Cosmological Evidences of Dark Matter from the Cosmic Microwave Background

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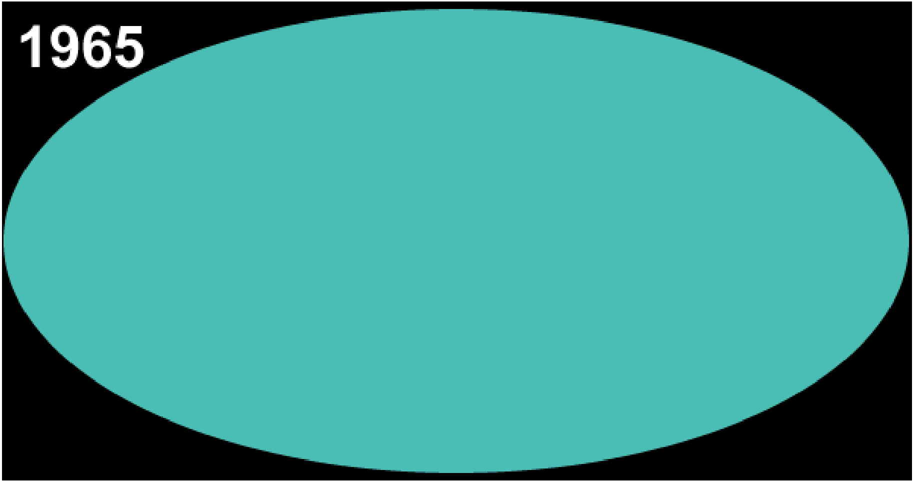
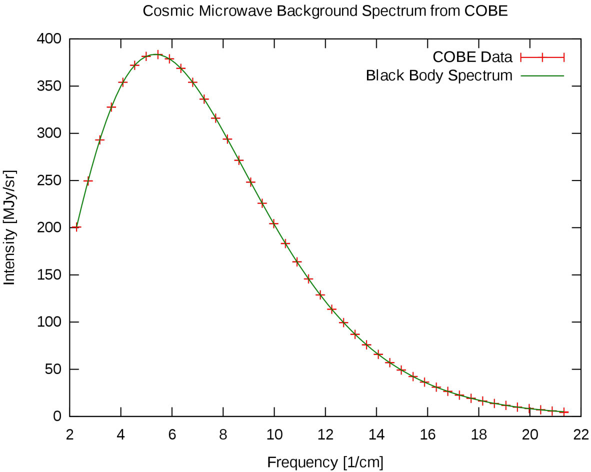
Outline

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

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

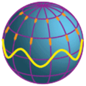
If the CMB energy density u were of equal magnitude, temperature fluctuations in the CMB should be of order 10^{-3} because

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

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

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

Einstein's field equations reduce to Friedmann's equations

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

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

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

Matter content & Cosmic Rule

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:

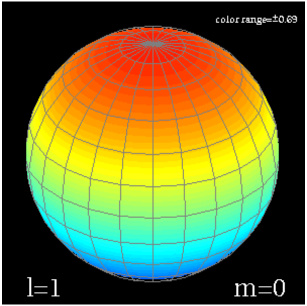
$$\Omega_R = \frac{8\pi G \rho_R}{3H_0^2} \qquad \Omega_M = \frac{8\pi G \rho_M}{3H_0^2} \qquad \Omega_\Lambda = \frac{\Lambda}{3H_0^2} \qquad \Omega_K = -\frac{K}{a_0^2 H_0^2}$$

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

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

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

Multipoles Decomposition



Spherical Harmonics

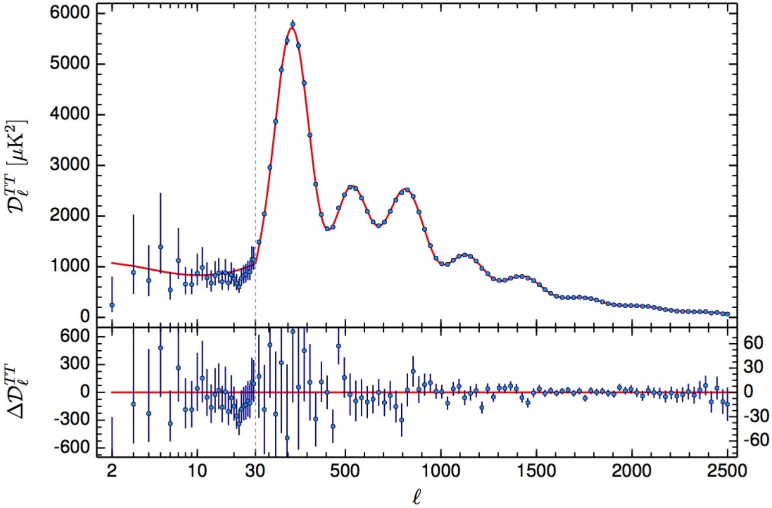
Projection of the temperature fluctuations onto another set of basis functions which are orthonormal on the sky:

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

And

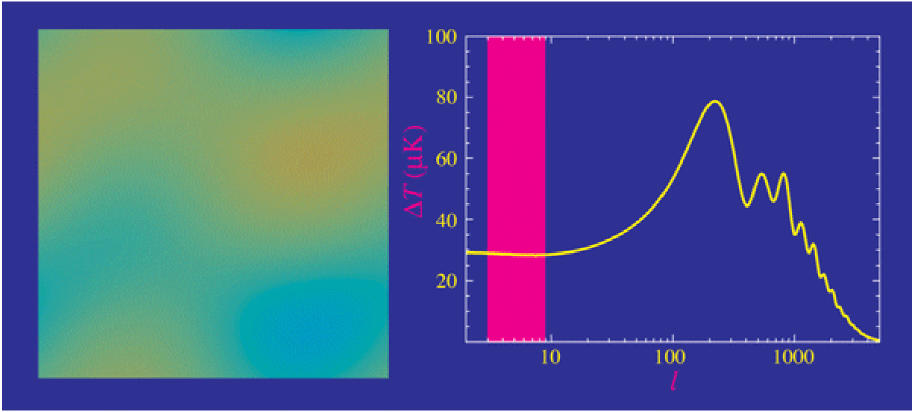
$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2$$

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

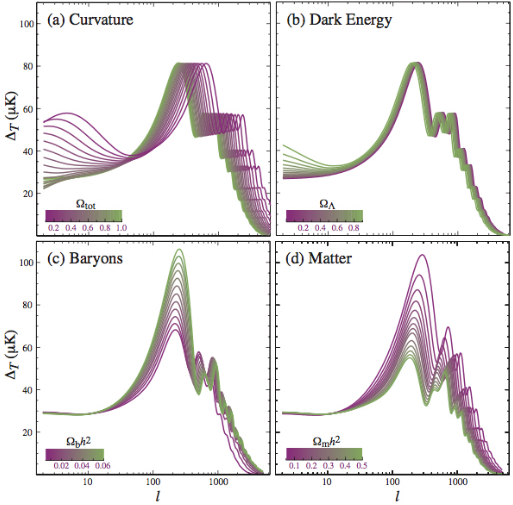
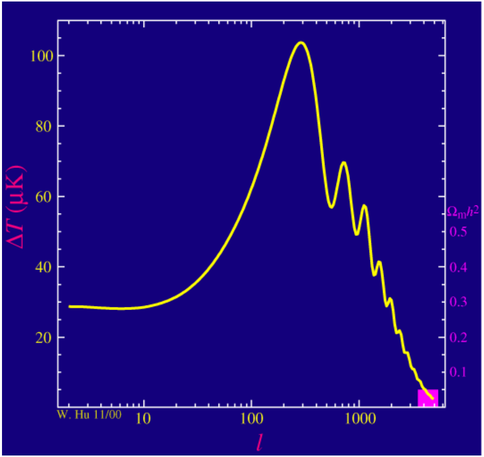


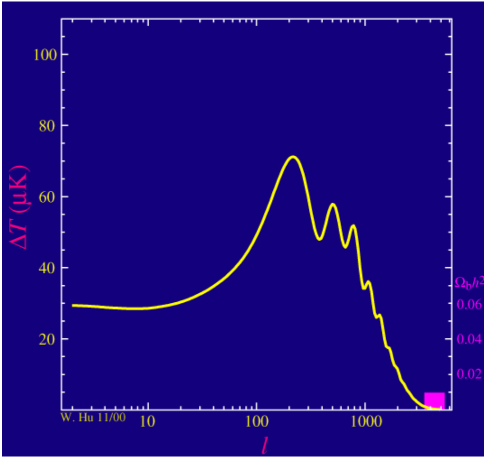
Plate 4: Sensitivity of the acoustic temperature spectrum to four fundamental cosmological parameters (a) the curvature as quantified by $\Omega_{\rm tot}$ (b) the dark energy as quantified by the cosmological constant Ω_Λ ($w_\Lambda = -1$) (c) the physical baryon density $\Omega_b h^2$ (d) the physical 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

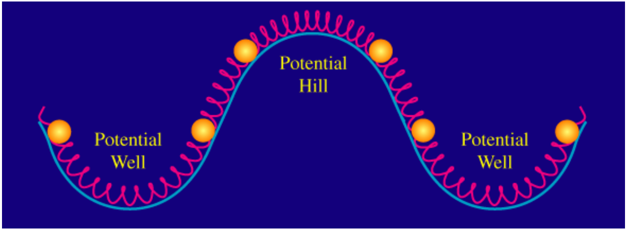


- Power spectrum shows baryons enhance every other peak
- Second peak is suppressed compared with the first and third
- Adding baryons to the plasma decrease the frequency of the oscillations pushing the position of the peaks to slightly higher multipoles l

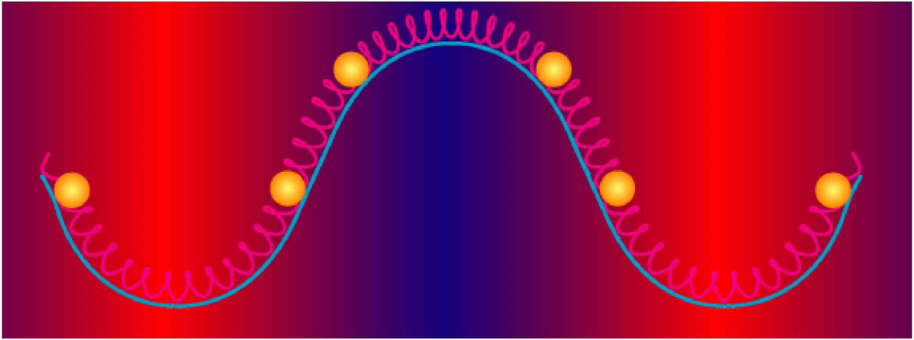
Acoustic Oscillations

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.

- Dark-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

Wayne Hu.
http://background.uchicago.edu/~whu/index.html.

Matthias Bartelmann.
The Standard Model of Cosmology: ΛCDM.
page 117.

Martin Bucher.
Physics of the cosmic microwave background anisotropy.
January 2015.

Planck Collaboration.
Planck 2015 results. XIII. Cosmological parameters.
February 2015.

References II

Scott Dodelson.
Modern Cosmology.
Academic Press, San Diego, Calif, 1 edition edition, March 2003.

Juan Garcia-Bellido.
Astrophysics and Cosmology.
April 2000.

Wayne Hu.
Wandering in the Background: A CMB Explorer.
August 1995.

Wayne Hu and Scott Dodelson.
Cosmic Microwave Background Anisotropies.
October 2001.

References III

Nikhil Padmanabhan and Douglas P. Finkbeiner.
Detecting Dark Matter Annihilation with CMB Polarization : Signatures and Experimental Prospects.
Physical Review D, 72(2), July 2005.