Cosmic Microwave Background – Post Planck

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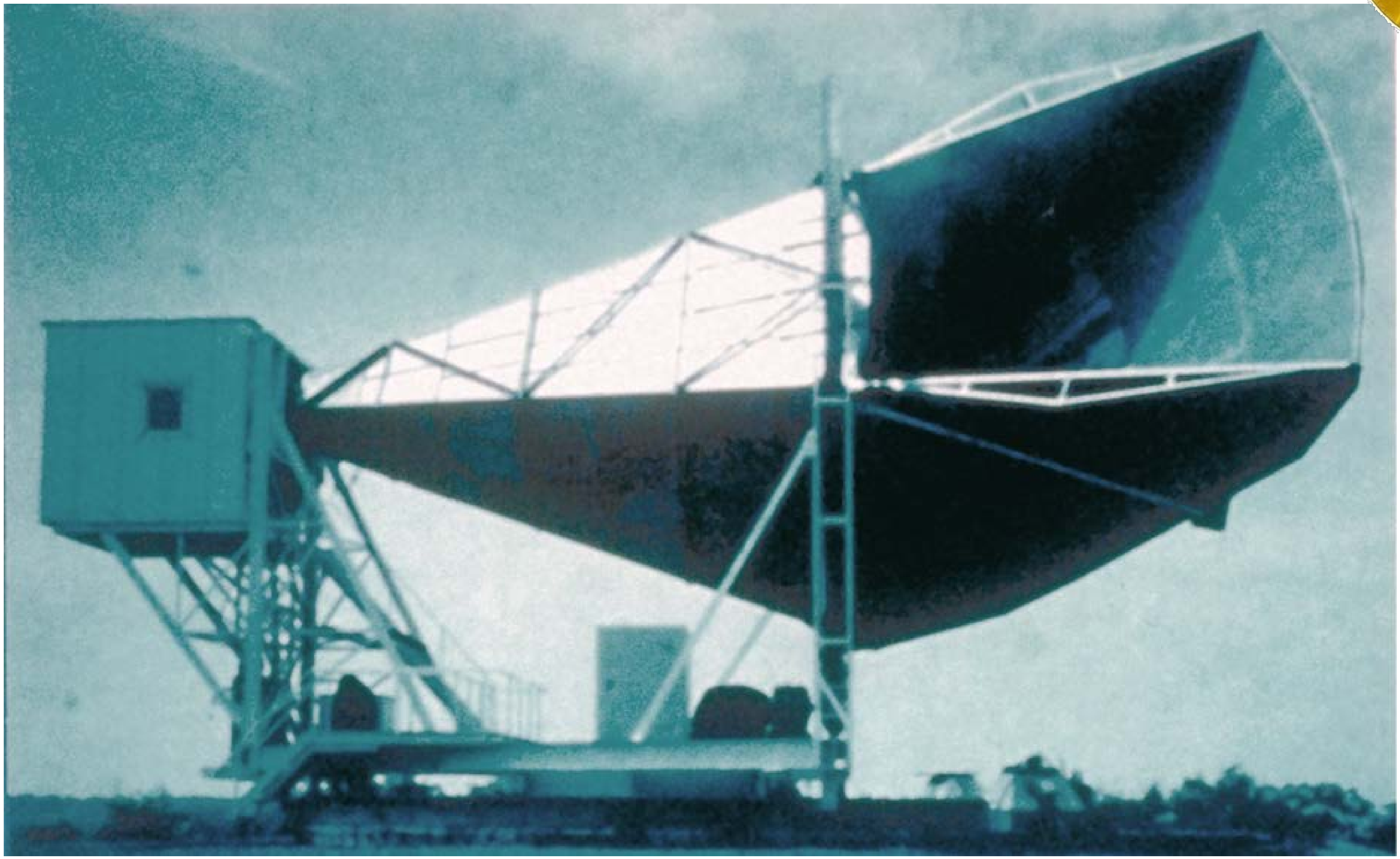
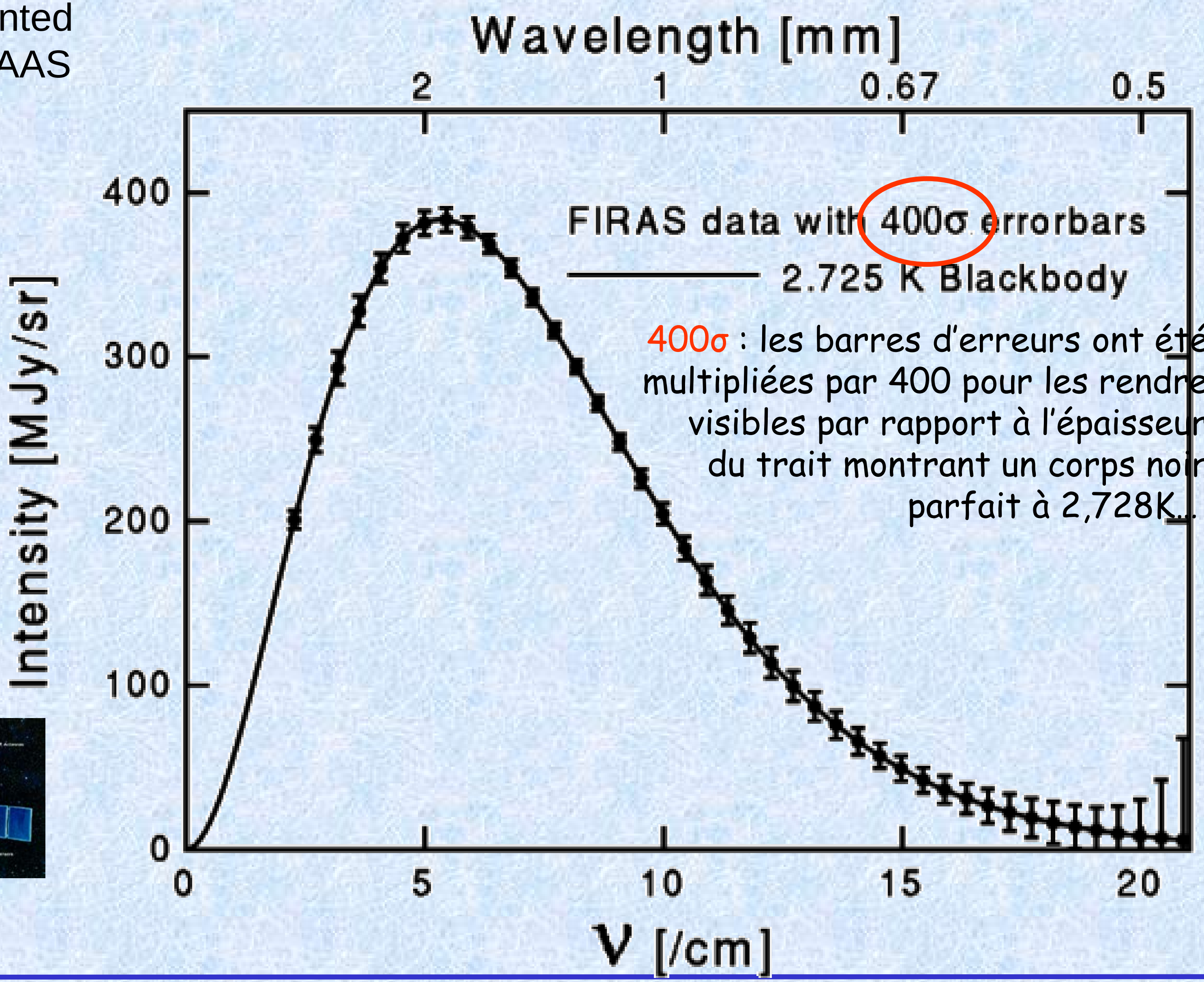
Penzias et Wilson antenna…
(Physics Nobel prize winners in 1978)



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.

FREQUENCY SPECTRUM FROM COBE/FIRAS

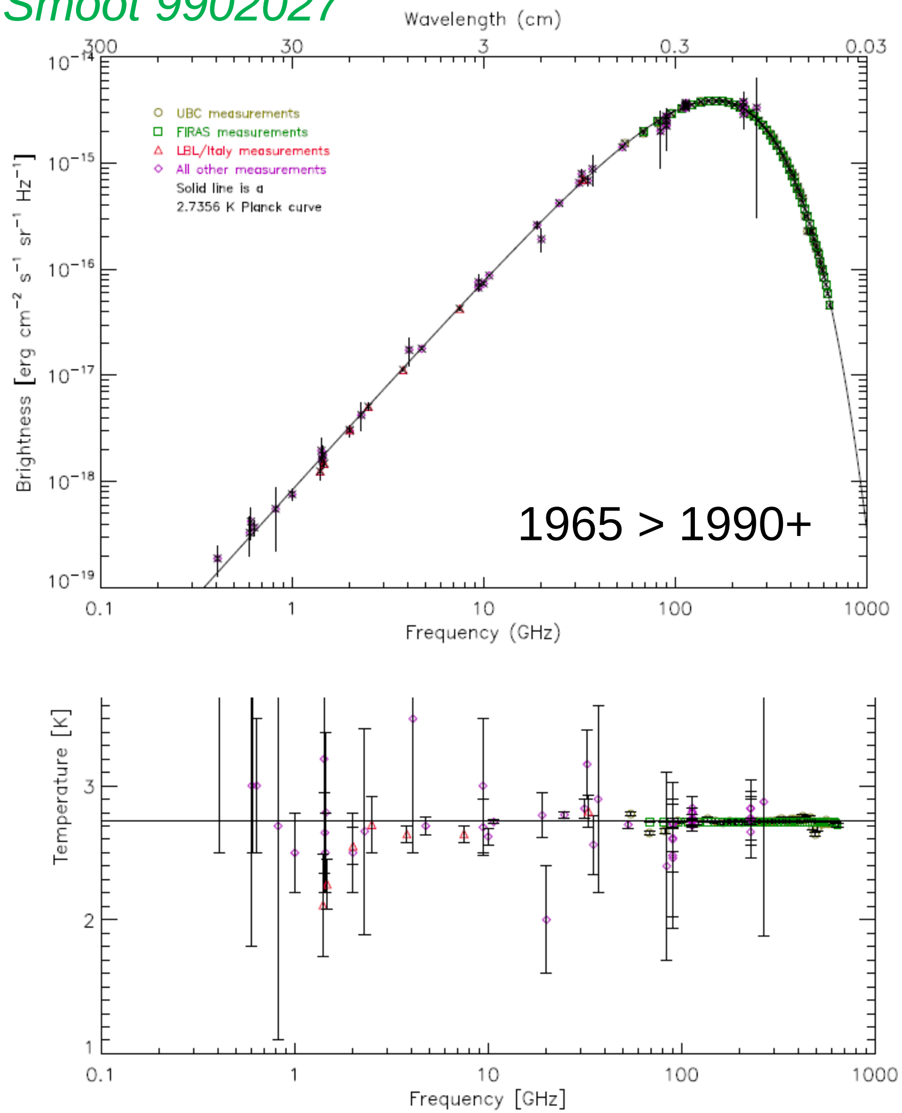
1st presented 1990 @ AAS



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…

Tight contraints on spectrum distortion from BB

Smoot 9902027



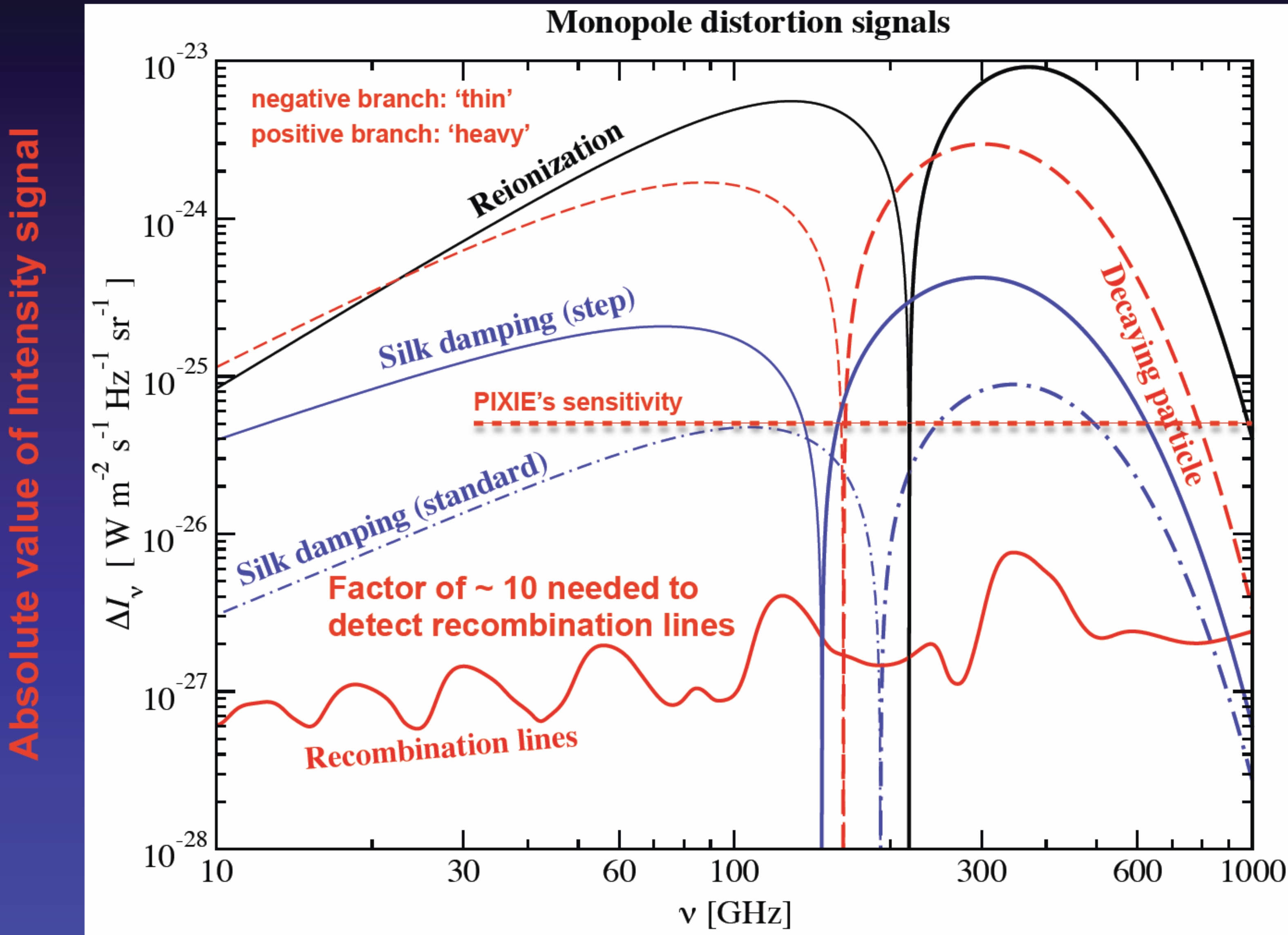
- Compton scatterings of γ by hot e depletes low E (Rayleigh-Jeans, hν/kT <1) for high E (Wien), thereby imposing a well defined distortion characterised by the single Compton parameter y (if non-relativistic)
- At $z > 10^5$, $y > 1$ (in standard BB), the plasma can reach statistical equilibrium. But when $z < 10^7$, there is no photon production, therefore no thermodynamical equilibrium; leads to a Bose-Einstein spectrum characterised by a chemical potential μ
- Very late energy release, at $z \ll 10^3$, can create free-free distortion, characterised by Y_{ff}.

$$
\begin{aligned}
T_0 &= 2.7377 \pm 0.0038\ \mathrm{K} \quad (95\%\ \mathrm{CL}) \\
Y_{\mathrm{ff}} &= -1.1 \times 10^{-5} \pm 2.3 \times 10^{-5} \quad (95\%\ \mathrm{CL}) \\
\mu_0 &= -3.0 \times 10^{-5} \pm 1.2 \times 10^{-4} \quad (95\%\ \mathrm{CL}) \\
y &= 1.6 \times 10^{-6} \pm 9.6 \times 10^{-6} \quad (95\%\ \mathrm{CL})
\end{aligned}
$$

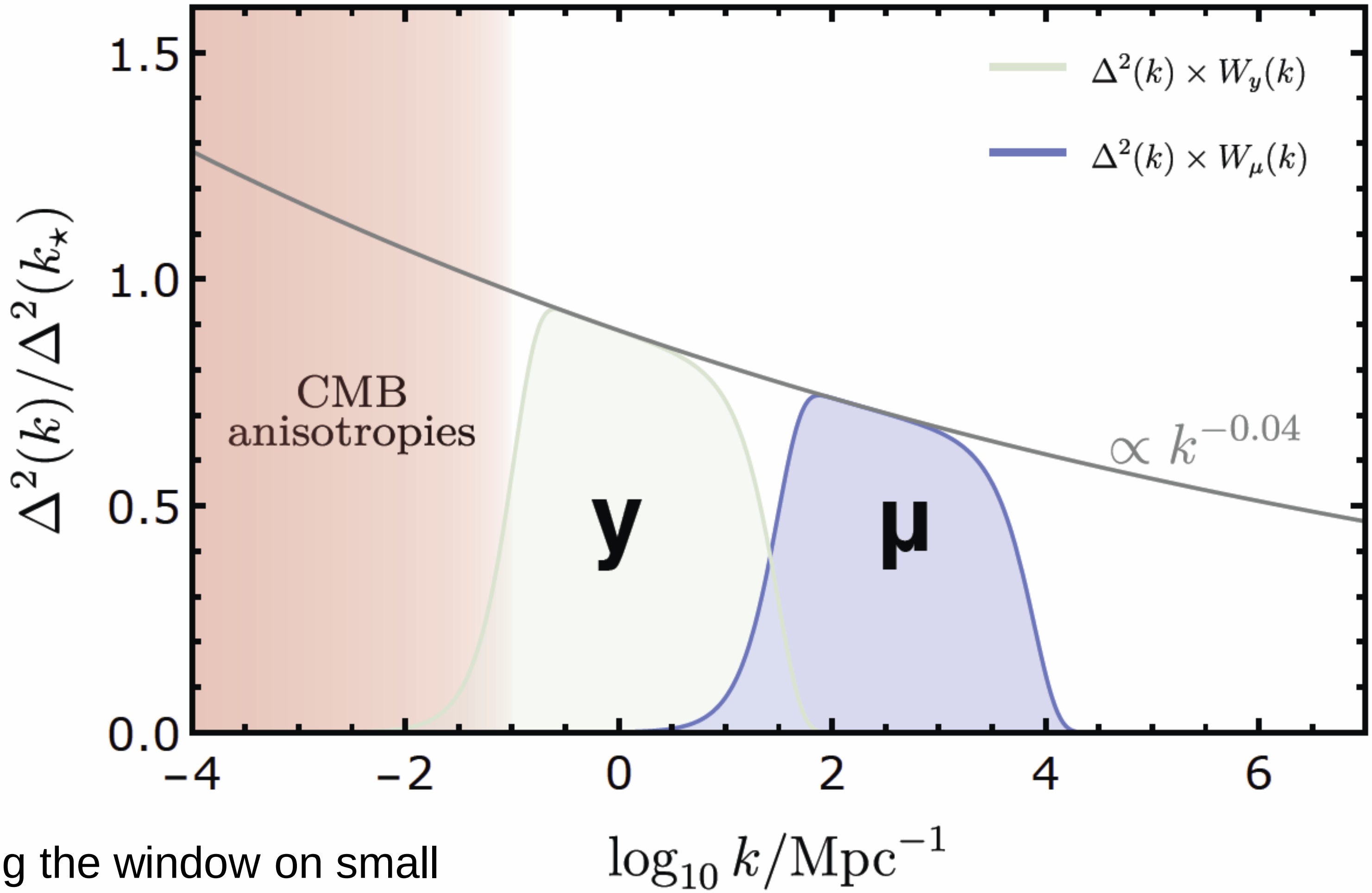
Correlation matrix =

	T_0	Y_{ff}	μ_0	y
T_0	1.00	0.01	0.06	0.09
Y_{ff}	0.01	1.00	−0.27	−0.18
μ_0	0.06	−0.27	1.00	0.82
y	0.09	−0.18	0.82	1.00

Average CMB spectral distortions



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

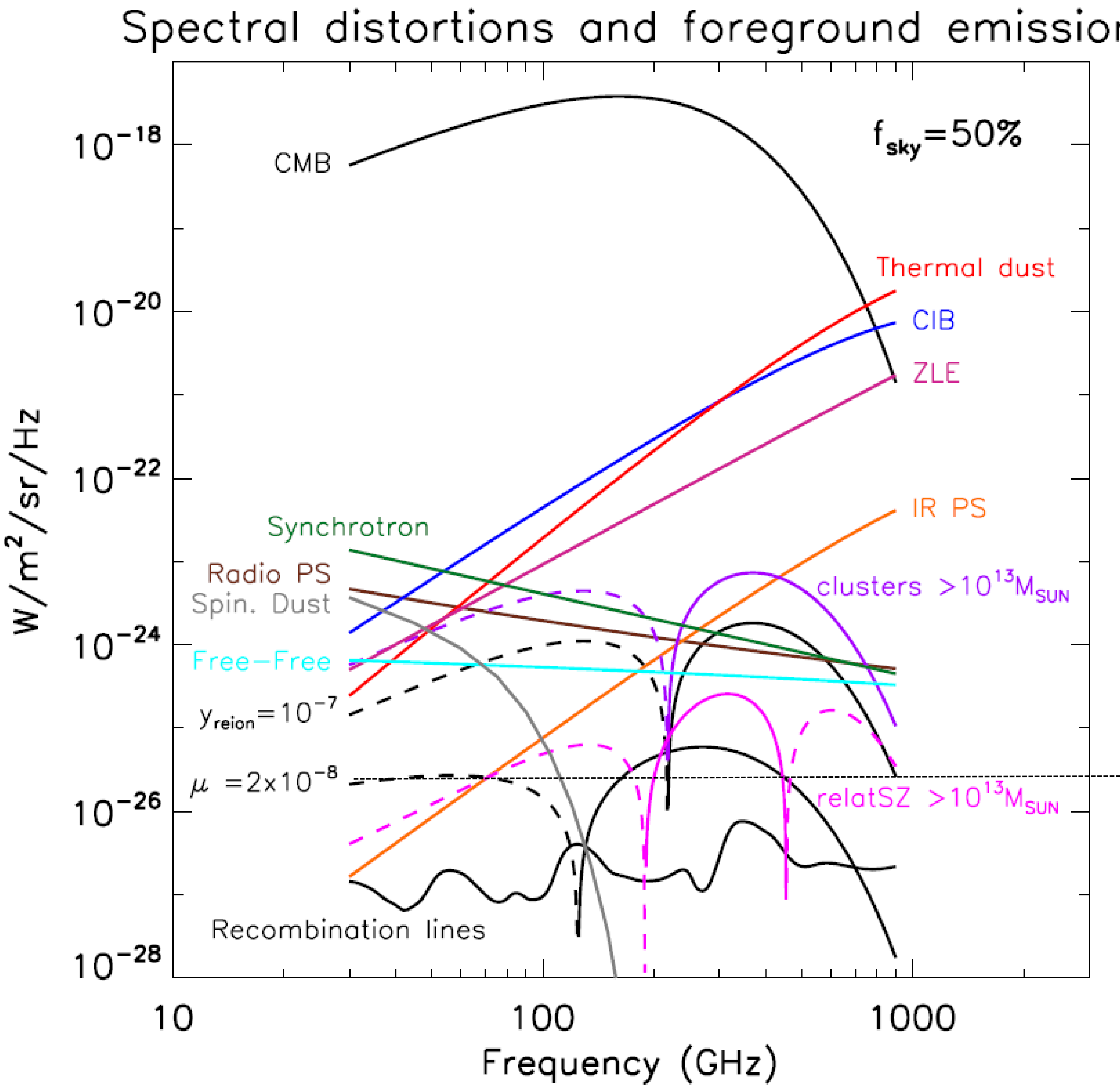
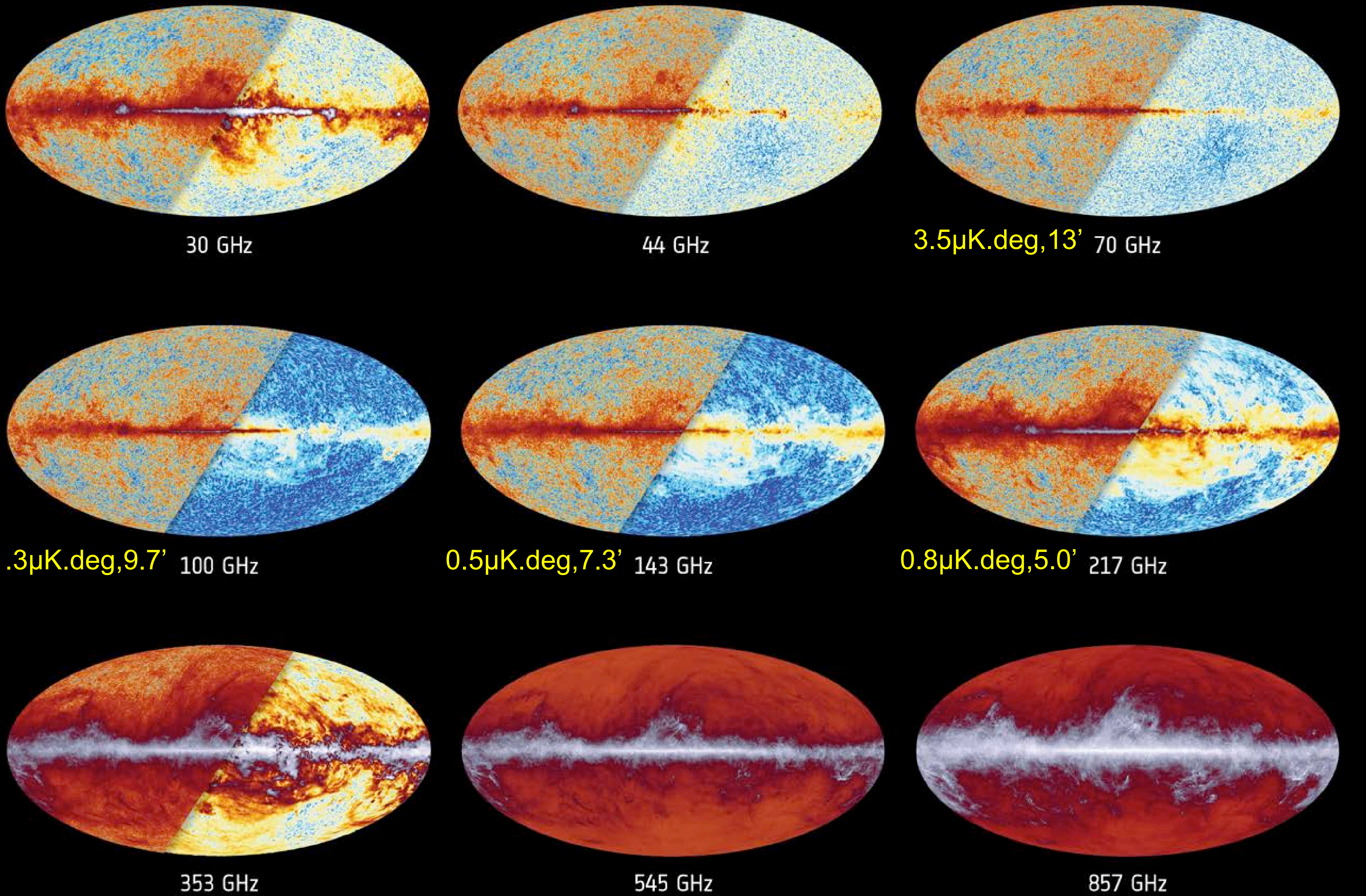
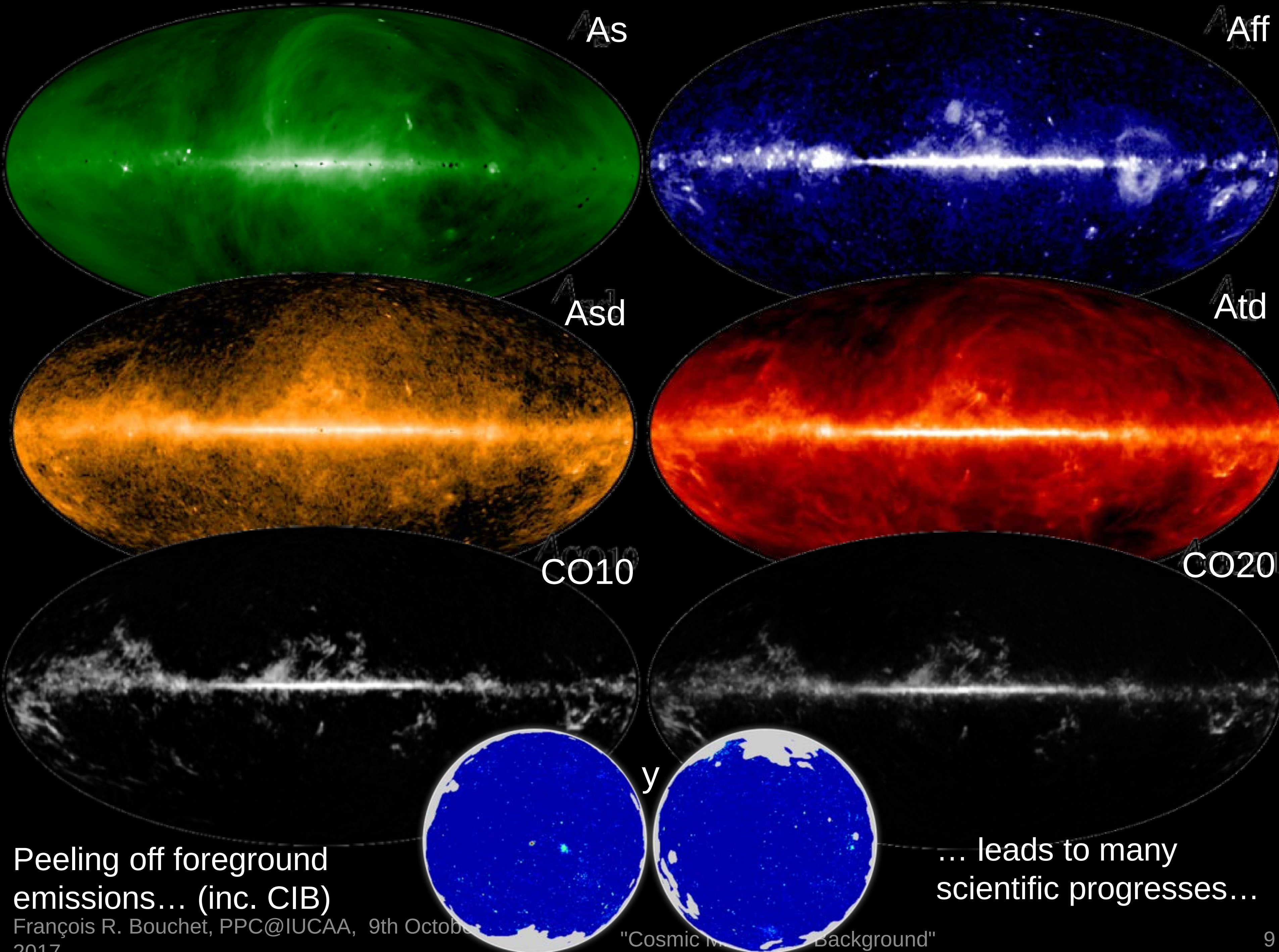


Fig. Delabrouille

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

Planck 2015 maps (←pla.esac.esa.int)



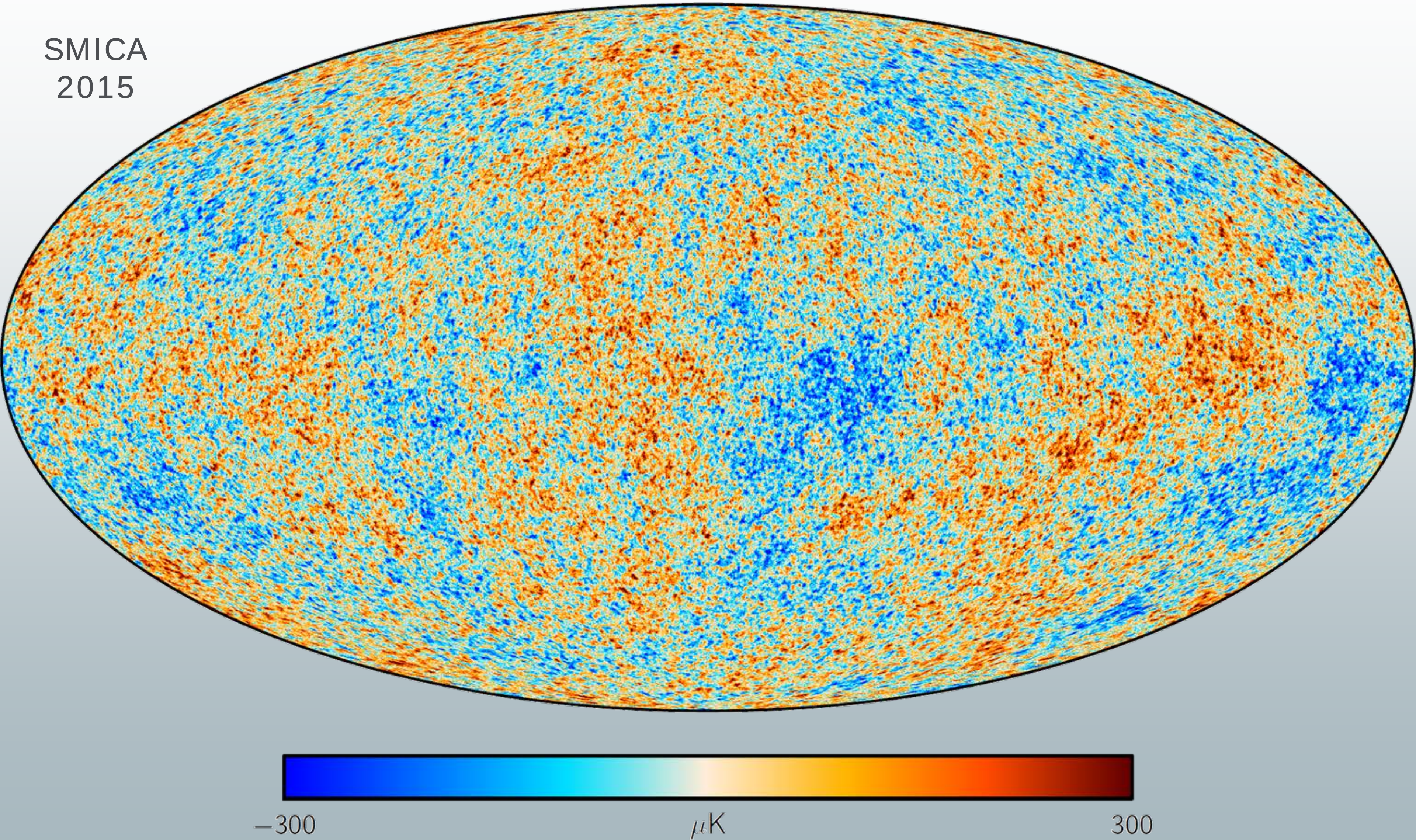


Peeling off foreground emissions… (inc. CIB)

… leads to many scientific progresses…

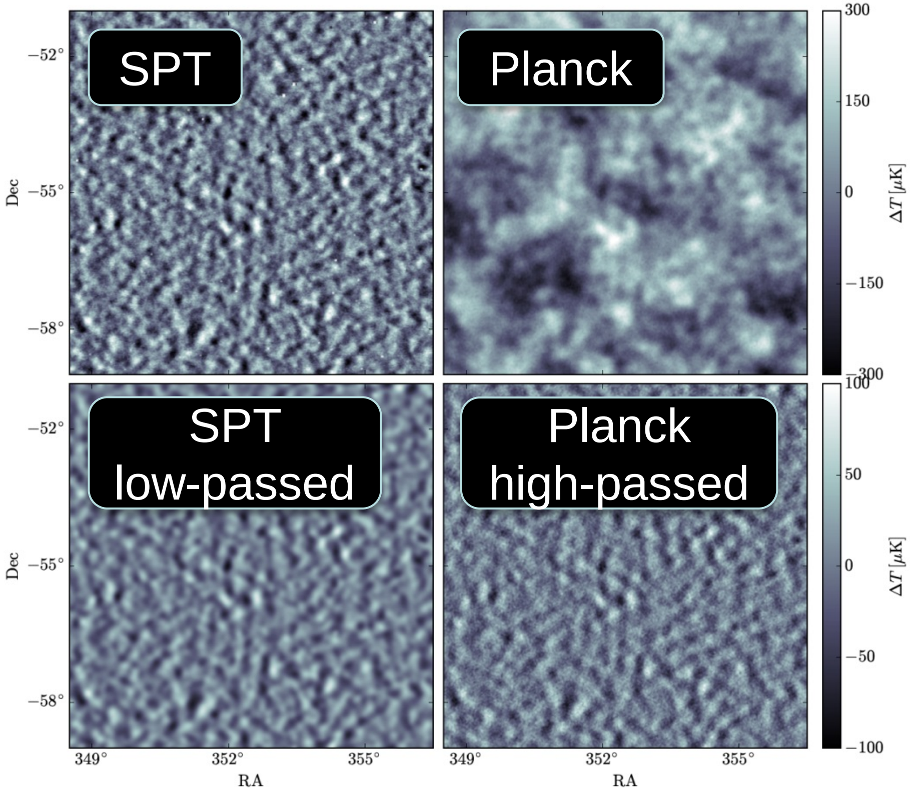
Planck 2015 T anisotropies map

SMICA
2015

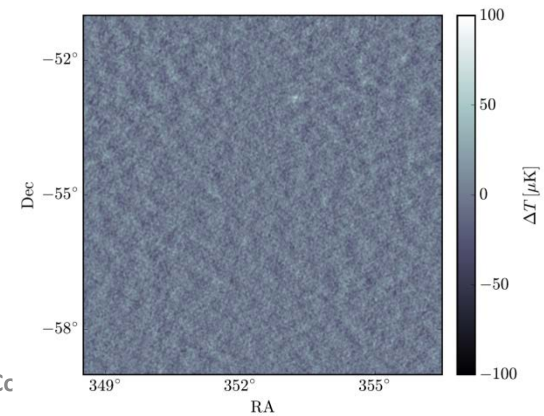


SPT@150GHz vs planck@143GHz

Hou+ arXiv:1704.00884v1



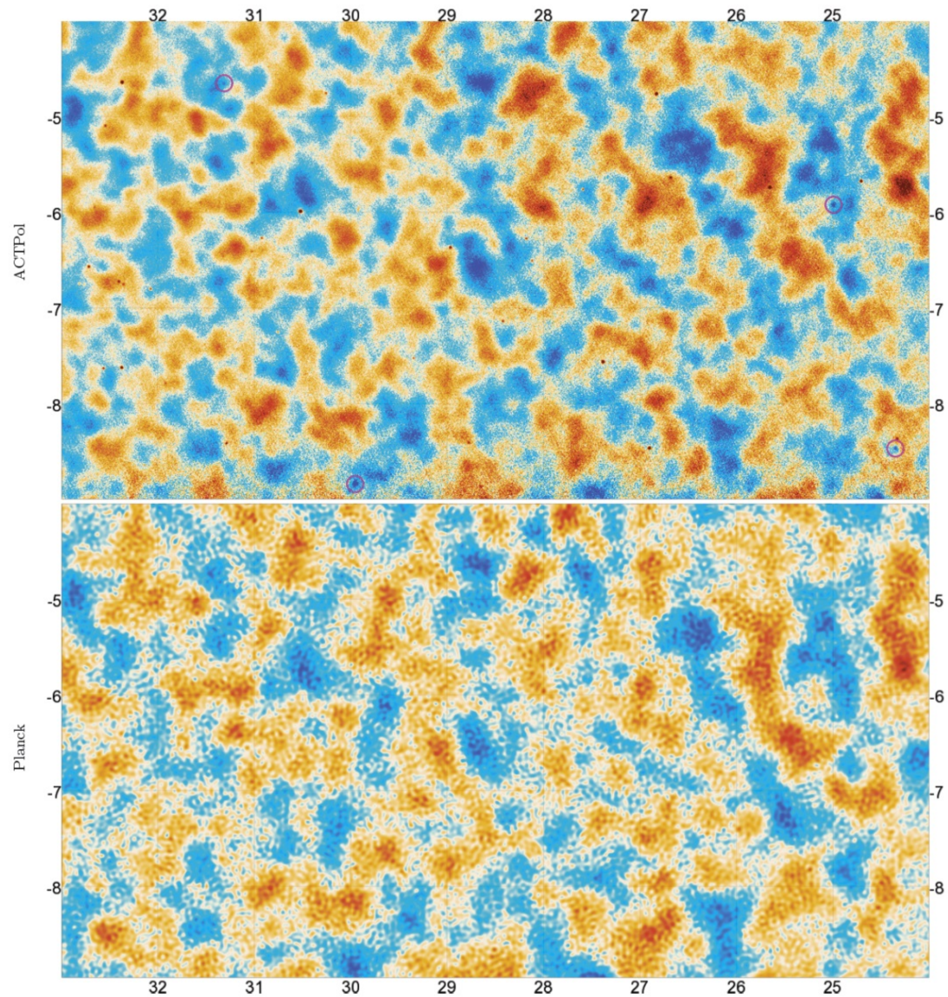
Little residual in SPT-low minus Planck-high, but a variable source



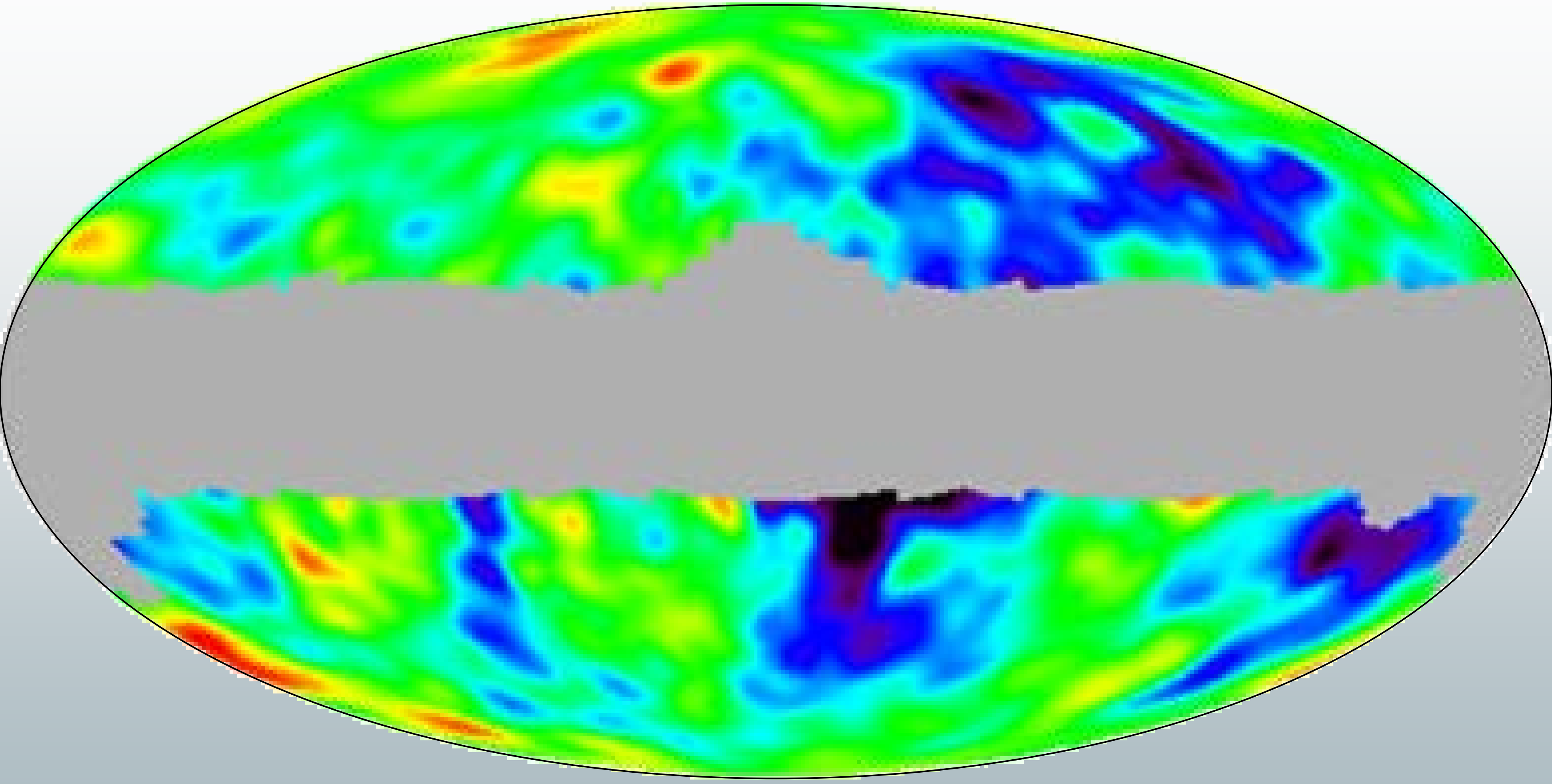
"Cc

ACT@150GHz vs planck@143GHz

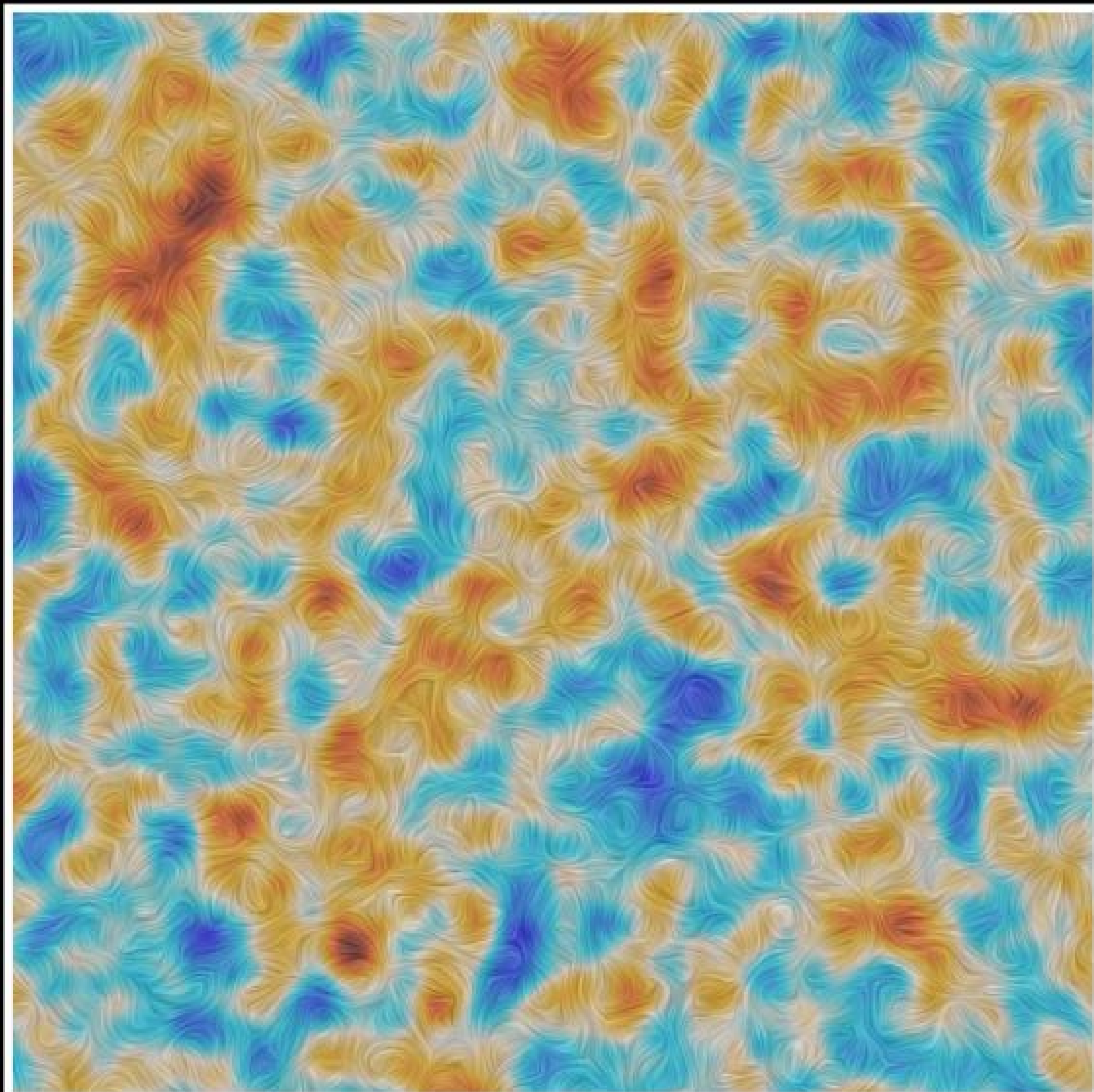
Louis+ arXiv:1610.02360v1

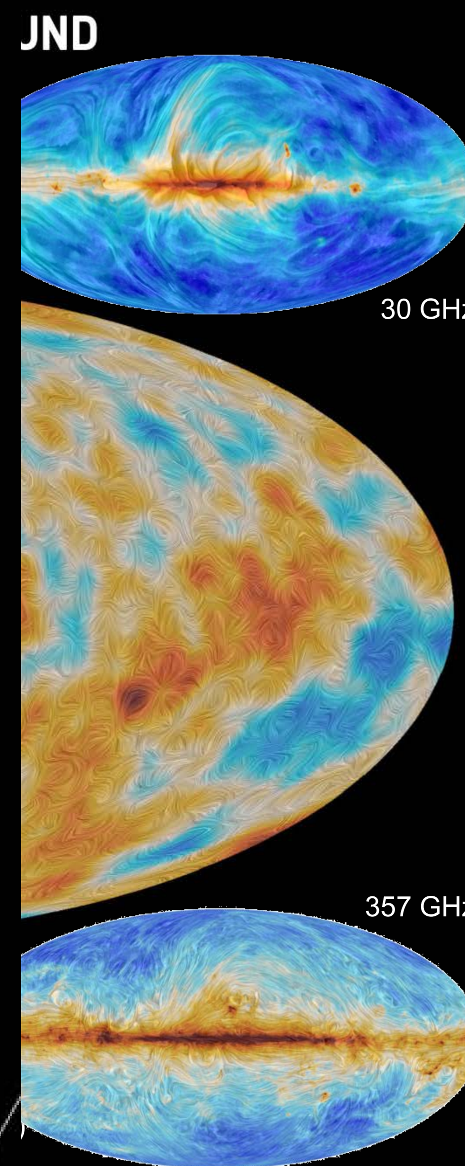


COBE/DMR T anisotropies map



We have essentially finished mining the cosmological Temperature anisotropies revealed by DMR

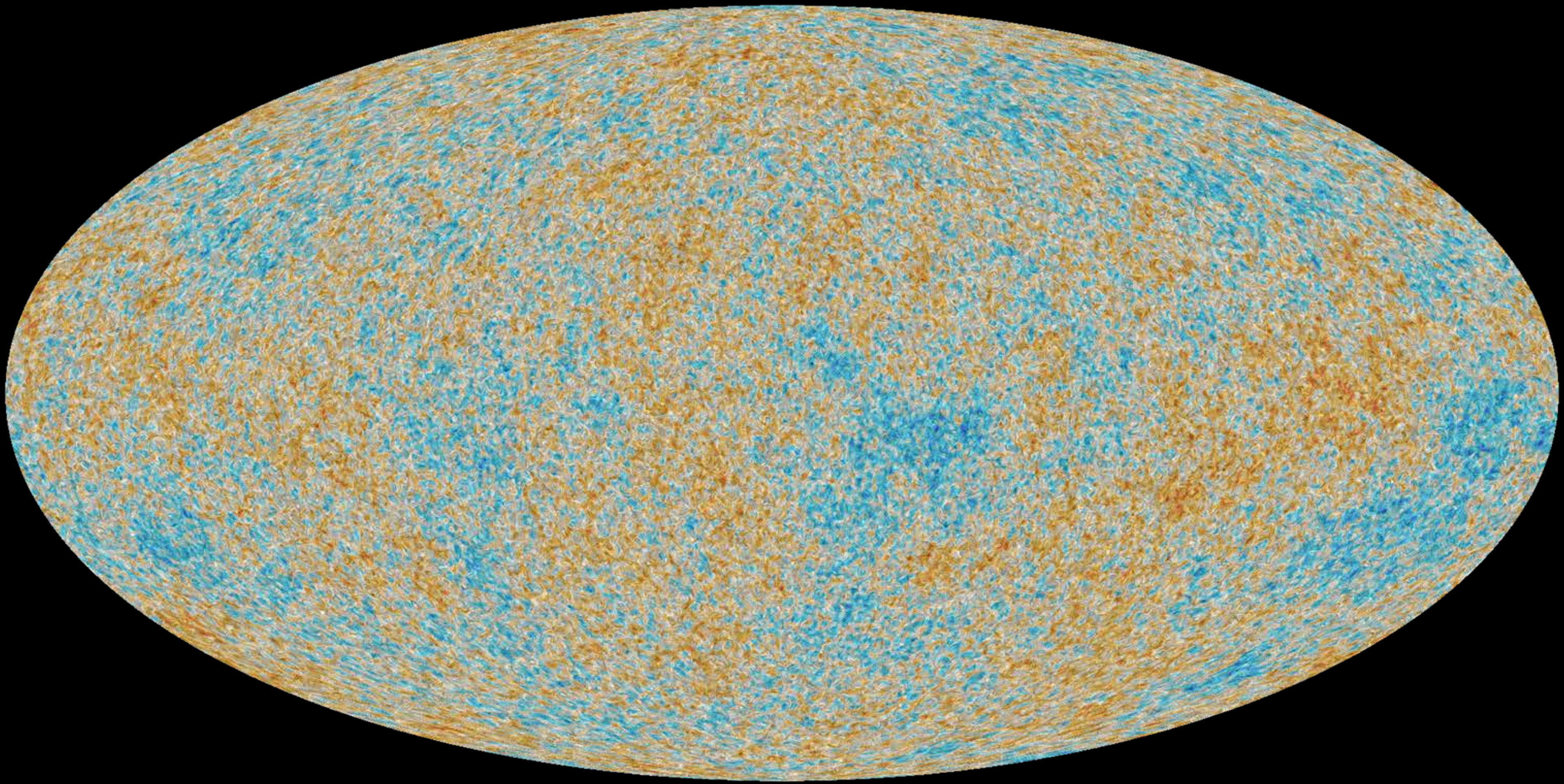




Filtered at 20 arcminutes

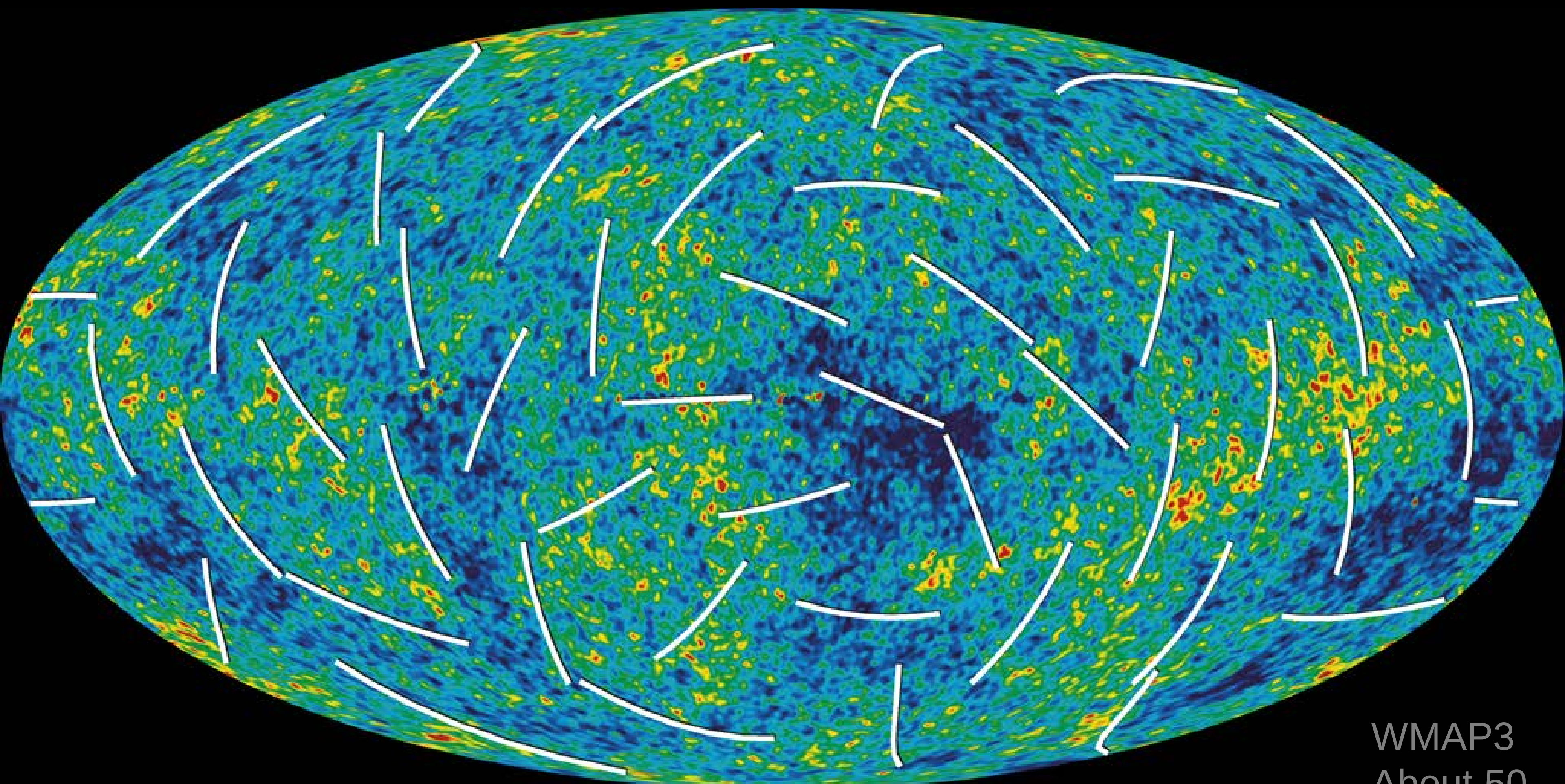
The Planck 2015 CMB polarisation sky

at 5 arc minute resolution



(largest scales have been filtered out)

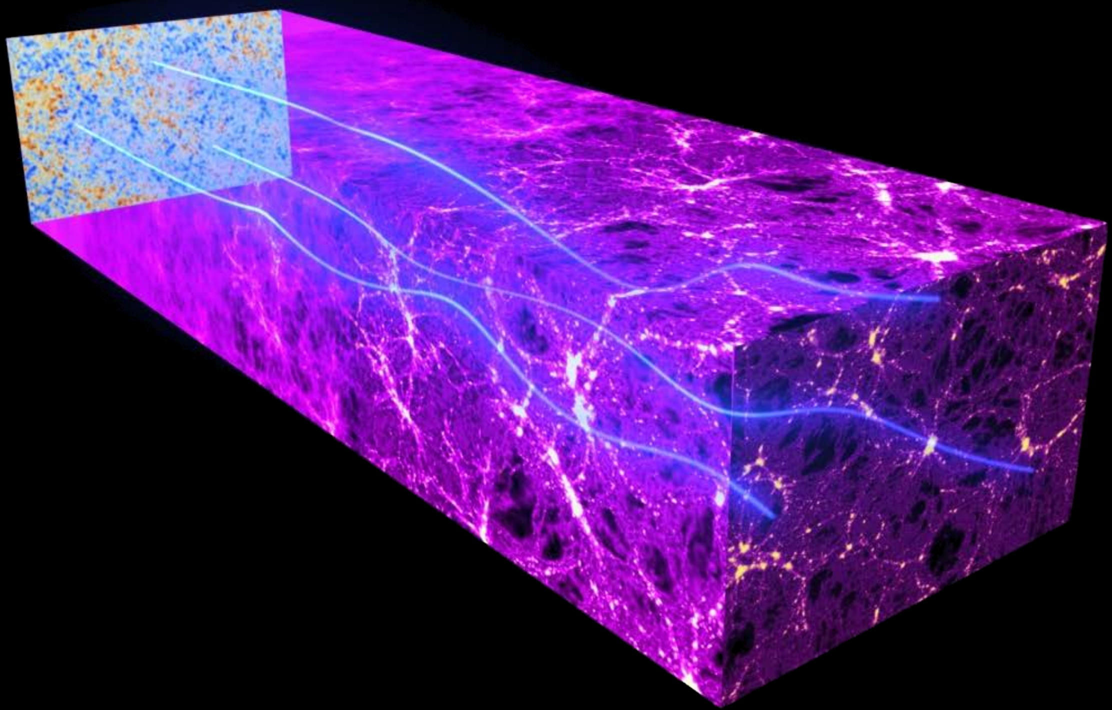
What we already knew



WMAP3
About 50
locations?

GRAVITATIONAL LENSING DISTORTS IMAGES

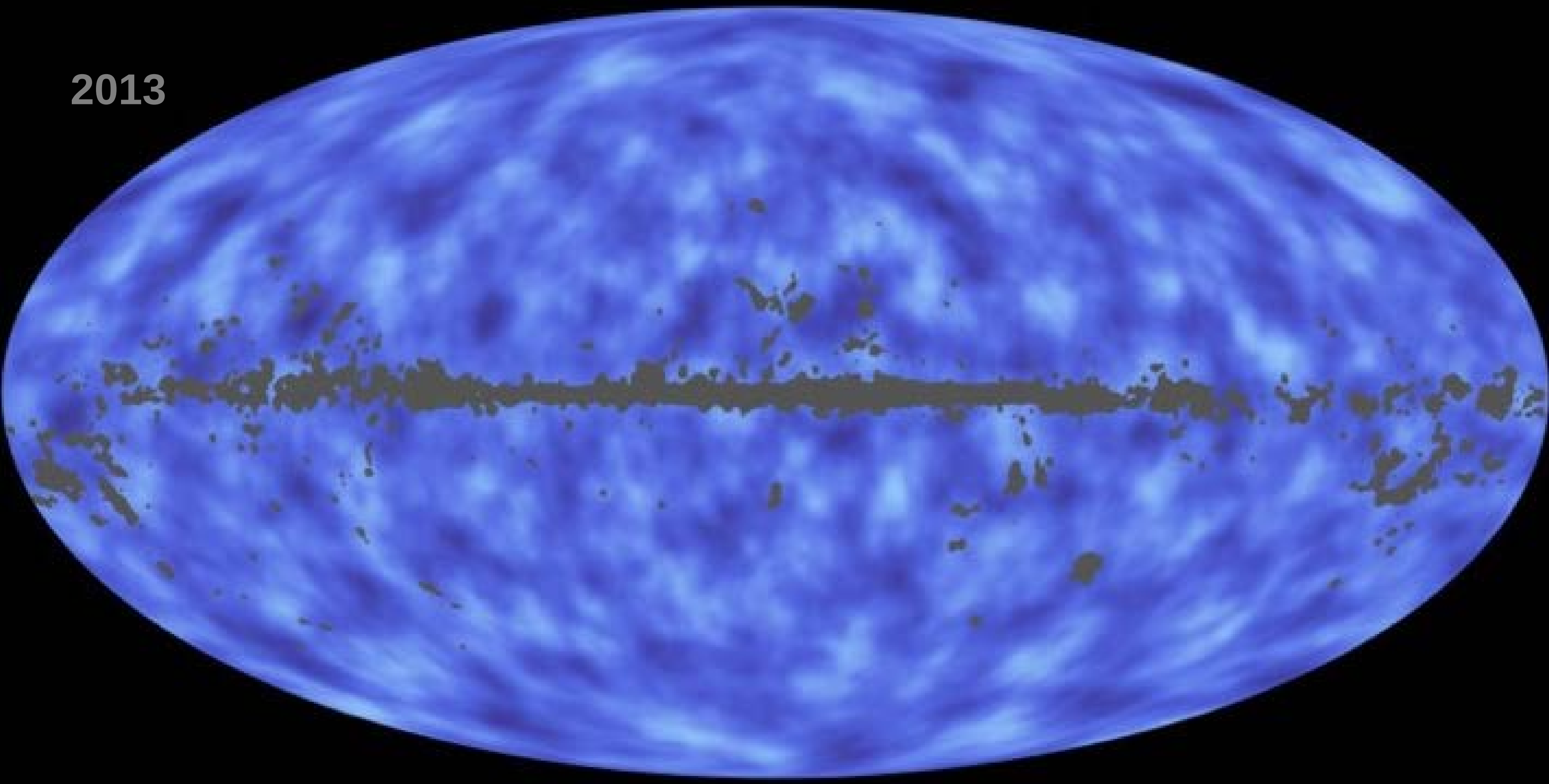
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This "gravitational lensing" distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



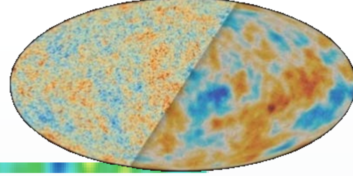
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \ldots$$

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

Projected mass map



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

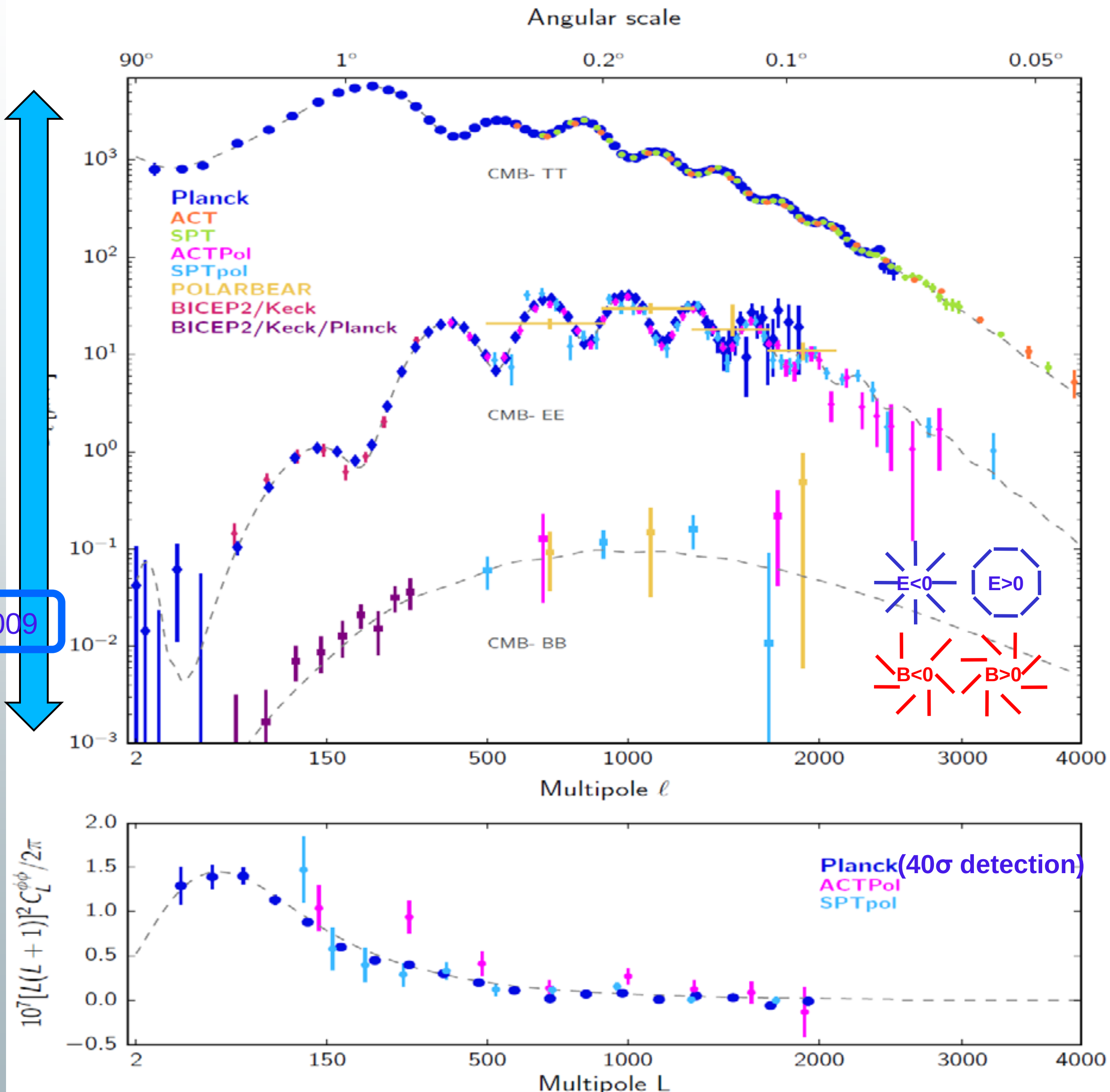


TT, EE, BB, ΦΦ – early 2017 status

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

10^7

τ = 0.055±0.009



And statistically isotropic…

1 114 000 Modes measured with TT,

60 000 with TE (not shown)

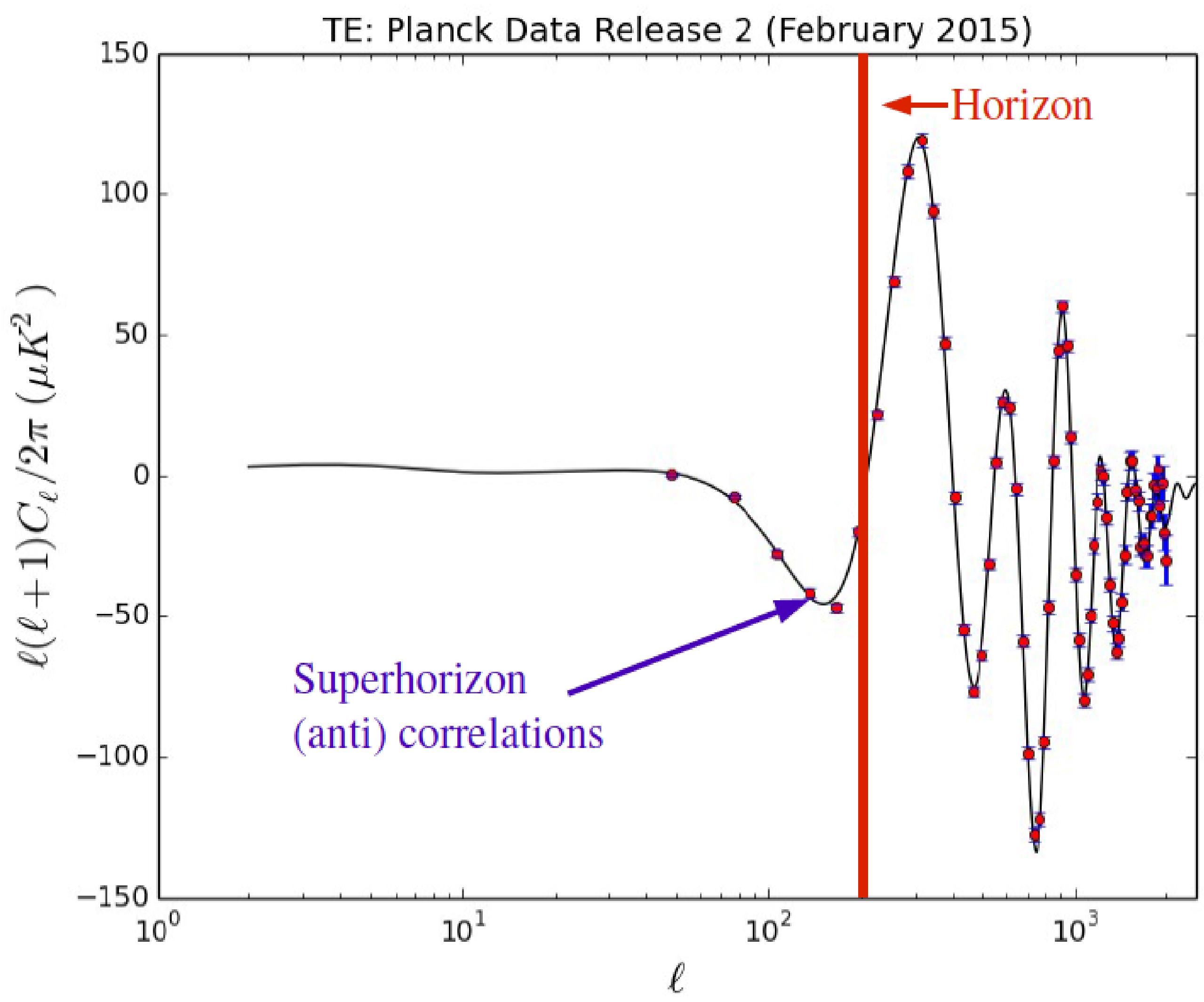
96 000 with EE

… and 10's in BB and φφ

+ weak constraints with TB and EB

WHAT HAVE WE LEARNT SO FAR?

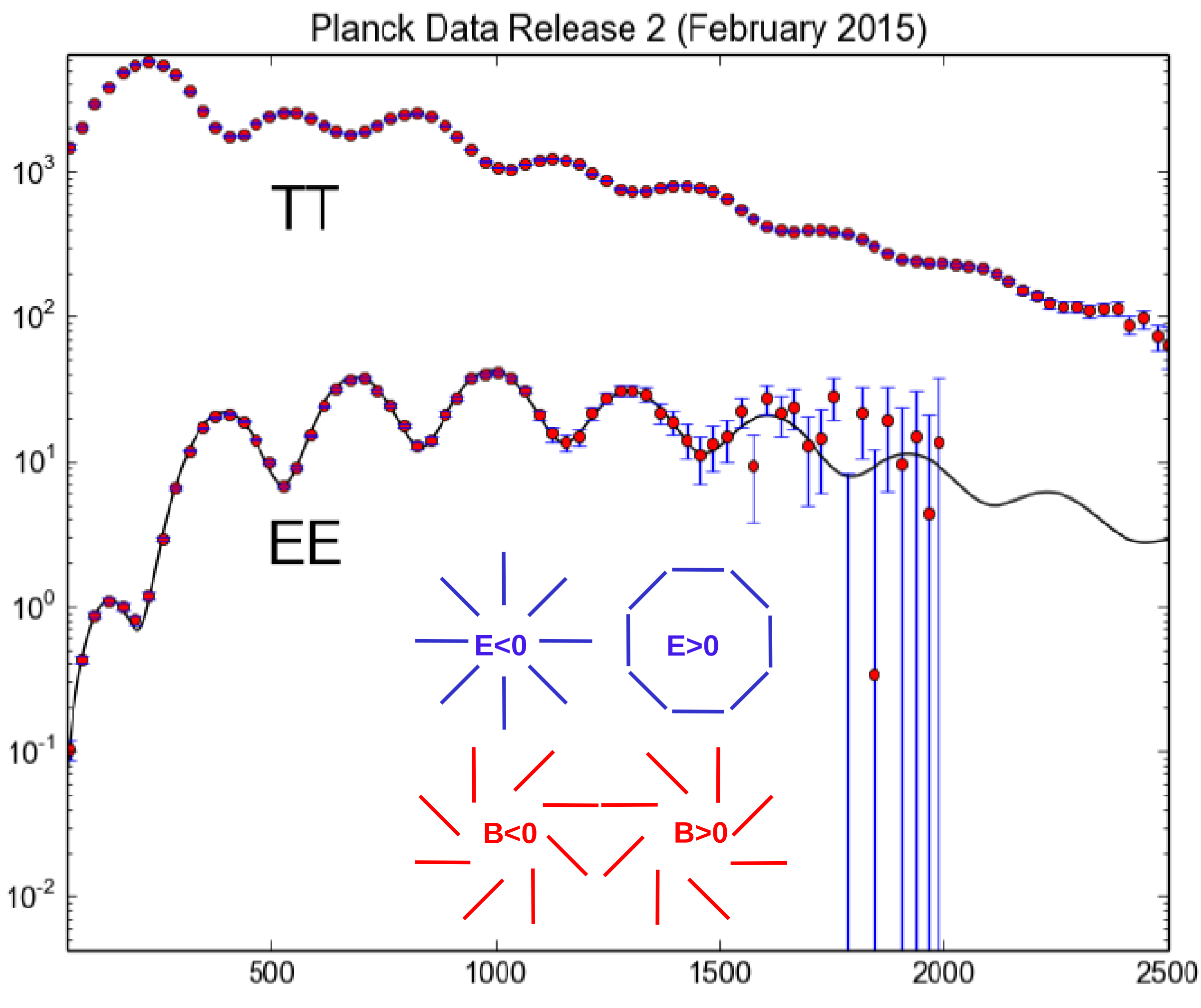
TE large scale correlation



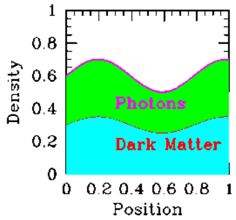
apparently a-causal physics, calling for a period of accelerated expansion (Spergel & Zaldariaga 97)

So the (apparent) horizon is actually only the Hubble length

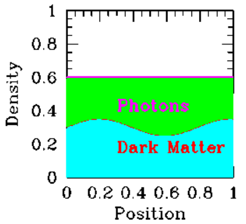
Adiabaticity ?



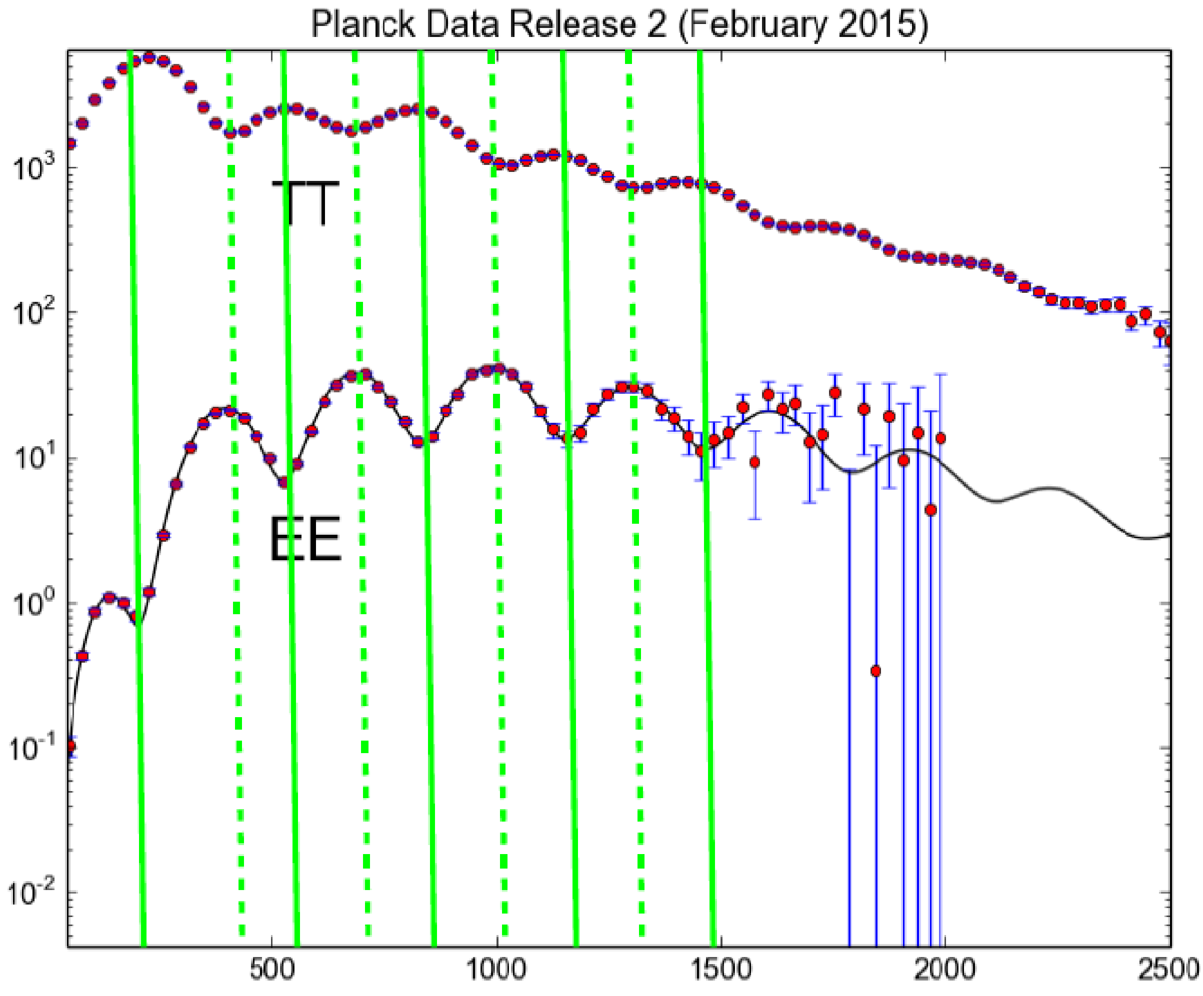
Adiabatic IC



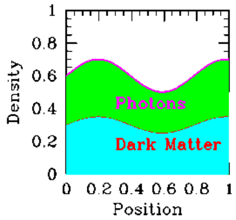
Isocurvature IC



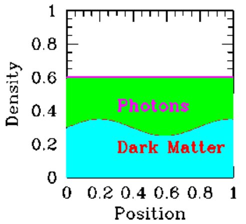
Adiabaticity ✔



Adiabatic IC

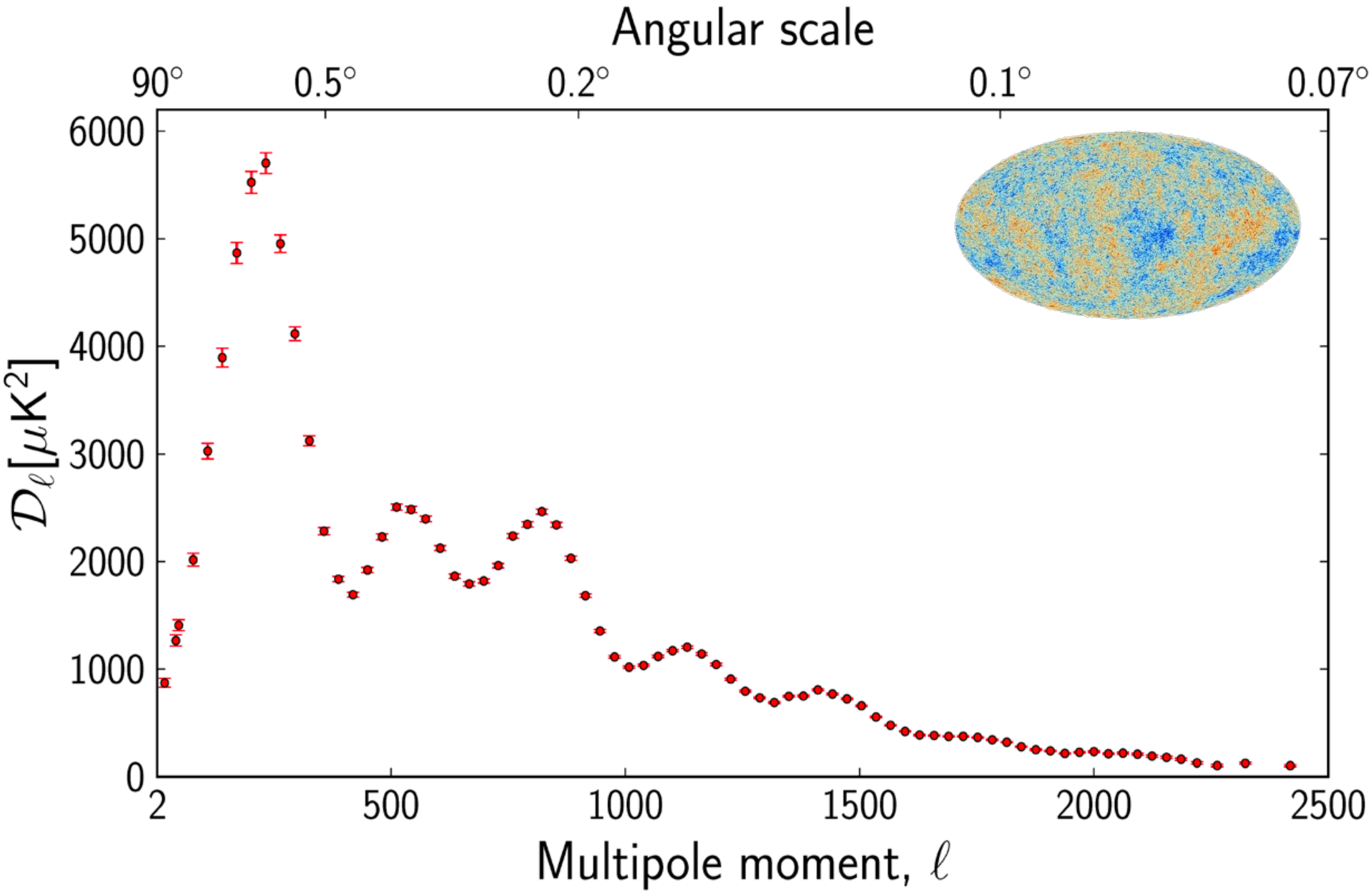


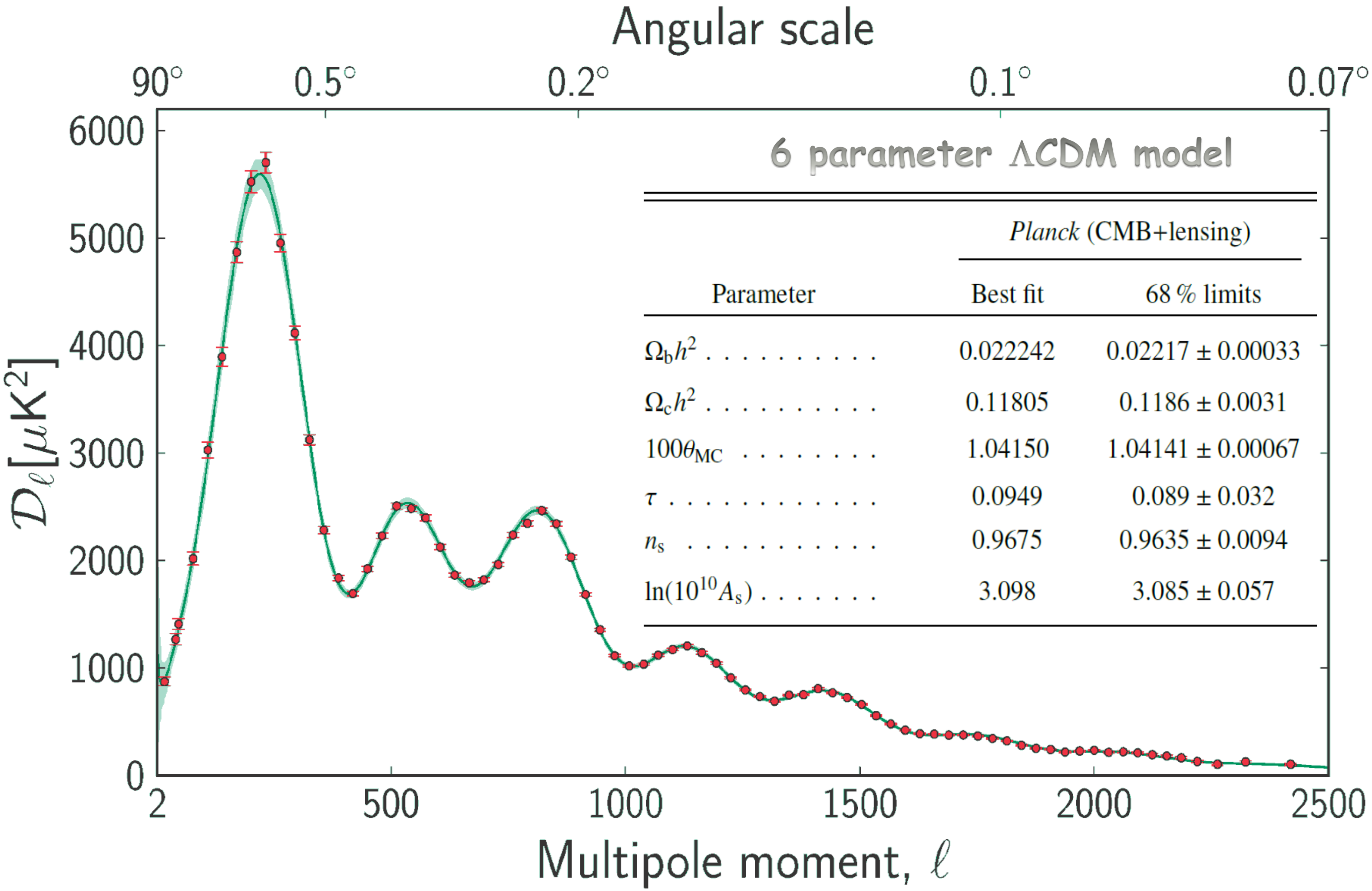
Isocurvature IC



Kinney

The Planck power spectrum of Temperature anisotropies

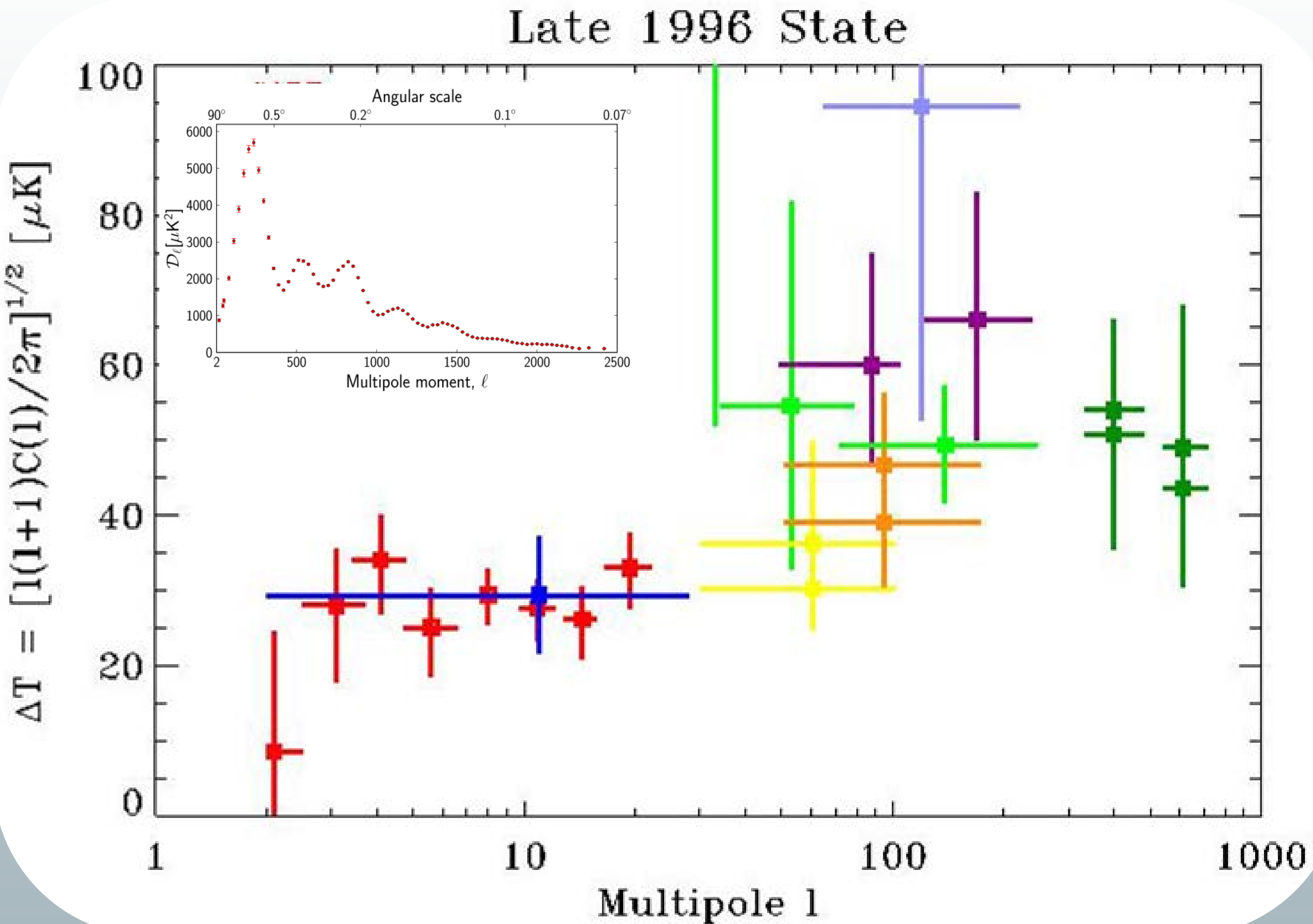




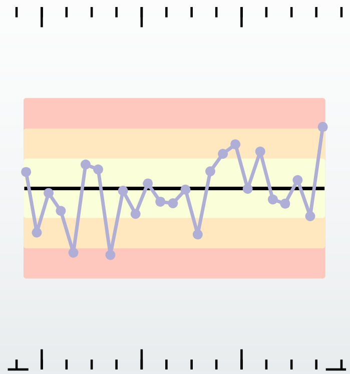
6 parameter ΛCDM model

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

When Planck (& WMAP) were selected



TT Consistency checks (freq, DS..)



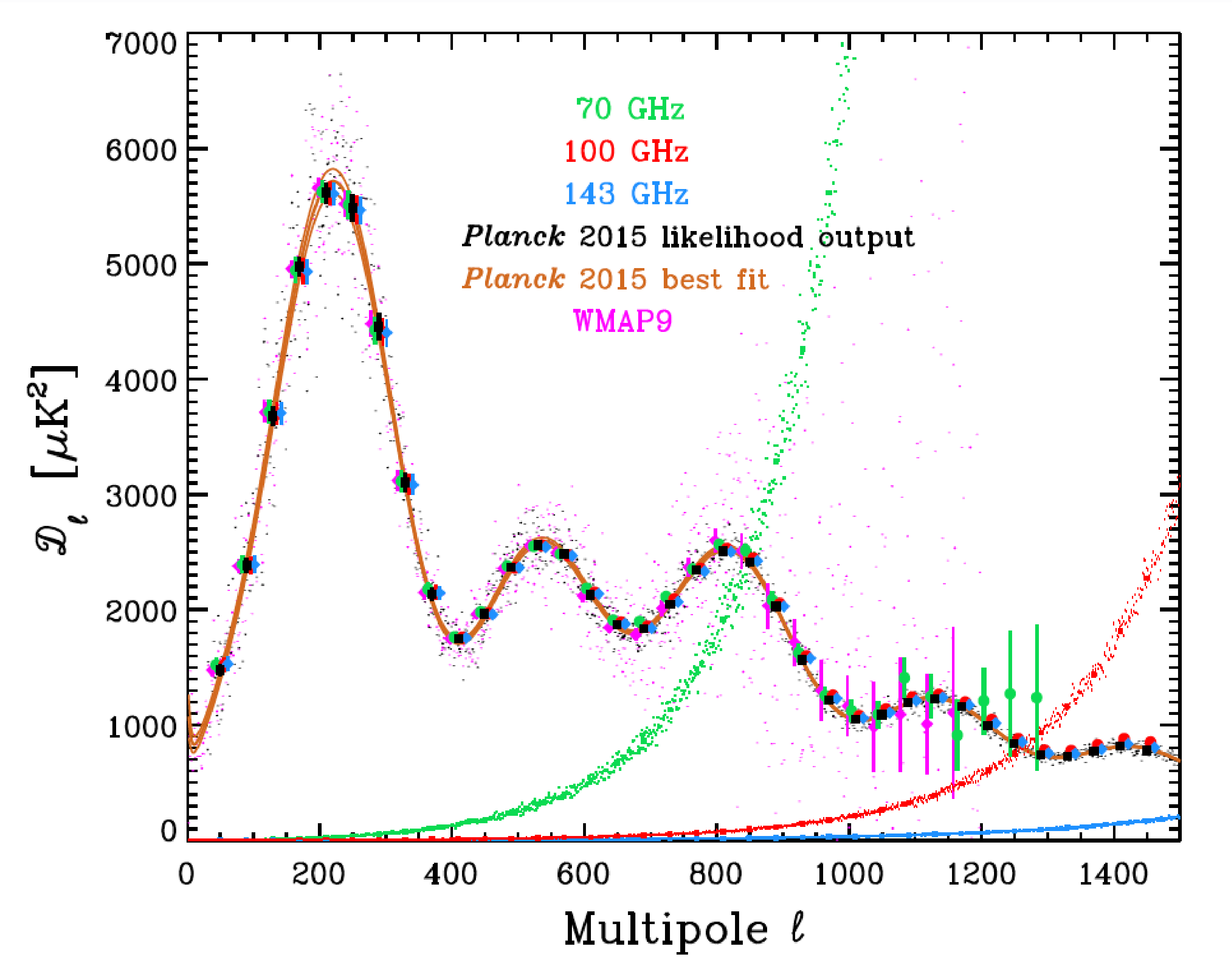
12 different CMB takes are being differenced and expressed in CMB Sigma Units

➔ All null tests OK

(+checks with WMAP, ACT, SPT...)

NB: DS not used but for consistency checks

Planck large scales confirm WMAP

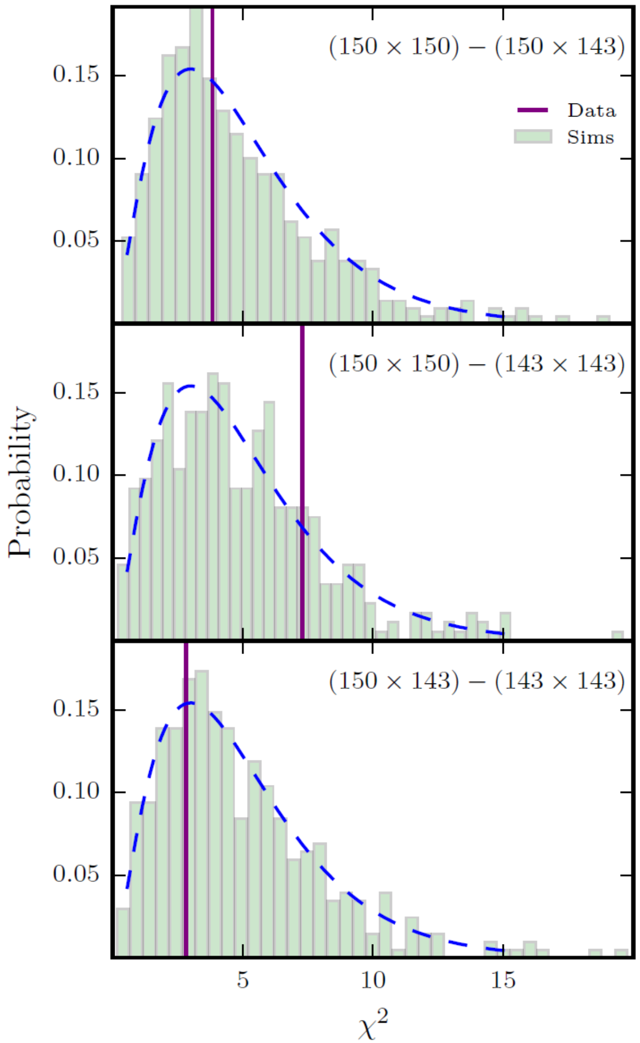


to the extent permitted by the much higher WMAP noise level

P15

Planck/SPT LCDM parameters consistency

(Using 2540 deg2 SPT-SZ, Aylor+ arXiv:1706.10286v1



PTEs Between Parameters in SPT Sky Patch.

	$\ell_{\max}$		
	2000	2500	3000
$150 \times 150 - 150 \times 143$	0.74	0.66	0.57
$150 \times 150 - 143 \times 143$	0.32	0.38	0.20
$150 \times 143 - 143 \times 143$	0.62	0.73	

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

PTEs Between PlanckFS and In-patch Parameters.

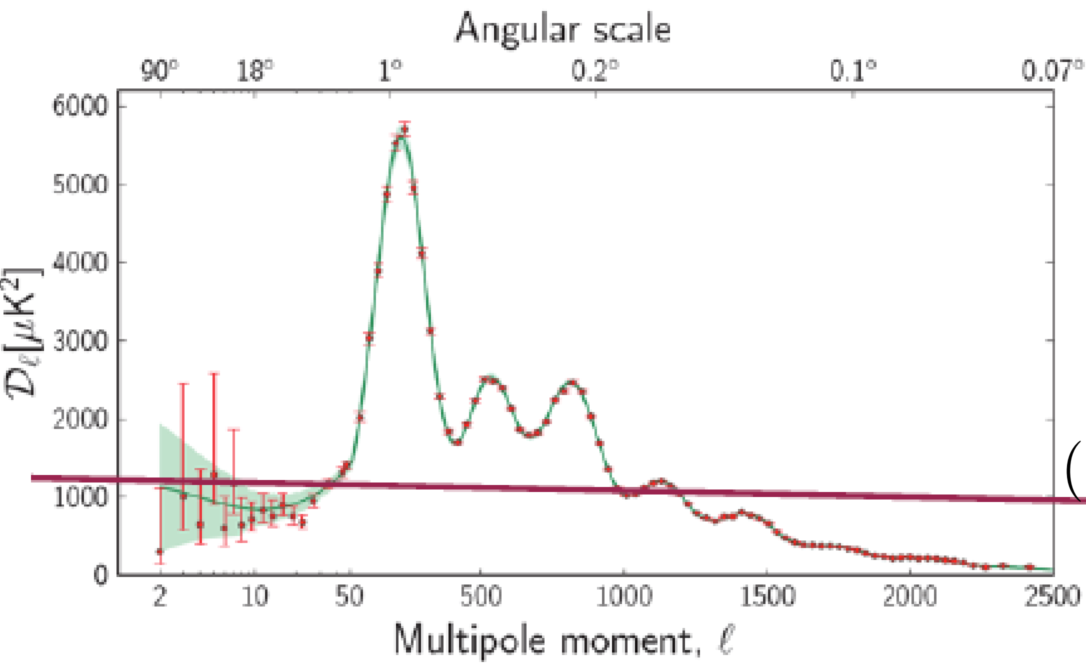
	$\ell_{\max}$		
	2000	2500	3000
150×150	0.24	0.094	0.032
150×143	0.19	0.18	
143×143	0.29	0.31	

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

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)

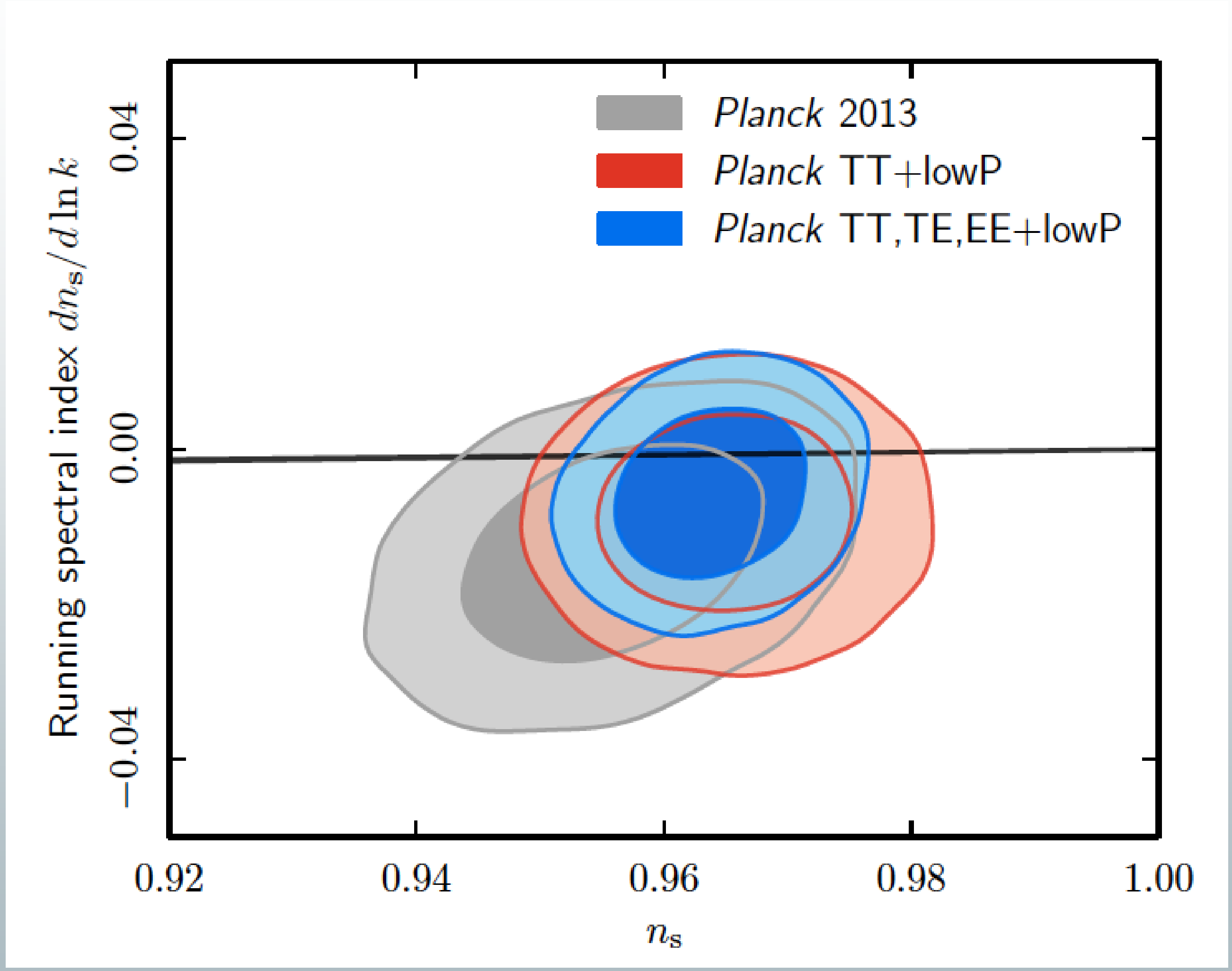
$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)

$(n_s = 0.965 \pm 0.006$ 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.

Planck 2015 on running

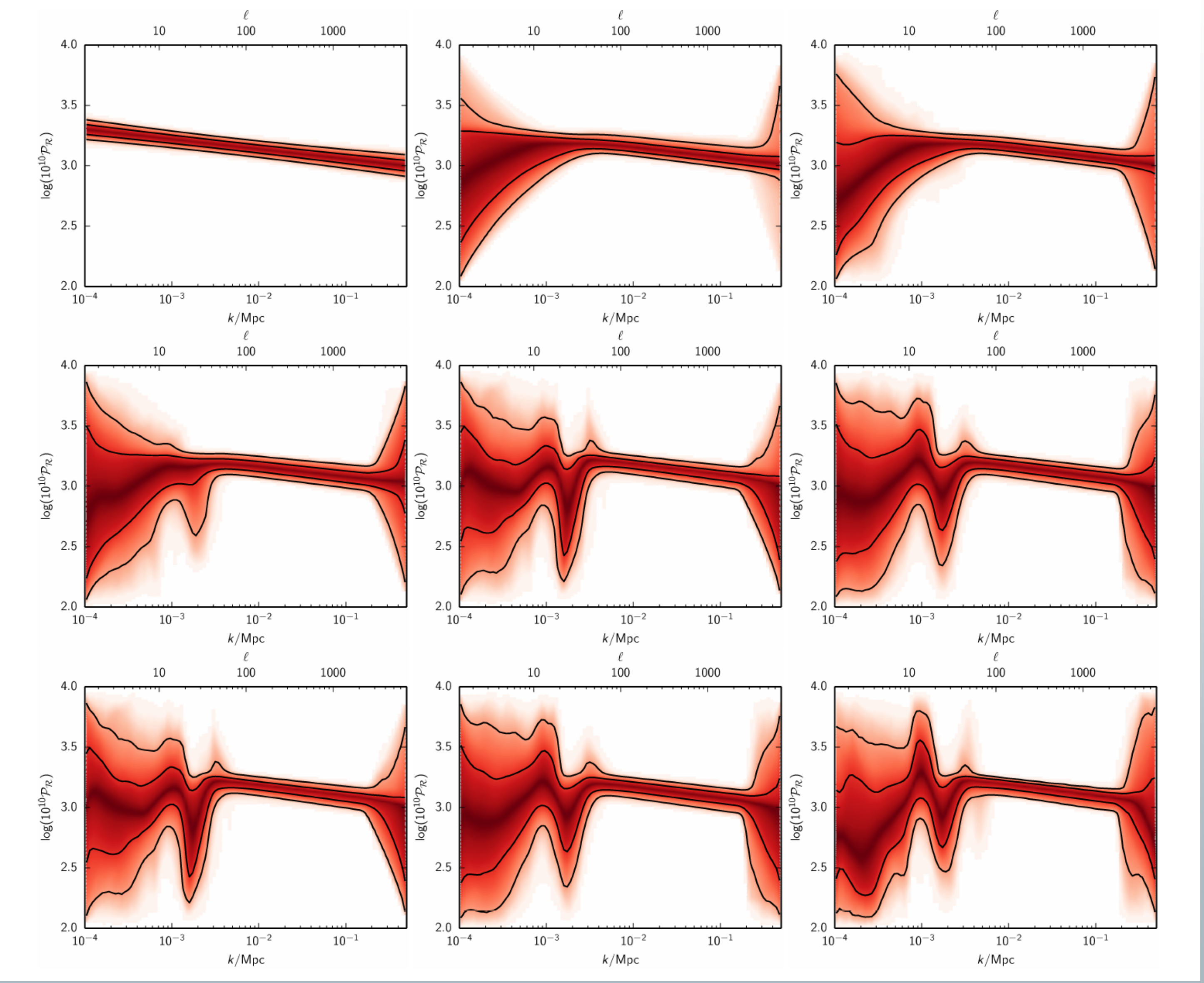


The thin black stripe shows the prediction for single-field monomial chaotic inflationary models with 50 < N < 60.

Bayesian moveable knot PS reconstruction

Adding
0 to 8
knots

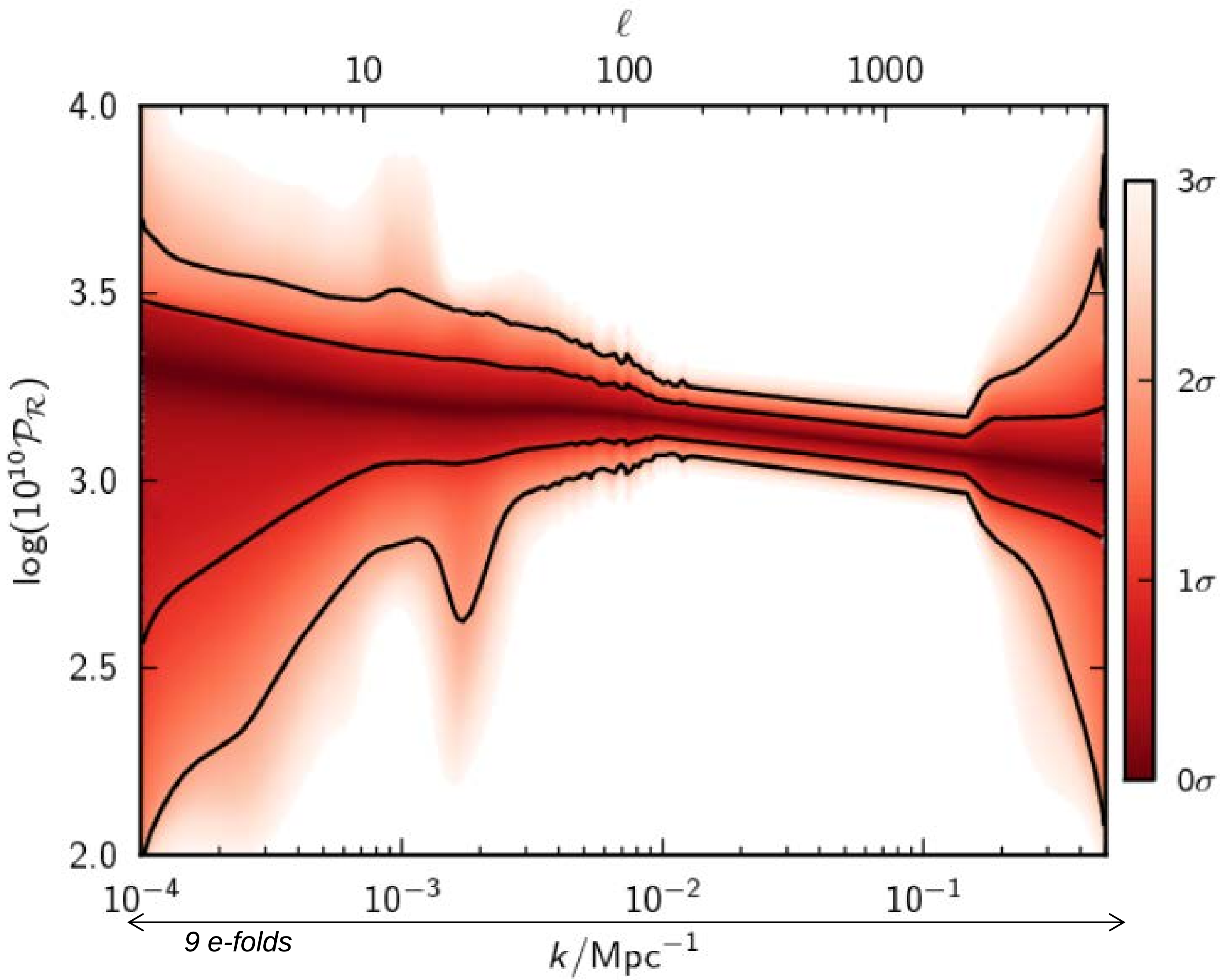
(in addition to
minimum 2)



No truly significant deviation found

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

Power spectrum reconstruction

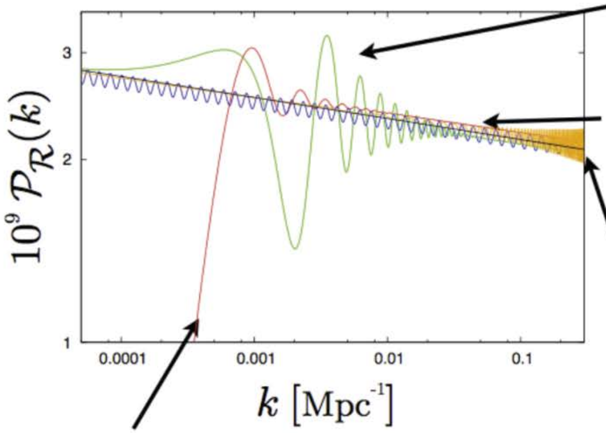


Bayesian reconstruction with varying number of nodes (<9) reconstructions weighted by their respective evidence.

No strong evidence for feature or anomaly.

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

(Unsuccessful) Search for features



Feature in the potential:

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Non vacuum initial conditions/instanton effects in axion monodromy

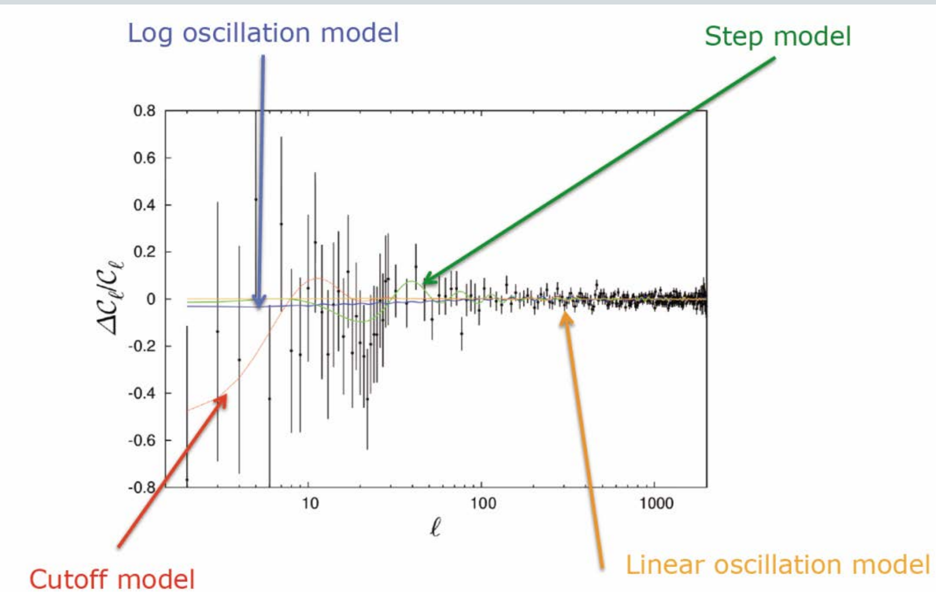
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

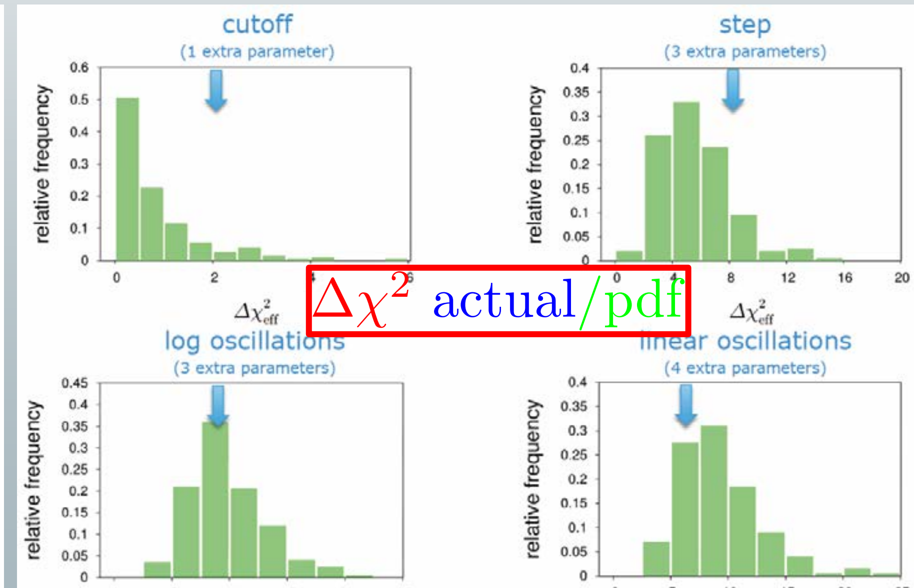
$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^{0}(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

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

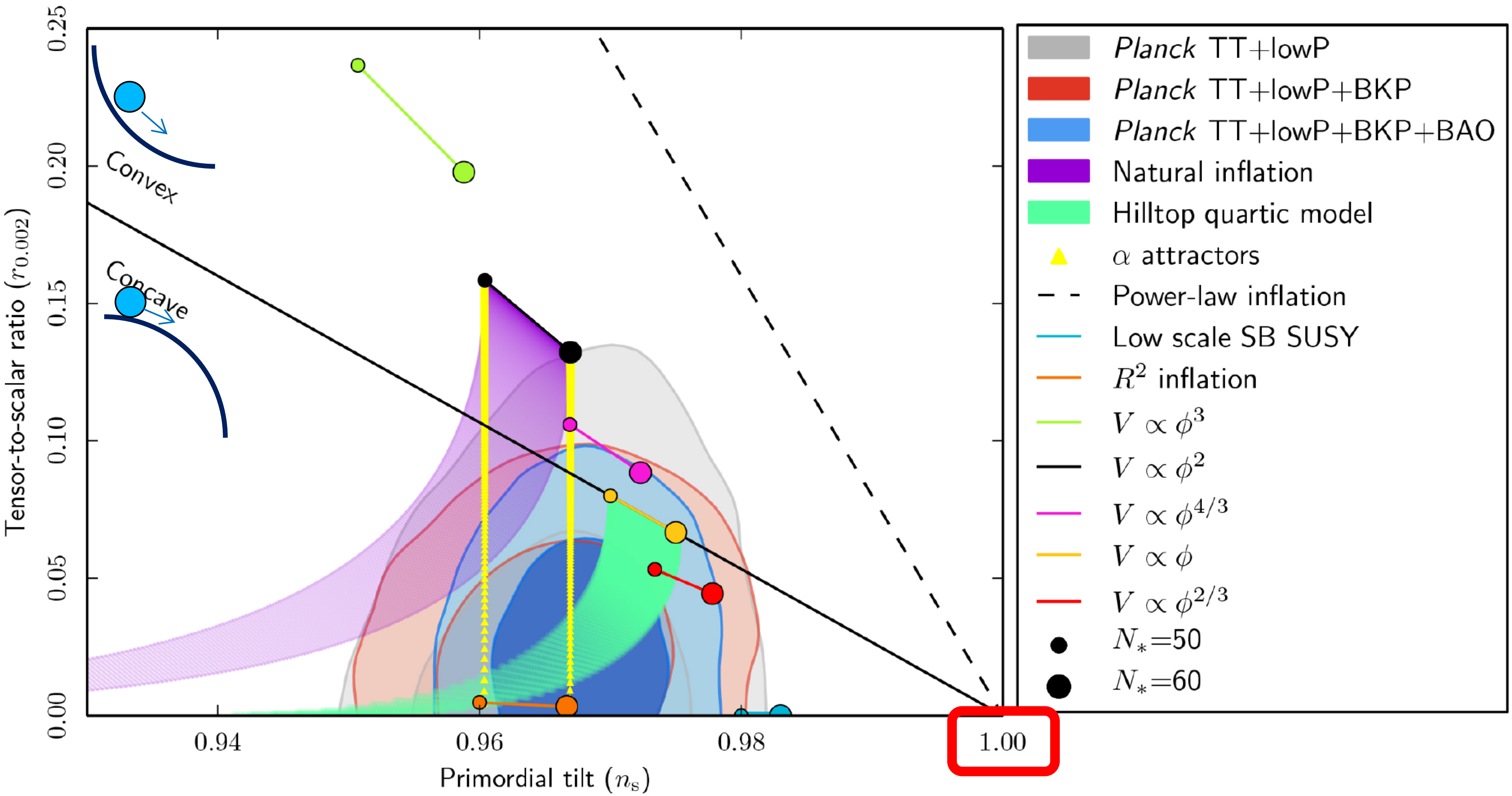
Just enough e-folds, i.e. inflation preceded by a kinetic stage





Planck 2015: n_s vs r

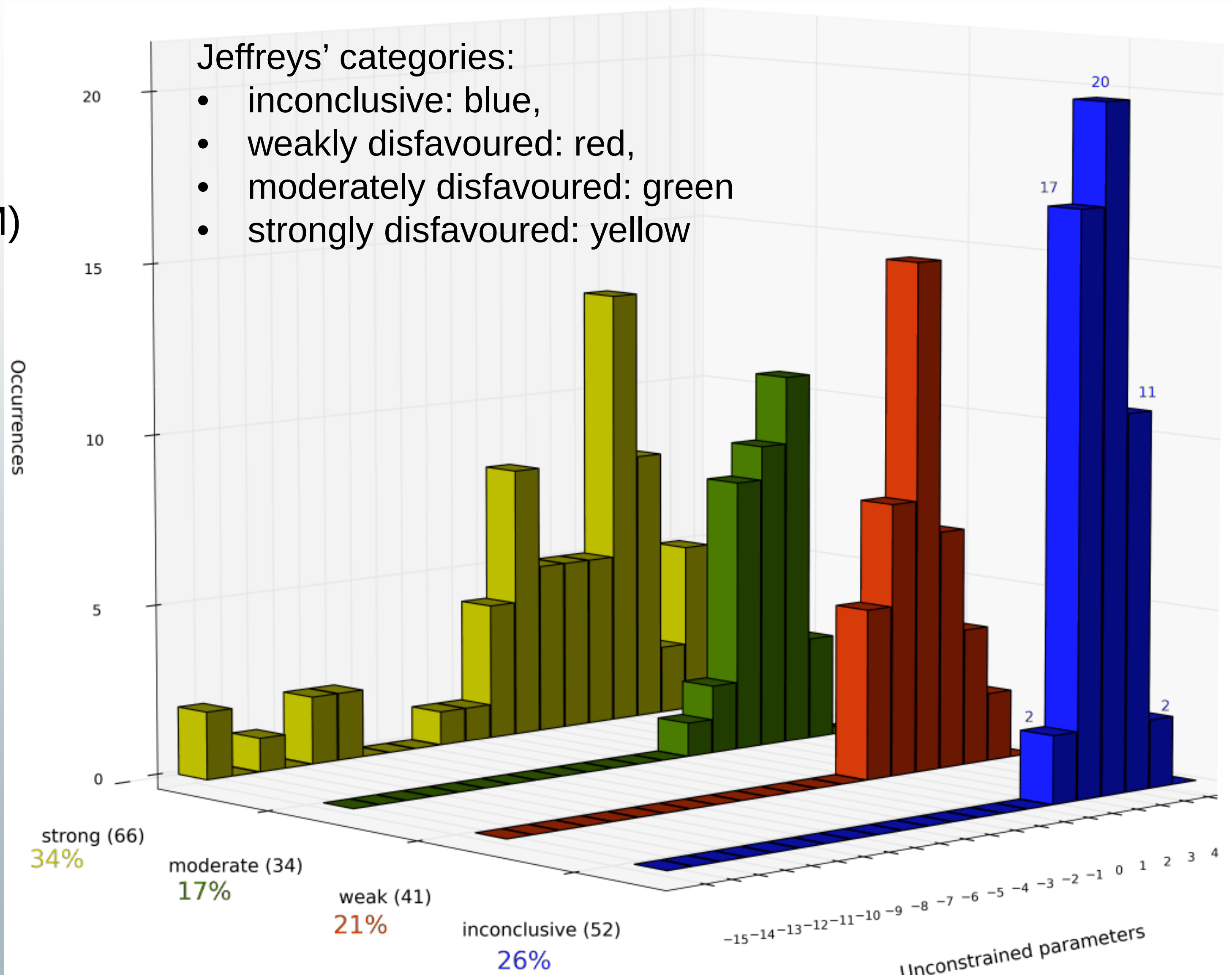
$V_* = (1.9 \times 10^{16}\ \mathrm{GeV})^4\ (r/0.12)$



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

Sorting Single field slow-roll models…

(ranking vs LCDM)

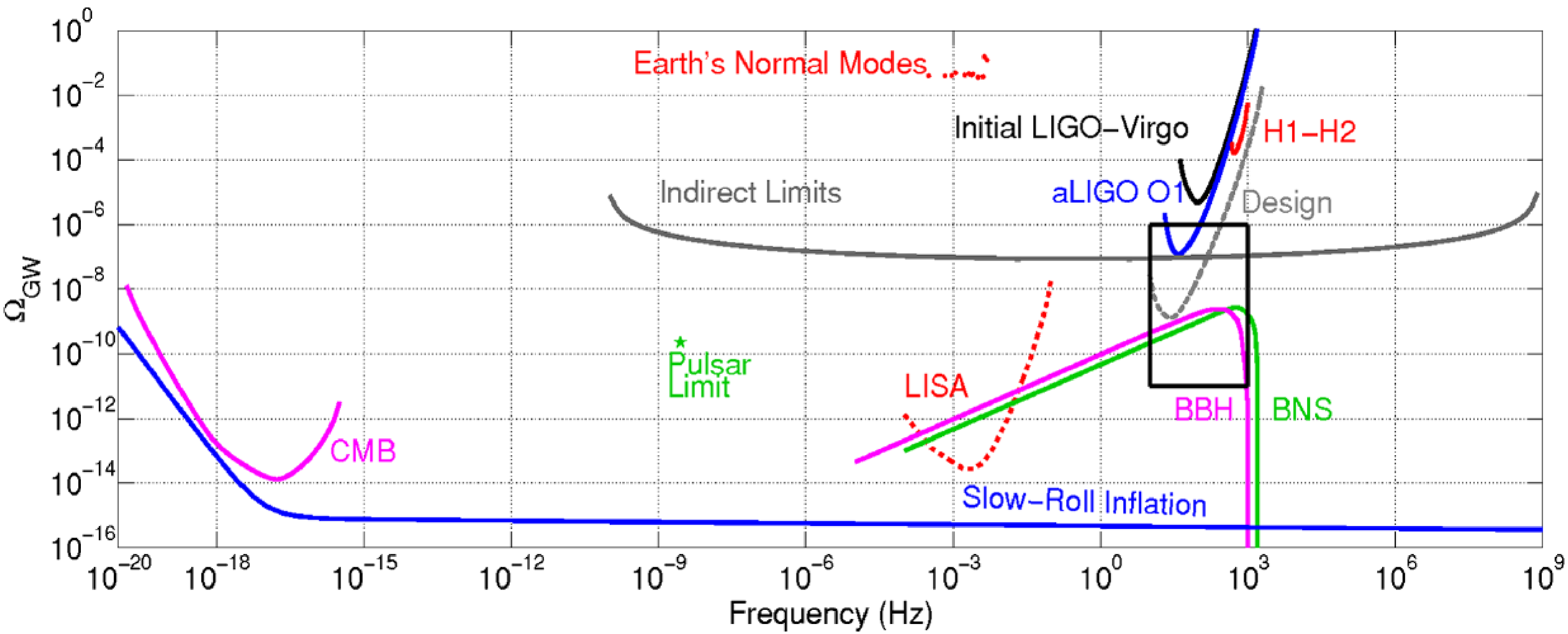


ASPIC arXiv/1303.3787

"models" include different priors

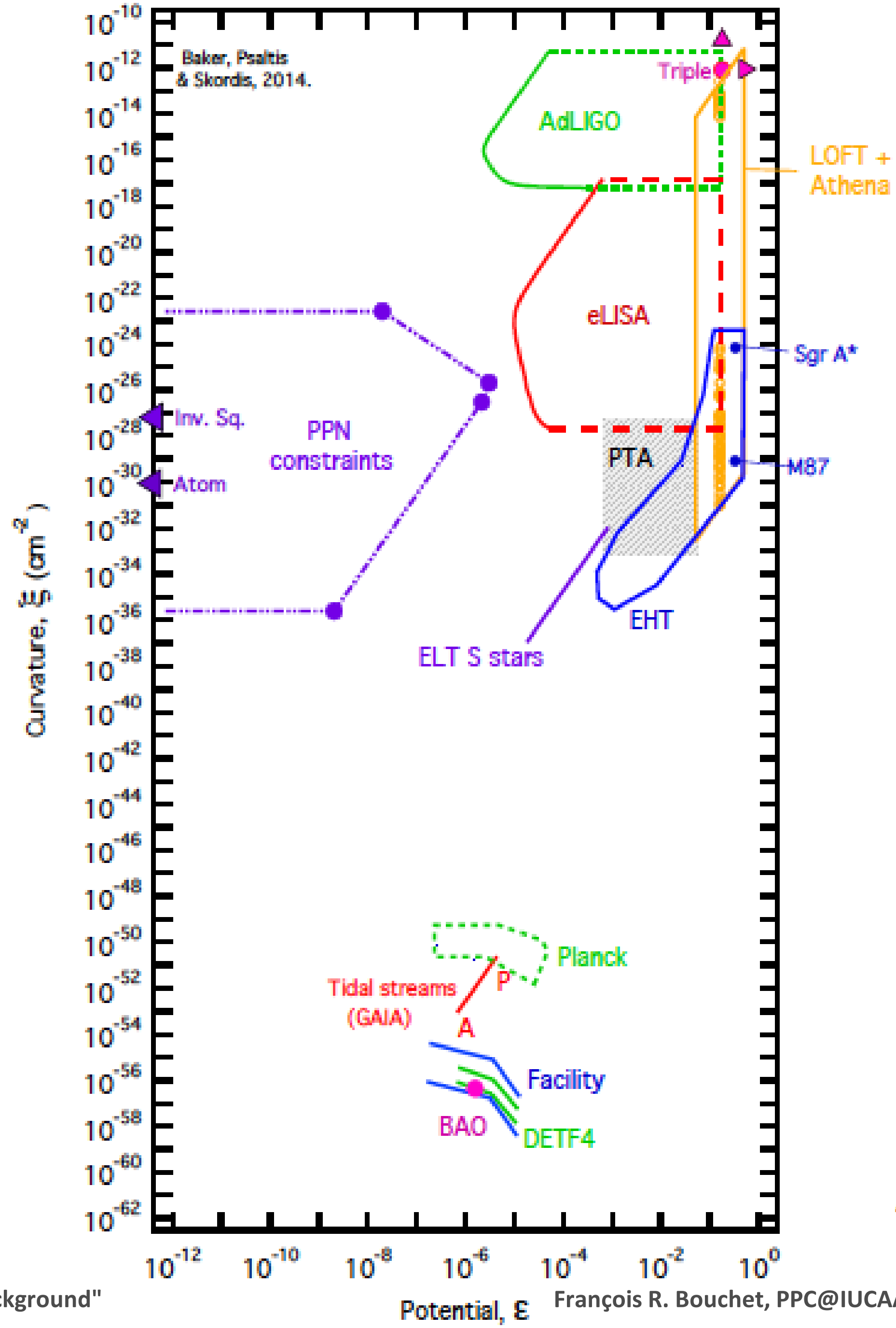
CMB versus other GW detectors

2017) March 27 PHYSICAL REVIEW LETTERS



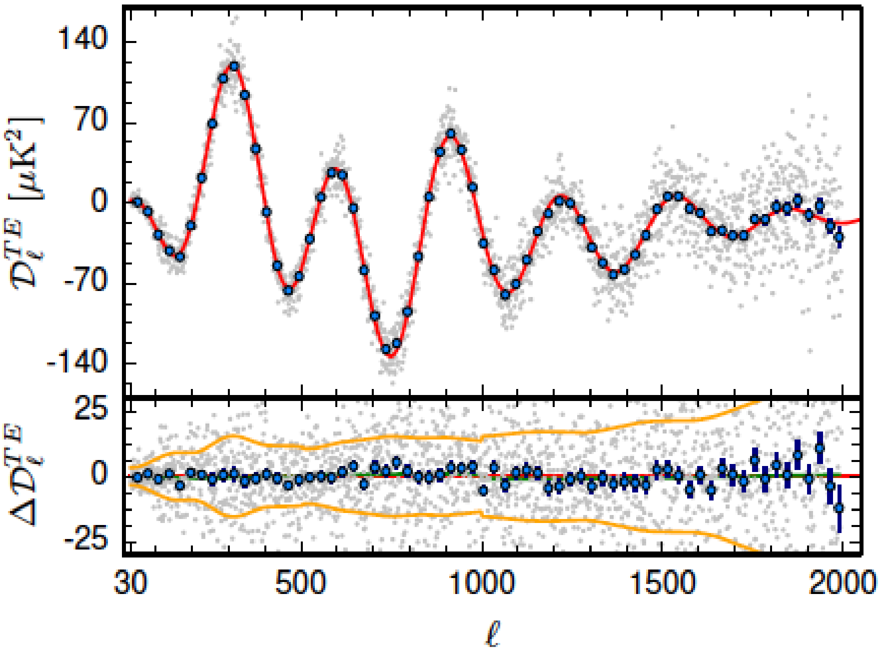
For the not-too-distant future, direct local detections can only constrain non-scale (blue) invariant primordial GW backgrounds

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

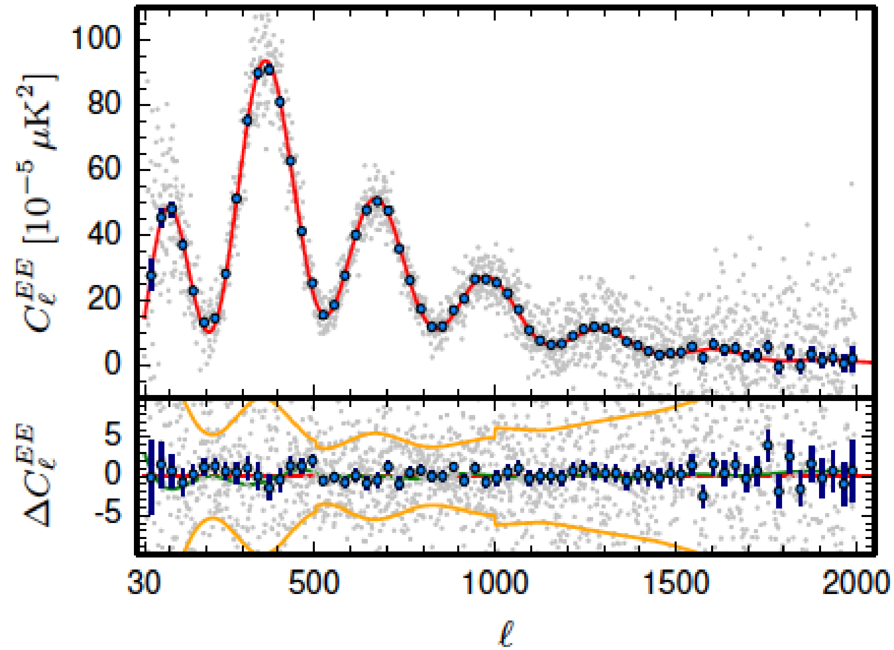


Baker et al 2014
ArXiv:1412:3455

Planck 2015 - TE & EE spectra



Frequency averaged spectrum reduced ^{2} = 1.04



Frequency averaged spectrum reduced ^{2} = 1.01

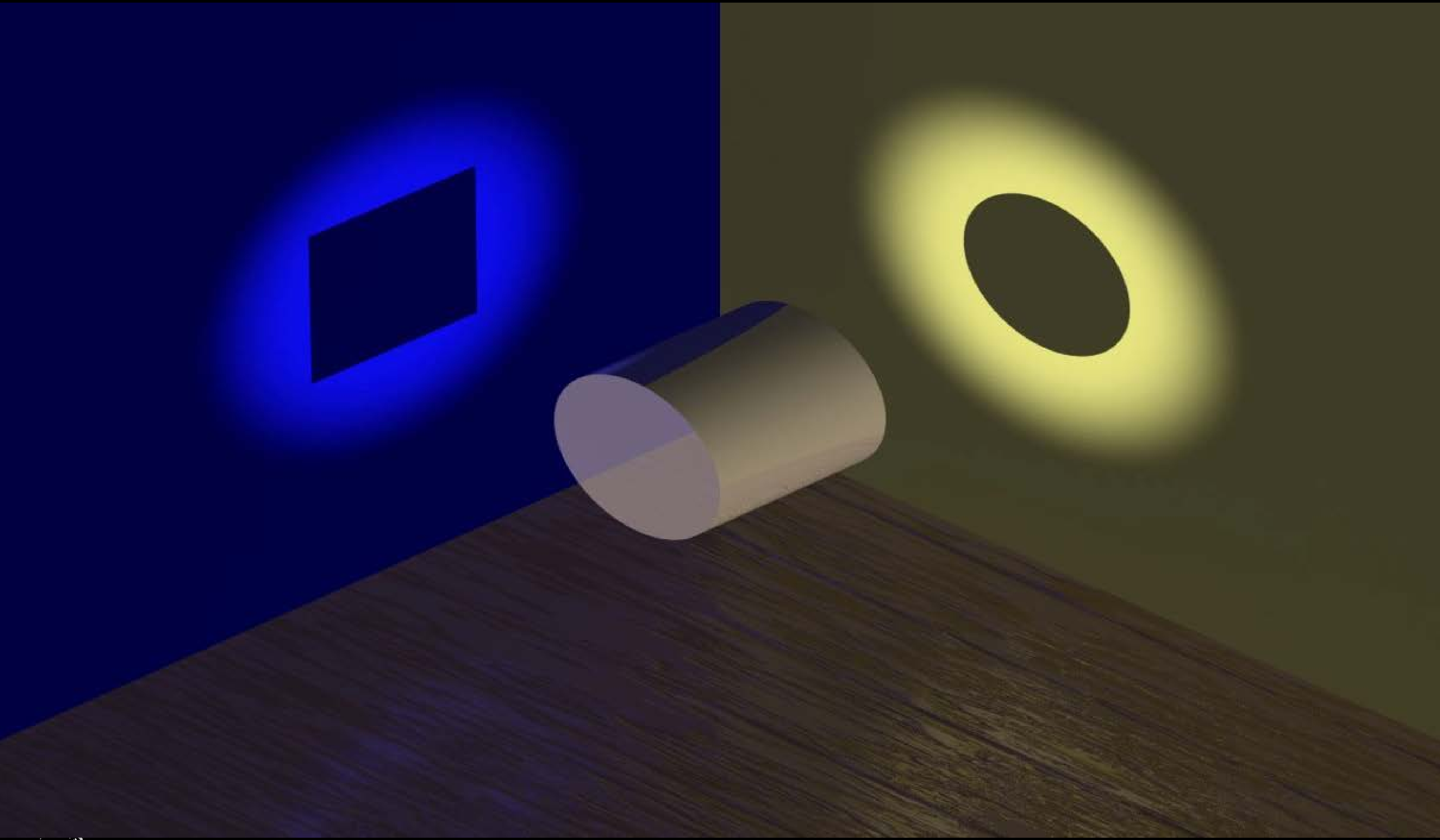
- Red curve is the *prediction* based on the best fit TT in base ΛCDM
- Albeit *magnificent*, 2015 polarisation data and results are *preliminary* because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

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

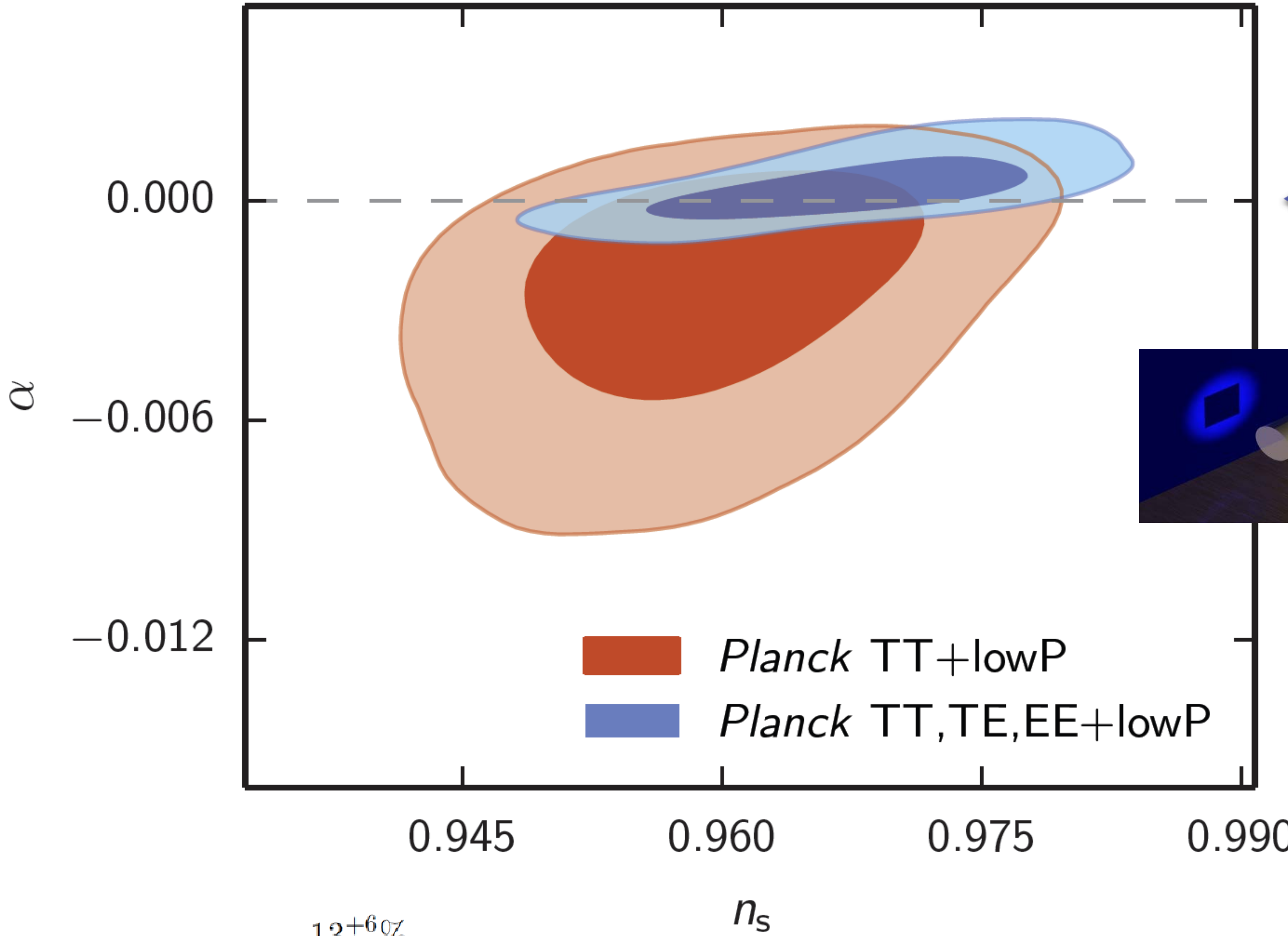
Note that parameters from TT & TE have *similar uncertainties*,
but beware that they are still some low level systematics in the polarisation data

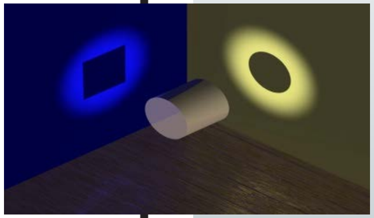
It could have been otherwise!



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

Isocurvature modes fraction



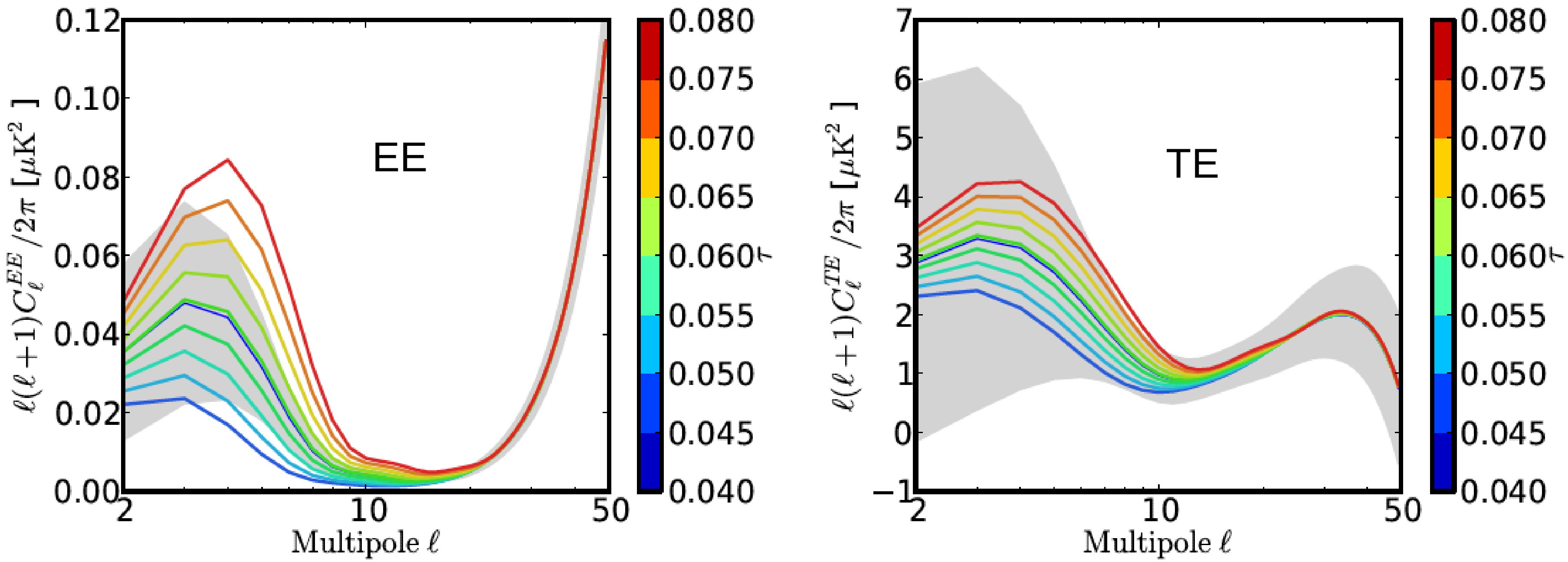


Percentage of isocurvature: $13^{+6}_{-6}\%$ Moodley, Ferreira et al (2004)

$1^{+0.5}_{-0.9}\%$ Planck (2015) (conservative, improvement ~ 10 in 10 years).

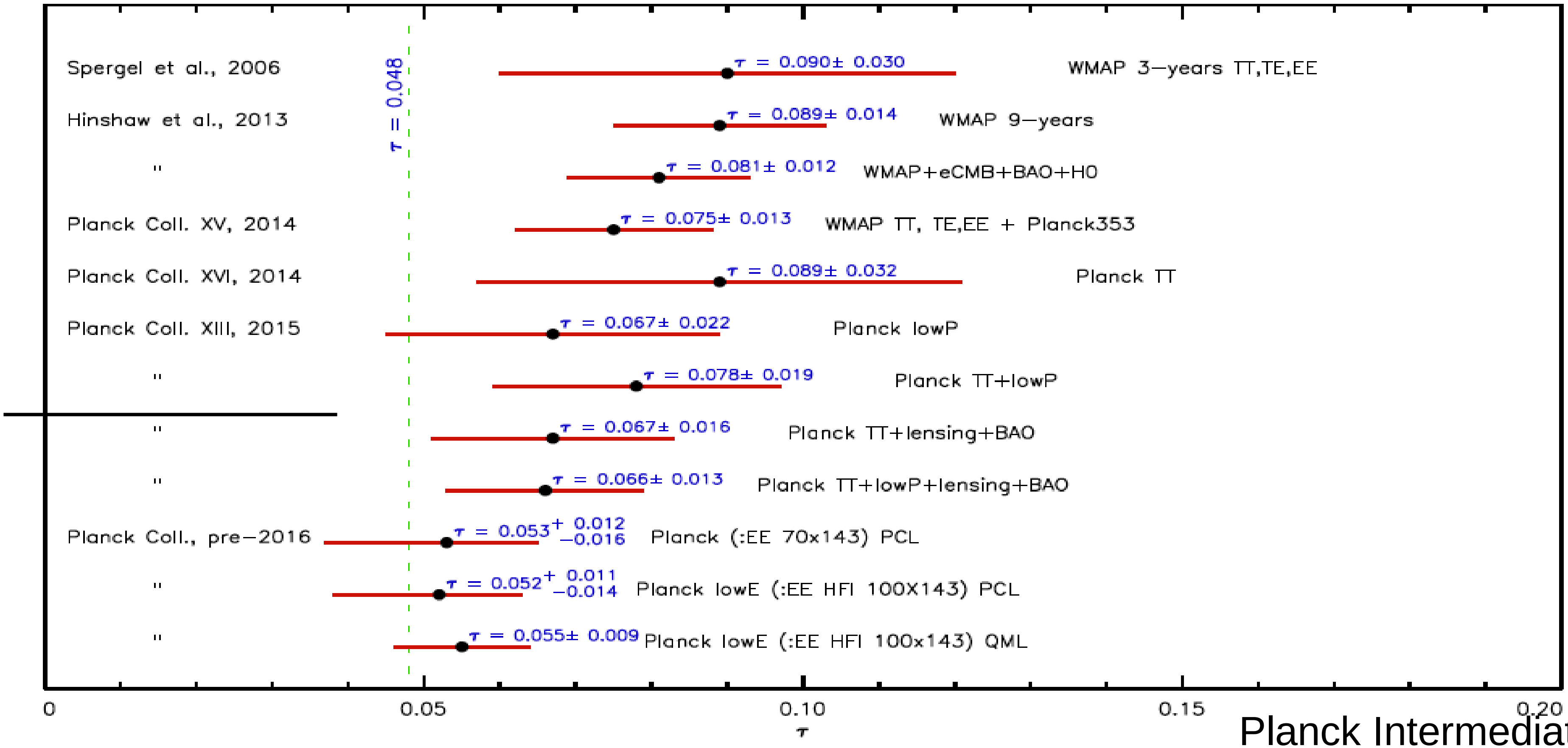
Optical depth to reionization, τ

- The scattering of CMB photons when the Universe reionized reduced the amplitudes (TT \propto $A_s$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 …

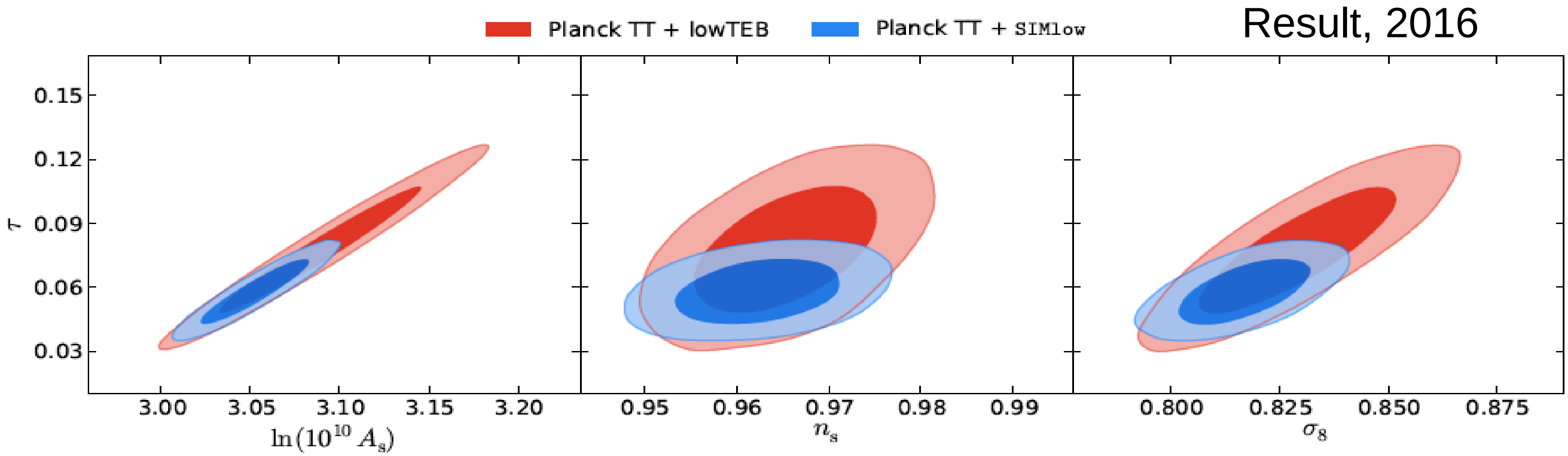


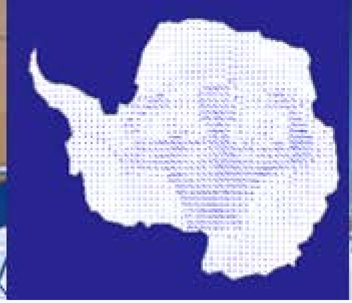
Grey bands = full sky sample variance if tau = 0.06

Planck Collaboration 2016



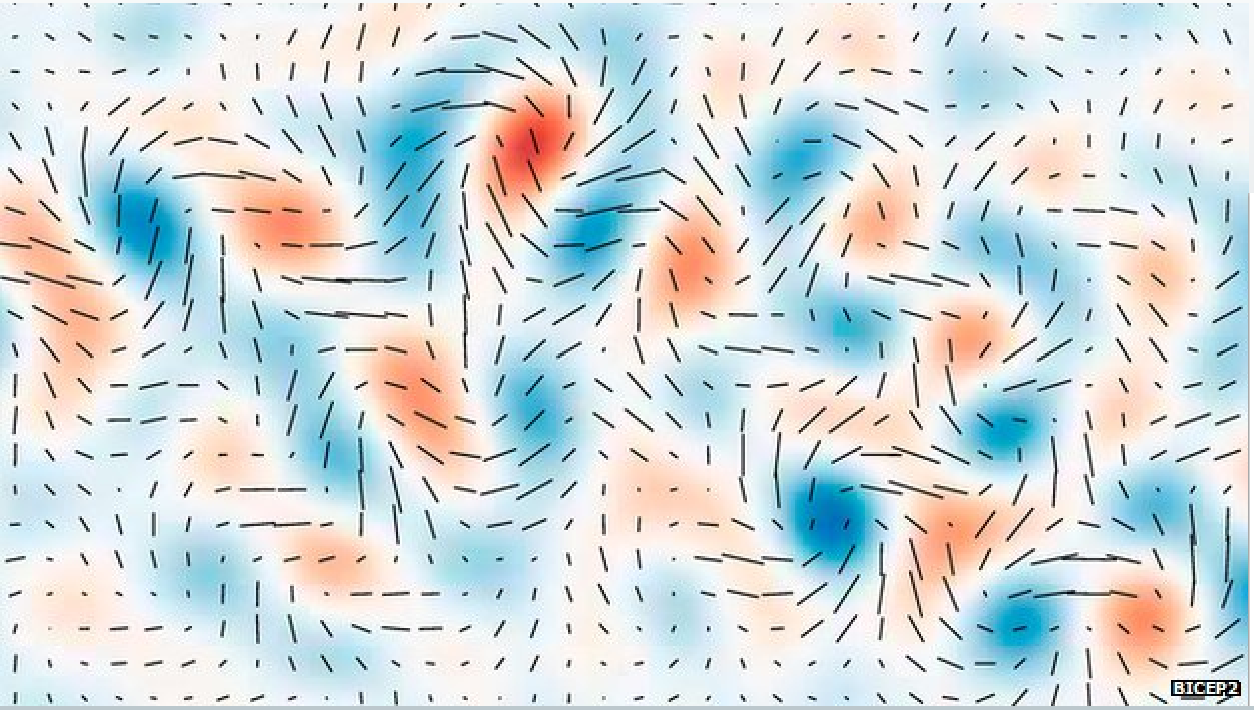
Planck Intermediate Result, 2016

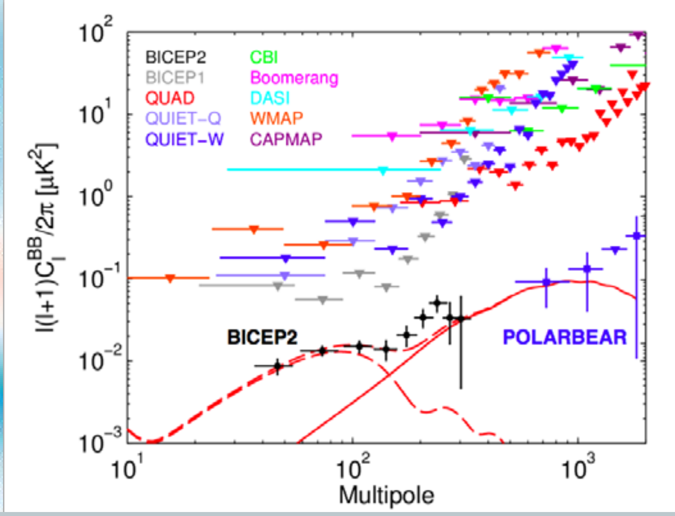



BICEP2

March 17th 2014





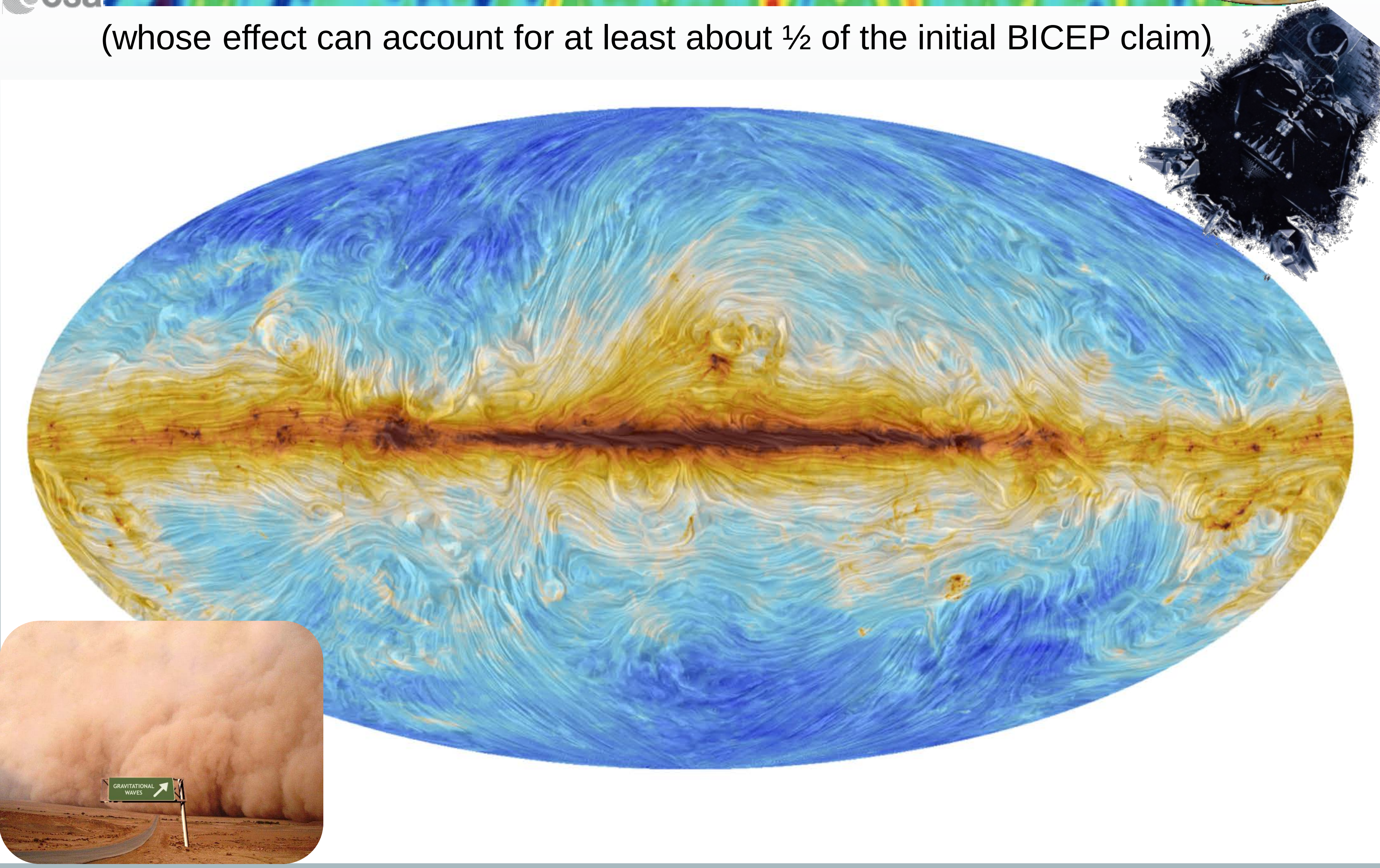
The world of physics is taken aback:

« The search for primordial gravitationnal waves is over »

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

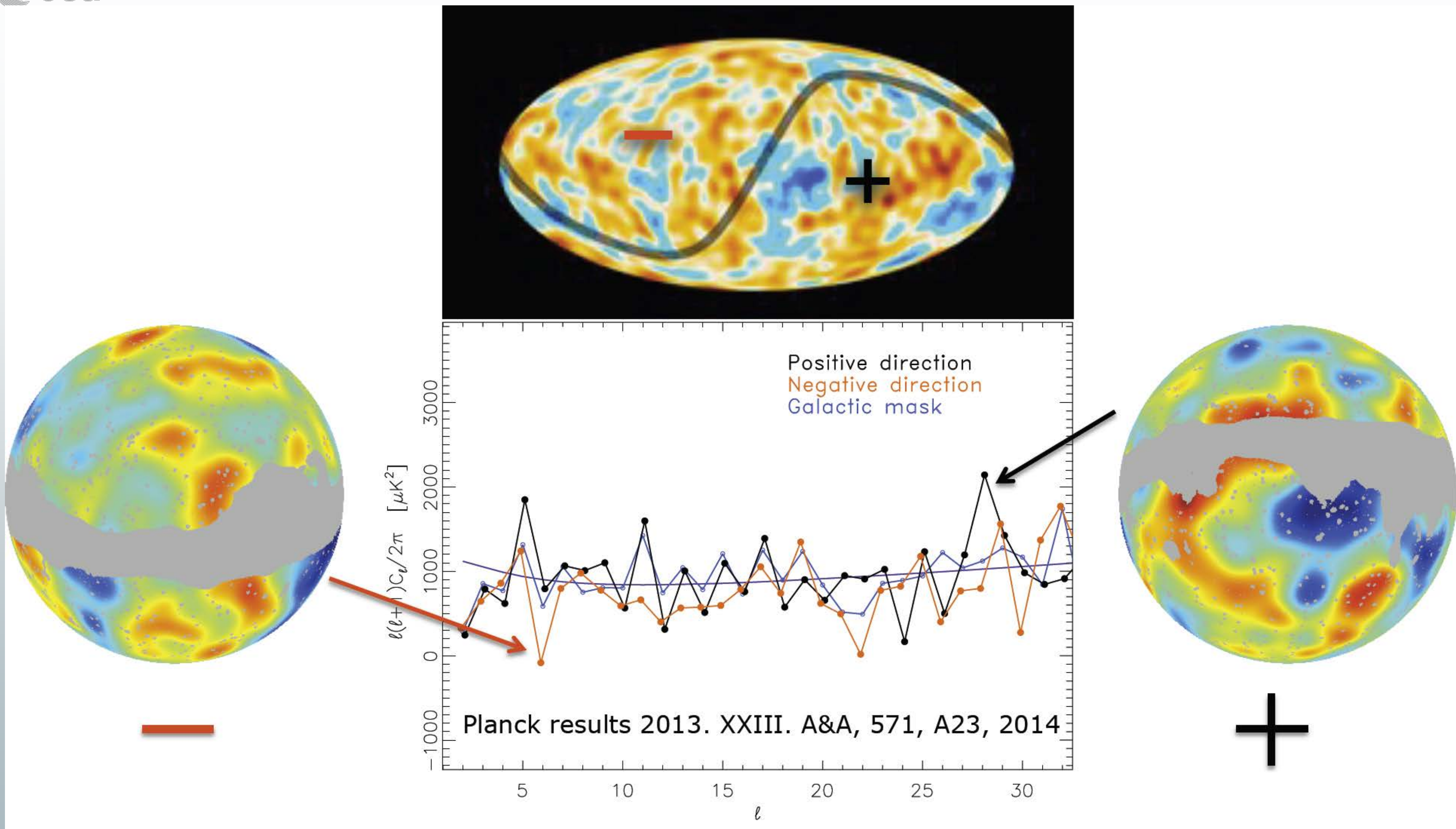
Planck 353GHz reveals the Galactic magnetic field

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



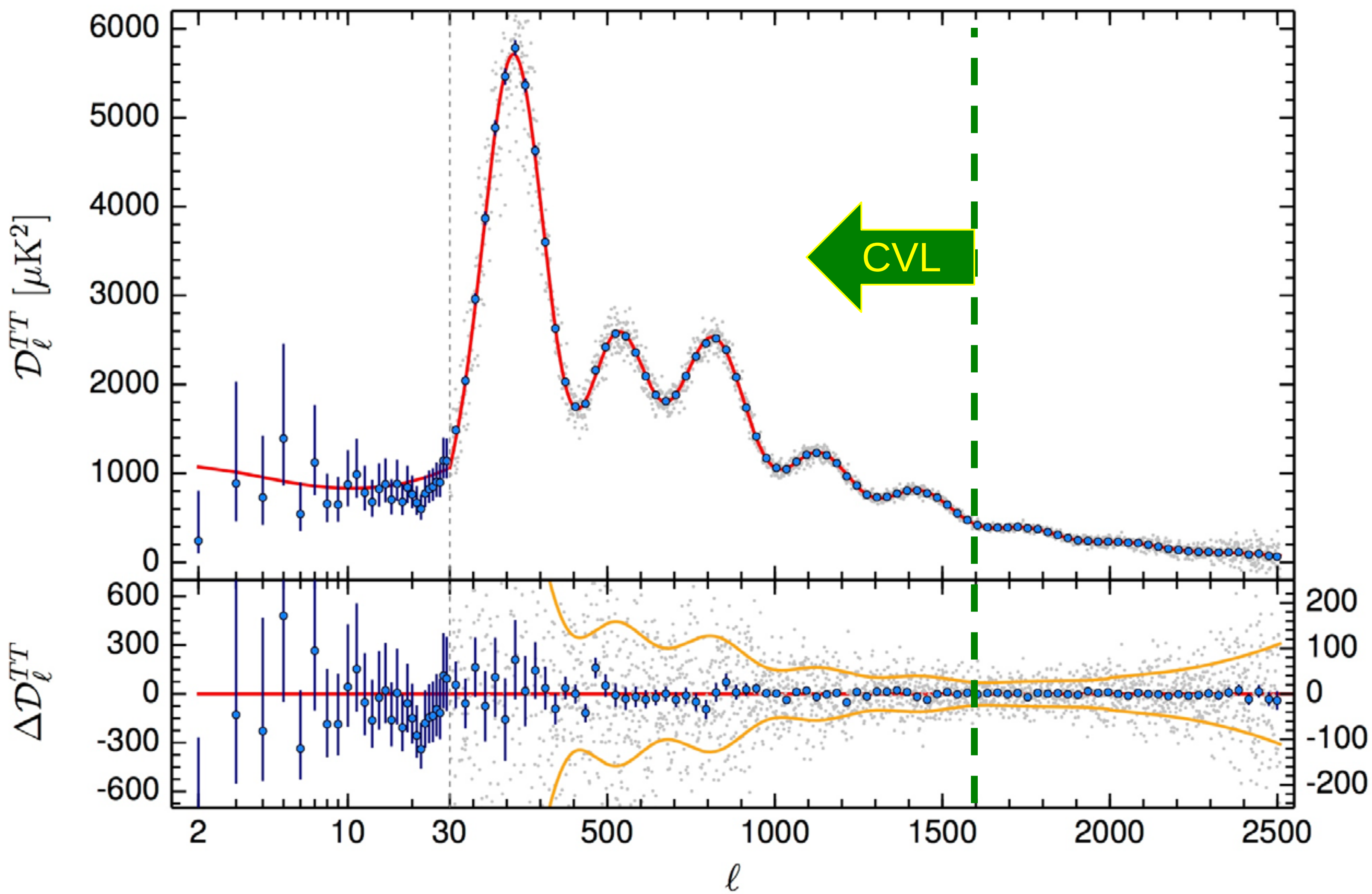
NON-GAUSSIANITY / ISOTROPY

Power asymmetry



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

Planck 2015 TT spectrum



8 acoustic peaks well detected

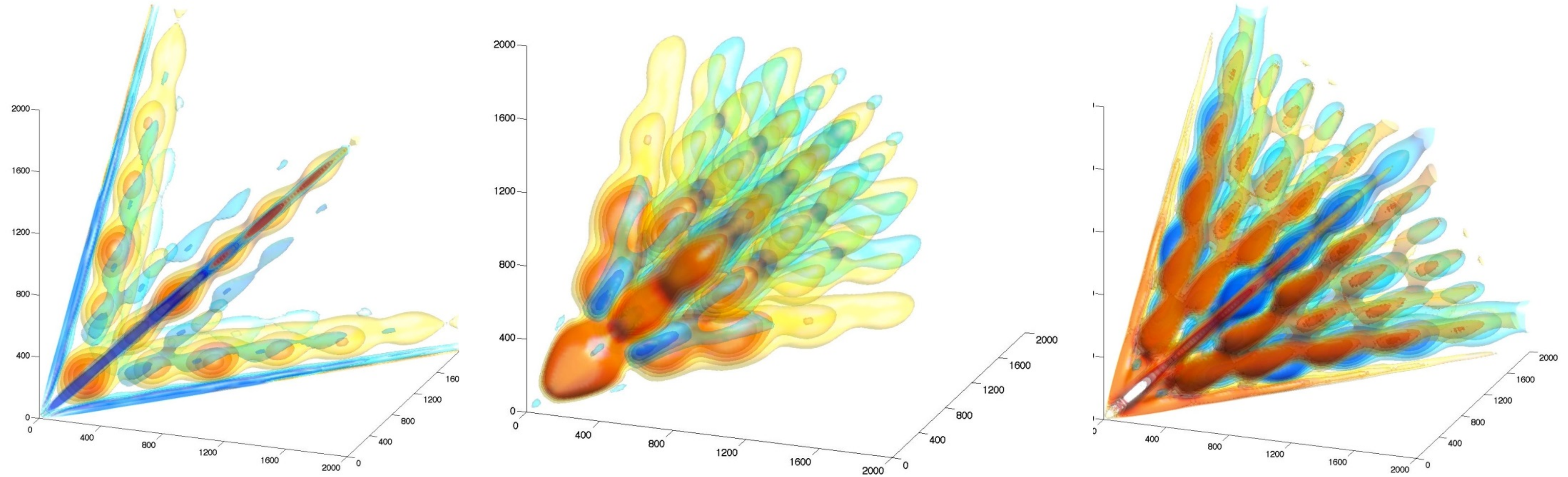
CVL till l~1600 on 40-70% of the sky

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)…

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

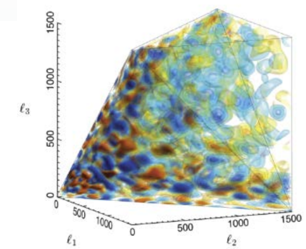
NG of ***orthogonal*** type ($k_1 \sim 2k_2 \sim 2k_3$) :

- 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	

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



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

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

non-Gaussian potential

Gaussian field

$|f^{Loc}_{NL}| < 10^3$ (Maxima 2001), 10^2 (WMAP7), 10 (Planck15)

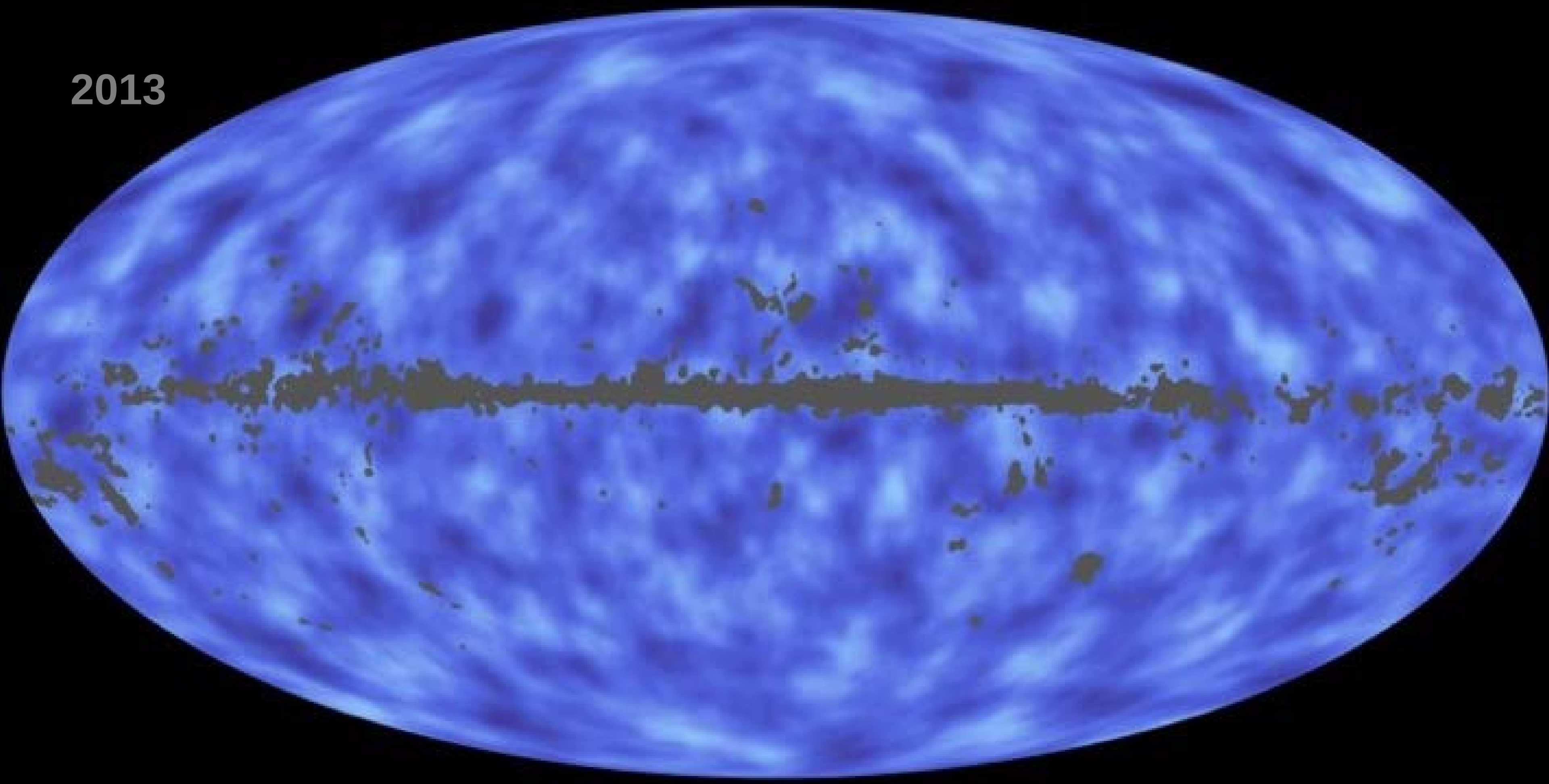
A hundred-fold improvement in 14 years

Next steps?

- Generically, NG constraints scale with one over the square root of the number of modes used.
  - *Plank measured/used about all T modes. I.e., only the polarised modes are left to measure in the CMB, which means that we can improve the constraints by at most about a factor of 2.*
  - *So we cannot get to the Weakly non-linear effect of GR which are typically of fnl ~ O(1), and even less reach the Maldacena bound for single field slow roll of O(n_s-1), i.e., O(0.04)!*
  - *Of course a detection is still possible at any time and would be extremely significant!*
- To go forward further, turn to 3D modes rather than 2D CMB modes, hopefully in linear or perturbative regime.
  - *Intensity mapping will help, but to get close to Maldacena bound, we need to go on far side of the moon… Money…*

SPHEREX

Projected mass map



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

"Cosmic Microwave Background"

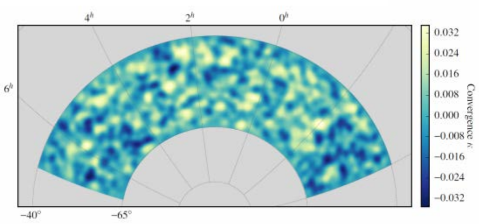
A foretaste of the CMB lensing near future…

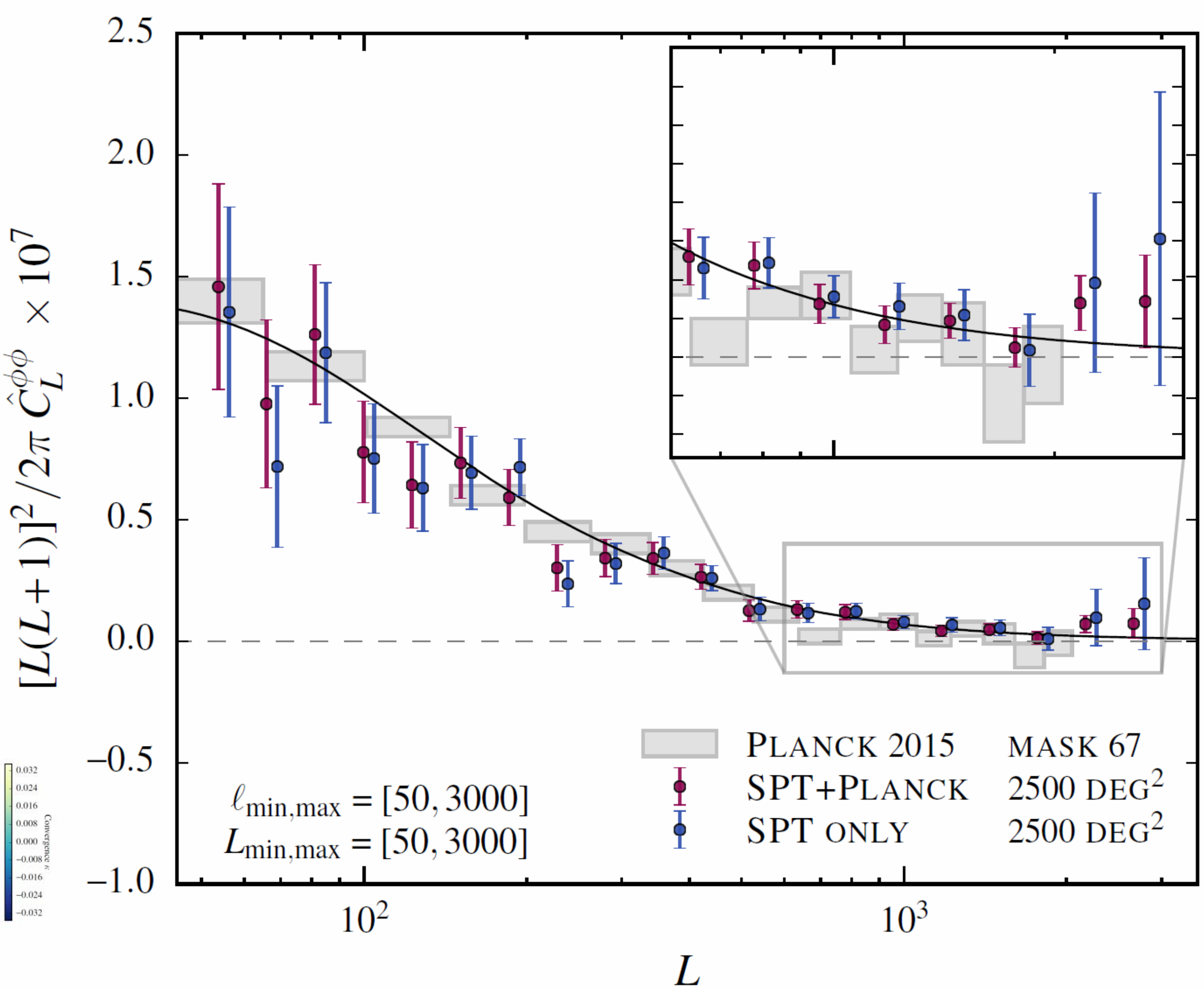
Omori+ arXiv:1705.00743: A 2500 deg2 CMB LENSING MAP FROM COMBINED SOUTH POLE TELESCOPE AND PLANCK DATA

Start by creating first a temperature map of the SZ-SPT area that has a broader ell coverage and less noise than either individual map.

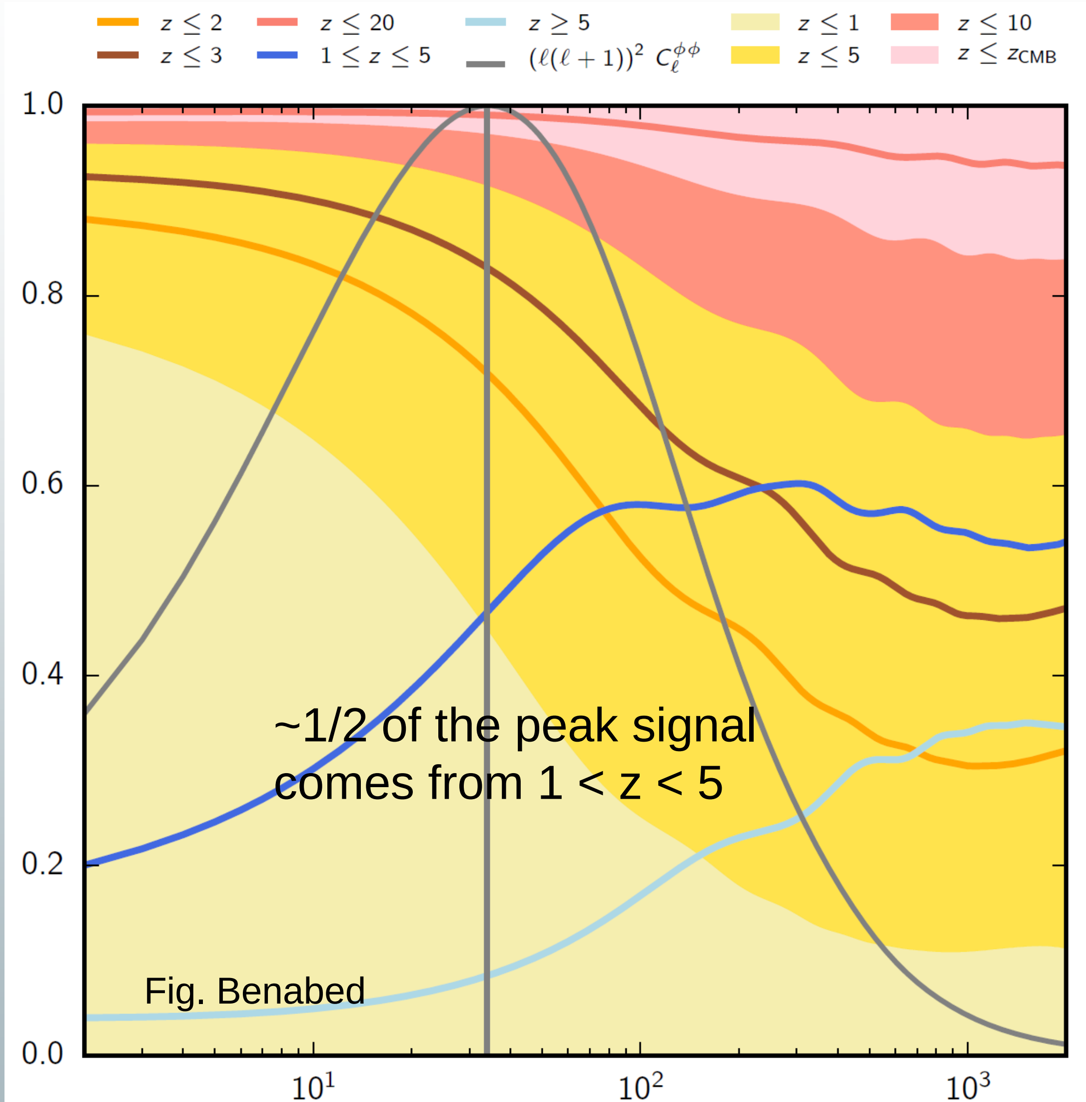
In practice Planck provide the large scale modes and those missing due to SPT scanning strategy, and is completed with SPT information at other ell.

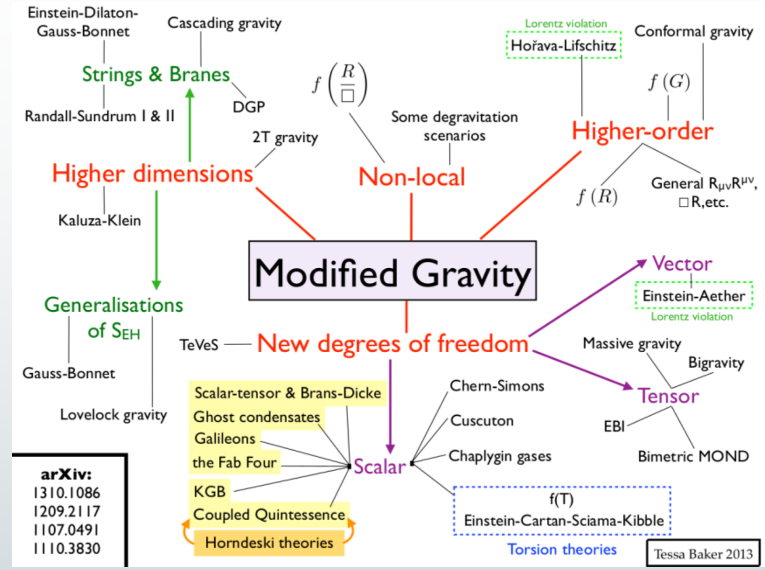
We shall see a lot more of this data merging ! (Indeed Planck will not be superseded anytime soon, at least in some regions/scales)

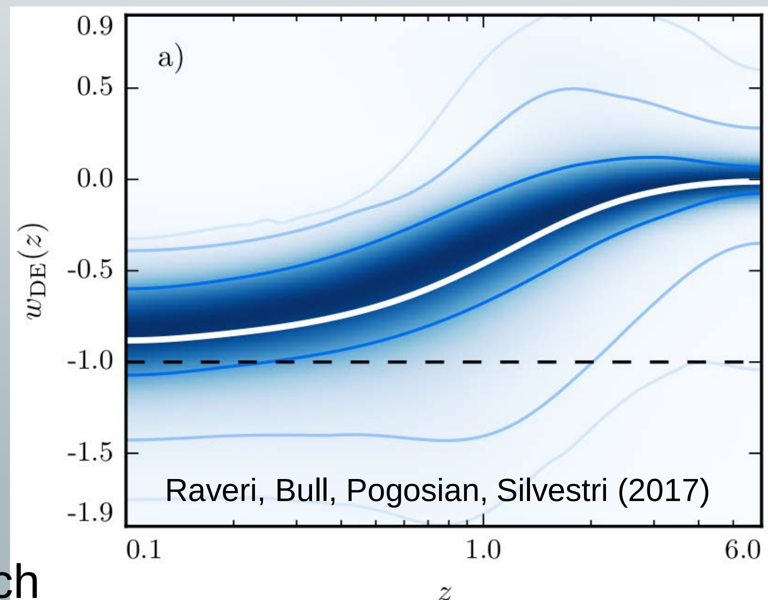




Lensing comes from a broad redshift range

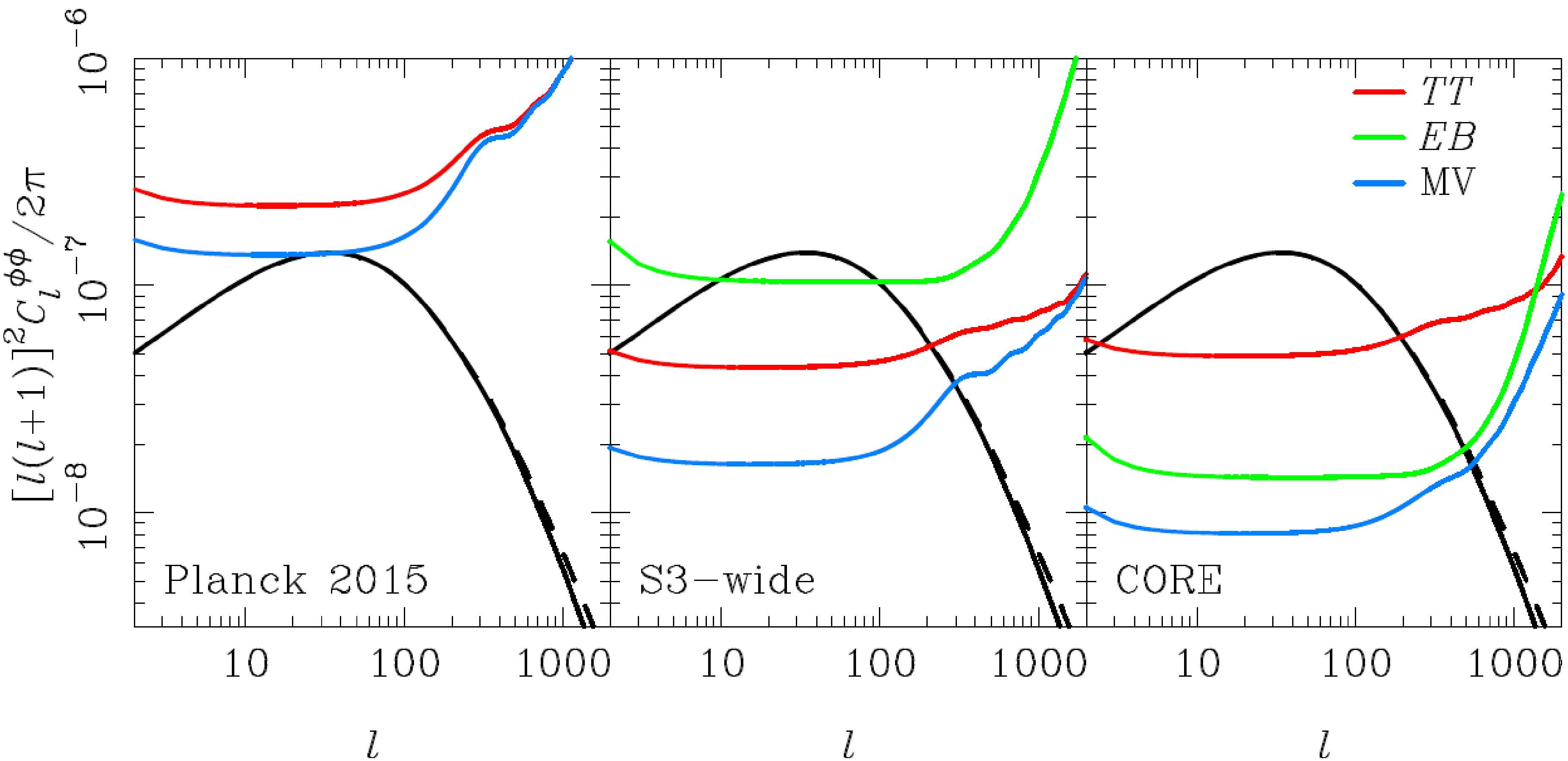






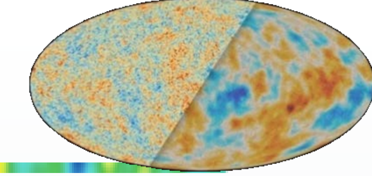
A unique contribution of CMB lensing to DE/MG search

Next step?



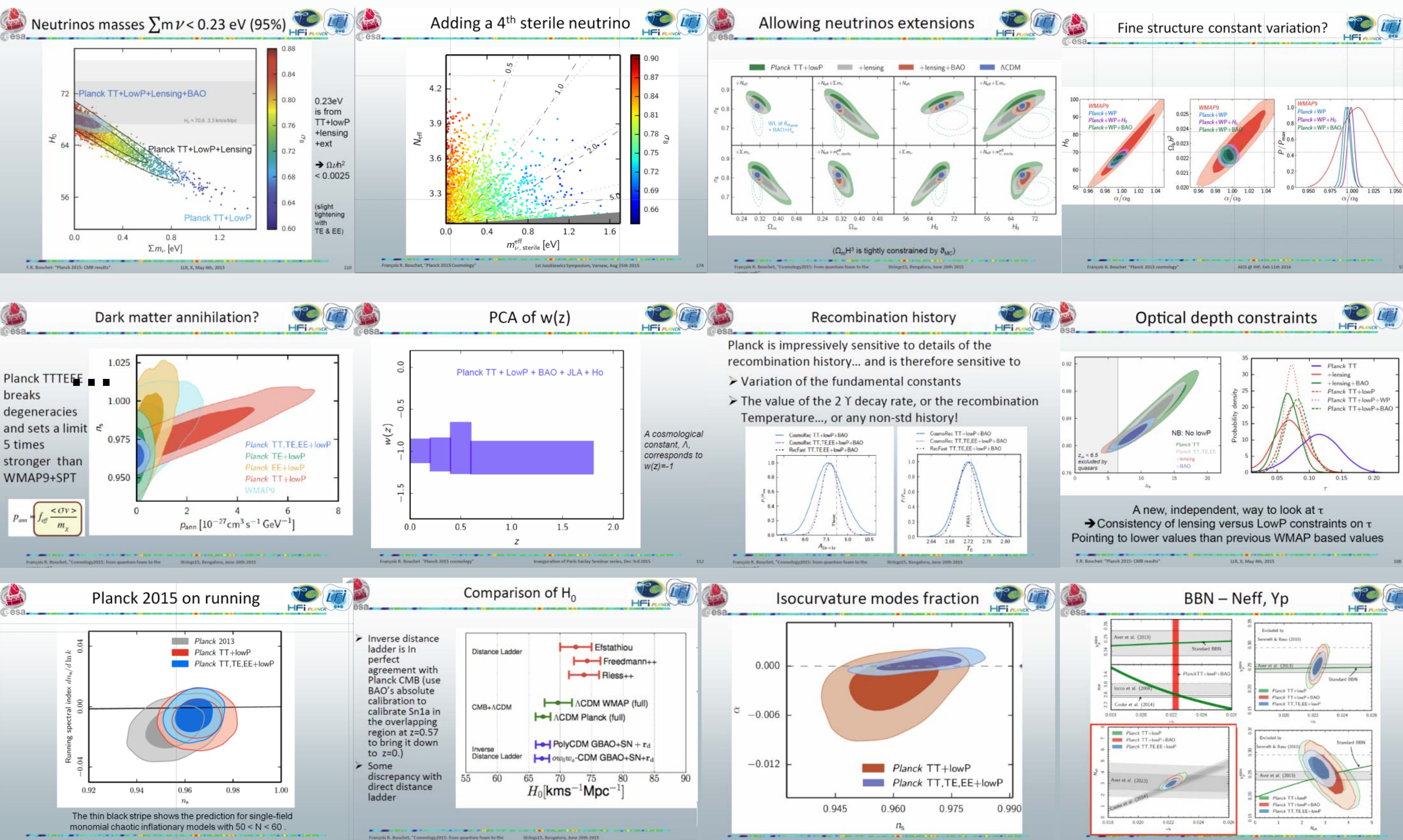
Reconstruction noise of the lensing detection power spectrum from Planck 2015 (left) and forecasts. The detection power spectrum is plotted based on the linear matter power spectrum (black solid) and with non-linear corrections (black dashed). [MV=minimum Variance].

Standard cosmological model - LCDM

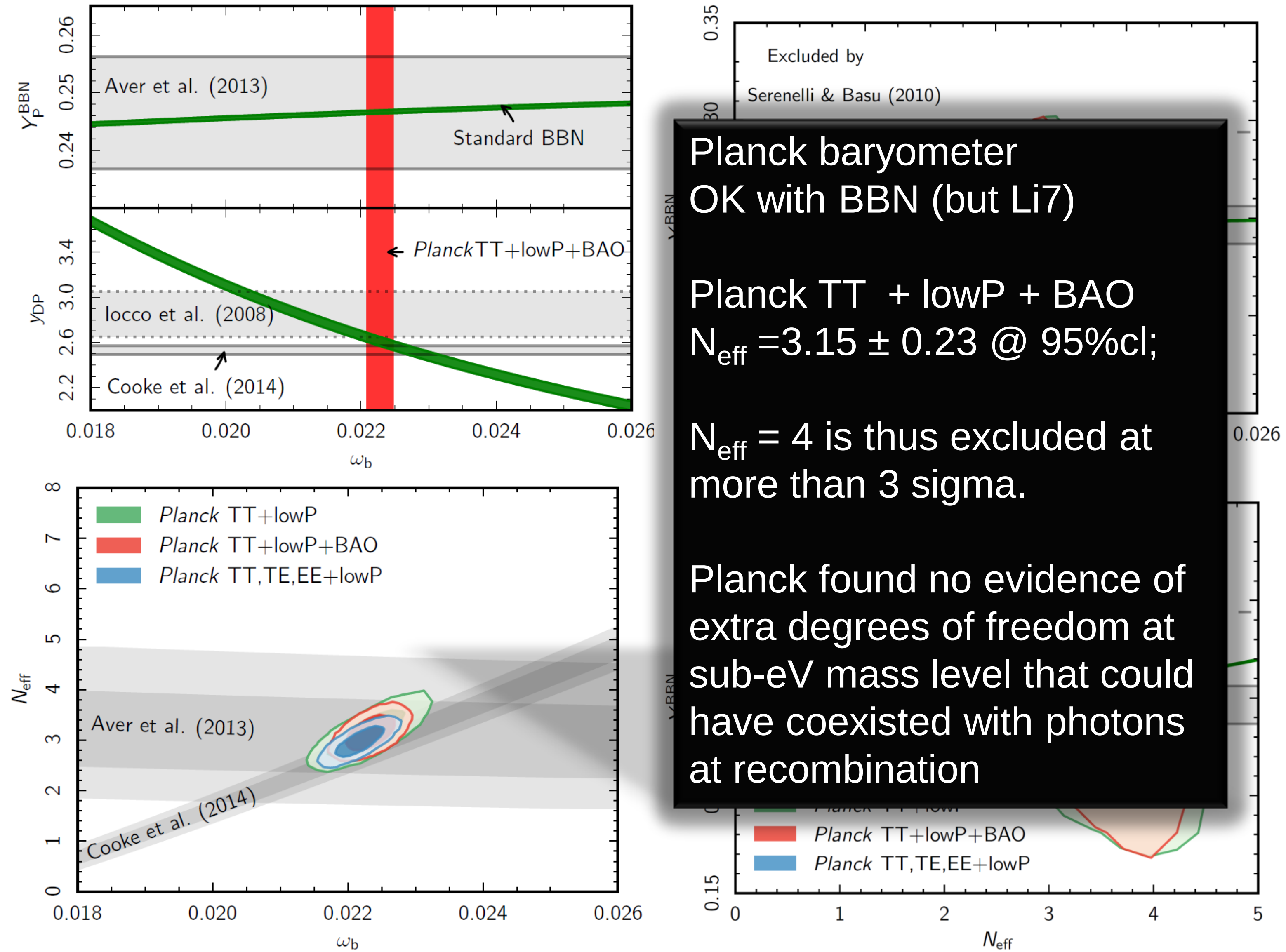


- The CMB TT, TE, EE, Φ-Φ, as well as BAO, BBN (but Li7), and SN1a measurements are all consistent, among themselves and across experiments, **within LCDM**.
- This network of consistency tests is passed **with per cent level precision. Idem for most parameters.**
- These tests allow <u>many</u> different 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 ($A_{2s\rightarrow1}$, T_0, and also fundamental constants variation, or any energy input…).

We tested & constrained a lot more…



BBN – N_{eff}, Y_p



Planck baryometer
OK with BBN (but Li7)

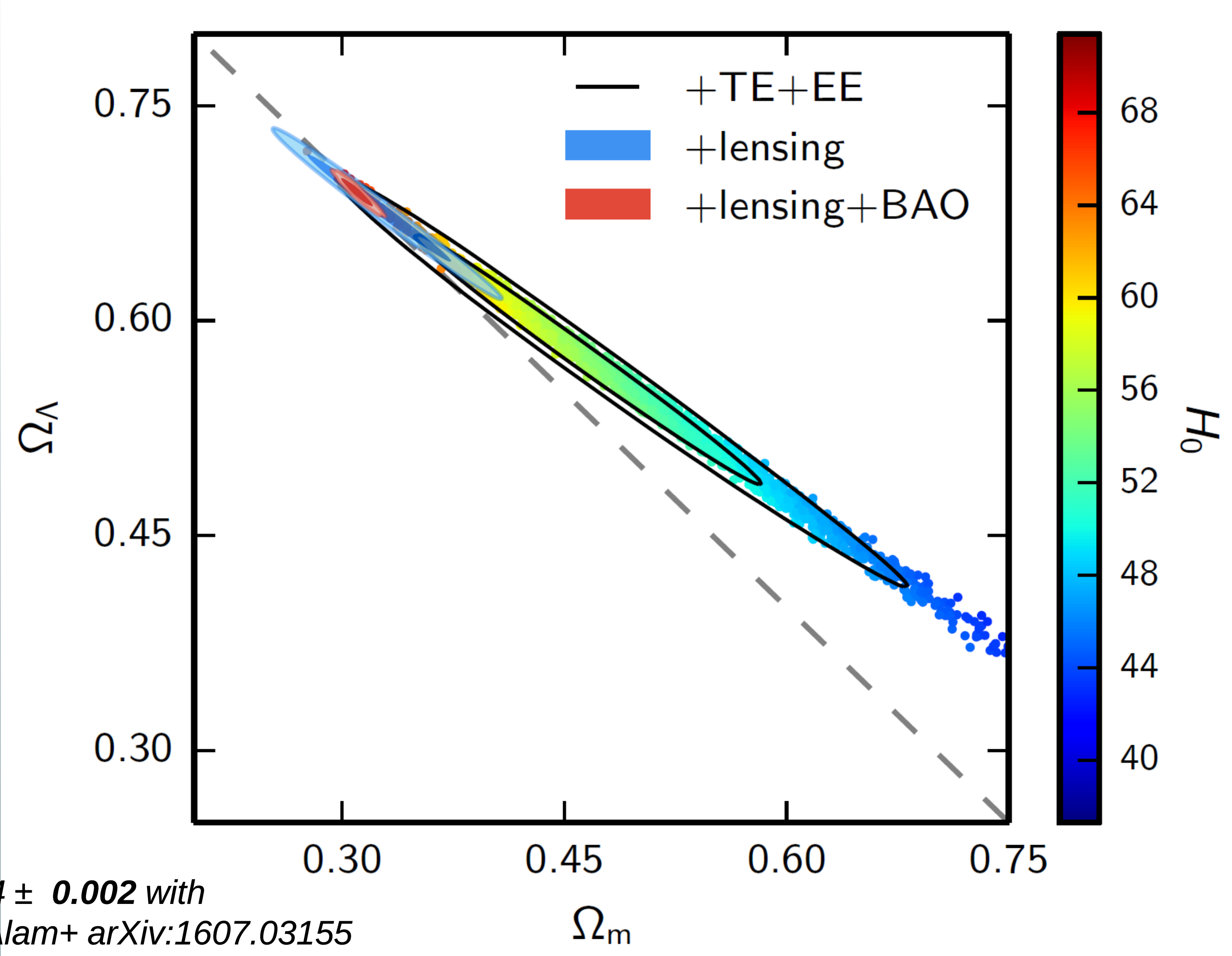
Planck TT + lowP + BAO
N_{eff} =3.15 ± 0.23 @ 95%cl;

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

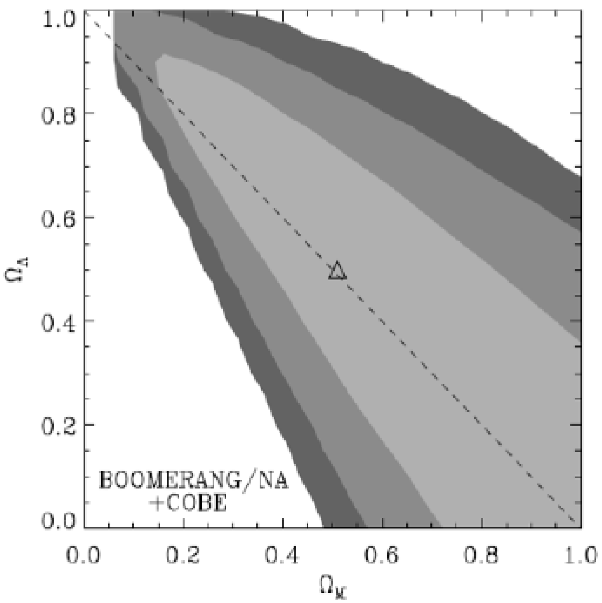
Spatial curvature constraint

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



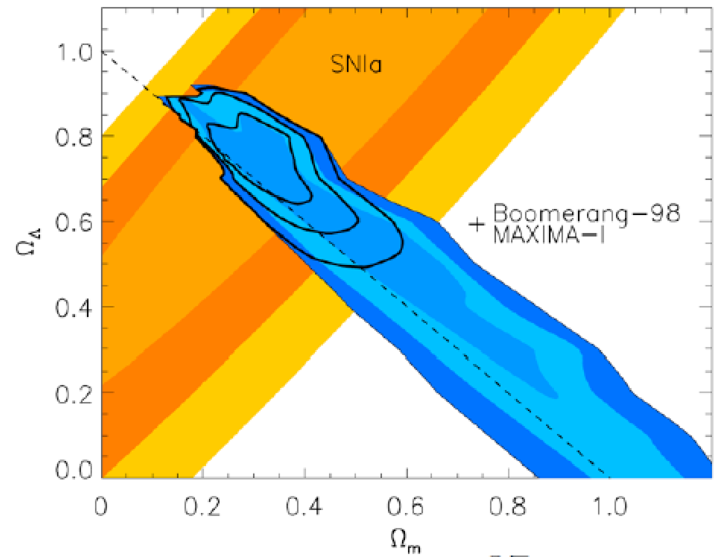
*NB: Ωk =0.0004 ± **0.002** with SDSS3-DR12 Alam+ arXiv:1607.03155*

Spatial curvature constraint



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

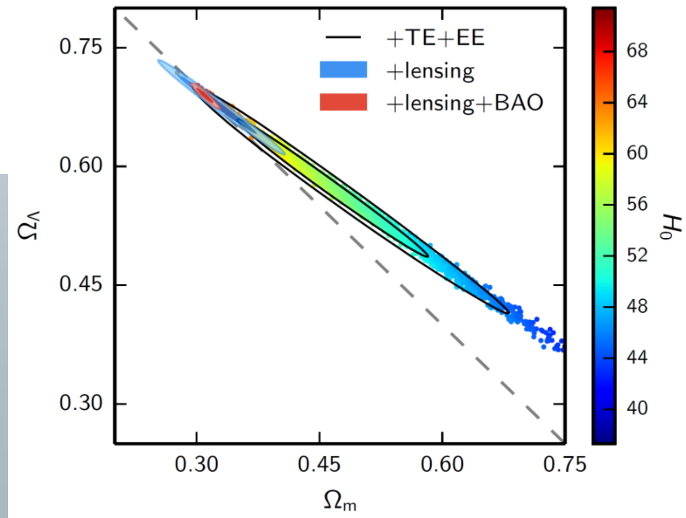
Melchiorri et al. 2000



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

Jaffe et al. 2001

Note the change of axes
For Planck below



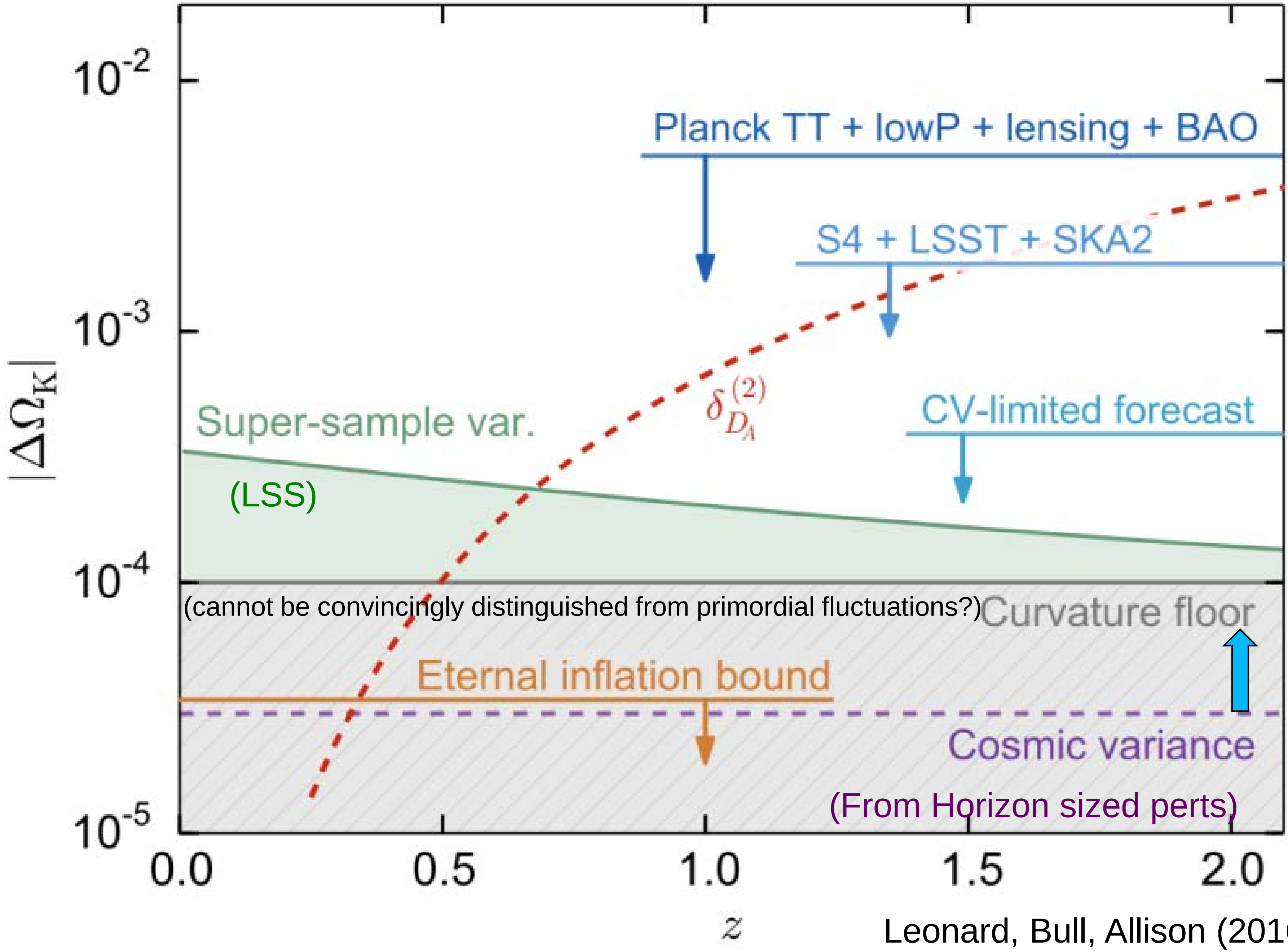
Planck 2015

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

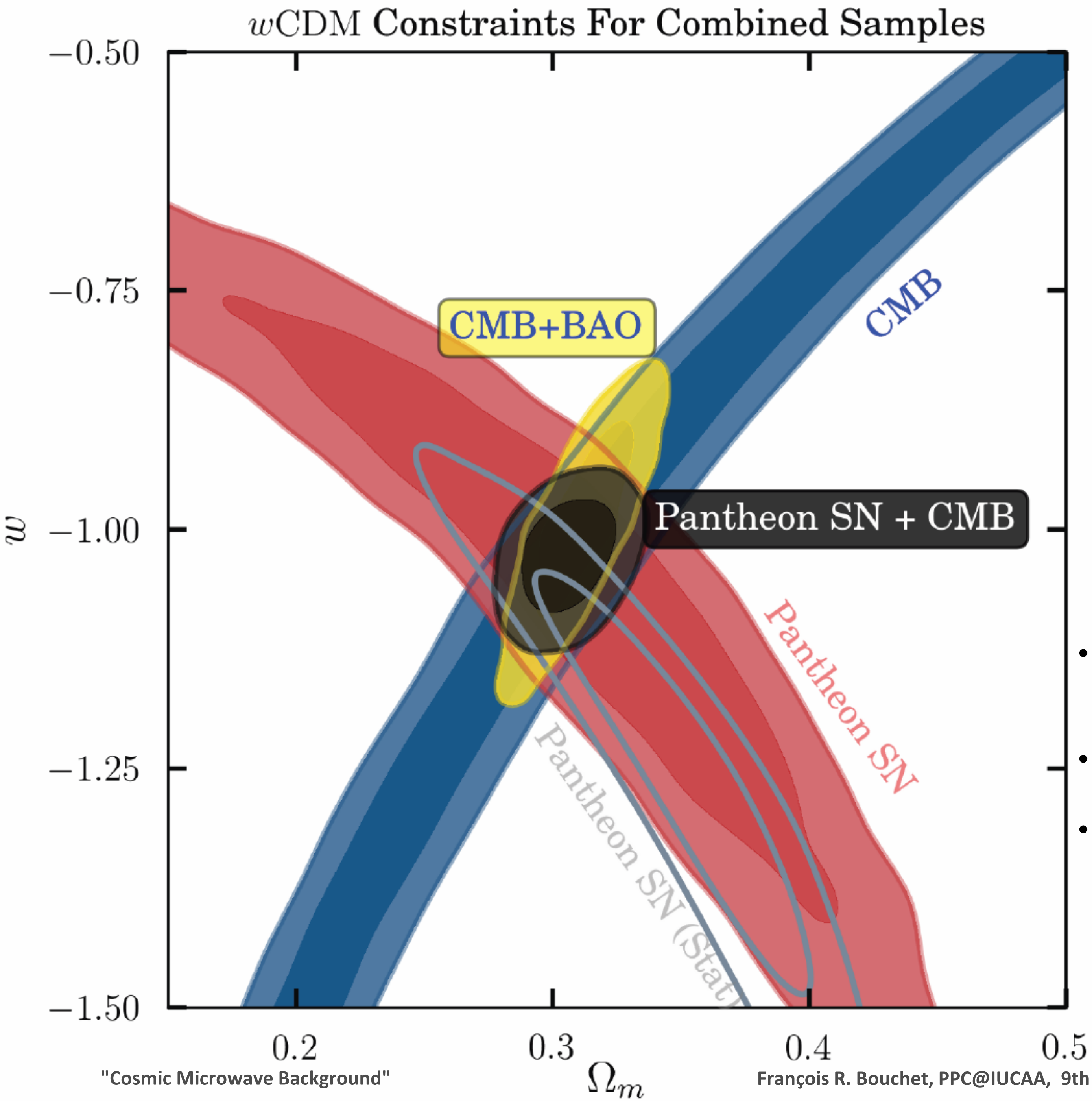
A hundred-fold improvement in 15 years

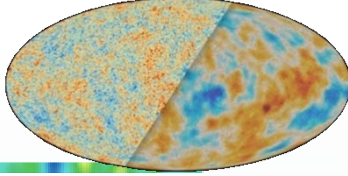
Next step?

- 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)





Scolnic+
arXiv:1710.00845v1

Claim: The systematic uncertainties on our measurements of dark energy parameters are now smaller than the statistical uncertainties.

- CMB from Planck Collaboration et al. (2016a) (Planck TT + lowP),
- local value of H0 from (Riess et al. 2016),
- BAO from the SDSS Main Galaxy Sample (Ross et al. 2015), the Baryon Oscillation Spectroscopic Survey and CMASS survey (Anderson et al. 2014).

Next steps?

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

  ➔ *measure E-polarisation to cosmic variance to much smaller scales, thx to <u>much</u> more benign foregrounds than in Temperature.*

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

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

  ➔*deal with intrinsic foreground of lensing-induced B-modes, i.e., know the lensed E-modes very well over broad range of scales, and a tracer of the lensing gravitational potential (either non-CMB, e.g., CIB -- or internal, a great goodie!).*

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

Testing inflation with CMB, optical, and IM surveys

[AP 2016]

Running uncertainty

Survey	$\sigma(n_\mathrm{s})$	$\sigma\,(\alpha_\mathrm{s})$
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

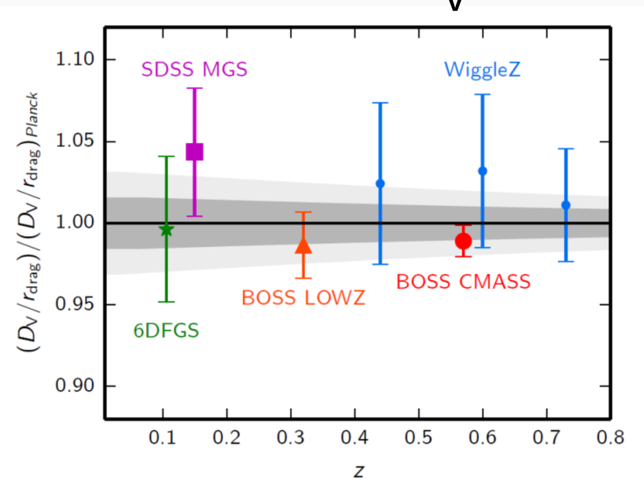
(not enough for Generic model)

gives required precision < 0.001

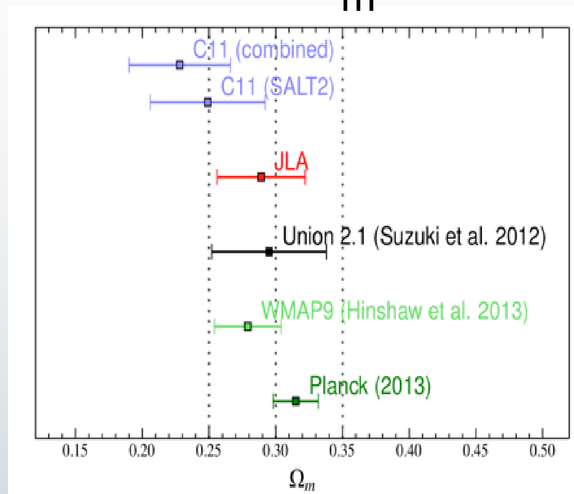
[see also Munoz et al 2016]

The good, the ?, the ??

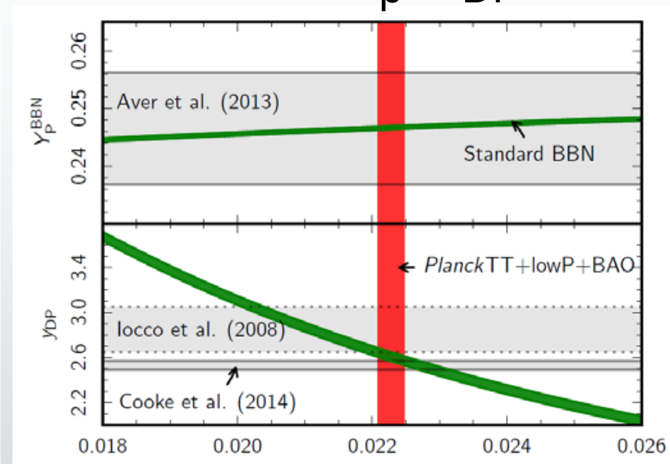
BAO D_v



SN Ω_m

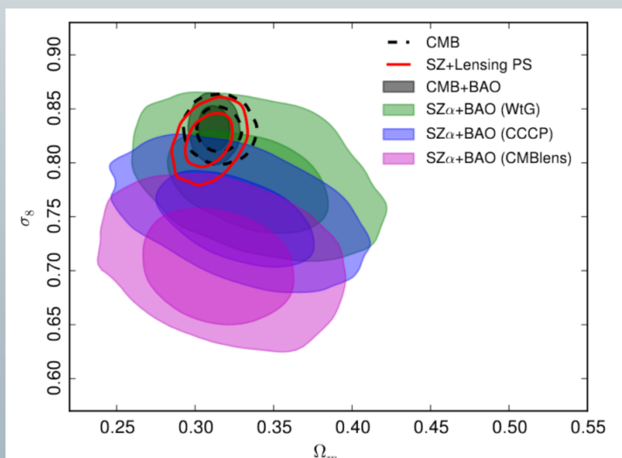


BBN Y_p Y_{DP}



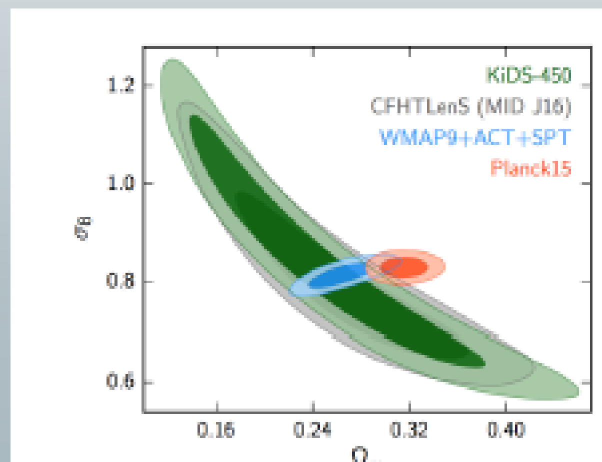
(but 2.3 sig w. latest Y_{DP})

SZ



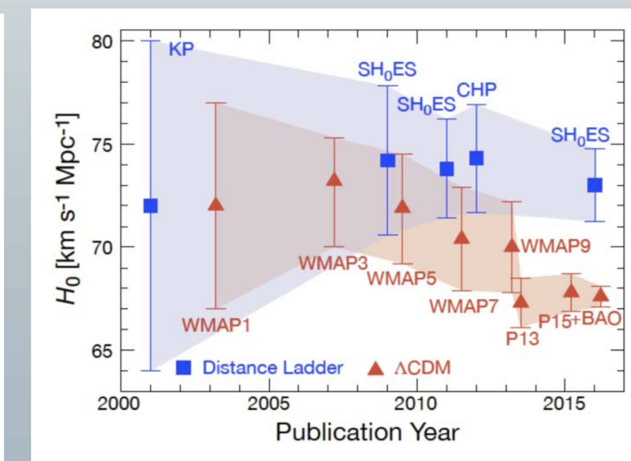
Medezinski+ arXiv:1706.00434: a cluster mass dependence of the bias?

WL



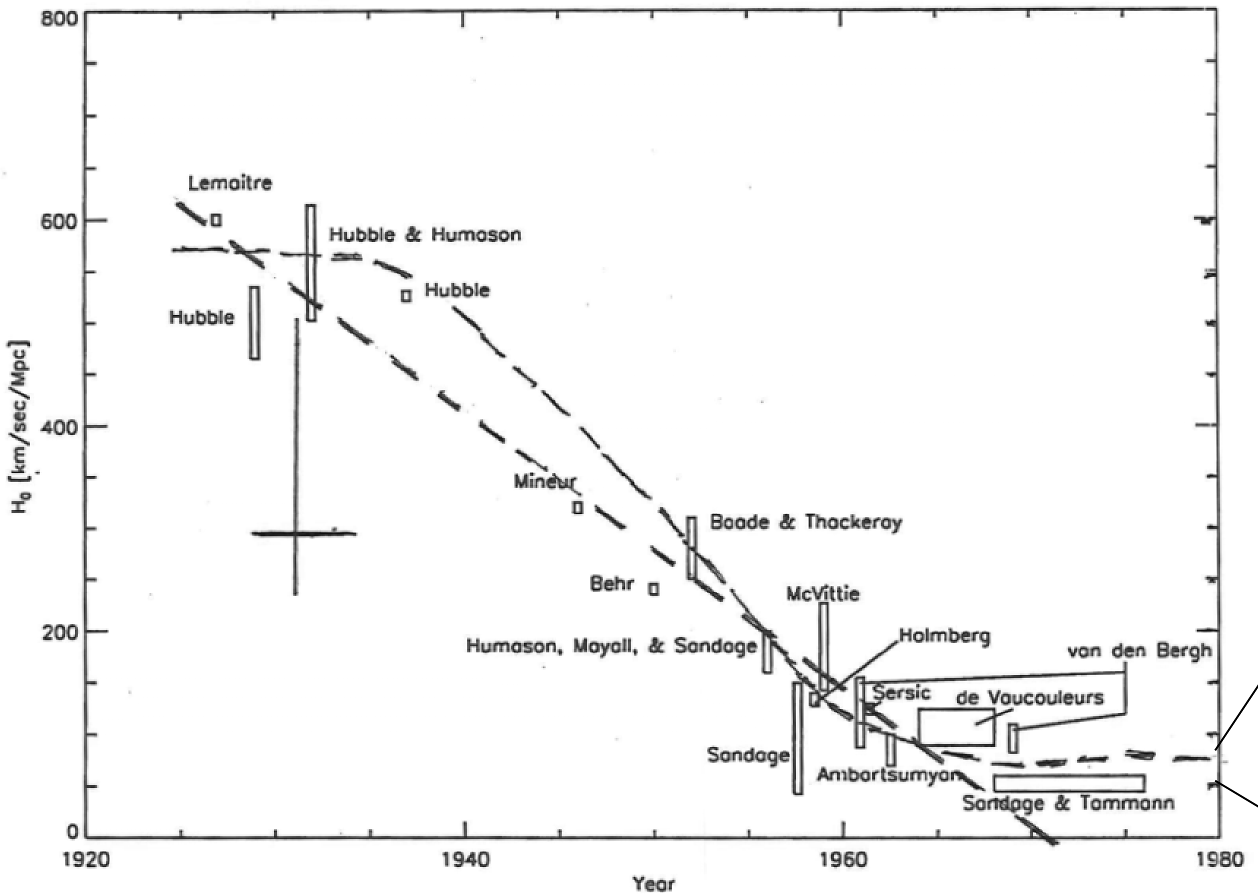
Hildebrandt+ 16 BUT GPE+ arXiv:1707.00483

H0

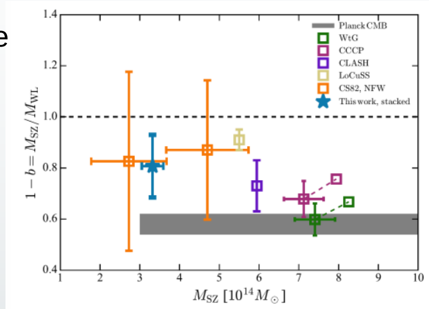


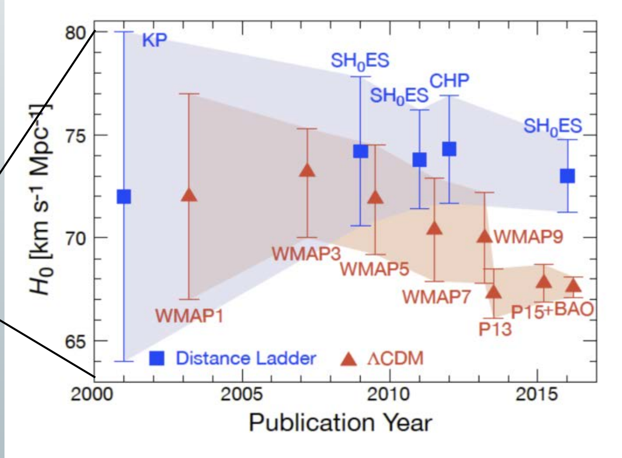
Freedman, arxiv/1706.02739

No-luck, Systematics, or new physics?

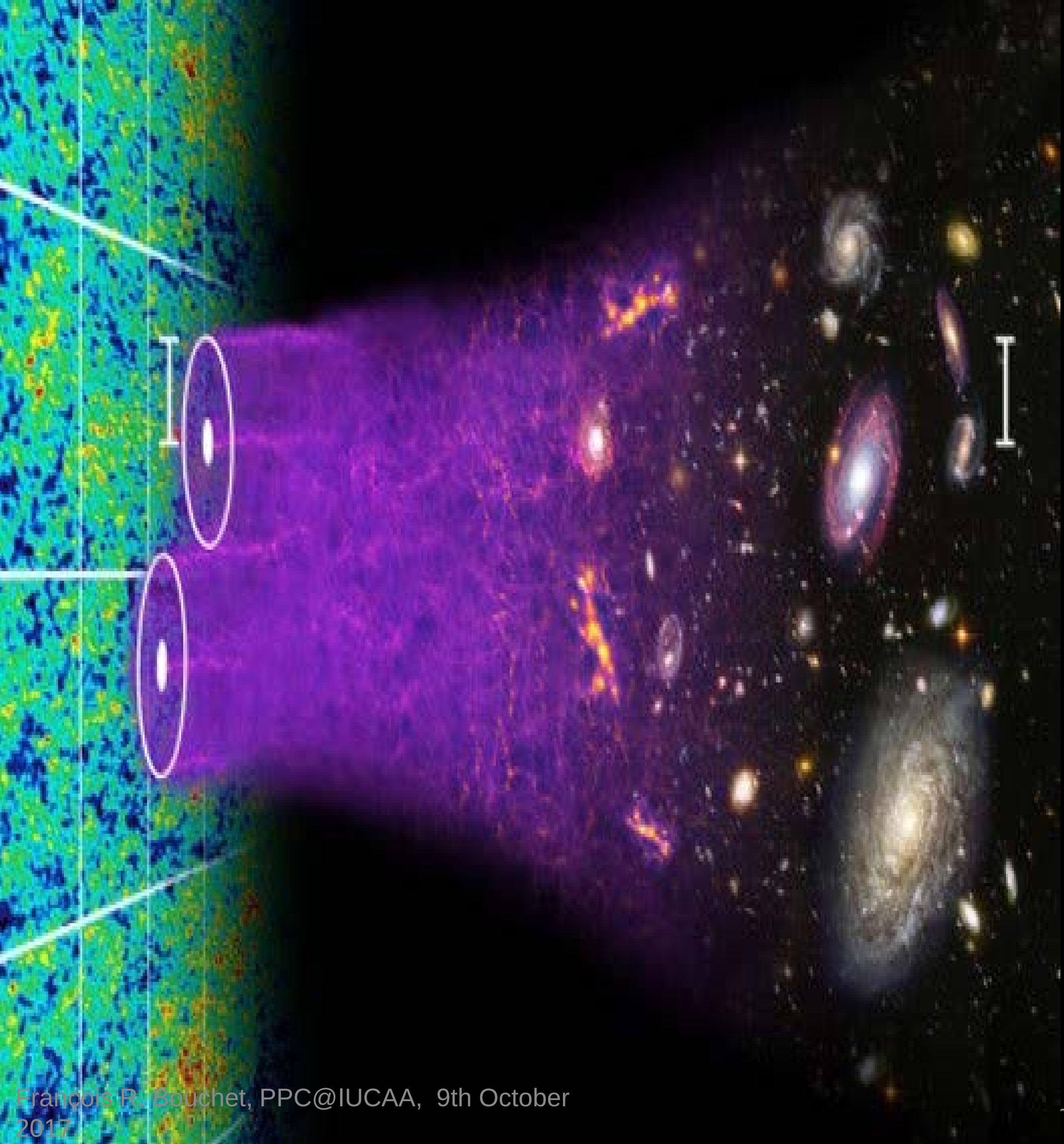


a cluster mass dependence of the bias?

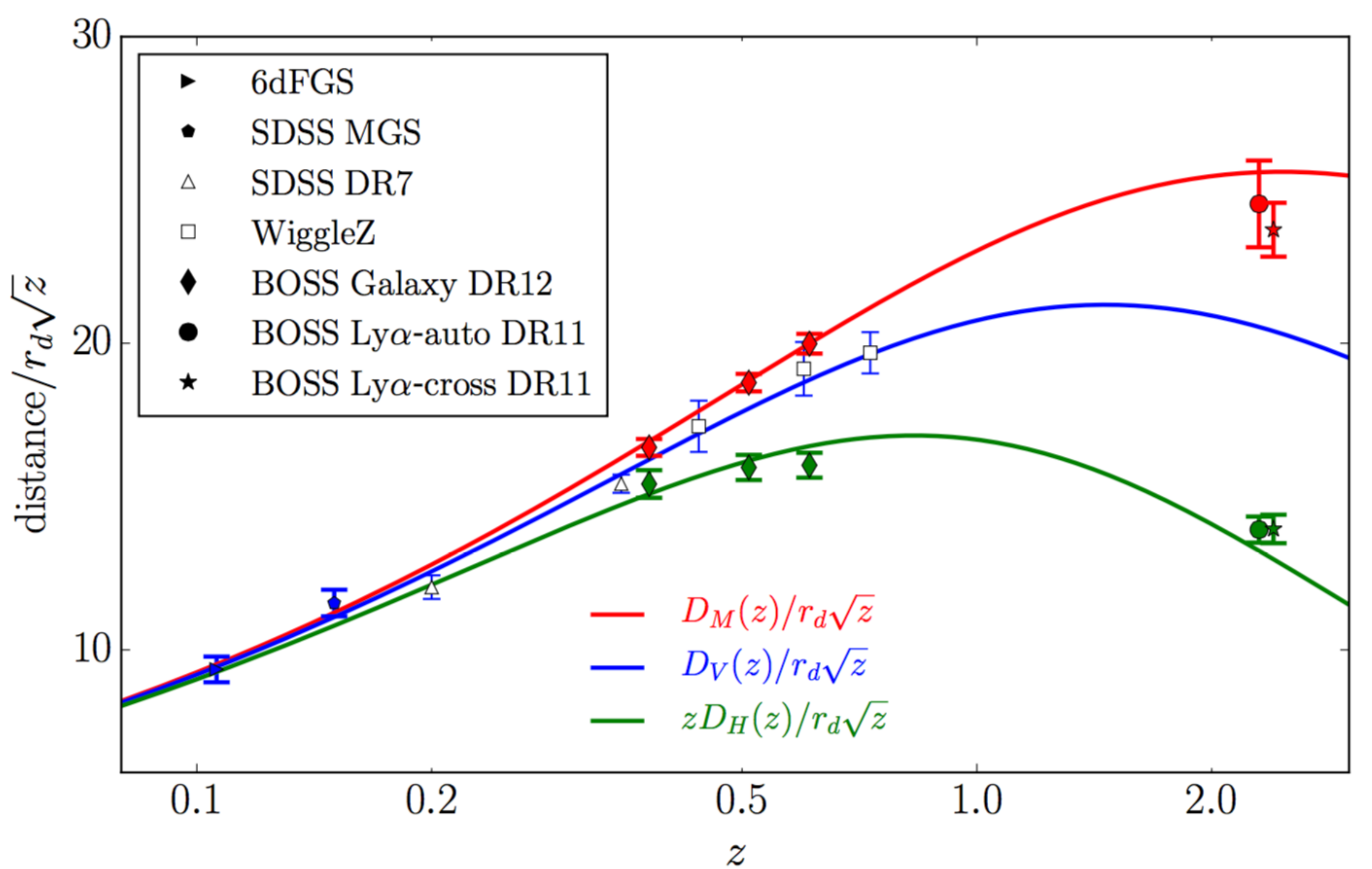




- Planck consistent with BAO, SN, BBN <u>within</u> LCDM.
- H_0 tension present also in WMAP+BAO+SN.
- WMAP and Planck in very good agreement if compared at same scales.
- WMAP+SPT do not have statistical power of Planck
- Planck low-l & Planck high-l are in good statistical agreement
- Smoothing of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



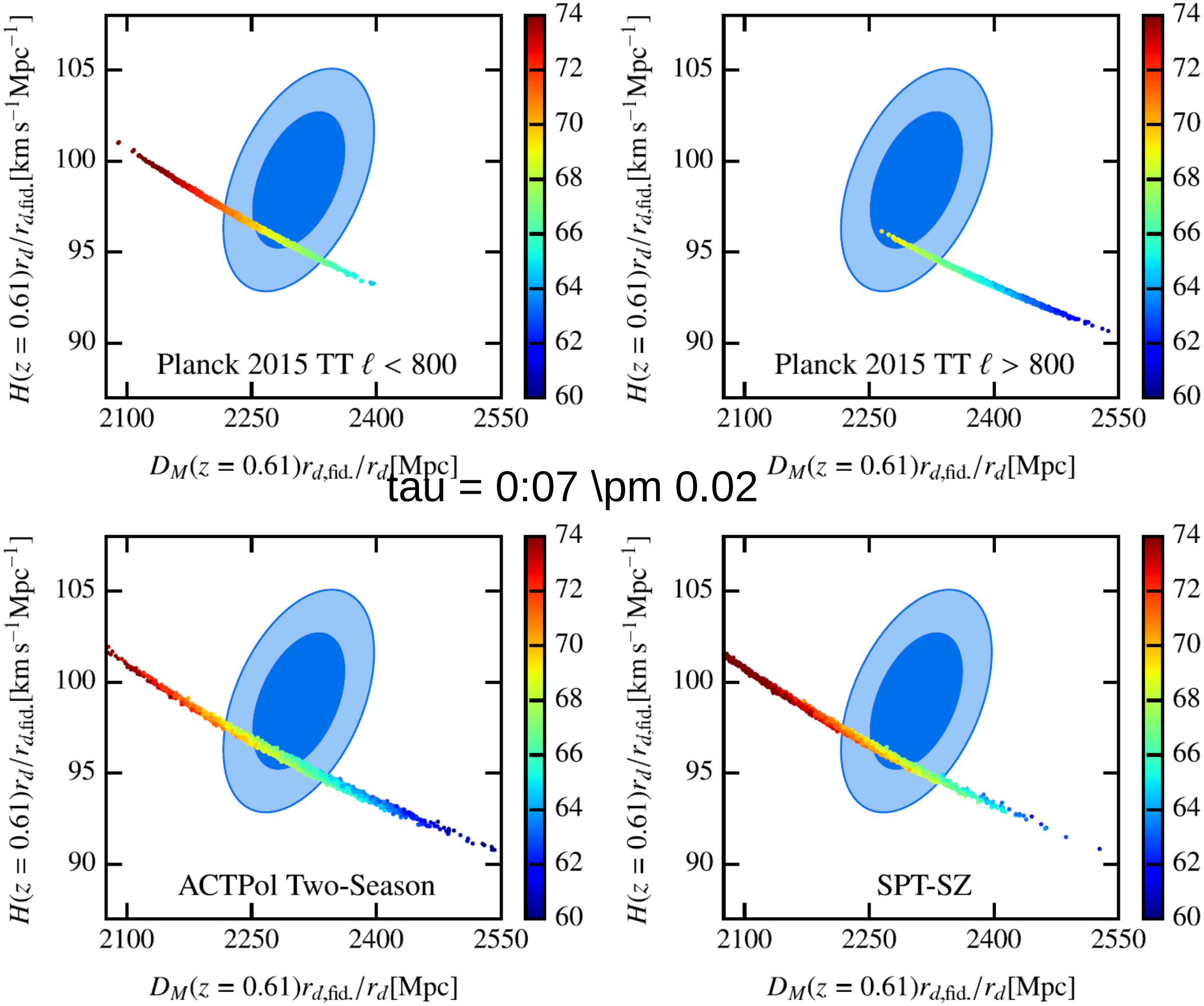
BOSS RD12, Alam+2016, arXiv:1607.03155v1



CMB, BAO... and Ho

(Addison+ arXiv:1707.06547)

blue shaded contours are the measurements from the final BOSS DR12 analysis (Alam et al. 2016)



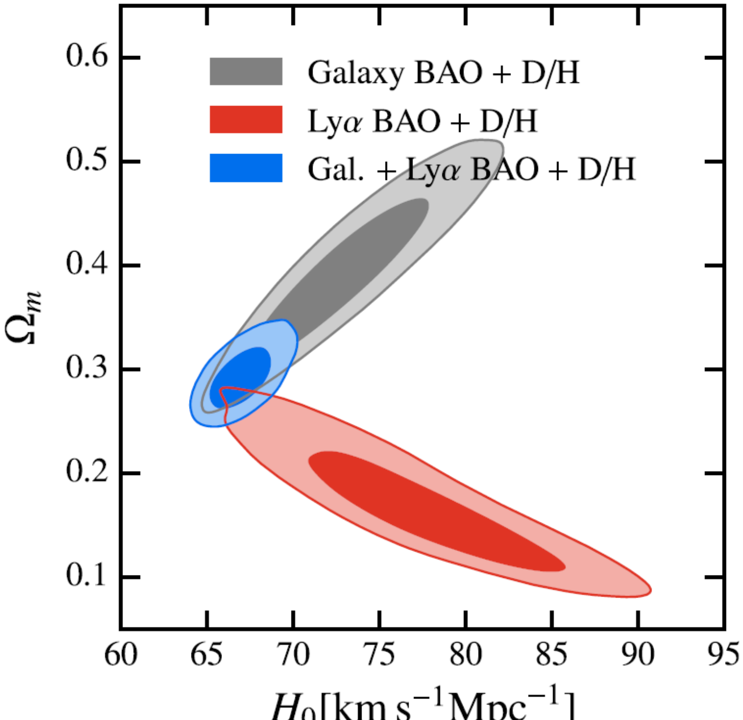
tau = 0:07 \pm 0.02

CMB, BAO… and Ho

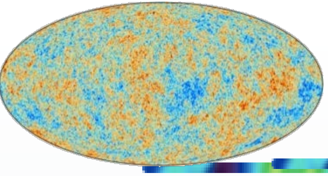
(Addison+ arXiv:1707.06547)

ΛCDM constraints from the BAO+D/H fits, using either the theoretical or empirical $d(p,\gamma)^3$He reaction rate, with CMB anisotropy constraints from *WMAP* and *Planck* included for comparison

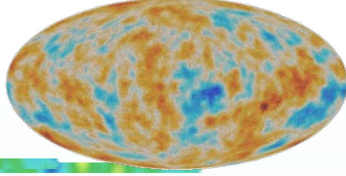
Parameter	BAO+D/H (theoretical)	BAO+D/H (empirical)	*WMAP* 9-year	*Planck* 2016
$100\Omega_b h^2$	2.156 ± 0.020	2.257 ± 0.034	2.265 ± 0.049	2.215 ± 0.021
$100\Omega_c h^2$	10.94 ± 1.20	11.19 ± 1.29	11.37 ± 0.46	12.07 ± 0.21
$100\theta_{\rm MC}$	1.0292 ± 0.0168	1.0320 ± 0.0173	1.04025 ± 0.00223	1.04076 ± 0.00047
H_0 [km s^{-1} Mpc^{-1}]	66.98 ± 1.18	67.81 ± 1.25	69.68 ± 2.17	66.89 ± 0.90
Ω_m	0.293 ± 0.019	0.293 ± 0.020	0.283 ± 0.026	0.321 ± 0.013
r_d [Mpc]	151.6 ± 3.4	149.2 ± 3.6	148.49 ± 1.23	147.16 ± 0.48



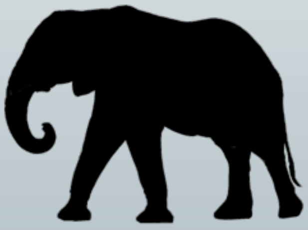
These two results taken together (BAO + CMB, BAO+D/H) indicate that it is not possible to resolve the H_0 disagreement solely through some systematic error specific to the Planck dataset.

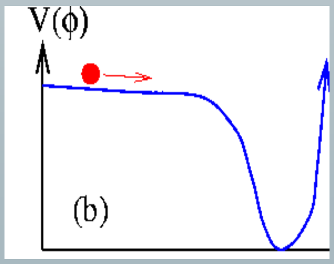


Summary: Basic ΛCDM fits



- 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?

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, chains and parameters, component maps, NG analysis, etc.

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