Title: New results from the Planck satellite

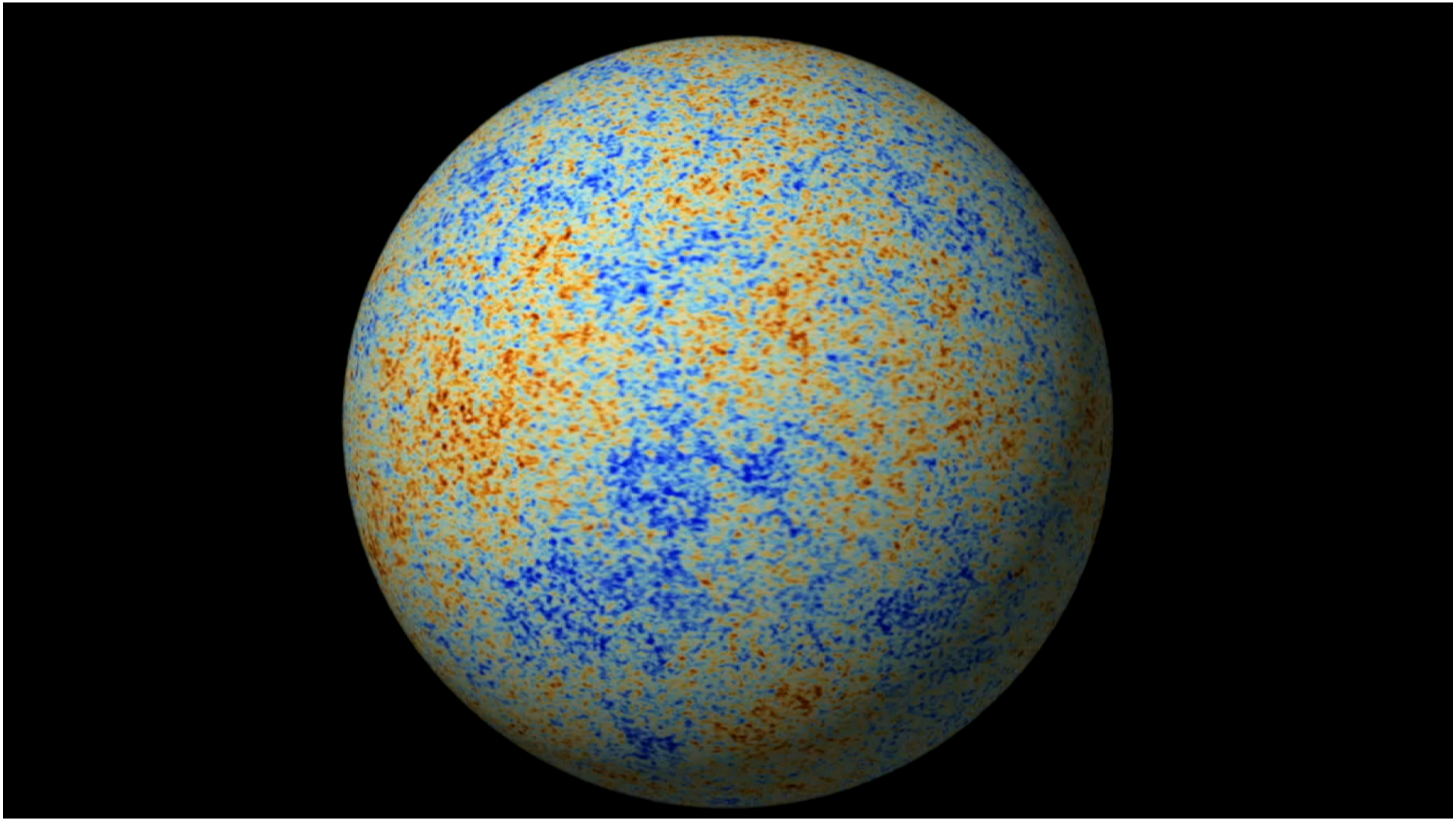
Date: Jan 28, 2015 02:00 PM

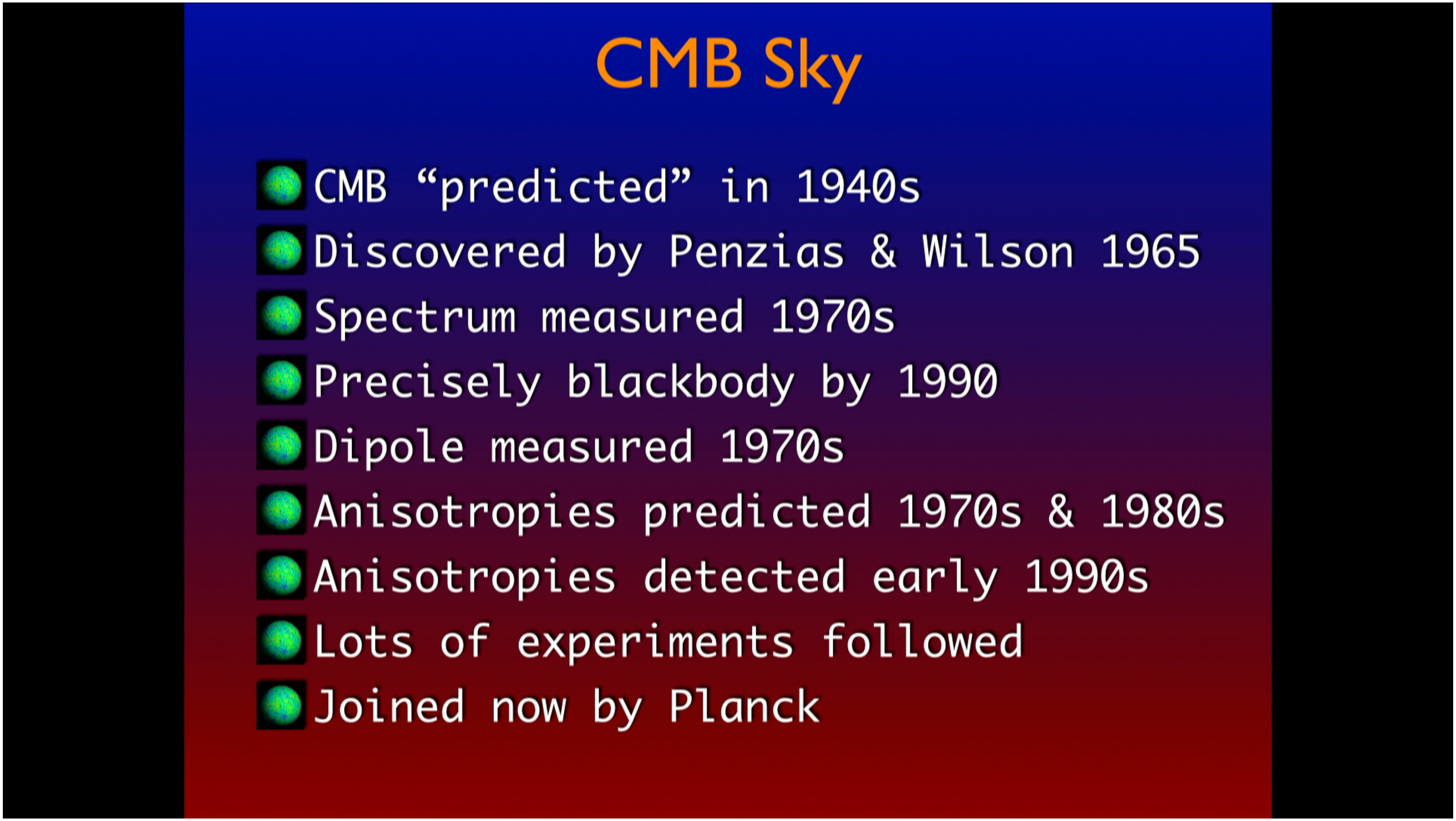
URL: http://pirsa.org/15010075

Abstract:

The Universe According to Planck

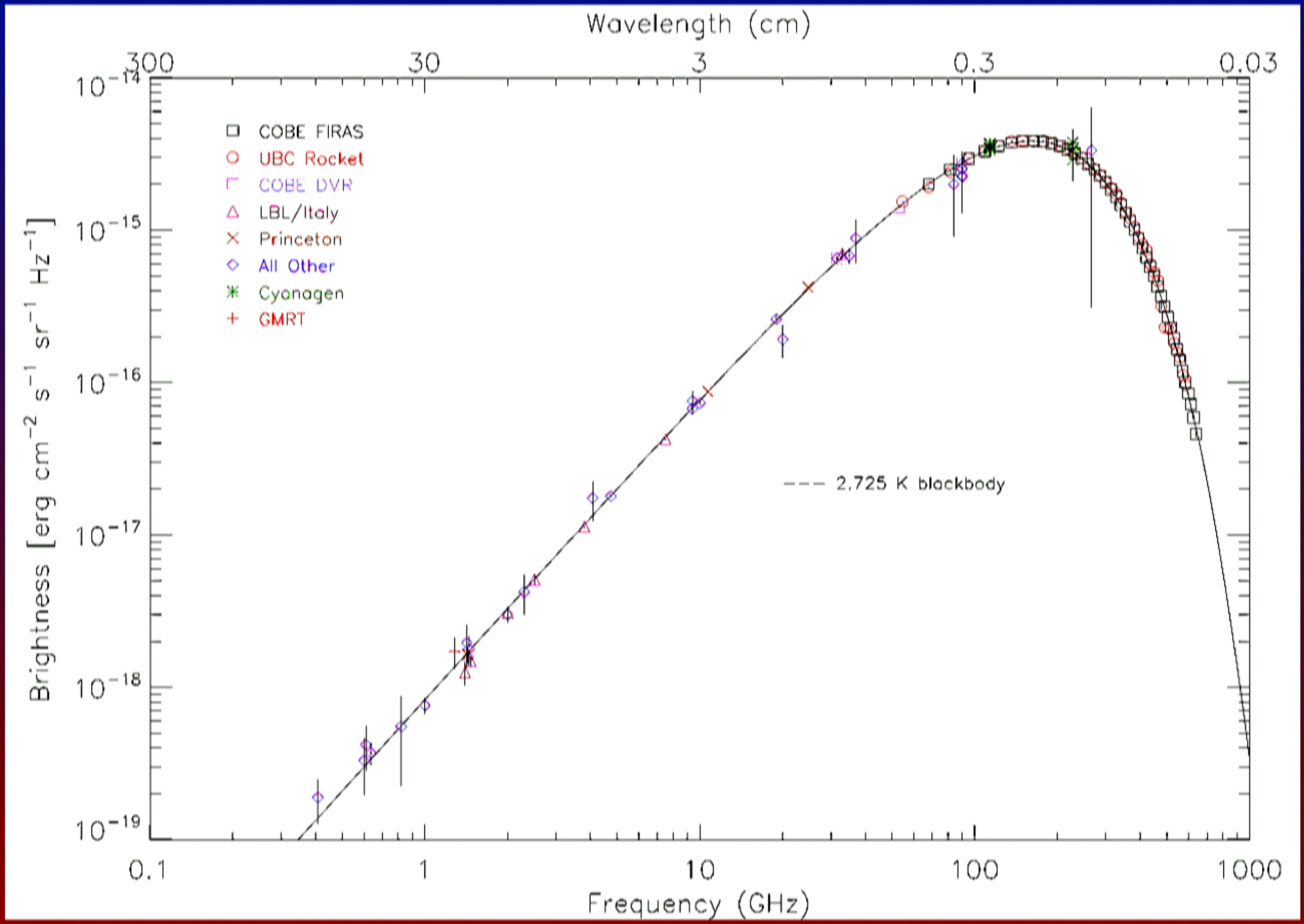
Douglas Scott
UBC
(on behalf of the Planck Collaboration)



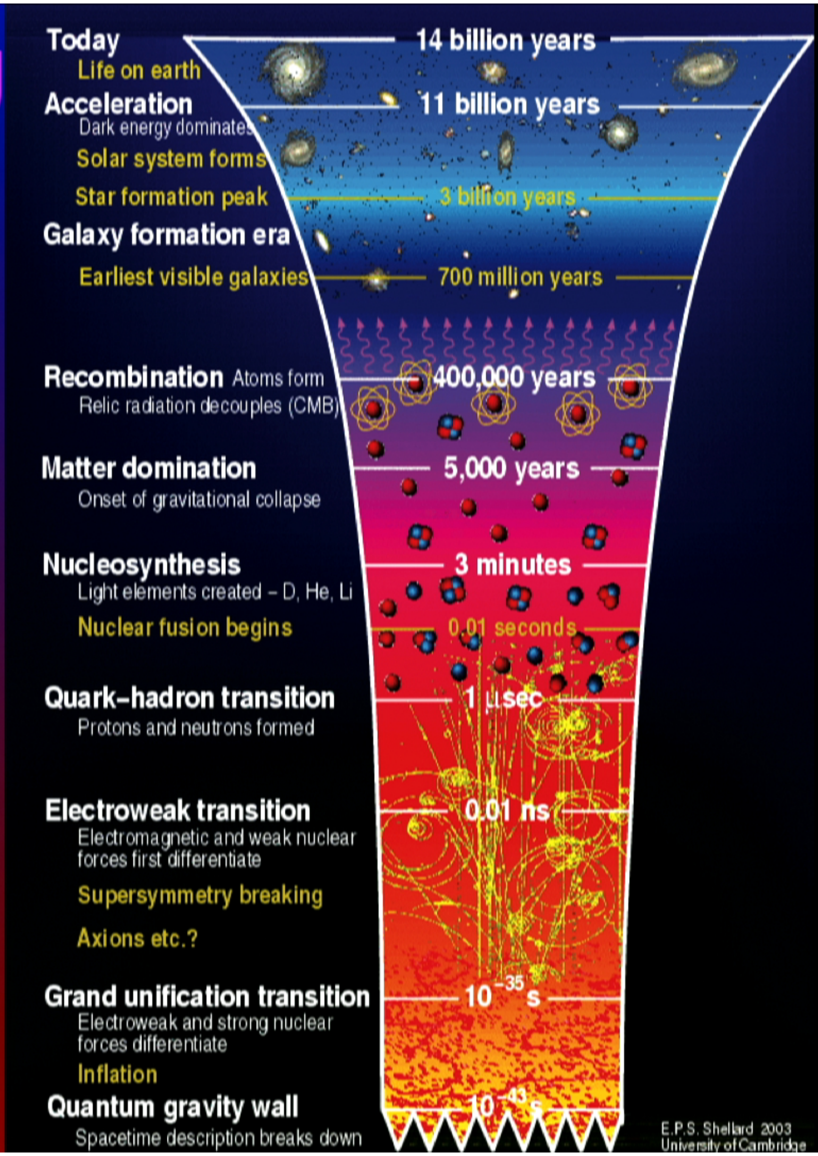


CMB Sky
CMB “predicted” in 1940s
Discovered by Penzias & Wilson 1965
Spectrum measured 1970s
Precisely blackbody by 1990
Dipole measured 1970s
Anisotropies predicted 1970s & 1980s
Anisotropies detected early 1990s
Lots of experiments followed
Joined now by Planck

CMB Spectrum

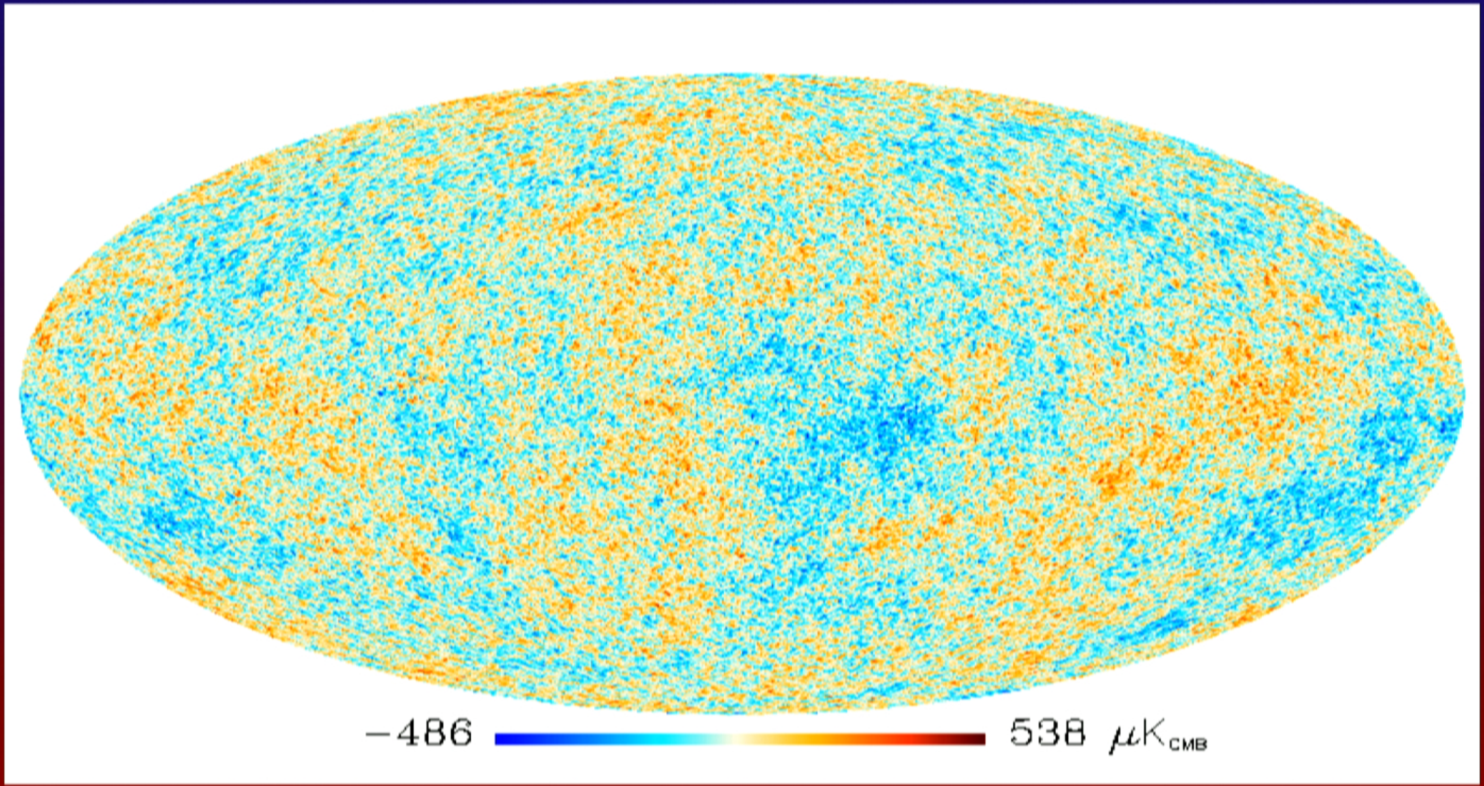


The Hot Big Bang

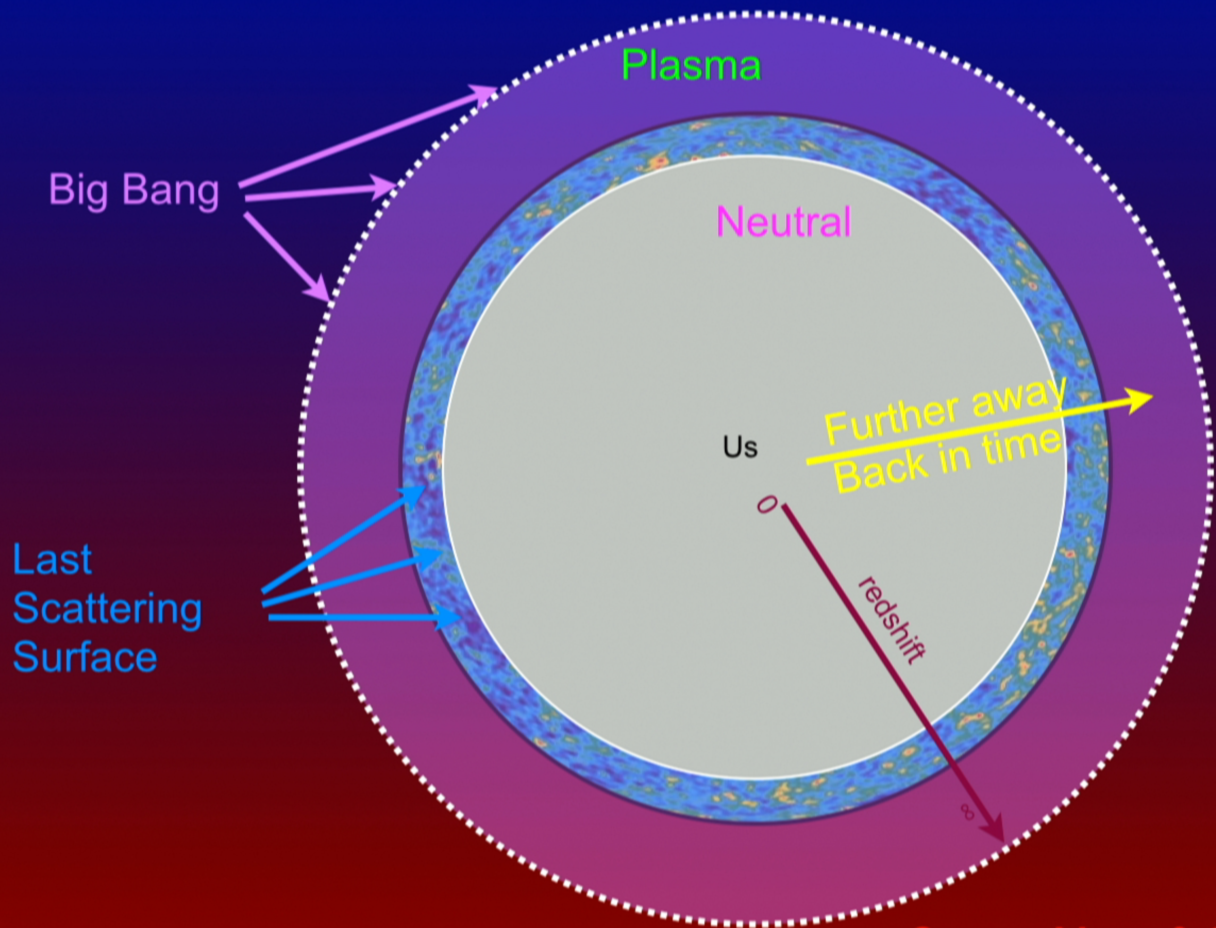


The CMB Sky

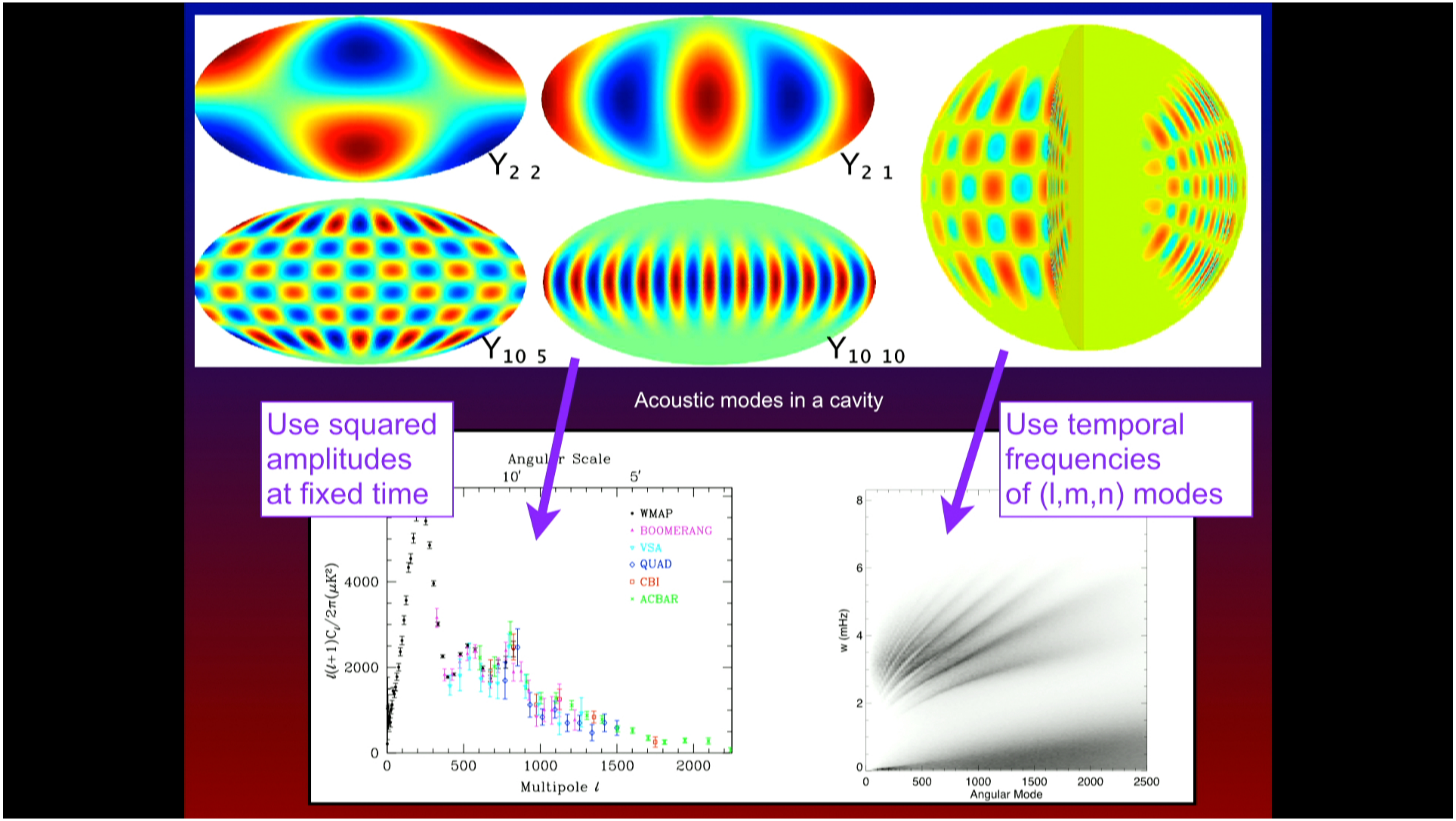
Temperature anisotropies at ~400,000 years



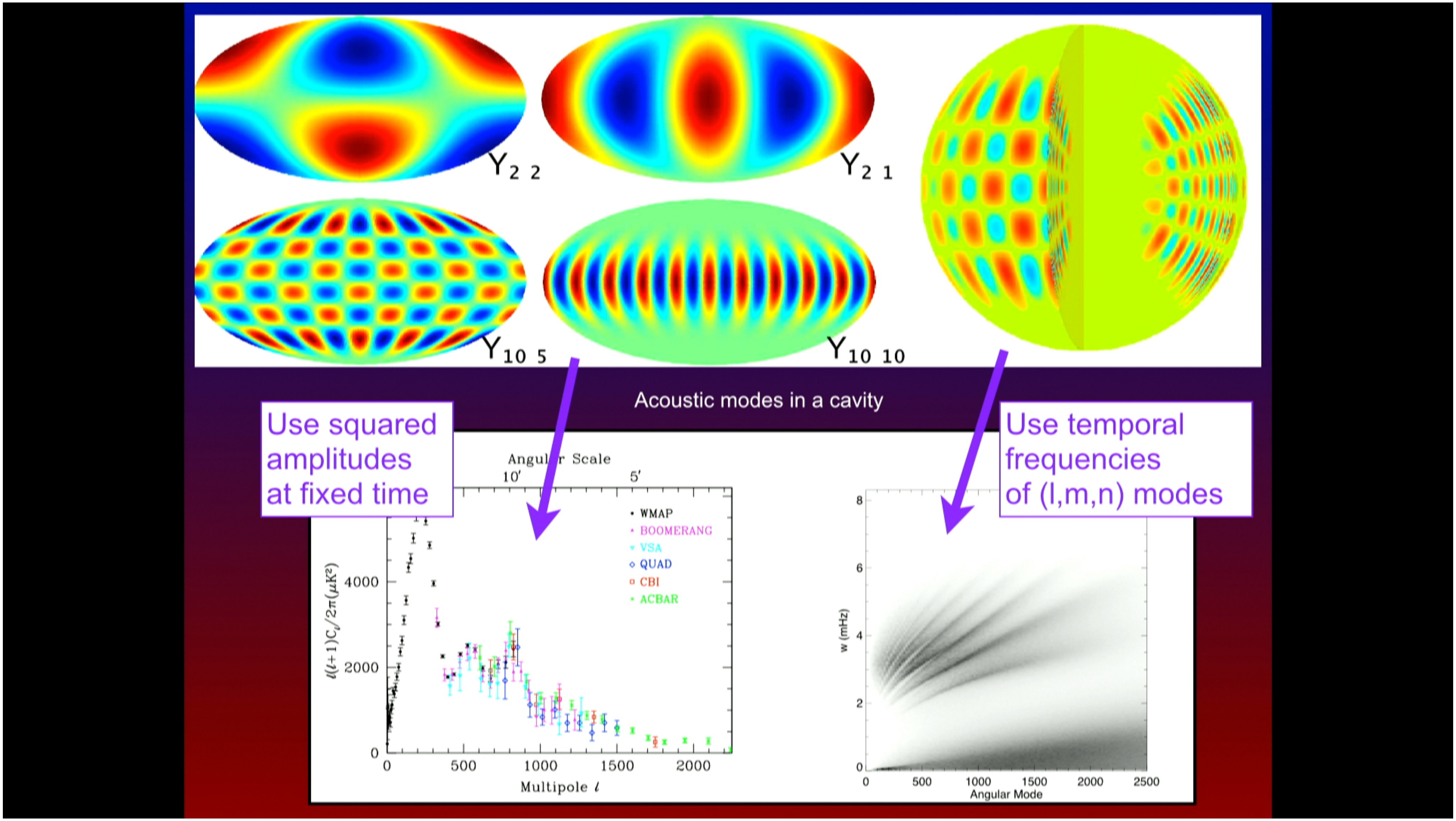
The Universe is an inside-out star!



Crowe, Moss & Scott (2008)



Y2 2
Y2 1
Y10 5
Y10 10
Acoustic modes in a cavity
Use squared amplitudes at fixed time
Use temporal frequencies of (l,m,n) modes
Angular Scale
10′
5′
WMAP
BOOMERANG
VSA
QUAD
CBI
ACBAR
ℓ(ℓ+1)Cℓ/2π(μK²)
Multipole ℓ
w (mHz)
Angular Mode



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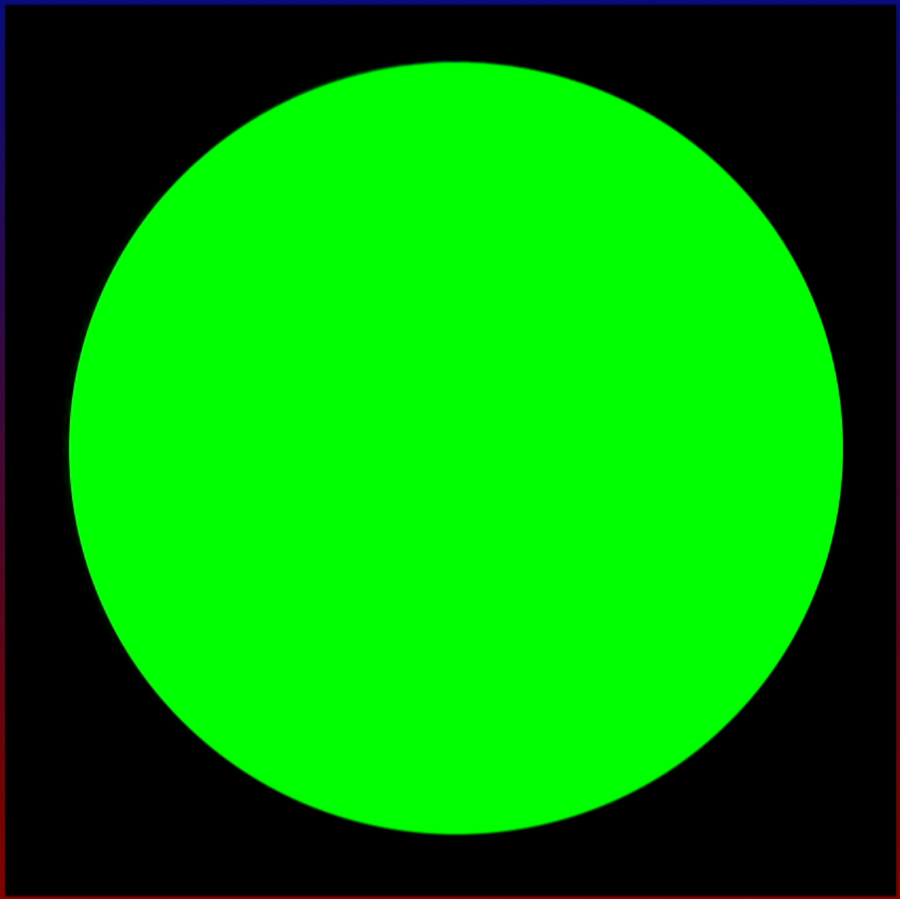
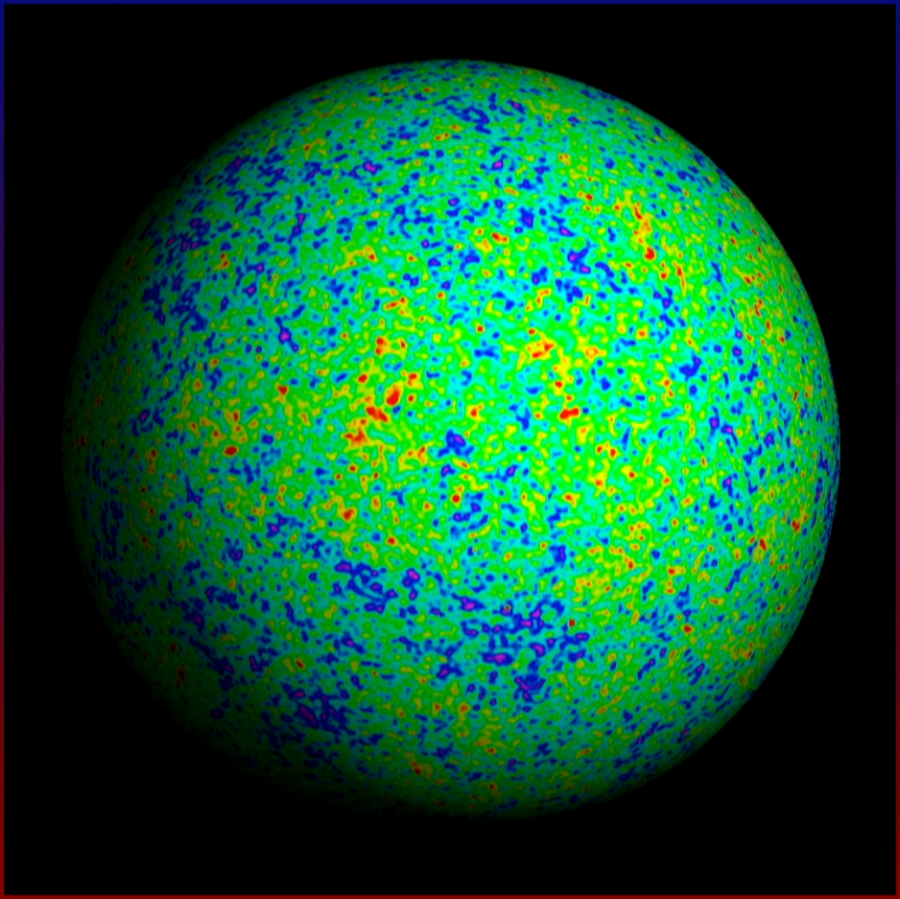
CMB Sky



CMB Sky



Statistical description of anisotropies

Expand sky in spherical harmonics

$$T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

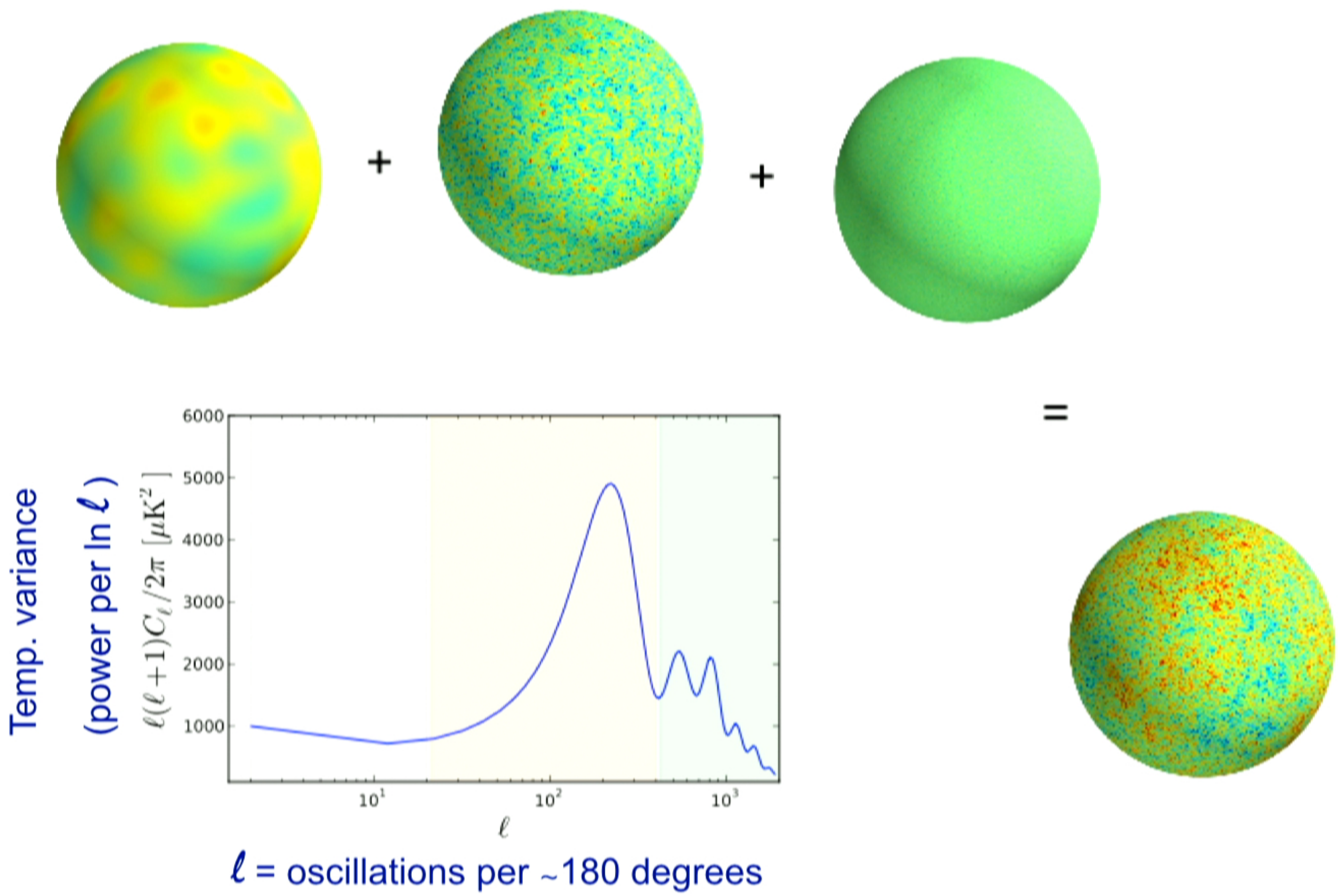
Monopole is T_0 (=a_{00})

Dipole is our "absolute motion"

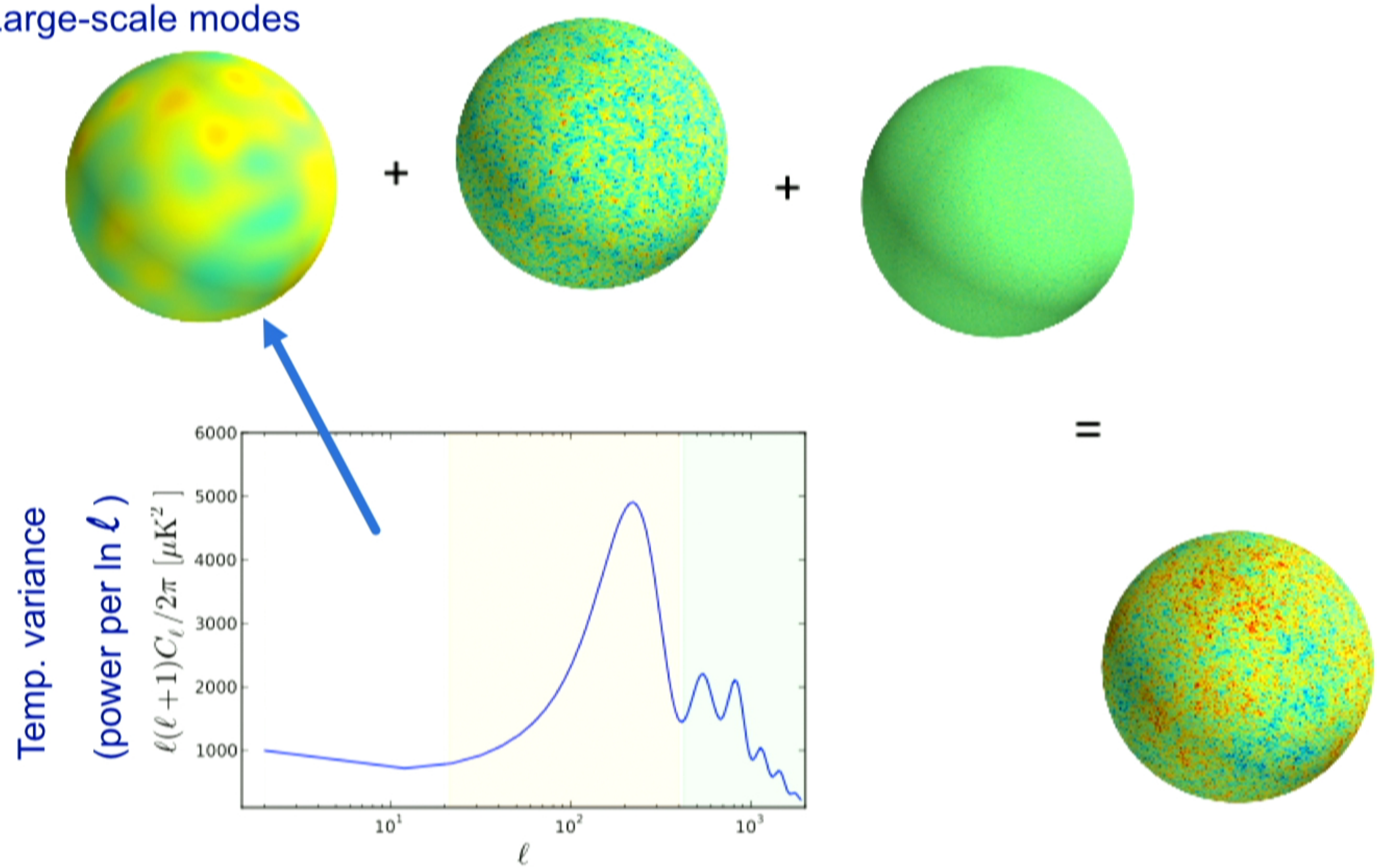
$l \geq 2$ modes give info on perturbations

$C_\ell \equiv \left\langle |a_{\ell m}|^2 \right\rangle$ i.e. average over *ms*

$(2\ell + 1)C_\ell / 4\pi$ is power at each l


+
+
=
Temp. variance
(power per ln ℓ)
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
6000
5000
4000
3000
2000
1000
10^1
10^2
10^3
ℓ
ℓ = oscillations per ~180 degrees

Large-scale modes



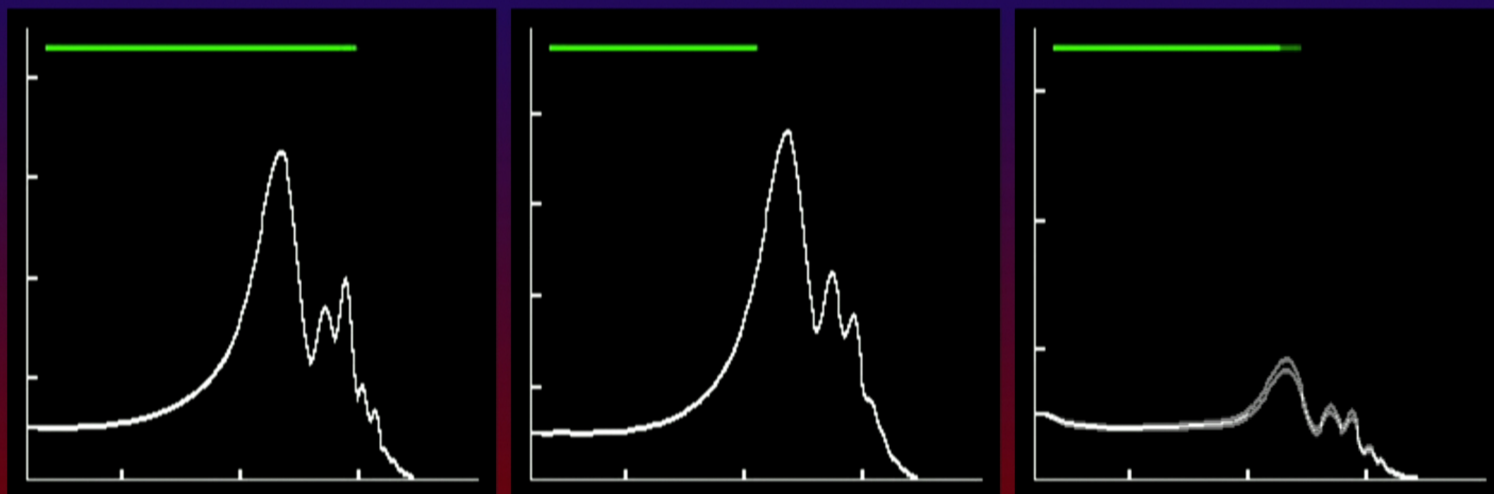
ℓ = oscillations per ~180 degrees

- Individual hot/cold spots are just the particular realisation of our sky
- Actually anisotropies look very Gaussian (i.e. maximally random)
- This is what is expected from inflation
- Gaussian ⇒ all information in variance

  (or power spectrum)
- Shape of power spectrum varies with cosmological parameters

Parameters affect peak structure in different ways

Baryons | Dark Energy | “Tilt” of ICs



Movies from Martin White

Data compression

Data compression

- Trillions of bits of data
- Billions of measurements at 9 frequencies
- 50 million pixel map of whole sky
- 2 million harmonic modes measured
- 1000σ detection of CMB anisotropy power
- Fit with just 6 parameters!

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So what are these 6 parameters?

The 6 parameters

(Planck 2013 results alone here)

Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

The 6 parameters

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Physical CDM density	$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
Sound hor./ang.diam.dist.	$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
Reionization optical depth	τ	0.0925	0.097 ± 0.038
Slope of initial P(k)	n_s	0.9624	0.9616 ± 0.0094
Amplitude of initial P(k)	$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

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Amount of atoms	$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
Amount of dark stuff	$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
Stretch factor for wiggles	$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
Fraction of recent scattering	τ	0.0925	0.097 ± 0.038
Scale variation of lumpiness	n_s	0.9624	0.9616 ± 0.0094
Strength of lumpiness	$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072

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And some derived parameters
($+ t_0 + \sigma_8 + \ldots$)

H_0	67.11	67.4 ± 1.4
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020

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There are somewhat different constraints for Planck + other data

Main message from Planck

- A 6 parameter model continues to fit!
- With only some simple (and testable) assumptions
- We appear to have a fairly precise model for the Universe on the largest scales
- But: Where did the parameters come from?
  - Will further precision uncover more parameters?
  - Could any of the basic assumptions turn out to be wrong?

Assumptions underlying the SMC

1 Physics is the same throughout the observable Universe.

2 General Relativity is an adequate description of gravity.

3 On large scales the Universe is statistically the same everywhere.

4 The Universe was once much hotter and denser and has been expanding.

5 There are five basic cosmological constituents:

- 5a Dark energy behaves just like the energy density of the vacuum.
- 5b Dark matter is pressureless (for the purposes of forming structure).
- 5c Regular atomic matter behaves just like it does on Earth.
- 5d Photons from the CMB permeate all of space.
- 5e Neutrinos are effectively massless (again for structure formation).

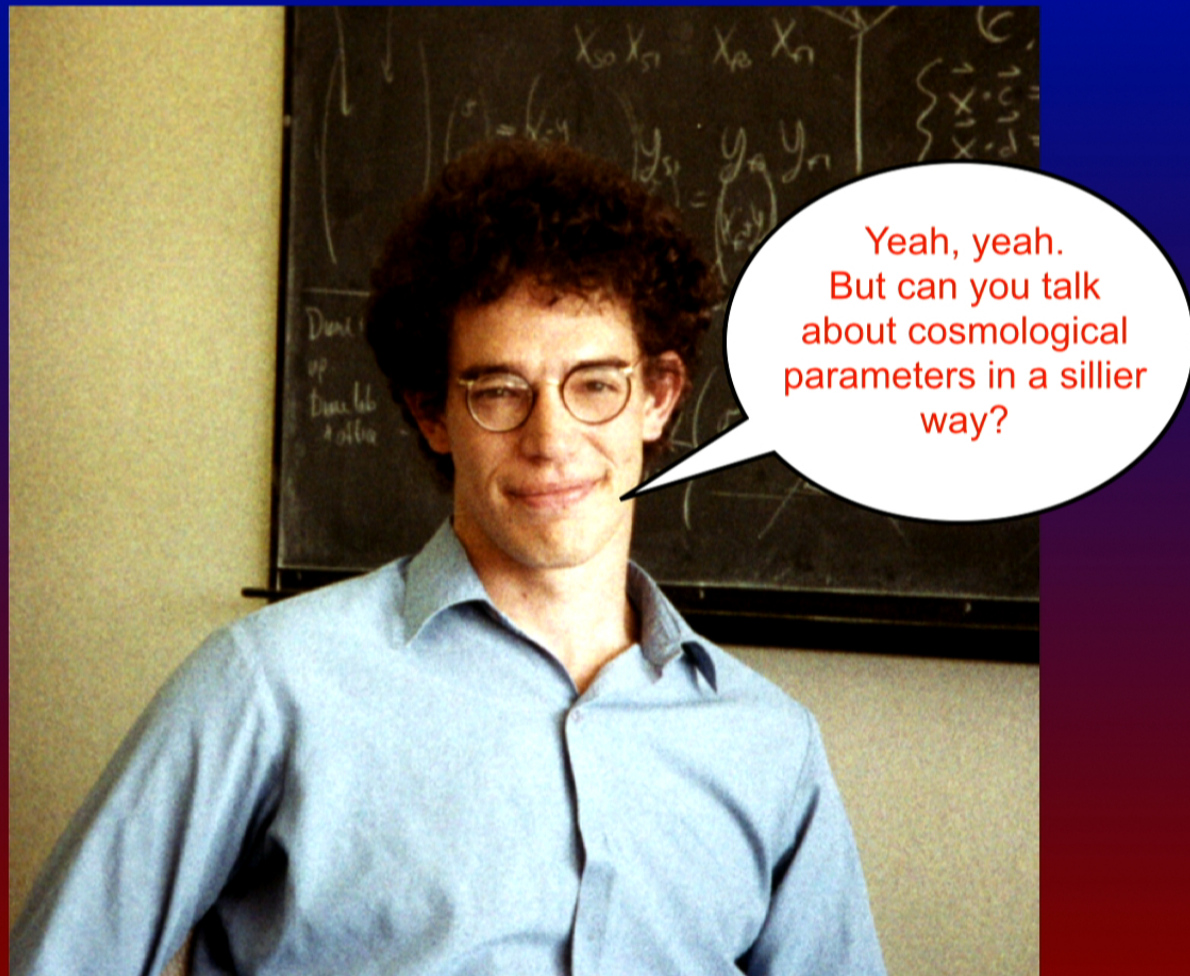
6 The overall curvature of space is flat.

7 Variations in density were laid down everywhere at early times, proportionally in all constituents.

The 6 parameters

(Planck 2013 + WP + HighL + BAO here)

Standard cosmological parameters		
Parameter	Description	Value
$\Omega_{\mathrm{b}} h^2$	Baryon density	0.0221 ± 0.0002
$\Omega_{\mathrm{c}} h^2$	Cold dark matter density	0.1187 ± 0.0017
θ_*	Acoustic angular scale	0.010415 ± 0.000006
A_{s}	Amplitude of density perturbations	$(2.20 \pm 0.06) \times 10^{-9}$
n	Logarithmic slope of perturbations	0.961 ± 0.005
τ	Optical depth due to reionisation	0.092 ± 0.013


Yeah, yeah.
But can you talk
about cosmological
parameters in a sillier
way?

Cosmic Mnemonics

With Ali Narimani + Don Page (+Jim Zibin) arXiv:1309.2381, Phys. in Canada

Cosmic Mnemonics

•Using the chains from "Planck+WP+HighL+BAO":

• Age of the Universe

t_0 = (13.80±0.04)Gyr = 0.435 exaseconds

$\approx 10^8/\alpha$ years

$\approx 5 \times 2^{200}\ t_{\text{Planck}}$

$\approx$ 5 trillion days

$\approx$ 3 × (age of the Earth)

With Ali Narimani + Don Page (+Jim Zibin) arXiv:1309.2381, Phys. in Canada

Cosmic Mnemonics

- Hubble constant:
  - $H_0 t_0$ = 0.957±0.009
  - $H_0 t_0$ = n (!) [$H_0 t_0$/n=0.996±0.007]
  - Ht will be unity in about 1 billion years
  - H ($t \rightarrow \infty$) = (56.4±1.1)km/s/Mpc

With Ali Narimani + Don Page (+Jim Zibin) arXiv:1309.2381, Phys. in Canada

Cosmic Mnemonics

- Critical density ($3H_0^2/8\pi G$):
  - $\rho_{crit} = (8.6\pm0.2)\times10^{-27}$kg m^{-3} = 5 nucleons m^{-3}
- Cosmological constant:
  - $\Lambda = (1.00\pm0.01)\times10^{-35}$s^{-2} = ten square attohertz

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- Cosmological constant:
  - $\Lambda = (1.00\pm0.01)\times10^{-35}s^{-2}$ = ten square attohertz
- Distance to last-scattering:
  - $d_{LSS} = (430.1\pm1.4)\times10^{24}$m $\sim$400 Yottametres
- Photons within last-scattering volume:
  - $N_\gamma = (1.443\pm0.013)\times10^{89} \sim \alpha^{-42}$

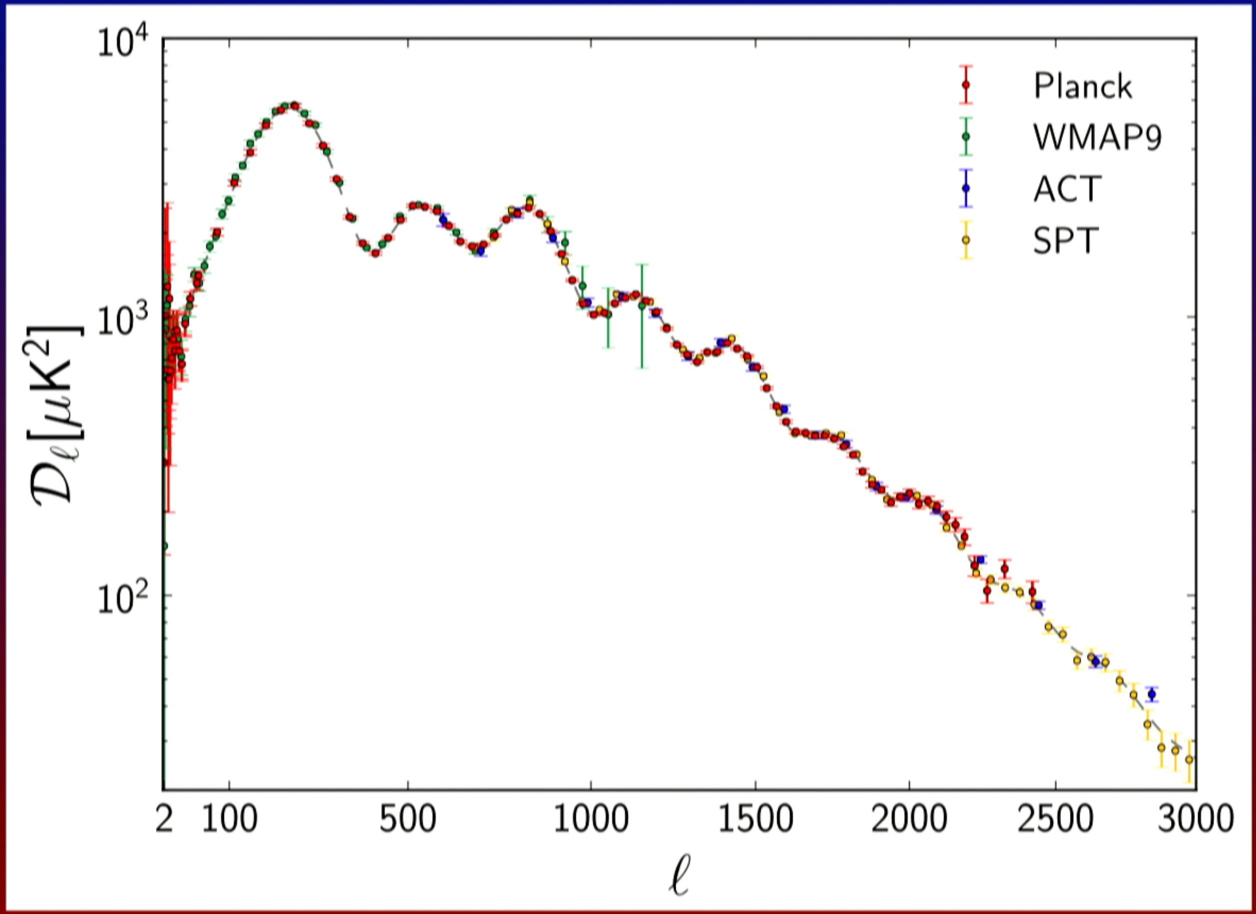
With Ali Narimani + Don Page (+Jim Zibin) arXiv:1309.2381, Phys. in Canada

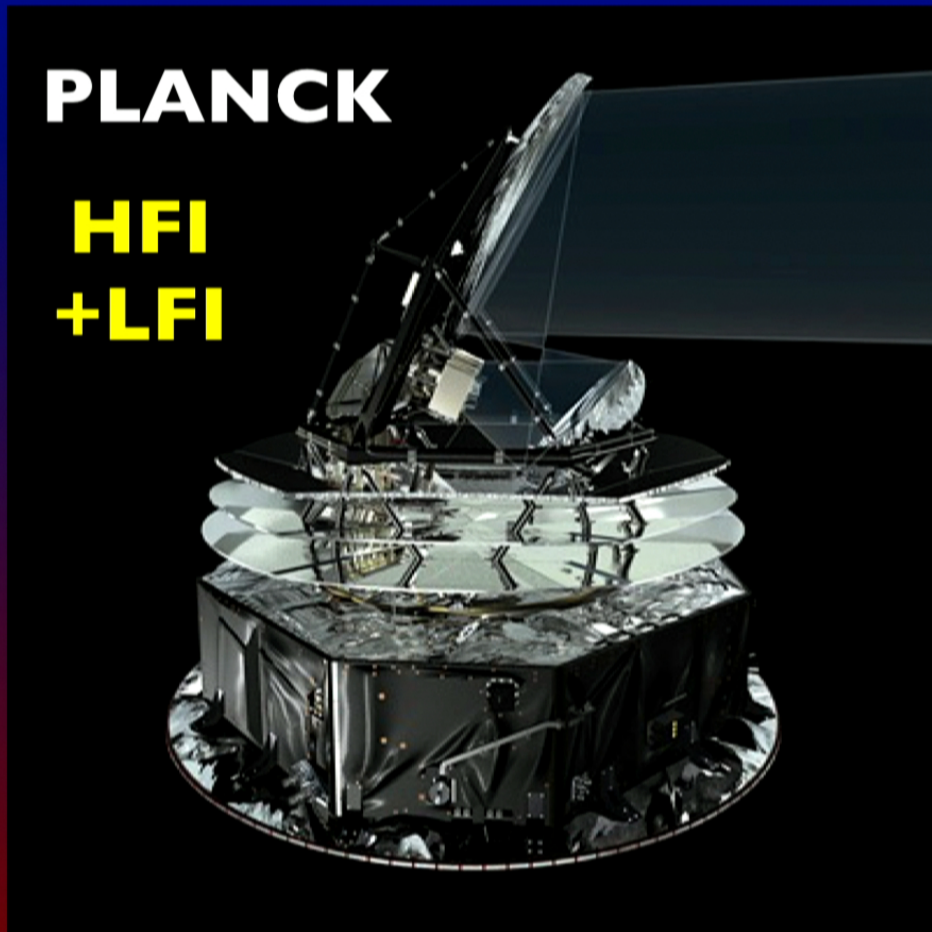
Cosmic Mnemonics

- Amplitude: σ_8=0.826±0.012 at 8 h^{-1}Mpc
  - But $\sigma(R)$= 1 for R=(8.9±0.3)Mpc [no h!]
- Growth factor today: g=0.784±0.006
- Reionization: fraction of CMB scattered = 8.8%
- Scaling of acoustic peaks = 0.6° (=Sun or Moon)
- $\Omega_m/\Omega_b = 2\Omega_\Lambda/\Omega_m$ (=5.4)
- $\Omega_\gamma = 5.4\times10^{-5} = \alpha^{-2}$
- ...

With Ali Narimani + Don Page (+Jim Zibin) arXiv:1309.2381, Phys. in Canada

Such numerology only possible because of the "precision era"





2 instruments, the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI) in a shared focal plane containing 74 channels (in 9 separate frequencies) and covering 8 degrees on the sky.

ESA Mission (+ European national agencies +NASA +CSA)

Planck/Herschel

14th May 2009 Kourou, French Guiana

Launched successfully and worked as planned!

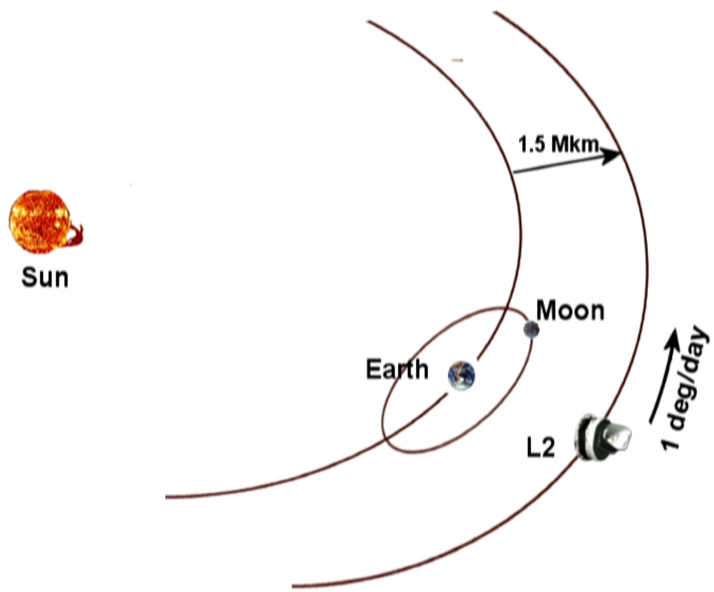
Planck papers

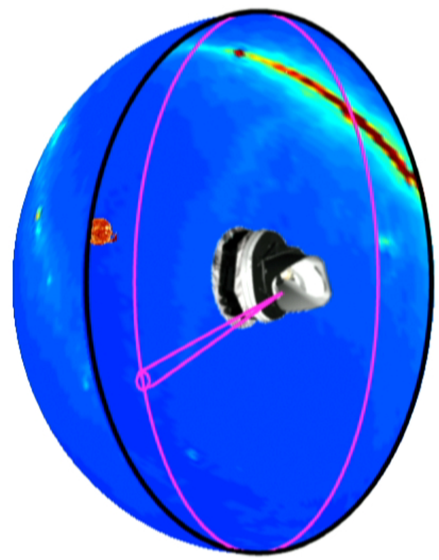
- "Planck pre-launch status"
  - 14 papers
- "Planck early results"
  - 26 papers
- "Planck intermediate papers"
  - 34 papers (so far)
- "Planck 2013 results"
  - 31 papers
- "Planck 2015 results"
  - many papers soon!

Instrumentaion
Cosmic rays
Zodiacal emission
Component separation
Interstellar medium
Galactic cold clumps
Anomalous microwave emission
Polarized dust radiation
All-sky CO map
Nearby galaxies
Extragalactic sources
Cosmic infrared background
CMB power spectra
Cosmological parameters
Gravitational lensing
Integrated Sachs-Wolfe effect
SZ cluster cosmology
Cluster physics
Constraints on inflation
Topological defects
Non-Gaussianity
Isotropy & Statistics
Geometry & Topology
...

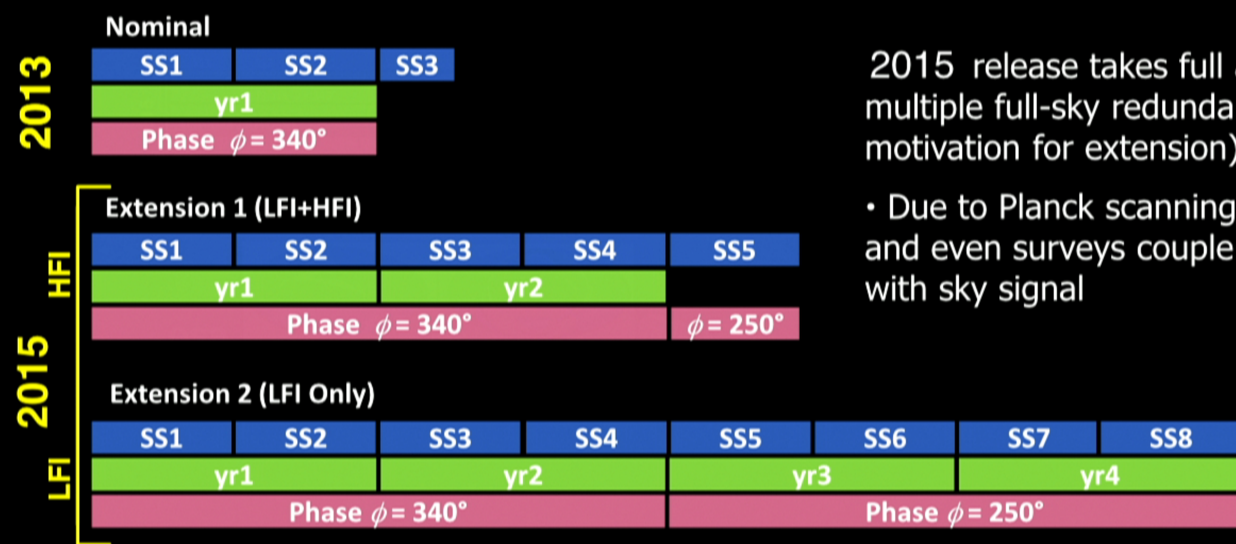
The orbit

Planck made a map of the full sky every ~6 months.





2015 release: Planck full mission

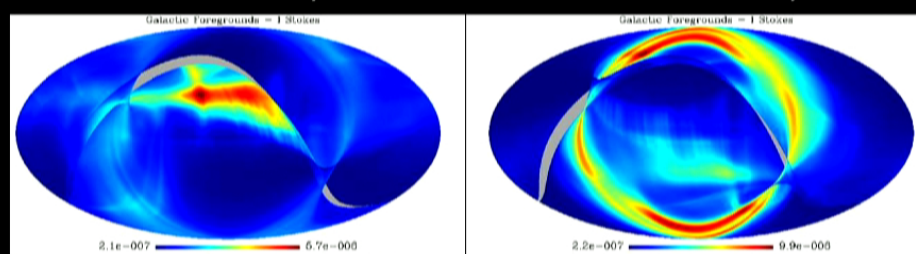


2015 release takes full advantage of multiple full-sky redundancies (main motivation for extension)

- Due to Planck scanning strategy, odd and even surveys couple differently with sky signal

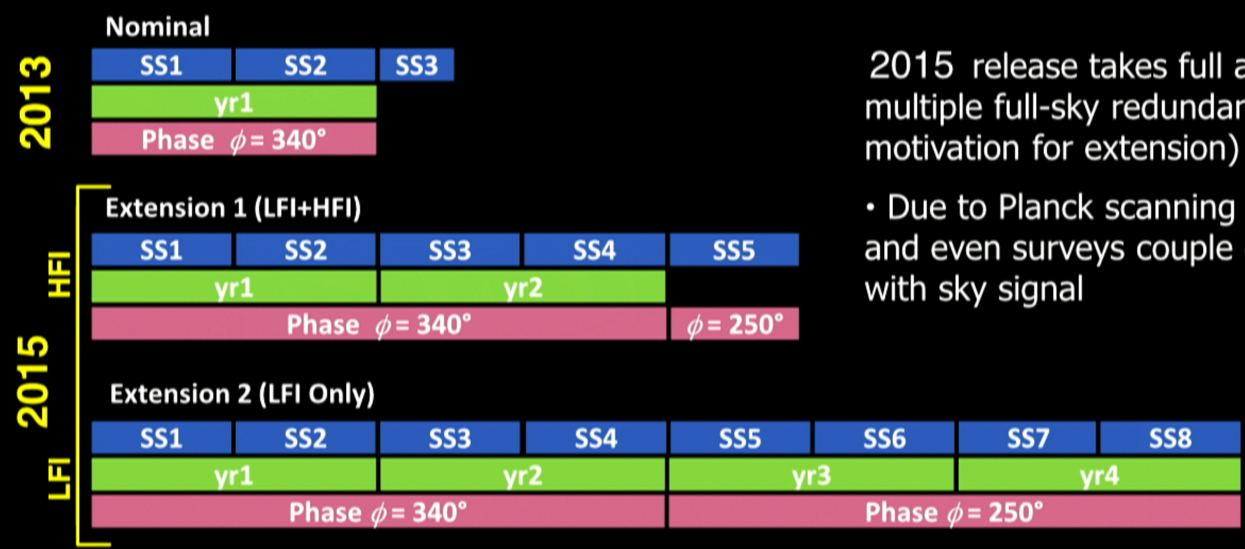
Galactic straylight (simulation)

Odd survey Even survey



esa

2015 release: Planck full mission



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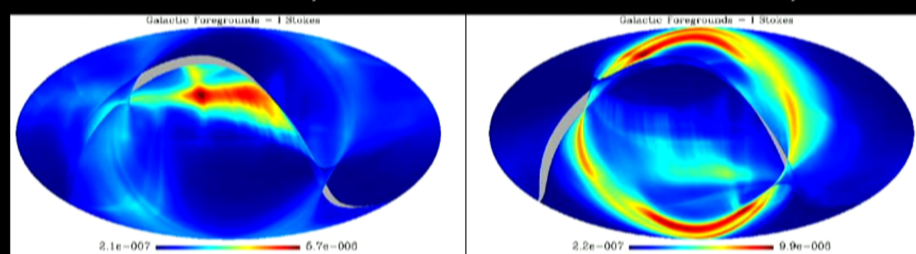
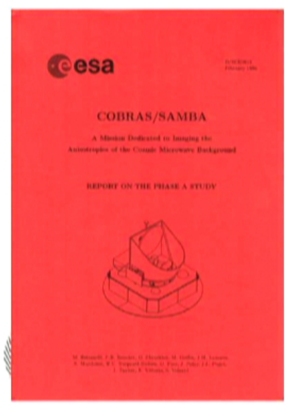
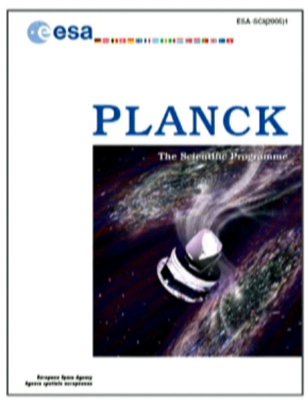


Planck sensitivity

Noise **measured in-flight**, full mission (CMB channels)

	30GHz	44GHz	70GHz	100GHz	143GHz	217GHz	353GHz
Angular resolution [arcmin]	33.2	28.1	13.1	9.7	7.3	5.0	4.9
Noise sensitivity [$\mu K_{CMB}\ s^{1/2}$]	148.5	173.2	151.9	41.3	17.4	23.8	78.8
NOISE/PIXEL							
From detector sensitivity [μK_{CMB}]	9.2	12.7	23.9	9.6	5.4	10.7	36.5
Measured from maps [μK_{CMB}]	9.2	12.5	23.2	11.2	6.6	12.0	43.2
Extended mission [months]	*48*	*48*	*48*	*29*	*29*	*29*	*29*
End-of-missioni [μK_{CMB}]	5.2	7.1	13.2	8.2	4.8	8.8	31.6
Measured End-of-Mission [$\Delta T/T$, $\mu K/K$]	**1.9**	**2.6**	**4.8**	**3.0**	**1.8**	**3.2**	**11.6**
2005: Blue book GOAL [$\Delta T/T$, $\mu K/K$]	**2.0**	**2.7**	**4.7**	**2.5**	**2.2**	**4.8**	**14.7**
1996: Red book GOAL [$\Delta T/T$, $\mu K/K$]				**~ 2**			





At end of mission Planck fulfills completely the very ambitious sensitivity goals proposed in the design phase several years ago

Current data release: 2015

- What has changed:
  - More data (29/49 months vs. 15.5) enabling further checks.
  - Improved systematics removal, calibration and beams.
  - More simulations (10x) used to assess uncertainties.
  - More sky used, improved foreground model (incl. dust at all freq.).
  - Lensing now 40σ (and best modes have S/N~1 per mode)!
  - Polarization!!!
- What has not changed (much):
  - ΛCDM still a good fit.
  - The Universe is still very flat
  - Parameters and major cosmological inferences from 2013.

Dipole calibration: Planck vs WMAP

- 2015: Orbital dipole calibration for both LFI and HFI

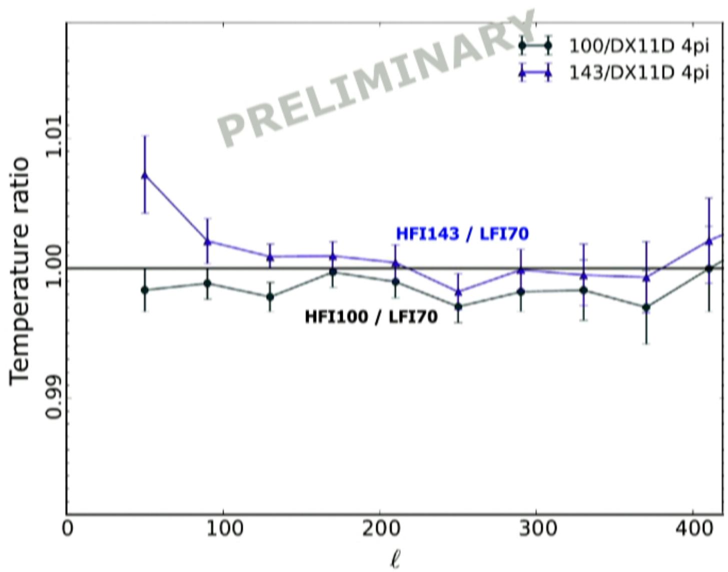
	Amplitude (μK)	**Latitude** (deg)	**Longitude** (deg)
LFI	3365.5±2	48.26	264.01
HFI	3364.1±2	48.23±0.1	263.96±0.03
Planck (LFI+HFI)	3364.5±2	48.24±0.1	264.00±0.03
WMAP	3355±8	48.26±0.03	263.99±0.14

PRELIMINARY

- Accuracy ~0.05%, limited by foregrounds
- Residual dipoles from component separation: ~1μK
- Very good agreement with WMAP
  (1σ, 0.3% amplitude, 3′ direction)

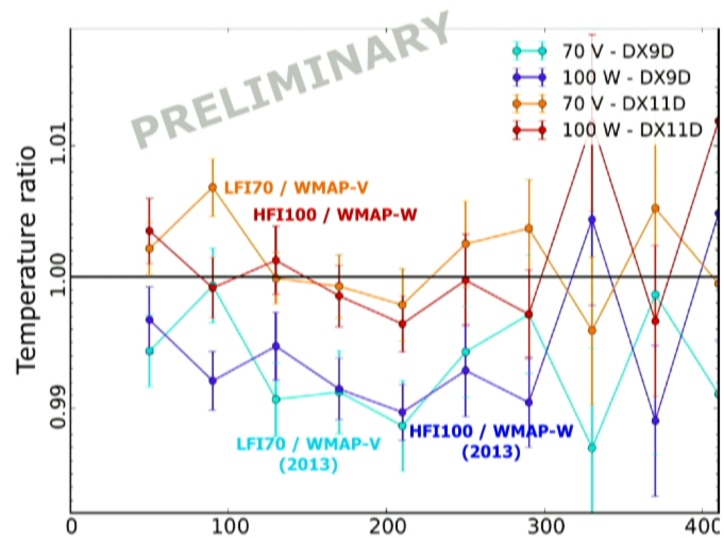
Calibration consistency
LFI vs HFI, Planck vs WMAP

LFI vs HFI



Internal consistency confirmed by tests from component separation analysis

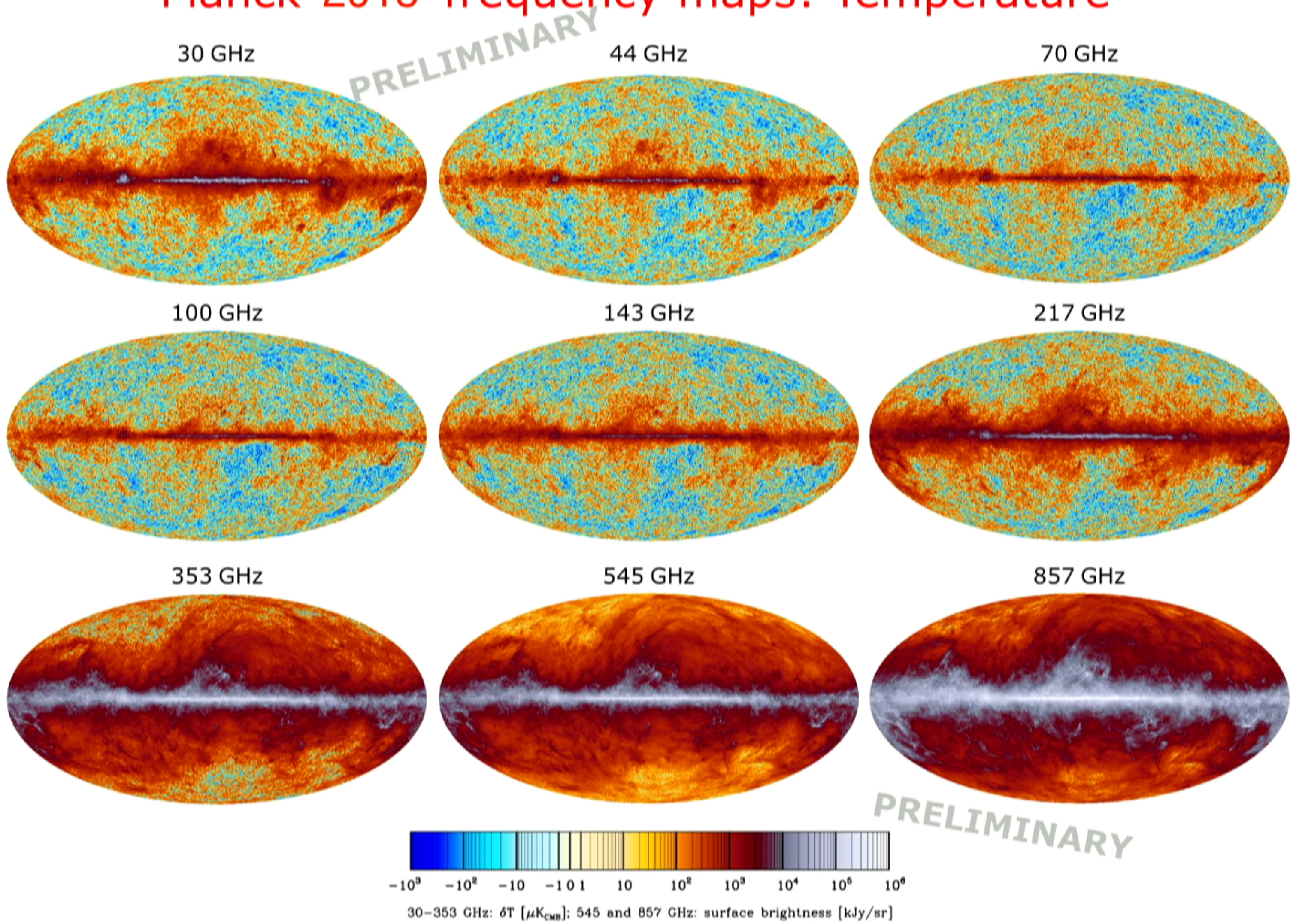
Planck vs WMAP



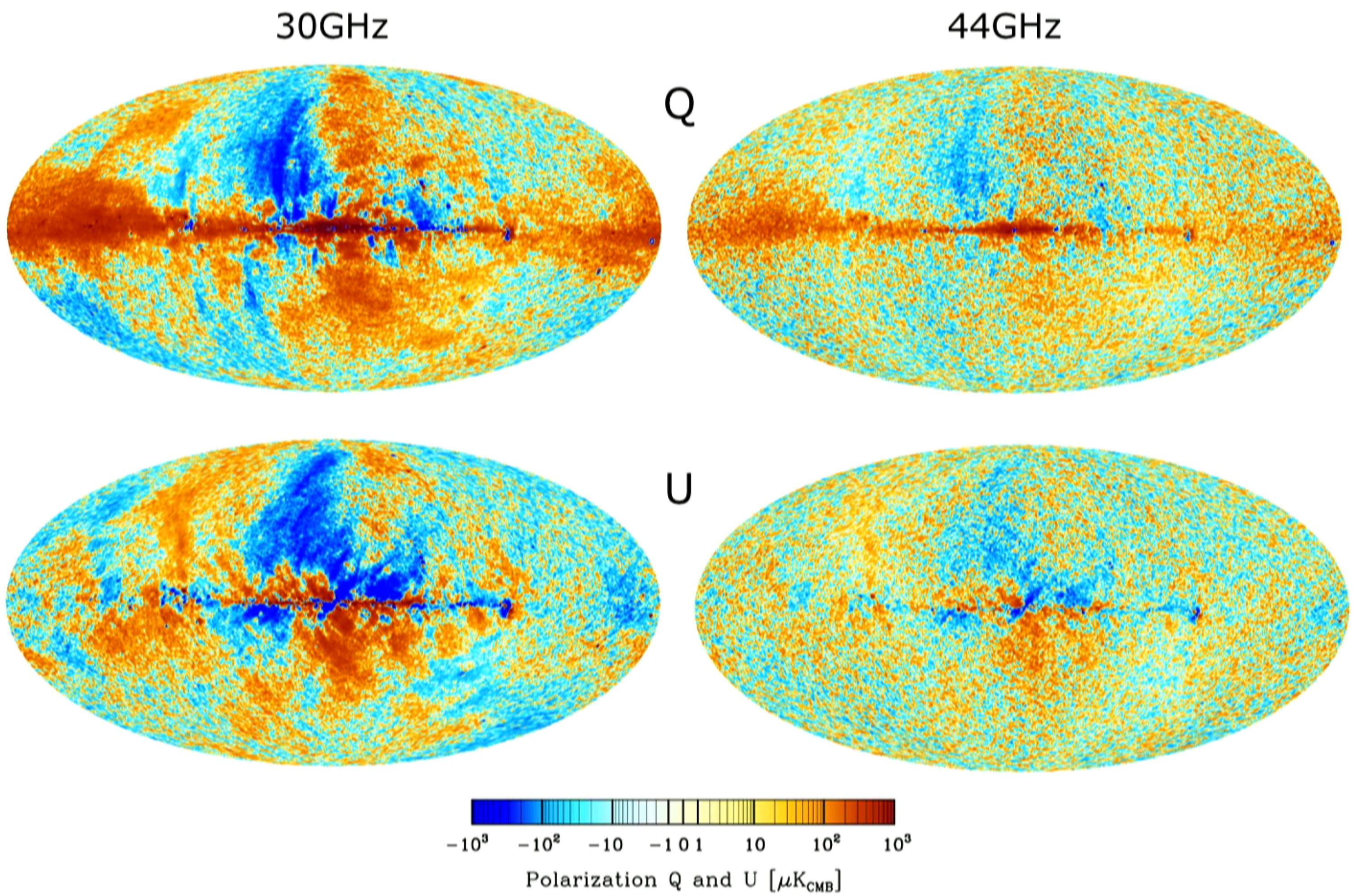
Changes in LFI and HFI since 2013 from better control of (independent) systematics and beams

Excellent consistency between independent experiments

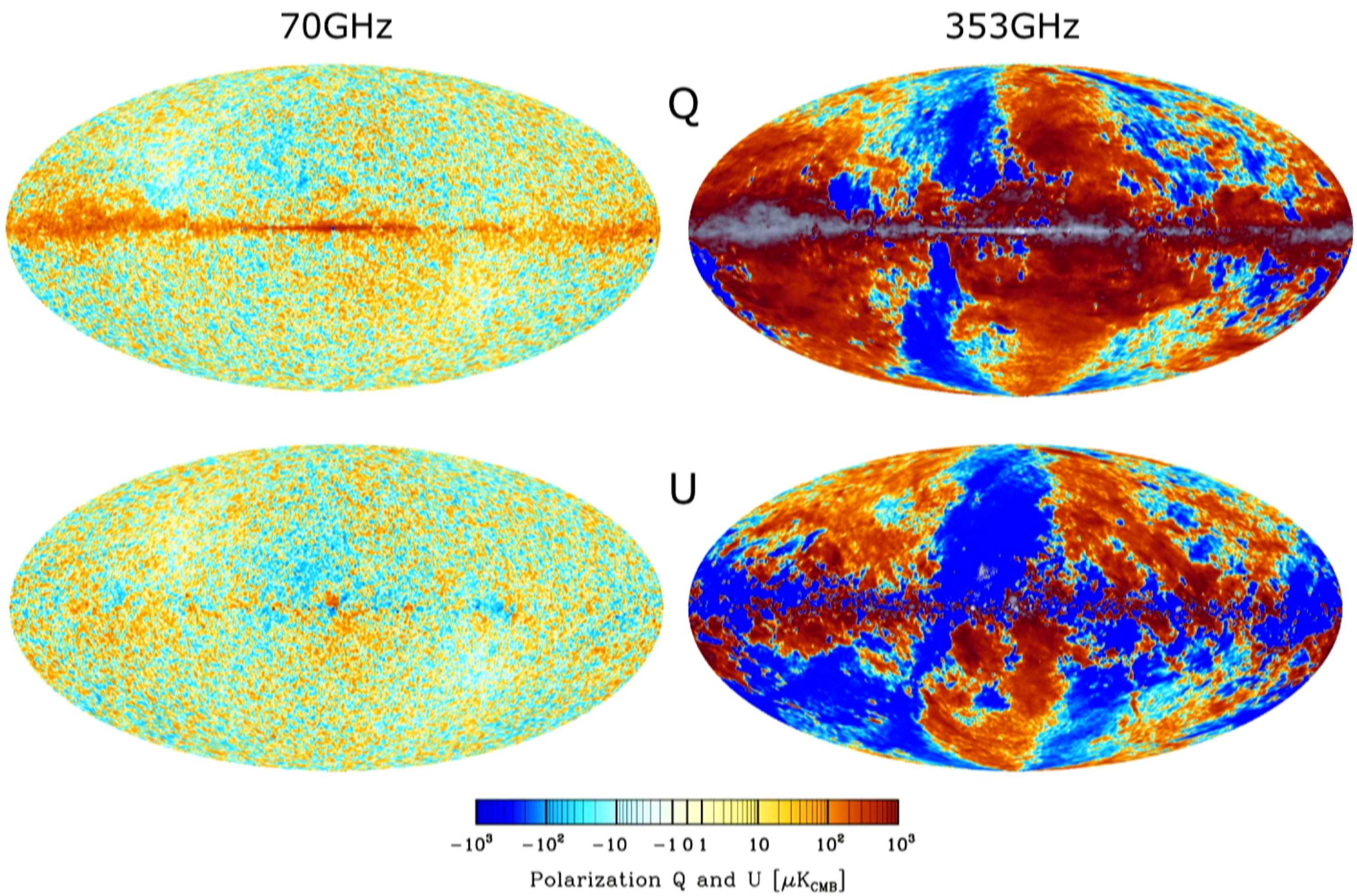
Planck 2015 frequency maps: Temperature



Planck 2015 frequency maps: Polarisation



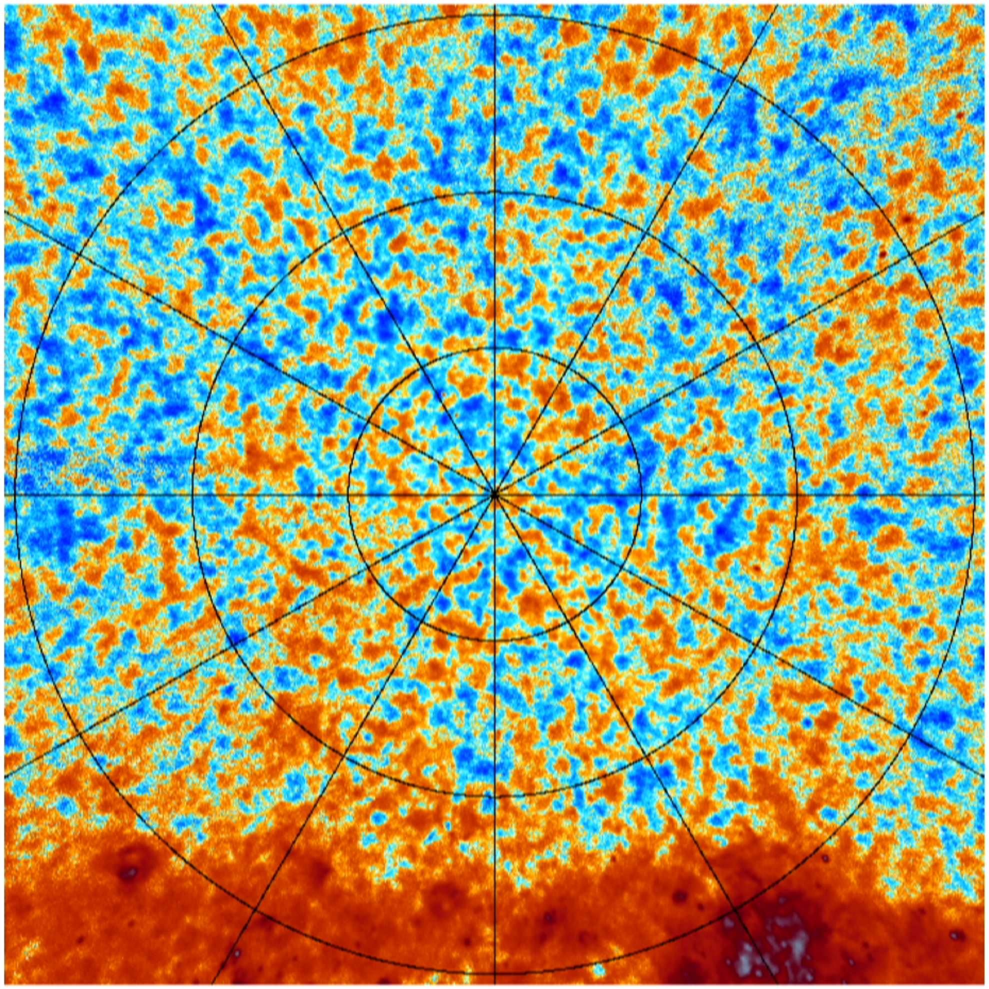
Planck 2015 frequency maps: Polarisation



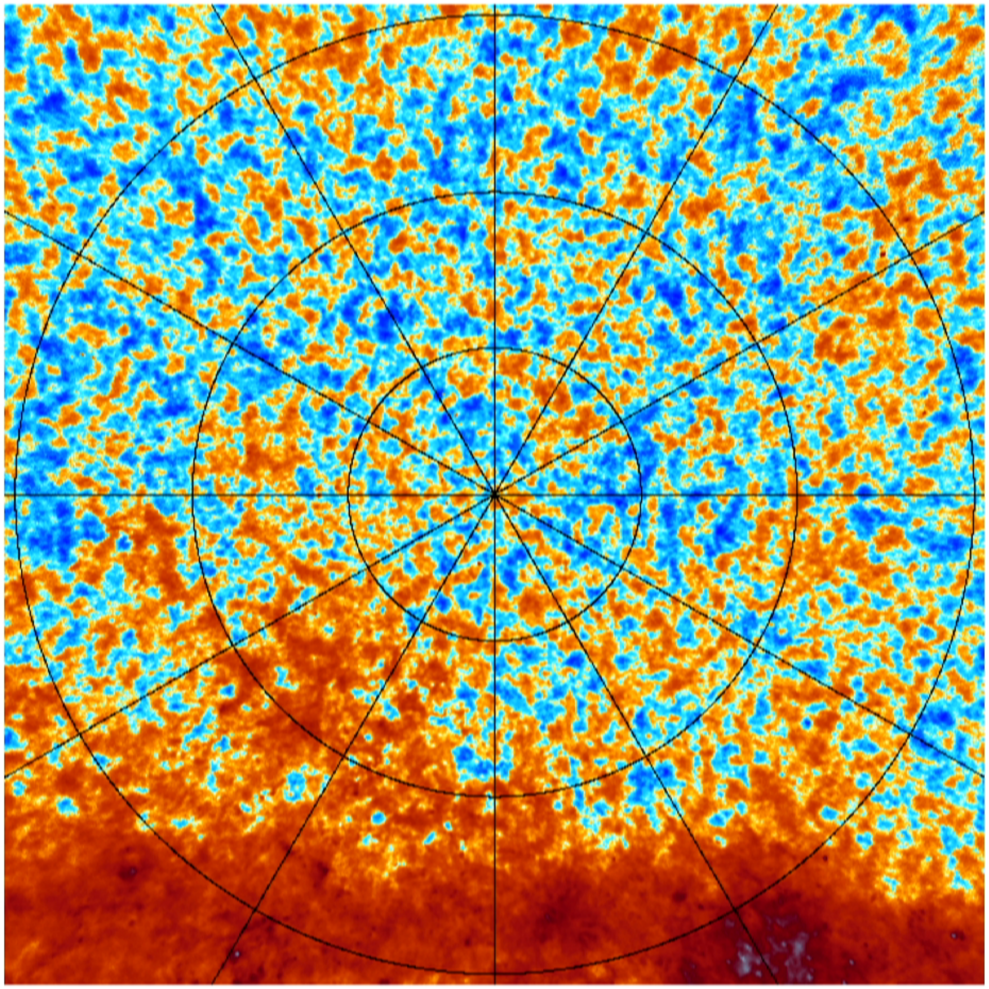
Planck maps are awesome

- The data are too good to see properly at the resolution of this projector!
- Let's zoom in
- And also remember that although the CMB looks noisy, these maps aren't noise!

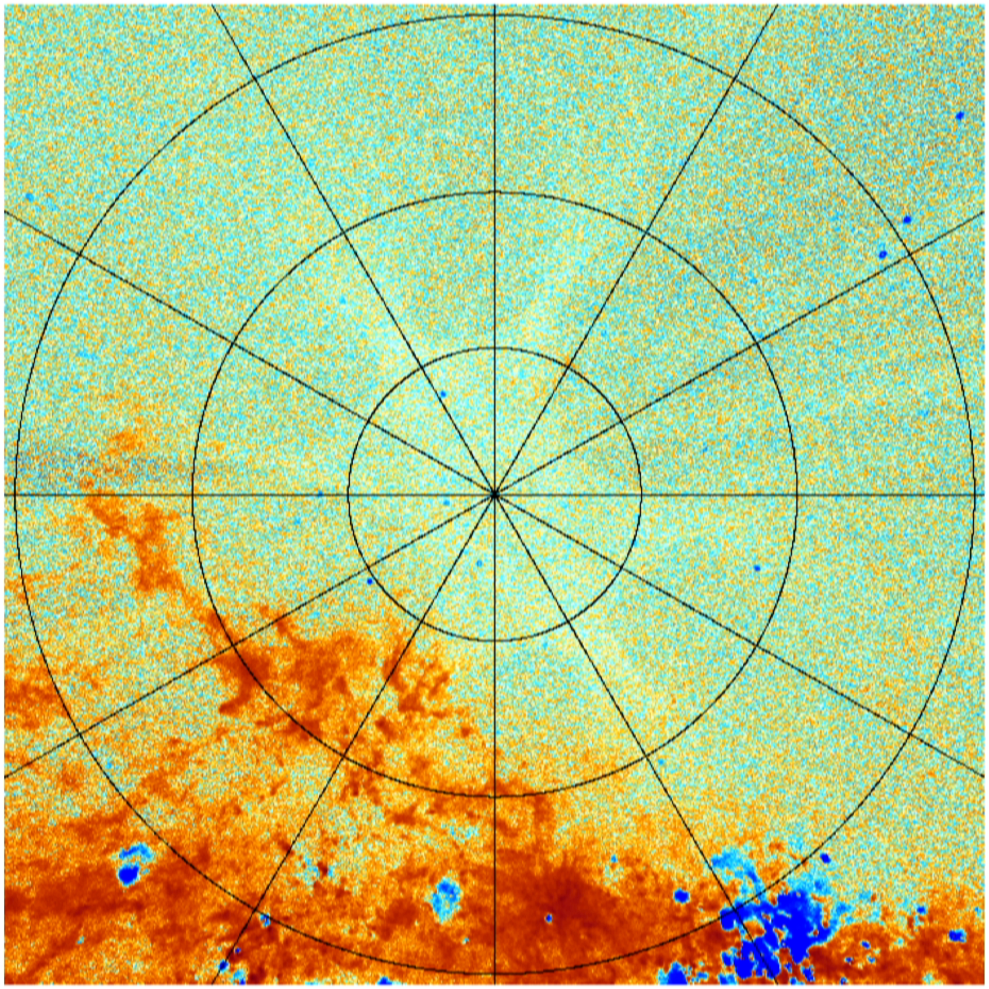
North Ecliptic Pole: 70



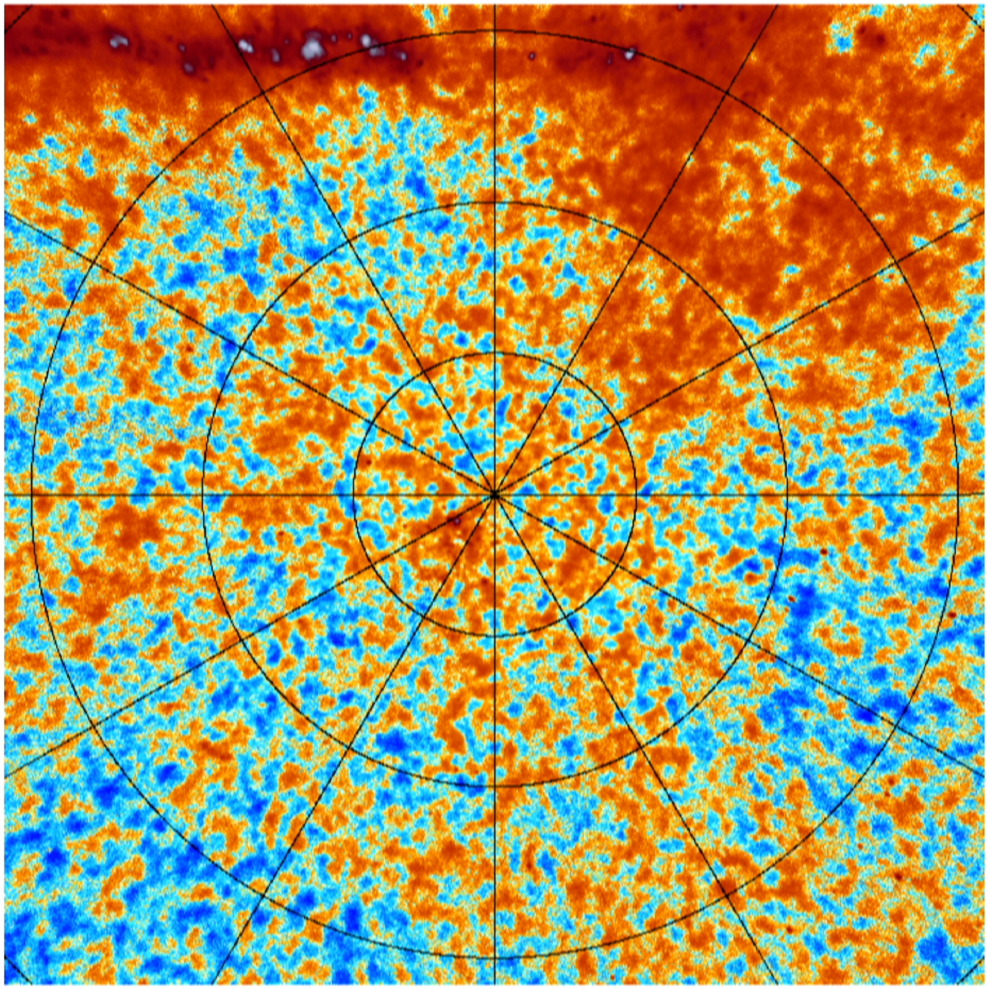
North Ecliptic Pole: 100



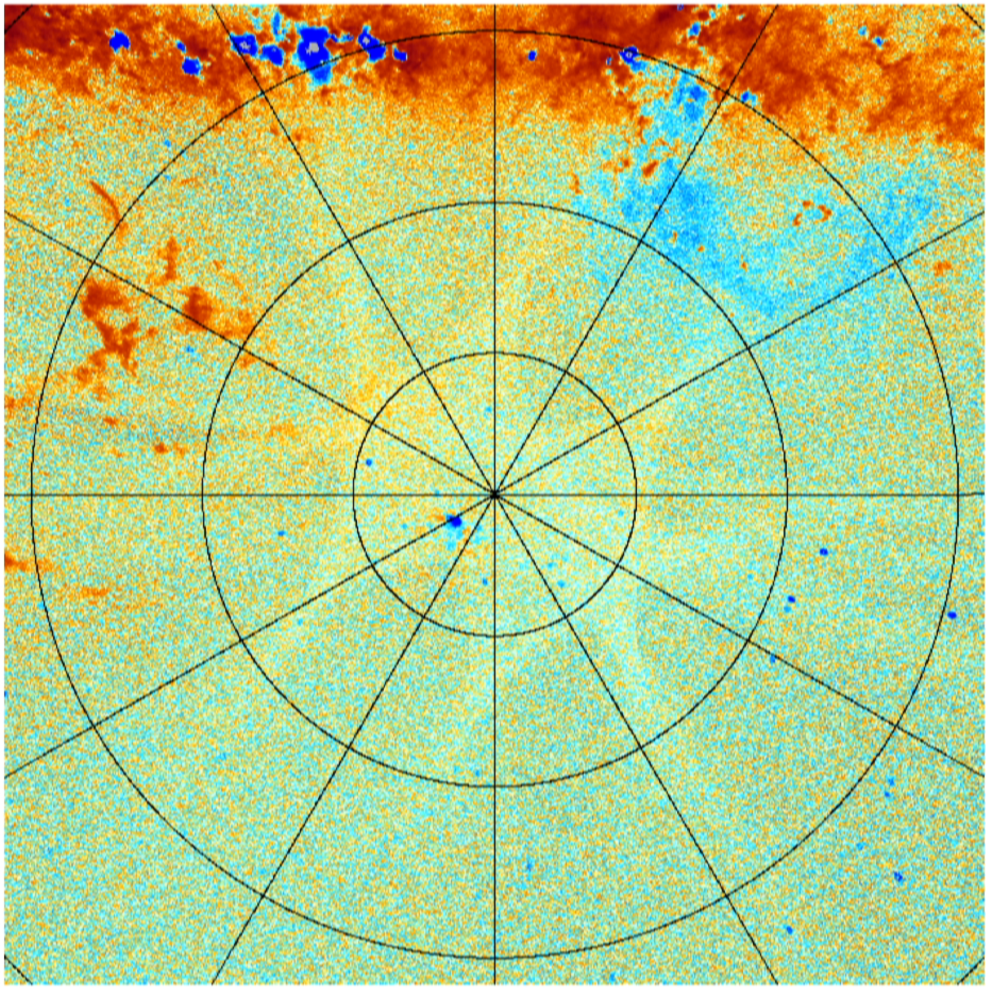
North Ecliptic Pole: Diff



South Ecliptic Pole: 70



South Ecliptic Pole: Diff



Component separation

Temperature

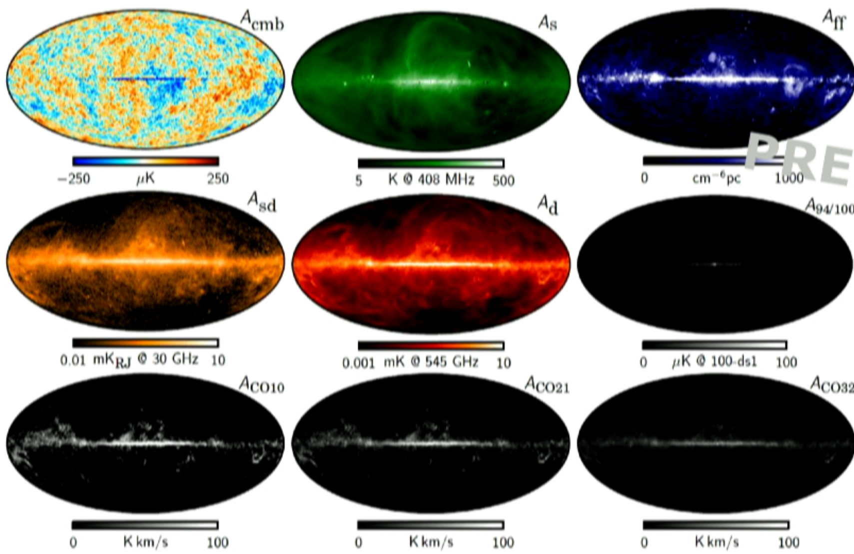
CMB maps: 4 versions coming from different methods

SMICA, SEVEM, COMMANDER, NILC

→ Excellent agreement

PRELIMINARY

Foregrounds: dust, synchrotron, free-free, spinning dust, diffuse SZ, CO

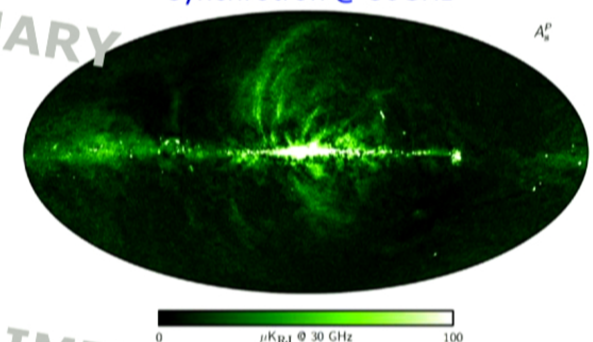


Polarisation

CMB map (ell>30)

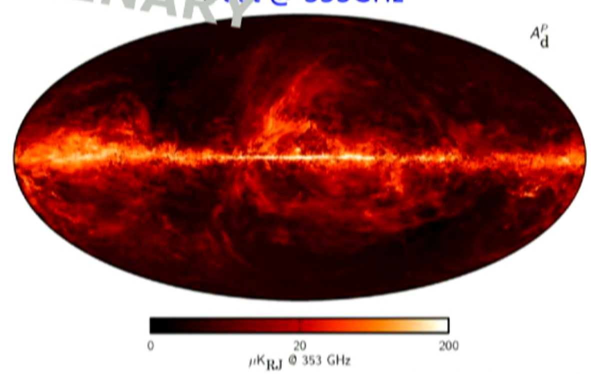
Foregrounds: dust, synchrotron

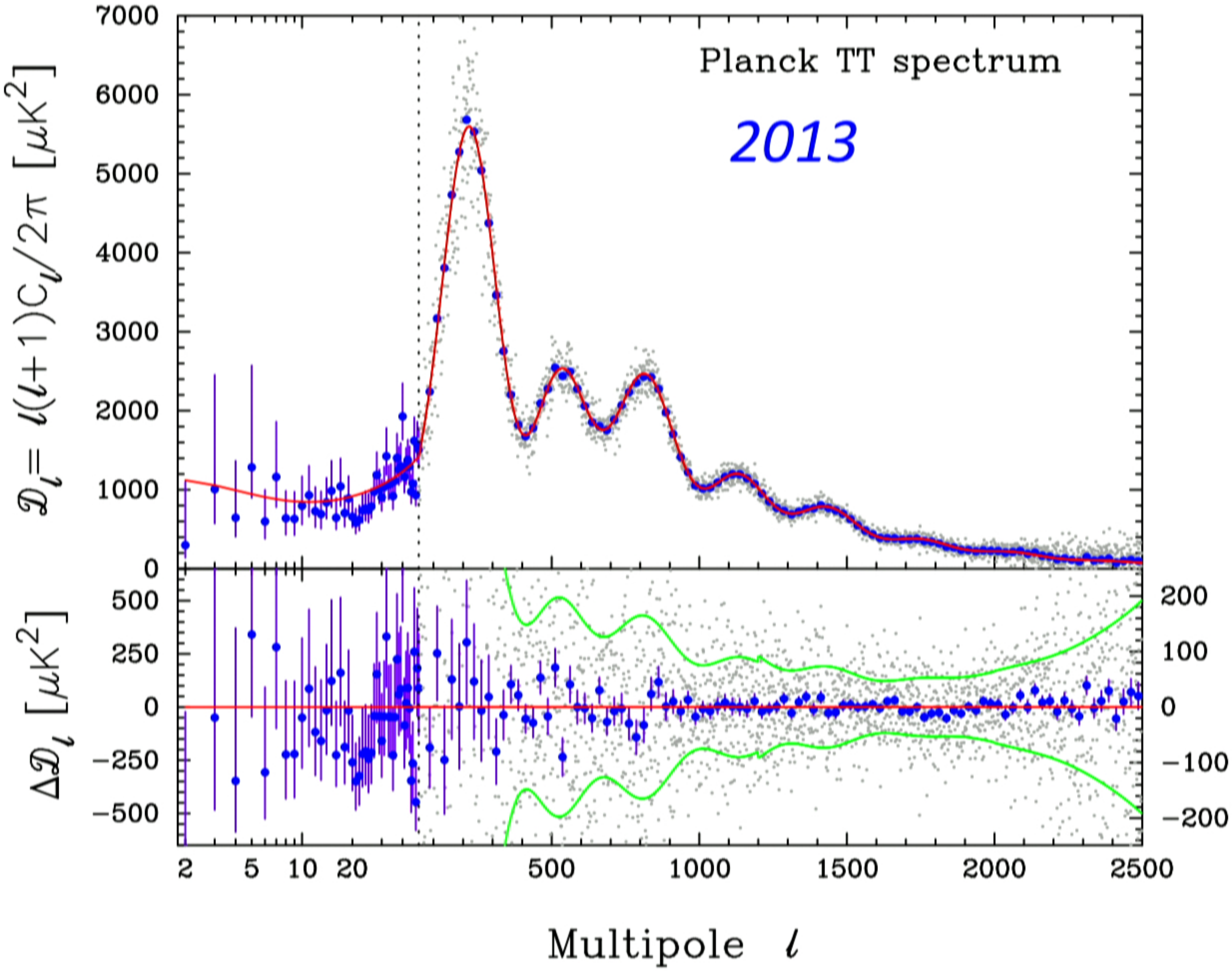
Synchrotron @ 30GHz



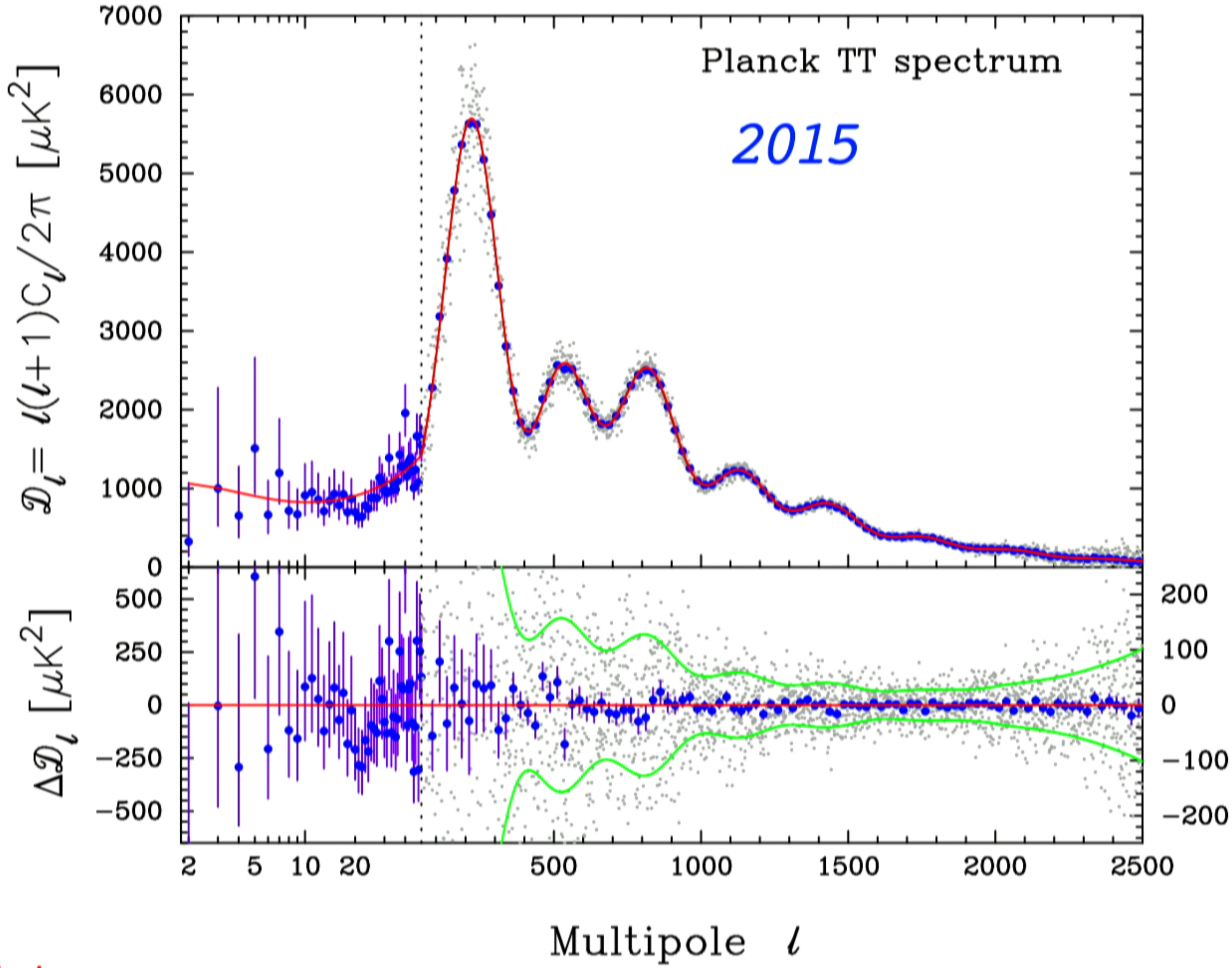
PRELIMINARY

Dust @ 353GHz



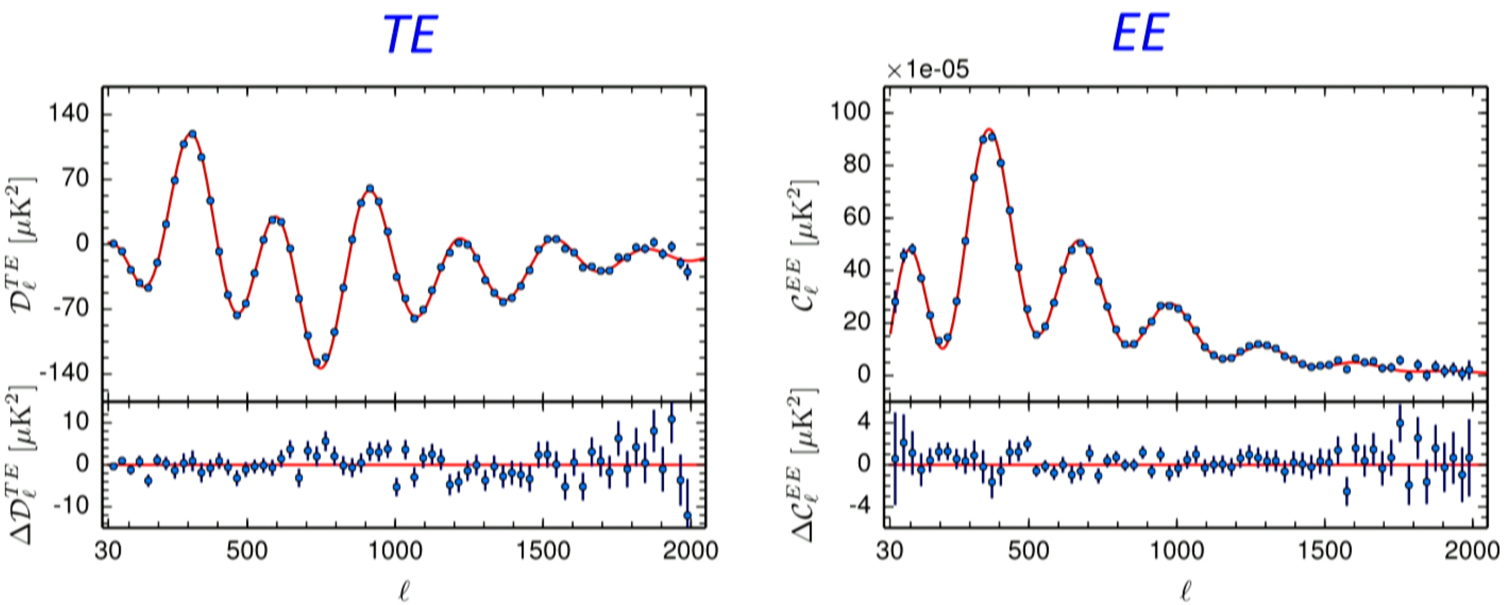


Planck TT spectrum
2013
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

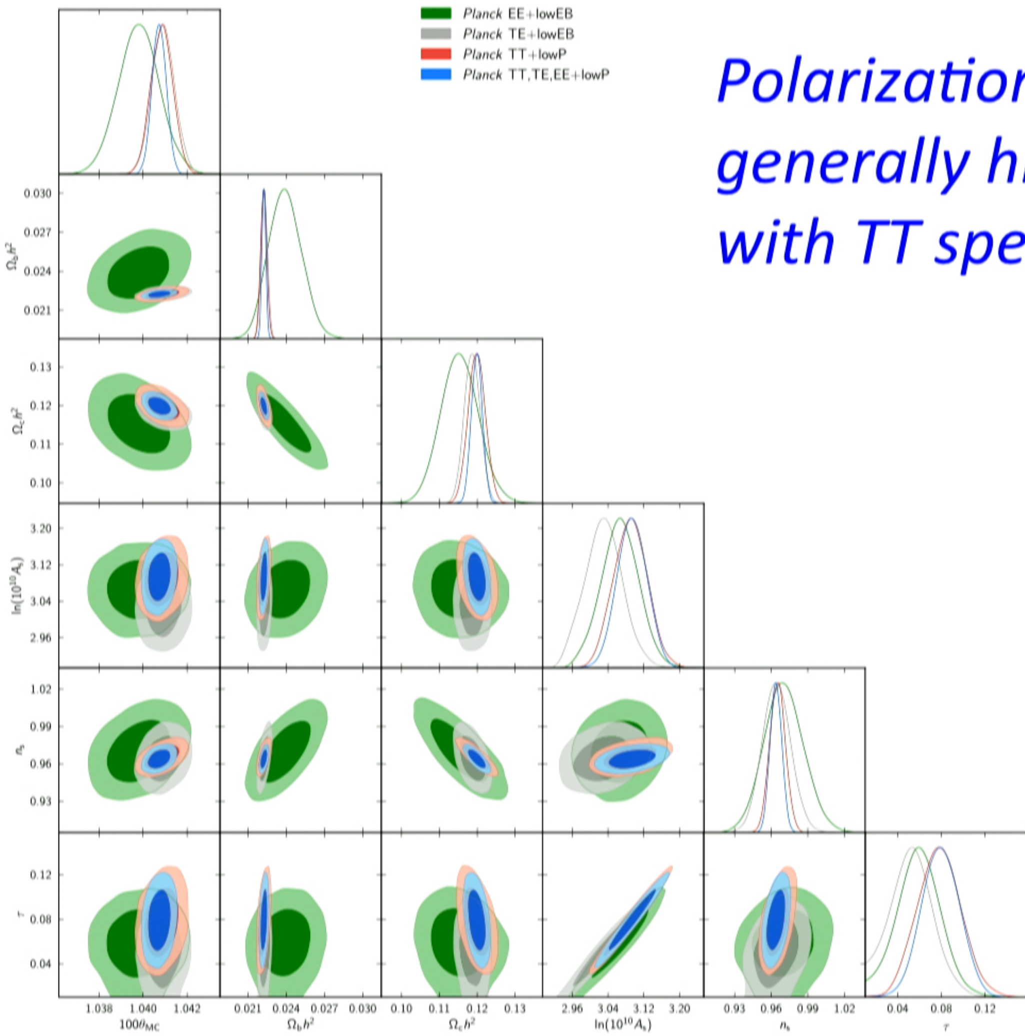


preliminary

… and beautiful polarization spectra



preliminary



Polarization spectra are generally highly consistent with TT spectra.

preliminary

BASE ΛCDM MODEL

Parameter	TT	TT,TE,EE
$\Omega_b h^2$	0.02222±0.00023	0.02224±0.00015
$\Omega_c h^2$	0.1199±0.0022	0.1199±0.0014
$100\theta_*$	1.04086±0.00048	1.04073±0.00032
τ	0.078±0.019	0.079±0.017
n_s	0.9652±0.0062	0.9639±0.0047
H_0	67.3±1.0	67.23±0.64
Ω_m	0.316±0.014	0.316±0.009
σ_8	0.830±0.015	0.831±0.013
z_{re}	9.9±1.9	10.7±1.7

...but beware there are still low level systematics in the polarization spectra

preliminary

Changes in parameters: standard model

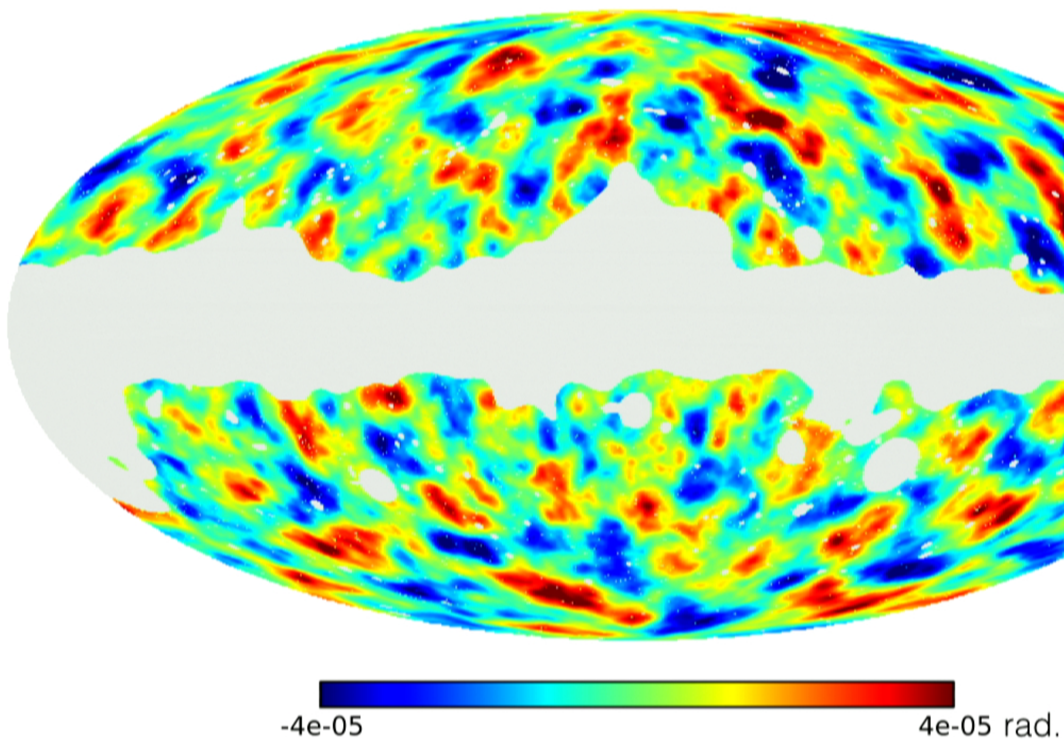
- Typical uncertainty reduced by more than 25%.
- Photometric calibration increased by 0.8%.
  - Uncertainty now 0.05%. Excellent agreement on orbital dipole between WMAP, LFI & HFI!
- Thomson τ lower by ~1σ (so z_{re} decreased $\sim 1\sigma$)
  - but calibration increased power so σ_8 hardly changed
- n_s increased by $\sim 0.7\sigma$
- ω_b increased by ~0.6σ *and* error decreased.
- Limits on isocurvature modes, Ω_K, m_ν, ΔN_{eff}, f_{NL}, DM annihilation etc. all tighter. No deviations detected.

CMB lensing

- Photons from the CMB are deflected on their way to us by the potentials due to large-scale structure.
- The typical deflection is 2-3 arcmin but deflections are coherent over degrees.
  - Signal dominated by structures of tens of Mpc at z~2.
- Gives sensitivity to the “low z” Universe.
  - Allows us to break some degeneracies from purely within the Planck dataset.
  - Provides a cross-check on the paradigm: are the structures we infer at z~2 consistent with the “initial conditions” measured at z~1,000?
- Provides a map, over the whole sky, of the (projected) mass back to the surface of last-scattering (98% of the way to the horizon).

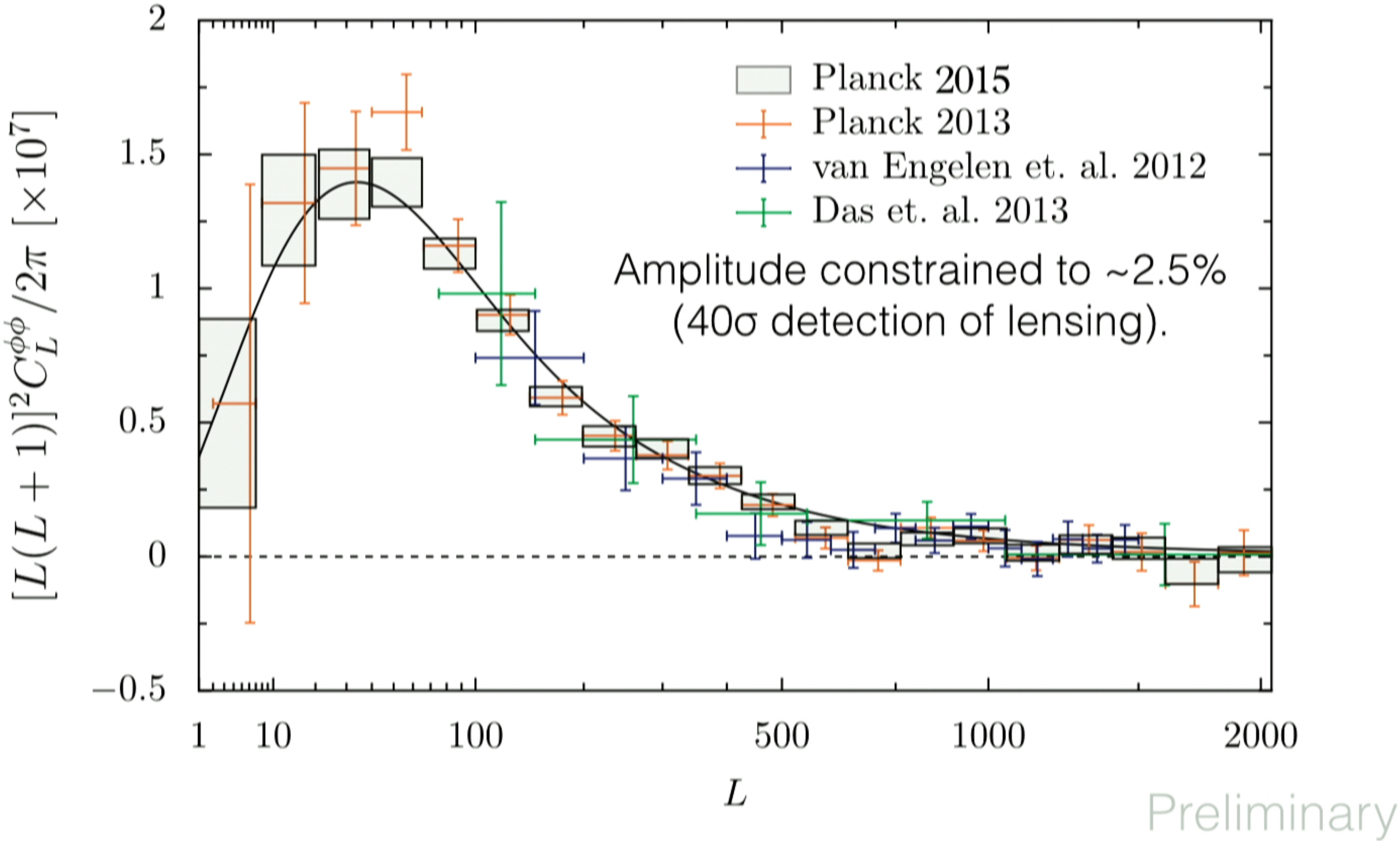
Preliminary

Weighted map of lensing estimators



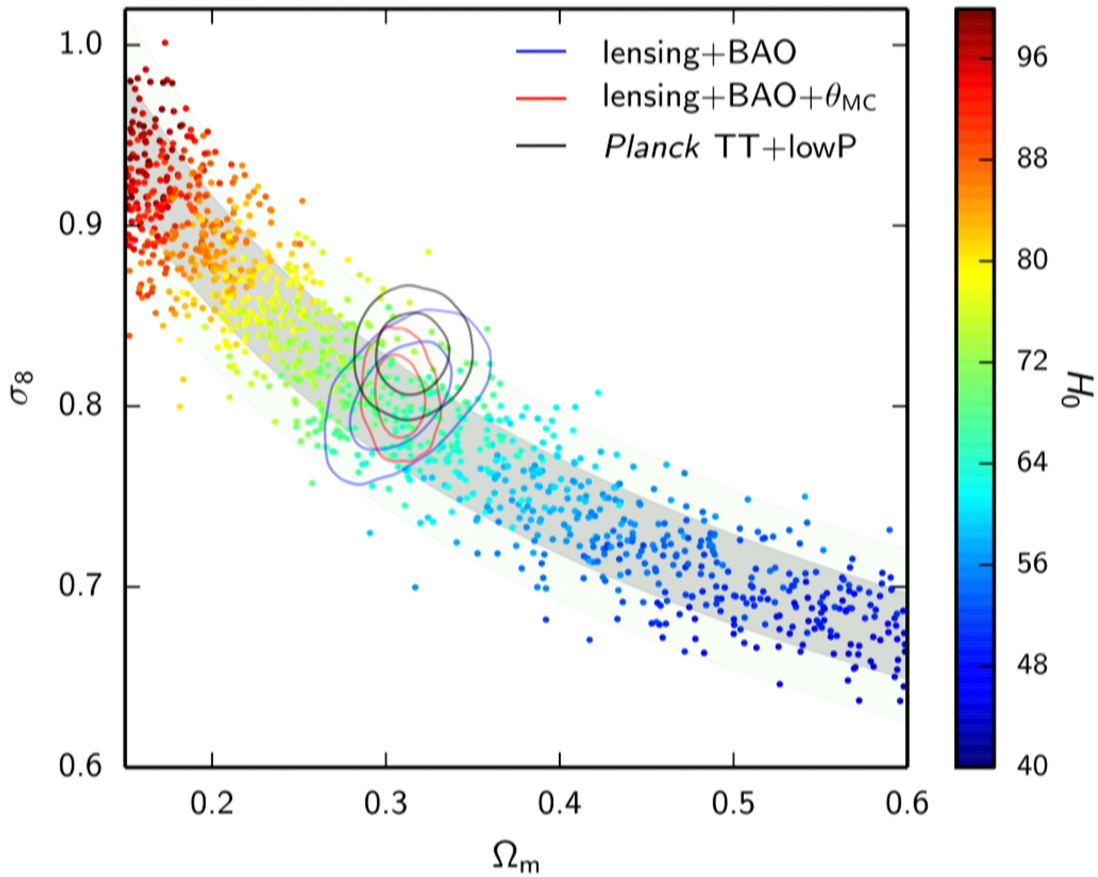
(based on SMICA CMB map) S/N$-$filtered, $10 \leq L \leq 2048$

Lensing Power Spectrum

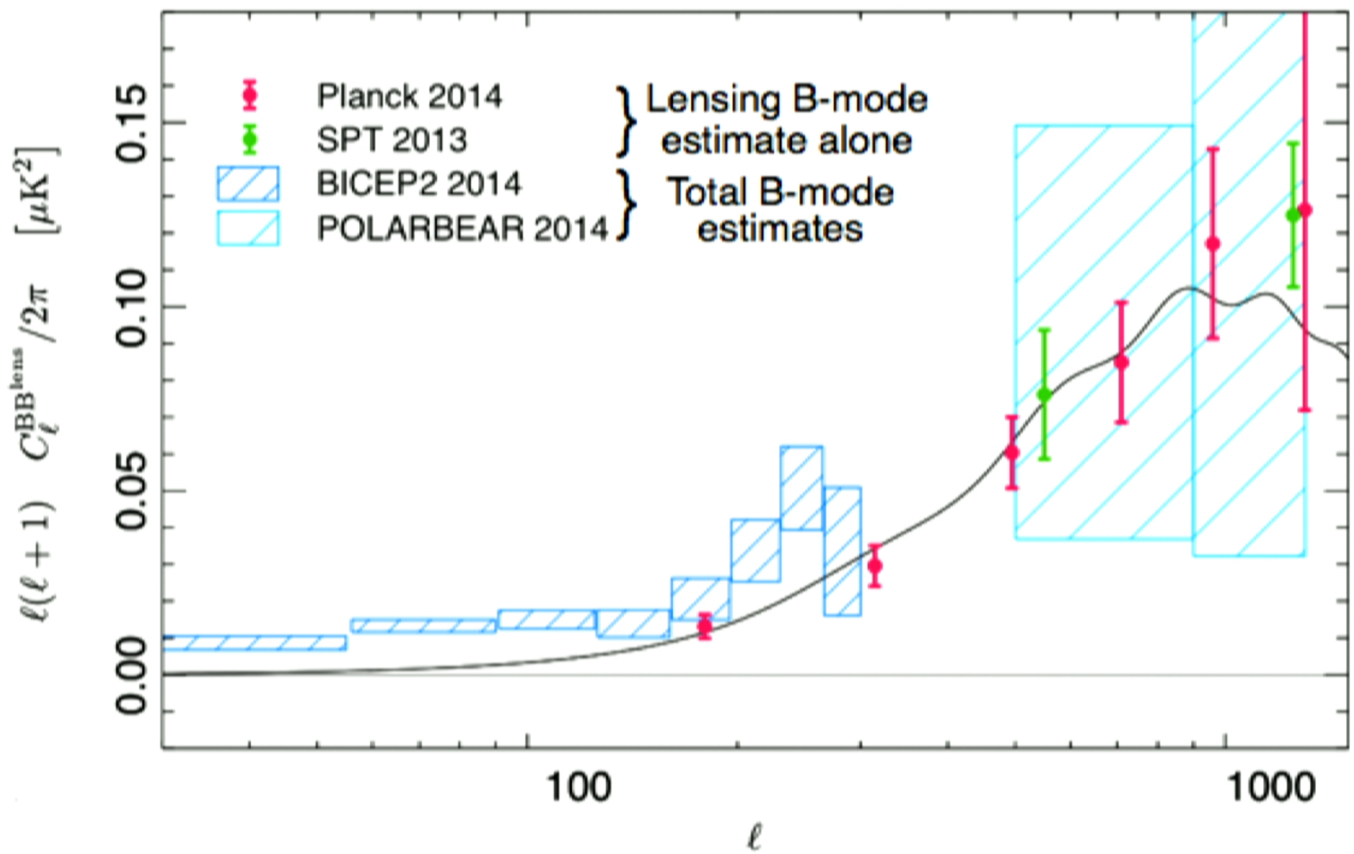


Independent check on the amplitude of matter fluctuations in the Universe: σ_8

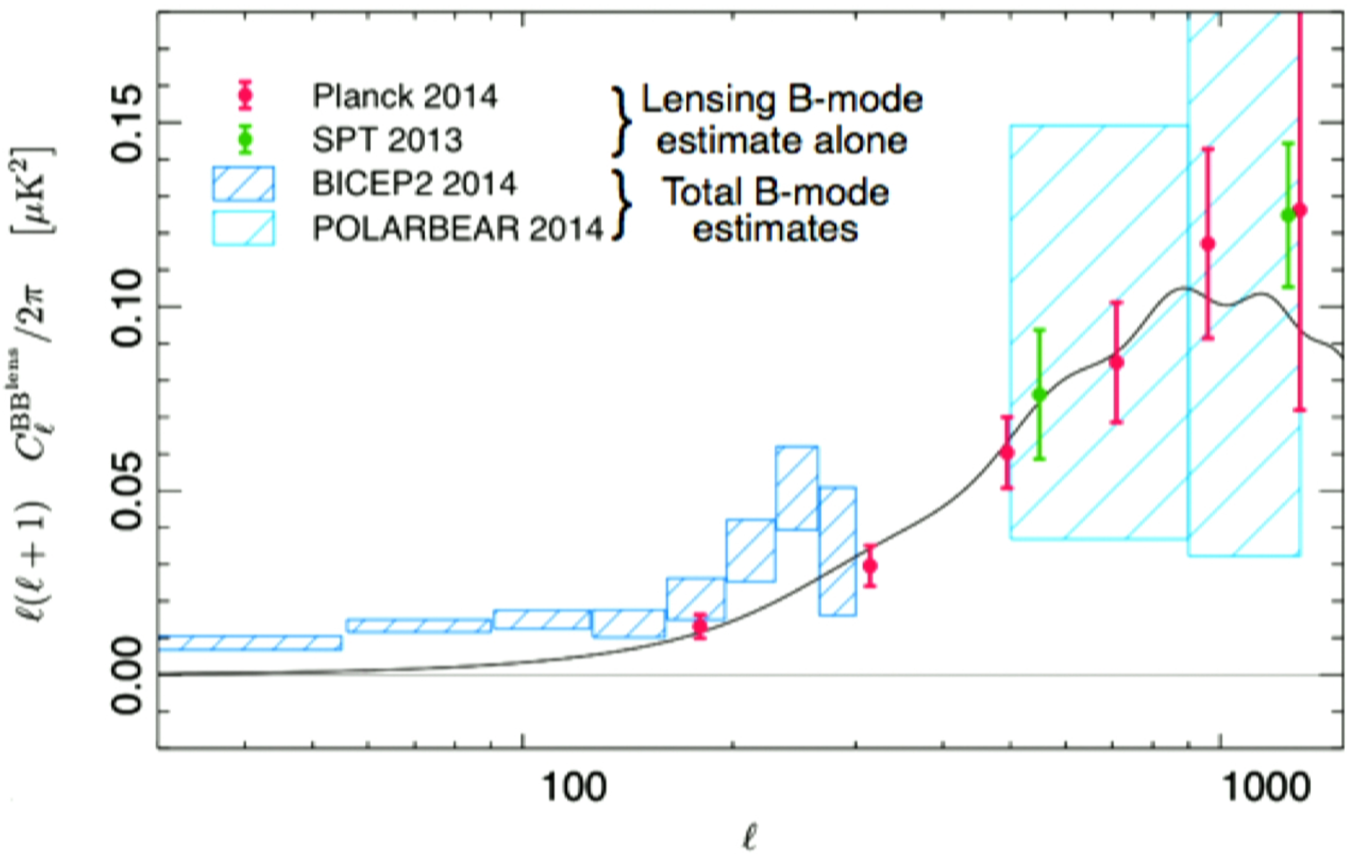
Lensing allows an independent check on the normalization. Consistent with primary anisotropy results. Higher than some probes had found.



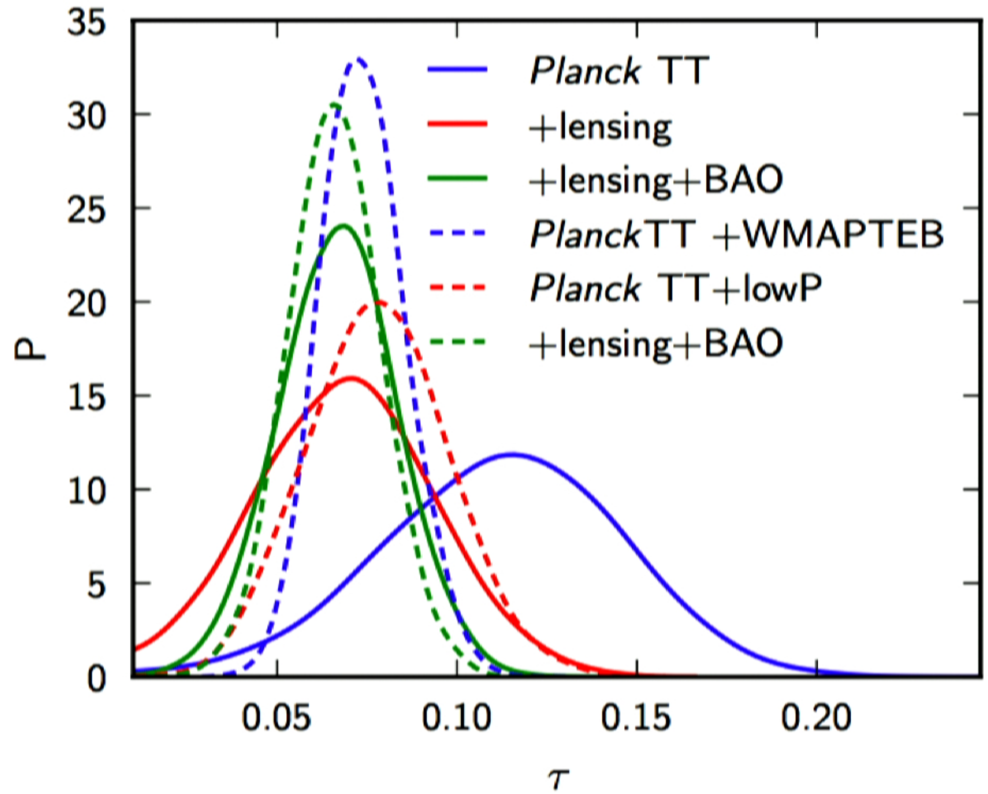
Plus lensing B-mode estimate (from correlations)



Plus lensing B-mode estimate (from correlations)

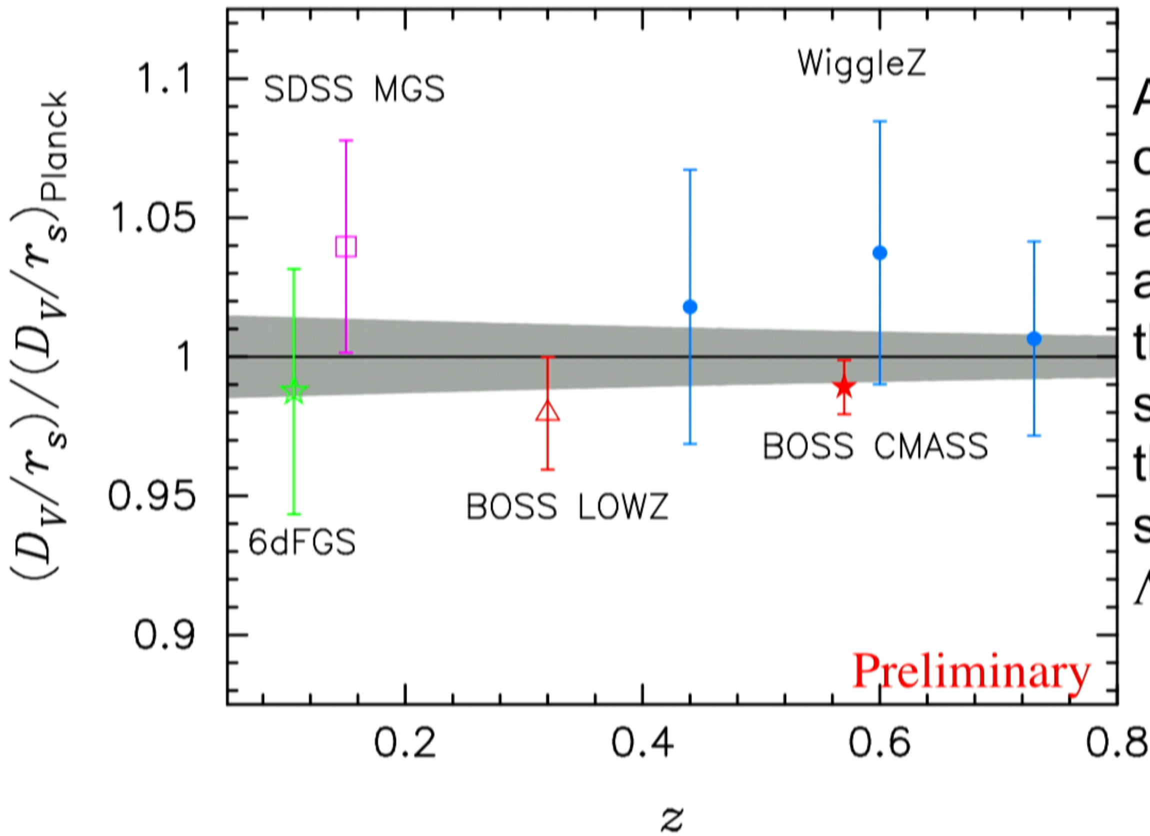


Constraints on reionization optical depth τ



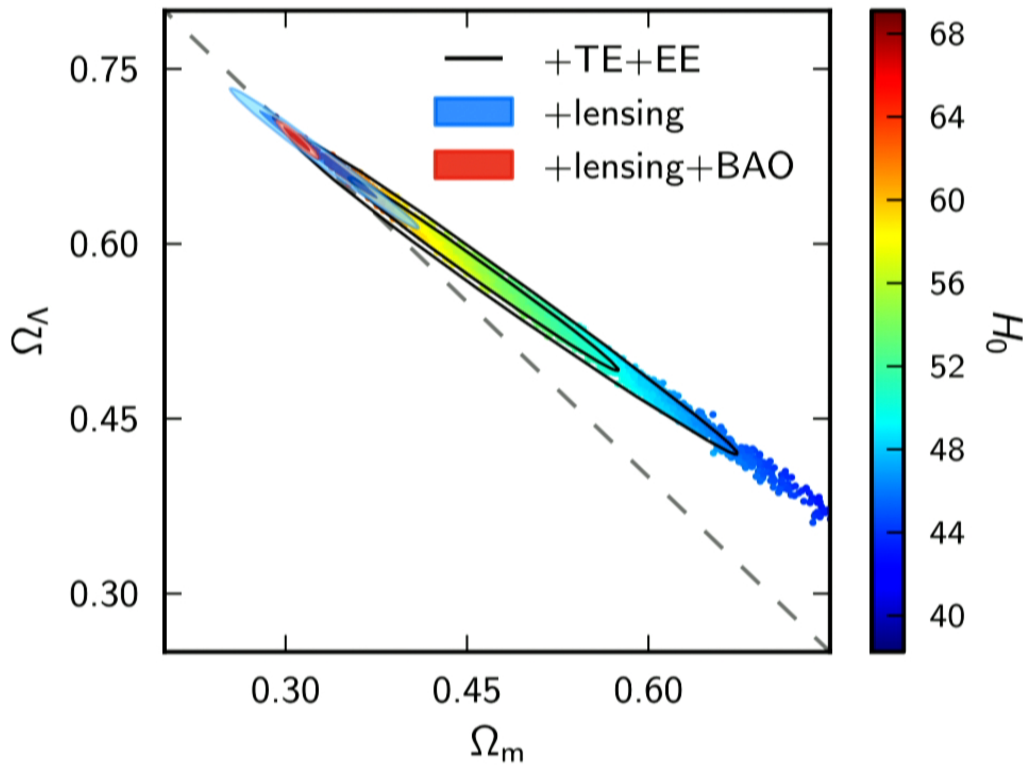
preliminary

Distance scale comparison: BAO



Acoustic oscillations at z~1100 and z<1 tell the same story about the distance scale: ΛCDM!

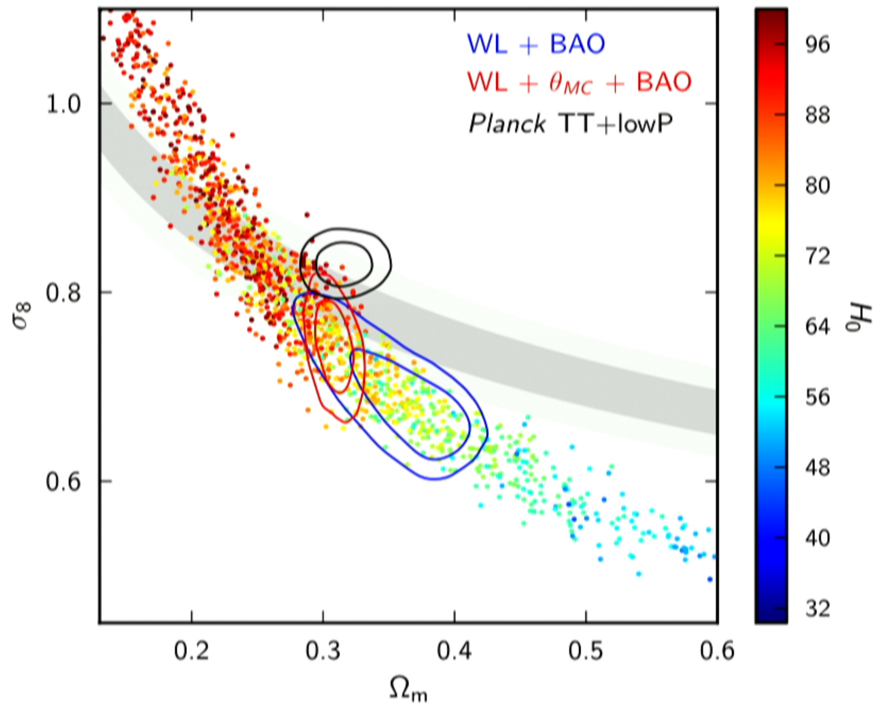
Adding BAO gives strong constraints on spatial curvature Ω_k=0.000±0.005 (95%)



preliminary

Still flat after all these years …

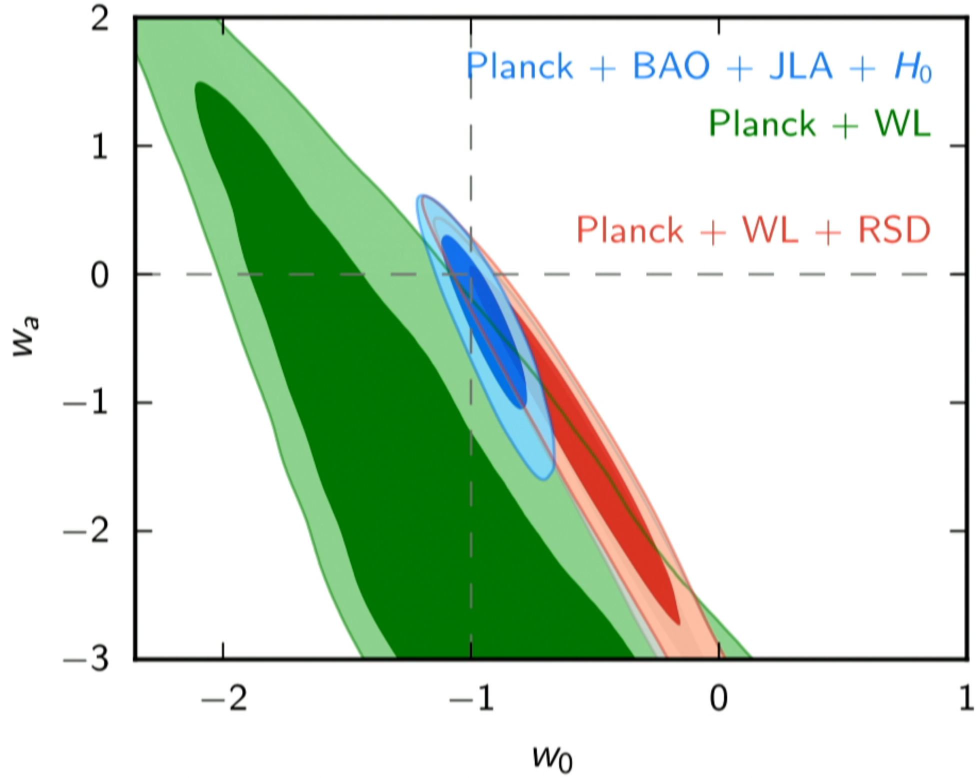
Possible tensions: Weak gravitational lensing (CFHTlens)



preliminary

….. and one example of what these tensions can do…….

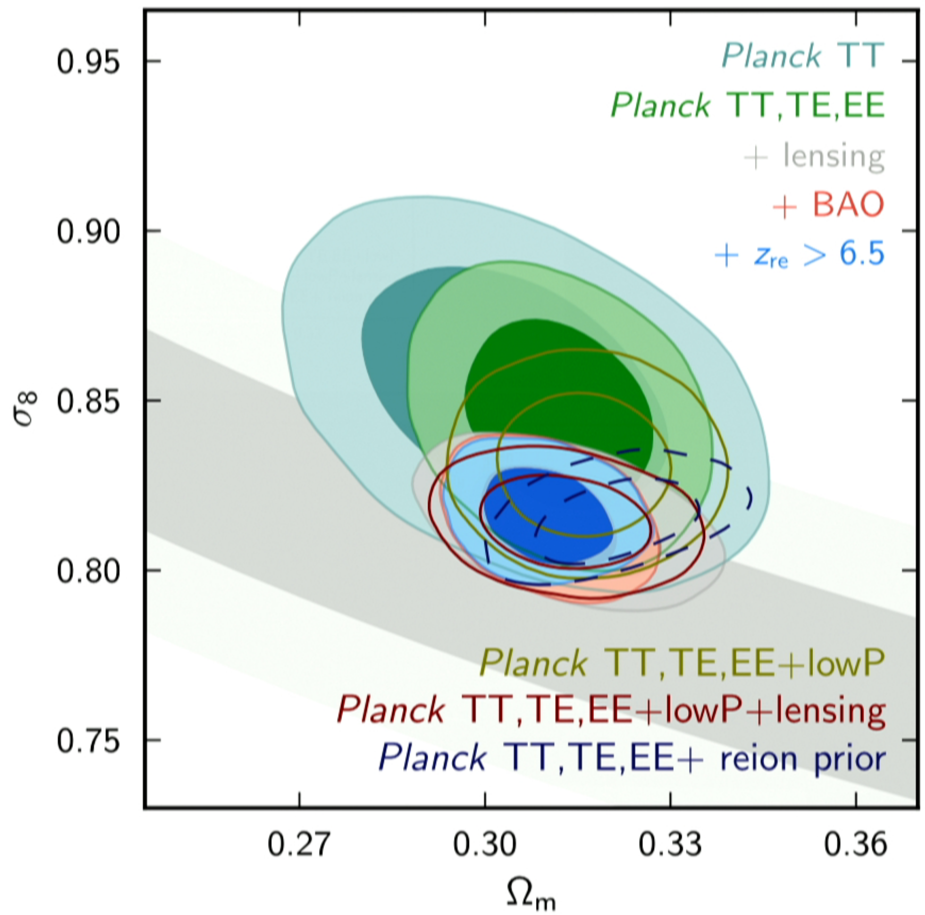
$$w(a) = w_0 + (1-a)w_a$$



preliminary

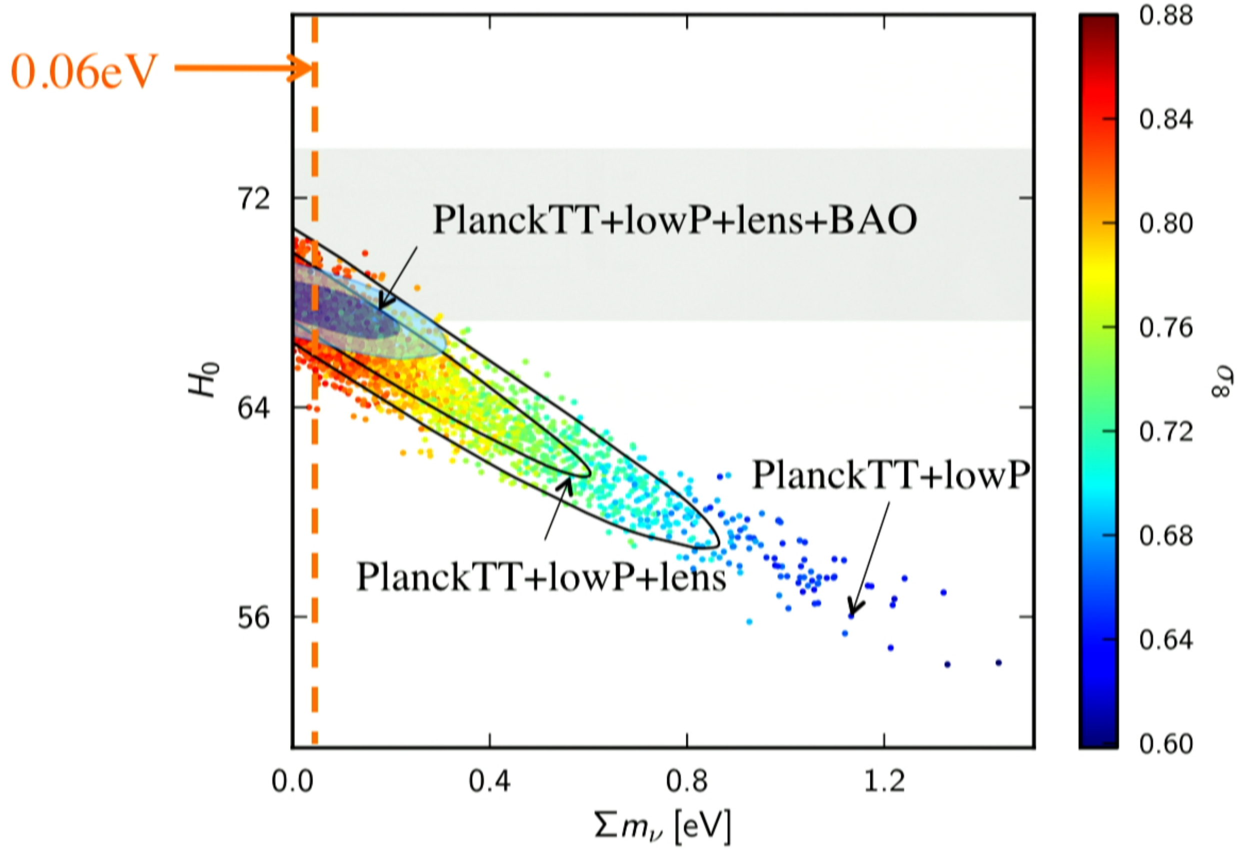
Plus tests of Modified Gravity - see next talk by Ali Narimani

There is no doubt that in base ΛCDM Planck wants high σ_8:



preliminary

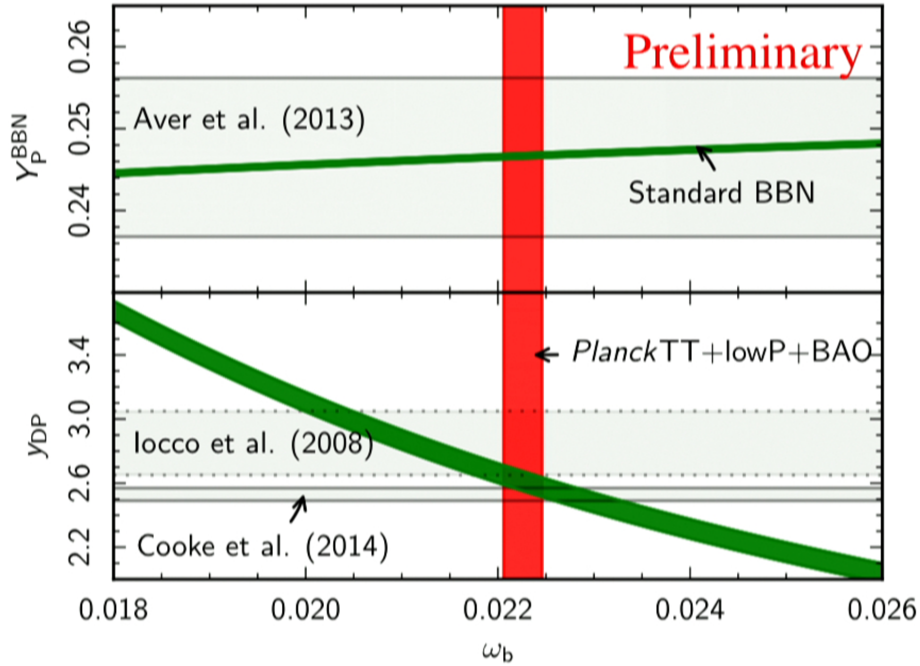
Constraints on neutrinos now tighter



Preliminary

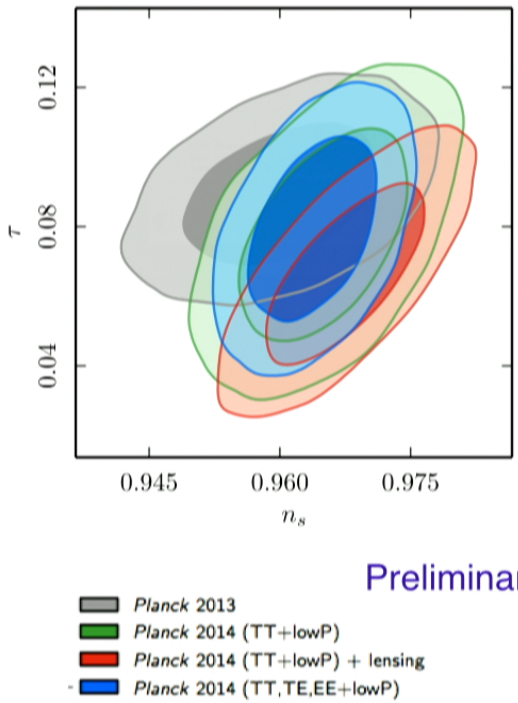
Physics is Universal!

Baryon density measured by BBN and CMB are in excellent agreement … comparison uses all known laws of physics!



[And we also have a measurement of the Hydrogen 2s➔1s transition which is 5x better than the lab measurement, and in fantastic agreement with the theoretical calculation!]

Planck 2015 n_s



Preliminary

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$n_s = 0.9652 \pm 0.0062 \quad (68\,\%\mathrm{CL}\,,\,\mathit{Planck}\,\mathrm{TT}+\mathrm{lowP})$$

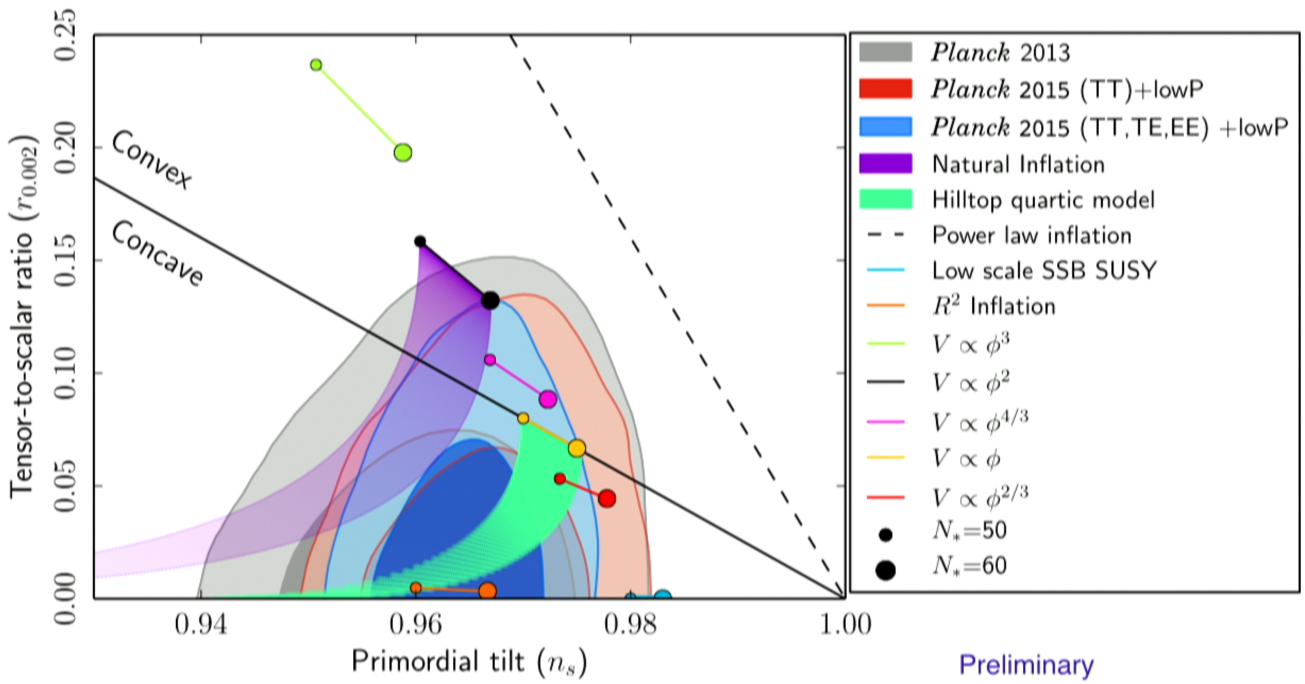
$$\tau = 0.078 \pm 0.019 \quad (68\,\%\mathrm{CL}\,,\,\mathit{Planck}\,\mathrm{TT}+\mathrm{lowP})$$

Compare with Planck 2013 results:

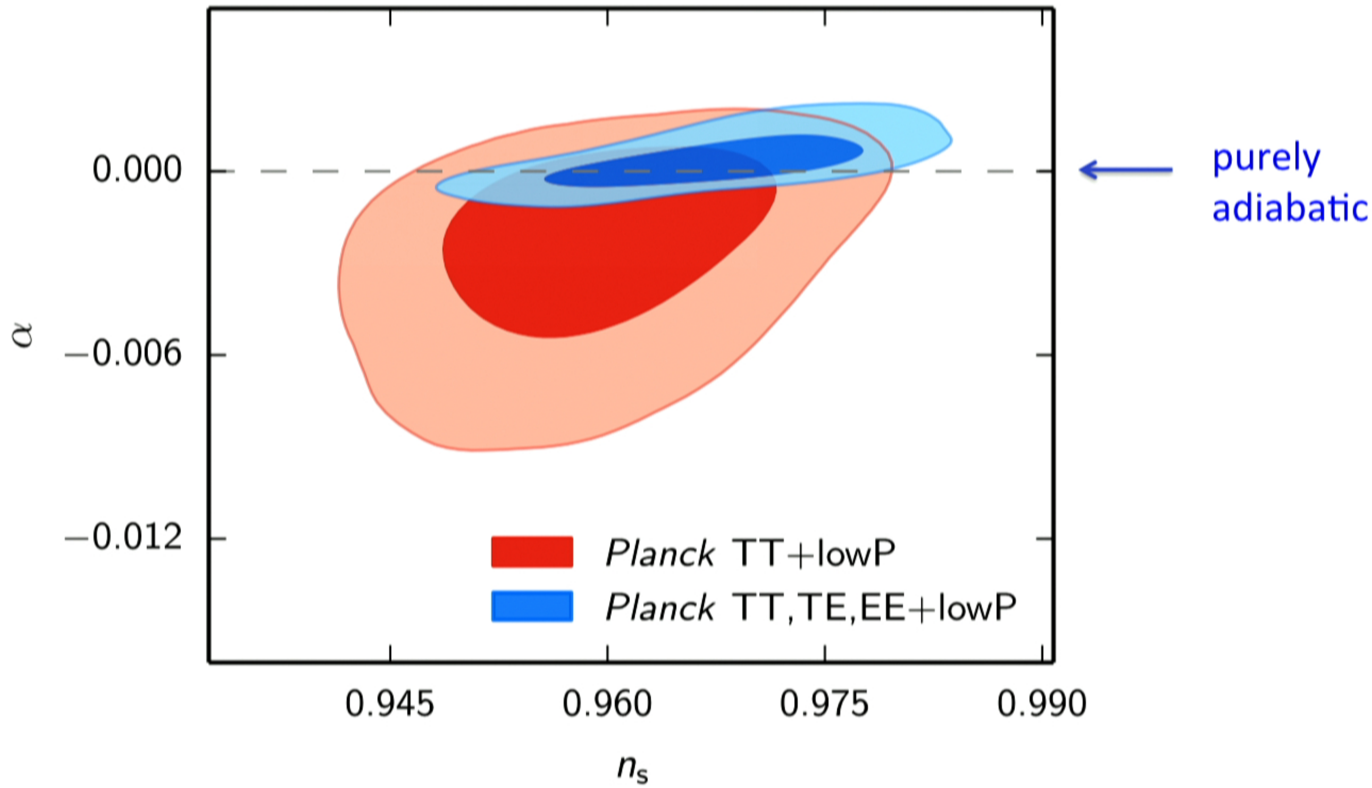
$$n_s = 0.9603 \pm 0.0073 \quad (68\,\%\mathrm{CL}\,,\,\mathit{Planck}\,2013)$$

The polarization results reported here and in the folllowing slides are preliminary, because we do not yet have confidence that all systematic and foreground uncertainties have been properly characterized, and the results may therefore be subject to revision.

Inflationary models & Planck

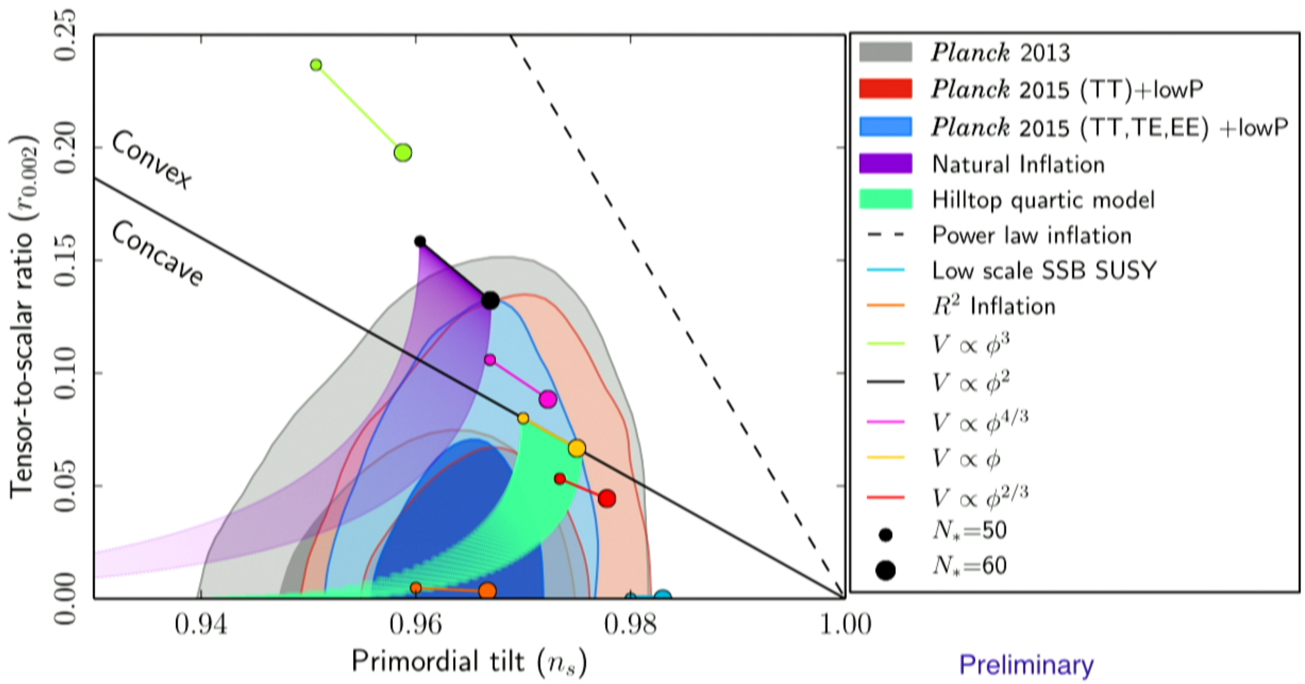


Isocurvature modes
(simple case of fully correlated matter isocurvature modes)



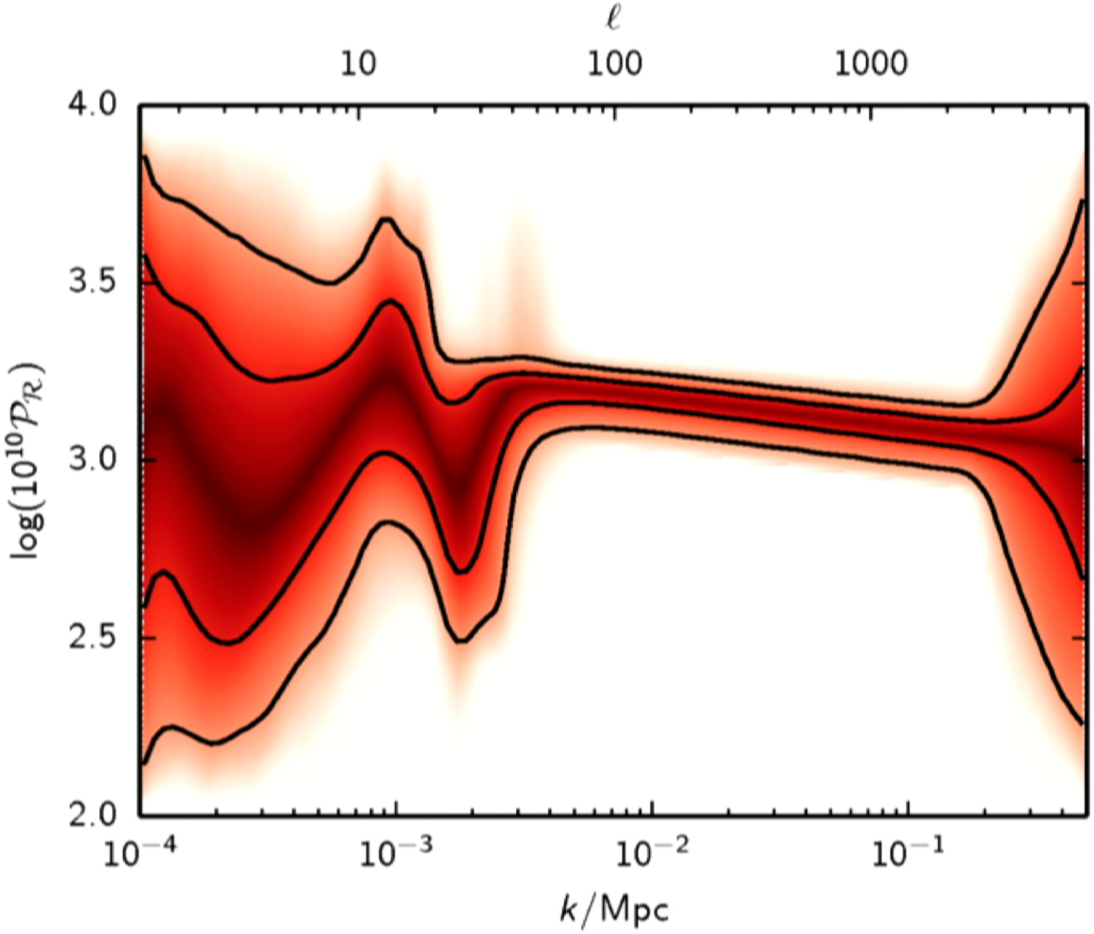
preliminary

Inflationary models & Planck



Preliminary

Power spectrum reconstruction (typical example)



preliminary

- As in 2013 base ΛCDM continues to be a good fit to the Planck data, *including polarization*.
- No convincing evidence for any simple extensions.
- Some tensions with astrophysical data that measure the amplitude of matter fluctuations.
- Planck constraints on r as in 2013

  $r<0.11$ (95%)

  (but this constraint is model dependent).
- Scalar fluctuations consistent with pure adiabatic modes with a featureless tilted spectrum.

preliminary

2015 Data Release

- (Joint Planck + BICEP2/Keck paper)
- 2015 release imminent
- Full mission *T* data, with some *P*
- Accompanied by >20 papers
- Full *P* release will follow later in 2015

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.

Large Angle Anomalies