II. The Thermal Beginning of the Universe: CMB

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CMB discovery time-line

-1947-1948 Gamow, Alpher and Hermans model of nucleosynthesis predicts relic millimeter radiation, but the models´ difficulties to produce elements heavier than Li, leads to its neglect.

-1965 Arno Penzias & Robert Wilson´s serendipitous discovery of a constant excess isotropic noise with their antena at Bell Labs (Nobel 1978).

-late 60´s many groups made measurements of the intensity of the radiation and a temperature collectively showing the spectrum is that of a BB (to 10% accuracy)

-1969 Tentative detection of a dipole anisotropy by Conklin, confirmed in 1971-1977 by Henry, Wilkinson, and Smooth et al.

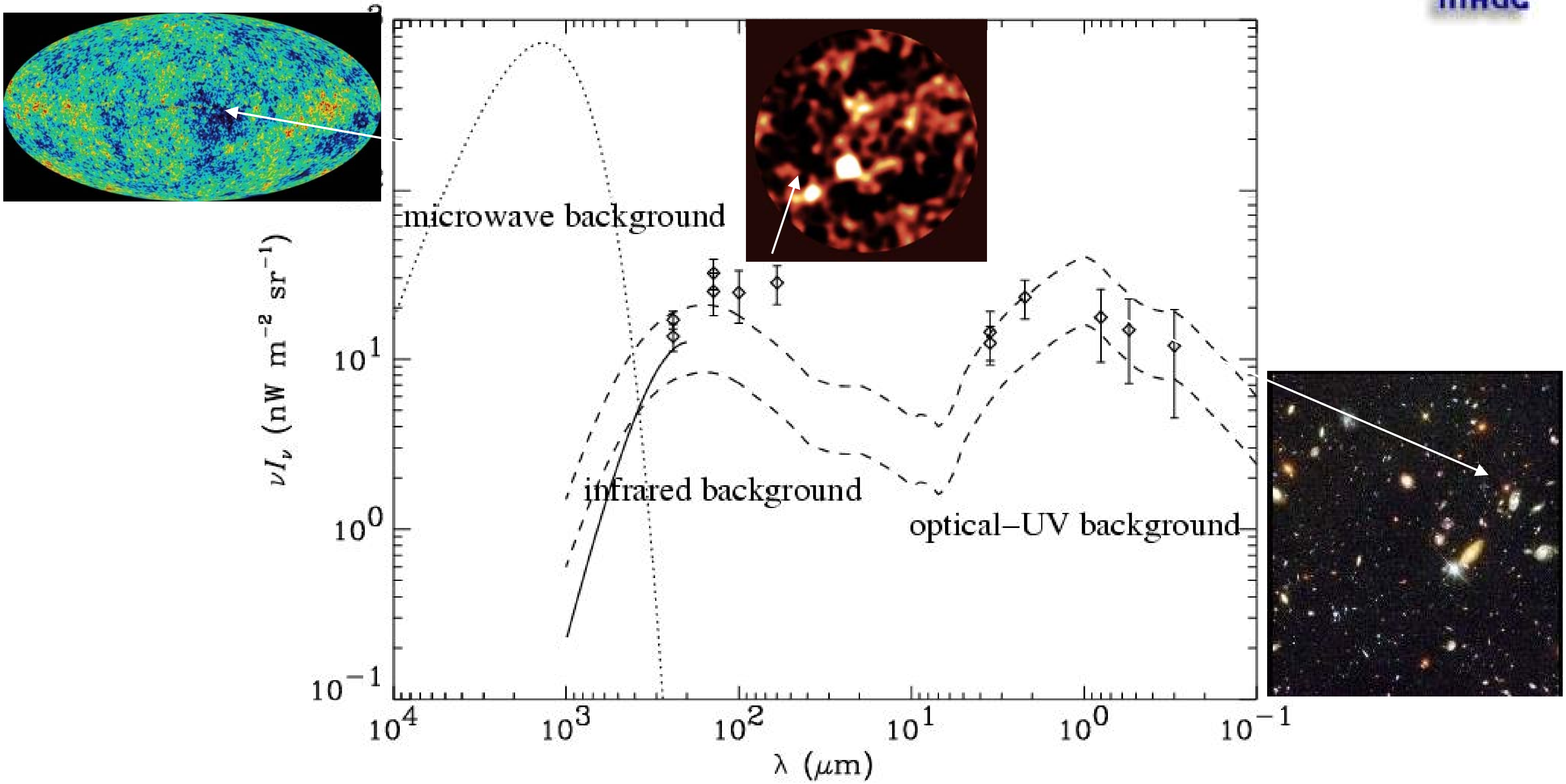
-1989 COBE (COsmic Background Explorer) launched, in 1990 first results confirming BB spectrum.

-1992 COBE's detection of non-dipole anisotropies (Nobel 2006 for inst. PI's George Smooth & John Mather).

-2003 WMAP results on precission cosmology through CMB anisotropies

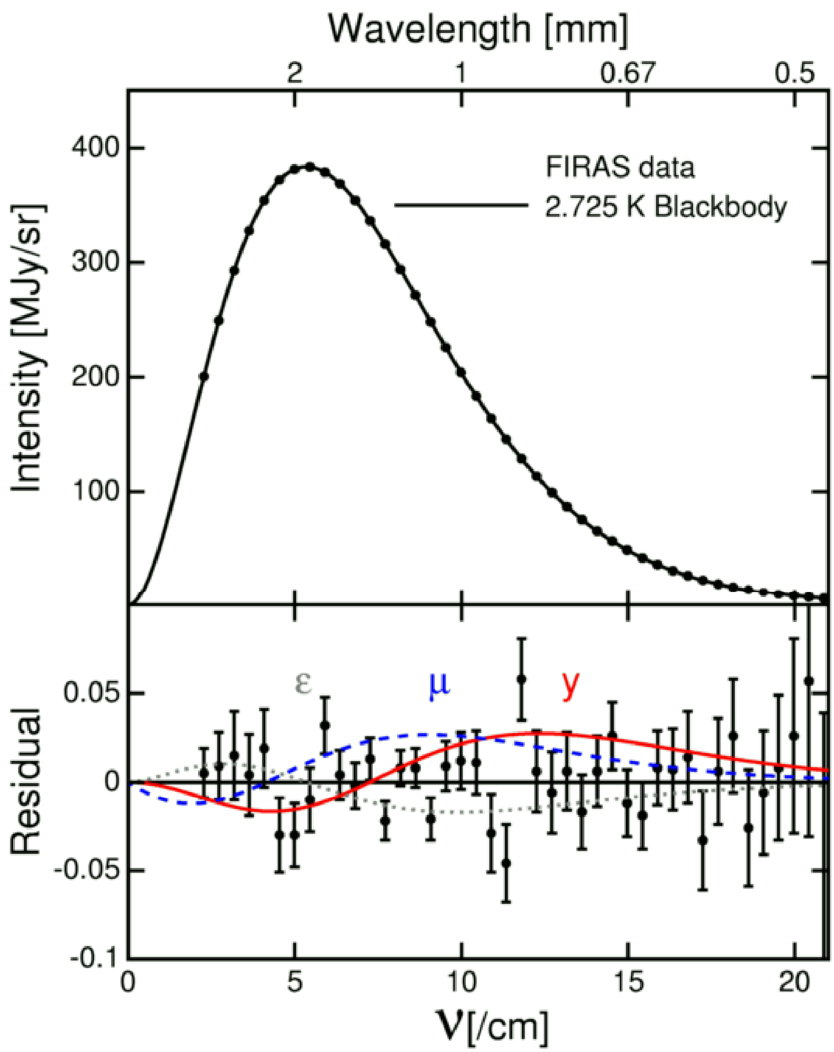
(Following E. Wright's CMB review paper)

Dominant background radiation

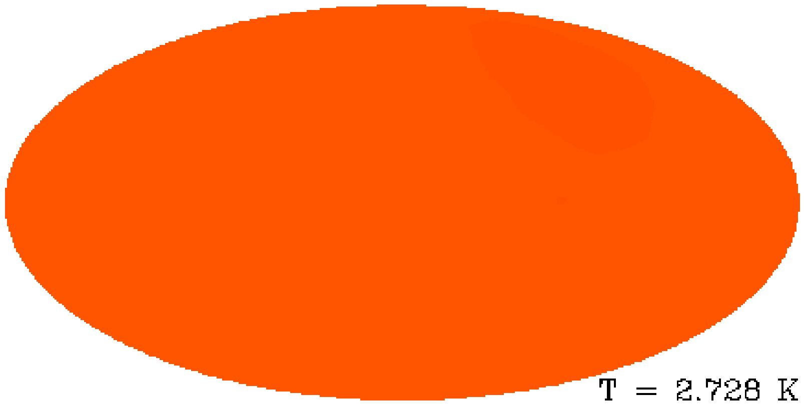


The photons of the CMB are still the largest contributors to the radiation energy in the Universe.

CMB spectrum



(Fixen & Mather 2002)



An almost perfect BB was measured by the FIRAS instrument aboard COBE when it was compared to a very good BB calibrator.

T=2.725±0.002 K

(Following E. Wright's CMB review paper)

CMB spectrum

The energy density of this radiation is

$$\varepsilon_{rad} = \rho_{rad} c^2 = aT^4 = 4.17 \times 10^{-14}\, Jm^{-3} \Rightarrow \rho_{rad} = 4.63 \times 10^{-31}\, Kgr\, m^{-3}$$

$$a \equiv 4\sigma / c = 7.565 \times 10^{-16}\ \mathrm{Jm}^{-3} K^{-4}$$

Dividing this by the critical density $\rho_c = \frac{3H^2}{8\pi G} = 1.88\, h^2 \times 10^{-26} Kgr\, m^{-3}$

we obtain the CMB density parameter $\Omega_{rad} = 2.47 \times 10^{-5}\, h^{-2}$

Because $\rho \propto T^4$, and $\rho \propto a^{-4} \Rightarrow$ $T \propto 1/a$ a scale factor

The radiation was hotter and had a higher energy density in the past

But was it a blackbody as well?

(From M. Georganopoulos' lecture lib)

CMB spectrum: *z* evolution

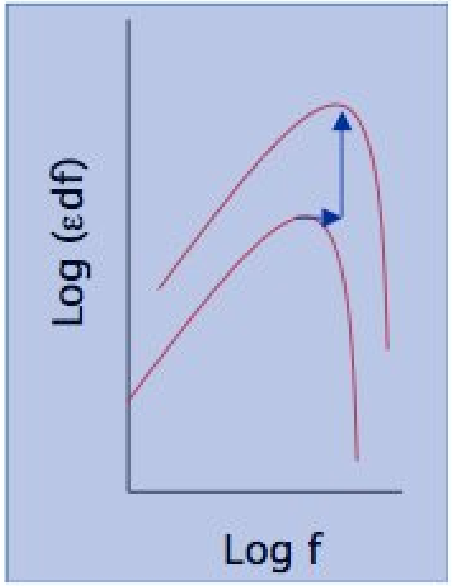
$$\varepsilon(f)df = \frac{8\pi h}{c^3}\frac{f^3 df}{\exp(hf/kT)-1}$$

Going to earlier times, as a decreases, T increases. The denominator is invariant for f/T=constant.

If a_1 is the scale factor at given instance in the past, the peak of the emission will be at $f_{1,peak} = f_{peak}/a_1$, since $T_1 = T/a_1$. Also,

$$f_{1,peak}^3 df_{1,peak} = f_{peak}^3 df_{peak}/a_1^4$$

The peak of the curve will shift up in frequency by a factor $1/a_1$ and up in energy density by a factor $1/a_1^4$. This is the case not only for the peak frequency but for any frequency:
<u>the blackbody shape is preserved, shifting up in frequency by $1/a_1$ and in energy density by $1/a_1^4$.</u>



(From M. Georganopoulos' lecture lib)

CMB spectrum: *z* evolution

The almost perfect BB shape of the CMB backs up the expansion of the Universe, and the existence of a hotter earlier universe.

◆ If the CMB were just a tired relic light: $n_\gamma(z=0)=(1+z_e)^3 B_\nu(T_e)$ but FIRAS imposes that the factor in front of $B_\nu(T_e)$ is 1 with a precission better than 10^{-4}. Hence $(1+z_e)=1\pm1\times10^{-4}$ $\Rightarrow z_e<0.000033$ and opaque from that onwards. But we have sources at $z>1$! So this is not a possibility.

◆ If the steady model were correct, there would be no evolution. Today we see CMB + FIR radiation from stars and galaxies. Energy added between 1 month and a few thousand yrs after BB will produce

$$I_{BE}(\nu,T)=\frac{2\pi\nu^3}{c^2}\frac{1}{\exp(h\nu/kT+\mu)-1}$$

but there are no deviations to the BB spectrum

(Following E. Wright's CMB review paper)

Photon/baryon ratio

If no particles are created or destroyed, is this ratio conserved?

Yes, both photon and baryon number densities scale as $1/a^3$

What is the current number density of CMB photons?

Their energy density is :

$$\varepsilon_{rad} = aT^4 = 2.6 \times 10^5\, eV\, m^{-3}$$

Dividing this by their mean energy E_{mean}=3kT=7.05 10^{-4} eV gives

$$n_{rad} = \frac{\varepsilon_{rad}}{E_{mean}} = 3.7 \times 10^8\, m^{-3}$$

(From M. Georganopoulos' lecture lib)

Photon/baryon ratio

What is the current number density of baryons?

Their density parameter, derived from nucleosynthesis, is :

$\Omega_B \approx 0.02\, h^{-2}$ This can be converted into an energy density:

$$\varepsilon_B = \rho_B c^2 = \Omega_B \rho_c c^2 \approx 3.4 \times 10^{-11}\, J\, m^{-3} = 2.1 \times 10^8\, eV\, m^{-3}$$

Divide this by the proton rest mass, E_B=939 MeV: $n_B = 0.22\, m^{-3}$

Recall : $\varepsilon_{rad} = 2.6 \times 10^5\, eV\, m^{-3}, n_{rad} = 3.7 \times 10^8\, m^{-3}$

Currently: ›the baryon energy density dominates over that of CMB photons by ~1000.
›the CMB number density dominates over that of baryons by ~10^9. (valid for all times).

$$\Omega_B / \Omega_\gamma \approx 1000 \quad , \quad n_\gamma / n_B \approx 10^9$$

(From M. Georganopoulos' lecture lib)

CMB origin

$T \propto 1/a$ ->

In very early times, the energy of the CMB photons was much greater than the 13.6 eV required to ionize H. just a soup of photons, e and p (for simplicity, ignore the few He nuclei produced in nucleosynthesis).

All the mater in the Universe was ionized. If a p manages to capture an e and form an H atom, the H atom was immediately ionized by one of the abundant photons with E>13.6 eV.

In this soup of e,p, and photons, the interaction that insures thermodynamic equilibrium (a single temperature for all three species) is electron Thomson scattering:

$$\gamma + e^- \rightarrow \gamma + e^-, \quad \text{Thomson cross section } \sigma_T = 6.65 \times 10^{-29} m^2$$

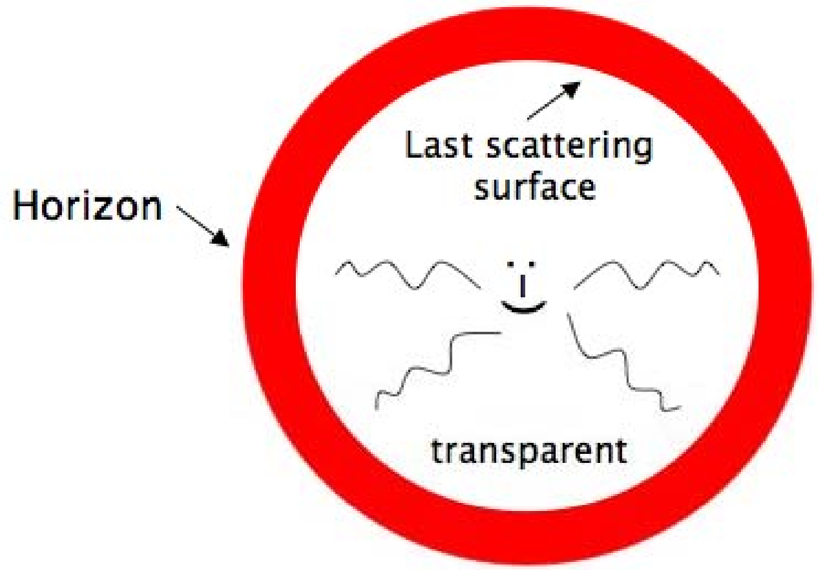
As time was passing, the CMB photons cooled down due to the expansion of the Universe, and eventually they were not able to ionize H, the Universe became neutral.

Since there were no free electrons left, the CMB photons stopped getting scattered and, after a last scattering, kept propagating unobstructed.

(From M. Georganopoulos' lecture lib)

CMB origin

The last scattering surface.



Every observed is surrounded by a spherical last scattering surface. The CMB photons emerge from the last scattering surface and propagate in a straight line all the way to the observed with no further scatterings.

(From M. Georganopoulos' lecture lib)

CMB origin

3 important epochs:

1. **Recombination**, the time when the baryonic component of the Universe became neutral (number of ions=number of neutral atoms)

2. **Photon decoupling,** the time when the rate of photon scattering becomes smaller than H.
In other words, this is the epoch when the time between scatterings for a photon, becomes larger than the Hubble time.
When photons decouple, they cease to interact with electrons and the Universe becomes transparent.

3. **Last scattering.** This is the time when a typical CMB photon underwent its last scattering from an electron.

The last scattering time is very close to the photon decoupling time

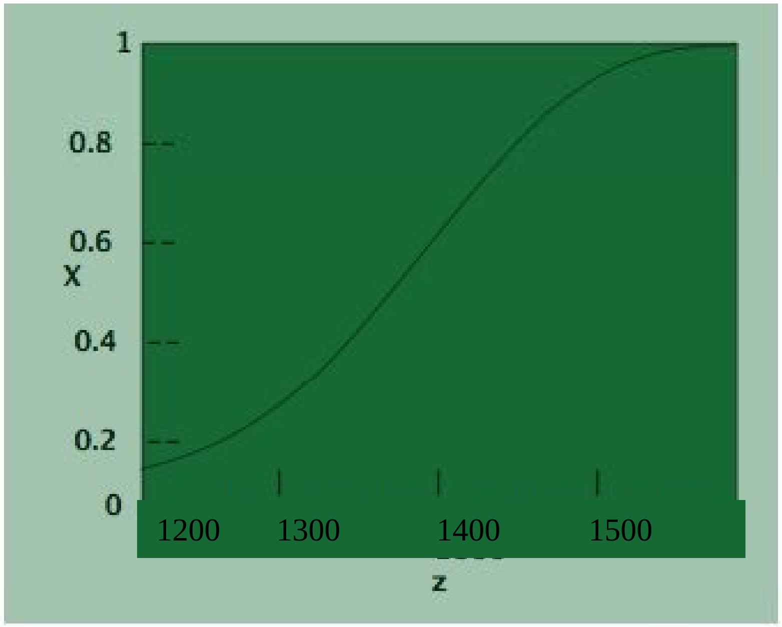
(From M. Georganopoulos' lecture lib)

CMB origin: recombination

the Saha equation gives us the ionization fraction X as a function of the ionization potential Q and the baryon to photon ratio η:

$$\frac{1-X}{X^2} = 3.84\eta\left(\frac{kT}{m_e c^2}\right)^{3/2} \exp\left(\frac{Q}{kT}\right)$$

$$X \equiv n_e / n_B = n_e / (n_H + n_p)$$



Recombination is a gradual process. Defining the moment of recombination at X=1/2 we obtain:

$$kT_{rec} = 0.323\,eV \Rightarrow T_{rec} = 3740\,K,\quad 1+z_{rec} = \frac{1}{a_{rec}} = \frac{T_{rec}}{T_{CMB,0}} = \frac{3740\,K}{2.73\,K} \approx 1371$$

(From M. Georganopoulos' lecture lib)

CMB origin: decoupling

The photon scattering rate is:

$$\Gamma = \frac{c}{\lambda} = n_e(z)\sigma_e c = X(z) n_{B,0}(1+z)^3 \sigma_e c = 4.4\times 10^{-21} X(z)(1+z)^3 s^{-1}$$

Recombination and decoupling take place during the matter dominated era, so Friedmann's eq. is:

$$\frac{H^2}{H_0^2} = \frac{\Omega_{m,0}}{a^3} = \Omega_{m,0}(1+z)^3 \Rightarrow H = 1.24\times 10^{-18}(1+z)^{3/2}$$

Setting Γ=H, we obtain

$$1+z_{dec} = \frac{43.0}{X(z_{dec})^{2/3}} \Rightarrow z_{dec} = 1130$$

(From M. Georganopoulos' lecture lib)

CMB origin: decoupling

In our calculation we used the Saha equation, which assumes that photoionization is always in equilibrium. This is not true when Γ becomes comparable to H. A detailed calculation gives:

$$z_{dec} \approx 1100, T_{dec} \approx 3000\,K.$$

Event	Redshift	Temperature	Time(yr)
Radiation-mattter equality	3570	9730	47,000
Recombination	1370	3740	240,000
Photon decoupling	1100	3000	350,000
Last scattering	1100	3000	350,000

›Before decoupling, photon pressure on the matter smoothed out density fluctuations in the photon baryon field at distances smaller than the horizon distance back then.

›After, the hydrogen gas was free to collapse under its self gravity (and that of the dark matter) to form structure in the Universe

(From M. Georganopoulos' lecture lib)

Radiation era

We have that $\rho_M \propto R^{-3}$

$\rho_{rad} \propto R^{-4}$

There must be a z at which $\rho_M = \rho_{rad}$

Taking into account that nucleosynthesis predicts $n_\nu = 0.68\, n_\gamma$, then $\Omega_{rad} = 4.2 \times 10^{-5}\, h^{-2}$

$$1 + z_{eq} = 23900\,\Omega_m h^2 \quad \Rightarrow \; z_{eq} \approx 3100$$

(From M. Plionis' notes or Peacock 1999)