Image: Dark Energy Camera, from http://darkenergydetectives.org

Introduction to Cosmology 2: CMB and LSS

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CIEMAT

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Centro de Ciencias Pedro Pascual, Benasque
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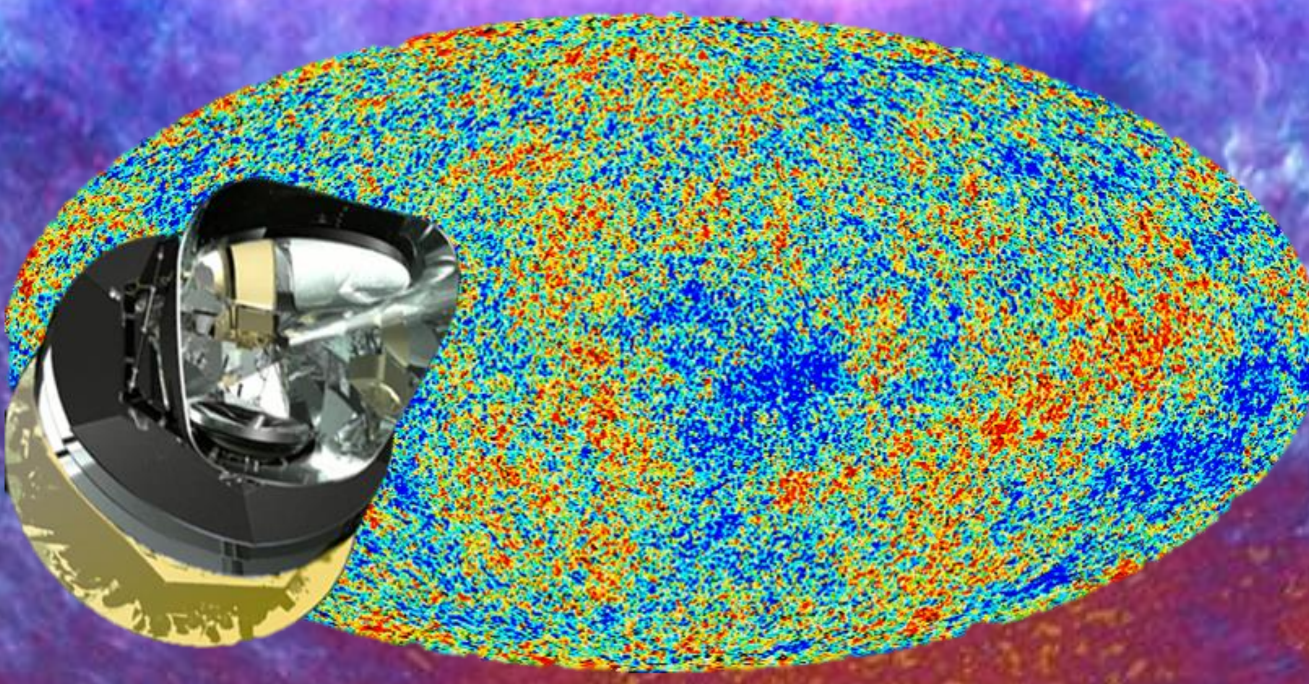
THE COSMIC MICROWAVE BACKGROUND (CMB)

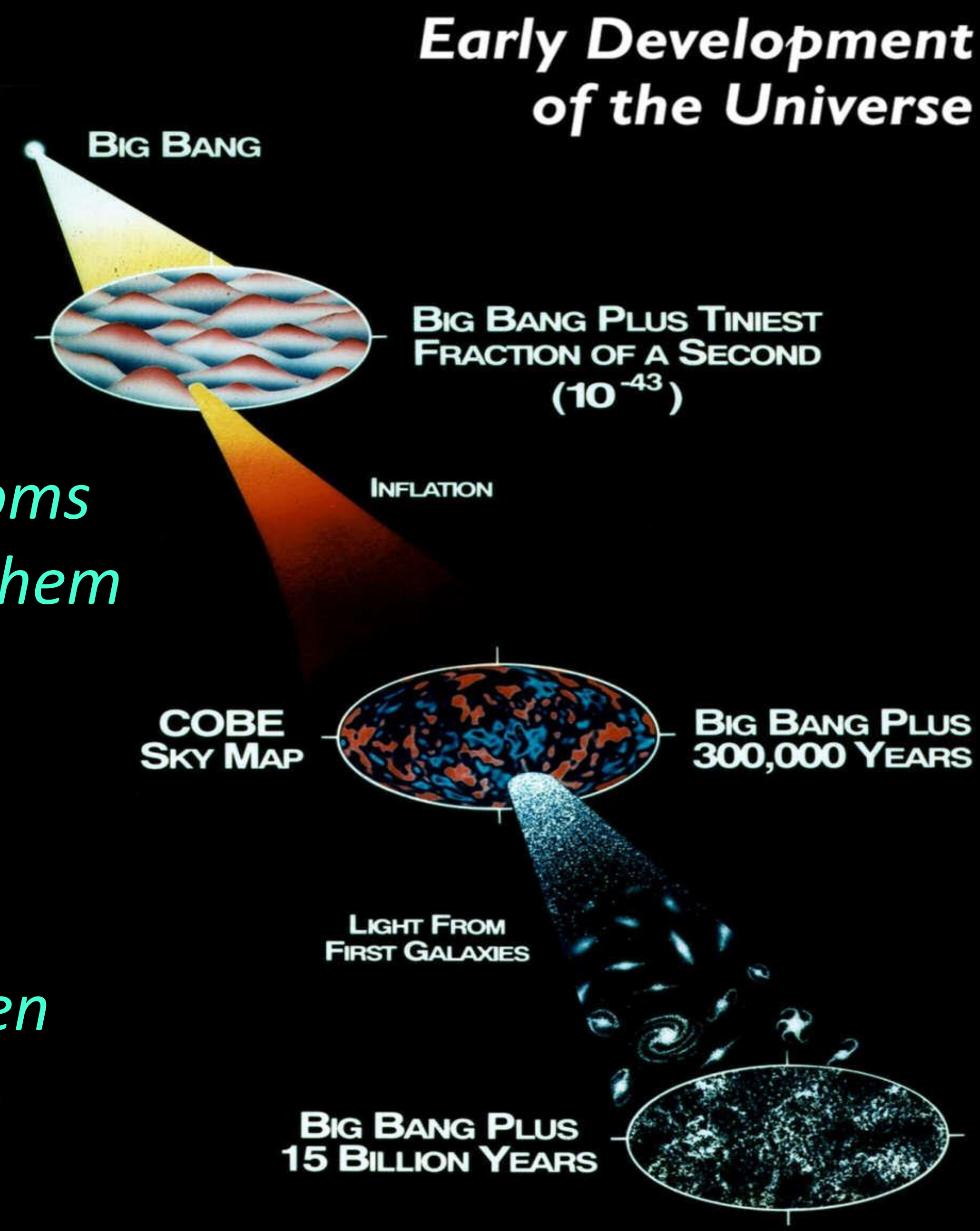


Before recombination

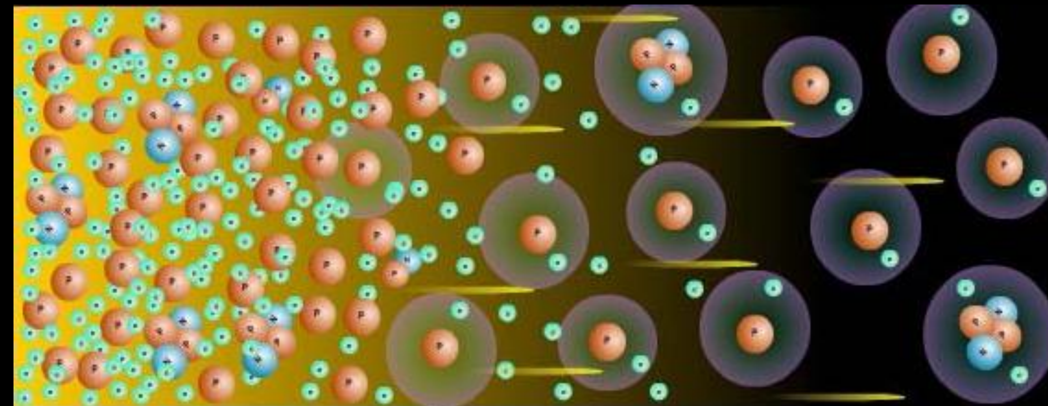
- Early Universe
- High temperature
  - *Electrons are not in atoms*
  - *Photons interact with them*

Recombination

- Late Universe
- Lower Temperature
  - *e- and p+ form hydrogen*
  - *Photons travel freely*



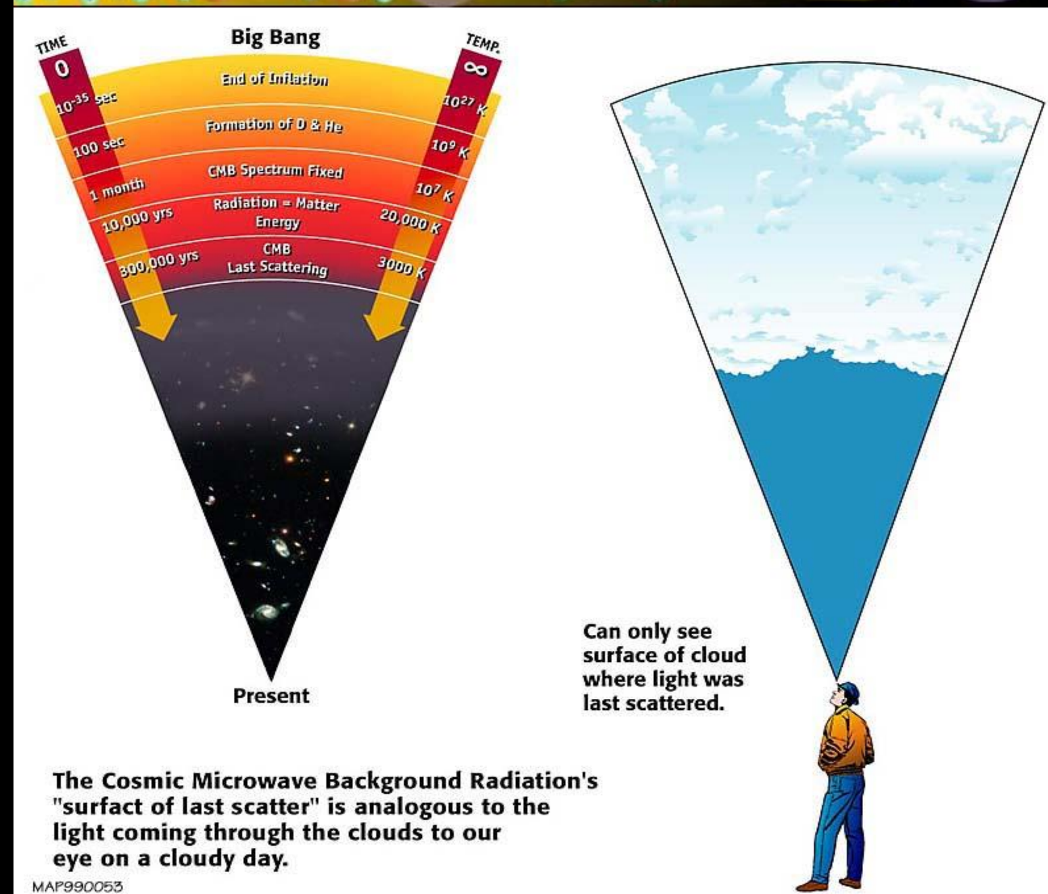
Cosmic Microwave Background (CMB)



Thermal radiation from the formation of atoms ~380000 years after BB or…. 3800 Myears ago!!

Discovered in 1965
Small anisotropies discovered in 1992. These are the sedes of all structure in the Universe

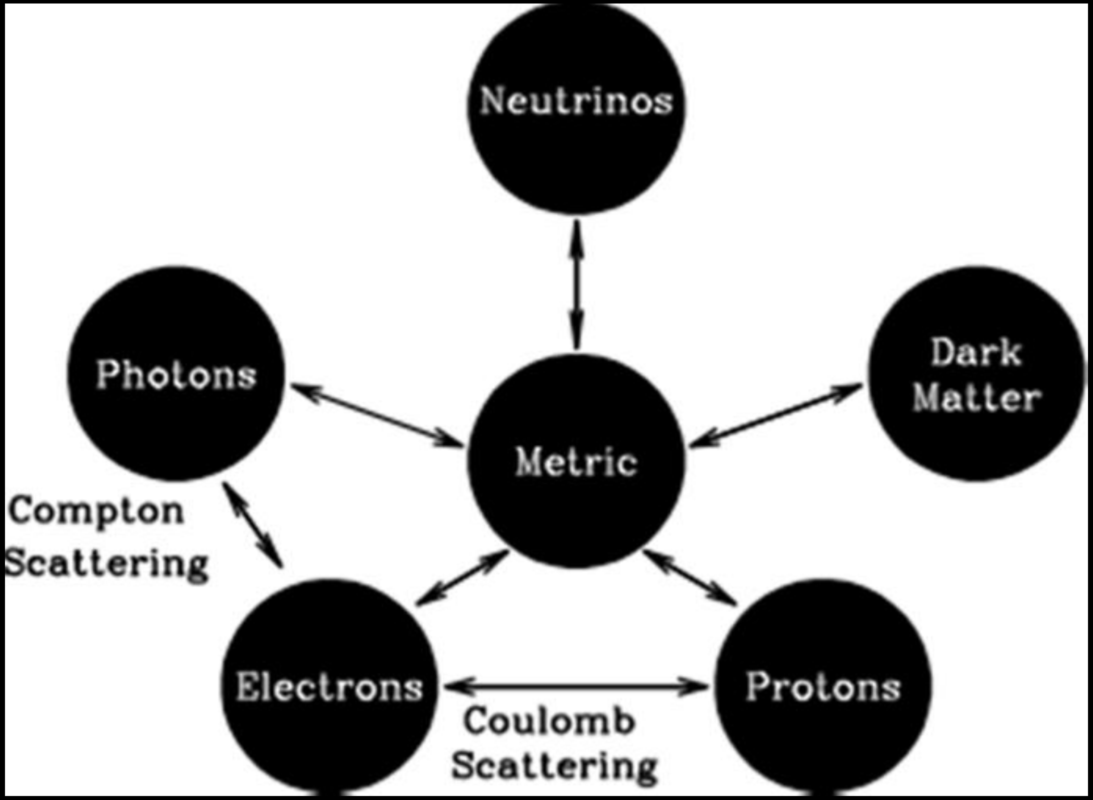
The most precise measurements of cosmological parameters come from the CMB



Cosmic Microwave Background (CMB)

Ingredients:

- Thomson scattering for $e^- \gamma$ collisions
- Physics of recombination $e^- + p \leftrightarrow H + \gamma$
- General Relativity
- Boltzmann equation



$$\frac{d\ Photons}{dt} = Metric + Compton\ Scattering$$

$$\frac{d\ (Electrons{+}Hadrons)}{dt} = Metric + Compton\ Scattering + Weak\ Interaction$$

$$\frac{d\ Neutrinoss}{dt} = Metric + Weak\ Interaction$$

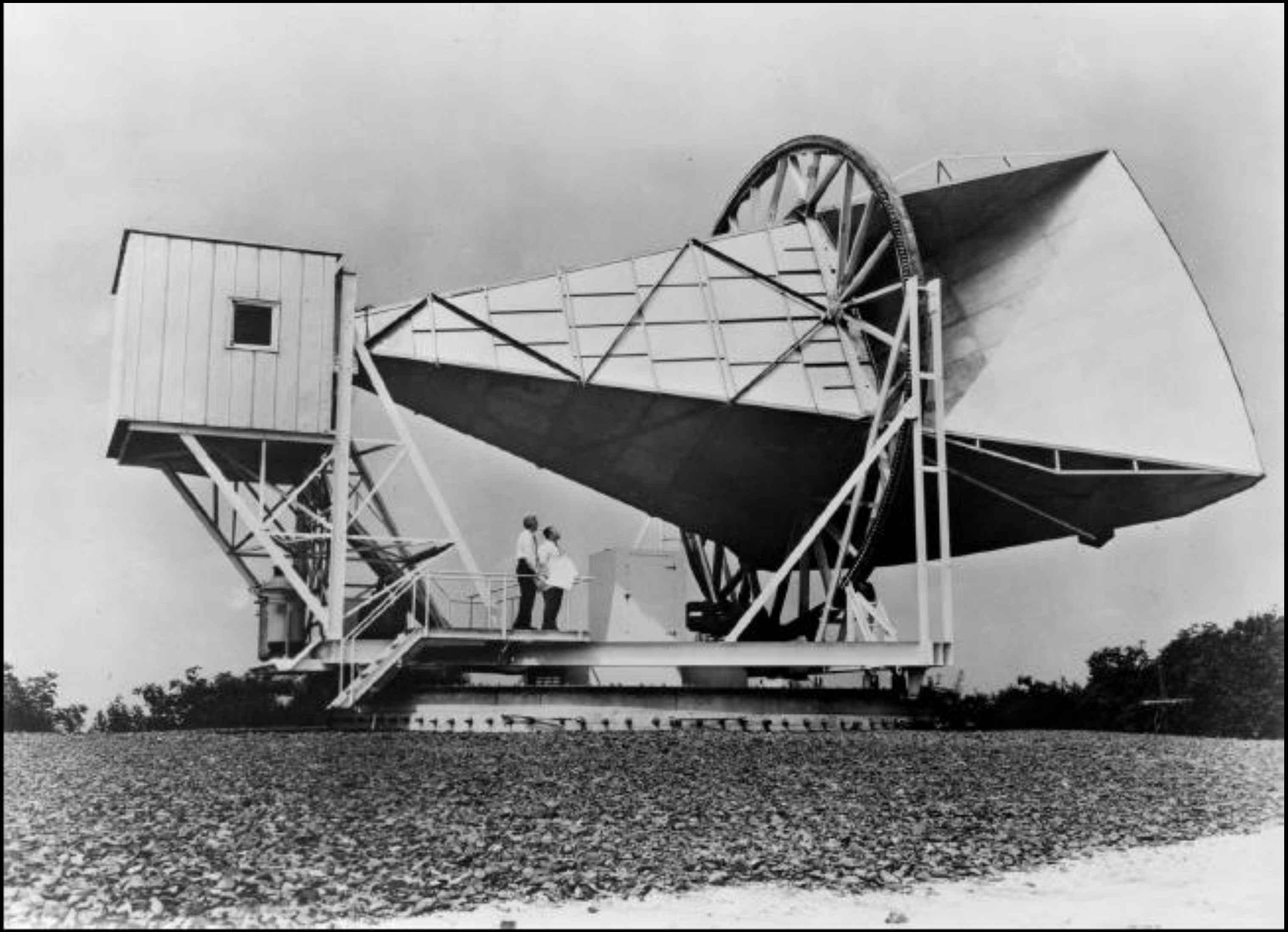
$$\frac{d\ Dark\ Matter}{dt} = Metric + ??$$

Discovery of the CMB: Horn antenna for radio waves

Arno Penzias y Robert Wilson of Bell Labs (1965)

Low and permanent noise in the receiver

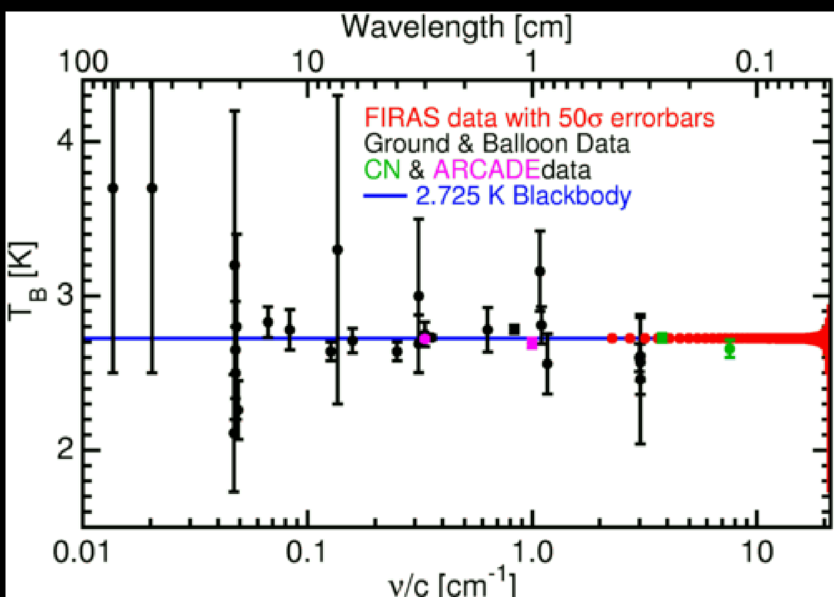
Accidental discovery

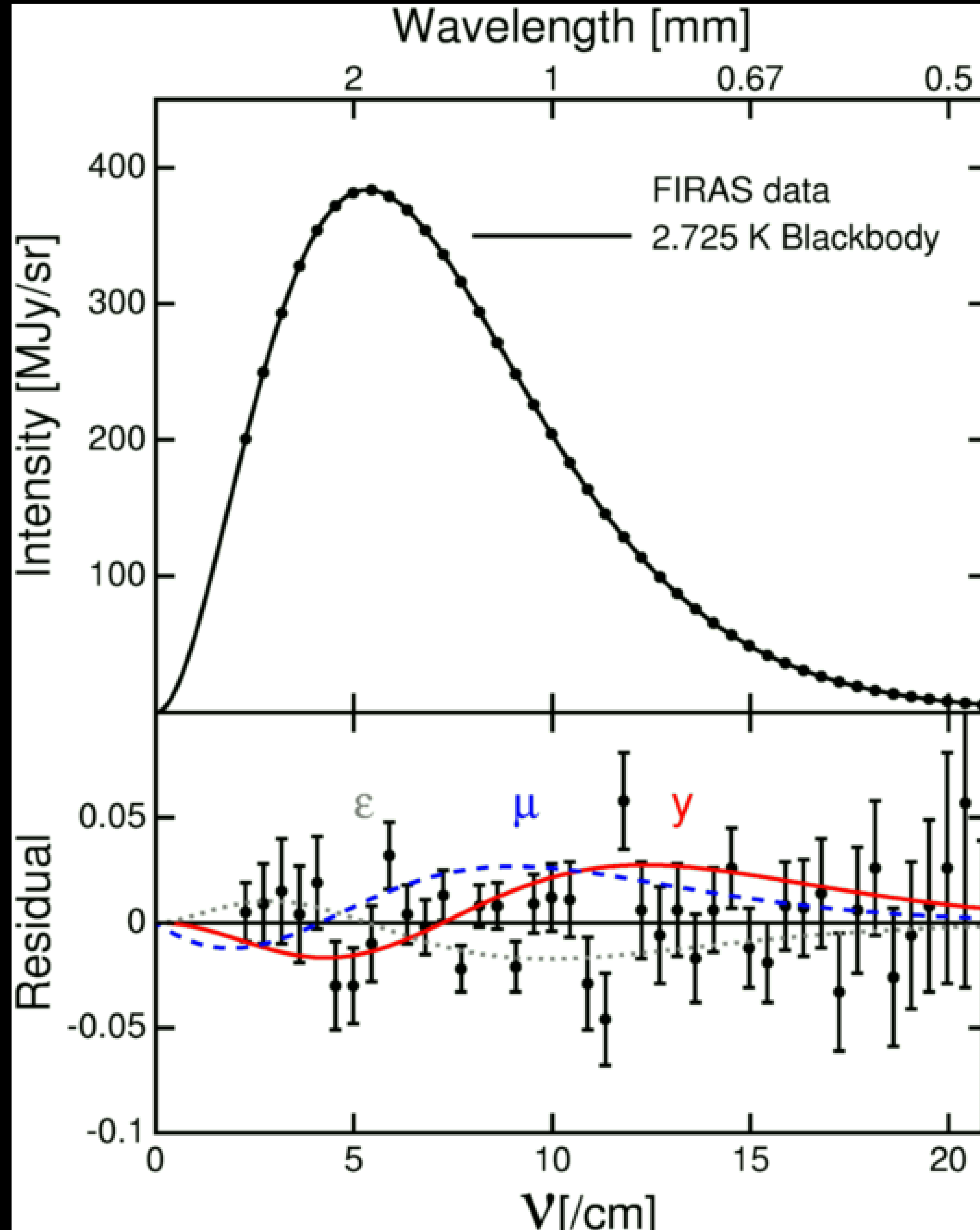


National Historic Landmark (1988)

The frequency spectrum:
A perfect black body at 2.725K

The Universe was in thermal equilibrium before recombination: *The collision rate was much larger than the expansion rate*





On the CN non-discovery

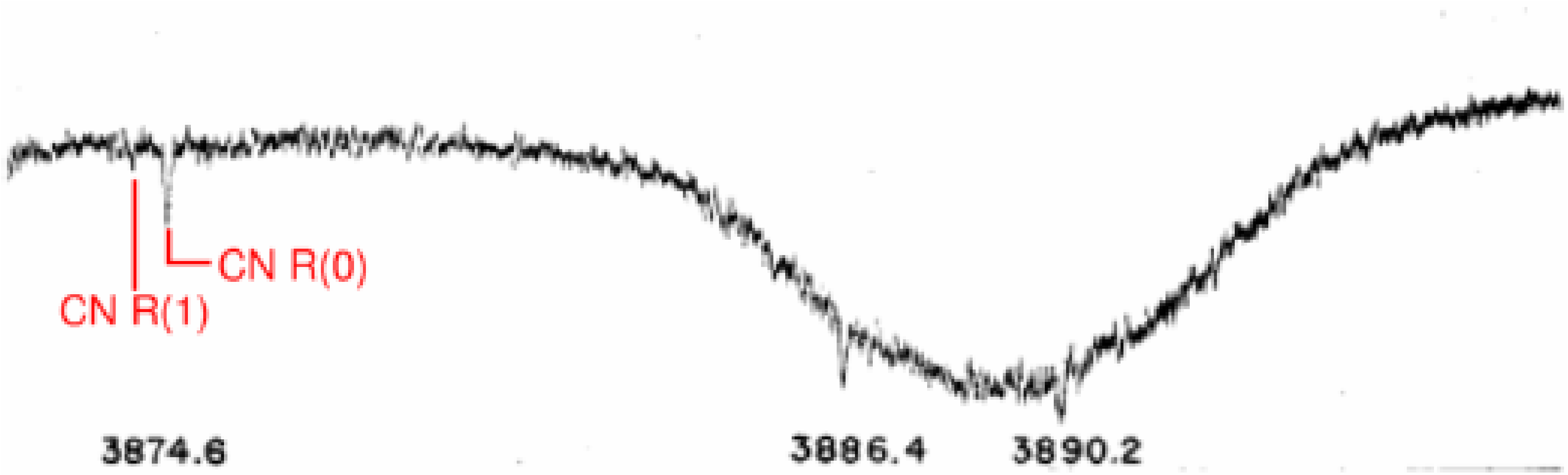


Plate 3 of Adams (1941, ApJ, 93, 11-23)

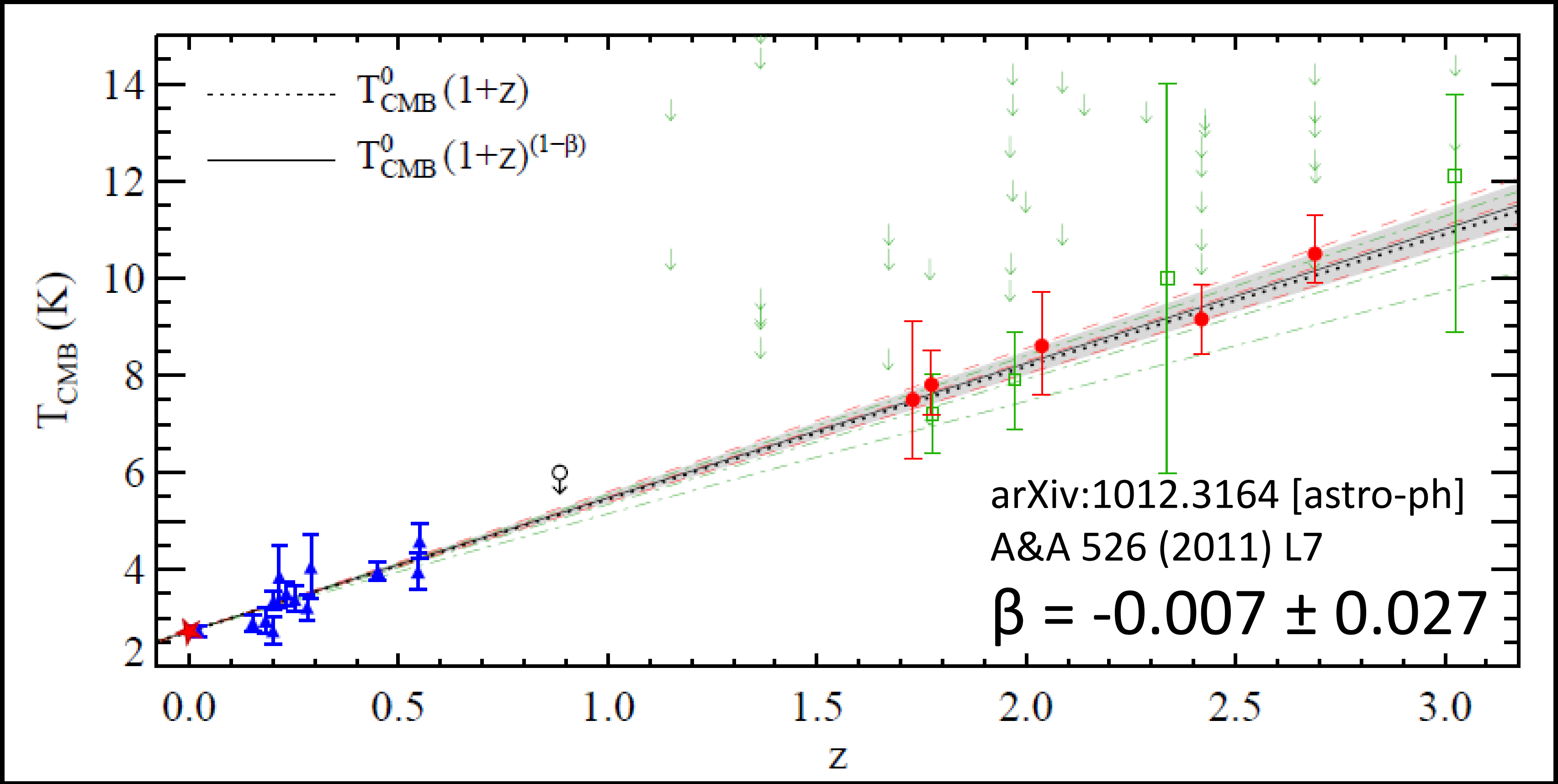
Herzberg (1950) in *Spectra of Diatomic Molecules*, p 496:

"From the intensity ratio of the lines with K=0 and K=1 a rotational temperature of 2.3° K follows, which has of course only a **very restricted meaning**."

There went Herzberg's [second] Nobel Prize.

Slide from Ned Wright

CMB Temperature . vs . z



COBE

CO Molecule lines

SZ Effect

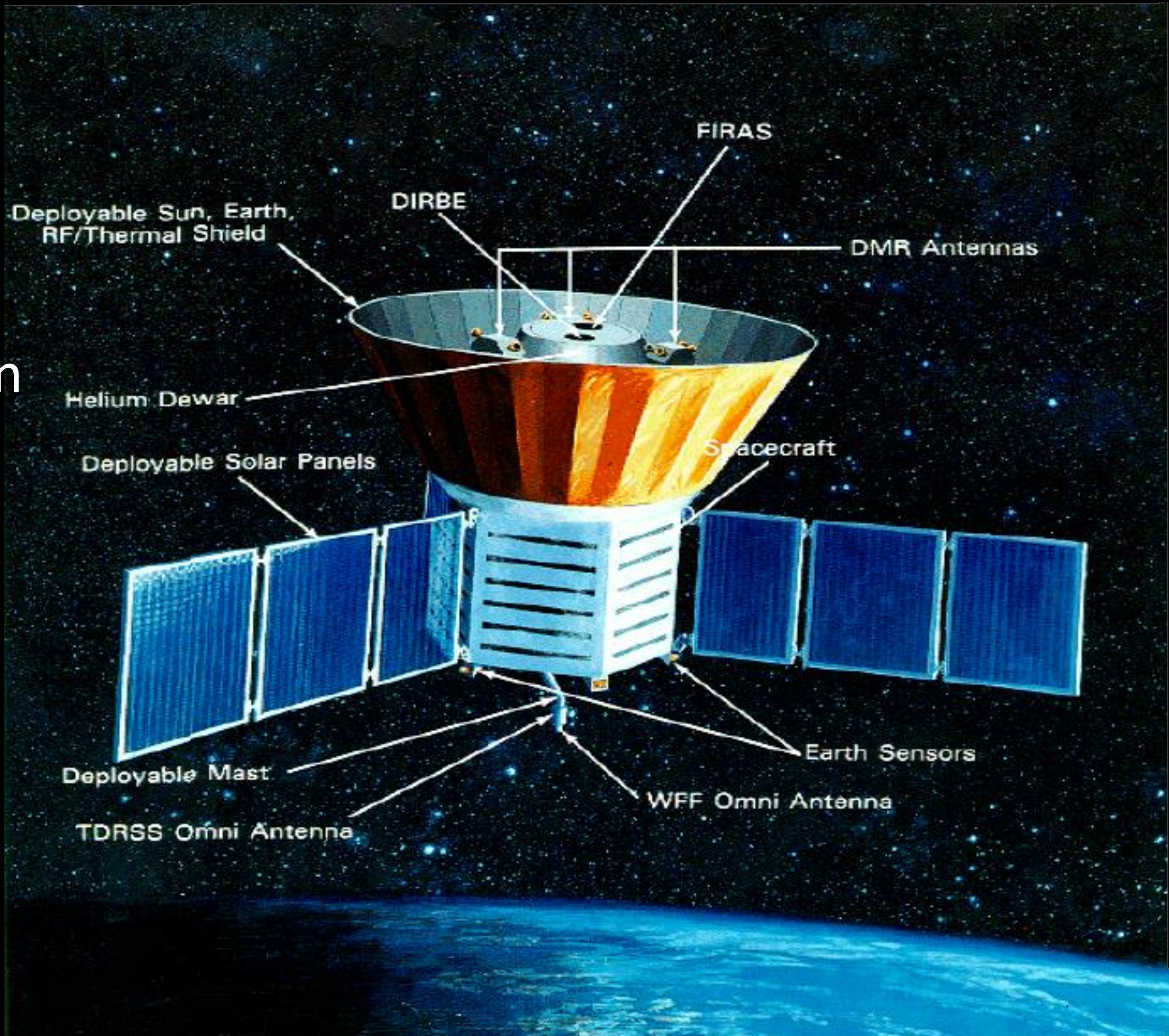
C atom lines

COBE Satellite

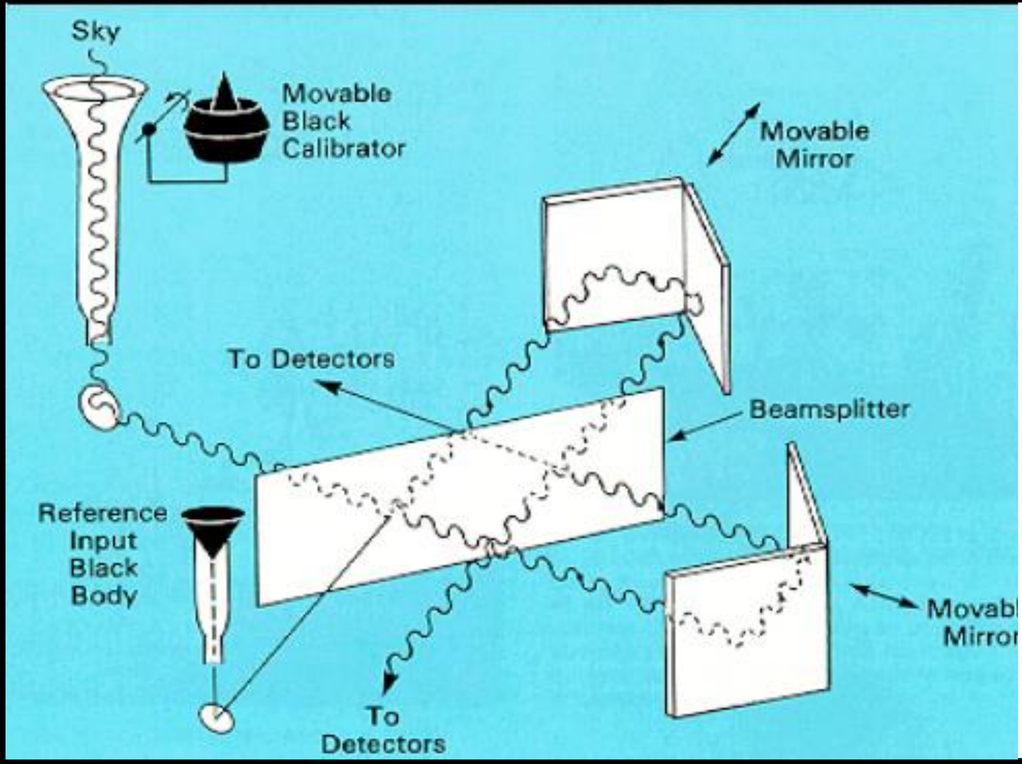
Launched in 1989, for a 4 years misión

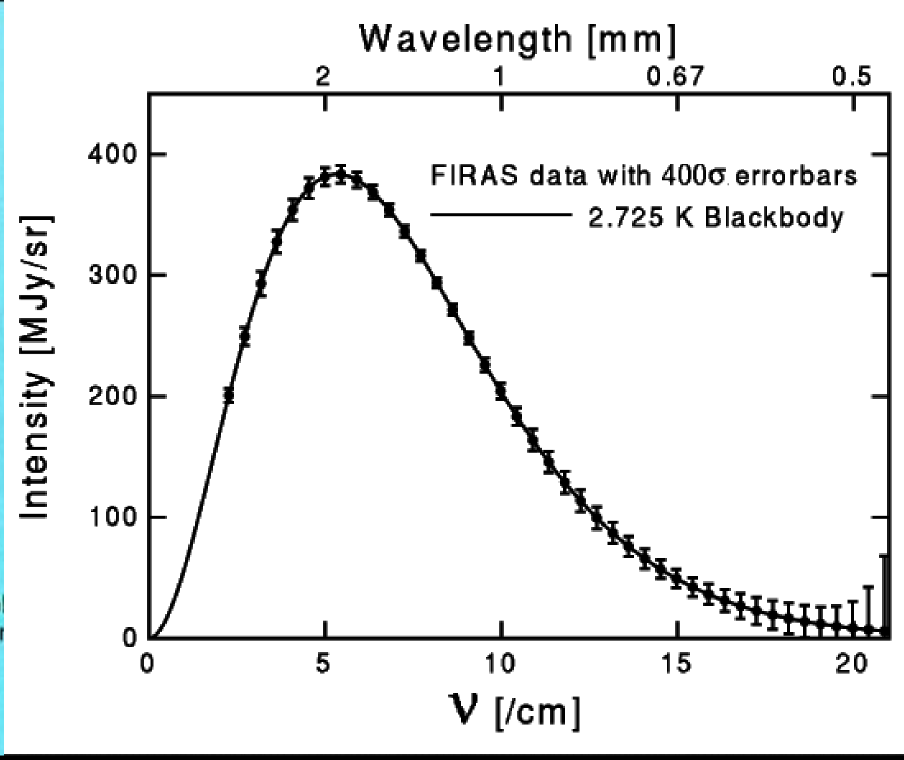
A high precision measurement of the CMB temperature (1990)

First detection of anisotropies (1992)



FIRAS detector: Temperature of the CMB

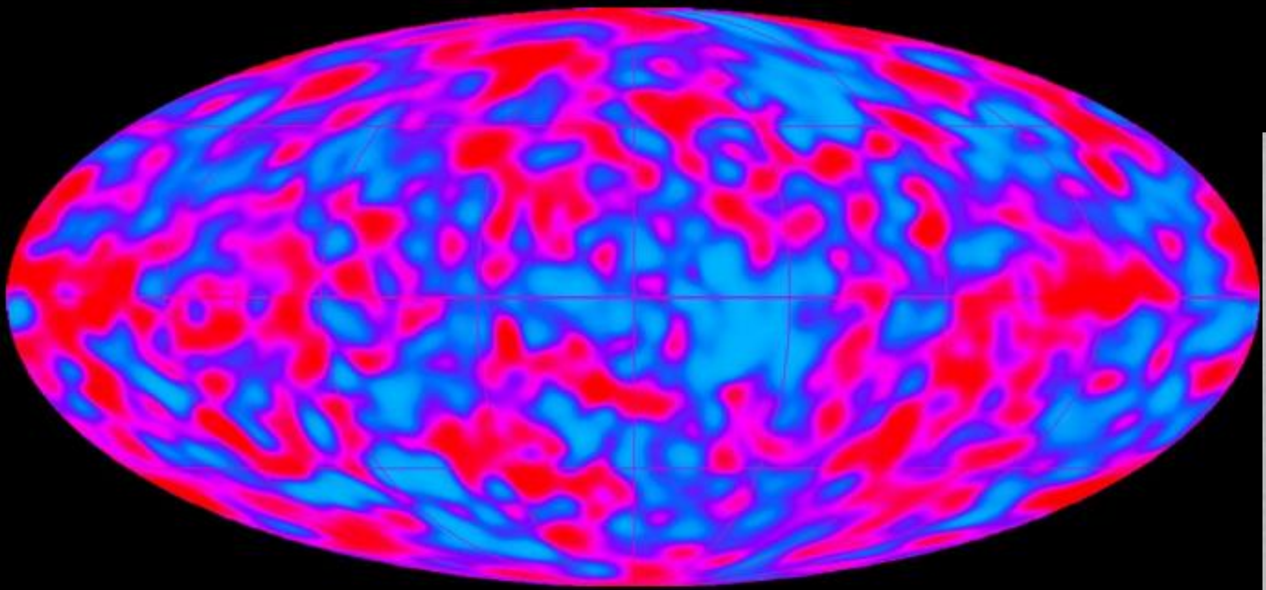


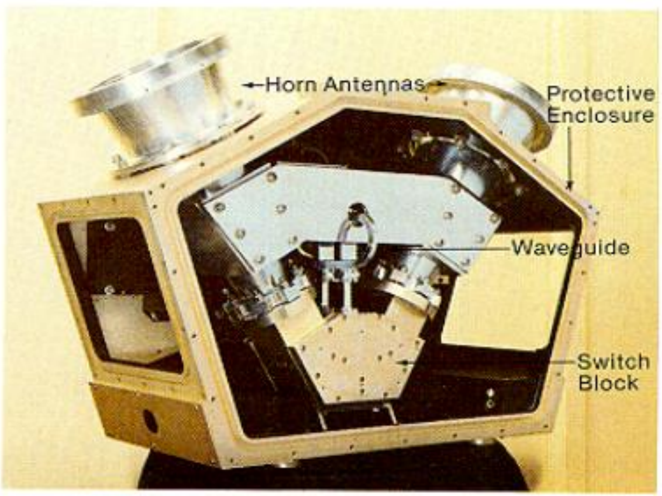


$$T_{CMB} = 2.72548 \pm 0.00057\ K$$

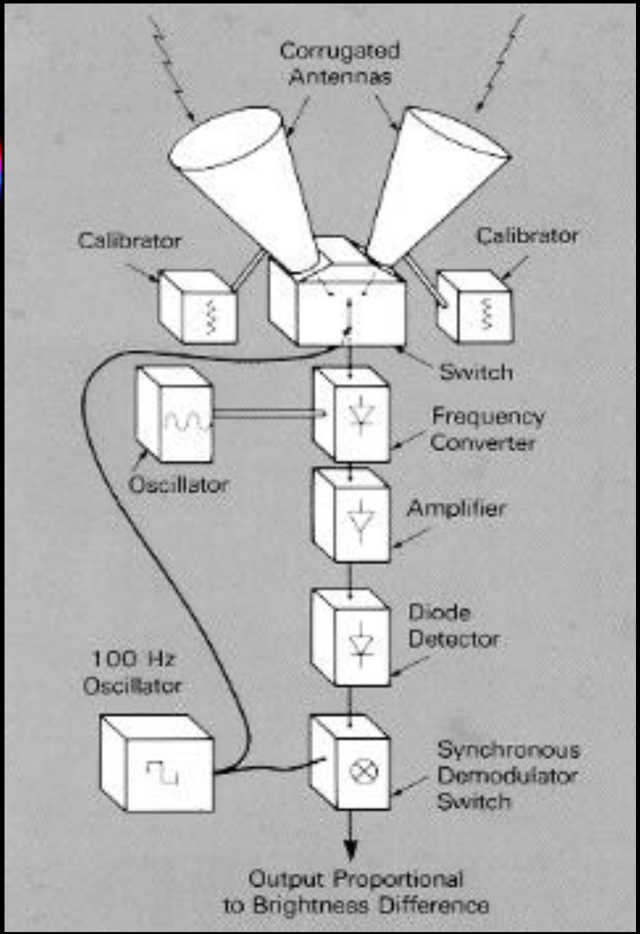
(ApJ 707 2009, 916-920)

DMR detector: CMB fluctuations





The 9.6 mm DMR receiver partially assembled. Corrugated cones are antennas.

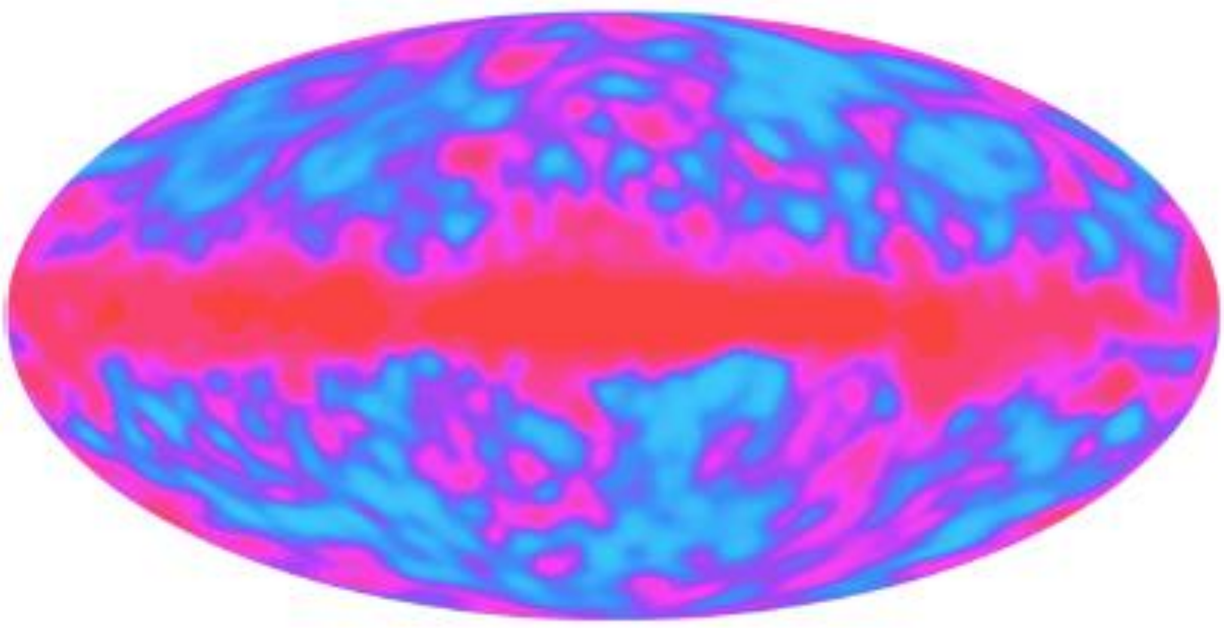


A Big Media Splash in 1992:

THE TIMES

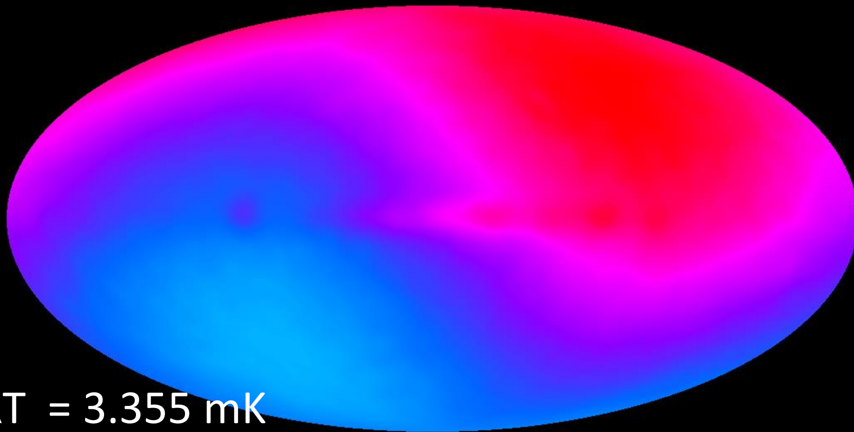
25 April 1992

Prof. Stephen Hawking of Cambridge University, not usually noted for overstatement, said: “It is the discovery of the century, if not of all time.”

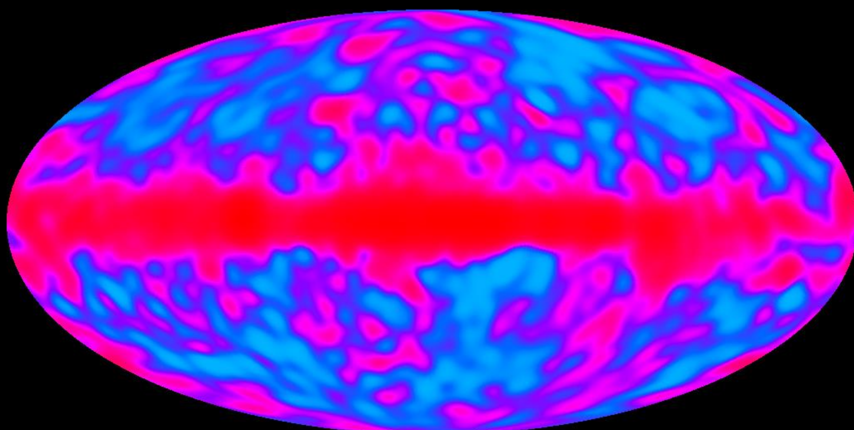


Slide from Ned Wright

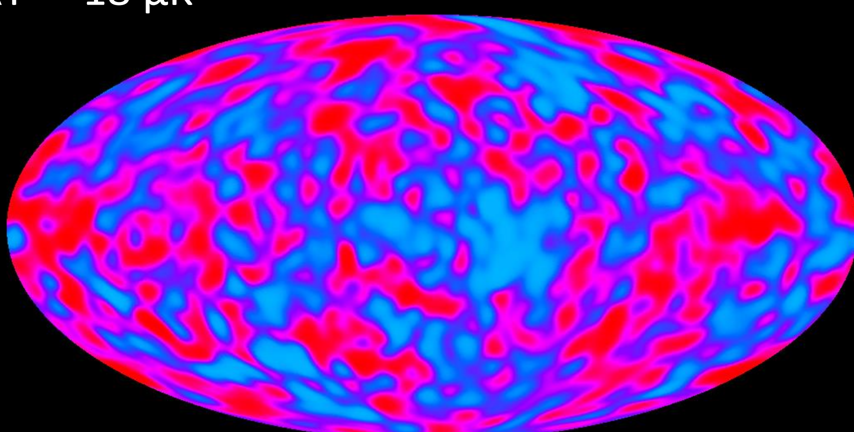
Dipolar anisotropy from the movement of the Earth

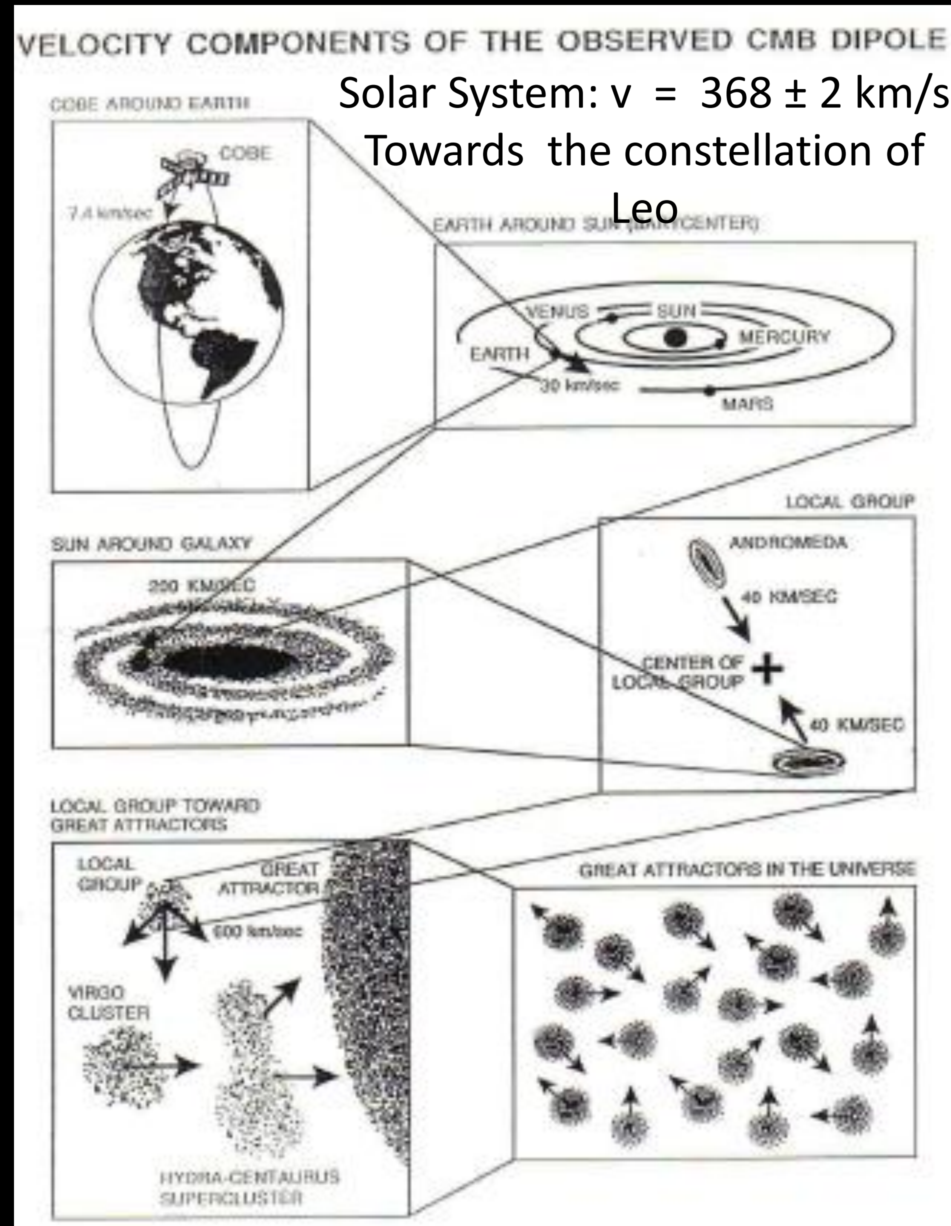


$\Delta T = 3.355$ mK



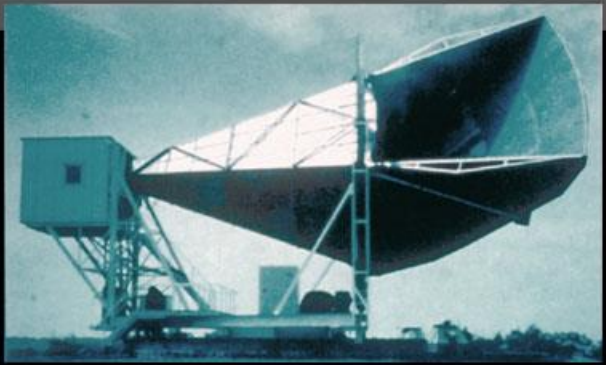
$\Delta T = 18$ µK

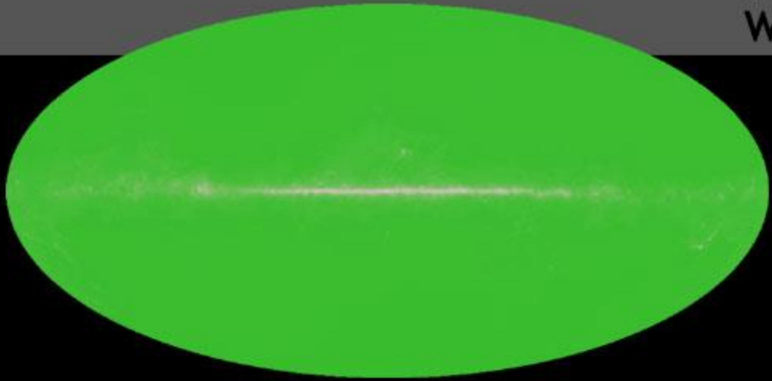




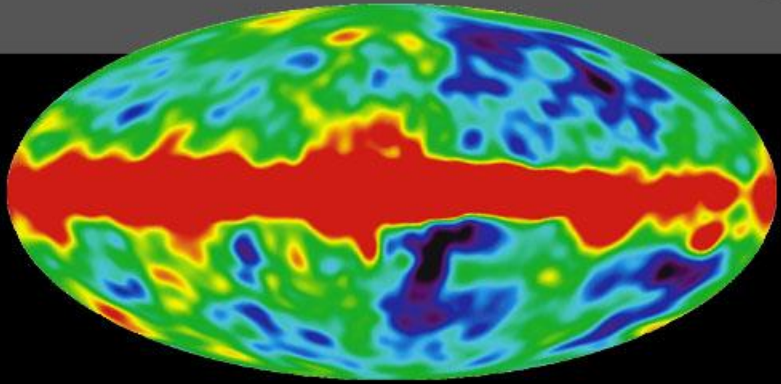
Solar System: v = 368 ± 2 km/s
Towards the constellation of Leo

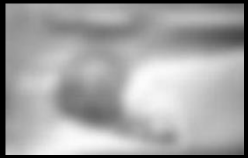
1965 Penzias and Wilson



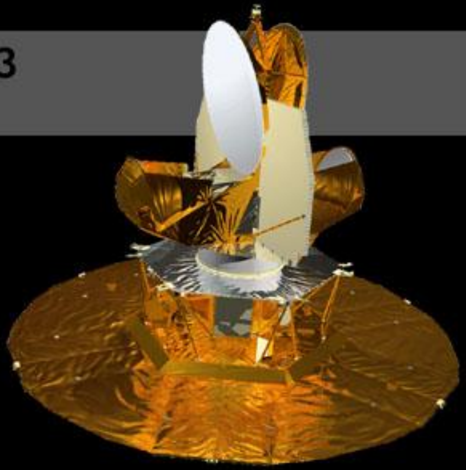


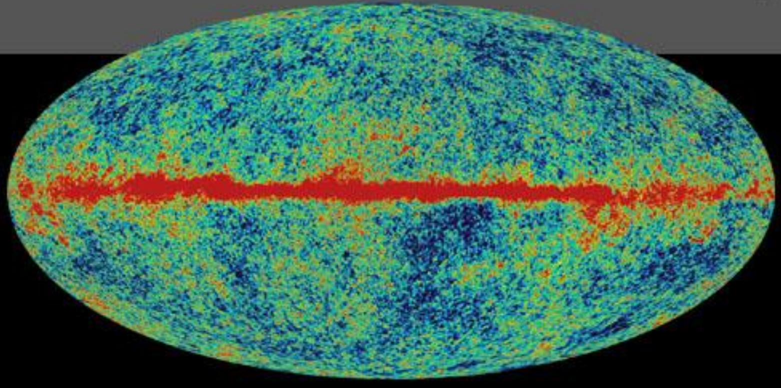
1992 COBE





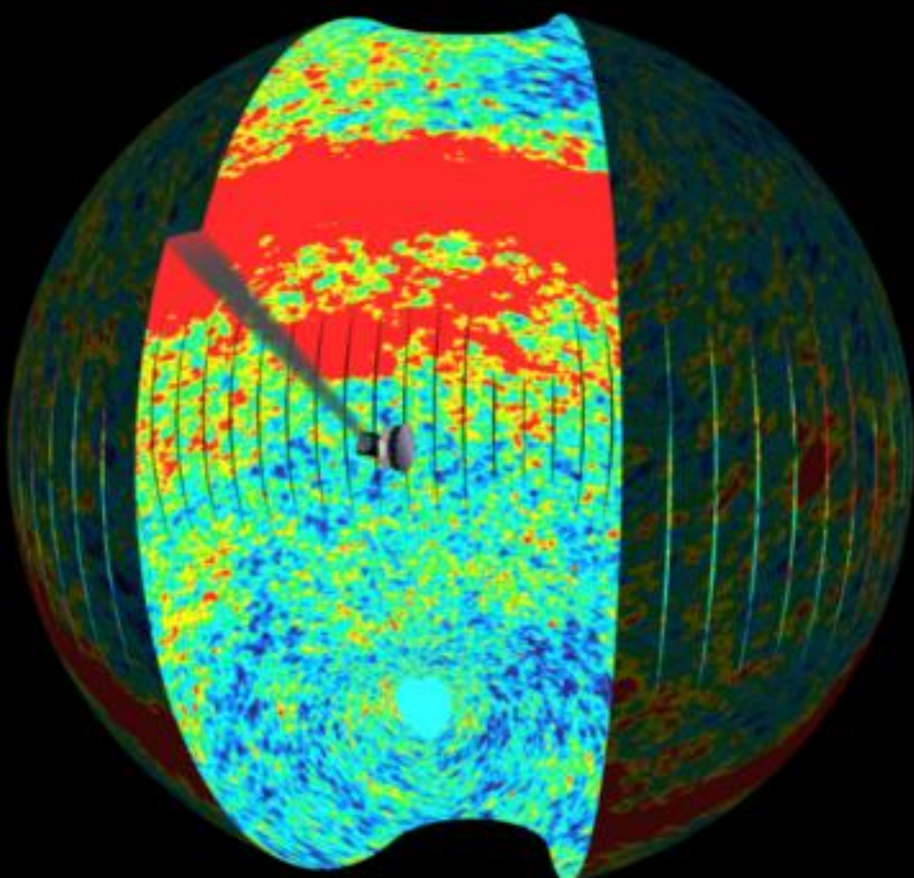
2003 WMAP





Planck: The most recent satellite

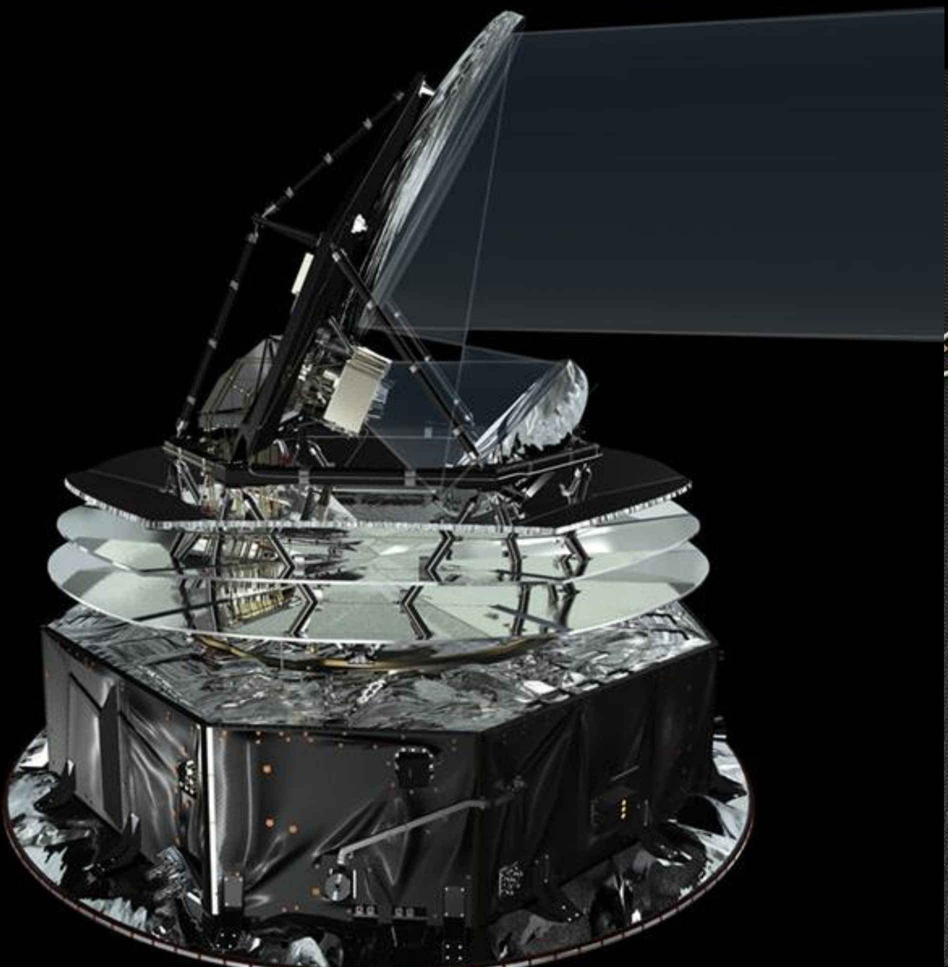
May 2009 – october 2013
More precise than WMAP
Able to measure polarization
Arrived at L2 in july 2009.

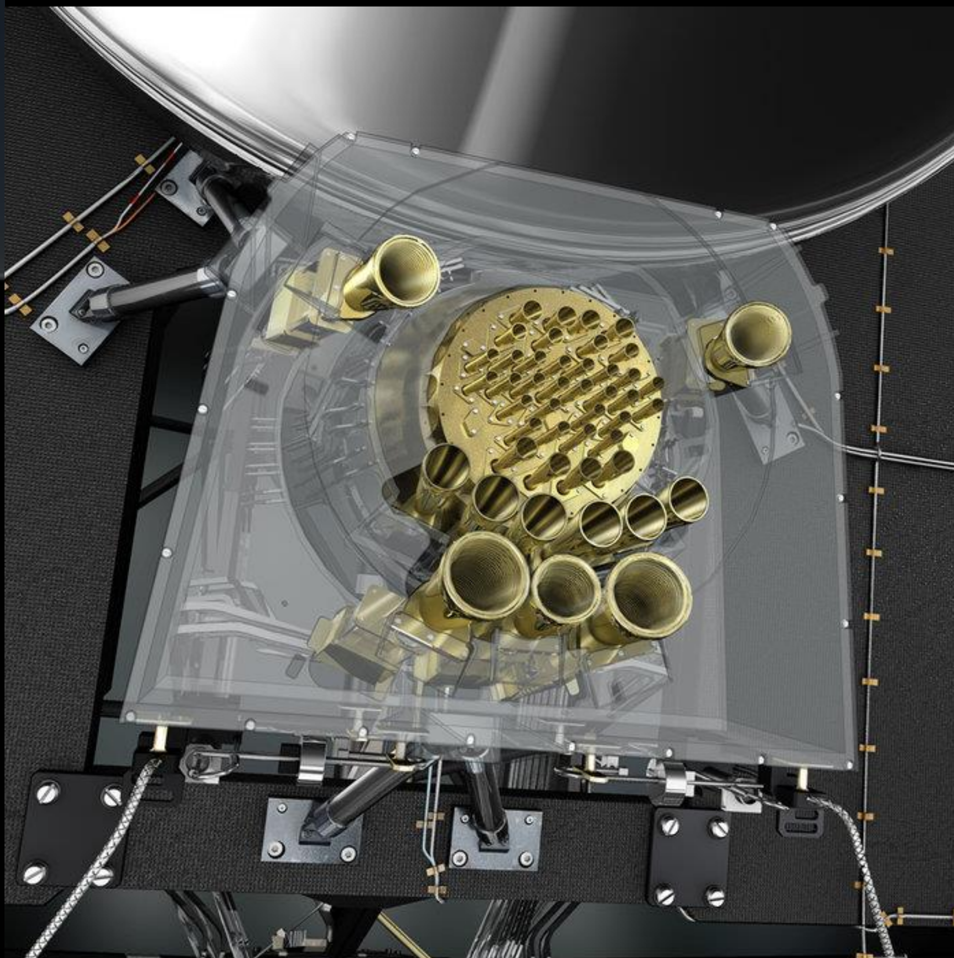


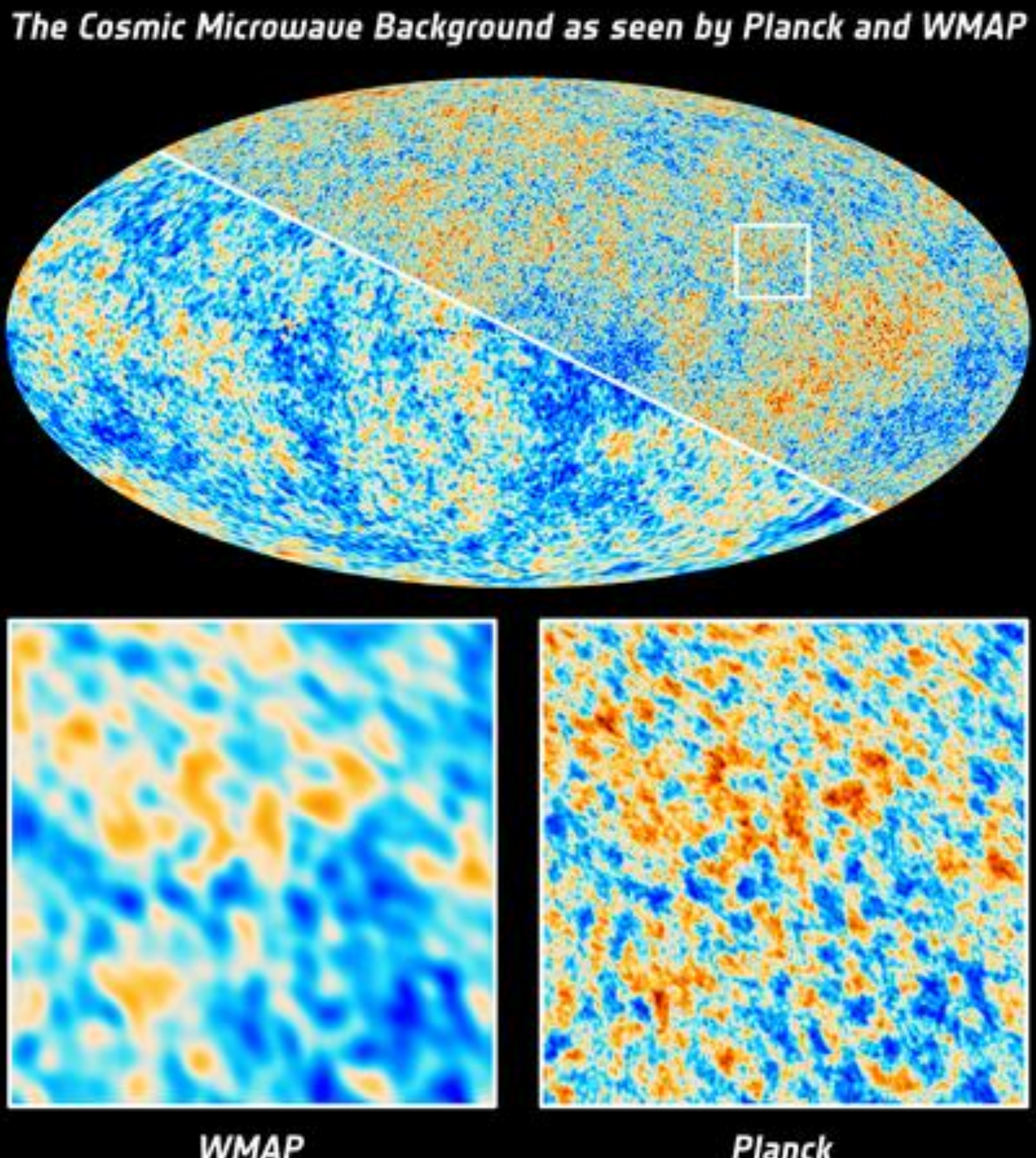
The Planck telescope

Mirror of 1.5 m diameter

2 instruments: High (> 100 GHz) and low (< 100 GHz) frequency





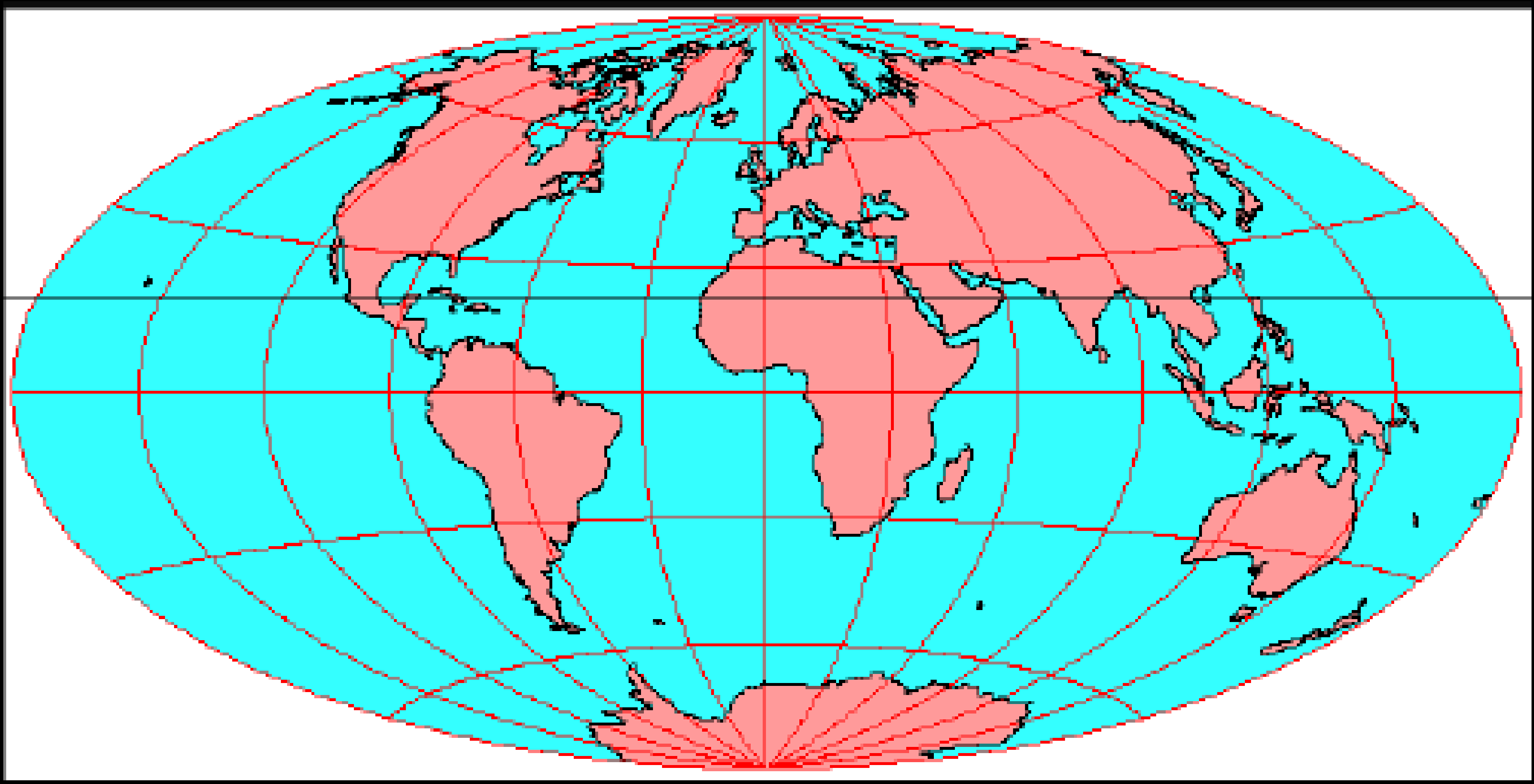


Final results published 17 july 2018

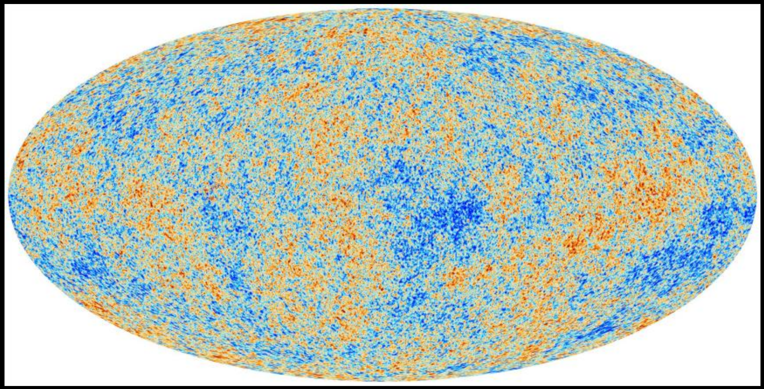
Highest precisión confirmation of ΛCDM

¿How are the data analysed?

Map of the full sky in Aitoff projection



Statistical Properties

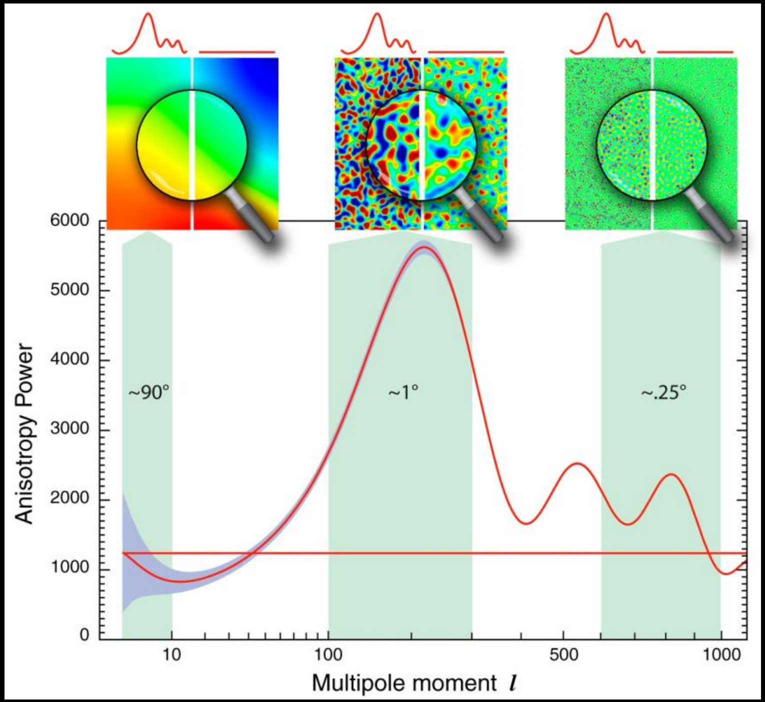


Expansion in Spherical harmonics (Fourier transform in the sphere)

Quantifies the clustering in different scales

$T_0 = 2.726K$

$\Delta T(\theta,\phi) = T(\theta,\phi) - T_0$



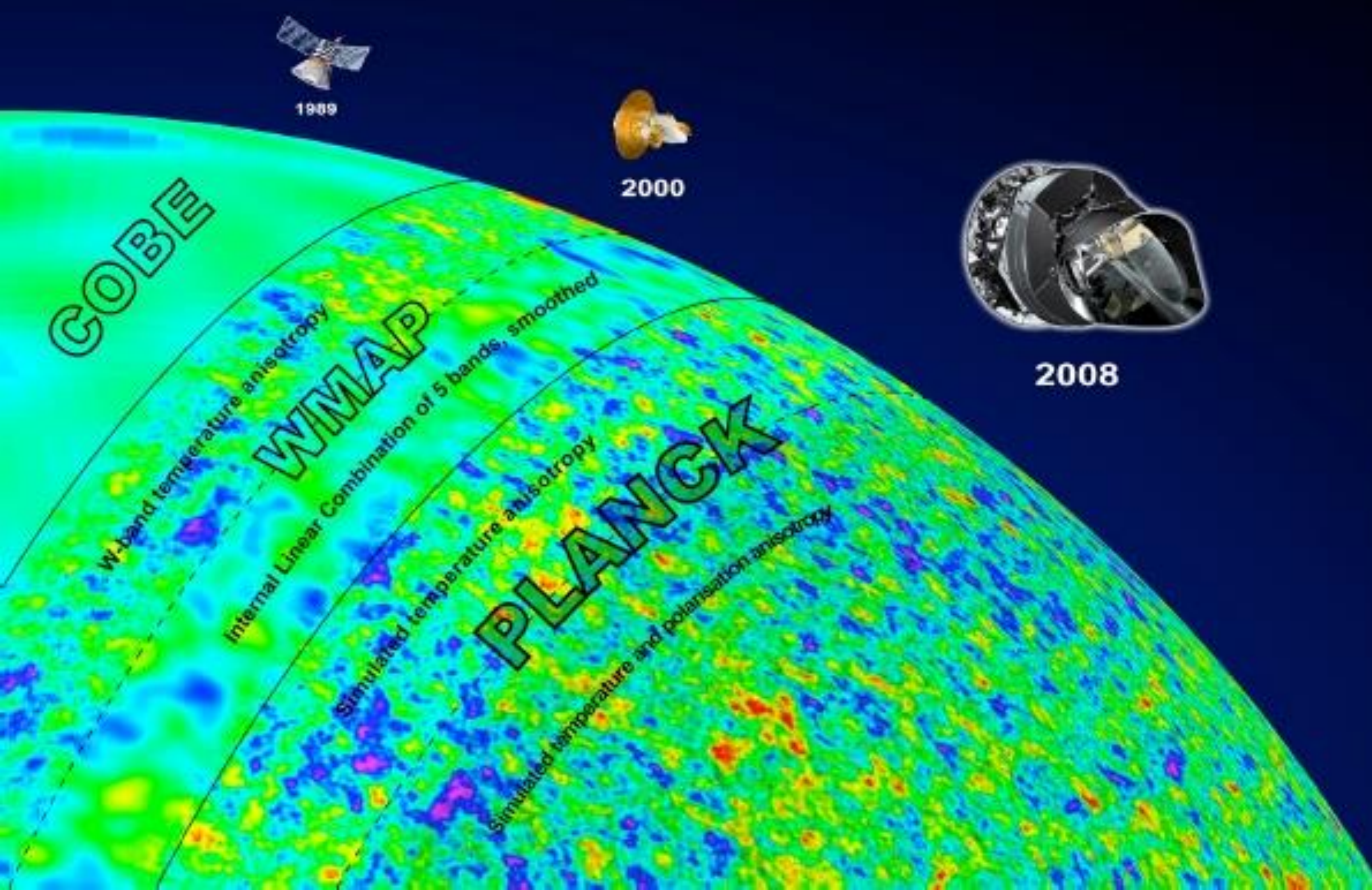
$$\frac{\delta T}{T_0}(\theta,\phi) = \sum a_{\ell m} Y_{\ell m}(\theta,\phi)$$

$$a_{\ell m} = \int Y^*_{\ell m}(\theta,\phi) \frac{\delta T}{T_0}(\theta,\phi) d\Omega$$

$$C_\ell \equiv \langle |a_{\ell m}|^2 \rangle = \frac{1}{2\ell+1} \sum_m \langle |a_{\ell m}|^2 \rangle$$

Cosmology from CMB

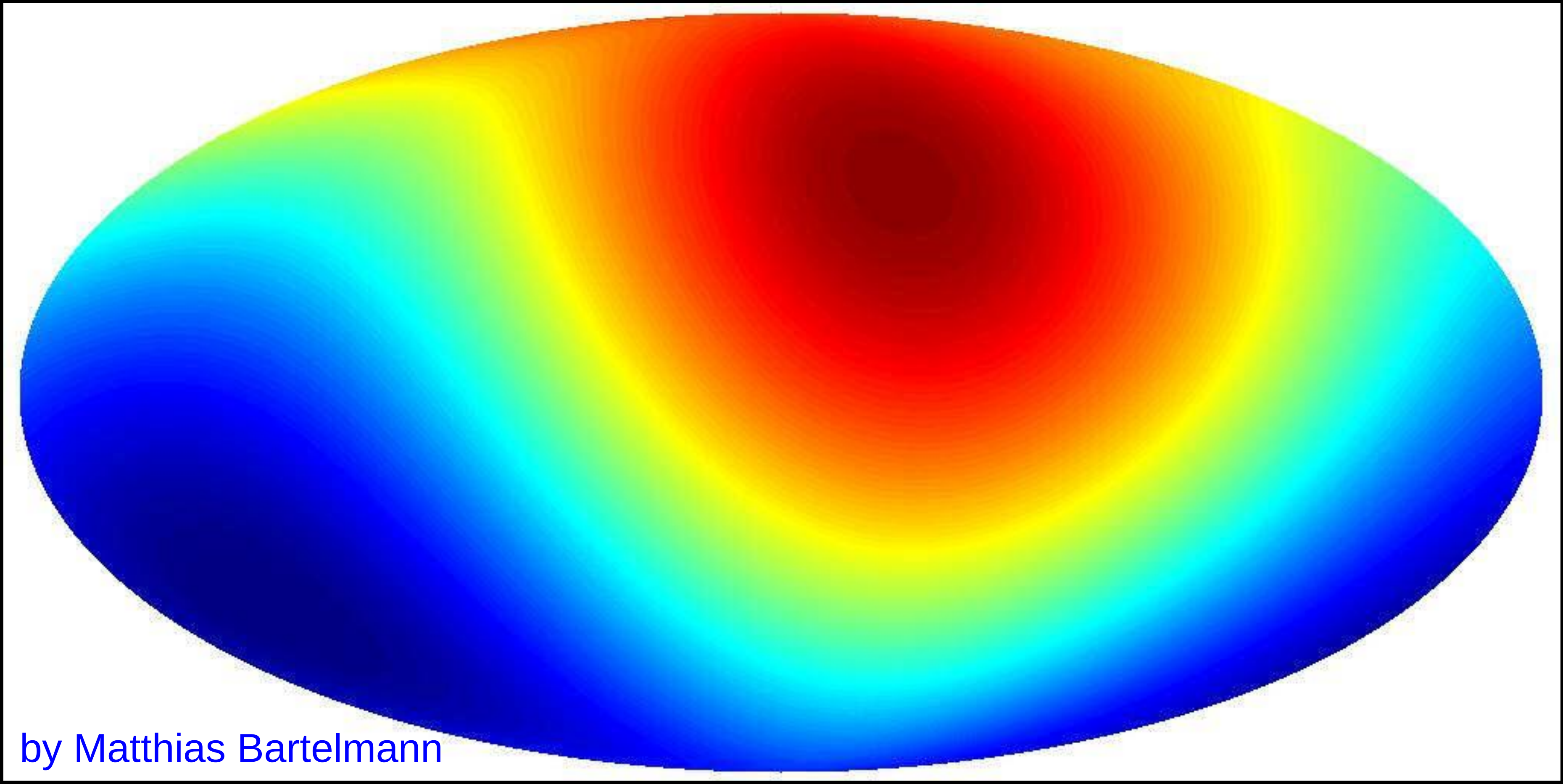
Measure temperature distribution (fluctuations)
Build a map of the anisotropies
Obtain power spectrum from the map
Fit cosmological parameters to the measured power spectrum



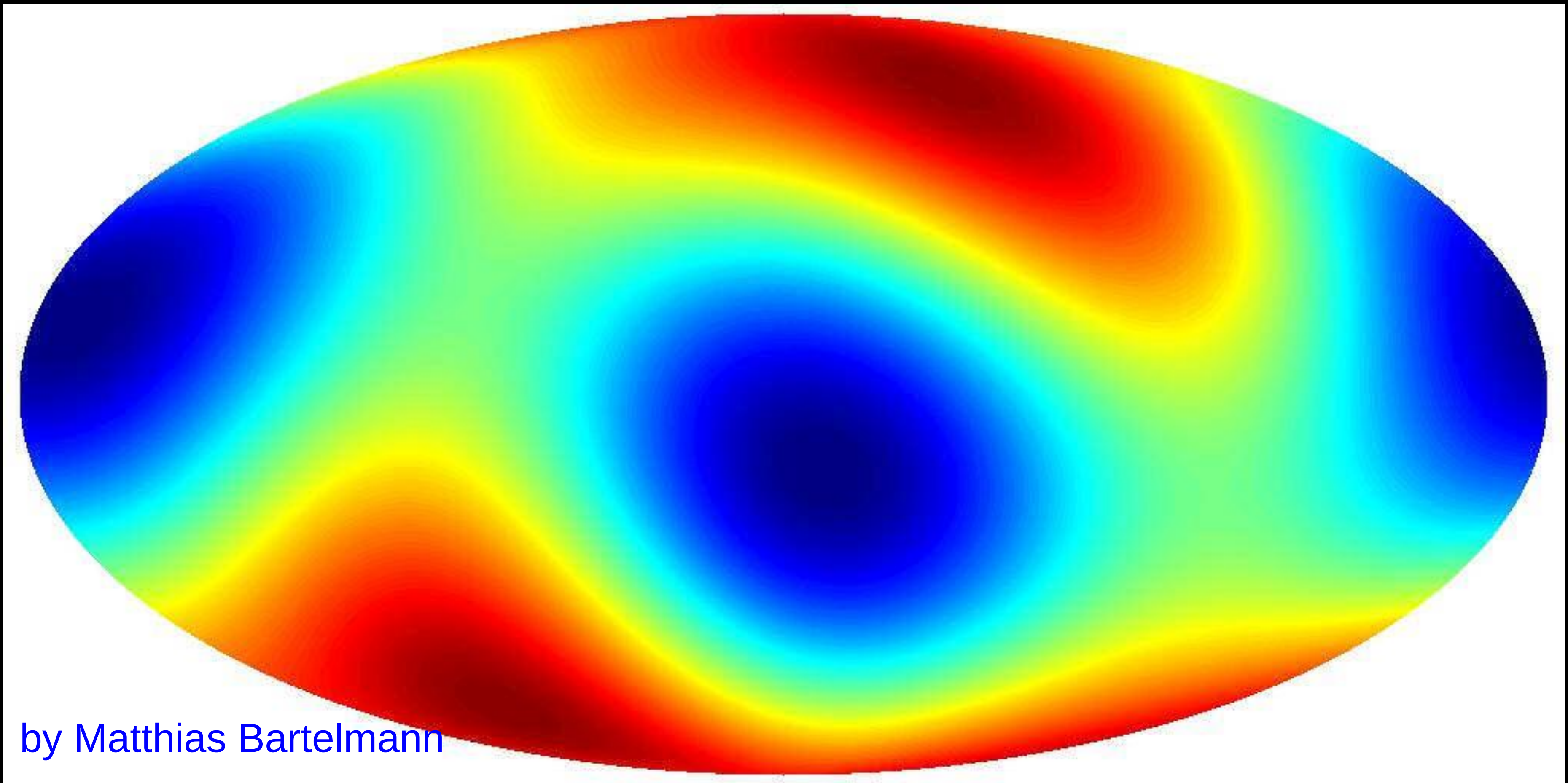
Spherical harmonics:

Spherical version of sine waves

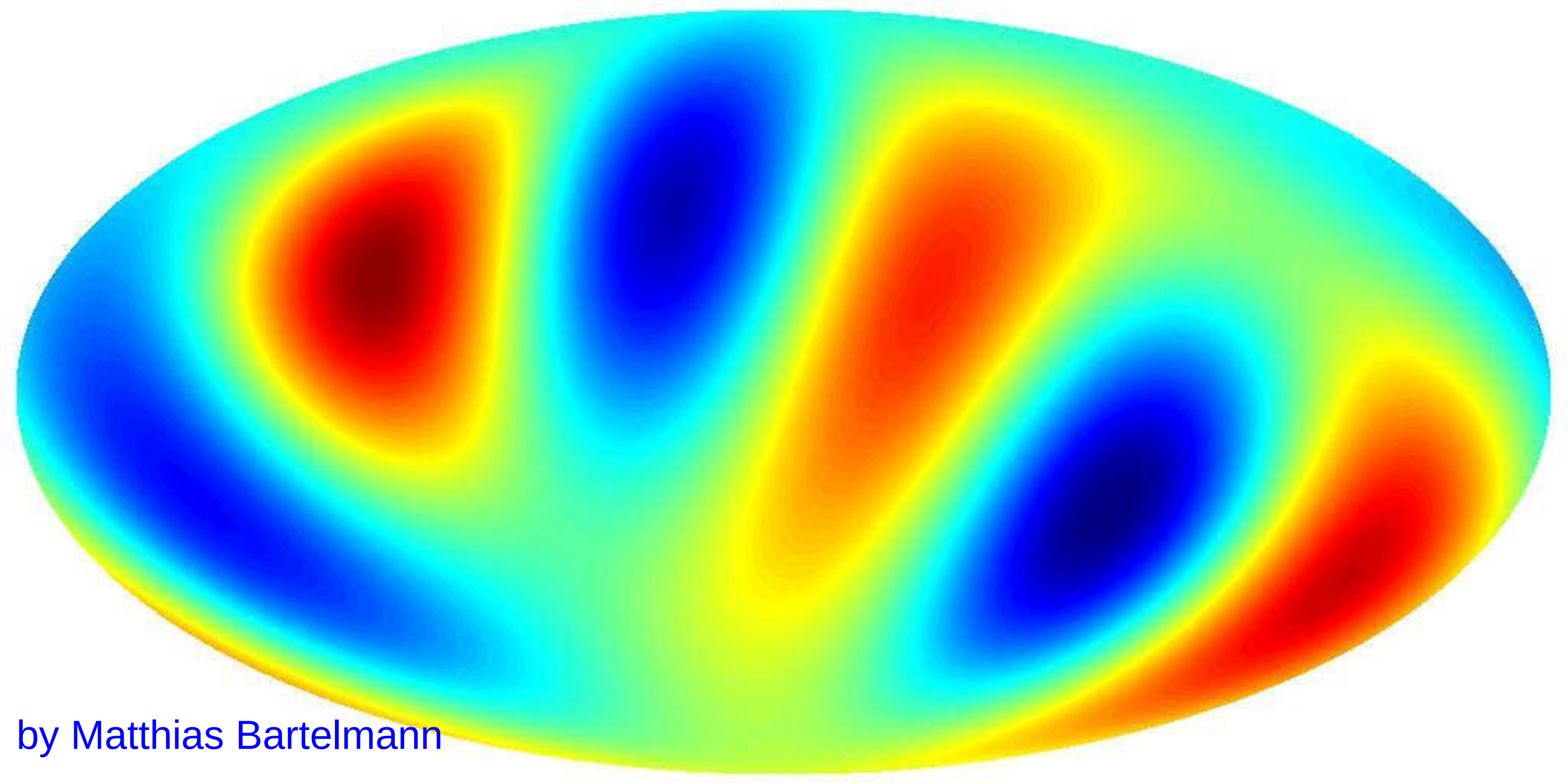
l=1



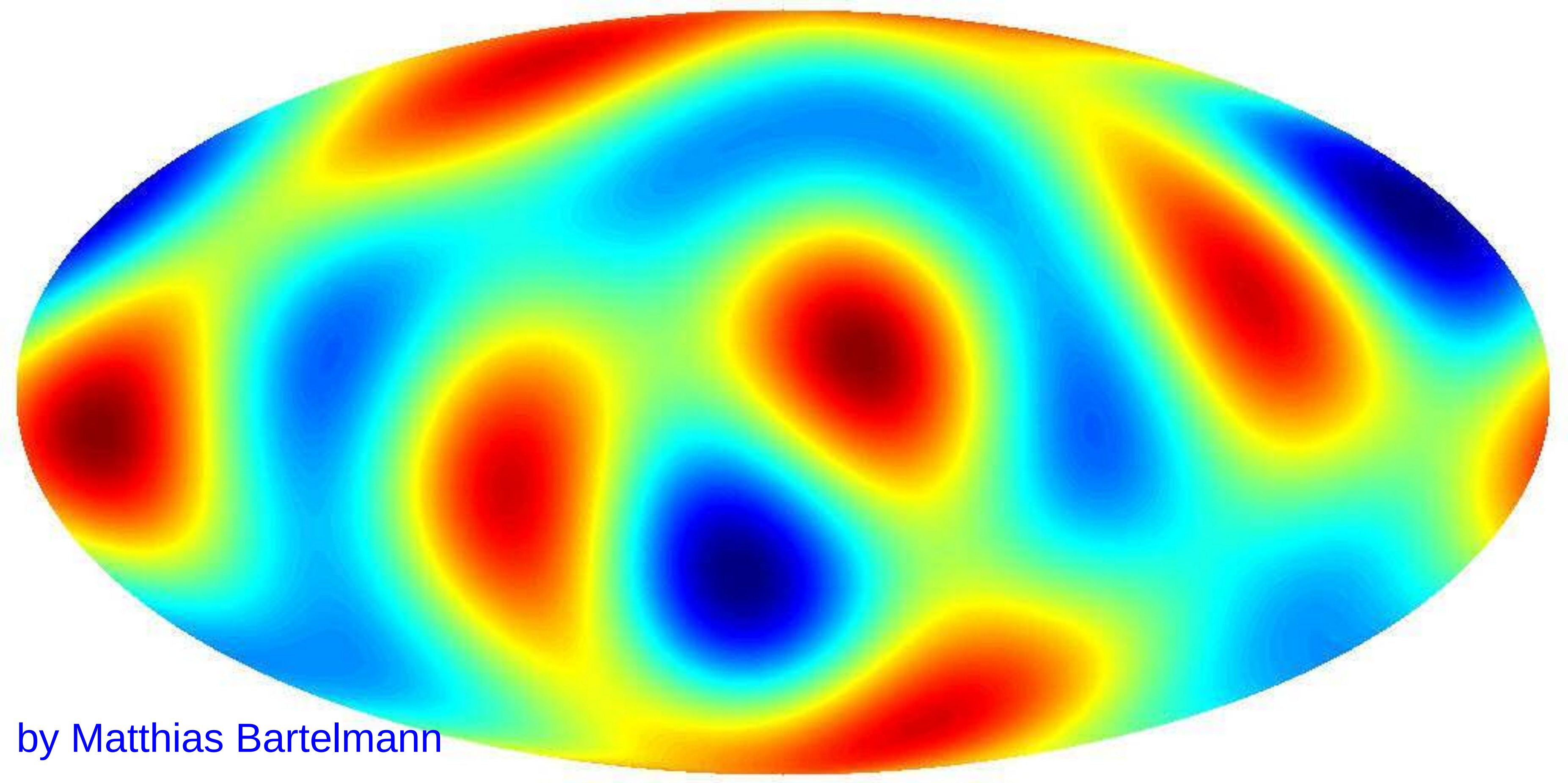
l=2



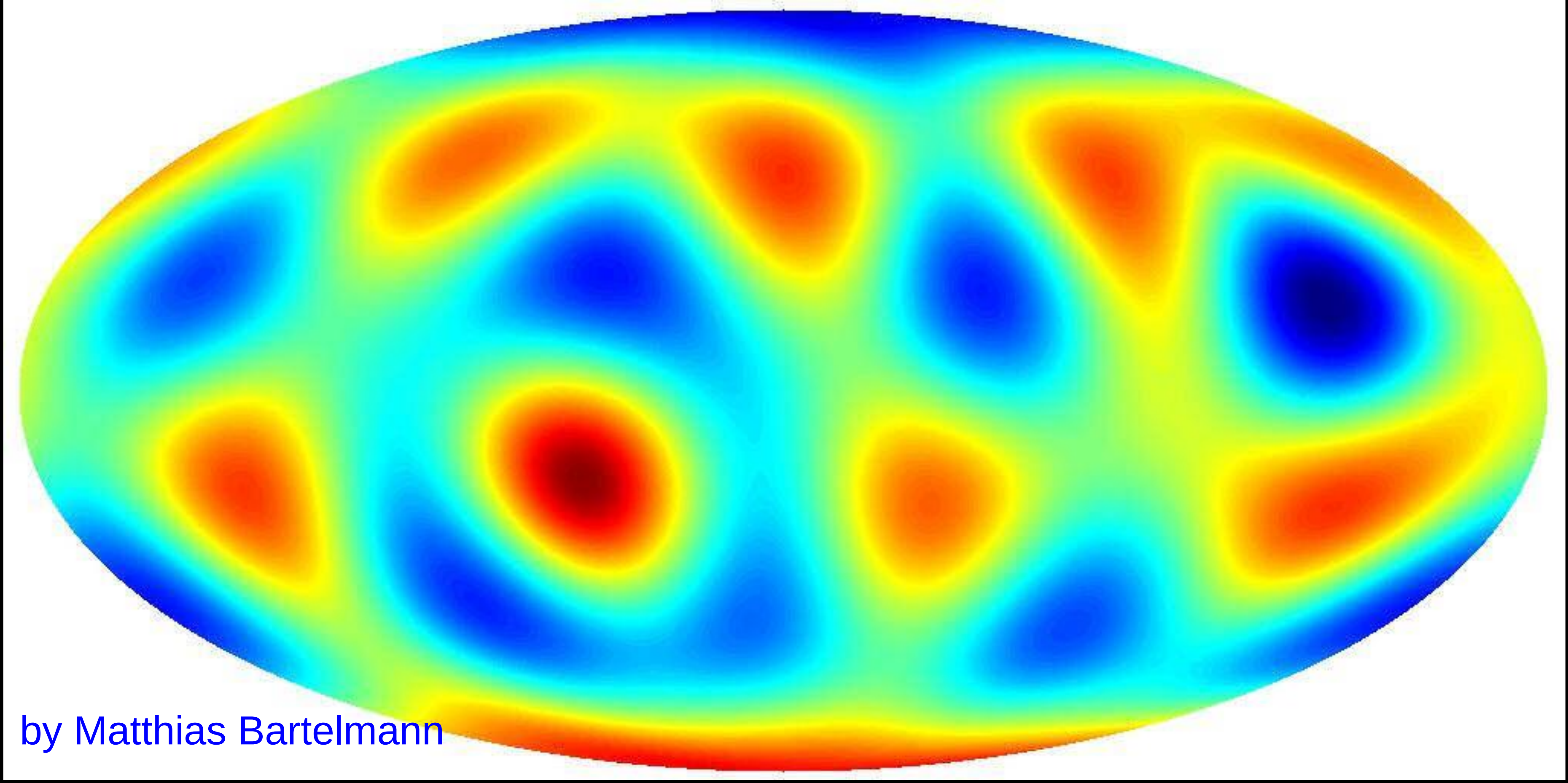
l=3



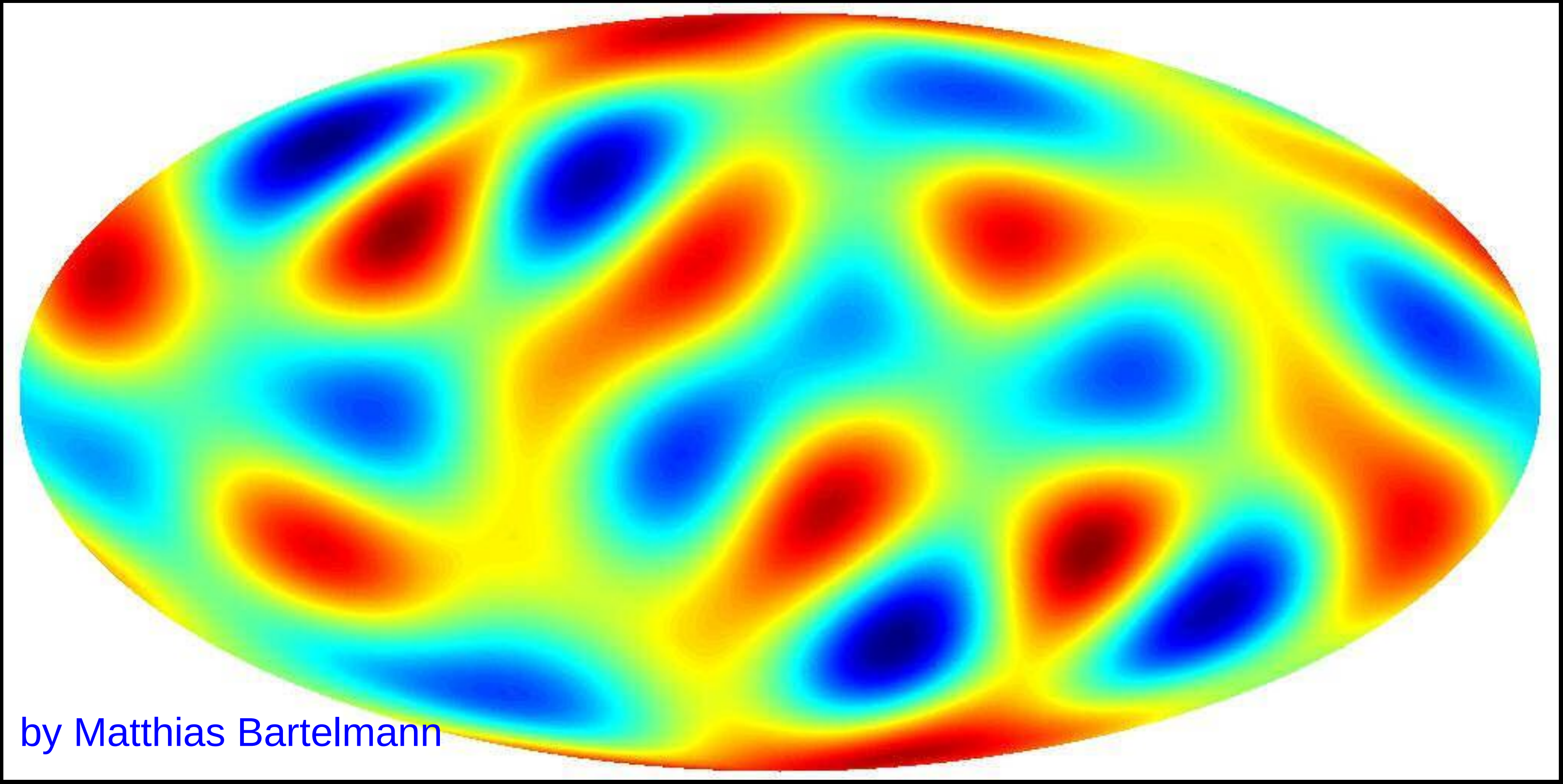
l=4



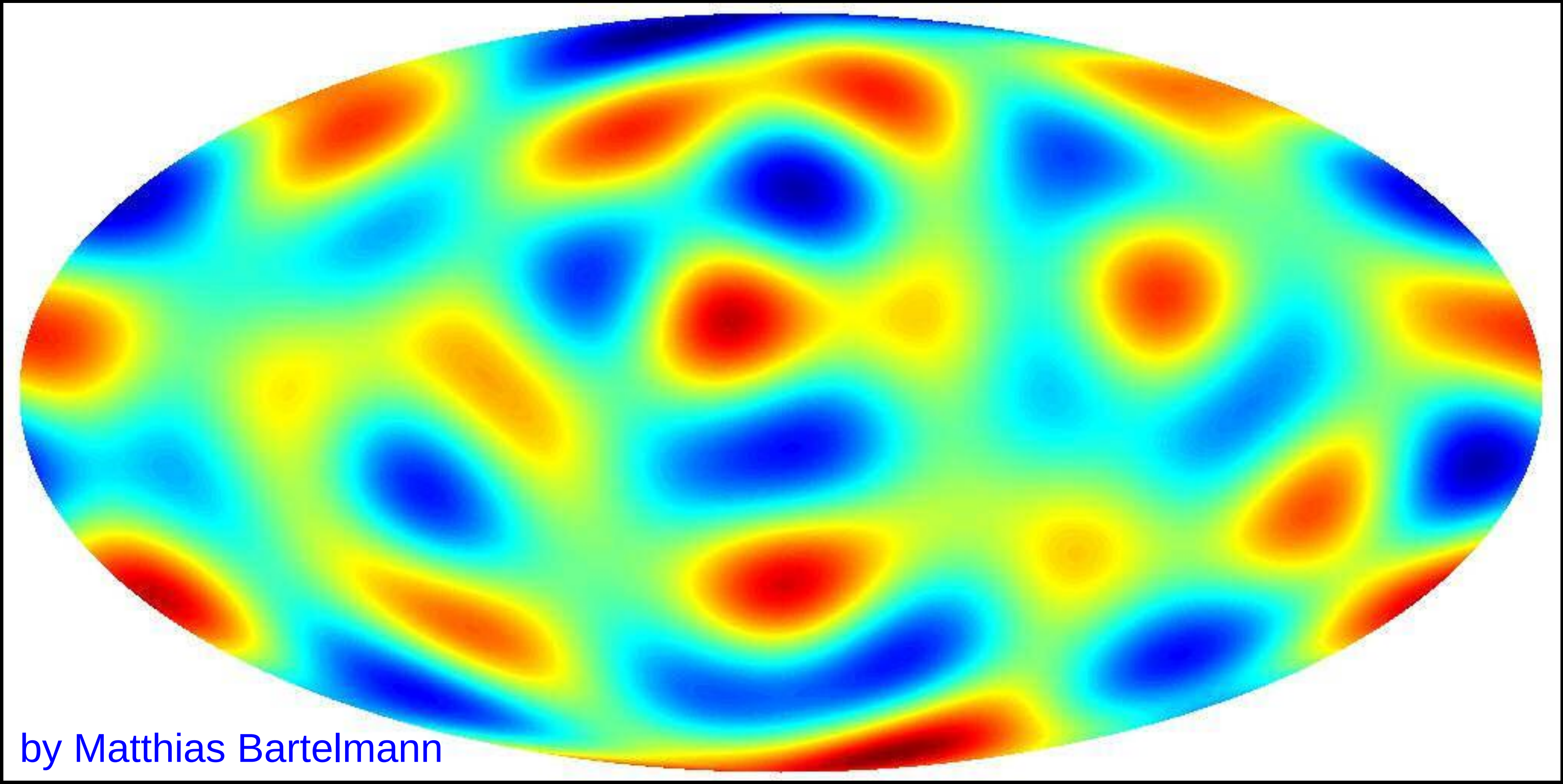
l=5



l=6

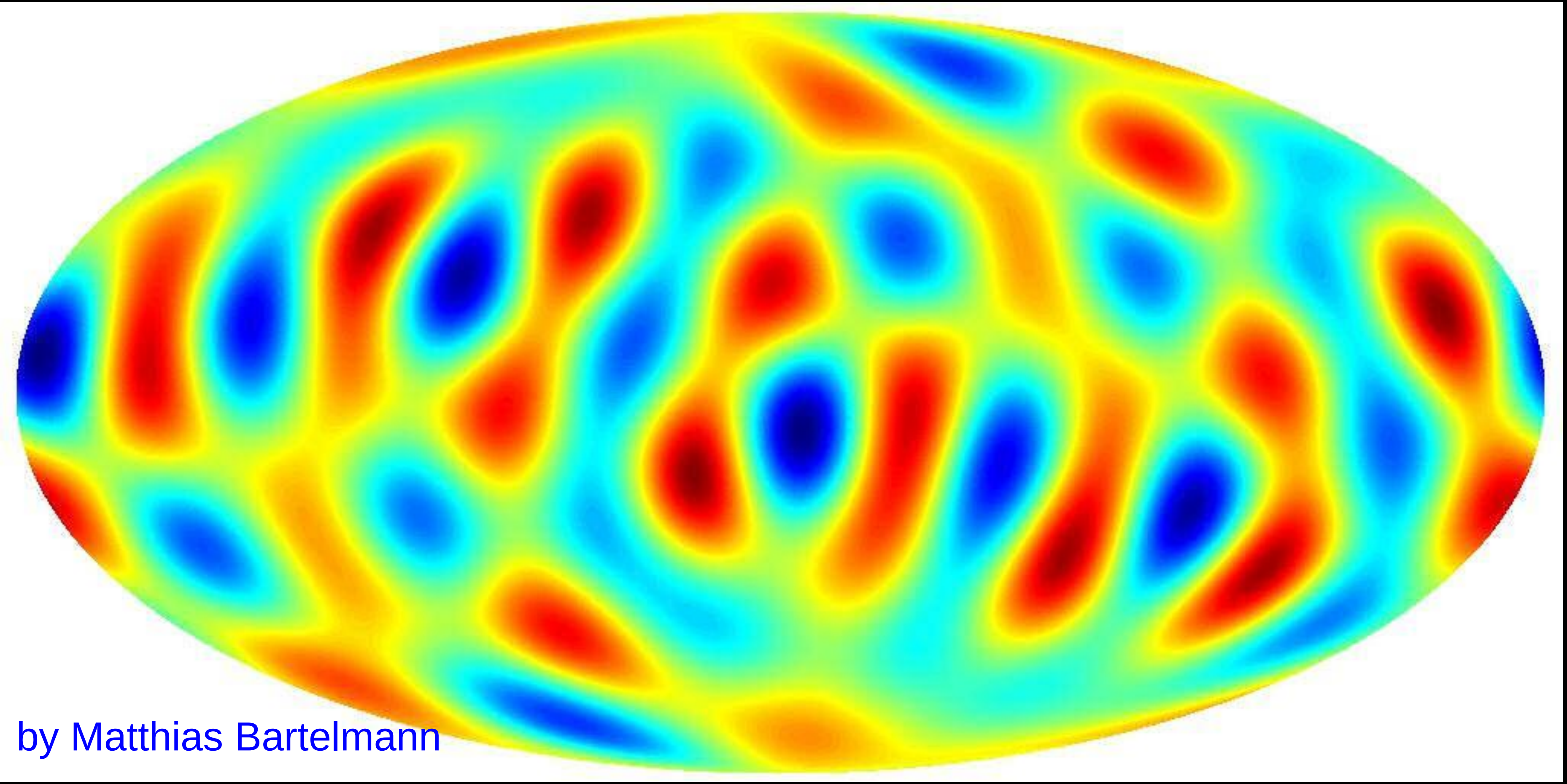


l=7

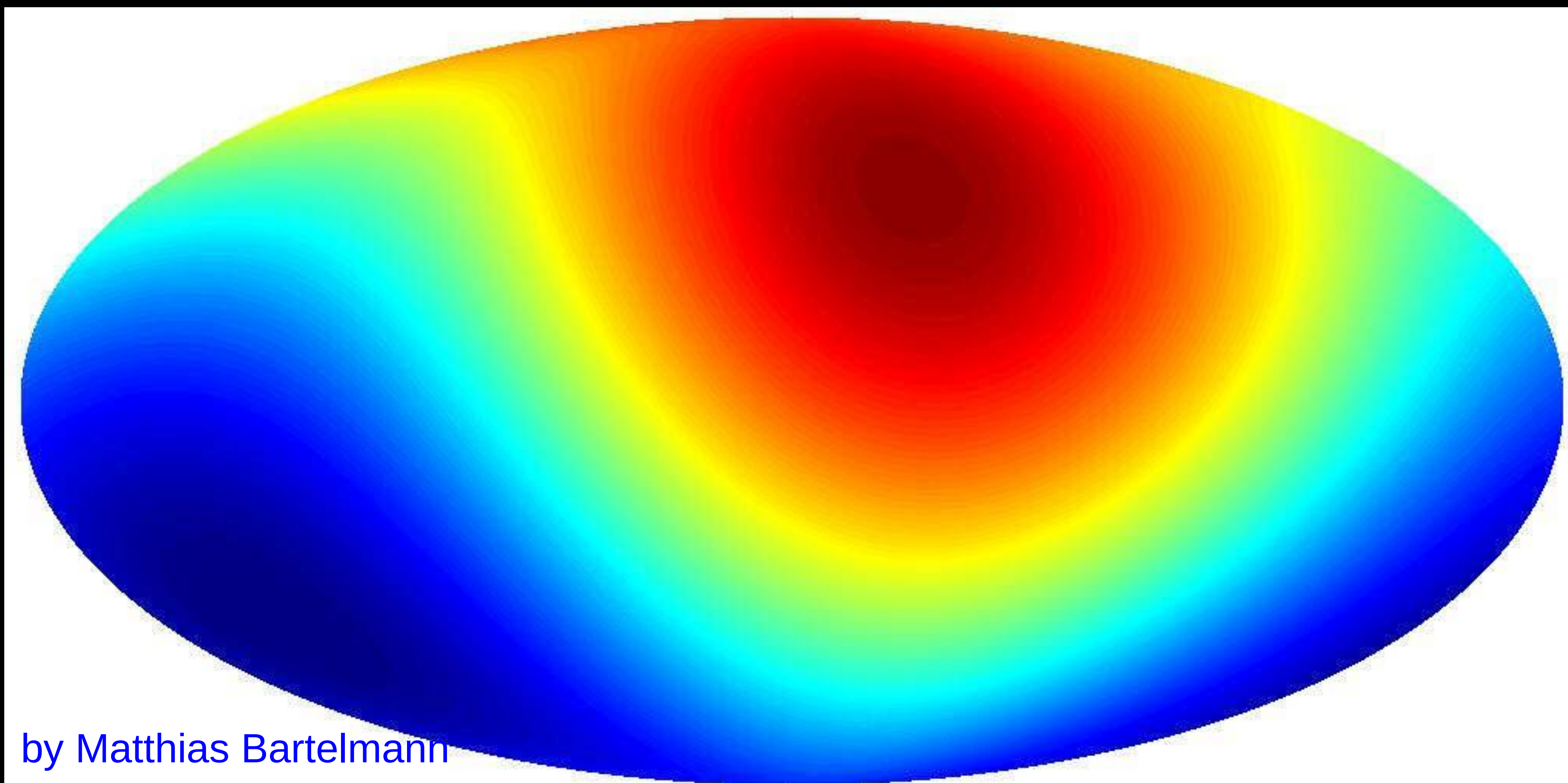


Higher l means smaller scales; l~π/θ

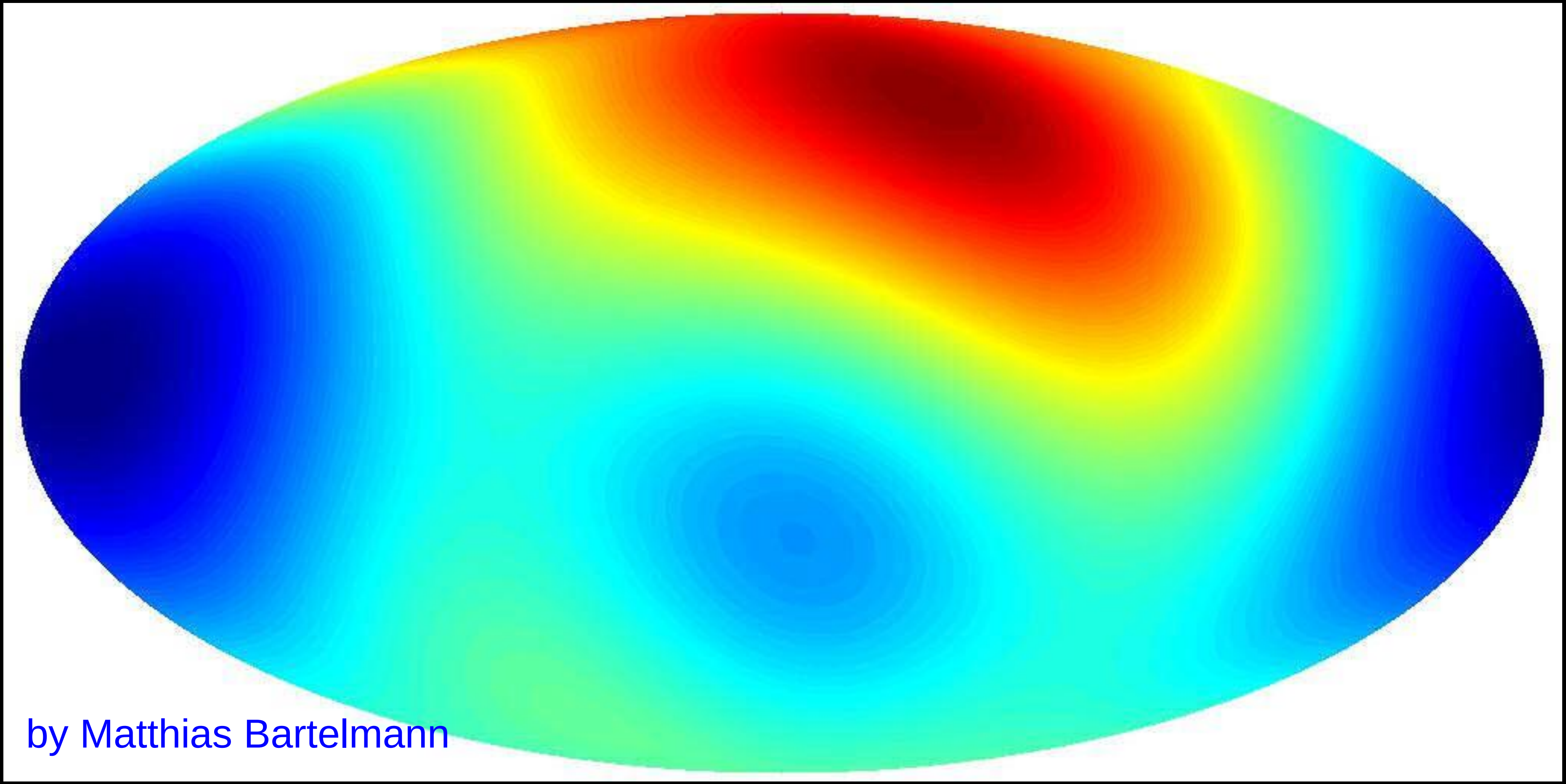
l=8



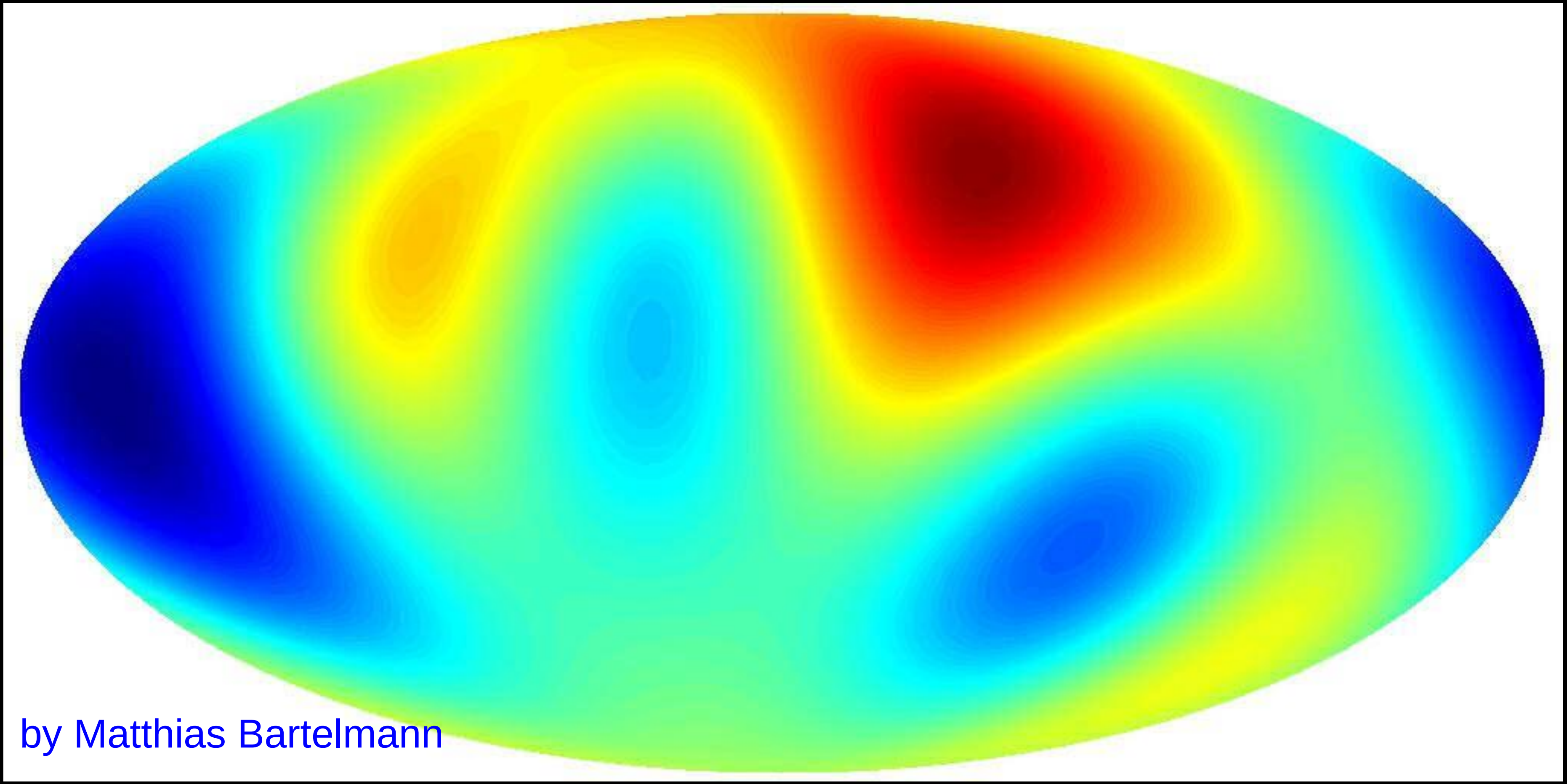
# Map reconstruction
l=1



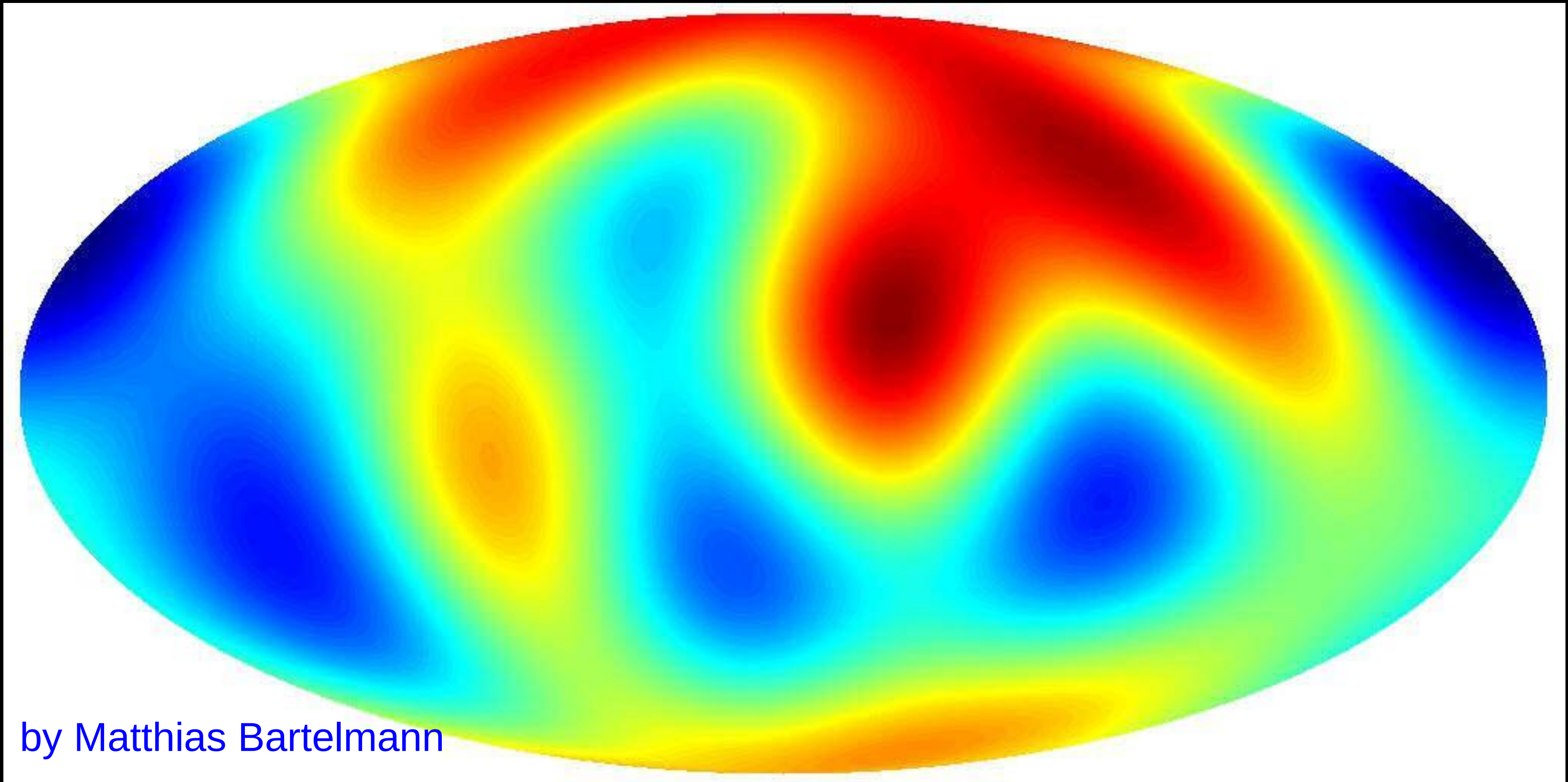
l=1 + l=2



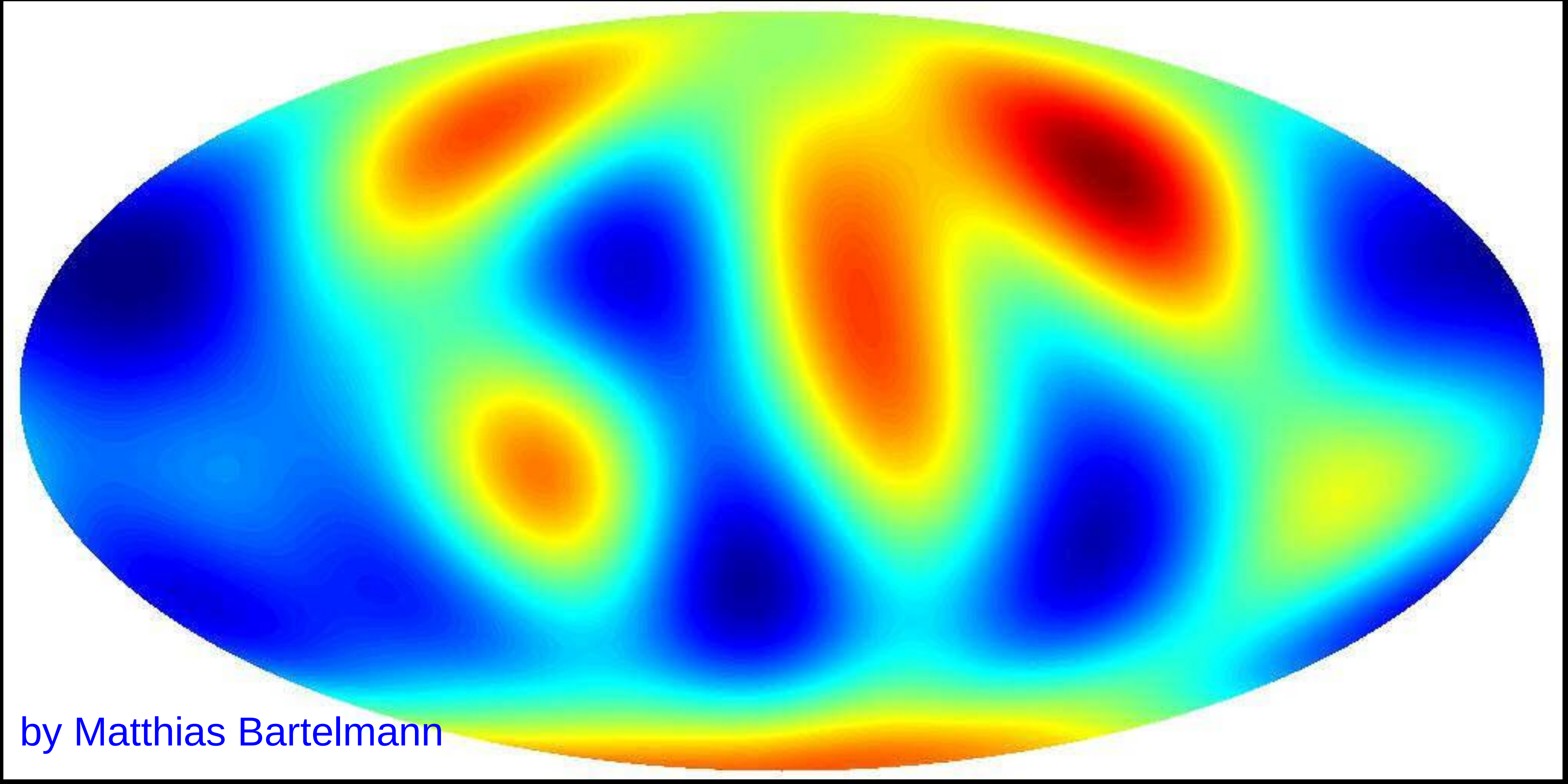
l = 1 - 3



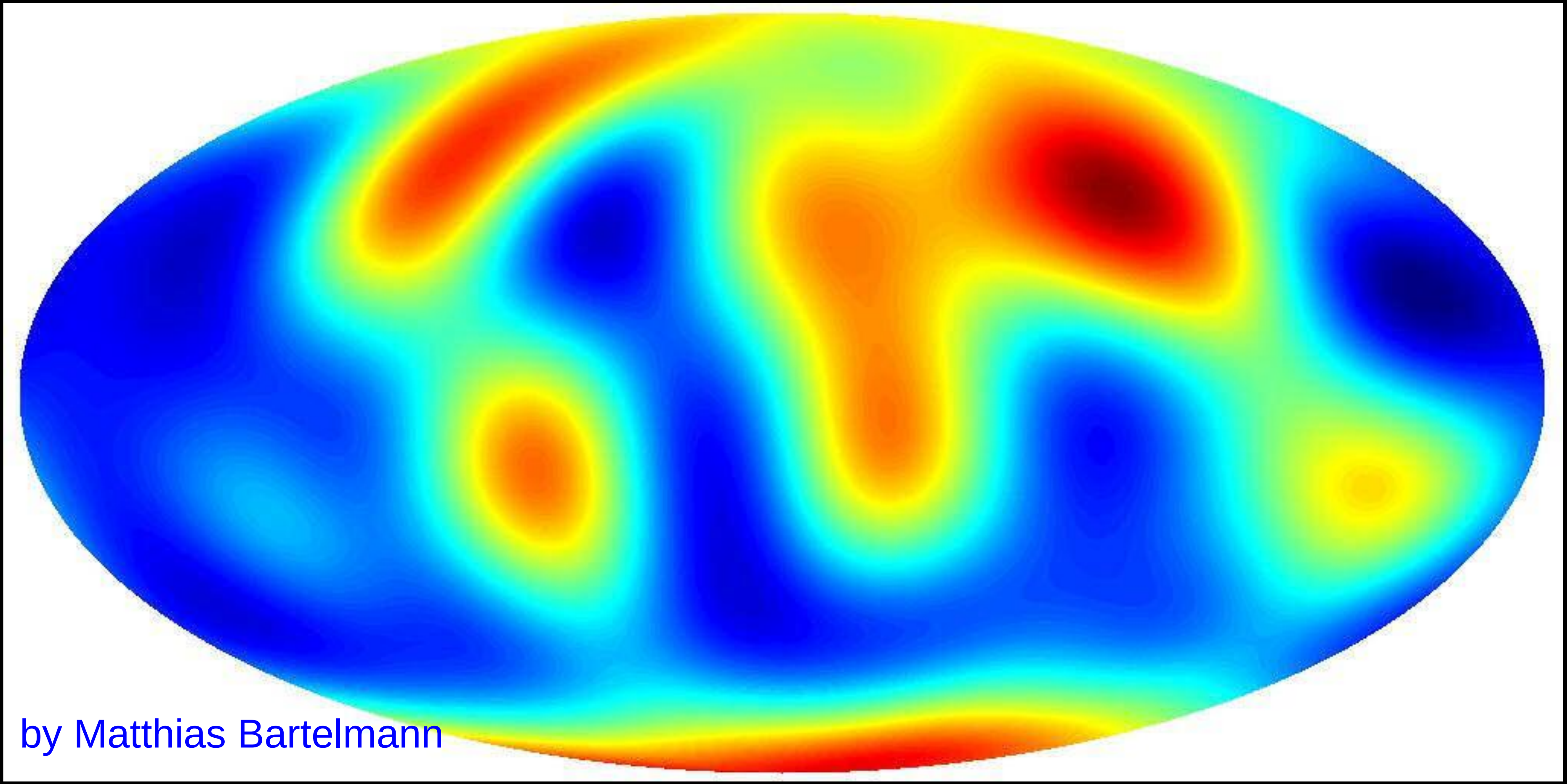
l= 1- 4



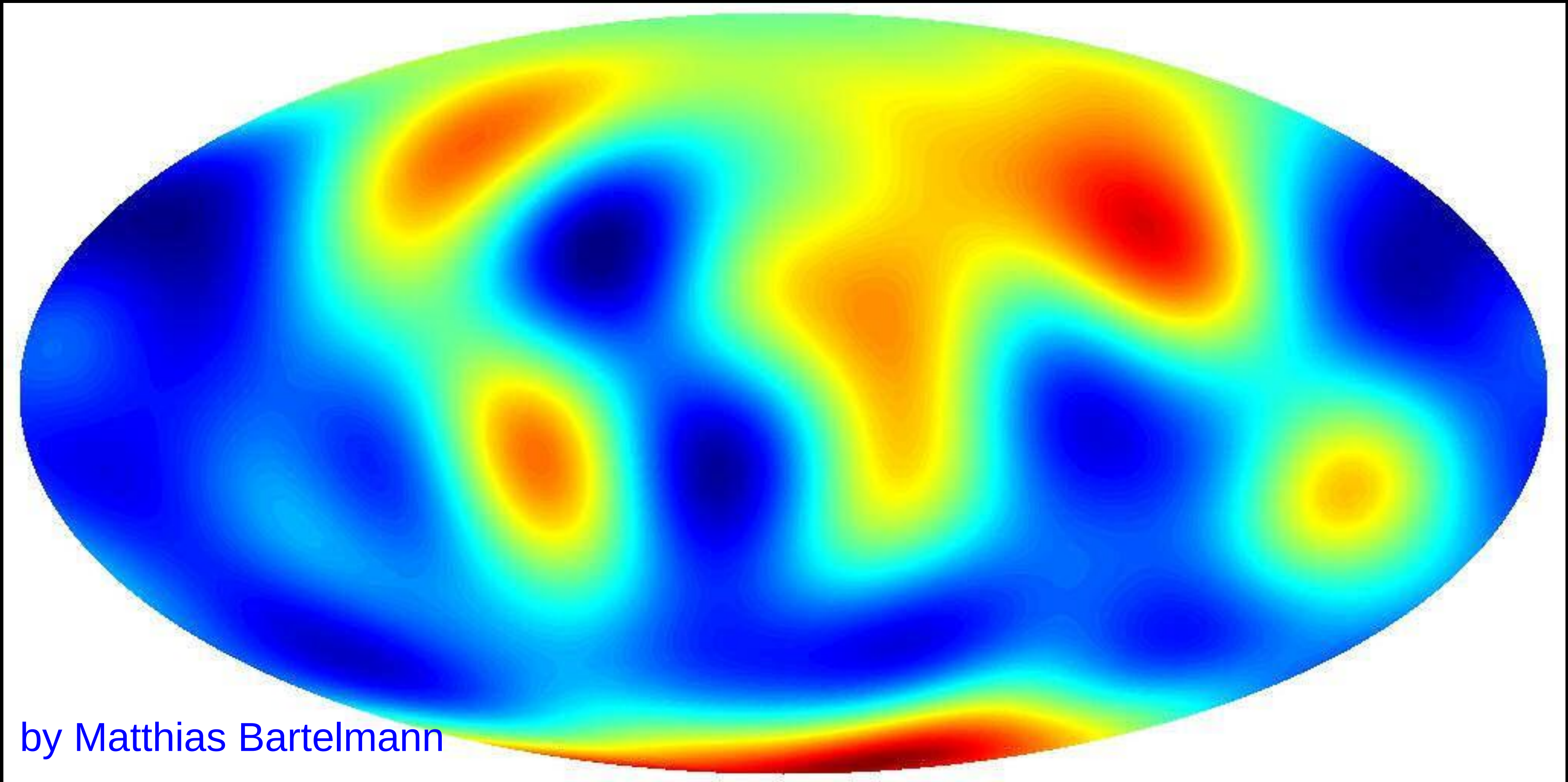
l= 1- 5



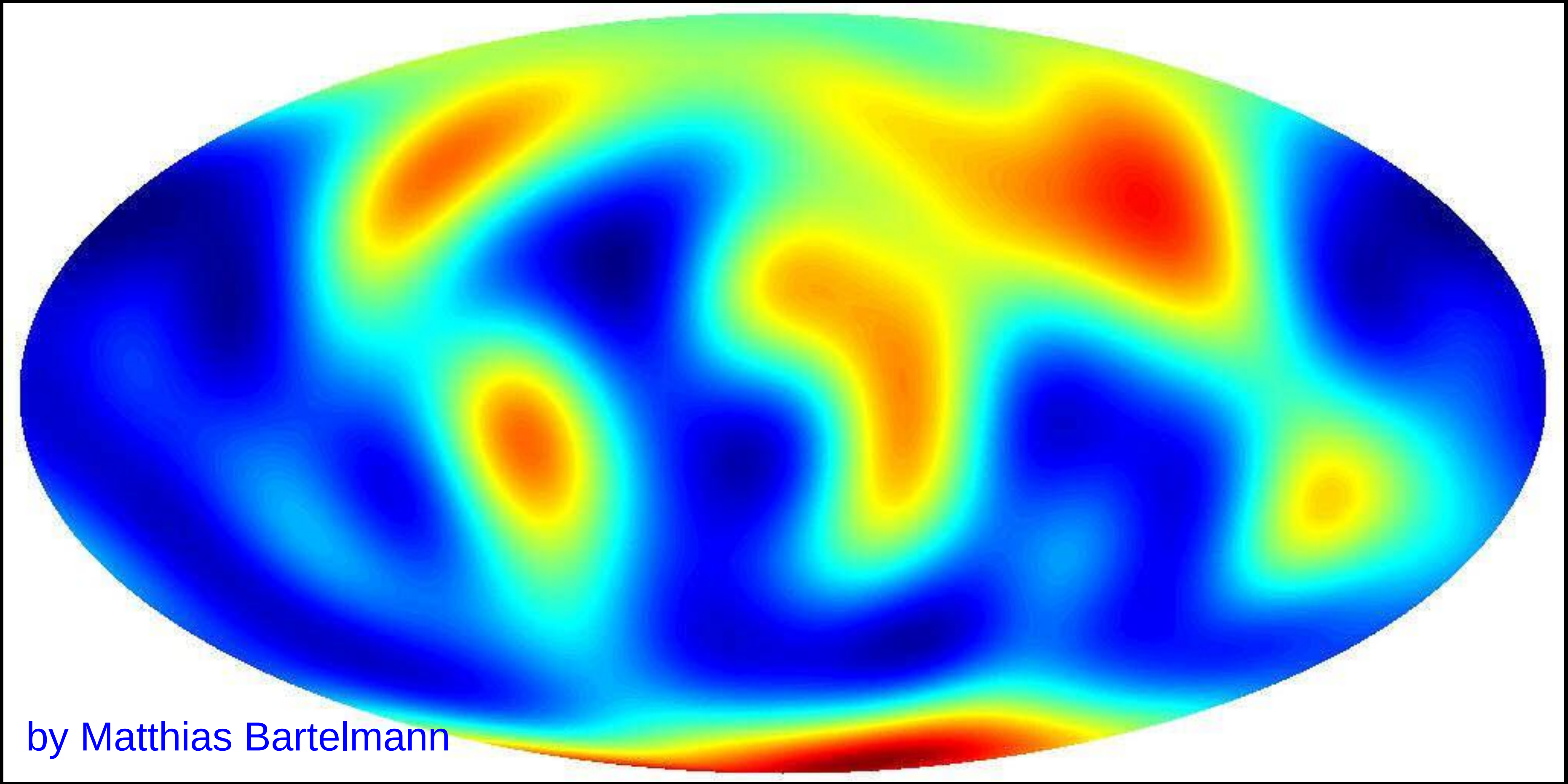
l= 1 - 6



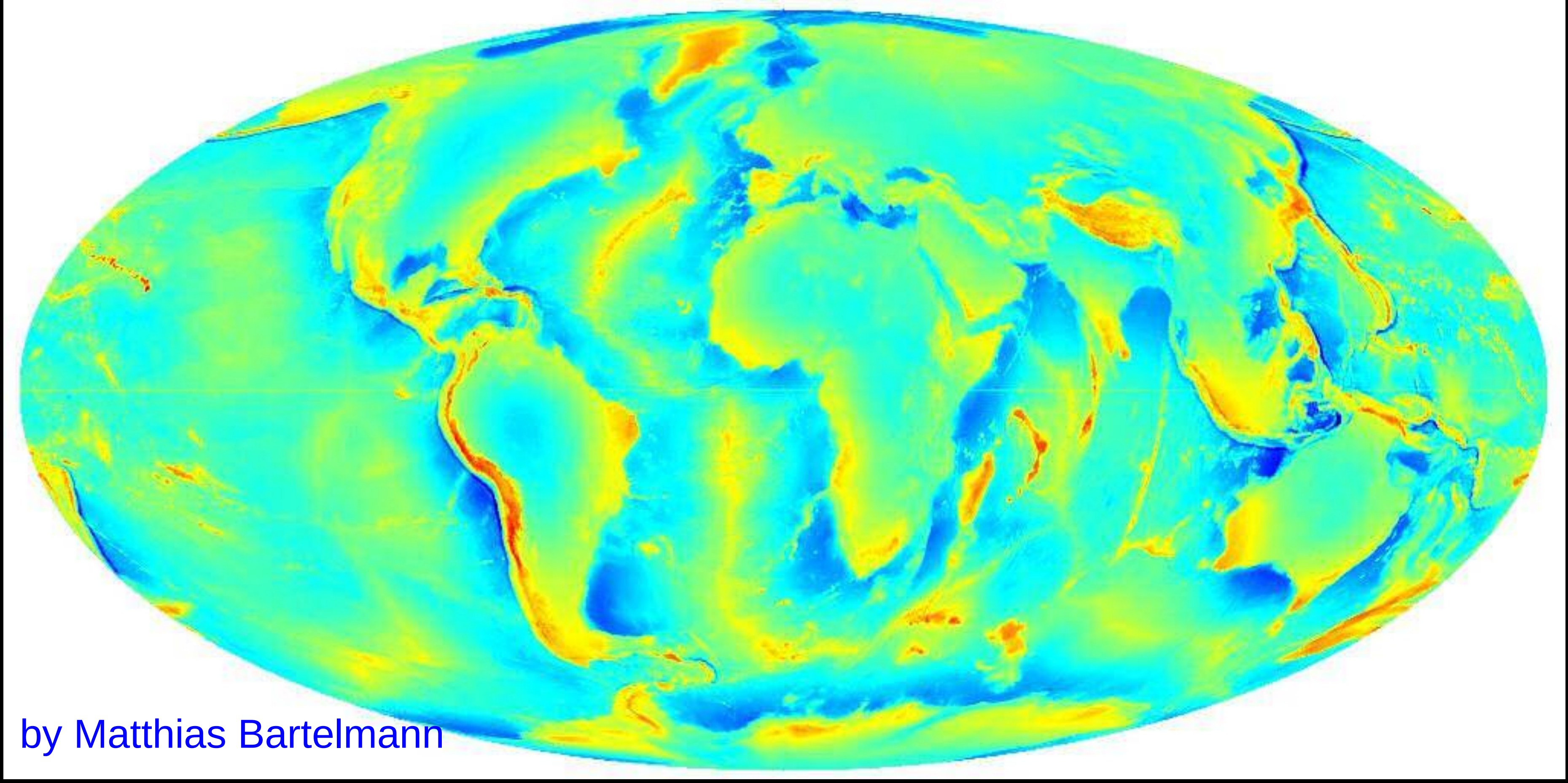
l= 1 – 7



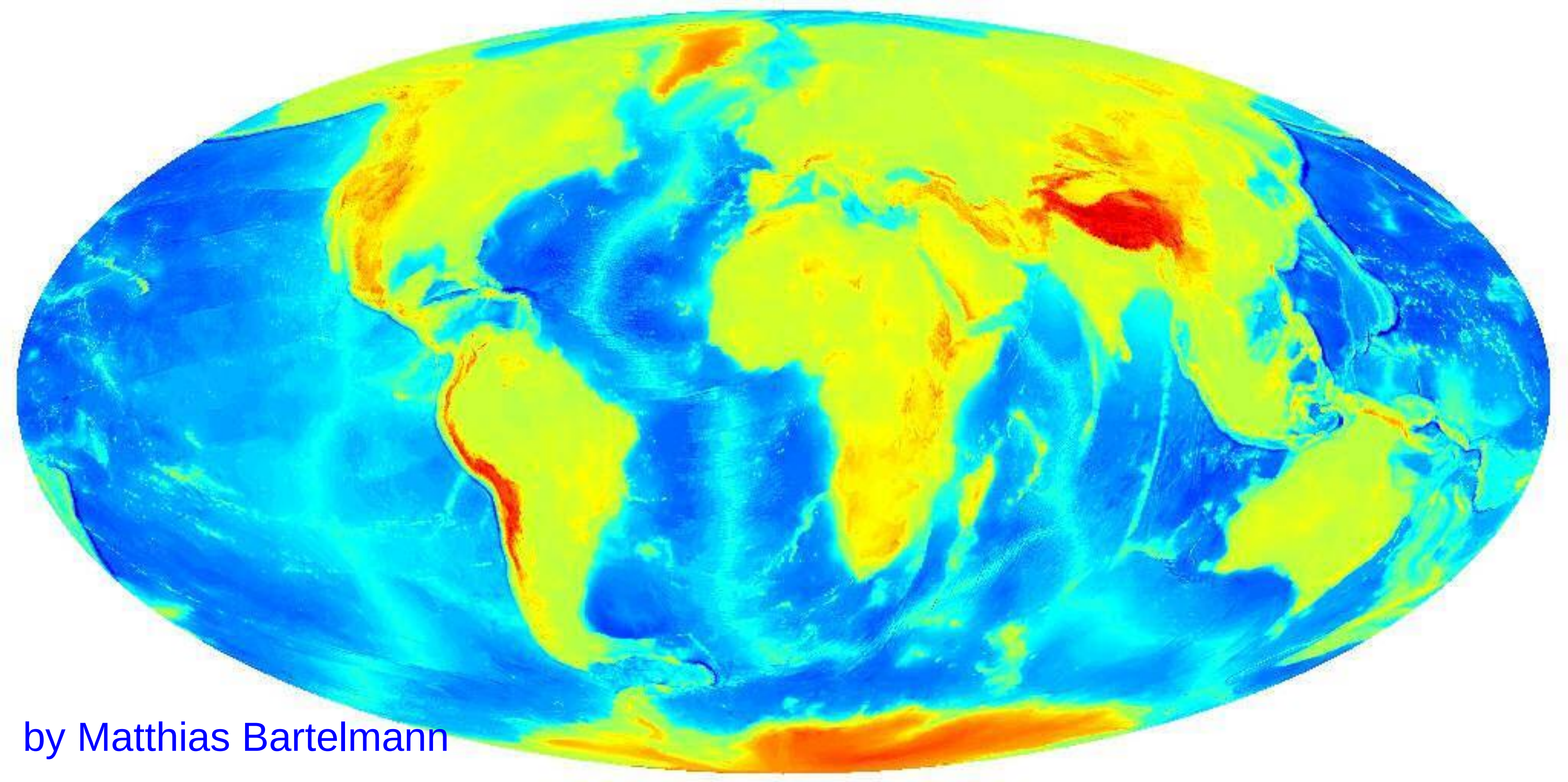
l= 1 - 8



To higher l

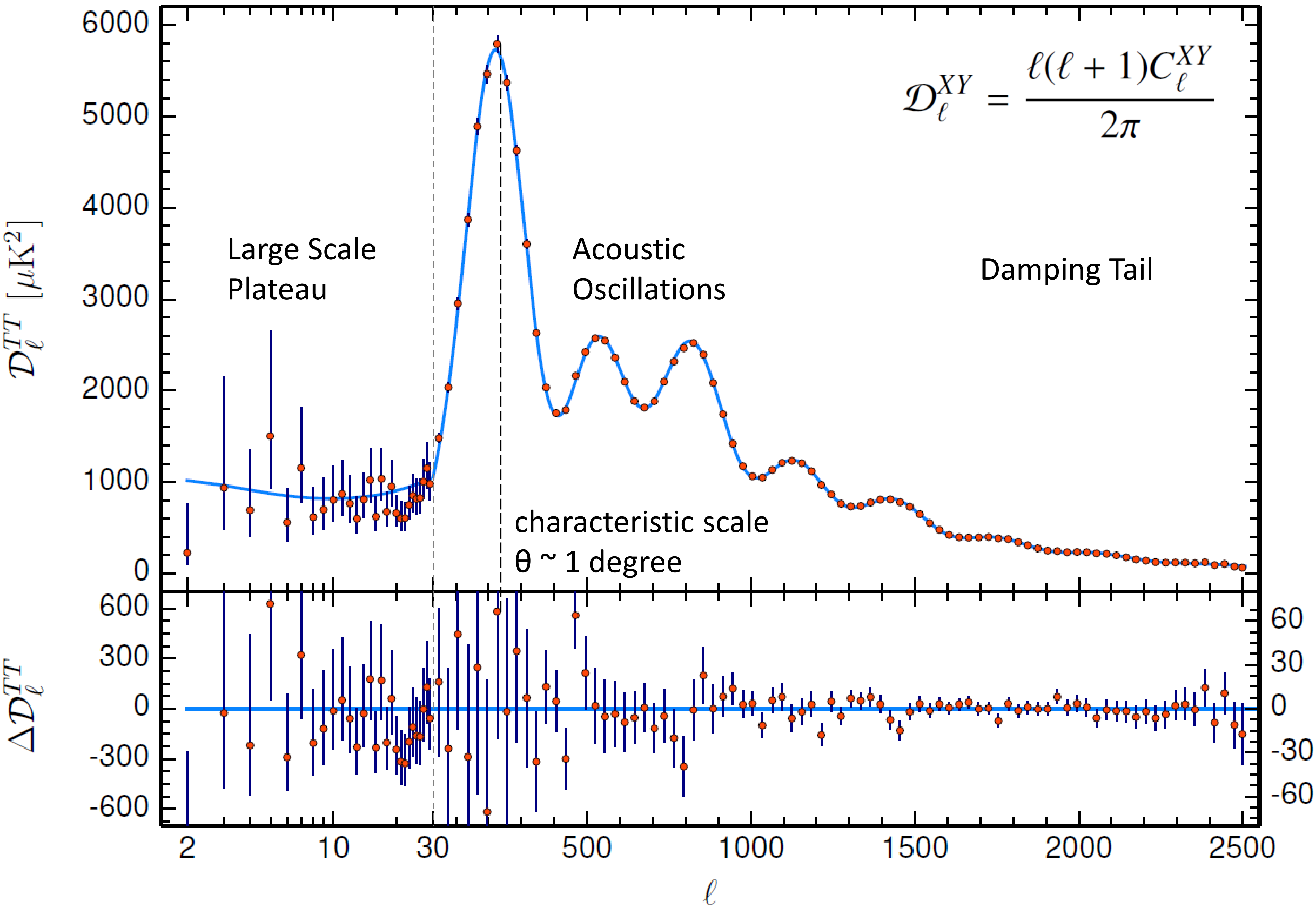


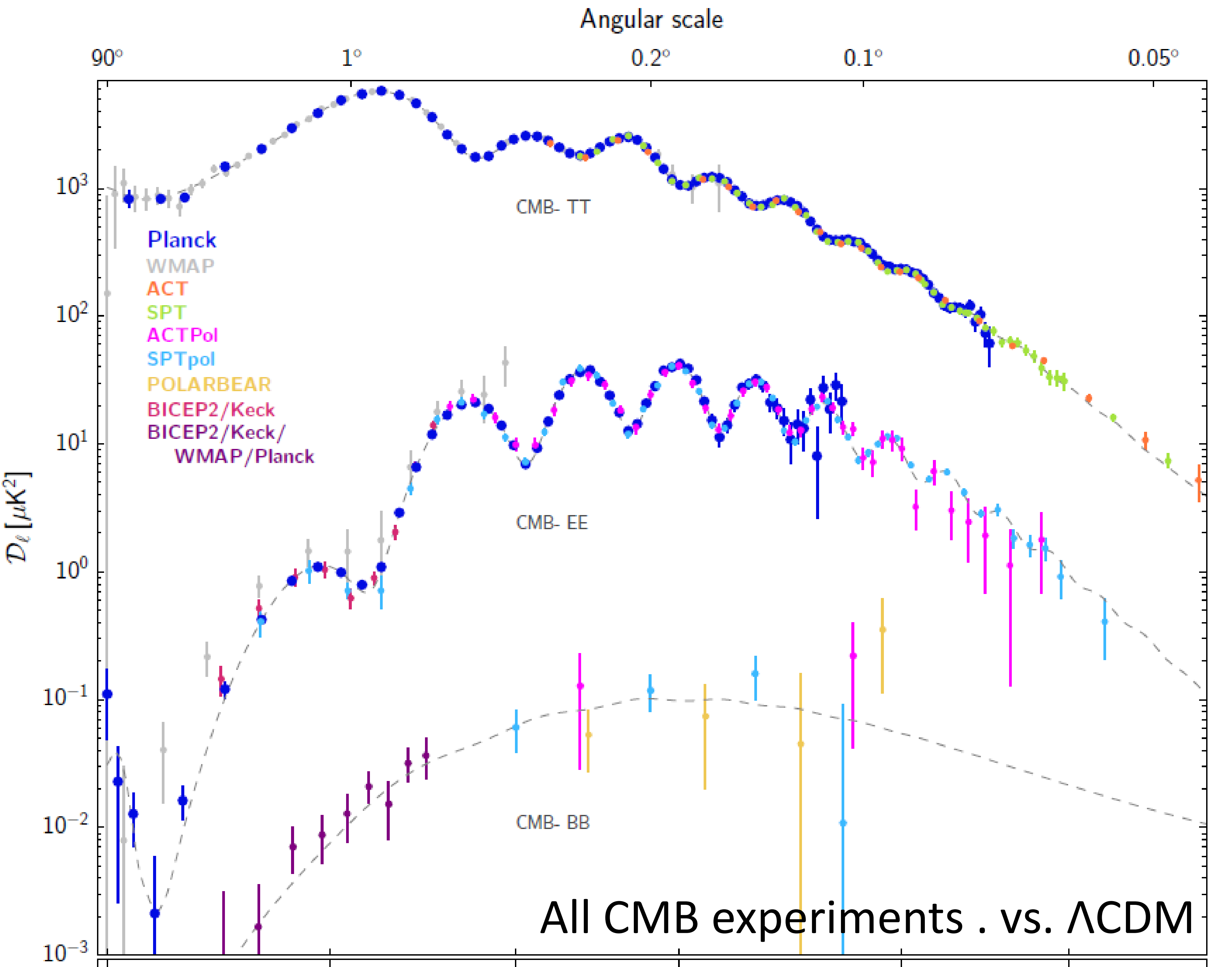
Original map



by Matthias Bartelmann

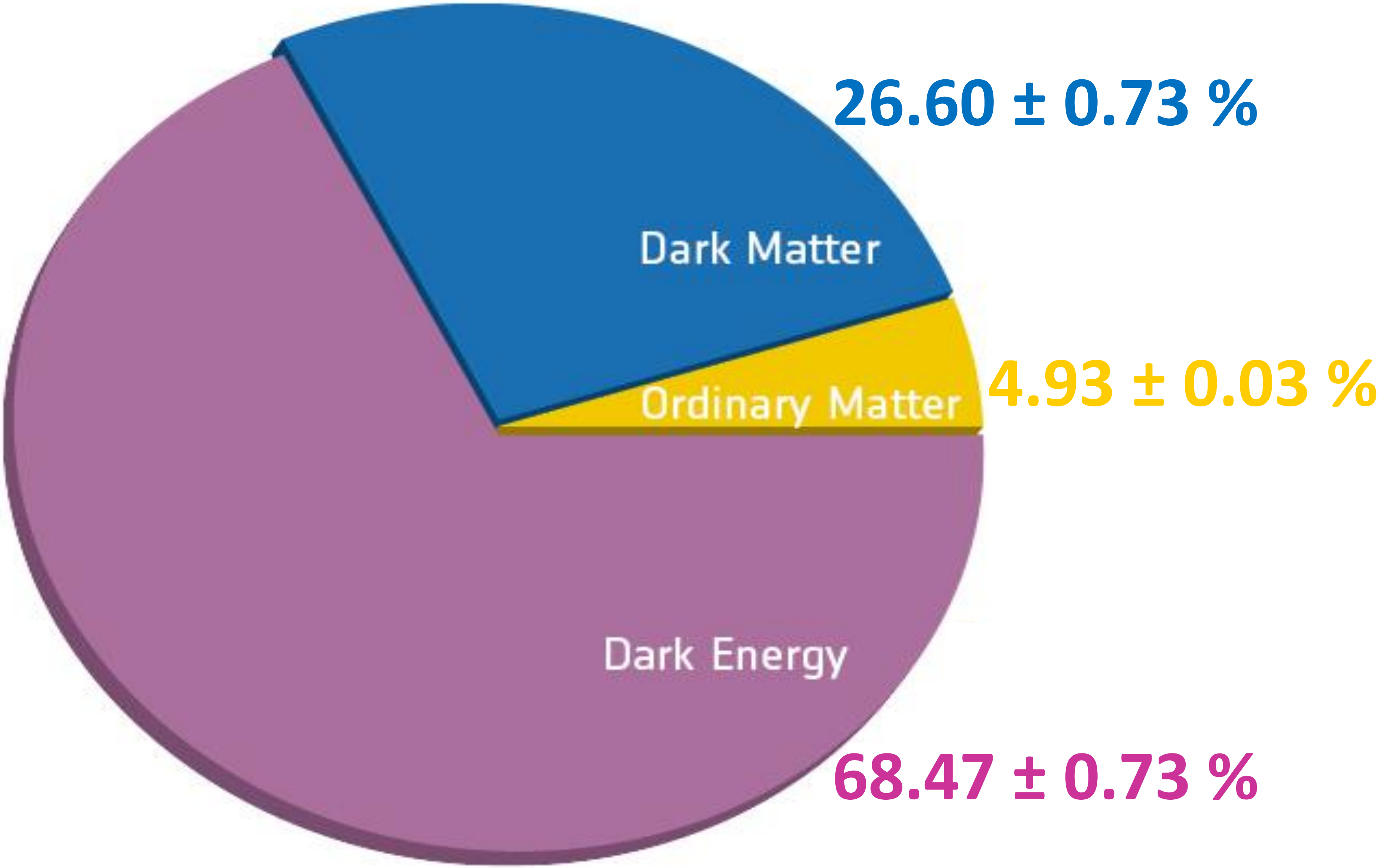
Planck .vs. ΛCDM





Angular scale
90°
1°
0.2°
0.1°
0.05°
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$\mathcal{D}_\ell\,[\mu K^2]$
CMB- TT
CMB- EE
CMB- BB
Planck
WMAP
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck
BICEP2/Keck/ WMAP/Planck
All CMB experiments . vs. ΛCDM

PLANCK 2018


26.60 ± 0.73 %
Dark Matter
Ordinary Matter
4.93 ± 0.03 %
Dark Energy
68.47 ± 0.73 %

LARGE SCALE STRUCTURE

Summary of the formation and evolution of structure in the Universe

10^{-35} s

Quantum Fluctuations during inflation

$V(\phi)$

→

$\sim 10^{5}$ years

Perturbation Growth: Pressure. vs. Gravity

Ω_M, Ω_r, Ω_b, f_ν

→

Photons freestream: Inhomogeneities turn into anisotropies

z_{reion}, Ω_Λ, w

→

Matter perturbations grow into non-linear structures observed today

Fluctuations are small. We can use perturbation theory

$$g_{\mu\nu}(\eta, \boldsymbol{x}) = \bar{g}_{\mu\nu}(\eta) + \delta g_{\mu\nu}(\eta, \boldsymbol{x})$$

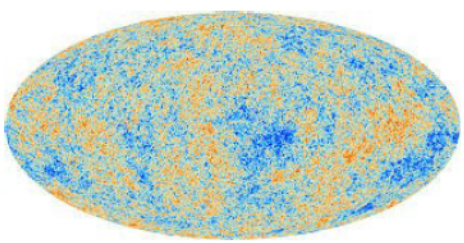
$$T_{\mu\nu}(\eta, \boldsymbol{x}) = \bar{T}_{\mu\nu}(\eta) + \delta T_{\mu\nu}(\eta, \boldsymbol{x})$$

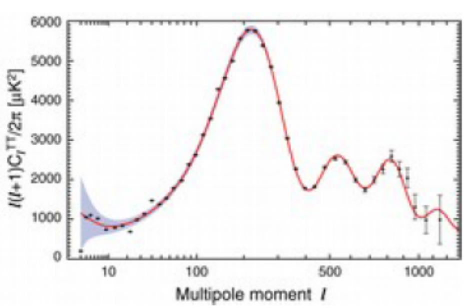
2 types of perturbations: metric perturbations, density perturbations

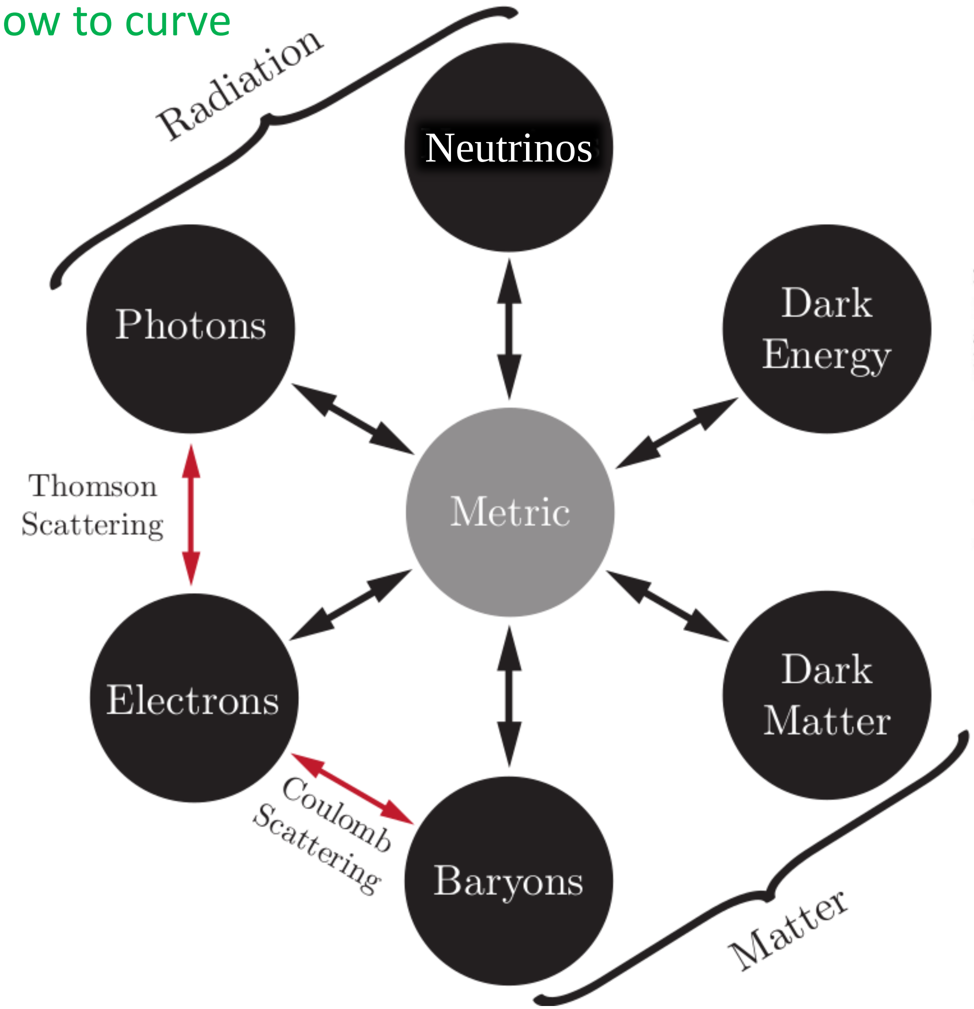
$$\Rightarrow \Phi, \delta\rho_m, \delta\rho_r$$

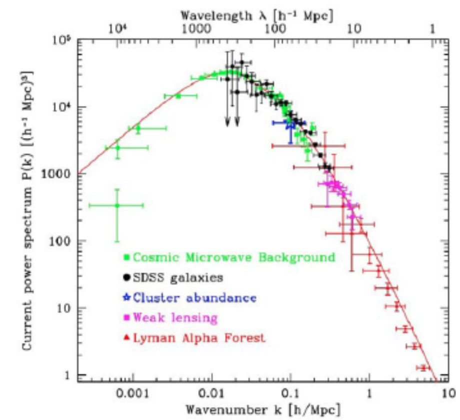
Remember: Spacetime tells matter how to move, matter tells spacetime how to curve

CMB $\Leftarrow$









$\Rightarrow$ LSS

Matter perturbations

Use newtonian gravity.

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0 \\
\frac{\partial v}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} &= -\frac{1}{\rho}\nabla p - \nabla \phi \\
\nabla^2 \phi &= 4\pi G \rho.
\end{aligned}$$

Since dark energy is smooth (has no fluctuations), only radiation and matter are included in the eqs.

3 regimes:

$\delta \ll 1$: linear theory

$\delta \sim 1$: need specific assumptions (i. e. spherical symmetry)

$\delta \gg 1$: non-linear regime. Solve numerically, simulations (also higher order perurbations)

In general: Universe is lumpy on small scales and smoother on large scales – consider inhomogeneities as a perturbation to the homogeneous solution

Matter perturbations

$$\rho \to \bar{\rho}(t) + \delta\rho \equiv \bar{\rho}(t)(1+\delta)$$

$$P \to \bar{P}(t) + \delta P$$

$$\mathbf{u} \to a(t)H(t)\mathbf{x} + \mathbf{v}$$

$$\Phi \to \bar{\Phi}(\mathbf{x}, t) + \phi\,.$$

Linearizing the equation:

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\rho_0\delta + \frac{c_s^2}{a^2}\nabla_c^2\delta$$

Using the Fourier transform, we can write eqs. For the Fourier modes:

$$\delta(\boldsymbol{x}, t) = \sum_{\boldsymbol{k}} \delta_{\boldsymbol{k}}(t)\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

$$\delta_{\boldsymbol{k}}(t) = \frac{1}{V}\int \delta(\boldsymbol{x}, t)\, e^{-i\boldsymbol{k}\cdot\boldsymbol{x}}\, d^3x$$

$$\ddot{\delta}_k + 2H\dot{\delta}_k = \left(4\pi G\rho_0(t) - \frac{k^2c_s^2}{a^2}\right)\delta_k.$$

For baryonic matter

$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho_m(t)\delta_k = 0$$

For dark matter

Matter perturbations

We can linearize this equation because δ is very small . The linear regime is very important:

- On all scales, primordial fluctuations were extremelly small, $\delta << 1$. On all scales, the seeds of structure formation were linear
- The linear stage of structure formation is a relatively long lasting one.
- One may always find large scales where the density and velocity perturbations are still linear. Today, scales larger than ~10 h^{-1} Mpc behave linearly
- CMB measurements have established the linear density fluctuations at the recombination era. By studying the linear structure growth, we are able to translate these into the amplitude of fluctuations at the current epoch, and compare these predictions against the measured LSS in the Galaxy distribution

$$\boxed{\delta(\mathbf{x}, t) = \frac{\rho(\mathbf{x}, t) - \rho_0(t)}{\rho_0(t)}}$$

Matter perturbations

Matter Dominated Universe

$$\delta = A(x)t^{2/3} + B(x)t^{-1}$$

Linear growth

Structure formation is only possible in the matter dominated era

Radiation Dominated Universe

$$\delta_{\boldsymbol{k}}(t) = A + B\ln t$$

No significant growth

Lambda Dominated Universe

$$\delta = A(x) + B(x)e^{-2Ht}$$

Frozen fluctuations

Matter perturbations

Baryon photon fluid
Jeans length and scales for collapse

$$\ddot{\delta}_k + 2H\dot{\delta}_k = \left(4\pi G\rho_0(t) - \frac{k^2 c_s^2}{a^2}\right)\delta_k.$$

GRAVITY PRESSURE

Jeans Length: Both effects are equal

$\frac{c_s^2 k^2}{a^2} > 4\pi\rho_0$ → Oscillating solution

$\frac{c_s^2 k^2}{a^2} < 4\pi\rho_0$ → Perturbations grow

$$k_J = \frac{a}{a_0}\frac{\sqrt{4\pi G\bar{\rho}}}{c_s}$$

Jeans wavenumber

$$\lambda_J = \frac{2\pi}{k_J}$$

Jeans wavelength

the perturbations grow exponentially (if no expansion) with time or oscillate as sound waves depending on whether their wave number is greater than or less than the Jeans wave number

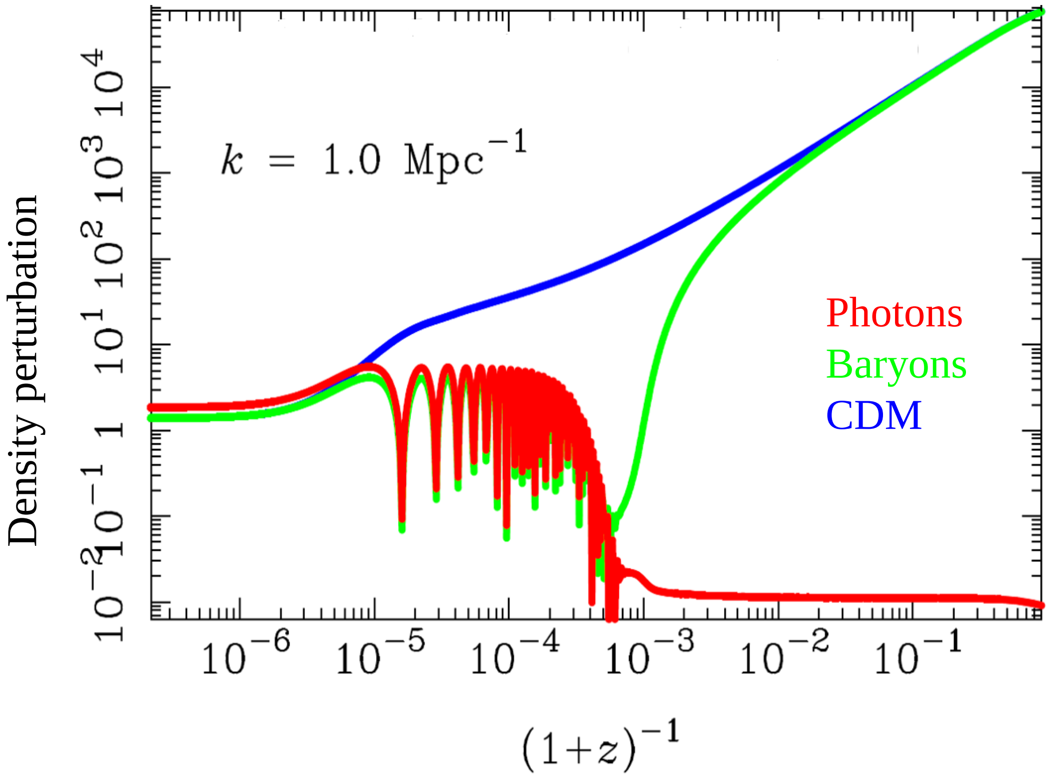
For $k > k_J$ we have sound waves, for $k < k_J$ we have collapse. The expansion adds a sort of friction term on the left-hand side: The expansion of the universe slows the growth of perturbations down.

Matter perturbations: dark matter

CMB shows that at z~1100, perturbations are of the order 10^{-5}. If they grow as $\delta \sim t^{2/3}$, then for z=0 they grow a factor of 1000, becoming of the order 1% → NOT ENOUGH!!

DARK MATTER ROLE

- Dark matter is not coupled to photons.
- Density fluctuations in dark matter can start growing from the start of the matter-dominated era (z_{rm} ~ 3300).
- At the time of decoupling, the baryons fell in the pre-existing gravitational wells of dark-matter and the baryon perturbations grew from there.
- This explains the observed structure. → **LSS requires the existence of dark matter**

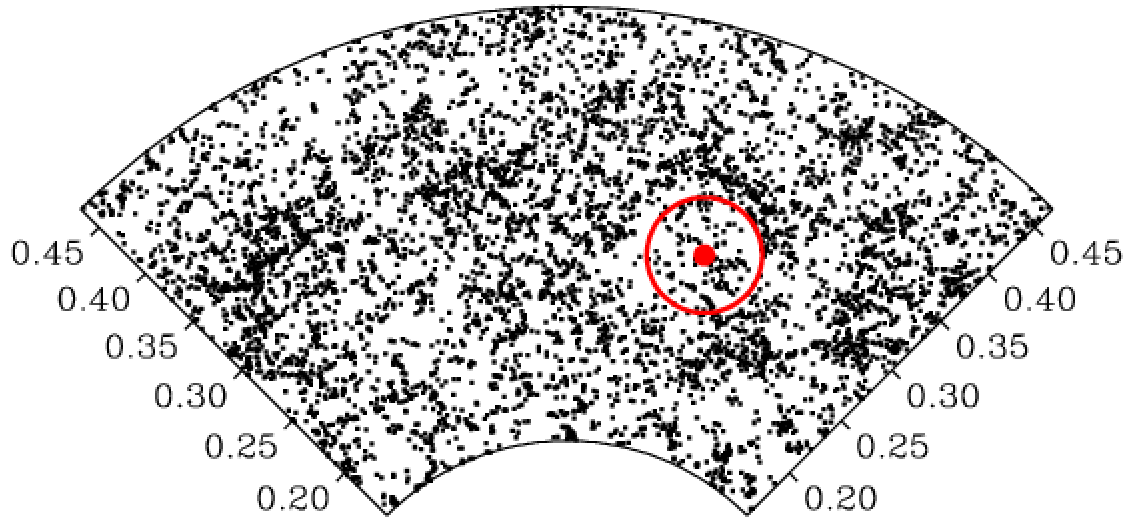


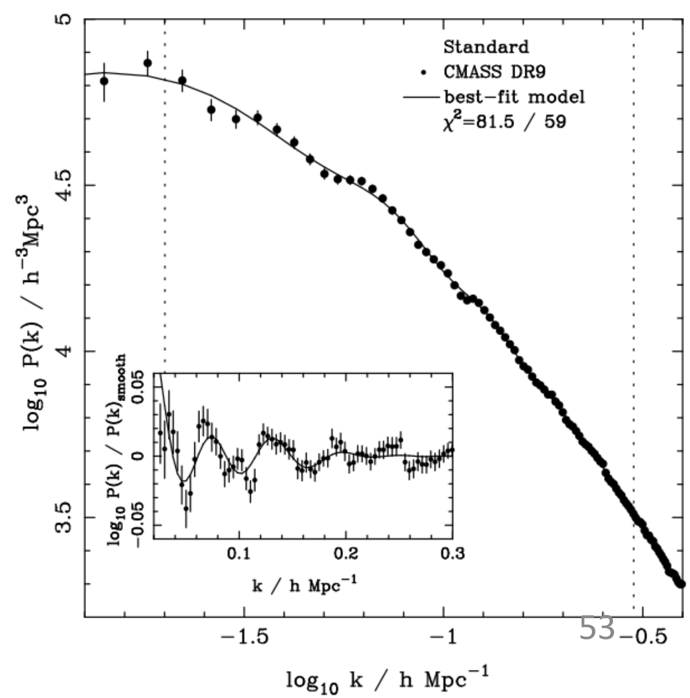
Matter perturbations: Comparing the theory to the observations

- Galaxy surveys provide galaxy maps.
- Similarly to the CMB, we want to study the statistical properties of the **density** fluctuations
- Since the maps are in 3D, we use Fourier transforms and the power spectrum:

$$\delta(\mathbf{r}) = \frac{V}{(2\pi)^3}\int \delta_{\mathbf{k}} e^{-i\mathbf{k}\cdot\mathbf{r}}\, d^3\mathbf{k}$$

$$P(k) = \left\langle \left|\delta_{\mathbf{k}}\right|^2 \right\rangle$$





Matter perturbations: Comparing the theory to the observations

Inflation as primordial perturbations generator → initial perturbations are Gaussian. The density contrast δ is a homogeneous, isotropic Gaussian random field (Fourier modes are uncorrelated)

Its statistical properties are completely determined by 2 numbers: mean and variance. The variance is described in terms of a function called the **POWER SPECTRUM**

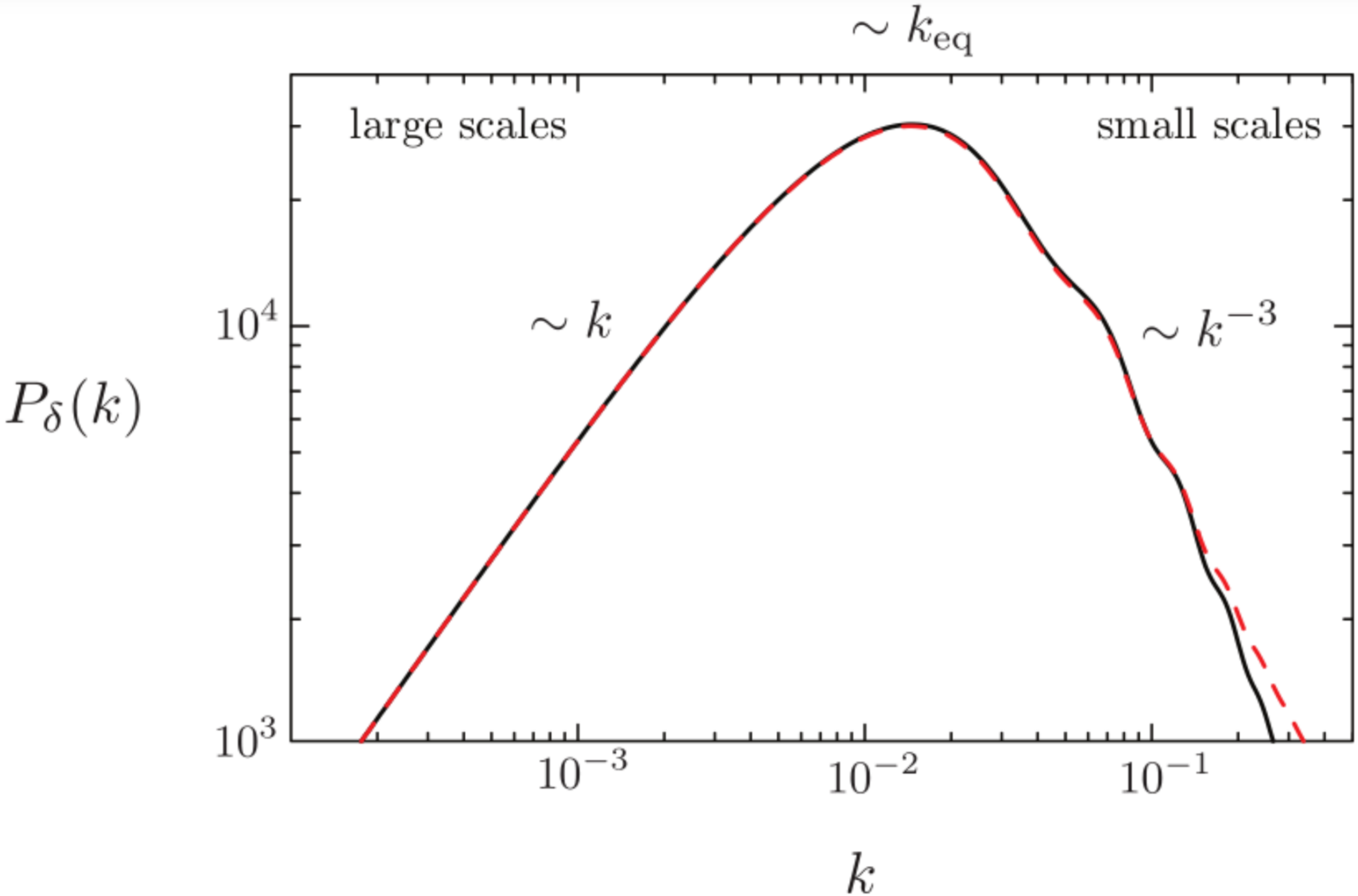
$$\left\langle \hat{\delta}(\vec{k})\hat{\delta}^{*}(\vec{k}')\right\rangle \equiv (2\pi)^3 P(k)\delta_{\mathrm{D}}\left(\vec{k}-\vec{k}'\right)$$

The initial power spectrum has the Harrison-Zel´dovich form:

$P(k) \propto k^{n_S}$, $n_S \sim 1$ Spectral index

Matter perturbations

The full power spectrum shape



Matter perturbations

Measured power spectrum for different cosmological tracers

Linear approximation

ΛCDM is a good description