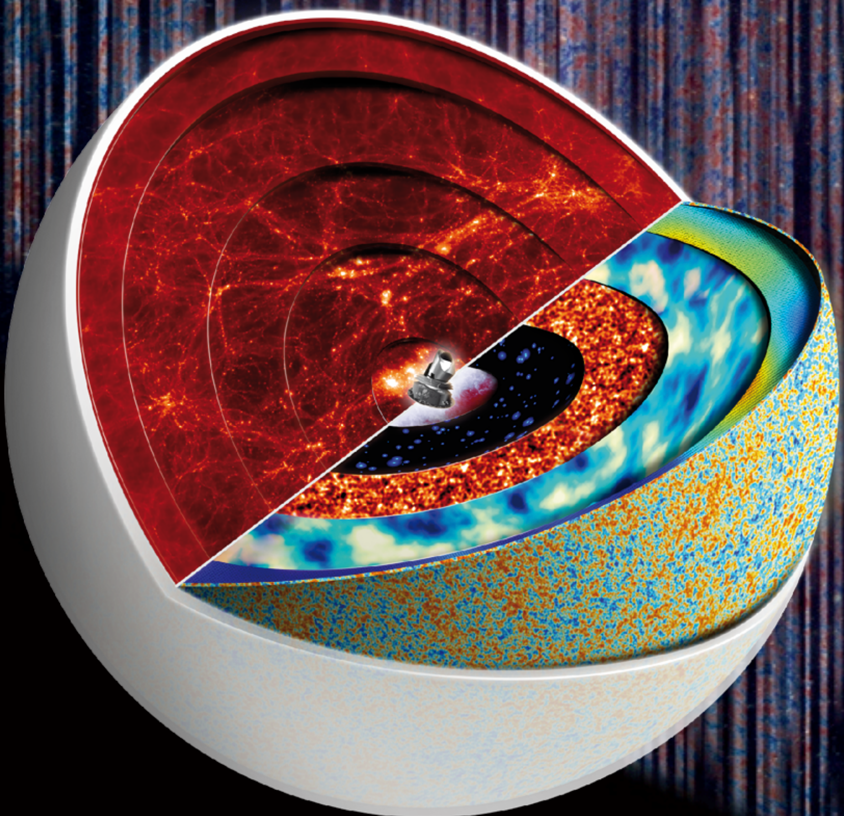
Peaking through the veils

... in order to trace the
origin of the cosmic web
to quantum foam



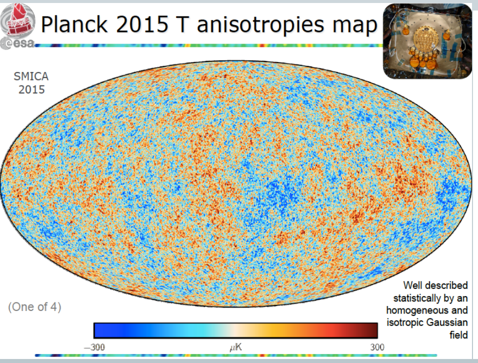
YKIS2018a Symposium

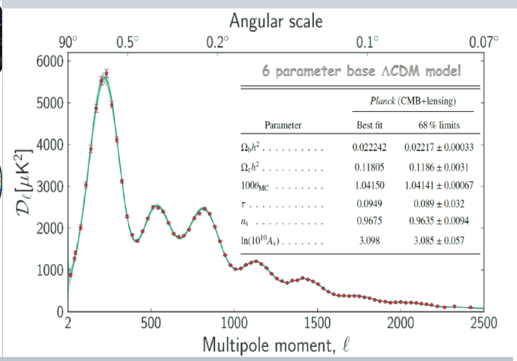
François R. Bouchet

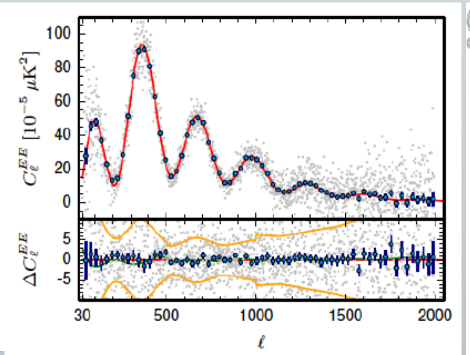
Collaborators

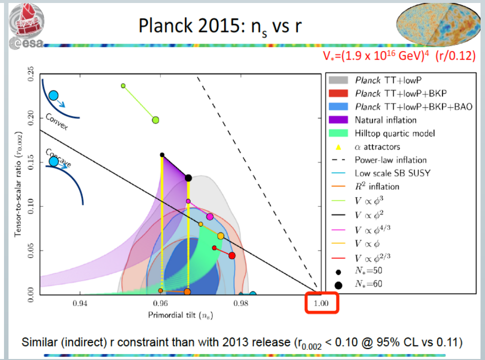
Preamble

- I gave a colloquium talk here two weeks ago and I'd like to avoid being too boring for those we attended.
- Many Planck results are very well known to this audience, and actually used by quite a number of the previous speakers. At least those results regarding primordial cosmology.
- Of course, the iconic results (in some circles) are only a small fraction of Planck results. We wrote about 150 papers, ~½ in cosmology, and among those, many were on astrophysical cosmology (SZ, CIB, point sources…). But this is probably not the right audience for an exhaustive/exhausting overview ☺.
- So should we break for coffee?









Some questions to address

- How did Planck achieve such a huge increase of sensitivity as compared to anything pre-existing?
- Are the derived results as accurate as they are precise?
- Which new science was made possible with the very large increase in the number of CMB modes measured?
- Is there any fly in the ointment?
- What to expect next, from Planck and others?

The Planck mission concept/challenge

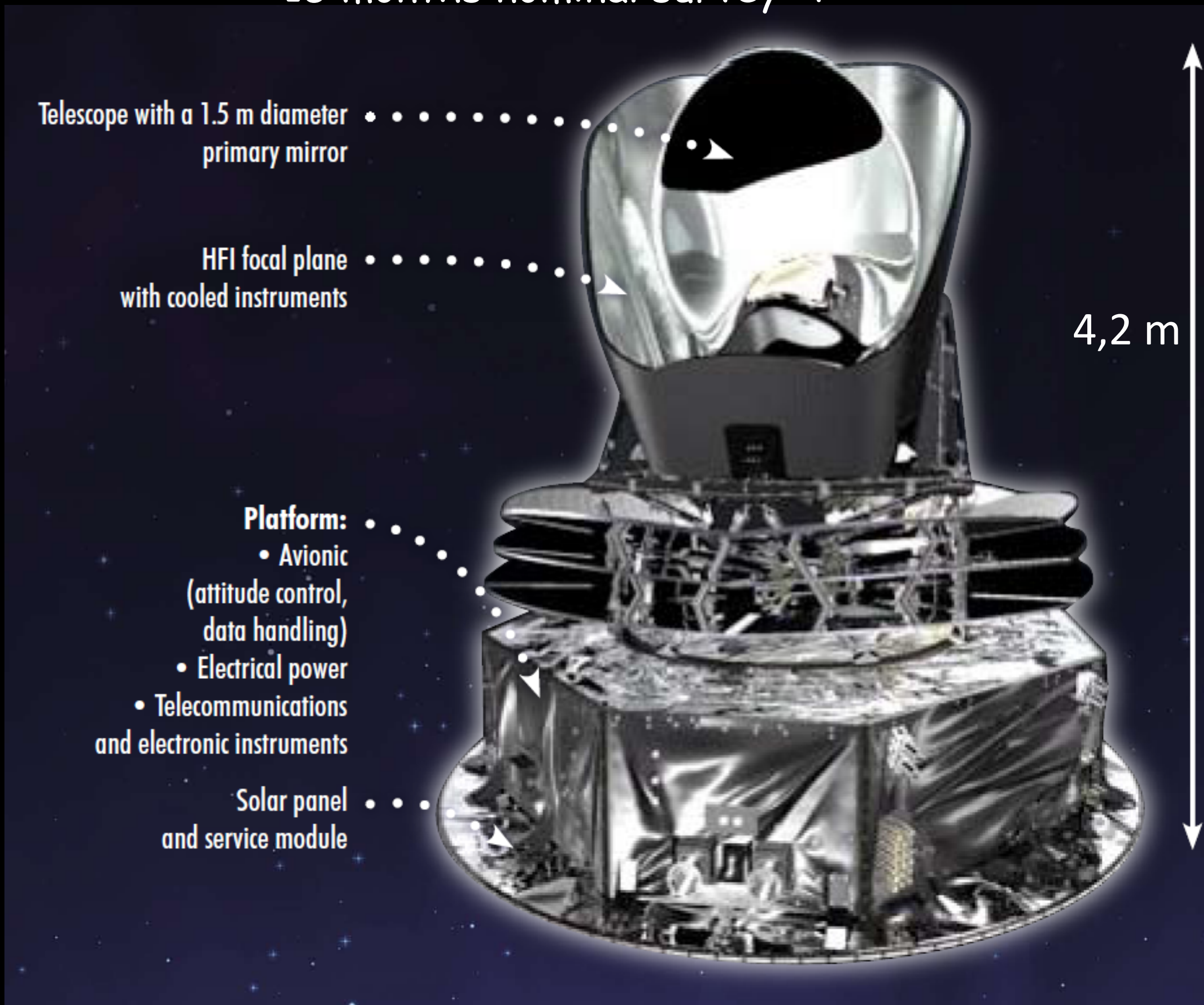
- to perform the “ultimate” measurement of the Cosmic Microwave Background (CMB) temperature anisotropies:
  - *full sky coverage & angular resolution / to survey all scales at which the CMB primary anisotropies contain information (~5’)*
  - *sensitivity / essentially limited by ability to remove the astrophysical foregrounds*
  - ⇒ *enough sensitivity within large frequency range [30 GHz, 1 THz]*
    (~CMB photon noise limited for ~1yr in CMB primary window)
- get the best performances possible on the polarization with the technology available

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

NB1: This required a number of technological breakthroughs.

NB2: with the Ariane-501 failure delaying us by several years (2003 → 2007) and WMAP then flying well before us, polarization measurements became more and more a major goal

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



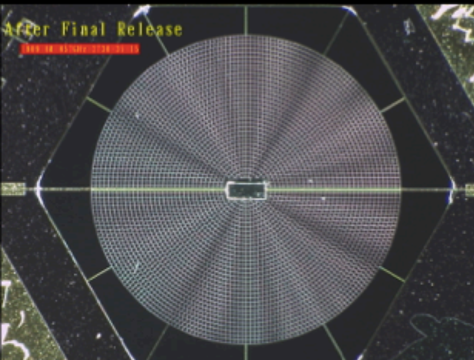
4,2 m

4,2 m

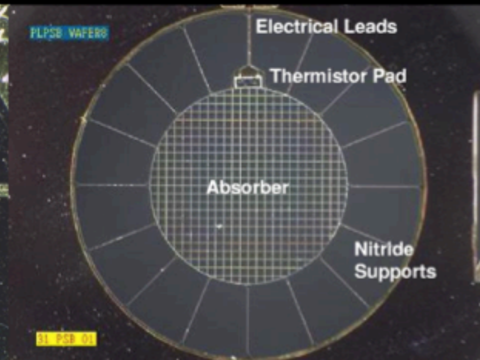
50 000 electronic components
36 000 l ^{4}He
12 000 l ^{3}He
11 400 documents
20 years between the first project and first results (2013)

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

HFI Spider Web Bolometers & PSBs



857 GHz SpiderWeb Bolometer

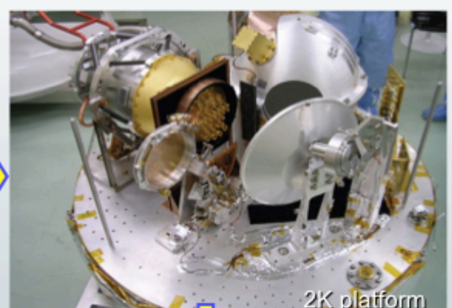


145 GHz PolarSensitiveBolometers

HFI flight bolometers have been built by Caltech/JPL,
integrated into pixels and tested in Cardiff,
integrated into HFI – notably: IAS + JFET (Rome) + REU (CESR) + DPU (LAL)
and then tested at instrument level @ IAS, Orsay.
(and all their data is collected/processed @ IAP, Paris)

HFI Integration & Calibration @ IAS

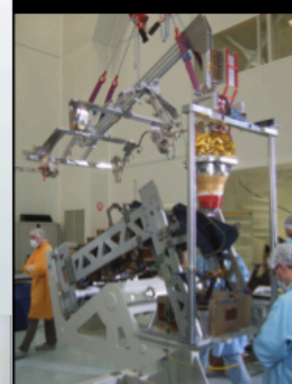
(reproduction of spatial and micro-wave environment)



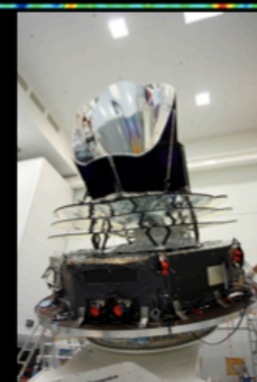
DESIGN GOALS MET !

WMAP would need ~500 years of survey time to reach HFI 1yr sensitivity

Integration at Thales-Cannes



HFI + LFI integration

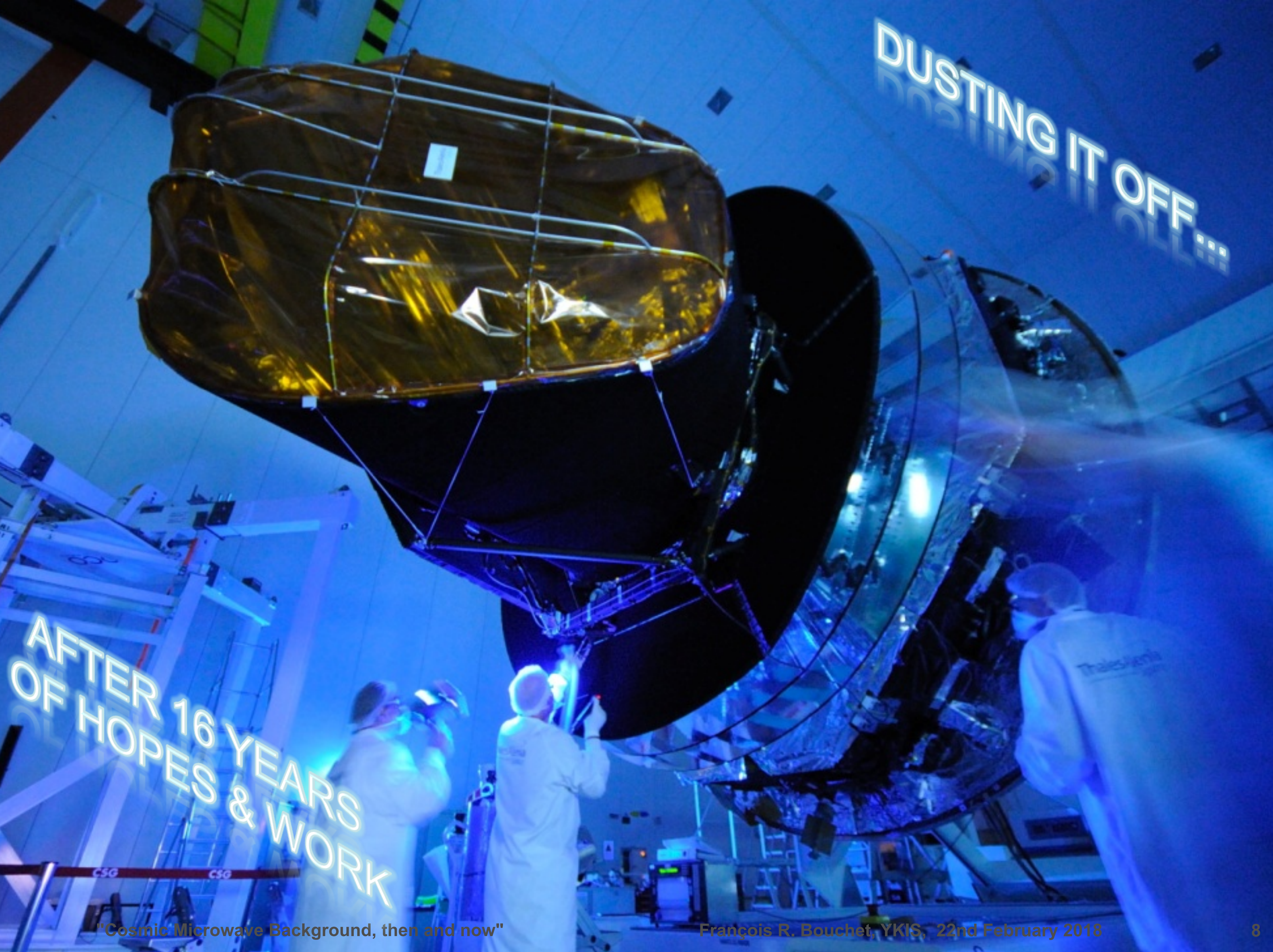


Dec 9th 2007, Ready for vibration testing

April 7th 08: load balancing

April 18th 2008: preparing ESTEC → CSL

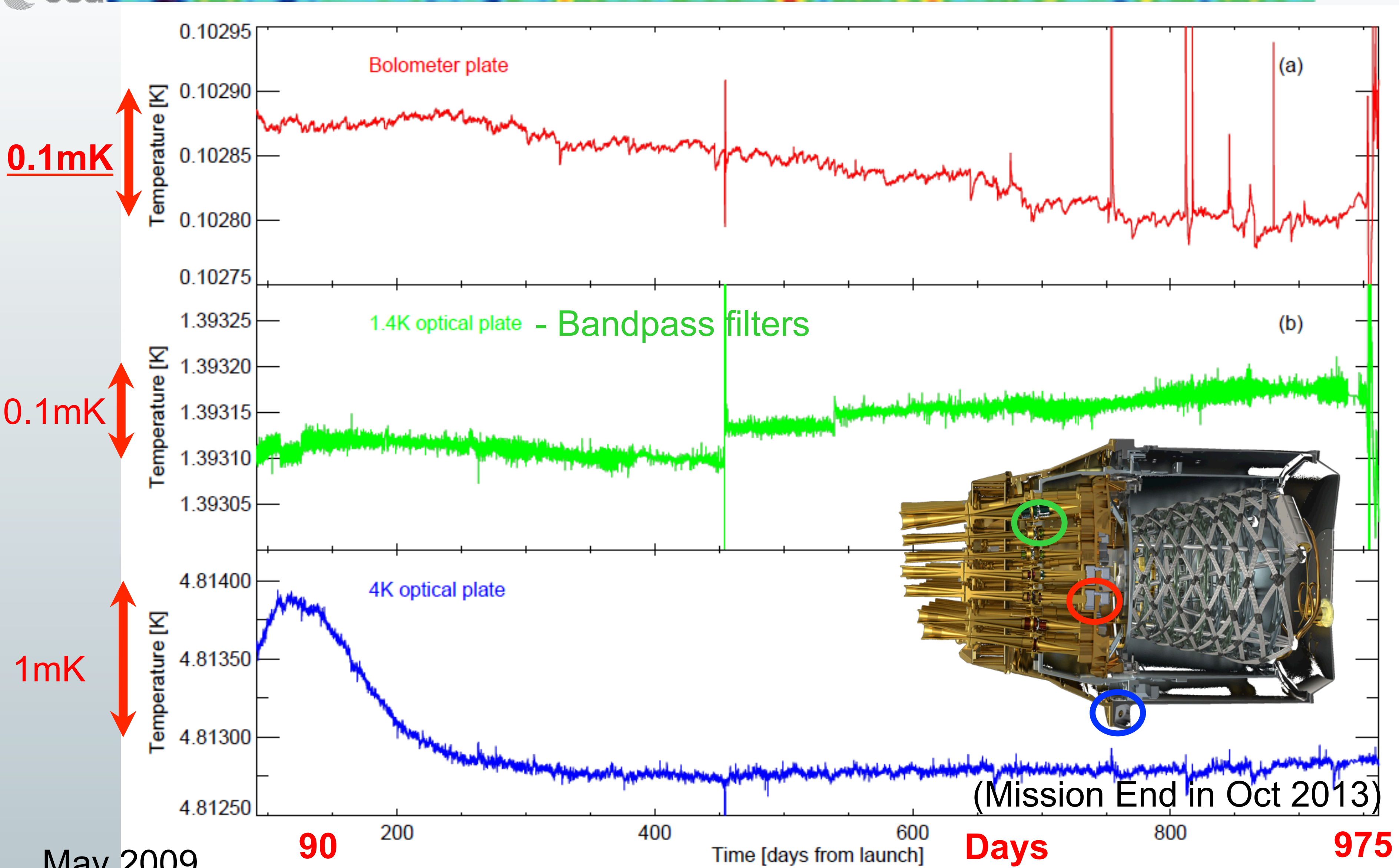
03/08: Antonov Nice → ESTEC


DUSTING IT OFF…
AFTER 16 YEARS
OF HOPES & WORK

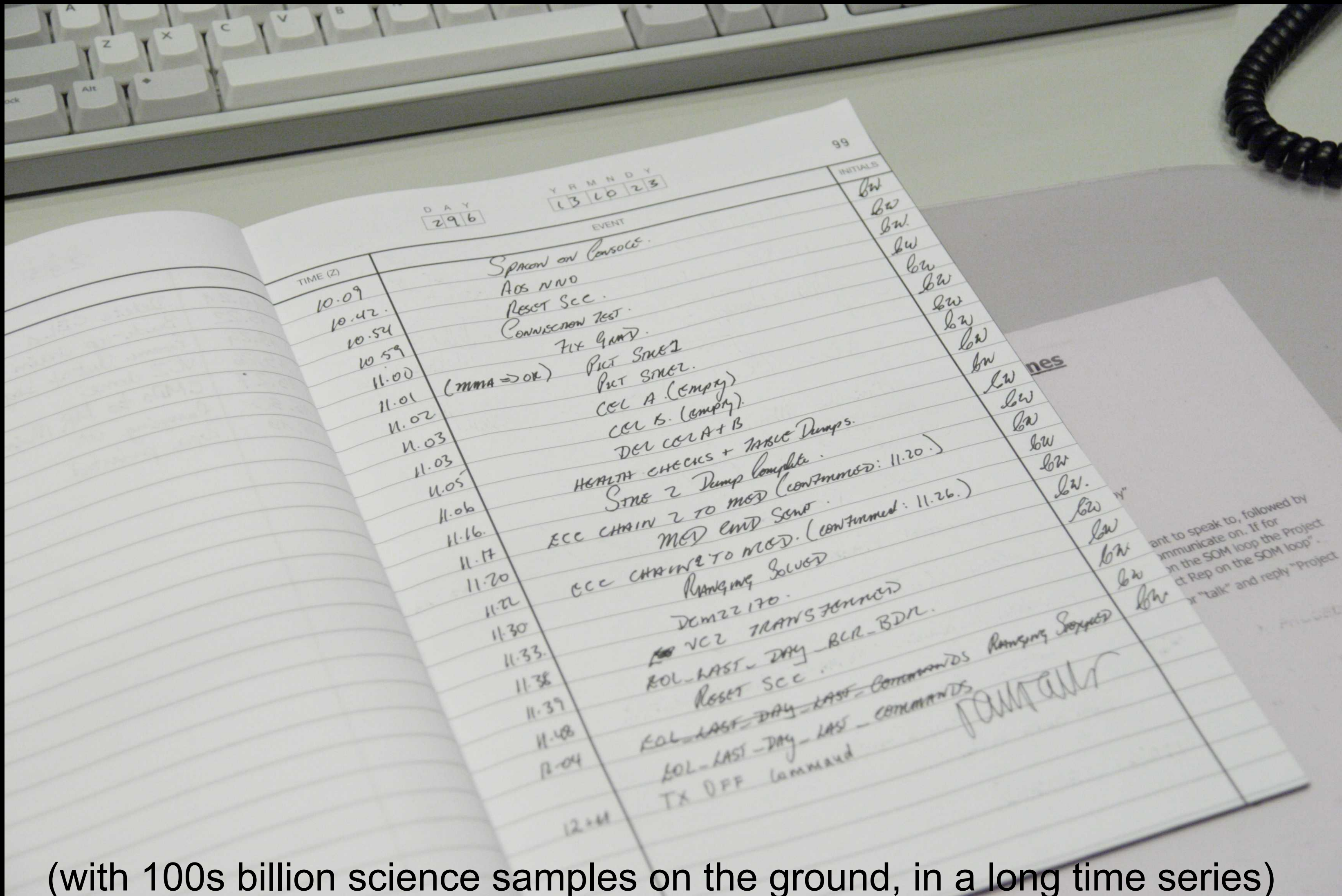

Ariane 5 ECA Launch • HERSCHEL – PLANCK - May 14, 2009

Planck as last seen from the sky

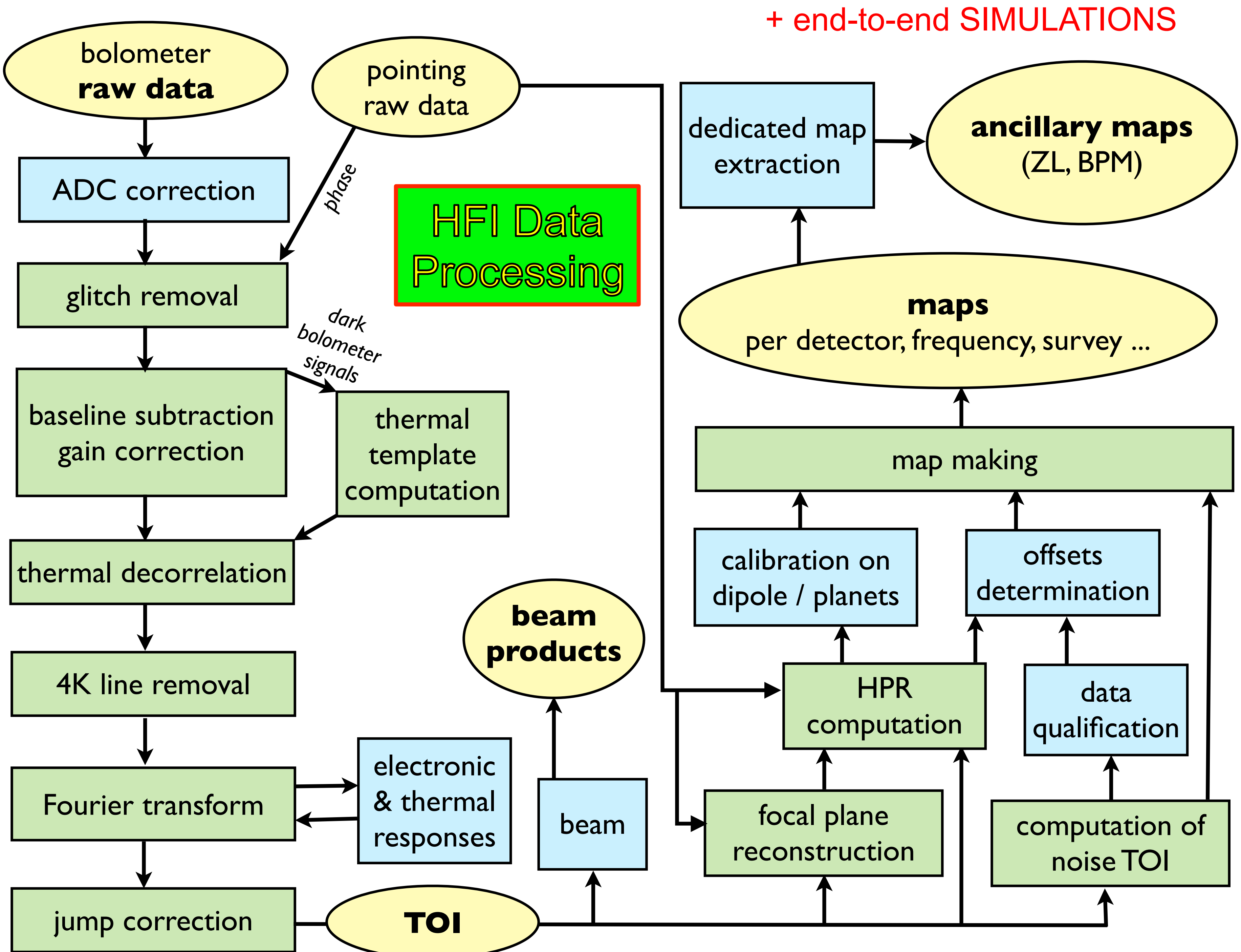
Quietly cool…



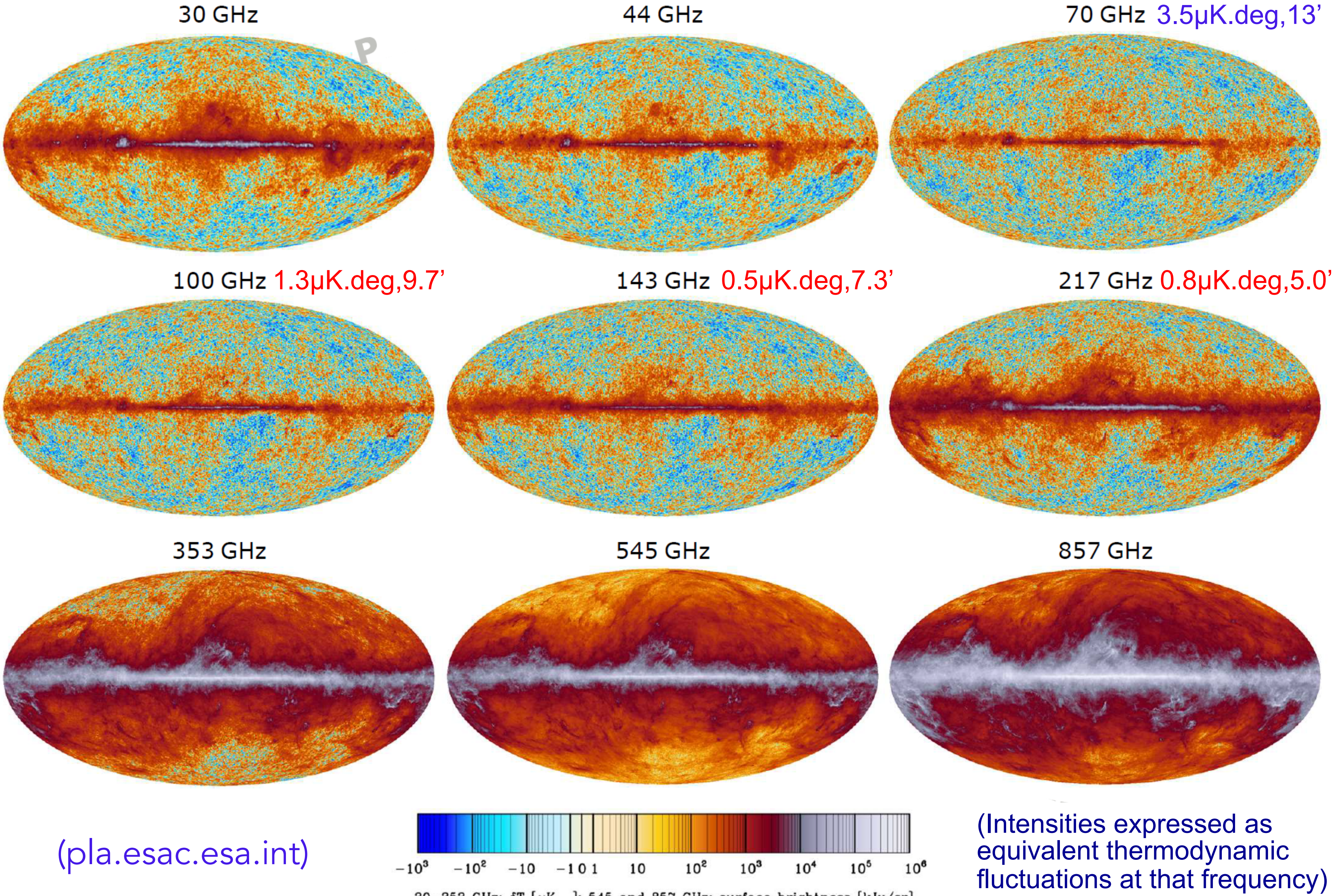
Last commands
Darmstadt, October 23rd 2013



(with 100s billion science samples on the ground, in a long time series)


+ end-to-end SIMULATIONS
bolometer raw data
pointing raw data
phase
HFI Data Processing
ADC correction
glitch removal
dark bolometer signals
baseline subtraction gain correction
thermal template computation
thermal decorrelation
4K line removal
Fourier transform
electronic & thermal responses
jump correction
TOI
beam
beam products
focal plane reconstruction
HPR computation
calibration on dipole / planets
offsets determination
data qualification
computation of noise TOI
map making
maps
per detector, frequency, survey ...
dedicated map extraction
ancillary maps
(ZL, BPM)

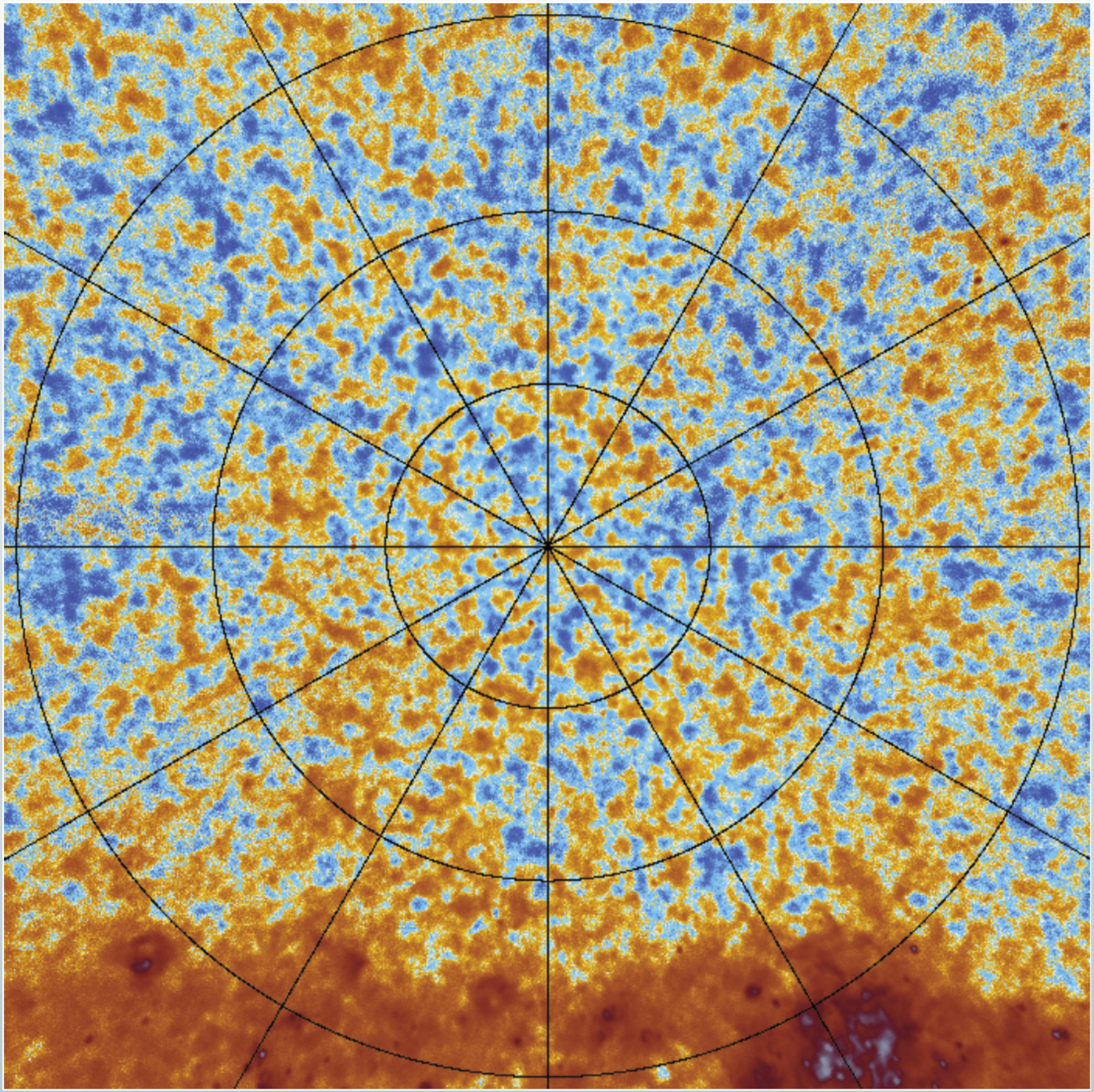
Planck 2015 Temperature maps



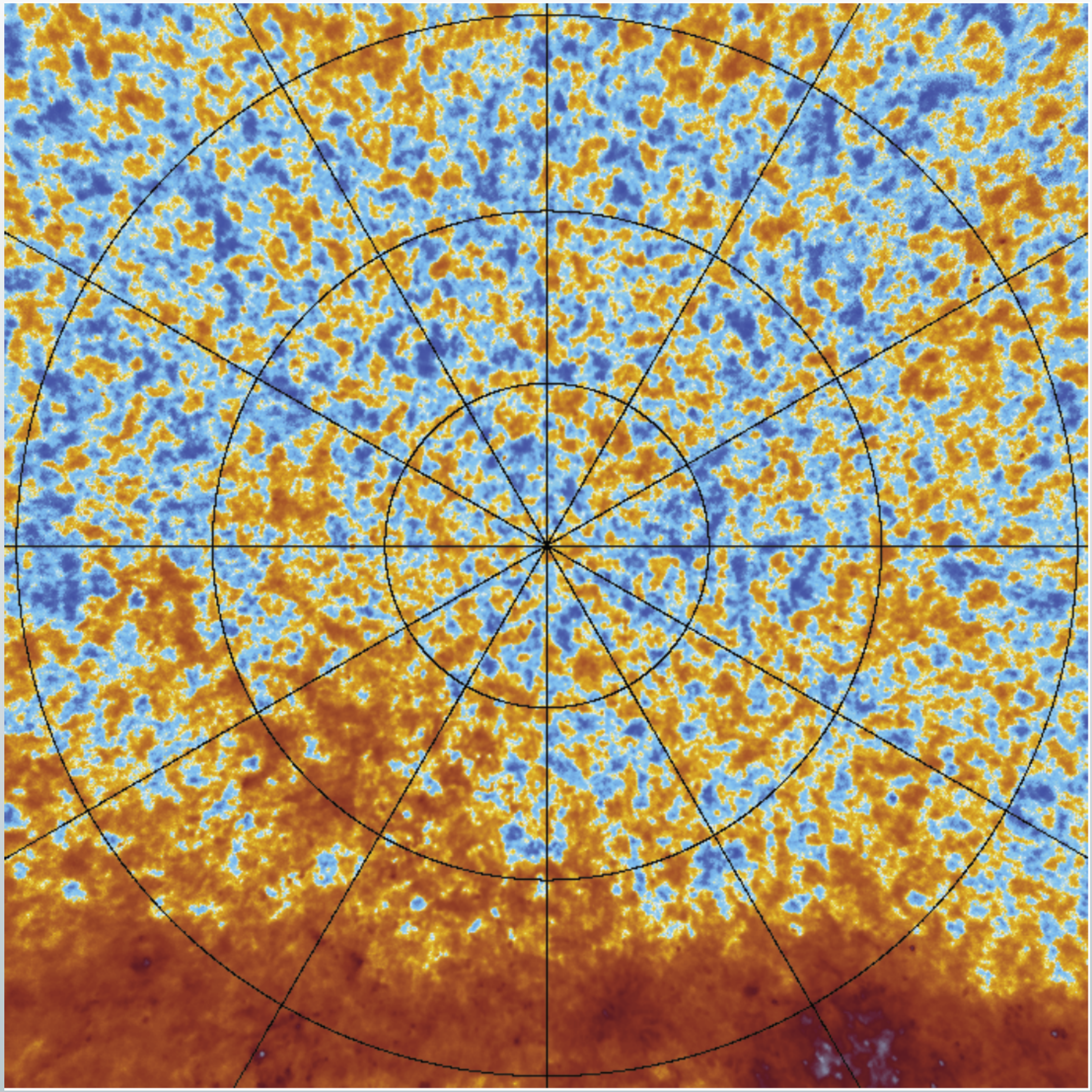
(pla.esac.esa.int)

(Intensities expressed as equivalent thermodynamic fluctuations at that frequency)

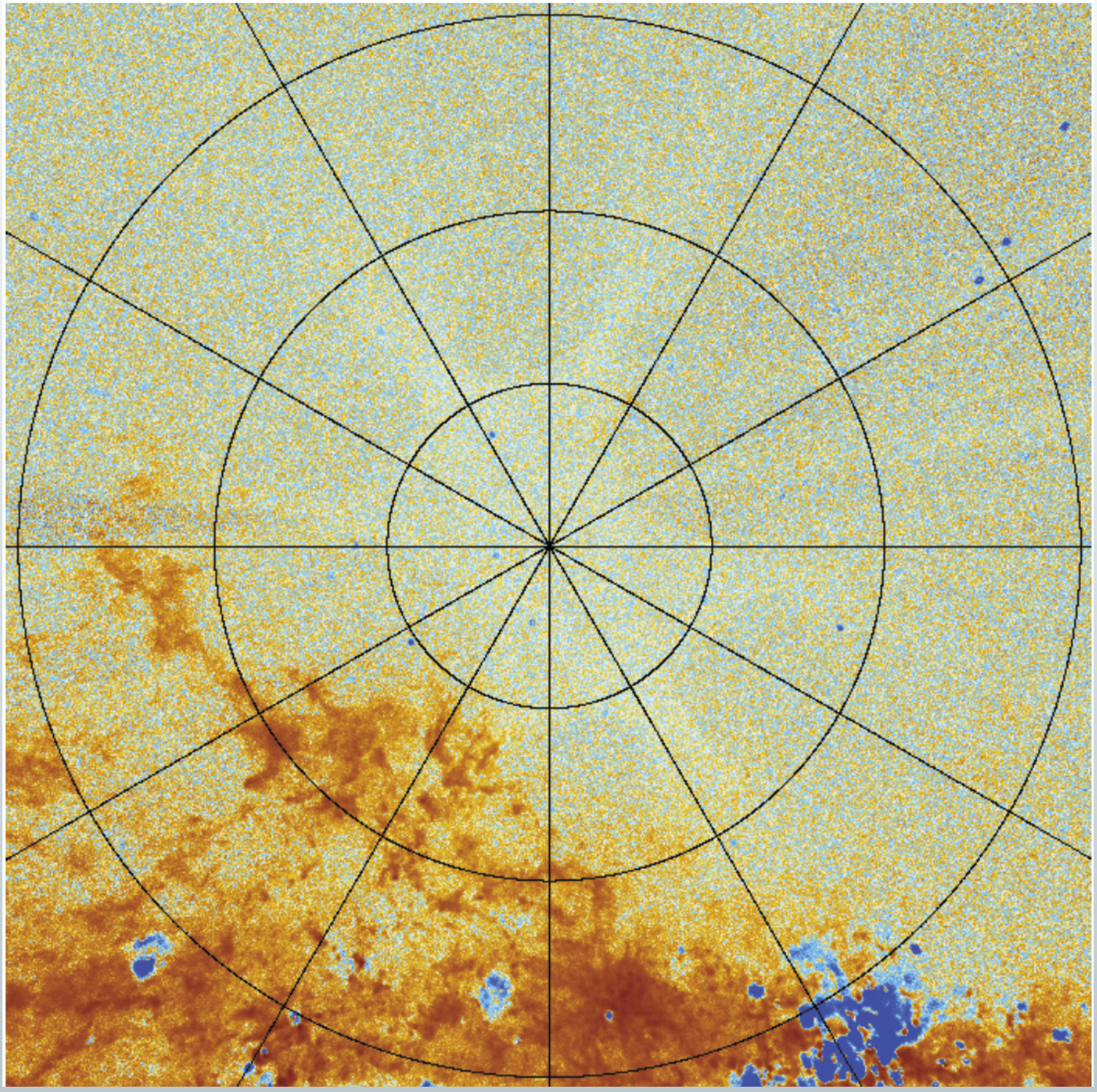
North Ecliptic pole: LFI @ 70 GHz



North Ecliptic pole: HFI @ 100 GHz

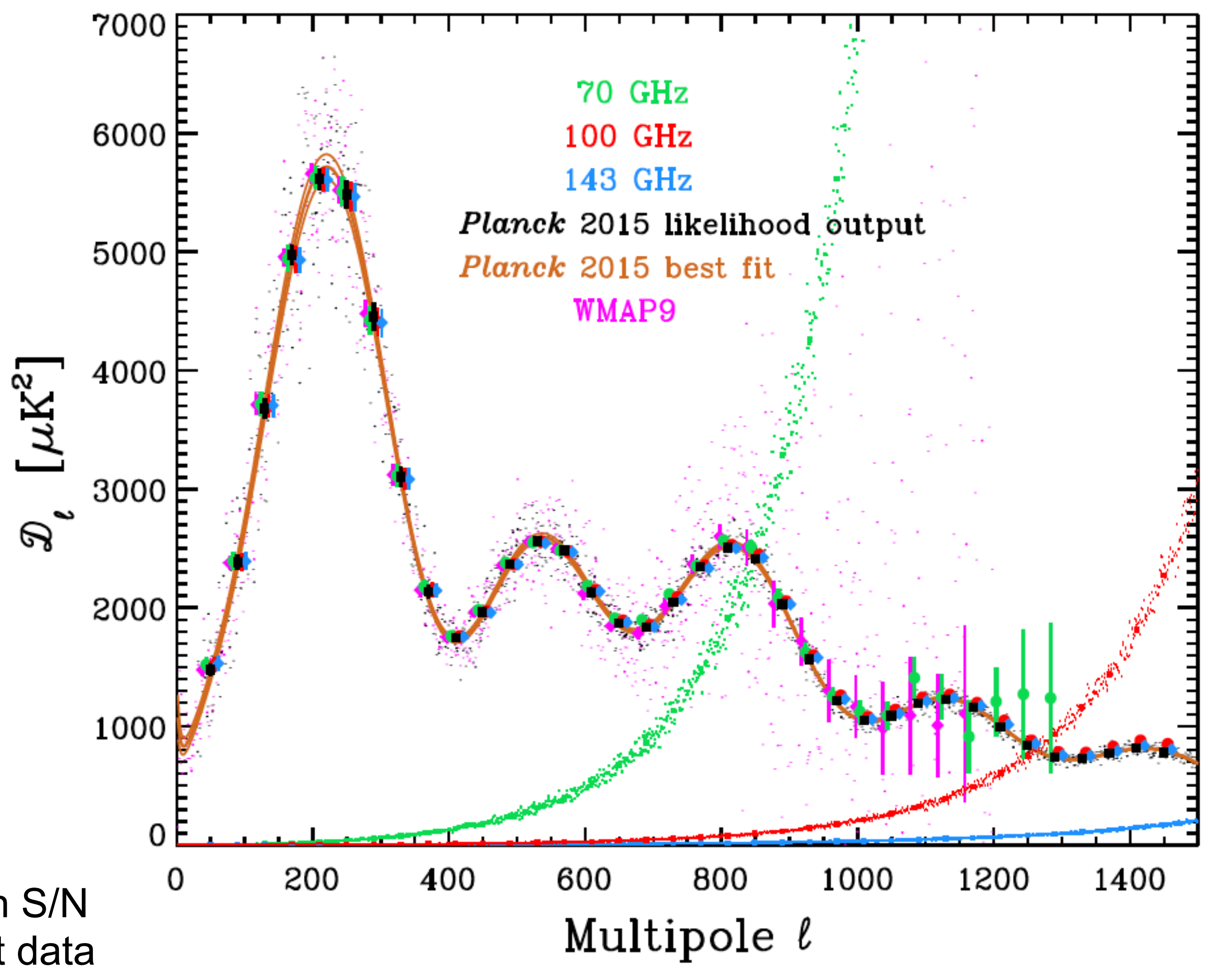


North Ecliptic pole: 100-70 GHz



The two Planck instruments / technologies measure the same CMB anisotropies

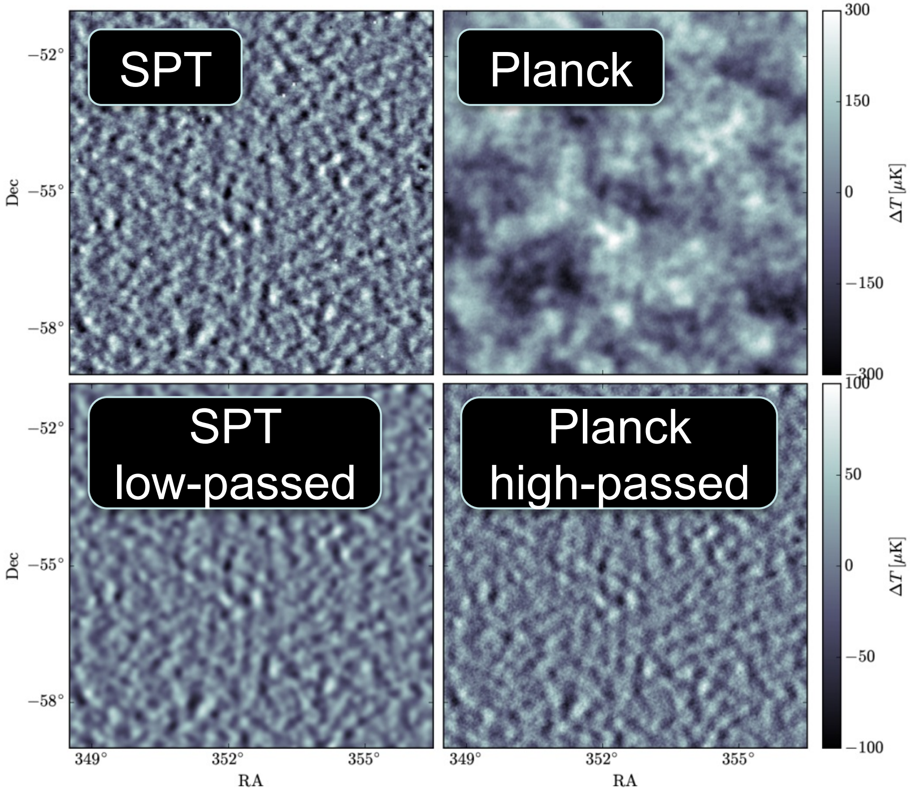
Channels consistency / noise levels



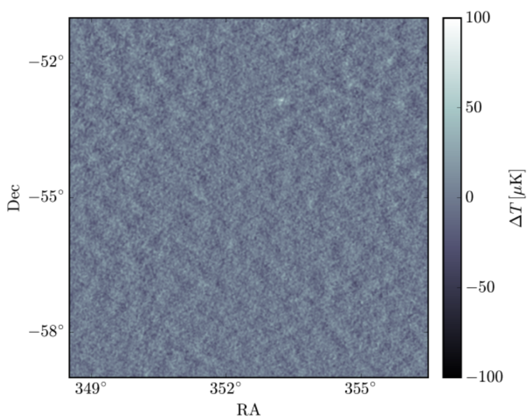
Many high S/N redundant data

SPT@150GHz vs planck@143GHz

Hou+ arXiv:1704.00884v1

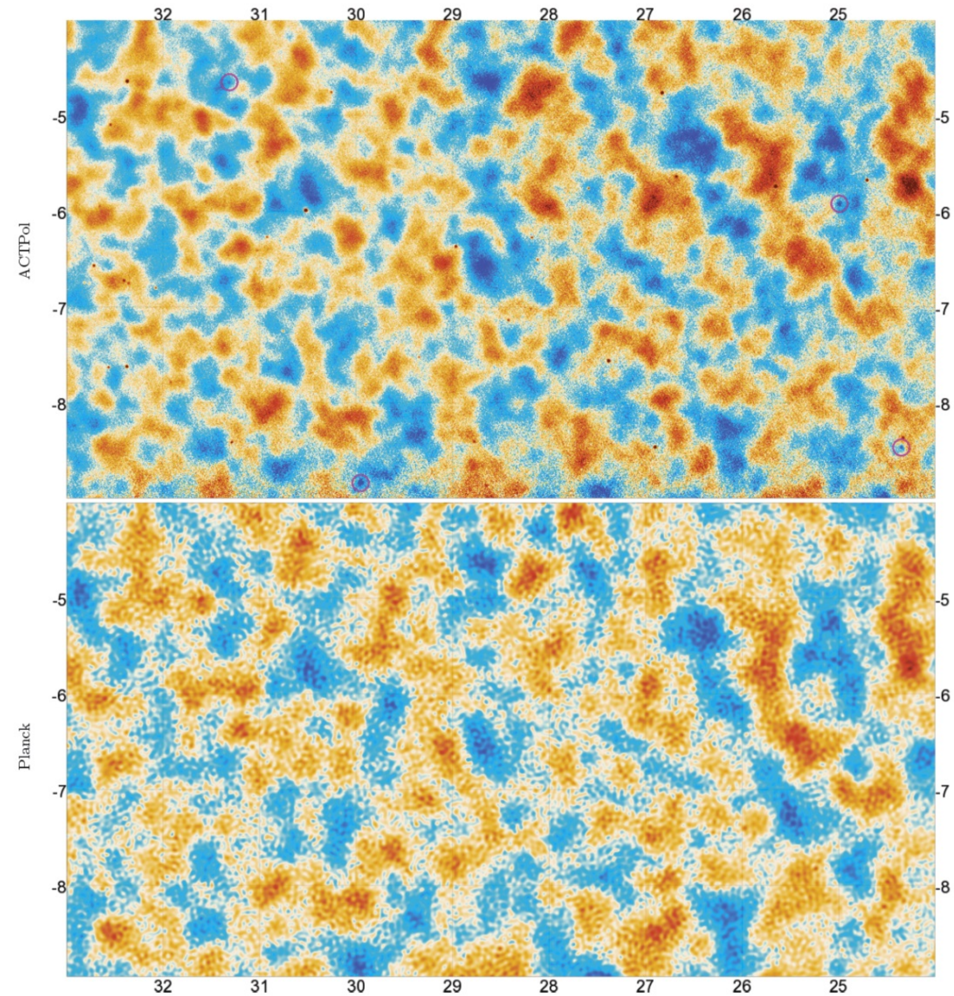


Little residual in SPT-low minus Planck-high, but a variable source



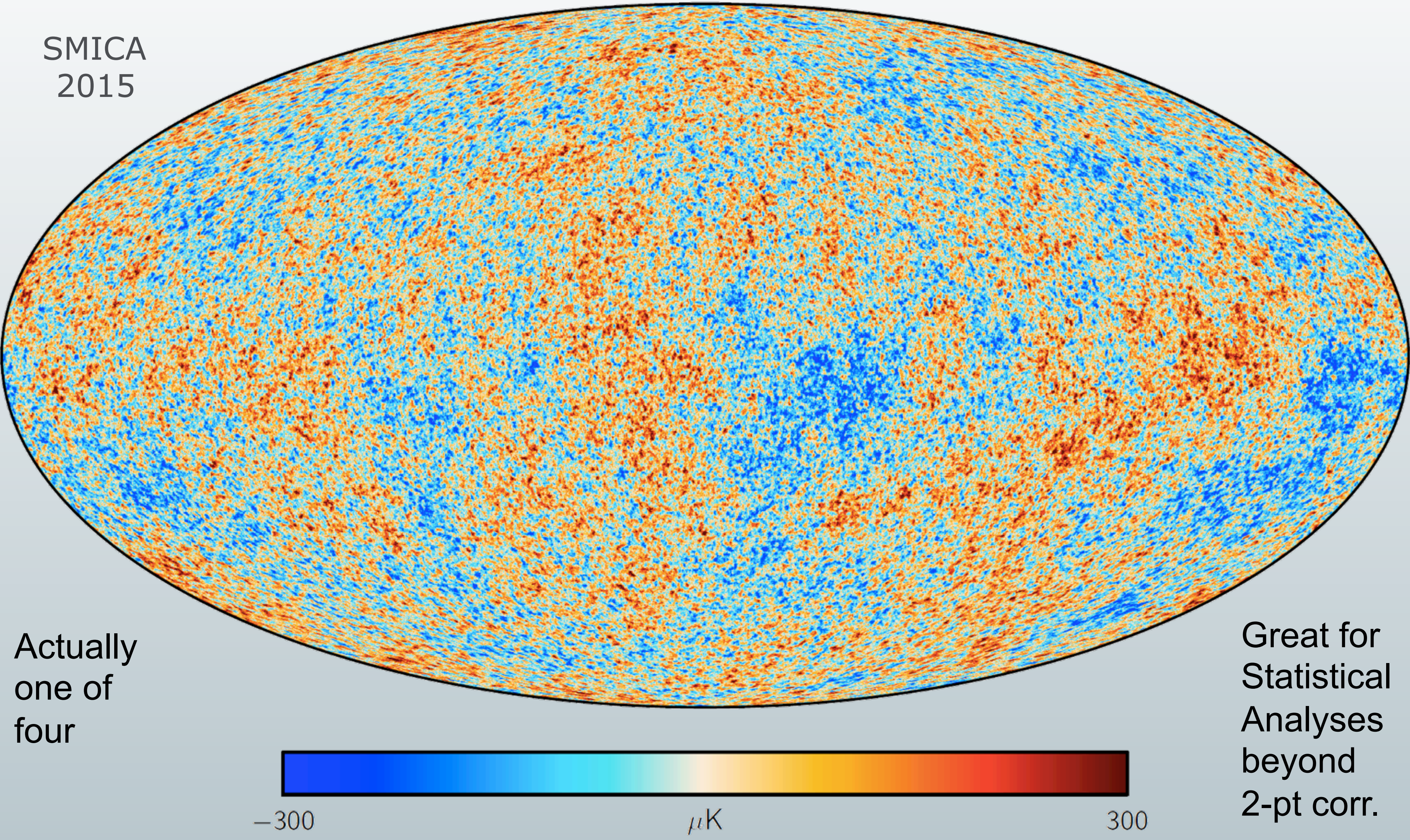
ACT@150GHz vs planck@143GHz

Louis+ arXiv:1610.02360v1



Planck 2015 T anisotropies map

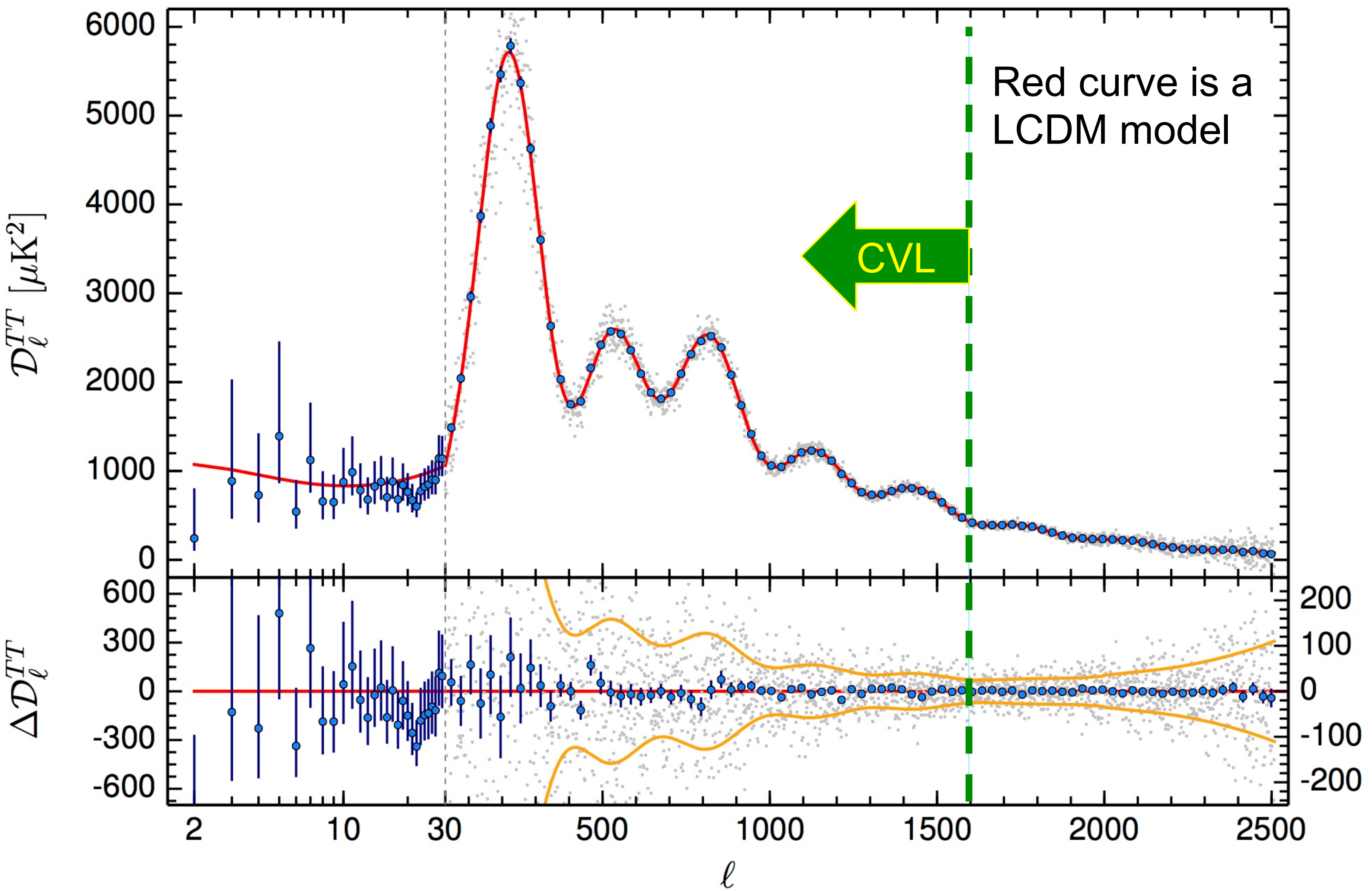
SMICA
2015



Actually one of four

Great for Statistical Analyses beyond 2-pt corr.

Planck 2015 TT spectrum



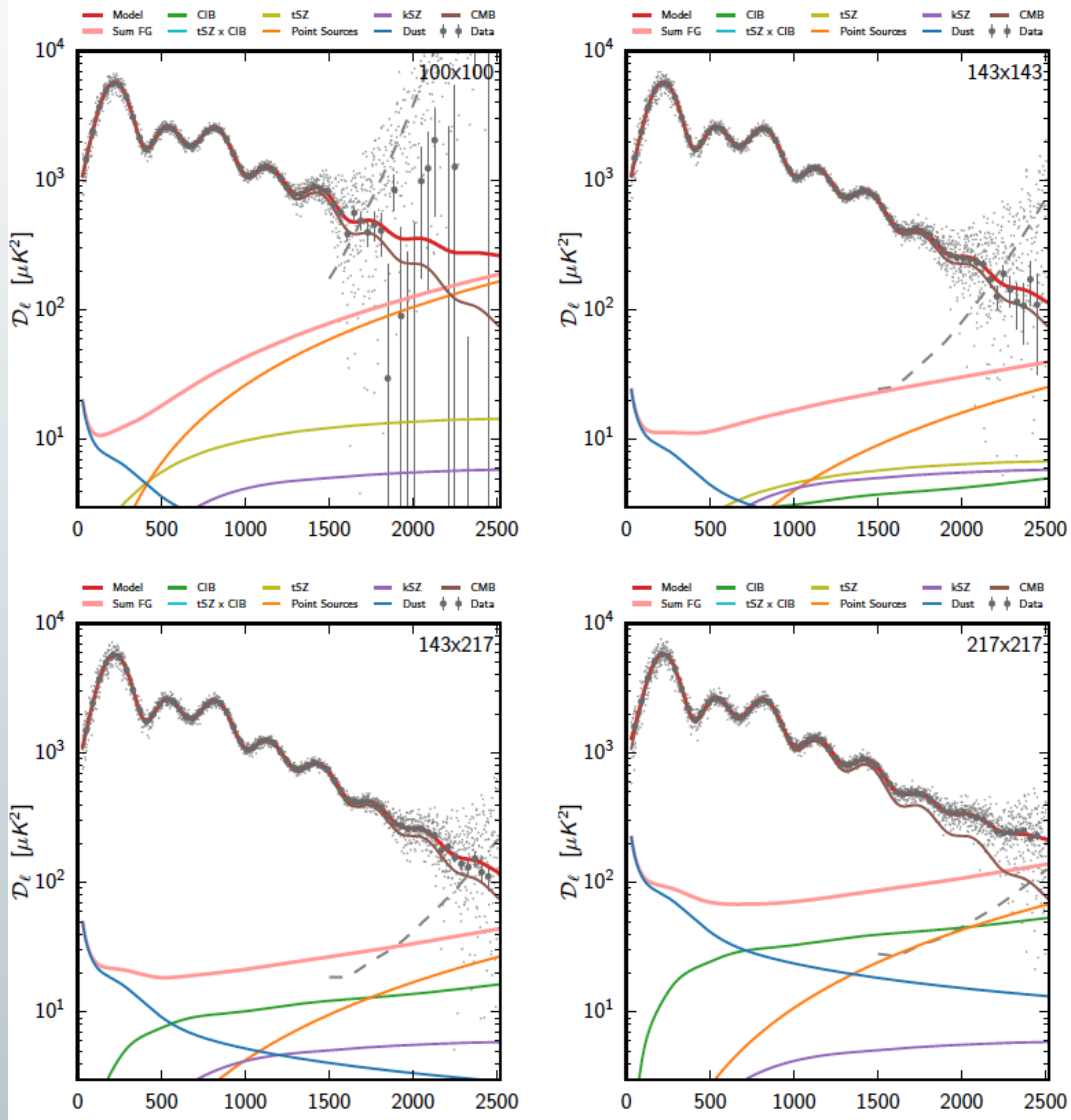
8 acoustic peaks well detected

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

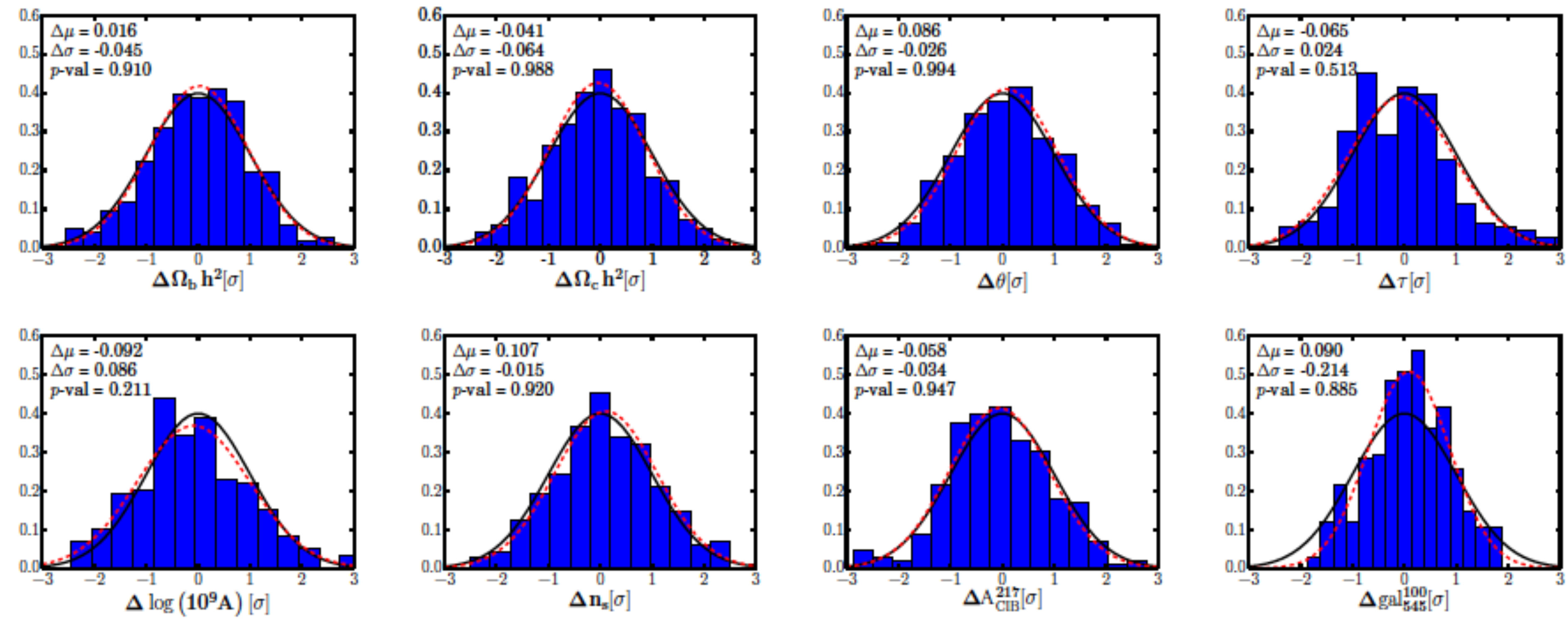
The high-ell likelihood (l>30)

We construct a Gaussian likelihood, using

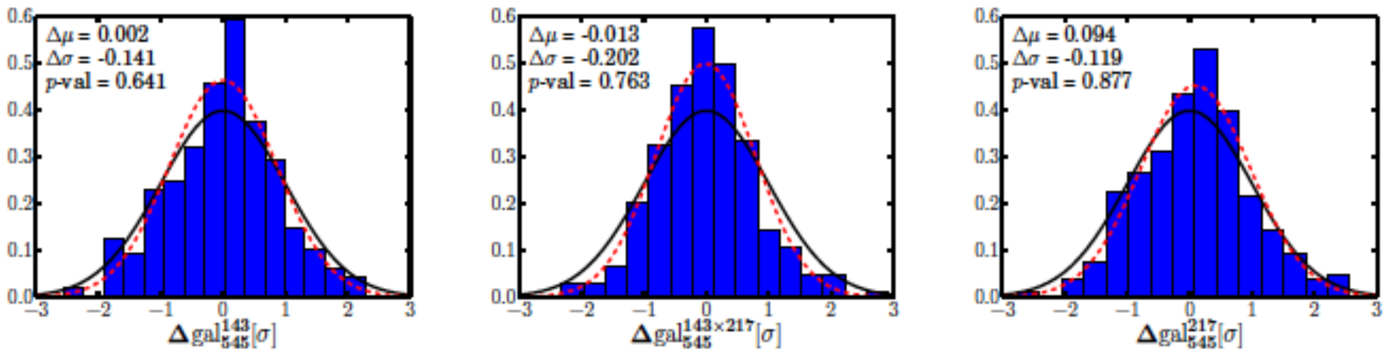
- A parameterised foreground model to, in the end, marginalise over (12 parameters)
- a covariance matrix which includes signal, noise, FG, masks… Full TT, TE, EE reduces to 2300^2 elements when binned instead of 23000^2 (Condition Number~ $O(10^{11})$)
- In practice, many detailed, intertwined choices, e.g., of masks, l-ranges, FG model, cross-spectra combination, etc.
- Test, test, test



Methodological tests on sims, better than 0.1σ



Each sims analysed like real data, from nu maps to parameters



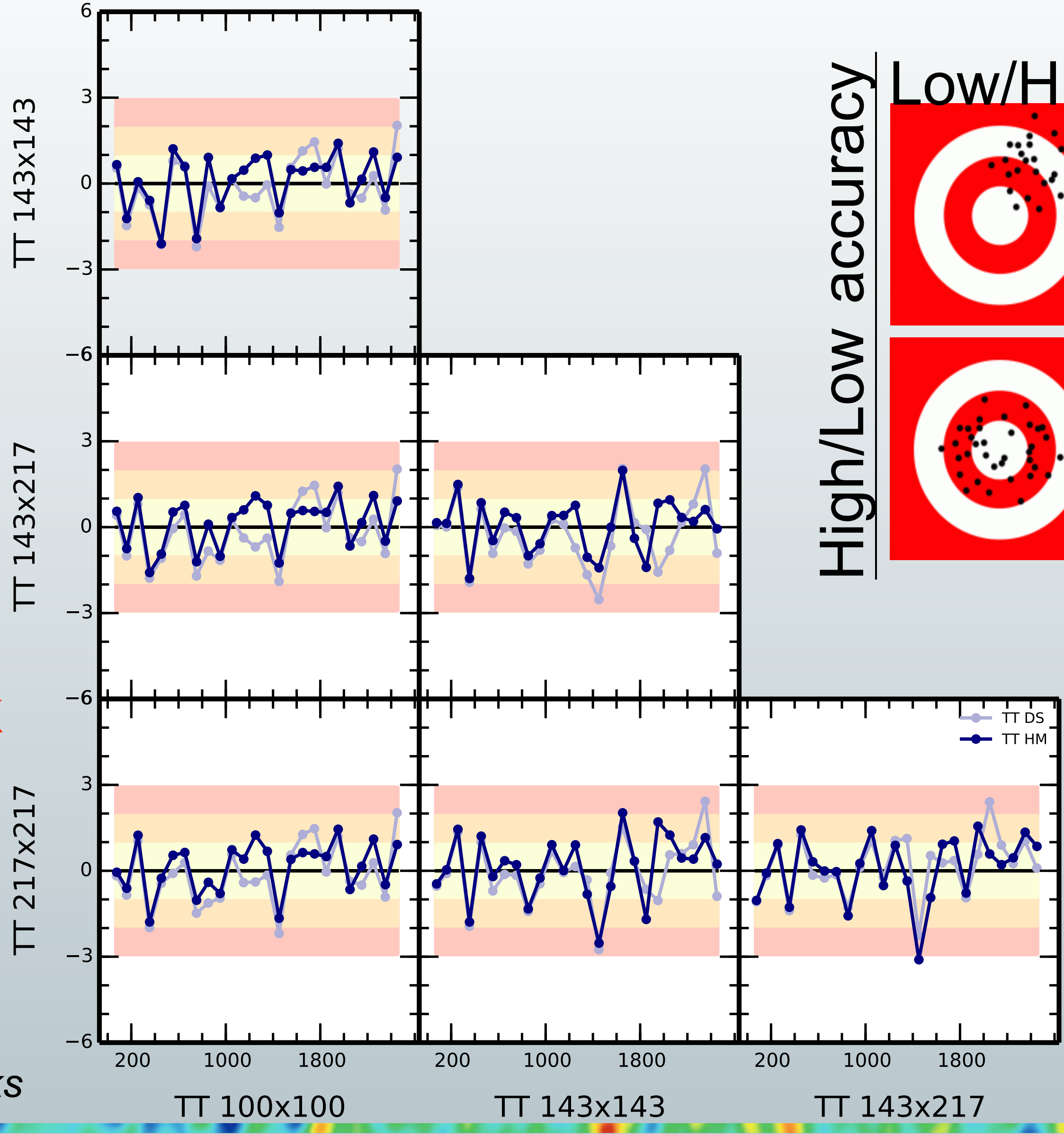
Distribution of deviation of mean posterior vs input sims params, in units of expected rms.

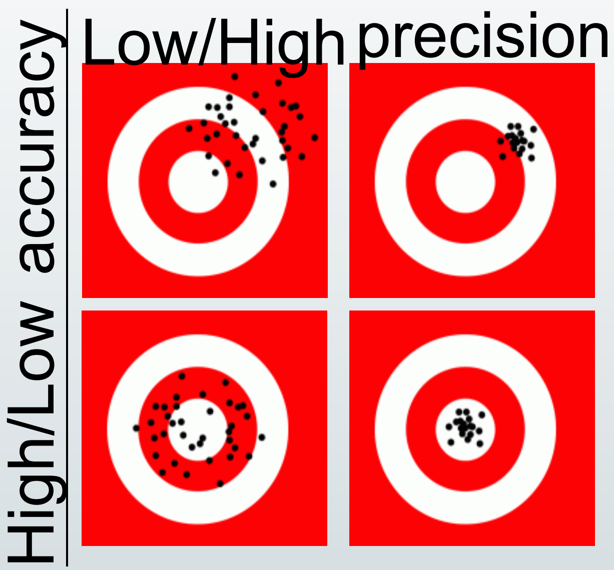
.

Consistency checks (interfreq., DetSets)

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

➔ All null tests OK



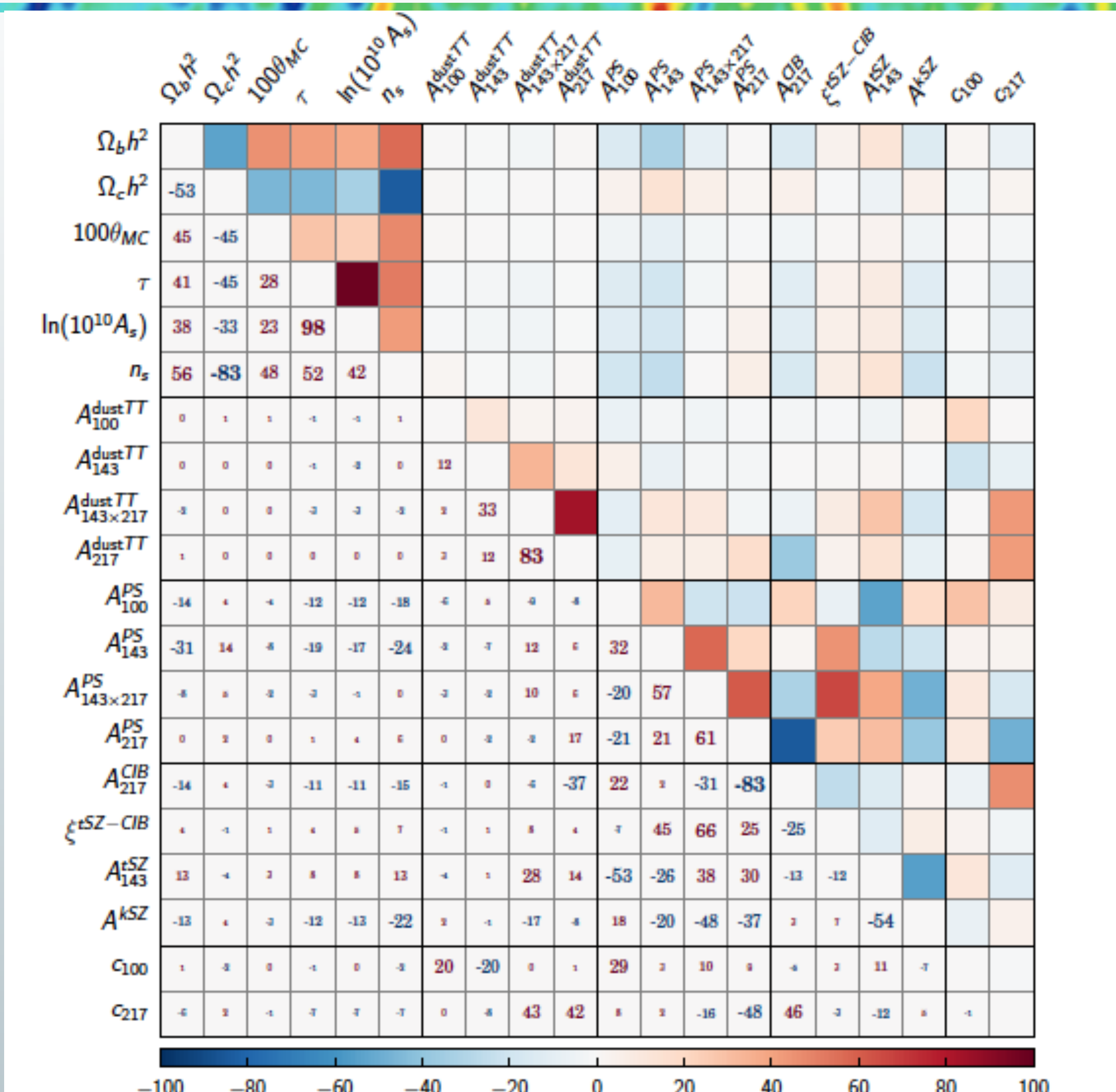


NB: DS not used but for consistency checks

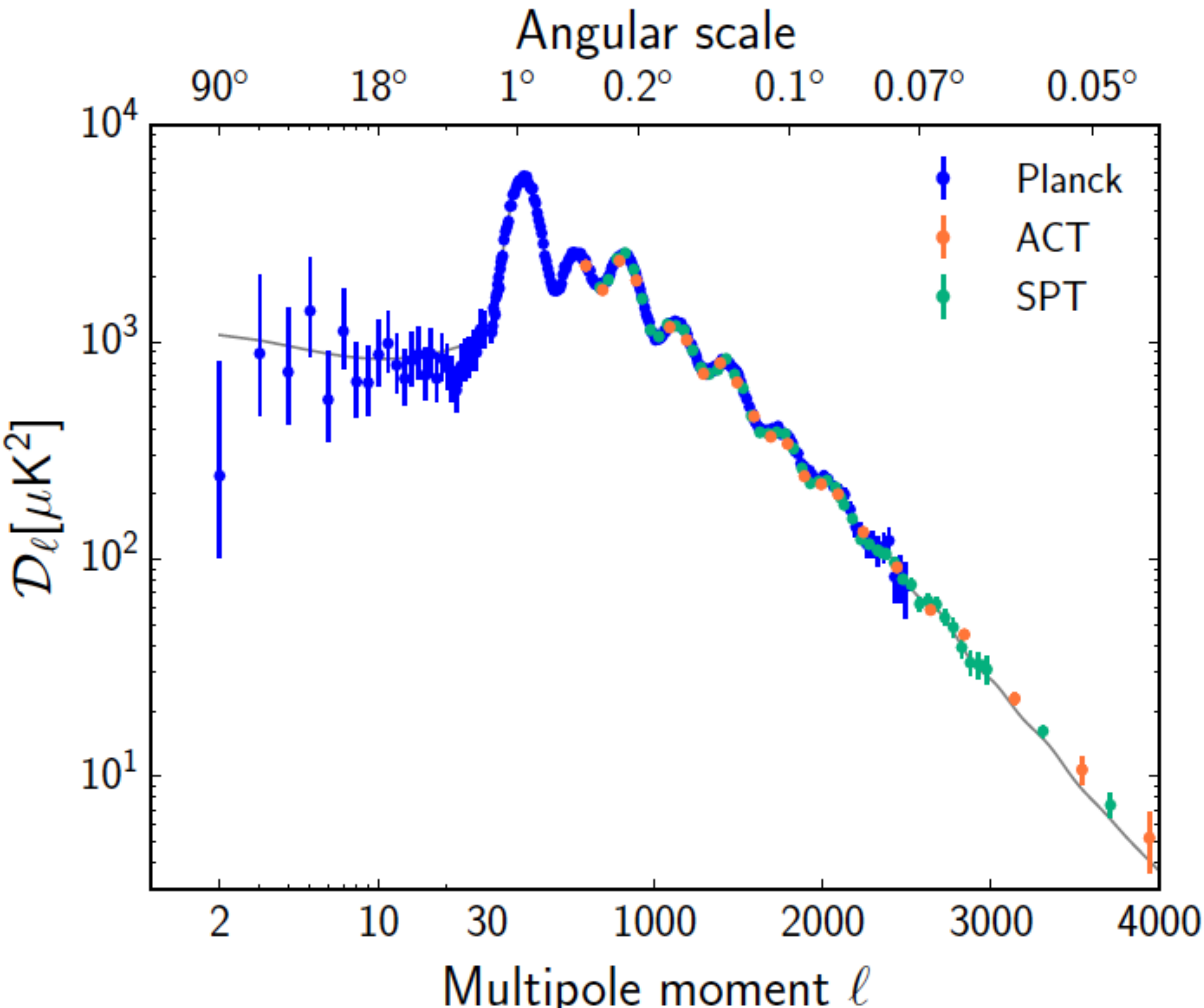
About degeneracies…

→ Cosmology & foreground parameters are largely decoupled

(with these masks,ell-cuts, & sensitivities)

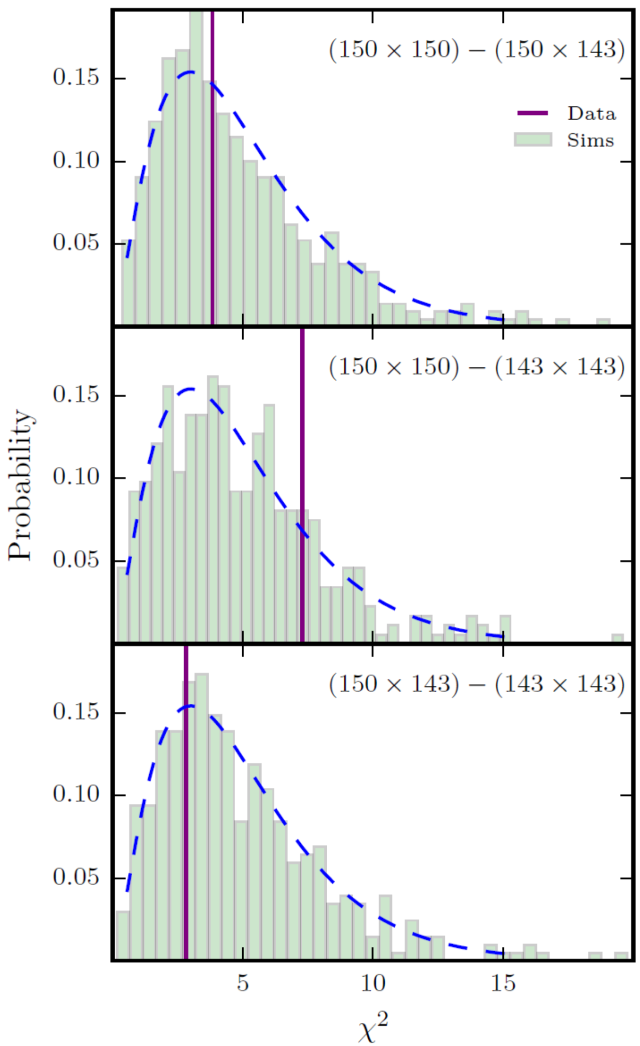


So very robust to inaccuracies in modelling of gastrophysics


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

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 × 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	

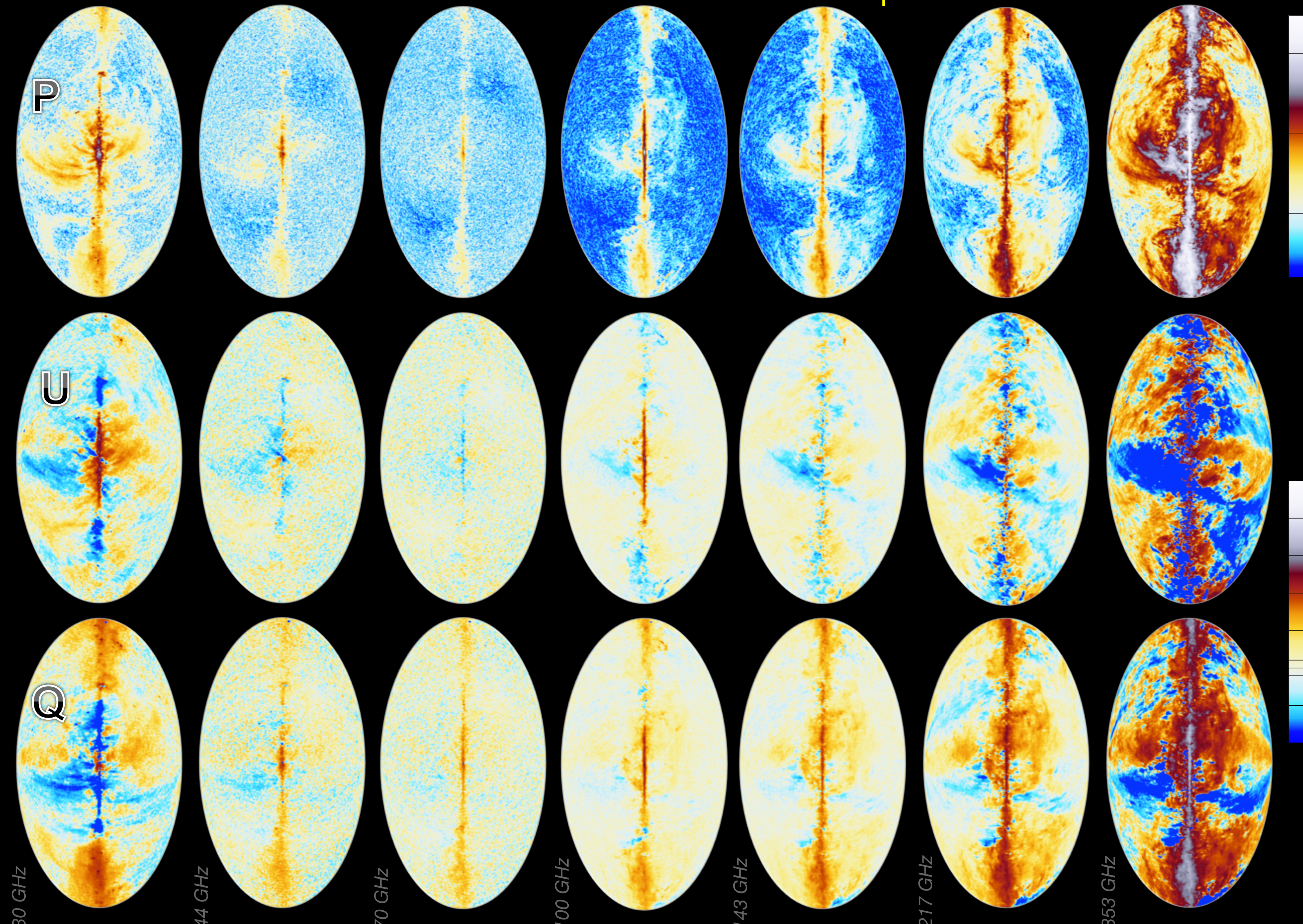
Planck and SPT LCDM parameters fully consistent WITHIN the SPY sky patch

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	

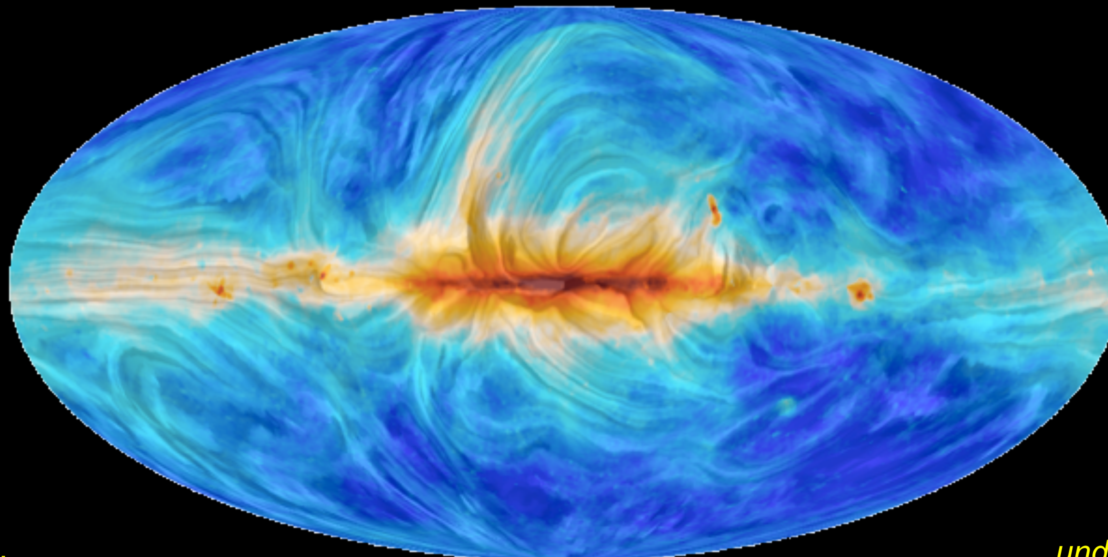
Planck Full sky is consistent with SPT in-patch at all scale probed well by Planck (lmax =2000).
Need to go to lmax_SPT=3000 to find some tension (at 3.2% PTE) [where SPT goes to larger H0

Planck 2015 Polarisation maps



Planck 2015 Polarisation & Galactic foregrounds

30 GHz

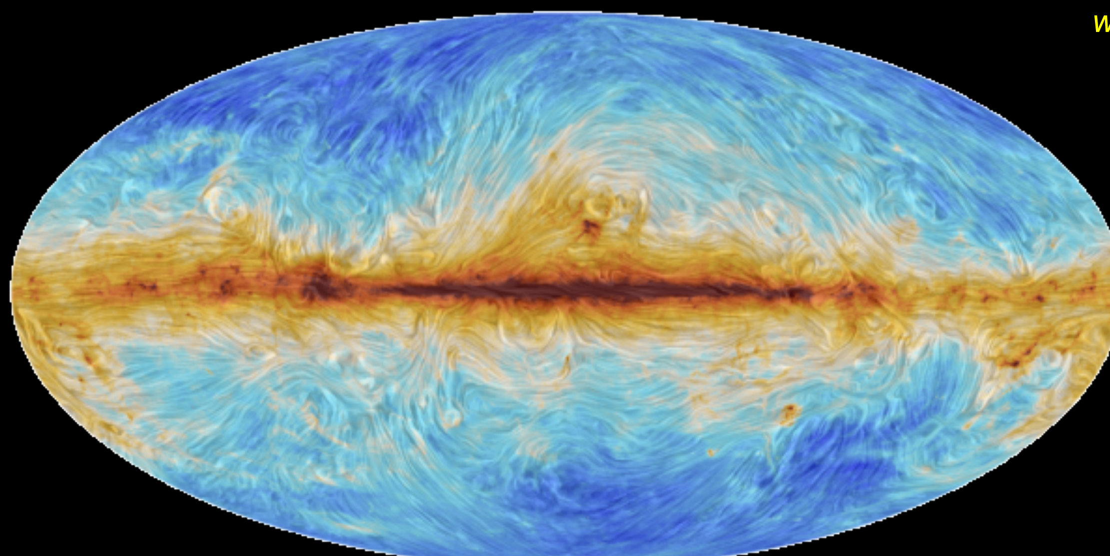


Synchrotron

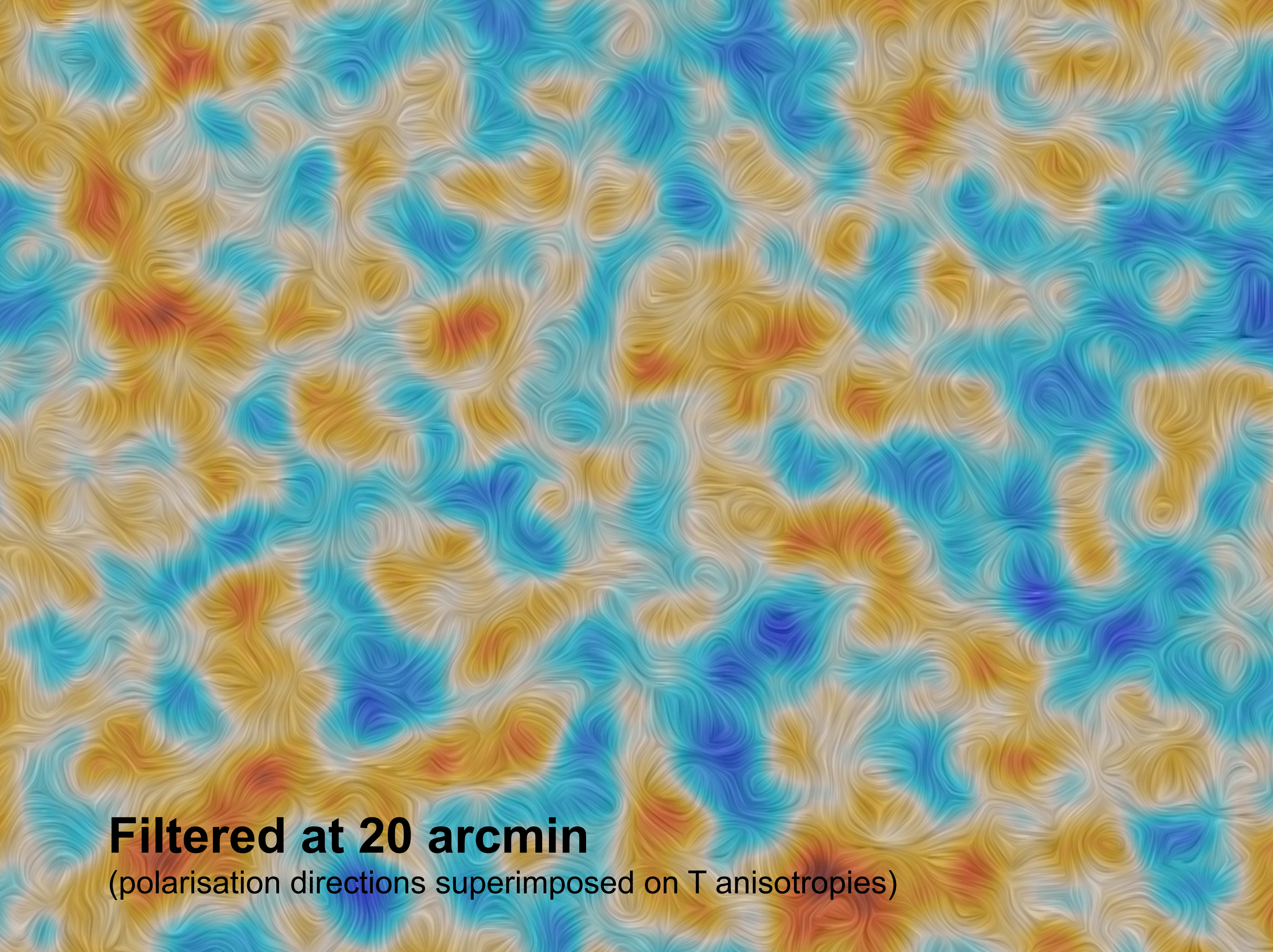
Lines indicate the magnetic field direction, (90deg wrt pol dir)
Colors indicate the emission intensity

Lots of information to understand better our cradle, with details inaccessible in other galaxies

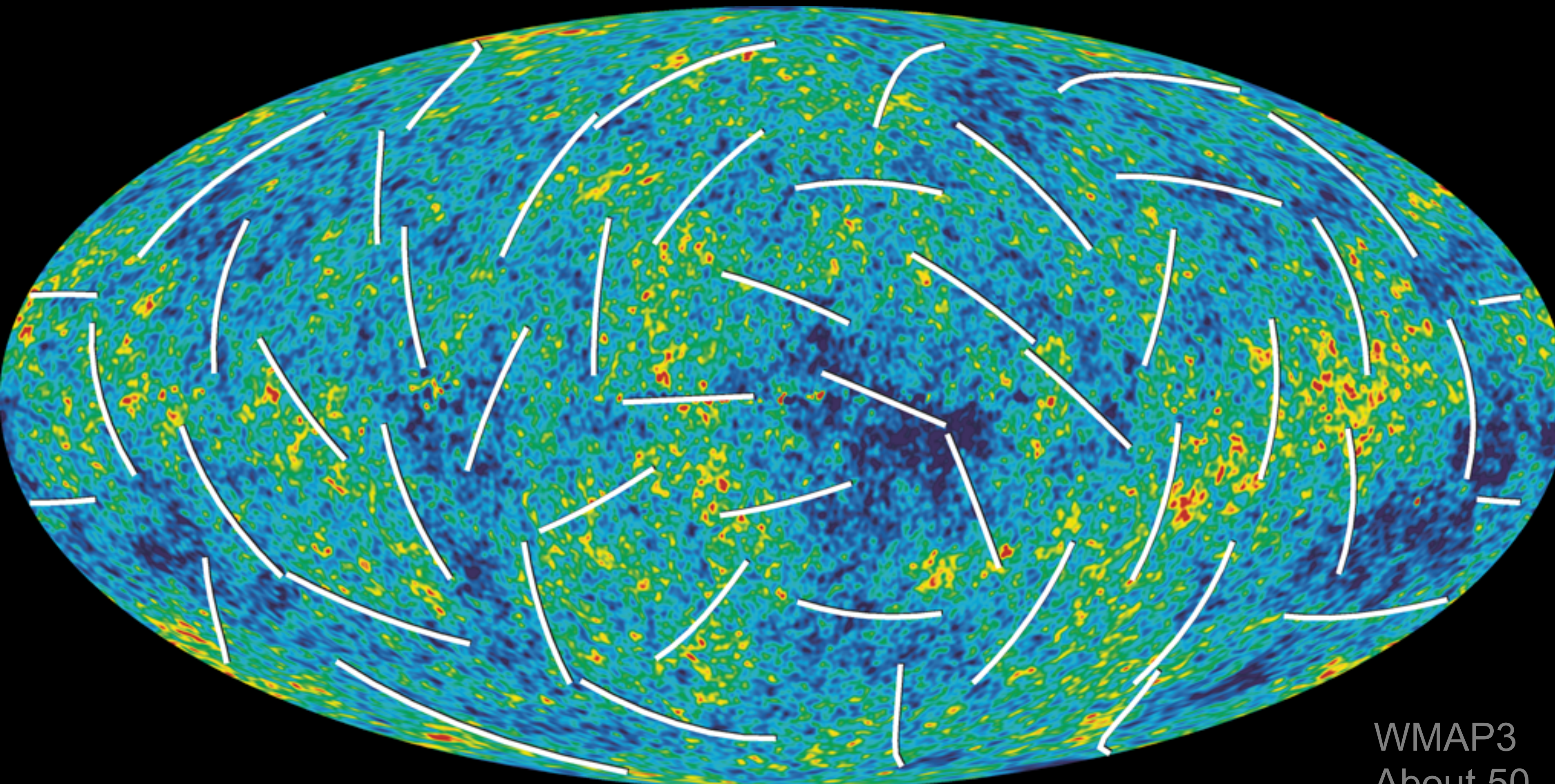
357 GHz



Thermal dust in magnetic field

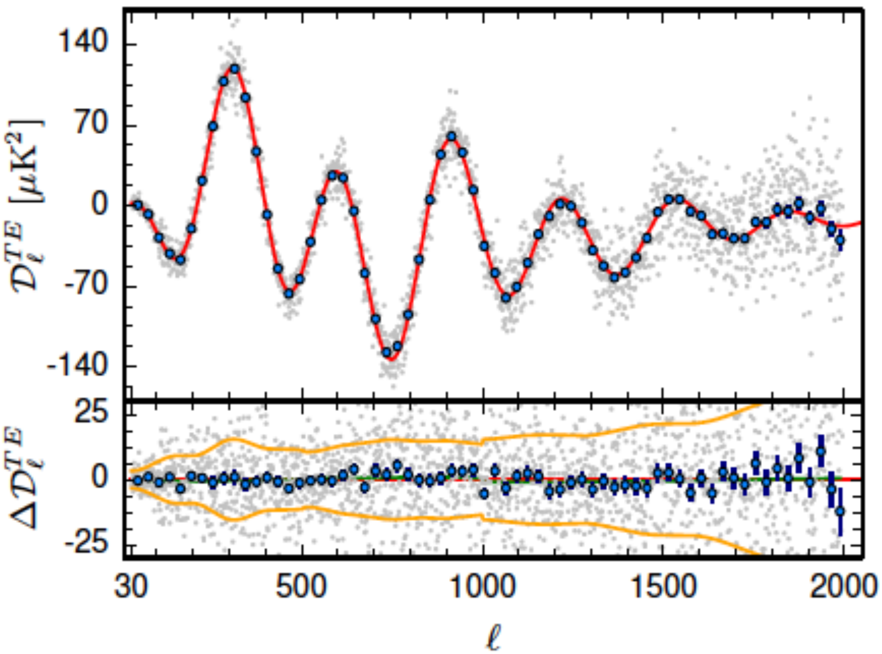

Filtered at 20 arcmin
(polarisation directions superimposed on T anisotropies)

What we already knew

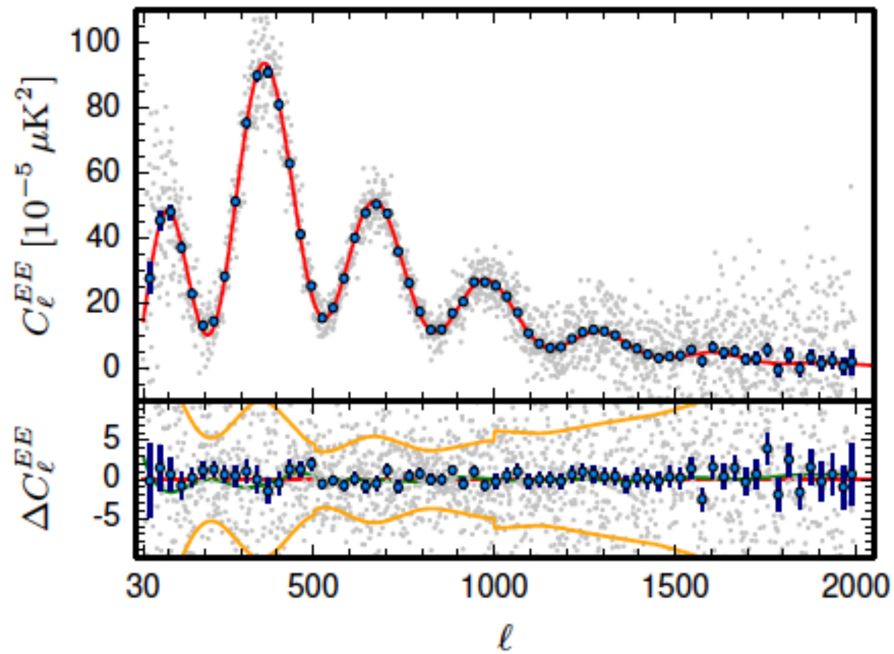


WMAP3
About 50
locations?

Planck 2015 - TE & EE spectra



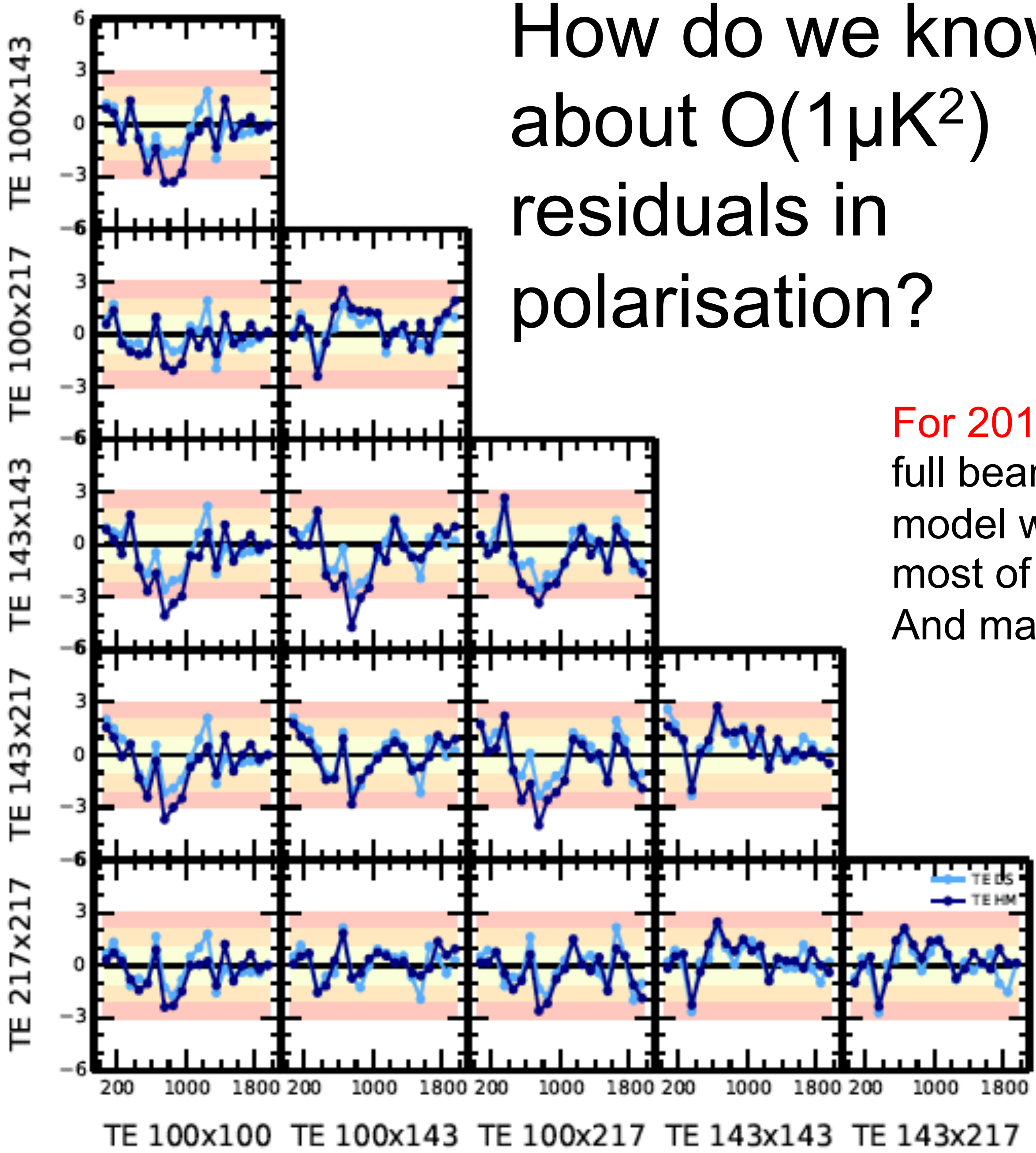
Frequency averaged spectrum reduced ^{2} = 1.04



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 levels below O(1μK^2).

How do we know about O(1μK^2) residuals in polarisation?

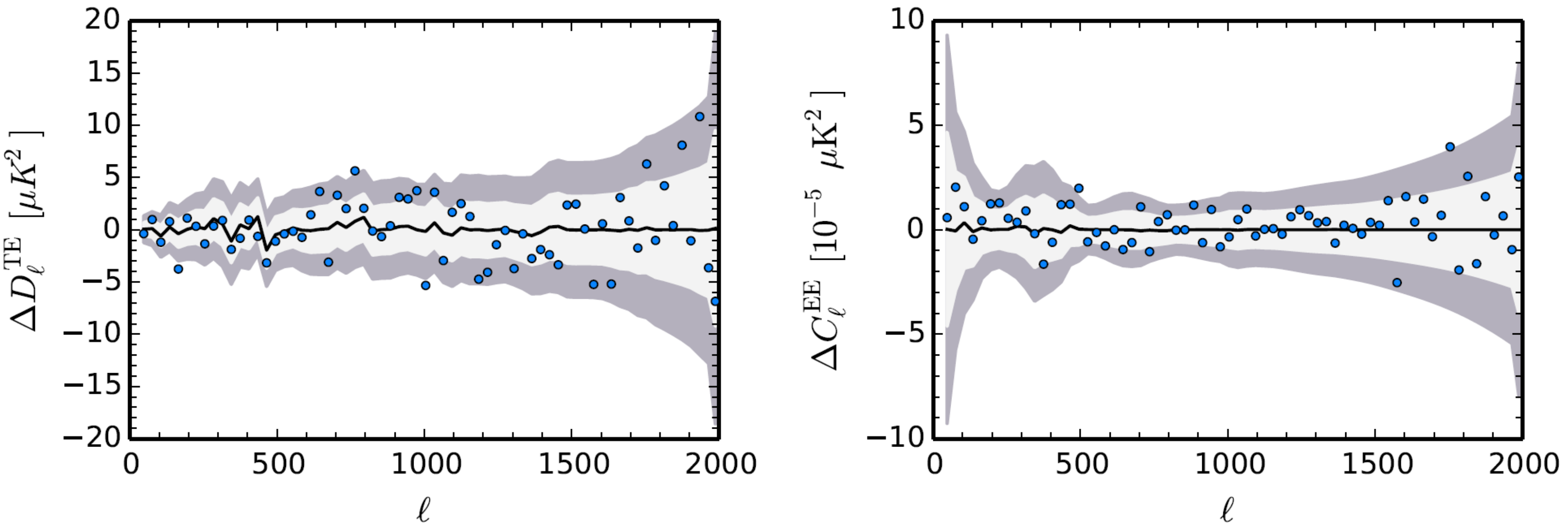


For 2018, we have developed a full beam and leakage physical model which predicts *ab initio* most of these differences… And many other improvements.

Spectra conditionned on TT

Conditional spectra and covariances

$$C_\ell^{PP}|_{C_\ell^{TT}} = \langle C_\ell^{PP}\rangle + \mathbf{C}_{PP,TT}\mathbf{C}^{-1}_{TT,TT}(C_\ell^{TT} - \langle C_\ell^{TT}\rangle)$$
$$\mathbf{C}_{PP,PP}|_{C_\ell^{TT}} = \mathbf{C}_{PP,PP}\mathbf{C}_{PP,TT}\mathbf{C}^{-1}_{TT,TT}\mathbf{C}_{TT,PP}$$



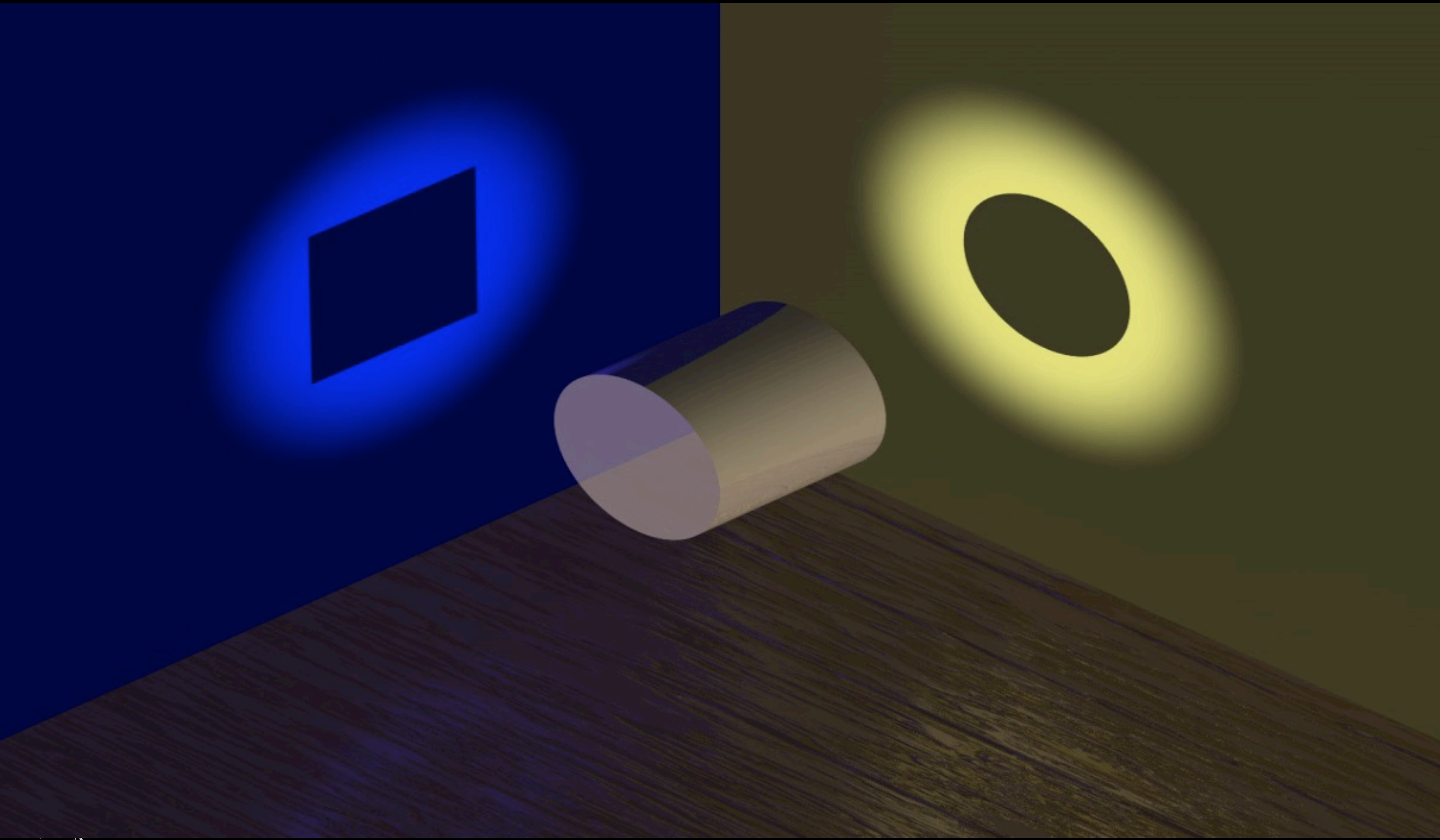
Excellent consistency of Polarisation with Temperature anisotropies within LCDM

Base ΛCDM model

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

TT & TE have quite similar uncertainties (but for n_s)… and point ot the same model!

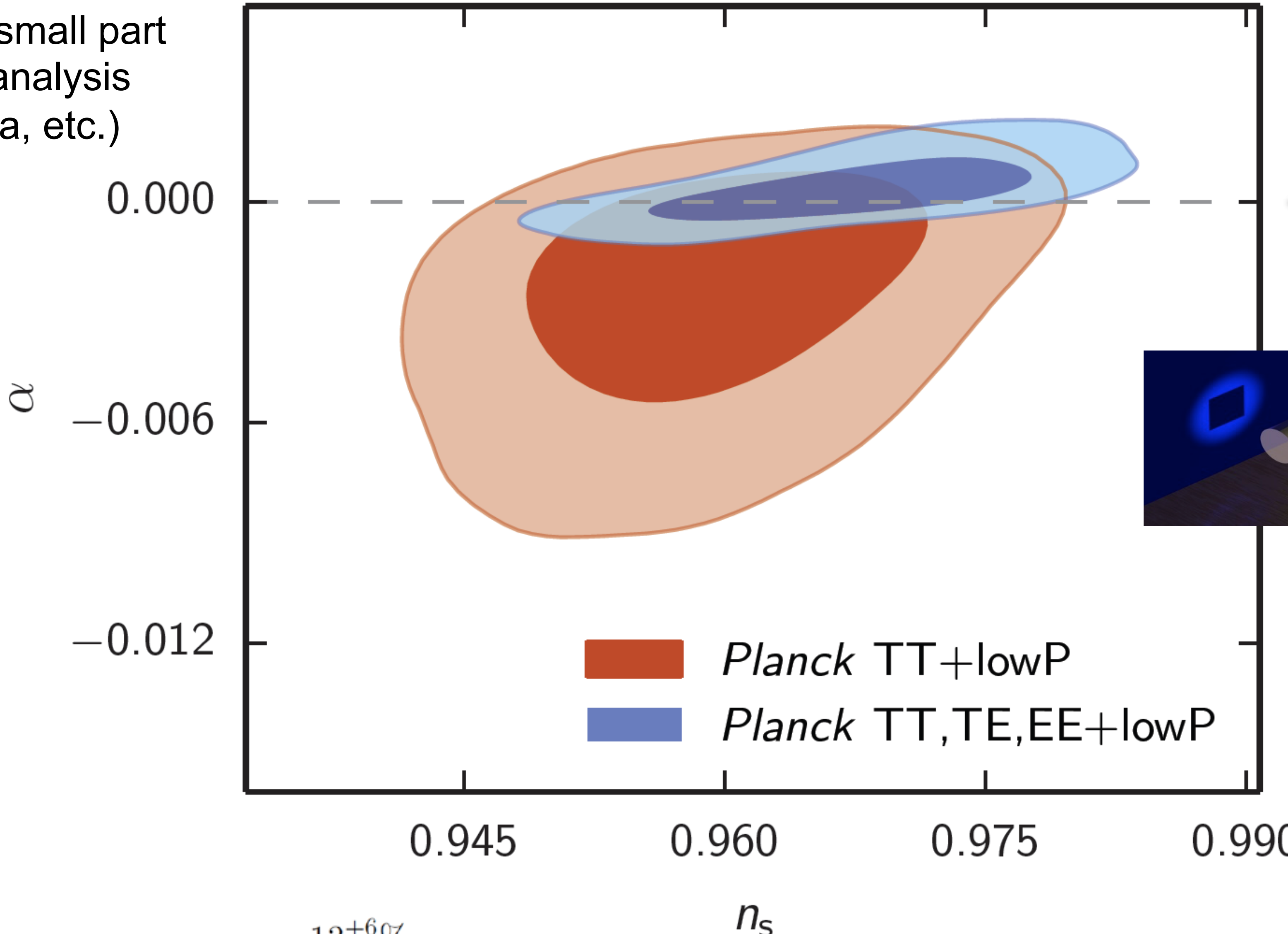
It could have been otherwise!



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

Isocurvature modes fraction

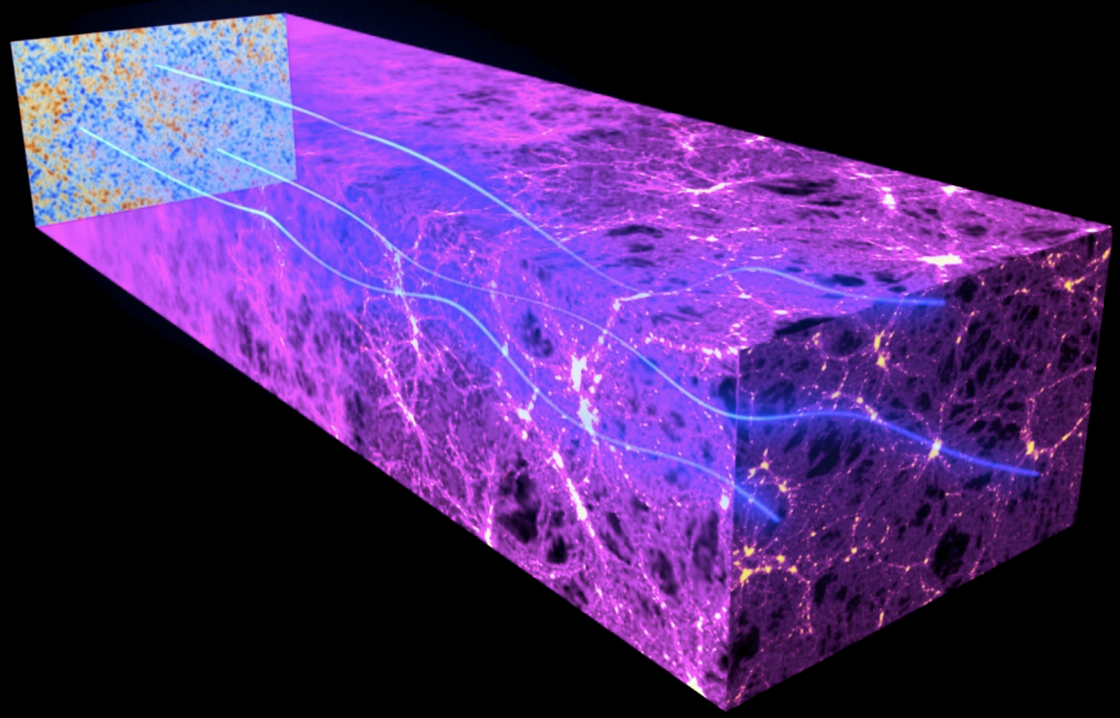
Just a small part of the analysis (spectra, etc.)



Percentage of isocurvature: $13^{+6}_{-6}\%$ Moodley, Ferreira et al (2004)
$1^{+0.5}_{-0.9}\%$ Planck (2015) (conservative)

GRAVITATIONAL LENSING DISTORTS IMAGES

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

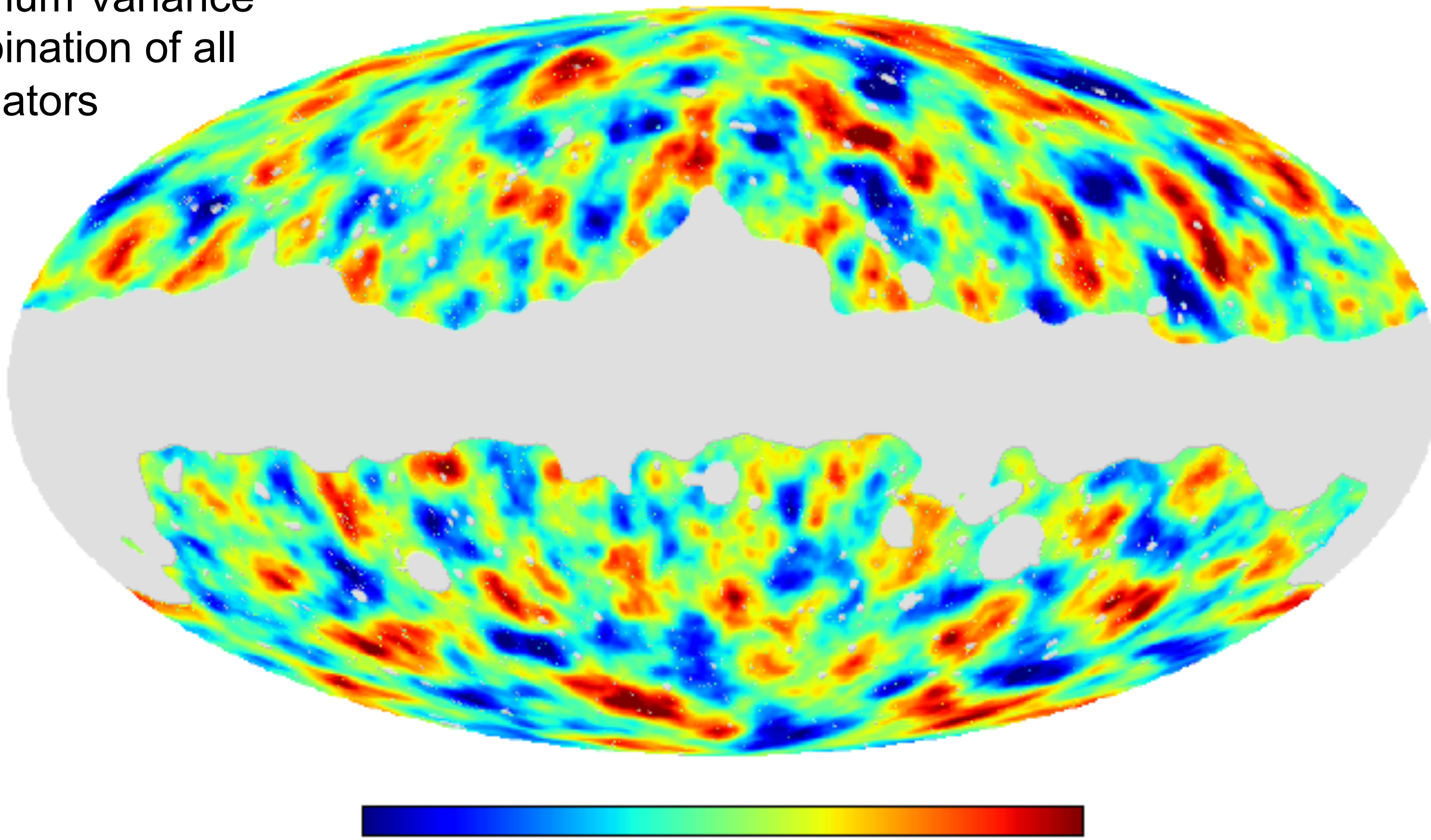


$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + \dots$$

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

Planck 2015 Lensing map

Minimum Variance combination of all estimators

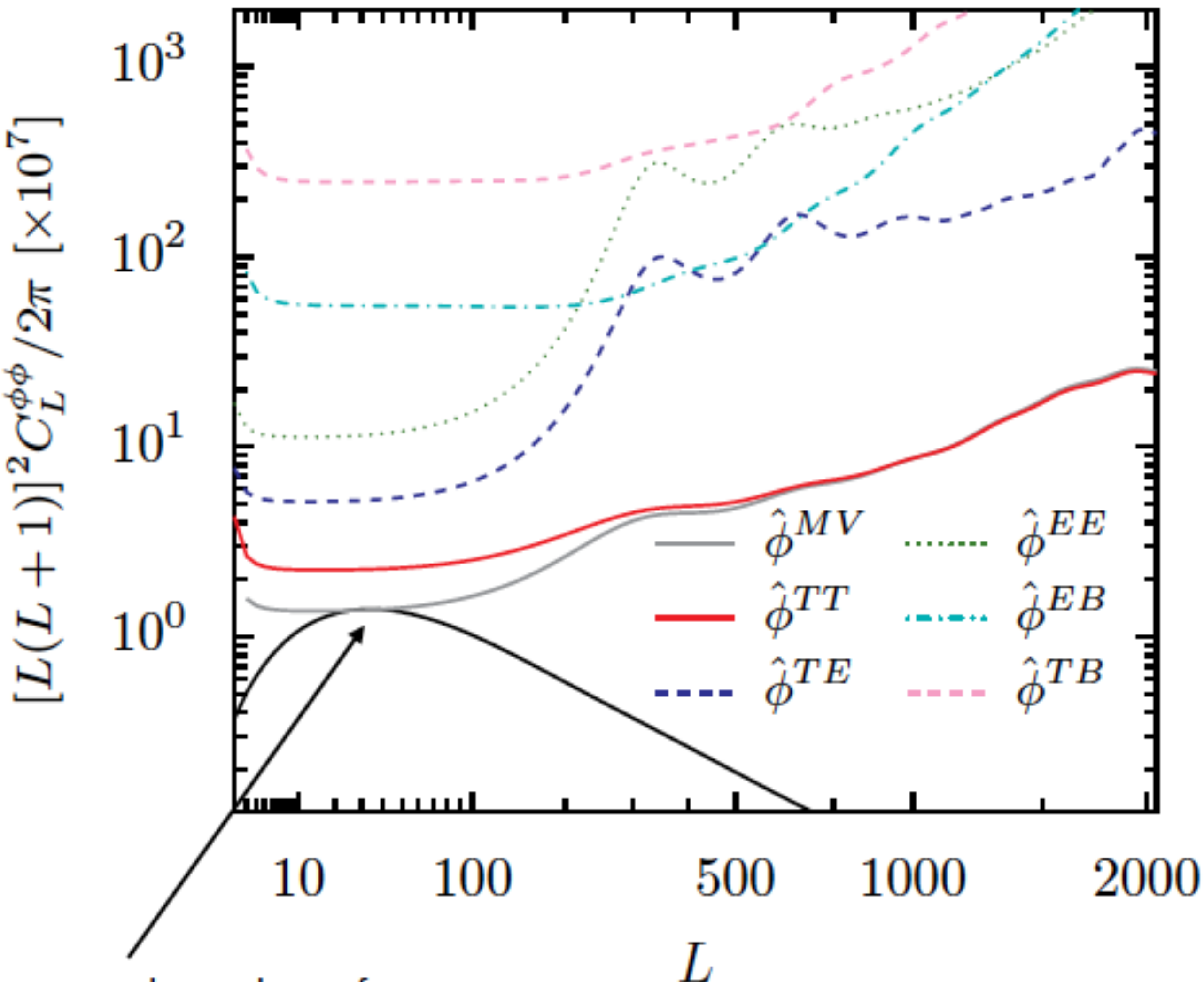


(based on SMICA CMB map)

S/N−filtered, $10 \leq L \leq 2048$

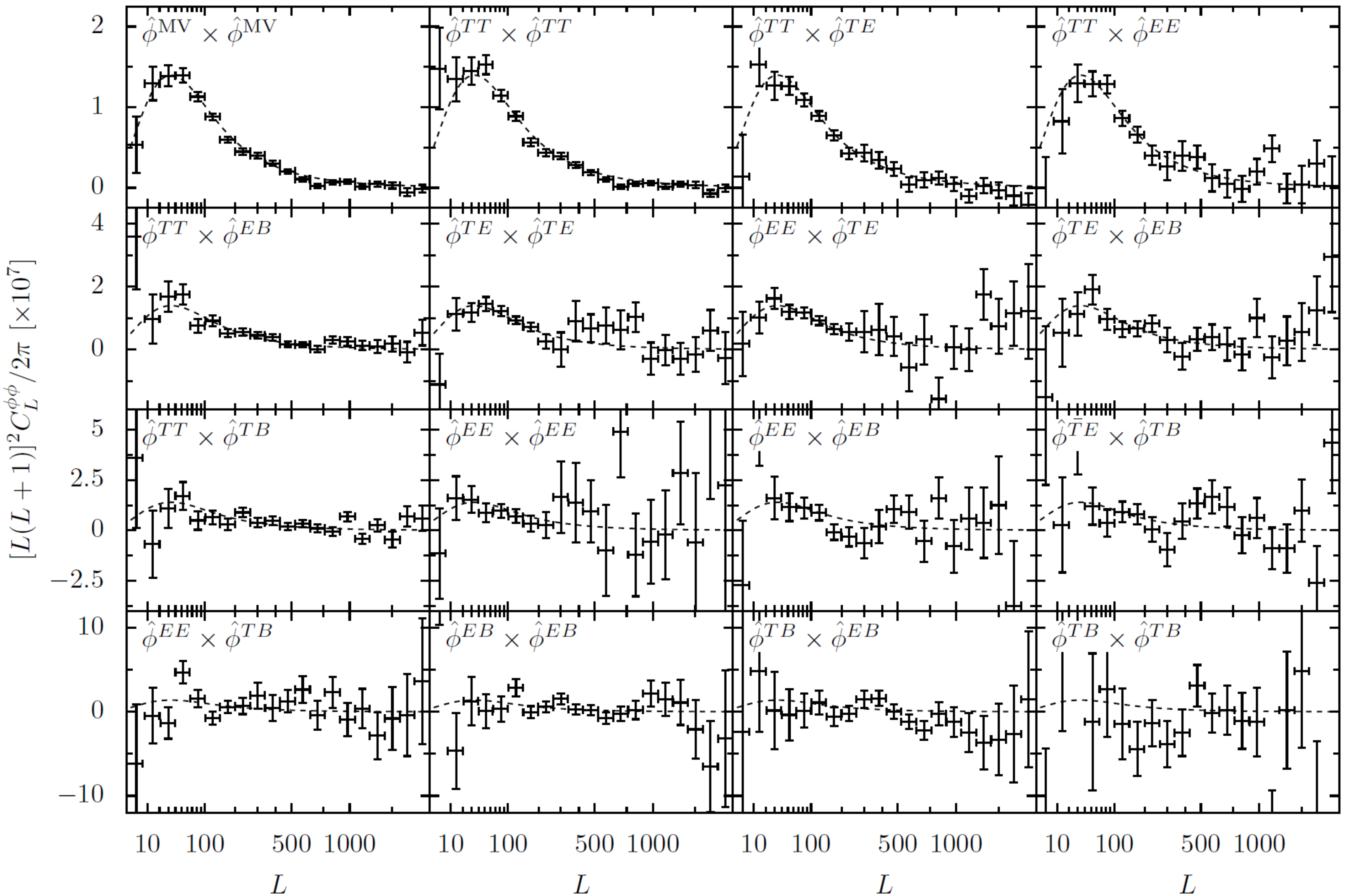
(S/N =1 @ l~30)

Noise power spectra for lensing estimators

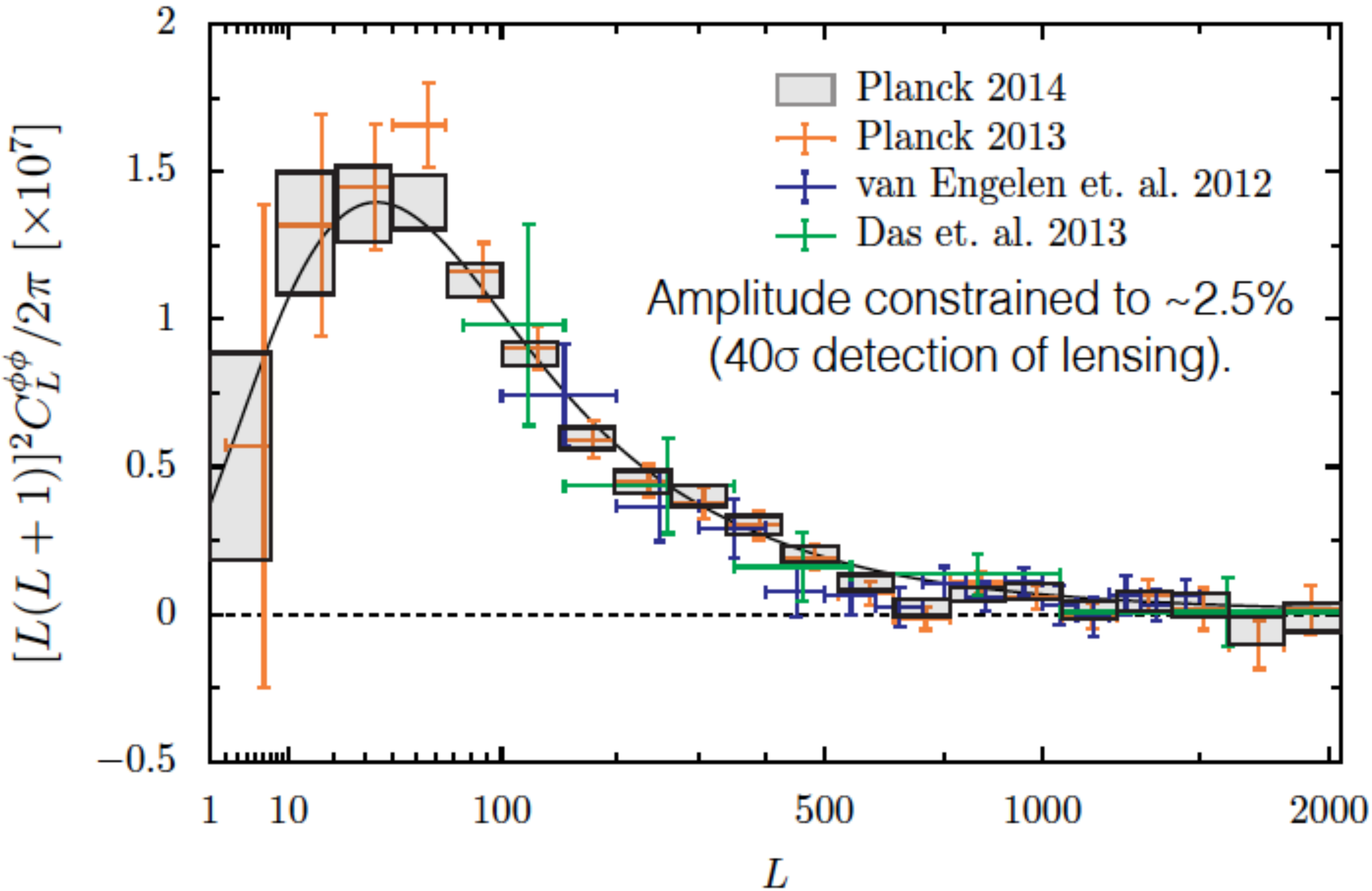


Best measured modes of
MV estimator have S/N=1.

Individual lensing cross-spectra

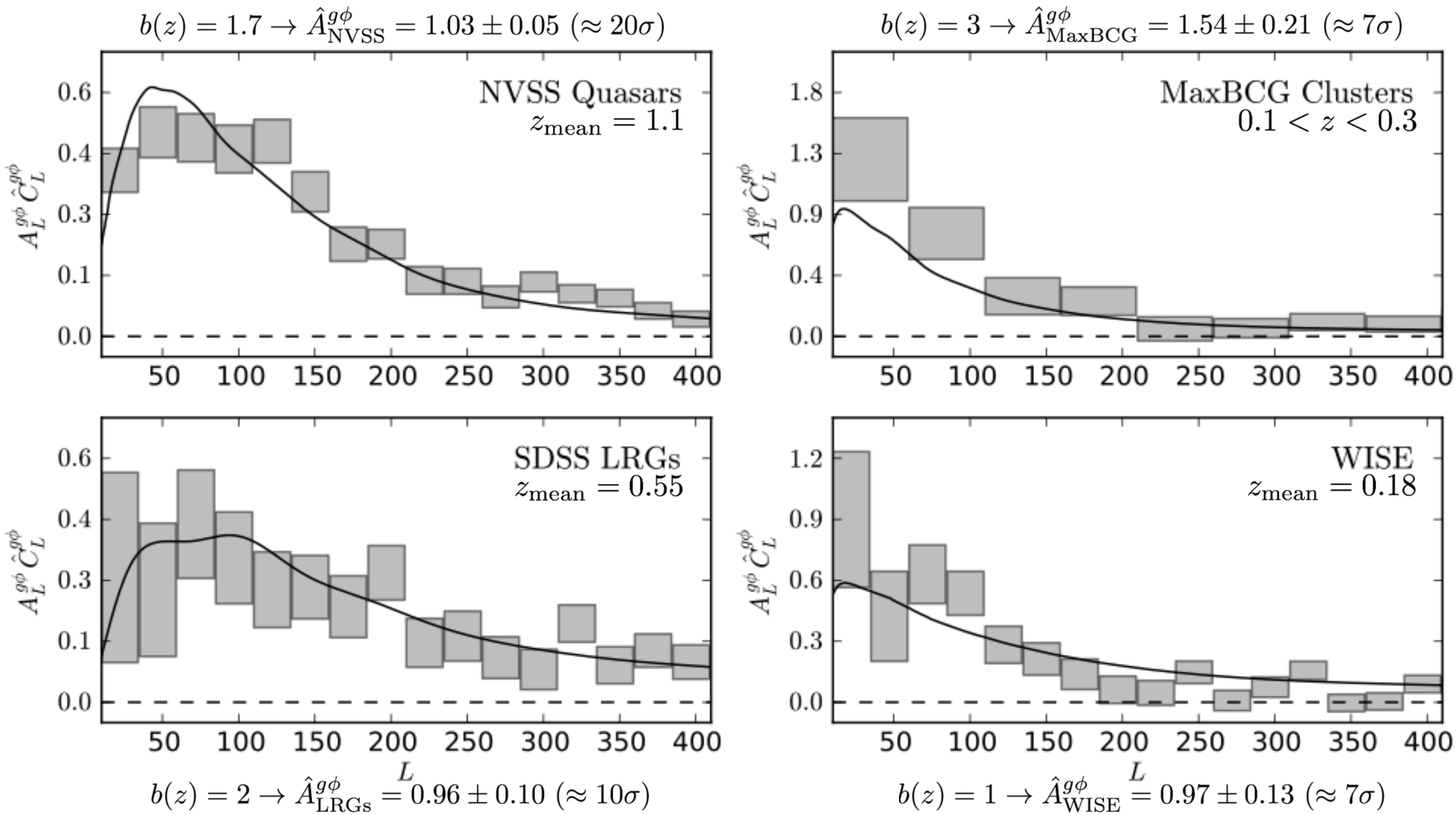


2015 Lensing power spectrum



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

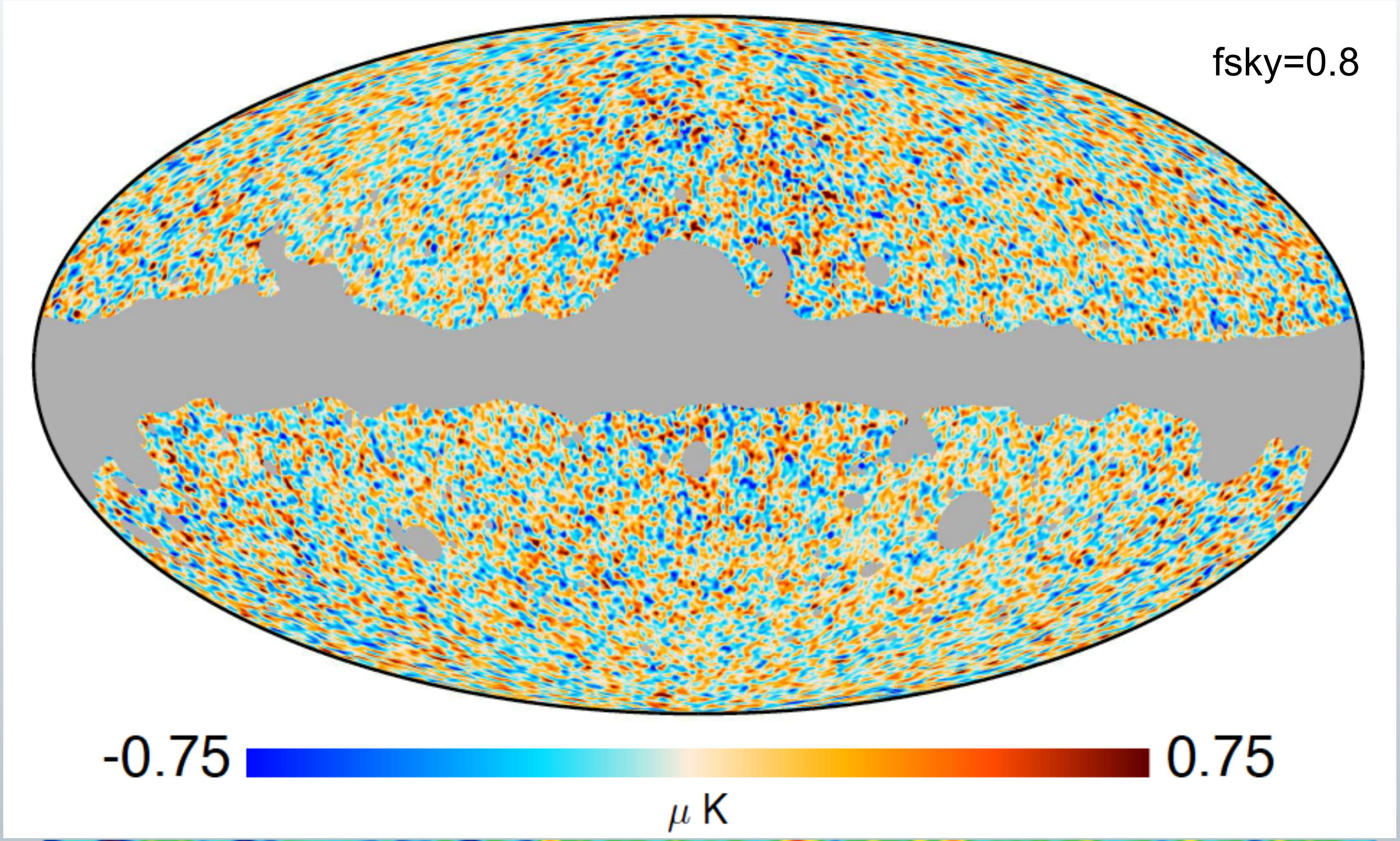
Lensing potential versus distribution of external tracers



No particular effort here to optimize the model for the external survey

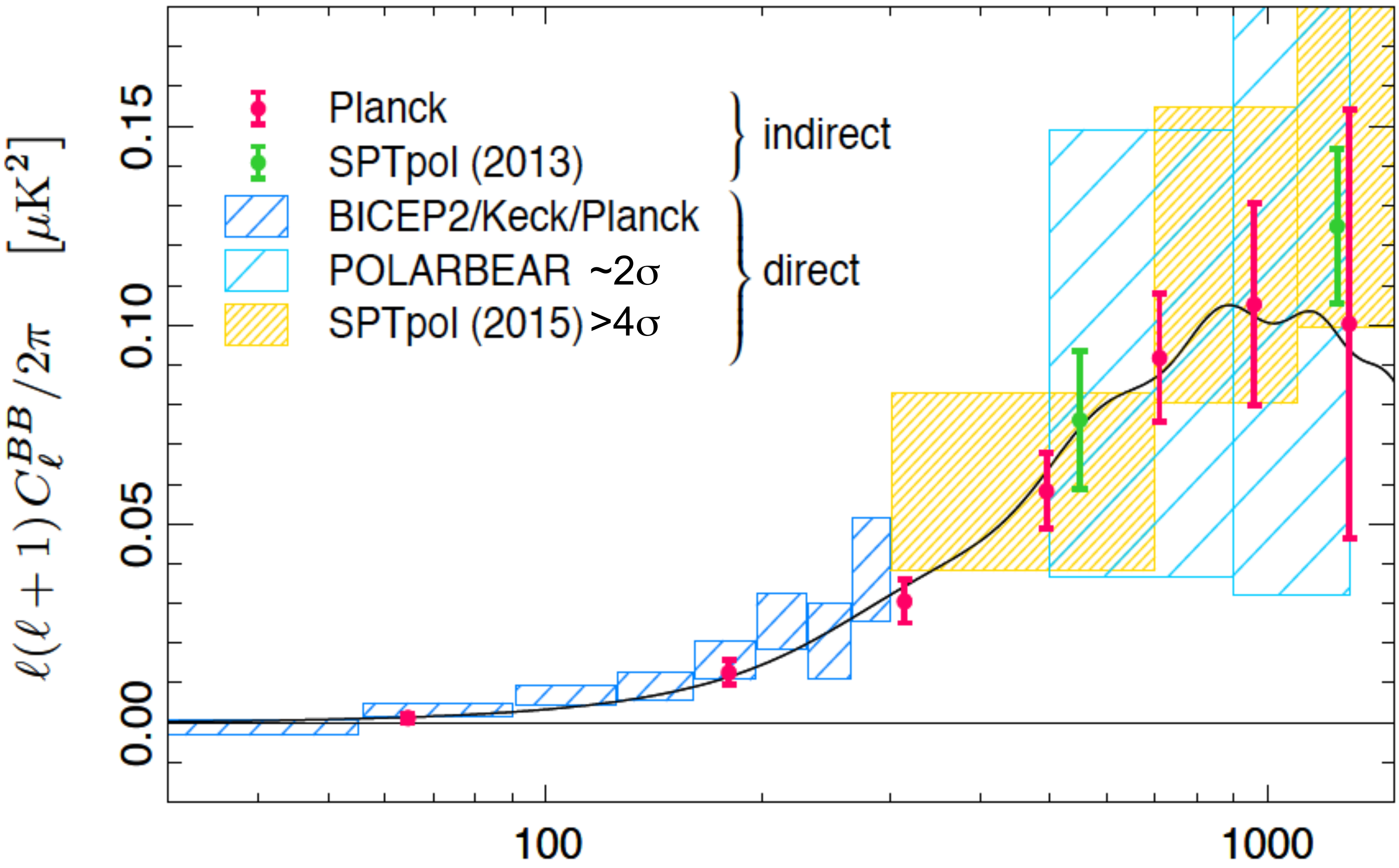
Planck *lensing* B-modes map

T & ∂T → ϕ; ϕ & E → B^L ; (here smoothed at 60')



Arxiv 1512.02882

Planck *lensing* B-modes spectrum

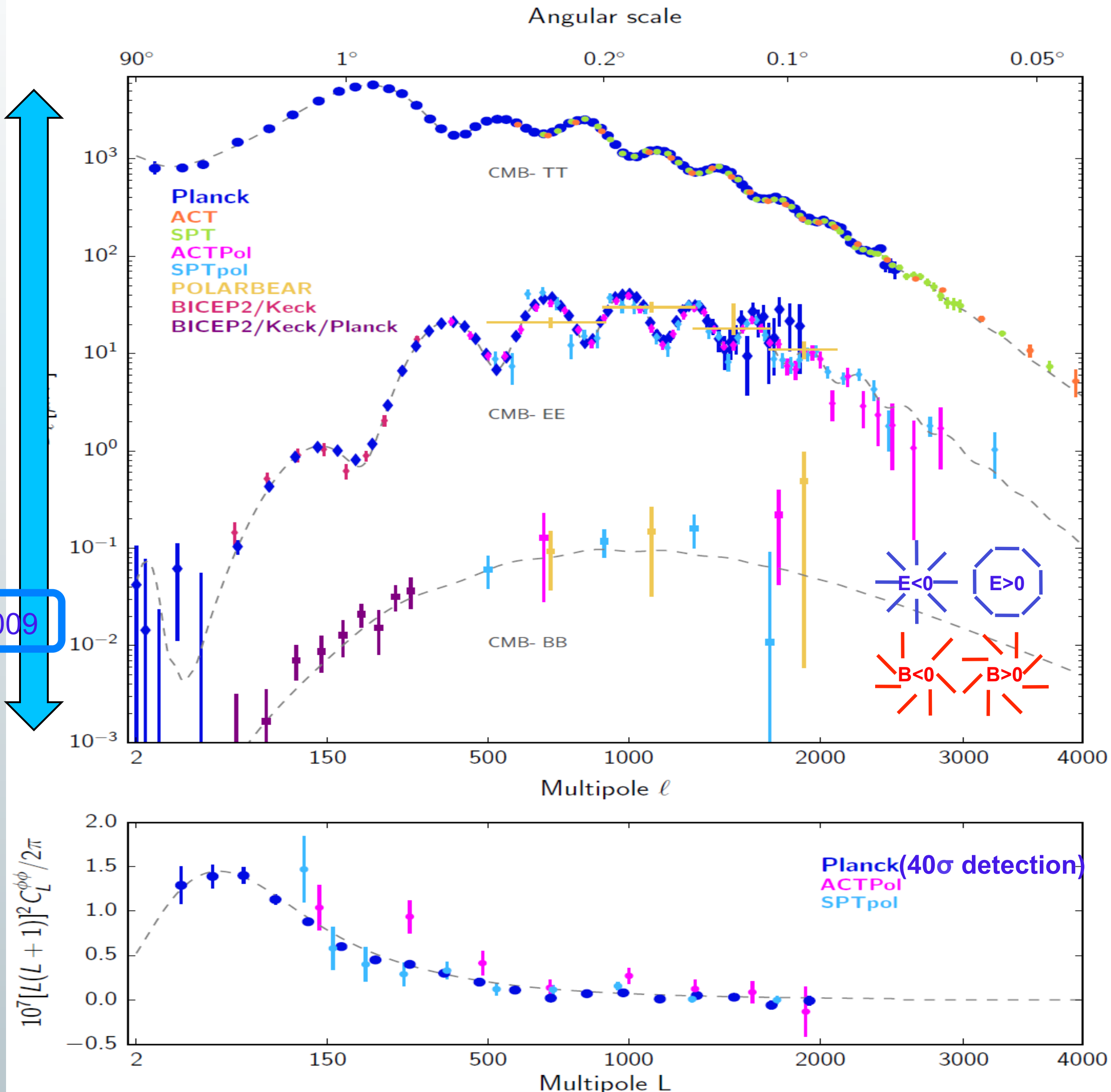


$A_{Blens} = 0.97 \pm 0.08$ (SMICA) $11.8\,\sigma$

arXiv:1512.02882

TT, EE, BB, ΦΦ – 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

Data compression…

~ 900 billion time samples in ~100 Timelines

~ 1 billion pixel values (7*{I,Q,U} +2*I=23 maps of ~50 million pixels)

~ 150 million CMB pixel values (3 map of ~50 million pixels, I, E, B)

~10 million harmonic modes (2l+1 m-modes/l, TT+TE+EE+ΦΦ+B's)

- Fit with just 6 parameters
- *With no significant evidence for a 7th*

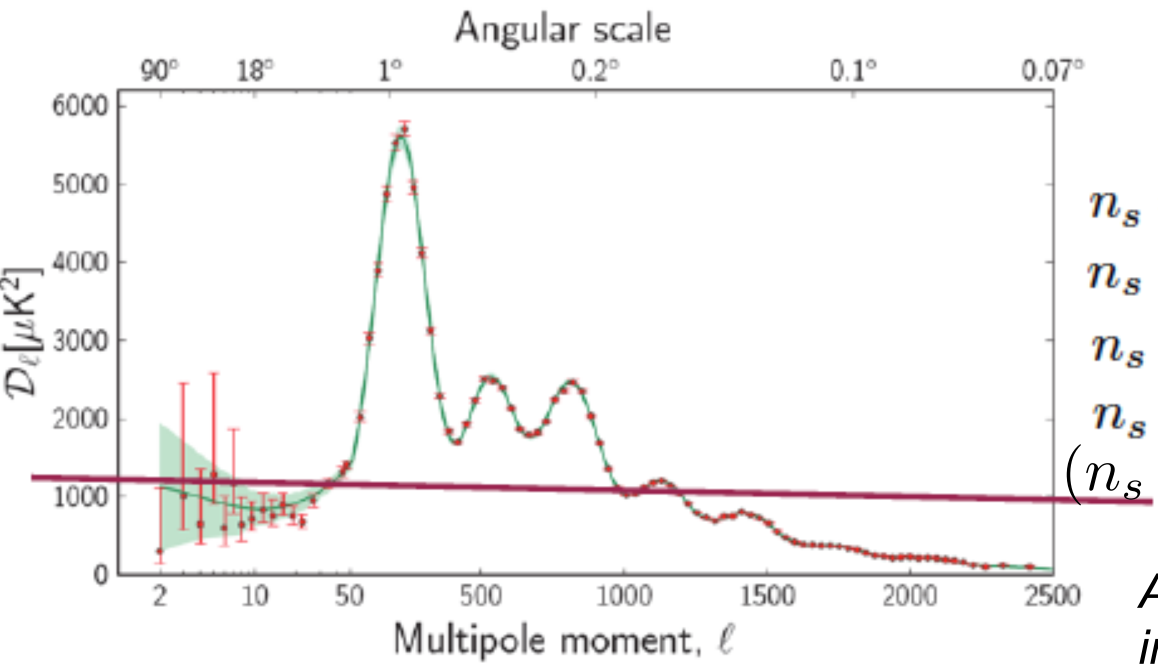
Pre-Conclusions/CMB Anisotropies post-Planck

- **The LCDM model fits all CMB data in T, E, B, ϕ.**
  - *No need for an extension. A lavish source of unique constraints / negative results / papers…*
  - *Same model parameters, determined at the per cent level, also fit other data (BAO, and also BBN, SN1a…).*
  - *Some tensions (anomalies, SZ, H0, WL), whose actual meaning remains unclear as of now.*
- T anisotropies information essentially exhausted (but much still to learn on CMB foregrounds, e.g., from SZ).
- CMB polarisation anisotropies are also a powerful source of information. Much of it unique and untapped (millions of modes up for grap).
- A new field, CMB lensing, has emerged (observationally).

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)

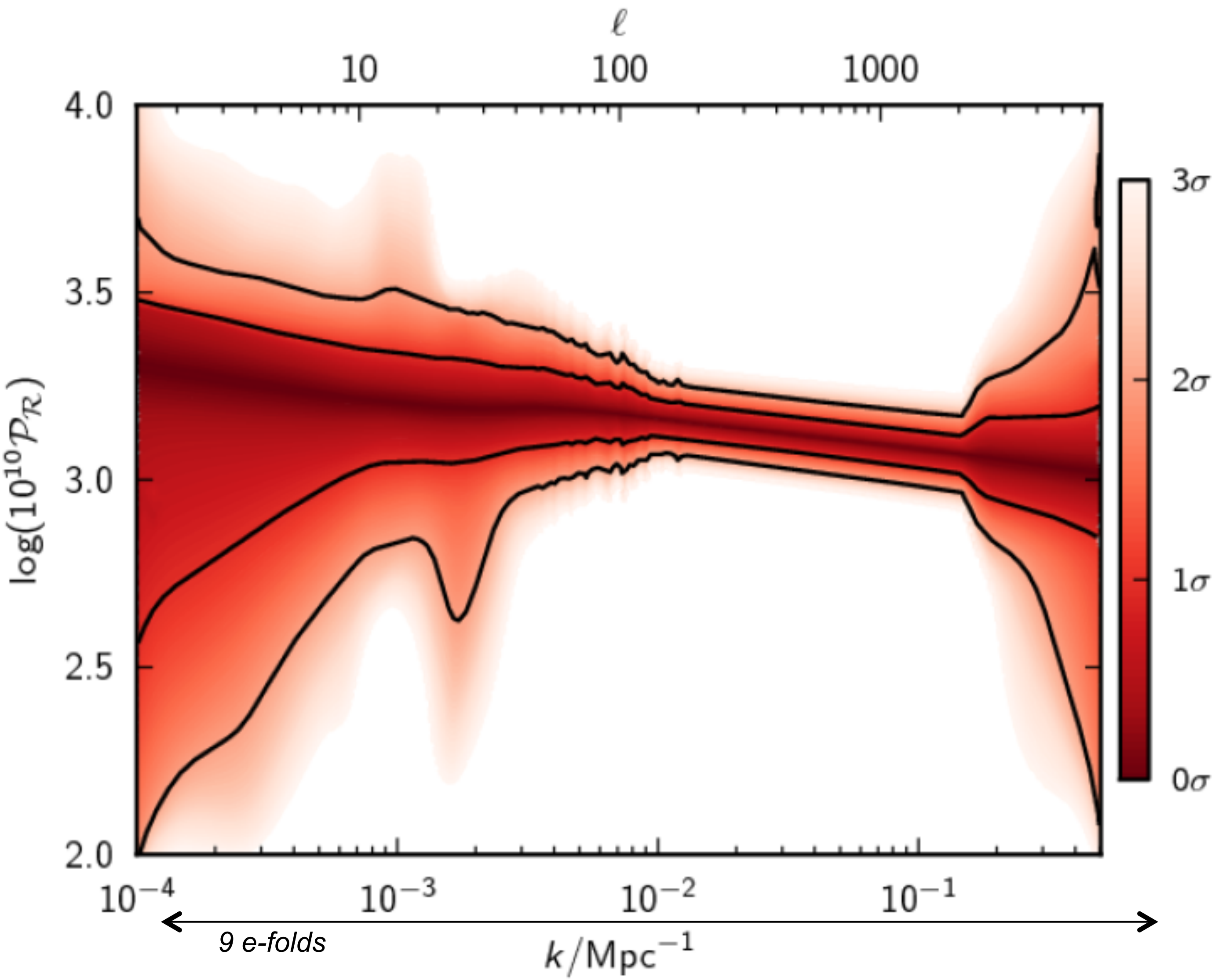
$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)

$(n_s = 0.965 \pm 0.006$ 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 spectrum reconstruction

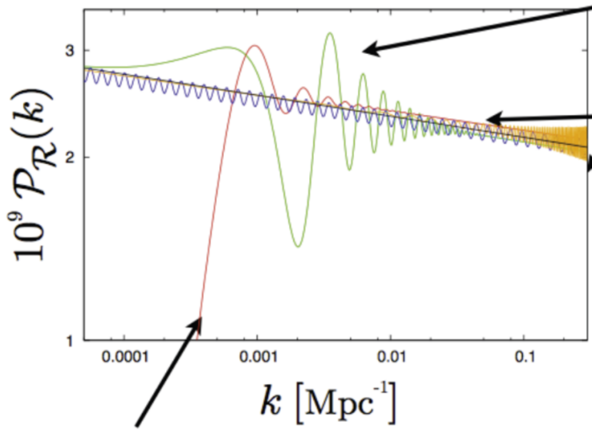


Bayesian reconstruction with varying number of nodes (<11). Reconstructions are then weighted by their respective evidence.

➔ No strong evidence for feature or anomaly.

(We actually used 3 different methods, all with similar conclusions)

(Unsuccessful) Search for features



Feature in the potential:

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

Non vacuum initial conditions/instanton effects in axion monodromy

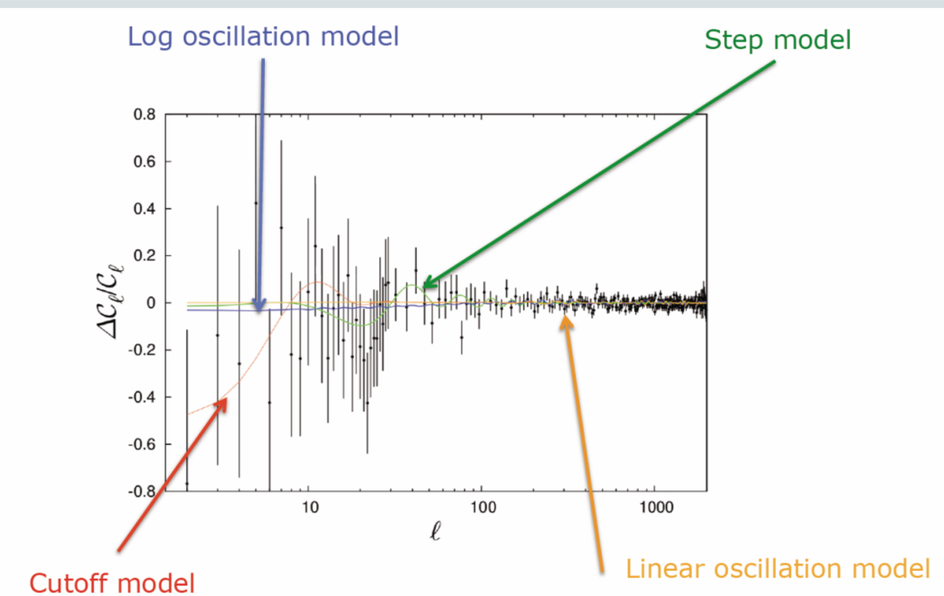
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

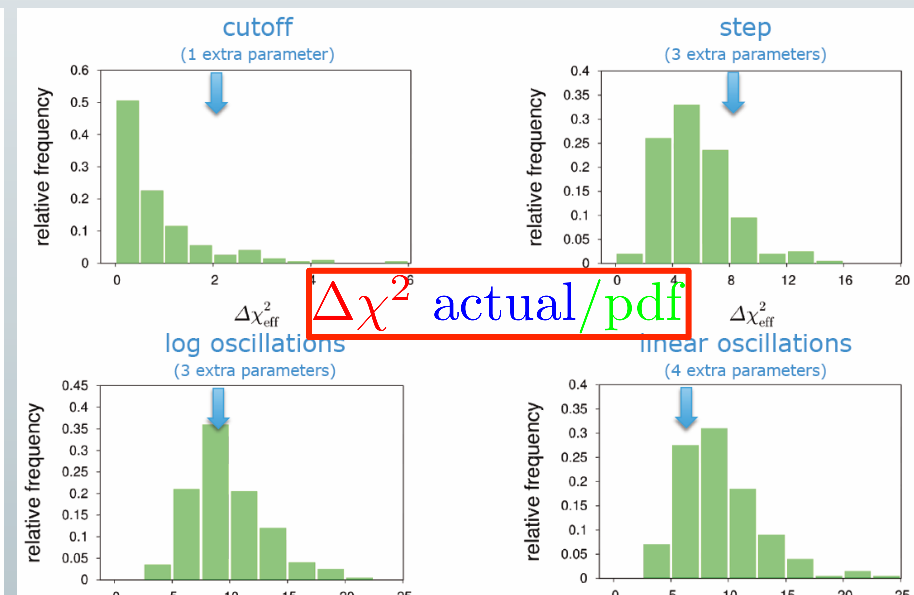
$$\mathcal{P}_{\mathcal{R}}^{\log}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

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

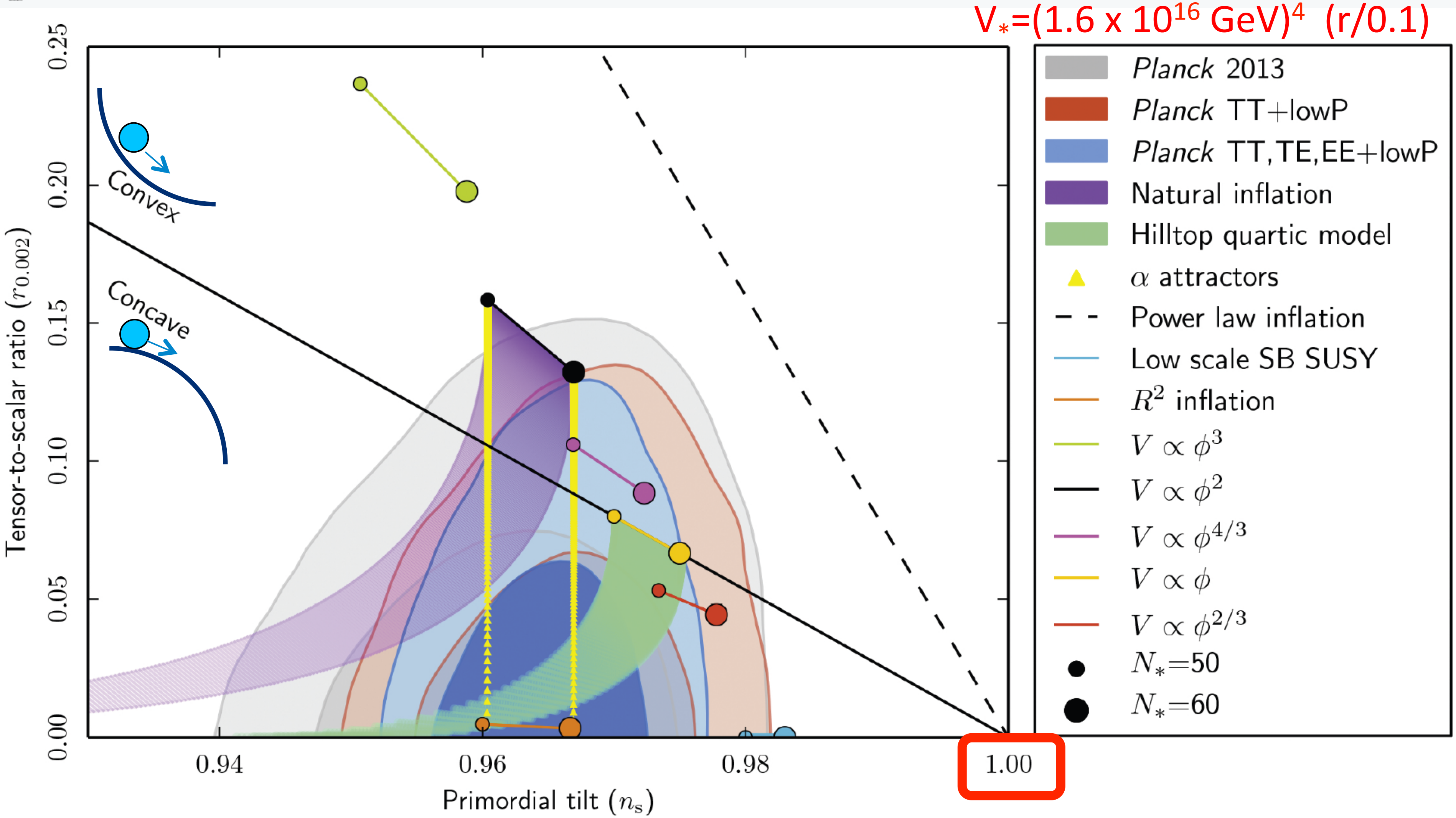
Just enough e-folds, i.e. inflation preceded by a kinetic stage





Planck 2015: n_s vs r

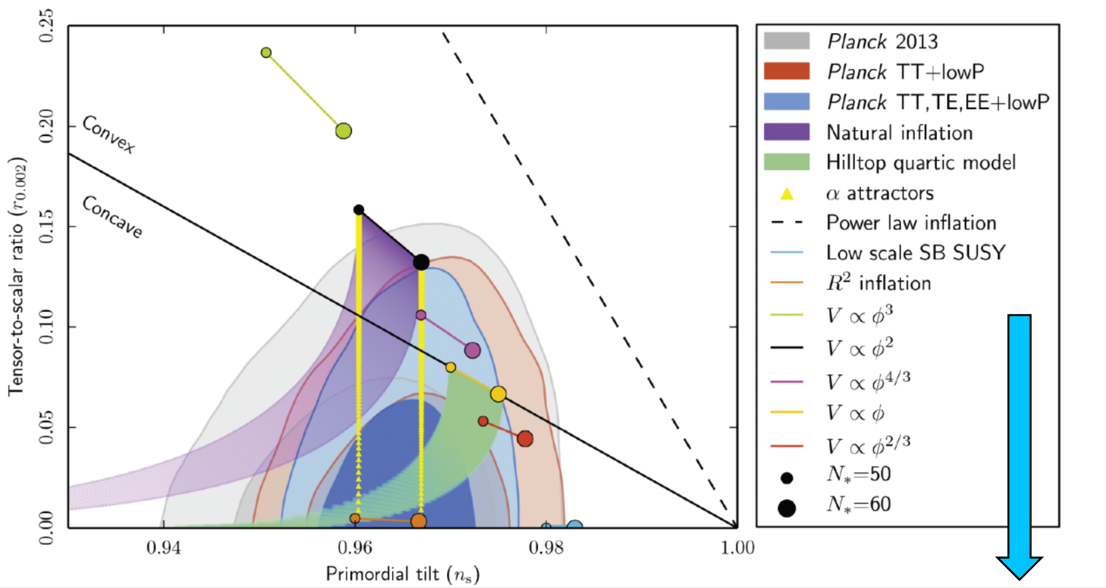
$V_* = (1.6 \times 10^{16}\ \mathrm{GeV})^4\ (r/0.1)$

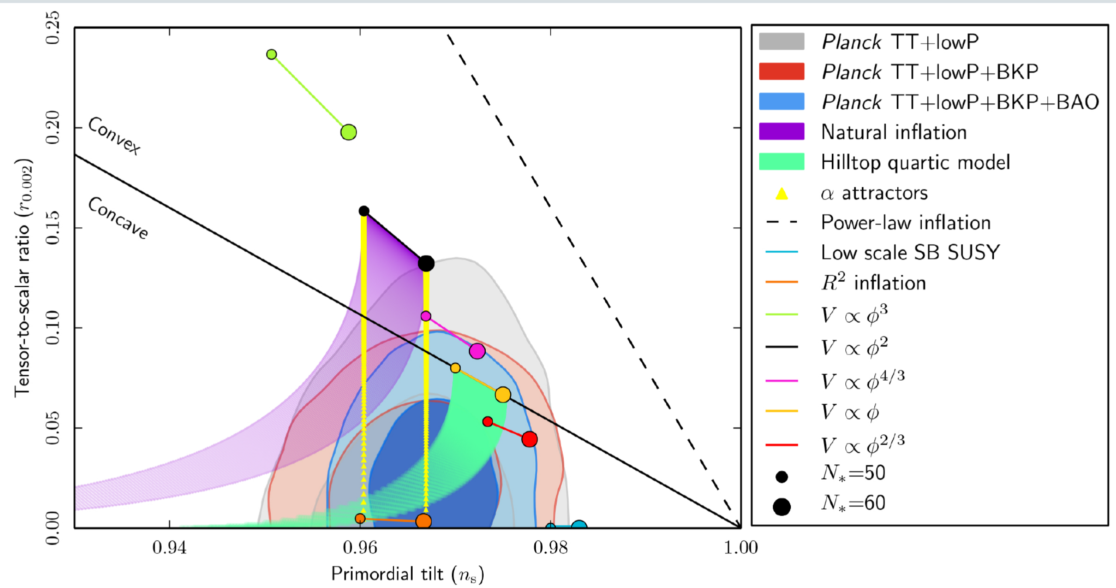


$r_{0.002} < 0.10$ @ 95% CL, similar (indirect) r constraint than with 2013 release (was 0.11)


GRAVITATIONAL
WAVES

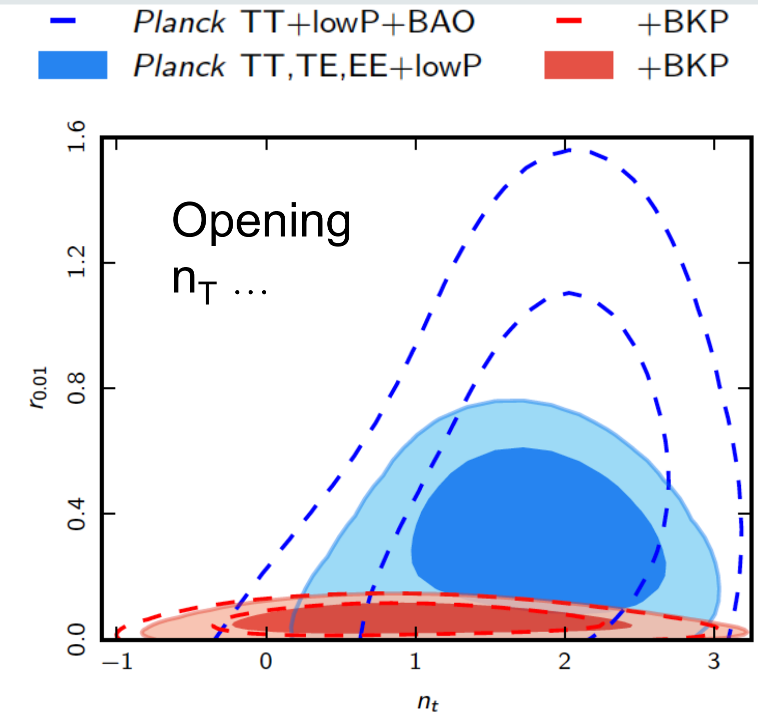
Planck + BK X Planck





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
Planck+BKP15 $r_{0.05}$<0.07 @95%cl (+95GHz)



(k=0.02 is ~decorrelation scale here)

Next steps?

- Improve determination of P_ζ: consider a longer lever arm.

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

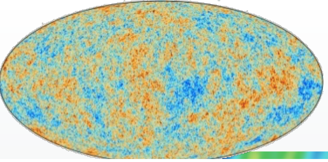
- Improve direct constraints/detect a primordial stochastic background of gravitational waves (goal $\sigma\_r \sim$ few 10^{-4}):

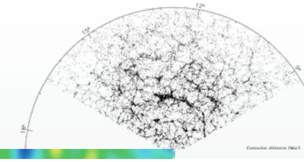
  ➔*measure B-mode polarisation at relatively large scales, and deal with the not-so benign Dust foreground.*

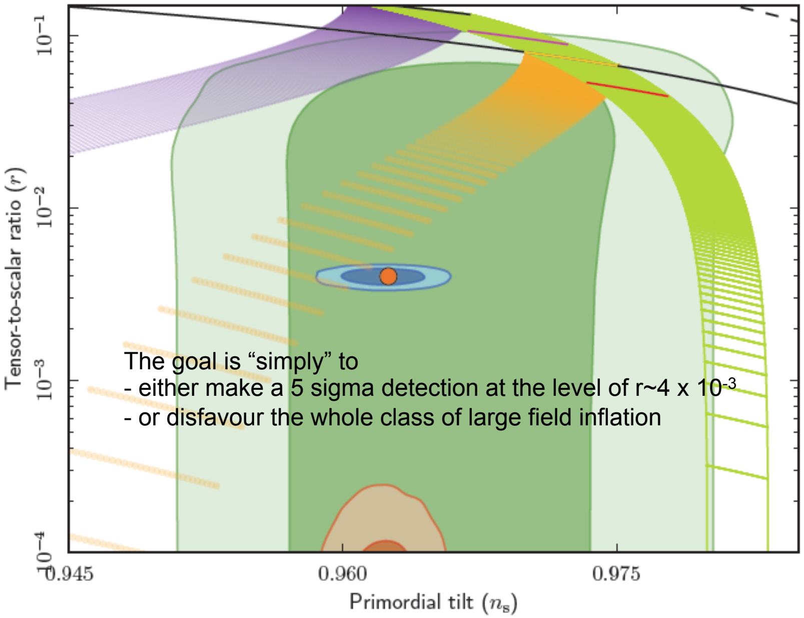
  ➔*deal with intrinsic foreground of lensing-induced B-modes, i.e., know the lensed E-modes very well over broad range of scales, and a tracer of the lensing gravitational potential (either non-CMB, e.g., CIB -- or internal, a great goodie!).*

- Of course future data will also be searched for “features”

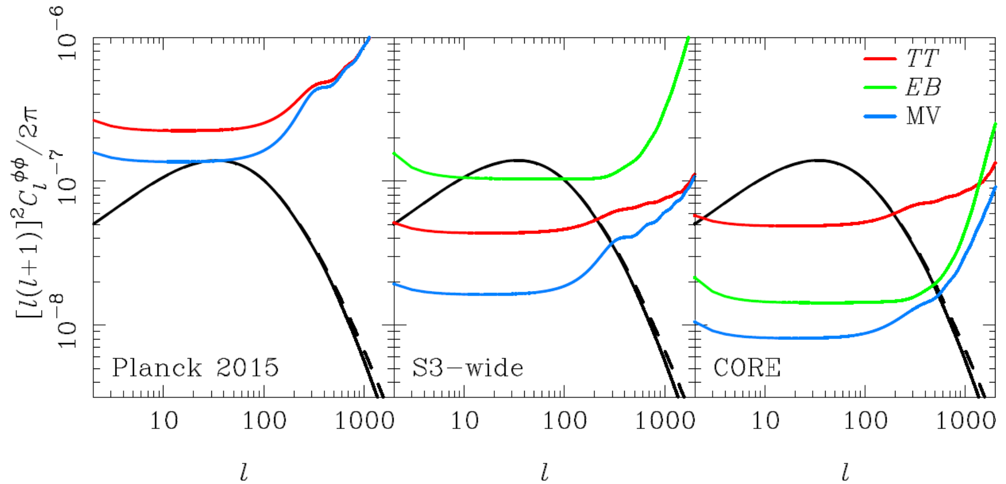
CORE examples of CMB potential



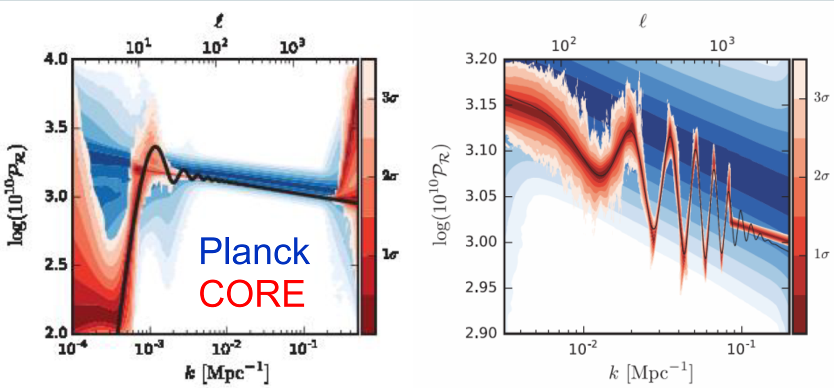




The goal is "simply" to
- either make a 5 sigma detection at the level of r~4 x 10^{-3}
- or disfavour the whole class of large field inflation



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]. → Mν, N_{eff} …



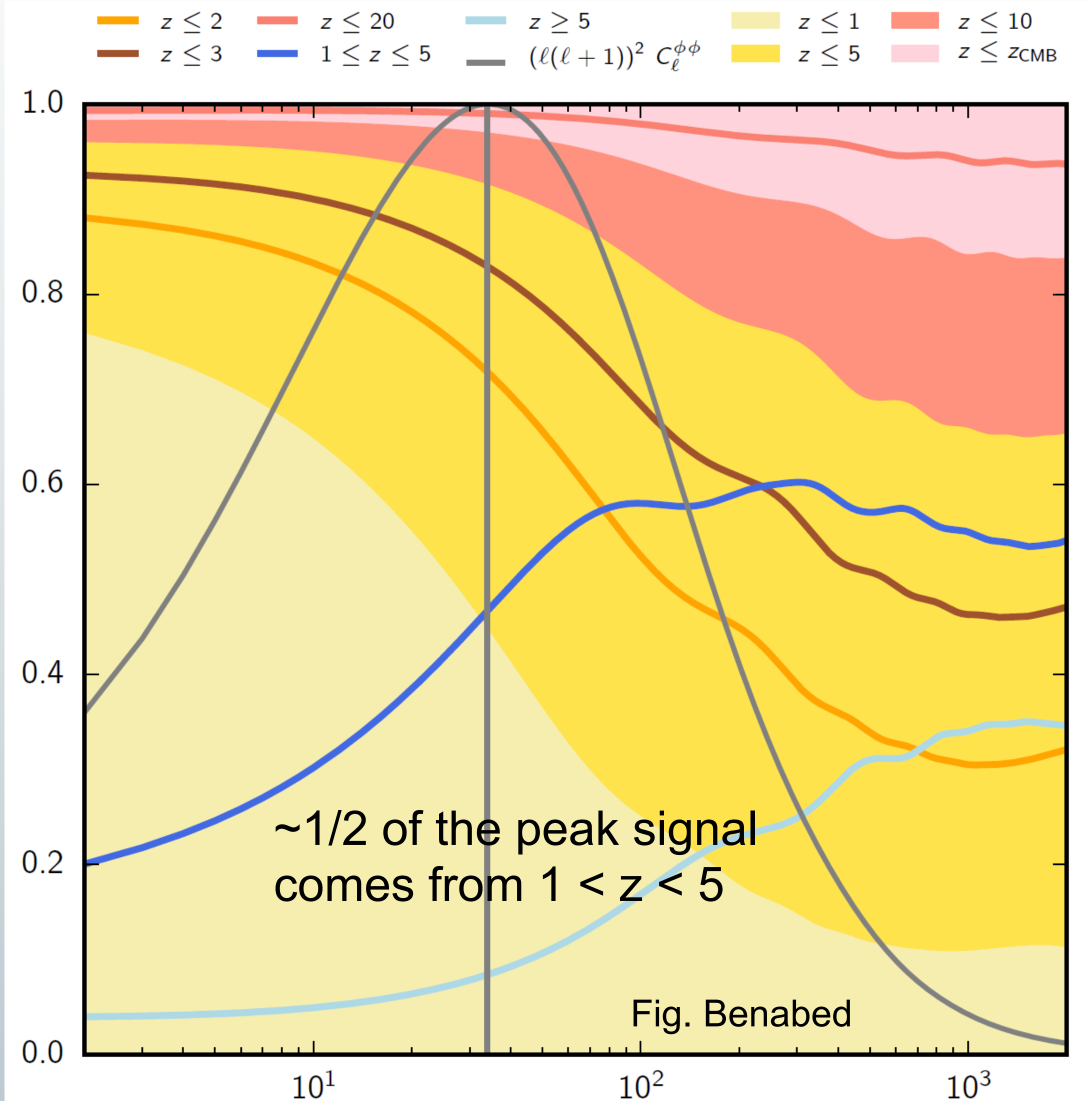
Power spectrum reconstruction
(linearly-sinusoidal wiggles generated by an inflaton cs reduction)

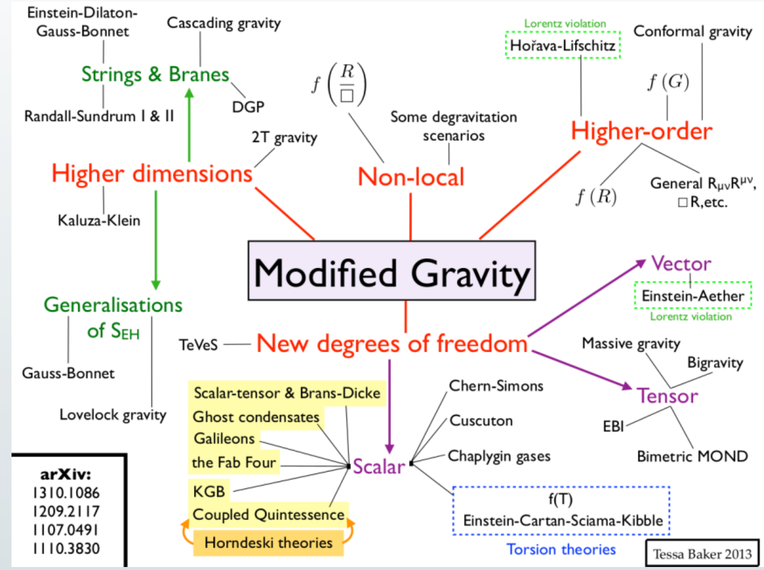
Model	*Planck*15+BAO	*CORE*	*CORE*+BAO
ΛCDM	3.3	2.3×10^3	2.3×10^3
$\Lambda\text{CDM} + \sum m_\nu$	11	8.9×10^3	2.0×10^4
$\Lambda\text{CDM} + w$	24	5.4×10^3	2.2×10^4
$\Lambda\text{CDM} + \sum m_\nu + N_{\rm eff}$	15	4.7×10^4	1.0×10^5
$\Lambda\text{CDM} + w_0 + w_a$	42	4.7×10^3	1.3×10^5
$\Lambda\text{CDM}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

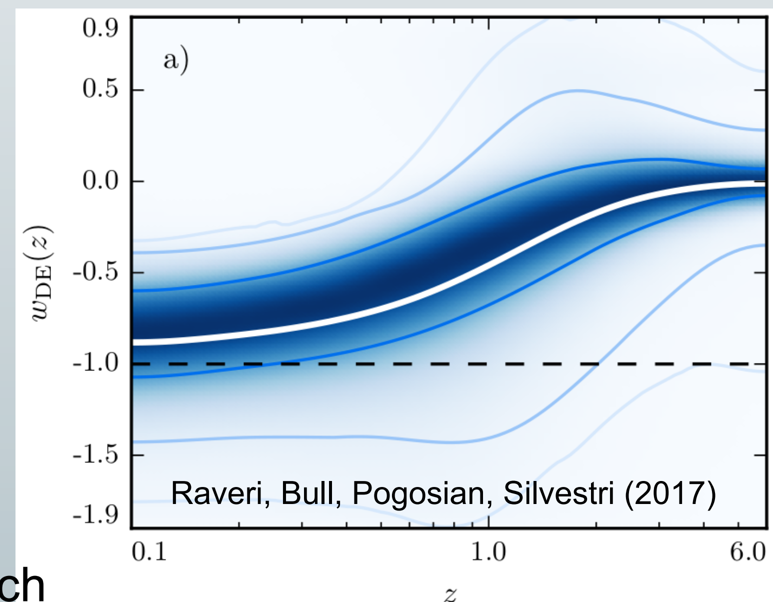
Table 2: Improvement with respect to *Planck*15 of the global figure of merit (see text) in the different cosmological scenarios specified in the first column for various data combinations involving *CORE* and future BAO measurements.

Capability to find limitations of ΛCDM

Lensing comes from a broad redshift range



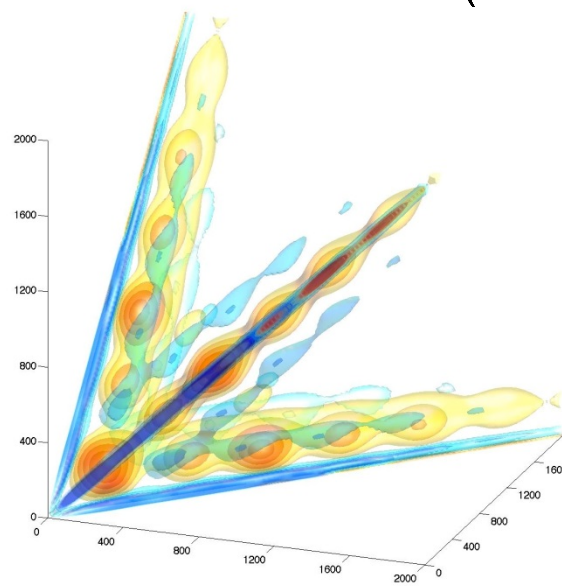


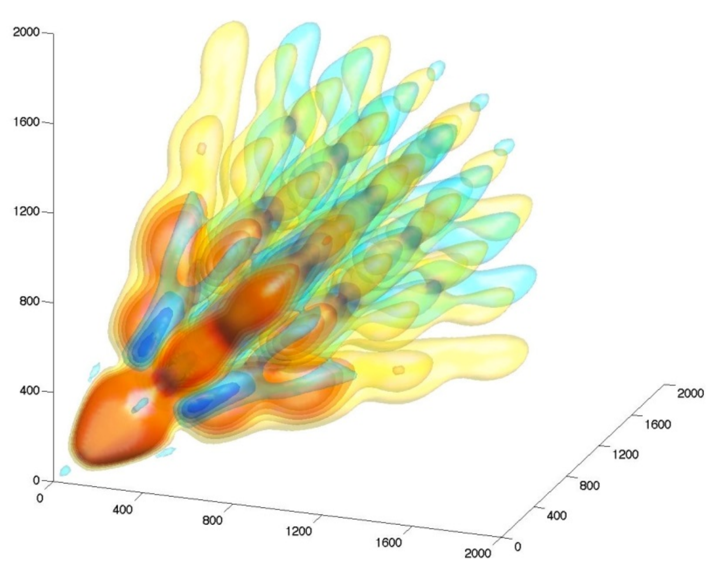


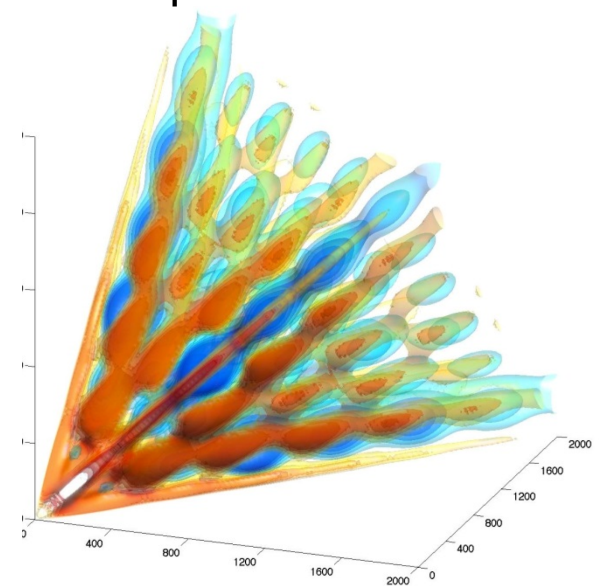
A unique contribution of CMB lensing to DE/MG search

CMB bispectrum fingerprinting

LEO (Local, Equilateral, Orthogonal) are common outputs







NG of ***local*** type ($k_1 \;\; k_2 \sim k_3$):

- Multi-field models
- Curvaton
- Ekpyrotic/cyclic models

(Also NG of **Folded** type

- Non Bunch-Davis
- Higher derivative)

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

- Non-canonical kinetic term
  - K-inflation
  - DBI inflation
- Higher-derivate terms in Lagrangian
  - Ghost inflation
- Effective field theory

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

- Distinguishes between different variants of
  - Non-canonical kinetic term
  - Higher derivative interactions
- Galileon inflation

Planck 2015 - Bispectrum constraints

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	9.5 ± 5.6	**1.8 ± 5.6**
Equilateral	−10 ± 69	**−9.2 ± 69**
Orthogonal	−43 ± 33	**−20 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.1	
Equilateral	−8.9 ± 44	
Orthogonal	−35 ± 22	

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

Planck 2013

ISW-lensing subtracted KSW	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

Plus f_{nl}^{tens}, scale-dependent, g_{NL}, etc…

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

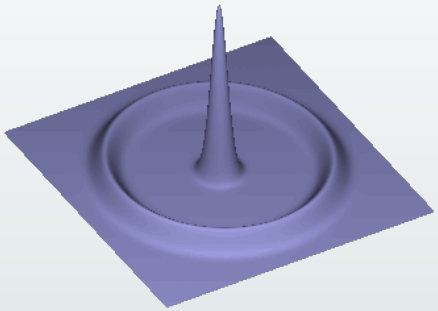
Next steps?

- 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…*

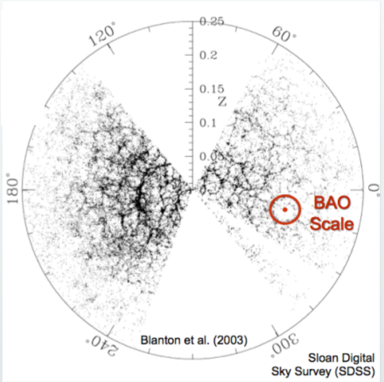
SPHEREX

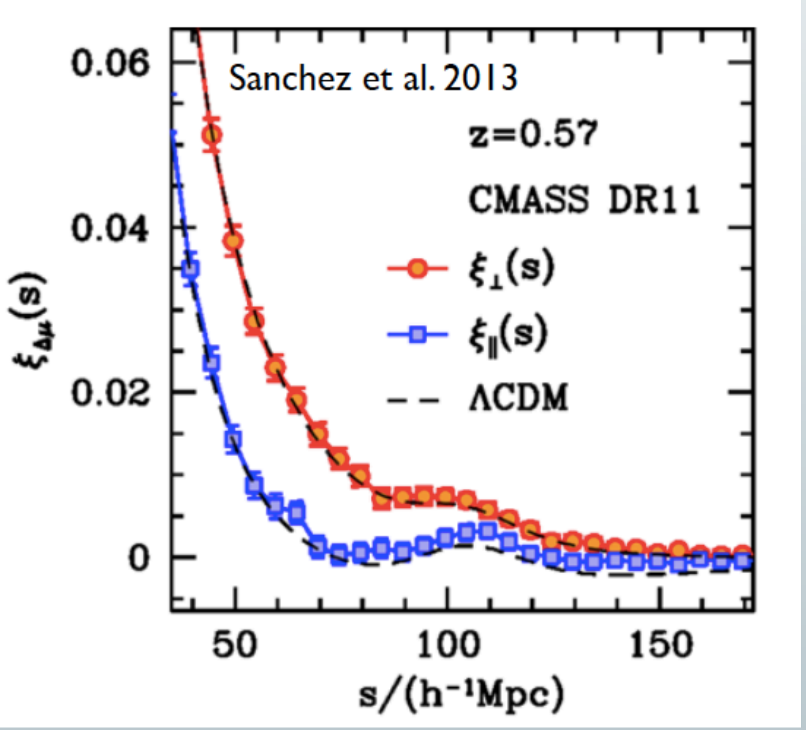
CMB VERSUS OTHER PROBES

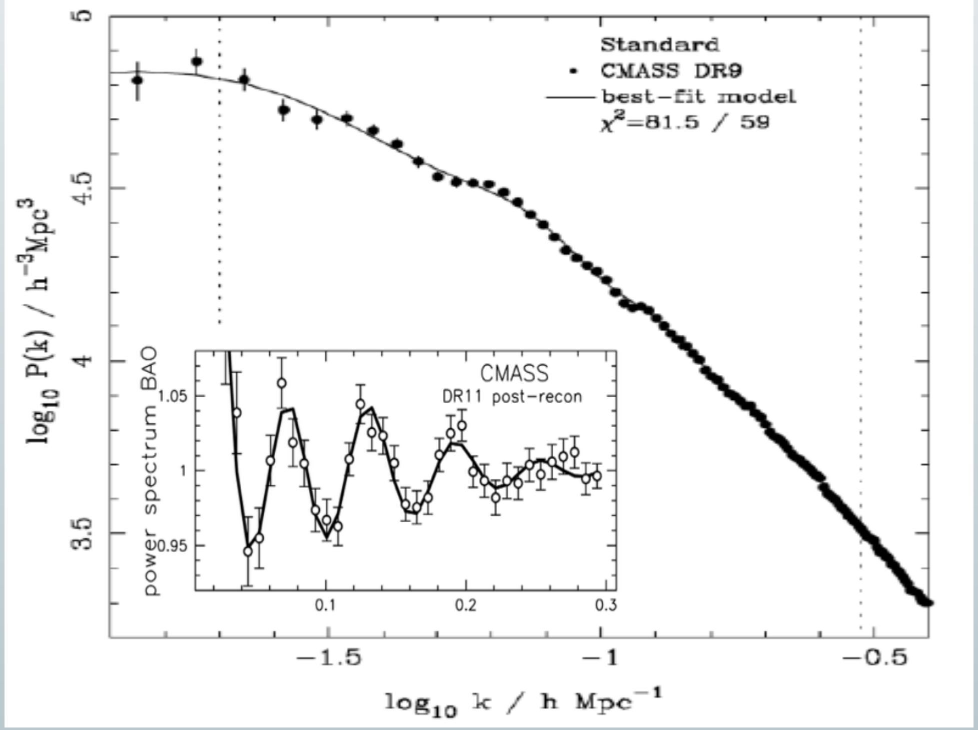
BAO: correlation function & power spectrum



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

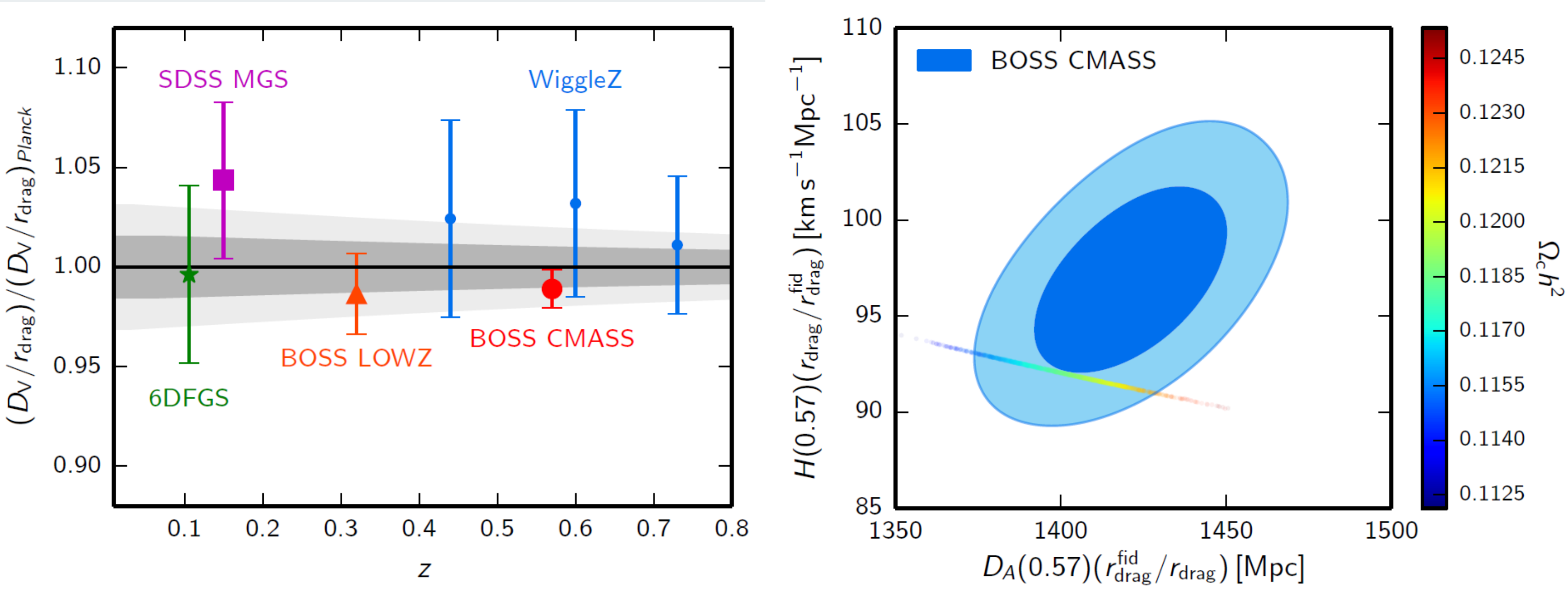






Baryonic Acoustic Oscillations / Planck

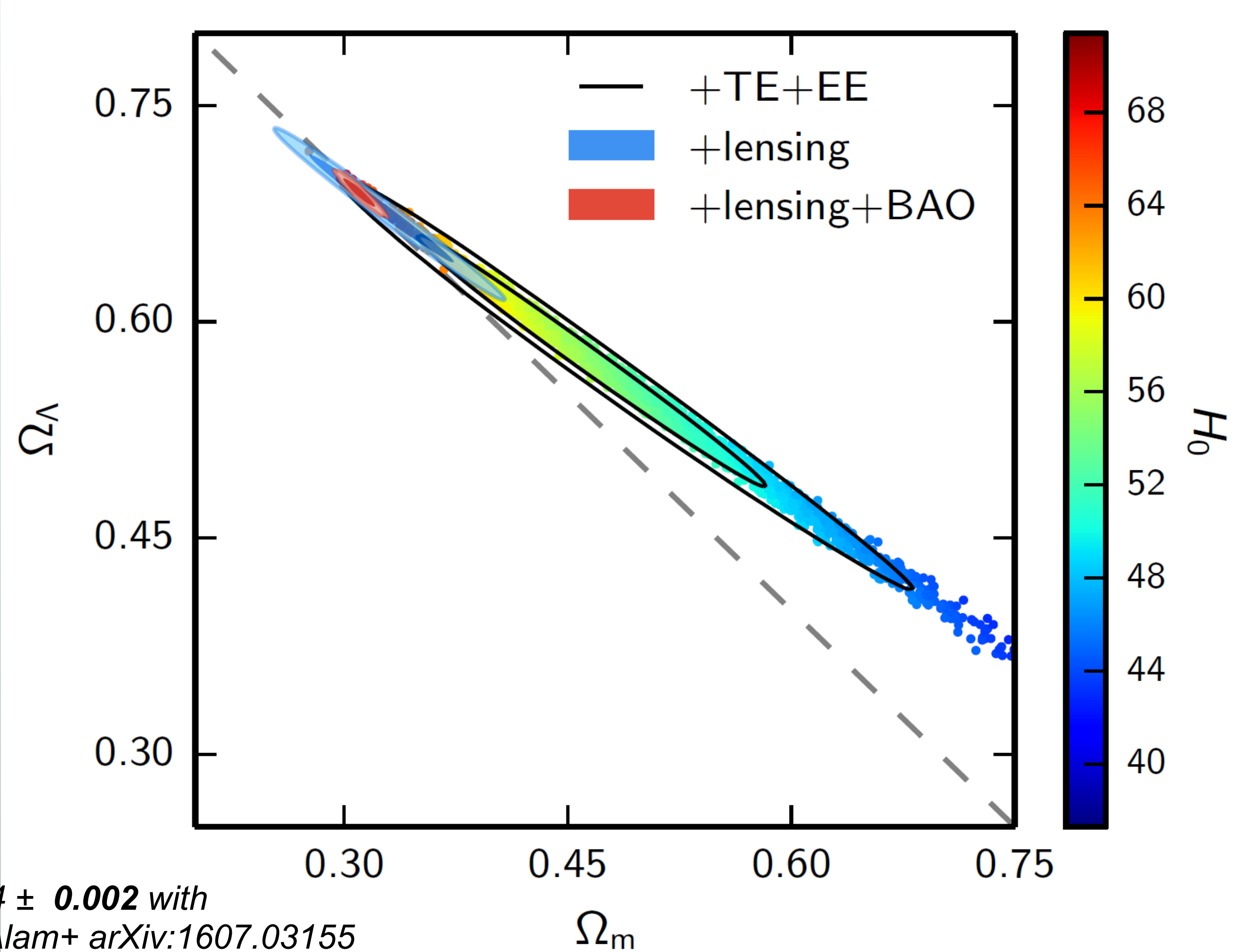
Grey band is Planck TT+LowP 1(2) sigma range



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

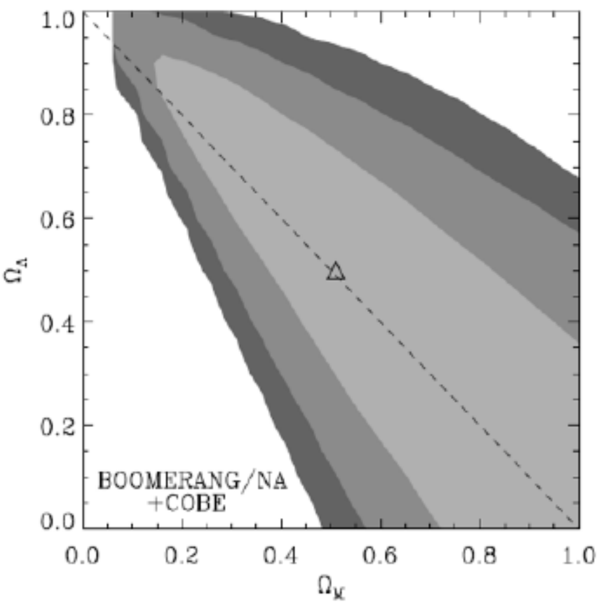
Spatial curvature constraint

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



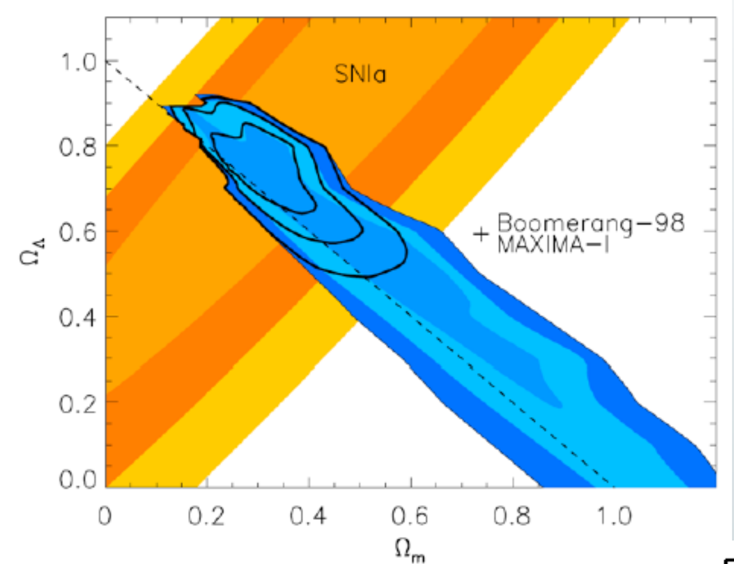
*NB: Ωk =0.0004 ± **0.002** with SDSS3-DR12 Alam+ arXiv:1607.03155*

Spatial curvature constraint



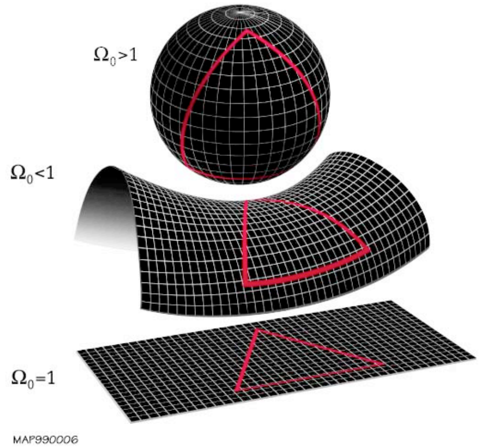
$$\Omega_K = -0.05^{+.40}_{-.40}$$

Melchiorri et al. 2000



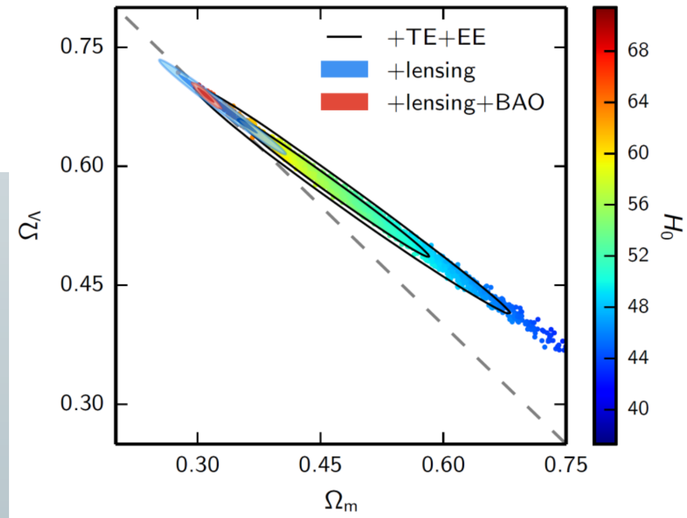
$$\Omega_K = -0.11^{+.07}_{-.07}$$

Jaffe et al. 2001



Flat space ←→ $\Omega_k=0$

Note the change of axes
For Planck below

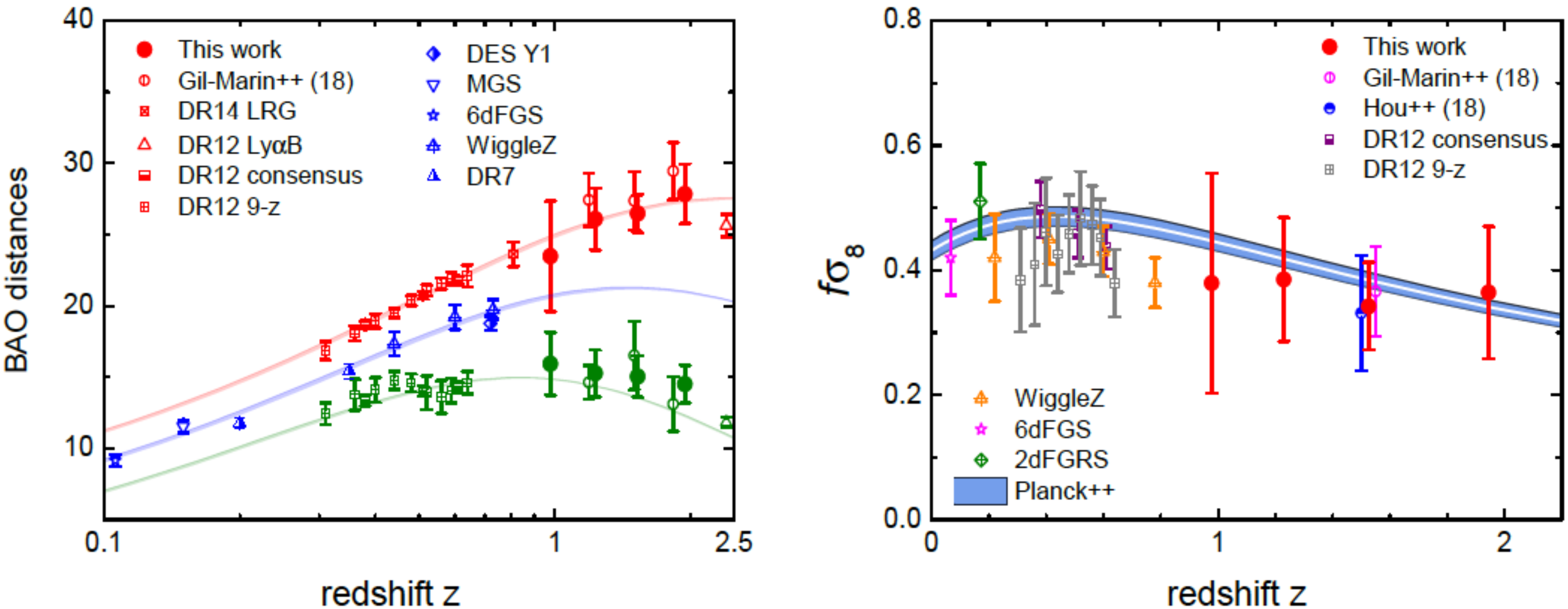


Planck 2015

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

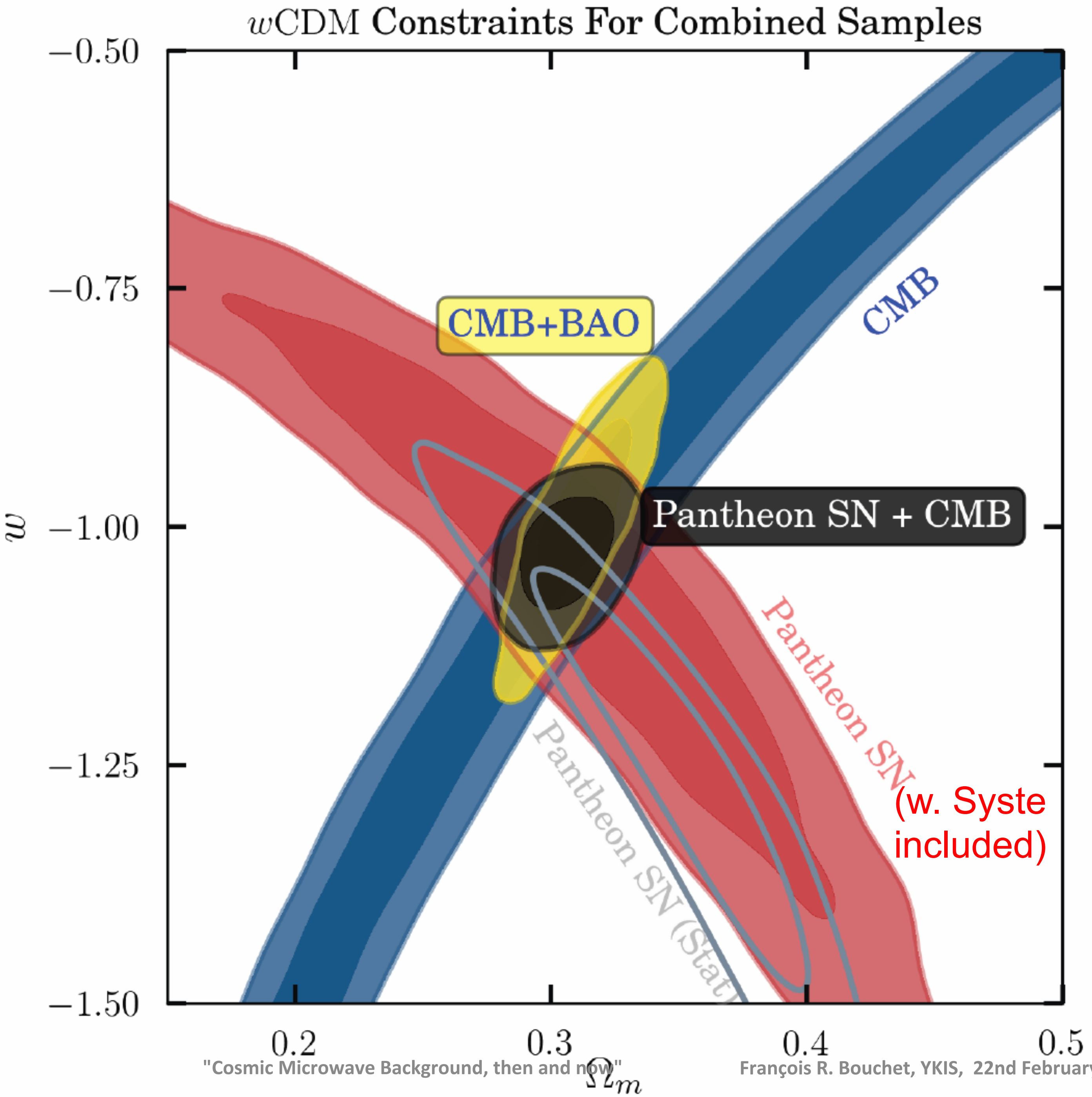
A hundred-fold improvement in 15 years

Latest BAO data



… still agree very well with Planck data prediction within LCDM

Zhao+ arXiv:1801.03043v



Scolnic+ arXiv: 1710.00845v1

Pantheon= 1049 SN Ia from 0.01 <z<2.3,

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

CMB+ BAO was:
Ω_m=0.312+_0.013
w =_0.991+_0.074
Now SN+CMB:
Ω_m=0.303+_0.012
w =_1.031+_0.040
Twice more data, + better Syst analysis
➔ W≠-1 *gone*

NB: Other data:
- CMB=(Planck TT + lowP)15,
- BAO=SDSS Main Galaxy Sample (Ross et al. 2015)+BOSS and CMASS survey (Anderson et al. 2014).

A perfect (-ly boring) Universe?

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

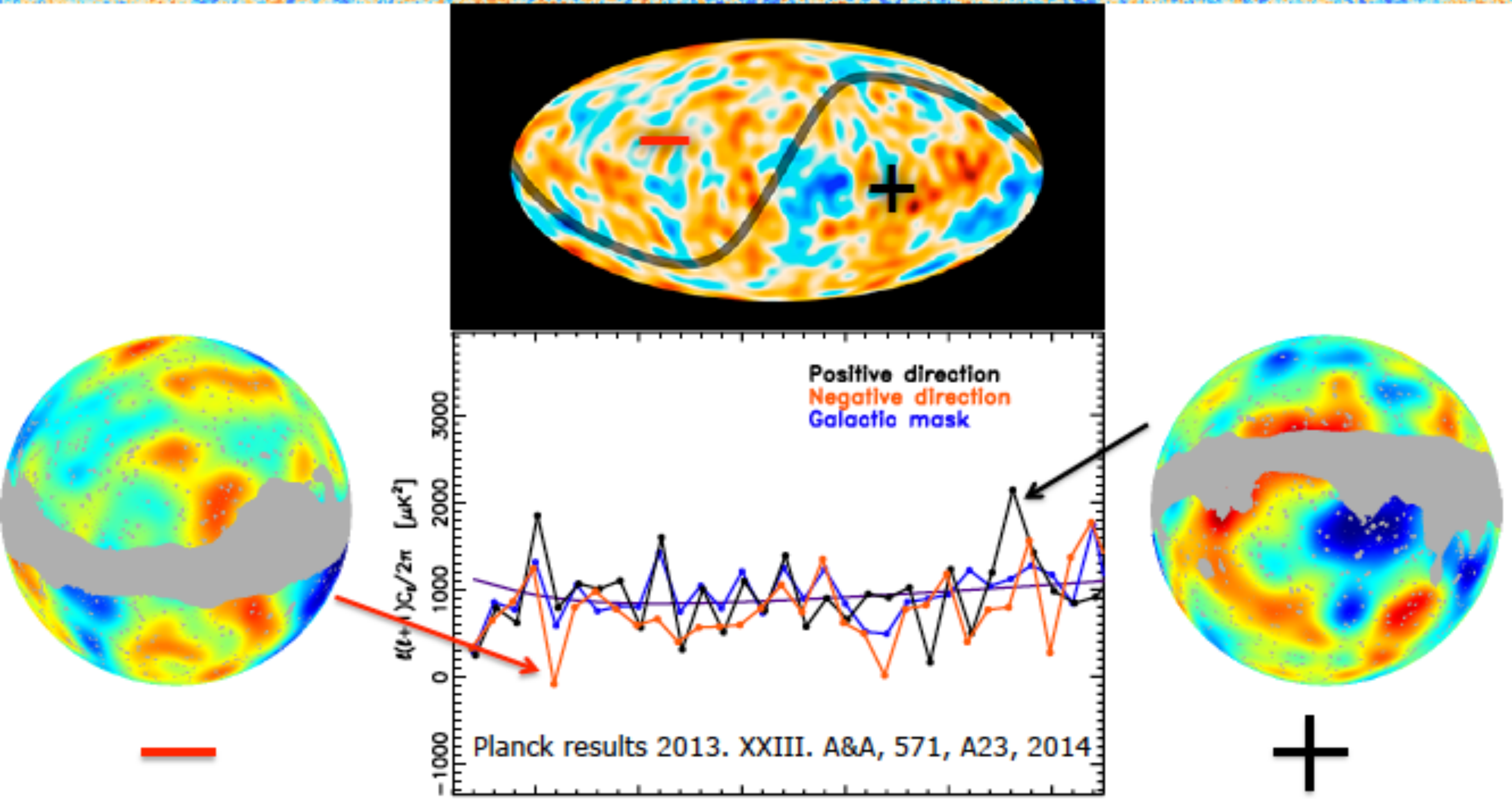
$f^{local}_{NL} = 0.8 \pm 5.0$
$f^{equil}_{NL} = -4 \pm 43$
$f^{ortho}_{NL} = -26 \pm 21$

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

α_{ISO}
α (Fine structure constant)
P_{ann}
c_s
$A_{2s\text{->}1s}$
…

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

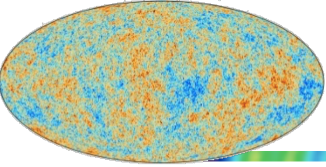
Power asymmetry in *Planck* 2013 nominal mission data



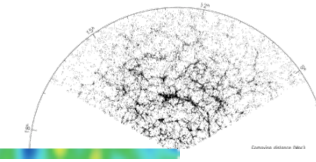
Large scale feature in 2015 full mission data are very similar to those in 2013 nominal mission data

Next steps?

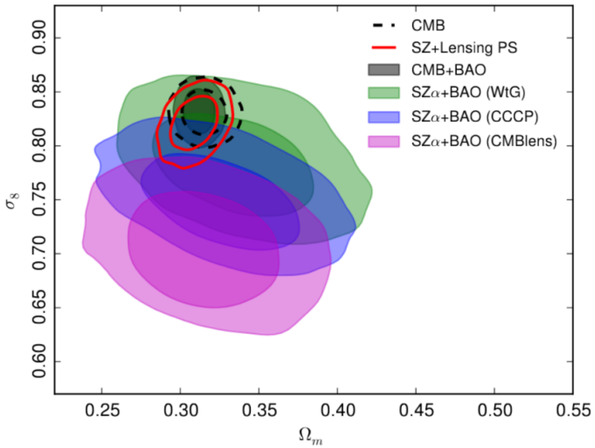
- There are a number of tantalizing “anomalies” (l~20 dent, low multipoles alignment, statistical anisotropy, etc.).
- These are at very large scales in Temperature, and not really statistically significant. (+pb of *a posteriori* statistics, recall SH)
- Large scales in polarisation are quite hard to 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 in a few months.
- 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)…



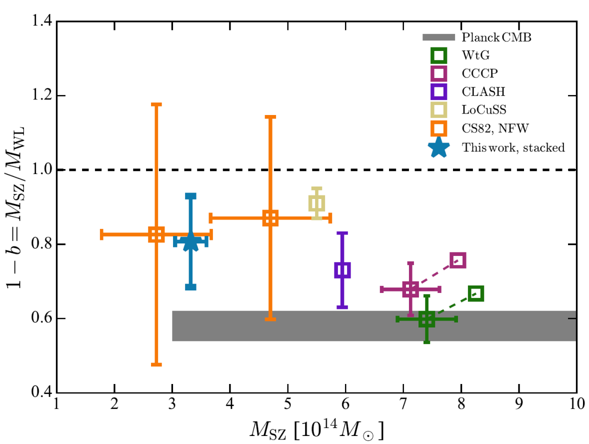
Some tensions do exist



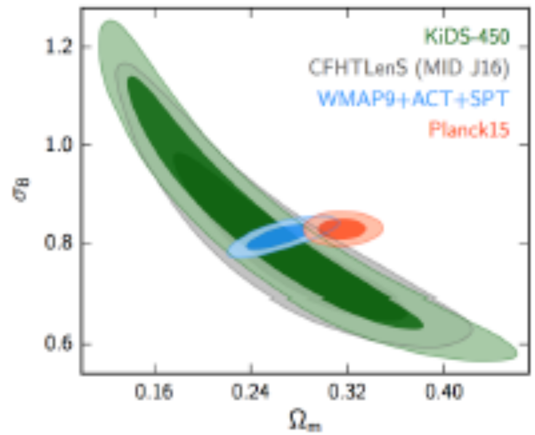
SZ



Medezinski+ arXiv:1706.00434: a cluster mass dependence of the bias? (HSC new poont)



WL

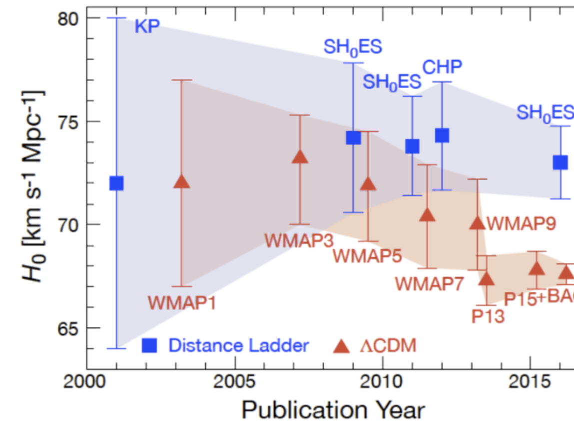


Hildebrandt+ 16 BUT GPE+ arXiv:1707.00483

Ly BAO measurements at high redshift are discrepant at 2.7sig; it is quite difficult to find a physical explanation not disrupting BAO consistency elsewhere, see, e.g., Aubourg etal. 2015

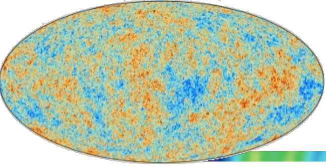
Dark Matter- Dark Radiation interaction? (Pan+ arXiv: 1801.07348)

H0

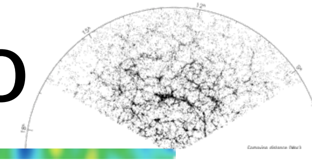


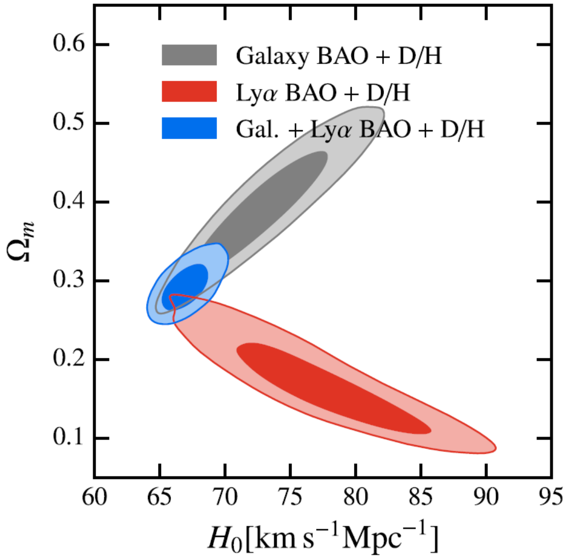
Freedman, arxiv/1706.02739

- Planck consistent with BAO, SN, BBN within 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.



CMB, BAO, SN1A, D/H… and Ho





(Addison+ arXiv:1707.06547)

"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."

☺

- Complete distance ladder: Geometry -> Cepheid -> SN1a -> redshift
- Inverse distance ladder: Use rd=sound horizon at radiation drag (~recombination) as a rod. Connect high-z to low-z by using BAO + SN (i.e. rd+BAO normalise the SNs). Aubourg+ (1411.1074) and then Cuesta+ (1411.1094) find very good agreement with Planck H_0 value for LCDM. Also Gomez-Valent & Amendola (1802.01505) with essentially all current ways to infer H(z). Others confirm that direct H_0 appears as outlier. NB: ways to change rd appear contrived to most.
- But no problem identified with Sh0ES, i.e., the Geometry/Cepheid anchor!

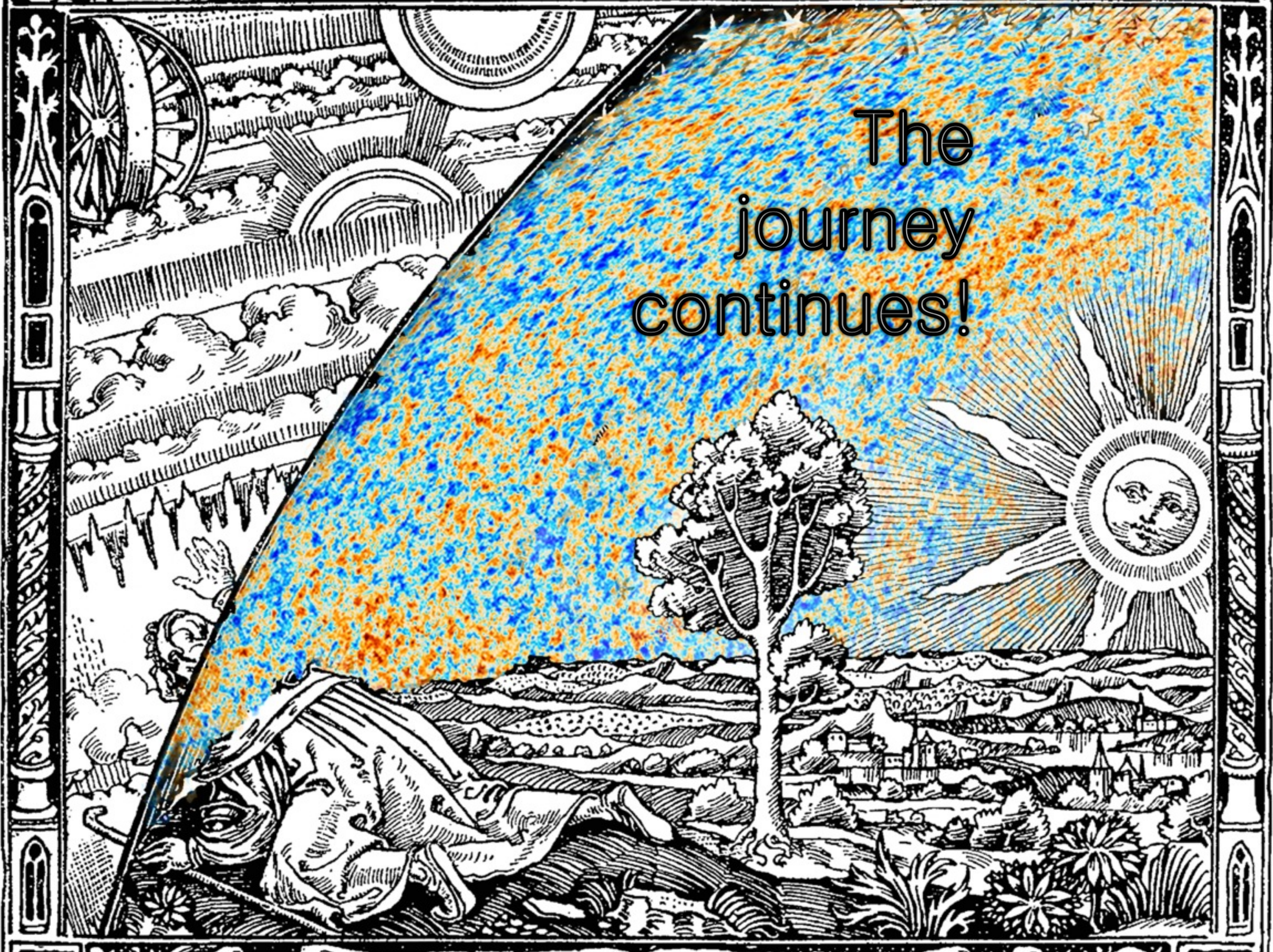
CMB Anisotropies post-Planck

- The LCDM model fits all CMB data in T, E, B, ϕ.
  - *No need for an extension. A lavish source of constraints /papers…*
  - *Same model parameters, determined at the per cent level, also fit other data (BAO, and also BBN, SN1a…).*
  - *Some tensions (anomalies, SZ, H0, WL), whose meaning remains unclear as of now.*
- LCDM is a tilted model (n_s <1) and the inflationary phase models check all the generic boxes. Many specific models have been ruled out though.
- Alternatives have either been falsified, or they mostly/only do post-dictions so far. We now want $\sigma_r < 10^{-3}$!
- T anisotropies information essentially exhausted (as we promised to ESA back in 1996), but much still to learn on foregrounds, e.g. from SZ. Polarisation promises a very rich harvest at all angular scales.
- A new field, CMB lensing, has emerged (observationally), with a great scientific potential. It has unique advantages (known source plane, well understood, mostly linear physics at work); but it is a foreground to be removed for improving the detection capability of a Primordial Gravitation wave stochastic background. In any case, it is a great source of problem to solve for astrophysicists.
- Large scales/High frequencies, to best do r & τ, require space, again!

Planck 2018 “Legacy” Release

- Expected around fool’s day (of 2018!)…

- 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 describe much smaller effects (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 analyses, etc.


The
journey
continues!