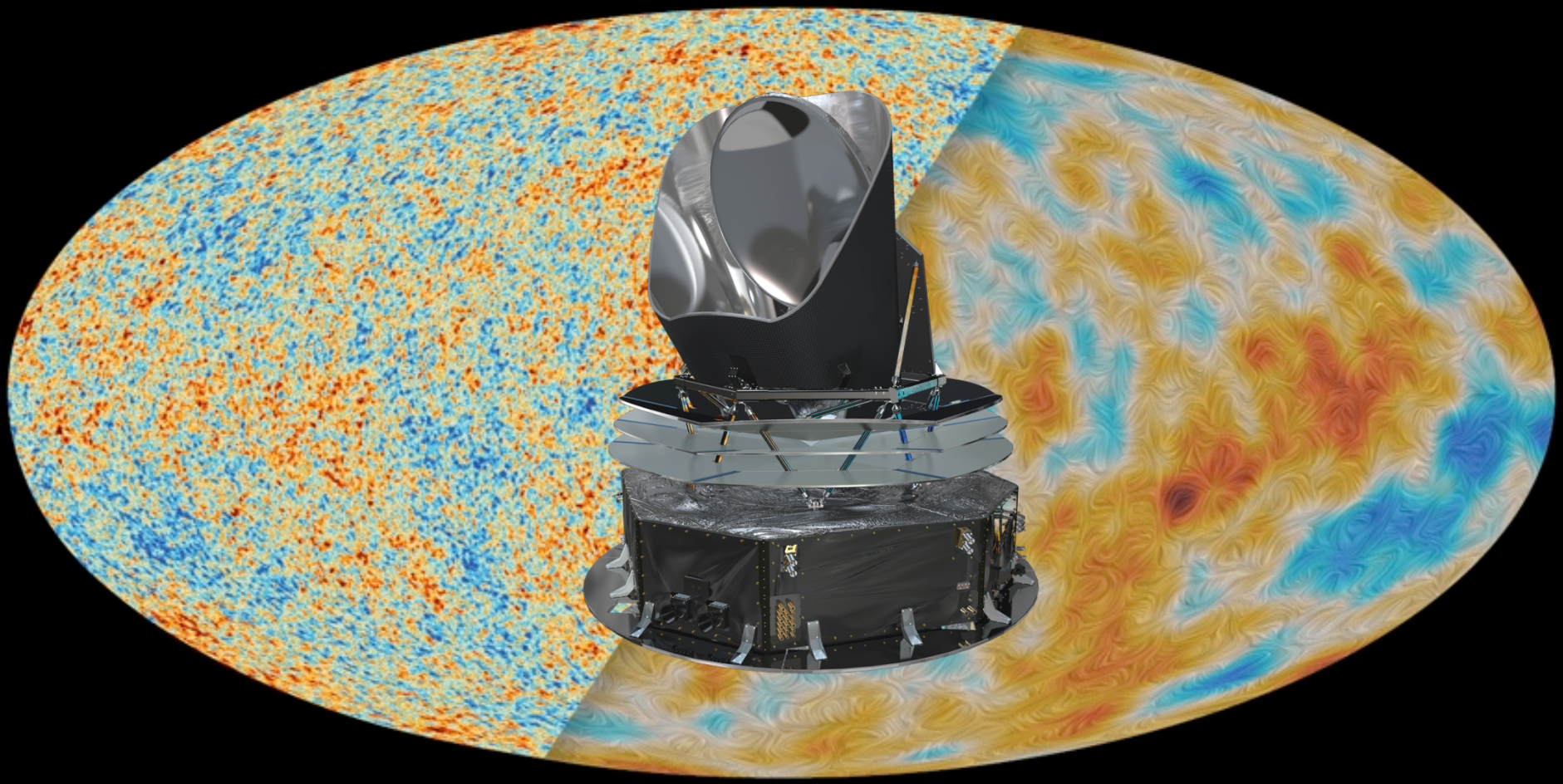
PLANCK 2016 COSMOLOGY



Eric Hivon on behalf of the Planck Collaboration

The Planck mission concept/challenge

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

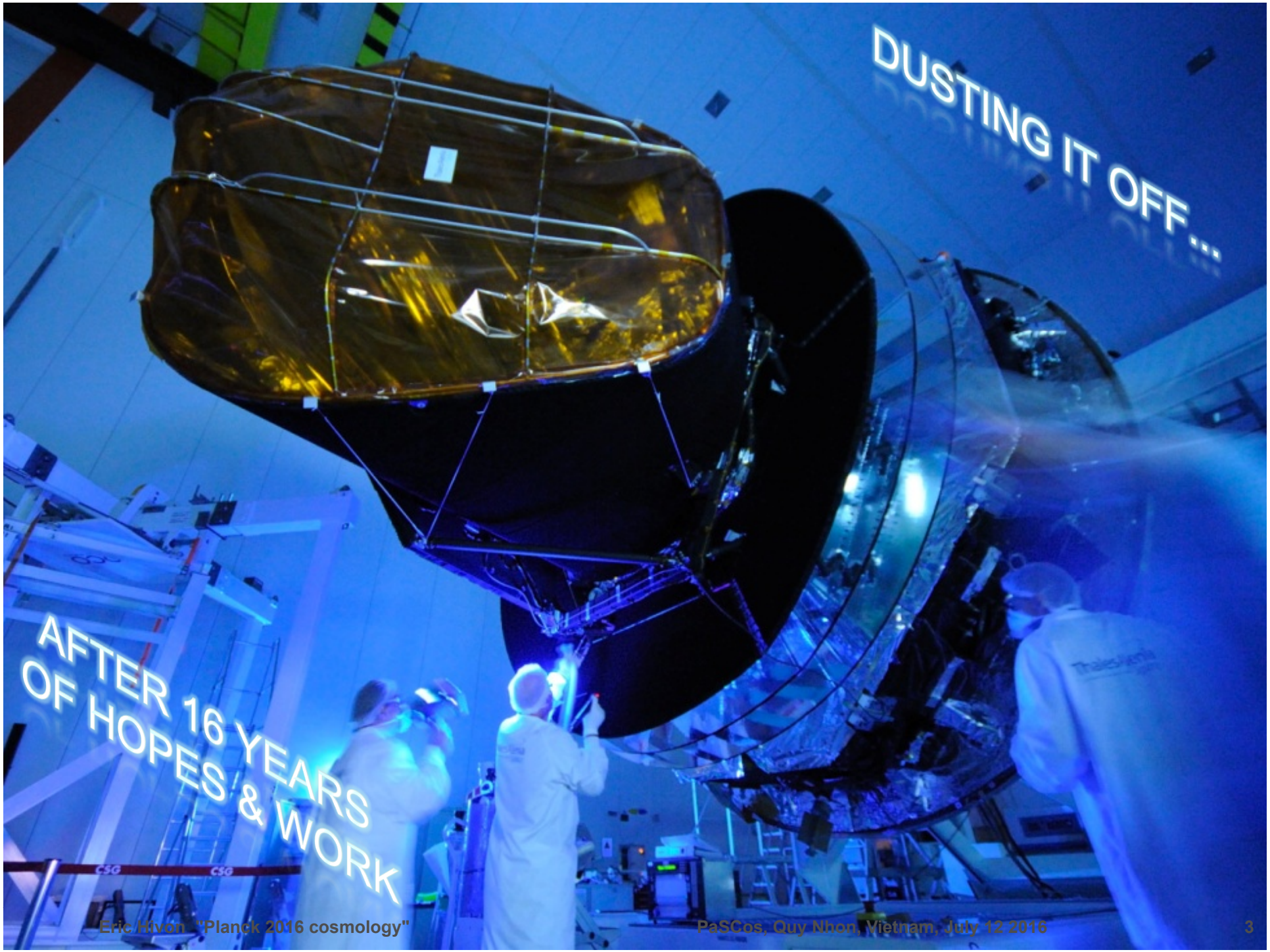
  ⇒ *enough sensitivity within large frequency range [30 GHz, 1 THz]*
  (~CMB photon noise limited for ~1yr in CMB primary window)

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

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

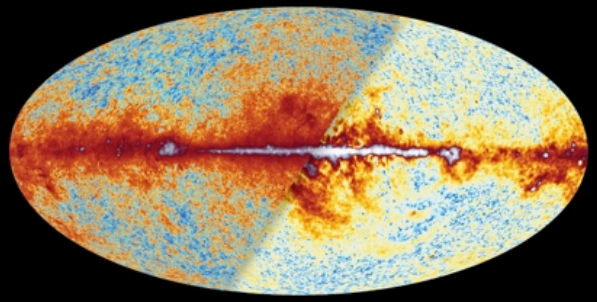
NB: This required a number of technological breakthrough

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

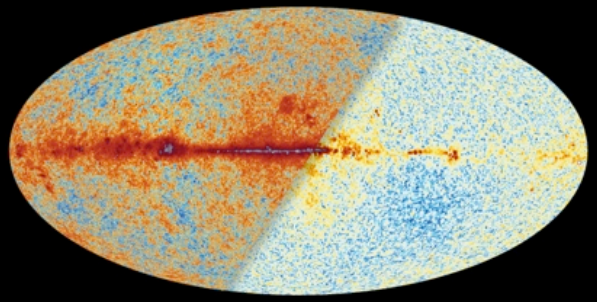

DUSTING IT OFF...
AFTER 16 YEARS
OF HOPES & WORK


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

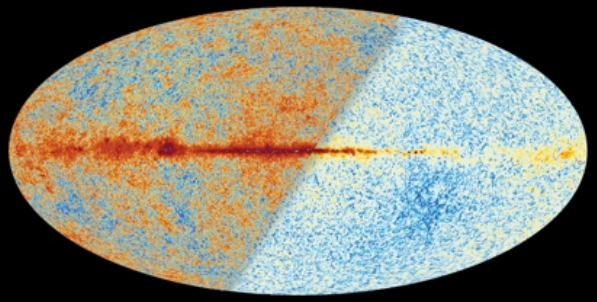
Now available in a store near you



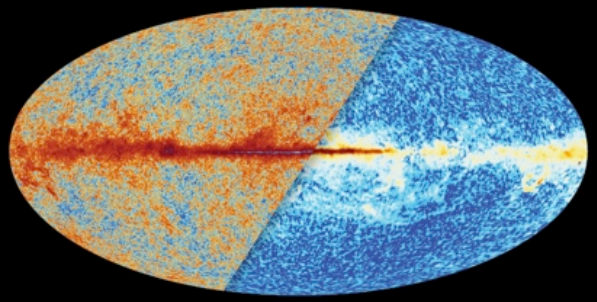
30 GHz



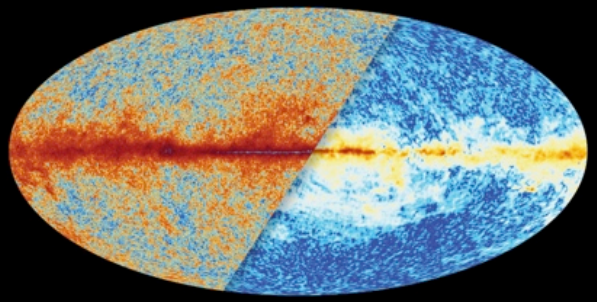
44 GHz



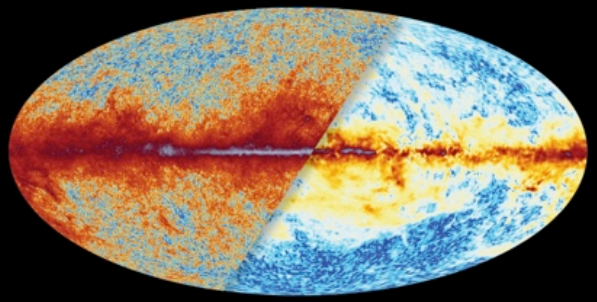
3.5μK.deg,13’ 70 GHz



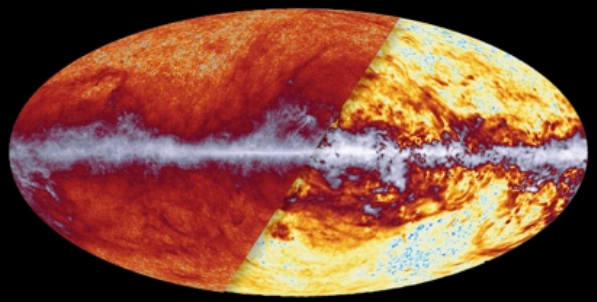
1.3μK.deg,9.7’ 100 GHz



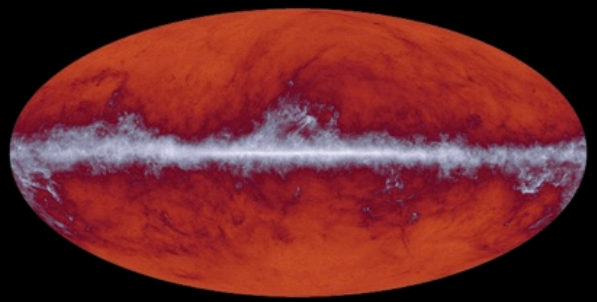
0.5μK.deg,7.3’ 143 GHz



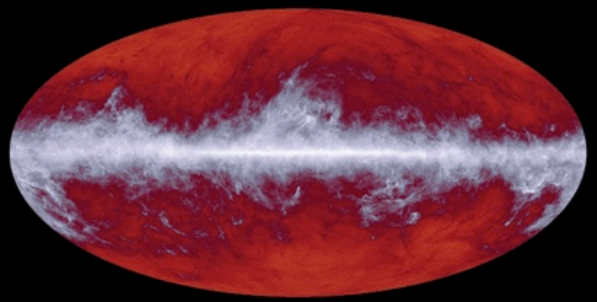
0.8μK.deg,5.0’ 217 GHz



353 GHz

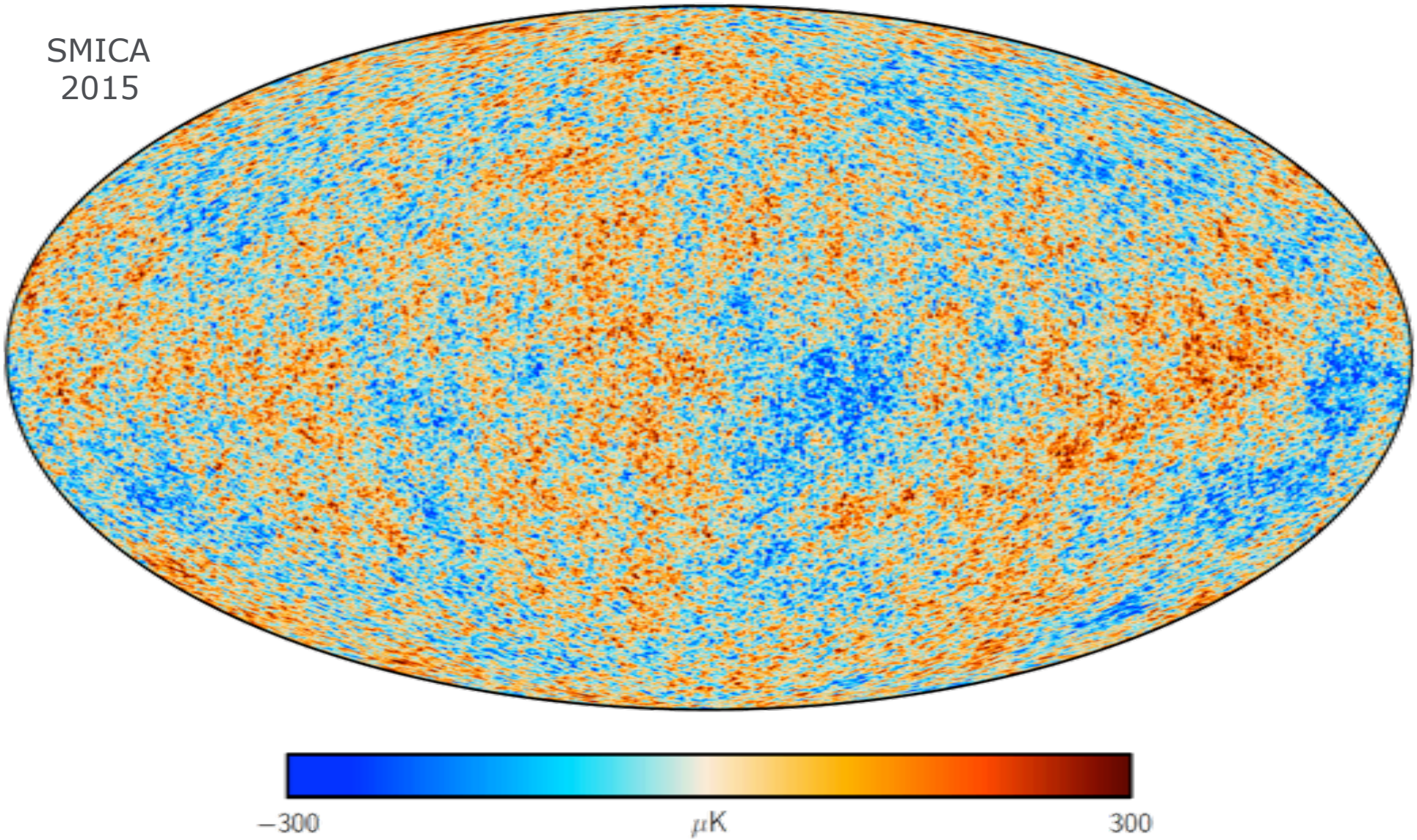


545 GHz



857 GHz

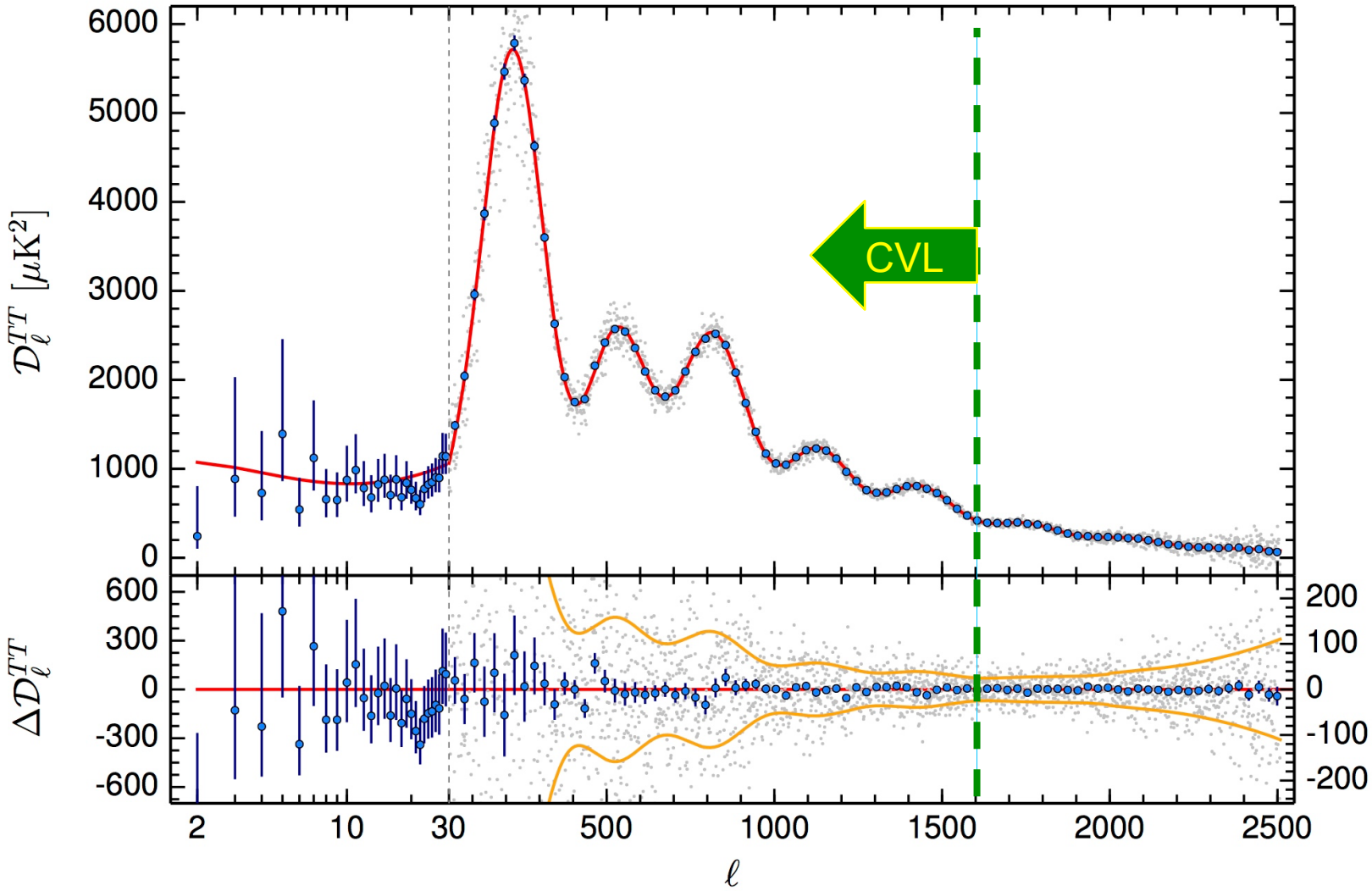
Planck 2015 T anisotropies map



Planck cosmology

- Planck ?
- **CMB Temperature anisotropies**
  - *Universe initial conditions*
    - Primordial power spectrum
    - (Non-)Gaussianity
  - *Constraints on Inflation*
- CMB Polarization
  - *Consistency with temperature*
  - *Adiabaticity of initial conditions*
- Secondary anisotropies
  - *Gravitational lensing*
  - *Re-ionization*
- Consistency with other probes
  - *BAO, BBN, SN1a*
  - *ΛCDM fits all ?*
- Tensions
- Overall picture

Planck 2015 TT power spectrum



8 acoustic peaks well detected

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

Base ΛCDM model with 6 parameters

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

- 2 parameters to describe the characteristics of *primordial fluctuations*,
  - A_s *Amplitude of the curvature power spectrum*
    Overall contrast of primordial fluctuations)
  - n_s *Scalar power spectrum power law index*
    (n_s-1 measures departure from scale invariance)

- 1 parameter to capture the effect of *reionisation* (end of the dark ages),
  - τ *Optical depth at reionisation (due to Thomson scattering of photons on e^-), ie, fraction of the CMB photons re-scattered during that process*

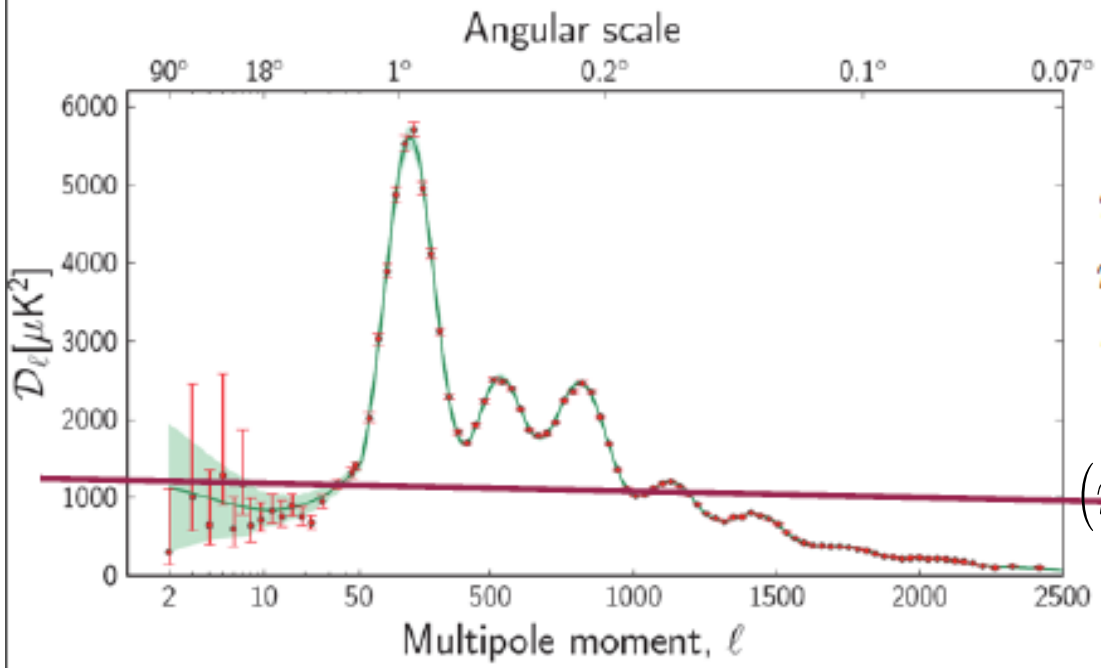
- *Flat spatial geometry* assumed.

- Others parameters are *derived* parameters within the model, in particular
  - Ω *"Dark Energy" fraction of the critical density (derived only if assumed flat)*
  - H_0 *the expansion rate today (in km/s per Mpc of separation)*
  - t_0 *the age of the universe (in Gy)*
  - σ_8 *linear density contrast at 8 h^{-1}Mpc*

What is the value of n_s ?

Initial Conditions: quasi-scale invariant

$$g_{ij} = a^2(\tau)\,[1 - 2\Phi]\,\gamma_{ij} \longrightarrow k^3 \langle |\Phi_k|^2 \rangle \propto k^{n_s - 1}$$



$n_s = 1 \pm 0.6$ 1992 (COBE)

$n_s = 1.03 \pm 0.09$ 2001 (MaxiBoom)

$n_s = 0.963 \pm 0.014$ 2009 (WMAP5)

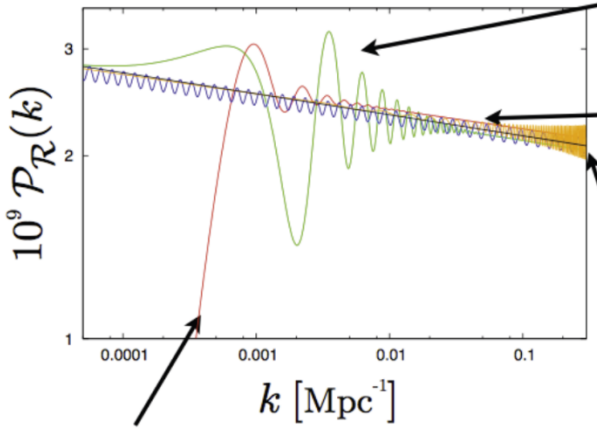
$n_s = 0.9603 \pm 0.0073$ 2013 (Planck+)

$(n_s = 0.965 \pm 0.006$ 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.

(Unsuccessful) search for features



Feature in the potential:

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

Non vacuum initial conditions/instanton effects in axion monodromy

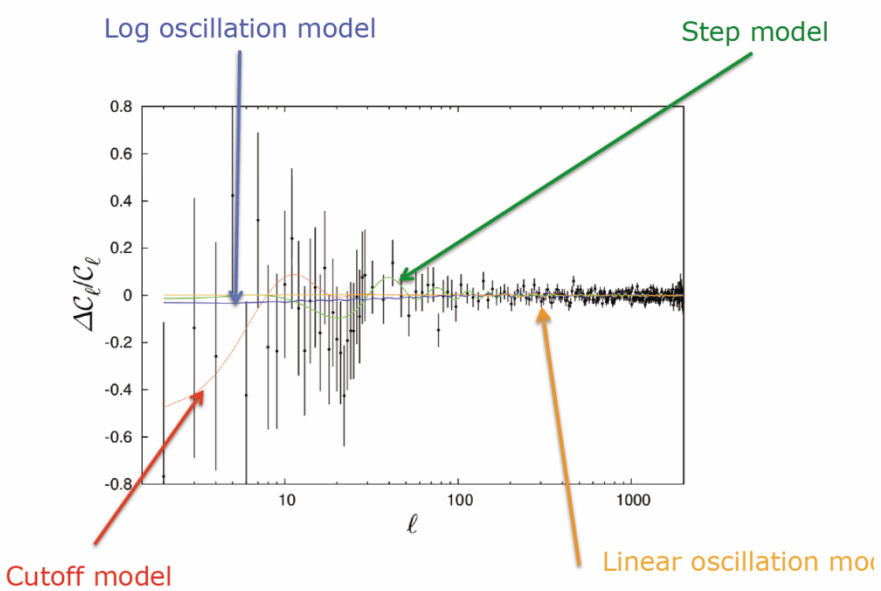
$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

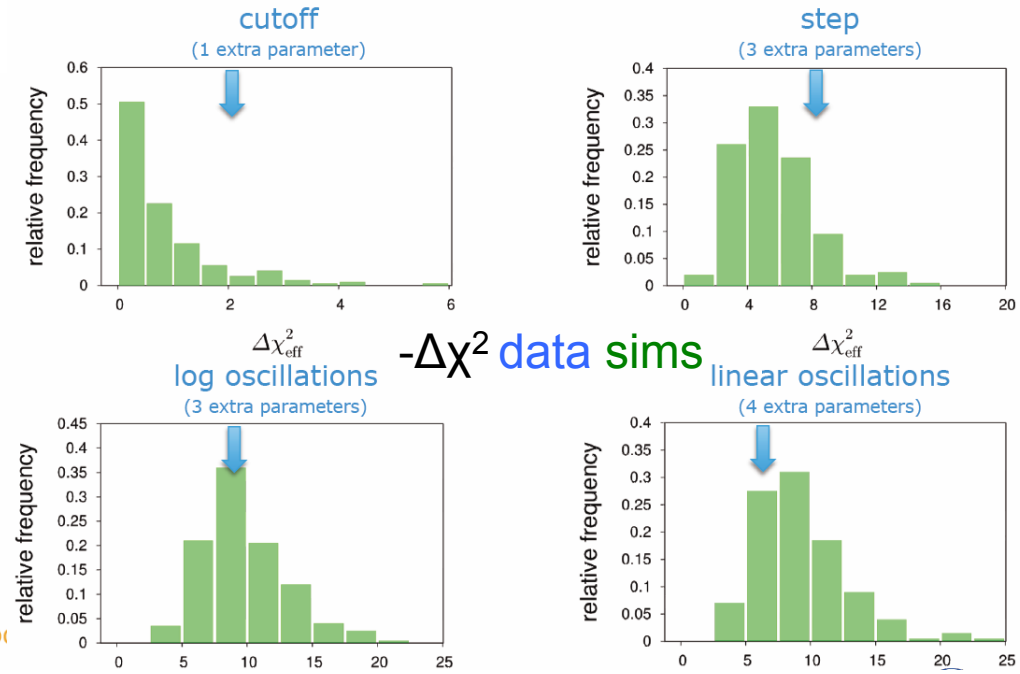
$$\mathcal{P}_{\mathcal{R}}^{\log}(k) = \mathcal{P}_{\mathcal{R}}^{0}(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

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

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

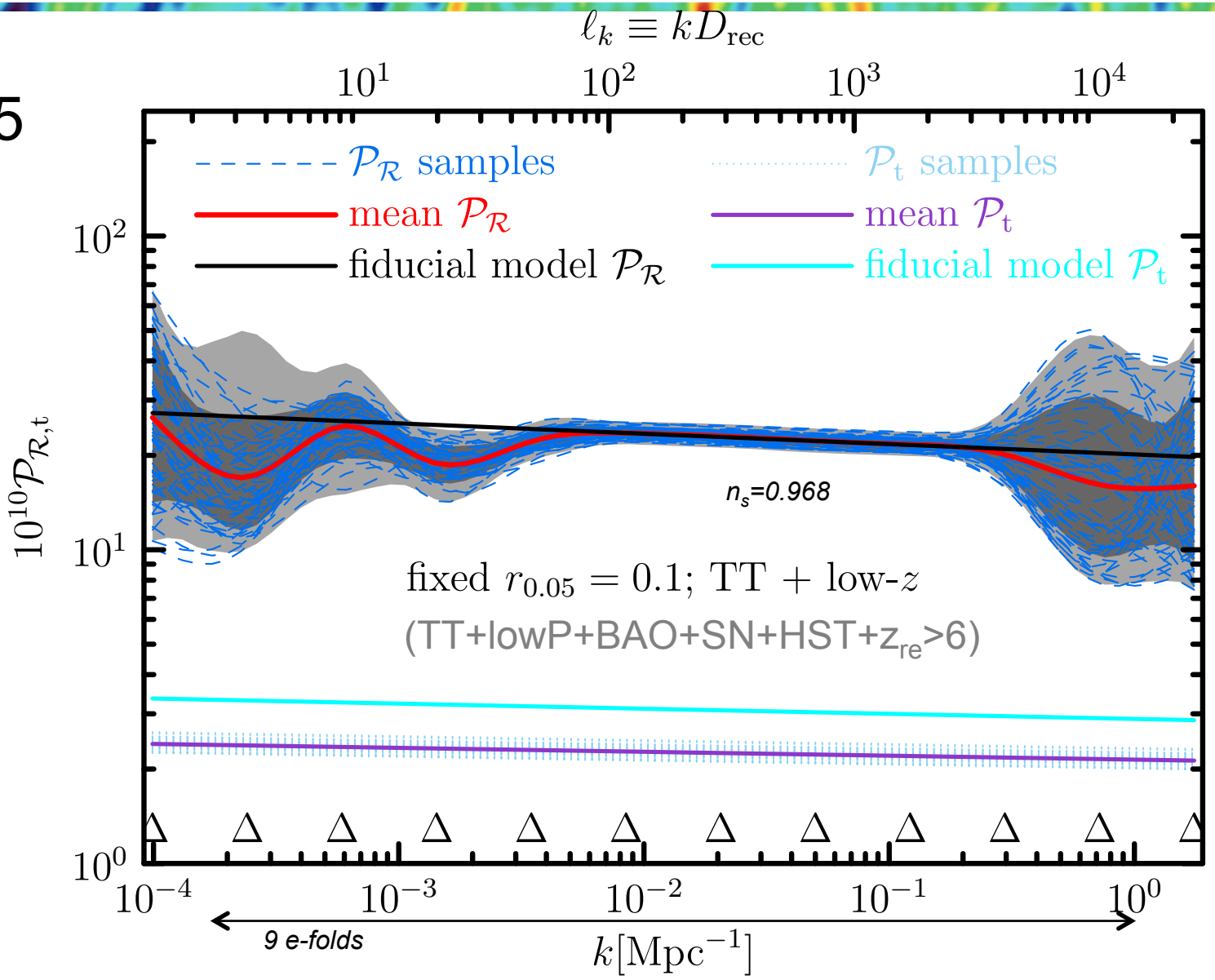




$-\Delta\chi^2$ data sims

Power spectra reconstruction

2015

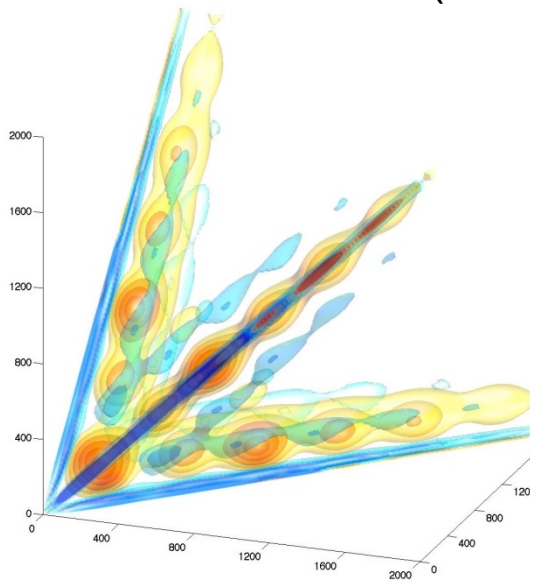


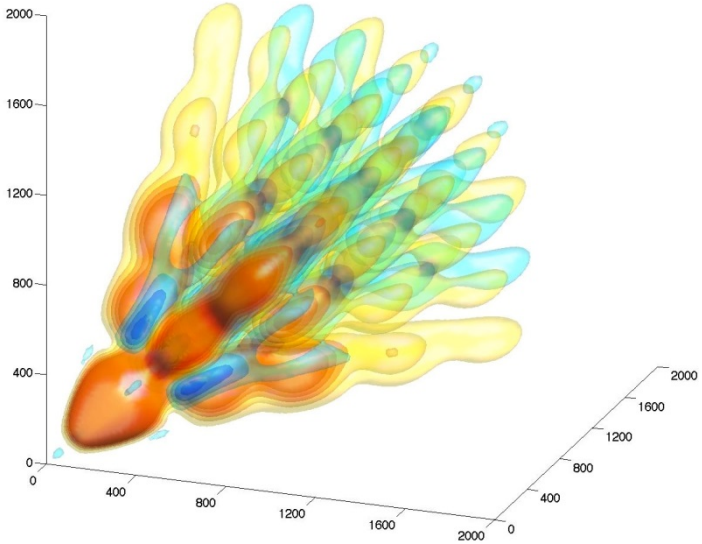
12-knots power spectra

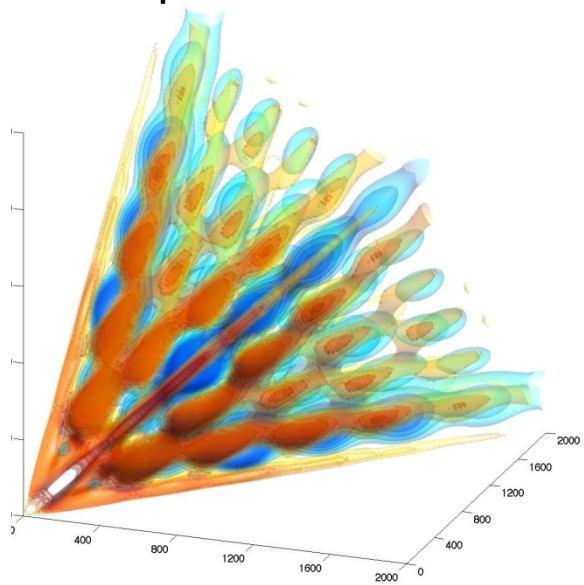
(actually used 3 different methods, all with similar results)

CMB bispectrum fingerprinting with Planck

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

New bispectrum constraints w. full mission data

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. wrt Planck 2013

$$\Phi = \phi + f_{NL}(\phi^2 - \langle\phi^2\rangle) \quad |f^{Loc}_{NL}| <$$

non-Gaussian potential

Gaussian field

10^3 (Maxima 2001),
10^2 (WMAP7),
10 (Planck 2015)

A hundred-fold improvement in 14 years

Planck cosmology

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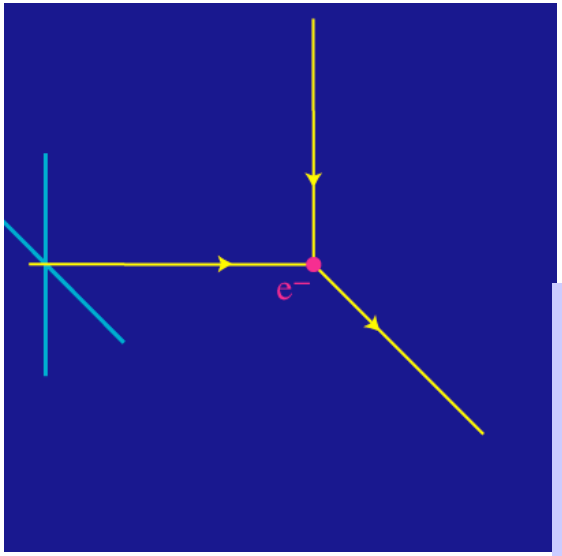
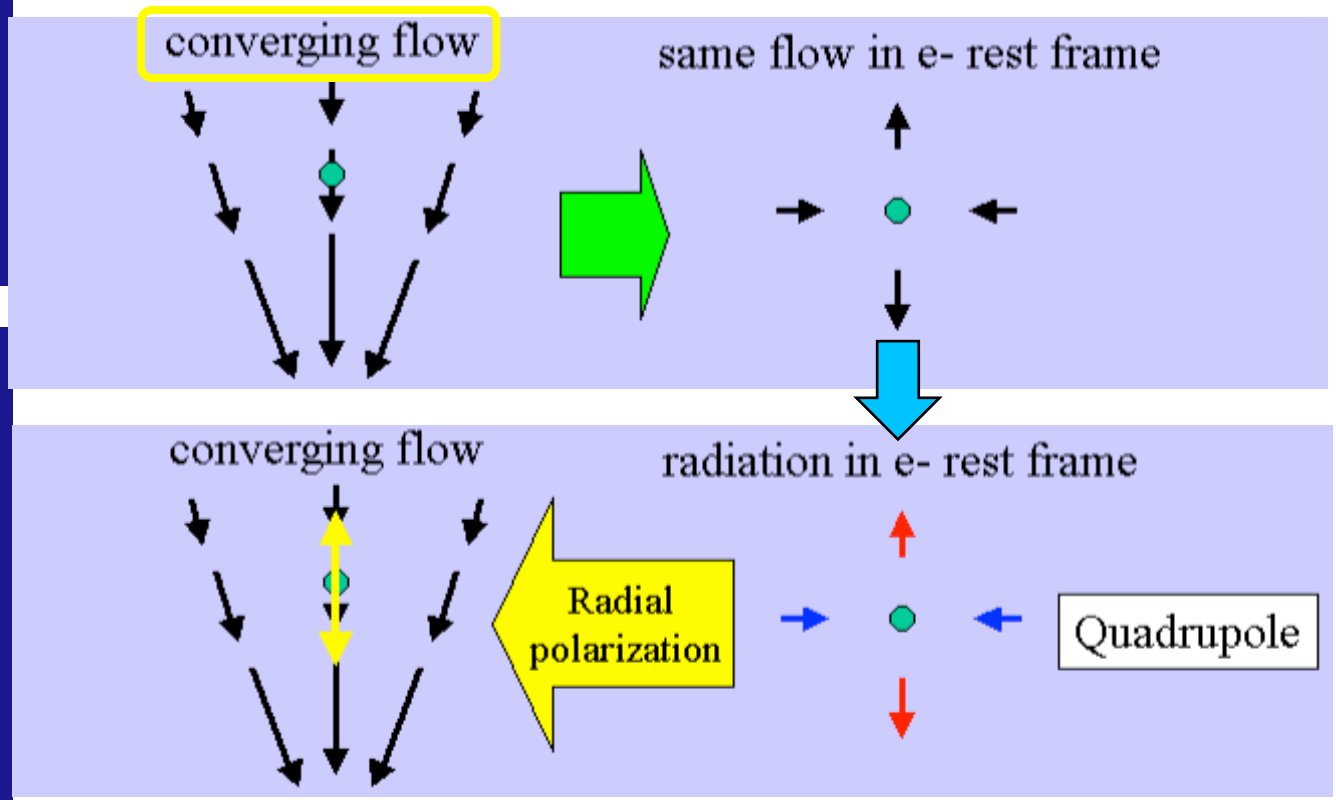
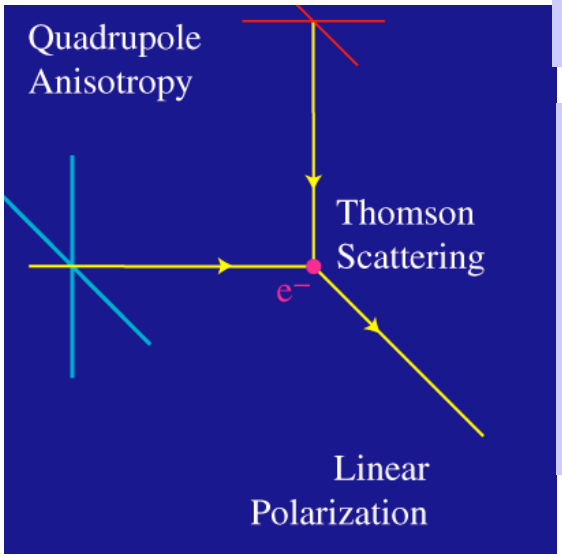
Thomson scatterings are polarised



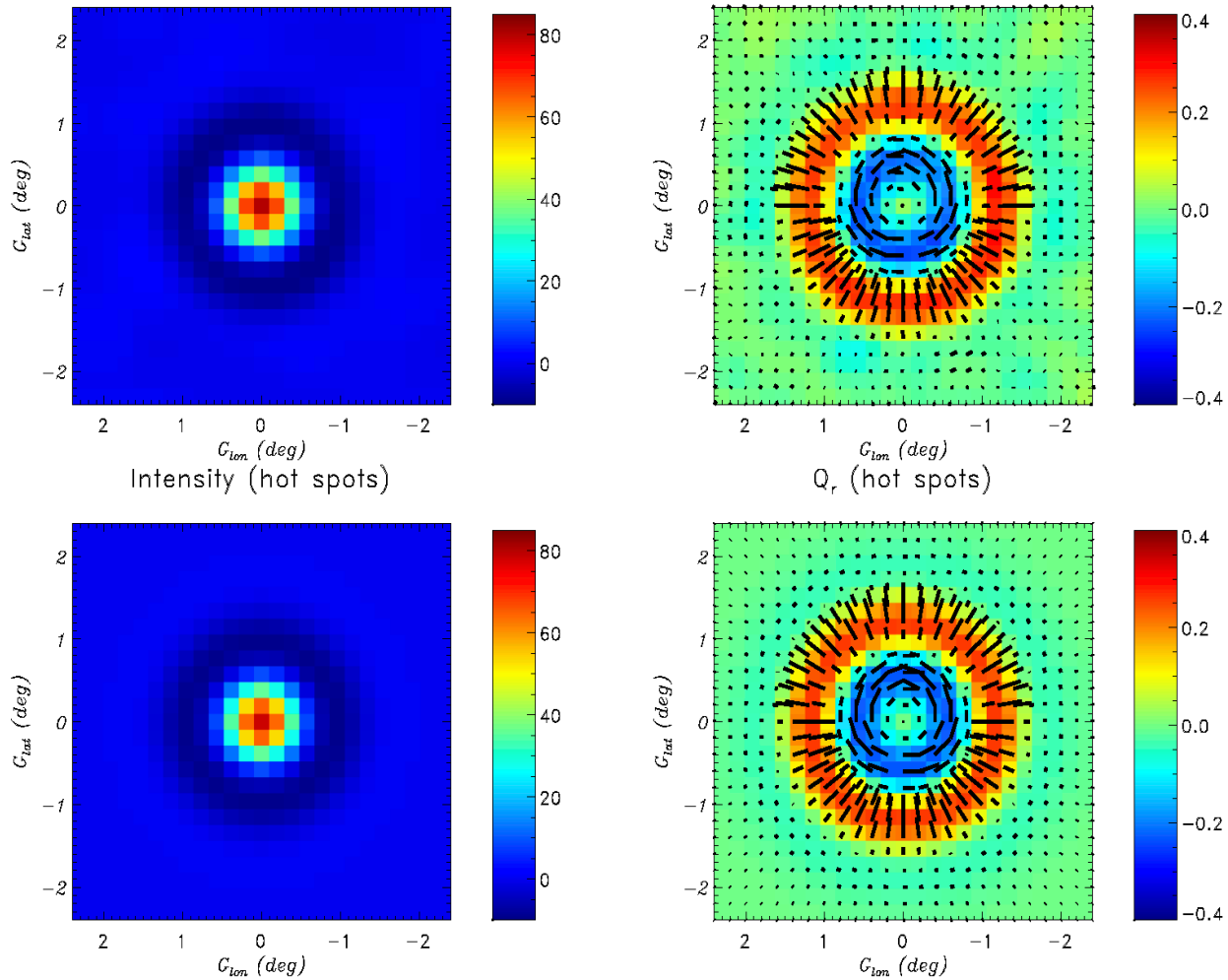
- Before recombination, successive scatterings destroy polarization and the radiation arrives at recombination unpolarized.
- During recombination, Gradients in the velocity field can produce a quadrupole in the rest frame of the scattering electron.





- A *diverging* flow leads to a *tangential* pattern of polarization

Polarisation around hot spots

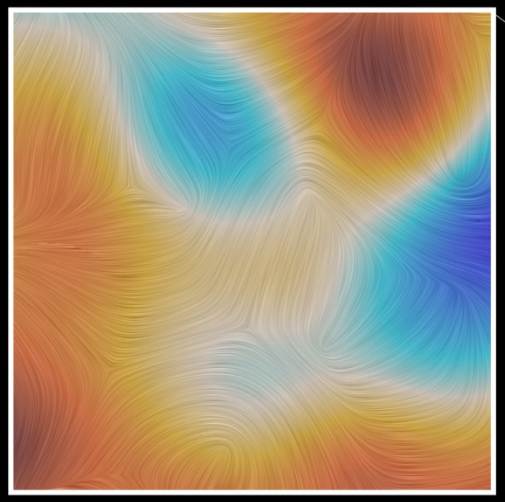


Data (top) versus expectation (bottom)

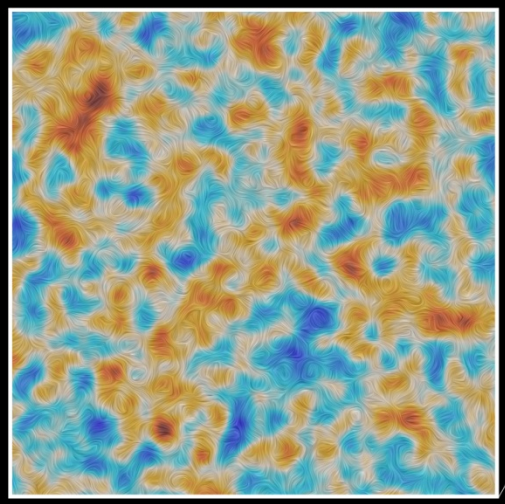
➔ Planck "sees" precisely the dynamics of fluctuations, at ~380 000 years

➔ It would be different with a different content

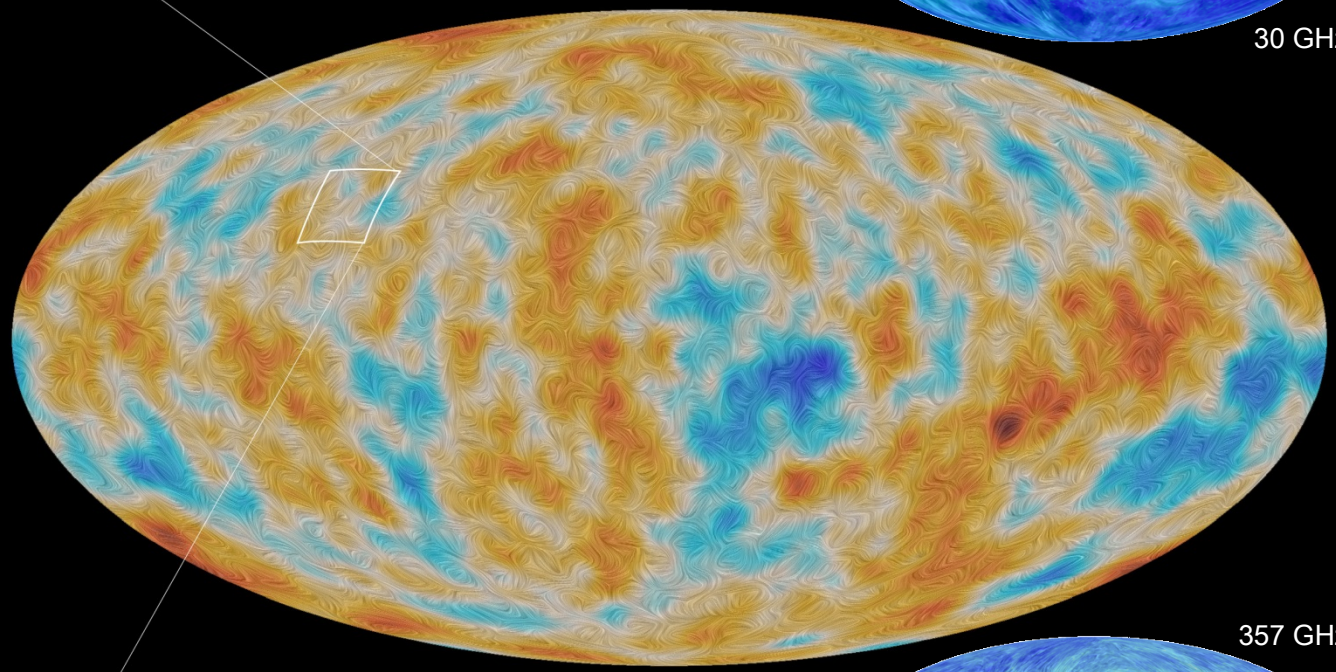
→ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND



Filtered at 5 degrees

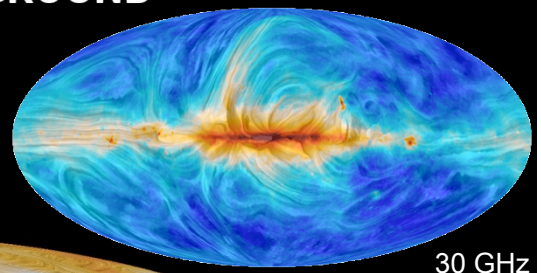


Filtered at 20 arcminutes

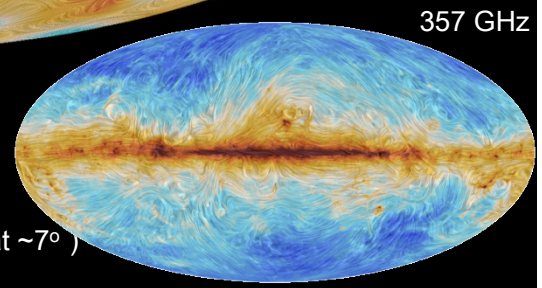


Full sky map
Filtered at 5 degrees

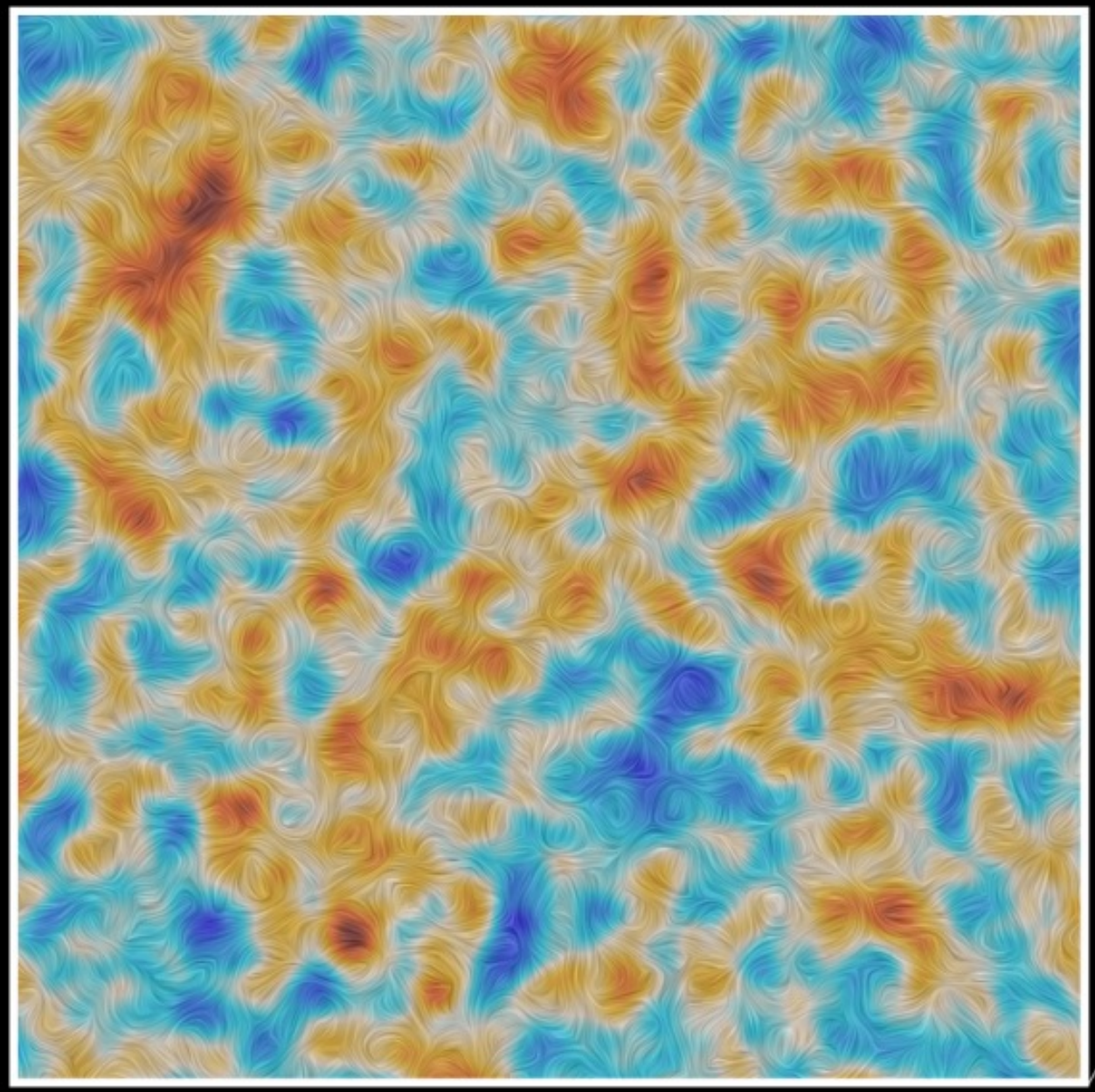
(and high-passed filtered at ~7°)



30 GHz

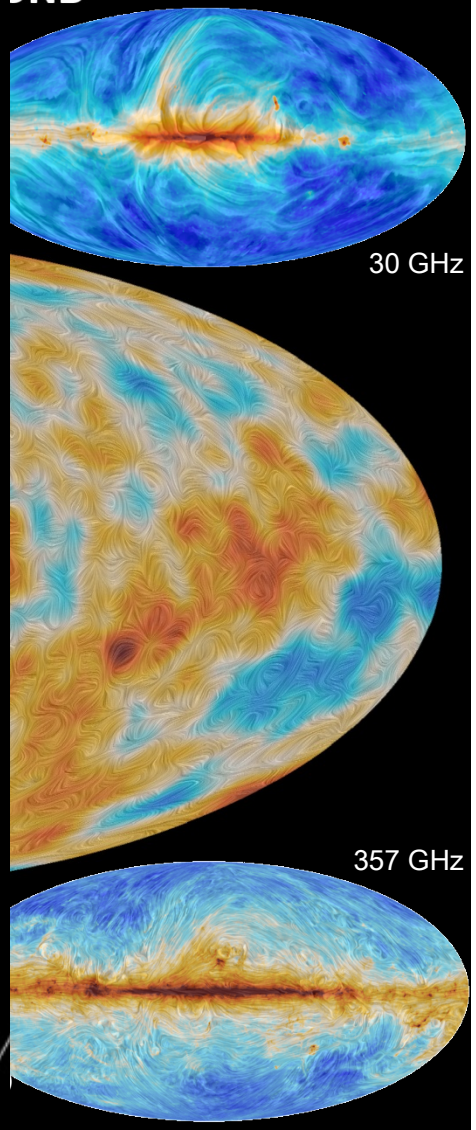


357 GHz



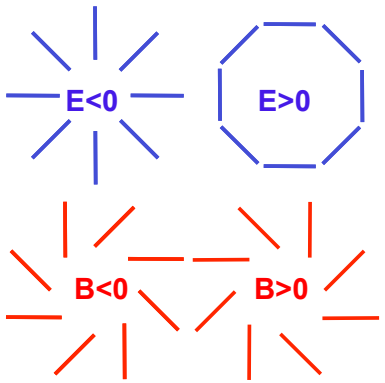
Filtered at 20 arcminutes

JND



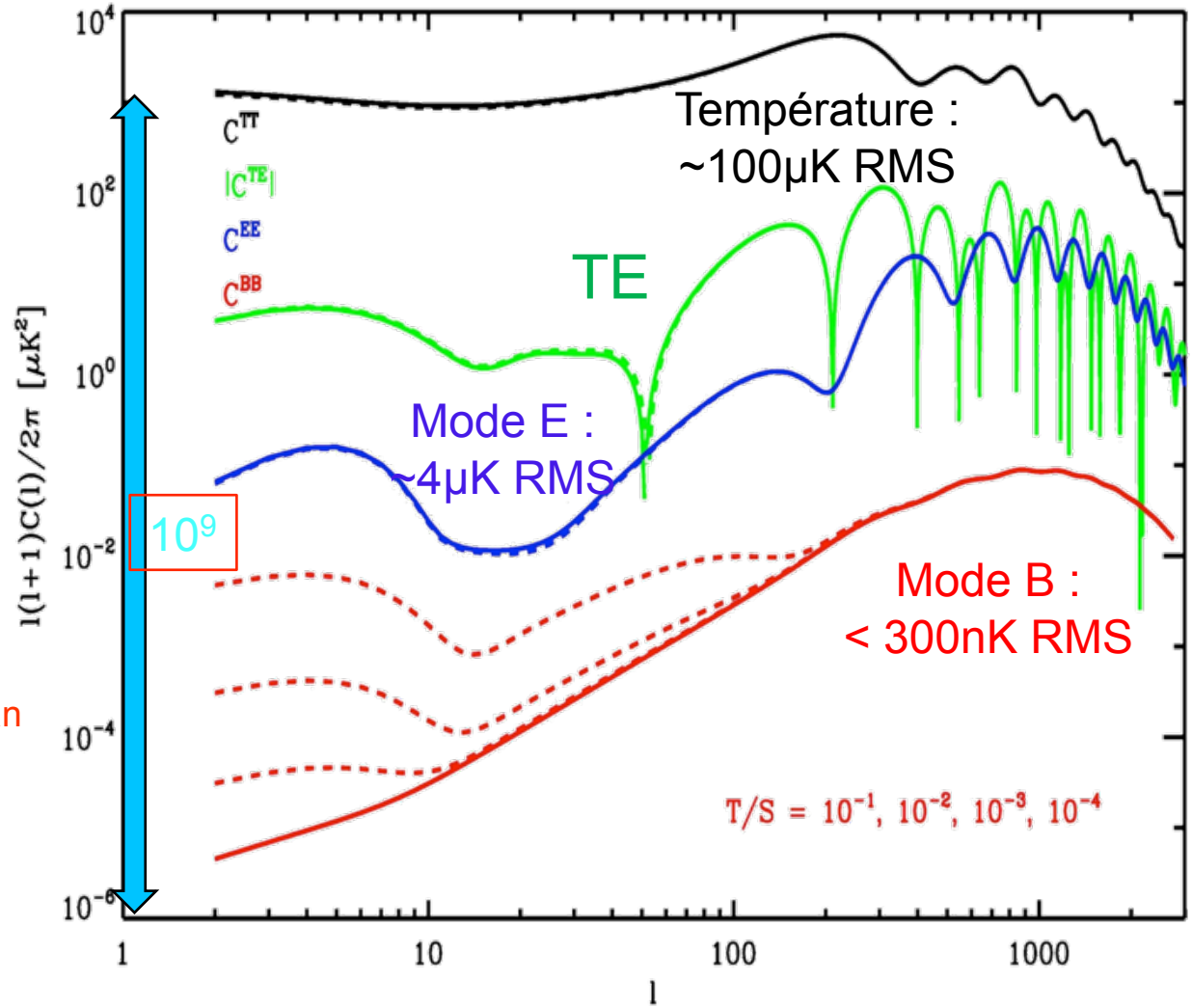
CMB angular power spectra

- 3 observables : T, E, B



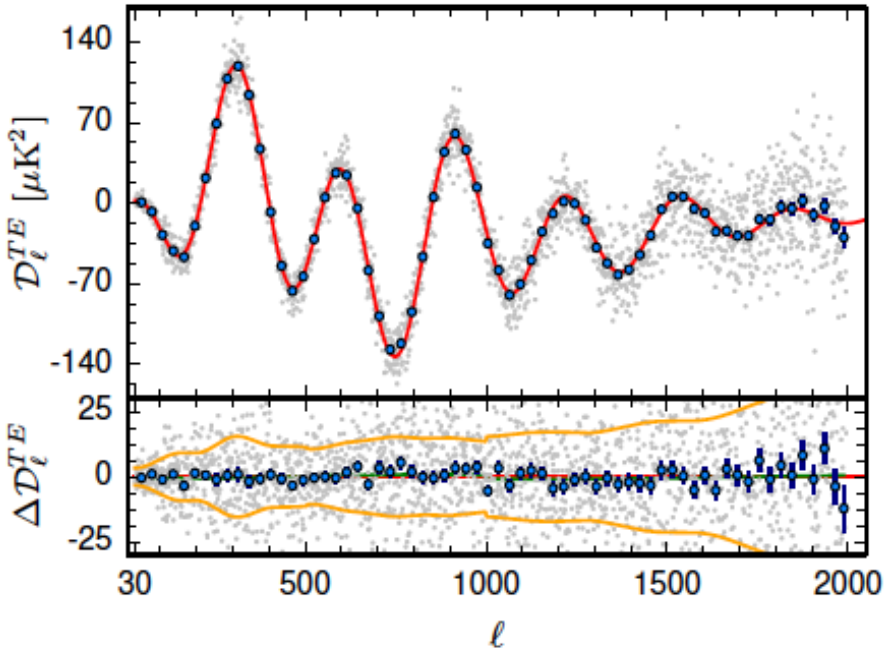
- B Modes:
  - **Not** generated by scalar modes
  - "Smoking gun" of tensorial perturbations
  - At best 300 times weaker than T fluctuations
  - case T/S = r = 0.1 (cf. fig),
  - E_{inf}=1.6 x 10^{16} GeV (~GUT).

- B mode Spectrum peaks at l < 200, i.e. θ > 1 deg

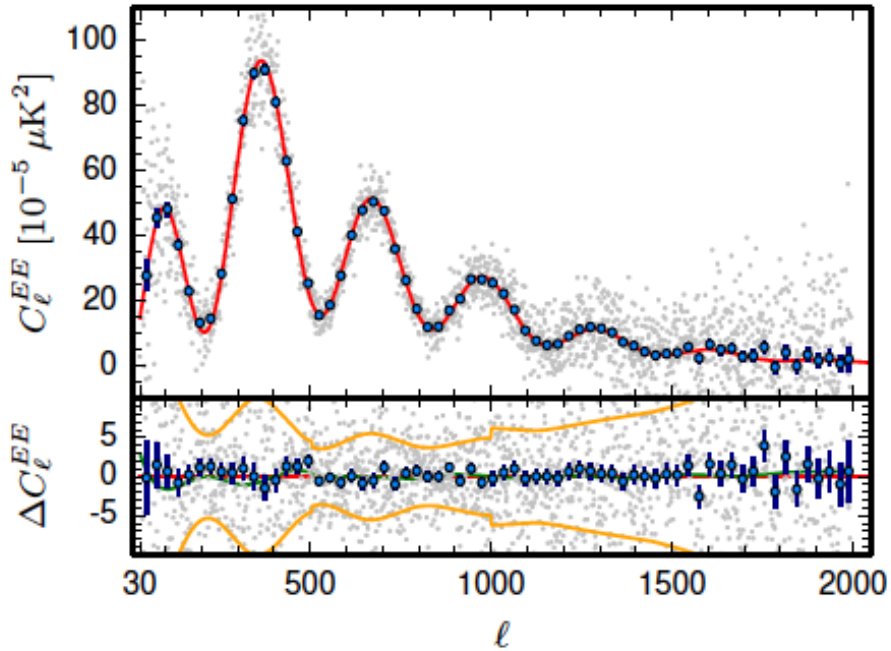


(θ ≈ 180 / l)

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
- 2015 polarisation data and results are not final yet because all systematic and foreground uncertainties have not been *exhaustively* characterised at O(1μK^2).

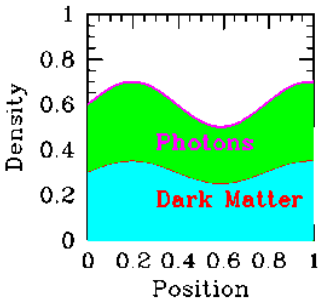
Base ΛCDM model

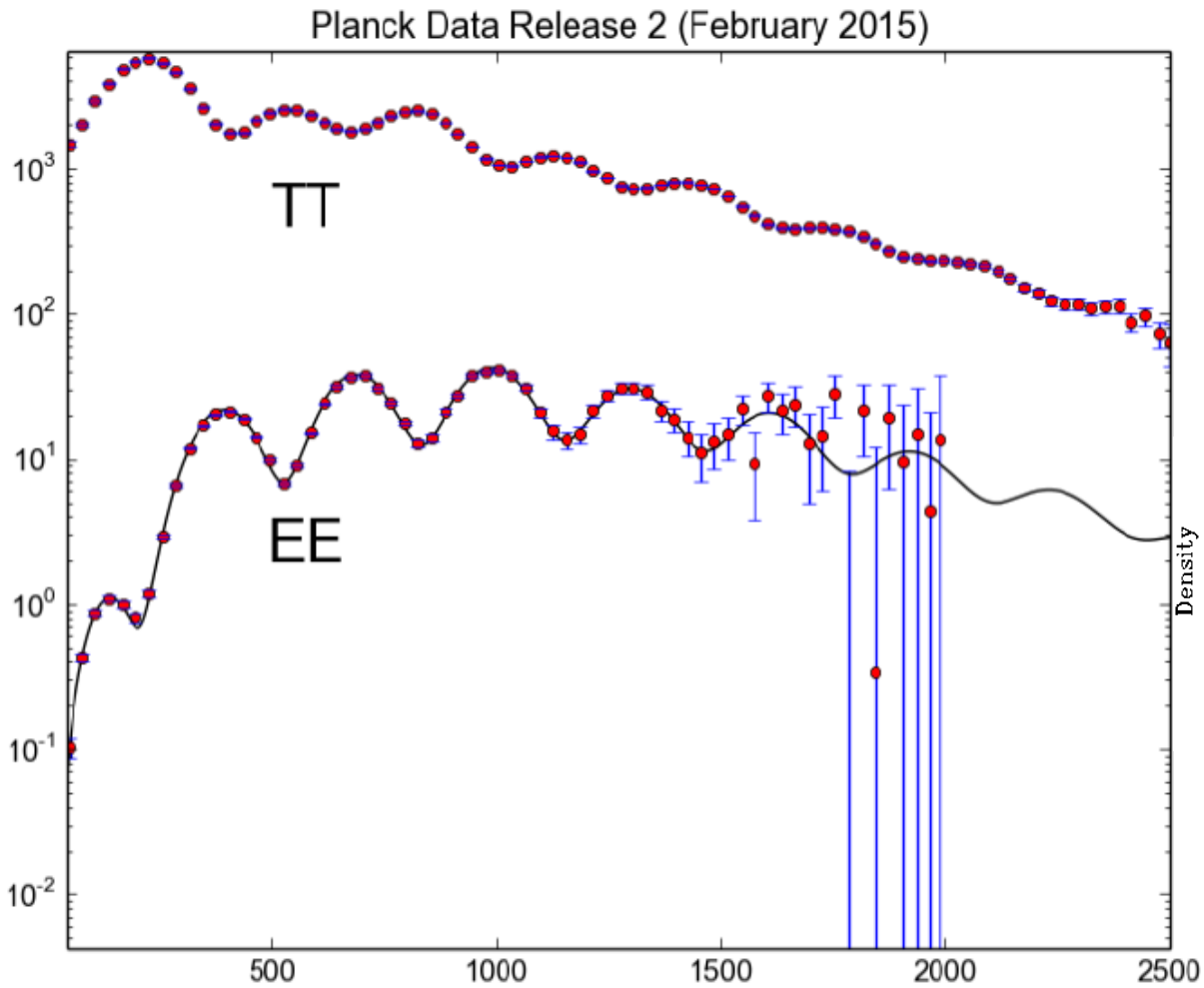
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051
τ	0.078 ± 0.019	0.053 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041
n_s	0.9655 ± 0.0062	0.965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

TT & TE have quite similar uncertainties (but for n_s),
but beware that they are still some low level systematics in the polarisation data

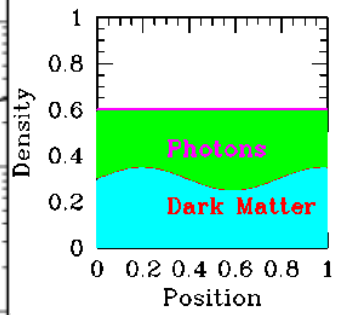
Adiabaticity ?

Adiabatic IC



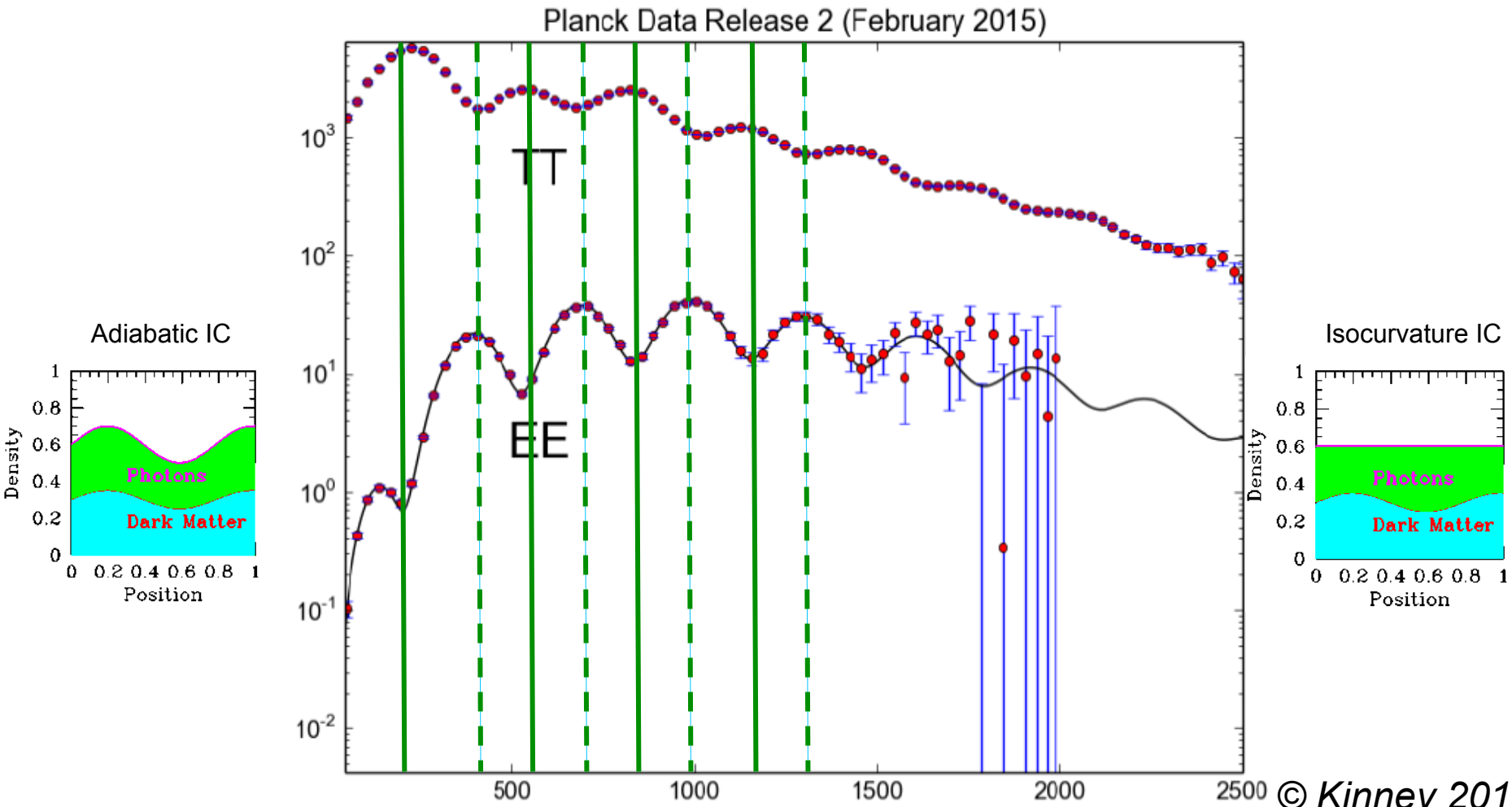


Isocurvature IC



(Data: Planck Legacy Archive)

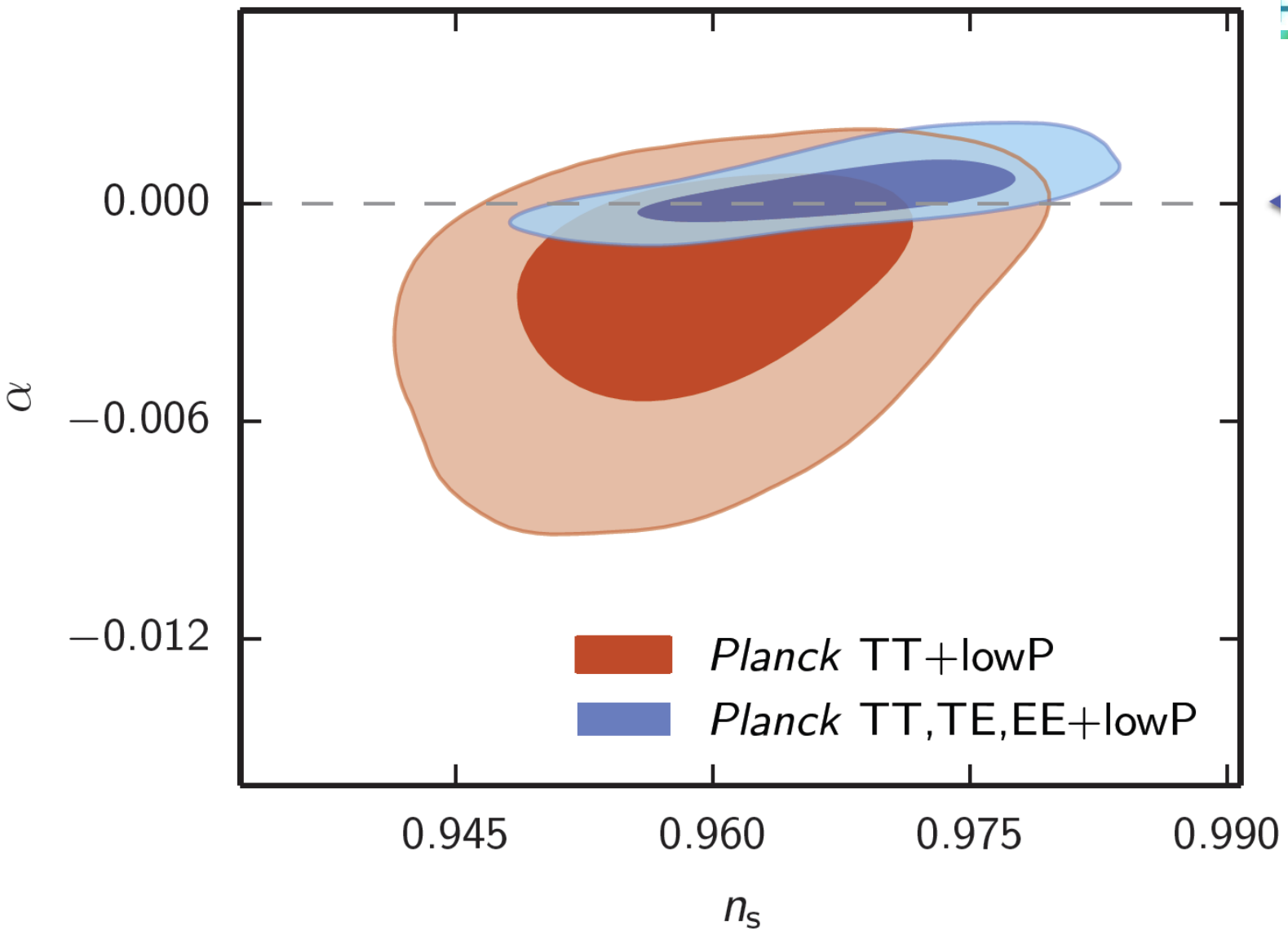
Adiabaticity ✔



© *Kinney 2015*

(Data: Planck Legacy Archive)

Isocurvature modes fraction

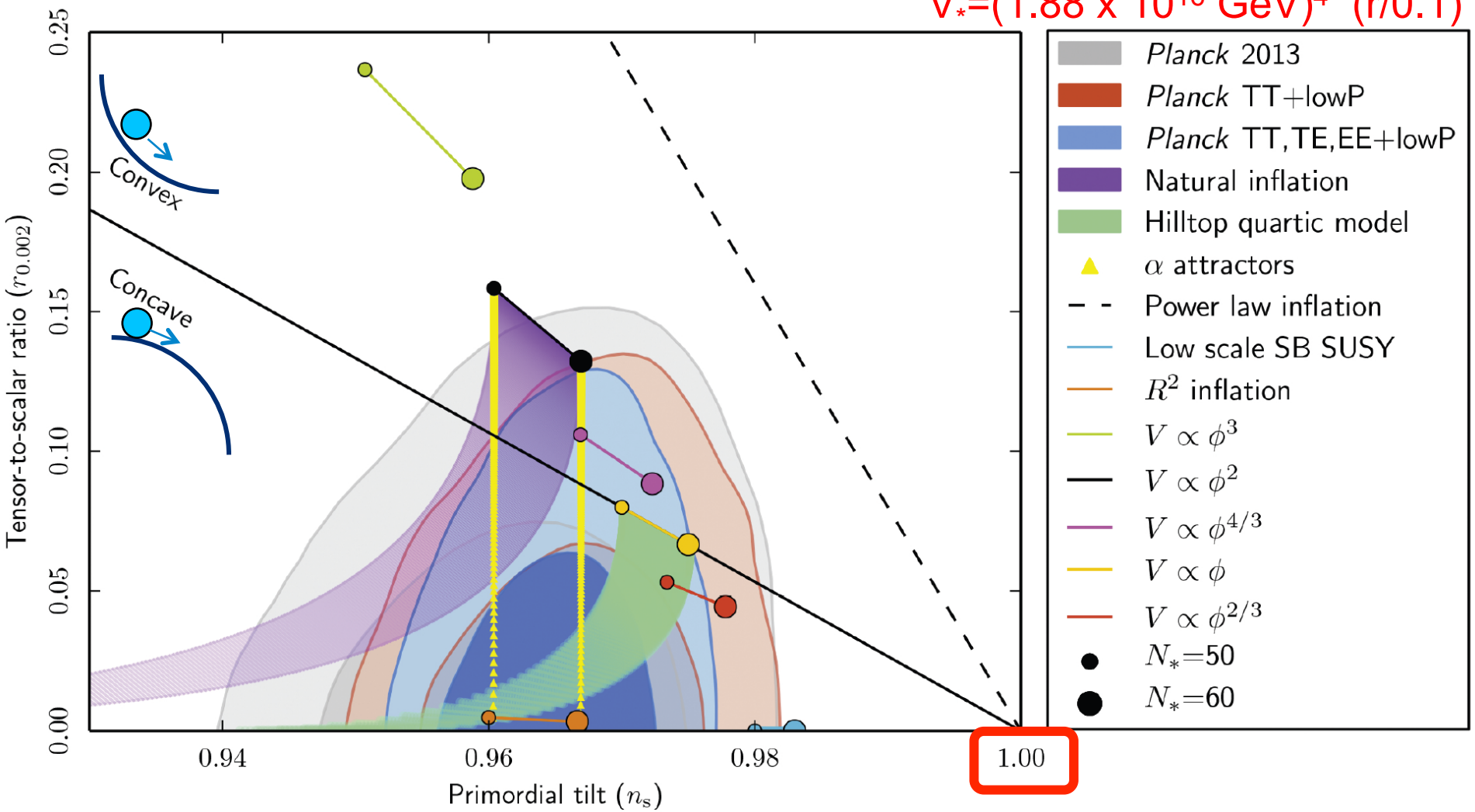


Percentage of isocurvature: $13^{+6}_{-6}\%$ Moodley, Ferreira et al (2004)

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

Planck 2015: n_s vs r

$V_*=(1.88 \times 10^{16}\ \mathrm{GeV})^4\ (r/0.1)$



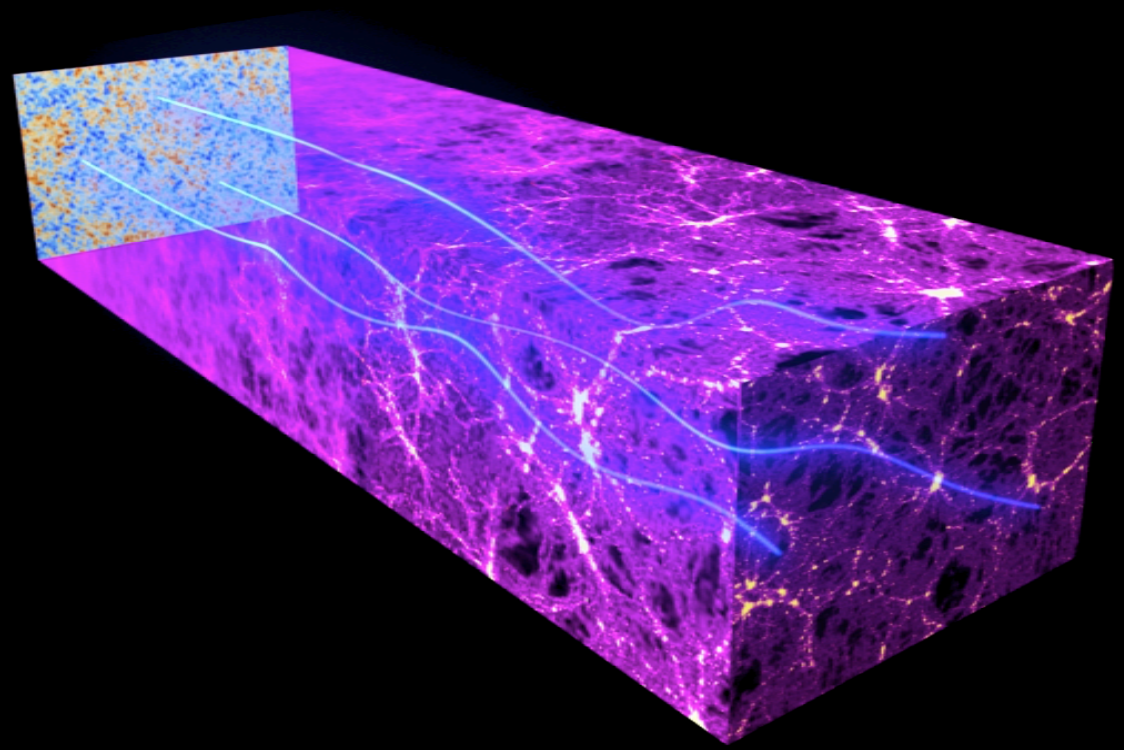
$r_{0.002} < 0.10$ @ 95% CL, similar (indirect) r constraint than with 2013 release (was 0.11)

Planck cosmology

- Planck ?
- CMB Temperature anisotropies
  - *Universe initial conditions*
    - Primordial power spectrum
    - (Non-)Gaussianity
  - *Constraints on Inflation*
- CMB Polarization
  - *Consistency with temperature*
  - *Adiabaticity of initial conditions*
- **Secondary anisotropies**
  - *Gravitational lensing*
  - *Re-ionization*
- Consistency with other probes
  - *BAO, BBN, SN1a*
  - *ΛCDM fits all ?*
- Tensions
- Overall picture

GRAVITATIONAL LENSING DISTORTS IMAGES

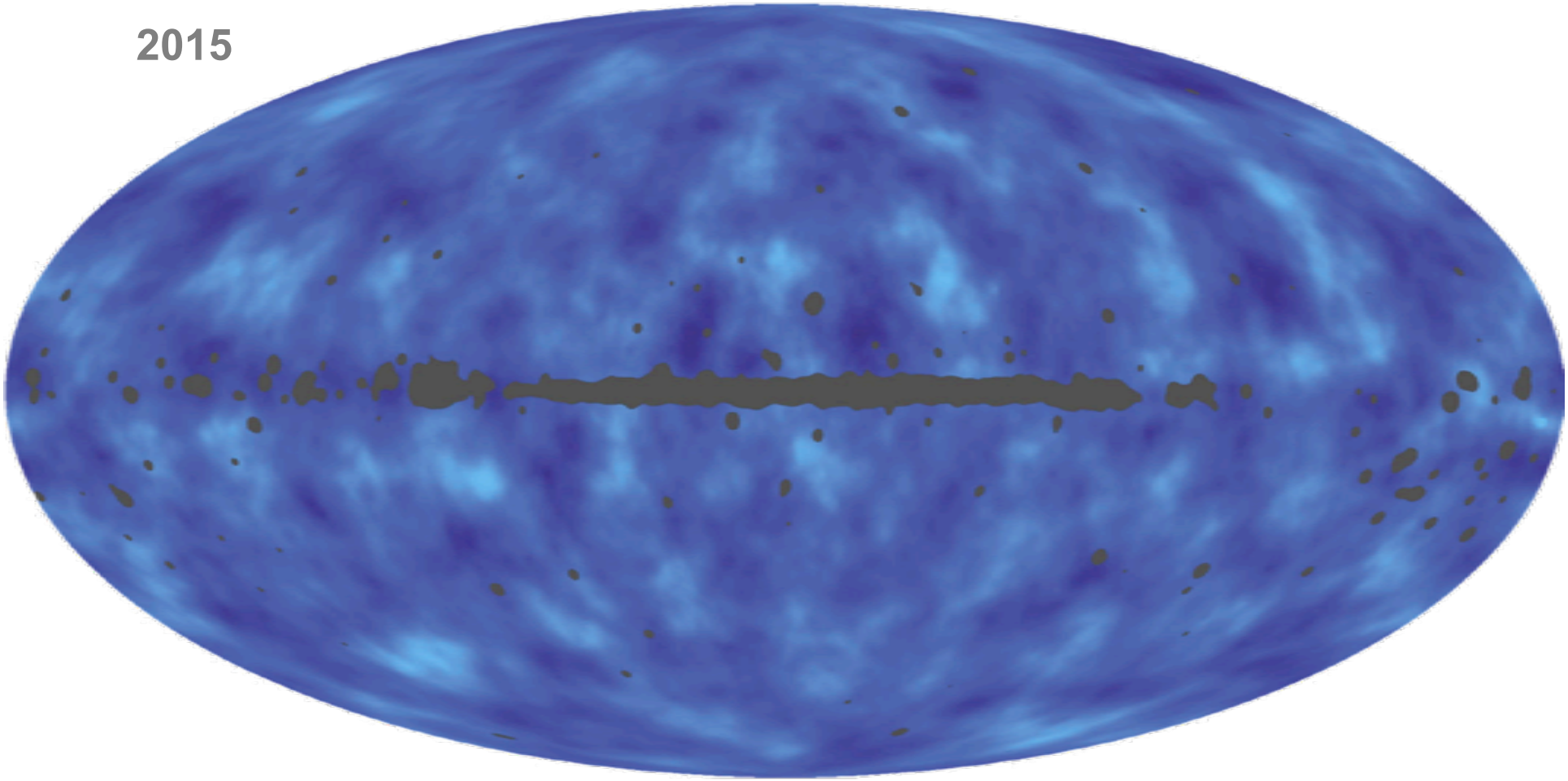
The gravitational effects of intervening matter bend the path of CMB light on its way from the early universe to the Planck telescope. This “gravitational lensing” distorts our image of the CMB (smoothing of the power spectrum, and correlations between scales).



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

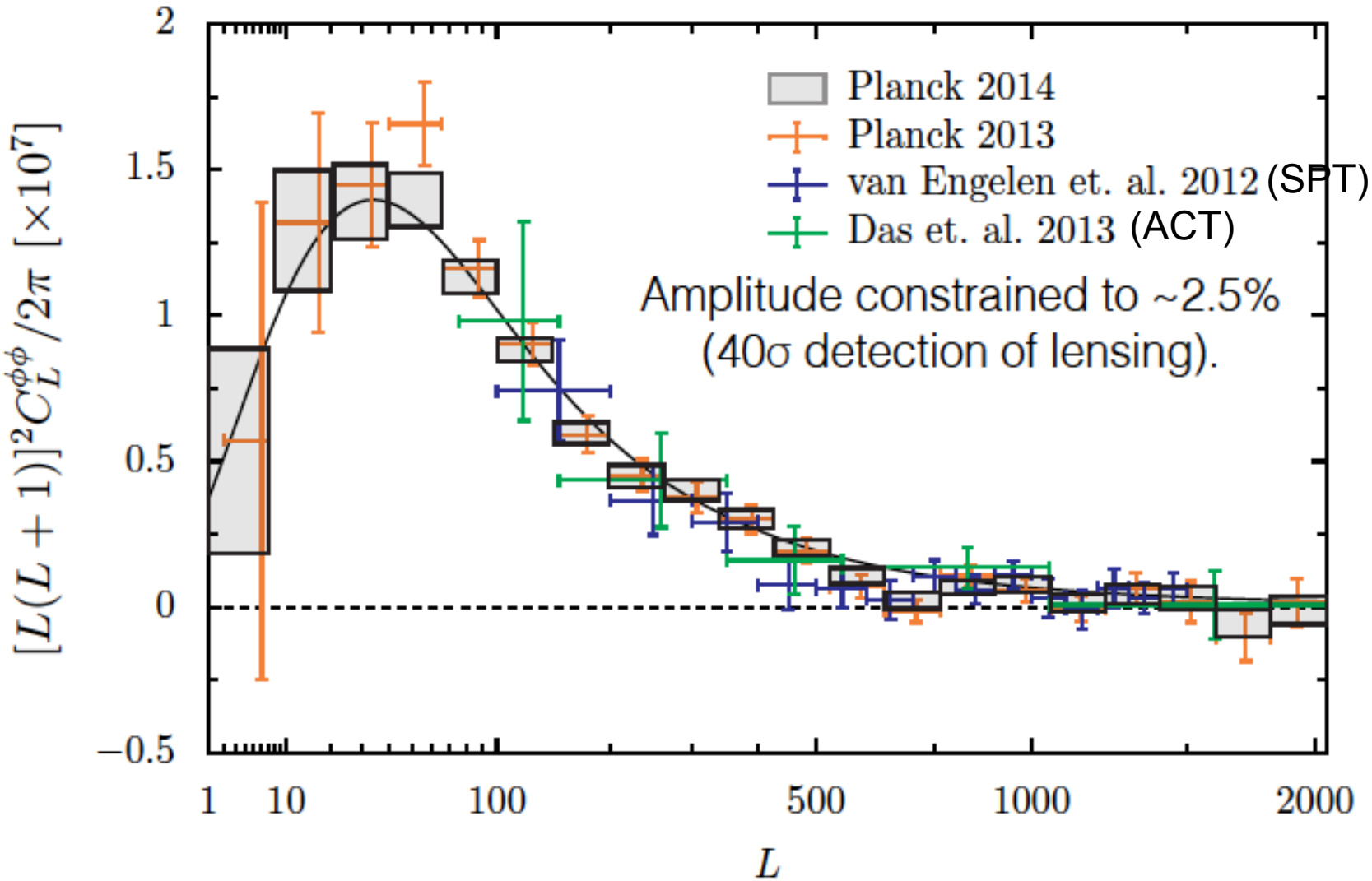
$$\bar{\phi} = \Delta^{-1}\vec{\nabla} \cdot [C^{-1}T\ \vec{\nabla}(C^{-1}T)]$$

Projected mass map



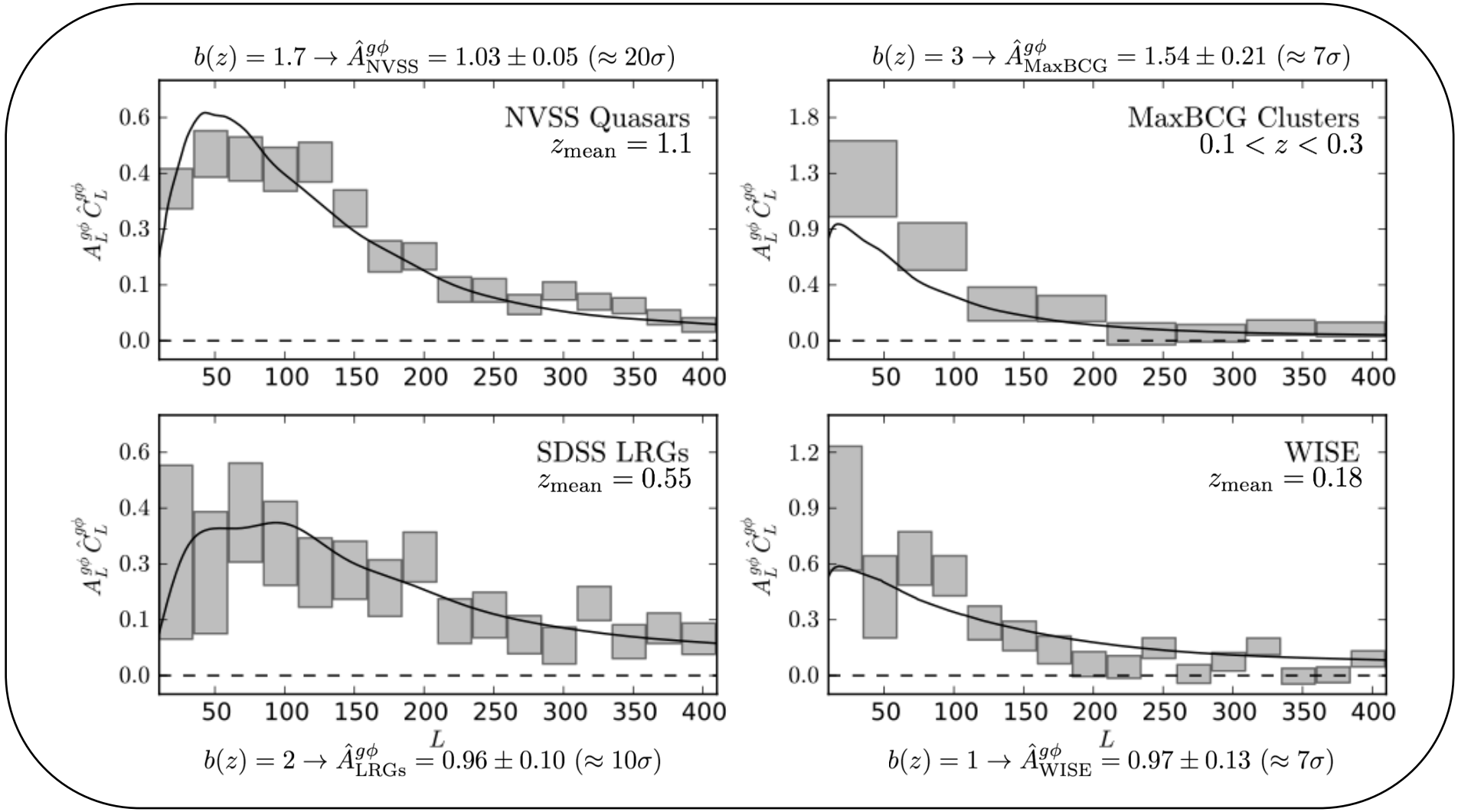
The (grey) masked area is where foregrounds are too strong to allow an accurate reconstruction

Lensing power spectrum



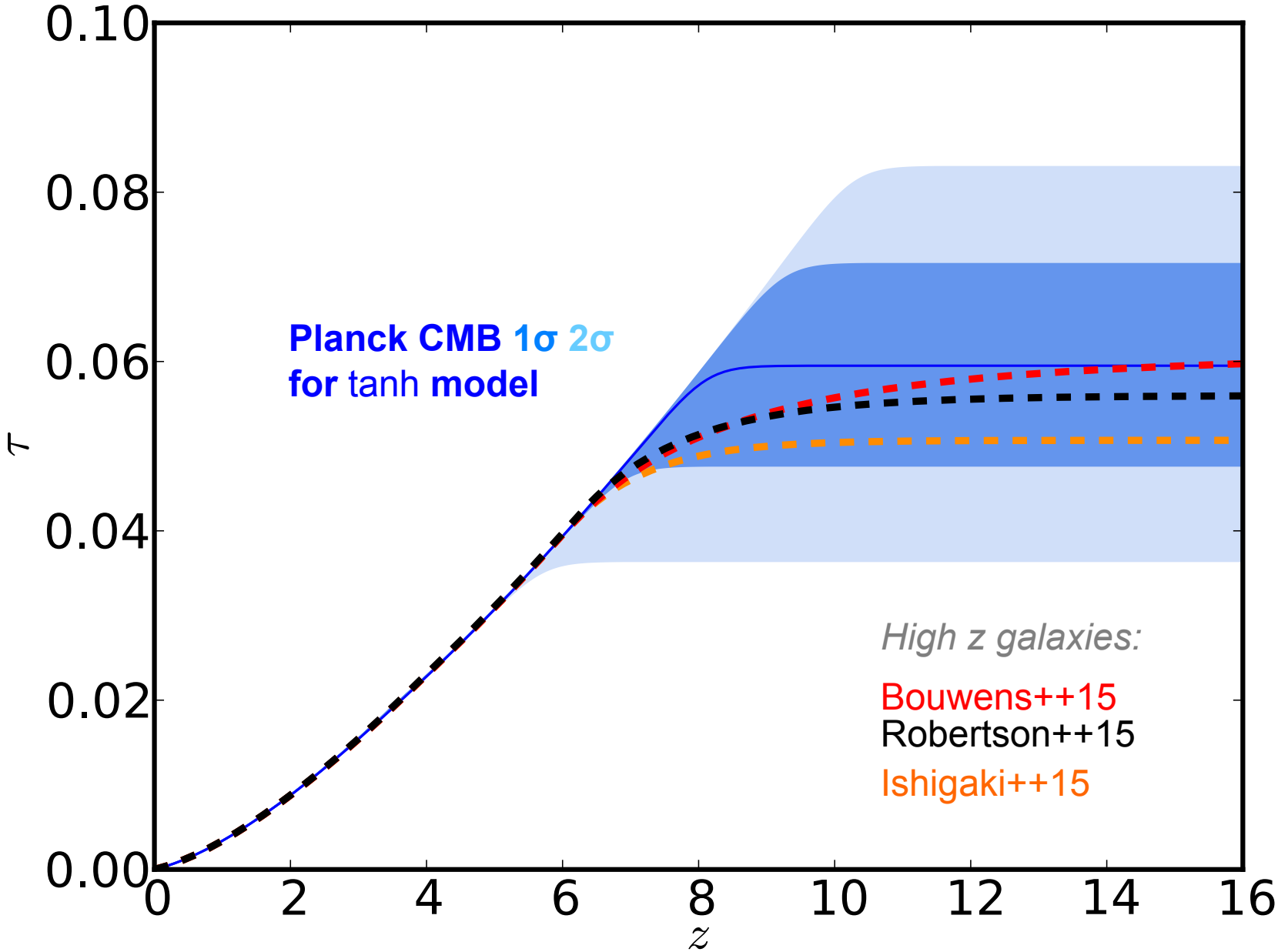
Planck for the first time measured the lensing power spectrum with higher accuracy than it is predicted by the base CDM model that fits the temperature data

Lensing potential versus distribution of external tracers

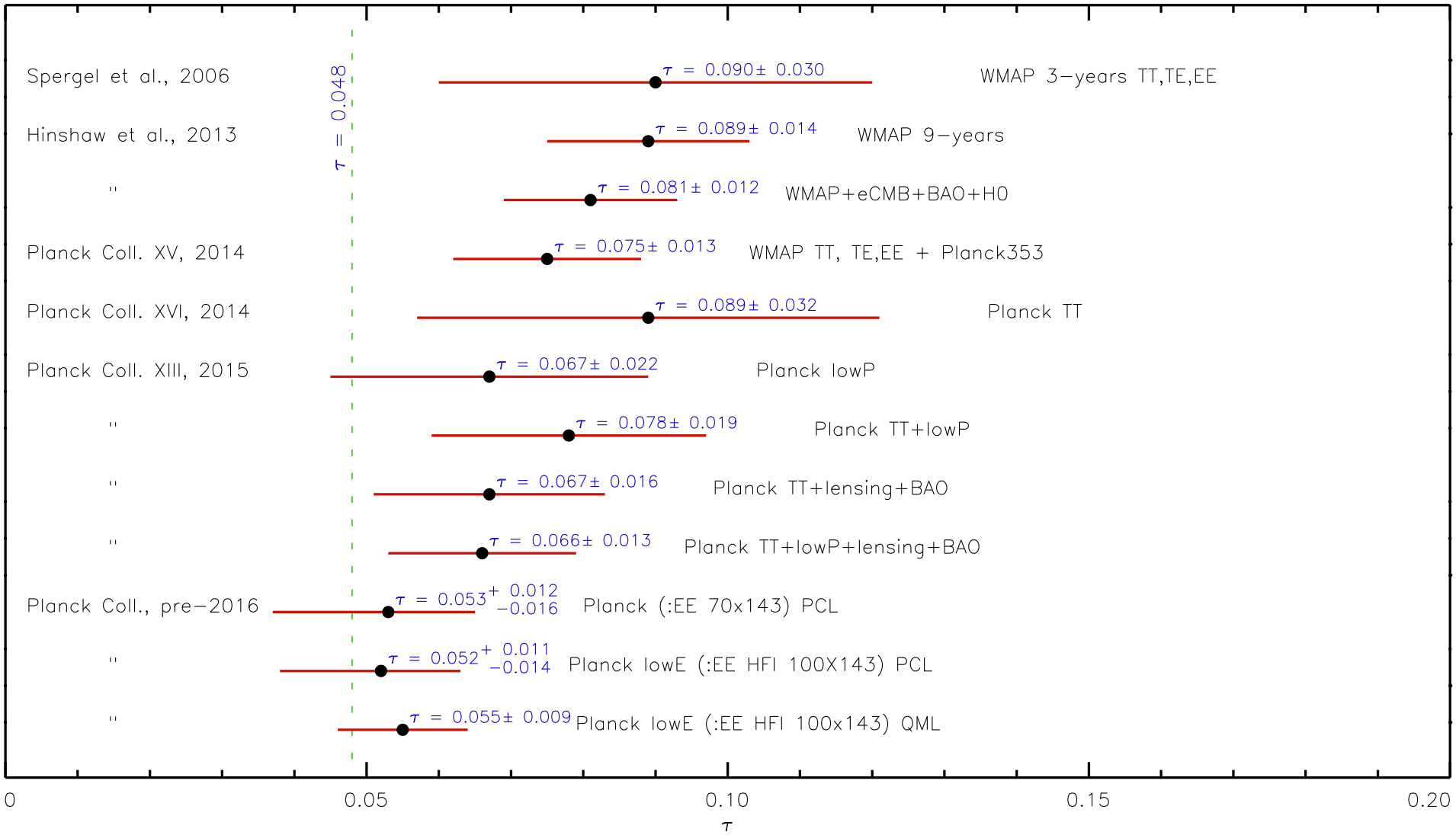


No particular effort here to optimize the model for the external survey

Optical depth τ vs z



Optical depth τ vs time



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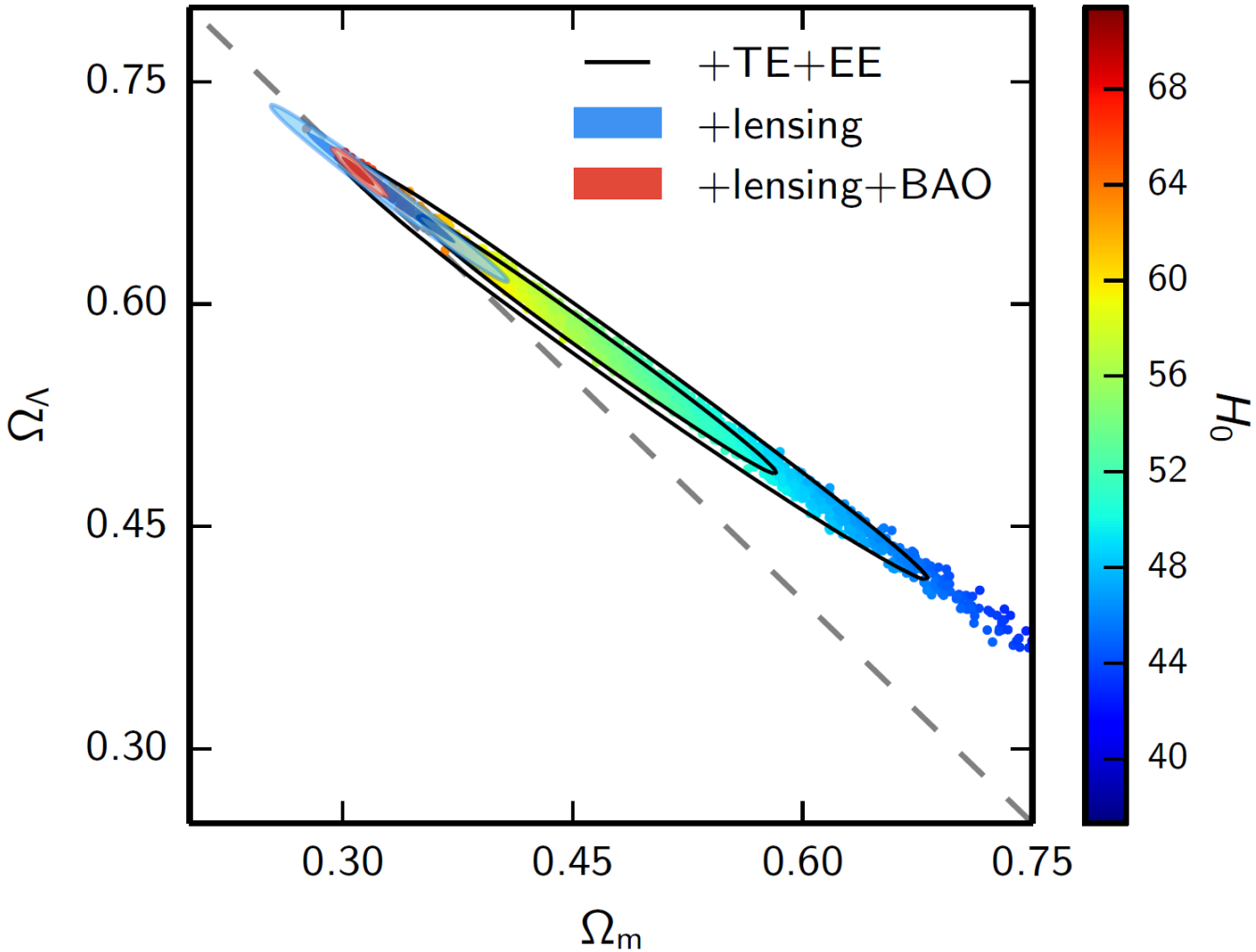
Spatial curvature constraint

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



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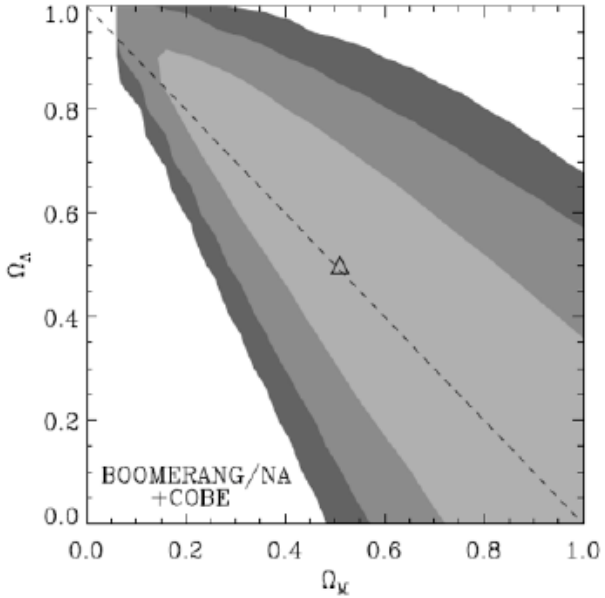
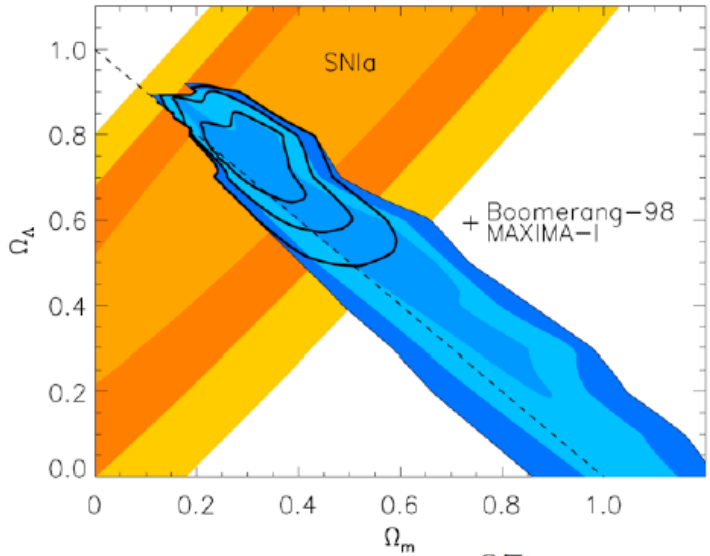


$$\Omega_K = -0.05^{+.40}_{-.40}$$

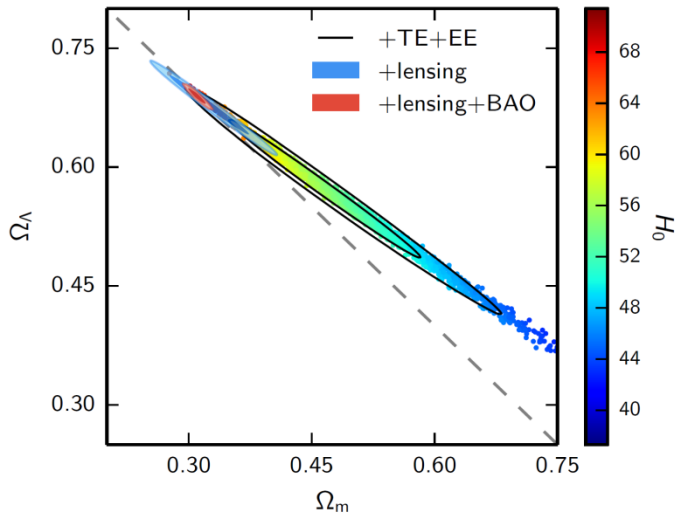
Melchiorri et al. 2000



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

Jaffe et al. 2001

Note the change of axes
For Planck below

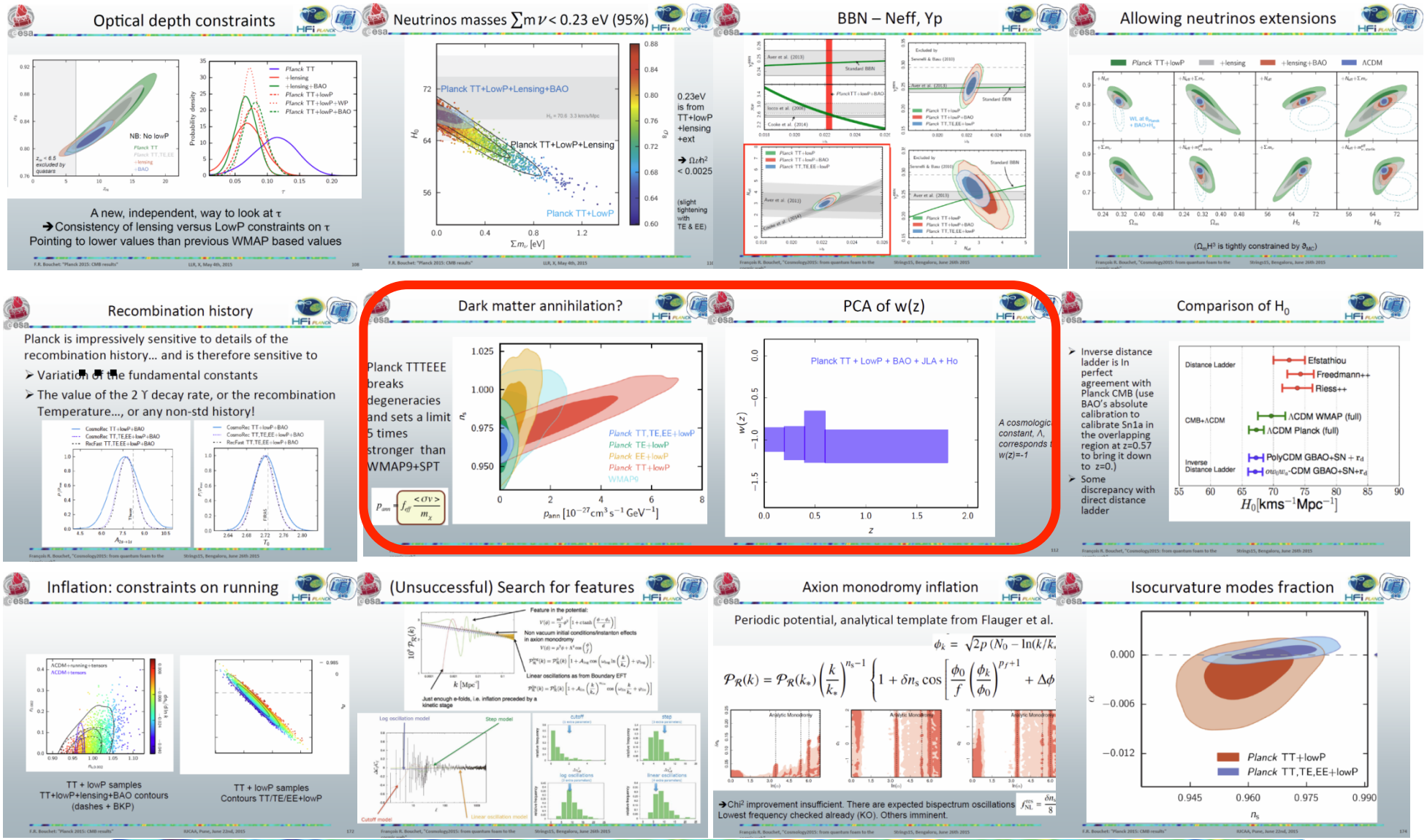


Planck 2015

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

A hundred-fold improvement in 15 years

We can test & constrain a lot more…



Standard cosmological model - ΛCDM

- The CMB TT, TE, EE, Φ-Φ, as well as BAO, BBN (^{2}H and He), and SN1a measurements are all consistent, among themselves and across experiments, within ΛCDM.
- This network of consistency tests is passed **with per cent level precision.**
- These tests allow <u>many</u> different checks of the robustness of this base ΛCDM model and of some of its extensions, including
  - *τ constrained two-ways thanks to CMB lensing,*
  - *flatness at 5 x 10^{-3} level,*
  - *neutrinos masses and number,*
  - *DM annihilation limits,*
  - *w(z),*
  - *details of the recombination history ($A_{2s\rightarrow 1}$, T_0, and also fundamental constants variation, or any energy input…).*

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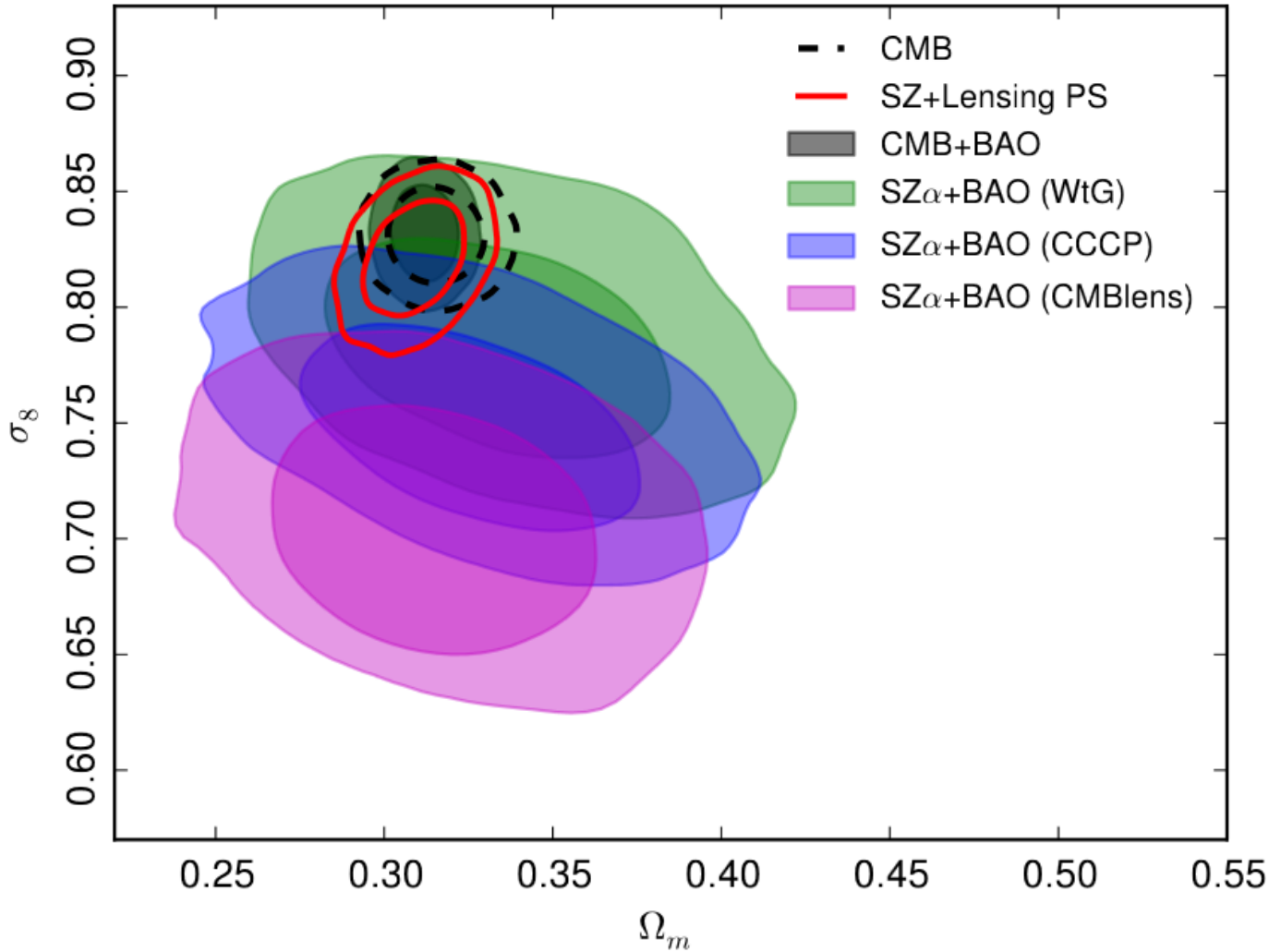
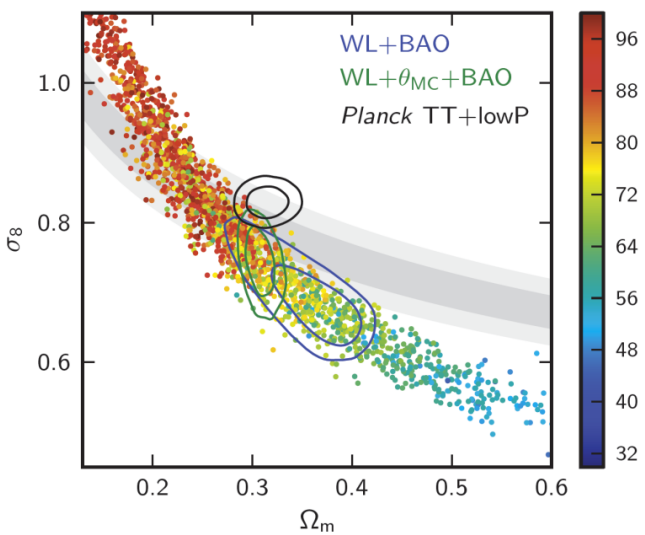
Number counts of SZ clusters



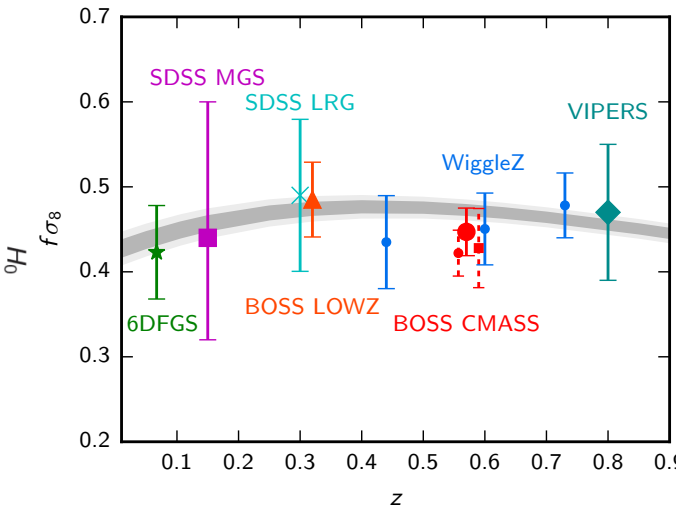
2013 tension only remains with **some** mass proxy calibration

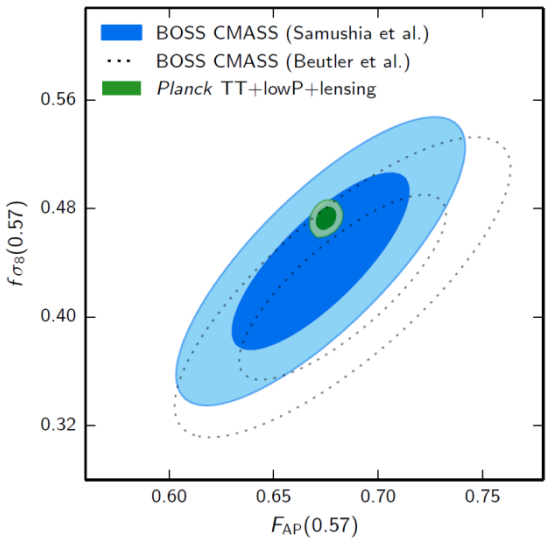
Some tensions exist

Weak Lensing from CFHTLens



Growth rate of fluctuations from redshift space distortions





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

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

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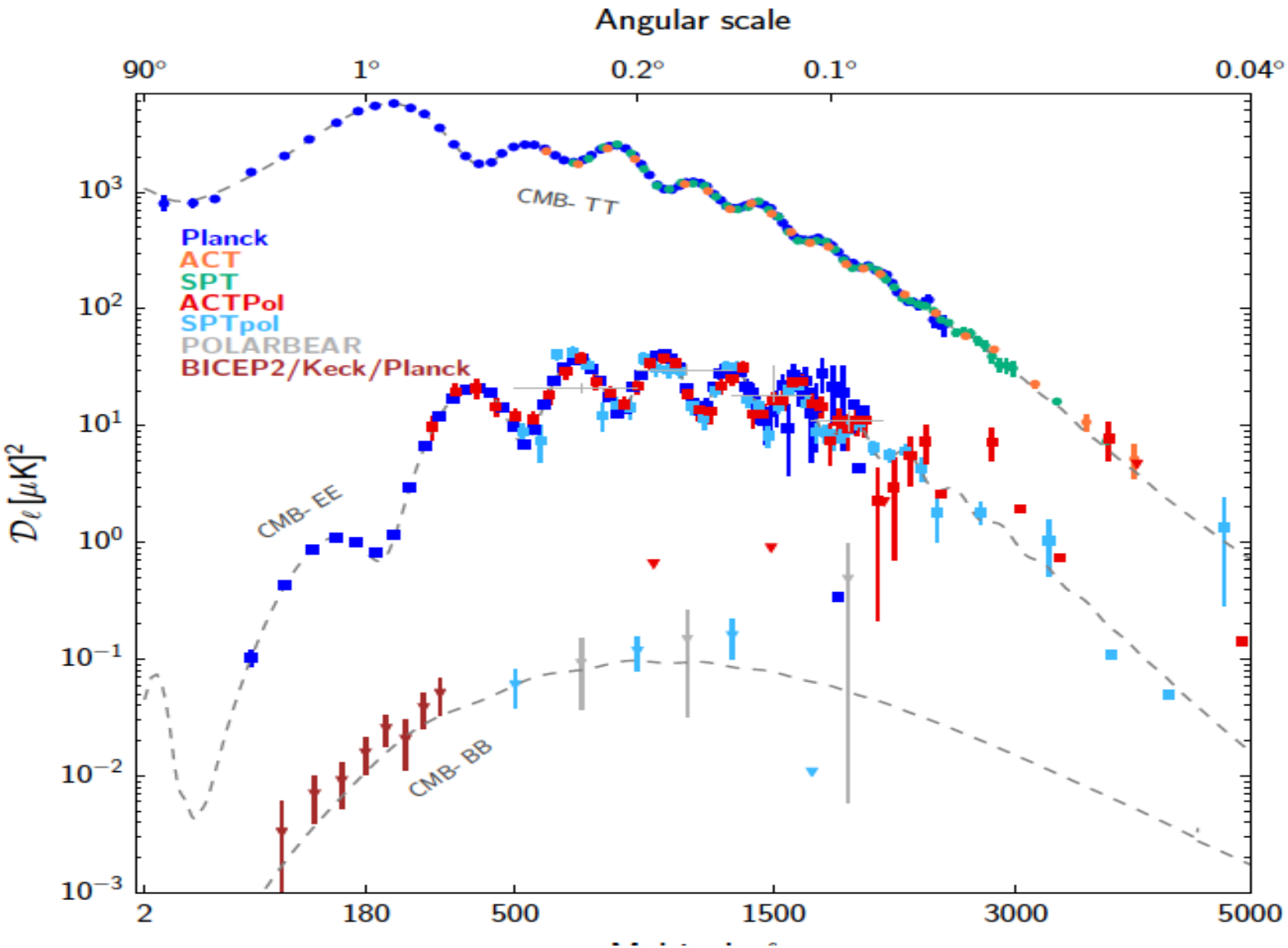
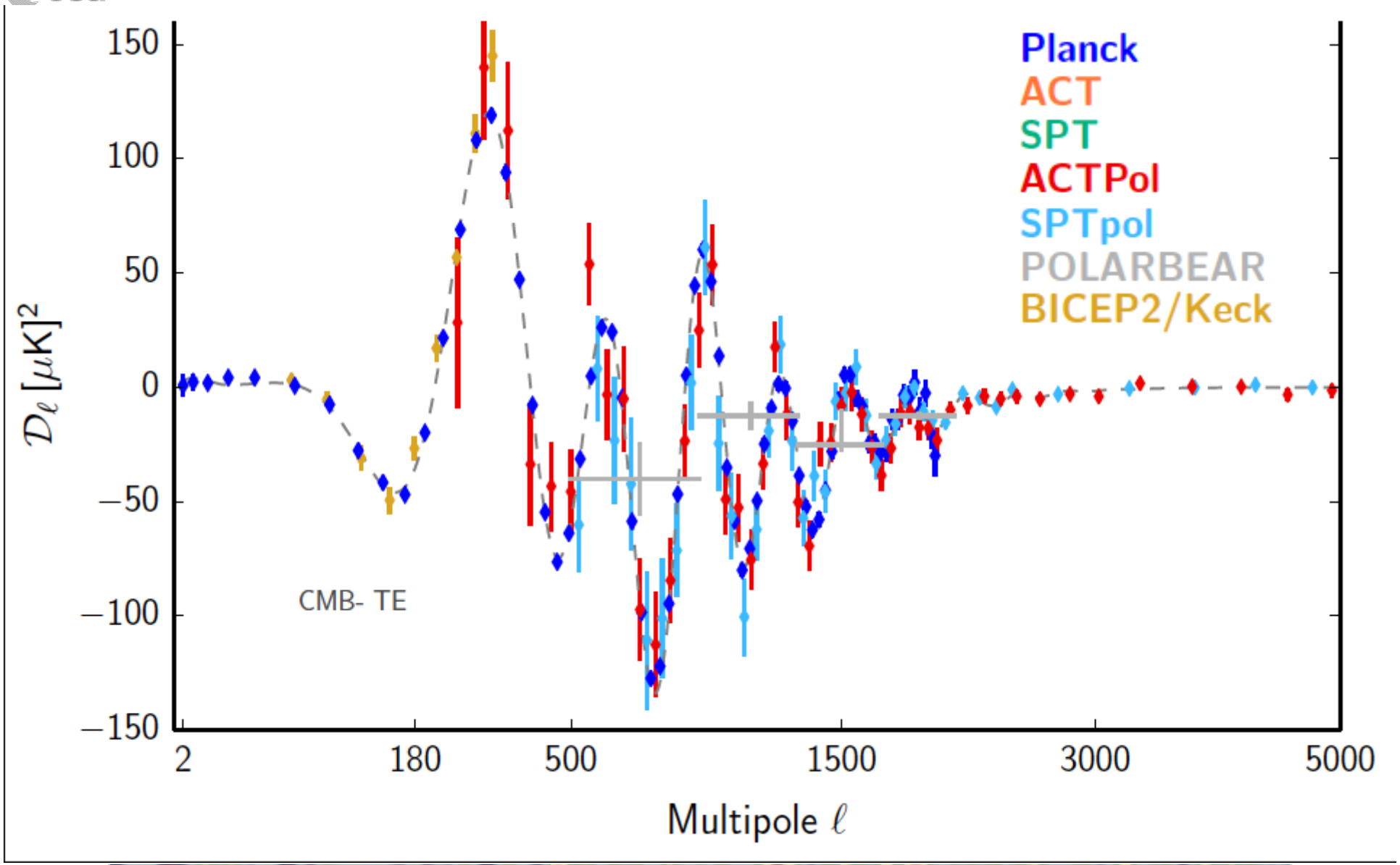
TT, EE, BB – mid 2015 status



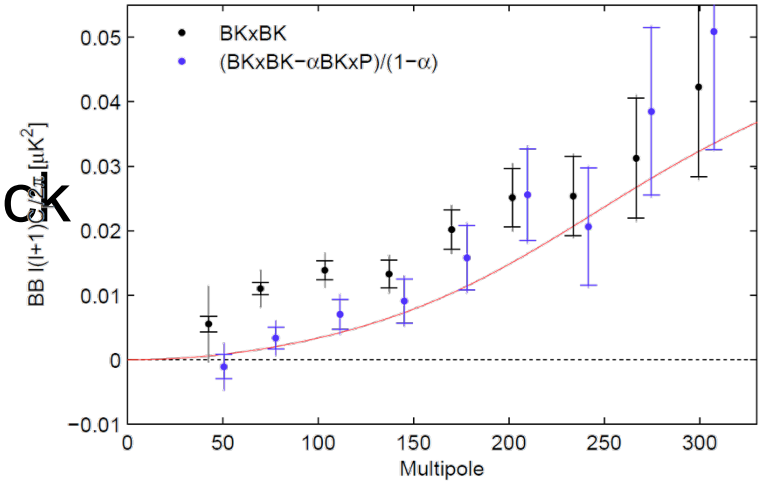
Only keeping points w. sufficiently small error bars

and TE !

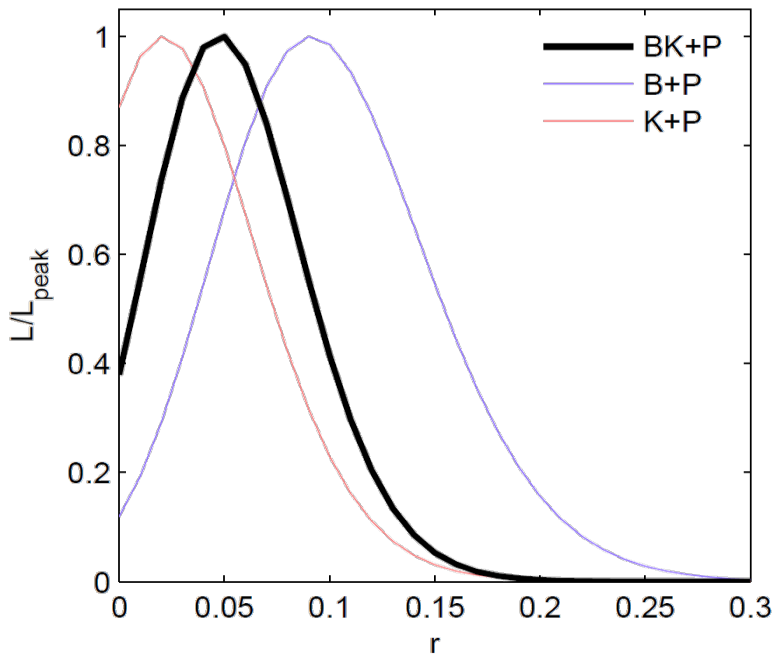

Planck
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck
CMB- TE
150
100
50
0
−50
−100
−150
$\mathcal{D}_\ell$ [μK]^2
2
180
500
1500
3000
5000
Multipole ℓ

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
  ($r = A_T/A_S$ at, e.g., $k=0.05 Mpc^{-1}$)



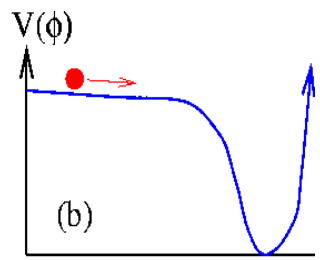
- A new era has begun…

Summary: Basic ΛCDM fits

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

➔ I.e. all consistent within the generic inflationary framework, completing the standard model of cosmology (w. Hot Big Bang phase

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



The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

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

Thank you