Dark Energy

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Content

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Literature:

- Kolb and Turner, The Early Universe, Addision Wesley (1990)
- Scientific Background on the Nobel Prize in Physics 2011, Nobelprize.org
- Frieman, Lectures on Dark Energy and Cosmic Acceleration, arXiv:0904.1832

FRW Metric

Flat spatial models

Distribution of matter is homogeneous and distribution of radiation is isotropic ⇒ metric

$$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right) \tag{1}$$

Calculate for the metric (1)

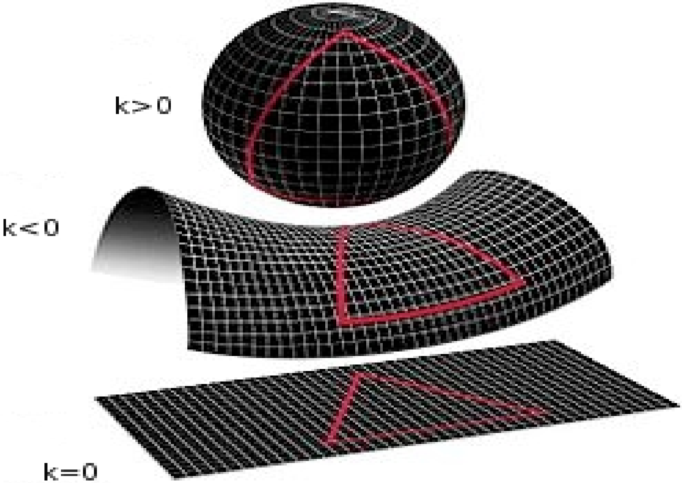
$$\Gamma^i_{jk} = \frac{1}{2} h^{il}(h_{lk,k} + h_{lk,j} - h_{jk,l})\,, \quad \Gamma^0_{ij} = \frac{\dot{R}}{R} h_{ij}\,, \quad \Gamma^i_{0j} = \frac{\dot{R}}{R}\delta^i_j \tag{2}$$

$$R_{00} = -3\frac{\ddot{R}}{R}\,, \quad R_{ij} = -\left(\frac{\ddot{R}}{R} + 2\frac{\dot{R}^2}{R^2} + 2\frac{k}{R^2}\right) h_{ij}\,, \quad R = -6\left(\frac{\ddot{R}}{R} + \frac{\dot{R}^2}{R^2} + \frac{k}{R^2}\right) \tag{3}$$

FRW Metric

1 a) Flat spatial models

$$ds^2 = dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$



Causal contact (horizon)

Comoving observer at time t recieves light from previous emission moment $t = 0$.

$\Rightarrow$ boundary of visible universe

$$d_H(t) = R(t) \int_0^t \frac{dt'}{R(t')} \tag{4}$$

Red shift

Three momentum $|\vec{u}|$ gets red shifted

$$|\vec{u}| \sim \frac{1}{R(t)} \tag{5}$$

Definition of redshift z in Astronomy

$$1 + z = \frac{\lambda_0}{\lambda_1} = \frac{R(t_0)}{R(t_1)} \tag{6}$$

Equations of motion

Einstein - Hilbert action gives

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu} \tag{7}$$

Matter stress energy tensor conserved

$$T^{\mu\nu}{}_{;\nu} = 0 \tag{8}$$

asume ideal fluid

$$T^{\mu}_{\nu} = diag(\rho, -\vec{p}) \tag{9}$$

Equations of motion

Friedman equations

$$\frac{\dot{R}^2}{R^2} + \frac{k}{R^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} \quad (10)$$

$$2\frac{\ddot{R}}{R} + \frac{\dot{R}^2}{R^2} + \frac{k}{R^2} = -8\pi G p + \Lambda \quad (11)$$

equation of state

$$p = -\frac{d(\rho R^3)}{d(R^3)} \quad (12)$$

Friedman equations

Define critical density ρ_c and dimensionless density Ω_i

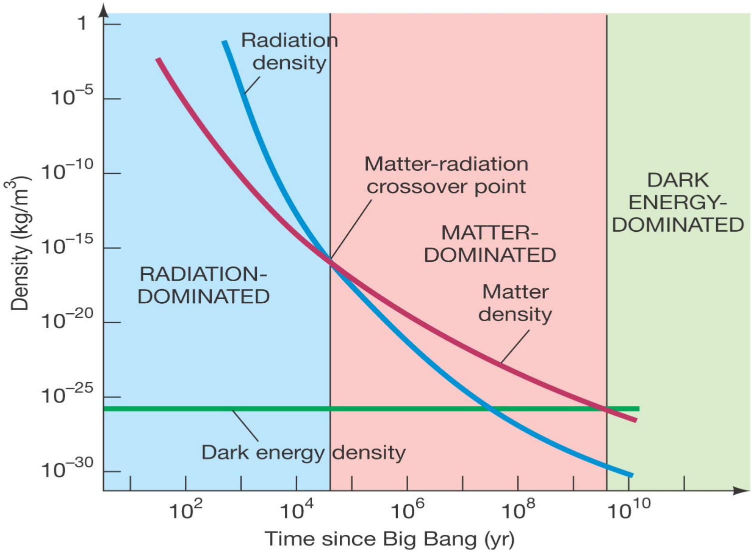
$$\rho_c = \frac{3H^2}{8\pi G} \quad , \text{and} \quad \Omega_i = \frac{\rho_i}{\rho_c} \tag{13}$$

The universe is closed for $\Omega > 1$, flat for $\Omega = 1$, and open for $\Omega < 1$. Also find

$$\rho = \begin{cases} \sim R^{-3} & \text{for matter} \\ \sim R^{-4} & \text{for matter} \\ \sim cte. & \text{for} \quad \Lambda \end{cases} \tag{14}$$

Standard Cosmology

2 b) Solutions of the Friedman equations



Hubble expansion measured for close Glaxies

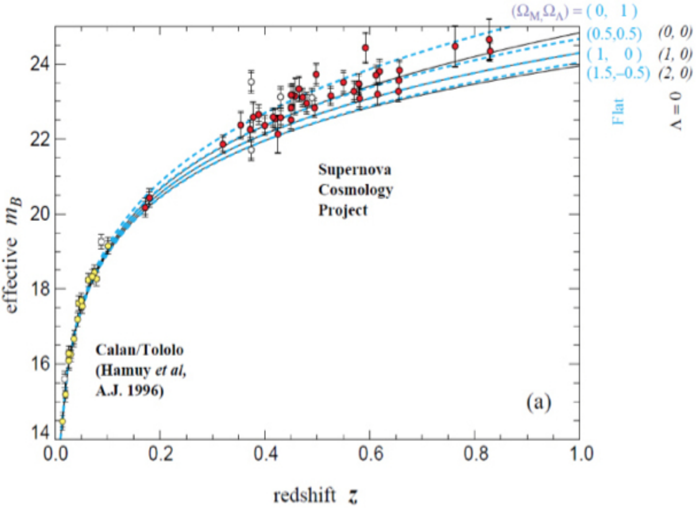
$$H_0 = 72 \pm 8 \frac{km}{s \cdot Mpc} \tag{15}$$

Need standard source "candle" in order to translate Luminosity into distance.

$$d_L = \sqrt{\frac{L}{4\pi l}} \tag{16}$$

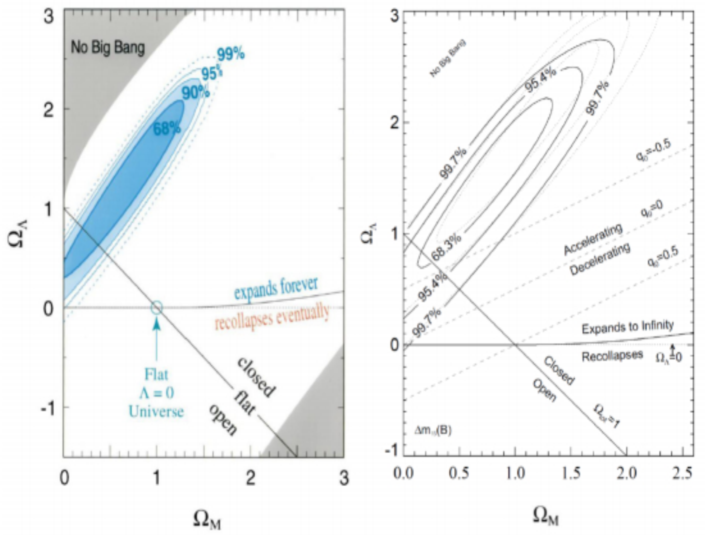
With the model for the universe

$$d_L(z, H_0, \Omega_m, \Omega_\Lambda) = \frac{1+z}{H_0} \int_0^z dz \frac{1}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \tag{17}$$



SN 1a is very good standard candle

Vary parameters Ω_Λ and Ω_m



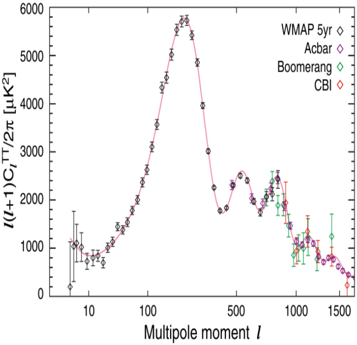
No Big Bang
99%
95%
90%
68%
expands forever
recollapses eventually
Flat
Λ = 0
Universe
closed
flat
open
Ω_Λ
Ω_M
No Big Bang
95.4%
99.7%
68.3%
q_0=-0.5
q_0=0
q_0=0.5
Accelerating
Decelerating
Expands to Infinity
Recollapses
Closed
Open
Ω_{tot}=1
Ω_Λ=0

The Cosmic Microwave Background

Waves in early Baryon-γ plasma

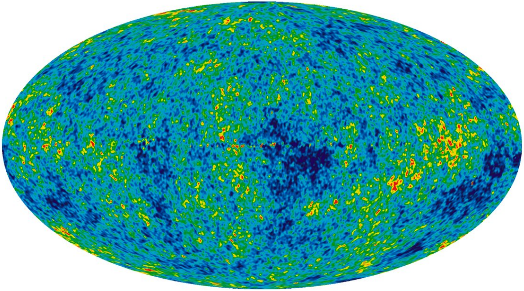
$$d_0 \approx c_s t_s \tag{18}$$

evolve until today with $H(t)$



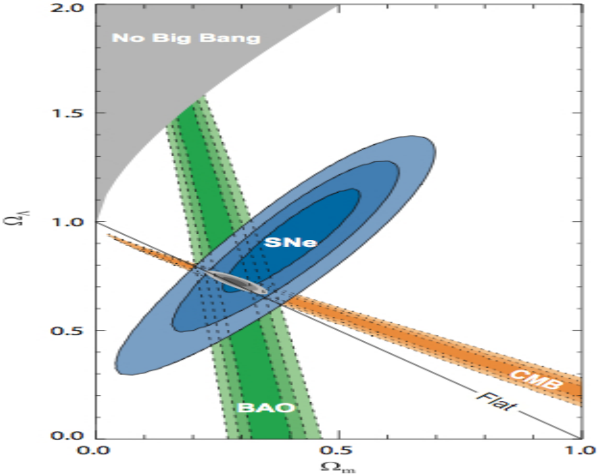
The Baryon Acoustic Oscillations

Same waves in early Baryon plasma give density fluctuations $\Delta\rho$ which are seed for Galaxy formation.



Fluctuations in CMB

Putting the evidence together



Thank You!