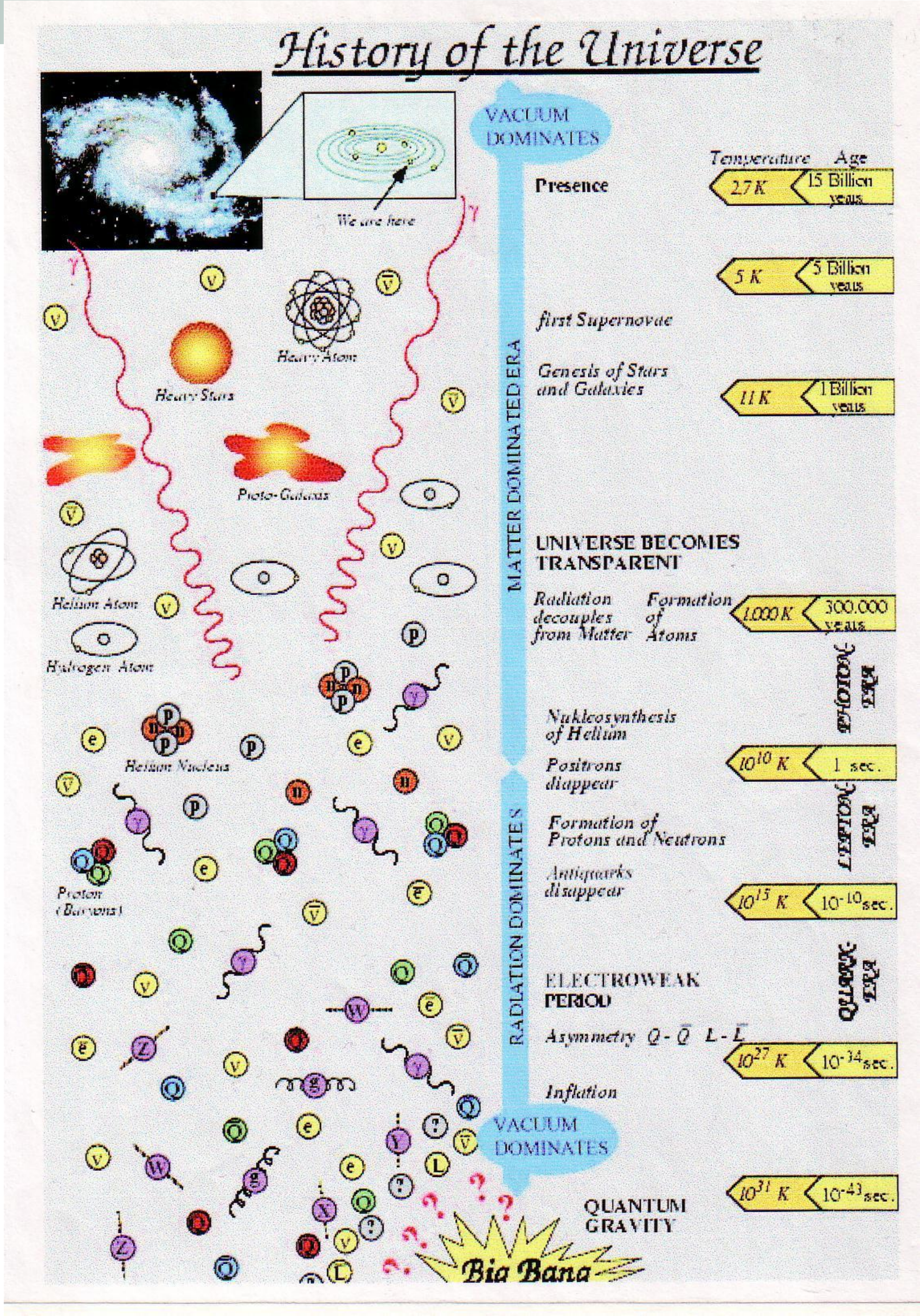
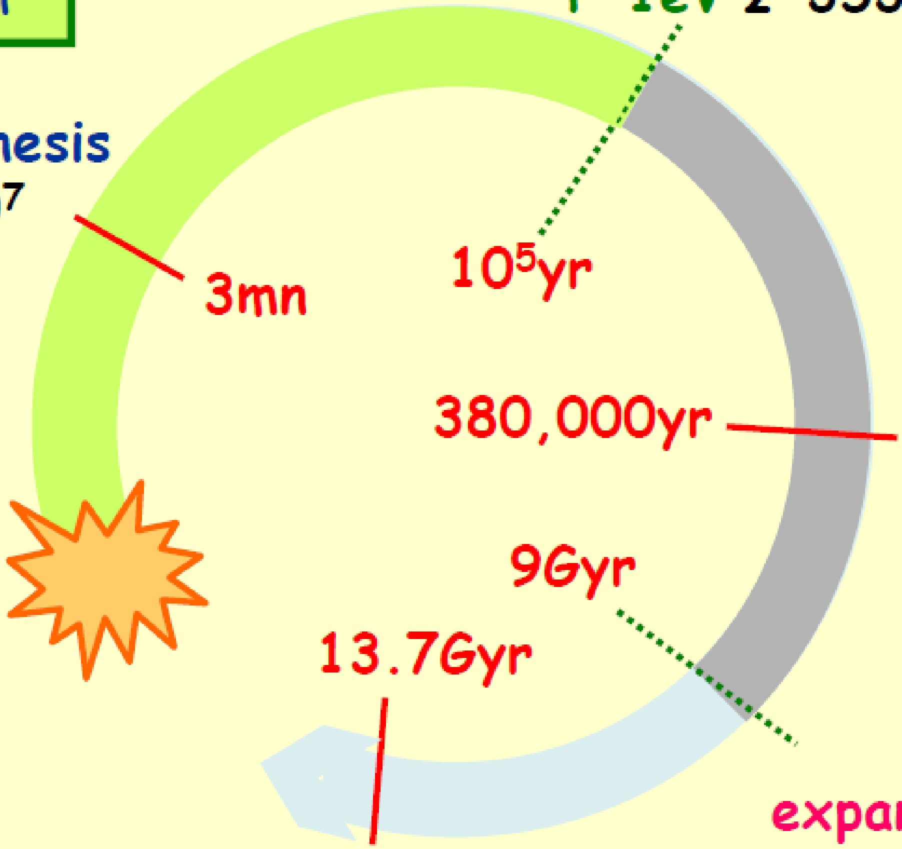
FIZIKALNA

KOZMOLOGIJA

VIII. FIZIKA CMB-a



“KOZMIČKI SAT”



radiation
domination

matter-radiation equality
T~1eV z~3530

D, ^{4}He nucleosynthesis
T~60keV z~10^7

3mn

10^5yr

matter
domination

CMB
T~0.26eV z=1100

380,000yr

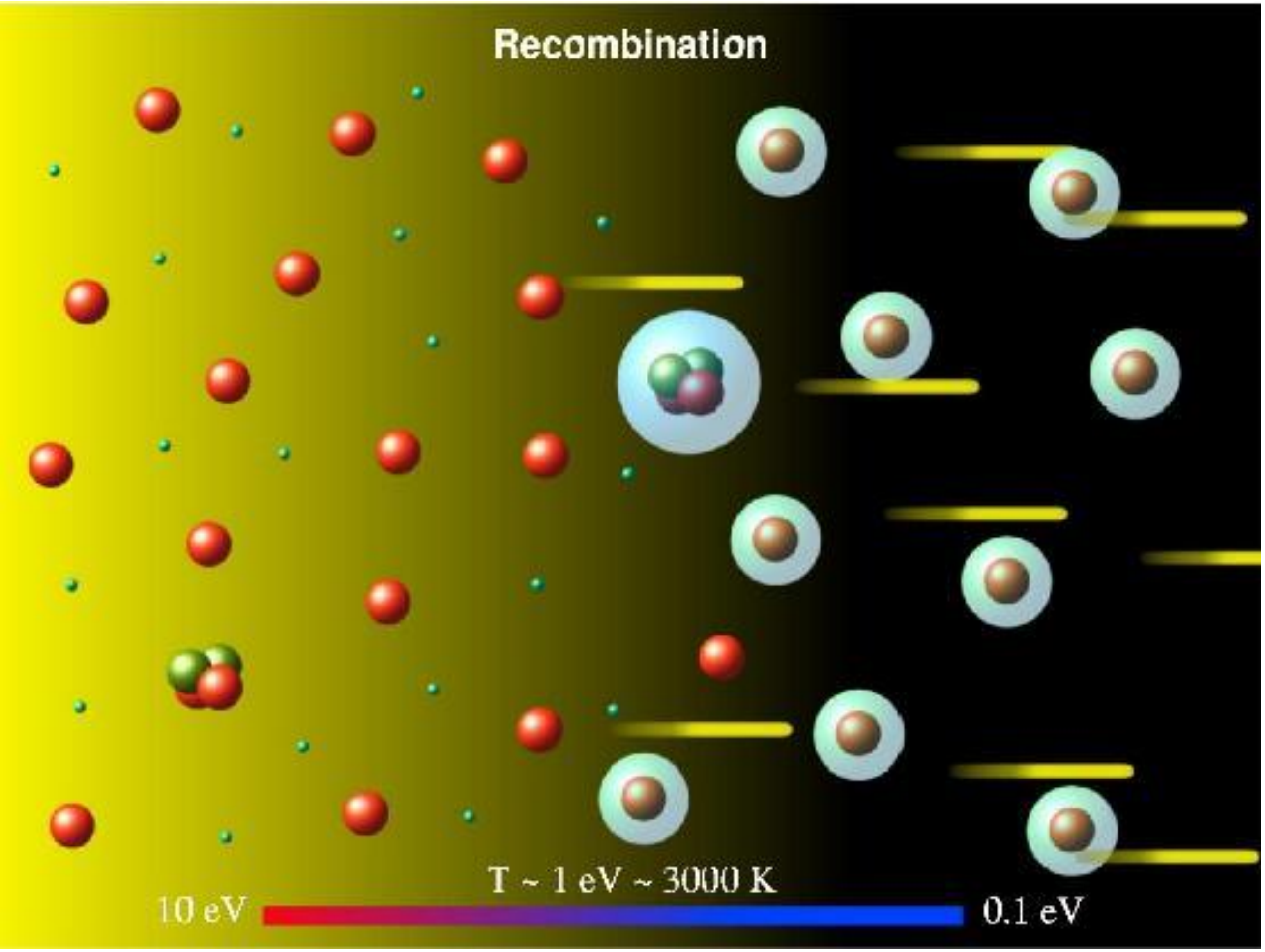
9Gyr

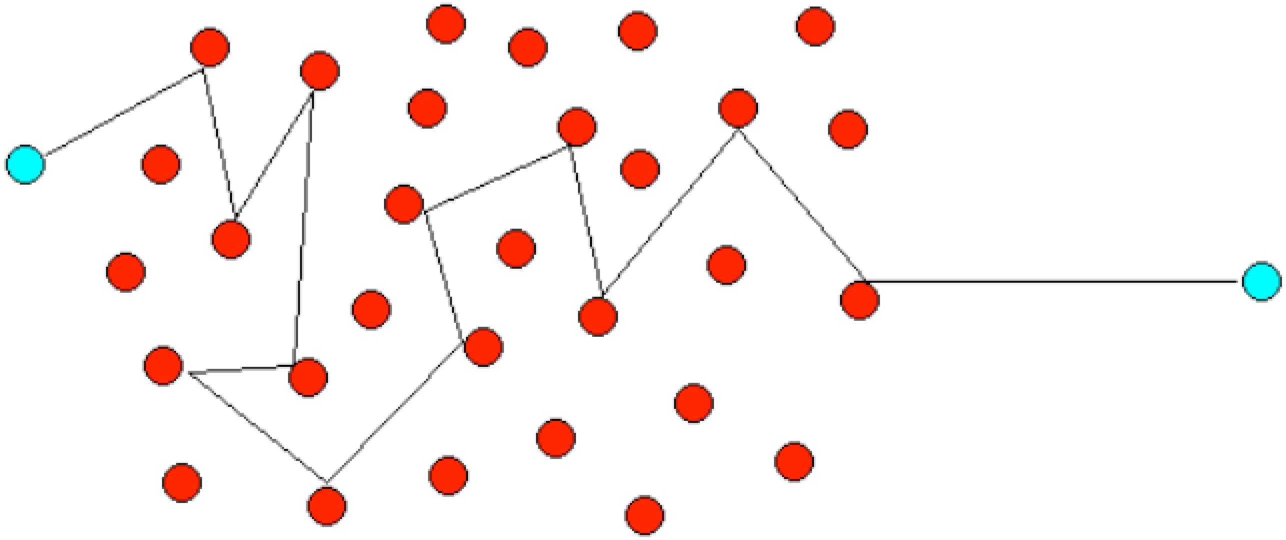
13.7Gyr

expansion acceleration
T~3.5 10^{-4}eV z~0.5

today
T~2.35 10^{-4}eV z=0

SVEMIR U ODREĐENOM TRENUTKU IZLAZI IZ FAZE PLAZME





the Universe is opaque at high densities (the mean free path of a photon is very short), as the density drops with time, the Universe becomes transparent (the mean free path of a photon becomes very large).

The ionisation fraction x_e drops rapidly at (re)combination so the Thomson scattering rate also decreases sharply below the Hubble expansion rate … this defines a ***last scattering surface*** for the relic photons … which we see today as the cosmic microwave background

Thomson scattering on electrons: $\gamma + e \rightarrow \gamma + e$

Interaction rate for photons:

$$\Gamma_{\text{Thomson}} = n_e \langle \sigma_T |v| \rangle \propto x_e T^3 \sigma_T$$

Expansion rate of the universe (MD era): $H \propto T^{3/2}$

$\Gamma_{\text{Thomson}} > H$: Photons and matter *in equilibrium*

$\Gamma_{\text{Thomson}} < H$: Photons and matter stop interacting

Na T~1eV fotoni vezani za e$^-$ Compt.raspršenjem

Visok omjer fotona prema barionima $(\eta_b)^{-1}$ →neutralnog H vrlo malo

Jedn.ravnoteže za e$^-$ + p ↔ H + γ , uz $n_\gamma = n_\gamma^{(0)}$:

$$\frac{n_e n_p}{n_H} = \frac{n_e^{(0)} n_p^{(0)}}{n_H^{(0)}}$$

Neutralnost svemira: $n_e = n_p$

def.omjer slobodnih e$^-$: $X_e \equiv \frac{n_e}{n_e + n_H} = \frac{n_p}{n_p + n_H}$

Uz $n_i^{(0)} = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$ imamo:

$$\frac{X_e^2}{1 - X_e} = \frac{1}{n_e + n_H} \left[\left(\frac{m_e T}{2\pi} \right)^{3/2} e^{-[m_e + m_p - m_H]/T} \right] \quad \text{Saha}$$

energija ionizacije: $m_e+m_p-m_H=\varepsilon_0=13.6$ eV

$X_e \sim 1$ (sav H ioniziran) sve dok T ne padne na $T \ll \varepsilon_0 \rightarrow$ rekobinacija → Boltzm.jedn. daje evoluciju X_e

- Boltzmannova jedn. uz uvrštavanje $n_e^{(0)} n_p^{(0)}/n_H^{(0)}$ iz Sahine :

$$a^{-3}\frac{d\left(n_e a^3\right)}{dt} = n_e^{(0)} n_p^{(0)} \langle\sigma v\rangle \left\{ \frac{n_H}{n_H^{(0)}} - \frac{n_e^2}{n_e^{(0)} n_p^{(0)}} \right\} = n_b \langle\sigma v\rangle \left\{ (1-X_e)\left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\epsilon_0/T} - X_e^2 n_b \right\}$$

Brzina ionizacije: $\beta \equiv \langle \sigma v \rangle \left(\frac{m_e T}{2\pi} \right)^{3/2} e^{-\epsilon_0/T}$, $\alpha^{(2)} \equiv \langle \sigma v \rangle$

Samo rekombinacija pobuđog stanja, $\alpha^{(2)}$, daje doprinos

→Boltzmannova jedn.:

$$\frac{dX_e}{dt} = \left\{ (1 - X_e)\beta - X_e^2 n_b \alpha^{(2)} \right\}$$

numeričko rješavanje

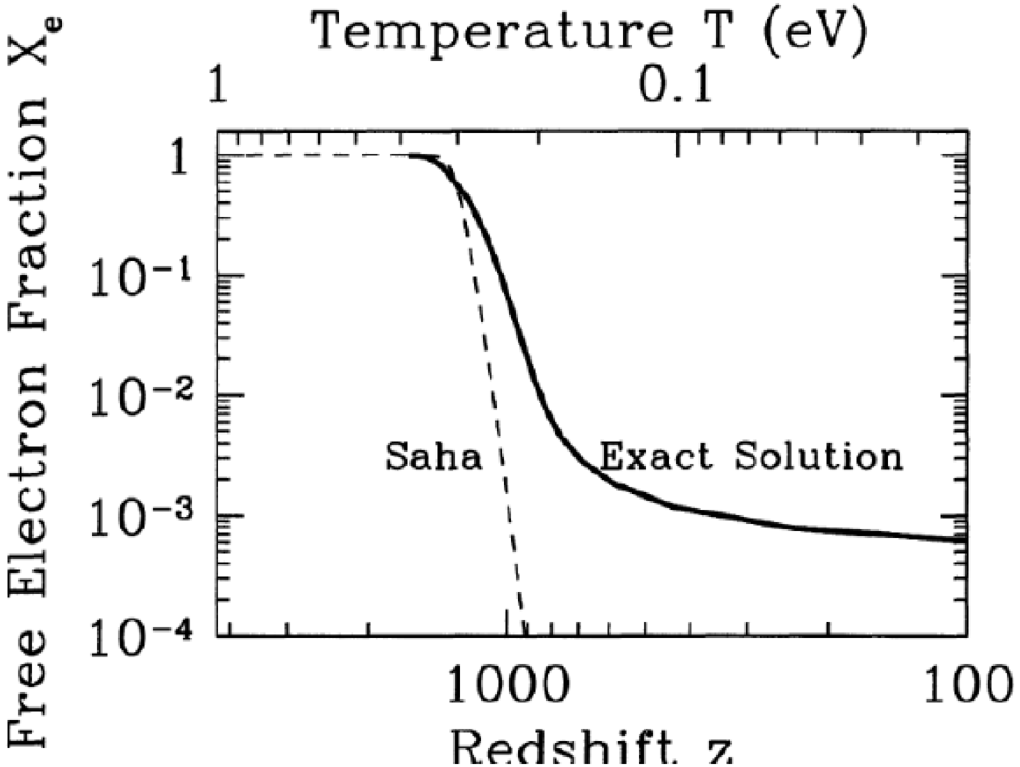
Rekomb.postaje značajna

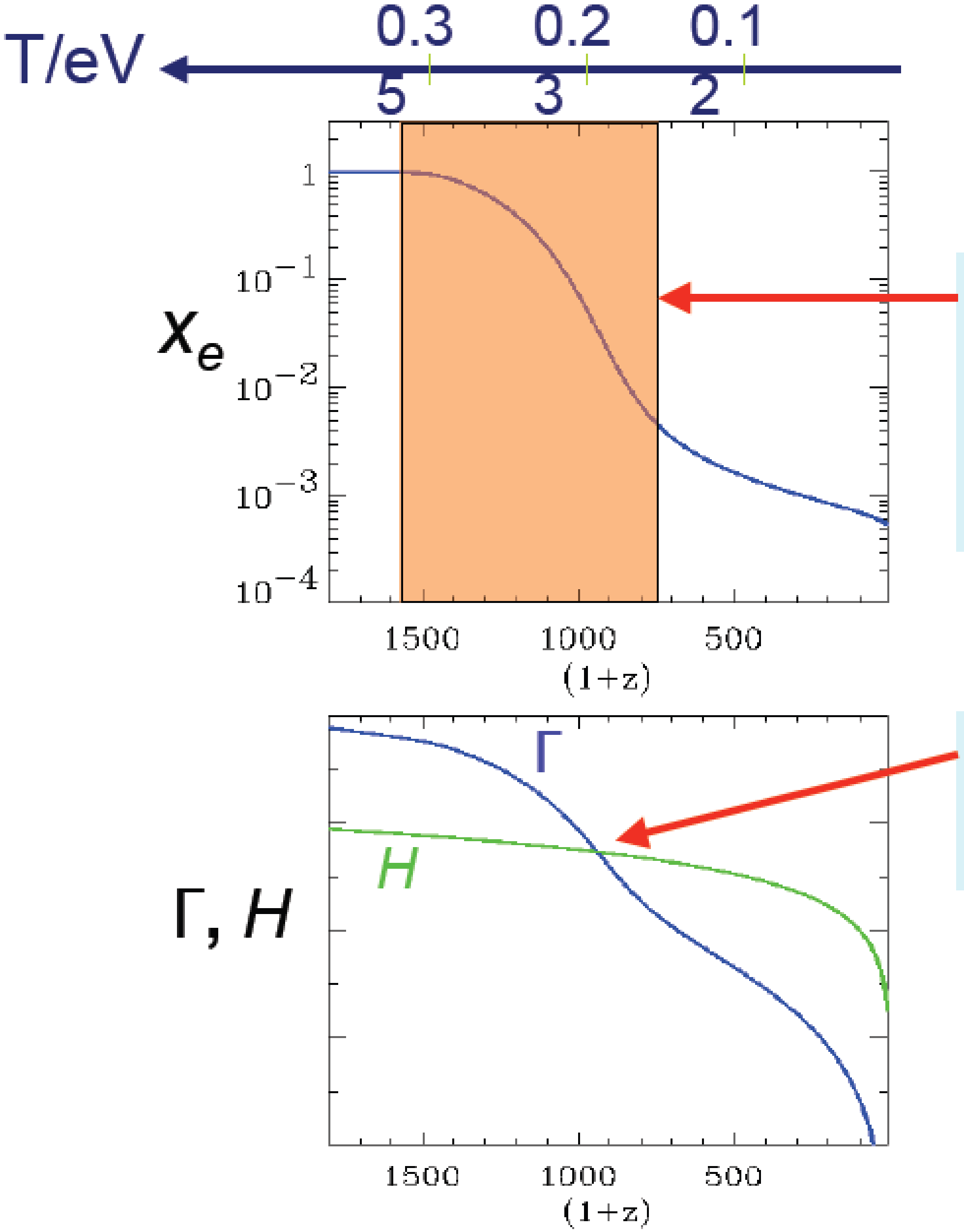
na T~ ¼ eV

to odgovara crvenom pomaku

z ~ 1000

odvezivanje fotona





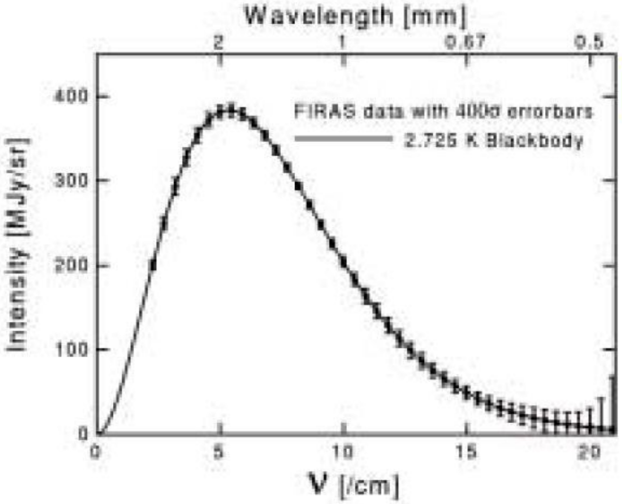
Recombination

(according to the Saha ionisation eq.)

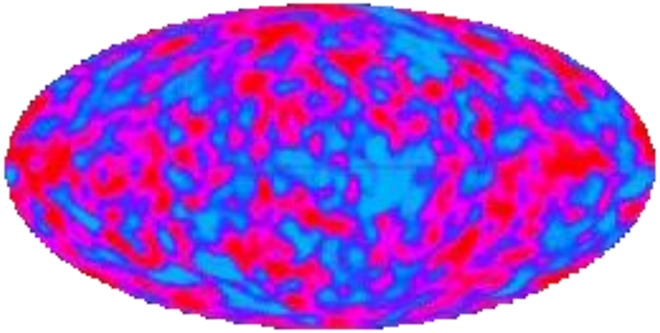
Decoupling of photons and baryons

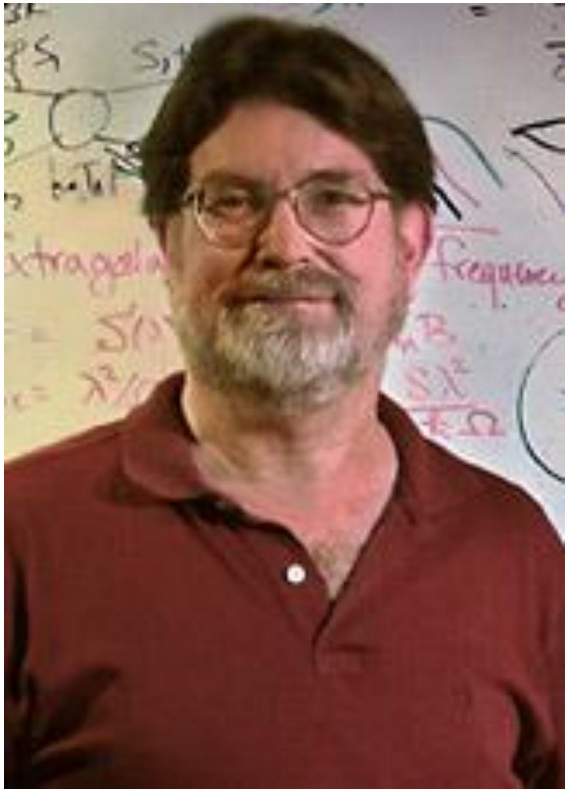
Nobelova nagrada iz fizike za 2006:

"za otkriće prirode CMB-a" – John C. Mather & George F. Smoot (vidjeti MFL 2/226, str. 104)

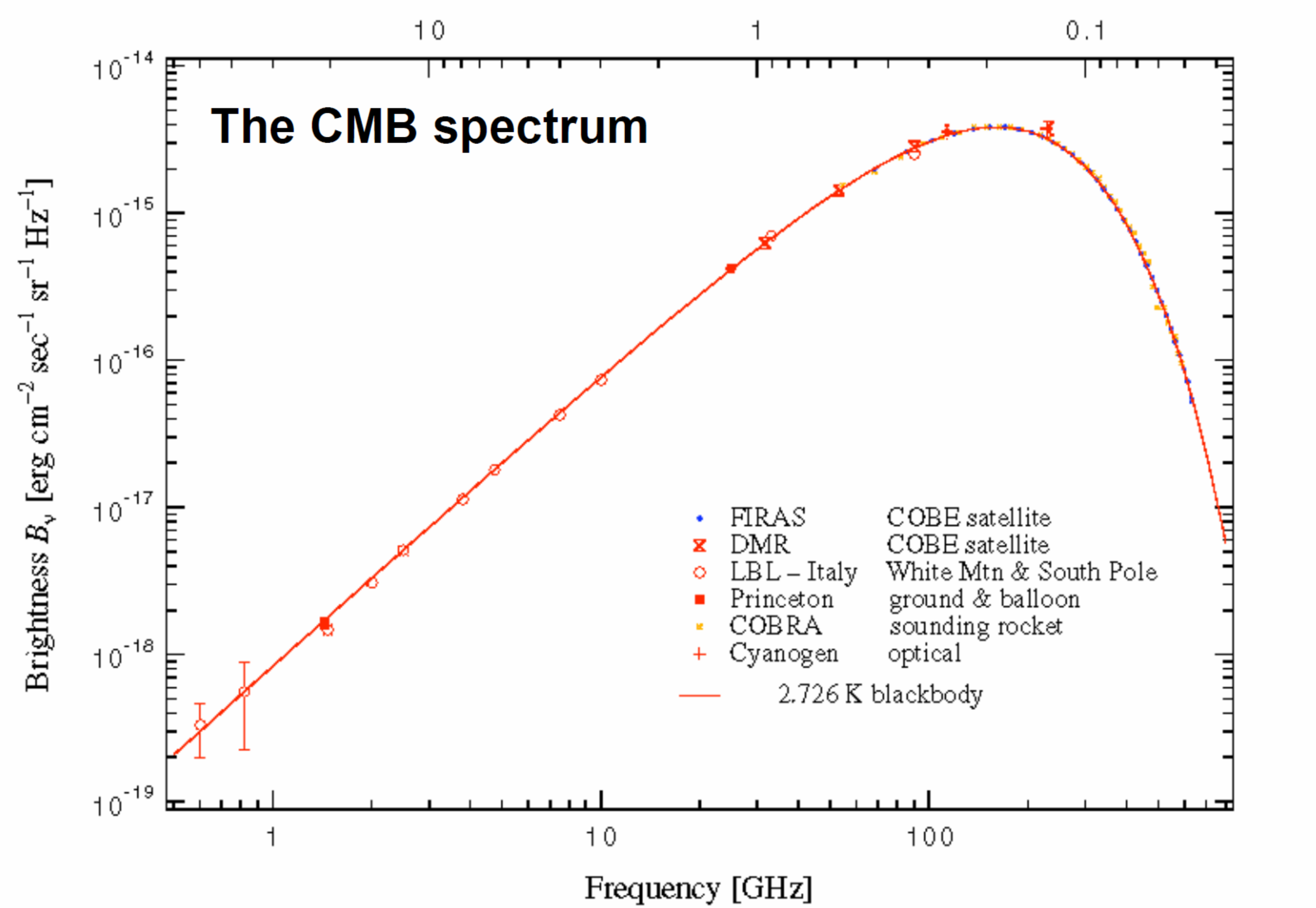


FIRAS spectrum (frequency vs. intensity) with errors expanded 400 times





The CMB spectrum



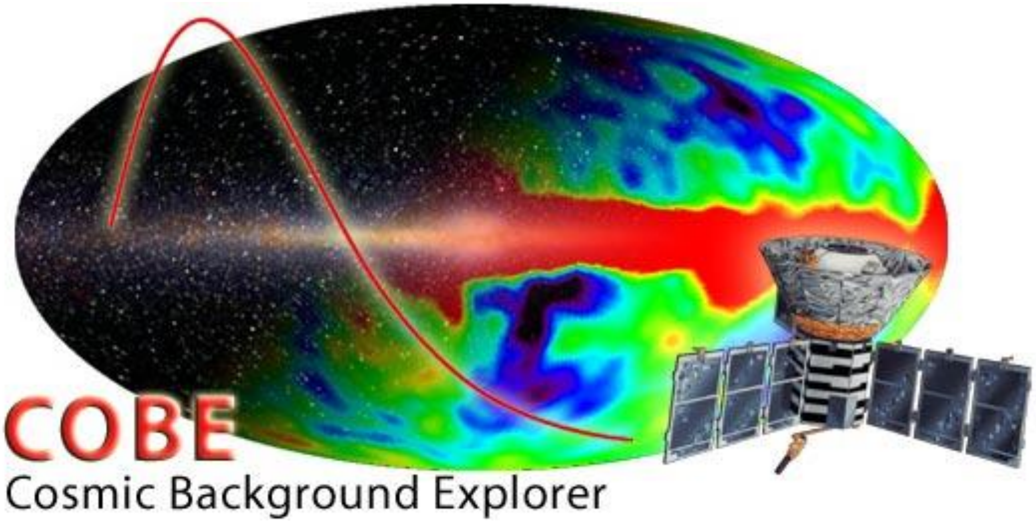
Such a perfect blackbody is testimony to our hot, dense past

POZADINSKO ZRAČENJE (CMB) - spektar zračenja crnog tijela, za DZ:

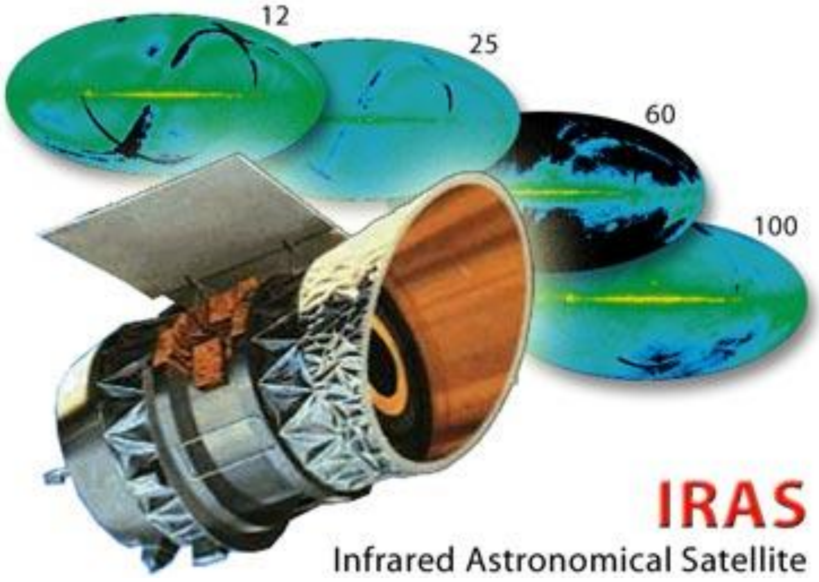
- OBLIK SPEKTRA OČUVAN PRI EKSPANZIJI SVEMIRA
- SPEKTAR CRNOG TIJELA U SVAKOM INERCIJALNOM SUSTAVU
- PROBLEM HORIZONTA

SATELITSKI POKUSI (MJERENJA POZADINSKOG ZRAČENJA)

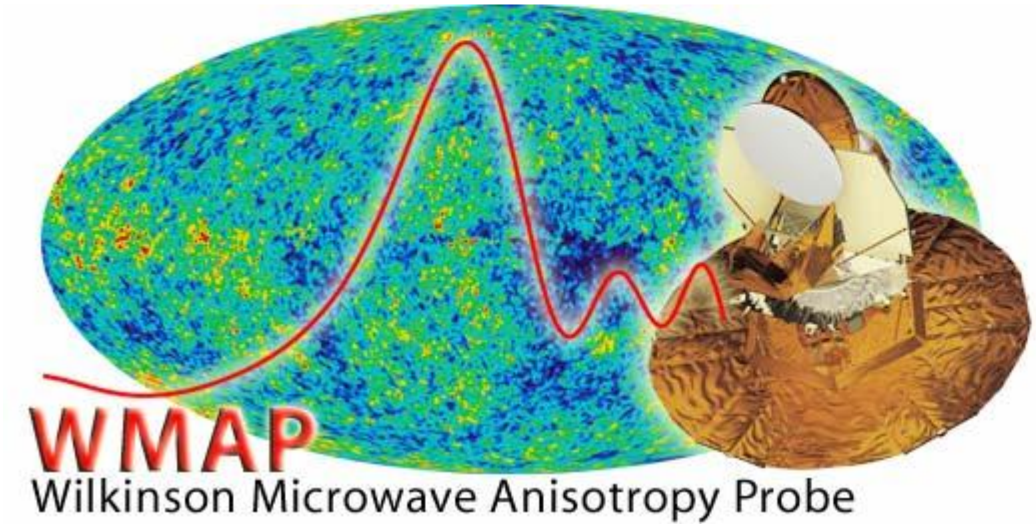
1989 – 93.



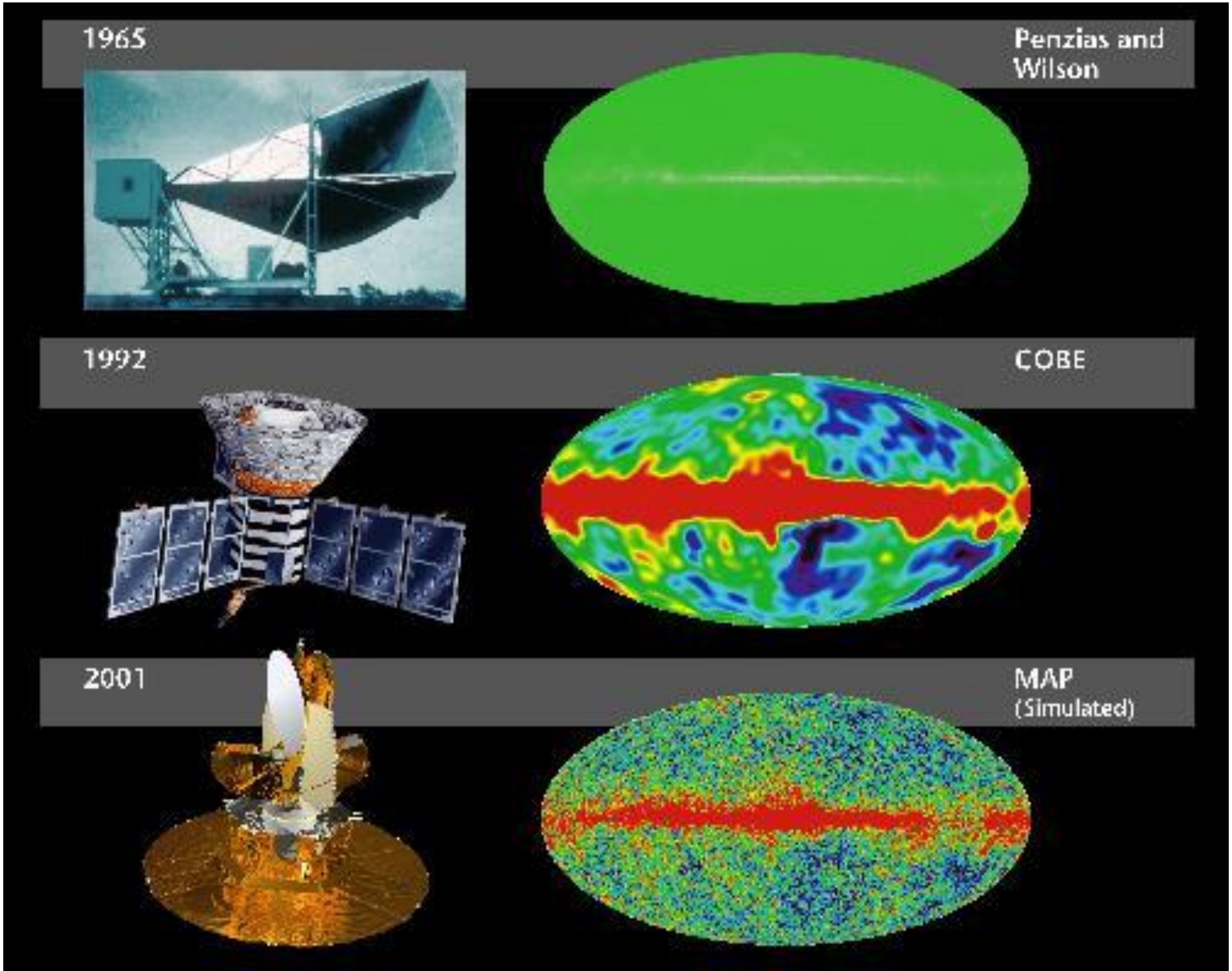
1983.



2001 –



POZADINSKO MIKROVALNO ZRAČENJE



ESA lansirala Herschel Space Laboratory i PLANCK Satelite

DIPOLNA ANIZOTROPIJA CMB-a

Motion of the Earth wrt to the CMB retains exactly the thermal spectrum, but the temperature is boosted:

(1) $$T_{\mathrm{obs}} = \mathcal{D} T_0$$

where $\mathcal{D}$ is the general form of the Doppler factor:

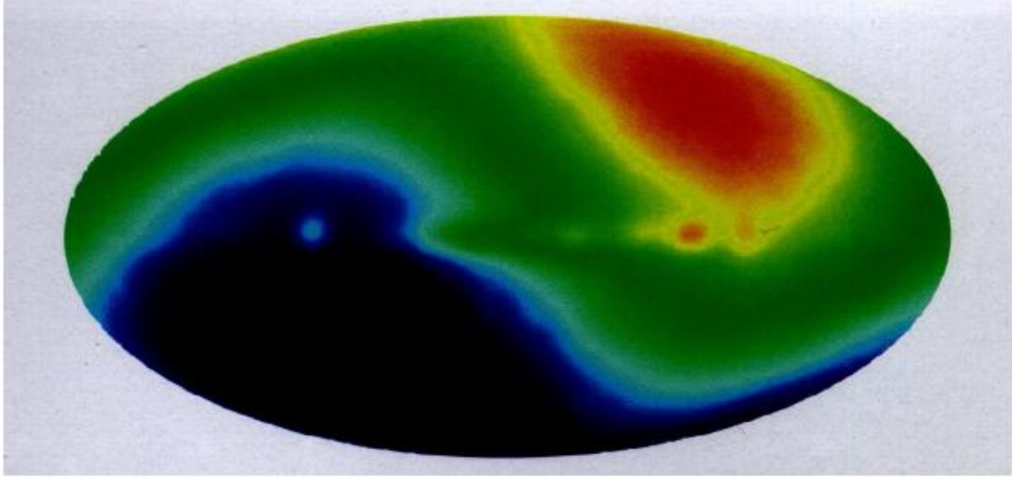
(2) $$\mathcal{D} = \gamma^{-1}[1 - (v/c)\cos\theta]^{-1}$$

(3) $$T_{\mathrm{obs}} = \frac{T_0}{\gamma[1 - (v/c)\cos\theta]}$$

which can be expanded as a series of multipoles:

(4) $$T_{\mathrm{obs}} = T_0\left[1 + \frac{v}{c}\cos\theta + \frac{1}{2}\left(\frac{v}{c}\right)^2 \cos 2\theta + O(v^3)\right]$$

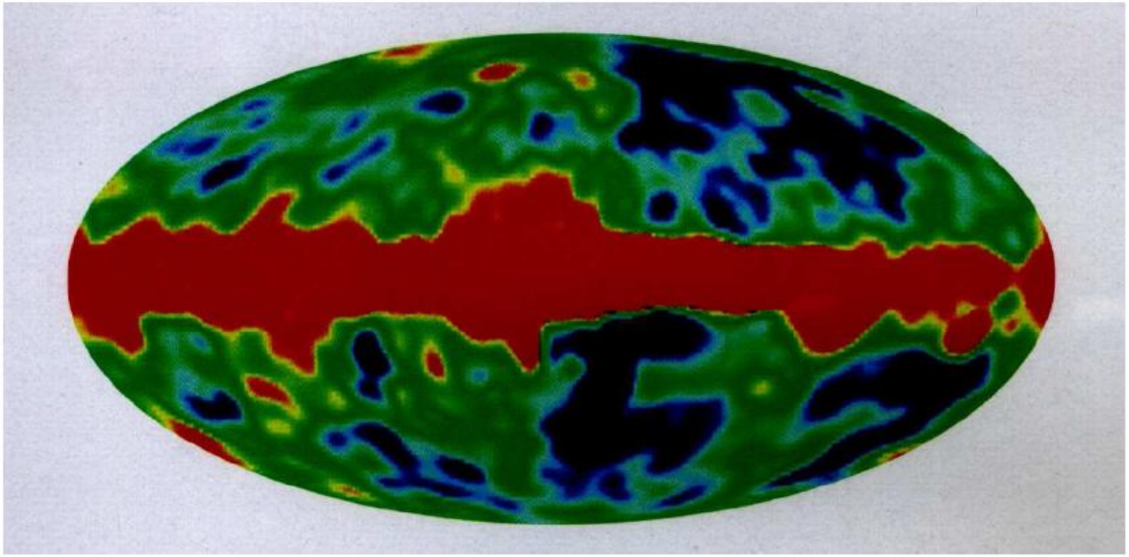
DIPOLNA ANIZOTROPIJA CMB-a



COBE measured: $v = 371 \pm 1\,\mathrm{km\,s^{-1}}$, which gives T
differences of about 3 mK in each direction.

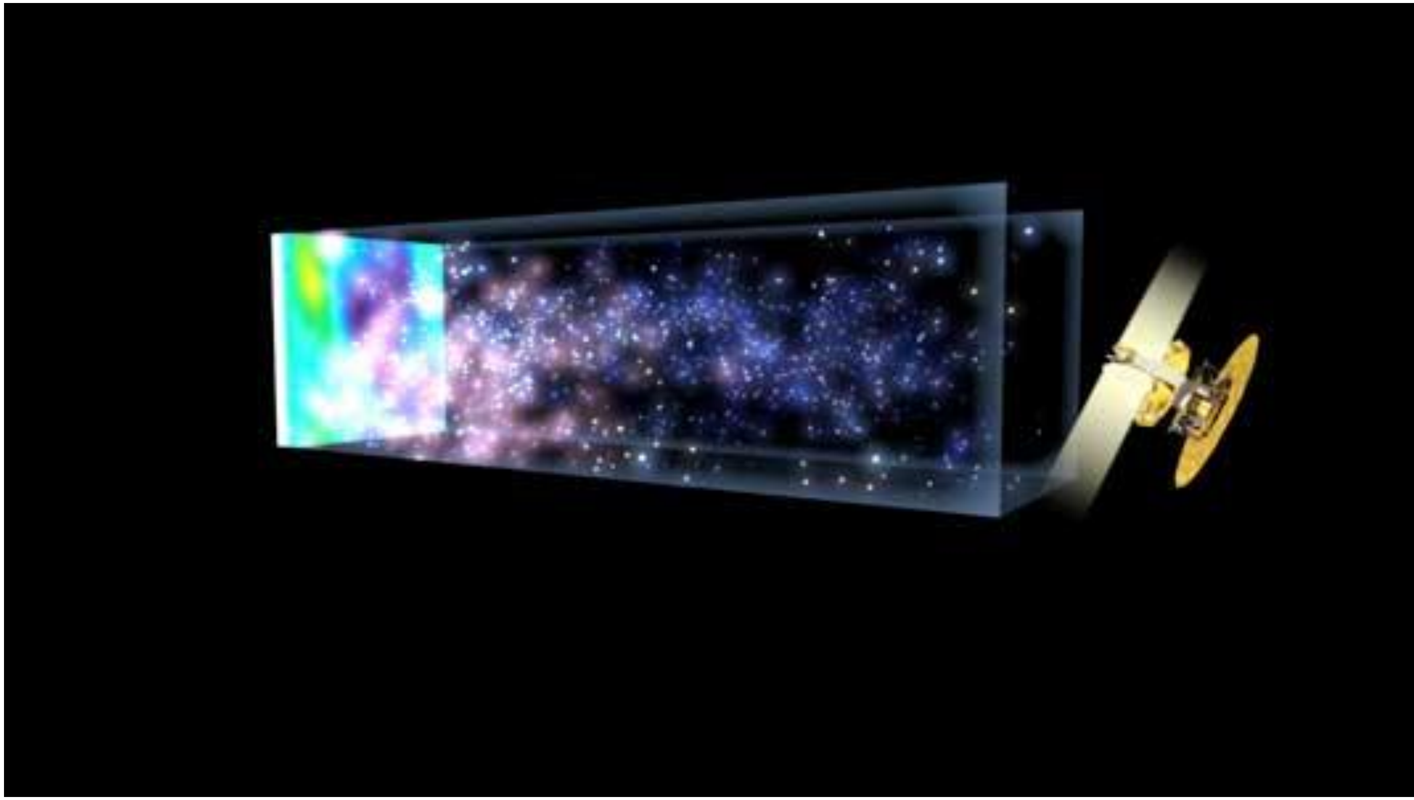
ANIZOTROPIJA 1 u 100 000

The view from COBE

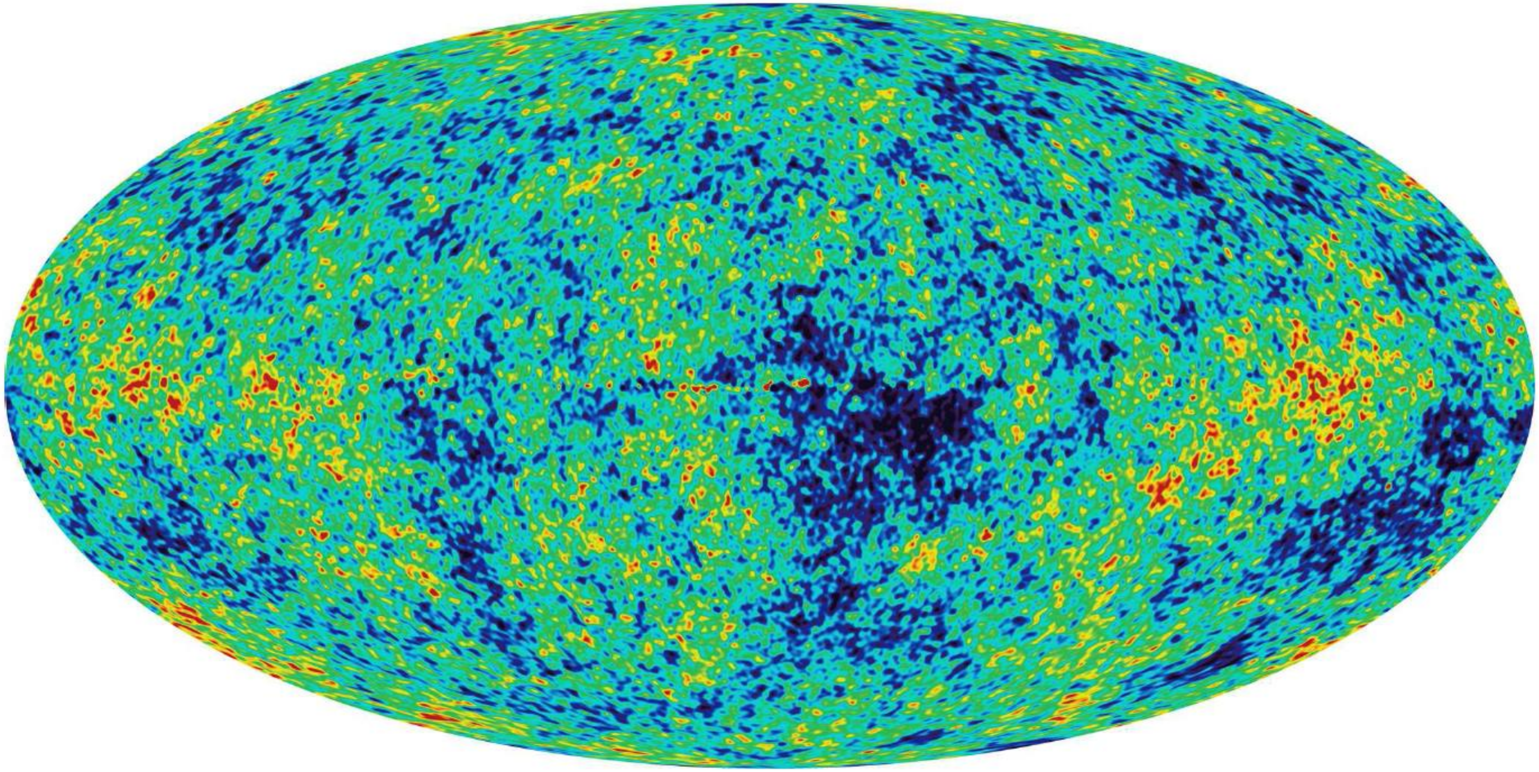


The map is in galactic co-ordinates. The red stripe is emission from the galactic plane.

PORIJEKLO STRUKTURA NA NAJVEĆOJ SKALI – u kvantnim fluktuacijama sa samog početka svemira



ANIZOTROPIJA nastala na z= 1100 –sjeme formiranja opaženih struktura u svemiru



NASA/WMAP science team

Spektar intenziteta zračenja – ("power spectrum"), gdje se temp. fluktuacija oko srednje temp. u smjeru α izražava **autokorelacijskom funkcijom:**

$$C(\theta) = \langle \frac{\delta T}{T}(\alpha)\frac{\delta T}{T}(\alpha+\theta)\rangle$$

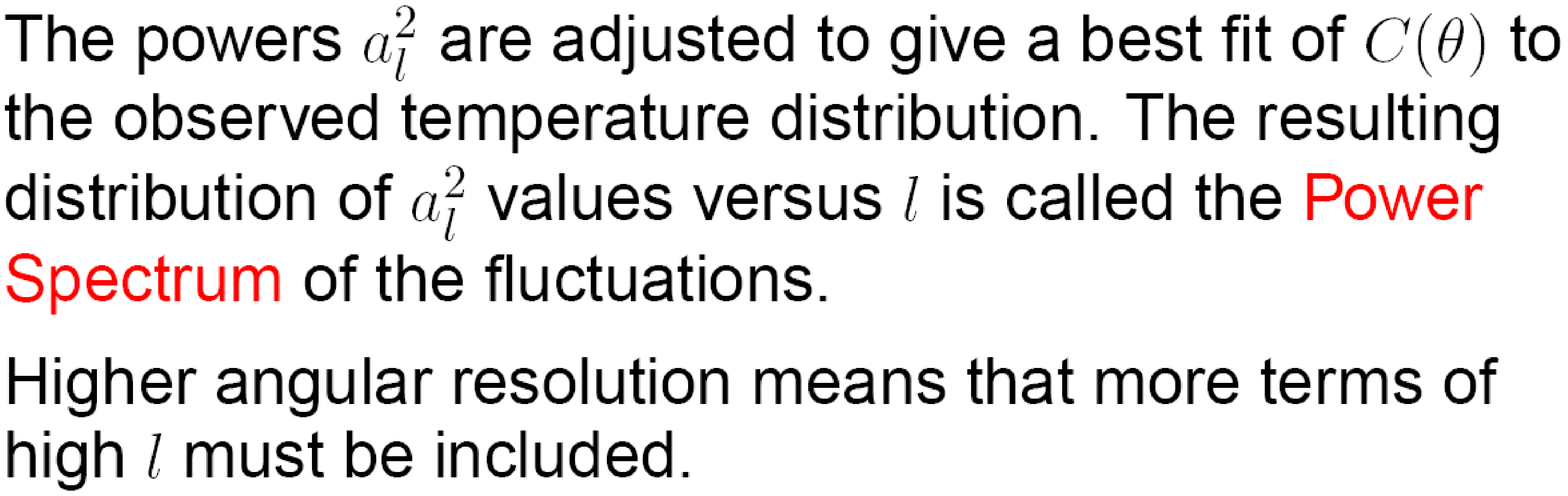
MULTIPOLNI RAZVOJ

$$C(\theta) = \frac{1}{4\pi}\sum_{l=2}^{\infty} a_l^2 (2l+1) P_l(\cos\theta)$$

- ***l=0*** **–srednja temperatura neba**
- ***l=1*** **– dipolna anizotropija**
- **Viši multipoli odgovaraju fluktuacijama kutnih veličina:**

$$\theta \approx \frac{180^\circ}{l}$$

Spektar intenziteta fluktuacija

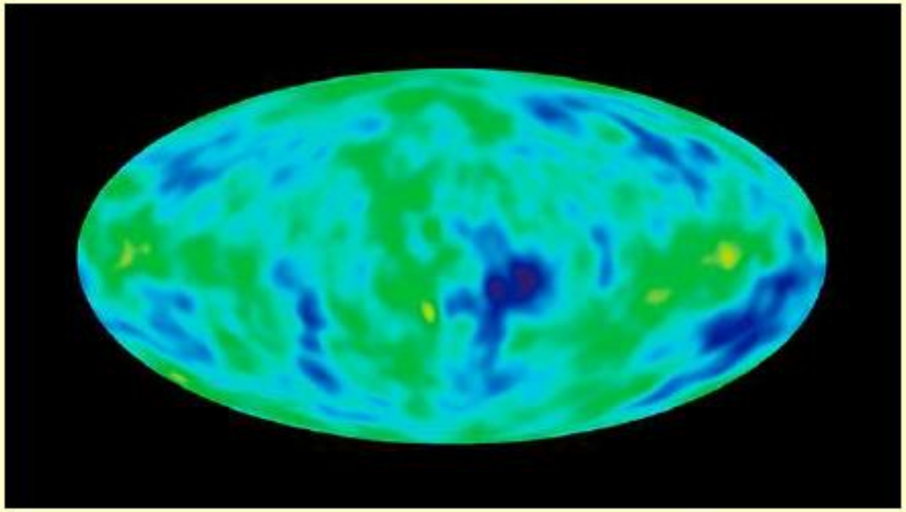


The powers a_l^2 are adjusted to give a best fit of $C(\theta)$ to the observed temperature distribution. The resulting distribution of a_l^2 values versus l is called the Power Spectrum of the fluctuations.

Higher angular resolution means that more terms of high l must be included.

ANIZOTROPIJE CMB-a

COBE (1993)

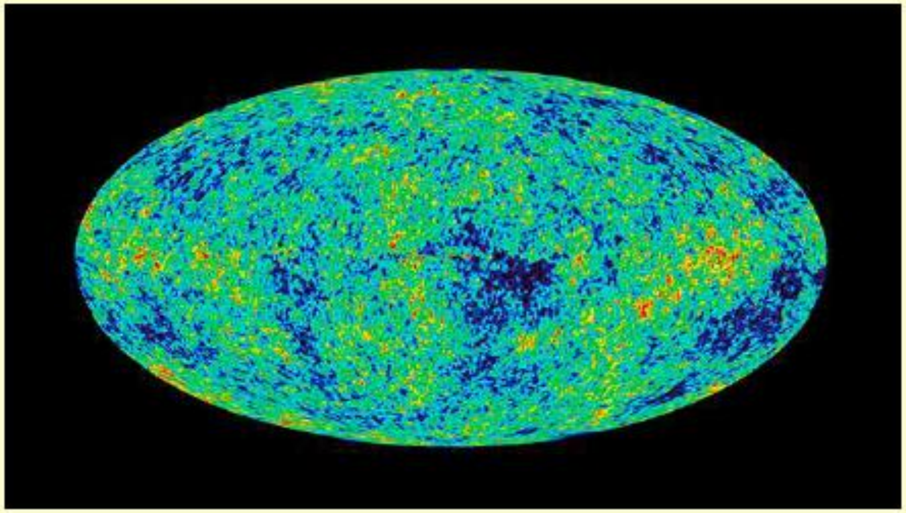


Sky map, all foregrounds subtracted

WMAP 7 years (2008)

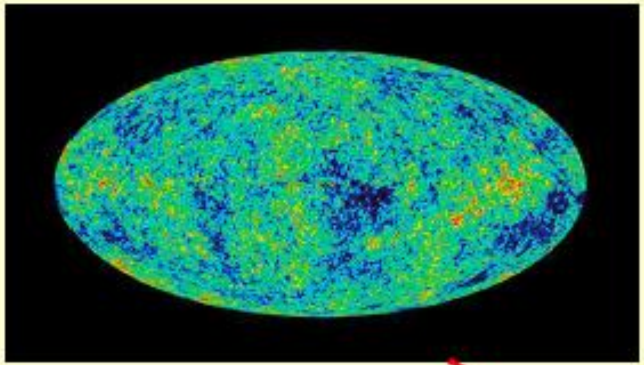
- CMB: anisotropies are very small:

$$\Delta T \sim 18\mu K \Rightarrow \Delta T / T \sim 10^{-5}$$



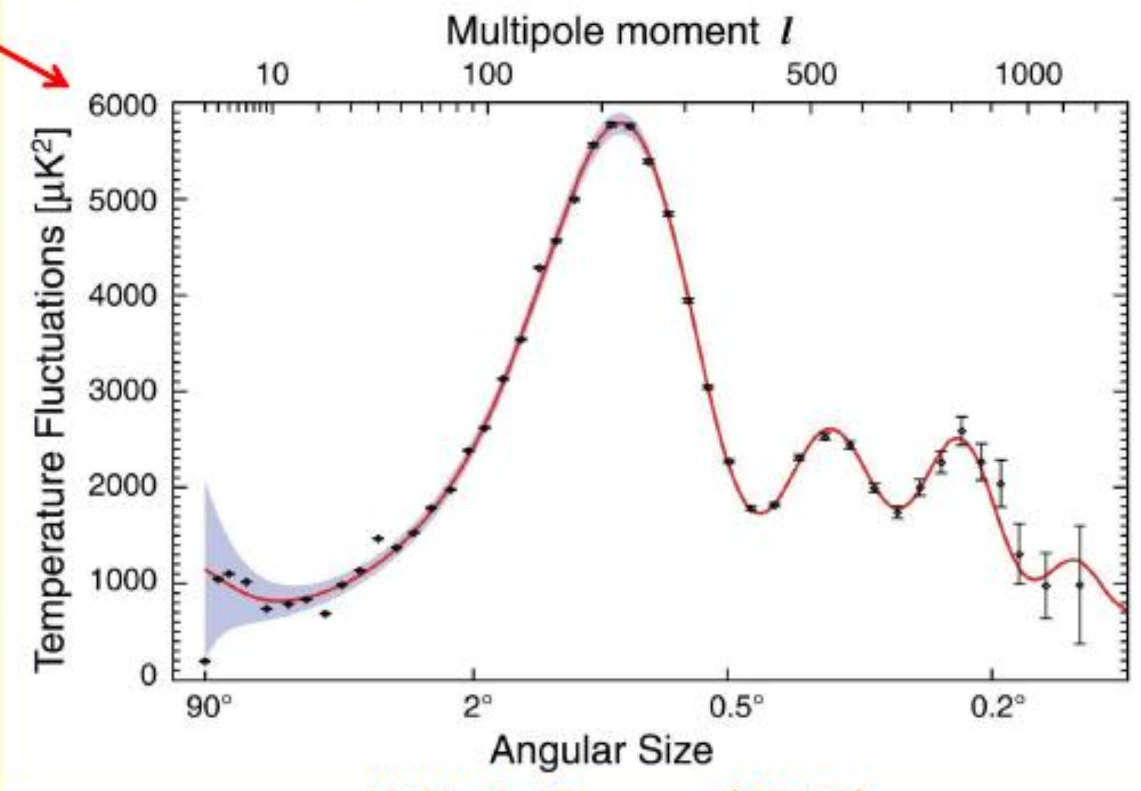
@WMAP web site

Analysis of T anisotropies



- Angular fluctuation spectrum:

strength of T fluctuations (hot and cold spots) as a function of angular size



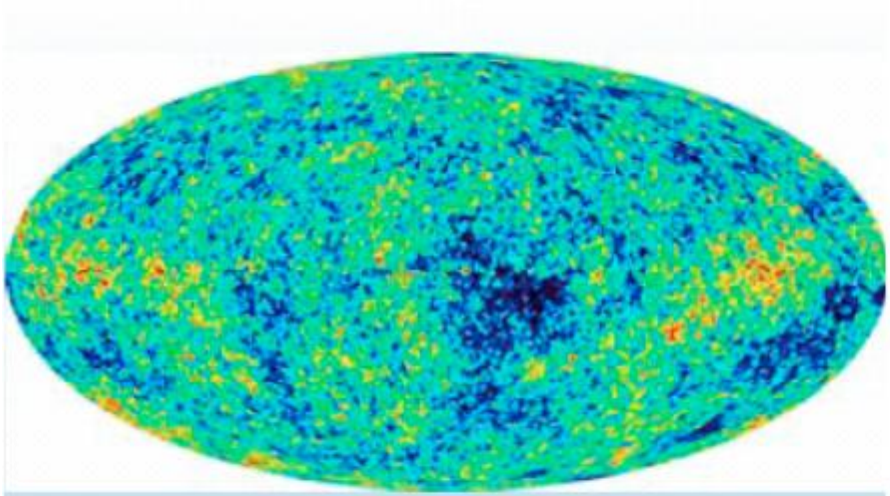
WMAP 7 years (2008)

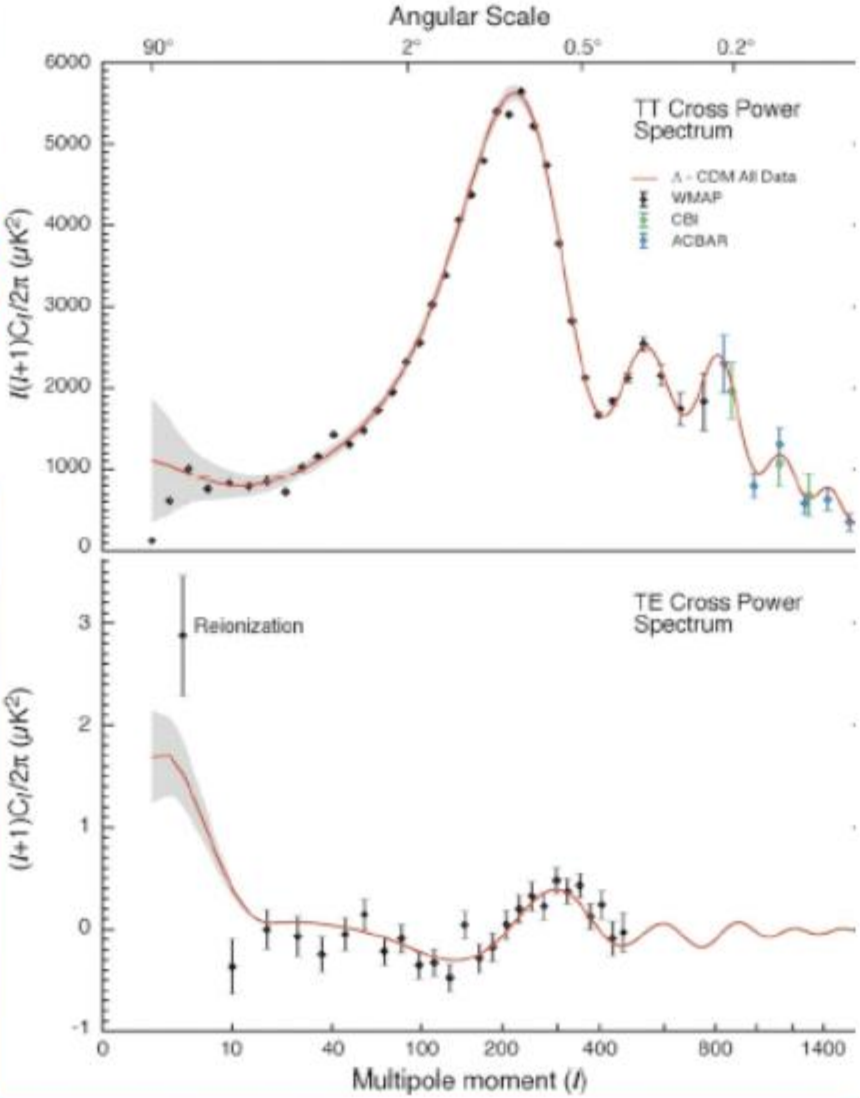
- main T fluctuations: angular size of ~1° (l~200)

$$\Delta\theta \approx \frac{\pi}{l} \approx \frac{s_*}{D_*}$$

s_* = distance traveled by sound since t=0 (sound horizon)

D_* = comoving distance to z_* (angular diameter distance)



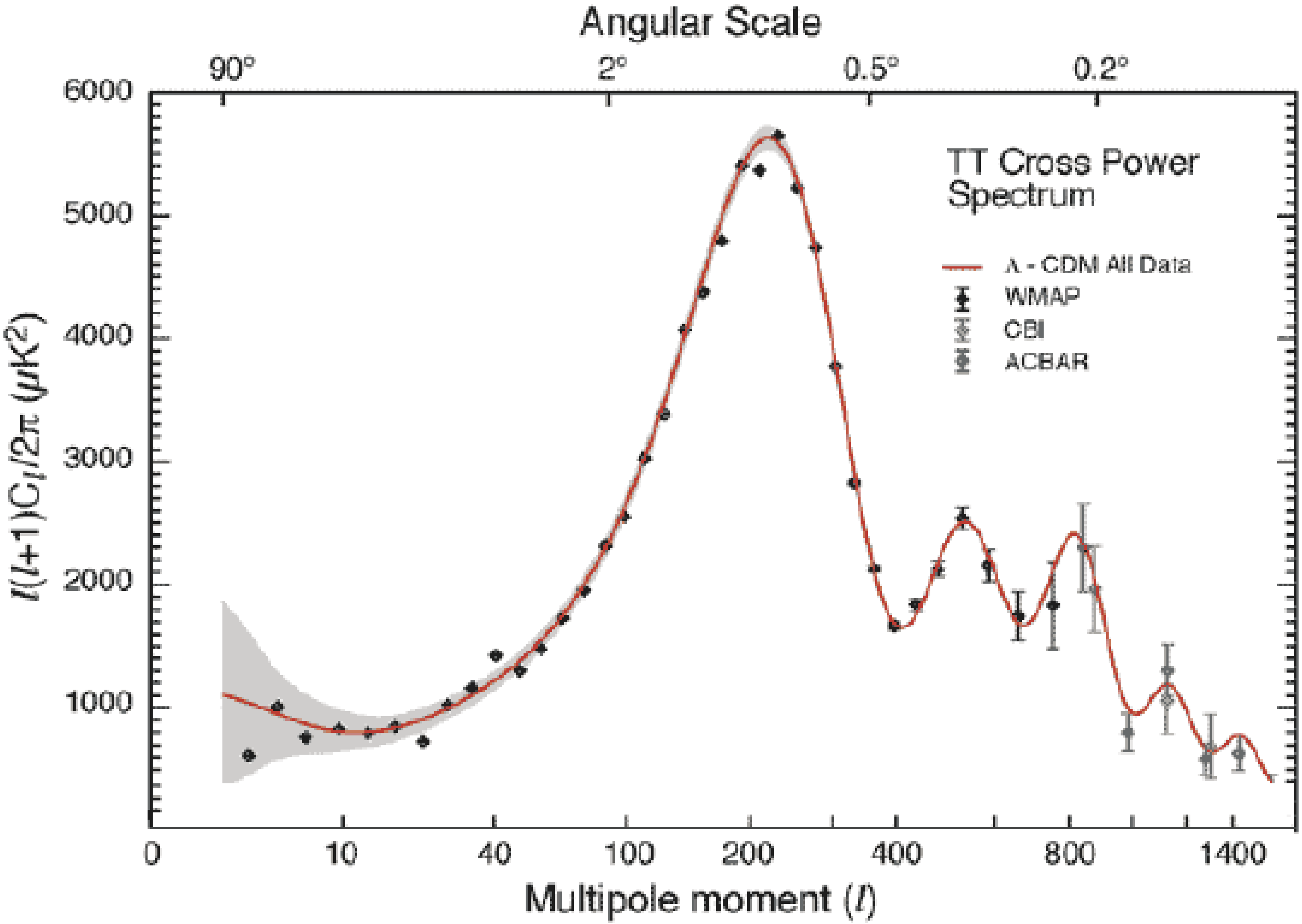


WMAP best fit (WMAPext + 2dFGRS + Lyman α +running sp. index)

$$\Omega_B h^2 = 0.0224 \pm 0.0009$$

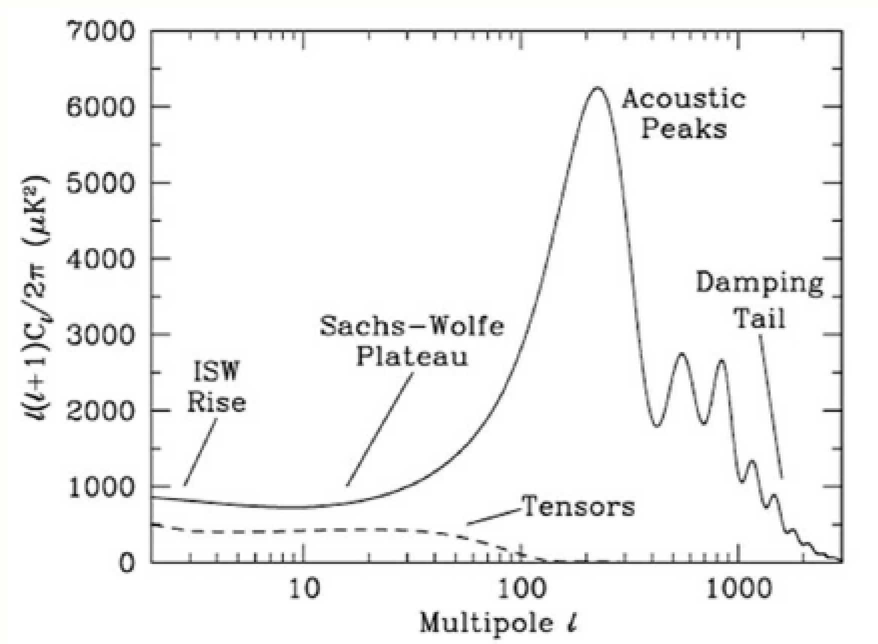
$$\eta_{10} = 6.14 \pm 0.25$$

Rezultati WMAPA-a

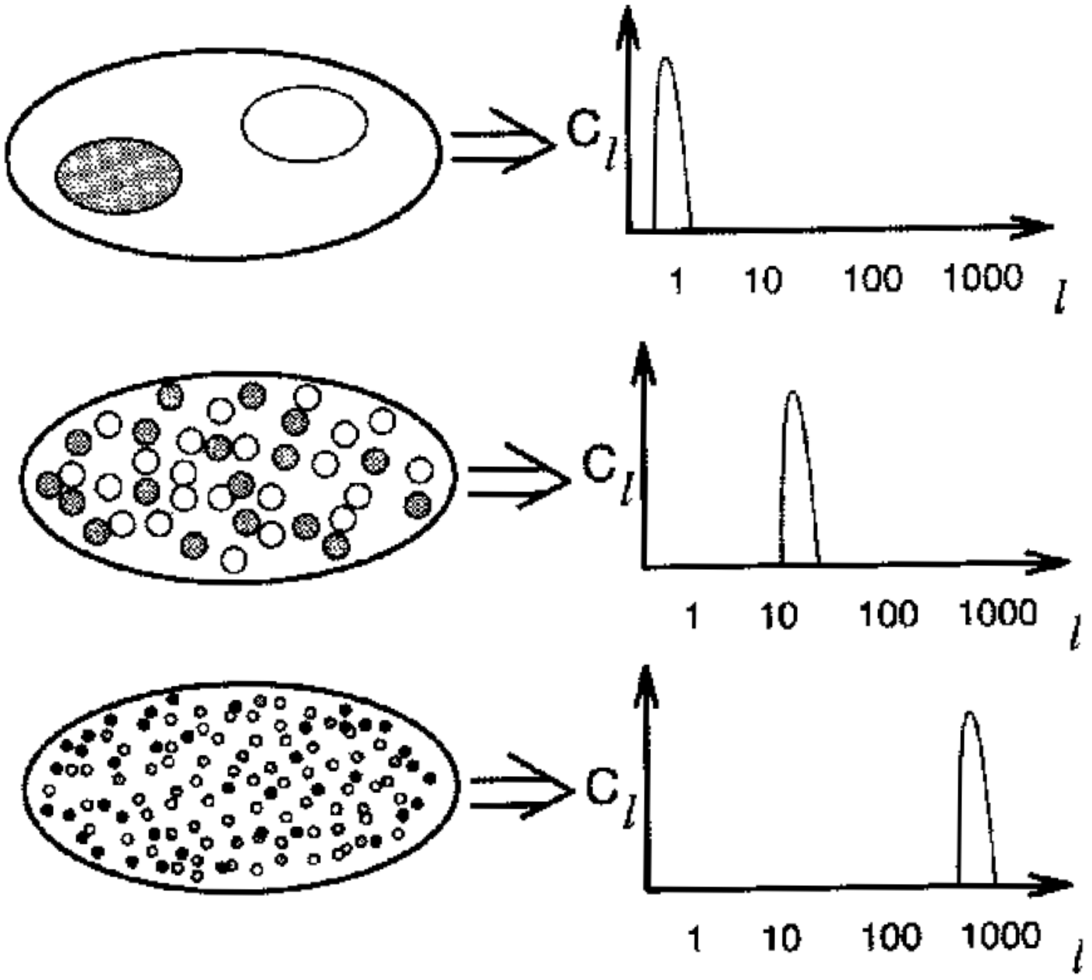


PORIJEKLO ANIZOTROPIJA

- variations in the density or velocity of the plasma at the last scattering surface: acoustic peaks
- variations in the gravitational potential at the LSS or along the photon path: low multipole plateau (large scales)



KARAKTERISTIČNE SKALE ANIZOTROPIJA CMB-a



IZVORI ANIZOTROPIJA CMB-a koje nastaju u vrijeme rekombinacije

- **GRAVITACIJSKE/Sachs-Wolfeove** perturbacije
- **INTRISIČNE/adijabatske** perturbacije
- **DOPPLEROVE** perturbacije

Sachs-Wolfeov efekt

- **GRAVITACIJSKE/Sachs-Wolfeove perturbacije: fotoni koji izlaze iz područja veće (manje) gustoće, doživljavaju crveni (plavi) pomak pri penjanju uz (kotrljanju niz) gravitacijski potencijal. Gravitacijski crveni pomak (praćen dilatacijom vremena) vodi na fluktuacije (do 3 stupnja) ,**δT/T **koje su linearne u fluktuacijama gustoće** δρ/ρ:

$$\frac{\delta T}{T} \approx -\frac{1}{3}\left(\frac{L}{ct}\right)^2 \frac{\delta\rho}{\rho}$$

Intrisične perturbacije

- **U područjima velike gustoće zračenje je komprimirano i time dodatno ugrijano. Suptilnost je da gušća područja rekombiniraju kasnije – imaju manji crveni pomak i pojavljuju se kao vruća. Opažene temp. perturbacije:**

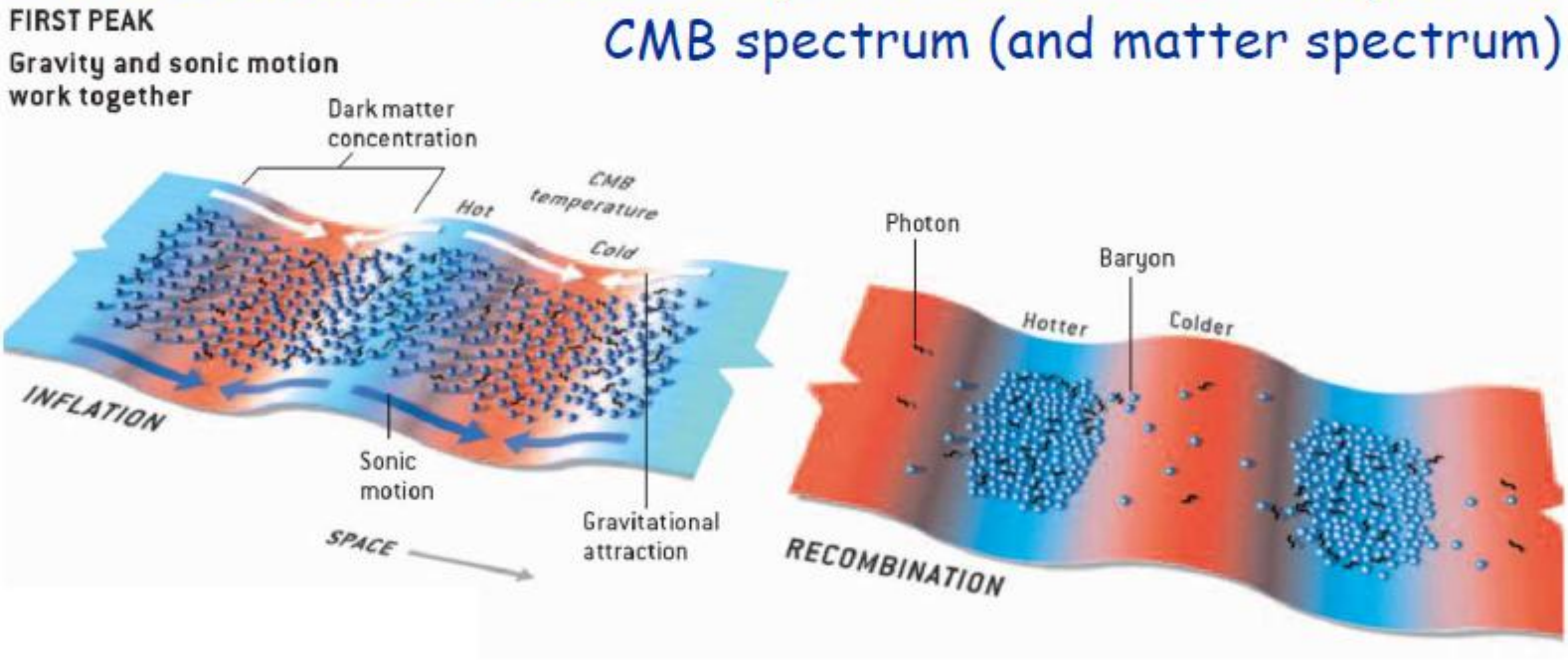
$$\left(\frac{\delta T}{T}\right)_{\rm obs} = \frac{\delta \rho}{\rho}$$

Dopplerove perturbacije

- **Konačna brzina plazme u vrijeme rekombinacije daje Dopplerove pomake u frekvenciji, a time i u temperaturi. Taj se efekt opaža na najmanjoj kutnoj skali**

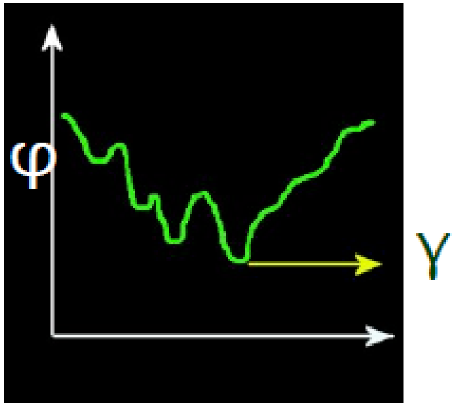
PORIJEKLO ANIZOTROPIJA

- dark matter collapse creates over-densities, making the photon-baryon plasma to oscillate into and out of these over-densities.
- At recombination: oscillation pattern is frozen ⇒ imprint in CMB spectrum (and matter spectrum)

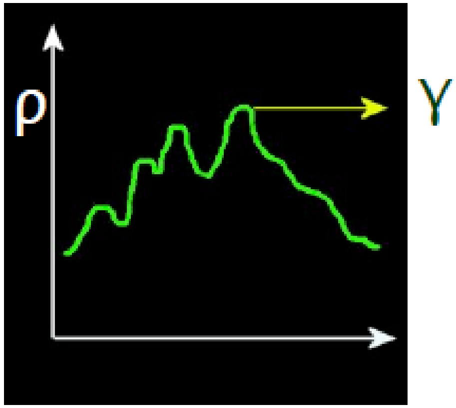


Hu and White, Scientific American, 2004

Fluctuations in the matter density → fluctuations in the CMB temperature

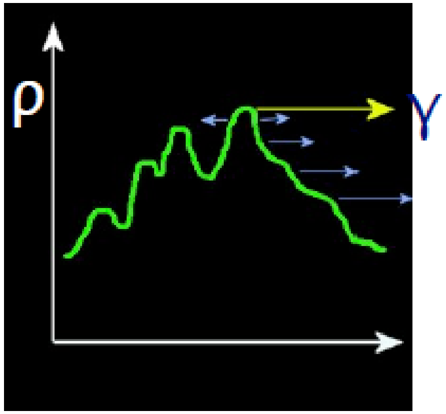


Photons are redshifted as they move out of gravitational potential wells



Dense regions have higher temperature

⇒ photons have higher energy



Photons emitted from a moving surface are red/blue-shifted

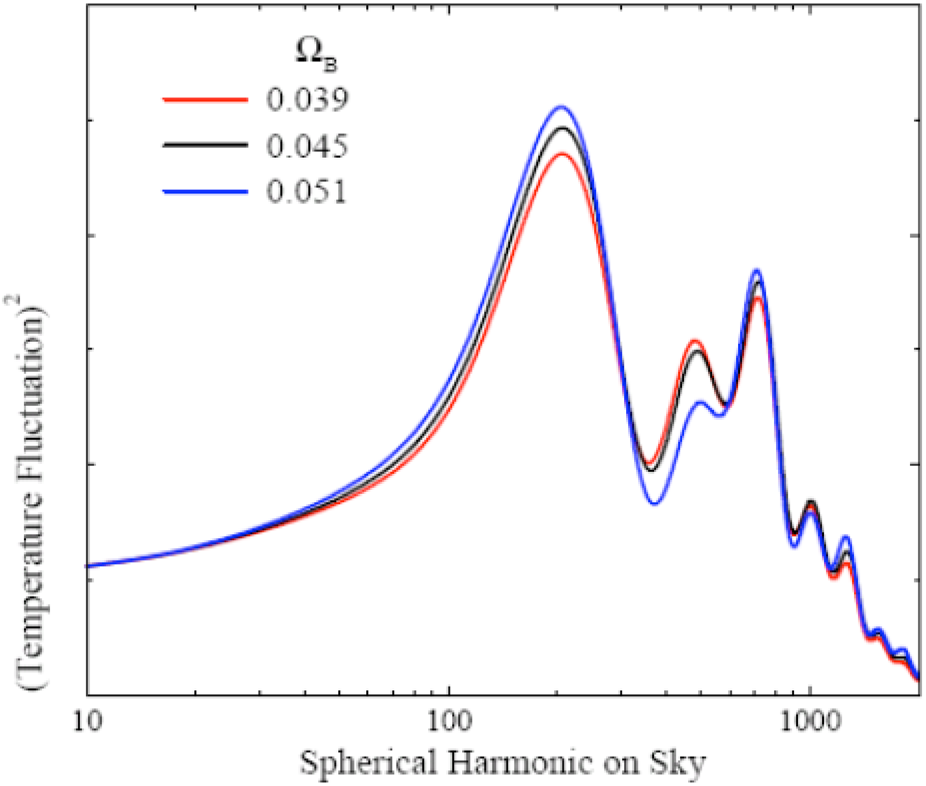
Fortunately the effects do not *quite* cancel so the CMB carries a memory of the past

CMB KAO "BARYOMETAR"

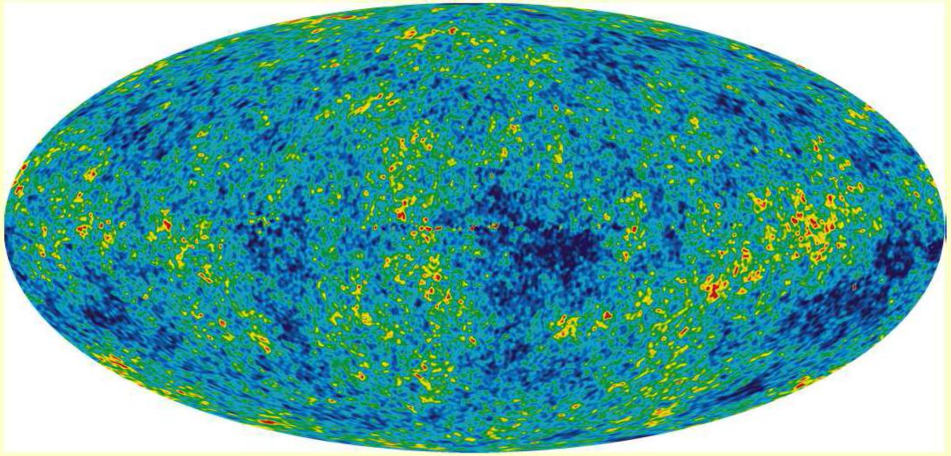
ΔT_ℓ provide *independent* measure of $\Omega_B h^2$

Acoustic oscillations in (coupled photon-baryon fluids Imprint features at < 1° in angular power spectrum

Peak positions and heights sensitive to cosmological parameters e.g.
Ratio of 2nd peak/1st peak ⇒ baryon density



BBN vs CMB determinations of baryon density → fundamental test of cosmology and thermal history at $z \sim 10^3 - 10^{10}$



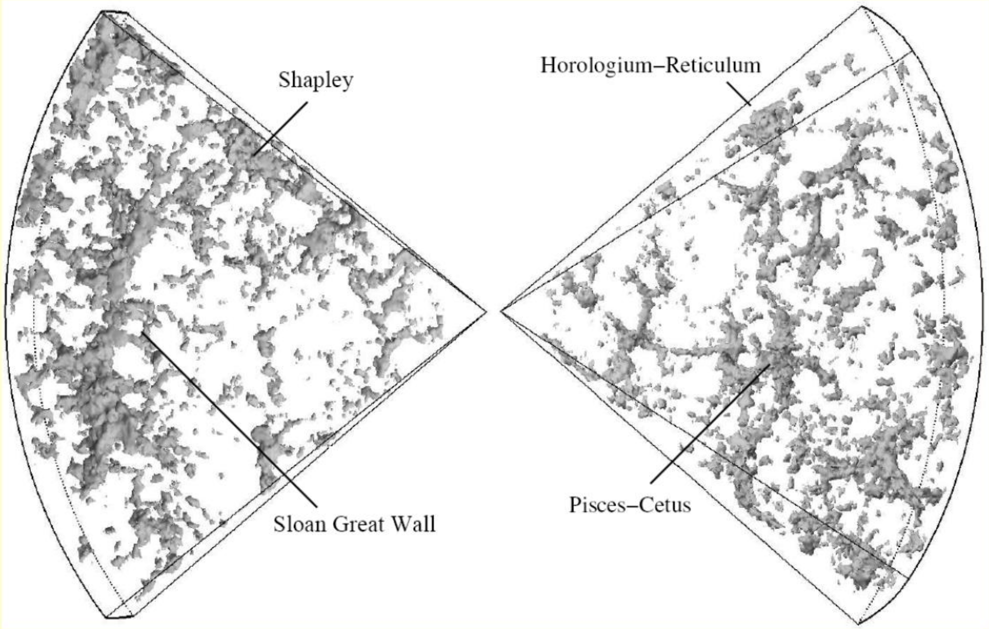
WMAP (2008), all foregrounds subtracted

- CMB: very small anisotropies

$$\Delta T/T = 10^{-5}$$

- matter density inhomogeneities, amplified by gravitation after decoupling → structures

- Large scale structures today: galaxies, clusters, superclusters, voids and filaments
- Formation of structures: cold dark matter mandatory



2dF Galaxy Redshift Survey, (2007)

A possible scenario