THE BIG BANG THEORY: AN INTRODUCTION (Gravitation and Cosmology)

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Outline of the talk

- Expansion of the Universe.
- Theory: General Relativity and Friedmann equations.
- The Cosmic Microway Background (Planck satellite).
- Cosmological parameters.
- Nucleosynthesis.
- Dark Matter.
- Problems of the Standard Cosmological Model (ΛCDM):
  - Cosmological Constant.
  - Flatness.
  - Monopoles.
  - Horizons.
  - Antimatter.

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated January 17, 1929

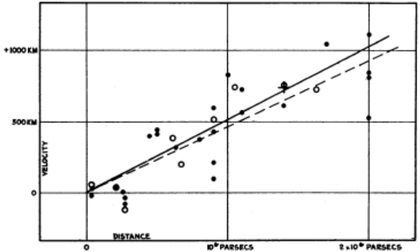


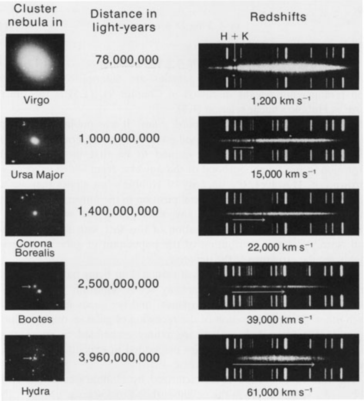
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

$$v = H_0 d, \;\; H_0 \simeq 500 \frac{\text{km}}{\text{s Mpc}} \, .$$

$$H_0^{-1} \simeq 2 \times 10^9 \text{years.}$$

Expansion of the universe (II)



$$z = \frac{\lambda_g - \lambda_o}{\lambda_0}$$

Absolute and Apparent magnitudes of a atar

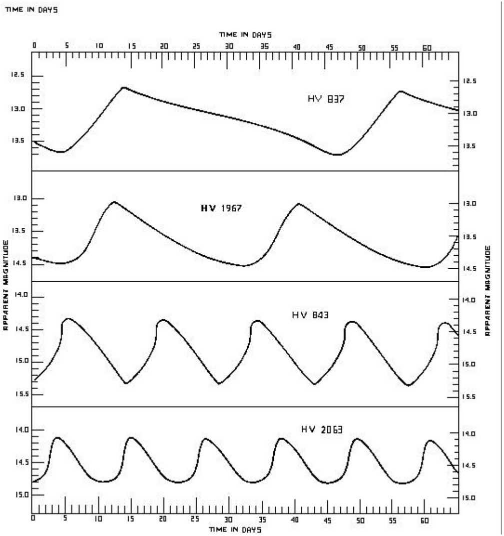
- Absolute Luminosity (L): Total power emitted by the star.
  - Absolute Magnitude (M): $L = 10^{-2M/5} \times 3 \times 10^{32}$ J/s .
- Apparent Luminosity (l): Power per unit surface received on the Earth.
  - Apparent Magnitude (m): $l = 10^{-2m/5} \times 2.5 \times 10^{-8}$ J/m^2/s .

$$l = \frac{L}{4\pi D_L^2} \,,$$

$$5 \log_{10} \left(\frac{D_L}{10\text{pc}} \right) = m_B - M_B \,.$$

Expansion of the universe (III)

Light curves for the Cepheids.



Expansion of the universe (IV)

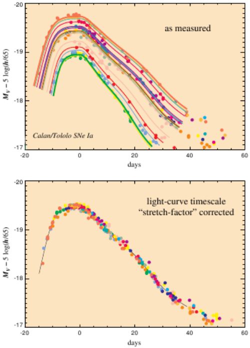
Cepheids: Luminosity-Period (Henrietta Swan Leavitt).

$$M_v = -2.81 \log_{10}(P) - (1.43 \pm 0.1)\,.$$

$$5 \log_{10}\left(\frac{D_L}{10\mathrm{pc}}\right) = m_B - M_B\,.$$

Expansion of the universe (V)

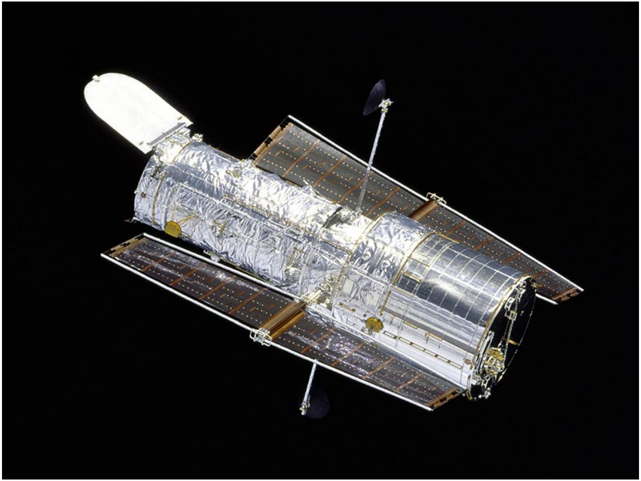
Supernovae SNIa.



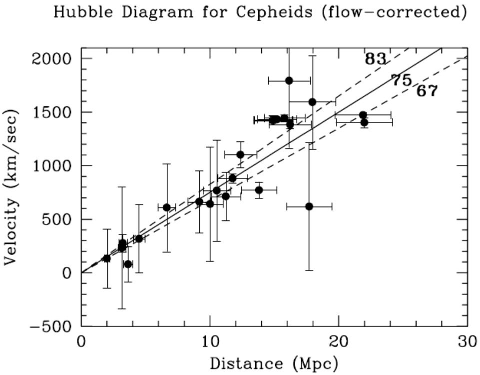
$$5\log_{10}\left(\frac{D_L}{10\mathrm{pc}}\right) = m_B - M_B + \alpha(s-1) - \beta c\,.$$

Edwin Hubble

Hubble Space Telescope (NASA)



Expansion of the universe (VI)



$$v = H_0 d, \;\; H_0 \simeq 75 \frac{\text{Km}}{\text{s Mpc}} \, .$$

$$H_0^{-1} \simeq 13 \times 10^9 \text{years.}$$

Friedmann equations(I)

- Perfect Cosmological Principle:
  All the observers of the Universe see the same cosmo-history.
- The universe is homogeneous and isotropic.
- Maximally symmetric spaces.
- Robertson-Walker line element

$$ds^2 = -c^2 dt^2 + a(t)^2 \left[\frac{d\sigma^2}{1 - k\sigma^2} + \sigma^2 d\theta^2 + \sigma^2 \mathrm{sen}^2\theta d\phi^2 \right] .$$

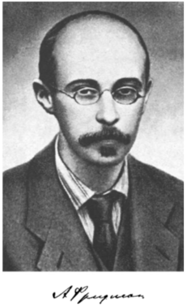
- Energy-Momentum tensor of an ideal fluid

$$T_{\mu\nu} = p g_{\mu\nu} + \left(\frac{p}{c^2} + \rho \right) U_\mu U_\nu .$$

Friedmann equations(II)

- Plugging these assumptions into the Einstein's equations we obtain

$$\begin{aligned}
\dot{a}^2 &= \frac{8\pi}{3} G\rho a^2 - kc^2 \\
\ddot{a} &= -\frac{4\pi}{3} G(\rho + 3\frac{p}{c^2})a \,.
\end{aligned}$$



Critical density

- Friedmann equation

$$\dot{a}^2 = \frac{8\pi}{3} G\rho a^2 - kc^2 \,.$$

- $k = 0$, $H(t) \equiv \dot{a}/a$.
- Critical density

$$\rho_c = \frac{3H^2}{8\pi G} \,.$$

- In terms of the critical density

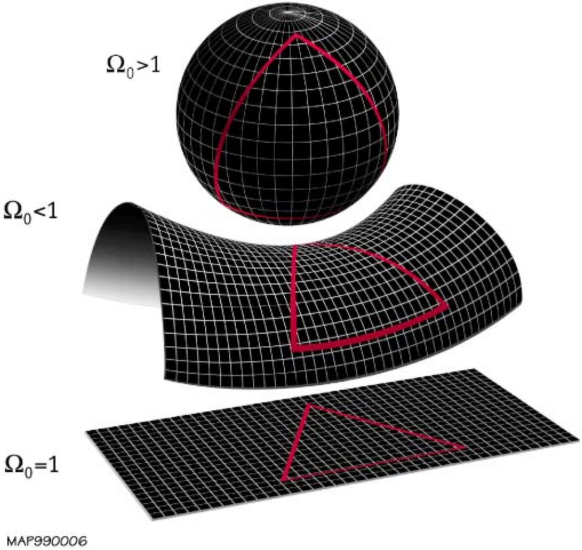
$$\Omega_i \equiv \frac{\rho_i}{\rho_c} \,,$$

$$\Omega = \sum_i \Omega_i \,.$$

- The curvature scalar is given by

$$R = 6H^2(\Omega - 1)$$

Curvature



The Cosmological Constant as the vacuum energy (I)

Friedmann equations with cosmological constant (Λ):

$$\begin{aligned} \dot{a}^2 &= \frac{8\pi}{3} G \rho a^2 + \frac{1}{3} \Lambda c^2 a^2 - k c^2 \\ \ddot{a} &= -\frac{4\pi}{3} G (\rho + 3 \frac{p}{c^2}) a + \frac{1}{3} \Lambda c^2 a \,. \end{aligned}$$

Friedmann equations with density $(\rho + \rho_{\rm v})$ and pressure $(p + p_{\rm v})$

$$\begin{aligned} \dot{a}^2 &= \frac{8\pi}{3} G (\rho + \rho_{\rm v}) a^2 - k c^2 \\ \ddot{a} &= -\frac{4\pi}{3} G (\rho + \rho_{\rm v} + 3 \frac{p}{c^2} + 3 \frac{p_{\rm v}}{c^2}) a \,. \end{aligned}$$

We get

$$\rho_{\rm v} = \frac{\Lambda c^2}{8\pi G} \,, p_{\rm v} = -\frac{\Lambda}{8\pi G} \,.$$

Therefore

$$p_{\rm v} = -\rho_{\rm v} c^2 \,.$$

The Cosmological Constant as the vacuum energy (II)

Conservation of the energy-momentum

$$\frac{d}{dt}\left(\rho_{\rm v} c^2 R(t)^3\right) + p_{\rm v}\frac{d}{d}\left(R(t)^3\right) = 0\,.$$

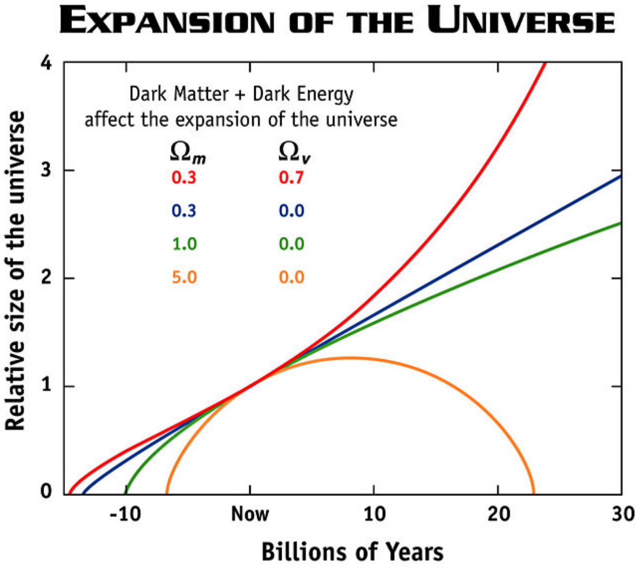
If the density of the vacuum is constant, it is possible to obtain the following equation of state

$$p_{\rm v} = w\rho_{\rm v} c^2\,,\text{con } w = -1\,.$$

Quantum vacuum:

- Ground state of the “Universe”.
- Composed by virtual particles and antiparticles ($\Delta E \Delta t \simeq \hbar$). Casimir Effect.
- Sum of all the zero point energies of all the quantum fields presented in the universe.

Evolution of the relative size of the universe

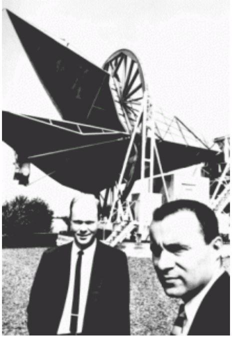


The Cosmic Microway Background (CMB) (I)

Discovered by A. Penzias and R. Wilson (1964).

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and



CMB (II): Cosmic CN

COSMIC MICROWAVE RADIATION AT 2.63 mm
FROM OBSERVATIONS OF INTERSTELLAR CN

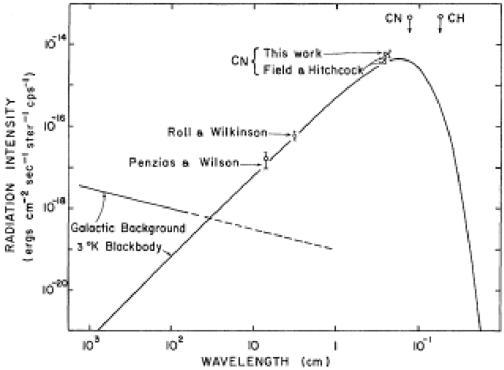
Patrick Thaddeus

Goddard Institute for Space Studies, New York, New York

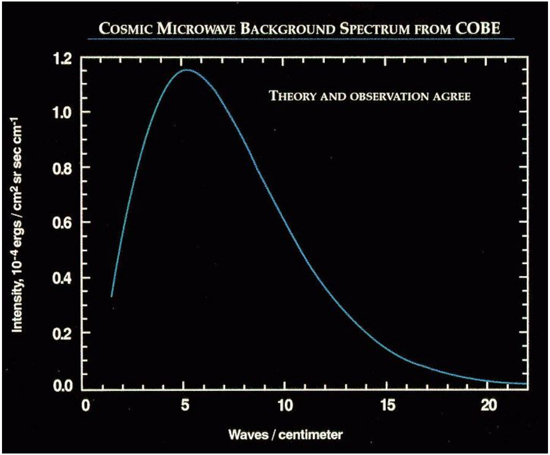
and

John F. Clauser

Department of Physics, Columbia University, New York, New York
(Received 25 March 1966)



CMB (III)

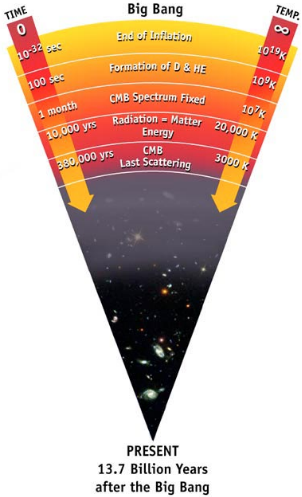


$$T = 2.725 \pm 0.001\mathrm{K}(1\sigma)\,.$$

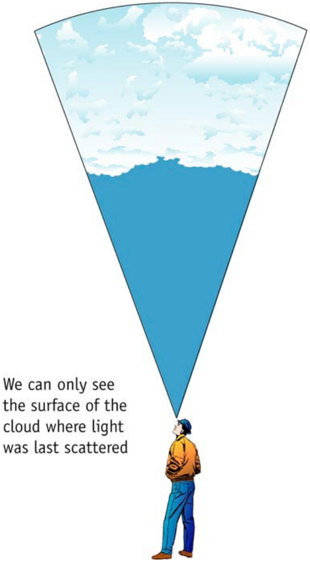
Origin of CMB

- The universe was 10^5 years old.
- "Soup" of protons, electrons, photons and light nucleus.
- The atomic binding energy is approx. 1 eV [equivalent to 10^4 K].
- The expansion of the universe reduces its temperature: $T \propto 1/a$.
- 50 % of protons and 50% of Hydrogen at $T \simeq 0.3$ eV.
- It occurred 400 000 years after the BB.
- The universe was 1200 times smaller than at the present.
- TRANSPARENT Universe (neutral!!).
- It occurred after the equilibrium matter-radiation (100000 years after the BB): $\rho_{\rm mat} = \rho_{\rm rad}$.

Last Scattering Surface (LSS)



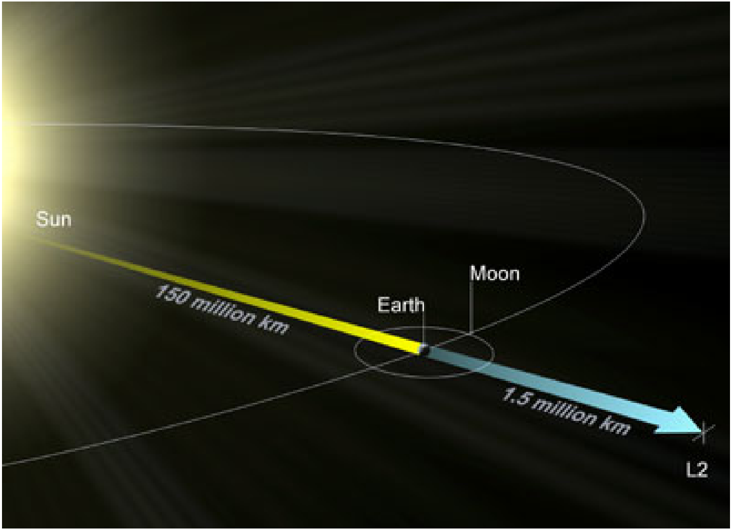
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



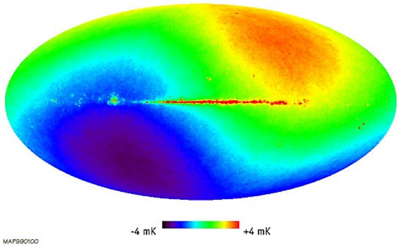
Planck Satellite (I) (European Space Agency)

It was launched in May/2009.

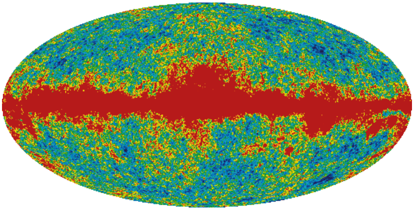
Planck Satellite (II)



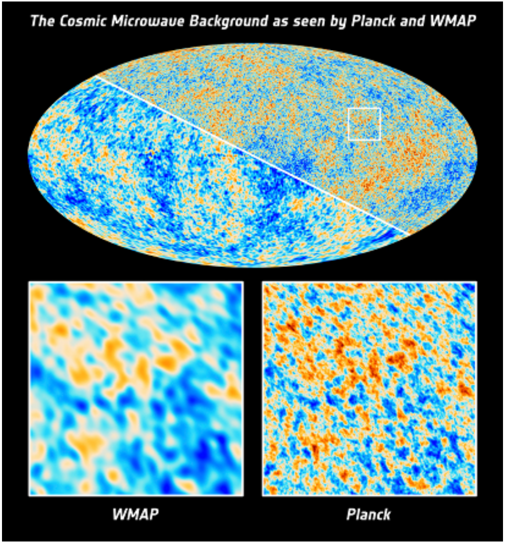
Temperature fluctuations of the CMB (I) [WMAP]



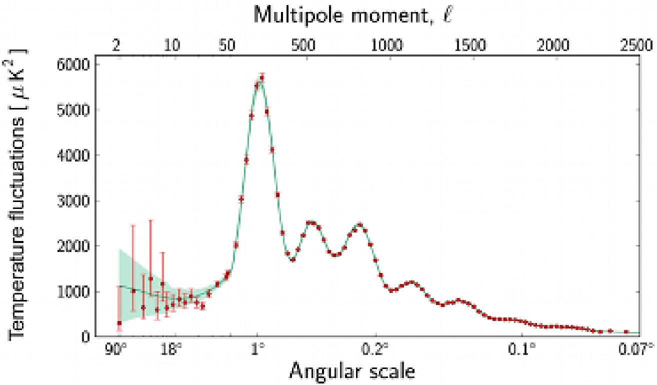
The solar system is moving in the direction [Planck Data] (Eppur si muove) $(l, b) = (263.99^o \pm 0.14^o, 48.26^o \pm 0.03^o)$ con $v = 369.0 \pm 0.9$ km s^{-1}.



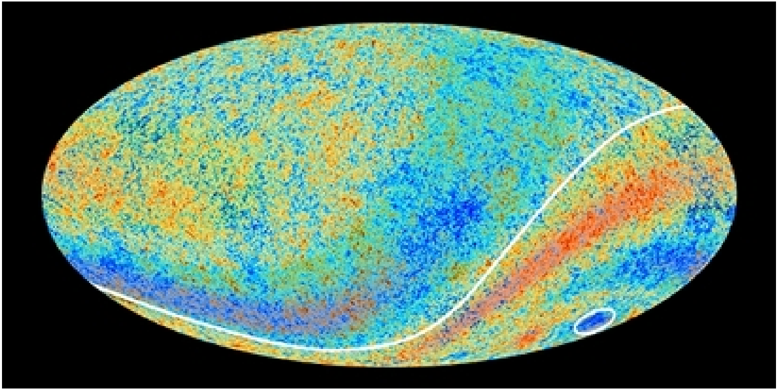
Temperature fluctuations of the CMB (I)(II): Comparison between Planck and WMAP



Analysis of the CMB fluctuations (III) [Planck]



Temperature anomalies in the CMB



Cosmological Parameters

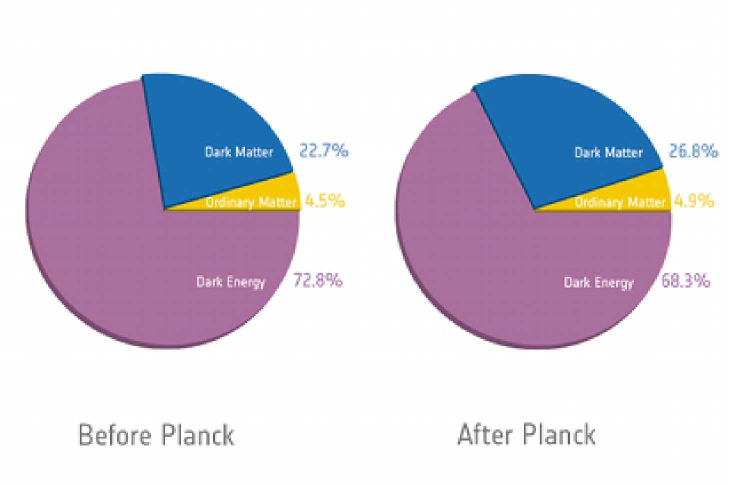
Planck Data, Assuming ΛCDM.

- Hubble parameter: $h = 0.6766 \pm 0.0042$.
- Matter: $\Omega_{\rm m} h^2 = 0.1428 \pm 0.0011$.
    1. Baryons : $\Omega_{\rm b} h^2 = 0.02233 \pm 0.00015$.
    2. Dark Cold Matter: $\Omega_{\rm c} h^2 = 0.1198 \pm 0.0012$.
- Matter (cold+"normal"): $\Omega_{\rm m} = 0.3111 \pm 0.0056$.
- Cosmological Constant: $\Omega_\Lambda = 0.6889 \pm 0.0056$
- Total Energy: $\Omega_{\rm tot} = 1.000 \pm 0.0078$.

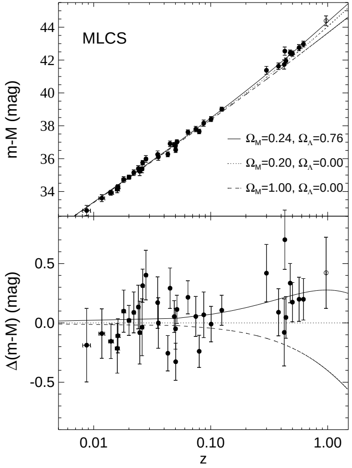
$$H_0 t_0 \simeq \frac{2}{3} \left(0.7\Omega_{\rm m} + 0.3 - 0.3\Omega_\Lambda\right)^{-0.3}$$

$$t_0 = (13801 \pm 24) \times 10^6 \text{years}.$$

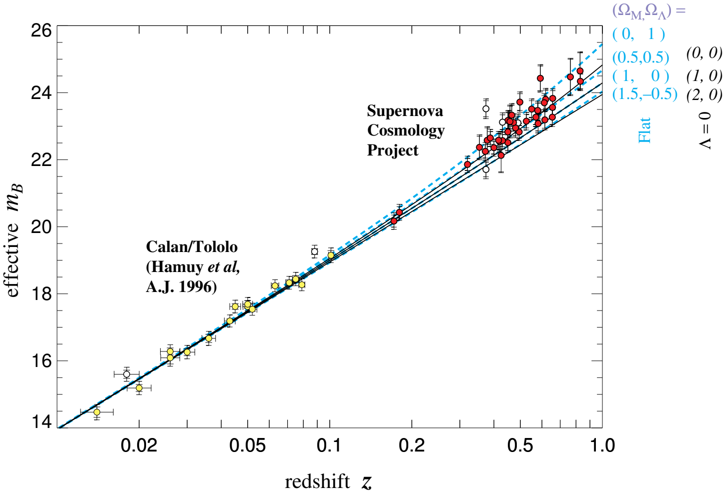
The recipe of our universe



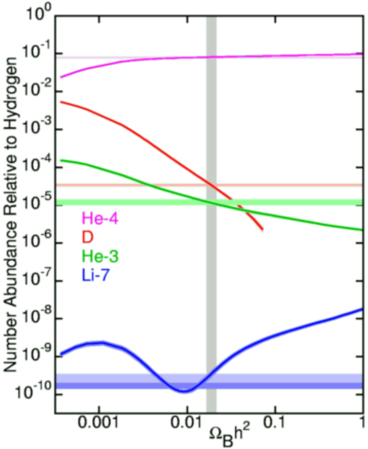
Cosmological parameter by SNIa (I)



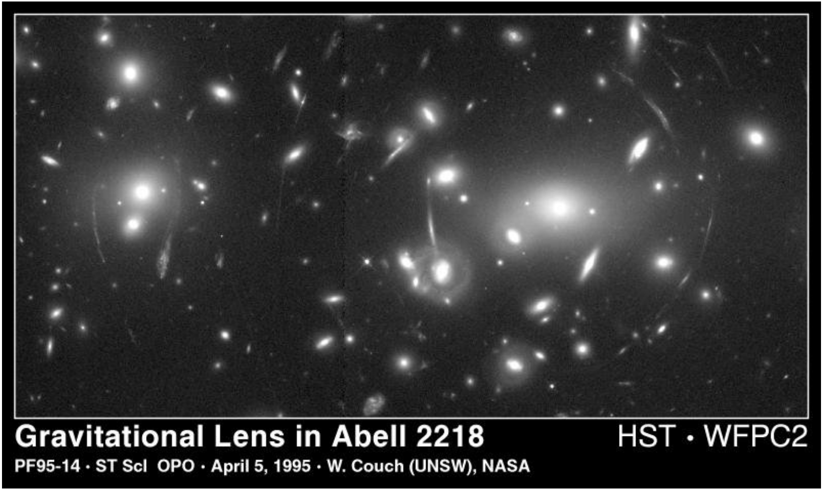
Cosmological parameters by SNIa (II)



Nucleosynthesis



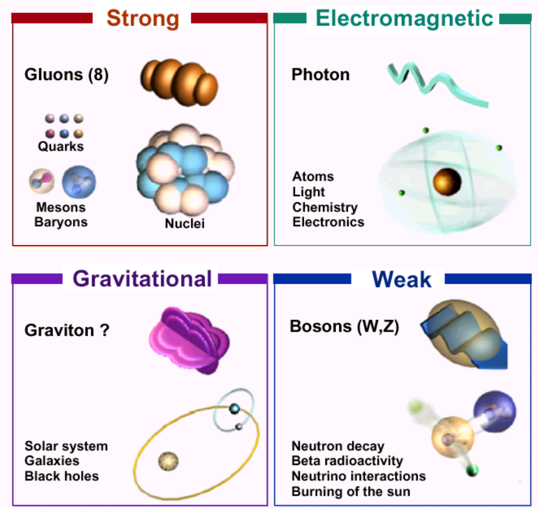
Dark matter (Gravitational lens) (I)



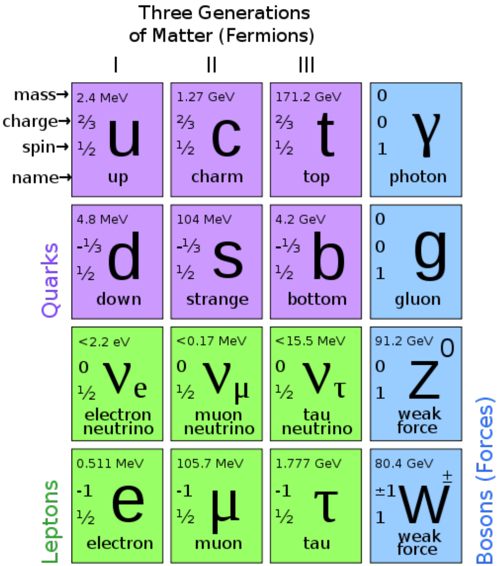
Dark Matter (II)

- "Normal" dark matter (baryonic): brown dwarf, interstellar dust, Massive Astrophysical Compact Halo Object (MACHO), etc. 15% of the total dark matter.
- Exotic dark matter (85% of the total matter) . Candidates:
  1. Weakly Interacting Massive Particles (WIMP)
  2. Heavy Neutrins.
  3. Axions.
  4. Primordial black holes.
  5. ...

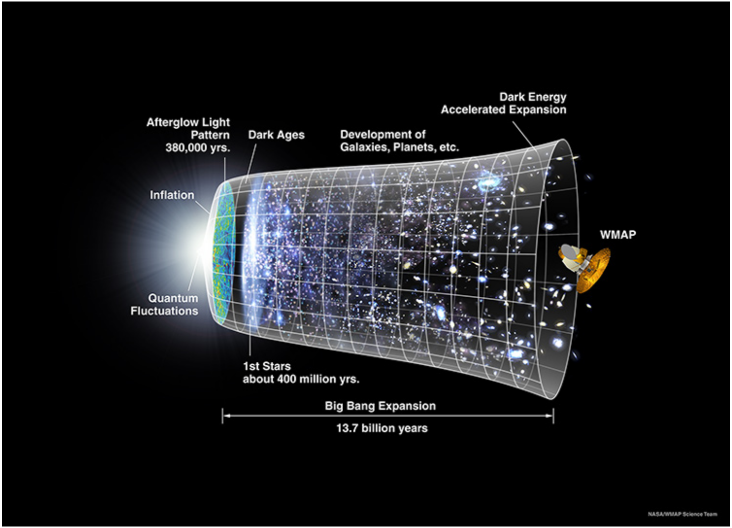
The four forces



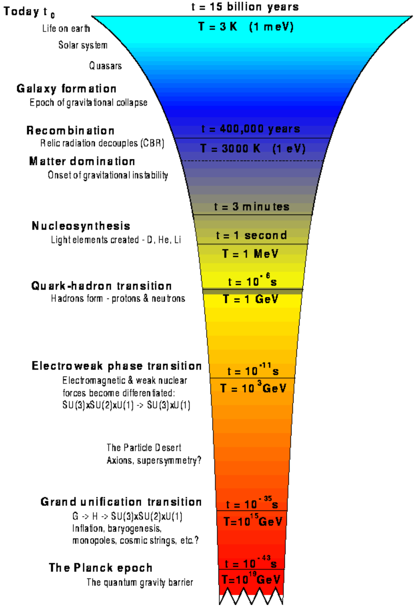
Elementary particles



History of the universe



History of the "baby" universe



The big problem of the cosmological constant

Using $\hbar$, c and G_N we can build the following magnitudes:

- Planck length: $l_P = \left(\frac{\hbar G_N}{c^3}\right)^{1/2} \simeq 10^{-35}\text{m}$
- Planck energy: $E_P = \left(\frac{\hbar c^5}{G_N}\right)^{1/2} \simeq 10^{19}\text{GeV}$

A naive estimate of the cosmological constant could be

$$\Lambda \simeq l_P^{-2} \simeq 10^{70}\text{m}^{-2}$$

But we know from CMB that

$$\Lambda_{\text{obs}} = \frac{3H^2\Omega_\Lambda}{c^2} \simeq 10^{-52}\text{m}^{-2}$$

Assuming that the scale is that of QCD (10^{-15} m), the results may be

$$\Lambda \simeq 10^{30}\text{m}^{-2}$$

Other poblems of ΛCDM

- Horizons
- Flatness: "Fine Tuning" of Ω's
  - $|\Omega(t_{\rm initial}) - 1| < 10^{-22} \left(E_{\rm initial}/{\rm GeV}\right)^{-2}$
  - Planck Scale: One part in 10^{60}
- Magnetic Monopoles
- Antimatter
  - Today $N_p/N_\gamma \sim 10^{-9}$ but $N_{\overline{p}}/N_\gamma \simeq 0$.
  - Conservation of the baryon number: $N_p/N_{\overline{p}} = 1 + O(10^{-9})$ when $k_B T >> m_p c^2$. What is the origin of this initial asymmetry?
- Formation of structures

Solutions: Inflation+....