Part 4. Practical work

Simulations in GLESP using angular power spectrum

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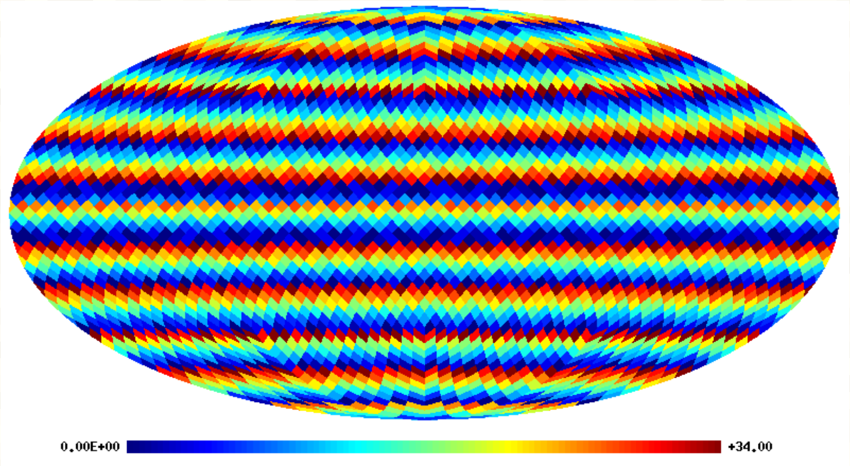
Data analysis of CMB

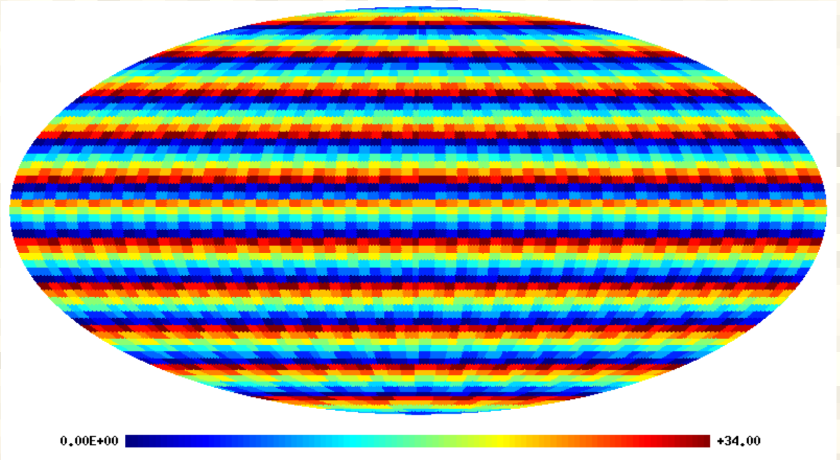
- Registration: time odered data: $T(t)=T(l,b)$
- Pixelization: map-making and restoration data in pixels
- Component separation
- Multipole analysis
- Pixel statistics of the CMB map
- Angular power spectrum analysis and determination of cosmological parameters

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)

What is GLESP ?

Basic idea of GLESP

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

Quadrature of Gauss:

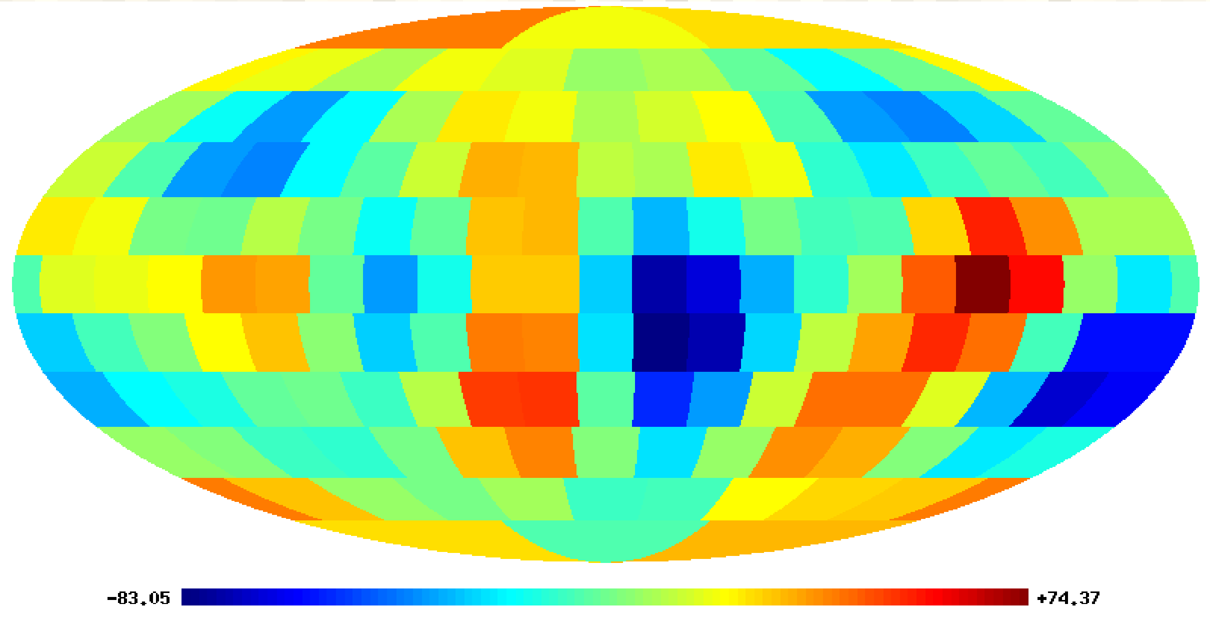
Exact equality (~10^-8 or 10^-16)
(float or double)

$$\int_{-1}^{1} dx \Delta T(x, \phi) Y^*_{l,m}(x, \phi) = \sum_{j=1}^{N} w_j \Delta T(x_j, \phi) Y^*_{l,m}(x_j, \phi)$$

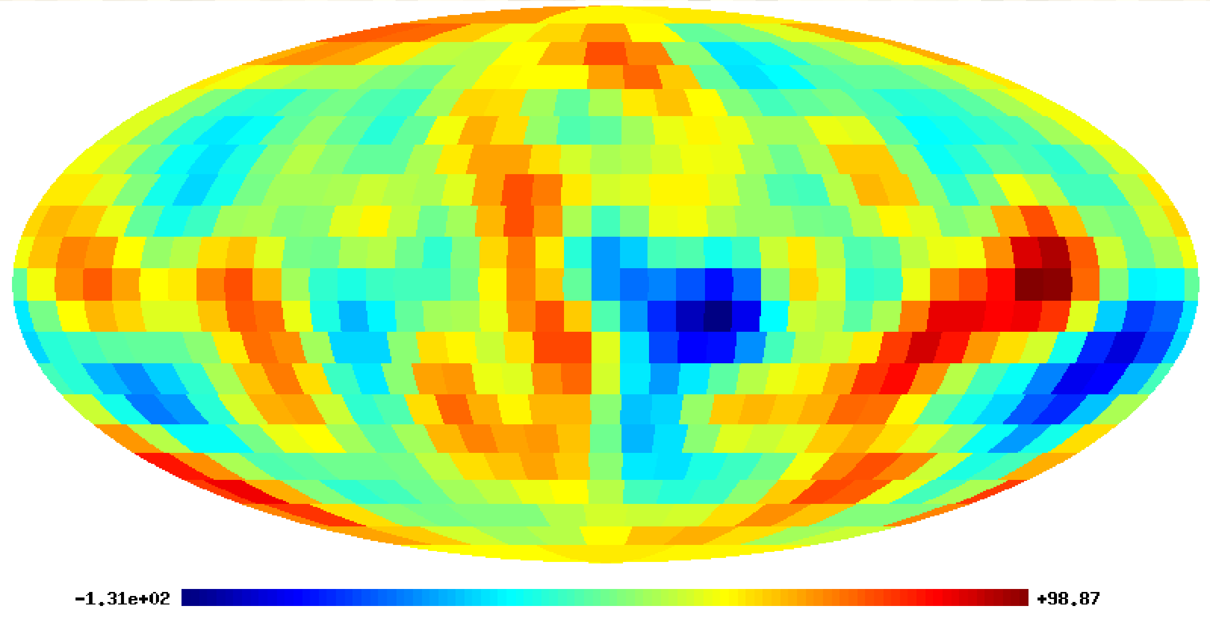
Pixelization knots by polar angle are in zeros of Legendre polynomials

GLESP: Gauss-LEgendre Sky Pixelization

Resolution parameters: *Lmax*, *Nx* > 2*Lmax*, *Nphi* >= 2*Nx*



Lmax=5
Nx = 11
Nphi = 22



Lmax=10
Nx=21
Nphi=42

GLESP

1) Specially for adanced multipole operation

2) Stricltly orthogonal decompostion and no interations in map-multipole conversion

3) Non-hierarchical scheme

4) Realization in GNU C

GLESP: main procedures

1) Conversion: anisotropy maps -> harmonics a_lm-s -> maps
2) conversion: polarization Q,U -> harmonics E,B_lm -> Q,U
3) arithmetic for maps & harmonics: summarizing, difference, multiplication, division, correlation, repixelization, rotation
4) calculation of angular power spectrum and pixel statistics
5) masking
6) graphics
7) simulations and producing of pattern maps
8) phase analysis
9) extracting areas

GLESP installation
(Linux, BSD, MacOS)

http://www.glesp.nbi.dk

FFTW: The Fastest Fourier Transform in the West

http://www.fftw.org

Let us prepare a random CMB map,
add point or/and extended radio sources
and calculate an angular power spectrum in GLESP

Angular power spectrum of CMB anisotropy

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

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

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

Selection of angular power spectrum

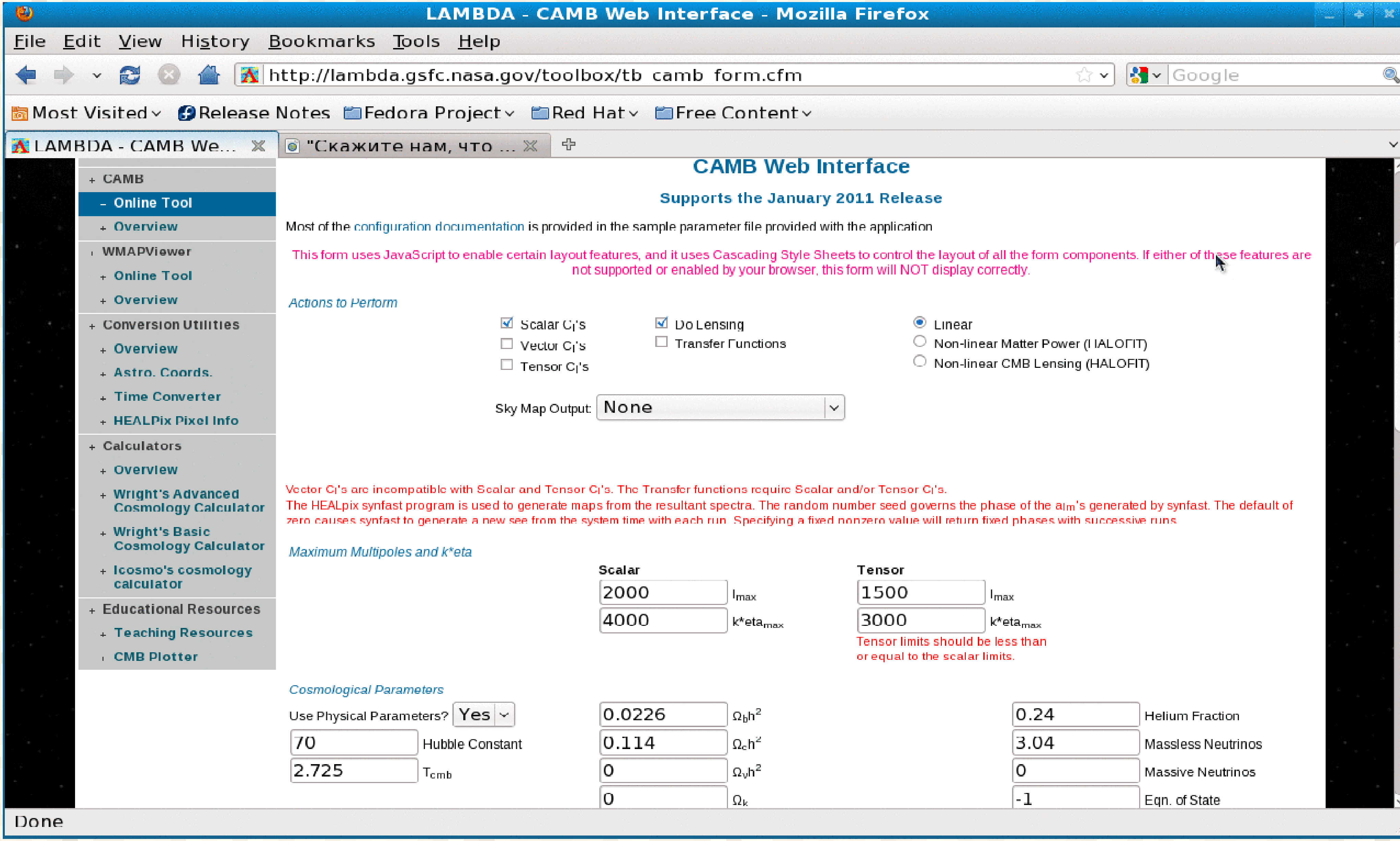
(in forms of dat- or FITS-file)

Angular power spectrum of CMB

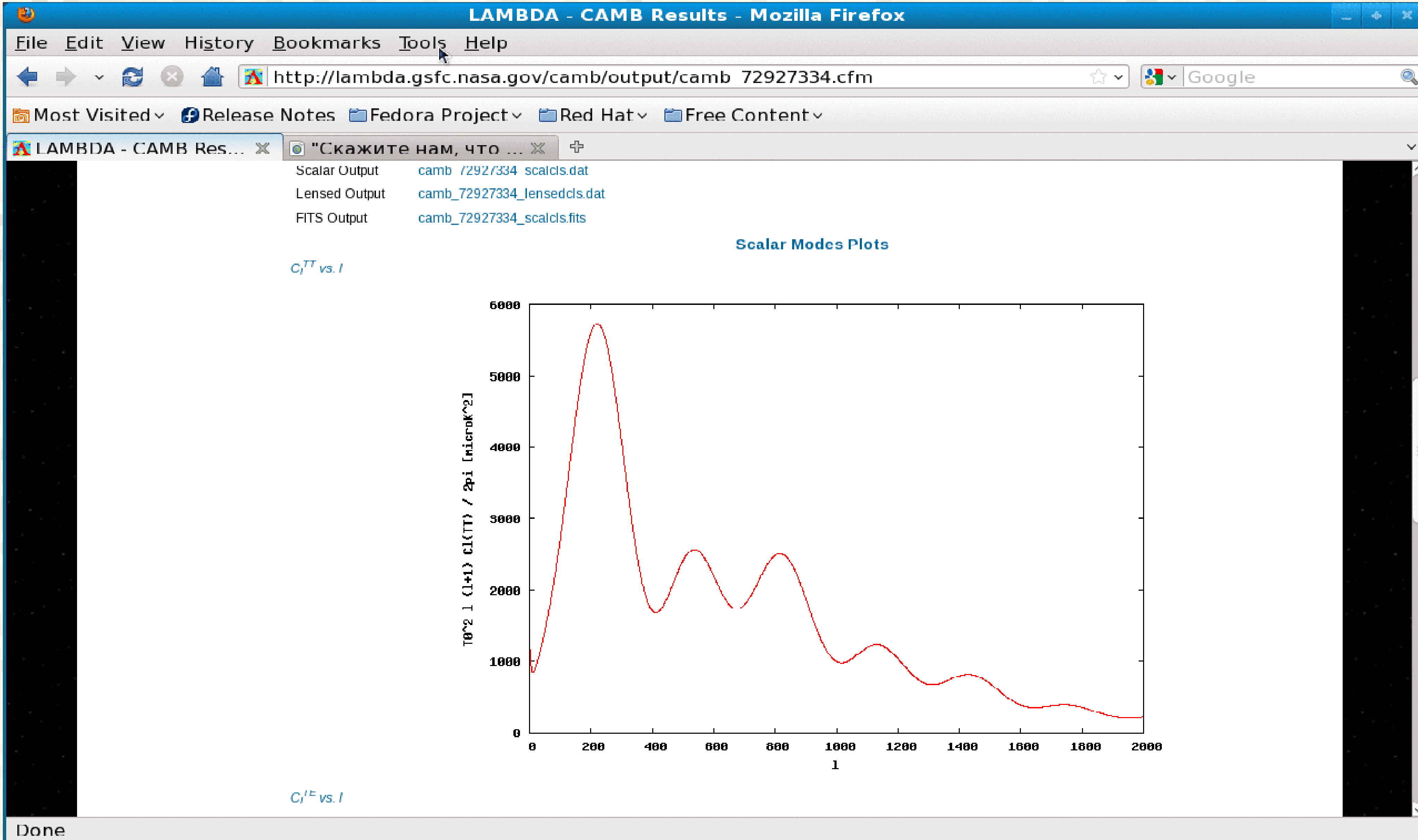
$$C_\ell \equiv C_\ell(h, \Omega_b h^2, \Omega_{CDM} h^2, \Omega_\Lambda, \Omega_\nu, n, \ldots)$$

CAMB: *Lewis, Challinor, Lasenby, 2000*

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



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



Map simulation in LCDM-cosmology

cl2map -r 6 -cl clcdm.dat -lmax 100 -nx 201 -np 402 -ao a6.fts -o m6.fts

'-*r 6*' – number of random realization (No 6)
'-*cl clcdm.dat*' - file with LCDM *C(l)*-spectrum data
'-*lmax 100*' – resolution parameter: maximul l on a map
'-*nx 201*' – number of rings on a sphere
'-*np 402*' – number of pixels at equator
'-*ao a6.fts*' – FITS-file of a_lm-coefficients
'-*o m6.fts*' – GLESP FITS-file of a CMB random realization

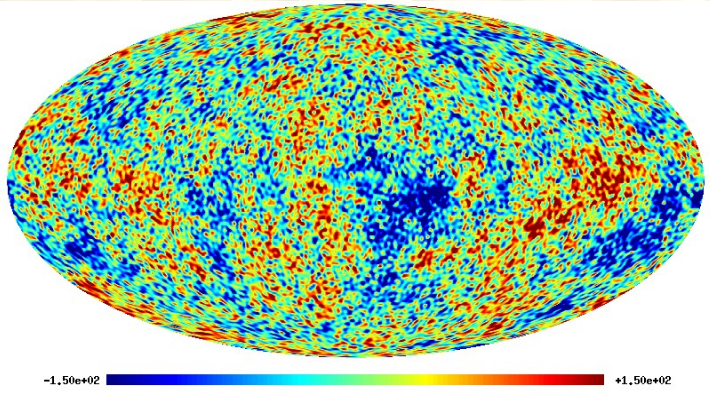
Graphics: preparation of GLESP maps

f2fig map.fts -o map.gif

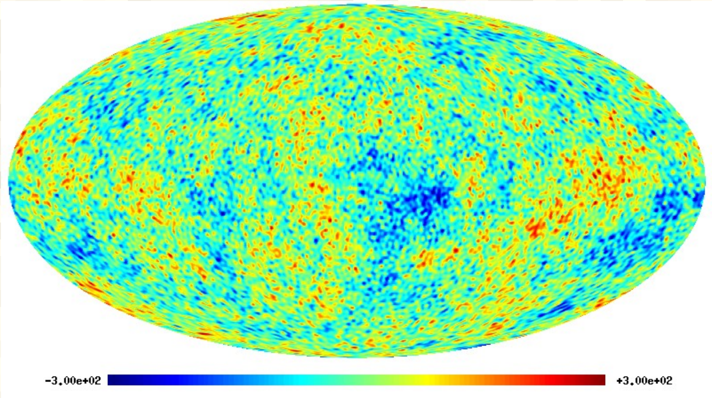
Some flags more:

'-*Cs a,b*' – sets cut levels [a,b] on output image
'-*gre'* – outputs ecliptic system grids
'-*grq'* – output equatorial system grids
'-*grg'* – outputs galactic system grids

f2fig cut-limits

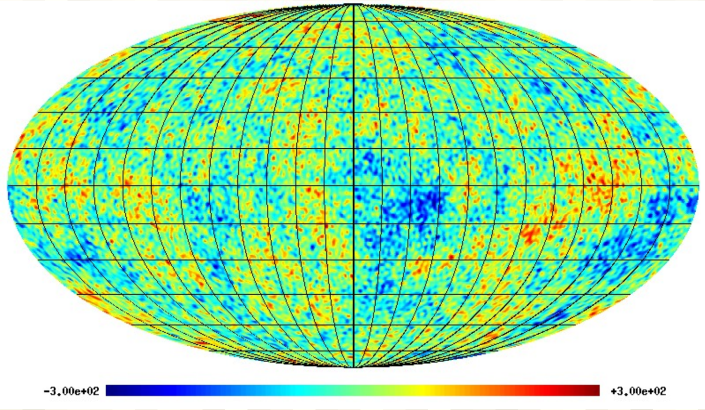


-0.1mK < v < 0.1mK

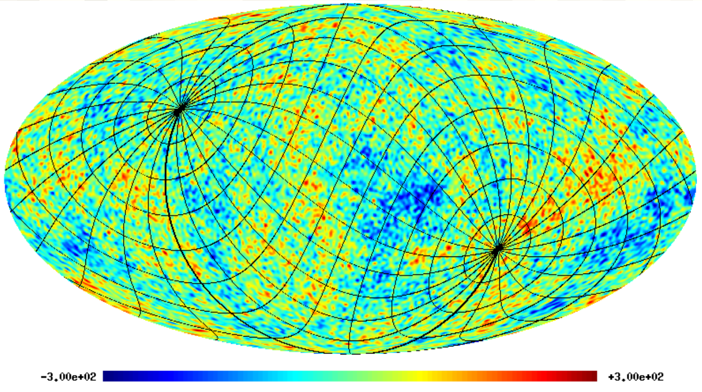


-0.3mK < v < 0.3mK

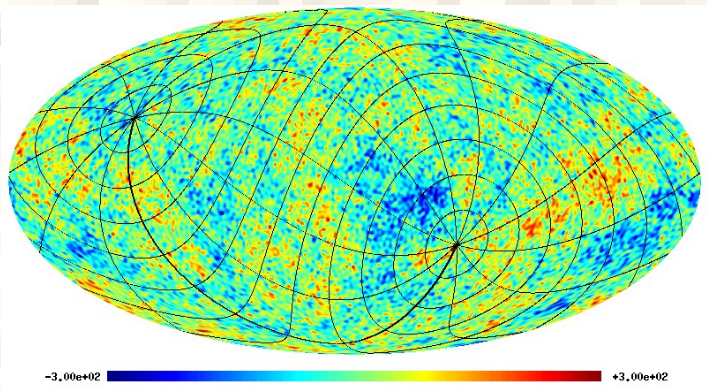
f2fig coordinate system grids



galactic

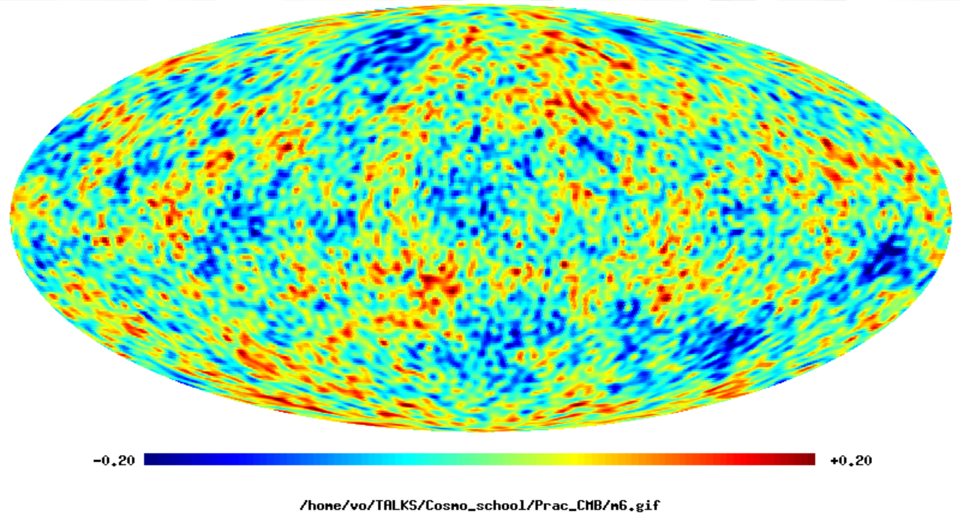


ecliptic

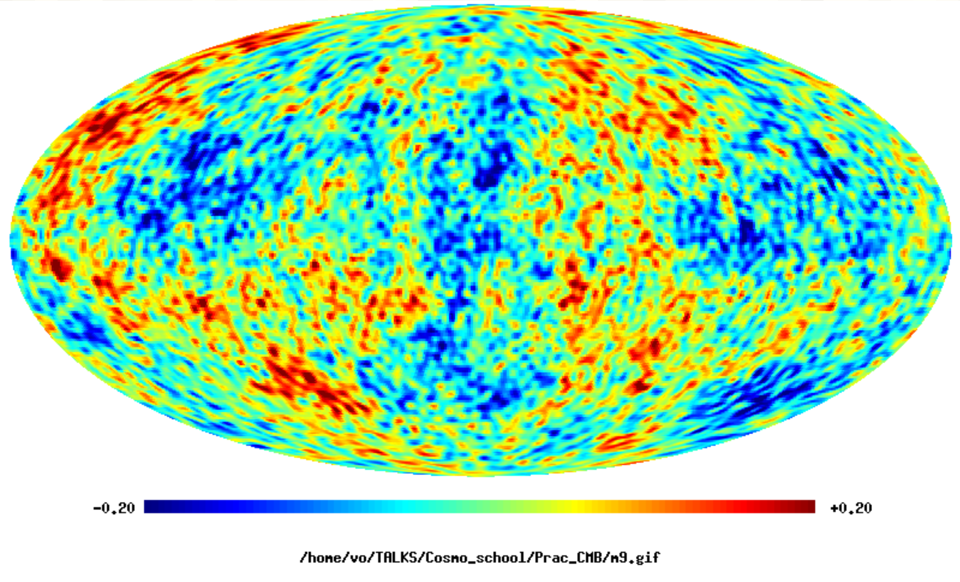


equatorial

Example of random simulation for LCDM-cosmology

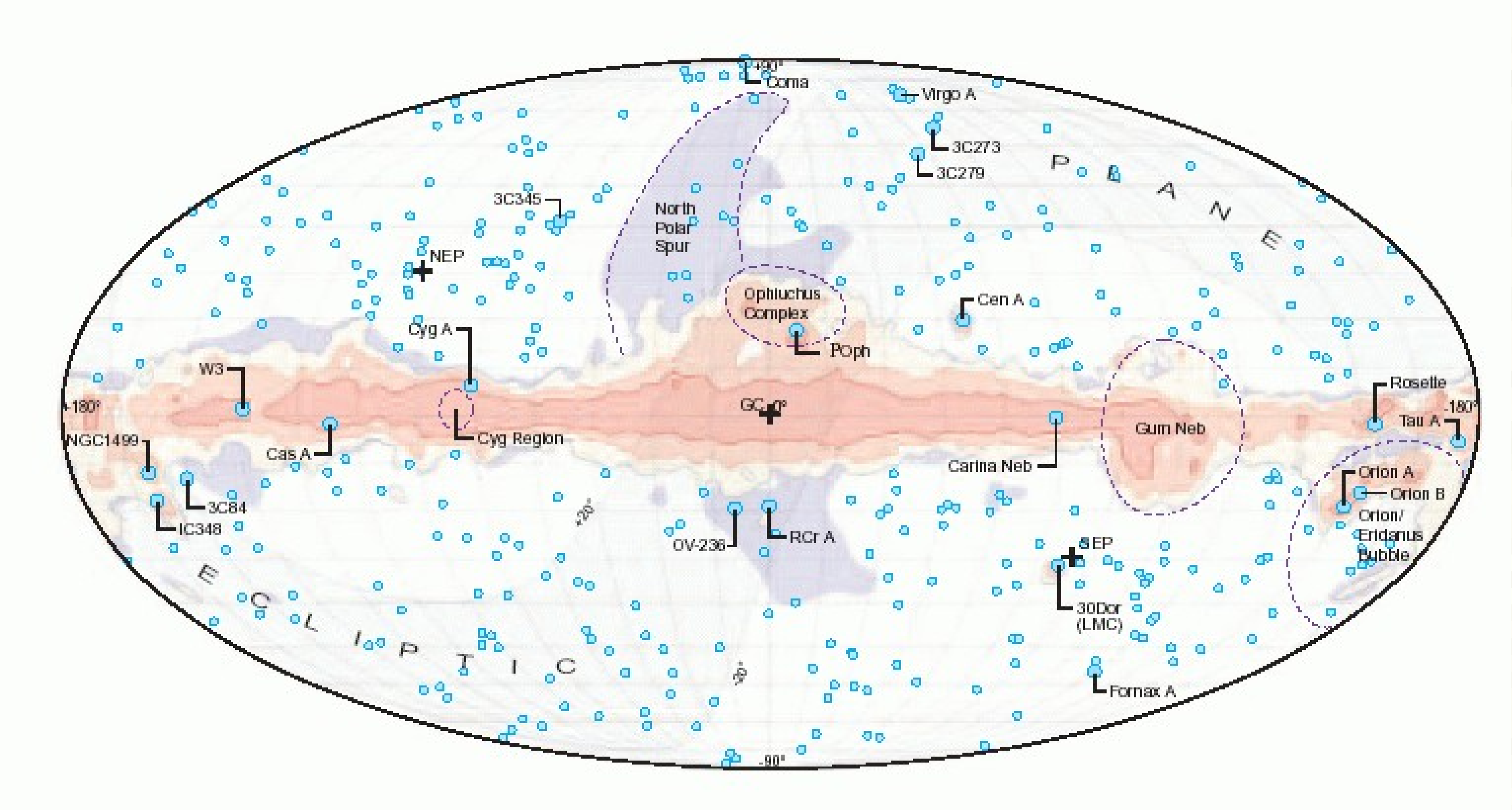


r=6



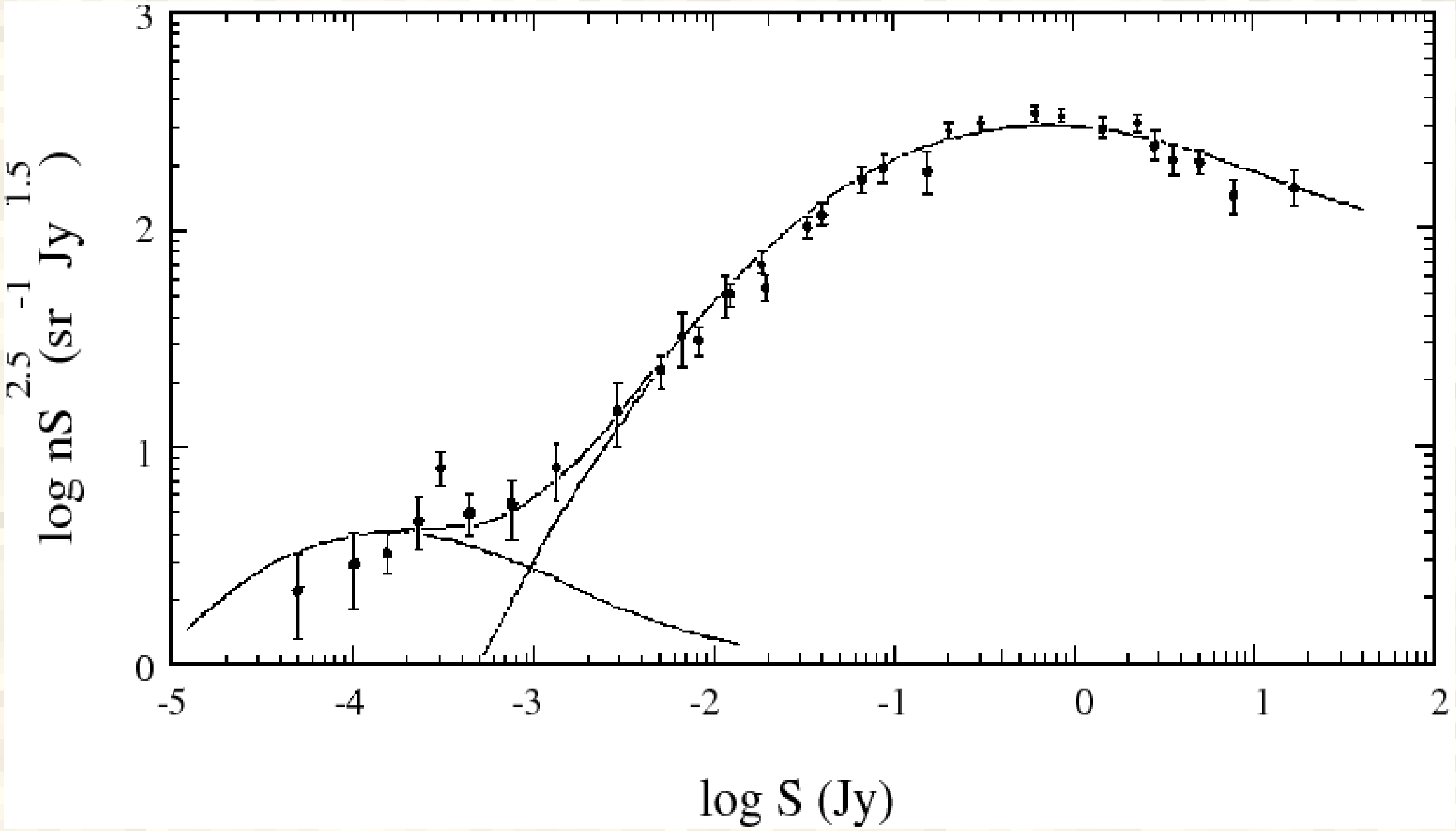
r=9

Preparation of the map with object data



Preparation of a pattern map

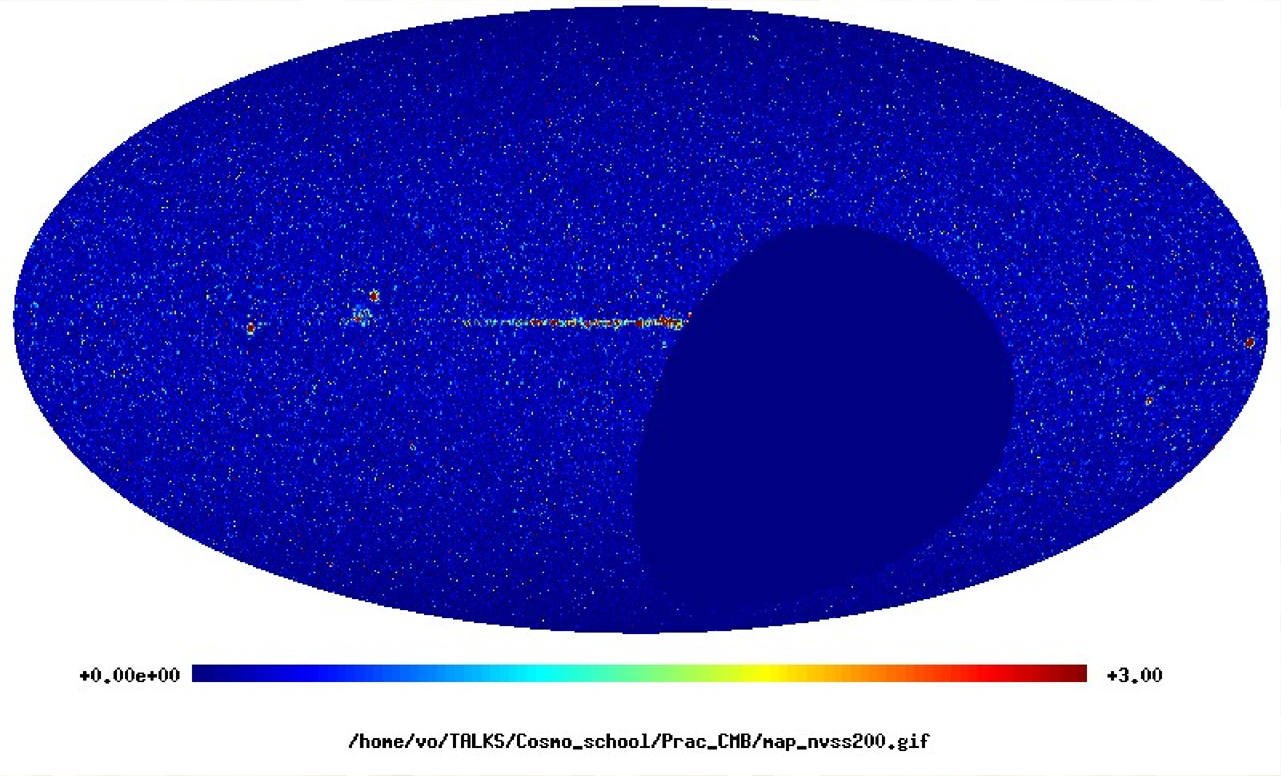
E.g. one can produce a random simulation of Poisson distribution and flux densities corresponding to 'log *N* – log *S*' counts



Or one can prepare a pattern from NVSS catalog

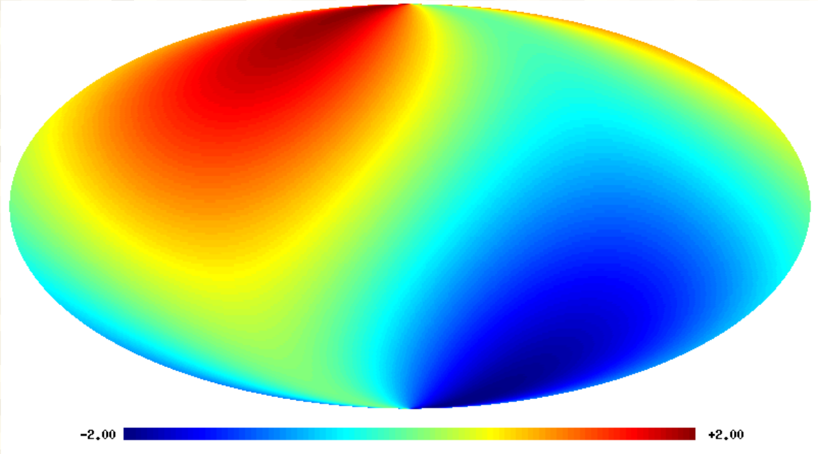
mappat -fp source.list -nx 401 -np 802 -o m_src.fts

(when the pixelization is of higher resolution then the pattern map should be smoothed)

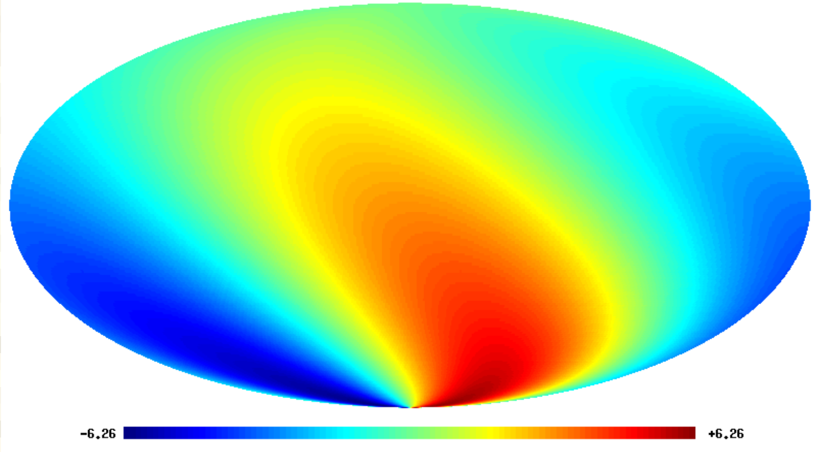


One more possibity of 'mappat'

Patterns by algerbraic formula (examples)



y = cos(theta) + sin(phi)

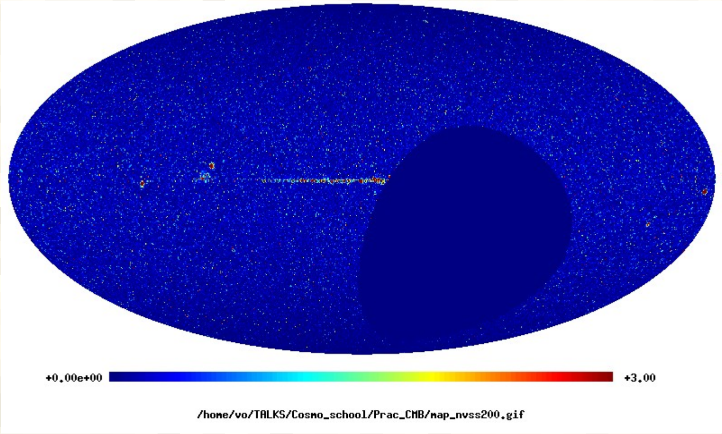


y = 2 (sin(theta+phi)+theta

Preparation of a pattern map with NVSS catalog

To escape domination of radio sources over the CMB-signal, one can decrease by hands a flux from source, e.g. in 20 times:

difmap -cf 0.05 m_src.fts -o m_nv.fts



Then, a_lm-s 'a_nv.fts' для карты '*m_nv.fts*' are calculated:

cl2map -lmax 200 -map m_nv.fts -ao a_nv.fts

Decompose a map onto harmonics and smooth it up to *Lmax*=100

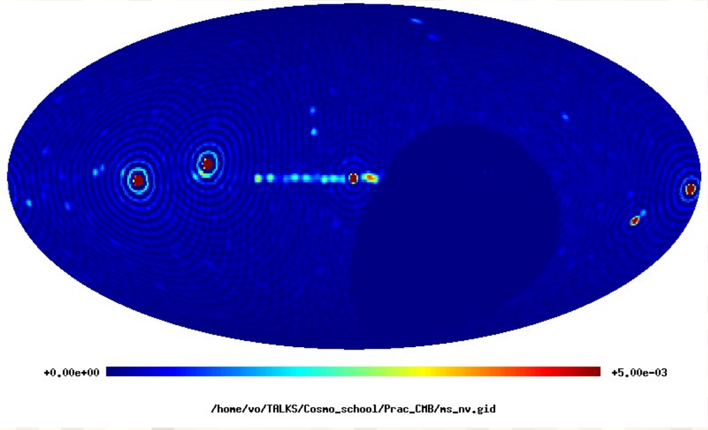
rsalm -fw 55 a_nv.fts -o as_nv.fts

'-fw 55' – sets the size of Gaussian bin in arcmin:
55' --> Lmax=100
a_nv.fts – input file of a_lm-s
'-*o as_nv.fts*' – output file of smoothed a_lm-s.

One generates a smoothed map file 'as_nv.fts' containing radio sources and cut by freauency

cl2map -fa as_nv.fts -lmax 100 -nx 201 -np 402 -o ms_nv.fts

Where rings are from ?



Preparion of source patterns by hand

mappat -fp source.list -nx 401 -np 802 -o m_src.fts

'-fp source.list' – input source list
'-nx 401' – number of rings on a sphere
'-np 802' – number of pixels on an equator
'-o m_src.fts' – output map

Format of the input 'source.list' (for equatorial coordinate system):

hh:mm:ss1 dd:mm:ss1 amp1
hh:mm:ss2 dd:mm:ss2 amp2
......

Sum of CMB simulations and sources

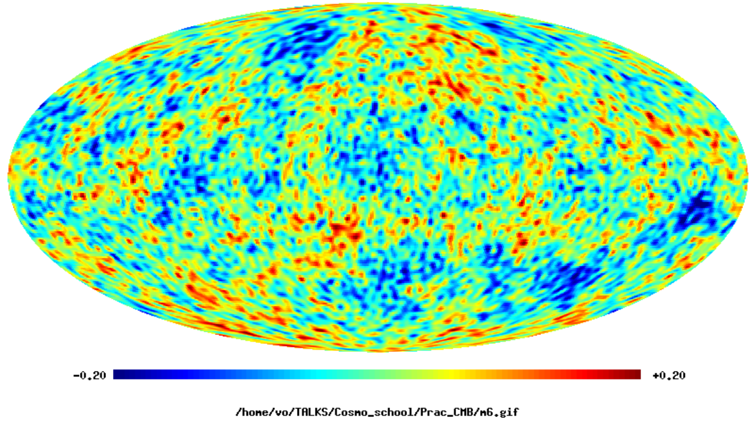
In pixel domain:

difmap -sum m6.fts ms_nv.fts -o ms6.fts

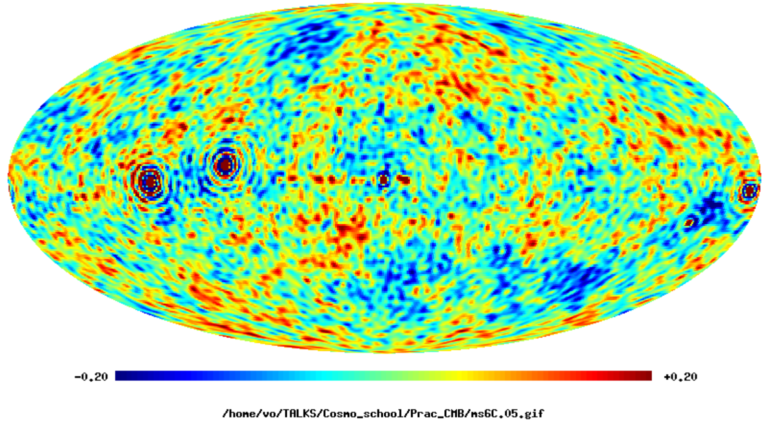
In multipole domain:

difalm -sum a6.fts as_nv.fts -o as6.fts

And converse with *'cl2map'*.

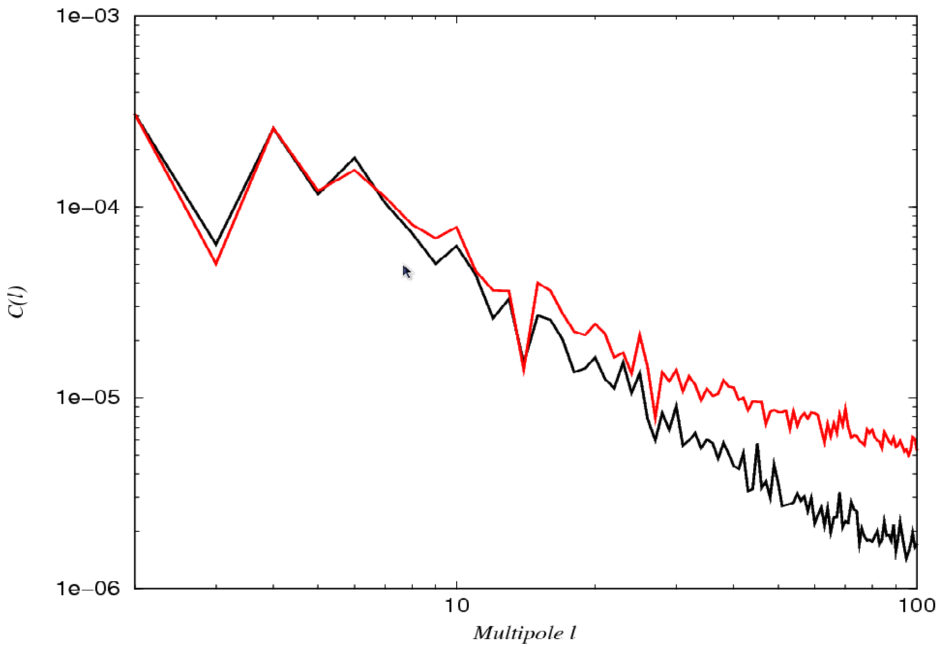


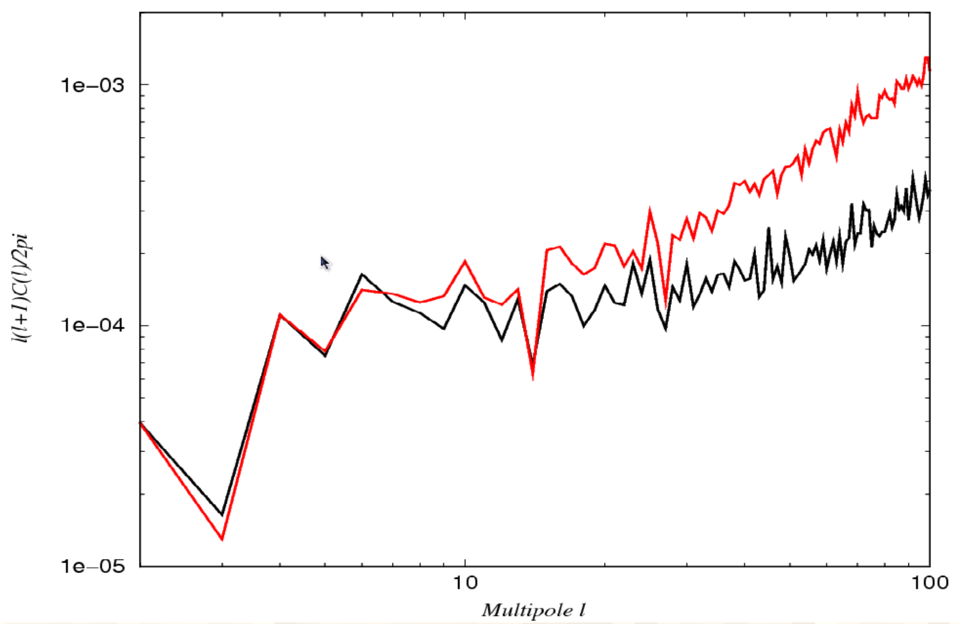
Before



After

Power spectrum

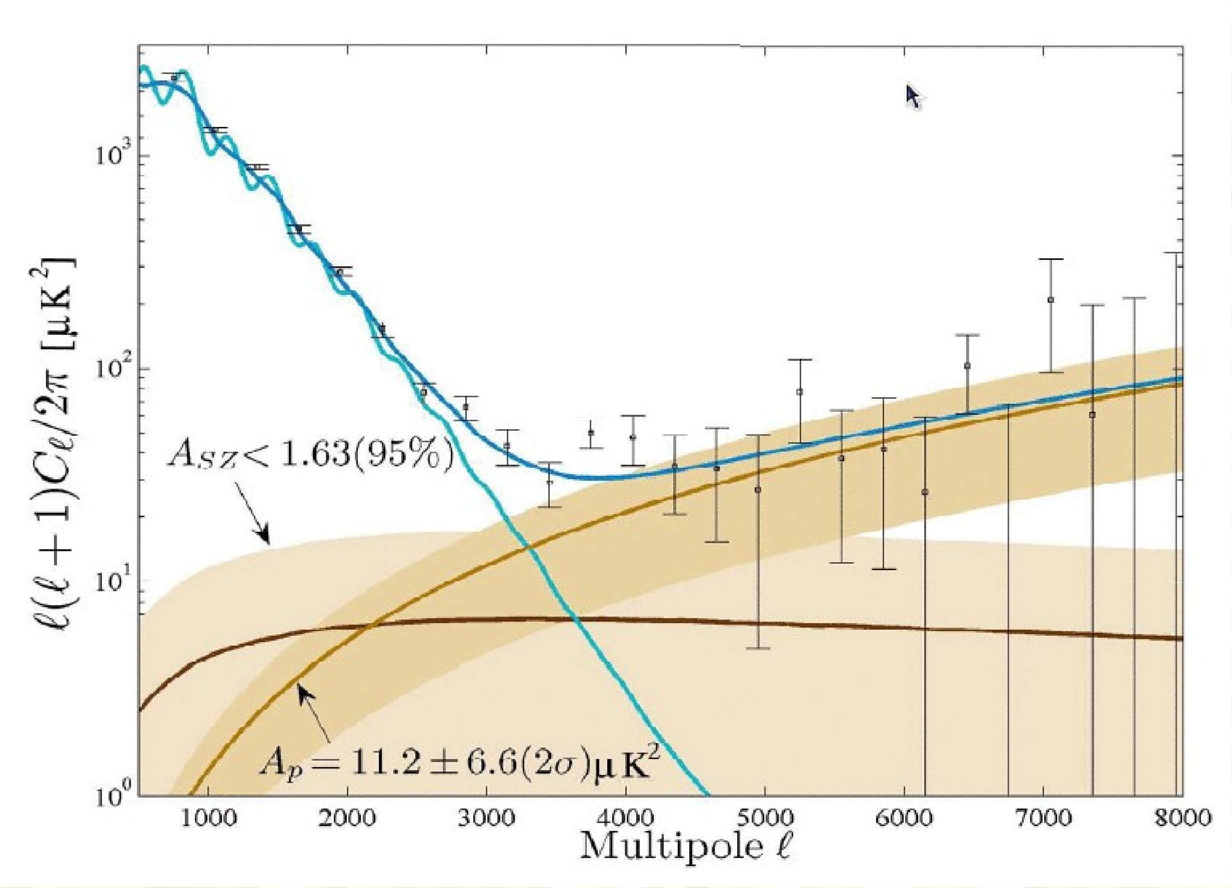




C(l):
Flattenning of specrum

D(l)=l(l+1)C(l)/2pi

Example from reality:
Atacama Cosmology Telescope



(Fowler at al., arXiv:1001.2934), 148 GHz, *theta*=1.4'.

Actually, the procedure is more complex and uses Monte Carlo simulations:

1) Simulation of sources (>=1000 times)
2) Simulation of signal separation and source removing from CMB (>1000 time).

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And you are invited to do this by yourself...