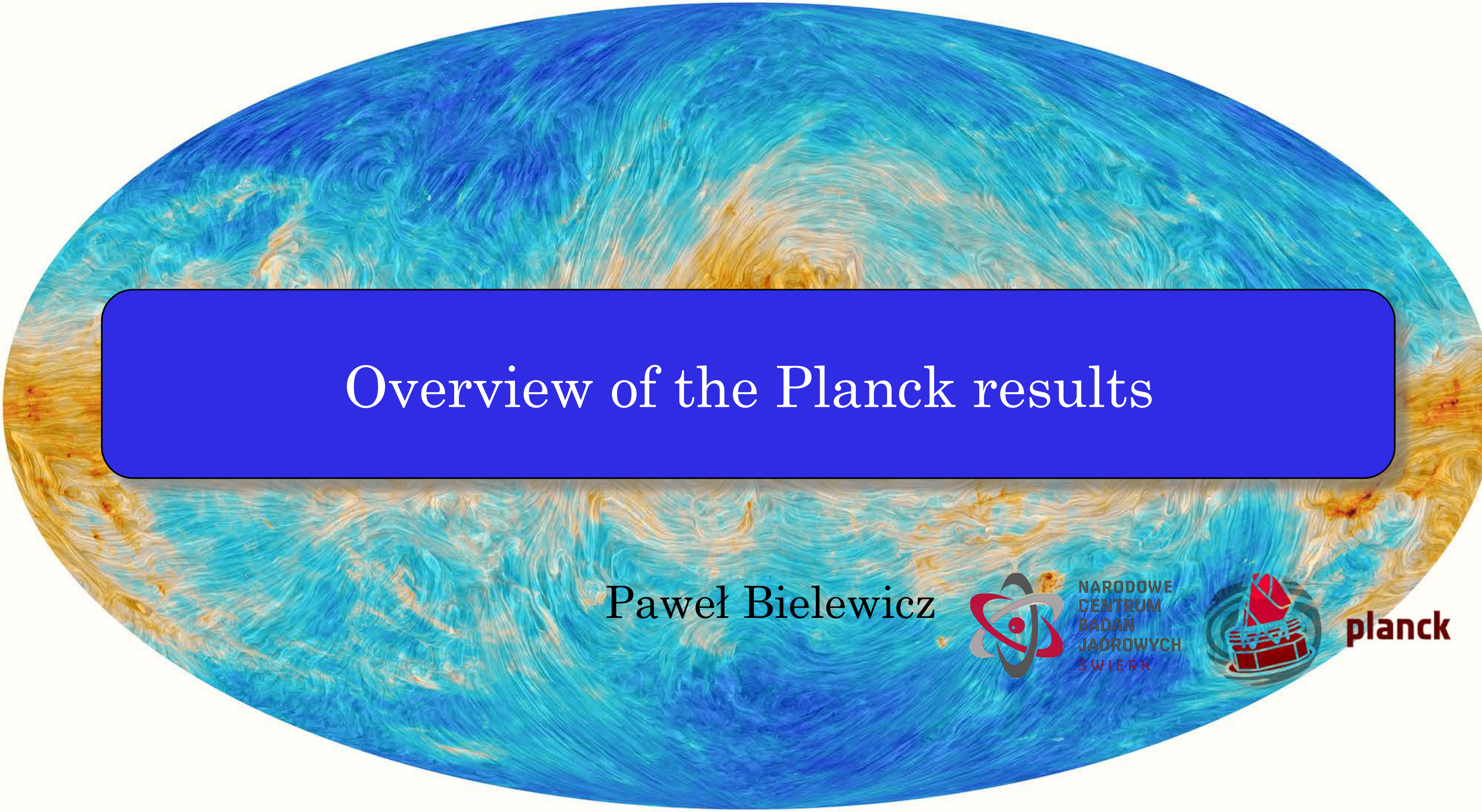
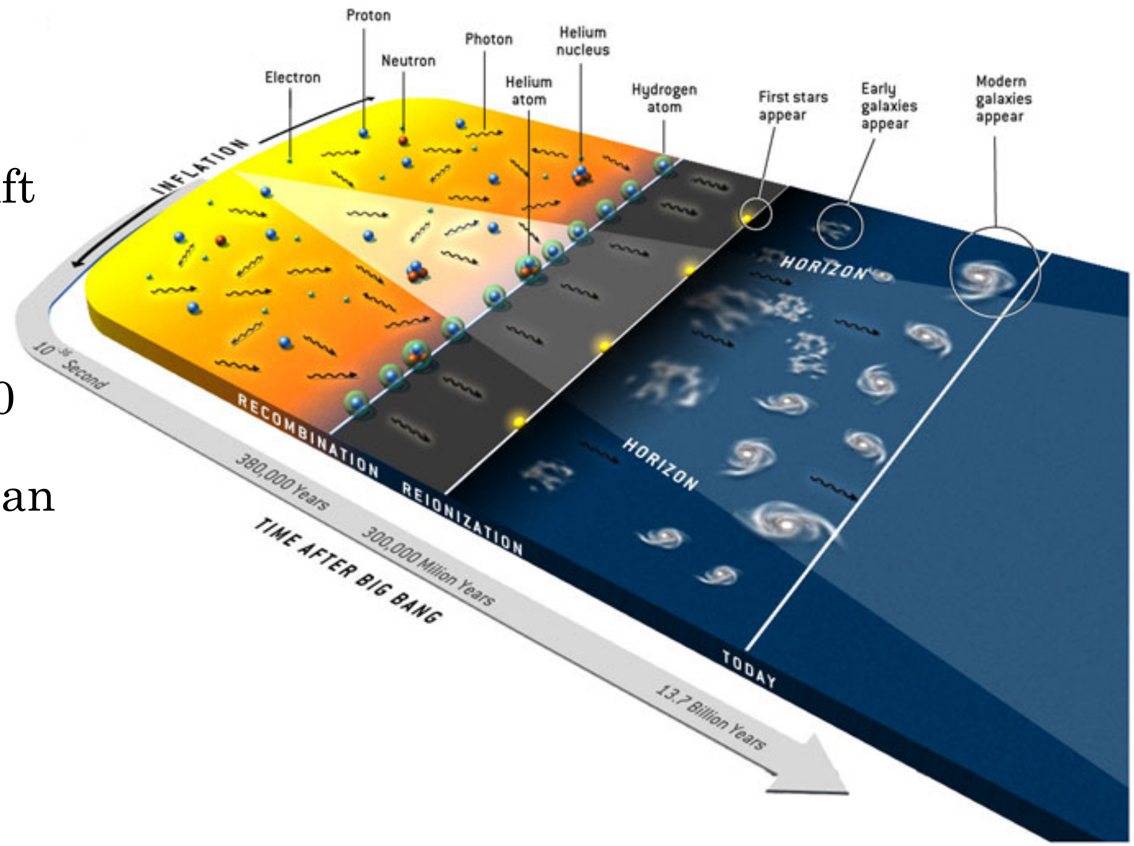


Overview of the Planck results

Paweł Bielewicz

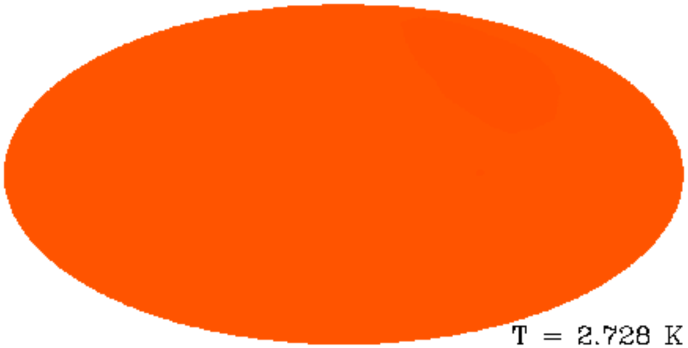
Cosmic Microwave Background

- Thermal radiation coming from early epochs of the Universe
- Blackbody power spectrum with temperature T = 2.7 K currently
- Decoupled from baryonic matter at redshift z = 1100 (~380 000 years after Big Bang)
- Anisotropy of order $\frac{\Delta T}{T_0} \approx 10^{-5}$ shows distribution of baryonic matter at z = 1100
- Inflationary models predict nearly Gaussian fluctuations with statistically isotropic distribution in the sky

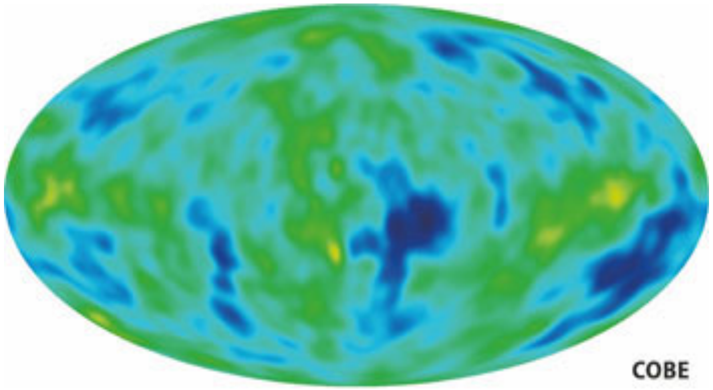


CMB observations

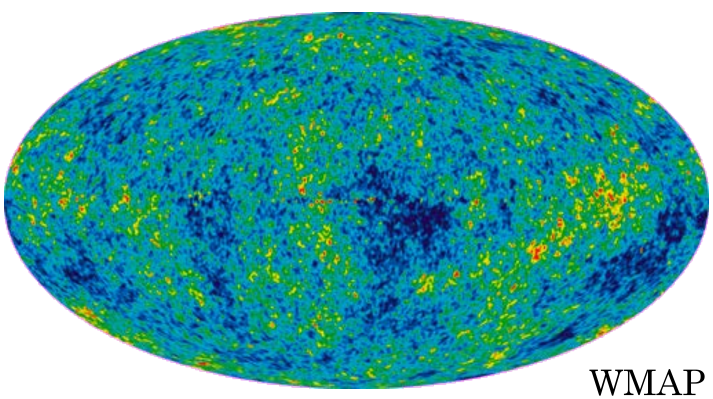
- Penzias & Wilson (1965): discovery of CMB (monopole T_0=2.7 K)
- COBE satellite (1992): blackbody spectrum, CMB primordial anisotropy $\frac{\Delta T}{T_0} \approx 10^{-5}$
- WMAP satellite (2003): establishment of the ΛCDM model



T = 2.728 K



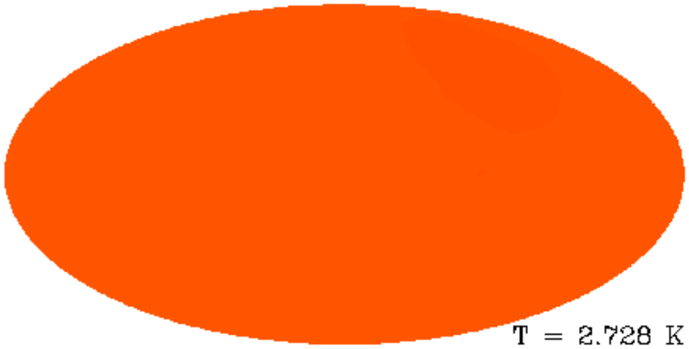
COBE

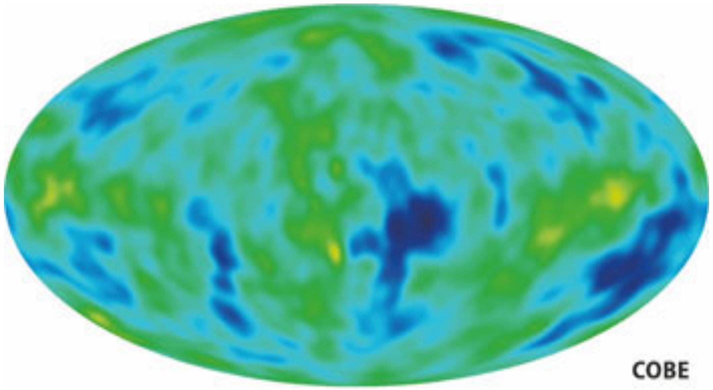


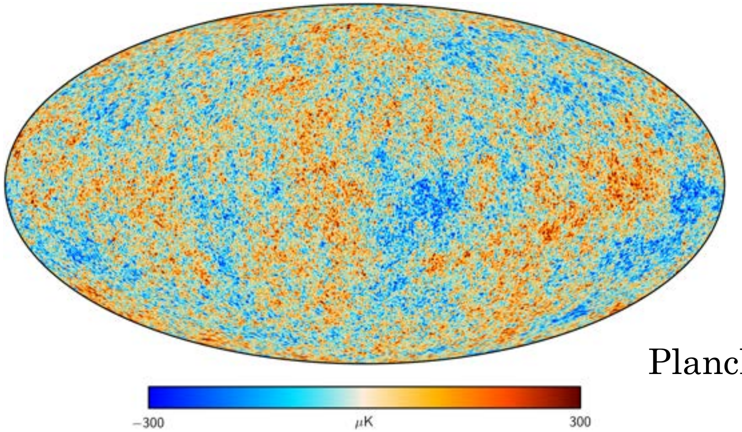
WMAP

CMB observations

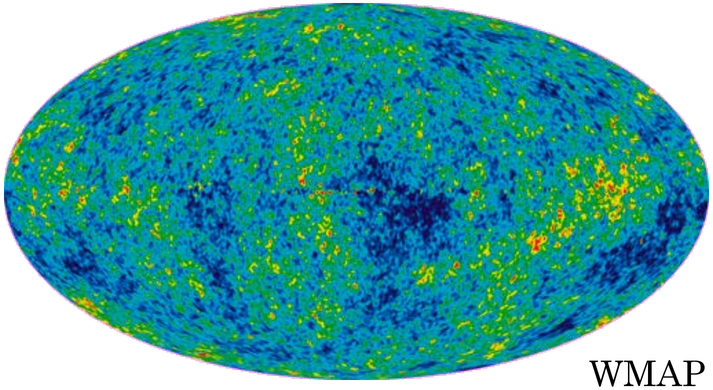
- Penzias & Wilson (1965): discovery of CMB (monopole T_0=2.7 K)
- COBE satellite (1992): blackbody spectrum, CMB primordial anisotropy $\frac{\Delta T}{T_0} \approx 10^{-5}$
- WMAP satellite (2003): establishment of the ΛCDM model
- Planck satellite (2014, 2016, 2020): cosmological parameters with precision better than 1%, scalar perturbation spectral index $n_s < 1$, tight constraints on Gaussianity of CMB anisotropy, first full sky submillimetre survey, better understanding of polarisation of Galactic emission







Planck



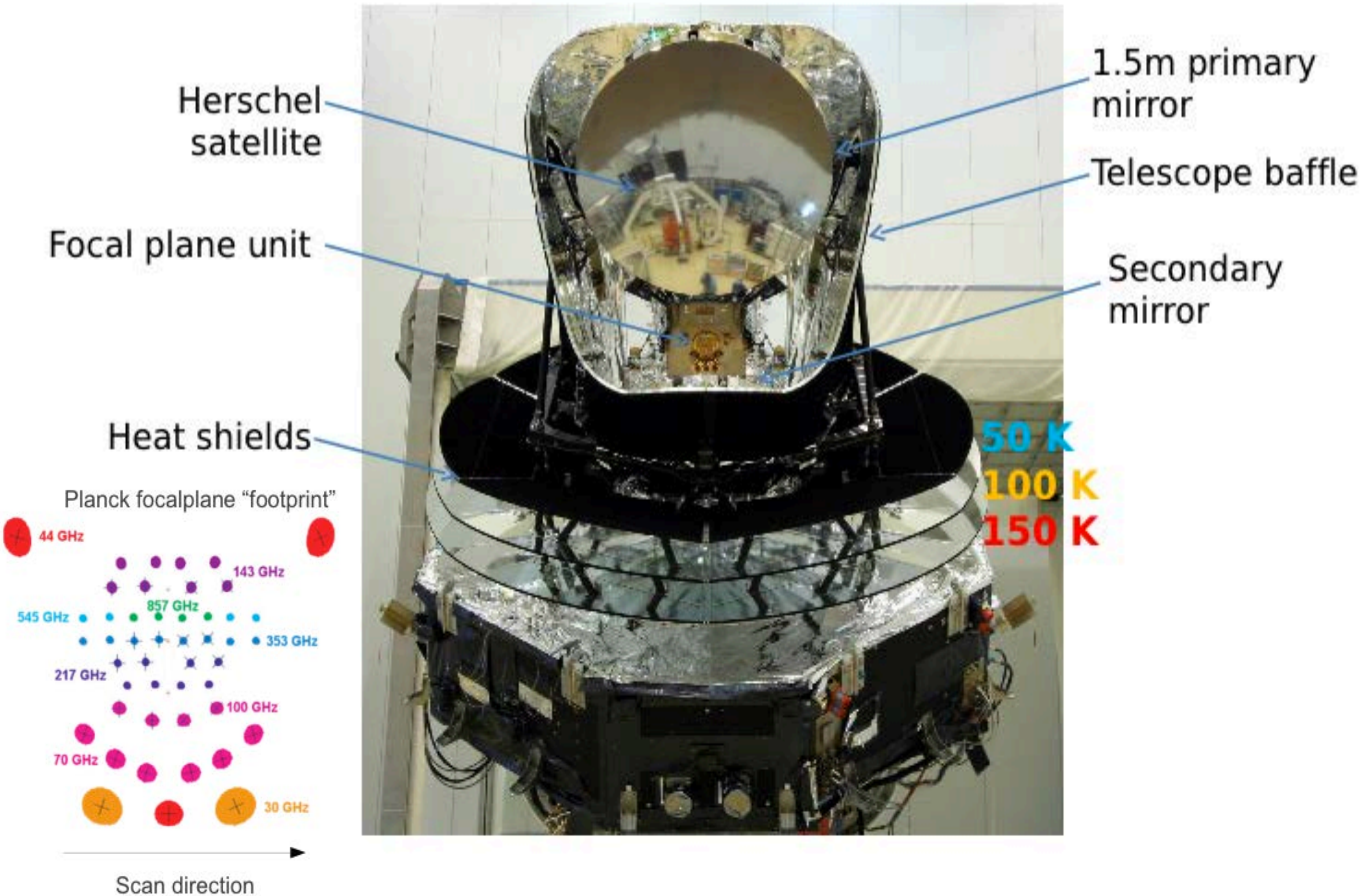
WMAP

Planck satellite

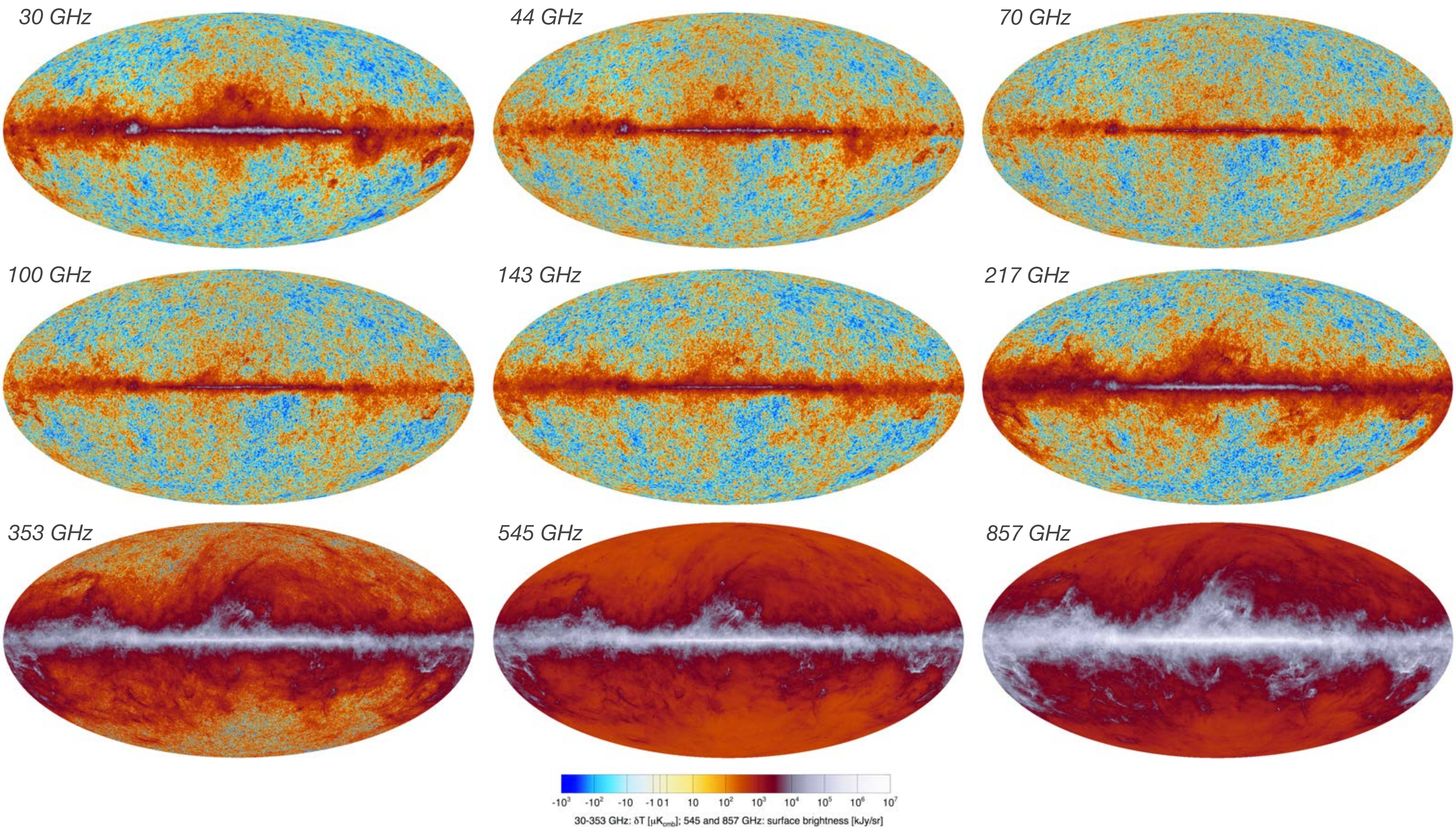
- Planck is an ESA satellite mission designed to perform the „final" measurement of the Cosmic Microwave Background (CMB) temperature fluctuations in the region where the primary contribution is dominant. It was also designed to measure to high accuracy polarization of the CMB anisotropies
- Two instruments on board:
  - Low Frequency Instrument (LFI) (HEMT low noise amplifiers)
  - High Frequency Instrument (HFI) (spider web and polarisation sensitive bolometers)
- Wide frequency coverage with nine channels from 30 to 857 GHz
- Full sky coverage
- Angular resolution from 33' down to 5'
- High sensitivity
- Launched in May 2009, observations till August 2013

The scientific results that we present today are the product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

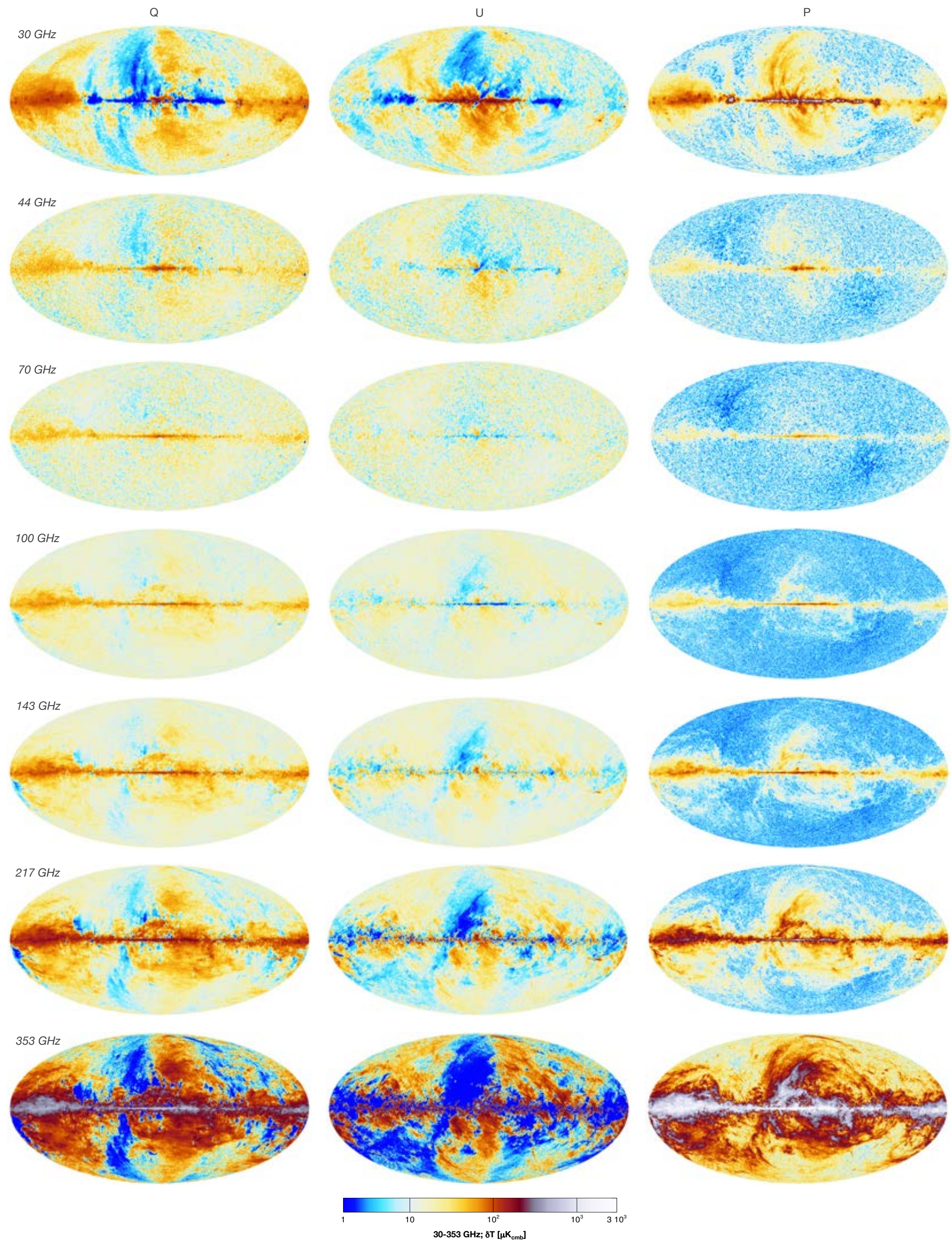
Planck satellite



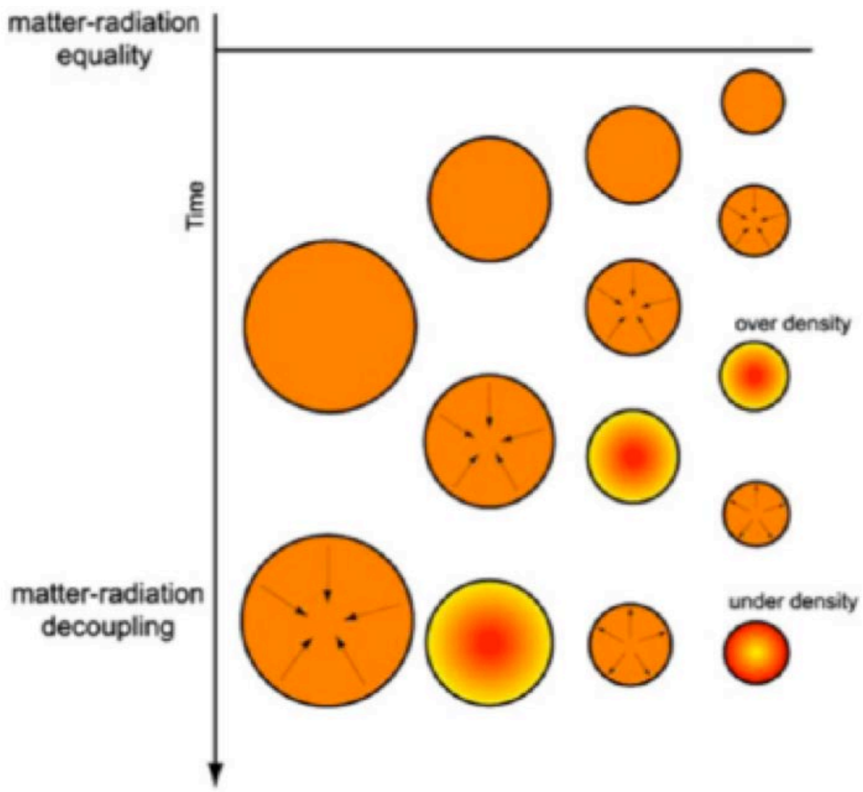
CMB temperature maps

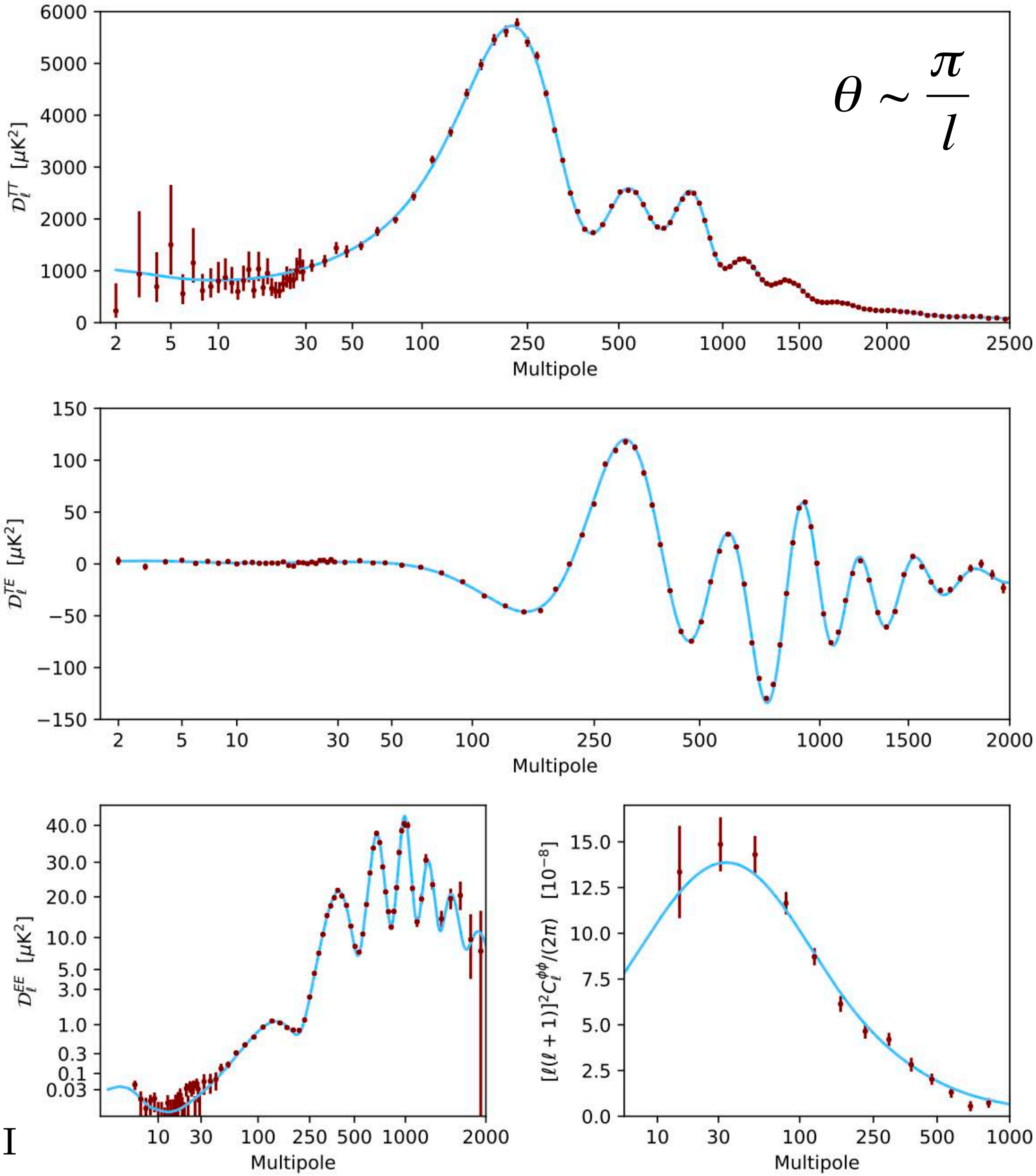


CMB polarisation maps



Angular power spectra of CMB maps

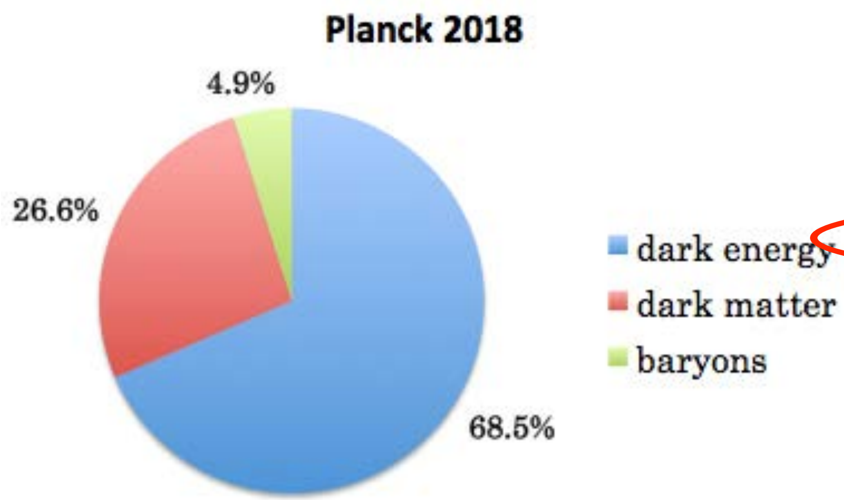




Planck 2018 results I

The base ΛCDM model

- Planck 2018 CMB data sufficiently well described by six parameter model
- Cosmological parameters estimated with precision of order percent or smaller

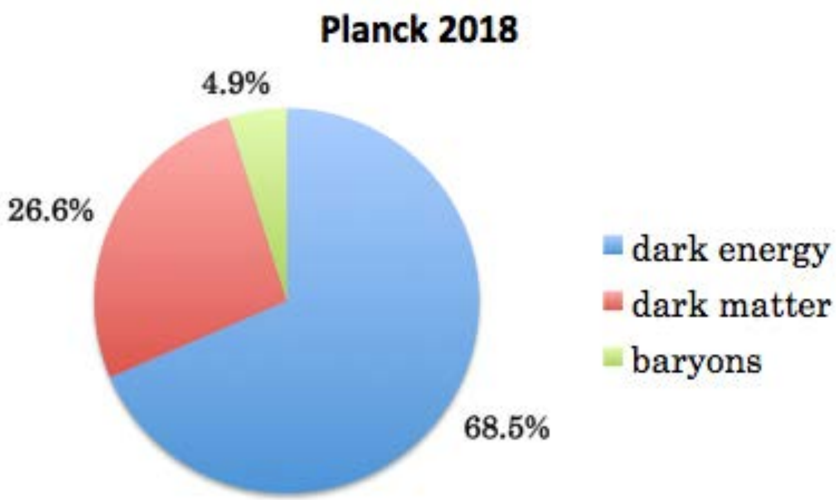


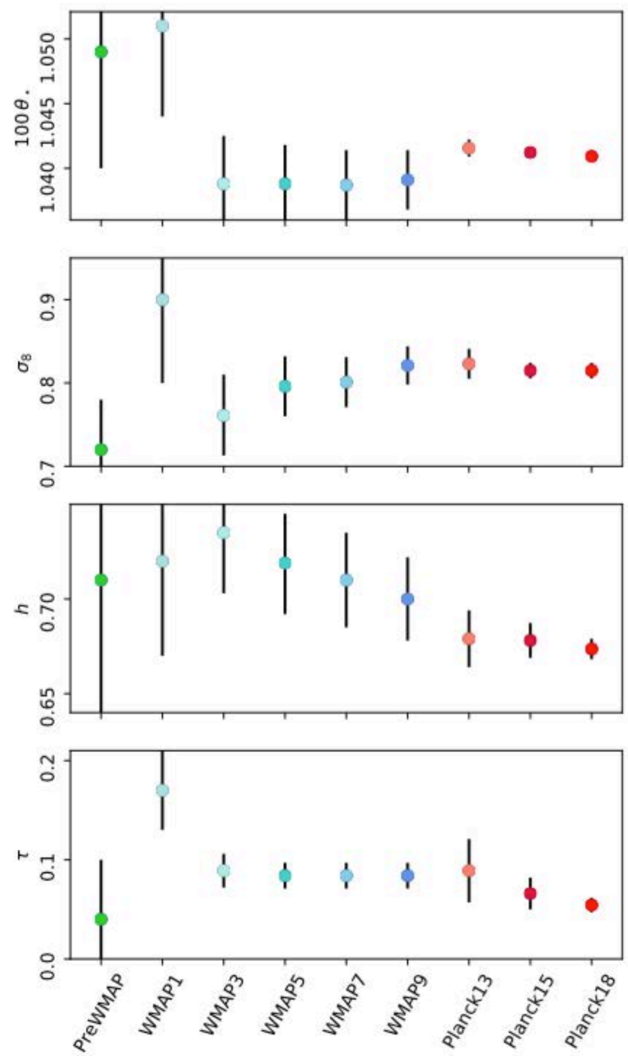
Parameter	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056

Planck 2018 results VI

The base ΛCDM model

- Planck 2018 CMB data sufficiently well described by six parameter model
- Cosmological parameters estimated with precision of order percent or smaller



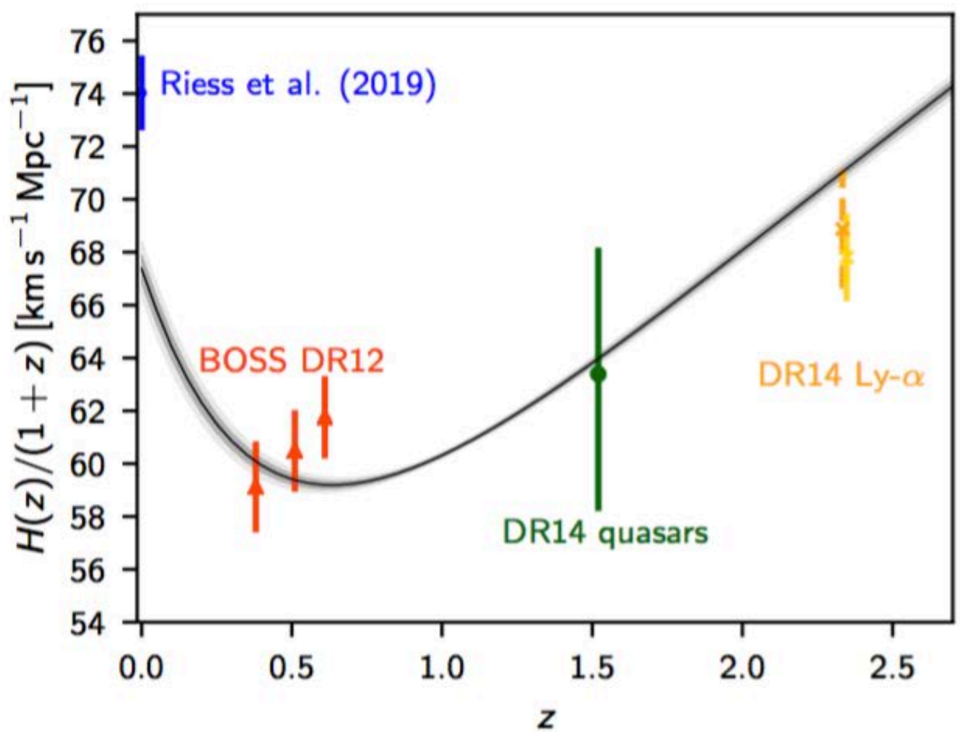


Planck 2018 results VI

The Hubble constant

$$H_0 = 67.36 \pm 0.54 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (68\%; \text{ Planck TT,TE,EE + lowE + lensing})$$

- In tension at ~4.5σ level with some estimates based on supernovae (SH0ES project)
- Estimation of the Hubble constant from CMB data is highly model dependent



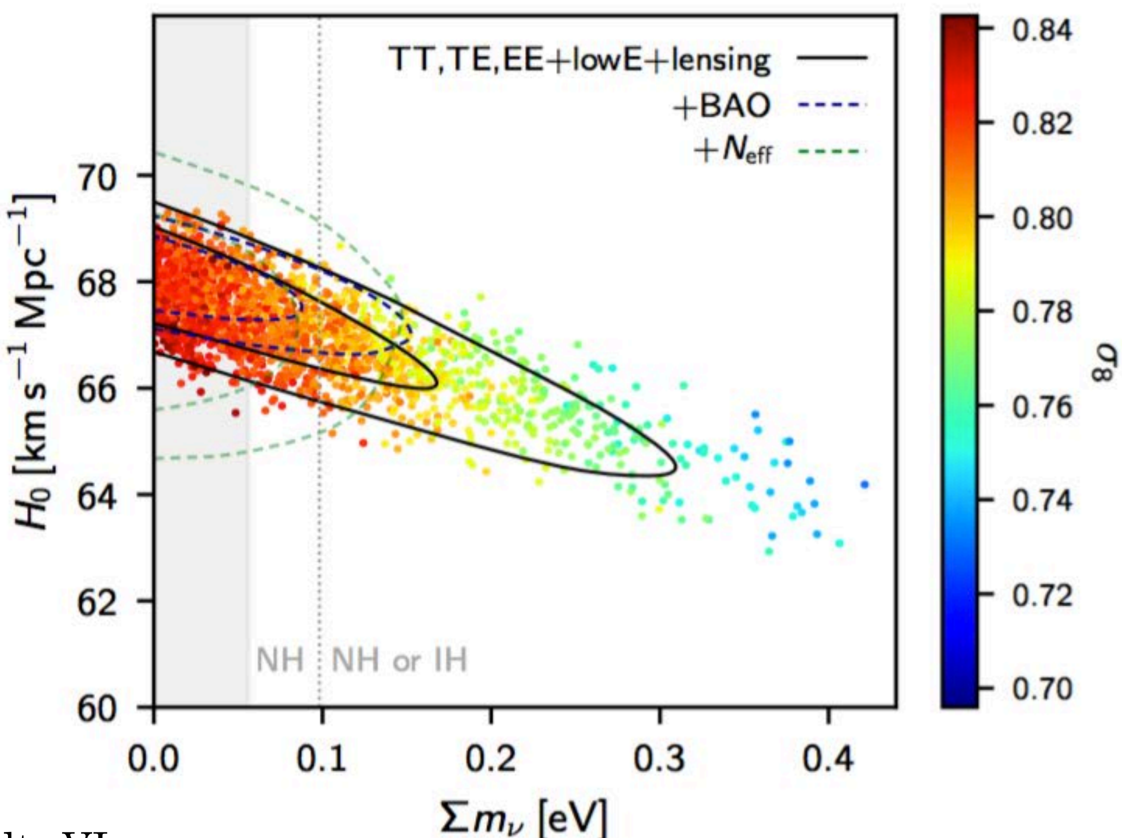
Planck 2018 results VI

Constraints on total mass of neutrinos

- The Planck base ΛCDM model assumes a normal mass hierarchy with $\sum m_\nu = 0.06\,\mathrm{eV}$
- Model dependent estimation of total mass of neutrinos from CMB

$$\sum m_\nu < 0.24\,\mathrm{eV} \quad (95\%;\ \text{Planck TT, TE, EE + lowE + lensing})$$

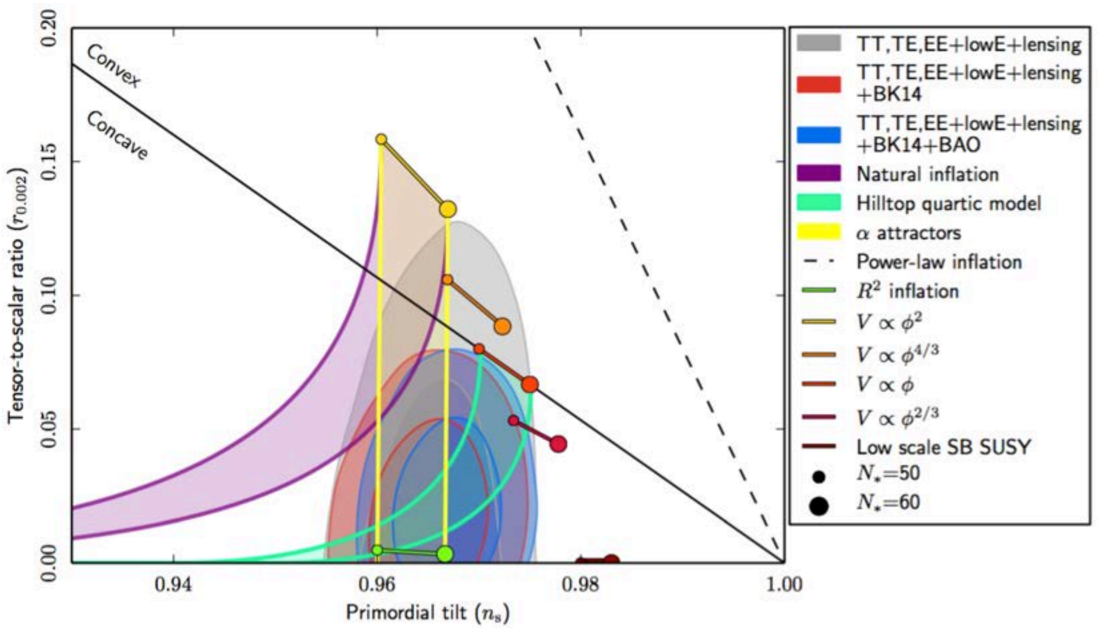
$$\sum m_\nu < 0.13\,\mathrm{eV} \quad (95\%;\ \text{Planck TT, TE, EE + lowE + lensing + BAO})$$



Planck 2018 results VI

Constraints on primordial gravitational waves

- Tensor-to-scalar ratio $r \equiv \dfrac{P_t(k_0)}{P_R(k_0)}$
- No detection of B-mode polarisation generated by tensor modes
- Upper bound based on contribution of tensor modes to the temperature and E-mode polarisation anisotropy (indirect constraint, dependent on theoretical model)

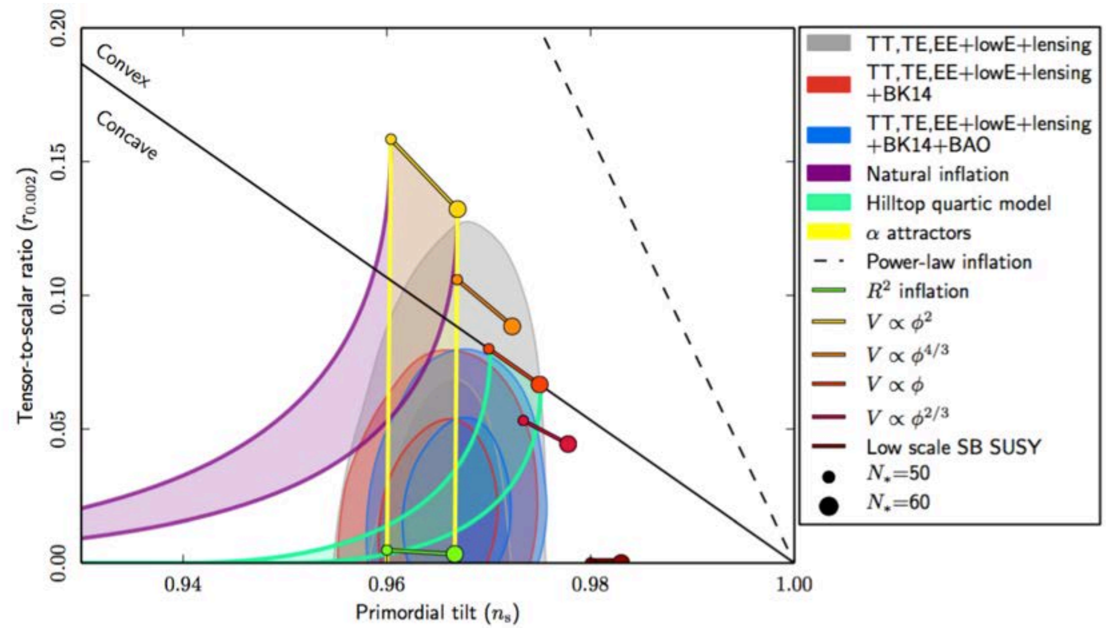


$r_{0.002} < 0.10$ (95%; Planck TT,TE,EE +lowE +lensing)

Planck 2018 results X

Constraints on primordial gravitational waves

- Tensor-to-scalar ratio $r \equiv \frac{P_t(k_0)}{P_R(k_0)}$
- No detection of B-mode polarisation generated by tensor modes
- Upper bound based on contribution of tensor modes to the temperature and E-mode polarisation anisotropy (indirect constraint, dependent on theoretical model)



$$r_{0.002} < 0.10 \quad (95\%;\ \text{Planck TT,TE,EE} + \text{lowE} + \text{lensing})$$

Planck 2018 results X

- Upper bound including BICEP2 data (direct constraint on B-mode polarisation)

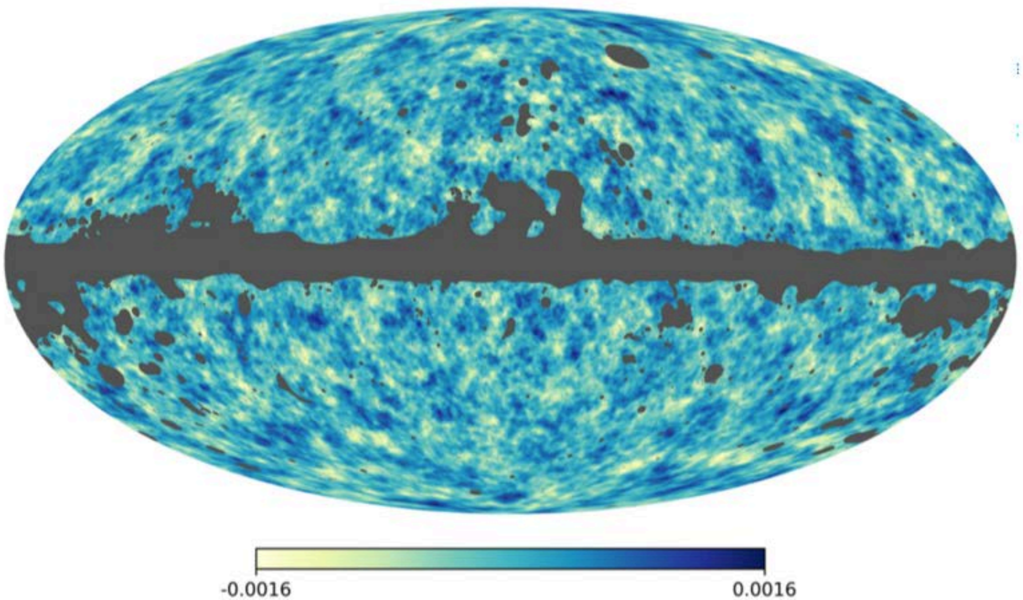
$$r_{0.002} < 0.058 \quad (95\%;\ \text{Planck TT,TE,EE} + \text{lowE} + \text{lensing} + \text{BK14} + \text{BAO})$$

$$E_{\text{inf}} < 1.7 \times 10^{16}\ \text{GeV} \quad (95\%)$$

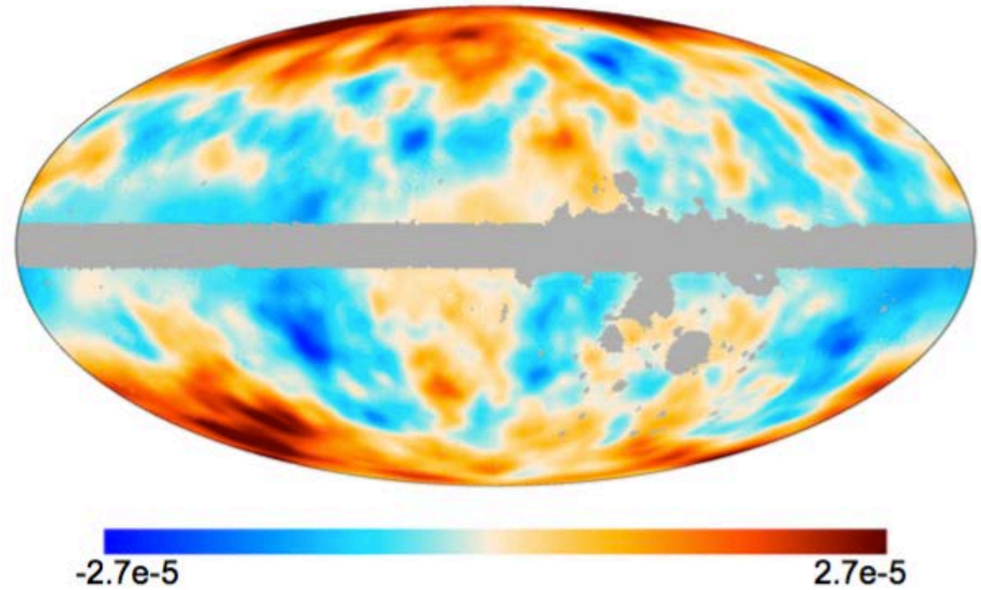
- Slow-roll single-field inlationary models preferred ($n_s < 1$)

Measurements of secondary CMB anisotropies

Gravitational lensing of CMB

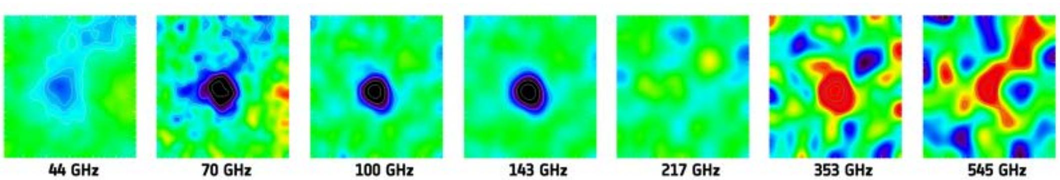


Integrated Sachs-Wolfe effect

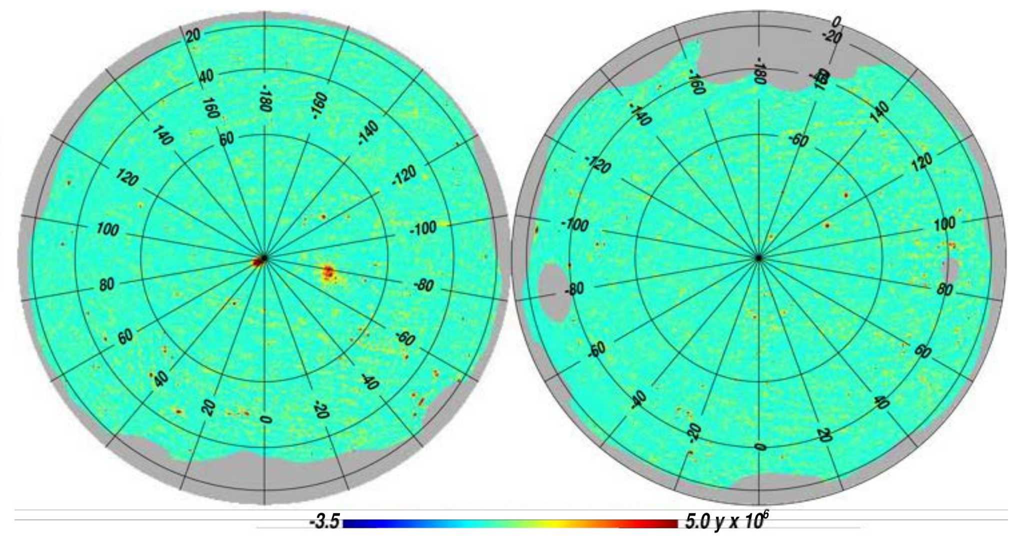


Thermal Sunyaev-Zeldovich effect

1653 SZ clusters detected



Abell 2319 cluster



Summary

- The Planck satellite performed final measurement of primary CMB temperature anisotropy
- Observations confirm the standard ΛCDM model (no need of extension)
- Cosmological parameters with precision better than 1%
- Spectral index of scalar perturbations < 1 (single-field inflationary models preferred)
- Neutrino masses constrained to be < 0.1 eV
- Full sky map of the CMB lensing potential (tracer of dark matter)
- The Hubble constant in tension at ~4.5 σ level with estimates based on supernovae
- No detection of primordial non-Gaussianity
- Upper bound on tensor-to-scalar ratio < 0.06
- Better understanding of polarisation of Galactic emission (necessary in search for signatures of the primordial gravitational waves)