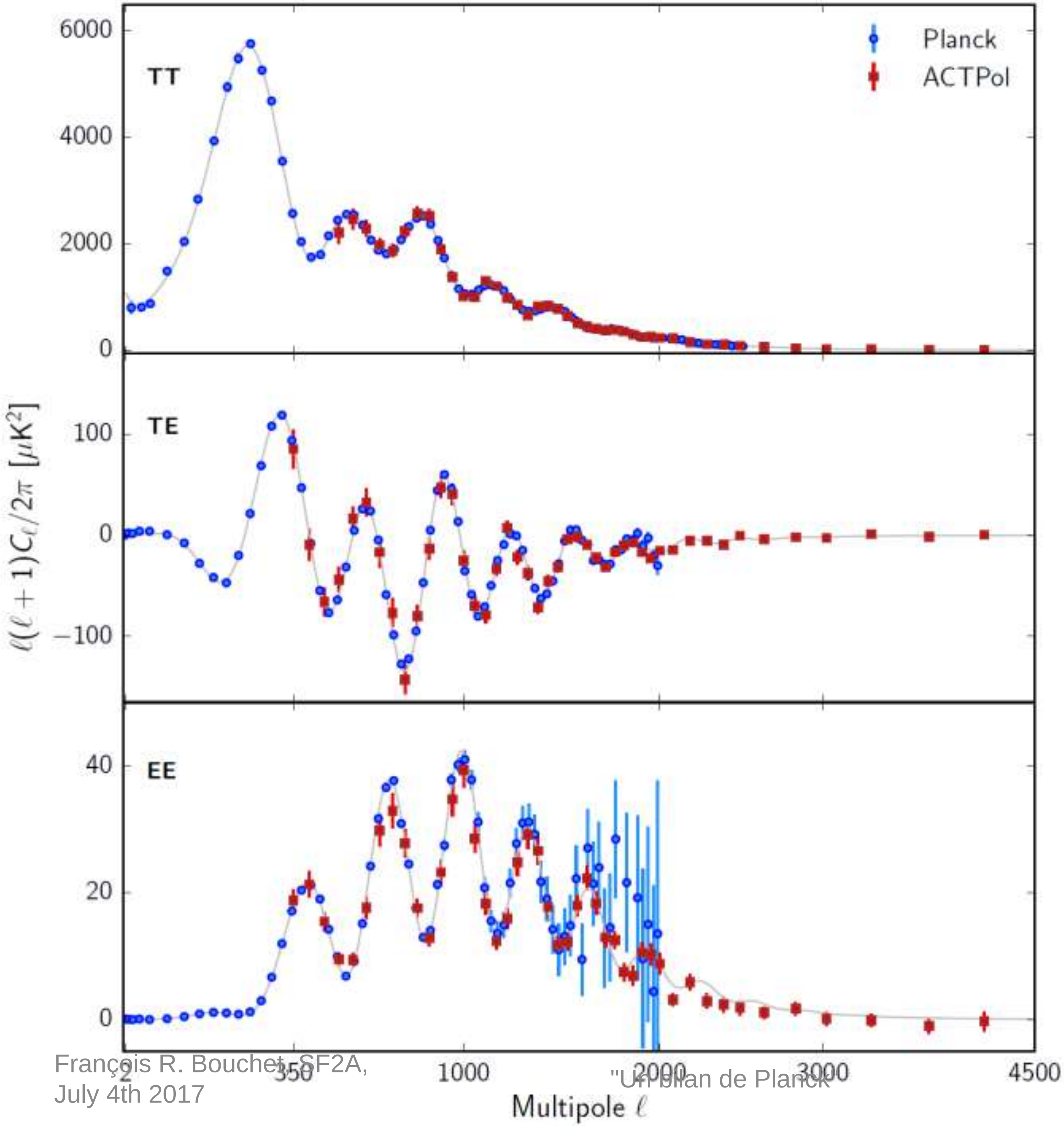
Planck Full sky is consistent with SPT in-patch
At all scale probed well by planck (lmax =2000)
Need to go to lmaxSPT=3000 to find some tens
(at 3.2% PTE) [where SPT goes to larger H0

ACT

Louis+ arXiv:1610.02360v1

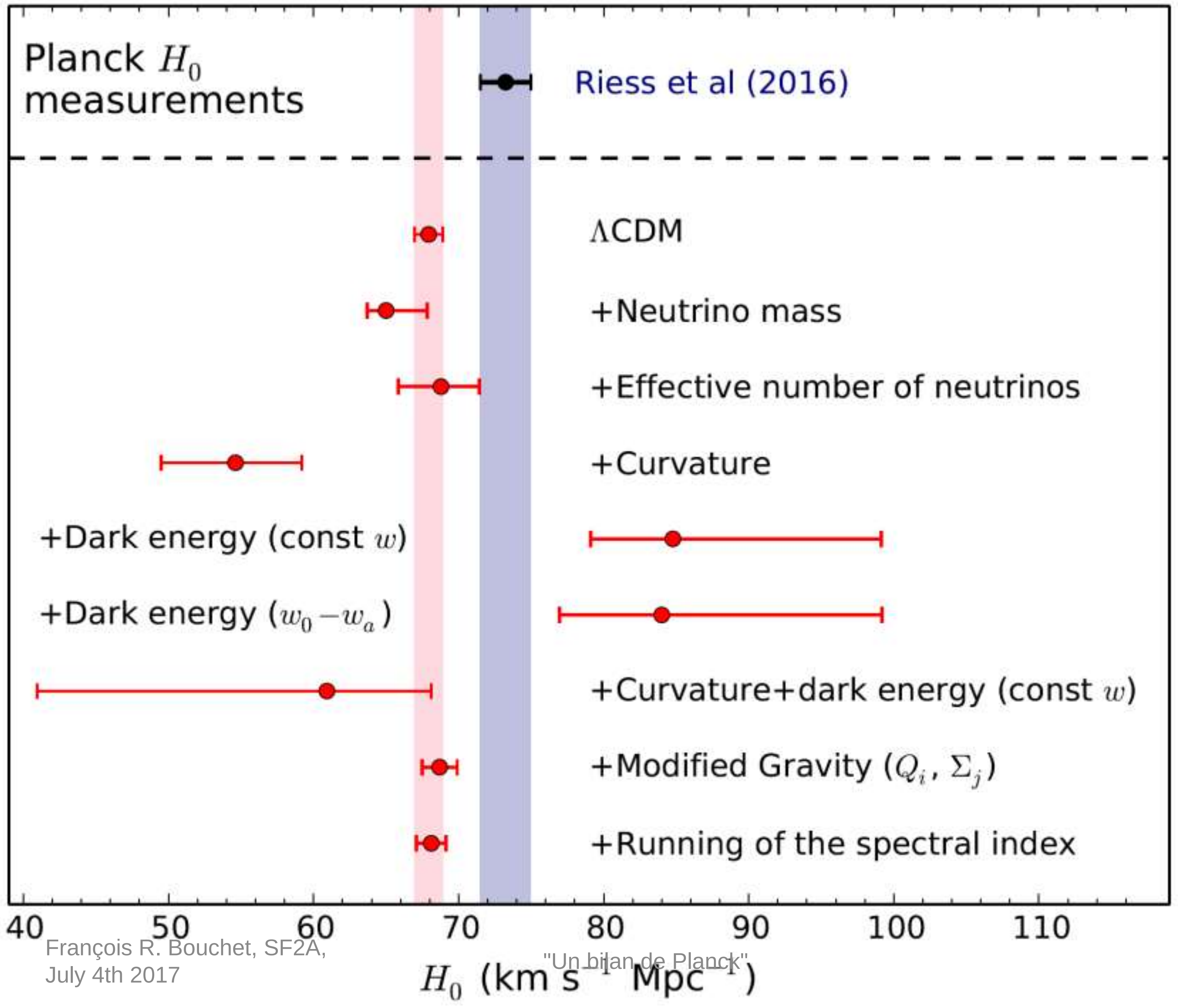

32
31
30
29
28
27
26
25
-5
-6
-7
-8
ACTPol
Planck


×10^9
AxA
AxP
$\ell^2 D_\ell^{TT} [\mu K^2]$
2.0
1.5
1.0
0.5
$D_\ell^{TE} [\mu K^2]$
150
100
50
0
−50
−100
−150
$D_\ell^{EE} [\mu K^2]$
50
40
30
20
10
0
−10
500
1000
1500
2000
Multipole ℓ


Planck
ACTPol
TT
TE
EE
6000
4000
2000
0
100
0
−100
40
20
0
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
2
350
1000
2000
3000
4500
Multipole ℓ

KIDS

arXiv:1610.04606v1


Planck H_0 measurements
Riess et al (2016)
ΛCDM
+Neutrino mass
+Effective number of neutrinos
+Curvature
+Dark energy (const w)
+Dark energy ($w_0 - w_a$)
+Curvature+dark energy (const w)
+Modified Gravity (Q_i, Σ_j)
+Running of the spectral index
40
50
60
70
80
90
100
110
H_0 (km s^{-1} Mpc^{-1})

Recent H_0 values

- H0=67.3±0.96 (PlanckTT+lowP_LFI)
- H0=66.9±0.91 (PlanckTT+SIMlowHFI) (ie new tau) – Planck latest

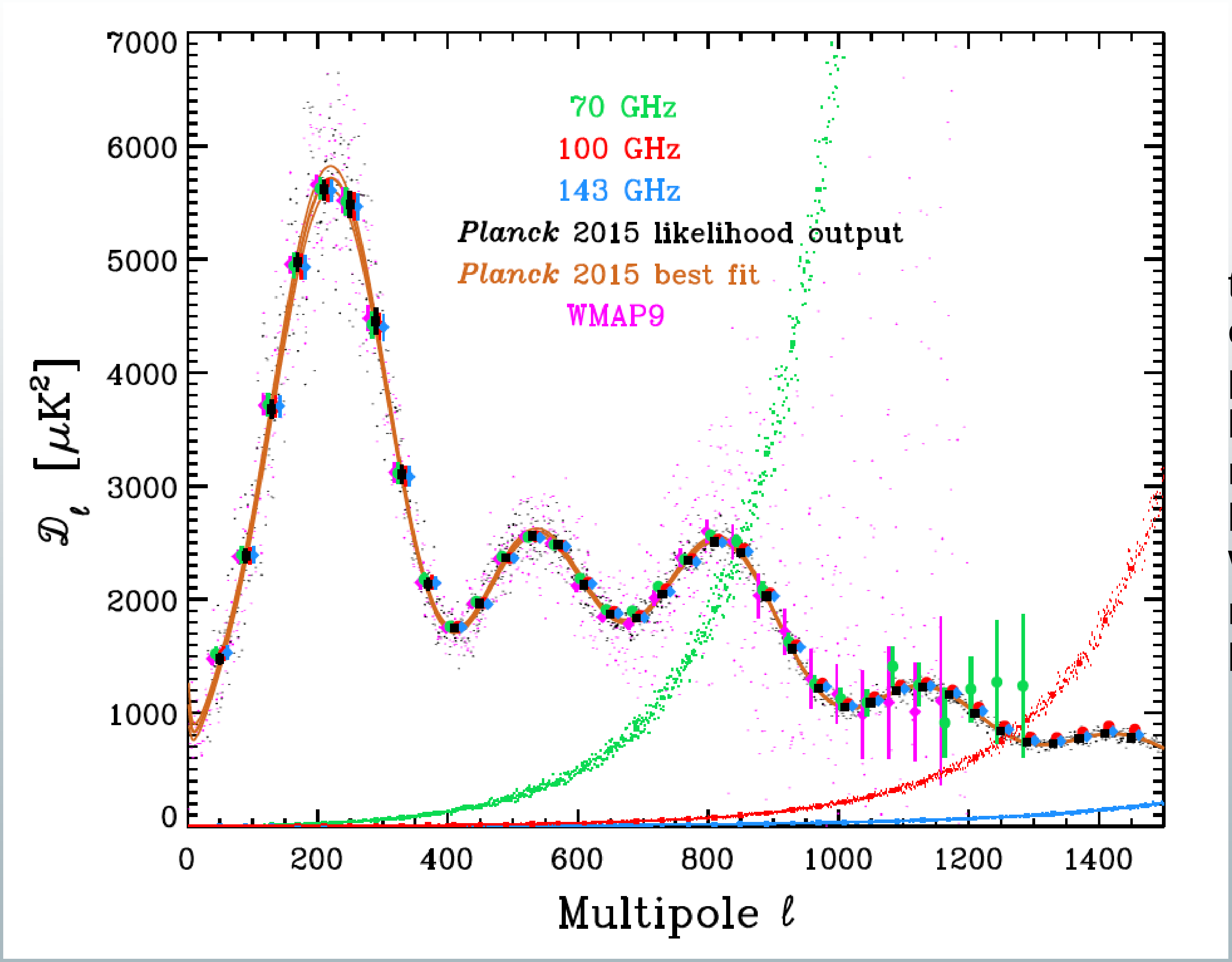
- H0=72.8±2.4 [2σ tension] (Riess+11)
- H0=70.6 ± 3.3 [1σ tension] (Efstathiou+14)
- H0=74.3 ± 2.6 [2.5σ tension] (Freedman+12)
- H0=73.±1.8 [3σ tension] (Riess+16) [3 anchors]

- H0=71.9 +2.4-3.0 [1.7σ tension] H0licow, Bonvin et al. arXiv:1607.01790

- NB: Not only a Planck tension (wrt Riess+16) :

- H0=68.1 ± 0.7 [2.5σ tension] (Aubourg+2015) for WMAP9+BAO (BOSSDR11+6dFGS+Lyman α)+high-z Sne
- H0=69.3 ± 0.7 [1.9σ tension] (Bennet+2014) WMAP9+ACT+SPT+BAO (BOSSDR11+6dFGS)
- SPT alone prefers very high H0=75.0 ±3.5
- (NB: H0=69.7 ±2.1 [Km/s/Mpc] WMAP alone has much larger error bars)

Planks@low res/ell all agree w. WMAP

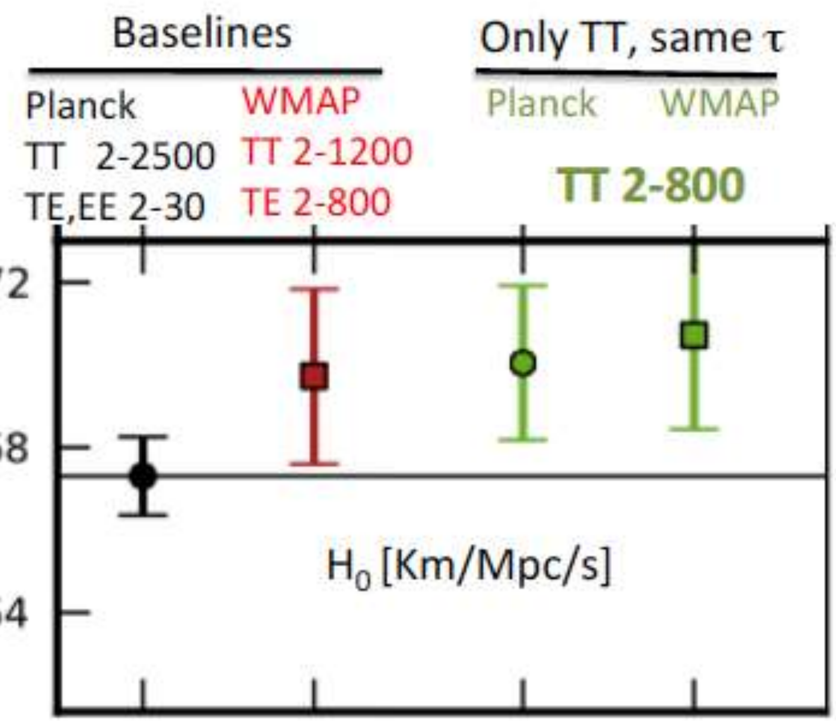


to the extent permitted by the much higher WMAP noise level

P15

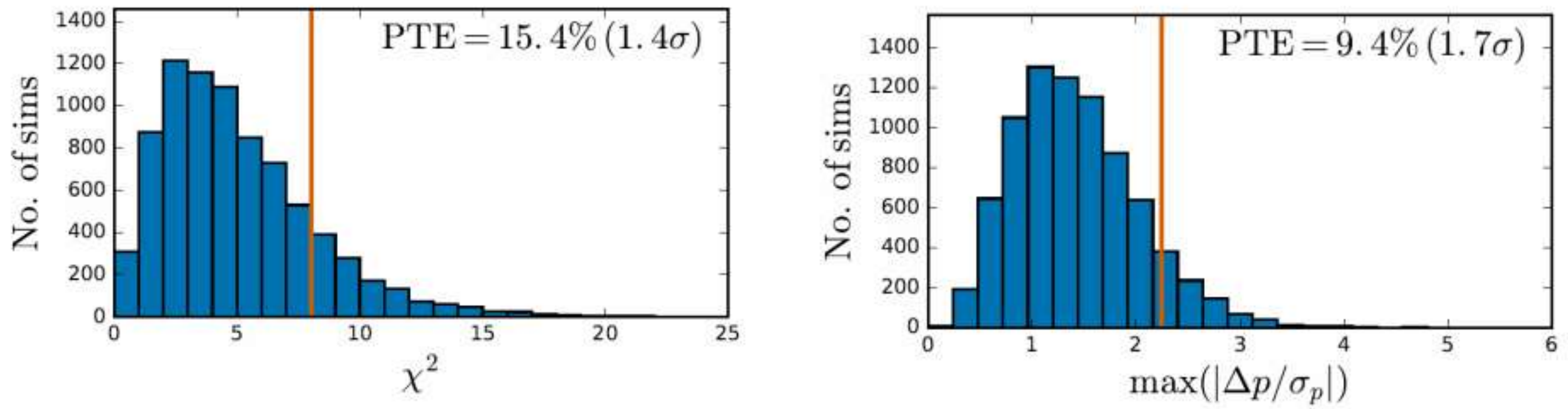
Compare apples to apples

- Same prior on the optical depth, temperature only, same multipole region (although noise properties and fsky are still different).



- Planck and WMAP agree very well when compared properly.
- This confirms the findings of comparison at map/power spectrum level.
- **Still need to prove that shifts between lmax=800 and lmax=2500 for Planck itself are consistent with expectations!**

Is the shift from WMAP (l<800) to Planck cosmology (l<2500) surprising?



For both statistics (chi^2 and largest deviation), we find that the observed shifts are largely consistent with expectations from 5000 simulations. Including for other data splits:

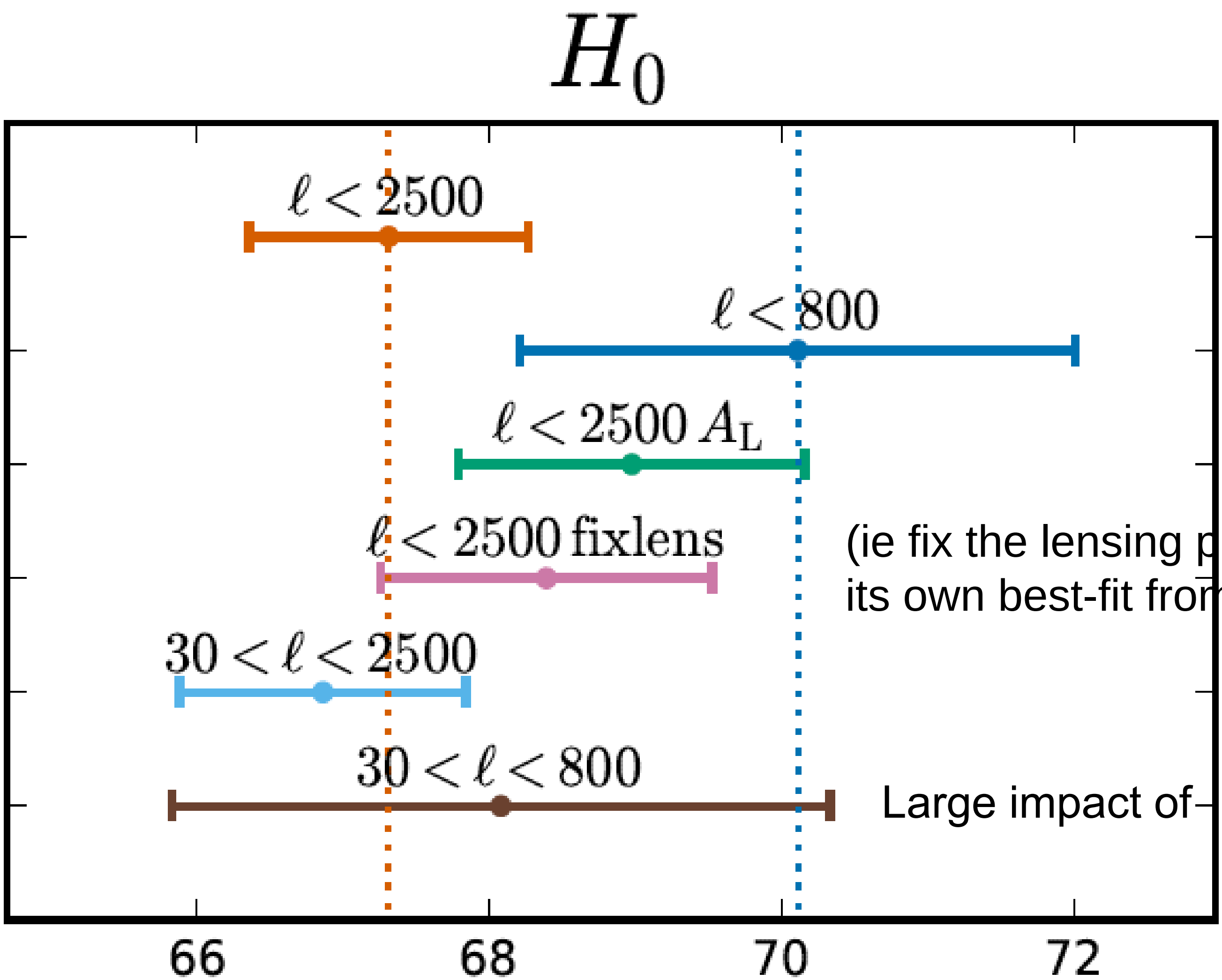
Data set 1	Data set 2	Test: χ^2	Test: max-param
$\ell < 800$	$\ell < 2500$	$1.4\sigma^\dagger$	1.7σ $(A_s e^{-2\tau})$
$\ell < 800$	$\ell > 800$	1.6σ	2.1σ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell < 2500$	$1.8\sigma^\dagger$	1.5σ $(A_s e^{-2\tau})$
$\ell < 1000$	$\ell > 1000$	1.6σ	1.6σ (ω_m)
$30 < \ell < 800$	$\ell > 30$	$1.2\sigma^\dagger$	1.3σ (τ)
$30 < \ell < 800$	$\ell > 800$	1.2σ	1.2σ $(A_s e^{-2\tau})$
$30 < \ell < 1000$	$\ell > 30$	$1.4\sigma^\dagger$	1.5σ (τ)
$30 < \ell < 1000$	$\ell > 1000$	1.2σ	0.7σ (ω_m)

(NB: Change of [-0.1,0.3] σ when using prior on tau=0.055\pm0.01 instead of 0.07\pm 0.02)

Planck IR-LI, arXiv:1608.02487v1

What drives the shift ?

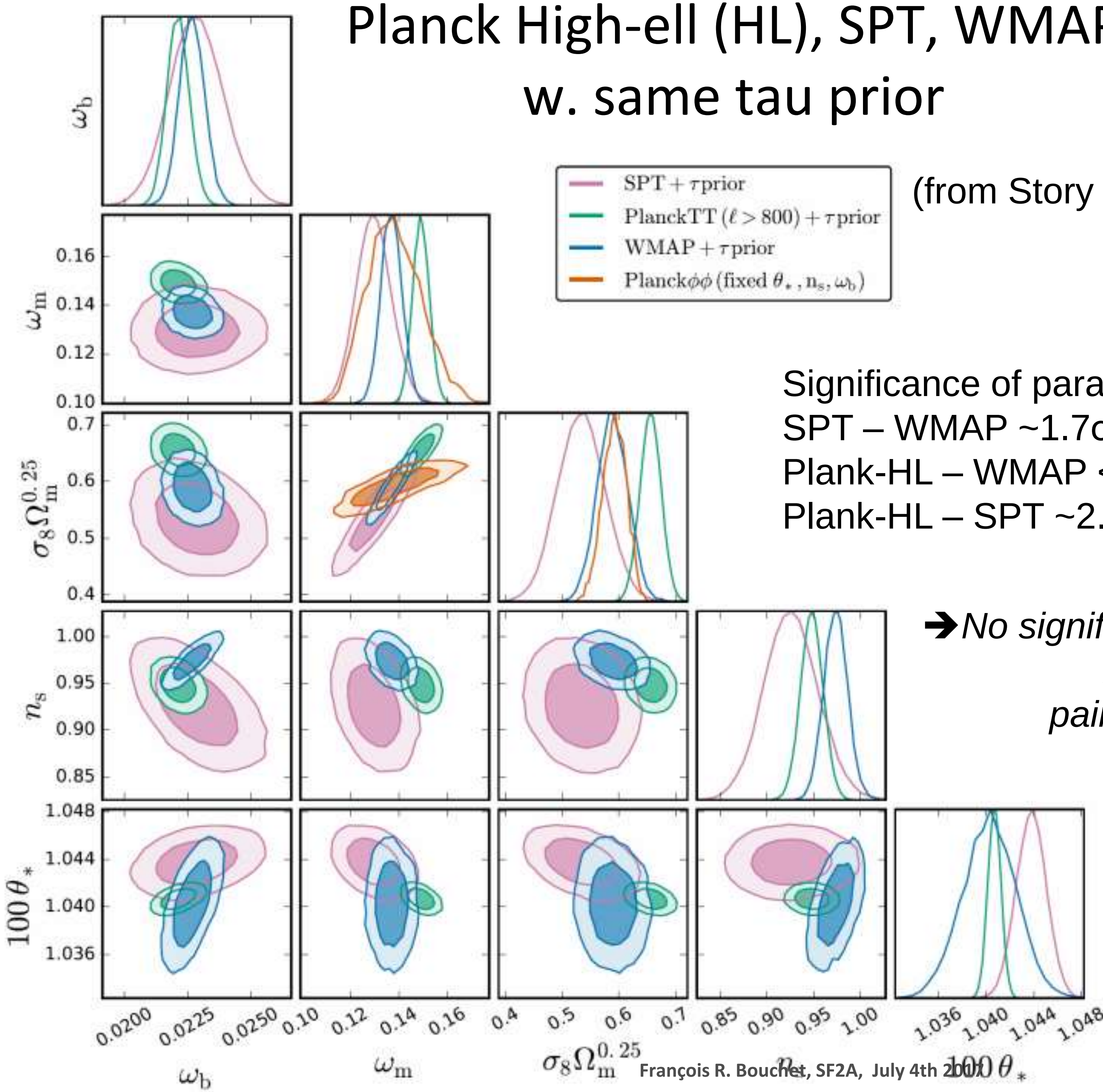
The PS deviation **looks** like extra smoothing like from extra lensing, but…



(ie fix the lensing potential to its own best-fit from l < 2500)

Large impact of l˜20 anomaly

Planck High-ell (HL), SPT, WMAP w. same tau prior



(from Story et al. 2013)

Significance of parameter shifts:
SPT – WMAP ~1.7σ
Plank-HL – WMAP <1.1σ
Plank-HL – SPT ~2.1σ

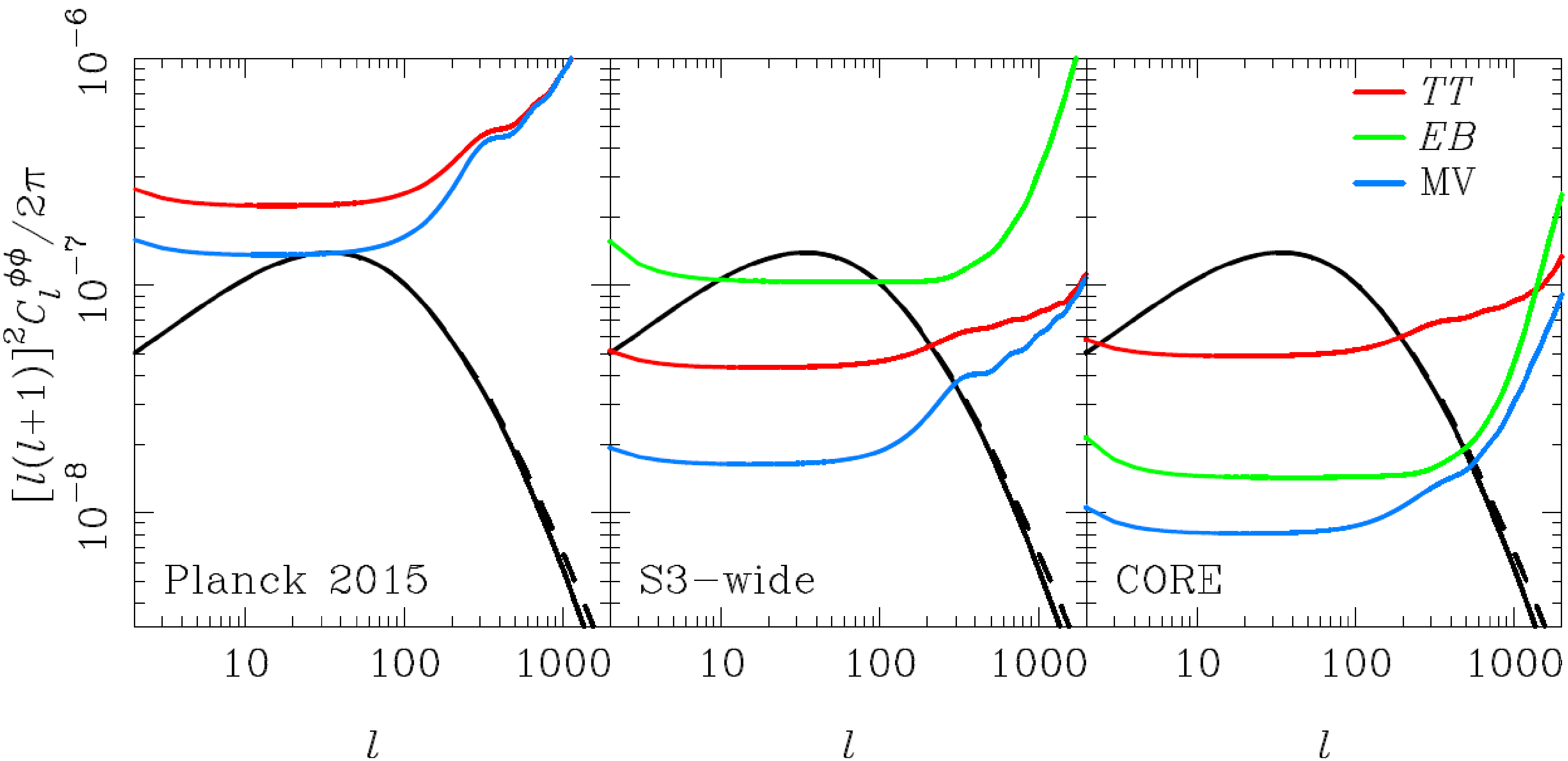
➔*No significant tension between any pair of data sets*

Planck IR-LI, arXiv:1608.02487v1

Partial (H0) Summary

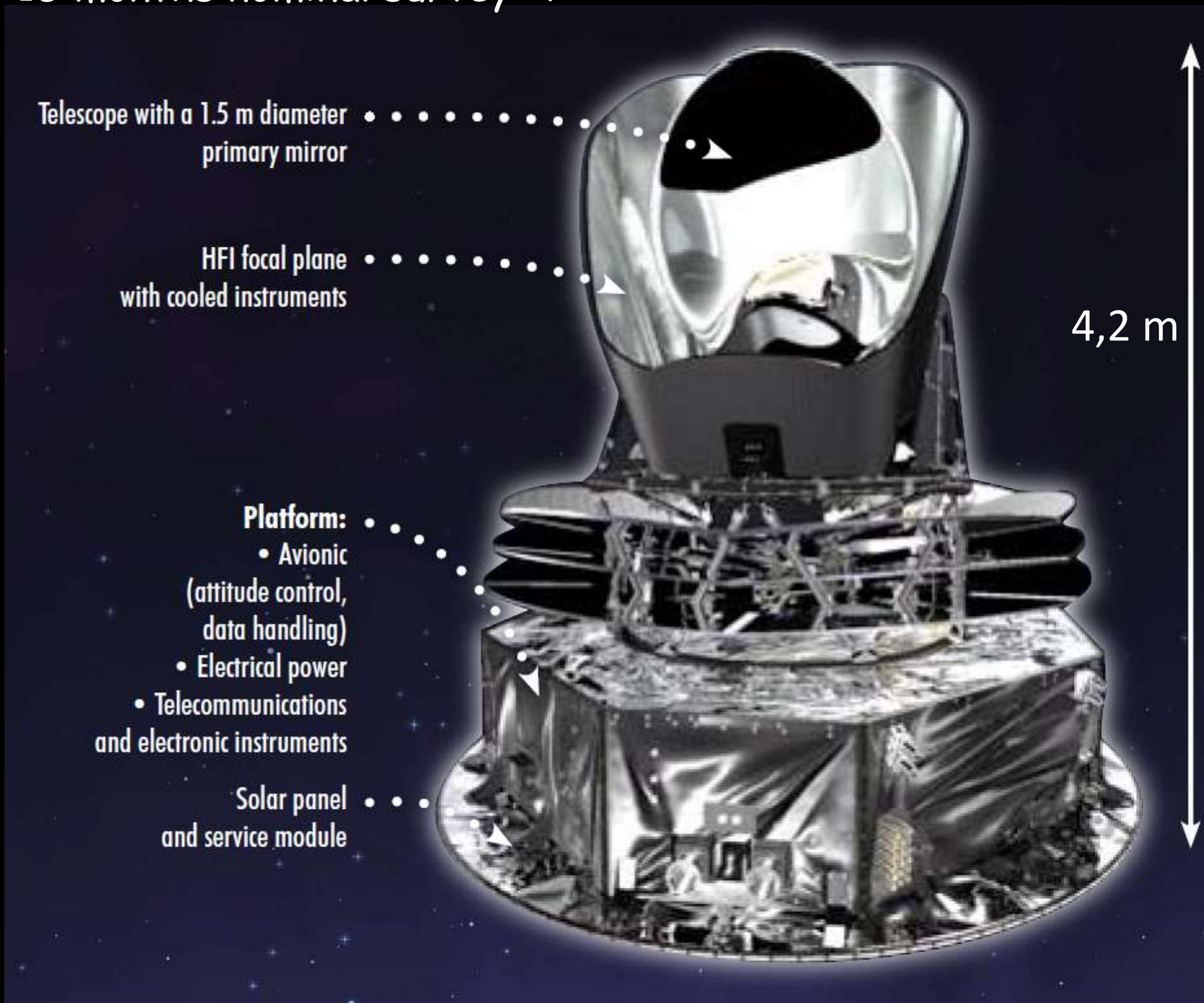
- Planck consistent with BAO, SN, BBN within LCDM.
- Tensions with clusters, weak lensing, and direct measurements of H_0.
- H_0 tension present also in WMAP+BAO+SN.
- WMAP and Planck in very good agreement if compared at same scales.
- WMAP+SPT do not have statistical power of Planck
- Planck low-l & Planck high-l are in good statistical agreement
- Smoothing of high-l peaks and low-l deficit possibly responsible for shifts between low and high-l.

Next step?



Reconstruction noise of the lensing detection power spectrum from Planck 2015 (left) and forecasts. The detection power spectrum is plotted based on the linear matter power spectrum (black solid) and with non-linear corrections (black dashed). [MV=minimum Variance].

2000 Kg
1600 W consumption
2 instruments - HFI & LFI
15 months nominal survey+4

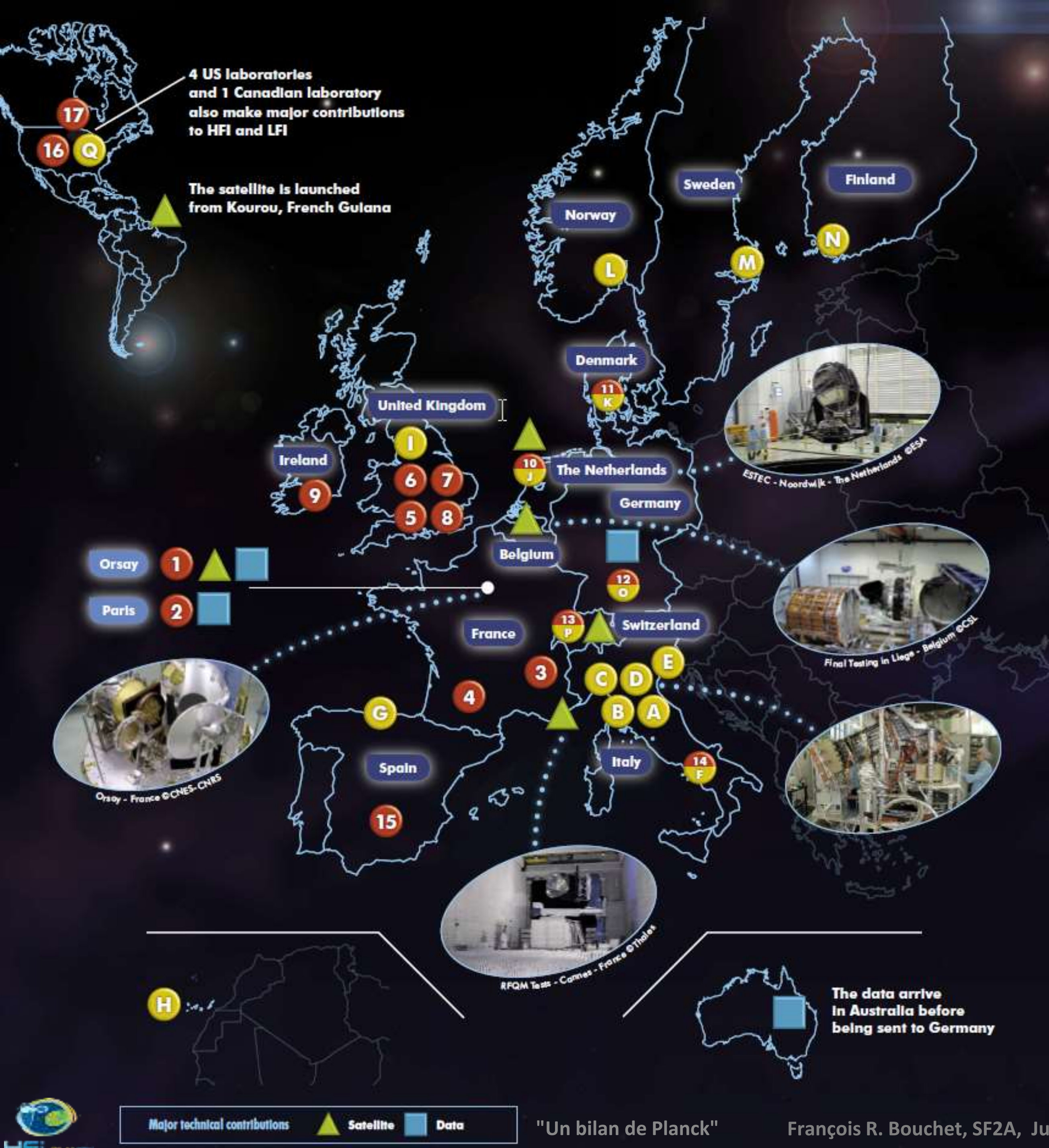


4,2 m

50 000 electronic components
36 000 l ^4He
12 000 l ^3He
11 400 documents
20 years between the first project and first results (2013)

6c per European per year
16 countries
400 researchers among 1000

4,2 m



Research Laboratories in the HFI Collaboration

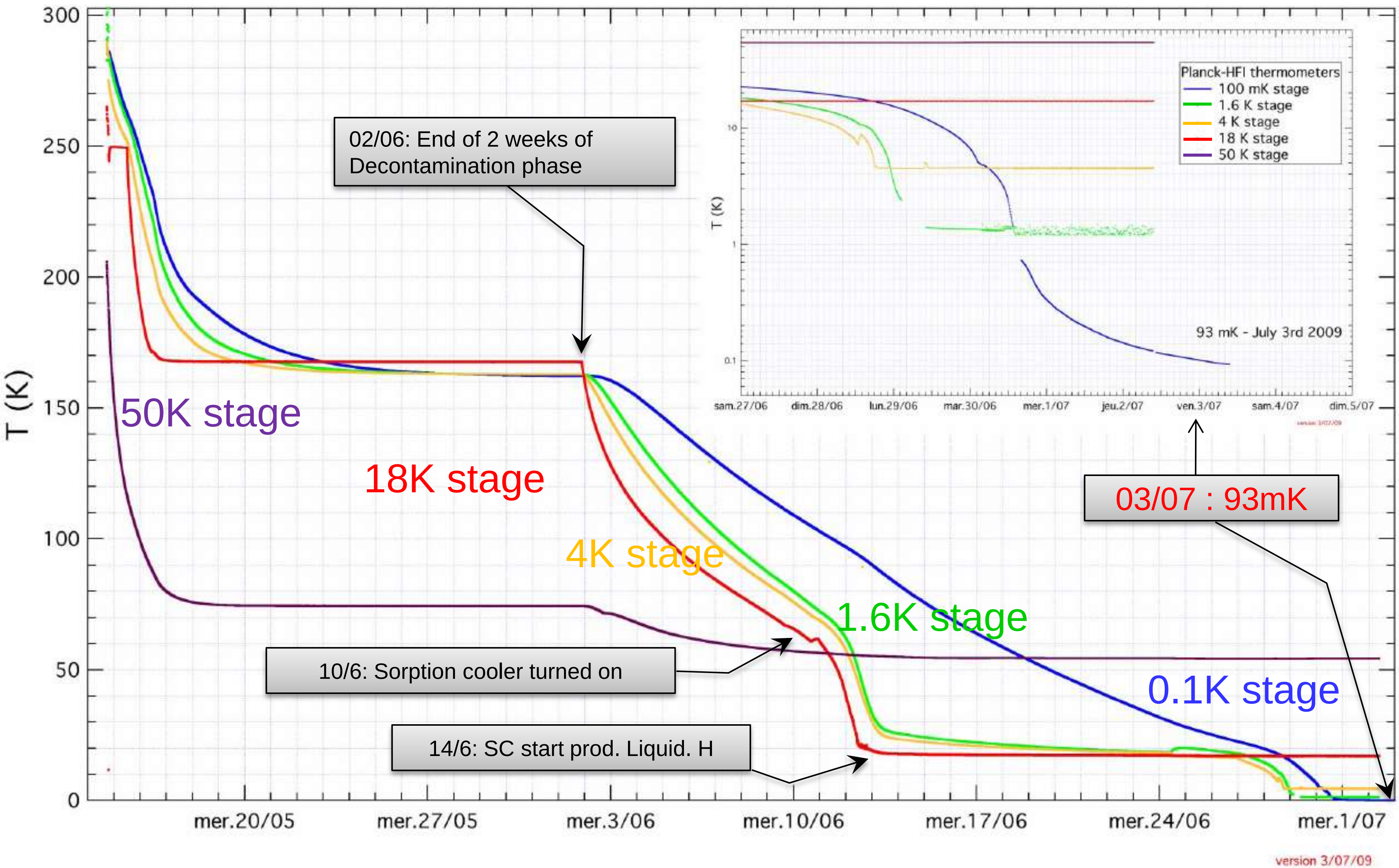
1 Institut d'Astrophysique Spatiale, Orsay (F)
1 Laboratoire de l'Accélérateur Linéaire, Orsay (F)
1 Commissariat à l'Énergie Atomique, Gif-sur-Yvette (F)
2 Institut d'Astrophysique de Paris, Paris (F)
2 Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique, Paris, (F)
2 AstroParticule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

Research Laboratories in the LFI Collaboration

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

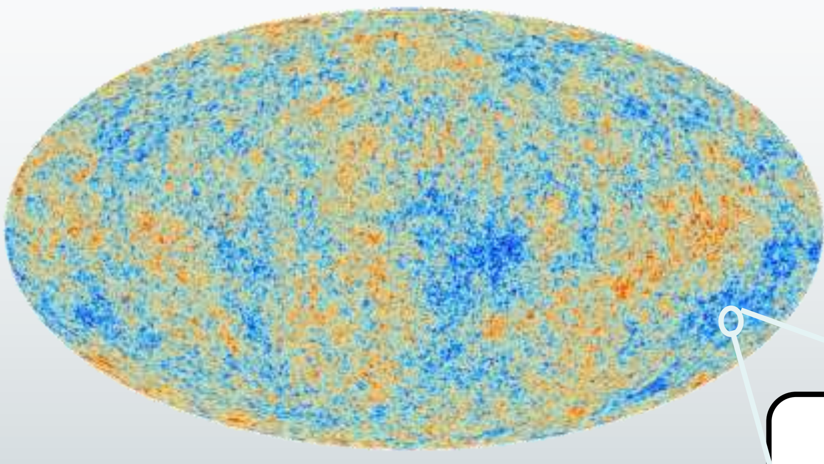

Ariane 5 ECA Launch • HERSCHEL – PLANCK - May 14, 2009

Planck is cool...

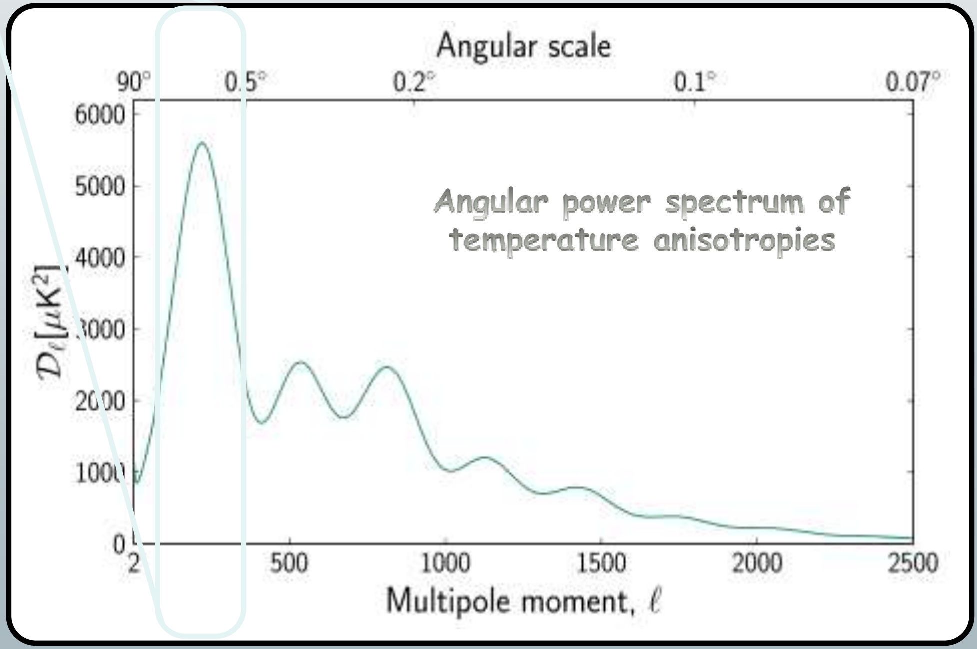


Ce qu'en dit la théorie…

(bien avant les observations…)



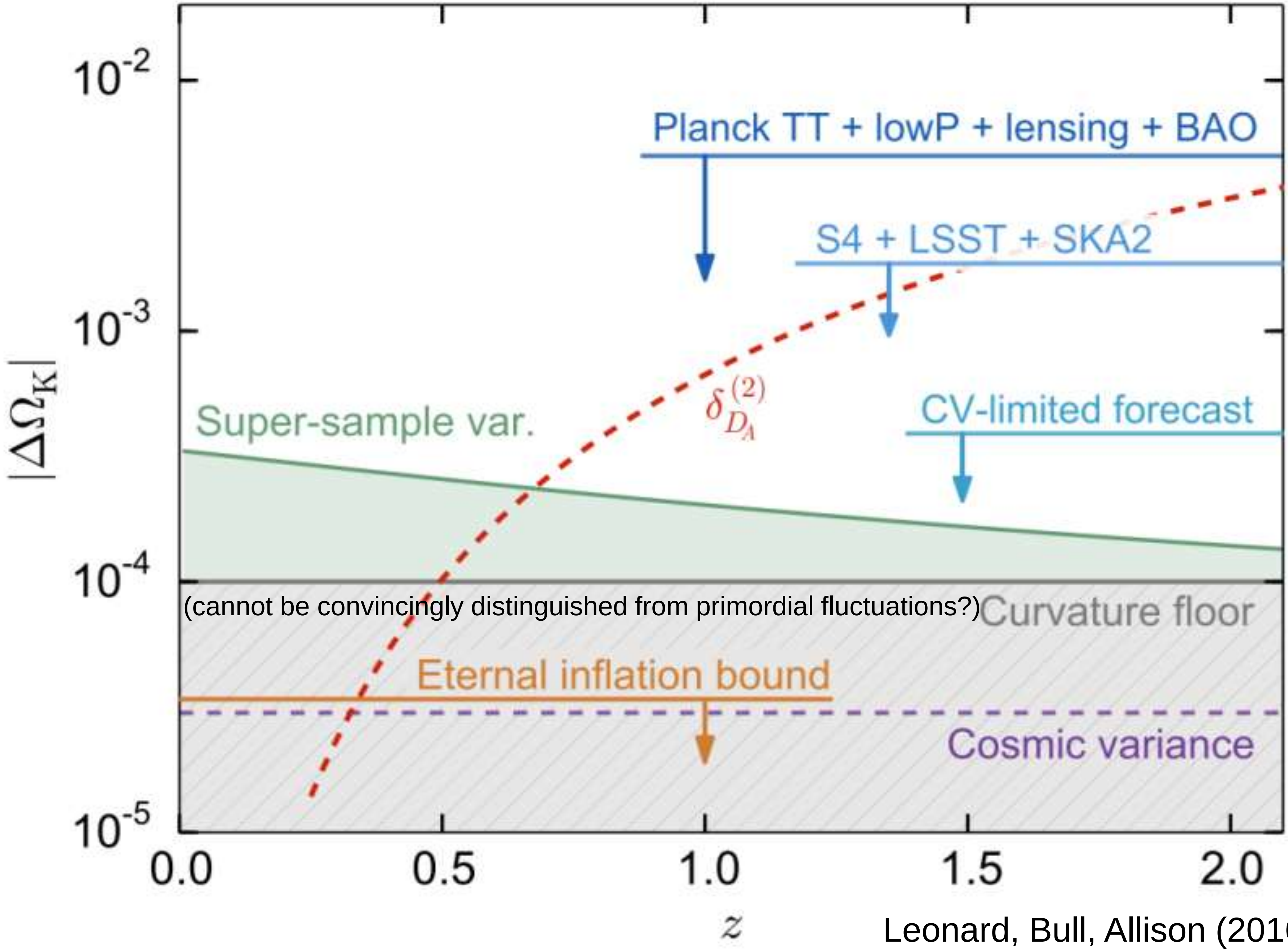
On ne peut prédire la carte des anisotropies, telle que nous l'observons...



Mais on peut prédire ses propriétés statistiques ! (comme par exemple la hauteur typique des vagues en fonction de leur distance crête à crête)

Next step?

- The Planck+ BAO tight constraint $|\Omega_K| \lesssim 5 \times 10^{-3}$ (95% C.L.) shows that spatial curvature is *dynamically negligible*, affecting cosmic expansion by less than 1% at any epoch.
- Still, curvature detection could also constrain inflation. Indeed, possible Ω_K is restricted by the flatness of the inflaton potential, IC, etc. E.g.:
  - *Slow roll eternal inflation strongly predicts* $|\Omega_K| < 10^{-4}$
  - *False vacuum eternal inflation ruled out if* $\Omega_K < -10^{-4}$ *(Kleban & Schillo 2012; Guth & Nomura 2012)*
- BUT Cosmic variance limits how well we can measure the spatial curvature of the Universe.



Leonard, Bull, Allison (2016)

Next steps?

- There are a number of tantalizing “anomalies” (l~20 dent, low multipoles alignment, statistical anisotropy, etc.).
- These are at very large scales in Temperature, and not really statistically significant. (+pb of a posteriori statistics, recall SH)
- Large scales in polarisation are quite hard to measure. So far the Planck teams have improved the tau measurement from EE (wrt 2015). We are working toward further improvements at the map level. Stay tuned for our so-called legacy release after the summer (TBC).
- It is unclear (unlikely?) that ground CMB measurements can achieve very reliable results on these largest scales (e.g. ground pick-up, sky and frequency (FG) coverage).
- No post-Planck satellite decided ☹ (yet?)
- Non-CMB experiments (21cm Intensity mapping…) will be even more challenging if at all doable (for that purpose)…

Next steps?

- Improve constraints on running: need a longer lever arm.

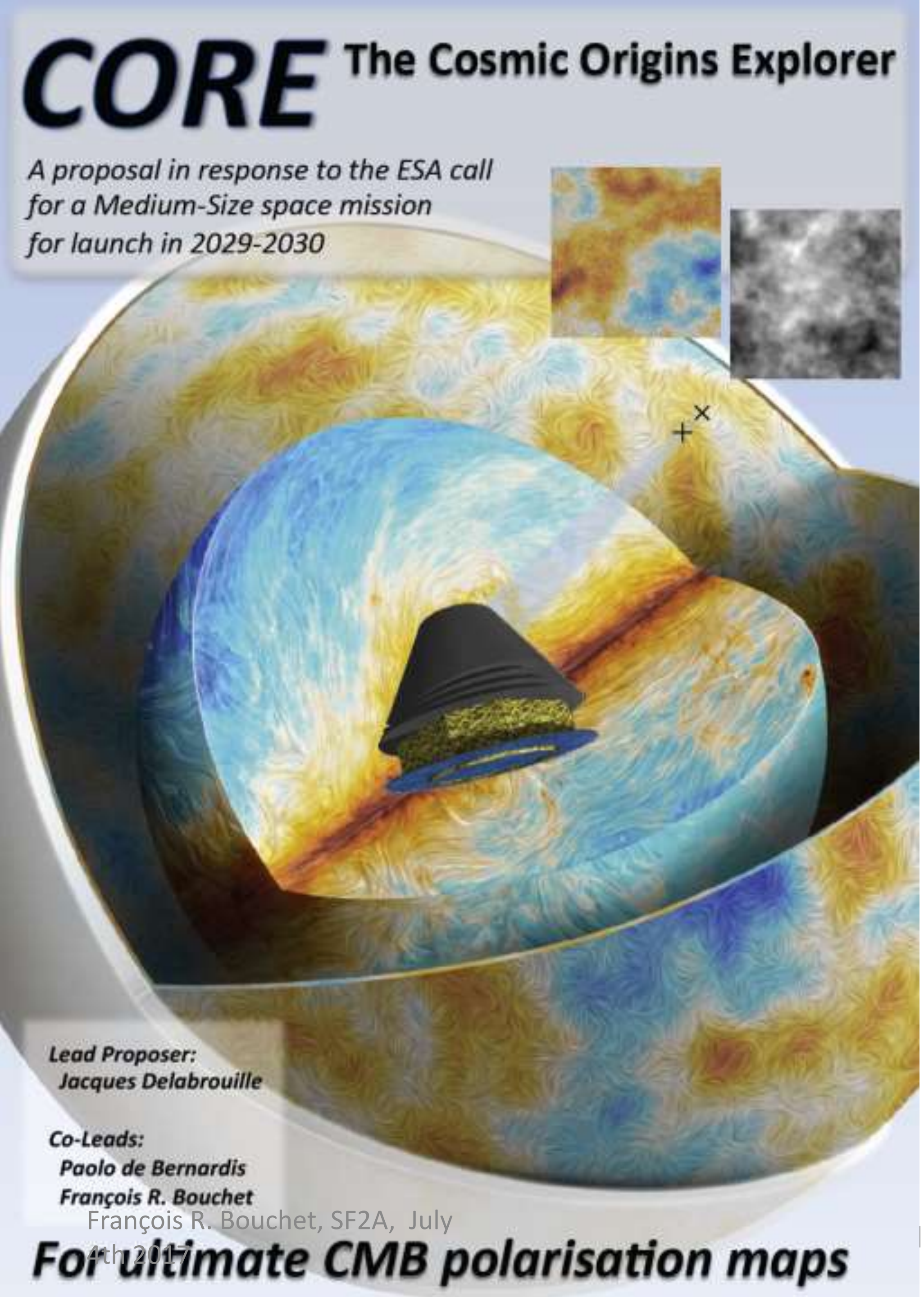
  ➔ *measure E-polarisation to cosmic variance to much smaller scales, with much more benign foregrounds than in Temperature.*

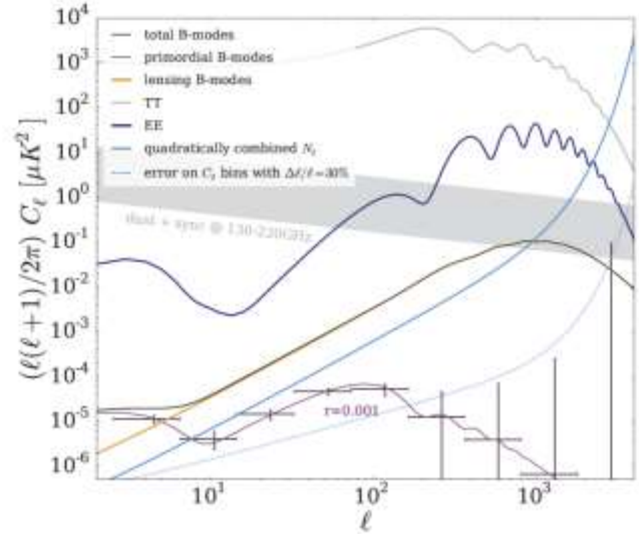
- Improve direct constraints/detect a primordial stochastic background of gravitational waves (goal sig_r ~ few 10^{-4})

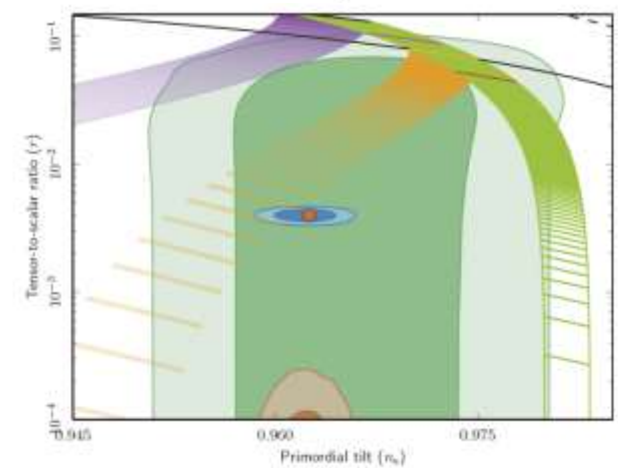
  ➔ *measure B-mode polarisation at relatively large scales, and deal with the intrinsic foreground of lensing-induced B-modes, and the not-so benign Dust foreground.*

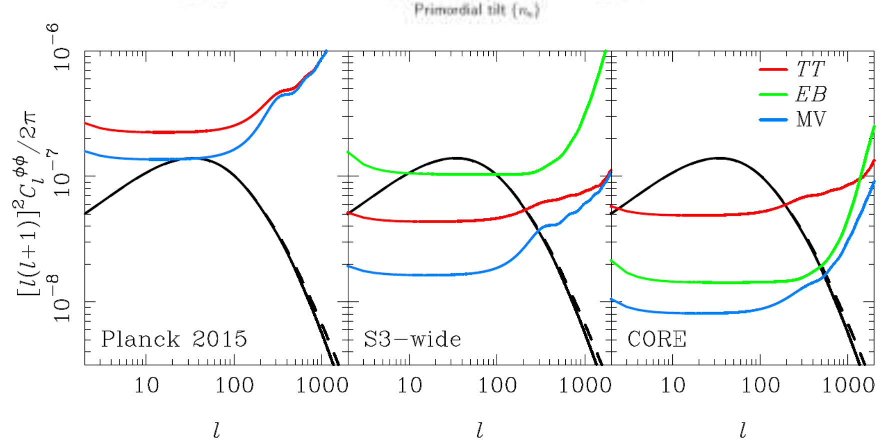
  ➔ *Also need to know the lensed E-modes very well over broad range of scales, and a tracer of the lensing gravitational potential (Either external – e.g., CIB -- or internal).*

- Of course future data will also be searched for "features"


CORE The Cosmic Origins Explorer
A proposal in response to the ESA call
for a Medium-Size space mission
for launch in 2029-2030
Lead Proposer:
Jacques Delabrouille
Co-Leads:
Paolo de Bernardis
François R. Bouchet
For ultimate CMB polarisation maps


total B-modes
primordial B-modes
lensing B-modes
TT
EE
r=0.001
$(\ell(\ell+1)/2\pi)\ C_\ell\ [\mu K^2]$
ℓ

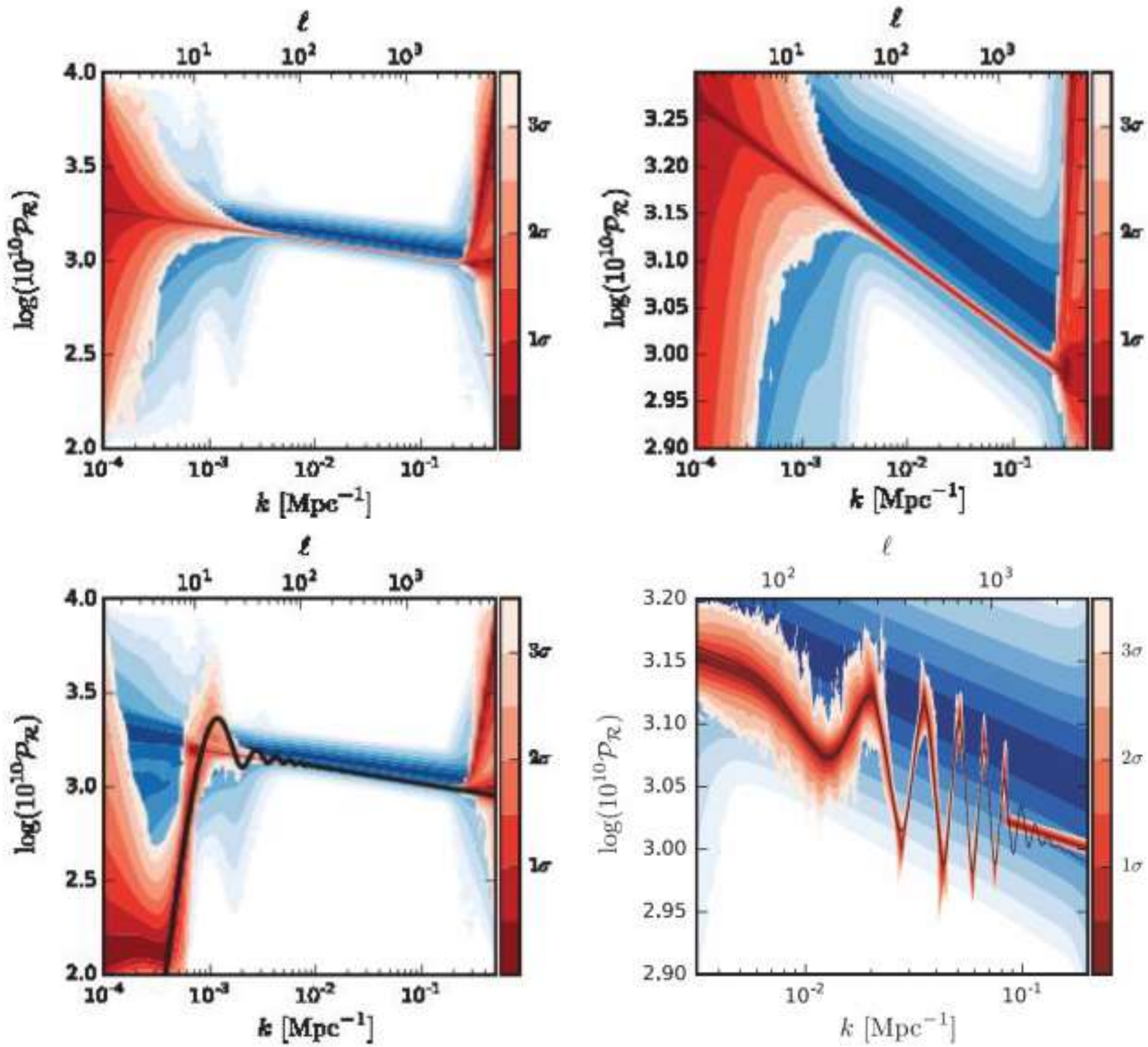

Tensor-to-scalar ratio (r)
Primordial tilt (n_s)
0.945
0.960
0.975


$[l(l+1)]^2 C_l^{\phi\phi}/2\pi$
TT
EB
MV
Planck 2015
S3−wide
CORE
10
100
1000
l

Power spectrum reconstruction

Planck

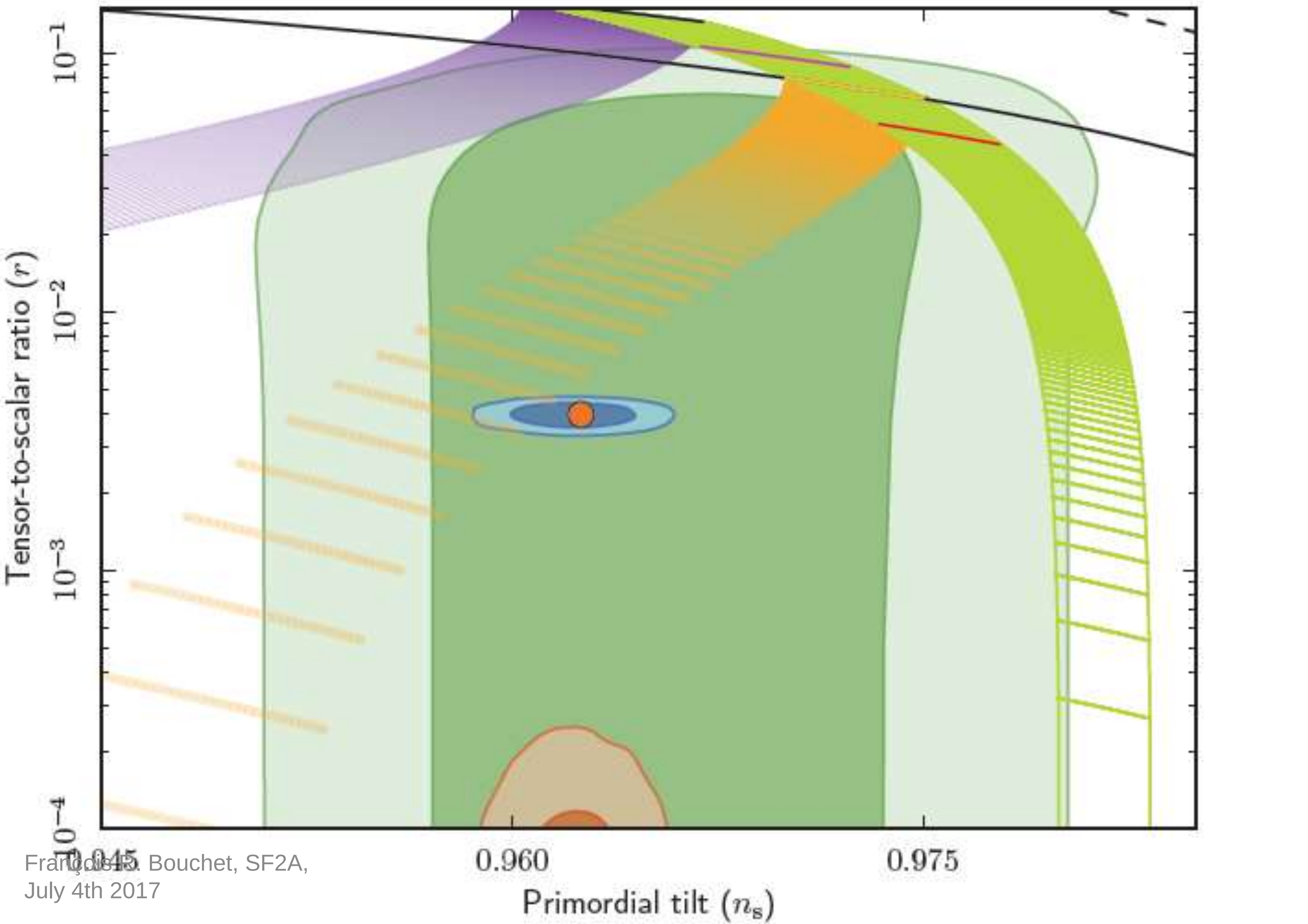
CORE



featureless

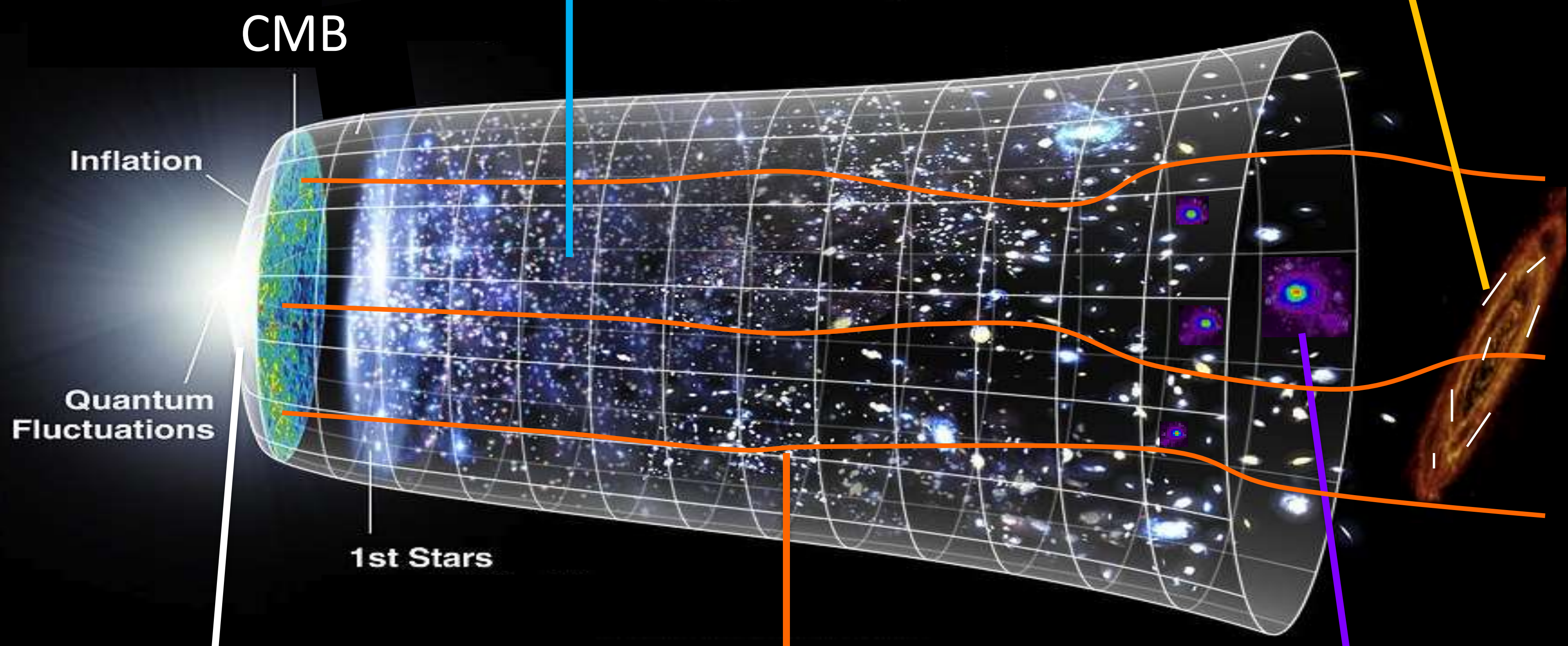
Or not!

CORE teaser (for 2 fiducial cases)



Extragalactic Astrophysics

Interstellar medium (magnetic field)



Univers primordial
Physique à ≈ 10^{16} GeV
$E_{CMB} > 10^{12} \times E_{LHC}$

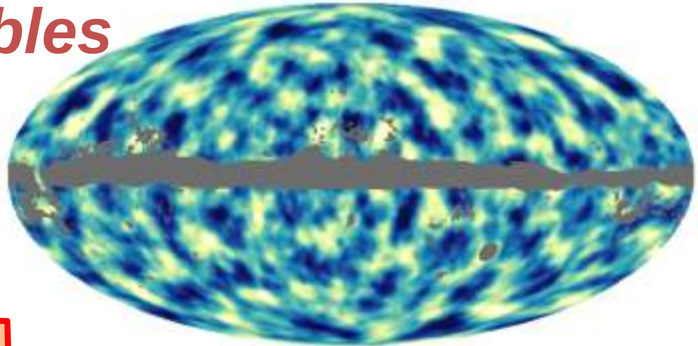
z ≈ 1-3
Gravitational lensing
Dark matter distribution

z ≈ 0-2
Sunyaev-Zeldovich effect:
Distribution of the hot gas and velocity field

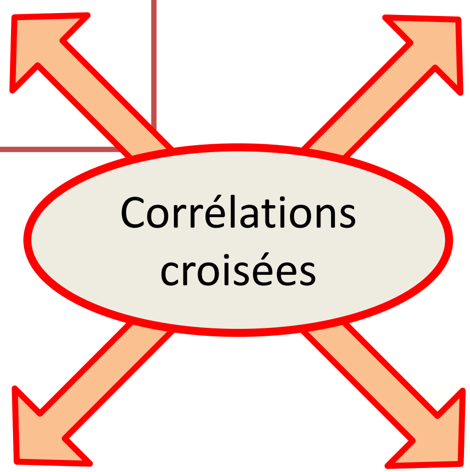
Corrélations et tomographie tridimensionnelle

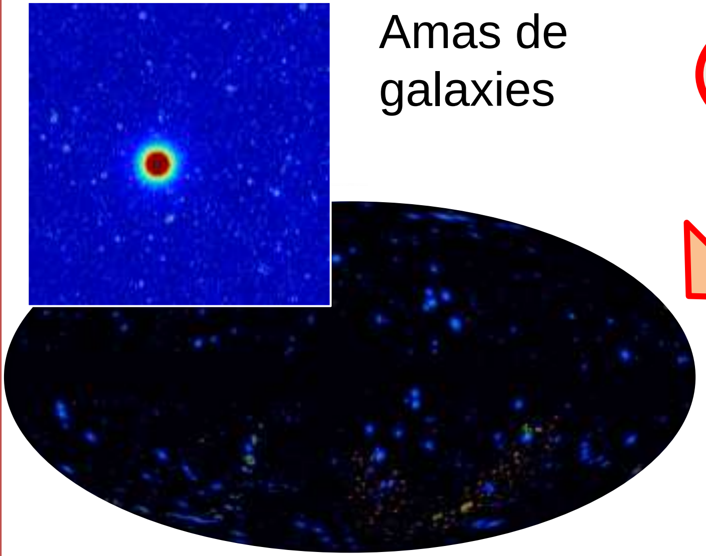
Sondage des structures

Observables CORE

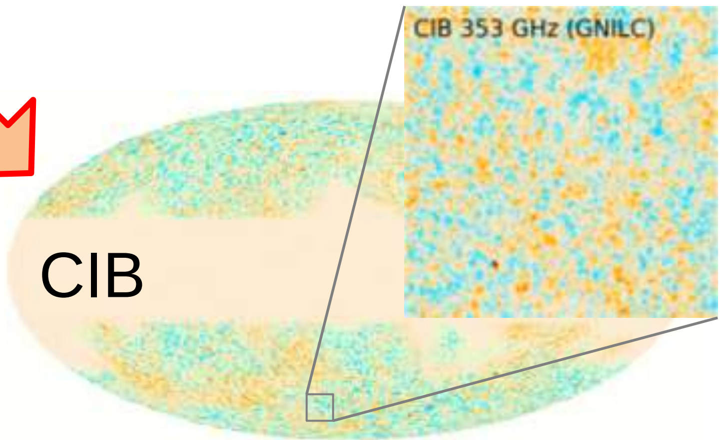


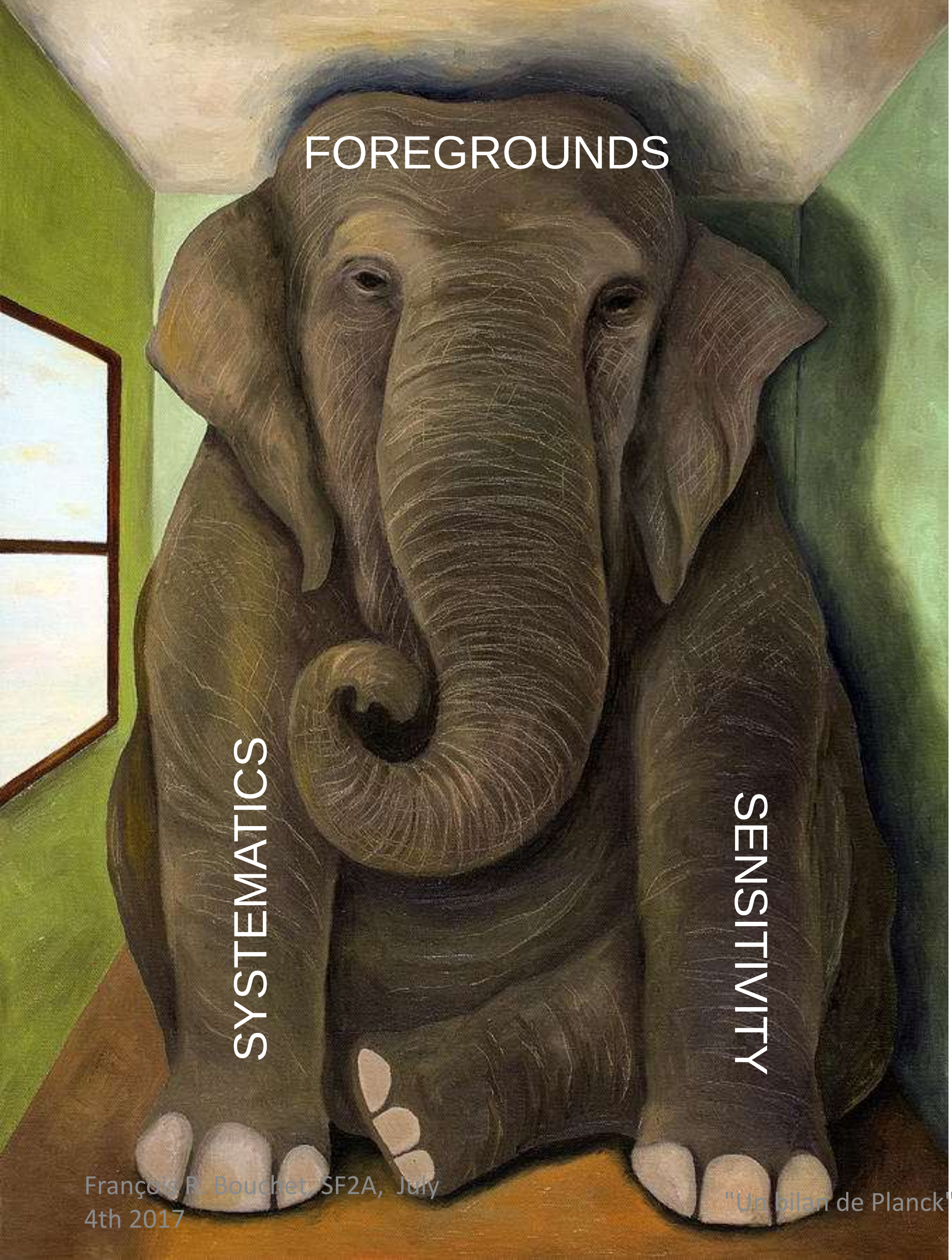
Potentiel de lentille CMB





Amas de galaxies





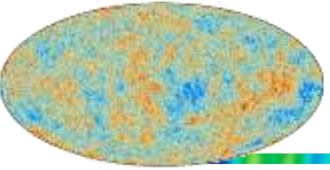
CHALLENGES

- **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

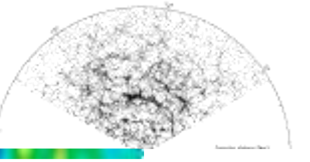
AND Data/Analysis challenges

- 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!

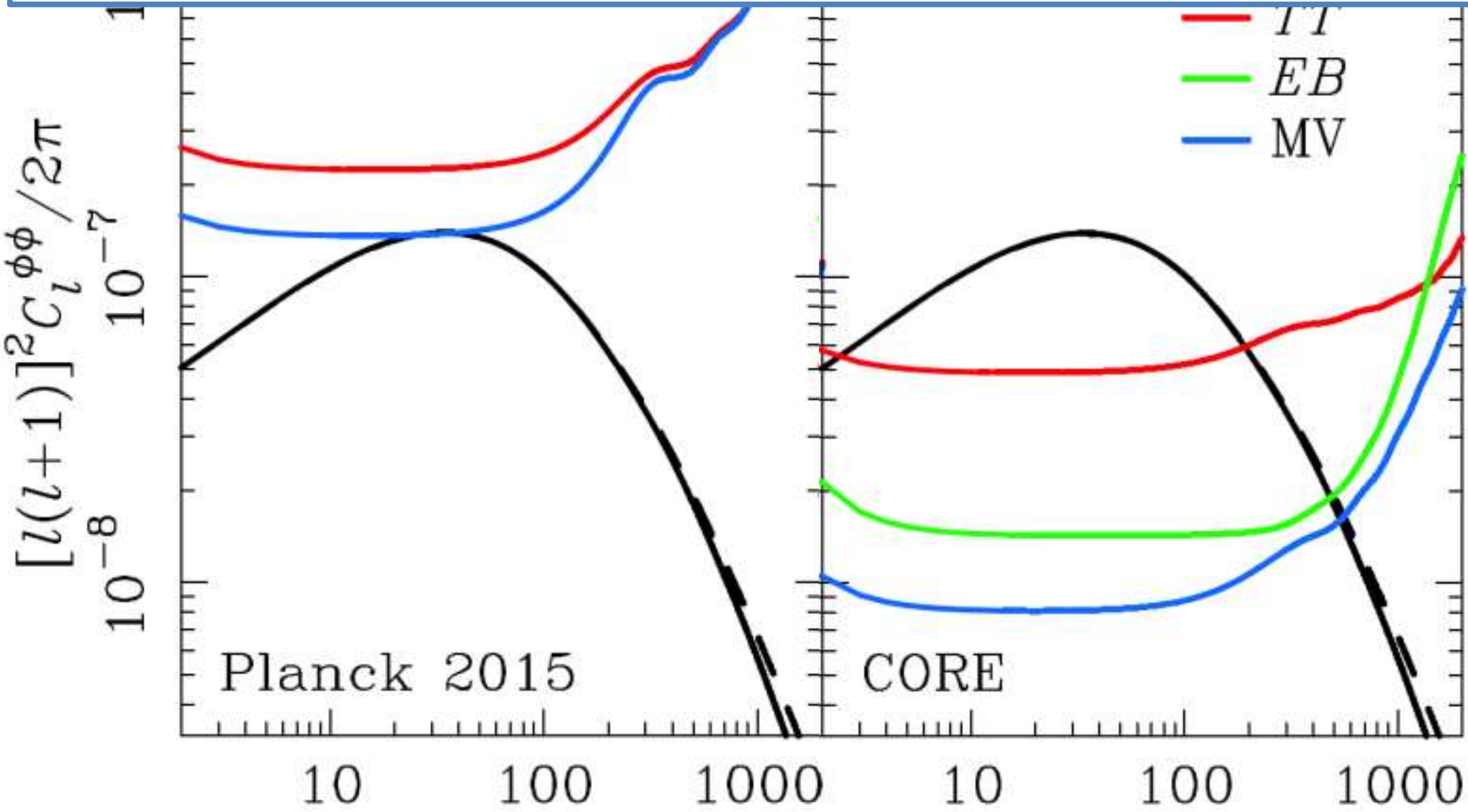


Concluding remarks



- 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!

Lentillage



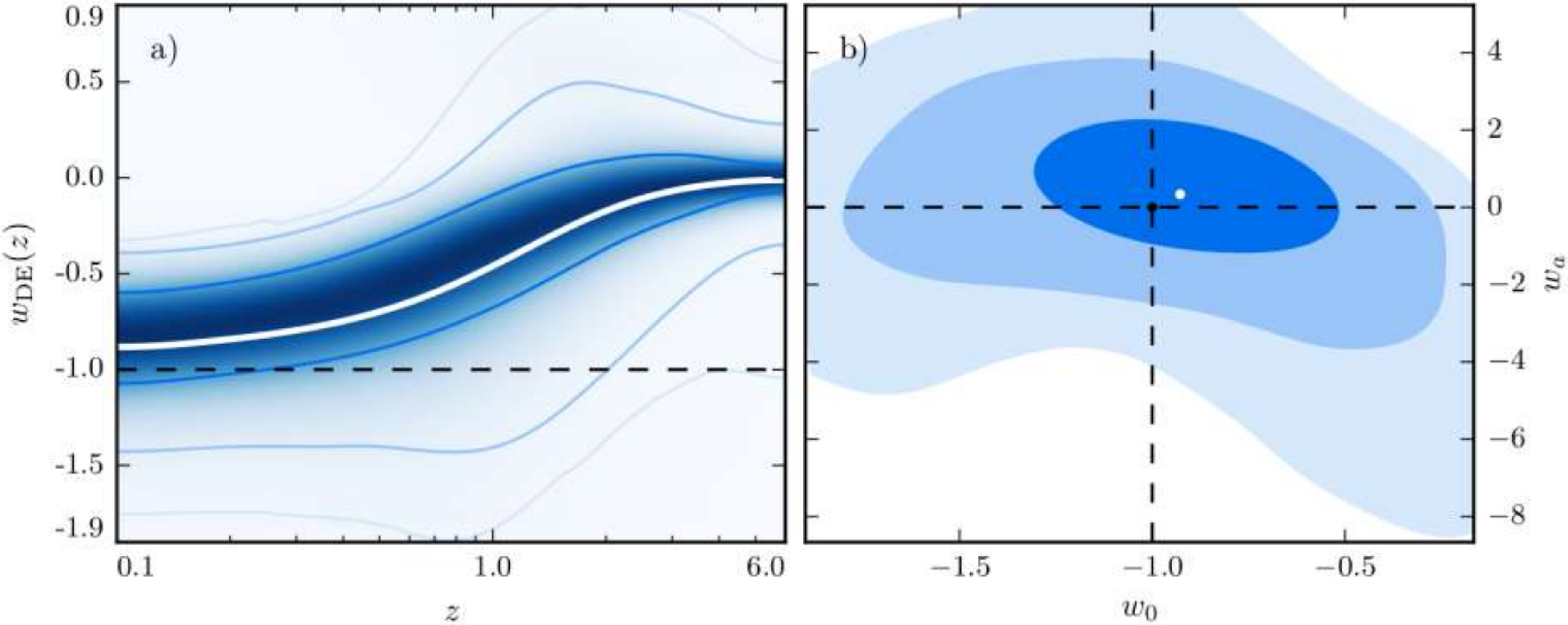
Reconstruction noise of the lensing detection power spectrum from Planck 2015 (left) and as forecast for CORE. The detection power spectrum is plotted based on the linear matter power spectrum (black solid) and with non-linear corrections (black dashed). MV=minimum Variance.

- A slide on anomalies…
- A slide about the CMB anisotropies 25 yrs ago?

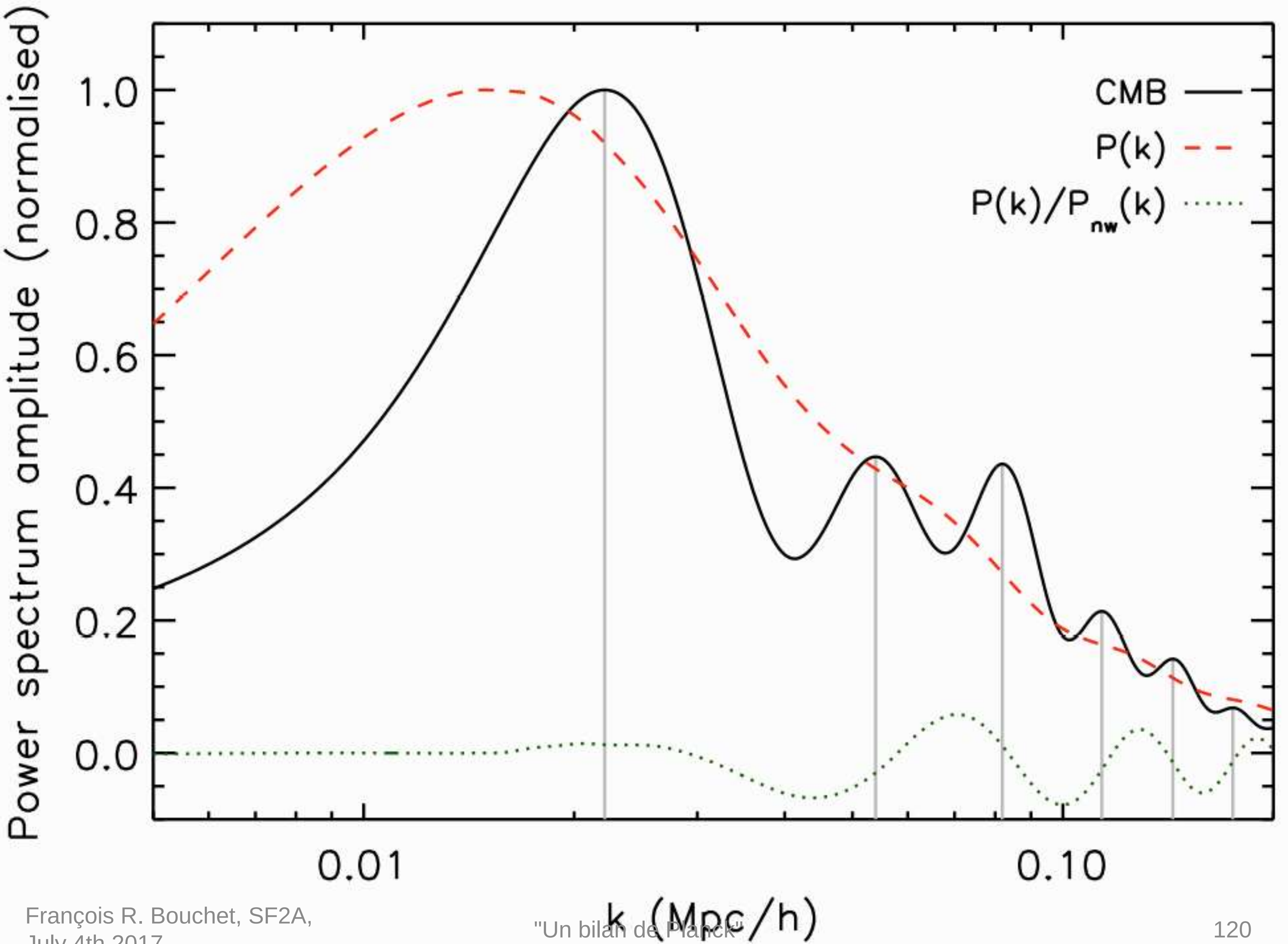
- complete the Future for NG... (according to JS?)

Menu items - 30mn → 25mn, <50 slides

- Current status / LCDM, tensions
- Inflation (OK˜1, isot, Gauss, adia, polar consistency (low-ell TE corr), ns…)
  - *Dns/dlnk*
  - *R*
  - *Omega_k*
  - *Fnl / NG*
  - *PS Deviations at scales smaller than Silk damping*
- Content
  - *Neutrinos*
  - *DM*
  - *DE/ MG*

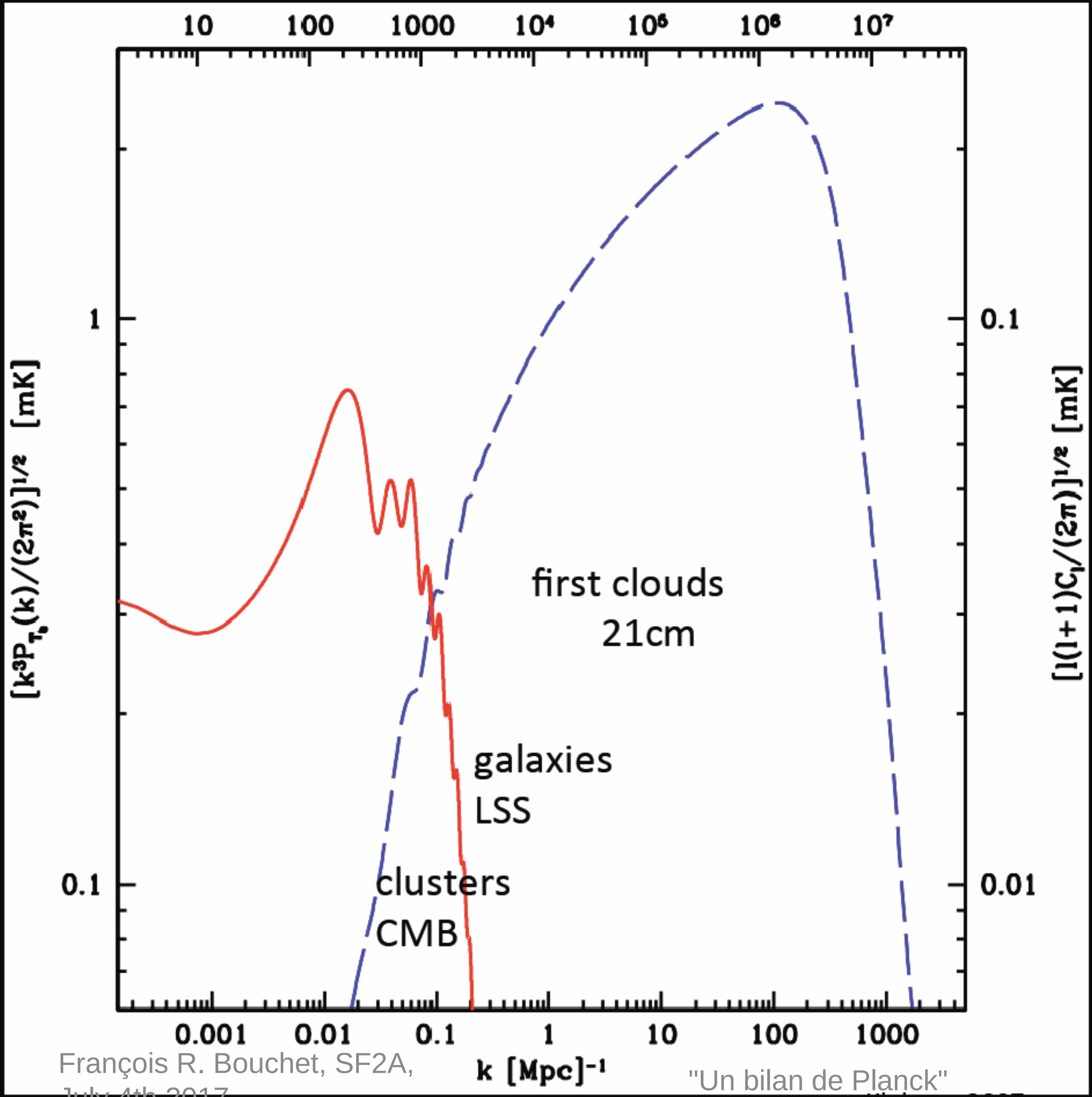


Raveri, Bull, Pogosian, Silvestri (2017) Predict the **allowed range** of observables like w(z) given a
broad class of **viable** theories
Monte Carlo exploration of entire Horndeski class:
Most models predict $w \gg 1$ at $z > 2$!



Power spectrum amplitude (normalised)
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.10
k (Mpc/h)
CMB
P(k)
$P(k)/P_{nw}(k)$

Power spectrum: CMB vs 21cm



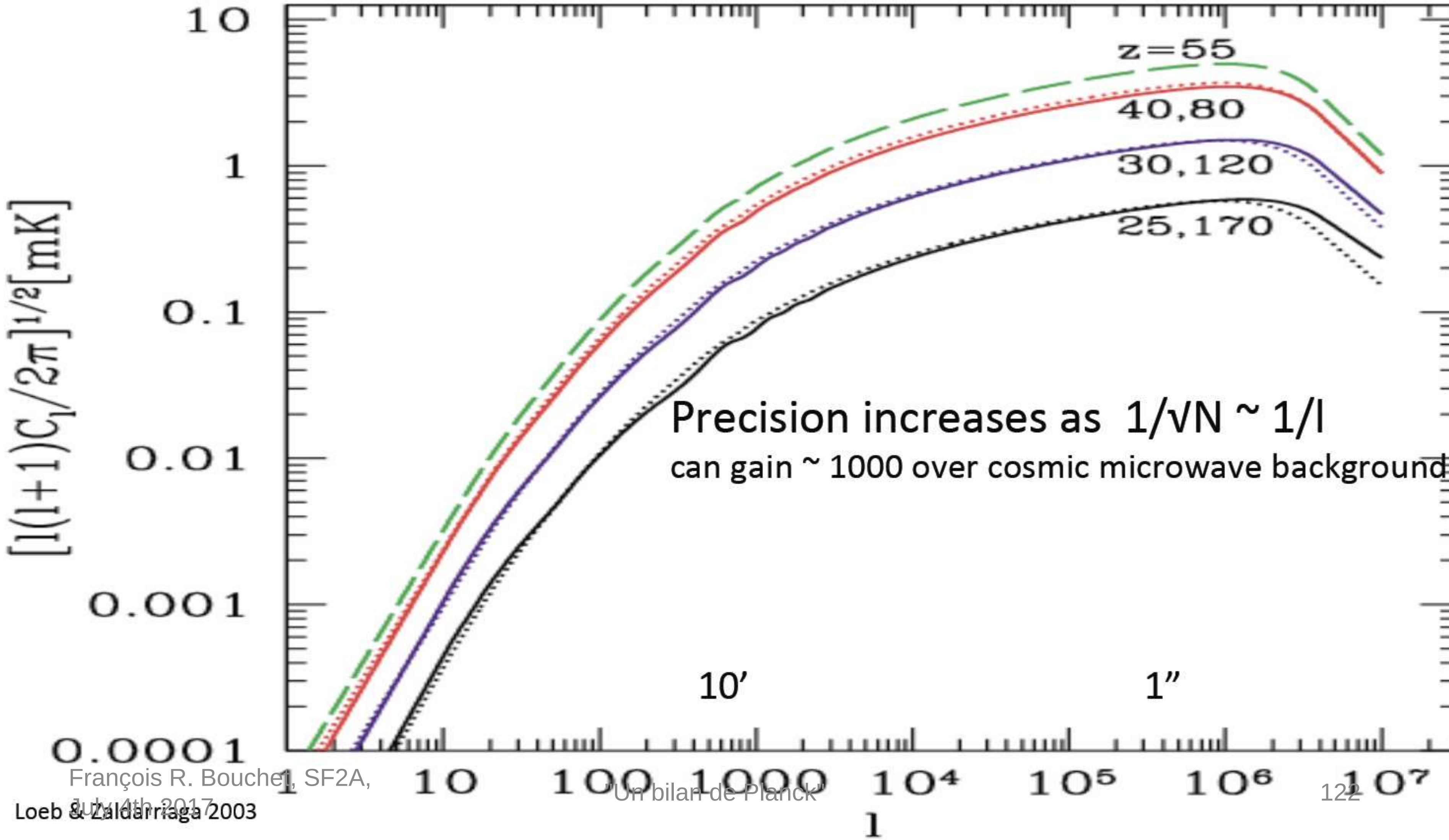
CMB has only $\ell \sim 10^3$ or $\sim 10^6$ modes

$f_{nl}\delta\phi > 1/\sqrt{N} \sim 10^{-3}$

Many more modes at 21cm

21cm absorption at z~ 50 or frequency ~ 30 MHz

$f_{nl}\delta\phi \sim (n_s-1)\,\delta\phi \sim 10^{-6}$ requires $N\sim10^{12}$ modes (or a few arc-sec resolution)
can slice sky in 3D: eg $\Delta\nu\sim0.1$ MHz at $\ell \sim 10^5$ for $N \sim 10^{10} \times 10^2$



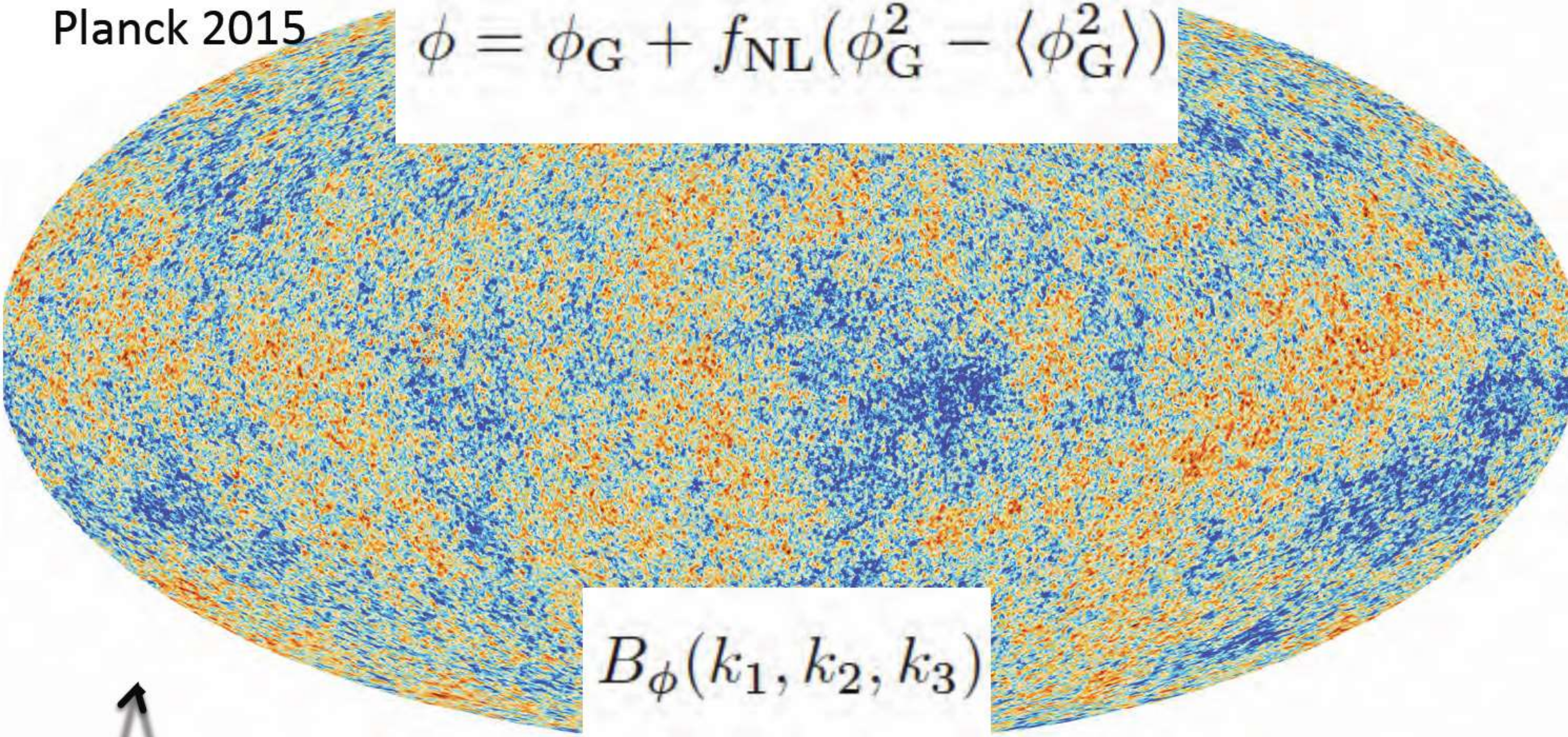
Loeb & Zaldarriaga 2003

The ultimate goal: primordial nongaussianity

- Target simplest inflation prediction $f_{NL} \sim 0.03$
- SKA-LOW can outperform CMB and galaxy surveys
- From f_{NL}~10 to 1 to 0.1, at l~10^3 to 10^4 to 10^5, or k~0.1 to 1 to 10 Mpc^{-1}
- more modes: N~10^6 vs ~10^8 vs ~10^{10} ,eventually 10^{12}
- Win in precision by $N^{1/2}$, so target f_{NL}~ 0.1 at z~ 50
- Achievable with frequency tomography at 30 MHz?
- Next, in ~ 20yrs:

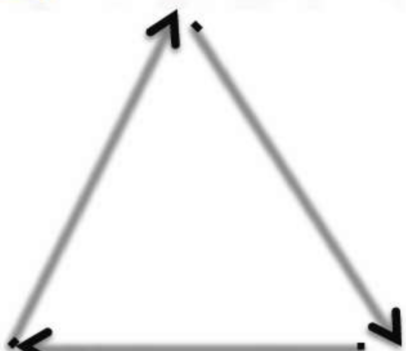
SKA-low on far side of moon to do $N^{1/2}$ ~ 10 x better

Planck 2015



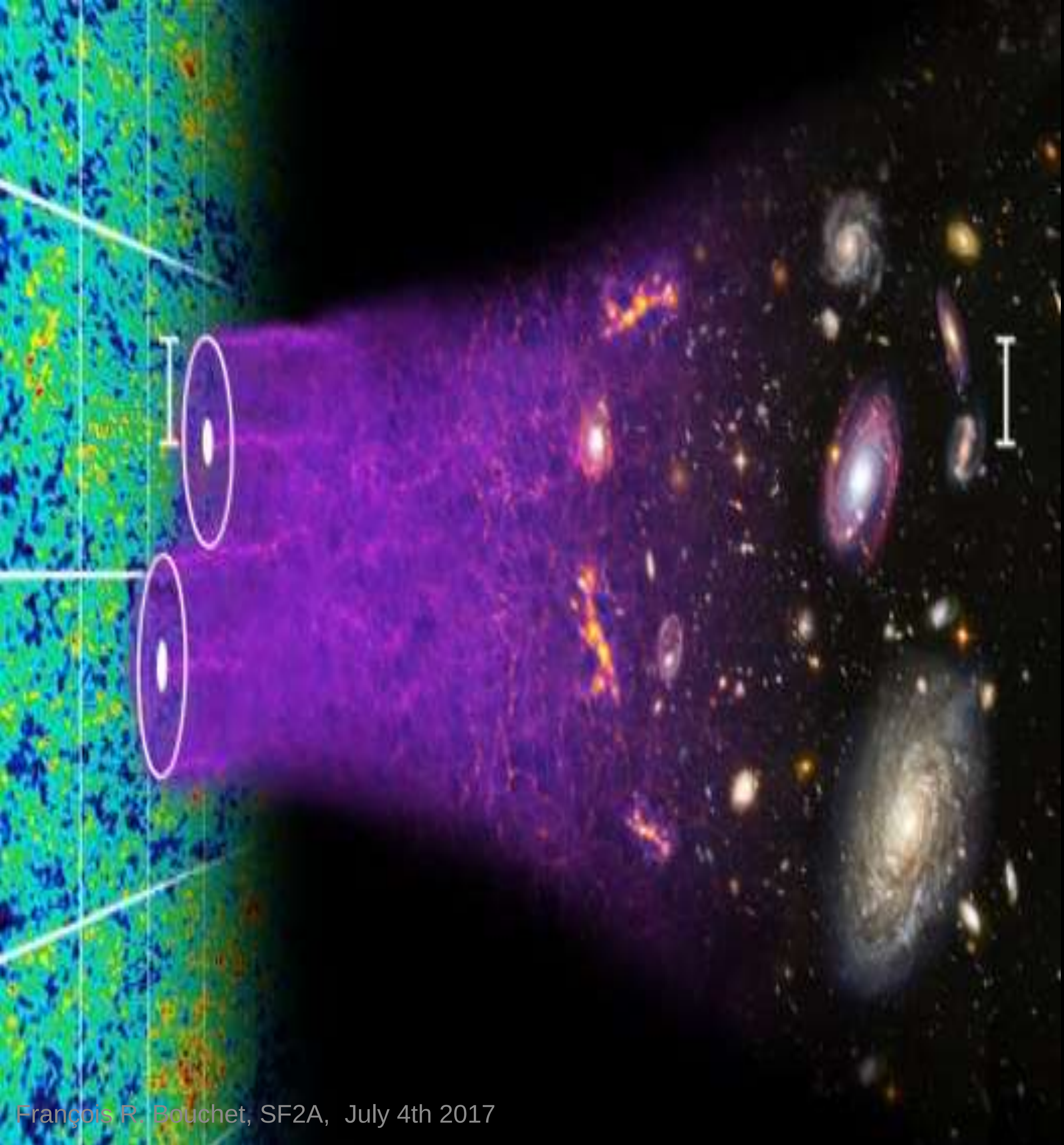
$$\phi = \phi_G + f_{NL}(\phi_G^2 - \langle \phi_G^2 \rangle)$$

$$B_\phi(k_1, k_2, k_3)$$

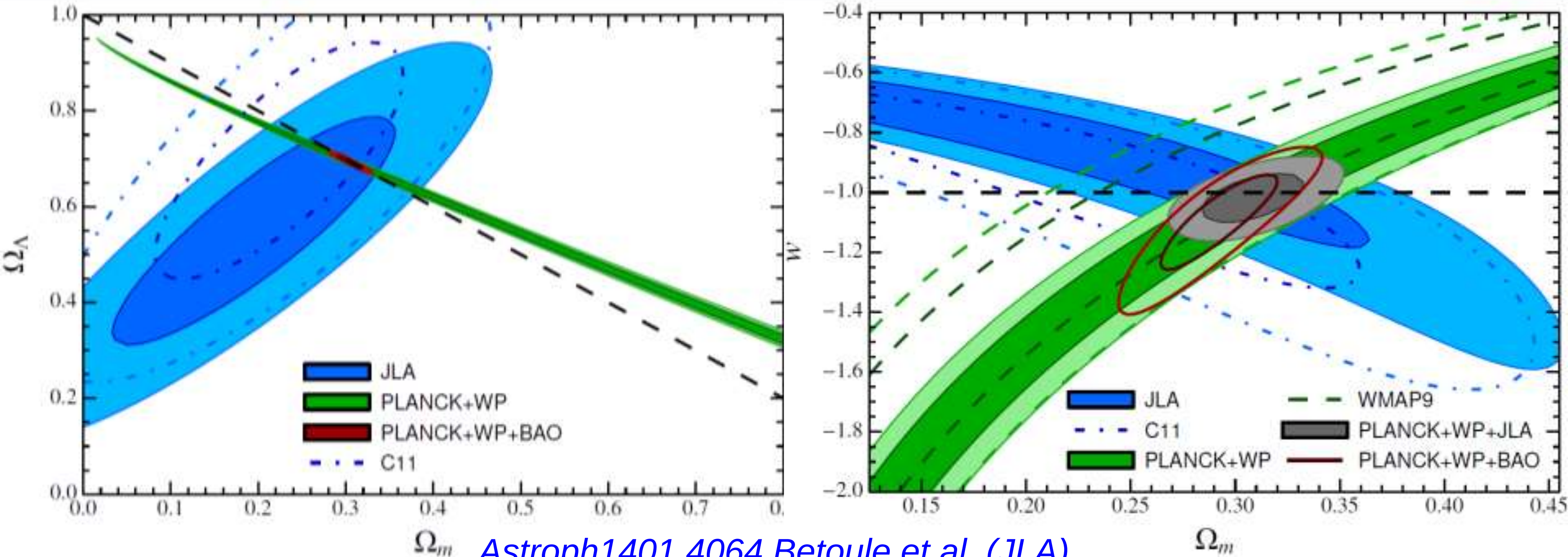


Independent shape

$$f_{NL}^{local} = 0.8 \pm 5.0,\ f_{NL}^{equil} = -4 \pm 43 \text{ and } f_{NL}^{ortho} = -26 \pm 21$$



Planck versus JLA (SNLS +SDSS)

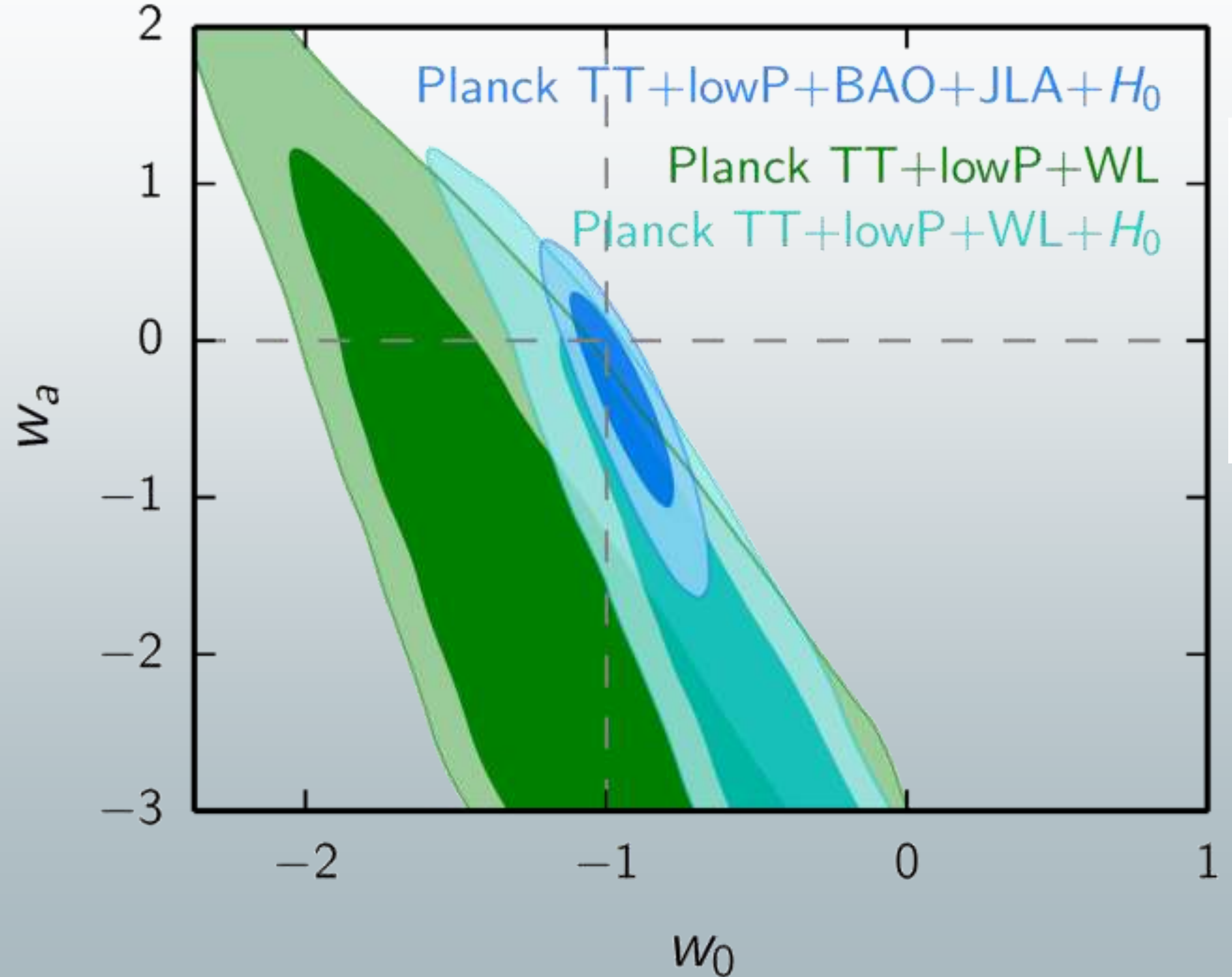


Astroph1401.4064 Betoule et al. (JLA)

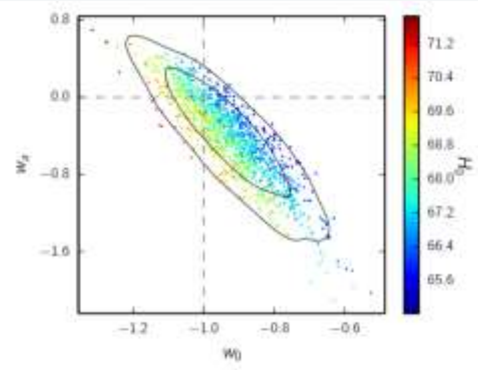
	Ω_m	w	H_0	$\Omega_b h^2$
Planck+WP+BAO+JLA	0.303 ± 0.012	-1.027 ± 0.055	68.50 ± 1.27	0.0221 ± 0.0003
Planck+WP+BAO	0.295 ± 0.020	-1.075 ± 0.109	69.57 ± 2.54	0.0220 ± 0.0003
Planck+WP+SDSS	0.341 ± 0.039	-0.906 ± 0.123	64.68 ± 3.56	0.0221 ± 0.0003
Planck+WP+SDSS+SNLS	0.314 ± 0.020	-0.994 ± 0.069	67.32 ± 1.98	0.0221 ± 0.0003
Planck+WP+JLA	0.307 ± 0.017	-1.018 ± 0.057	68.07 ± 1.63	0.0221 ± 0.0003
WMAP9+JLA+BAO	0.296 ± 0.012	-0.979 ± 0.063	68.19 ± 1.33	0.0224 ± 0.0005
Planck+WP+C11	0.288 ± 0.021	-1.093 ± 0.078	70.33 ± 2.34	0.0221 ± 0.0003

What these tensions can do…

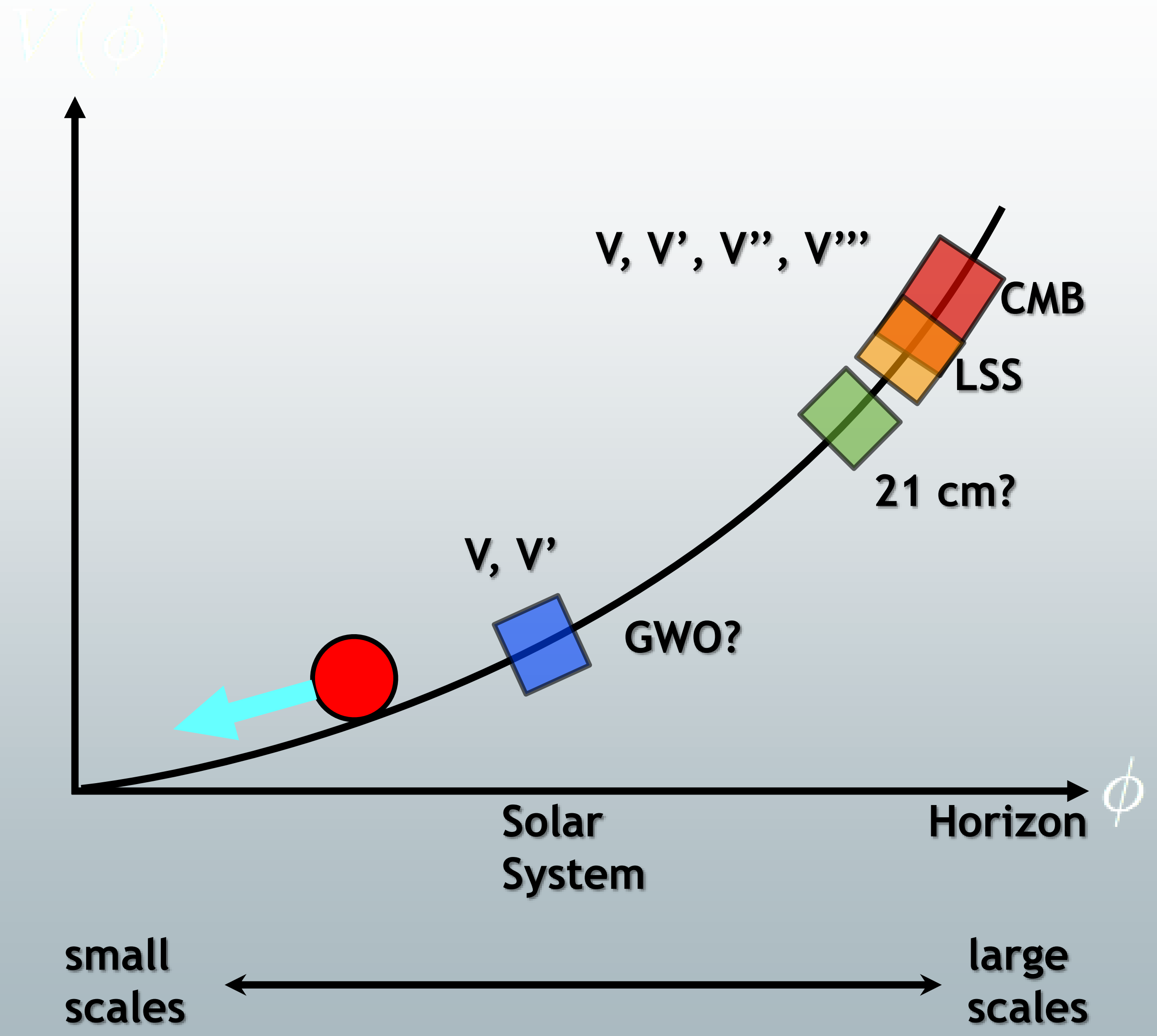
$W(a) = w_0 + (1-a)\, w_a$



Ref.



Fingerprints of the early universe



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.

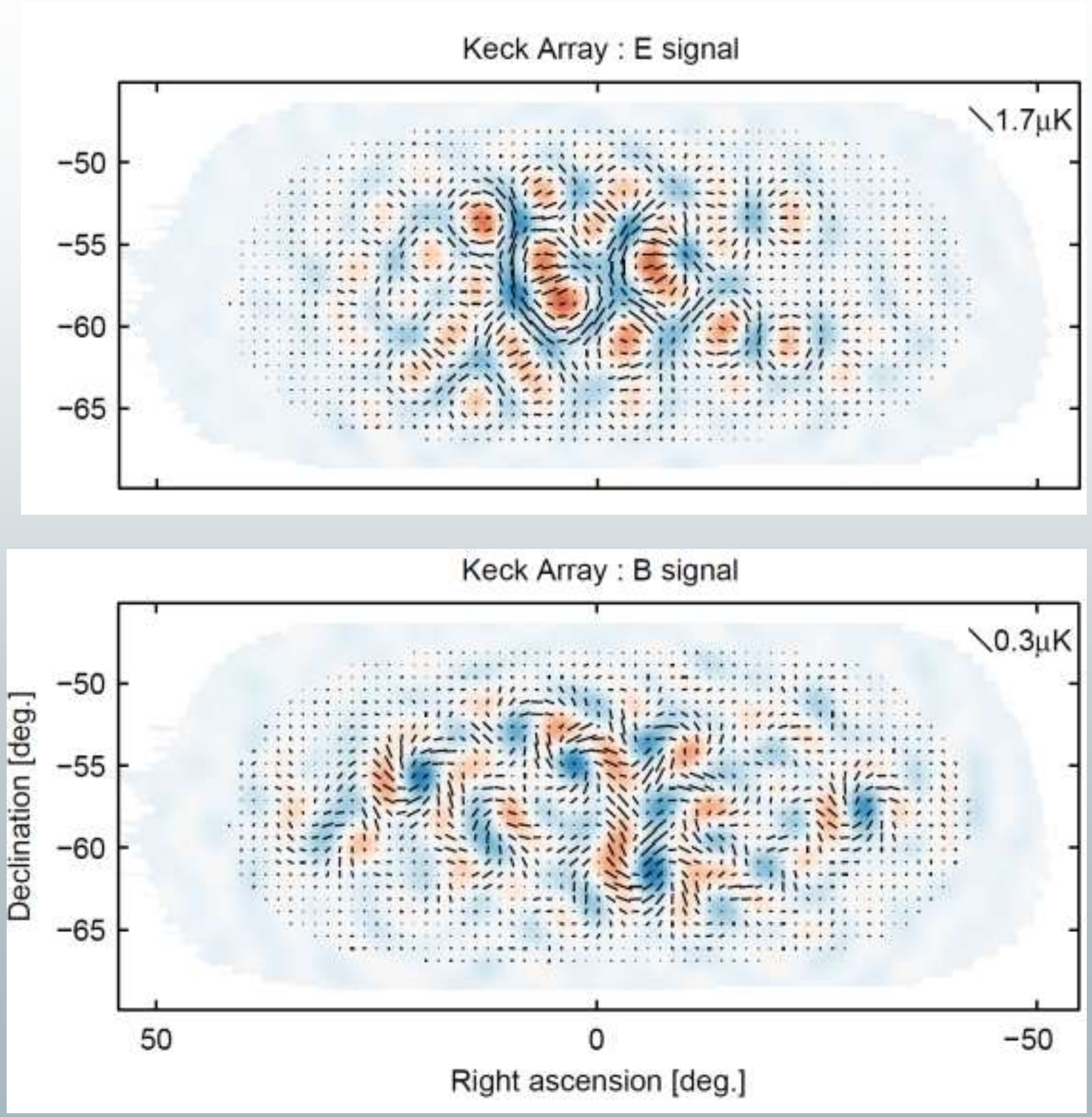
- $\Omega_b h^2$ Baryon density today - The amount of ordinary matter
- $\Omega_c h^2$ Cold dark matter density today – only weakly interacting
- Θ Sound horizon size when optical depth τ reaches unity
  (Distance traveled by a sound wave since inflation, when universe became transparent at recombination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

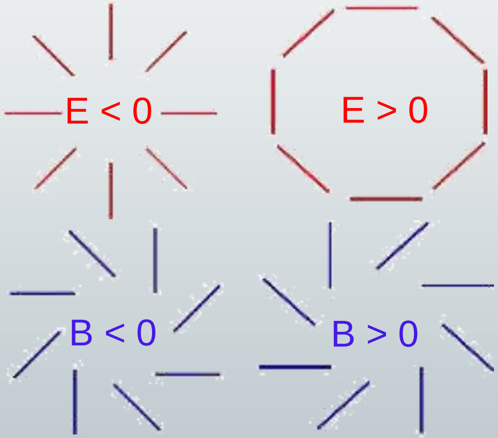
- τ Optical depth at reionisation (due to Thomson scattering of photons on e^-), i.e.
  fraction of the CMB photons re-scattered during that process

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

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

Polarisation patterns





2015 Datasets & shorthands

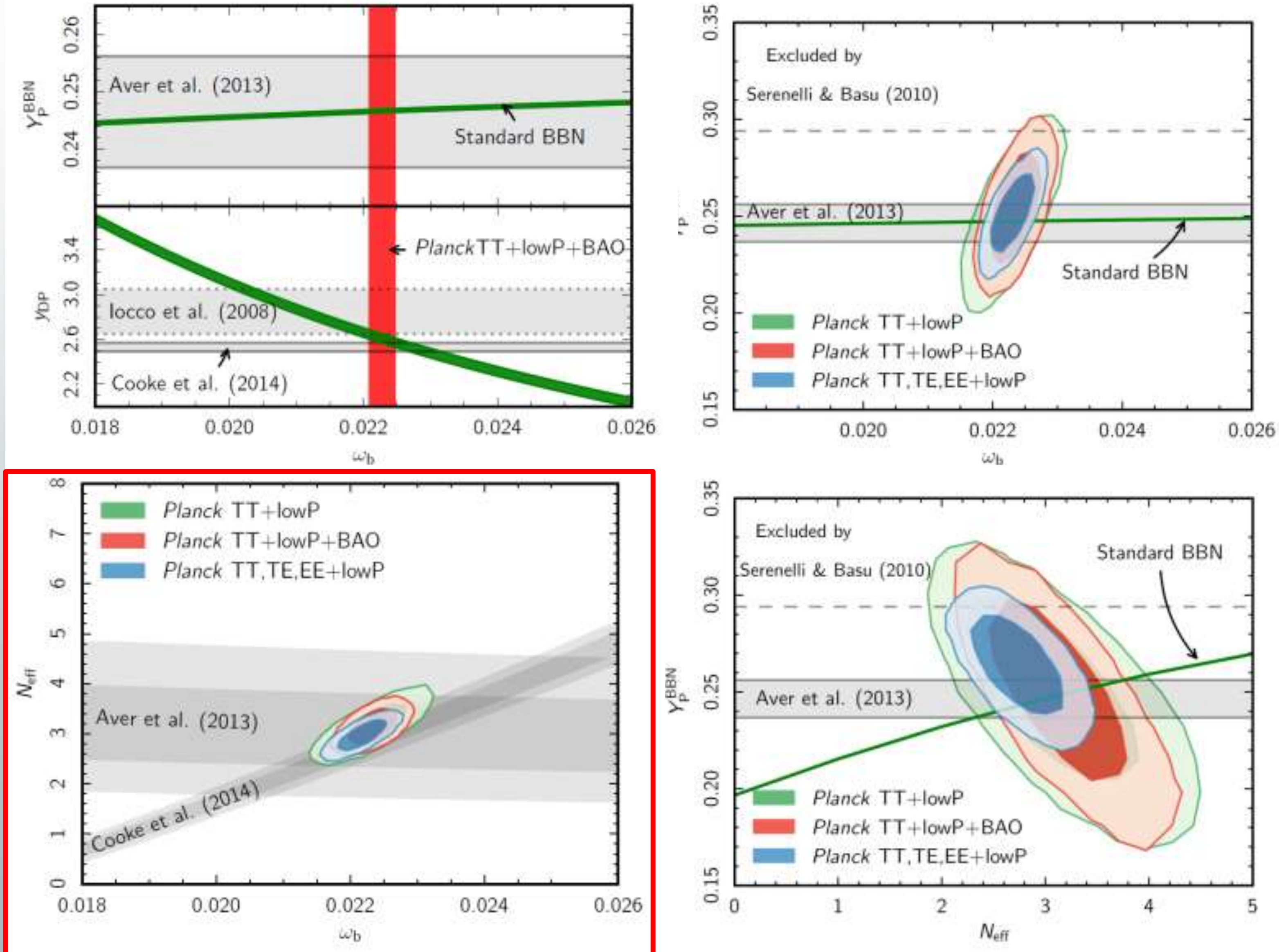
- Planck TT: Planck TT for 2 < ell < 2500.
- lowP: low-ell Planck polarization, 2 < ell < 30. (For 2013 results, this will indicate low-l WMAP polarization, WP).
- Planck TE, EE: Planck TE & EE at high-ell, 30 < ell < 2000.

- Lensing: Planck lensing potential at 40 < ell < 400, extracted from 4-points correlation function (i.e. conservative cuts)

- External datasets:
  - *BAO (6dFGS, SDSS-MGS, BOSS-LOWZ, CMASS DR11)*
  - *JLA: Type Ia Supernovae (SNLS +SDSS+low z Sne)*
  - *H0: Hubble constant (Reanalysis by Efstathiou 2014 of Riess et al. 2011)*

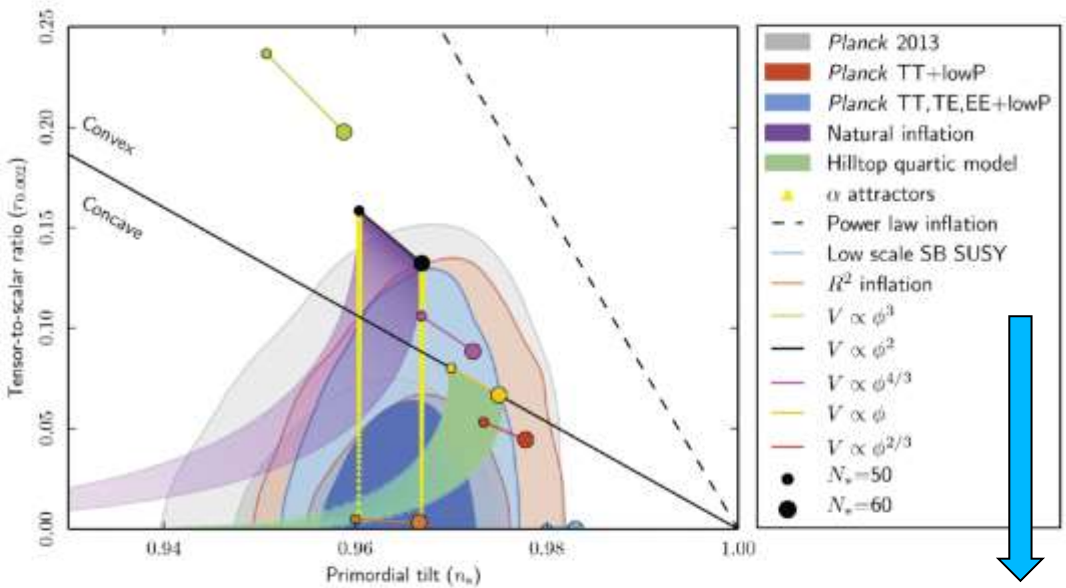
- NB: Whenever not specified, we assume N_{eff}=3.046, Σm_ν=0.06eV (1 massive, two massless).

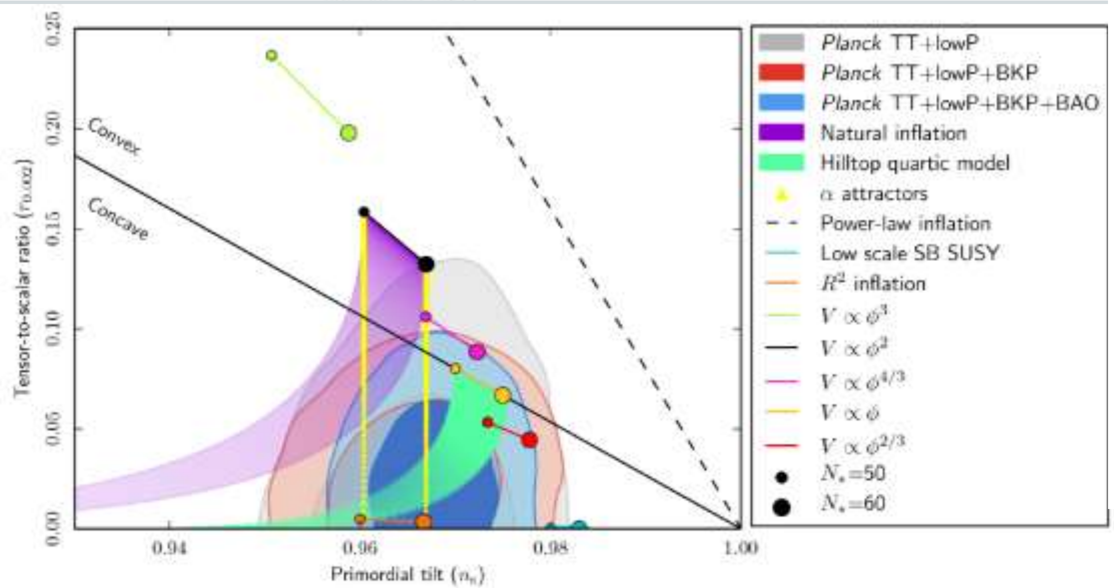
BBN



Aver et al. (2013)
Standard BBN
Planck TT+lowP+BAO
Iocco et al. (2008)
Cooke et al. (2014)
0.018
0.020
0.022
0.024
0.026
ω_b
Y_P^{BBN}
y_{DP}
Excluded by
Serenelli & Basu (2010)
Planck TT+lowP
Planck TT+lowP+BAO
Planck TT,TE,EE+lowP
N_{eff}

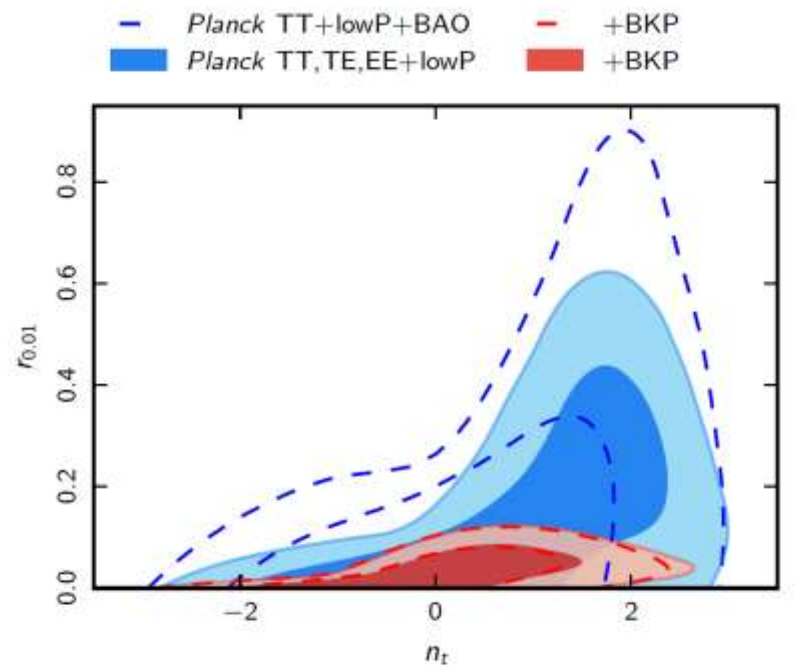
Planck + BK X Planck



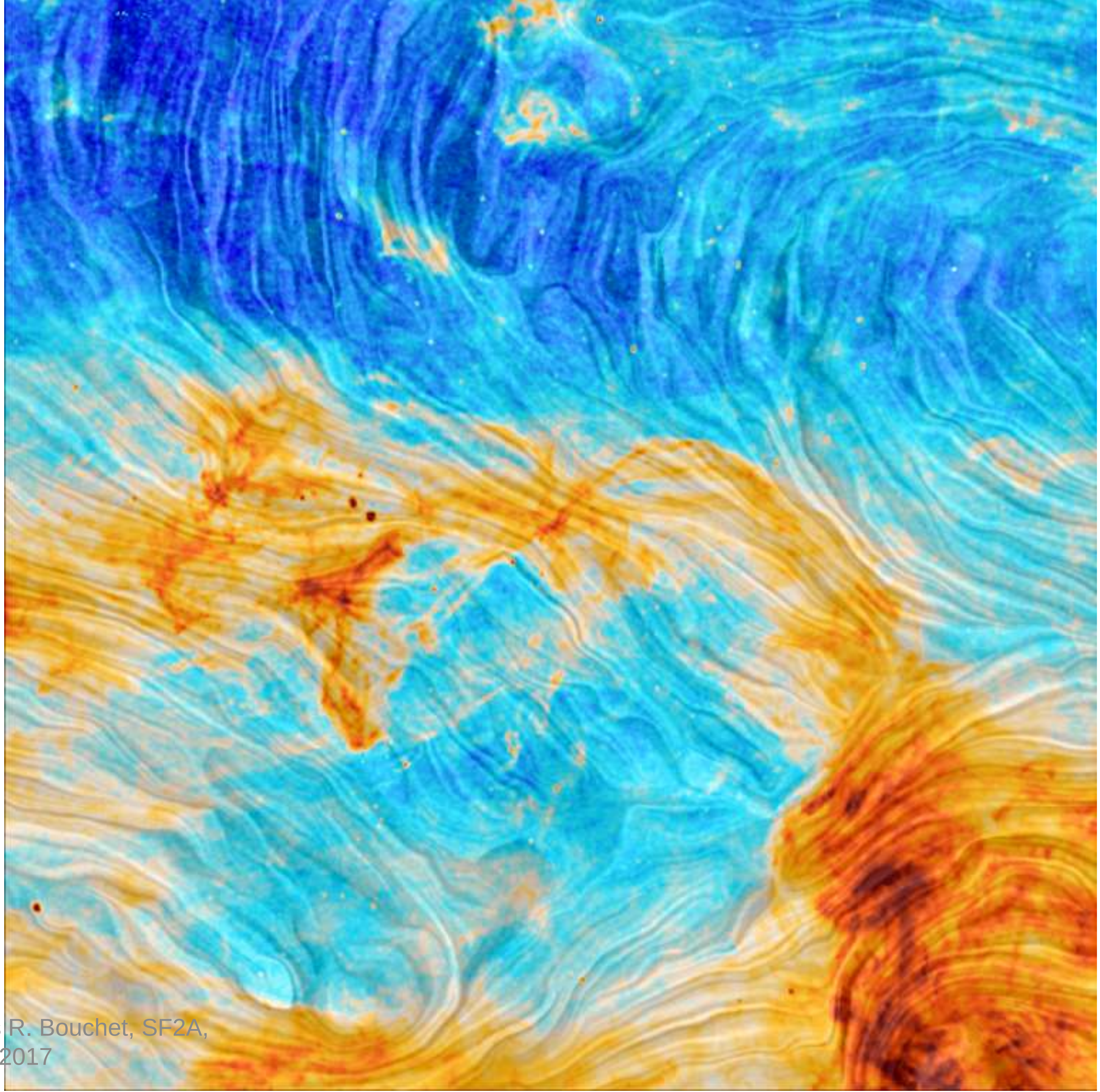


Planck 2013: $r_{0.002}$ < 0.11 @95%cl
Planck 2015: $r_{0.002}$ < 0.10 @95%cl
BKP : $r_{0.002}$ < 0.12 @95%cl

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



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



CMB B Modes

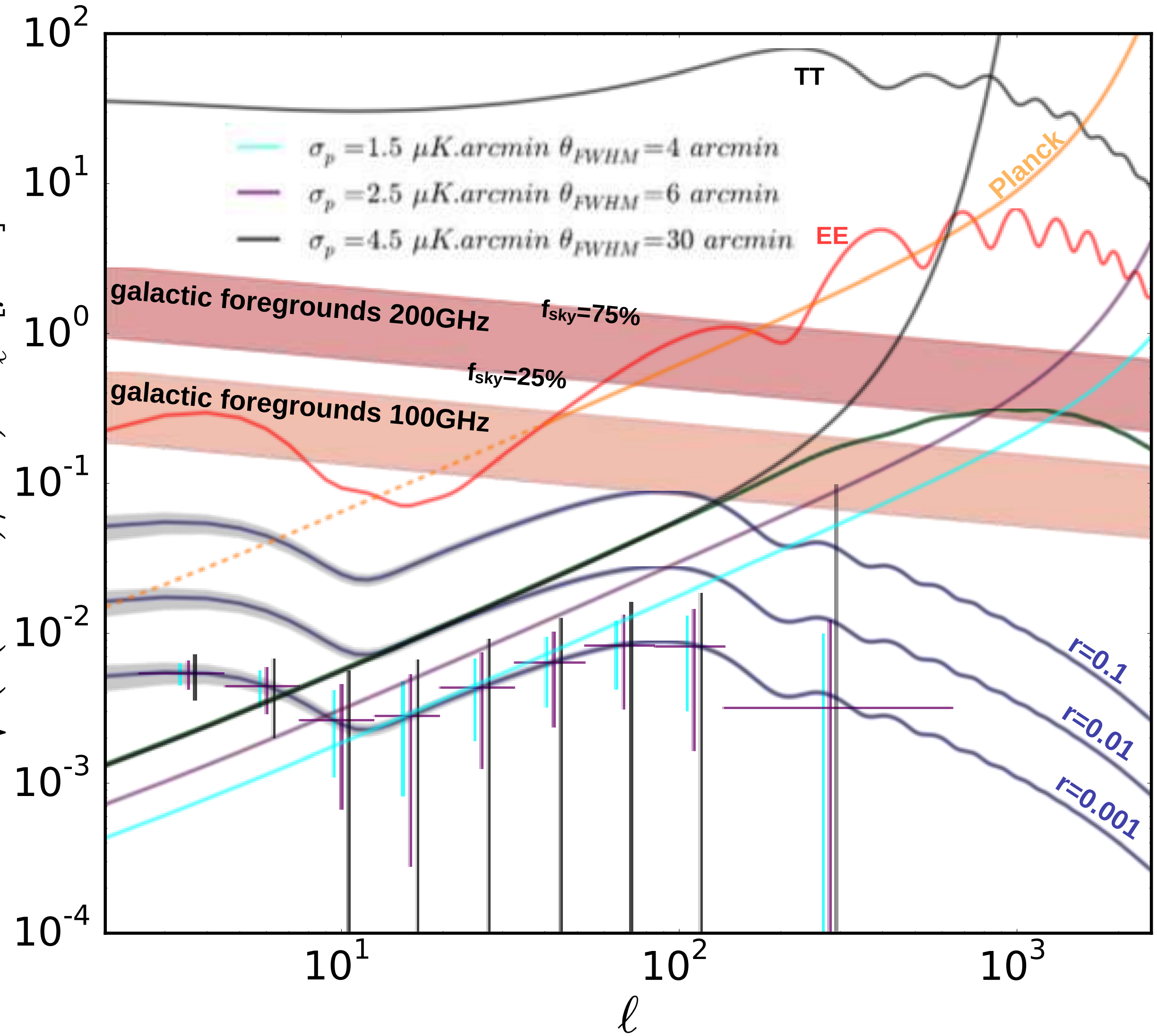


Figure by Josquin Errard

NB: Single iteration delensing

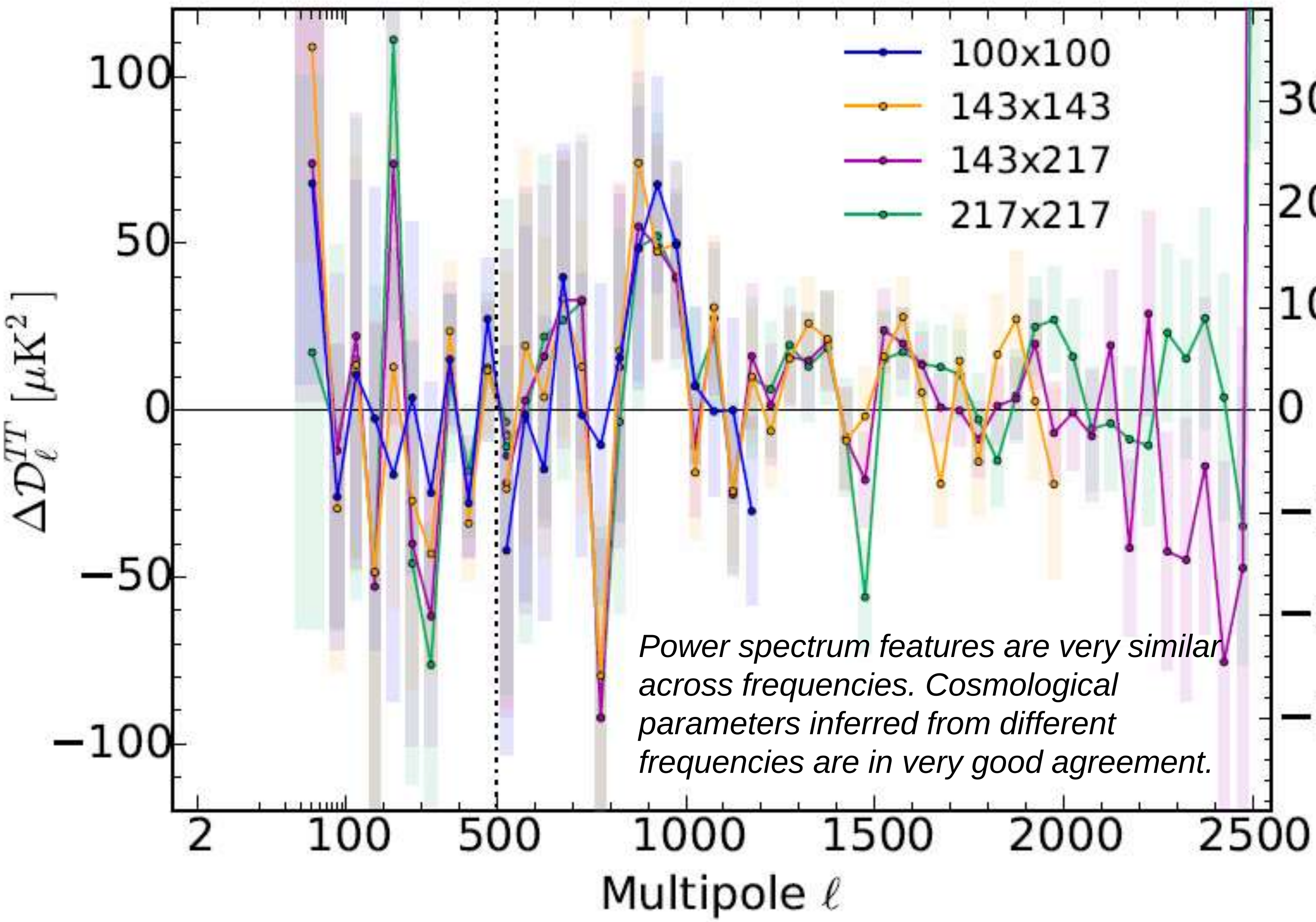
In the r=0.001 case, even with this plot broad binning, not a single bin detection at l>10 with 4.5μKarcmin and 30arcmin.

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

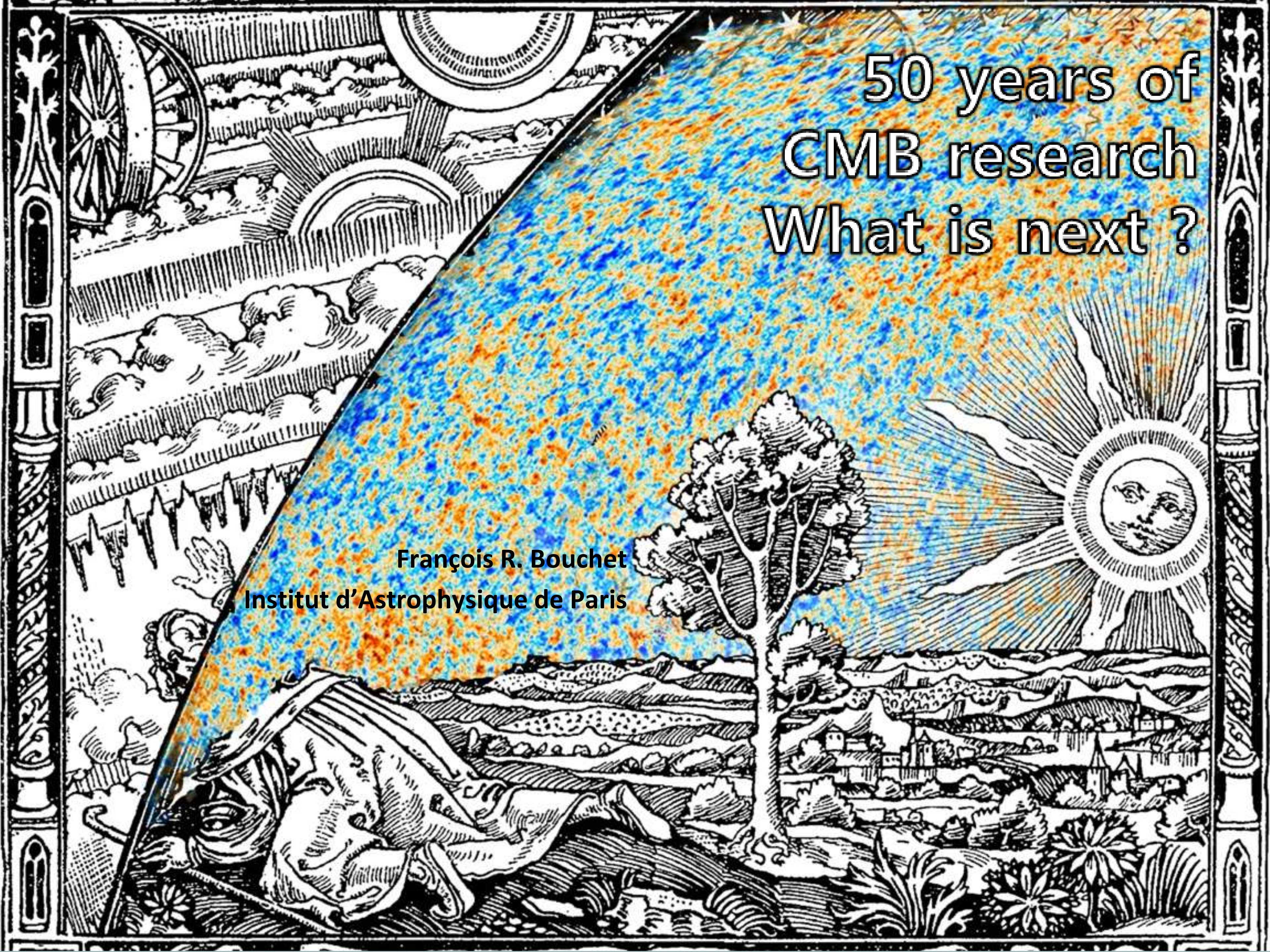
NB: If space data would only be used for getting E and Phi, how to clean the (ground) B-modes from foregrounds?

Residuals for different frequency combinations wrt to the l = 2–800 best-fit model

Planck IR-LI, arXiv:1608.02487v1



Power spectrum features are very similar across frequencies. Cosmological parameters inferred from different frequencies are in very good agreement.

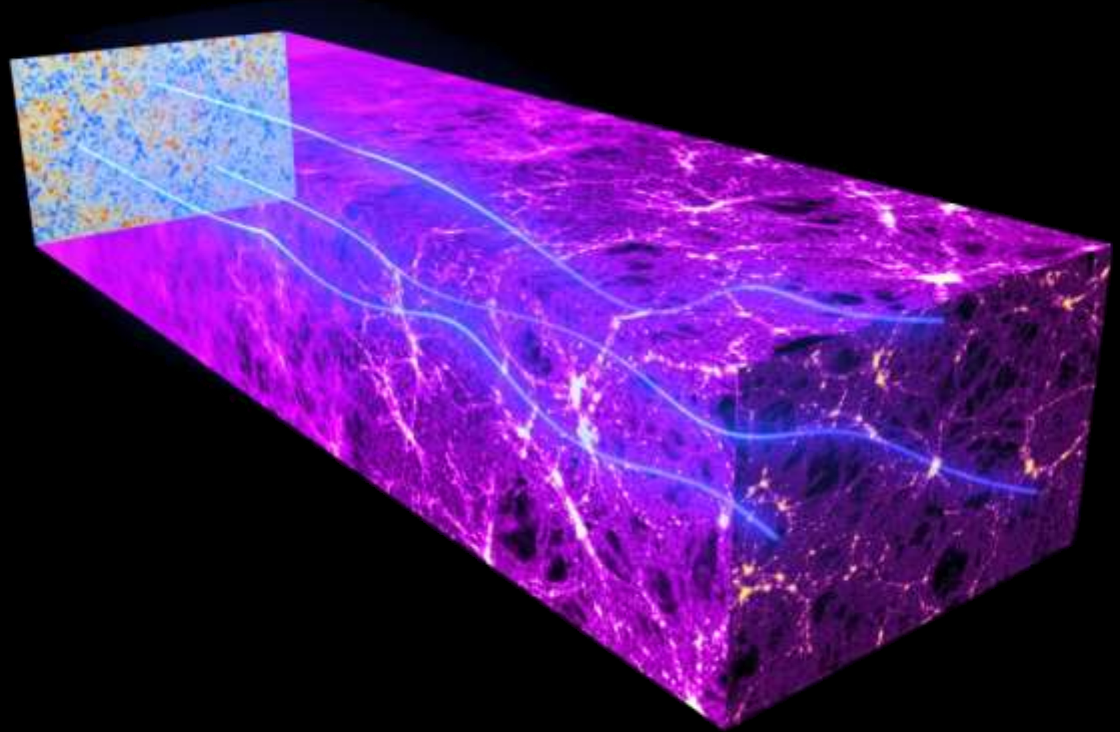


50 years of CMB research What is next ?

François R. Bouchet
Institut d'Astrophysique de Paris

GRAVITATIONAL LENSING DISTORTS IMAGES

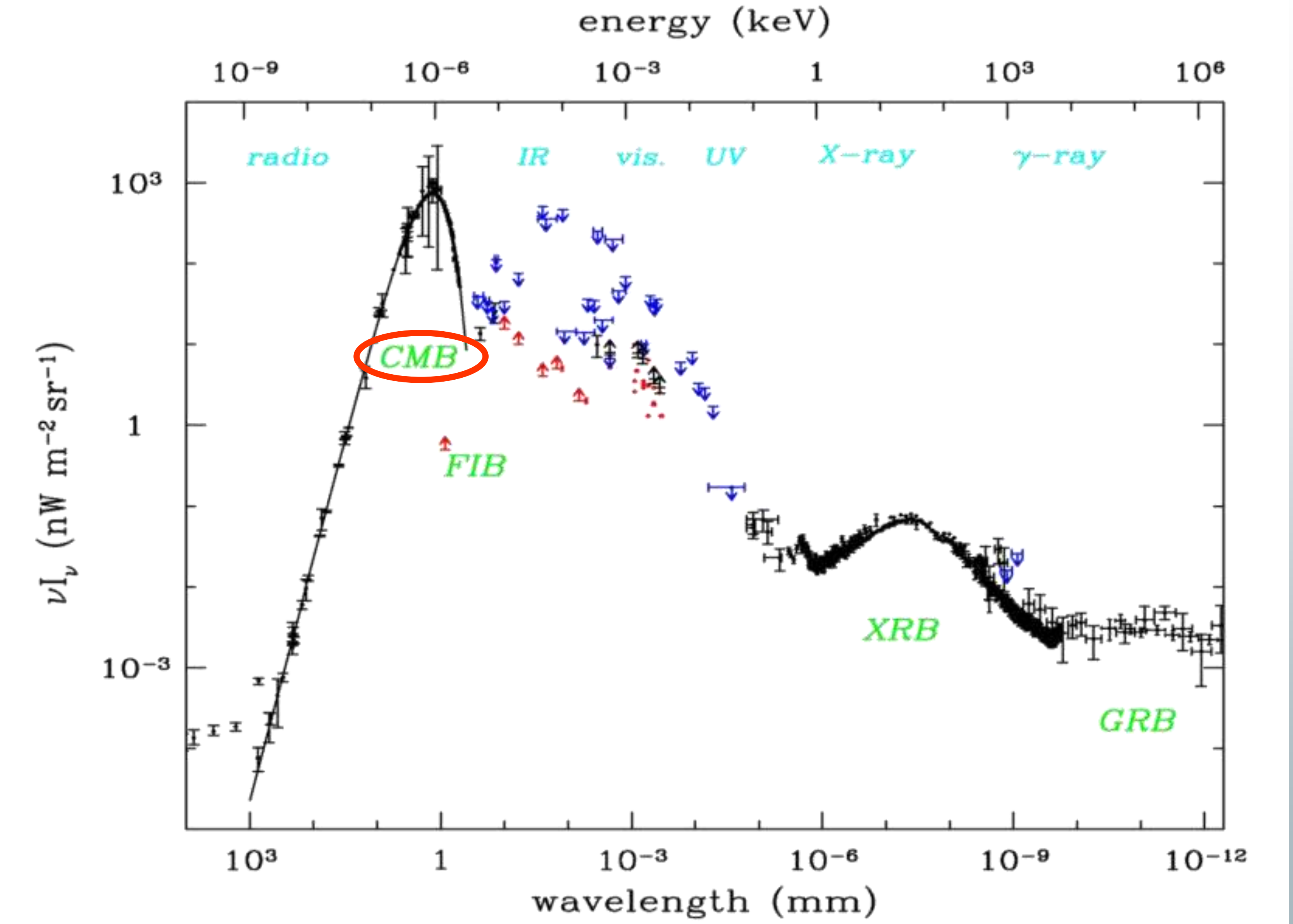
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



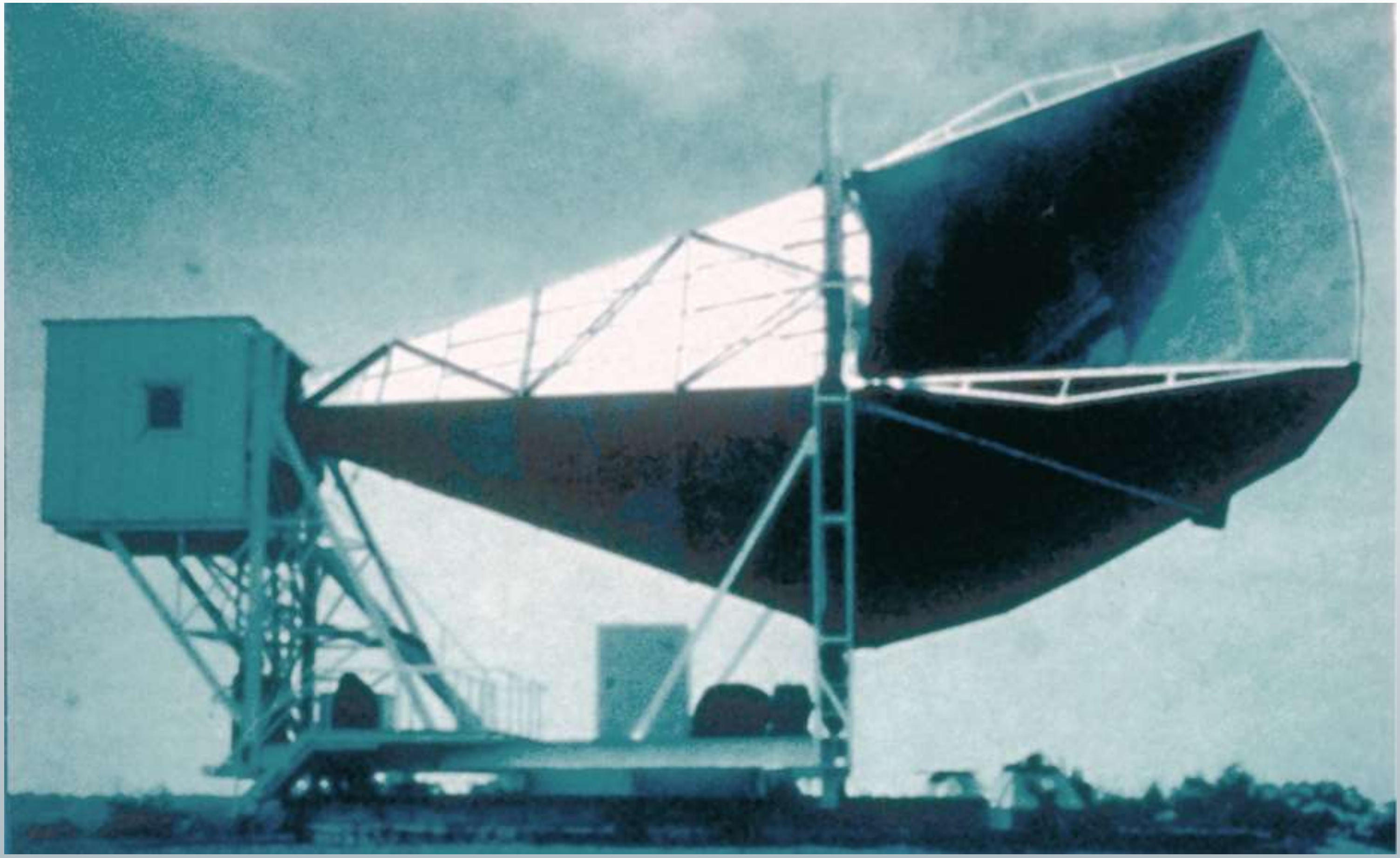
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$

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

CMB dominates (~93%) the landscape



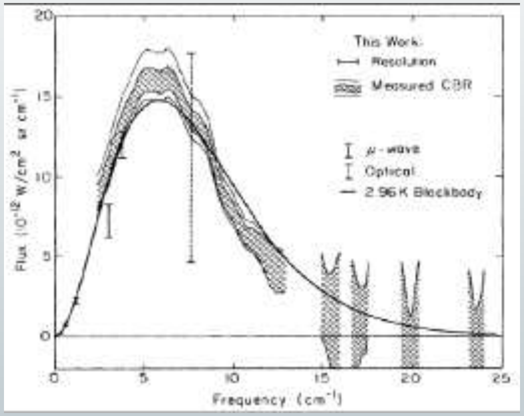
Penzias et Wilson antenna…
(Physics Nobel prize winners in 1978)

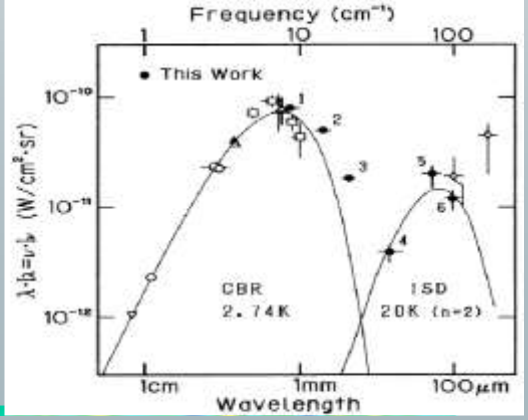


Cosmic Background predicted by Gamow in 1948, and by Ralph Alpher & Robert Herman in 1950. Serendipitously observed in 1965 par Arno Penzias and Robert Wilson at the Murray Hill Centre (NJ) of the Bell Telephone Laboratories as « A source of excess noise in a radio Receiver ». Joint interpretation article in Physical Review by Dicke, Peebles, Roll, Wilkinson…(Princeton), contacted via Bernie Burke.

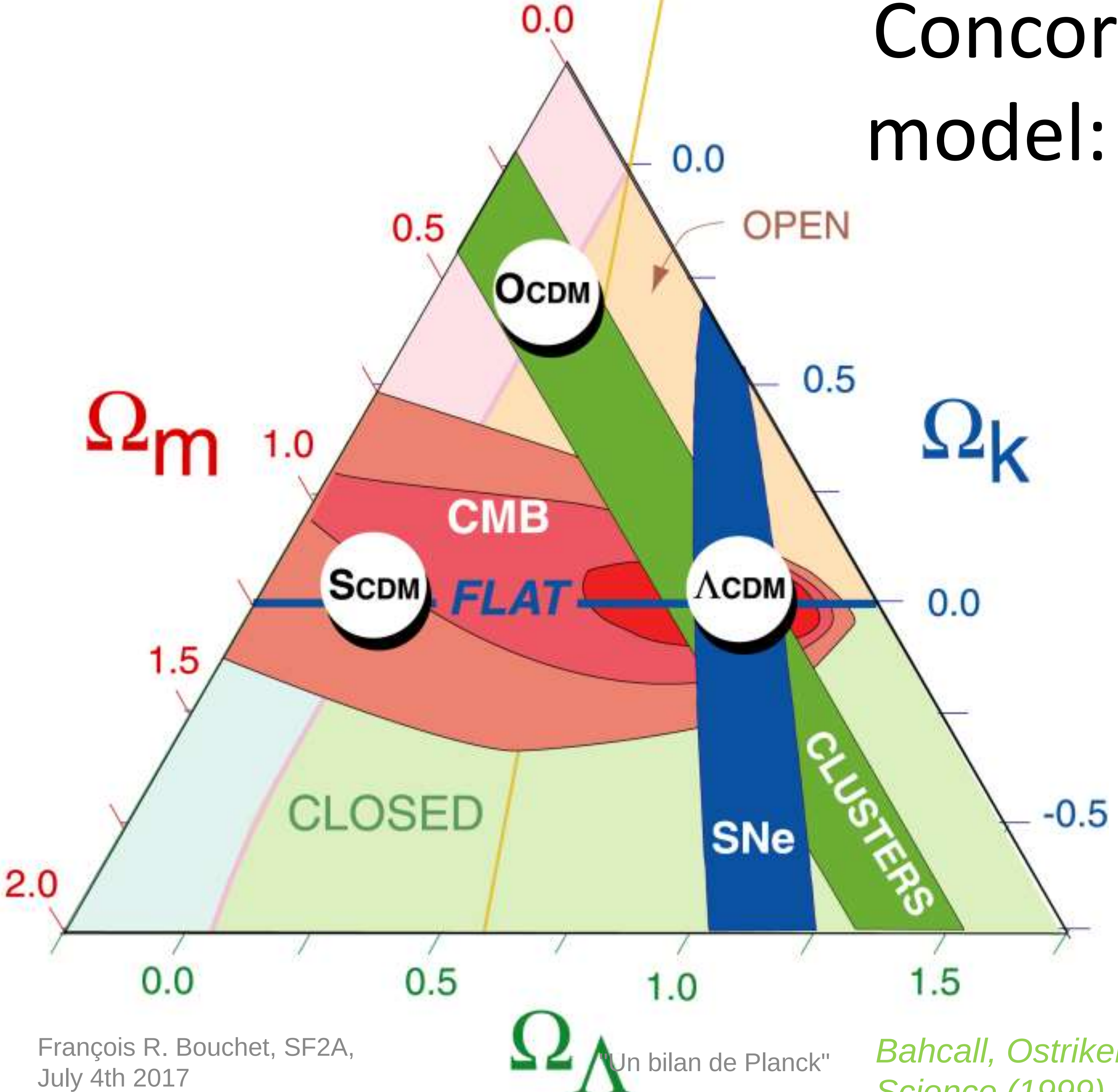
A long march ensues

- Many ground-based and mountain-top measurements filled in the 0.3-20 cm wavelength range, giving T = 2.73±0.08 K.
- Reworking and reobserving the CN lines gave 2.78±0.10 K at 2.64 mm. (Thaddeus, 1972, ARAA, 10, 305-334), 2.73±0.05 K (ςOph) and 2.75±0.04 K (ςPer) by M.B. Kaiser & EL Wright (1990)
- Big excesses over blackbody seen or not seen by different rocket and balloon experiments.
  - *2000 MJy/sr excess at 0.8 mm seen by Houck & Harwit(1969, ApJL, 157, L45)*
  - *No excess seen by MIT group (Muehlner& Weiss 1972)*
  - *Woody & Richards 2 mm excess in rocket (Phys. Rev. Lett. 42, 925 – 929 -1979)*
  - *Berkeley-Nagoya rocket experiment (Matsumoto et al. 1988, ApJ, 329,567) with TB= 2.80 K at 1.1 mm; 2.96 K at 0.7 mm & 3.18 K at 0.5 mm.*



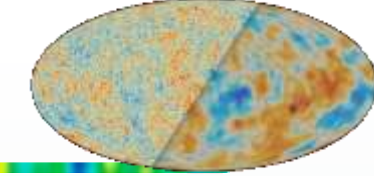


Concordance model: LCDM

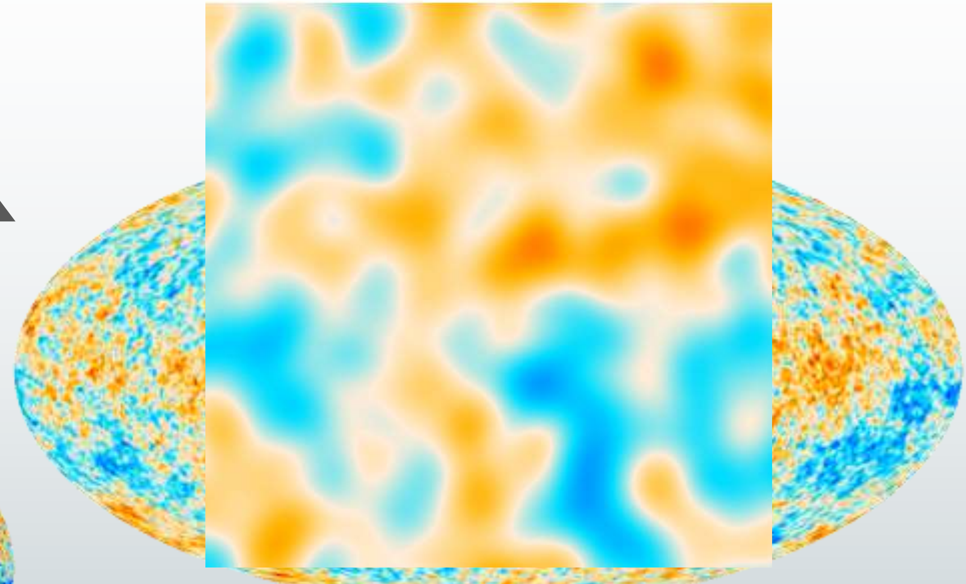


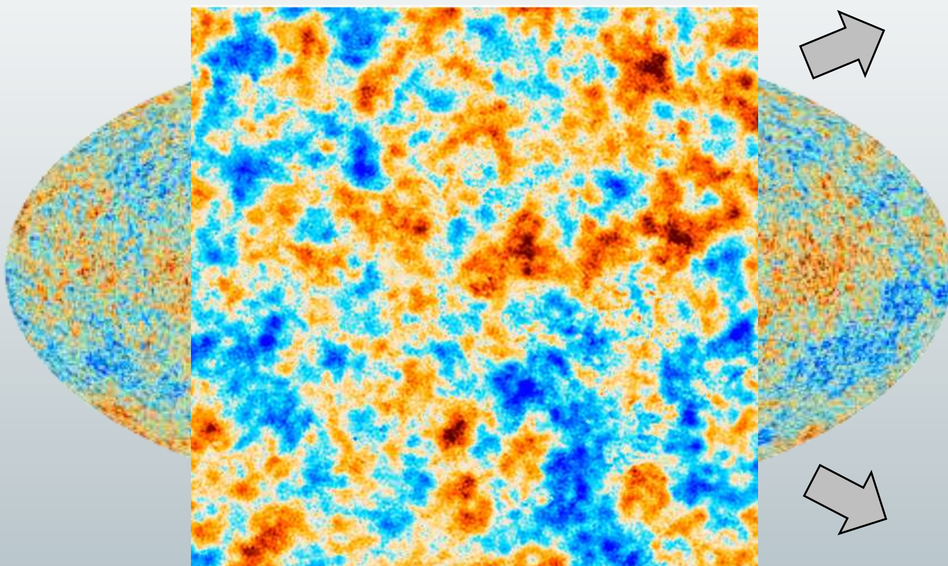
Bahcall, Ostriker, Perlmutter, Steinhardt, Science (1999), 284, 5419,1481

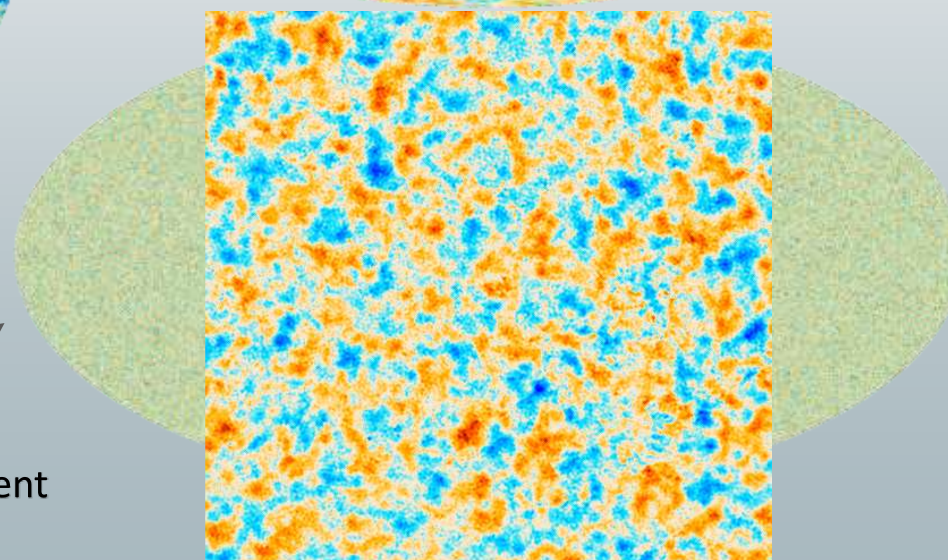
Our window



Smoothed map (suppressing scales $\theta < 1$ deg) :
Quantum Fluctuations imprinted
When the age of the Universe was in the
interval $[10^{-39}, 10^{-12}]$ seconds





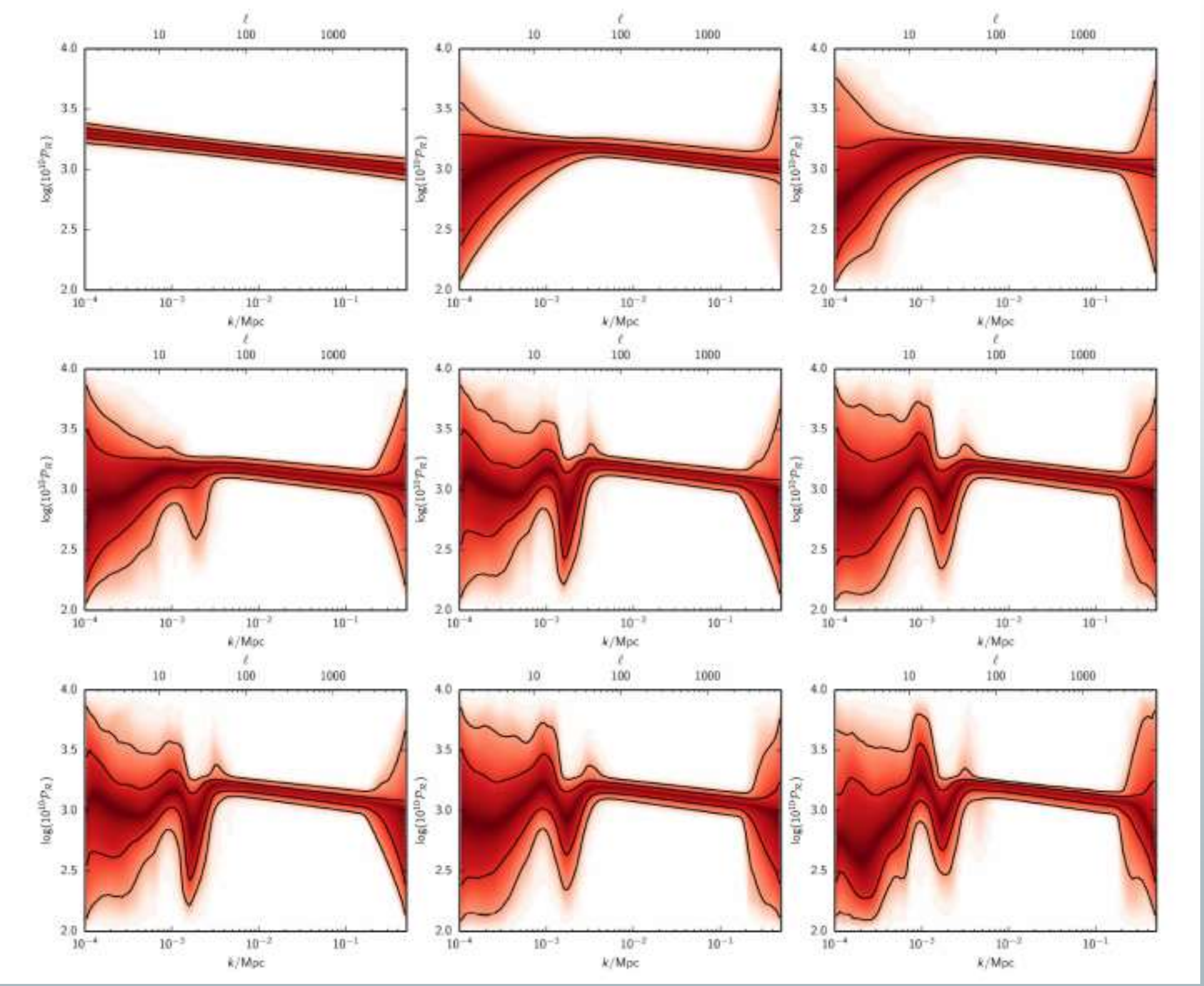


Difference map (scales $\theta < 1$ deg) :
Acoustic oscillations at small scales
< ct when t=380 000 years (~150 Mpc today).
Which allows to take a census of the Universe content

Bayesian moveable knot PS reconstruction

Adding
0 to 8
knots

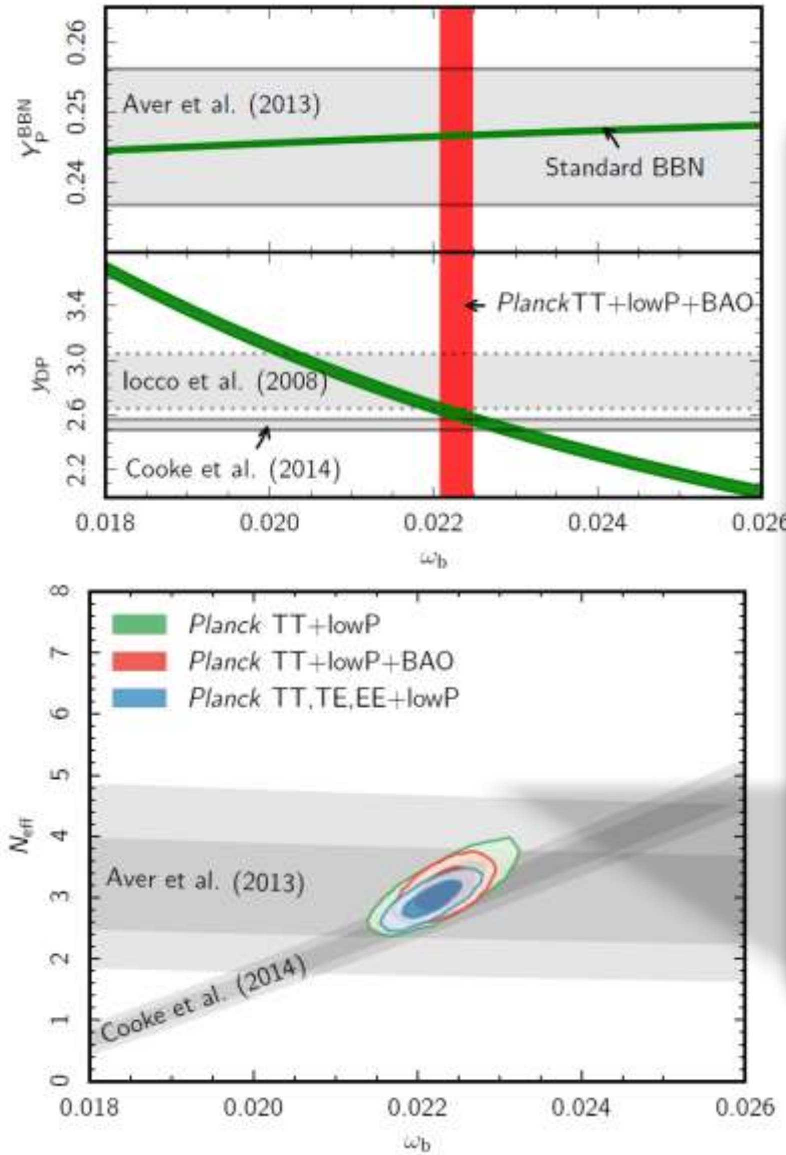
(in addition to
minimum 2)

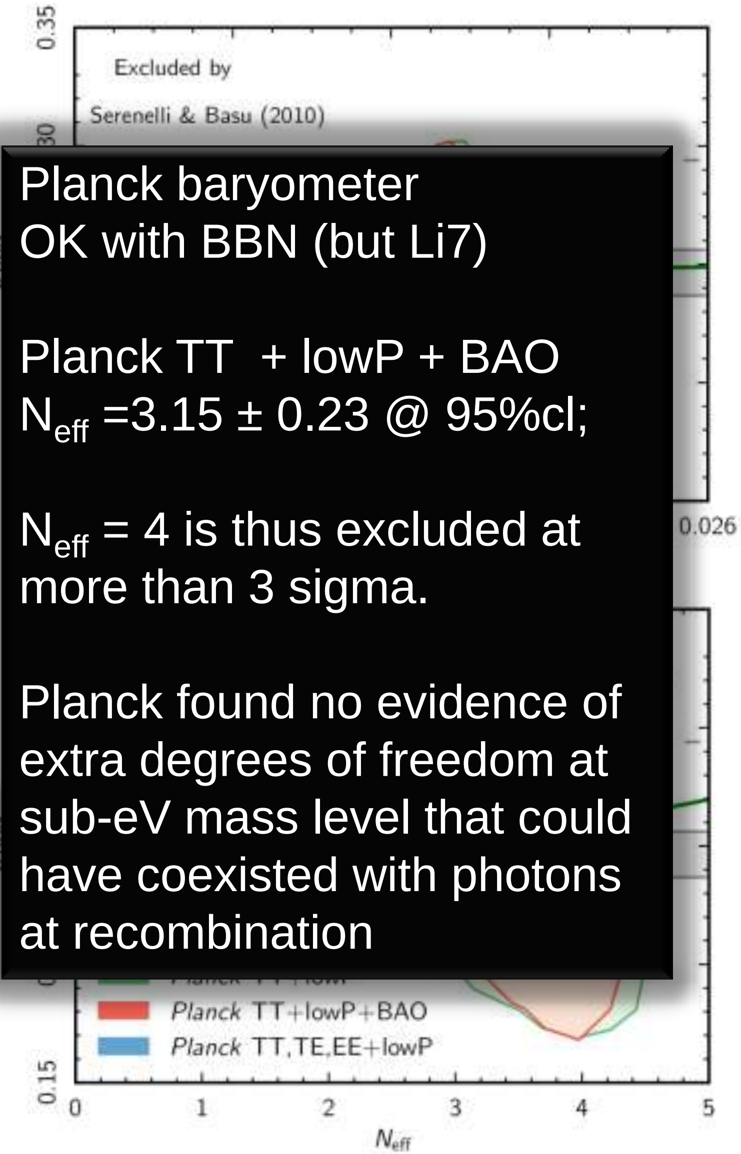


No truly significant deviation found

i.e.
l=20 dent is only tantalising (as most other anomalies)

BBN – N_{eff}, Y_p





Planck baryometer
OK with BBN (but Li7)

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

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

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

6 parameters Base LCDM model

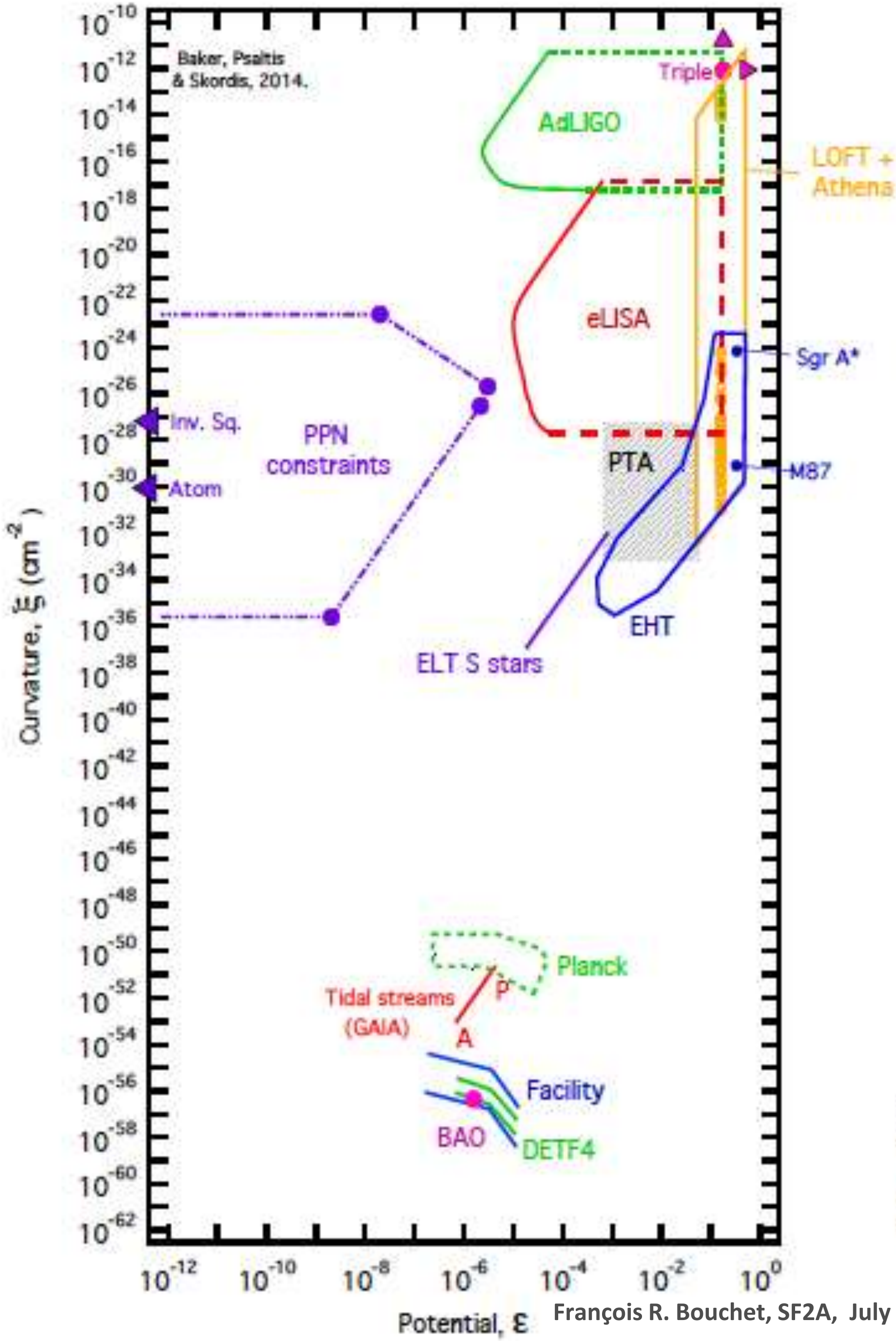
- A beautiful, incredibly minimal model
- Deceptively simple

since it completely relies on our two main fundamental theories, GR & QM and far reaching assumptions, e.g.,

- *The Physics laws are everywhere the same at all times*
- *The Universe is at large homogeneous and isotropic*
- *GR can be applied at scales much larger than directly tested; quoting J. Peebles at IAU2000:*

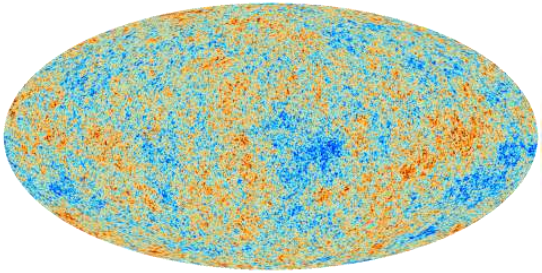
  "The elegant logic of general relativity theory, and its precision tests, recommend GR as the first choice for a working model for cosmology. But the Hubble length is fifteen orders of magnitude larger than the length scale of the precision tests, at the astronomical unit and smaller, a spectacular extrapolation."
- *Ditto for Quantum Mechanics*
- *Intertwined with much of classical physics in clockwork fashion*

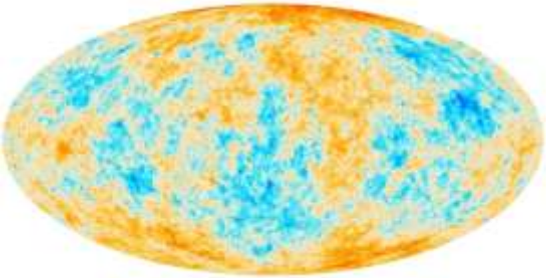
… assumptions which can now actually be tested…



Baker et al 2014
ArXiv:1412:3455

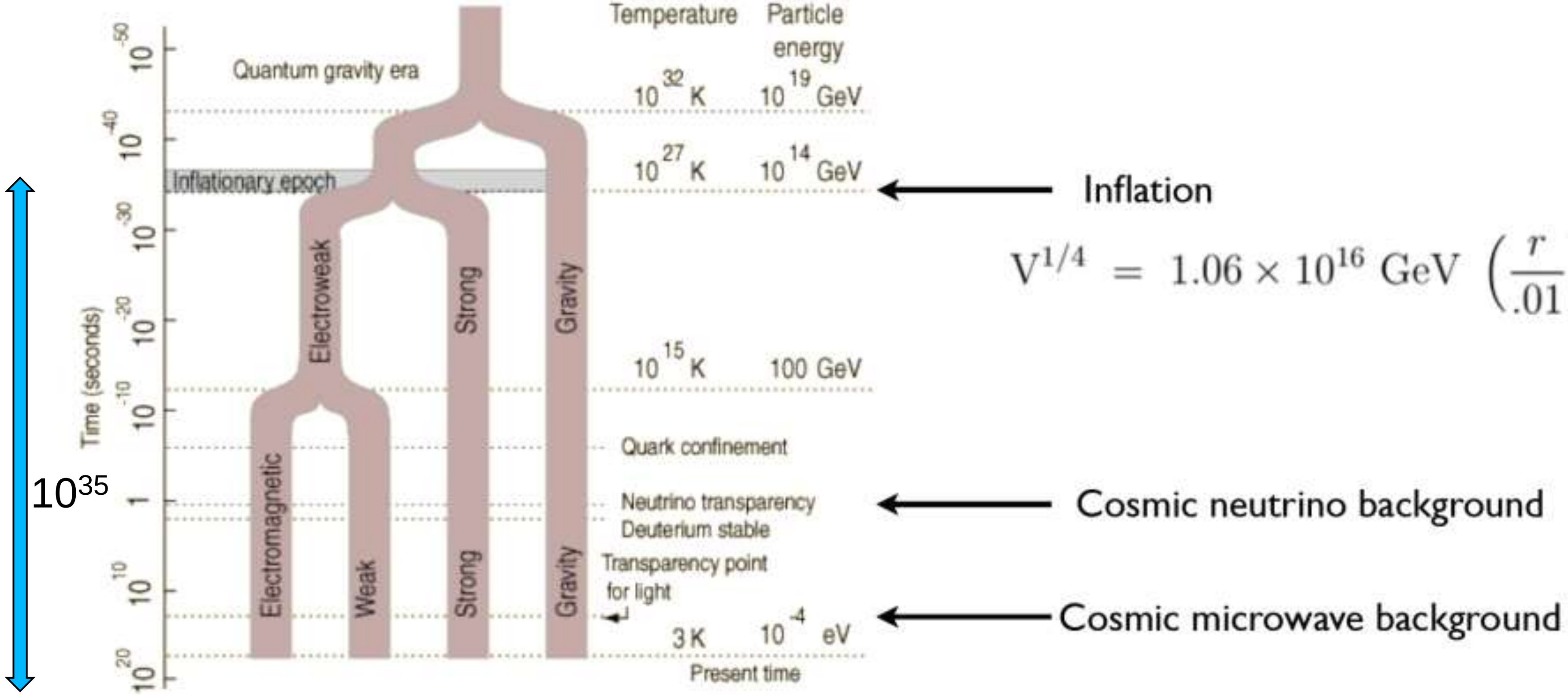
Theorists precomputed possible imprints in various scenarii





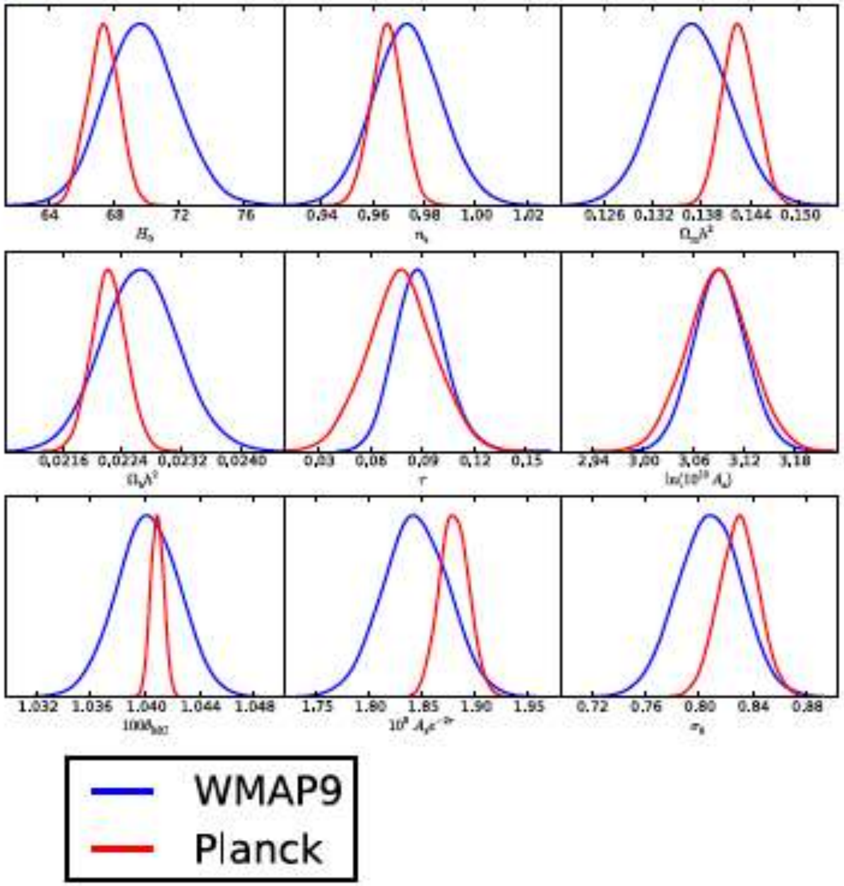
Gamow, Peebles, Yu, Sachs & Wolf, Sunyaev, Zeldovich, Silk, Vittorio, Wilson, Mukhanov, Chibisov, Bardeen, Linde, Bond, Efstathiou, Bouchet, Bennett, Gott, Kaiser, Stebbins, Allen, Shellard, Seljack, Zaldariaga, Kamionkowski, Hu, …

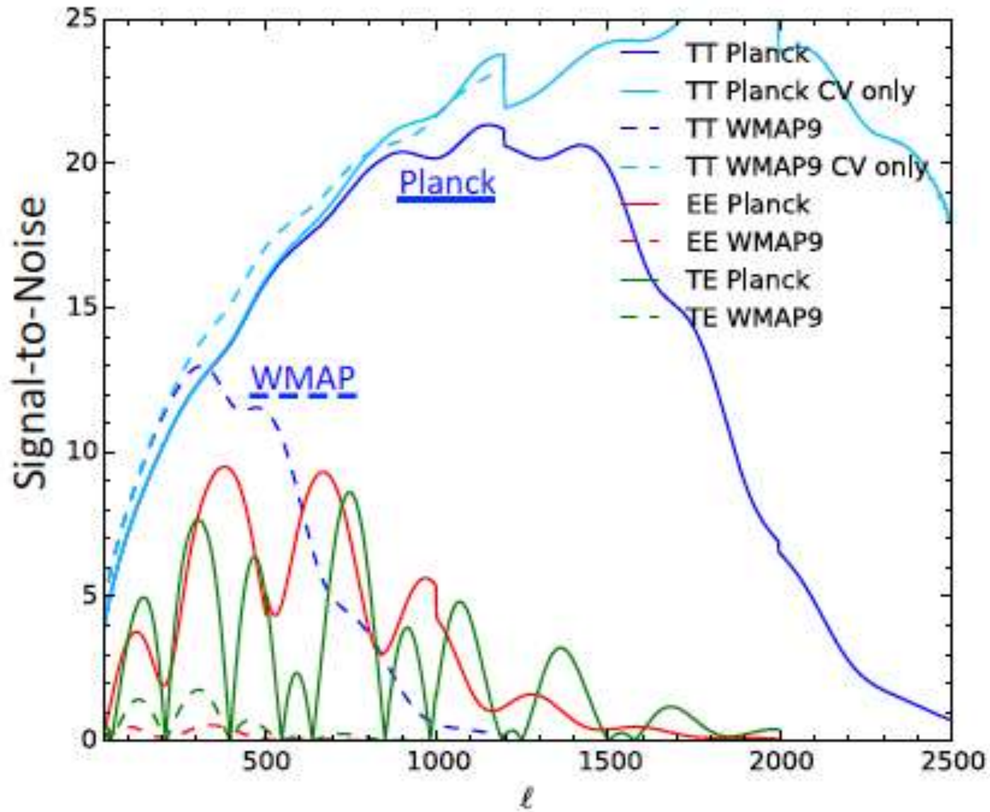
The primordial Universe, Fundamental physics Ultimate laboratory



$$V^{1/4} = 1.06 \times 10^{16}\ \mathrm{GeV} \left(\frac{r}{.01}\right)^{1/4}$$

Planck and WMAP

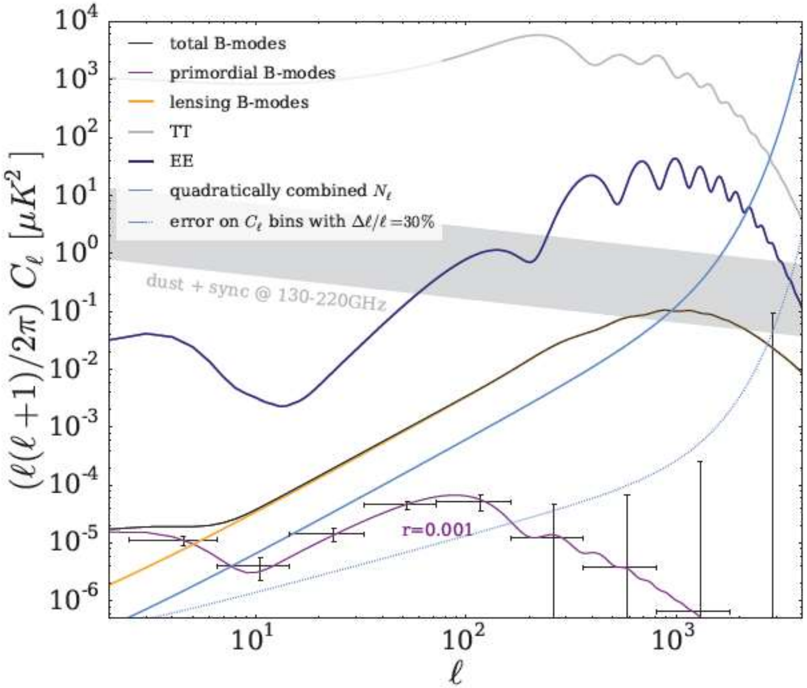




Planck sample variance limited till **l~1600** (data points till ~2500, fsky~40-70%)

WMAP sample variance limited till **l~600** (data points till l~1200)

Inflation



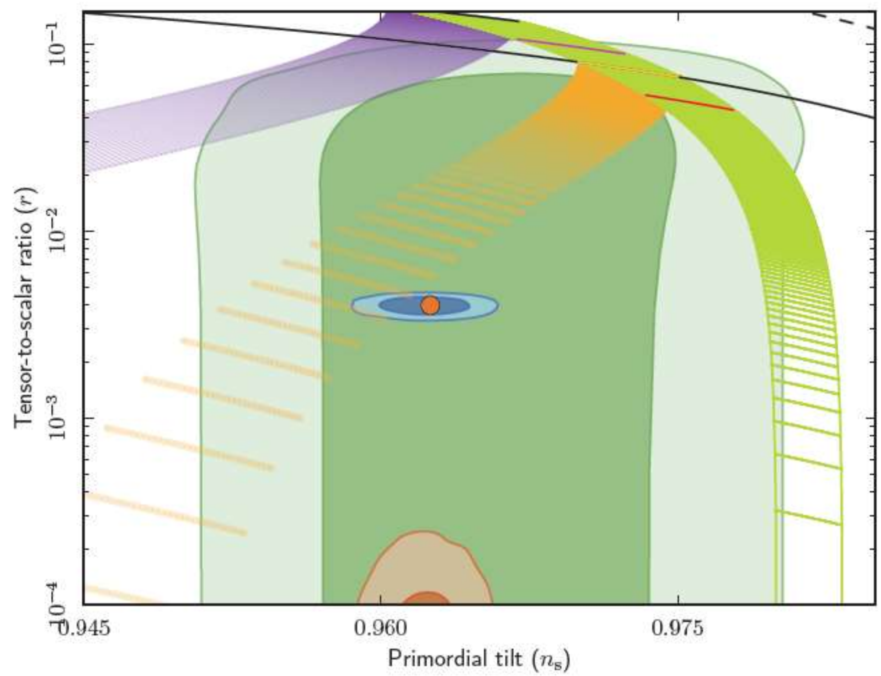
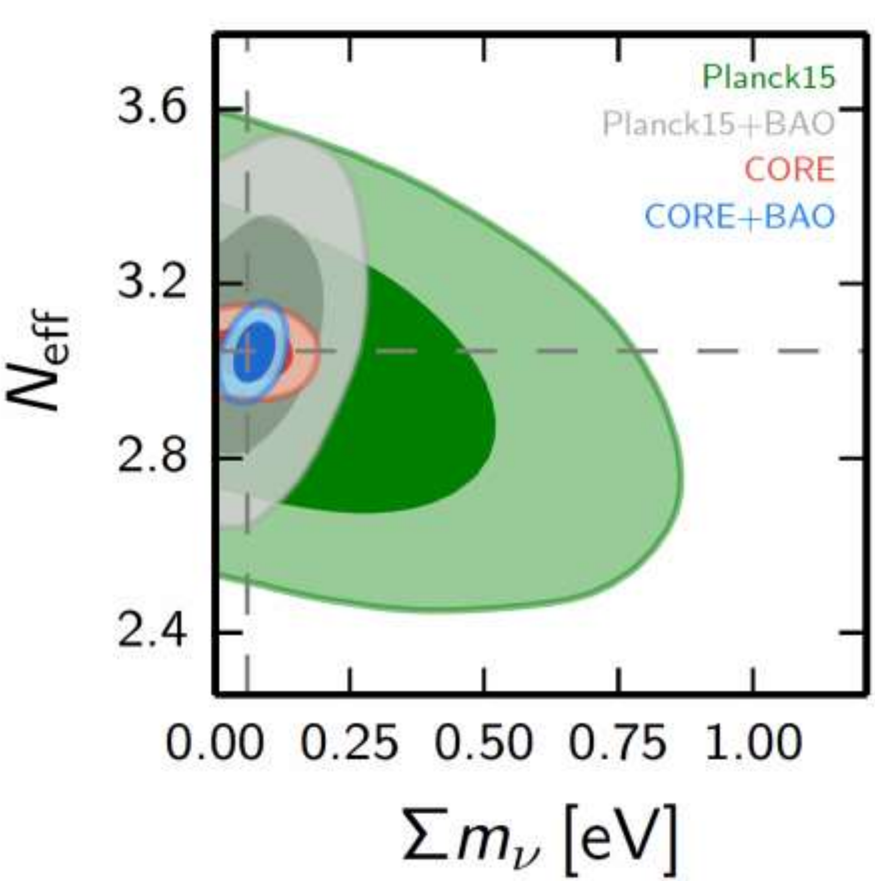
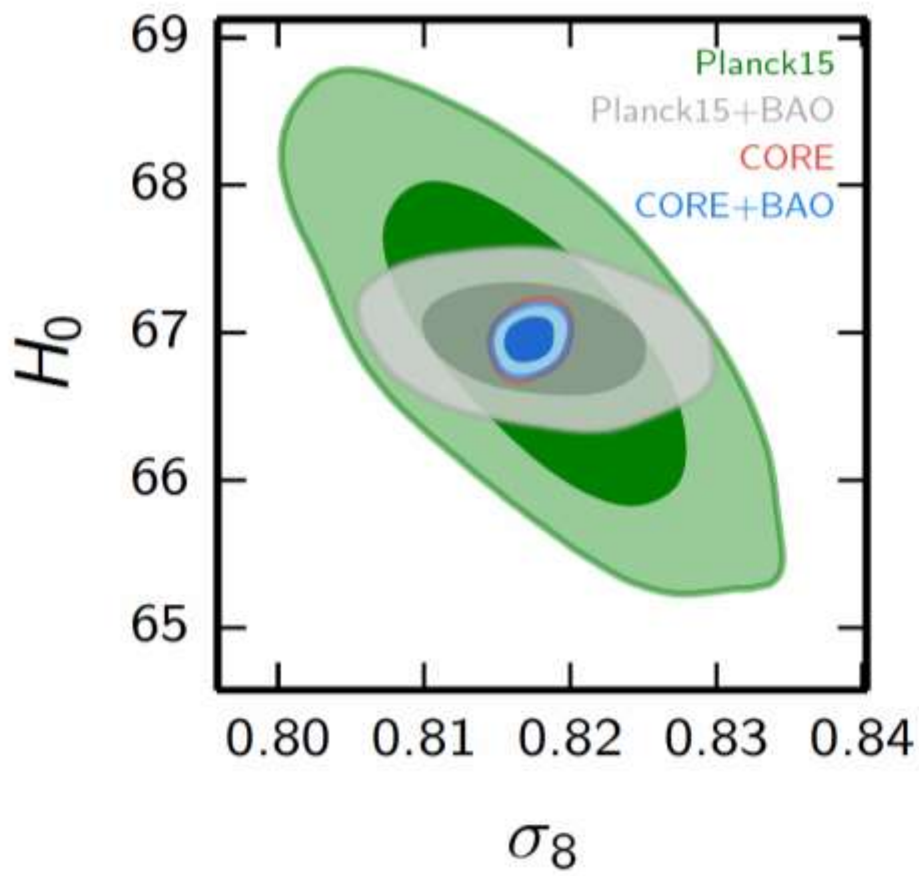


Figure 1: Left: Projected 68% CL error bars (crosses) and the theoretical prediction (purple line) for the primordial B-mode power spectrum with a tensor-to-scalar ratio of $r = 0.001$. The orange line shows the secondary B-mode power spectrum from gravitational lensing while the black line shows their sum. The top two lines show the power spectra of the temperature and E-mode polarization, respectively. The solid blue line shows the noise power spectrum, while the dotted line shows the error bar on the B-mode power spectrum due only to noise in the 130-220 channels. Right: Forecasts for marginalized contours for (n_s, r) at the 68 % and 95 % CL for *CORE* for two scenarios. The fiducial model at the center of the blue marginalized contours (orange dot) has $r = 0.004$, a value consistent with the Starobinsky model, and a second fiducial model (red contours) has a level of primordial GW undetectably small for *CORE*. The green contours show the 68 % and 95 % CL for Planck 2015 data combined with the BICEP2-Keck Array-Planck B-mode likelihood [11]. We show the predictions for natural inflation (purple band), hilltop quartic model (orange discrete band) and power law chaotic (light green discrete band) models. These inflationary models consistent with the current data can be ruled out by *CORE*.

Examples (from CORE-M5)



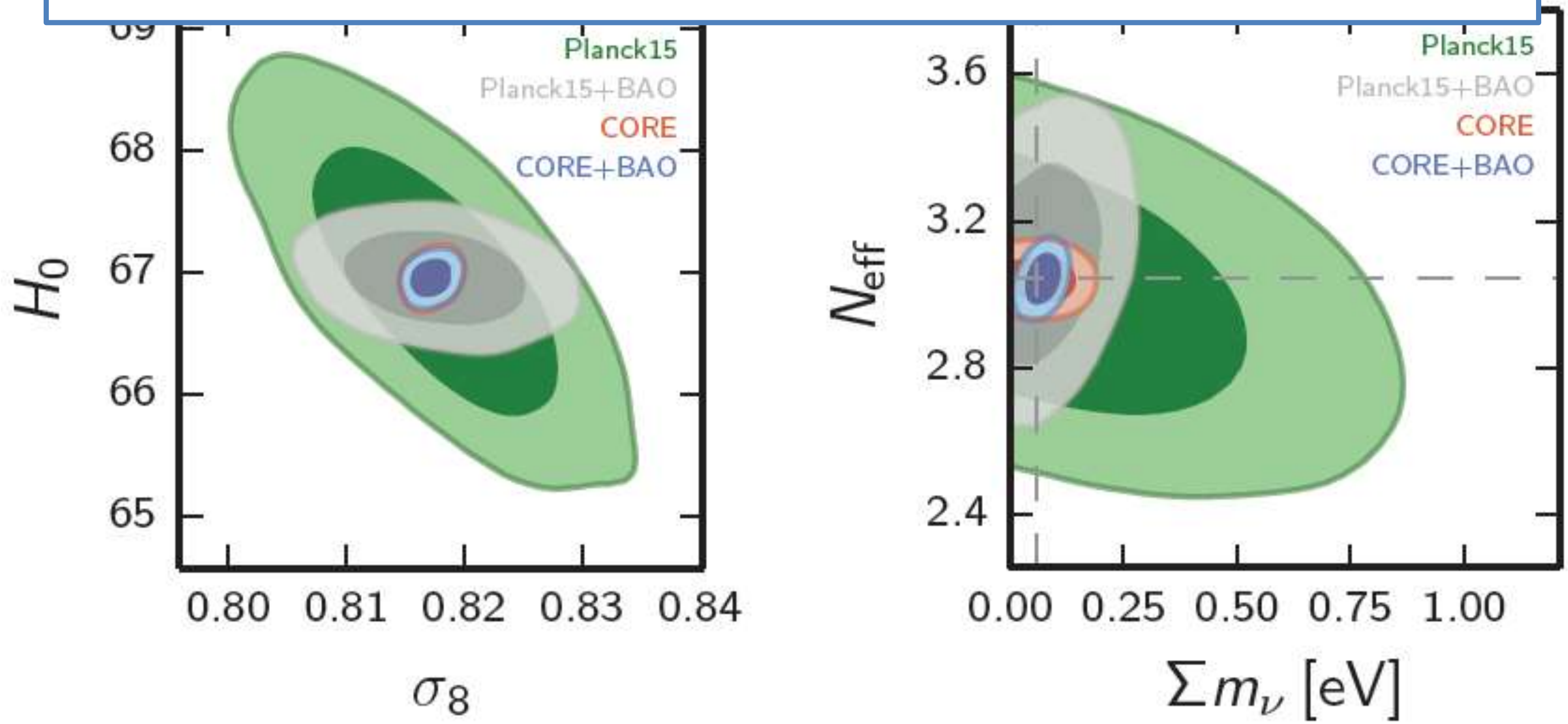


Exemples augmentation "Figure of Merit" (FOM) / Planck

Model	Planck+DESI	CORE-M5	CORE-M5+DESI
ΛCDM	3.3	2.3×10^3	2.3×10^3
$\Lambda\text{CDM} + w + Y_P + M_\nu + N_{eff}$	140	5.2×10^5	9.1×10^6

Traduction du "volume" permis de l'espace des paramètres /data

Cosmological Parameters Constraints



Examples of augmentation "Figure of Merit" (FOM) / Planck

Model	Planck+DESI	CORE-M5	CORE-M5+DESI
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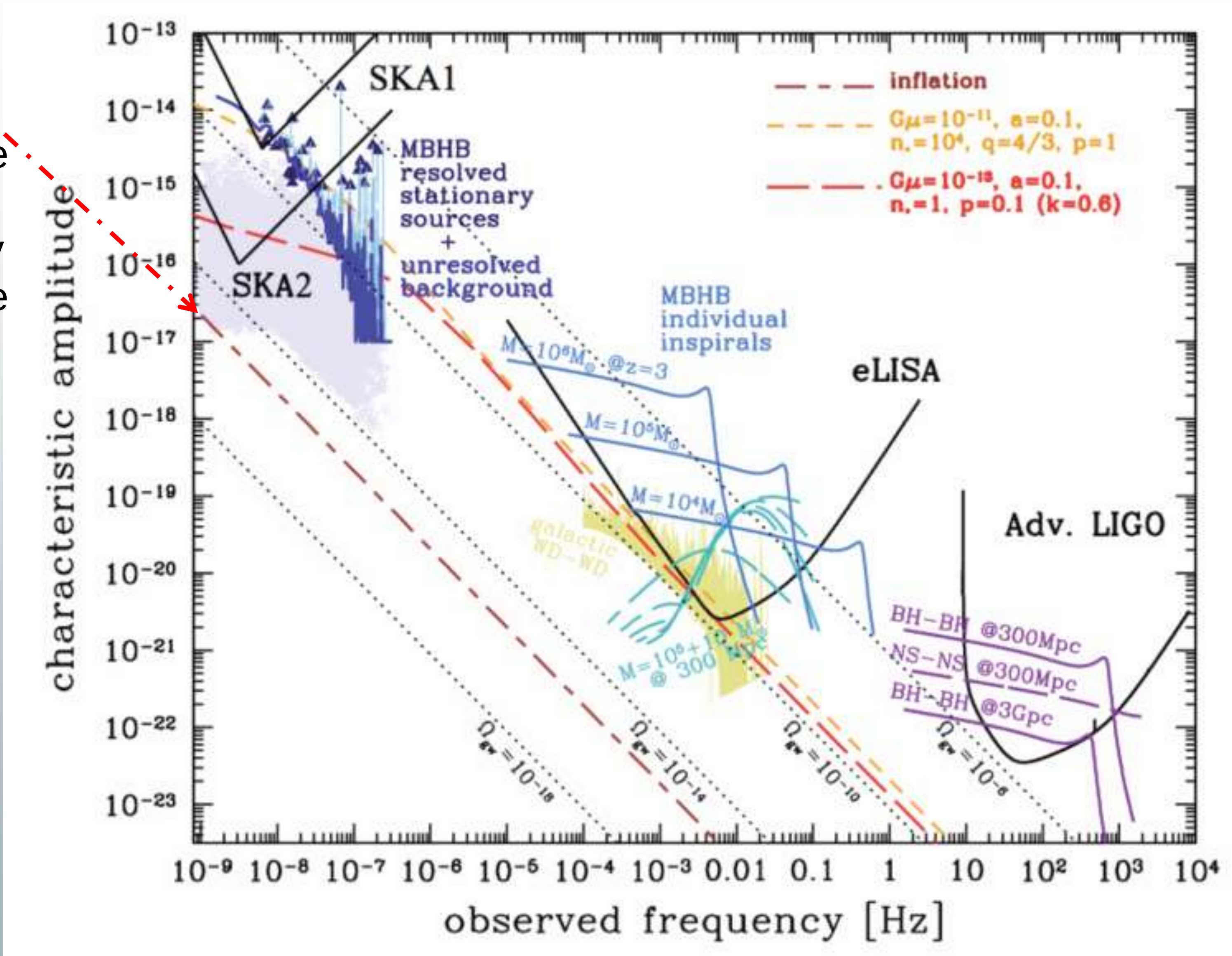
Traduction du "volume" permis de l'espace des paramètres /data

CMB versus other GW detectors

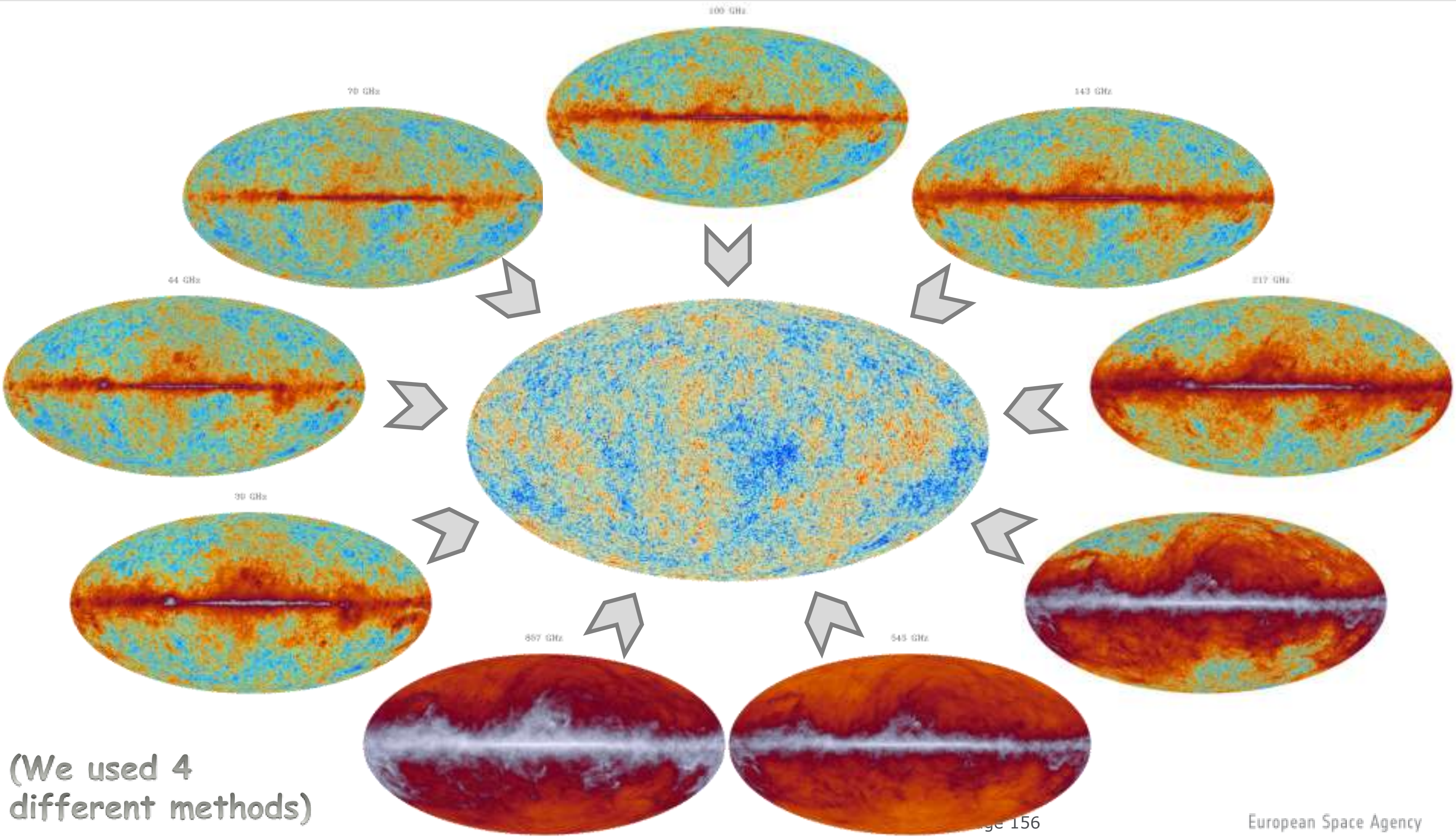
For the foreseeable future, direct local detections can only constrain non-scale invariant primordial GW backgrounds

➔ Dedicated experiments might soon (or not) yield a detection

(CMB constraints corresponds to much lower frequencies and higher strain)



Cleaning the background from its 7 veils



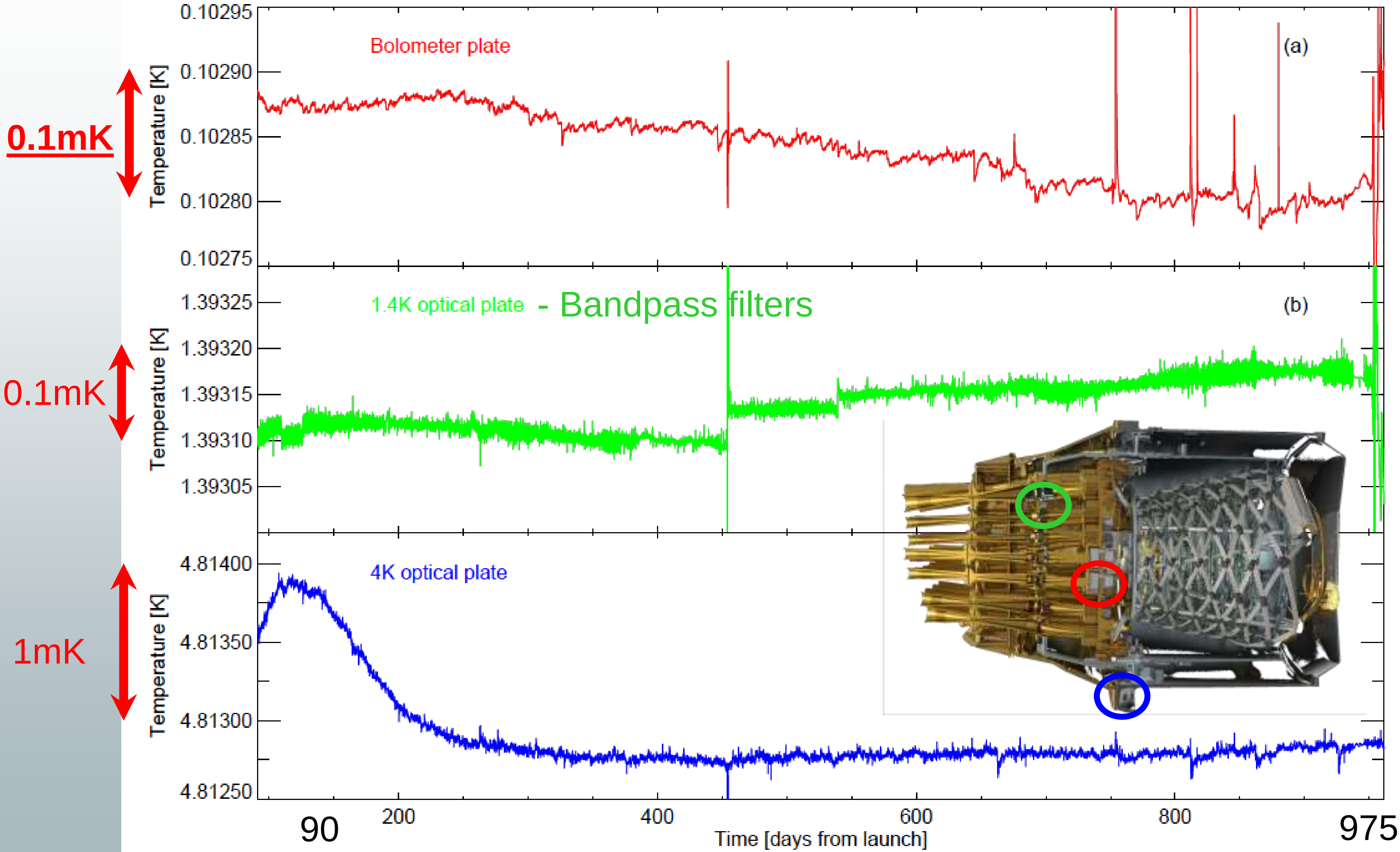
(We used 4 different methods)

European Space Agency

"Un bilan de Planck"

3% of the CMB sky replaced by a Gaussian Random realisation

Très froid, très stable, très longtemps...



A la Cave de l'IAP…

+ CC/CINECA/ Darwin/NERSC…

Testing inflation with CMB, optical, and IM surveys

[AP 2016]

Survey	$\sigma(n_s)$	$\sigma(\alpha_s)$
Planck	0.006	0.007
COrE-like	0.0019	0.0025
COrE-like + SKA1-MID (sd)	0.0013	0.0021
COrE-like + SKA2-MID-like (sd)	0.0011	0.0019
COrE-like + HIRAX	0.0012	0.0020
COrE-like + HIRAX (higher k_{NL})	0.0011	0.0015
COrE-like + SKA2-LOW-like (compact)	0.0006	0.0007
COrE-like + Euclid-like	0.0011	0.0018

(not enough for Generic model)

gives required precision < 0.001

[see also Munoz et al 2016]