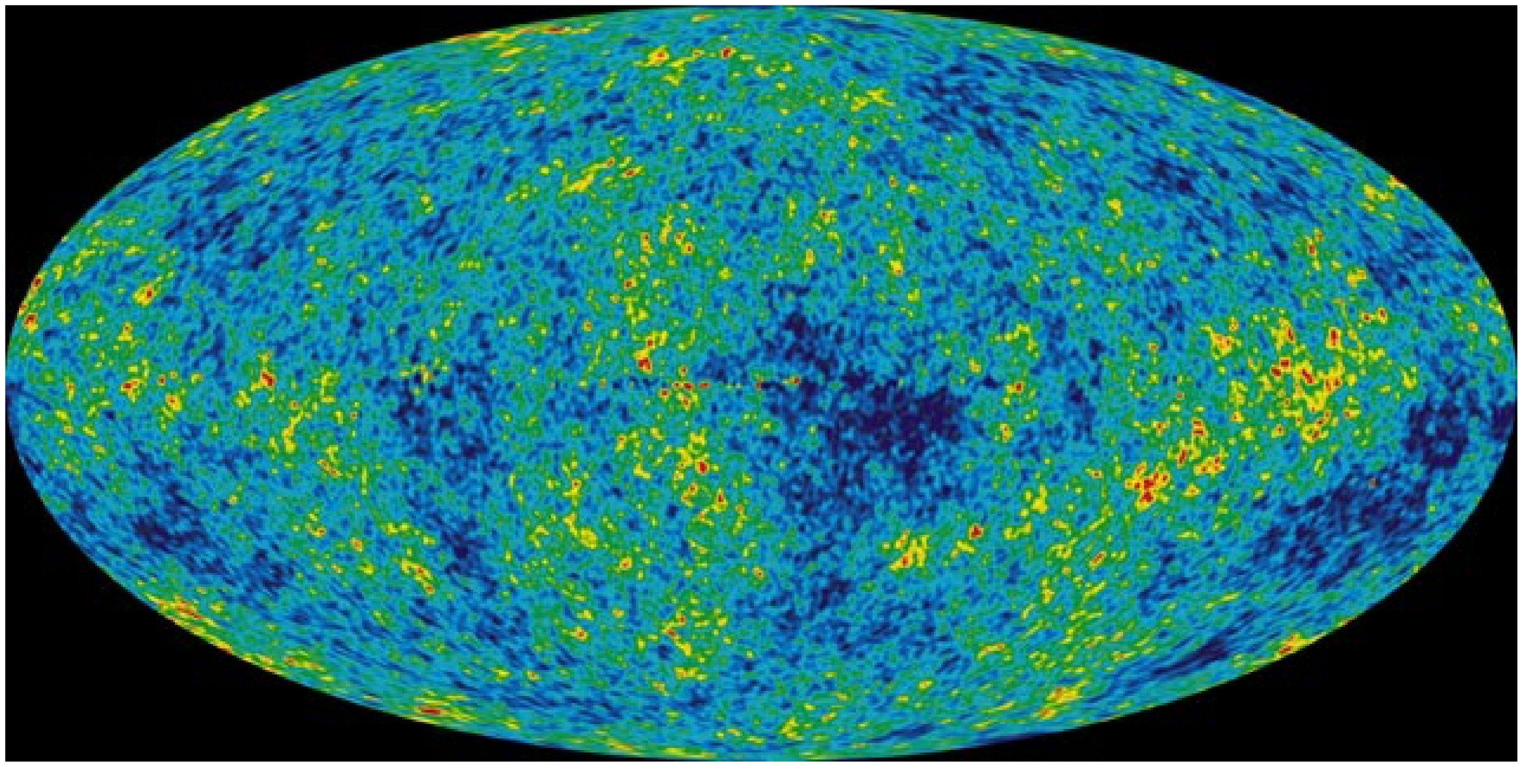
Cosmology 1FA209, 2017
Lecture 7:
Cosmic Microwave Background Radiation

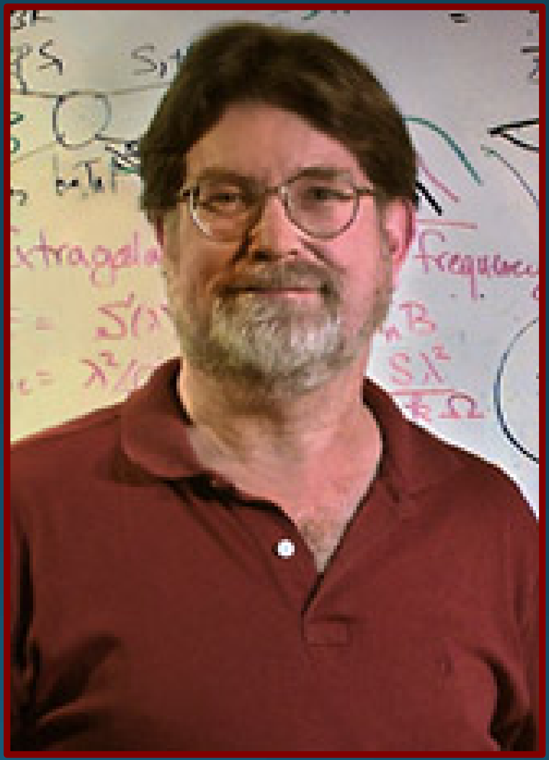


Outline

- 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 8 in Ryden

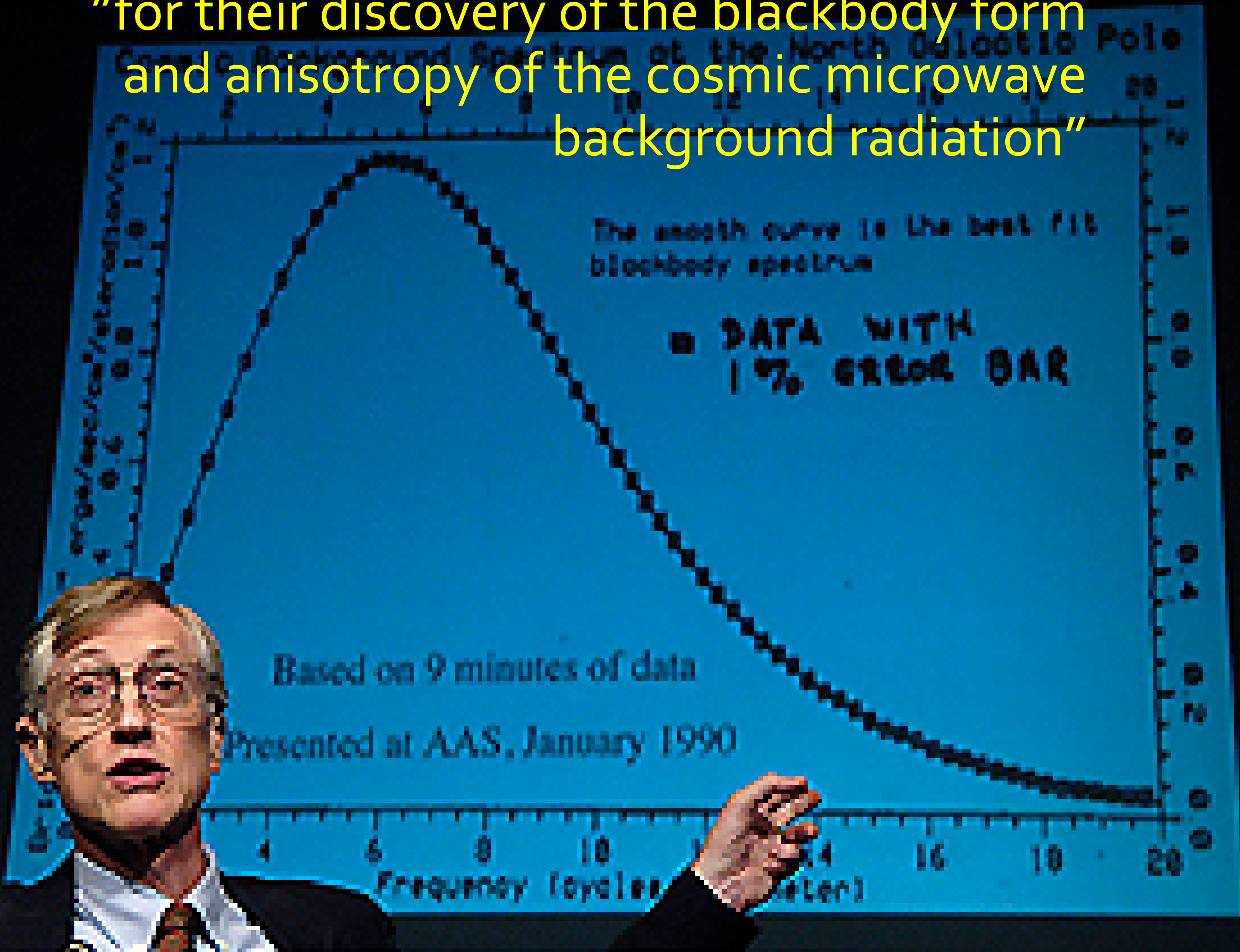
2006 Nobel prize in Physics



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

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

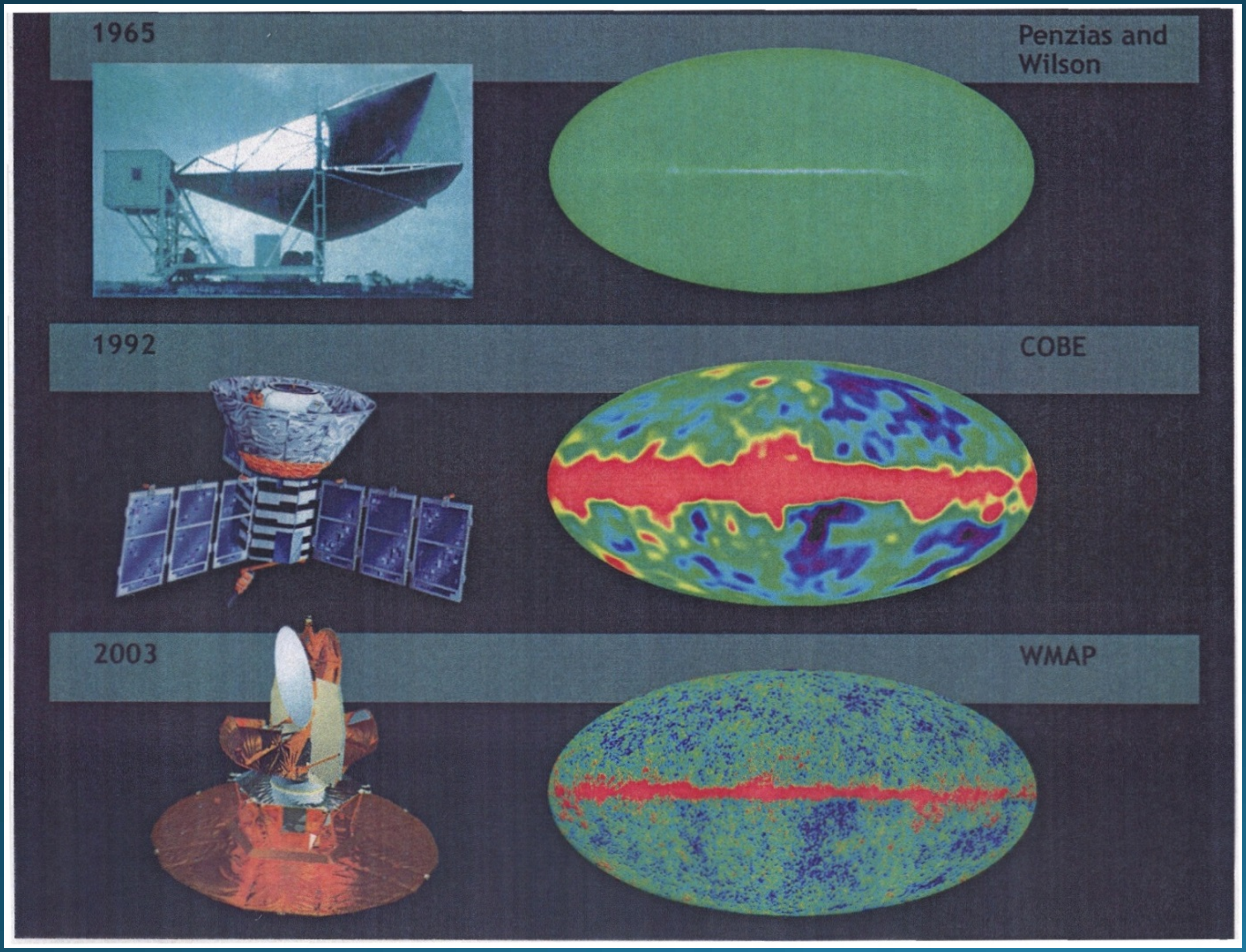
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



Cosmic Microwave Background Radiation (CMBR) - Quick Facts -

- Comes from all directions in the sky
- Black body spectrum with:
  - $T_0 \approx 2.73$ K
  - Peak wavelength ≈ 2 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



Nobel prize to
Smoot and Mather
for their work
with COBE

History of CMBR research II

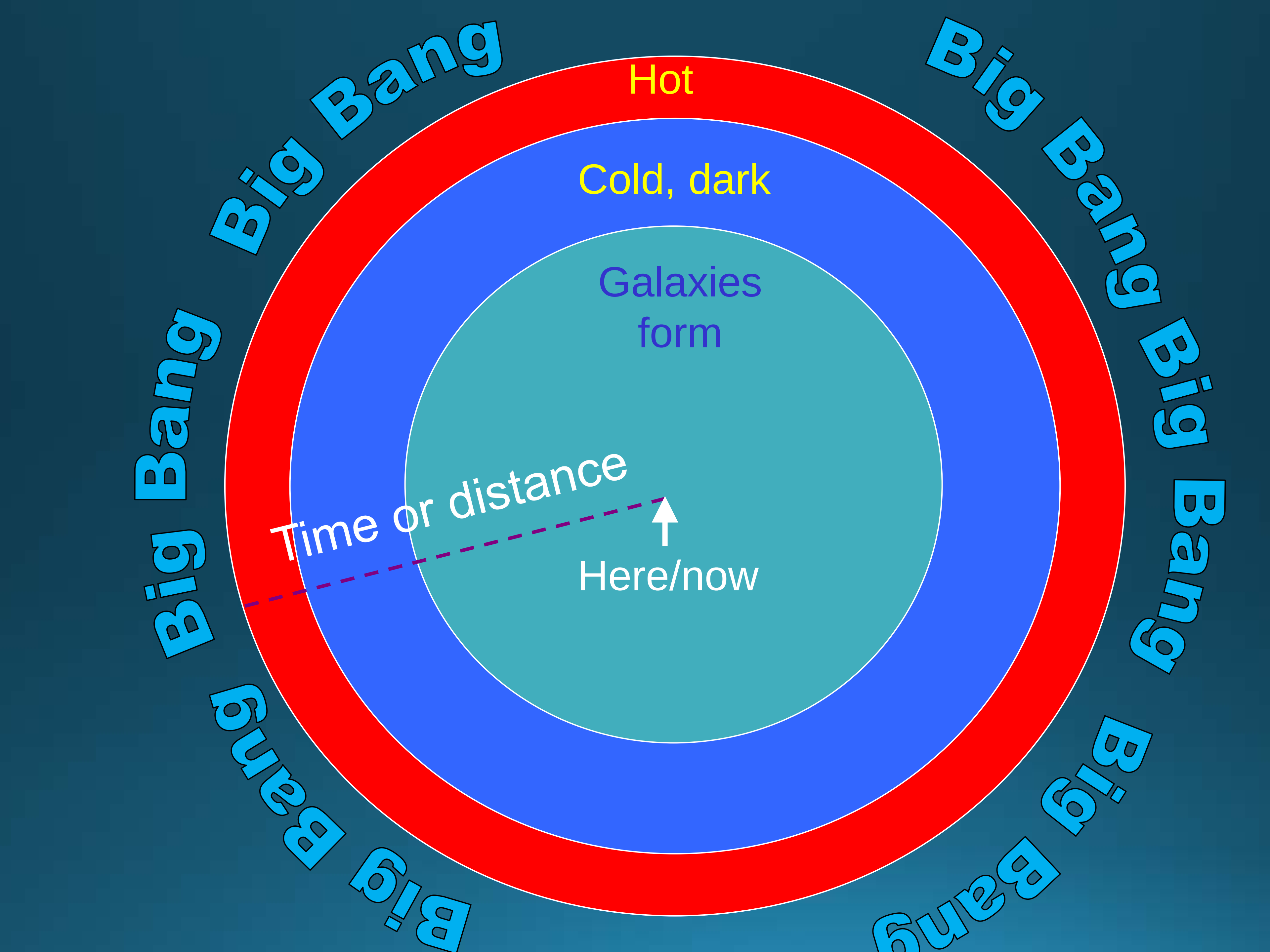
- 1934: First prediction of the existence of the CMBR
  - Tolman: Expanding Universe should be filled by thermal radiation from its hot past
- 1948: First prediction of the current CMBR temperature
  - Gamow, Alpher & Herman: $T_0 \approx 5$ K
- 1965: CMBR discovered by Wilson & Penzias
  - Temperature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

History of CMBR research III

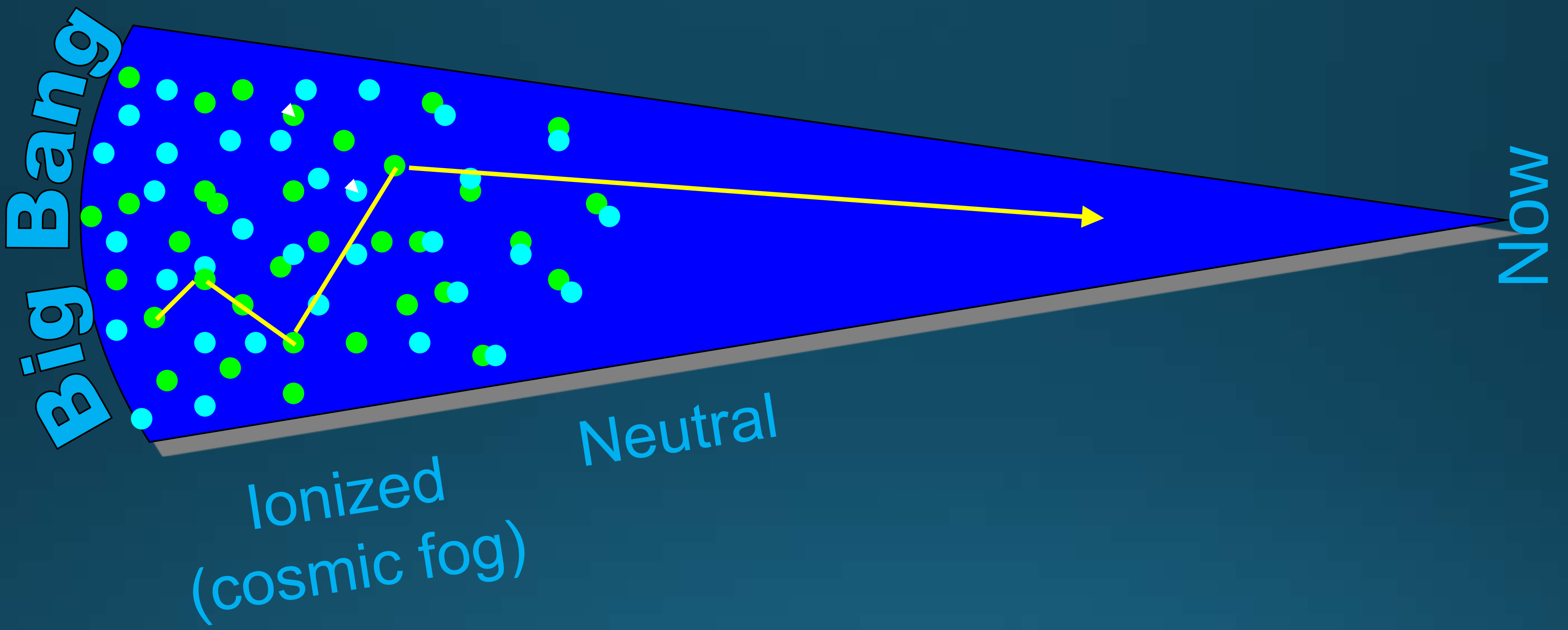
- 1992: COBE satellite
  - Close to perfect BB, with $T \approx 2.73$ K
  - Large-scale dipole
  - Small-scale temperature fluctuations (~10^{-5} K)
- Late 90s: MAXIMA & BOOMERanG balloons
  - Small-scale temperature and polarization variations
- 2001 - 2010: WMAP satellite
  - Full-sky maps of polarization 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 $\rightarrow$
  - Baryons ionized
  - Universe opaque to photons
  - Photon-baryon plasma
- Cosmic expansion $\rightarrow$
  - Universe neutral at $t \sim 240\,000$ yr
  - Universe transparent to photons


Hot
Cold, dark
Galaxies form
Time or distance
Here/now
Big Bang

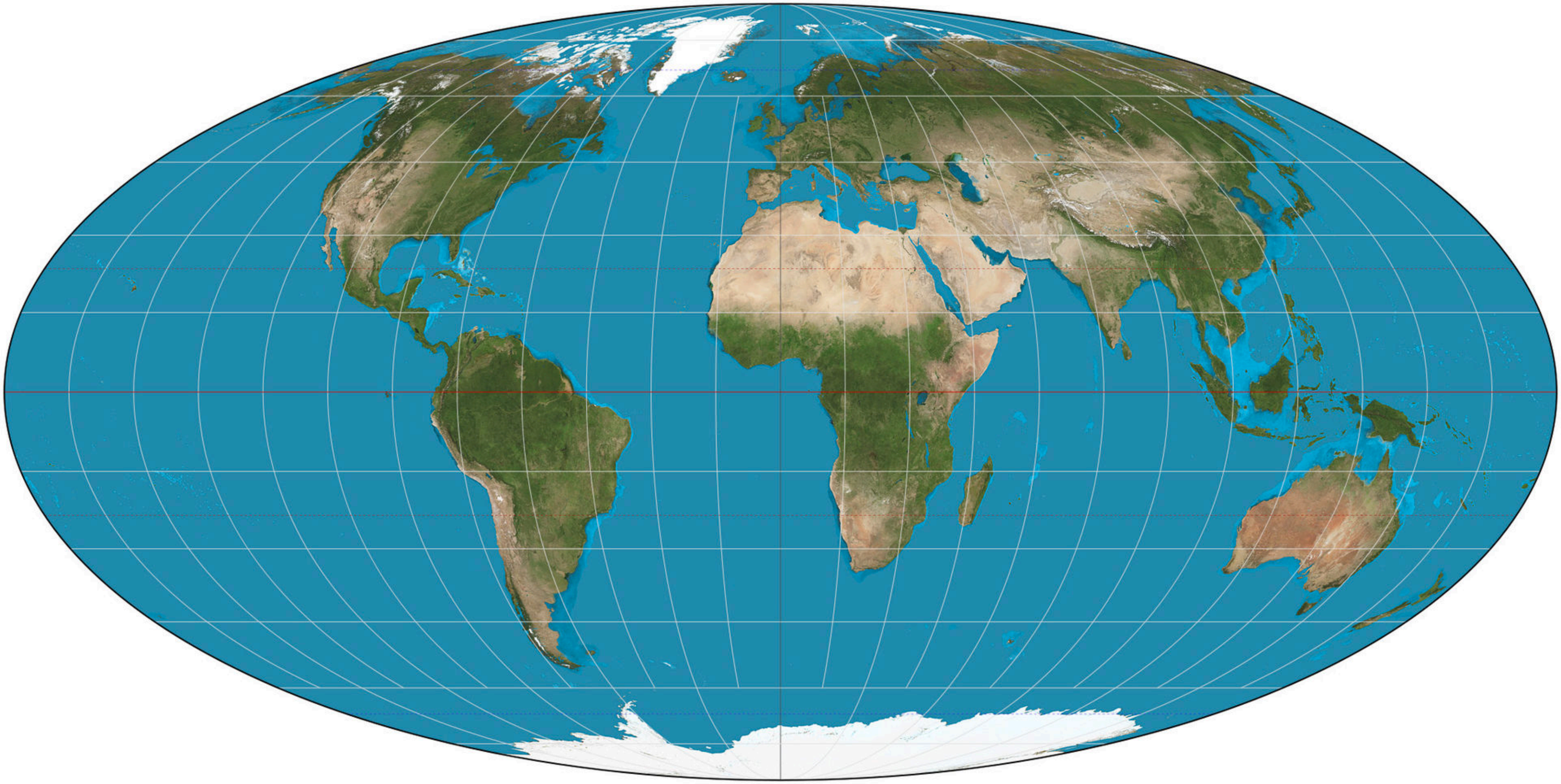
Photon trajectories from the Early Universe



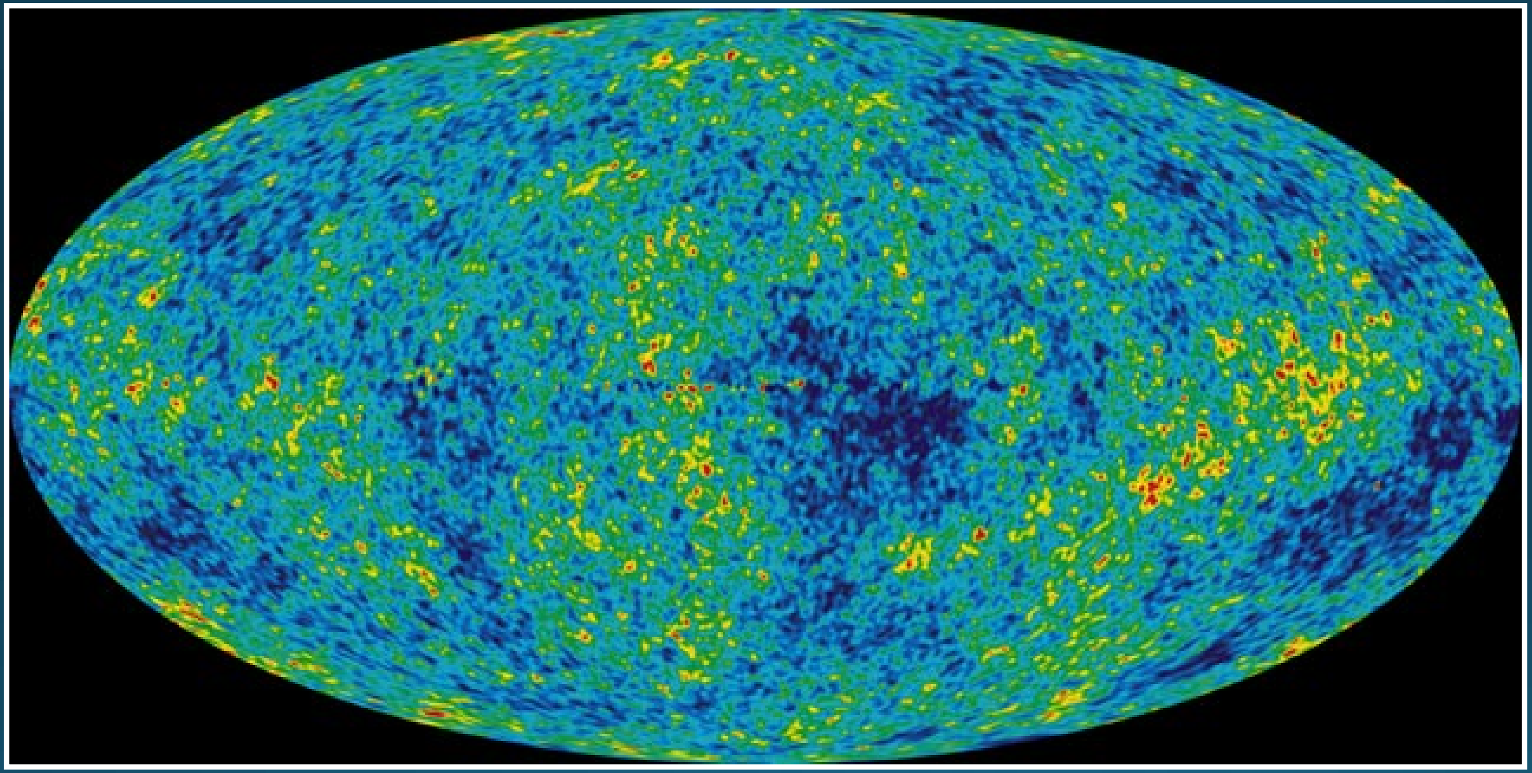
The temperature of the plasma was about 3000 K when the CMBR was emitted.

Cosmic expansion $\rightarrow$ Energy loss due to redshift $\rightarrow$ 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

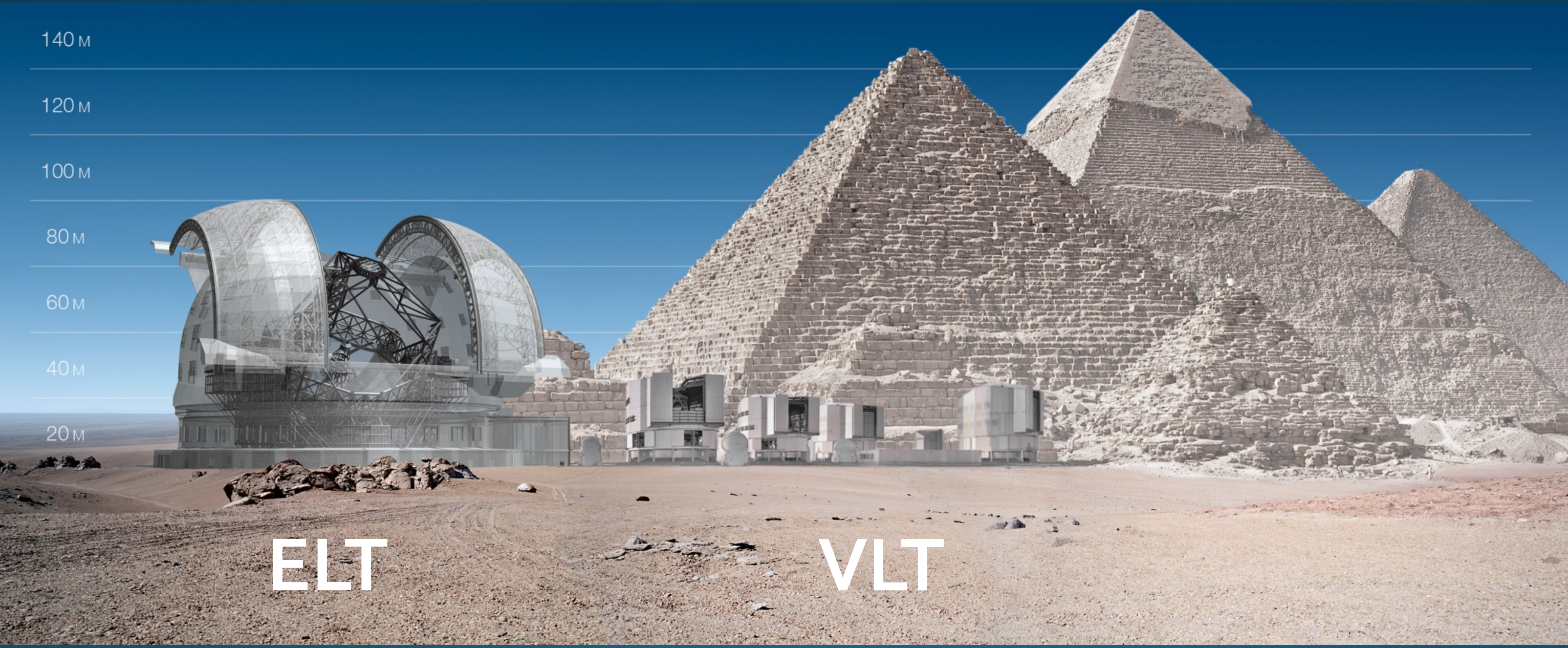
The CMBR as support for the Big Bang model I

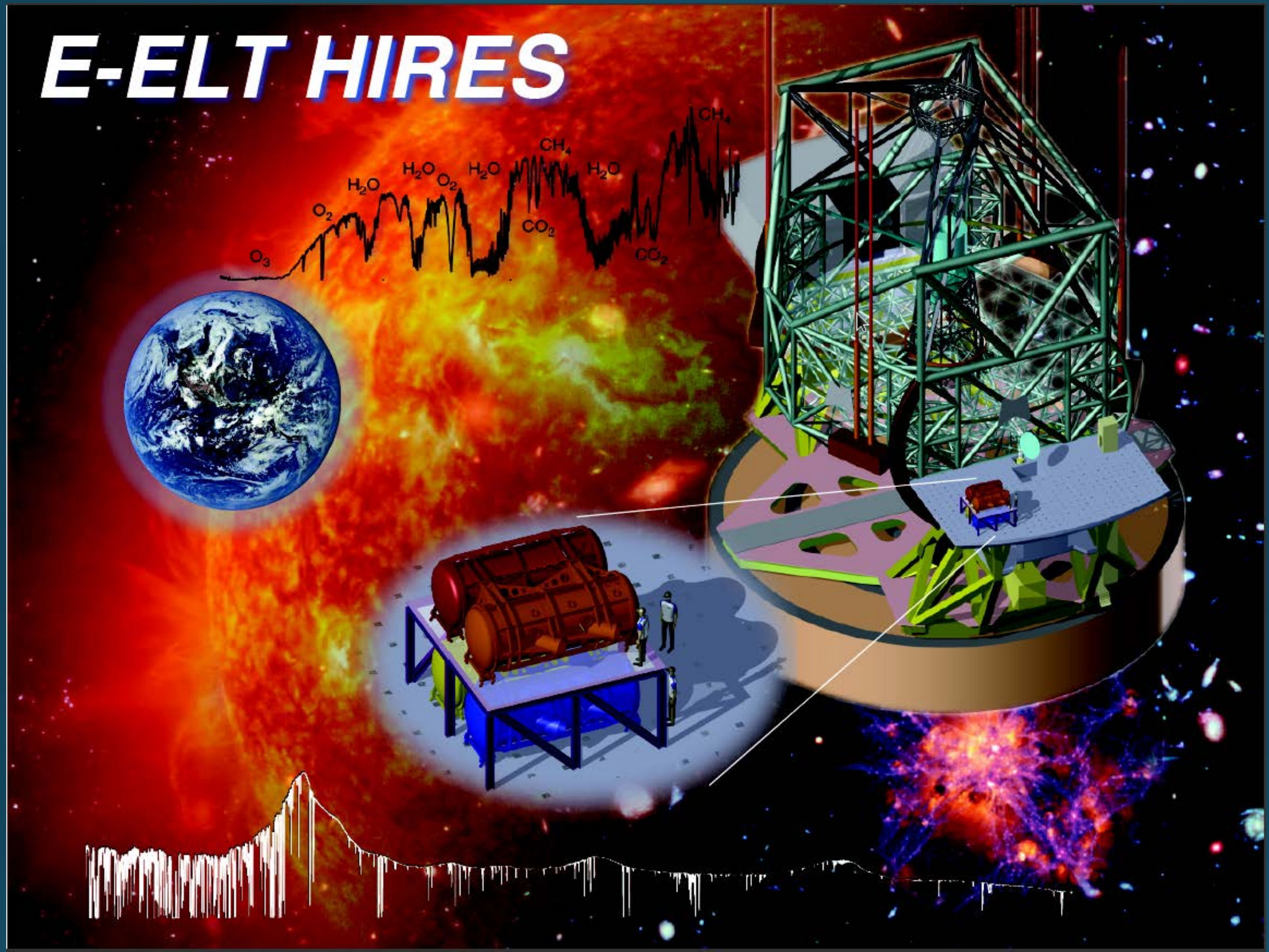
- Existence of the CMBR :
  - Richard Tolman (1934): Expanding Universe should be filled with thermal radiation from hot past
  - CMBR ≈ "Afterglow of the Big Bang"
  - Difficult to understand in Steady State-type cosmologies

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

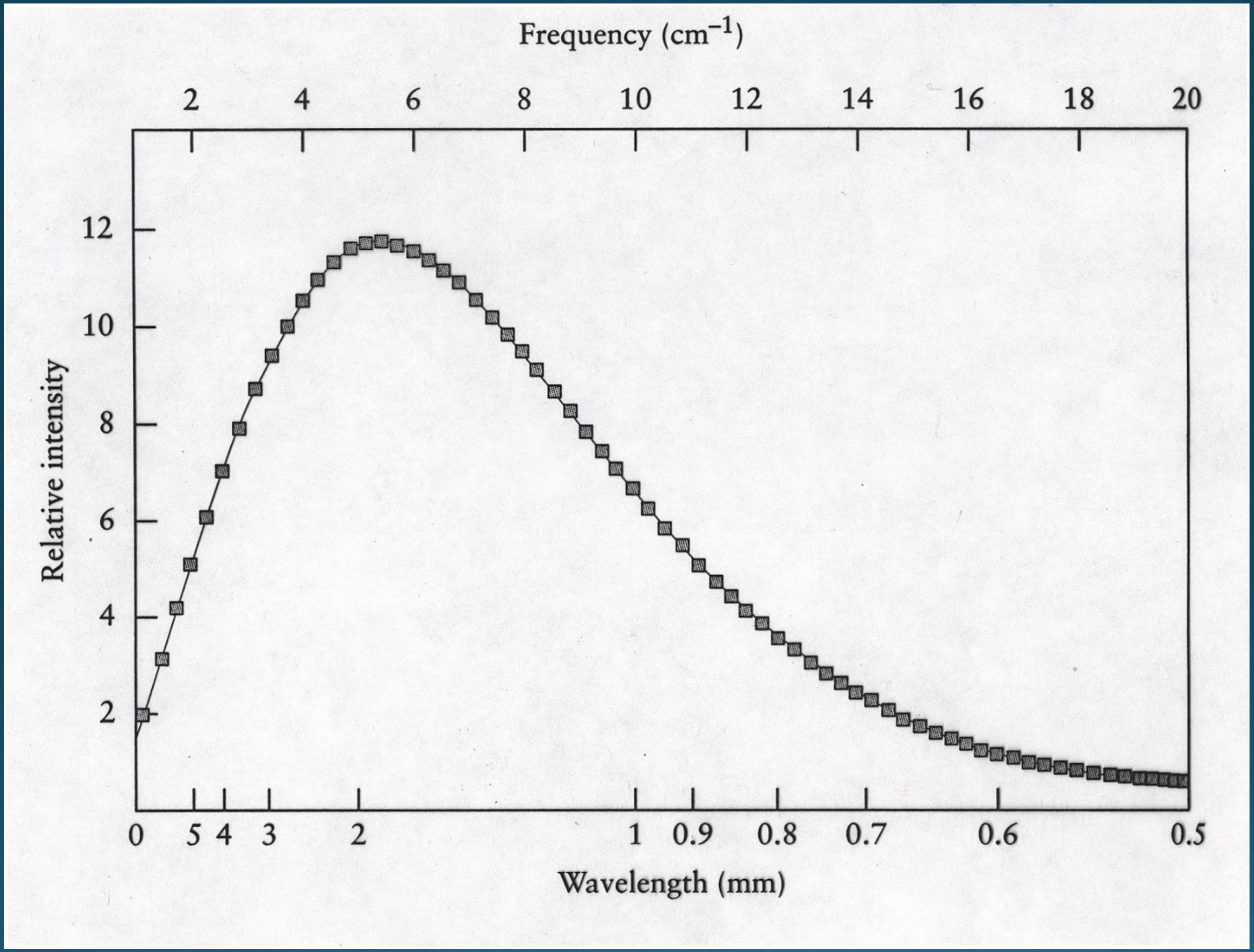
Intermission: What do the acronyms mean?





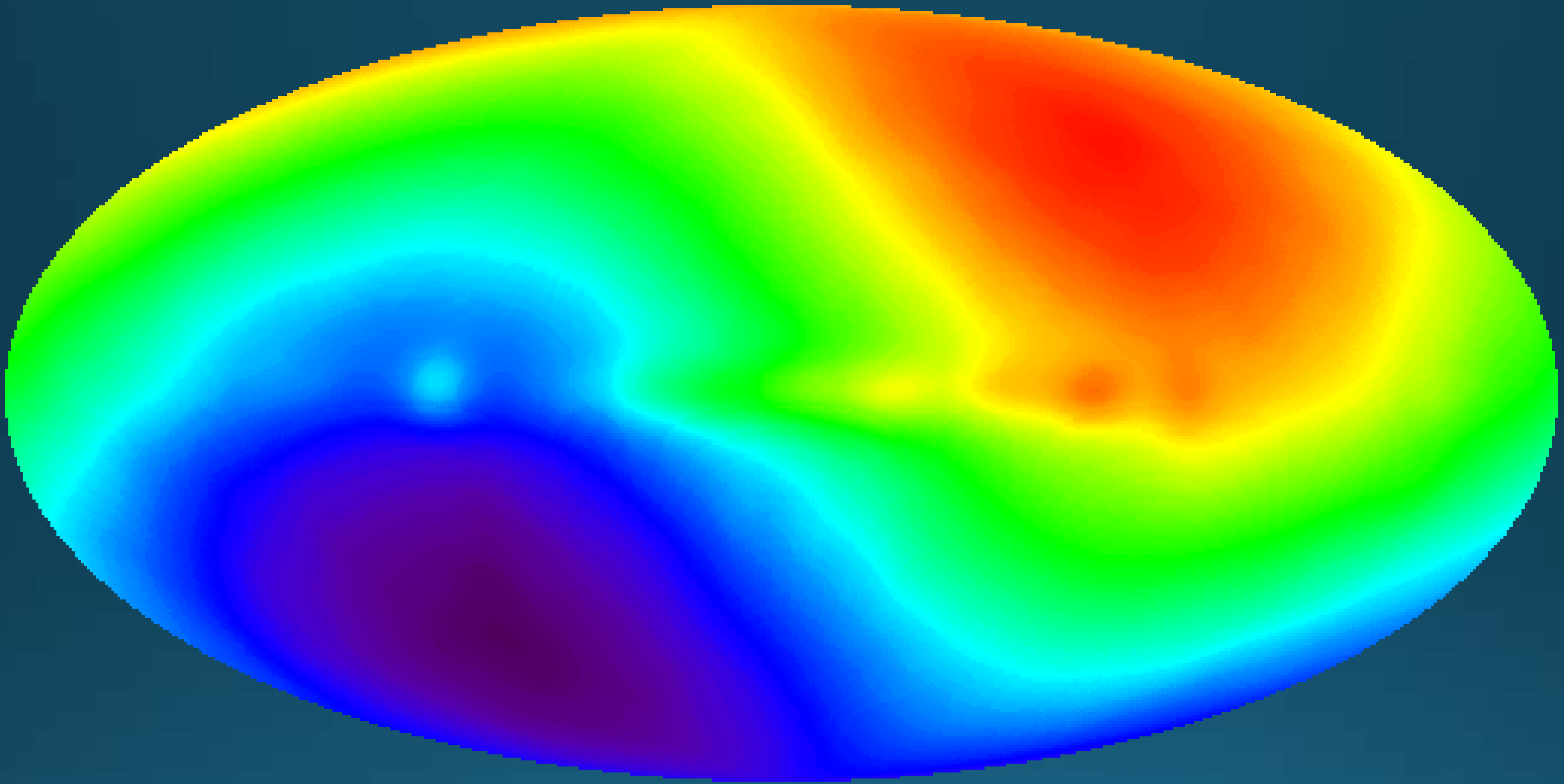
Uppsala is deeply involved in the development of the HIRES instrument, which will allow unprecedented tests of the $T(z) = (1+z)\,T_0$ relation . HIRES will also look for variation in fundamental constants of nature, signatures of first stars, biosignatures in exoplanet atmospheres etc.

Properties of the CMBR I: Spectral shape and temperature



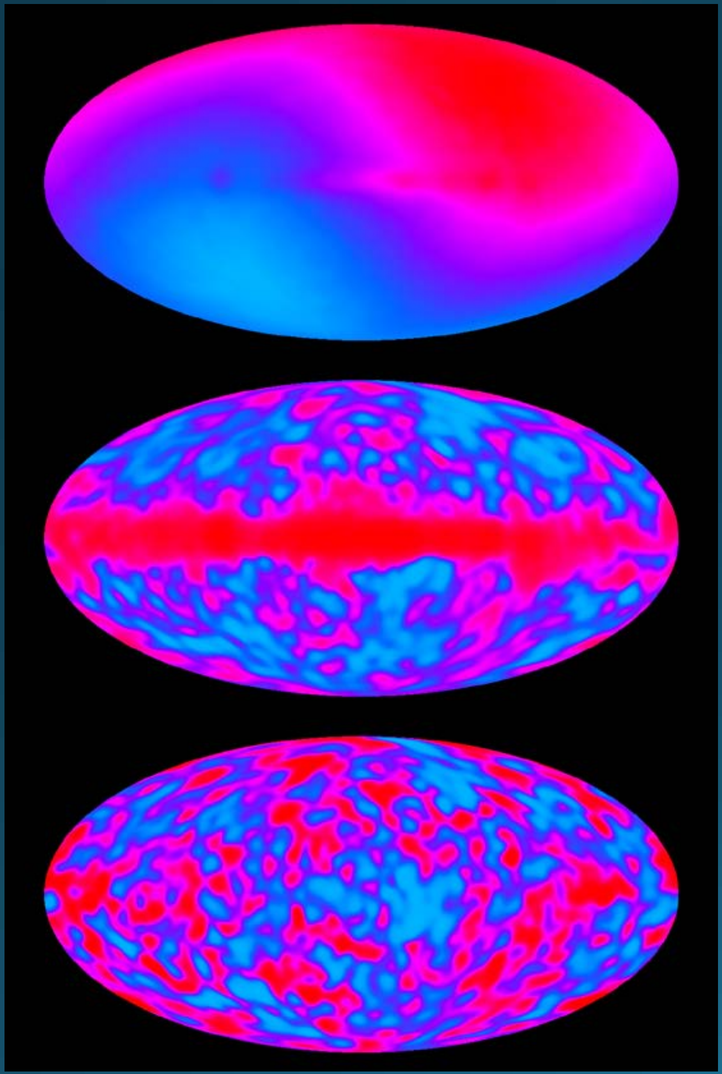
Temperature average over all directions: <T> ≈ 2.73K

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



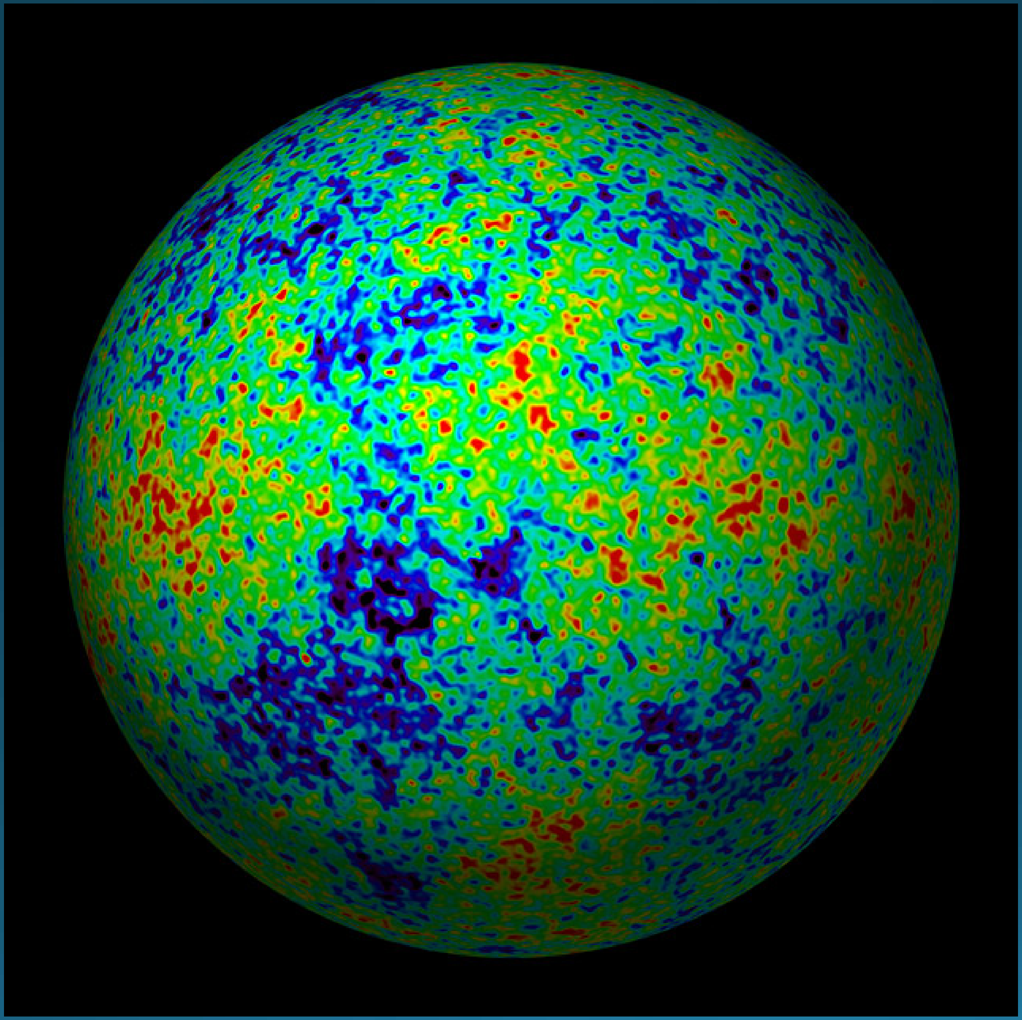
Overall CMBR, including Doppler dipole

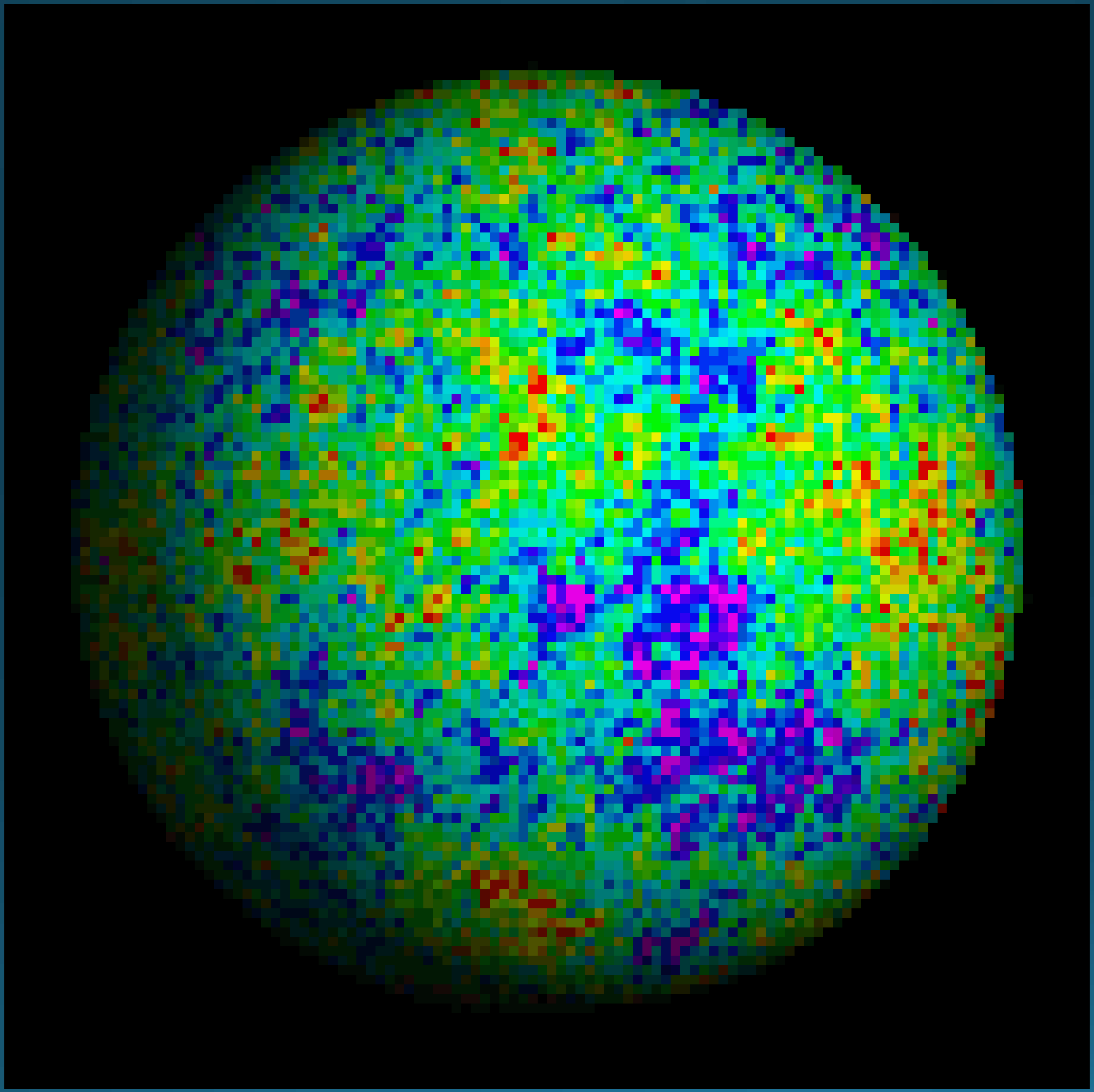
CMBR with dipole subtracted

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

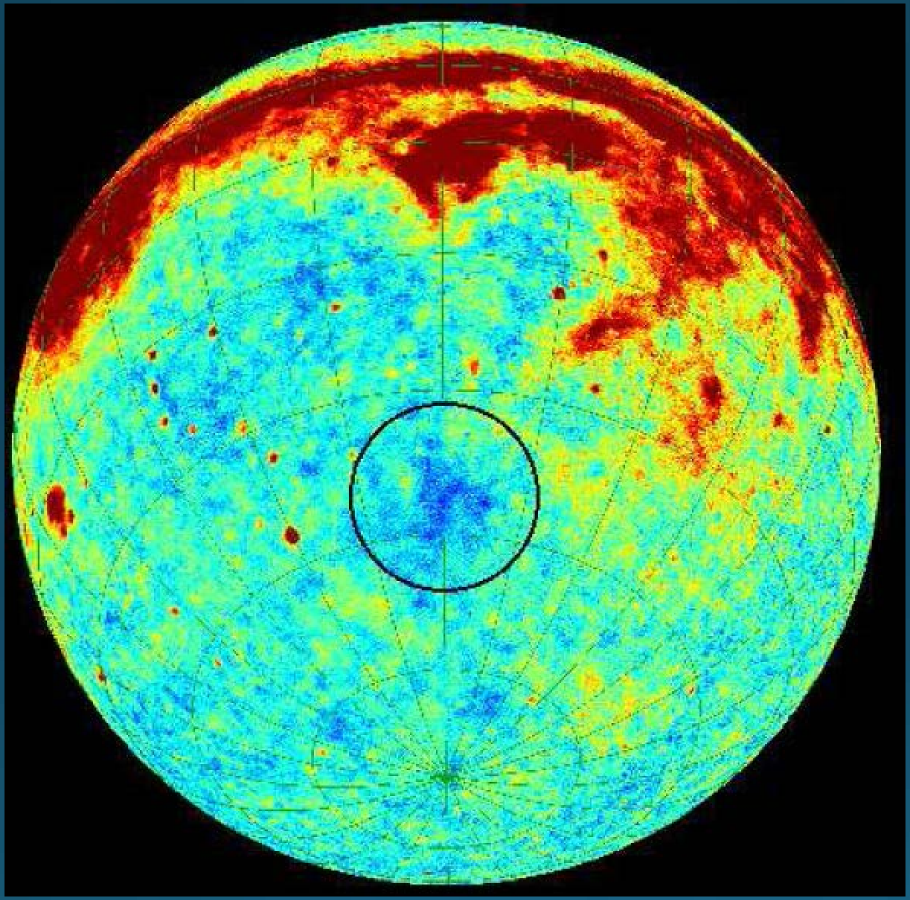
Very important for cosmological model fitting!

Intermission: What is this image showing?

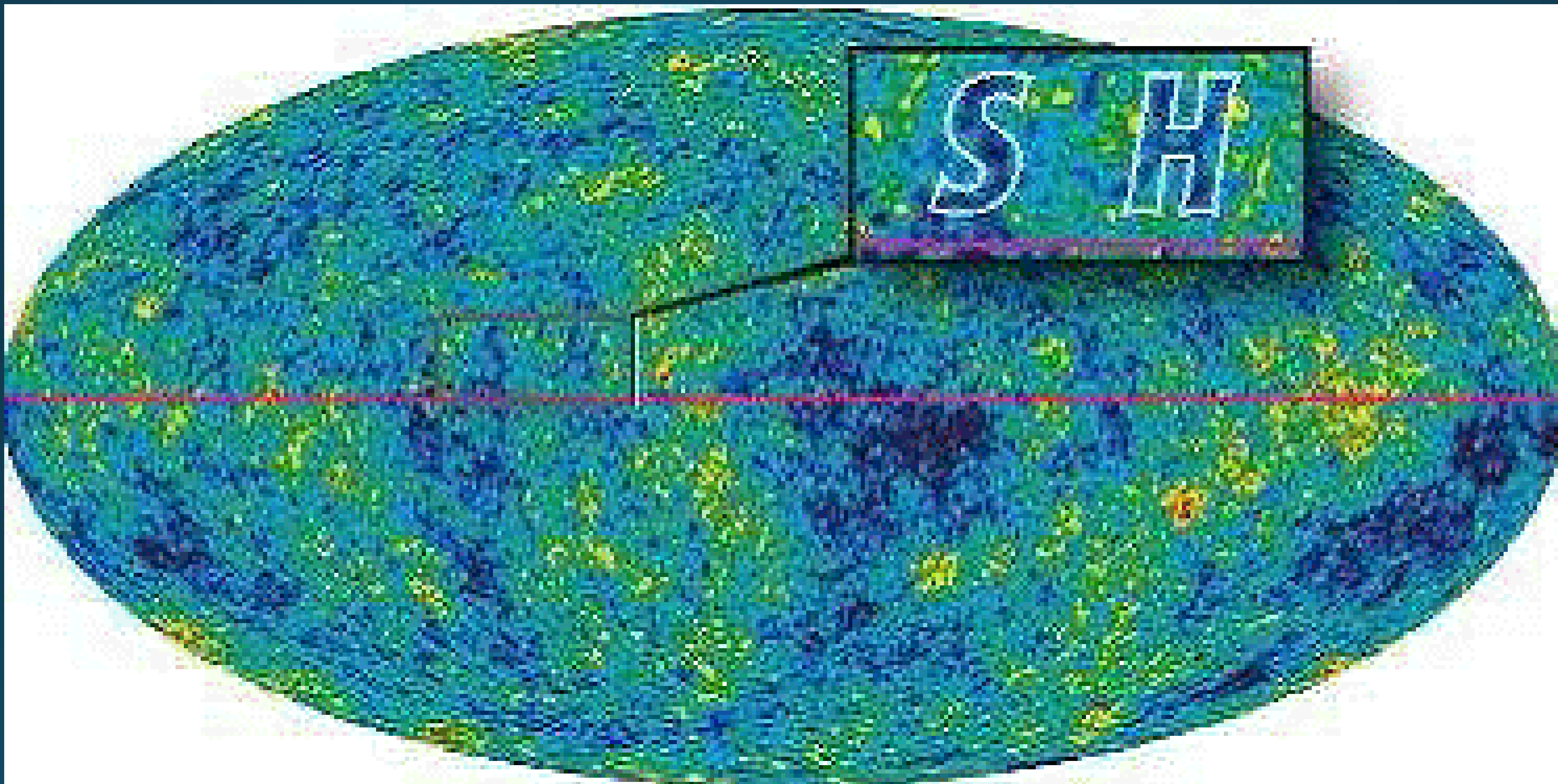




Suggestion for literature exercise: Strange CMBR anisotropies



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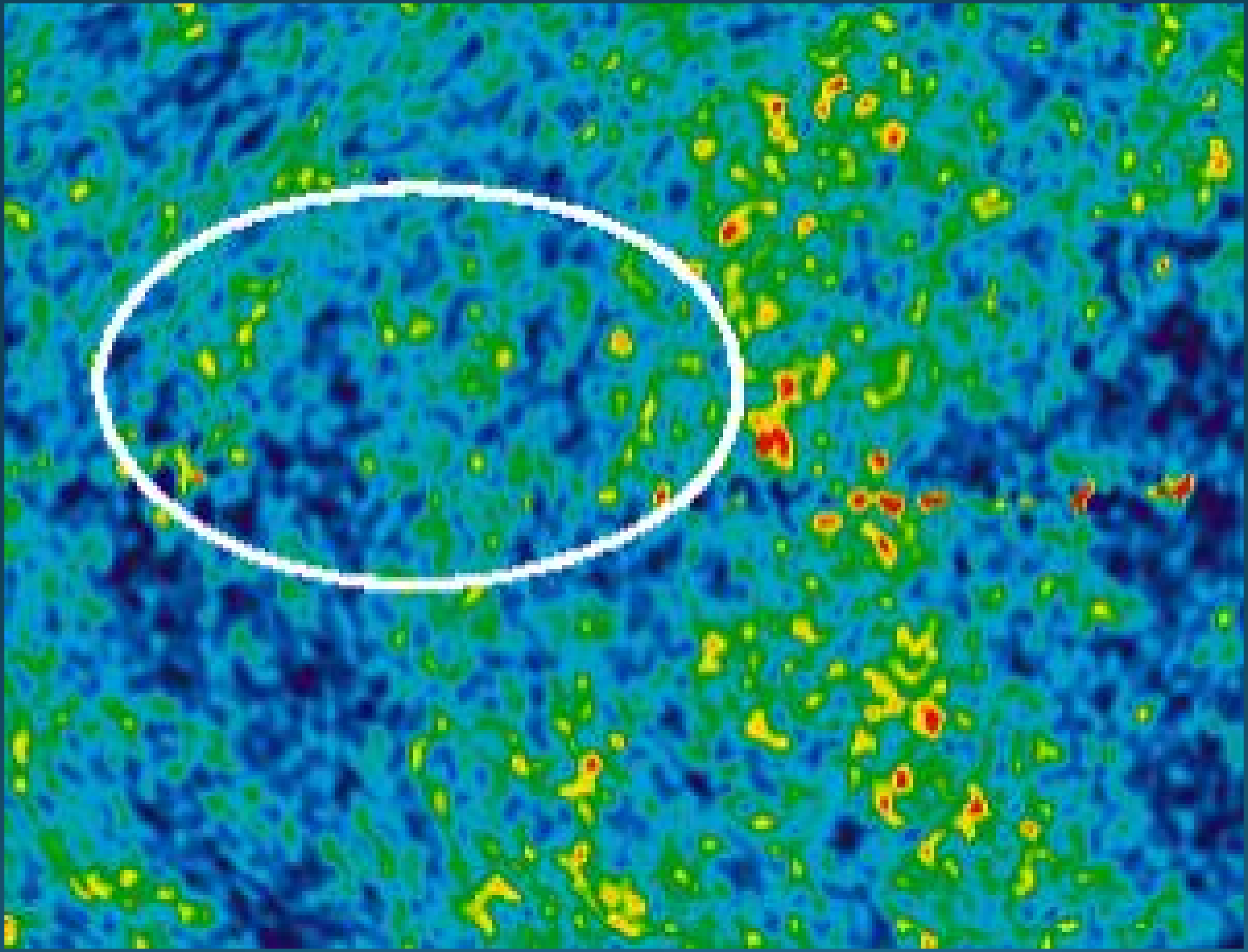
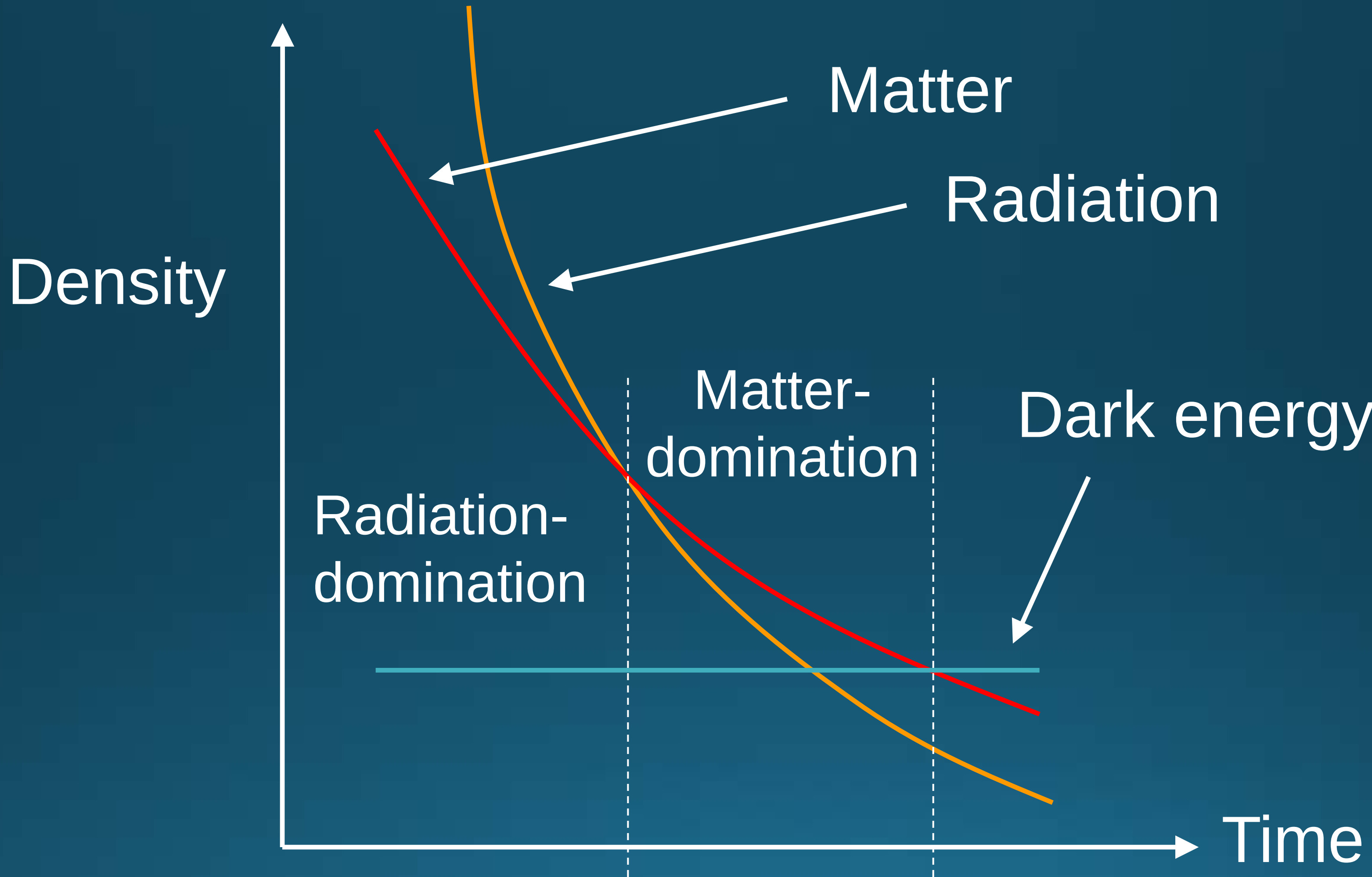


Origin of the CMBR: Important Concepts

- 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:

$$\gamma + \mathrm{e}^- \rightarrow \gamma + \mathrm{e}^-$$

Mean free path of photons:

$$\lambda = \frac{1}{n_{\mathrm{e}}\sigma_{\mathrm{e}}}$$

Origin of the CMBR: Decoupling II

Rate of scattering interactions for this process:

$$\Gamma = \frac{c}{\lambda} = n_{\mathrm{e}} \sigma_{\mathrm{e}} c$$

This process freezes out when:

$$\Gamma < H$$

This leads to decoupling of photons from the baryonic plasma

$\rightarrow$ Baryons and photons evolve separately

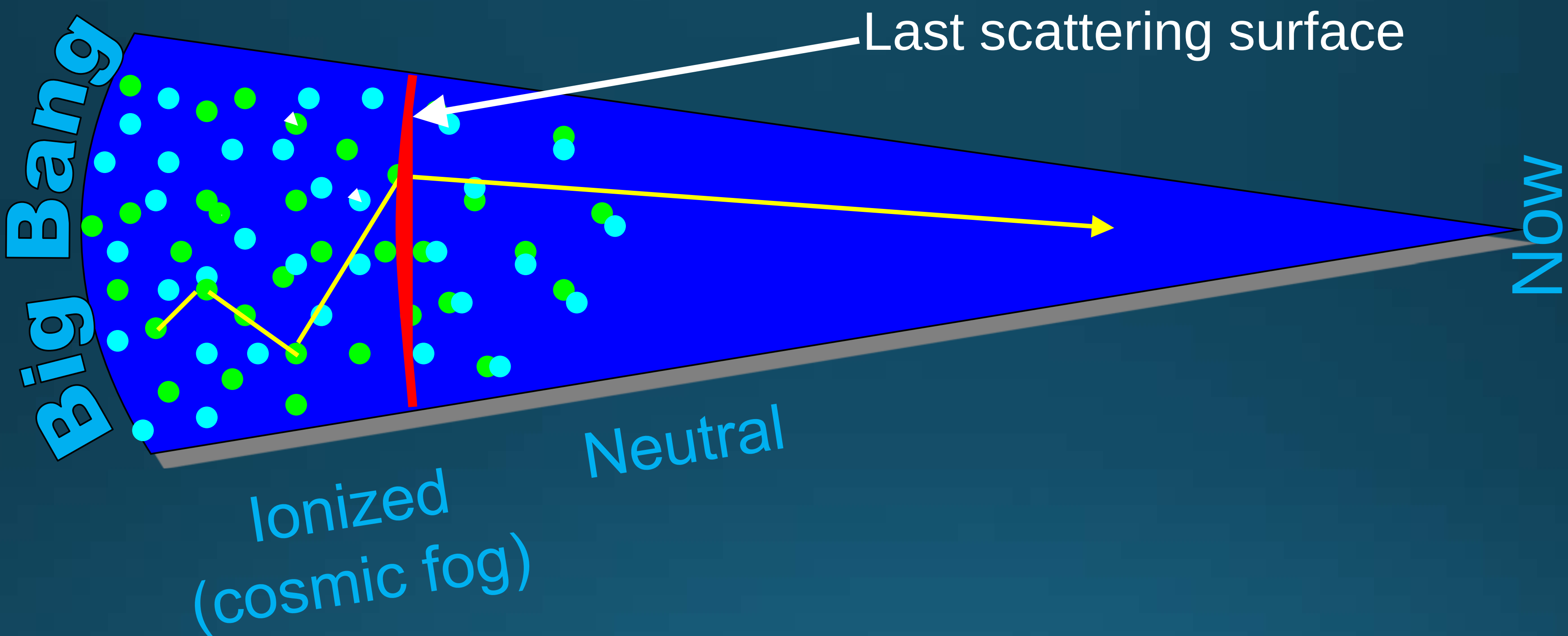
Origin of the CMBR: Recombination

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

Recombination happened at
$z \approx 1380$, $T \approx 3760$ K, $t \approx 250\,000$ yrs

Photon decoupling happened at
$z \approx 1090$, $T \approx 2970$ K, $t \approx 370\,000$ yrs

Origin of the CMBR: Last Scattering Surface



CMBR photons reach us from a fog-like ’wall’. This last scattering surface is located at $z \approx 1090$, $T \approx 2970$ K, $t \approx 370\,000$ 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~370 000 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

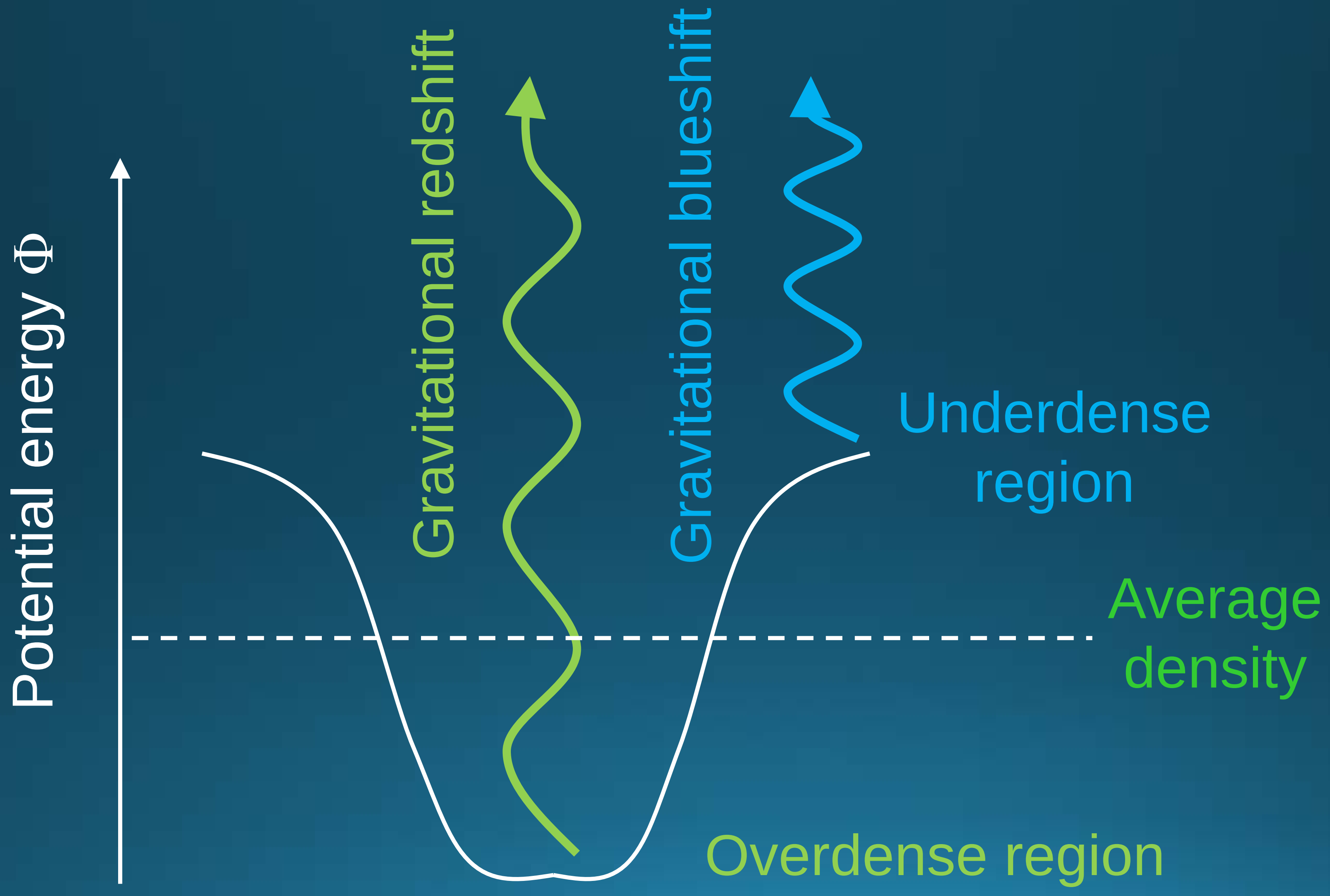
Density fluctuations present at the time of last scattering are evident as spatial temperature fluctuations in the CMBR

$$\text{Recall}: \ \theta = \frac{l}{d_{\mathrm{A}}}$$

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

- 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



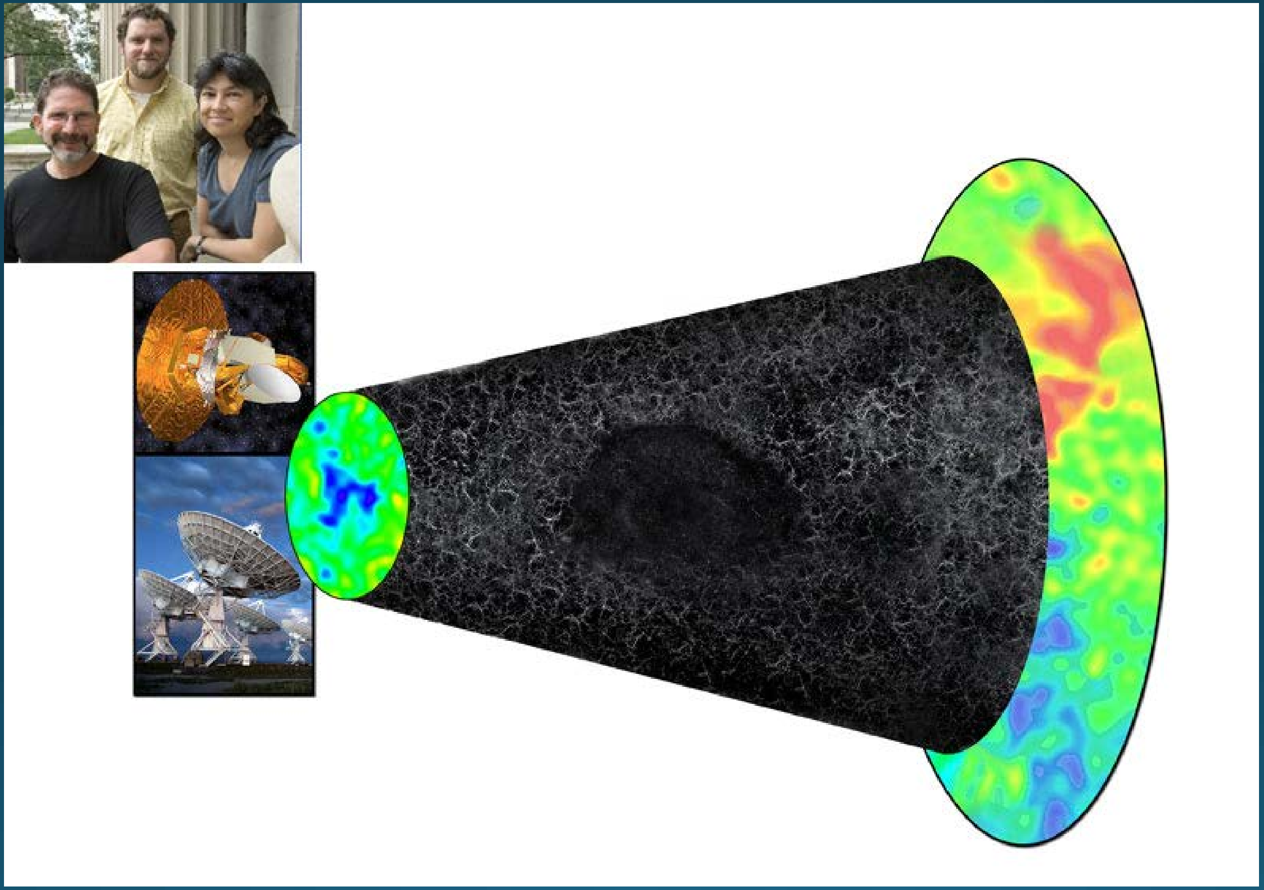
The late/integrated Sachs-Wolfe effect (or Rees-Sciama effect)

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)

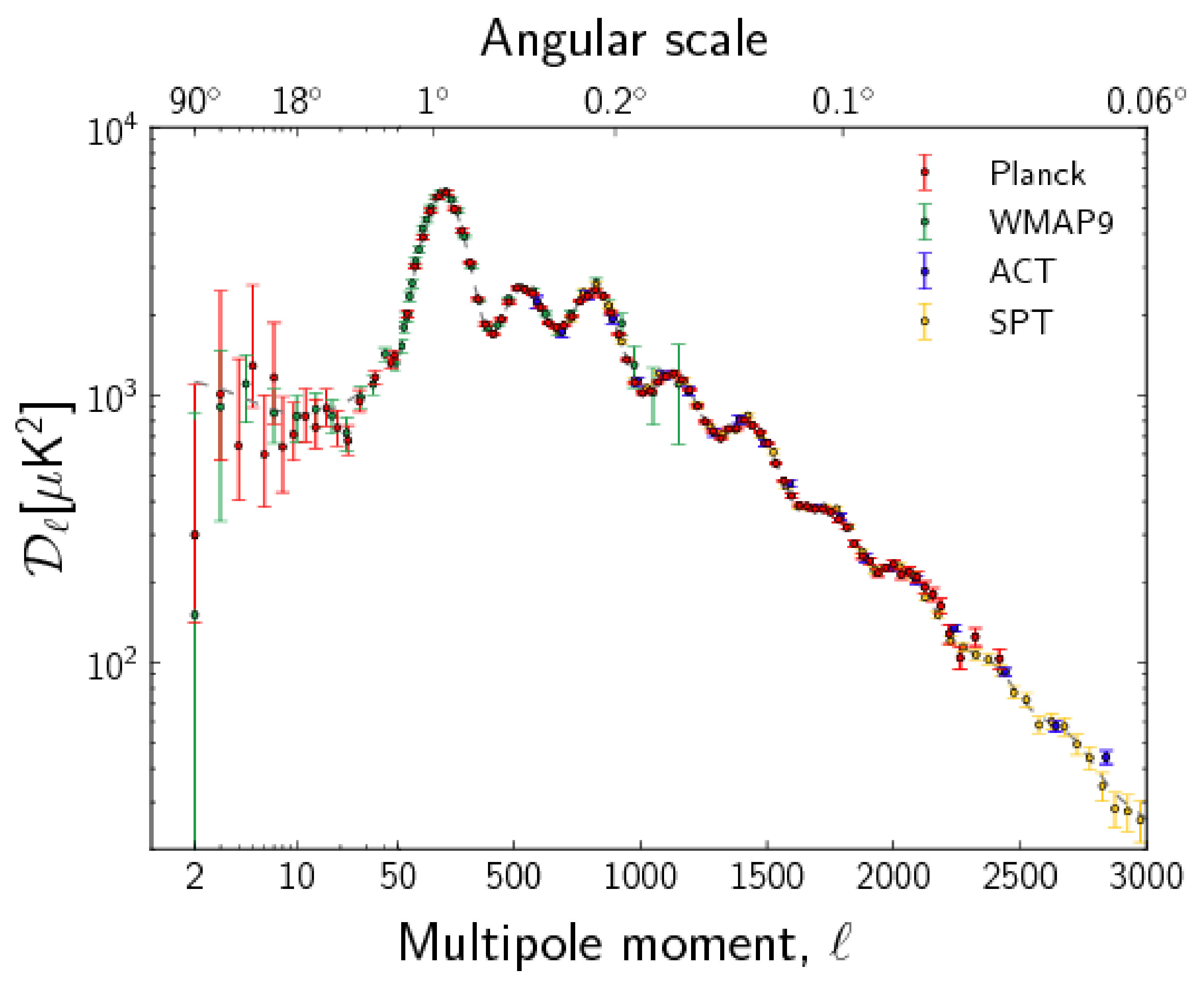
But net redshifts/blueshifts will happen if the potential well gets shallower/deeper while crossing!

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:

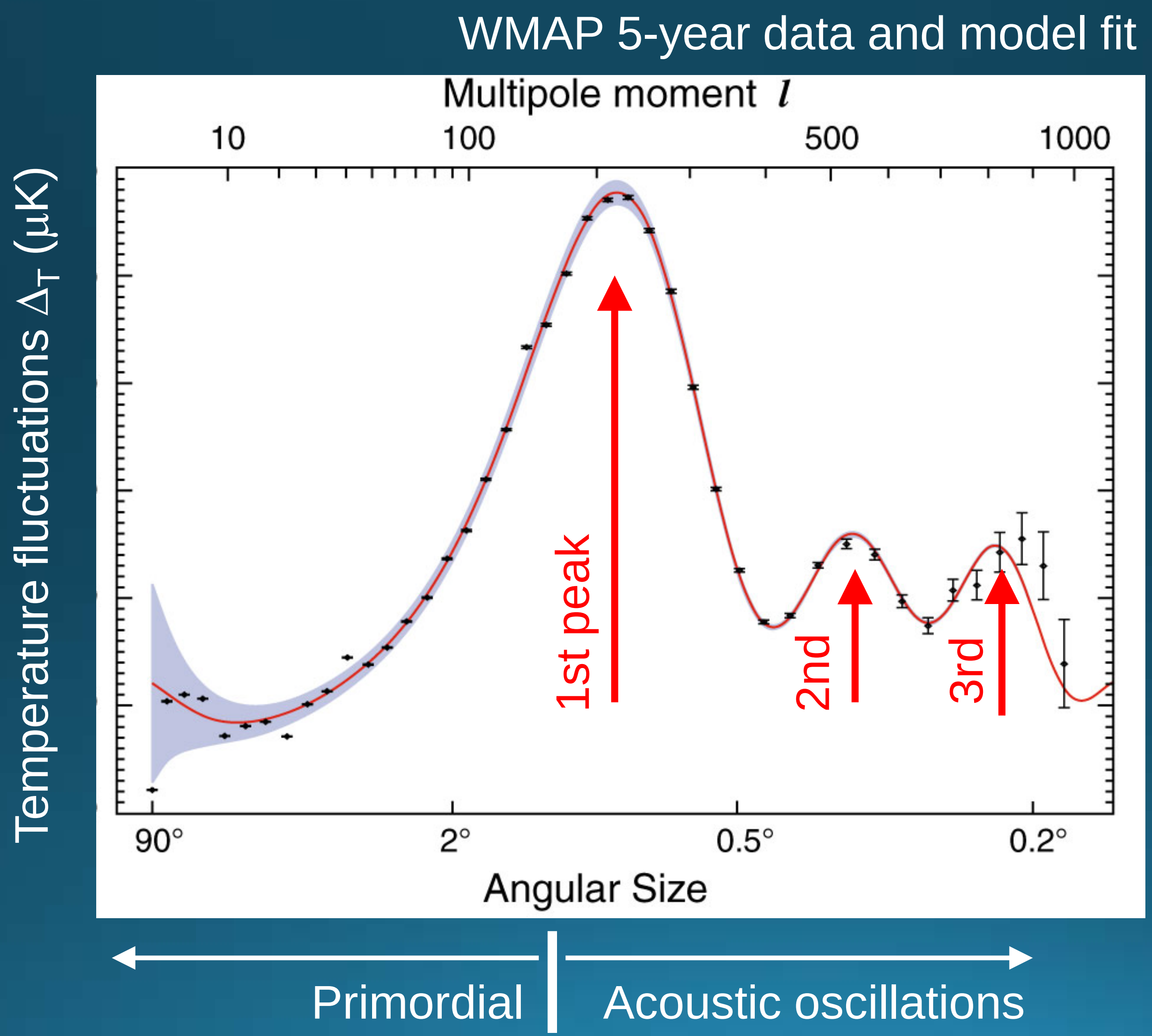
$$\Delta_T = \left(\frac{l(l+1)}{2\pi} C_l \right)^{1/2} \langle T \rangle$$

where:

l is the multipole (note: high l means small θ)

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

The Angular Power Spectrum II

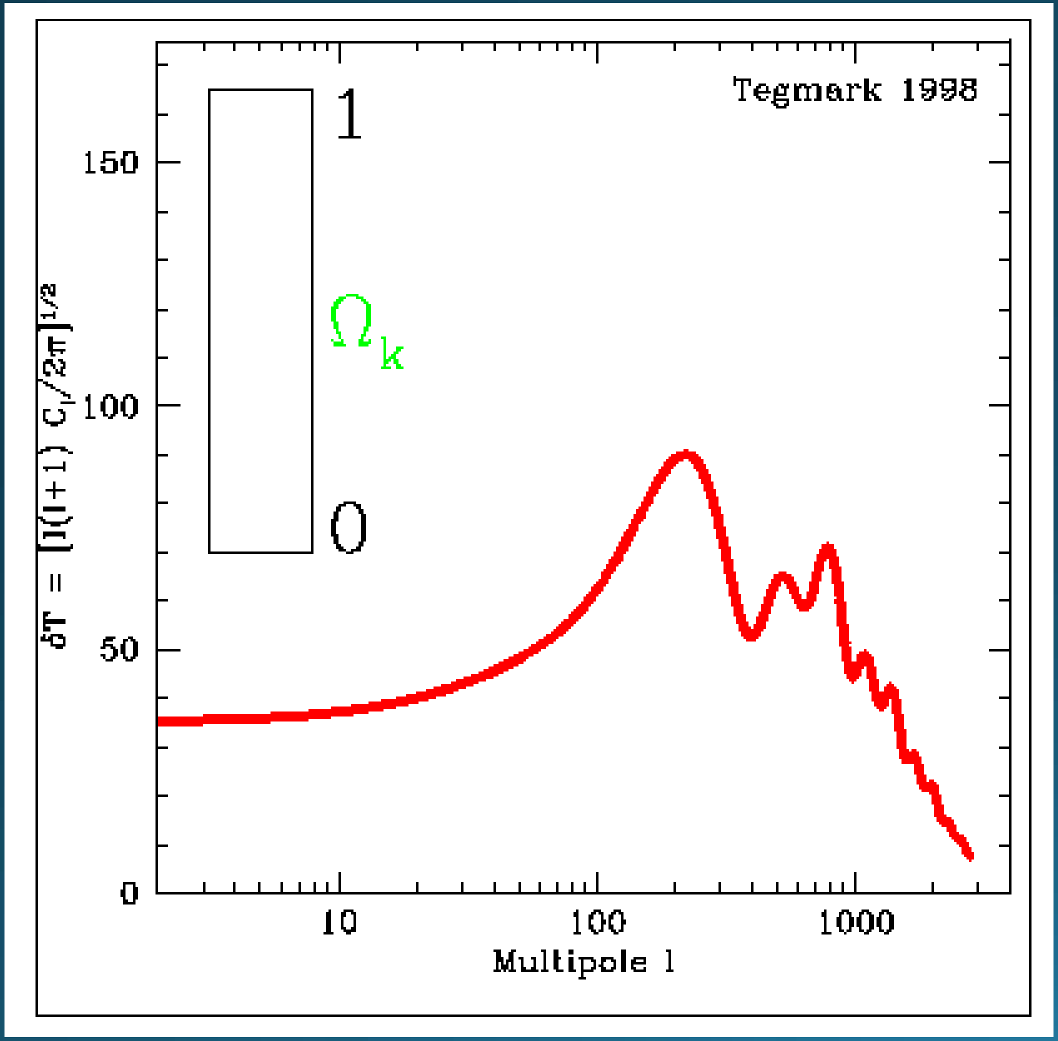


"The sound of the Big Bang"

- 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

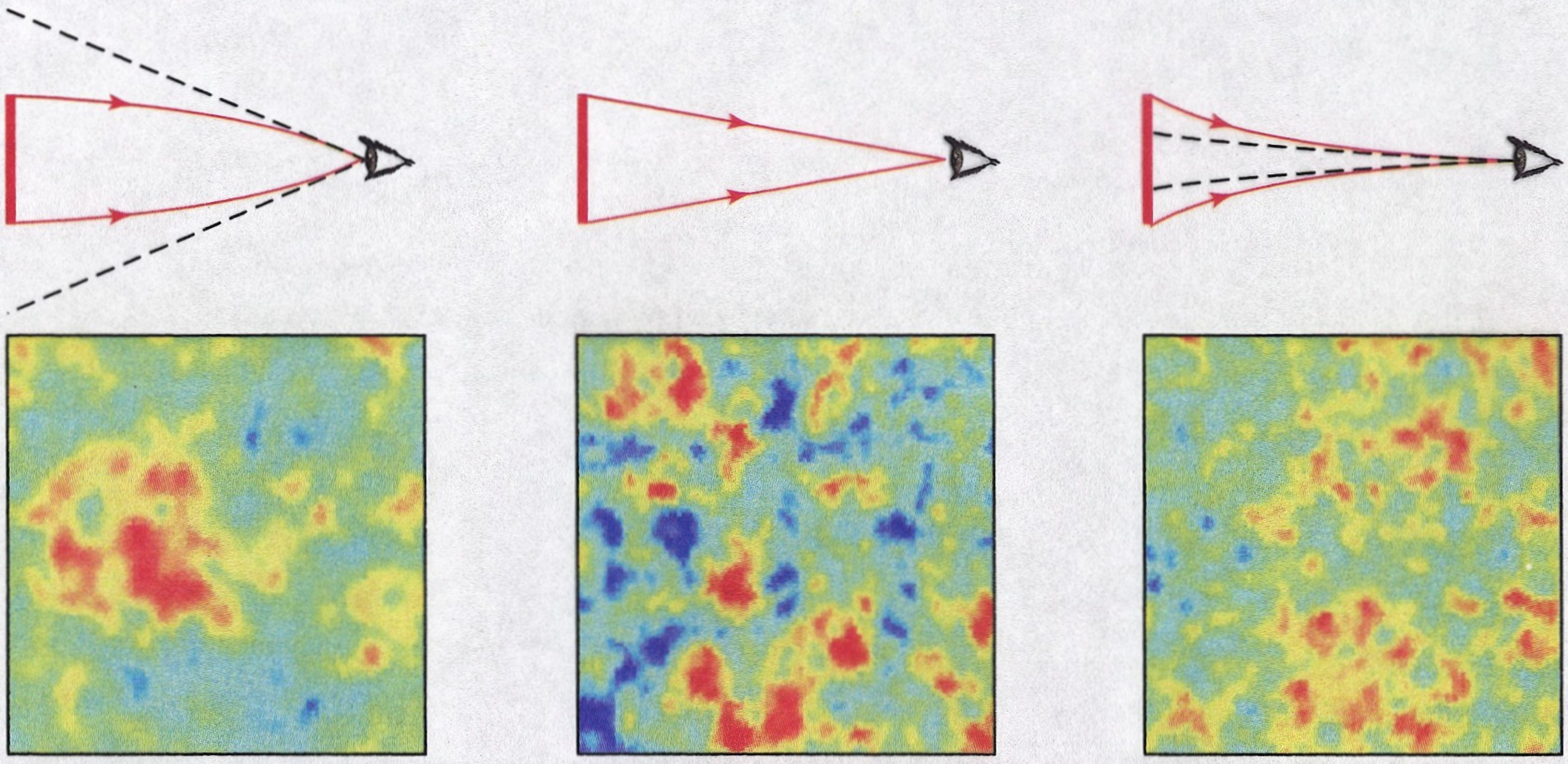
John Cramer's homepage:
http://faculty.washington.edu/jcramer/BBSound.html

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!

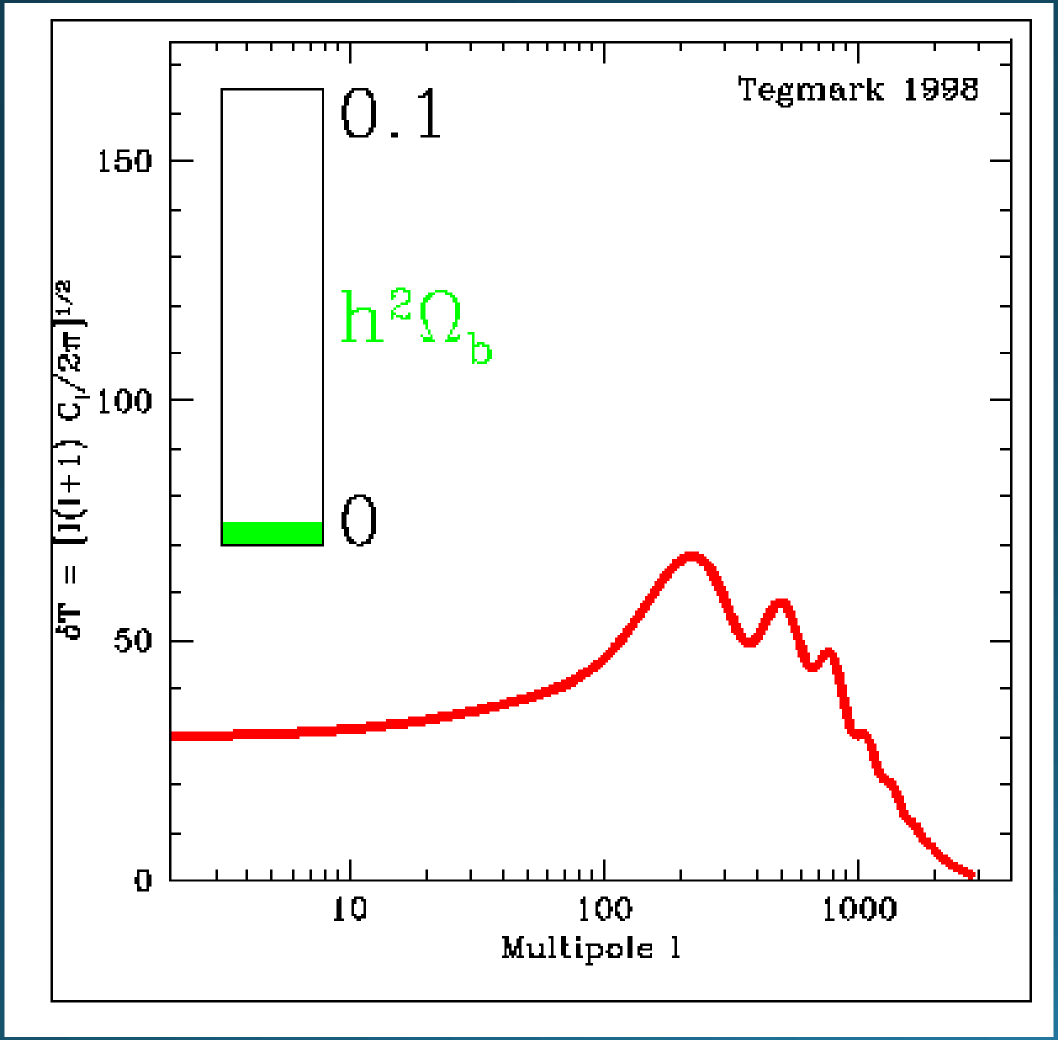


a If universe is closed, "hot spots" appear larger than actual size

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

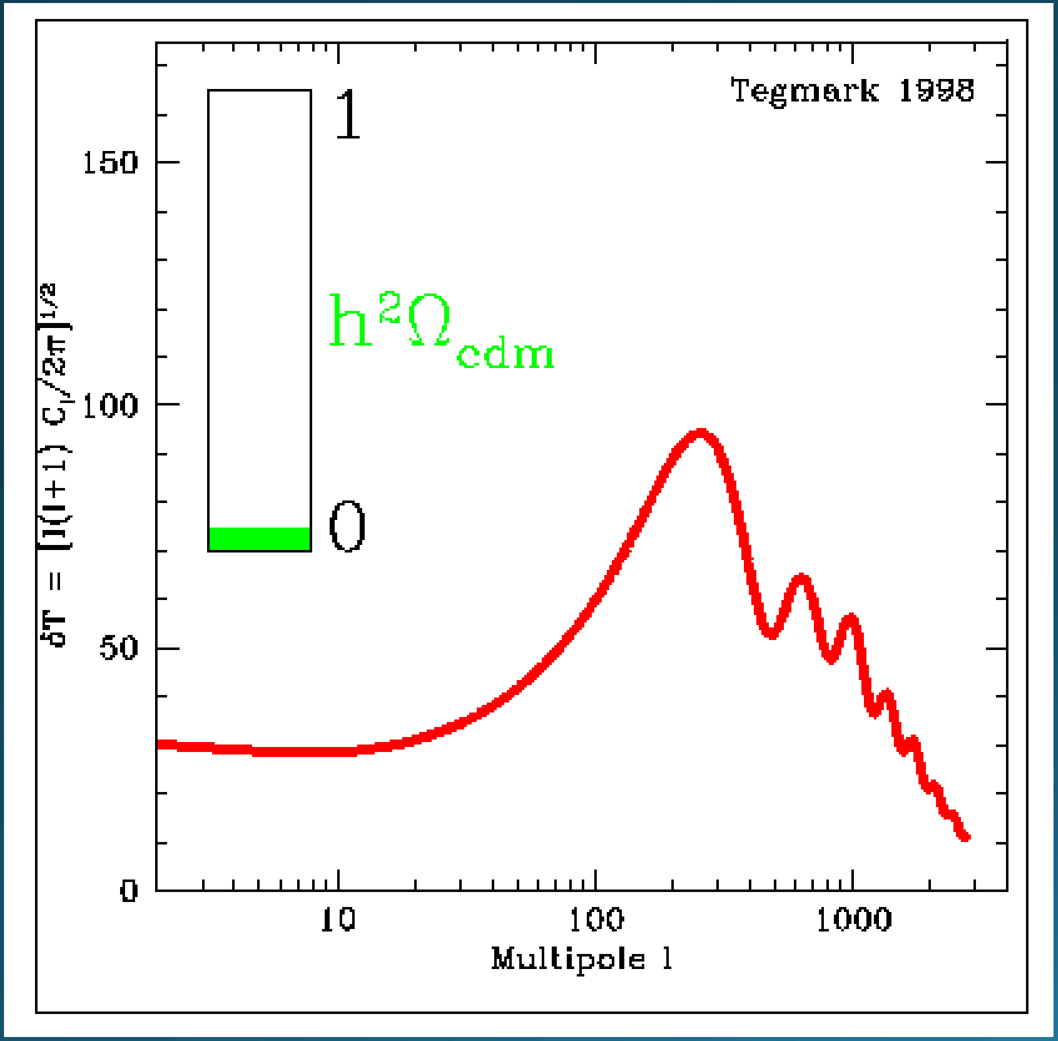
c If universe is open, "hot spots" appear smaller than actual size

Cosmological Information II



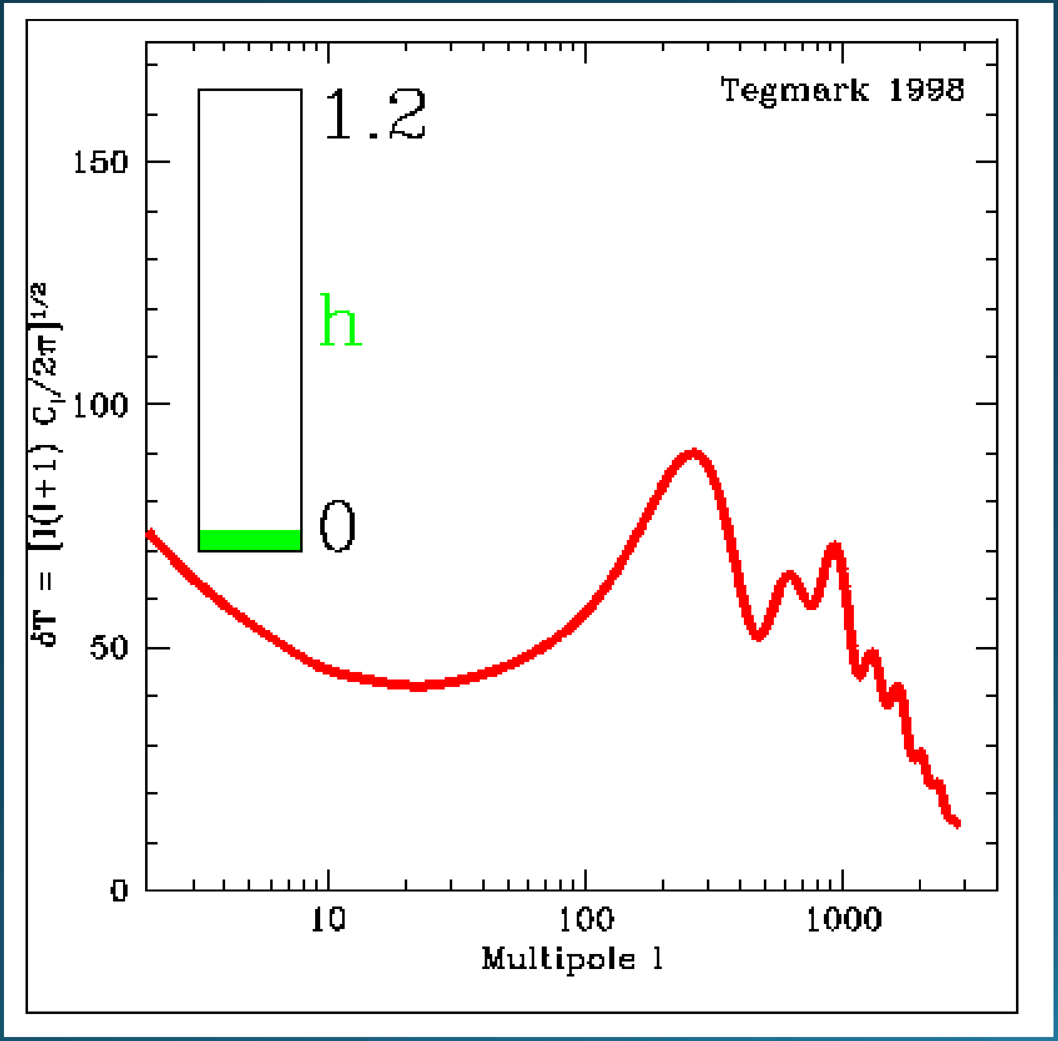
Mild degeneracy:
The amplitude ratios of the first three peaks are sensitive to the baryon density

Cosmological Information III



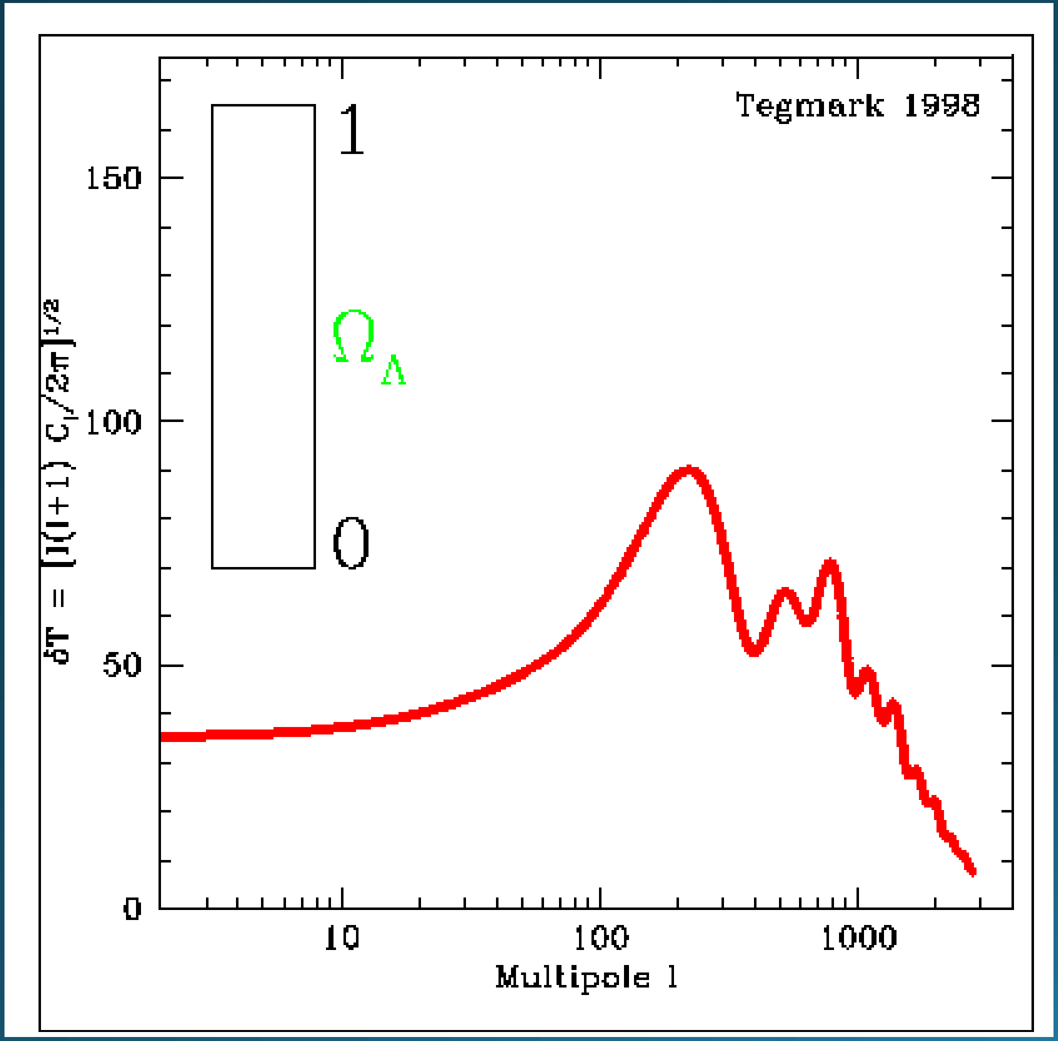
Mild degeneracy:
The amplitude ratios of the first three peaks are also sensitive to the CDM density

Cosmological Information IV



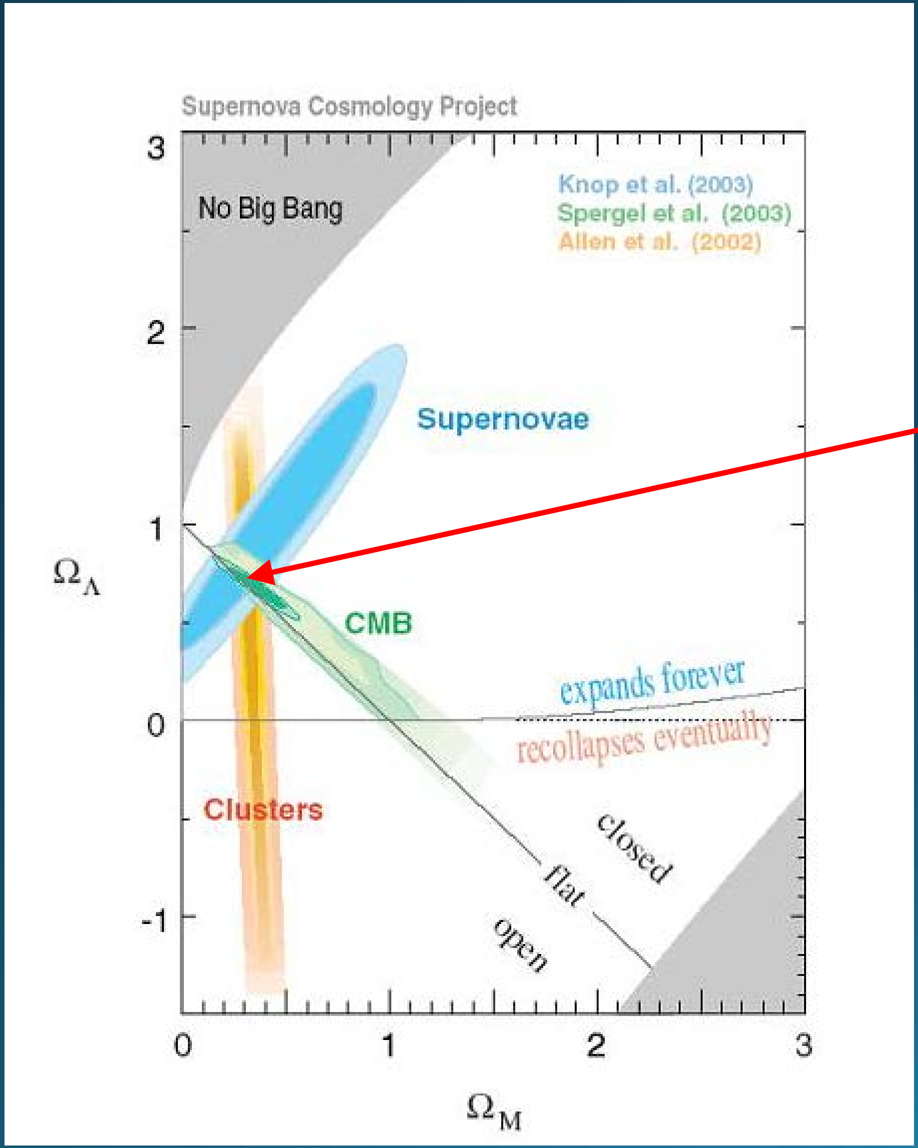
Example of strong degeneracy:
Hubble constant and Ω_Λ variations mimic each other (if other parameters are held fixed)

Cosmological Information V



Example of strong degeneracy:
Hubble constant and Ω_Λ variations mimic each other
(if other parameters are held fixed)

Cosmological information VI



Benchmark model

$\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$

$H_0 \approx 70$ km s^{-1} Mpc^{-1}