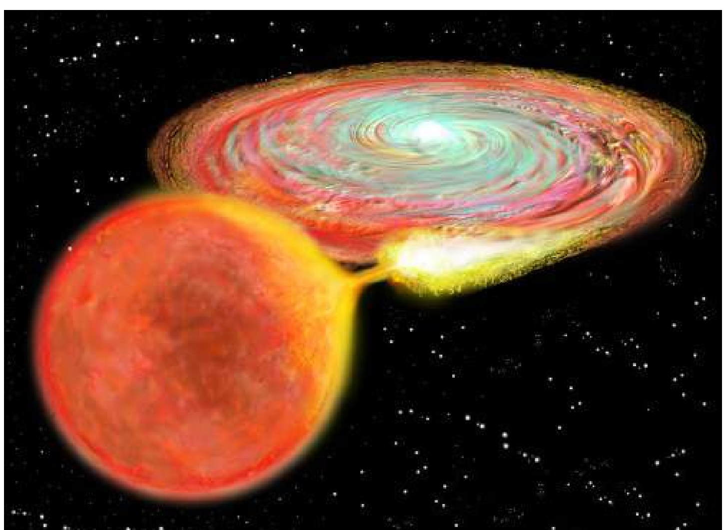
SEMINAR

# Short introduction to the accelerating Universe

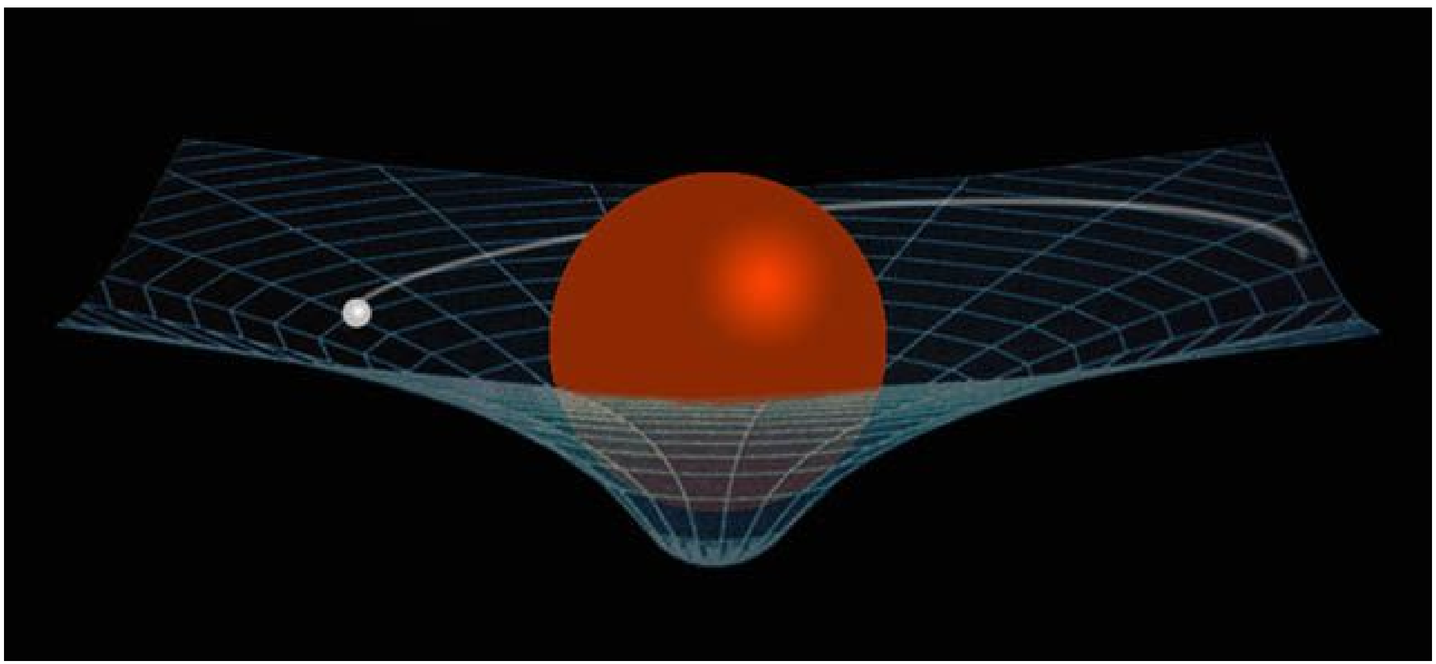


Gašper Kukec Mezek

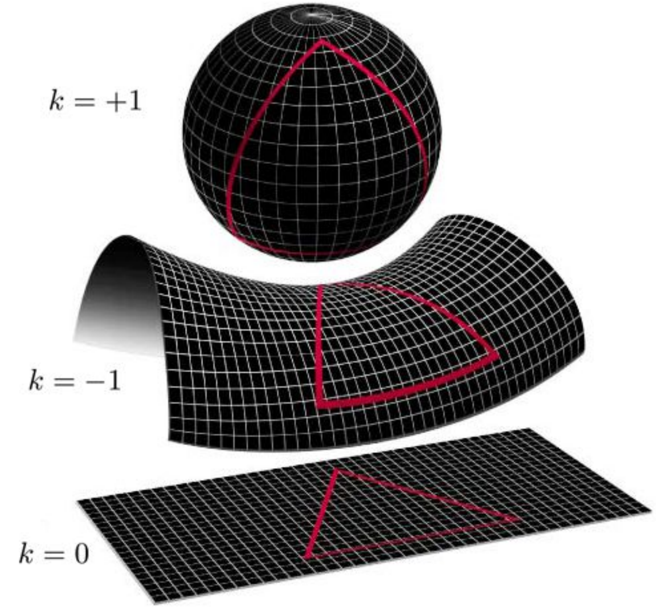
# Our expanding Universe

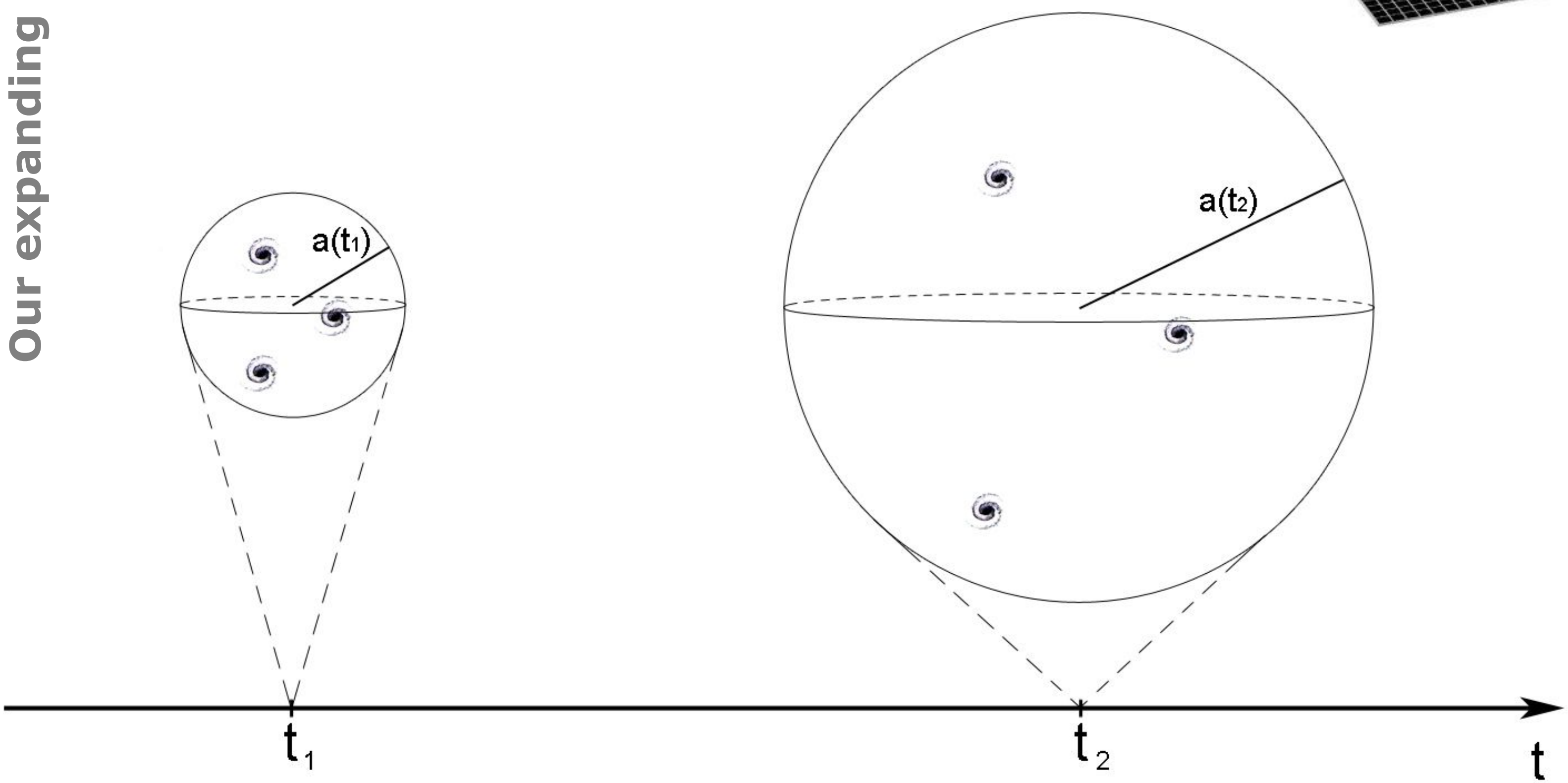
- Albert Einstein – general relativity (1917):

Curvature = Energy



- Alexander Friedmann – first view of a non-static Universe (1922) and his calculations on the negative curvature of space

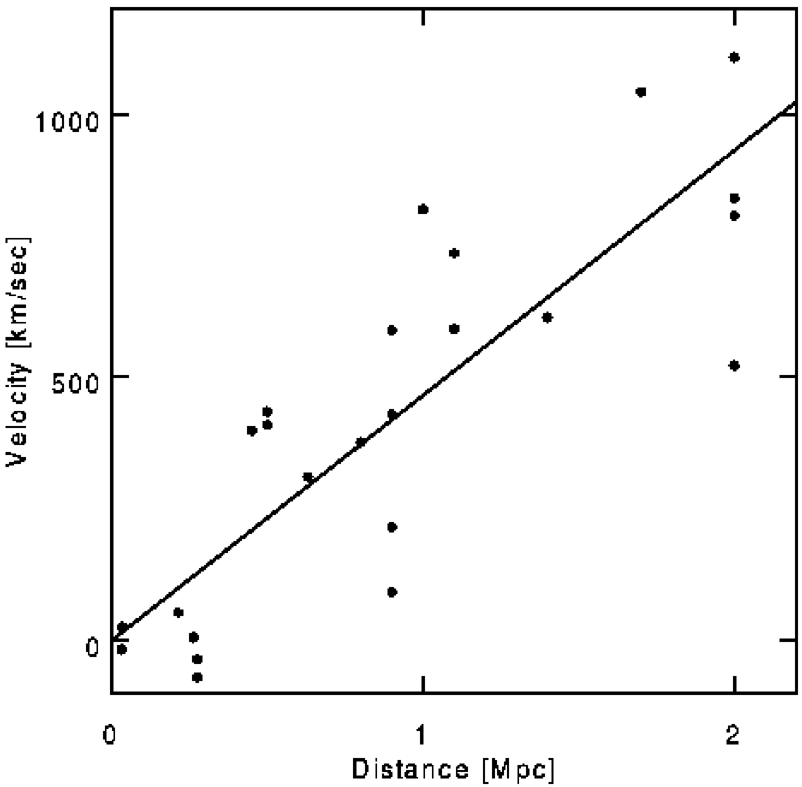


# Standard candles in cosmology

- Standard candles are celestial objects, that have know luminosity through some special characteristic
- From the luminosity, we can determine their distance from us

- Vesto Slipher, Carl Wirtz, Knut Lundmark, Georges Lemaître, Edwin Hubble – expansion of the Universe, Hubble's law (1929)




$$H = \frac{\dot{a}(t)}{a(t)} \;\rightarrow\; v = H_0 d$$

# Deceleration or acceleration?

- From the Friedmann equation

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

we can determine the density fractions $\Omega$ of constituents

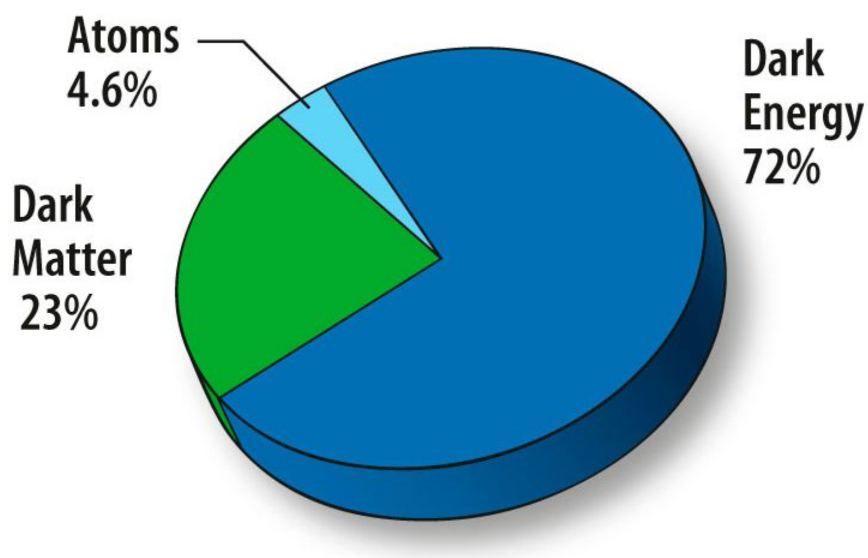
$$\Omega_i = \frac{\rho_i}{\rho_c} \qquad \Omega_k = -\frac{k}{H^2a^2} \qquad \Omega_\Lambda = \frac{\Lambda}{8\pi G}$$

where:

$$\rho_c = \frac{3H^2}{8\pi G} \qquad \Omega_{tot} = \sum_i \Omega_i + \Omega_k + \Omega_\Lambda = 1$$

Deceleration or acceleration?

- Constituents of the Universe:
  - ~ 4.6% of ordinary matter
  - ~ 23% of dark matter
  - ~ 72% of dark energy (currently contributed to the cosmological constant)
- Tug of war between matter and dark energy



- From Friedmann evolution equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i (\rho_i + 3p_i) + \frac{\Lambda}{3}$$

we define the deceleration parameter $q_0$

$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\sum_i \Omega_i \left(1 + 3w_i\right)$$

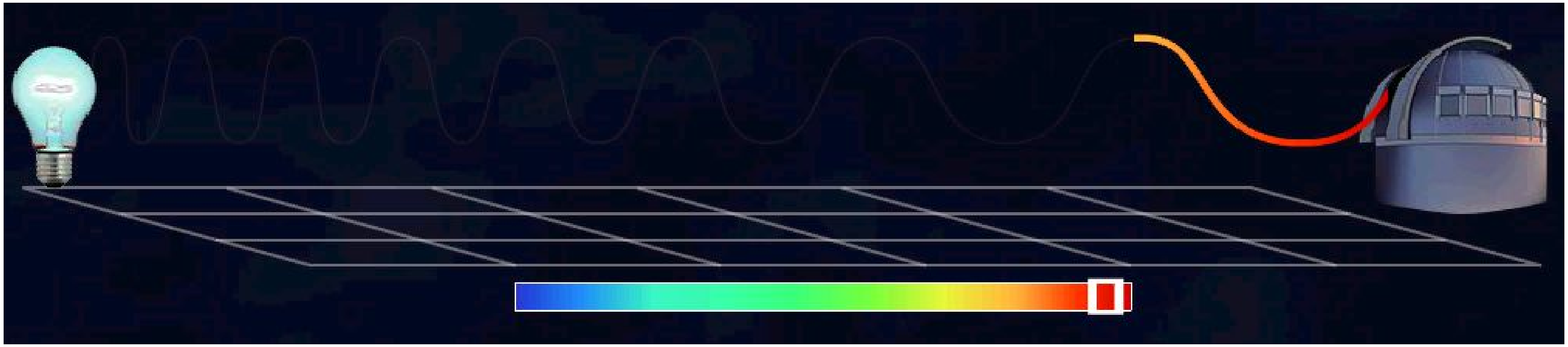
where $p_i = w_i \rho_i$

| | |
|---|---|
| $w = 0$ | dust, non-relativistic matter |
| $w_R = \frac{1}{3}$ | radiation, relativistic matter |
| $w_\Lambda = -1$ | vacuum, cosmological constant |

# Redshift

- Measure of shift towards longer wavelengths for objects moving away from the observer

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = \frac{\nu_e - \nu_o}{\nu_o} = \frac{a(t_o)}{a(t_e)} - 1$$



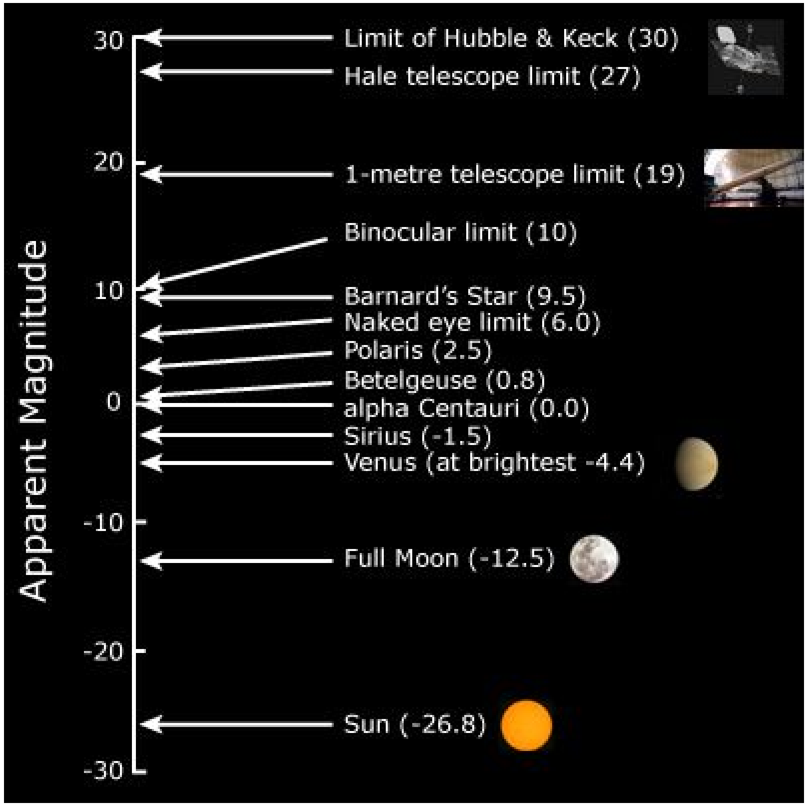
# Magnitude and luminosity

- Values determining the brightness of an object
- Apparent magnitude $m$:

$$m = -2.5 \log l_s + C$$

- Absolute magnitude $M$:

$$M = m - 5 \log \frac{d}{10}$$




Deceleration or acceleration?

- Luminosity is the amount of light coming from a celestial object
- Absolute luminosity $L$ (emitted energy per second) and apparent luminosity $l$ (received energy per second per area):

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

- Connecting it to magnitude:

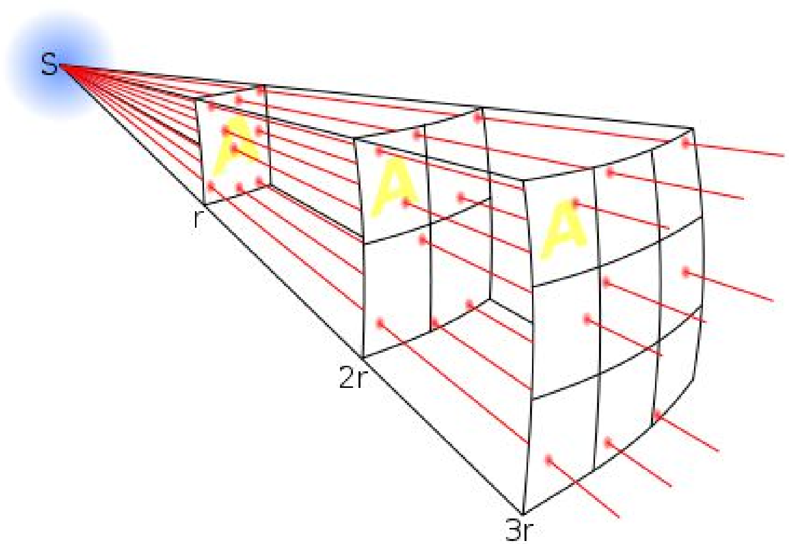
$$l_{bol} = 10^{-2m_{bol}/5} \times 1.573 \times 10^7 \ \frac{\text{eV}}{\text{cm}^2\text{s}}$$

$$L_{bol} = 10^{-2M_{bol}/5} \times 1.885 \times 10^{47} \ \frac{\text{eV}}{\text{s}}$$

# Luminosity distance

- Due to expansion, the distances are time dependent
- We can express the luminosity distance with redshift and deceleration parameter:

$$d_L = \frac{1}{H_0}\left(z + \frac{1}{2}(1 - q_0)z^2 + \ldots\right)$$



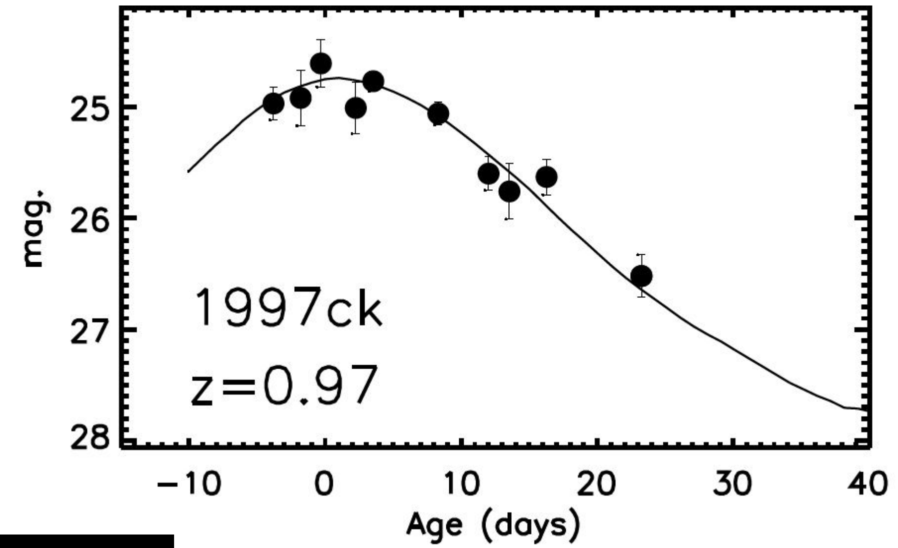
# Cepheid variable stars

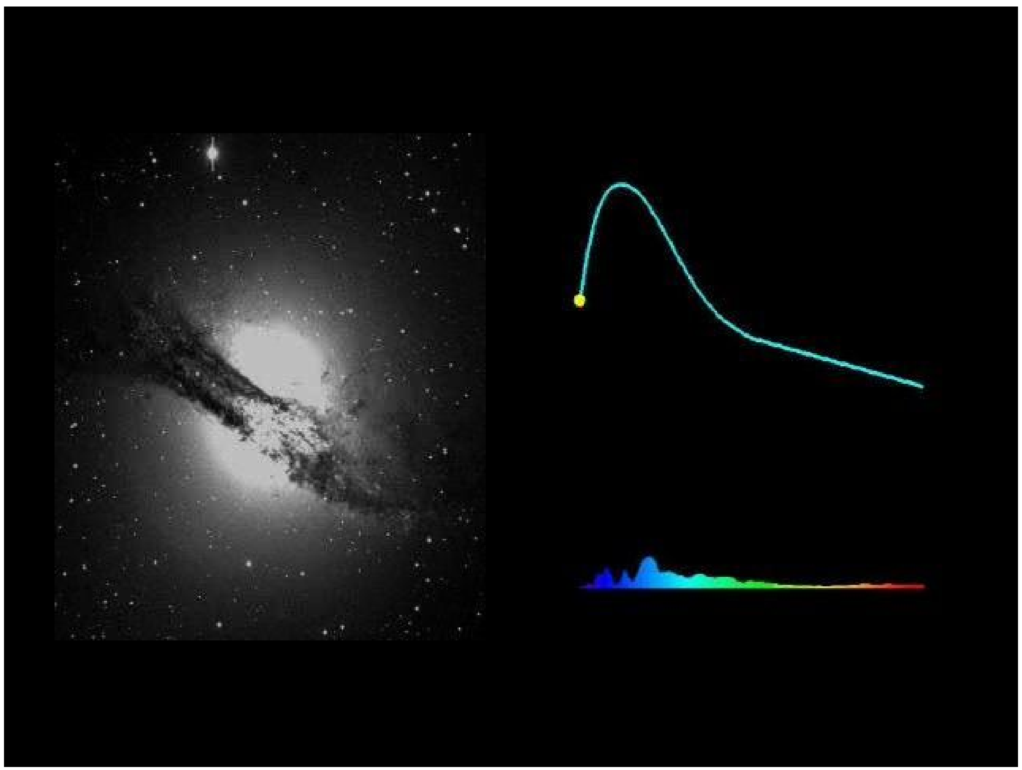
- Bright, pulsating stars
- Luminosity is correlated with the pulsation period, that ranges from 2 to 45 days
- Longer periods correspond to brighter objects
- Can be observed relatively close and up to ~20 Mpc (redshifts up to ~0.005)

# Supernovae Type Ia

- Observed much further away than Cepheid stars
- Binary star system, accretion of matter to smaller star, that eventually explodes
- Extremely bright explosion – total energy output equal to our sun during a 10 billion year period
- Intensity raised for several weeks

- Supernova light curve and a simulation of an explosion, with added spectrum



Supernovae Type Ia

# Observing supernovae

- Detectors consist of large telescope systems observing a large portion of the sky
- After two measurements a supernova peak is determined
- Calán/Tololo Supernova Survey (1990-1993): 50 low-redshift supernovae
- SCP (since 1988): 42 high-redshift supernovae[1]
- HZT (since 1994): additional high-redshift supernova search group[2]

1 – S. Perlmutter et al.: *Measurements of $\Omega$ and $\Lambda$ from 42 high-redshift supernovae*, Astrophysics Journal, **517**, 565-586, (1999).

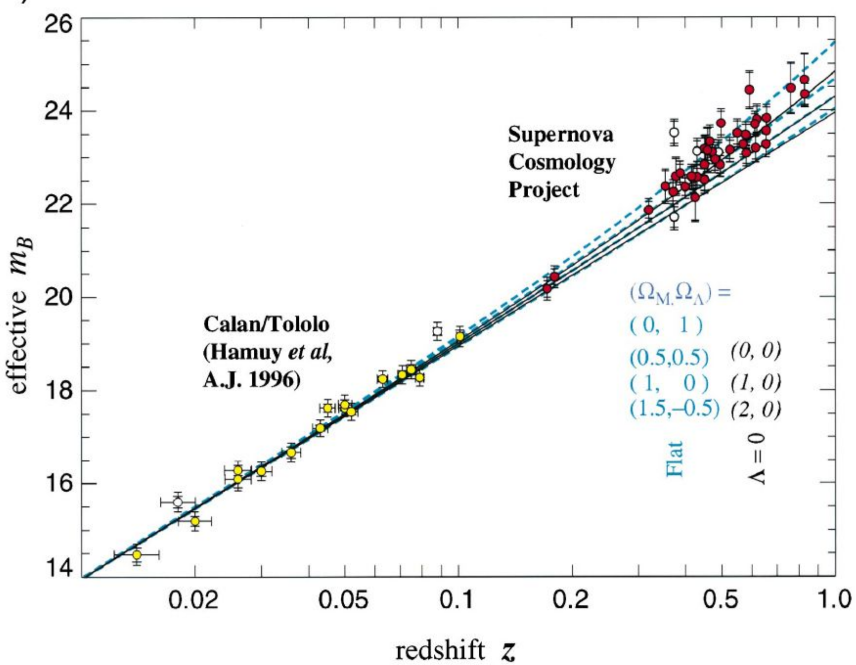
2 – A.G. Riess et al.: *Observational evidence from supernovae for an accelerating universe and a cosmological constant*, Astronomy Journal, **116**, 1009-1038 (1998).

# Results

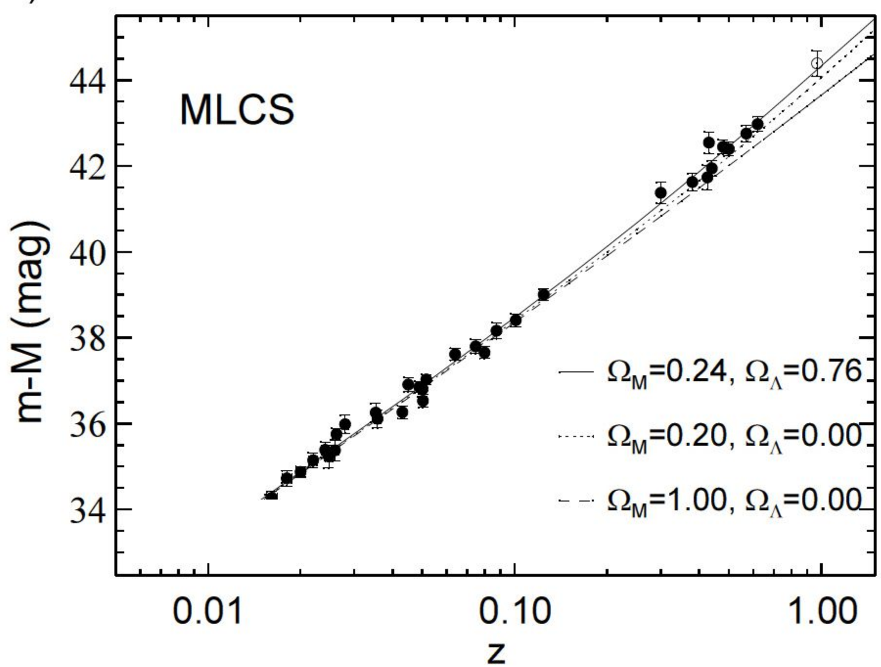
- Hubble diagrams for the gathered measurements:

$$m_B^{\text{eff}} = M_B + 25 + 5\log d_L(z;\, \Omega_M, \Omega_\Lambda)$$

a)



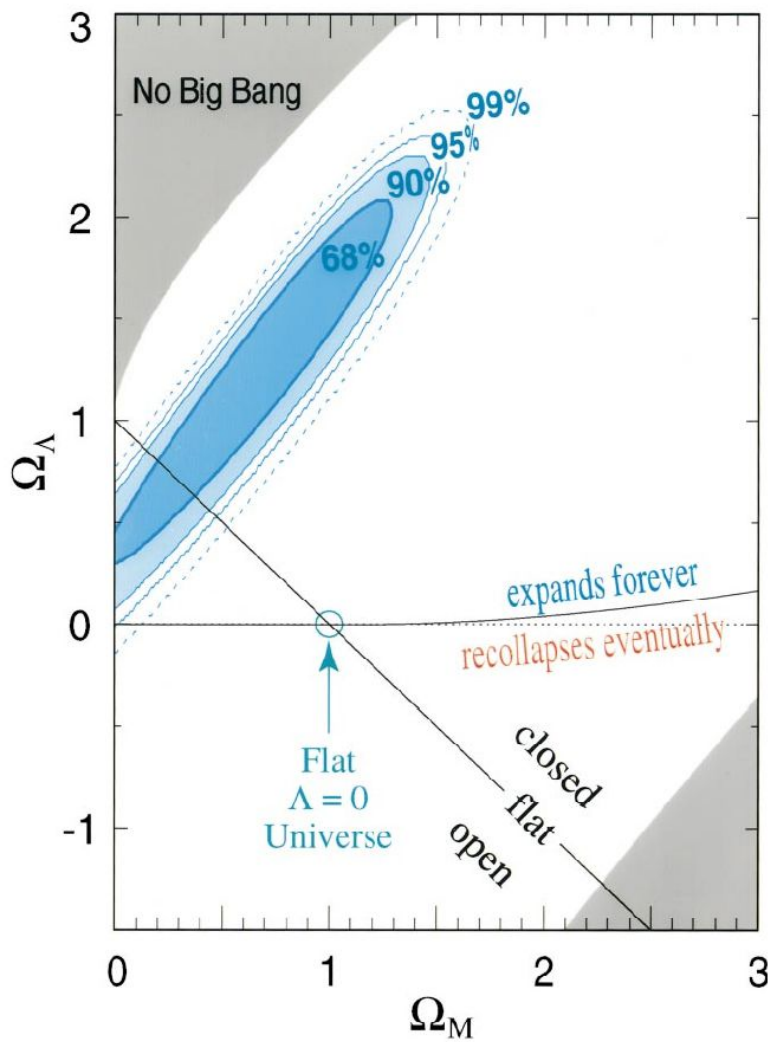

b)

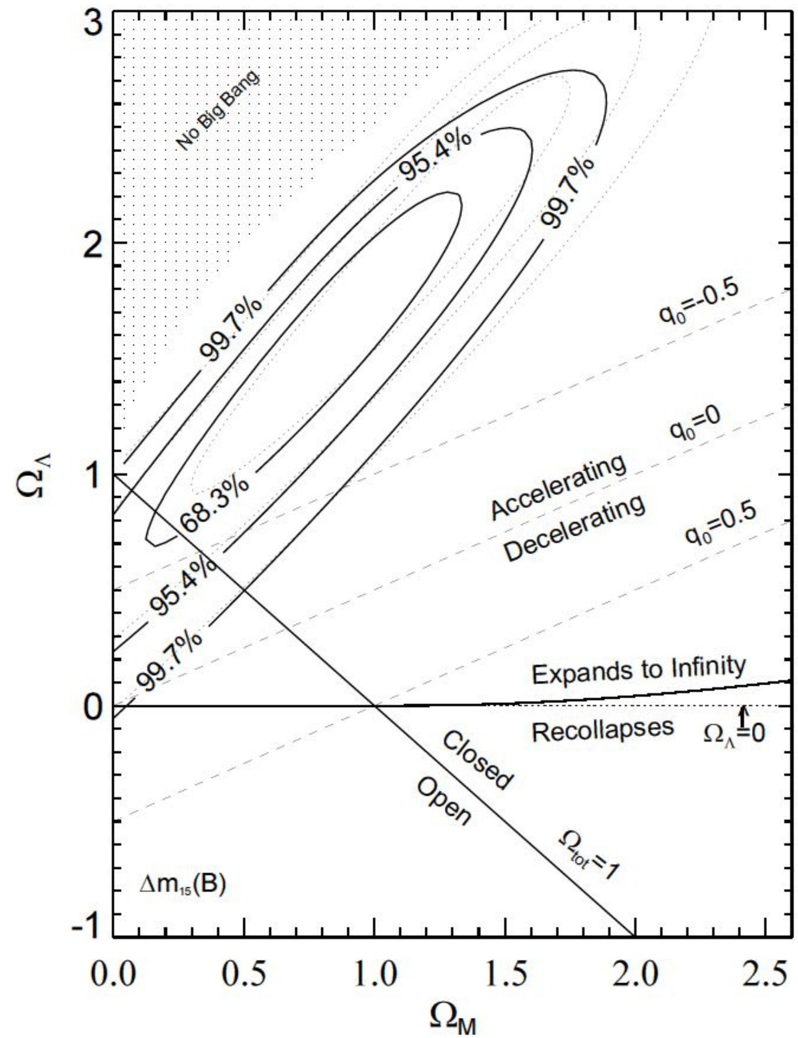


## Results

$$\Omega_M = 0.28^{+0.14}_{-0.12} \qquad \Omega_\Lambda = 1 - \Omega_M$$

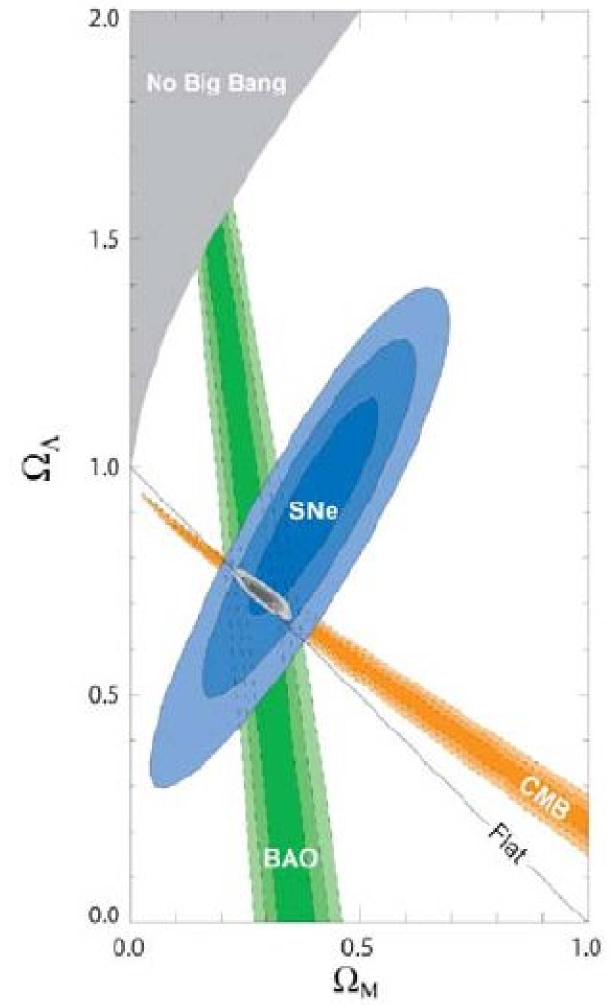
$$t_0 = 13.4^{+1.3}_{-1.0} \text{ Gyr}$$



# Where to next?

- Results are in favour of a vacuum energy dominated Universe
- Using comparative methods to confirm the results (CMB, baryon acoustic oscillations,...)



- Some effects that might alter the results:
  - Active debate about absorption of light by the material after supernova explosion
  - Luminosity may depend on the evolution of the supernova
  - Is the cosmological constant really a constant?