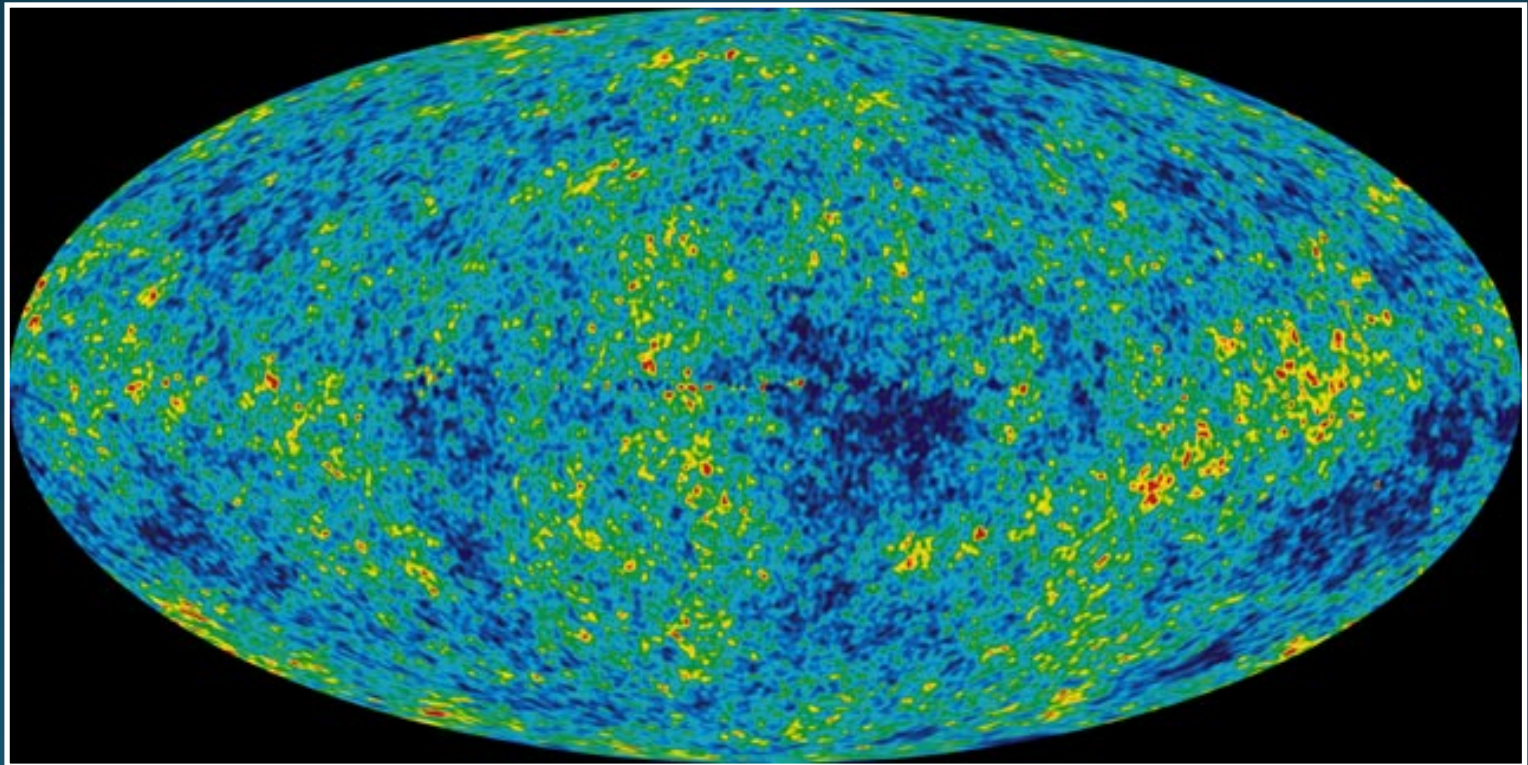


Cosmology 1FA209, 2016

Lecture 7:

# Cosmic Microwave Background Radiation



# Outline

- Introduction to the CMBR
  - History of CMBR research
  - Support for the Big Bang model
- Properties of the CMBR
  - Temperature
  - The dipole anisotropy
  - Small-scale temperature fluctuations
- Origin of the CMBR
  - Recombination
  - Decoupling
  - Last scattering surface
  - Small-scale temperature fluctuations
- Cosmological information

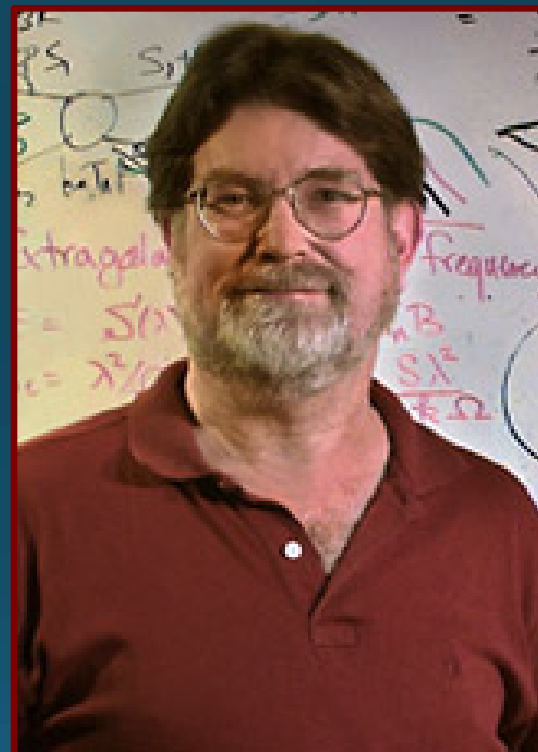
Covers chapter 9 in Ryden



# 2006 Nobel prize in Physics

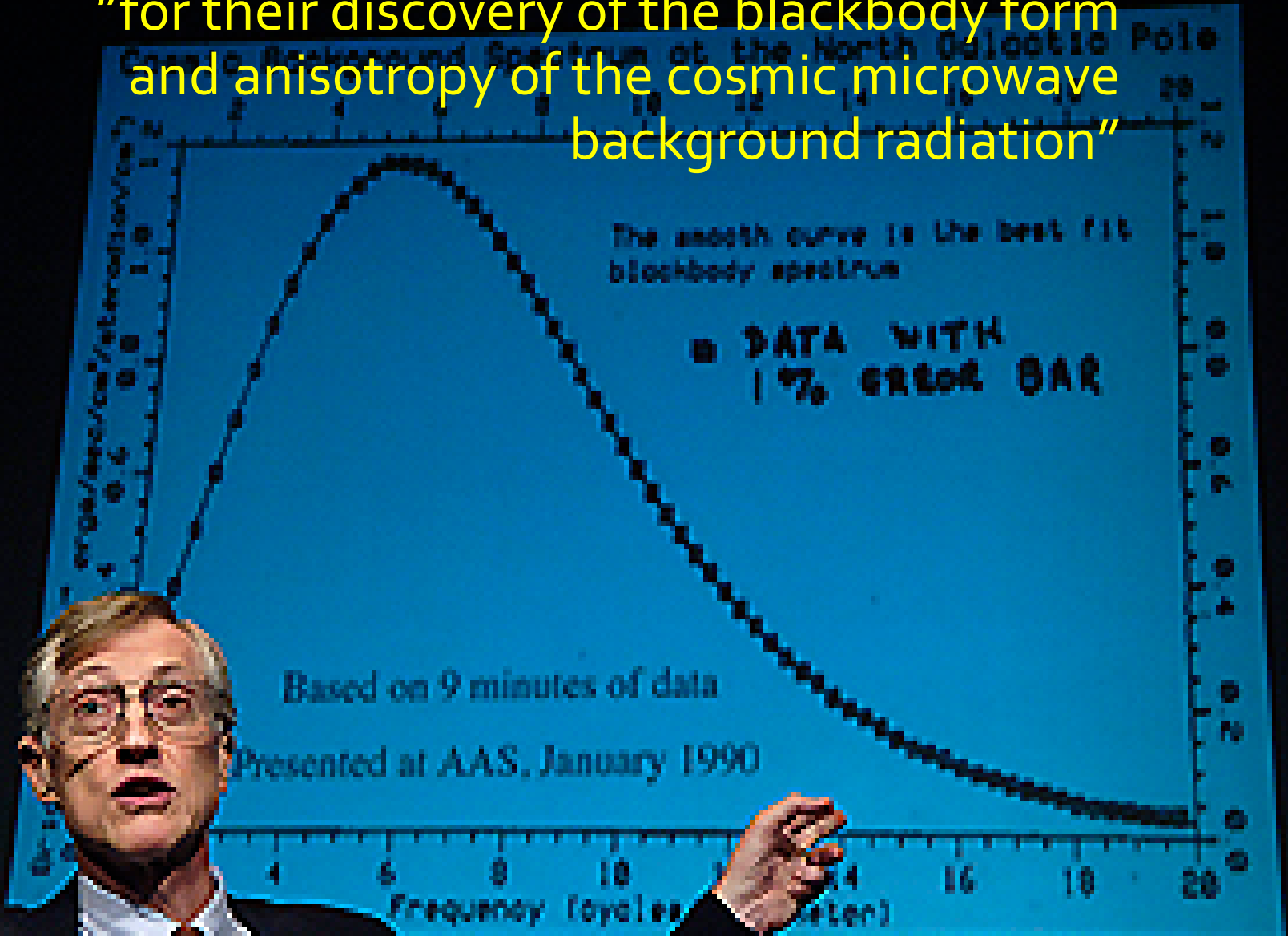


**John C. Mather**  
NASA Goddard Space  
Flight Center  
Greenbelt, MD, USA



**George F. Smoot**  
University of California  
Berkeley, CA, USA

“for their discovery of the blackbody form  
and anisotropy of the cosmic microwave  
background radiation”



# Cosmic Microwave Background Radiation (CMBR)

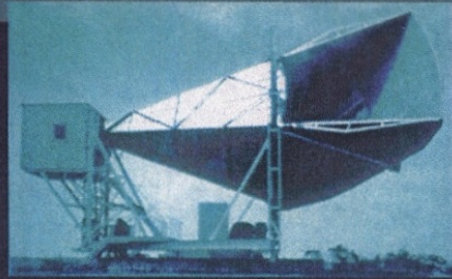
## - Quick Facts -

- Comes from all directions in the sky
- Black body spectrum with:
  - $T_0 \approx 2.73 \text{ K}$
  - Peak wavelength  $\approx 2 \text{ mm}$
- Close to isotropic, except for:
  - Large-scale doppler (dipole) anisotropy due to our motion with respect to the CMBR
  - Small-scale temperature fluctuations due to density fluctuations at  $z \approx 1100$

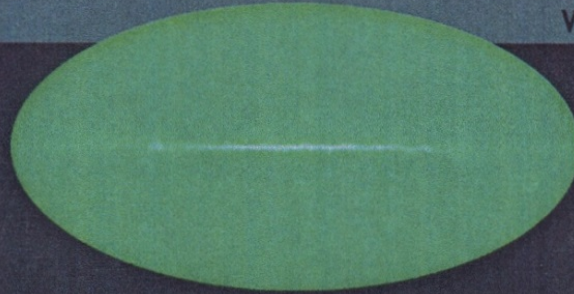


# History of CMBR research I

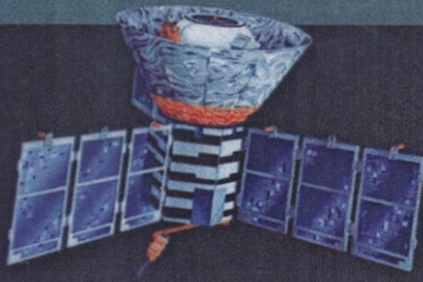
1965



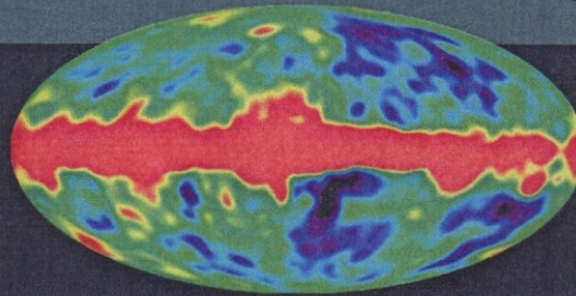
Penzias and  
Wilson



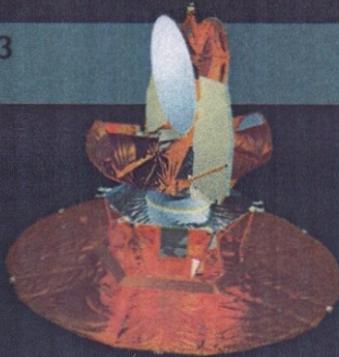
1992



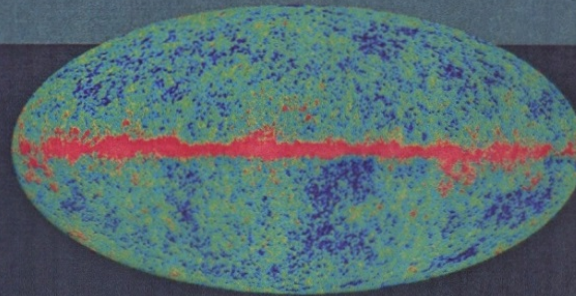
COBE



2003



WMAP



Nobel prize to  
Smoot and Mather  
for their work  
with COBE

# History of CMBR research II

- 1934: First prediction of the existence of the CMBR
  - Tolman: Expanding Universe should be filled by thermal radiation from its hot past
- 1948: First prediction of the current CMBR temperature
  - Gamow, Alpher & Herman:  $T_0 \approx 5 \text{ K}$
- 1965: CMBR discovered by Wilson & Penzias
  - Temperature measured to be  $T_0 \approx 3.5 \text{ K}$



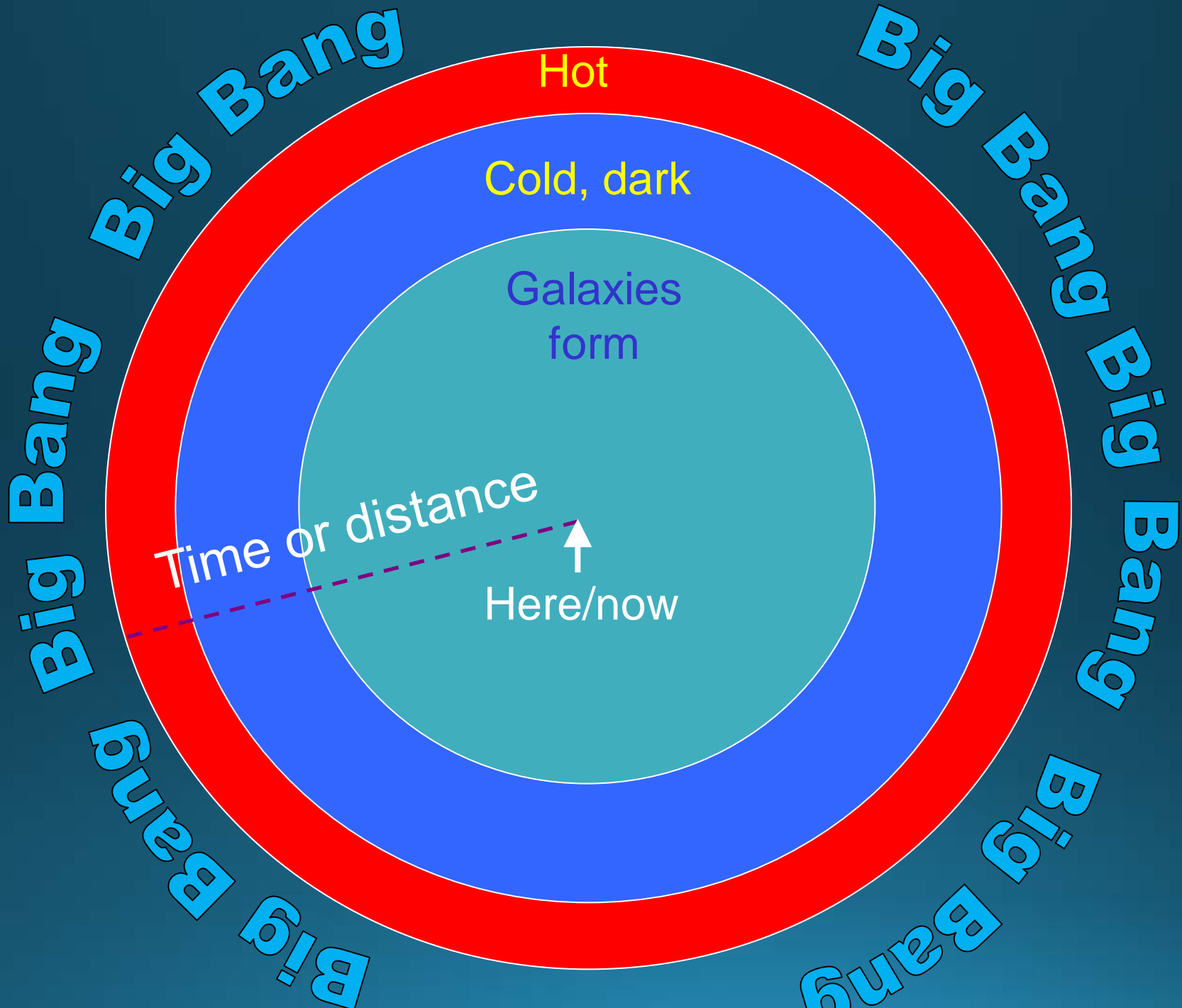
# History of CMBR research III

- 1992: COBE satellite
  - Close to perfect BB, with  $T \approx 2.73$  K
  - Large-scale dipole
  - Small-scale temperature fluctuations ( $\sim 10^{-5}$  K)
- Late 90s: MAXIMA & BOOMERanG balloons
  - Small-scale temperature and polarization variations
- 2001 - 2010: WMAP satellite
  - Full-sky maps of polarization and small-scale temperature variations
- 2009 – 2013: Planck satellite
  - Superior polarization measurements
  - Helps debunk claimed detection of gravitational waves from BICEP2 team

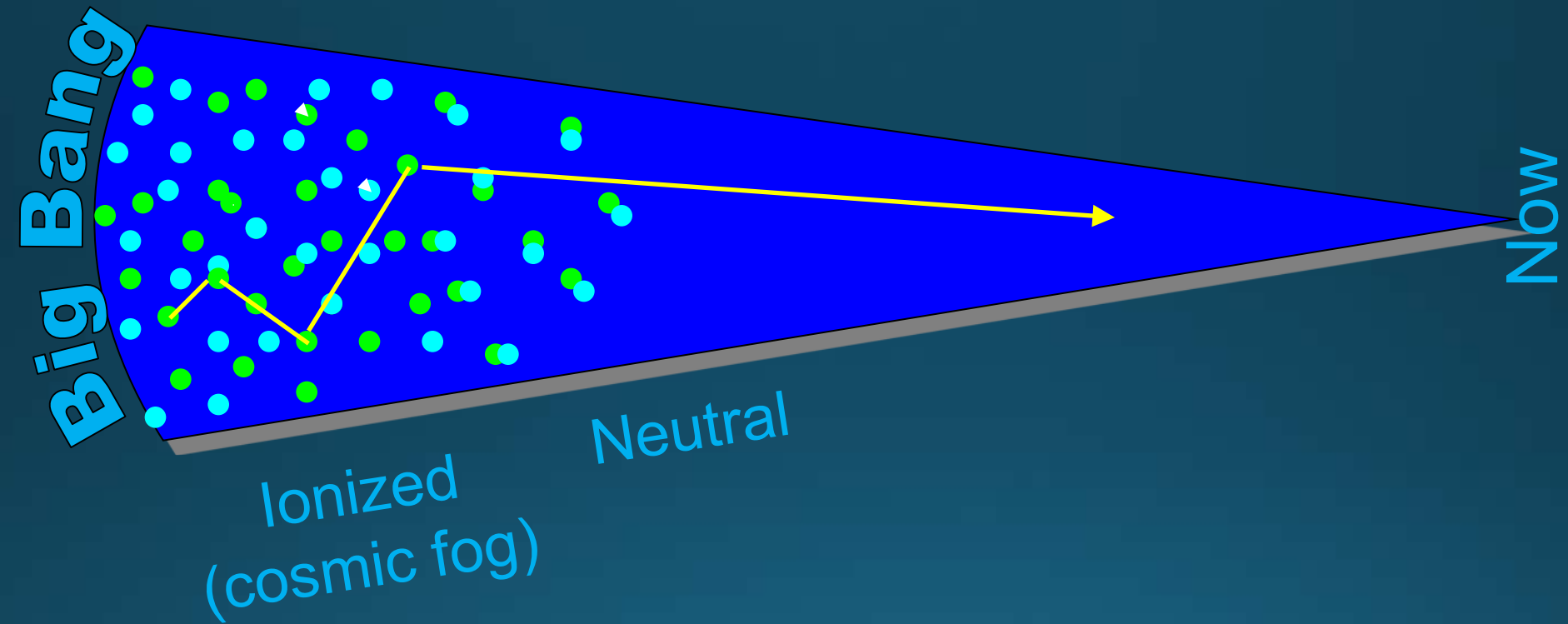


# Why is there a CMB?

- Early Universe ( $t < 240\,000$  yr): Hot →
  - Baryons ionized
  - Universe opaque to photons
  - Photon-baryon plasma
- Cosmic expansion →
  - Universe neutral at  $t \sim 240\,000$  yr
  - Universe transparent to photons



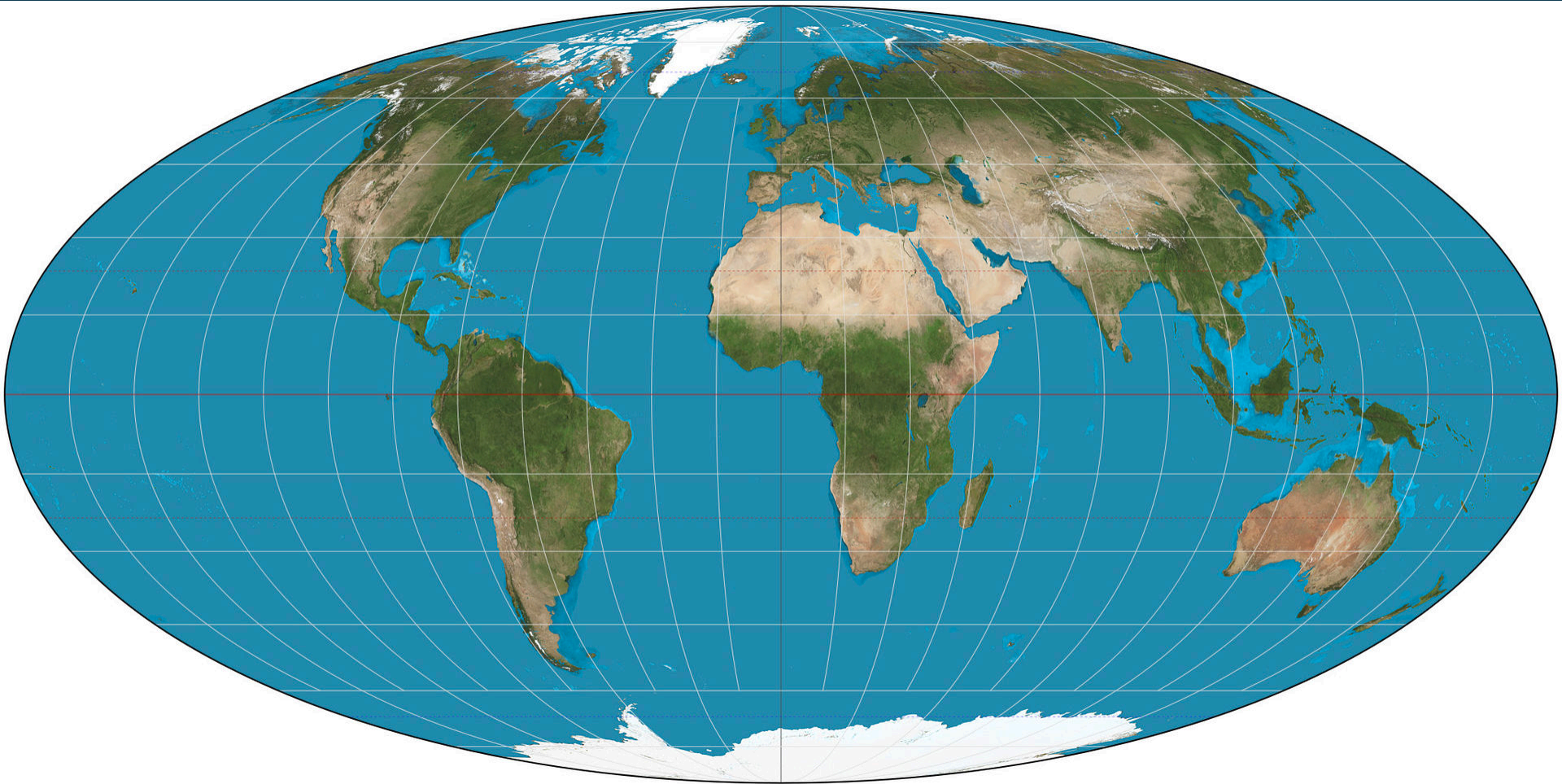
# Photon trajectories from the Early Universe



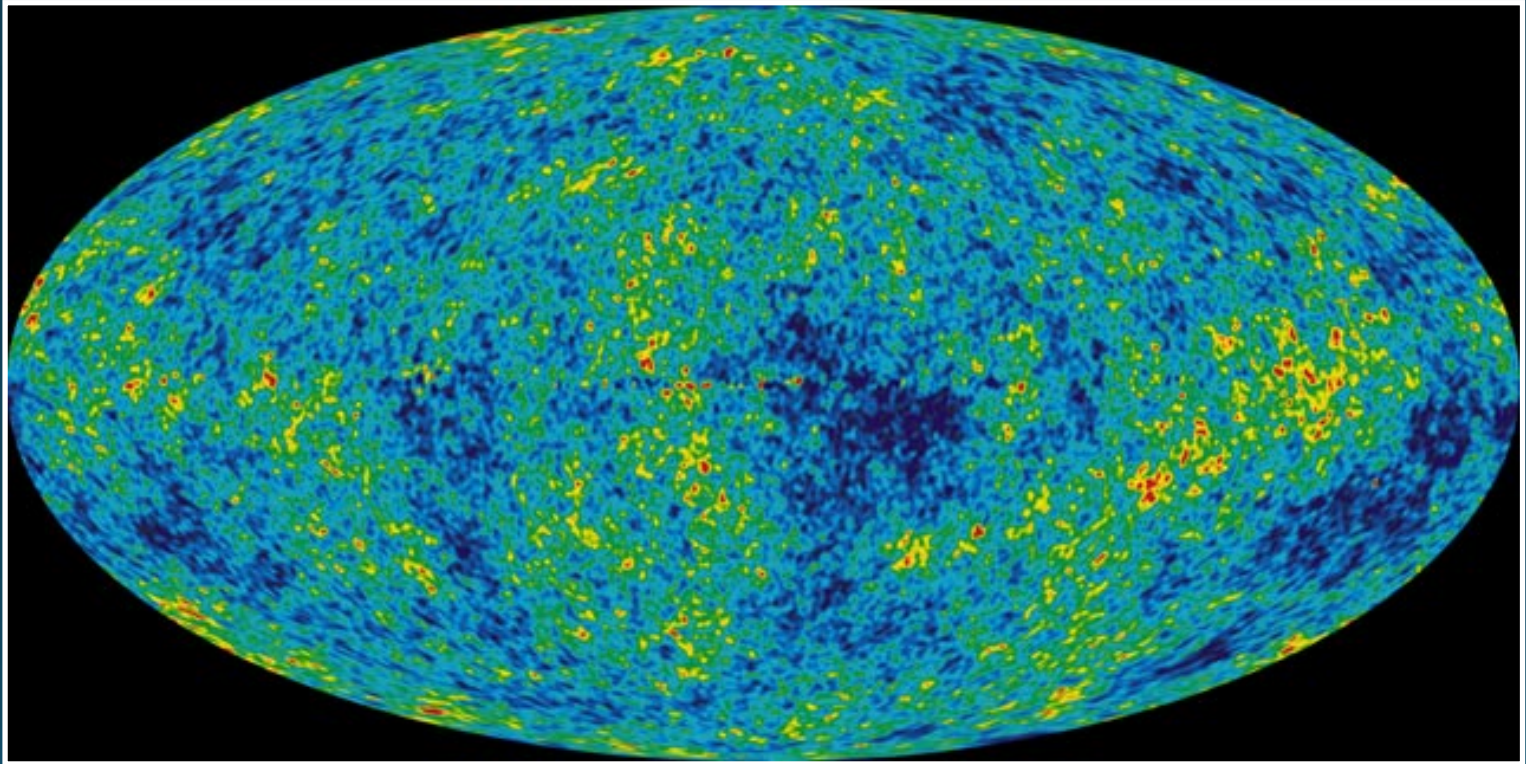
The temperature of the plasma was about 3000 K  
when the CMBR was emitted.

Cosmic expansion → Energy loss due to redshift →  $T \approx 2.73$  K now

Intermission: What is the relevance of this image for the CMBR lecture?



# Mollweide projection





# Support for the Big Bang model

- Expansion of the Universe
- The primordial abundances of light elements
- The age consensus
- The CMBR

# The CMBR as support for the Big Bang model I

- Existence of the CMBR :
  - Richard Tolman (1934): Expanding Universe should be filled with thermal radiation from hot past
  - CMBR  $\approx$  "Afterglow of the Big Bang"
  - Difficult to understand in Steady State-type cosmologies

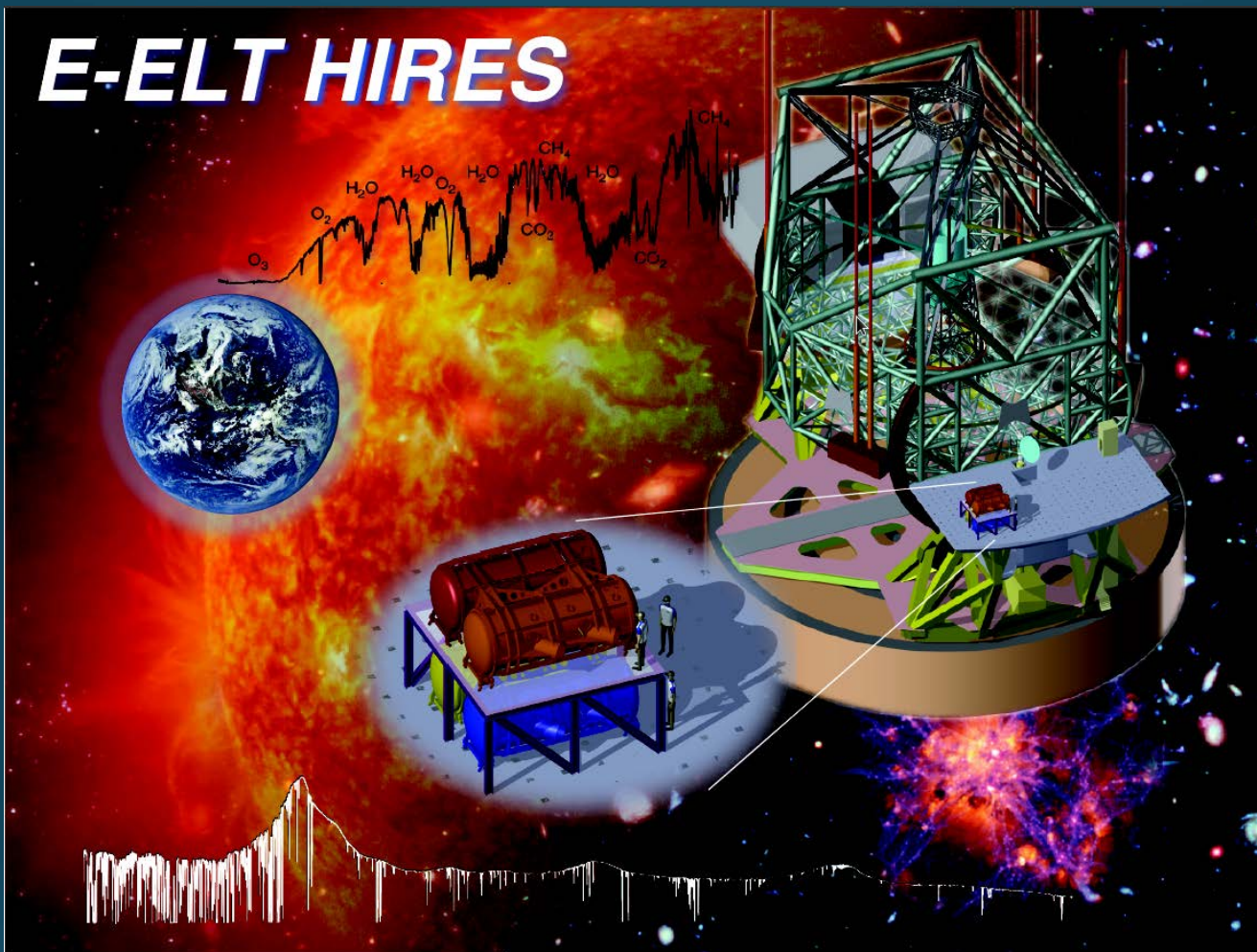
# The CMBR as support for the Big Bang model II

- Temperature of the CMBR:
  - $T_0 = 2.73$  K fits Big Bang model  
(but note: the a priori prediction was not this precise)
  - Standard Big bang model predicts:  $T(z) = (1+z) T_0$   
Confirmed by measurements up to  $z \approx 3$
- Small-scale temperature anisotropies:
  - Results in cosmological parameter values consistent with other methods

# Intermission: What do the acronyms mean?



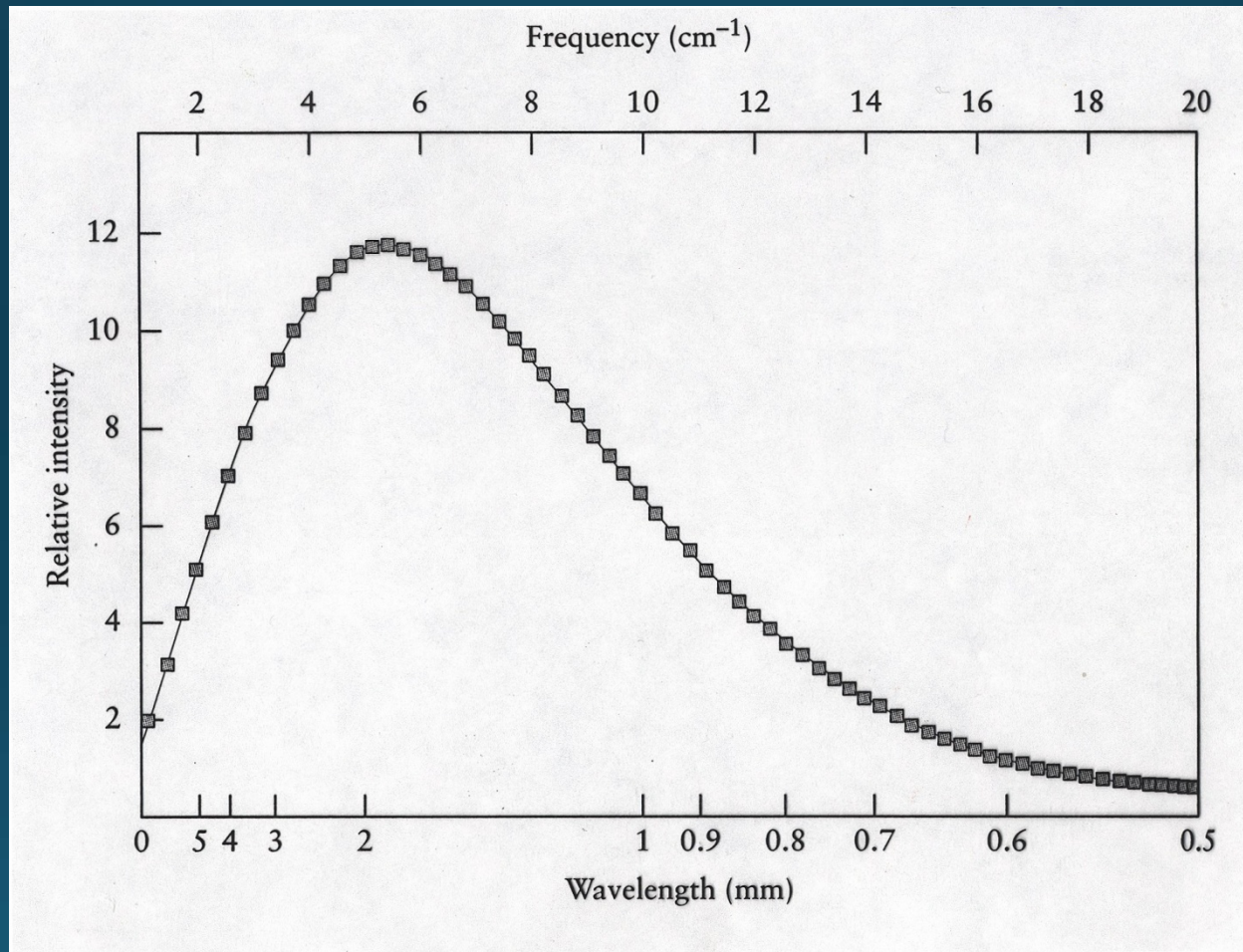




Uppsala is deeply involved in the development of the HIRES instrument, which will allow unprecedented tests of the  $T(z) = (1+z) T_0$  relation. HIRES will also look for variation in fundamental constants of nature, signatures of first stars, biosignatures in exoplanet atmospheres etc.

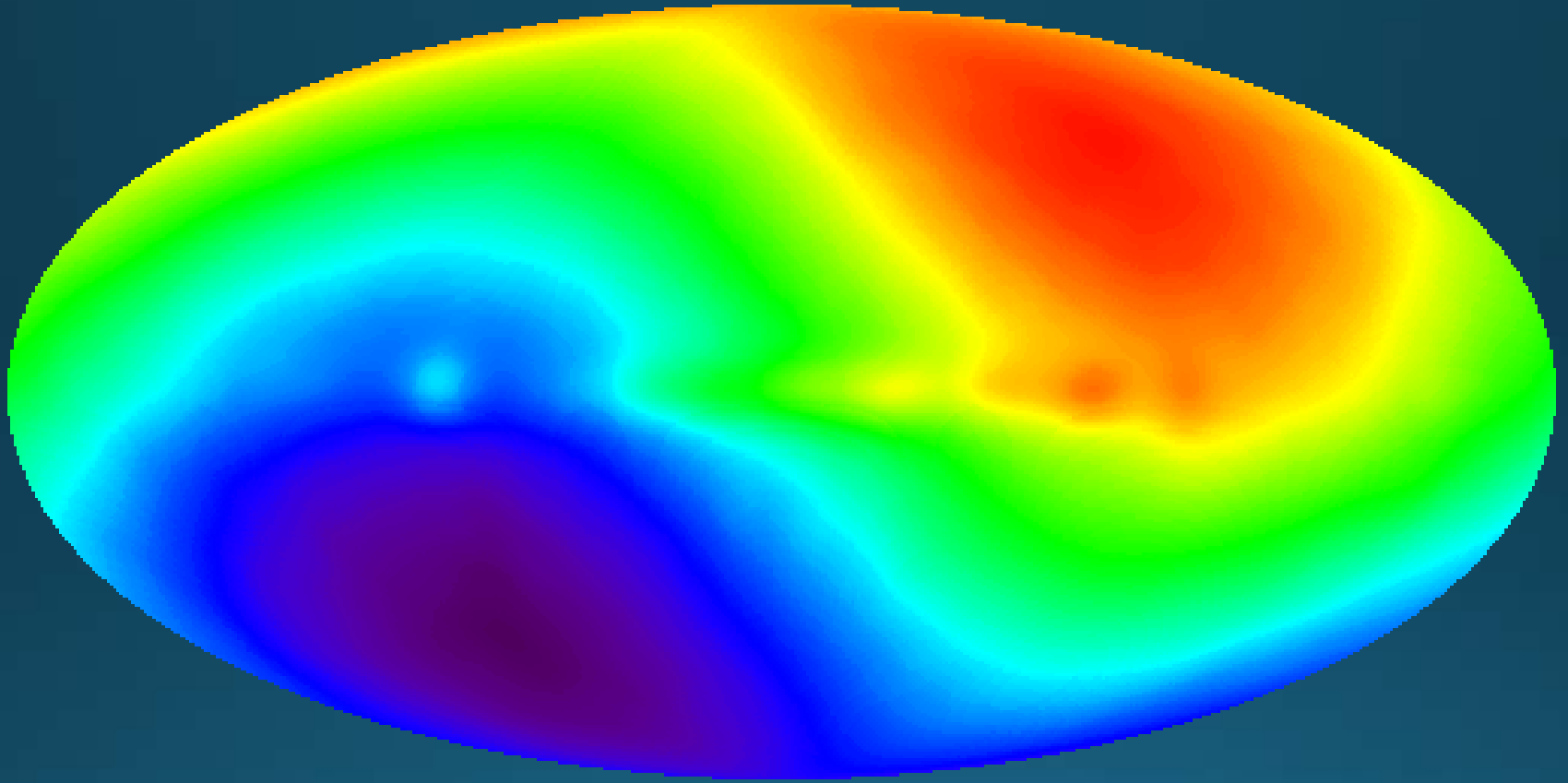


# Properties of the CMBR I: Spectral shape and temperature



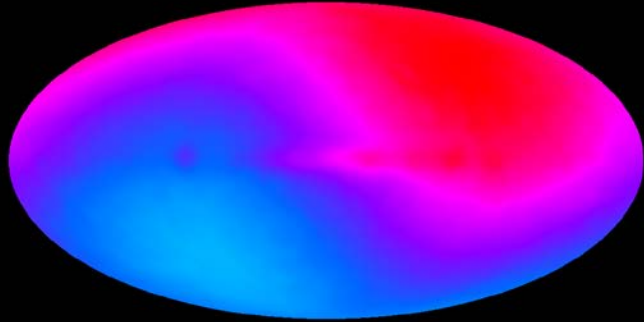
Temperature average over all directions:  $\langle T \rangle \approx 2.73\text{K}$

# Properties of the CMBR II: The Dipole Anisotropy

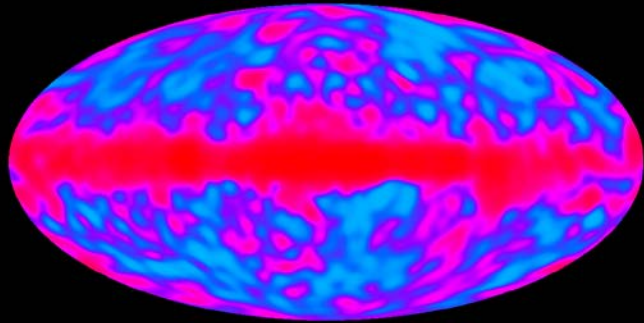


Doppler shift due to our movement (dominated by the motion of the Sun around the Milky Way and of the Local Group towards Hydra) relative to the CMBR

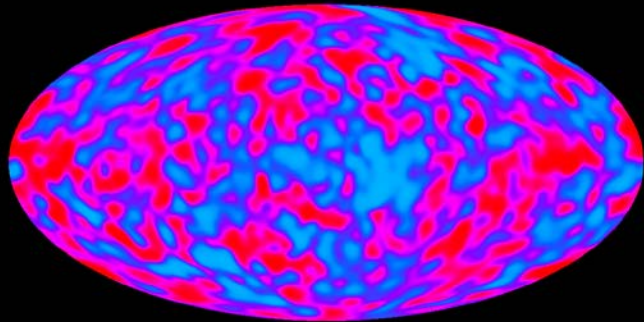
# Properties of the CMBR III: Small-scale temperature fluctuations



Overall CMBR, including Doppler dipole



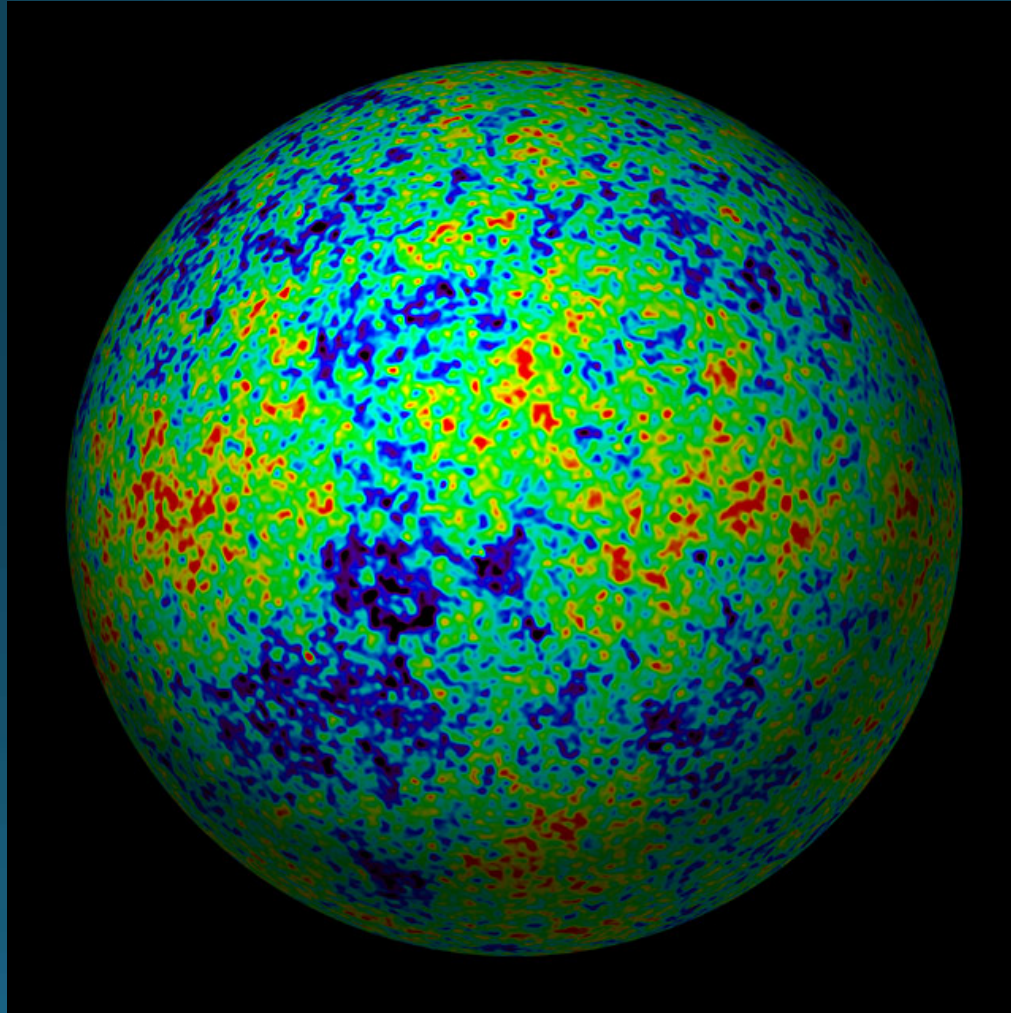
CMBR with dipole subtracted

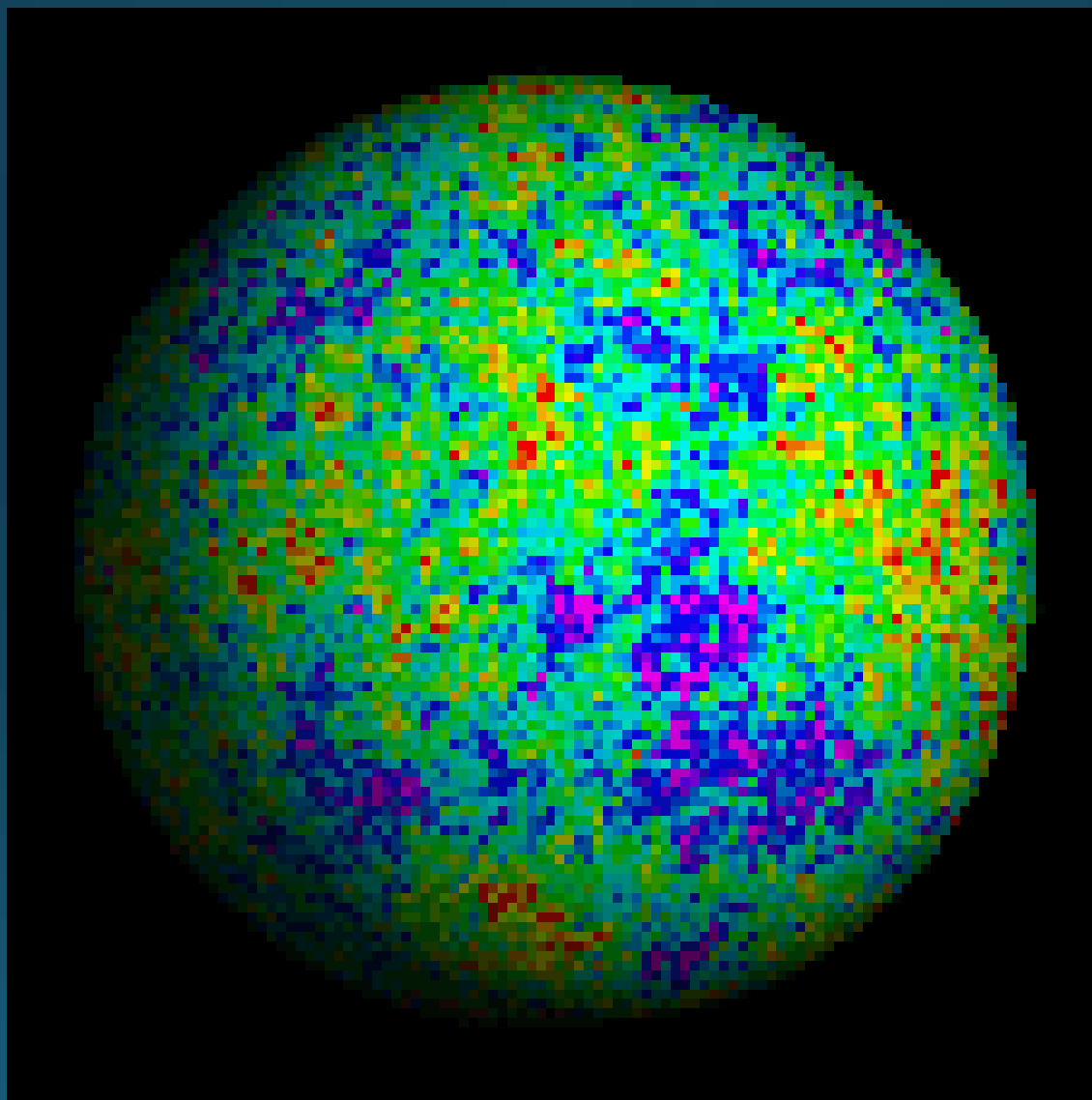


CMBR with Milky Way and nearby  
structure subtracted → Small-scale  
temperature fluctuations (RMS  $10^{-5}$  K)

Very important for cosmological  
model fitting!

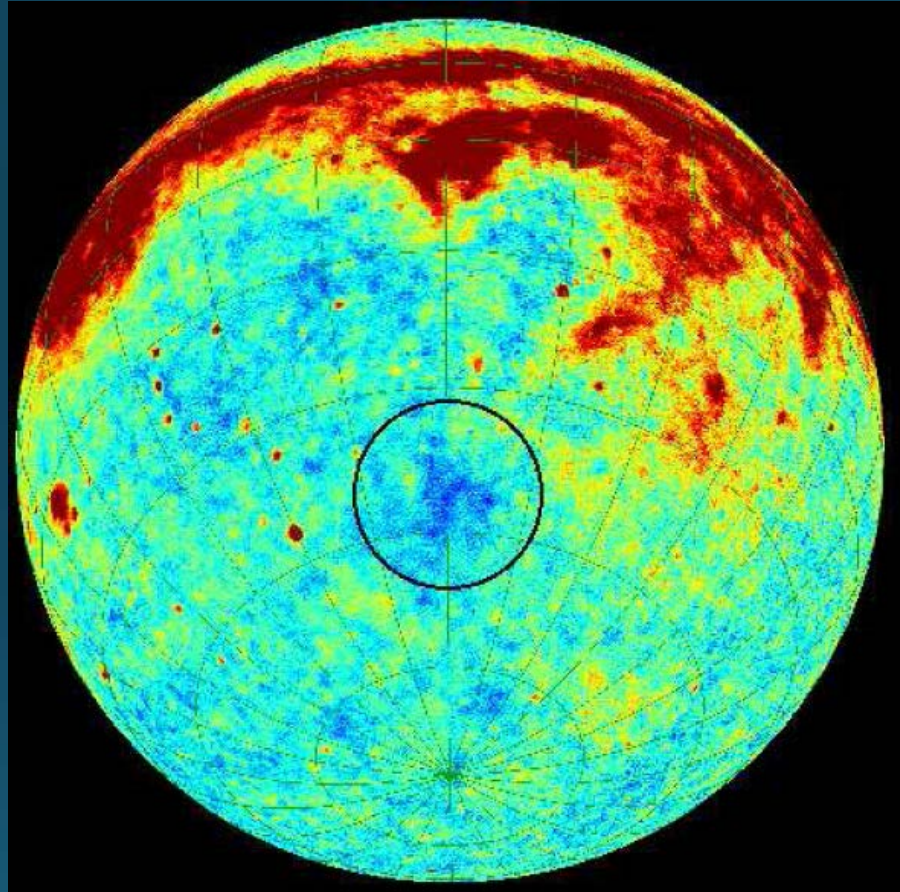
Intermission: What is this image showing?



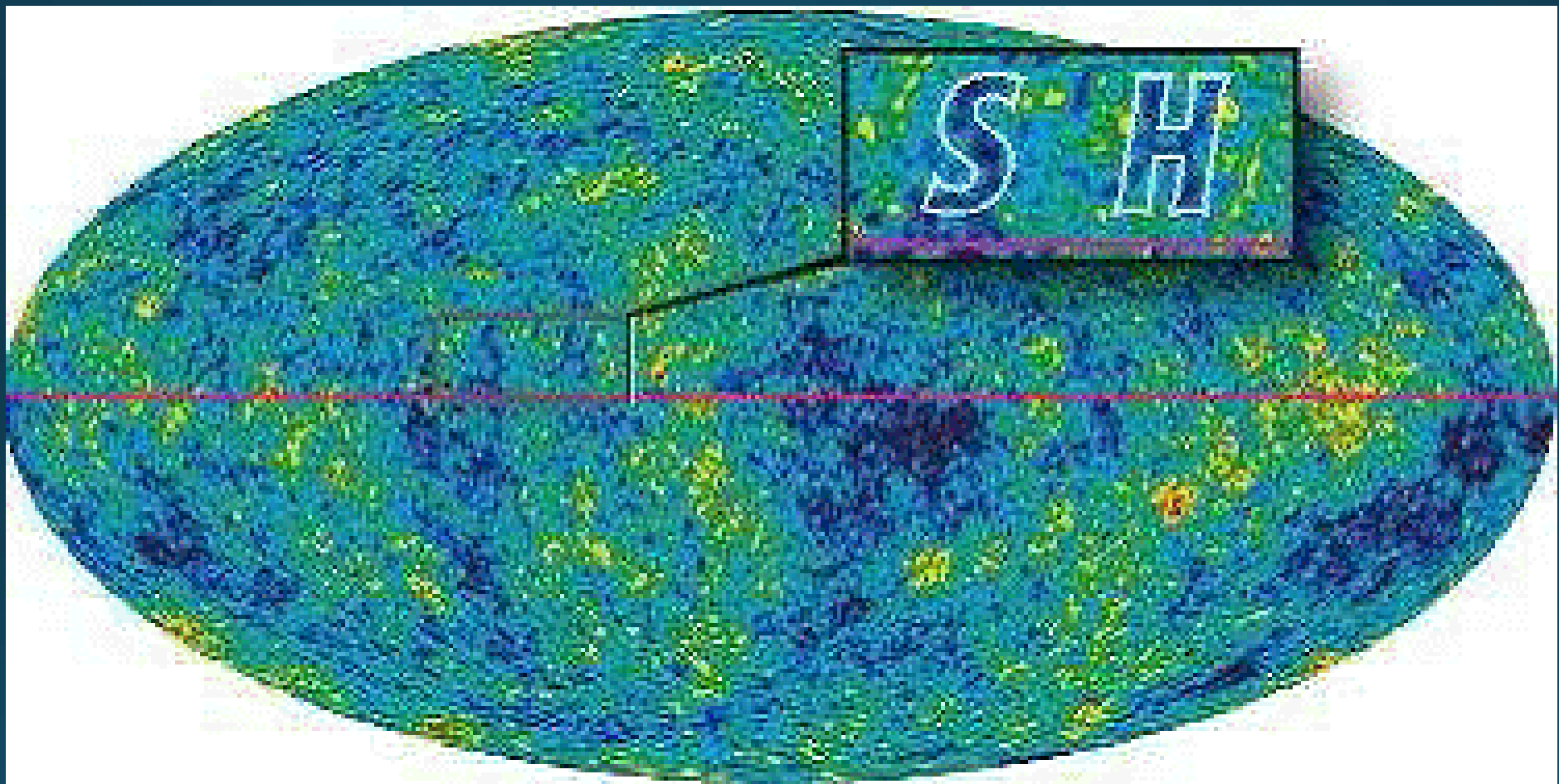


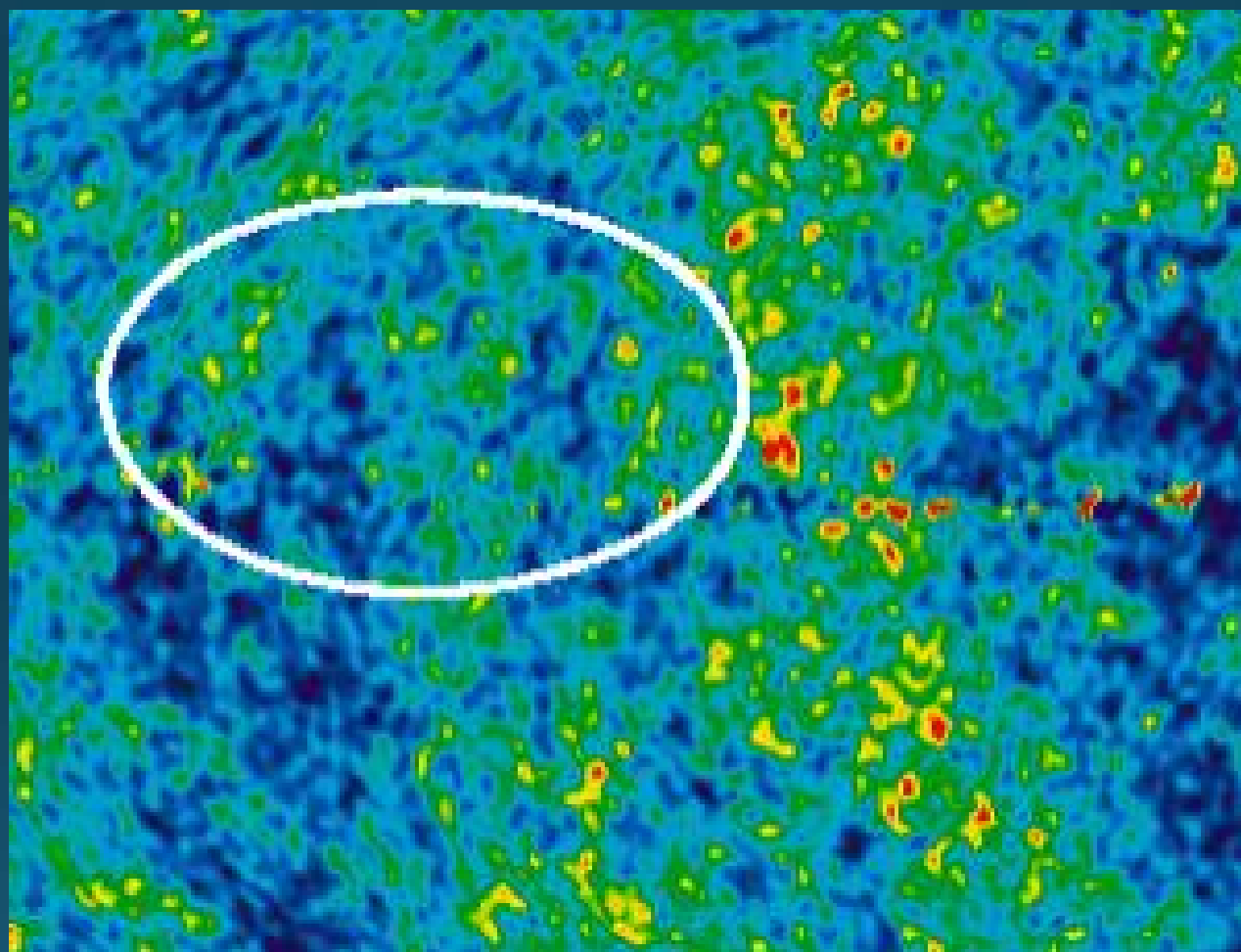


# Suggestion for literature exercise: Strange CMBR anisotropies



The "Axis of evil" & the cold spot:  
Signatures of non-standard cosmology?

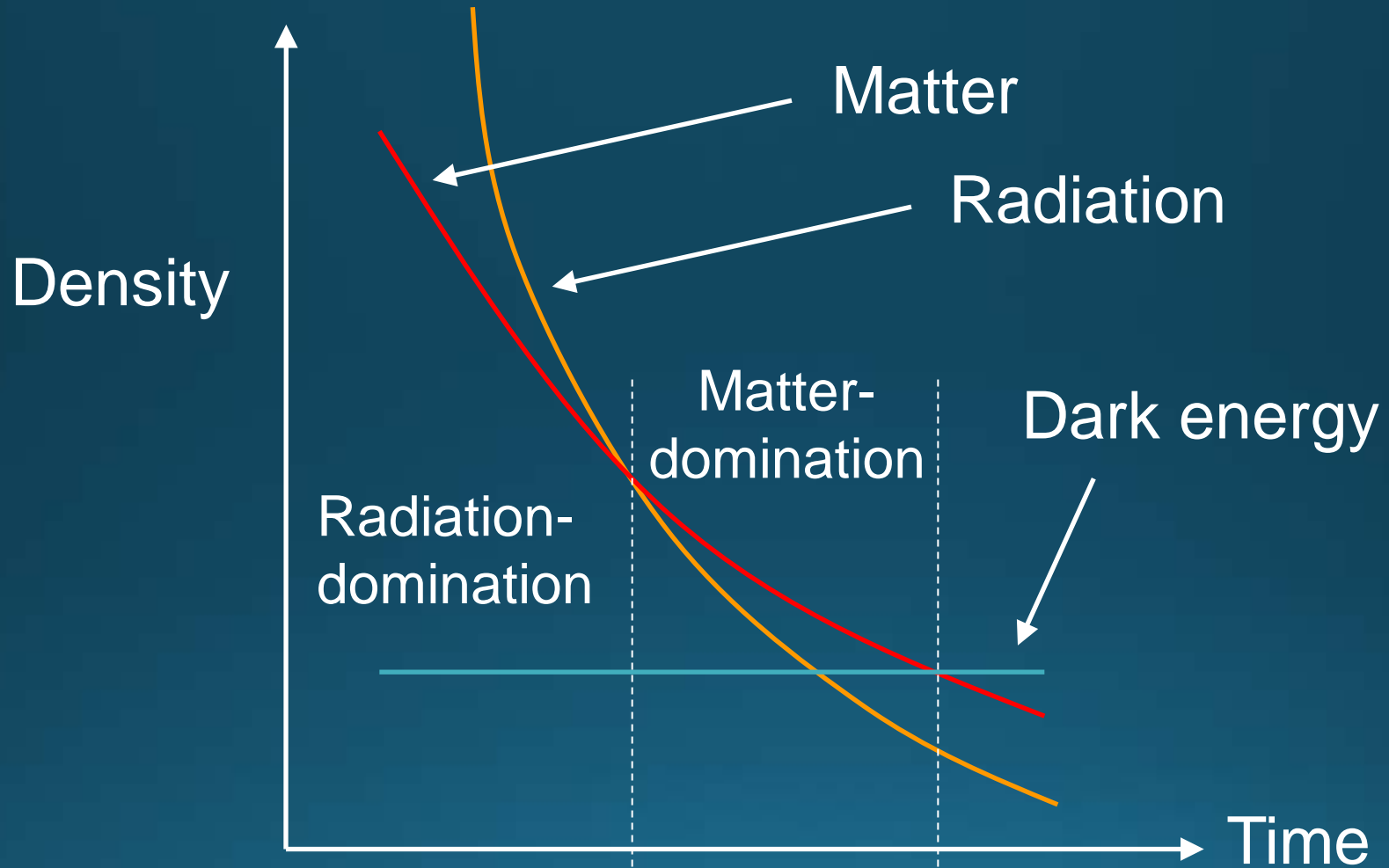




# Origin of the CMBR: Important Concepts

- Radiation-matter equality
- Photon decoupling
- Recombination
- Last scattering surface
- The Sachs-Wolfe effect
- Acoustic peaks

# Origin of the CMBR: Radiation-matter equality



Radiation-matter equality happened at  
 $z \approx 3570$ ,  $T \approx 9730$  K,  $t \approx 47\,000$  yrs



# Origin of the CMBR: Decoupling I

During radiation-domination, and during a short period in the matter-dominated era, photons kept the atoms ionized

Thomson scattering :

$$\gamma + e^- \rightarrow \gamma + e^-$$

Mean free path of photons:

$$\lambda = \frac{1}{n_e \sigma_e}$$

# Origin of the CMBR: Decoupling II

Rate of scattering interactions for this process:

$$\Gamma = \frac{c}{\lambda} = n_e \sigma_e c$$

This process freezes out when:

$$\Gamma < H$$

This leads to decoupling of photons from the baryonic plasma  
→ Baryons and photons evolve separately

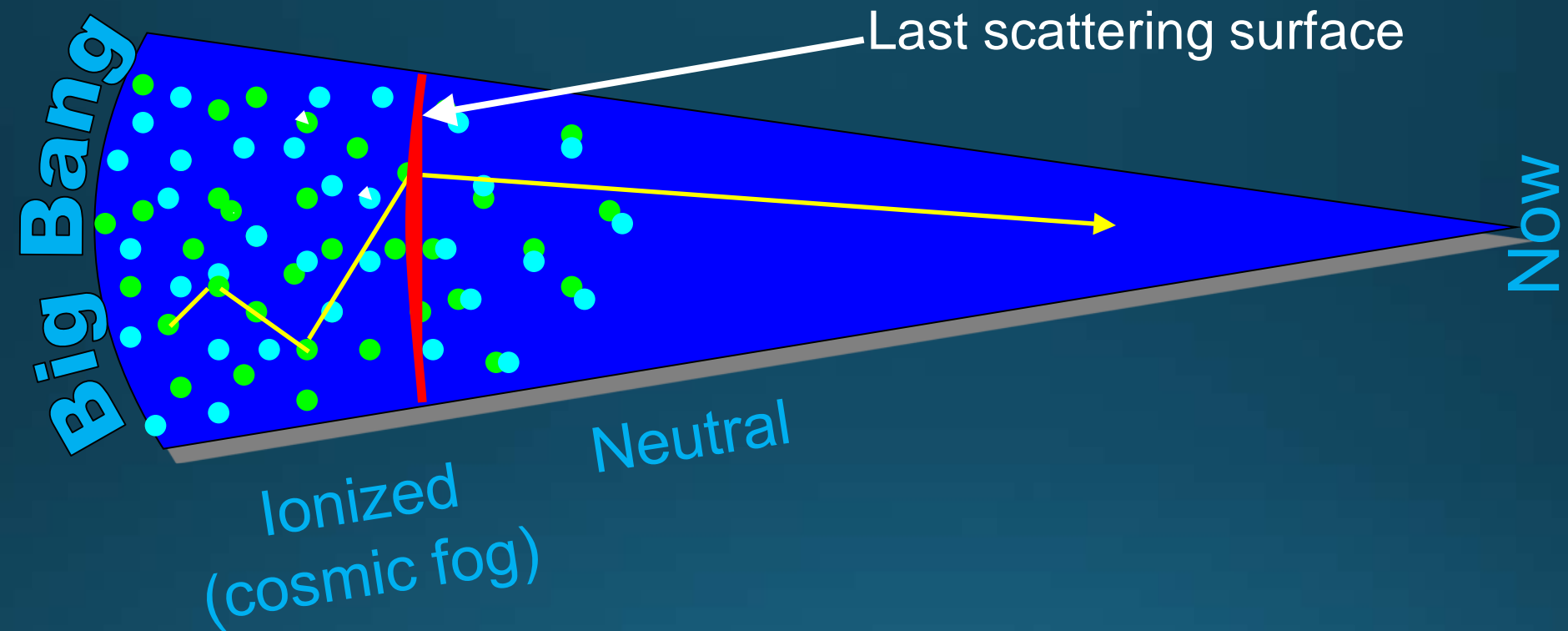
# Origin of the CMBR: Recombination

At around the same time, the expansion of the Universe causes the energy of the photons to drop below 13.6 eV  
→ Hydrogen starts (re)combining and the Universe goes from ionized to neutral, which speeds up the decoupling

Recombination happened at  
 $z \approx 1370$ ,  $T \approx 3740$  K,  $t \approx 240\,000$  yrs

Photon decoupling happened at  
 $z \approx 1100$ ,  $T \approx 3000$  K,  $t \approx 350\,000$  yrs

# Origin of the CMBR: Last Scattering Surface



CMBR photons reach us from a fog-like 'wall'.  
This last scattering surface is located at  
 $z \approx 1100$ ,  $T \approx 3000$  K,  $t \approx 350\,000$  yrs

# Intermission: Wait... What?

Statements that get confusing when combined out of context:

- Plasma (ionized gas) is non-transparent
- The Universe was non-transparent prior to decoupling ( $t \sim 380\,000$  yr) because it was ionized until then
- The Universe was reionized at an age of 300 Myr - 1 Gyr (likely due to first galaxies)
- The CMBR photons from the decoupling era has reached us without scattering



# Origin of the CMBR:

## Small-scale temperature fluctuations

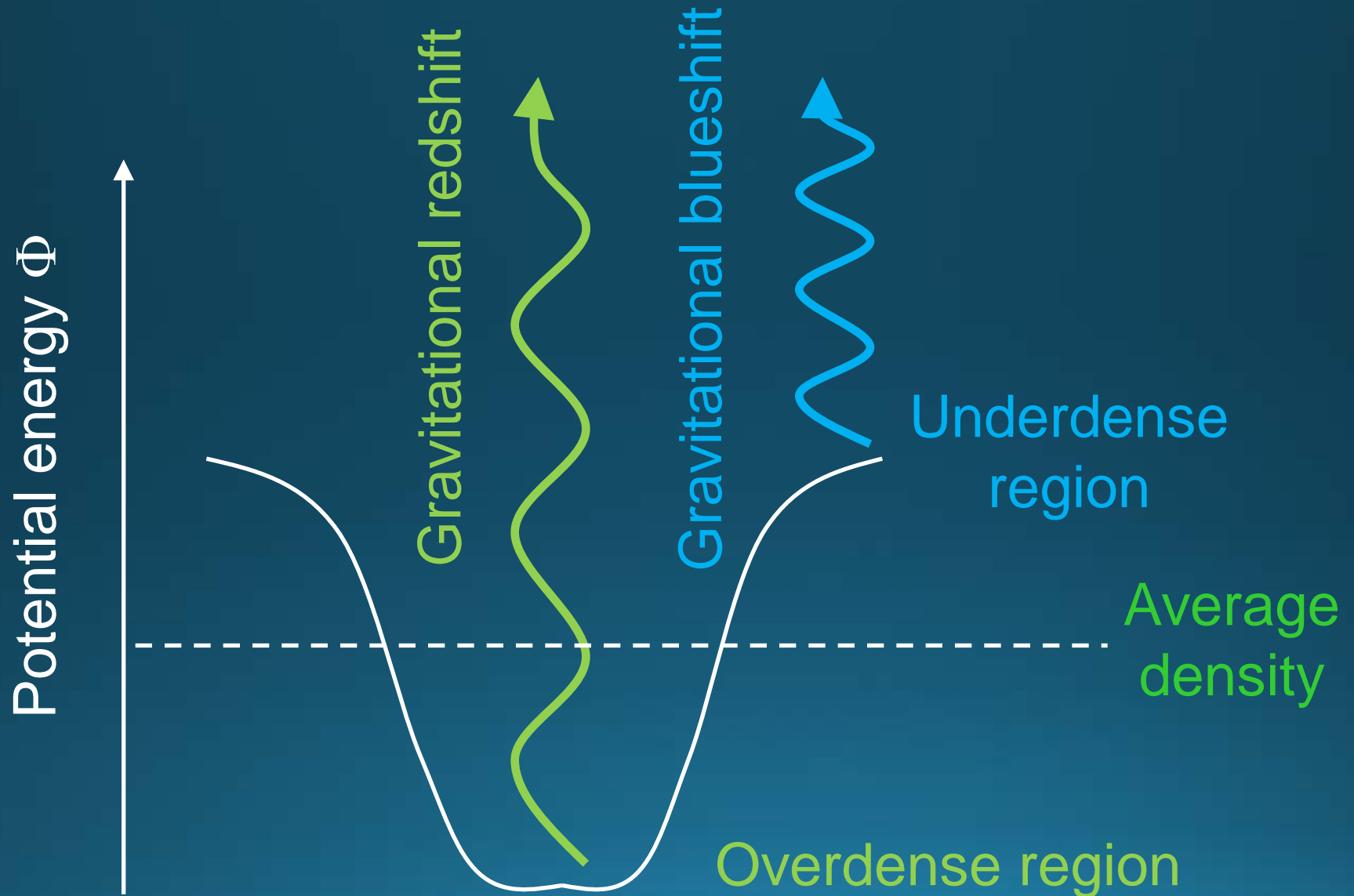
Density fluctuations present at the time of last scattering are evident as spatial temperature fluctuations in the CMBR

$$\text{Recall: } \theta = \frac{l}{d_A}$$

In the benchmark model, the horizon distance at  $z_{\text{CMBR}}$  corresponds to  $\theta_H \approx 1^\circ$

- On scales  $\theta > \theta_H$ : Primordial CDM density fluctuations
- On scales  $\theta < \theta_H$ : Acoustic oscillations in the photon-baryon fluid

# The Sachs-Wolfe effect



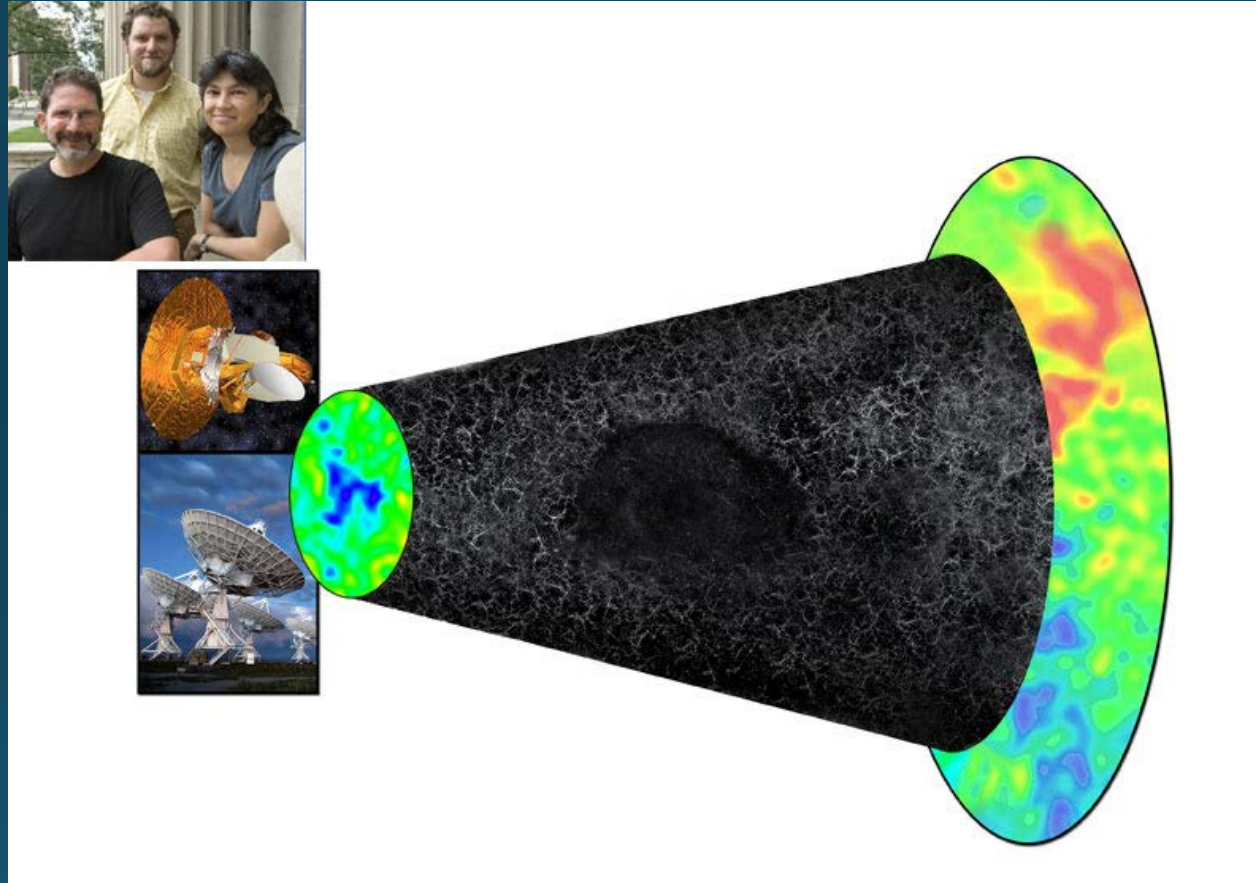
# The late/integrated Sachs-Wolfe effect (or Rees-Sciama effect)

The gravitational red/blueshift of CMBR photons due to structure along the line of sight towards the last scattering surface.

Static potential well  $\rightarrow$  Blueshift climbing in, redshift climbing out (no net effect)

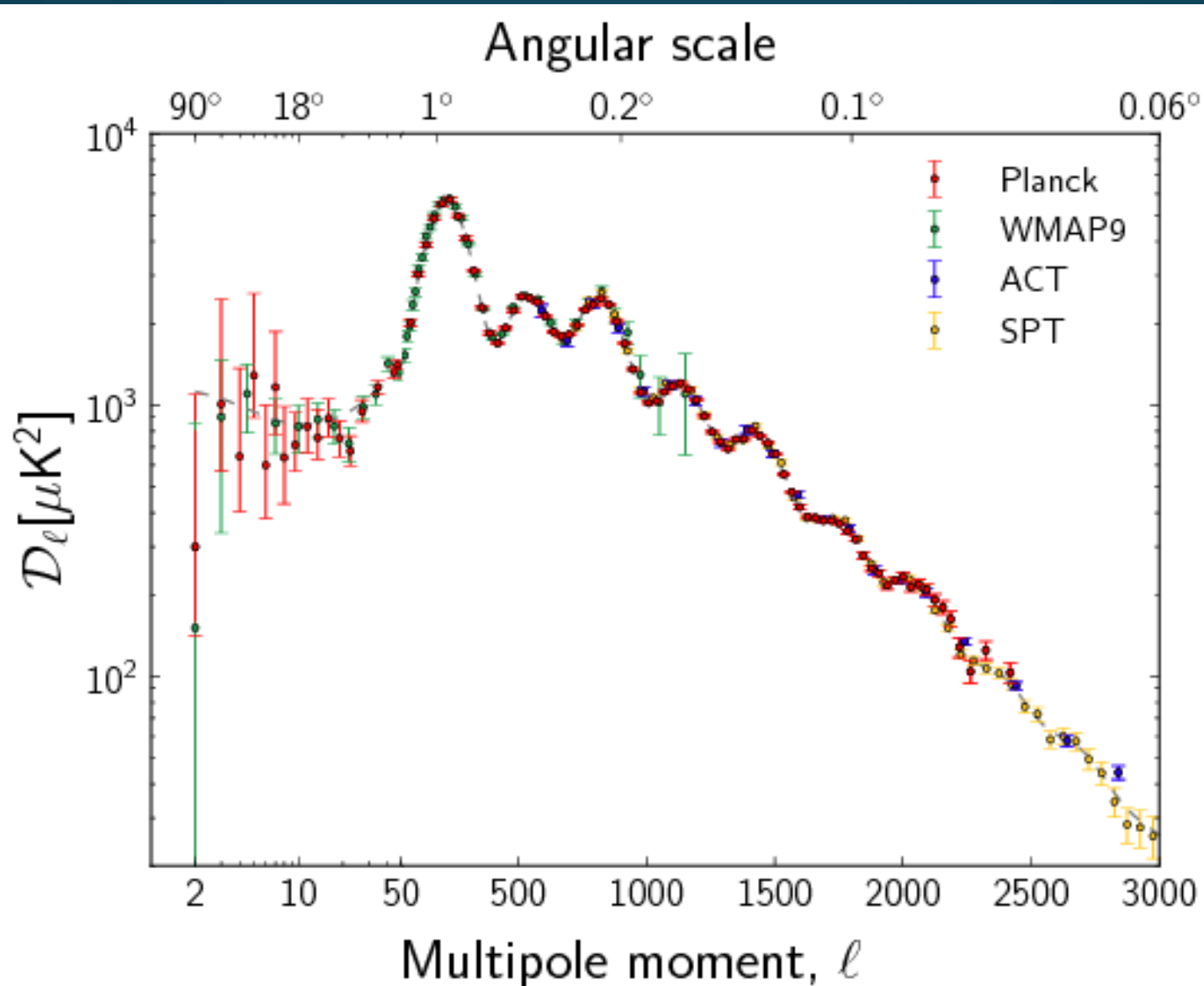
But net redshifts/blueshifts will happen if the potential well gets shallower/deeper while crossing!

# The late/integrated Sachs-Wolfe effect (or Rees-Sciama effect)



Is a huge, expanding void along the line of sight the reason for the CMBR 'cold spot'?

# The Angular Power Spectrum I





# The Angular Power Spectrum II

When studying CMBR temperature fluctuations as a function of angular scale, one usually plots:

$$\Delta_T = \left( \frac{l(l+1)}{2\pi} C_l \right)^{1/2} \langle T \rangle$$

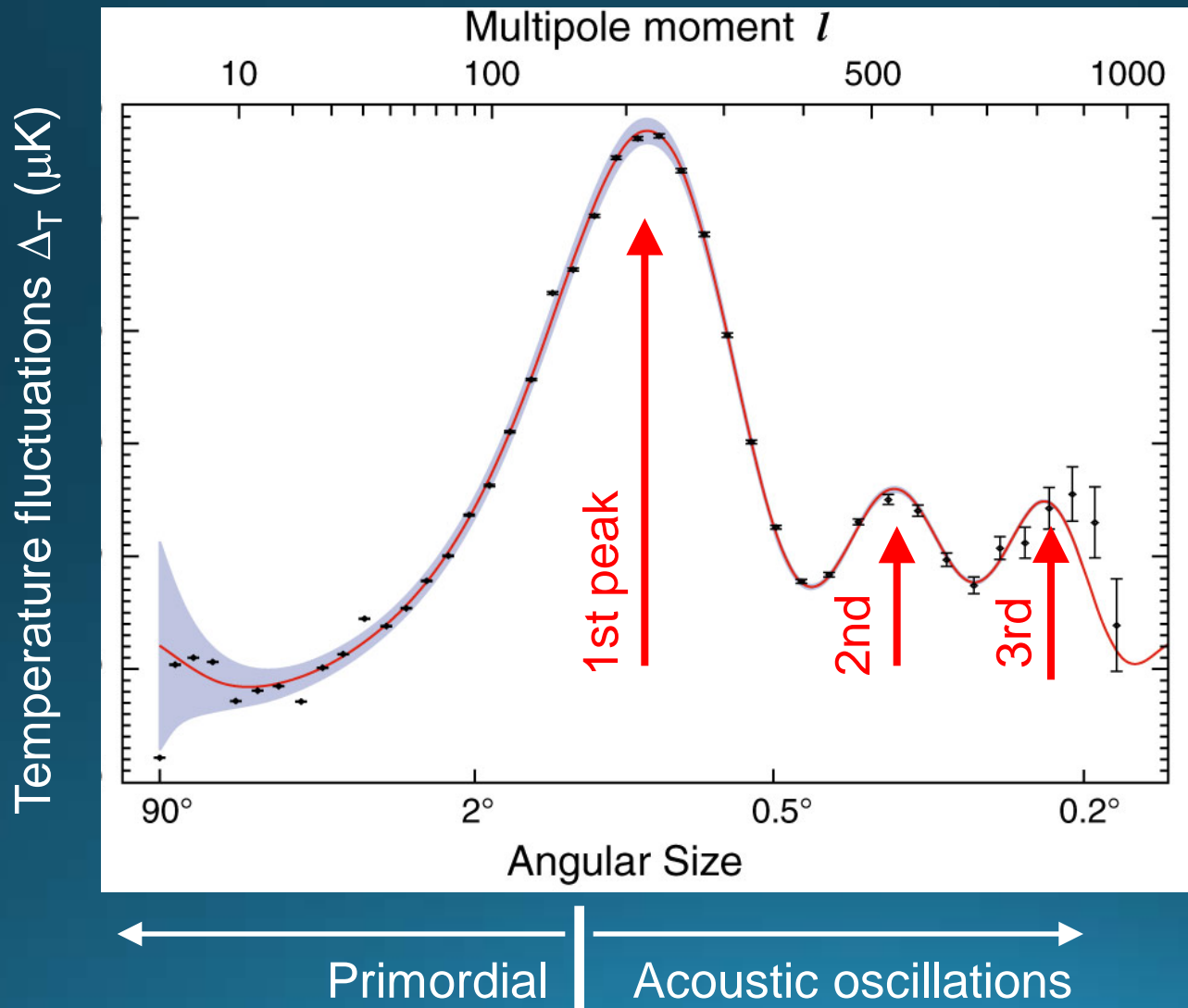
where :

$l$  is the multipole (note : high  $l$  means small  $\theta$ )

$C_l$  is the angular correlation function of  $\frac{\delta T}{T}$

# The Angular Power Spectrum II

WMAP 5-year data and model fit



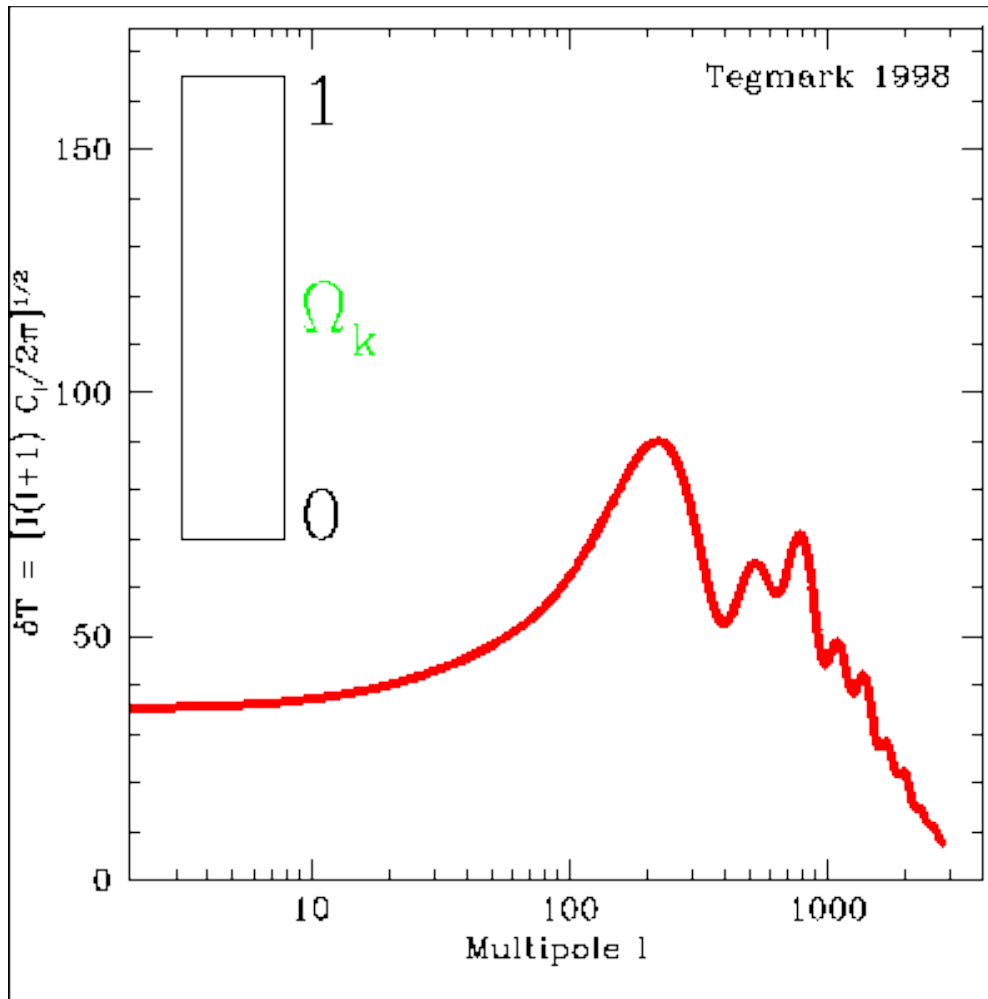
# "The sound of the Big Bang"

- The vibrations (sounds) that permeated the cosmos at the time when the CMBR was emitted can be turned into an audible sound if raised about 50 octaves
- Theoretical calculations can also predict how this sound changed in the first million years

John Cramer's homepage:

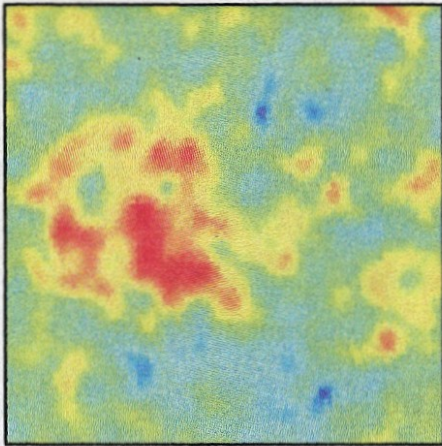
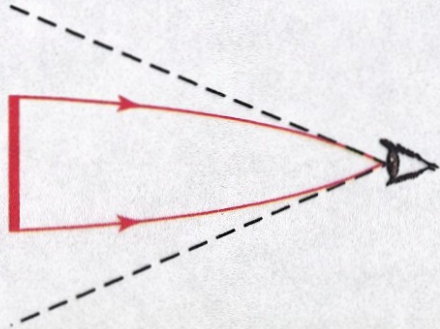
<http://faculty.washington.edu/jcramer/BBSound.html>

# Cosmological Information I

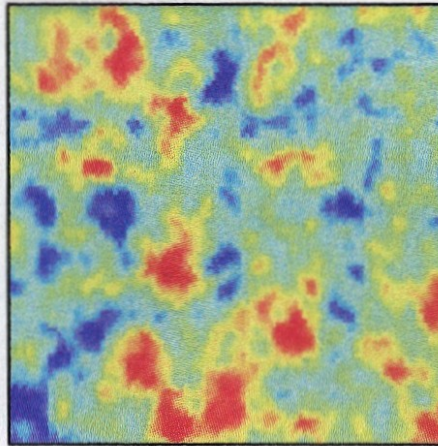
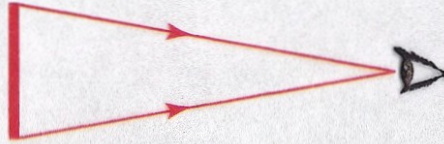


$$\Omega_k = 1 - (\Omega_M + \Omega_\Lambda) \Rightarrow$$
$$\Omega_k = 0 \Rightarrow \text{Flat}$$

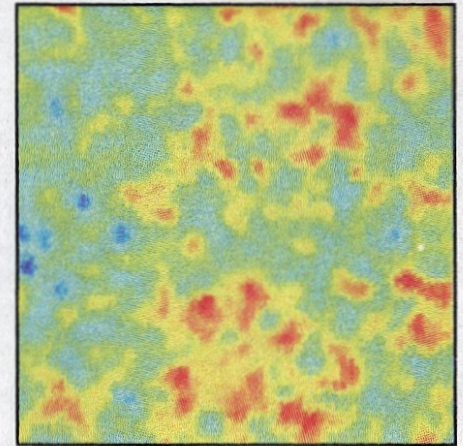
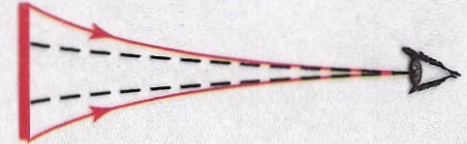
The positions of the CMBR peaks are very sensitive to the geometry. The observed positions indicate that our Universe is very close to flat!



**a** If universe is closed, "hot spots" appear larger than actual size



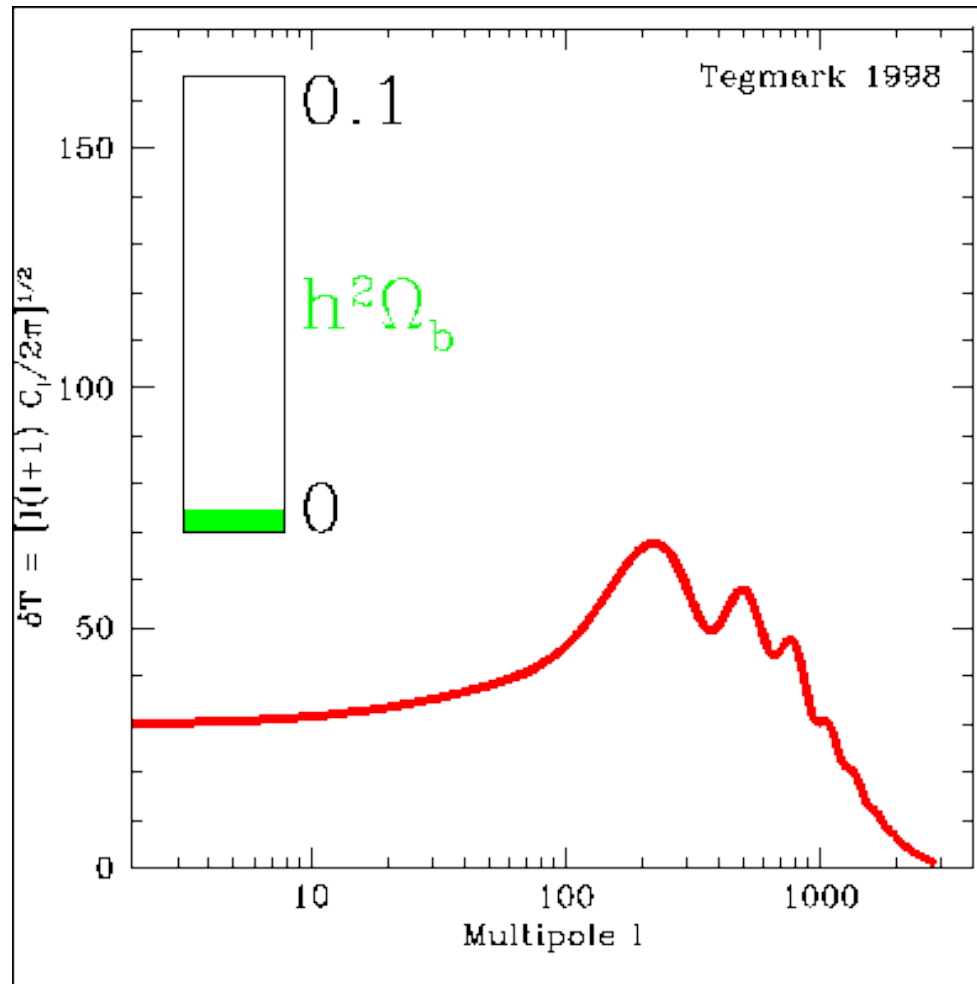
**b** If universe is flat, "hot spots" appear actual size



**c** If universe is open, "hot spots" appear smaller than actual size

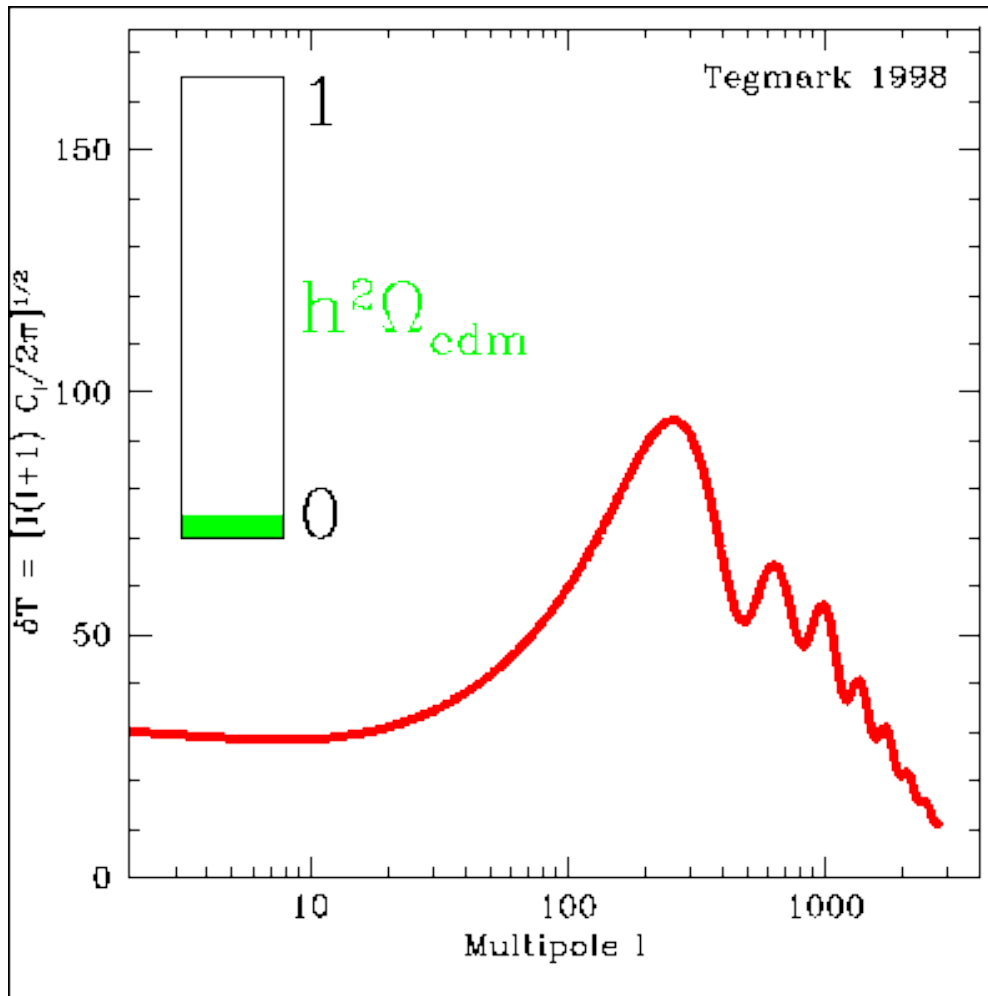


# Cosmological Information II



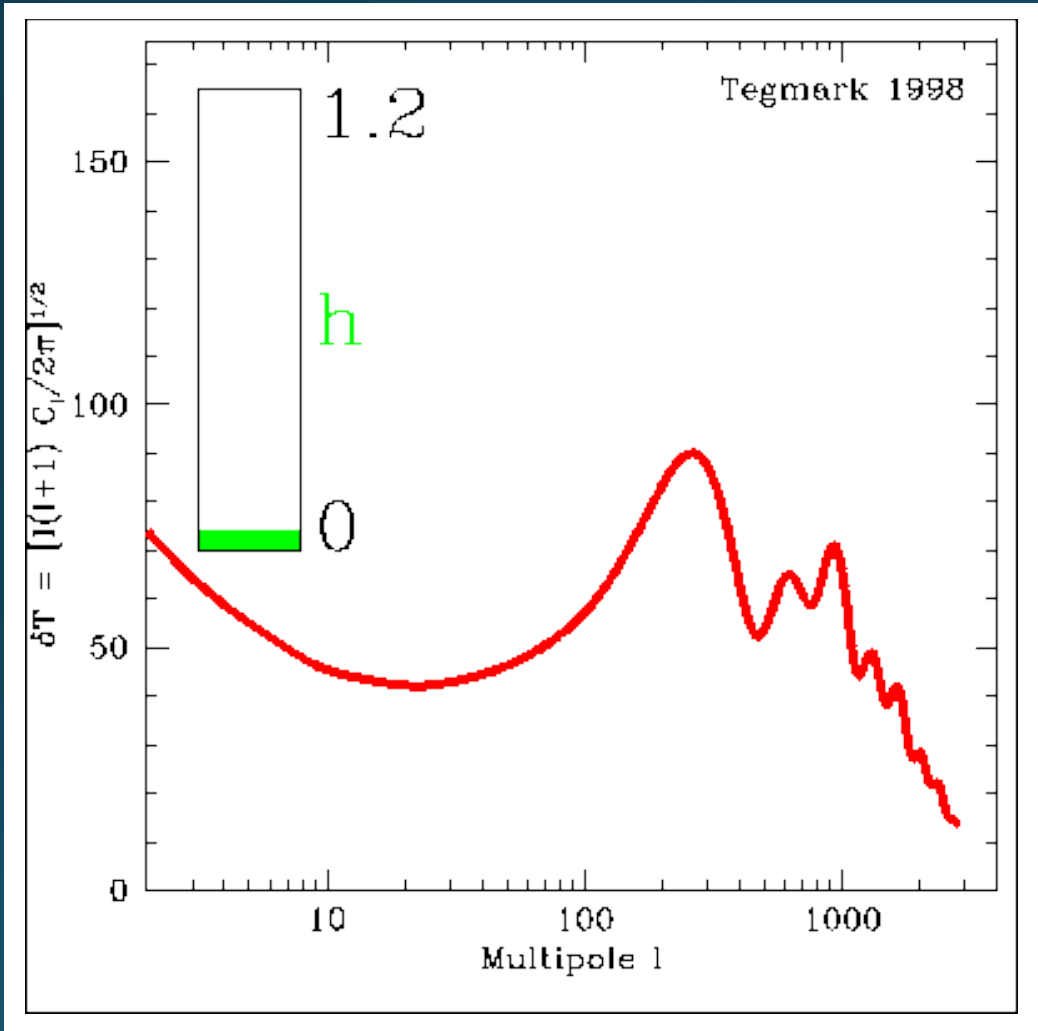
Mild degeneracy:  
The amplitude ratios of  
the first three peaks  
are sensitive  
to the baryon  
density

# Cosmological Information III



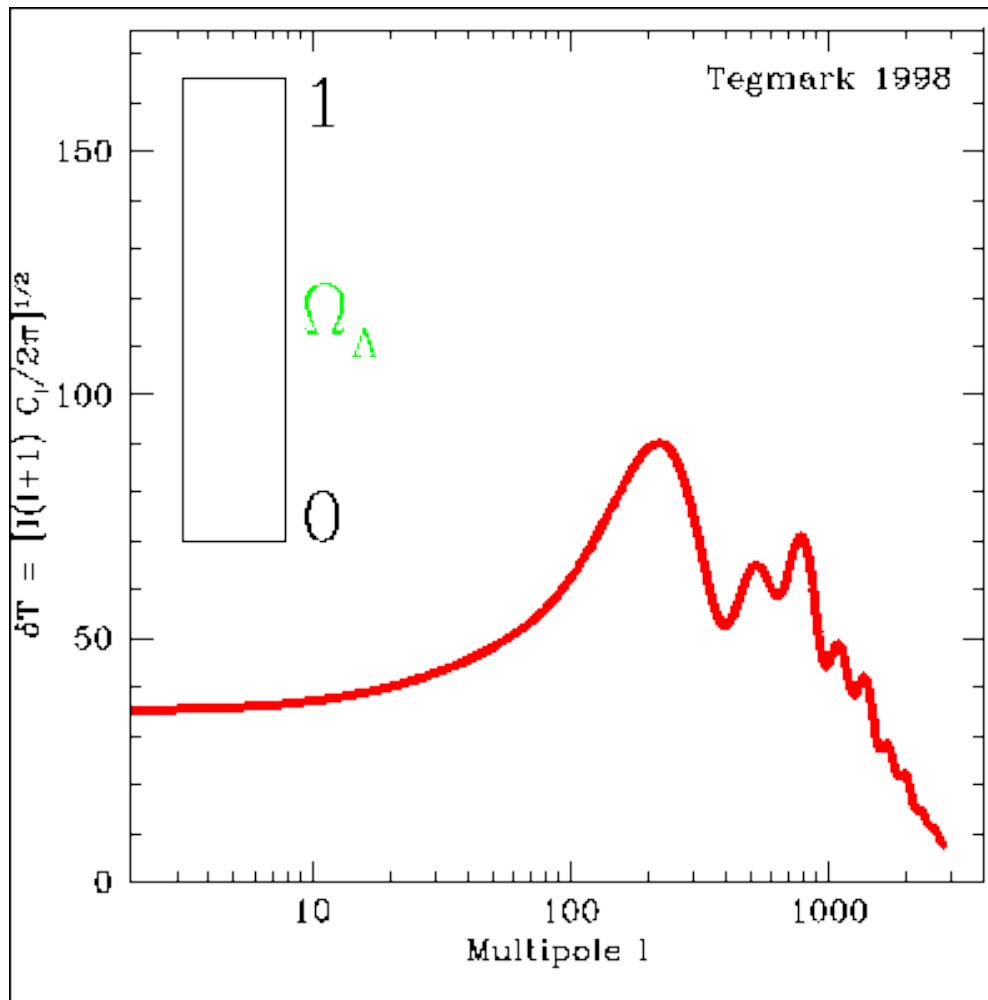
Mild degeneracy:  
The amplitude ratios of  
the first three peaks  
are also sensitive  
to the CDM  
density

# Cosmological Information IV



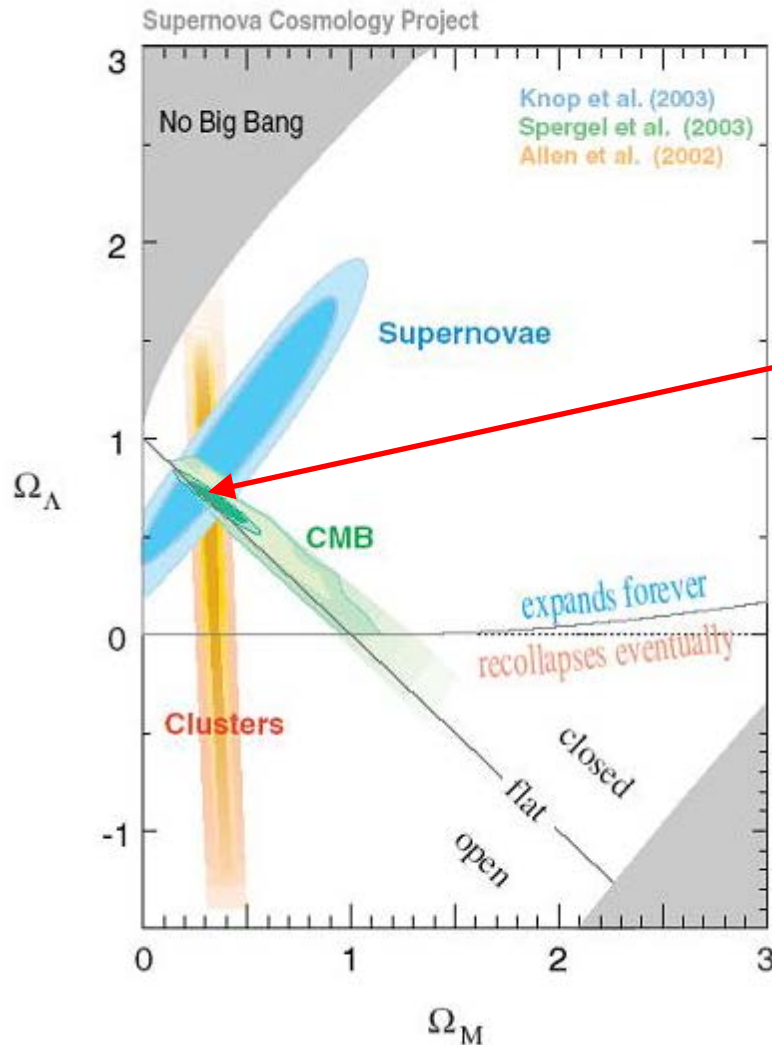
Example of strong degeneracy:  
Hubble constant and  $\Omega_\Lambda$  variations  
mimic each other  
(if other parameters are held fixed)

# Cosmological Information V



Example of strong degeneracy:  
Hubble constant and  $\Omega_\Lambda$  variations  
mimic each other  
(if other parameters are held fixed)

# Cosmological information VI



Benchmark model  
 $\Omega_M=0.3, \Omega_\Lambda=0.7$   
 $H_0=72 \text{ km s}^{-1} \text{ Mpc}^{-1}$