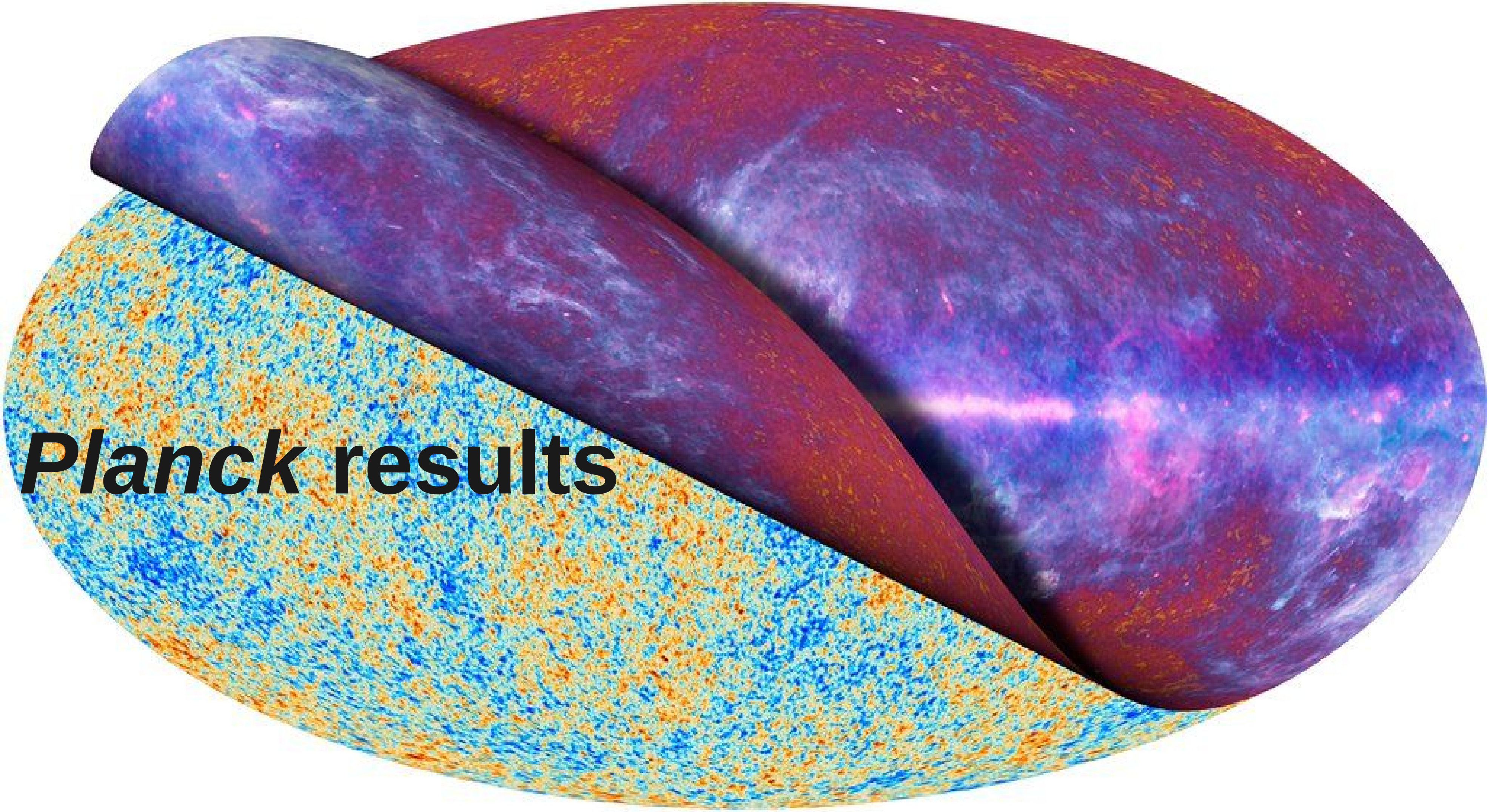


Planck results

Nabila Aghanim
Institut d'Astrophysique Spatiale, CNRS-Univ. Paris Sud
on behalf of the *Planck* collaboration

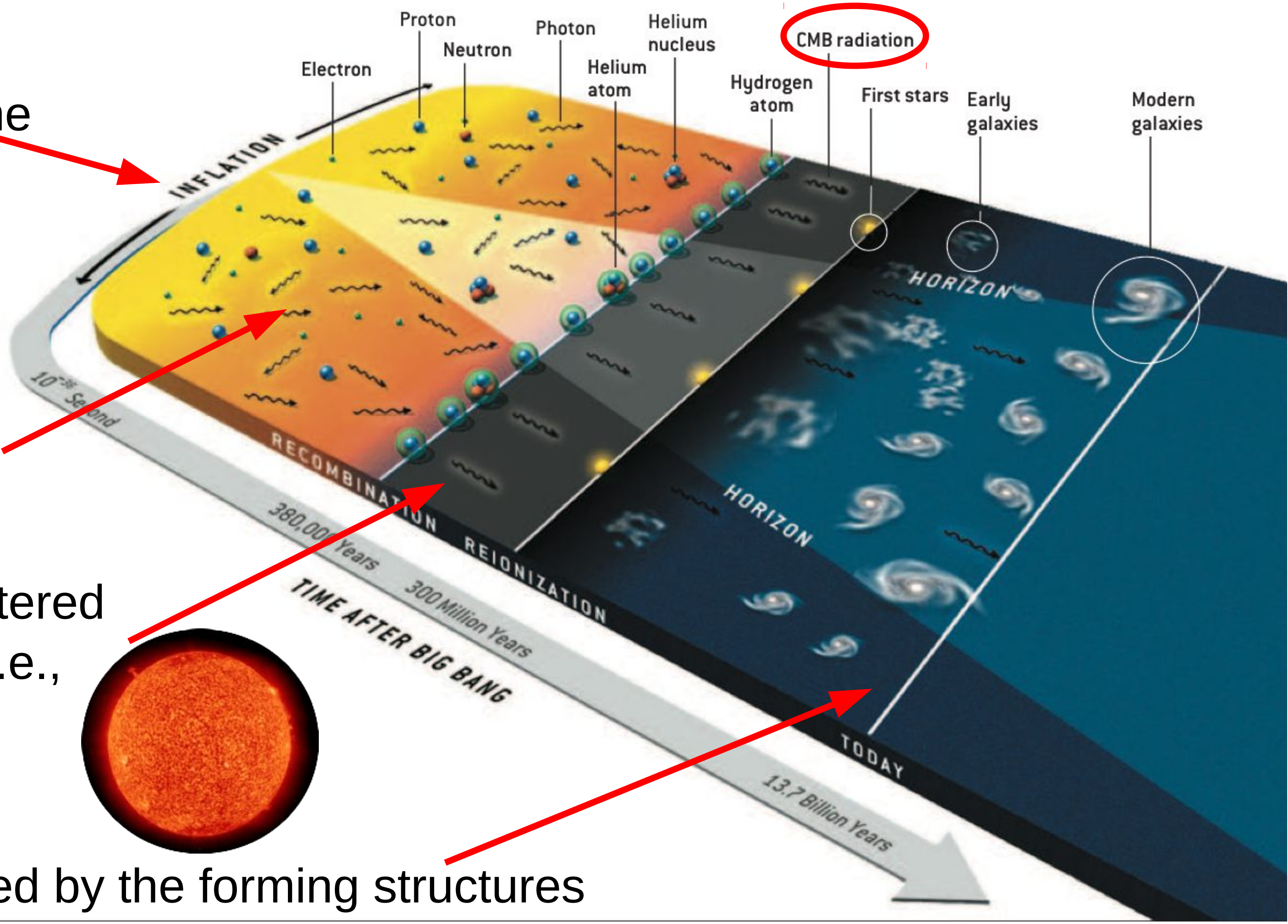
March 2013 (20 years after the first proposal): *Planck*'s first cosmological results

CMB offers a view of the whole universe through space and time

Information about the early universe

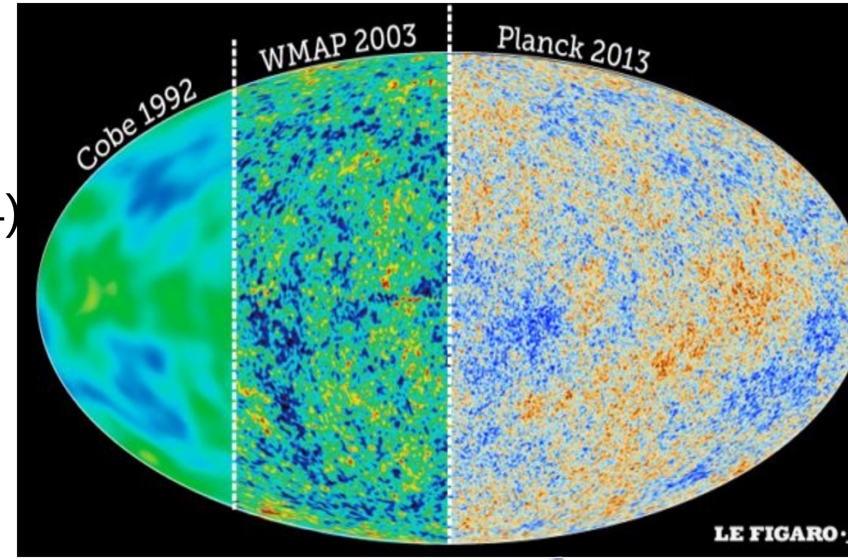
Through photons produced here

Then photons scattered at recombination (i.e., photosphere of universe)



Photons altered by the forming structures observed today

Measuring the CMB anisotropies



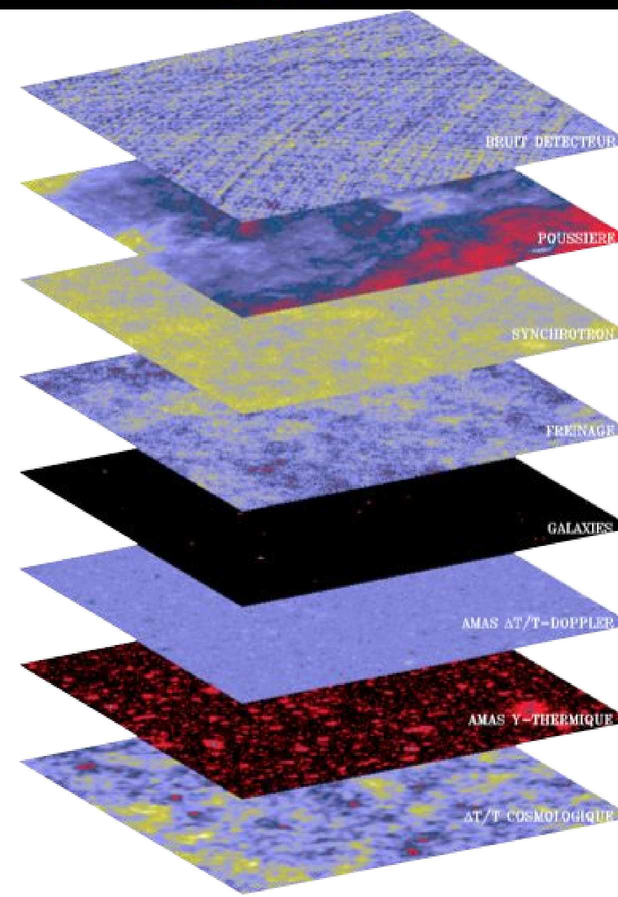
First two generations of space missions

→COBE : CMB spectrum (1992),anisotropy at ~10^0 (1994)

→WMAP : CMB anisotropies down to 12' (2003-2012)

Ultimate measurements of CMB temperature anisotropies & best polarisation measurements with available technology

- full sky coverage & good angular resolution *(~5')*
- high sensitivity: *limited by ability to remove astrophysical foregrounds*
- CMB and foreground channels



Two instruments proposed to ESA in 1993 for CMB anisotropy measurement

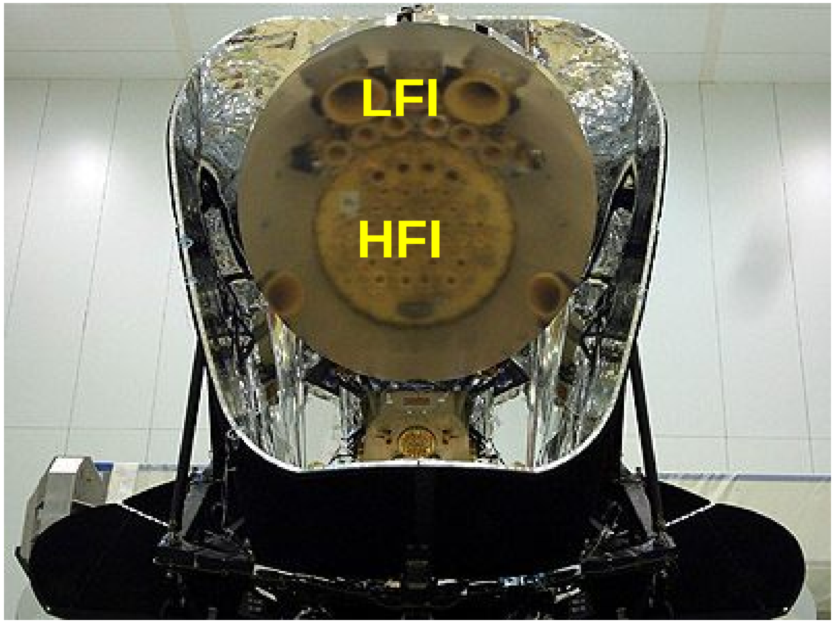
Selected by ESA in 1996 as **COBRAS** (aka *Planck*-LFI) **/ SAMBA** (aka *Planck*-HFI)

20 years of efforts, 17 countries & ~100 institutions, ~600 people

including ~300 researchers

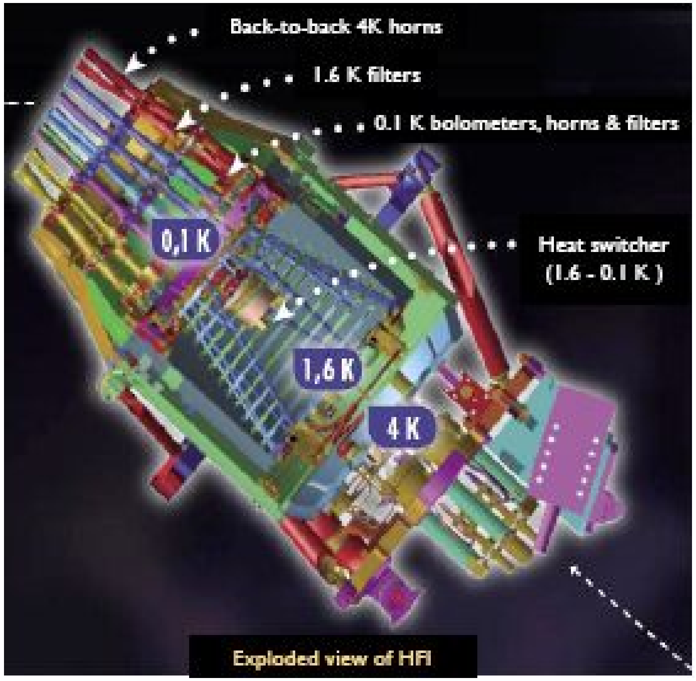
~7 cents/european/year (during 20 years)

- Two instruments on board *Planck*
  - LFI (P.I. N. Mandolesi): 22 radiometers
  - HFI (P.I. *J.-L. Puget*, IAS): 56 sensitive/fast bolometers
- Complex cryogenic chain: 5 stages including 0.1K dilution cooler
- 3 (LFI) & 6 (HFI) channels 30-857GHz
- Polarisation from 30-353GHz channels

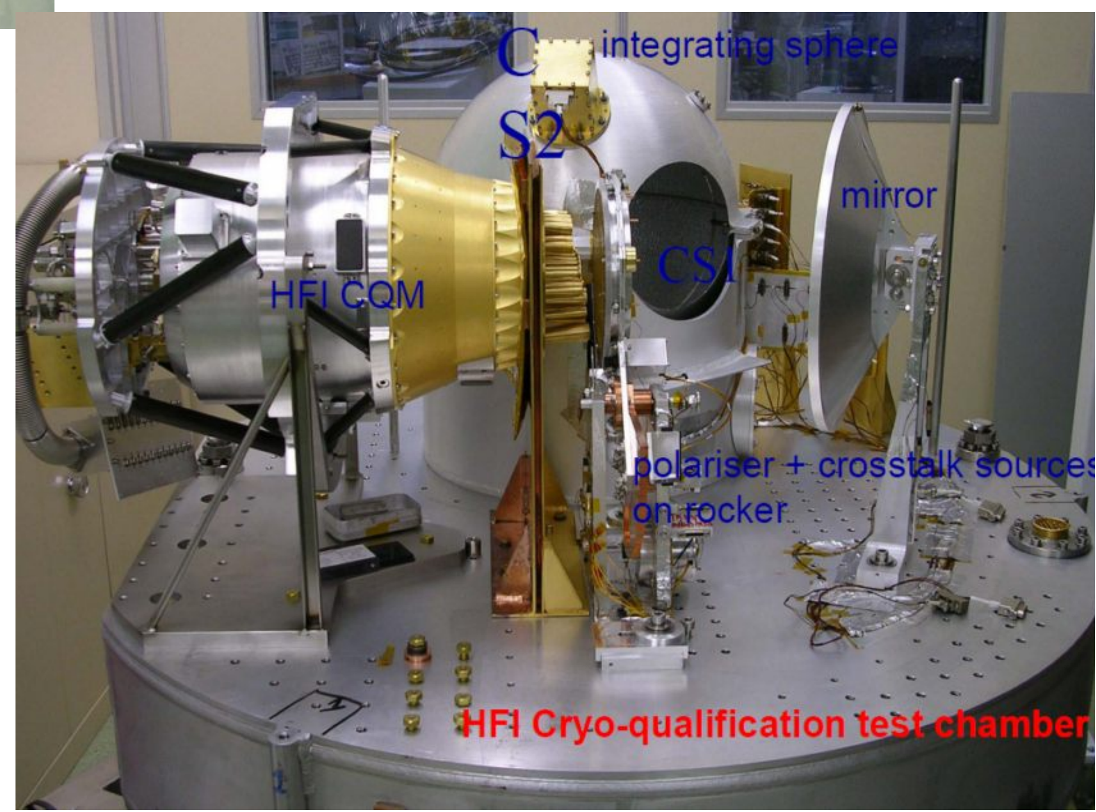


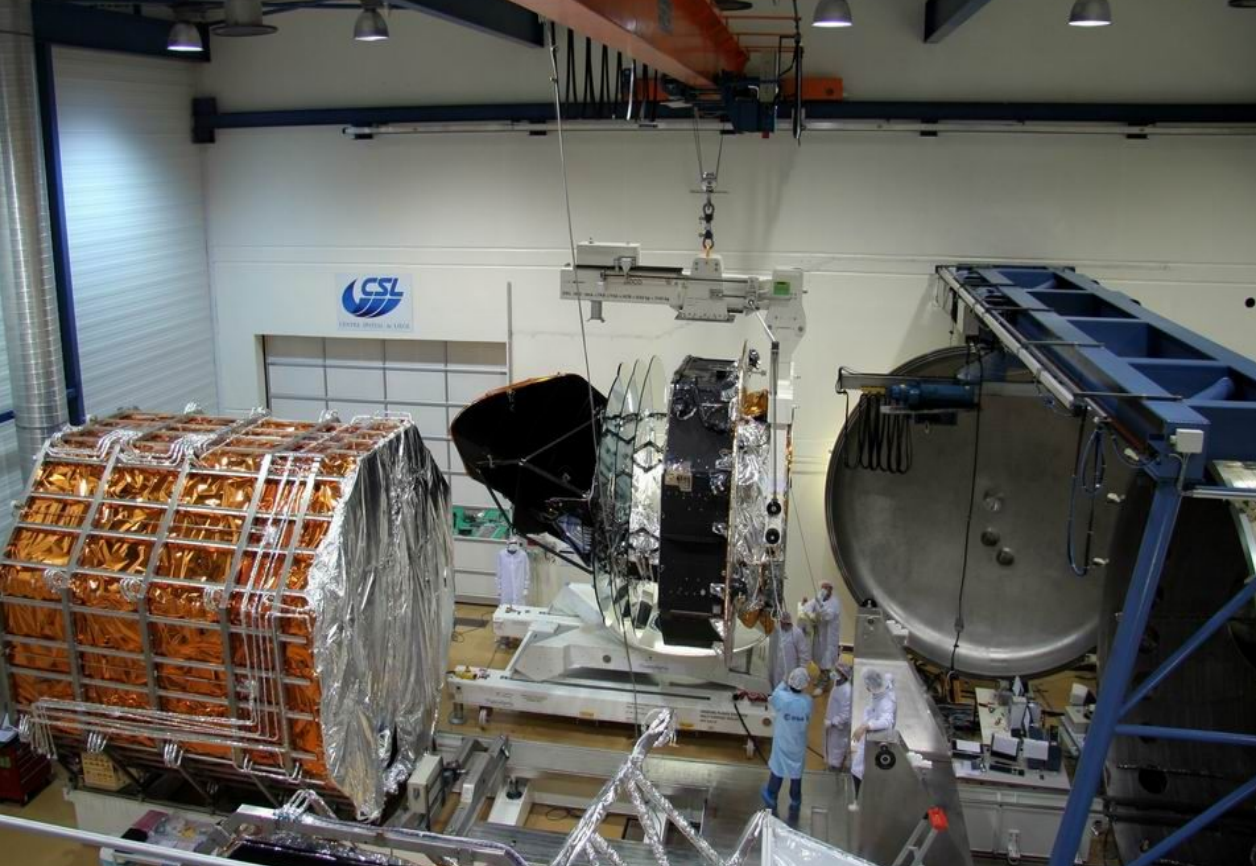
Heavy involvement within P2IO **at all stages and in all activities** of *Planck*-HFI:

- ✓ Management
- ✓ Design
- ✓ Building
- ✓ Testing
- ✓ Data processing
- ✓ Product delivery
- ✓ Science exploitation



Pre-launch *Planck*-HFI cryo-qualification campain at IAS's calibration facility

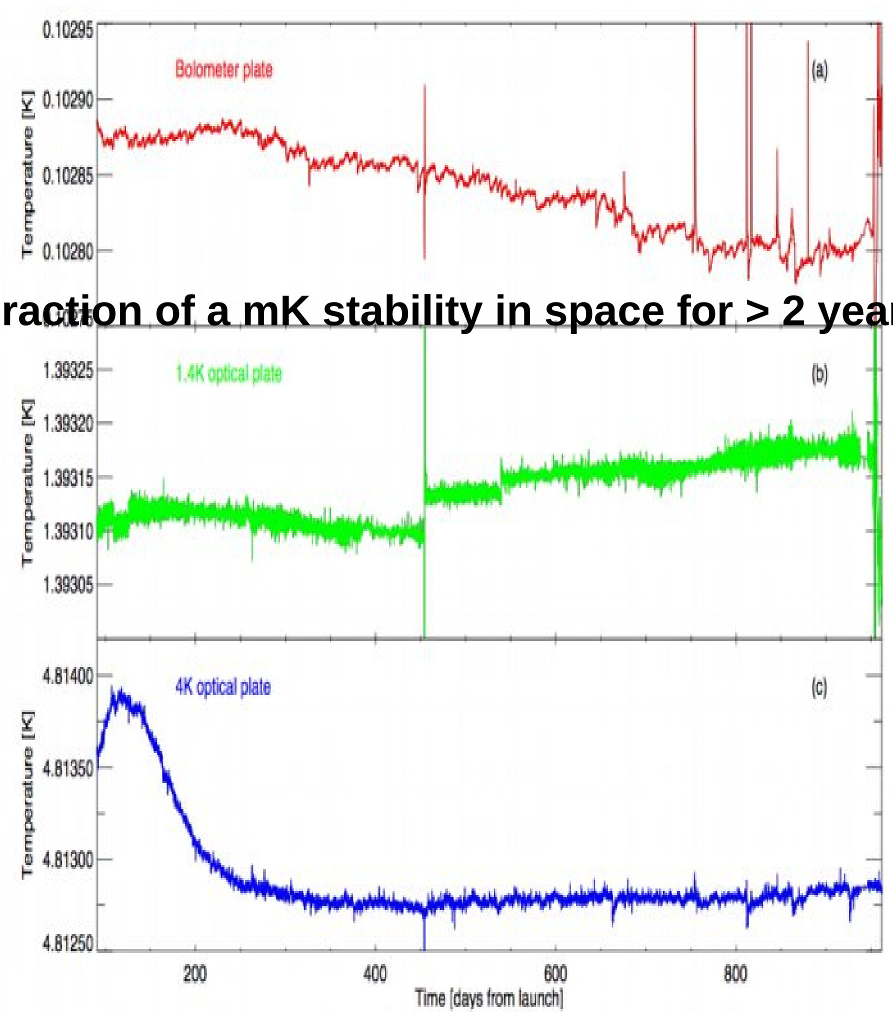




Last tests before launch at Liège test facility (CSL)

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

Planck-HFI operated from IAS from Aug. 2009 to Jan. 2012



Fraction of a mK stability in space for > 2 years!

Data processing challenge

- One circle per minute
- 200 sky measurements per sec and detector, during 30 months

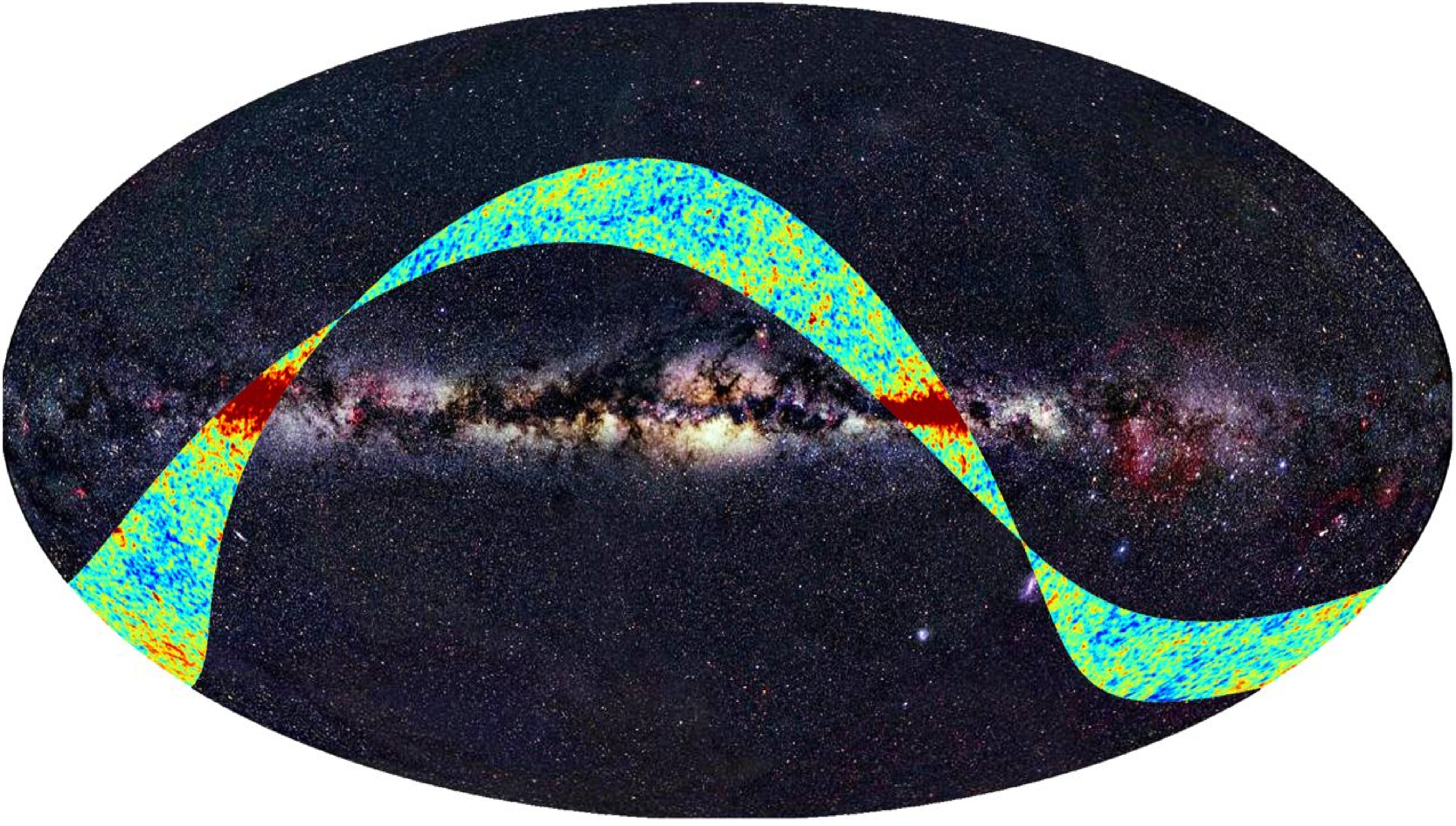
- ~1000 billions of samples (72 channels, 30 months) – several billions of telemetry packets
- 50 Go Raw data per detector (NB1 we have 52 detectors, NB2 often several versions)!

- 1 release = 1 month processing, 2500 maps
- Sky maps: 50 Millions of pixels (6 frequency for HFI + 3 LFI)

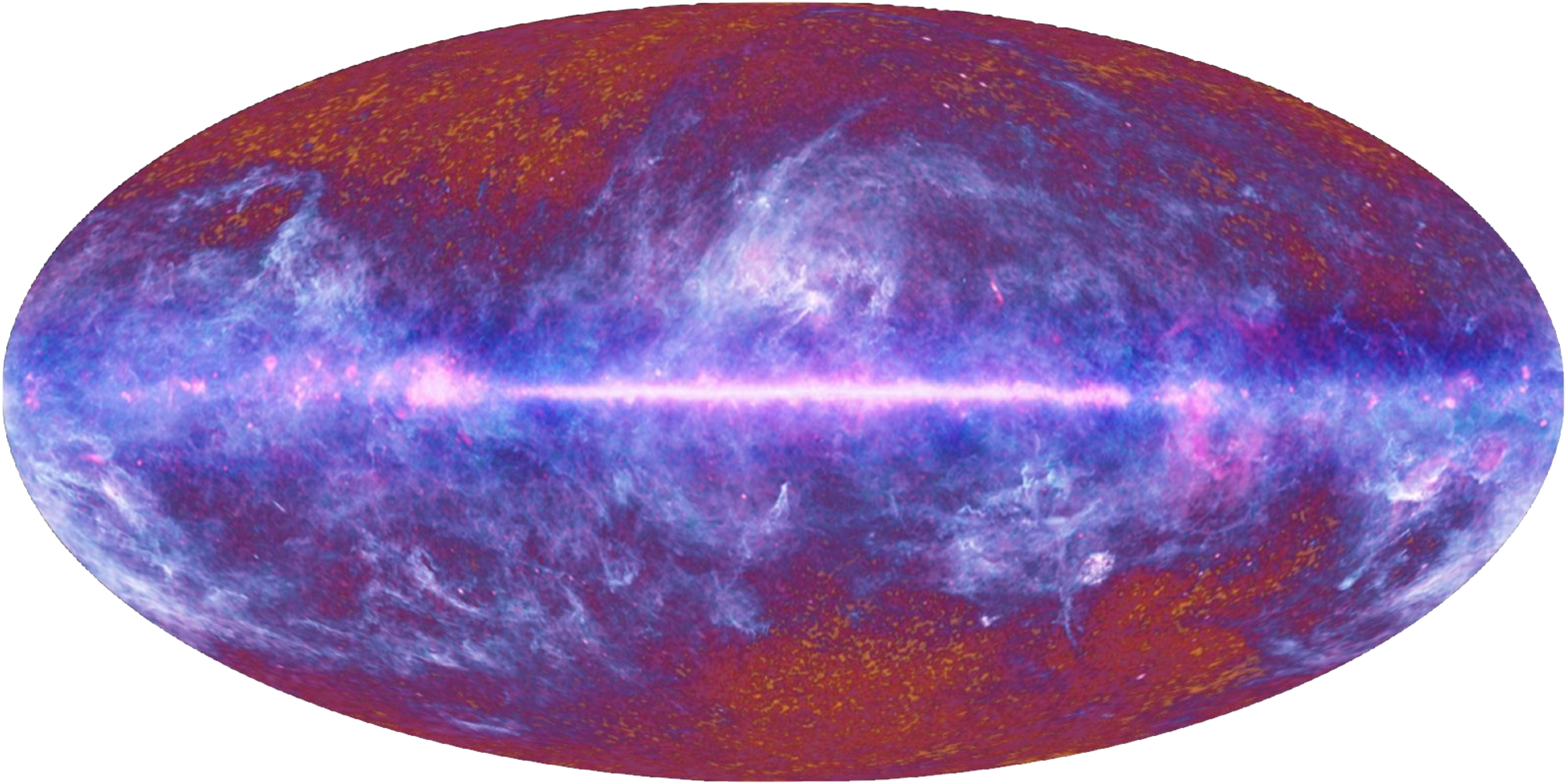
September 2009: *Planck*'s first-light survey

Planck started its survey Aug. 2009

Image exemplifying the technical and data processing success



Planck in 2011



The whole sky as observed by *Planck*

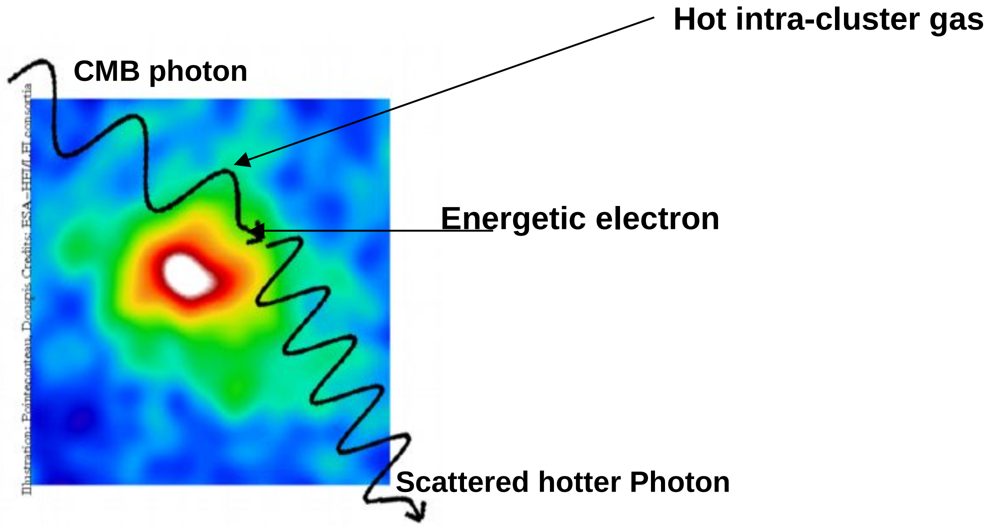
Jan. 2011: *Planck* early release based on 10 months of data

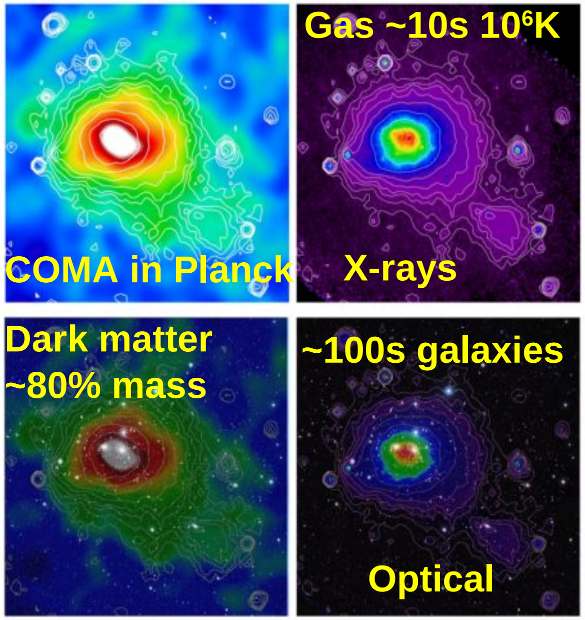
- Two first products delivered (catalogues of clusters and sources)
- 26 early-result articles (our galaxy, nearby galaxies, clusters of galaxies, radio sources, CIB)

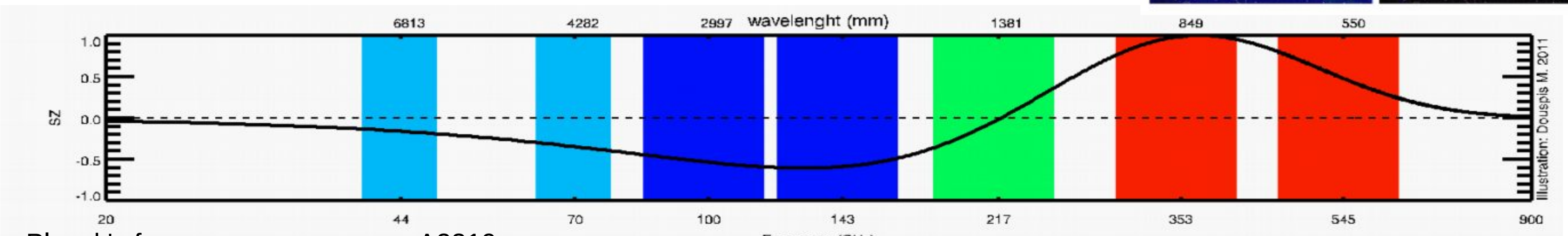
Lead, co-lead | Major contribution

- Planck early results. XXVI. Detection with Planck and confirmation by XMM-Newton of PLCK G266.6-27.3, an exceptionally X-ray luminous and massive galaxy cluster at z ~ 1
- Planck early results. XXV. Thermal dust in nearby molecular clouds
- Planck early results. XXIV. Dust in the diffuse interstellar medium and the Galactic halo
- Planck early results. XXIII. The first all-sky survey of Galactic cold clumps
- Planck early results. XXII. The submillimetre properties of a sample of Galactic cold clumps
- Planck early results. XXI. Properties of the interstellar medium in the Galactic plane
- Planck early results. XX. New light on anomalous microwave emission from spinning dust grains
- Planck early results. XIX. All-sky temperature and dust optical depth from Planck and IRAS. Constraints on the "dark gas" in our Galaxy
- Planck early results. XVIII. The power spectrum of cosmic infrared background anisotropies
- Planck early results. XVII. Origin of the submillimetre excess dust emission in the Magellanic Clouds
- Planck early results. XVI. The Planck view of nearby galaxies
- Planck early results. XV. Spectral energy distributions and radio continuum spectra of northern extragalactic radio sources
- Planck early results. XIV. ERCSC validation and extreme radio sources
- Planck early results. XIII. Statistical properties of extragalactic radio sources in the Planck Early Release Compact Source Catalogue
- Planck early results. XII. Cluster Sunyaev-Zeldovich optical scaling relations
- Planck early results. XI. Calibration of the local galaxy cluster Sunyaev-Zeldovich scaling relations
- Planck early results. X. Statistical analysis of Sunyaev-Zeldovich scaling relations for X-ray galaxy clusters
- Planck early results. IX. XMM-Newton follow-up for validation of Planck cluster candidates
- Planck early results. VIII. The all-sky early Sunyaev-Zeldovich cluster sample
- Planck early results. VII. The Early Release Compact Source Catalogue
- Planck early results. VI. The High Frequency Instrument data processing
- Planck early results. IV. First assessment of the High Frequency Instrument in-flight performance
- Planck early results. II. The thermal performance of Planck
- Planck early results. I. The Planck mission

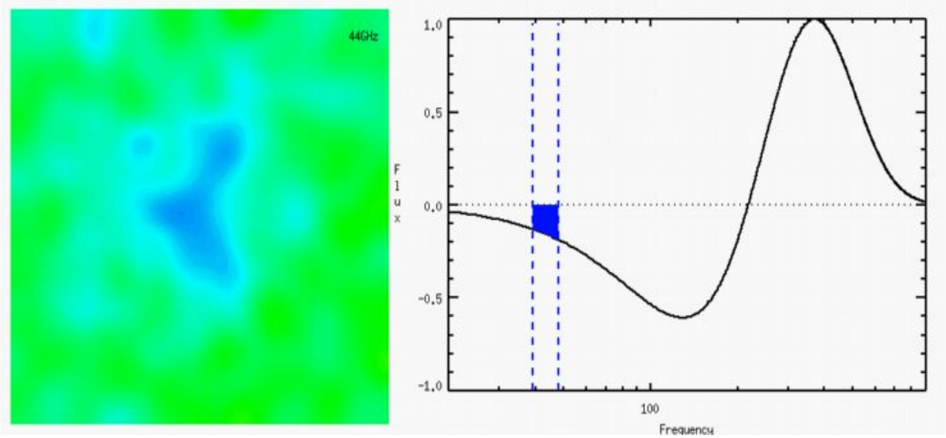
Sunyaev-Zeldovich effect detection with *Planck*





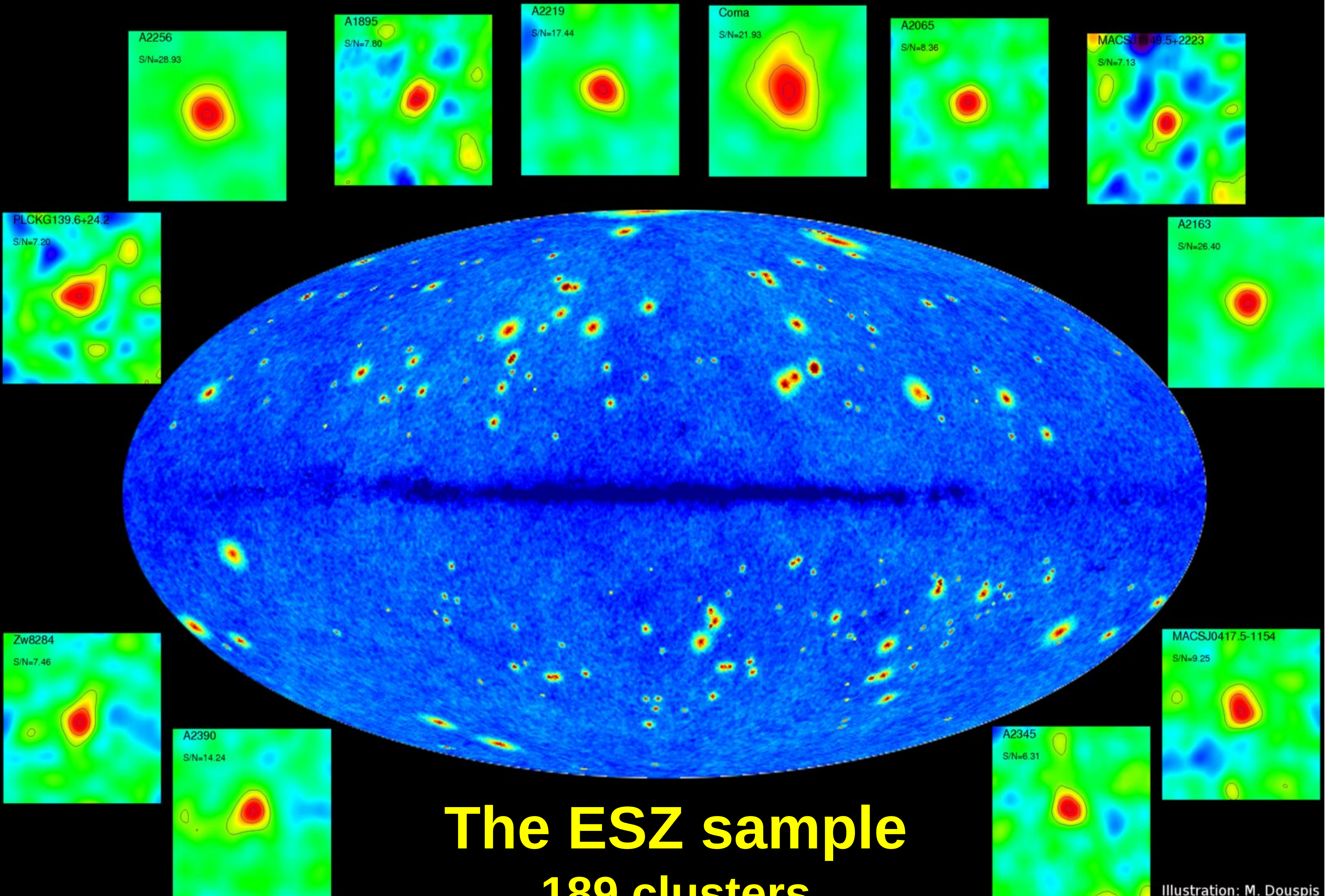


Planck's frequency coverage on A2319



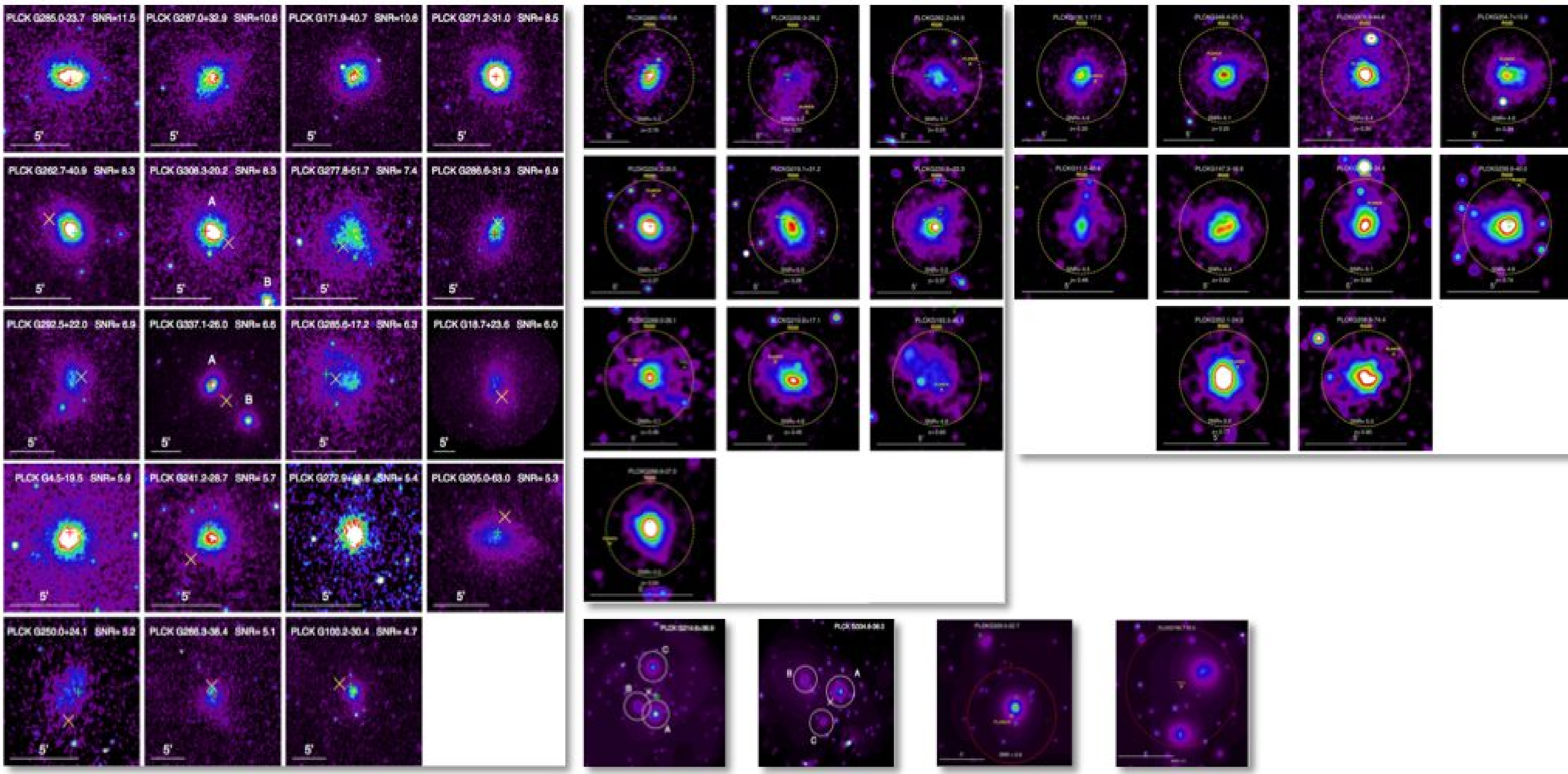
→ *Planck*, designed from the start to measure SZ

- All-sky survey
- Frequency range from 30 to 857 GHz
- **Largest published SZ cluster catalogue “Early SZ” sample**



The ESZ sample

189 clusters



51 new clusters (including 4 double systems and 2 triple systems) confirmed and characterised With XMM-Newton data

Planck in 2012

15 articles on Planck intermediate results (our galaxy, radio and IR galaxies, clusters of galaxies)

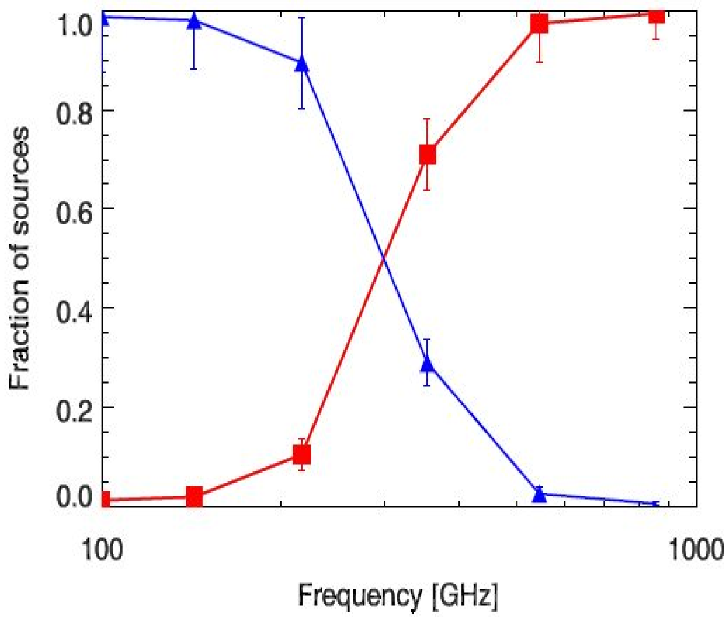
Planck intermediate results. XV. A study of anomalous microwave emission in Galactic clouds
Planck intermediate results. XIV. Dust emission at millimetre wavelengths in the Galactic plane
Planck intermediate results. IX. Detection of the Galactic haze with Planck
Planck intermediate results. XII: Diffuse Galactic components in the Gould Belt System

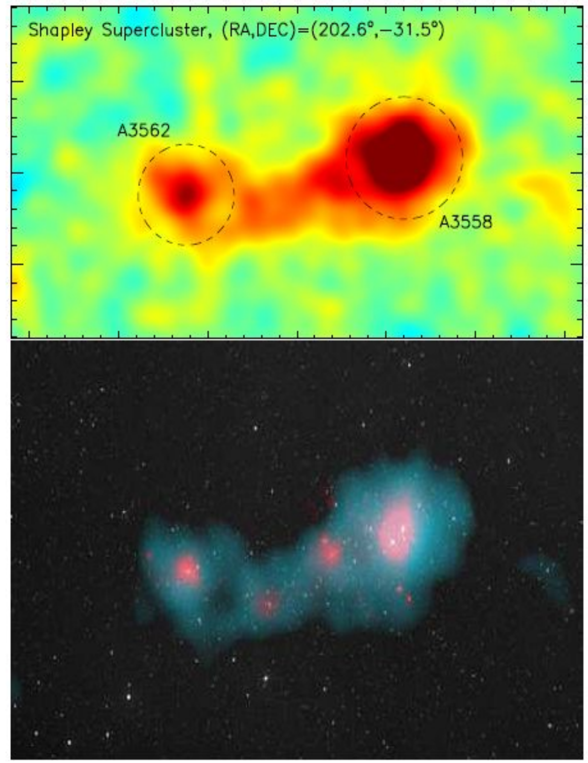
Planck intermediate results. VII. Statistical properties of infrared and radio extragalactic sources from the Planck Early Release Compact Source Catalogue at frequencies between 100 and 857 GHz

Planck intermediate results. XIII. Constraints on peculiar velocities
Planck Intermediate Results. XI: The gas content of dark matter halos: the Sunyaev-Zeldovich-stellar mass relation for locally brightest galaxies
Planck intermediate results. X. Physics of the hot gas in the Coma cluster
Planck intermediate results. VIII. Filaments between interacting clusters
Planck intermediate results. VI. The dynamical structure of PLCKG214.6+37.0, a Planck discovered triple system of galaxy clusters
Planck intermediate results. V. Pressure profiles of galaxy clusters from the Sunyaev-Zeldovich effect
Planck intermediate results. IV. The XMM-Newton validation programme for new Planck galaxy clusters
Planck intermediate results. III. The relation between galaxy cluster mass and Sunyaev-Zeldovich signal
Planck intermediate results. II. Comparison of Sunyaev-Zeldovich measurements from Planck and from the Arcminute Microkelvin Imager for 11 galaxy clusters
Planck intermediate results. I. Further validation of new Planck clusters with XMM-Newton

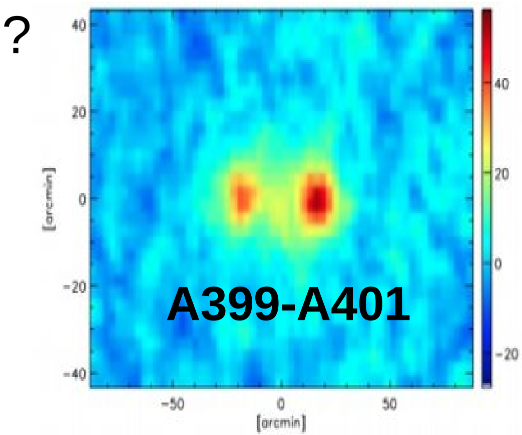
Intermediate results on galaxy statistical properties, gas content & physics in clusters

Dusty & synchrotron galaxy fractions

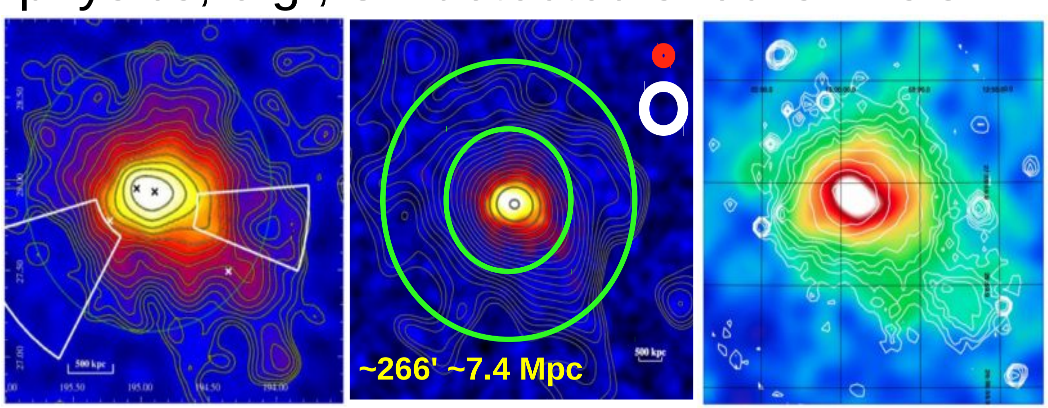




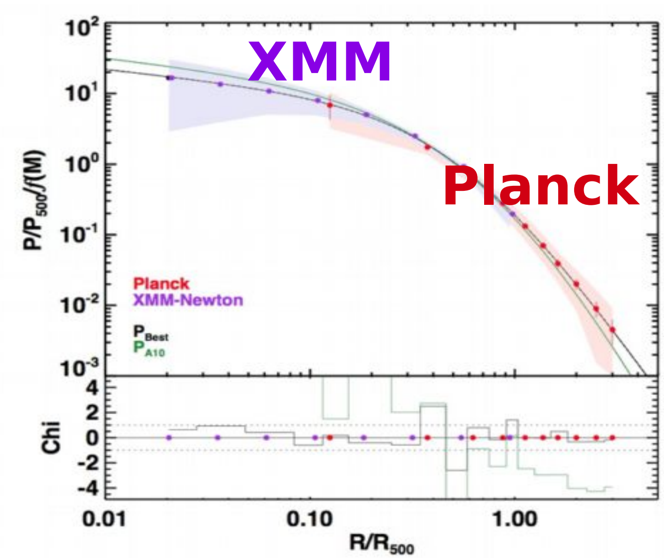
Intercluster gas in multiple systems: Gravitational interaction or compressed filaments?



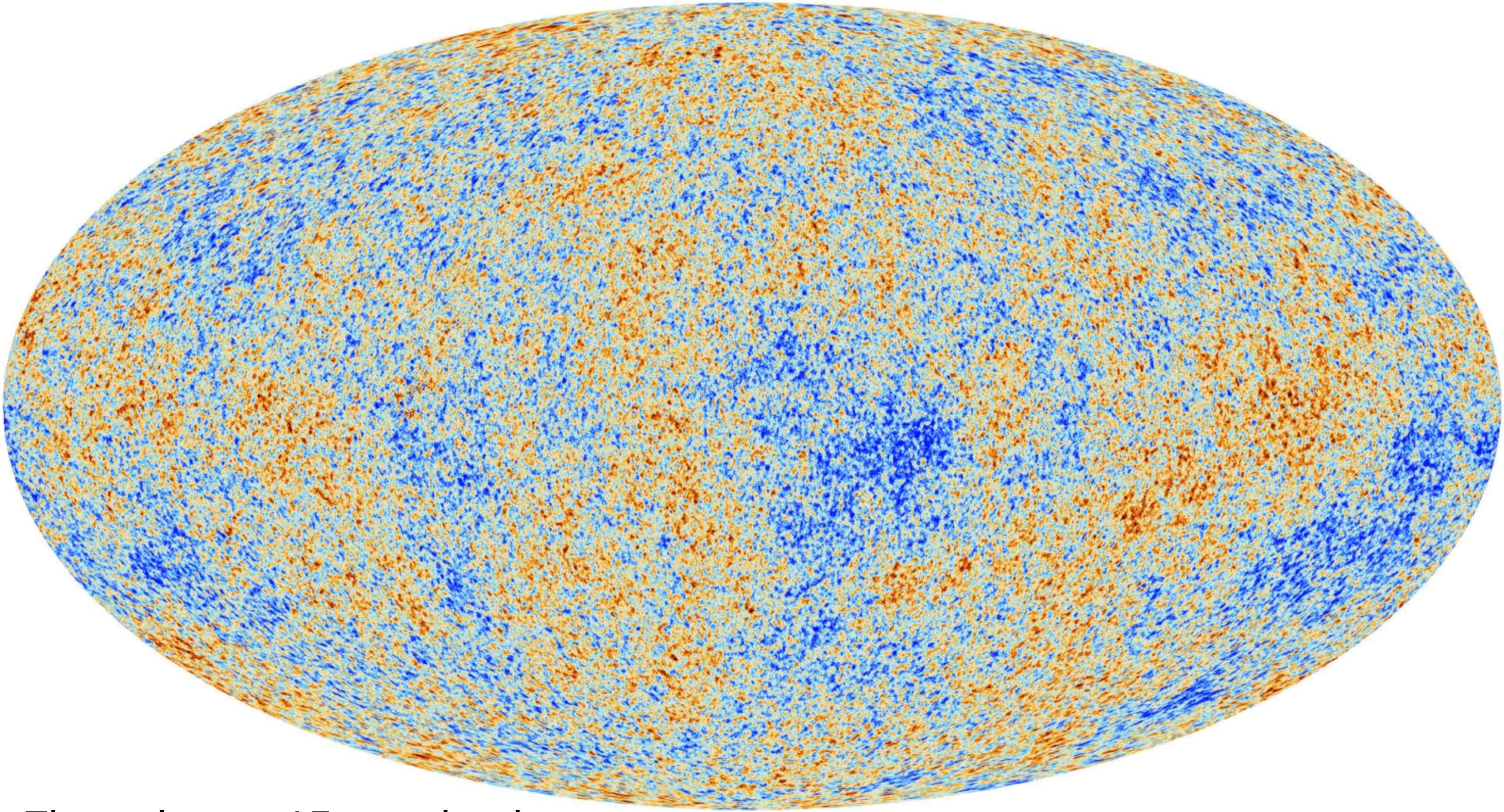
Spatially resolved SZ signal: Complex physics, e.g., SZ-detected shocks in COMA



SZ signal & **pressure profile** out to $3R_{500}$



Planck in 2013



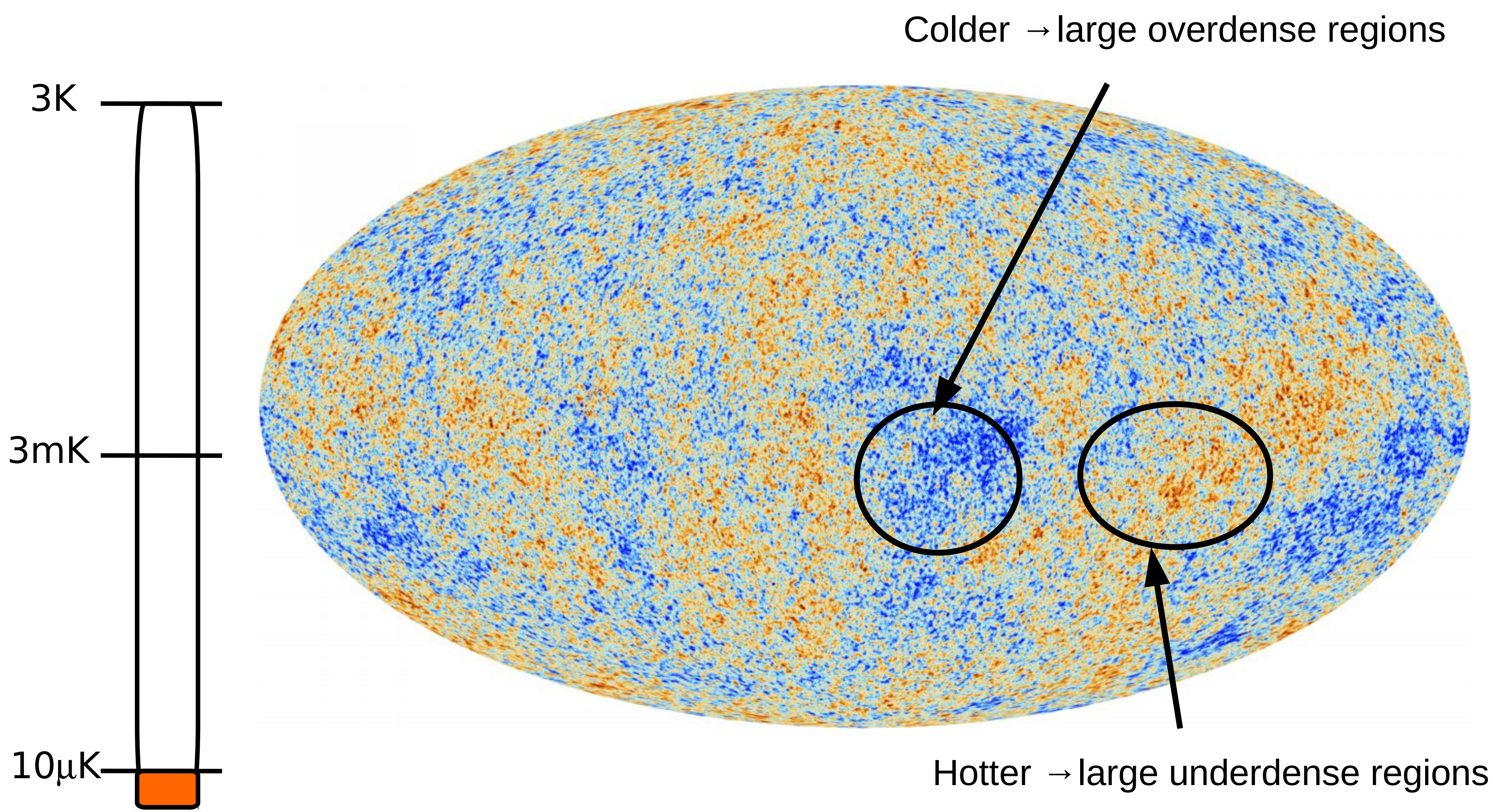
First release, 15 months data:

- SZ source catalogue, SZ cosmological sample, 9 compact source catalogues
- 9 frequency maps & component maps (CMB, matter density, CO, dust, etc)
- Likelihood code
- 29 articles (data/instrument, products, science)

29 papers on *Planck* 2013 results

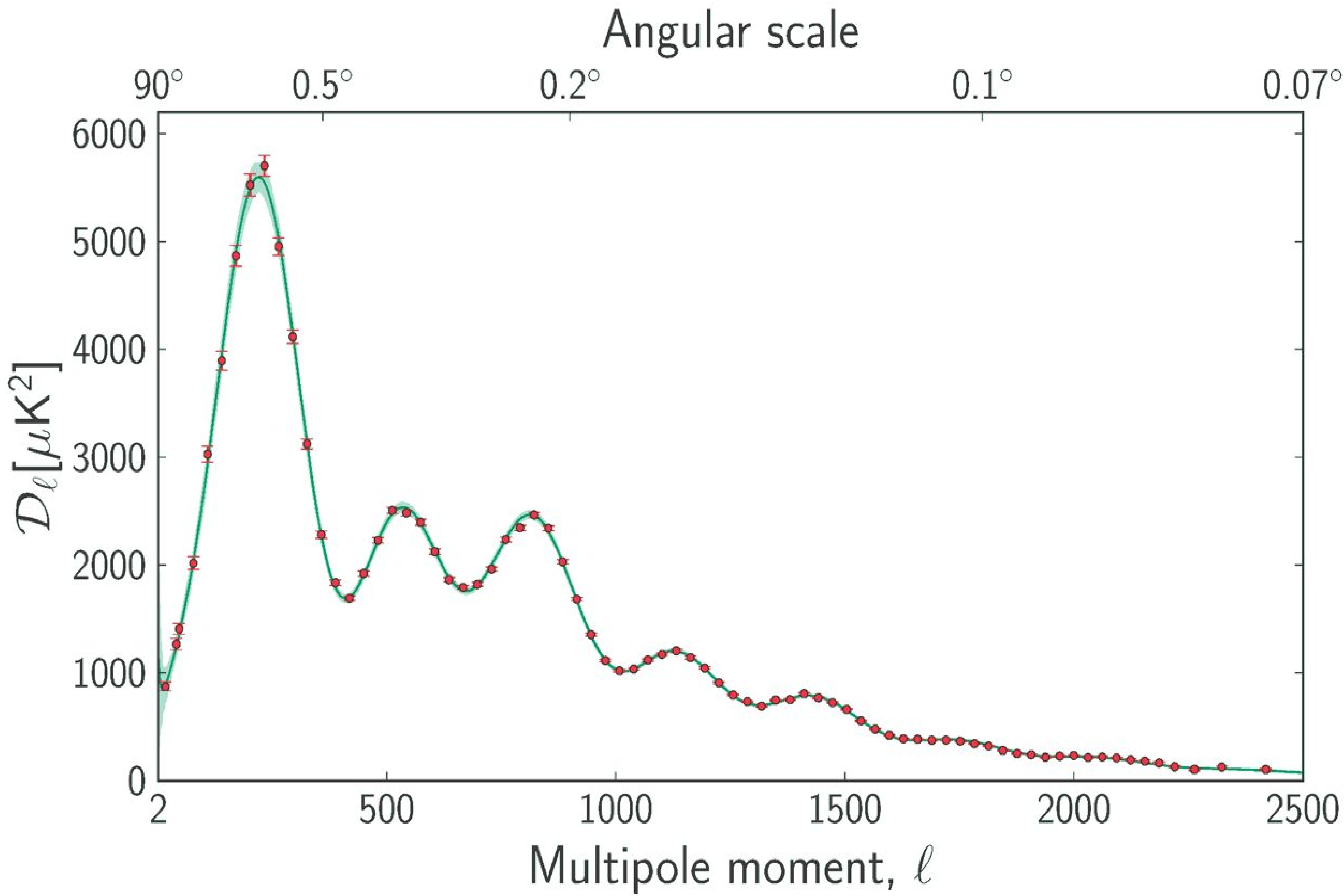
- Planck 2013 results. I. Overview of products and results
- Planck 2013 results. II. Low Frequency Instrument data processing
- Planck 2013 results. III. LFI systematic uncertainties
- Planck 2013 results. IV. LFI beams
- Planck 2013 results. V. LFI calibration
- Planck 2013 results. VI. High Frequency Instrument data processing
- Planck 2013 results. VII. HFI time response and beams
- Planck 2013 results. VIII. HFI calibration and mapmaking
- Planck 2013 results. IX. HFI spectral response
- Planck 2013 results. X. HFI energetic particle effects
- Planck 2013 results. XI. Consistency of the data
- Planck 2013 results. XII. Component separation
- Planck 2013 results. XIII. Galactic CO emission
- Planck 2013 results. XIV. Zodiacal emission
- Planck 2013 results. XV. CMB power spectra and likelihood
- Planck 2013 results. XVI. Cosmological parameters
- Planck 2013 results. XVII. Gravitational lensing by large-scale structure
- Planck 2013 results. XVIII. The gravitational lensing-infrared background correlation
- Planck 2013 results. XIX. The integrated Sachs-Wolfe effect
- Planck 2013 results. XXX. Cosmic Infrared Background
- Planck 2013 results. XX. Cosmology from Sunyaev-Zeldovich cluster counts
- Planck 2013 results. XXI. All-sky Compton-parameter map an d characterization
- Planck 2013 results. XXII. Constraints on inflation
- Planck 2013 results. XXIII. Isotropy and statistics of the CMB
- Planck 2013 results. XXIV. Constraints on primordial non-Gau ssianity
- Planck 2013 results. XXV. Searches for cosmic strings and ot her topological defects
- Planck 2013 results. XXVI. Background geometry and topolog y of the Universe
- Planck 2013 results. XXVII. Special relativistic effects on th e CMB dipole
- Planck 2013 results. XXVIII. The Planck Catalogue of Compa ct Sources
- Planck 2013 results. XXIX. The Planck catalogue of Sunyaev -Zeldovich sources
- Planck 2013 results. Explanatory supplement

CMB fluctuations as seen by *Planck*



Inhomogeneities from inflation = density perturbations

Spherical harmonic analysis of the CMB map



Cosmological parameters from *Planck*

Derived from the **probability of a model given the data**

Data = auto and cross frequency spectra

Mask the galactic plane

Model = cosmology +

- Residual galactic dust emission
- Radio or infrared sources
- Cosmic IR background (CIB)
- Thermal & kinetic SZ from clusters

28 fold reduction in constraint volume compared to WMAP9

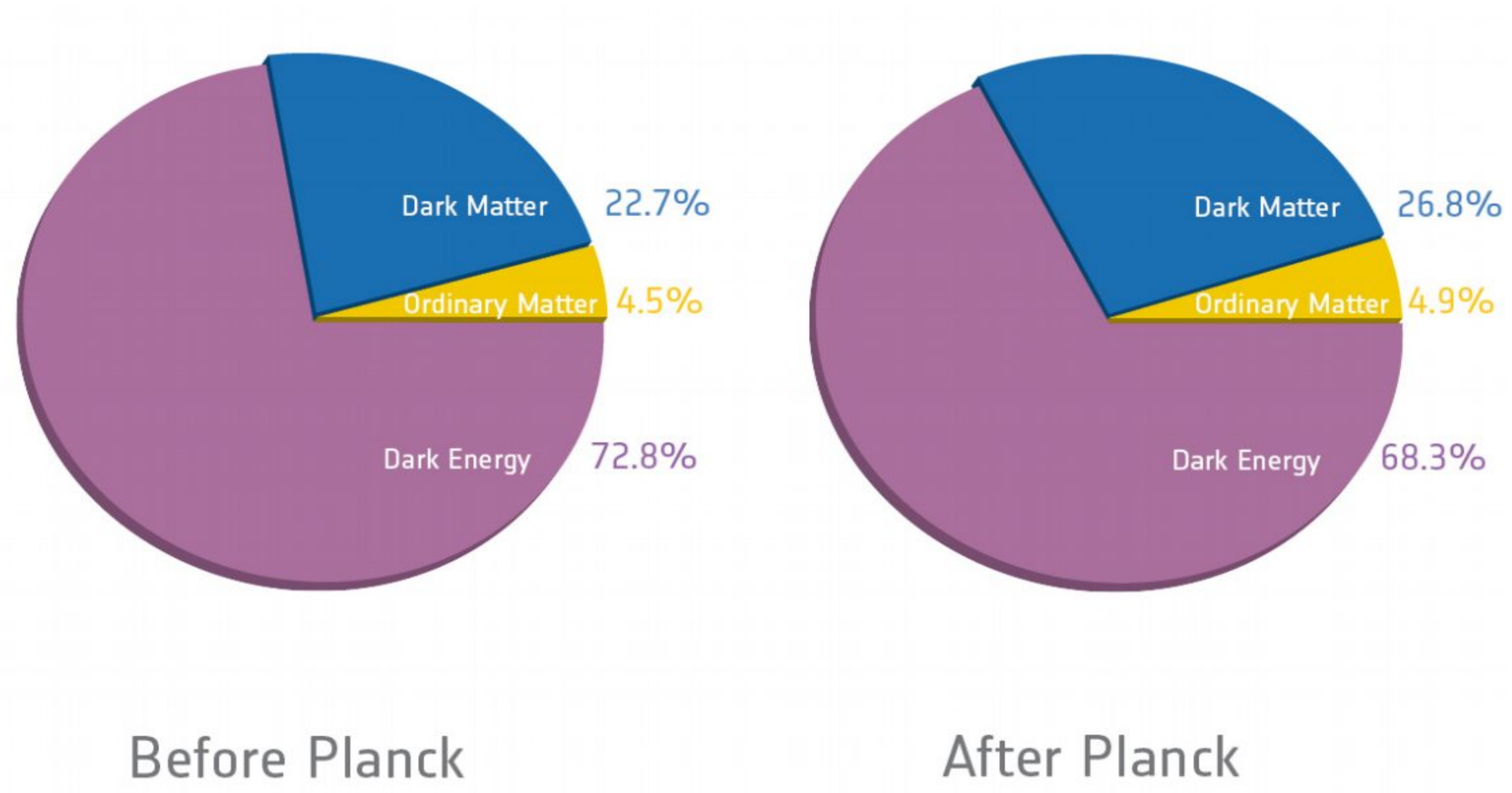
18 fold reduction in constraint volume compared to WMAP9 + SPT

Parameter	Prior range	Baseline	Definition
$\omega_b \equiv \Omega_b h^2$	[0.005, 0.1]	...	Baryon density today
$\omega_c \equiv \Omega_c h^2$	[0.001, 0.99]	...	Cold dark matter density today
$100\theta_{MC}$	[0.5, 10.0]	...	$100\times$ approximation to r_*/D_A (CosmoMC)
τ	[0.01, 0.8]	...	Thomson scattering optical depth due to reionization
Ω_K	[−0.3, 0.3]	0	Curvature parameter today with $\Omega_{tot} = 1 - \Omega_K$
$\sum m_\nu$	[0, 5]	0.06	The sum of neutrino masses in eV
$m^{eff}_{\nu,\ sterile}$	[0, 3]	0	Effective mass of sterile neutrino in eV
w_0	[−3.0, −0.3]	−1	Dark energy equation of state[a], $w(a) = w_0 + (1-a)w_a$
w_a	[−2, 2]	0	As above (perturbations modelled using PPF)
N_{eff}	[0.05, 10.0]	3.046	Effective number of neutrino-like relativistic degrees of freedom (see text)
Y_P	[0.1, 0.5]	BBN	Fraction of baryonic mass in helium
A_L	[0, 10]	1	Amplitude of the lensing power relative to the physical value
n_s	[0.9, 1.1]	...	Scalar spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
n_t	$n_t = -r_{0.05}/8$	Inflation	Tensor spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
$dn_s/d\ln k$	[−1, 1]	0	Running of the spectral index
$\ln(10^{10}A_s)$	[2.7, 4.0]	...	Log power of the primordial curvature perturbations ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$)
$r_{0.05}$	[0, 2]	0	Ratio of tensor primordial power to curvature power at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
Ω_Λ		...	Dark energy density divided by the critical density today
t_0		...	Age of the Universe today (in Gyr)
Ω_m		...	Matter density (inc. massive neutrinos) today divided by the critical density
σ_8		...	RMS matter fluctuations today in linear theory
z_{re}		...	Redshift at which Universe is half reionized
H_0	[20,100]	...	Current expansion rate in $\mathrm{km\,s^{-1}Mpc^{-1}}$
$r_{0.002}$		0	Ratio of tensor primordial power to curvature power at $k_0 = 0.002\,\mathrm{Mpc}^{-1}$
$10^9 A_s$		...	$10^9\times$ dimensionless curvature power spectrum at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
$\omega_m \equiv \Omega_m h^2$		...	Total matter density today (inc. massive neutrinos)
z_*		...	Redshift for which the optical depth equals unity (see text)
$r_* = r_s(z_*)$		...	Comoving size of the sound horizon at $z = z_*$
$100\theta_*$		...	$100\times$ angular size of sound horizon at $z = z_*$ (r_*/D_A)
z_{drag}		...	Redshift at which baryon-drag optical depth equals unity (see text)
$r_{drag} = r_s(z_{drag})$		...	Comoving size of the sound horizon at $z = z_{drag}$
k_D		...	Characteristic damping comoving wavenumber (Mpc^{-1})
$100\theta_D$		...	$100\times$ angular extent of photon diffusion at last scattering (see text)
z_{eq}		...	Redshift of matter-radiation equality (massless neutrinos)
$100\theta_{eq}$		...	$100\times$ angular size of the comoving horizon at matter-radiation equality
$r_{drag}/D_V(0.57)$		...	BAO distance ratio at $z = 0.57$ (see Sect. 5.2)

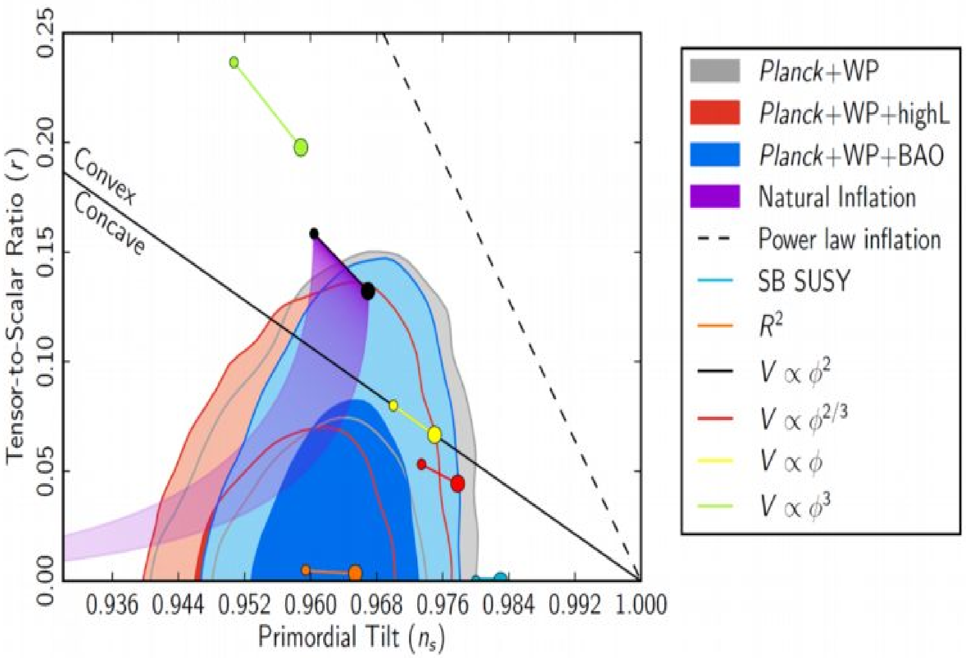
H_0	67.11	67.4 ± 1.4
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020

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

Baryonic and dark matter increased by ~10% (dark energy decreased by ~10%)
Hubble constant decreased by ~10%

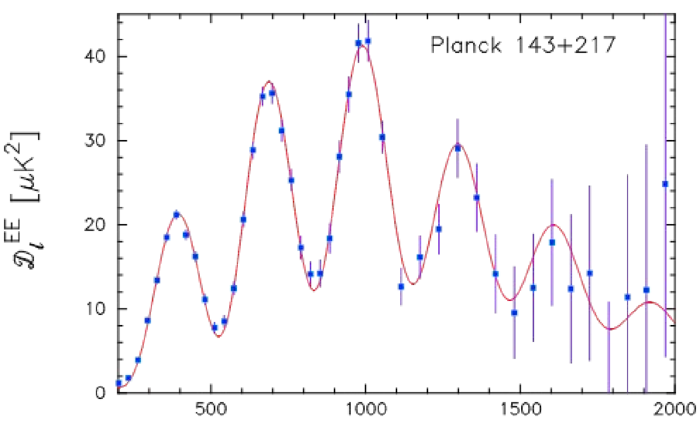


Constraints on inflation and initial conditions



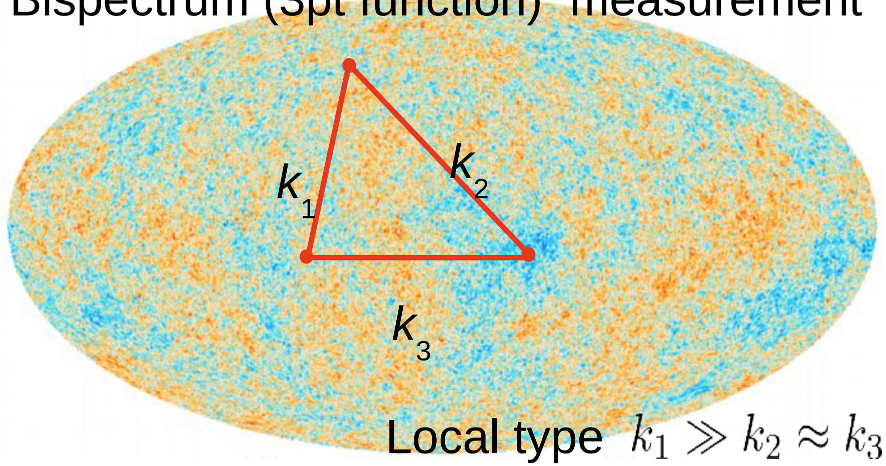
Scale invariant n_s=1 perturbation excluded

n_s~0.96 as predicted by single-field inflation



Adiabatic perturbations from polarisation

Bispectrum (3pt function) measurement



Local type $k_1 \gg k_2 \approx k_3$

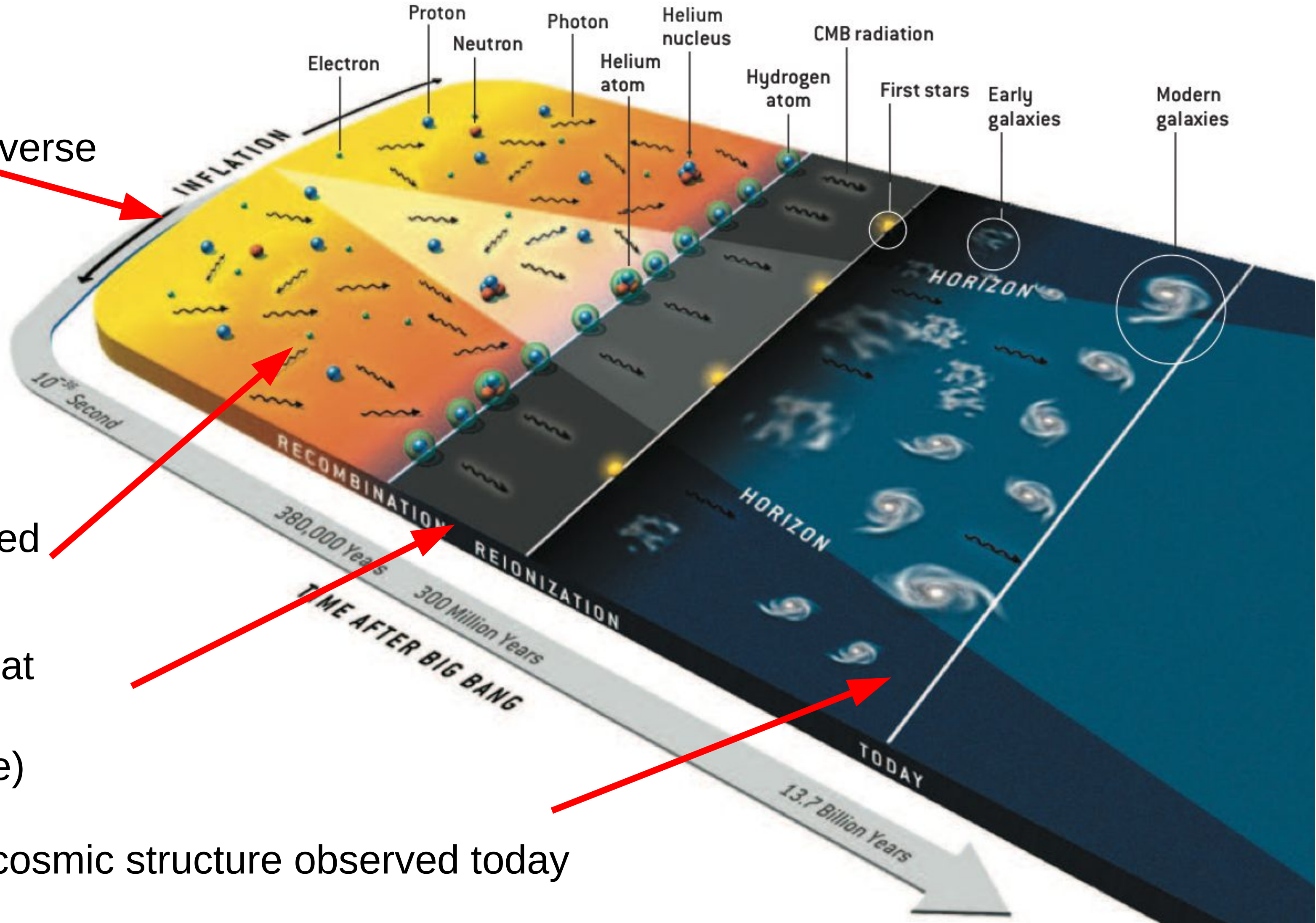
WMAP9 constraints on quadratic type NG from non-linearity parameter local () f_{NL} = 37 ± 20

	Independent				ISW-lensing subtracted		
	KSW	Binned	Modal		KSW	Binned	Modal
SMICA							
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9	. . . . .	2.7 ± 5.8	2.2 ± 5.9	1.6 ± 6.0
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77	. . . . .	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41	. . . . .	**−25 ± 39**	−17 ± 41	−14 ± 42

Six-parameter flat ΛCDM model: no obvious need for extensions nor for extra relativistic species

Simple slow-roll inflation with concave potentials seems favoured

Unveiling the cosmic structure with *Planck*



Information the early universe

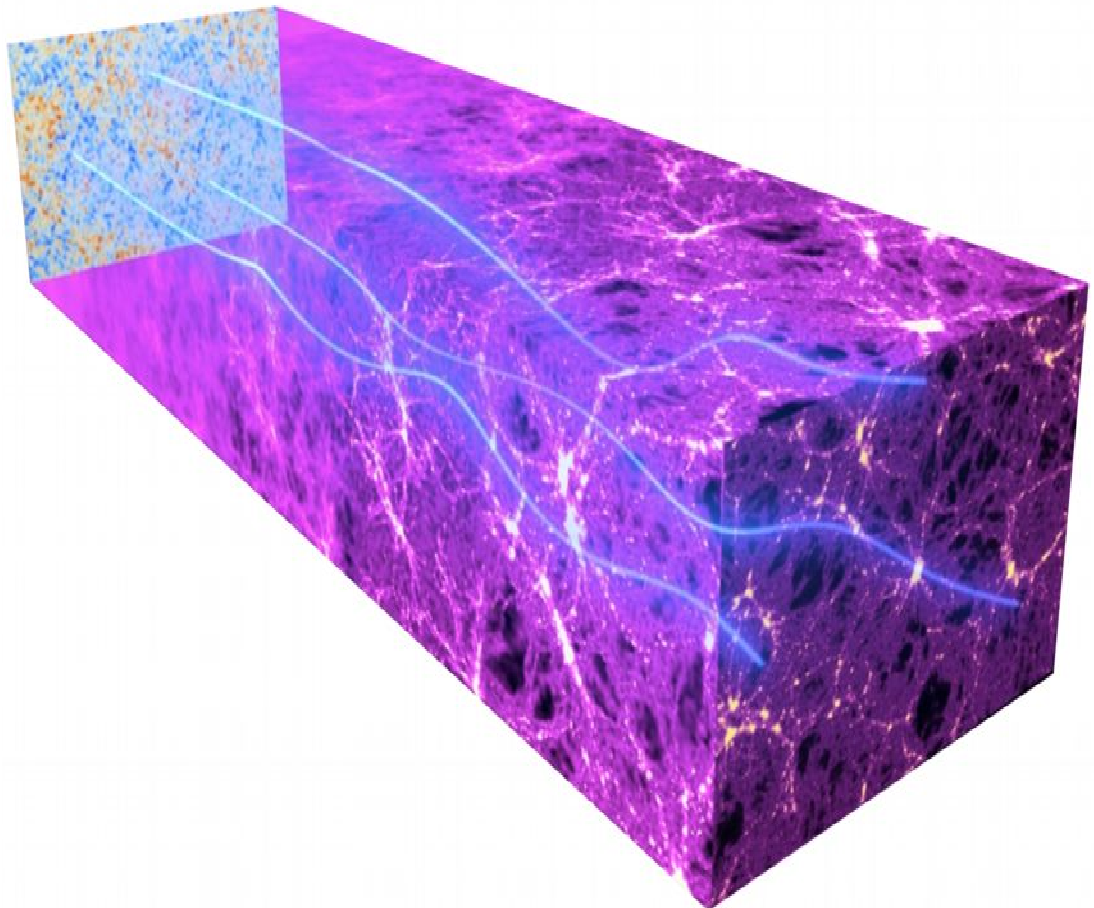
Through photons produced here

Then photons scattered at recombination (photosphere of universe)

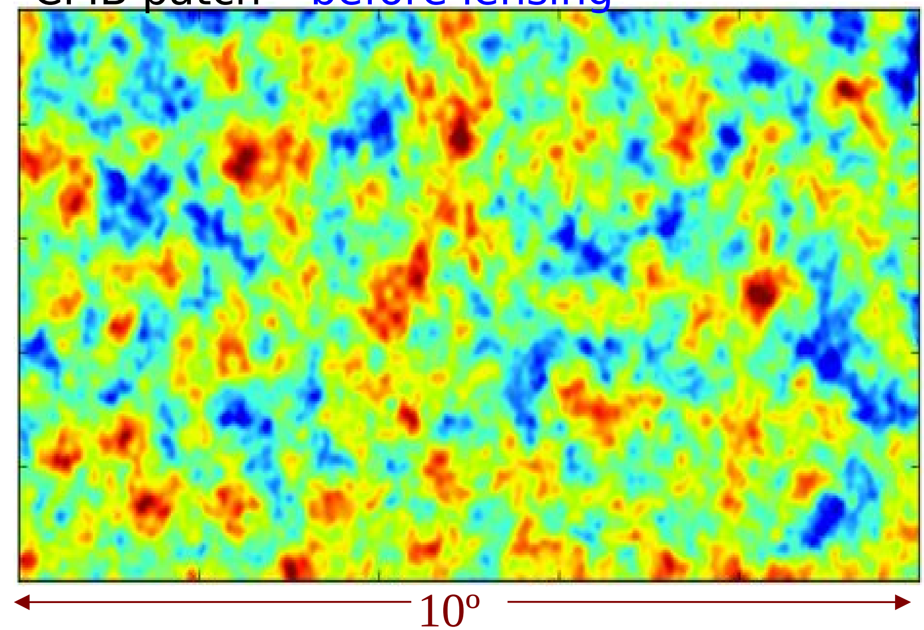
Photons altered by the cosmic structure observed today

Imprints of cosmic structure on CMB = dark matter (lensing), hot gas (SZ effect) and stars (IR background)

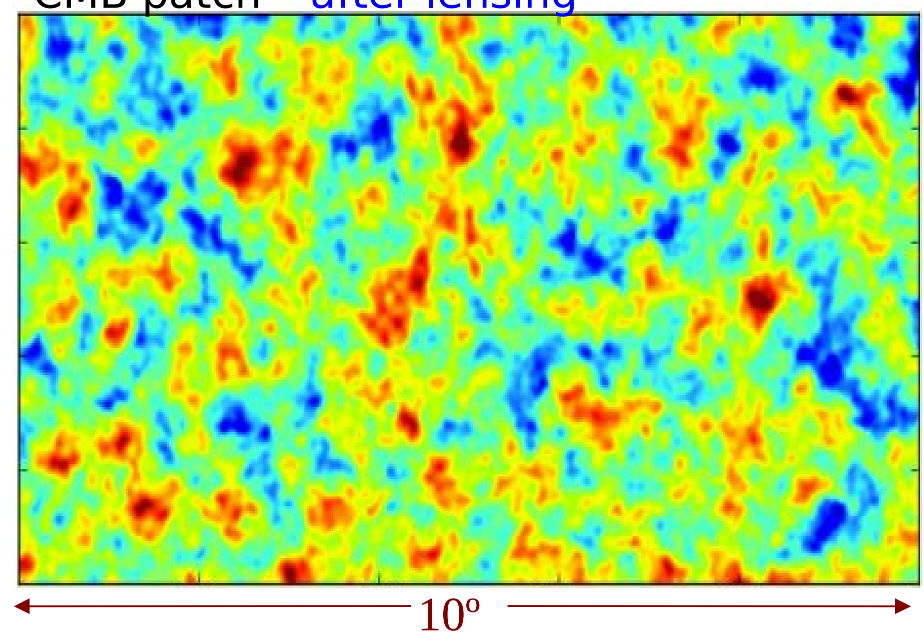
CMB Lensing: dark matter content



CMB patch – before lensing



CMB patch – after lensing

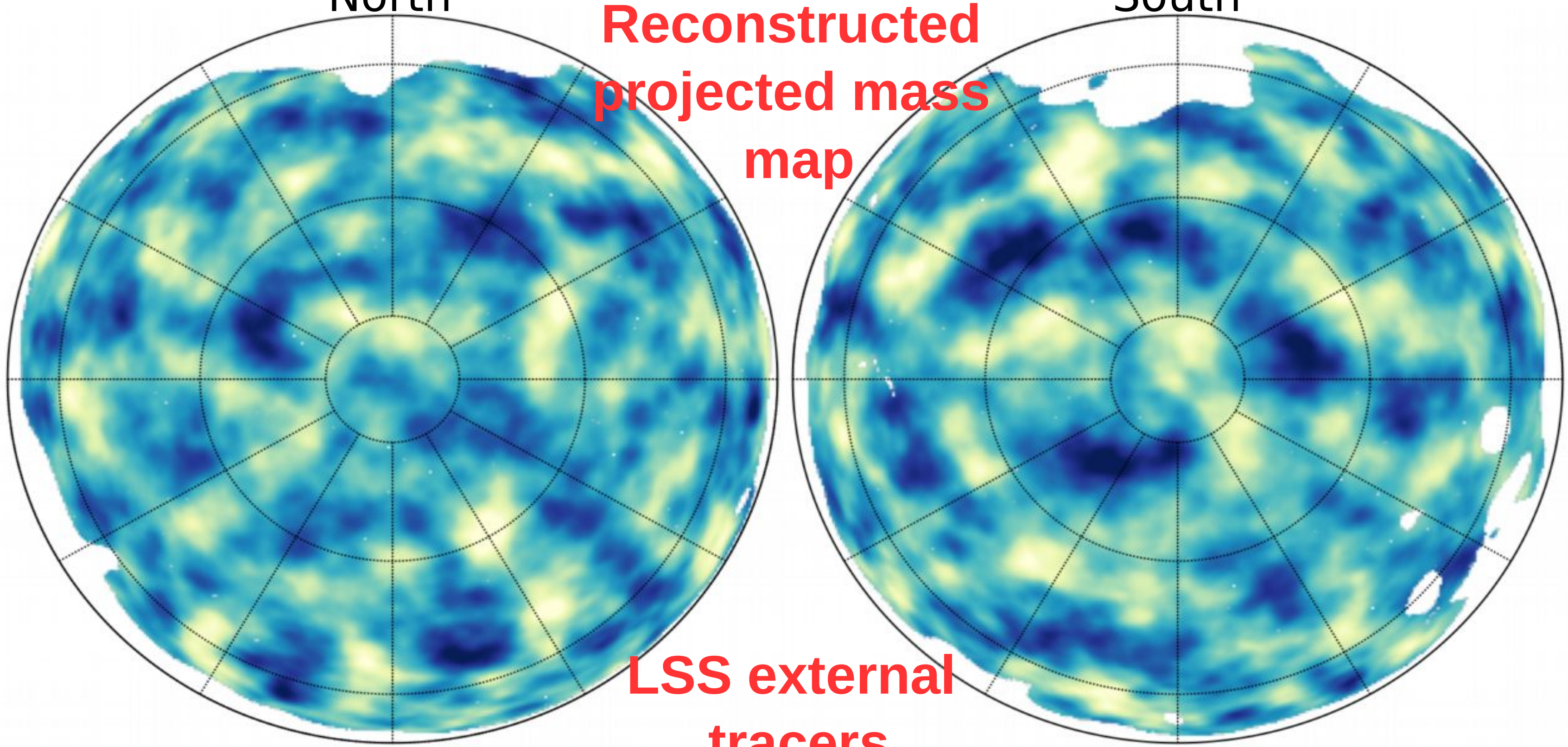


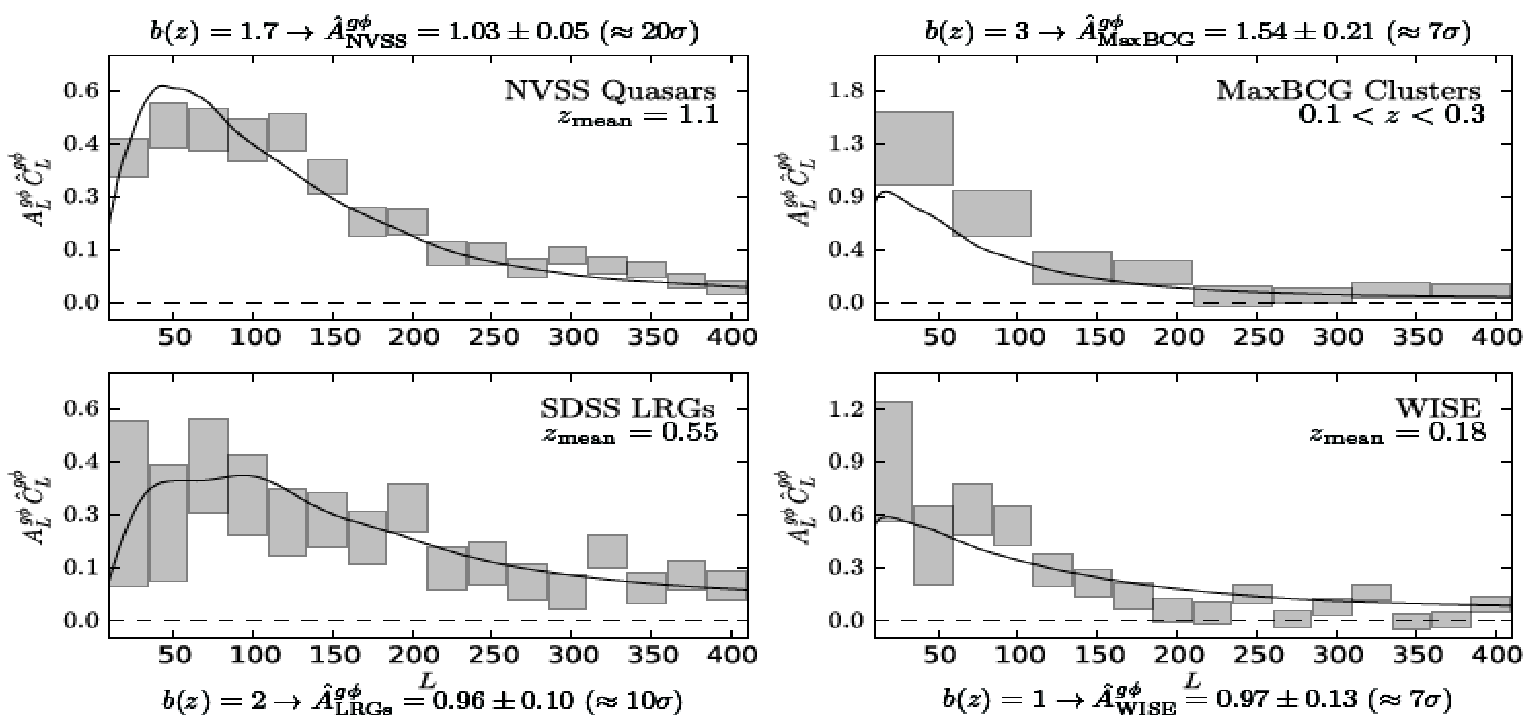
typical deflection: 2.4 arcmin

Gravitational effect of the cosmic structure (LSS) @z~2 disturbs the observed CMB → smoothing of the small anisotropies

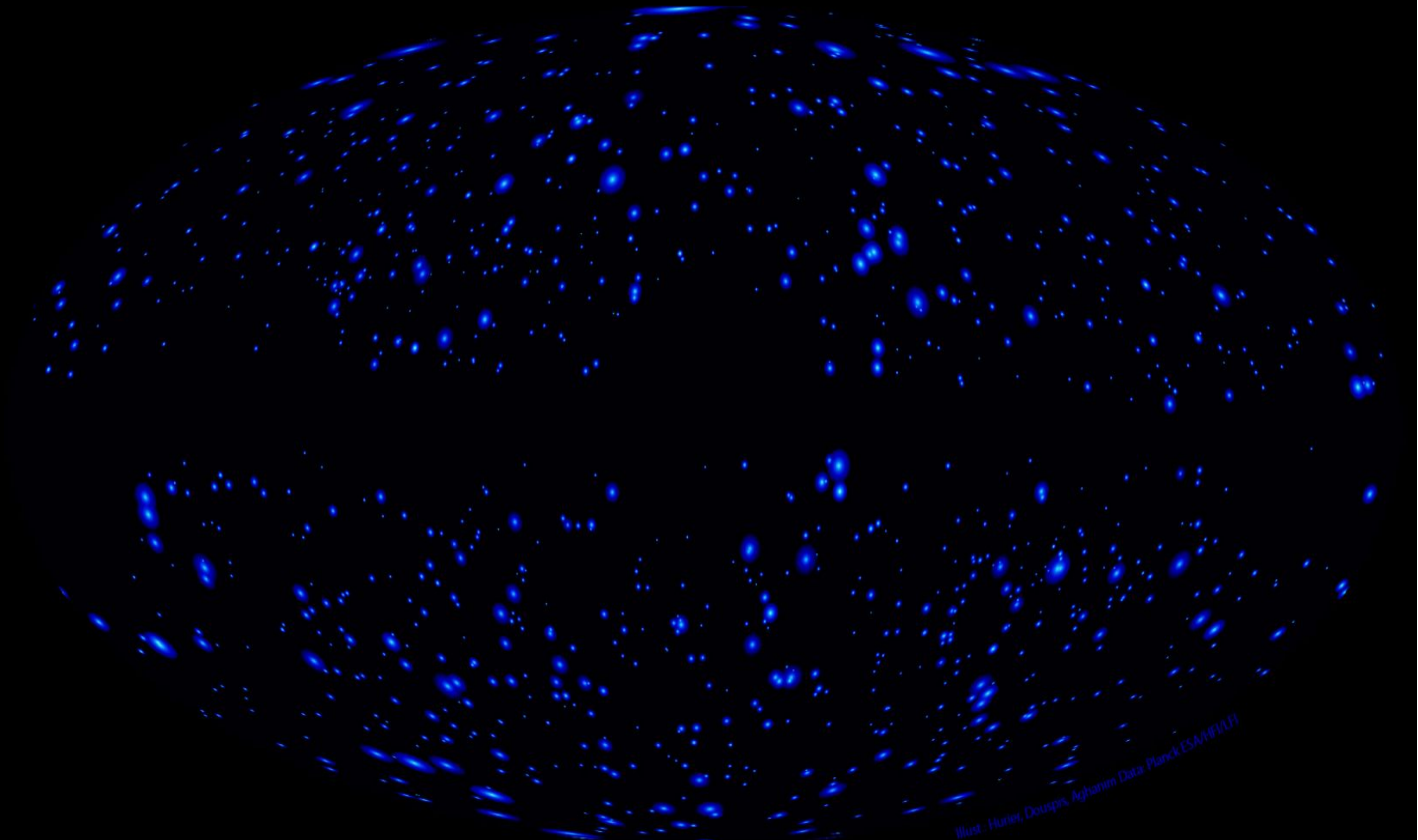
Reconstruction from temperature gradients in *Planck* data

CMB lensing measured at ~10-20σ significance





1227 *Planck* SZ sources

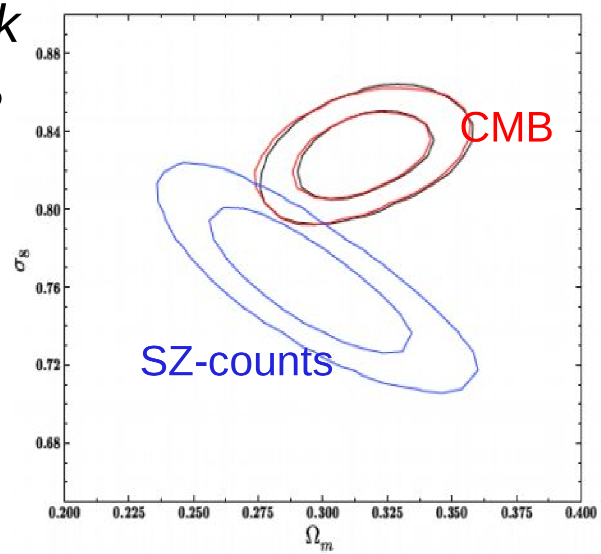


Including 178 new clusters; 813 redshifts & masses and 366 cluster candidates

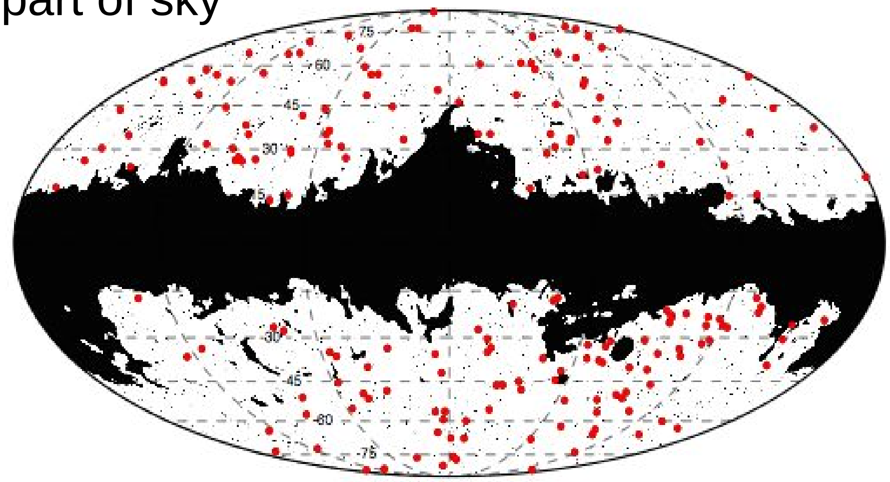
Cosmology from SZ effect

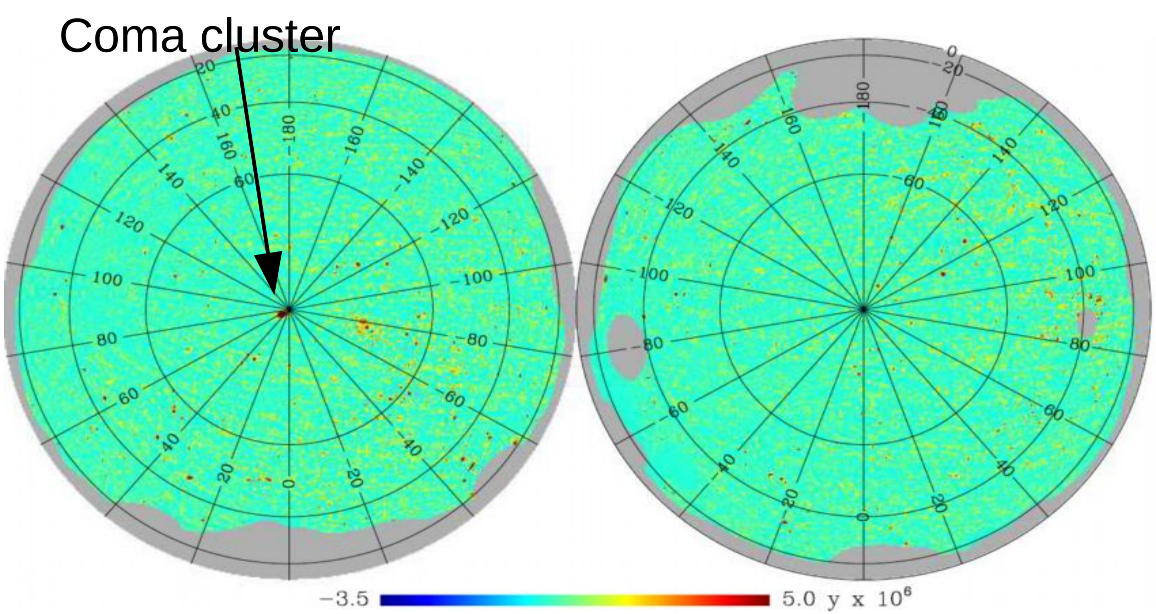
Tension between *Planck* cluster counts and CMB constraints:

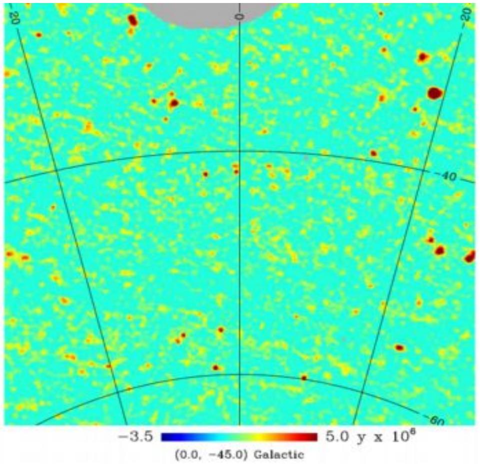
- Baryon physics?
- Hints of massive neutrinos?
- Biases?



188 clusters @S/N≥7 on 65% cleanest part of sky





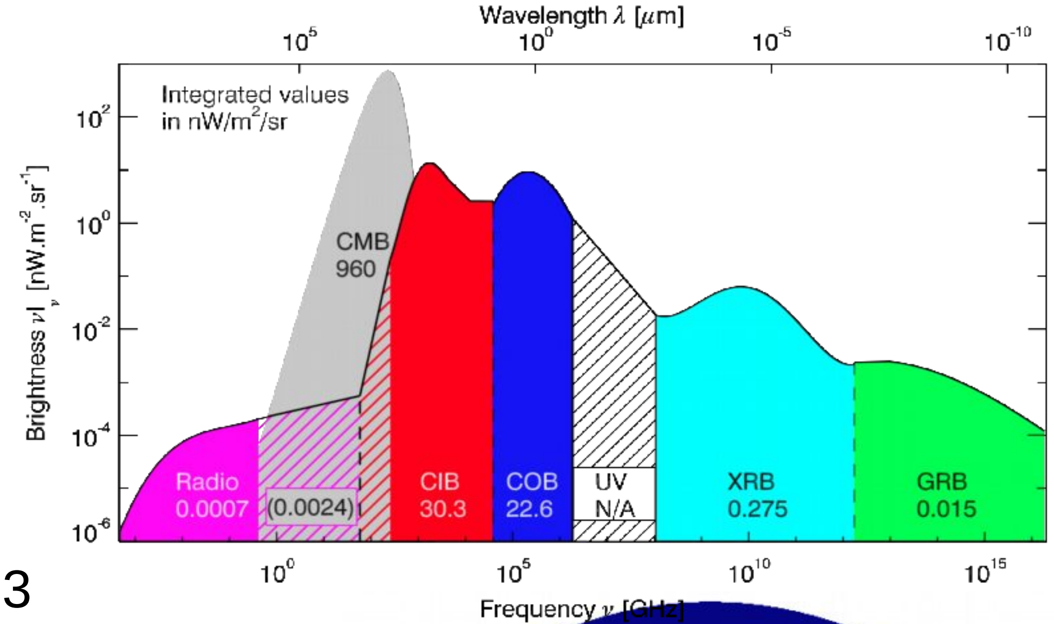


The first image the hot gas (baryons) distribution in the low-z universe using the SZ spectral signature

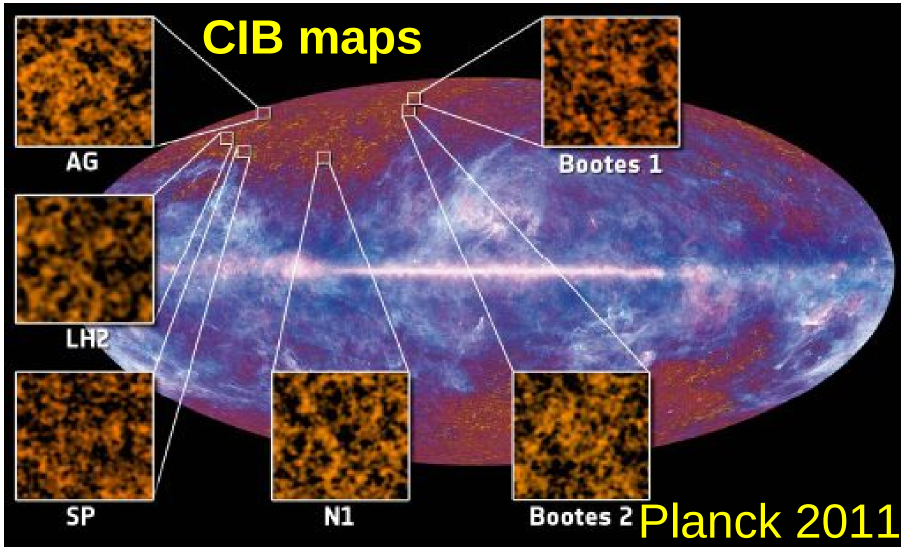
Star content of DM halos: Cosmic Infrared Background

CIB = star-heated dust within galaxies

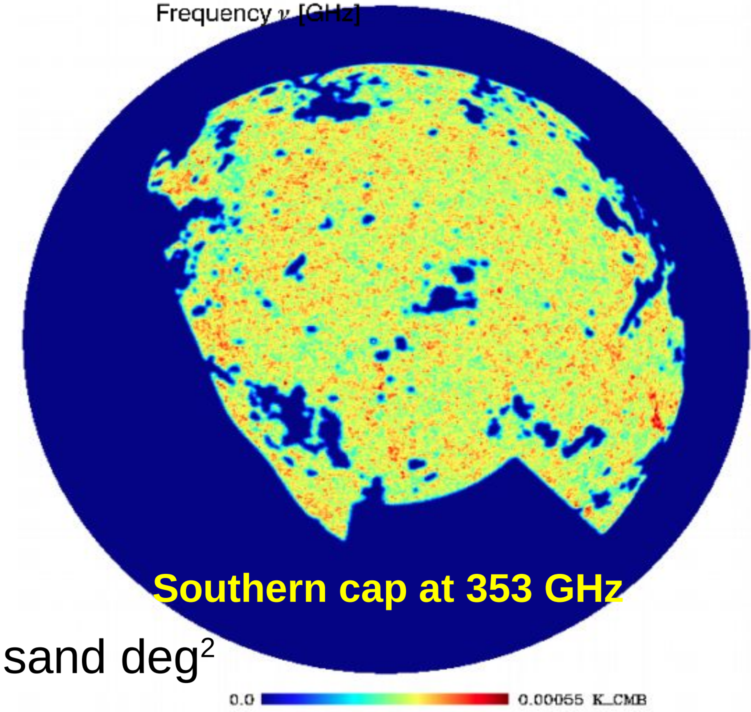
CIB = diffuse, background light from galaxies formed throughout cosmic history → wealth of information about the process of star formation



CIB by *Planck* → Forming galaxies @z~2-3



Sub-degree clustered structure, correlated across frequencies



From CIB anisotropies from ~40deg^2

To CIB on a few thousand deg^2

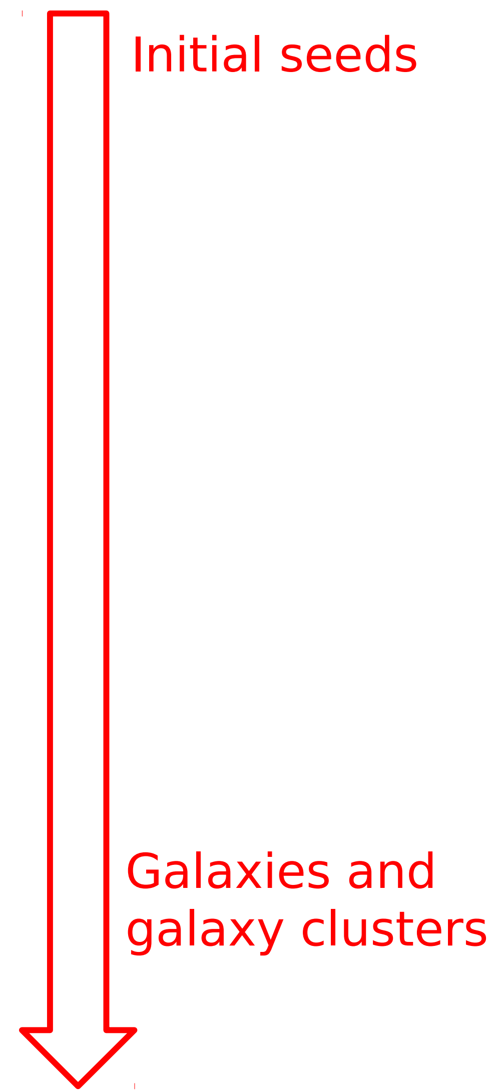
Planck's results

- The most precise image of CMB anisotropies
  - Thightest contraints on inflation
  - Challenge Λ-CDM cosmological model

- Test the dark energy component
  - correlation between the CMB and large-scale evolving gravitational potentials

- Test the structure growth by the weak lensing of CMB photons

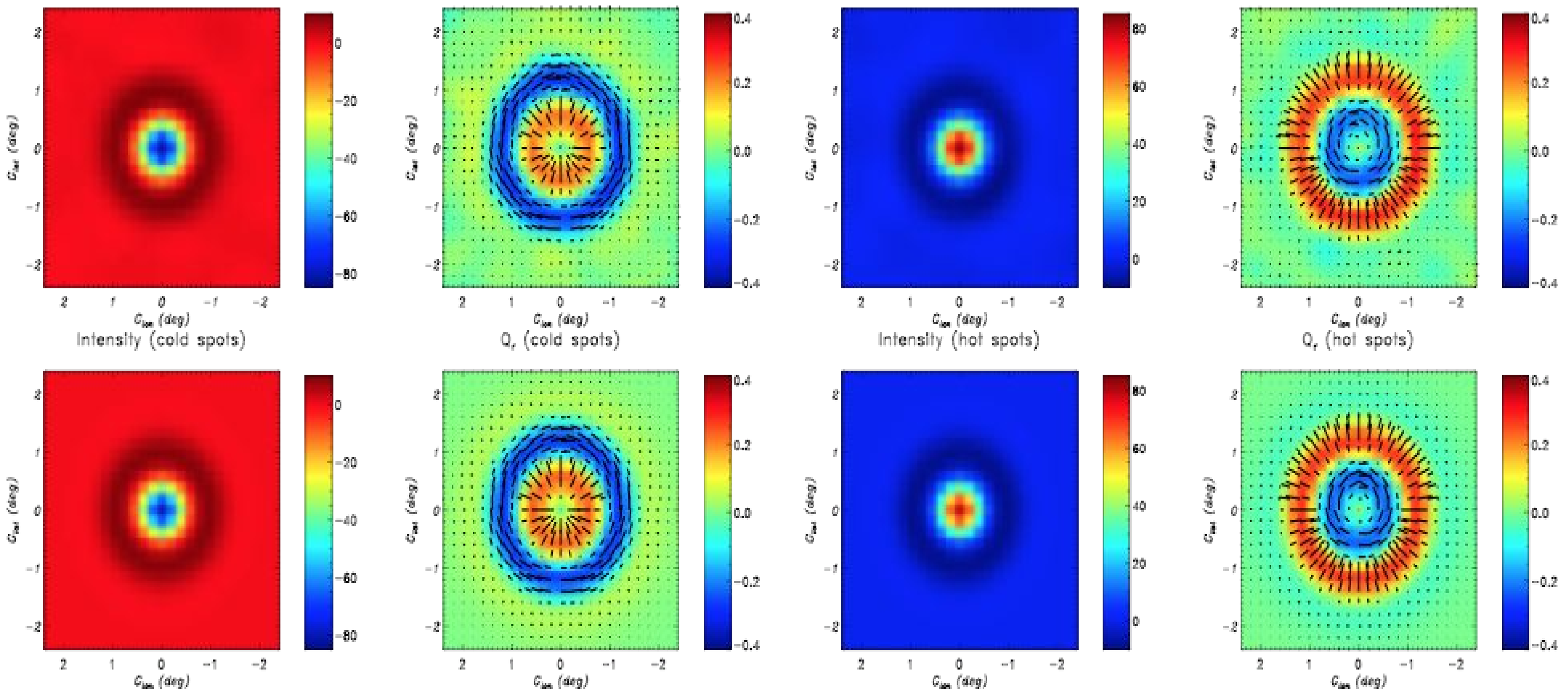
- Test the structure evolution and star formation history
  - Using SZ galaxy clusters
  - Using cross-correlation between the CMB Lensing and galaxy surveys
  - Using CIB anisotropies



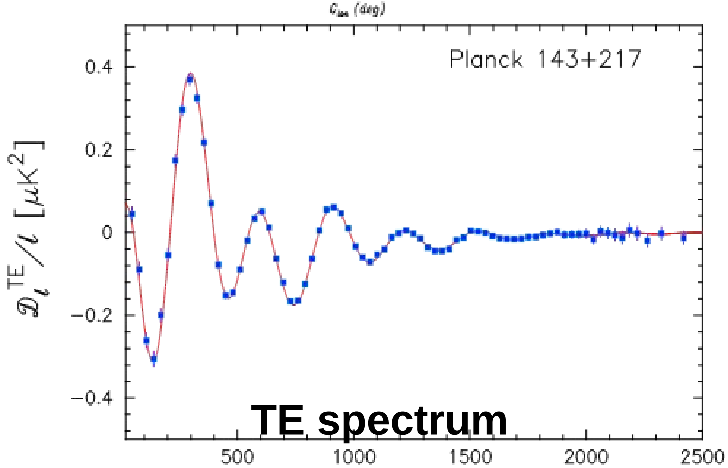
Planck is a CMB experiment with very wide astrophysical capabilities

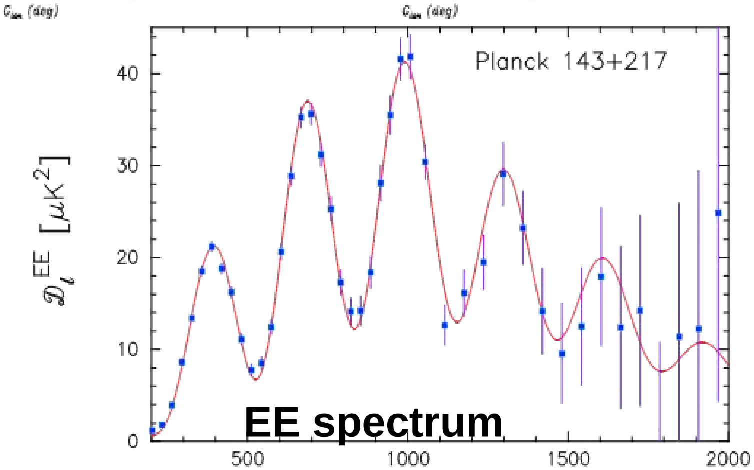
- All-sky survey
- Simultaneous observation from 30 to 857GHz
- First ever survey between 100-900GHz

In 2014 → Second release (5 surveys, 30 months) including polarisation



Planck polarisation pattern around **cold (red)** and **hot (blue)** spots






Thank you
Illust : Hurier, Douspis, Aghanim Data: Planck ESA/HFI/LFI