Cosmology with Planck

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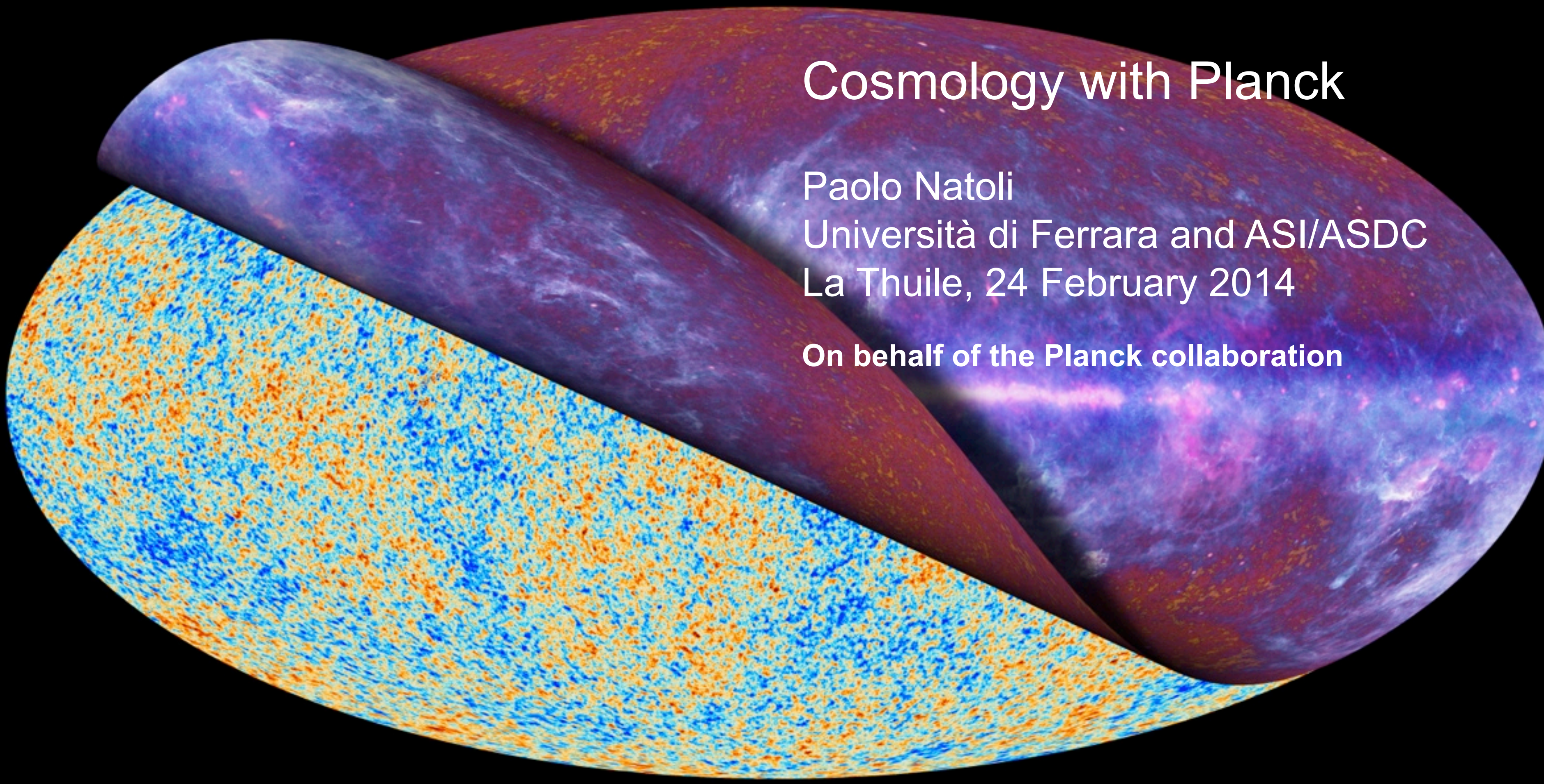
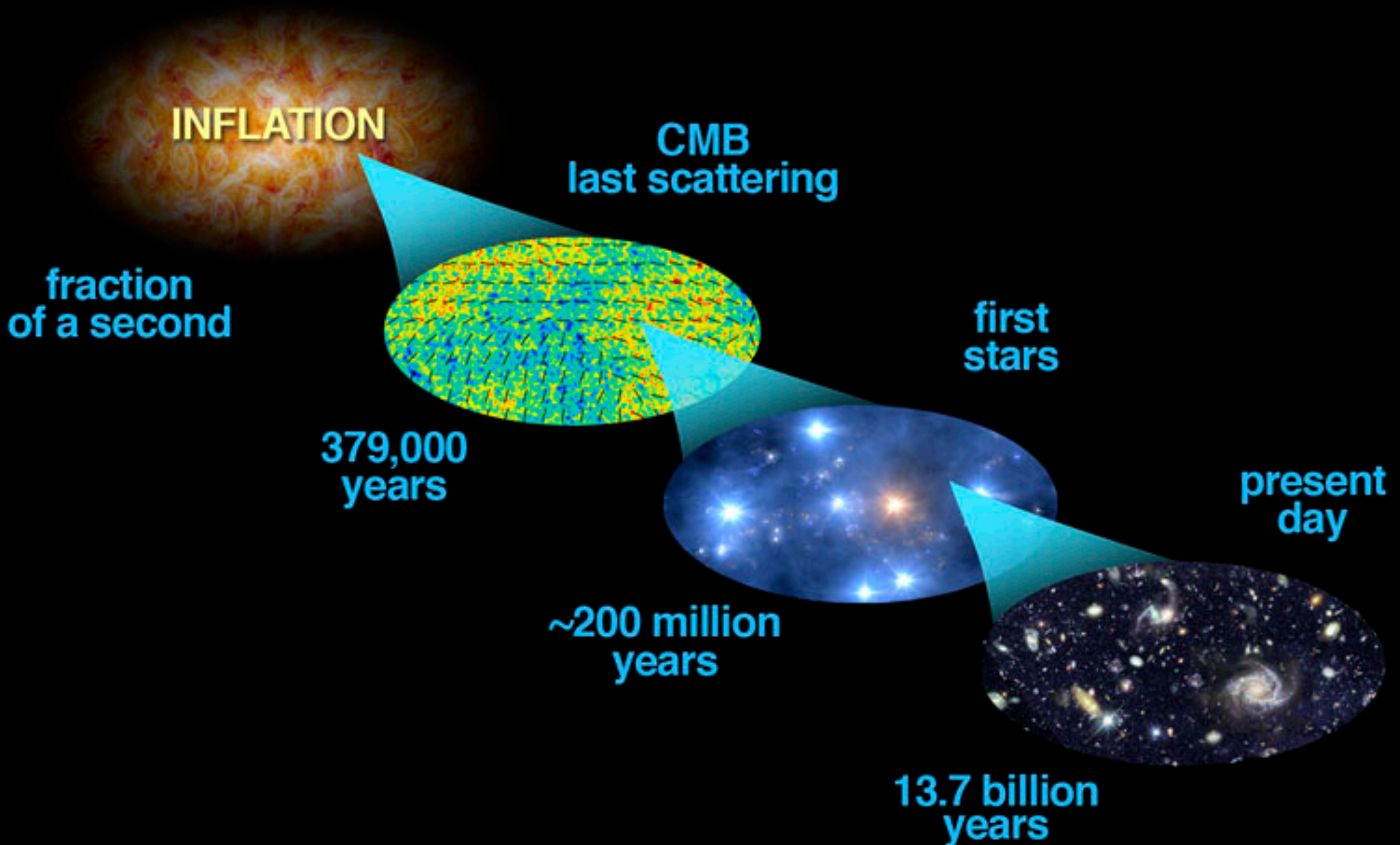
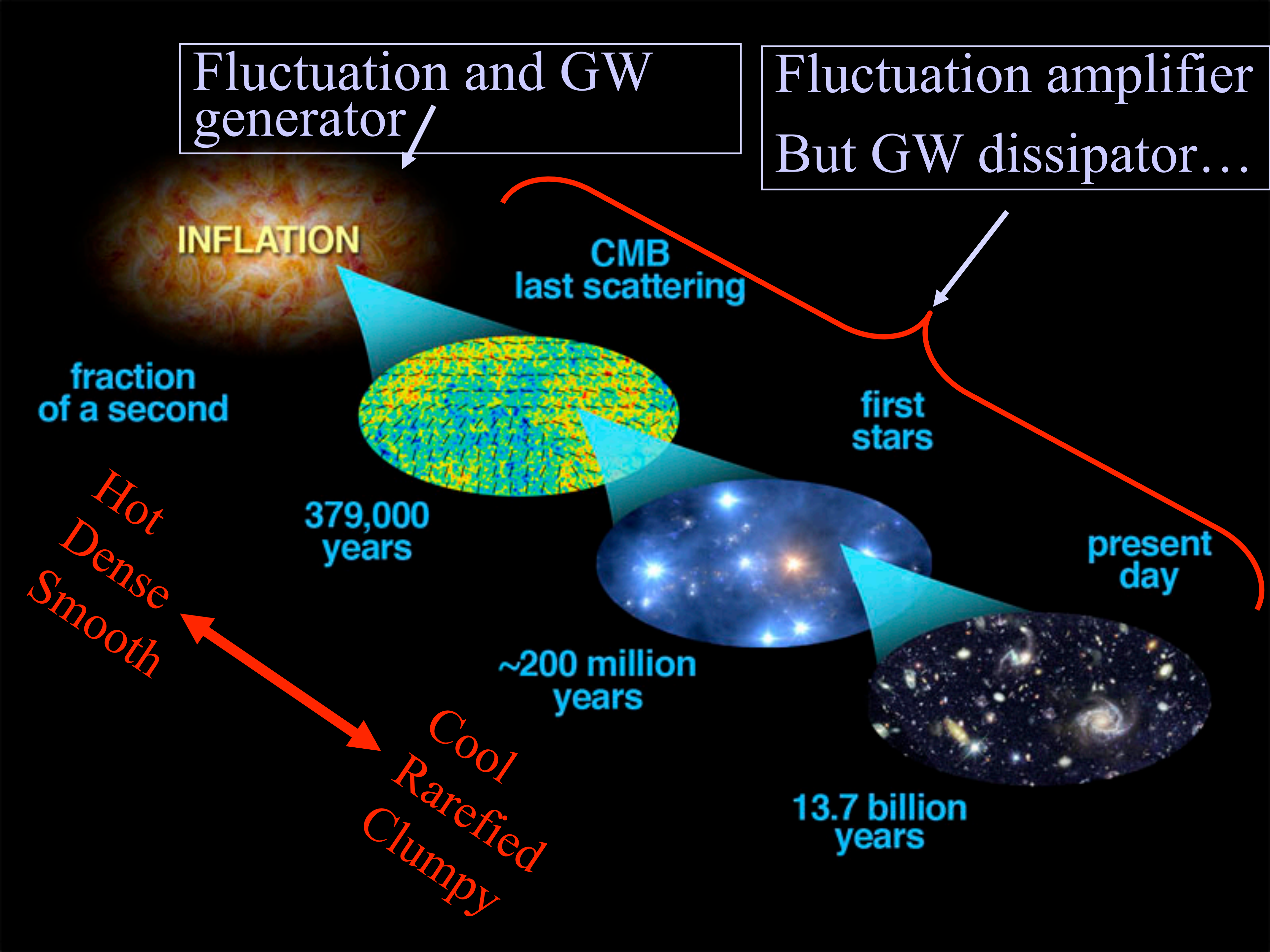
Università di Ferrara and ASI/ASDC
La Thuile, 24 February 2014

On behalf of the Planck collaboration



Planck unveils the Cosmic Microwave Background

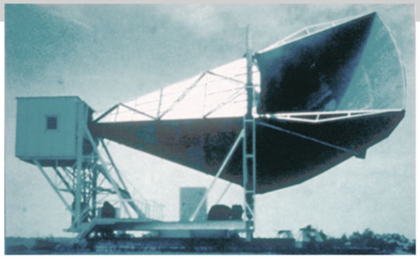

INFLATION
CMB
last scattering
fraction
of a second
first
stars
379,000
years
present
day
~200 million
years
13.7 billion
years

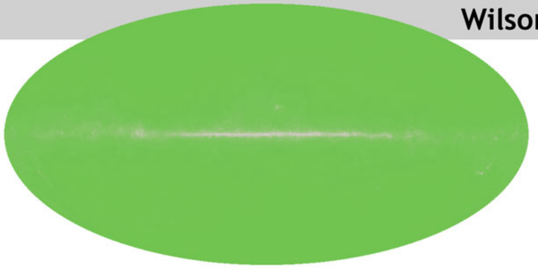

Fluctuation and GW generator
Fluctuation amplifier
But GW dissipator…
INFLATION
CMB
last scattering
fraction
of a second
first
stars
379,000
years
present
day
~200 million
years
13.7 billion
years
Hot
Dense
Smooth
Cool
Rarefied
Clumpy

Cosmic Microwave Background Radiation Overview

The oldest light or the first light of the Universe

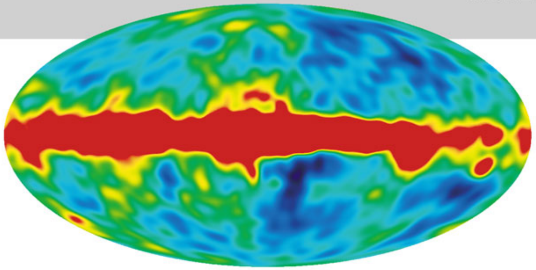
1965 — **Penzias and Wilson**





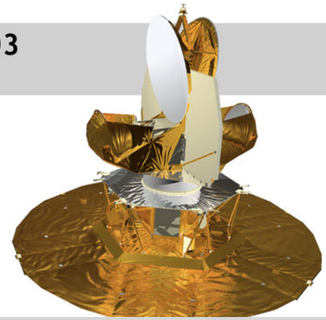
Discovered the remnant afterglow from the **Big Bang**.
→ **2.7 K**

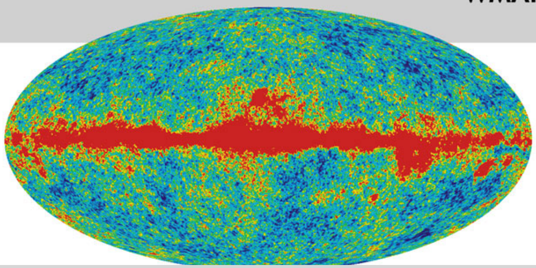
1992 — **COBE**



Blackbody radiation, Discovered the patterns (**anisotropy**) in the afterglow.
→ **angular scale ~ 7°** at a level ΔT/T of 10^{-5}

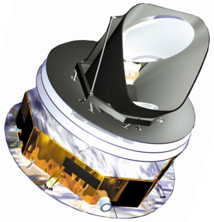
2003 — **WMAP**

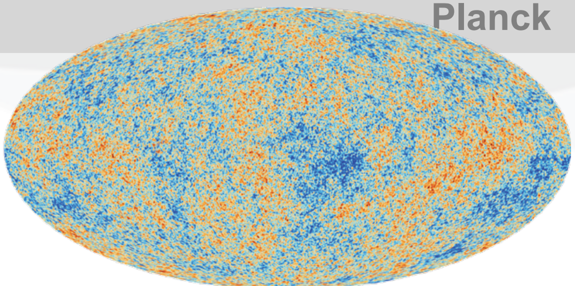




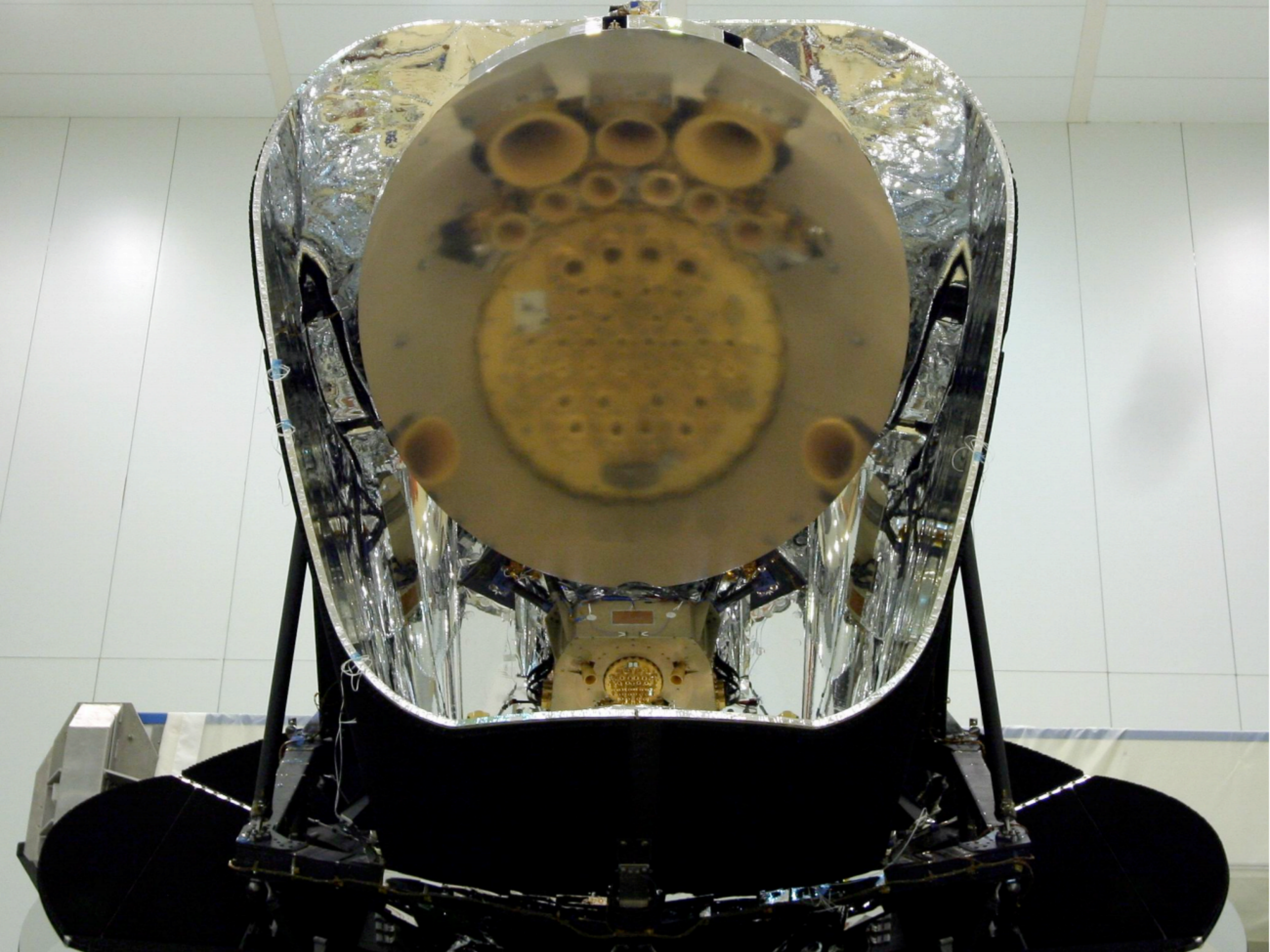
(Wilkinson Microwave Anisotropy Probe):
→ **angular scale ~ 15'**

2009 — **Planck**

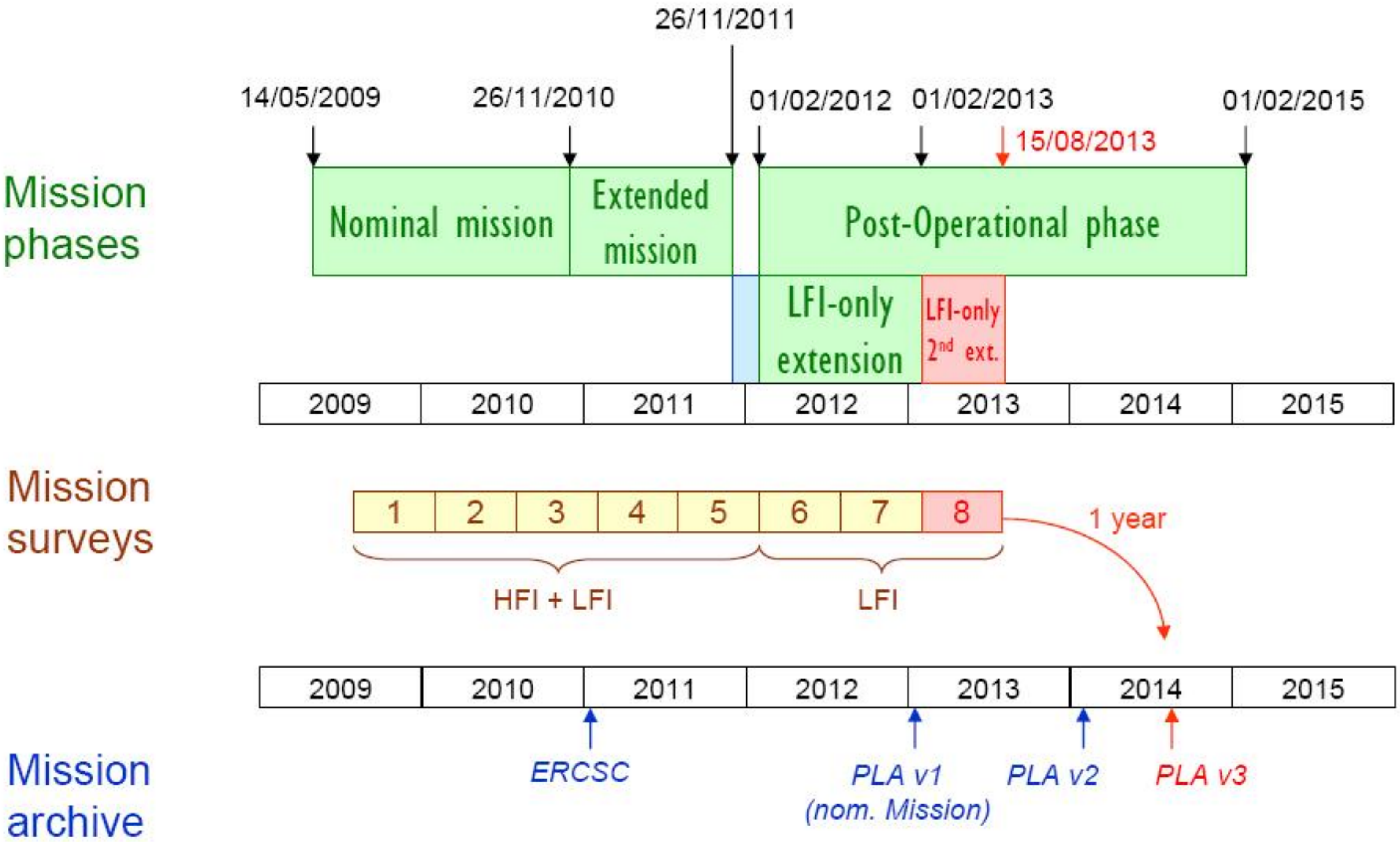




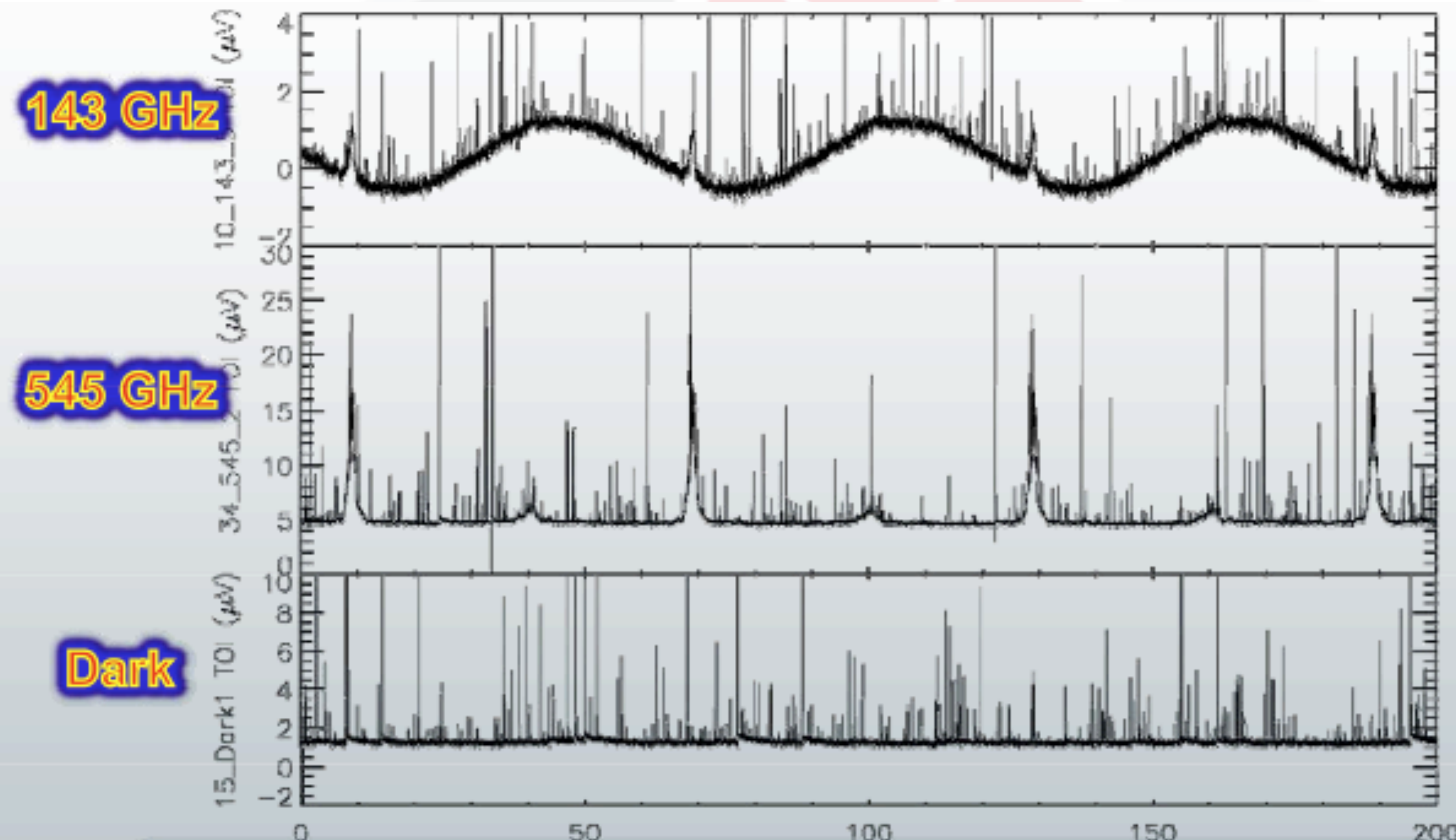
→ **angular scale ~ 5',**
ΔT/T ~ 2×10^{-6}, 30~867 Hz



Planck's operational timeline



Raw data stream

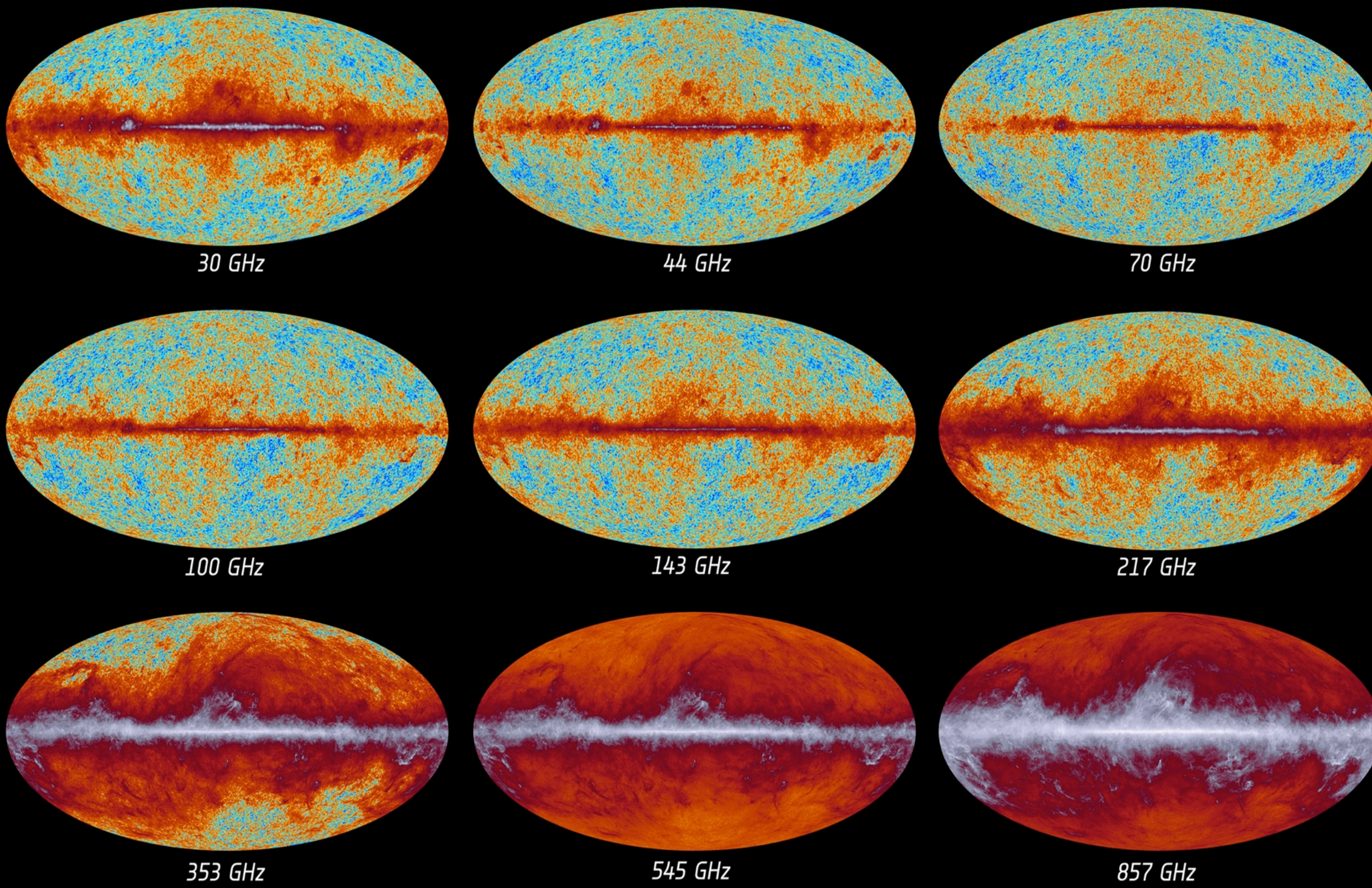


3 minutes of quasi 'raw" data (i.e. only demodulated).The Solar (cosmological) dipole is clearly visible at 145GHz with a 60 seconds period (the satellite rotates at 1 rpm), while the Galactic plane crossings (2 per rotation) are more visible at 545 GHz than at 143 GHz. The Dark bolometer sees no sky signal, but displays a similar population of glitches from cosmic rays.

planck

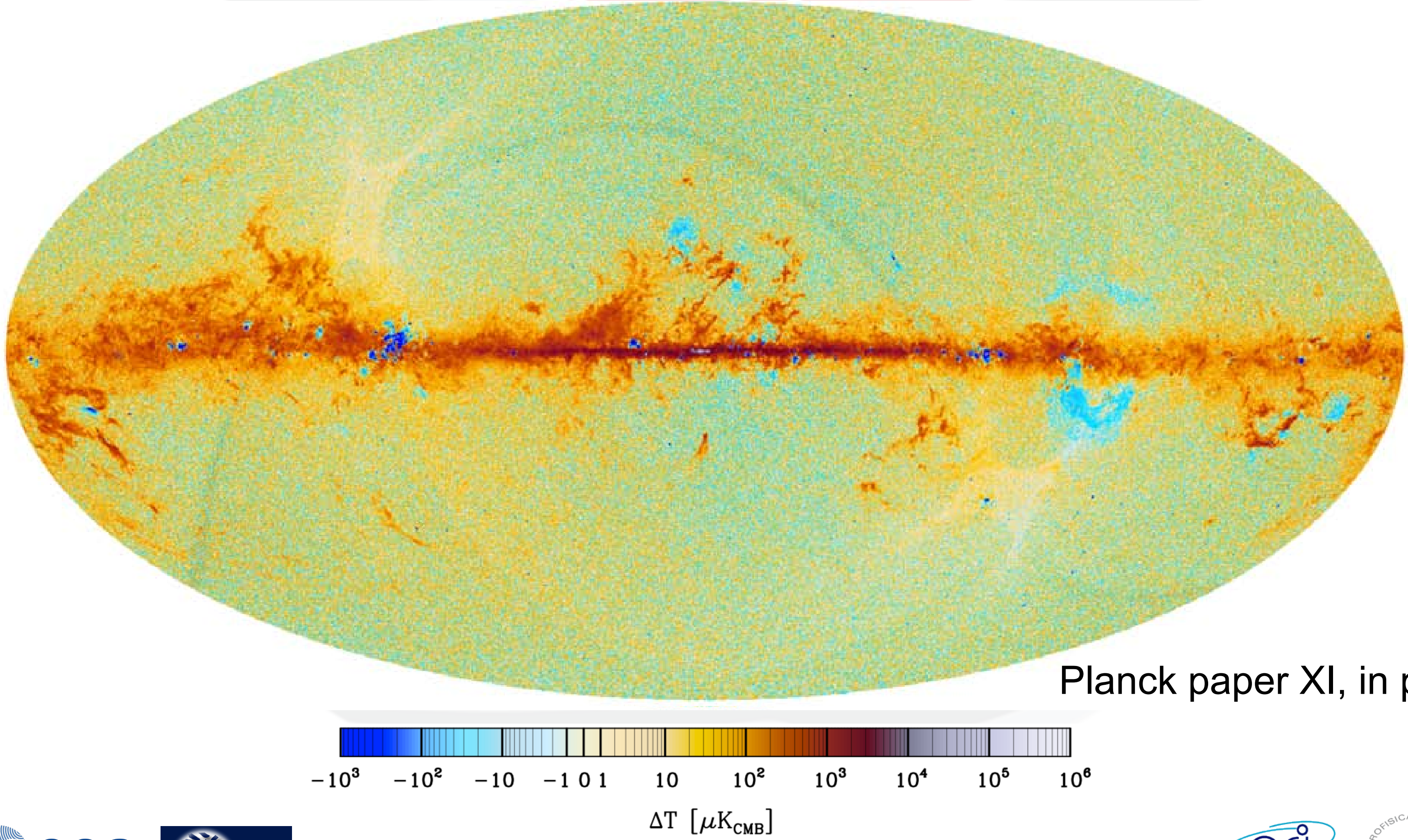
The sky as seen by Planck

esa



Consistency: HFI 100 GHz – LFI 70 GHz

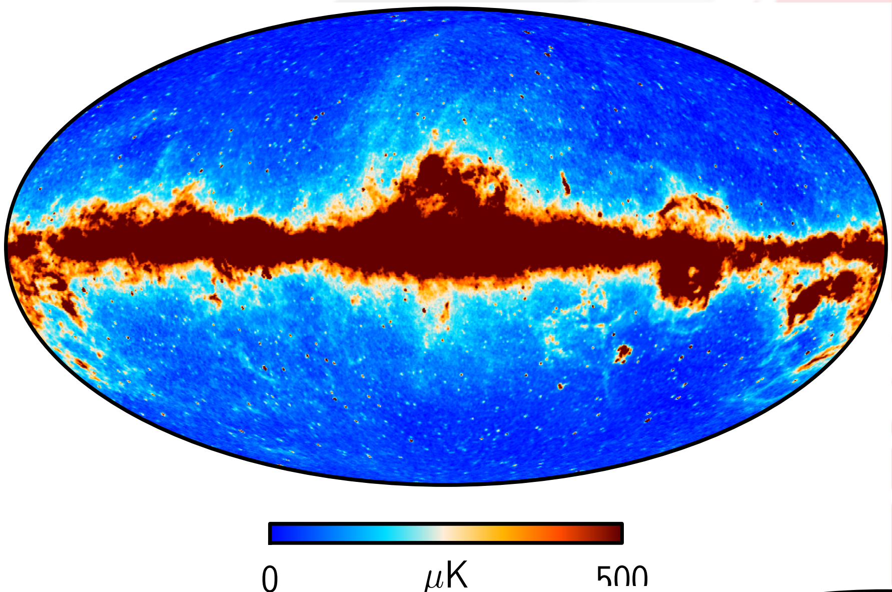
Red is mostly CO, Blue is mostly free-free. CMB is gone!



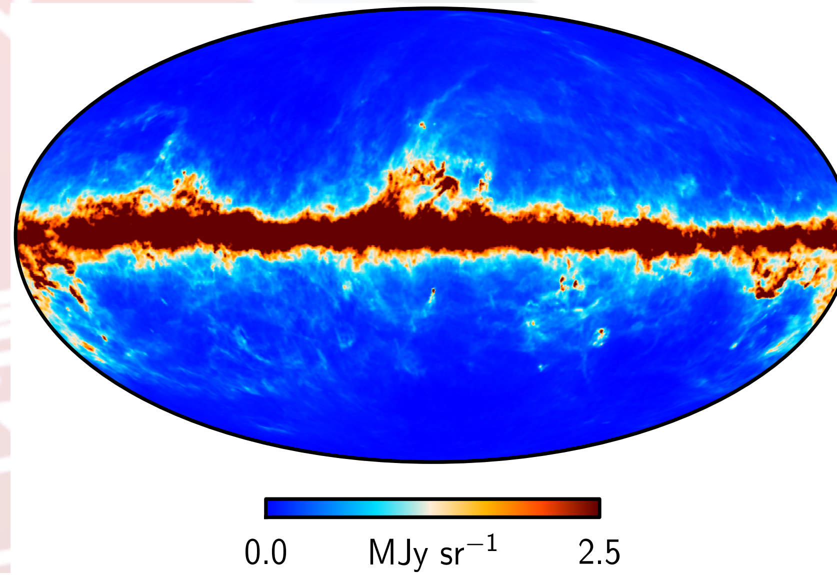
Planck paper XI, in prep.

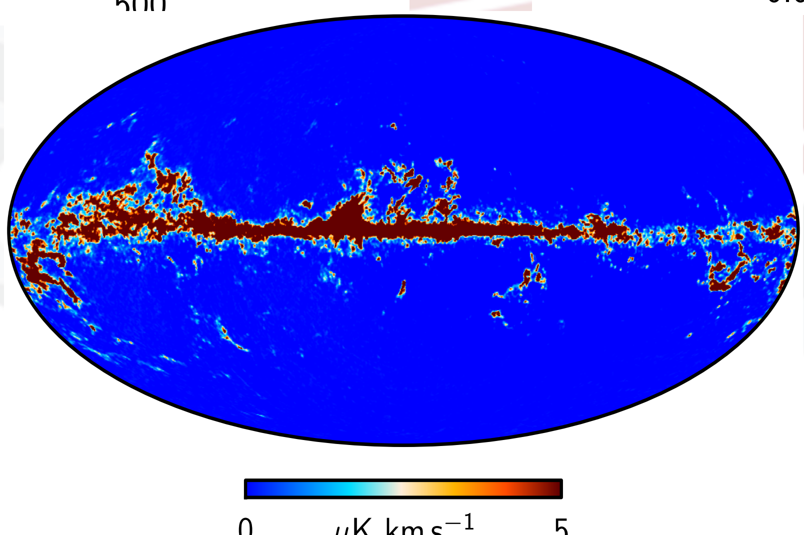
Emission from the Milky Way

Non-thermal radio emission



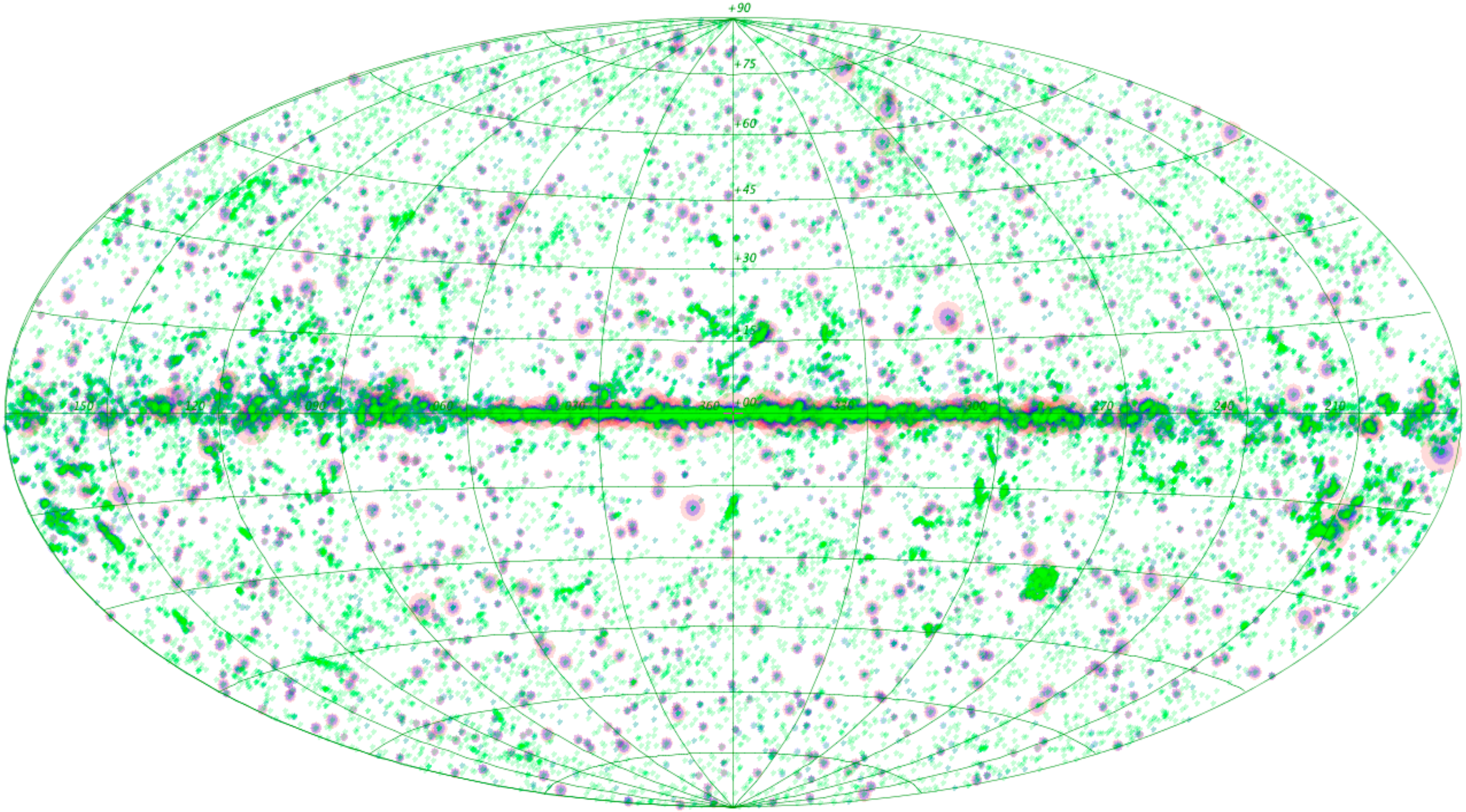
Thermal dust emission



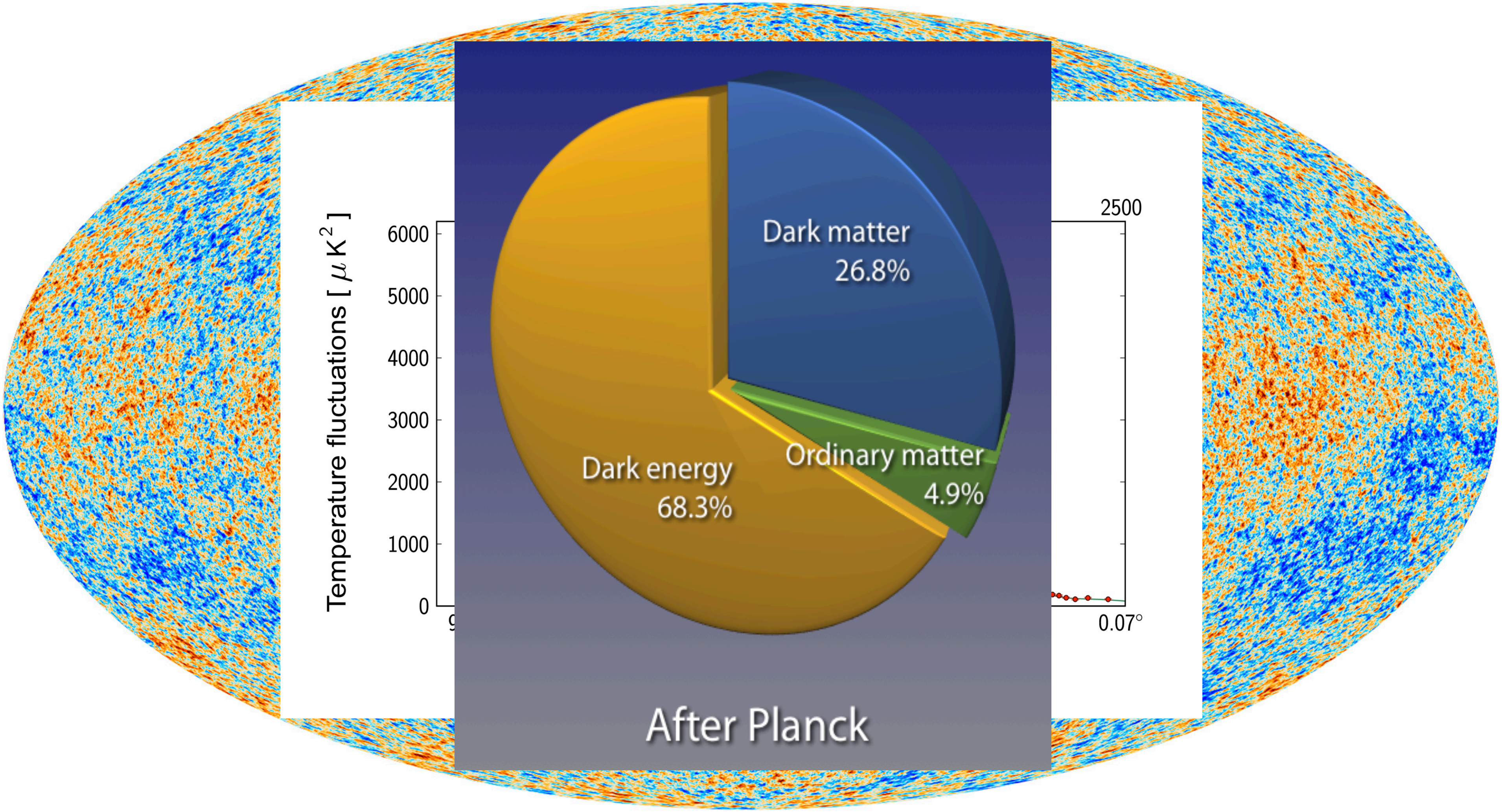


Carbon monoxide

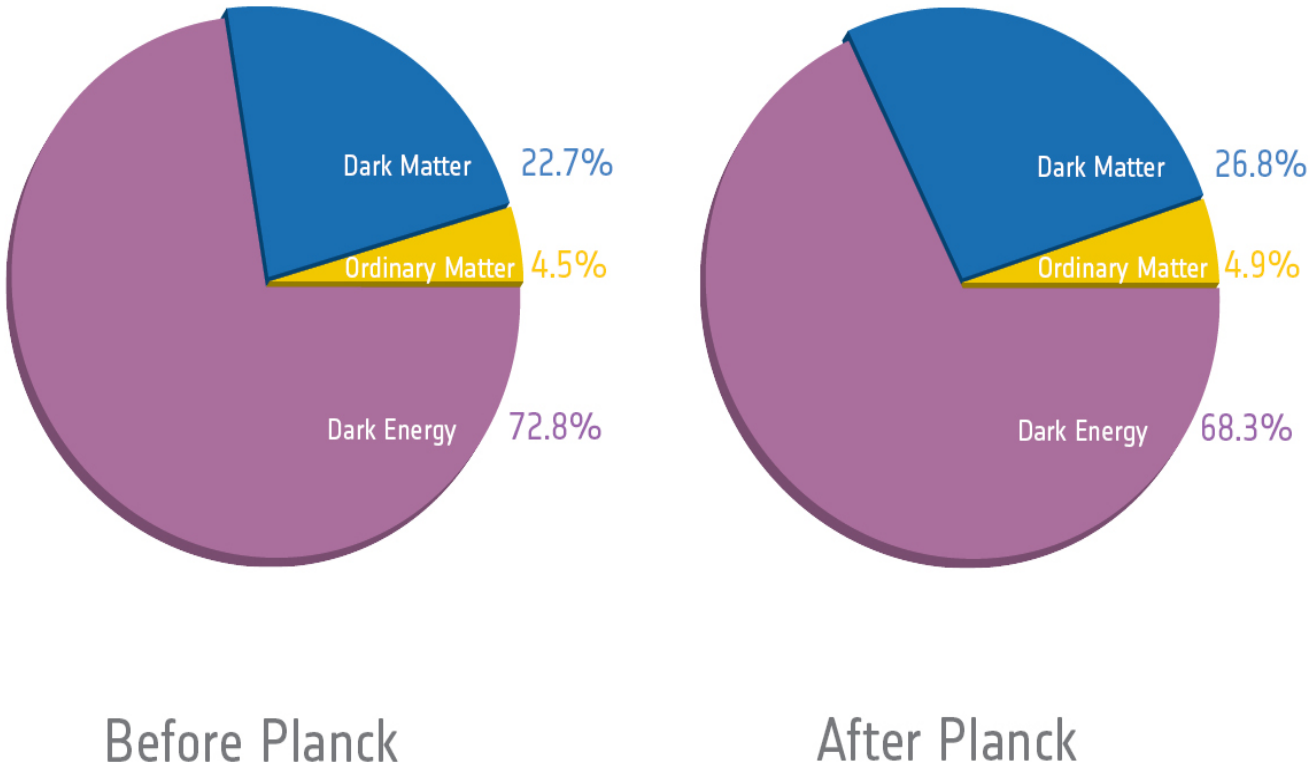
Compact galactic and extragalactic sources



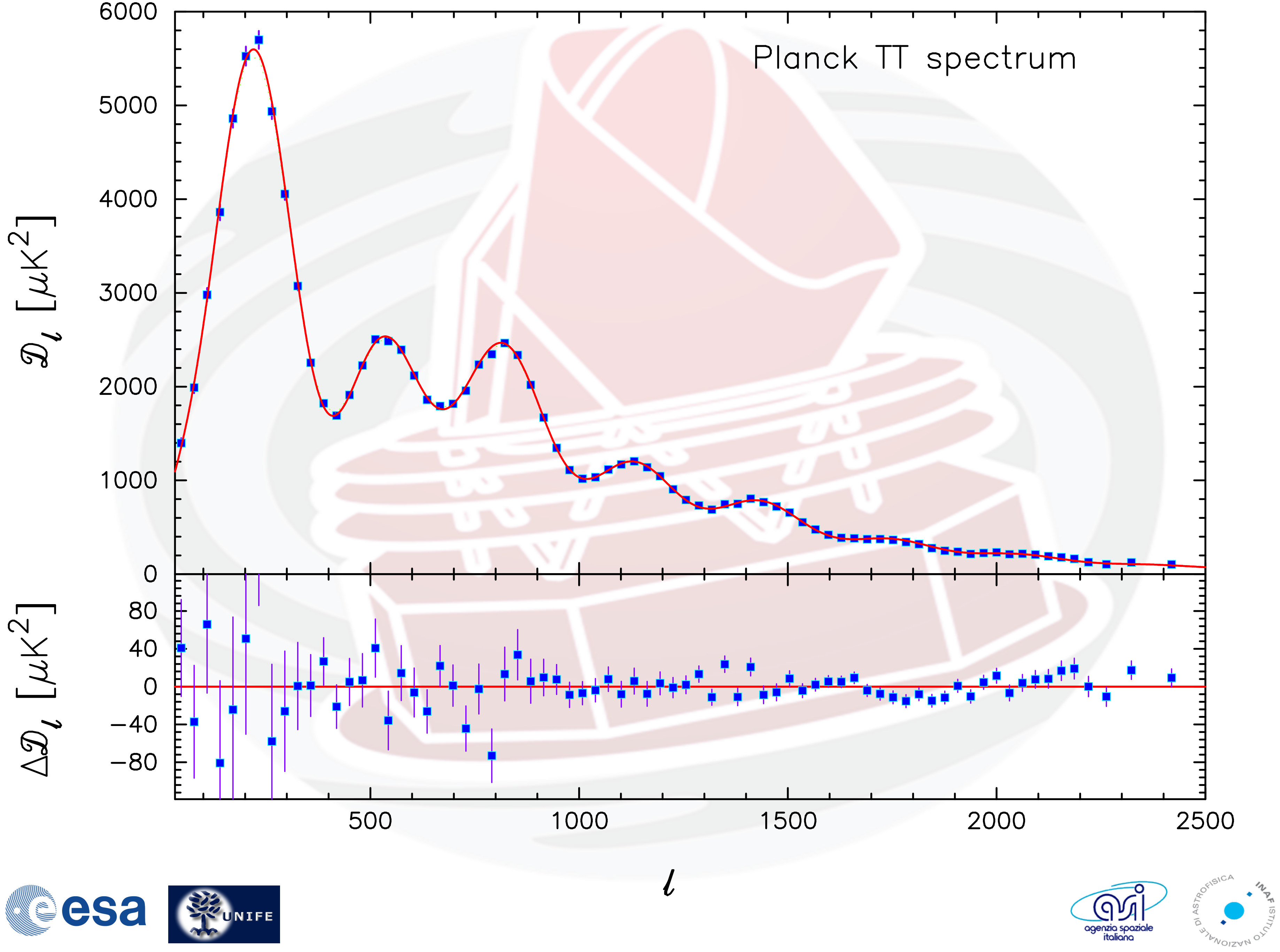
The anisotropies of the CMB



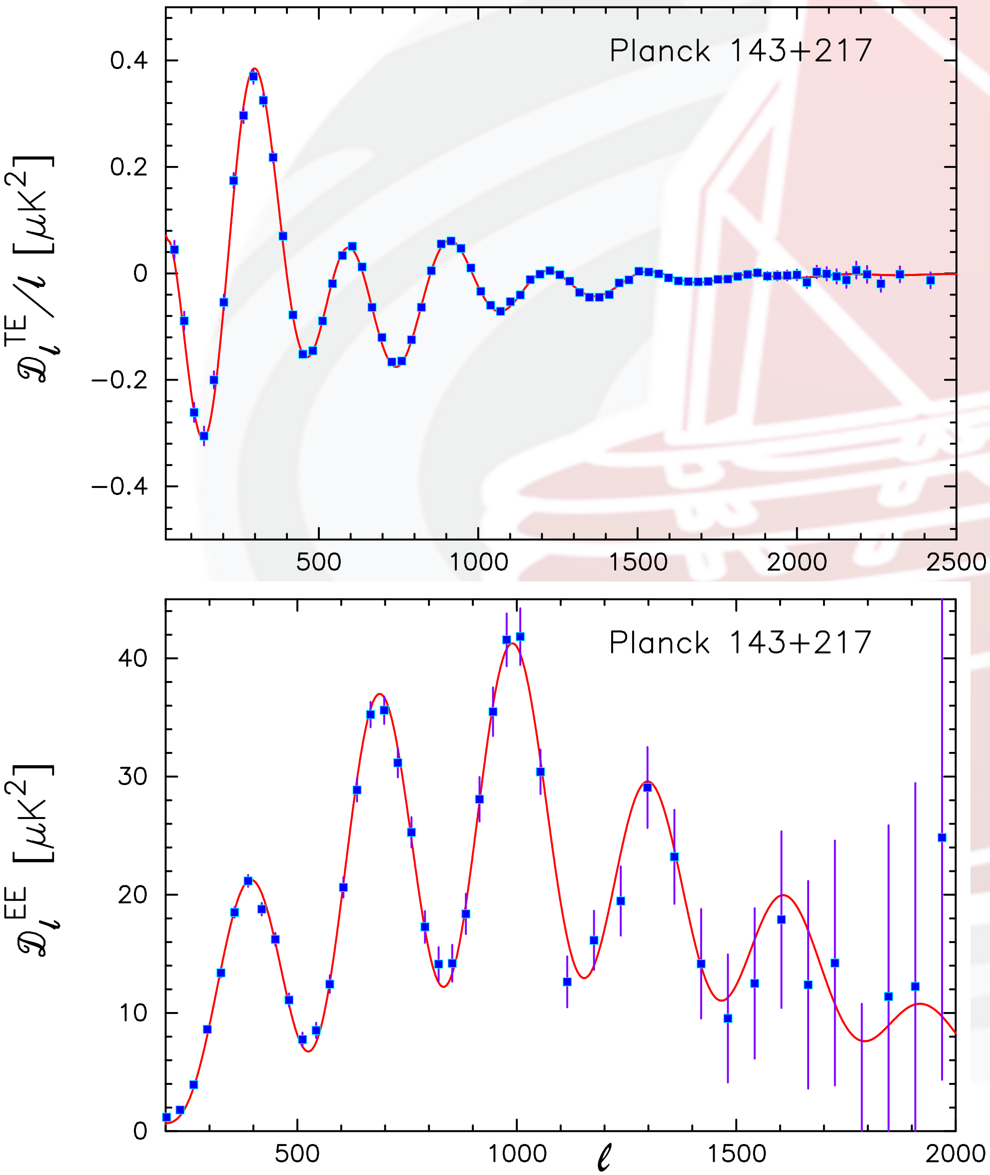
The basic content of the Universe



...has changed!


Planck TT spectrum
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
2500
$\mathcal{D}_\ell$ [μK^2]
$\Delta\mathcal{D}_\ell$ [μK^2]
ℓ
esa
UNIFE
asi
agenzia spaziale italiana
INAF
ISTITUTO NAZIONALE DI ASTROFISICA

CMP polarization with Planck



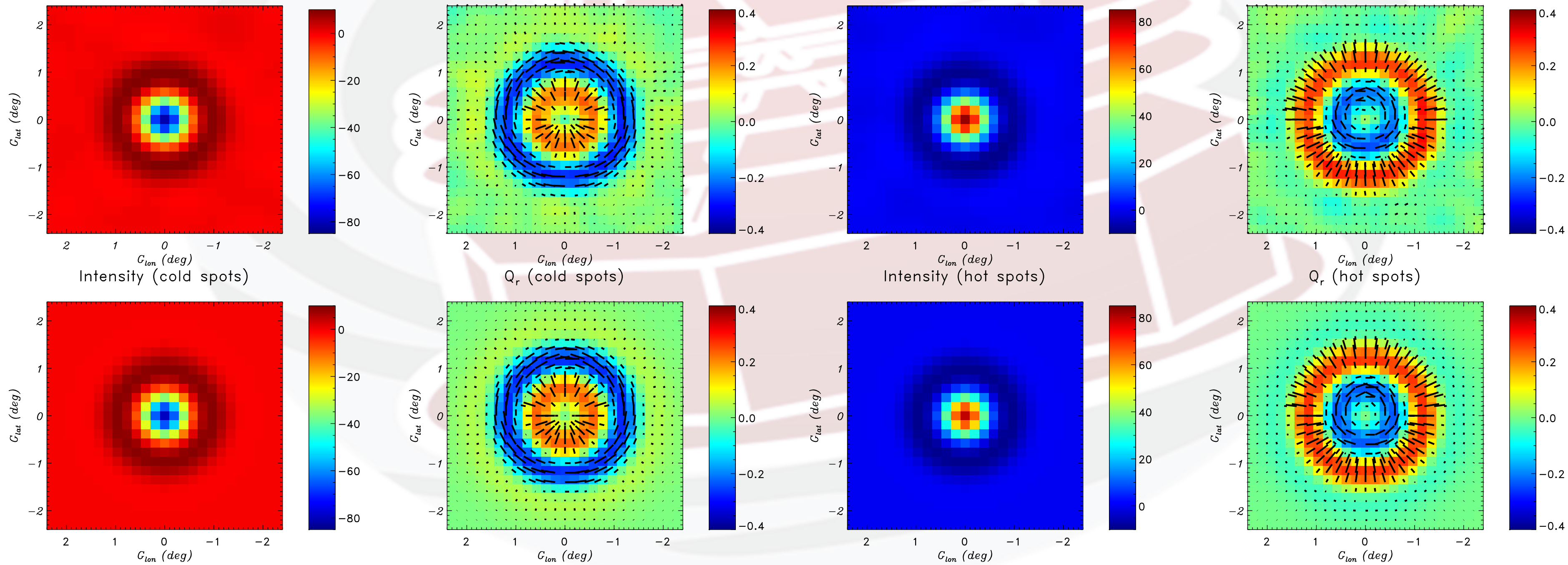
Polarization not delivered in 2013. Large angular scales need better cleaning. Small angular scale are already in good shape as shown.

The red line is not a fit to the polarization data, but the predicted curve from the ΛCDM model assuming the temperature data!

Polarization and hot spots

Stack hot/cold spots in the CMB. See the TE correlation in real space!

Remarkable proof of inflation: existence of super-horizon fluctuations



The ΛCDM model of the Universe

ΛCDM = « Lambda-cold-dark-matter » model

- General Relativity [lots of laboratory test]
- Isotropic and homogeneous Universe [CMB, Copernican principle]
- Expanding space (hot big bang) → H_0 ($h = H_0/[100km/s/Mpc]$)
- Contents:
  - Ordinary (baryonic) matter → Ω_b [probes the physics of early universe]
  - Cold dark matter → Ω_c [galaxy rotation curves, slows down expansion]
  - Dark energy → Ω_Λ [distance scale measurements, accelerated expansion]
- Small Gaussian initial fluctuations → A_s (amplitude), n_s (tilt) [inflation]
- Space is flat → $\Omega_b + \Omega_c + \Omega_\Lambda = 1$ [inflation]
- Late-time reionization → τ → **6 parameters in total** [τ is WMAP provided for now]

BASE ΛCDM MODEL (Planck + WP + HL)

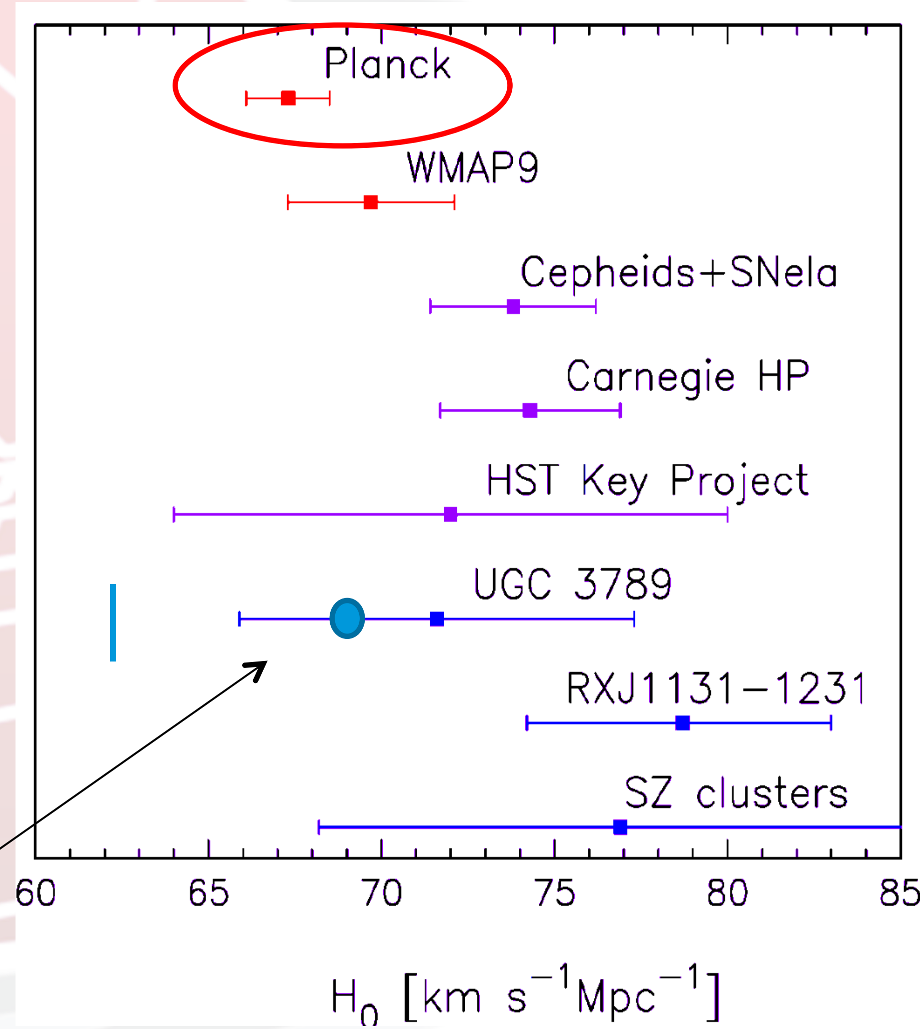
Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)
H_0	67.3±1.2 (is it low?)
Ω_Λ	0.685±0.017
σ_8	0.828±0.012
z_{re}	11.1±1.1

Tension with Hubble Constant astrophysical measurements

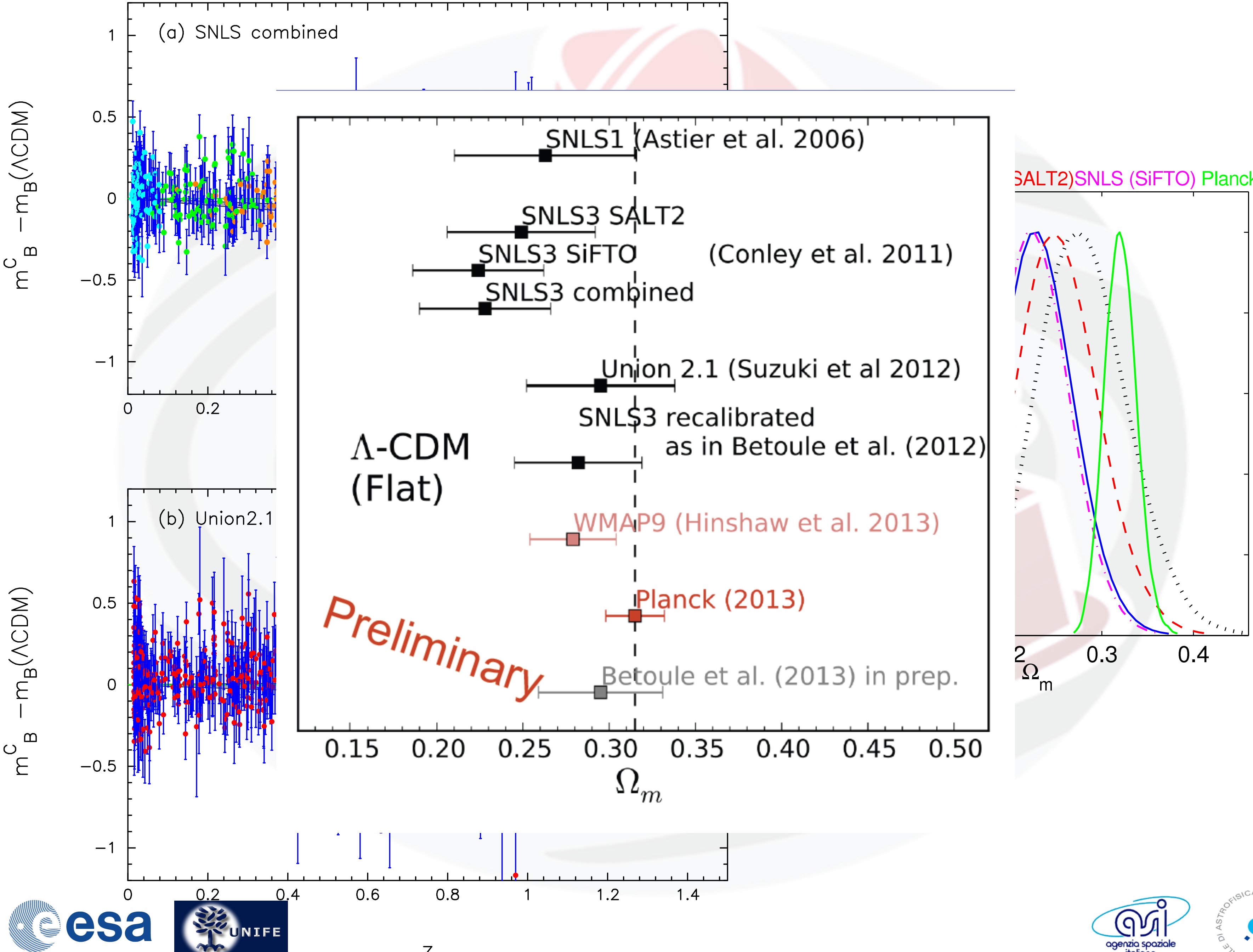
Planck value for the Hubble constant is in at tension with several other measurements (most notably the HST determination).

Systematics in luminosity distance measurements can be clearly there, however this tension could be also hinting towards new physics.

The determination of H_0 from Planck is indeed **model dependent**.

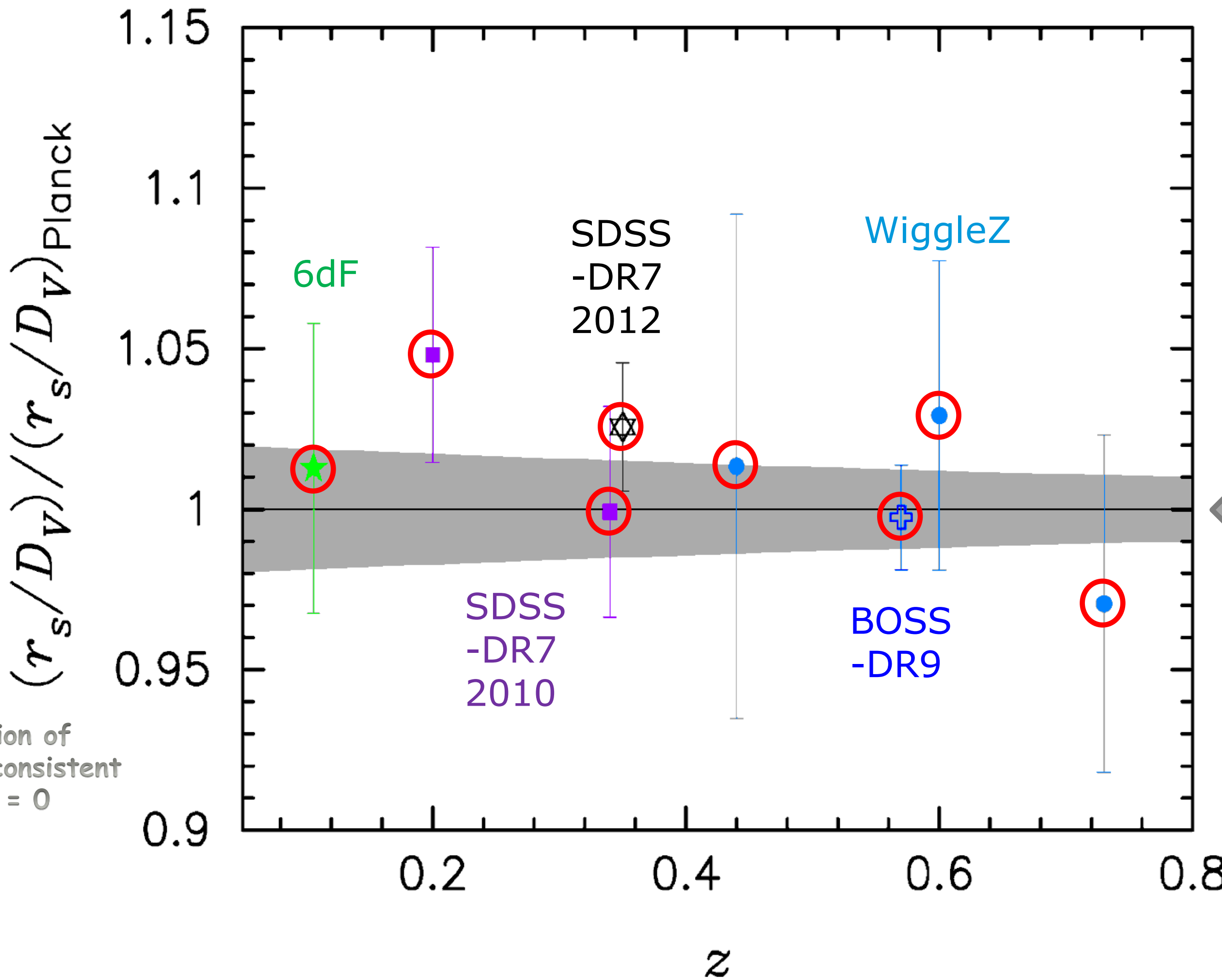


UGC 3789 distance recalibrated, now H_0 = 68.9 ± 7.1 Km/s/Mpc



(a) SNLS combined
(b) Union2.1
SNLS1 (Astier et al. 2006)
SNLS3 SALT2
SNLS3 SiFTO
(Conley et al. 2011)
SNLS3 combined
Union 2.1 (Suzuki et al 2012)
SNLS3 recalibrated
as in Betoule et al. (2012)
Λ-CDM
(Flat)
WMAP9 (Hinshaw et al. 2013)
Planck (2013)
Preliminary
Betoule et al. (2013) in prep.
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
Ω_m
SALT2)SNLS (SiFTO) Planck
0.3
0.4
z

BAO scale distance ratio



Planck Prediction (shaded area)

→ Planck & BAO are in tight agreement (and thus can be used jointly)

DE equation of state is consistent with 1+w = 0

Further tests of the standard model

- Sum of neutrino masses:
  - We know that neutrinos are massive (oscillations)
  - Minimum possible sum mass is around 0.07 eV
  - Planck: **no detection**, limit from all data is 0.23 eV
- Extra particles? **N_{eff} consistent with 3 neutrinos only, $N_{eff} < 4$ at 95%**
- Is 'Λ' really a cosmological constant ? **Consistent with $p=-\rho$**
- Topology of the universe: **limits close to horizon size**
- decaying dark matter, varying constants: **no detections**
- tests of assumptions (isotropy, Gaussianity): **strong limits**, **some anomalies**
- Tensor fluctuations**: $r < 0.11$** (from temperature, model dependent, no B mode polarization so far).
- Tests of initial conditions for perturbations: **no surprises**
- Further constraints on inflation (running spectra index, etc) …

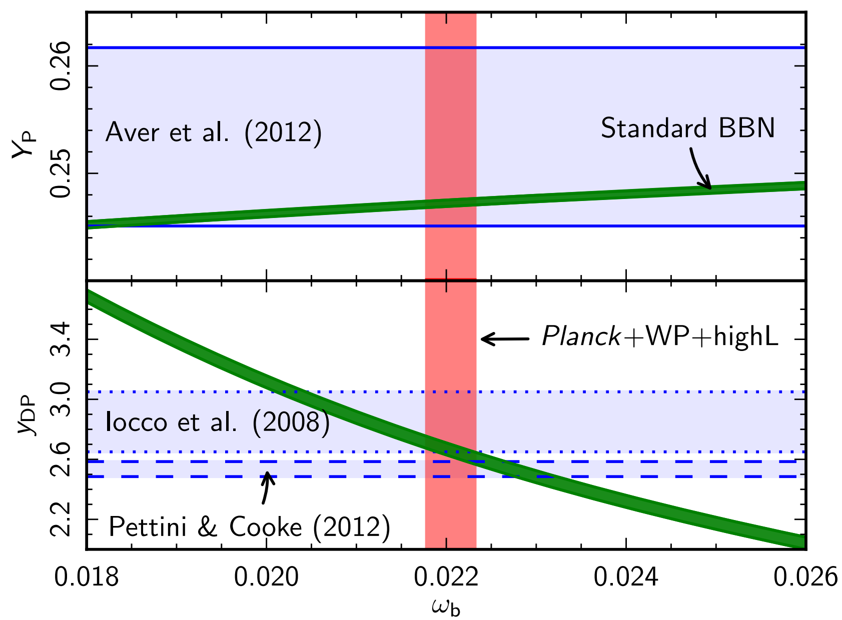
EXTENDED ΛCDM MODELS (Planck +BAO)

Parameter	Value (95%)
Ω_K	-0.0005±0.0066
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040
$dn_s/d\ln k$	-0.014±0.017
$r_{0.002}$	<0.11
w	-1.13±0.24

the first three minutes

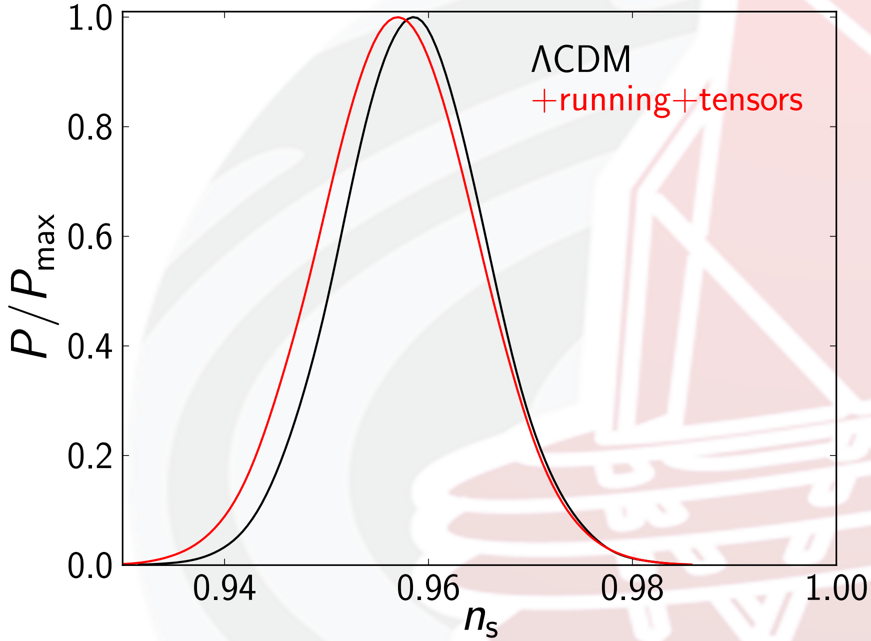
Looking into the fireball, back to the first three minutes

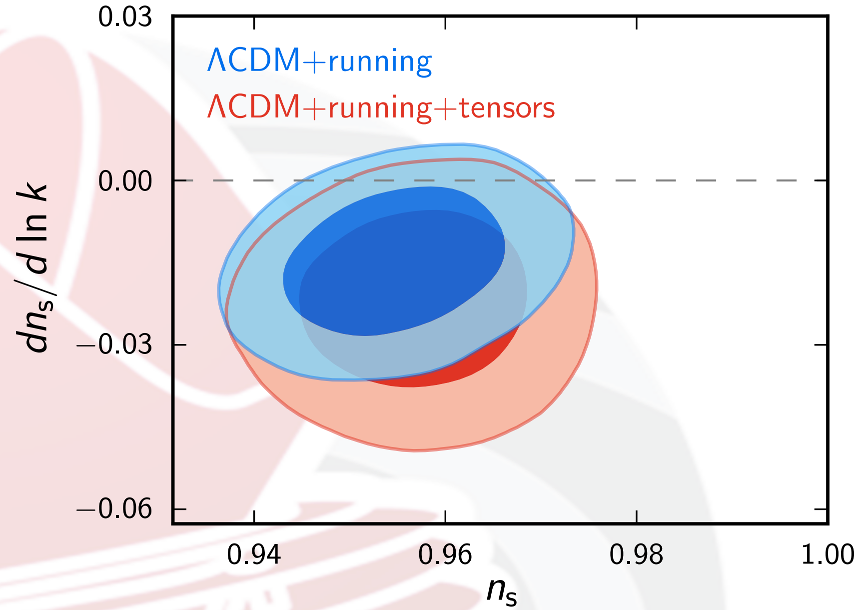
- at high energies the nuclei of heavier elements are kicked apart by the high energy photons, they can only form at ~ 0.1 MeV
- final abundance depends strongly on baryons to photon ratio
- CMB measures both, so can compare to direct observations!

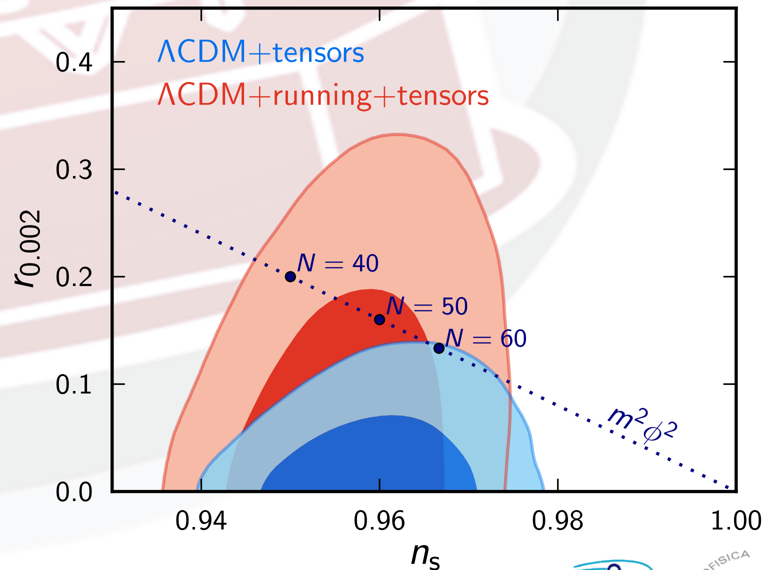


Great consistency test using known physics over most of the age of the universe!

Also tests for extra relativistic degrees of freedom, **N_{eff} = 3.36±0.34** (Planck+WP+highL, expected 3.05)

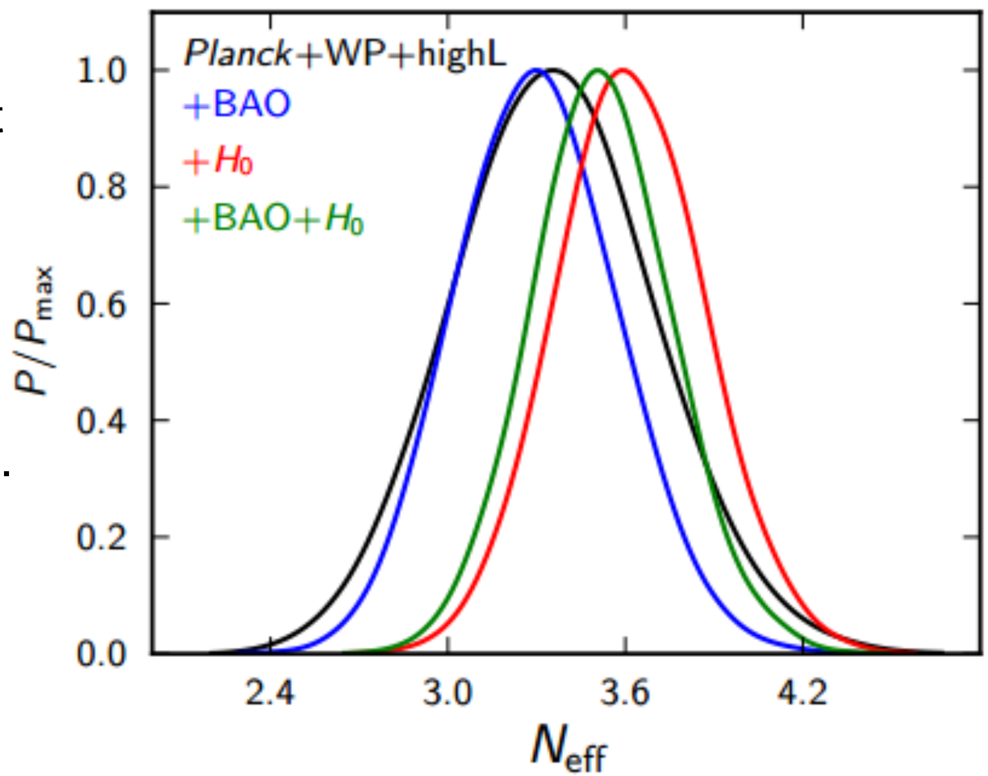

1.0
0.8
0.6
0.4
0.2
0.0
P/P_{max}
0.94
0.96
0.98
1.00
n_s
ΛCDM
+running+tensors


0.03
0.00
−0.03
−0.06
$dn_s/d\ln k$
ΛCDM+running
ΛCDM+running+tensors
0.94
0.96
0.98
1.00
n_s


0.4
0.3
0.2
0.1
0.0
$r_{0.002}$
ΛCDM+tensors
ΛCDM+running+tensors
$N = 40$
$N = 50$
$N = 60$
$m^2\phi^2$
0.94
0.96
0.98
1.00
n_s

Example: extra degrees of freedom from Planck+HST ?

While the Planck+WP+highL dataset is consistent with the standard 3 neutrino families framework, when we include the HST value for the Hubble constant we see a preference for extra degrees of freedom at about 95% c.l. with Neff=3.6.



A sterile neutrino with non standard decoupling could explain this effect.

Other new physics mechanisms could explain this tension.

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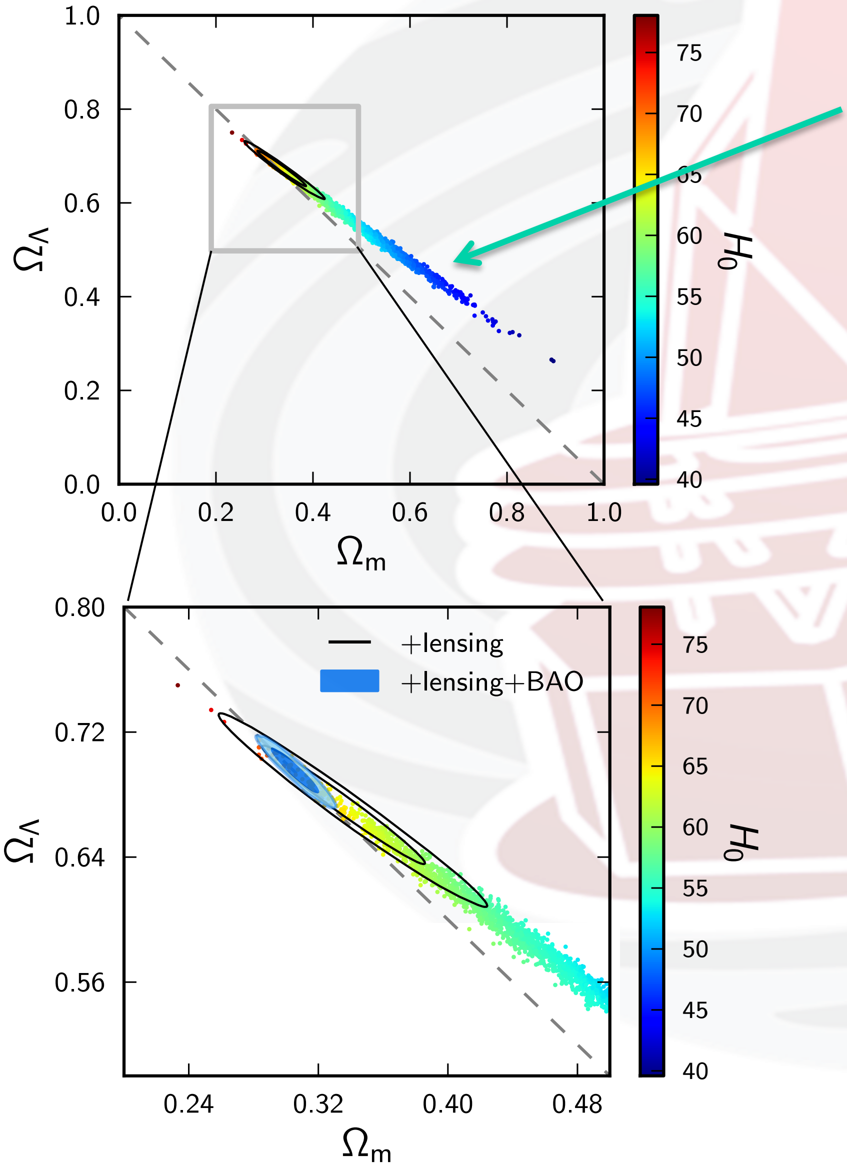
Is space really flat?



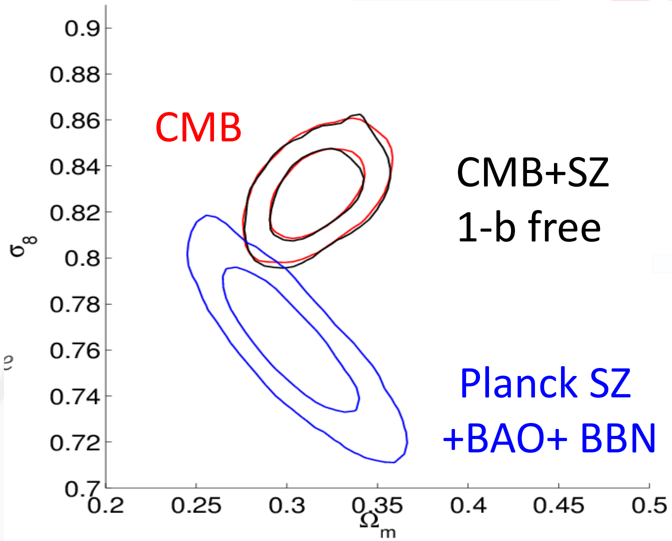
The 0.06% precision measurement of the sound horizon scale at last scattering gives us a known ruler!

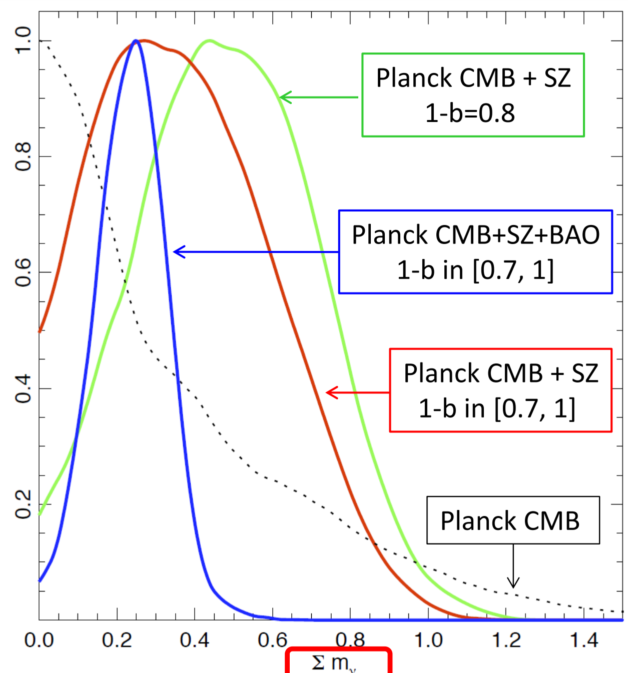
A single measurement only gives one constraint → *geometric degeneracy*

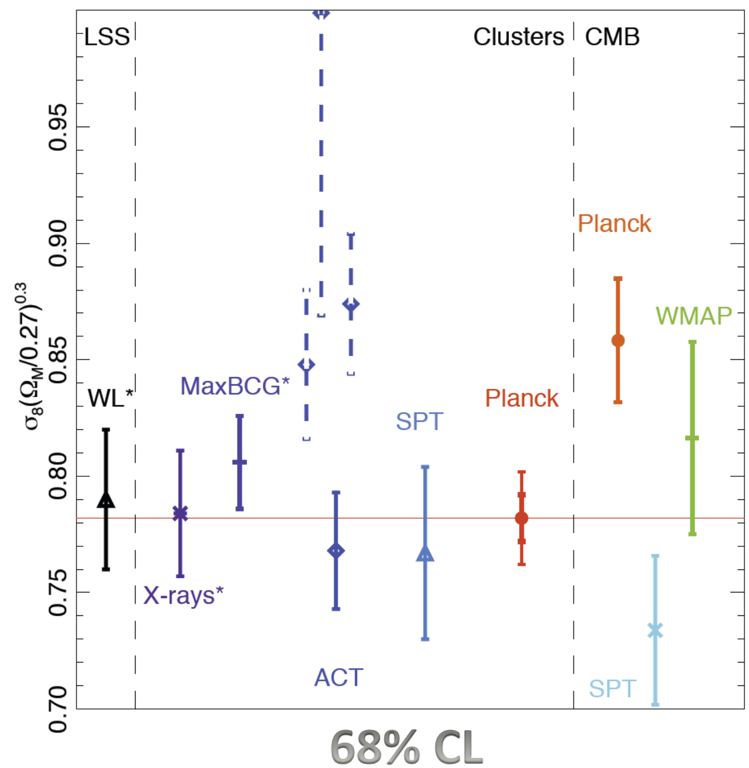
The models in the tail have a higher lensing signal, and so CMB lensing breaks partially the geometric degeneracy, allowing us to rule out Λ=0 and constrain Ω_k at the percent-level with CMB data alone.

(first done by ACT/SPT in 2011/12)

Planck clusters (SZ) vs CMB

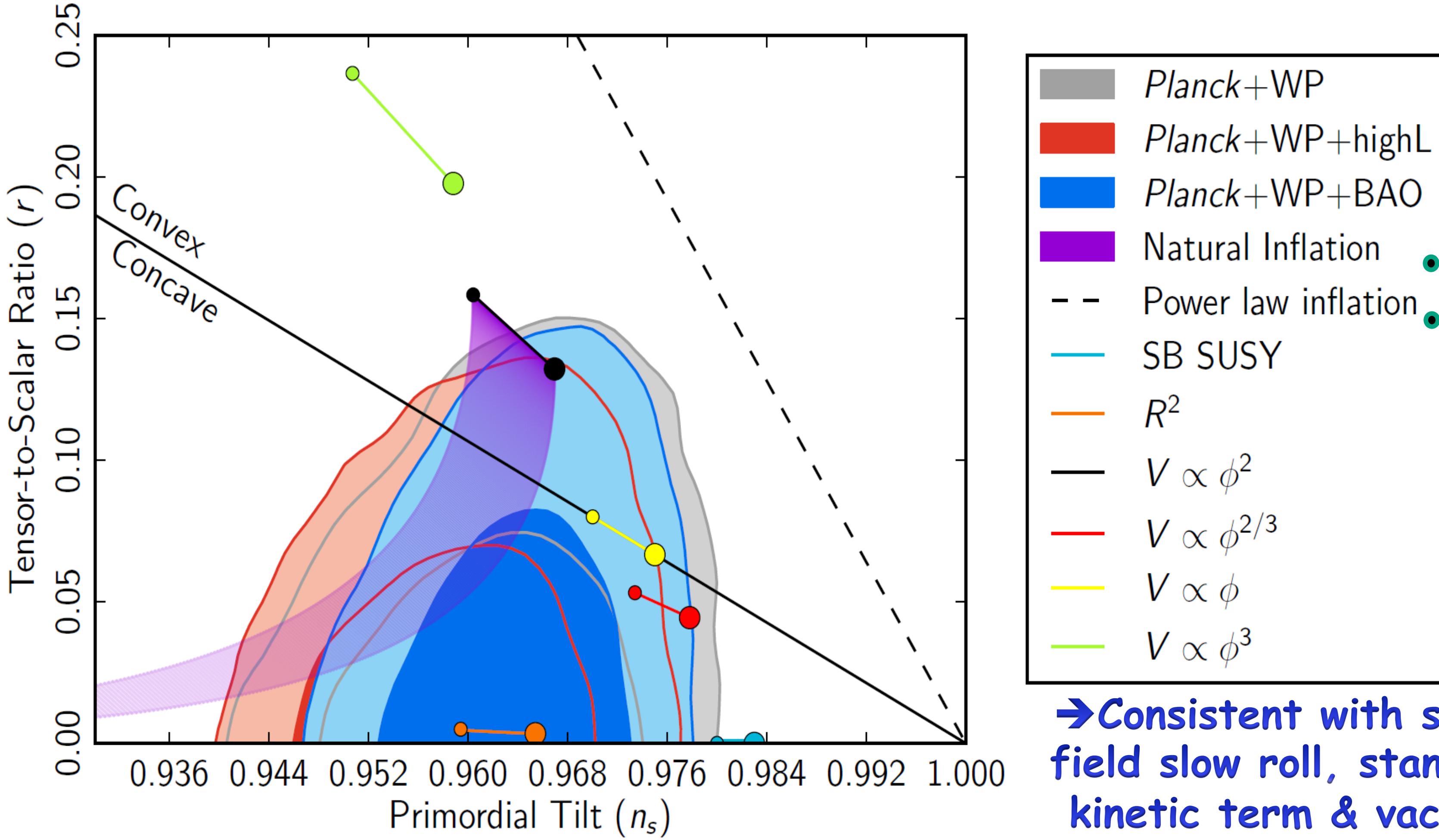






Corrected an error in Planck Cosmology from clusters paper: now m_nu > 0.06 consistently. Still a three sigma discrepancy.

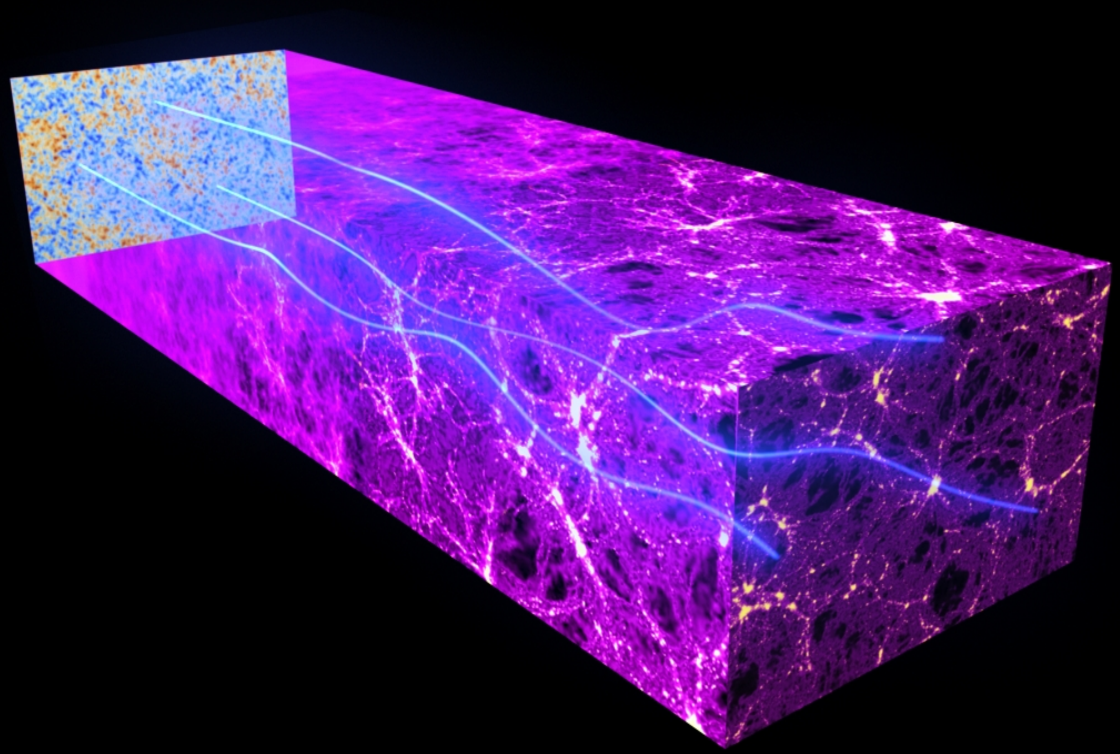
Main constraint on Inflation physics



→Consistent with single field slow roll, standard kinetic term & vacuum (with f_{NL} upper limits).

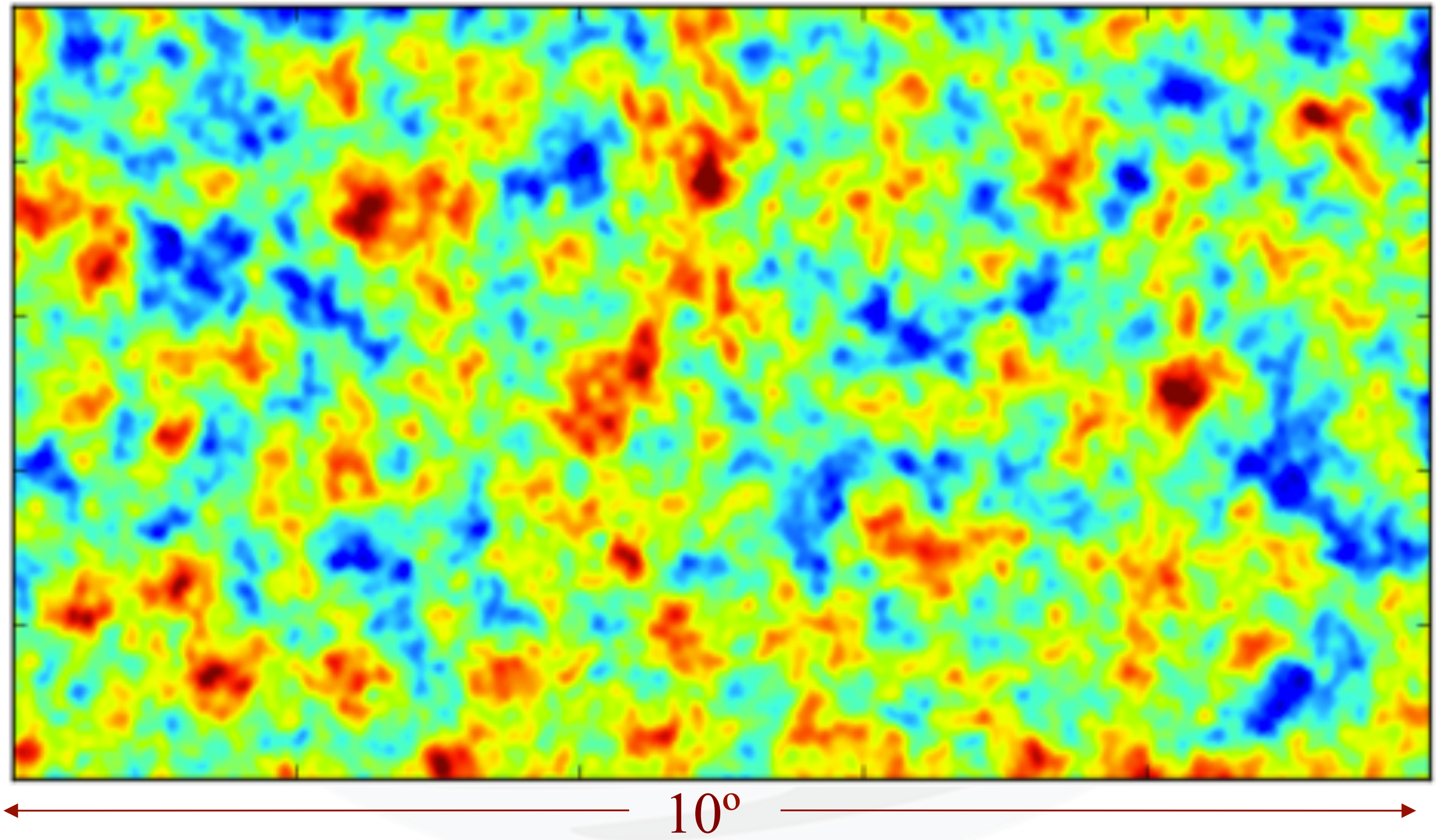
PLANCK PROBES AND EXPLOITS CMB LENSING

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



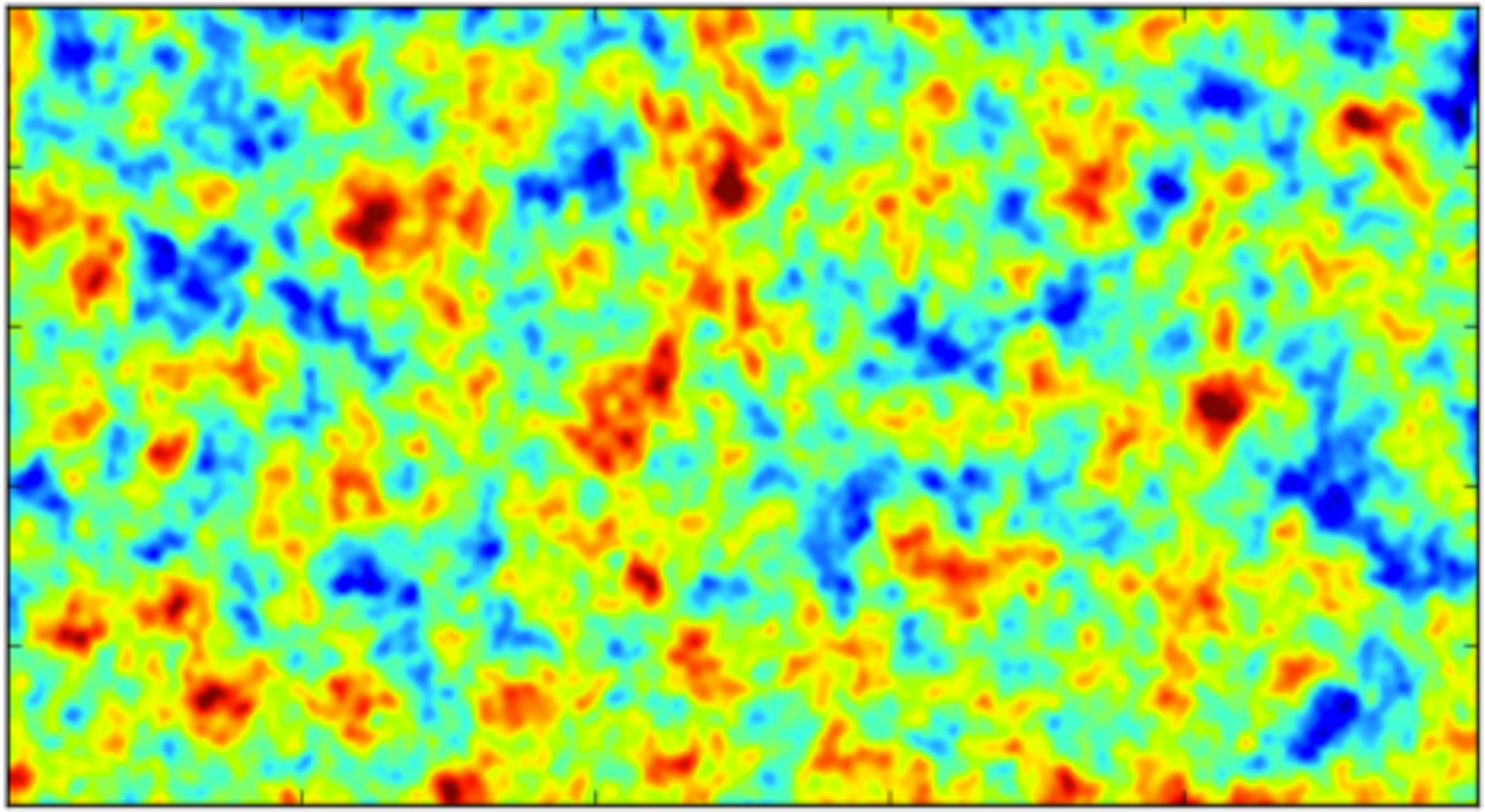
GRAVITATIONAL LENSING OF THE CMB

A simulated patch of CMB sky – **before lensing**



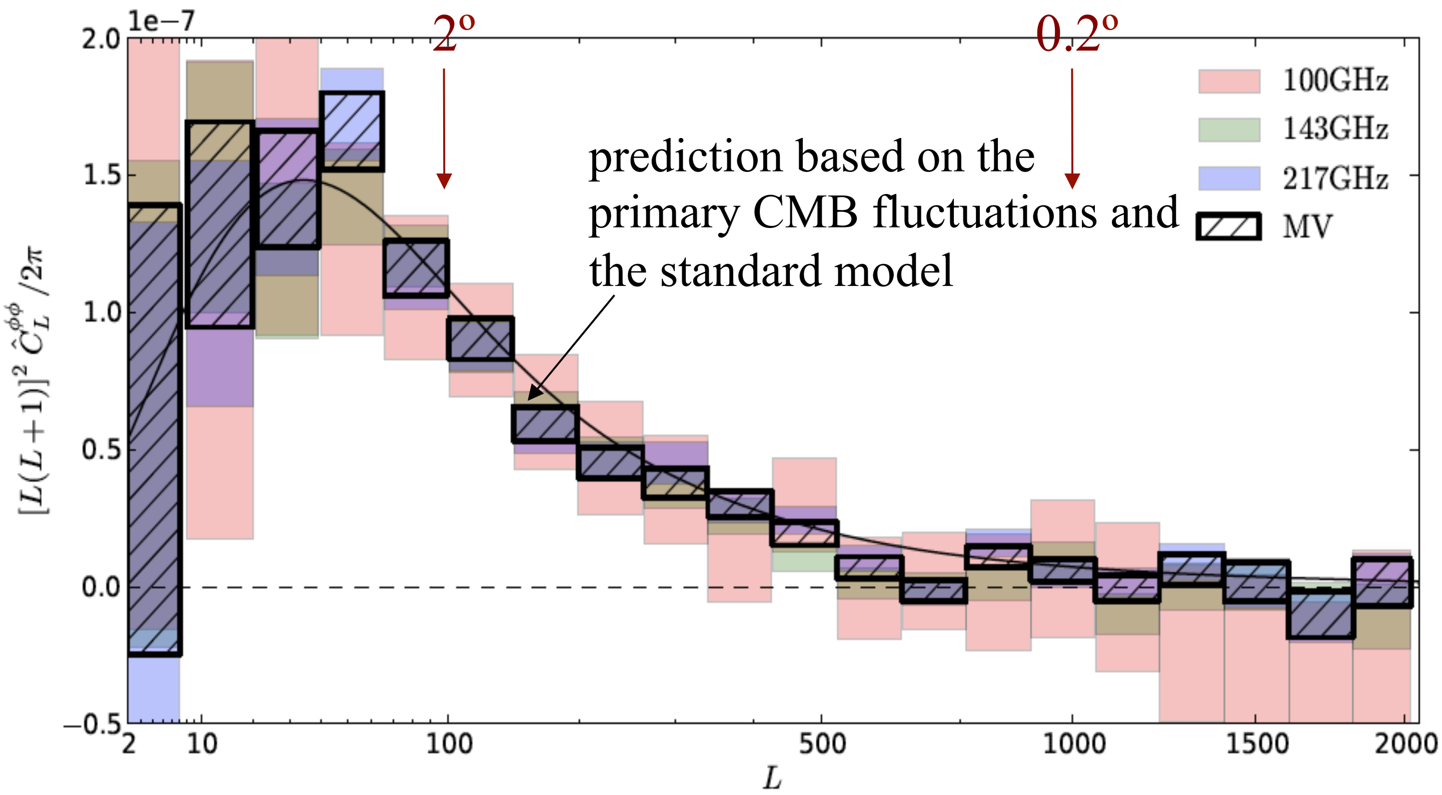
GRAVITATIONAL LENSING OF THE CMB

A simulated patch of CMB sky – **after lensing**



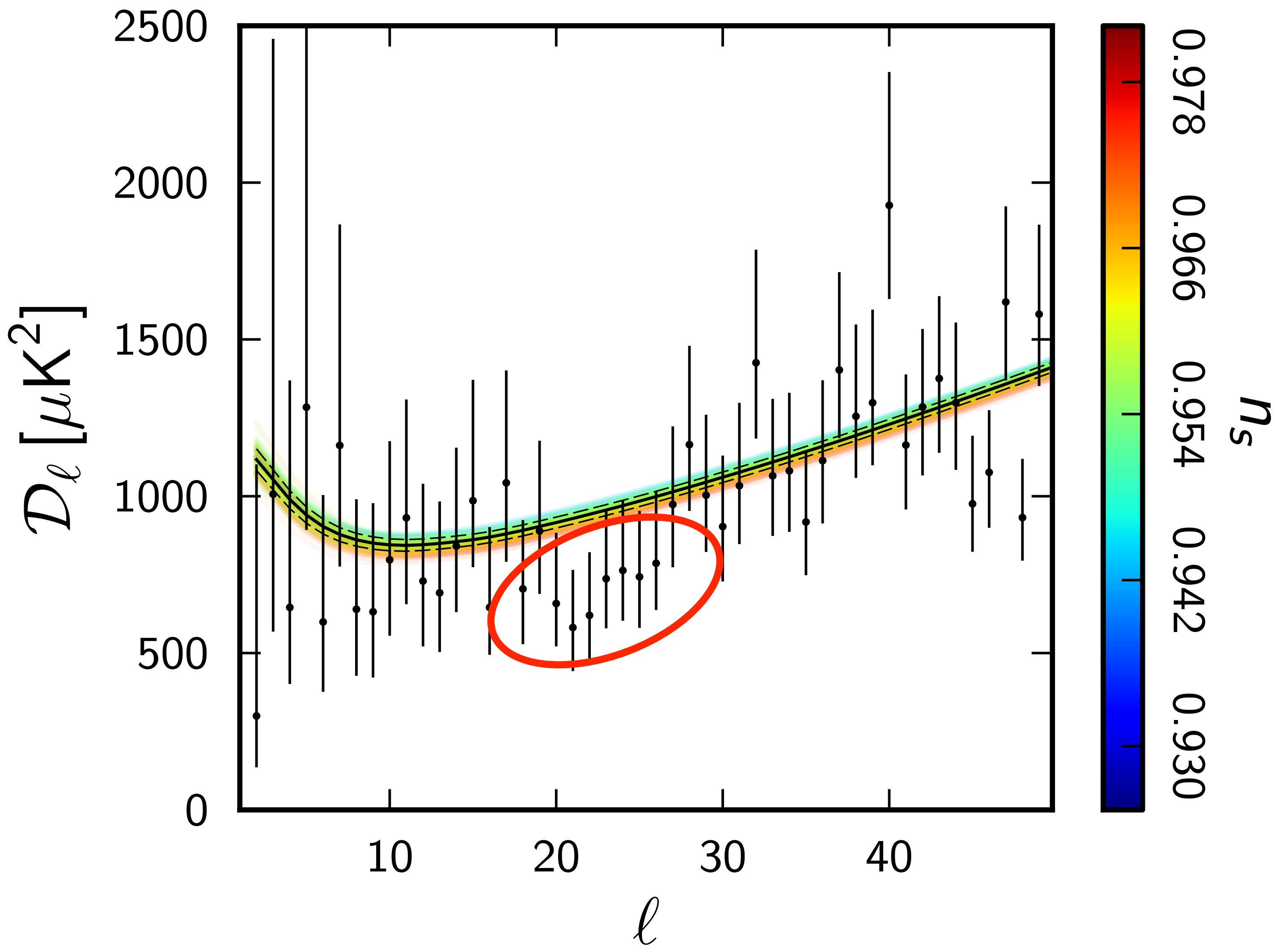
10º

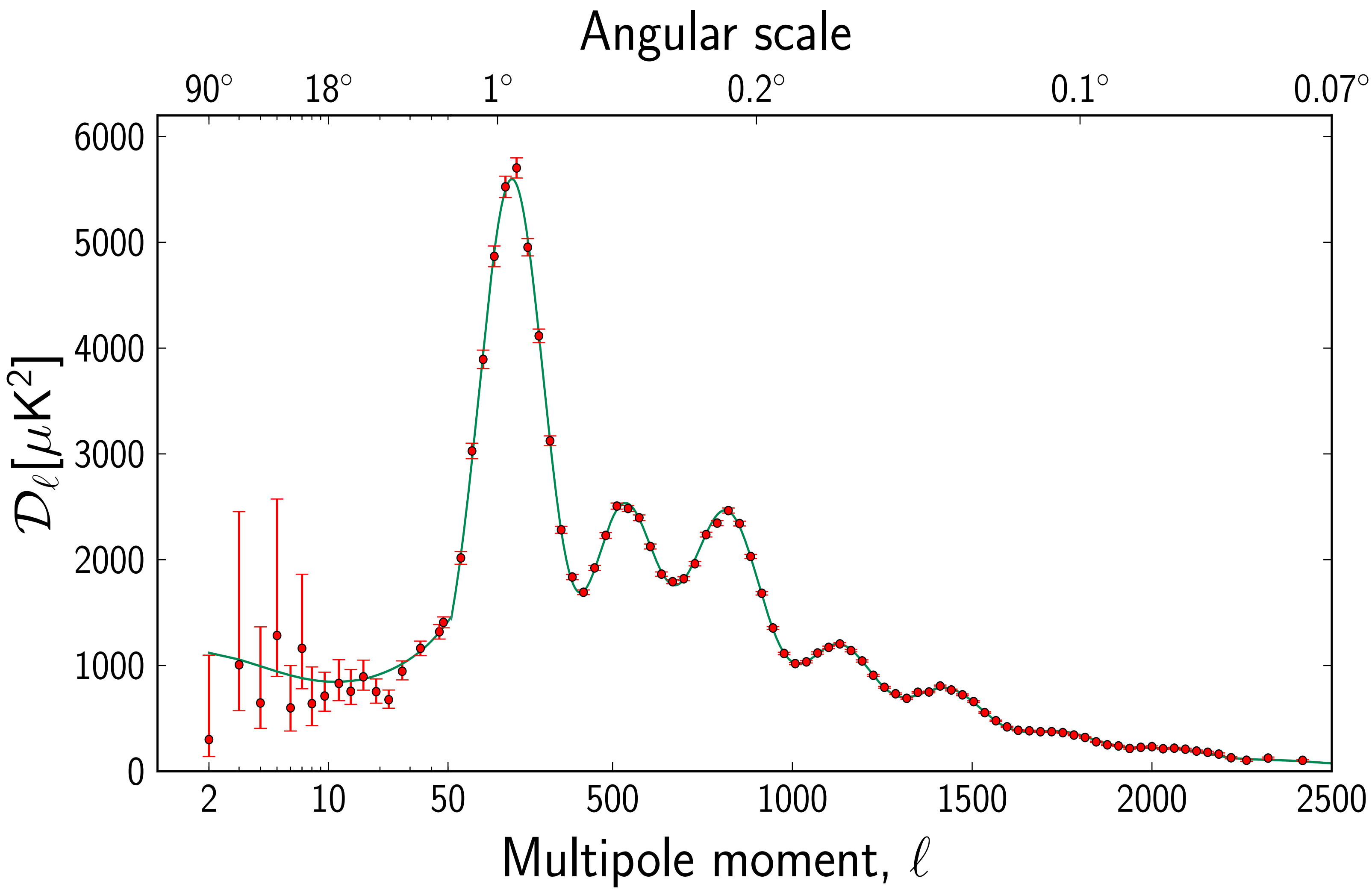
PLANCK LENSING POTENTIAL POWER SPECTRUM



It is a 25 sigma effect!!

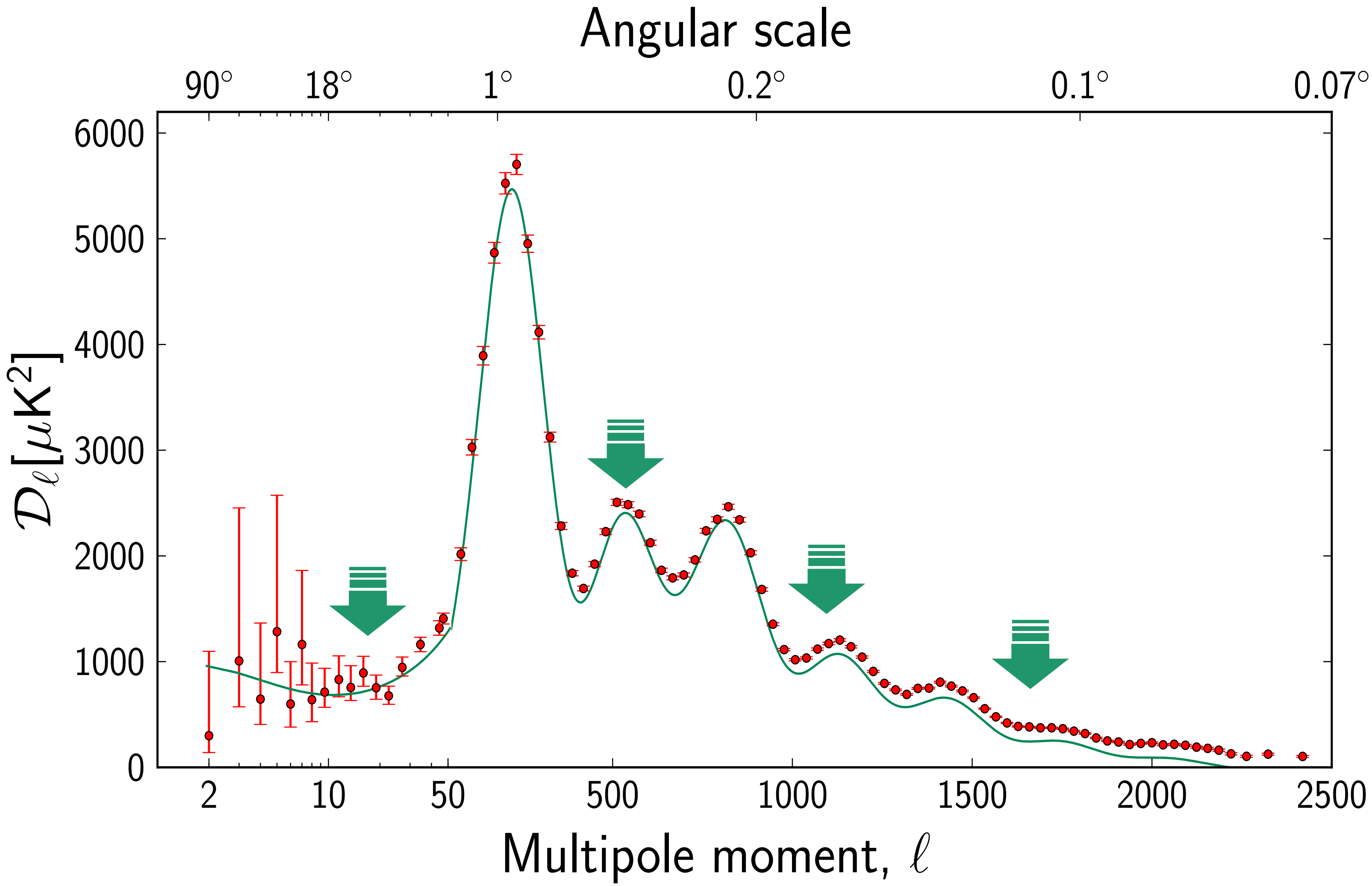
No surprises?



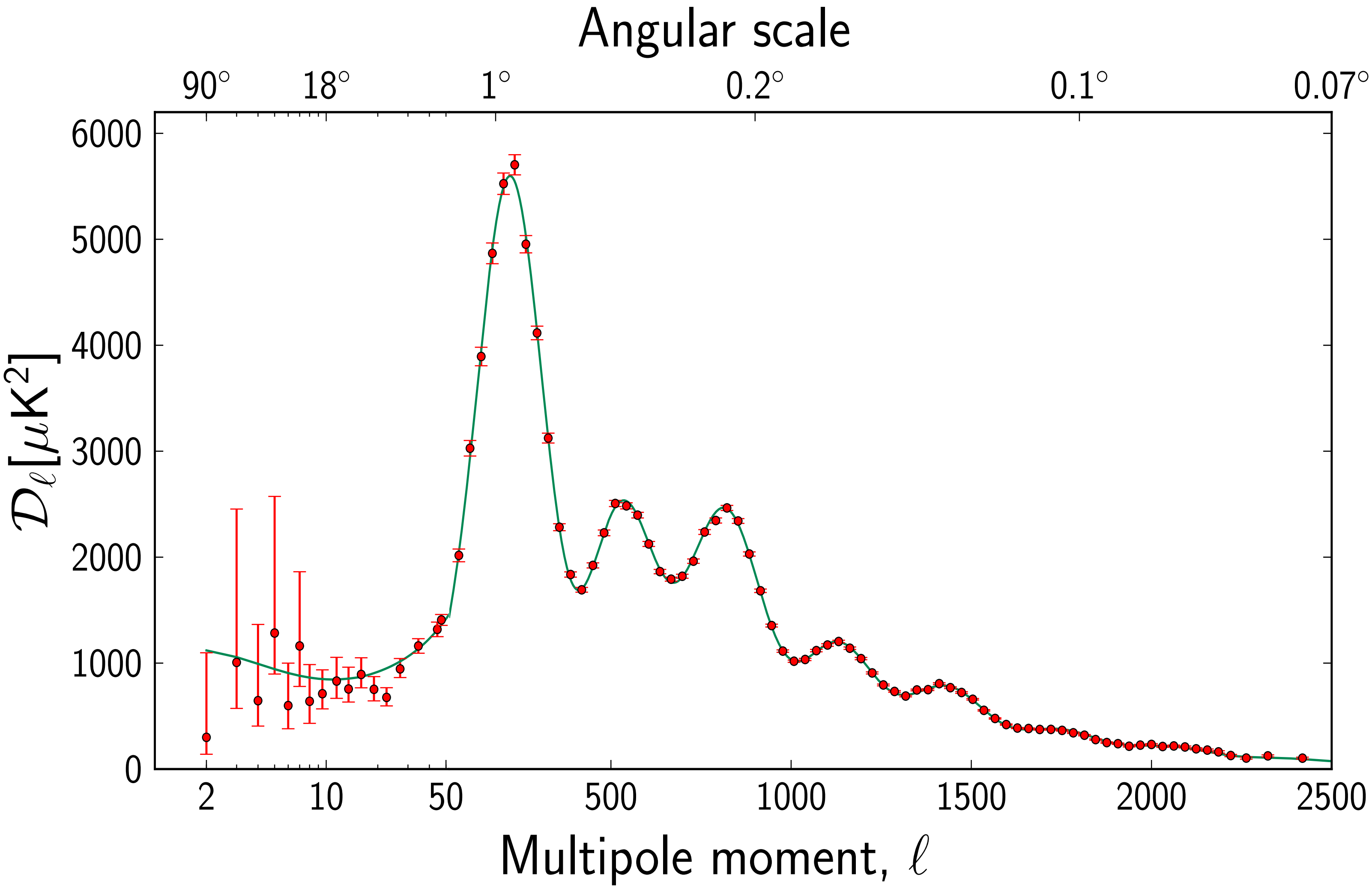


Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

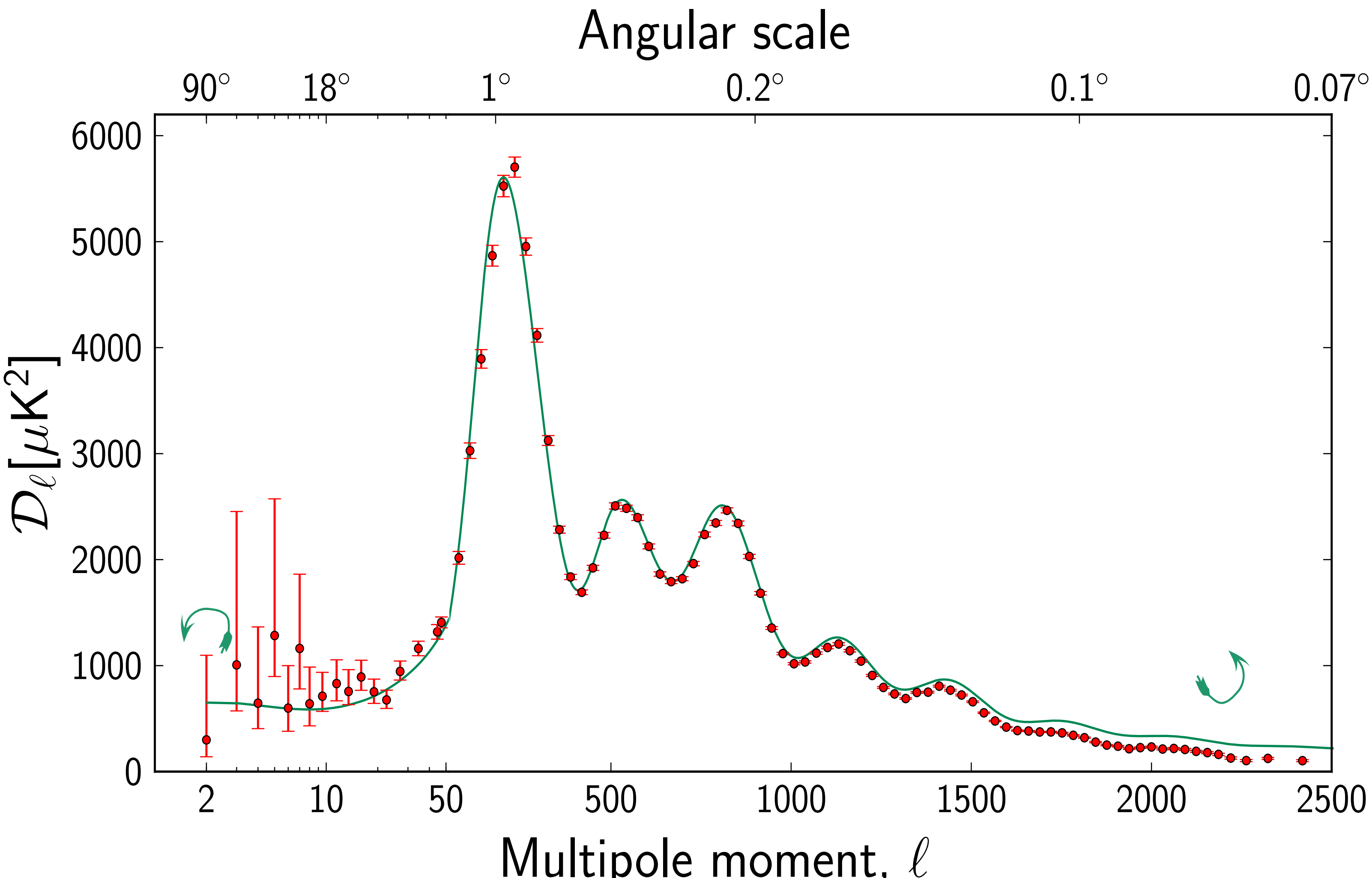
The low-l anomaly



The low-l anomaly



The low-l anomaly

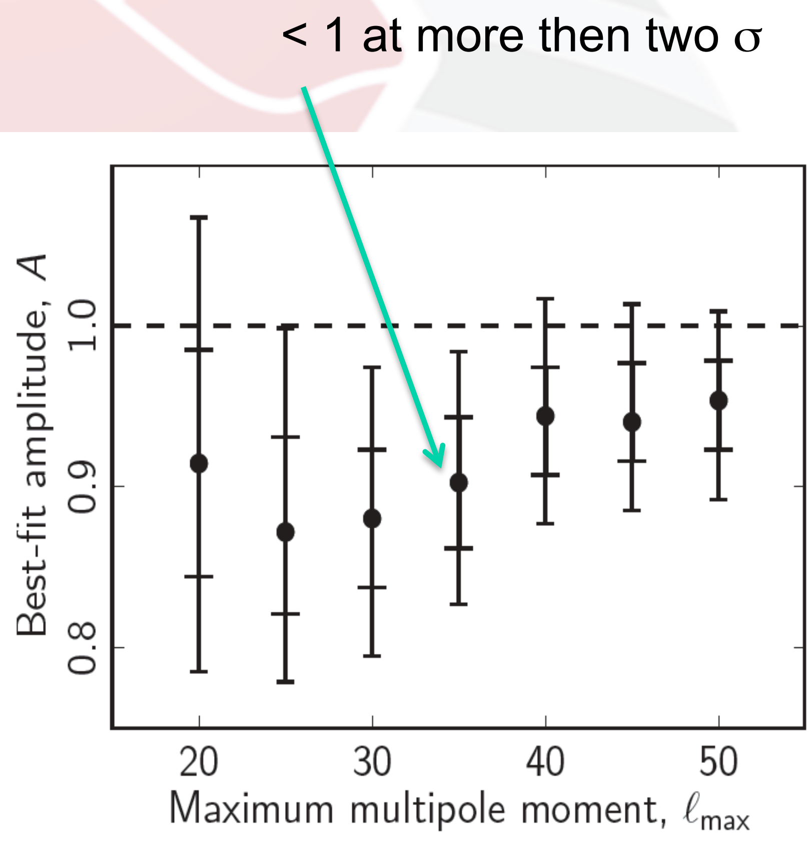


A simple amplitude test

- Rescale the power spectrum in amplitude:

$$C_\ell(A) = A\ C_\ell^{\Lambda CDM}$$

- Find the best-fit A as a function of maximum multipole l.
- There is a 99% “anomaly” for l_{max}=30.
- The anomaly fades away at higher multipoles → where theory and data agree remarkably well.



Conclusions

- The 2013 Planck T map anisotropy leaves behind it a legacy which will stay for many years (…before next Planck release) and will not be replaced easily.
- Excellent agreement between the Planck temperature spectrum at high l and the predictions of the ΛCDM model.
- But…anomalies are also seen and will be investigated

Cosmological parameters

6-parameters model

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Baryon density today	$\Omega_b h^2$	0.00028	0.00013
Cold dark matter density today	$\Omega_c h^2$	0.0027	0.0010
Thomson scattering optical depth	τ	0.013	0.0042
Hubble constant [km/s/Mpc]	H_0	1.2	0.53
Scalar spectrum power-law index	n_S	0.007	0.0031

Constraints on other parameters

Parameter		2013 uncertainty (Planck+WP)	Expected 2014 (Planck T+P)
Effective number of neutrino species	N_{eff}	0.42	0.18
Fraction of baryonic mass in helium	Y_p	0.035	0.010
Dark energy equation of state	w	0.32	0.20
Varying fine-structure constant	α/α_0	0.0043	0.0018

→ Expected reduction in error bars by factors of 2 or more

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.

A. Zacchei "Frequency maps

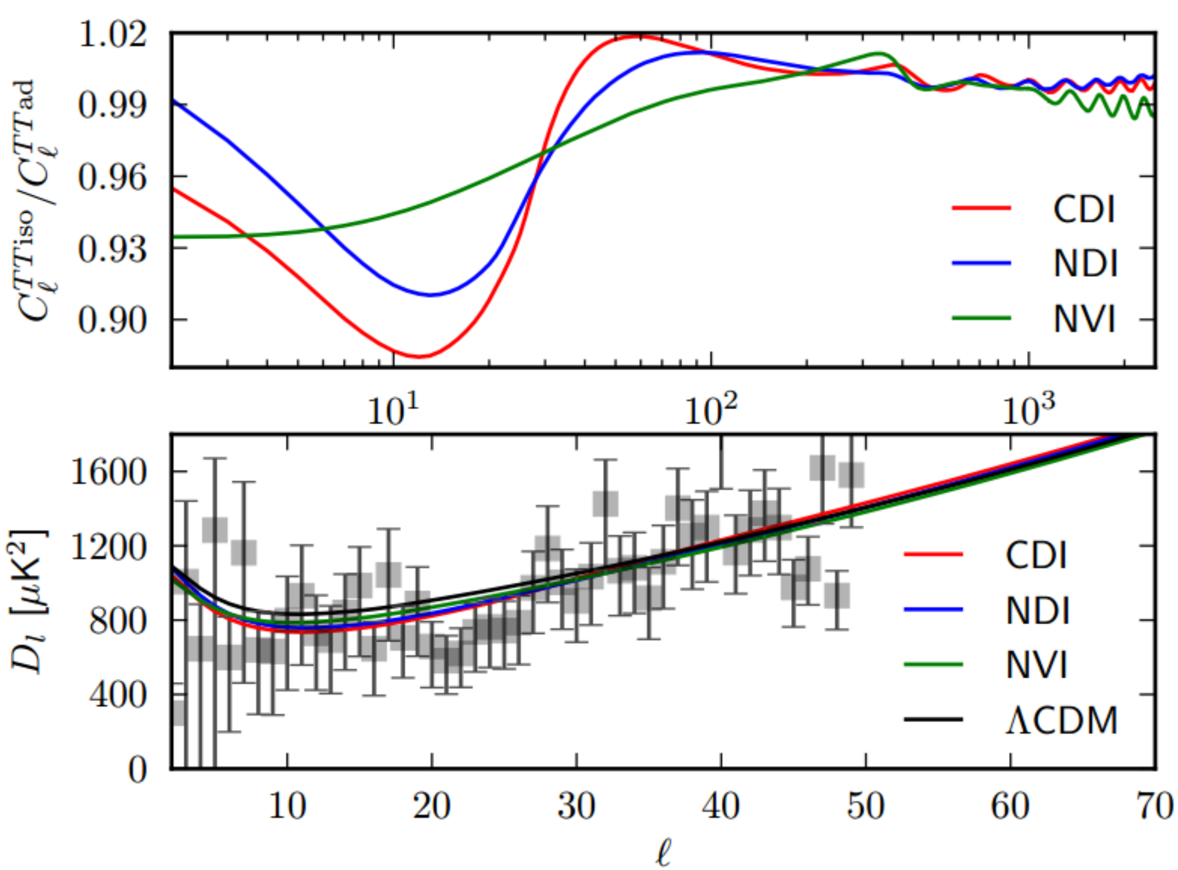
EXTRA SLIDES

Isocurvature modes ?

A mixed adiabatic-isocurvature model can provide a better Fit to the low-l region.

In the Figure we see 3 models:

CDI: Cold Dark Matter Density Isocurvature Mode
NDI: Neutrino Density Isocurvature Mode
NVI: Neutrino Velocity Isocurvature Mode



The isocurvature mode is favoured at the level of 2 sigmas.
This kind of model is compatible with multi-field inflation.
But as we can see from the data, isocurvature modes are not enough to compensate the low-low-l signal !

Checking consistency by SFH

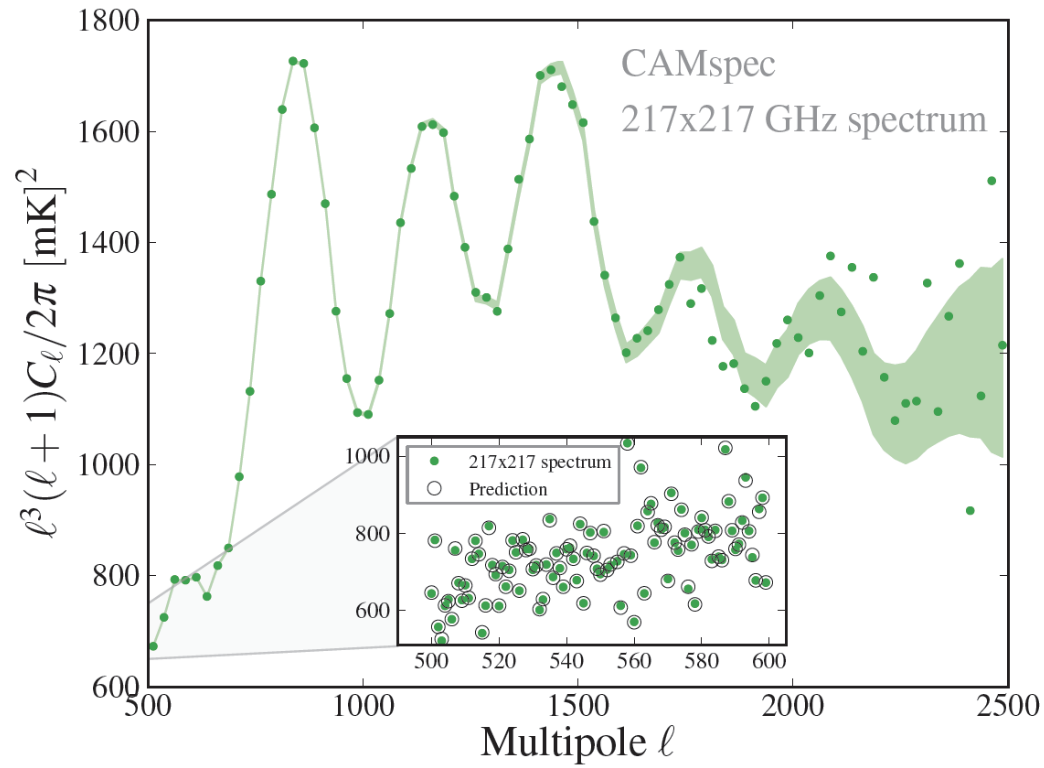
SFH draw 500 samples of the 217x217 spectrum from the CamSpec covariance, *conditioning* on the observed 100x100, 143x143, and 143x217 spectra, assuming no beam uncertainty.

They then compare with our 217 X 217 GHz spectrum (below); they also replace the observed 217x217 spectrum in the likelihood by their sampled spectra and run to parameters (next).

The 217GHz Planck points appear:

- low at l ~ 1800, on the downside of the 6th peak
- High at l $\gtrsim$ 2100, after the 7th peak

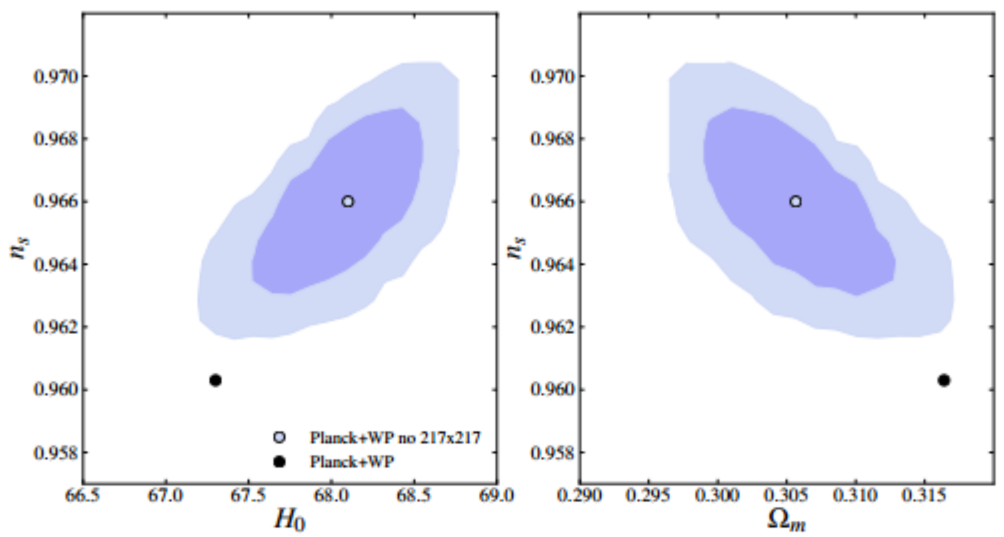
as compared to the expectation from the other cross-spectra



Claim 1

The parameter shift is larger than expected.

Fig 1 reproduced below shows the (Planck+ WP - 217x217) best fit value, surrounded by contours of the expected difference between when adding the 217x217 samples. Our actual Planck+WP values is the black point, suggesting it is moving by more than anticipated



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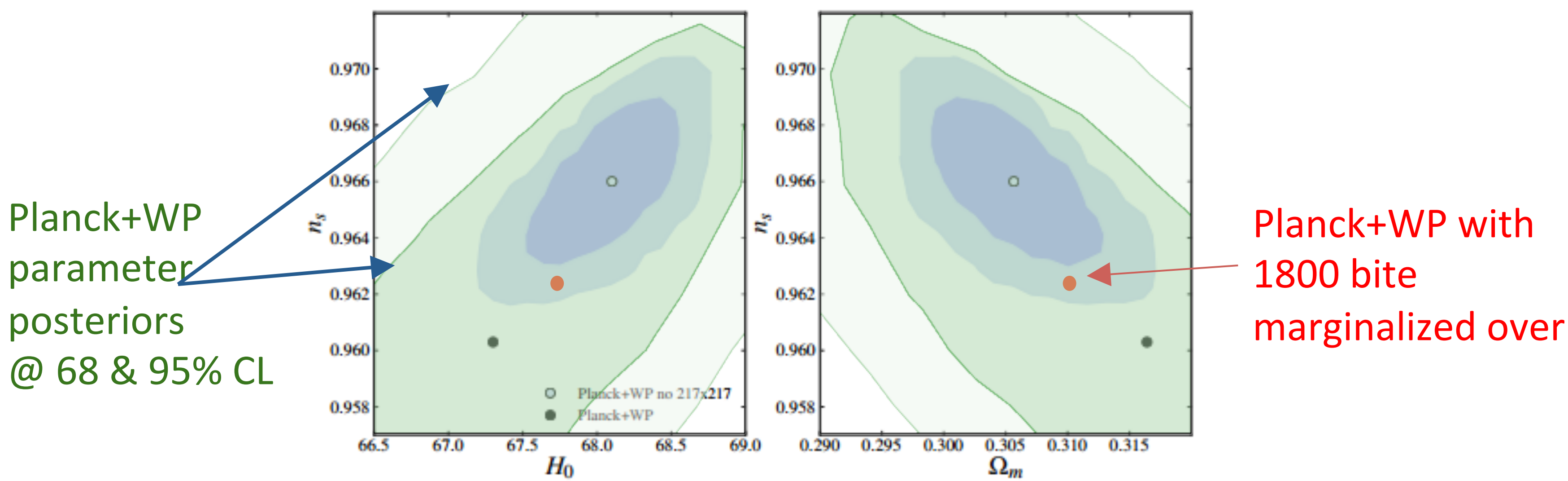
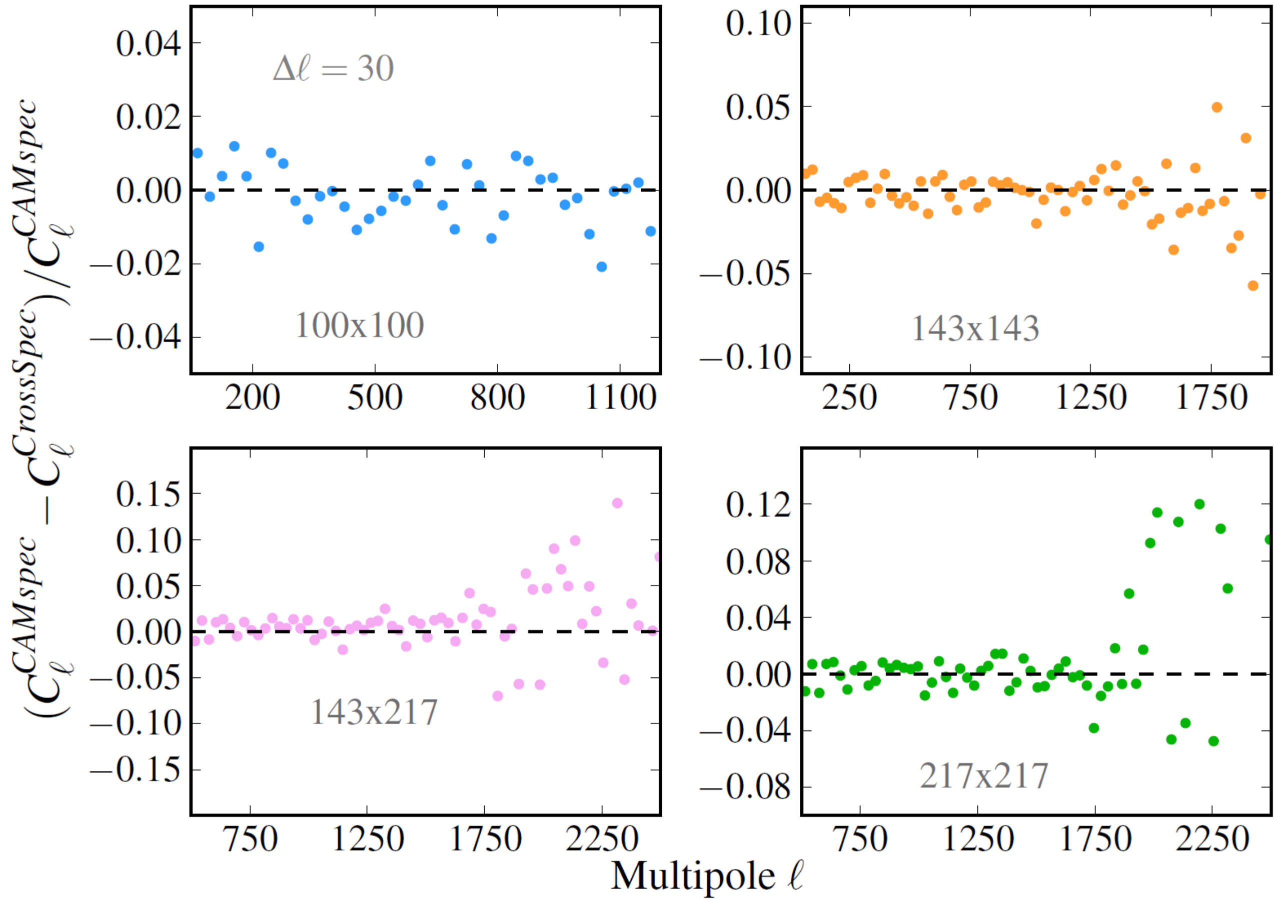


- The shift is quite small as compared to the final parameter uncertainty (green bands)
- We acknowledged ourselves the effect of the l~1800 bite – red point
- *SFH agree with us that this has very little impact on cosmological parameters*

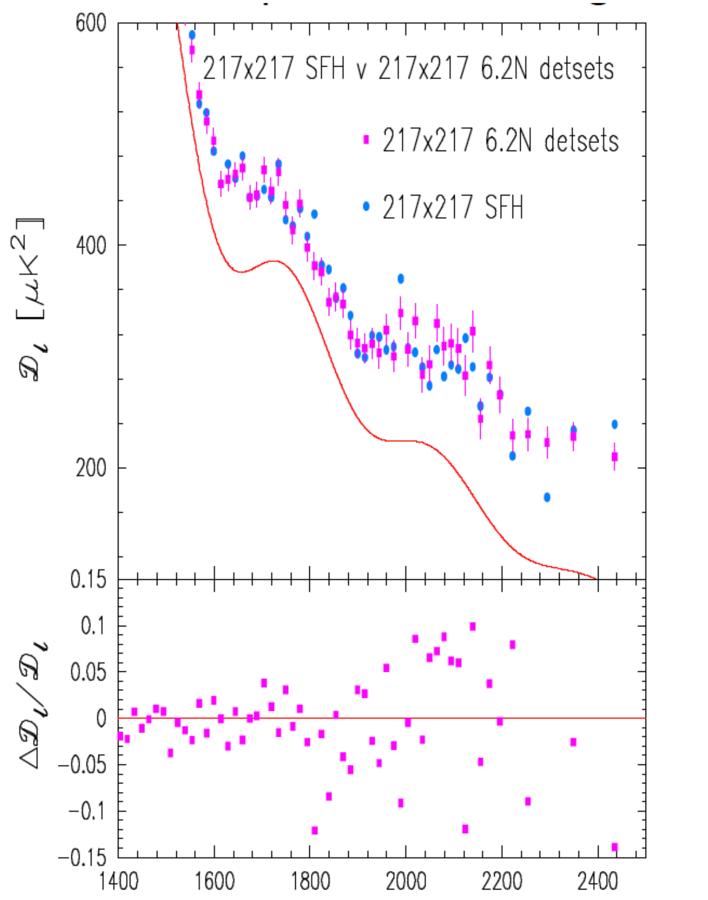
Claim 2

At 217 GHz, l ≳ 2100, detector set spectra are 10% higher than season cross-spectra



Claim 2

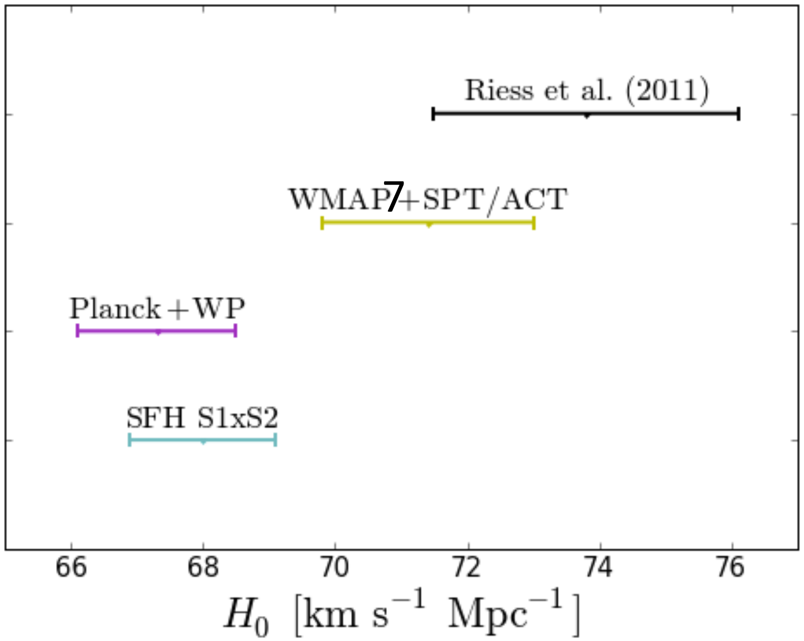
At 217 GHz, l ≳ 2100, detector set spectra are 10% higher than season cross-spectra

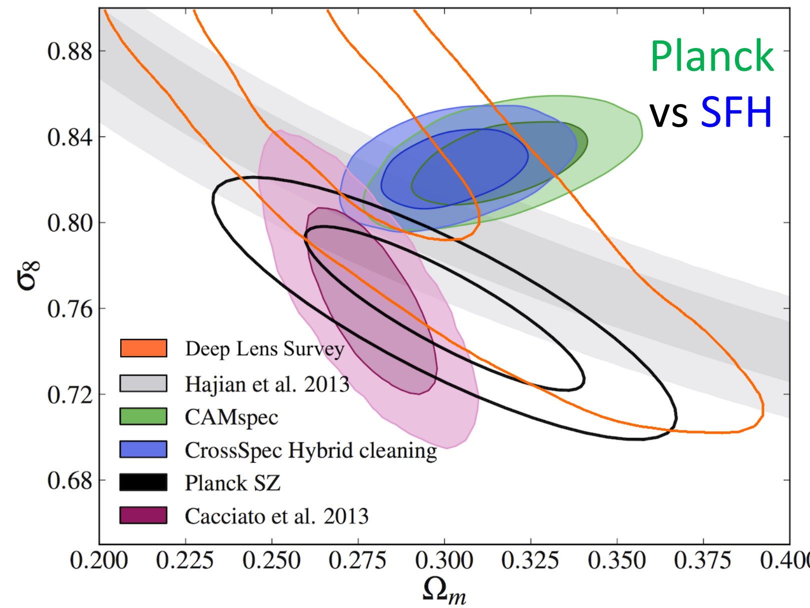


This figure compares the 217x217 detset spectrum of the publically released nominal mission likelihood with the S1xS2 cross-survey spectrum computed by SFH. No corrections for foregrounds have been made to either spectrum. The lower panel shows the difference between these spectra. Note that the precision of this test is limited by the lower signal-to-noise of the S1xS2 spectrum. There is some evidence of a deficit at ell = 1800, but *no evidence of large systematic differences at higher multipoles*. This disagrees with Figure 12 of SFH.

Claim 3

Differences in parameters, with SFH rendition fitting better some LSS probes





- ❑ Keep the problem in perspective. Eg. difference between Planck+WP and SFH in H_0 is 0.7 km/s/Mpc in base cosmology. Difference between Planck+WP+BAO and SFH is only 0.2 km/s/Mpc.
- ❑ It may be difficult to identify reasons for ~1σ shifts in parameters. For base ΛCDM, uncertainties in the Planck foreground model cause ~02-0.3σ shifts in parameters.
- ❑ Differences in foreground cleaning and likelihood accuracy might be reponsible for larger shifts.