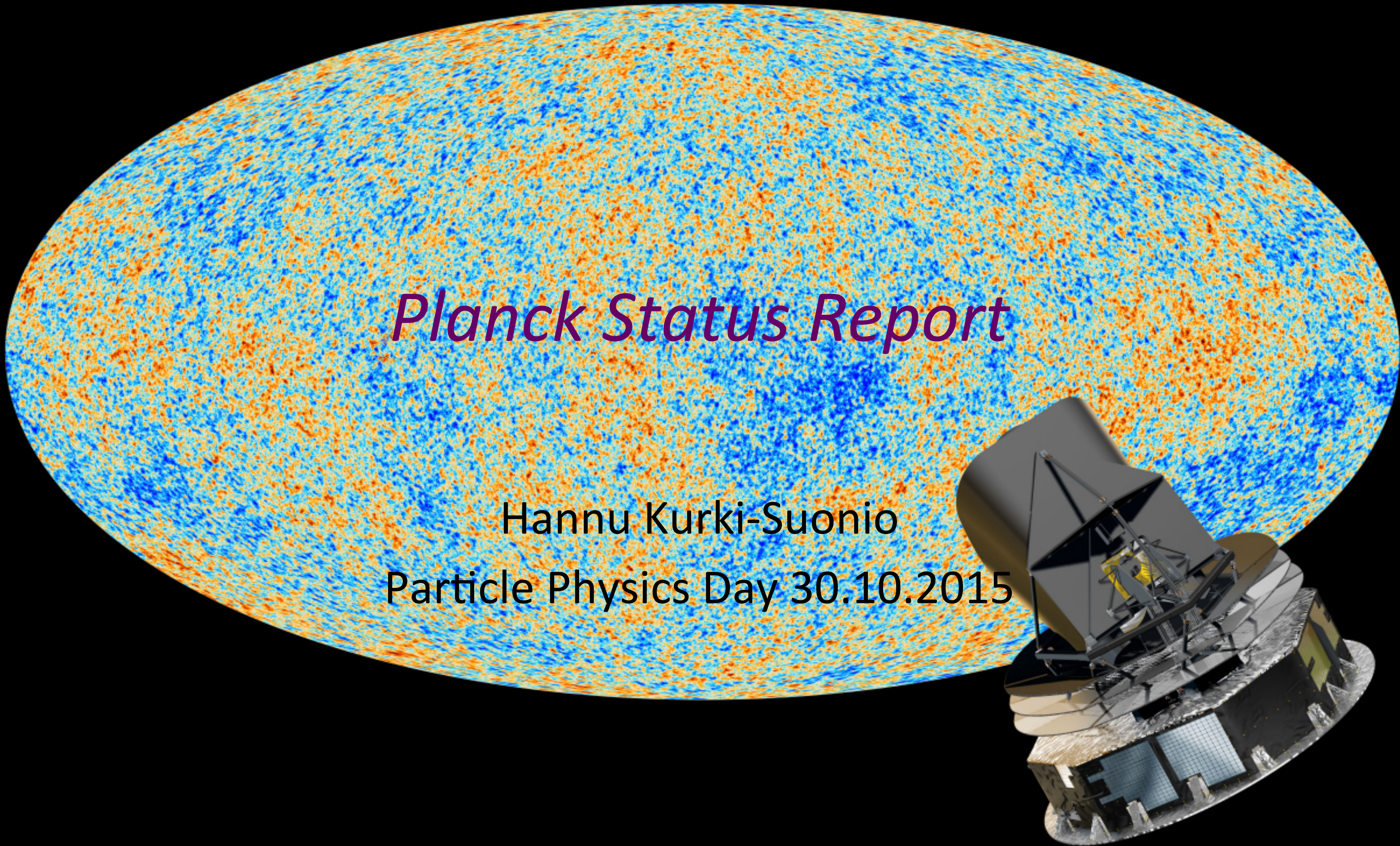
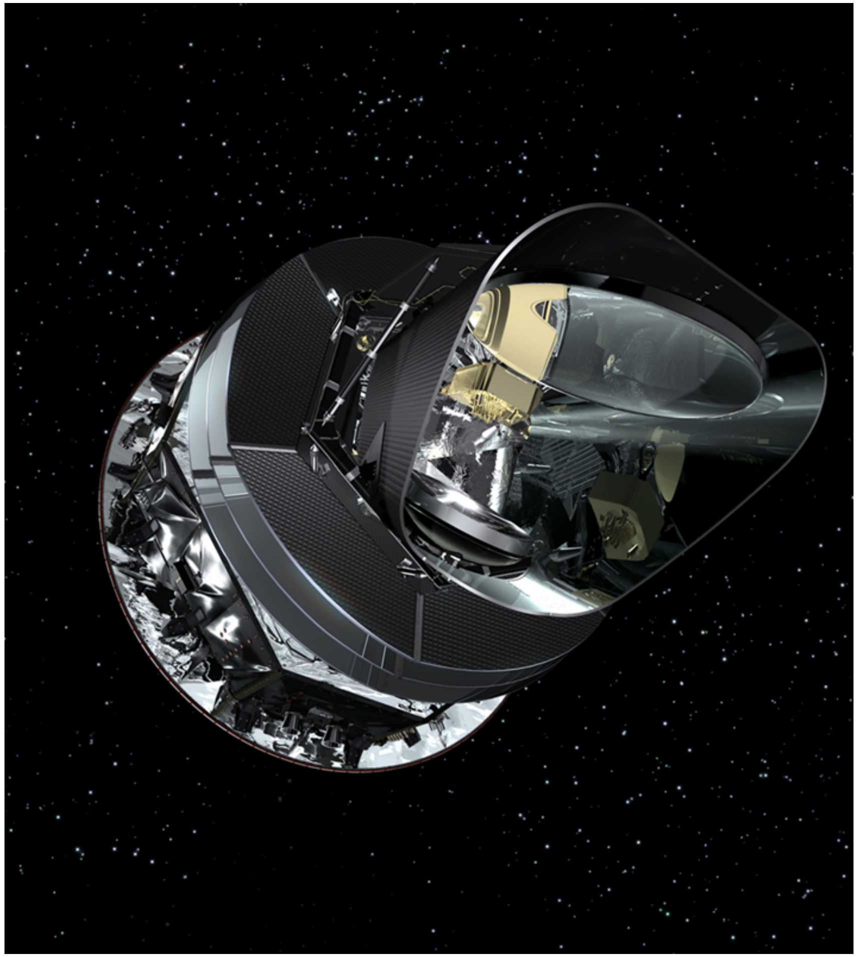
Planck Status Report

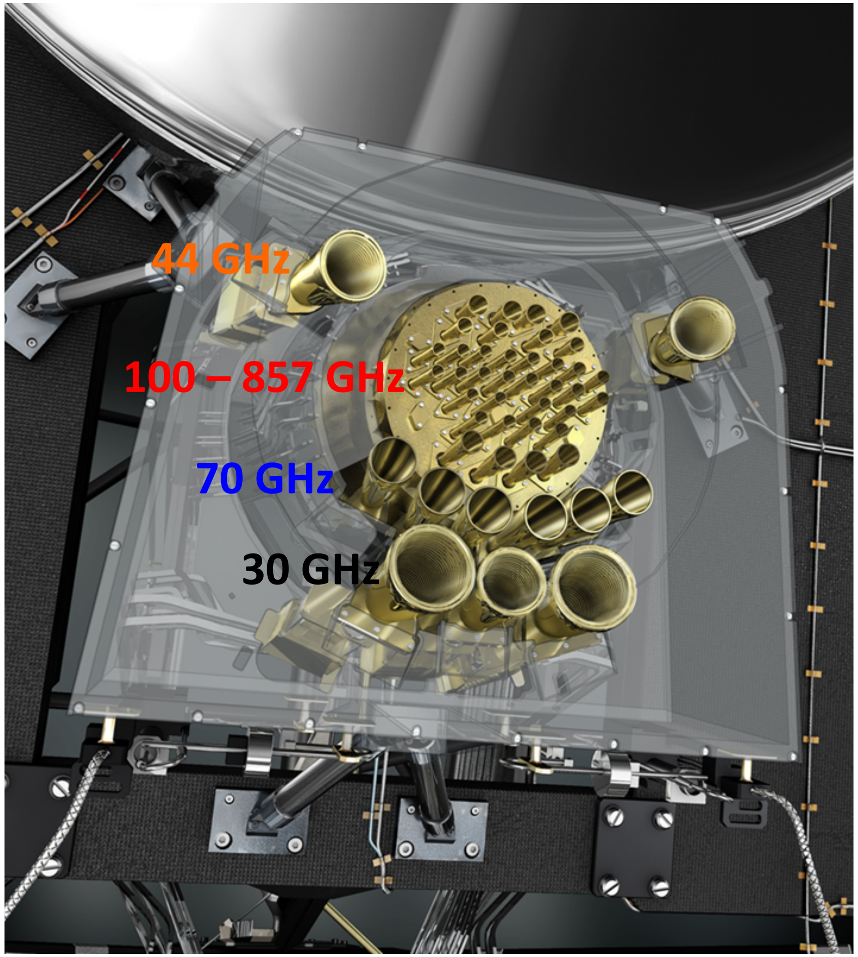


Hannu Kurki-Suonio

Particle Physics Day 30.10.2015

on behalf of the Planck Collaboration





Planck = The European Space Agency (ESA) satellite to observe the Cosmic Microwave Background (CMB) at 9 frequency bands

Two instruments:
Low Frequency Instrument (LFI): 30, 44, 70 GHz
High Frequency Instrument (HFI): 100, 143, 217, 353, 545, 857 GHz

Finnish Contribution

- The 70 GHz radiometers (MilliLab, Ylinen Electronics / DA-Design)
- On-board software (Space Systems Finland)
- Data analysis and science (University of Helsinki, HIP, Metsähovi Observatory, Tuorla Observatory)

Timeline

- Launch 14 May 2009
- Observations begin 12 Aug 2009
- HFI observations end 13 Jan 2012
- LFI observations end 23 Oct 2013
- First data release March 2013
- Second data release February – July 2015
- Final data release 2016

Planck Legacy Archive

Release PR

WELCOME TO THE PLANCK LEGACY ARCHIVE

The European Space Agency's Planck space telescope, dedicated to studying the early Universe and its subsequent evolution, was launched on May 14th, 2009 and scanned the microwave and submillimetre sky continuously for more than four years between Aug. 12th, 2009 and Oct. 3rd, 2013.

The Planck Legacy Archive provides online access to all official data products generated by the Planck mission.

http://pla.esac.esa.int/pla/

PLANCK LEGACY ARCHIVE CONTENTS

MAPS
Search through all maps stored in the Planck Legacy Archive.

CATALOGUES
Perform queries on all catalogues in the Planck Legacy Archive.

COSMOLOGY
Browse cosmology products of the Planck Legacy Archive.

TIMELINES
Perform coordinate-based and time-based queries on all Planck time-ordered data.

INSTRUMENT MODELS & SOFTWARE
Browse instrument models and software of the Planck Legacy Archive.

OPERATIONAL DATA
Spacecraft and instrument house-keeping data acquired during Planck operations.

USEFUL INFORMATION

EXPLANATORY SUPPLEMENT
Detailed information on all Planck Legacy Archive products.

EXTERNAL DATA & SOFTWARE
Links to external data related to Planck products.

PLANCK COLLABORATION PAPERS
List of scientific publications by the Planck consortium.

USE OF PLANCK DATA
How to acknowledge the use of Planck products.

PLANCK LEGACY ARCHIVE UPDATE HISTORY
Changes to Planck Legacy Archive products and functionalities.

PLANCK SCIENCE TEAM HOME
General information on Planck directed to the astronomical community.

Planck data products and results

- Maps of the sky at 9 microwave frequencies (polarization for 7)
- Maps of CMB and foreground components
- Map of CMB lensing potential (projected mass)
- Catalogs of compact sources
- Likelihood code (for CMB angular power spectrum and lensing)
- Cosmological parameters
- Upper limits to extensions of standard model of cosmology

Planck impact and Finland

Planck	Papers	Citations (INSPIRE)	Mean #authors	authors from Finland
Early Results	26	1634	202	7.7 (3.8%)
2013 Results	31	9160	239	8.9 (3.7%)
Intermediate Results	39	834	192	5.6 (2.9%)
2015 Results	28	1869	237	7.3 (3.2%)
Total	124	13497		

Non-Planck Papers using Planck data: 704 by Sep 10, 2015

The *Planck* Collaboration acknowledges the support of: ESA; CNES and CNRS/INSU-IN2P3-INP (France); ASI, CNR, and INAF (Italy); NASA and DoE (USA); STFC and UKSA (UK); CSIC, MINECO, JA, and RES (Spain); Tekes, AoF, and CSC (Finland); DLR and MPG (Germany); CSA (Canada); DTU Space (Denmark); SER/SSO (Switzerland); RCN (Norway); SFI (Ireland); FCT/MCTES (Portugal); ERC and PRACE (EU).

Finland 6th country

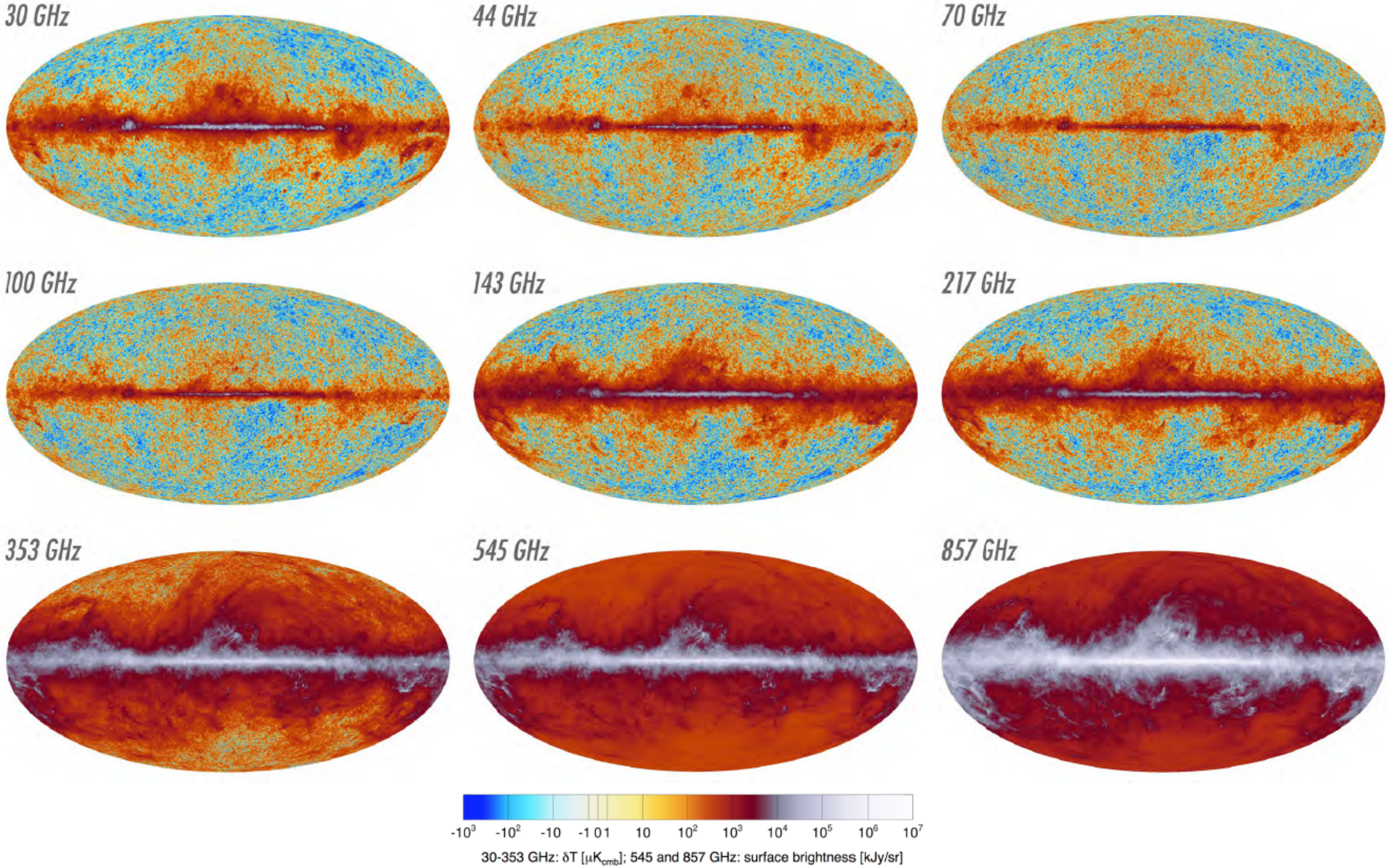
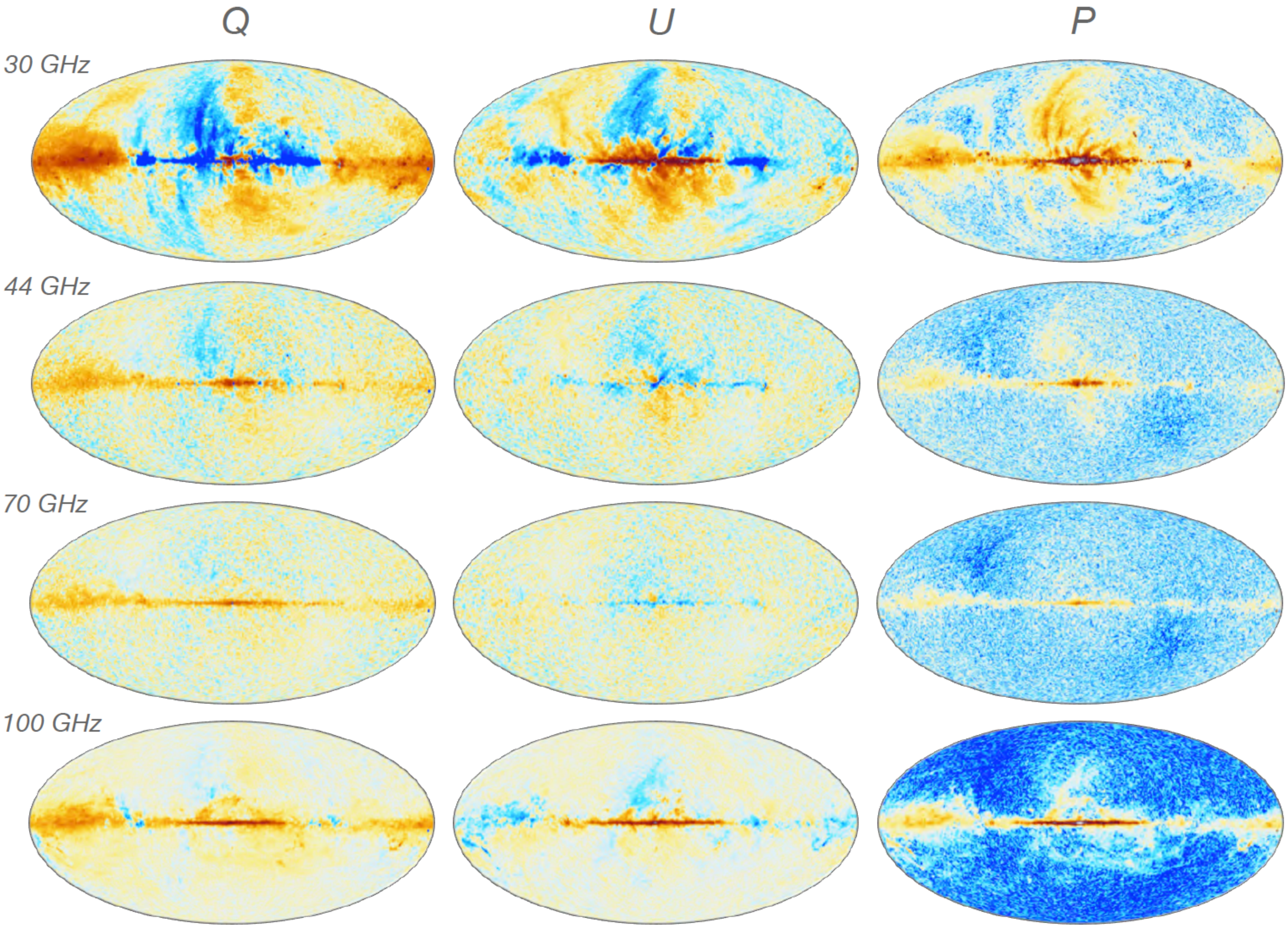
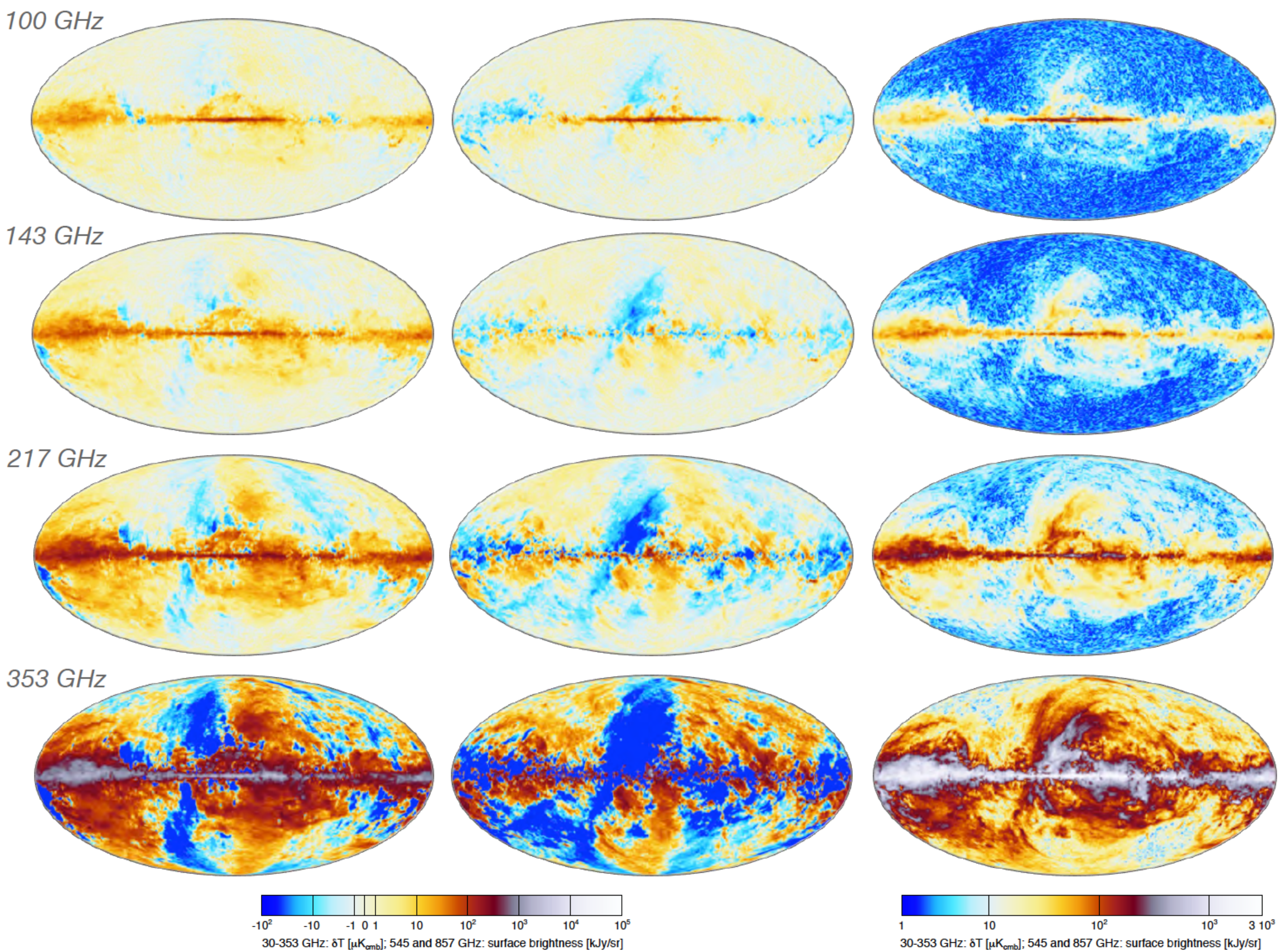


Fig. 7. The nine *Planck* frequency maps show the broad frequency response of the individual channels. The color scale (identical to the one used in 2013), based on inversion of the function $y = 10^x - 10^{-x}$, is tailored to show the full dynamic range of the maps.


Q
U
P
30 GHz
44 GHz
70 GHz
100 GHz


100 GHz
143 GHz
217 GHz
353 GHz
-10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5
30-353 GHz: δT [μK_cmb]; 545 and 857 GHz: surface brightness [kJy/sr]
1 10 10^2 10^3 3 10^3
30-353 GHz: δT [μK_cmb]; 545 and 857 GHz: surface brightness [kJy/sr]

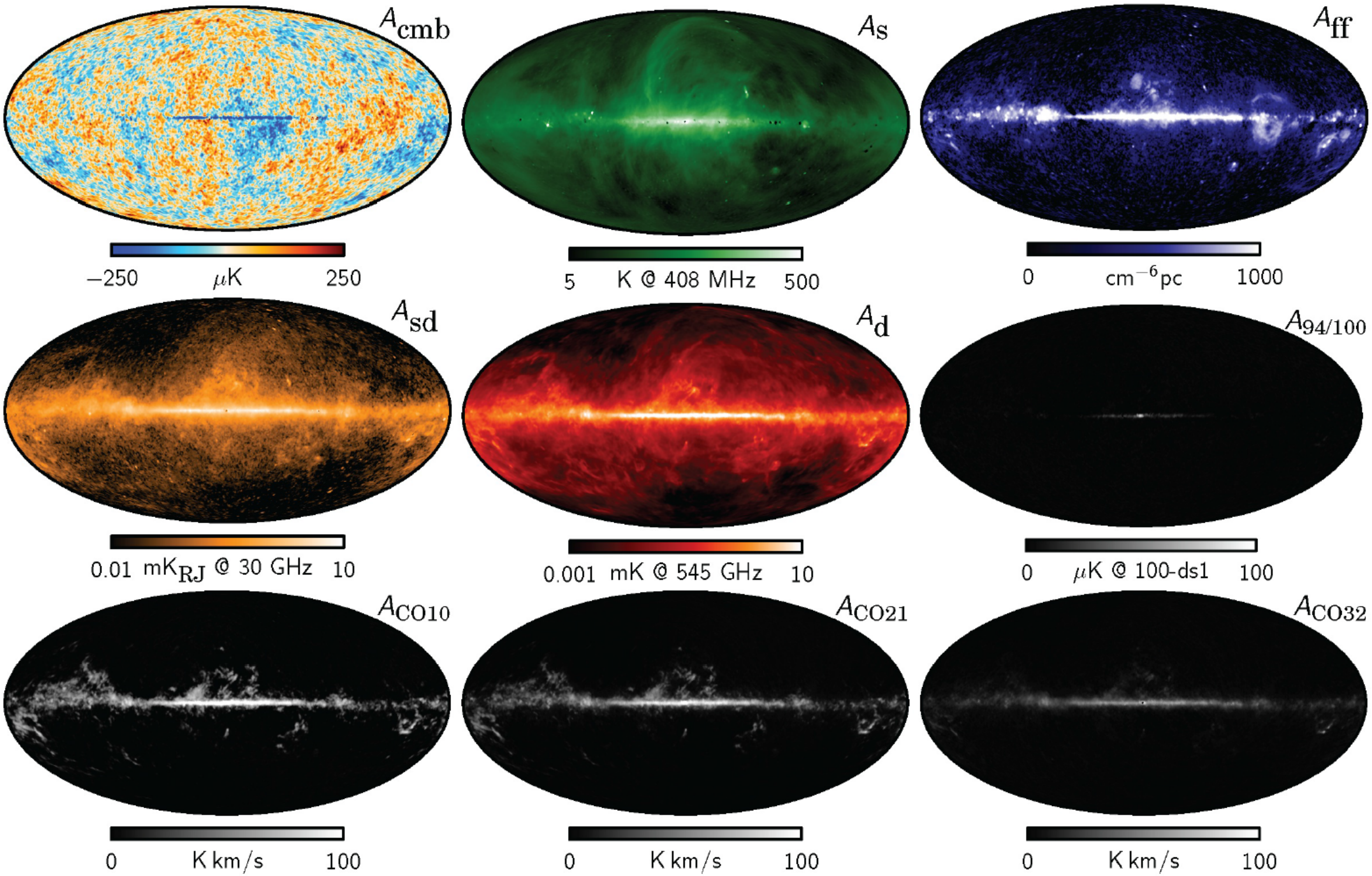
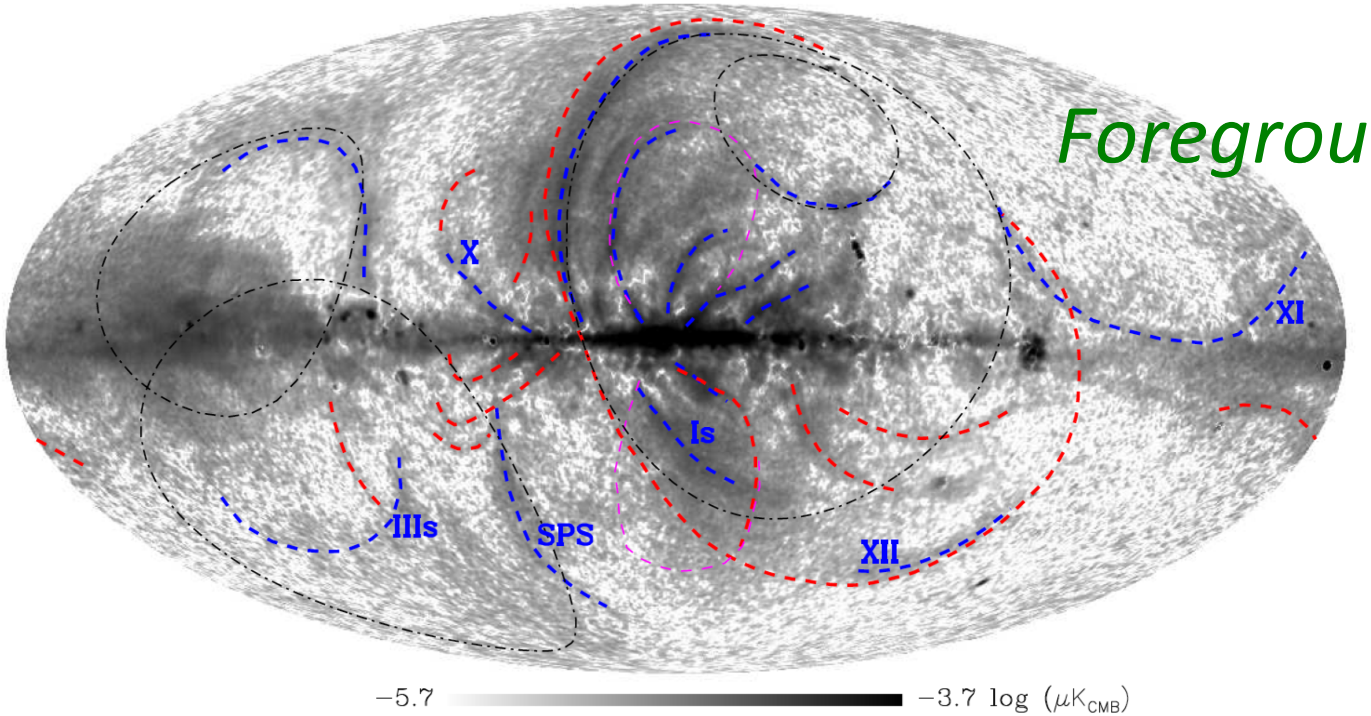
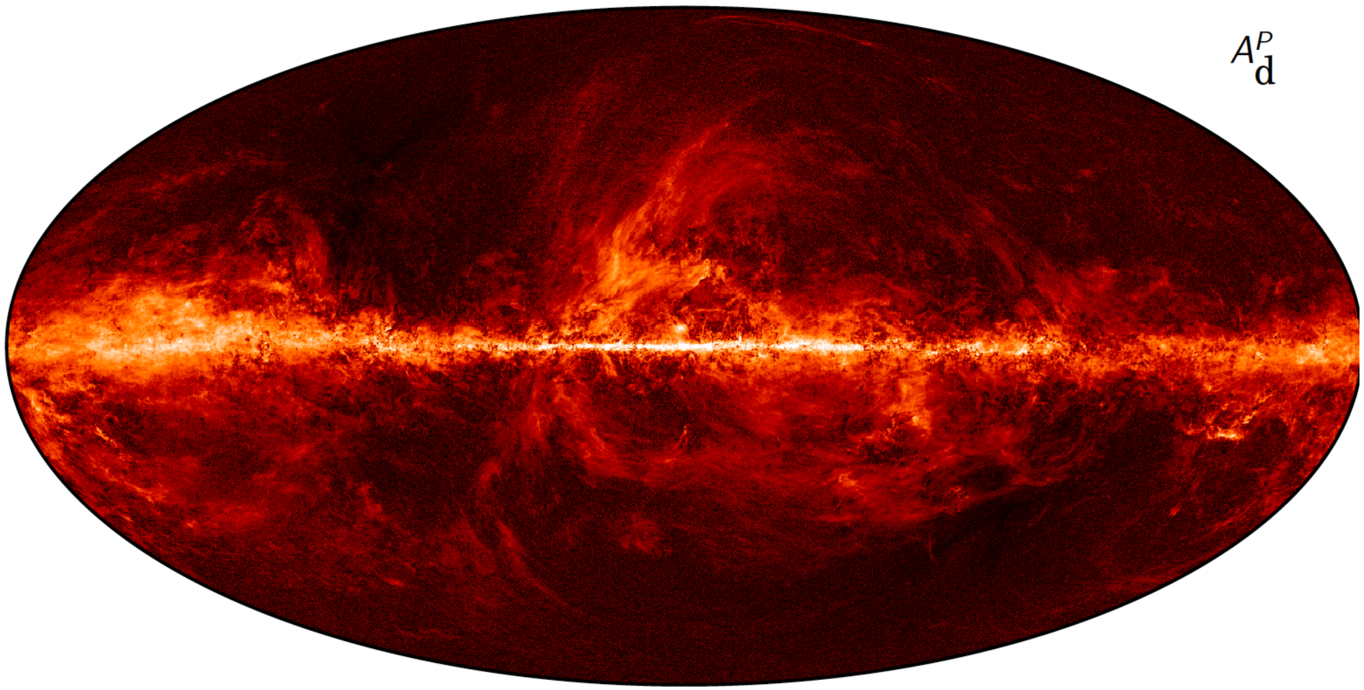


Fig. 16. Maximum posterior intensity maps derived from the joint analysis of *Planck*, WMAP, and 408 MHz observations (Planck Collaboration X 2015). From left to right, top to bottom: CMB; synchrotron; free-free; spinning dust; thermal dust; line emission around 90 GHz; CO $J = 1 \rightarrow 0$; CO $J = 2 \rightarrow 1$, and CO $J = 3 \rightarrow 2$.

Foreground polarization

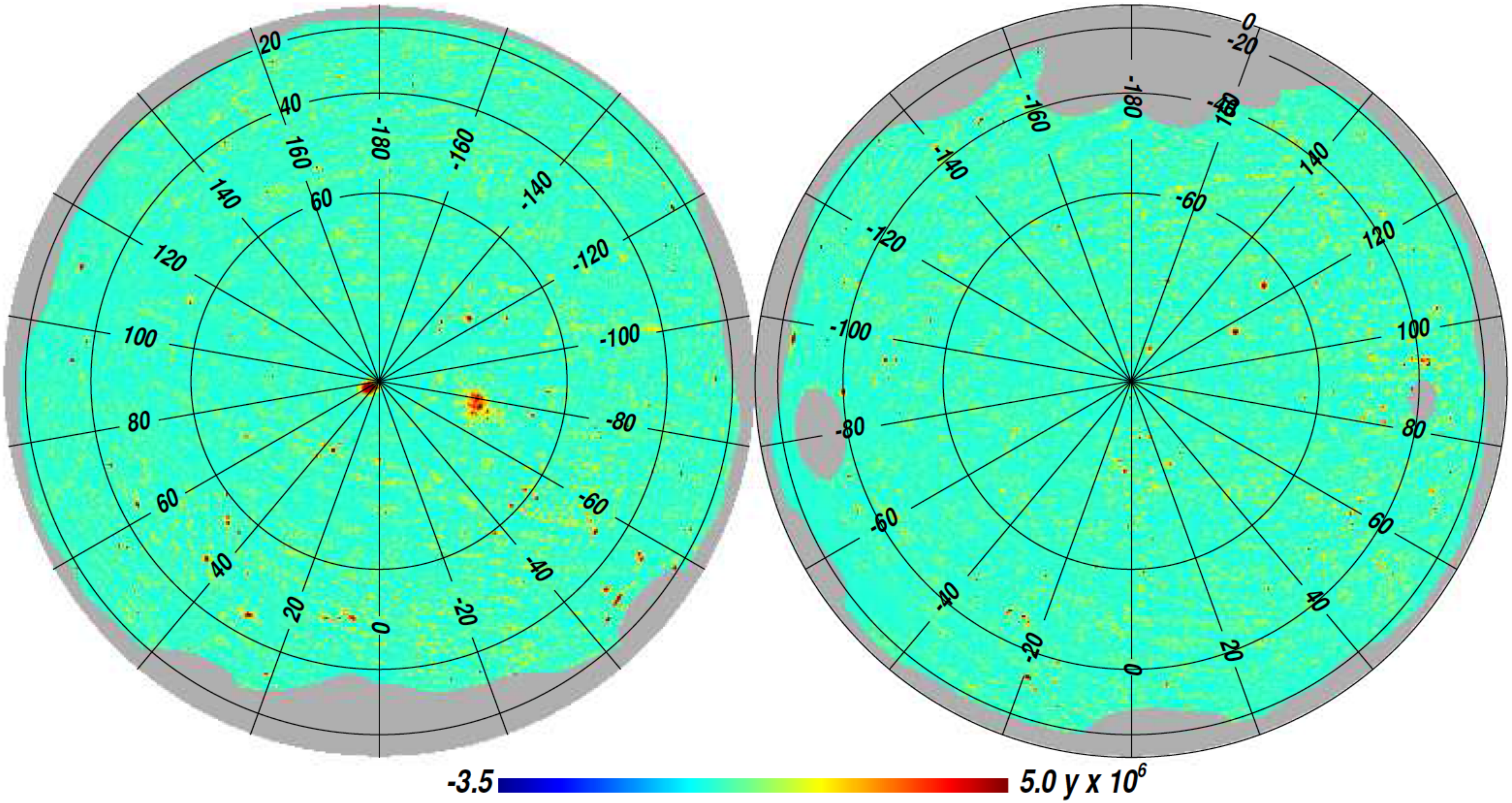


Synchrotron radiation

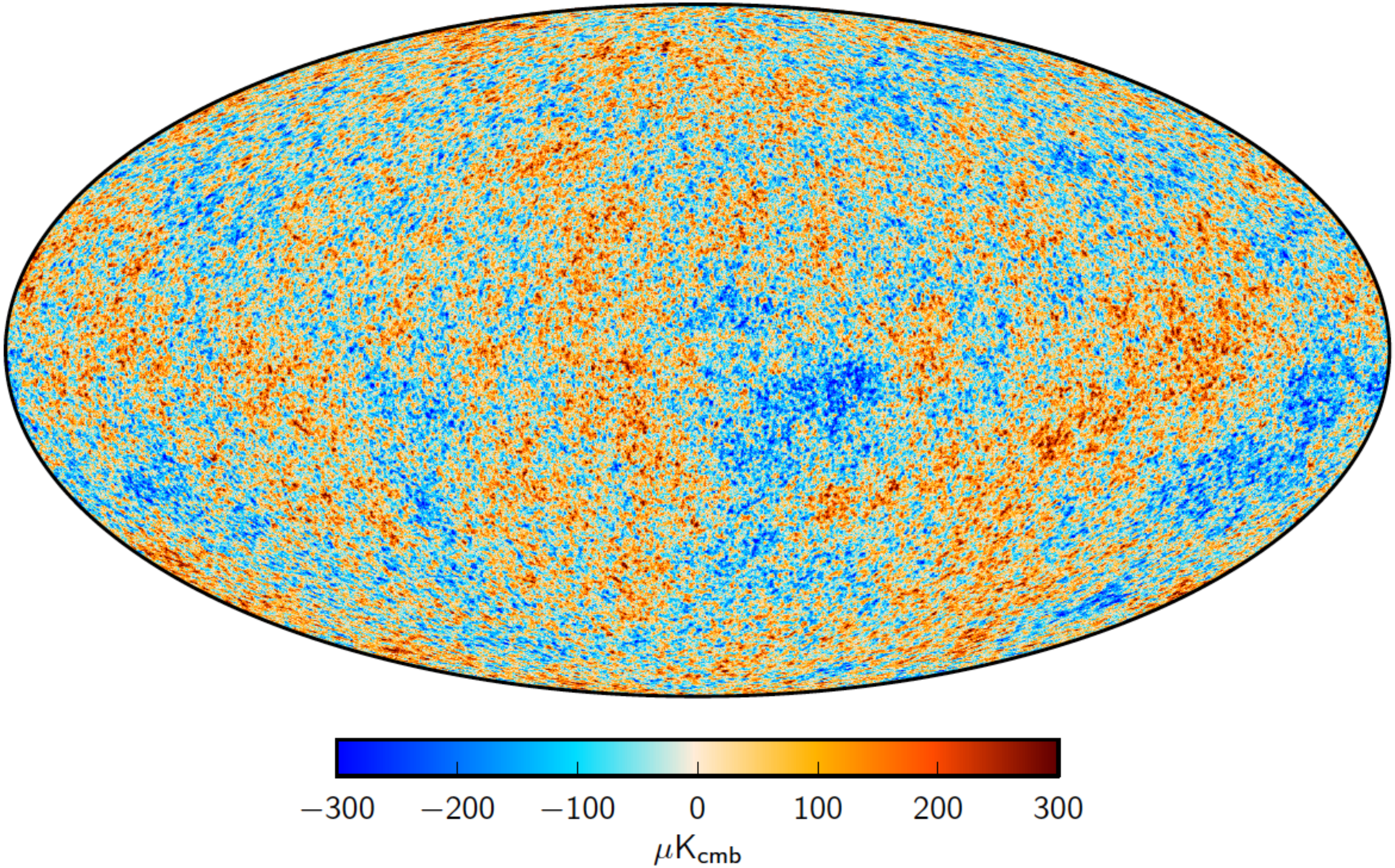


Dust

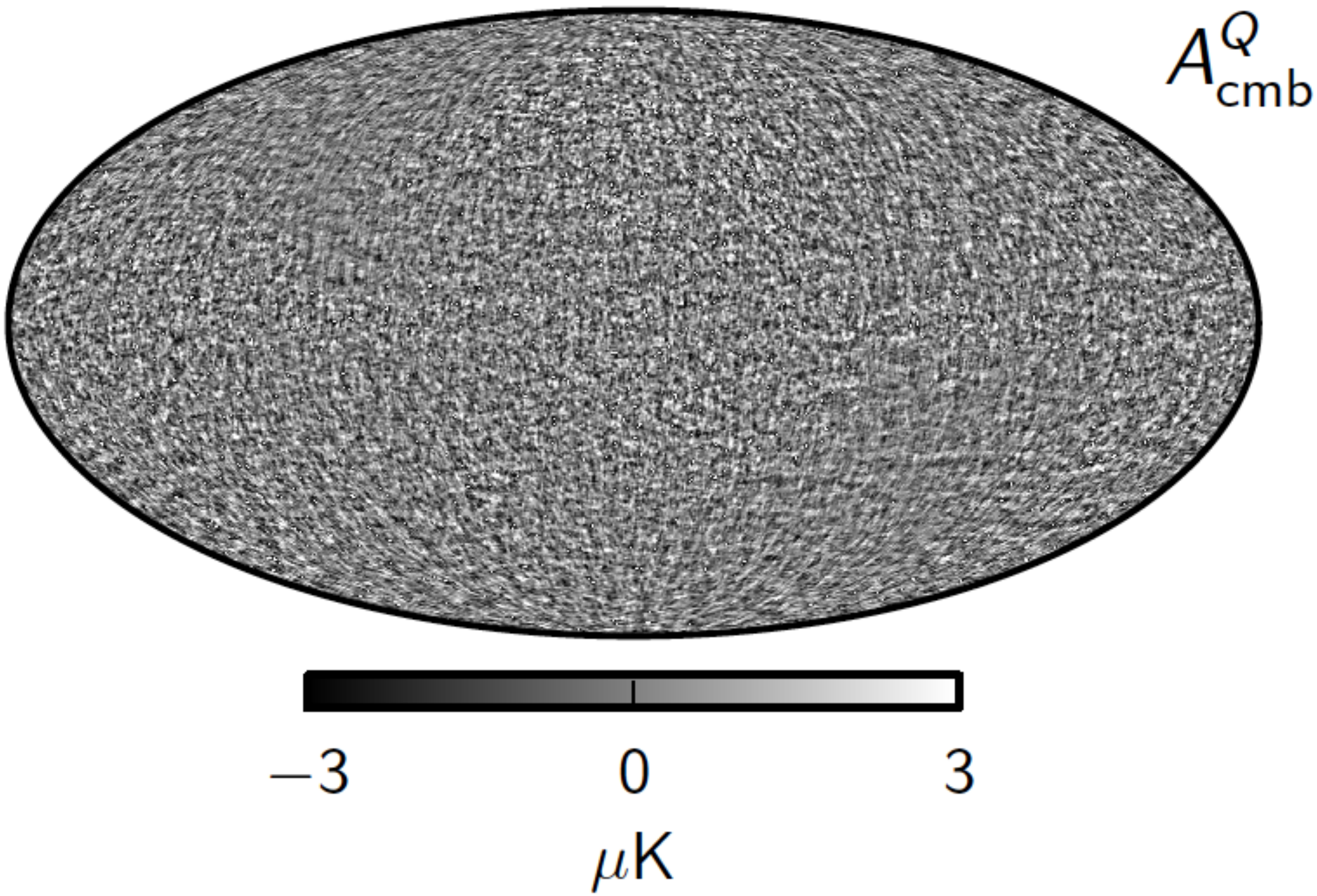
Sunyaev-Zeldovich effect



Cosmic microwave background T

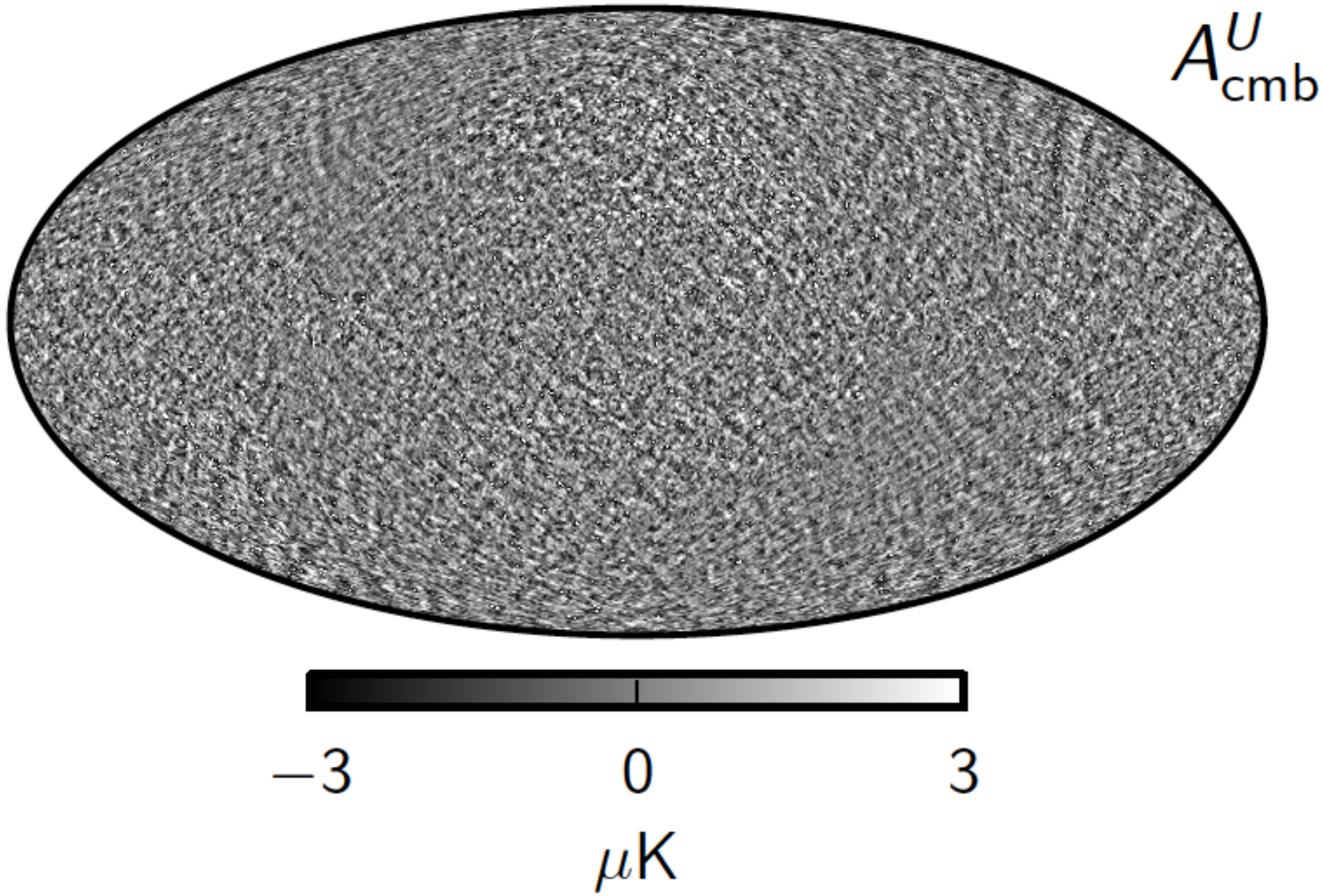


CMB Polarization Q



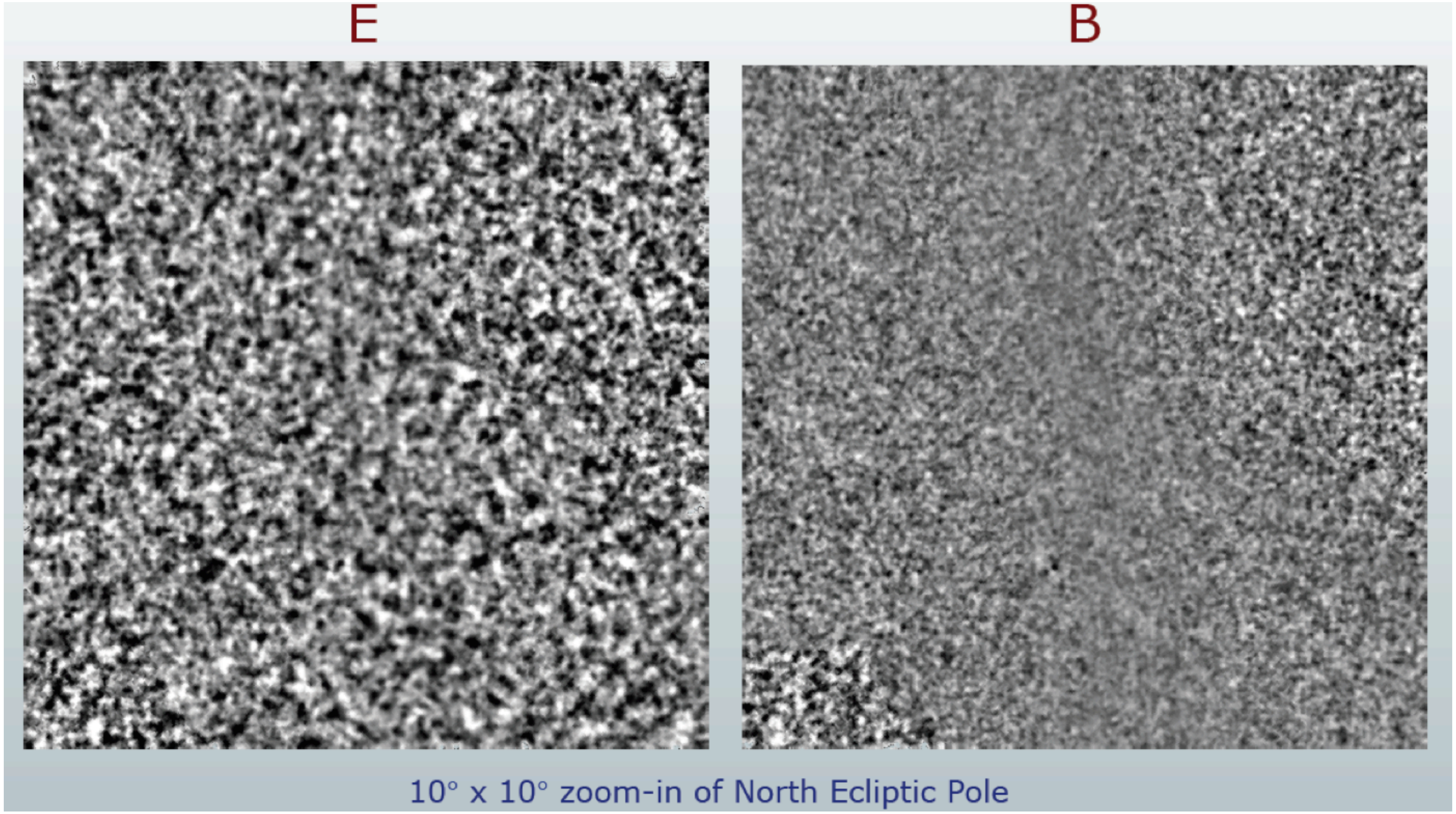
high-pass filtered (i.e., large scales removed)

CMB Polarization U

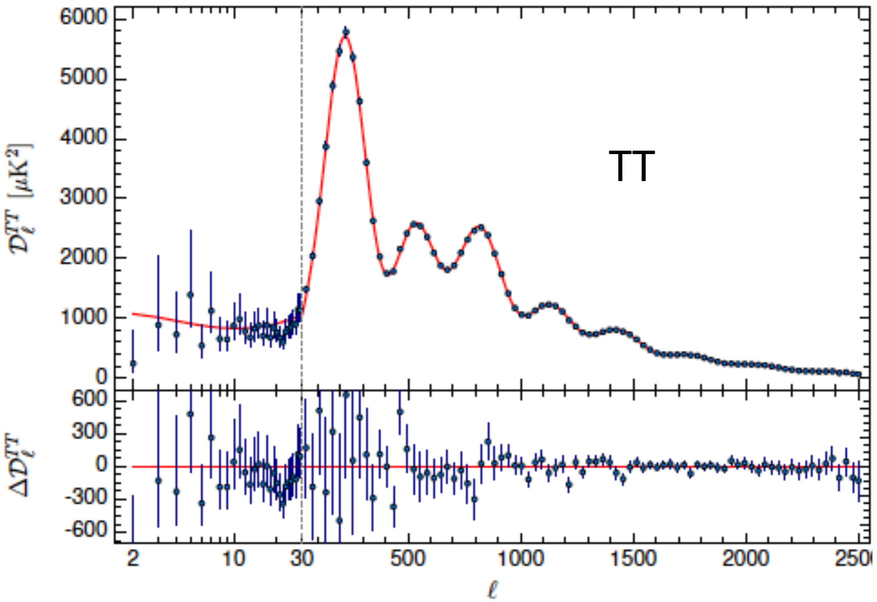


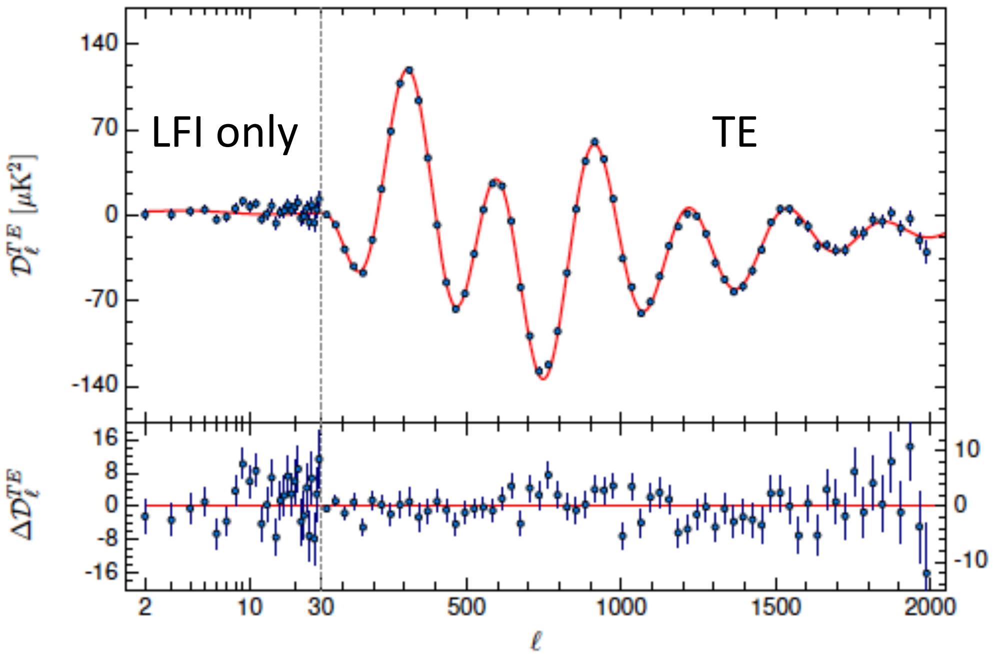
high-pass filtered (i.e., large scales removed)

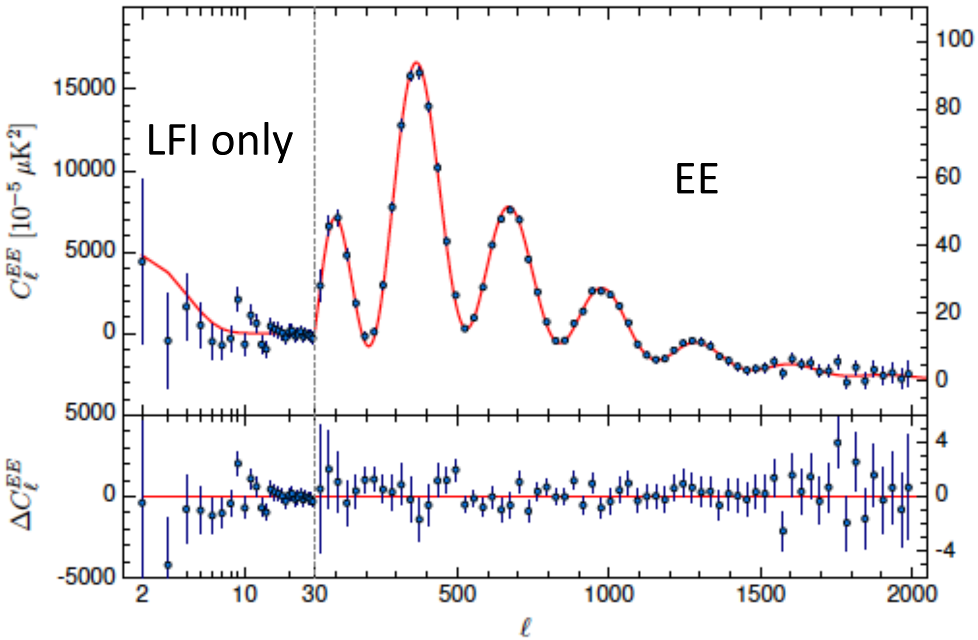
E and B modes



CMB Angular Power Spectra





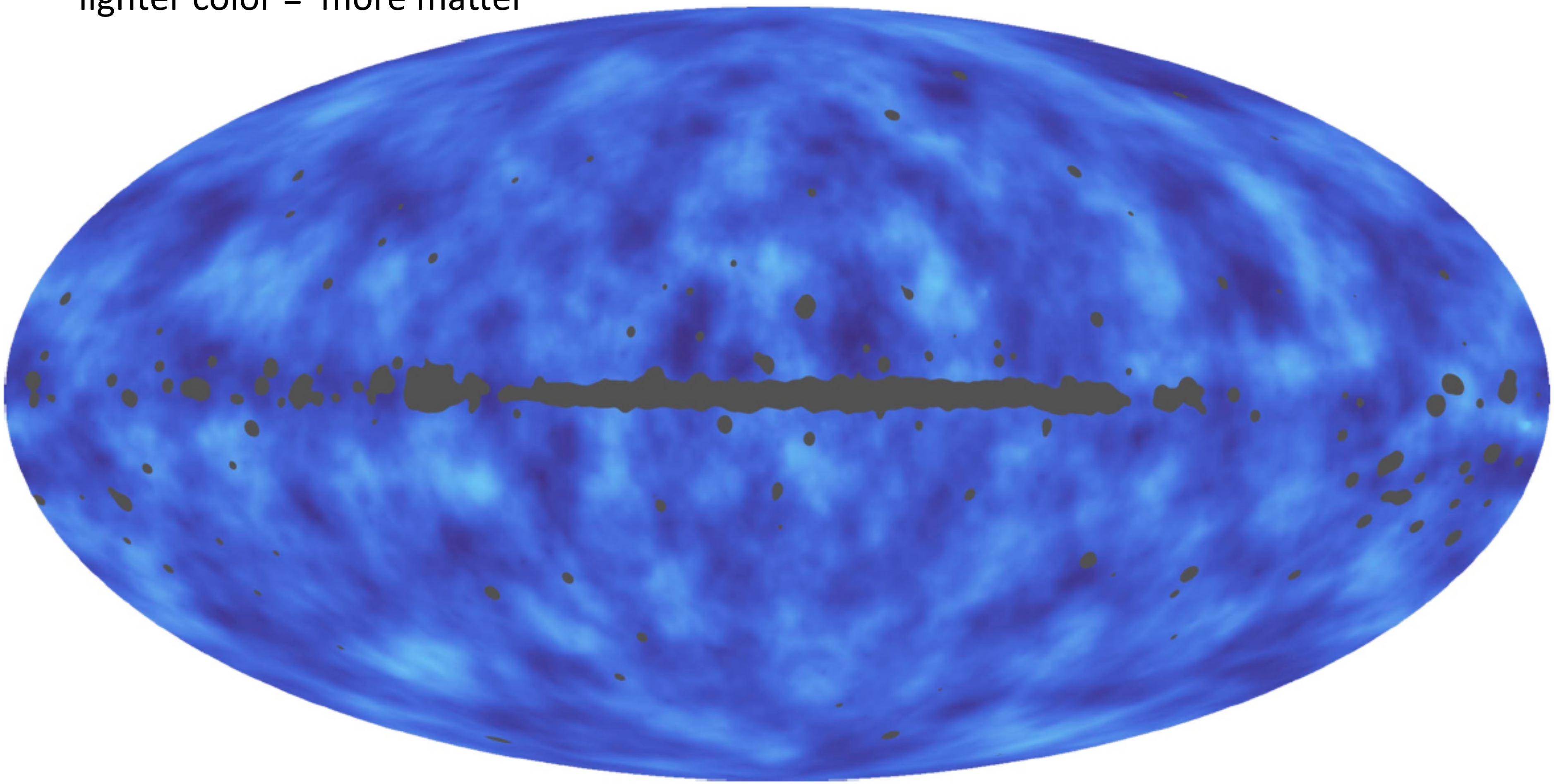


—— best-fit (to TT) ΛCDM model

CMB gravitational lensing potential

= projected (and weighted) mass (mostly dark matter) along the line of sight

lighter color = more matter



No deviations from ΛCDM

- Planck results agree to high accuracy with the standard 6-parameter model of cosmology ΛCDM:
  - standard model particles
  - cold dark matter
  - cosmological constant
  - flat FRW background geometry
  - Gaussian adiabatic primordial perturbations with power-law spectrum
- No evidence for
  - primordial gravitational waves: $r < 0.11$
  - extra "neutrinos", i.e., additional relativistic particle species: $N_{eff} = 3.15 \pm 0.23$
  - large neutrino masses: $\Sigma m_\nu < 0.23$ eV
- However, there are intriguing "large scale anomalies" (cold spot, hemispherical asymmetry, ...) in CMB temperature at about 3 σ

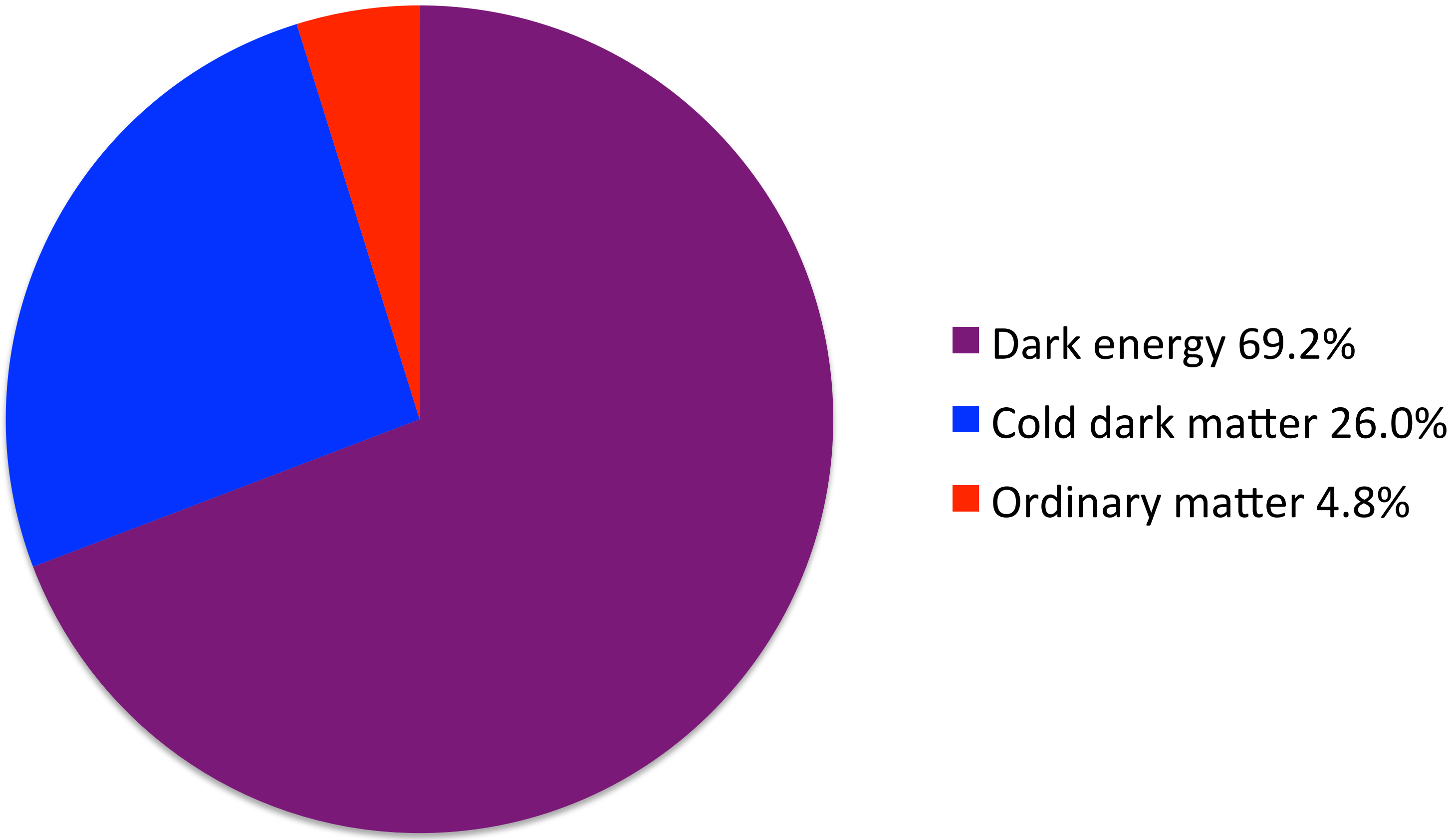
ΛCDM Cosmological Parameters

Parameter	WMAP 9-year	Planck 2013	Planck 2015
$\Omega_b h^2$	0.02264±50	0.02205±28	0.02226±23
$\Omega_c h^2$	0.1138±45	0.1199±27	0.1186±20
Ω_Λ	0.721±25	0.685±17	0.692±12
τ	0.089±14	0.089±13 (used WMAP P)	0.066±16
n_s	0.9720±130	0.9603±73	0.9677±60
H_0	70.0±2.2	67.3±1.2	67.8±0.9
Age/Gyr	13.740±110	13.817±48	13.799±38

(errors refer to the least significant digits)

Smaller optical depth of CMB means first stars formed later: 550 Myr instead of 450 Myr

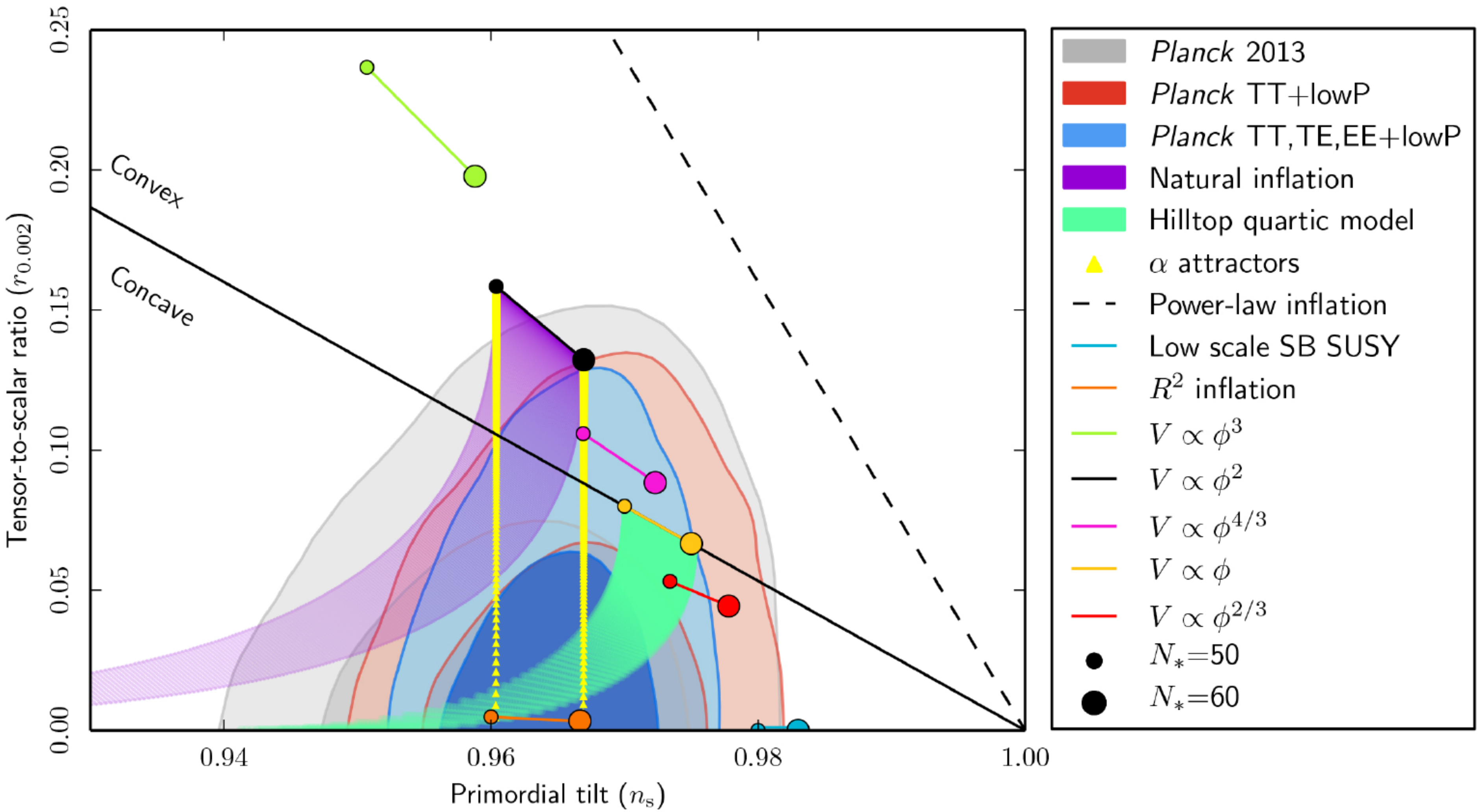
Recipe for the universe



Non-Gaussianity

	WMAP 9-year	Planck 2013	Planck 2015
f_{NL} (local)	37±20	2.7±5.8	0.8±5.0
g_{NL} (local)			-9.0±7.7 x 10^4

Inflation



Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Convex
Concave
Planck 2013
Planck TT+lowP
Planck TT,TE,EE+lowP
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
R^2 inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60

No "new physics" discovered by Planck

- But standard ΛCDM model confirmed and its parameters fixed to much higher accuracy than before
- Tighter limits to extensions
- The BICEP2 "detection" of primordial gravitational waves shown due to polarized emission from galactic dust
  - BICEP2/Keck & Planck Collaborations, PRL 114, 101301 (2015)
- Several subtle effects of standard model detected:
  - gravitational lensing of CMB (at 40 σ), and its correlations with cosmic infrared background and integrated Sachs-Wolfe Effect
  - effect of our motion on higher CMB multipoles

What is still missing?

- = what we mainly expect from the 2016 release
- Large scale polarization
  - especially HFI 100, 143, 217 GHz (the channels most sensitive to CMB polarization)
  - "Null test on data splits indicate inconsistency of polarization measurements on large angular scales at a level much larger than our instrument noise model. The reasons for this are numerous ..."
  - LFI polarization suffers from systematics as well, but LFI noise level is higher
- Main cosmological impact:
  - optical depth τ (HFI noise level would allow up to 3x better accuracy)
  - polarization B mode (primordial gravitational waves) detection from reionization bump (however, smaller τ makes this more difficult)
  - do we have similar large scale anomalies in P as in T?