

Part 4. Practical work

Simulations in GLESP
using angular power spectrum

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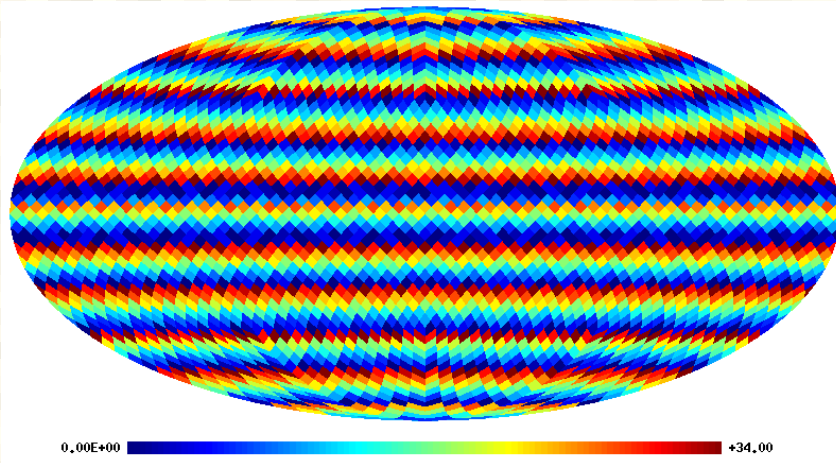
Special astrophysical observatory, Russia

Data analysis of CMB

- Registration: time ordered 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

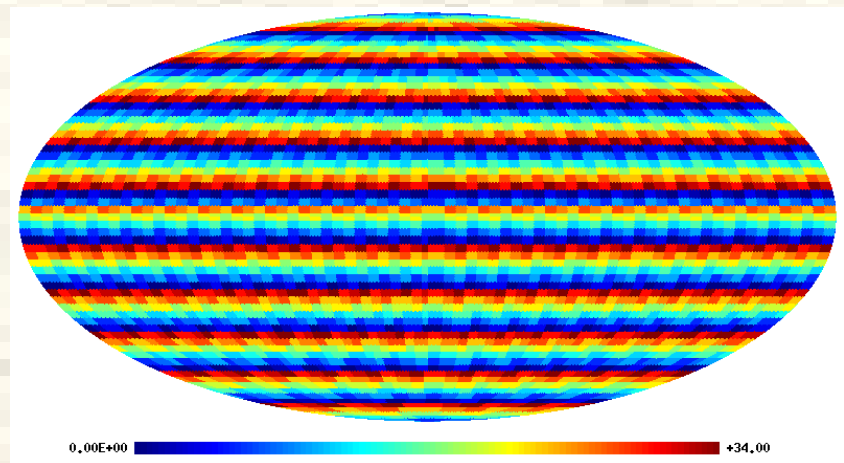
Packages for 2 schemes

HEALPix



Hierarchical scheme
pixel calculations
Based on $12 \cdot 2^n$ equal pixels
(Gorski et al., 1993, 2005)

GLESP



Non-hierarchical 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:

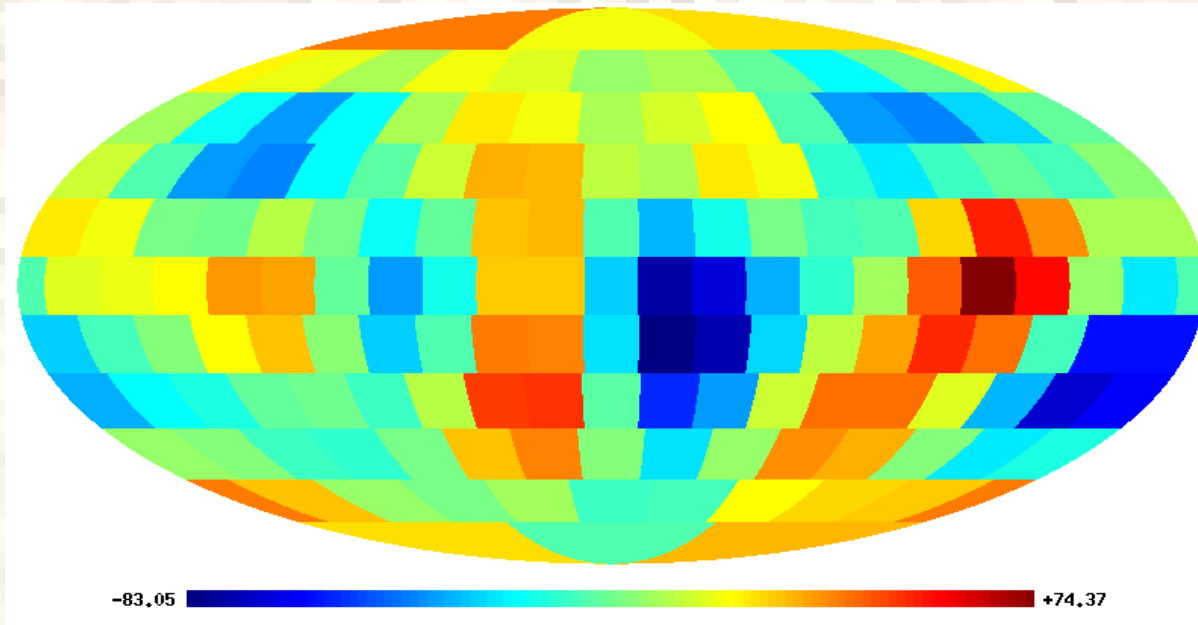
*Exact equality ($\sim 10^{-8}$ or 10^{-16})
(float or double)*

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

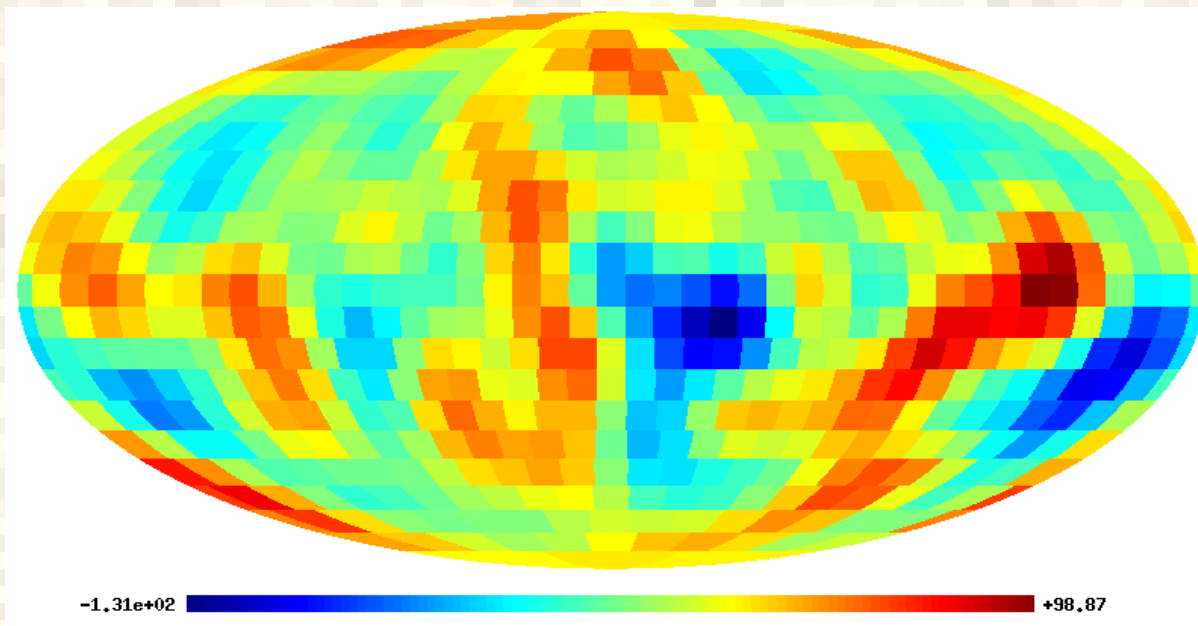
Pixelization knots by polar angle are in zeros of Legendre polynomials

GLESP: Gauss-Legendre Sky Pixelization

Resolution parameters: L_{max} , $N_x > 2L_{max}$, $N_{phi} \geq 2N_x$



$L_{max}=5$
 $N_x = 11$
 $N_{phi} = 22$



$L_{max}=10$
 $N_x=21$
 $N_{phi}=42$

GLESP

- 1) Specially for advanced multipole operation
- 2) Strictly orthogonal decomposition and no iterations in map-multipole conversion
- 3) Non-hierarchical scheme
- 4) Realization in GNU C

GLESP: main procedures

- 1) Conversion: anisotropy maps \rightarrow harmonics a_{lm} -s \rightarrow maps
- 2) conversion: polarization Q,U \rightarrow harmonics E,B $_{lm}$ \rightarrow 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

$$C(l) = \frac{1}{2l + 1} \left[|a_{l0}|^2 + 2 \sum_{m=1}^l |a_{l,m}|^2 \right]$$

$$a_{l,m} = \int_{-1}^1 dx \int_0^{2\pi} d\phi \Delta T(\theta, \phi) Y_{l,m}^*(x, \phi)$$

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

Selection of angular power spectrum
(in forms of dat- or FITS-file)

Angular power spectrum of CMB

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

CAMB: *Lewis, Challinor, Lasenby, 2000*

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

LAMBDA - CAMB Web Interface - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm

Most Visited Release Notes Fedora Project Red Hat Free Content

CAMB Web Interface

Supports the January 2011 Release

Most of the [configuration documentation](#) is provided in the sample parameter file provided with the application

This form uses JavaScript to enable certain layout features, and it uses Cascading Style Sheets to control the layout of all the form components. If either of these features are not supported or enabled by your browser, this form will NOT display correctly.

Actions to Perform

Scalar C_l's Do Lensing Linear
 Vector C_l's Transfer Functions Non-linear Matter Power (IALOFIT)
 Tensor C_l's Non-linear CMB Lensing (HALOFIT)

Sky Map Output:

Vector C_l's are incompatible with Scalar and Tensor C_l's. The Transfer functions require Scalar and/or Tensor C_l's. The HEALpix synfast program is used to generate maps from the resultant spectra. The random number seed governs the phase of the a_{lm}'s generated by synfast. The default of zero causes synfast to generate a new seed from the system time with each run. Specifying a fixed nonzero value will return fixed phases with successive runs.

*Maximum Multipoles and k*eta*

Scalar	Tensor
<input type="text" value="2000"/> l _{max}	<input type="text" value="1500"/> l _{max}
<input type="text" value="4000"/> k*eta _{max}	<input type="text" value="3000"/> k*eta _{max}

Tensor limits should be less than or equal to the scalar limits.

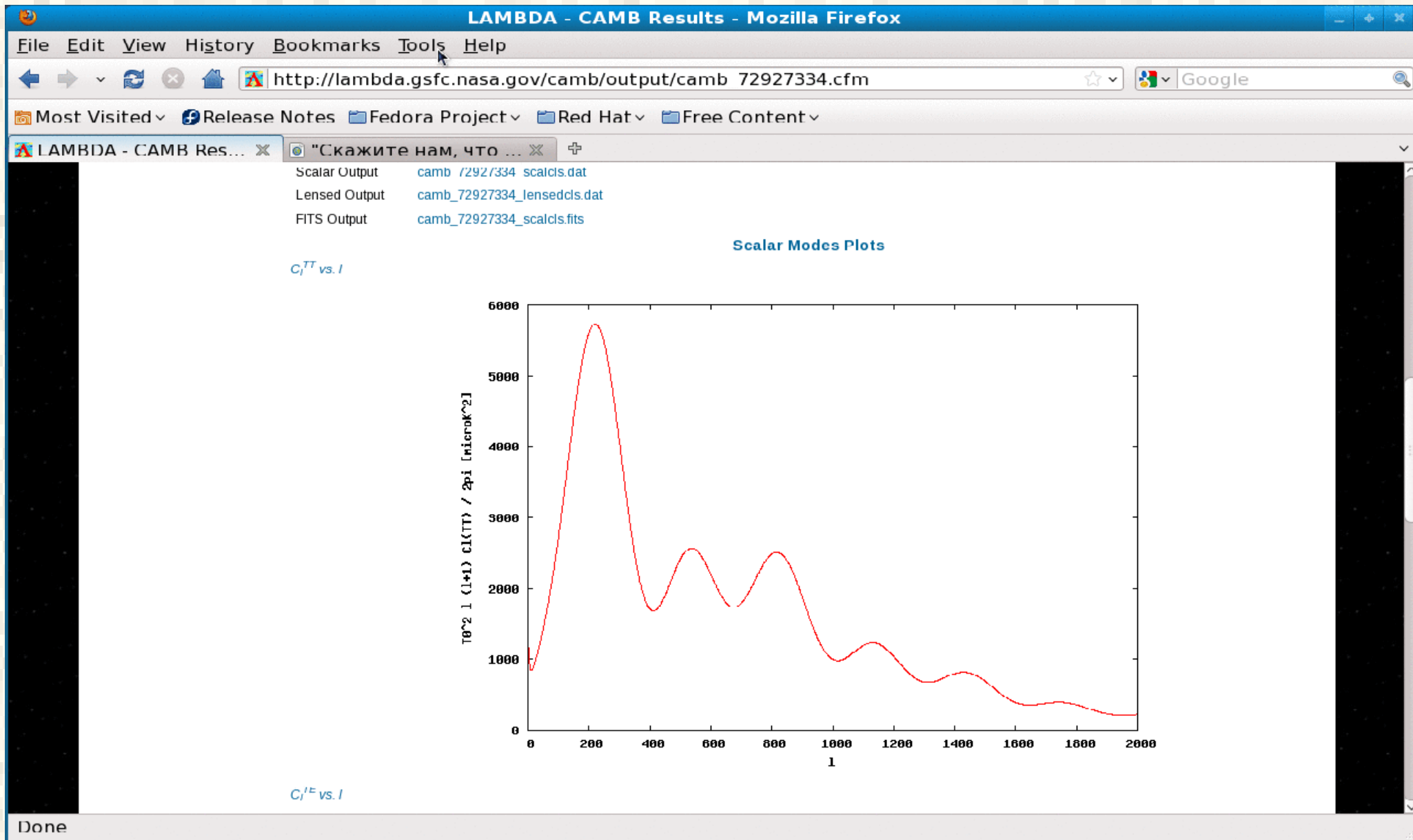
Cosmological Parameters

Use Physical Parameters?

<input type="text" value="70"/> Hubble Constant	<input type="text" value="0.0226"/> Ω _b h ²	<input type="text" value="0.114"/> Ω _c h ²	<input type="text" value="0.24"/> Helium Fraction
<input type="text" value="2.725"/> T _{cmb}	<input type="text" value="0"/> Ω _v h ²	<input type="text" value="0"/> Massive Neutrinos	<input type="text" value="3.04"/> Massless Neutrinos
	<input type="text" value="0"/> Ω _k	<input type="text" value="-1"/> Eqn. of State	

Done

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:

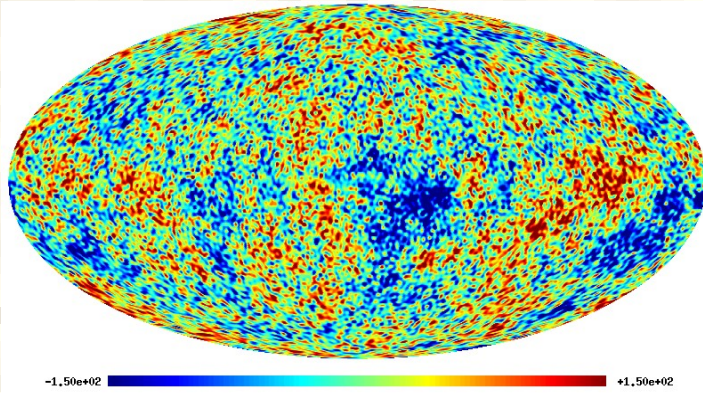
'-Cs a,b' – sets cut levels [a,b] on output image

'-gre' – outputs ecliptic system grids

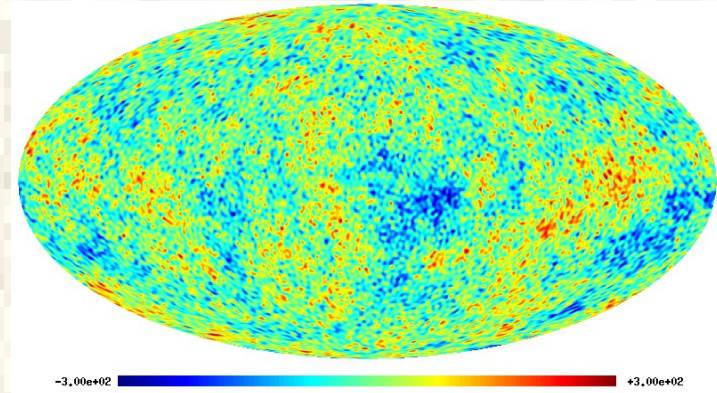
'-grq' – output equatorial system grids

'-grg' – outputs galactic system grids

f2fig cut-limits

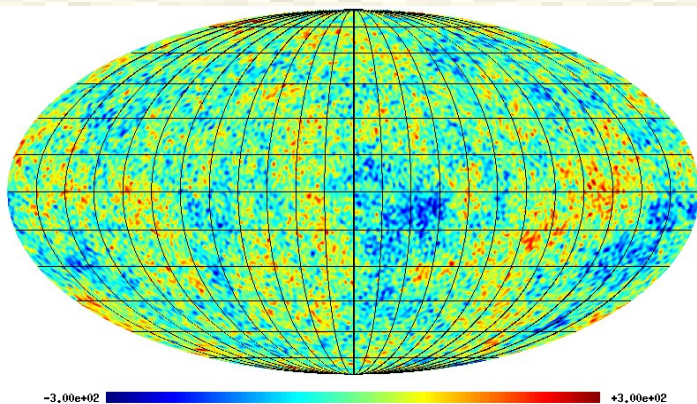


$-0.1\text{mK} < v < 0.1\text{mK}$

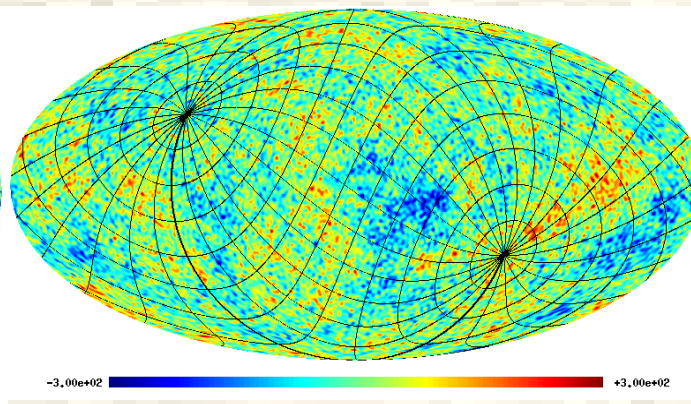


$-0.3\text{mK} < v < 0.3\text{mK}$

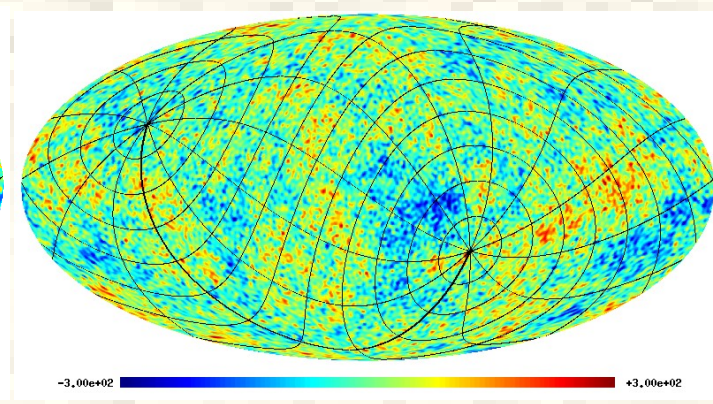
f2fig coordinate system grids



galactic

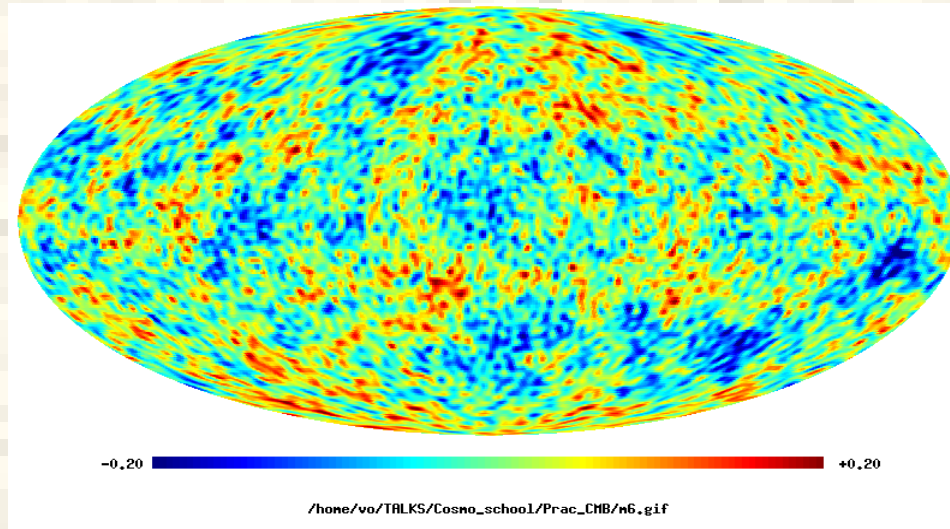


ecliptic

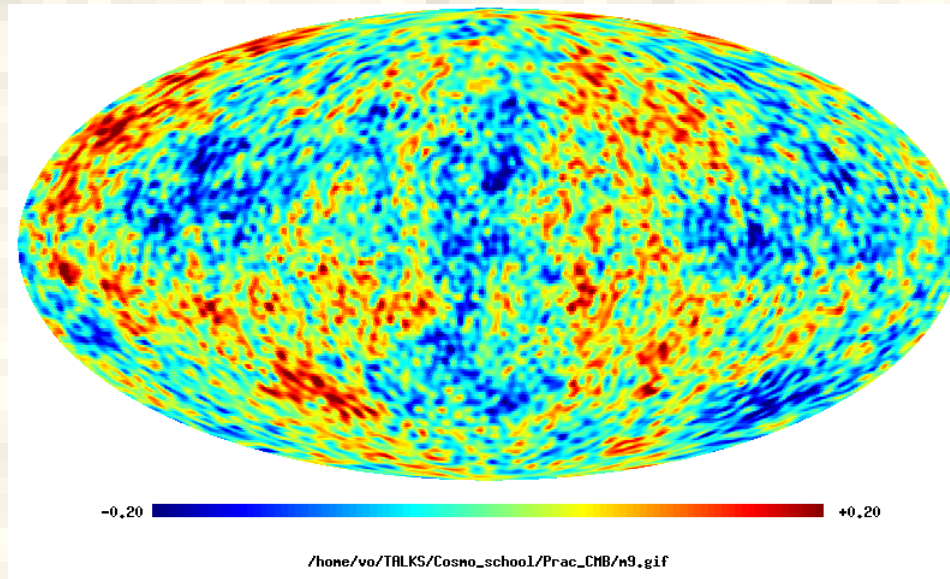


equatorial

Example of random simulation for LCDM-cosmology

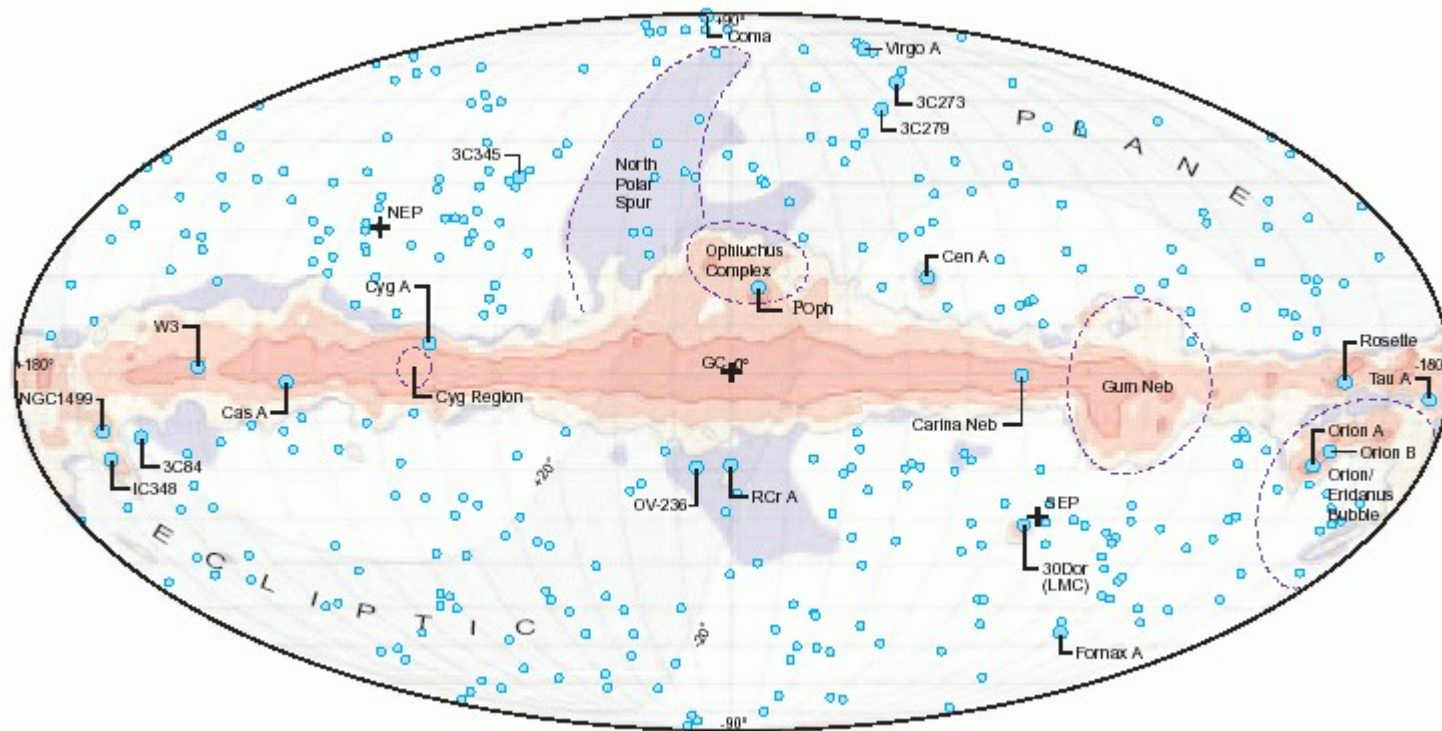


$r=6$



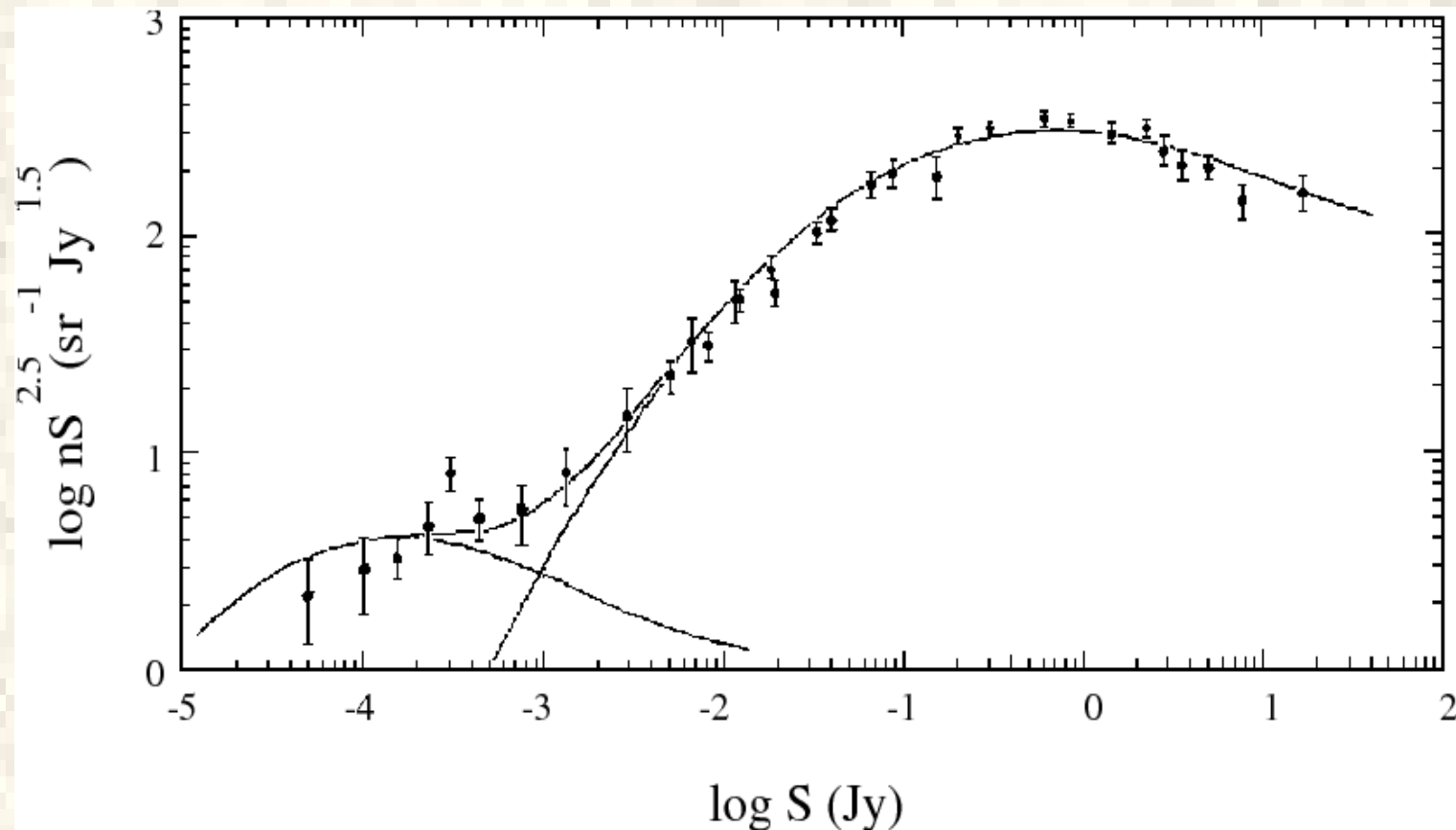
$r=9$

Preparation of the map with object data



Preparation of a pattern map

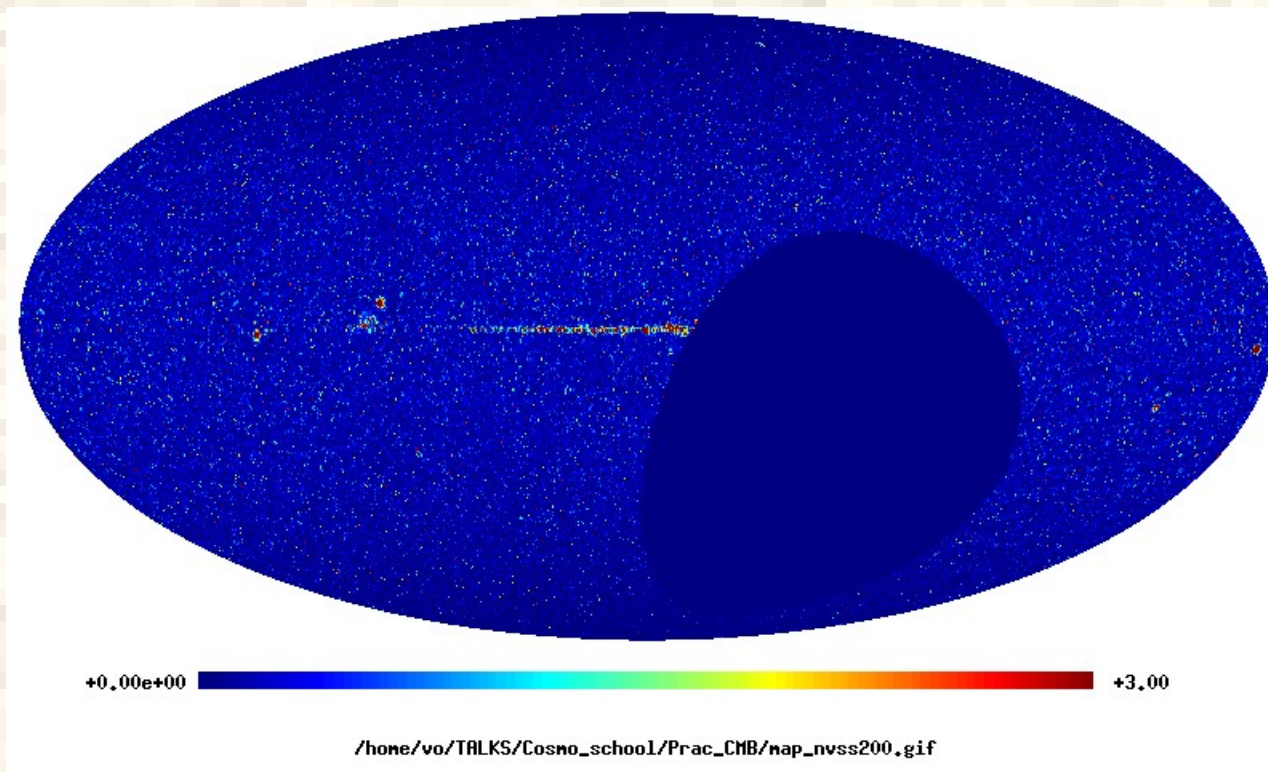
E.g. one can produce a random simulation of Poisson distribution and flux densities corresponding to 'log N – log S ' counts



Or one can prepare a pattern from NVSS catalog

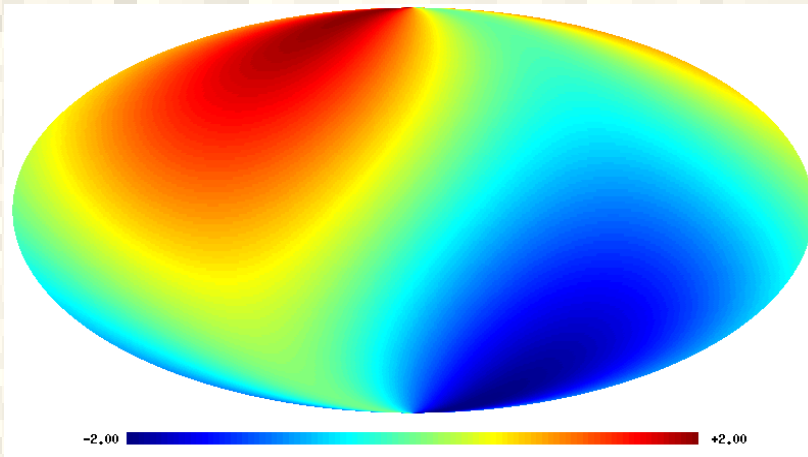
```
mappat -fp source.list -nx 401 -np 802 -o m_src.fts
```

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

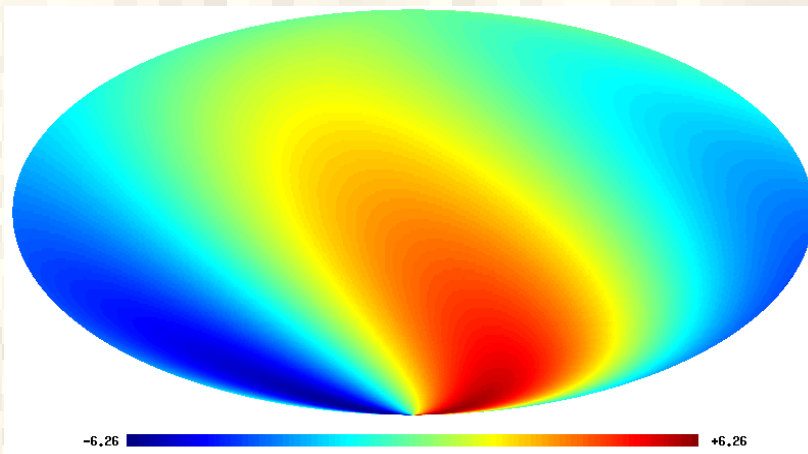


One more possibility of 'mappat'

Patterns by algebraic formula (examples)



$$y = \cos(\theta) + \sin(\phi)$$

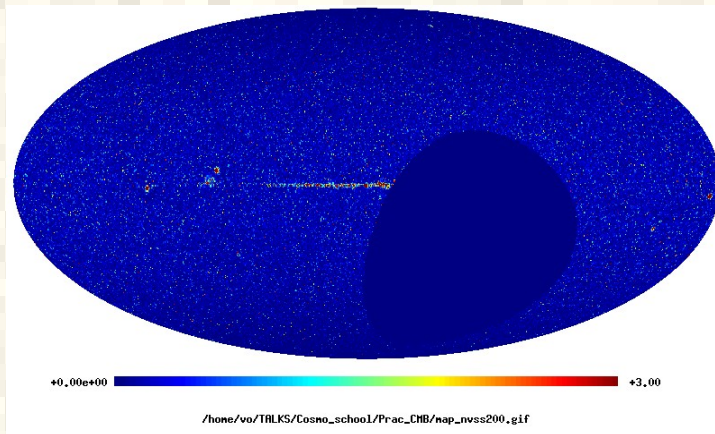


$$y = 2(\sin(\theta + \phi) + \theta)$$

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 $L_{max}=100$

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

'-fw 55' – sets the size of Gaussian bin in arcmin:

55' --> $L_{max}=100$

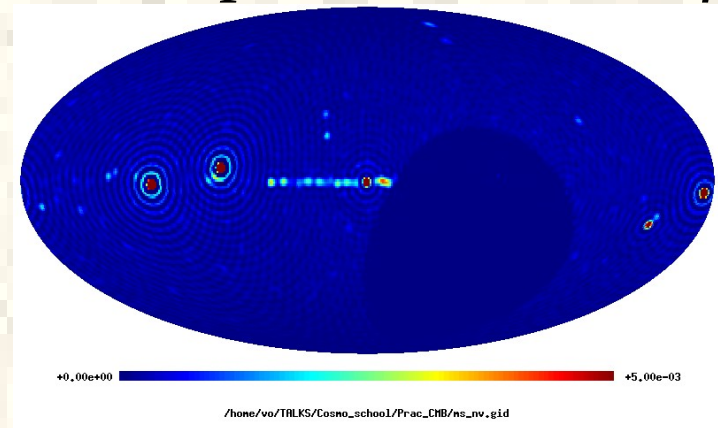
a_nv.fts – input file of *a_lm-s*

'-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 frequency

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

Where rings are from ?



Preparation 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

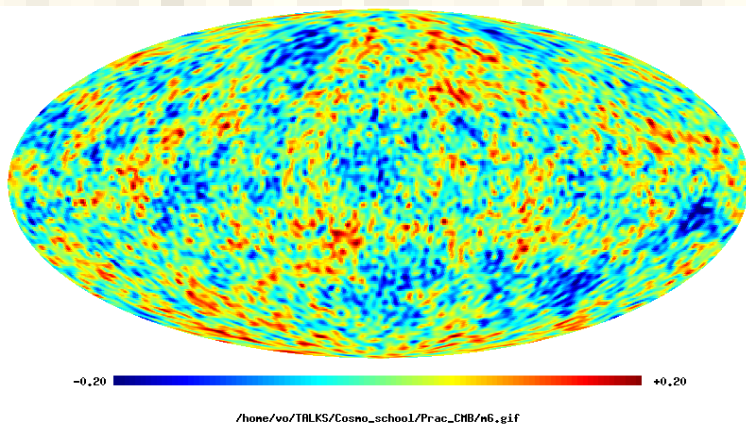
In pixel domain:

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

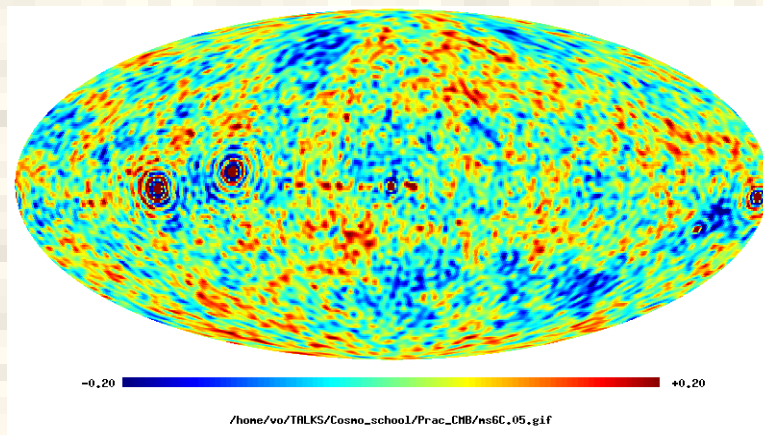
In multipole domain:

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

And converse with '*cl2map*'.

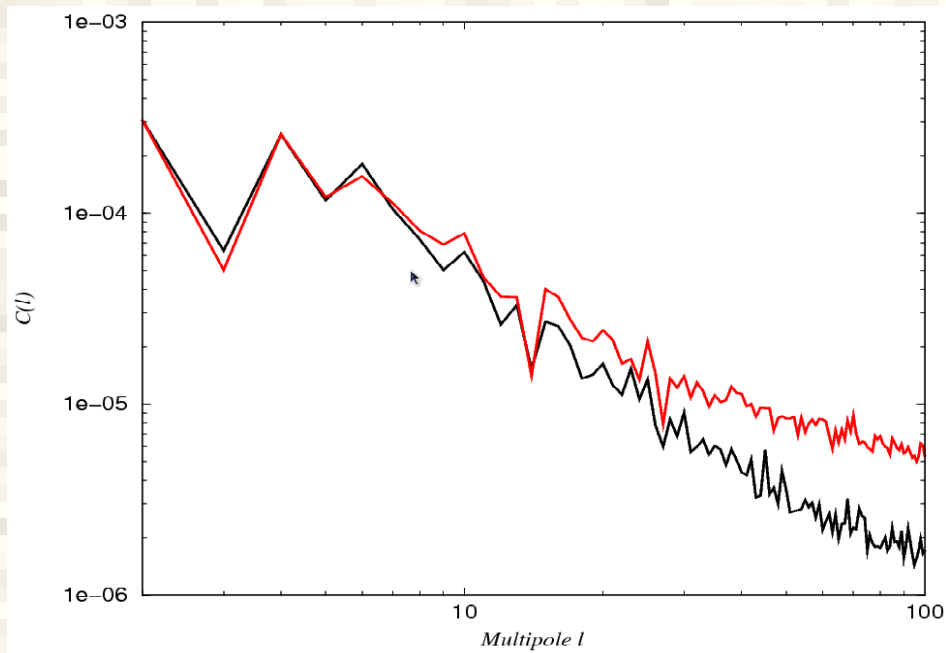


Before

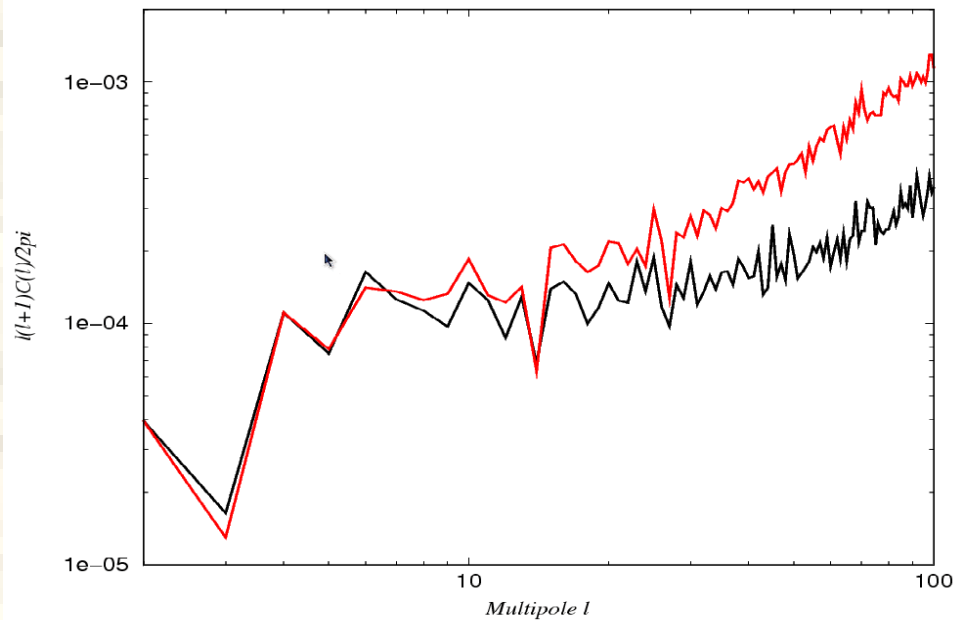


After

Power spectrum

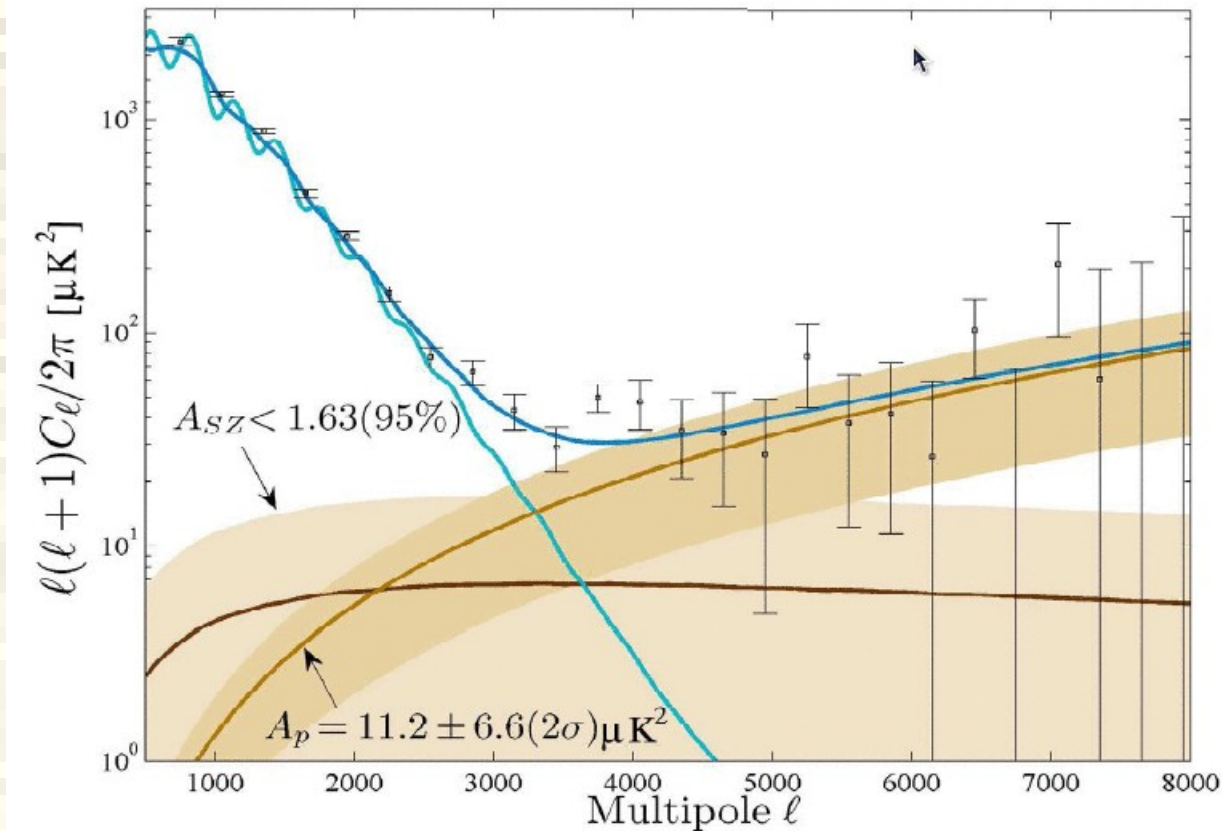


$C(l)$:
Flattening of
spectrum



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

Example from reality: Atacama Cosmology Telescope



(Fowler et 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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- 1) Simulation of sources (≥ 1000 times)
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And you are invited to do this by yourself...

