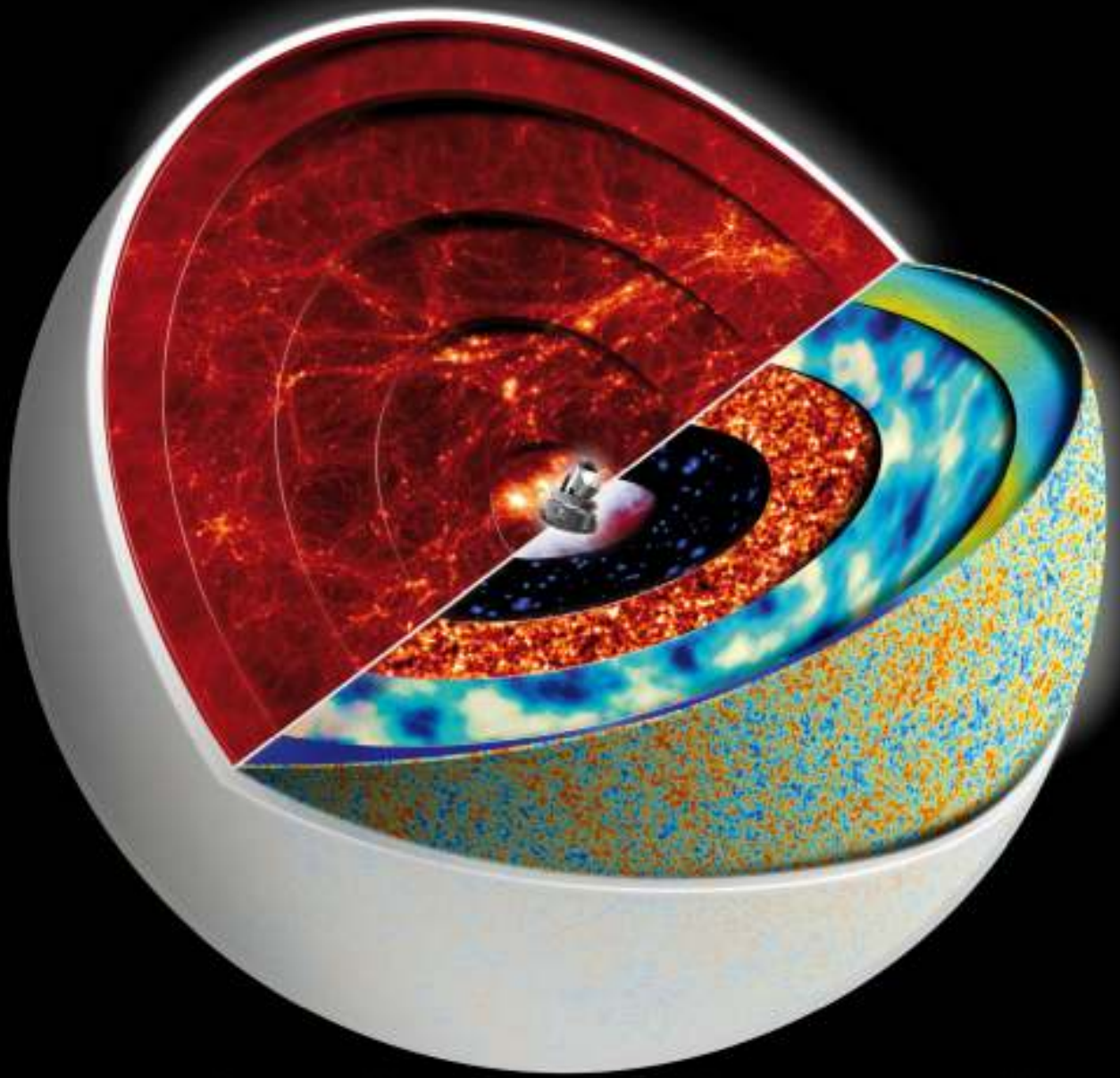
Cosmology 2015: GR100, CMB50, Planck23,BAO10…



From quantum foam to the cosmic web

Once upon a time…

COSMOLOGY: A SEARCH FOR TWO NUMBERS

Not anymore!!

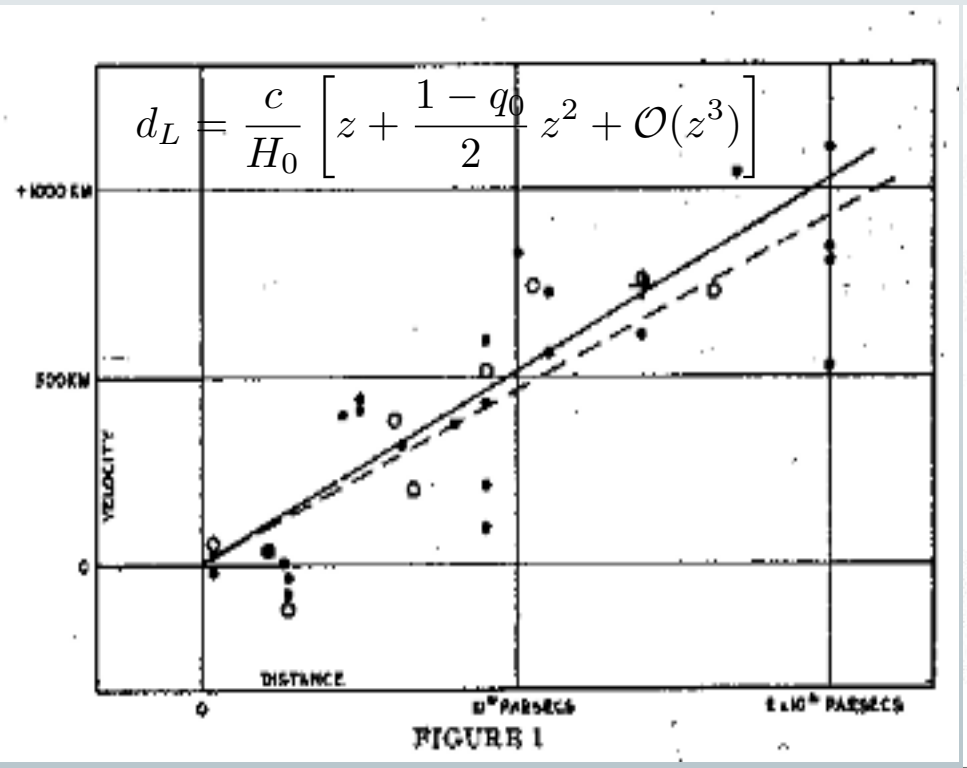
- Tens of millions of numbers (from CMB/LSS)
- Simple hypotheses explain much of them
  - *but pulled from nowhere*
- With kludges
  - *Those for Single Field Slow Roll inflation*
  - *Dark energy (dark matter)*
- Charge: survey past accomplishments in cosmology, look forward to the future.

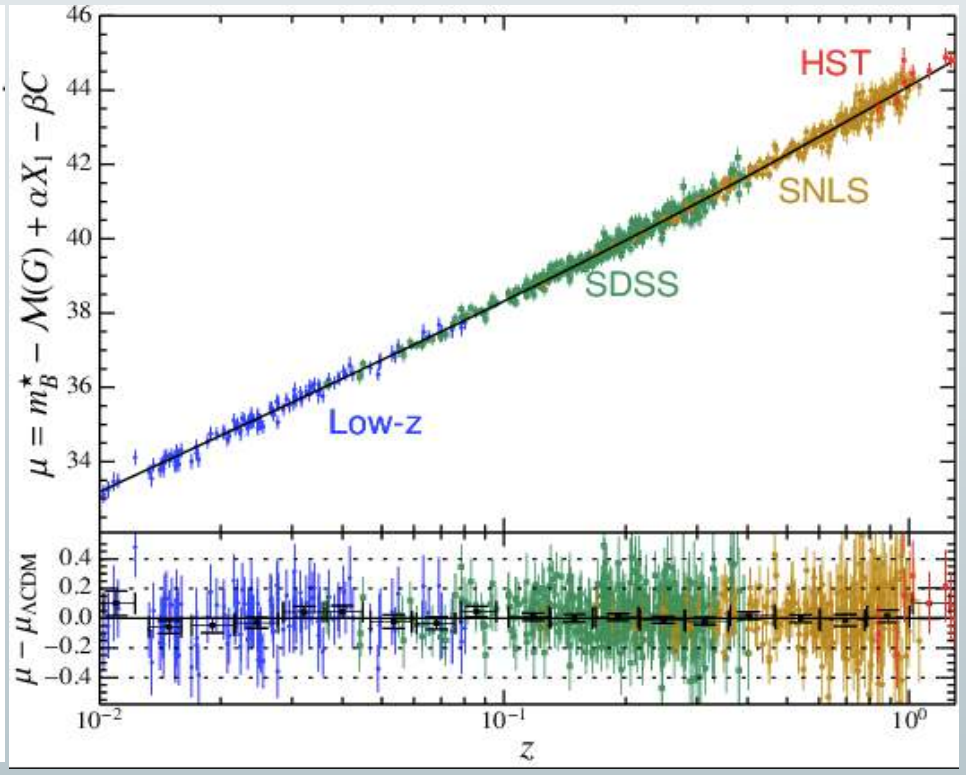
About these 2 numbers…

The redshift-distance relation, resting on Friedman equation and the energy content

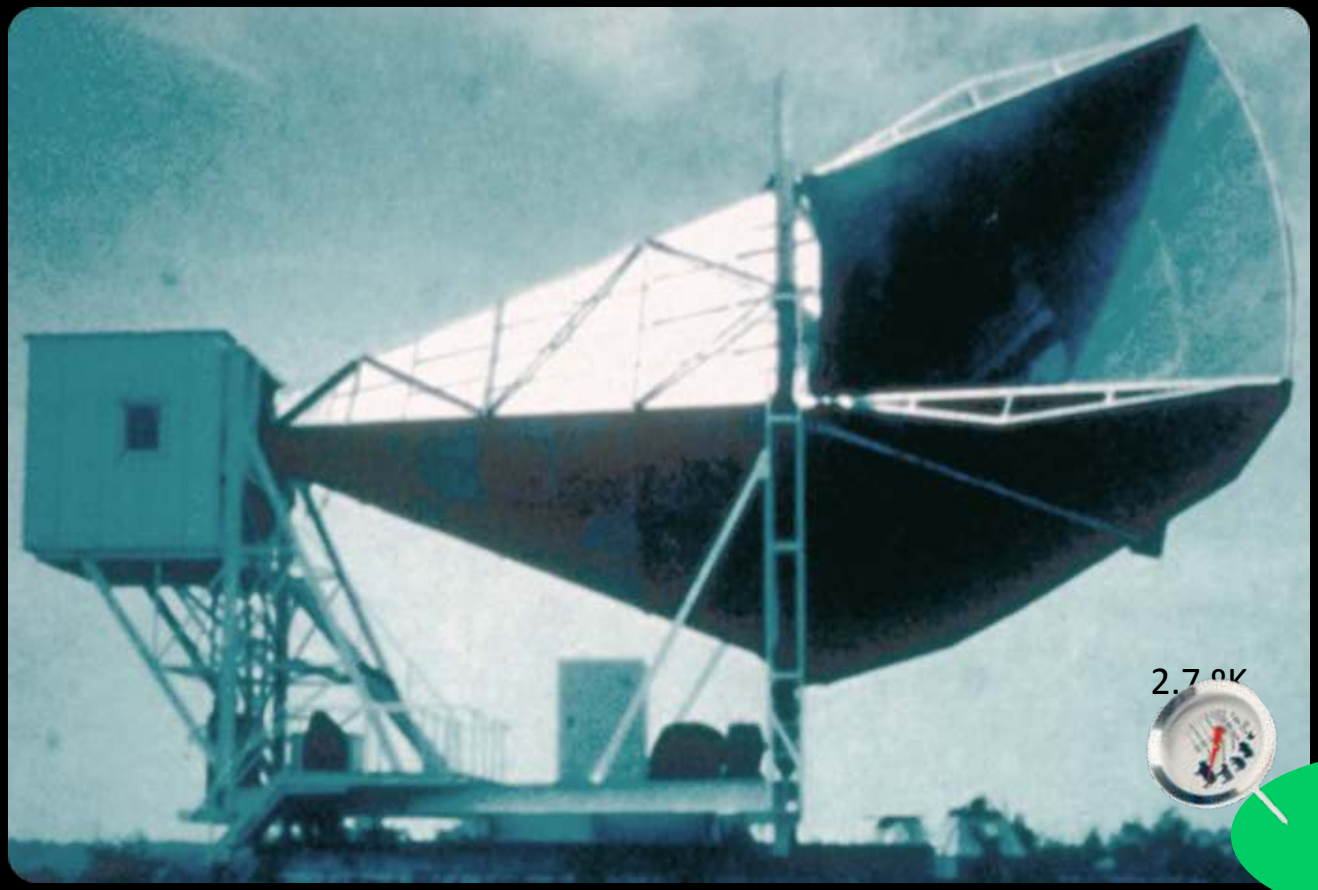
$$d_L(z) = a_0(1+z)S_k\left(\frac{c}{a_0 H_0}\int_0^z dz'\left[\sum_i \Omega_{i0}(1+z')^{3(1+w_i)} + \Omega_{k0}(1+z')^2\right]^{-1/2}\right),$$

has come a long way since the days of Hubble



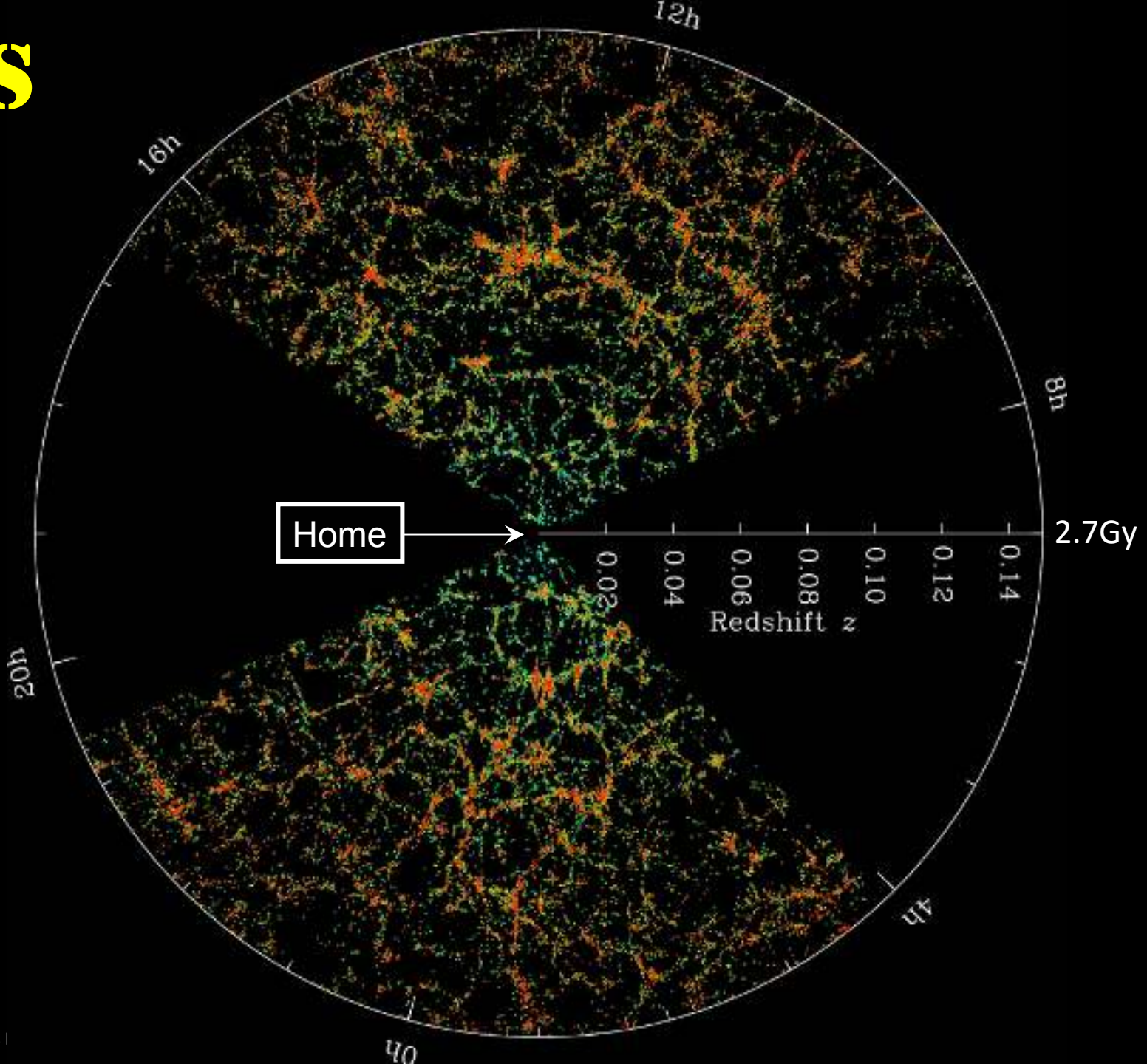


CMB

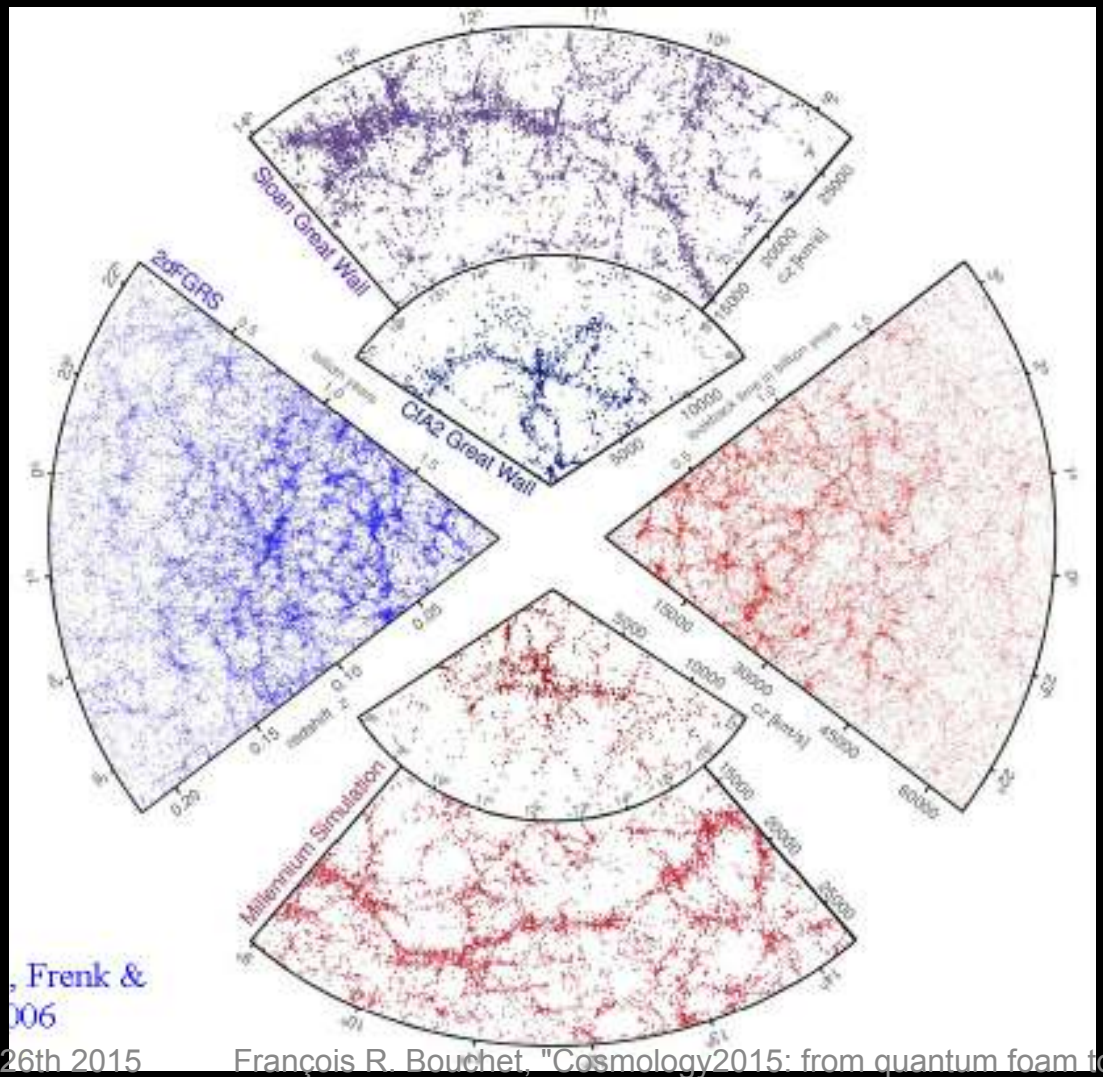


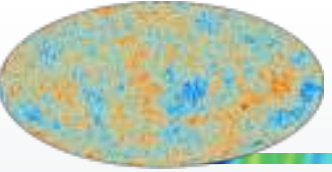
Première observation aux Bell Labs
A. Penzias & A. Wilson en 1965
Nobel 1978

LSS

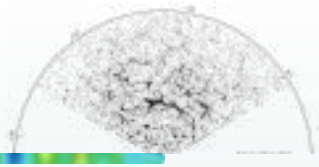

8h
4h
0h
20h
16h
12h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
Home
2.7Gy

THEORY + SIMULATIONS

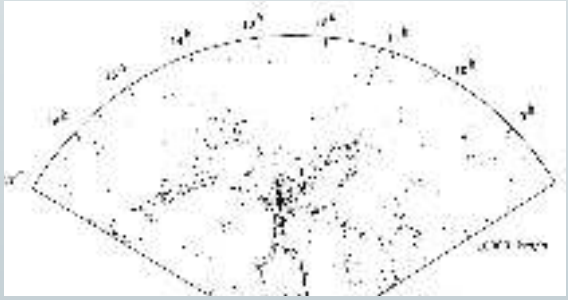




Amazing progress…



- In the 60's and 70's, the early CMB theory was quickly established; the Universe then was baryonic, but DM evidence was mounting.
- In the 80's
  - *The CDM miracle ("The hot, the warm, and the cold")*
    - The west hierarchical clustering (bottom-up) corresponded to iso-curvature primordial fluctuations
    - The east natural adiabatic fluctuations of HDM lead to pancake theory (top-down) with superclustering
    - CDM turns HZP n=1 adiabatic into the current hierarchical picture with superclustering, our cosmic web
  - *Two competing theories developed for the seeding of structures, both via quantum fluctuations of the vacuum*
    - Inflation
    - Cosmic strings
  - *1986 CfA "bubbly" redshift survey*
  - *No CMB anisotropies detection, but rapid progress*



- In the 90's
  - *CMB anisotropies detected, a number of BB pillars established*
  - *SN1a, and emergence of LCDM paradigm but many skeptics…*
- Since then, BAO, Lensing, CMB polar… Is precision cosmology accurate?

A theories-measurements contact

The harmonic modes

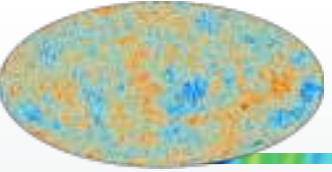
$$a_{lm} = \int d^2\hat{n}\, T(\hat{n})\, Y^*_{lm}(\hat{n}) \ ,$$

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

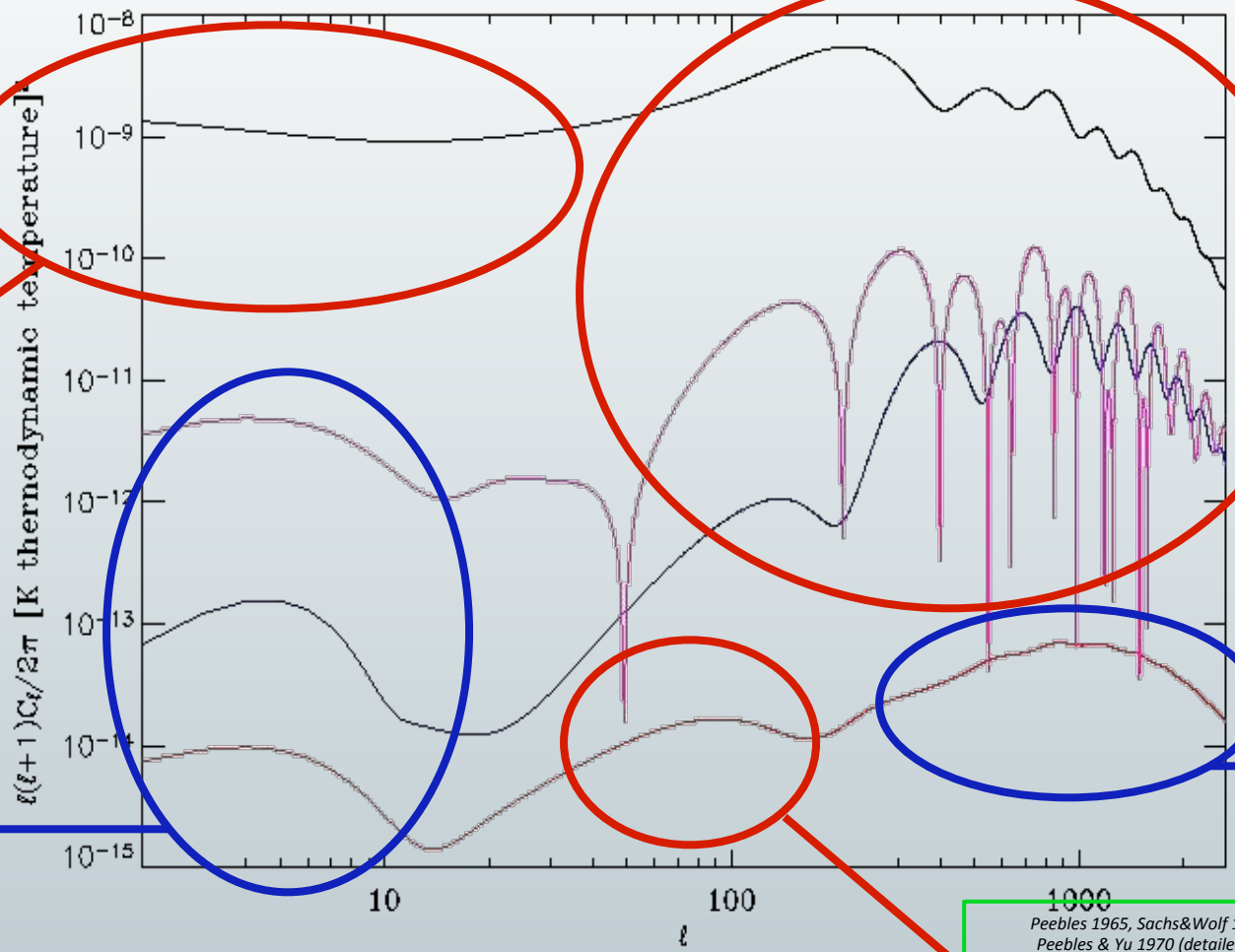
$$\widehat{C_\ell} = \sum_m \frac{|a_{\ell m}|^2}{2\ell + 1}$$



CMB information mine

Acoustic oscillations

Primordial power



Observable related to physical parameters through well-understood, mostly linear physics

Note ΔT values range

Lensing

Reionisation

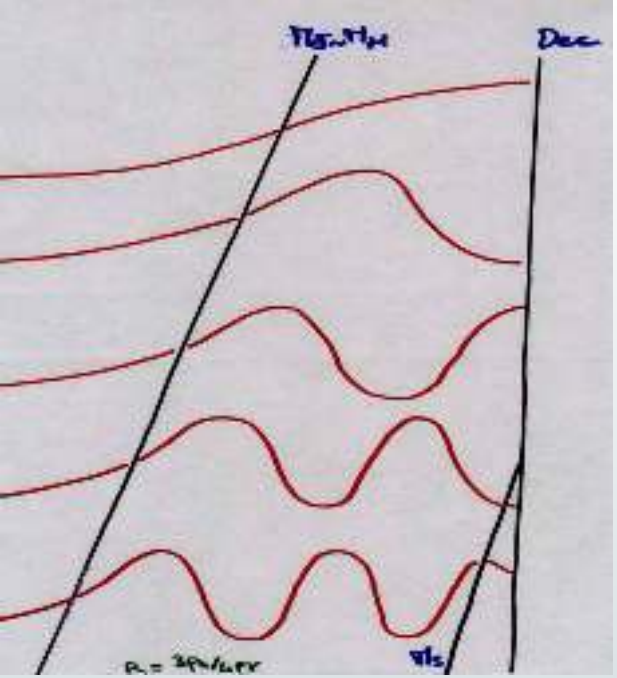
Peebles 1965, Sachs&Wolf 1967, Silk 1968, Sunyaev &Zeldovich 1969, Peebles & Yu 1970 (detailed rec.)… simulated maps Bond&Efstathiou 1987(Inflation) Bouchet,Bennett&Stebbins1988(strings)… public codes CMBFAST [Seljack & Zaldarriaga 96], CAMB [Lewis et al. 2000], CLASS… Kamionkowski et al 1997, Zaldarriaga & Seljak 1997 [E, B], NG…

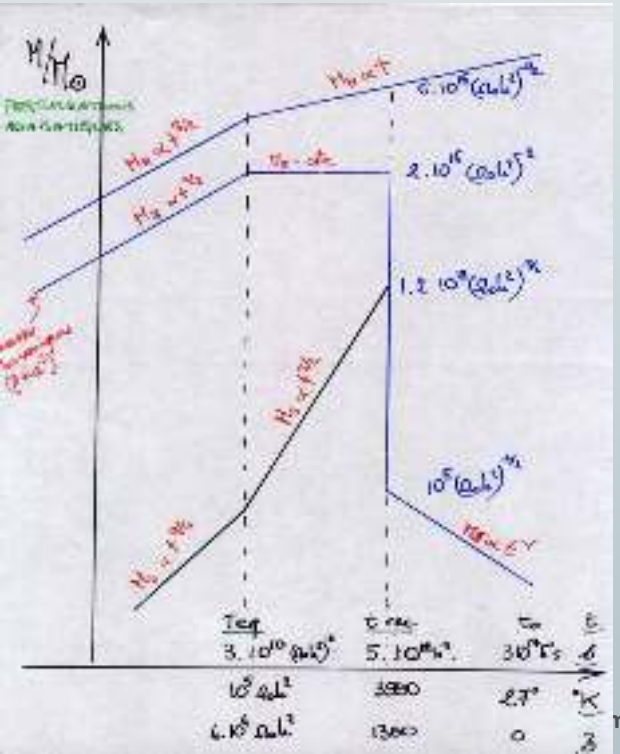
Angle ≈ 200/l degrees

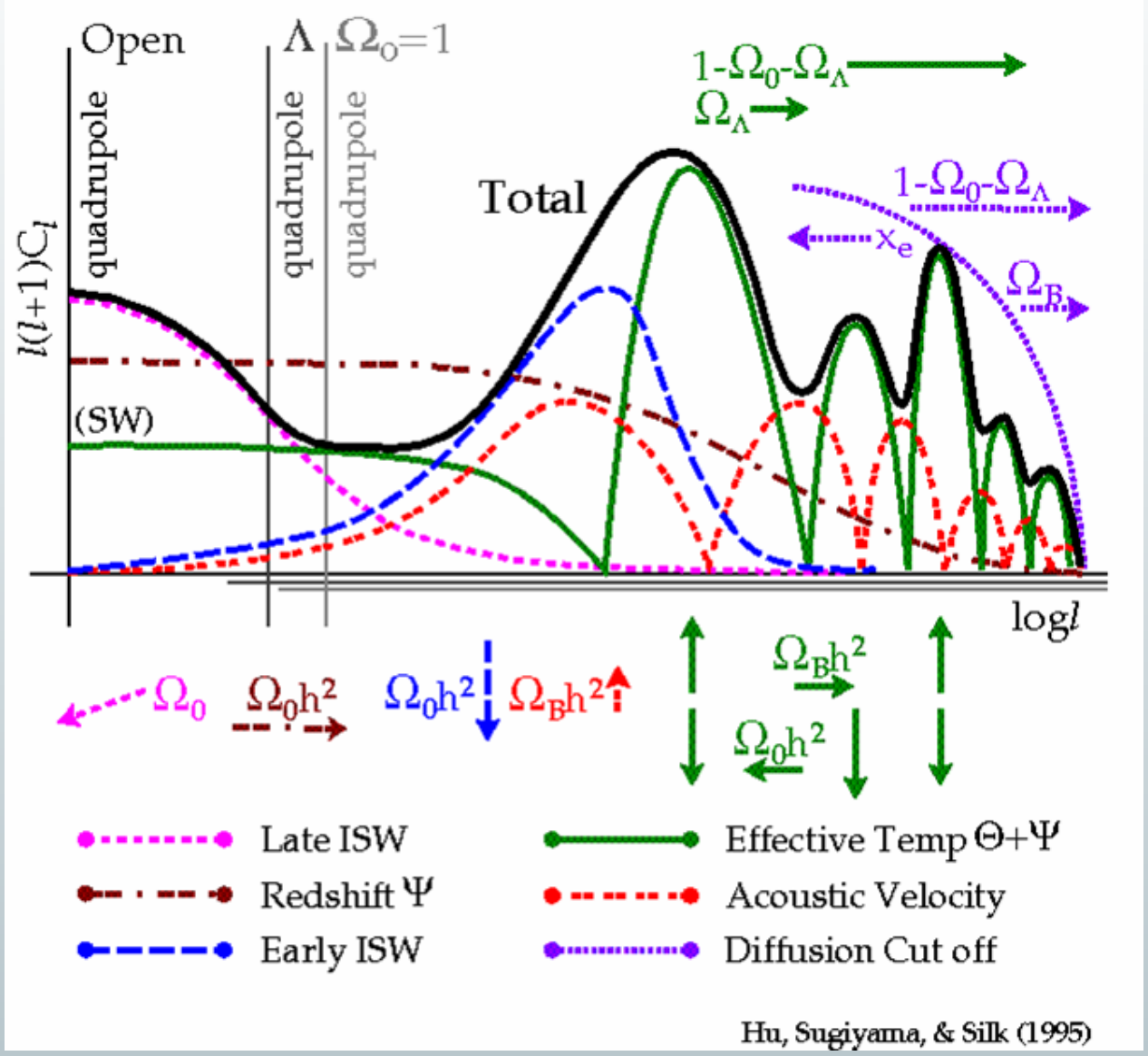
Gravity waves

+ all other statistical properties (NG)

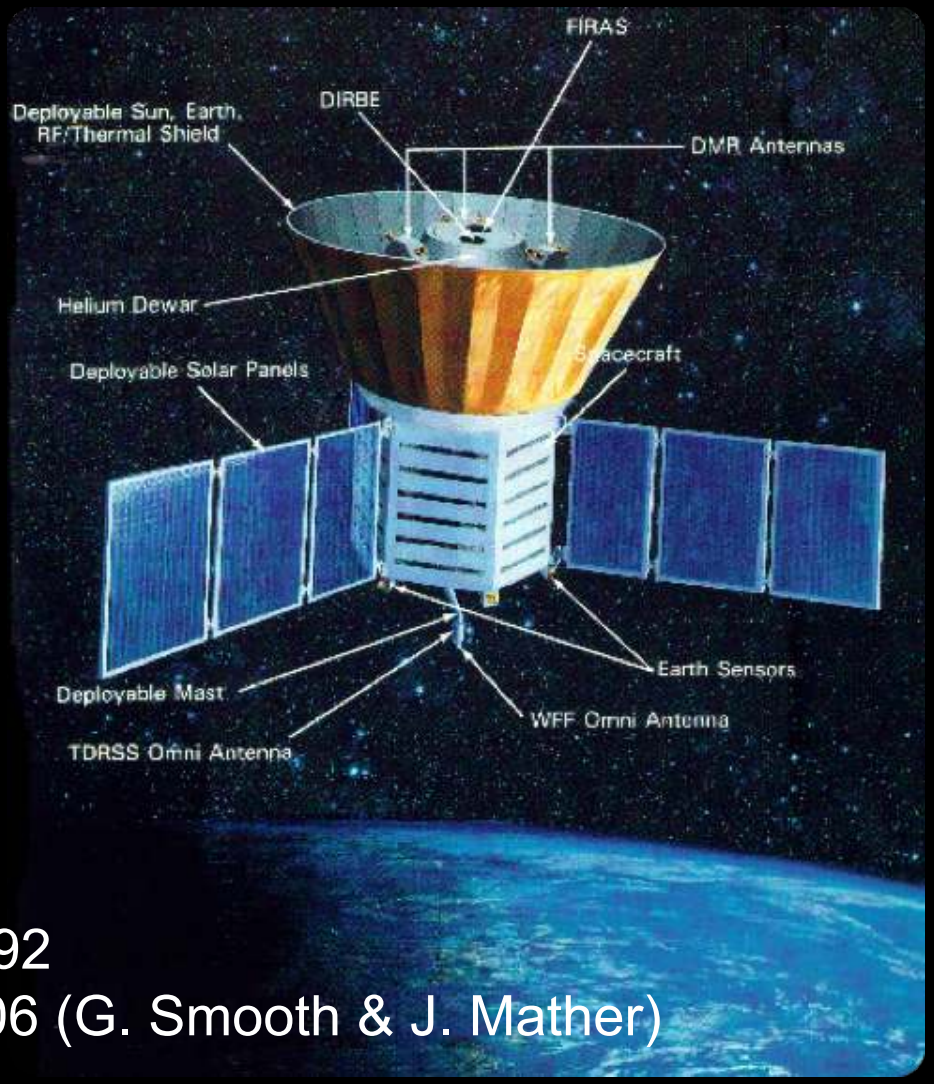
POWER SPECTRUM SHAPE AND COSMOLOGICAL PARAMETERS

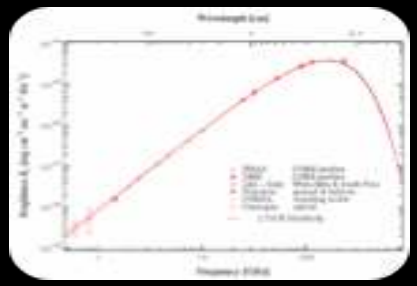


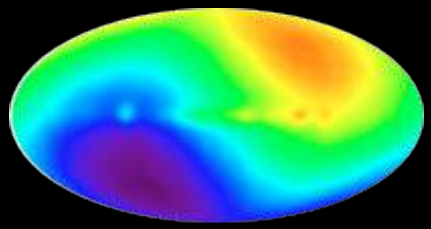


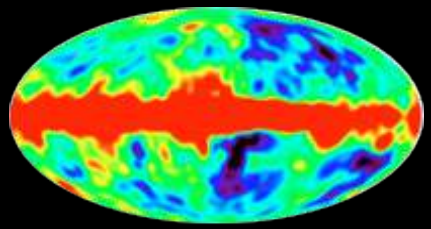


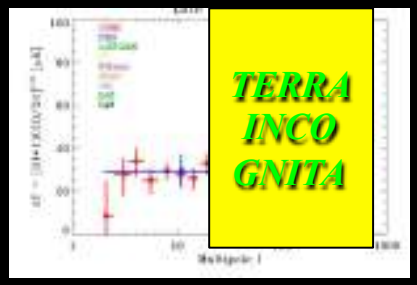
Hu, Sugiyama, & Silk (1995)



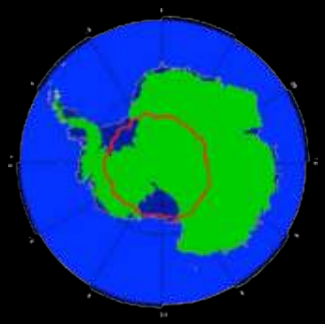


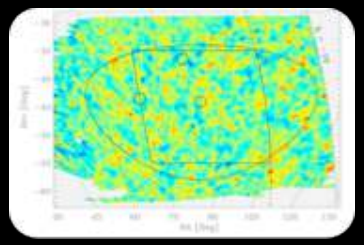


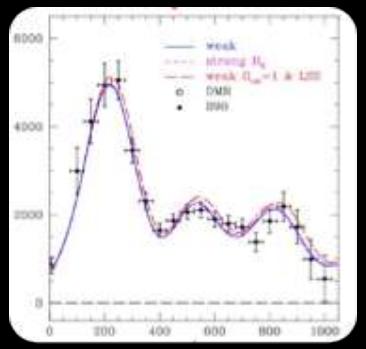




COBE 1992
Nobel 2006 (G. Smooth & J. Mather)

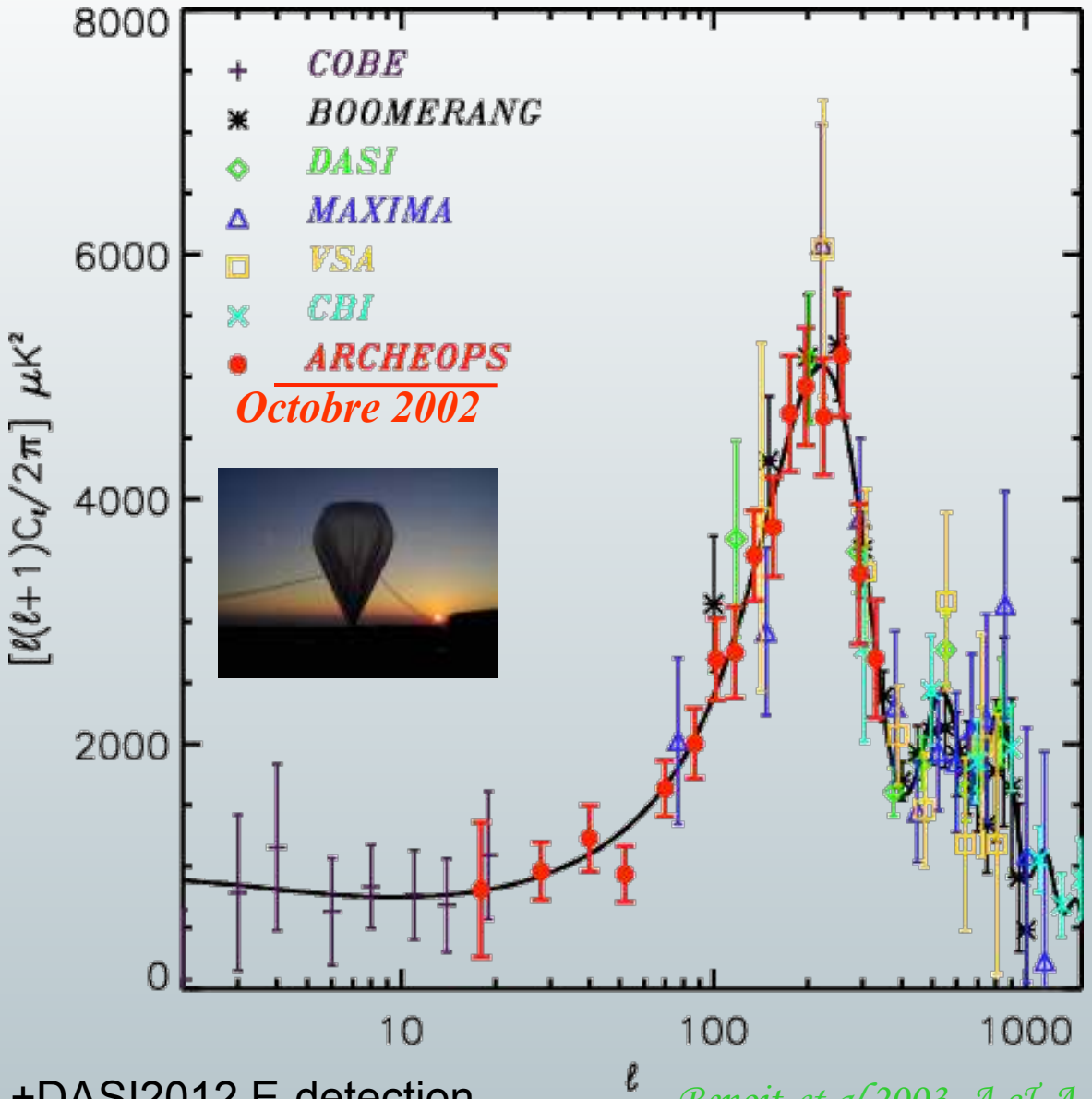


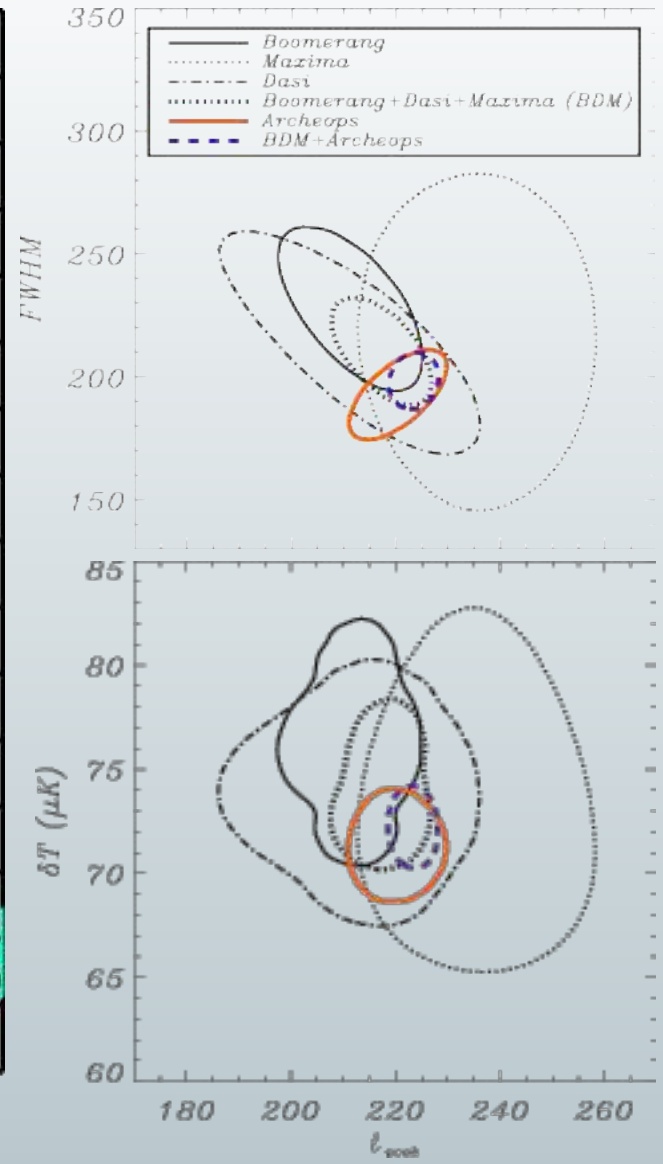




Boomerang 1998-2001 (& Maxima & TOCO)
First observations of the first peak

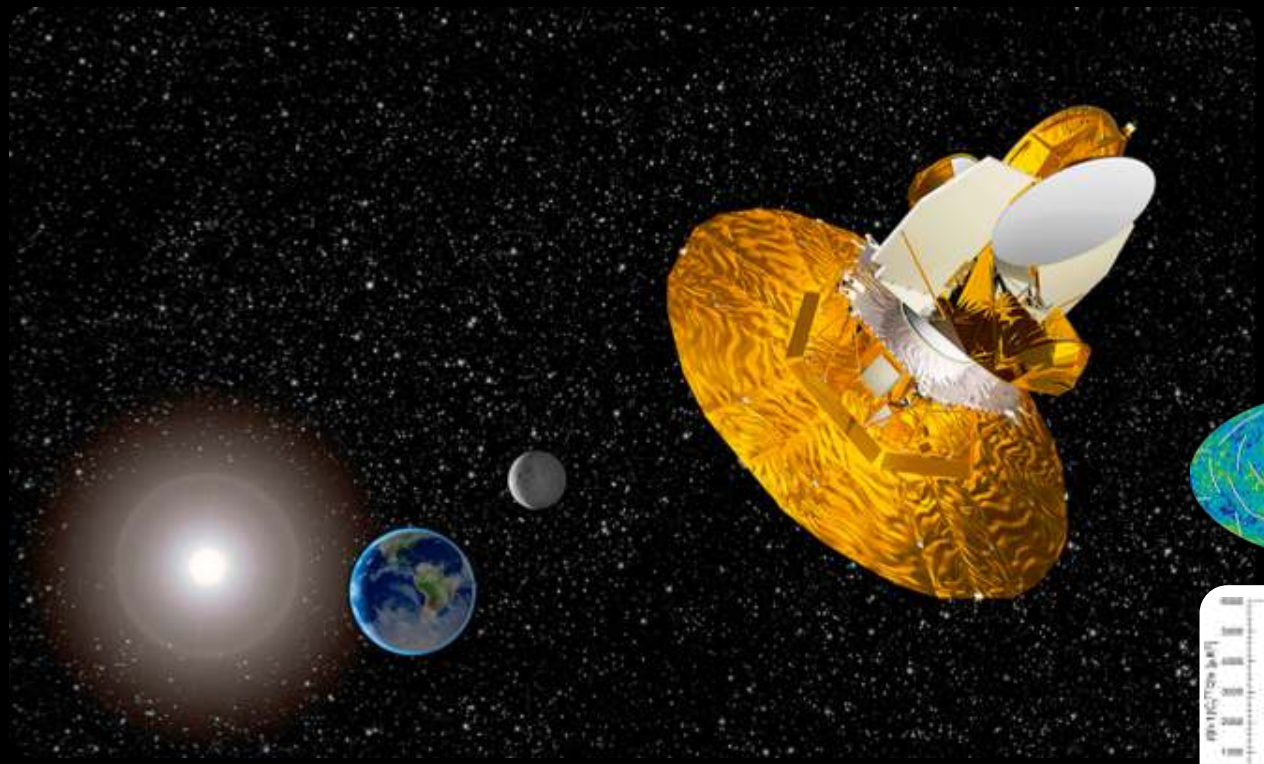
End of 2002 status… (pre-WMAP)

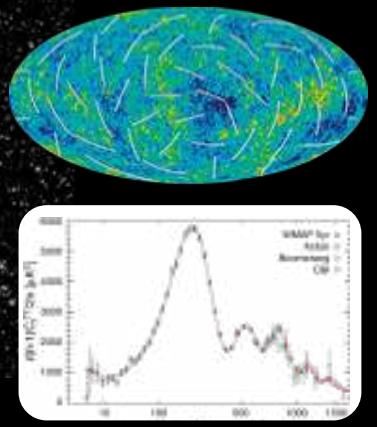


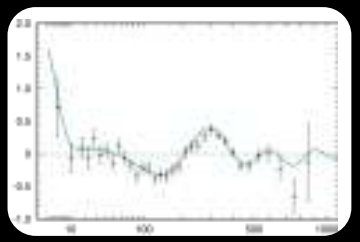


+DASI2012 E-detection

Benoit et al 2003, A & A, 399, L25



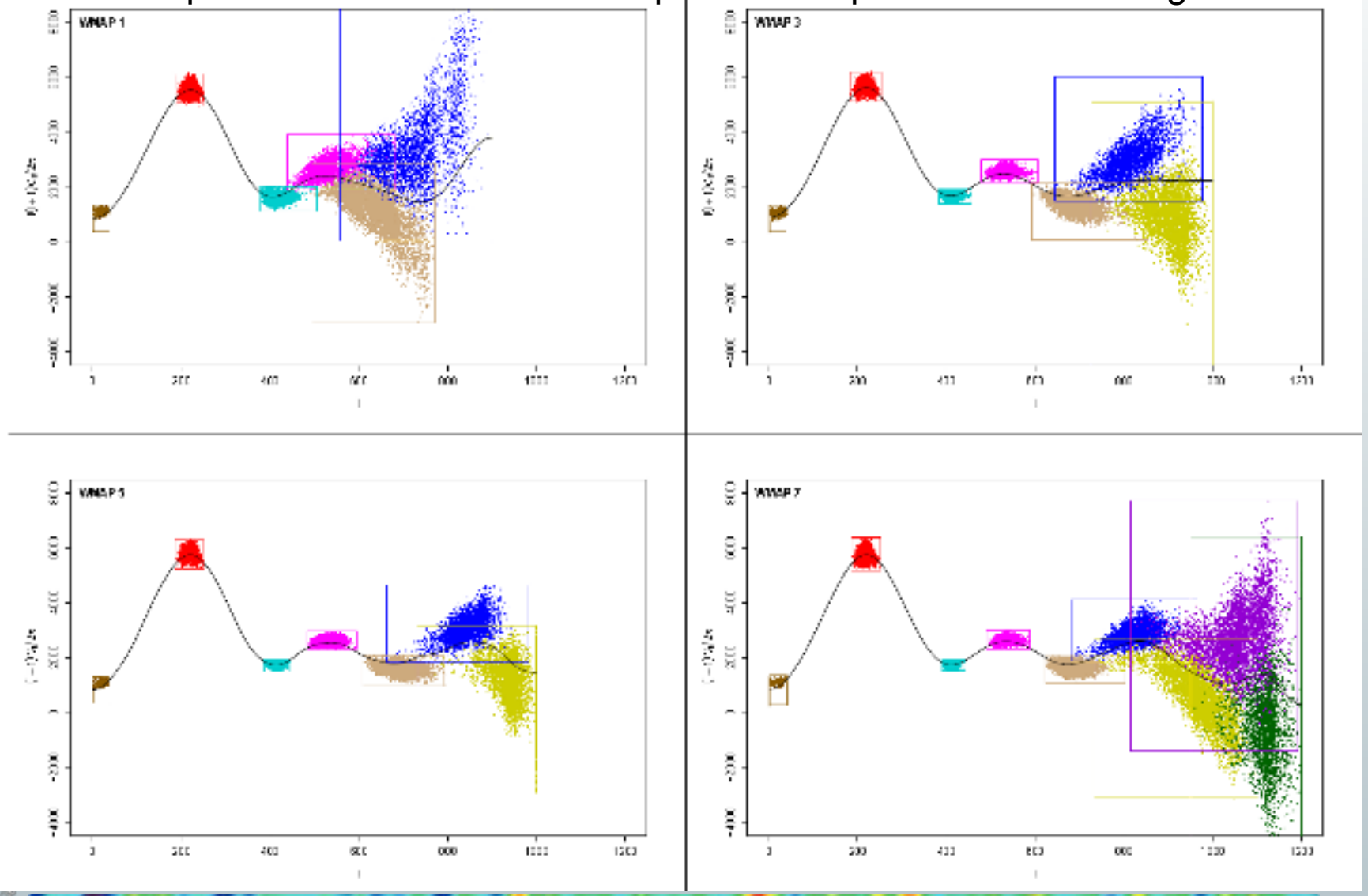




Wilkinson Microwave Anisotropie Probe (WMAP)
2003-2010
Observed first three peaks
Informations on polarisation

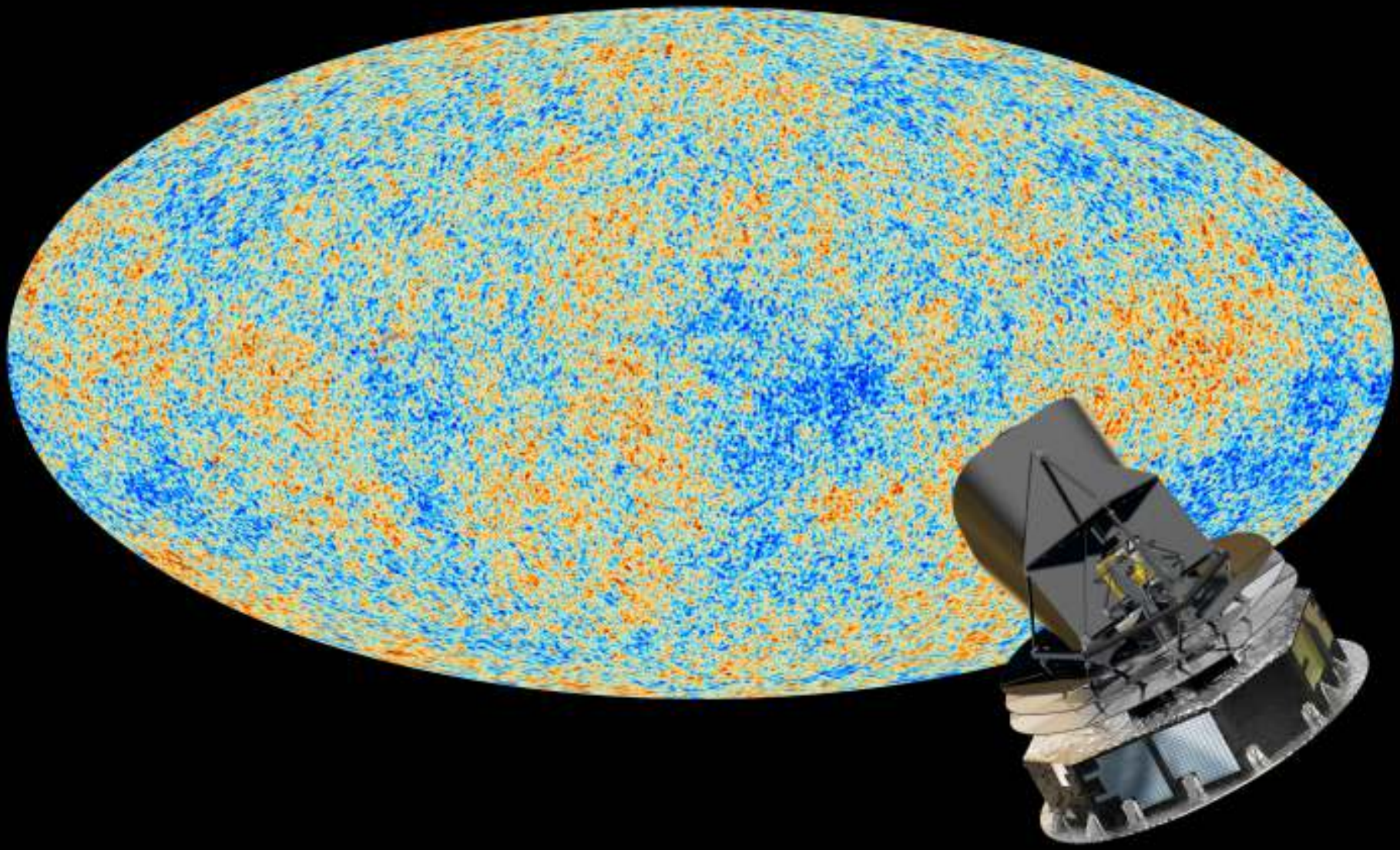
WMAP1, WMAP3, WMAP5, WMAP7

Nonparametric uncertainties on peak and dip locations and heights



Aghamousa et al. arXiv:1107.0516v2

Planck's exhaustive temperature anistropies map



Planck TT spectrum

(Aghamousa, Shafieloo, Arjunwadkar, Souradeep, JCAP 2015)

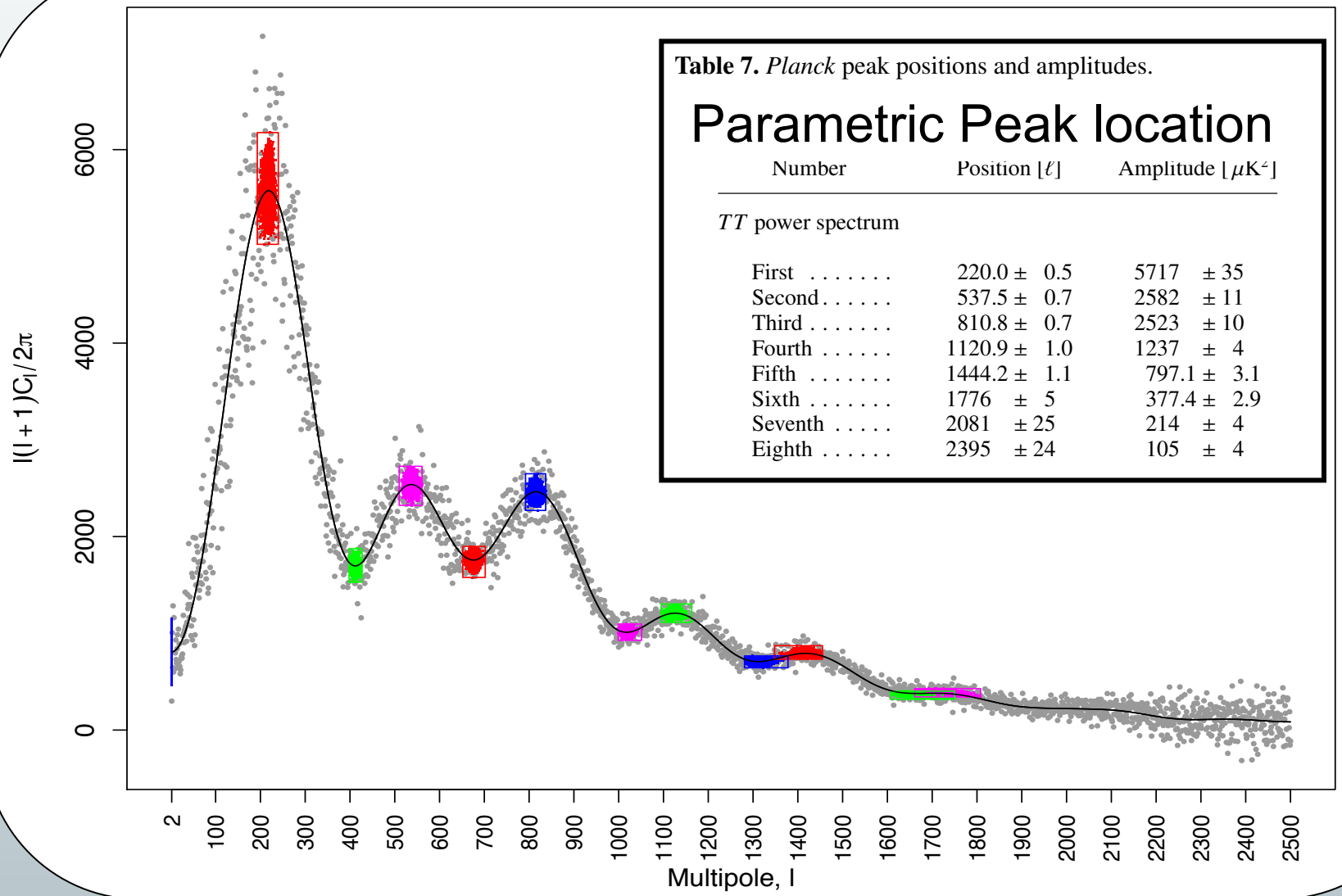
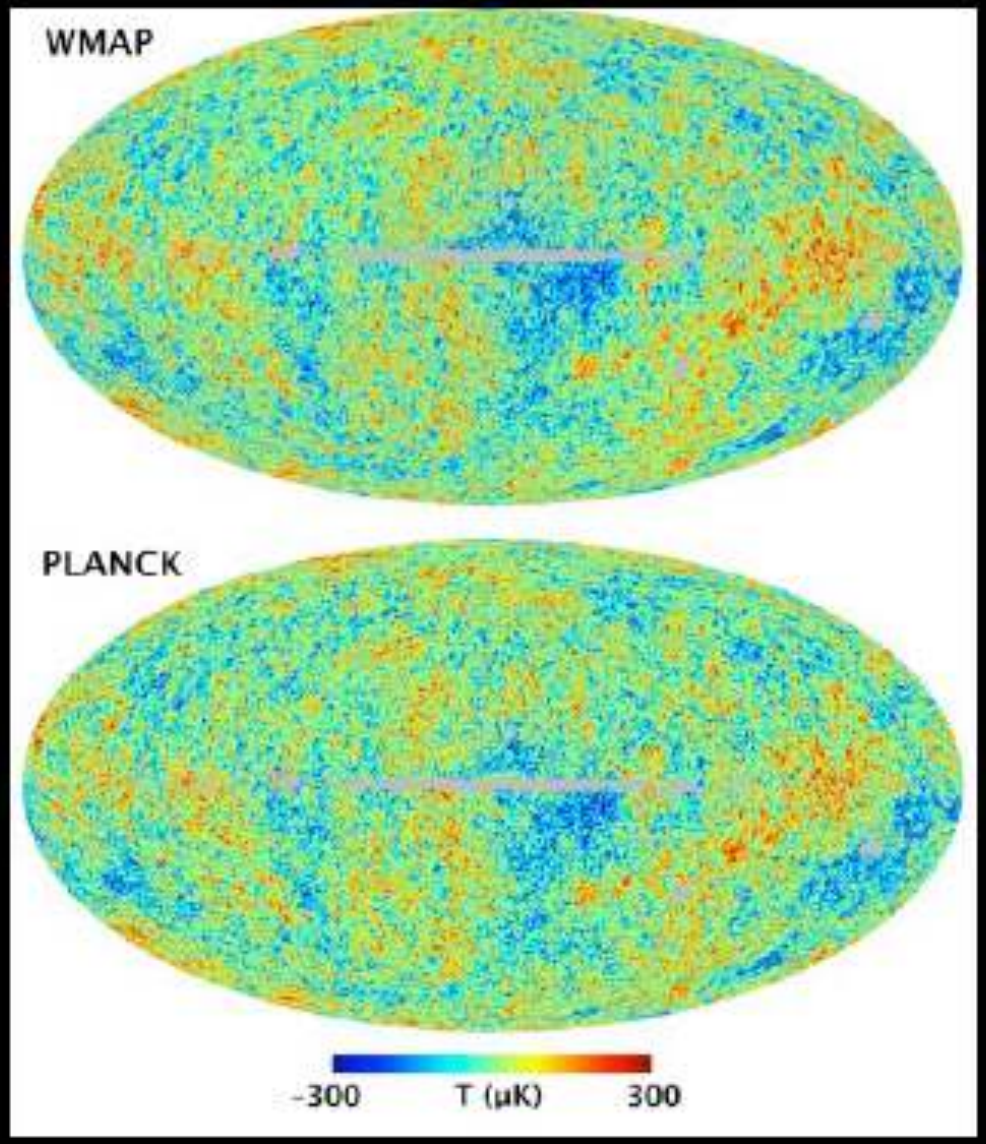


Table 7. *Planck* peak positions and amplitudes.

Parametric Peak location

Number	Position [ℓ]	Amplitude [μK^2]
TT power spectrum		
First	220.0 ± 0.5	5717 ± 35
Second	537.5 ± 0.7	2582 ± 11
Third	810.8 ± 0.7	2523 ± 10
Fourth	1120.9 ± 1.0	1237 ± 4
Fifth	1444.2 ± 1.1	797.1 ± 3.1
Sixth	1776 ± 5	377.4 ± 2.9
Seventh	2081 ± 25	214 ± 4
Eighth	2395 ± 24	105 ± 4

Planck and WMAP see the same sky

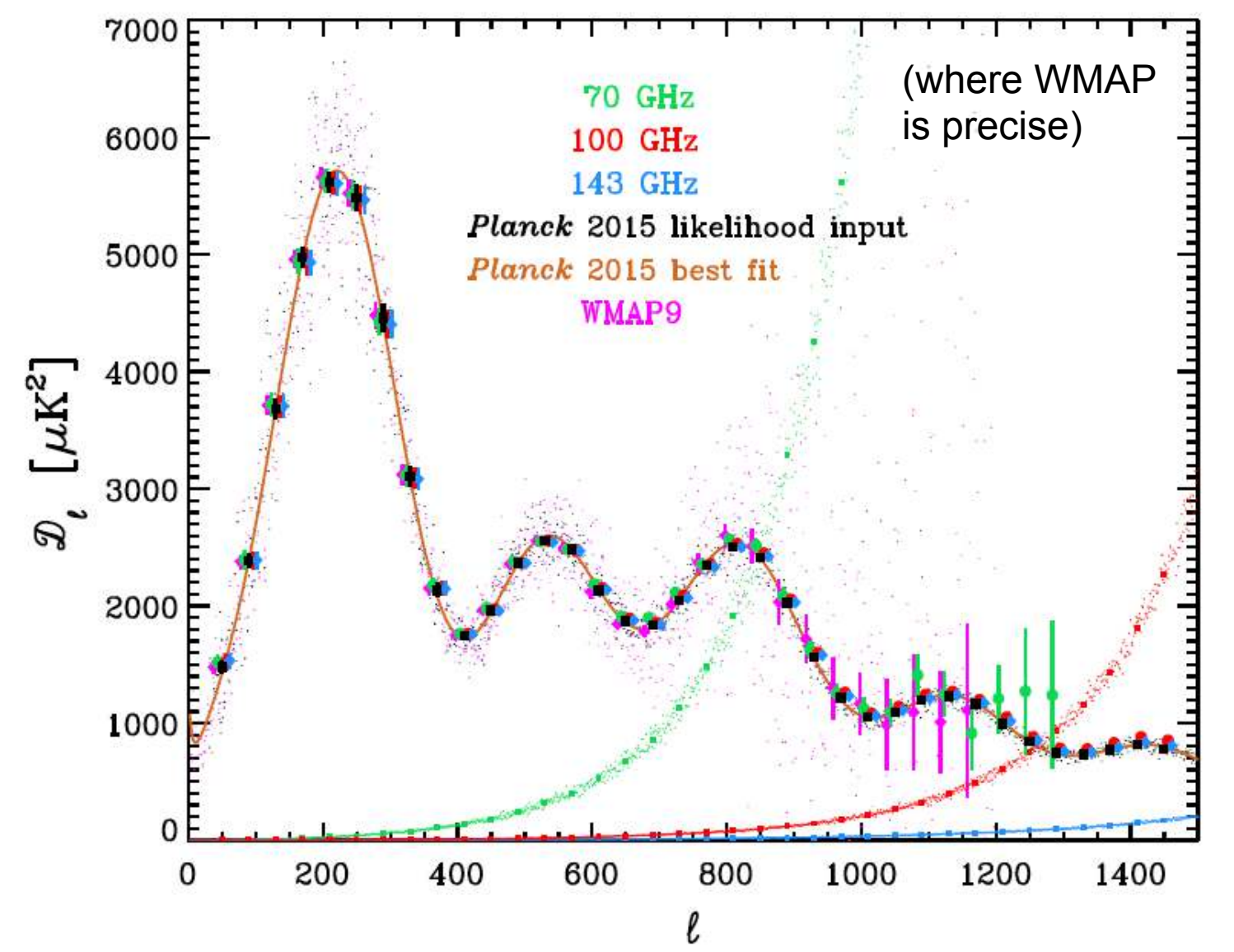


After

1) correcting the original WMAP map from some residual dust emission only traced by Planck/ HFI, and

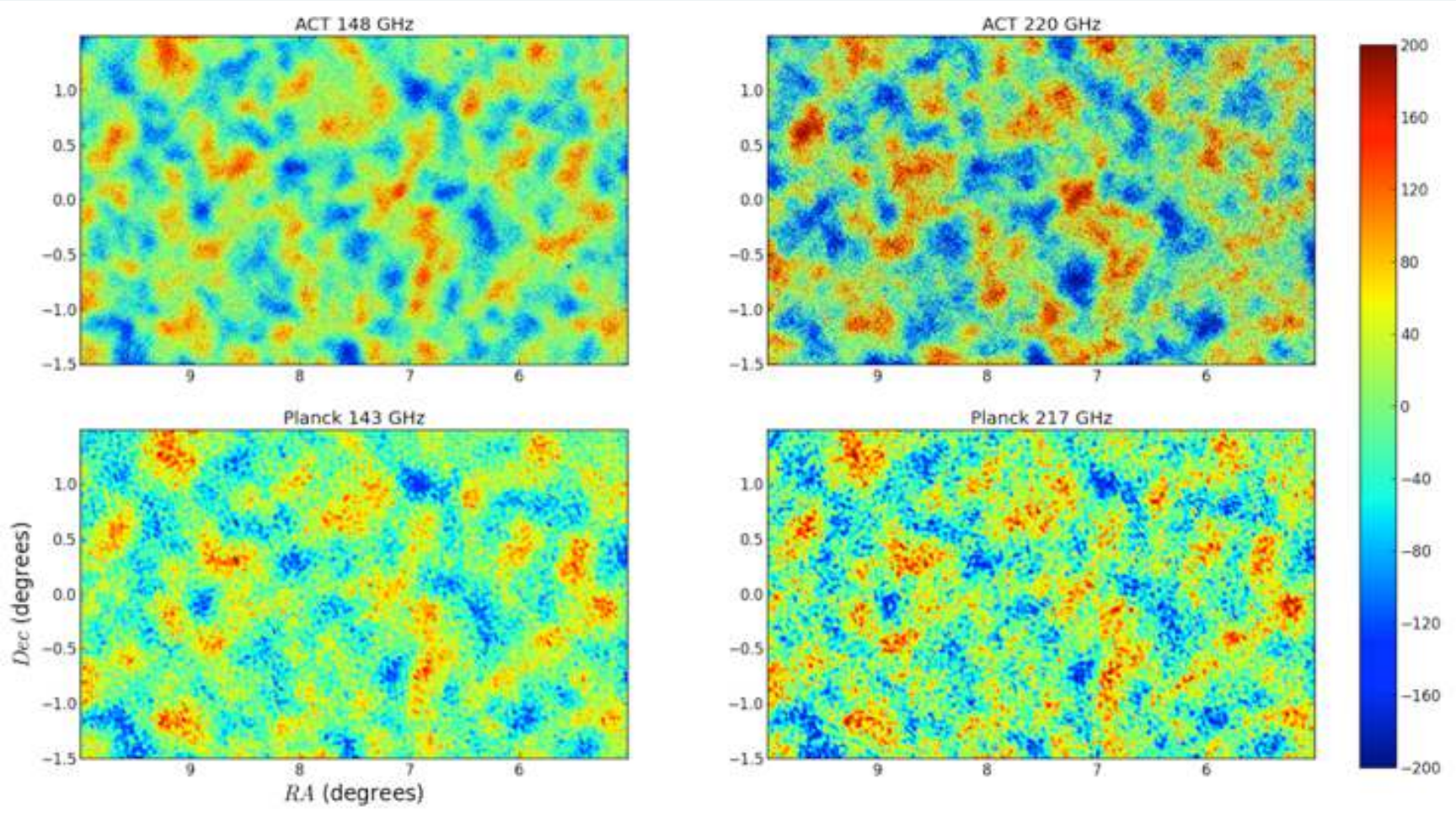
2) Downgrading Planck to WMAP resolution (de facto throwing out ~90% of Planck measured modes)

Excellent consistency at l ~< 800

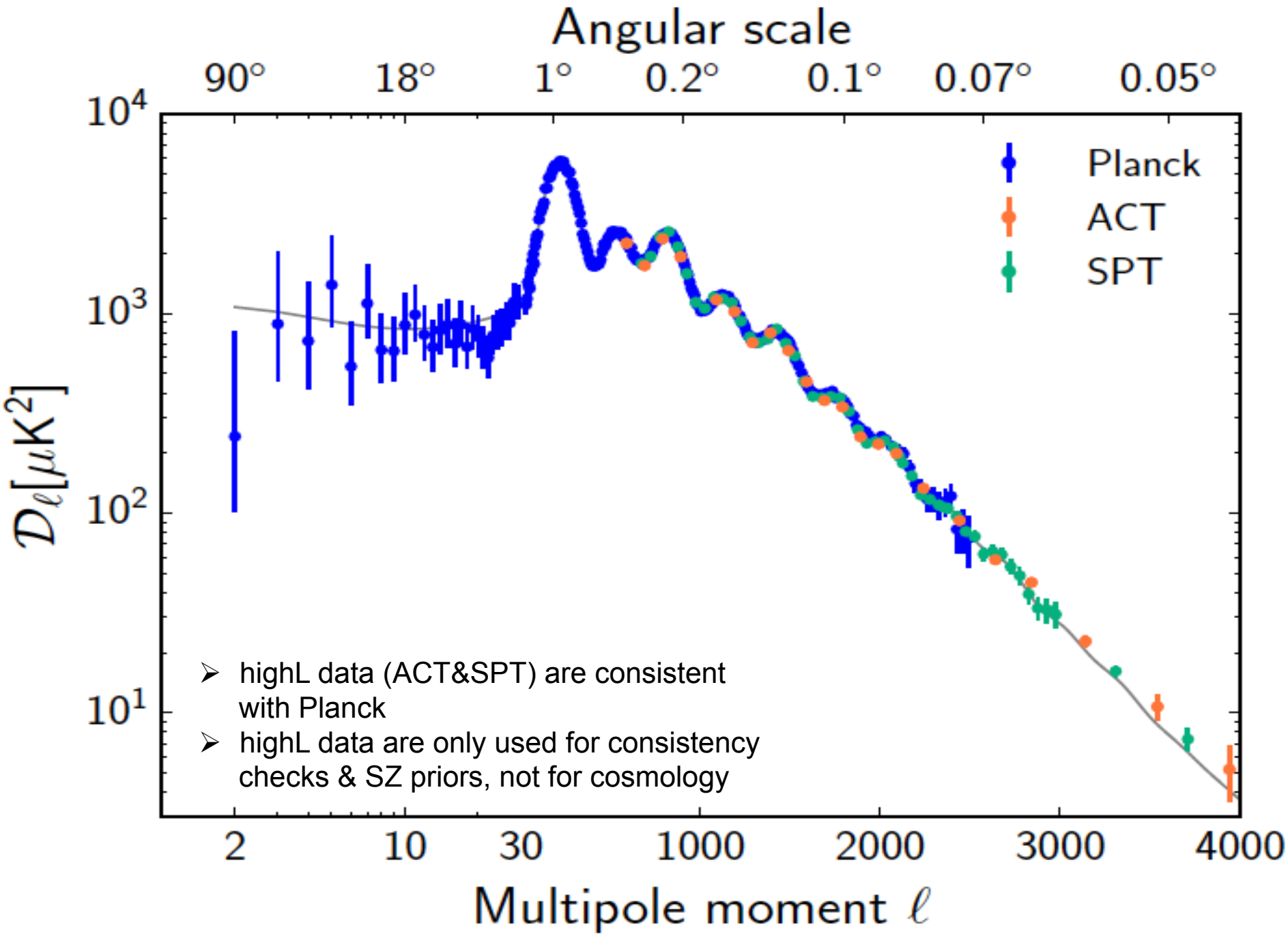


Planck & high-resolution experiments

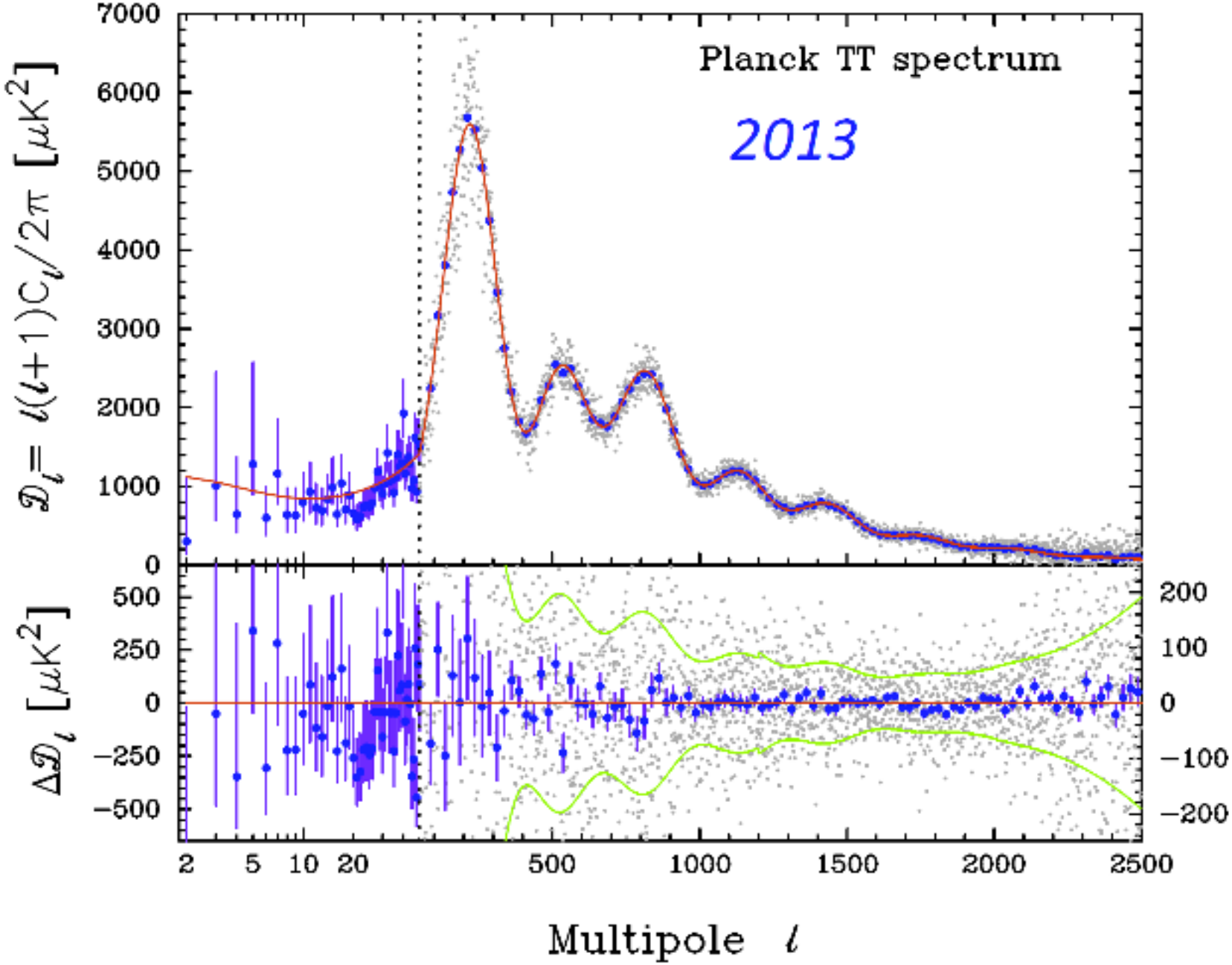
also see the same sky

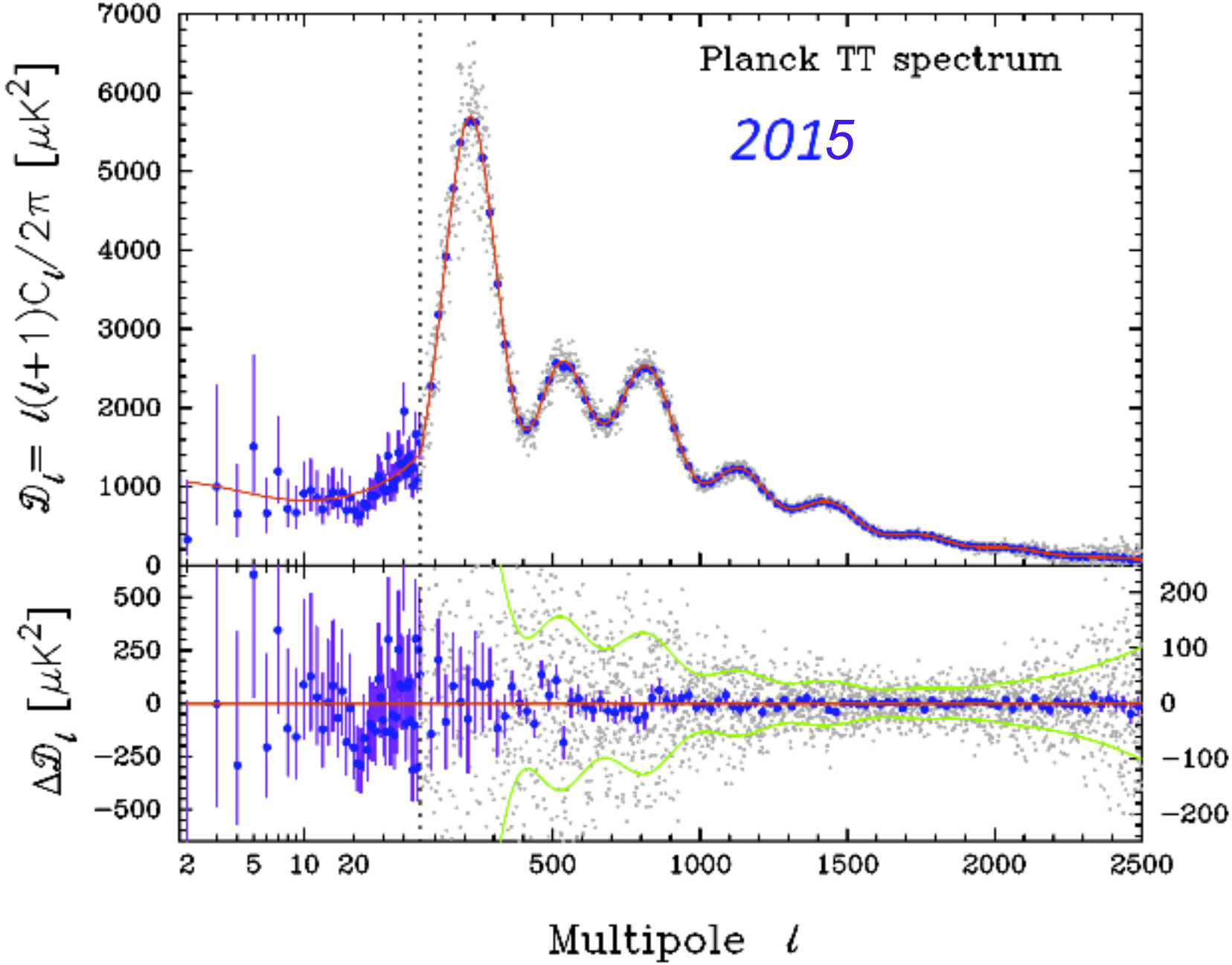


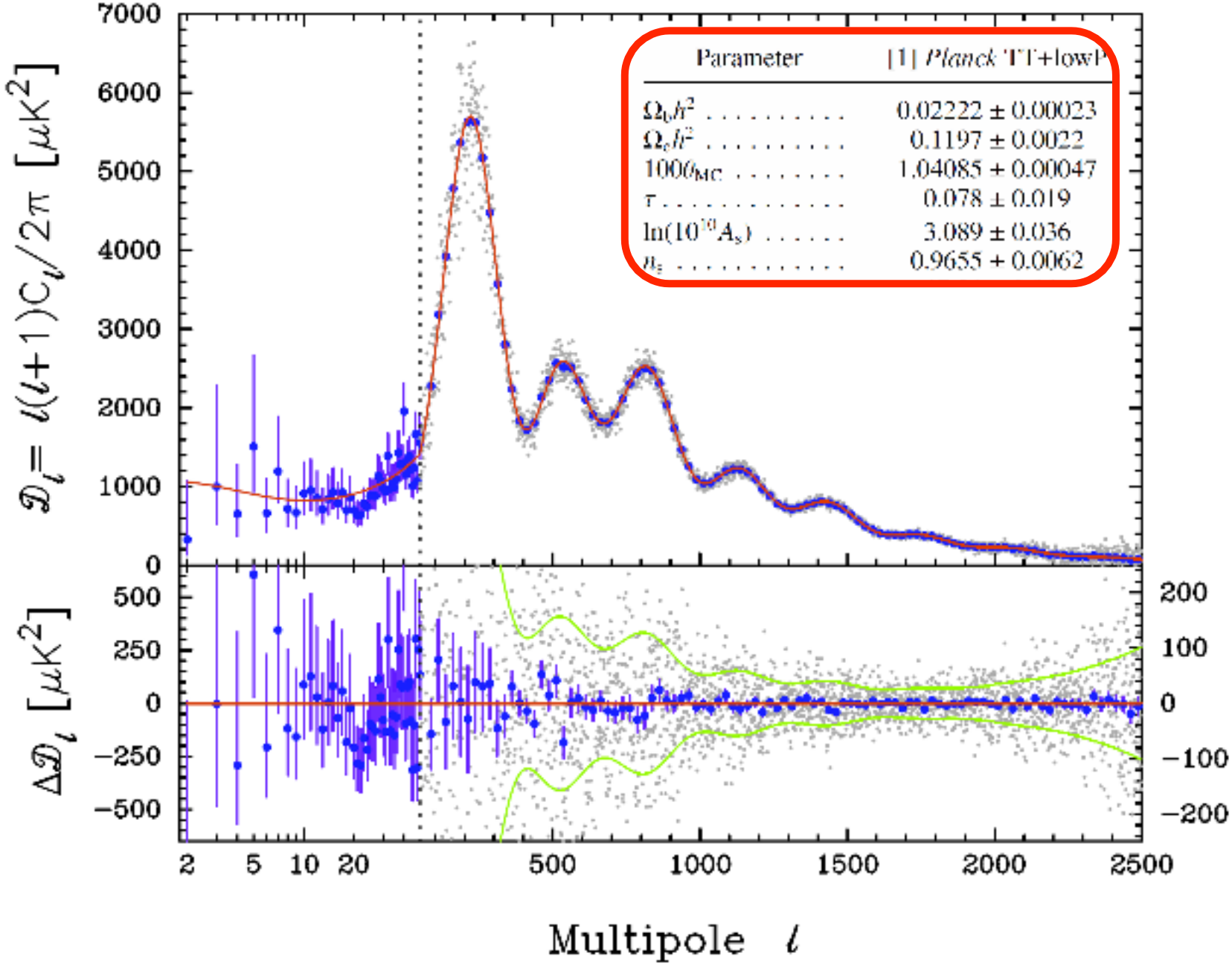
In the bands accessible from the ground. NB: This is Planck 2013 data



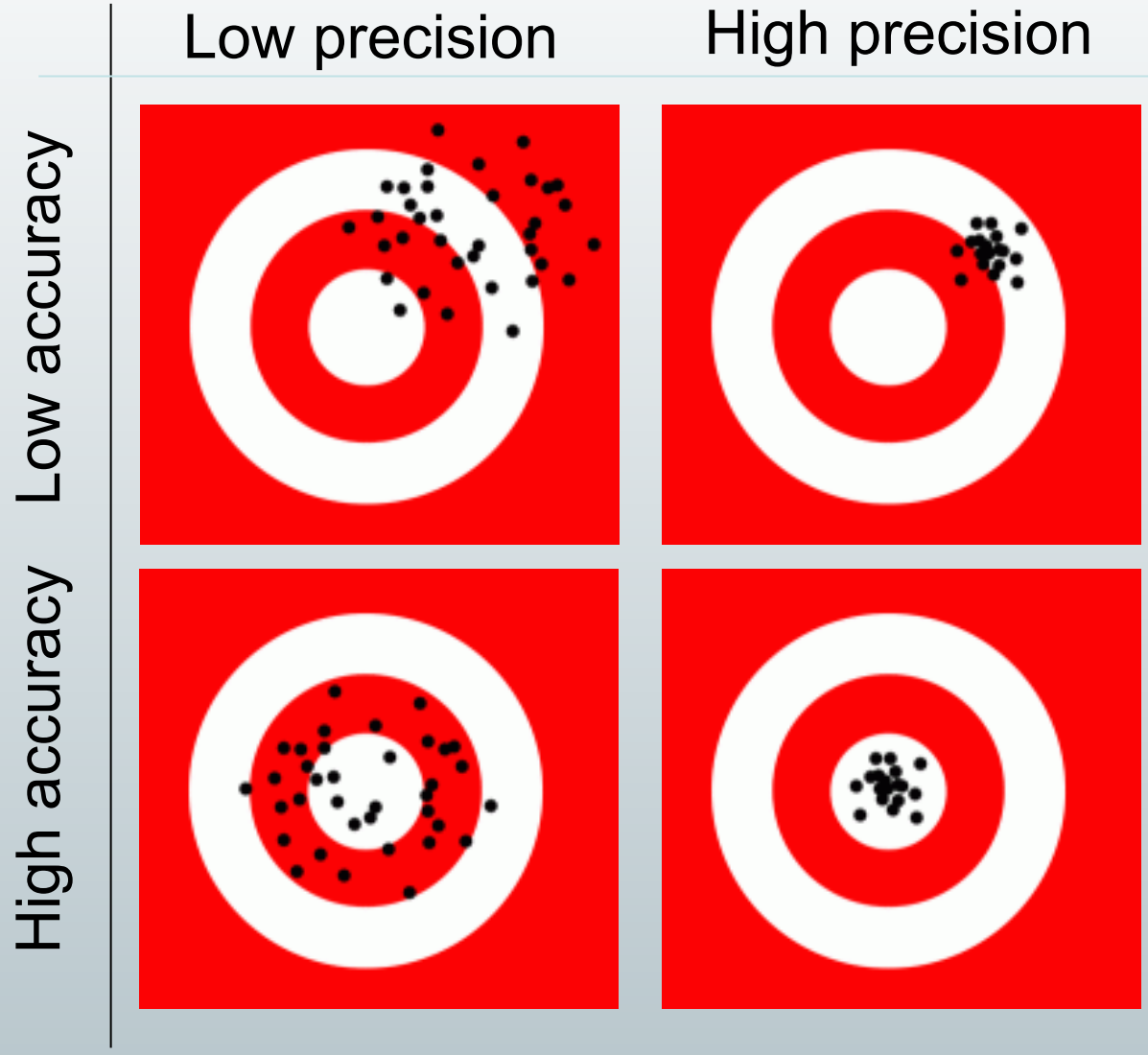
- highL data (ACT&SPT) are consistent with Planck
- highL data are only used for consistency checks & SZ priors, not for cosmology

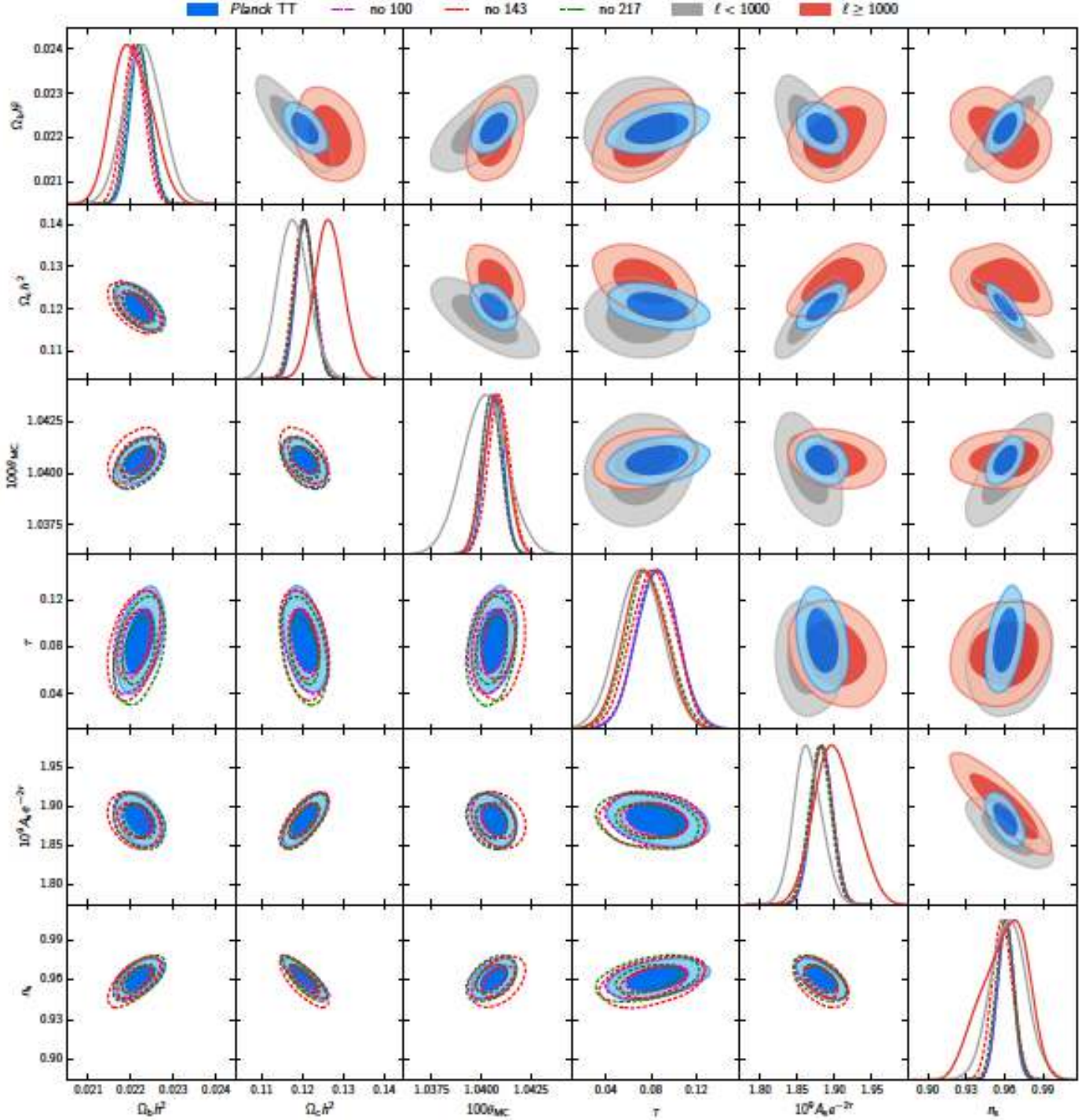

Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


Planck TT spectrum
2015
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500


Parameter
[1] Planck TT+lowP
$\Omega_b h^2$ . . . . . 0.02222 ± 0.00023
$\Omega_c h^2$ . . . . . 0.1197 ± 0.0022
$100\theta_{MC}$ . . . . . 1.04085 ± 0.00047
τ . . . . . 0.078 ± 0.019
$\ln(10^{10}A_s)$ . . . . . 3.089 ± 0.036
n_s . . . . . 0.9655 ± 0.0062
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ

Precision is not accuracy…

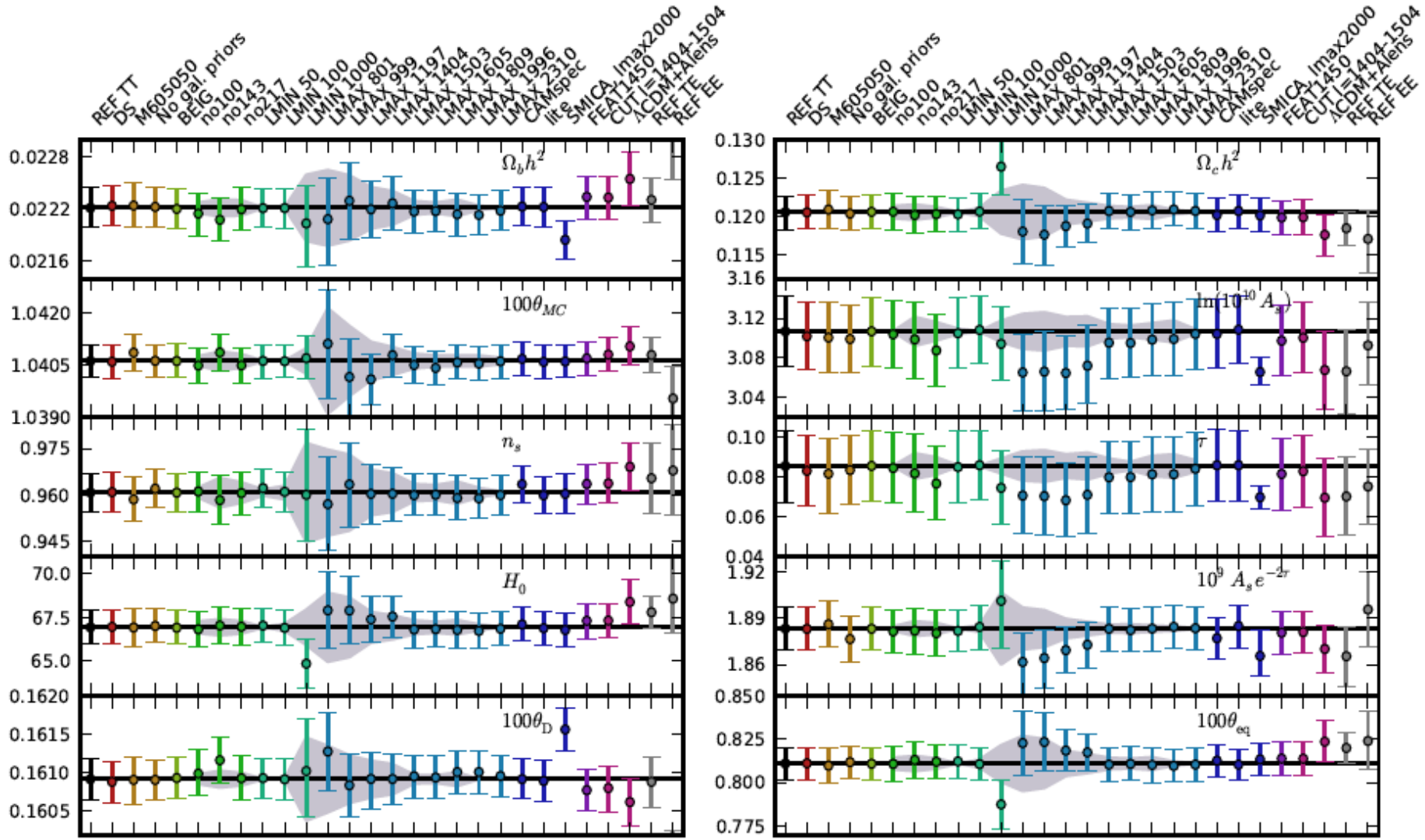


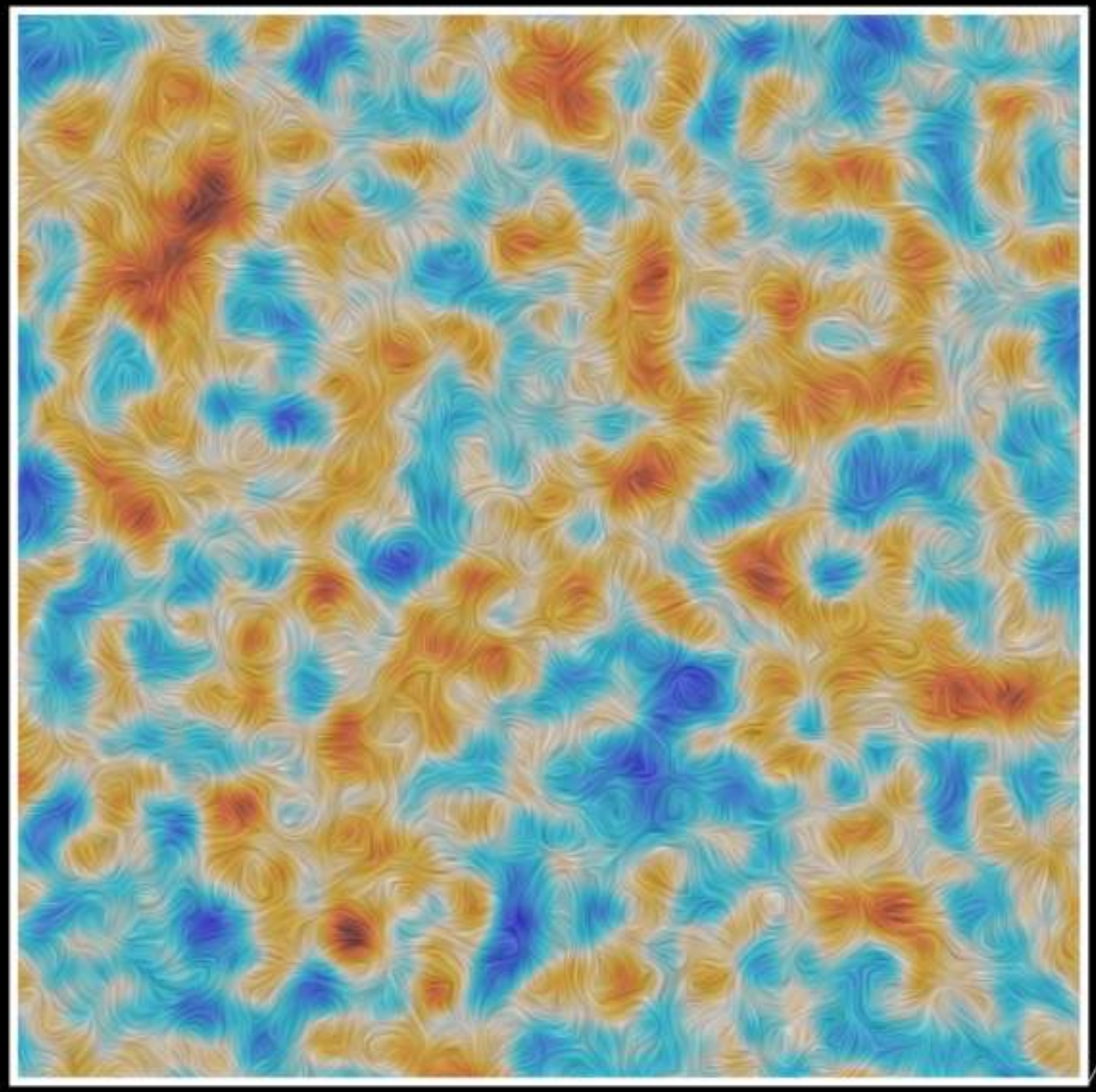


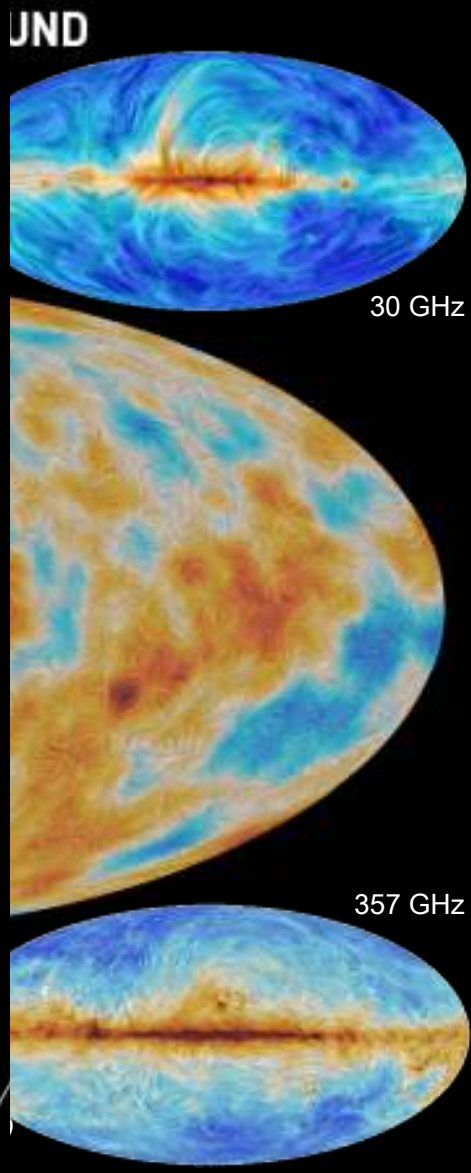
Apart from τ, 5 base LCDM parameters are determined with % level precision.

And are robust w.r.t. jack-knife tests like removing channels or even l-range.

And many other tests…

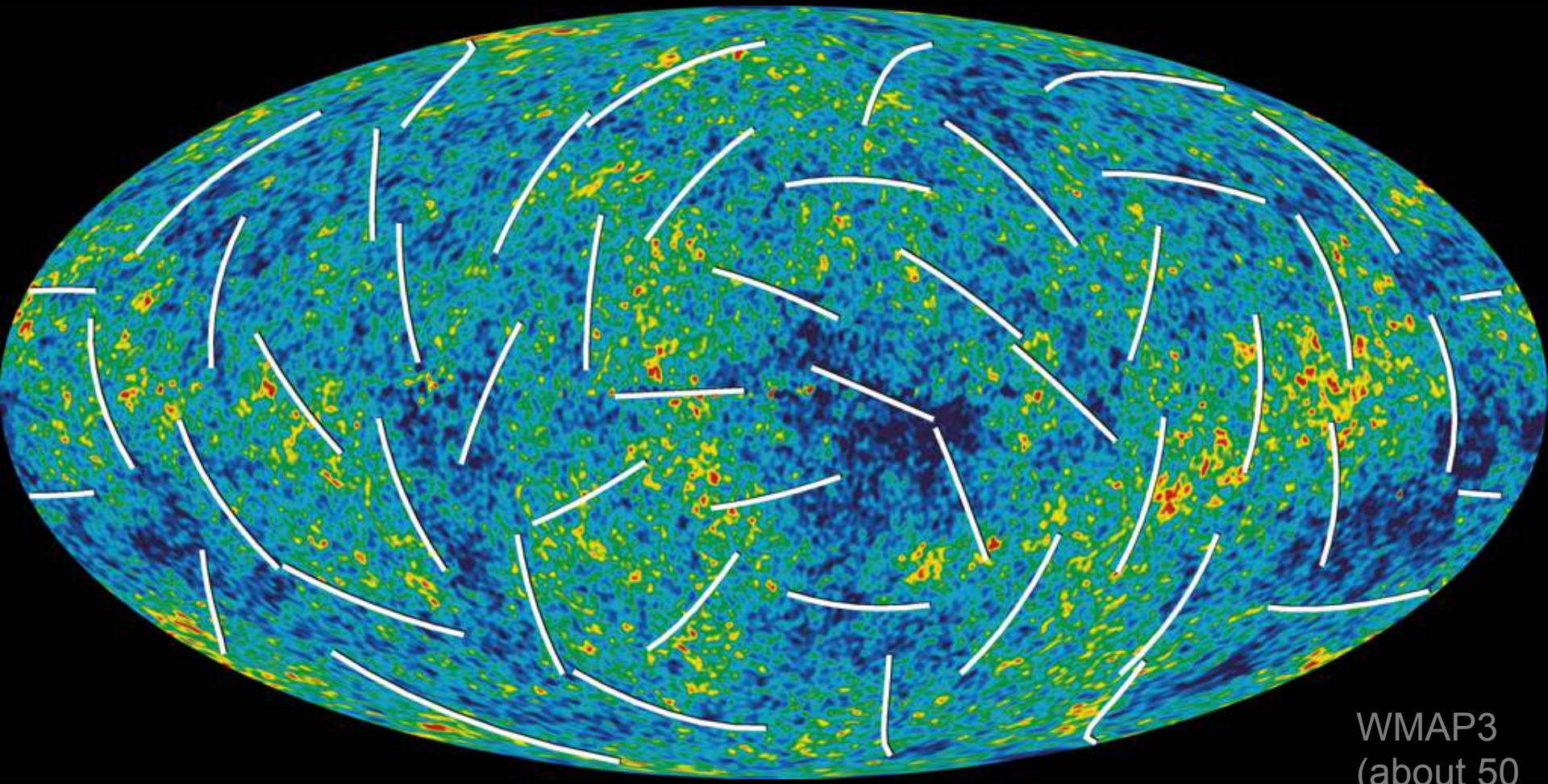






Filtered at 20 arcminutes

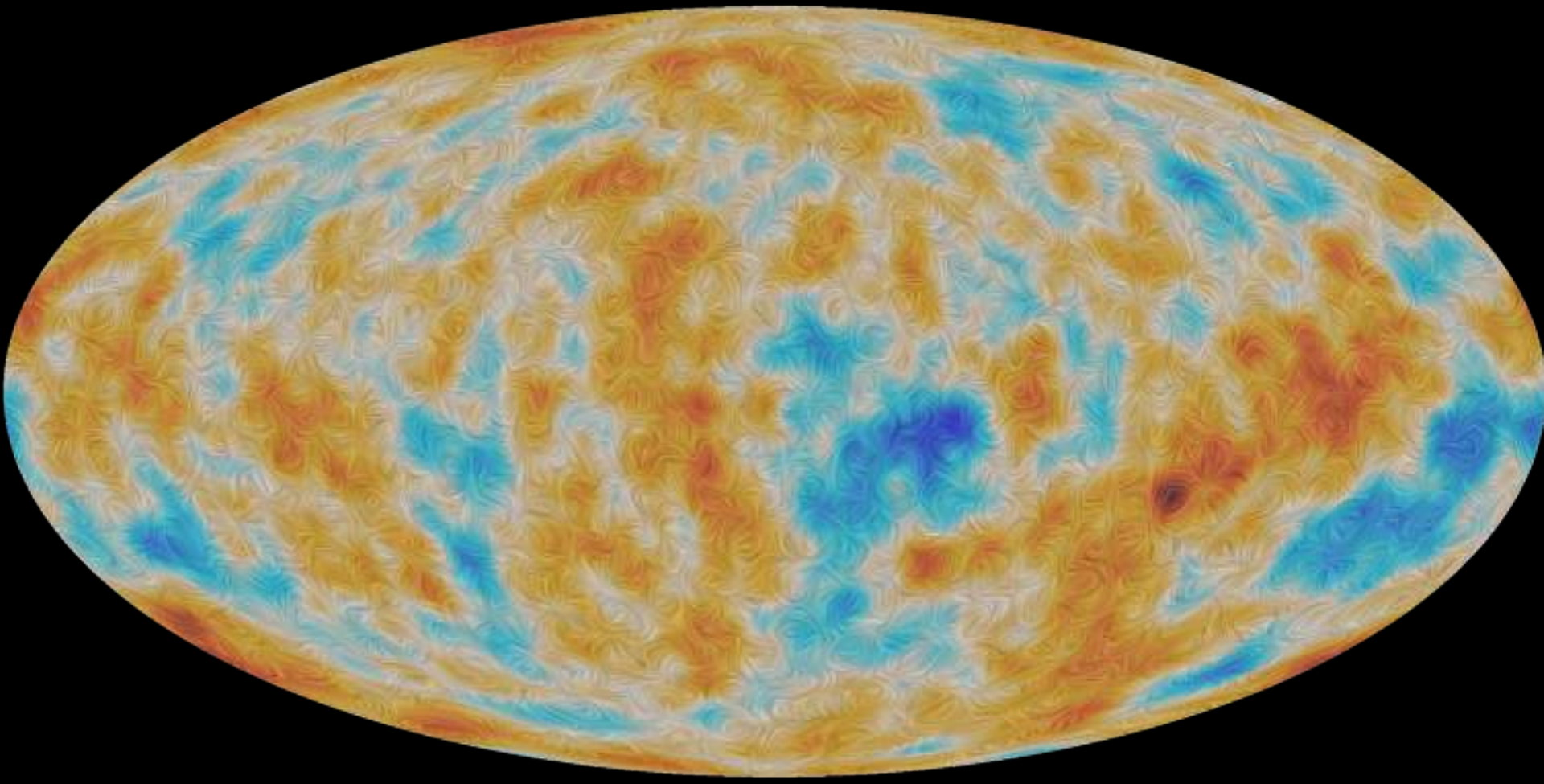
What we already knew



WMAP3
(about 50
locations)

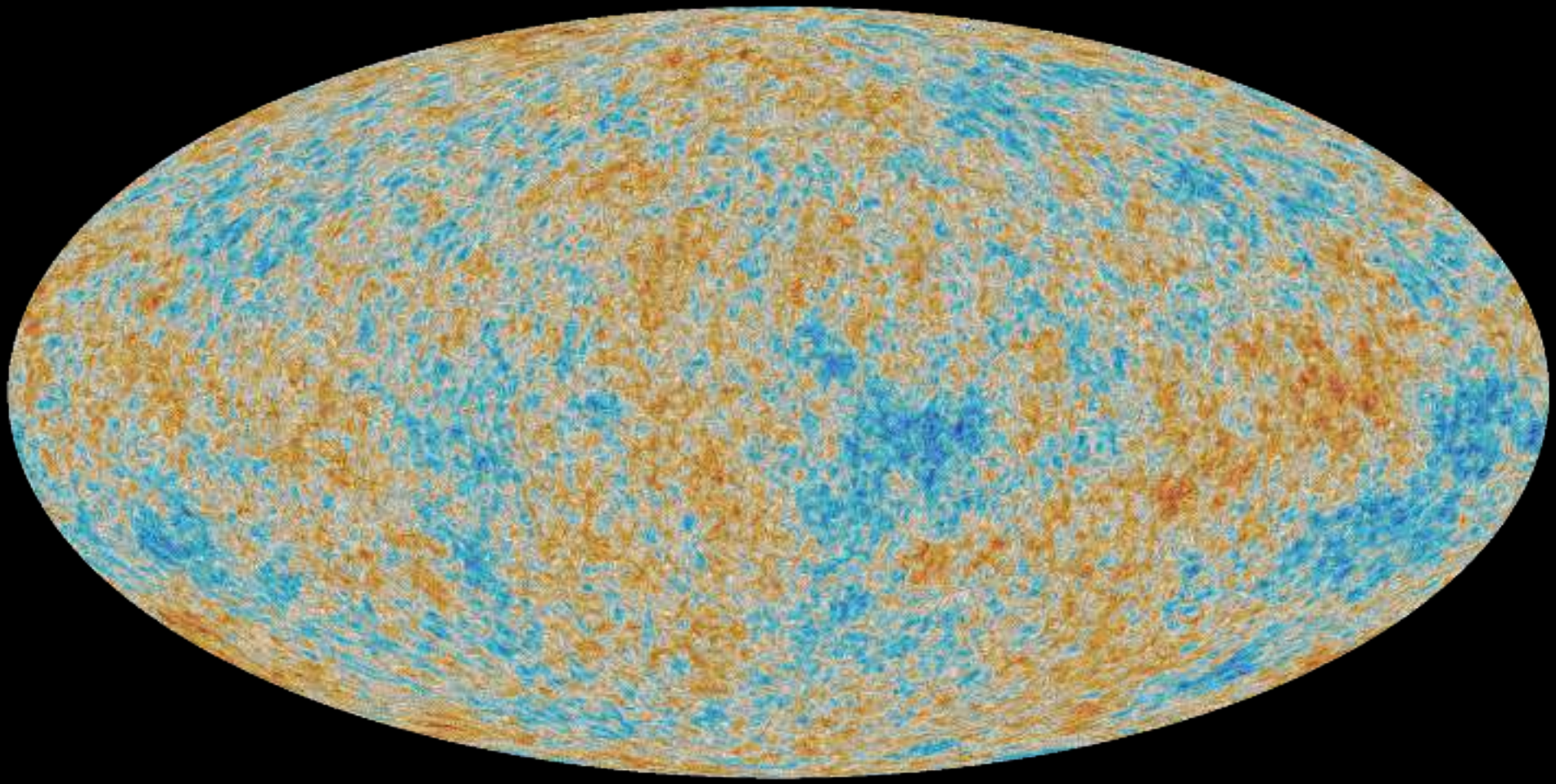
The Planck 2015 CMB polarisation sky

at 5 degree resolution



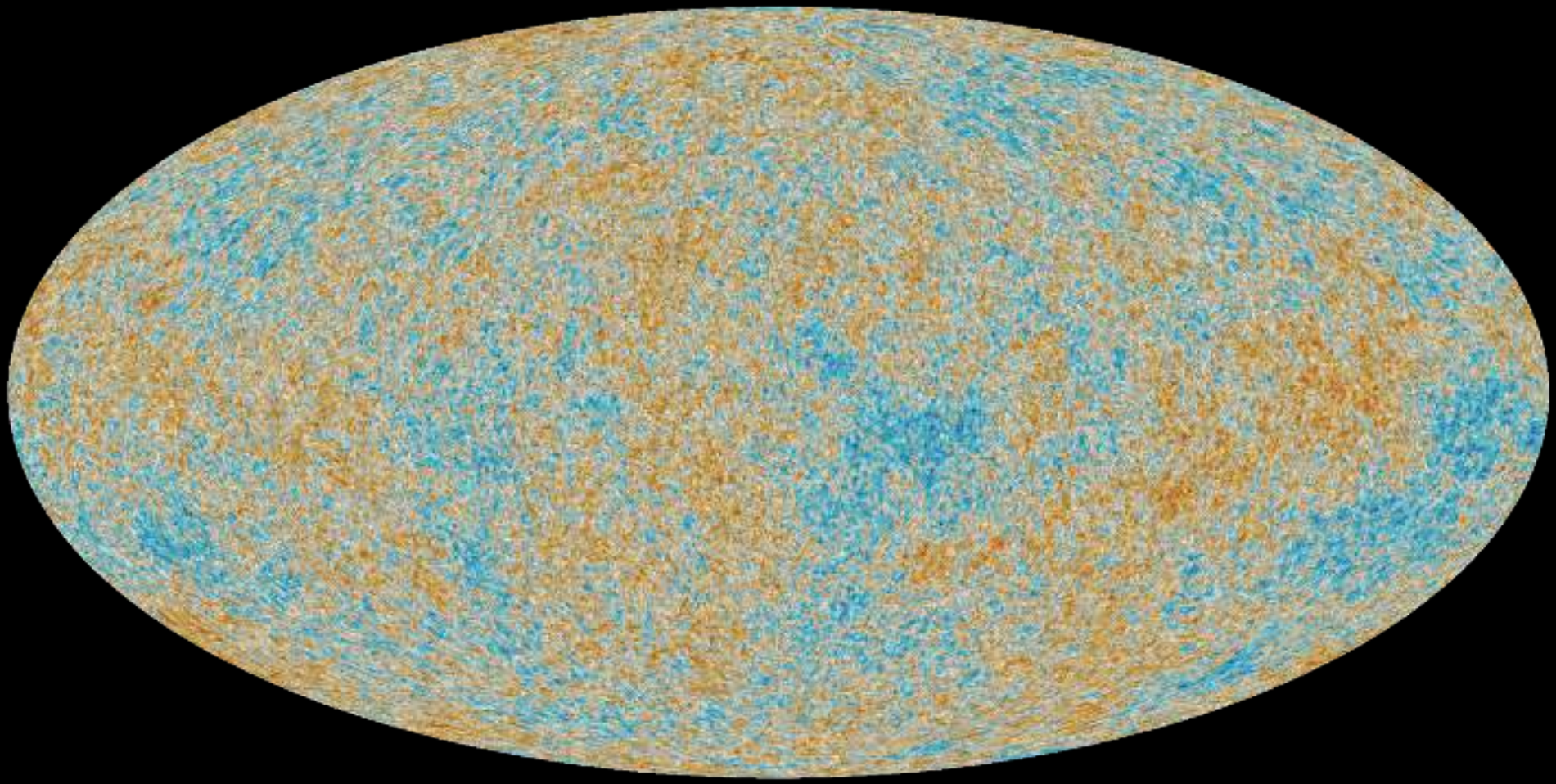
The Planck 2015 CMB polarisation sky

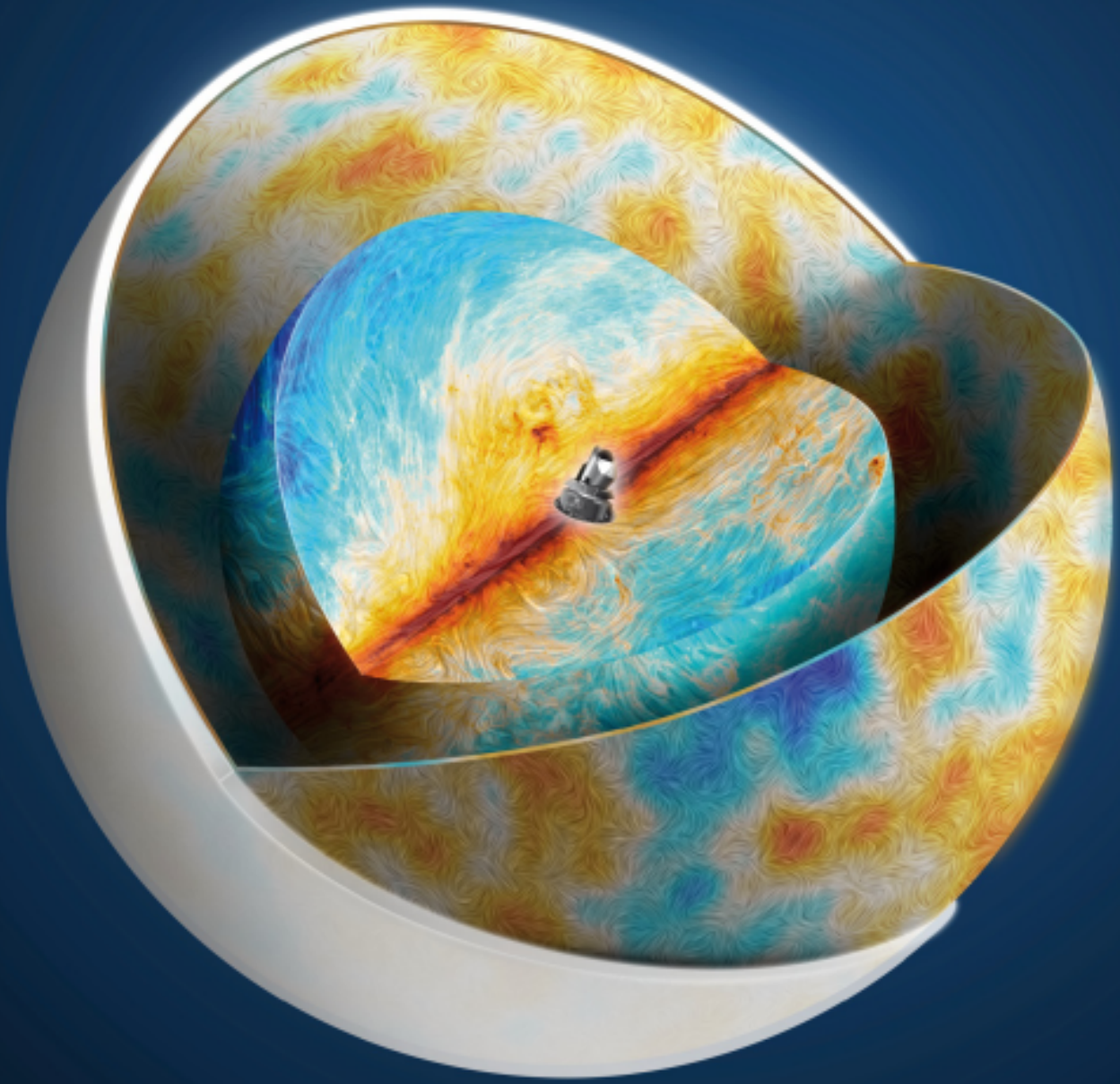
at 1 degree resolution



The Planck 2015 CMB polarisation sky

at 5 arc minute resolution

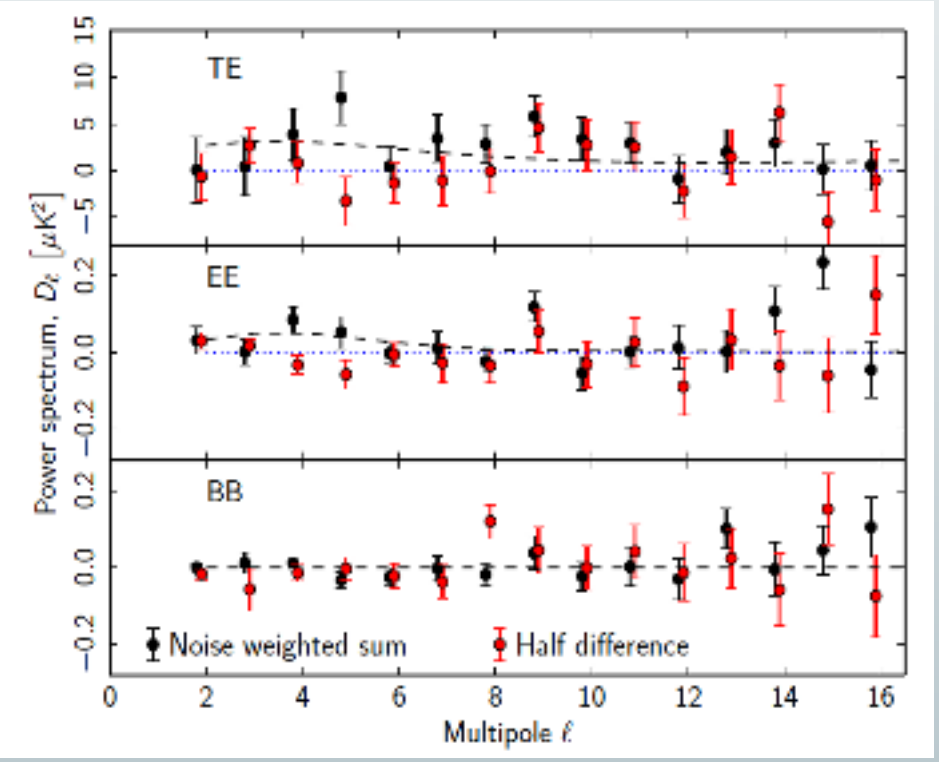


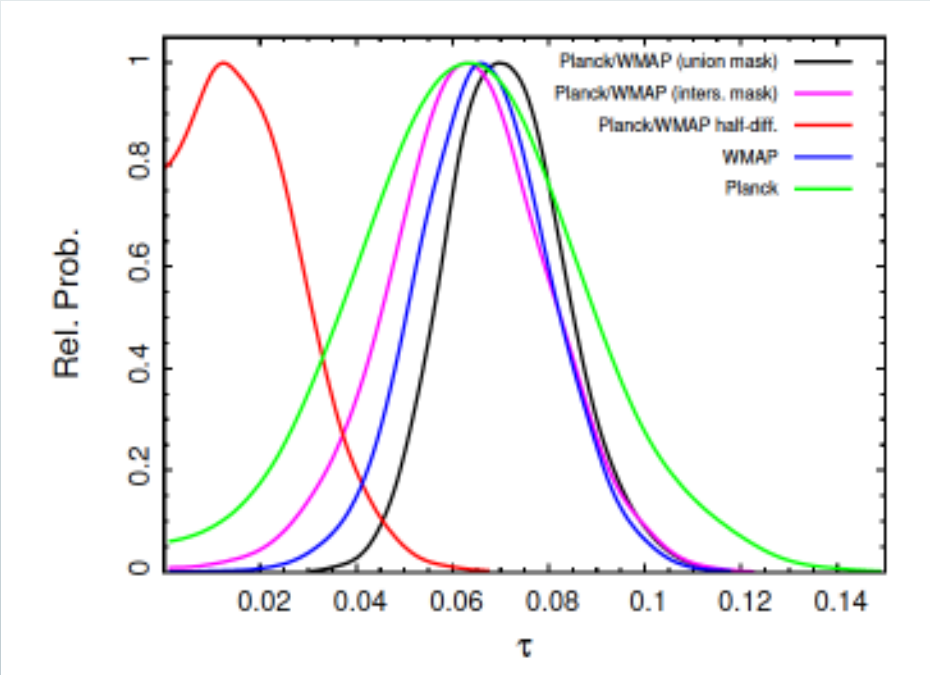


Low-ell (2<l<30) polarisation anisotropies

HFI 353 GHz polarisation data was used
to clean both WMAP and LFI 70GHz polarisation data.

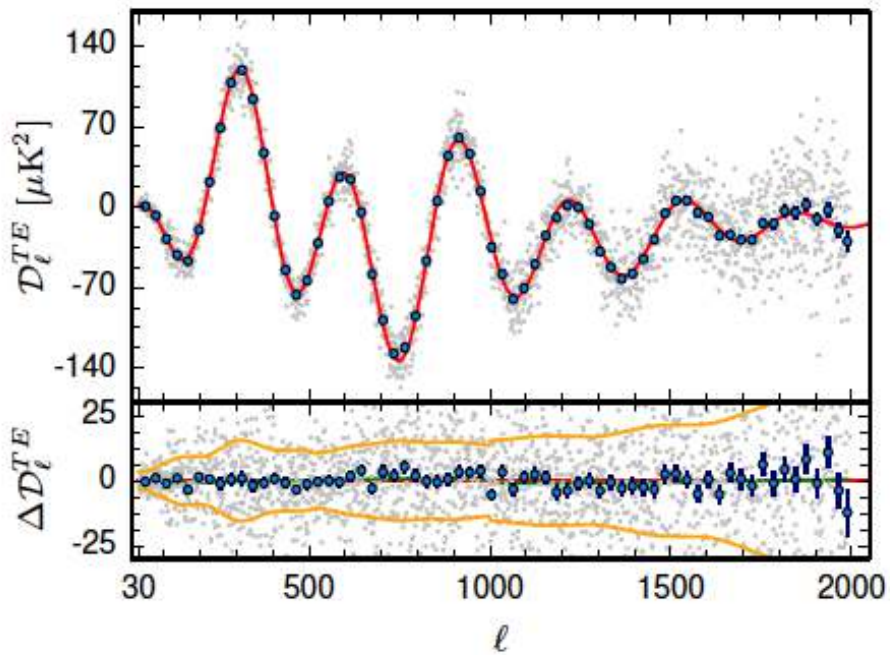
Results are compatible, and it shifts the optical depth
to reionization, τ, to lower values than previously thought.



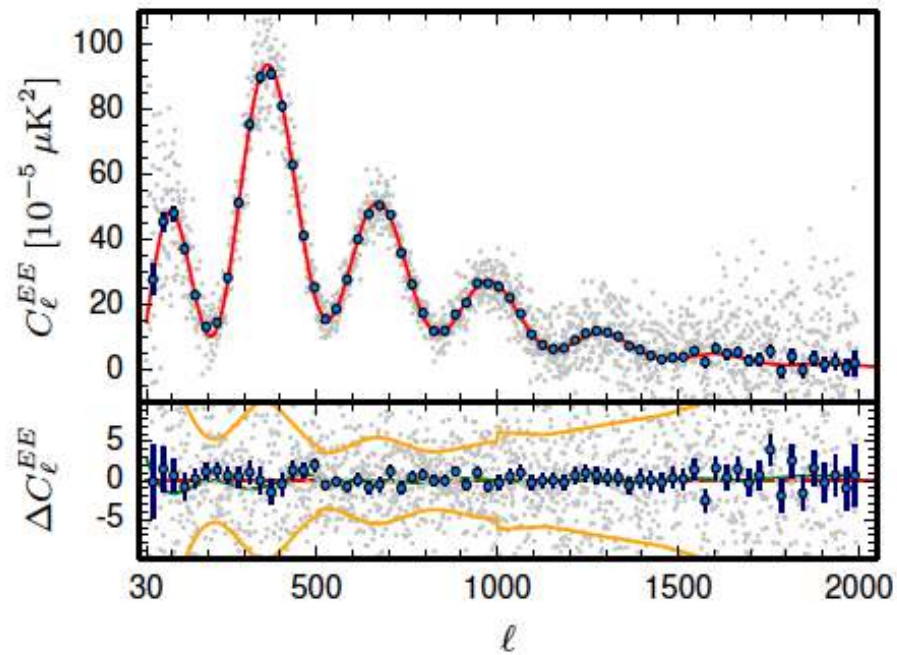


This plot is for low ell <30 only,
i.e. it is ***not*** the final, full likelihood, outcome

Planck 2015 - TE & EE power spectra



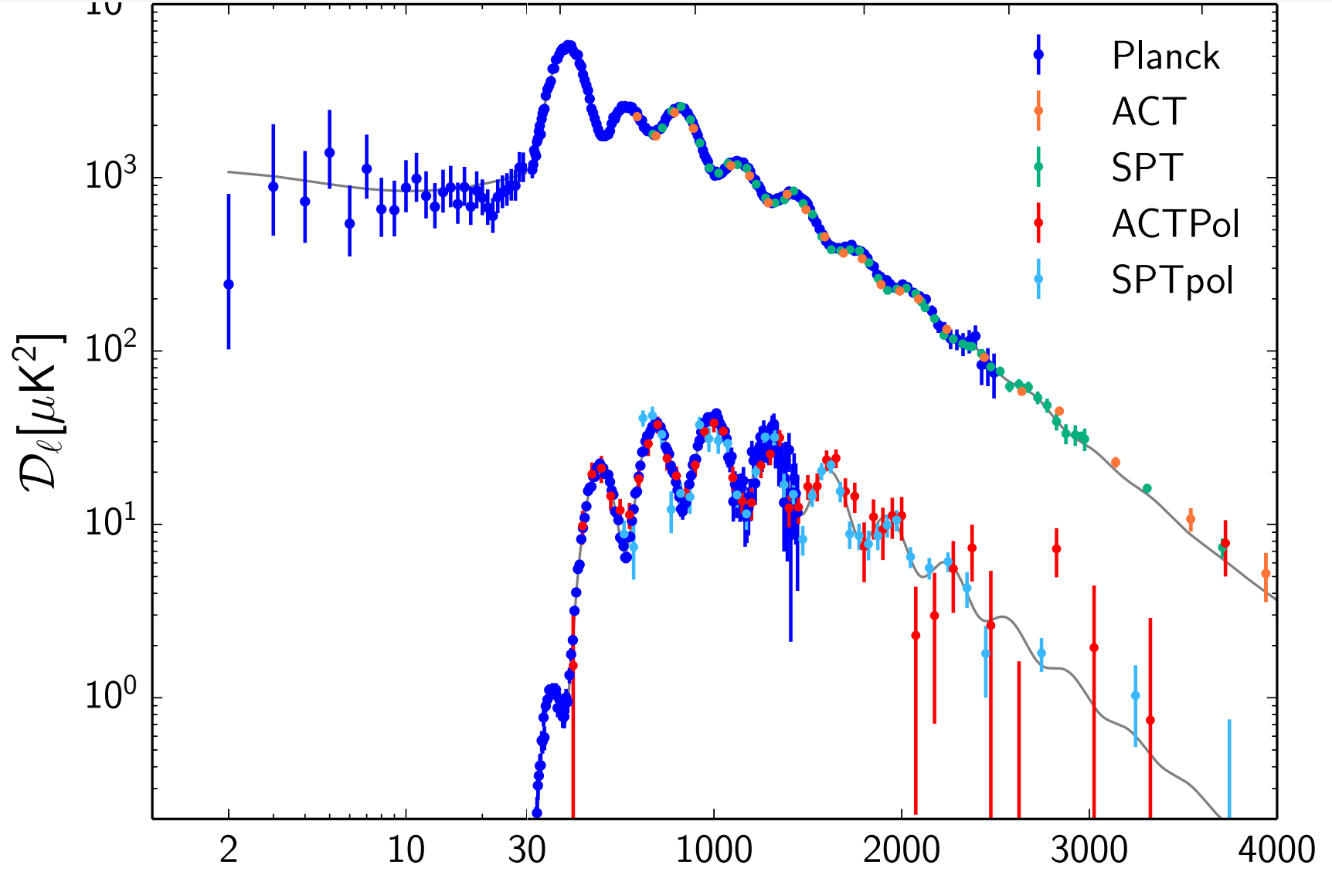
Frequency averaged spectrum reduced chi^2 = 1.04



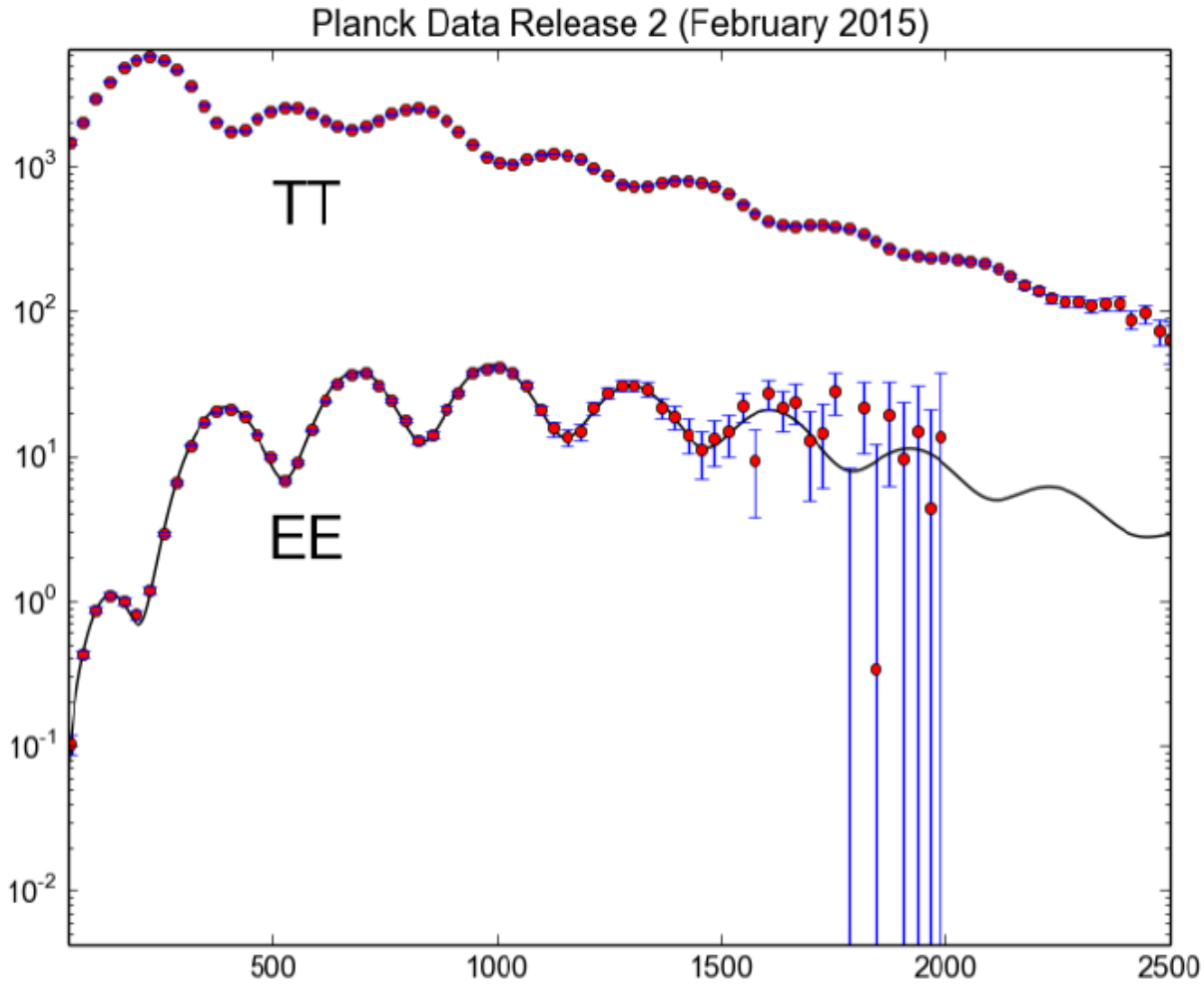
Frequency averaged spectrum reduced chi^2 = 1.01

- Red curve is the prediction based on the best fit TT in base ΛCDM
- Albeit quite precise already, 2014 polarisation data and results are not final yet because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

TT & EE spectra – mid 2015

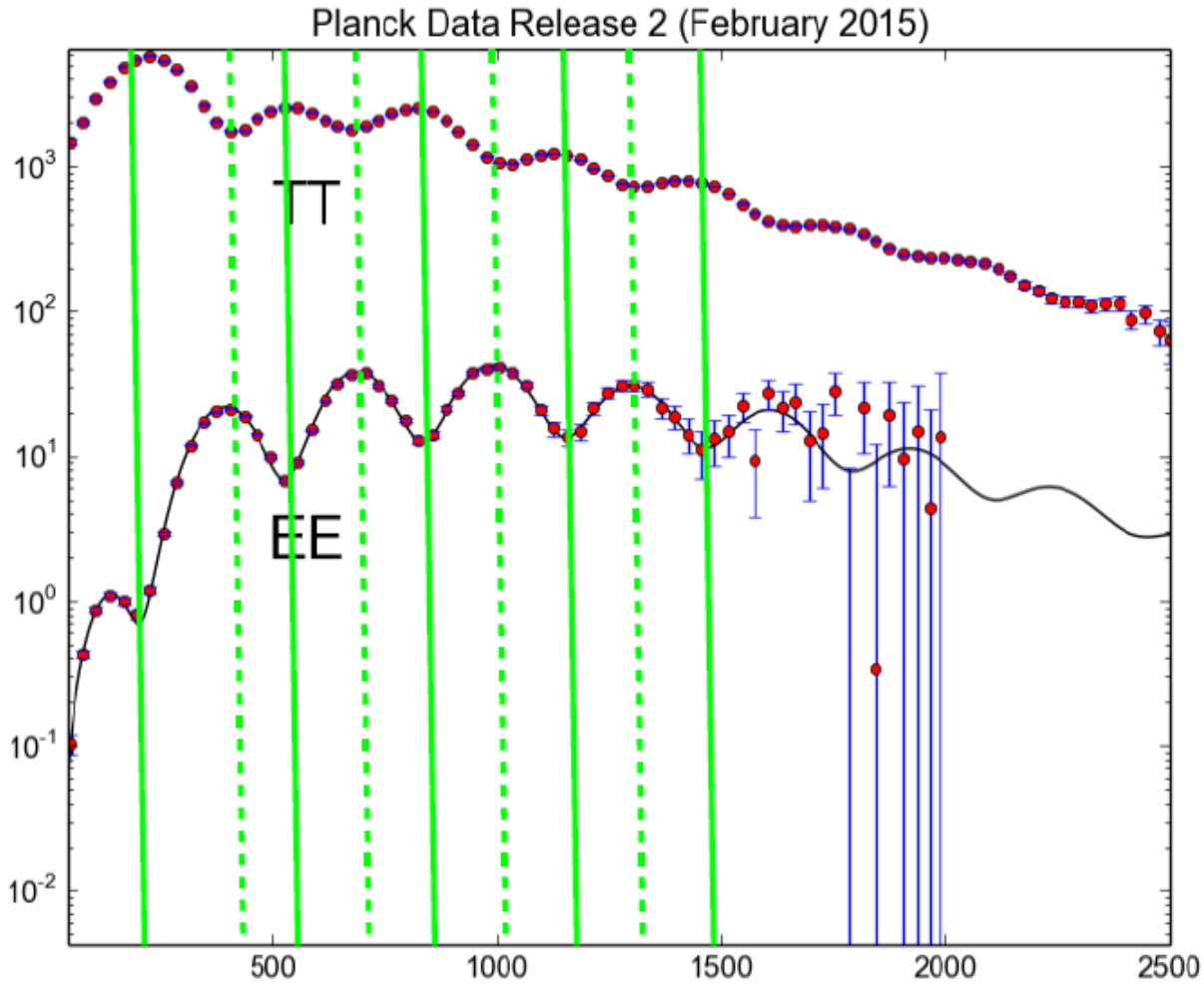


Adiabaticity



(Data: Planck Legacy Archive)

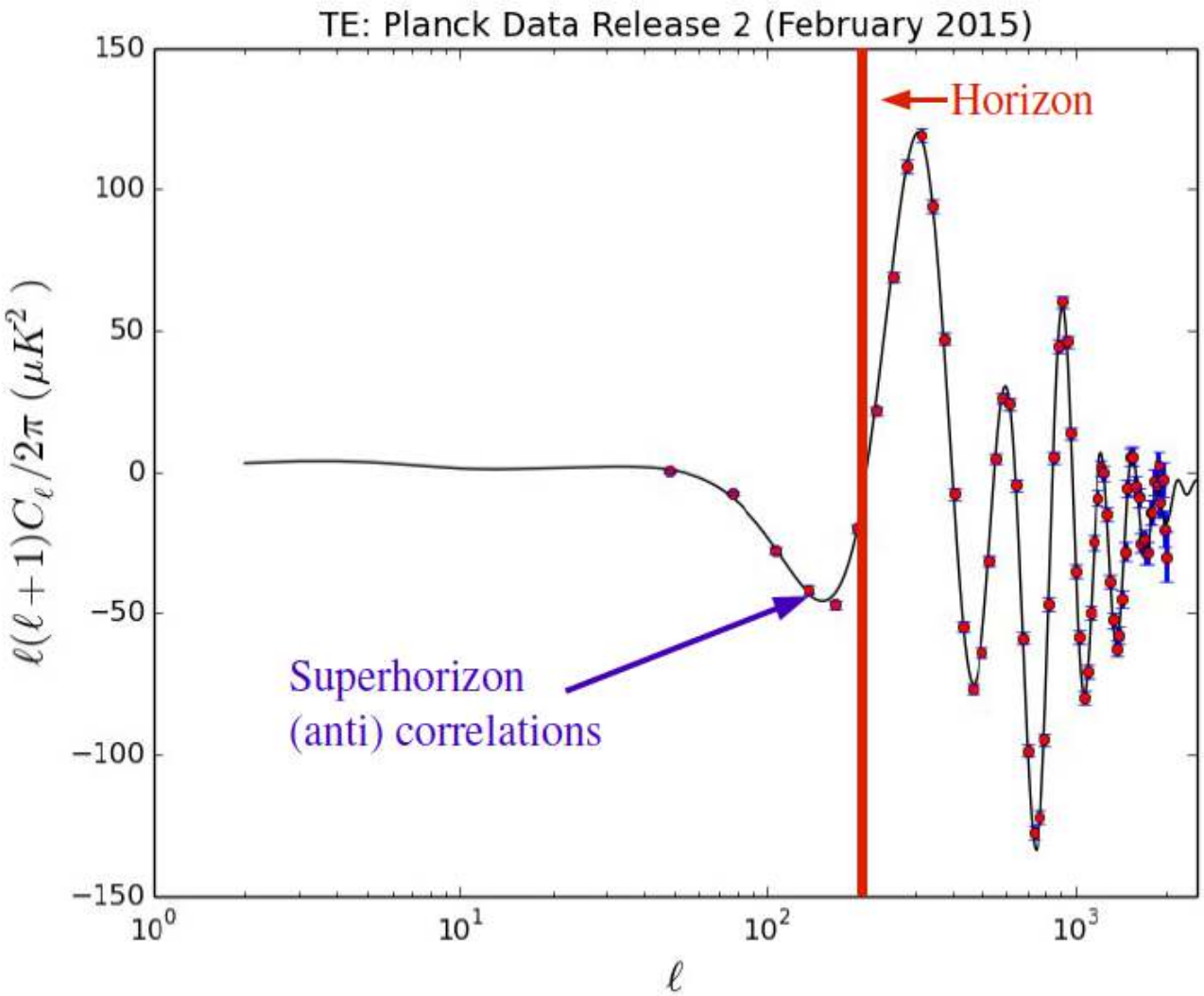
Adiabaticity



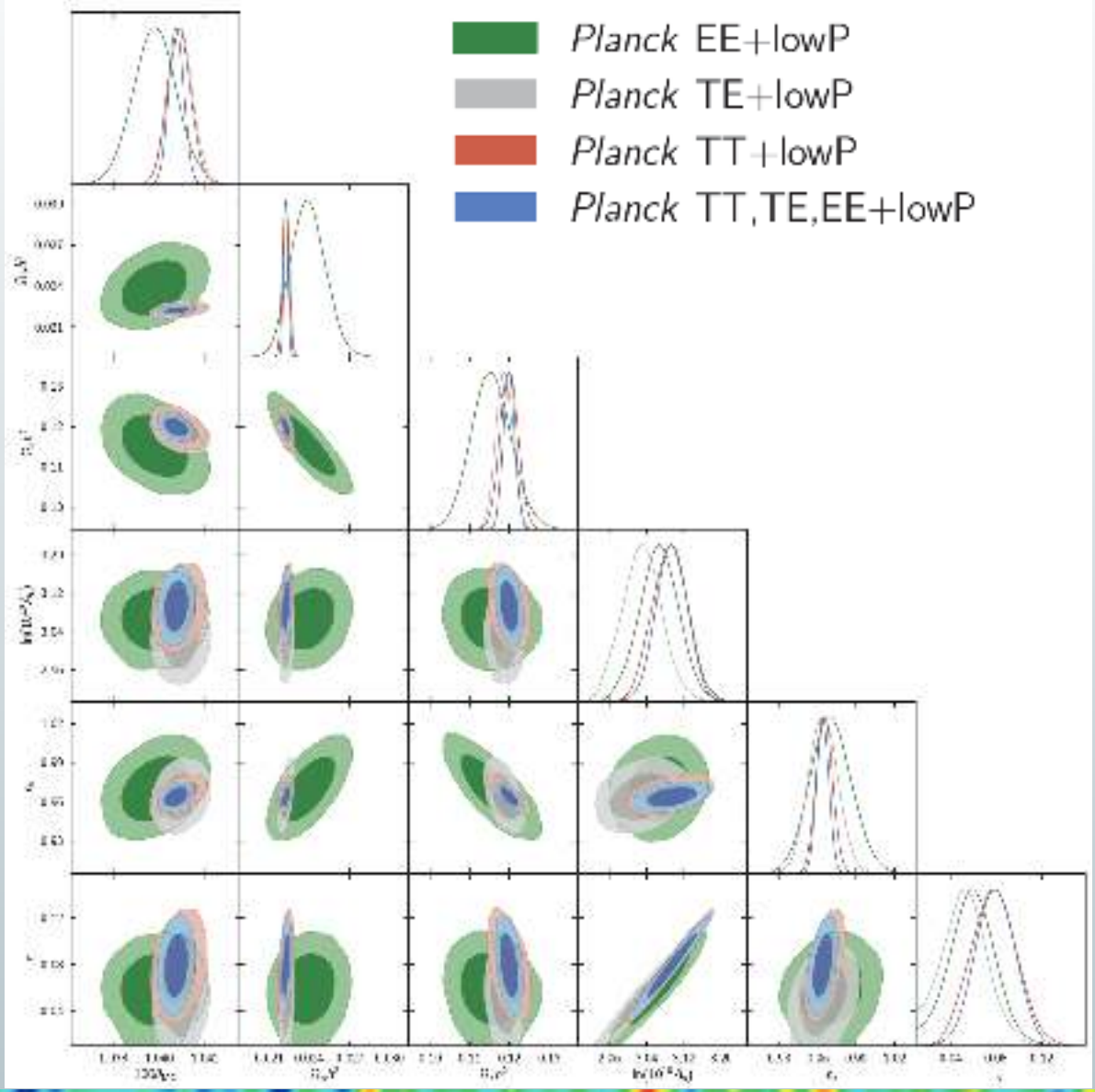
(Data: Planck Legacy Archive)

Kinney

TE large scale correlation



T & E – LCDM parameters



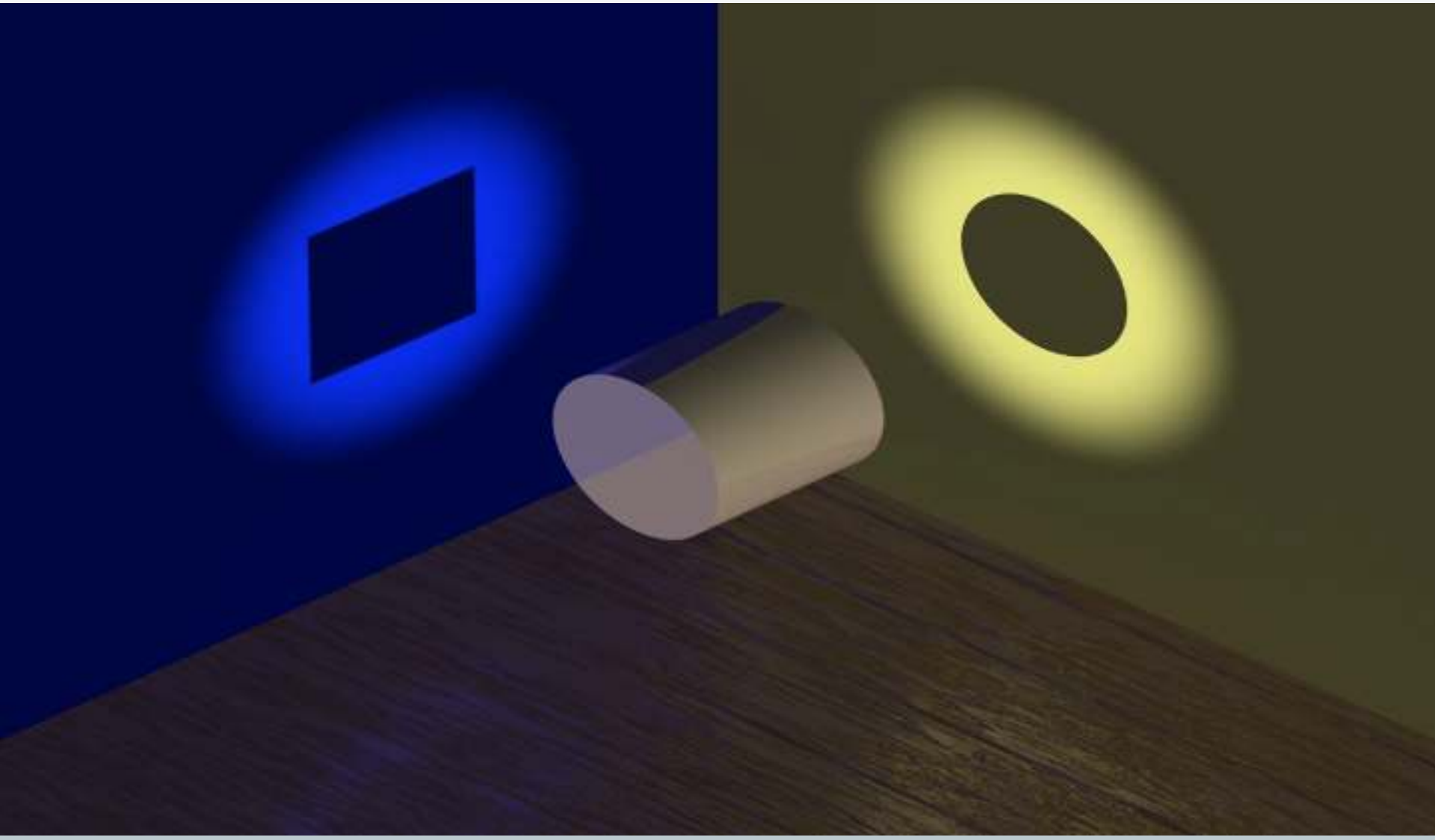
Parameters from polarisation spectra are ***highly consistent*** *with those from TT spectra.*

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

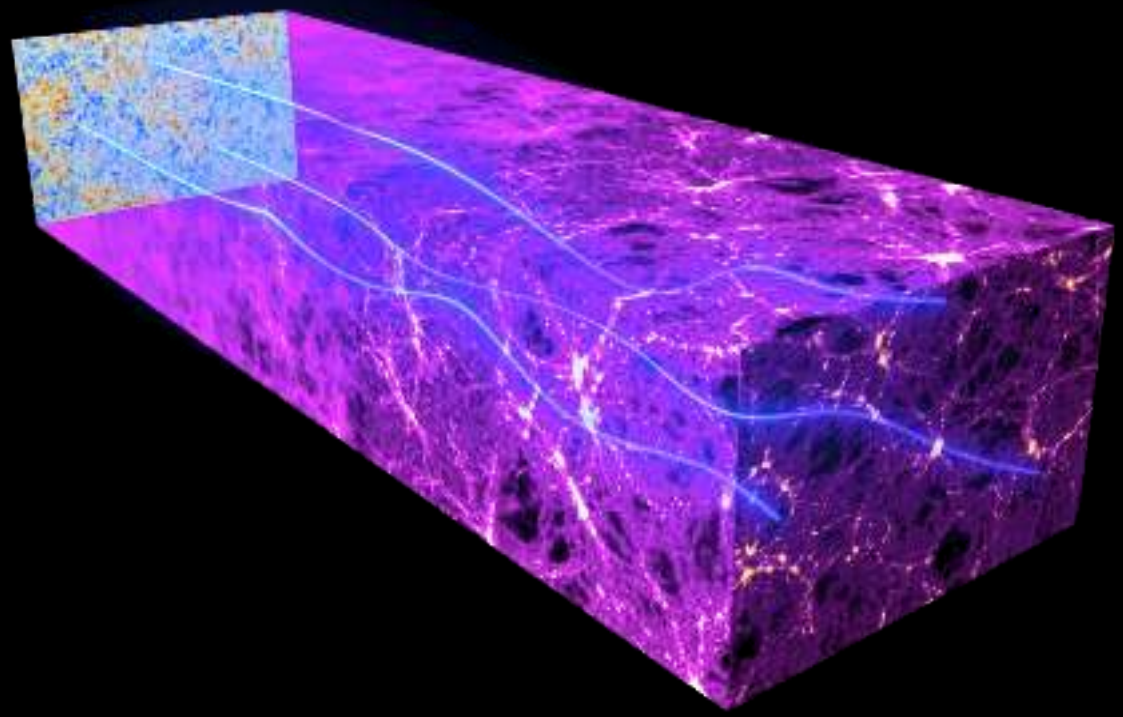
TT & TE have quite similar uncertainties (apart from n_s where l-range/noise counts most) but beware that they are still some low level systematics in the polarisation data

A different view may hold surprises



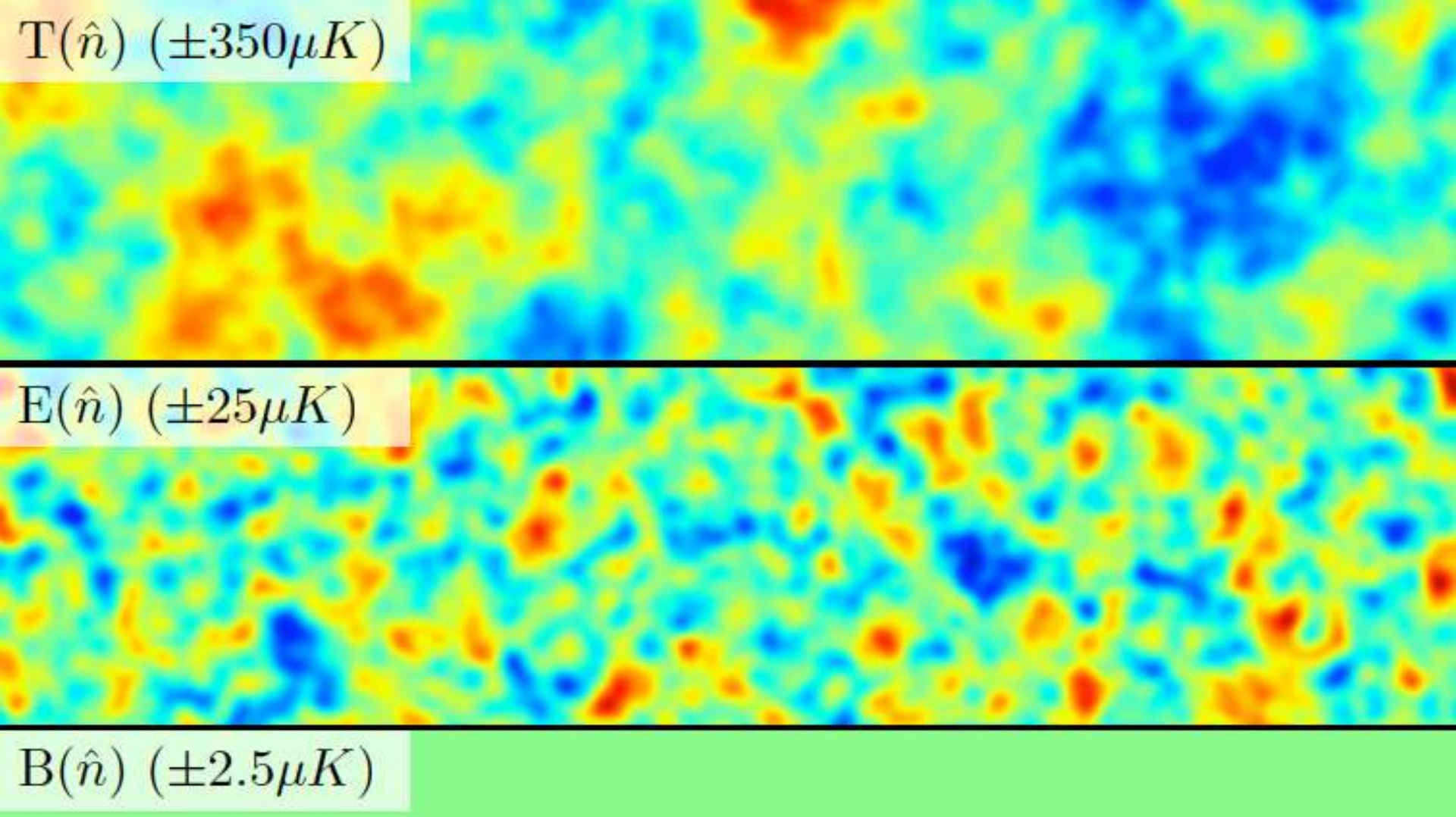
GRAVITATIONAL LENSING DISTORTS IMAGES

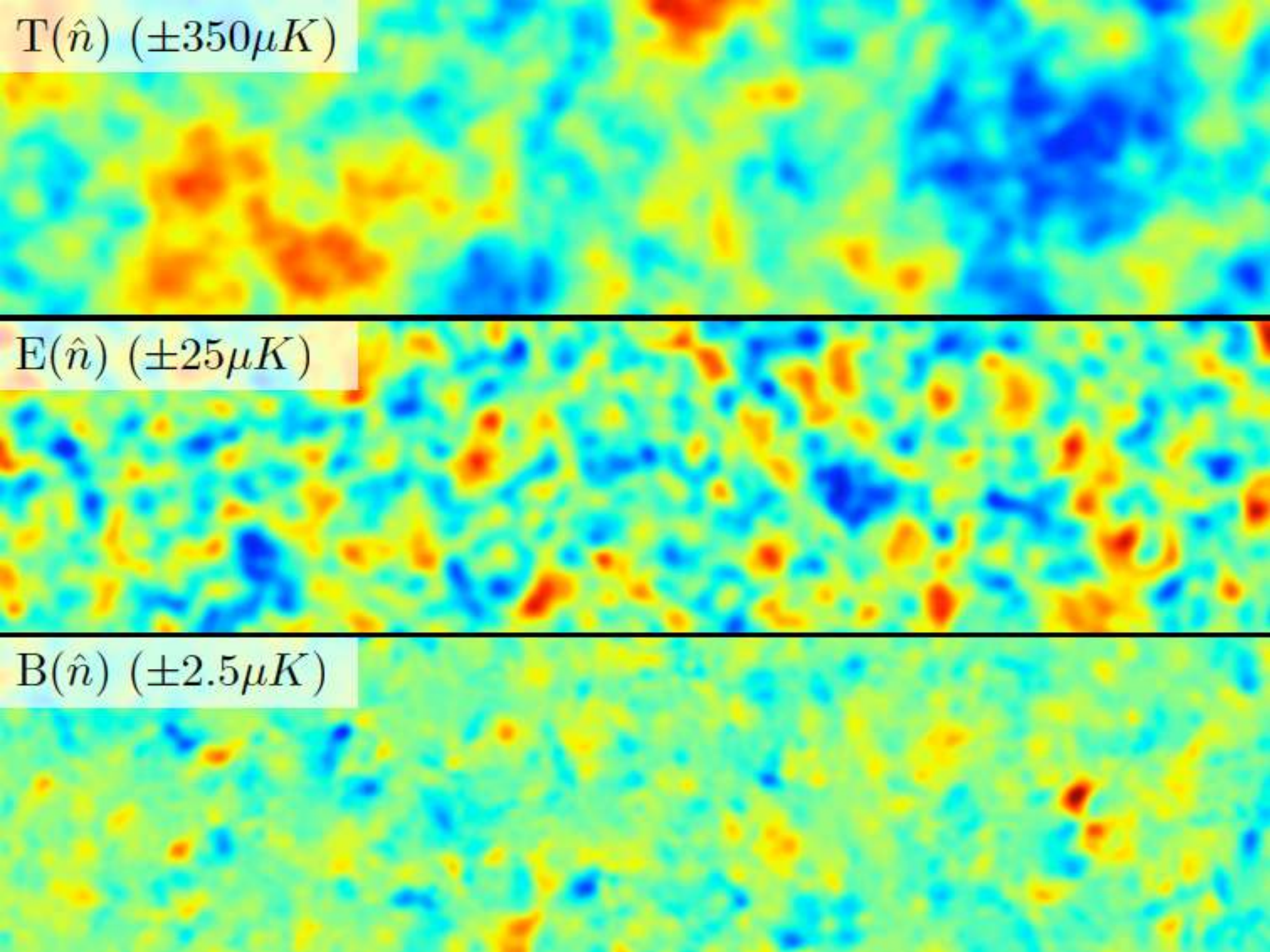
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing on the power spectrum, and correlations between scales)



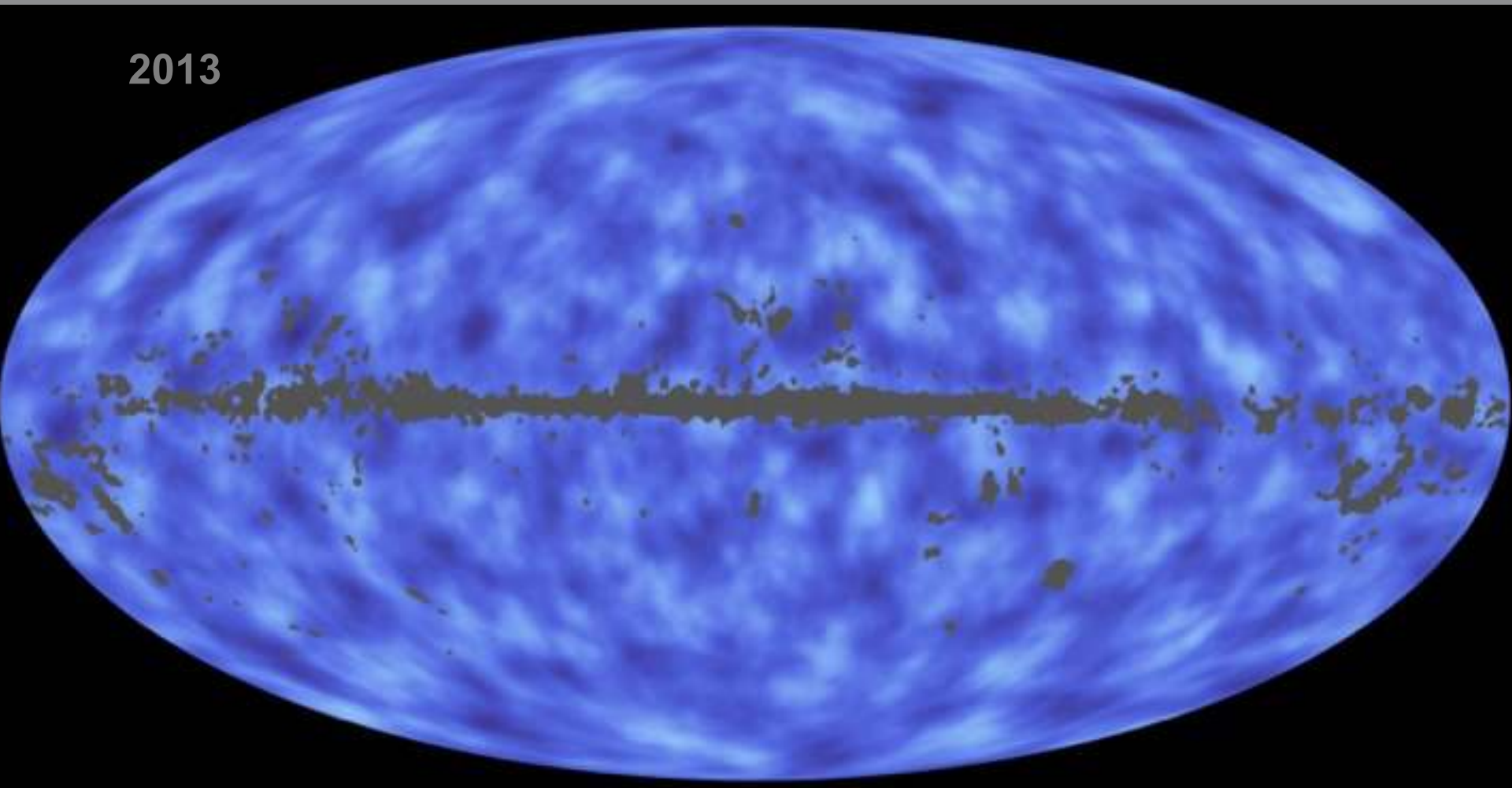
$$\hat{T}(\vec{\theta}) = T(\vec{\theta} + \vec{\nabla}\phi) \approx T(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T(\vec{\theta}) + ...$$

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


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


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

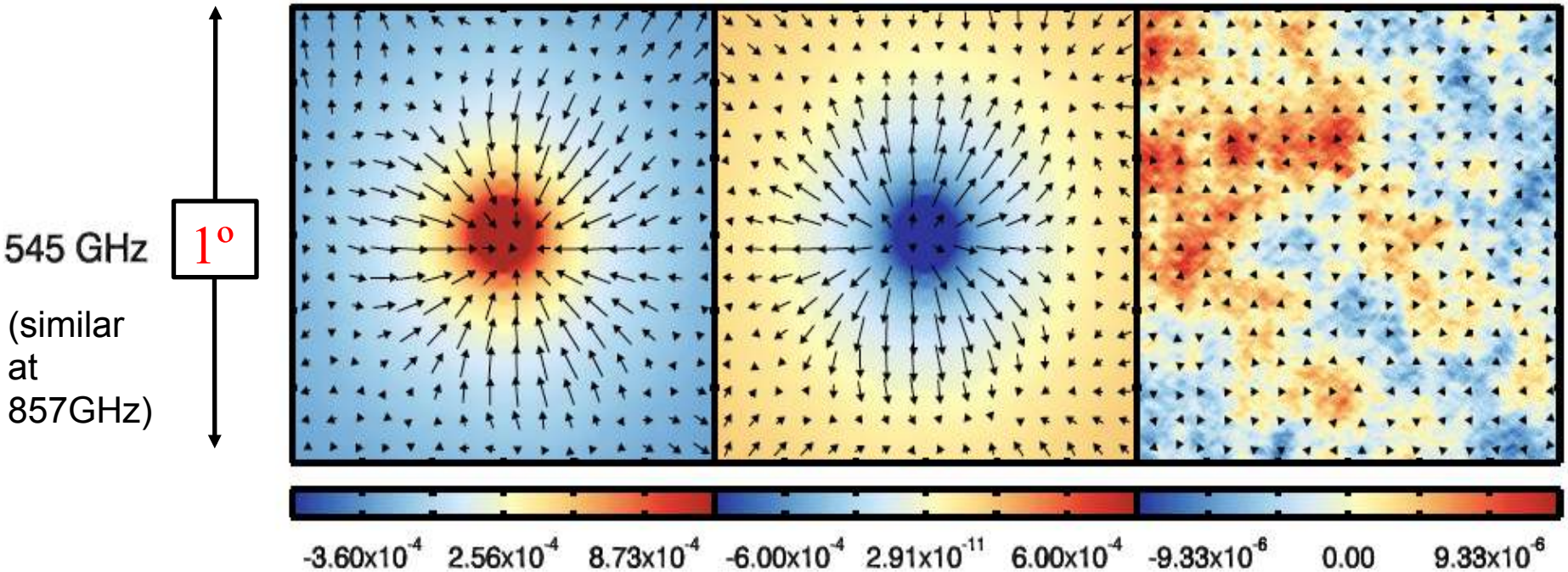
Planck projected mass map



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

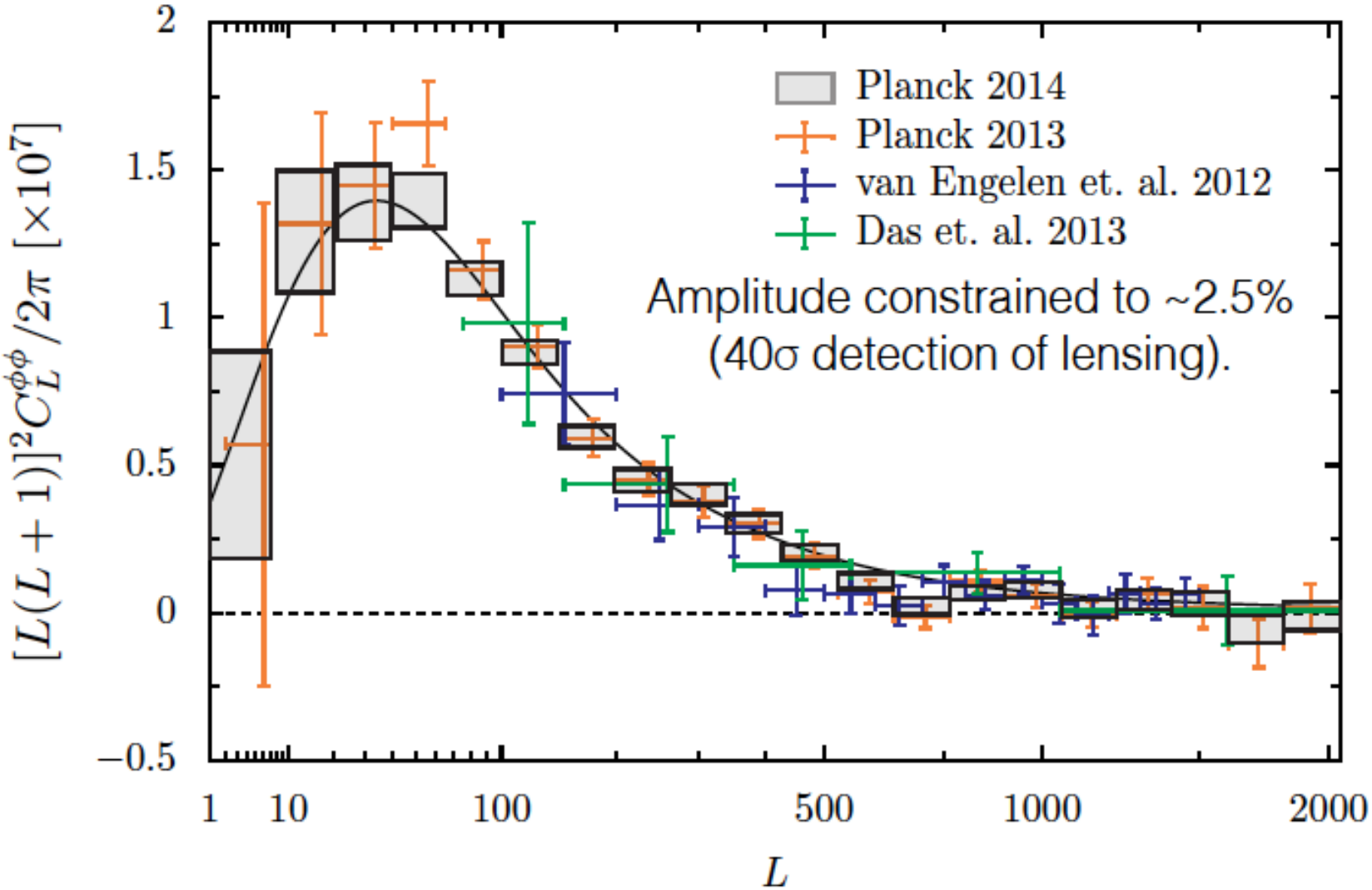
CIB peaks correspond to potential extrema

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



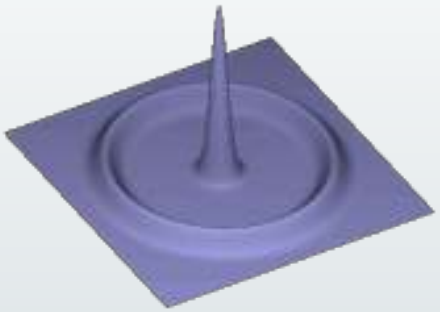
[Planck Collaboration XVIII 2013]

Lensing power spectrum

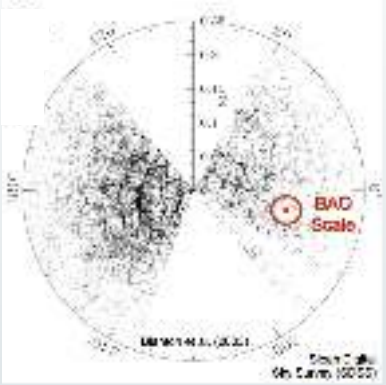


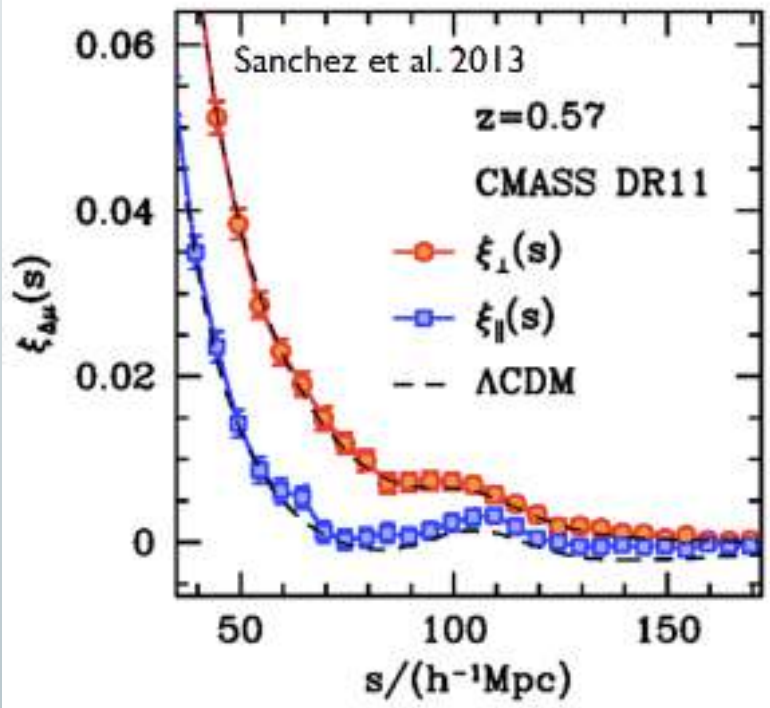
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

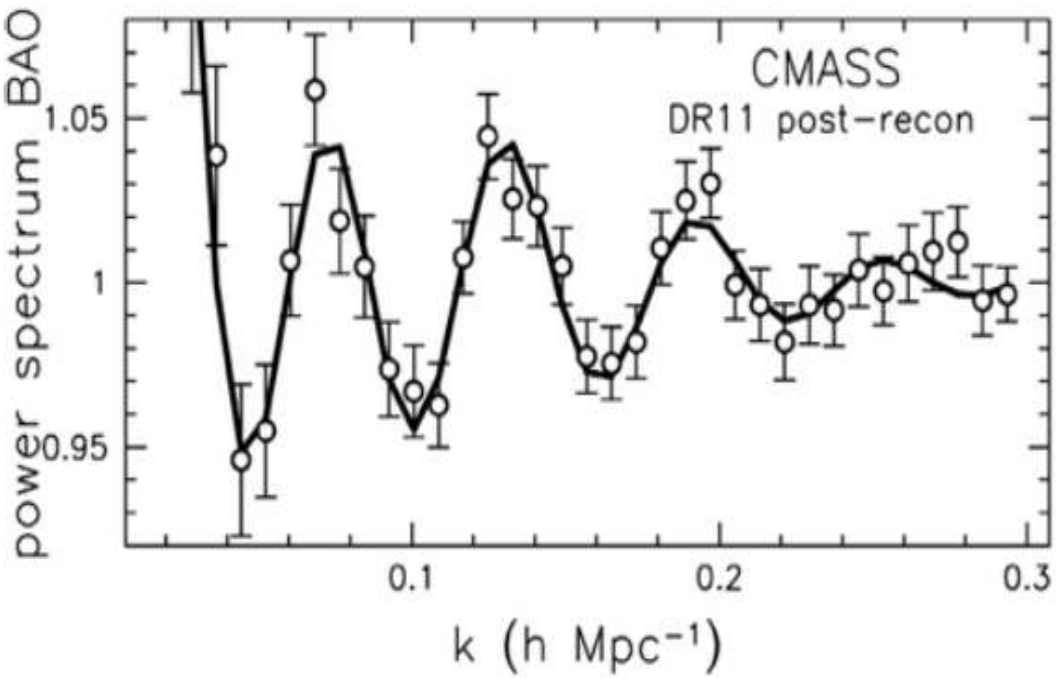
BAO: correlation function & power spectrum



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

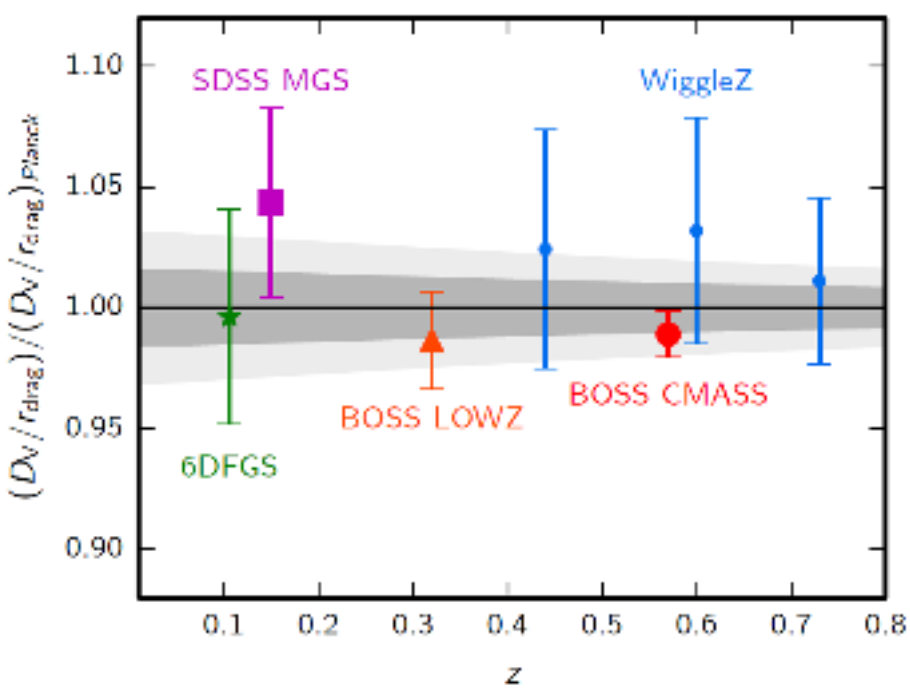


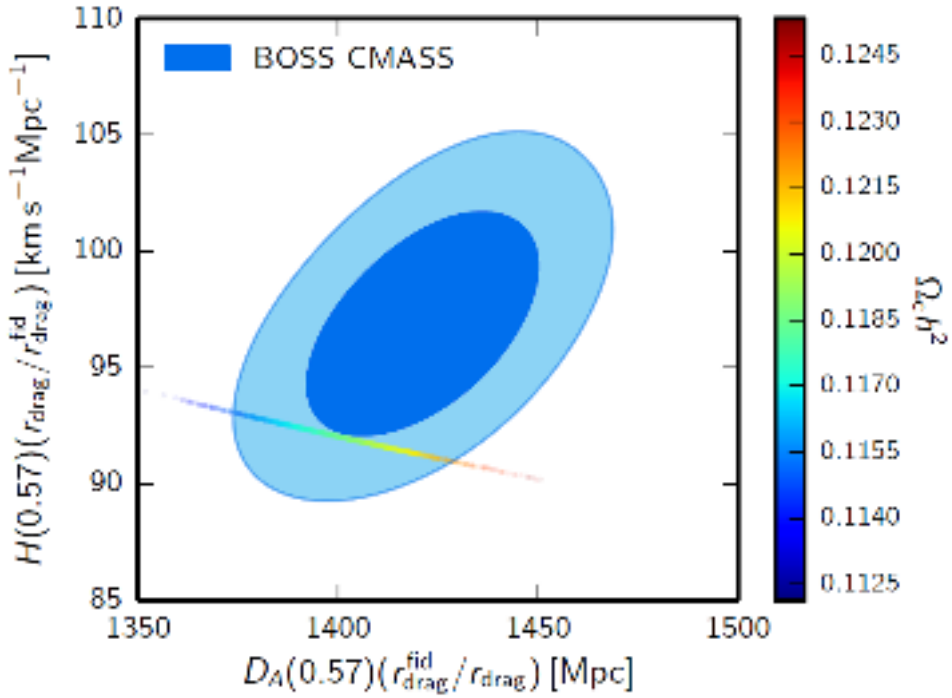




Planck and BAO

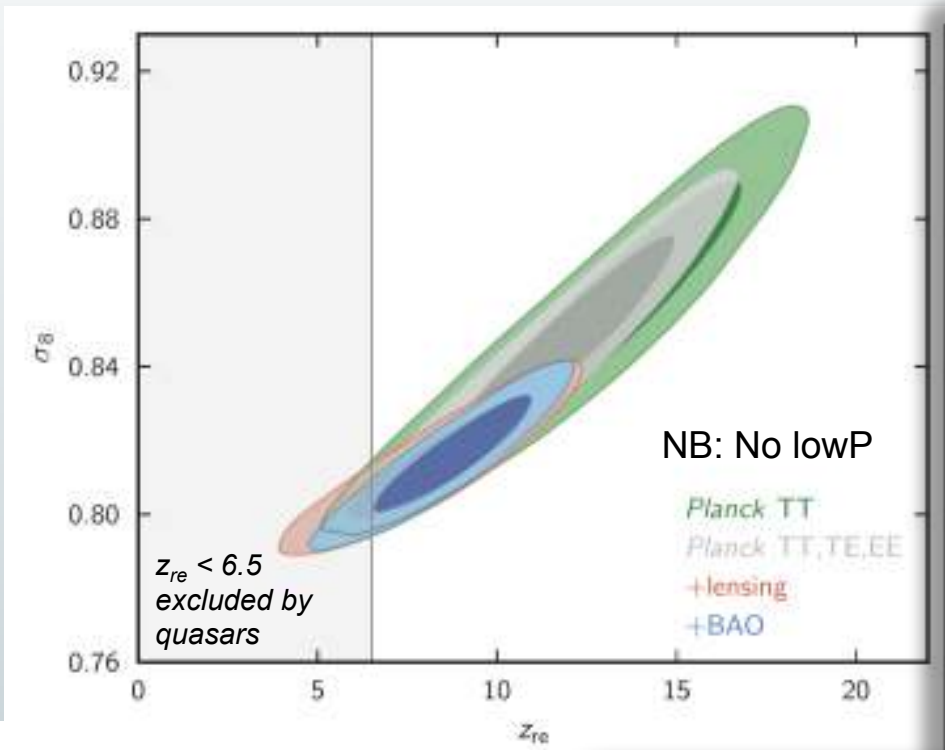
Grey band is Planck TT+LowP 1(2) sigma range

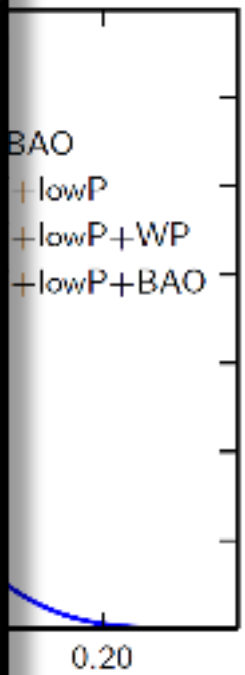




… are consistent.

Optical depth constraints





Dark ages therefore ended around 550 million years after the BB – more than 100 million years later than previously thought (note though That the sizeable uncertainties remain similar for now).

There is now little need for exotic/contrived sources of energy to explain the history of reionization.

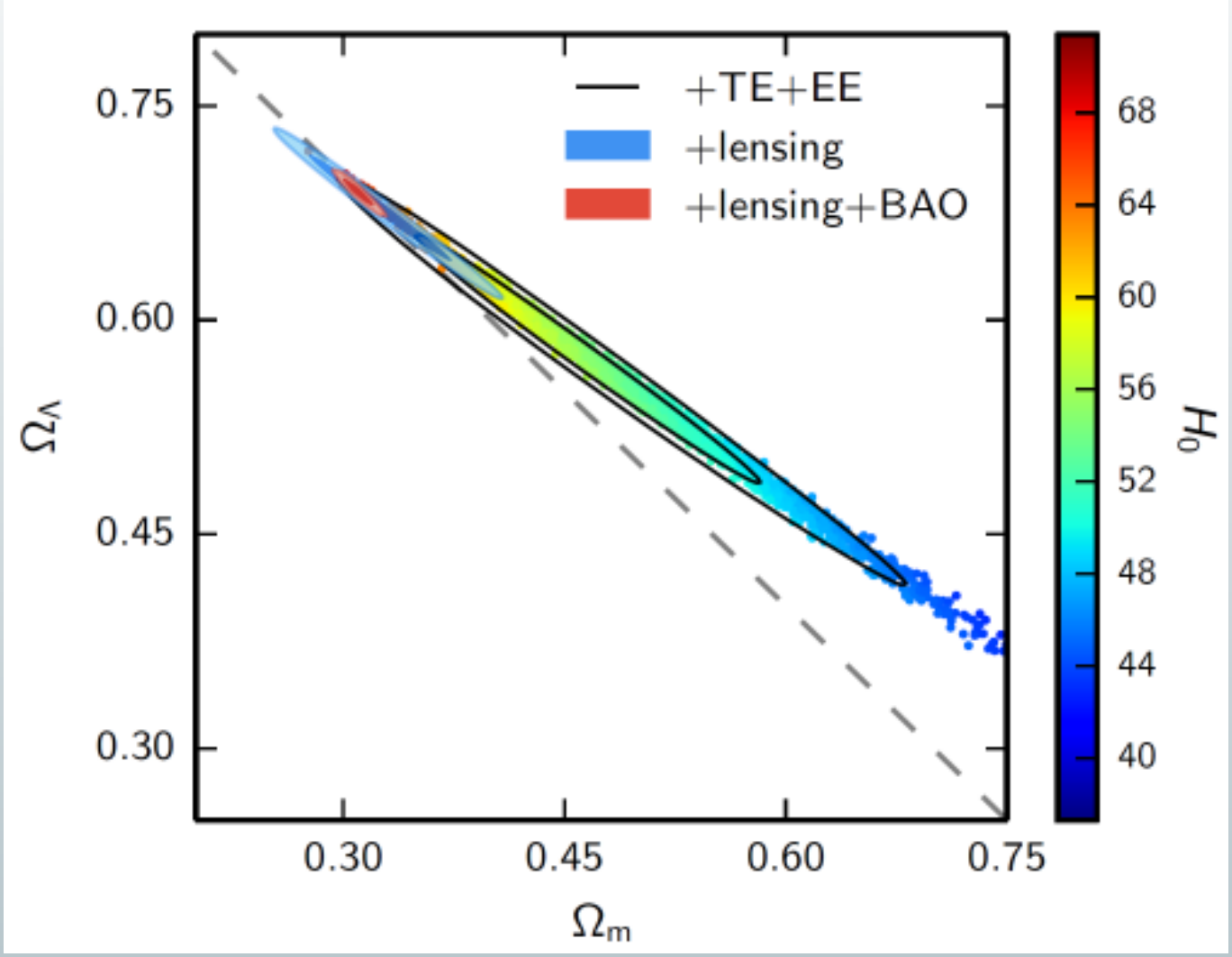
i.e. a tension between CMB and galaxy formation is now fading away.

A new, independe

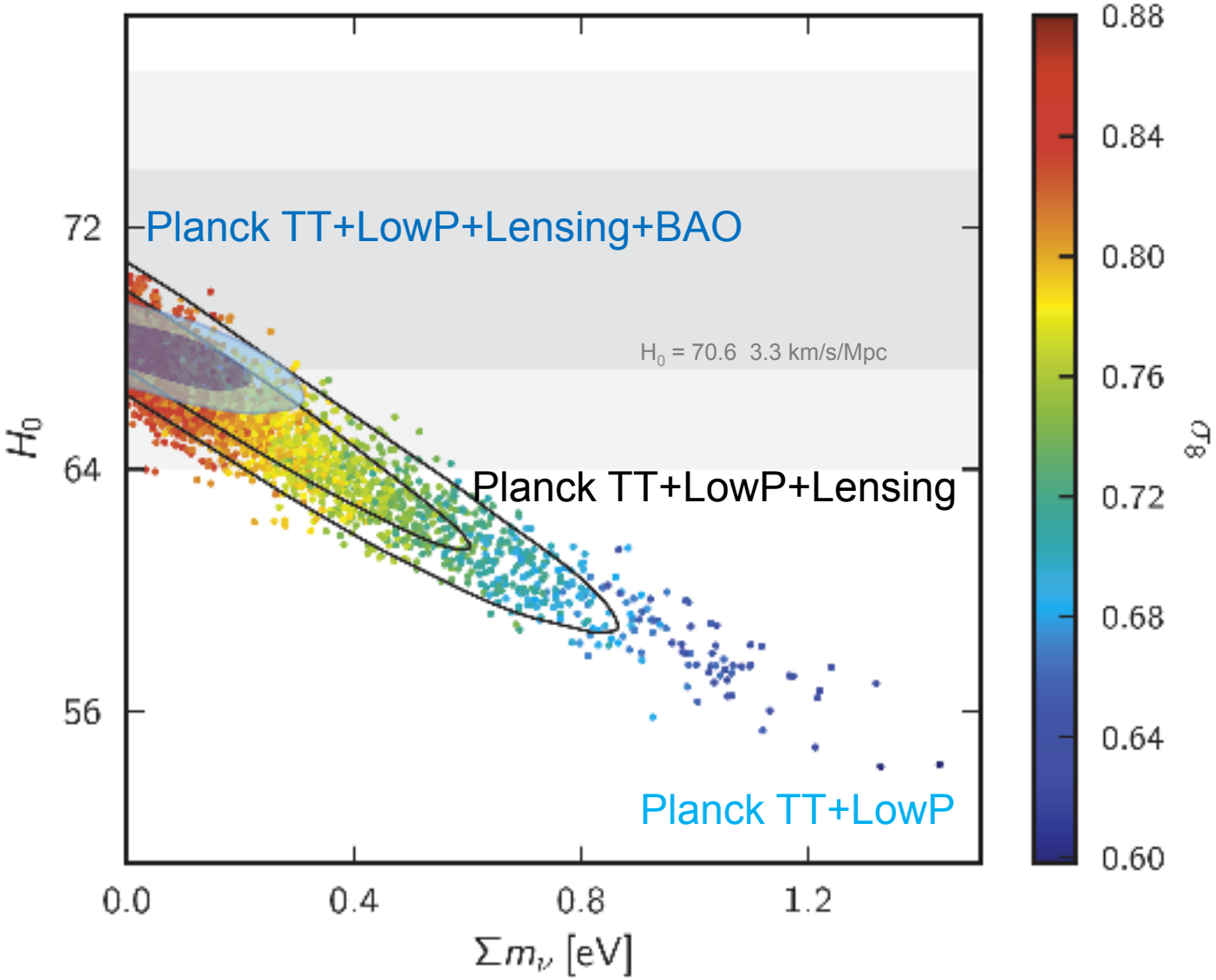
➔ Consistency of lensing τ

Pointing to lower τ values than earlier WMAP(1-9) based ones

Spatial curvature constraint



Neutrinos masses $\sum m\nu < 0.23$ eV (95%)

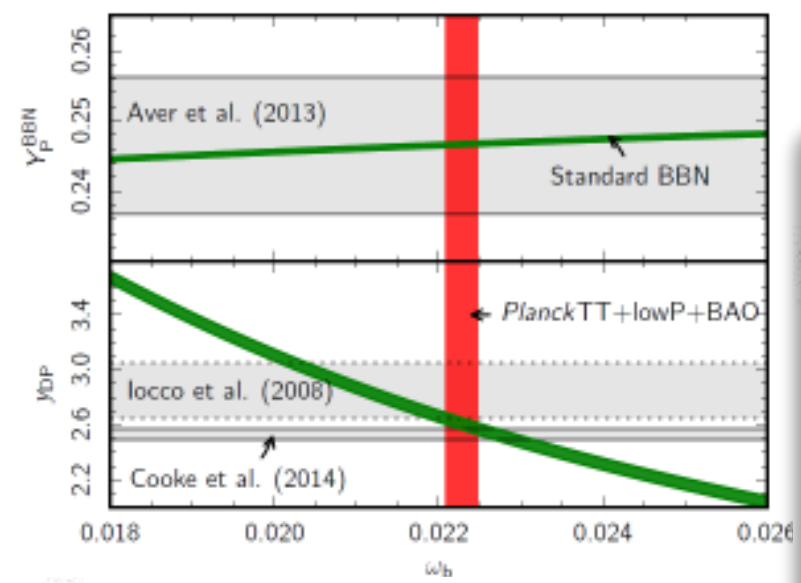


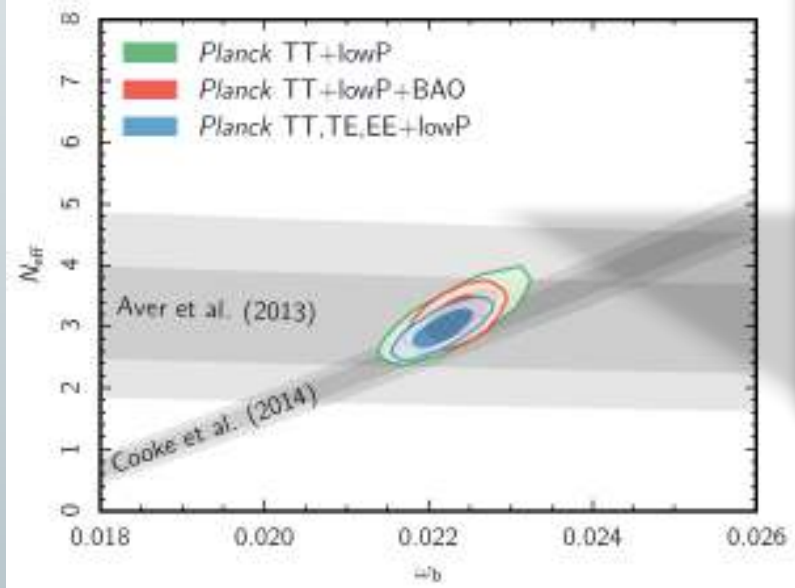
0.23eV is from TT+lowP +lensing +ext

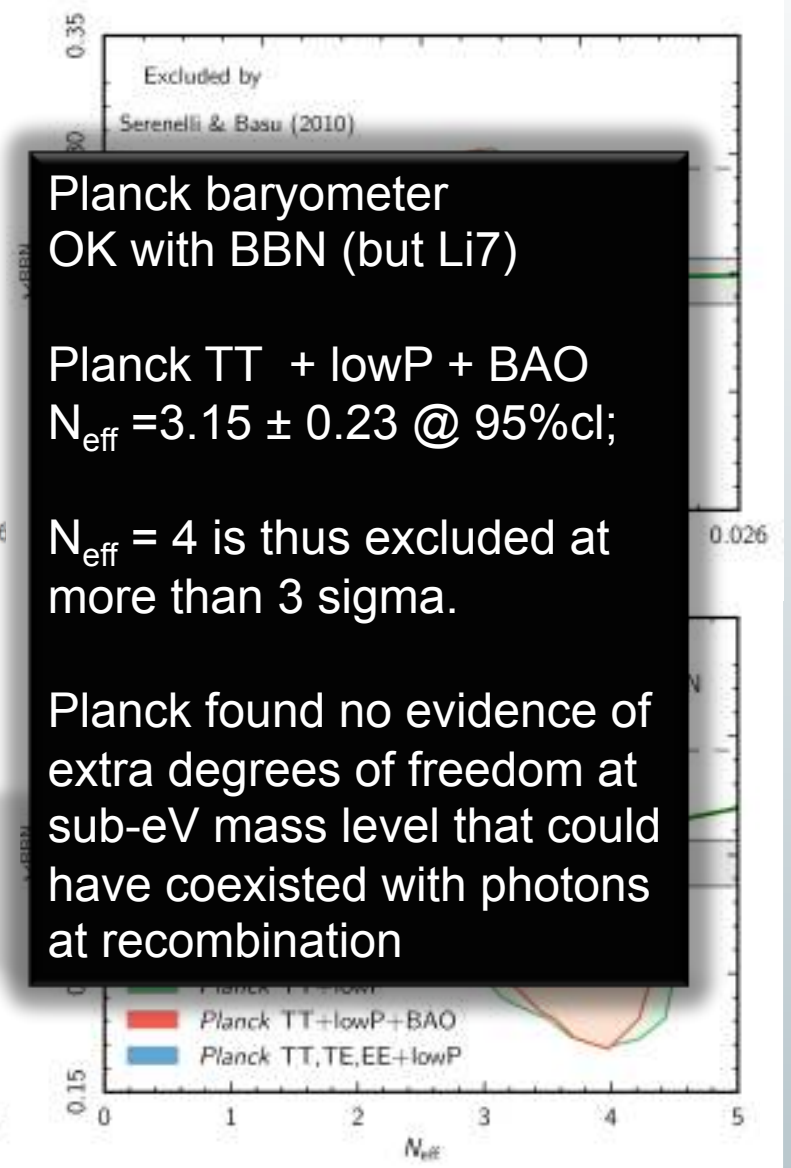
➔h^2 < 0.0025

(slight tightening with TE & EE)

BBN – N_{eff}, Y_p







Planck baryometer
OK with BBN (but Li7)

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

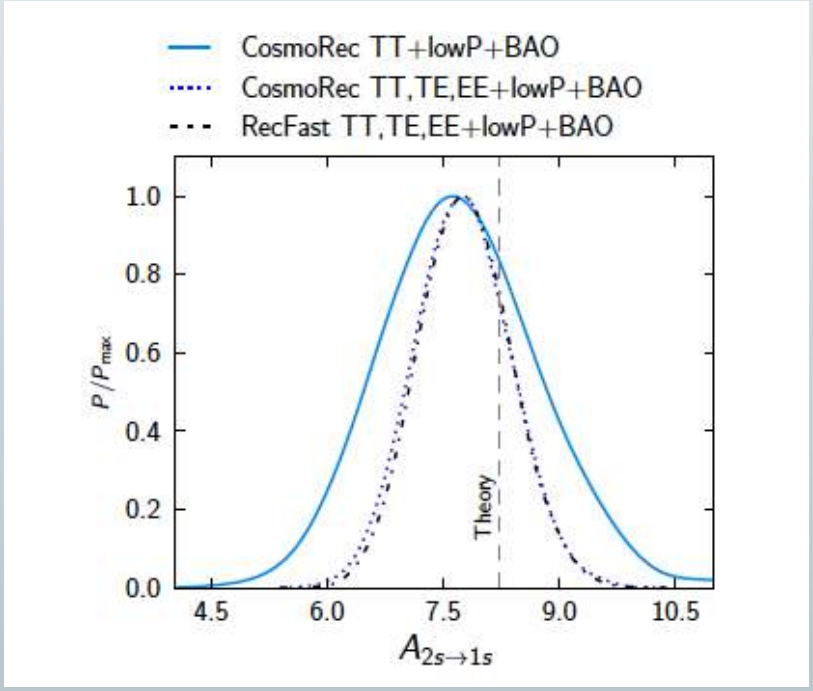
N_{eff} = 4 is thus excluded at more than 3 sigma.

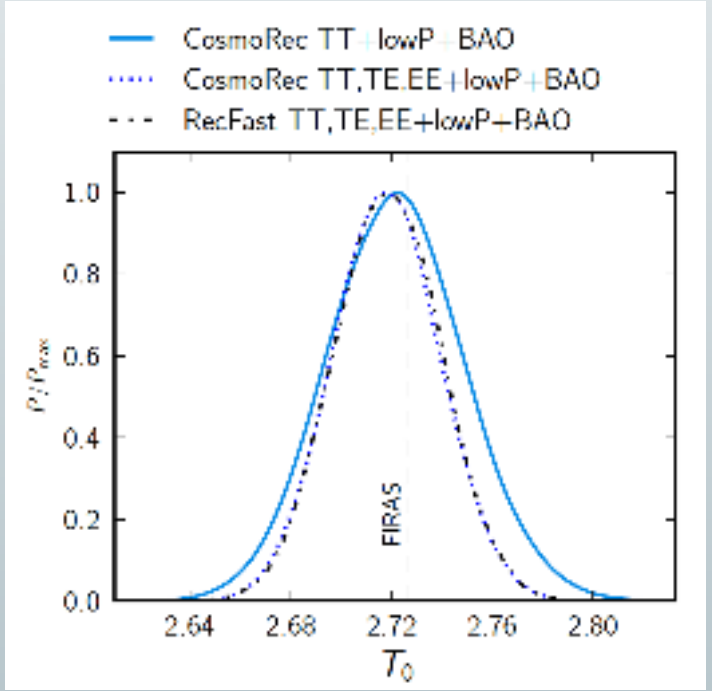
Planck found no evidence of extra degrees of freedom at sub-eV mass level that could have coexisted with photons at recombination

Recombination history

Planck is impressively sensitive to details of the recombination history… and is therefore sensitive to

- Variation of the fundamental constants
- The value of the 2 ϒ decay rate, or the recombination Temperature…, or any non-std history!

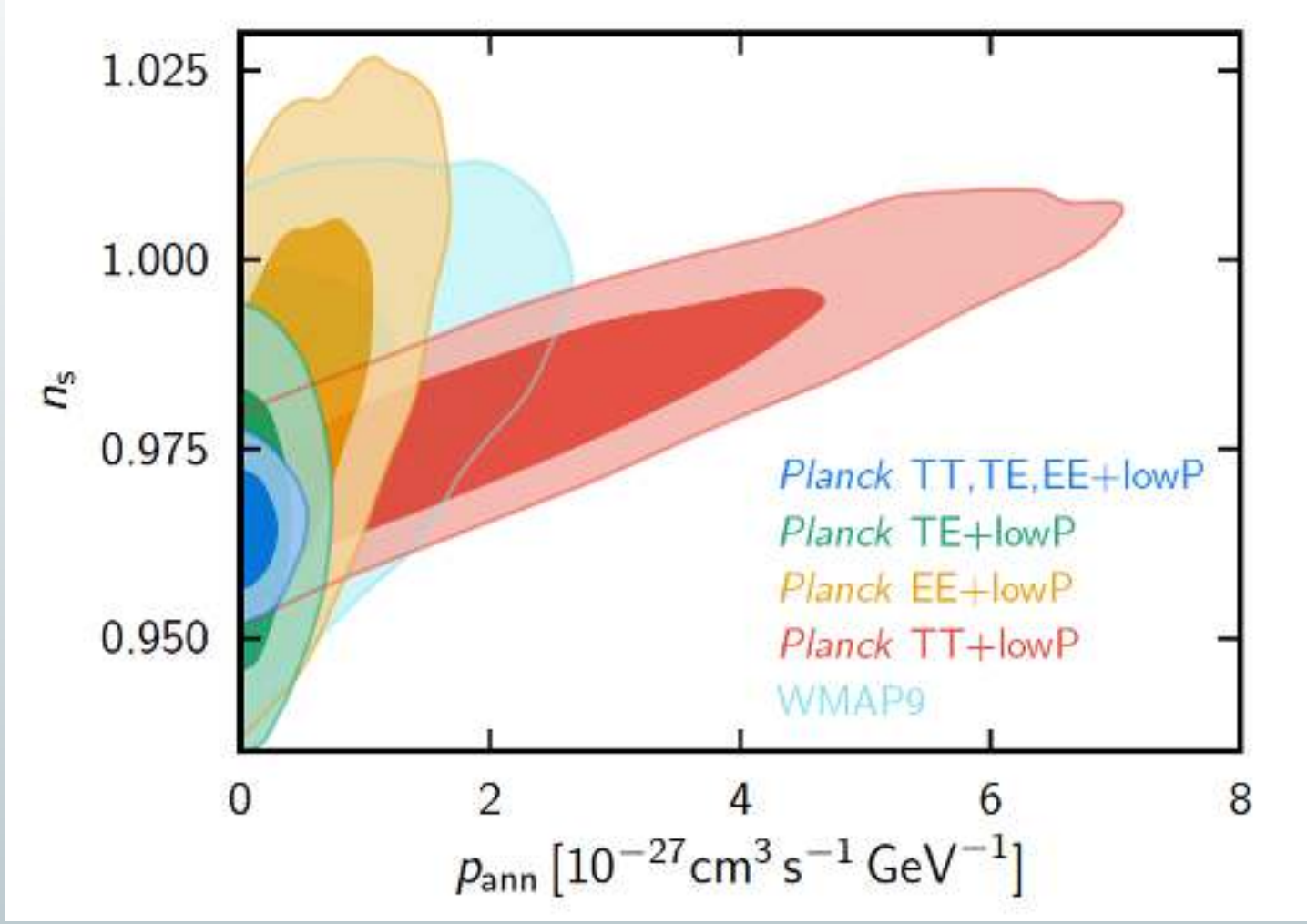




Dark matter annihilation?

Planck TTTEEE breaks degeneracies and sets a limit 5 times stronger than WMAP9+SPT

$$p_{ann} = f_{eff} \frac{<\sigma v>}{m_\chi}$$



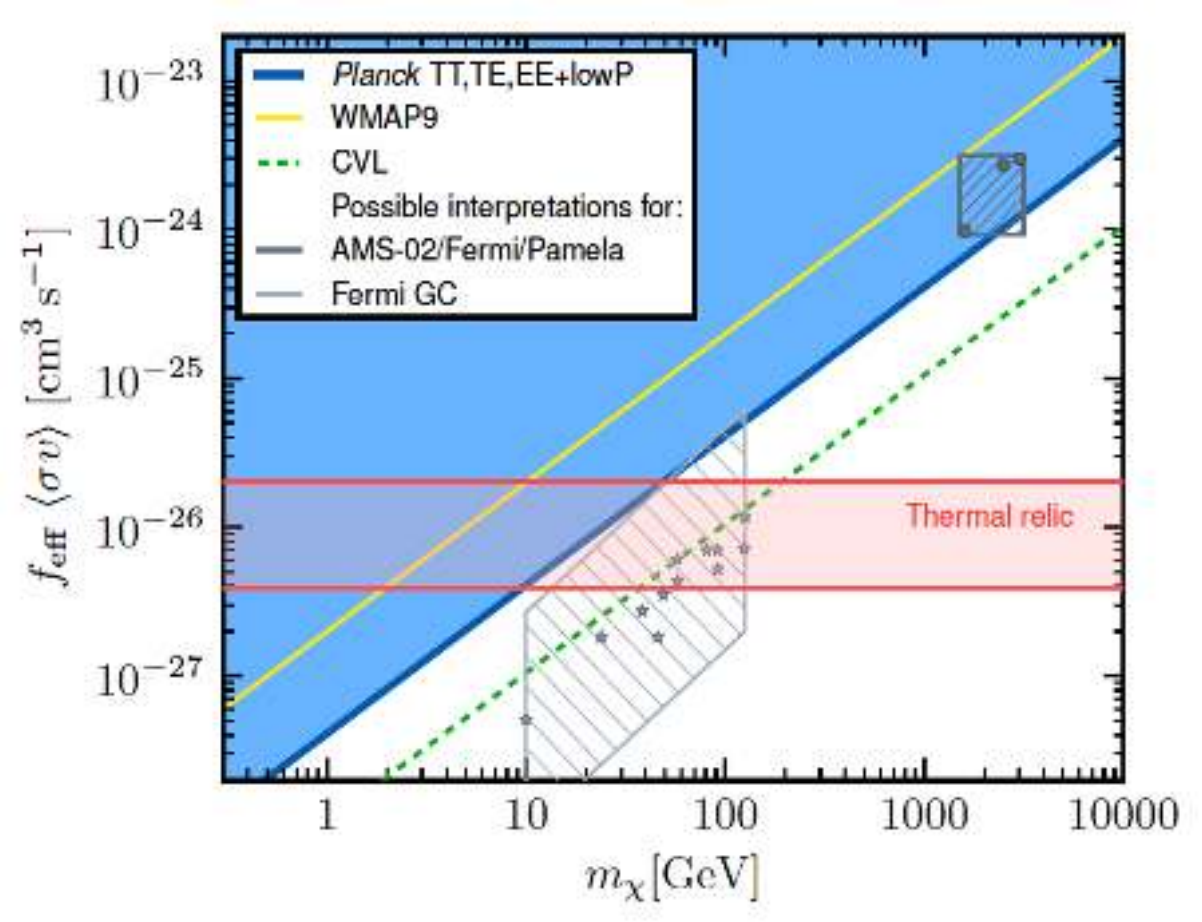
Dark matter annihilation?

Most of parameter space preferred by AMS-02/ Pamela/Fermi ruled out at 95%, under the assumption $\langle\sigma v\rangle(z=100)=\langle\sigma v\rangle(z=0)$

Thermal Relic cross sections at z~1000 ruled out for:

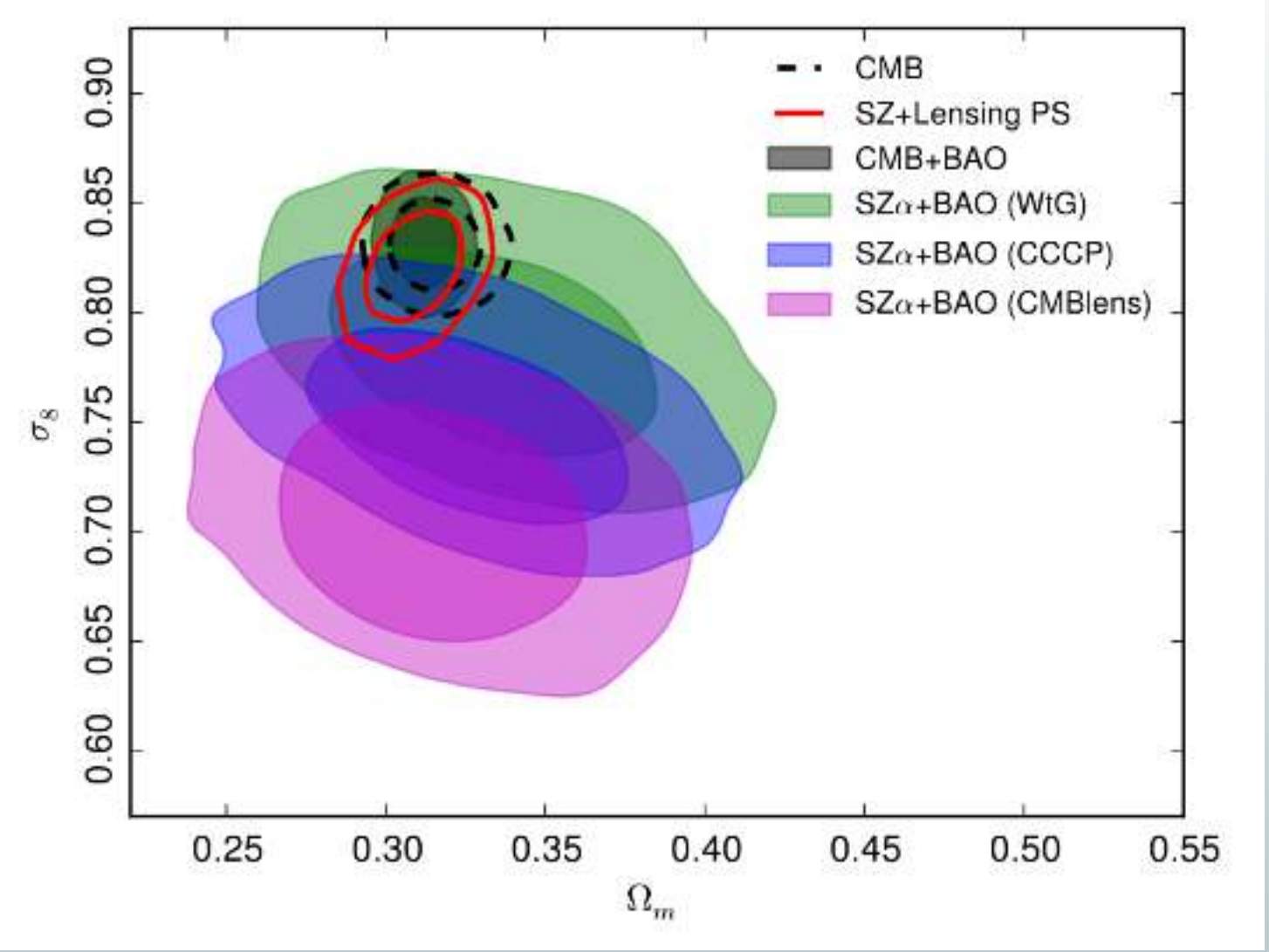
m~<40GeV (e^-e^+)
m~<20GeV ($\mu^+\mu^-$)
m~<10 GeV ($\tau^+\tau^-$).

Only a small part of the parameter space preferred by Fermi GC is excluded



See 1501.01618 for powerful other constraints

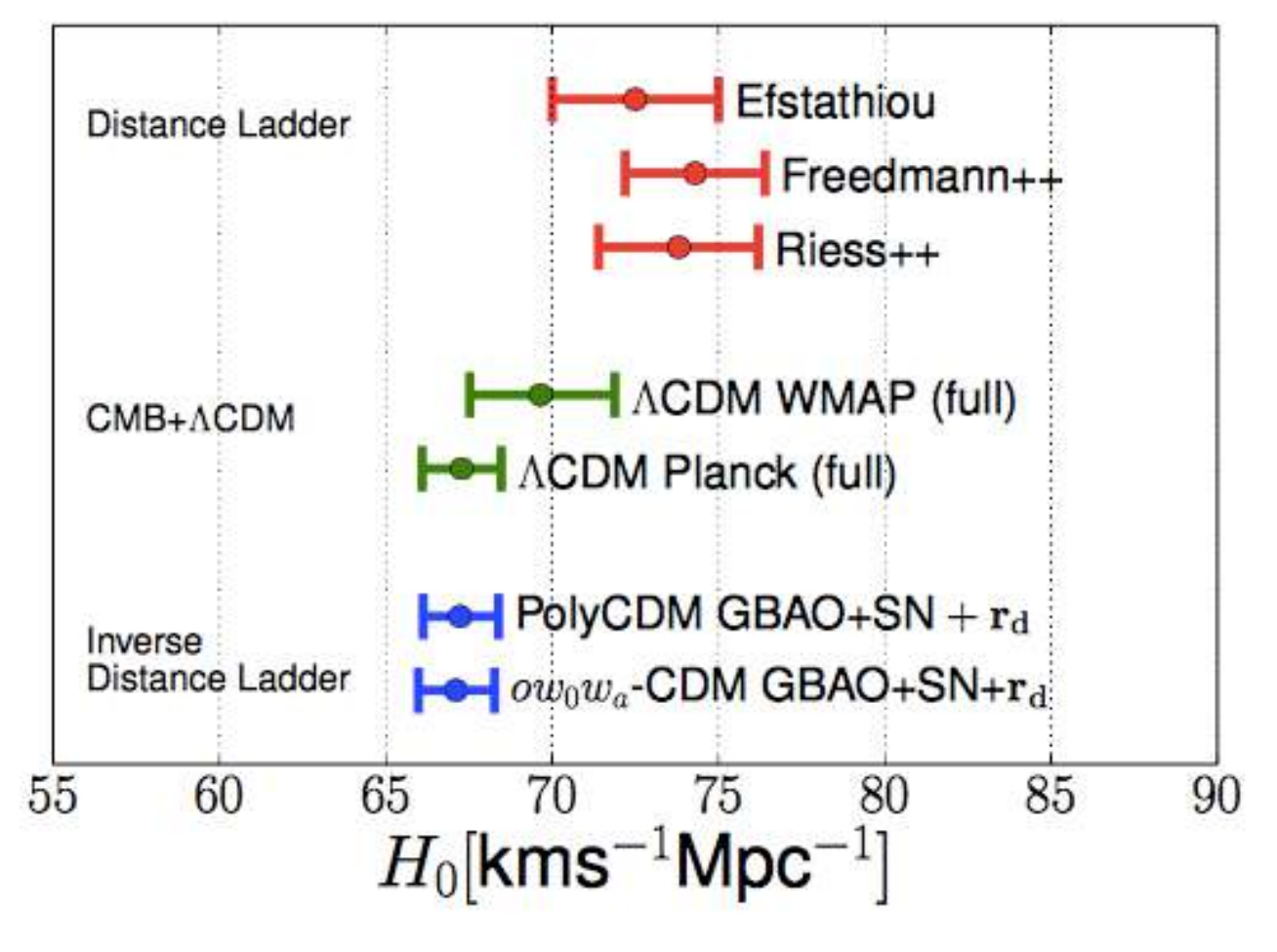
Number counts of SZ clusters



→ 2013 tension only remains with some mass proxy calibration.

Comparison of H_0

- Inverse distance ladder is In perfect agreement with Planck CMB (use BAO's absolute calibration to calibrate Sn1a in the overlapping region at z=0.57 to bring it down to z=0.)
- NB: some discrepancy with direct distance ladder

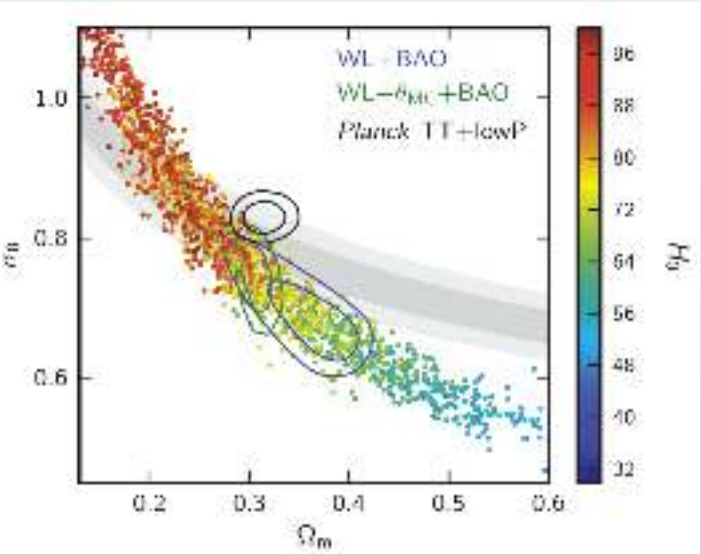


Standard cosmological model - LCDM

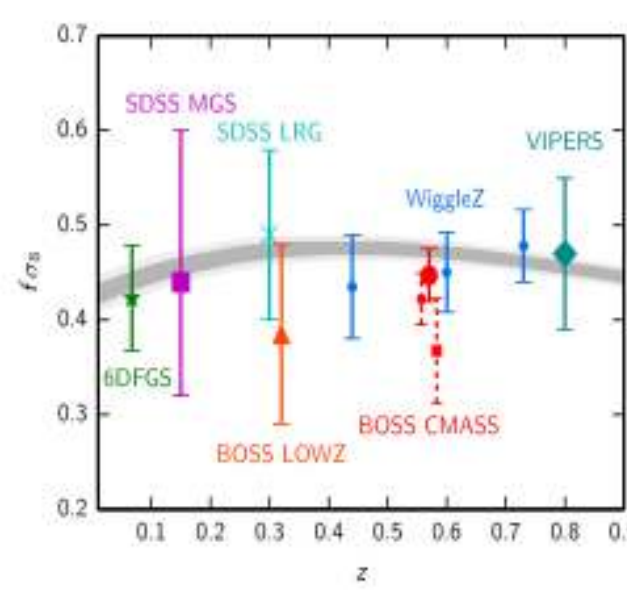
- So the CMB TT, TE, EE, Φ-Φ, as well as BBN (but Li7), the BAO and SN1a measurements are all consistent, among themselves and across experiments, despite the per cent level precision of the tests now performed.
- This consistency allows <u>many</u> different checks of the robustness of base LCDM and some of its extensions. e.g., so far base LCDM parameters and derived parameters (including τ constrained two-ways thanks to CMB lensing), flatness at 5 x 10^{-3} level, neutrinos masses and number, DM annihilation, recombination history ($A_{2s\rightarrow 1}$, T_0, and also fundamental constants variation, or any energy input).

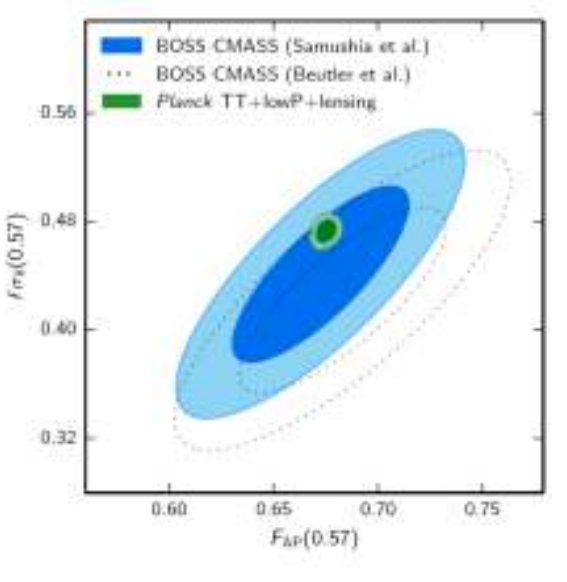
Some tensions

Weak Lensing from CFHTLens



Growth rate of fluctuations from redshift space distortions



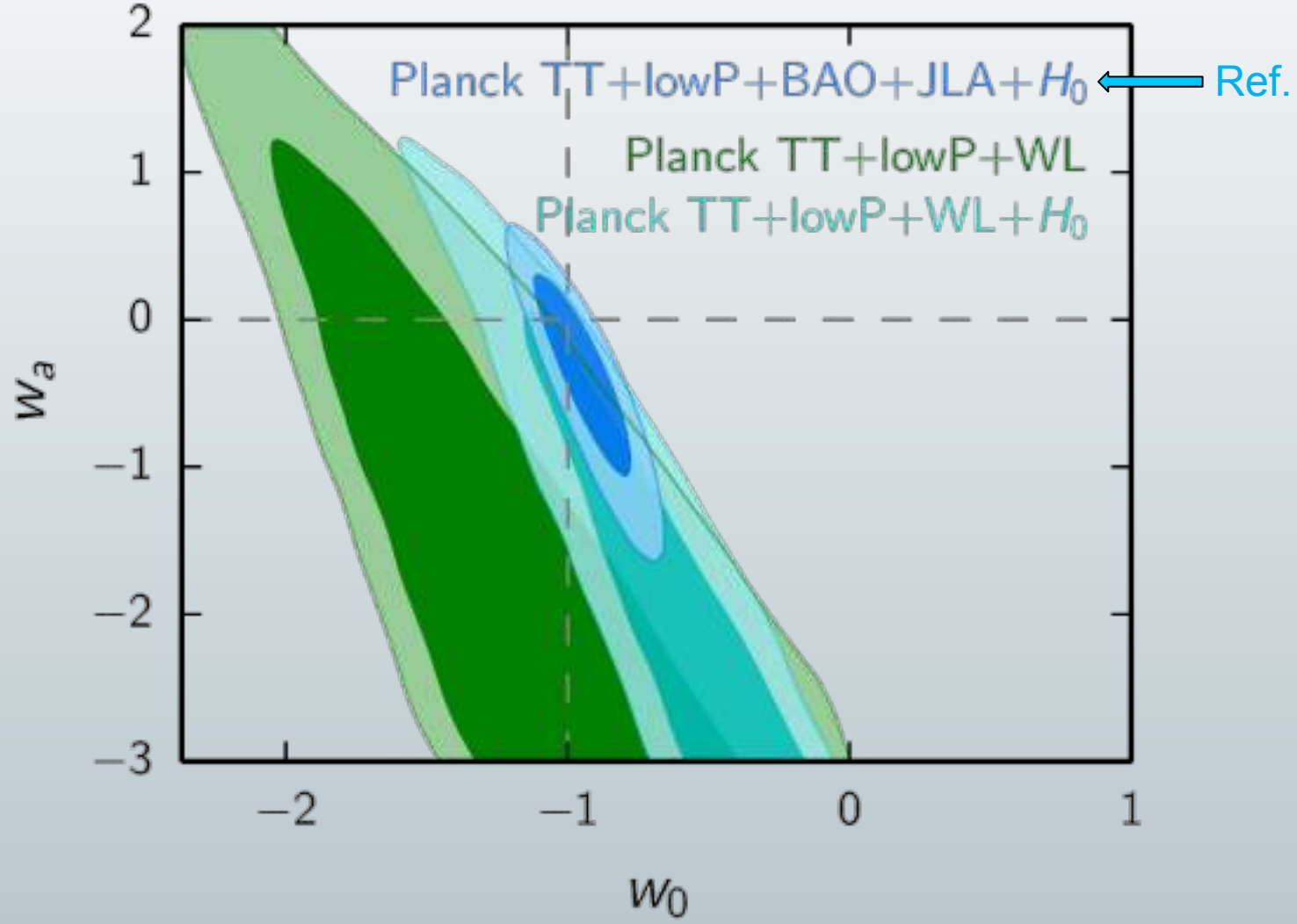


i.e. some tensions with astrophysical measurements of the amplitude of matter fluctuations at low z.

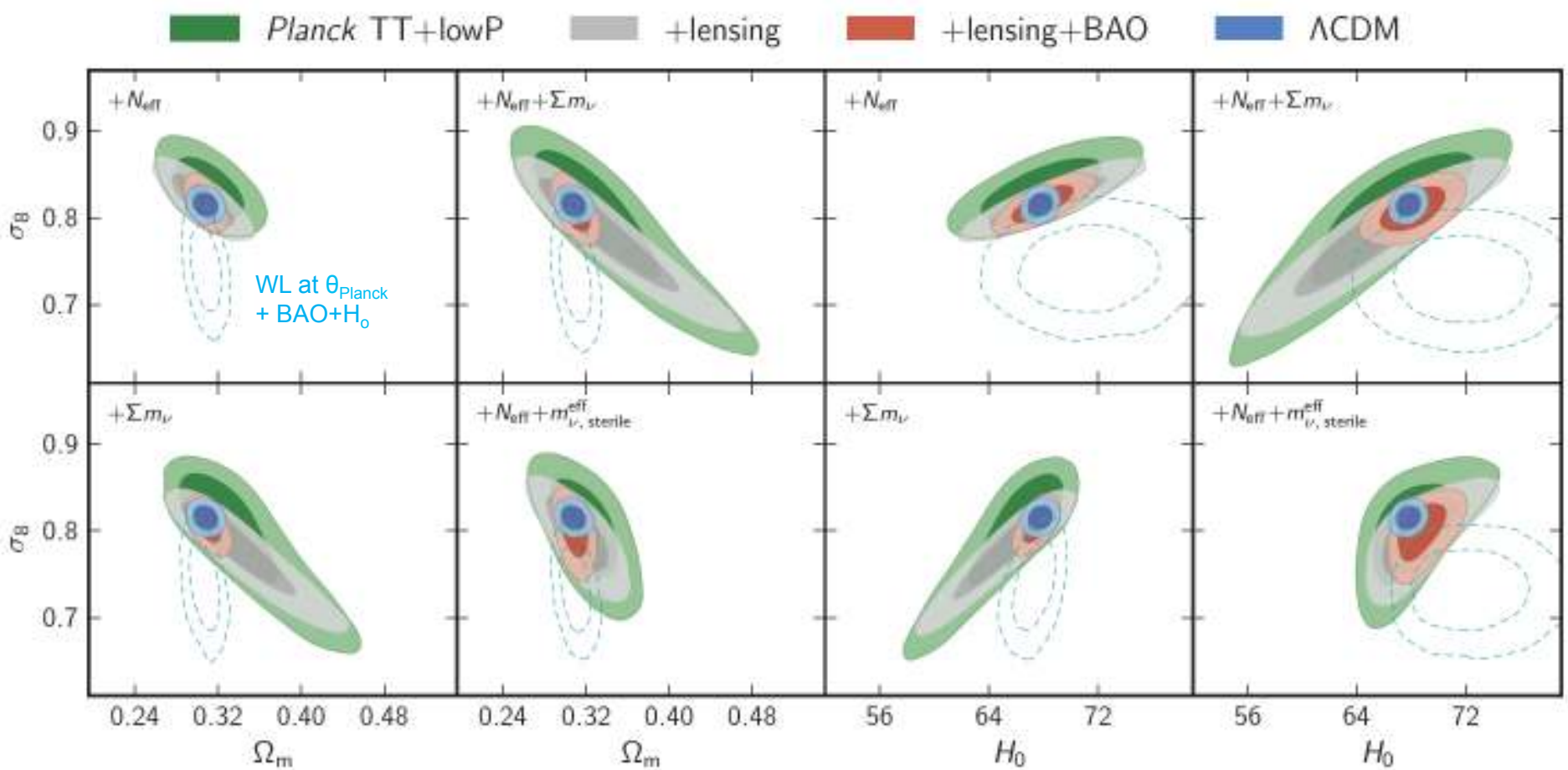
NB: Ly BAO measurements at high redshift are discrepant at 2.7sig, and it is quite difficult to find physical explanation not disrupting BAO consistency elsewhere, see eg Aubourg etal. 2015

What these tensions can do…

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

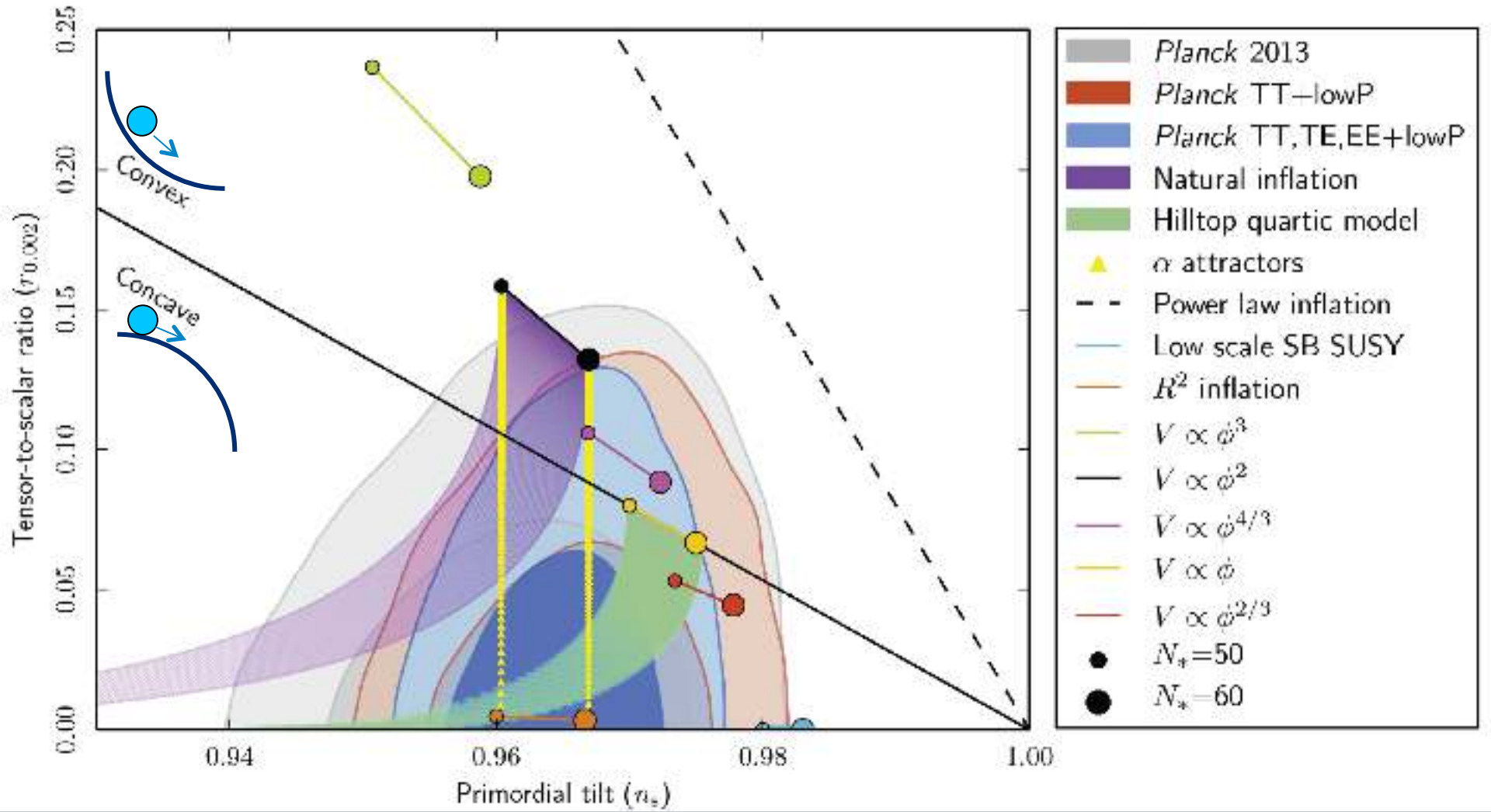


Allowing neutrinos extensions



($\Omega_m H^3$ is tightly constrained by ϑ_{MC})

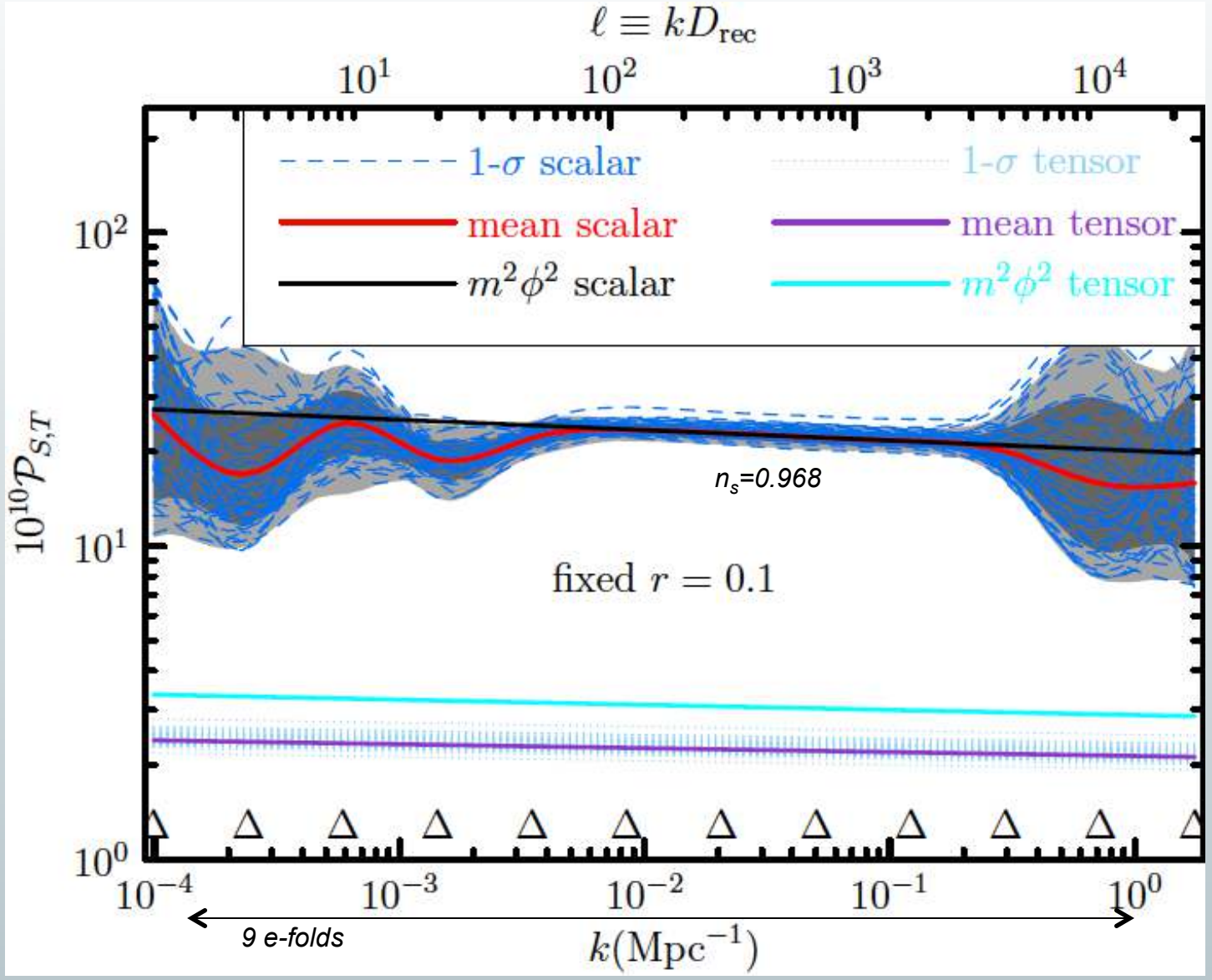
Planck 2015: n_s vs r



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

Power spectra reconstruction

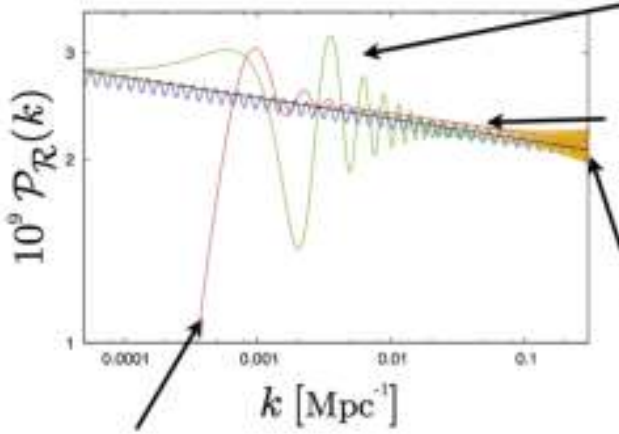
2015
TT+lowP
+BAO+JLA
+Hlow



12-knots power spectra

(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

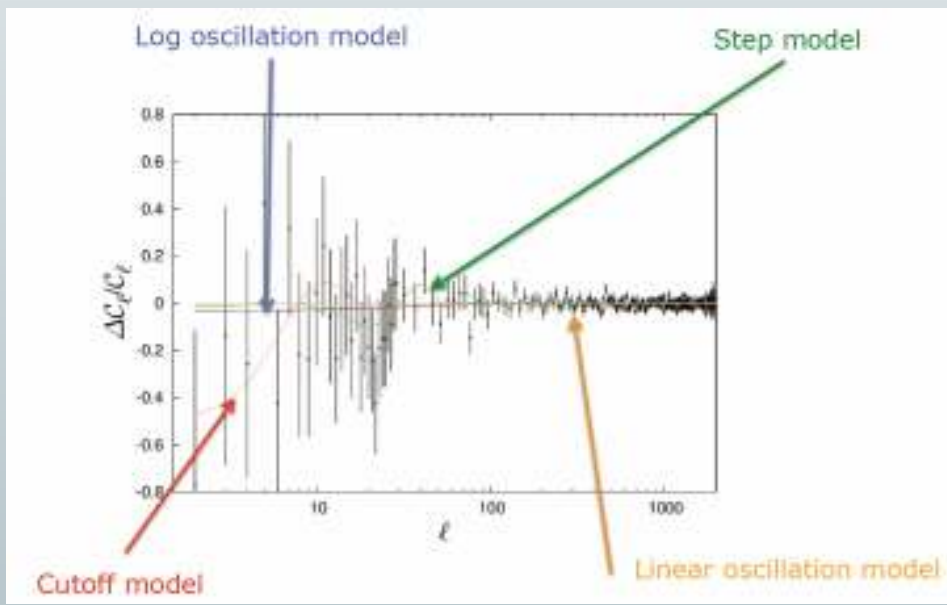
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

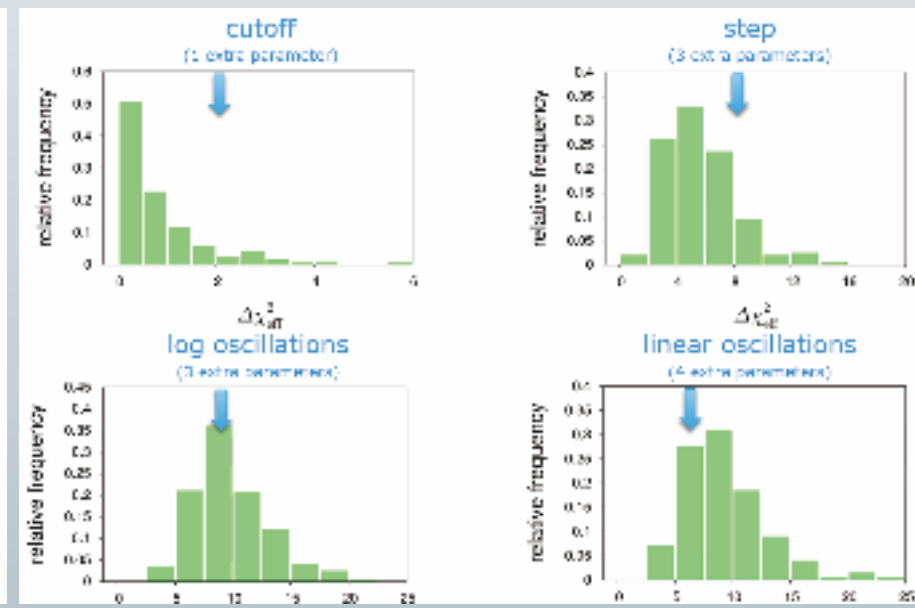
$$\mathcal{P}_{\mathcal{R}}^{\log}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

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

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



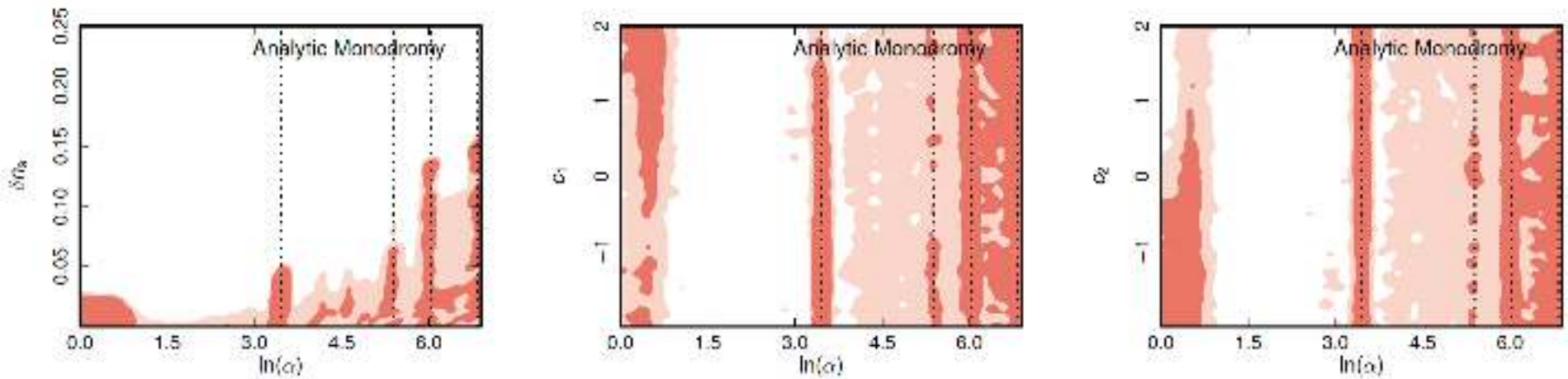


Axion monodromy inflation

Periodic potential, analytical template from Flauger et al.

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

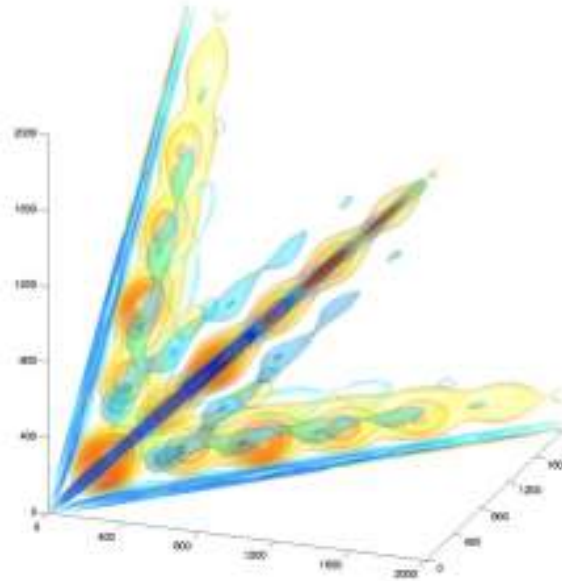
$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left\{1 + \delta n_s \cos\left[\frac{\phi_0}{f}\left(\frac{\phi_k}{\phi_0}\right)^{p_f+1} + \Delta\phi\right]\right\}$$

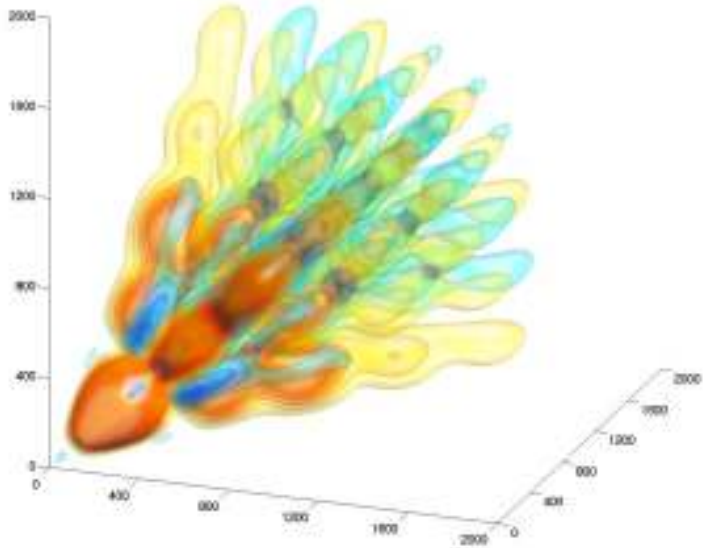


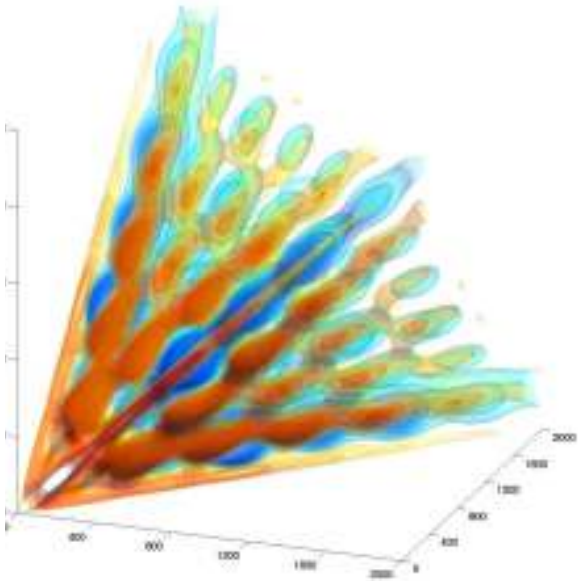
➔Chi^2 improvement insufficient. There are expected bispectrum oscillations $f_{\rm NL}^{\rm res} = \frac{\delta n_s}{8}\alpha^2$
Lowest frequency checked already (KO). Others imminent.

CMB bispectrum fingerprinting with Planck

LEO (Local, Equilateral, Orthogonal) are common outputs







NG of ***local*** type (k_1 k_2 ~ k_3):

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

(Also NG of **Folded** type

- Non Bunch-Davis
- Higher derivative)

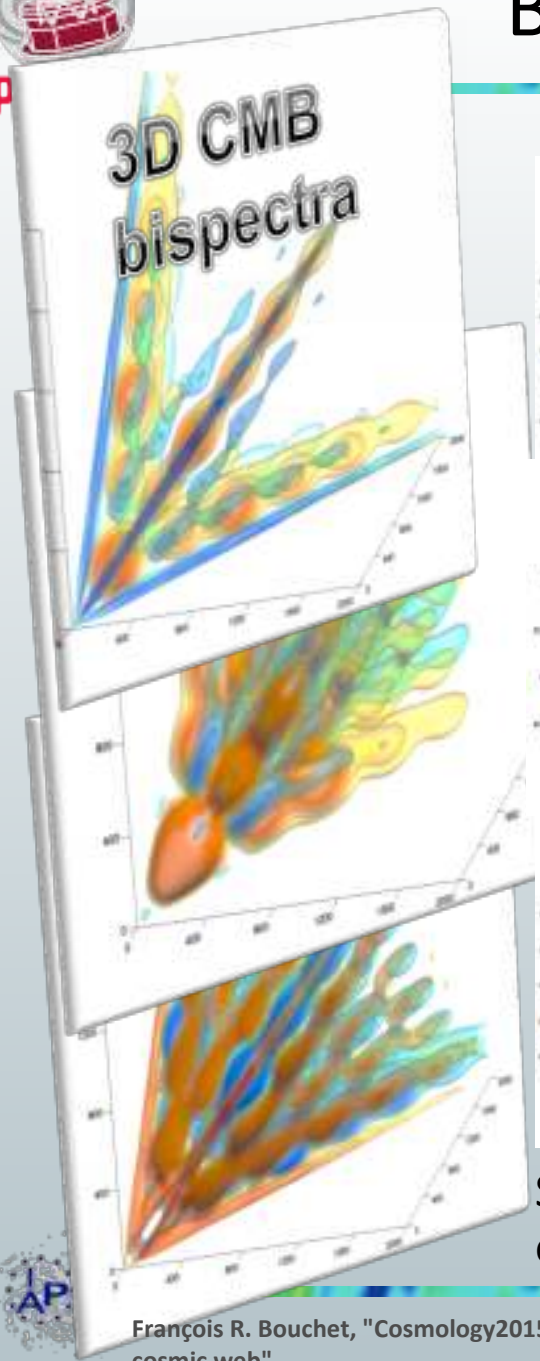
NG of ***equilateral*** type (k_1~k_2~ k_3):

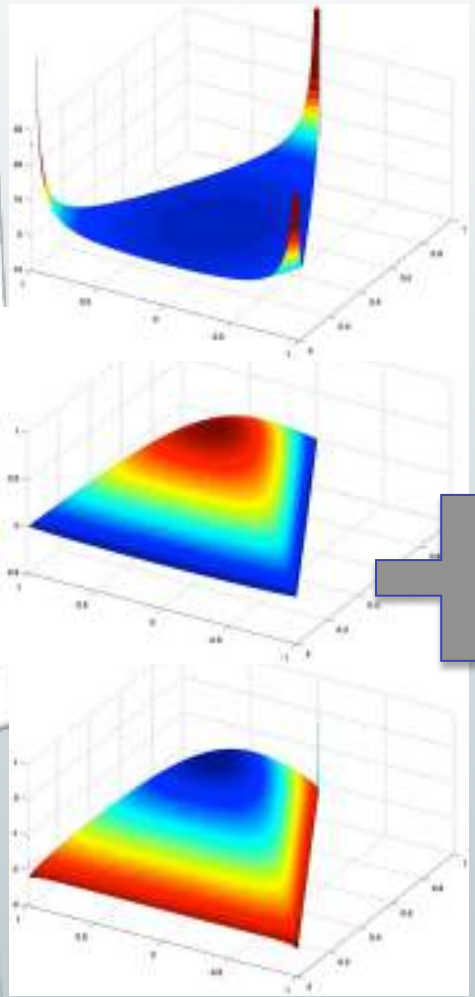
- Non-canonical kinetic term
  - K-inflation
  - DBI inflation
- Higher-derivate terms in Lagrangian
  - Ghost inflation
- Effective field theory

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

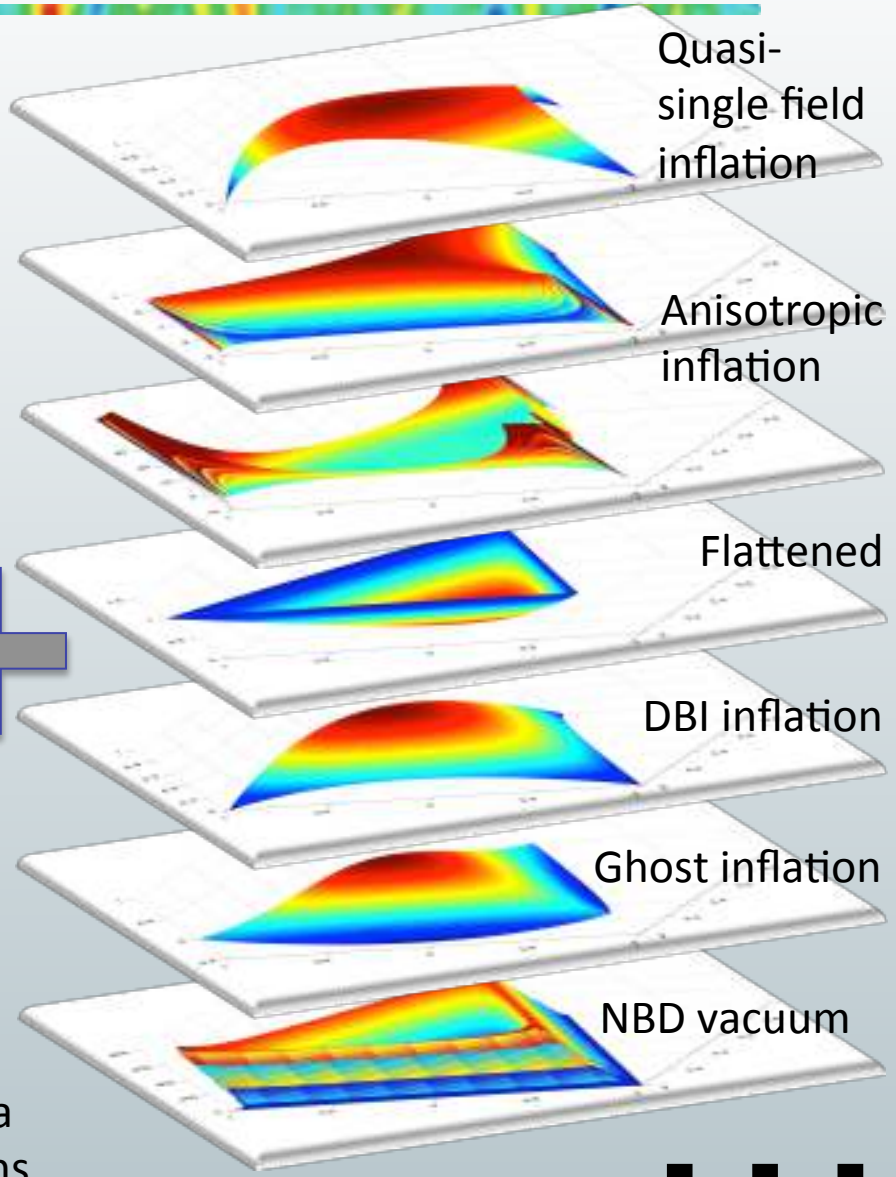
- Distinguishes between different variants of
  - Non-canonical kinetic term
  - Higher derivative interactions
- Galileon inflation

Bispectrum fingerprinting





Slices through bi-spectra of primordial fluctuations



The (local) f_{NL} hunt

TABLE II: Summary of constraints on local non-Gaussianity

Year	data	Method	$f_{\rm NL}^{local} \pm 2\sigma$ error	
2002	COBE	Bispectrum sub-optimal	$\lvert f_{\rm NL}\rvert < 1500$	Komatsu et al. [222]
2003	MAXIMA	Bispectrum sub-optimal	$\lvert f_{\rm NL}\rvert < 1900$	Santos et al. [223]
2003	WMAP 1-year	Bispectrum sub-optimal	39.5 ± 97.5	E. Komatsu et al. [23]
2004	VSA	Bispectrum sub-optimal	$f_{\rm NL} < 5400$	Smith et al. [224]
2005	WMAP 1-year	Bispectrum sub-optimal-v1	47 ± 74	Creminelli et al. [25]
2006	WMAP 3-year	Bispectrum sub-optimal	30 ± 84	Spergel et al. [24]
2006	WMAP 3-year	Bispectrum sub-optimal-v1	32 ± 68	Creminelli et al. [26]
2007	WMAP 3-year	Bispectrum near-optimal	87 ± 62	Yadav and Wandelt [28]
2007	Boomerang	Minkowski Functionals	110 ± 910	De Troia et al. [225]
2008	WMAP 3-year	Minkowski Functionals	10.5 ± 80.5	C. Hikage et al. [195]
2008	WMAP 5-year	Bispectrum near-optimal	51 ± 60	Komatsu et al. [51]
2008	ARCHEOPS	Minkowski Functionals	70^{1075}_{-950}	Curto et al. 2008 [226]
2009	WMAP 3-year	Bispectrum optimal	58 ± 46	Smith et al. [131]
2009	WMAP 5-year	Bispectrum optimal	38 ± 42	Smith et al. [131]
2009	WMAP 5-year	Spherical Mexican hat wavelet	31 ± 49	Curto, A et. al. [206]
2009	BOOMERanG	Minkowski Functionals	-315 ± 705	P. Natoli et al. [227]
2009	WMAP 5-year	Skewness power spectrum	11 ± 47.4	Smidt, Joseph et al. [228]
2010	WMAP 7-year	Bispectrum optimal	32 ± 42	Komatsu et al. [132]

Bispectrum constraints with full mission data

Planck 2015

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

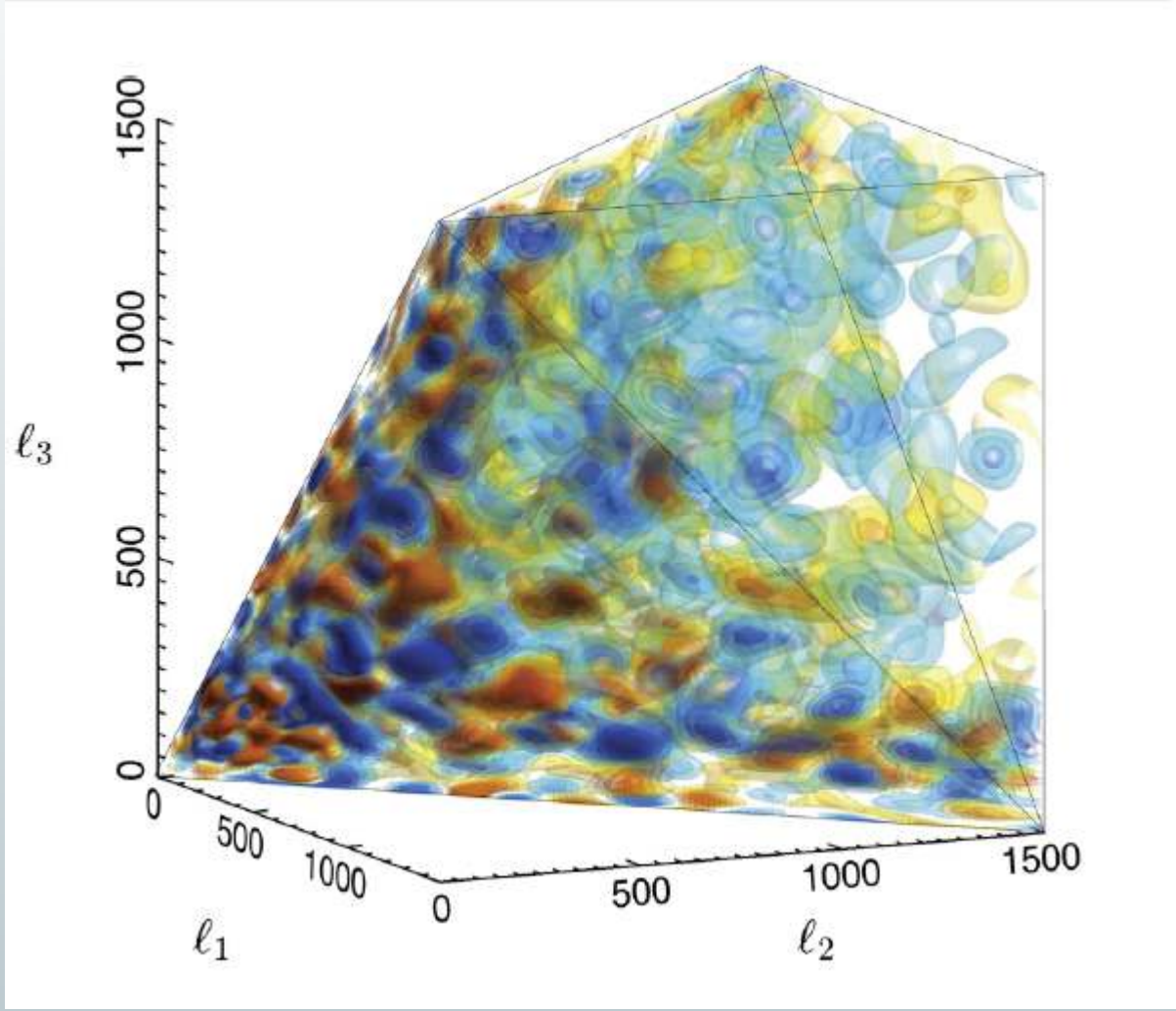
Planck 2013

ISW-lensing subtracted	KSW	Binned	Modal
Local	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	**−25 ± 39**	−17 ± 41	−14 ± 42

Constraint volume in LEO space shrunk by factor of 3.

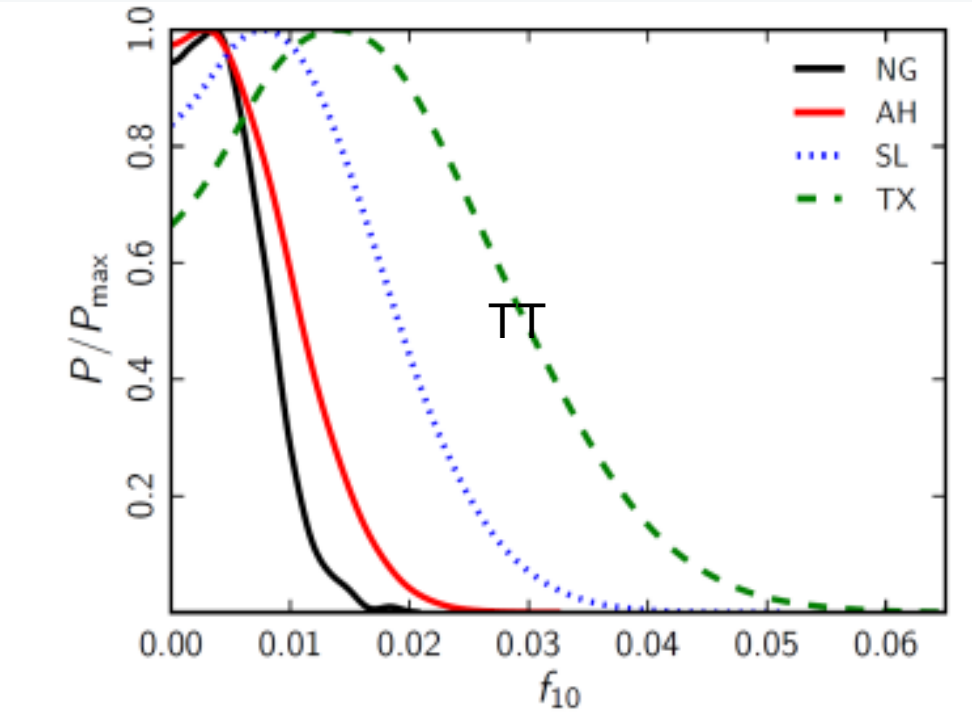
Tightest constraints on primordial non-Gaussianities so far: the highest precision test on the origin of structures

Planck 2015 TTT – 2001 modes

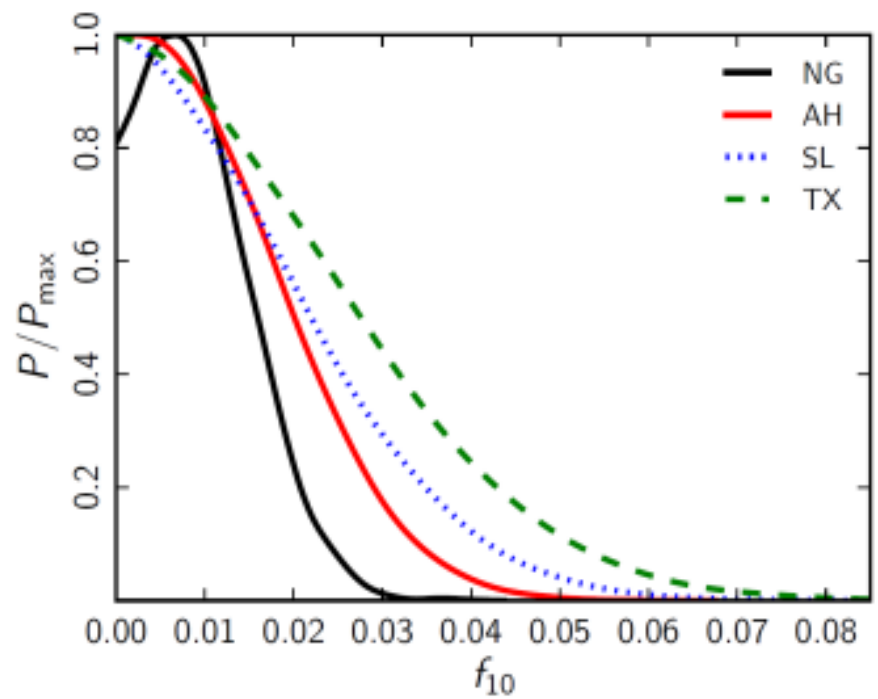


The 2015 analysis contains greatly extended analysis of template families + new techniques

Constraints on Defects



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



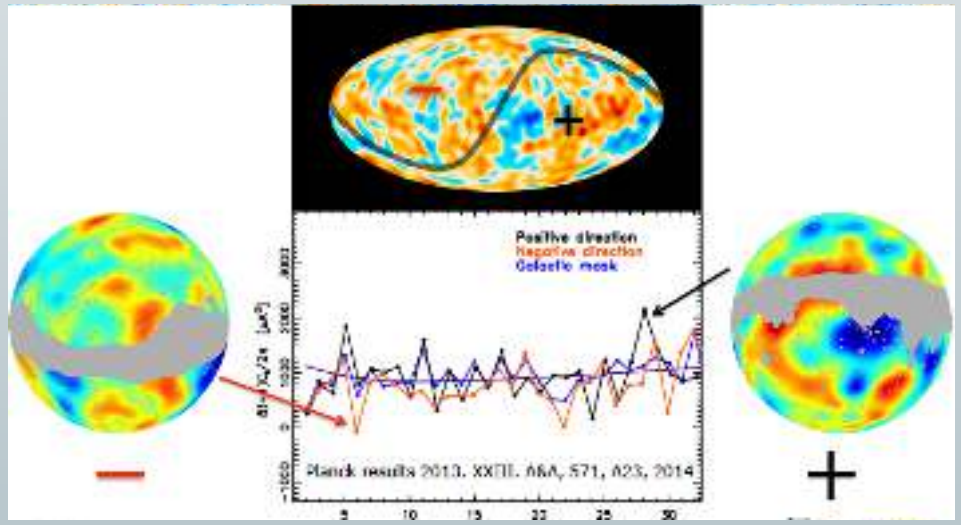
95%CL

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

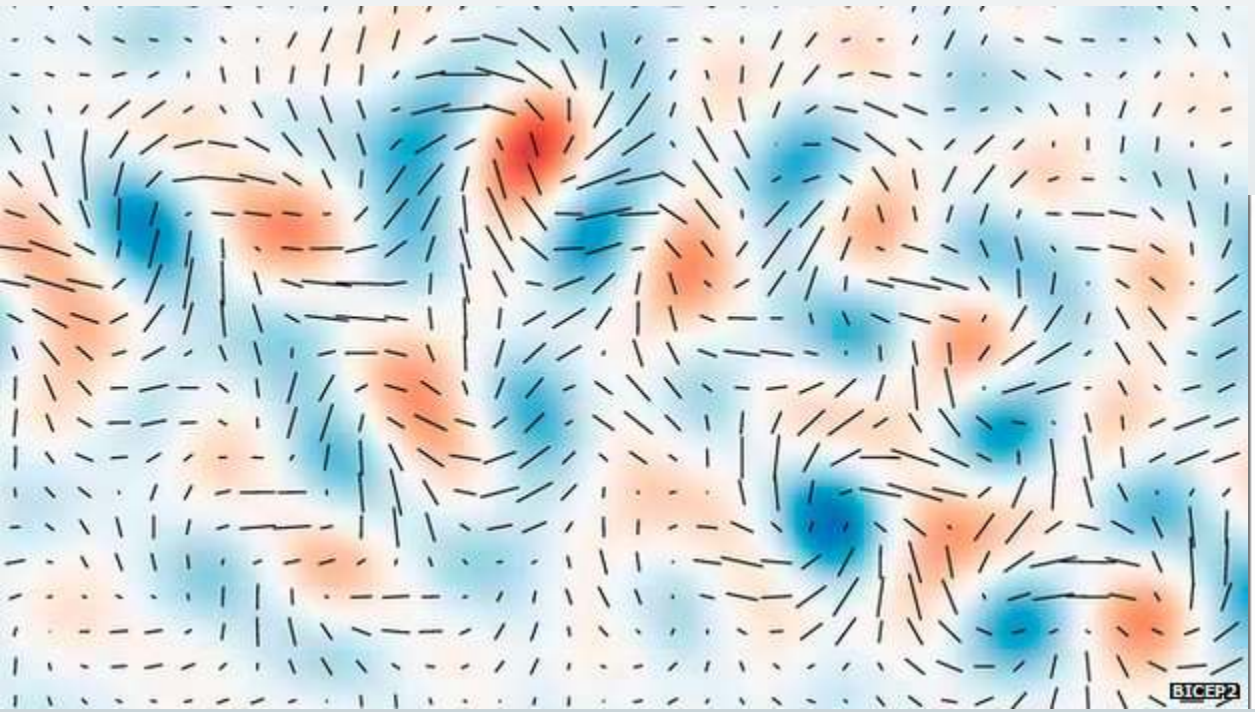
Large scale anomalies

All COBE or WMAP anomalies confirmed, albeit with updated level of significance. Specifically:

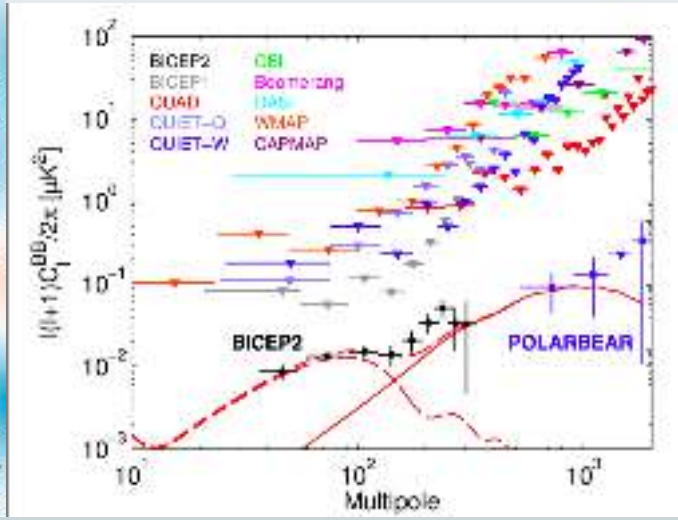
- Low quadrupole, C(Θ) ~ 0 at Θ>60deg
- Quadrupole / octupole alignment
- A rare cold spot
- CMB TT l=20-30 dip (about 2 sigma after marginalising over LCDM parameters)
- Hemispheric difference in TT power ~ 7% at low ell



BICEP2



March 17th 2014



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

The search for primordial gravitationnal waves is over.

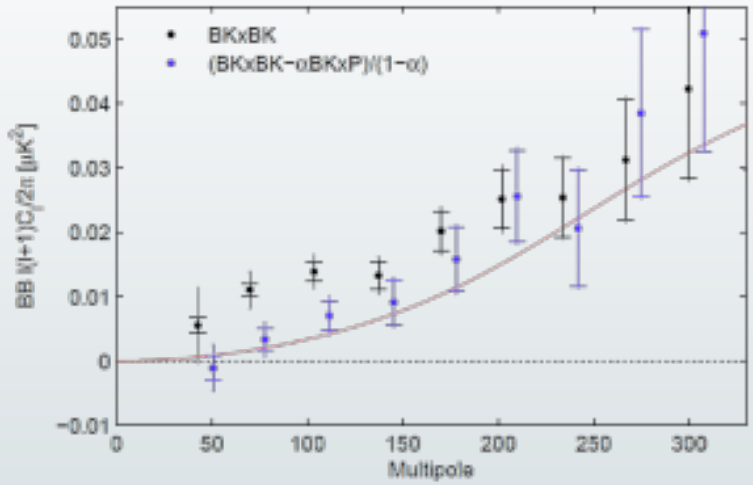
It is r=0.2 and it is 5 sigma!

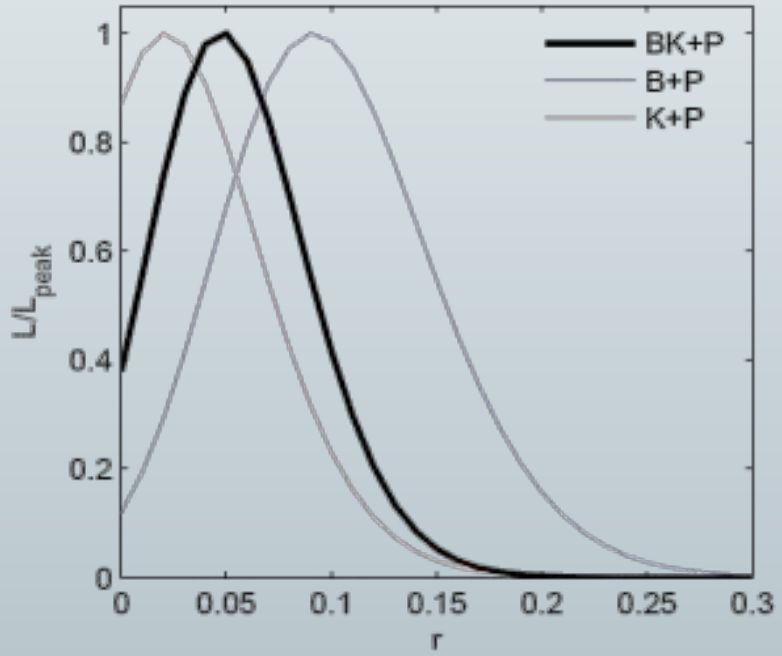
Planck X (Bicep2 & Keck)

- Since January 30th 2015, the **direct** constraints on r (Planck X Bicep2 & Keck) have reached the level of the previous best **indirect constraints** (from Planck alone T), i.e.

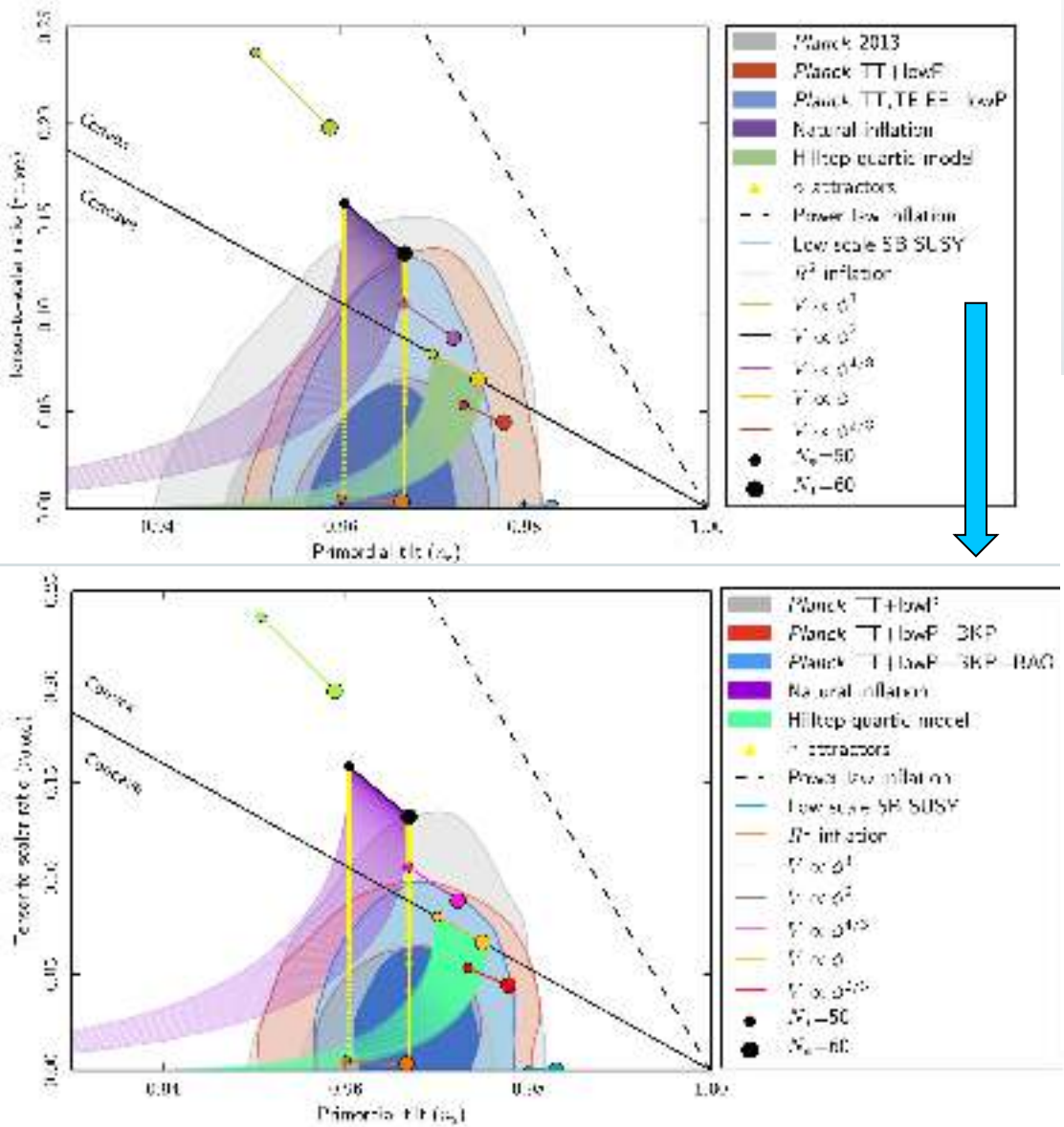
- $r < 0.11$ @ 95%CL
  ($r = A_s/A_T$ à, e.g., $k=0.05 Mpc^{-1}$)

- A new era began…



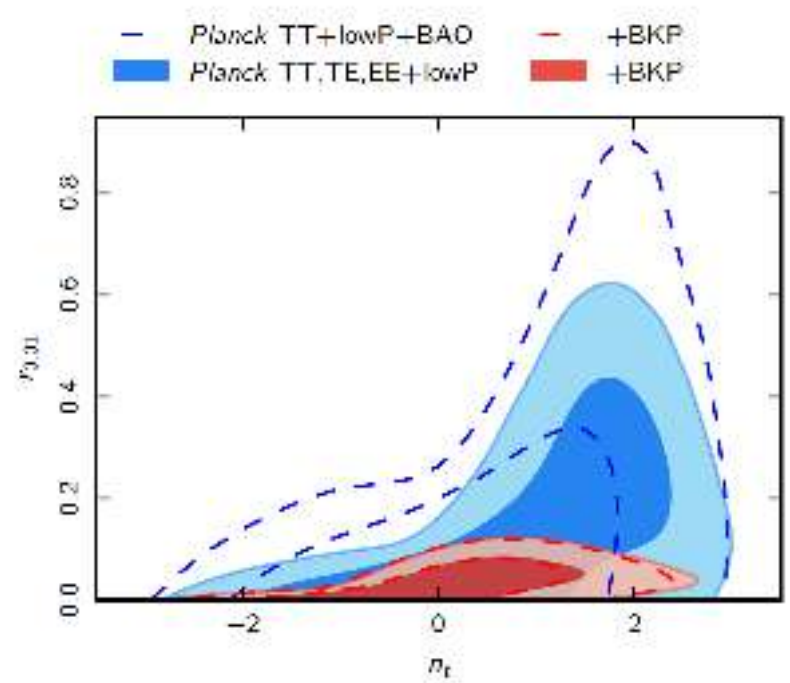


Planck + BK X Planck



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

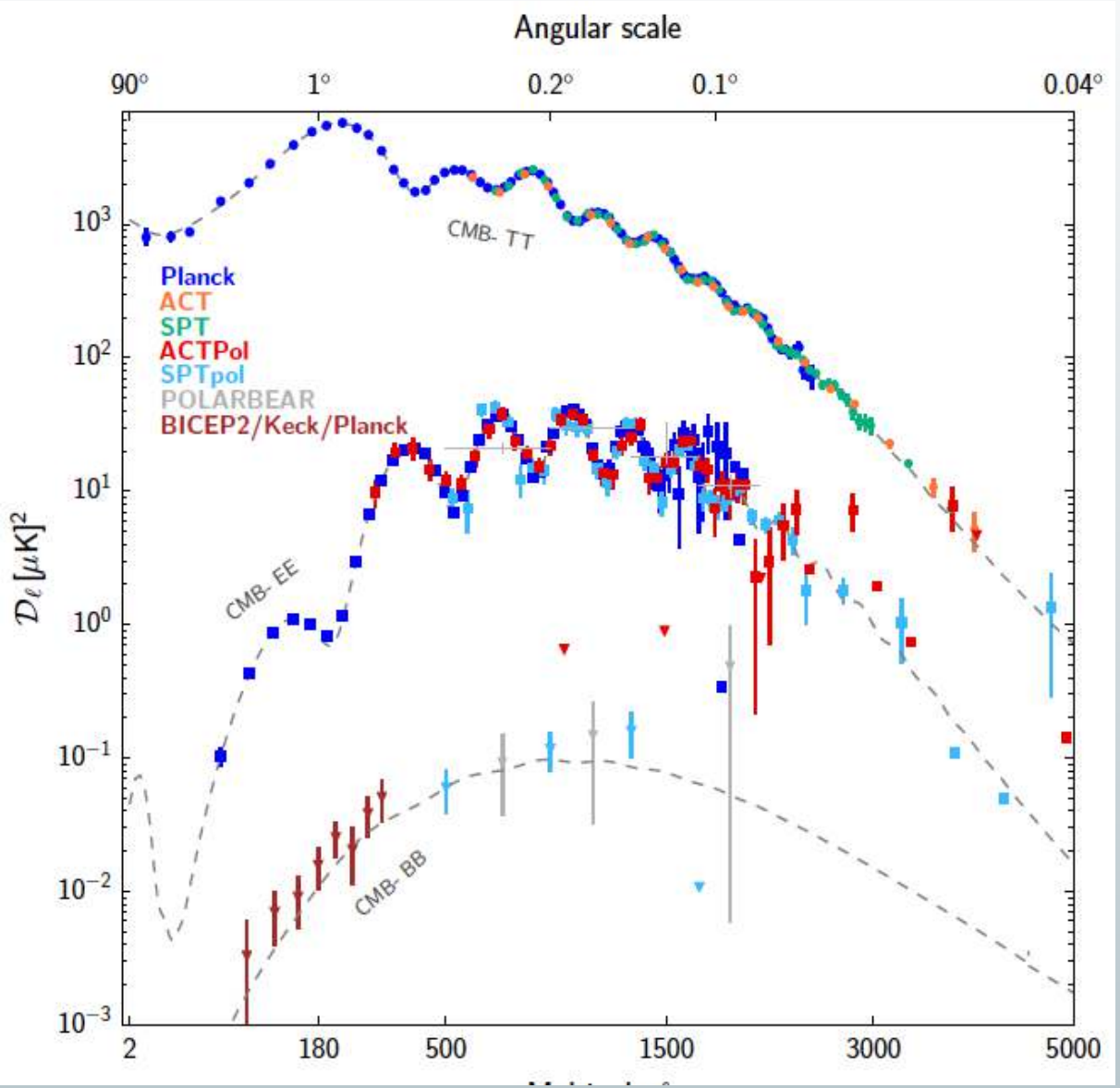
Planck+BKP: $r_{0.002} < 0.08$ @95%cl



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

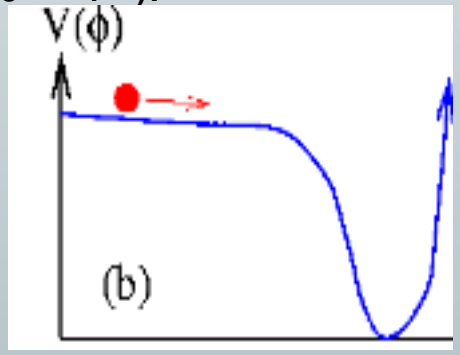
Plus the futures: S4, more ballooning, and back into space

TT, EE, BB – mid 2015



Summary: Basic ΛCDM fits

- 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 ($5^o > \vartheta > 1^o$):
  - *This Signature of « super-horizon » fluctuations at decoupling and adiabaticity of primordial fluctuations (phases TT/TE) provides an indication of apparently a-causal physics, calling for a period of accelerated expansion (Spergel & Zaldariaga 97)*



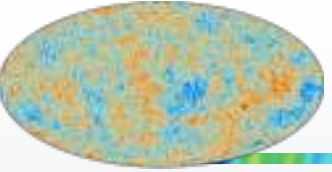
➔ I.e. all consistent with generic inflationary framework

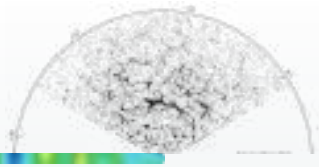
NB

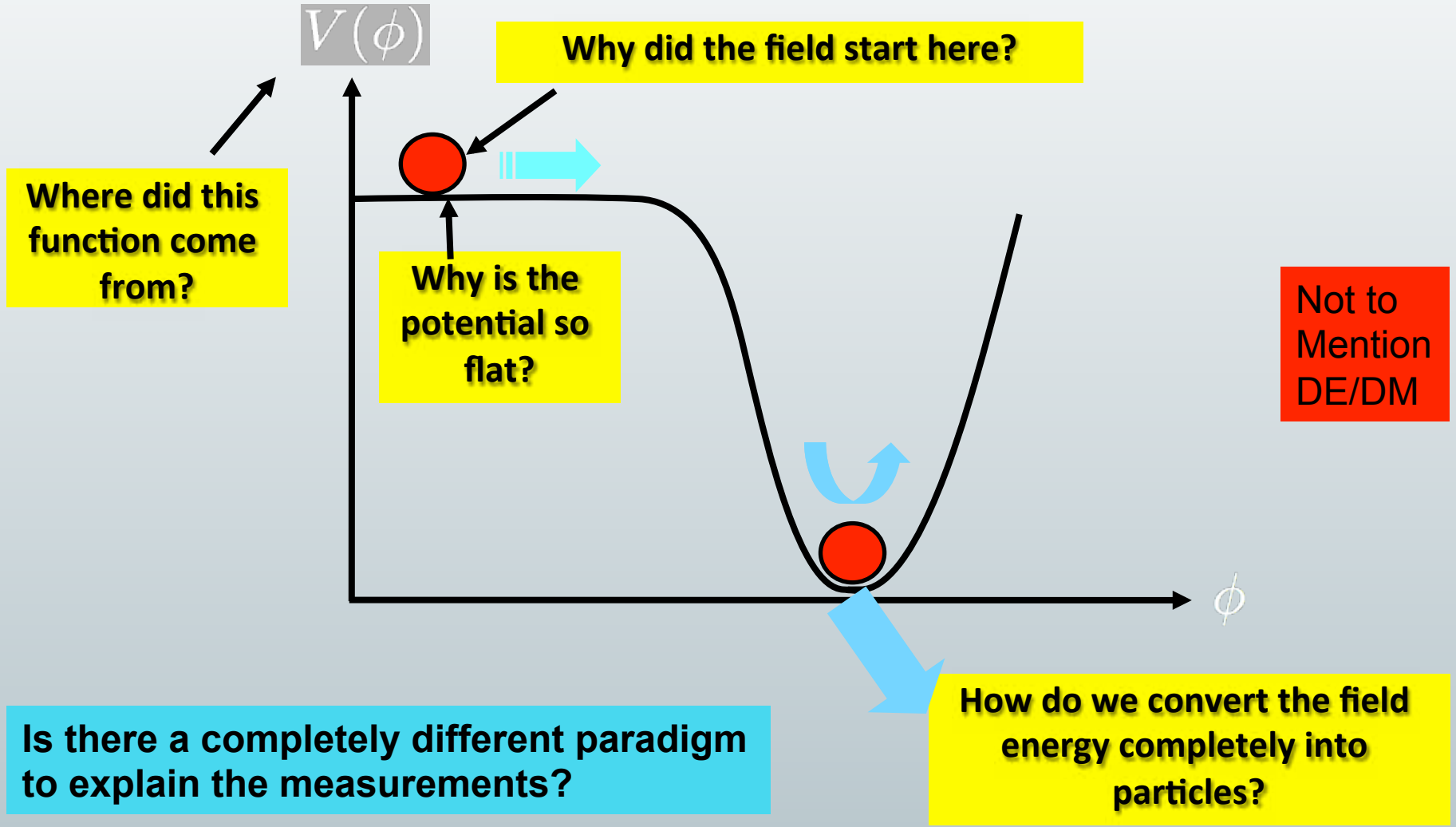
This tight agreement between theory and a large body of empirical facts is based on predictions of the evolution of vacuum quantum fluctuations amplified by gravity in an expanding background on scales which cross the Hubble scale, i.e. using GR successfully in a regime never probed before.

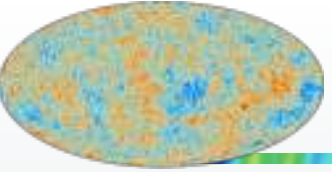
And we are hopeful that nature will allow us to detect primordial gravitational wave, i.e. direct signature of quantum fluctuations of the metric, a direct manifestation of quantum gravity, which should be doable for all large field models.

But what is the physics of inflation?

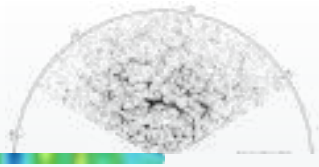








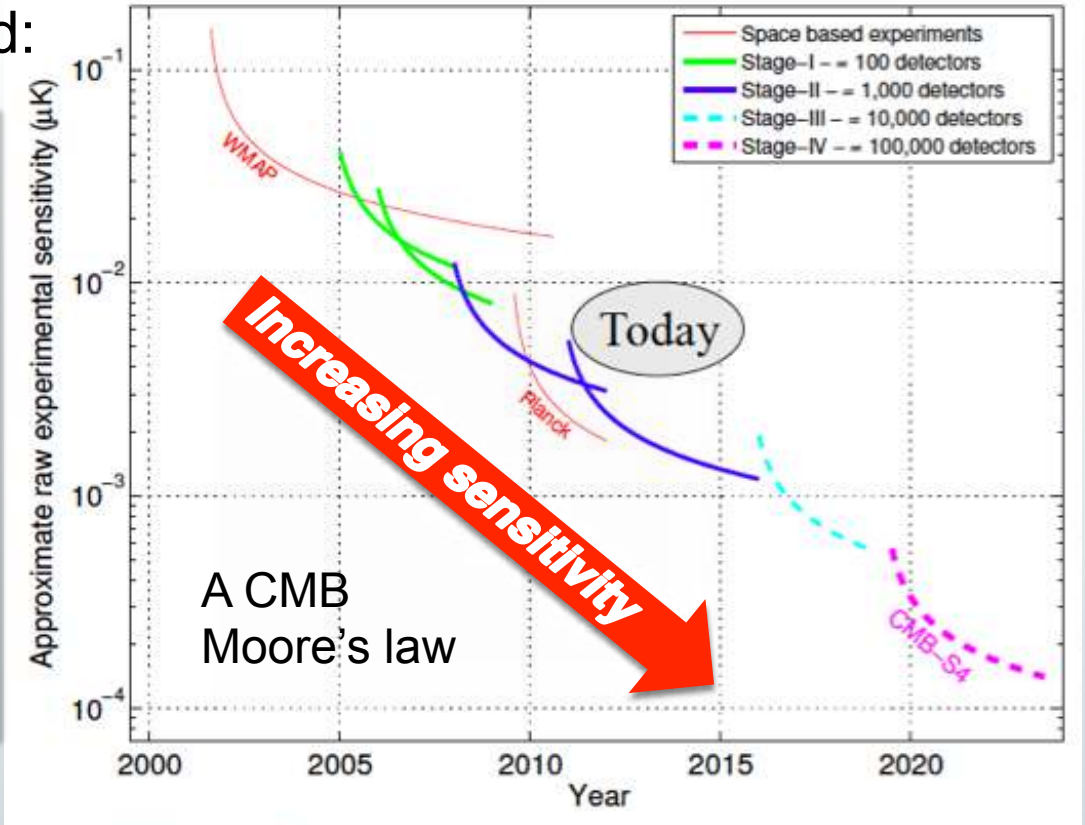
How to progress?



- No single "obvious" beyond Single-Field-Slow-Roll model.
  - *Must therefore leave no stone unturned.*
- There are established anomalies in the CMB, as well as tensions with the CMB to explore (in addition to r)
  - *Helas, nearly all anomalies so far are at large scale where we are limited by cosmic variance; can only progress with physical models to test them elsewhere.*
- Many constraints are statistical, scaling $\propto N_{\rm modes}^{-1/2}$.
- Happily, there are still very <u>many</u> modes awaiting to be measured, in E & B (r) & spectral distortions with CMB & in 3D (f_{nl}) from LSS (e.g., 21cm), providing many lottery tickets…
  - *Cosmology has not been sparing of (big) surprises till now.*

Suborbital, proposed or planned:

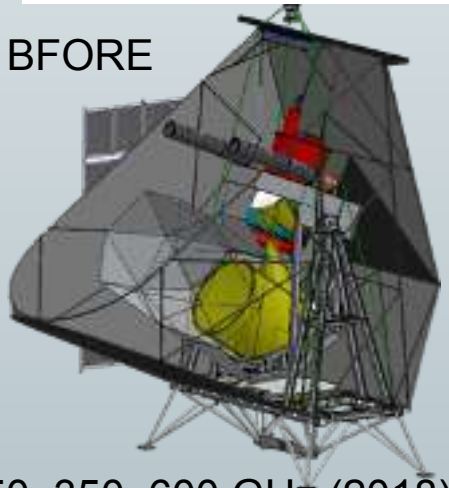
CMB-S4 with telescope multiplexing



Greenland: GLP

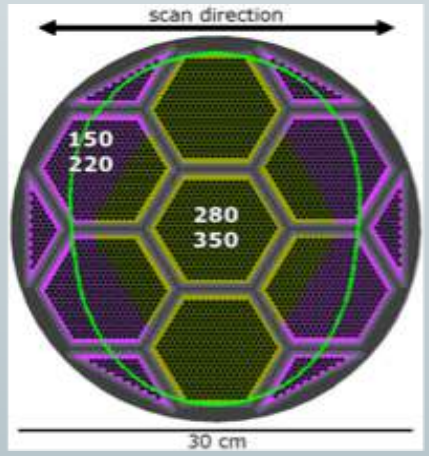
+Atacama: GroundBIRD, MuSE

Antarctic: BFORE



250, 350, 600 GHz (2018)

Antarctic: EBEX10K



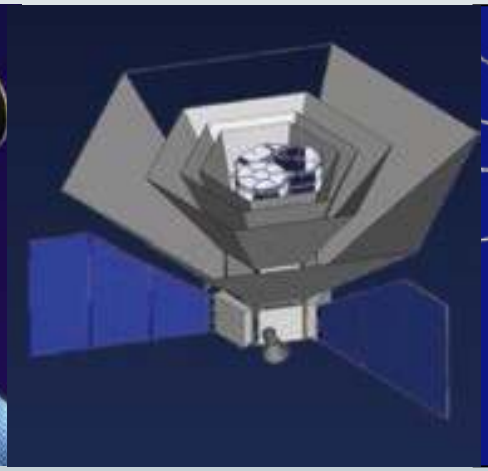
Proposed/planned CMB space missions

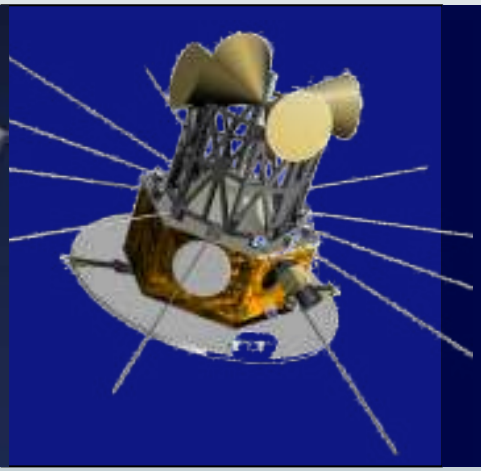
Each with rather different trade-offs/objectives… for now (targeted/fast/”cheap” versus definitive)

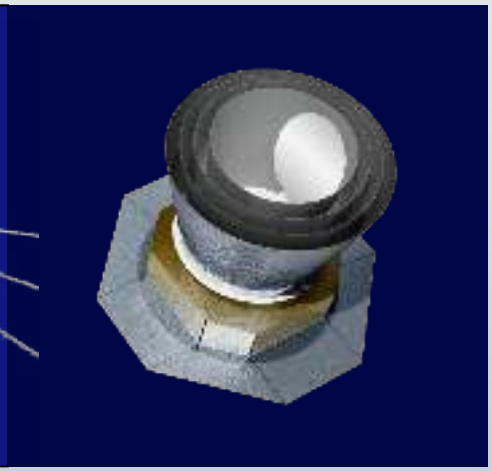
PIXIE, DARE, EPIC+? (NASA)

(PRISM, CORE+) CORE++? (ESA)

LiteBird (JAXA) down selected to a list of 3, early June 2015







….

LiteBIRD (JAXA)
30-60’ 2 uK/arcmin
6 bands, 15 xtendable?

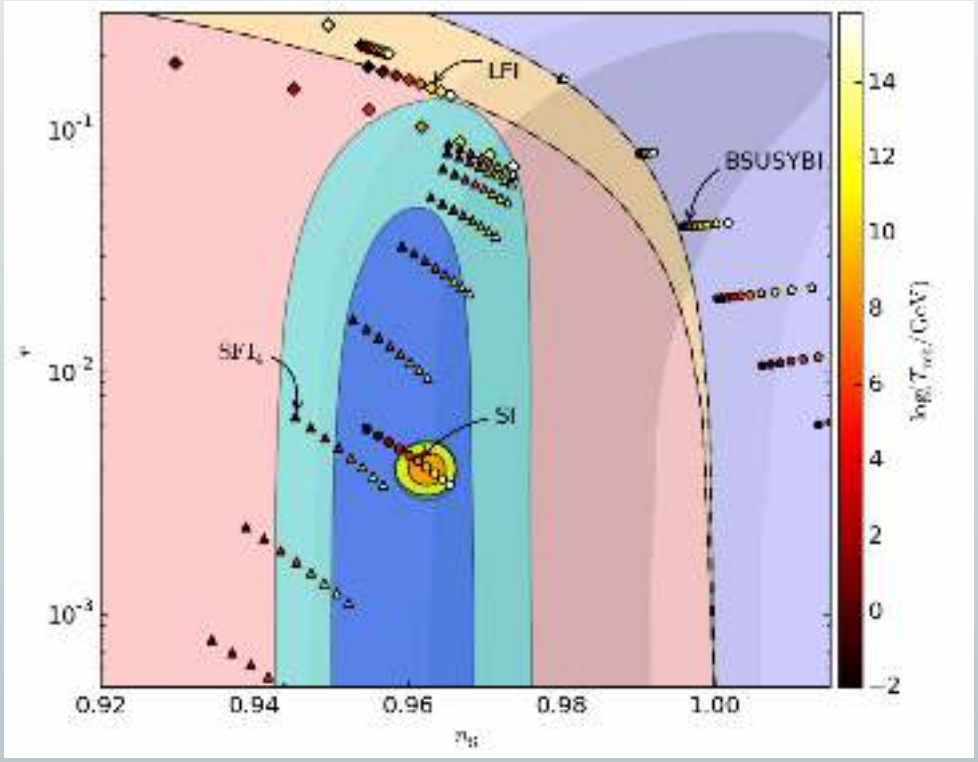
PIXIE (NASA)

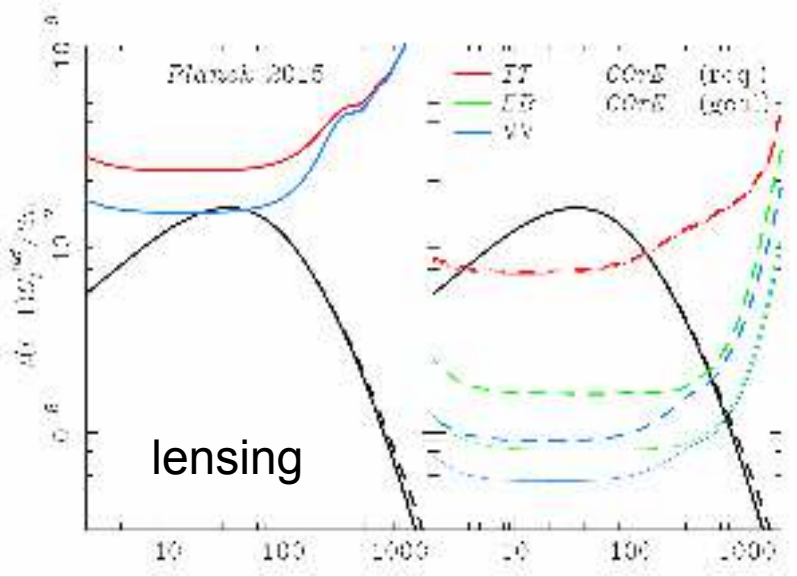
DARE (NASA)

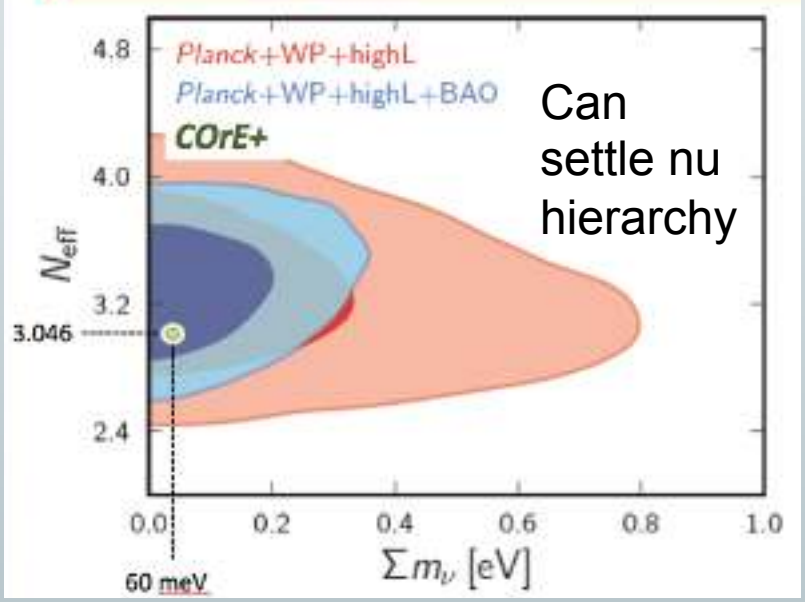
Core+ (ESA)

Example from the Core+ science case

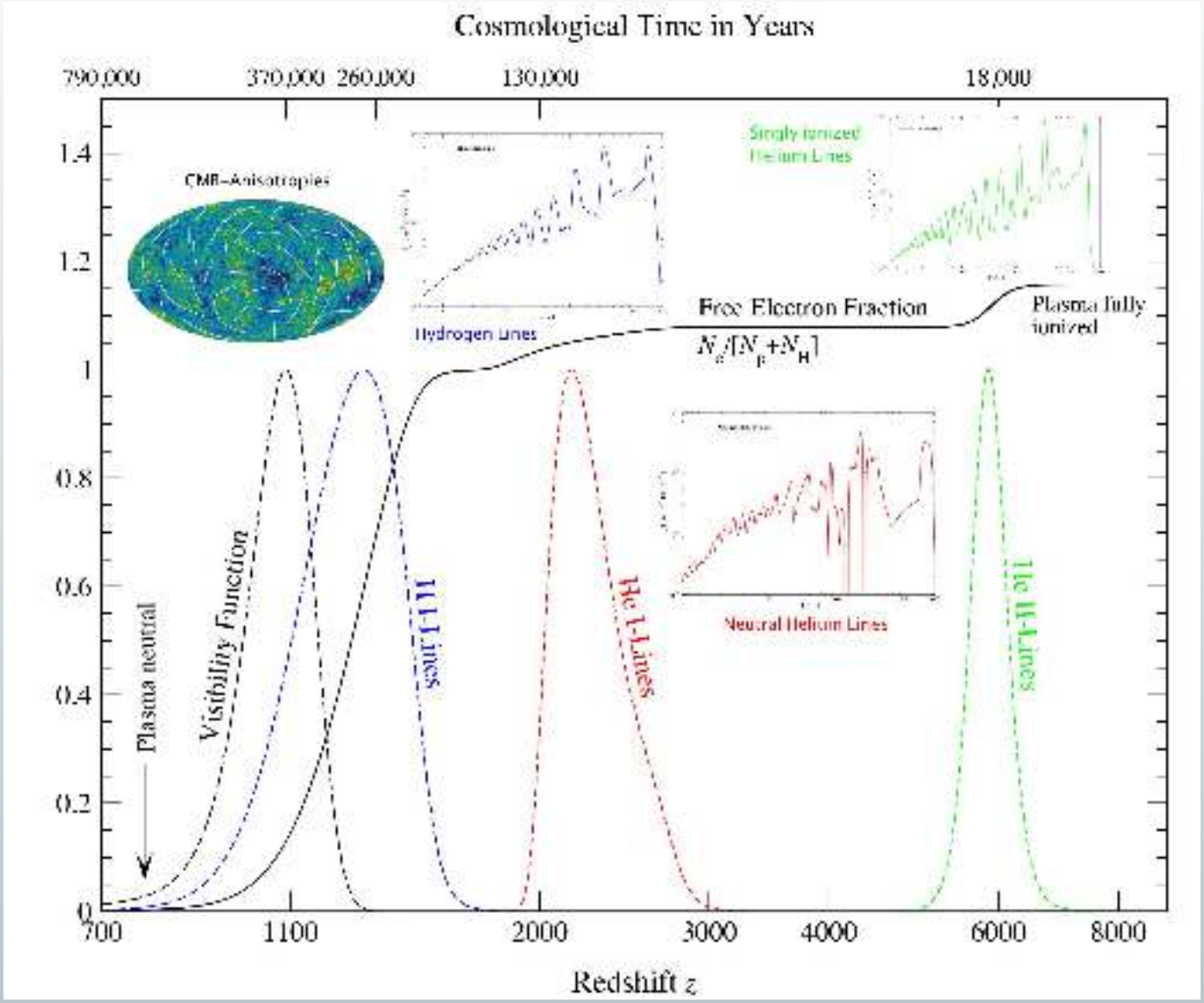
full sky CMB polarisation and lensing mapping, with enough sensitivity to detect unambiguously $r=10^{-3}$, and lots of frequency channels (FG + SZ, star formation science)







Spectral measurements (date back to FIRAS)

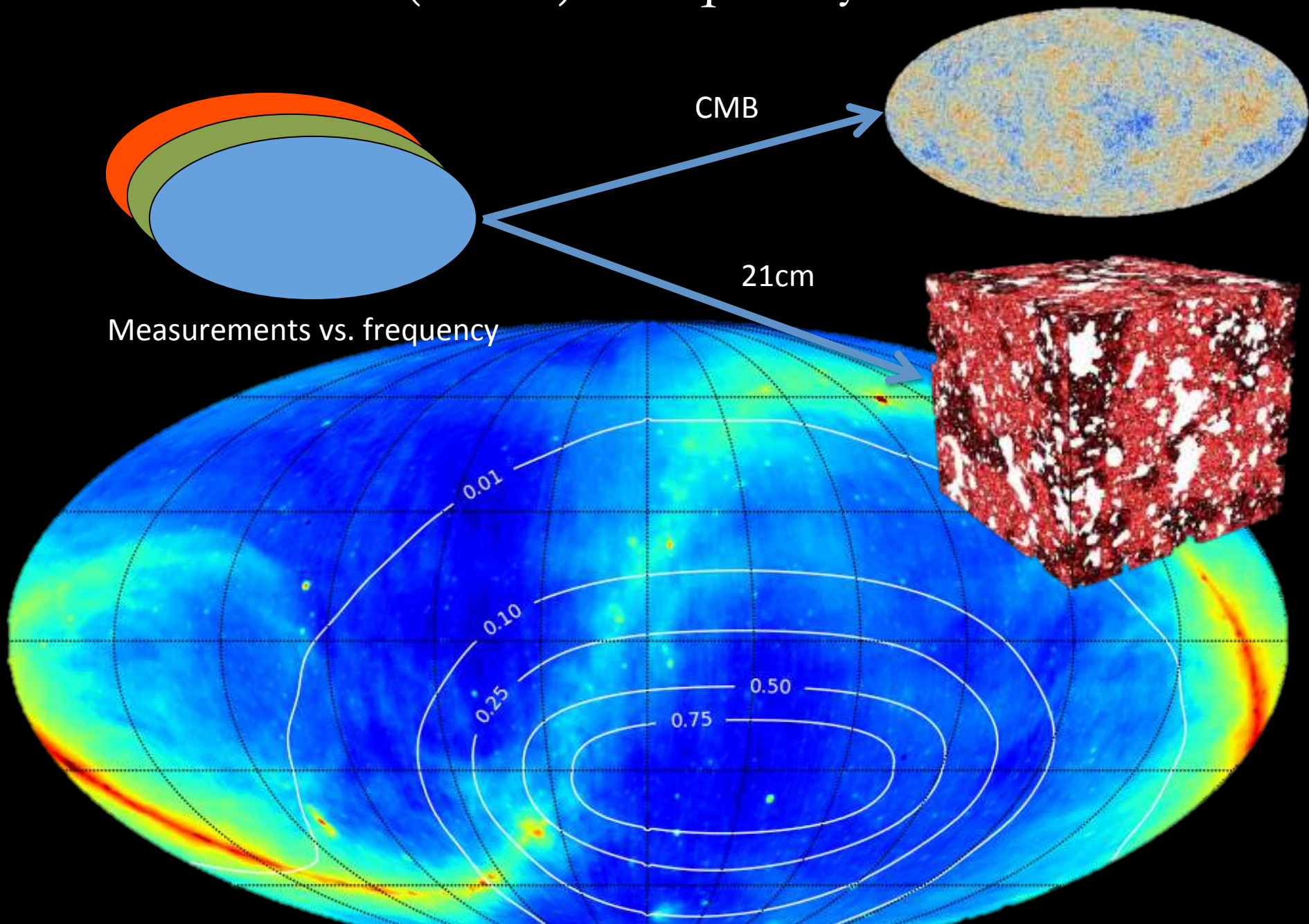


y and mu distortions reveal any energy release at any time after thermalisation (z ~ 10^8).

Notably the release from silk damping of small scale fluctuations. This will constrain (blue) values of ns at damped scales

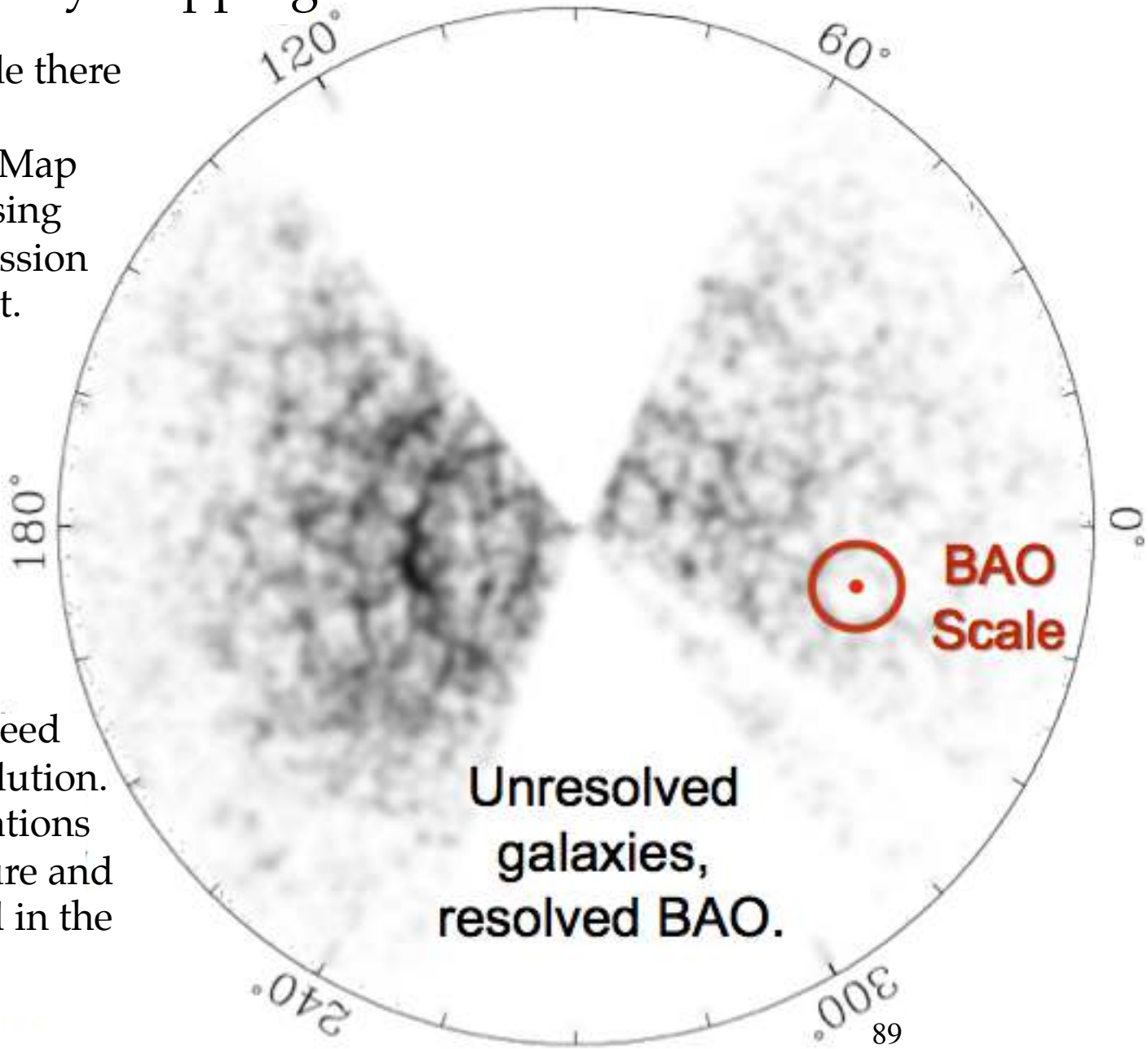
arXiv:0908.0435v1

The (21cm) Frequency Axis



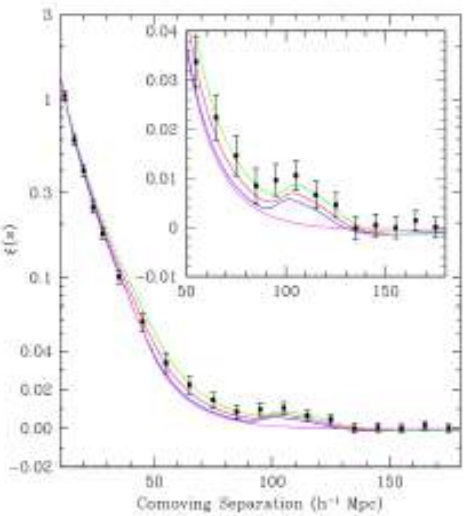
Hydrogen Intensity Mapping

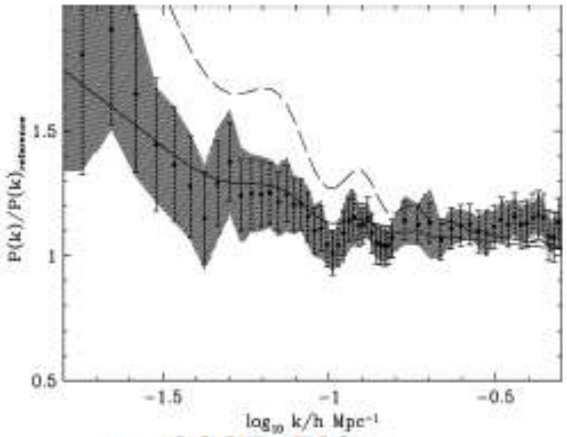
To measure BAO scale there is no need to resolve individual galaxies. Map intensity of HI gas using redshifted 21 cm emission along the line of sight.



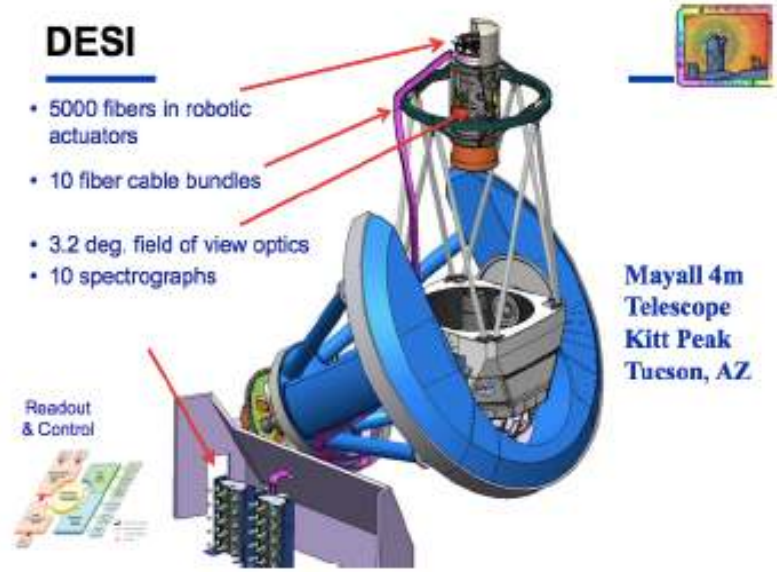
For 15 Mpc spatial resolution at z~1-2, need ~15-25' angular resolution. This requires observations with a ~100 m aperture and a fast mapping speed in the 400-800 MHz band.

CMB@50 ~ BAO@10





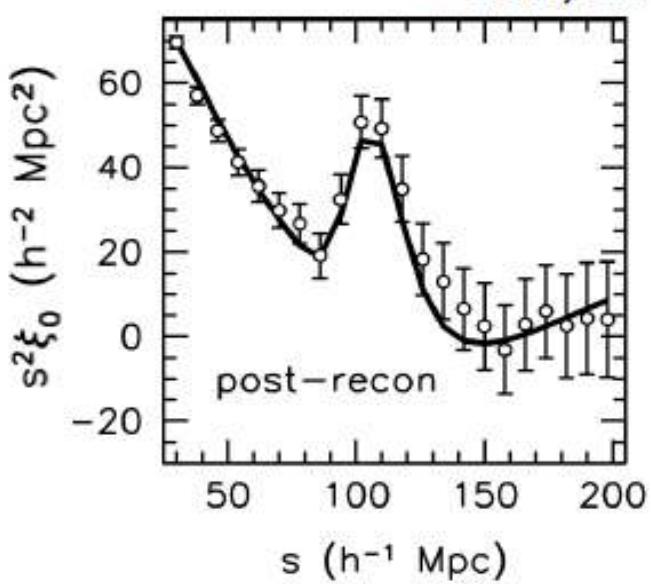
2005, 5%

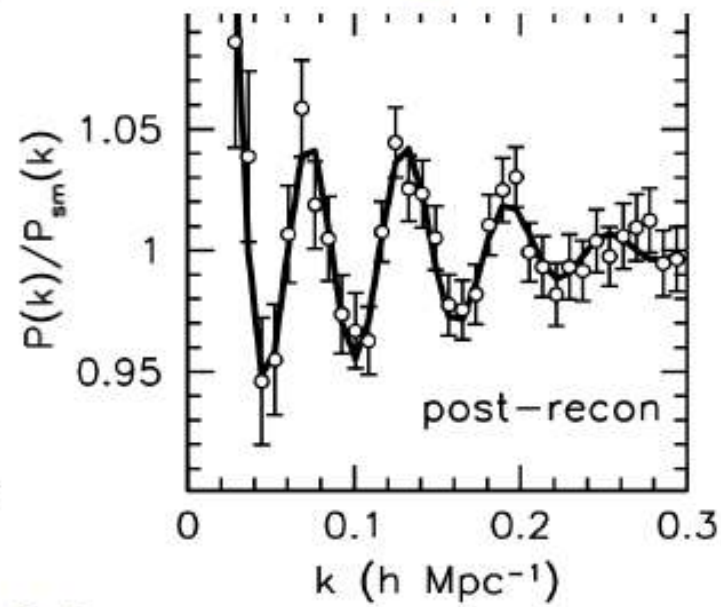


2014, 1%

2025, 0.2%

- SDSS, 2dF
- **WiggleZ, BOSS**
- *HETDEX, eBOSS, PFS*
- *DESI, Euclid, WFIRST*



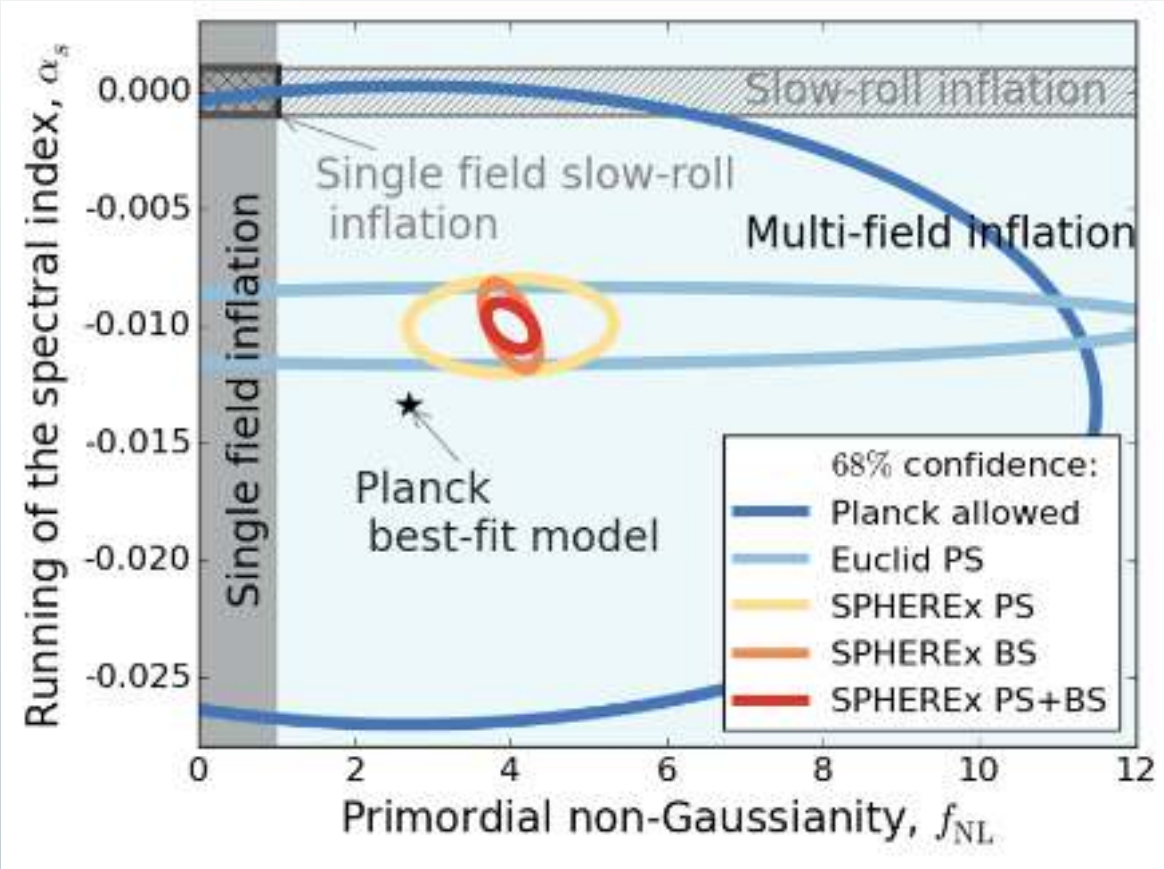


8 sigma

Some predictions for future data sets

Planck+DESI+LSST+S4+…

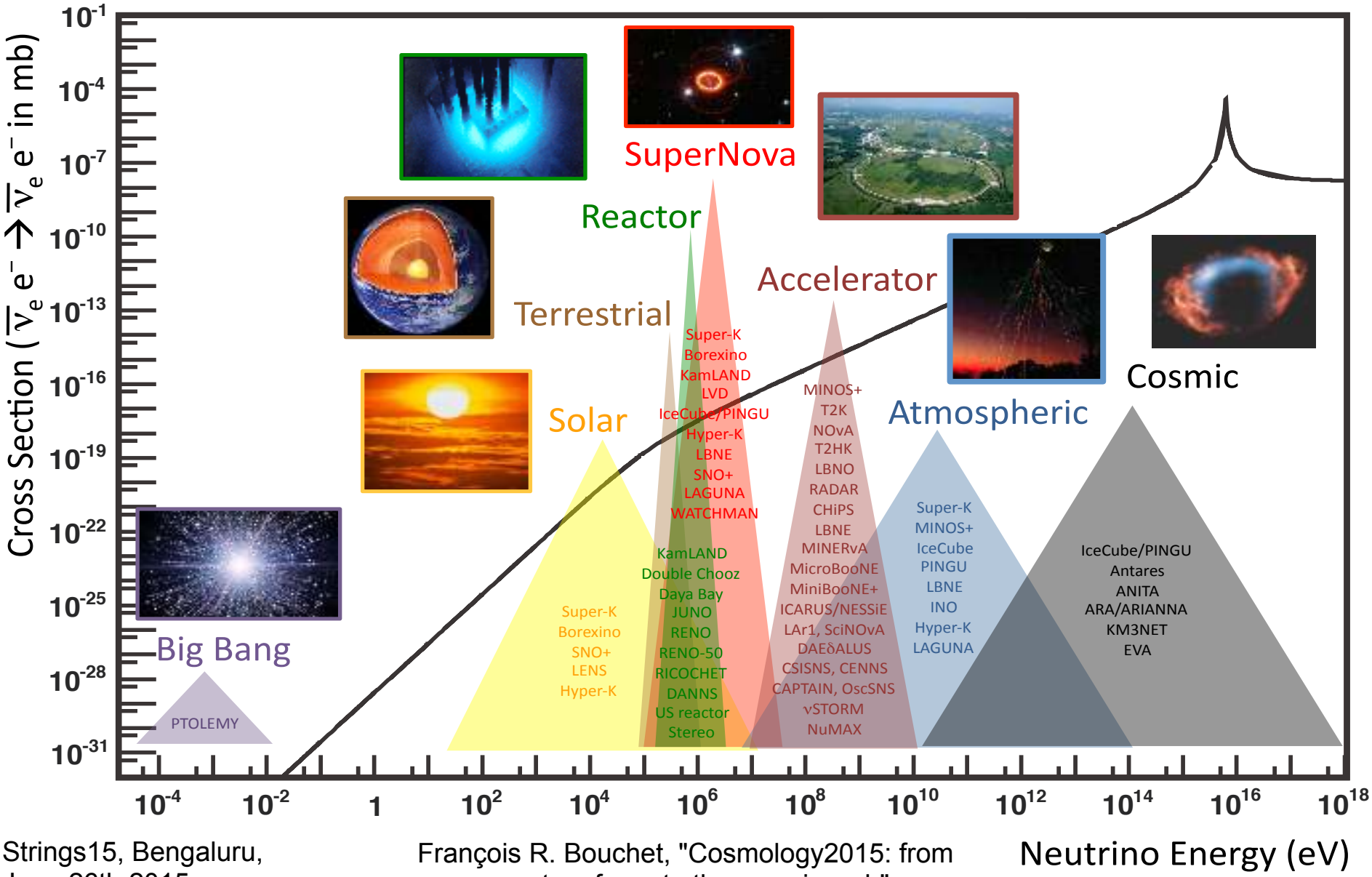
- Curvature Ω_k to 0.07%: could be improved with CMB lensing, but still a long way from cosmic variance limit
- n_s , $dn_s/d\ln k$ to 0.0015 with Lya forest P_{1d} , otherwise 0.005, Spherex can also reach 0.001: test inflation?
- f_{nl} to 1, possibly to 0.2 with Spherex
- M_ν to 0.02eV, limited by Planck optical depth uncertainty: can we do better (21cm?)

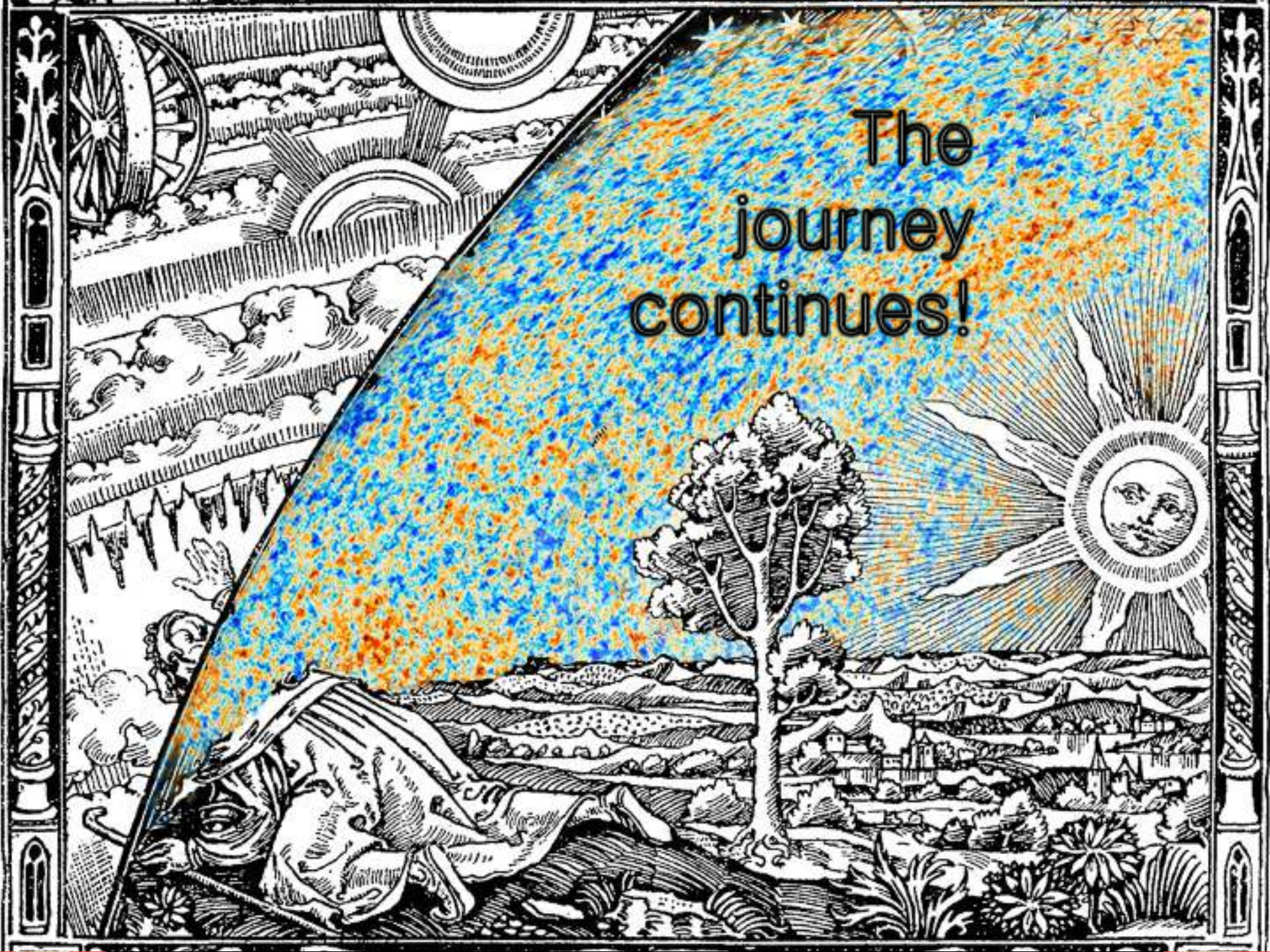


SPHEREX is a proposed All-Sky Spectral Survey

Font-Ribera et al 2014…

Neutrino Experiments




The
journey
continues!

The Planck results 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.

2015 constraints on single parameter extensions to base LCDM

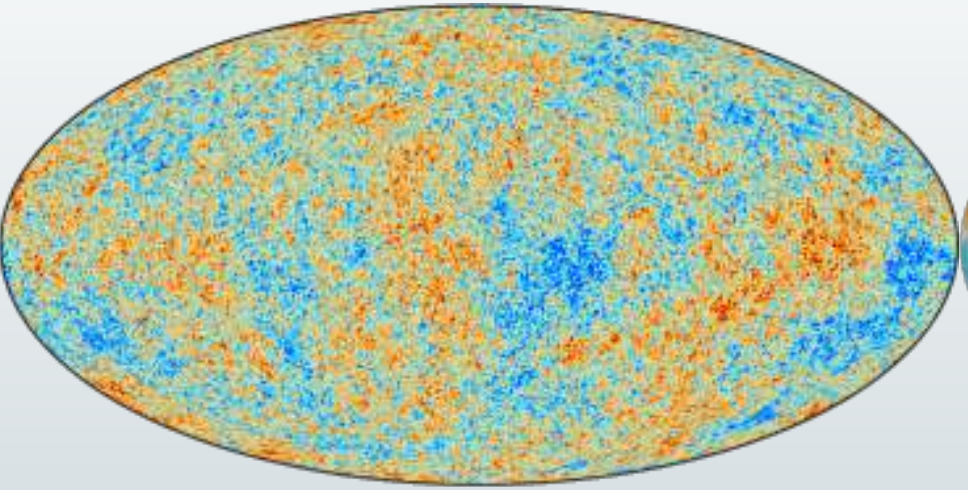
Table 5. Constraints on 1-parameter extensions to the base ΛCDM model for combinations of *Planck* power spectra, *Planck* lensing and external data (BAO+JLA+H_0, denoted "ext"). Note that we quote 95 % limits here.

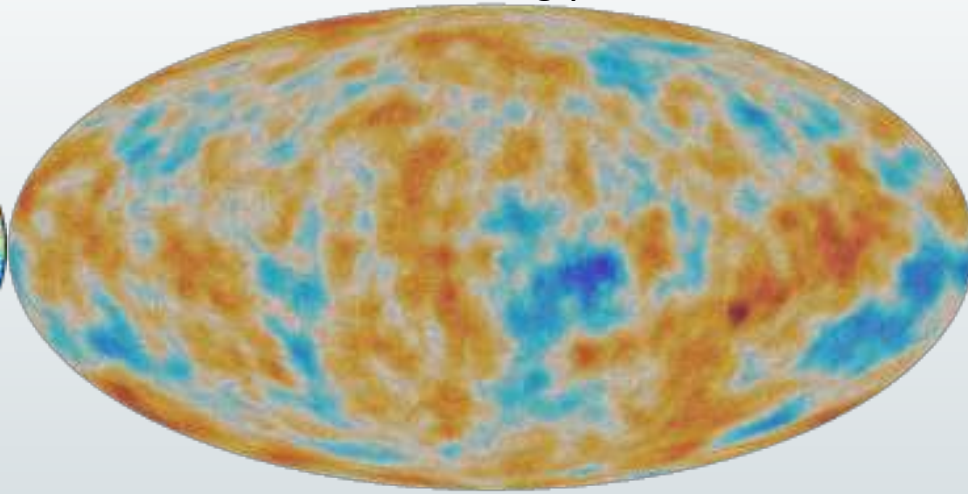
Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194
$N_{\rm eff}$	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
$Y_{\rm P}$	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114	< 0.0987	< 0.112	< 0.113
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$

➔ **no compelling evidence for deviations from the baseline model**

Conclusions

➔ base ΛCDM continues to be a good fit to the Planck data, *including polarisation*.

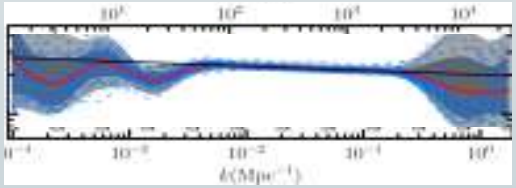


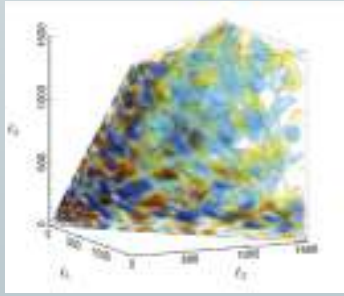


➔powerful evidence in favour of simple inflationary models, that match Planck data to very high precision.

Parameter	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02225 ± 0.00016
$\Omega_c h^2$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04077 ± 0.00032
τ	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.094 ± 0.034
n_s	0.9645 ± 0.0049
H_0	67.27 ± 0.66
Ω_m	0.3156 ± 0.0091
σ_8	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.882 ± 0.012

@95%cl





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	$-1.019^{+0.075}_{-0.080}$

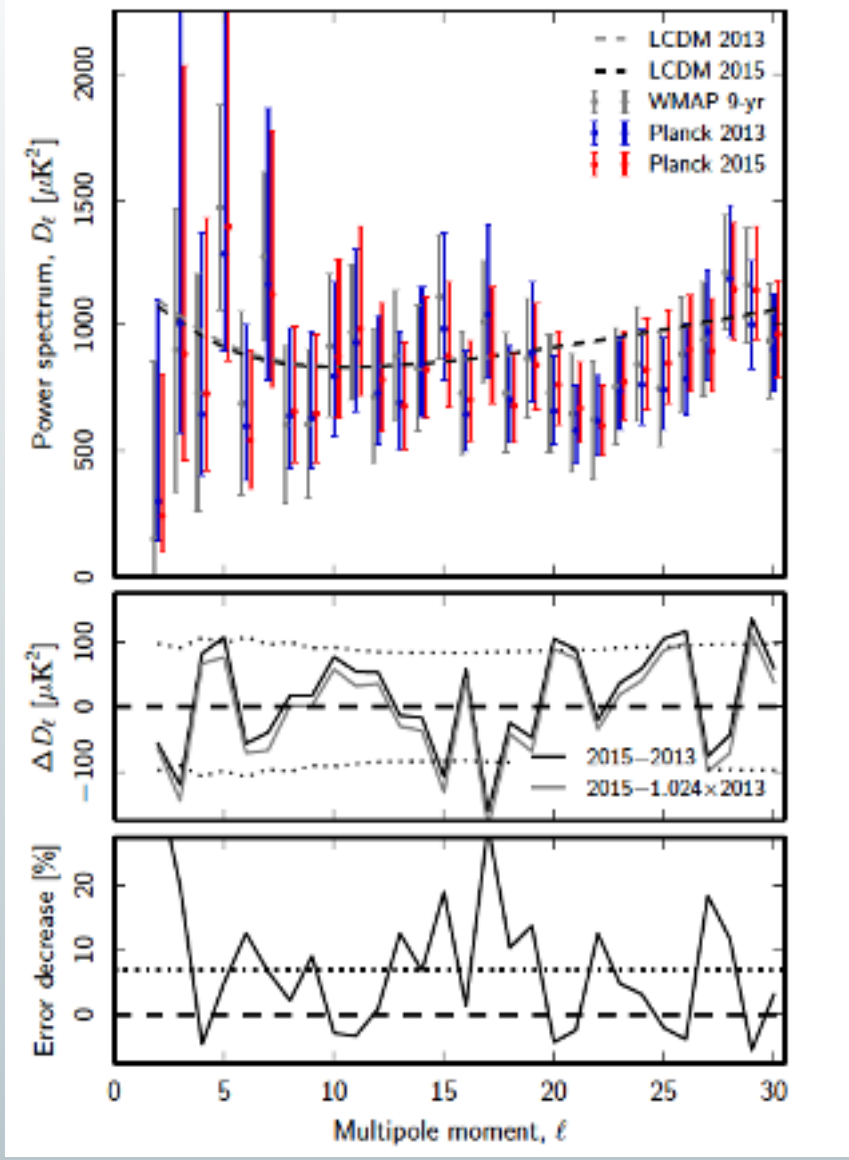
$f^{local}_{NL} = 0.8 \pm 5.0$
$f^{equil}_{NL} = -4 \pm 43$
$f^{ortho}_{NL} = -26 \pm 21$

α_{iso}
P_{ann}
...

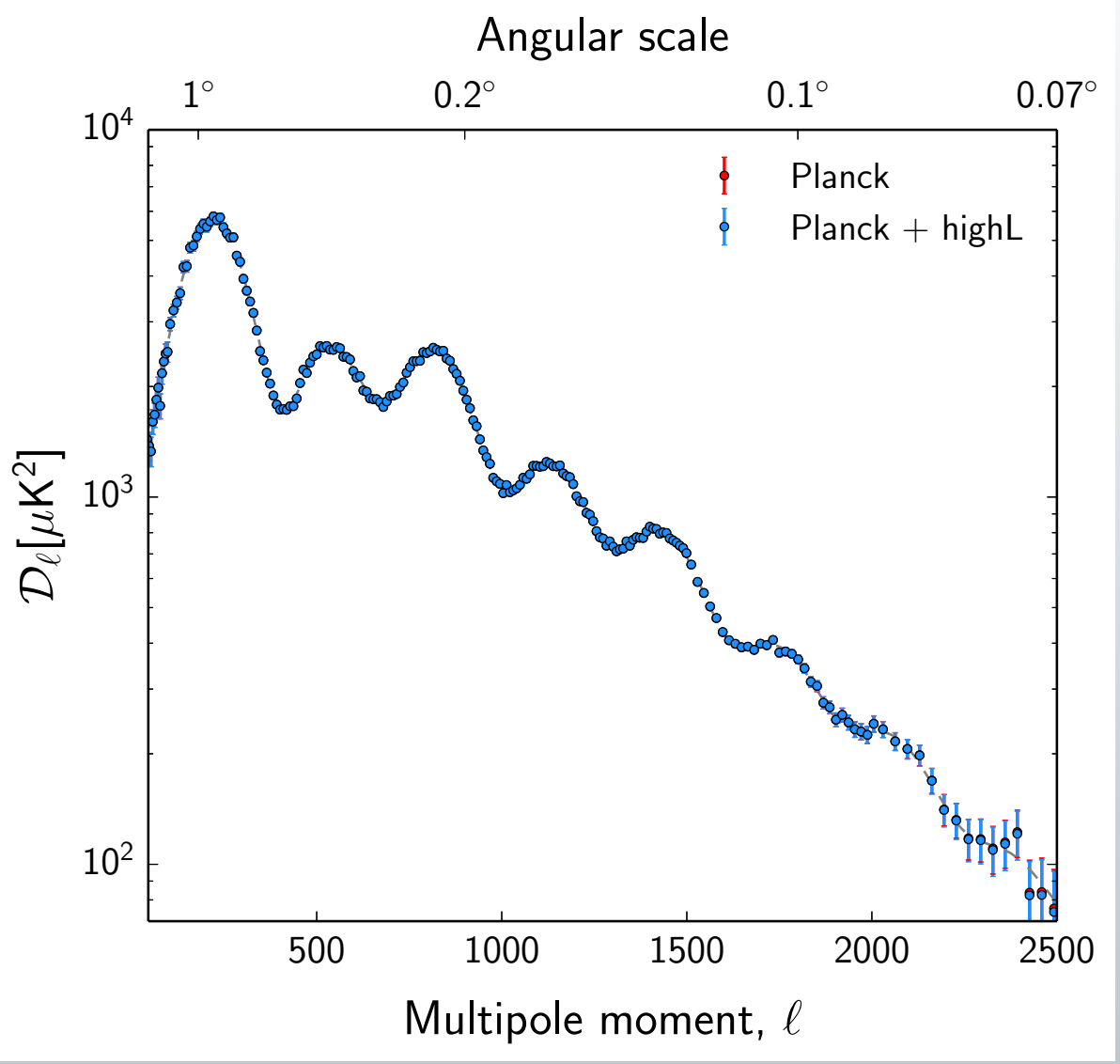
Detect	G_μ/c^2
NG . .	$< 1.2 \times 10^{-7}$
AH . .	$< 2.4 \times 10^{-7}$
SL . .	$< 8.5 \times 10^{-7}$
TX . .	$< 5.6 \times 10^{-7}$

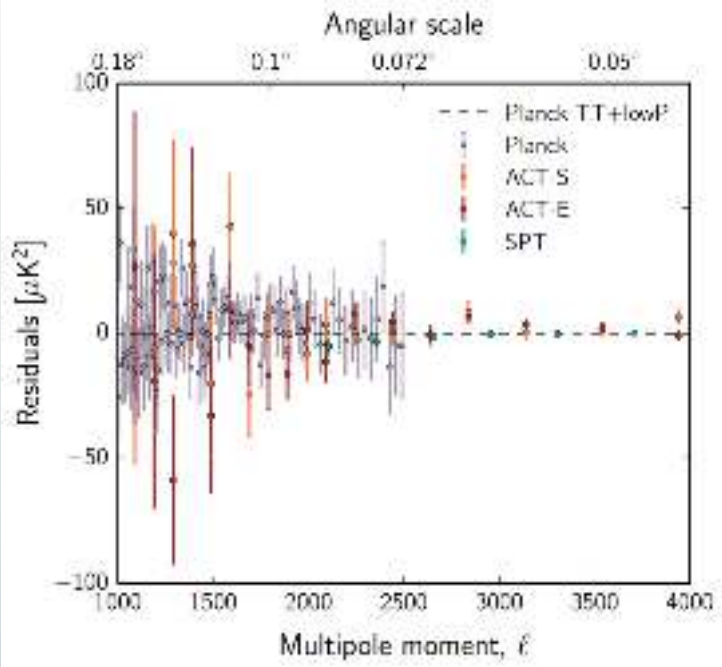
➔If there is new physics beyond base ΛCDM, its observational signatures in the CMB are weak & difficult to detect.

Planck & WMAP agree at very low ell



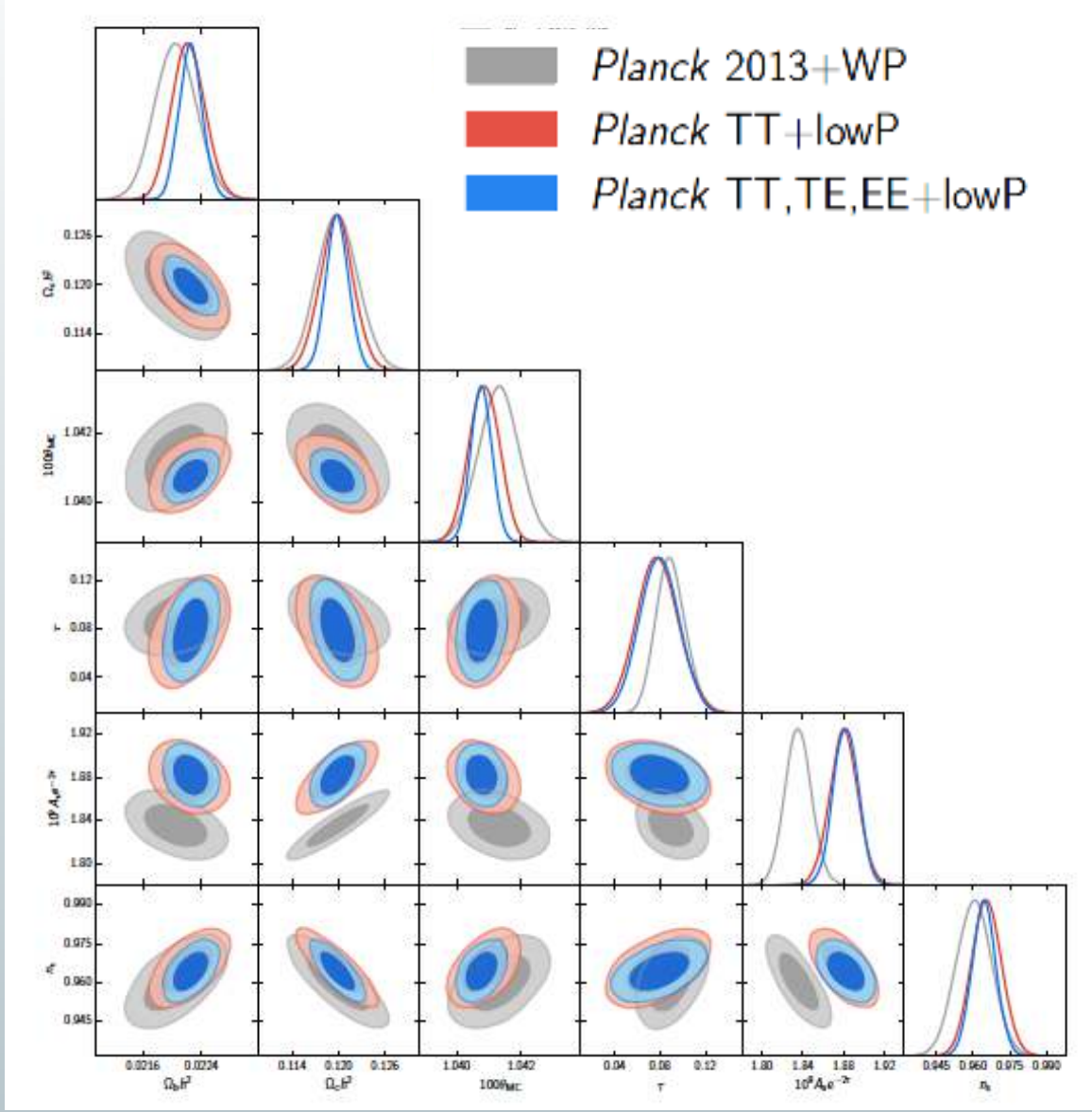
highL data (ACT&SPT) are consistent with Planck





➔ highL data only used for consistency checks, not for cosmology (but for SZ priors)

T & E – LCDM parameters



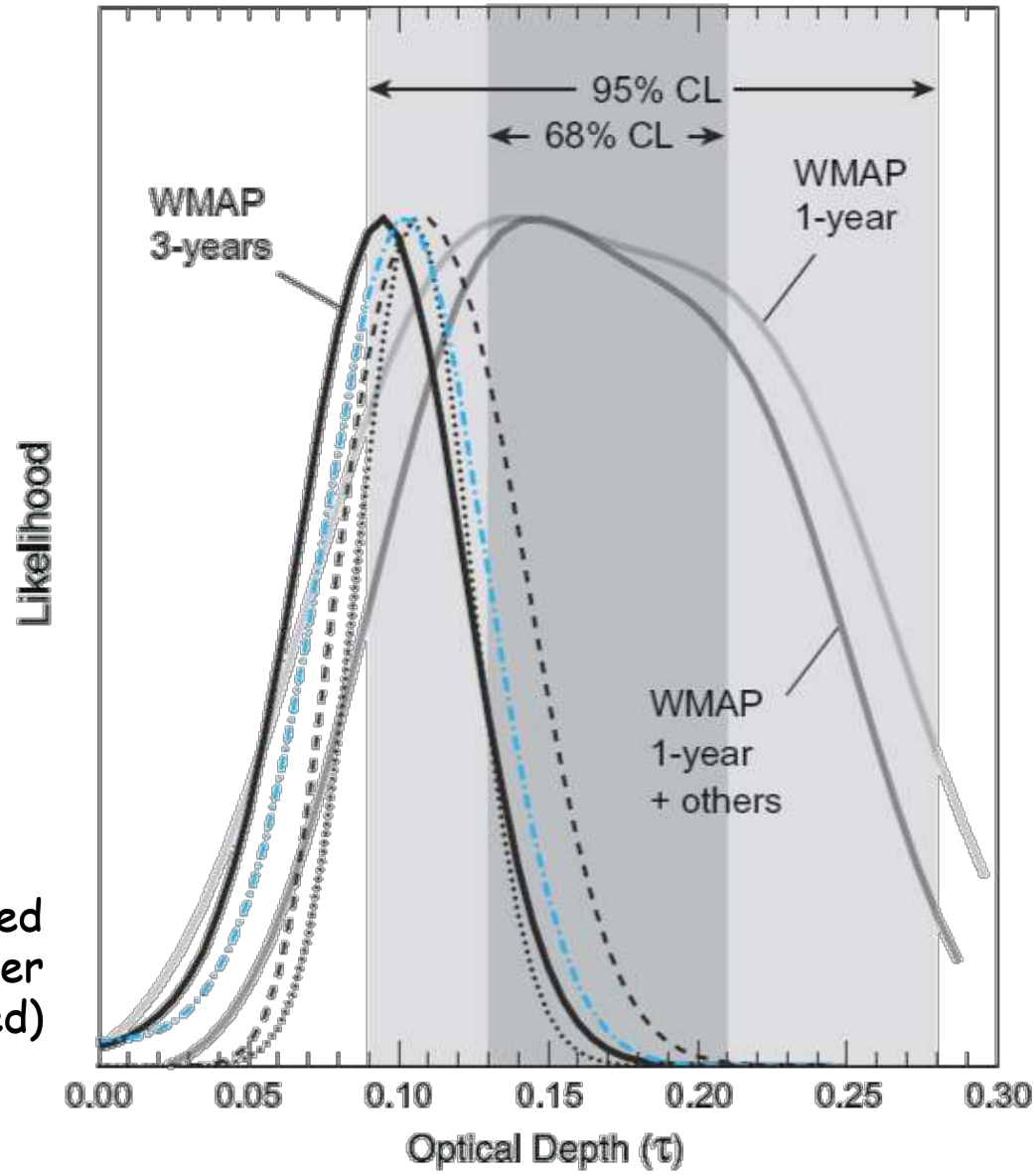
A series of increased precision, but for the overall % level recalibration

(which now sets the standard for mm sky studies -- absolute and accurate).

OPTICAL DEPTH

- TE-3 years contributes very little
- Alone would be an upper limit on tau
- New noise estimation (see Fisher) is the reason
- tau-1yr was based on TE
- tau from (EE-) 3yr is compatible at 2σ level with 1 yr data

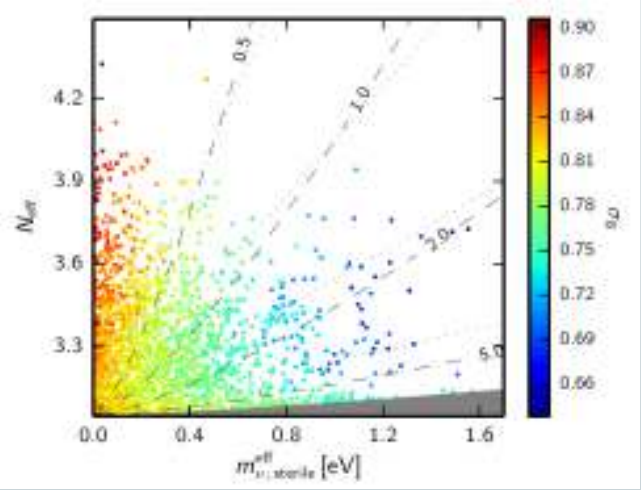
(likelihood plotted keeping all other parameters fixed)

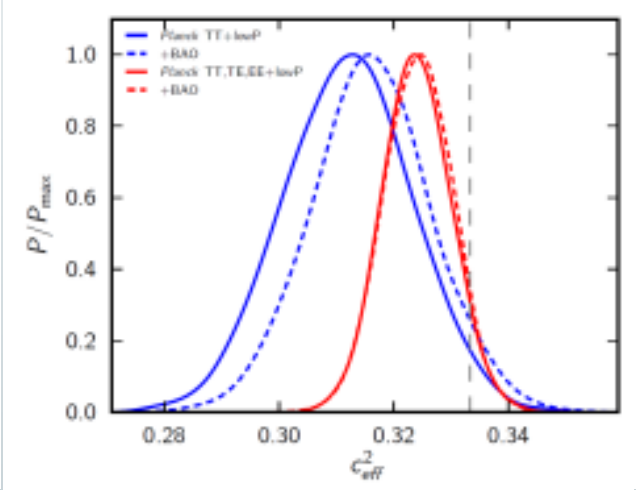


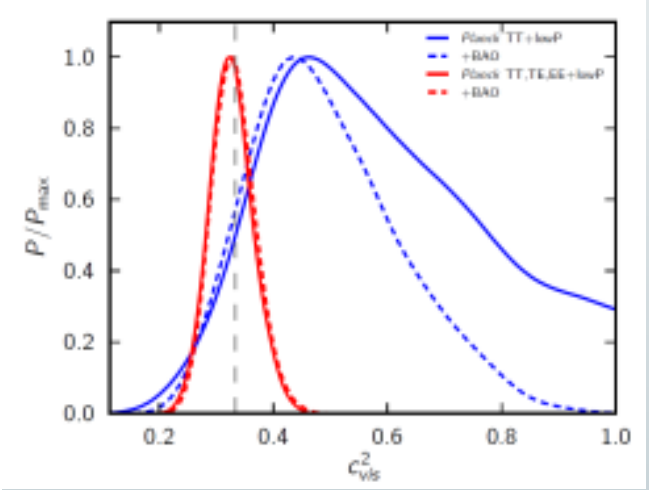
A slide from my second 2008 lecture at IUCAA school

Neutrinos extensions

$N_{eff} > 0$ at ~ 15σ, N_{eff} =4 excluded at 3-5σ







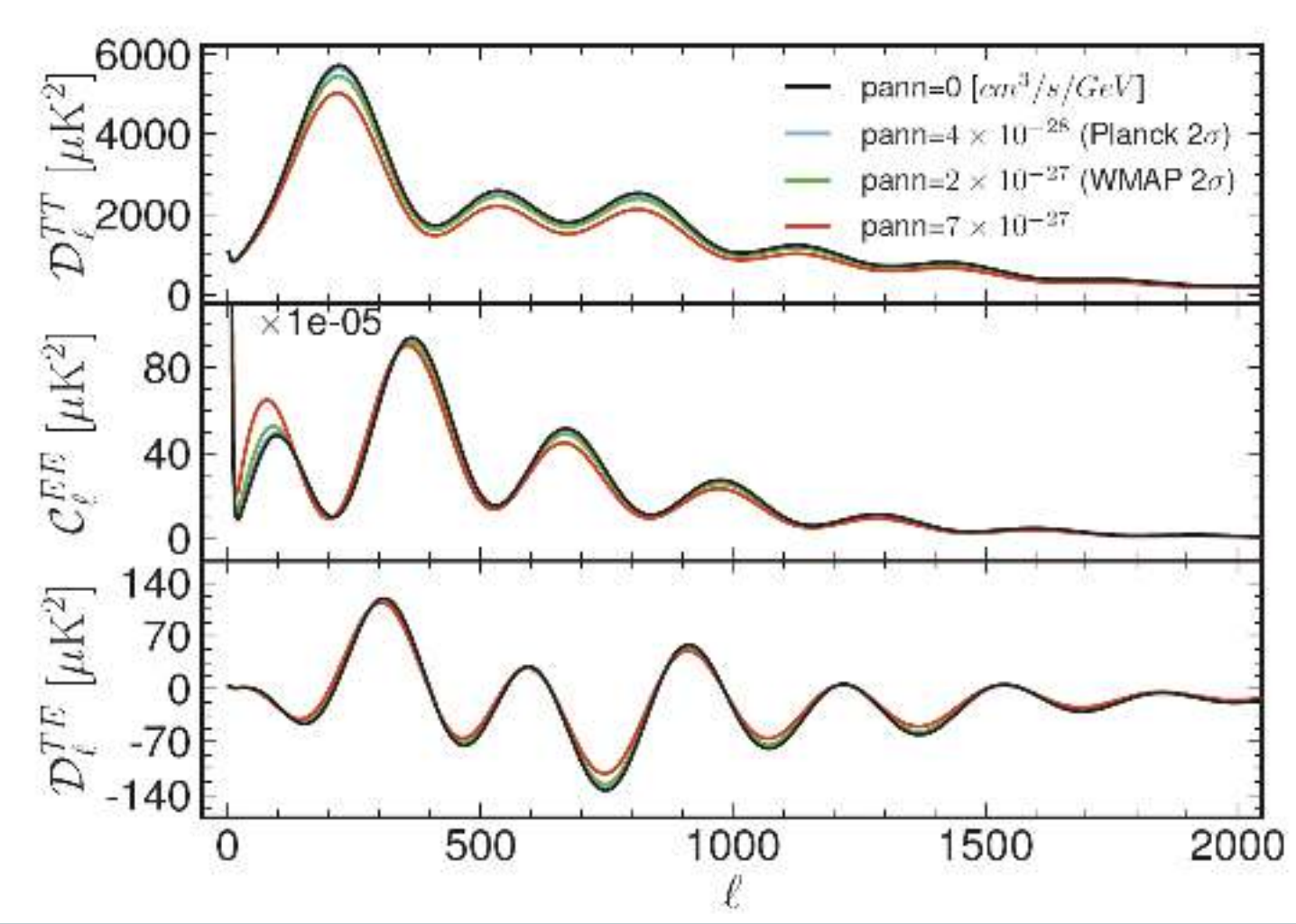
Free-streaming particles have (1/3, 1/3)
(a perfect fluid would have (1/3, 0))

Dark matter annihilation?

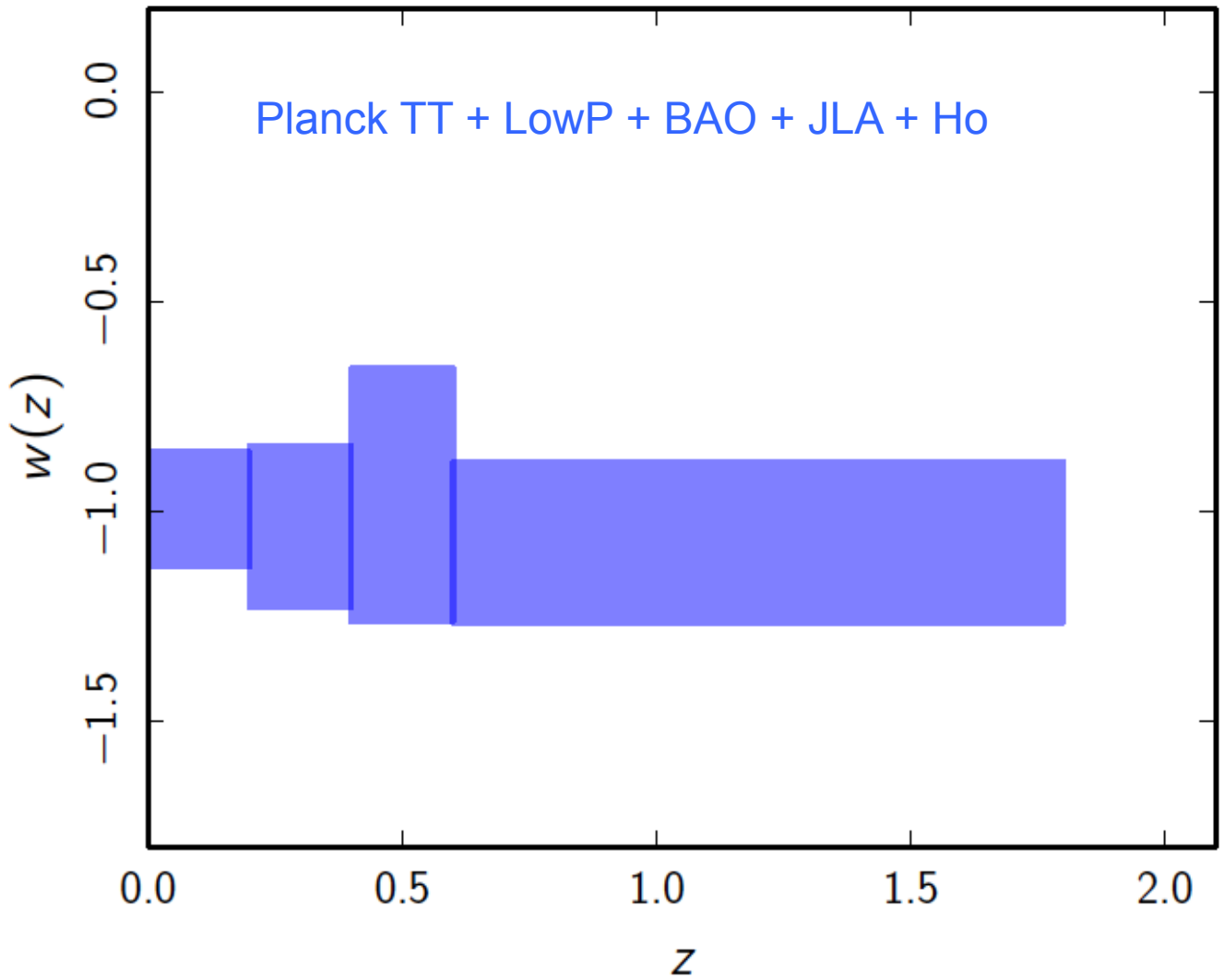
DM annihilation:

- Suppresses amplitude, albeit in a very degenerate way with other parameters
- Enhances polarisation at large scale (l ~< 300)

$$p_{ann} = f_{eff} \frac{<\sigma v>}{m_\chi}$$

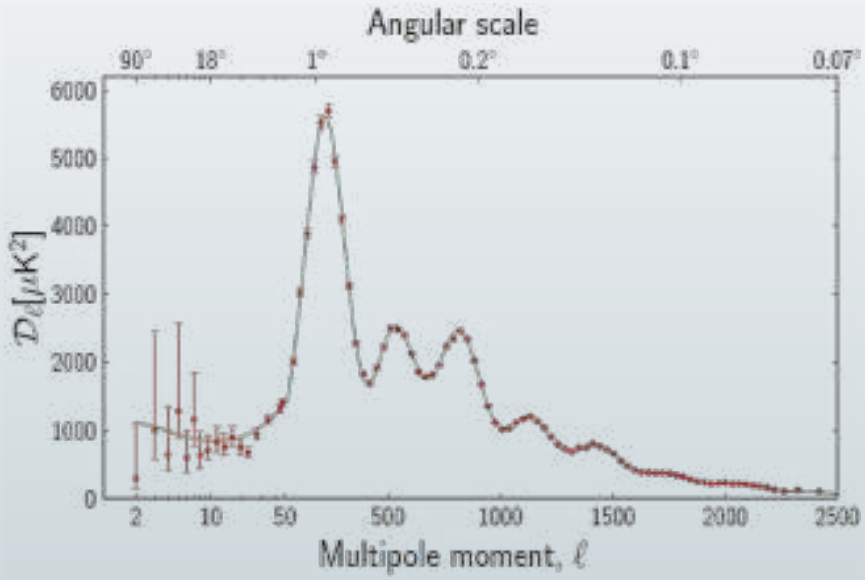


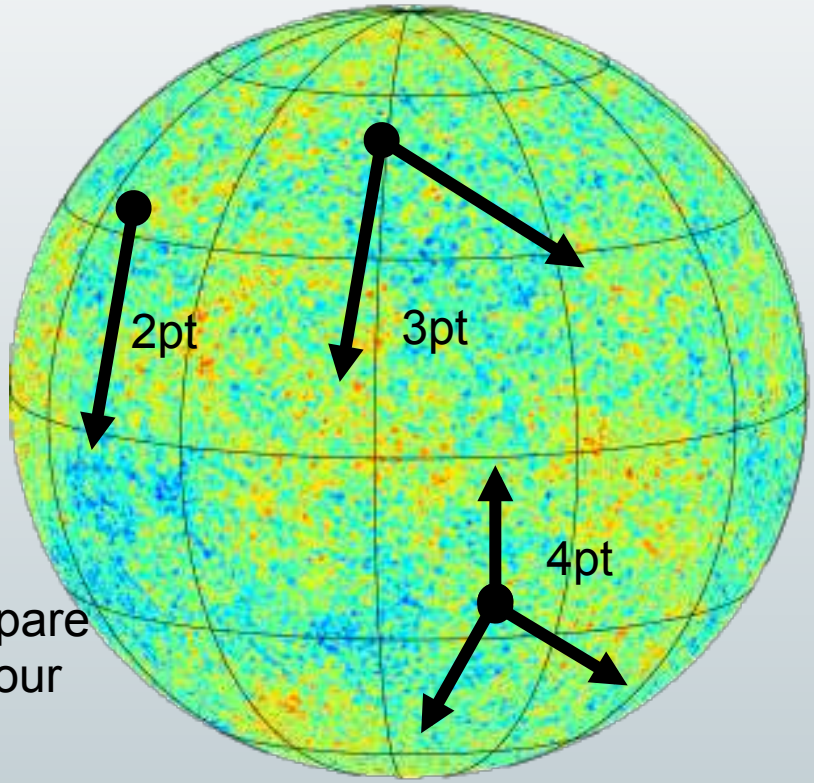
PCA of w(z)



Random field characterisation

The angular power spectrum compares two points separated by **one** angle





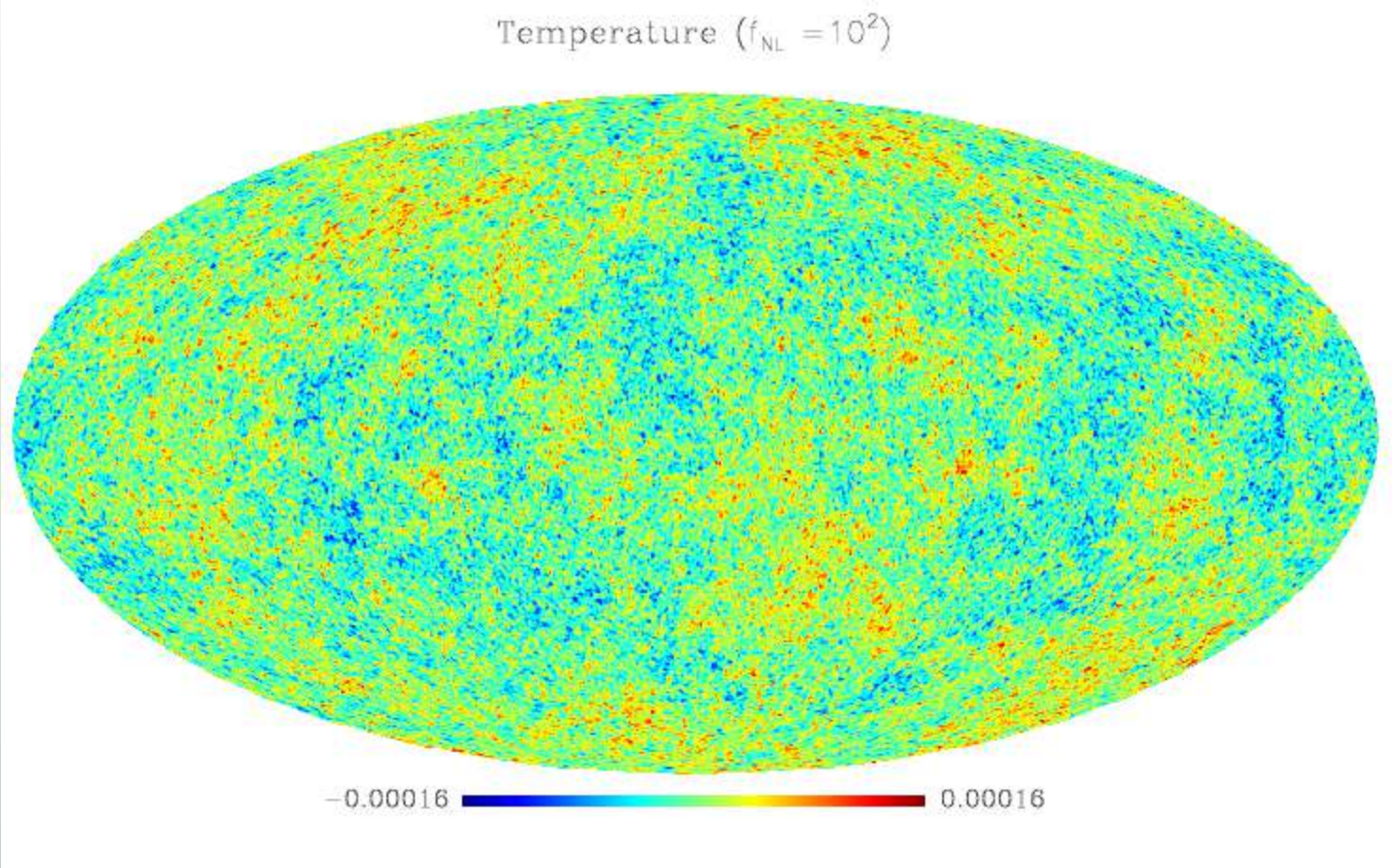
To assess non Gaussianity, one must compare fluctuations in three points (bi-spectrum), four point (tri-spectrum), etc.

Need **three** numbers to characterize a triangle

One origin of four point signal comes from lensing by Large Scale Structures.

f_{NL}= 100

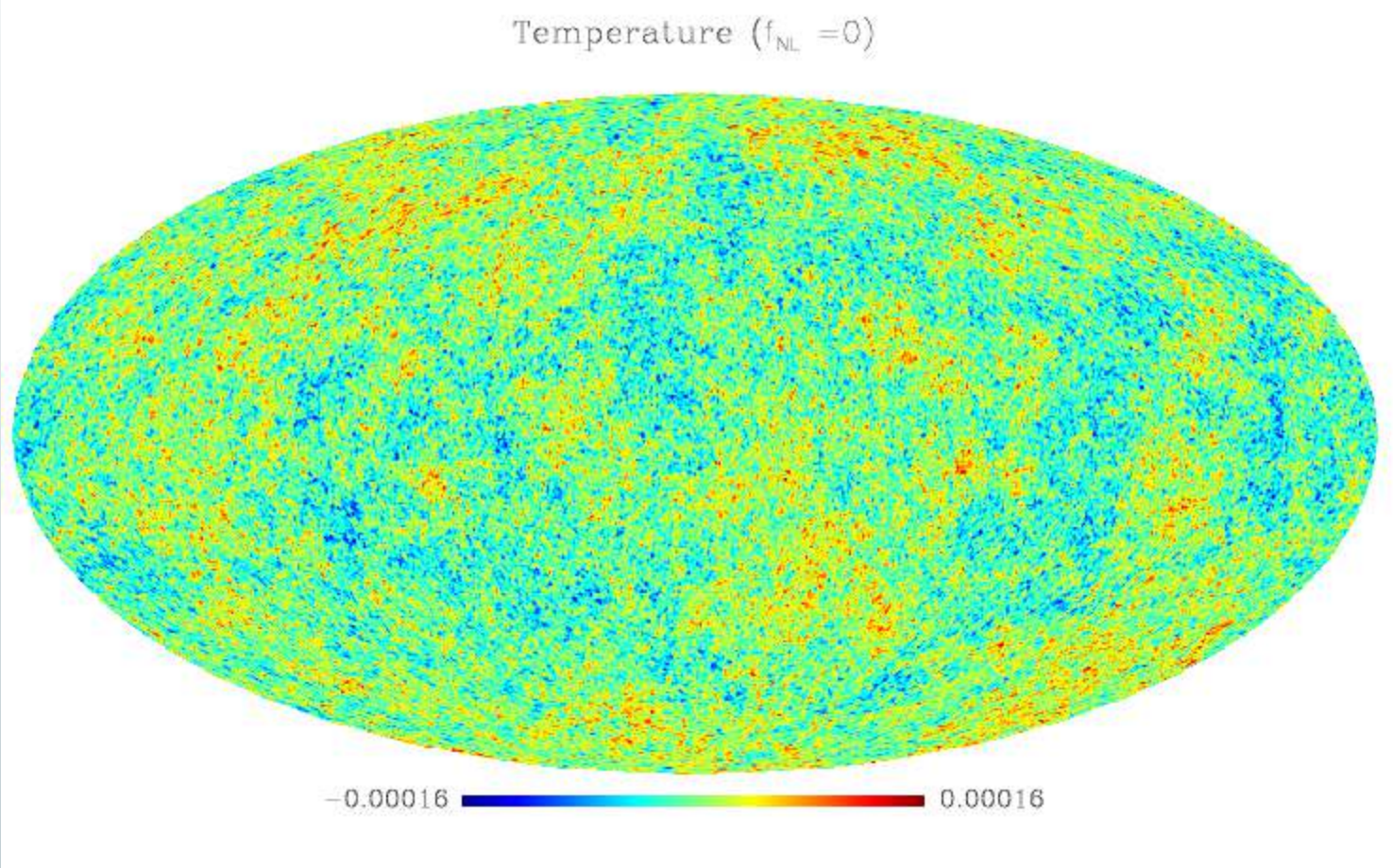
Positive f_{NL} = More Cold Spots

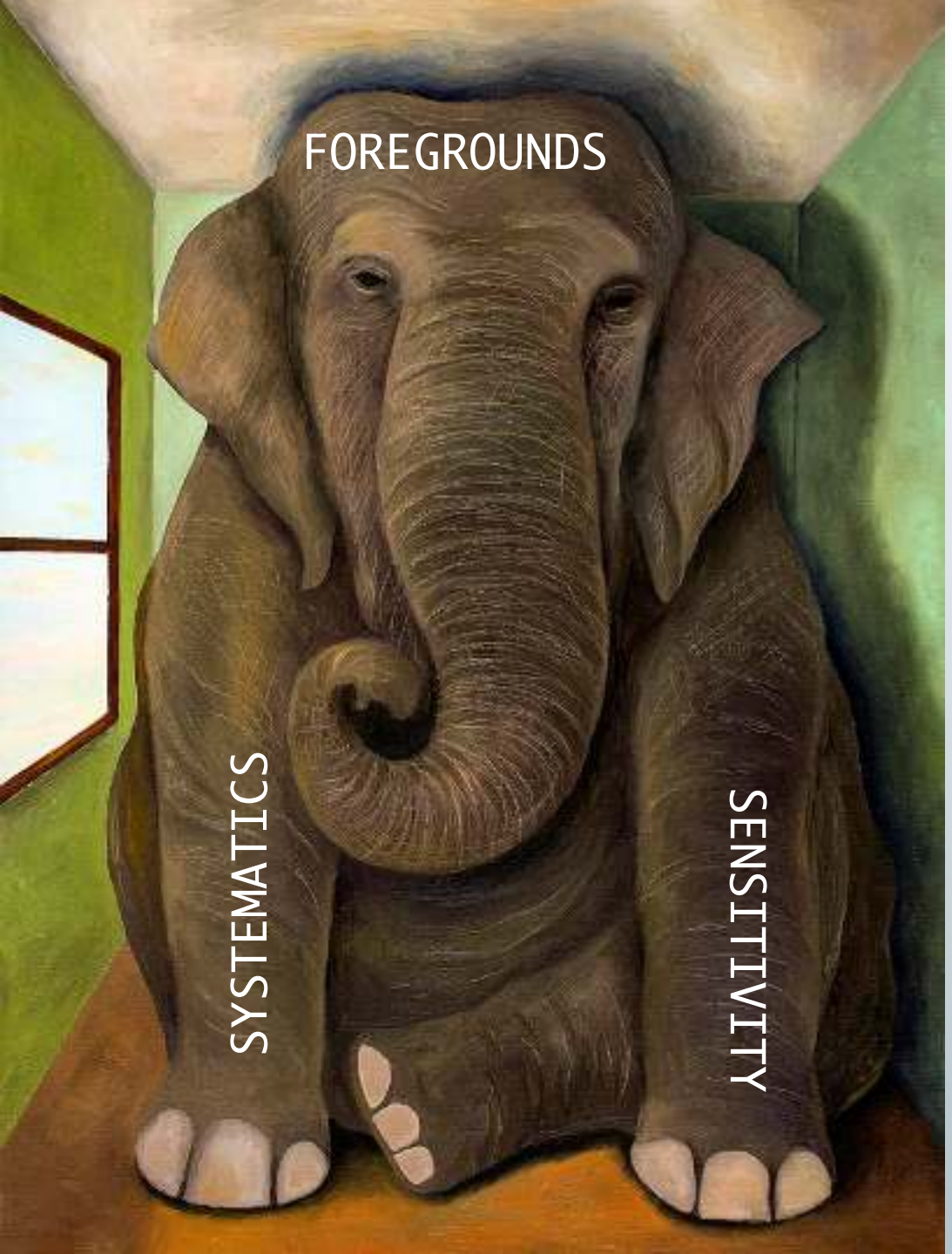


"The frightening power of statistics"

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

$f_{NL} = 0$





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

Towards exhausting k-modes