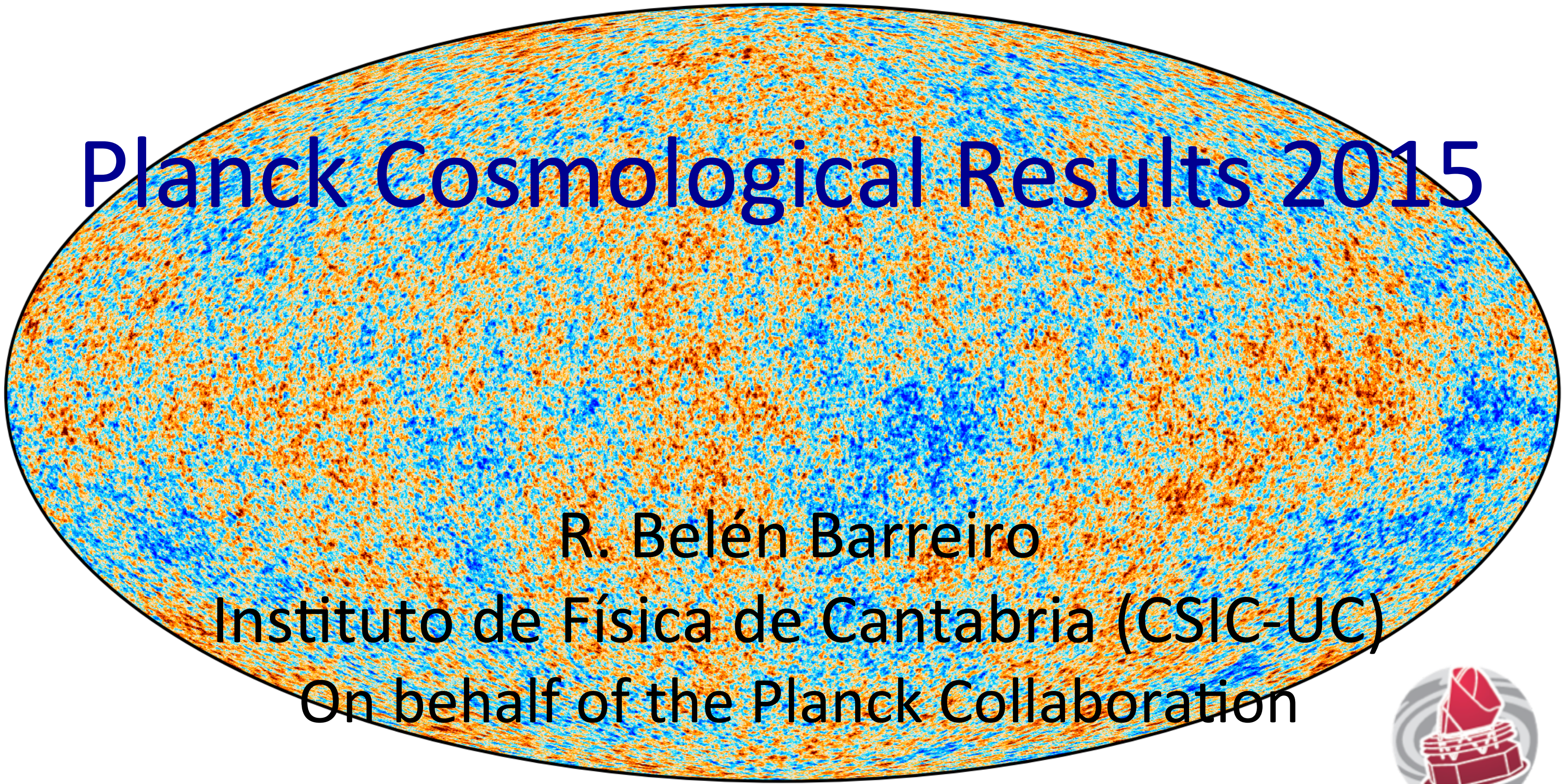
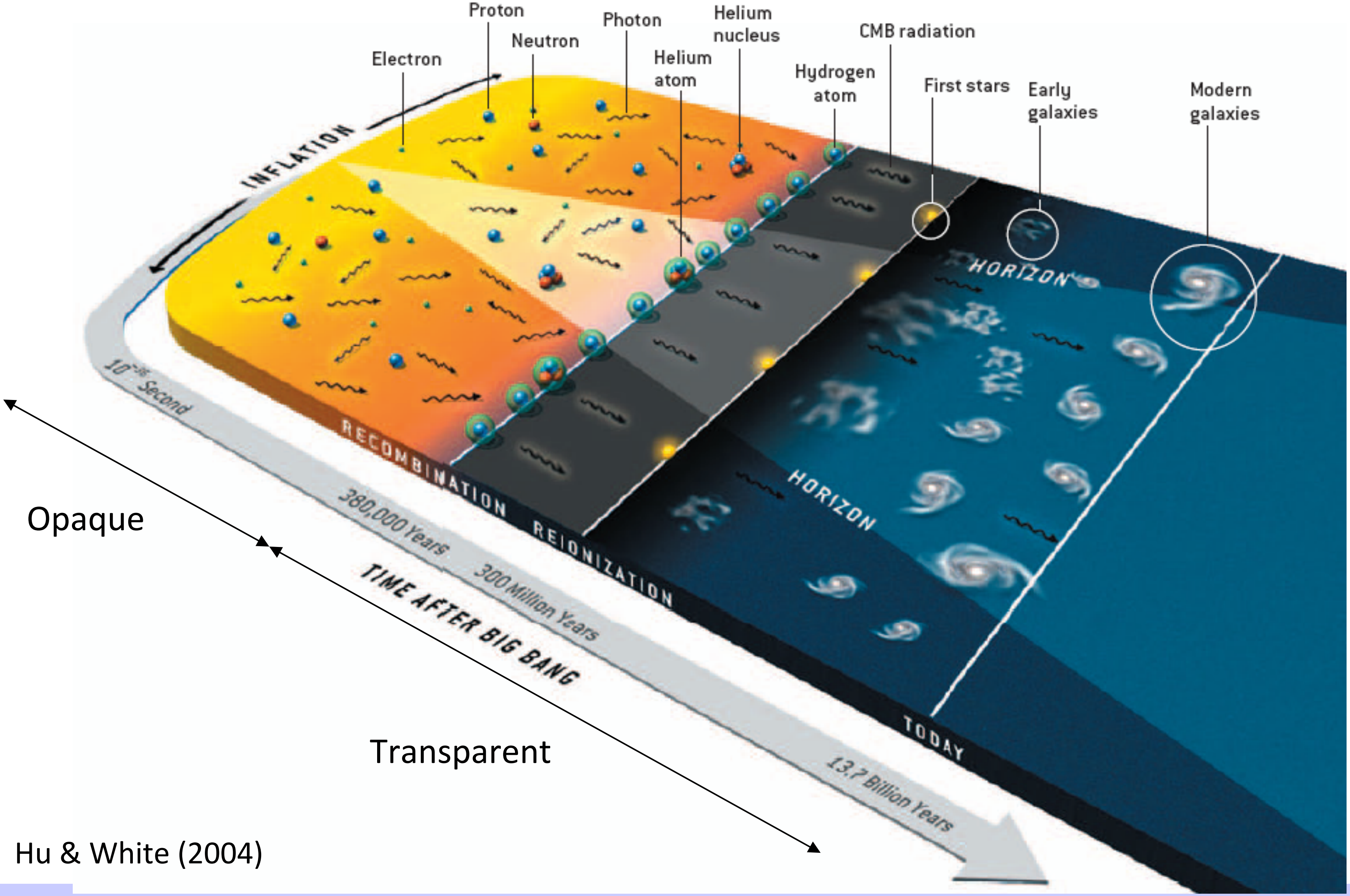


Planck Cosmological Results 2015

R. Belén Barreiro
Instituto de Física de Cantabria (CSIC-UC)
On behalf of the Planck Collaboration

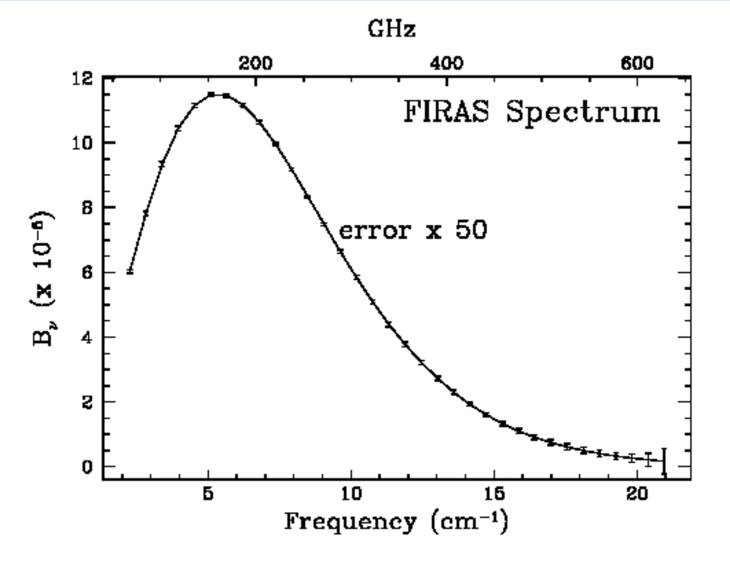
Cosmic evolution

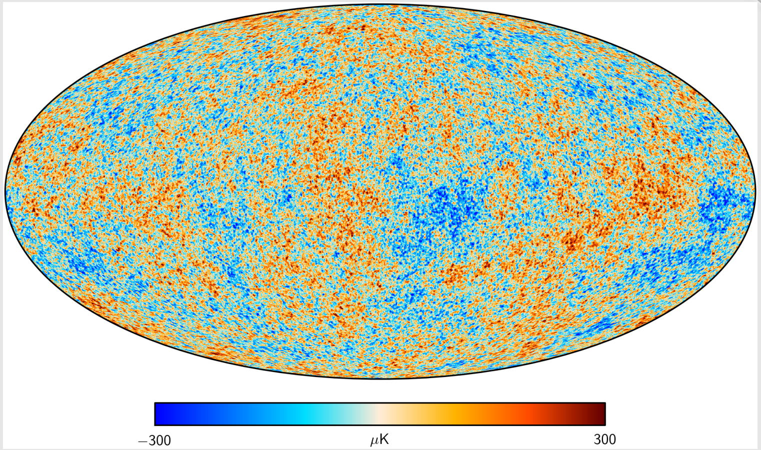


Hu & White (2004)

The Cosmic Microwave Background (CMB)

- The CMB is a homogeneous and isotropic radiation that fills the universe
- This radiation is a relic of the hot, dense, early phase of the Universe (the hot Big Bang)
- It has travelled to us from a surface of last scattering when the Universe was 380,000 years old
- The CMB has a blackbody spectrum with T_0=2.725K





- However, the CMB presents small anisotropies at the level of ~10^{-5}, which encode a wealth of information about the content and evolution of the universe
- Primary anisotropies: generated up to the last scattering surface
- Secondary anisotropies: generated in the path of the photons from last scattering until today

Description of the anisotropies

- The CMB fluctuations are described as a random field on the sphere. It is usually written as a expansion on spherical harmonics

$$\frac{\Delta T}{T_0}(\vec{n}) = \frac{T - T_0}{T_0}(\vec{n}) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n}) \ , \qquad \ell \sim 180^0 / \theta$$

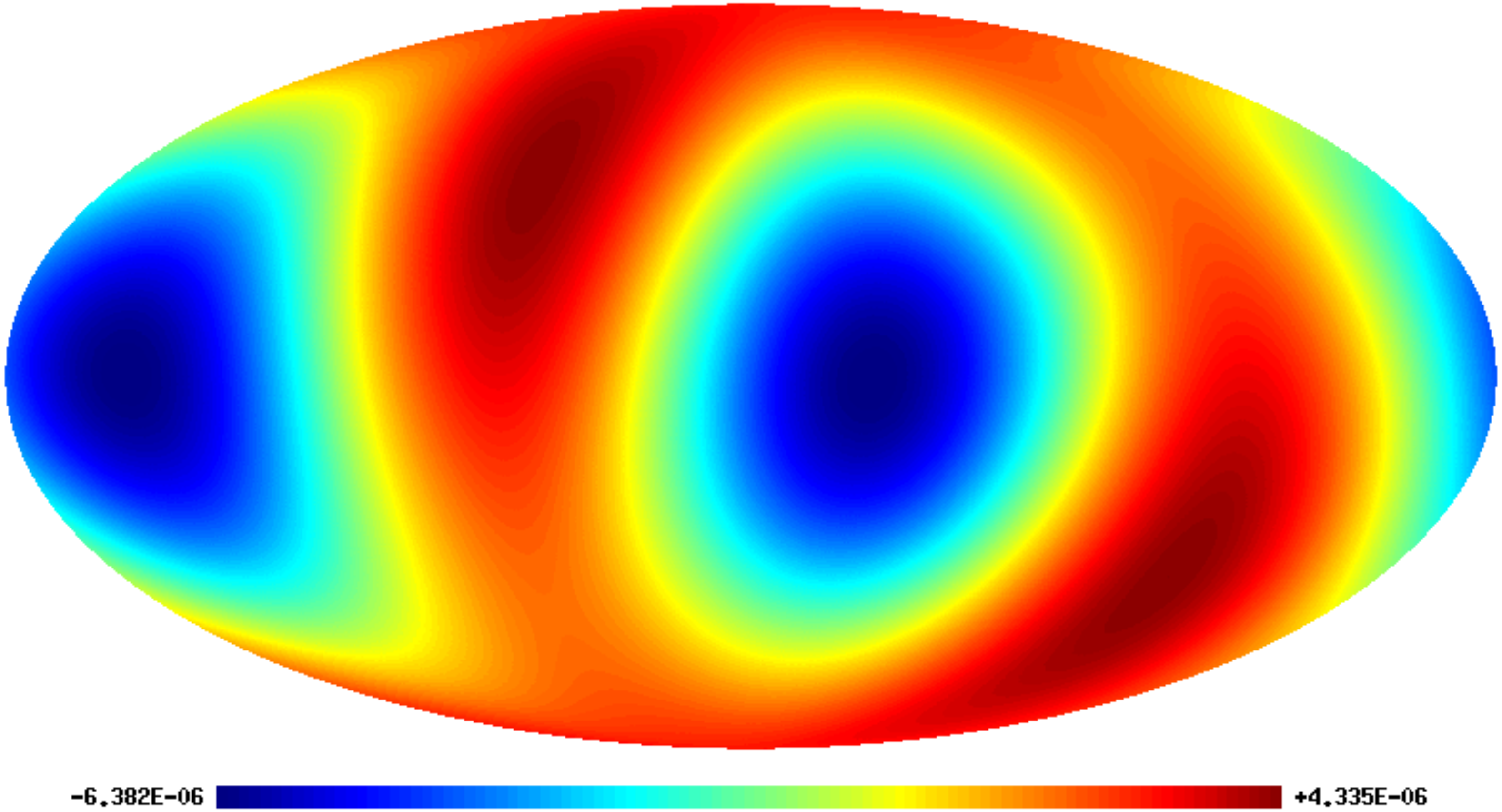
$\vec{n}$ is a unit vector on the sphere

- The $a_{\ell m}$ are complex random variables of zero mean that, assuming isotropy of the fluctuations, satisfy

$$\left\langle a_{\ell m} a^*_{\ell' m'} \right\rangle = C_\ell \delta_{\ell \ell'} \delta_{mm'}$$

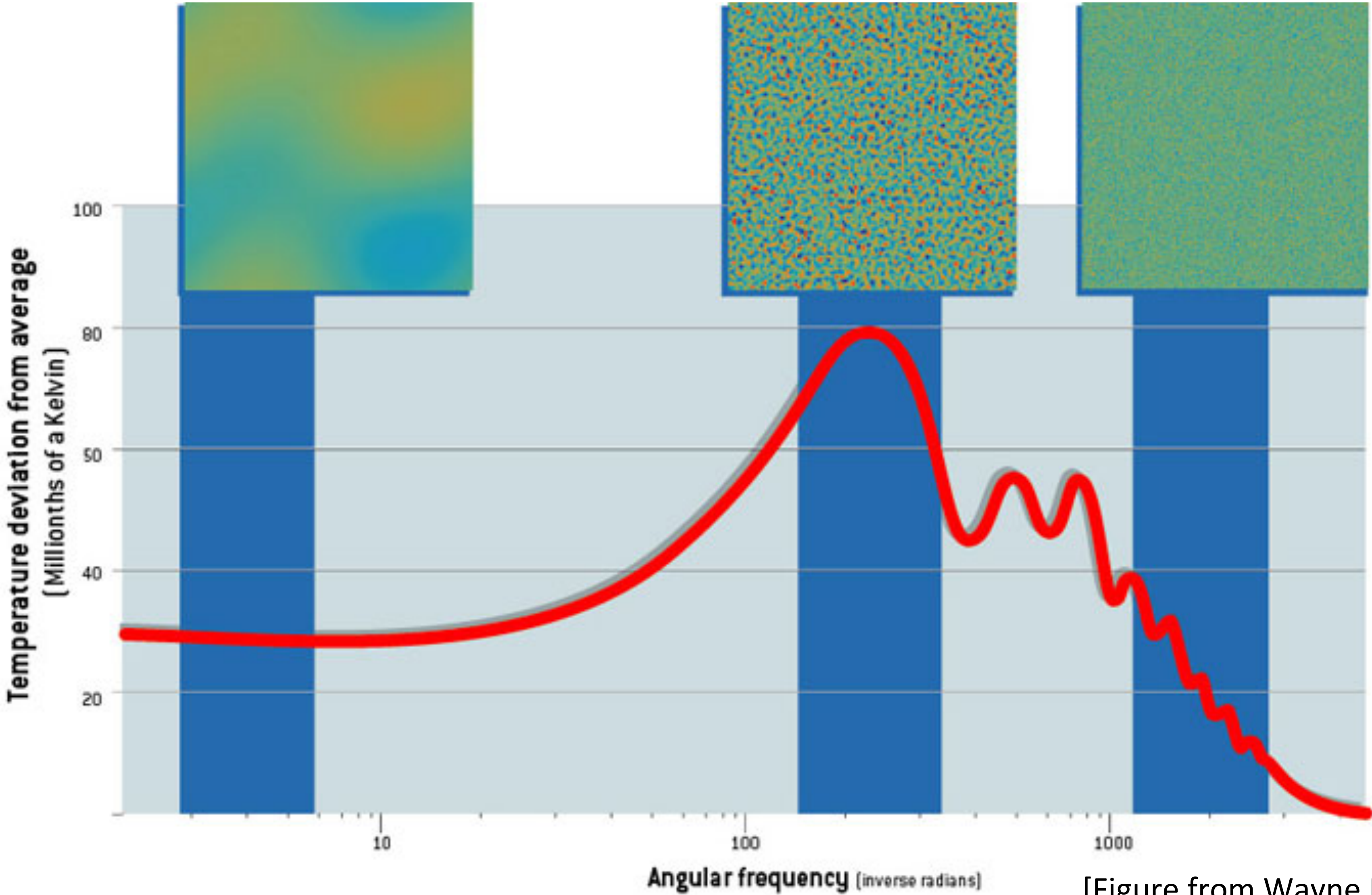
- The C_ℓs constitue the power spectrum, which is determined by the cosmological parameters

CMB temperature anisotropies



$$\frac{\Delta T}{T_0}(\vec{n}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\vec{n})$$

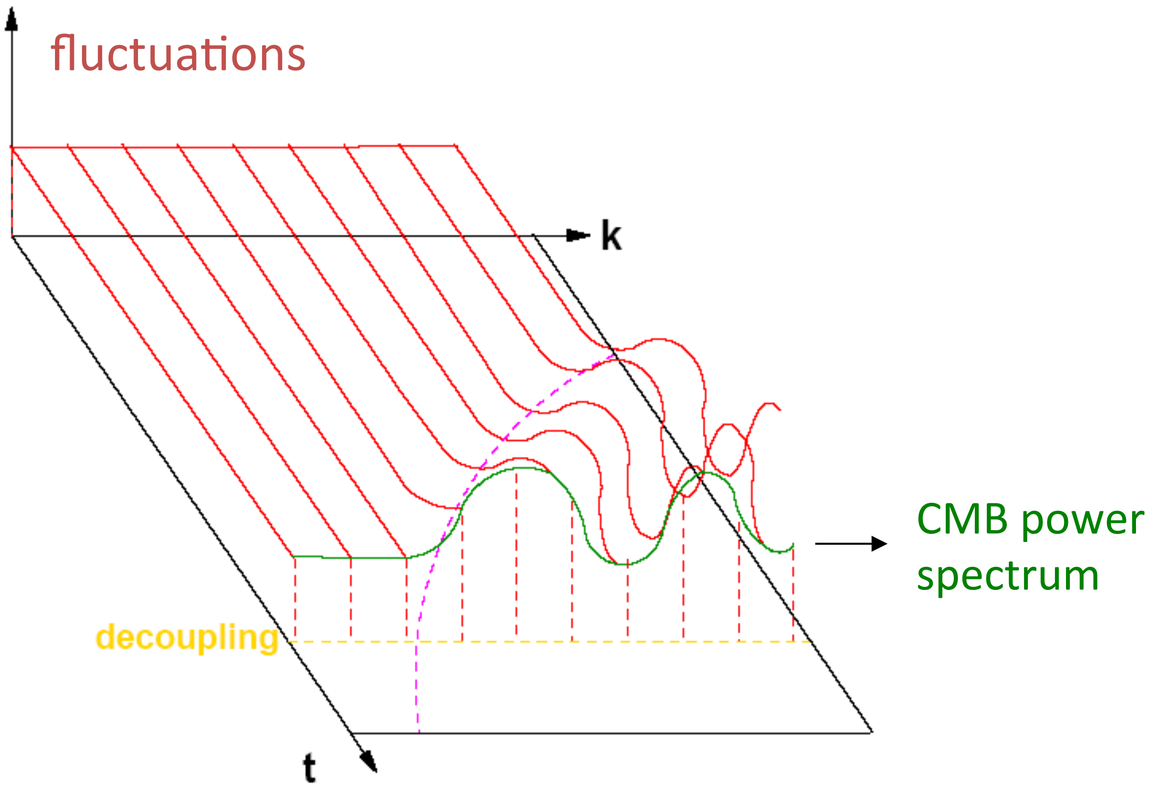
CMB temperature power spectrum



[Figure from Wayne Hu]

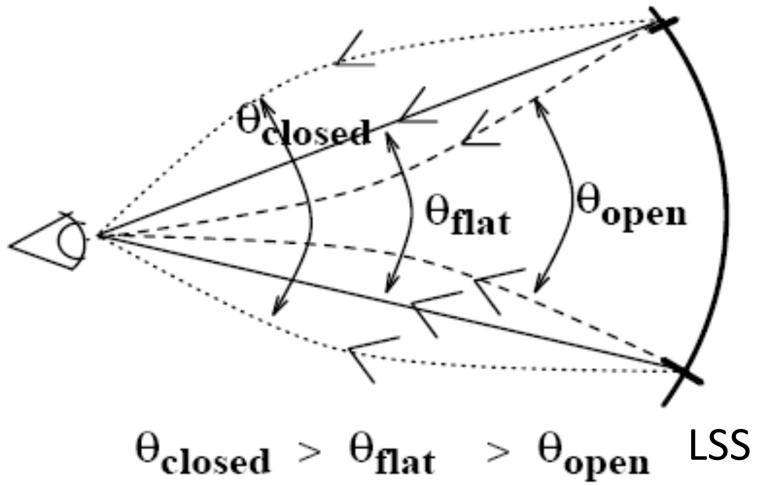
CMB power spectrum: acoustic oscillations

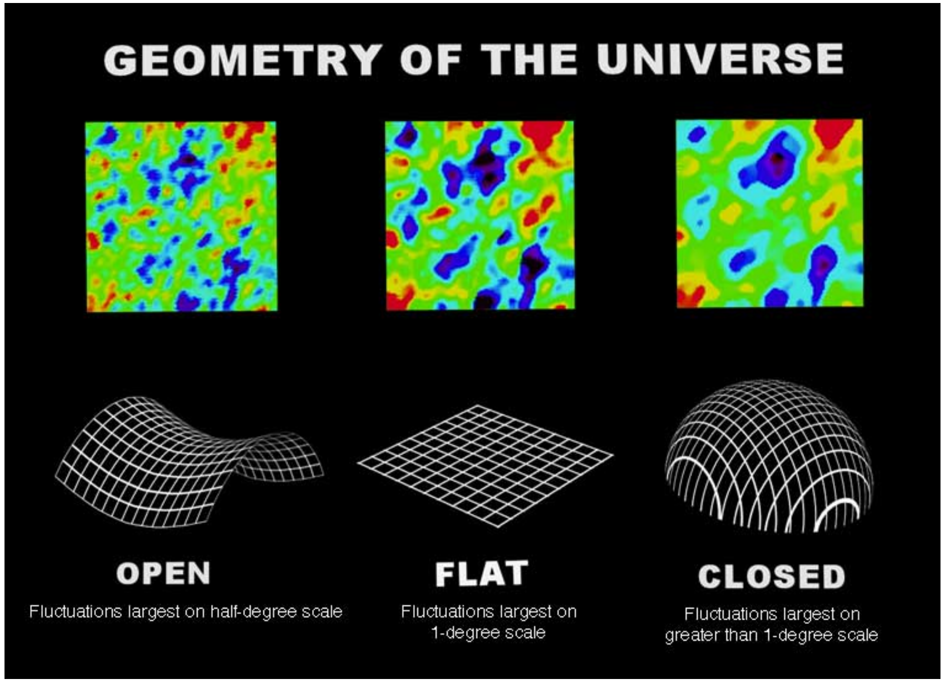
- Acoustic oscillations of the baryon-photon fluid when the fluctuations enter the horizon produce the characteristics CMB peaks
- The first acoustic peak corresponds to a scale that has just started to oscillate before recombination, corresponding approximately to the the sound horizon at recombination



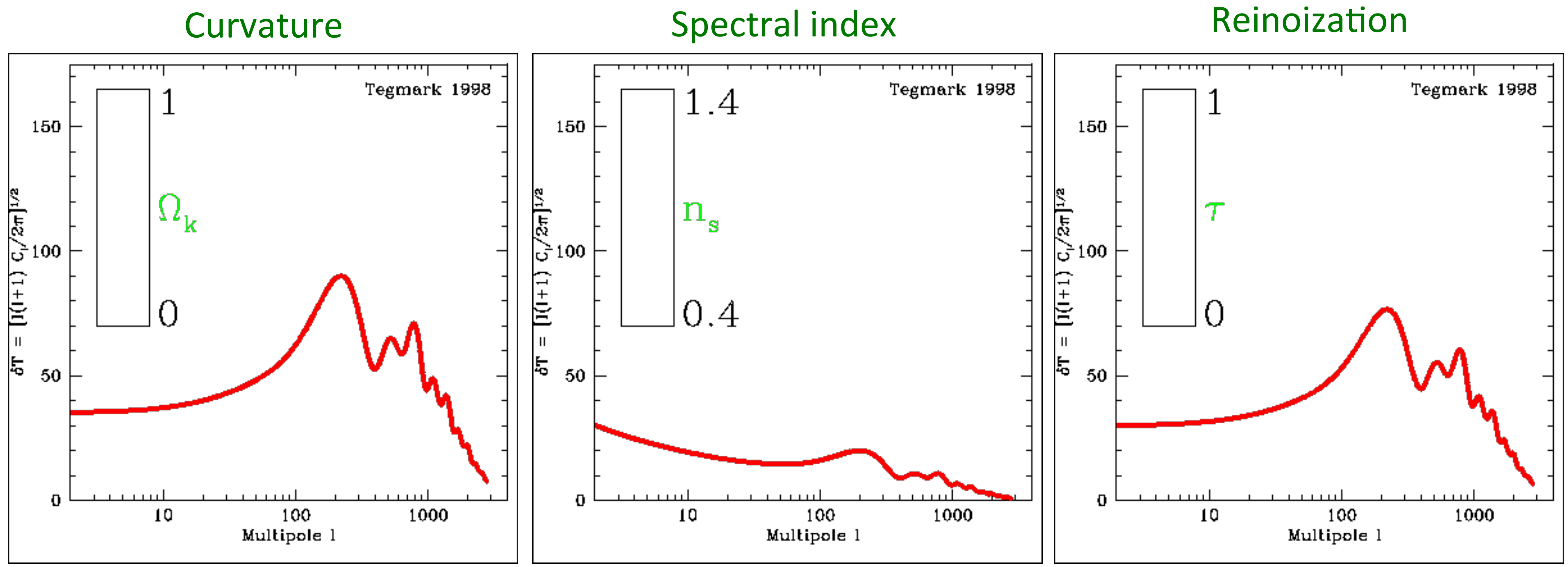
CMB power spectrum: dependence on geometry of the Universe

The same physical scale in the Last Scattering Surface corresponding to the first acoustic peak will be projected in a different angular scale in the sky depending on the geometry of the Universe. Therefore the position of the first peak and the characteristic size of the CMB anisotropies will be different





Dependence of CMB power spectrum on cosmological parameters

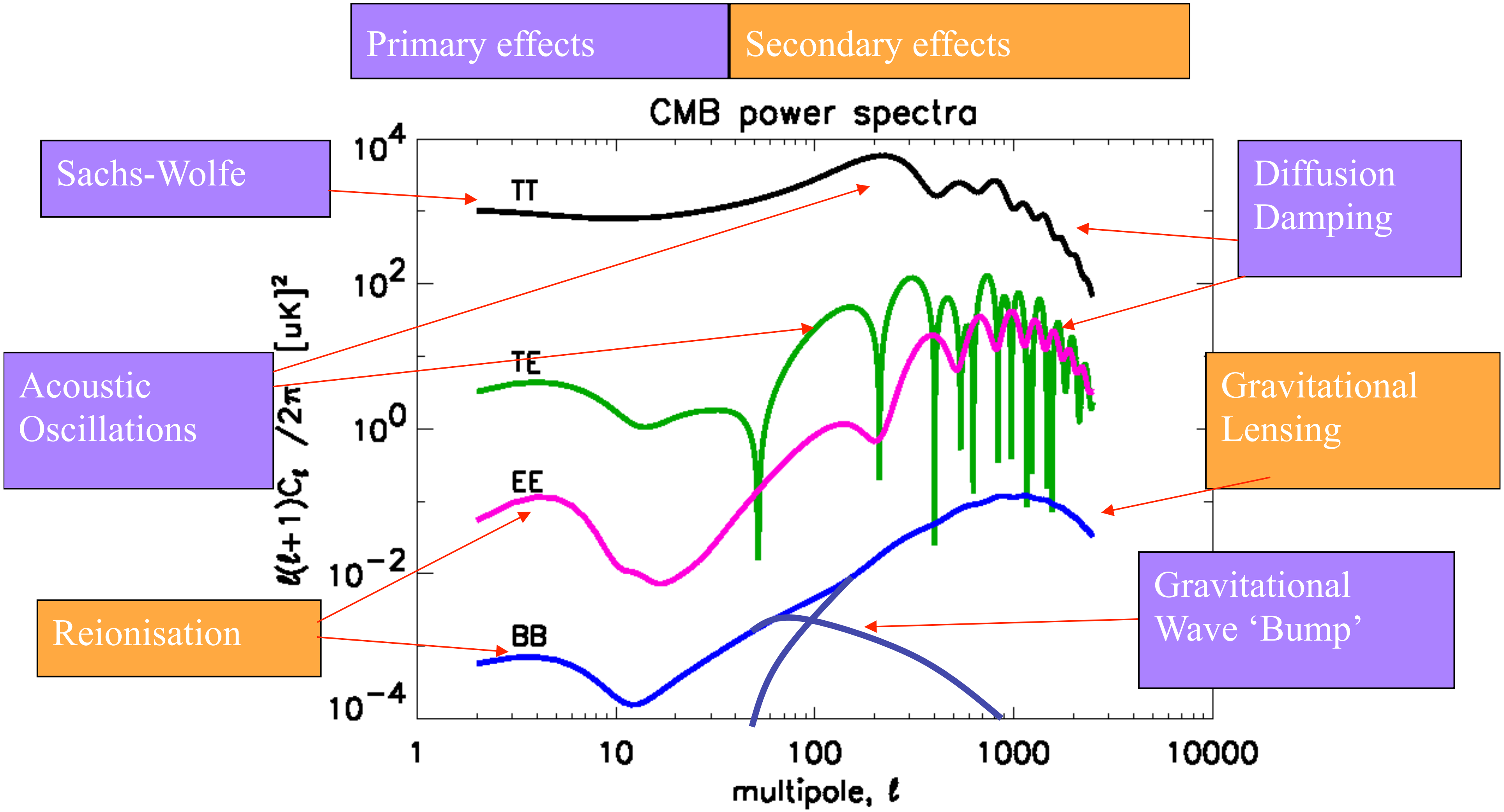


- Different cosmological parameters affect in different ways to the shape of the CMB power spectrum
- By fitting the observed C_ℓ´s to theoretical predictions, the cosmological parameters can be estimated

CMB polarization

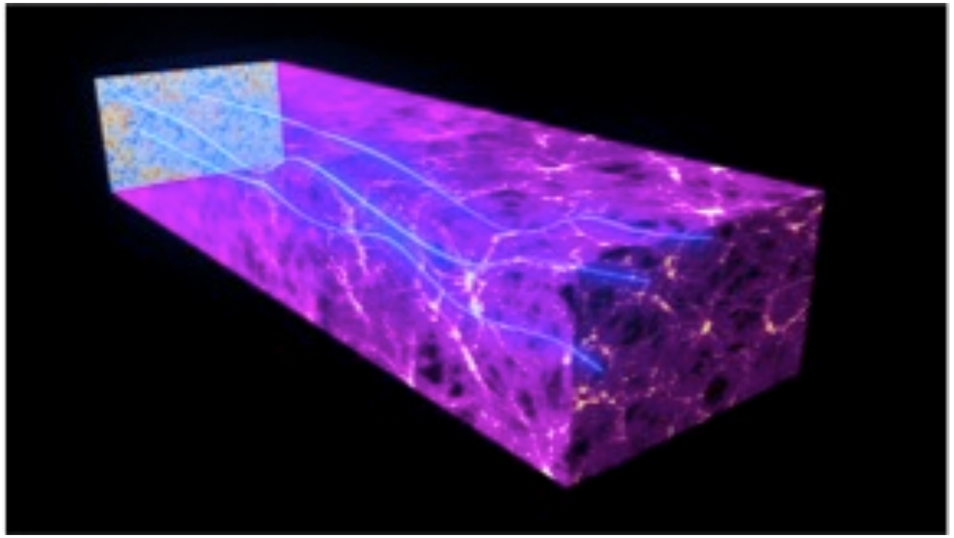
- CMB partially polarised (polarization produced by Thomson scattering in the Last Scattering Surface)
- Measured through Stokes parameters: I, Q, U (V=0 since polarization is linear)
- From Q and U, two quantities (invariant under rotation) are constructed: E and B
- Scalar perturbations produce only E-mode of polarization
- Primordial gravitational waves (predicted by inflation) produce both E and B-mode polarization → if we detect primordial B polarization, direct proof of GWB
- Secondary anisotropies can also be imprinted in the CMB polarization on its way to us (lensing, reionization)

CMB power spectra: TT, TE, EE, BB (TB=EB=0)



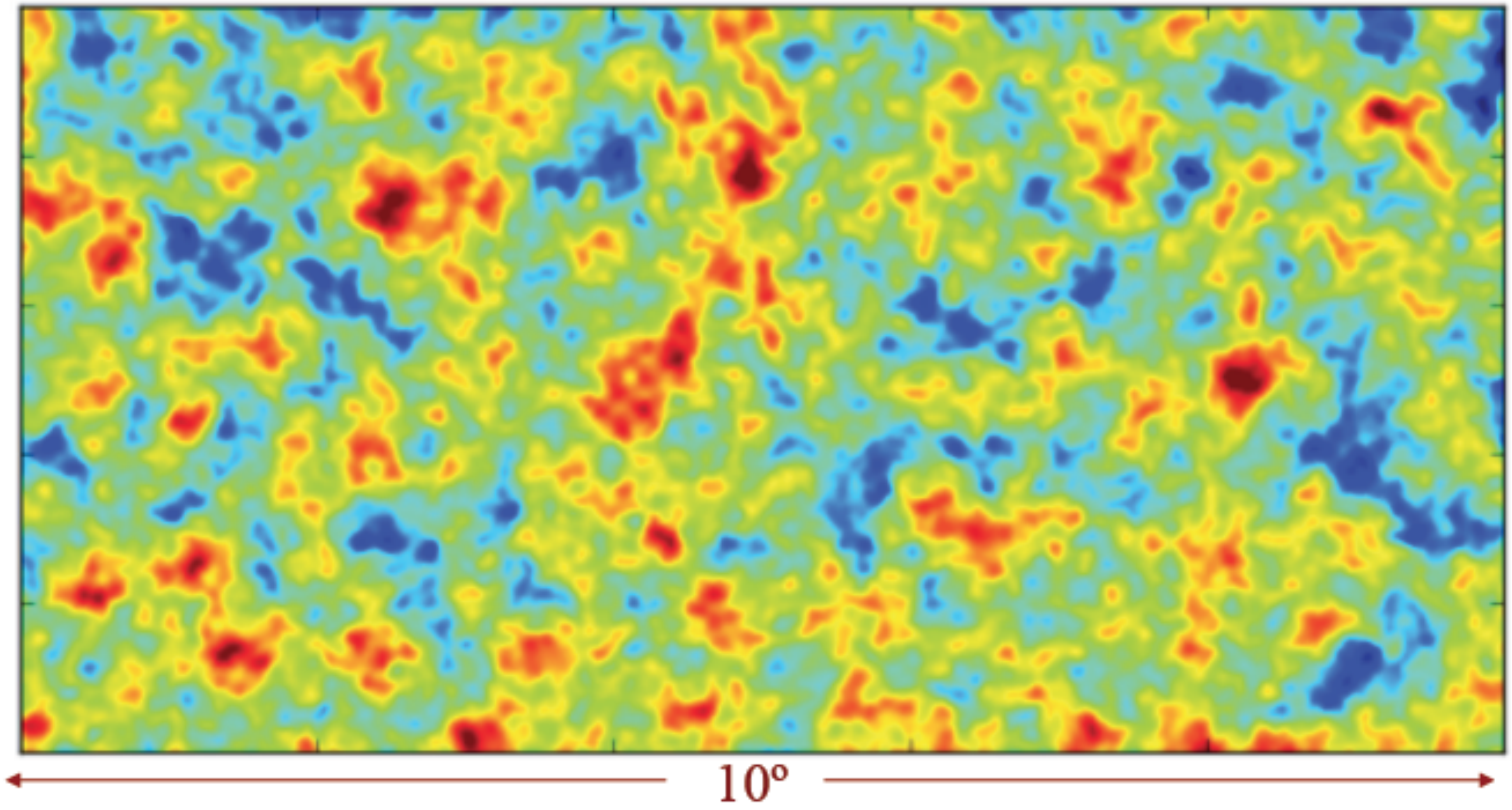
Secondary anisotropies: CMB lensing

- CMB photons are deflected (typically 2-3 arcminutes) on their way to us by the potentials of the large-scale structure
- It produces a smearing effect of the acoustic peaks of the TT power spectrum
- It transforms a fraction of E-mode polarization into B-mode at small scales
- It gives information about the low z universe
  - Peak sensitivity around z~2
- It allows to break some degeneracies between cosmological parameters from Planck data alone
- Provides a consistency check between the model inferred at low and high redshift



Secondary anisotropies: CMB lensing

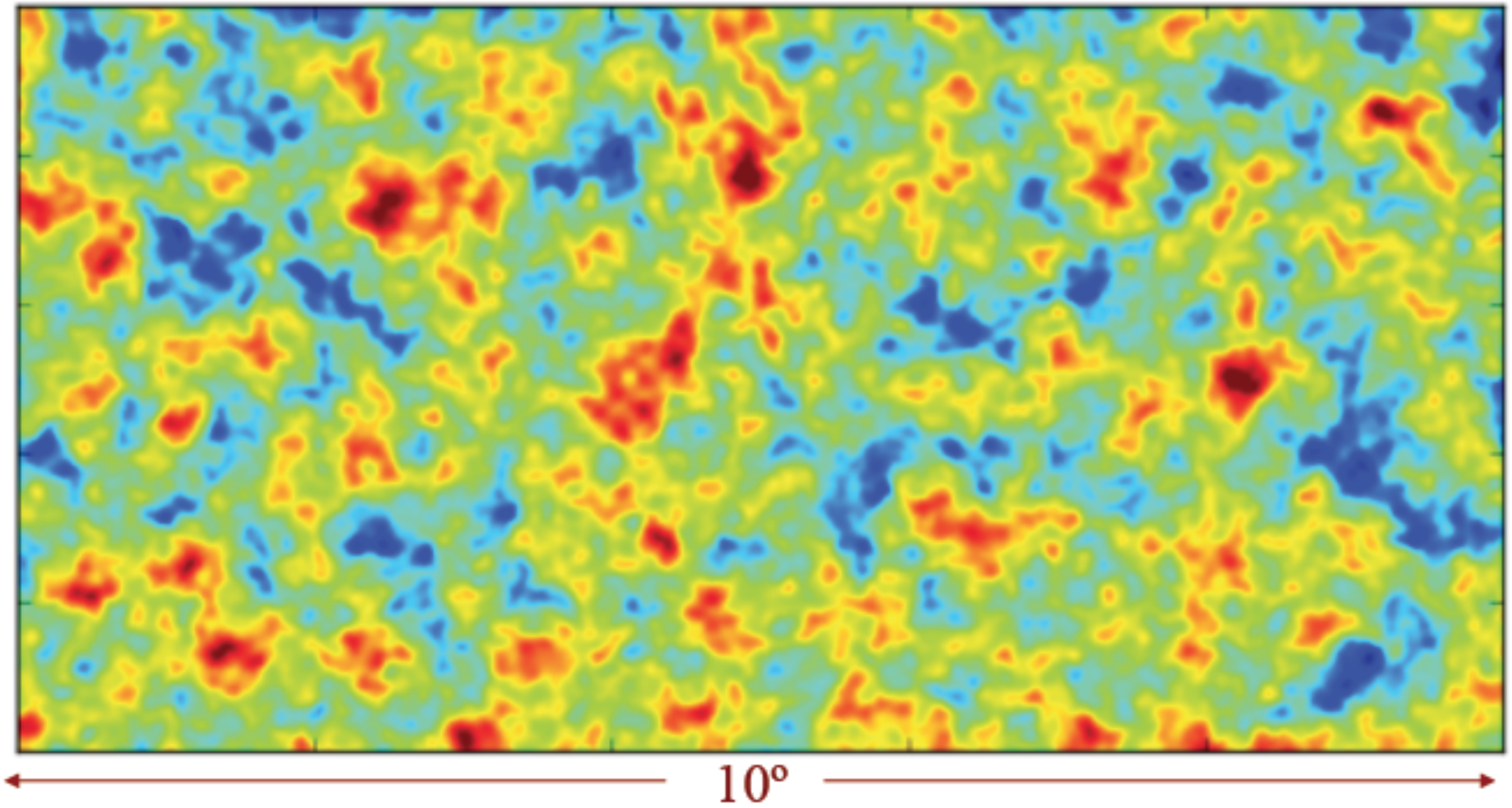
A simulated patch of CMB sky – before lensing



typical deflection: 2.4 arcmin

Secondary anisotropies: CMB lensing

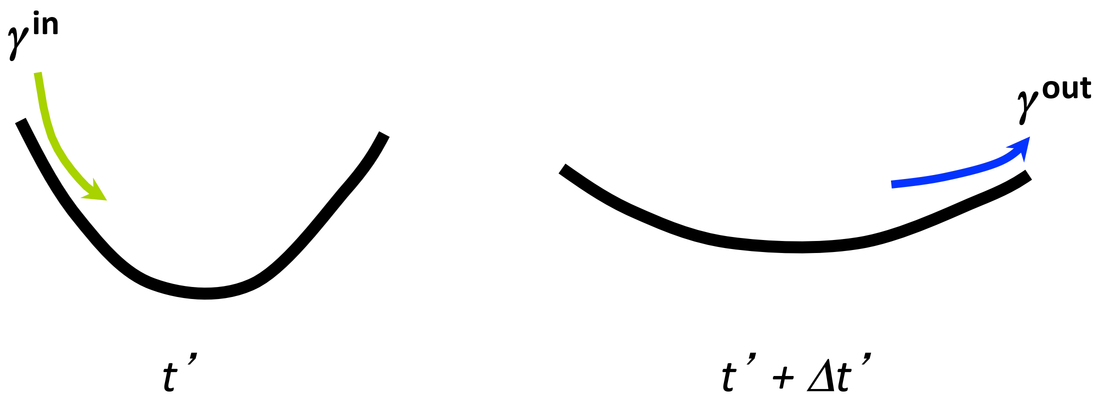
A simulated patch of CMB sky – after lensing

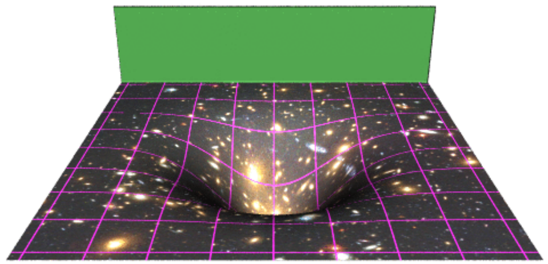


typical deflection: 2.4 arcmin

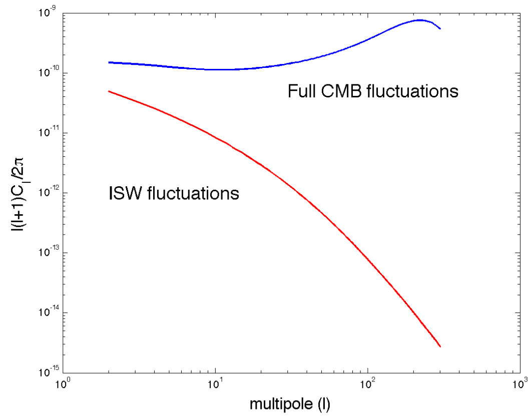
Secondary anisotropies: ISW effect

- CMB photons are blue (red) shifted when fall into (out of) gravitational potential wells
- An **evolution of the gravitational potential** during the photon crossing implies a **net change in the photon energy** ➔ **secondary anisotropy of the CMB anisotropies**
- Very weak signal → can be detected through cross-correlation with Large Scale Structure Surveys
- It provides an independent confirmation of Dark Energy (the effect is zero for a flat Universe without cosmological constant)





Granett et al.

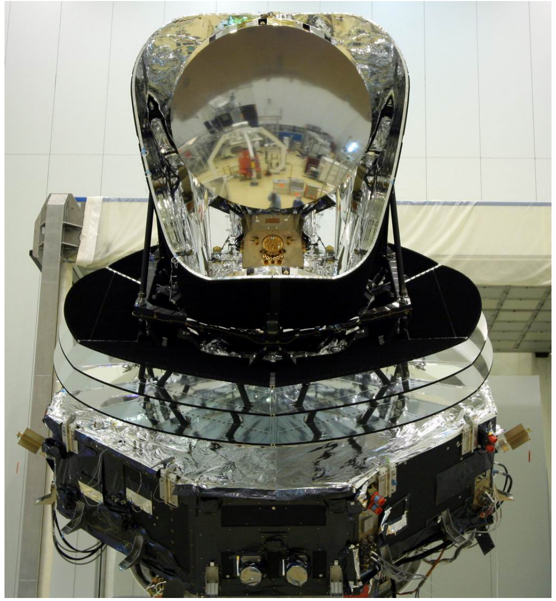


Isotropy and statistics of the CMB

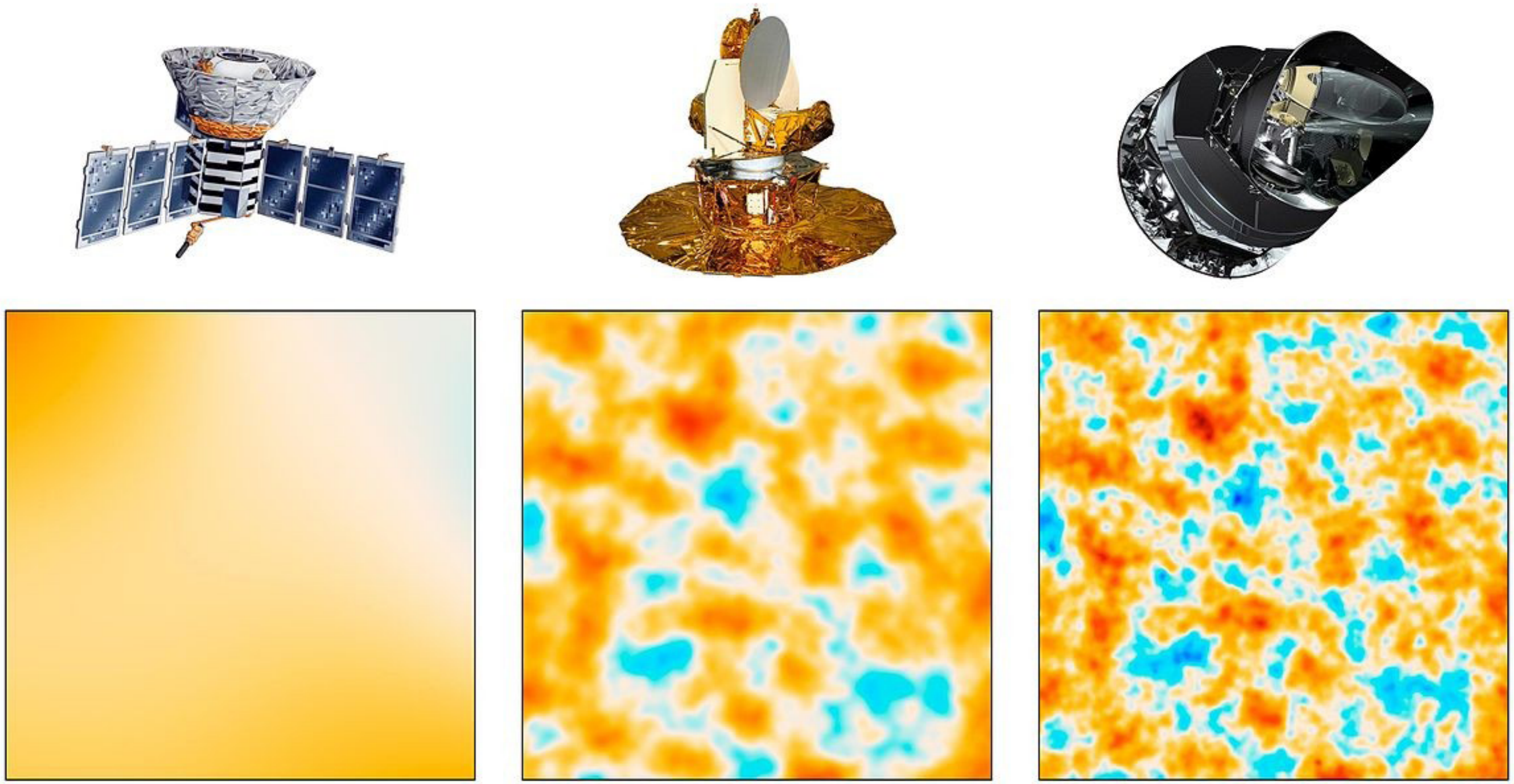
- According to the cosmological principle, the CMB is expected to be isotropic, i.e., to have the same properties in all directions
- CMB fluctuations are predicted to be very close to Gaussian in the simplest inflationary scenarios. Any intrinsic deviation from Gaussianity could be an indication of new physics beyond the standard cosmological model
- Detections of non-Gaussianity can also point out to the presence of secondary anisotropies, foreground contamination or systematics

The Planck Mission

- ESA satellite launched in May 2009 to measure the CMB temperature and polarization over the full sky with high sensitivity at an angular resolution ~5 arcminutes
- Two instruments:
  - LFI : observing at 30, 44 and 70 GHz (PI. N. Mandolesi)
  - HFI: observing at 100, 143, 217, 353, 545 and 857 GHz (PI. J.L. Puget)
- Nominal Mission
  - 2 full sky surveys
- Extended mission
  - 5 sky surveys with HFI
  - 8 sky surveys with LFI
- End of operations: October 2013



Planck: third generation space mission



COBE WMAP Planck

Planck publications and products

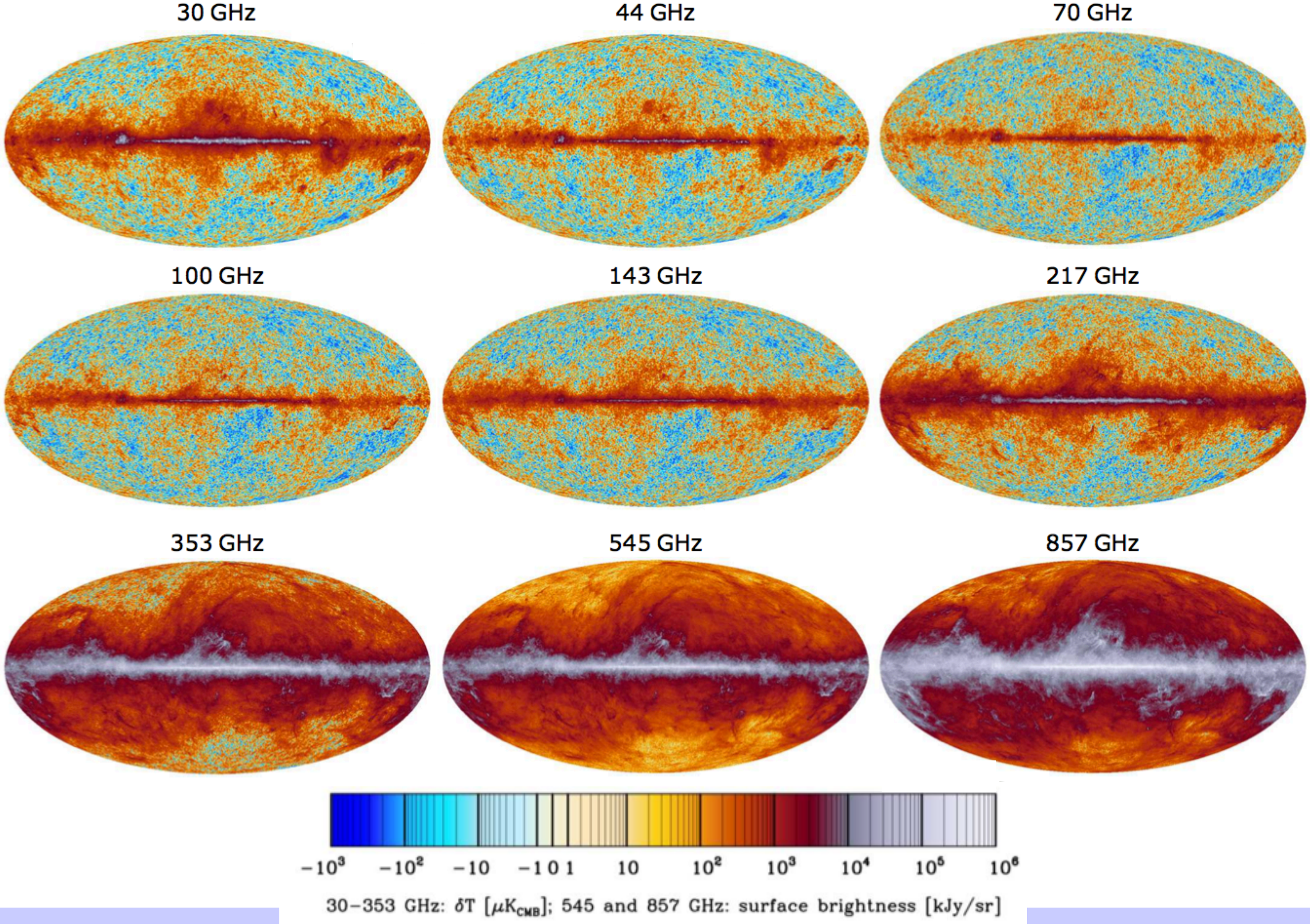
2010: Planck pre-launch papers	13 publications describing the technical capabilities of Planck's instruments
2011: Planck Early papers	26+1 publications coming with the 1st delivered product: The Early Release Compact Source Catalogue
2012 - : Planck intermediate papers	35 publications (and rising) on galactic and extragalactic astrophysics
2013 : Planck 2013 results	31 publications on cosmology science from CMB temperature data (published on 2014). Maps, C_l's and likelihoods delivered
2015 (Feb.-June): Planck 2015 results	28 publications mainly on cosmology science from CMB temperature and polarization data (full mission). Update of the delivered products, including polarization.
Early 2016: Planck 2016 results	Updated products and final results

Planck products can be found at: http://pla.esac.esa.int/pla/

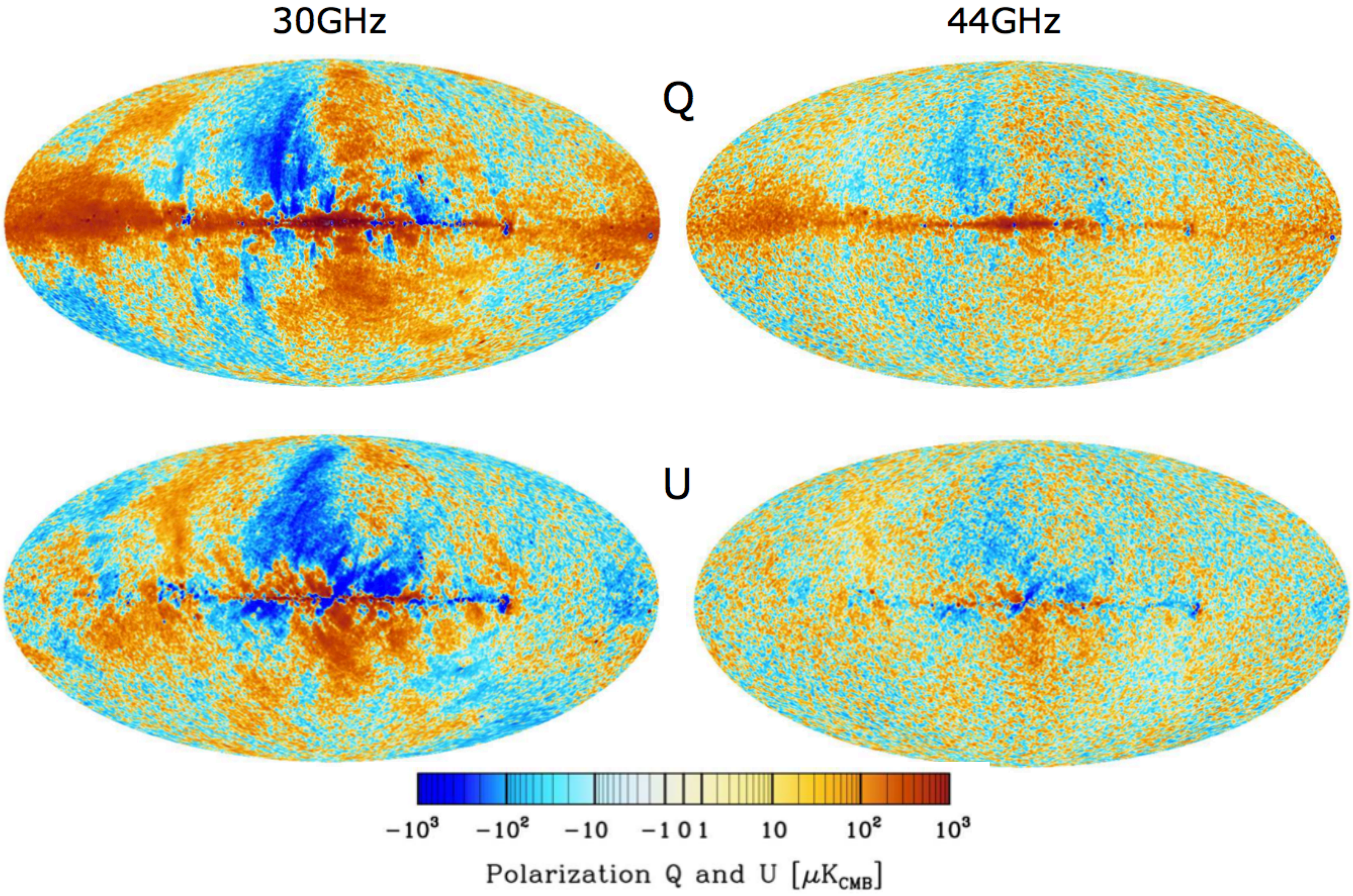
2015 Papers

I. Overview of products and results
II. Low Frequency Instrument data processing
III. LFI systematic uncertainties
IV. LFI beams and window functions
V. LFI calibration
VI. LFI maps
VII. High Frequency Instrument data processing: Time-ordered information and beam processing
VIII. High Frequency Instrument data processing: Calibration and maps
IX. Diffuse component separation: CMB maps
X. Diffuse component separation: Foreground maps
XI. CMB power spectra, likelihood, and consistency of cosmological parameters
XII. Simulations
XIII. Cosmological parameters
XIV. Dark energy and modified gravity
XV. Gravitational lensing
XVI. Isotropy and statistics of the CMB
XVII. Primordial non-Gaussianity
XVIII. Background geometry and topology of the Universe
XIX. Constraints on primordial magnetic fields
XX. Constraints on inflation
XXI. The integrated Sachs-Wolfe effect
XXII. A map of the thermal Sunyaev-Zeldovich effect
XXIII. The thermal Sunyaev-Zeldovich effect–cosmic infrared background correlation
XXIV. Cosmology from Sunyaev-Zeldovich cluster counts
XXV. Diffuse, low-frequency Galactic foregrounds
XXVI. The Second Planck Catalogue of Compact Sources
XXVII. The Second Planck Catalogue of Sunyaev-Zeldovich Sources
XXVIII. The Planck Catalogue of Galactic Cold Clumps

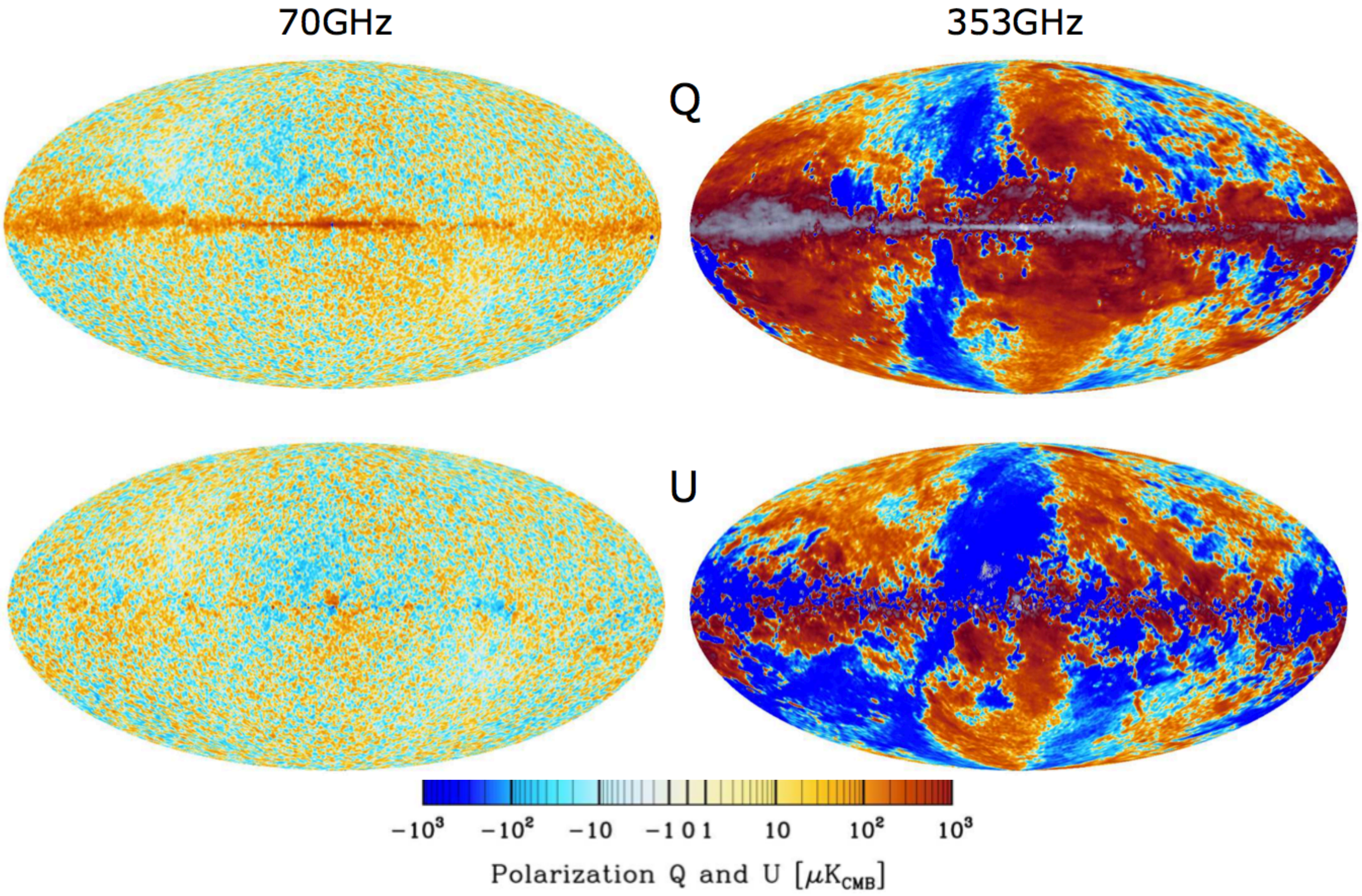
The sky as seen by Planck: intensity



The sky as seen by Planck: polarization



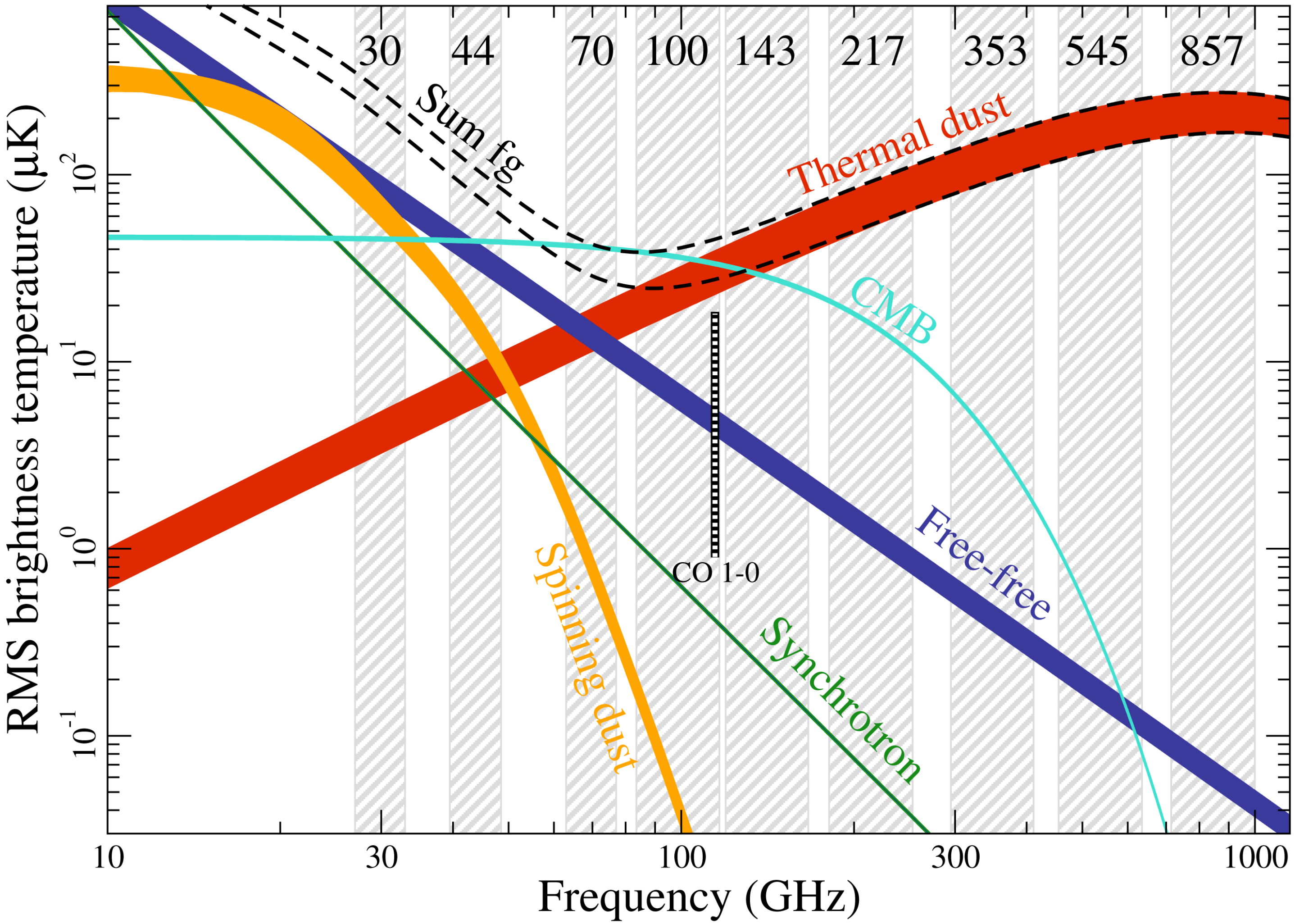
The sky as seen by Planck: polarization



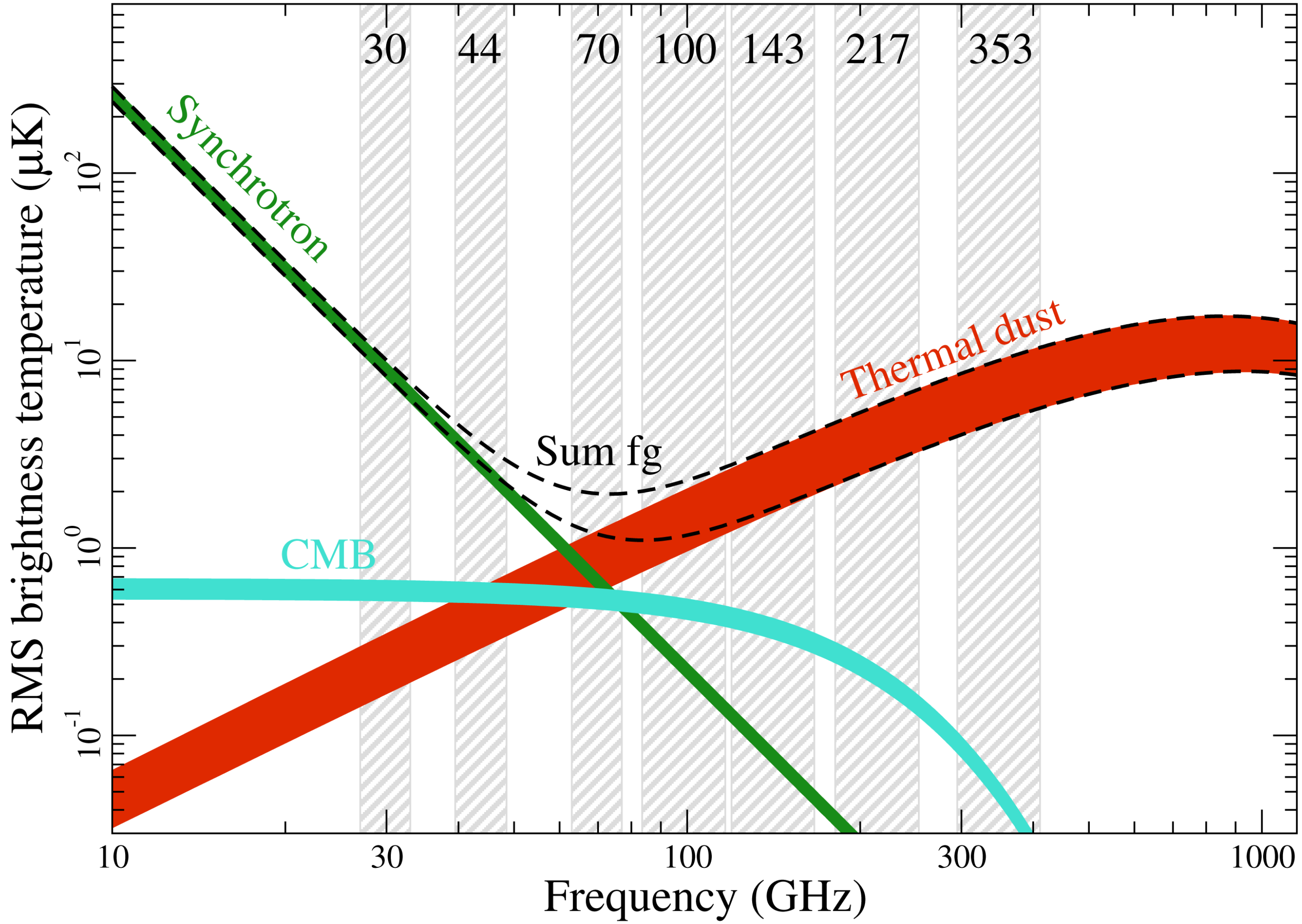
Component separation

- The observed microwave sky is the sum of the CMB plus other astrophysical signals (contaminants) along the line of sight
- The CMB and the contaminants have a different frequency dependence
- Planck observes at 9 frequencies in order to disentangle the different components
- The main contaminants are diffuse emission from our own Galaxy (synchrotron, free-free, thermal dust) and compact emission from extragalactic sources

CMB contaminants: intensity

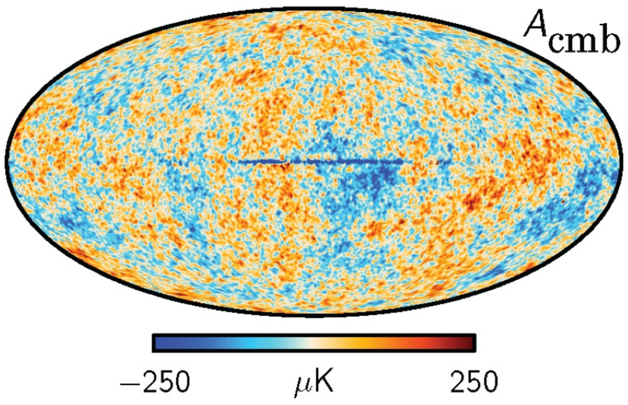


CMB contaminants: polarization

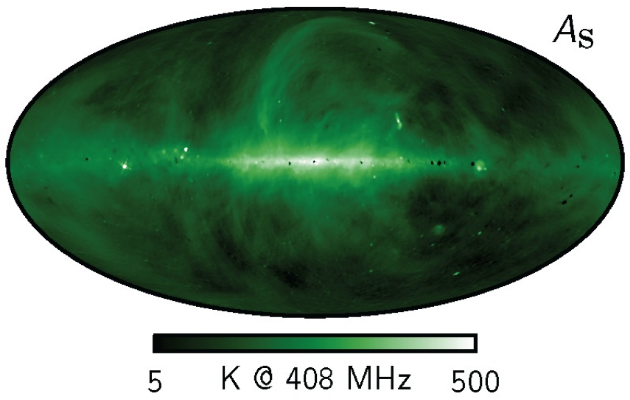


Recovered components: intensity

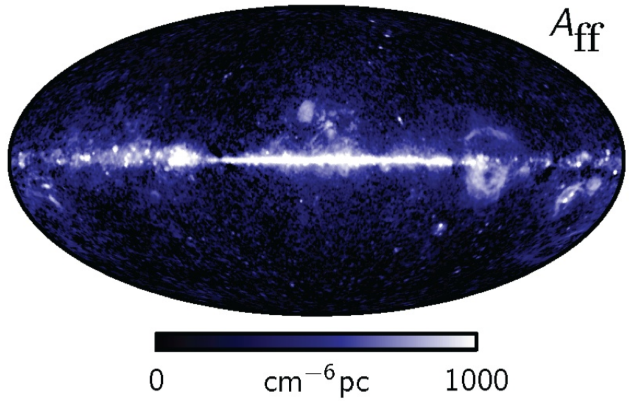
CMB

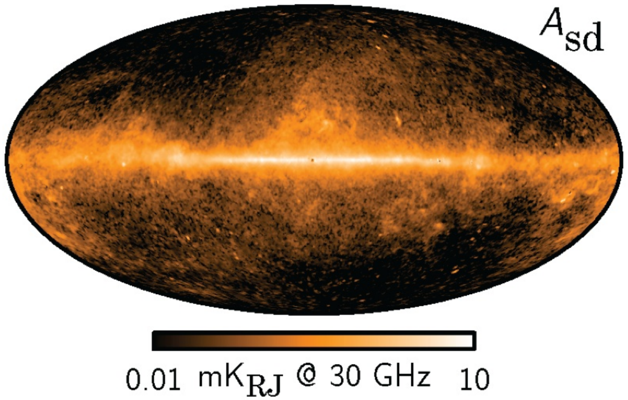


Synchrotron

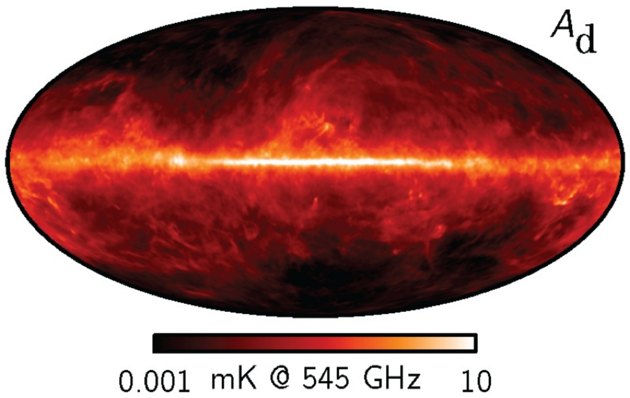


Free - free

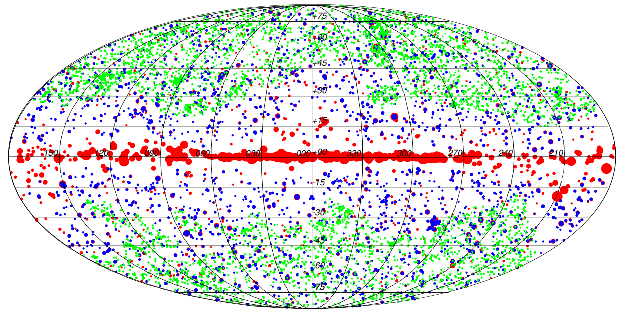




Spinning dust



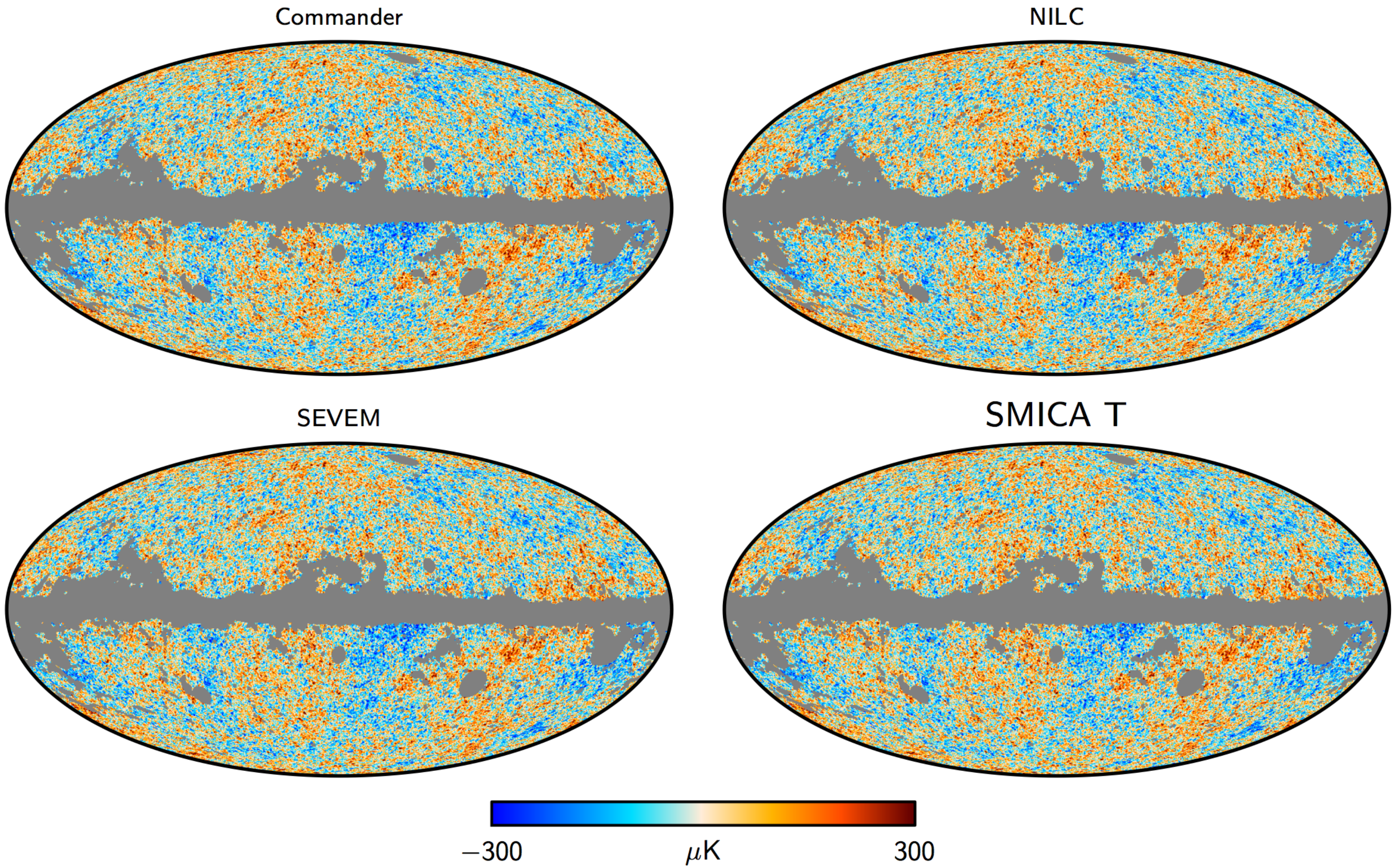
Thermal dust



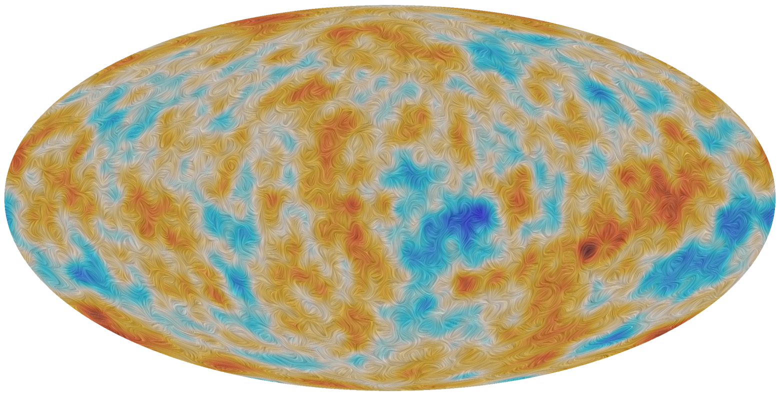
Positions of detected point sources (30,143 and 857 GHz)

CMB recovery: intensity

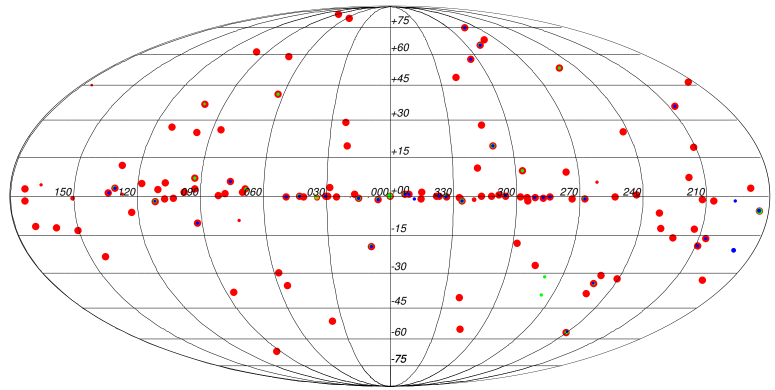
Robustness of reconstruction tested with four different component separation methods.
Unreliable regions are masked.



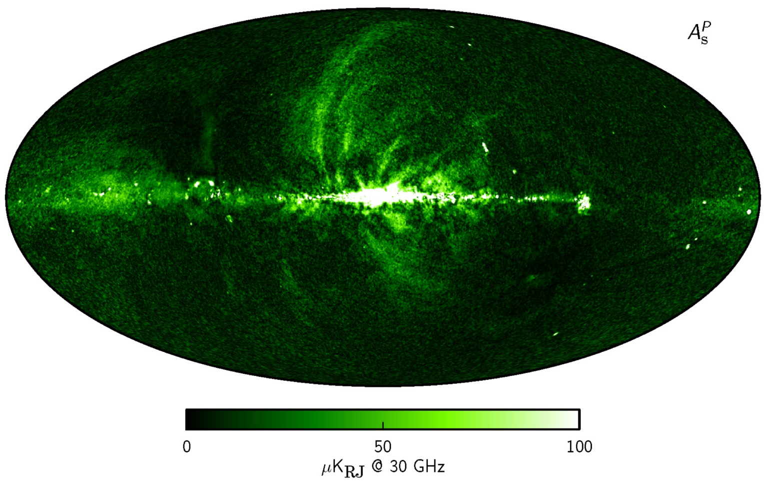
Recovered components: polarization



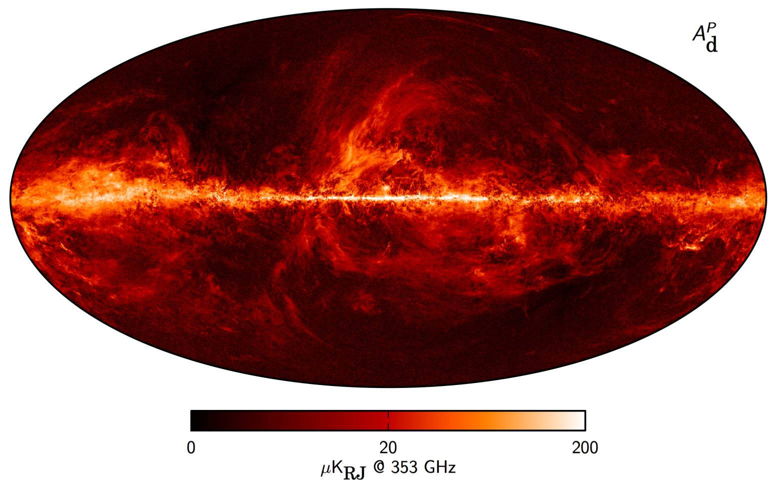
CMB intensity overlaid with polarization direction (5 degrees resolution)



Position of detected point sources (30, 44, 70 GHz)



Synchrotron polarization amplitude map P ($P^2=Q^2+U^2$)



Dust polarization amplitude map P ($P^2=Q^2+U^2$)

The flat ΛCDM cosmological model

During the last decades, the availability of high-quality data (CMB, SN, LSS, BBN…) has allowed the establishment of a concordance cosmological model

- The Universe is highly homogenous and isotropic at large scales due to an early phase of cosmic inflation
- Its spatial geometry is flat
- Most of the energetic content of the Universe is in one of following forms:
  - Baryonic matter (around 5%)
  - Weakly interactive cold dark matter (around 26%)
  - Dark energy (around 69%), which is responsible of the current accelerated expansion of the Universe

The flat ΛCDM model is defined with only 6 parameters

Cosmological parameters

Defining:

$\Omega_i = \rho_{i0}/\rho_{c0}$, $\rho_{c0} = 3c^2 H_0^2/8\pi G$ ⇨ critical density

- Ω_b : fraction of baryonic matter
- Ω_c: fraction of dark matter
- $\Omega_m = \Omega_c + \Omega_b$ fraction of total matter
- Ω_Λ : dark energy fraction
- $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$ curvature of universe

$$\Omega_k = \begin{cases} = 0 & \text{flat} \\ > 0 & \text{open} \\ < 0 & \text{close} \end{cases}$$

- H_0: Hubble parameter (at current time)

$$H(t) = \dot{a}(t) / a(t)$$

$h = H_0/[100 km/s/Mpc]$

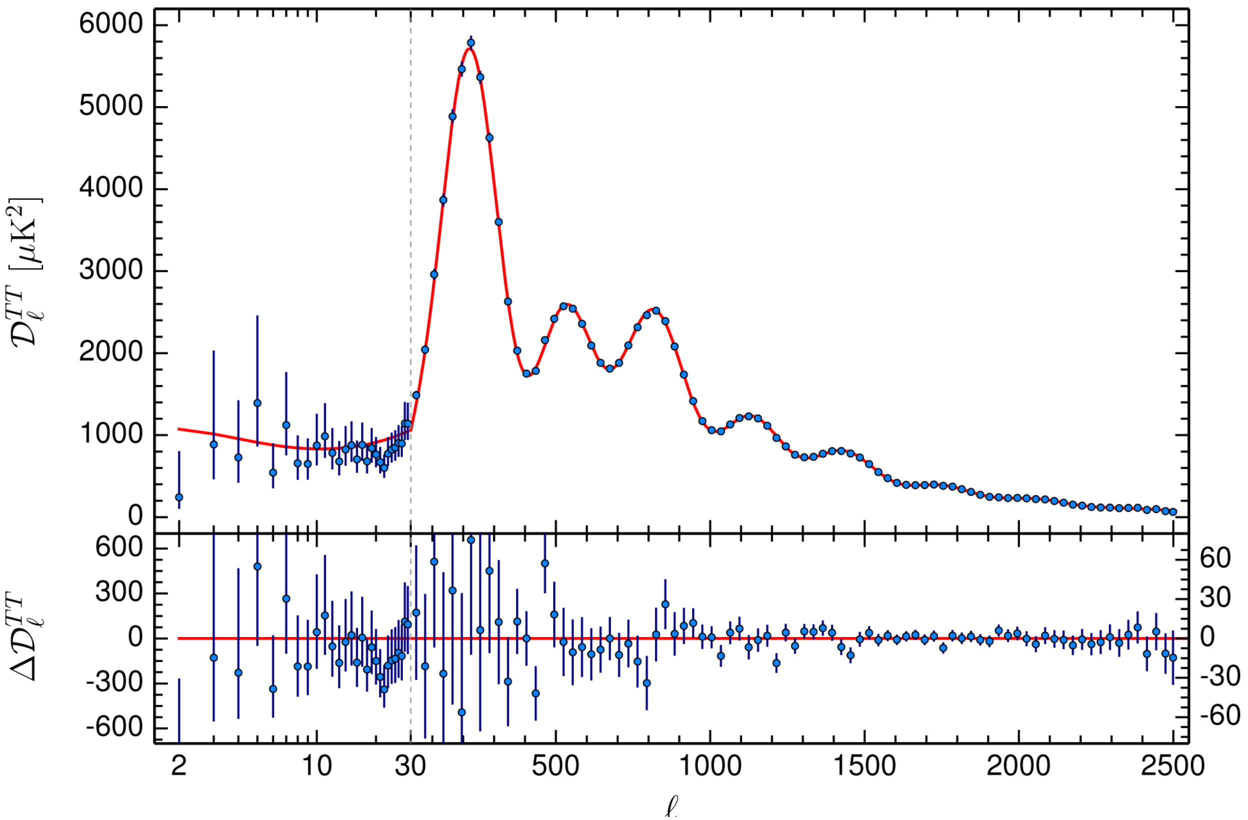
Cosmological parameters

- Primordial power spectrum of density fluctuations $P(k)=A_s k^{\wedge}(n_s-1)$
  A_s: amplitude of primordial power spectrum (scalar)
  n_s : spectral index (scalar)

- $r=A_t/A_s$ scalar to tensor ratio
- τ: optical depth at reionisation (fraction of CMB photons scattered during that process)

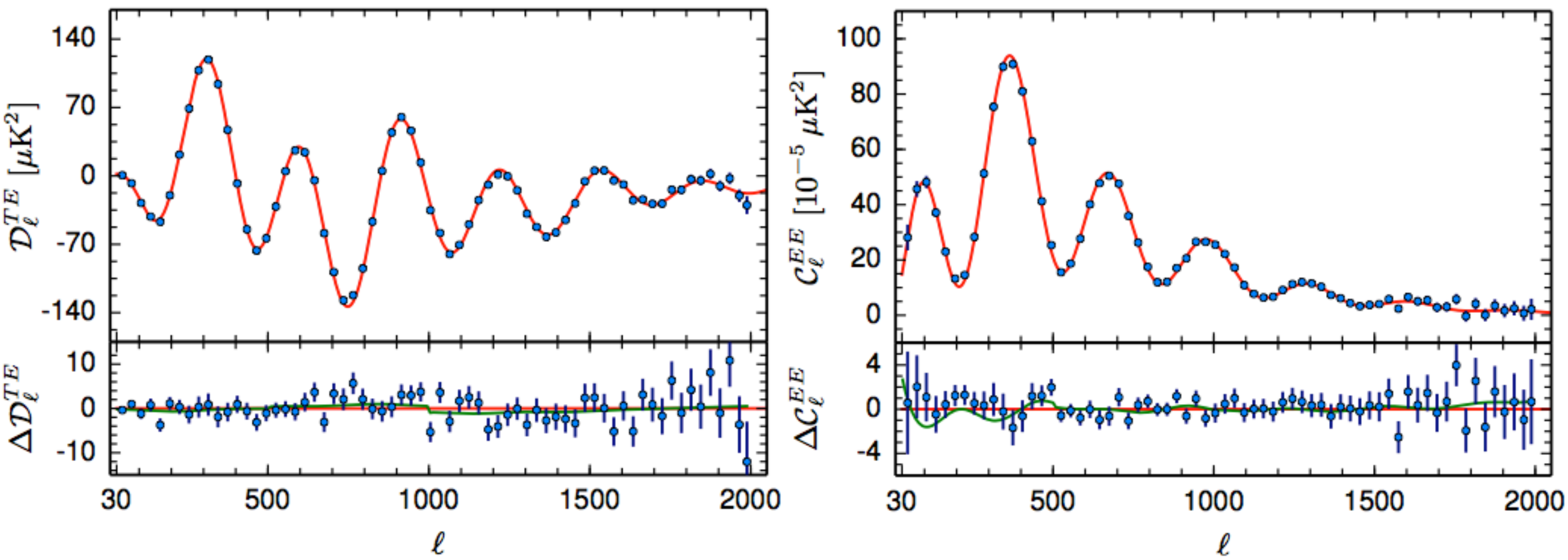
- For flat ΛCDM: $\Omega_k=0$, $r=0$
  6 parameters: $\{\Omega_b,\Omega_c,H_0,n_s,\tau,A_s\}$

CMB power spectrum: TT



Excellent fit to the standard flat ΛCDM model

CMB power spectrum: EE and TE



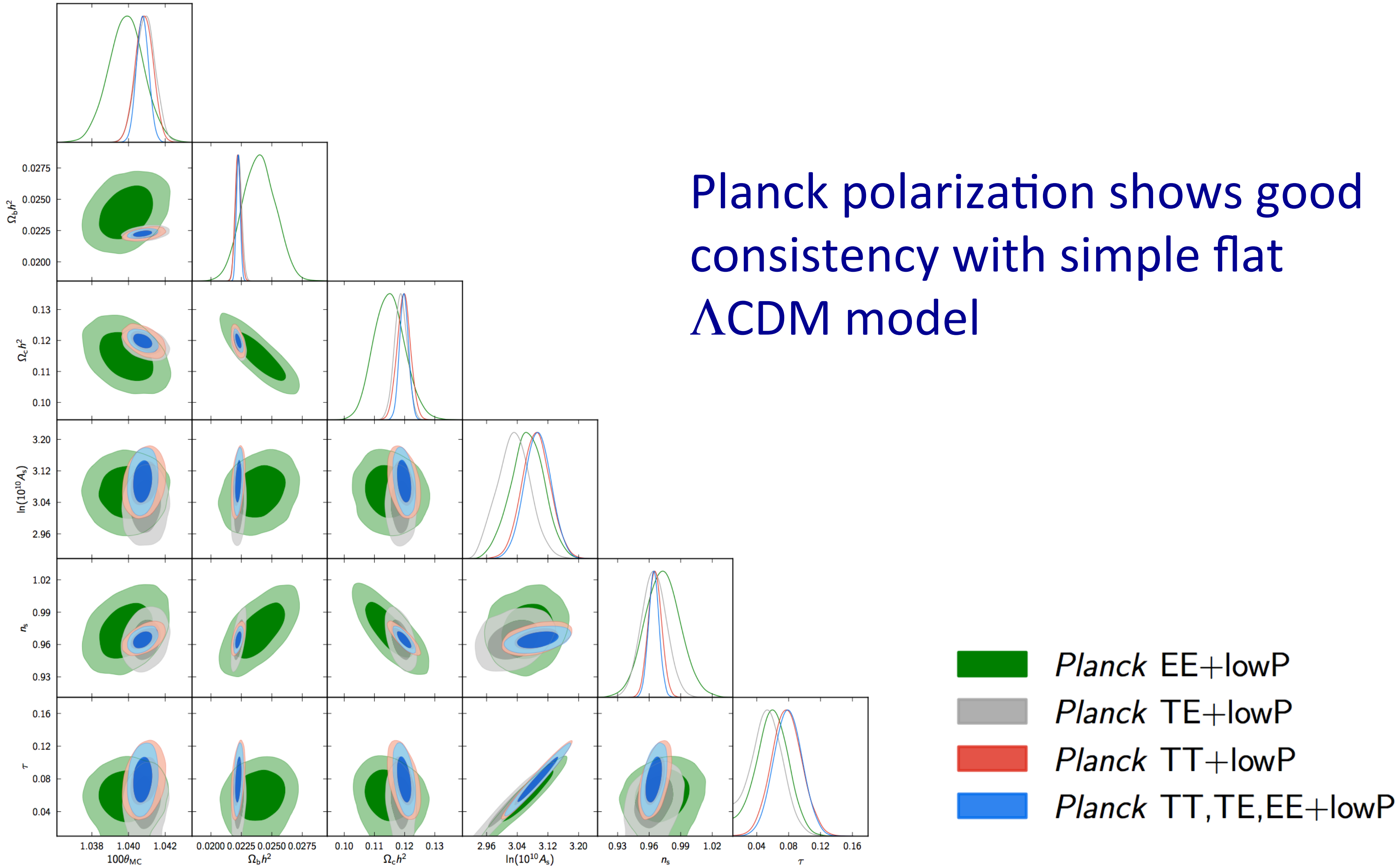
- The red line is not a fit to the data but corresponds to the best model derived from the TT power spectrum + polarization from low ℓ (from LFI)
- Systematics not well understood in polarization at large scales (HFI)
- Hints of systematics (at low level) in polarization ⇨ constraints using polarization should be taken with caution

Best fit model for flat ΛCDM model

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046
τ	0.078 ± 0.019	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060
H_0	67.31 ± 0.96	67.81 ± 0.92
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012
Ω_m	0.315 ± 0.013	0.308 ± 0.012

- Flat ΛCDM provides an excellent fit to Planck data
- No compelling evidence for extensions
- Percentage level precision on most parameters
- n_s significantly different from 1
- Reionization: τ significantly lower than before
  - WMAP: τ=0.089+/-0.014
- General good consistency between temperature, polarization and lensing results

Flat ΛCDM model: temperature vs polarization



Planck polarization shows good consistency with simple flat ΛCDM model

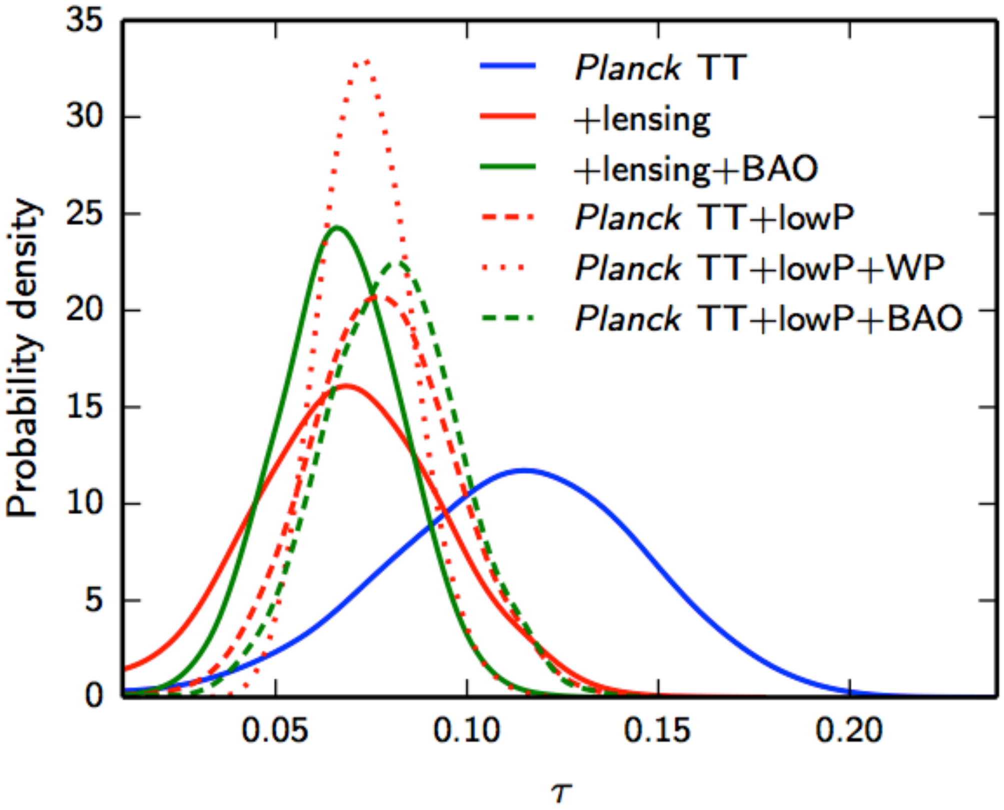
Reionization

- When the first stars forms, they ionised the universe
- The free electrons scattered the CMB photons in their way to us, which leaves imprints in the temperature and polarization power spectra
  - The earlier the first stars form, the stronger this effect
  - Measured through the optical depth τ, higher $\tau \Rightarrow$ earlier reionisation

- The previous analysis from WMAP implied that reionization occurred around ~420 millions years after the Big Bang (z_{re}~10.6)
- However, astrophysical surveys did not find enough luminous objects at sufficiently early times to support this timing → there did not seem to be enough objects during that era to reionize the universe

- Current value for Planck solves this problem, pushing the epoch of reionization to around ~560 millions years (z_{re}~8.8)

Reionization



WMAP: τ=0.089 ∓ 0.014

Planck TT + low P

τ=0.078∓0.019

Planck TT + lensing (independent of polarization)

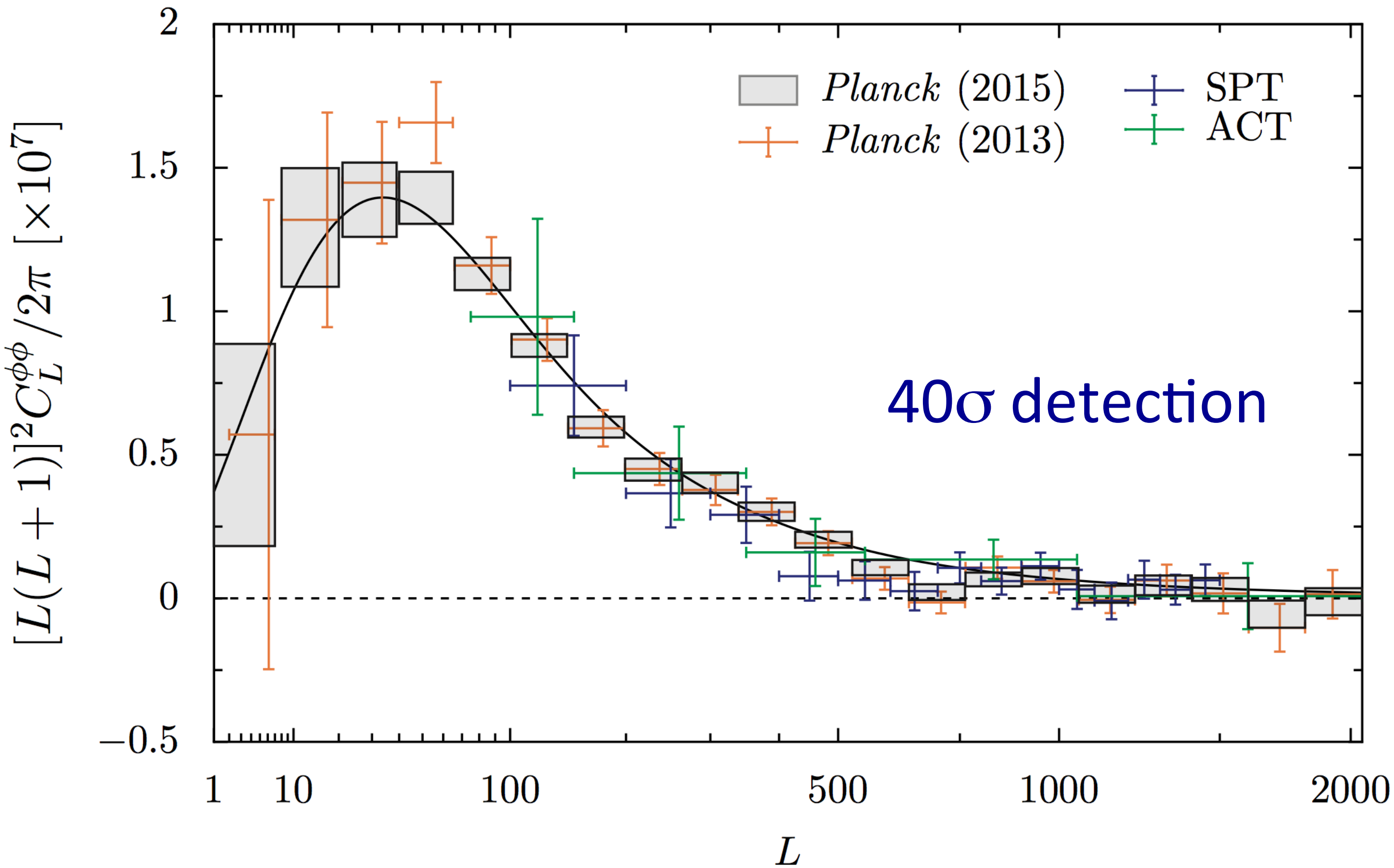
τ=0.079∓0.024

Planck TT + low P + lensing

τ=0.066∓0.016

WMAP (Galactic contamination cleaned with 353 GHz Planck channel): τ=0.075∓0.013

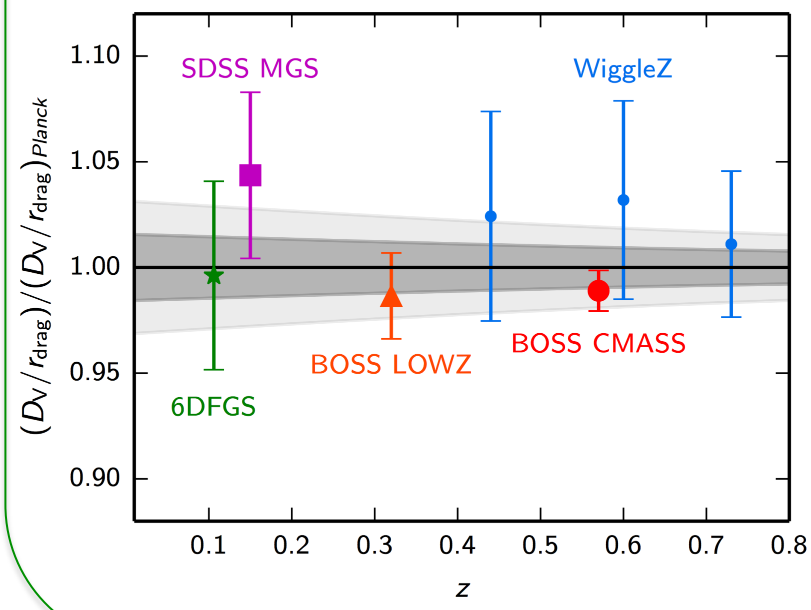
Consistency: CMB lensing



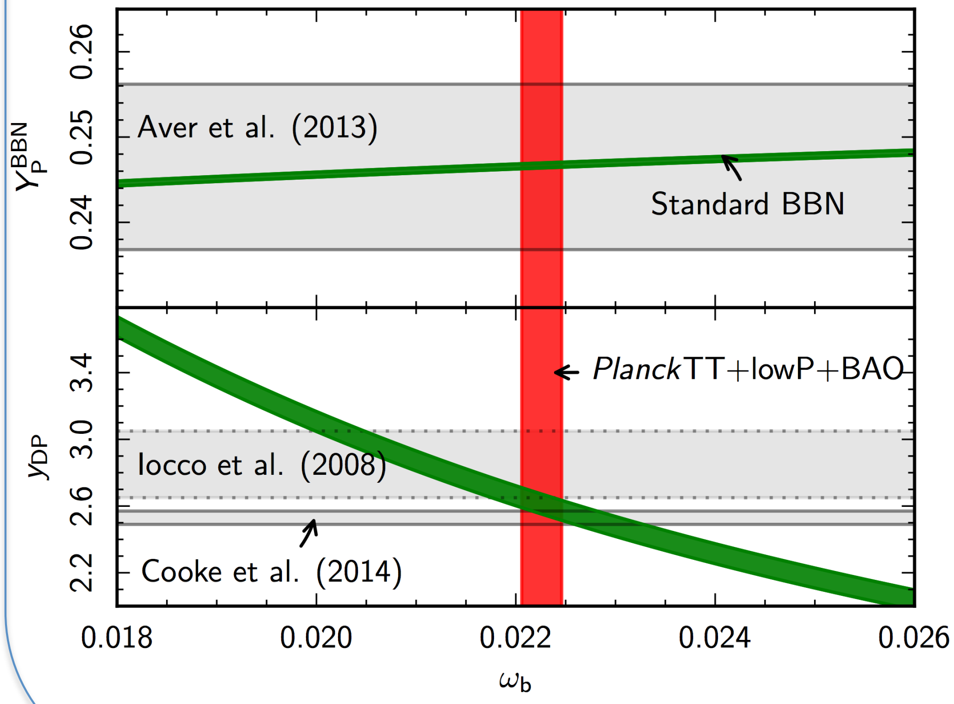
- The lensing potential is an integrated measure of the mass distribution back to the last scattering surface
- Generally good agreement with primary anisotropies results

Consistency with other data

BAO (Baryonic Acoustic Oscillations) : good



Good agreement with Big Bang Nucleosynthesis



Supernovae data

- Some tension between SN data and CMB in 2013 analysis
- Improved SN data: now consistent with CMB

Some tensions

Measurements of H_0

- Direct measurements find higher values of H_0 than CMB (or BAOs)
- Cepheid

  H_0=73.8∓2.4 (Riess et al. 2011)

  H_0=70.6∓3.3 (Efstathiou et al. 2014)
- CMB

  H_0= 67.8∓0.92 (TT+lowP +lensing)

Present-day matter fluctuations σ_8

Higher values inferred from CMB than from

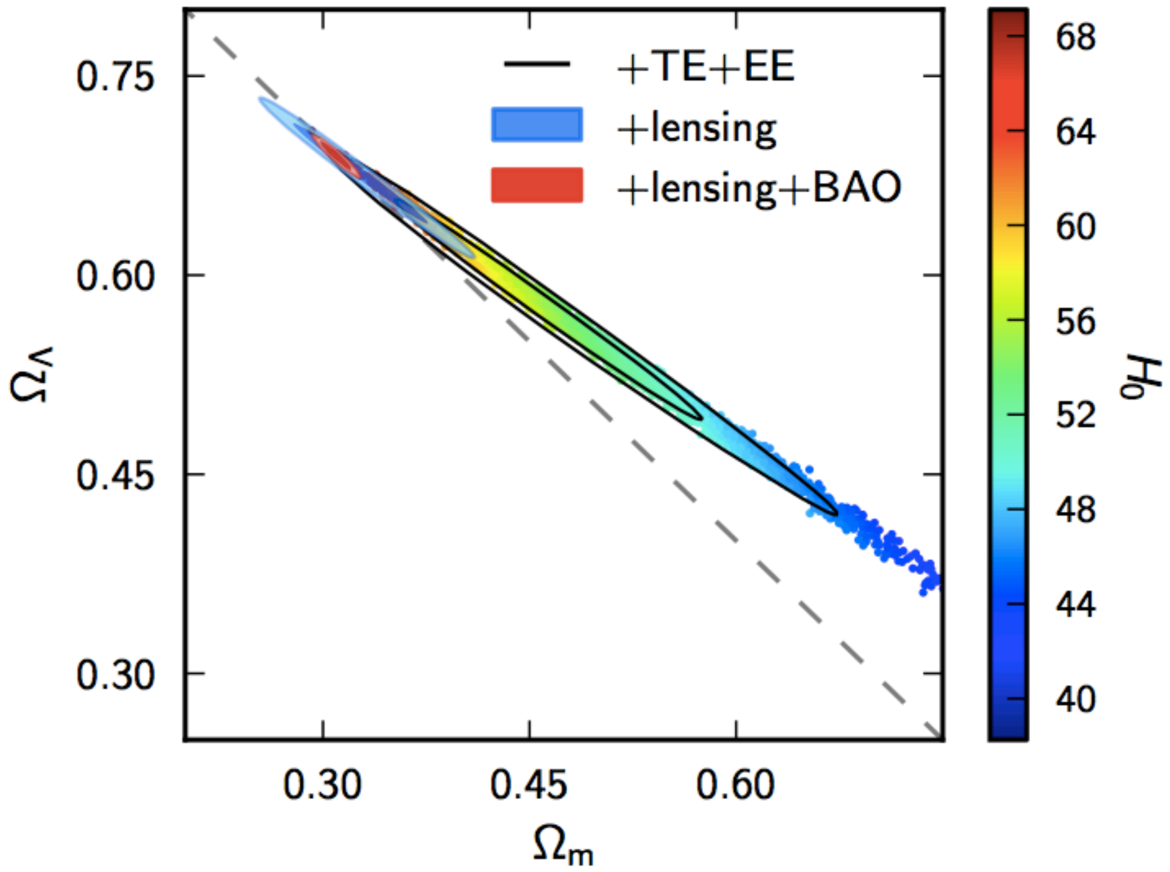
- Weak lensing
- Cluster counts

- Analysis and interpretation of this astrophysical data is complicated:
  - Systematics?
  - New physics?
- More work needs to be done

Extensions from ΛCDM: curvature

Impressive consistency with flat universe:

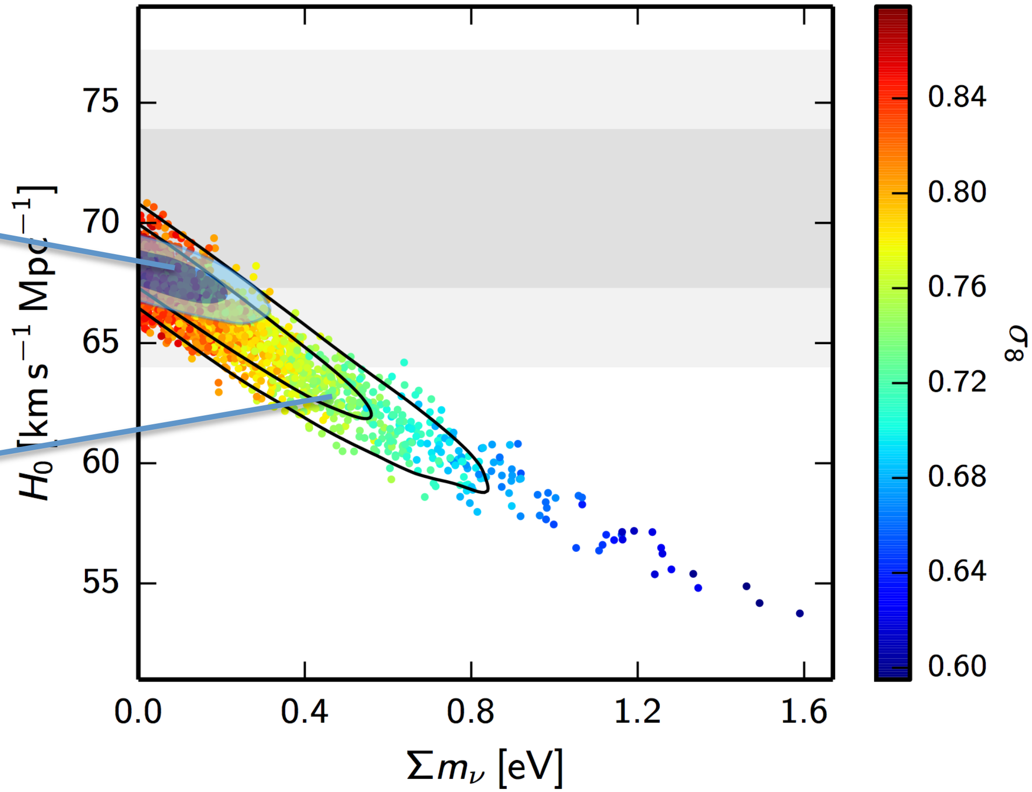
Ω_k=0.000±0.005 (95%, Planck TT+low P+lensing+BAO)



Extensions from ΛCDM: neutrino physics

Planck TT +low P +lensing +BAO

Planck TT +low P +lensing



$$\left.\begin{array}{r}\sum m_\nu < 0.23\ \mathrm{eV} \\ \Omega_\nu h^2 < 0.0025\end{array}\right\}\ 95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}ext.}$$

$$N_{\mathrm{eff}} = 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}$$

No evidence for new neutrino physics

More extensions from ΛCDM

- No evidence for tensor modes
  - $r < 0.11$ (95%) Planck TT + low P + lensing + ext
- No evidence of running of the spectral index of primordial fluctuations
- Isocurvature modes strongly constrained
  - Less than ~3% of the adiabatic modes
- Dark energy
  - Consistent with a cosmological constant ($w=p/\rho=-1$)
- No detection of topological defects
- No evidence of dark matter annihilation

None of the considered extensions can alleviate the tensions found with certain astrophysical data

The 6-parameter ΛCDM model provides an excellent match to the Planck data

Inflation and Planck

The simplest models of inflation predict:

A spatially flat Universe	Ω_K=0.000 ± 0.0025
with *nearly* scale-invariant (red) spectrum of density perturbations	0.968 ± 0.006
which is almost a power-law	$dn_s/d\ln k$ = -0.0065 ± 0.0076
dominated by scalar perturbations	$r_{0.002}$<0.09 (95%)
which are Gaussian	f_{NL} = 2.5 ± 5.7
and adiabatic	β_{iso} < 3% (95%)
with negligible topological defects	f_{10} < 0.04 ($G\mu/c^2 < 10^{-7} - 10^{-6}$)

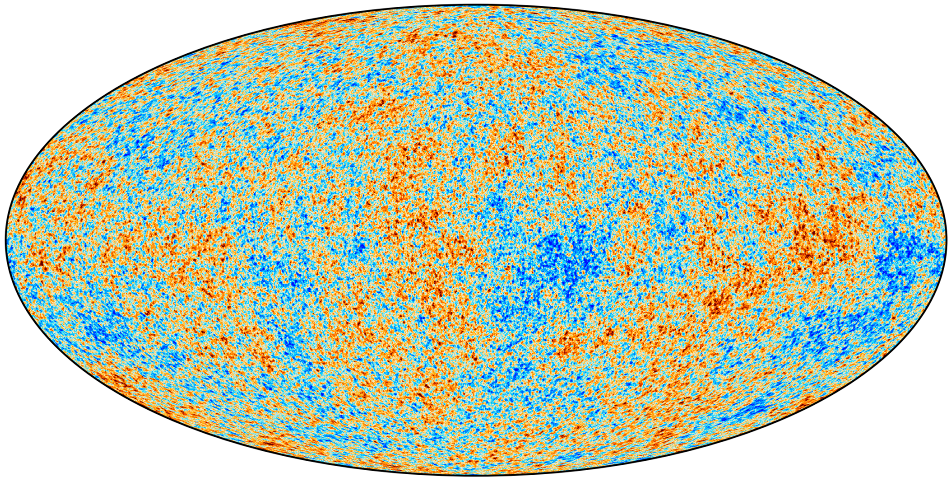
And a background of primordial gravitational waves… not detected yet

[Table from Martin White]

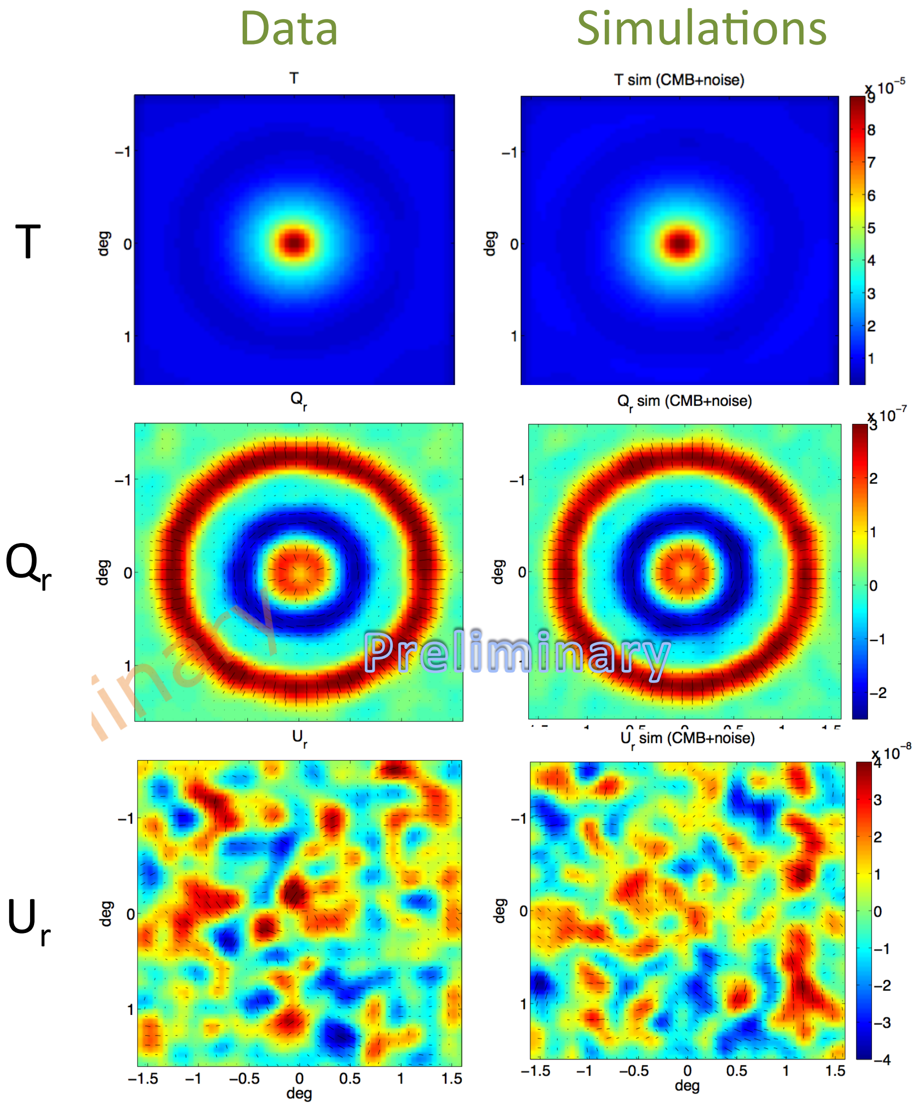
Isotropy and statistics

- Analyses based on clean CMB maps (not on power spectrum)
- In general, no deviations of the CMB from Gaussianity or isotropy found using a battery of (generic) tests:
  - Skewness, kurtosis
  - N-point distribution function
  - Minkowski functionals
  - Stacking of fluctuations

  …



Stacking in polarization

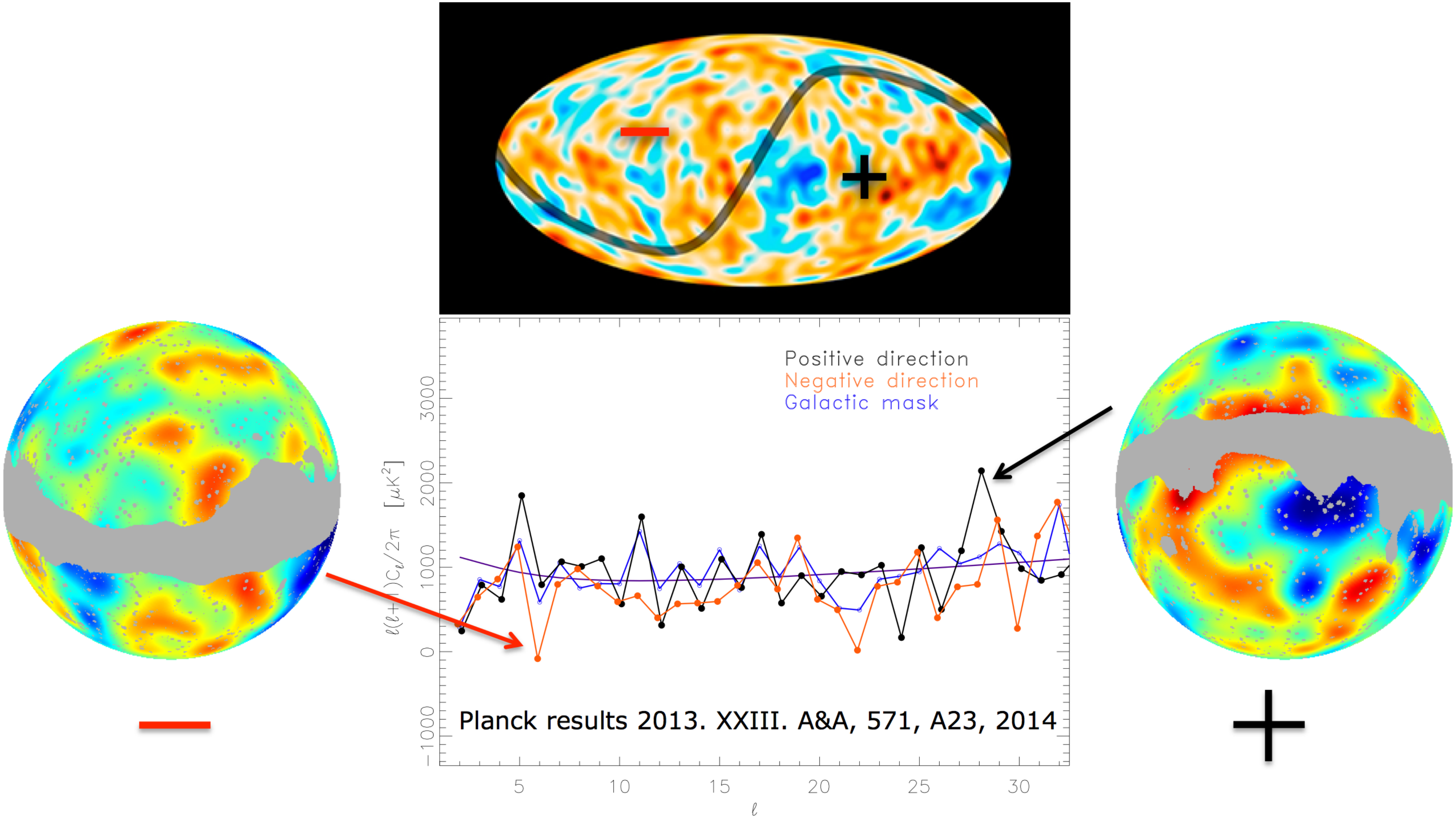


- Polarization is a very weak signal, maps have low signal to noise ratio.
- Not possible to see pattern in individual spots
- Use stacking: superimpose regions of the sky selected to have a hot (or cold) spot in intensity
- The stacking in polarization probes degrees angular scales and shows good consistency with Gaussianity

Anomalies

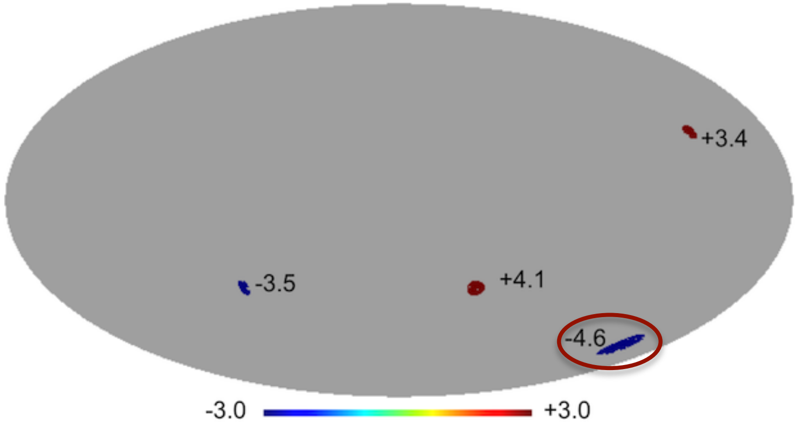
- However, some large scale anomalies, most of them found originally in WMAP, are present in Planck data, including:
  - Power asymmetry between hemispheres
  - Deficit of power at low multipoles
  - Dipolar modulation of the sky
  - Variance lower than expected from the best-fit model
  - A large and cold spot in the southern hemisphere
- The fact that the anomalies have been seen by two independent instruments increases confidence of these detections as real sky signals
- The origin of anomalies is uncertain
  - Foregrounds? Secondary anisotropies from our local universe? Anisotropic models of the Universe? Cosmic defects?

Power asymmetry



[Figure from G. Polenta]

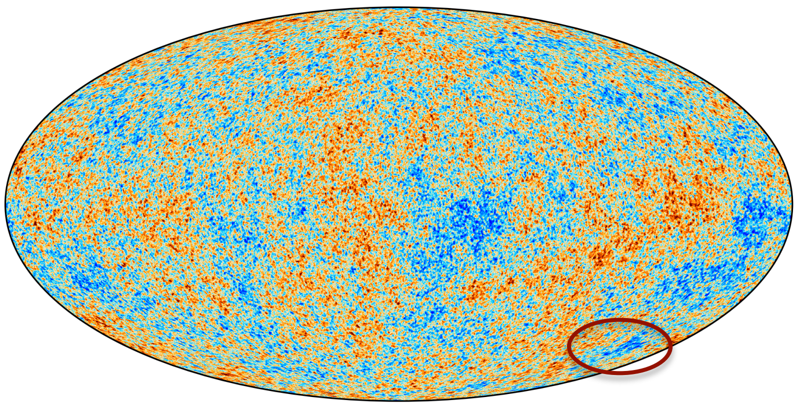
The Cold Spot



Pixels about 3σ in map filtered with the SMHW at R=300'

- Very large cold spot detected when filtering the map at large scales
- Probability of finding such a spot (obtained from simulations) is 0.3%

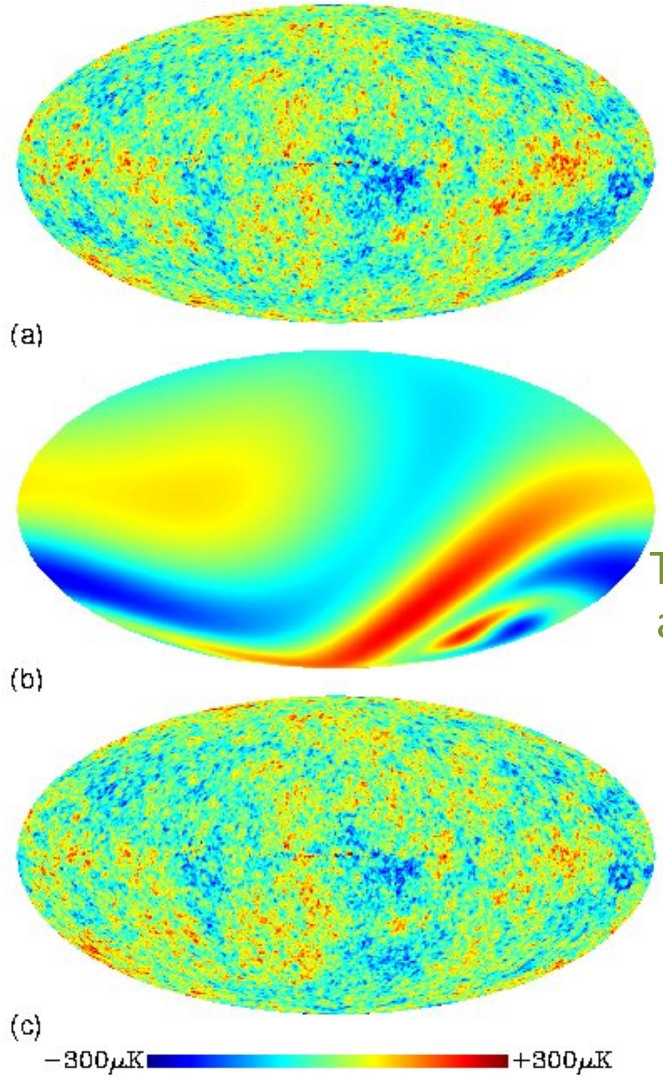
Area	Scale [′]	UTP C-R	UTP NILC	UTP SEVEM	UTP SMICA
Cold	200	1.6	1.1	1.2	1.1
	250	0.3	0.3	0.3	0.3
	300	0.3	0.3	0.3	0.3
Hot	200	2.3	1.6	1.8	1.6
	250	2.7	2.2	2.4	2.2
	300	4.9	3.7	4.1	3.8



A possible explanation: signature from a cosmic texture (not confirmed yet)

Planck 2013 results. XXIII

A curiosity: fit to an anisotropic model of the universe



WMAP data

Template(x4) from anisotropic model

WMAP data - template

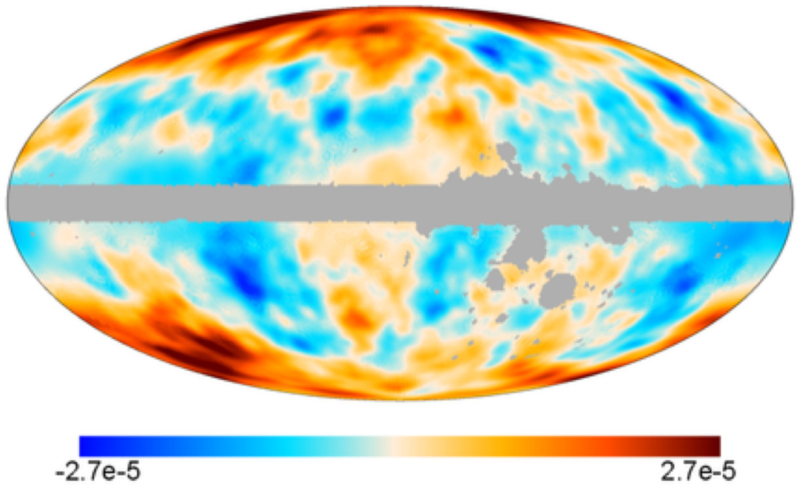
- WMAP data fitted to a an anisotropic model of the universe of Bianchi type VII_h
- Removing the template, reduces the power asymmetry and the cold spot
- Unfortunately, not consistent with best-fit cosmological parameters (Ω=0.5)
- Model also disfavoured by Planck data

Jaffe et al. 2005

ISW effect: cross-correlation with surveys and signal reconstruction

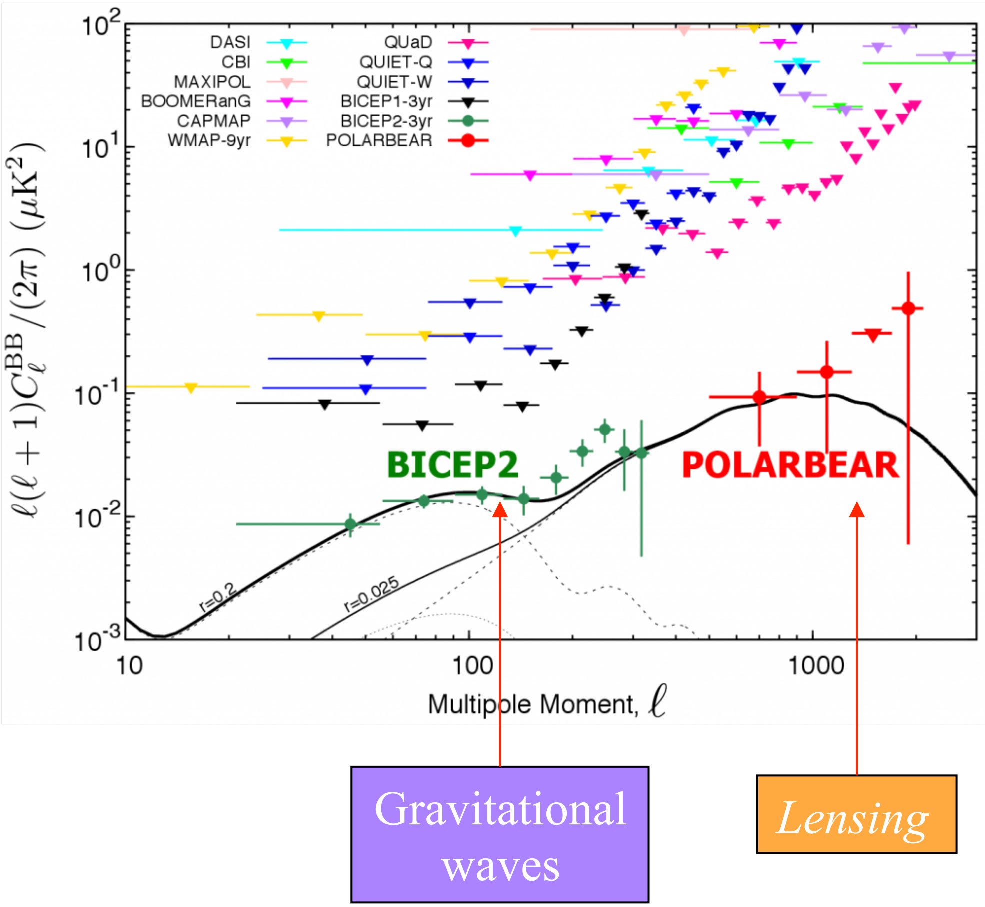
LSS data	SEVEM		Expected
	$A \pm \sigma_A$	S/N	S/N
NVSS	0.95 ± 0.36	2.62	2.78
WISE-AGN ($\ell_{\rm min} \geq 9$)	0.95 ± 0.60	1.58	1.67
WISE-GAL ($\ell_{\rm min} \geq 9$)	0.74 ± 0.53	1.38	1.89
SDSS-CMASS/LOWZ	1.37 ± 0.56	2.43	1.79
SDSS-MphG	1.61 ± 0.68	2.36	1.47
Kappa ($\ell_{\rm min} \geq 8$)	1.05 ± 0.33	3.17	3.03
NVSS and Kappa	1.05 ± 0.28	3.81	3.57
WISE	0.84 ± 0.45	1.88	2.22
SDSS	1.50 ± 0.55	2.74	1.82
NVSS and WISE and SDSS	0.89 ± 0.31	2.87	3.22
All	1.00 ± 0.25	4.00	4.00

Signal detected at 4σ as expected from ΛCDM



Reconstruction of ISW from all surveys (correlation with true signal ~0.67)

The quest for the primordial gravitational background



BICEP Collaboration 2014

BICEP2 (March 2014)

It observes a region of the sky of 380 squared degrees @ 150 GHz with high-sensitivity

$r=0.20^{+0.07}_{-0.05}$ (68% CL)

Constraint from Planck 2013 + other CMB experiments (flat ΛCDM)

$r < 0.11$ (95% CL)

¿Was the B-mode really detected?

- Galactic contamination?

- Only one frequency available
- Large uncertainty in level of foreground contamination

- Model extension?

$r<0.26$ (95% CL) Planck

BICEP2: data

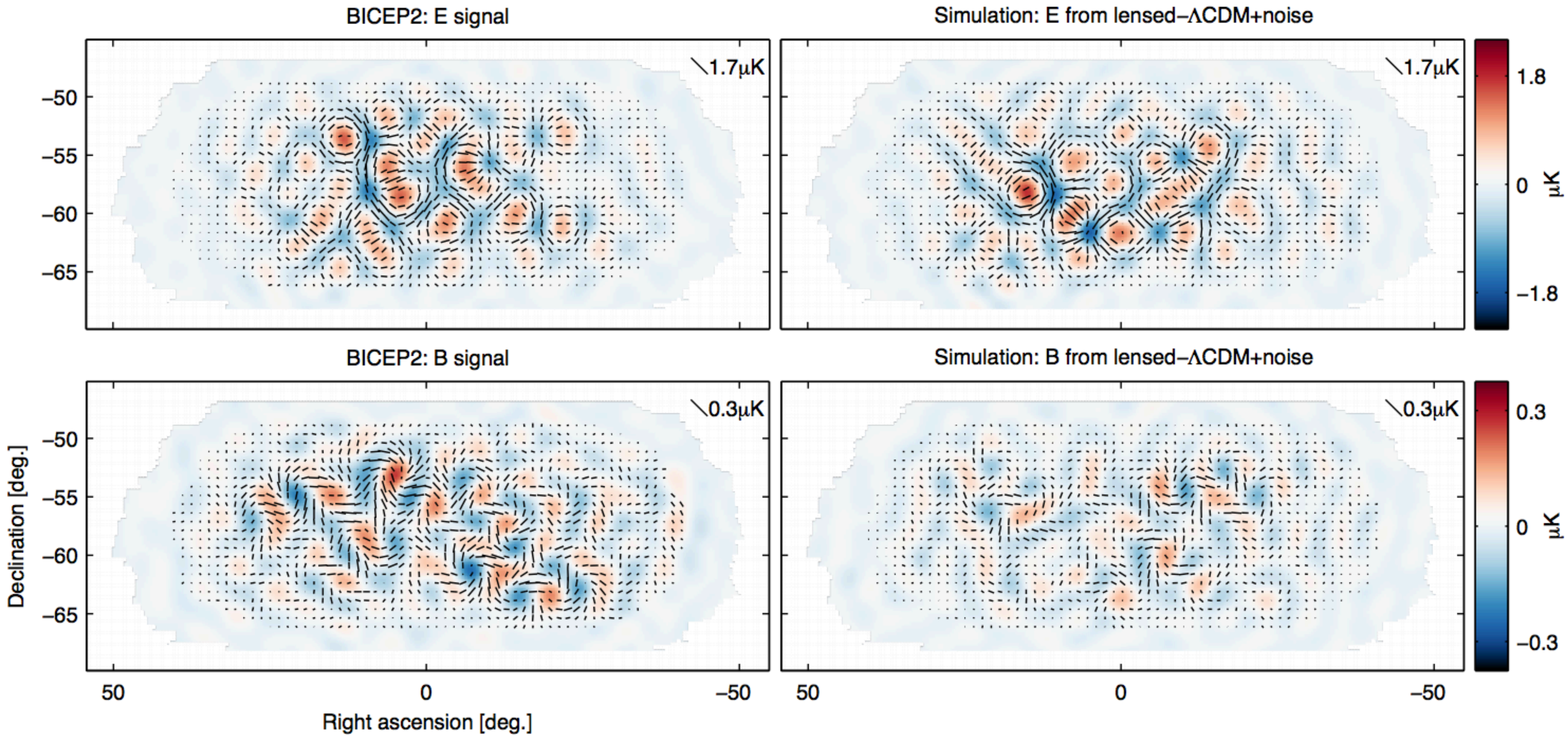
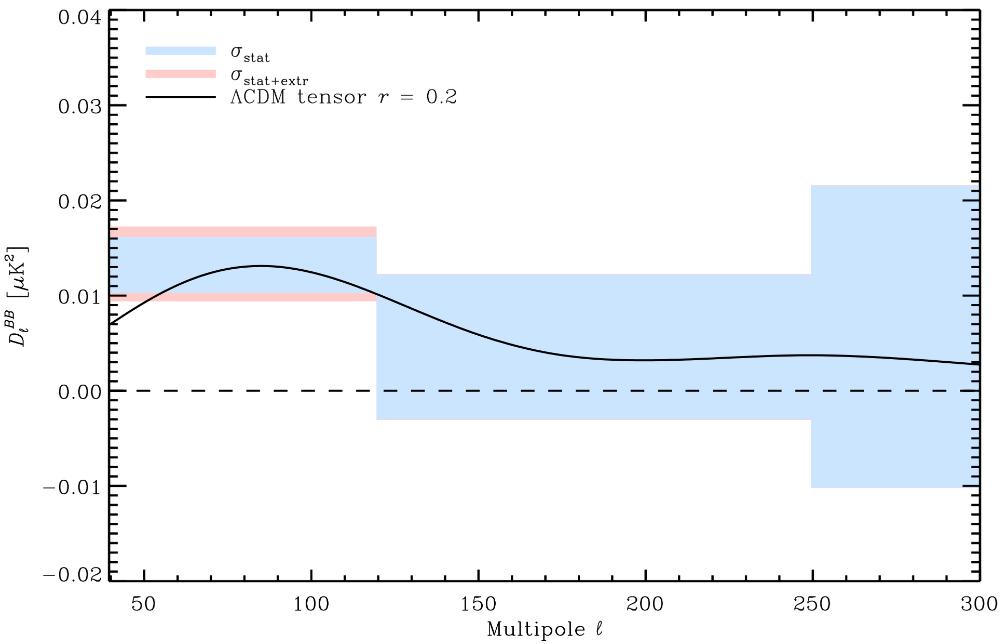


FIG. 3.— *Left:* BICEP2 apodized E-mode and B-mode maps filtered to $50 < \ell < 120$. *Right:* The equivalent maps for the first of the lensed-ΛCDM+noise simulations. The color scale displays the E-mode scalar and B-mode pseudoscalar patterns while the lines display the equivalent magnitude and orientation of linear polarization. Note that excess B-mode is detected over lensing+noise with high signal-to-noise ratio in the map ($s/n > 2$ per map mode at $\ell \approx 70$). (Also note that the E-mode and B-mode maps use different color/length scales.)

BICEP Collaboration 2014

Dust polarization from Planck

- Using Planck multifrequency observations, it is found that the dust polarised emission follows a modified blackbody spectrum with T_d=19.6 and β_d=1.59
- The Planck 353 GHz channel is dominated by dust, extrapolating to BICEP2 frequency → find a contribution from dust similar to the BICEP2 signal
- However, uncertainties are large → needs joint Planck+BICEP2 analysis

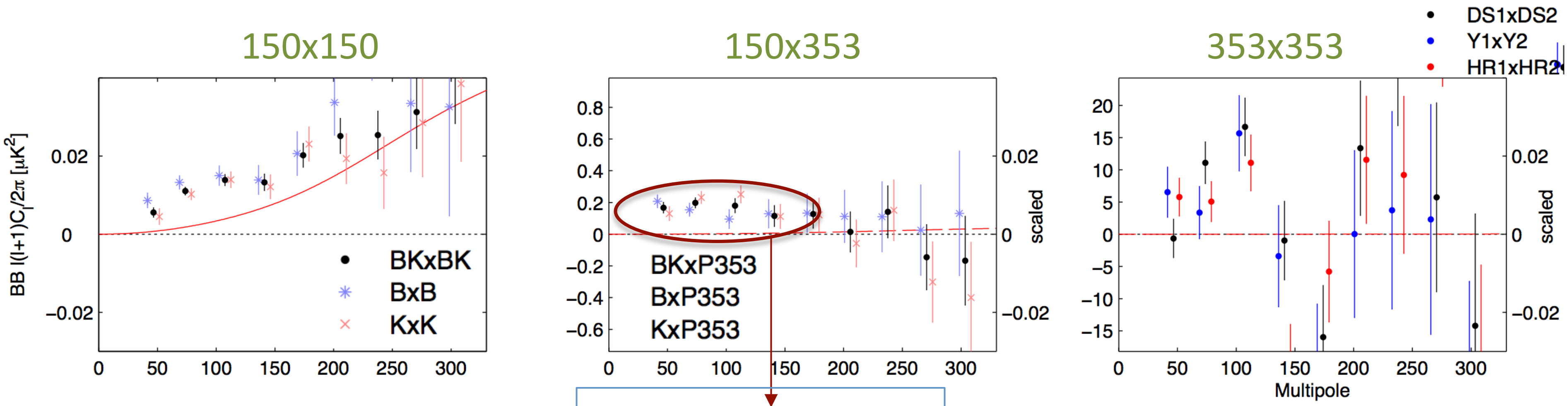


Planck prediction of dust contribution at 150 GHz in a region similar to BICEP2

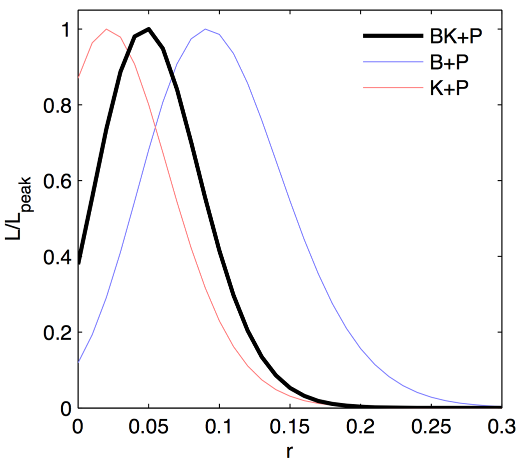
Joint Planck + Keck/BICEP2 analysis

Planck + BICEP2 + additional data from Keck Array (same region of the sky, same frequency)

150x150 | 150x353 | 353x353



Significant cross-correlation detected



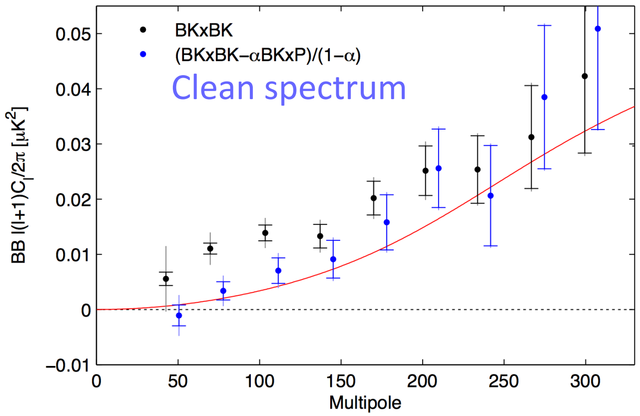
No GWB detection !!

$r_{0.05}$<0.12 (95 %)

BICEP2 signal was significantly contributed by dust

Constraint from Planck TT+BK + other astrohpysical data

$r_{0.002}$<0.09 (95%)

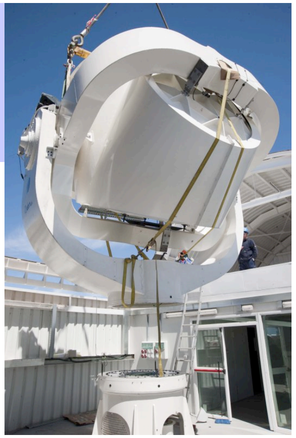


Polarization experiments

Name	Platform	Area [deg^2]	FWHM	Freq [GHz]	Detectors	r_{lim}	Starts
BICEP	Ground	800	~1°	100,150	PSB bolom.	0.1	2010
QUIET-II	Ground	1600	4'-30'	40, 90	MMIC HEMT	0.01	2010
QUIJOTE	Ground	5000	~1°	10-40	MMIC HEMT	0.05	2012
PolarBear	Ground	1200	3'-7'	90,150, 220	TES bolom	0.01	2012
QUBIC	Ground	800	~1°	90,150,220	Bol interf	0.01	2014
ACTPol	Ground	4000	~1'	150,218,277	Bolometer	0.03?	2013
SPTPol	Ground	500	1'-1.6'	100,150,220	TES Bolom.	0.03	2013
EBEX	Balloon	350	8'	150,250,350,450	TES bolom	0.03	2012
SPIDER	Balloon	24000	17'-50'	90,145,280	TES bolom	0.03	2013
LSPE	Balloon	9500	30'	40-250GHz	Bolo+HEMTs	0.03	2015
Planck	Satellite	Full sky	5'-33'	30-353	MMIC/Bol	0.05	2009
LiteBIRD	Satellite	Full sky	30'	50-270	TES bol	0.001	2020
PIXIE	Satellite	Full sky	1.6°	30-6000	Bolometers	0.001	2018 ?
PRISM	Satellite	Full sky	17'-5"	30-6000	Bolometers	0.0005	2028 ?
EPIC/ CMBPol	Satellite	Full sky	~10'	30-300	Bolometers	0.001	2025 ?

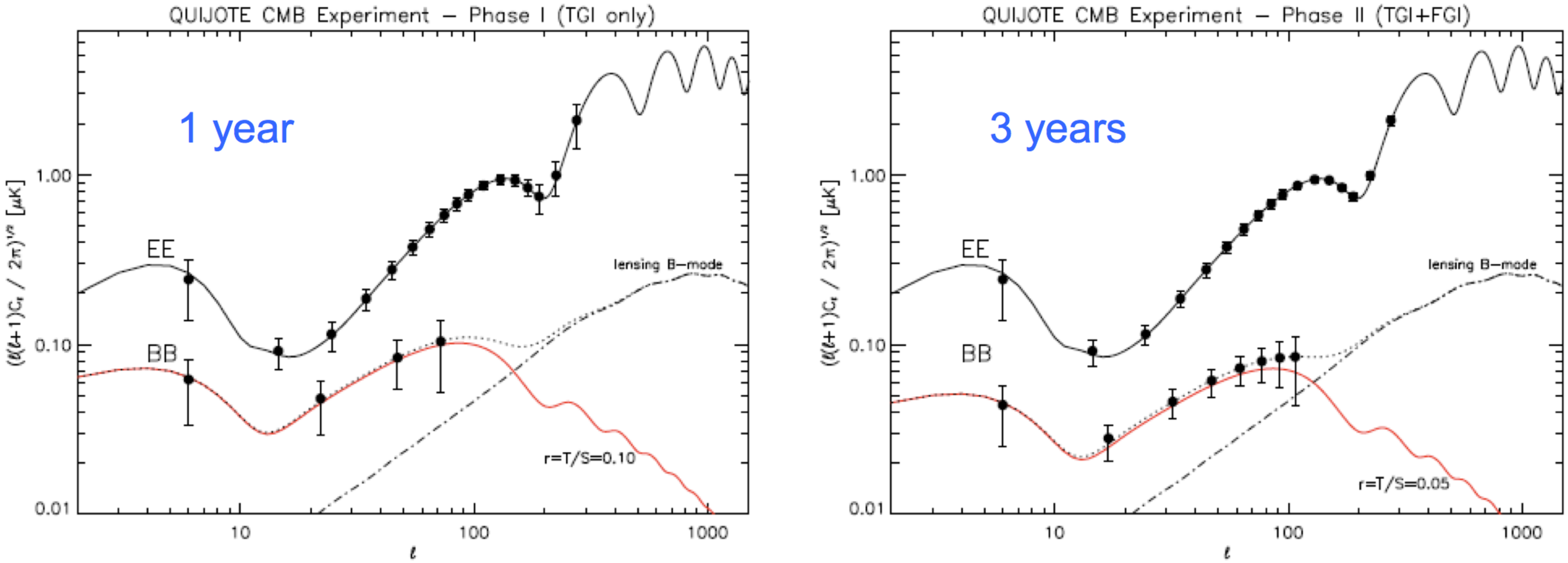
[Compilation from J.A. Rubiño-Martín (2013)]

The QUIJOTE experiment



- QUIJOTE Consortium
  - Instituto de Astrofísica de Canarias
  - Instituto de Física de Cantabria (CSIC-Univ. Cantabria)
  - DICOM (Univ. Cantabria)
  - Univ. of Manchester
  - Univ. of Cambridge
  - IDOM
- Three instruments
  - MFI, operating at 11, 13, 17 y 19 GHz (taking data since 2012)
  - TFI, at 30 GHz (to start operations in 2015)
  - FFI, at 40 GHz (on construction)
- Main goals
  - To detect the primordial B-mode (if r>0.05)
  - To improve our knowledge of Galactic polarised foregrounds at low frequency
- Unique frequency coverage
- Perfect complement for Planck low frequency channels

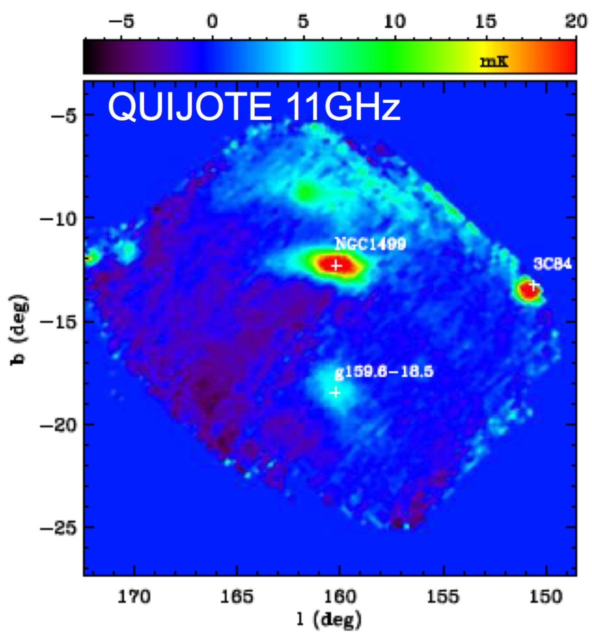
The QUIJOTE experiment

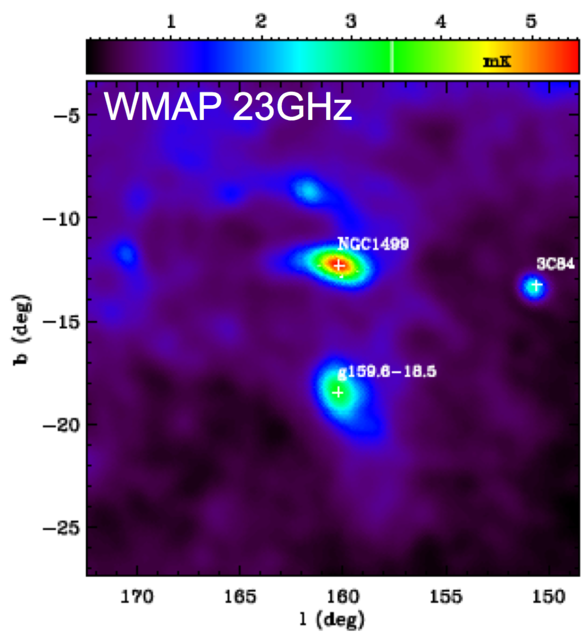


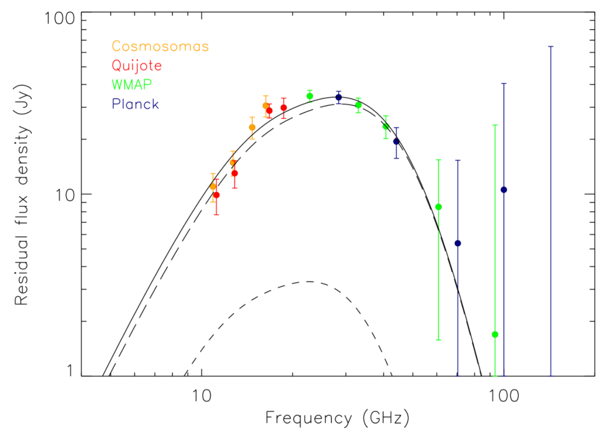
Left: Example of the QUIJOTE scientific goal after the Phase I: <u>1 year (effective)</u> observing time, and a sky coverage of 3,000 deg^2. The red line corresponds to r = 0.1.
Right: QUIJOTE Phase II. Here we consider <u>3 years of effective operations</u> with the TGI, and that during the last 2 years, the FGI will be also operative. The red line now corresponds to r = 0.05.

QUIJOTE: first scientific results

- Study of the anomalous microwave emission (AME) in the region of Perseus
- First constraints on AME polarization at 11-19 GHz frequencies







Spectrum of AME

Génova-Santos et al. 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.