Cosmology topics, collaborations

BOOMERanG, Cosmic Microwave Background
LARES (LAser RElativity Satellite), General Relativity and extensions, Lense-Thirring

Landau institute: CMB-SW
Caltech: dark energy
Institute d'Astrophysique (Paris): X-ray galaxy clusters
Zurich, Salento Univ.: galactic halo, dark matter

2007- 7 (5+2) PhDs defended

2007 - 49 articles (PL, PRL, A&A, EPL, J Phys…)

2008 - 462 citations

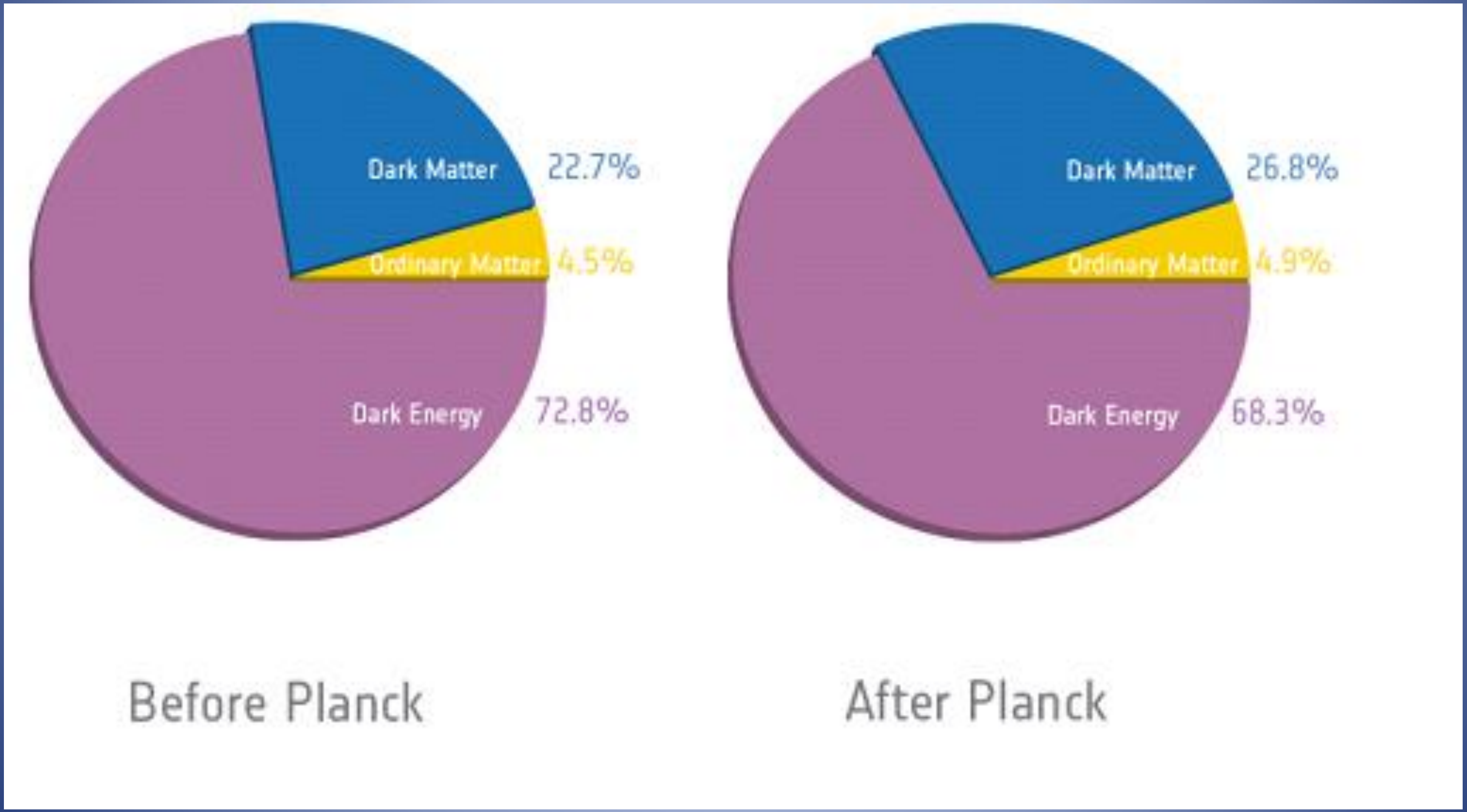
Cosmic Microwave Background radiation: window to early Universe

after PLANCK

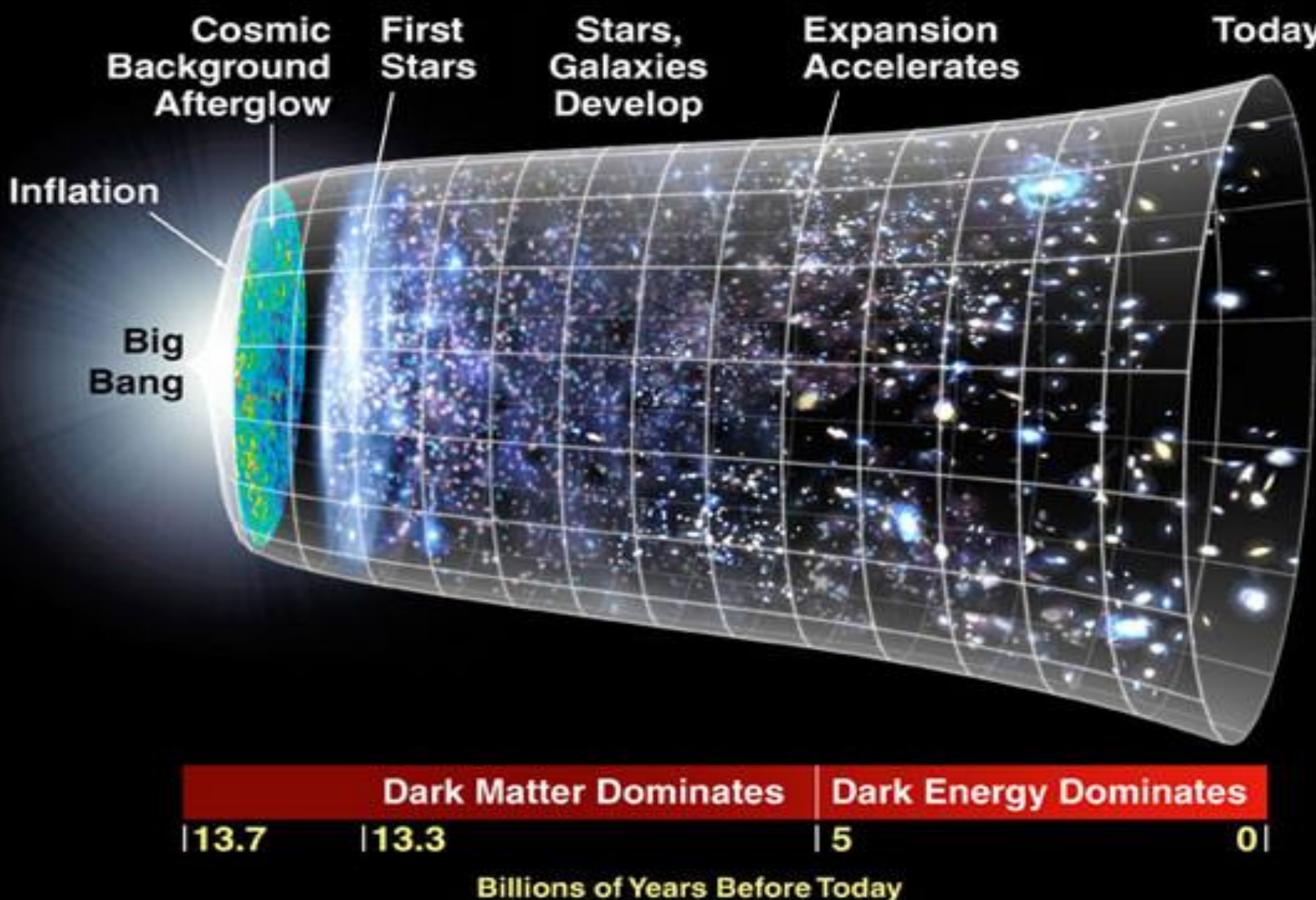
Gegham Yegoryan

Center for Cosmology and Astrophysics

Content of the Universe



The Expanding Universe: A Capsule History

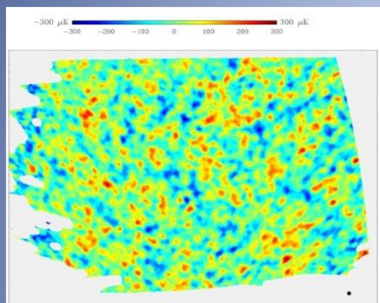


CMB Chronology

- **1940s – Gamow, Alpher, Herman – Big Bang, CMB**
- **1965 – Penzias and Wilson (McKellar; Shmaonov…)**
- **1992 – COBE, Temperature anisotropy discovered**
- **1998, 2003 – BOOMERanG**
- **2001 – WMAP**
- **2009 - Planck**

Cosmic Background Explorer (COBE): 1989 launch

COBE discovered temperature differences at large angular scales (10°)

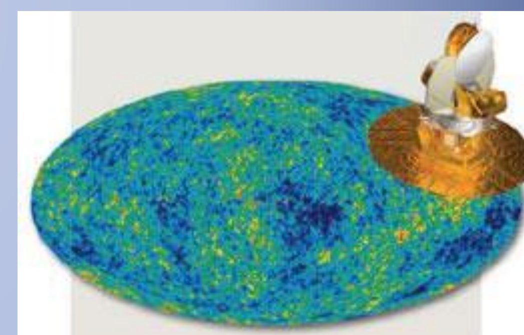


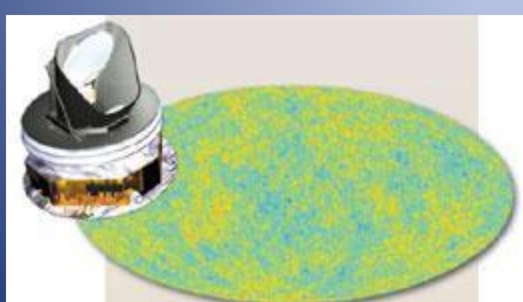
Boomerang (1998,2003)

2% of full sky , 0.11° angular resolution

Wilkinson Microwave Anisotropy Probe(WMAP): 2001 launch

WMAP had 45 times the sensitivity and 33 times (0.3°) the angular resolution of COBE.





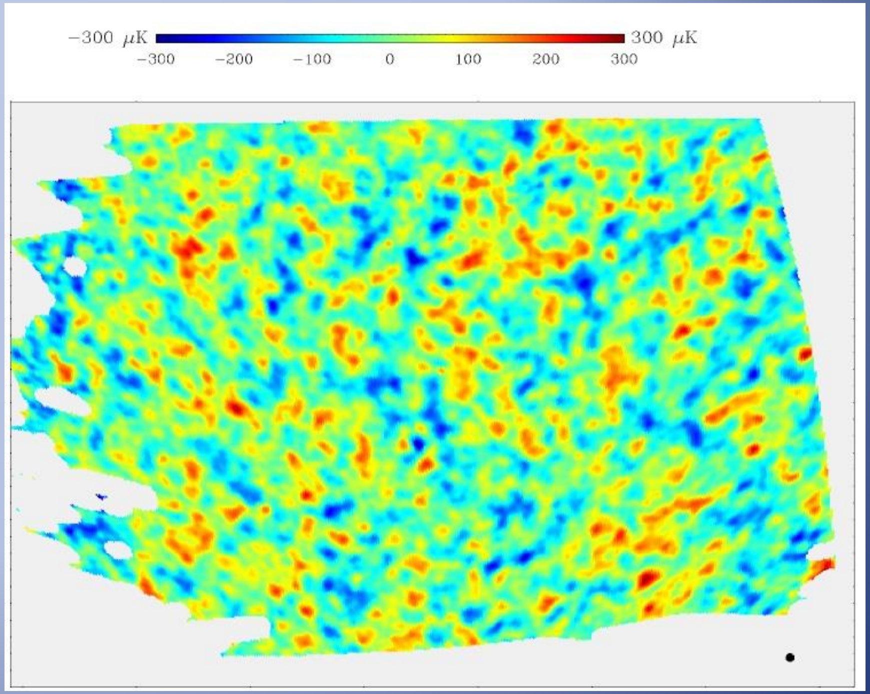
Planck: 2009 launch

More than 10 times the sensitivity and 3 times the angular resolution of WMAP

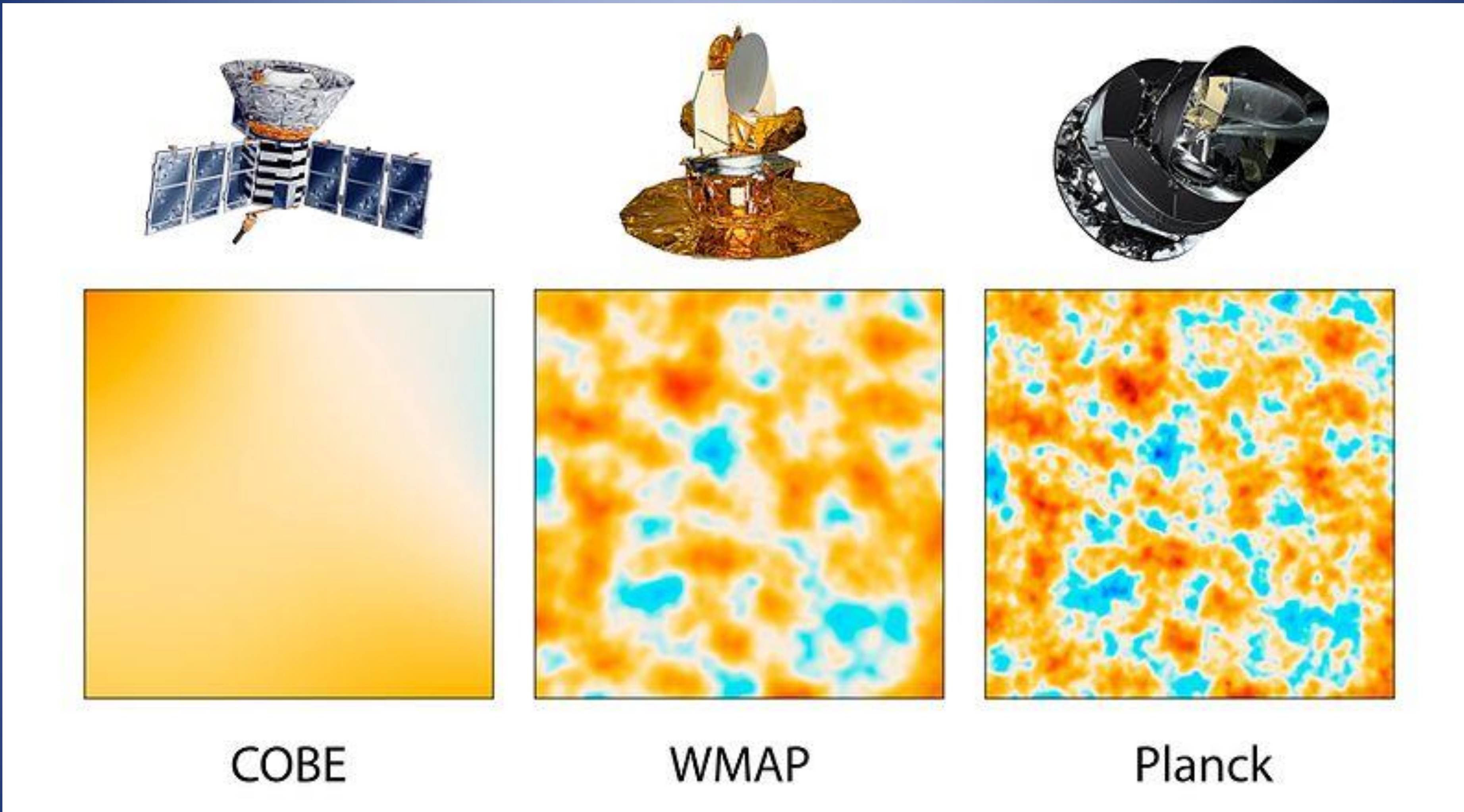
BOOMERANG

1998,2003 - two flights (Antarctica)

It used the polar vortex winds to circle around the south pole, returning after two weeks.



Resolution ~ 7 arc-min (35 times higher than COBE) at 90, 150 , 240, 410 GHz


COBE
WMAP
Planck

Anisotropy structure

Multipole decomposition of temperature in terms of spherical harmonics

$$T(\theta,\varphi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\varphi) \qquad Y_{lm} = e^{im\varphi} P_l{}^m(\cos\theta)\ ,$$

In the theory of the CMB temperature fluctuations each coefficient a_{lm} should have an average that depends only on *l*, not *m*. In addition, the distribution of the values should be Gaussian.

The power spectrum is defined as

$$C_l = \frac{1}{2l+1}\sum_{m=-l}^{l}\langle|a_{lm}|^2\rangle \quad \langle[\delta T(n)]^2\rangle = \sum_l \frac{2l+1}{4\pi} C_l \approx \int \frac{dl}{l}\frac{l(l+1)}{2\pi} C_l$$

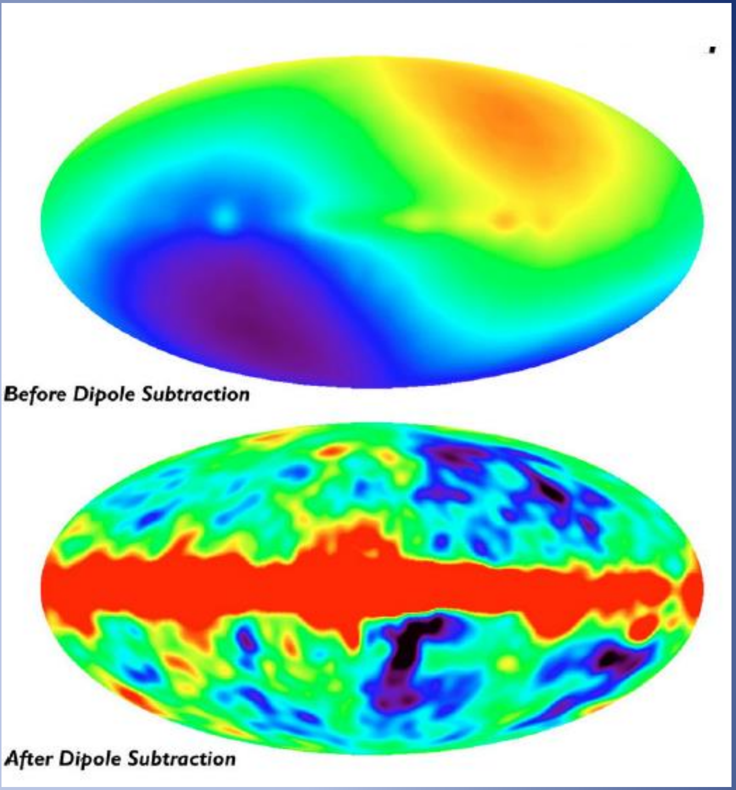
Monopole (l=0)

CMB has a mean temperature T = 2.7255 ± 0.0006 K.

Dipole (l=1)

The dipole is interpreted as a result of Doppler shift caused by Solar system's motion.

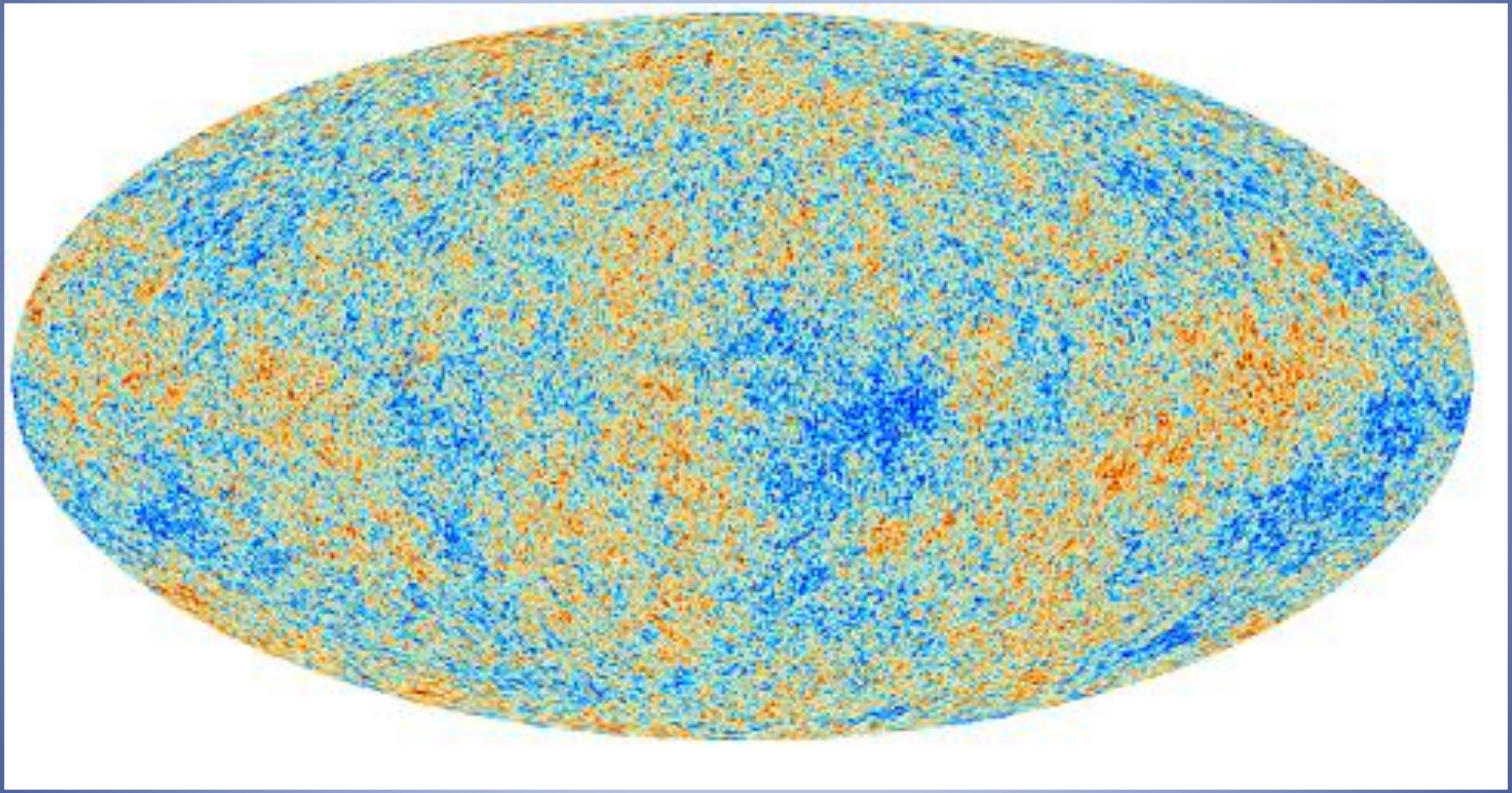
Amplitude: 3.355 ± 0.008 mK
V = 369 ± 0.9 kms−1 towards
(ℓ, b) = (276◦ ± 3◦,30◦ ± 3◦),



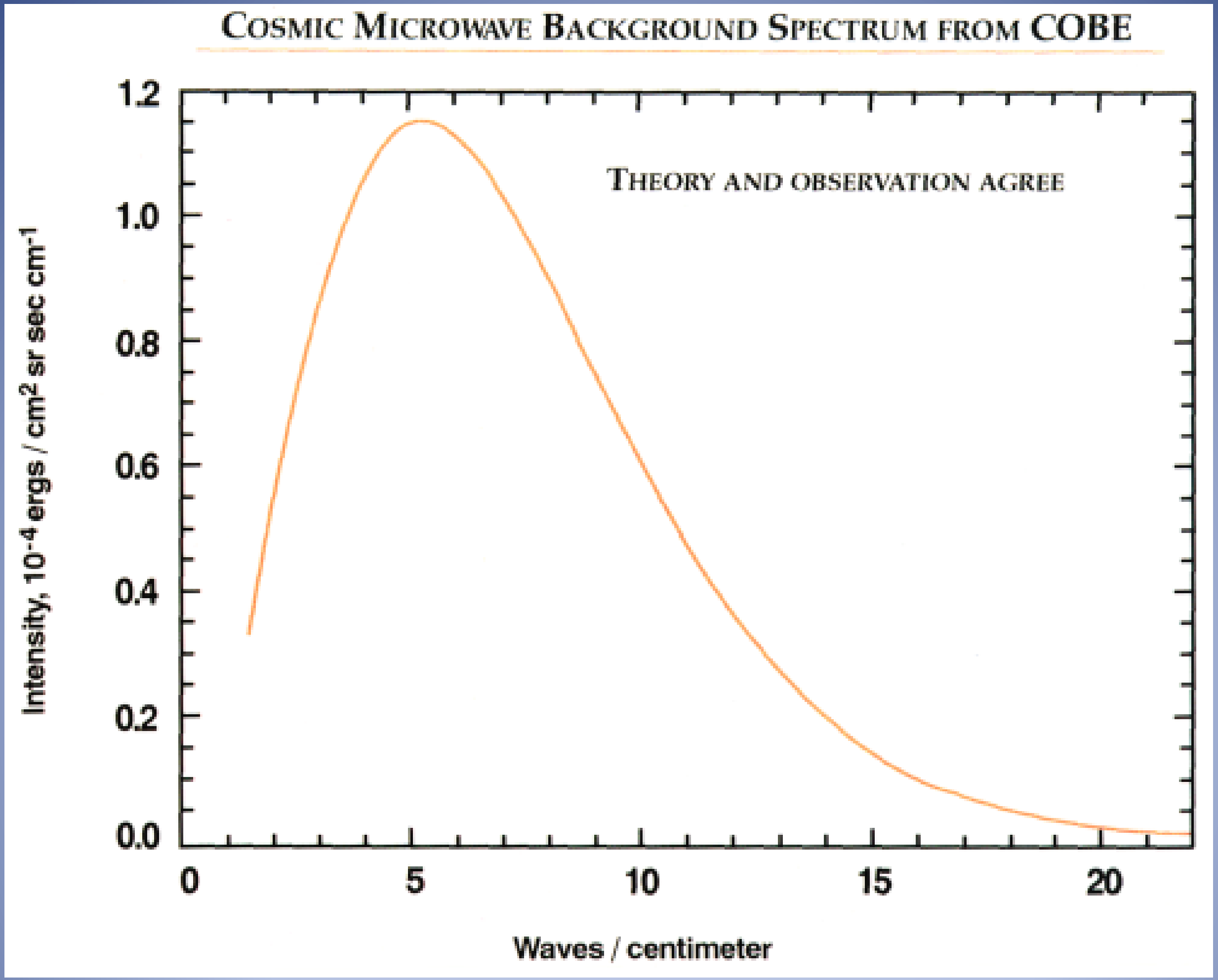
Velocity of the Local Group
V = 627 ± 22 kms−1
Higher-order multipoles

The variations in the CMB temperature at higher multipoles (ℓ ≥ 2) are mostly a result of perturbations in the density of the early Universe, originating at the epoch of the last scattering of the CMB photons.

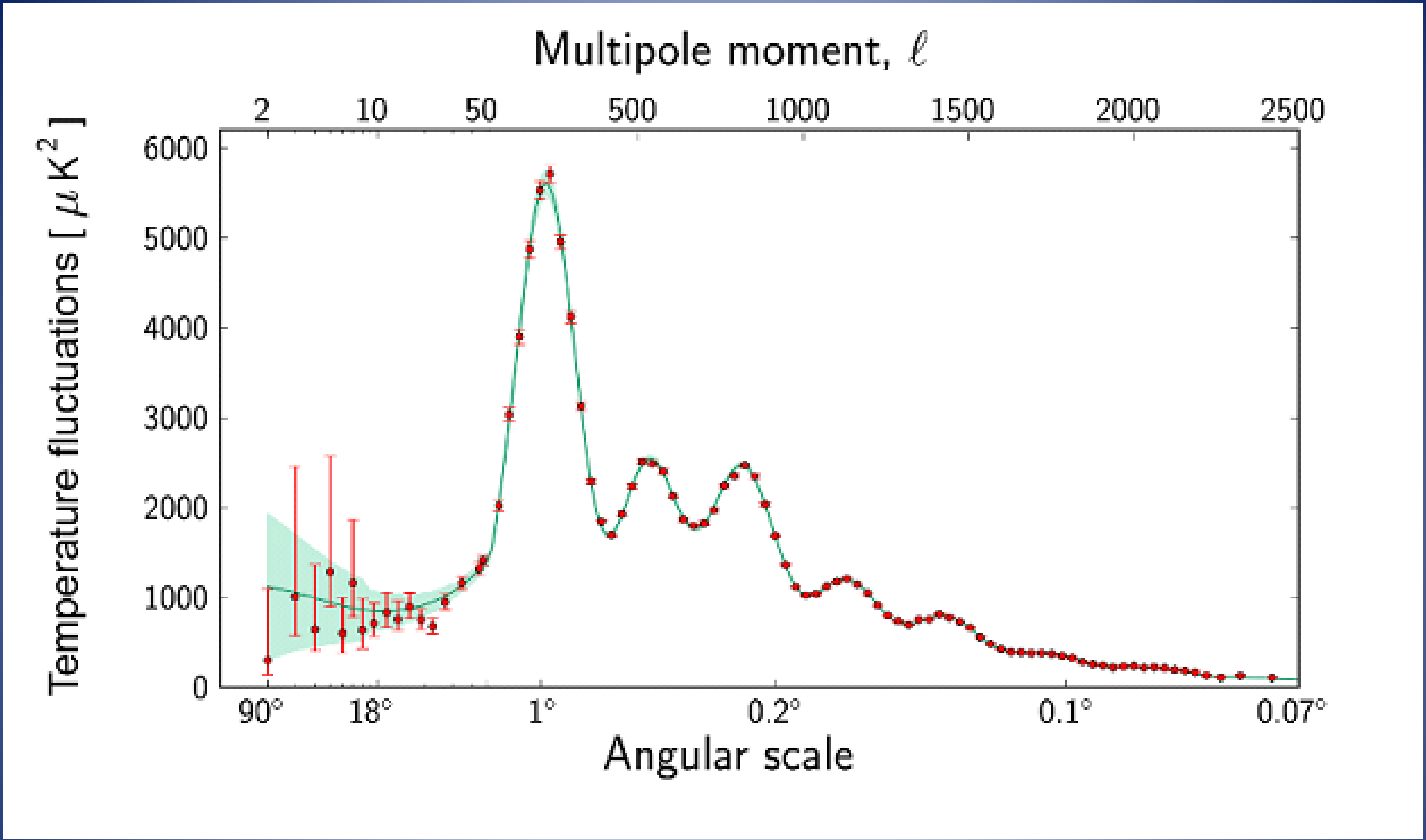
Planck CMB map



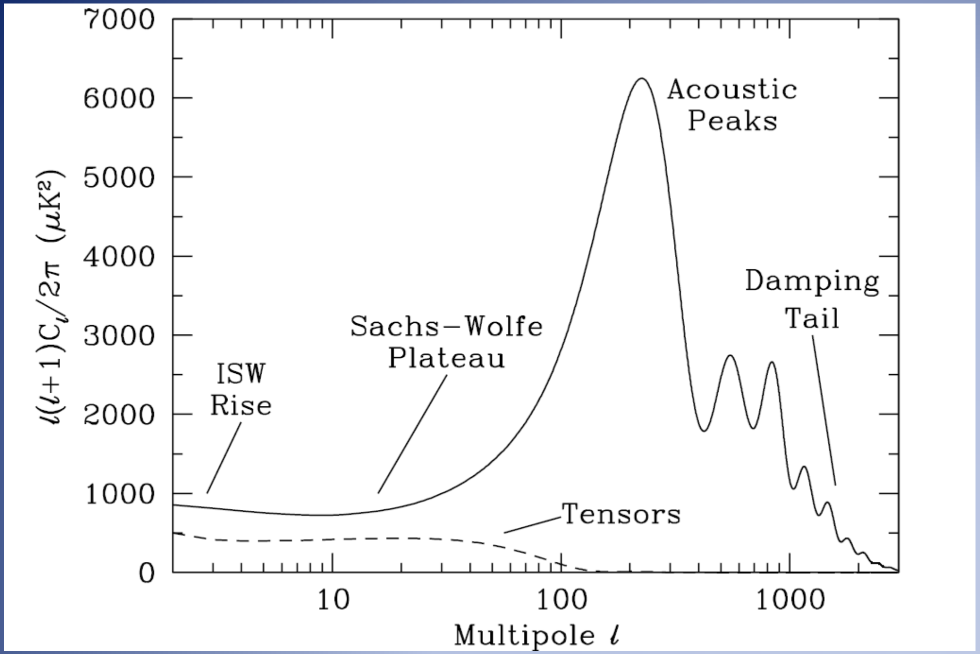
70 GHz (Galactic disk extracted).



Cosmic microwave background spectrum measured by the FIRAS - COBE, the most precisely measured black body spectrum in nature, error bars are too small to be seen even in enlarged image, impossible to distinguish the observed data from the theoretical curve.



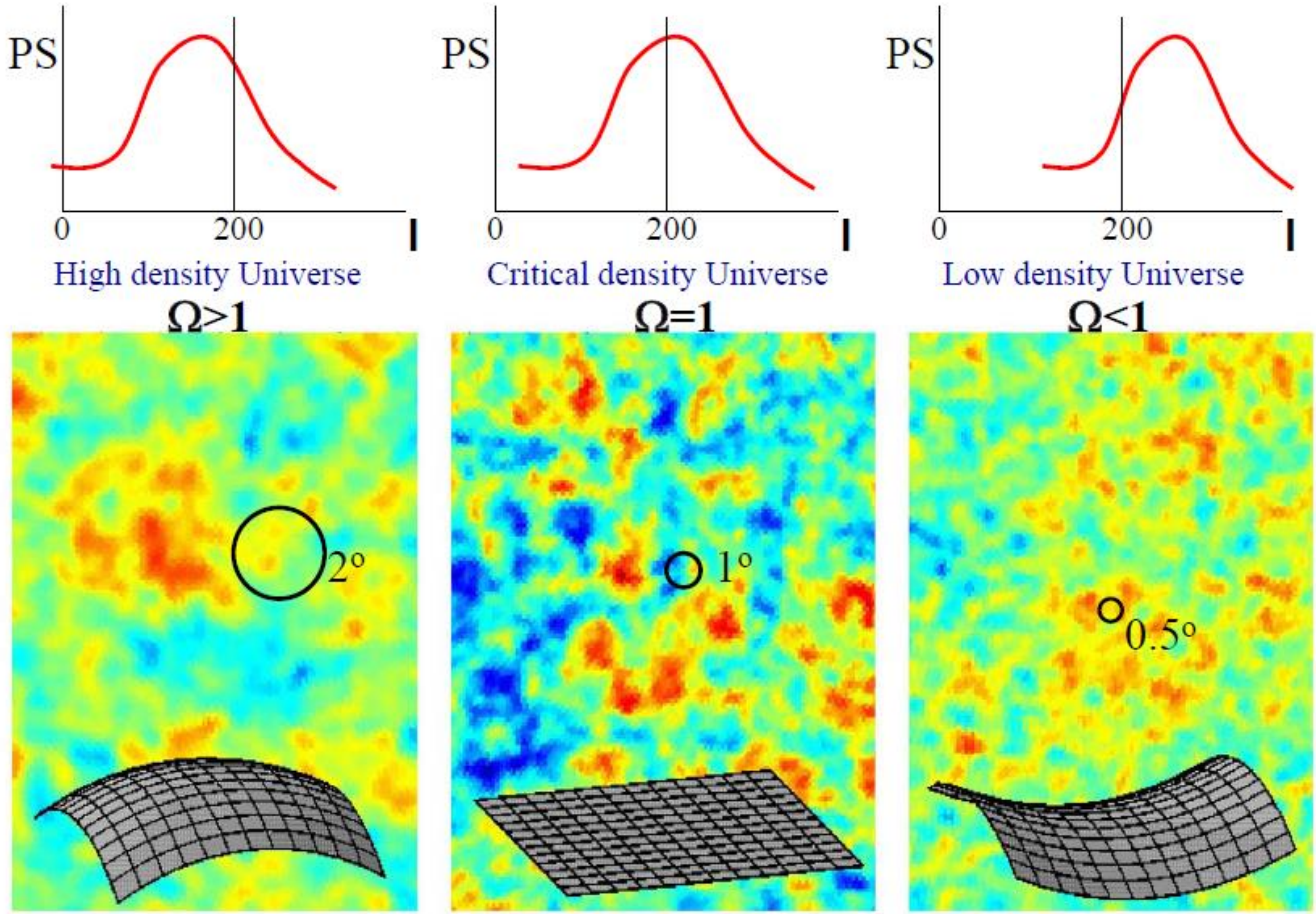
CMB temperature power spectrum as a function of angular scale.



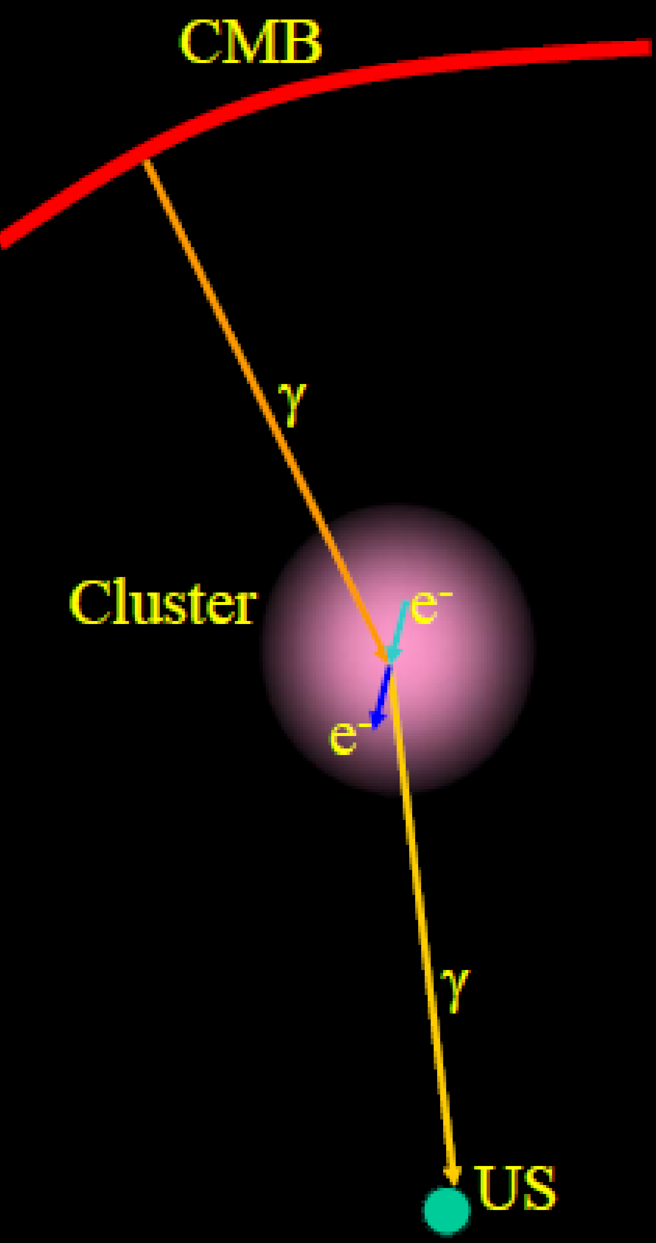
Sachs-Wolfe effect is caused by the change in potential and photons trapped in structures prior to recombination, suddenly leave those structures.

Integrated Sachs-Wolfe effect is caused by the switch-over to an accelerating expansion of Universe. This causes the depth of potential wells to decrease.

Acoustic peaks correspond to density variations in the early universe due to acoustical oscillations of plasma. The coupling between electrons and photons is not perfect, especially as one approaches the epoch of recombination, this leads to **damping** in the anisotropy spectrum: smaller scale inhomogeneities are smoothed out.


PS
0
200
l
High density Universe
Ω>1
2°
PS
0
200
l
Critical density Universe
Ω=1
1°
PS
0
200
l
Low density Universe
Ω<1
0.5°

Sunyaev-Zeldovich effect



Inverse Compton scattering of CMB photons against hot electrons in the intergalactic medium of rich clusters of galaxies

About 1% of the photons acquire about 1% boost in energy, thus slightly shifting the spectrum of CMB to higher frequencies.

$\Delta T/T \sim 10^{-4}$

The result is a decrease of CMB brightness in the line of sight crossing the cluster at $\nu<217$ GHz, and an increase at $\nu>217$ GHz

Independent of redshift !

Kompaneets equation

$$\frac{dN}{dy} = \frac{1}{x^2}\frac{d}{dx}\left\{x^4\left(\frac{dN}{dx} + N + N^2\right)\right\}$$

$$N = \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

$$x = \frac{h\nu}{kT_e}$$

Comptonization parameter

$$y = \frac{k\sigma_T}{m_e c^2}\int n_e T_e dl$$

SZ effect is used for distance estimations.

Concordance cosmological model

For Friedmann–Lemaitre–Robertson–Walker (FLRW) metric

ds^2$= -dt^2 + a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2(d\theta^2 + sin^2\theta d\varphi^2)\right]$, K – Spatial curvature

K=0, Flat Universe

K=1, Positive curvature

K=-1, Negative curvature

the solution of Einstein`s equations describe a homogeneous, isotopic expanding or contracting universe.

Friedmann equation in terms of density parameters

$\frac{H^2}{{H_0}^2} = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda,$ *a- scale factor, Hubble parameter* $H \equiv \frac{\dot{a(t)}}{a(t)}$

Ω_r- radiation density , Ω_m-matter density , Ω_k-spatial curvature density, Ω_Λ- cosmological constant.

Temperature as the function of redshift $T = T_0(1+z)$, T_0 = 2.732

Density perturbation evolution in expanding dark Universe is a challenge; Baryon acoustic oscillations, voids, lensing, etc.

The minimalist model with 6 free parameters - Ho, Ωo, Ωb, ΩΛ, n, tau - describing the angular power spectrum of the CMB.

Comparison of *Planck*-only and *WMAP*-only Six-Parameter ΛCDM Fits[a]

Parameter	*Planck* ("CMB+Lens")	*WMAP* (9-year)	Difference value	Difference *WMAP* σ
$\Omega_b h^2$	0.02217 ± 0.00033	0.02264 ± 0.00050	-0.00047	0.9
$\Omega_c h^2$	0.1186 ± 0.0031	0.1138 ± 0.0045	0.0048	1.1
Ω_Λ	0.693 ± 0.019	0.721 ± 0.025	-0.028	1.1
τ	0.089 ± 0.032	0.089 ± 0.014	0	0
t_0 (Gyr)	13.796 ± 0.058	13.74 ± 0.11	56 Myr	0.5
H_0 (km $s^{-1}Mpc^{-1}$)	67.9 ± 1.5	70.0 ± 2.2	-2.1	1.0
σ_8	0.823 ± 0.018	0.821 ± 0.023	0.002	0.1
Ω_b	0.0481[b]	0.0463 ± 0.0024	0.0018	0.7
Ω_c	0.257[b]	0.233 ± 0.023	0.024	1.0

Slide by P. de Bernardis (2010)

Open issues related to CMB anisotropy (1)

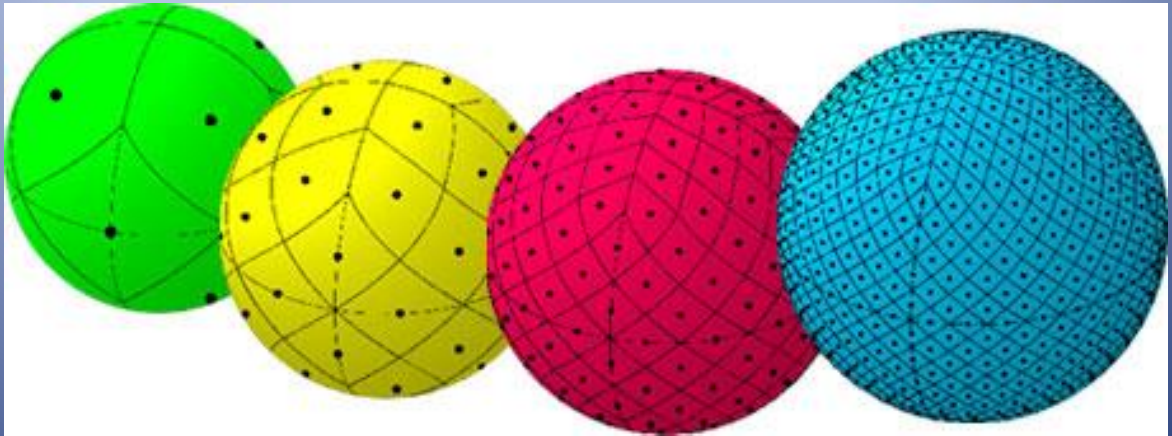
- Large angular scales :
  - The quadrupole component is somewhat low (confirmed in WMAP 3-yrs data)
  - There is some degree of alignment of the lowest multipoles
  - There is an evident galactic north-south anomaly in the CMB map of WMAP: the distribution is smoother in the north than in the south (see e.g. Eriksen 2004, Hansen 2004, Hansen 2006 …)
  - There is evidence for localized non gaussian spots in the maps (see e.g. Vielva 2004, Cruz 2006 ...) ➡
  - There is evidence for threshold-independent ellipticity of the cold and hot spots in WMAP and BOOMERanG data (see Gurzadyan et al. 2003,2004,2005)
- We should not forget that the full-sky CMB map from WMAP is the result of a components separation process
- All this seems enough to call for an independent measurement of CMB anisotropy at large angular scales, with wider frequency coverage to better monitor the foregrounds, and with the highest possible sensitivity to make it easier to detect instrumental systematics.
- The **Planck** mission will assess all these issues.

Data Analysys: HEALPix

- HEALPix - Hierarchical Equal Area isoLatitude Pixelization

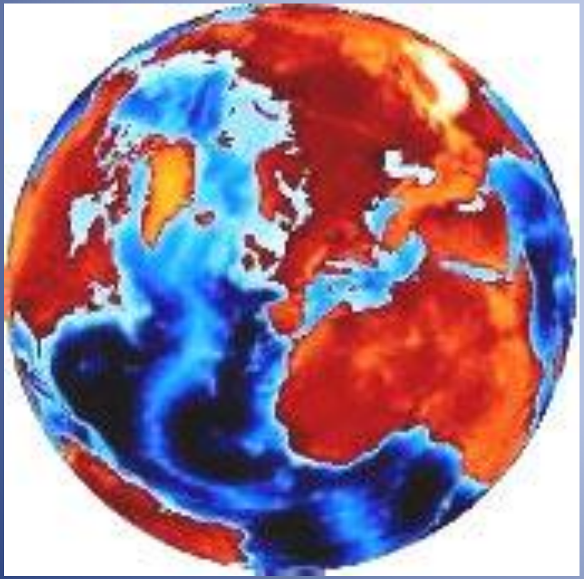
- Subdivision of a sphere at progressively higher resolutions. Green sphere represents the lowest resolution possible with HEALPix base partitioning of the sphere into 12 equal sized pixels.
- The yellow sphere - 48 pixels, the red sphere - 192 pixels, the blue sphere - 768 pixels (~7.3 degree resolution).

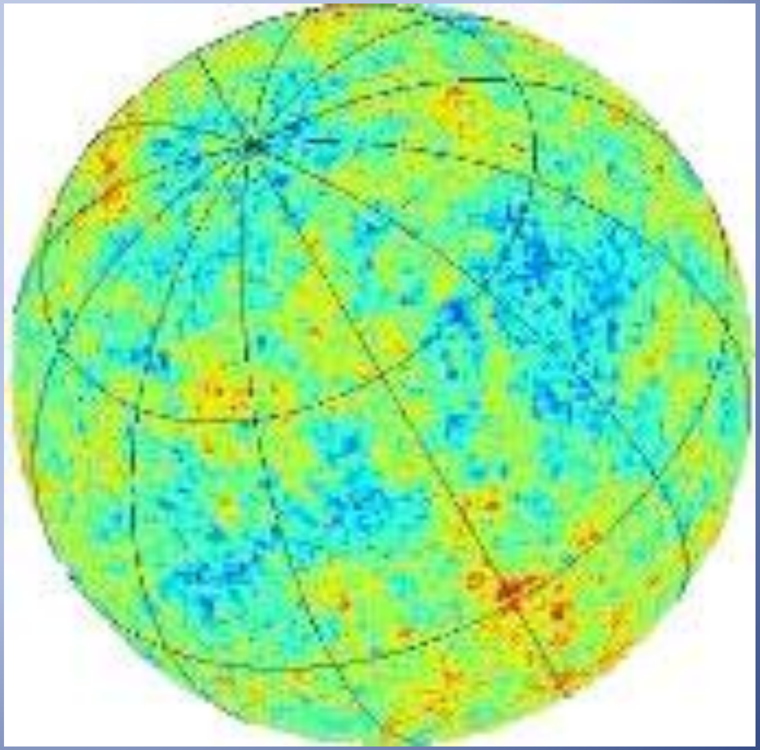
  HEALPix grid of pixel centers occurs on a discrete number of rings of constant latitude, their number depending on the resolution of the HEALPix grid. For the green, yellow, red, and blue spheres shown, there are 3, 7, 15, and 31 constant-latitude rings, respectively.



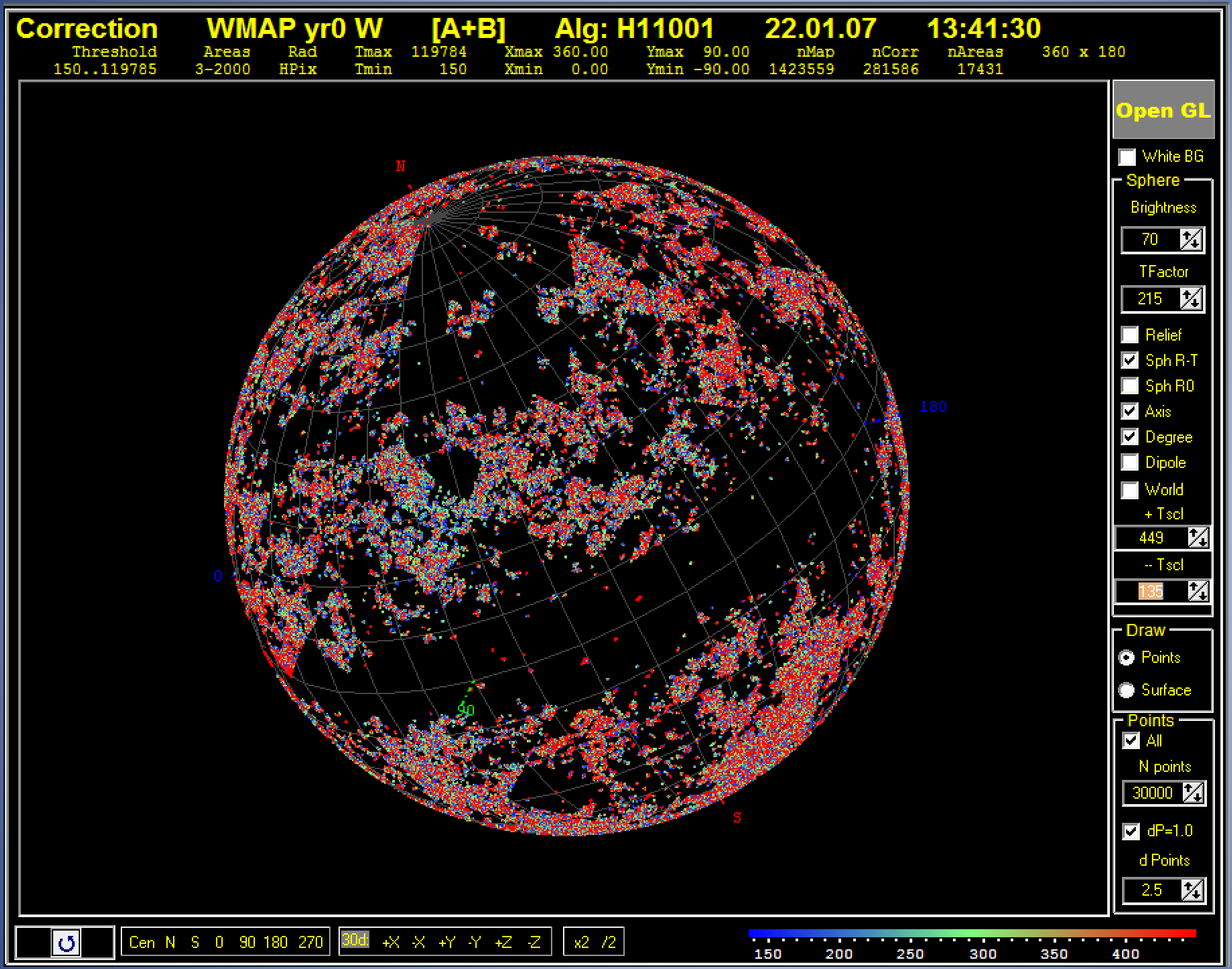
Two high-resolution HEALPix applications.

Earth's topography map is composed of 3,145,728 pixels (~7 arcmin resolution).
Cosmic Microwave Background temperature anisotropy map, is composed of 12,582,912 pixels (~3.4 arcmin resolution).

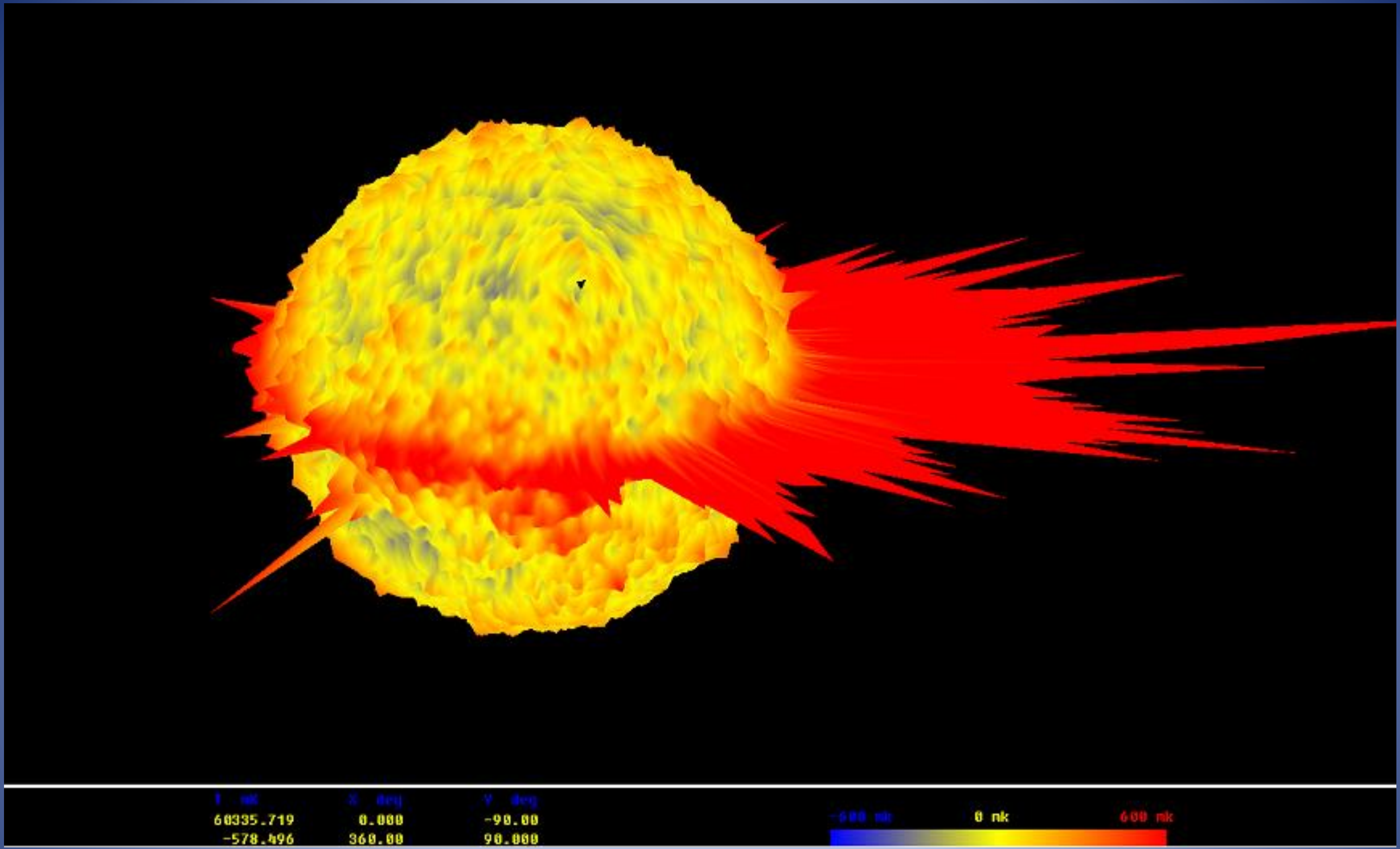




Algorithms and maps

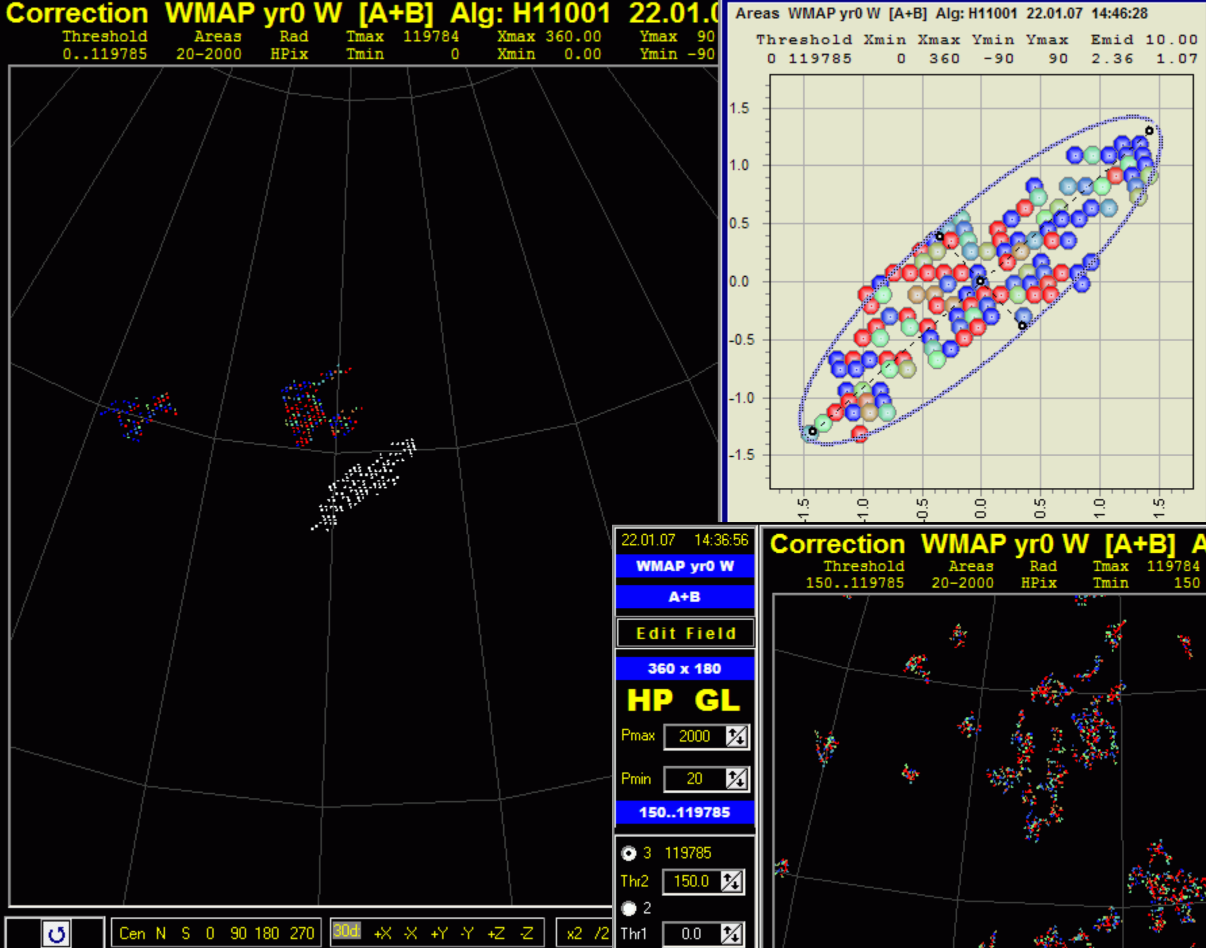


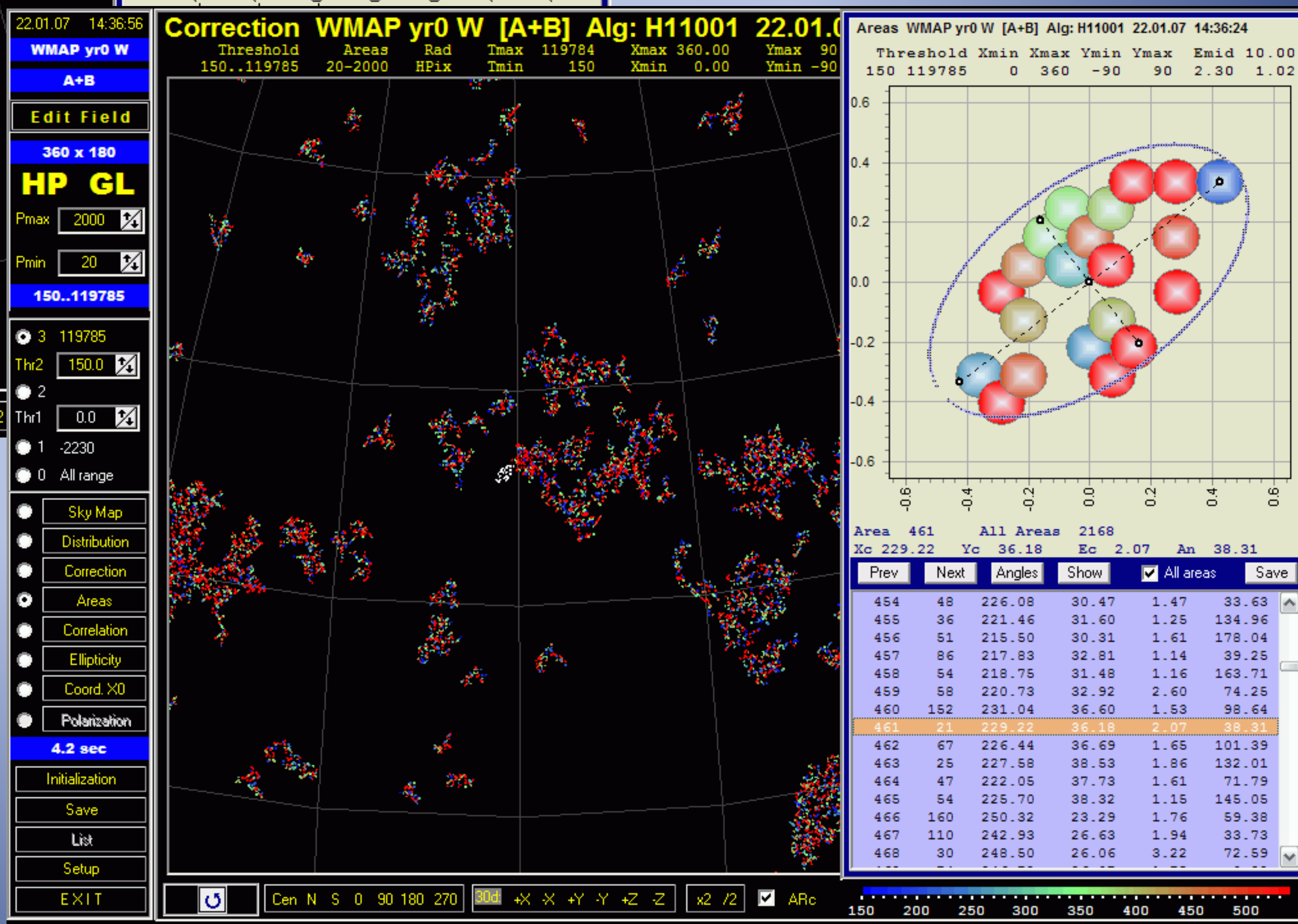
Cut-off WMAP CMB map created by our Software c

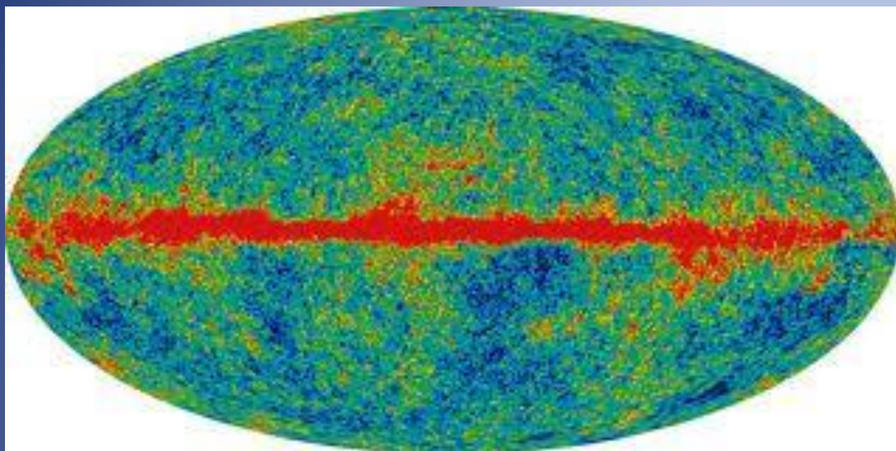


CMB 3D map with Galactic disk.

Excursion sets







WMAP CMB map, 94 GHz

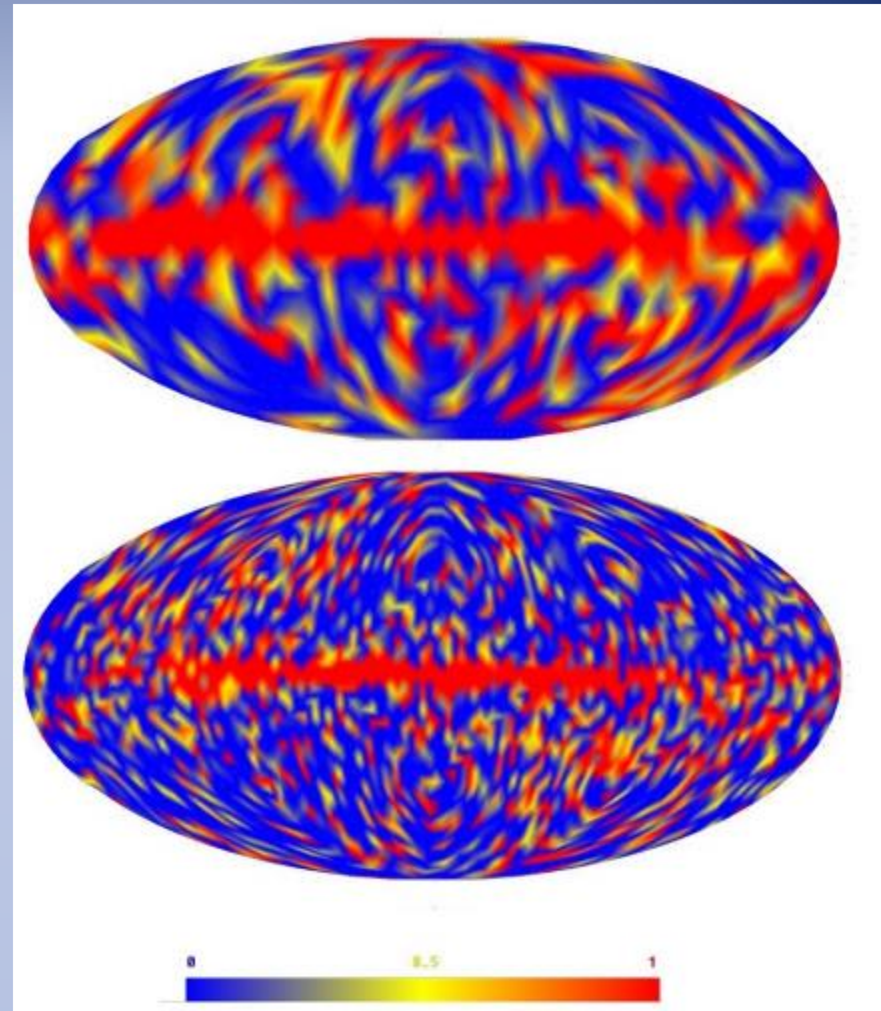


Fig. 1. Kolmogorov maps i.e. the degree of randomness in CMB sky. WMAP's 5-year W-band, 94 GHz data are used; upper map is for Nside=8, the lower for Nside=16. The Galactic disk is clearly distinguished.

From Gurzadyan et al 2009

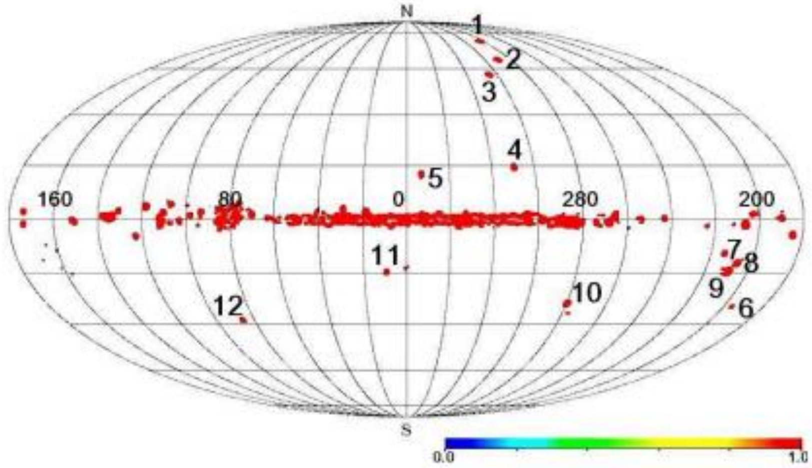


Fig. 1: The location of the 12 high Φ regions in the sky, i.e. those outside the Galactic disk with $|b| > 10°$.

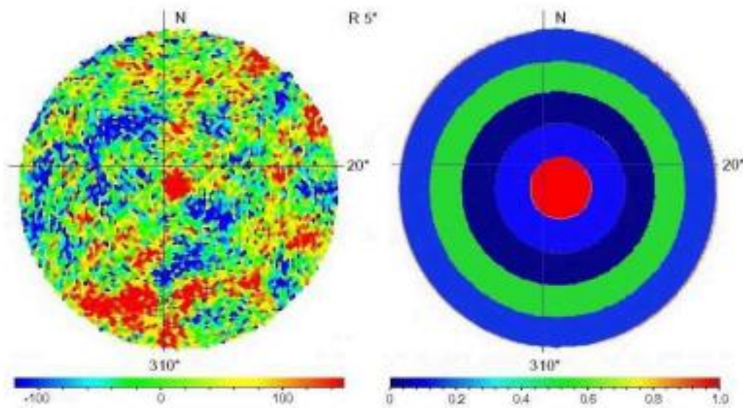
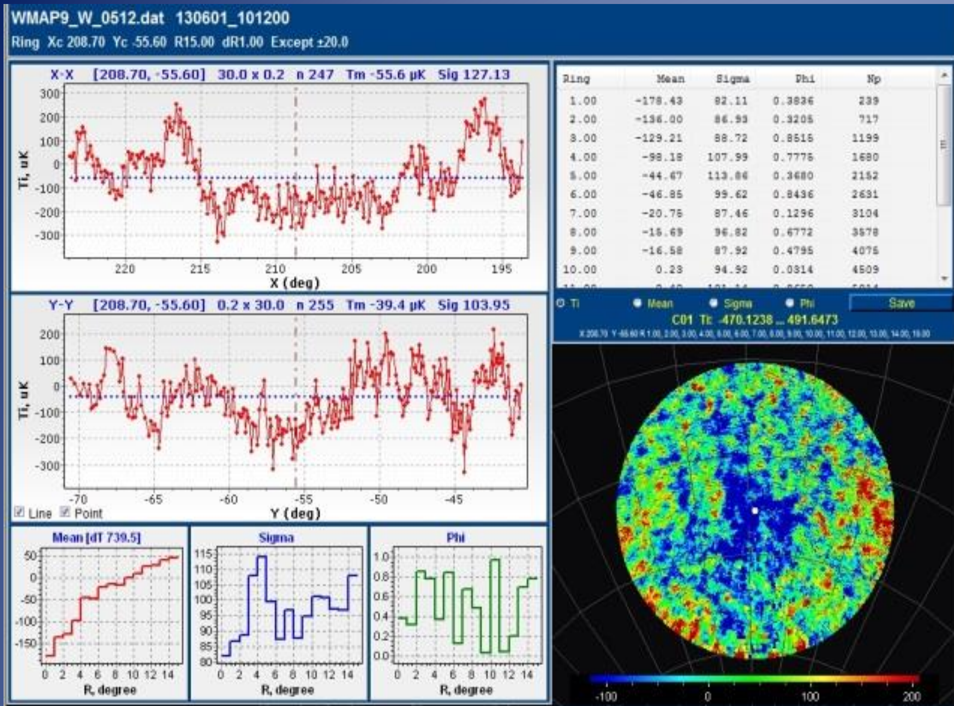


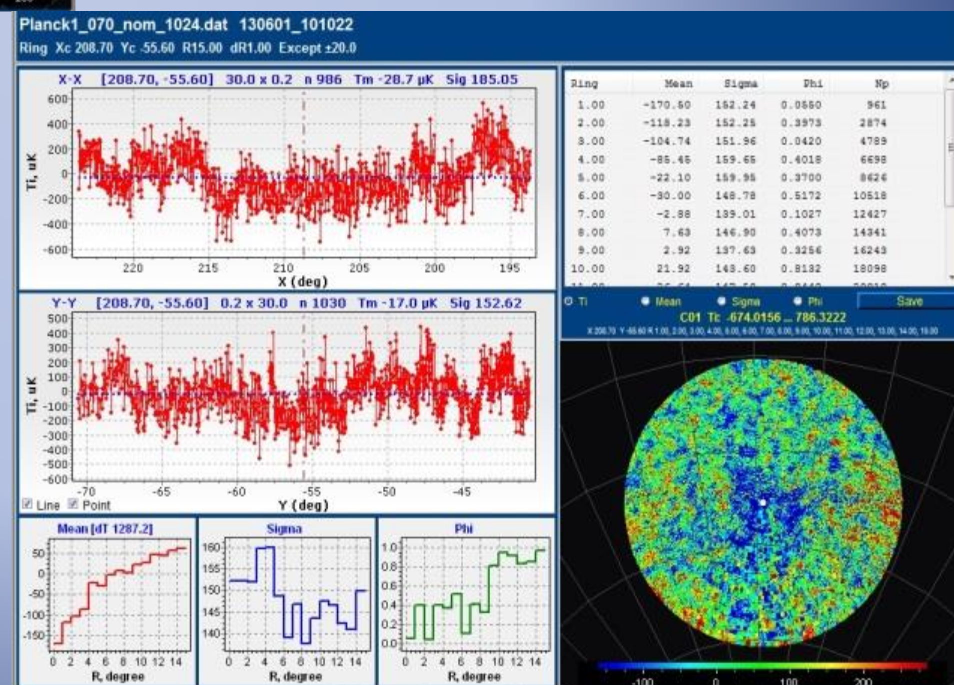
Fig. 2: The CMB temperature map region of 5° radius centered on No.04 (a), and its Φ distribution (b).

Detection of previously unknown point sources (active galaxies, quasars).



WMAP, 94 GHz

COLD SPOT



PLANCK, 70 GHz

PLANCK'S LESSONS

Concordance model survives, however values of some cosmological parameters (dark sector ratios, Hubble constant) are modified.

Challenges - alignments, non-Gaussianities - remain.

Dark energy & dark matter nature remains unknown.