The Planck satellite mission

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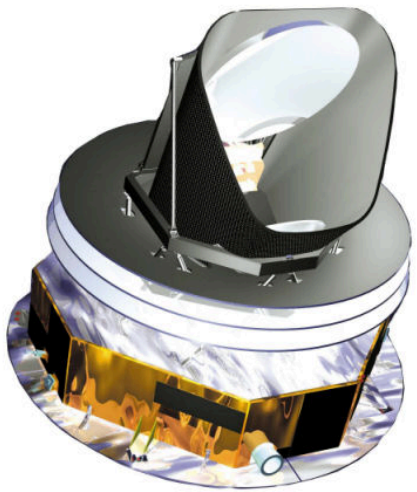
ESHEP School in Raseborg

June 25, 2010



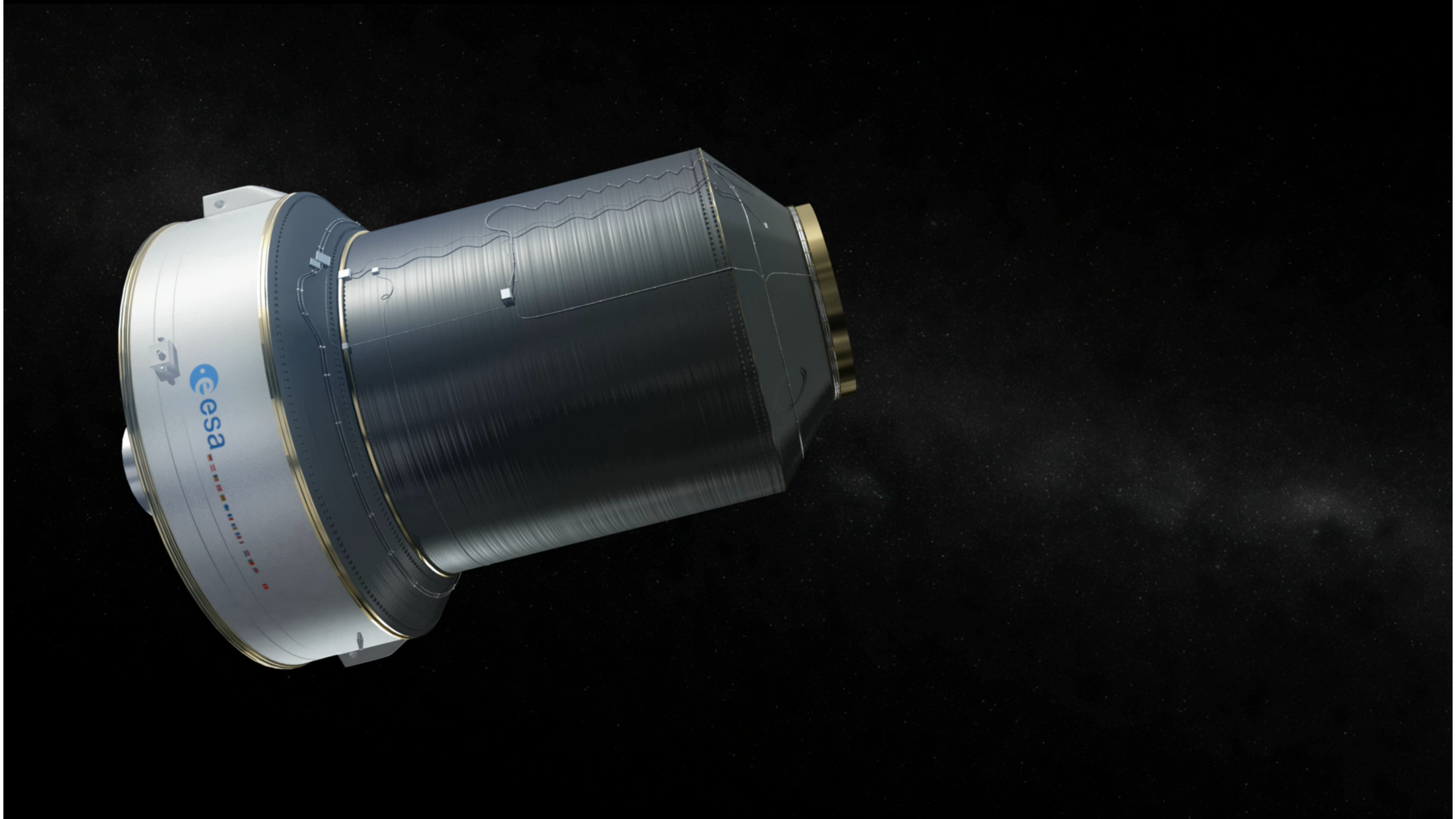
- Planck is a project of the European Space Agency - ESA - with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
- More information at http://www.esa.int/Planck

- Planck is a European Space Agency (ESA) mission to study the cosmic microwave background (CMB)
- Planck was launched together with the Herschel infrared telescope on May 14th, 2009.

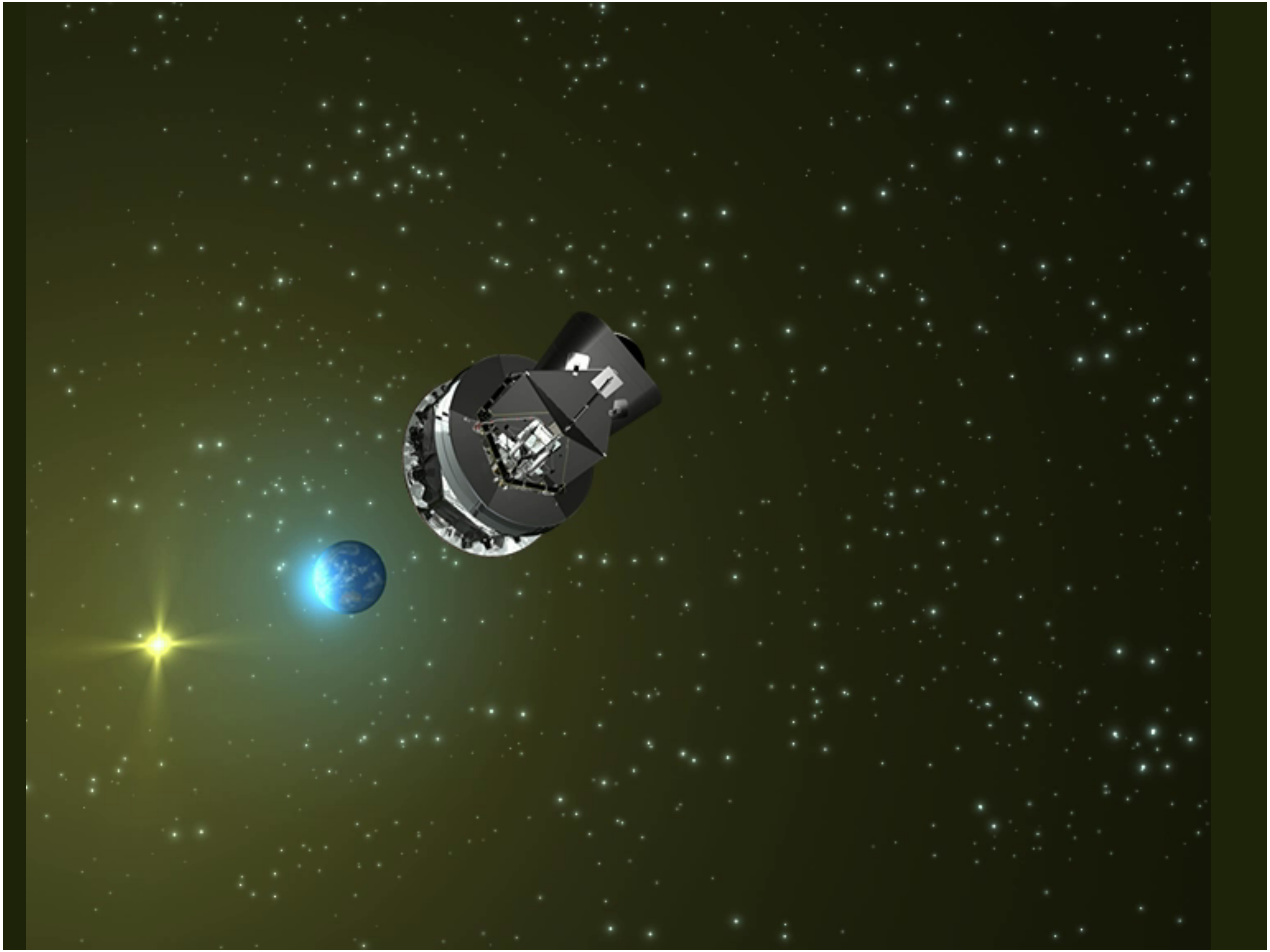

esa
ariane

Herschel separation

Planck separation

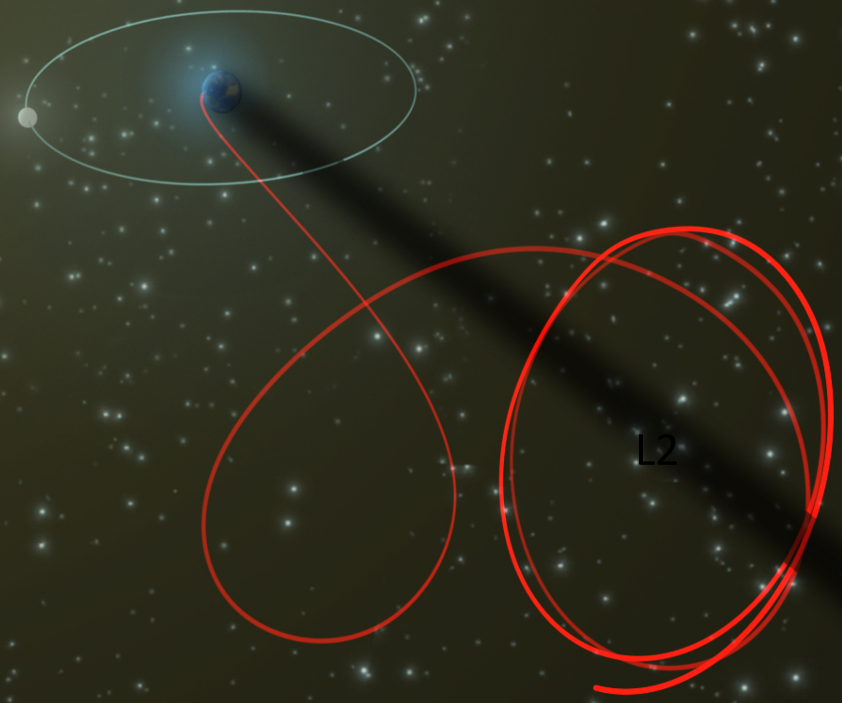


Herschel and Planck cruise to L2

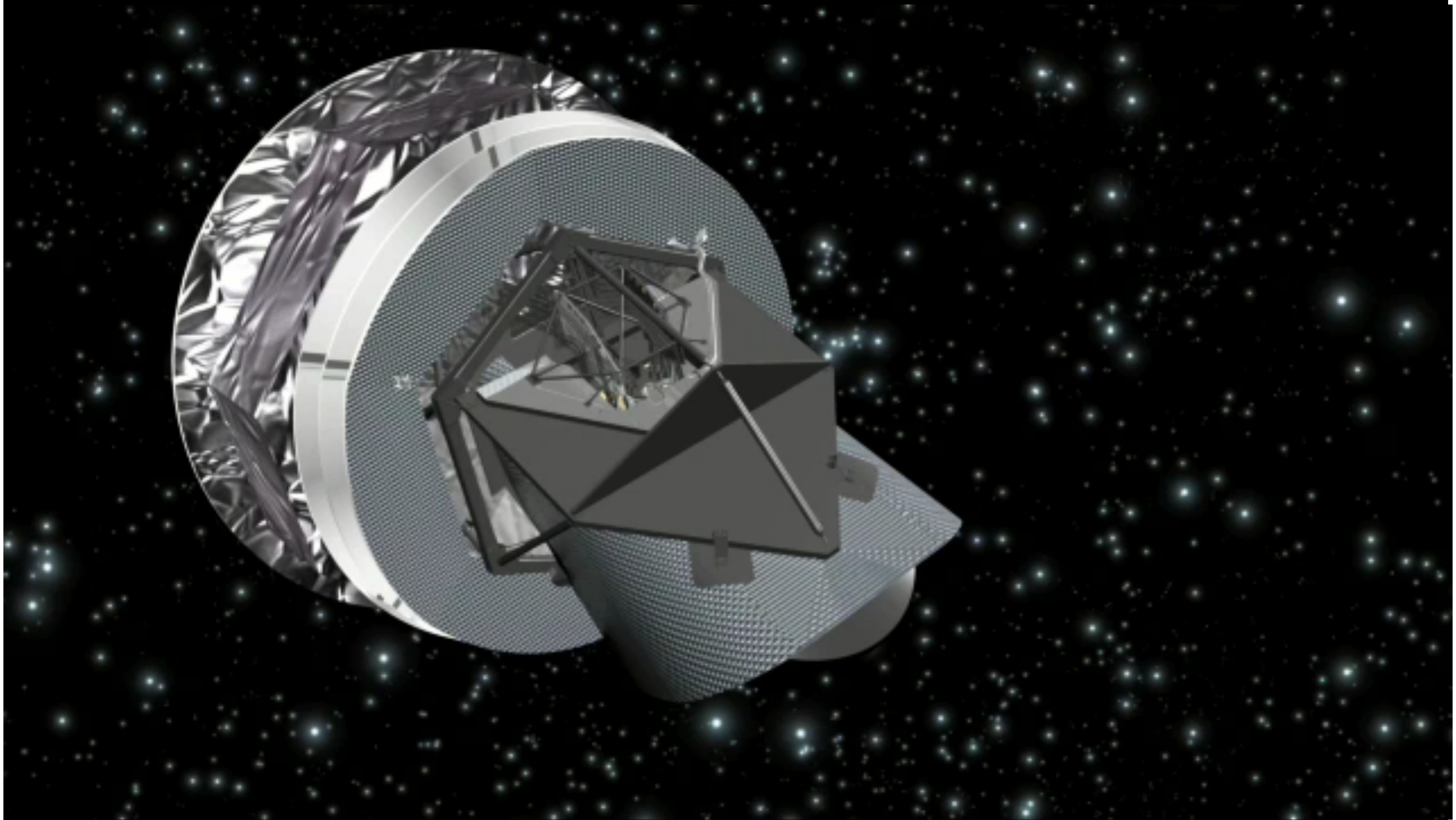


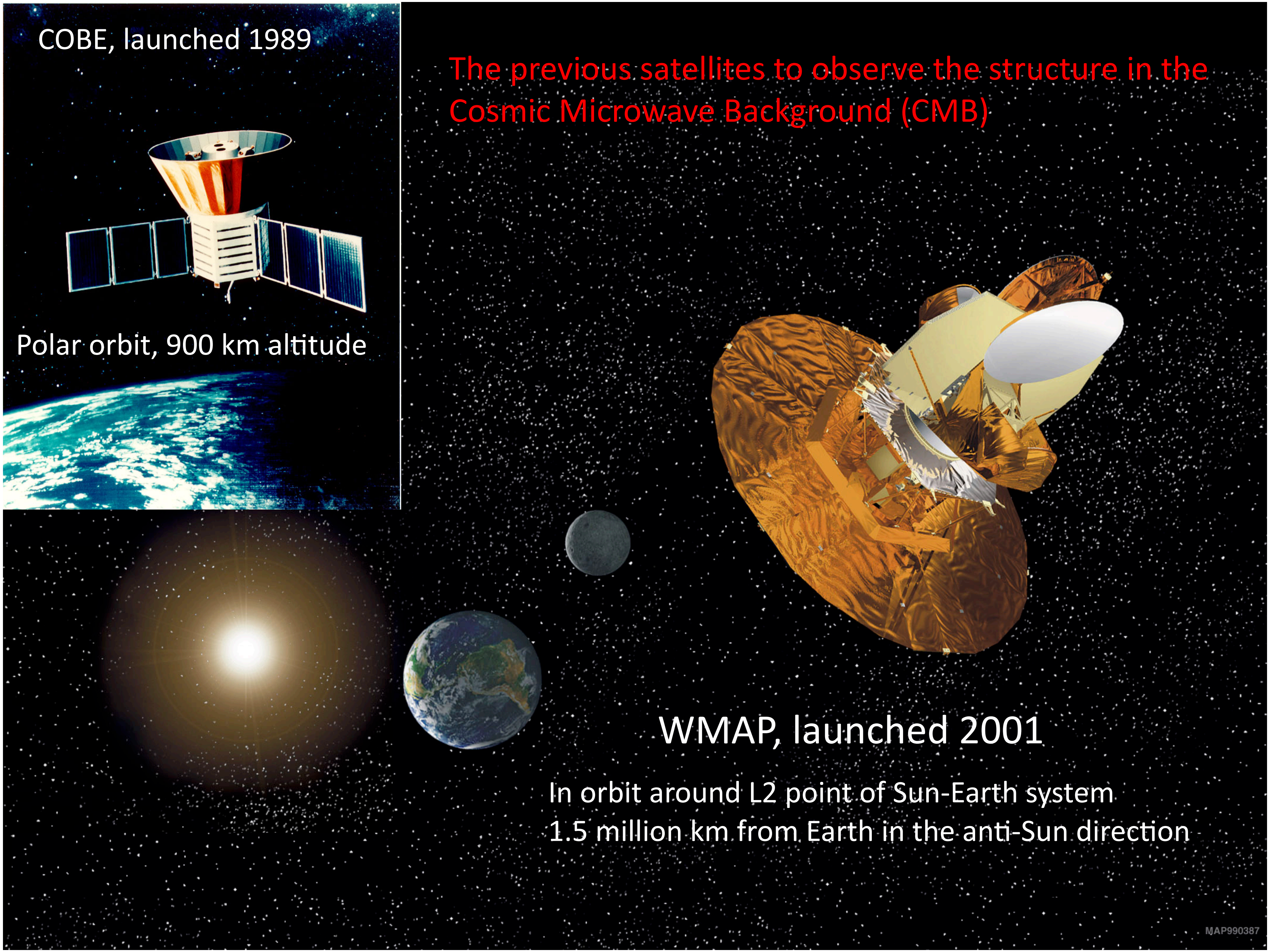
Orbit maneuvers

- Velocity at separation 10 km/s
- Injection orbit: perigee 270 km altitude, apogee 1.2 million km
- First signal acquisition (New Norcia) 15:49:00 CEST
- TCM 1a 15 May 20:01:05 CEST (14.35 m/s)
- TCM 1b 17 May was not needed
- By 21:00 CEST on 19 May, Herschel and Planck were located 617 287 km and 607 767 km from the Earth. The satellites were separated by 9917.35 km.
- TCM 2 5 June mid-course correction
- L2 is 1.5 million km from Earth
- TCM 3 2 July 19:00 CEST orbit insertion (to reduce radius of orbit)
- Lissajous orbit around L2
- Orbit radius 400 000 km

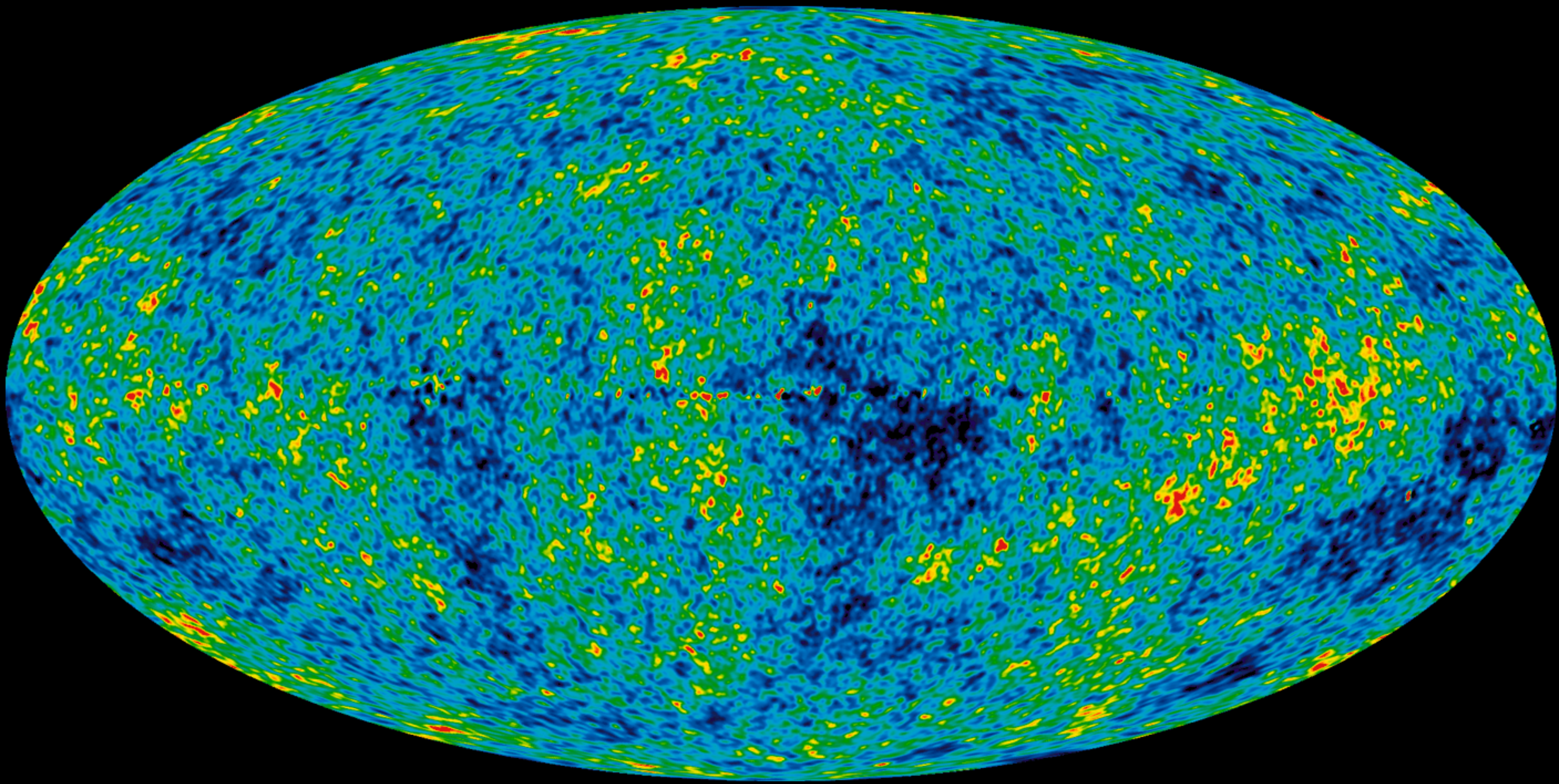


Planck scanning the sky

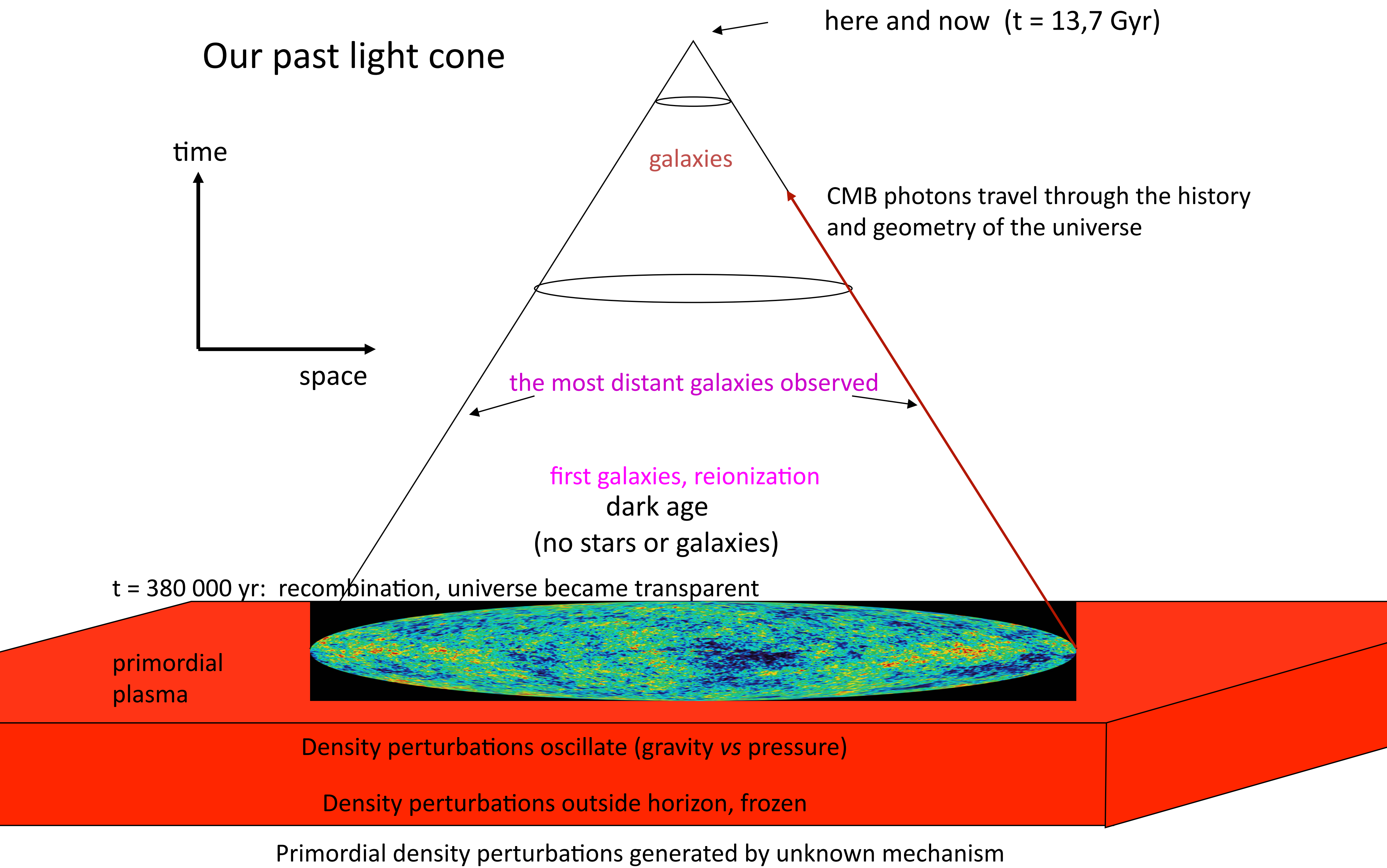



COBE, launched 1989
The previous satellites to observe the structure in the Cosmic Microwave Background (CMB)
Polar orbit, 900 km altitude
WMAP, launched 2001
In orbit around L2 point of Sun-Earth system
1.5 million km from Earth in the anti-Sun direction
MAP990387

CMB temperature variations (1 / 10 000)



WMAP 7-year data (NASA/WMAP Science team)



here and now (t = 13,7 Gyr)
Our past light cone
time
space
galaxies
CMB photons travel through the history and geometry of the universe
the most distant galaxies observed
first galaxies, reionization
dark age
(no stars or galaxies)
t = 380 000 yr: recombination, universe became transparent
primordial plasma
Density perturbations oscillate (gravity *vs* pressure)
Density perturbations outside horizon, frozen
Primordial density perturbations generated by unknown mechanism

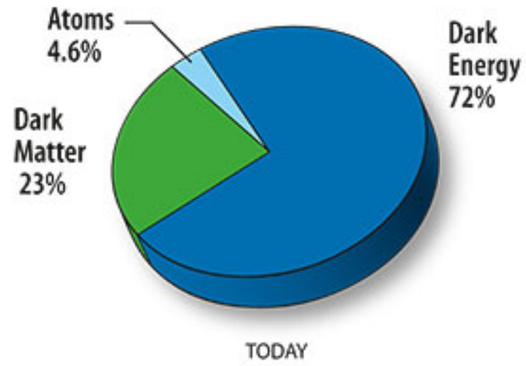
Inflation and the Origin of Structure

- Observed structure (in CMB) of primordial density perturbations indicate that they were earlier in causal contact
- This requires an early period of accelerating expansion:
- Inflation
  - Caused by some unknown field
  - In the very early universe (small fraction of the first second)
  - Expansion by a factor of 10^{30} or more
- Quantum fluctuations during inflation
  - Random process at microscopic scales
  - Expansion → cosmological scales
  - Fluctuations "freeze" and become density (scalar) perturbations
  - Also gravitational waves (tensor perturbations) produced
- We do not know what caused inflation (many models)
- Spectral index n of primordial density perturbations
  - Scale invariant: $n = 1$
  - Stronger at larger scales: $n < 1$
- Inflation => $n \sim 1$ *(to a few percent; distinguishes models)*

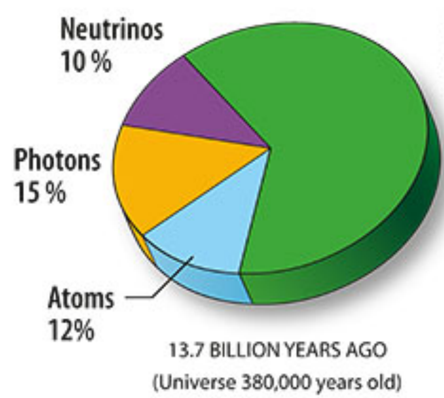
The ΛCDM model

- Current cosmological data fits a 6-parameter cosmological model: ΛCDM
  - geometry of universe is flat ($\Omega_{tot} = 1$)
  - scalar (density) perturbations only, with constant n
  - these are adiabatic
  - "dark energy" is just a cosmological constant Λ (vacuum energy)
  - neutrino masses are negligible (<< 1 eV)
- The parameters are:
  - primordial perturbation spectra (amplitude A_s, spectral index n_s)
  - "background" cosmological parameters (densities of baryonic matter ω_b, cold dark matter ω_c, cosmological constant Ω_Λ)
  - optical depth τ due to reionization (expectation number of scatterings)

WMAP 7-year results



- $A_s = 4.94 \pm 0.05 \times 10^{-5}$
- $n_s = 0.963 \pm 0.012$
- $\omega_b = 0.0226 \pm 0.0005$
- $\omega_c = 0.112 \pm 0.004$
- $\Omega_\Lambda = 0.728 \pm 0.015$
- $\tau = 0.087 \pm 0.014$



- Except for n_s, these are already quite good
- But if relax assumptions, error bars blow up!
- Planck will be about 3 times more accurate

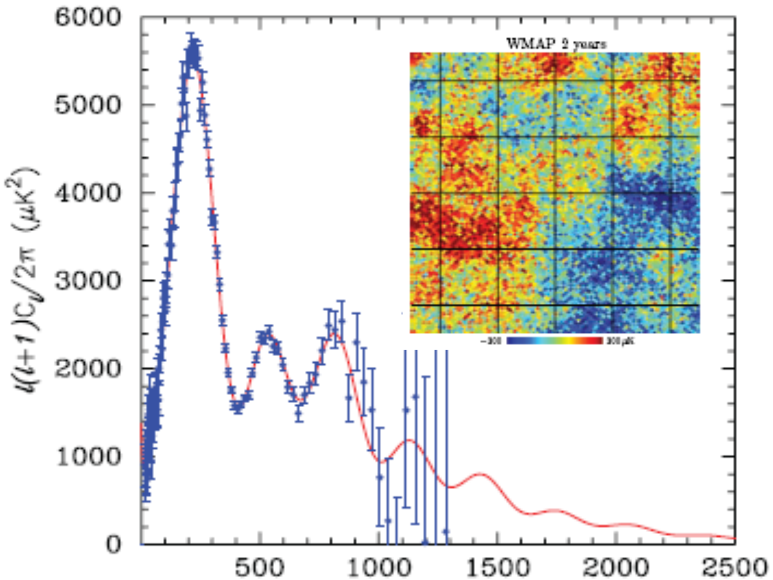
$$\omega_b \equiv \Omega_b h^2 = \rho_b / 1.88 \times 10^{-26} kg/m^3$$

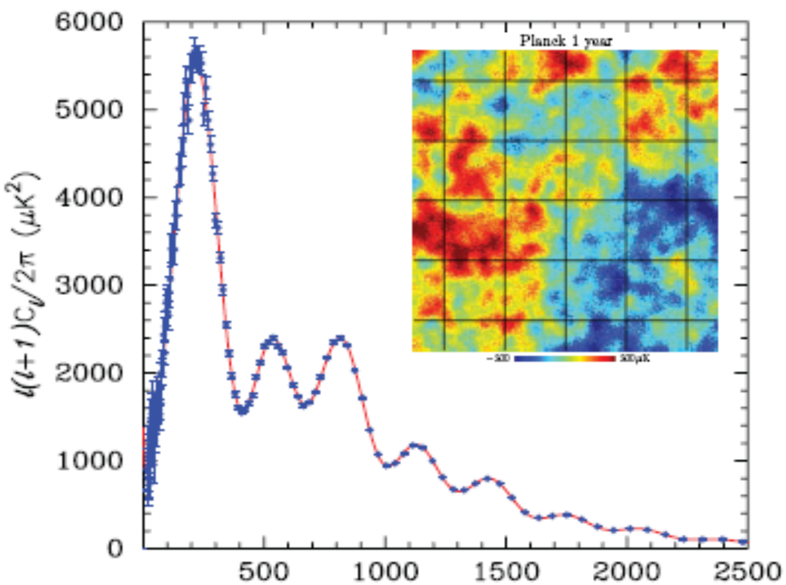
$$\omega_c \equiv \Omega_c h^2 = \rho_c / 1.88 \times 10^{-26} kg/m^3$$

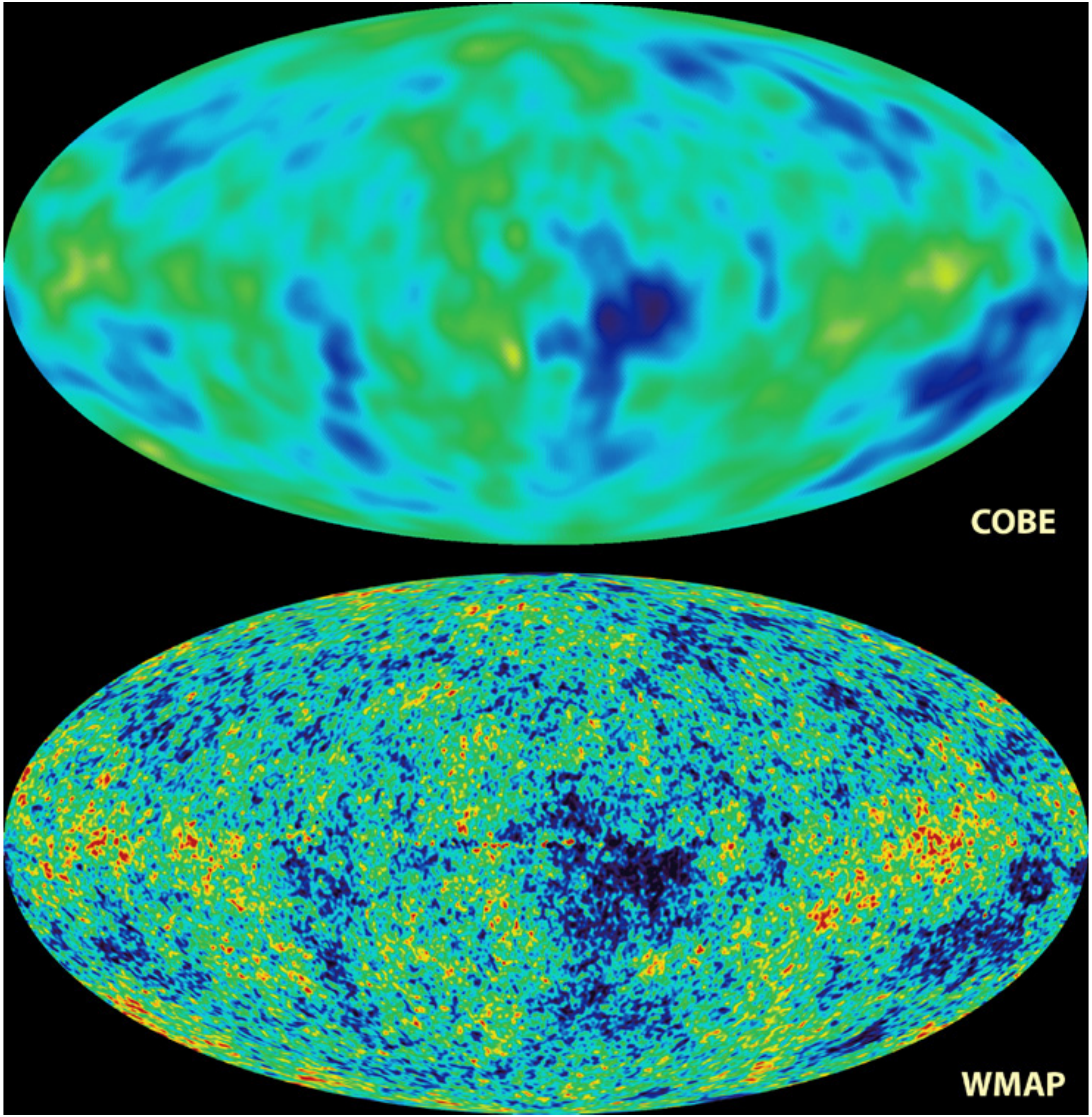
$$H_0 \equiv 100h \text{ km/s/Mpc}$$

Planck satellite (ESA)

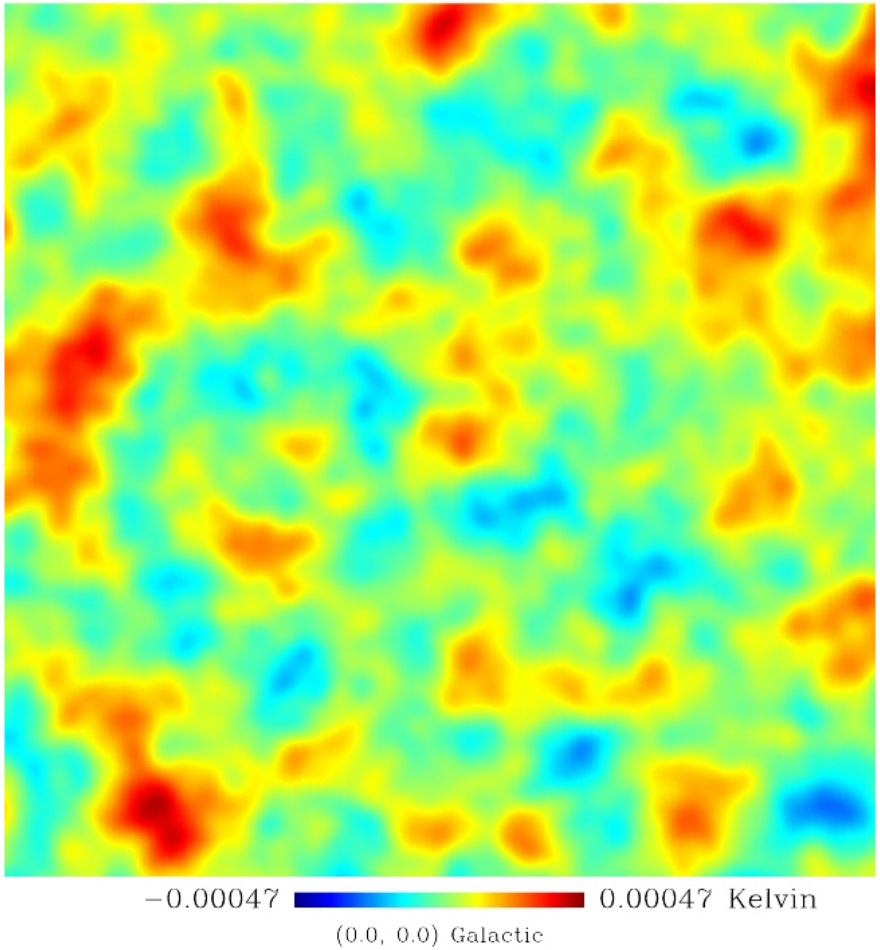
- Launch in 2009
- Orbit around L2
- Surpasses WMAP in
  - resolution   5 vs 14 arcmin
  - sensitivity: CMB polarization
  - frequency coverage: foreground separation

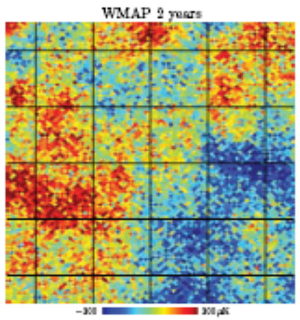




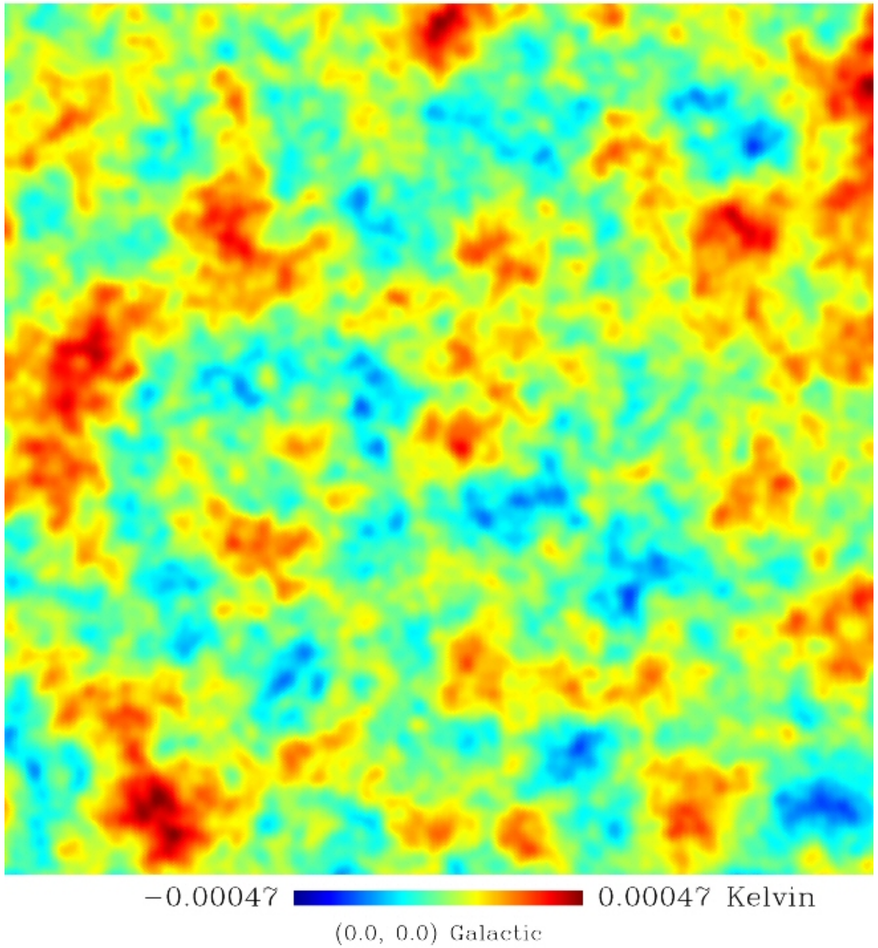

COBE
WMAP

WMAP


−0.00047
0.00047 Kelvin
(0.0, 0.0) Galactic


WMAP 2 years

Planck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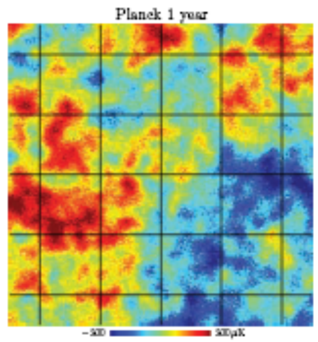

Planck 1 year

Planck measures the microwave sky at 9 frequencies

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

LFI

HFI

HFI

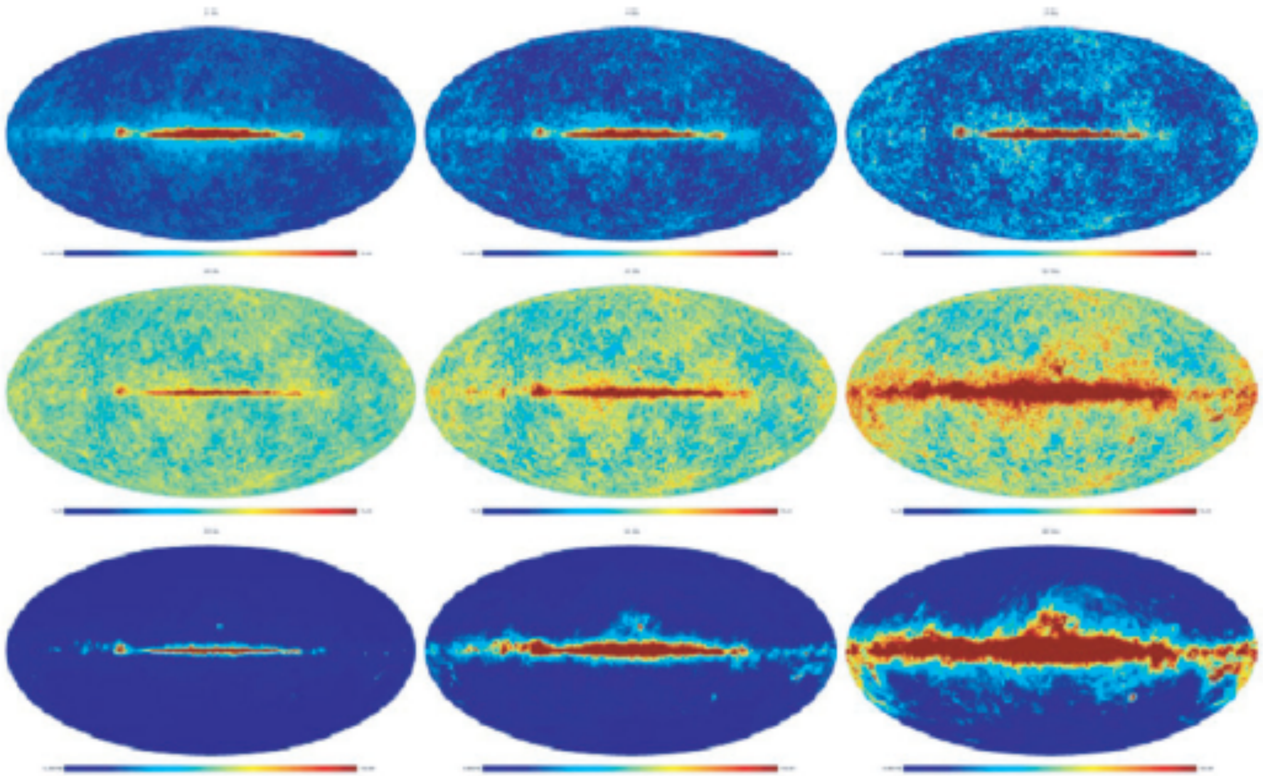


FIG 5.1.— False colour images of the simulated sky in the nine frequency channels of *Planck*, after subtraction of the monopole and dipole CMB components. From top left to bottom right: 30, 44, 70, 100, 143, 217, 353, 545, and 857 GHz channels.

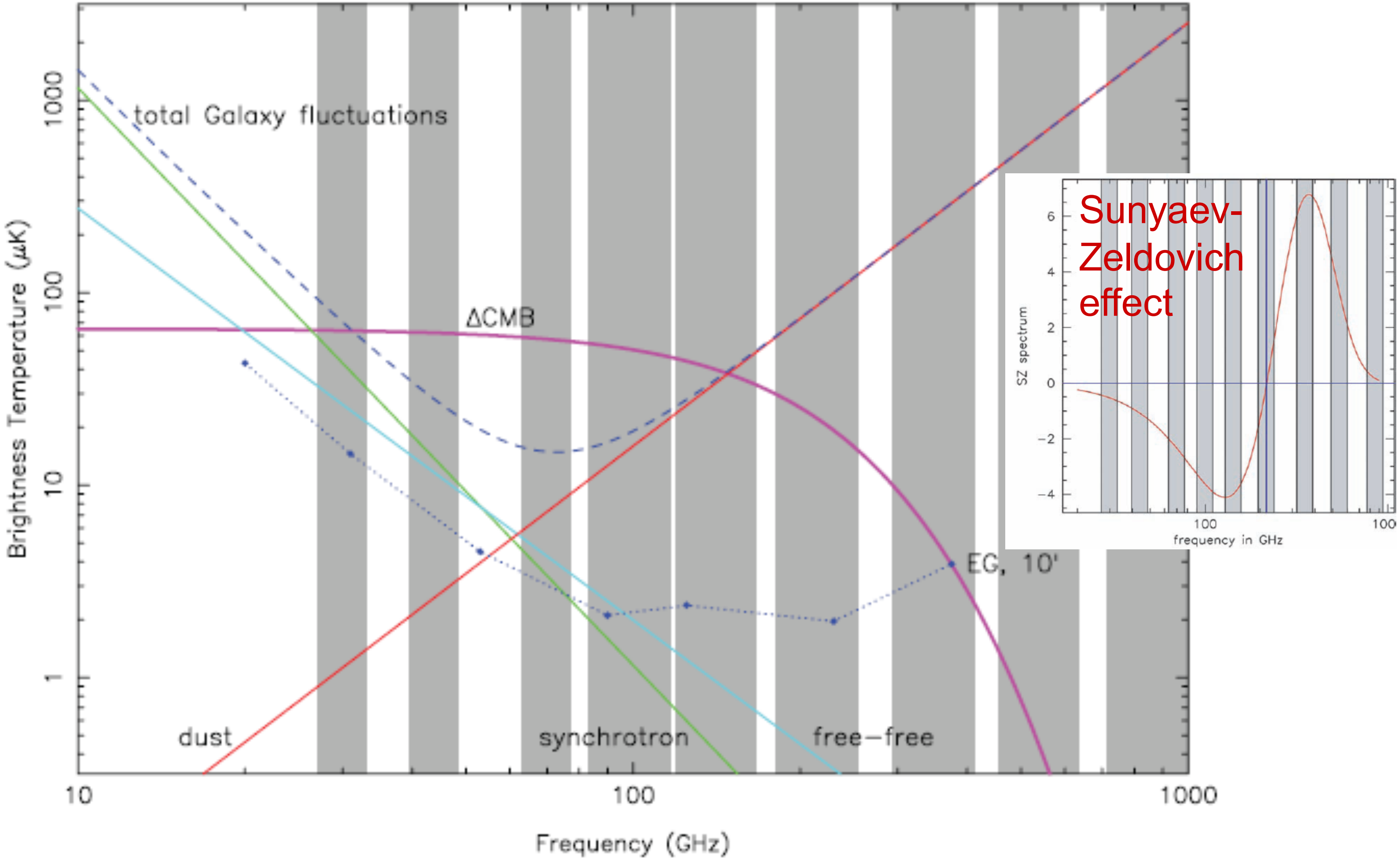


FIG 1.3.— Spectrum of the CMB, and the frequency coverage of the *Planck* channels. Also indicated are the spectra of other sources of fluctuations in the microwave sky. Dust, synchrotron, and free-free temperature fluctuation (i.e., unpolarized) levels correspond to the *WMAP* Kp2 levels (85% of the sky; Bennett et al. 2003). The CMB and Galactic fluctuation levels depend on angular scale, and are shown for ∼1°. On small angular scales, extragalactic sources dominate. The minimum in diffuse foregrounds and the clearest window on CMB fluctuations occurs near 70 GHz. The highest HFI frequencies are primarily sensitive to dust.

Polarization

- 7 channels (all except 545, 857GHz) measure polarization
- Probes different physics than temperature anisotropies
  - picks up signal only from photon scattering
  - no integrated Sachs-Wolfe effect
  - sensitive to reionization (low multipoles)
- Breaks degeneracies
- Signal weaker (the high sensitivity of Planck needed)
- The polarization field on the celestial sphere can be divided into E (curl-free) and B (source-free) parts (“modes”)
- B mode comes from tensor perturbations (Planck may detect if tensor-to-scalar ratio r ~ 0.1)

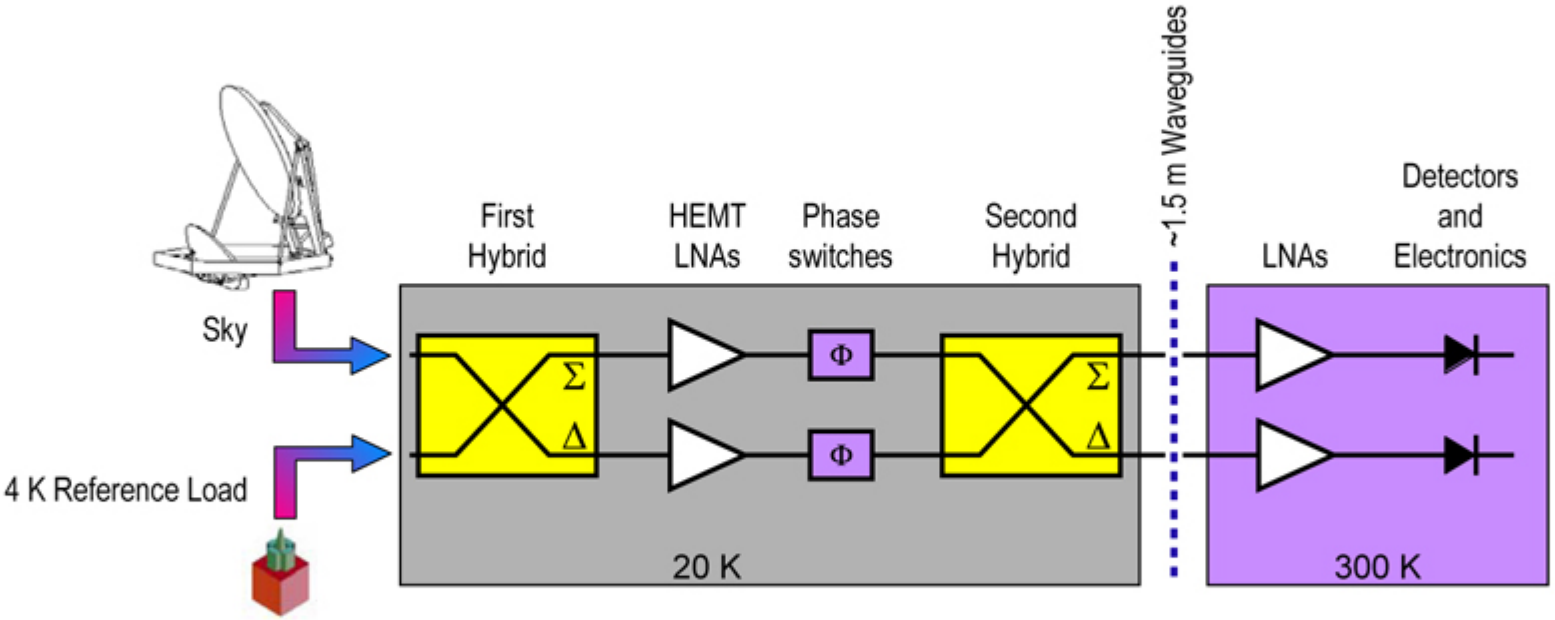
Coolers

- To achieve the high sensitivity (i.e., low noise), Planck detectors need to be cooled to low temperatures
- H_2 sorption cooler to 18 – 20 K (LFI)
- Joule-Thomson cooler to 4 K (HFI, provides reference load for LFI)
- He3-He4 dilution cooler to 0.1 K (HFI detectors)

  The coldest known place in space!

LFI radiometers

- Extremely sensitive “transistor radio”
- Noise dominated by low frequencies:
  - removed by continuously comparing temperature of the sky to temperature of a 4K reference load
- Pseudo-correlation continuous comparison receiver
  - switches these to signals between the two diodes at 8192 Hz



ESA’s 35-metre deep-space ground station at New Norcia

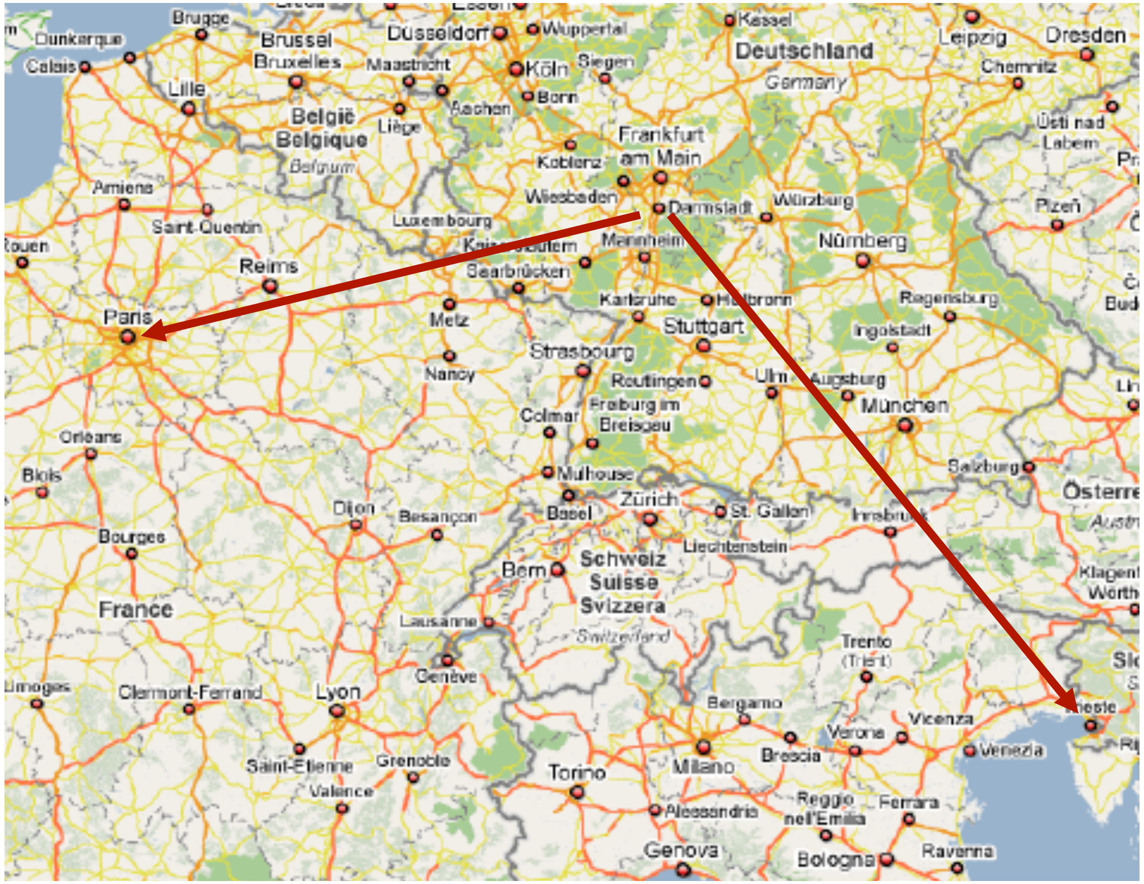
Planck and Herschel are visible for 10 hours per day.
Transmission time divided between them

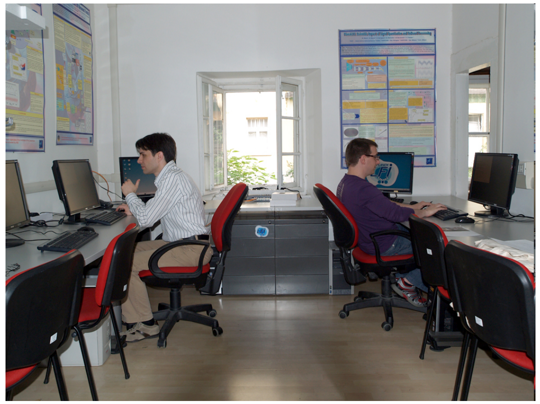
Data transmission

- Transmission rate 1.5 Mbps
- LFI produces science data at 85.33 Kbps
  - 32 b per sample
  - both sky and reference load transmitted to Earth
- Compression by factor 2.4 ➔ 35.55 Kbps
- Total LFI data rate 42.13 Kbps
- HFI rate about 7 times larger
- 24 h of data compressed into 4-5 h transmission

Data processing

- Mission operations control centre (MOC), Darmstadt
- LFI Data Processing Center (DPC): Osservatorio Astronomico di Trieste
- HFI DPC: Institut d’Astrophysique de Paris





Data Analysis Pipeline

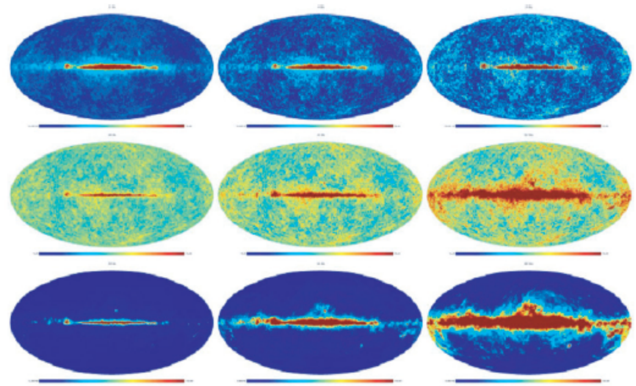
Raw data

↓ Cleaning, calibration

Time-ordered data

↓ Map-making

9 frequency maps (3 LFI, 6 HFI)



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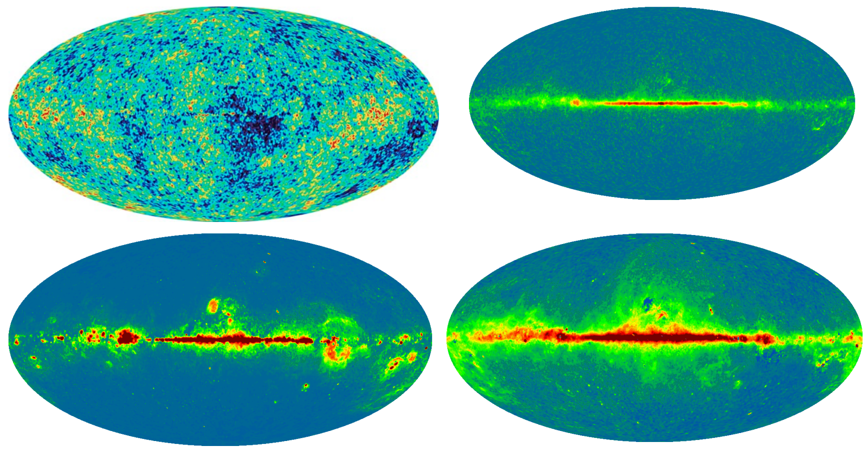
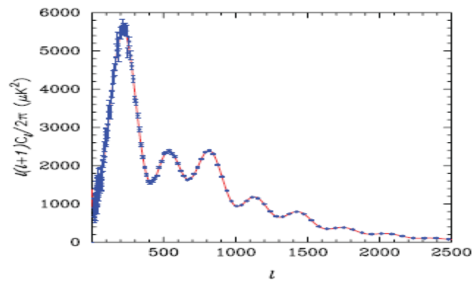
↓ Component separation

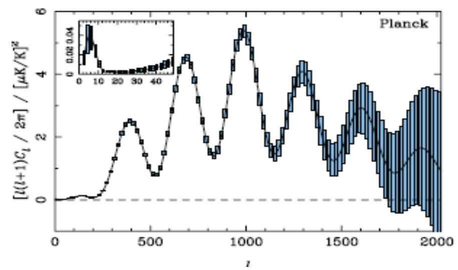
Component maps: CMB, foregrounds



↓ Power spectrum estimation

Angular power spectra

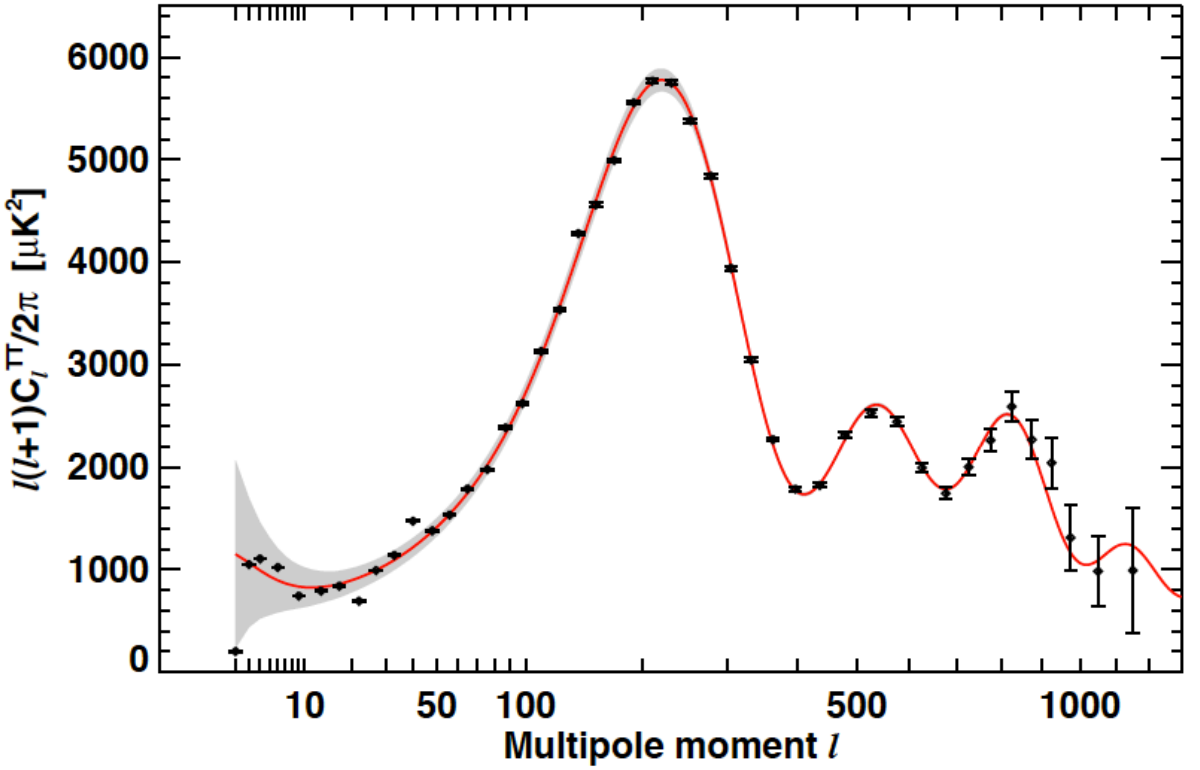




↓ Parameter estimation

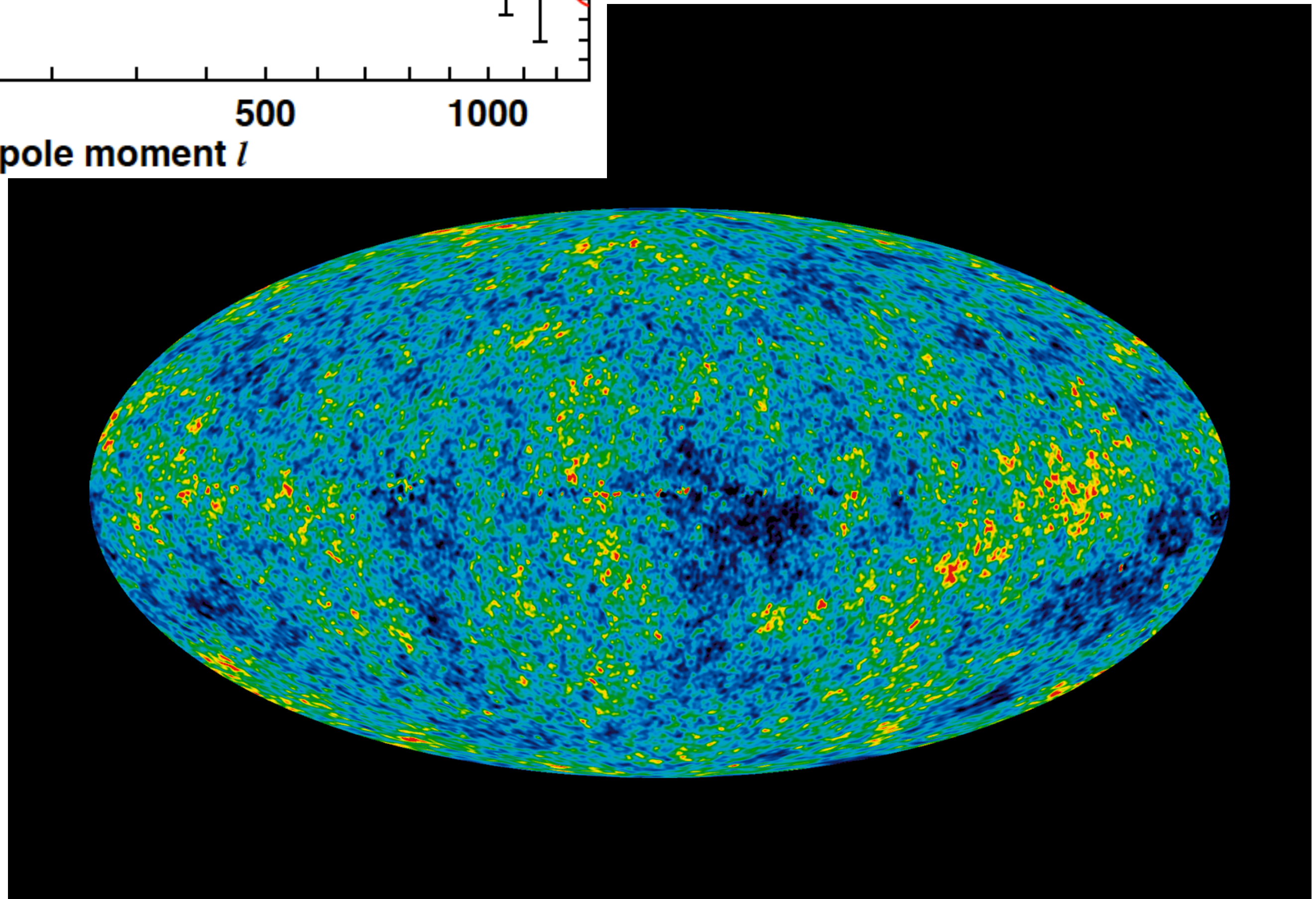
Cosmological parameters

$\Omega, \omega_b, \omega_{cdm}, \Omega_\Lambda, H_0, A, n_s, r, \tau$



Angular power spectrum:
How much structure at
each scale

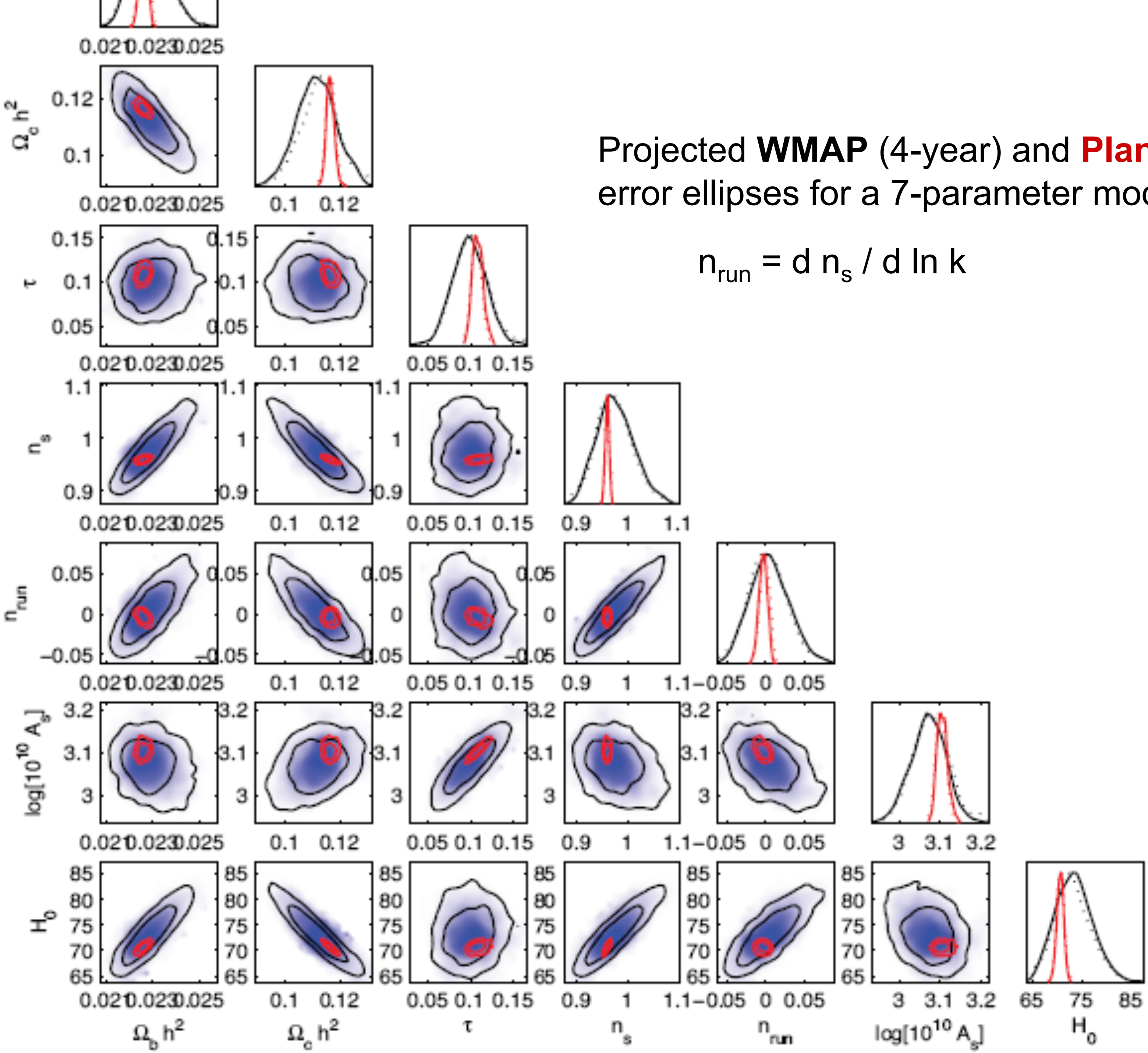
$\theta \sim 180°/\ell$



WMAP 7-year

Projected **WMAP** (4-year) and **Planck** error ellipses for a 7-parameter model

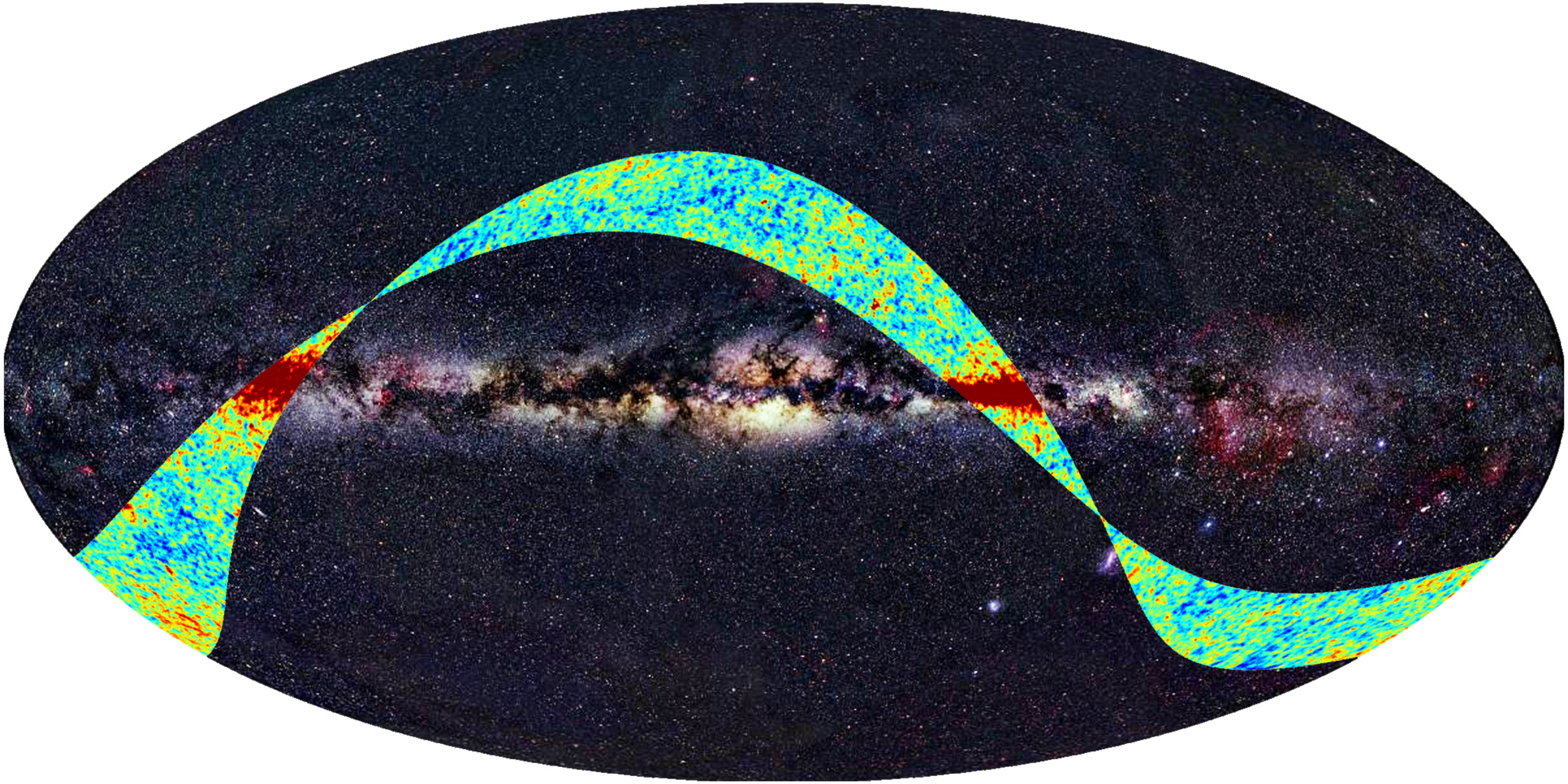
$$n_{run} = d\, n_s / d \ln k$$



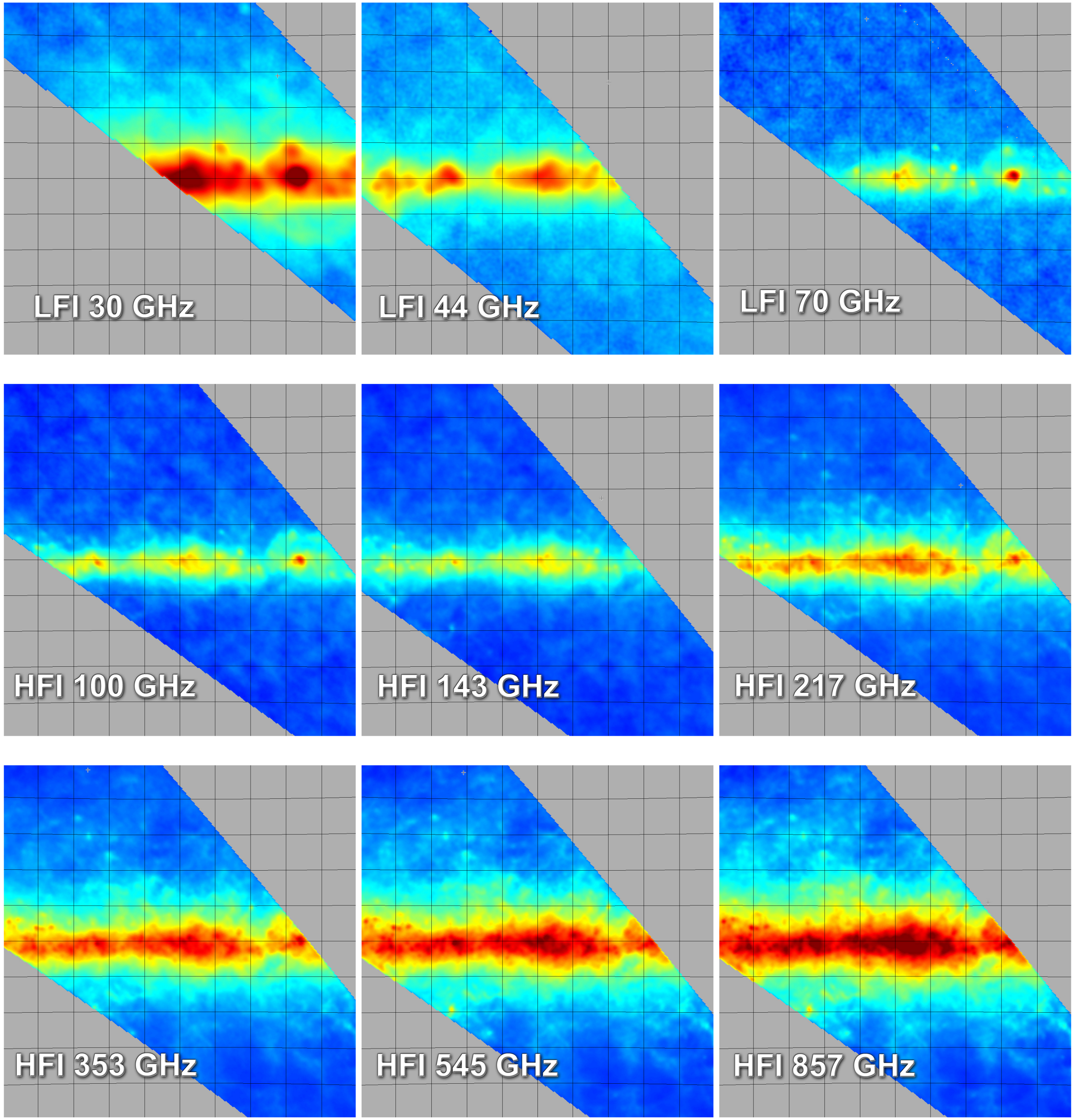
First Light Survey

- Planck was launched on May 14th, 2009.
- Reached orbit, around L2, on July 3rd,
- By then the instruments had also been cooled down to their operational temperature.
- Calibration and performance verification lasted until August 12th
- On August 12th, Planck began the two-week First Light Survey (FLS):
- Operated in survey mode, scanning the sky at 1 rpm, the spin axis reoriented by about 2 arcmin with intervals of about an hour or less.
- During the two weeks of FLS a 15 degree wide strip of the sky was observed.
- Preliminary analysis of the FLS data indicated that the quality of data was excellent, and FLS data will thus be considered as part of the first full-sky survey.

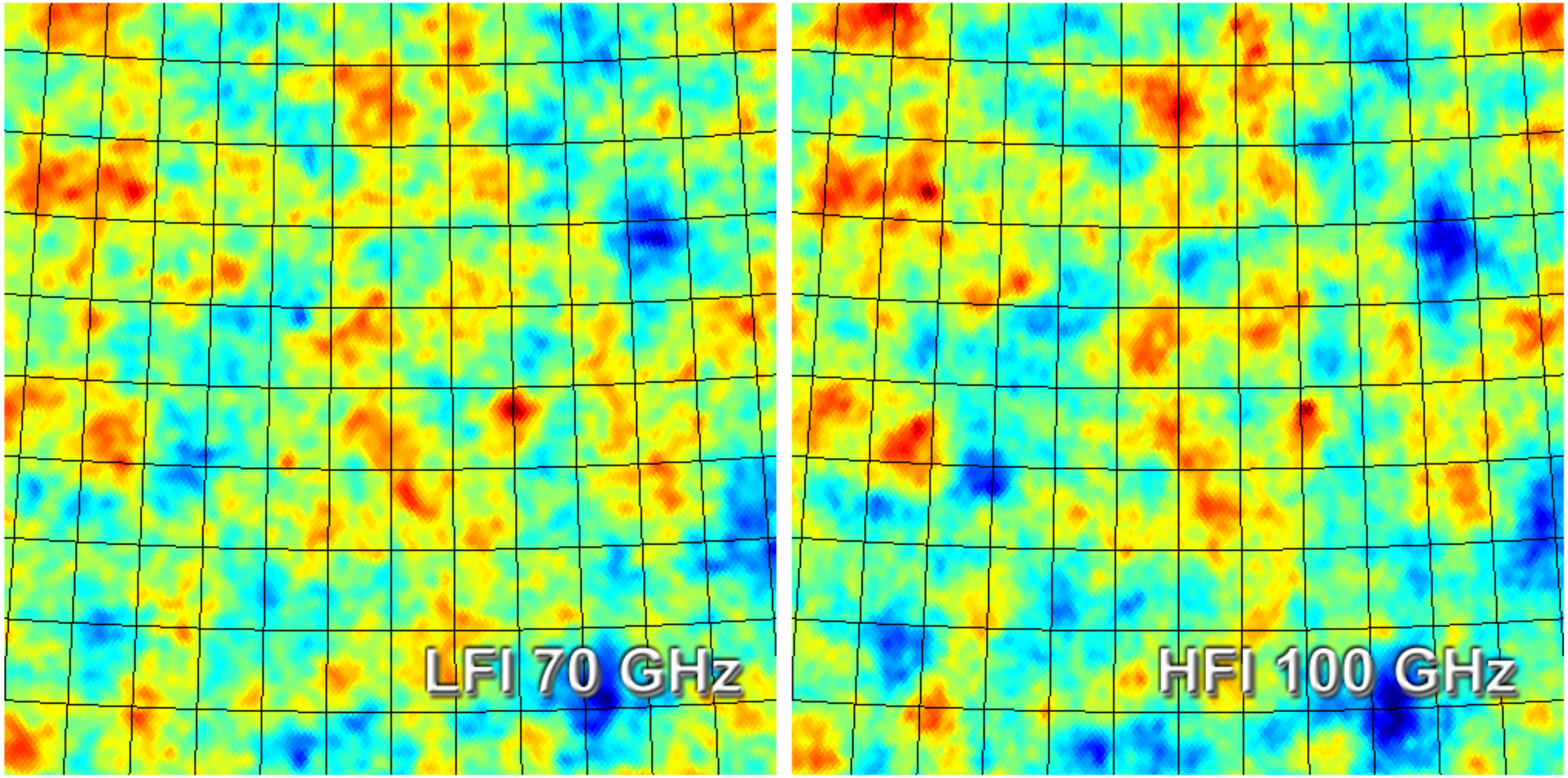
The 70 GHz FLS map



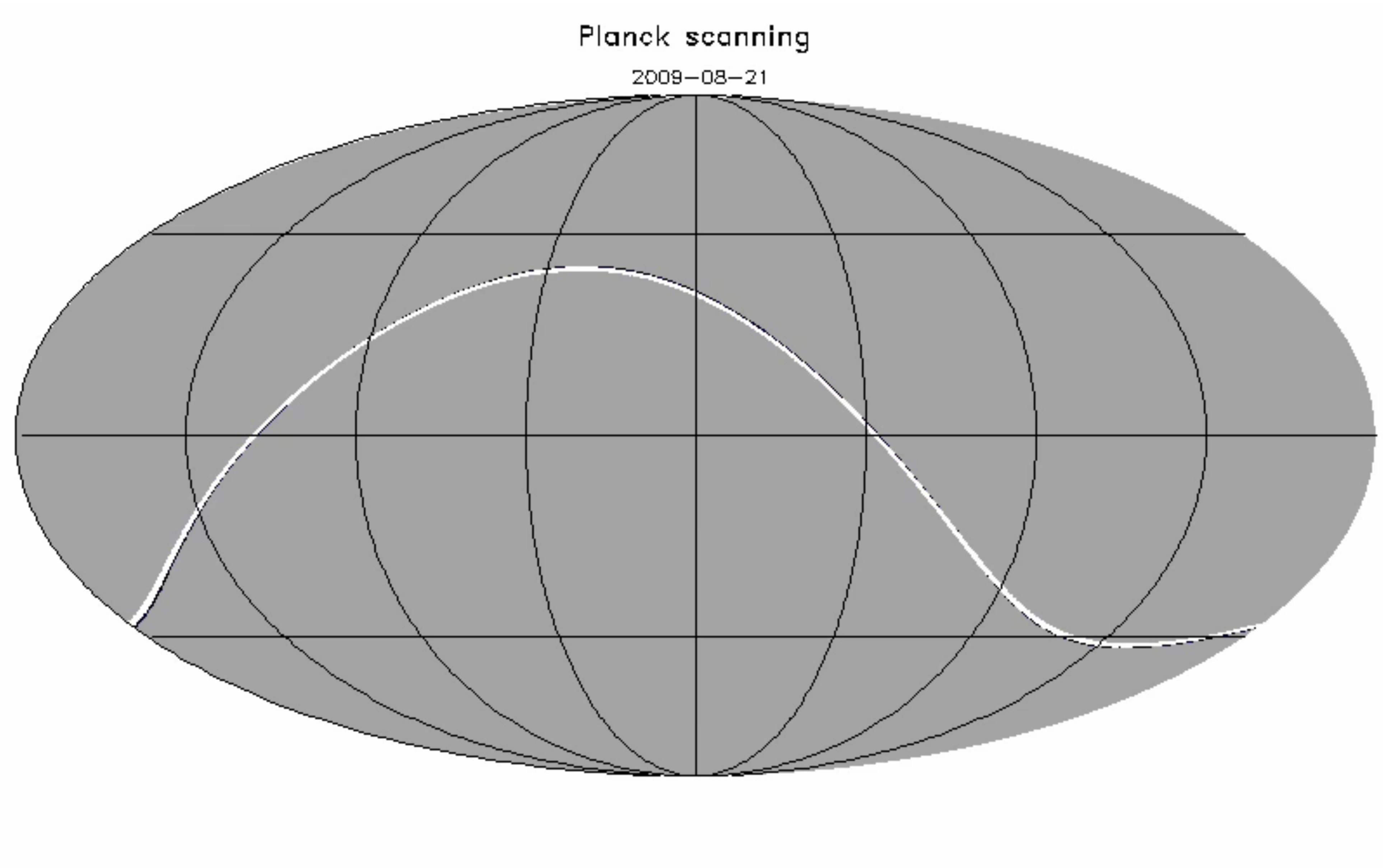
Credit: ESA, LFI & HFI Consortia (Planck), Background image: Axel Mellinger


LFI 30 GHz
LFI 44 GHz
LFI 70 GHz
HFI 100 GHz
HFI 143 GHz
HFI 217 GHz
HFI 353 GHz
HFI 545 GHz
HFI 857 GHz

10°x10° at 70 and 100 GHz

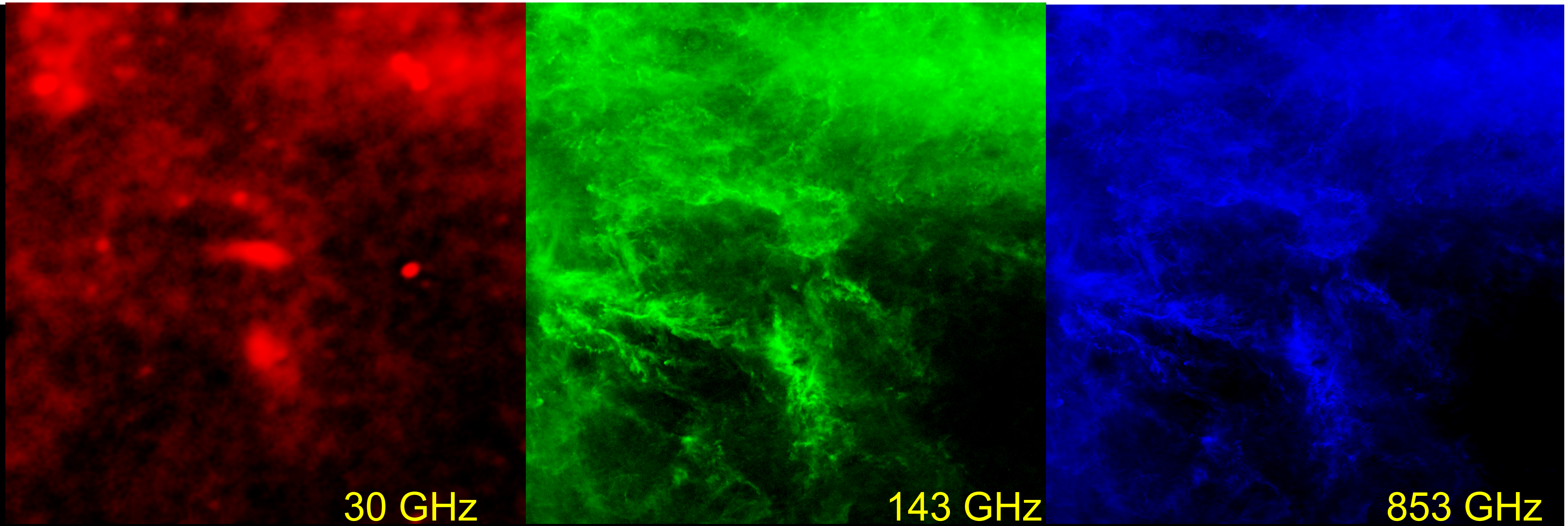


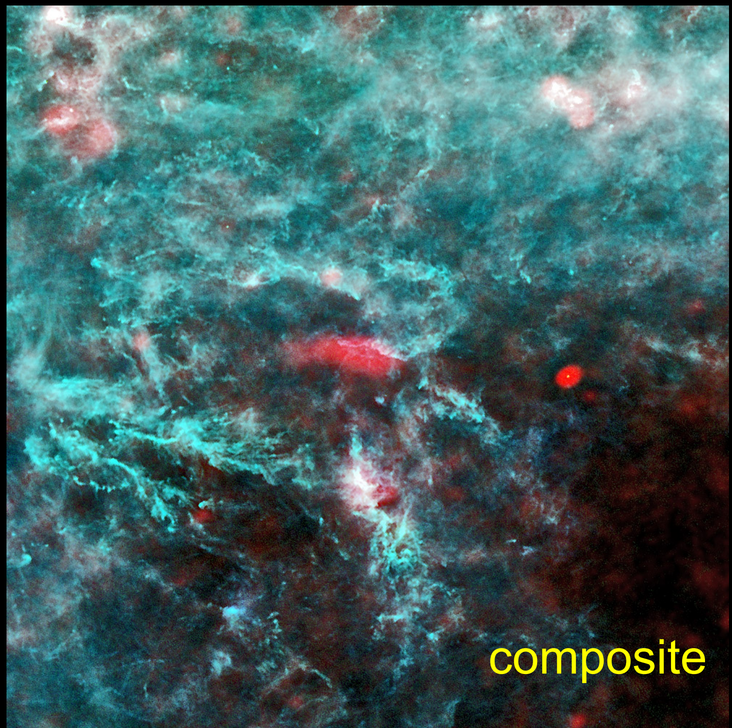
After FLS, Planck has continued operating in survey mode, and by now, it has observed the full sky

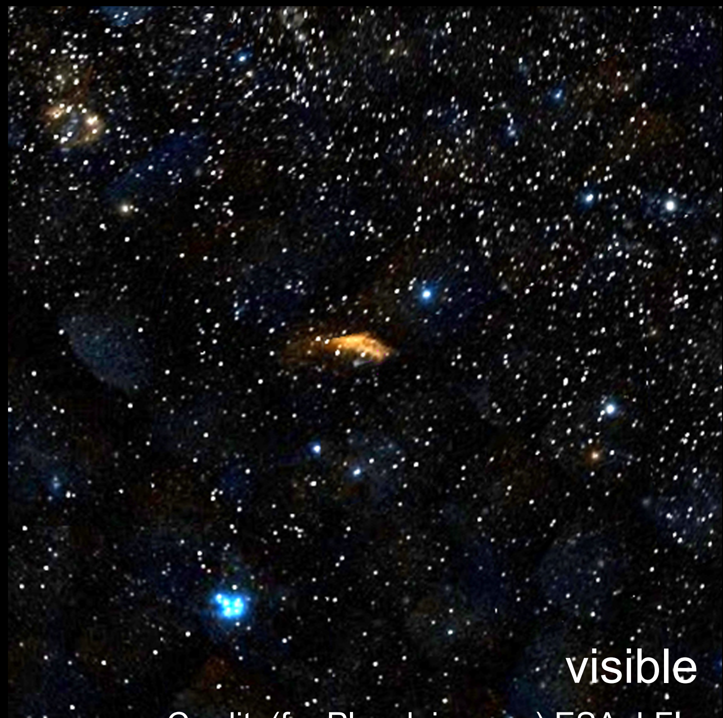


Foreground images

- After FLS, only foreground images (microwave radiation from our galaxy and extragalactic sources) have so far been made public
- The lowest (30 GHz) and highest frequencies are dominated by galactic microwave radiation





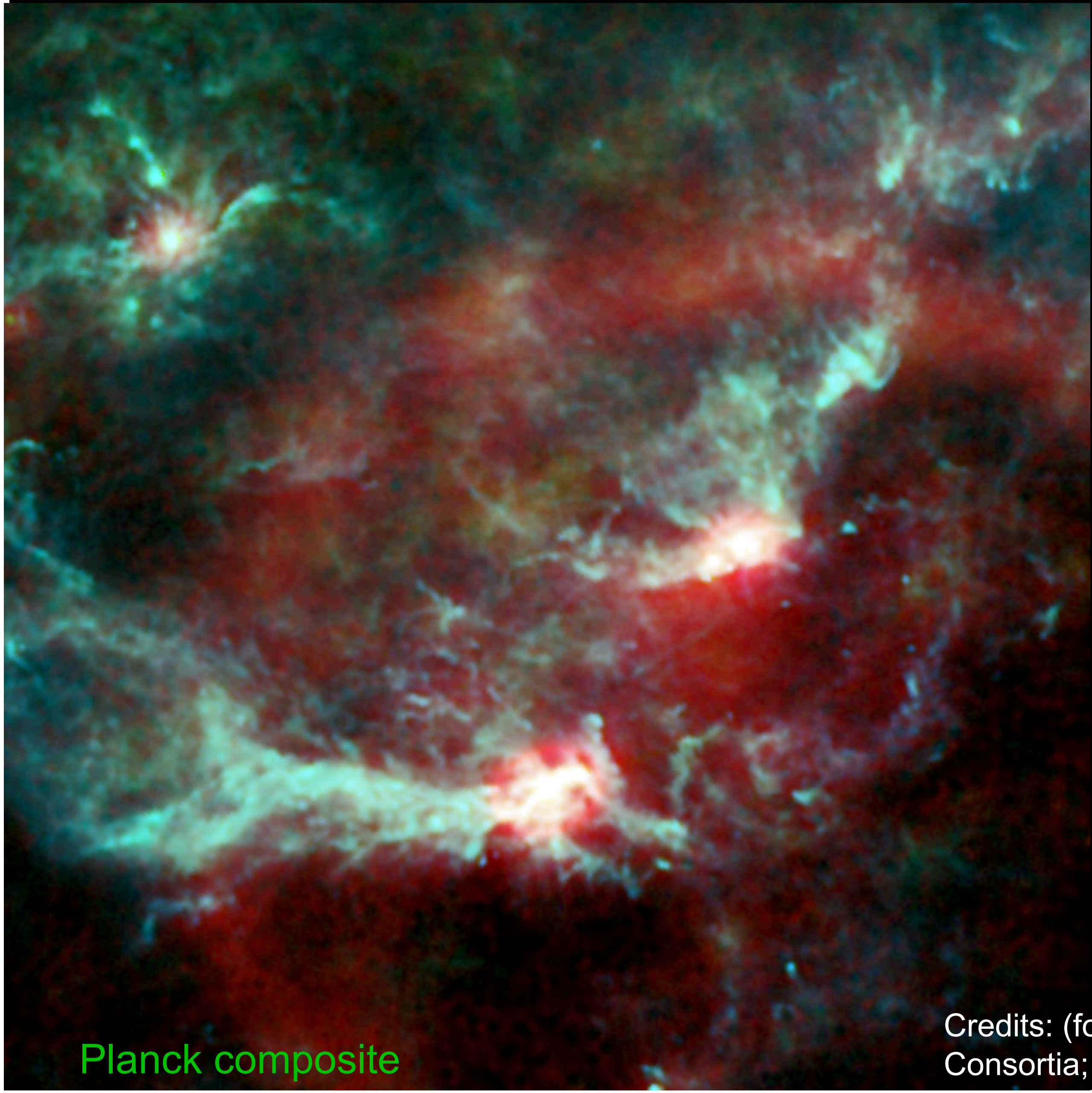


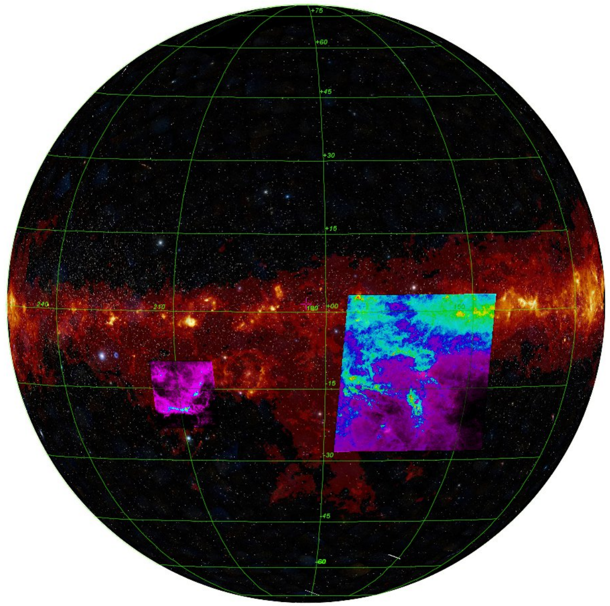
a region of low star formation in the Perseus constellation

Credit: (for Planck images) ESA, LFI and HFI Consortia; (for optical image) STScI DSS.

Orion Nebula

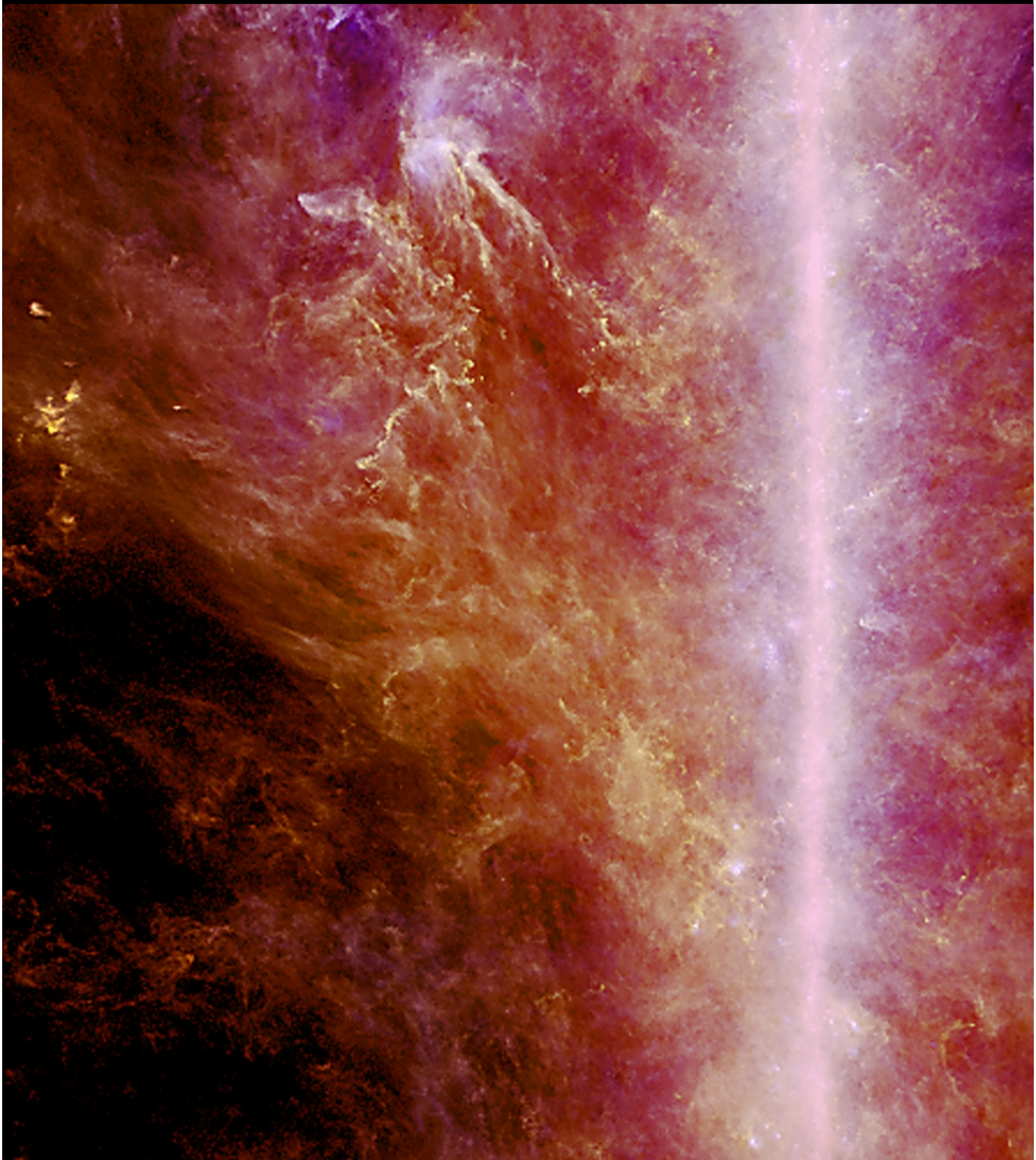
a region of active star formation





Credits: (for Planck images) ESA, LFI and HFI Consortia; (for optical image) STScI DSS

Credit: ESA and the HFI Consortium, IRAS



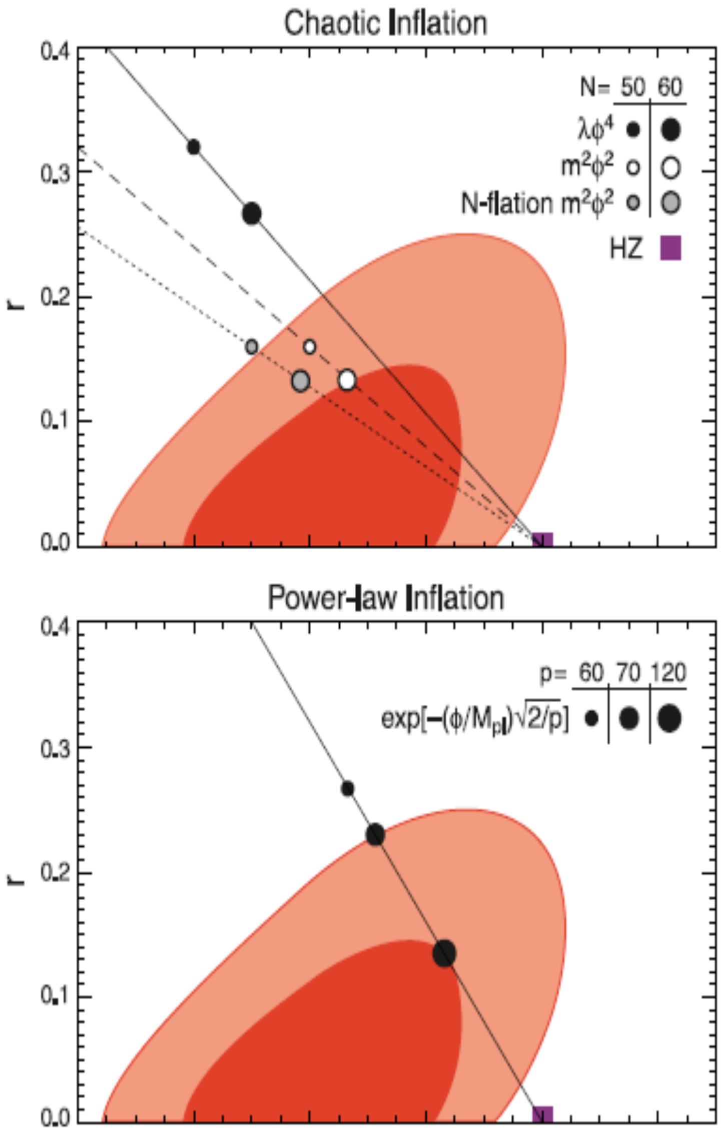
Timetable

- Launch May 14th, 2009
- 15 month survey: August 2009 – November 2010, full sky scanned twice
- 2 years reserved for data analysis
- Early release compact source catalog, January 2011
  - Early papers related to astrophysical foregrounds
- 15 month survey data becomes public near end of 2012
  - Cosmology papers not likely to be published earlier
- ESA has now granted a 1-year extension to the survey: => the full sky scanned 4 times

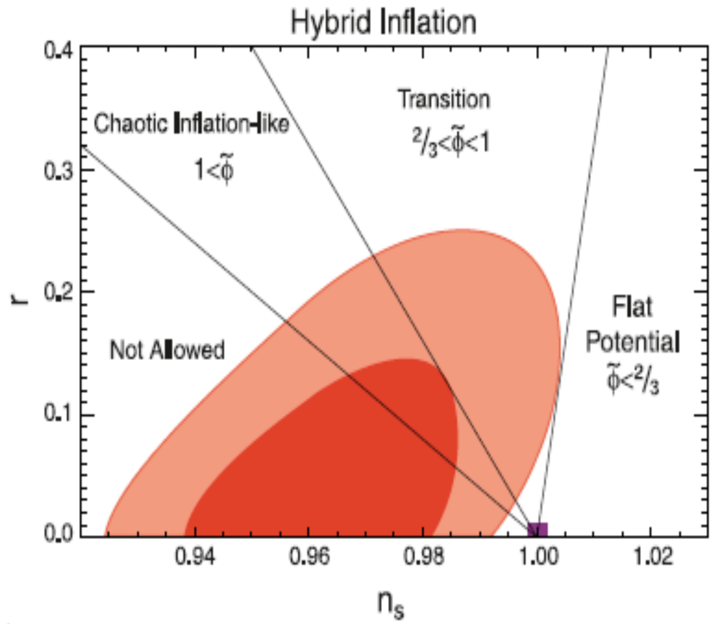
What cosmology expects from Planck

- The main interest is in the nature of primordial perturbations
  - Key to the mechanism for origin of structure in the universe
  - The favorite candidate: inflation
  - Probes very high energy physics—beyond the reach of accelerators

Spectral index and tensor perturbations

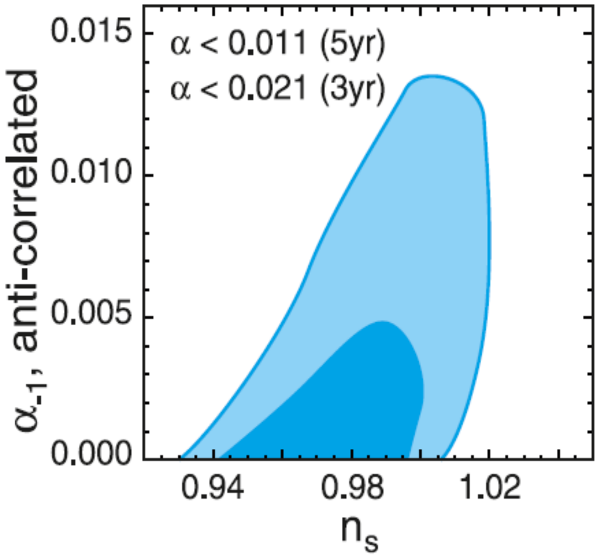


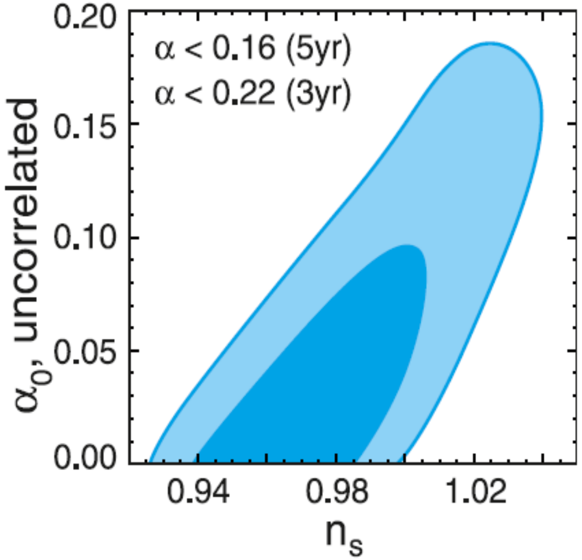
Excluding inflation models (WMAP 5-yr results) assuming adiabatic primordial perturbations but allowing tensor perturbations

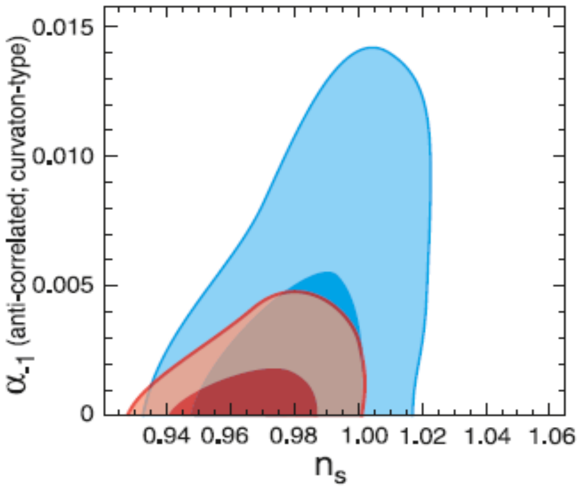


Are primordial perturbations adiabatic?

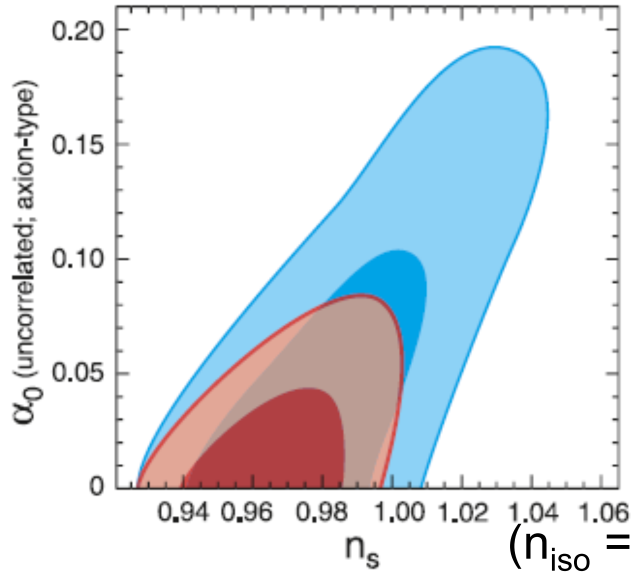
(That is: did we have the same density perturbations in matter and radiation)







($n_{iso} = n_s$)



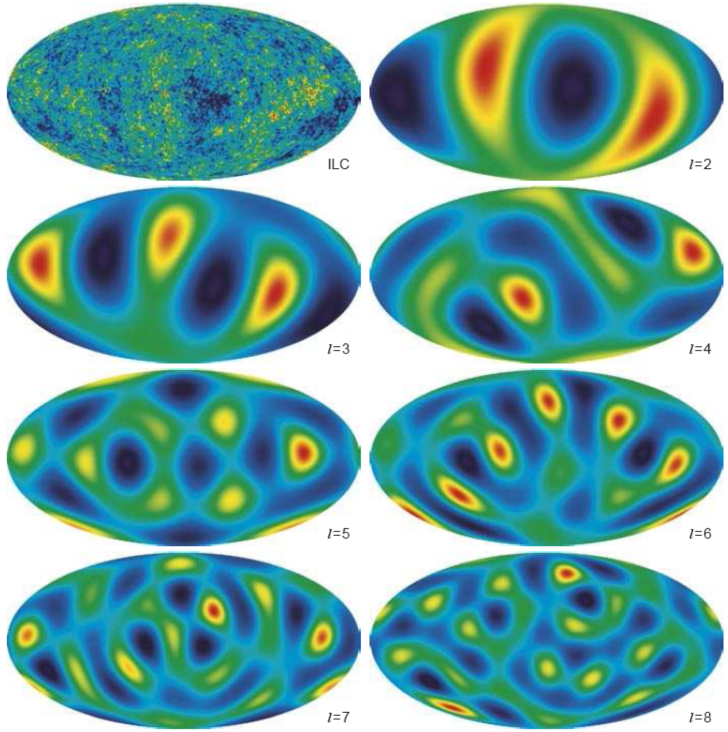
($n_{iso} = 1$)

Are primordial perturbations Gaussian?

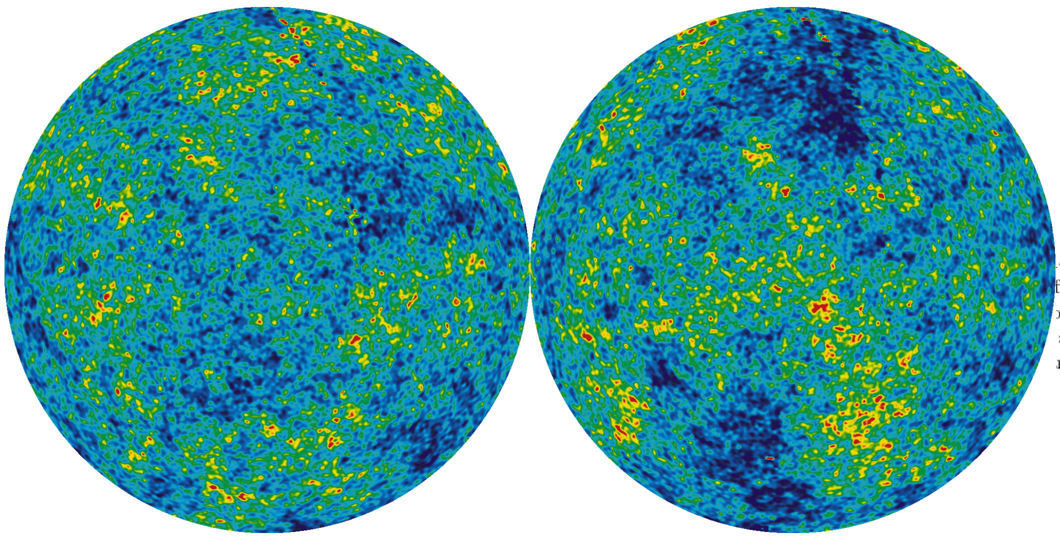
- Nongaussianity parameter f_{NL} (<1 for "standard" inflation models)
- The magnitude of the effect is $f_{NL}A_s$
- $-58 < f_{NL} < 134$ (WMAP 1-year)
- $-54 < f_{NL} < 114$ (WMAP 3-year)
- $-9 < f_{NL} < 111$ (WMAP 5-year)
  - $f_{NL} = 51 +/- 30$ (68%) "1.7σ detection"

Check WMAP Large-Scale Anomalies

- Low quadrupole
- Axis of Evil
- Cold spot
- Less large scale power at ecliptic north



.4.— Maps of power spectrum modes $l = 2 - 8$ computed from full-sky fits to the ILC map, shown at ft. Many authors note peculiar patterns in the phase of these modes, and many claim that the behavior onsistent with Gaussian random-phase fluctuations, as predicted by inflation. For example, the $l = 5$ appears strikingly symmetric (a non-random distribution of power in m), while the $l = 2$ and 3 modes r unusually aligned. The significance of these *a posteriori* observations is being actively debated. See a more detailed discussion.



Impact of Planck on cosmology (I)

- Planck will extract essentially all available information from CMB temperature anisotropy (limited by cosmic variance and foregrounds)
- Planck will accurately measure CMB polarization power spectra
- Planck will determine the 6 parameters of the ΛCDM model with higher accuracy
- 4 of these are already known to 10% or better, and τ to 20%
- But $1-n_s = 0.037 +- 0.014$

Impact of Planck on cosmology (II)

- Besides n_s, the main impact of Planck is to constrain/determine additional parameters
- Many of these are related to probing the mechanism that generated the primordial fluctuations – new physics (inflation?)
  - running spectral index
  - adiabaticity of primordial perturbations
  - nongaussianity
  - primordial gravitational waves (tensor perturbations)
- Planck will also probe the reionization history to more detail than just the optical depth τ (z_{reion})
- Lots of foreground science…
- check WMAP large-scale anomalies


THE END