Observational Cosmology: The CMB

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The Cosmic Microwave Background

After these lectures, you should be able to:

- Discuss the discovery of the CMB
- Define "recombination"
- Describe how the CMB arises and why it is a blackbody
- Redshifting of CMB photons
- Estimate the redshift of recombination from T_0=2.7K
- Discuss results on the frequency spectrum of the CMB
- Note that it is isotropic to 1 in 10^5

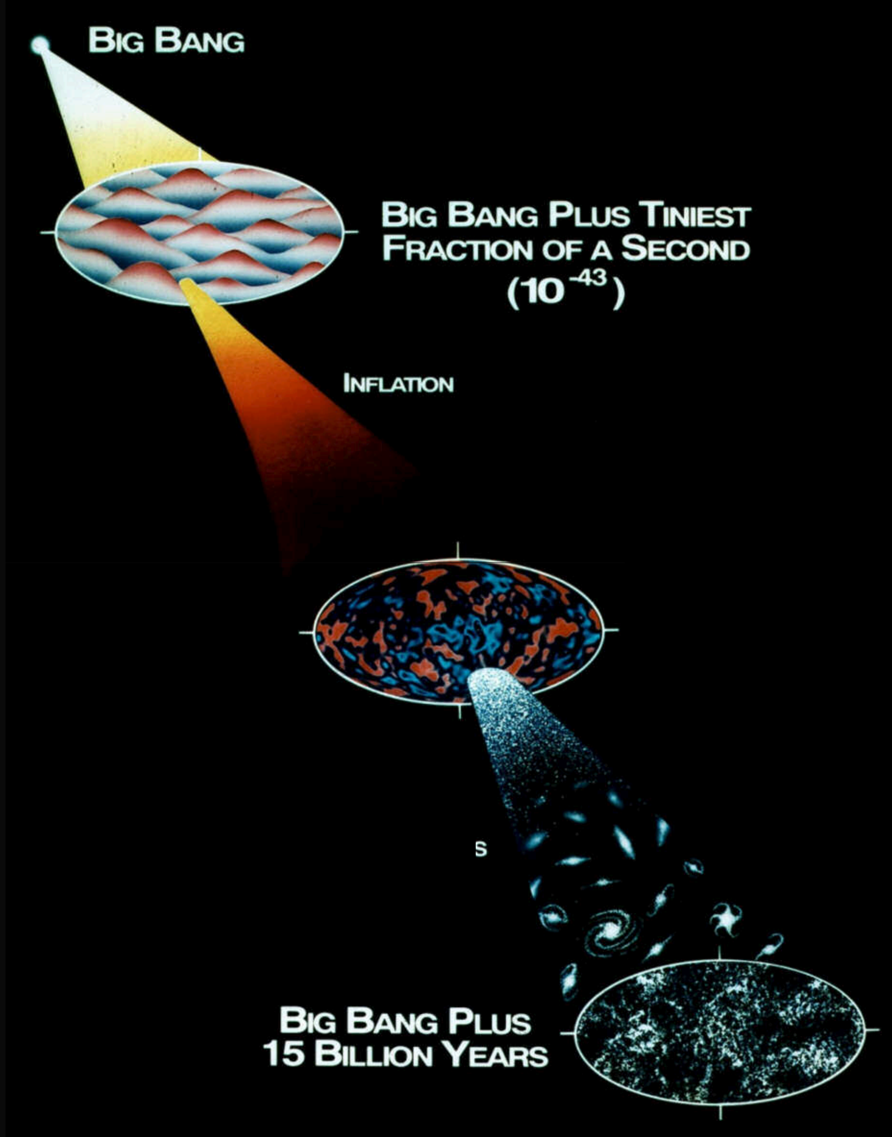
Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

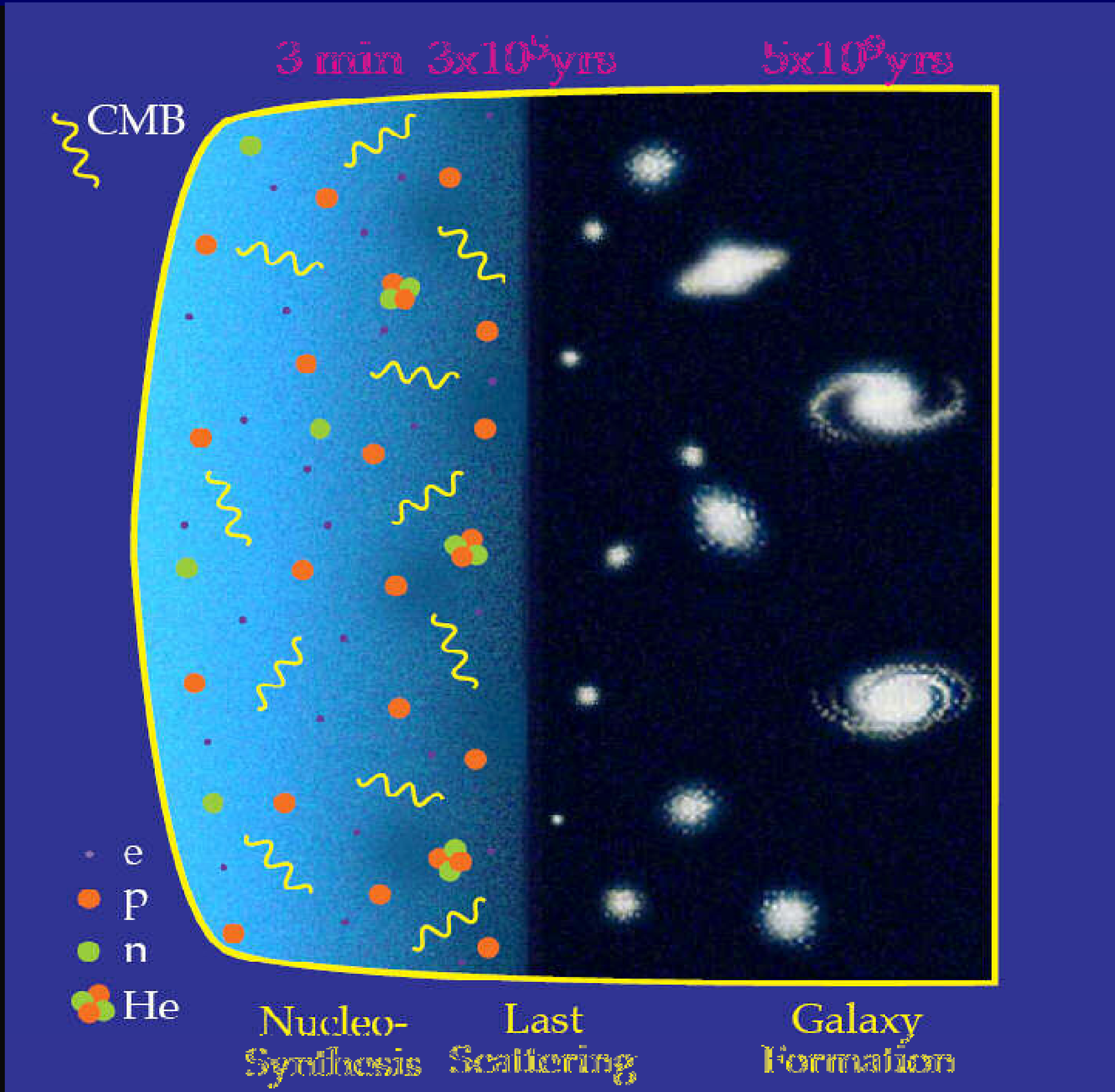
Recombination

- Early times
- Universe is hot
  - Electrons are free
  - Light scatters off electrons

- Recombination

- Late times
- Universe is cooler
  - e- and p+ form hydrogen
  - Light travels freely





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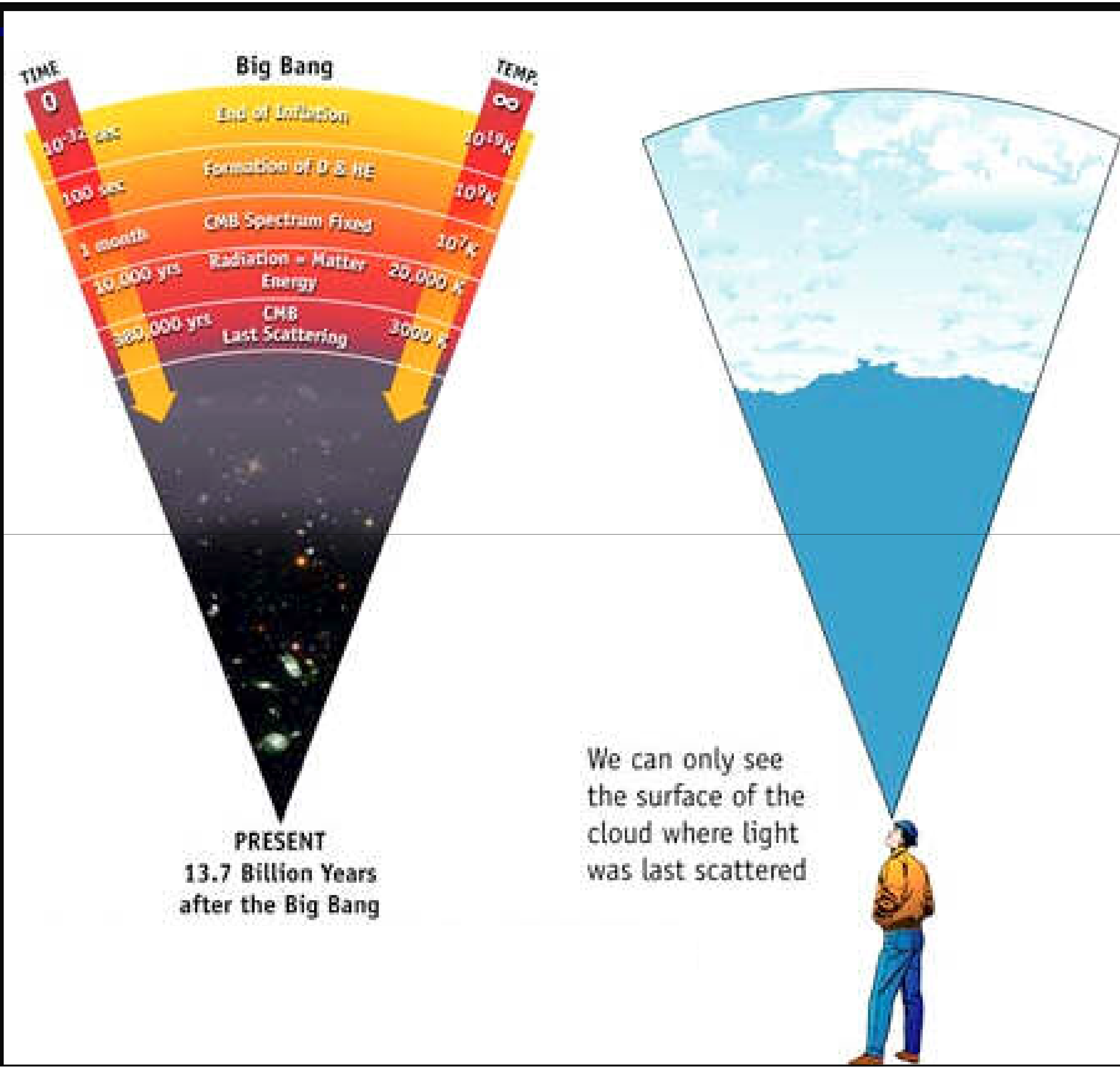
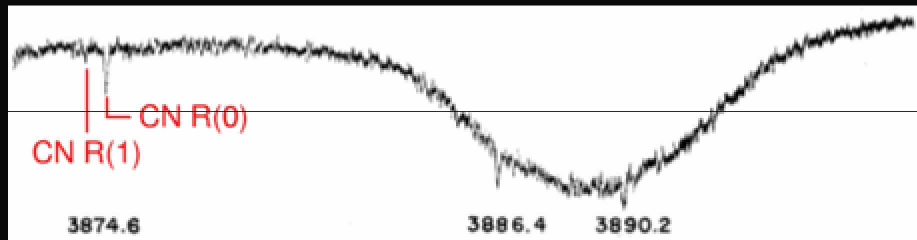


Graphic from WMAP website

Graphic from WMAP website

Interstellar Molecules

- The first measurements of the CMB
  – But no-one realised it at the time (cf “discovery” in 1965)
- 1940 McKellar measured CN lines
  – CN was at a temperature of 2.7K

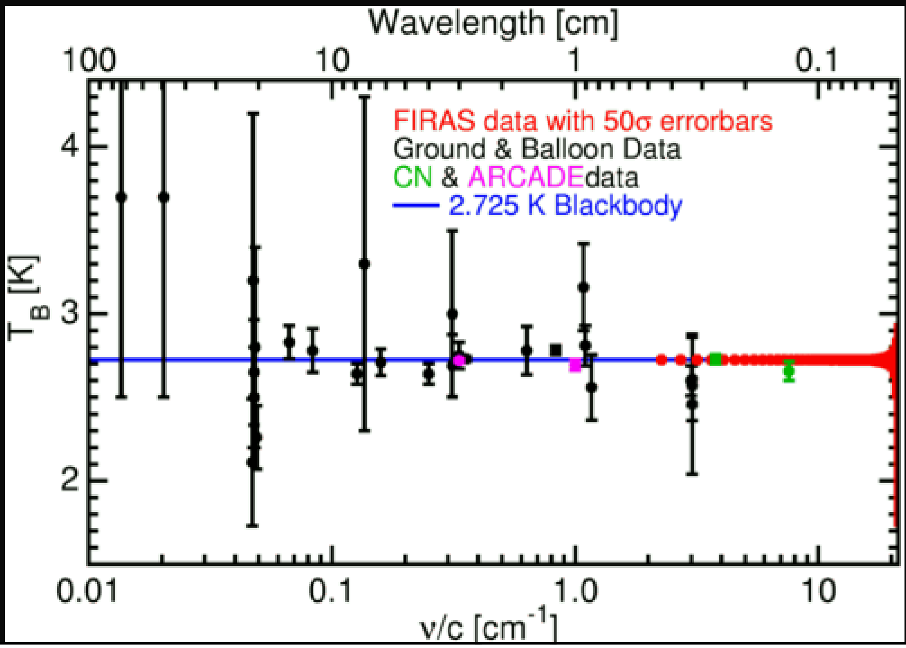


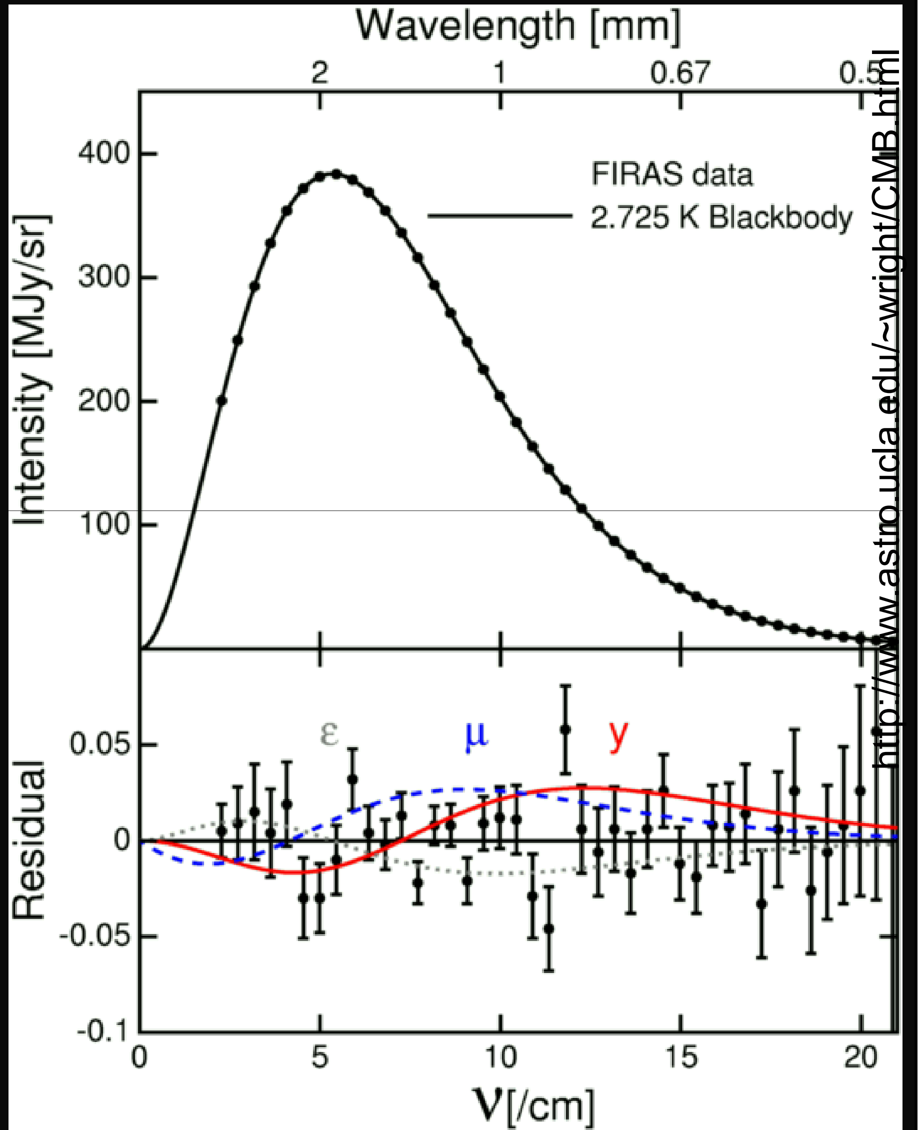
- Hoyle made the connection in 1950
  – "[the Big Bang model] would lead to a temperature of the radiation at present maintained throughout the whole of space much greater than McKellar's determination for some regions within the Galaxy."
- Yet other calculations of the Big Bang (Alpher and Herman 1949) predicted T ~ 1K to 5K

http://www.astro.ucla.edu/~wright/CMB.html

The frequency spectrum

- Observe perfect black body at 2.725K
- Implies Universe was in thermodynamic equilibrium before recombination
  - Collision rate >> expansion rate





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(Mather et al 1994)

Evolution of a black-body spectrum with time

- $\rho_R \propto a^{-4}$
- $\rho_R \propto T^4$ (from thermodynamics)
- Must have $T \propto 1/a$
- Revision: The Planck spectrum
  - Energy per unit volume, from photons with frequencies between ν and $\nu + d\nu$

$$E(\nu)\,d\nu = \frac{8\pi h}{c^3} \frac{\nu^3\,d\nu}{\exp(h\nu/k_B T) - 1}$$

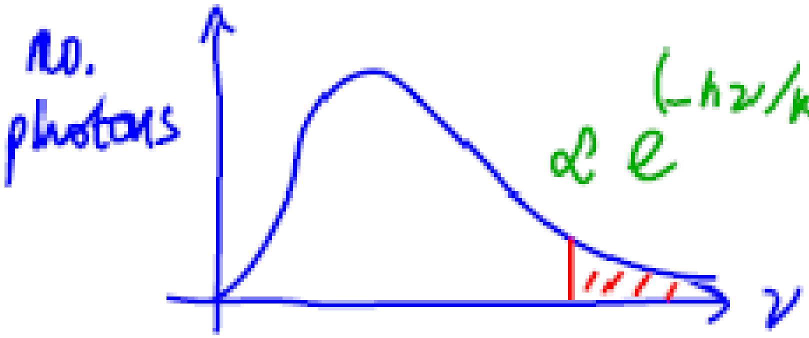
  - Mean energy of a photon is $\sim 3k_BT$

- To retain black-body shape, need
  - $\nu \propto T$
  - $\lambda \propto 1/T \propto a$
  - Light effectively stretches with the Universe

Estimate z_{rec} from T_0=2.73K

- z_{rec} = redshift of recombination
- Ionization energy of Hydrogen
  - Energy required to split H -> p + e
  - I =13.6 eV

- Simplest estimate:
  - Mean energy of photons in Universe at given time is $3k_B\,T$
  - Need $3\,k_B\,T \sim\;\;I$ for ionization
  - Gives T ~ 50,000K
- But: ratio of no. photons to no. baryons $\sim 10^9$
  - Can have a cooler Universe ionizing baryons completely
- Exact answer: T ~ 3000K see derivation in class



$\propto e^{(-h\nu/kT)}$ Boltzmann factor limit

↑ these photons continue causing $H \longrightarrow p + e$ long after $kT \approx 13.6\,eV$

- Fraction of photons with energy $> I$

$$f = \frac{\int_{\nu=I/h}^{\infty} n(\nu)\,d\nu}{\int_0^{\infty} n(\nu)\,d\nu}$$

$n(\nu)$ = Planck spectrum

$$\simeq \frac{\int_{\nu=I/h}^{\infty} e^{-h\nu/k_BT}\,d\nu}{\int_0^{\infty} e^{-h\nu/k_BT}\,d\nu}$$

for tail of Plank spectrum

$$= \frac{\left[-\frac{k_BT}{h}\, e^{-h\nu/k_BT}\right]_{\nu=I/h}^{\infty}}{\left[-\frac{k_BT}{h}\, e^{-h\nu/k_BT}\right]_0^{\infty}}$$

$$= e^{-I/k_BT}$$

- Need fraction $f = R^{-1}$ of photons with energy greater than $I = 13.6$ eV
- Rearrange eq^n for f to get corresponding T:

$$R^{-1} = e^{-I/k_BT}$$

$$k_BT \log(R^{-1}) = -I$$

$$T = \frac{I}{k_B \log R}$$

$$= \frac{13.6 \times 1.6\times10^{-19}\ \text{J}}{1.38\times10^{-23}\ \text{J K}^{-1}\ \log(10^9)}$$

$$\sim 10{,}000\ \text{K}$$

- $T \propto (1+z)$

$$\Rightarrow T_0 = \frac{T_{rec}}{1+z_{rec}}$$

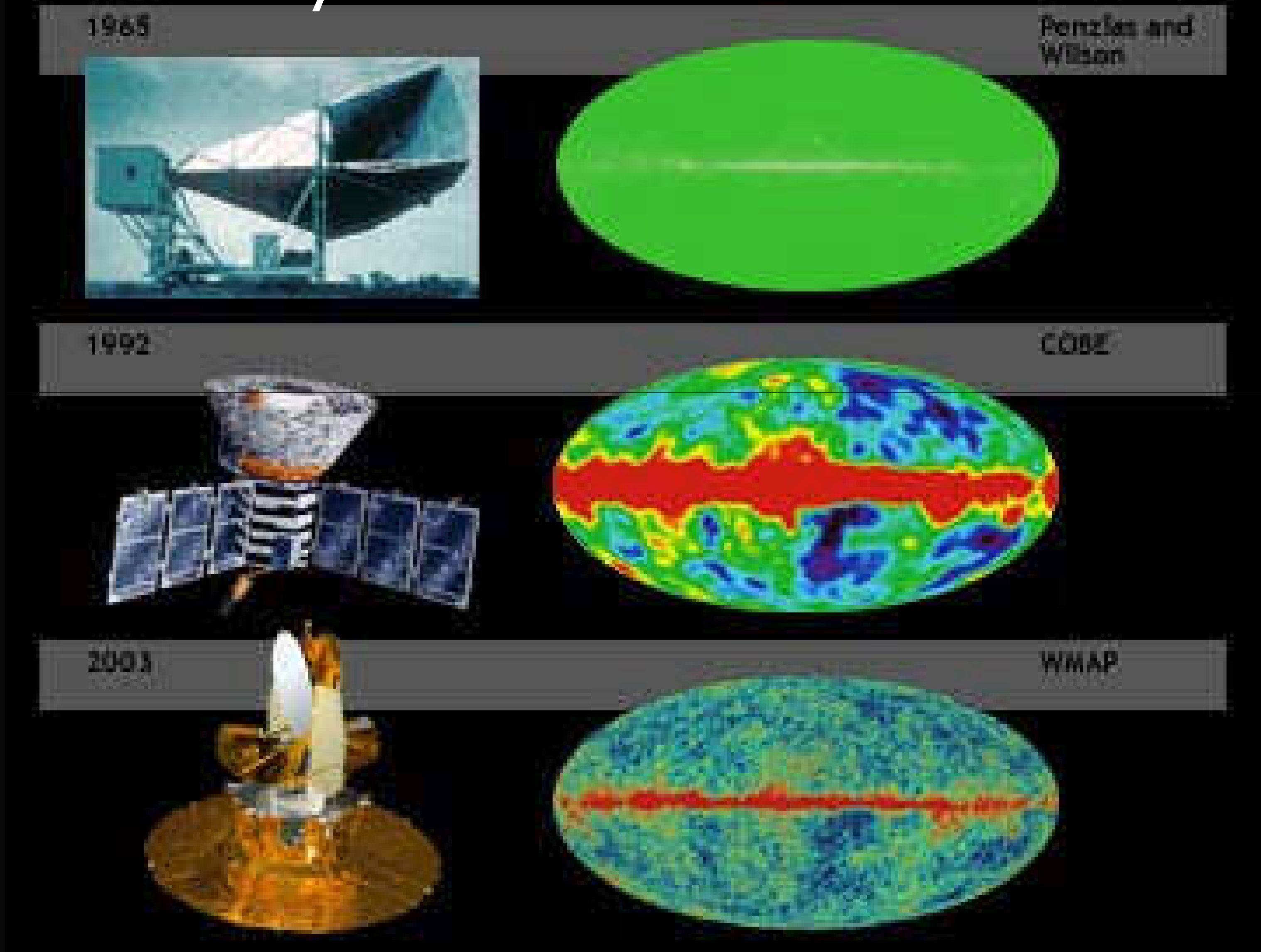
$$\Rightarrow z_{rec} \sim \frac{T_{rec}}{T_0} \sim \frac{10000}{2.7} \sim 3000$$

Exact answer: $T_{rec} \sim 3000$ K.

The History of CMB observations

1965

Discovery



1992

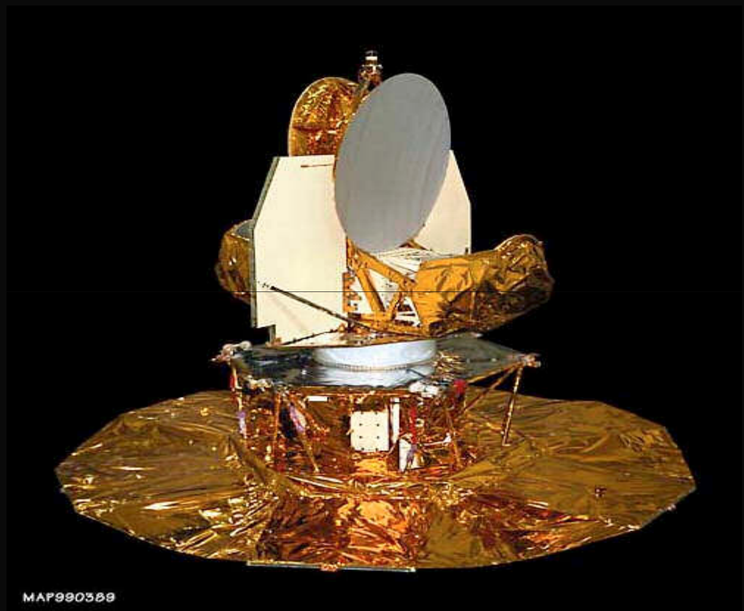
COBE

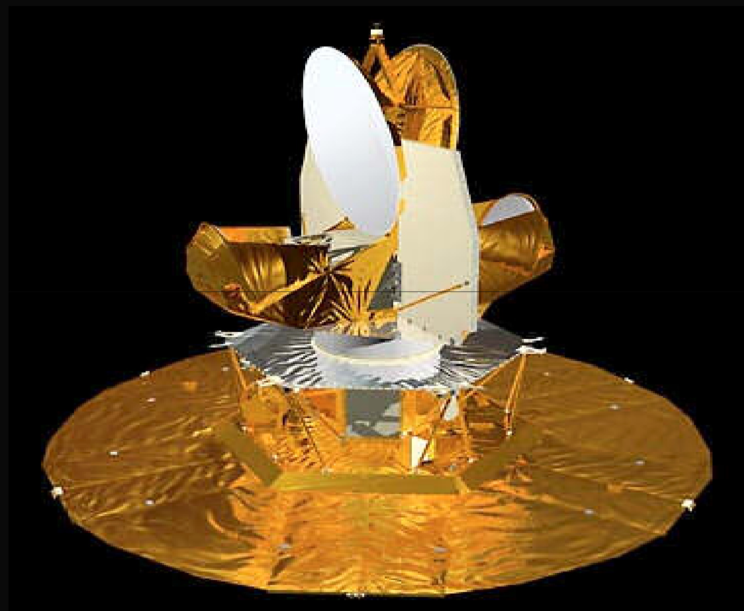
2003

WMAP

Graphic from WMAP website

The WMAP Satellite



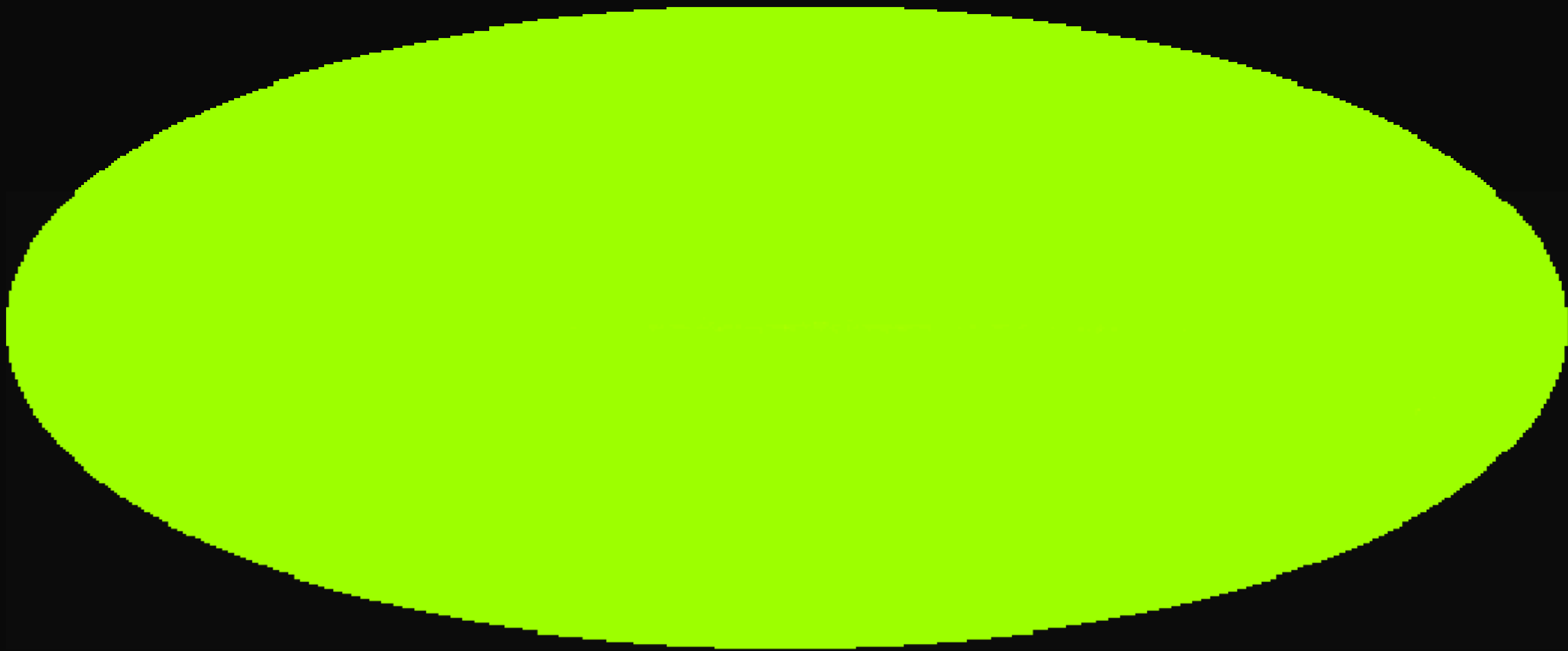


Graphic from WMAP website

WMAP=Wilkinson Microwave Anisotropy Probe

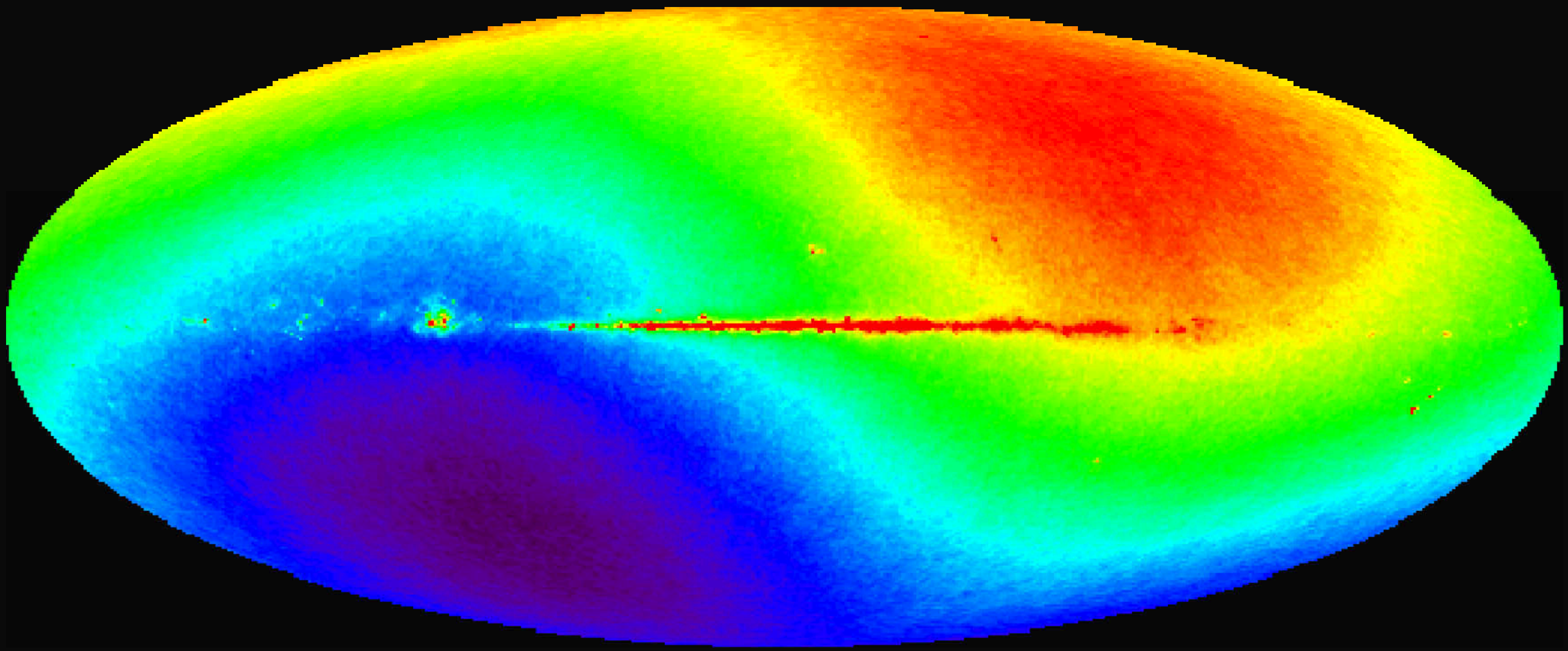
Launch June 2001

What WMAP saw



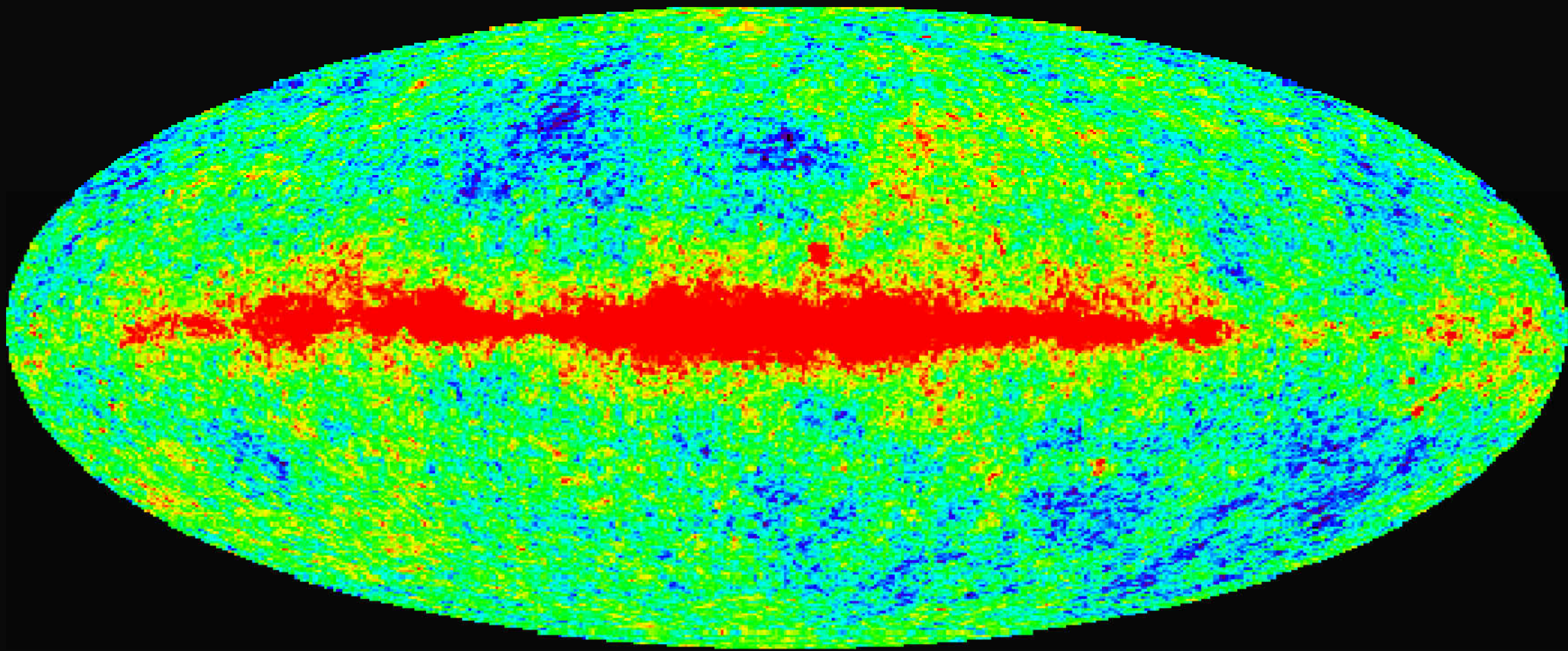
Graphic from WMAP website

Zooming the colour scale by factor of 1000



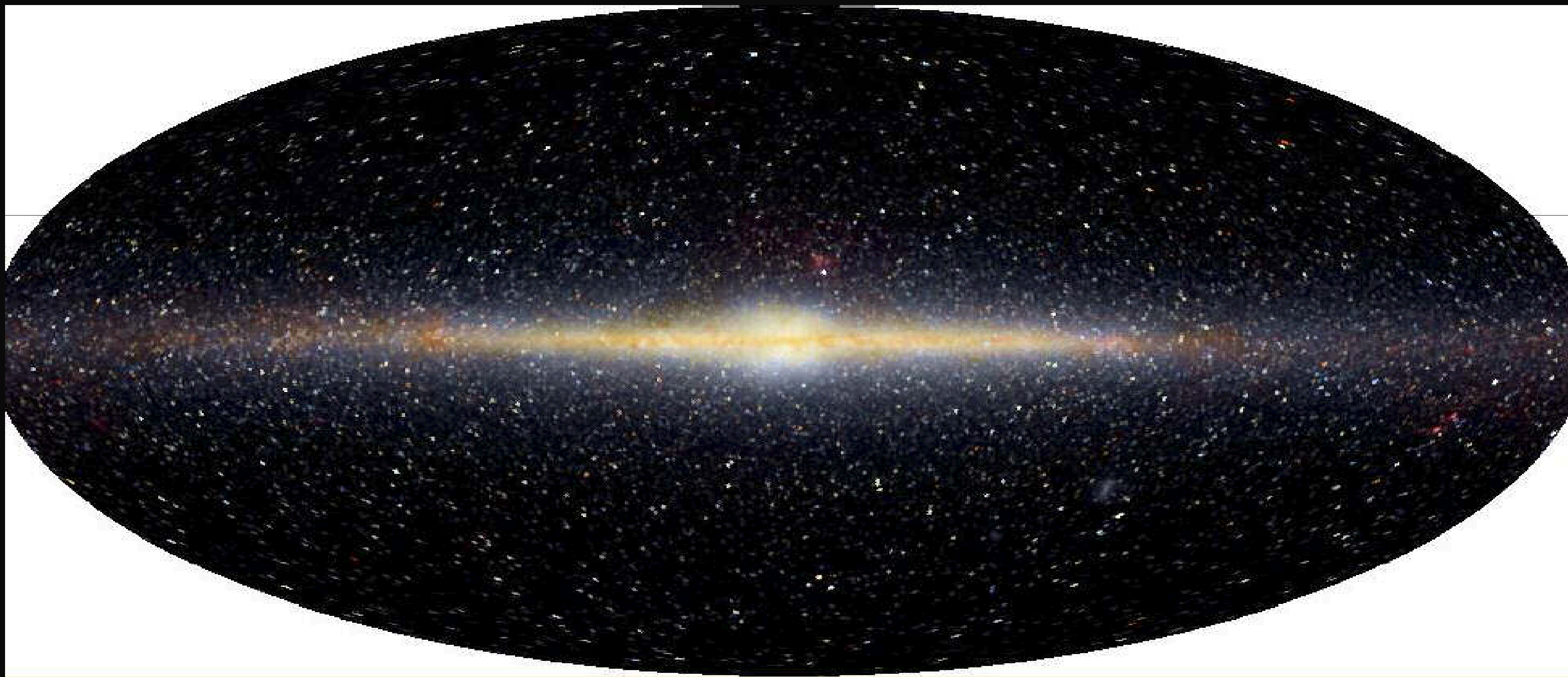
Graphic from WMAP website

Removing the effect of our motion through the galaxy

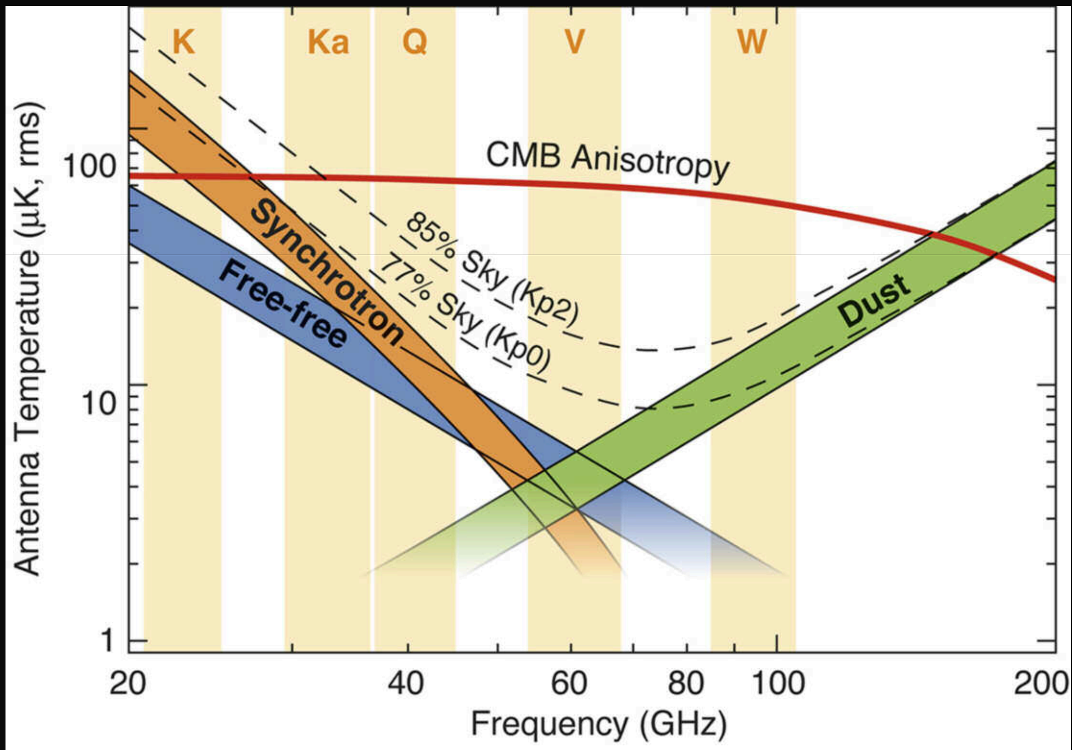


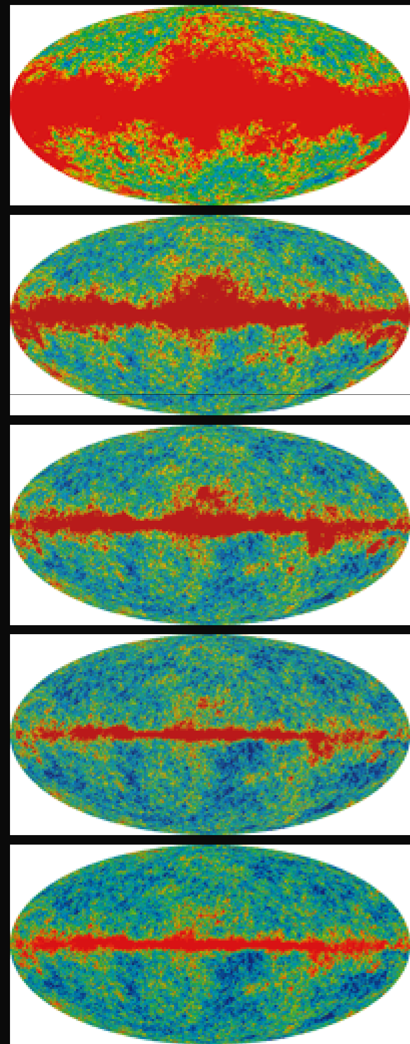
Graphic from WMAP website

We have to look through our own galaxy… How???



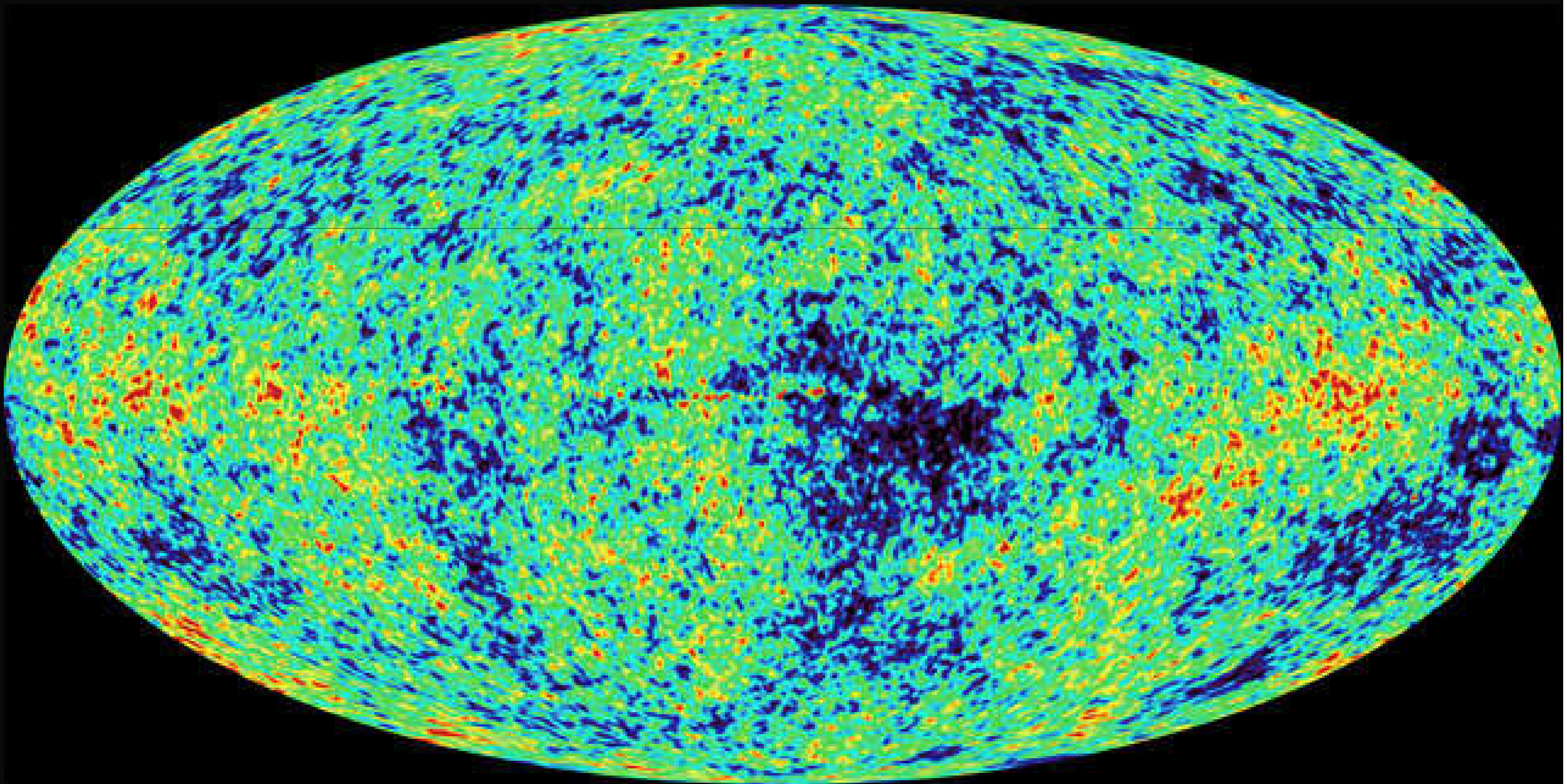
Can remove the foregrounds (i.e. the galaxy) with frequency:





After removing the contribution from dust in our galaxy

- Uniform to 1 in 100,000



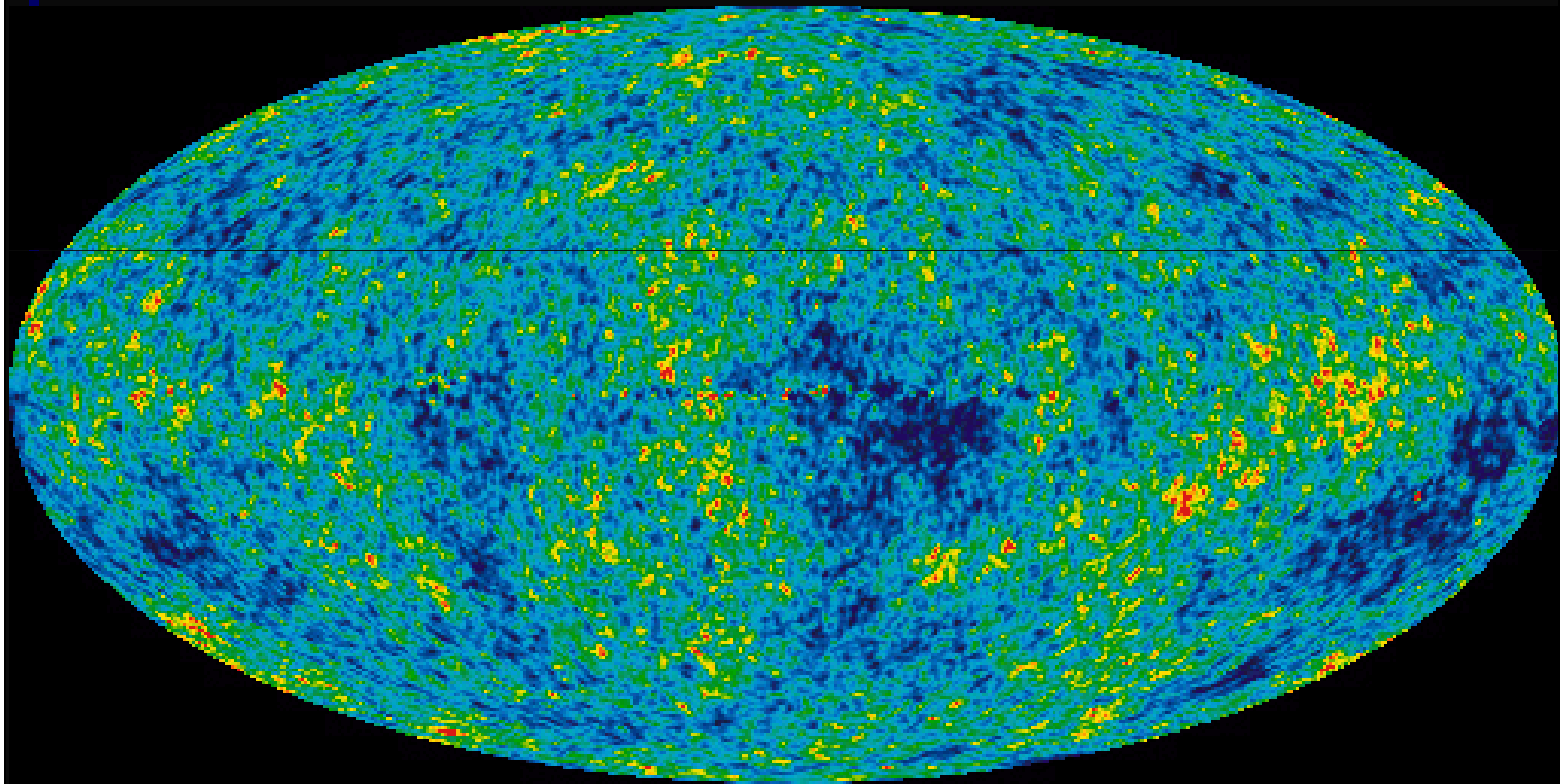
Graphics from WMAP website

CMB fluctuations

After these lectures, you should be able to:

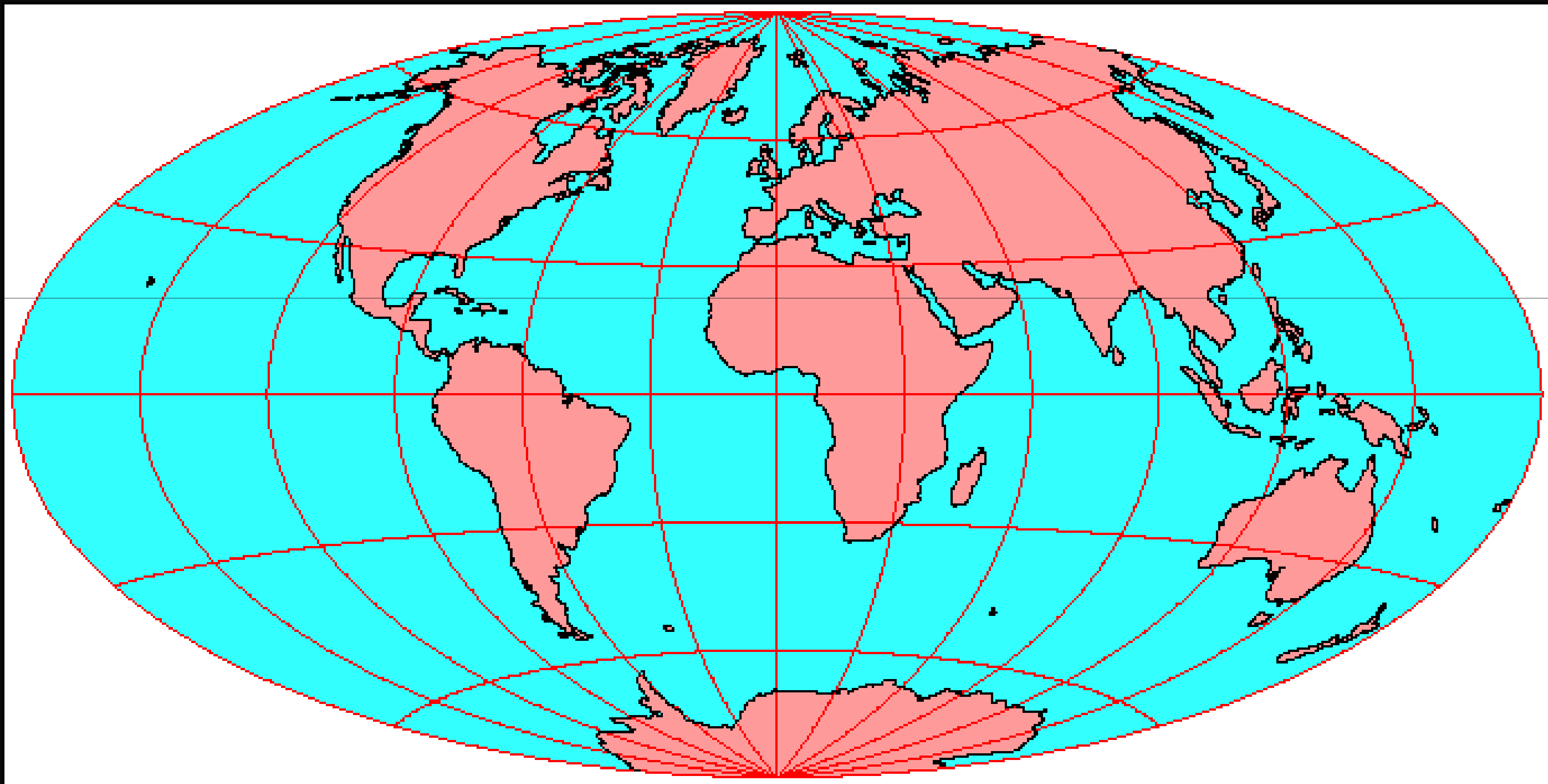
- Describe the acoustic oscillations in the photon-baryon fluid
- Explain the position of the first acoustic peak in the CMB in terms of the Hubble length at recombination and the geometry of the Universe
- Sketch temperature fluctuation spectrum and comment on the origin of the secondary peaks
- Describe the latest observations of CMB anisotropy and their implications for the geometry of the Universe
- Describe the other anisotropies in the CMB. ISW, SZ, Doppler, polarisation anisotropies.

WMAP5 – How do we study this?



Why is it an ellipse?

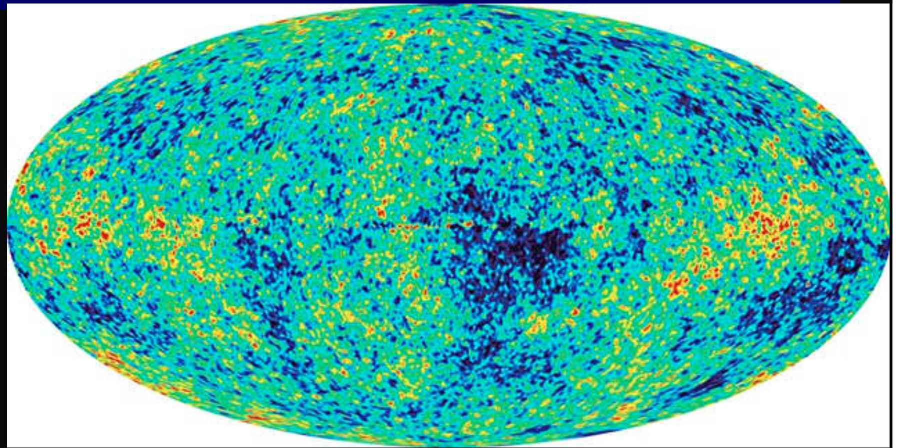
Just a projection of the whole sky (Aitoff)



http://www.heliheyn.de/Maps/L02P07AE.html

Statistical properties

- Spherical harmonic transform
- ~Fourier transform
- Quantifies clumpiness on different scales

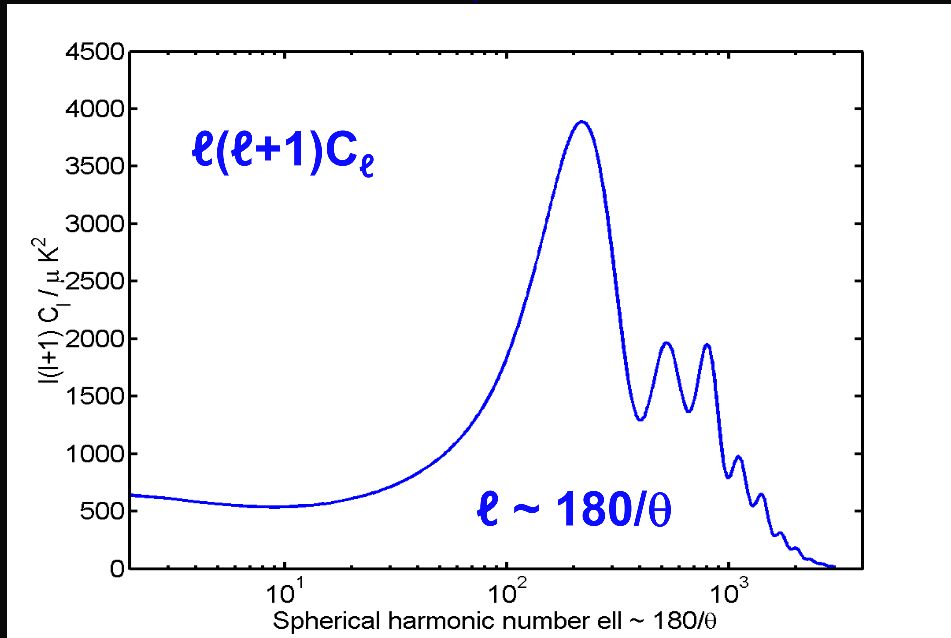


$$T_{\mathrm{CMB}} = 2.726K$$

$$\Delta T(\theta, \phi) = T(\theta, \phi) - T_{\mathrm{CMB}}$$

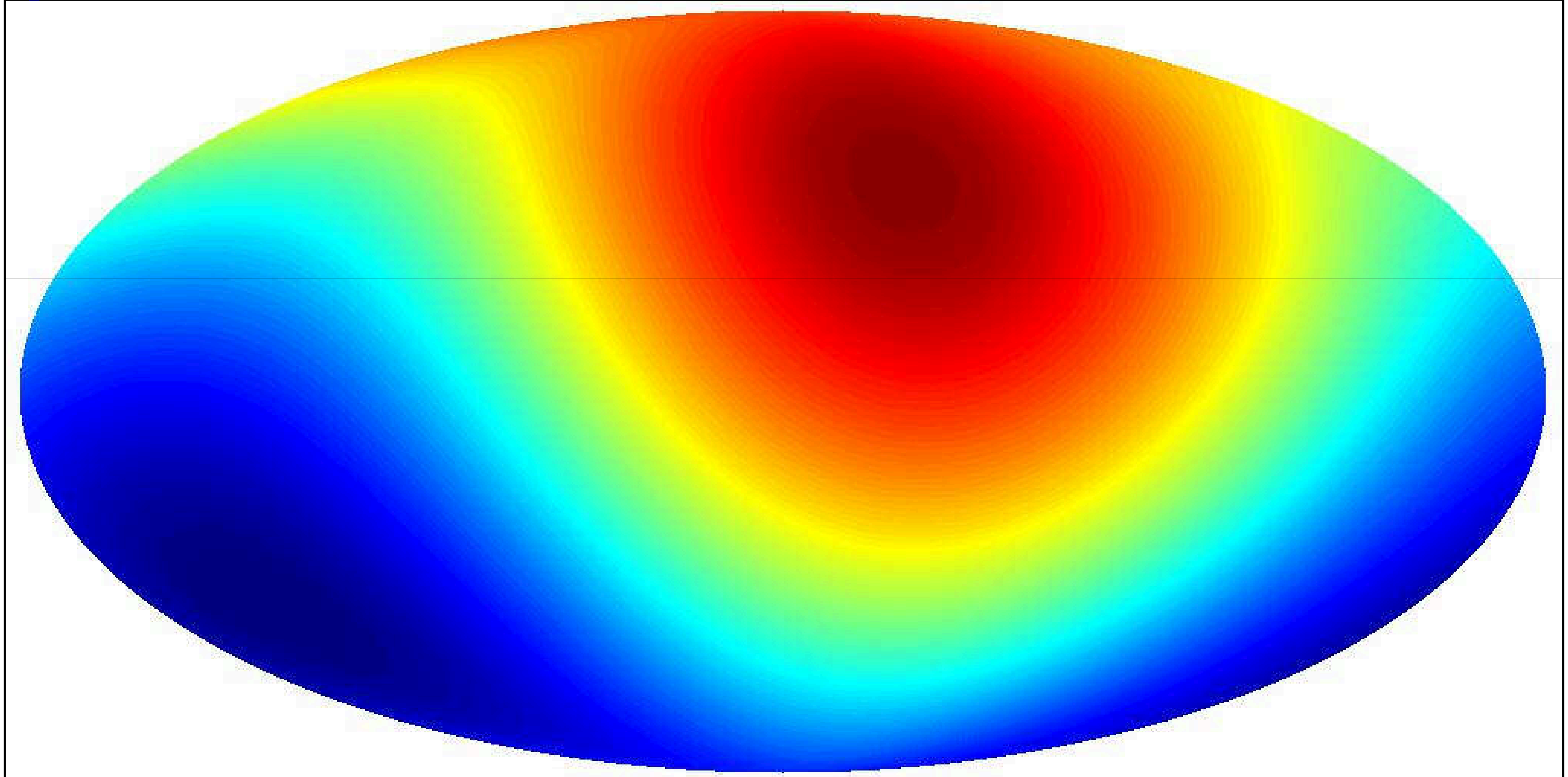
$$a_{\ell m} = \int \frac{\Delta T(\theta, \phi)}{\mathrm{T_{CMB}}} Y_{\ell m}(\theta, \phi)\, \mathrm{d}\Omega$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$



Large scales Small scales

Spherical harmonics:
The spherical equivalent of sine waves
$\ell=1$



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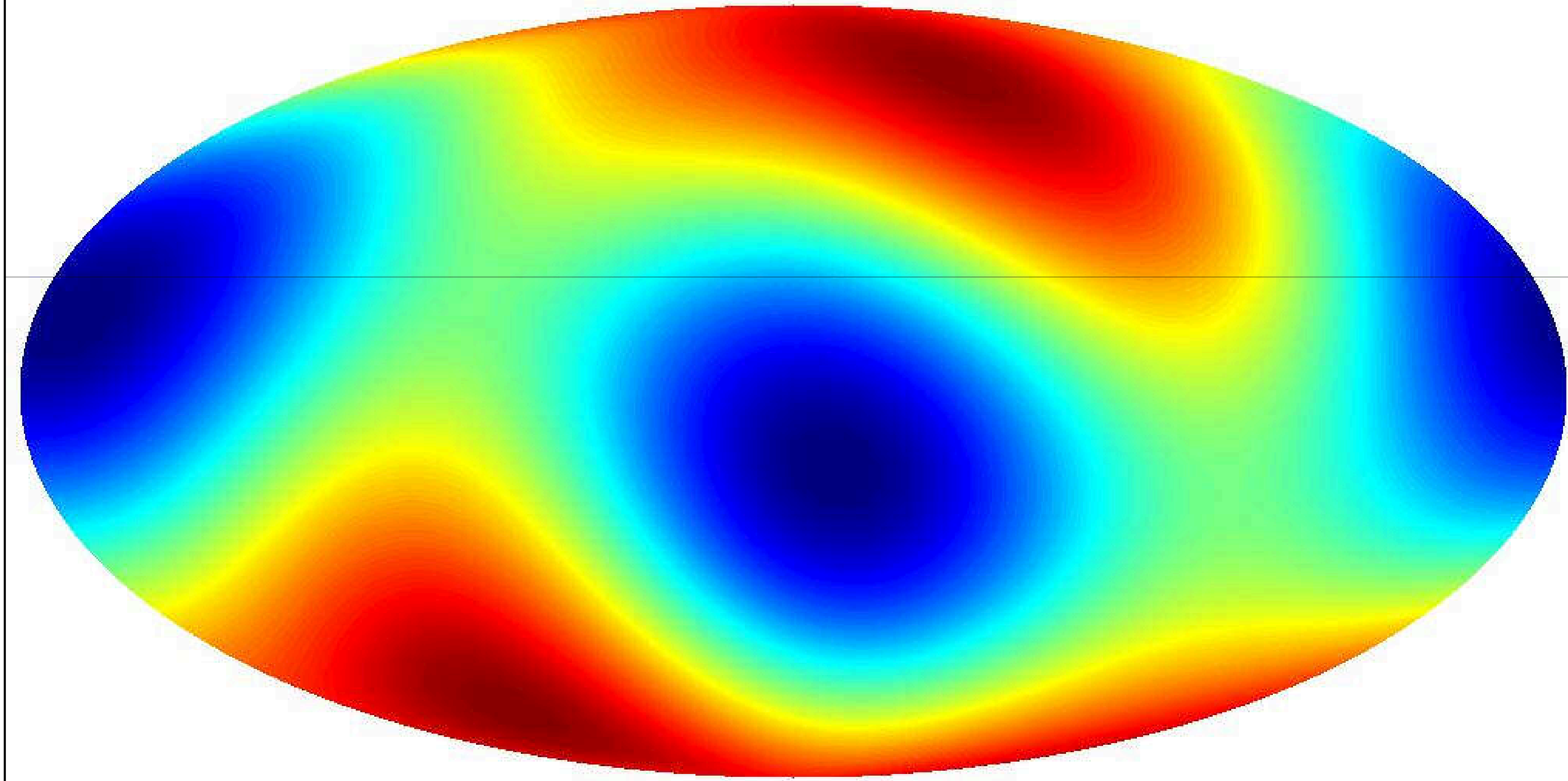
$\ell=2$



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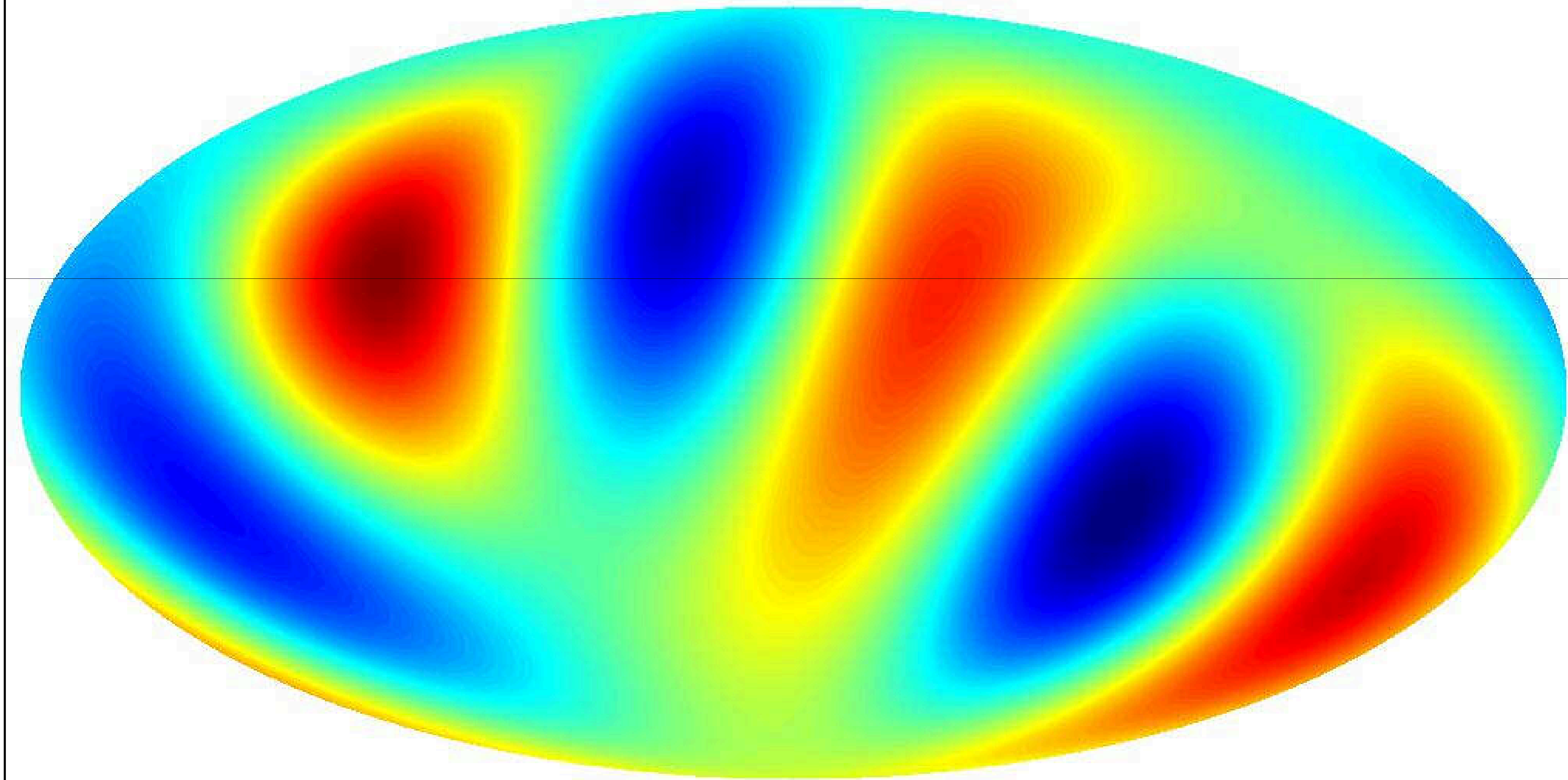
ℓ=3



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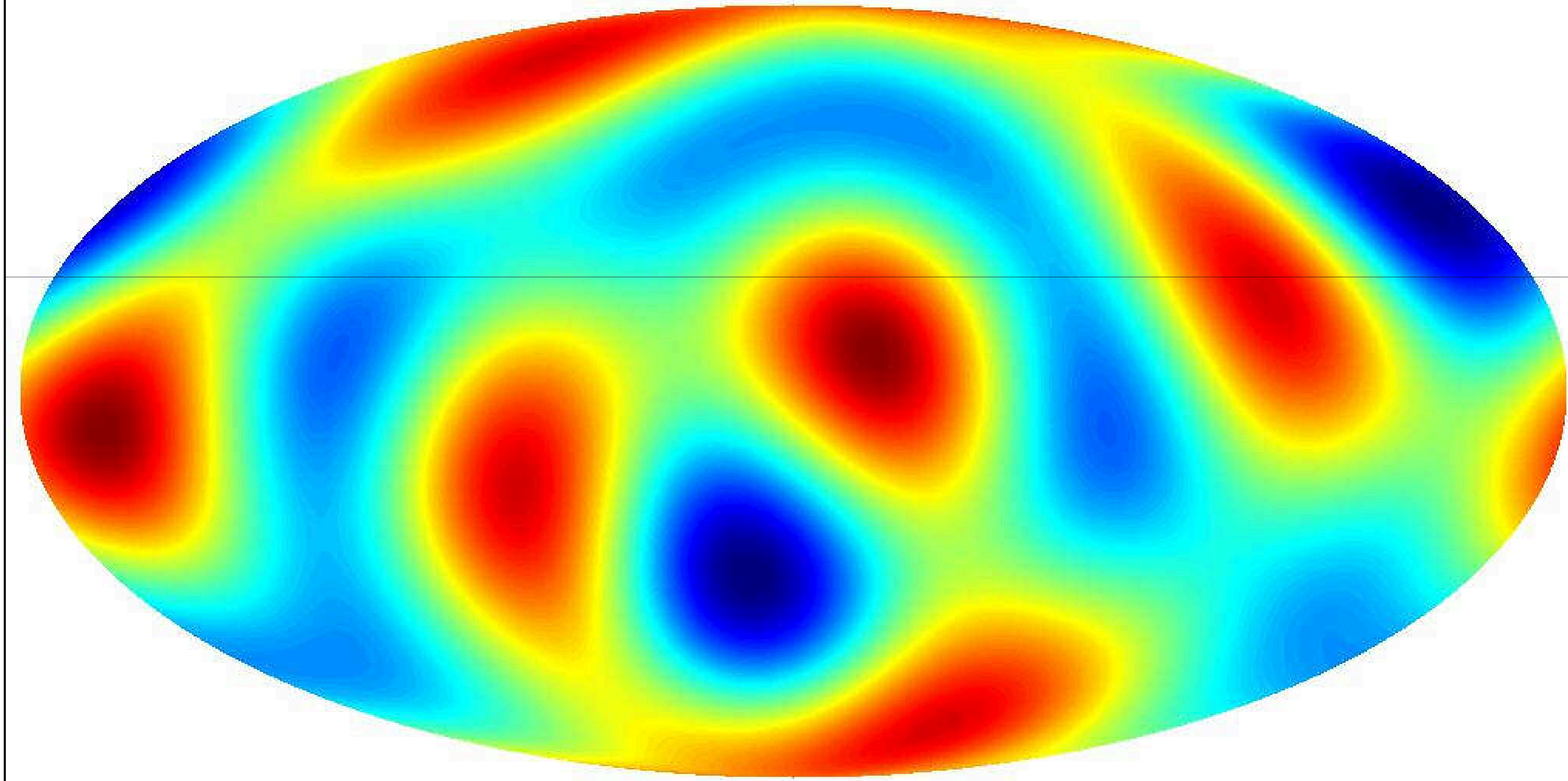
$\ell=4$



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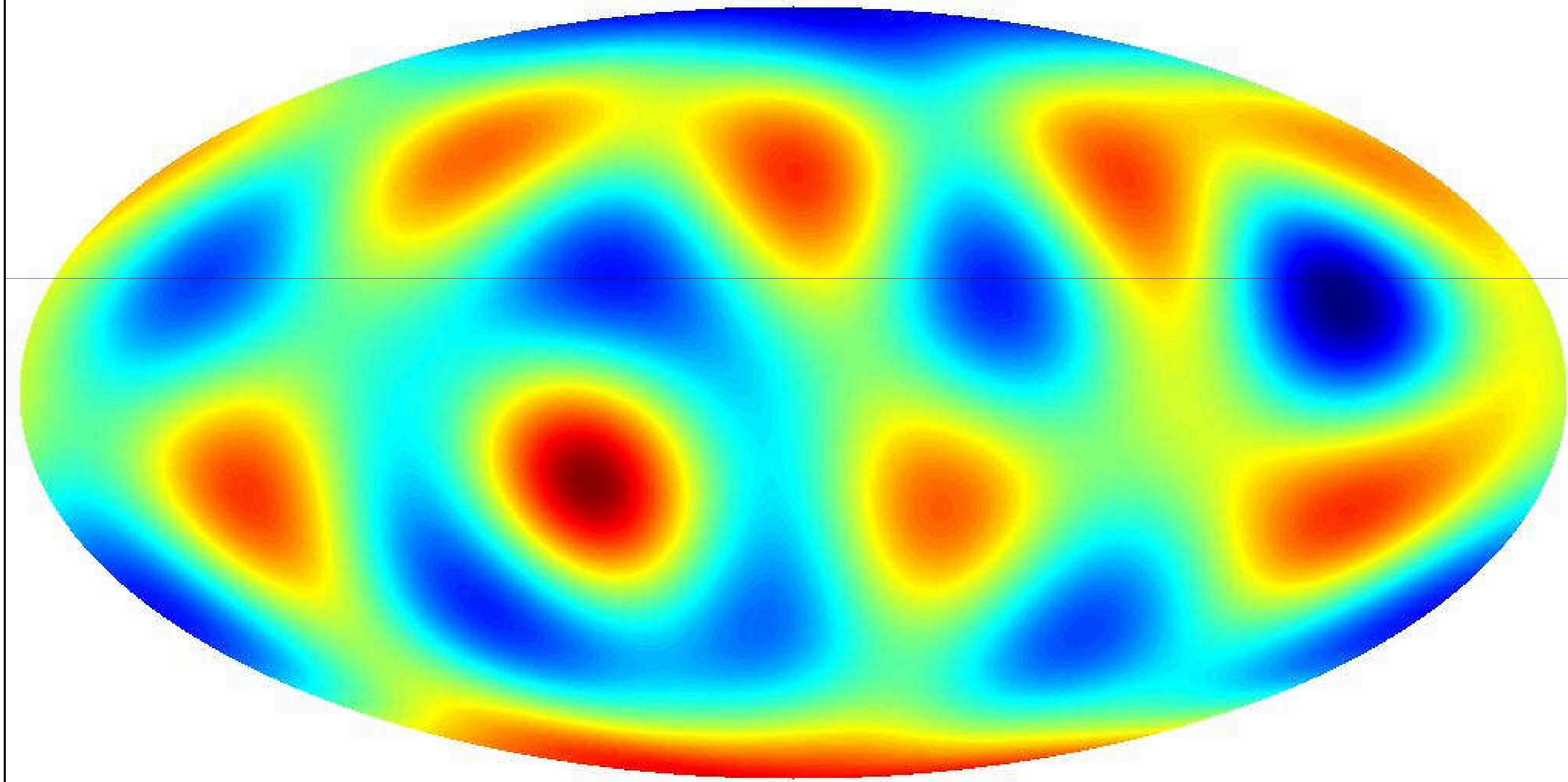
$\ell=5$



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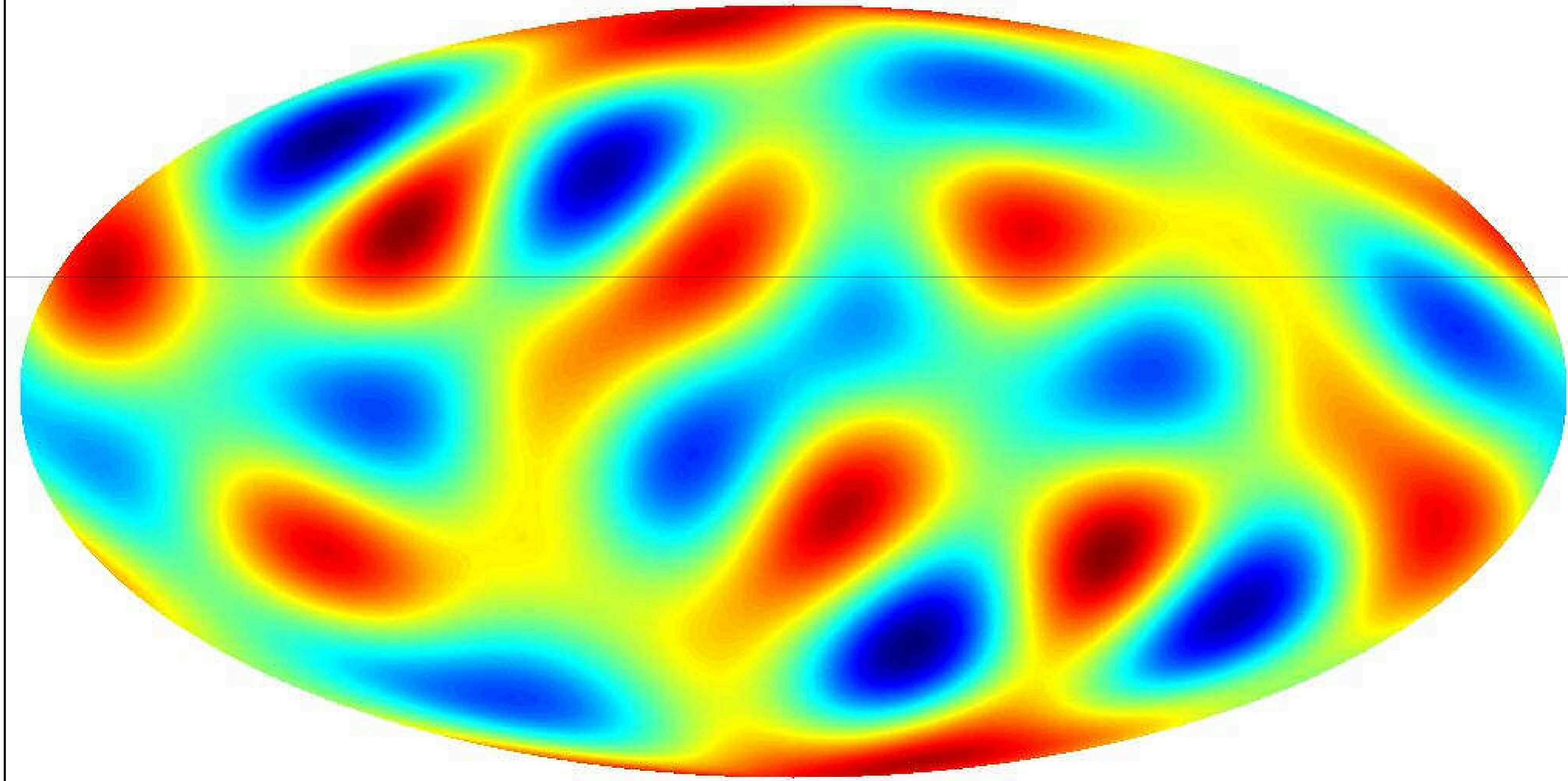
$\ell=6$



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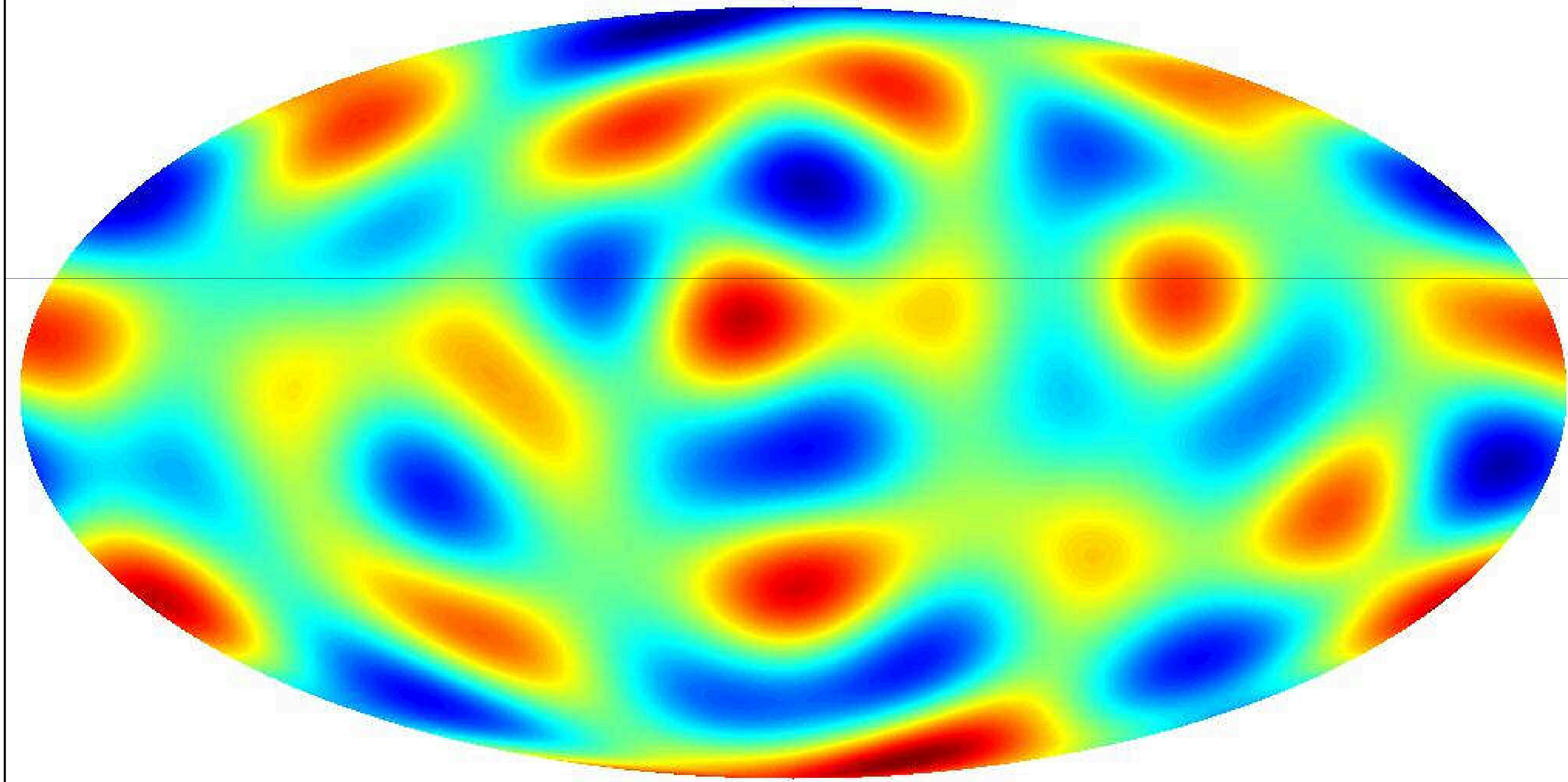
$\ell=7$



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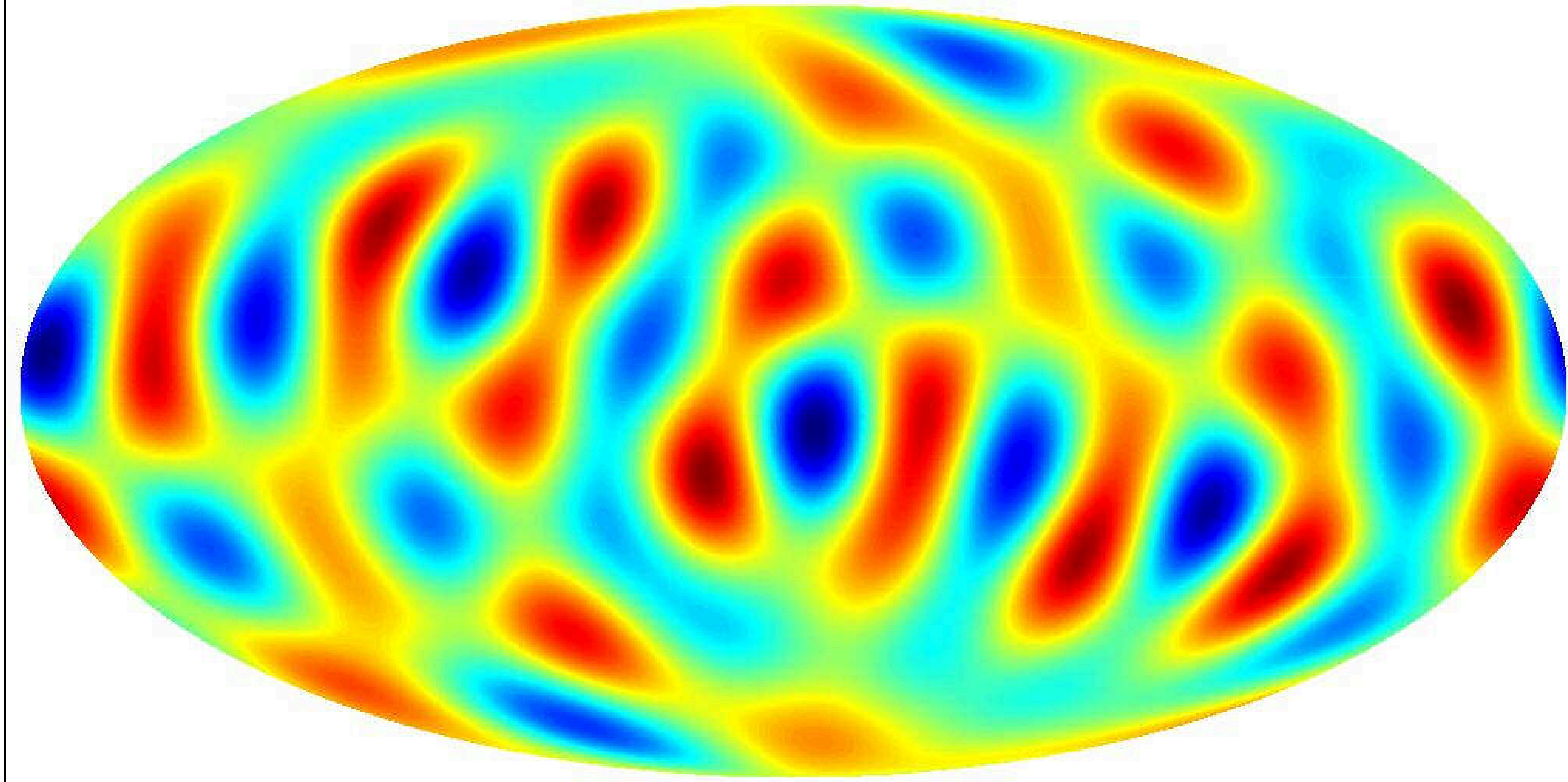
ℓ=8

i.e. larger ℓ means shorter wavelengths

i.e. ℓ is spherical equivalent of wavenumber

ℓ ~ pi / theta



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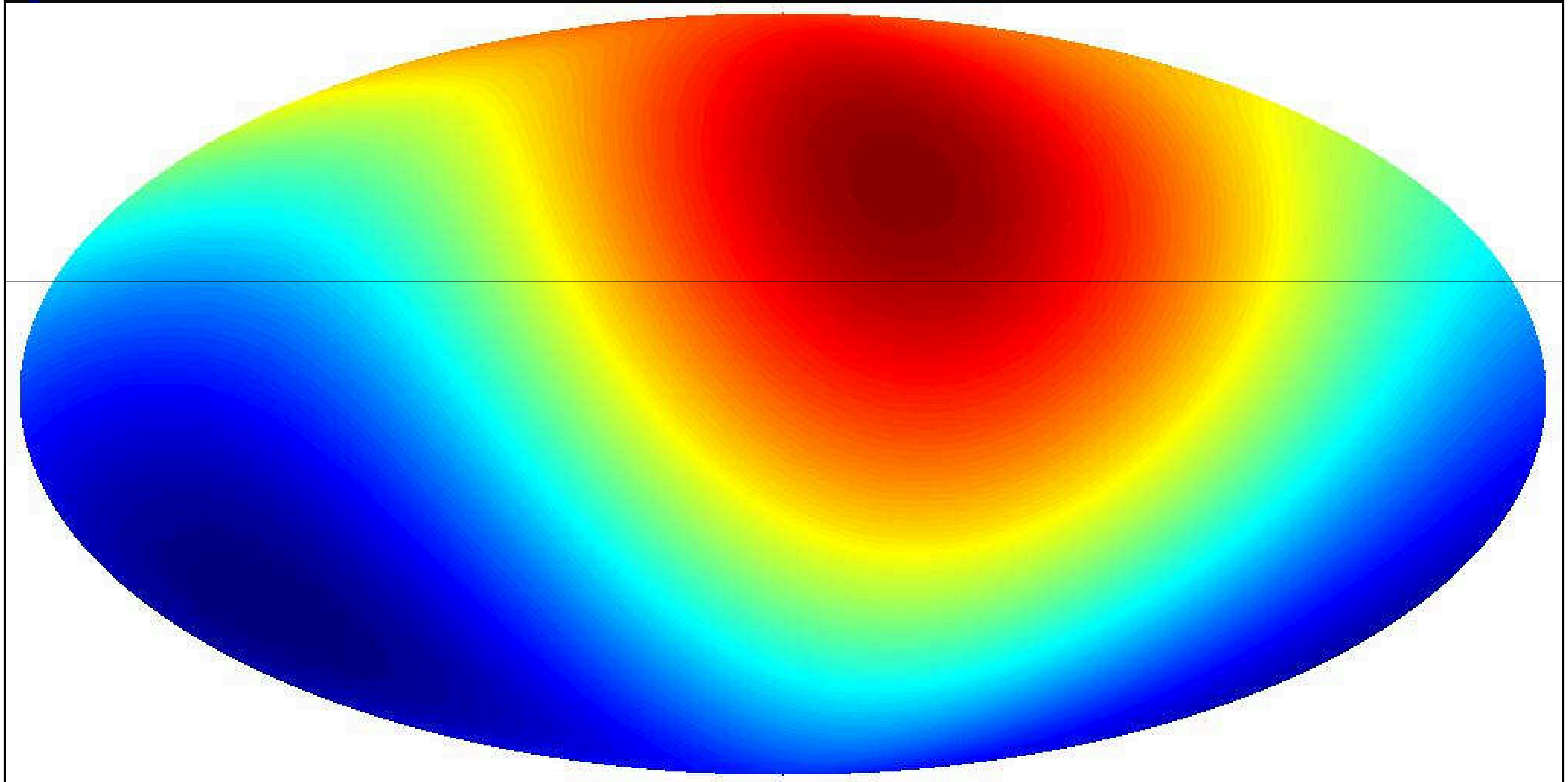
$\ell=1$



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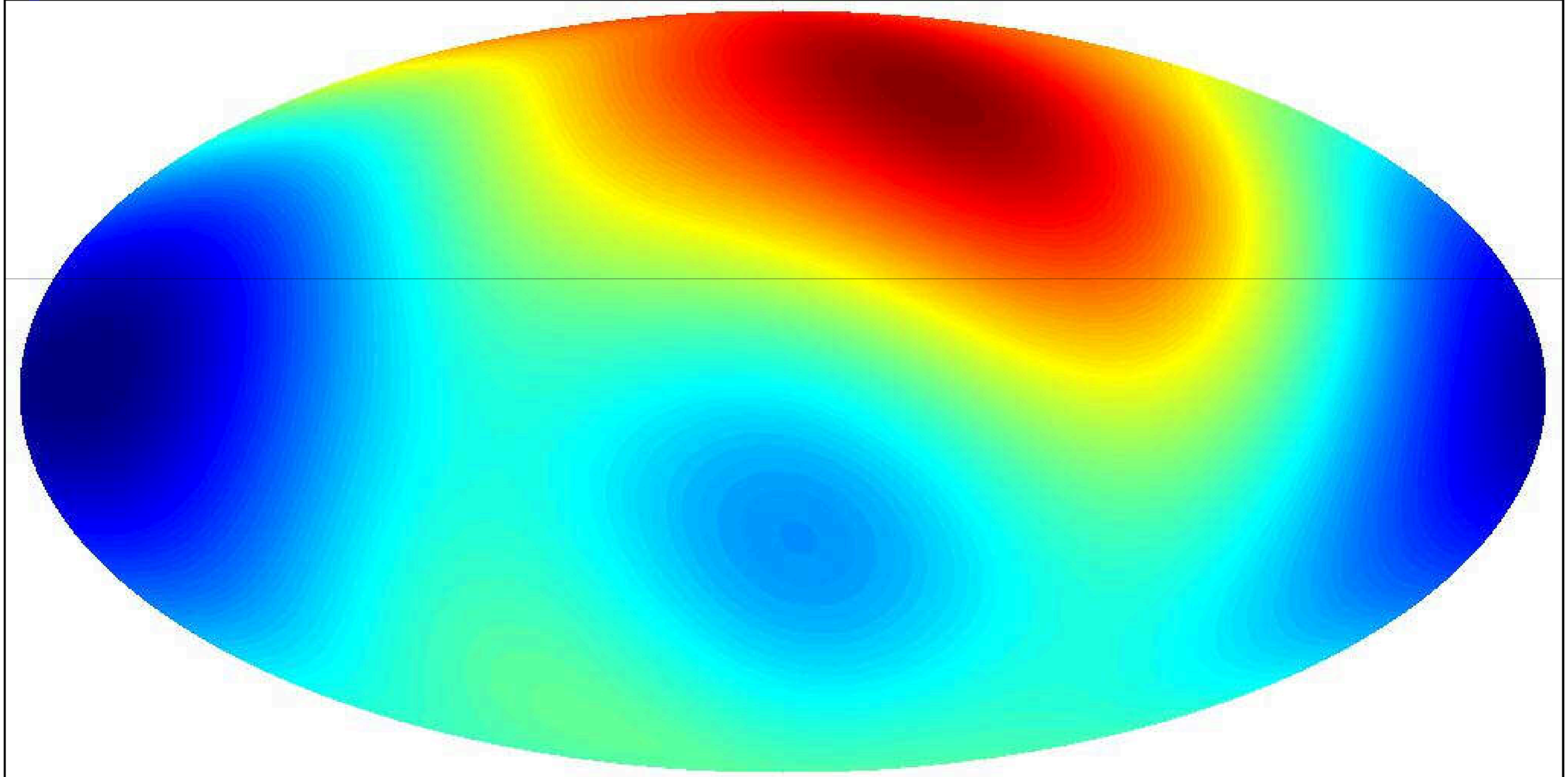
ℓ=1 plus ℓ=2



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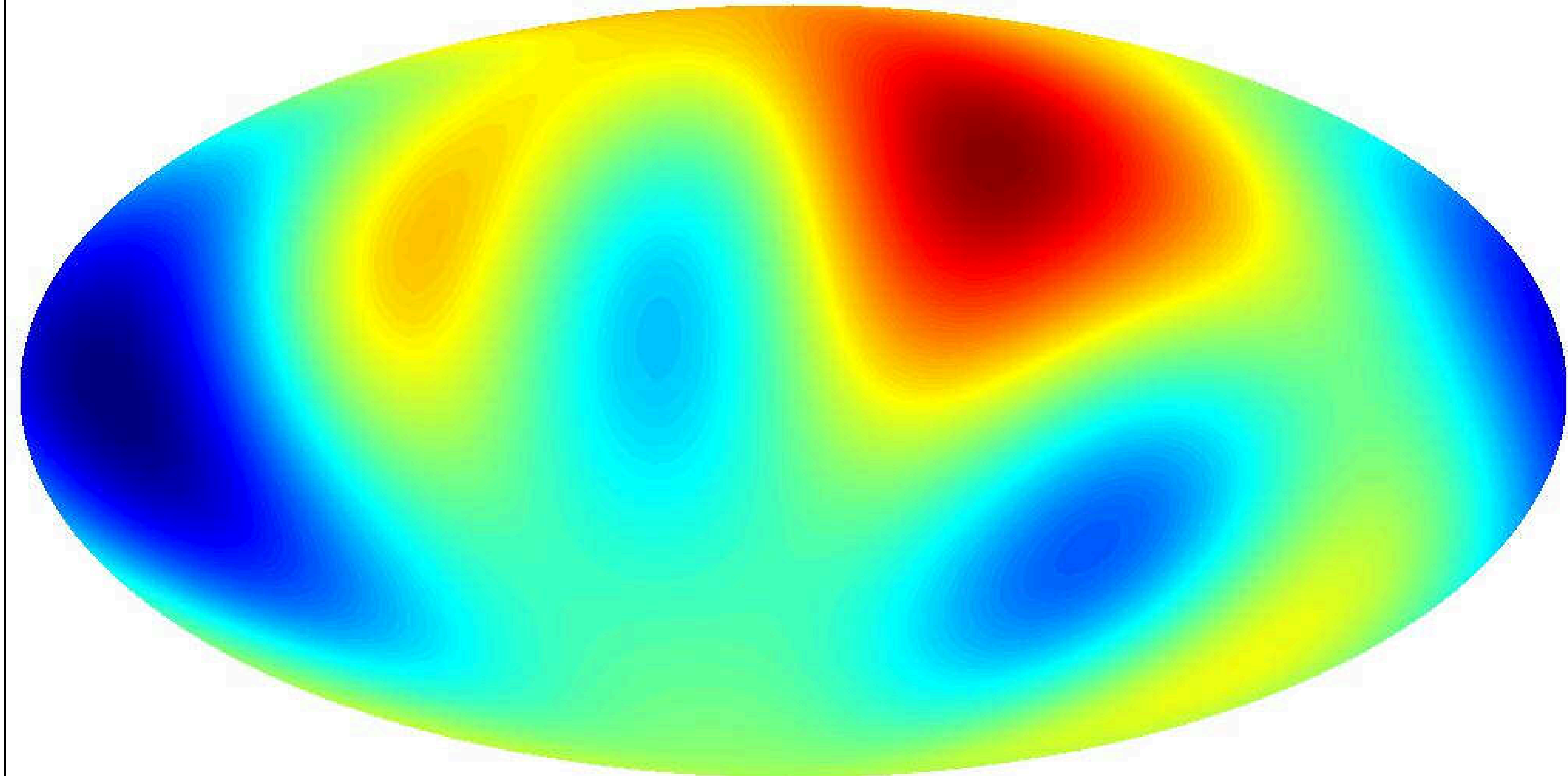
ℓ=1 plus ℓ=2 plus ℓ=3



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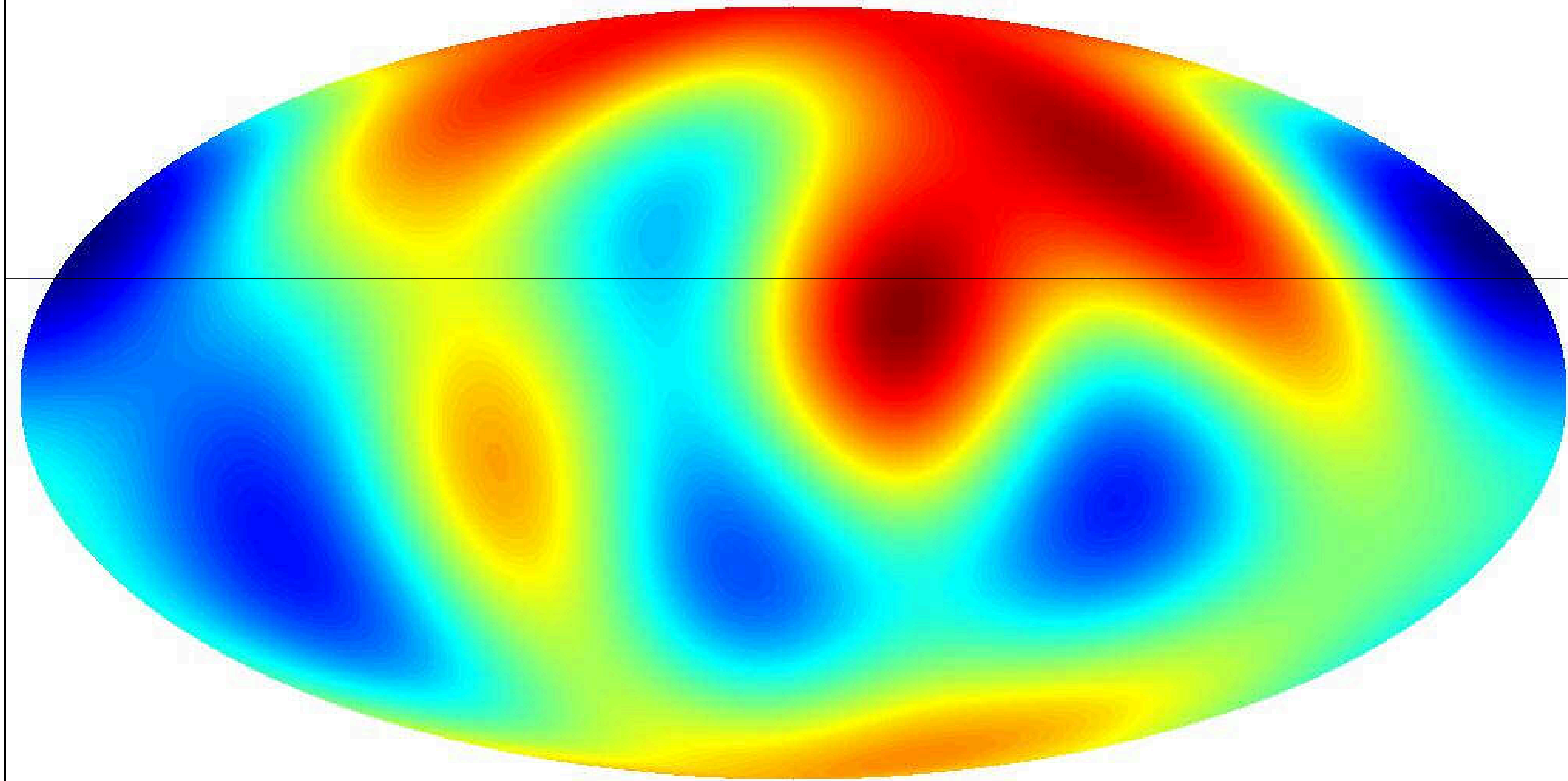
Sum ℓ=1 to 4



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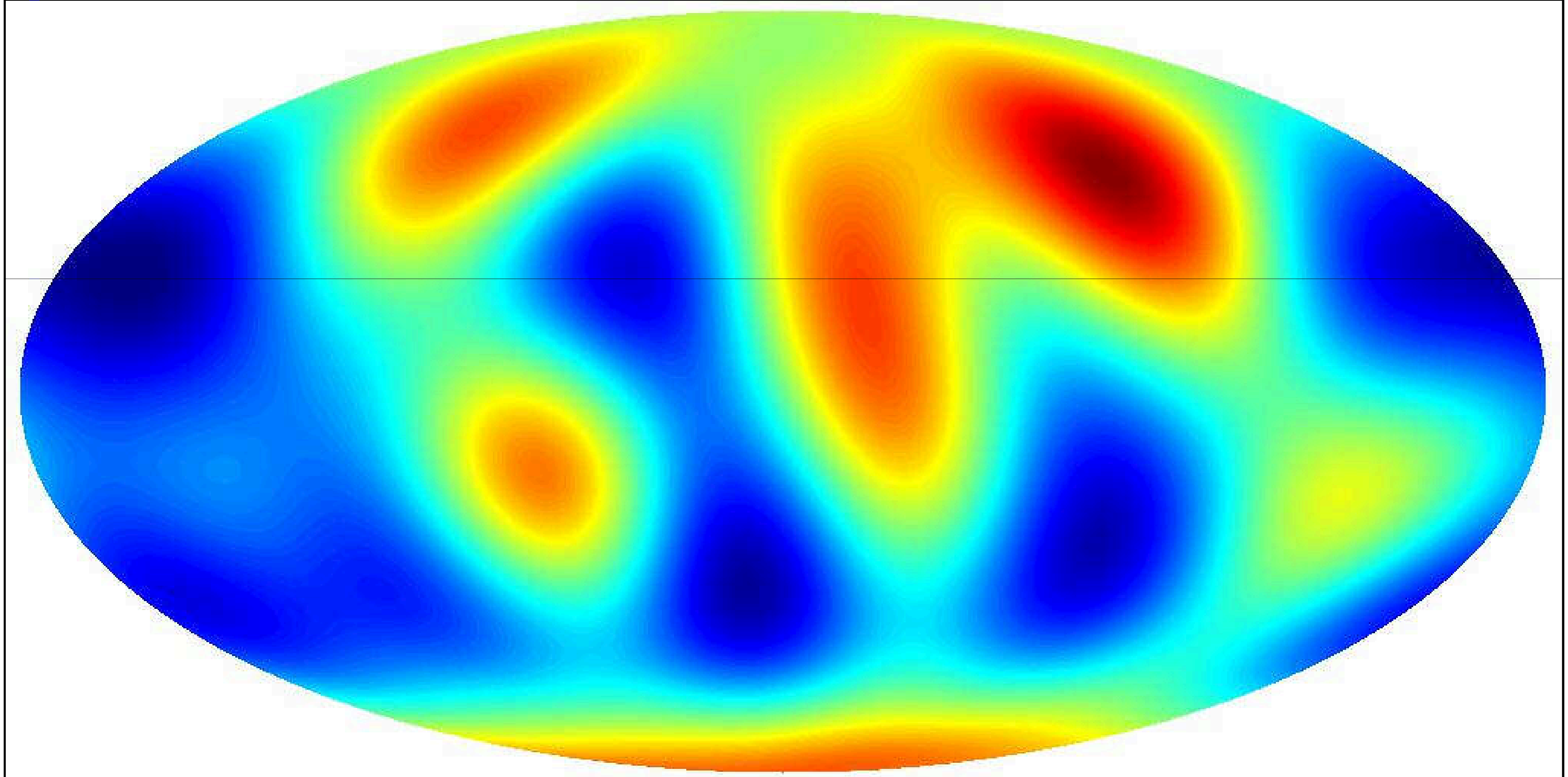
Sum ℓ=1 to 5



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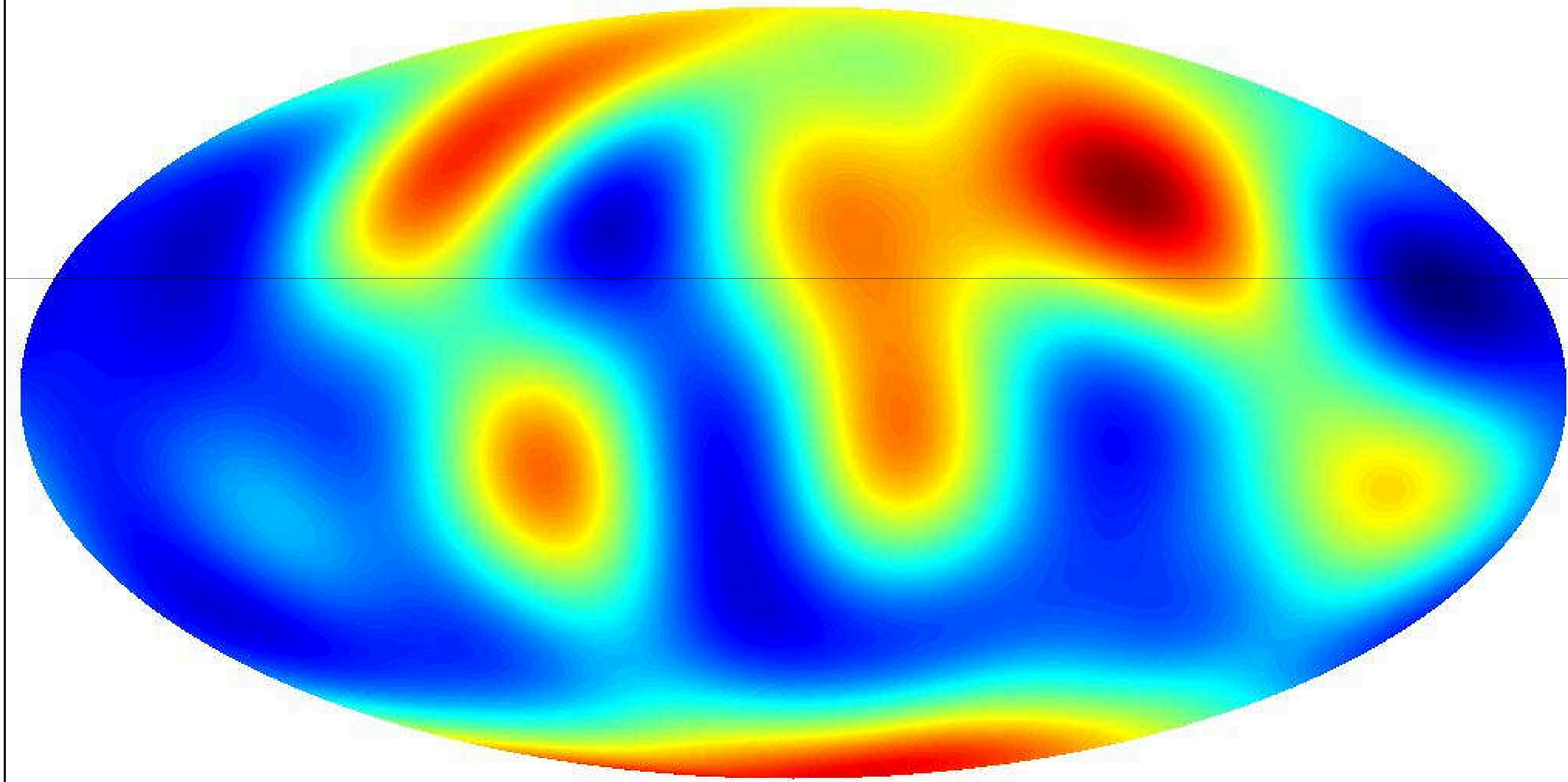
Sum ℓ=1 to 6



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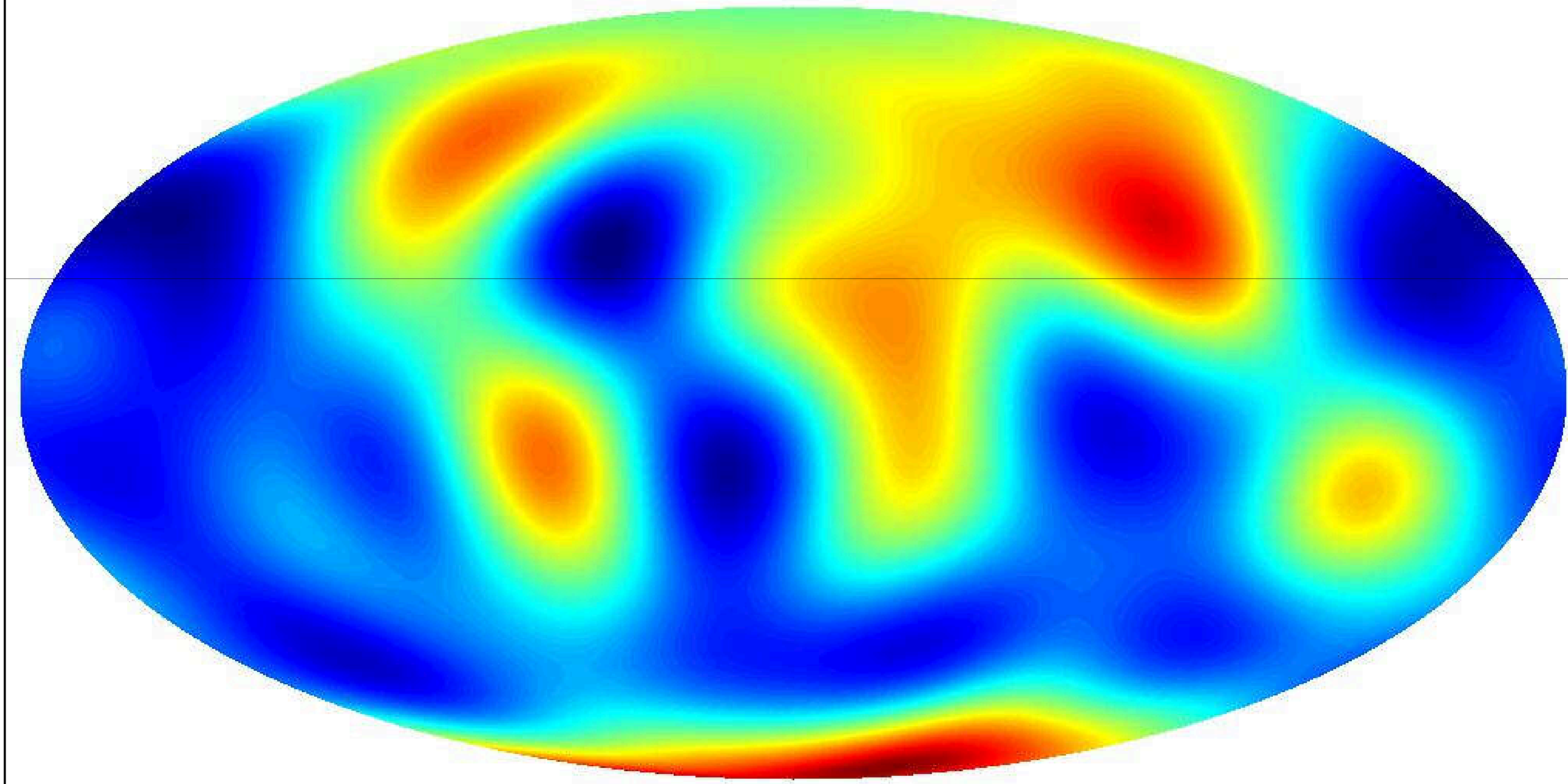
Sum ℓ=1 to 7



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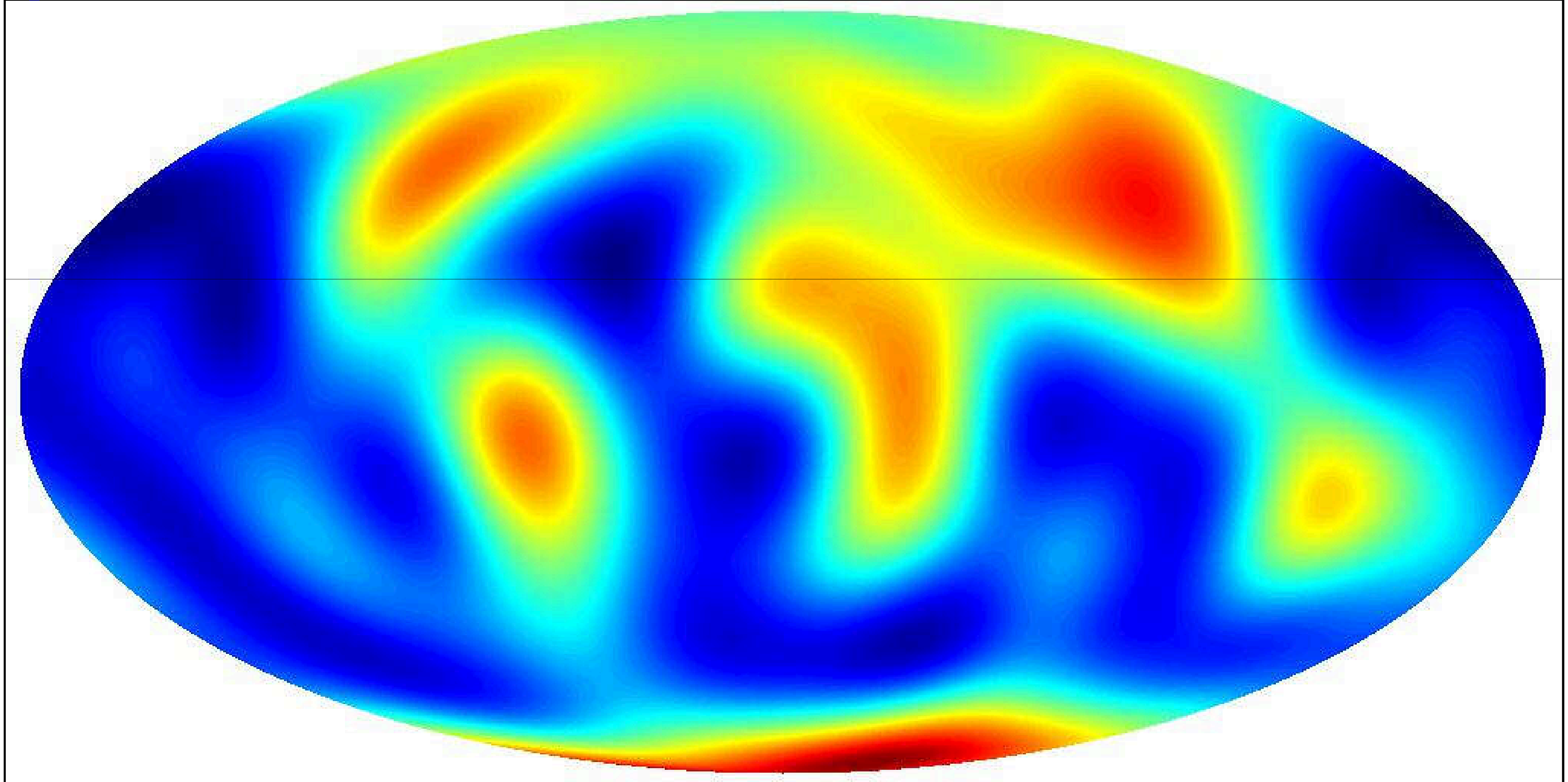
Sum ℓ=1 to 8



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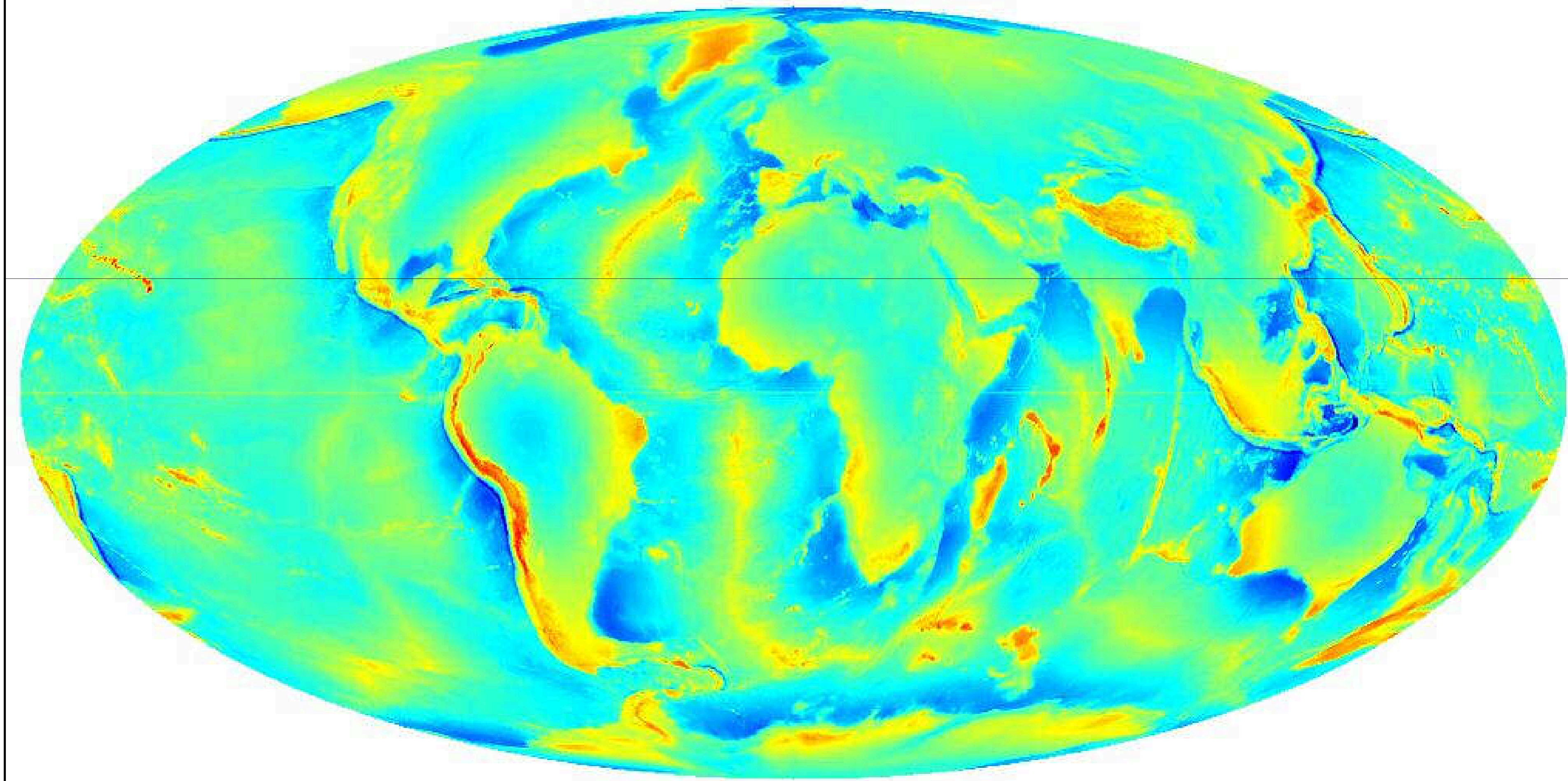
Sum up to some high ℓ



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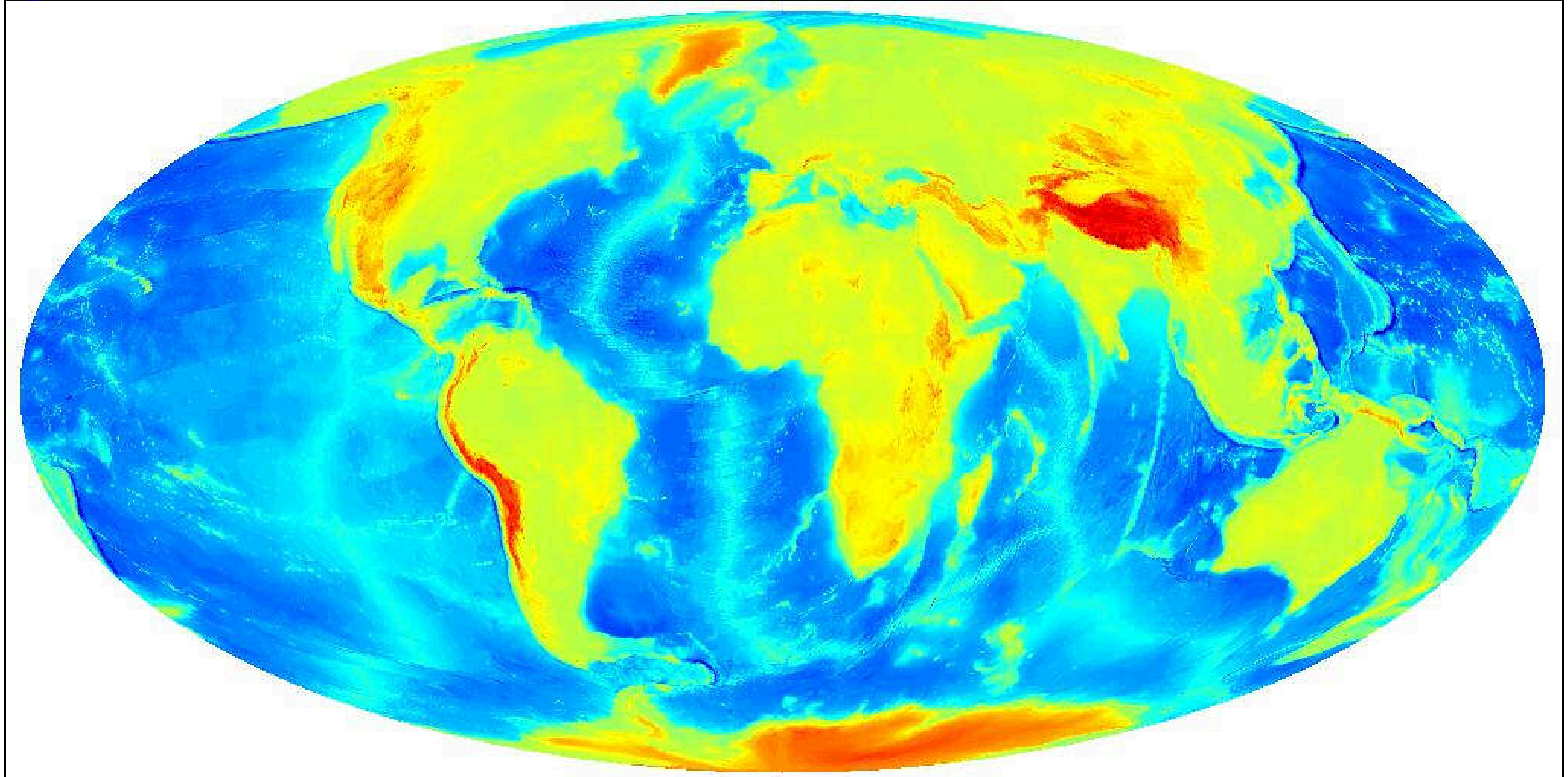
Exact image



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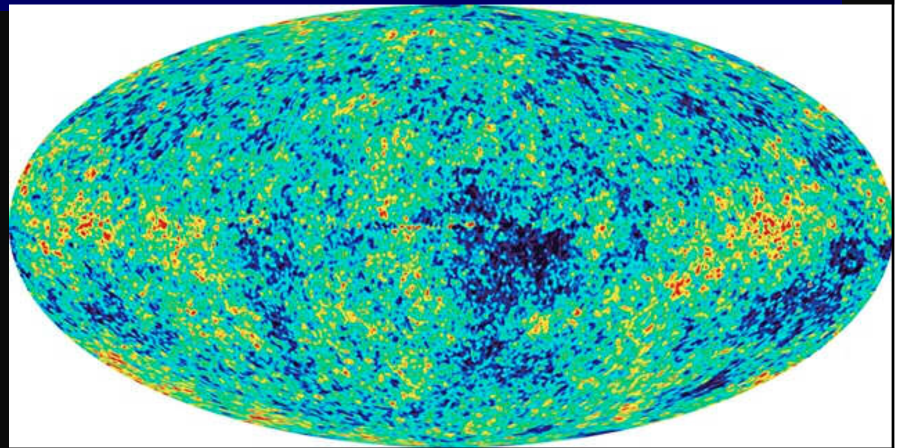

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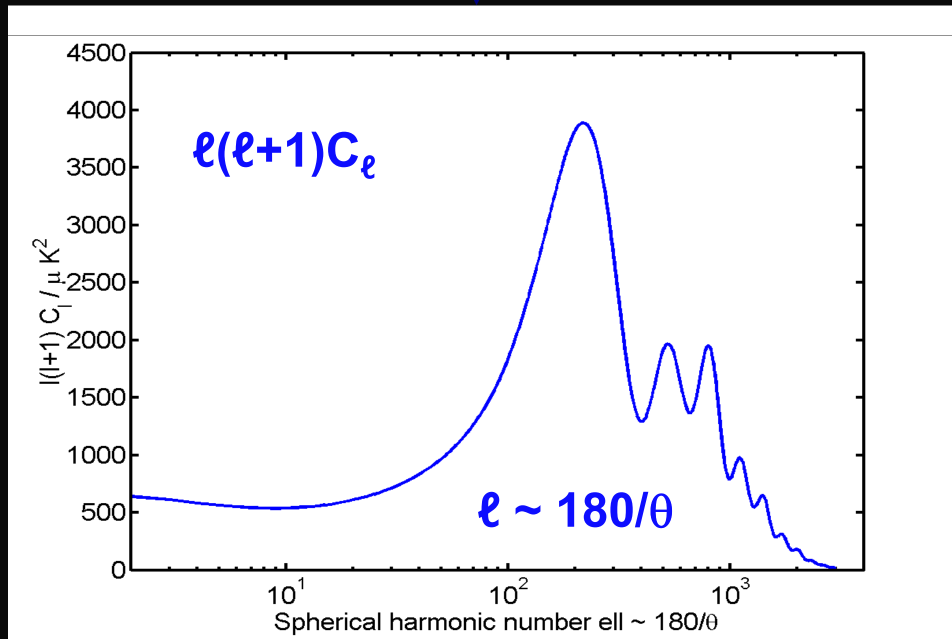
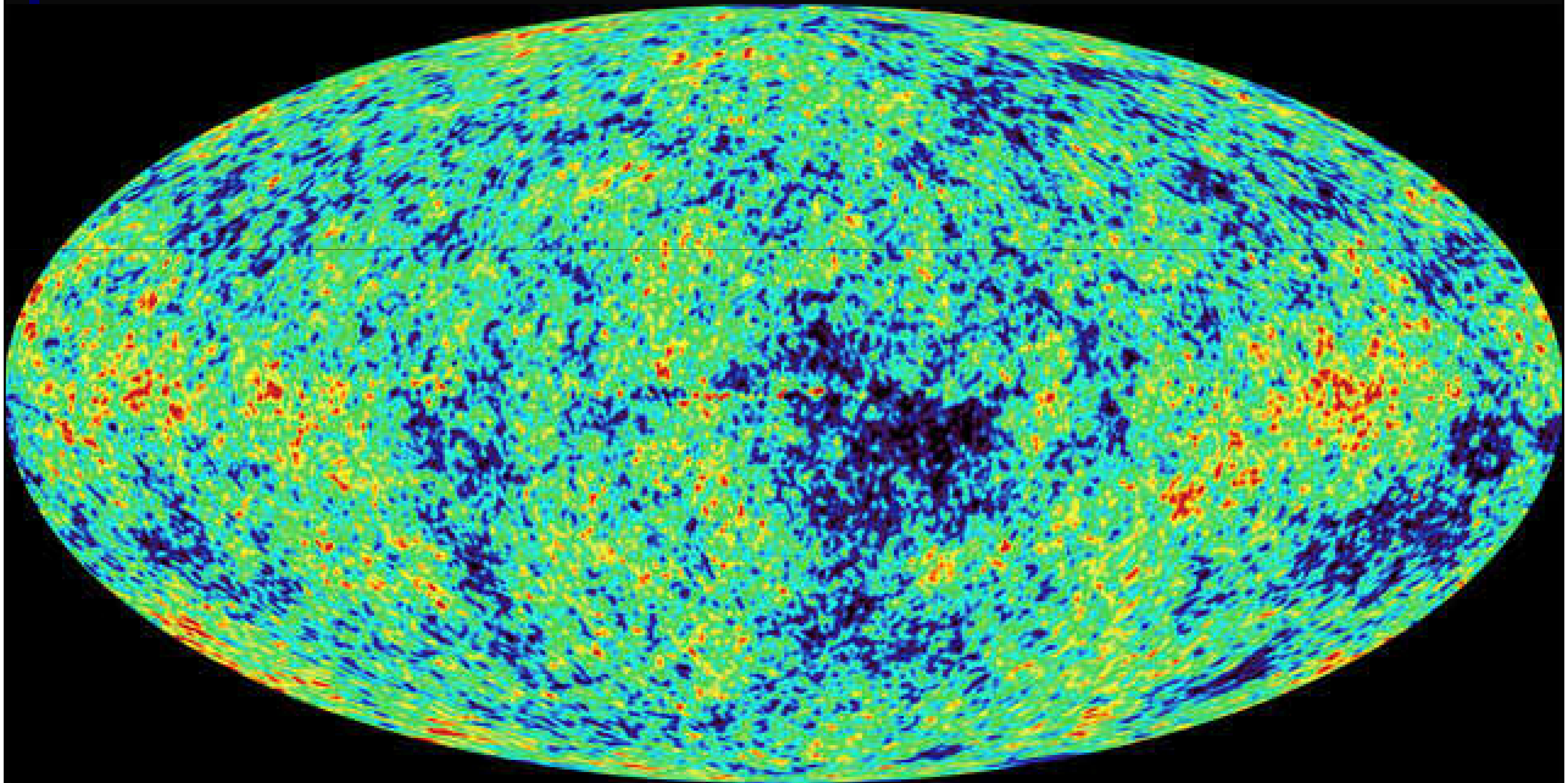


Large scales Small scales

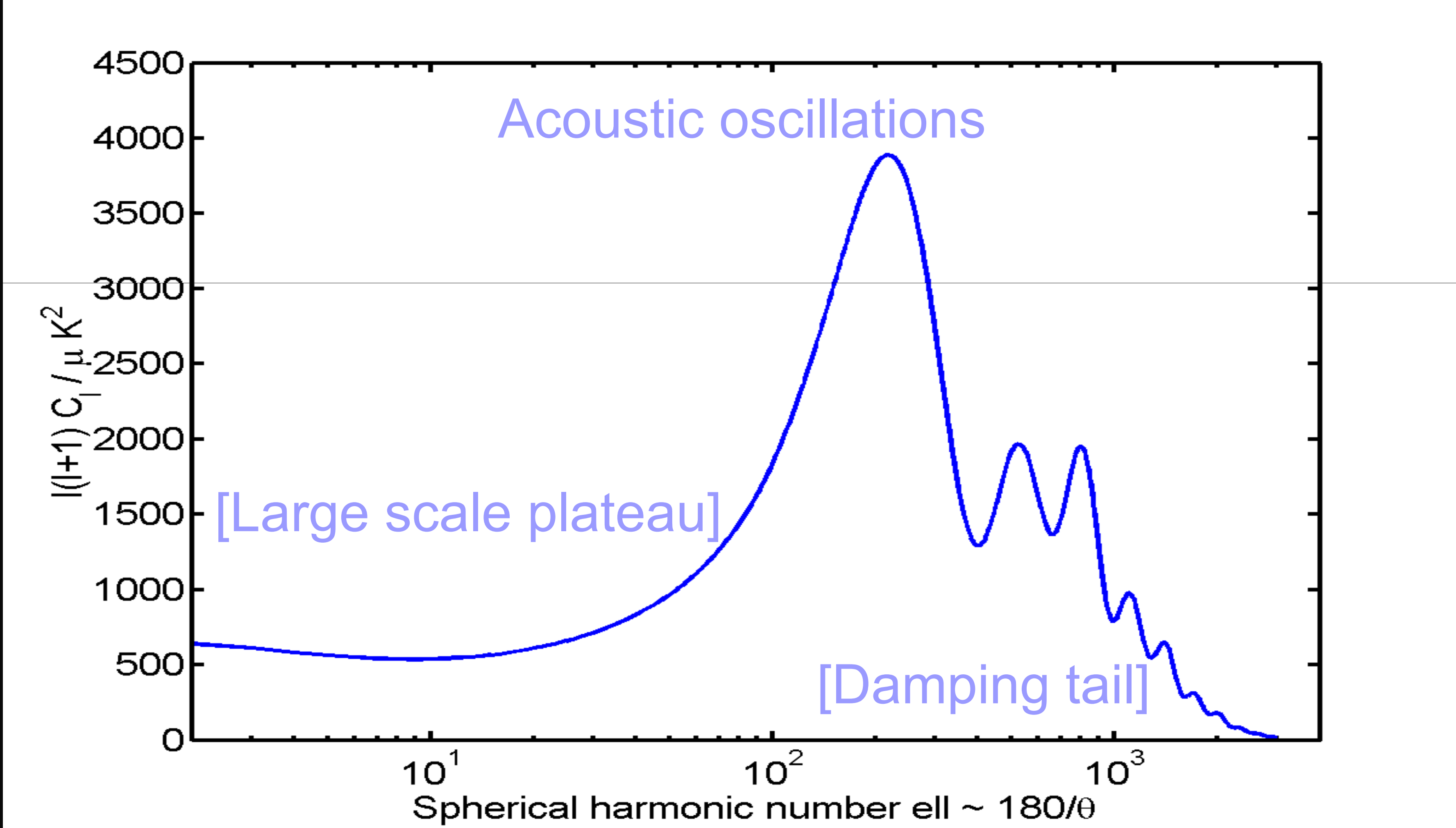
After removing the contribution from dust in our galaxy

- Uniform to 1 in 100,000

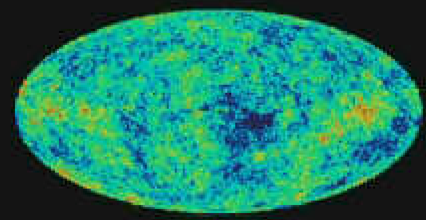


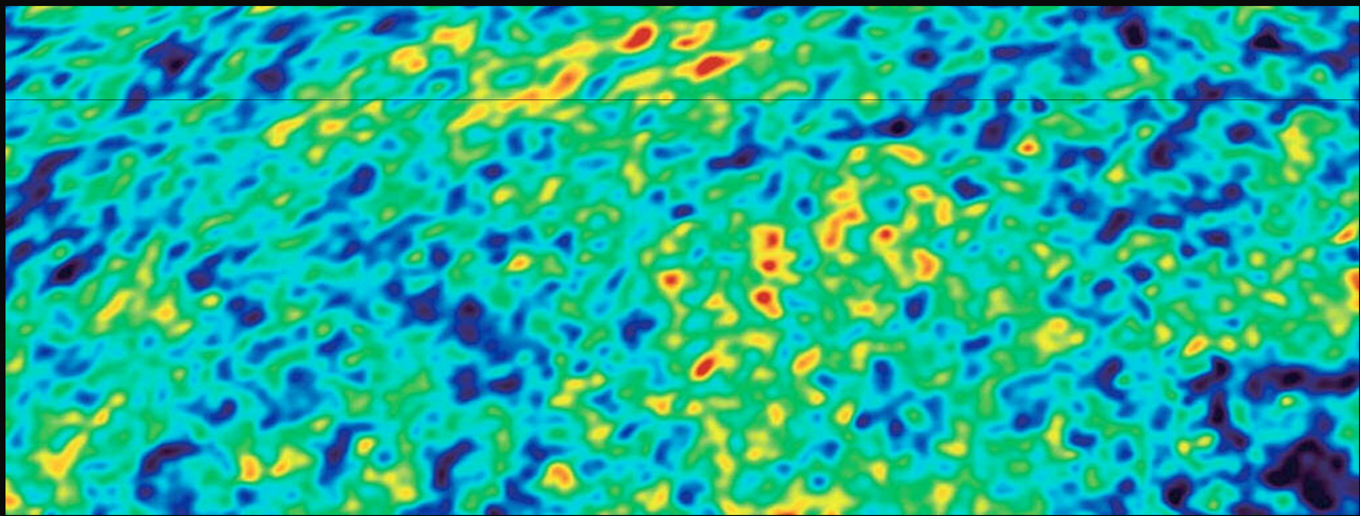
Graphics from WMAP website

3 regimes of CMB power spectrum



A characteristic scale exists of ~ 1 degree



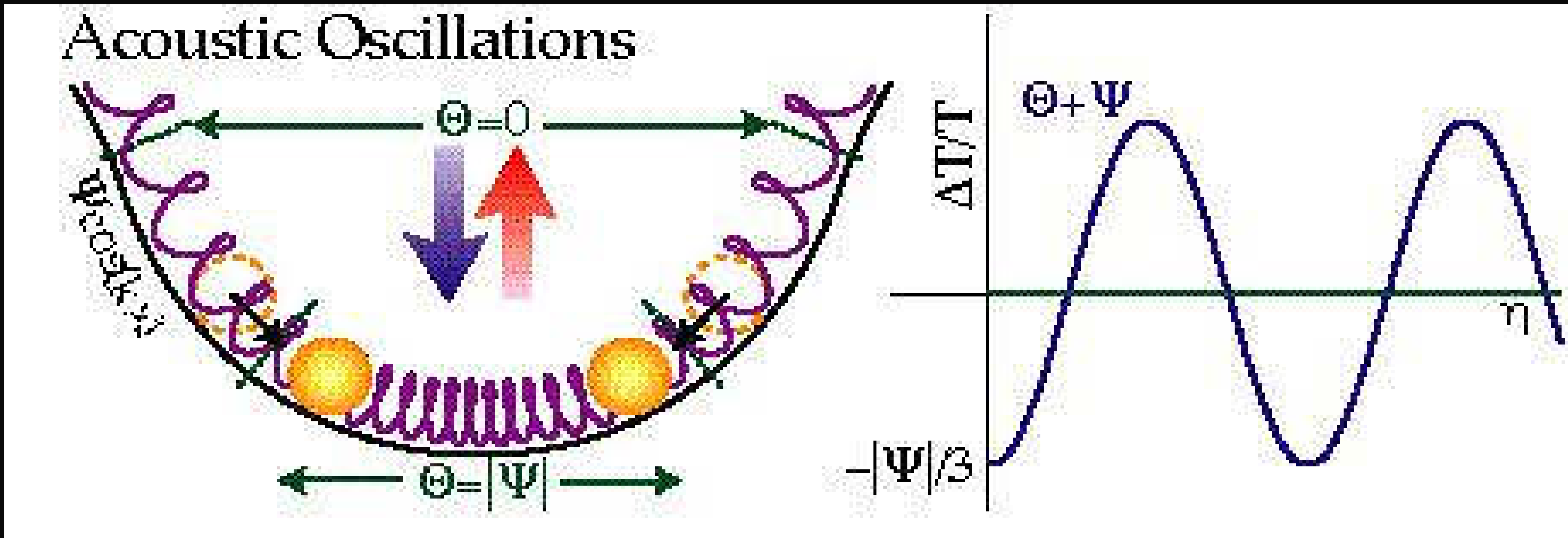


Understand main feature: position of 1st peak

Bouncing fluid causes peak structure

Curvature of Universe -> peak locations

- Photon-baryon fluid oscillates in dark matter potential wells
- Large scales oscillate slowest



Graphic by Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

An analogy

- Drop bouncy balls from different heights and wait 10 seconds
- Lower balls bounce more times
- Highest balls don't even reach the ground
- There is one ball that just touches the ground in the time available

- Balls bouncing
- 10 seconds
- Bouncing
- Original height of ball that only just reaches the ground

- Photon-baryon fluid oscillating
- Age of universe at recombination
- Peaks in CMB plot
- Position of first peak

The first acoustic peak

- Consider scale which had time only to collapse under gravity since big-bang
  - it is at maximum T => hot-spot
- Scale ~ Hubble length at z~1000

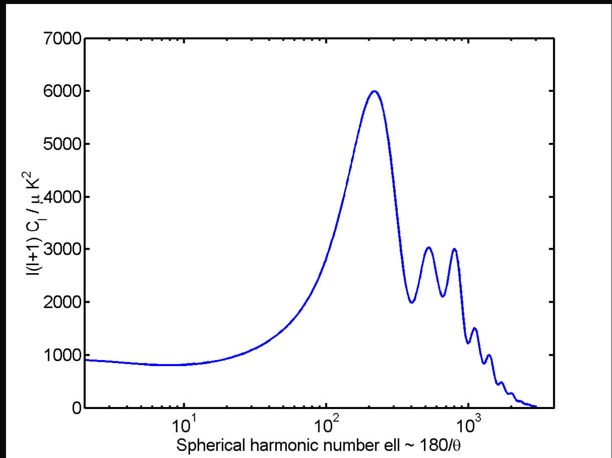
~ speed x age of universe at z~1000

= 3×10^8 m s^{-1} x 400,000 years

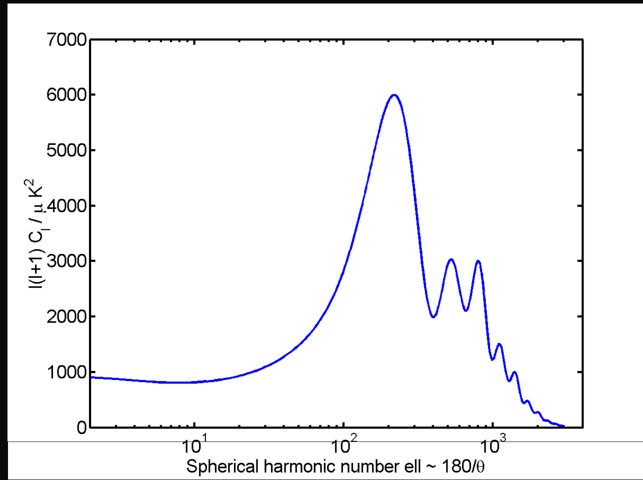
~ 4 x 10^{21} m

~ 0.1 Mpc

= 100 comoving Mpc



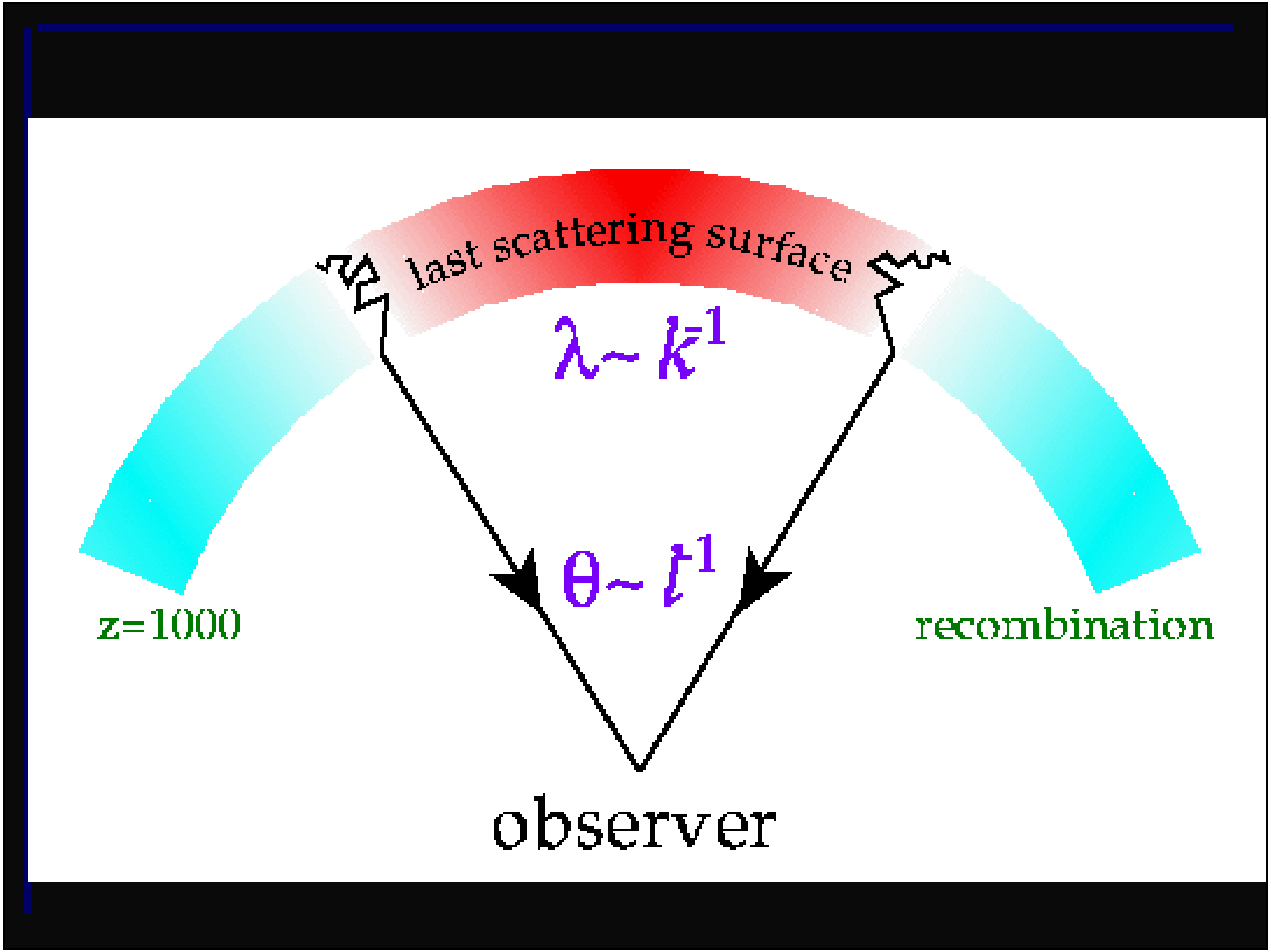
Angular Diameter Distance

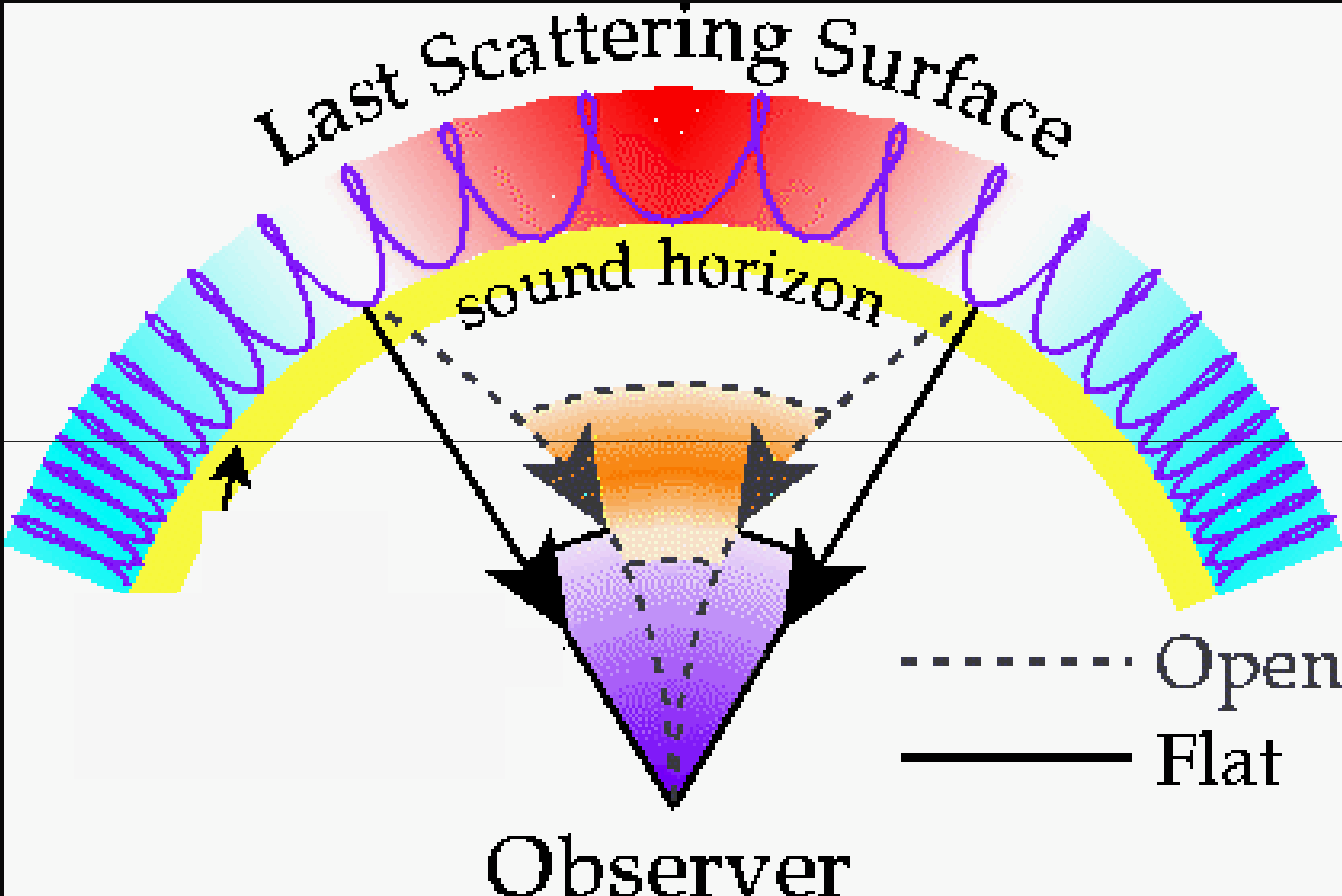


- Effective distance such that
  - $\theta = d / D_A$
  - d = comoving size of object
  - θ = angular size of object
  - D_A = angular diameter distance
- For a flat Universe
  - $D_A = D / (1+z)$
  - where D = integrated comoving distance as for D_L
- D_A to z_{CMB} is ~ 14 Gpc
- Therefore angular size

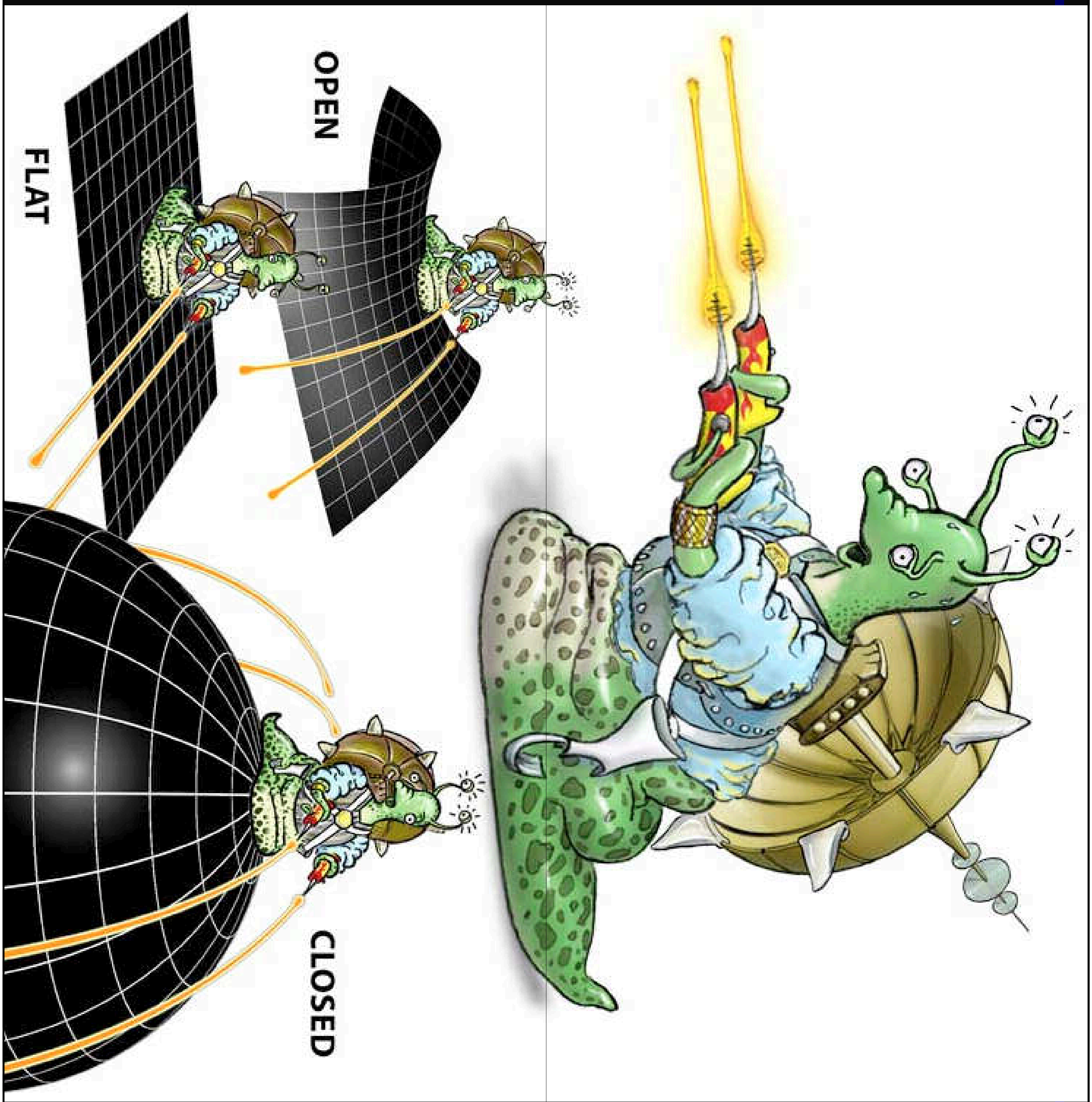
  ~ 100 / 1400 rad

  ~ 1 degree


last scattering surface
λ~k⁻¹
θ~ℓ⁻¹
z=1000
recombination
observer

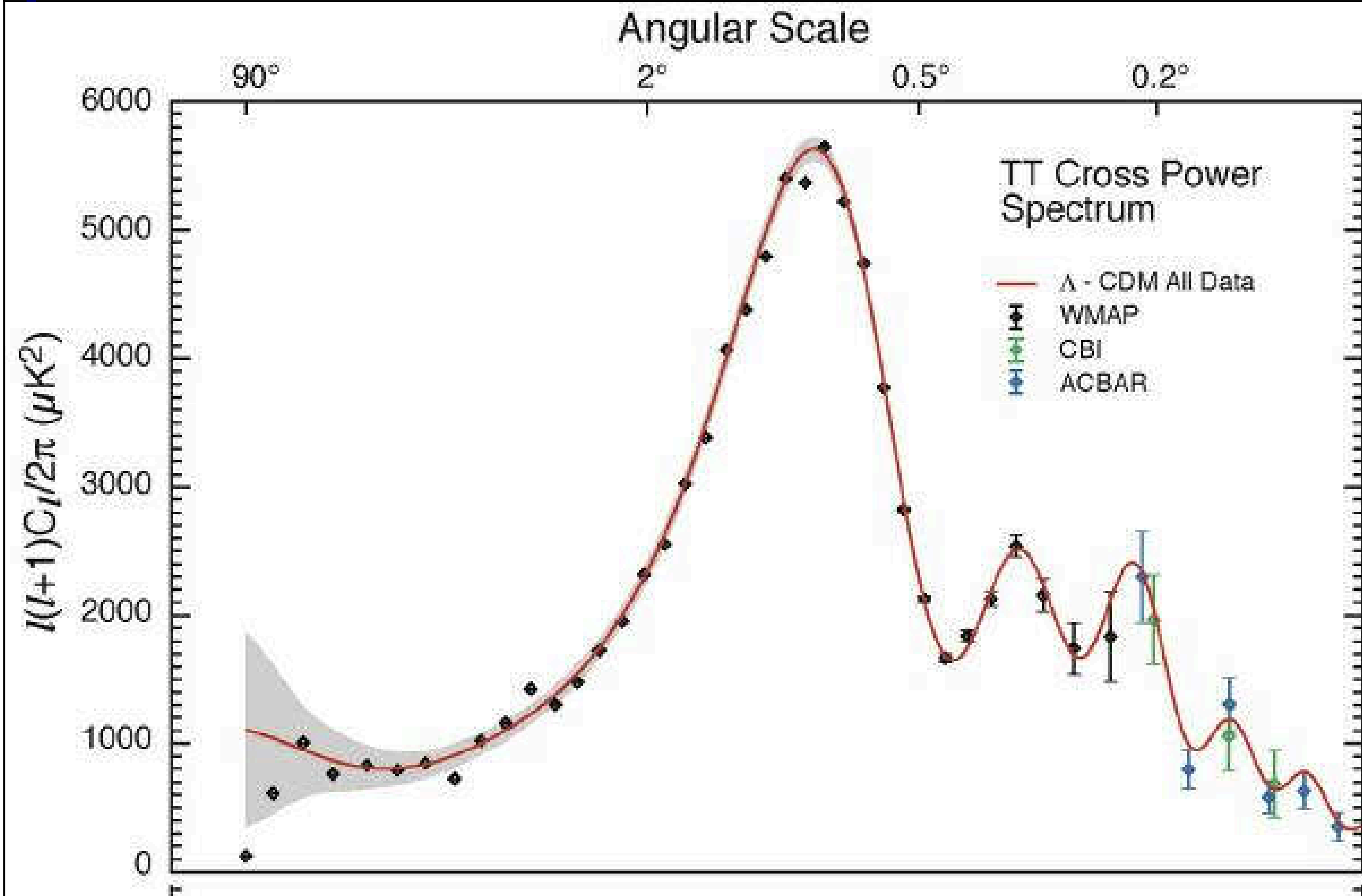


Graphic from WMAP website

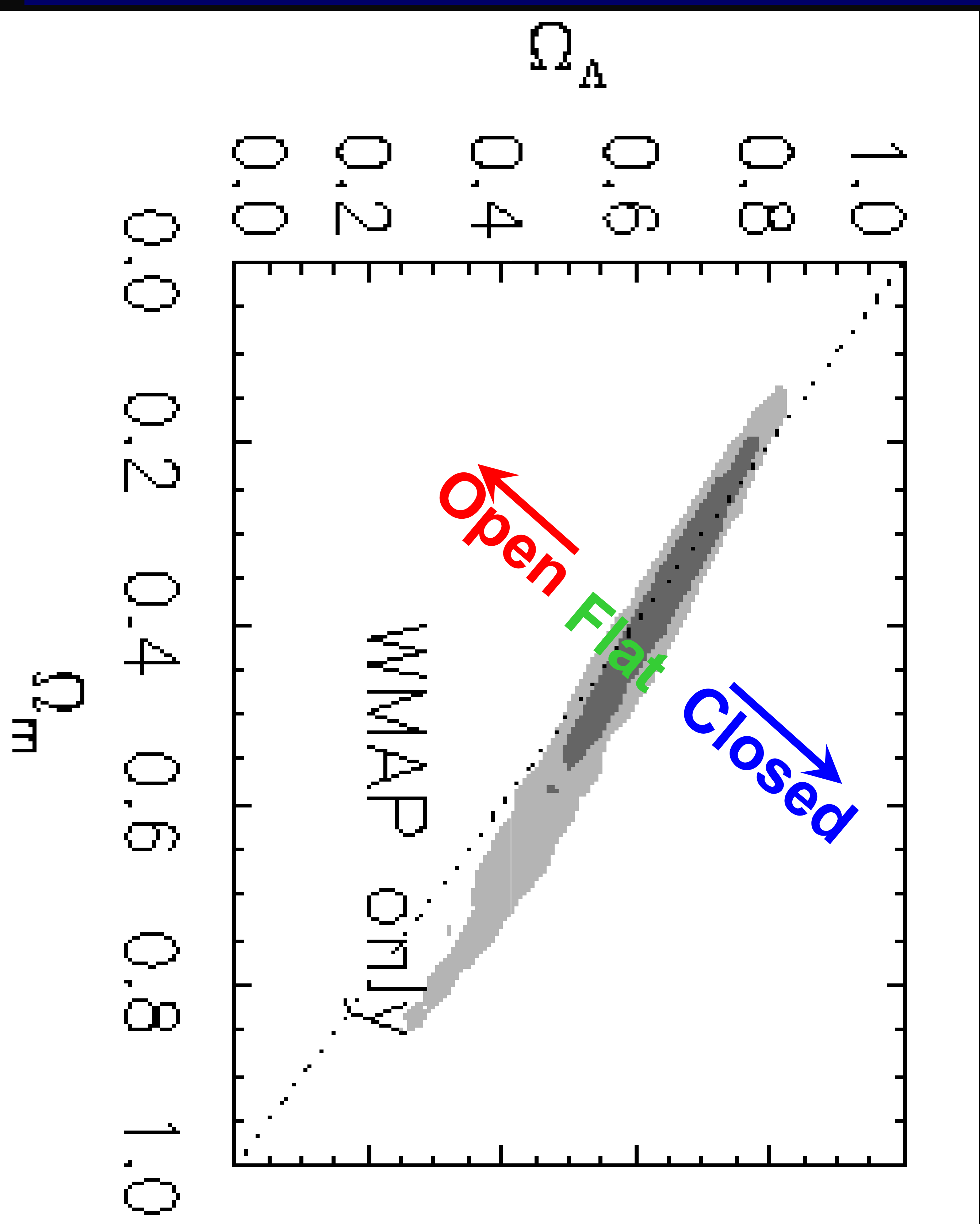


Graphic from WMAP website

WMAP results

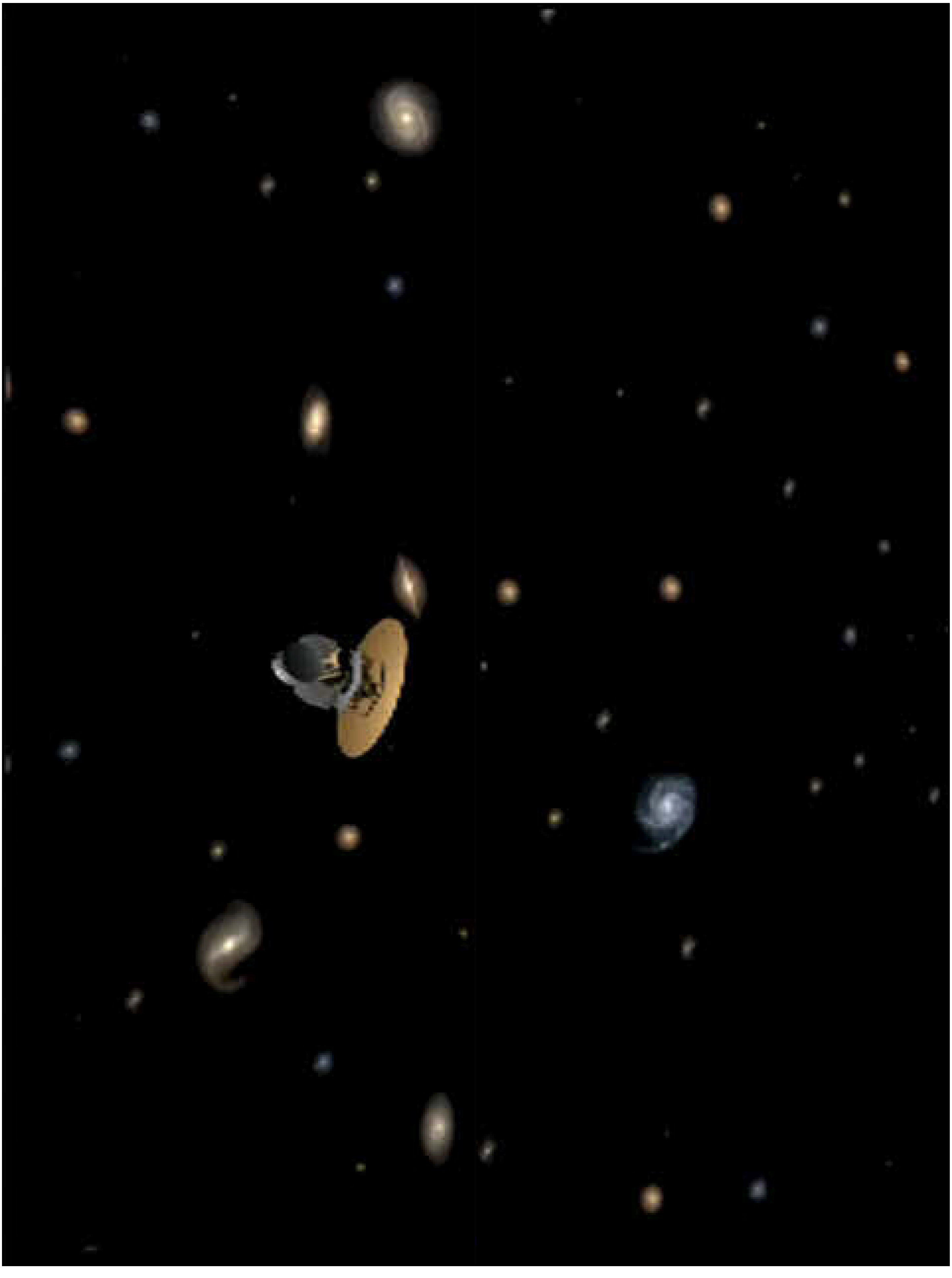


Graphic from WMAP website



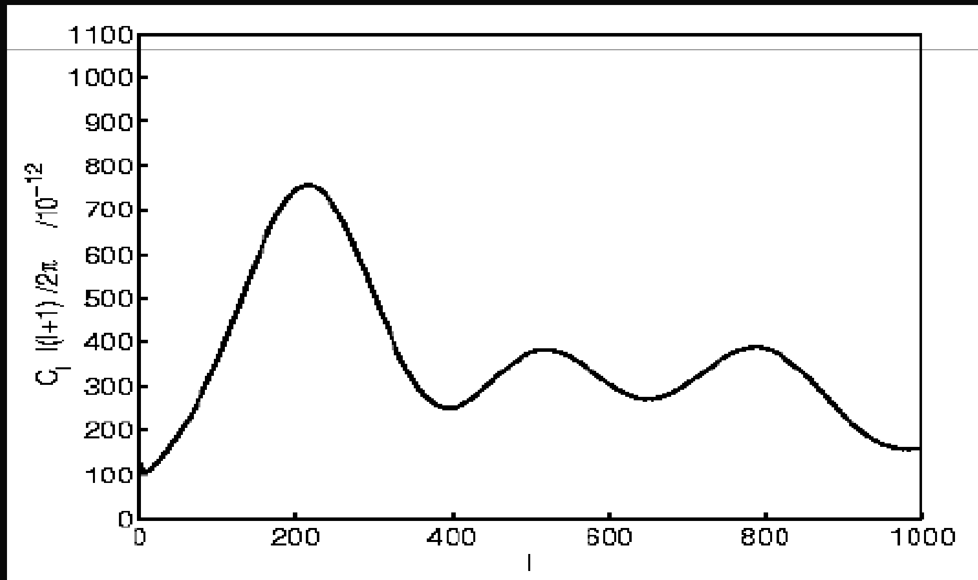
Ω_Λ
Ω_m
WMAP only
Open
Flat
Closed
0.0
0.2
0.4
0.6
0.8
1.0

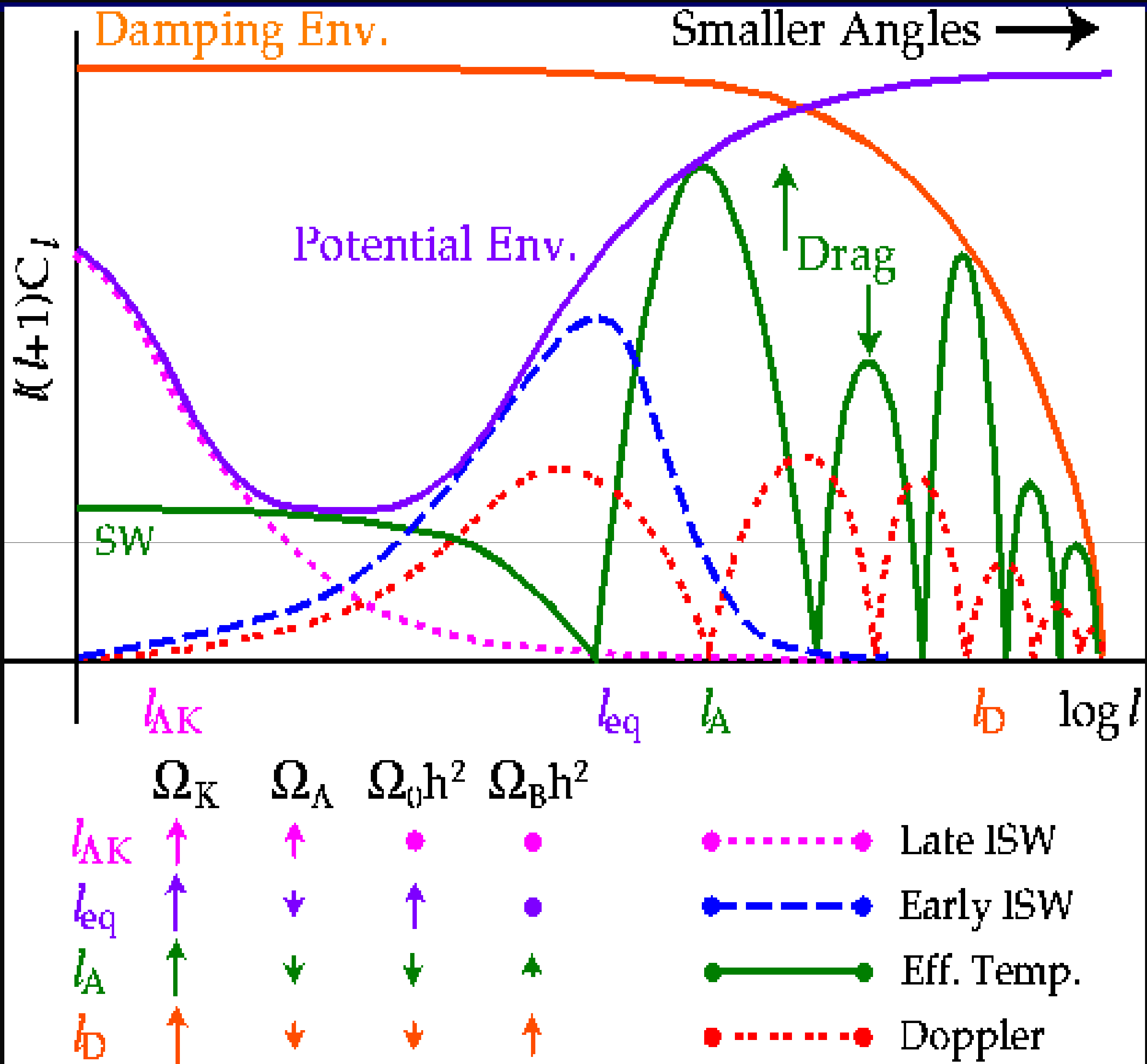
WMAP team



Secondary peaks

- Plot is ~ FT of (T(θ) - mean(T))
- Second peak = collapse, expand to max
- Third peak = collapse, expand, collapse
- etc..
- Expect peaks to be equally spaced in l



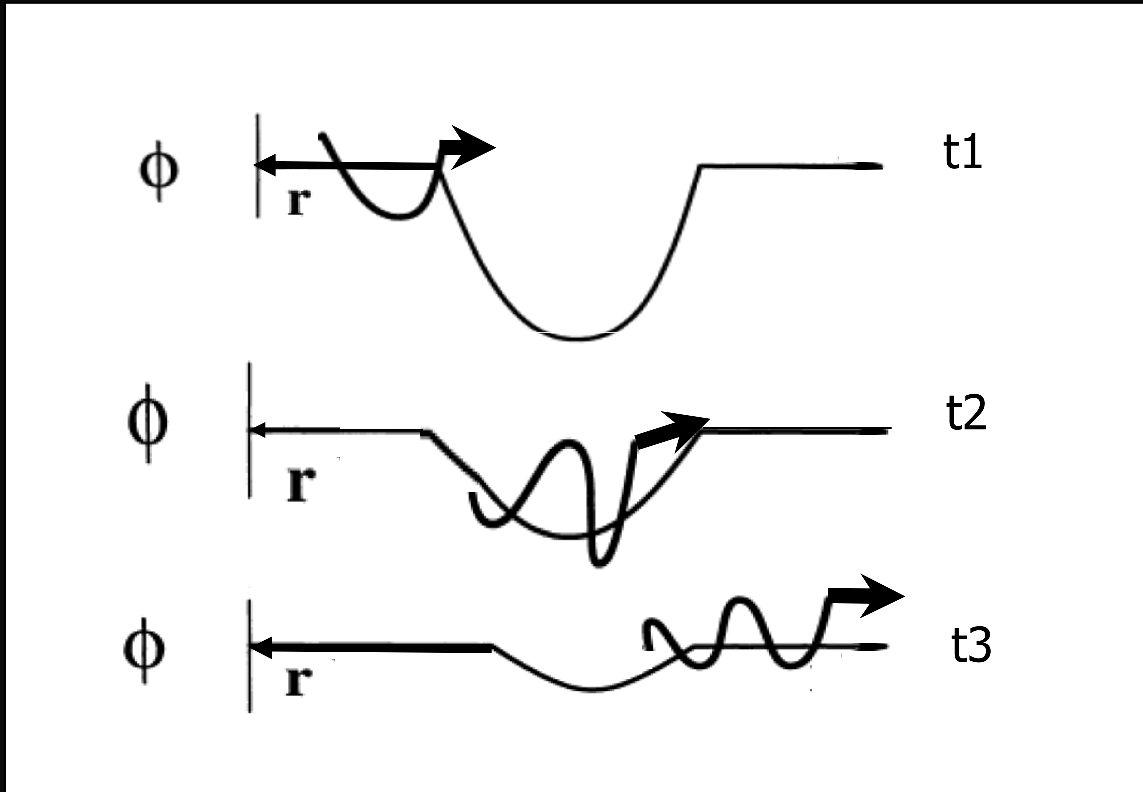


Graphic by Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

Sachs-Wolf effect and Doppler perturbations

- Matter is distributed in an anisotropic way.
- Photons climbing out of potential wells loose energy
- Photons emitted from regions of low density are blue shifted.
- gravitational redshift contribute to the dT/T in the CMB sky.
- Cold spots are over densities and hot spots are under densities.
- Has a net effect over large scales.
- Motion of the plasma has an influence on the frequency of the photons. This is important on smaller scales. This is in anti-phase with oscillations…

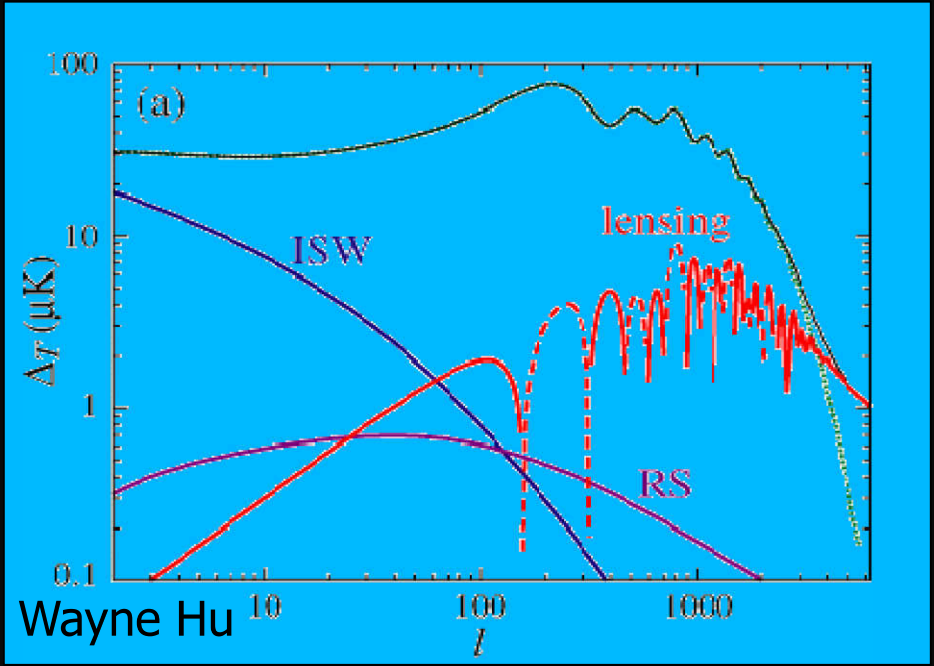
Integrated Sachs Wolfe effect

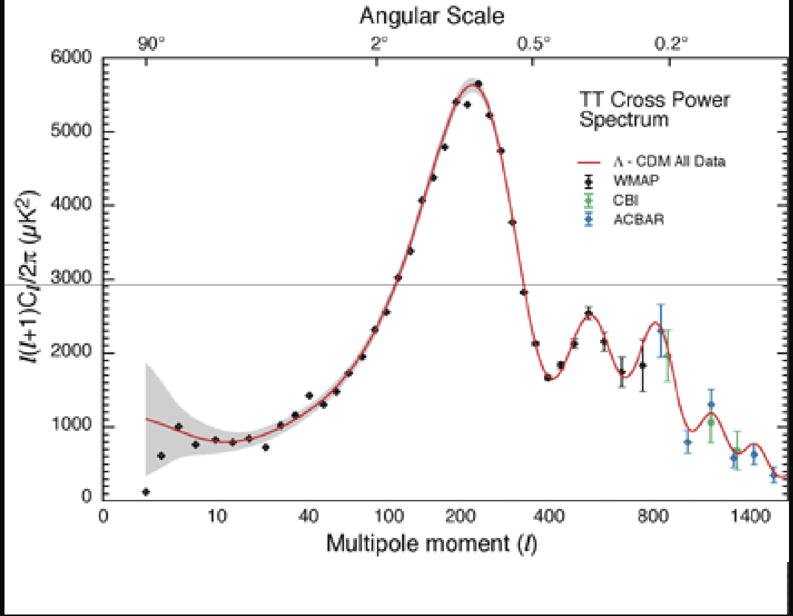


ISW is the gravitational redshift that photons coming from CMB undergo when they fall in a deep potential and come out.
This change in potential can be created when the Universe is not matter dominated.

How to detect ISW?

Temperature fluctuations created by ISW are difficult to see in power spectrum





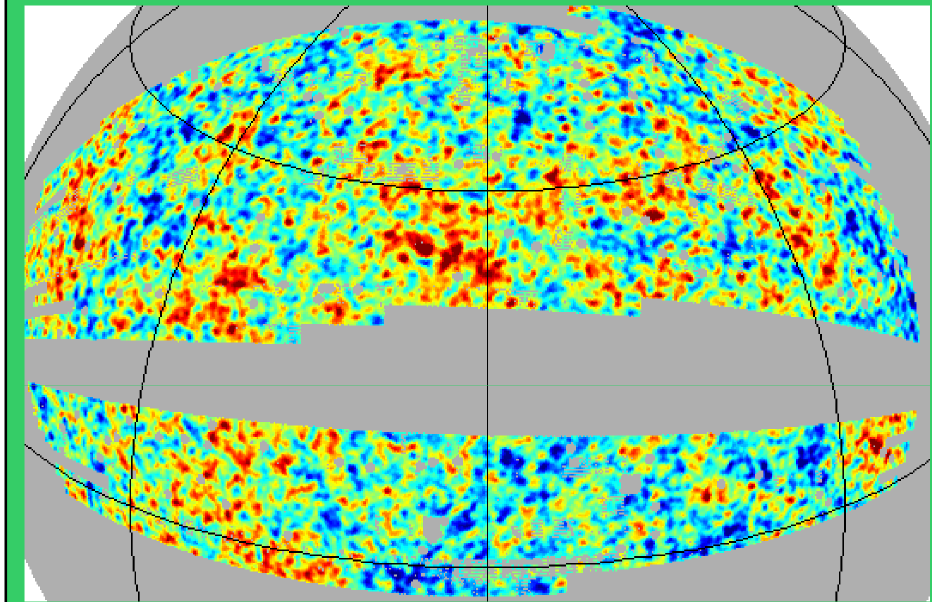
Alternative:

Cross correlating CMB temperature with potential traced by LSS

(Crittenden & Turok 1996)

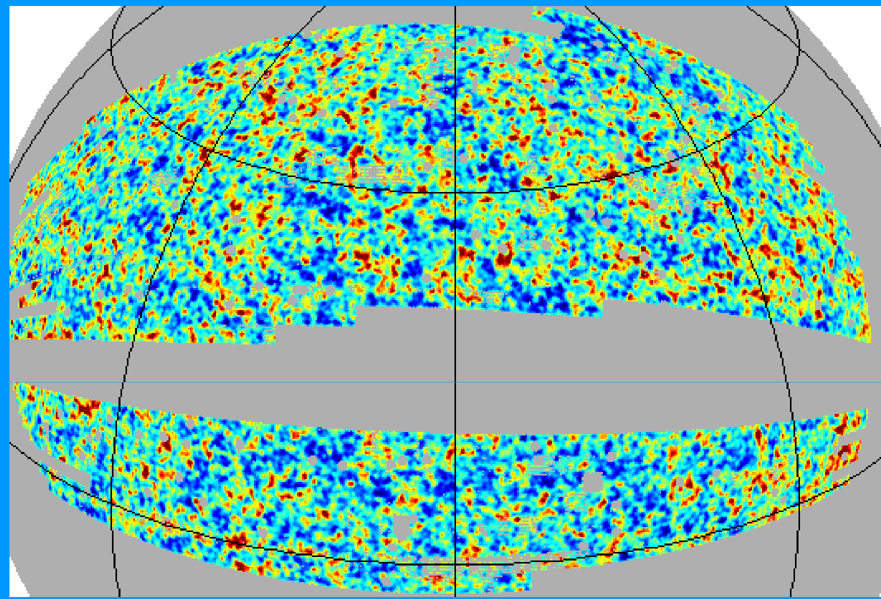
CMB data

WMAP



LSS data

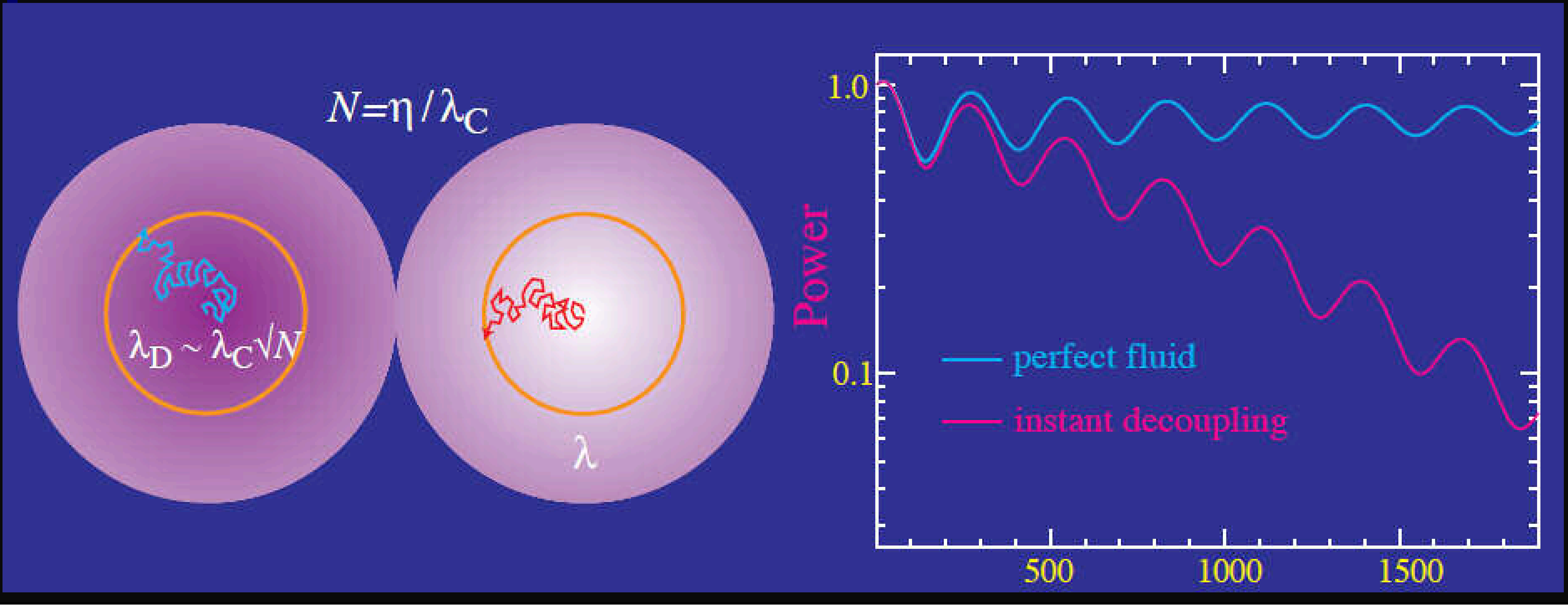
SDSS DR4



-5200 sq deg (13% sky)
-Selection of subsamples with different redshift distribution
-10^6 – 10^7 galaxies
-high redshift Luminous Red Galaxy (Eisentein et al. 2001

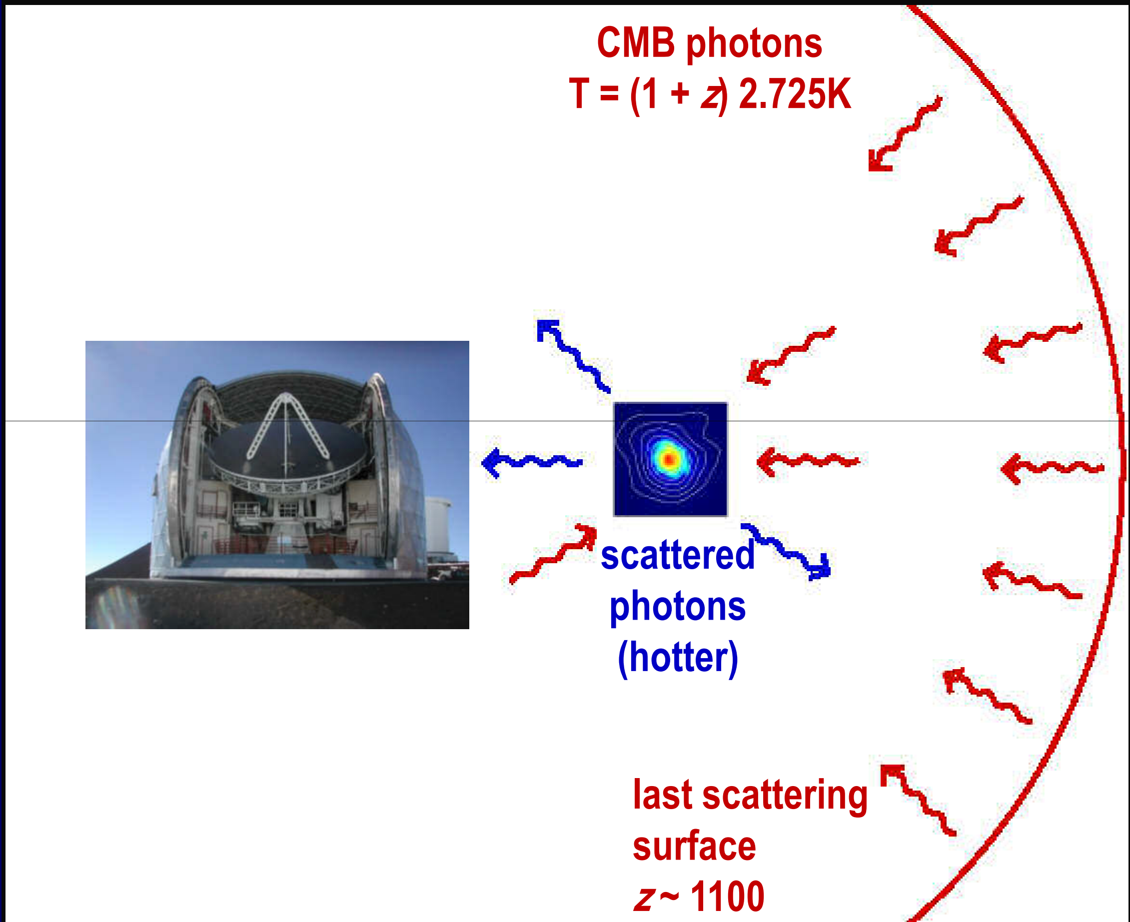
The Silk Tail: Dissipation / Diffusion Damping

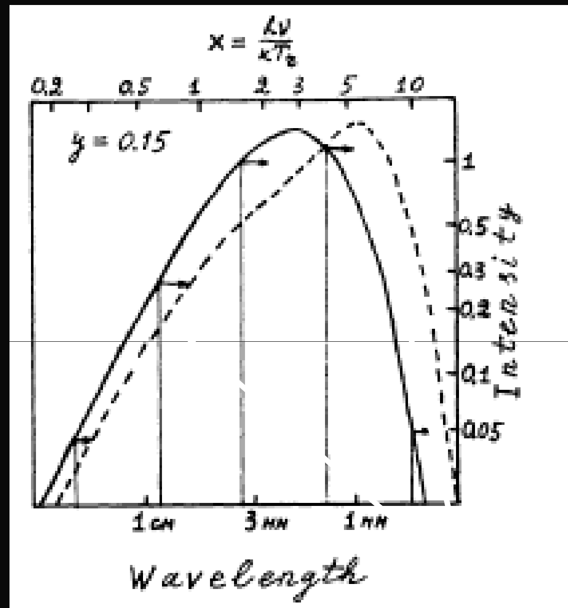
- Imperfections in the coupled fluid → mean free path λ in the baryons
- Random walk over diffusion scale: geometric mean of mfp & horizon



Physics of the SZ Effect

Mechanism & Thermal Effect





Sunyaev & Zeldovich (1970)

Spectral shift

CMB photons have a ~1% chance of inverse Compton scattering off of the ICM electrons; photon *number* is conserved -> changes the spectrum…

Physics of the SZ Effect

Functional Form (no need to remember formula)

$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell,$$

y parameter

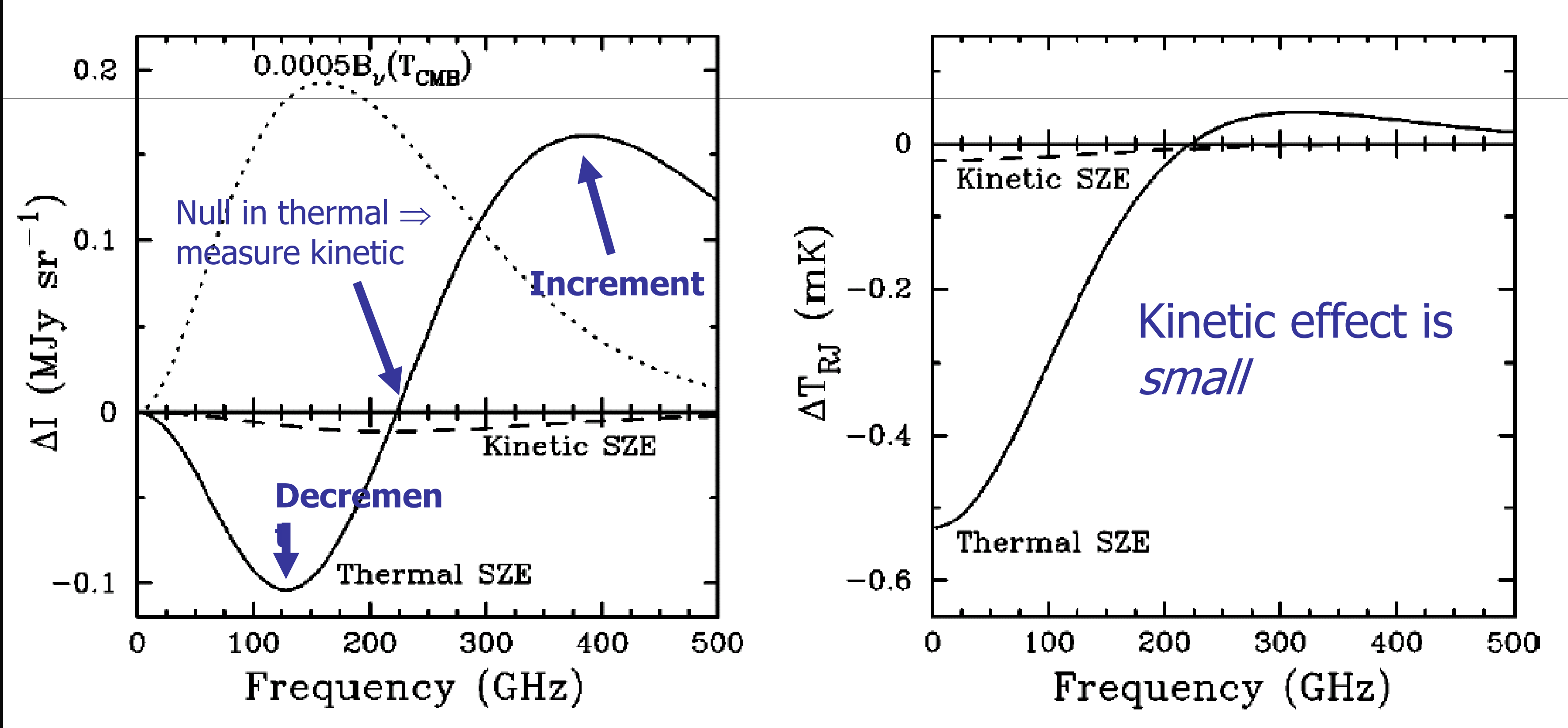
- Temperature shift proportional to the gas pressure, $n_e T_e$, & mass $\int dl$
- CMB photon energies boosted by $\sim kT_e/(m_e c^2)$
- $kT_e \sim 10$ keV, $Te \sim 10^8$ K
- $x = h\nu/(kT_e)$
- $f(x)$ is the spectral dependence

Physics of the SZ Effect

The Kinetic Effect: a Doppler boost from the peculiar velocity of the cluster

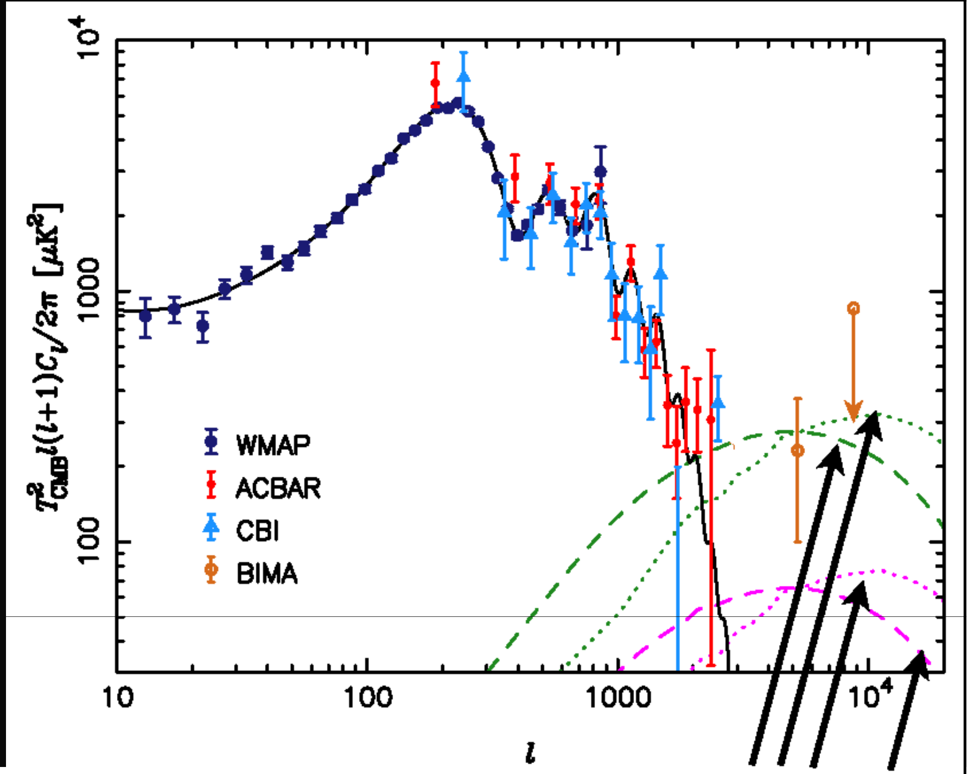
$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c} \right),$$

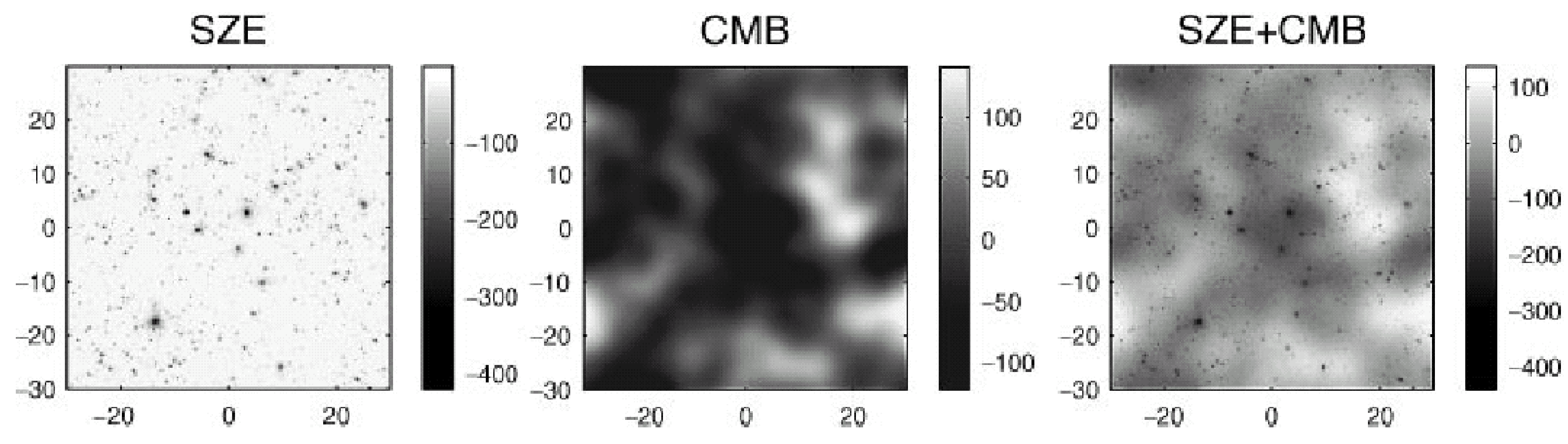
Spectral distortion:



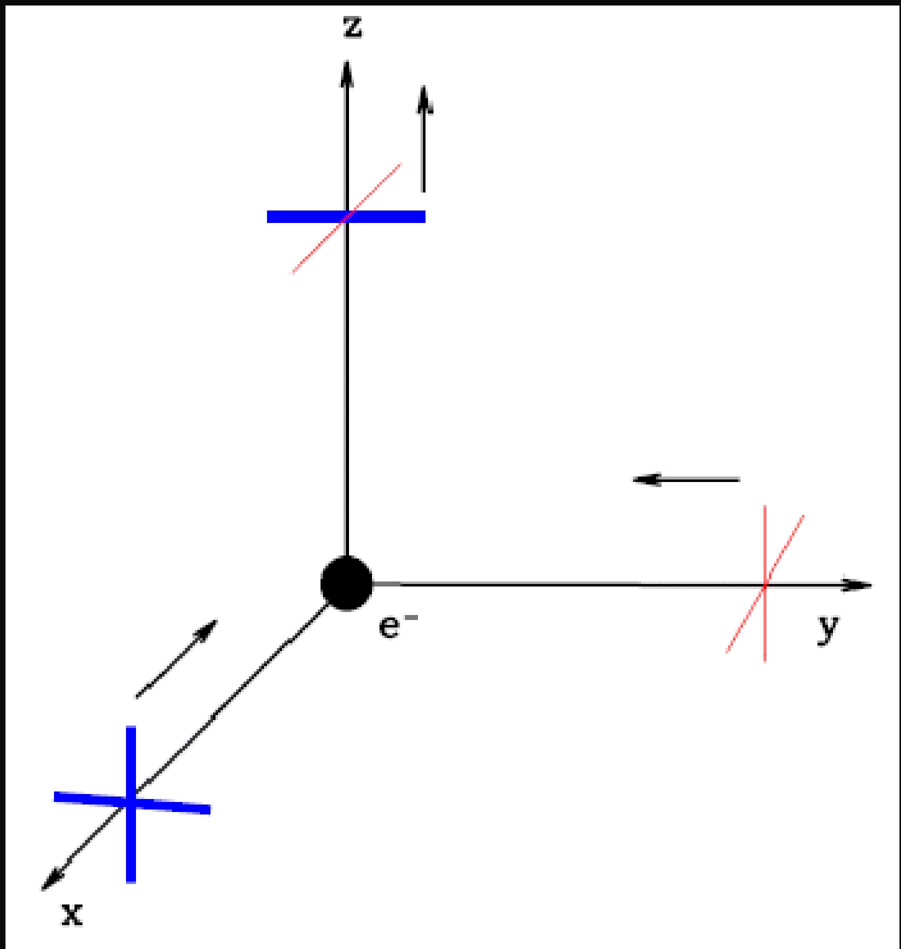
Physics of the SZ Effect

What the thermal effect looks like



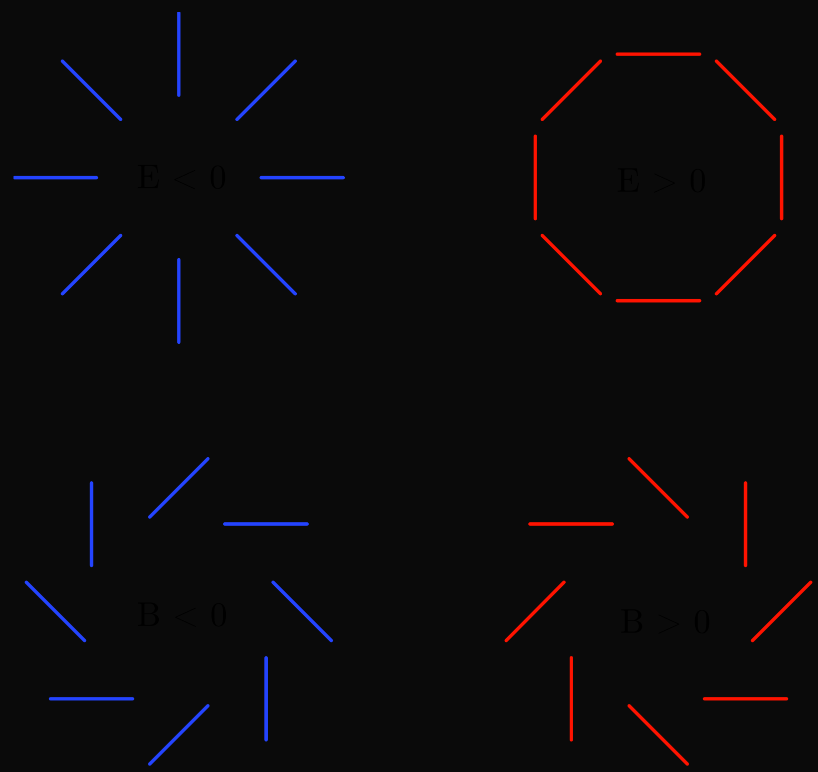


Compton scattering of unpolarized anisotropic radiation produces polarization

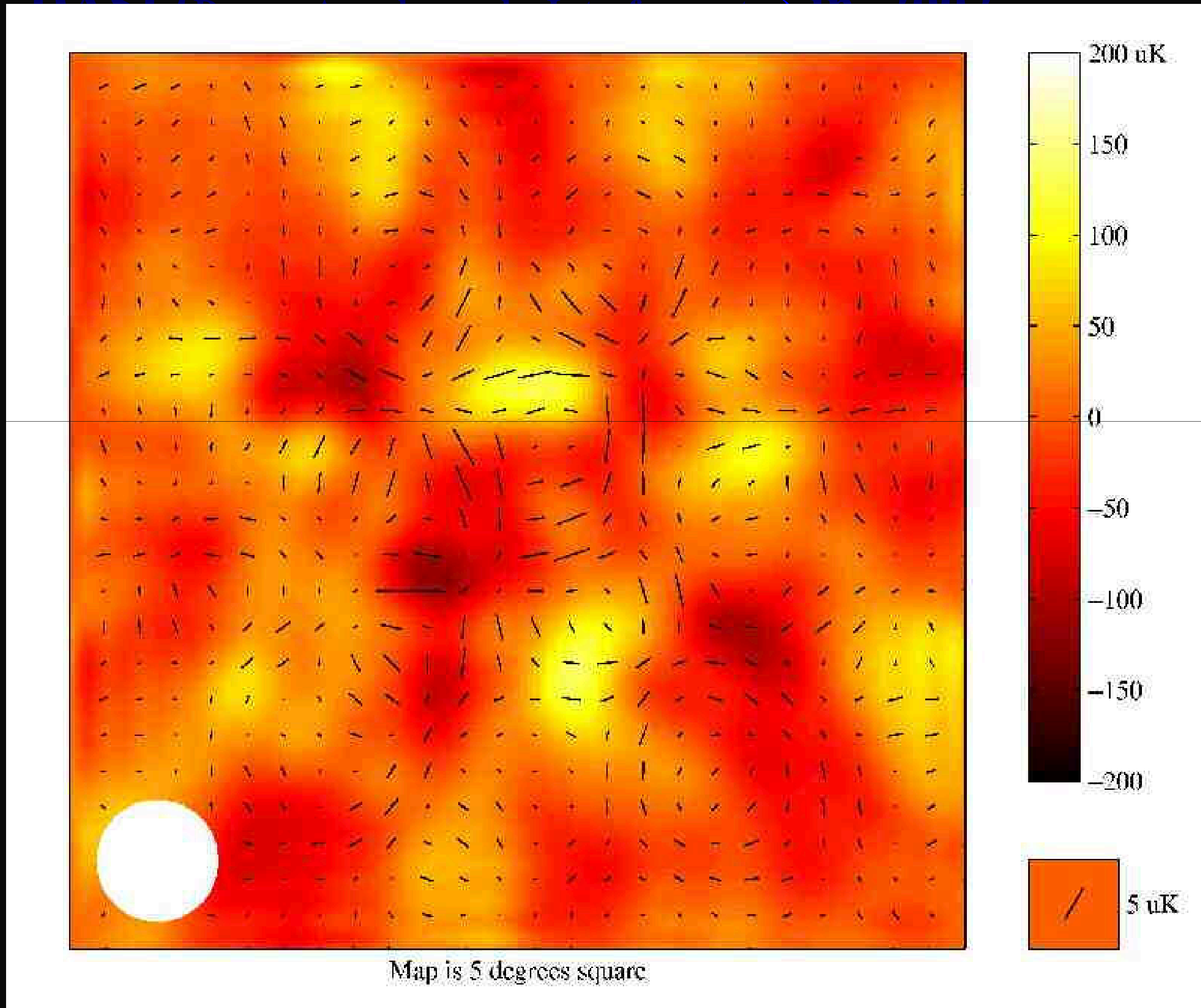


- Require Quadrupole (small before recombination)
- Require Compton scattering (rare after recombination)
- Signals factor of 10 smaller than temperature anisotropies
- Generated during 2 epochs: pre-recombination (*z~1000*) and after reionization (*z~10*)

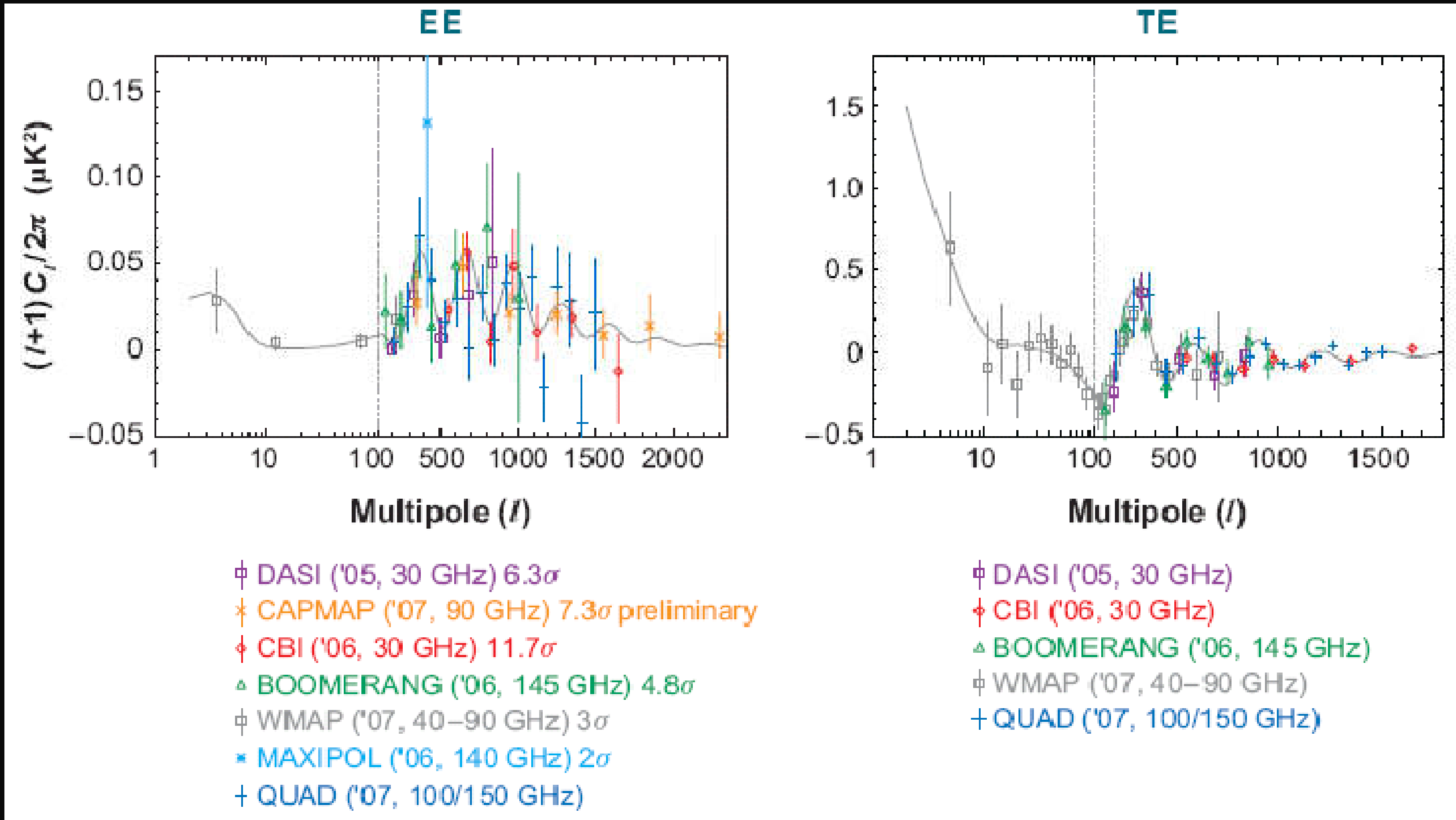
Polarization field decomposed into E- and B- modes



First detection of CMB Polarization

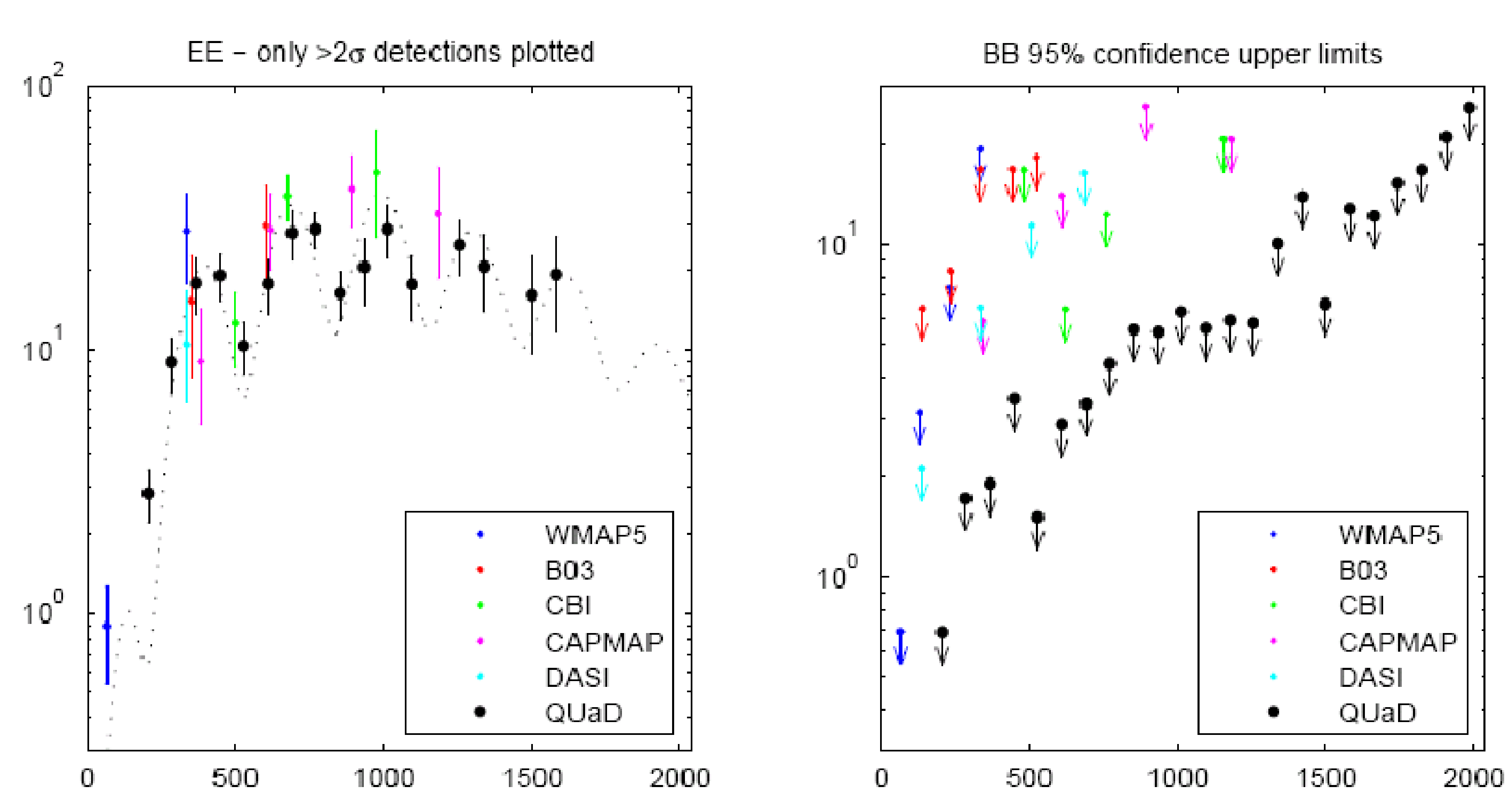


Results



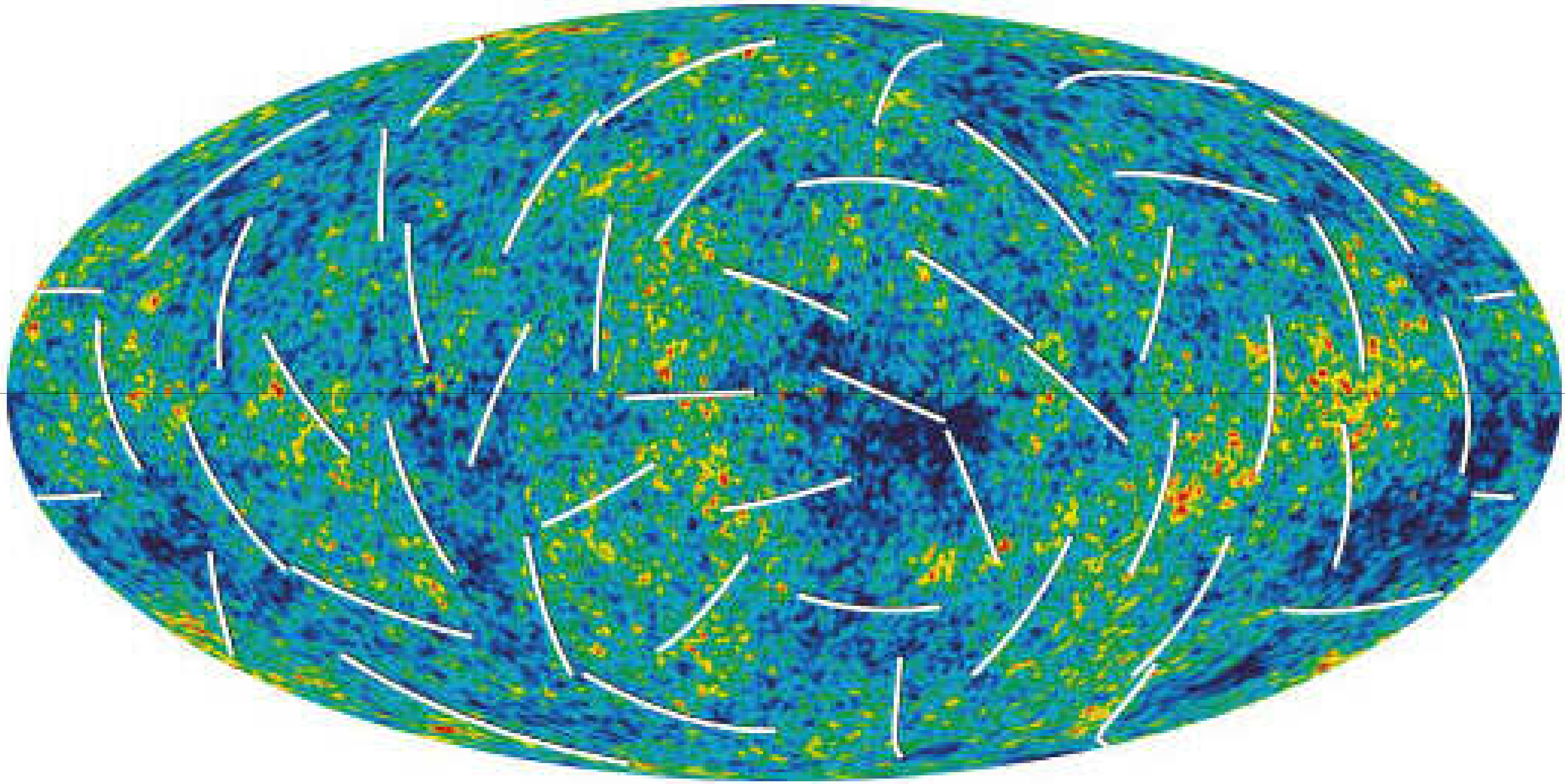
Samtleben, Staggs, & Winstein 2008

Results



Pryke et al. 2008

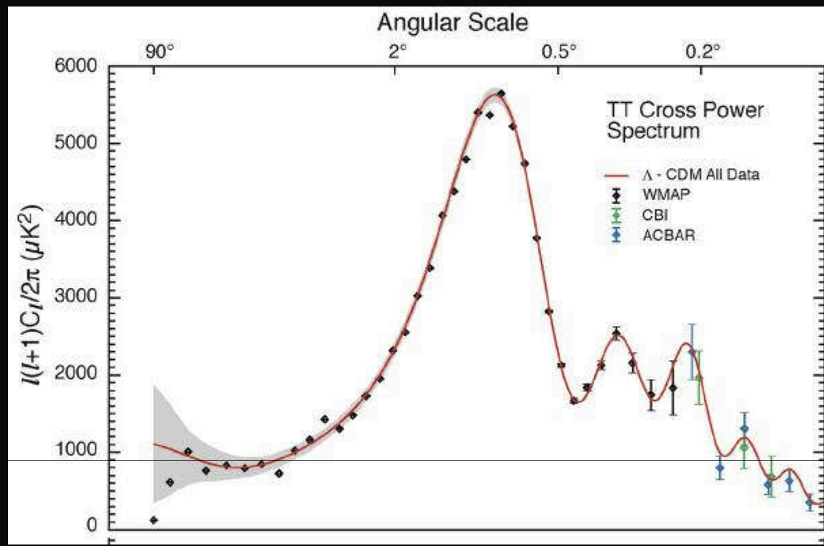
WMAP map of CMB Polarization

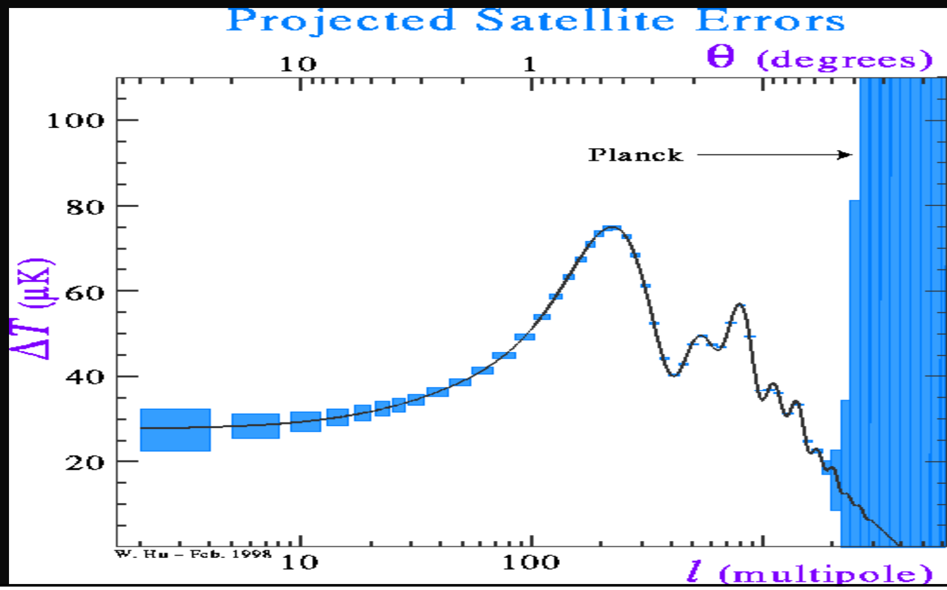


NASA/WMAP science team 2006

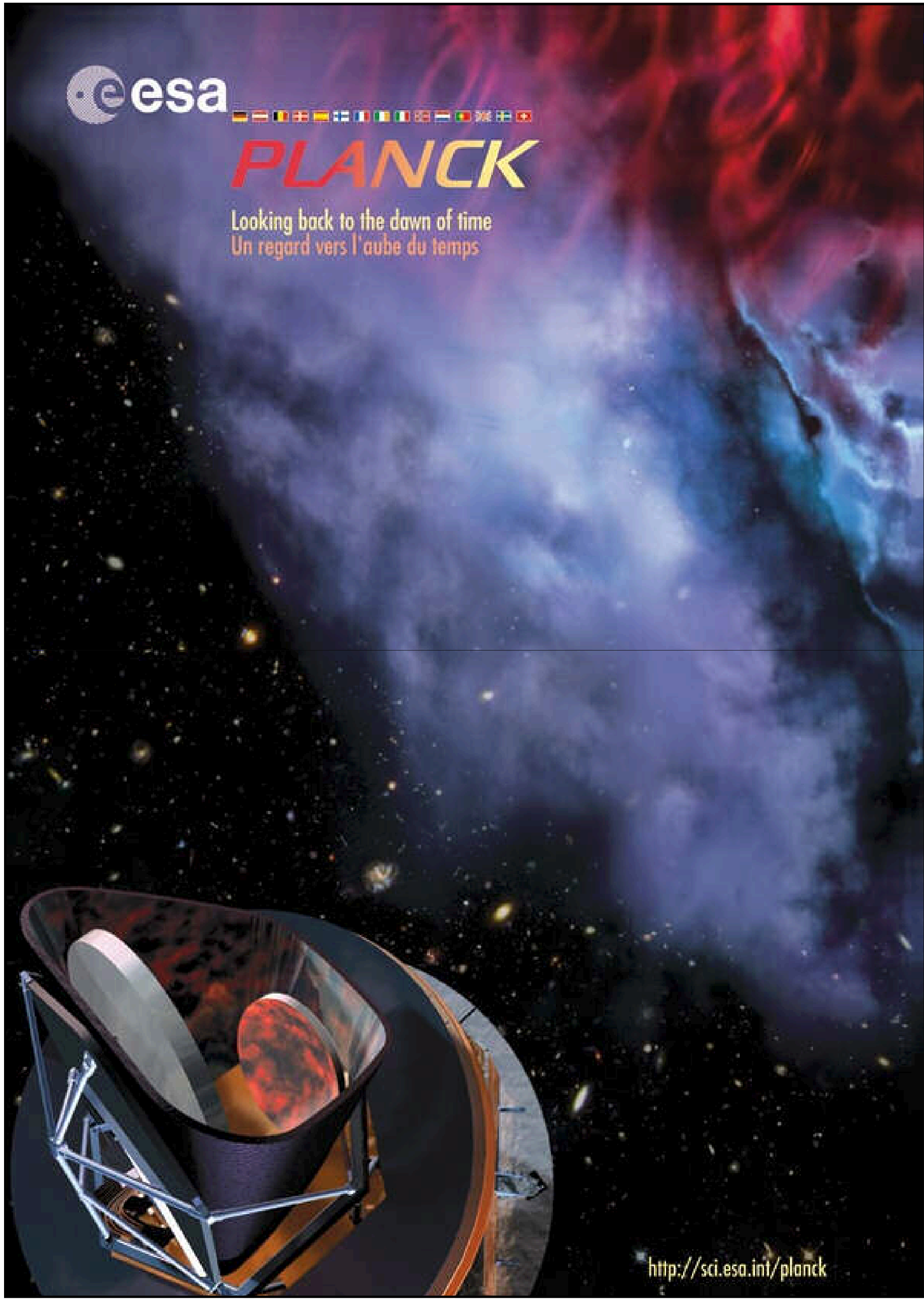
The near future

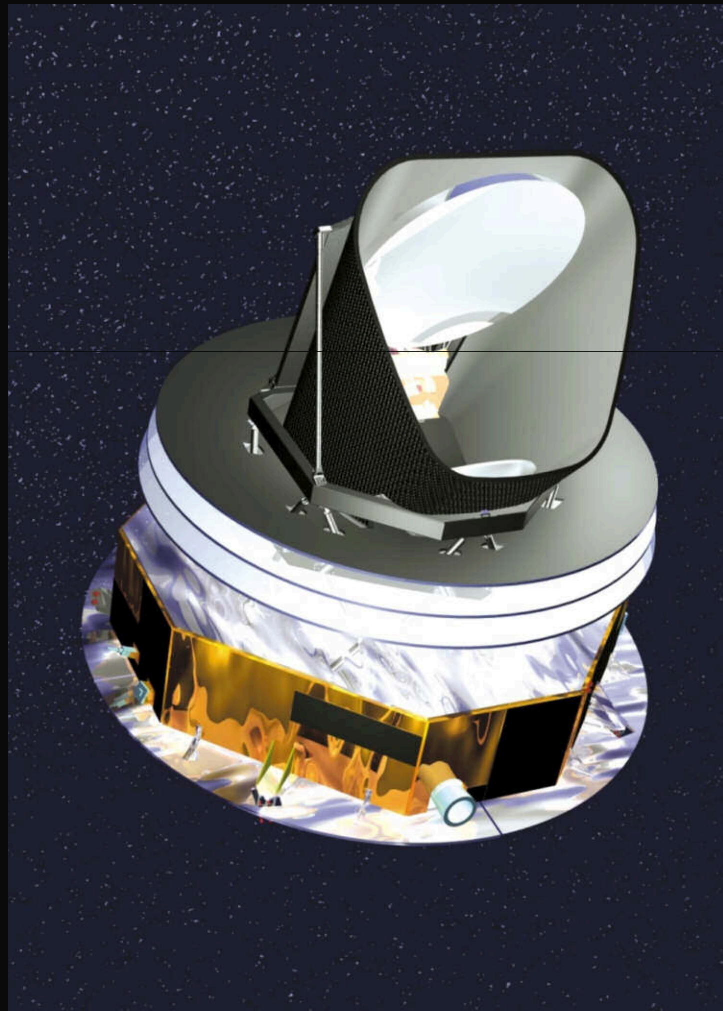
- Full WMAP data release
  - error bars shrink by factor of ~2
  - EE results
- Higher resolution data from ground based
  - CBI, VSAE, VSASE, ACBAR
- Polarization experiments
  - Boomerang, CBI, Pique, Clover, QUest
- Planck, launch = 2009



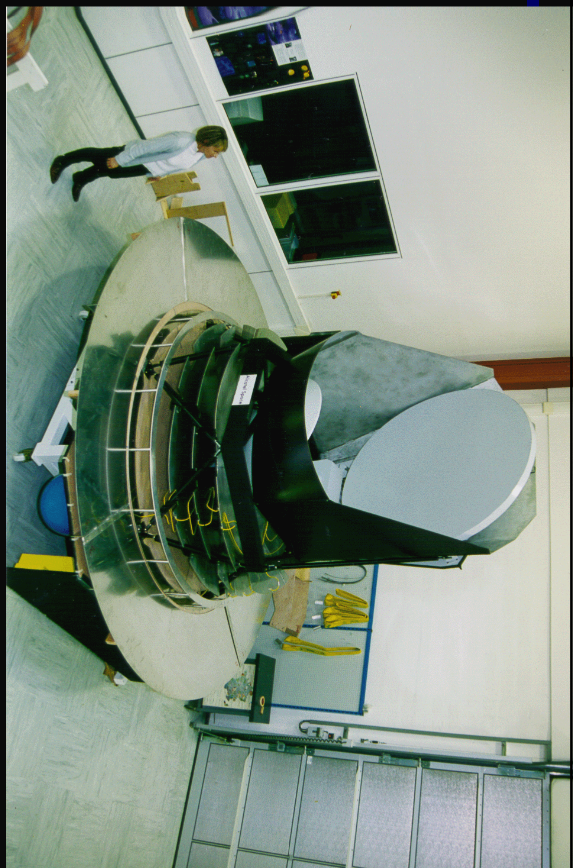


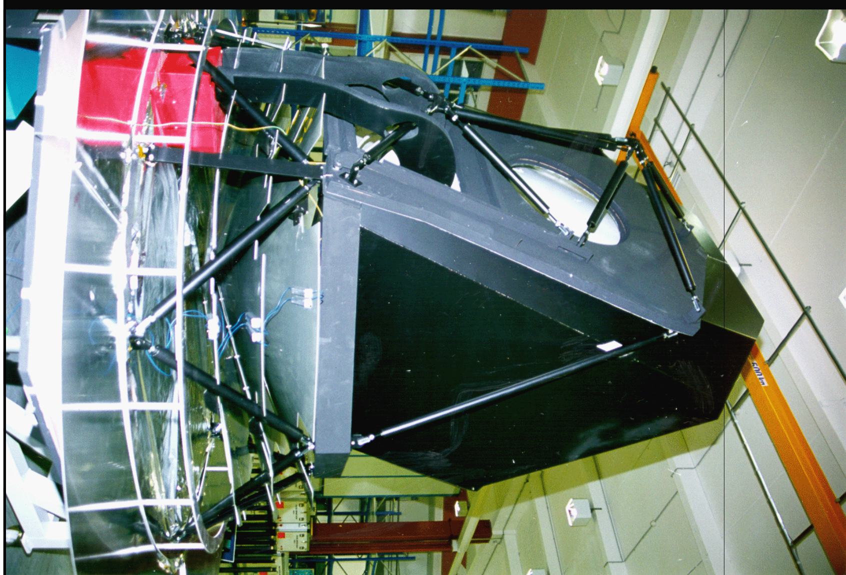
From Planck website





From Planck website



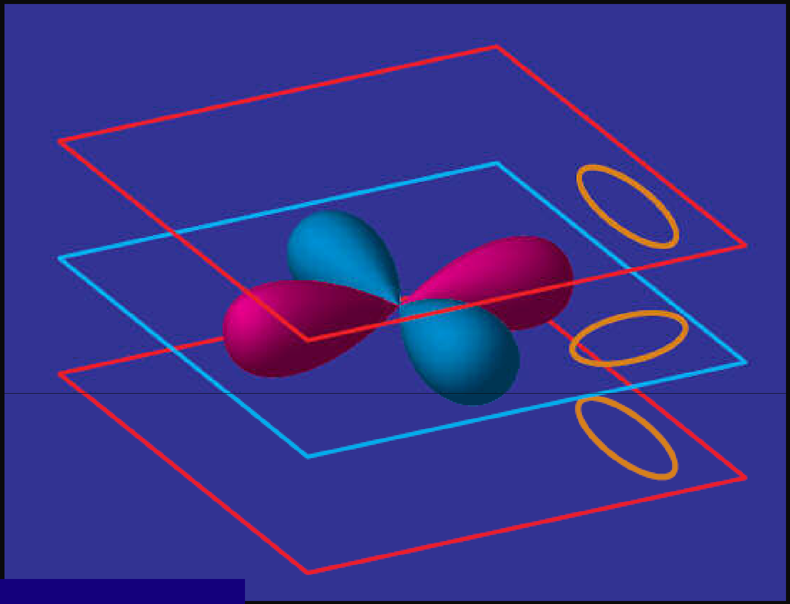


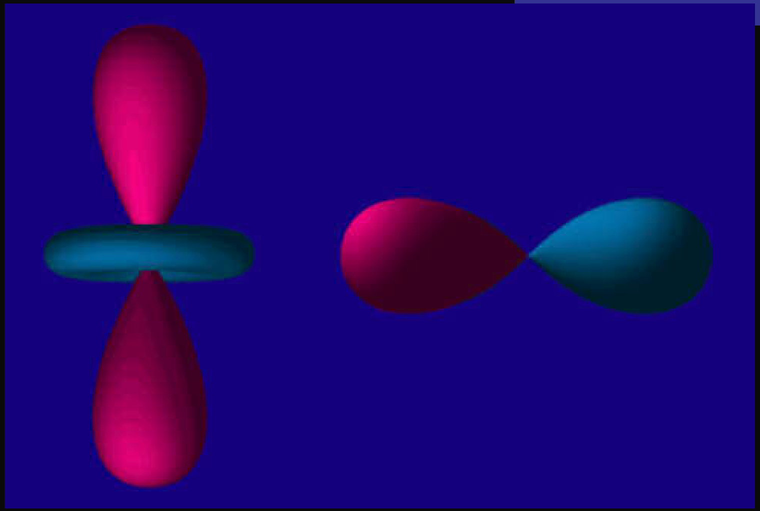
From Planck website

Quadrupoles from Gravitational Waves

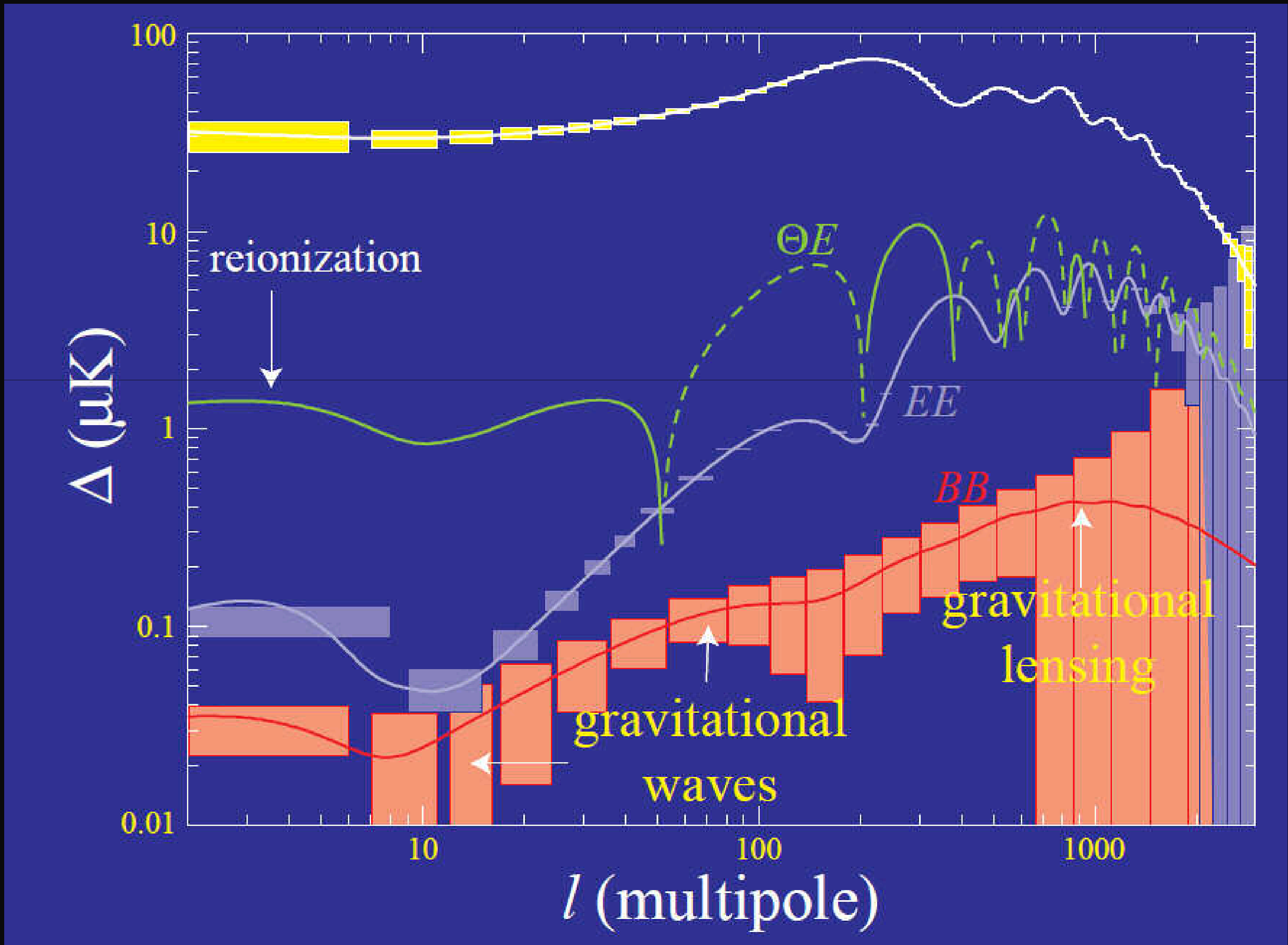
Transverse-traceless distortion provides temperature quadrupole

• Gravitational wave polarization picks out direction transverse to

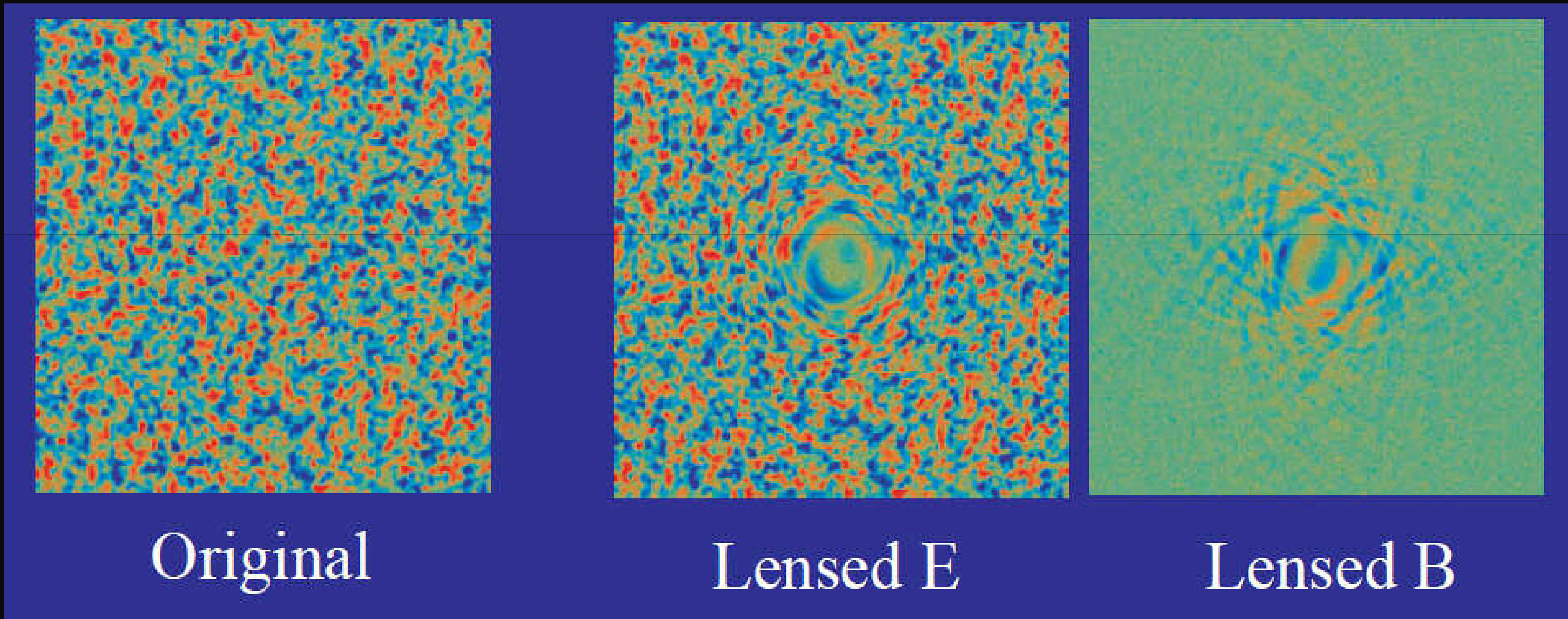




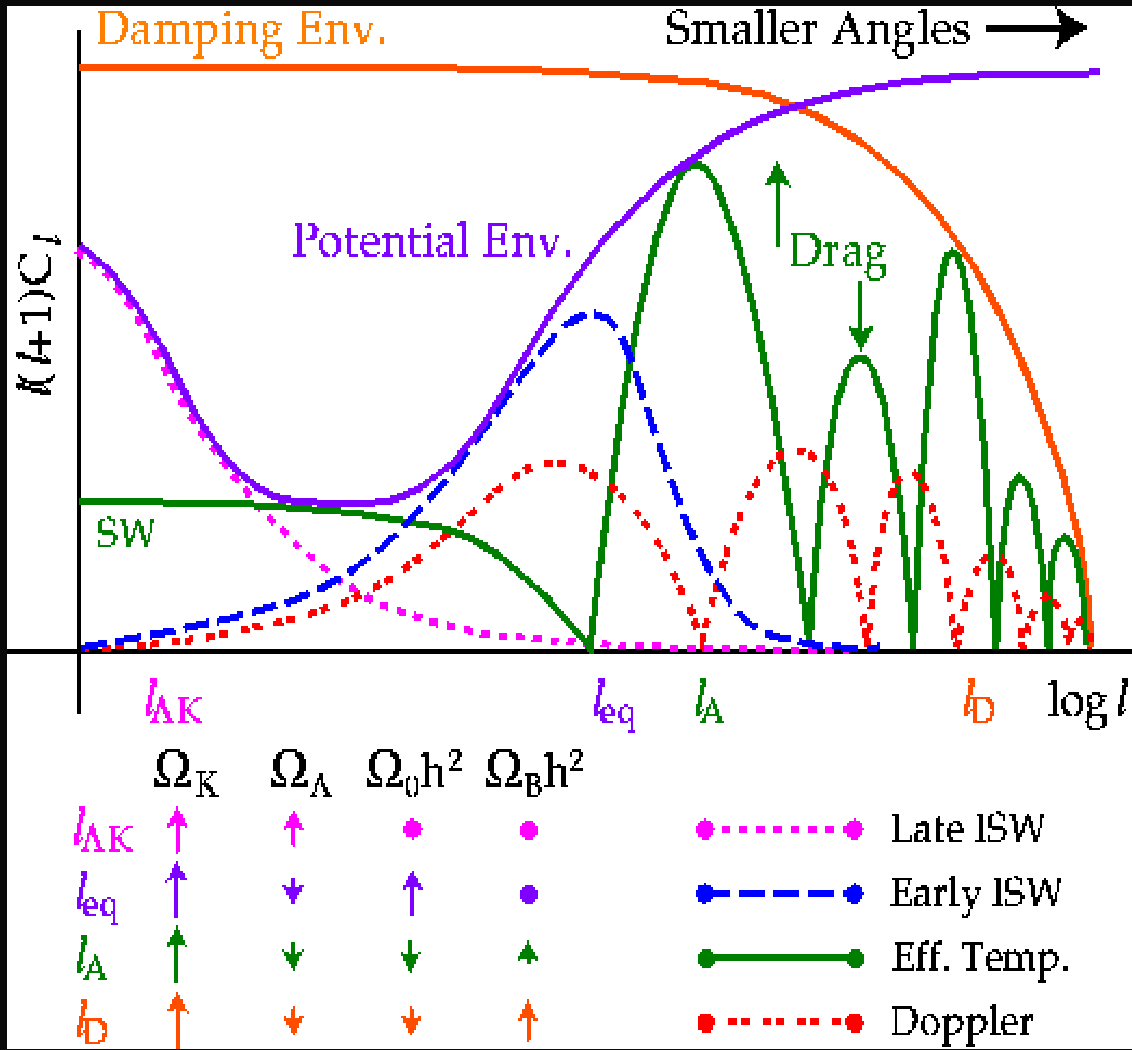
Plans to Detect B-Modes



E and B-Modes Lensing

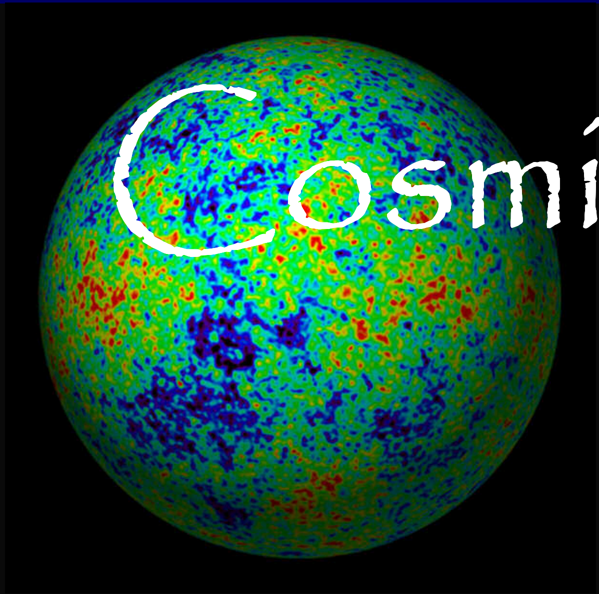


- Primary:
  - SW
  - Baryonic oscillations
  - Doppler
- Secondary:
  - ISW
  - SZ
  - Lensing
  - Etc… there are others… (Rees-Sciama, kinetic SZ, re-ionisation)

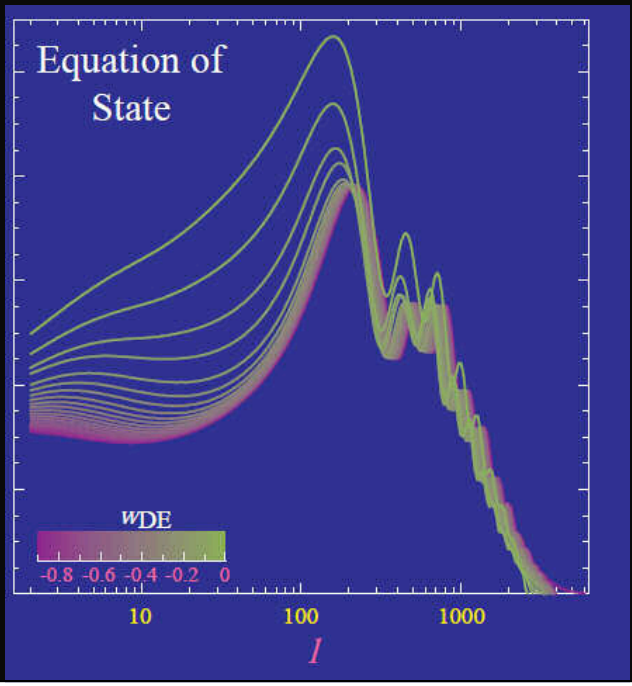


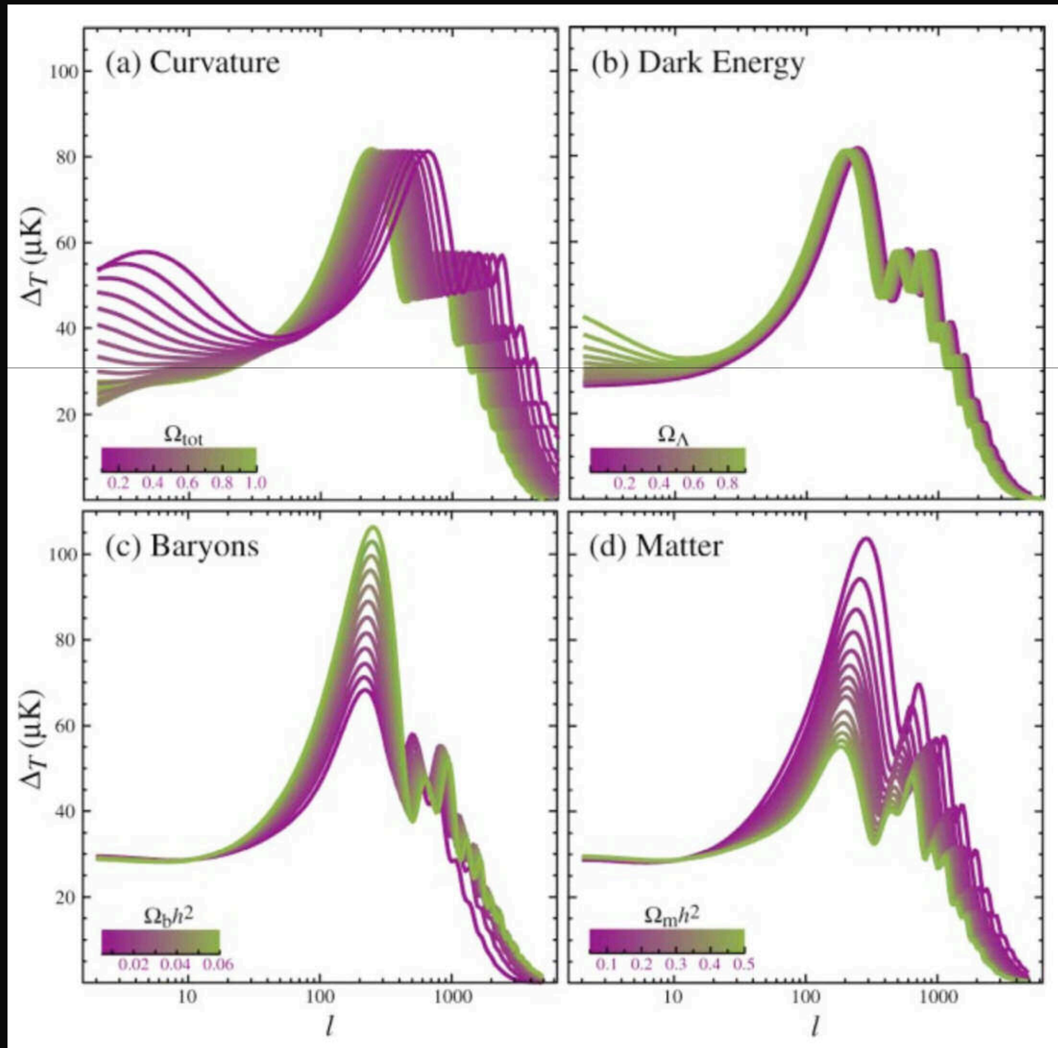
Graphic by Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

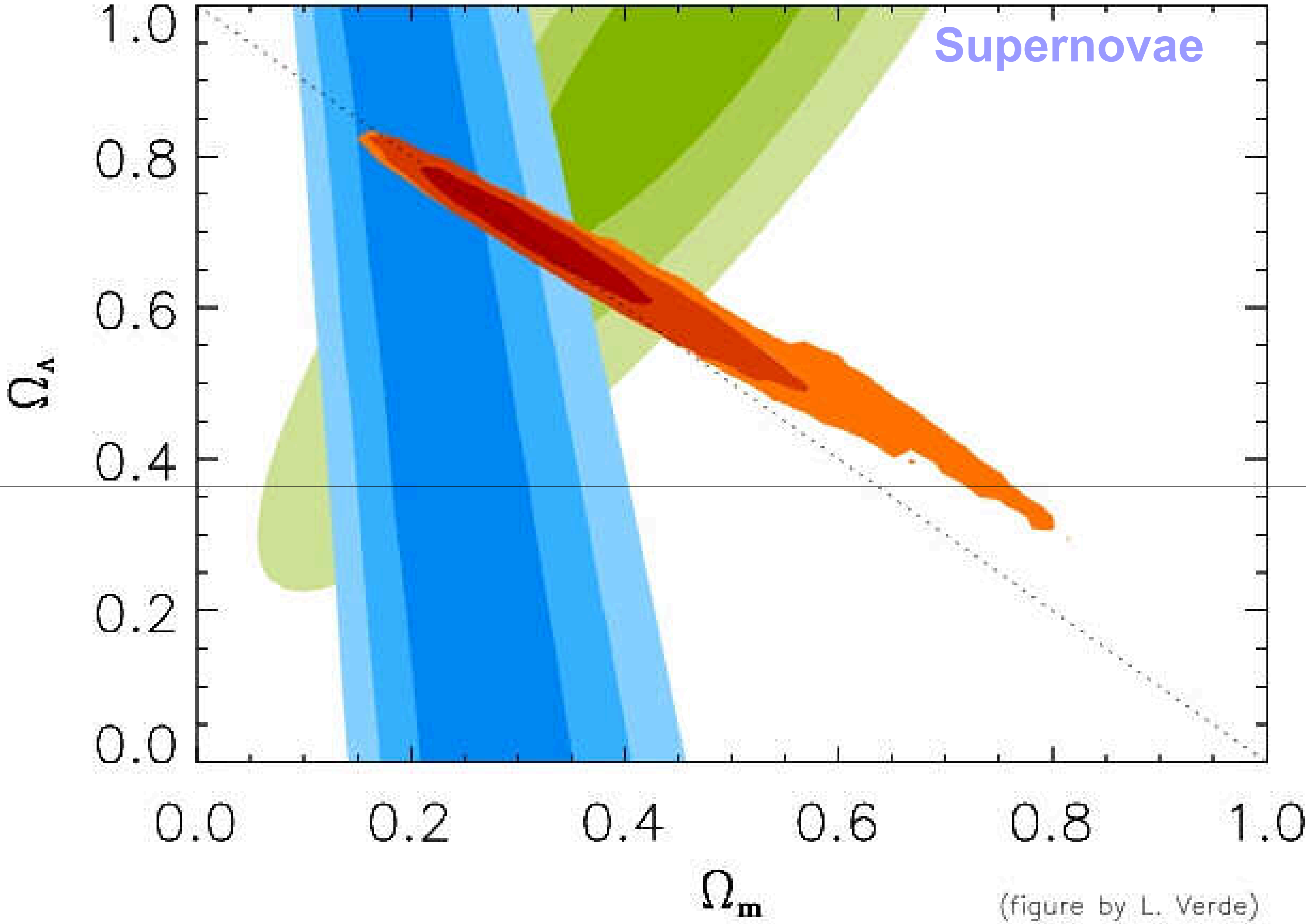
Cosmic Parameters



The WMAP CMB temperature power spectrum







http://www.physics.upenn.edu/~lverde/cosmmodel.html

END for now!!!