CMB Anistropies

The fundamental measurement is $T(\theta,\phi)$.

Measure the Temp. anisotropies:

$$\frac{\Delta T(\theta,\phi)}{T} = \frac{T(\theta,\phi) - \langle T \rangle}{\langle T \rangle}$$

Since these measurements are on a sphere, expand these fluctuation maps into spherical harmonics:

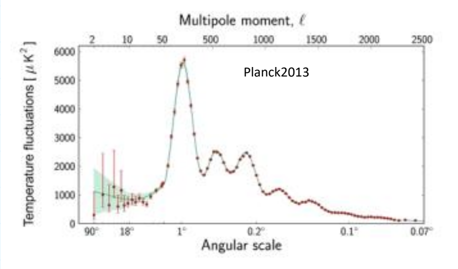
$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{l=1}^{\infty} \sum_{m=-l}^{+l} a_{lm} Y_m^l(\theta,\phi)$$

The coefficients a_{lm} tell us the size of the irreg. on different scales.

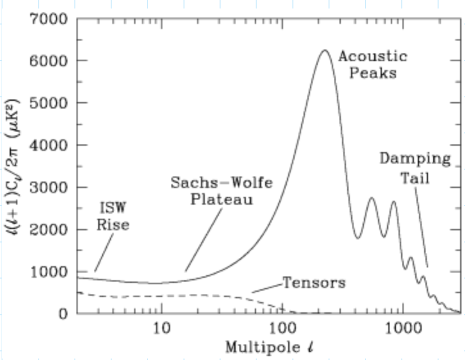
Define the rad'n angular power spectrum

$C_l = \langle |a_{lm}|^2 \rangle$. The average is over all m.

l can be mapped to angular scale w/ small l $\rightarrow$ large angular scales and large $l \rightarrow$ small angular scales. Rule of thumb, scale $\sim \frac{180°}{l}$



Below $\ell \sim 200$ is the Sachs-Wolfe plateau due to variations in the DM dist'n at the time of decoupling. The grav. pot variations lead to T variations b/c of grav. redshifts.



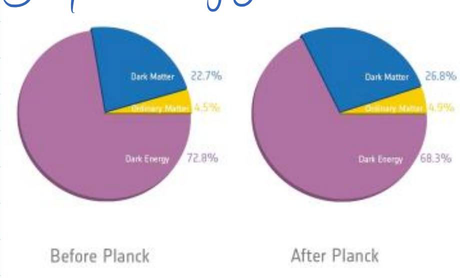
Above $\ell \sim 200$ the peaks are due to pressure waves in the photon/baryon fluid sloshing in the DM dist'n.

The most important scale is the Hubble time H^{-1} at z_d.

The peak structure comes from oscillations so the 1st peak (at the largest scale) comes from perturbations that had time to ~~et~~ undergo one oscillation so size scale is cH^{-1}.

Getting the ang. size of that scale depends on d_A at z_d which depends on cosmology, in particular geometry. The location of this first peak strongly suggests $K=0$. Given $\Omega_{m,0}=0.3$

$\rightarrow \Omega_\Lambda = 0.7$



Before Planck After Planck

The Early Universe

In addition to radiation, neutrinos are another relativistic particle that permeates the Univ.

Assume from now that neutrinos are massless then theoretically $\Omega_\nu = 3 \cdot \frac{7}{8} \cdot \left(\frac{4}{11}\right)^{4/3} \Omega_{rad}$

$$= 0.68\, \Omega_{rad}$$

$$\Omega_{\nu,0} = 1.68 \times 10^{-5} h^{-2}$$

$$\Omega_{rel,0} = \Omega_{\nu,0} + \Omega_{rad,0} = 4.15 \times 10^{-5} h^{-2}$$

Since $\rho_{rel} \propto \frac{1}{a^4}$; $\rho_{matt} \propto \frac{1}{a^3}$

$$\frac{\Omega_{rel}}{\Omega_{matt}} = \frac{4.15 \times 10^{-5}}{\Omega_{m,0} h^2} \cdot \frac{1}{a} \quad \text{where } a_0 = 1$$

So, at decoupling $\left(a \simeq \frac{1}{1000}\right)$

$$\frac{\Omega_{rel}}{\Omega_{matt}} = \frac{0.04}{\Omega_{m,0} h^2} = 0.27 \text{ for } \Omega_{m,0} = 0.3 \;;\; h = 0.7$$

So, the Univ. is matter dominated @ decoupling

Radiation/Matter equality occurs at

$$a_{rm} = \frac{1}{24000\, \Omega_{m,0} h^2} = \frac{1}{3528} \quad \text{for } \Omega_{m,0} = 0.3 \;;\; h = 0.7$$

Consider the evol. of T since know $T \propto \frac{1}{a}$

Assume $K=0$, $\Lambda=0$, since small early on

Then $a \propto t^{2/3}$ and $T \propto t^{-2/3}$. Assuming age of Univ. is 12 Gyr (to compensate for ignoring Λ):

$$\frac{T}{2.725\,K} = \left(\frac{4\times10^{17}\,s}{t}\right)^{2/3}$$

Then $T_{rm} = \dfrac{2.725\,K}{a_{rm}} = 66\,000\,\Omega_{m,0}h^2\,K \;(= 9614\,K)$

$\therefore$ time of equal. is $t_{rm} = 10^{11}\,\Omega_{m,0}^{-3/2}\,h^{-3}\,s$

$\simeq 3400\,\Omega_{m,0}^{-3/2}\,h^{-3}$ yrs

$\simeq 60\,000$ yrs

(really 4.7×10^4 yrs)

(compare decoupling @ 350,000 yrs)