Cosmological Evidences of Dark Matter from the Cosmic Microwave Background

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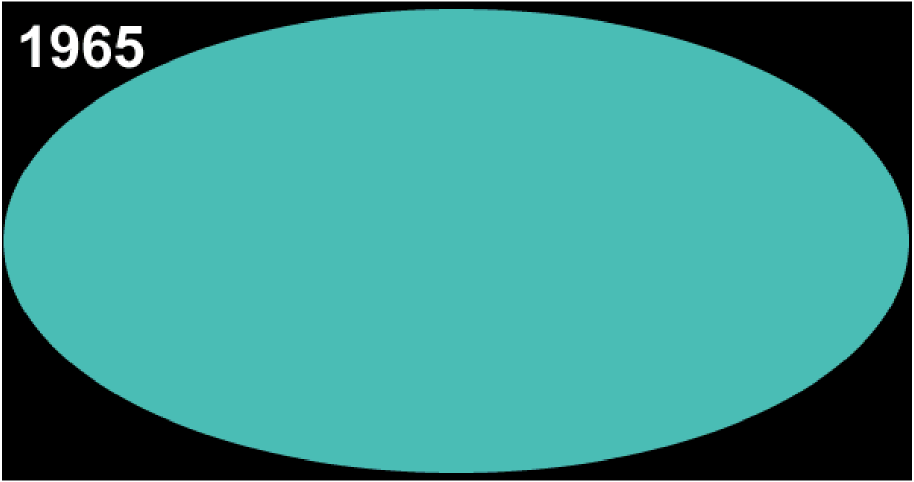
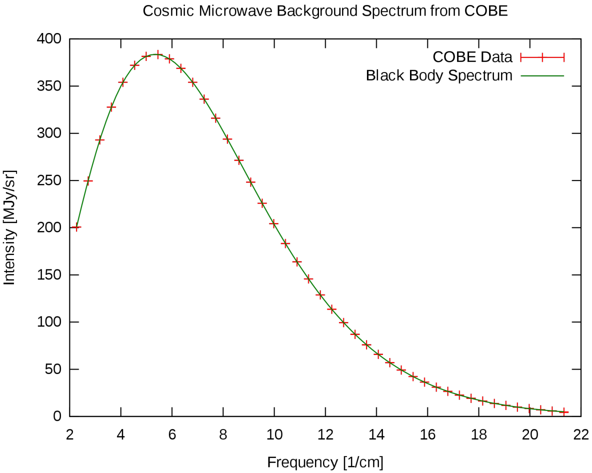
Outline

Cosmic Microwave Background



Accurate measurements of the temperature fluctuations of the CMB help us to understand the energy-matter content of our Universe

The best Black Body Spectrum



$$< T_{CMB} >= 2.728 \pm 0.004 \text{ K}$$

Dicrepancy between the expected temperature fluctuations

At the decoupling time, the density contrast

$$\delta\rho = \frac{\rho - <\rho>}{<\rho>} \approx 10^{-3}$$

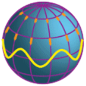
If the CMB energy density u were of equal magnitude, temperature fluctuations in the CMB should be of order 10^{-3} because

$$u \propto T^4 \quad \Rightarrow \quad \frac{\delta u}{u} = 4\frac{\delta T}{T}$$

But the measured temperature fluctuations are of order 10^{-5} !

Outline

Assumptions of the ΛCDM model



Spherical Harmonics

At 'enough' large scales > 100 Mpc, the Universe is

- Homogeneous
- Isotropic

So the line element can be expressed as

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = -c^2\mathrm{d}t^2 + a(t)^2\left(\frac{\mathrm{d}r^2}{1-Kr^2} + r^2\mathrm{d}\Omega^2\right)$$

where $a(t)$ is the scale factor and K is the curvature of the Universe

Friedmann Equations

In addition, we trust Einstein's General Theory of Relativity

$$R^{\mu\nu} - \frac{1}{2} R g^{\mu\nu} + \Lambda g^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

Einstein's field equations reduce to Friedmann's equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left\{\rho c^2 a^3\right\} + p \frac{\mathrm{d}}{\mathrm{d}t}\left\{a^3\right\} = 0$$

where the Hubble constant is defined as
$H_0 = H(t_0) = 100 h km s^{-1} Mpc^{-1} =$ and $h = 0.6727$

Radiation $p = \frac{\rho c^2}{3}$

$\rho = \rho_0 a^{-4}$

Dust $p = \rho \ll \rho c^2$

$\rho = \rho_0 a^{-3}$

Friedmann's equations can be rewritten using:

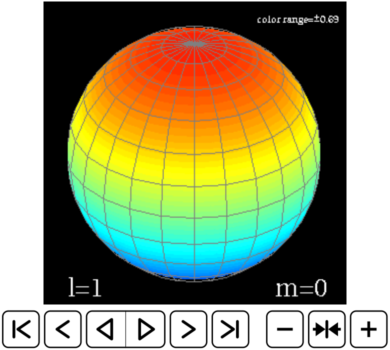
$$\Omega_R = \frac{8\pi G \rho_R}{3H_0^2} \qquad \Omega_M = \frac{8\pi G \rho_M}{3H_0^2} \qquad \Omega_\Lambda = \frac{\Lambda}{3H_0^2} \qquad \Omega_K = -\frac{K}{a_0^2 H_0^2}$$

$$H^2 = H_0^2 \left\{ \Omega_R \frac{a_0^4}{a^4} + \Omega_M \frac{a_0^3}{a^3} + \Omega_\Lambda + \Omega_K \frac{a_0^2}{a^2} \right\}$$

At $a = a_0 \Rightarrow$ today, we get the Cosmic Rule:

$$1 = \Omega_R + \Omega_M + \Omega_\Lambda + \Omega_K$$

Multipoles Decomposition



Spherical Harmonics

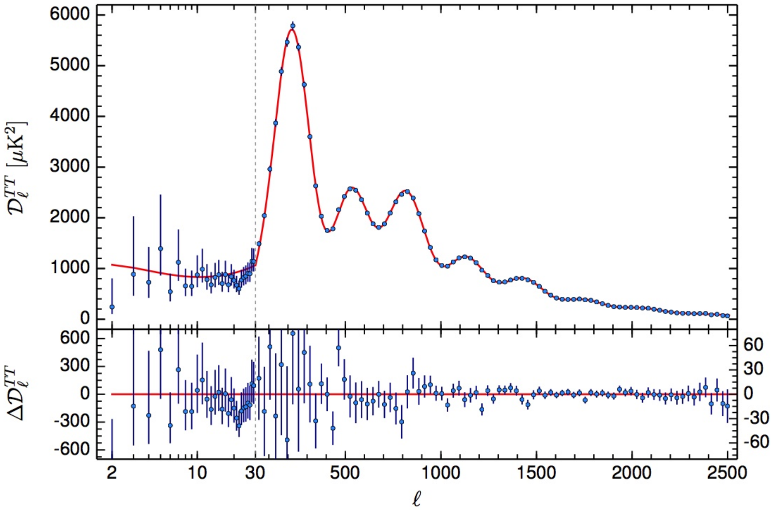
Projection of the temperature fluctuations onto another set of basis functions which are orthonormal on the sky:

$$T(\theta, \phi) = \sum_{l,m} a_{lm} Y_l^m(\theta, \phi)$$

And

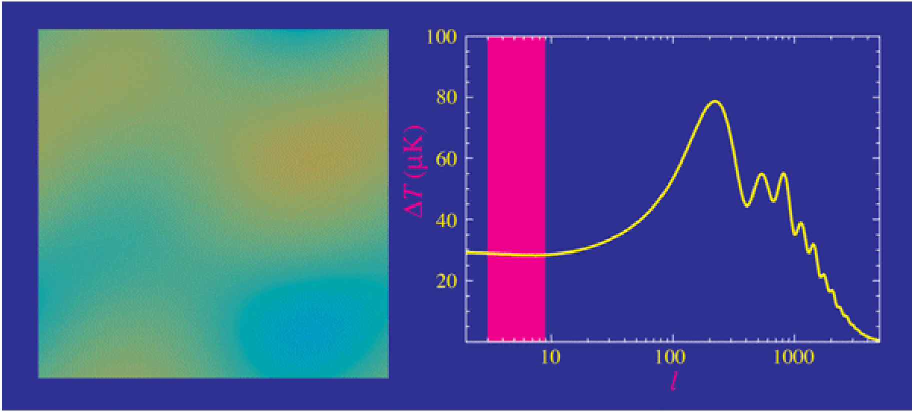
$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

Temperature Power Spectrum Planck 2015



$$D_l^{TT} = l(l+1)C_l/(2\pi)$$

Temperature Power Spectrum and Angular size



For large l, $\theta \sim 1/l$

Outline

Variations of the cosmological parameters

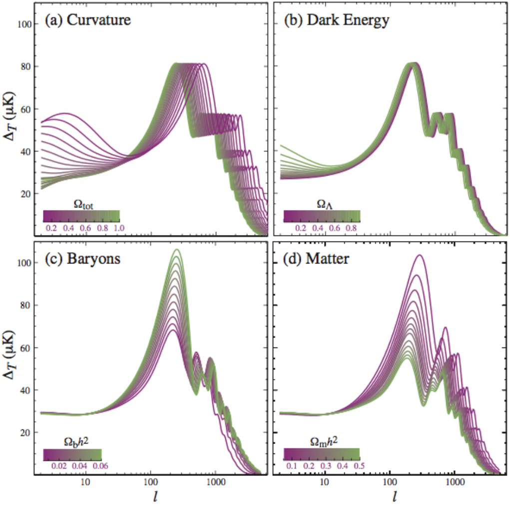
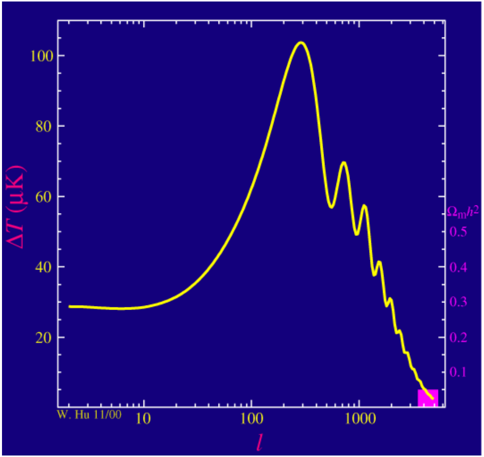


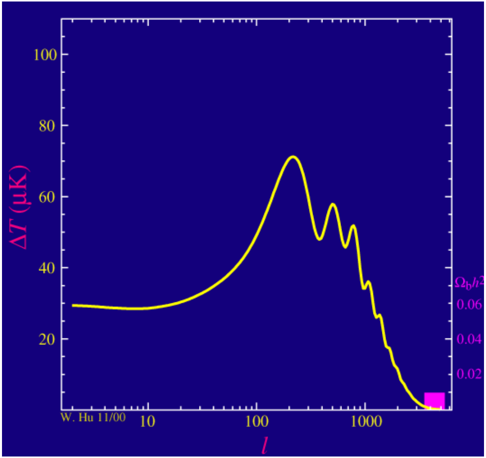
Plate 4: Sensitivity of the acoustic temperature spectrum to four fundamental cosmological parameters (a) the curvature as quantified by $\Omega_{\rm tot}$ (b) the dark energy as quantified by the cosmological constant Ω_Λ ($w_\Lambda = -1$) (c) the physical baryon density $\Omega_b h^2$ (d) the physical matter density $\Omega_m h^2$, all varied around a fiducial model of $\Omega_{\rm tot} = 1$, $\Omega_\Lambda = 0.65$, $\Omega_b h^2 = 0.02$, $\Omega_m h^2 = 0.147$, $n = 1$, $z_{\rm ri} = 0$, $E_i = 0$.

Variations of the Dark Matter density



- Raising the dark matter density reduces the overall amplitude of the peaks
- High third peak is an indication of dark matter

Variations of the Baryon density

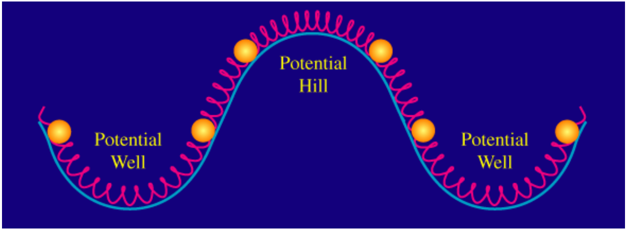


- Power spectrum shows baryons enhance every other peak
- Second peak is suppressed compared with the first and third
- Adding baryons to the plasma decrease the frequency of the oscillations pushing the position of the peaks to slightly higher multipoles l

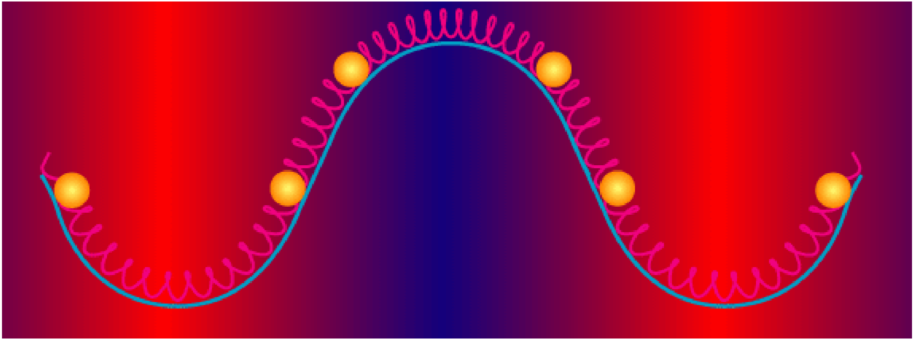
Acoustic Oscillations

At the time before recombination:

- Dark Matter is randomly distributed
- if a portion of photon-baryon fluid is in a potential well of the dark matter, it will fall to the center of the well
- gravity compresses the photon-baryon fluid
- pressure starts to rise
- the pressure is sufficient to cause the fluid to expand outward
- the pressure drops until gravity causes the photon-baryon fluid to fall inward again



Acoustic Oscillations: Simple Model



- Quantum fluctuations from the early universe generates both density enhancements and deficits
- During the inflation these quantum fluctuations had been stretched into cosmic scales

Parameters from Planck 2015

CMB & temperature power spectrum + nucleosynthesis analysis $\Rightarrow$ Dark-matter density.

- Derk-matter density 0.2647 $\Rightarrow$ relative error 1.6%
- Dark-energy density 0.6844 $\Rightarrow$ relative error 1.3%
- Baryonic matter density 0.04917 $\Rightarrow$ relative error 1.2%
- Radiation density 8.51×10^{-5} $\Rightarrow$ relative error 0.6%

Dark Matter matters ... for anisotropies!

- Dark Matter interacts with the photons and matter through the gravitational potentials causing fluctuations.
- Fluctuations are responsible for anisotropy formations
- The resultant fluctuations appear to the observer today as anisotropies on the sky

References I