

Cosmological Evidences of Dark Matter from the Cosmic Microwave Background

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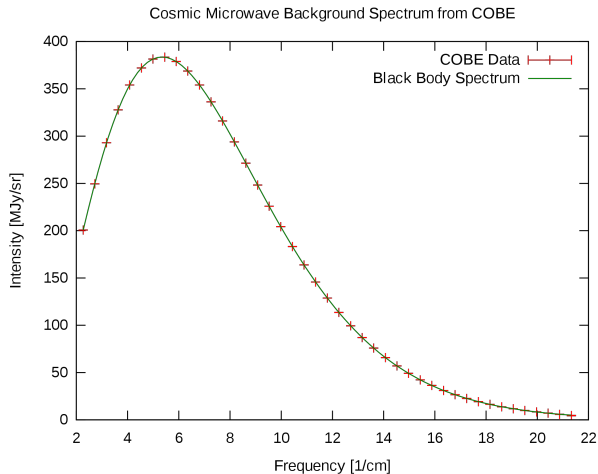
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- 1 Introduction
- 2 Λ CDM model
- 3 The role of the Dark Matter

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



$$\langle T_{CMB} \rangle = 2.728 \pm 0.004 \text{ K}$$

Dicrepancy between the expected temperature fluctuations

At the decoupling time, the density contrast

$$\delta\rho = \frac{\rho - \langle \rho \rangle}{\langle \rho \rangle} \approx 10^{-3}$$

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} !

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Assumptions of the Λ CDM model

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

- Homogeneous
- Isotropic

Spherical Harmonics

So the line element can be expressed as

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -c^2 dt^2 + a(t)^2 \left(\frac{dr^2}{1 - Kr^2} + r^2 d\Omega^2 \right)$$

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

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{Kc^2}{a^2} + \frac{\Lambda c^2}{3}$$
$$\frac{d}{dt}\{\rho c^2 a^3\} + p\frac{d}{dt}\{a^3\} = 0$$

where the Hubble constant is defined as

$$H_0 = H(t_0) = 100h km s^{-1} Mpc^{-1} = \text{and } h = 0.6727$$

Matter content & Cosmic Rule

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

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

$$\text{Dust } p = \rho \ll \rho c^2$$

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

Friedmann's equations can be rewritten using:

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

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

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

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

Multipoles Decomposition

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

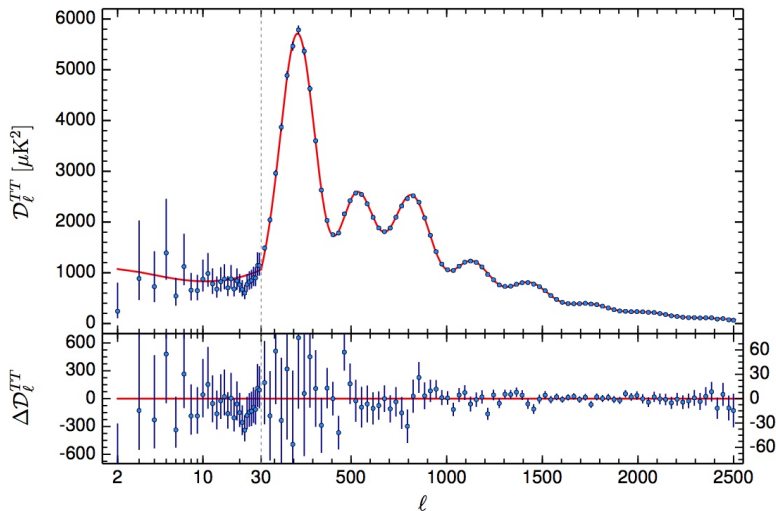
$$T(\theta, \phi) = \sum_{l,m} a_{lm} Y_l^m(\theta, \phi)$$

And

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

Spherical Harmonics

Temperature Power Spectrum Planck 2015



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

Temperature Power Spectrum and Angular size

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

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Variations of the cosmological parameters

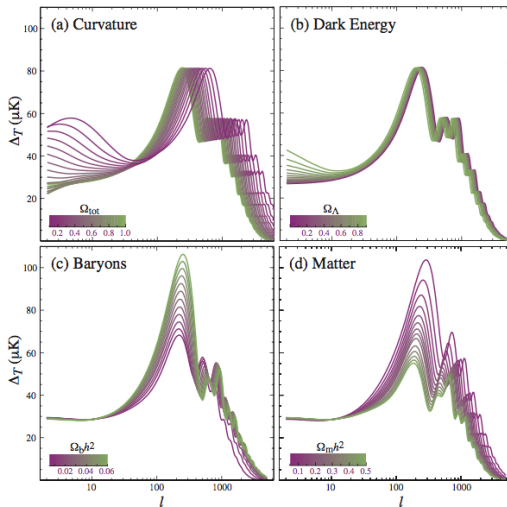


Plate 4: Sensitivity of the acoustic temperature spectrum to four fundamental cosmological parameters (a) the curvature as quantified by Ω_{tot} (b) the dark energy as quantified by the cosmological constant Ω_{Λ} ($w_{\Lambda} = -1$) (c) the physical baryon density $\Omega_b h^2$ (d) the physical matter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

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

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 $8.51 \times 10^{-5} \Rightarrow$ 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

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