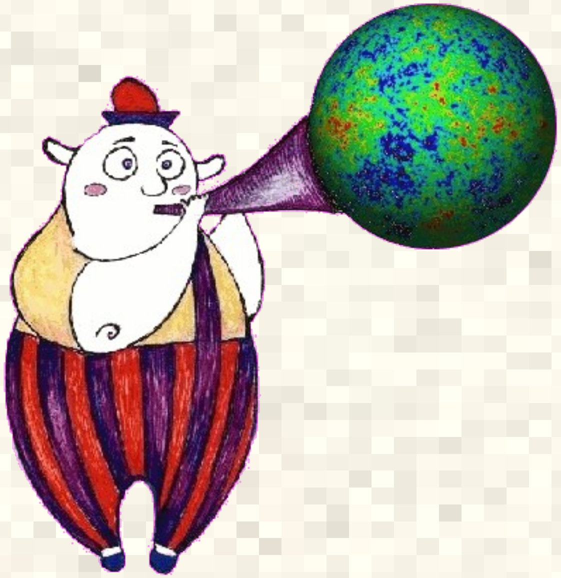
Lecture 2.

Cosmic microwave background

observations and data processing

Oleg Verkhodanov

Special astrophysical observatory, Russia



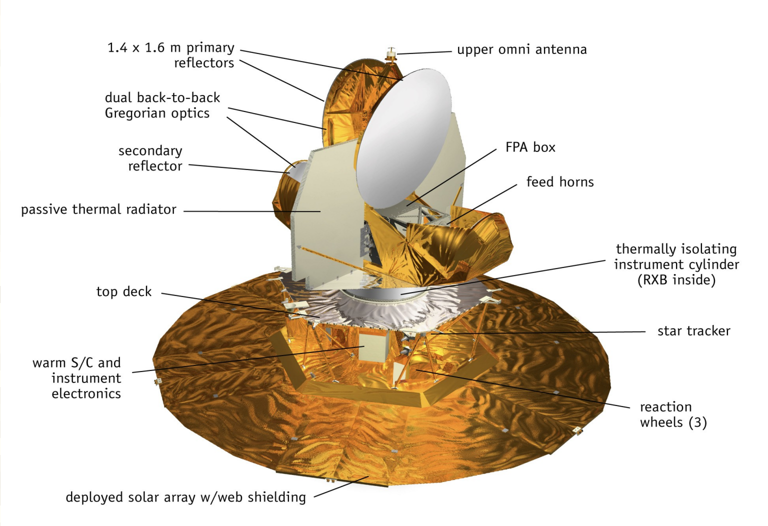
Cosmological tests

- ***Cosmic microwave background***
  а) Angular power spectrum
  б) Statistical properties (gaussianity)

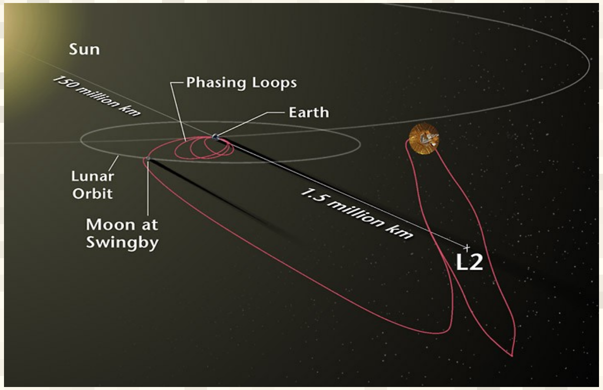
cosmological tests

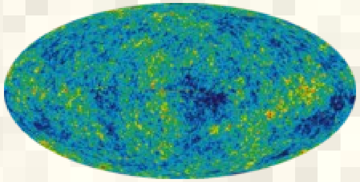
To solve problems, cosmic missions had launched and probably they are not the last

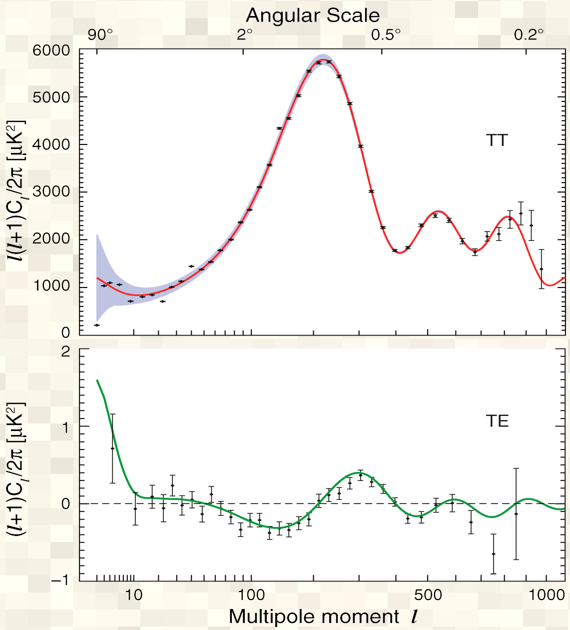
Wilkinson Microwave Anisotropy Probe (WMAP, NASA)



2001-2011



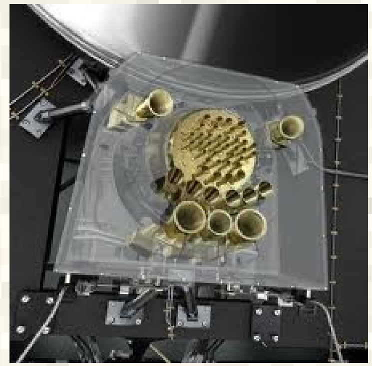


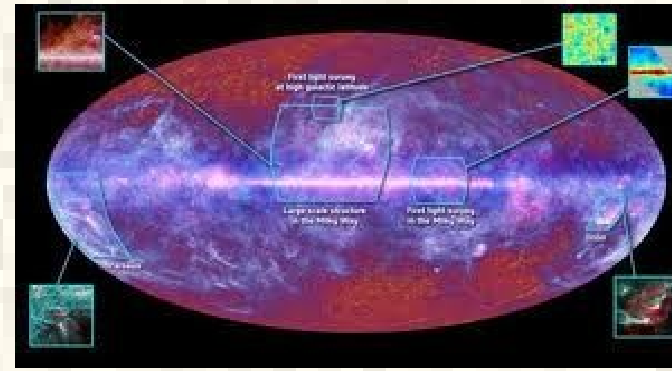


5 frequencies:
23, 33, 41, 61, 94 GHz

Best determination of
cosmological parameters till 2011 !

Planck mission, ESA

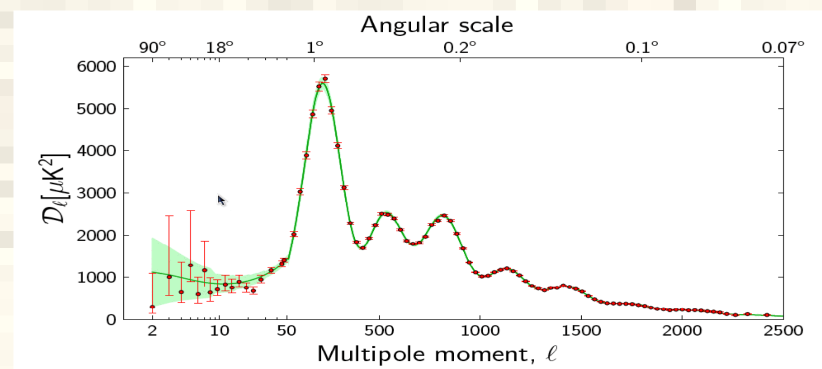




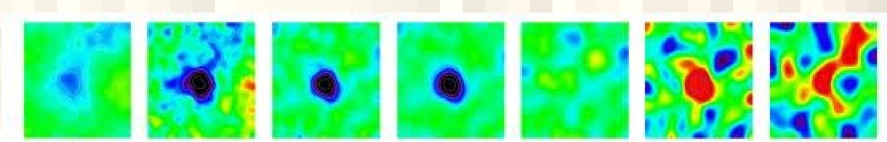
Low Frequency Instrument: 30,44,70
HFI: 100, 143, 217, 353, 545, 857 GHz

2010-2013

1)



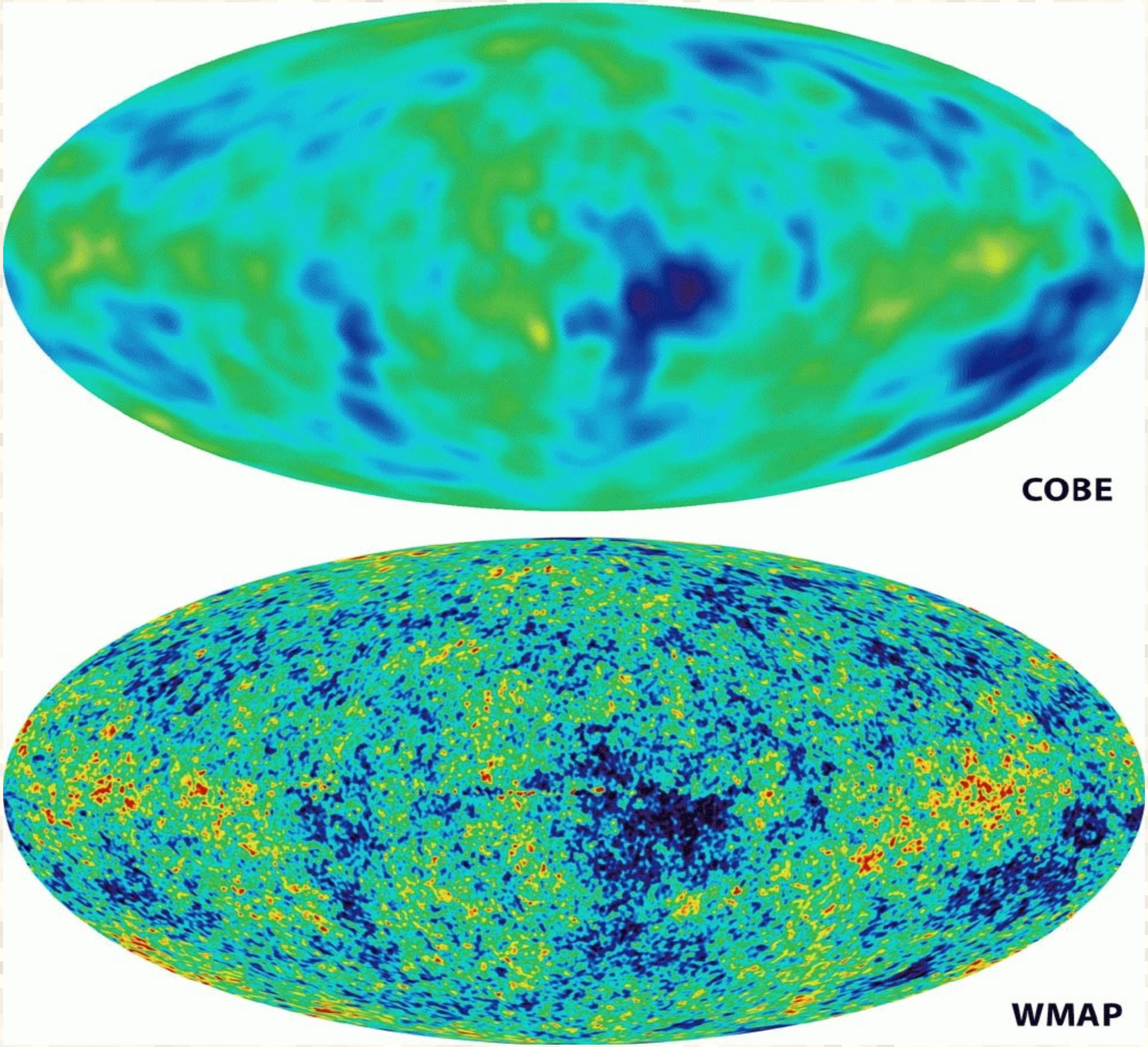
2) Zeldovich-Sunyaev effect



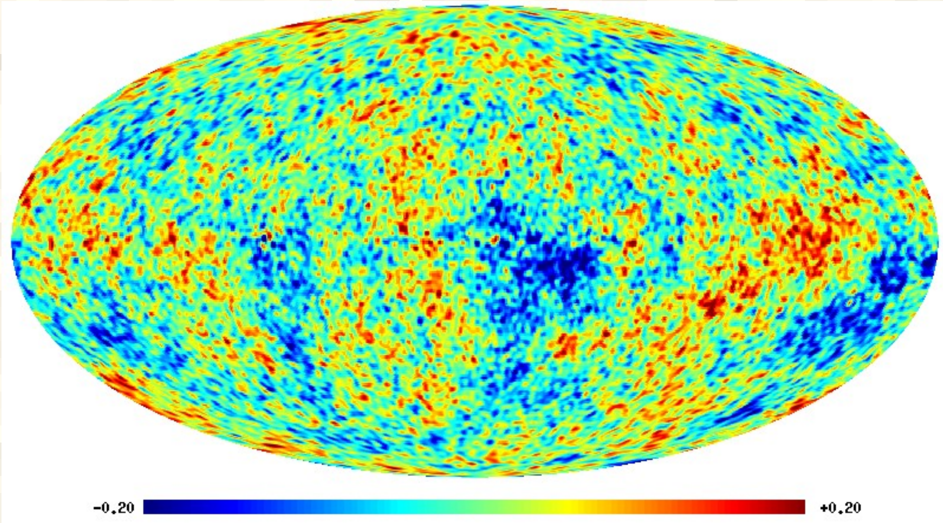
3) Gravitational waves in the B-mode of polarization ?

What do we analyze ?

Maps

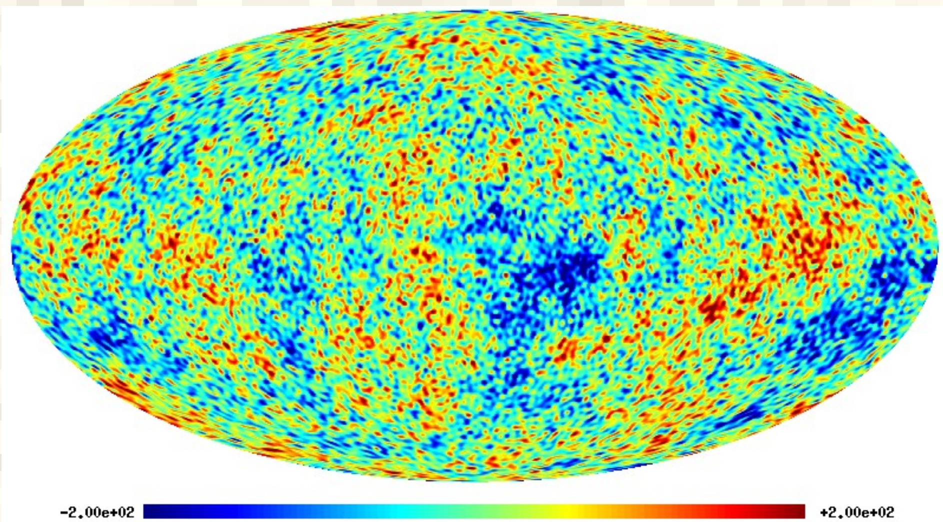


And more maps

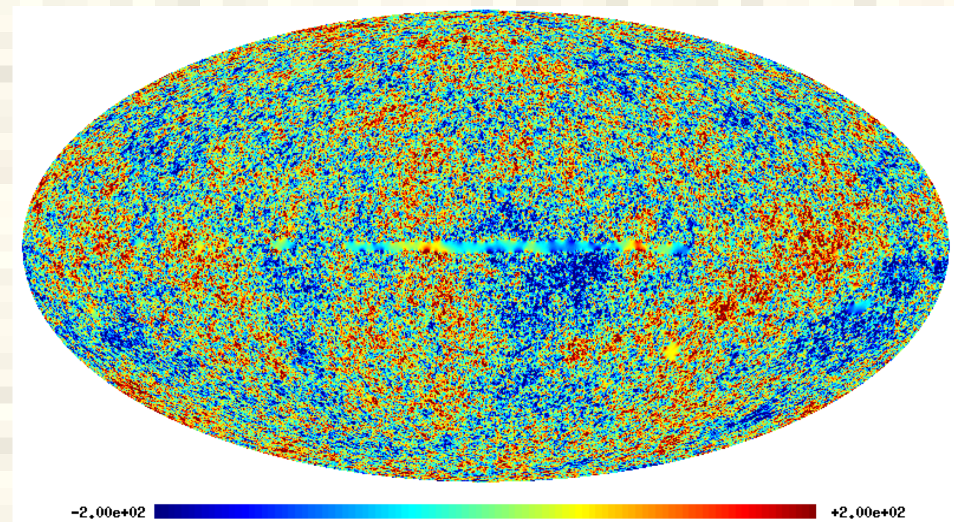


WMAP 9, Lmax=100
(Hinshaw et al., 2012)

Planck collaboration, 2013



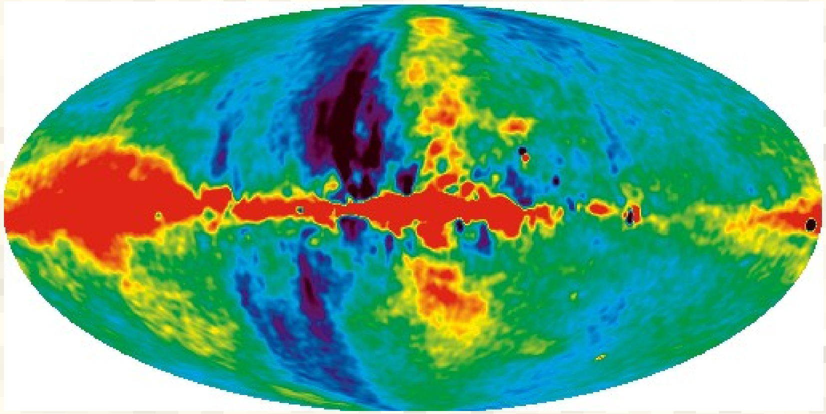
Planck, Lmax=100

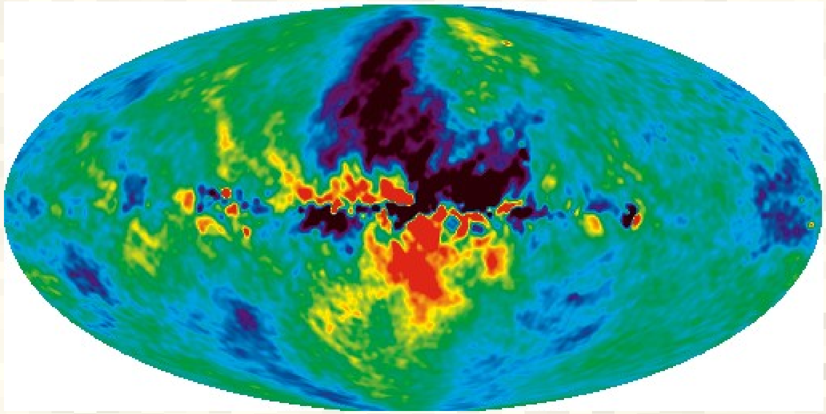


SMICA,
Lmax = 2500

And polarization WMAP maps too

K-band (23 GHz)

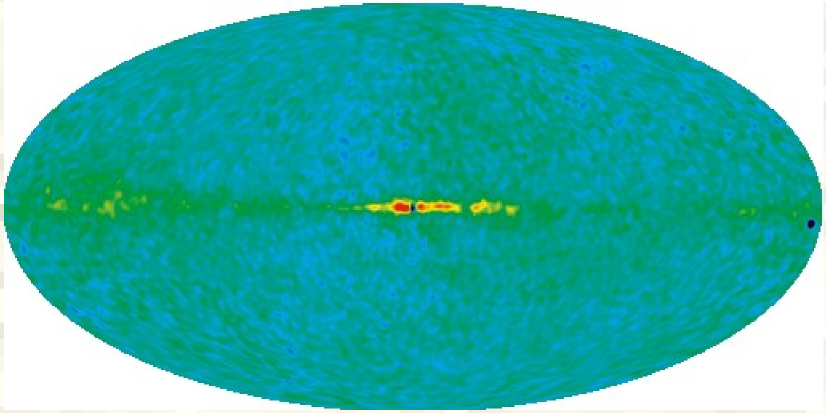


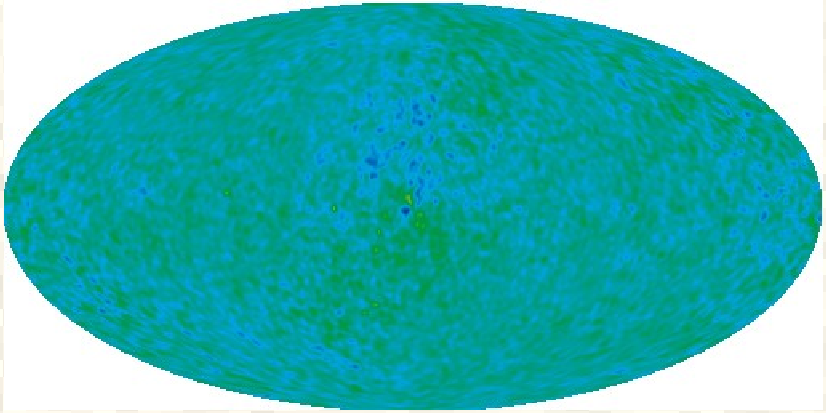


Q

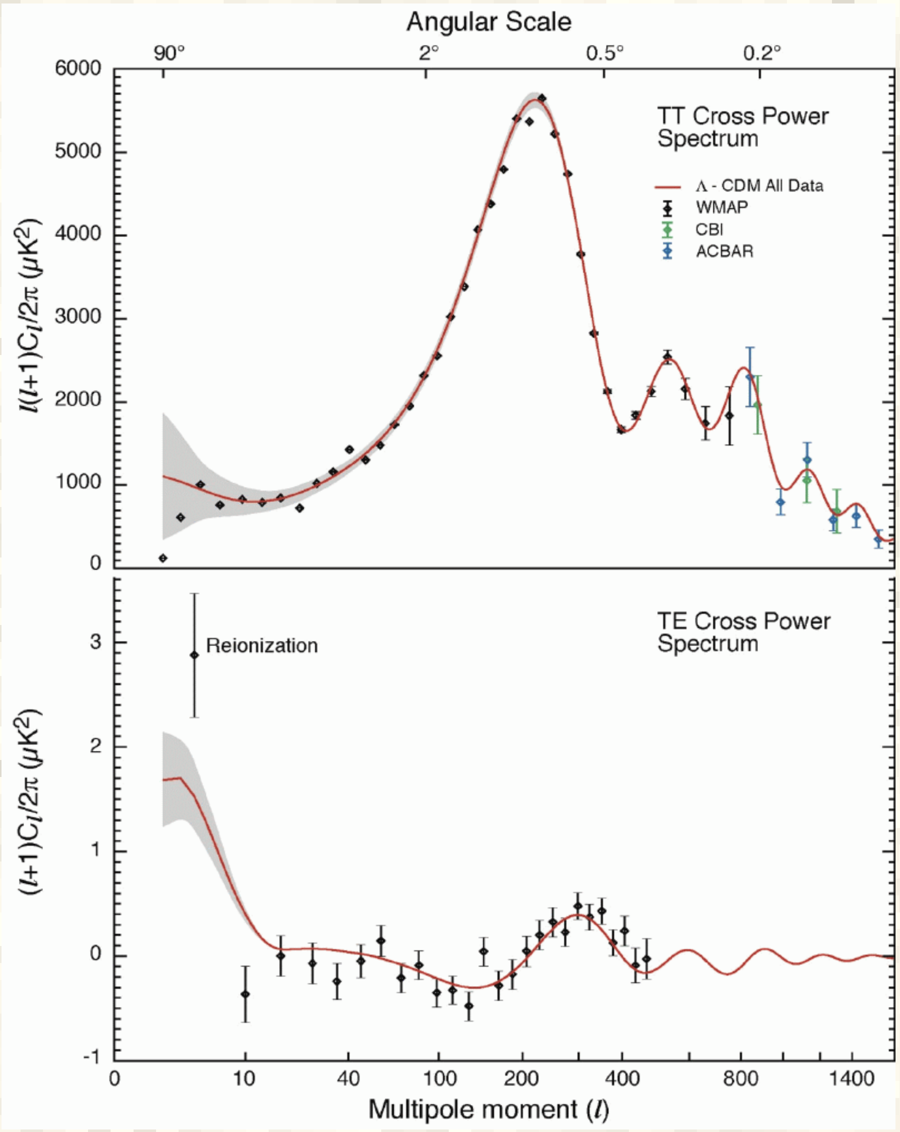
U

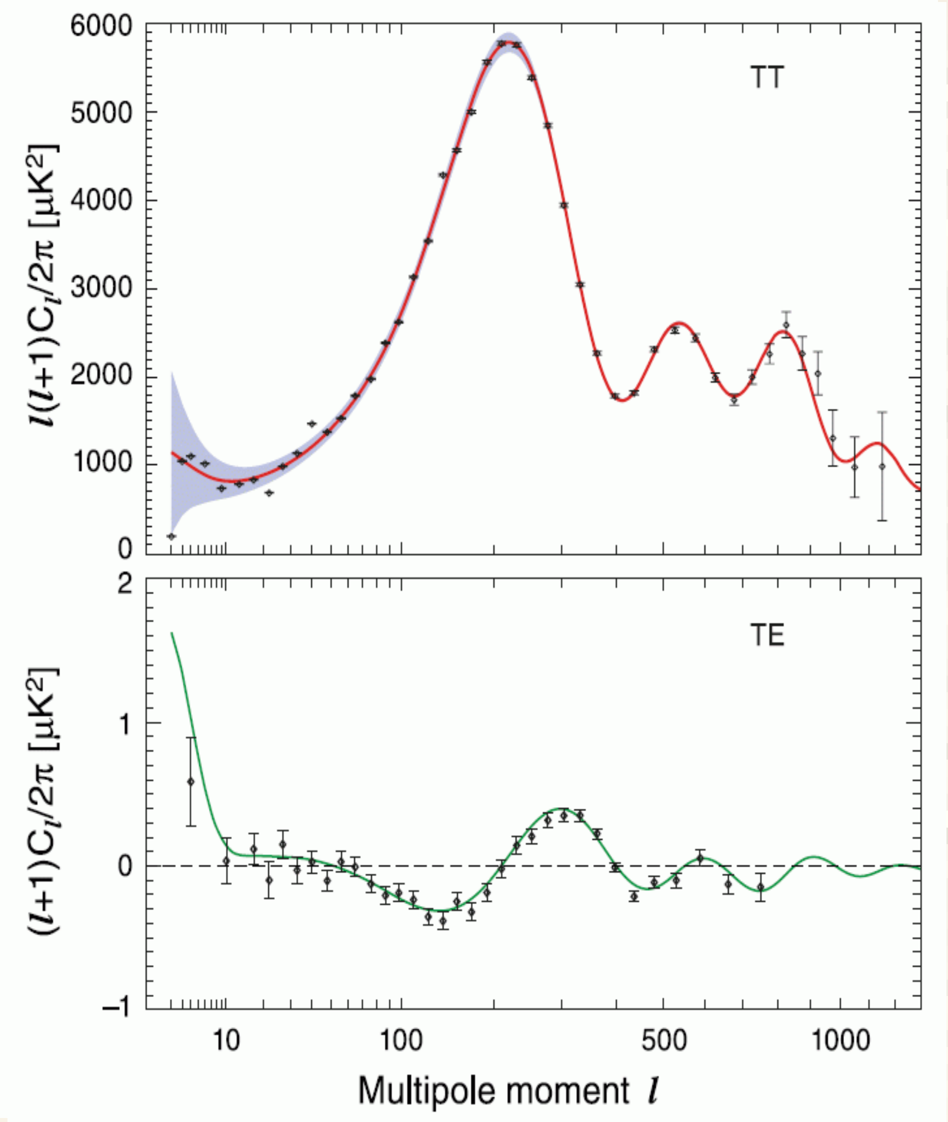
V-band (61 GHz):





Angular power spectrum of CMB

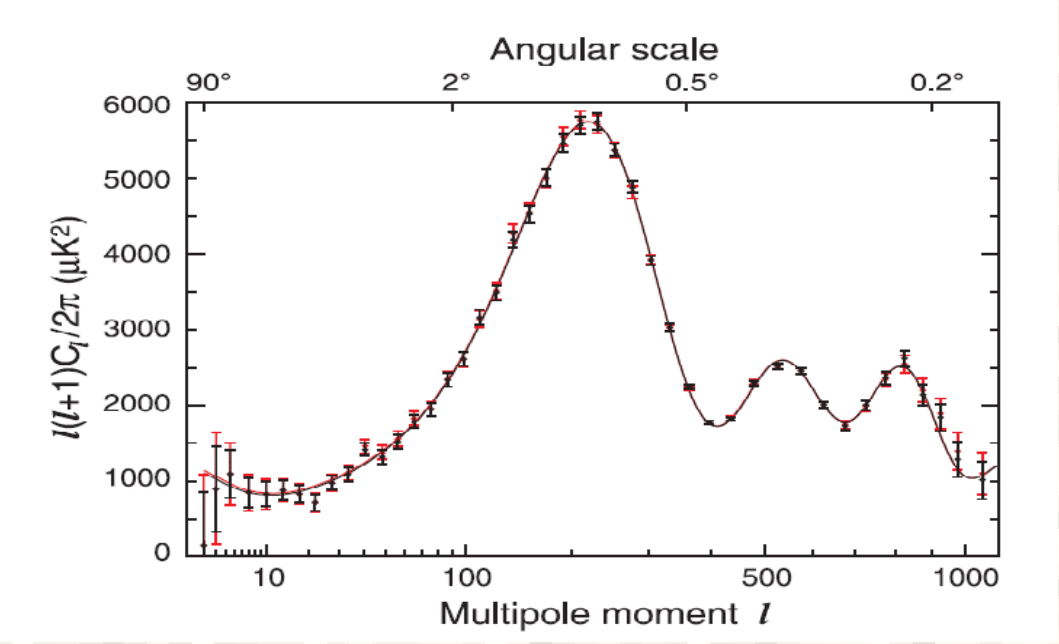




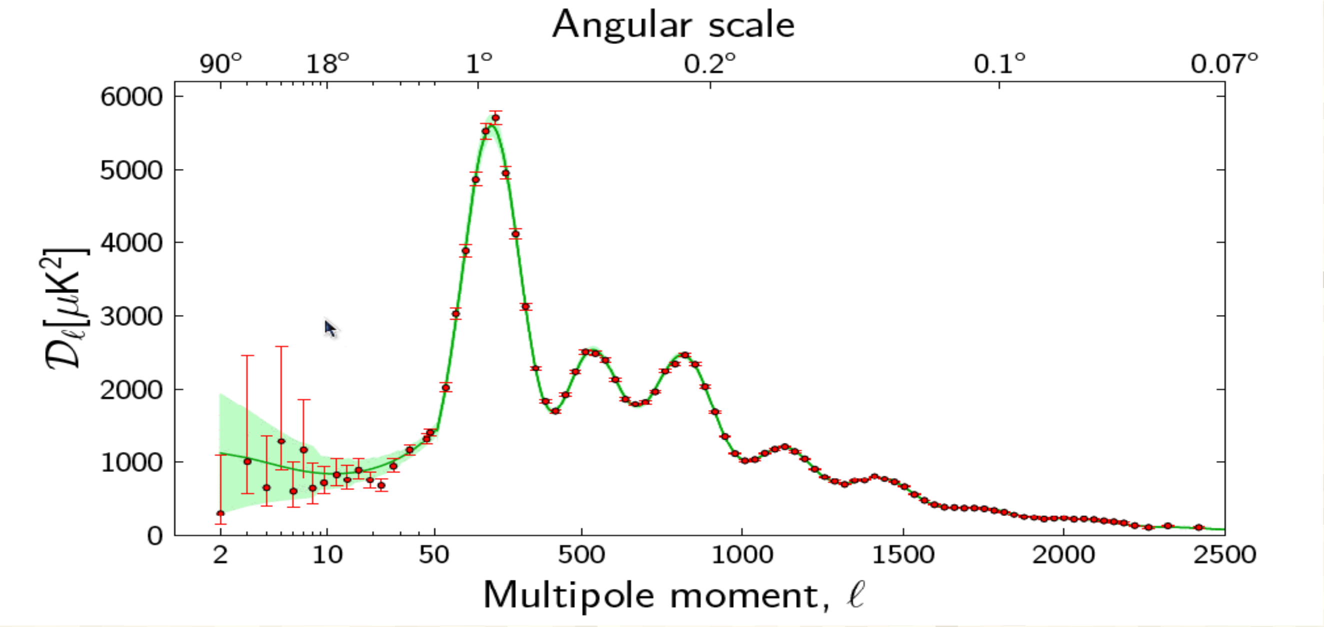
1st year

7 years

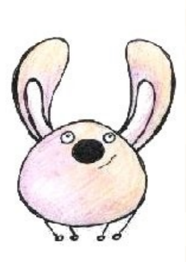
And more spectra



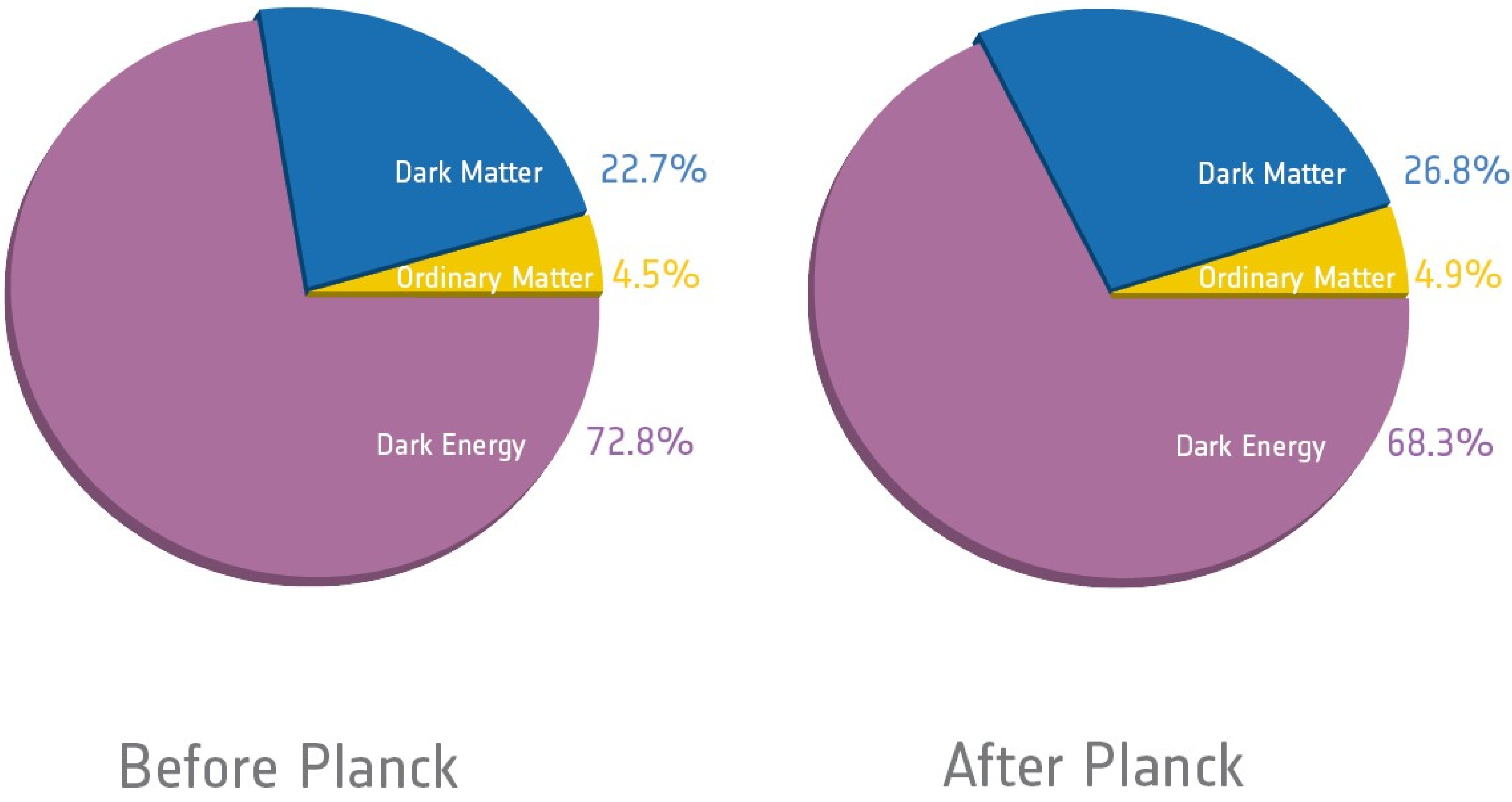
WMAP 9, 2012



Planck 2013

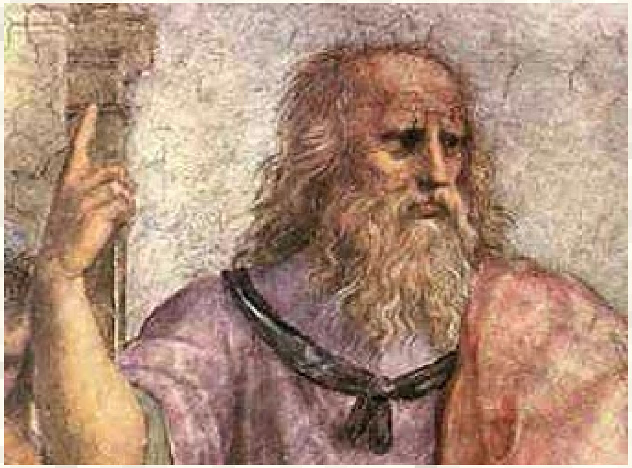


Description	Symbol	*WMAP*-only	*WMAP*+BAO+H_0
Parameters for Standard ΛCDM Model [a]			
Age of universe	t_0	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr
Hubble constant	H_0	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
Baryon density	Ω_b	0.0449 ± 0.0028	0.0456 ± 0.0016
Physical baryon density	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$	0.02260 ± 0.00053
Dark matter density	Ω_c	0.222 ± 0.026	0.227 ± 0.014
Physical dark matter density	$\Omega_c h^2$	0.1109 ± 0.0056	0.1123 ± 0.0035
Dark energy density	Ω_Λ	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
Curvature fluctuation amplitude, $k_0 = 0.002$ Mpc^{-1} [b]	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.801 ± 0.030	0.809 ± 0.024
Scalar spectral index	n_s	0.963 ± 0.014	0.963 ± 0.012
Redshift of matter-radiation equality	$z_{\rm eq}$	3196^{+134}_{-133}	3232 ± 87
Angular diameter distance to matter-radiation eq. [c]	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc	14238^{+128}_{-129} Mpc
Redshift of decoupling	z_*	$1090.79^{+0.94}_{-0.92}$	$1090.89^{+0.68}_{-0.69}$
Age at decoupling	t_*	379164^{+5187}_{-5243} yr	377730^{+3205}_{-3200} yr
Angular diameter distance to decoupling [c,d]	$d_A(z_*)$	14116^{+160}_{-163} Mpc	14073^{+129}_{-130} Mpc
Sound horizon at decoupling [d]	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc	146.2 ± 1.1 Mpc
Acoustic scale at decoupling [d]	$l_A(z_*)$	302.44 ± 0.80	302.40 ± 0.73
Reionization optical depth	τ	0.088 ± 0.015	0.087 ± 0.014
Redshift of reionization	$z_{\rm reion}$	10.5 ± 1.2	10.4 ± 1.2
Parameters for Extended Models [e]			
Total density [f]	$\Omega_{\rm tot}$	$1.080^{+0.093}_{-0.071}$	$1.0023^{+0.0056}_{-0.0054}$
Equation of state [g]	w	$-1.12^{+0.42}_{-0.43}$	-0.980 $\pm$ 0.053
Tensor to scalar ratio, $k_0 = 0.002$ Mpc^{-1} [b,h]	r	< 0.36 (95% CL)	< 0.24 (95% CL)
Running of spectral index, $k_0 = 0.002$ Mpc^{-1} [b,i]	$dn_s/d\ln k$	-0.034 ± 0.026	-0.022 ± 0.020
Neutrino density [j]	$\Omega_\nu h^2$	< 0.014 (95% CL)	< 0.0062 (95% CL)
Neutrino mass [j]	$\sum m_\nu$	< 1.3 eV (95% CL)	< 0.58 eV (95% CL)
Number of light neutrino families [k]	$N_{\rm eff}$	> 2.7 (95% CL)	$4.34^{+0.86}_{-0.88}$

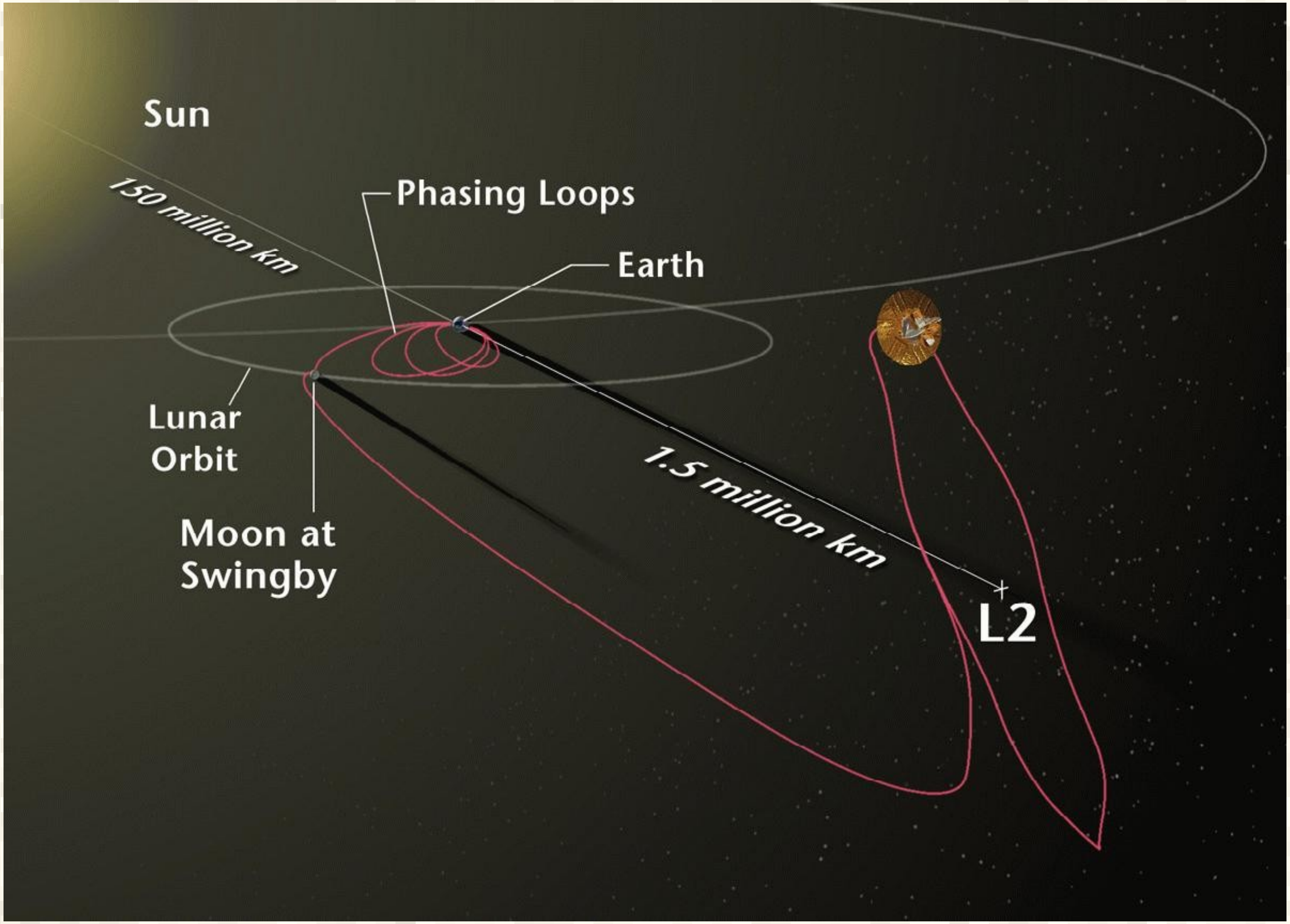

Dark Matter
22.7%
Ordinary Matter
4.5%
Dark Energy
72.8%
Before Planck
Dark Matter
26.8%
Ordinary Matter
4.9%
Dark Energy
68.3%
After Planck

How to investigate ?

1) Theory
2) Observations
3) Simulation



How to observe ?


Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2

Data analysis of CMB

- Registration: time odered data: T(t)=T(l,b)
- Pixelization: map-making and restoration data in pixels
- Component separation
- Multipole analysis
- Pixel statistics of the CMB map
- Angular power spectrum analysis and determination of cosmological parameters

Map-making procedure

$$\mathbf{d} = P\mathbf{m} + \mathbf{n}$$

d is the TOD, m is the map of pixels
P is the pointinx matrix of *(Nd, Np)* elements

To estimate **m**, the GLS method is used

$$\chi^2 = \mathbf{n}^{\mathrm{T}} V \mathbf{n} = (\mathbf{d}^{\mathrm{T}} - \mathbf{m}^{\mathrm{T}} P^{\mathrm{T}})\, V(\mathbf{d} - P\mathbf{m})$$

V minimizes variance of estimation of **m,**
taking noise inverse covariance matrix:

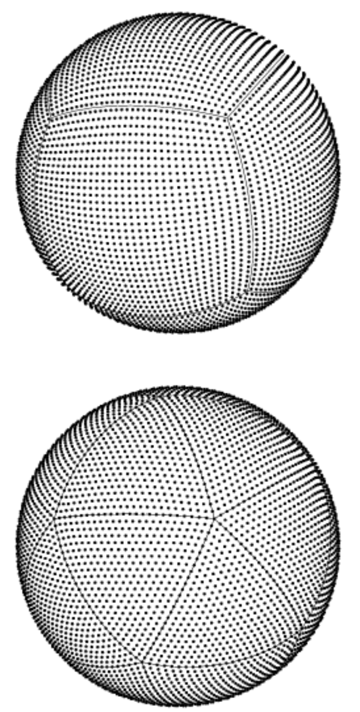
$$V^{-1} = N \equiv \langle \mathbf{n}\mathbf{n}^{\mathrm{T}} \rangle$$

Pixelization

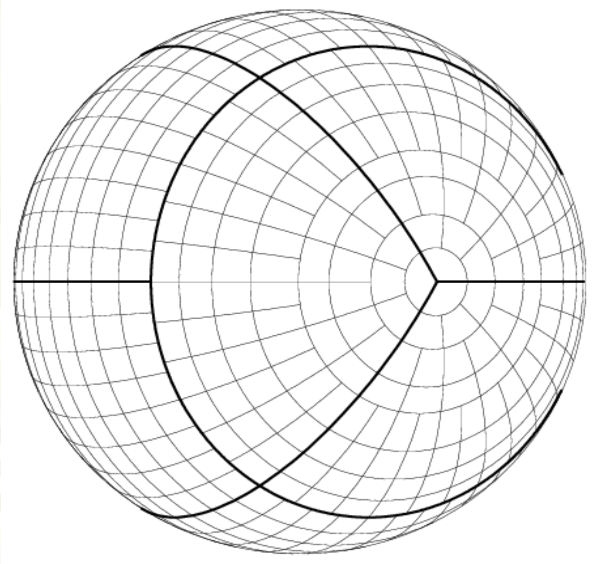
Intergration on a sphere: S.L.Sobolev (1974)

Some pxelization schemes:
1) Icosahedron (Tegmark, 1996)
2) Igloo (Crittenden, Turok, 1998)
3) HEALPix (Gorski et al., 1999)

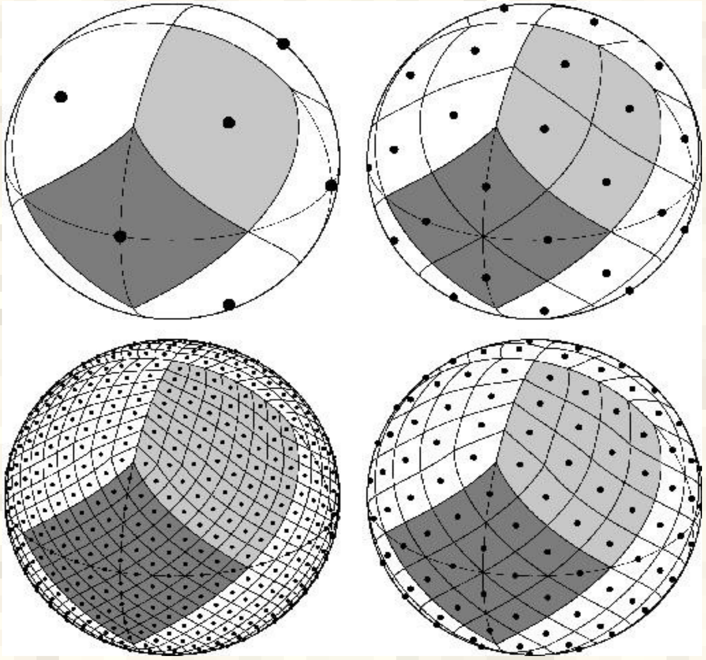
(1)



(2)



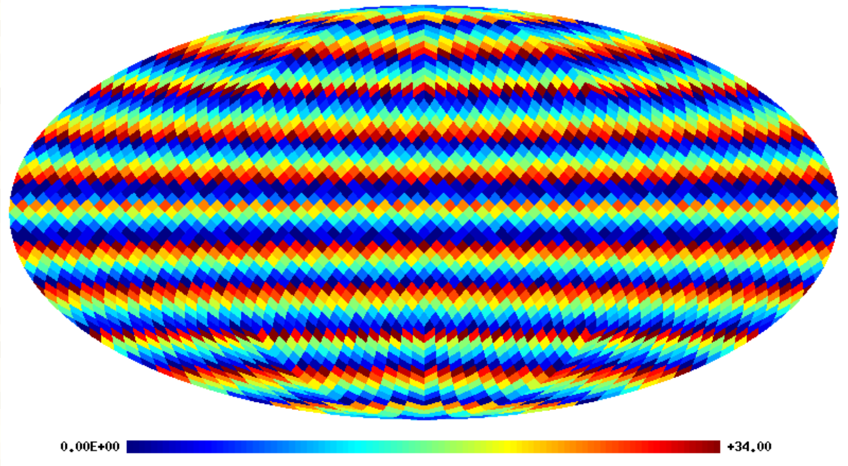
(3)

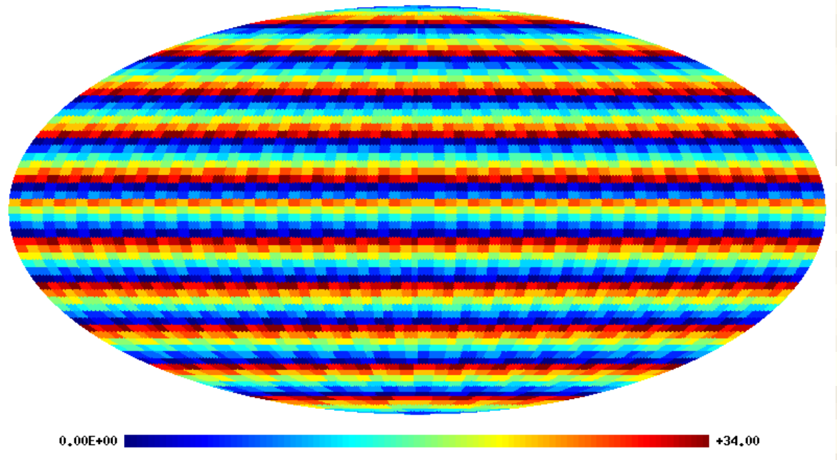


Packages for 2 schemes

HEALPix

GLESP





Hierarchical scheme
pixel calculations
Based on 12*2^n equal pixels

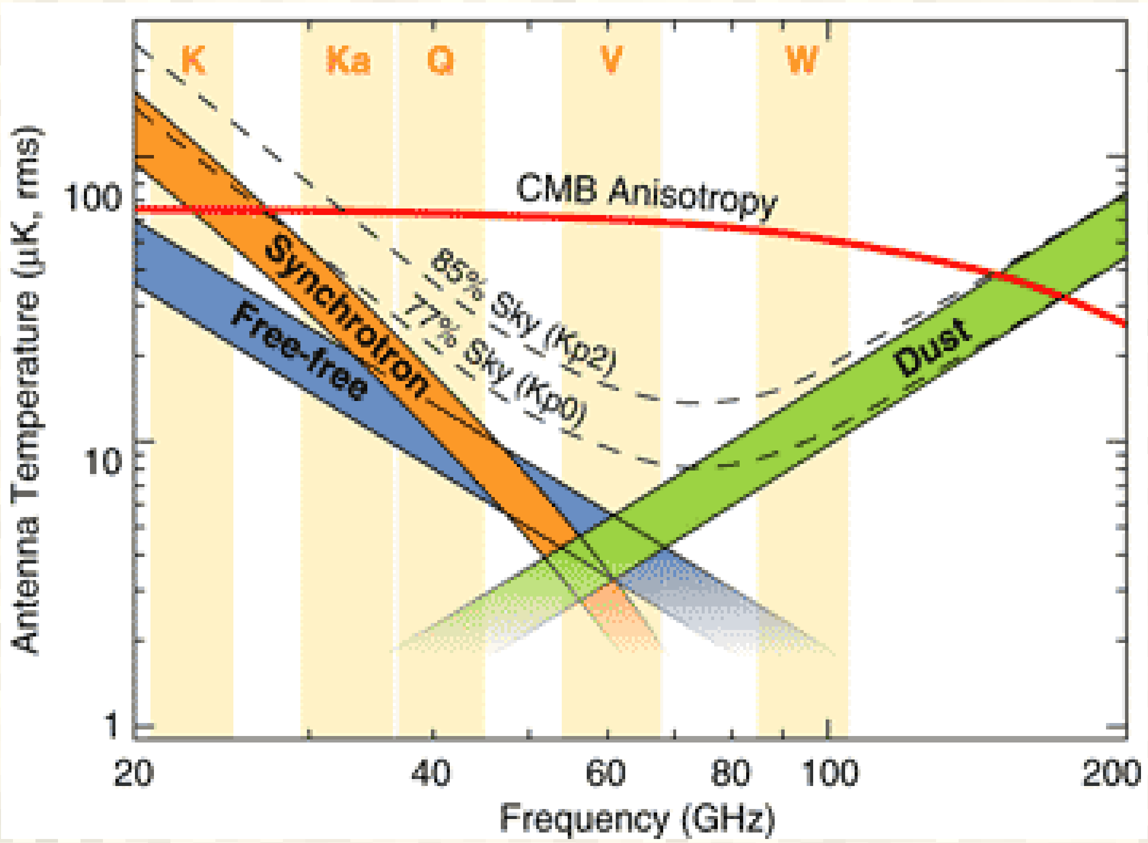
(Gorski et al., 1993, 2005)

Non-hierarchiacl scheme
harmonic calculations
Based on gaussian quadrature

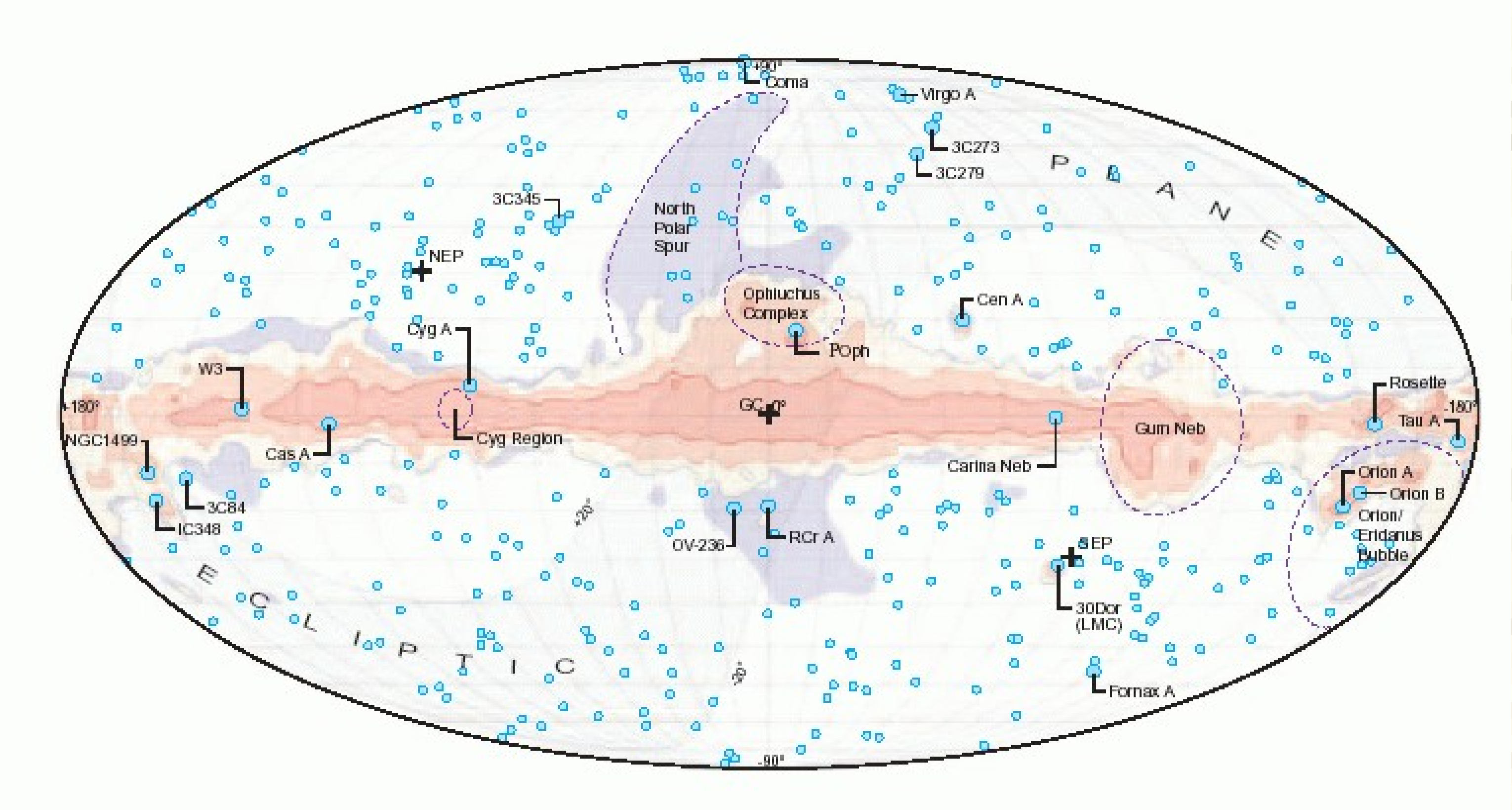
(Doroshkevich et al., 2005)

Component separation

Emission components (WMAP)

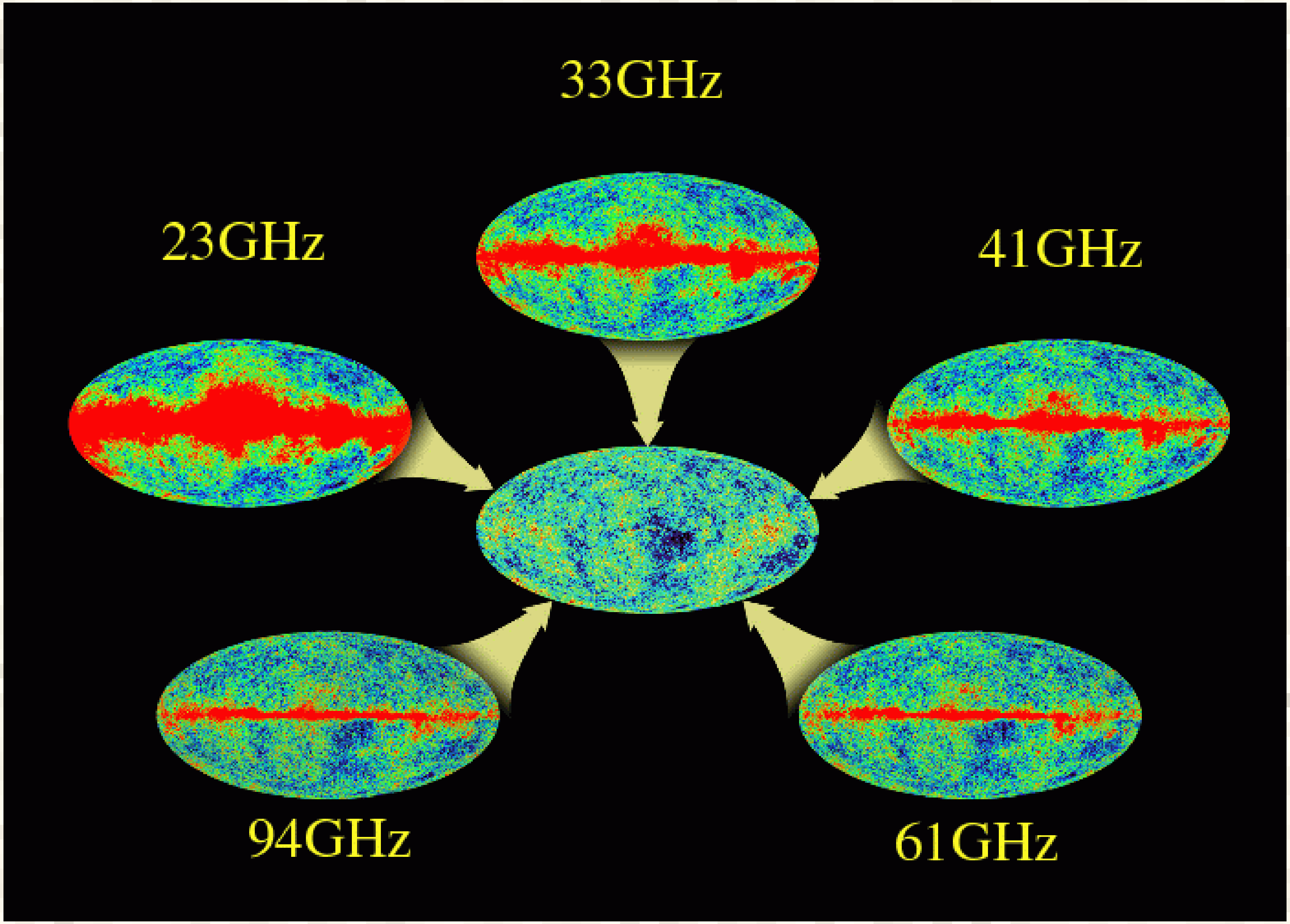


Radio sources



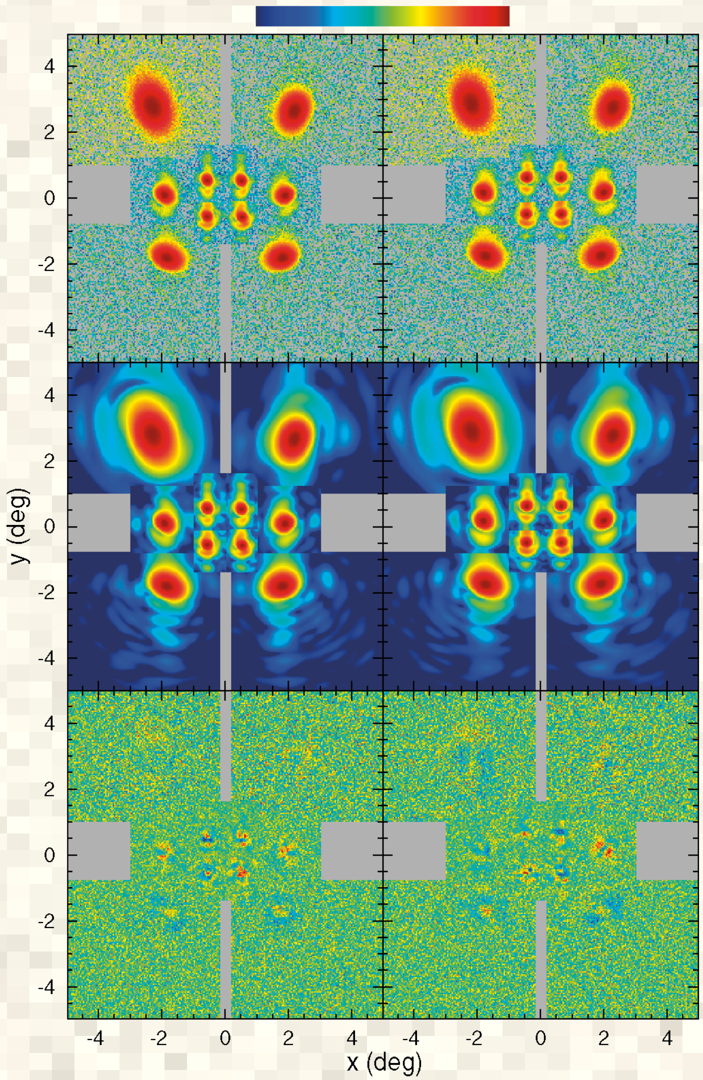
Component separation:

Signal = (**CMB** +Synchrotron+dust+FreeFree+CO+radiosouces)*Beam + Noise



WMAP

WMAP beams



Degrees:
0.88 (K),
0.66 (Ka),
0.51 (Q),
0.35 (V),
0.22 (W)

CMB restoration

Two basic properties of CMB:

1) Black body emission — same temperature at all wavelengthes;

2) Correlation of CMB and foregrounds should be close to zero: because CMB is a random gaussian process

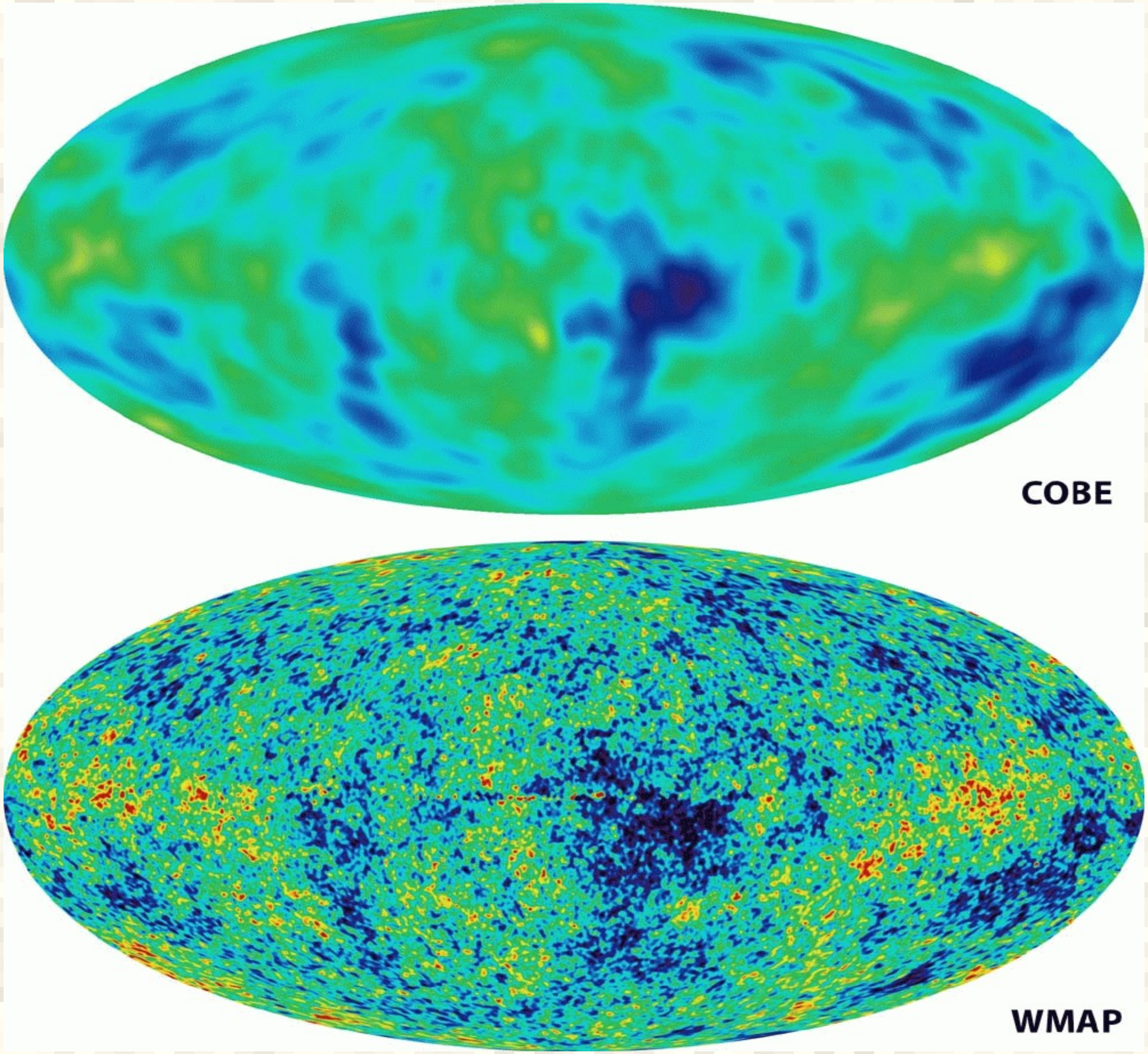
What is the CMB (ILC) map ?

$$\sum_k w_k = 1 \text{ and } Var(c_j) \rightarrow min(w_k).$$

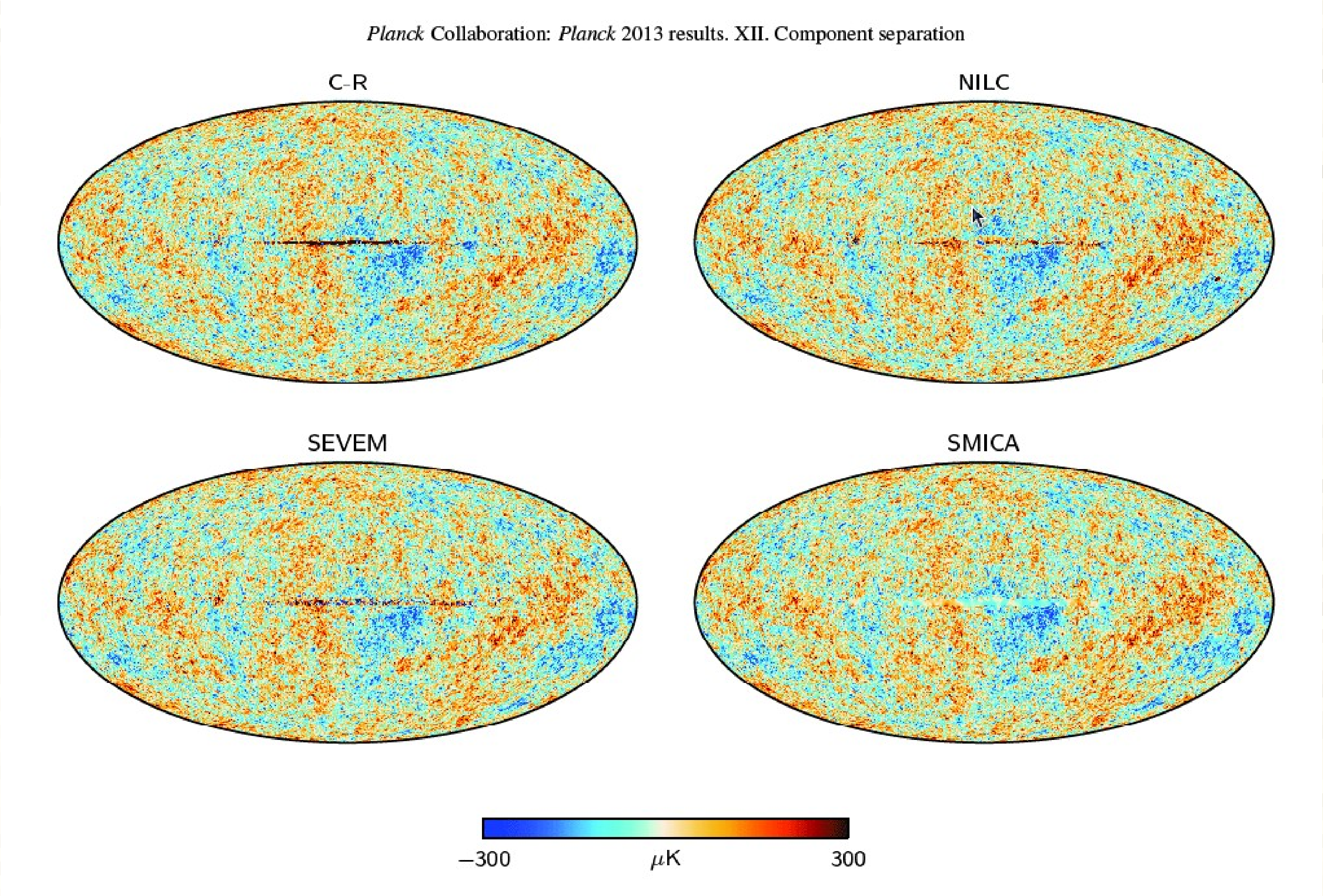
$$c_p = T(\theta_j, \phi_p, \nu_k) - \sum_{i=1}^{J-1} w_p \left(T(\theta_p, \phi_p, \nu_k) - T(\theta_p, \phi_p, \nu_i)\right),$$

$$Var(c_p) = \frac{1}{N_{tot}} \sum_{p \in \Re} \left[c_p - \langle c_p \rangle\right]^2, \qquad \frac{\delta Var(c_p)}{\delta w_j} = 0$$

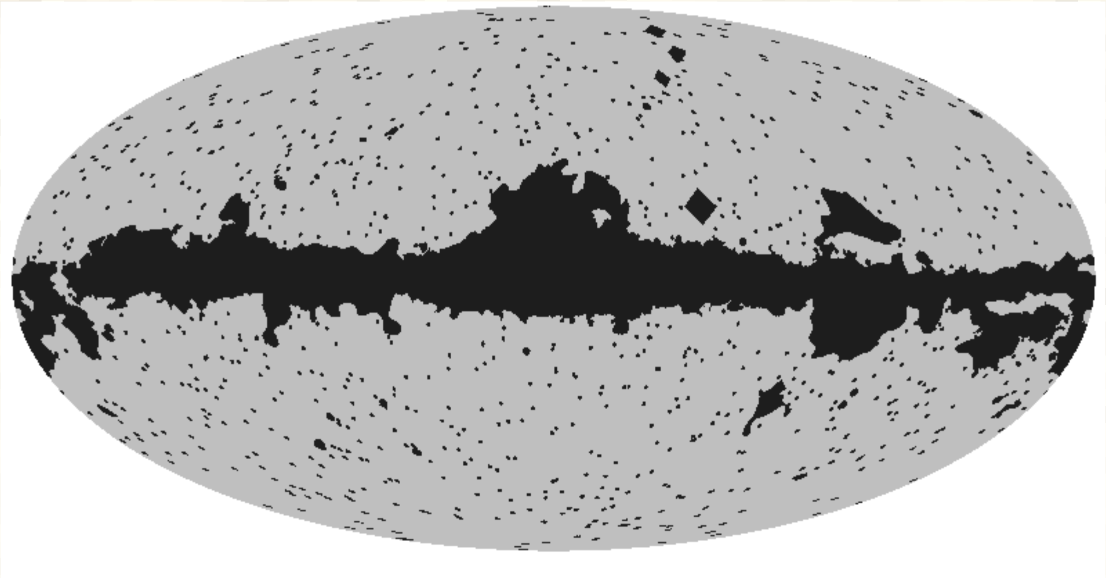
NASA maps

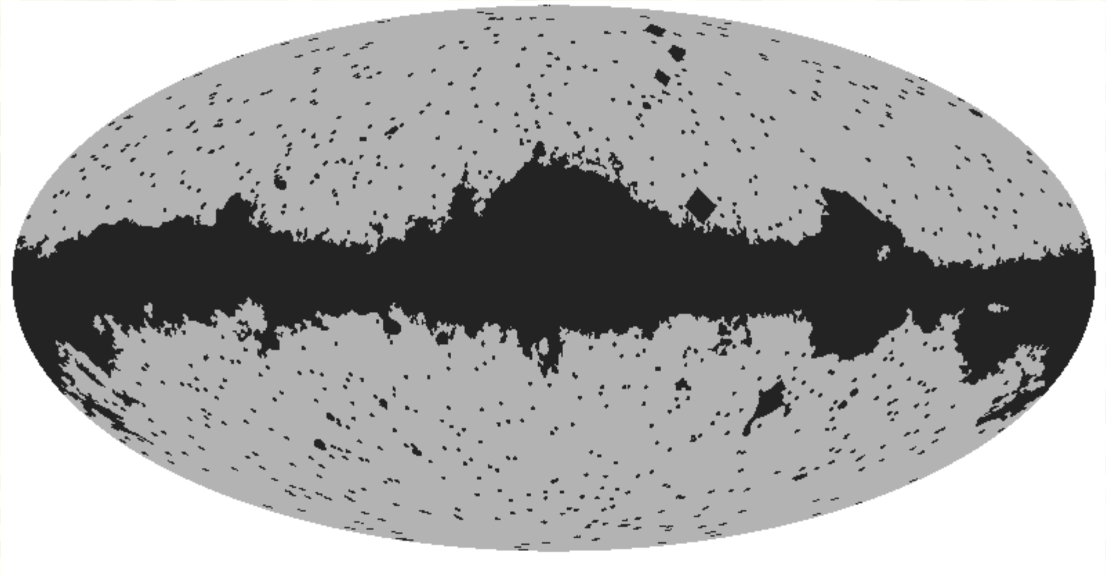


And Planck maps



Masks

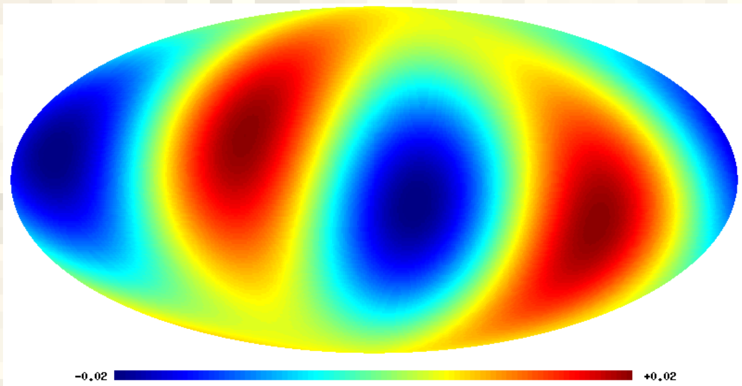




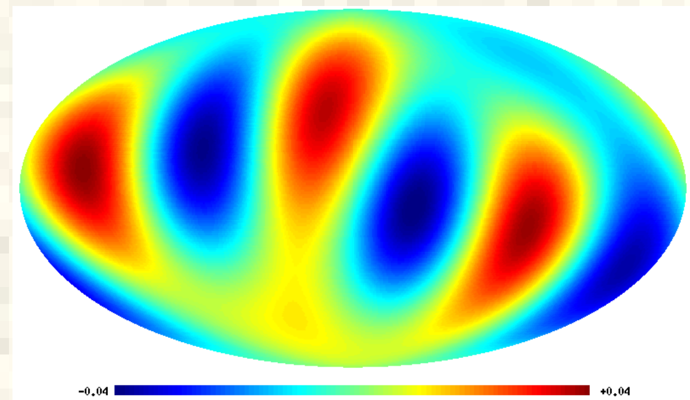
Multipole expansion

Multipole expansion

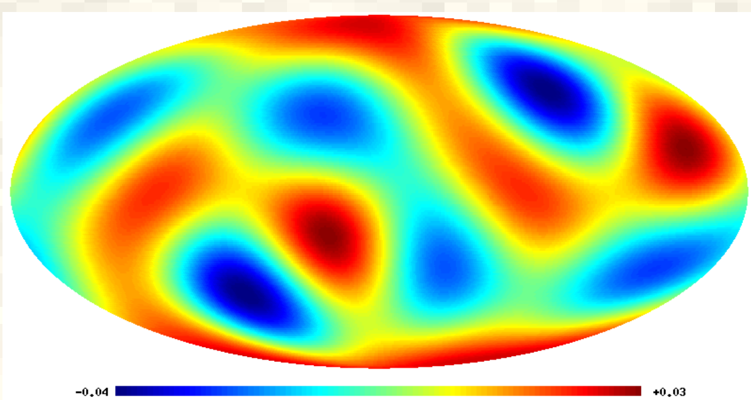
$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{m=l} a_{l,m} Y_{l,m}(\theta,\phi)$$



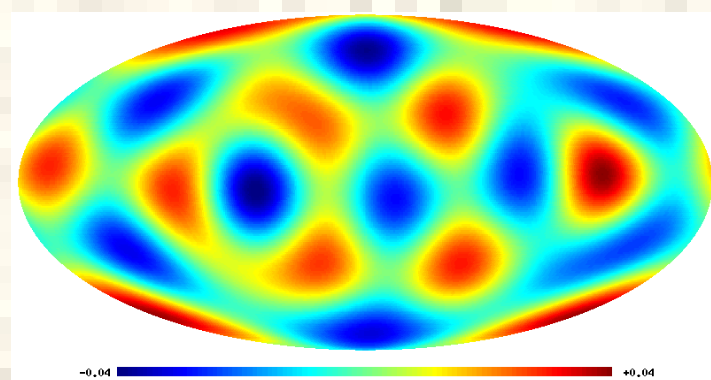
L = 2 (quadrupole)



L =3 (octupole)

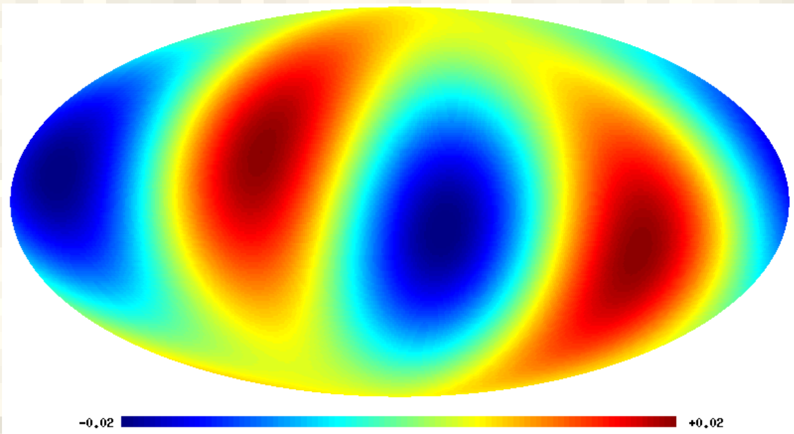


L = 4



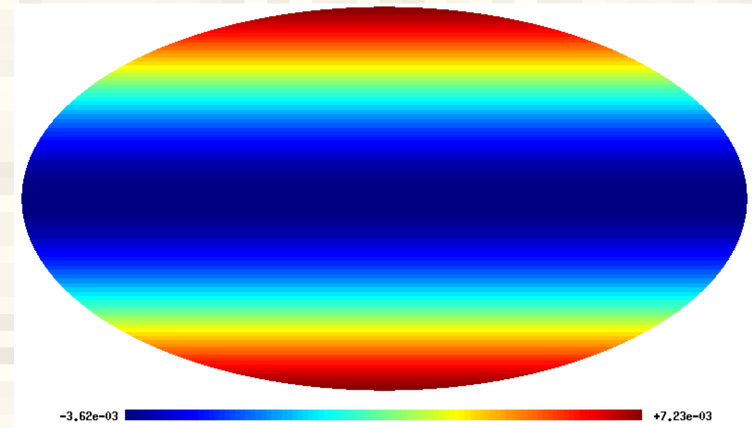
L = 5

Quadrupole



L=2

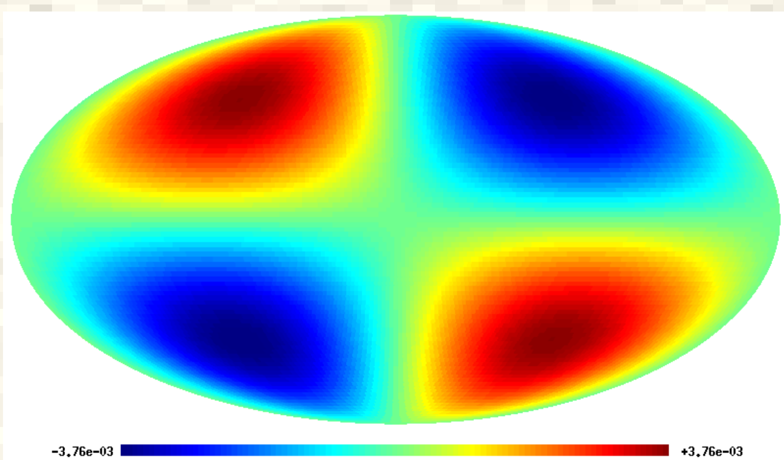
= a20



(2,0)

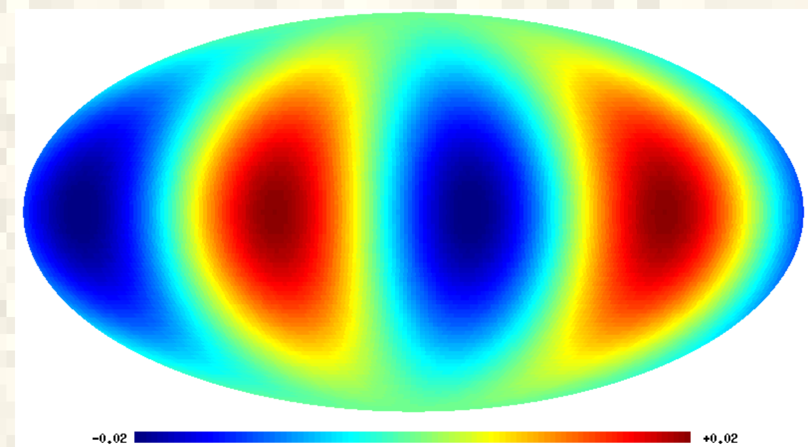
+

+ a21



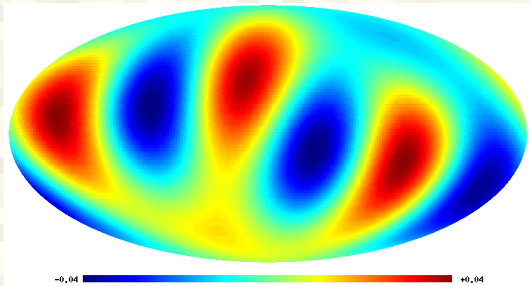
(2,1)

+ a22



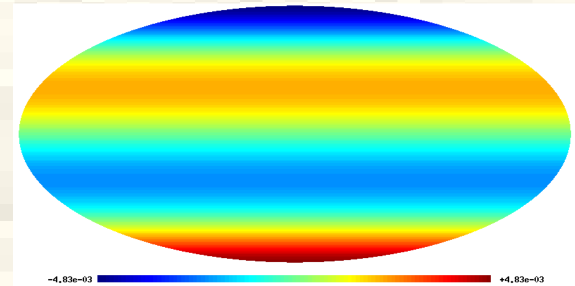
(2,2)

Octupole



L=3

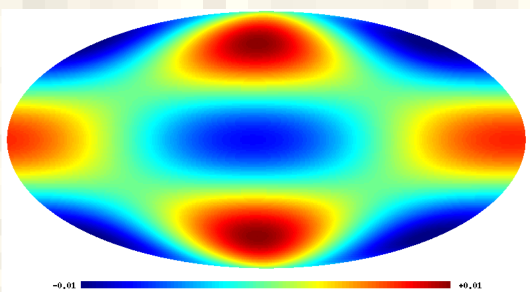
= a30



(3,0)

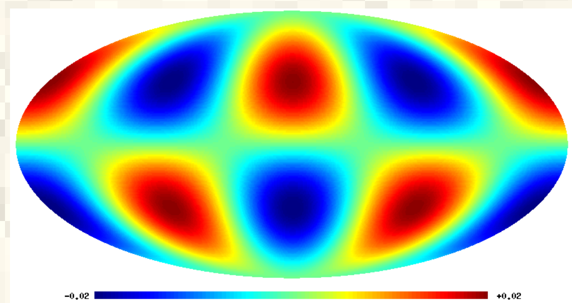
+

a31



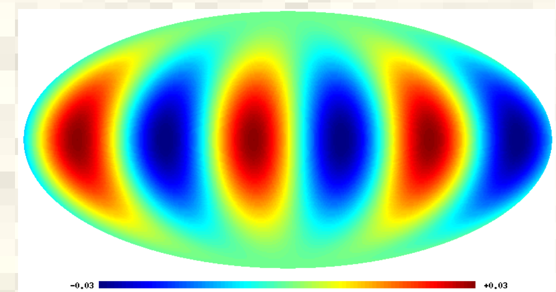
(3,1)

+a32



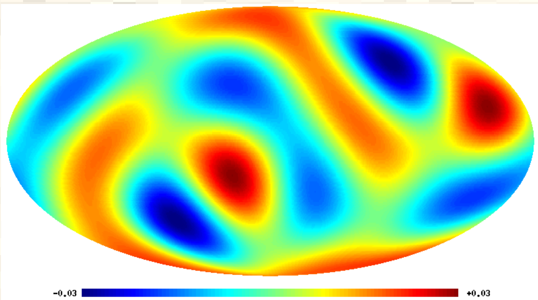
(3,2)

+ a33



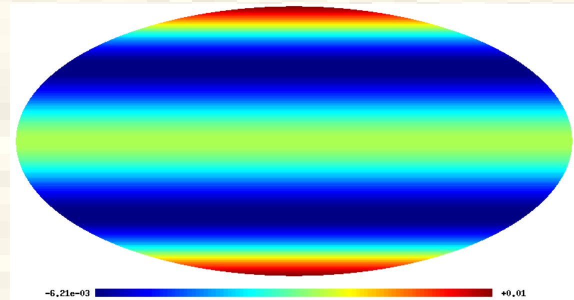
(3,3)

L=4



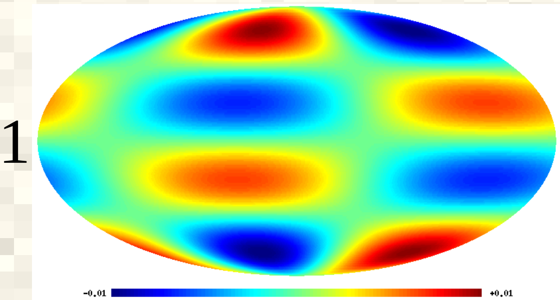
L= 4

= a40



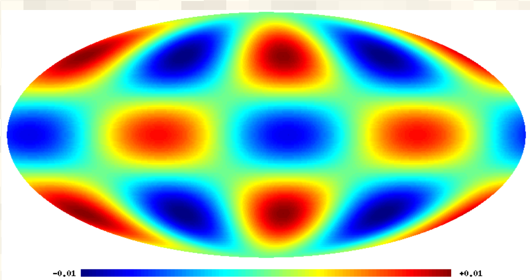
(4,0)

+ a41



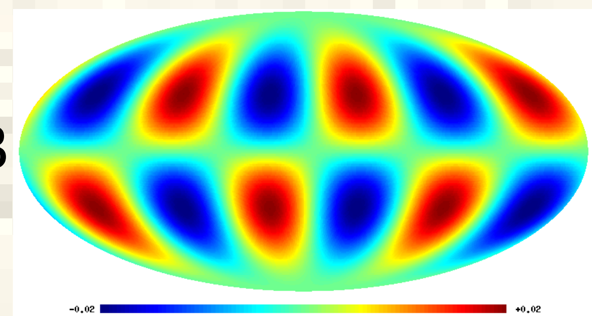
(4,1)

a42



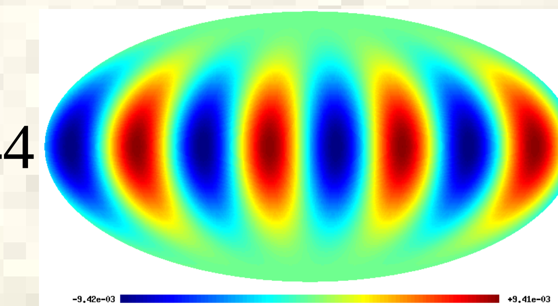
(4,2)

+ a43



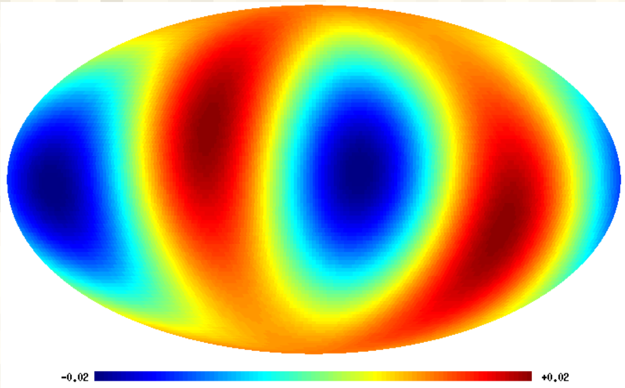
(4,3)

+ a44

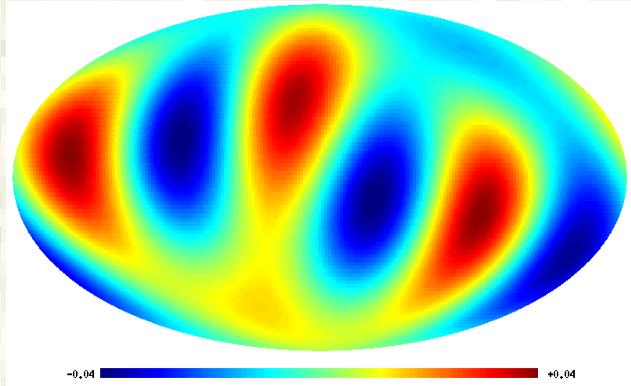


(4,4)

Low multipoles



L=2



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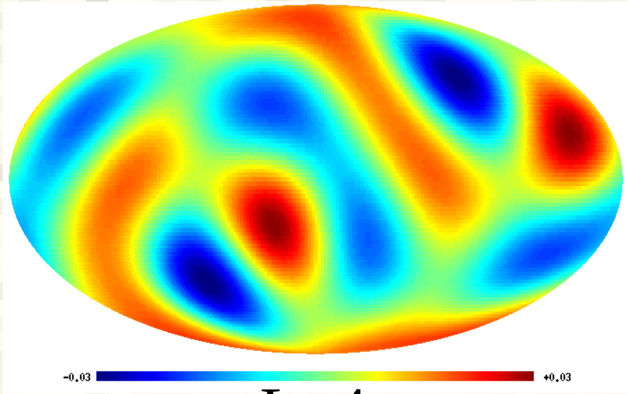

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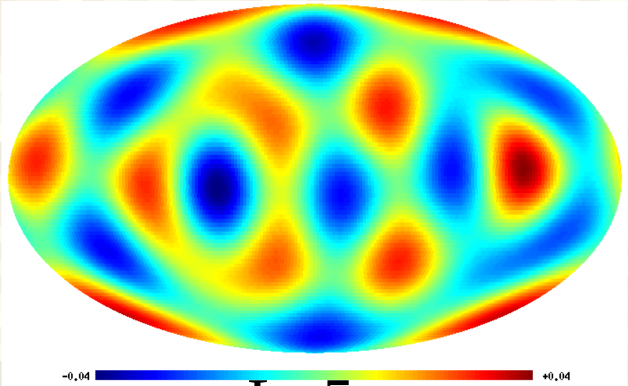

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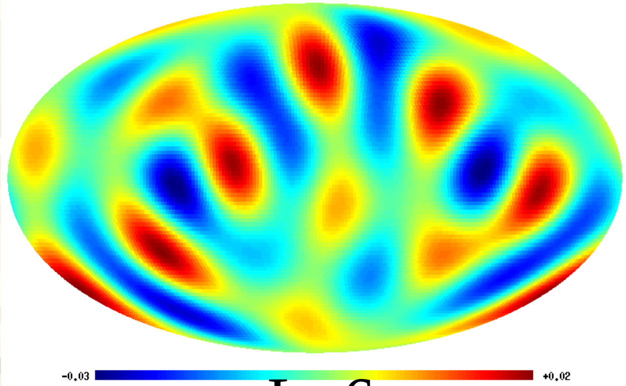

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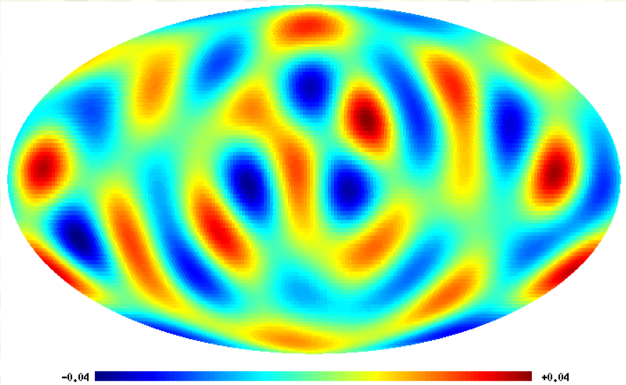
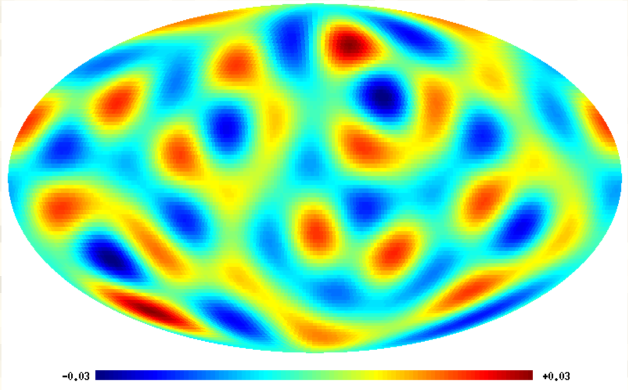
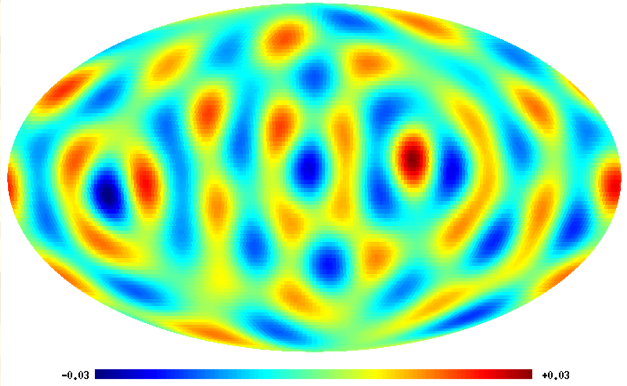


L=7



L=8



L=9

Formation of anisotropy:

Density perturbations arised in form of sound waves
(A. Sakharov, 1965)

$$a_{\ell m} = 4(-i)^{\ell} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \Phi(\mathbf{k}) g_{T\ell}(\mathbf{k}) Y_{\ell}^{*} m(\hat{\mathbf{k}})$$

Angular power spectrum of CMB anisotropy

$$C_\ell \equiv C_\ell(h, \Omega_b h^2, \Omega_{CDM} h^2, \Omega_\Lambda, \Omega_\nu, n, ...)$$

CMBfast: *Seljak & Zaltariaga, 1997*
CAMB: *Lewis, Challinor, Lasenby, 2000*

τ=0.000
Ω_Λ=0.000
ω_b=0.020
f_ν=0.000
n_t=−1.000
A_t=0.000
Multipole l
δT [μK]
P(k) [(h⁻¹Mpc)³]
k [1/h⁻¹ Mpc]

τ=0.000
ω_b=0.020
n_t=−1.000
A_t=0.000
χ²=0.000
Multipole l
δT [μK]
P(k) [(h⁻¹Mpc)³]
k [1/h⁻¹ Mpc]

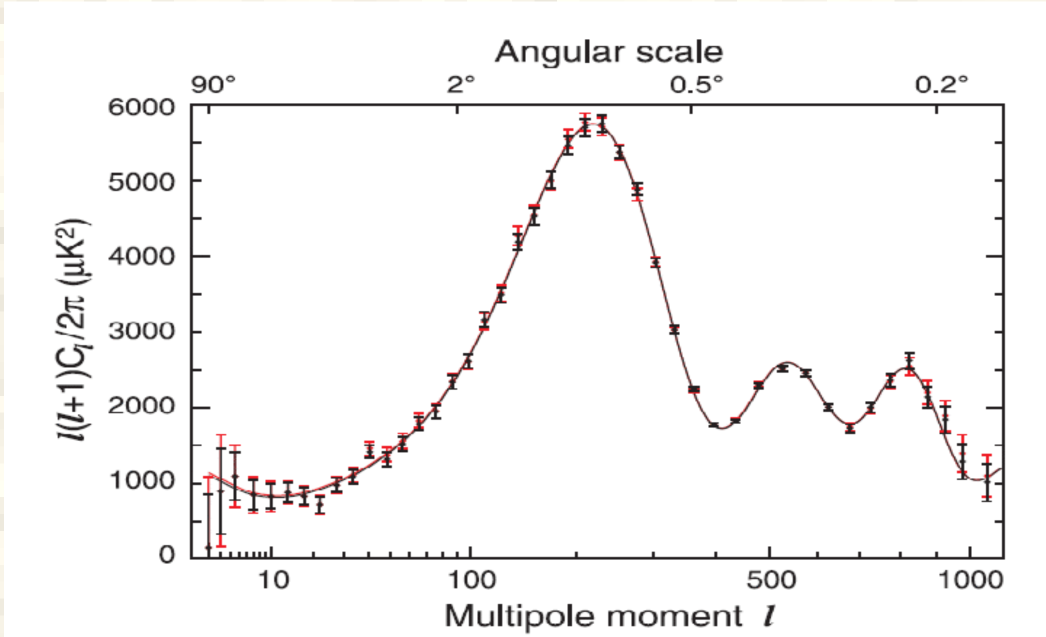
Angular power spectrum of CMB anisotropy

$$C(l) = \frac{1}{2l+1}\left[|a_{\ell 0}|^2 + 2\sum_{m=1}^{l} |a_{l,m}|^2\right]$$

$$a_{l,m} = \int_{-1}^{1} dx \int_{0}^{2\pi} d\phi \Delta T(\theta,\phi) Y^*_{l,m}(x,\phi)$$

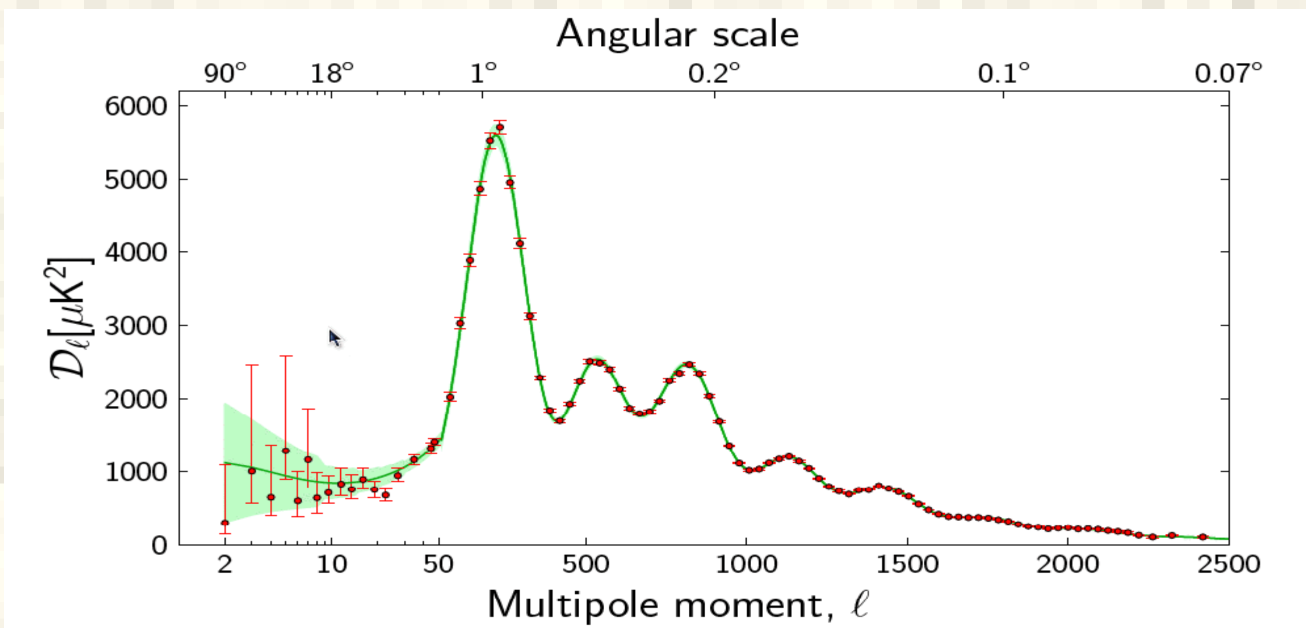
$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty}\sum_{m=-l}^{m=l} a_{l,m} Y_{l,m}(\theta,\phi)$$

Angular power spectrum

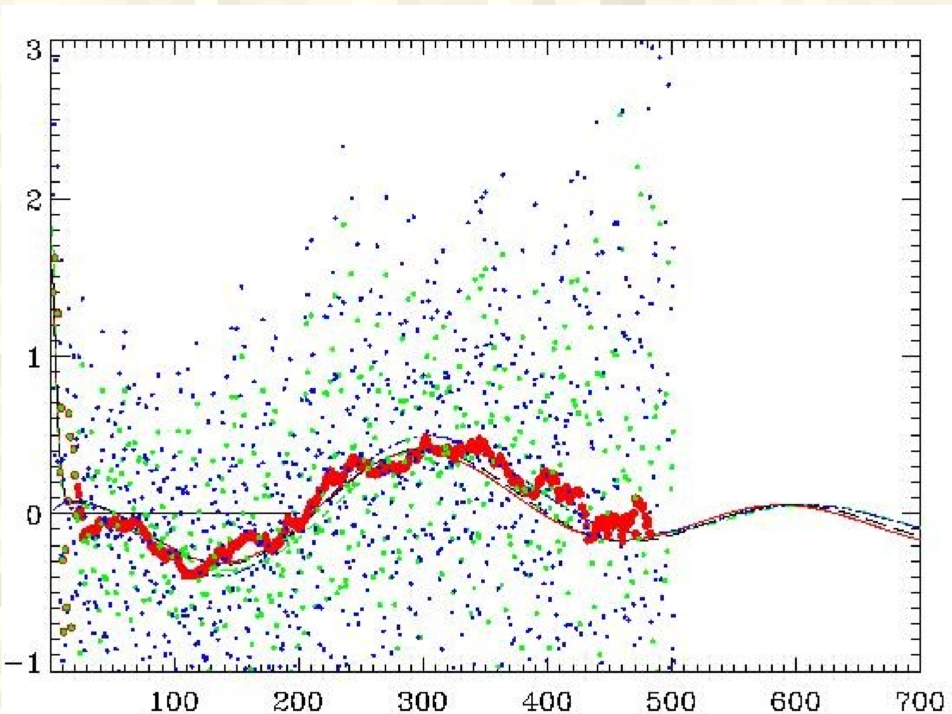


WMAP 9, 2012

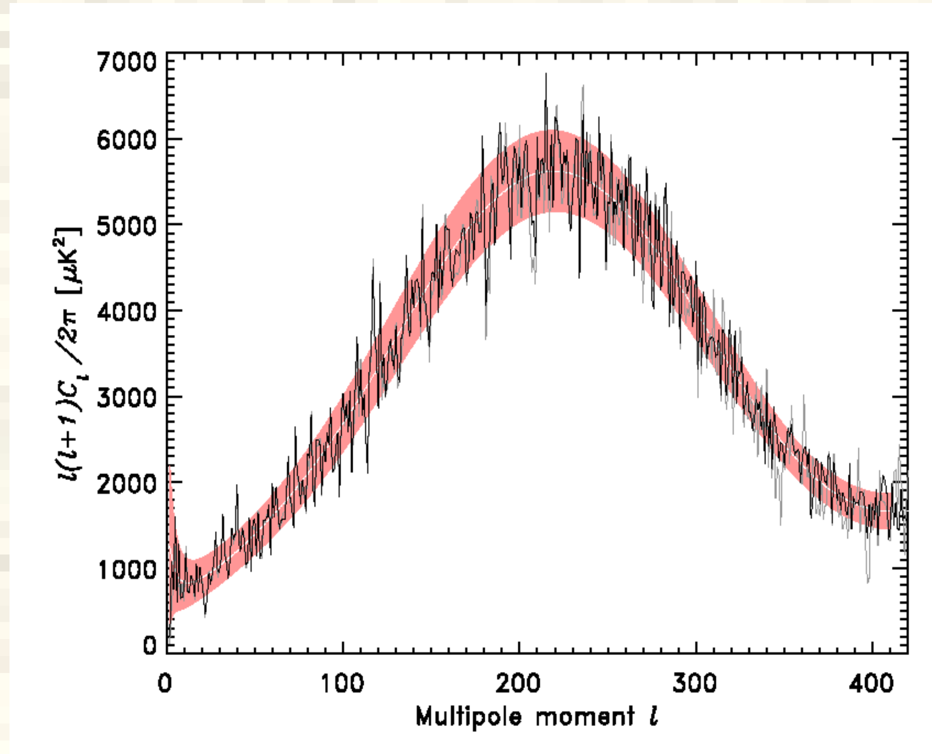
Planck 2013



Binning



3
2
1
0
−1
100
200
300
400
500
600
700



7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
0
100
200
300
400
Multipole moment l

Estimation of parameters

Data analysis of CMB

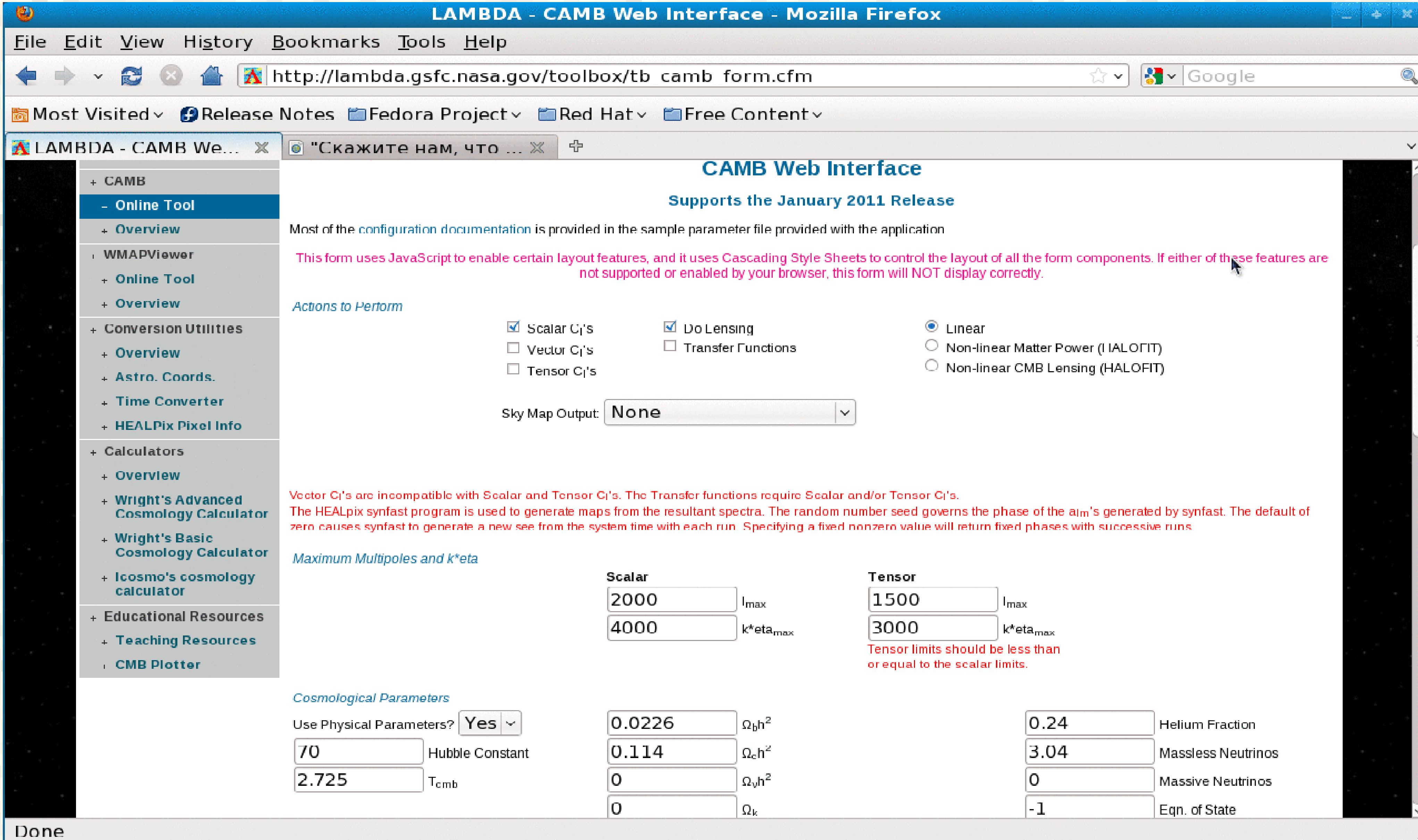
- Registration: time odered data: $T(t)=T(l,b)$
- Pixelization: map-making and restoration data in pixels
- Component separation
- Multipole analysis
- Pixel statistics of the CMB map
- Angular power spectrum analysis and determination of cosmological parameters

Angular power spectrum of CMB

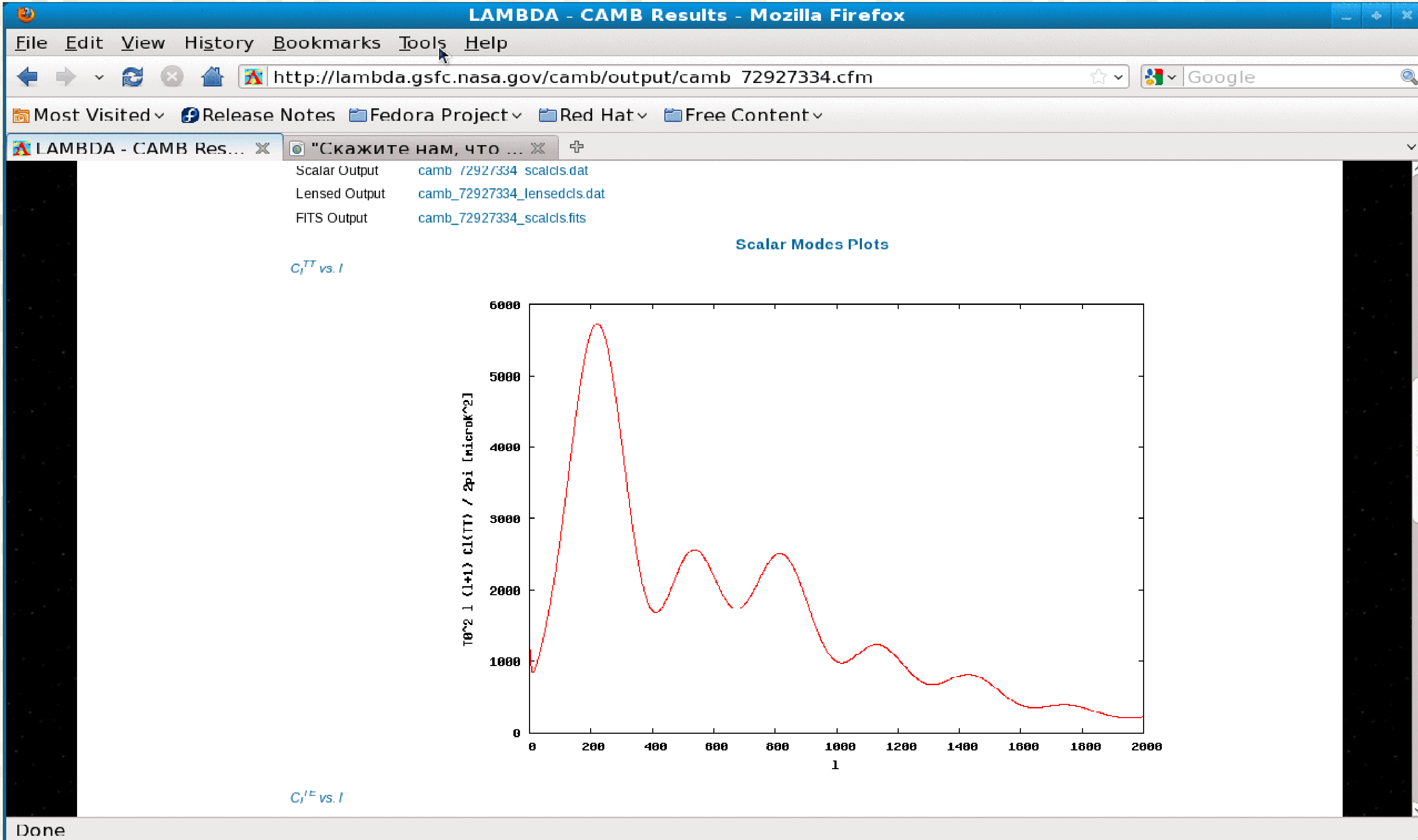
$$C_\ell \equiv C_\ell(h, \Omega_b h^2, \Omega_{CDM} h^2, \Omega_\Lambda, \Omega_\nu, n, ...)$$

CAMB: *Lewis, Challinor, Lasenby, 2000*

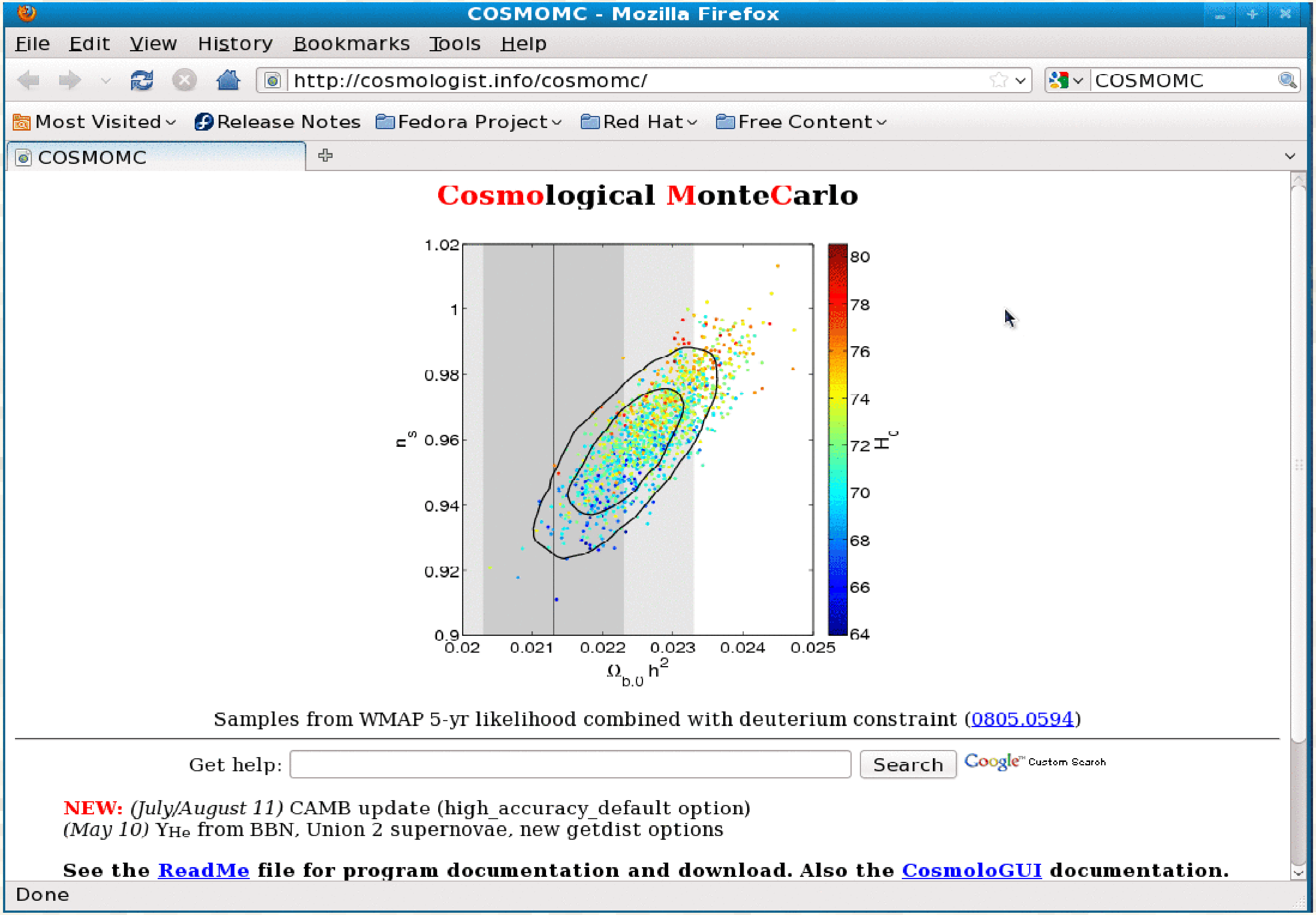
CAMB On-line: http://lambda.gsfc.nasa.gov



CAMB On-line: http://lambda.gsfc.nasa.gov



COSMOMC: COSMOlogical Monte Carlo



Basic input data:

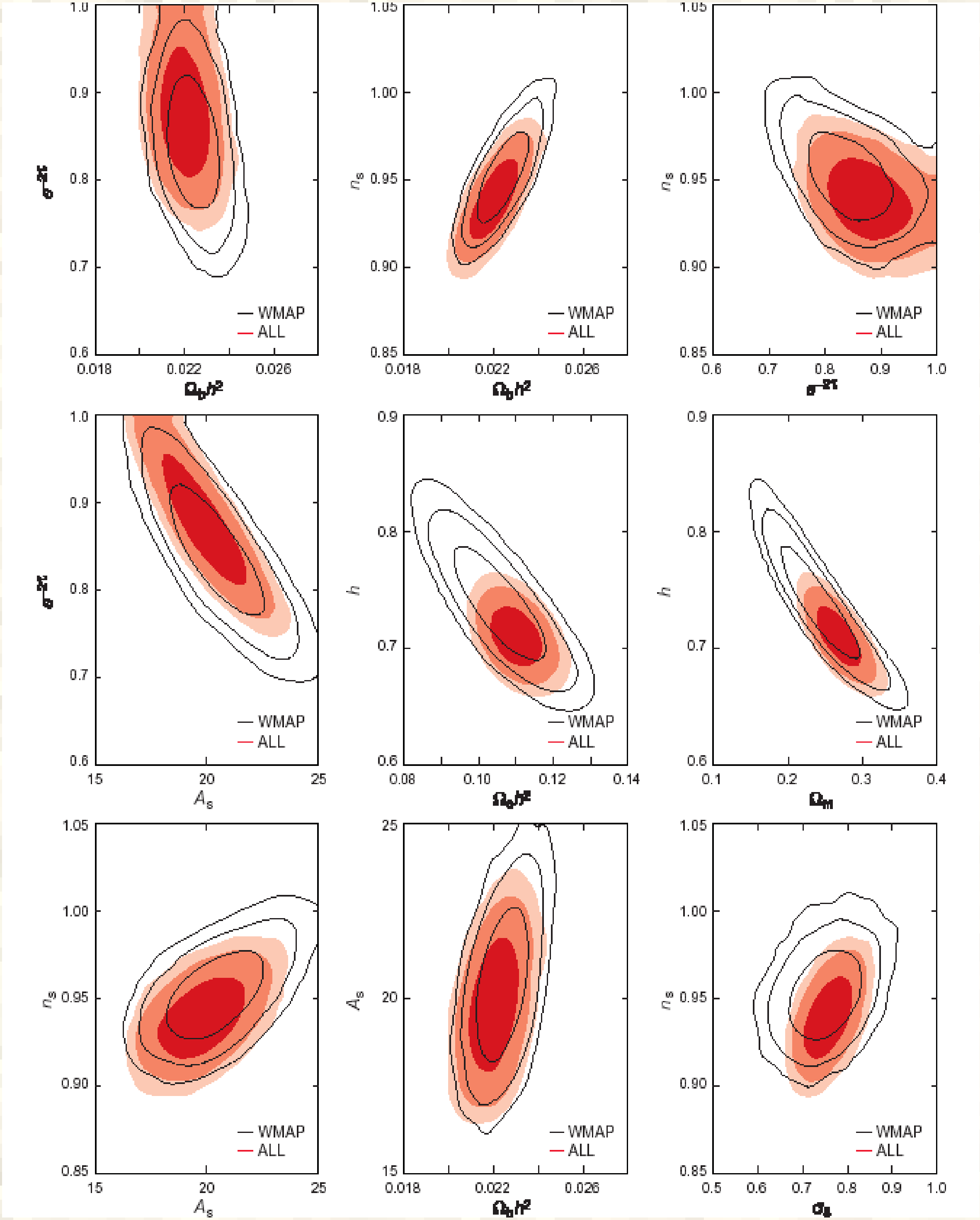
1. CMB C(l) data (CAMB)
2. SDSS Ly-alpha
3. SN Ia
4. Lensing
5. ...

Calculated parameters:

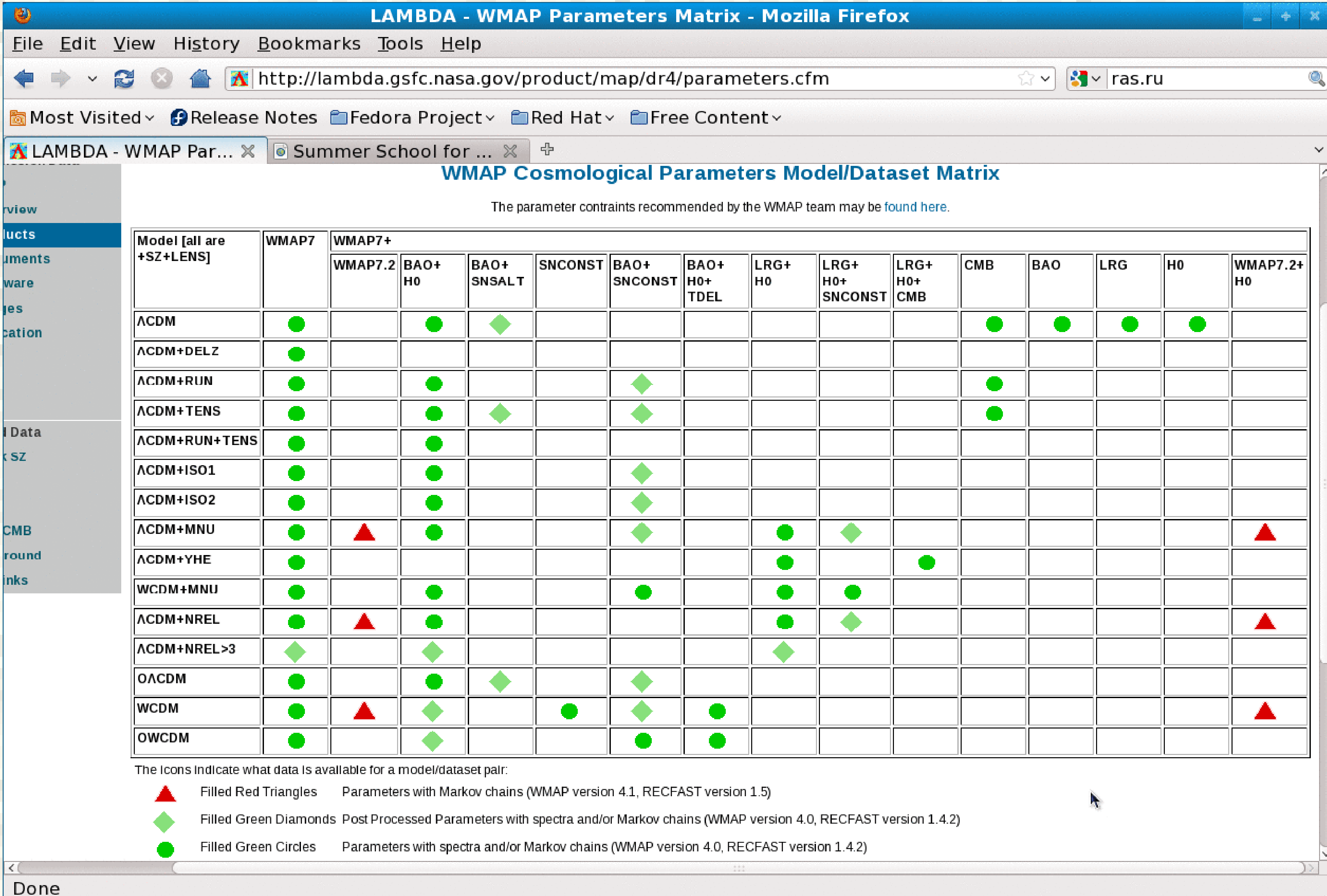
1. Om_b h^2 – density of barionic matter
2. Om_c h^2 – density of DM
3. theta (Om_L, H0) – sound horizon/angular distance
4. tau – optical depth of reionization
5. Om_k - curvatire
6. f_nu – amount of DM in heavy neutrino
7. w – equation of state
8. n_s – scalar spectral index
9. n_t – tenzor spectral index

10, 11, 12, 13, ...

Diagrams of parameters



Семейство LCDM-моделей



WMAP Cosmological Parameters Model/Dataset Matrix

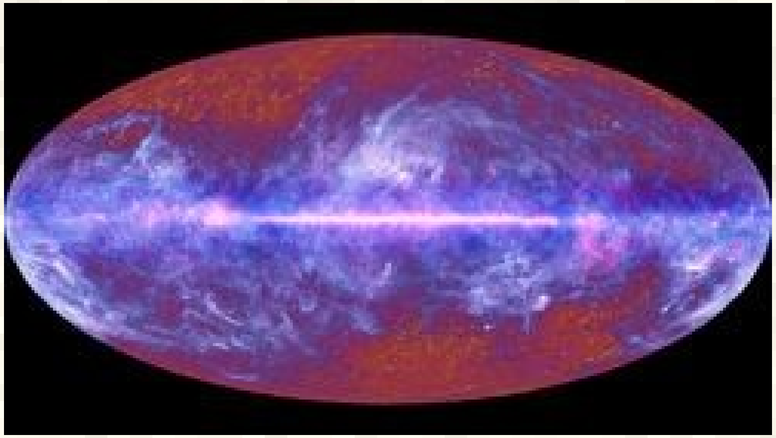
The parameter contraints recommended by the WMAP team may be found here.

Model [all are +SZ+LENS]	WMAP7	WMAP7+													
		WMAP7.2	BAO+ H0	BAO+ SNSALT	SNCONST	BAO+ SNCONST	BAO+ H0+ TDEL	LRG+ H0	LRG+ H0+ SNCONST	LRG+ H0+ CMB	CMB	BAO	LRG	H0	WMAP7.2+ H0
ΛCDM	●		●	◆							●	●	●	●	
ΛCDM+DELZ	●														
ΛCDM+RUN	●		●			◆					●				
ΛCDM+TENS	●		●	◆		◆					●				
ΛCDM+RUN+TENS	●		●												
ΛCDM+ISO1	●		●			◆									
ΛCDM+ISO2	●		●			◆									
ΛCDM+MNU	●	▲	●			◆		●	◆						▲
ΛCDM+YHE	●							●		●					
WCDM+MNU	●		●			●		●	●						
ΛCDM+NREL	●	▲	●					●	◆						▲
ΛCDM+NREL>3	◆		◆					◆							
OΛCDM	●		●	◆		◆									
WCDM	●	▲	◆		●	◆	●								▲
OWCDM	●		◆			●	●								

The icons indicate what data is available for a model/dataset pair:

▲	Filled Red Triangles	Parameters with Markov chains (WMAP version 4.1, RECFAST version 1.5)
◆	Filled Green Diamonds	Post Processed Parameters with spectra and/or Markov chains (WMAP version 4.0, RECFAST version 1.4.2)
●	Filled Green Circles	Parameters with spectra and/or Markov chains (WMAP version 4.0, RECFAST version 1.4.2)

We were waiting for Planck results



Cosmological results:
WMAP9 and Planck data

http://lambda.gsfc.nasa.gov

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

No revolution...

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No revolution... *But there are some strangeness...*

Cosmological results:
WMAP9 and Planck data

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No revolution... *But there are some strangeness, which we can see in the next lecture*