# Planck Mission & Cosmic Microwave Background

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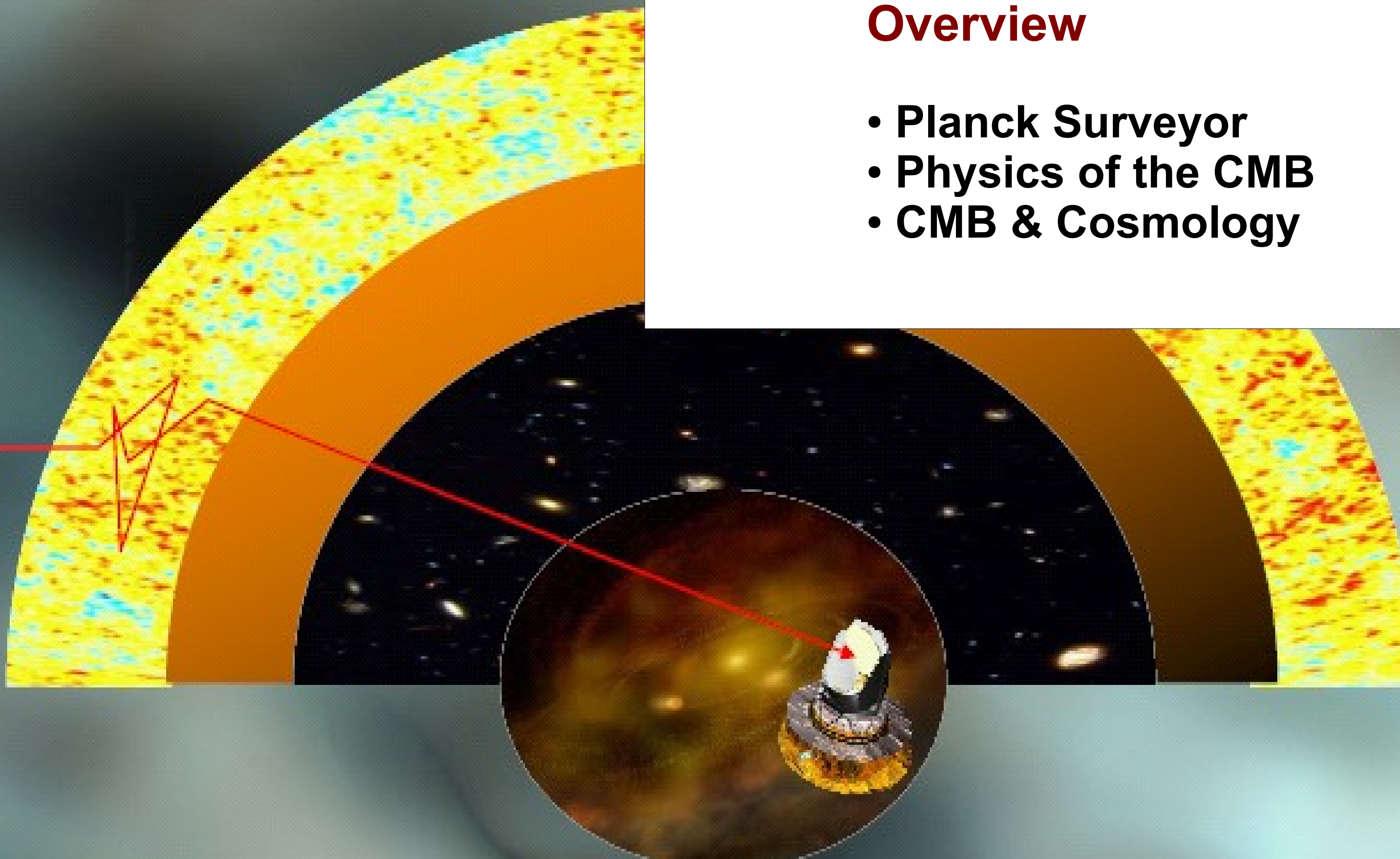
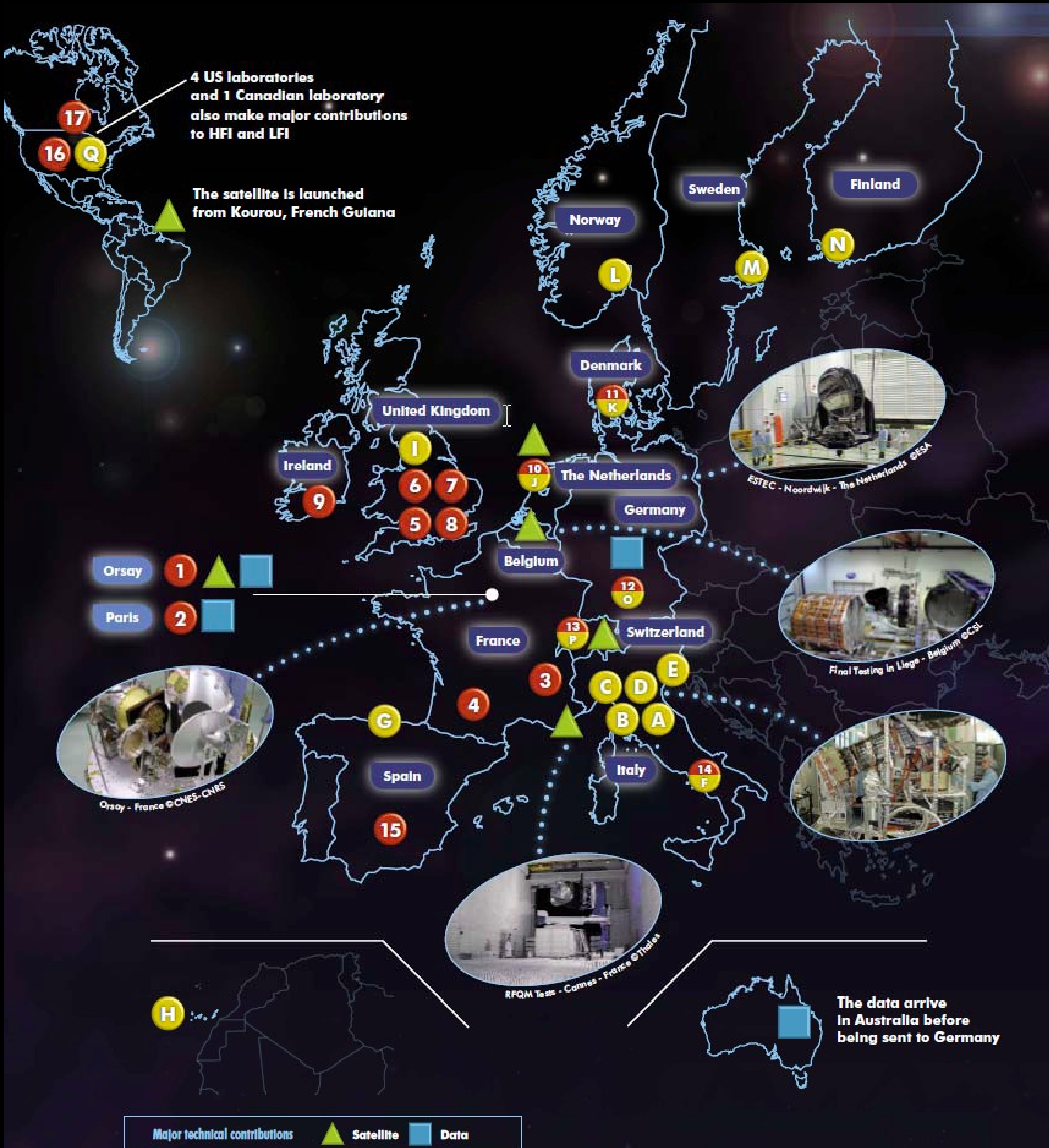
on behalf of the Planck collaboration
Max Planck Institut für Astrophysik



## Overview

- Planck Surveyor
- Physics of the CMB
- CMB & Cosmology




## Research Laboratories in the HFI Collaboration

1 Institut d'Astrophysique Spatiale, Orsay (F)
1 Laboratoire de l'Accélérateur Linéaire, Orsay (F)
1 Commissariat à l'Énergie Atomique, Gif-sur-Yvette (F)
2 Institut d'Astrophysique de Paris, Paris (F)
2 Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique, Paris, (F)
2 AstroParticule et Cosmologie, Paris (F)
3 Laboratoire de Physique Subatomique et de Cosmologie, Grenoble (F)
3 Institut Louis Néel, Grenoble (F)
4 Centre d'Études Spatiales des Rayonnements, Toulouse (F)
5 Cardiff University, Cardiff (UK)
6 Rutherford Appleton Laboratory, Chilton (UK)
7 Institute of Astronomy, Cambridge (UK)
7 Mullard Radio Astronomy Observatory, Cambridge (UK)
8 Imperial College, London (UK)
9 National University of Ireland, Maynooth (IR)
10 Space Science Dpt of ESA, Noordwijk (NL)
11 Danish Space Research Institute, Copenhagen (DK)
12 Max-Planck-Institut fuer Astrophysik, Garching (D)
13 Université de Genève , Geneva (CH)
14 University La Sapienza, Rome (I)
15 Universidad de Granada, Granada (E)
16 California Institute of Technology, Pasadena (USA)
16 Jet Propulsion Laboratory, Pasadena (USA)
16 Stanford University, Stanford (USA)
17 Canadian Institute for Theoretical Astrophysics, Toronto (Canada)

## Research Laboratories in the LFI Collaboration

A Istituto Nazionale di Astrofisica Spaziale et Fisica Cosmica, Bologna (I)
B Istituto CAISMI, Firenze (I)
C Istituto IASF (CNR), Milano (I)
C Istituto di Fisica del Plasma IFP (CNR), Milano (I)
D Osservatorio Astronomico di Padova, Padova (I)
E Osservatorio Astronomico di Trieste, Trieste (I)
E SISSA, Trieste (I)
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P Université de Genève, Geneva (CH)
Q University of California (Berkeley), Berkeley (USA)
Q University of California (Santa Barbara), Santa Barbara (USA)
Q Jet Propulsion Laboratory, Pasadena (USA)

# Many people ...


... and 20 years of work!

# Acknowledgments

• Planck is a project of the European Space Agency - ESA - 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.

• Prime industrial contractor: Thales Alenia Space (France)

• More than 50 scientific institutes and industry from all over Europe, and some from the USA, have collaborated with ESA over the last 16 years to develop this satellite and its payload

*Astronomy & Astrophysics* manuscript no. The*Planck*Mission
July 24, 2009



## Planck pre-launch status: The Planck mission

J. A. Tauber[36,*], N. Mandolesi[45], J.-L. Puget[52], T. Banos[82], M. Bersanelli[32], F. R. Bouchet[51], C. R. Butler[45], J. Charra[52], G. Crone[37], J. Dodsworth[38], G. Efstathiou[90], R. Gispert[52], G. Guyot[52], A. Gregorio[33], J. J. Juillet[82], J.-M. Lamarre[66], R. J. Laureijs[36], C. R. Lawrence[61], H. U. Nørgaard-Nielsen[35], T. Passvogel[37], J. M. Reix[82], D. Texier[39], L. Vibert[52], A. Zacchei[46], P. A. R. Ade[6], N. Aghanim[52], B. Aja[18], E. Alippi[84], L. Aloy[37], P. Armand[82], M. Arnaud[7], A. Arondel[52], A. Arreola-Villanueva[61], E. Artal[18], E. Artina[84], A. Arts[37], M. Ashdown[89], J. Aumont[12], M. Azzaro[80], A. Bacchetta[83], C. Baccigalupi[5], M. Baker[37], M. Balasini[84], A. Balbi[33], A. J. Banday[9,12], G. Barbier[64], R. B. Barreiro[58], M. Bartelmann[47,95], P. Battaglia[84], E. Battaner[91], K. Benabed[51], J.-L. Beney[63], R. Beneyton[53], K. Bennett[36], A. Benoit[64], J.-P. Bernard[12], P. Bhandari[61], R. Bhatia[63], M. 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Received May, 2009; accepted Sometime, 2009

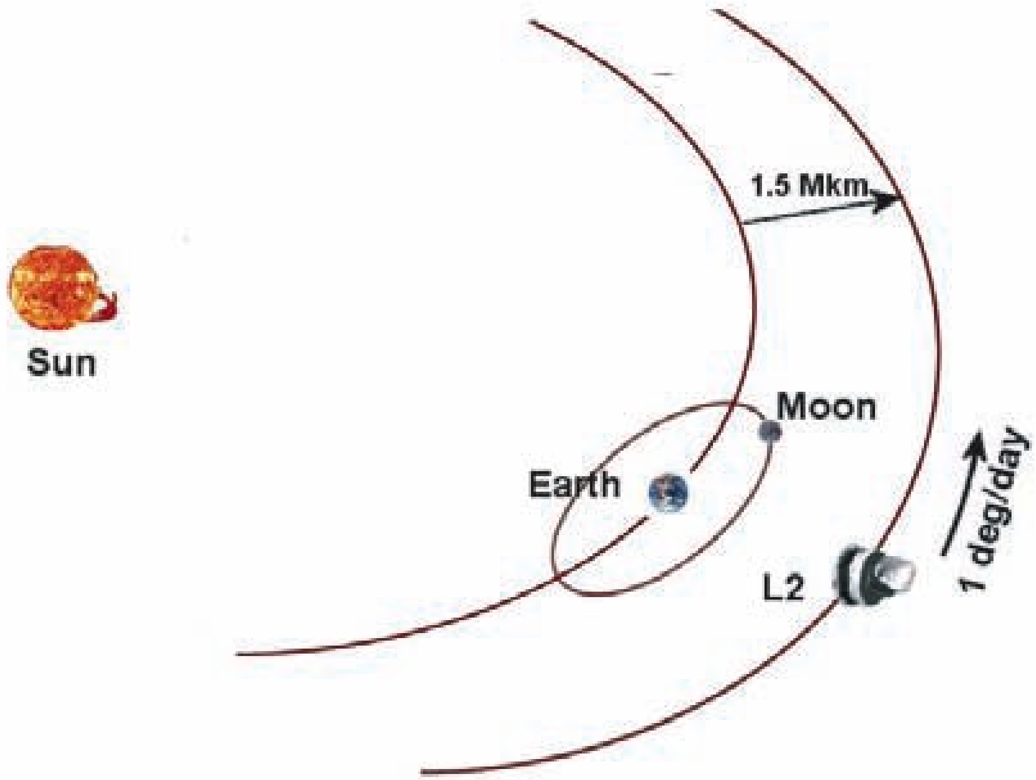
ABSTRACT

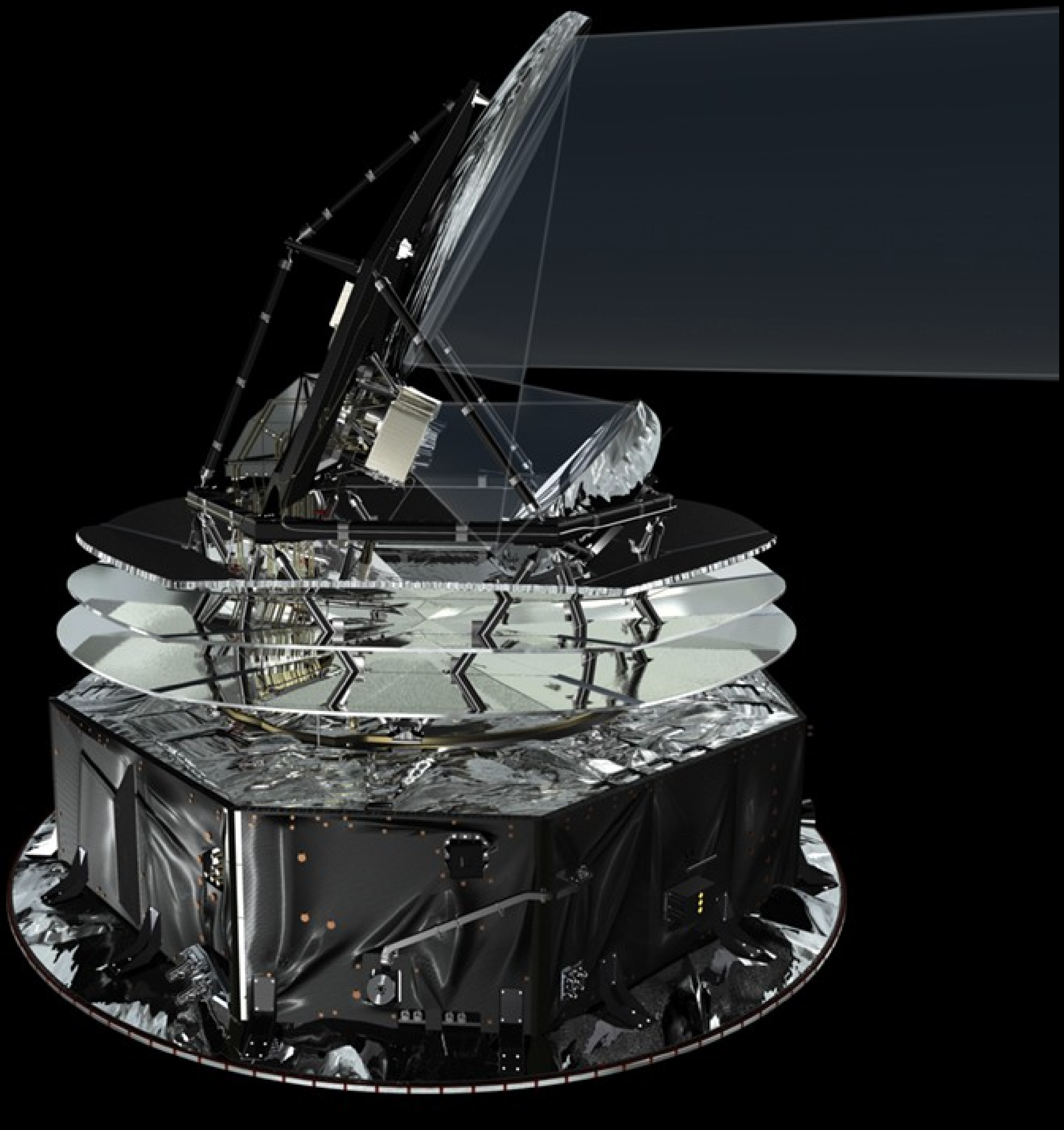
The European Space Agency's Planck satellite, launched on 14 May 2009, is the next-generation space experiment in the field of Cosmic Microwave Background (CMB) research. It will image the anisotropies of the CMB over the whole sky, with unprecedented sensitivity ($\frac{\Delta T}{T} \sim 2 \times 10^{-6}$) and angular resolution (∼5 arcminutes). Planck will provide a major source of information relevant to many fundamental cosmological problems and will test current theories of the early evolution of the Universe and the origin of structure. It will also address a wide range of areas of astrophysical research related to the Milky Way as well as external galaxies and clusters of galaxies. The ability of Planck to measure polarization across a wide frequency range (30 – 350 GHz), with high precision and accuracy, and over the whole sky, will provide unique insight, not only into specific cosmological questions, but also into the properties of the interstellar medium. This paper is part of a series which describes the technical capabilities of the Planck scientific payload. It is based on the knowledge gathered during the on-ground calibration campaigns of the major subsystems, principally its telescope and its two scientific instruments, and of tests at fully integrated satellite level. It represents the best estimate before launch of the technical performance that the satellite and its payload will achieve in flight. In this paper, we summarise the main elements of the payload performance, which is described in detail in the accompanying papers. In addition, we describe the satellite performance elements which are most relevant for science, and provide an overview of the plans for scientific operations and data analysis.

**Key words.** Cosmology: cosmic microwave background – Space vehicles: instruments – Instrumentation: detectors – Instrumentation: polarimeters – Submillimeter

# Planck Surveyor

# Courou at 10:12 on May $14^{th}$ 2009


Sun
1.5 Mkm
Moon
Earth
L2
1 deg/day



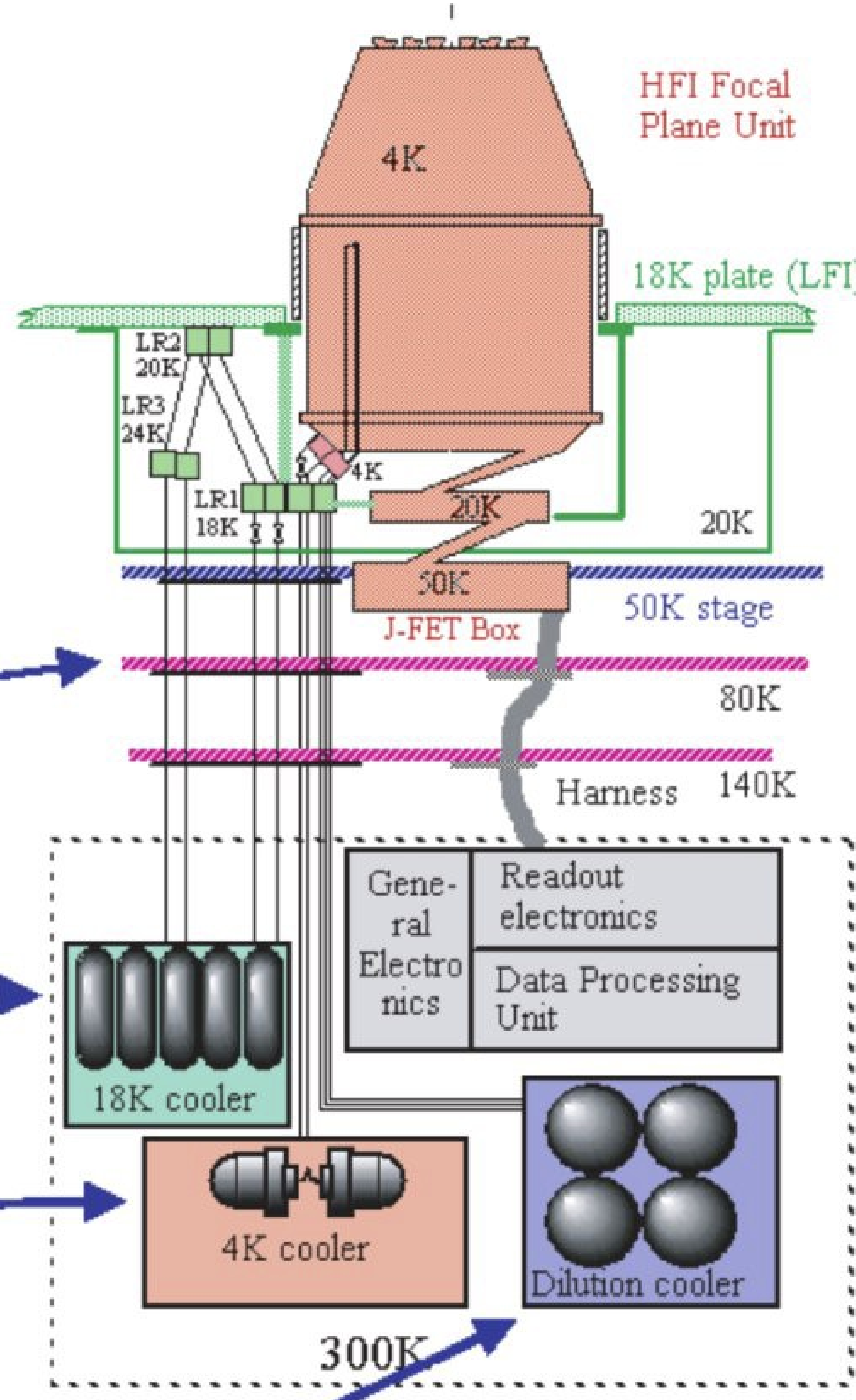
# Cooling system

V-groove radiators (to 60 K)

20 K $H_2$ sorption coolers (JPL)

4 K Stirling cooler (RAL/MMS)

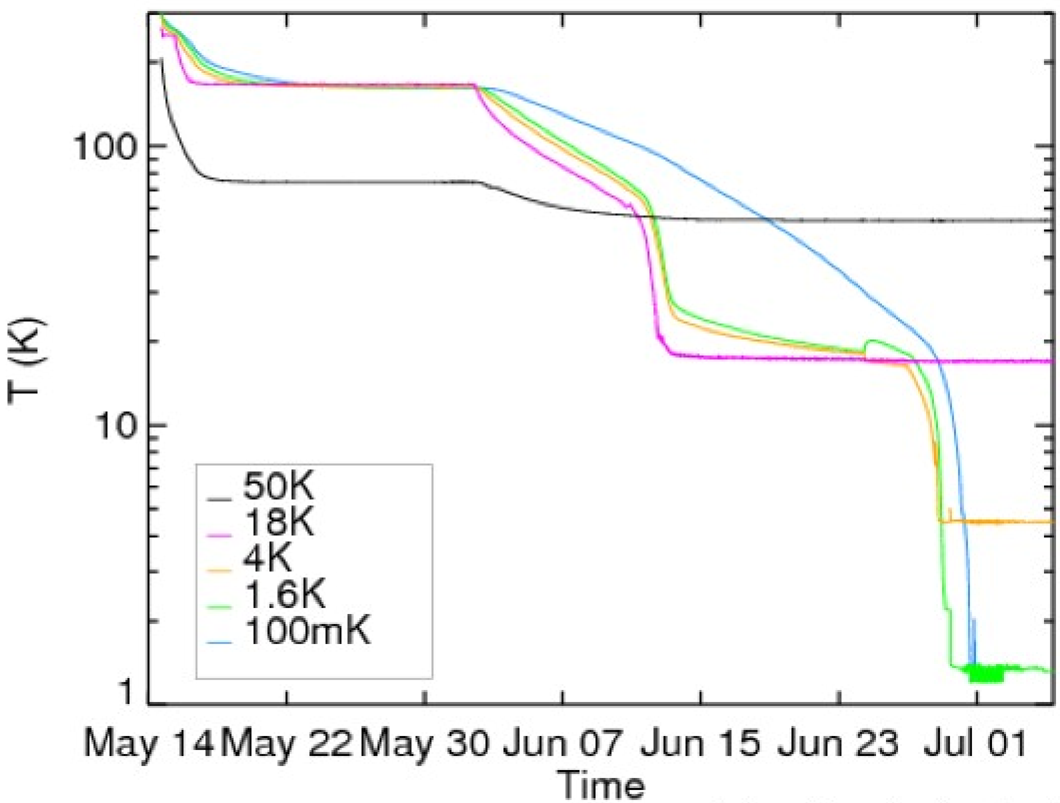
0.1 K $^3He/^4He$ dilution cooler (CRTBT)



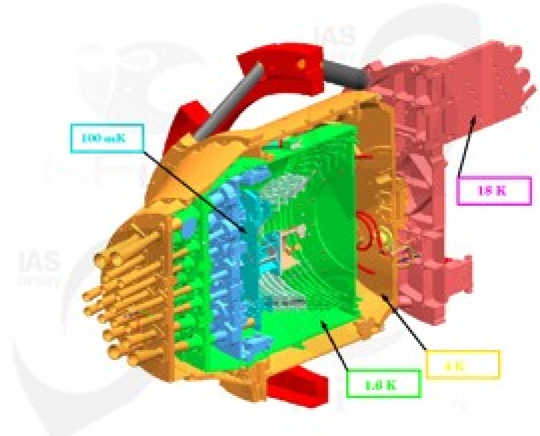
# Coolest spot in space, 0.1 Kelvin

**Cooldown**

July 6th, 2009




Institut d'Astrophysique Spatiale

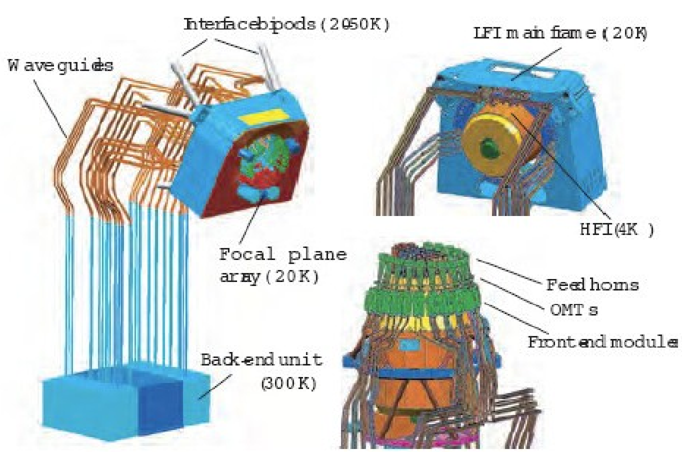



- Decontamination phase over
- Cooldown has resumed on June 1, 2009
- 18 K stage reached its nominal temperature on June 12, 2009
- June 24: configuration change of the 4K stage
- July 3rd: HFI reached 100mK

| Instrument Characteristic | LFI | | | HFI | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Detector Technology................ | HEMT arrays | | | Bolometer arrays | | | | | |
| Center Frequency [GHz]............ | 30 | 44 | 70 | 100 | 143 | 217 | 353 | 545 | 857 |
| Bandwidth ($\Delta\nu/\nu$) ................. | 0.2 | 0.2 | 0.2 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 |
| Angular Resolution (arcmin) ....... | 33 | 24 | 14 | 10 | 7.1 | 5.0 | 5.0 | 5.0 | 5.0 |
| $\Delta T/T$ per pixel (Stokes $I$)[a]........ | 2.0 | 2.7 | 4.7 | 2.5 | 2.2 | 4.8 | 14.7 | 147 | 6700 |
| $\Delta T/T$ per pixel (Stokes $Q$ &$U$)[a] ... | 2.8 | 3.9 | 6.7 | 4.0 | 4.2 | 9.8 | 29.8 | ... | ... |

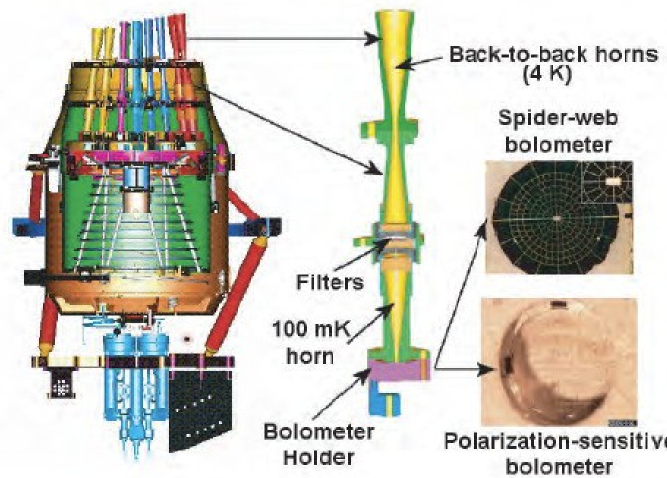
[a] Goal ($\mu$K/K, $1\sigma$), 14 months integration, square pixels whose sides are given in the row “Angular Resolution”.

Planck Bluebook



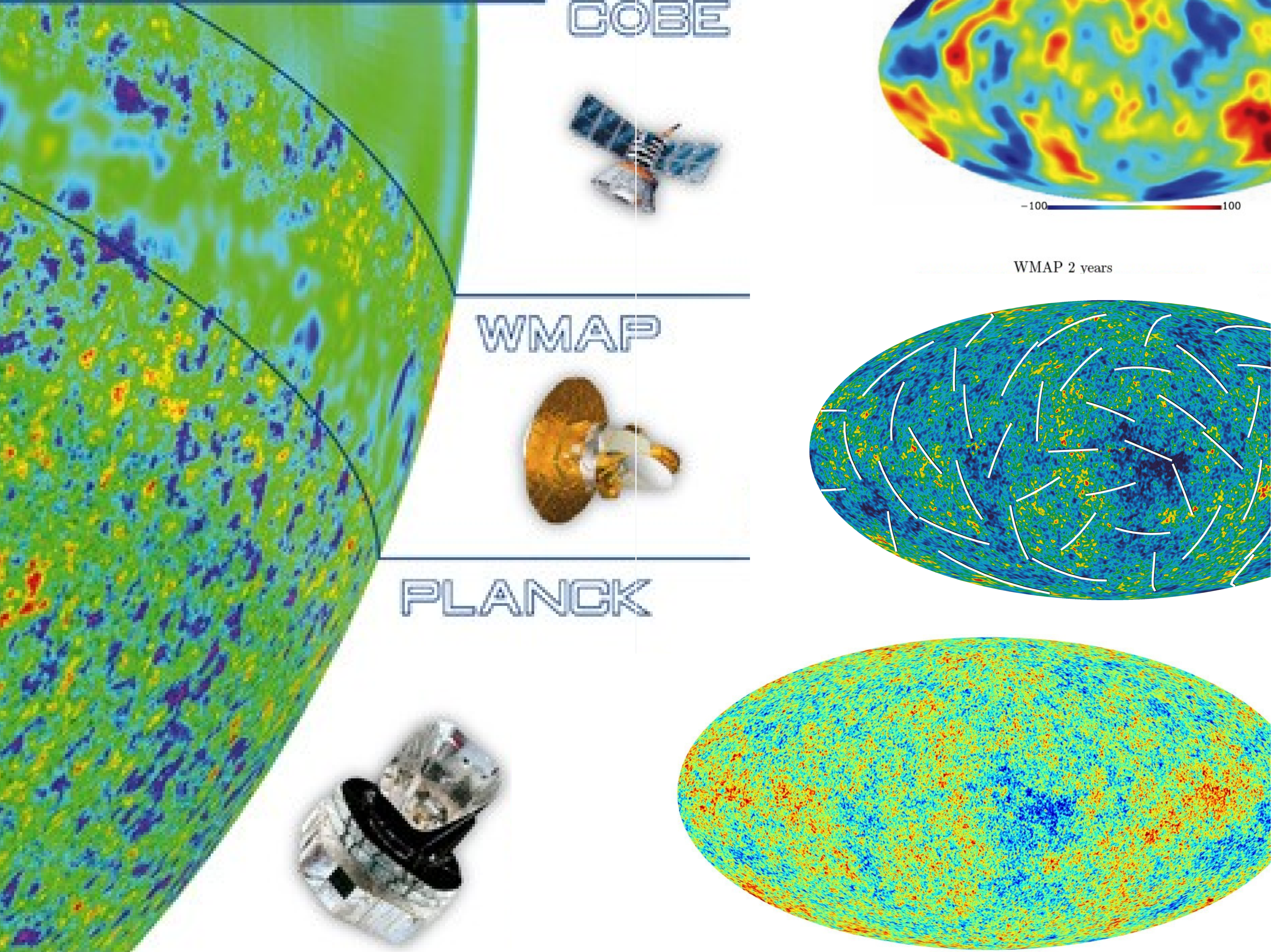

Planck Bluebook

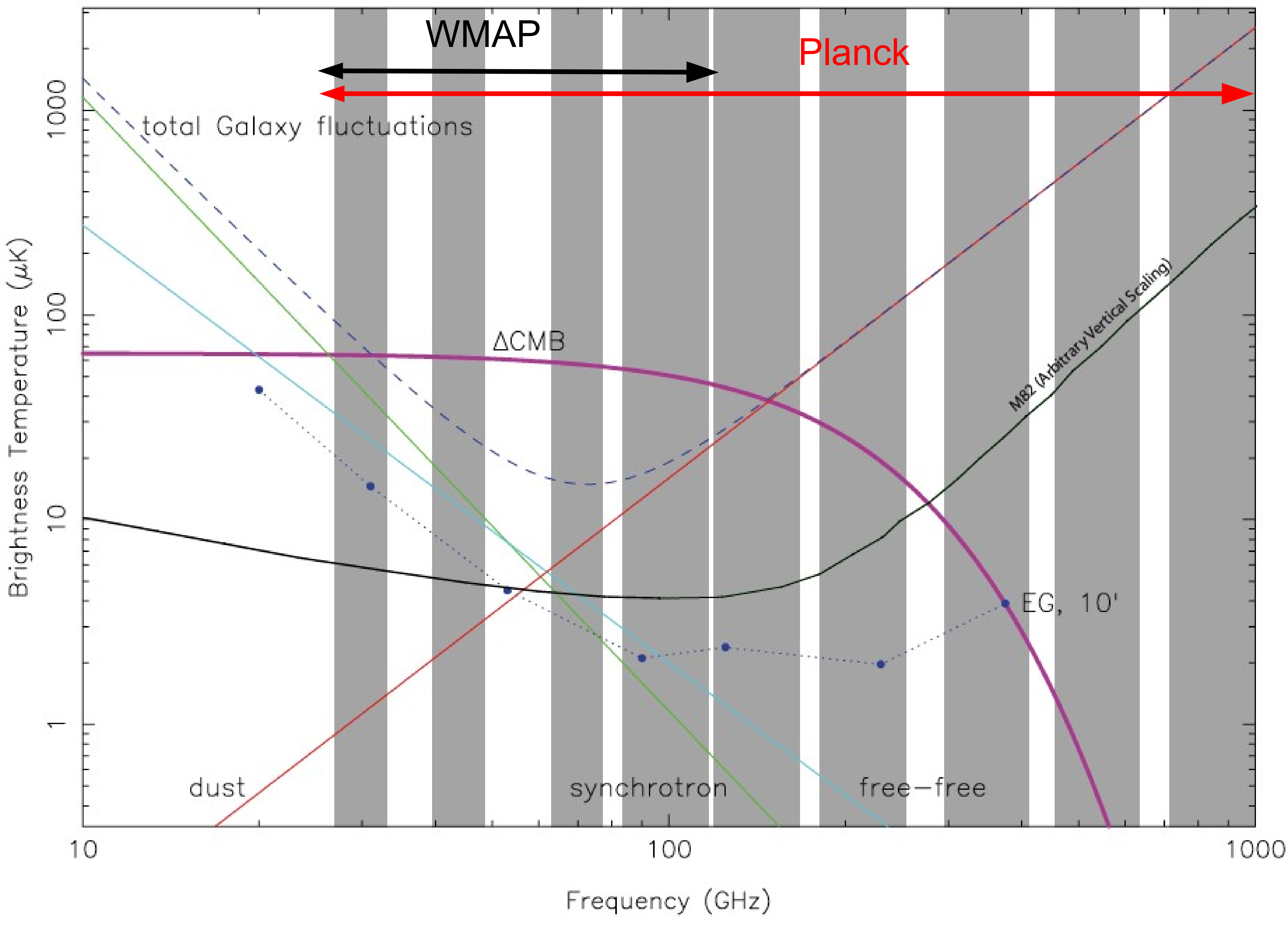
Thales/Alenia Space+ESA



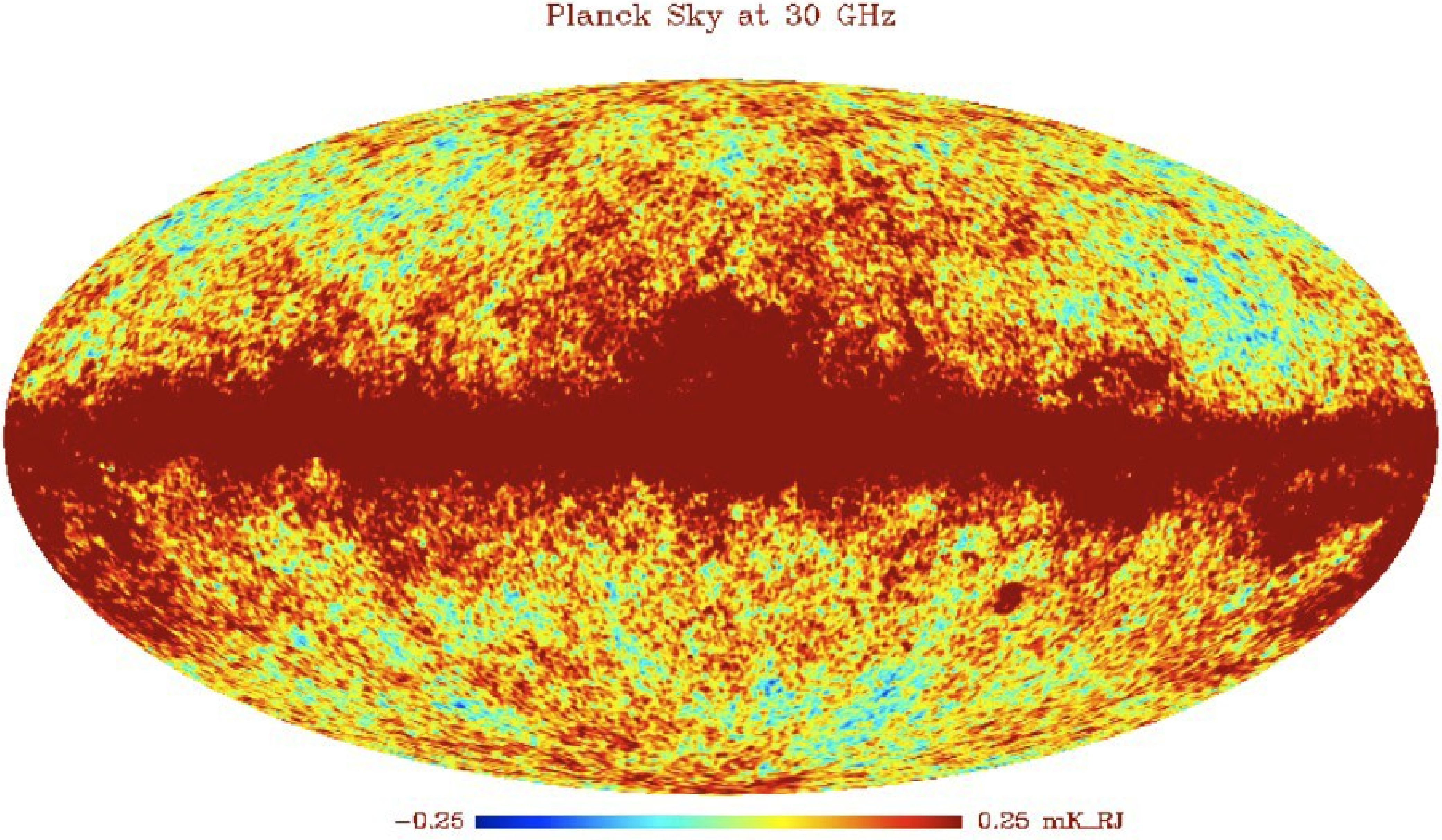

Planck Bluebook

# Sensitivity in PR representation

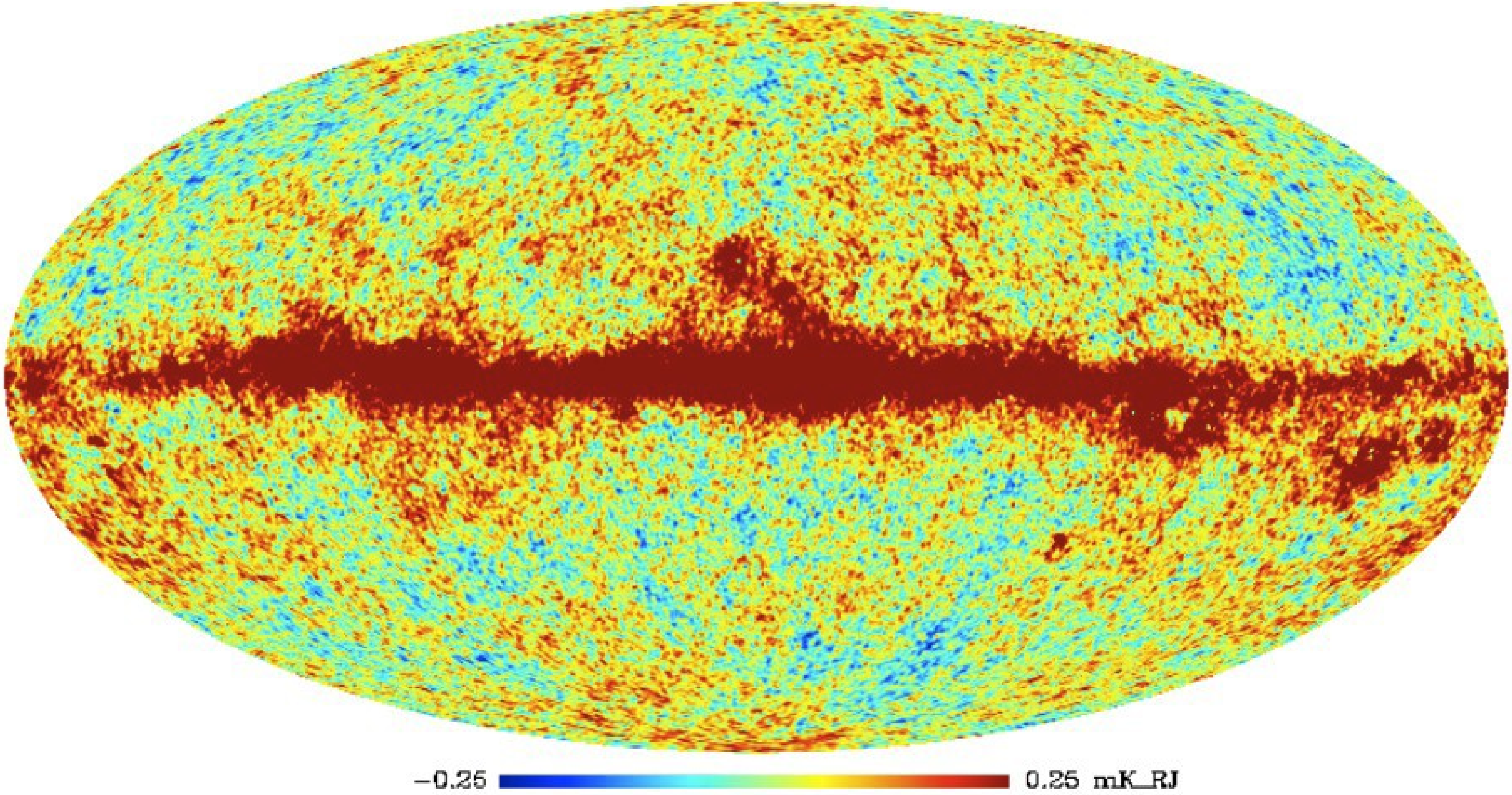

COBE
−100
100
WMAP 2 years
WMAP
PLANCK



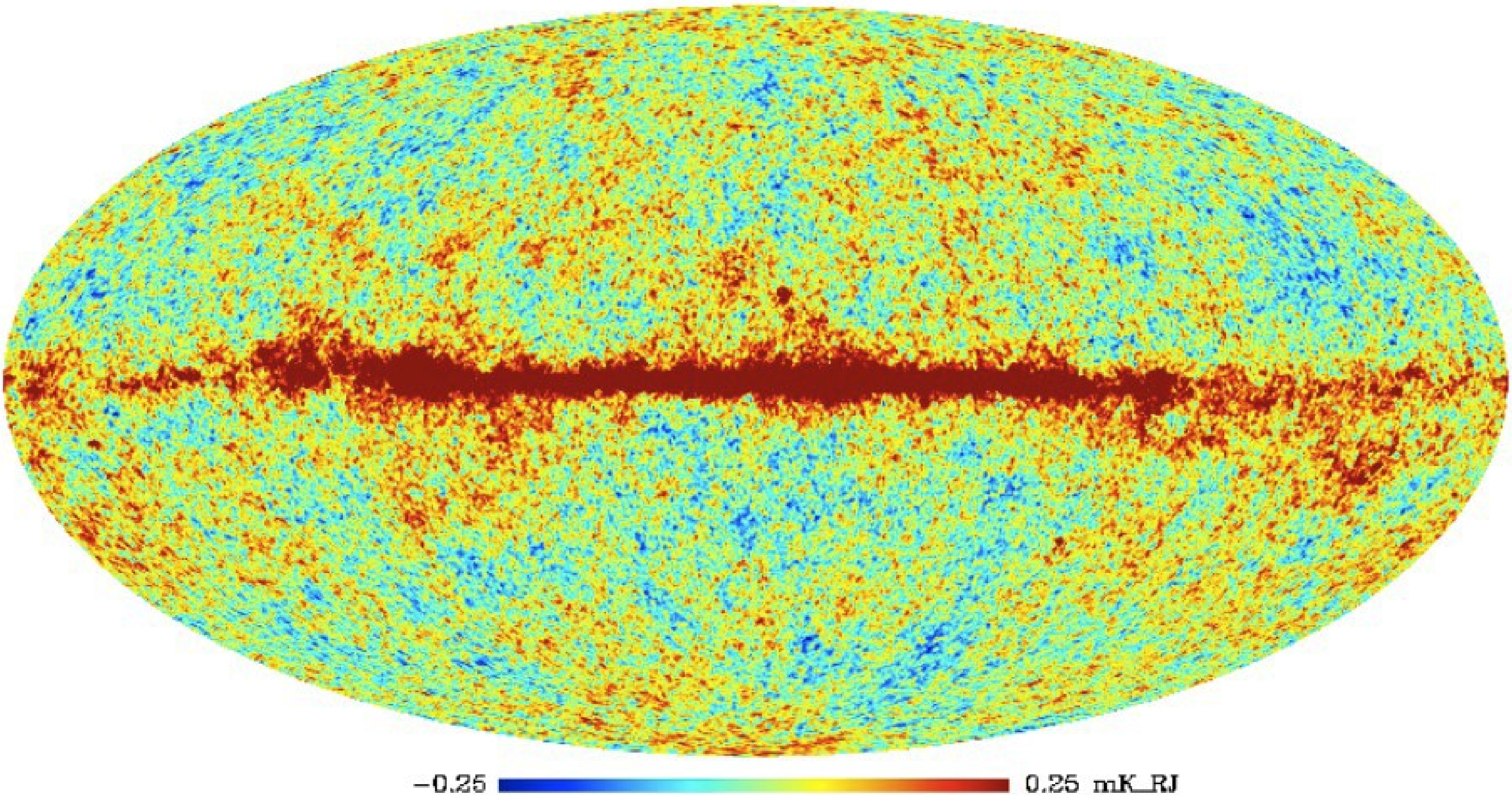
WMAP
Planck
total Galaxy fluctuations
ΔCMB
M82 (Arbitrary Vertical Scaling)
EG, 10'
dust
synchrotron
free−free
Brightness Temperature (μK)
1000
100
10
1
10
100
1000
Frequency (GHz)

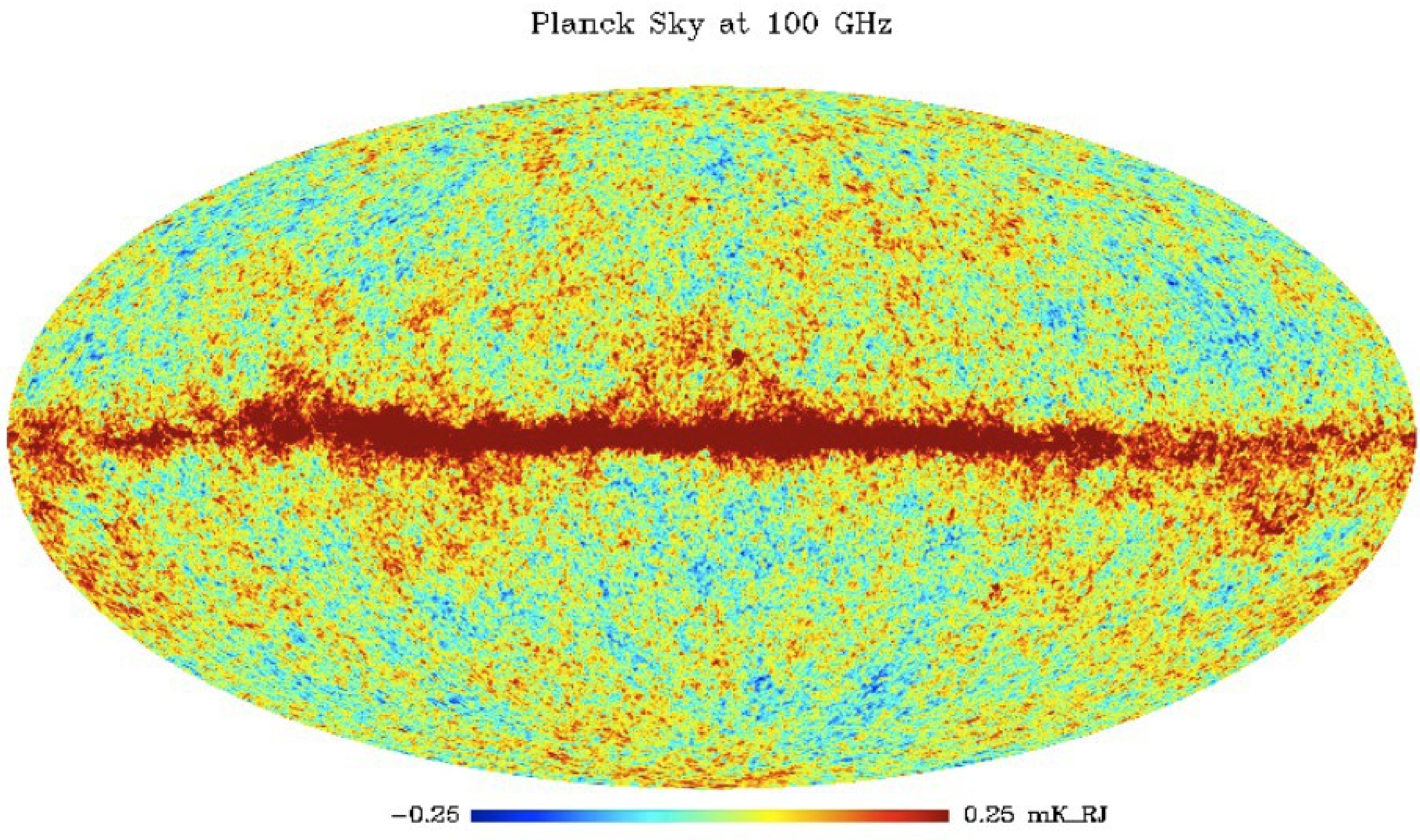

Planck Sky at 30 GHz
−0.25
0.25 mK_RJ

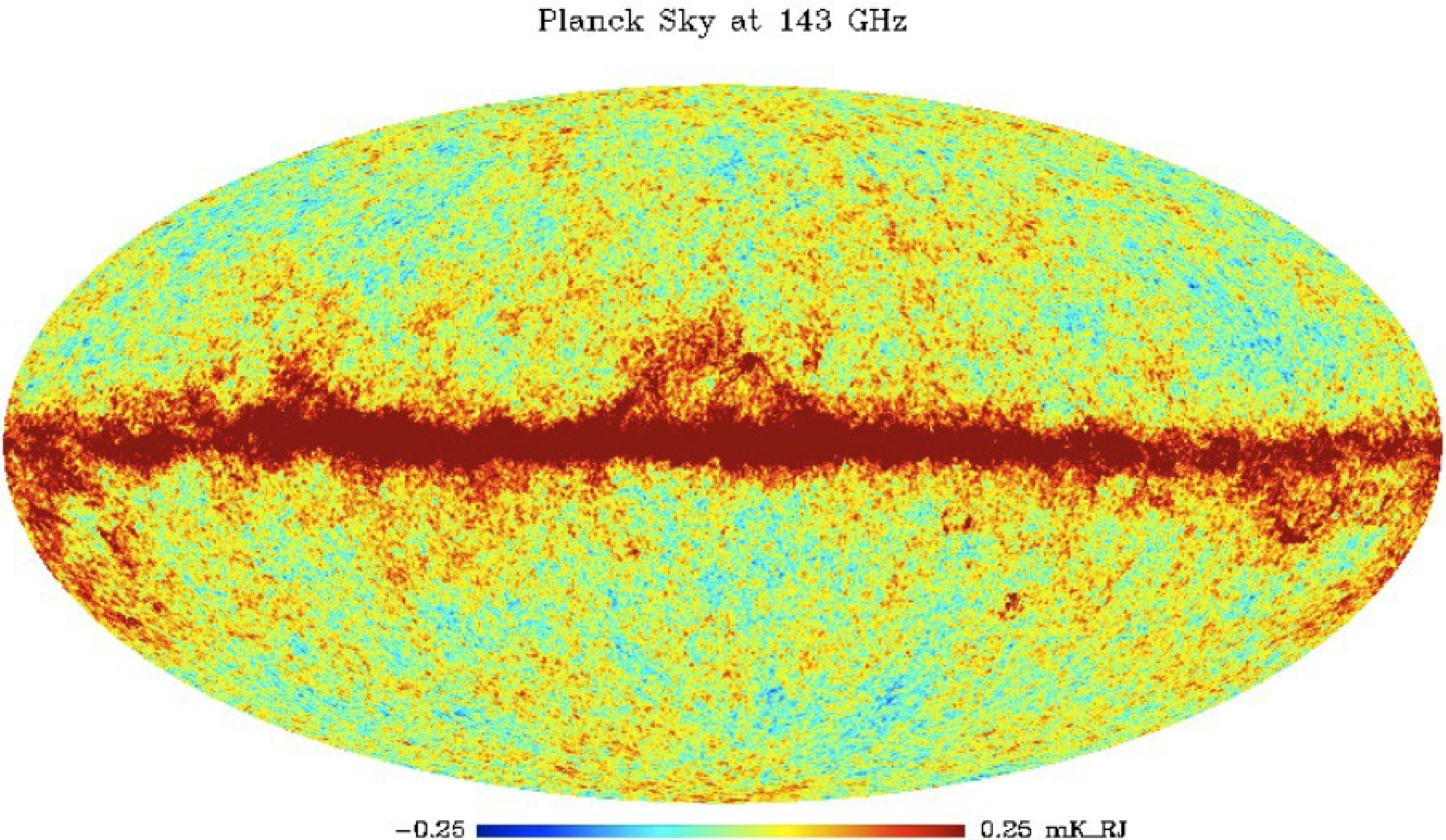
Planck Sky at 44 GHz



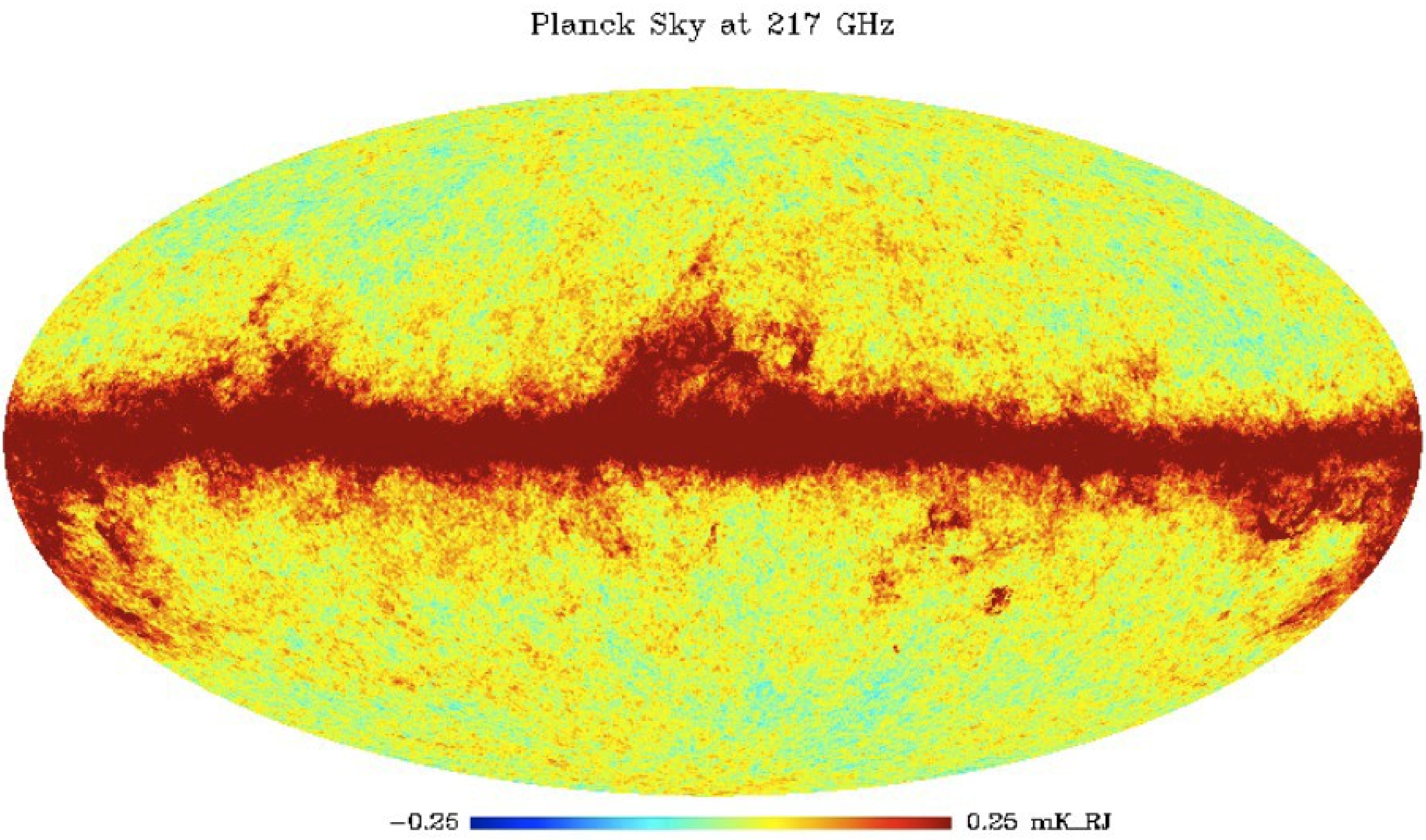
# Planck Sky at 70 GHz

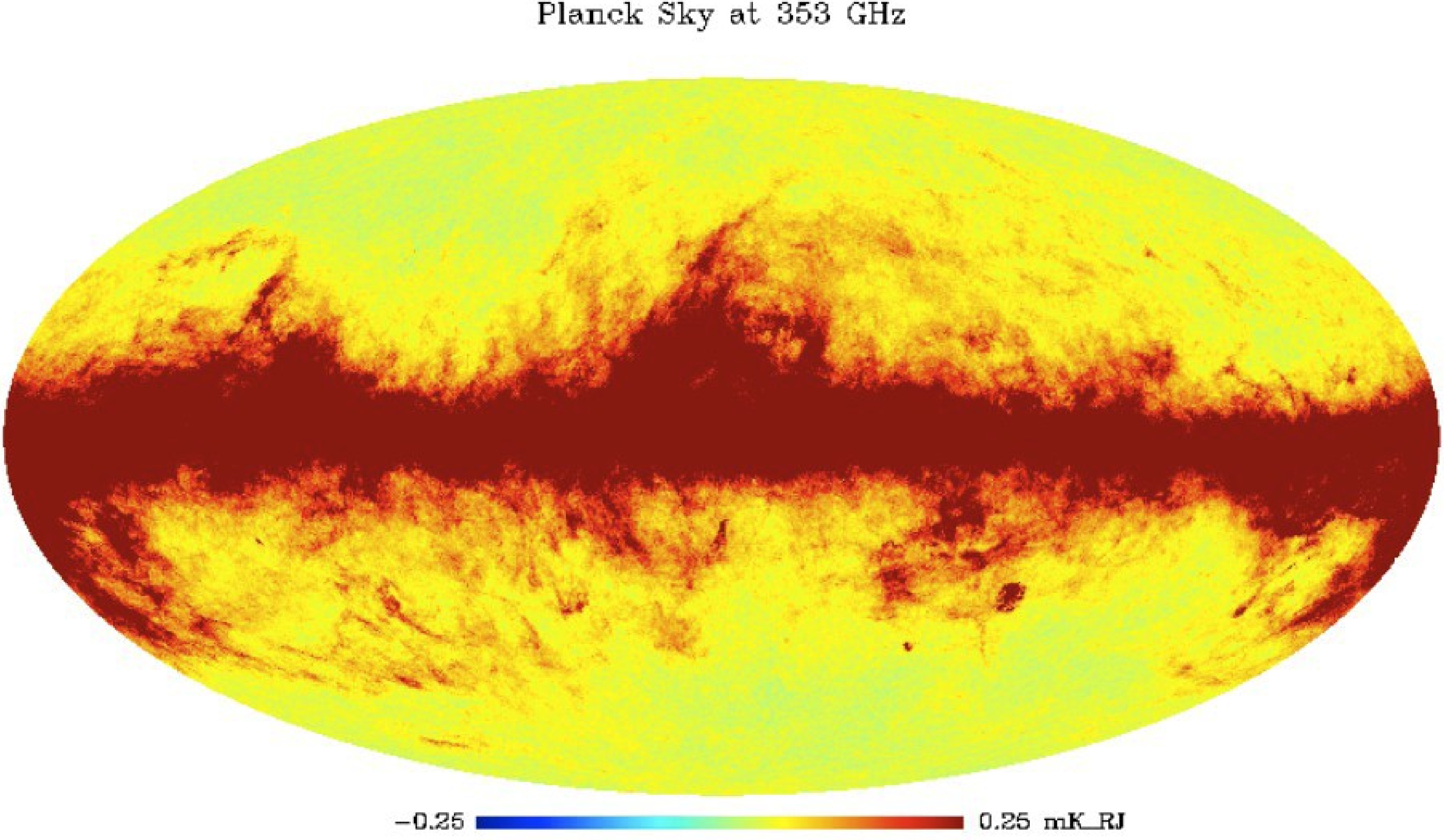


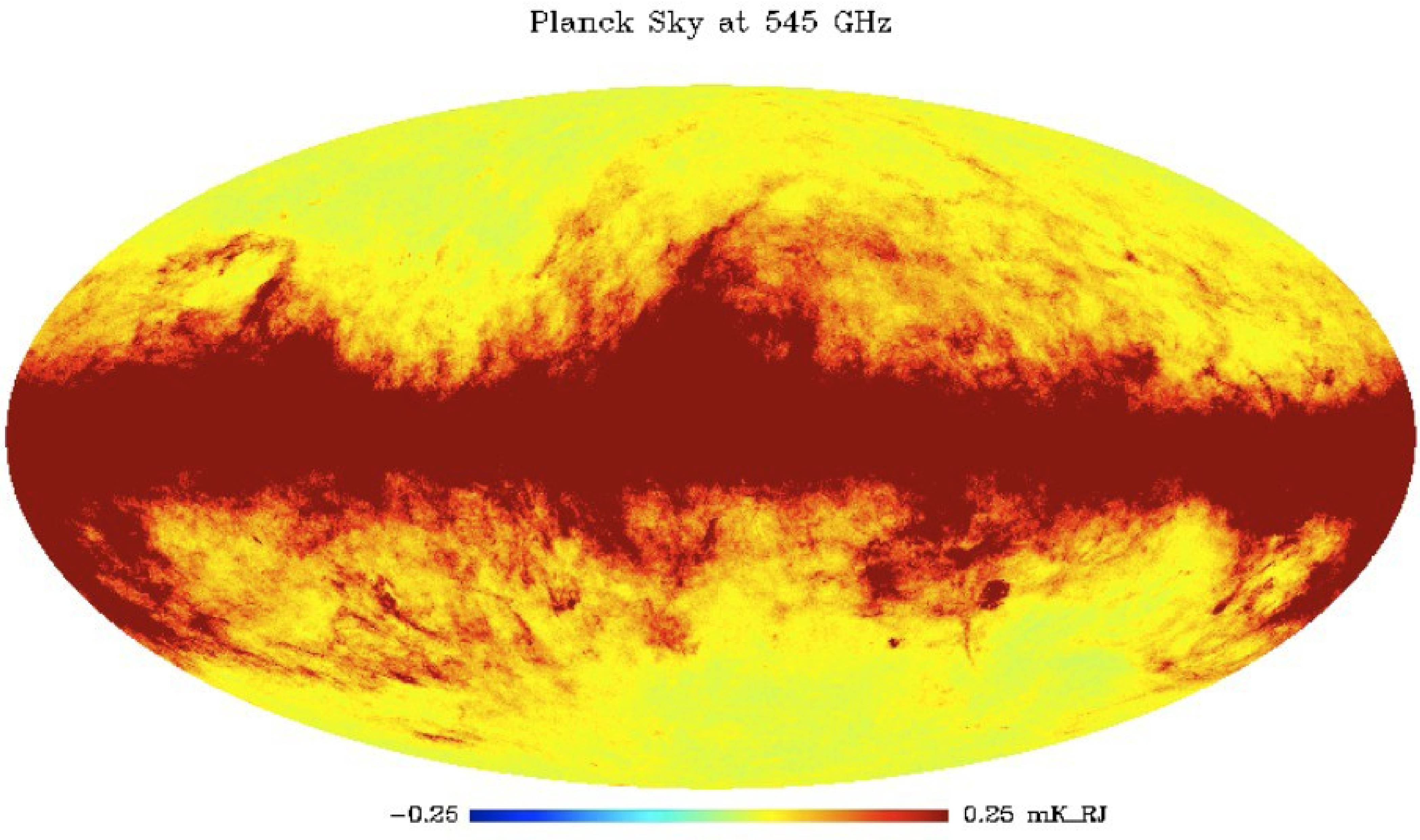

Planck Sky at 100 GHz
−0.25
0.25 mK_RJ

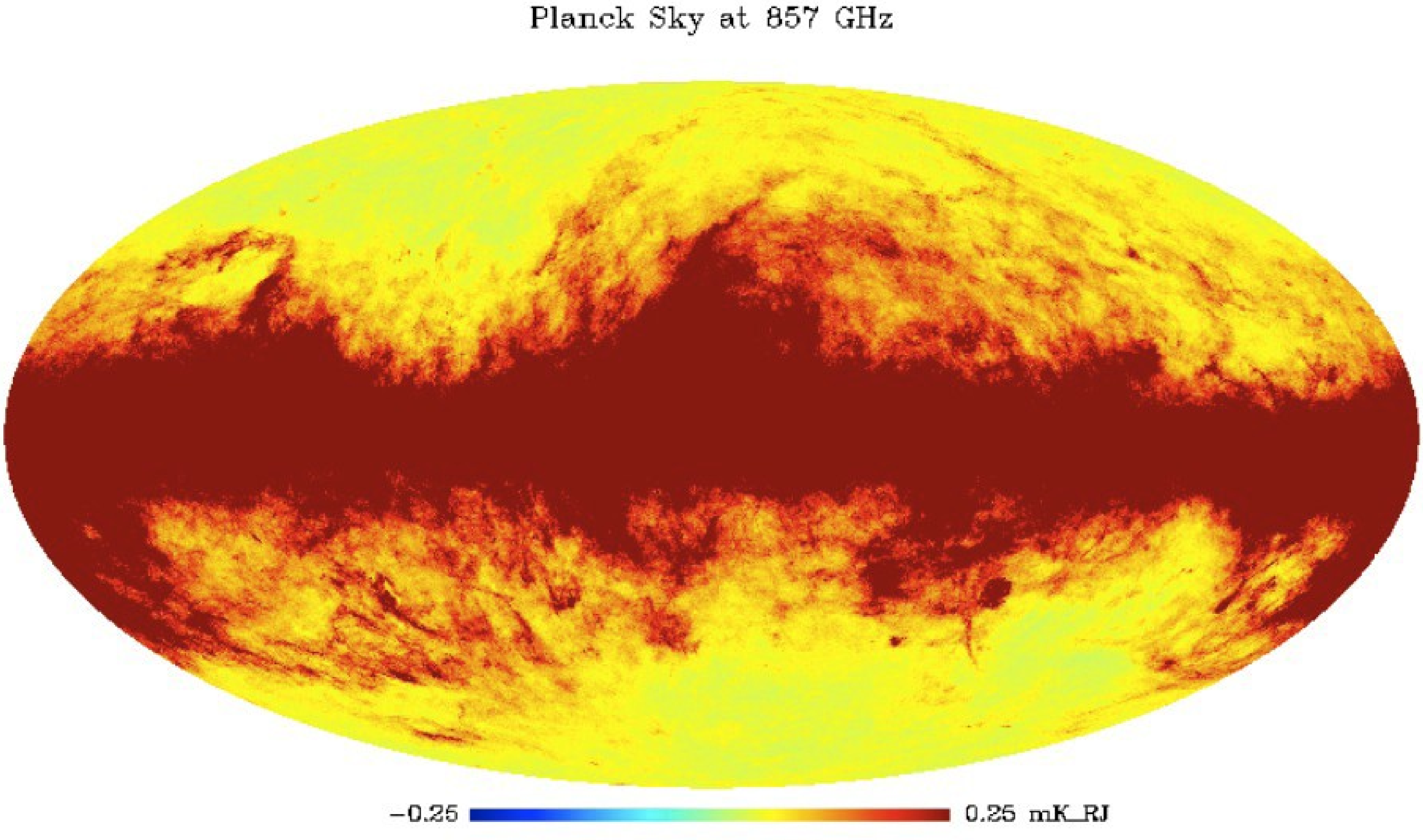


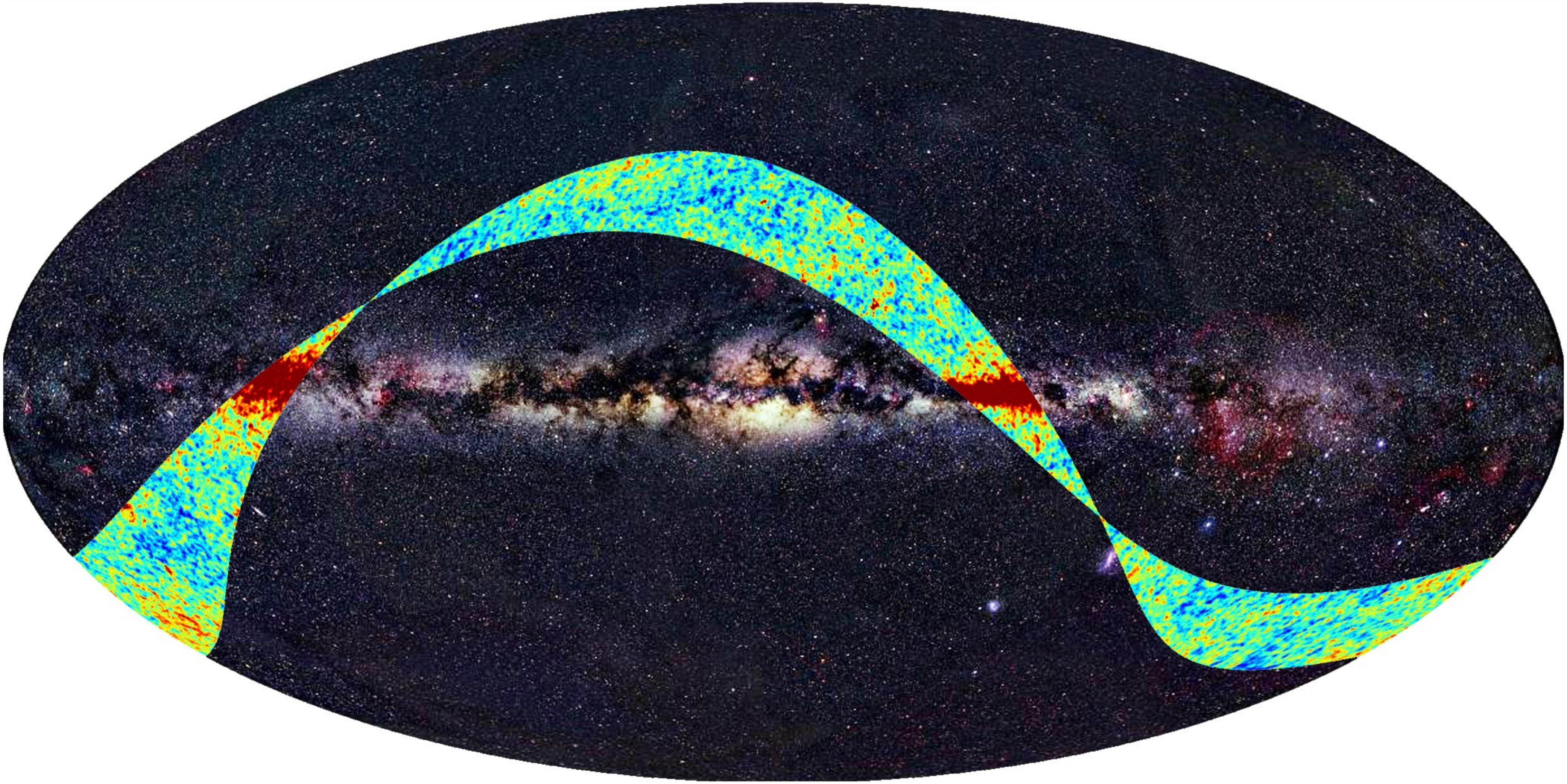
Planck Sky at 143 GHz
−0.25
0.25 mK_RJ


Planck Sky at 217 GHz
−0.25
0.25 mK_RJ

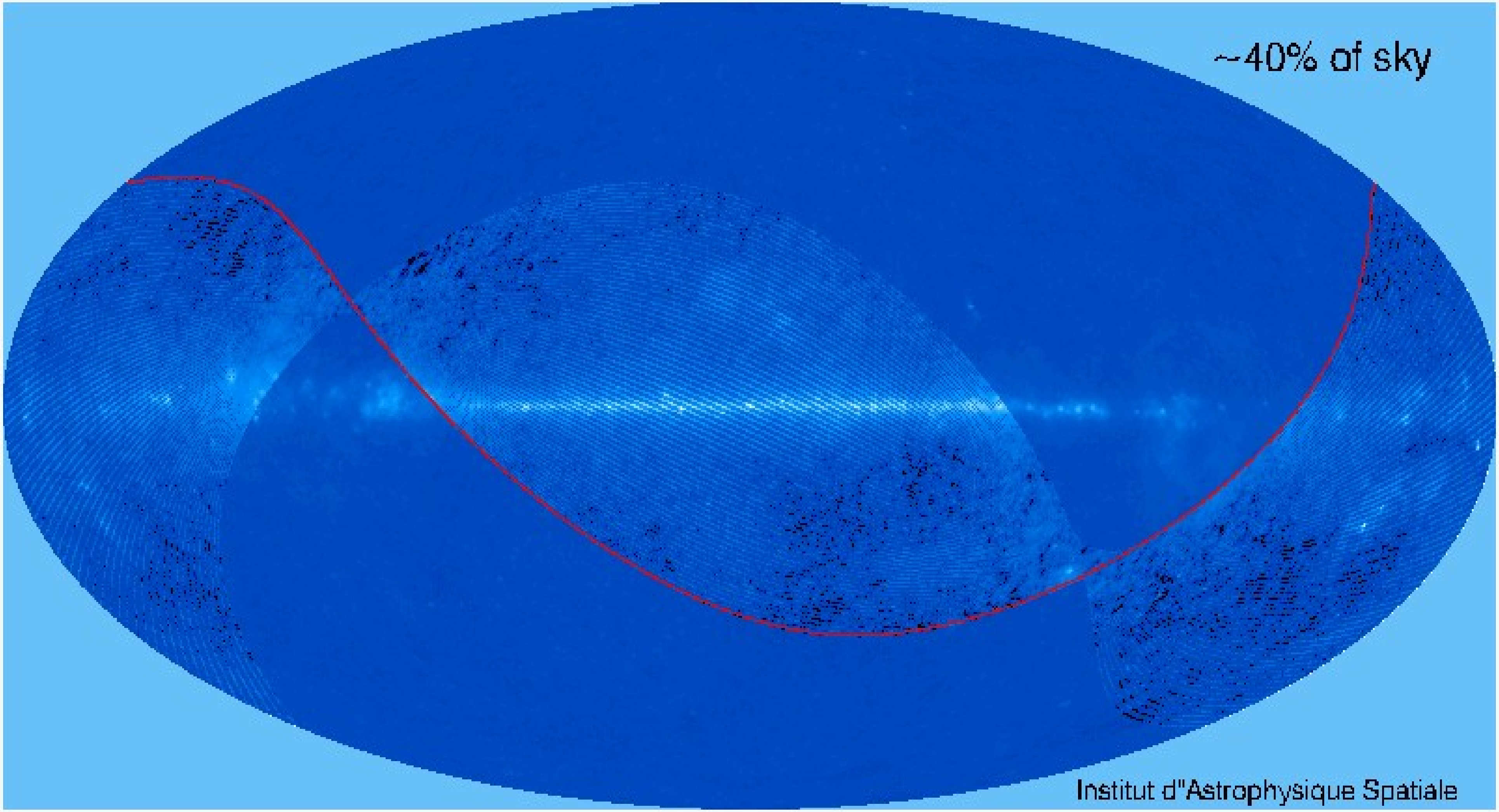

Planck Sky at 353 GHz
−0.25
0.25 mK_RJ

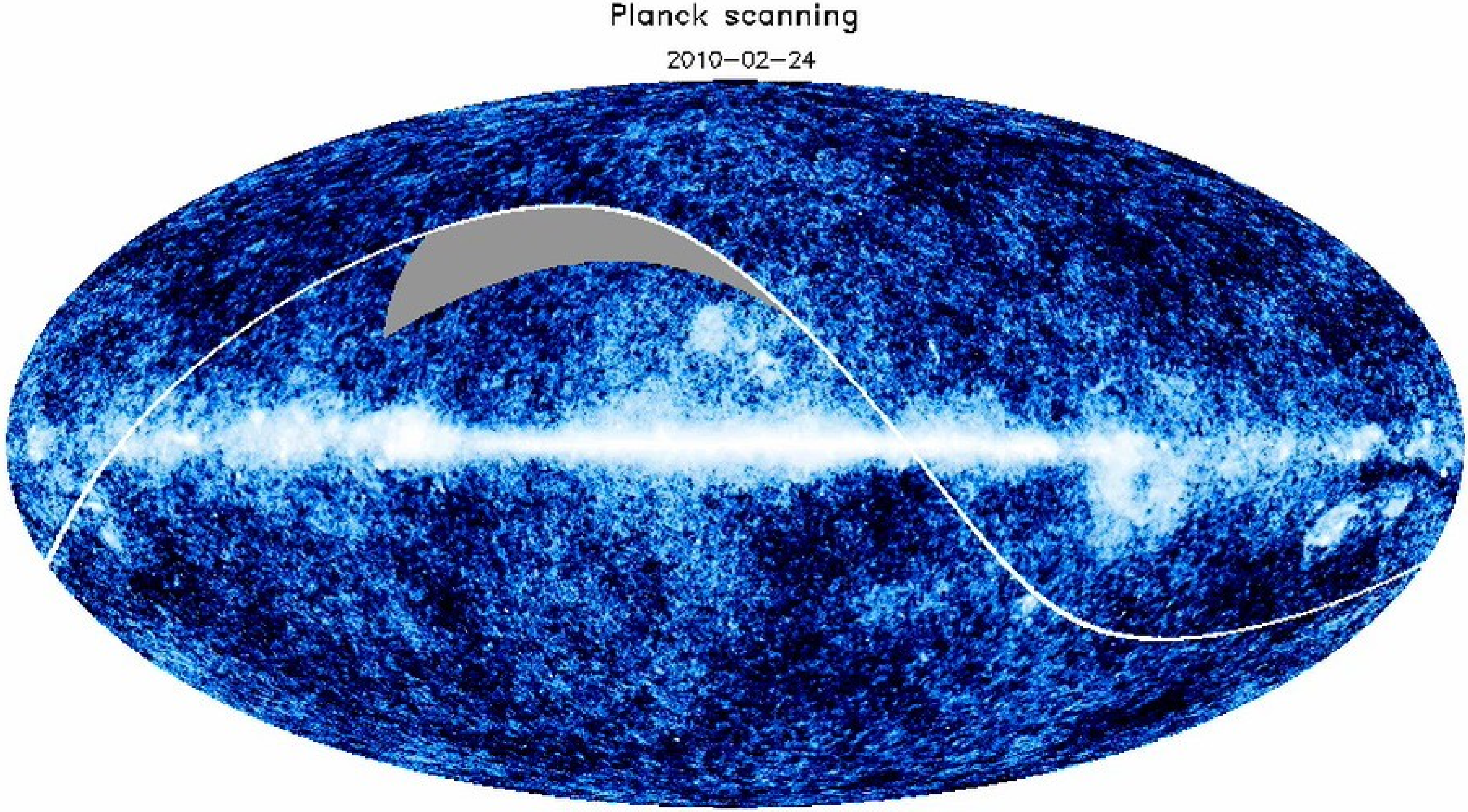

Planck Sky at 545 GHz
−0.25
0.25 mK_RJ

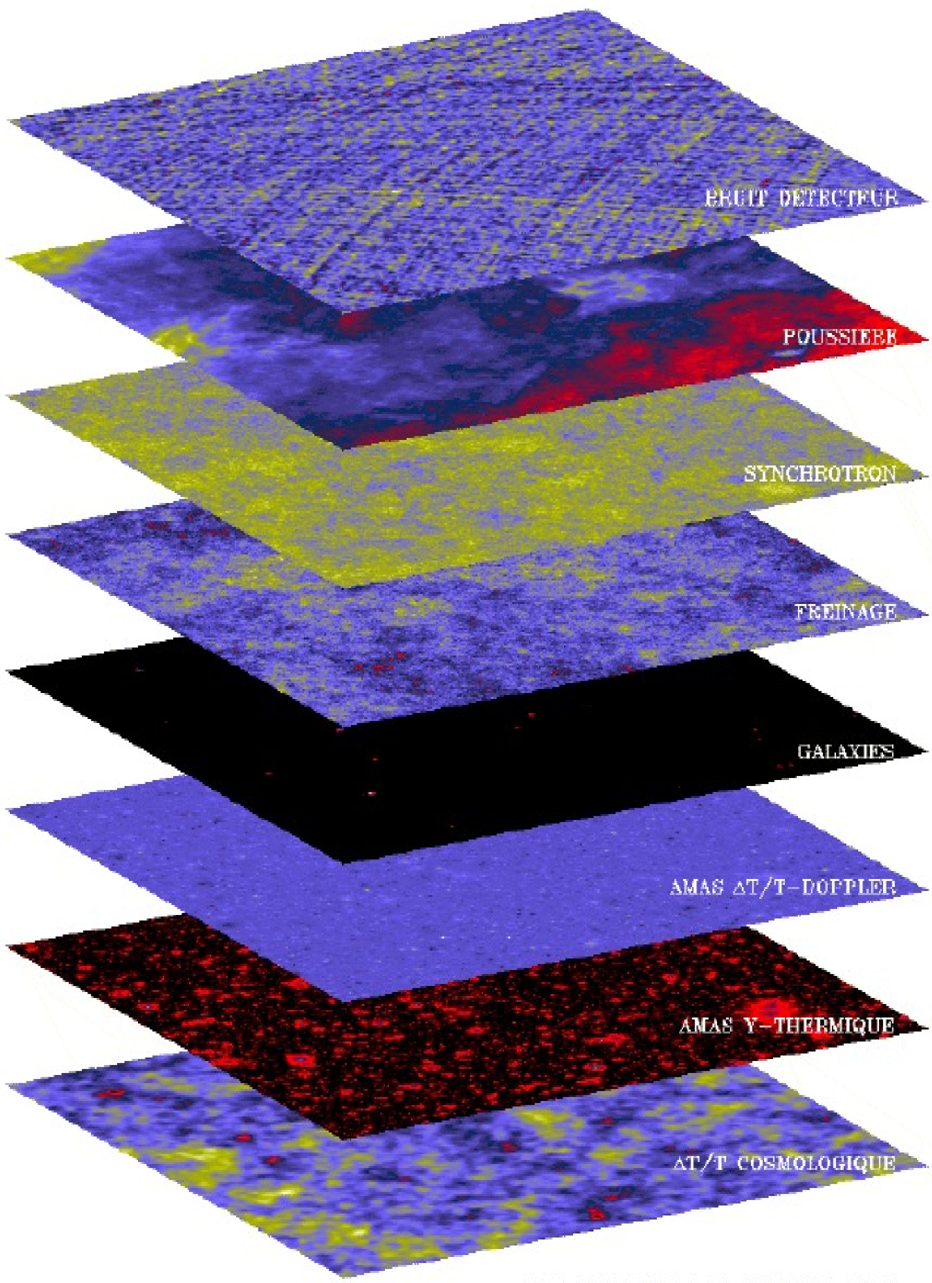

Planck Sky at 857 GHz
−0.25
0.25 mK_RJ



10/19/2009

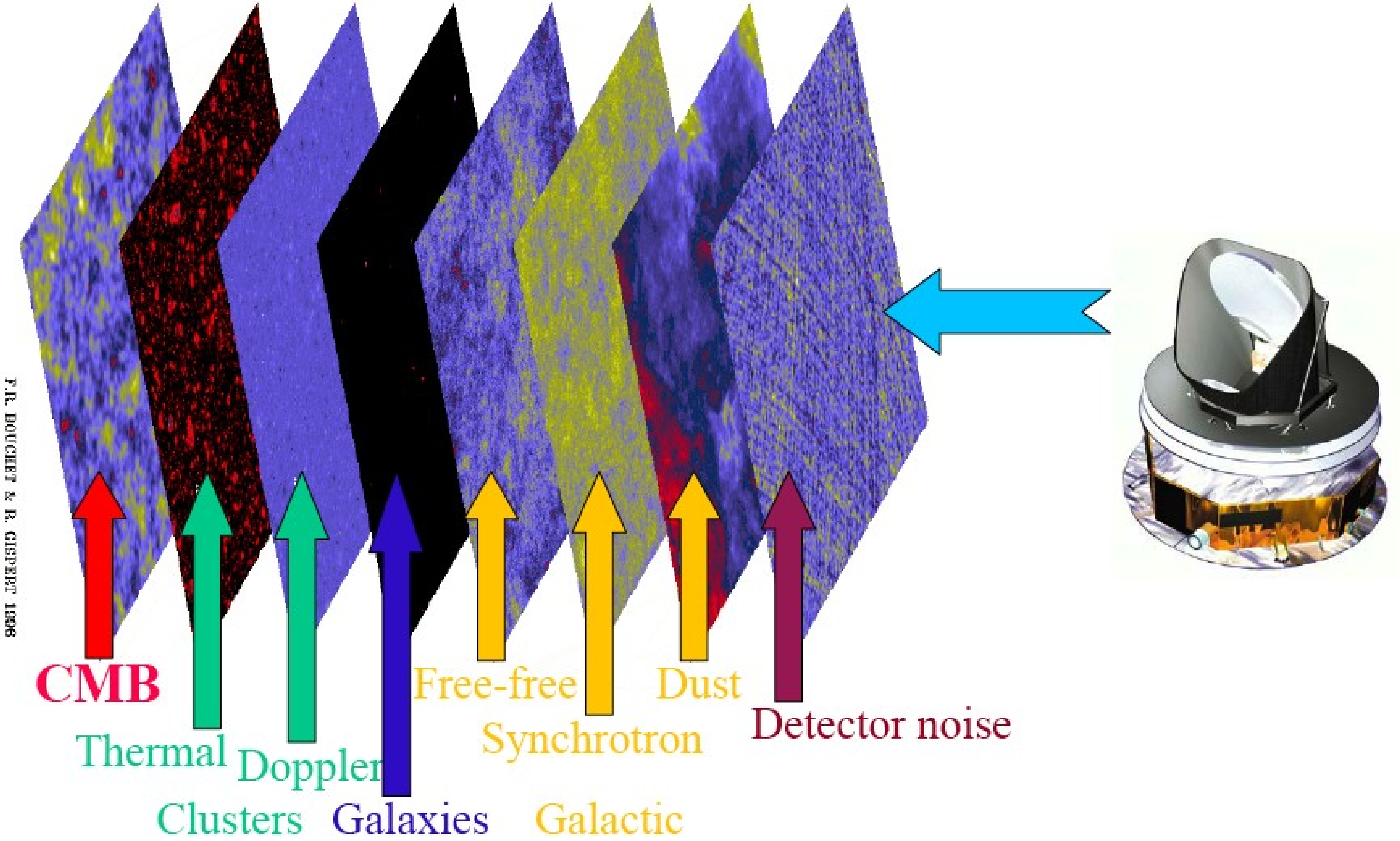


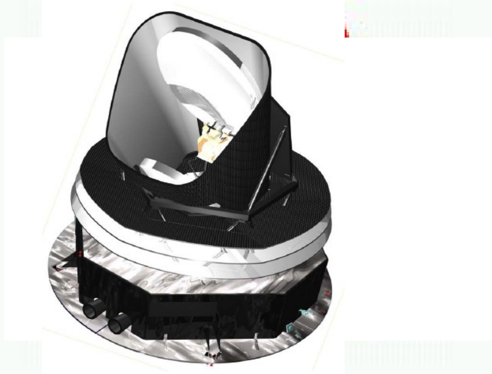

Planck scanning
2010-02-24



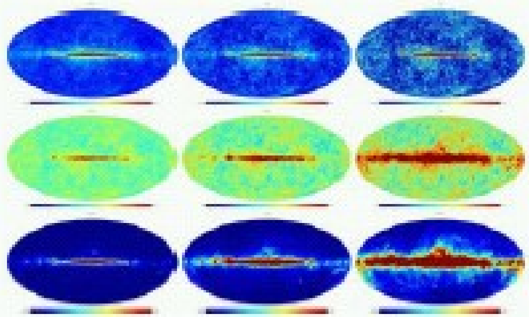

F.R. BOUCHET & R. GISPERT 1996

# Foreground separation

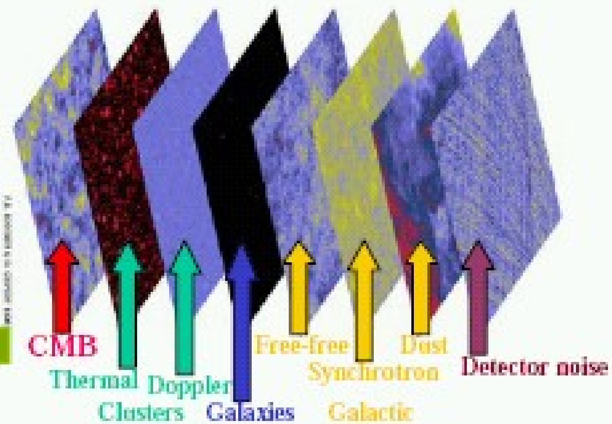




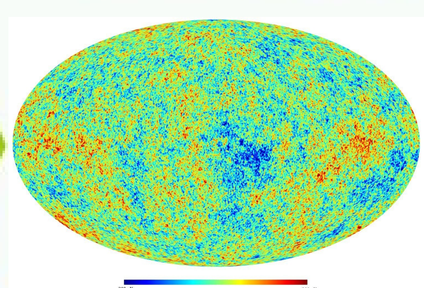
**Acquiring and processing time-ordered information**

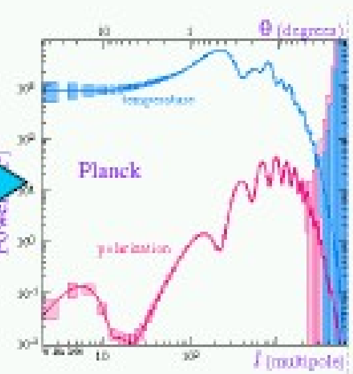


**Converting TOI to maps of the sky emission at many frequencies**




**Converting frequency maps to component maps**

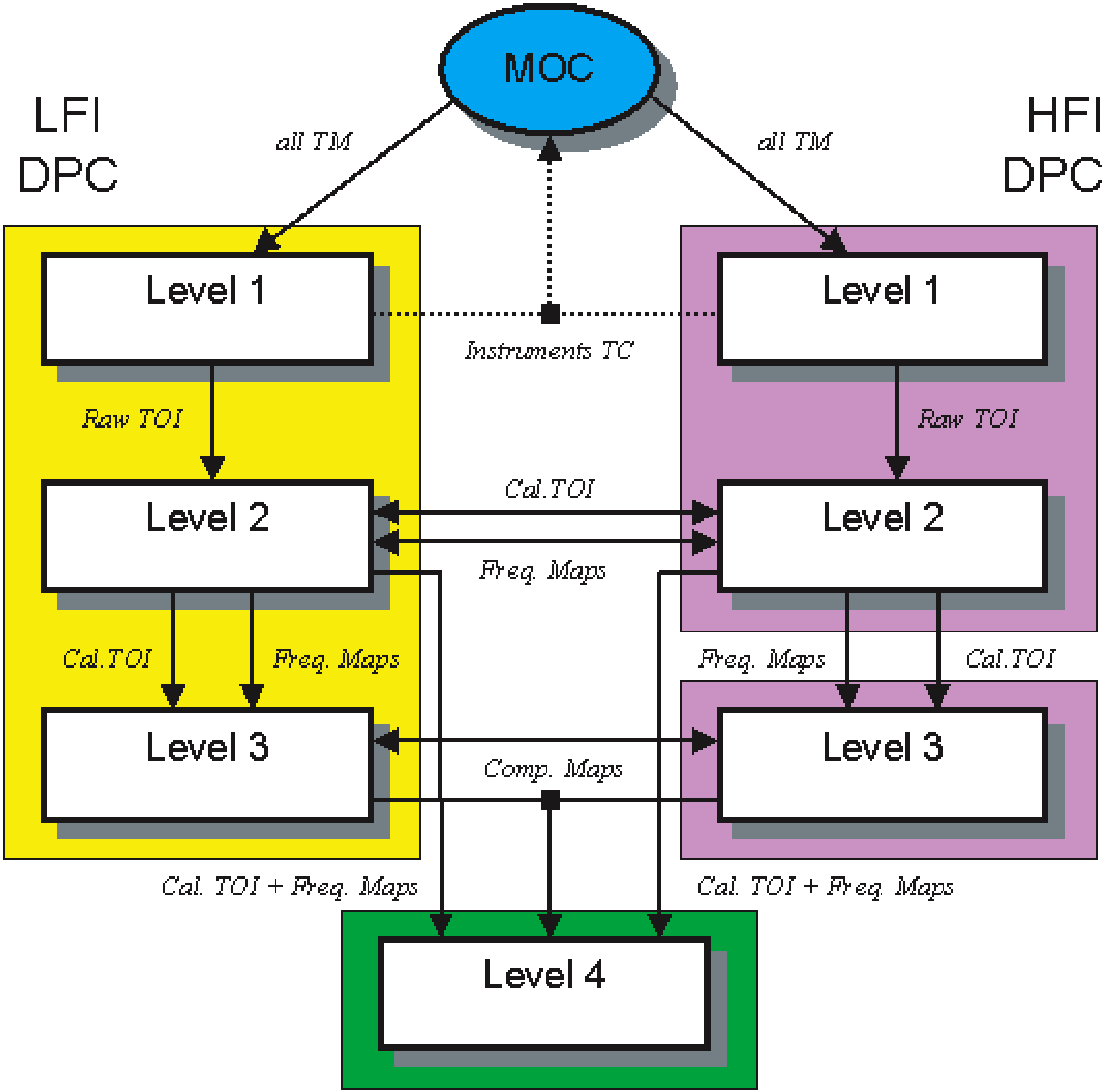




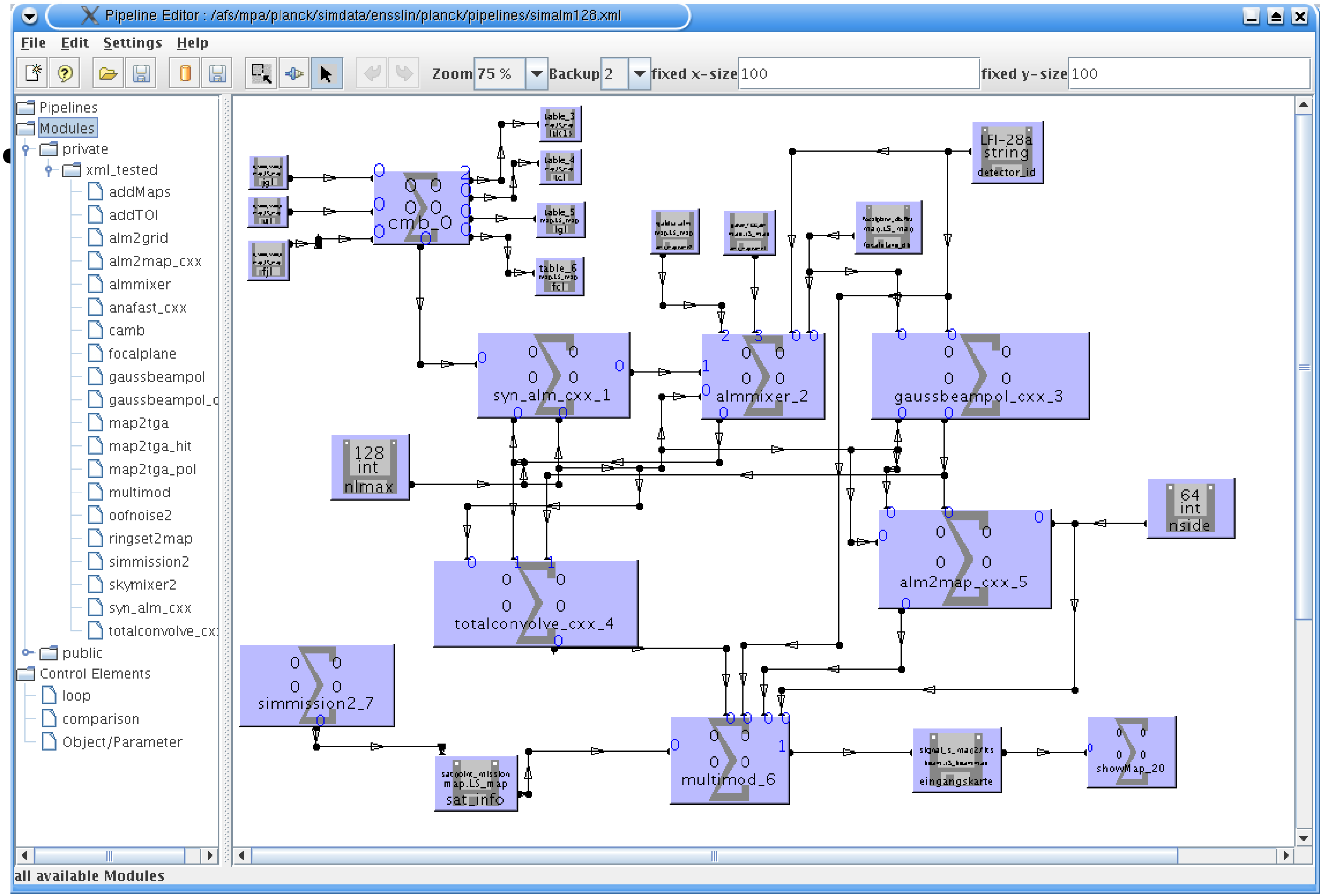

**Estimating the CMB angular power spectrum and cosmological parameters**

PLANCK

esa ASTROPHYSICS

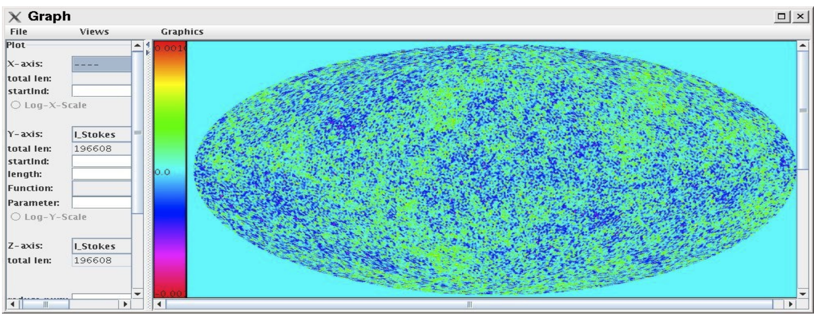

MOC
LFI DPC
HFI DPC
all TM
all TM
Level 1
Level 1
Instruments TC
Raw TOI
Raw TOI
Level 2
Level 2
Cal.TOI
Freq. Maps
Cal.TOI
Freq. Maps
Freq. Maps
Cal.TOI
Level 3
Level 3
Comp. Maps
Cal. TOI + Freq. Maps
Cal. TOI + Freq. Maps
Level 4

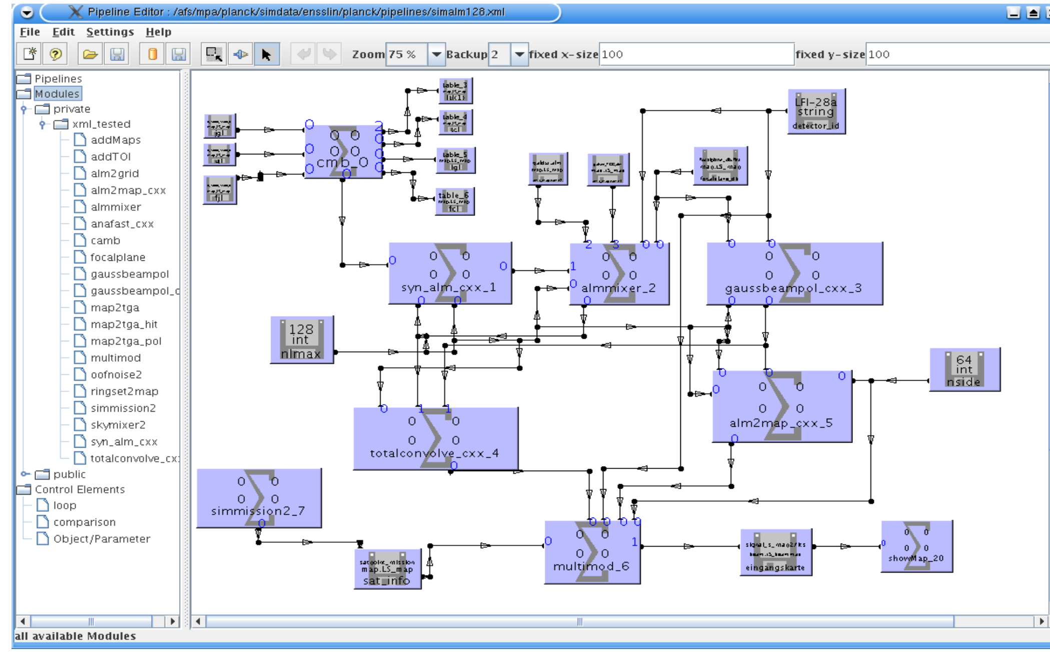
# Simulation Pipeline in the ProC Editor

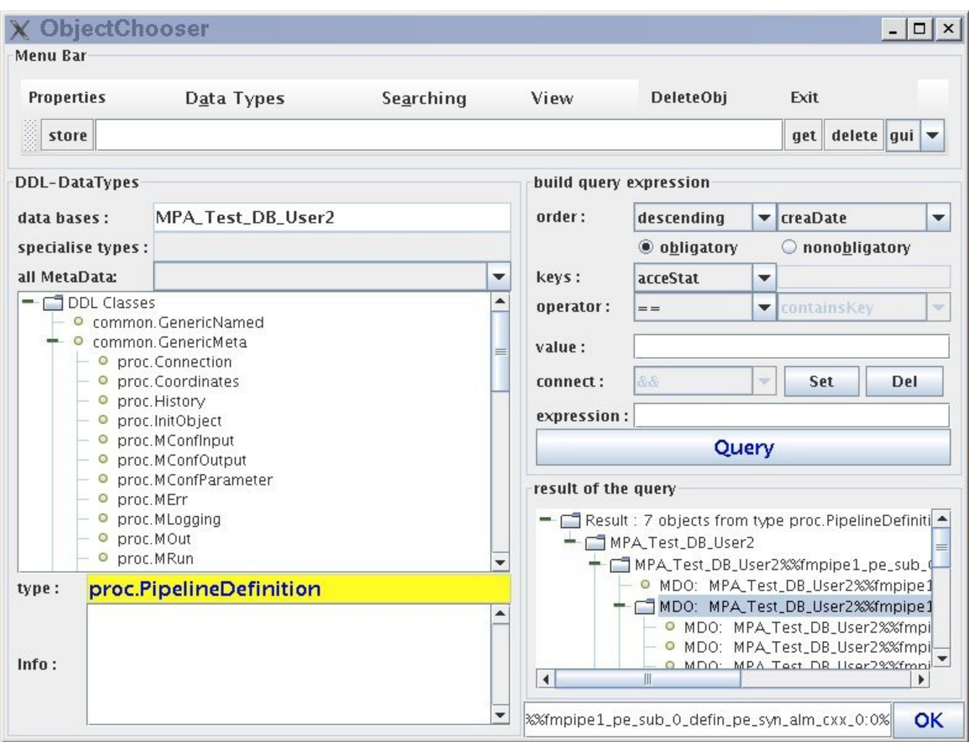


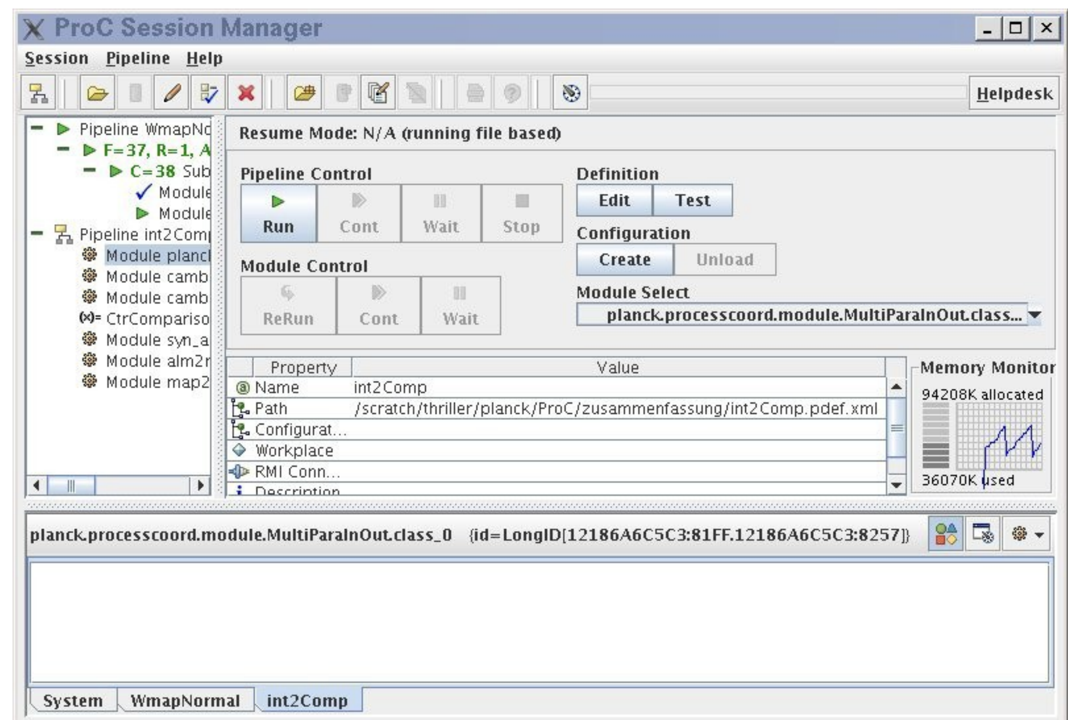
# German contributions to Planck

- Planck Simulation package
- ProC Workflow engine
- Data Management Component
- Scientific data analysis



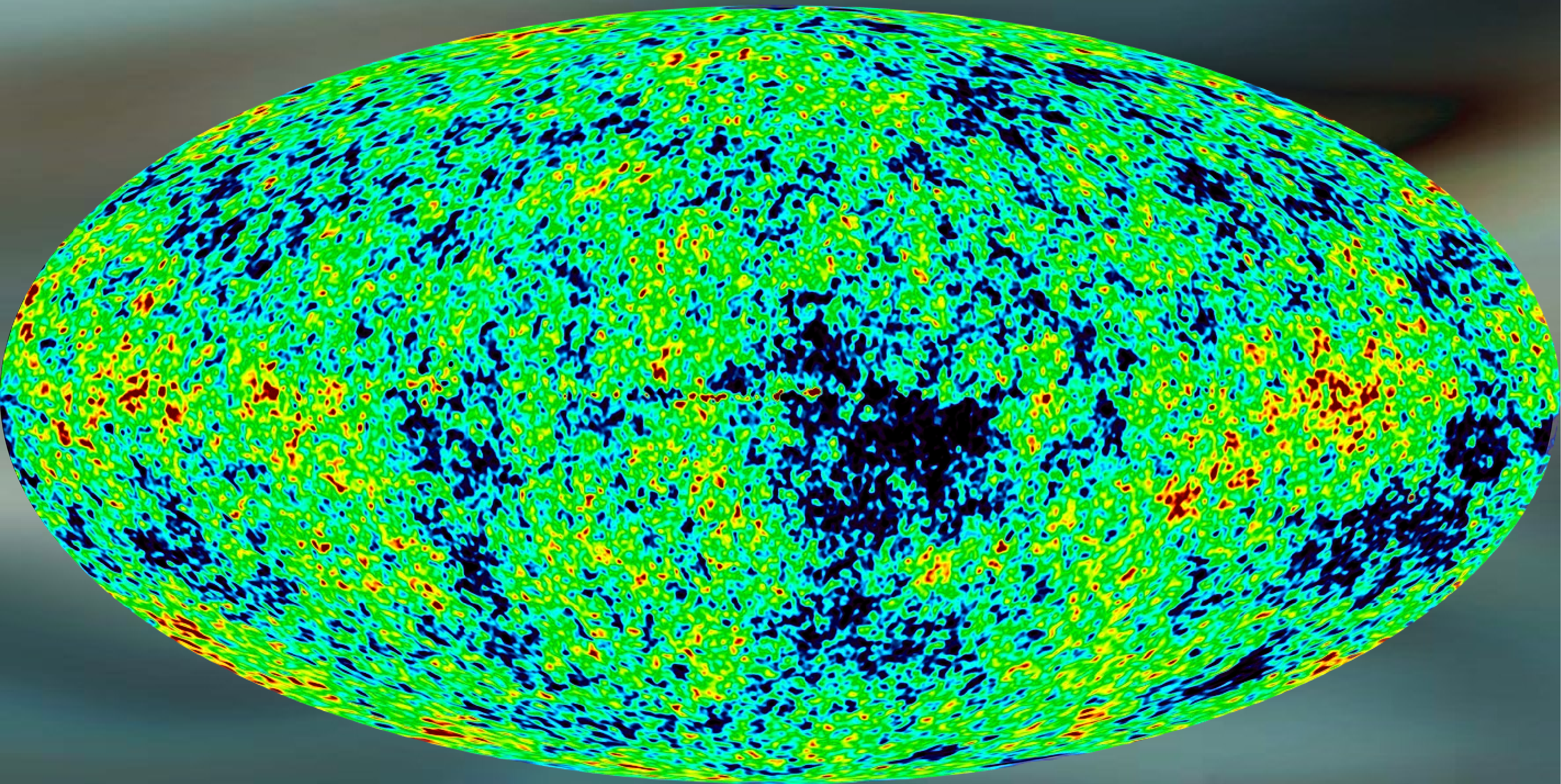



# Physics of the CMB

a) the CMB & history of the Universe
b) primordial CMB anisotropies
c) secondary CMB anisotropies



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a) the CMB & history of the Universe
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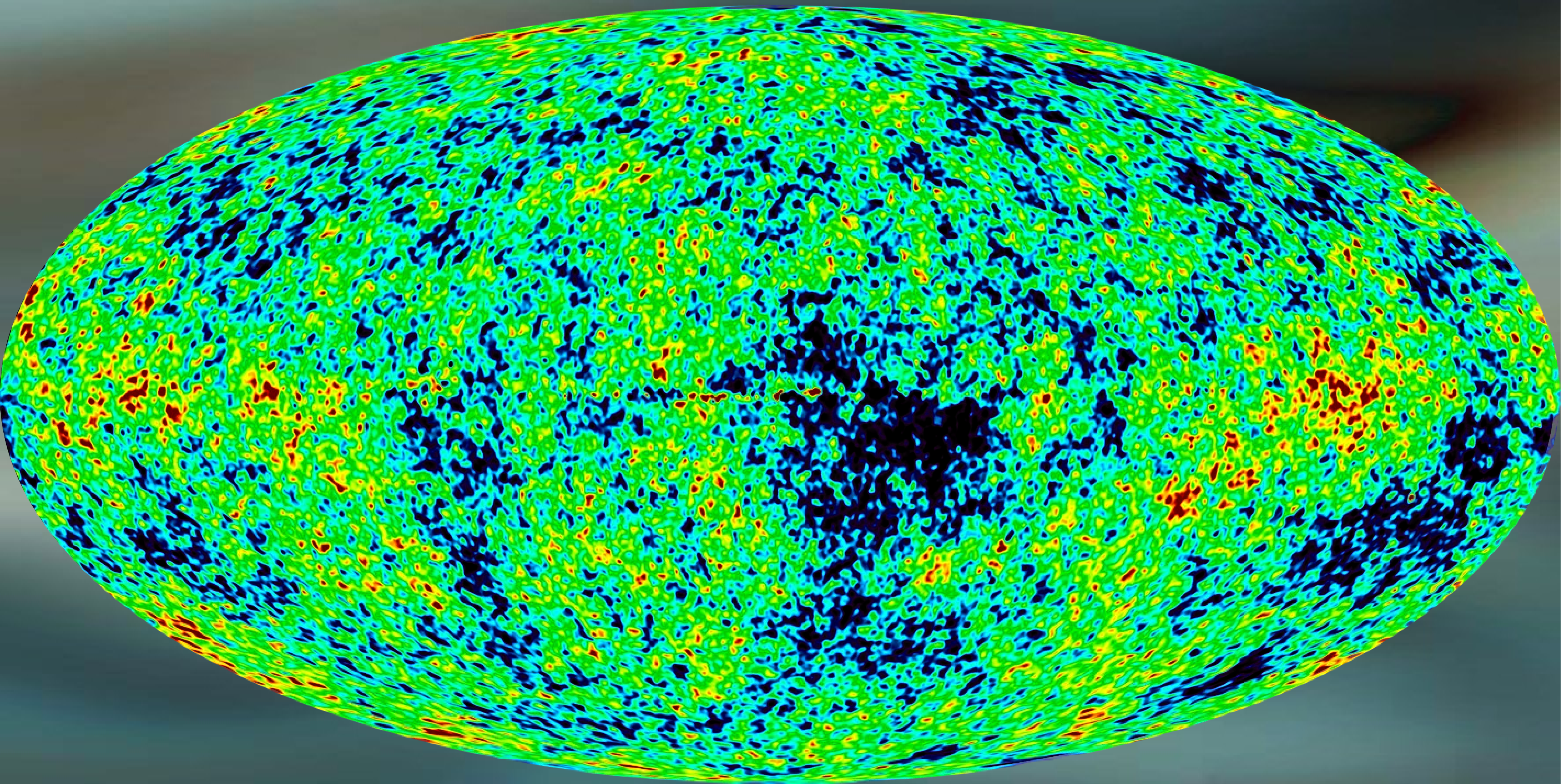
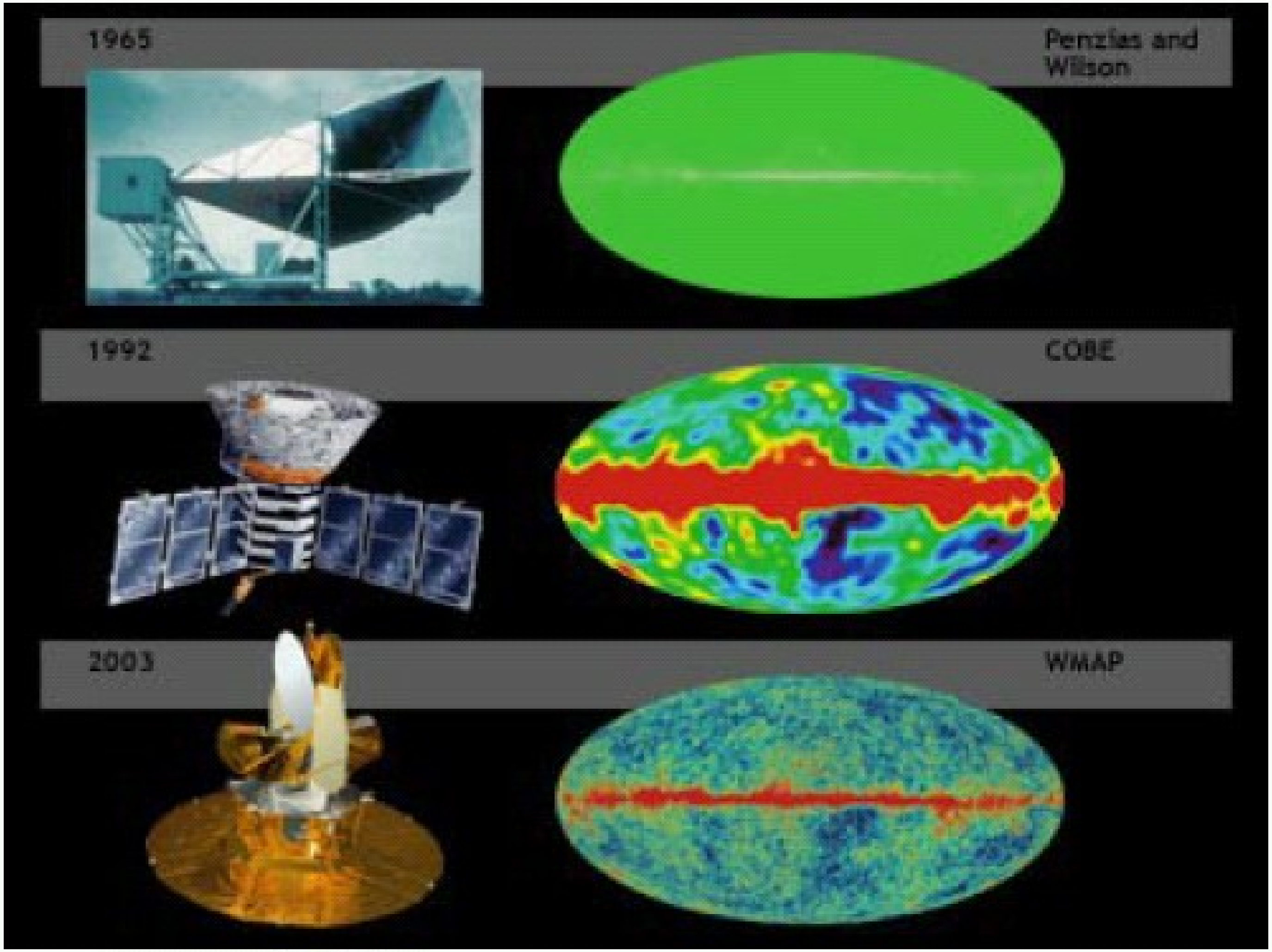


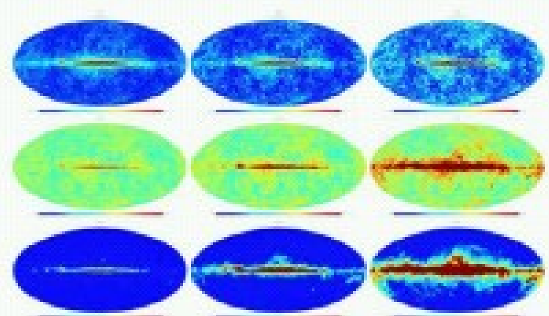
# CMB discovery by Penzias & Wilson 1965


Gamov 1946




# Planck: 3rd Generation CMB space experiment

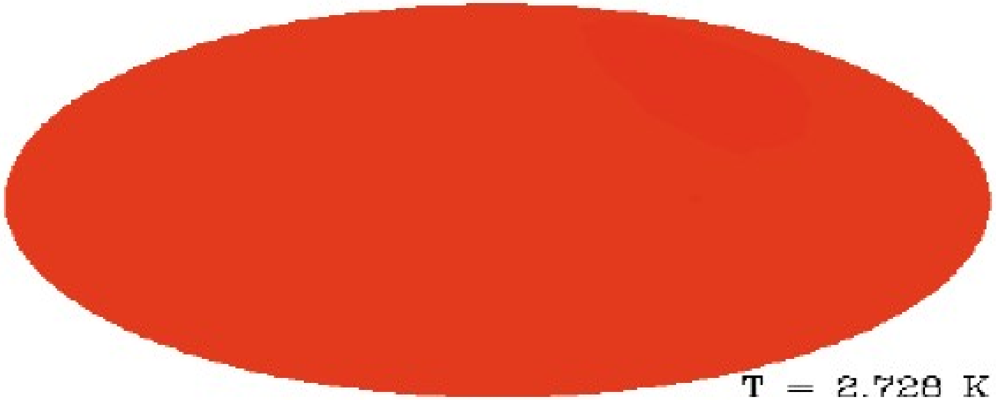
2010



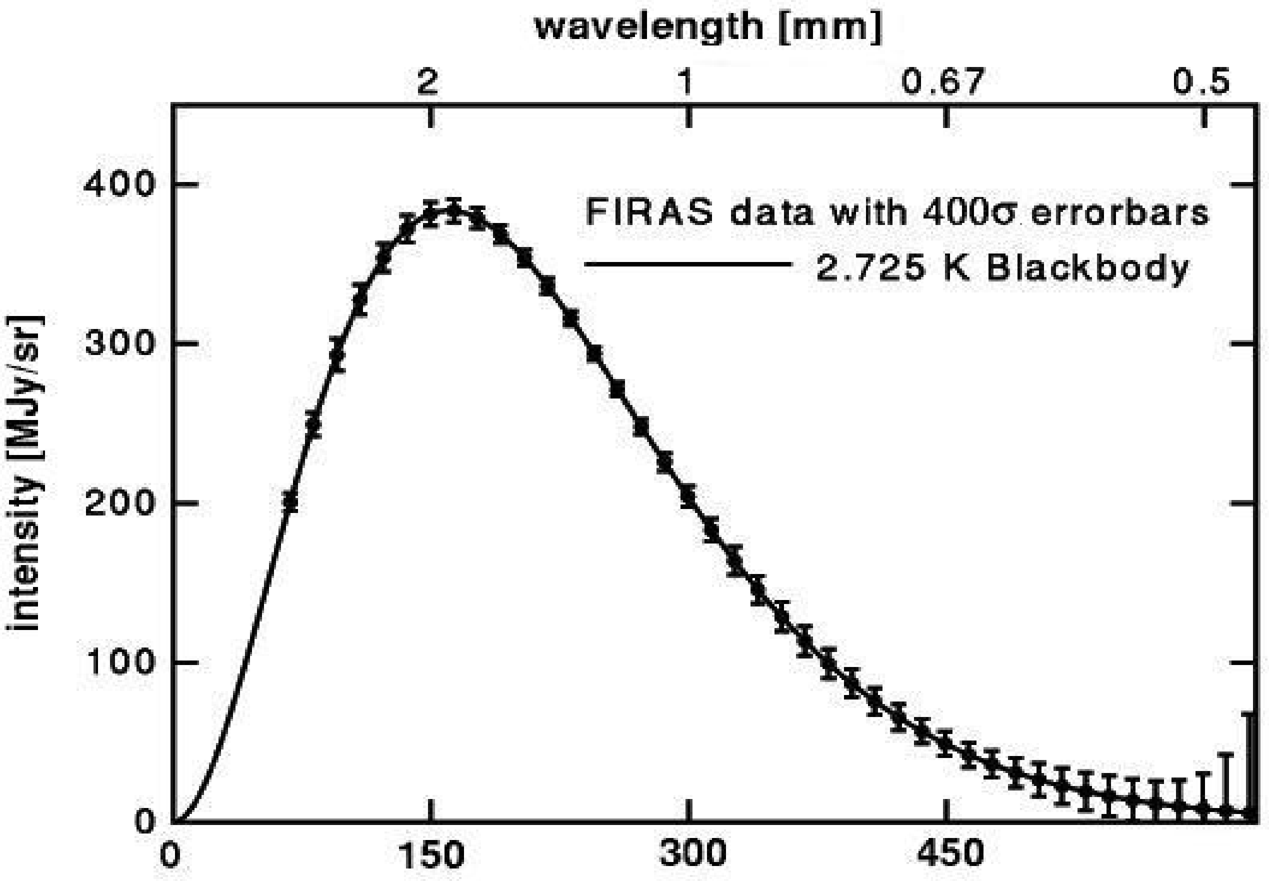
PLANCK

esa ASTROPHYSICS

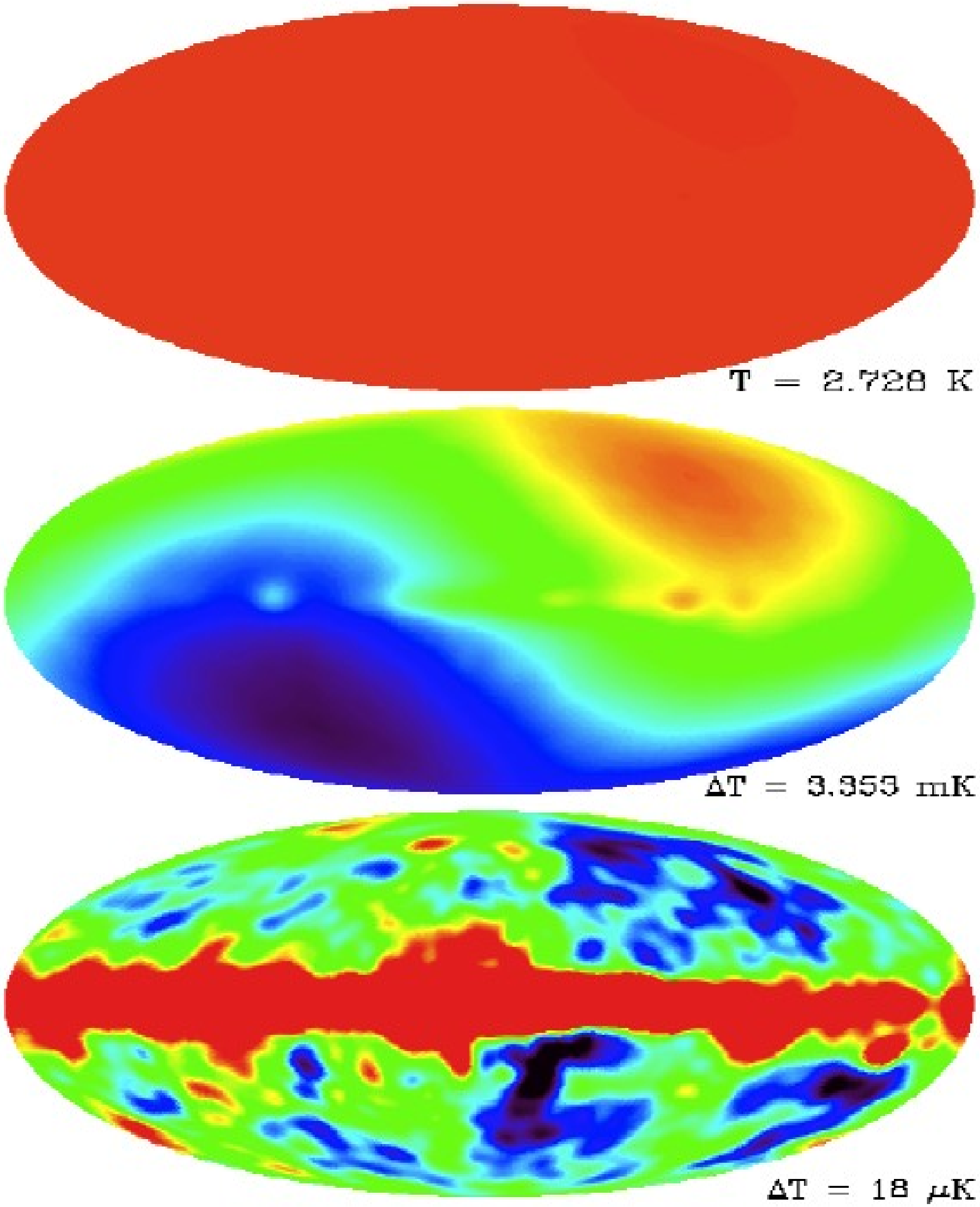
# CMB as seen by COBE



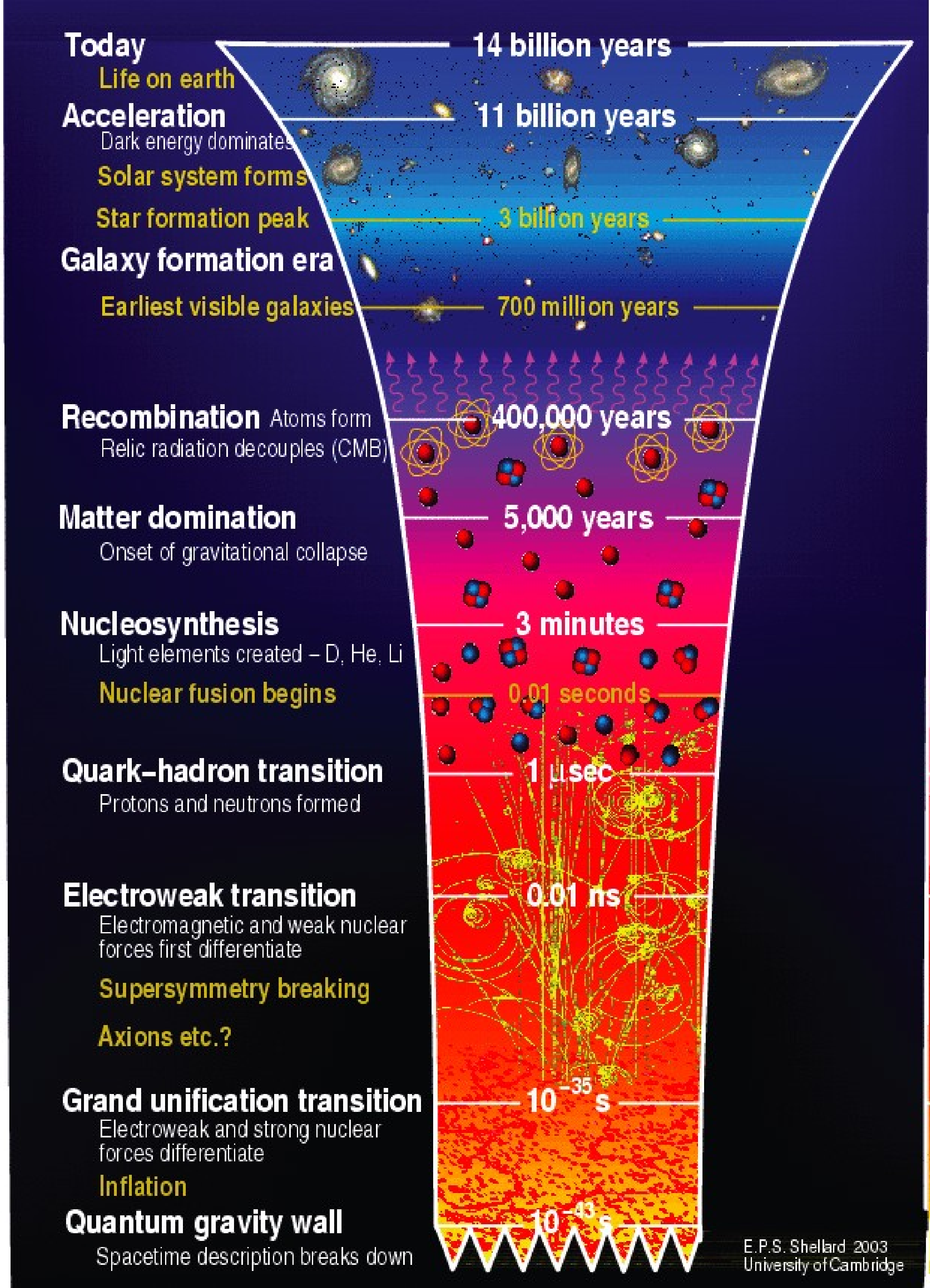

- mean temperature



# CMB as seen by COBE




- Universe extreme uniform on largest visible scales
- opposite directions not in causal contact even today
- small scale temperature variations on a level of 1:100.000 visible
- seeds for present day galaxies and clusters ...
- ... if dark matter is present in addition to normal, baryonic matter



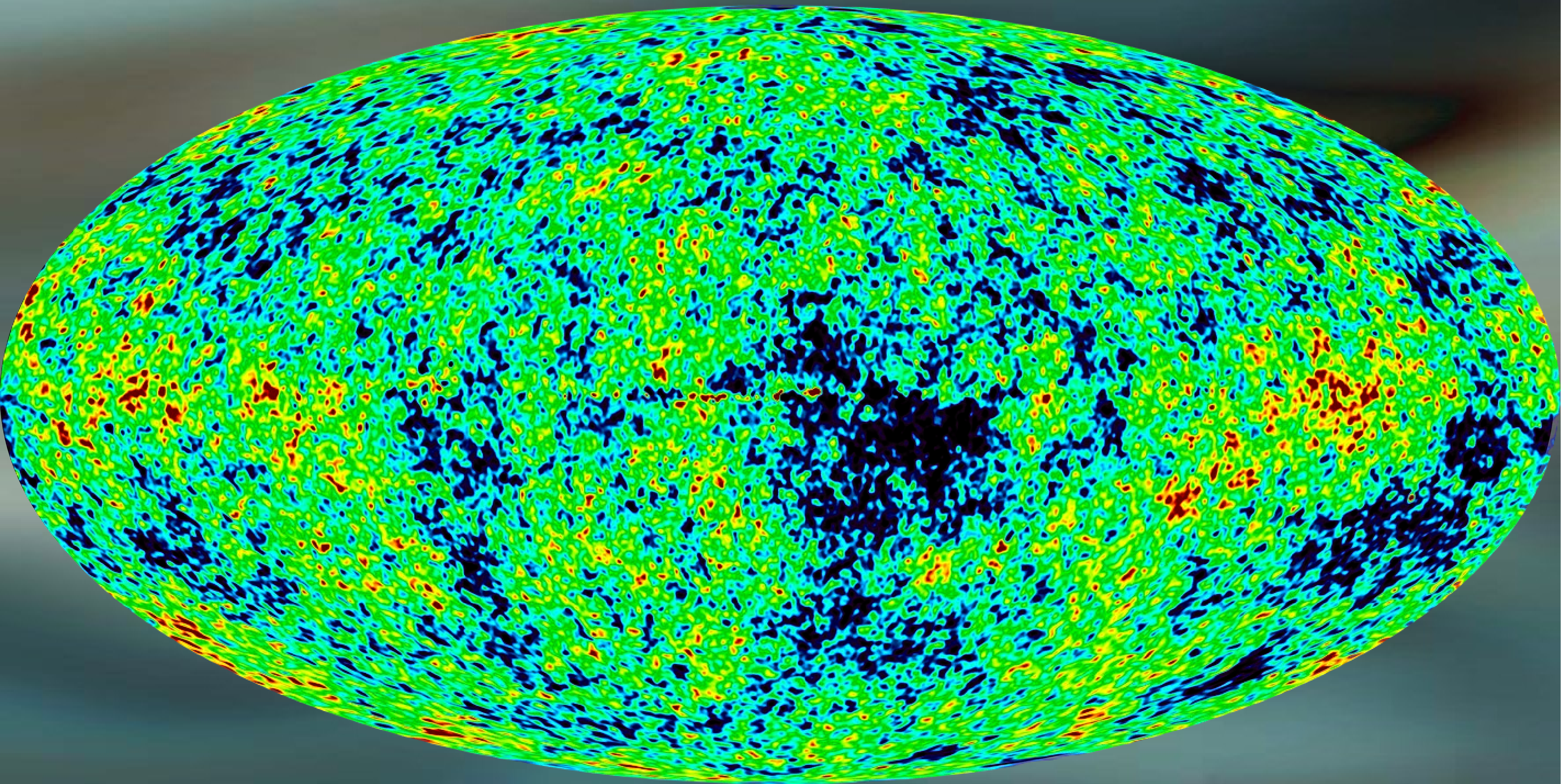
Today
14 billion years
Life on earth
Acceleration
11 billion years
Dark energy dominates
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
400,000 years
Relic radiation decouples (CMB)
Matter domination
5,000 years
Onset of gravitational collapse
Nucleosynthesis
3 minutes
Light elements created – D, He, Li
Nuclear fusion begins
0.01 seconds
Quark-hadron transition
1 µsec
Protons and neutrons formed
Electroweak transition
0.01 ns
Electromagnetic and weak nuclear forces first differentiate
Supersymmetry breaking
Axions etc.?
Grand unification transition
$10^{-35}$ s
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
$10^{-43}$ s
Spacetime description breaks down
E.P.S. Shellard 2003
University of Cambridge

# Physics of the CMB

a) the CMB & history of the Universe

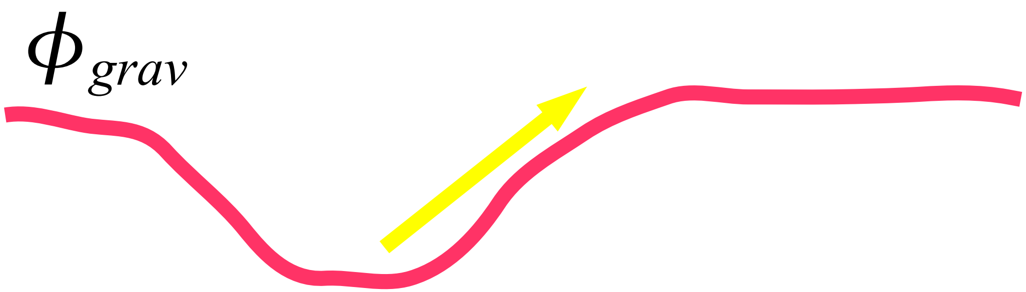
b) primordial CMB anisotropies

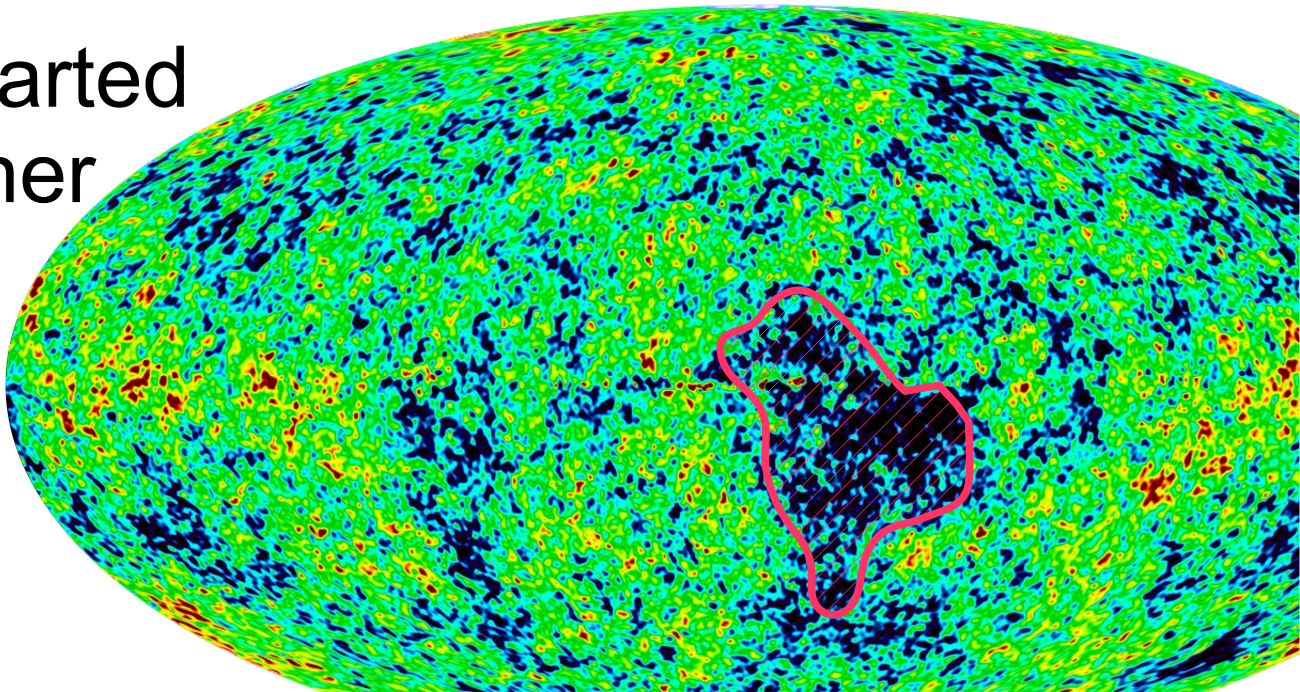
c) secondary CMB anisotropies



# Sachs-Wolfe effect

- gravitational potential = hilly landscape
- photons starting from lower positions loose energy on way to us
- however, they started with already higher temperature



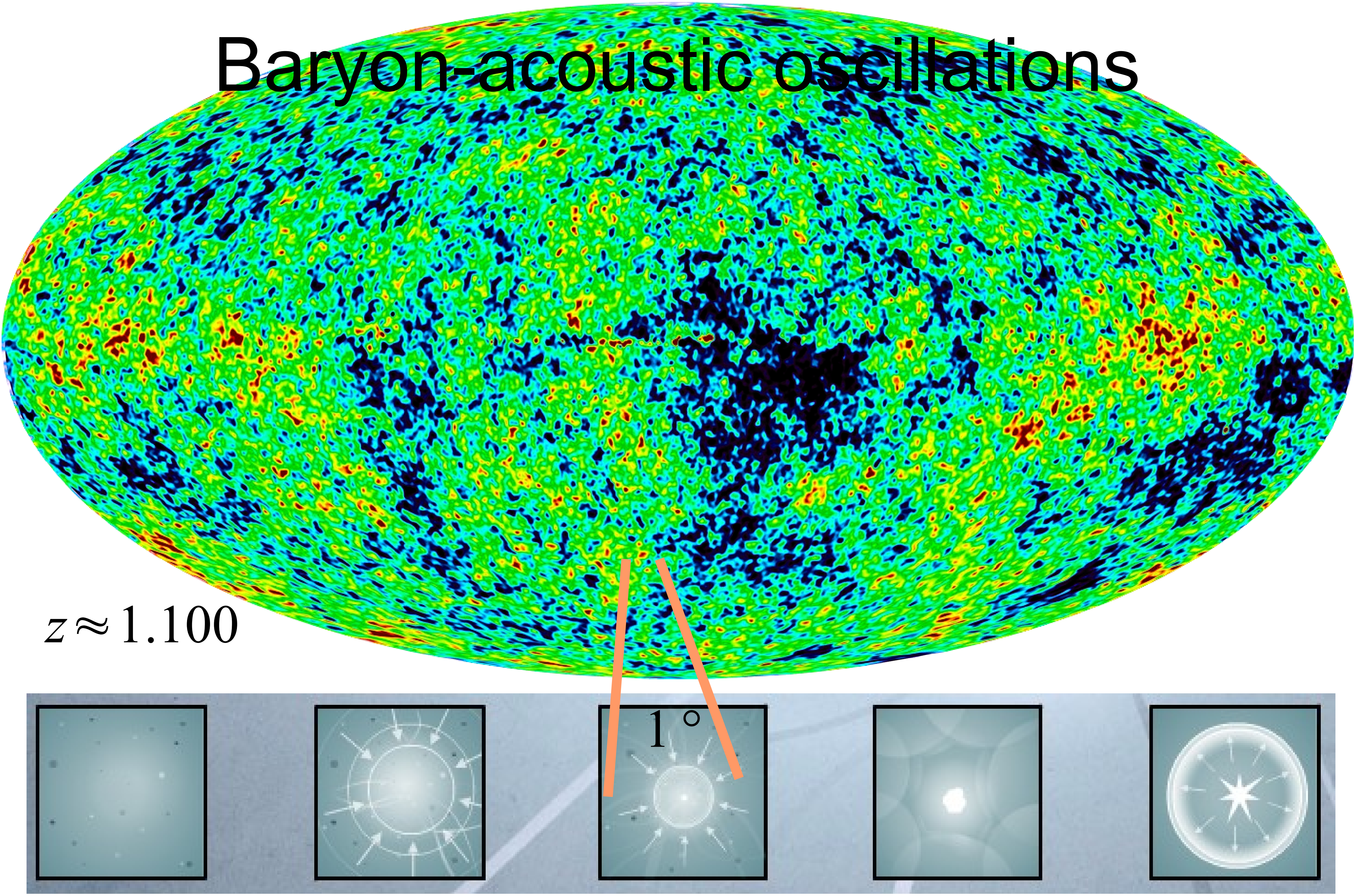



$$\frac{\delta T}{T} = \frac{1}{3}\phi_{grav}$$

# Baryon-acoustic oscillations

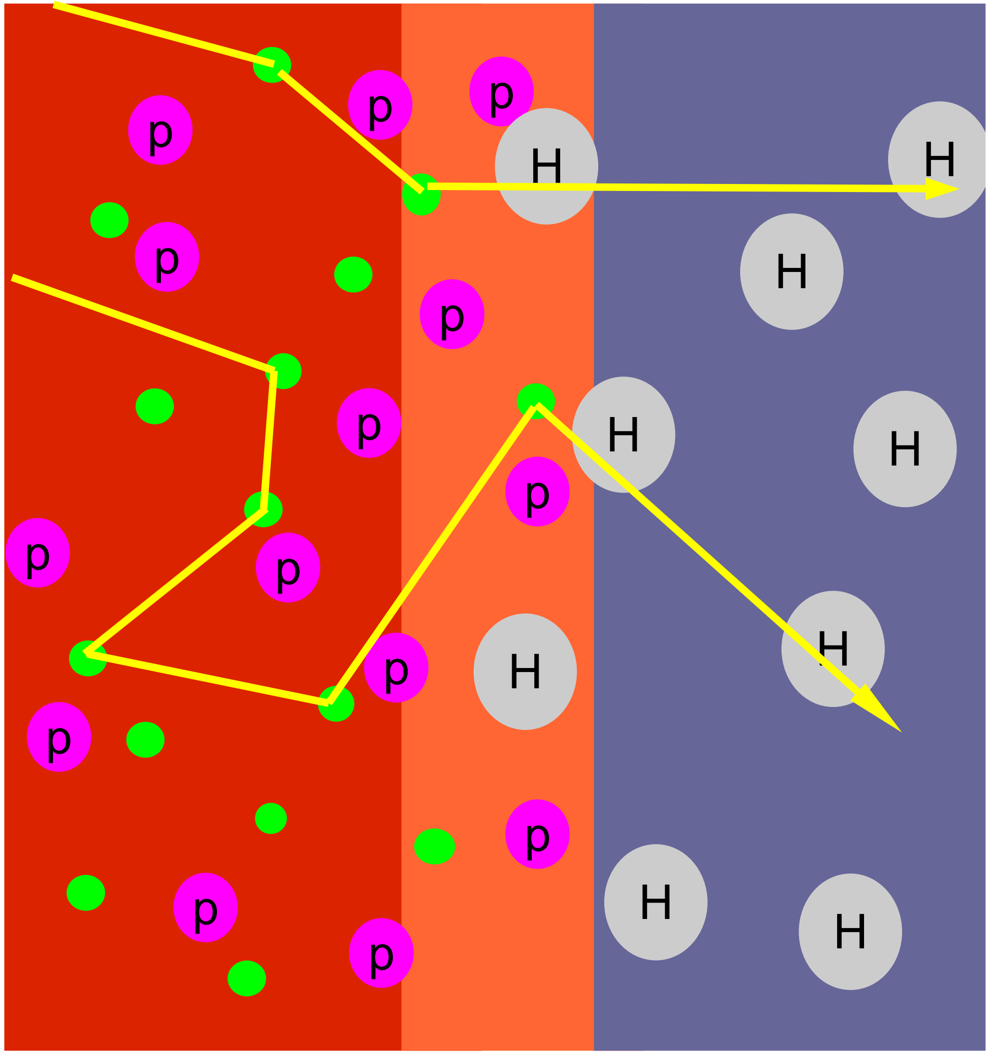
- subhorizon dark matter haloes grow after matter-radiation equality (5.000 yr or $z \approx 20.000$ )
- baryon-photon fluid follows gravitational pull
- photon pressure grows due to compression, ...
- and stops further plasma inflow ...
- and leads to an expansion

# Baryon-acoustic oscillations



# Recombination & Silk damping

- photons are scattered on free electrons before rec.
- photons free stream after
- visible CMB emerges from last scattering surface
- finite duration of rec. leads to finite width of surface & photon diffusion
- smearing of small scale structures => Silk damping
- CMB featureless for $\theta \ll 5'$




$z \approx 1.100$

# Gravitational lensing

$$T(\vec{\theta}) = \tilde{T}(\vec{\theta}) - \vec{\alpha}(\vec{\theta}) \cdot \vec{\nabla}\tilde{T}(\vec{\theta})$$

- lensing does not change surface brightness, but reshuffles brightness and polarisation on the sky
- most important on small angular scales, where CMB is more smooth
- produces intriguing polarisation patterns (B-modes)

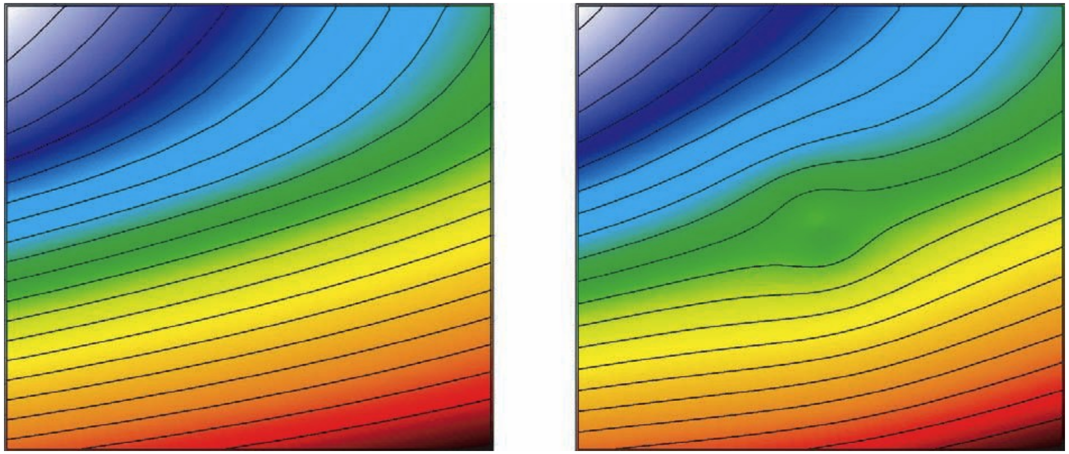
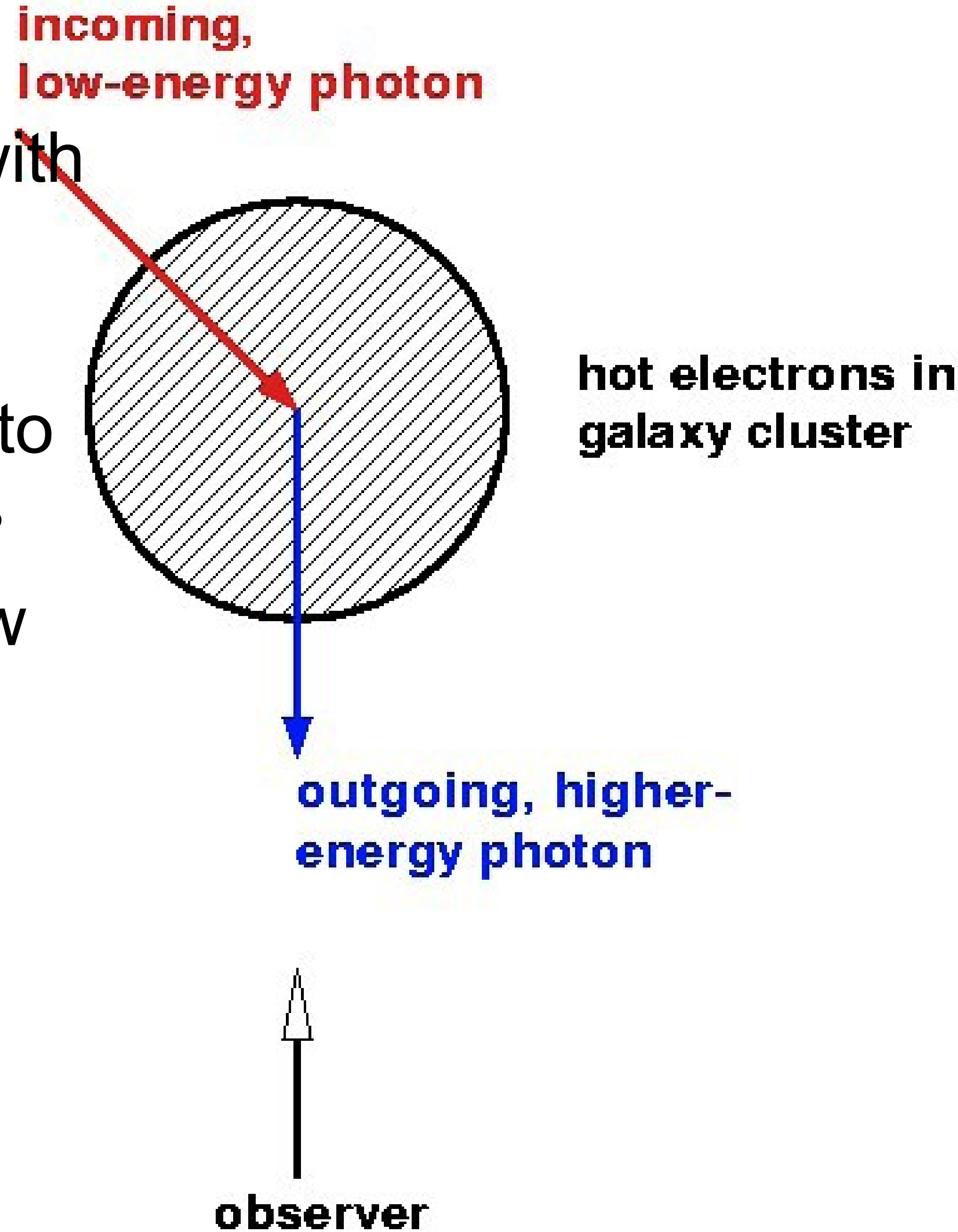


FIG 3.6.— Example of a CMB temperature field of area $10' \times 10'$ (left panel) lensed by a cluster of mass $10^{15}\,h^{-1}$ Mpc at redshift 0.4 in a ΛCDM universe (right panel). There is very little structure in the unlensed map, and lensing by the cluster creates a characteristic distortion most easily seen in the contours in the right panel.

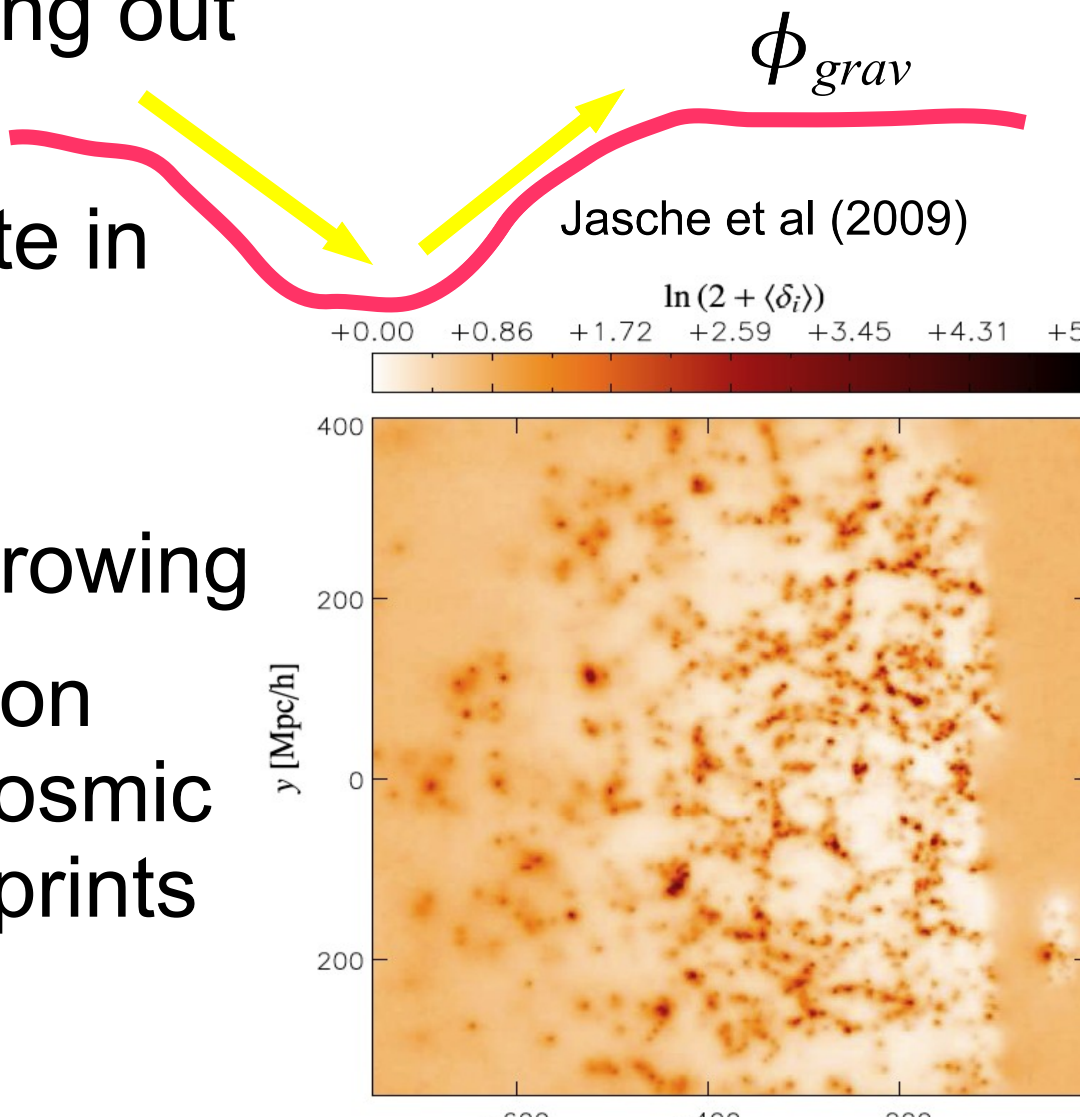
# Sunyaev Zeldovich effect

- galaxy clusters are filled with hot $(T \sim 1 - 10\, keV)$ plasma
- electrons scatter photons to slightly higher frequencies
- depletion of photons at low and increase at high frequencies
- characteristic spectral signature



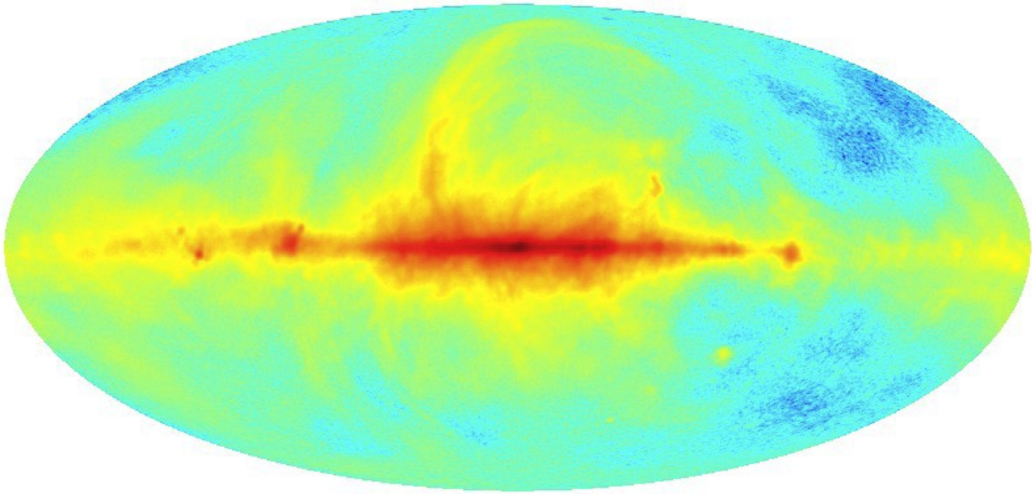
# Integrated Sachs Wolfe Effekt

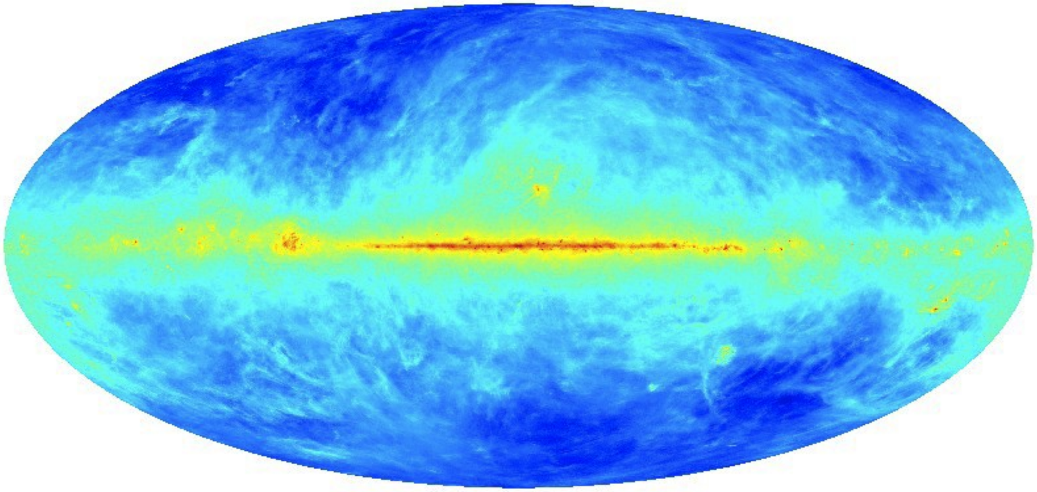
- photon gains/loses energy while falling into/climbing out of potential well
- gain & loss compensate in static potential
- gain/loss dominates if potential is decaying/growing
- recent cosmic expansion erases potentials => cosmic large scale structur imprints on CMB (small effect)



# Galactic foreground

- radio-synchrotron emission of relativistic electrons in galactic magnetic field
- free-free emission of hot thermal electrons in ionised part of the inter-stellar medium
- thermal emission of warm and hot dust

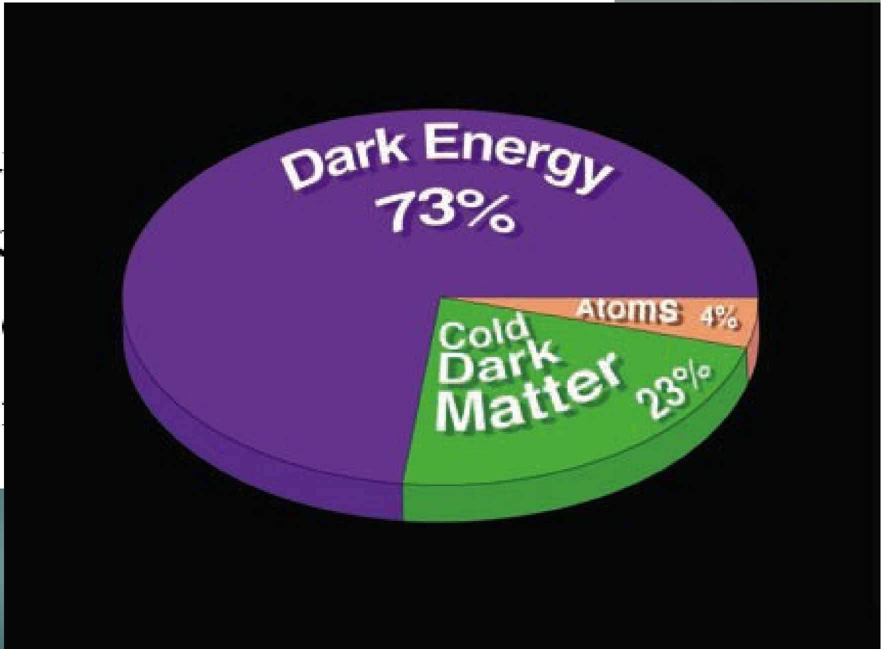




# CMB & Cosmology

## Main Cosmological Parameters

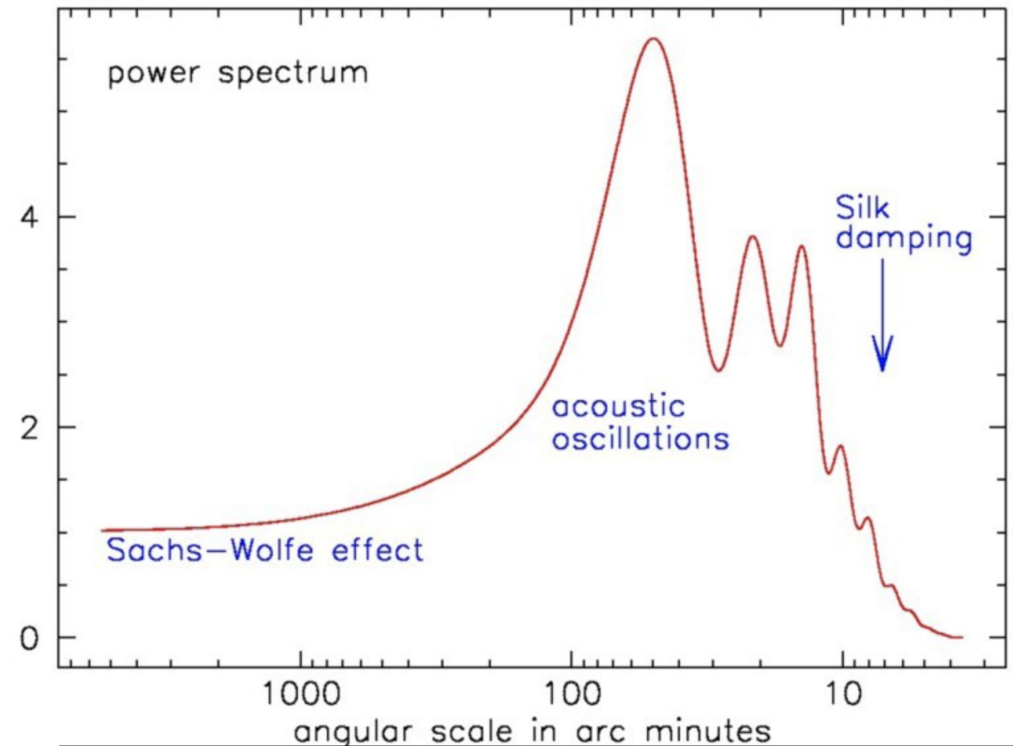
- $\Omega_o$ Cosmological total density parameter
- $H_o$ Hubble constant
- $\Omega_b$ Baryon density
- $\Omega_c$ Cold dark matter density
- $\Lambda$ Cosmological constant
- $n_s$ Spectral index of scalar pertu
- Q Amplitude of fluctuation spec
- r Ratio of Gravitational wave t
- $\tau_r$ Residual optical depth due to

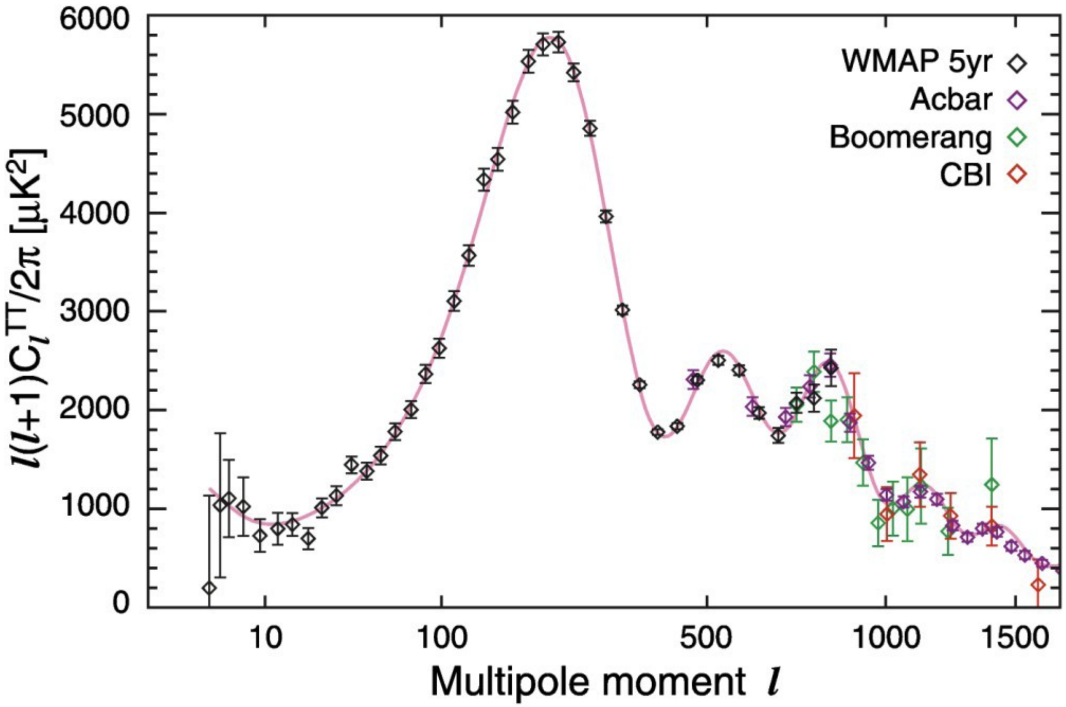


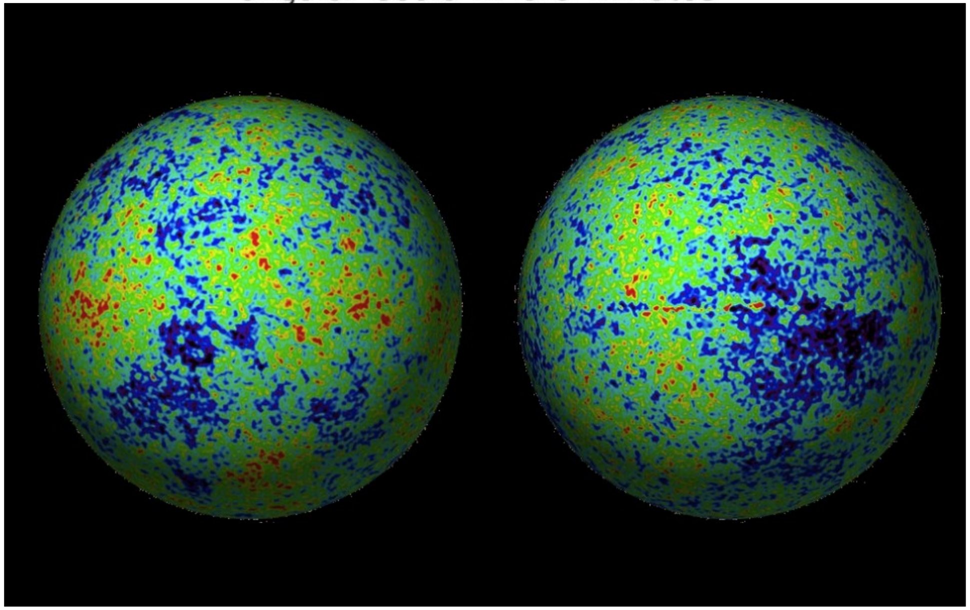
decomposition into spherical harmonics

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

$$C_\ell^T = \langle |a_{\ell m}|^2 \rangle$$



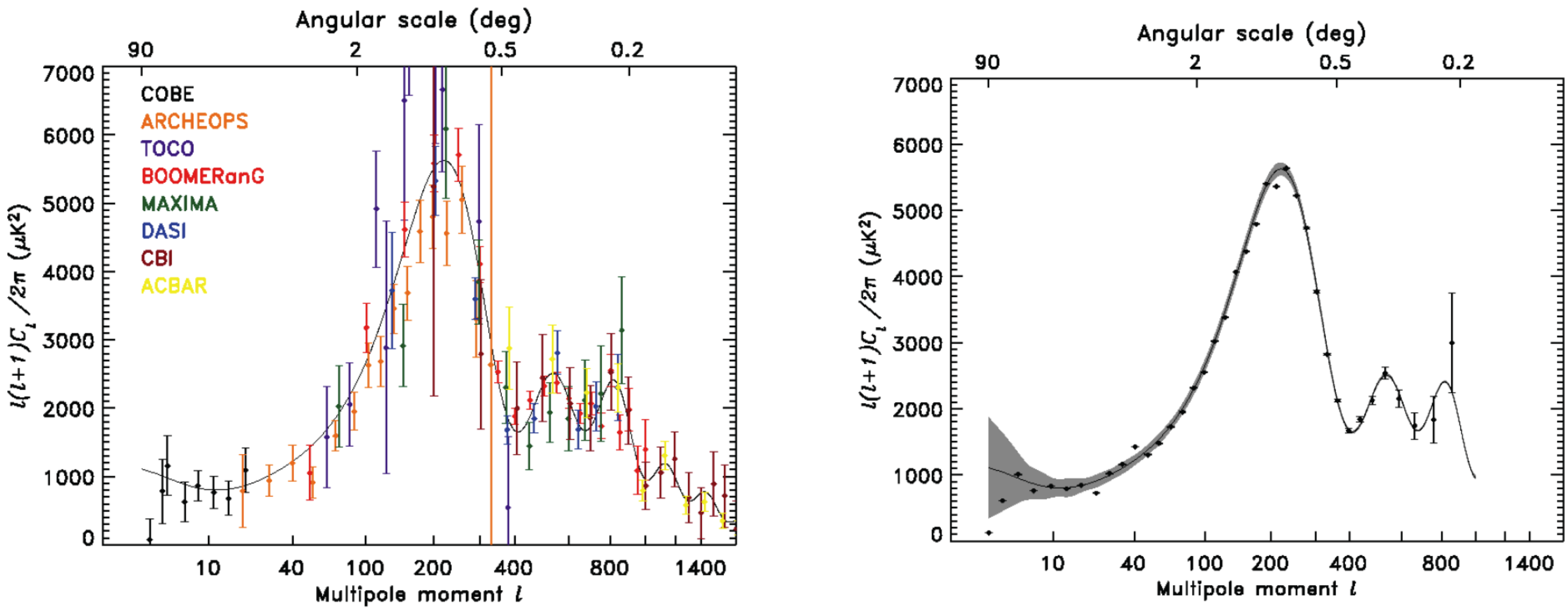



FIG 2.2.— The left panel (courtesy of the *WMAP* Science Team) shows a summary of CMB anisotropy measurements from various experiments prior to the release of the first year results from *WMAP*. The references to the experimental data are as follows: *COBE* (Tegmark 1996), Archeops (Benoit et al. 2003), TOCO (Miller et al. 2002), Boomerang (Ruhl et al. 2003), Maxima (Lee et al. 2001), DASI (Halverson et al. 2002), CBI (Pearson et al. 2003) and ACBAR (Kuo et al. 2004). The right panel shows results from the first year of *WMAP* data.

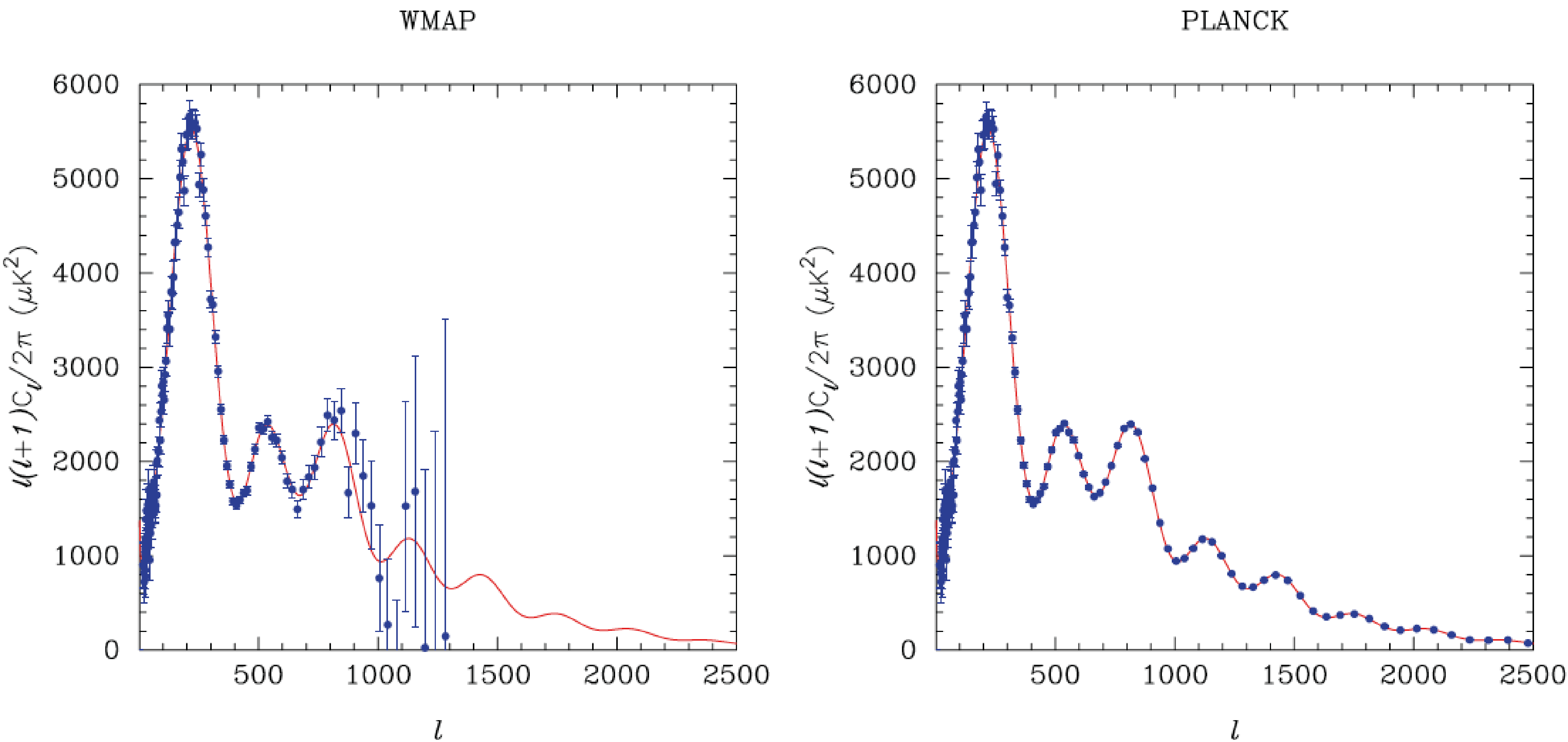
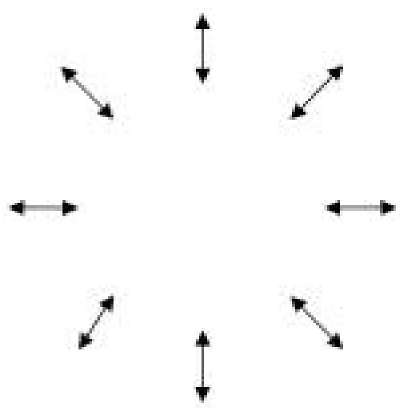


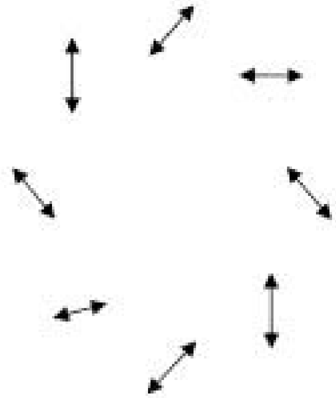

FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

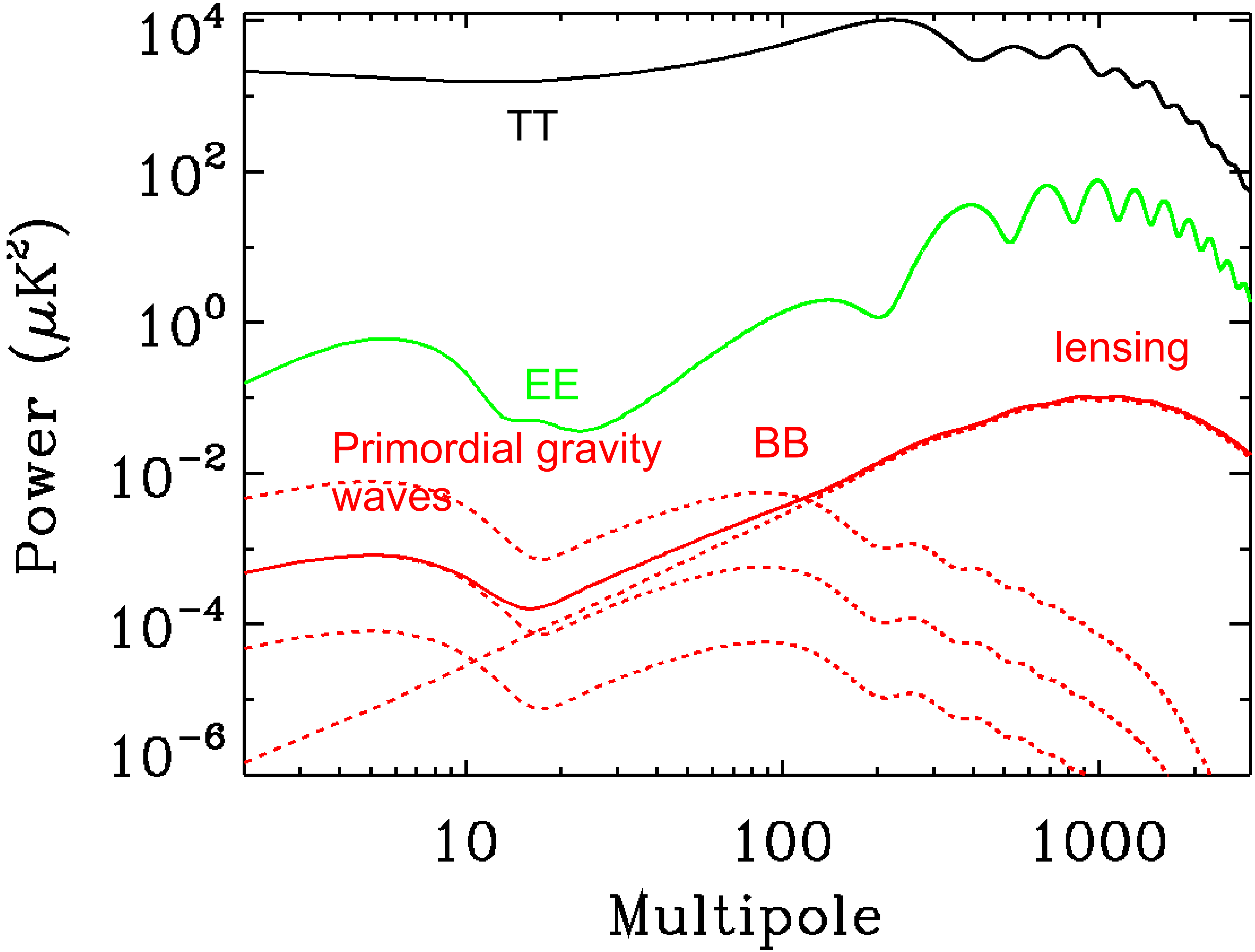
# Polarization E and B modes $P = \begin{pmatrix} Q & U \\ U & -Q \end{pmatrix}$

Gradient: E polarization

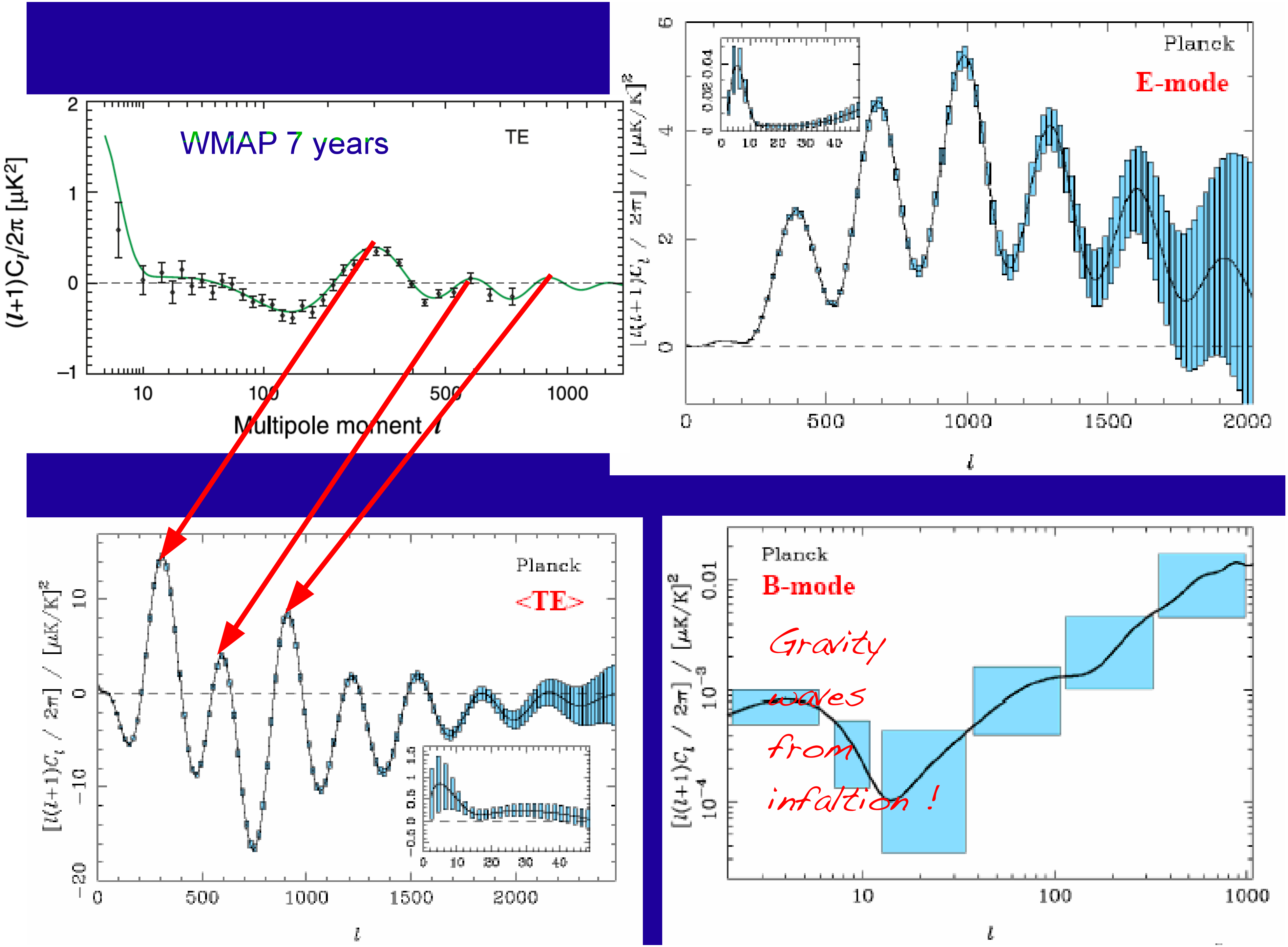


Curl: B polarization





$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
Power ($\mu K^2$)
TT
EE
lensing
BB
Primordial gravity waves
10
100
1000
Multipole


WMAP 7 years
TE
$(l+1)C_l/2\pi\ [\mu K^2]$
Multipole moment $l$
Planck
E-mode
$[l(l+1)C_l\ /\ 2\pi]\ /\ [\mu K/K]^2$
$l$
Planck
<TE>
Planck
B-mode
Gravity waves from infaltion !

# Sensitivity to spectral slope

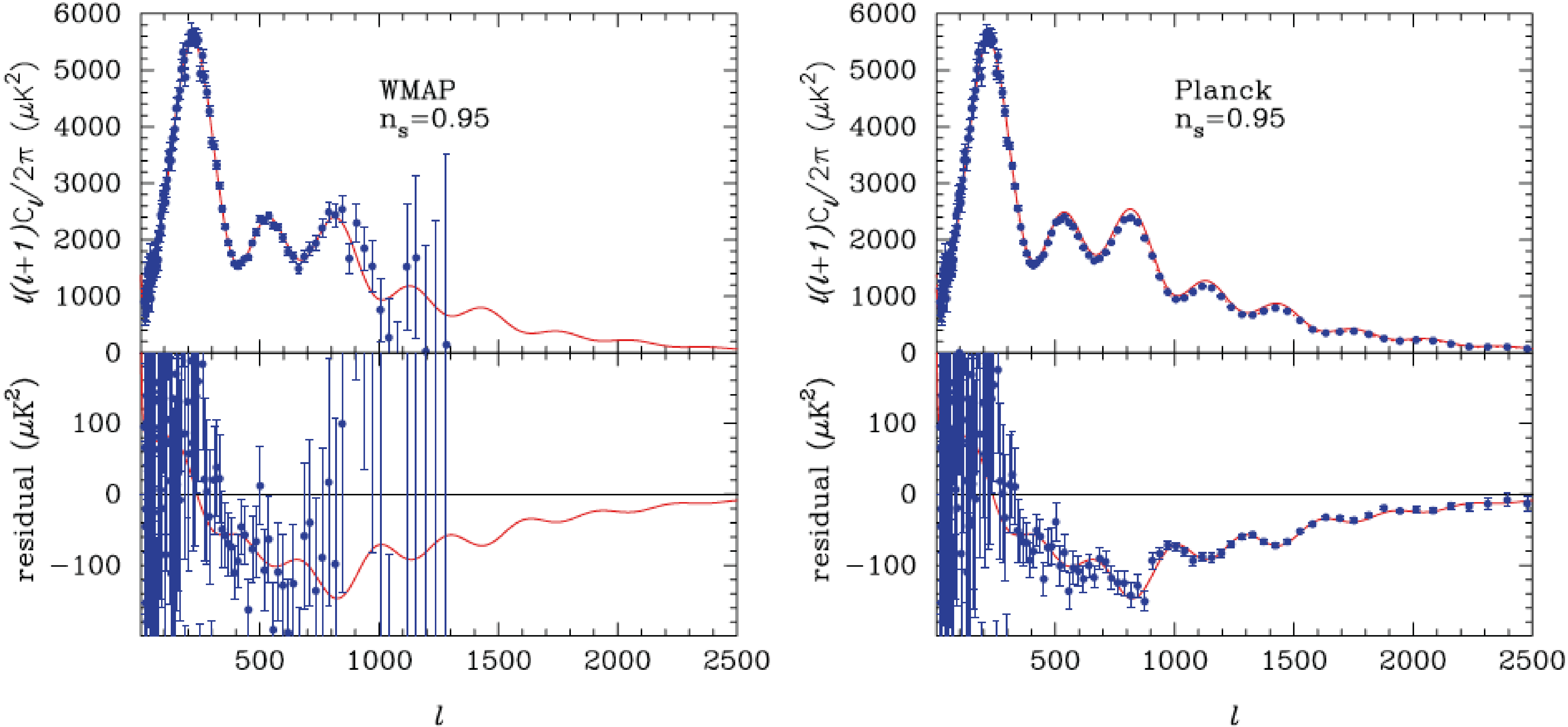
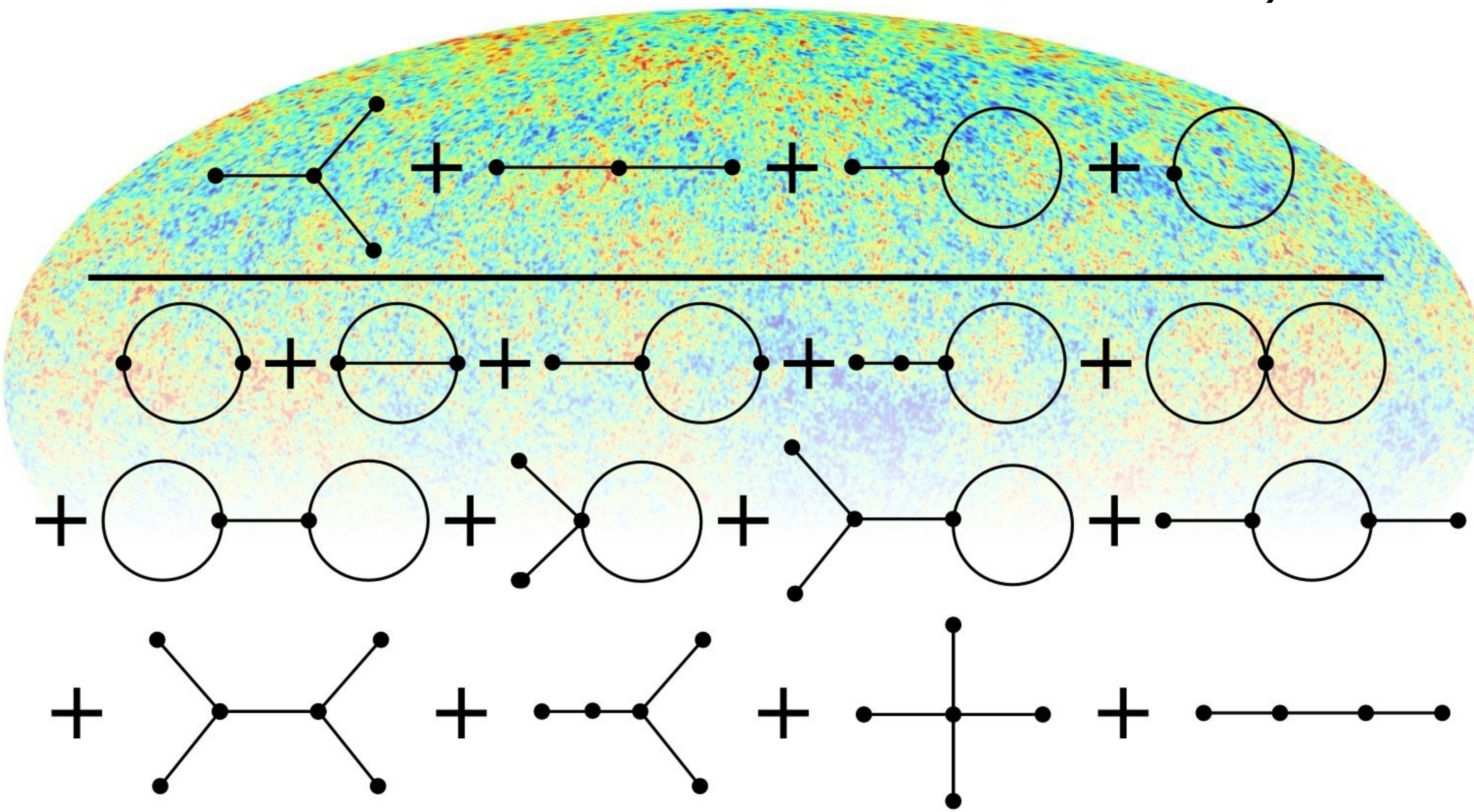



FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance $\Lambda$CDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals between the points and the $n_S = 1$ model, and the solid lines show the theoretical expectation for these residuals. The left and right plots show simulations for *WMAP* and *Planck*, respectively.

# Non-Gaussianity from Inflation & Information Field theory



# Sensitivity to ionisation history

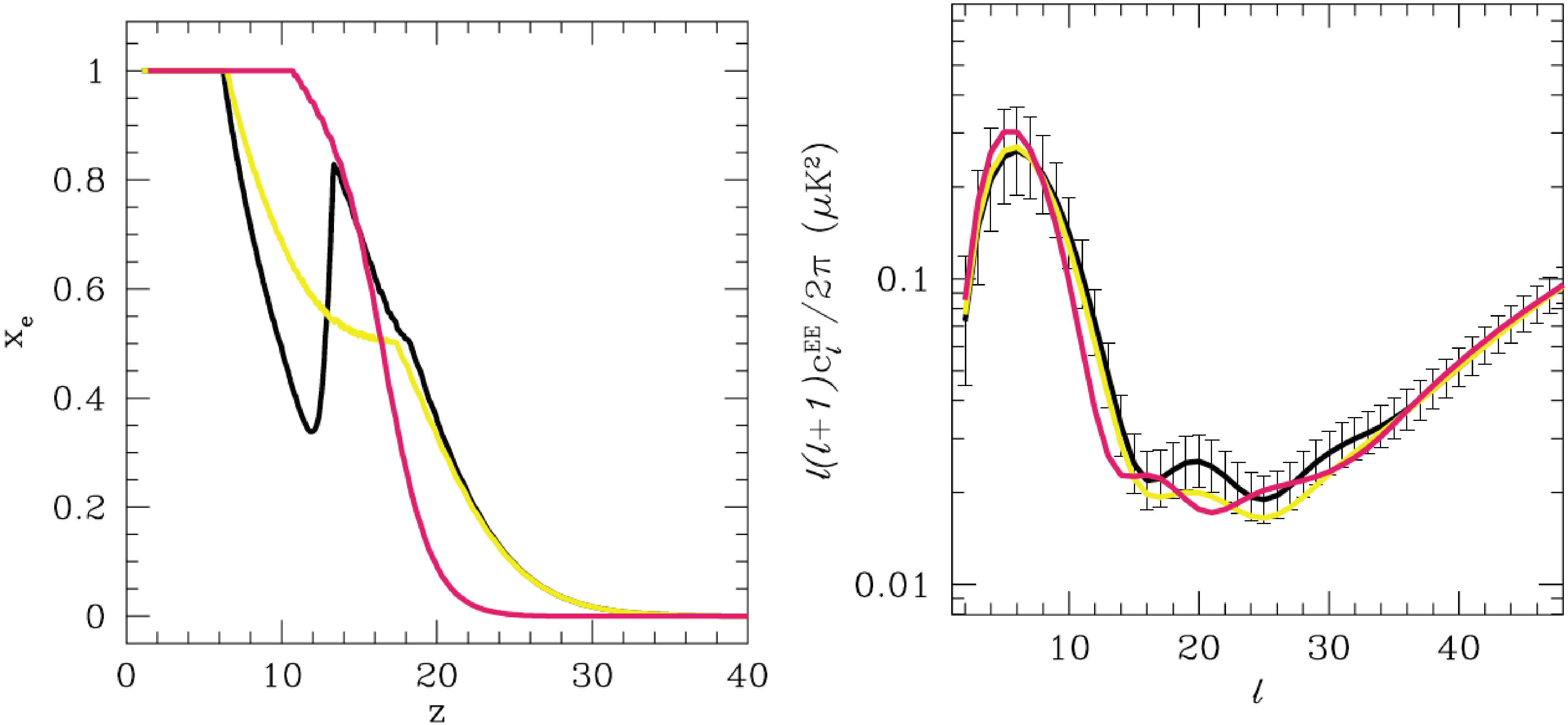
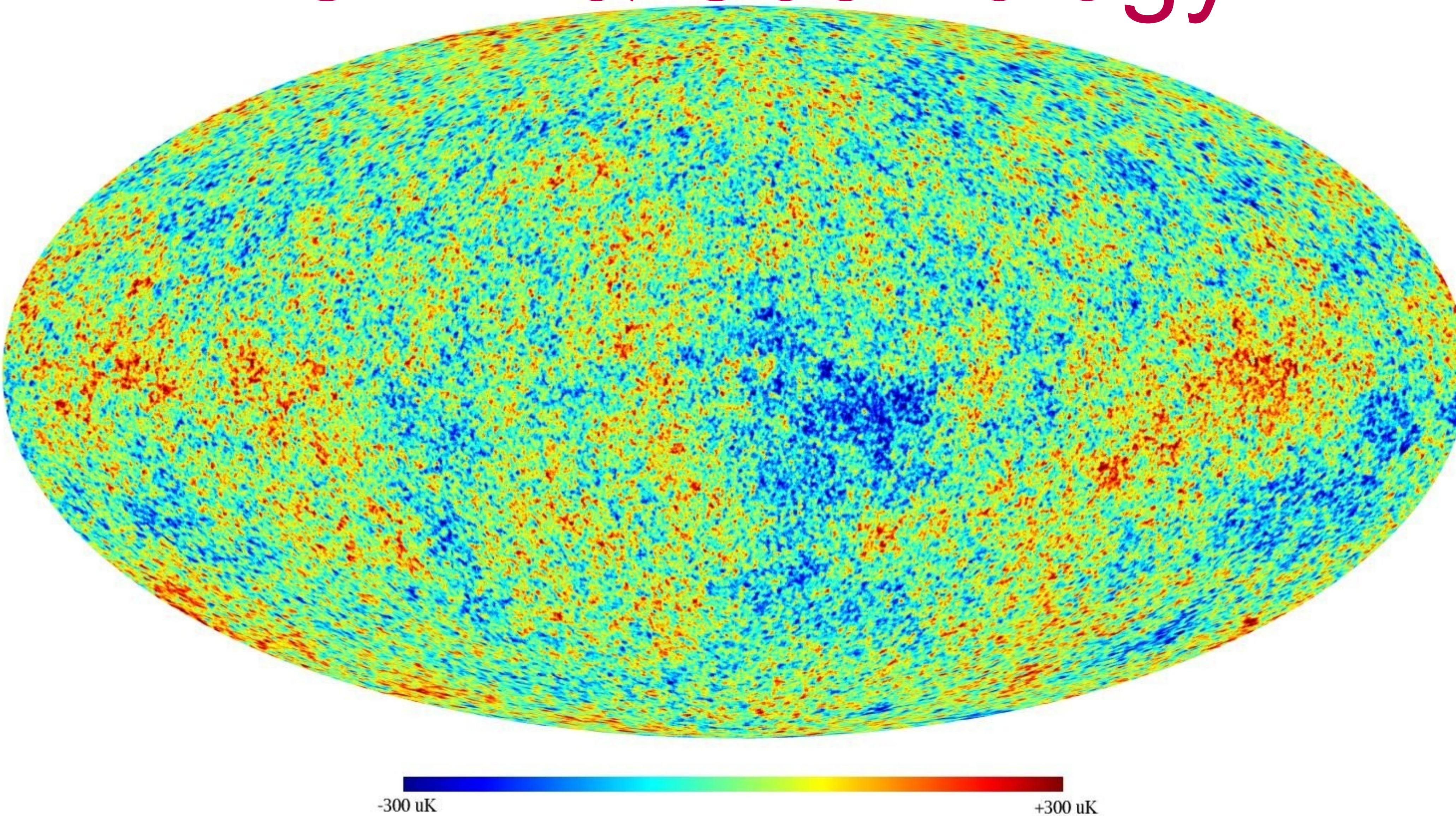
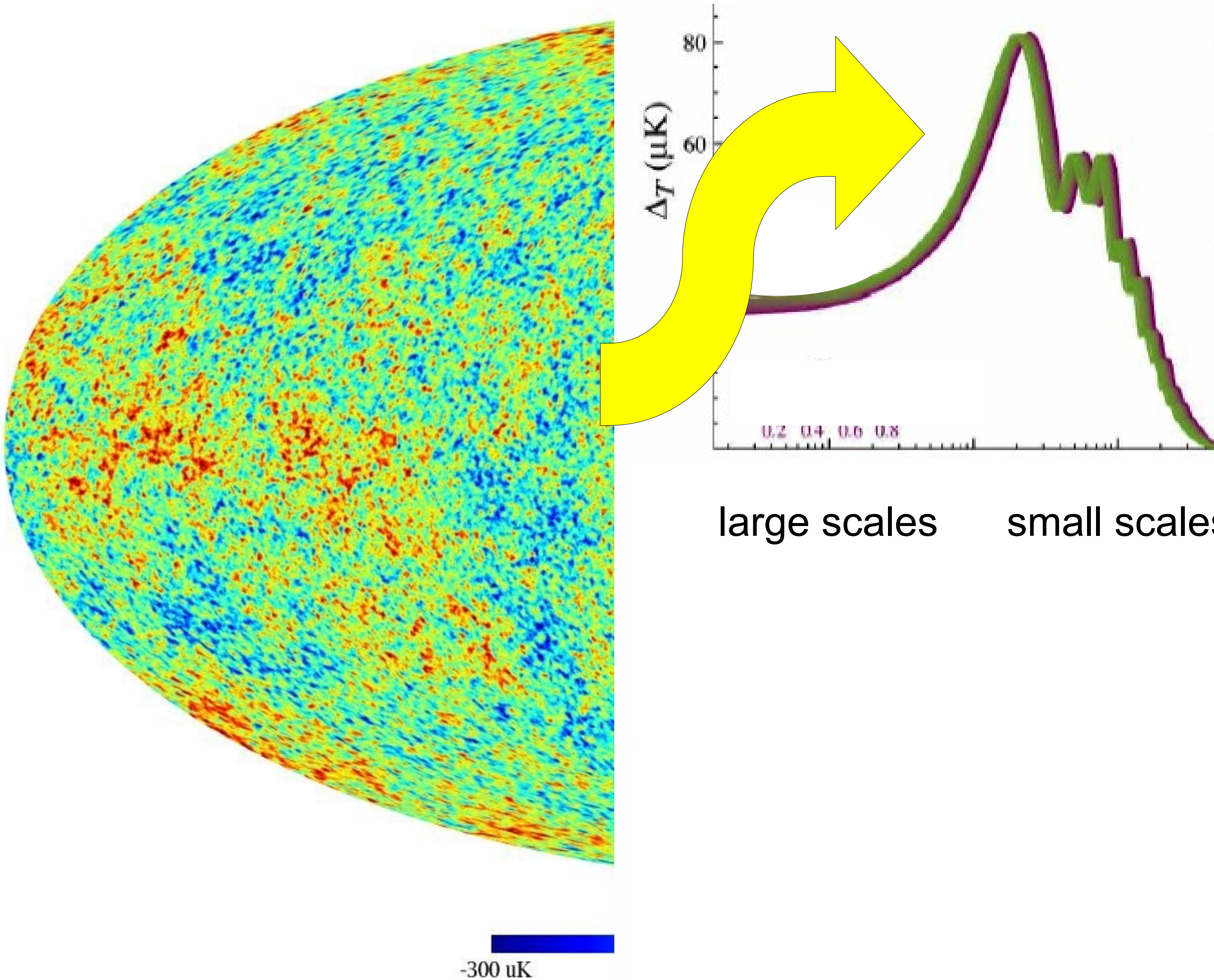


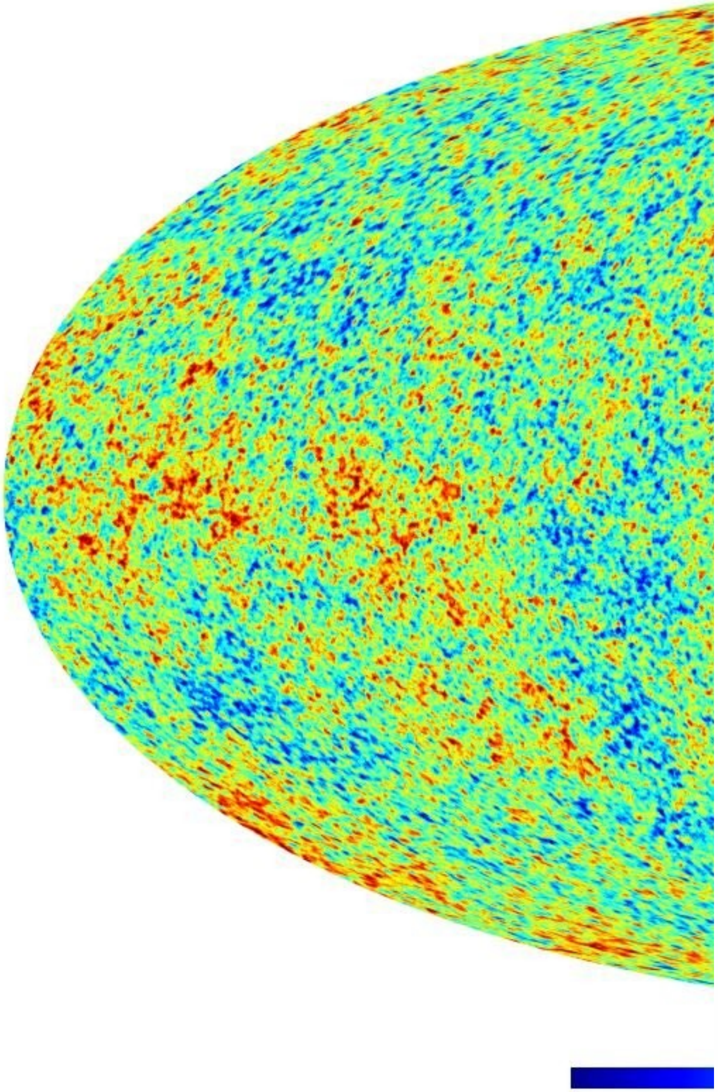

FIG 2.15.—Left: ionization histories for three physically-motivated models of reionization, each having the same optical depth ($x_e$ is the fractional abundance of ionized hydrogen). Right: large-scale $E$-mode polarization power spectra for the different ionization histories, with all other parameters held fixed. Cosmic variance errors for a full-sky experiment are plotted for the model shown in black. (Figures modified from Holder et al. 2003).

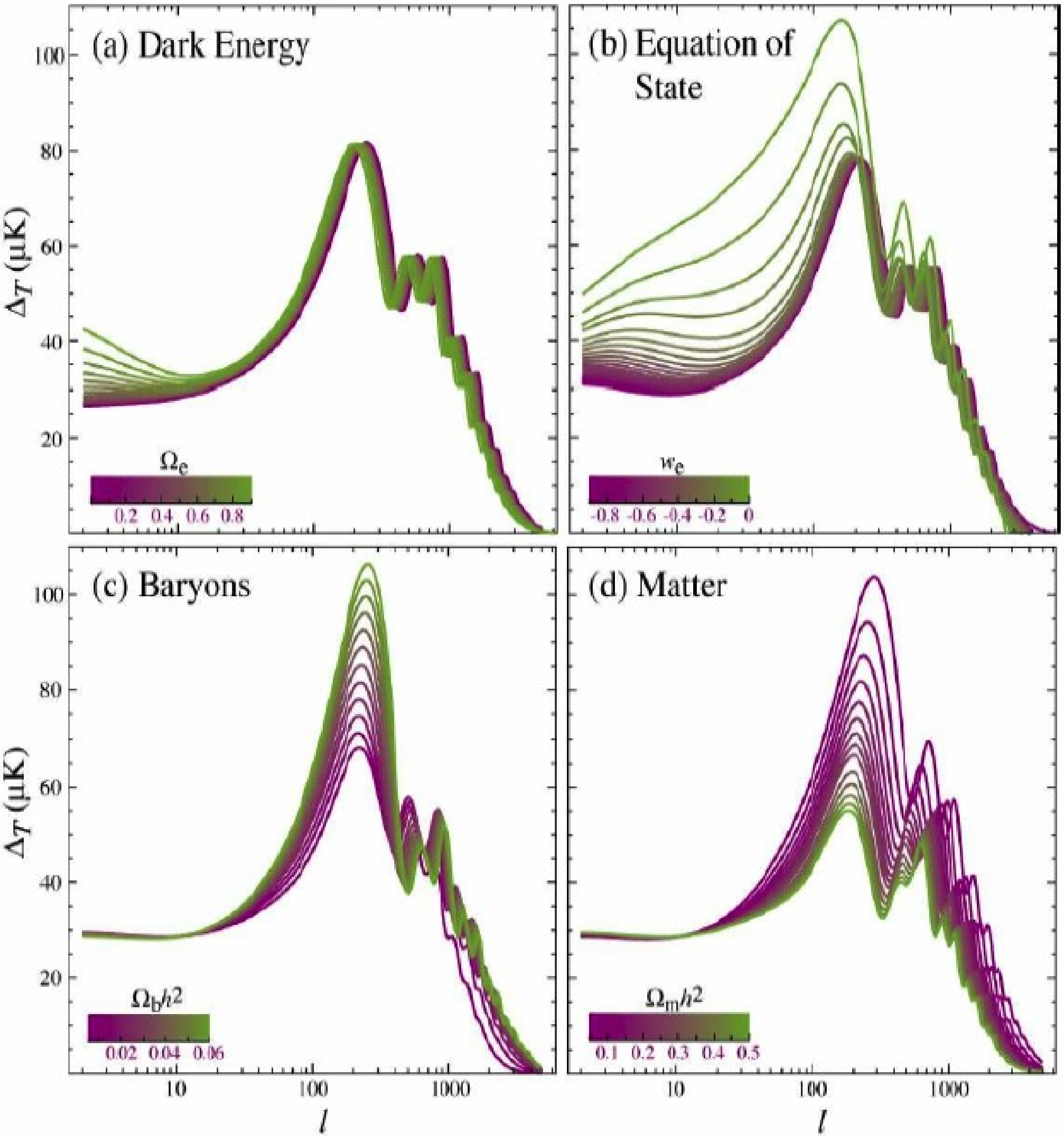
# CMB & Cosmology



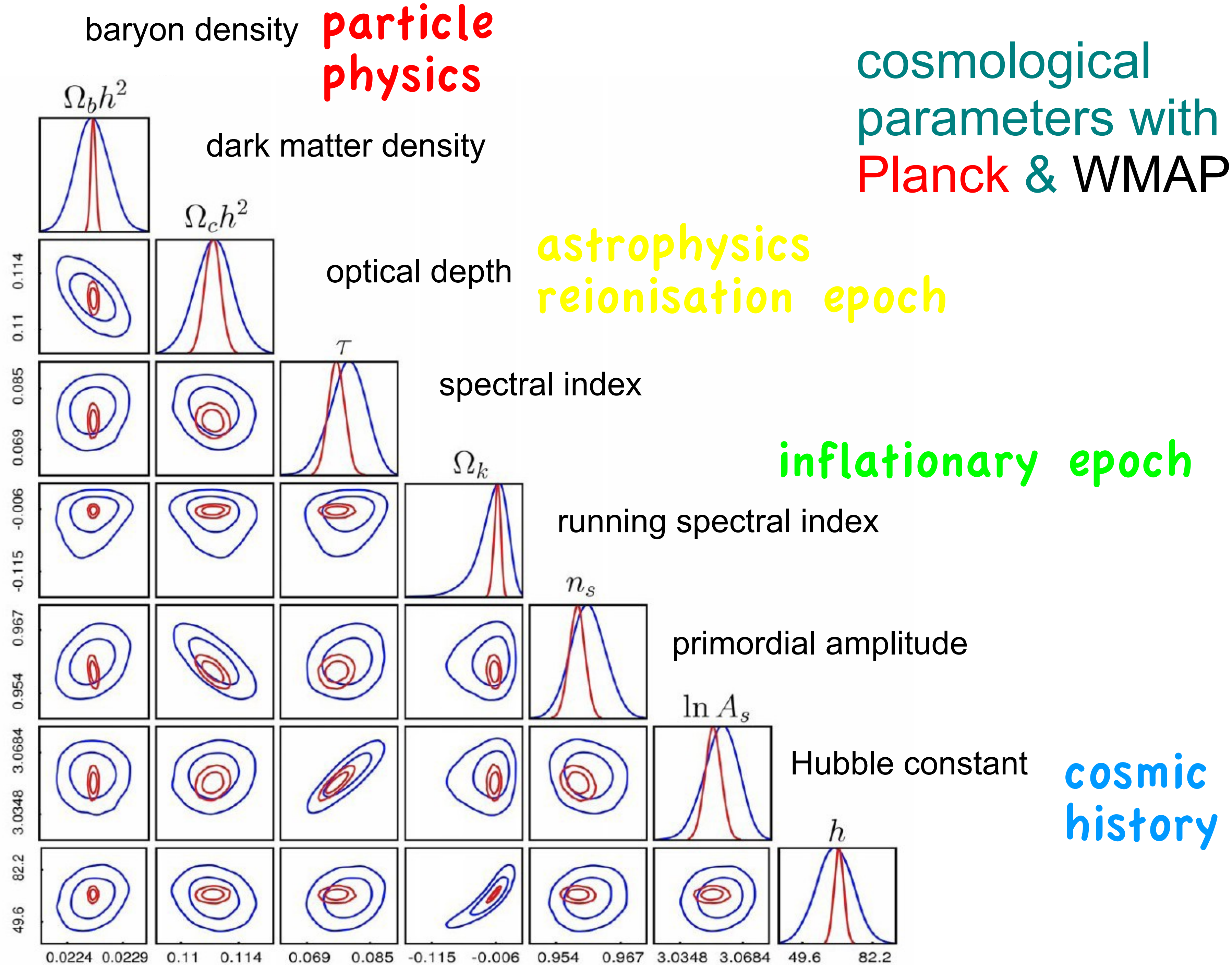



large scales small scales


-300 uK


(a) Dark Energy
(b) Equation of State
(c) Baryons
(d) Matter
$\Delta_T$ (μK)
$l$
$\Omega_e$
0.2 0.4 0.6 0.8
$w_e$
-0.8 -0.6 -0.4 -0.2 0
$\Omega_b h^2$
0.02 0.04 0.06
$\Omega_m h^2$
0.1 0.2 0.3 0.4 0.5
20 40 60 80 100
10 100 1000

# cosmological parameters with Planck & WMAP




**Planck will be close to fundamental limit to information gain due to cosmic variance !**

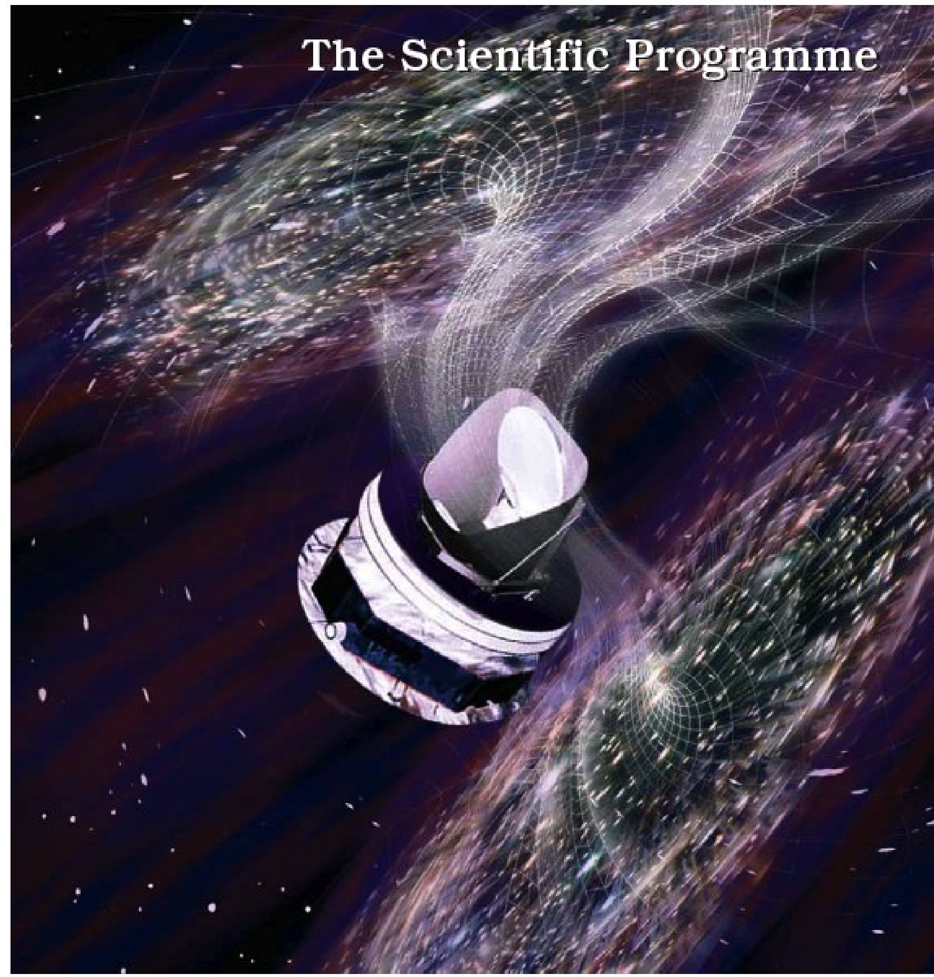
Figure courtesy B. Wandelt

Many thanks to

Jan Tauber, Jean Loup-Puget, Reno Mandolesi, Francois Bouchet, George Efstathiou, Ben Wandelt, Ken Ganga, Matthias Bartelmann, the WMAP team, ...

from whom I took many slides, figures and pictures !

# PLANCK




European Space Agency
Agence spatiale européenne

http://arxiv.org/abs/astro-ph/0604069

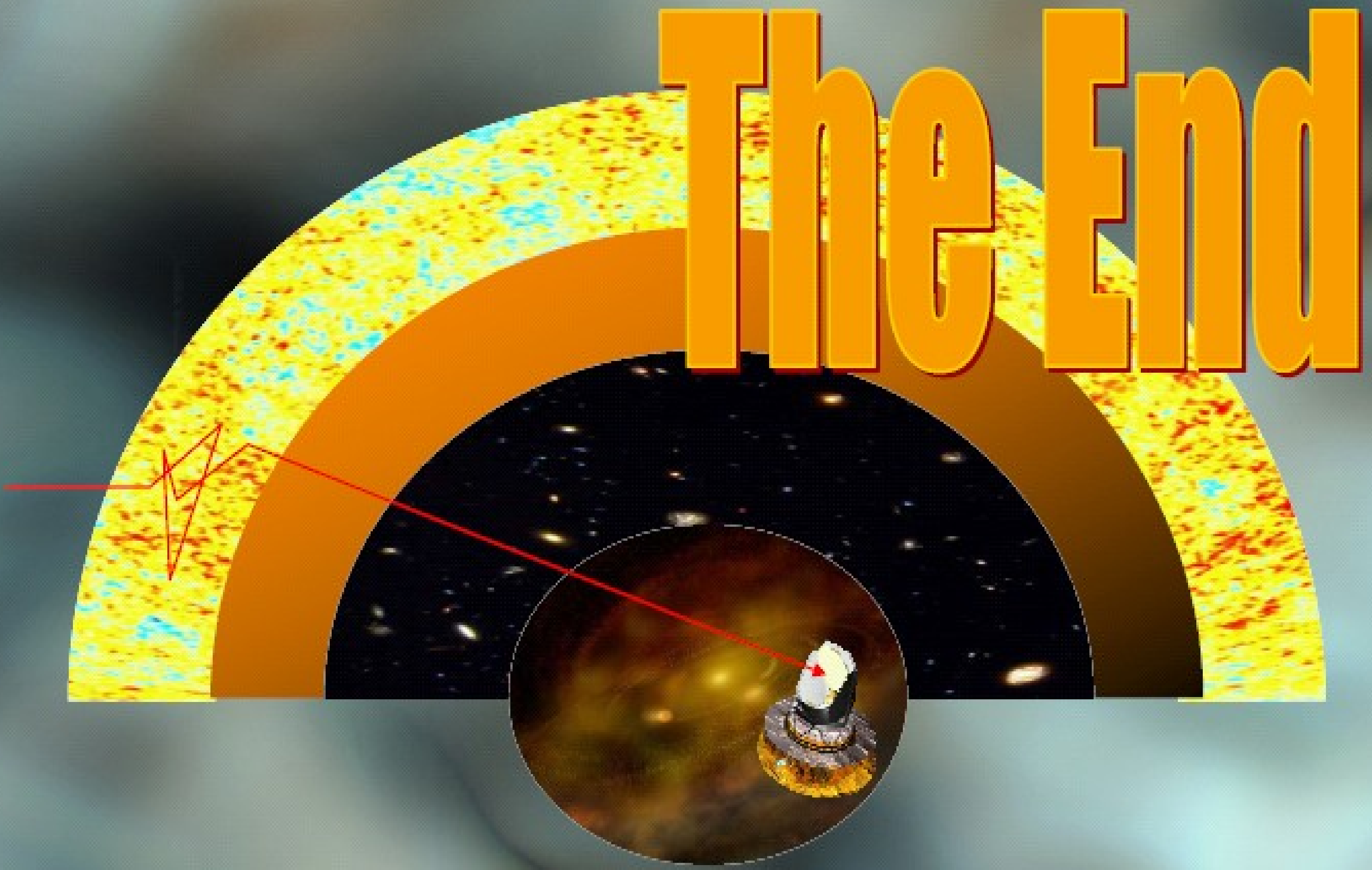
LEGACY ARCHIVE FOR MICROWAVE BACKGROUND DATA ANALYSIS

WMAP Team results @ http://lambda.gsfc.nasa.gov/

# Zusammenfassung

- Planck ist 2009 erfolgreich gestartet und hat den Routinebetrieb aufgenommen
- Die Instrumente erfüllen die Erwartungen
- Präzisionskosmologie (1% Fehler) und Test inflationärer Szenarien dürfen erwartet werden
- Überlapp mit Astroteilchenphysikprojekten:
  - Wissenschaft: frühe Universum, Inflation, galaktische kosmische Strahlung & Magnetfelder
  - Infrastruktur: komplexe Datenverarbeitung
  - Algorithmik: diffizile Signalextraktion

# Looking back in time




Mark & Enzo
Riding early waves
by Ensslin & Ensslin


Mark & Enzo
Riding early waves
WHIMP!
STAY HERE, DON'T BE A FOOL!
JIPPPIEEH!
WOW!
EINE MATERIEVERDICHTUNG! HÜBSCH.
www.mpa-garching.mpg.de
or google: „riding early waves“