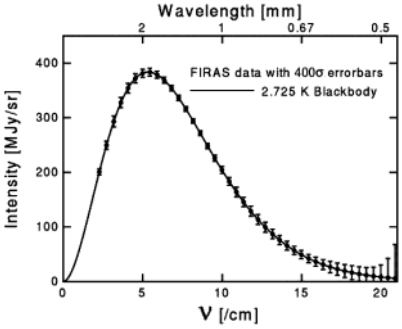
The Cosmic Microwave Background

Discovered by Penzias and Wilson (1964) at Bell Labs (sky glows at mm λs)



COBE showed that the spectrum is a BB w/ a $T = 2.725 \pm 0.001K$

Photons are spin=0 particles so their most probable dist'n is given by Bose-Einstein statistics. The energy density in a freq. interval $d\nu$ about ν is

$$e(\nu)d\nu = \frac{8\pi h}{c^3} \frac{\nu^3 d\nu}{e^{h\nu/kT}-1}$$

Diff. this & set to zero. Peak freq. is at

$$\nu_{peak} = \frac{2.8kT}{h}.$$ Corresponding to $E_{peak} = 2.8kT$

The mean energy of a photon in this dist'n is

$$E_{mean} \approx 3kT$$

The total energy density is the integral over freq. Set $y = \frac{h\nu}{kT}$

$$\epsilon_{rad} = \frac{8\pi(kT)^4}{h^3c^3}\int_0^\infty y^3 dy = \frac{8\pi(kT)^4}{h^3c^3}\frac{\pi^4}{15}$$

$\epsilon_{rad} = aT^4$ where $a = 7.56 \times 10^{-15}$ cgs

In an expanding Univ., freq./energy reduces by $\frac{1}{a}$

Volume increases by a^3. So, new energy density,

$$d\epsilon' = \frac{d\epsilon}{a^4} = \frac{8\pi h}{c^3 a^4} \frac{\nu^3 d\nu}{e^{h\nu/kT} - 1}$$

Sub. $\nu' = \frac{\nu}{a} \Rightarrow d\epsilon' = \frac{8\pi h}{c^3} \frac{\nu'^3 d\nu'}{e^{h\nu'a/kT} - 1}$

Which is identical to prev. expression if define $T' = \frac{T}{a}$, i.e., $T \propto \frac{1}{a}$

$\therefore$ As the Univ. expands, the photon distribution remains a BB, but w/ a lower temp.

The radiation 'cools'.

Also, if $T \simeq 3K$ today, then @ earlier times it was much hotter: $T(z) = T_0(1+z)$

'Hot Big Bang'

The present day $\epsilon_{rad}(t_0) = 4.17 \times 10^{-14}\ J\,m^{-3}$

Convert to mass density by $\div c^2$; then

$$\Omega_{rad,0} = 2.47 \times 10^{-5} h^{-2}$$

The current # density of CMB photons

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

Compare to baryon density

$$\epsilon_{bary} = \rho_B c^2 = \Omega_{B,0} \rho_{c,0} c^2 \simeq 3.38 \times 10^{-11}\ J\,m^{-3}$$

mean energy of a baryon $\simeq m_p c^2$

$$\therefore n_{bary} = 0.22\ m^{-3}$$

So, $\frac{n_{bary}}{n_{phot}} = 6\times10^{-10}$

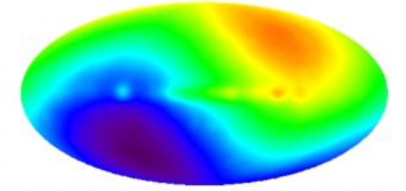
Will this ratio change w/ z?

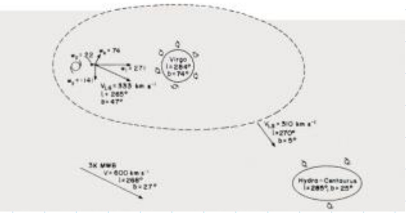
No, b/c both baryons & photons are conserved

∴ This ratio is constant, given a symbol η

Properties of CMB Spectrum

1) The spectrum at all (θ,ϕ) on the sky is an ideal BB to smaller than a fract. of a percent.





2) A temp. dipole of $\Delta T \sim 3\times10^{-3}\,K$ due to the motion of the LG towards the Virgo cluster (which is itself being accelerated to the Hydra-Centarus supercluster) $V_{LG} = 630 \pm 20\,\frac{km}{s}$