University of Padua

Department of Physics and Astronomy GALILELO GALILEI

Distance Measures in Cosmology and Supernovae Type Ia

Candidate: **Matteo De Leone**

Supervised by: **Prof. Nicola Bartolo**
Dott. Michele Liguori

2015/2016

Distance in Cosmology

It’s difficult to define what distance is in cosmology due to the continuous expansion of the Universe.

- *Luminosity Distance* → *Supernovae Type Ia*
- *Angular Diameter Distance* → *CMB*

Consequently:

- it’s possible to estimate some cosmological parameters;

- evidence of Dark Energy; → Cosmological Costant Problem → Coincidence Problem

- parameterizations.

Cosmological Principle

Isotropy and omogenity of the space on the large scale.
The dynamic of the Universe is described by Friedman's equations:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3\frac{p}{c^2}\right) + \frac{\Lambda}{3}$$

Deceleration parameter:

$q_0 = -\frac{\ddot{a}(t_0)}{a(t_0)H_0^2} = \frac{1}{2}\sum_i \Omega_i(1 + 3\omega_i)$ *there's acceleration when*: $w < -\frac{1}{3}$

Density parameters:

$\Omega_M = \frac{\rho}{\varphi_c}$ where $\rho_c = \frac{8\pi G}{3H^2}$ $\quad \Omega_\Lambda = \frac{\rho_\Lambda}{\varphi} = \frac{\Lambda}{3H^2}$ $\quad \Omega_k = -\frac{k}{a^2 H^2}$

The first Friedman equation can be written as: $1 = \Omega_M + \Omega_\Lambda + \Omega_k$

Luminosity Distance

Distance at which a source of luminosity L has an apparent flux S :

$$d_{lum} = \left(\frac{L}{4\pi S}\right)^{1/2} = a_0 r(1+z)$$

It can be expressed in terms of cosmological parameters:

$$d_{\mathrm{L}} = cH_0^{-1}(1+z)|\Omega_{\mathrm{k}}|^{-1/2} \sin n\Big\{|\Omega_{\mathrm{k}}|^{1/2} \int_0^z [(1+z)^2(1+\Omega_{\mathrm{M}}z) - z(2+z)\Omega_\Lambda]^{-1/2}\, dz\Big\}.$$

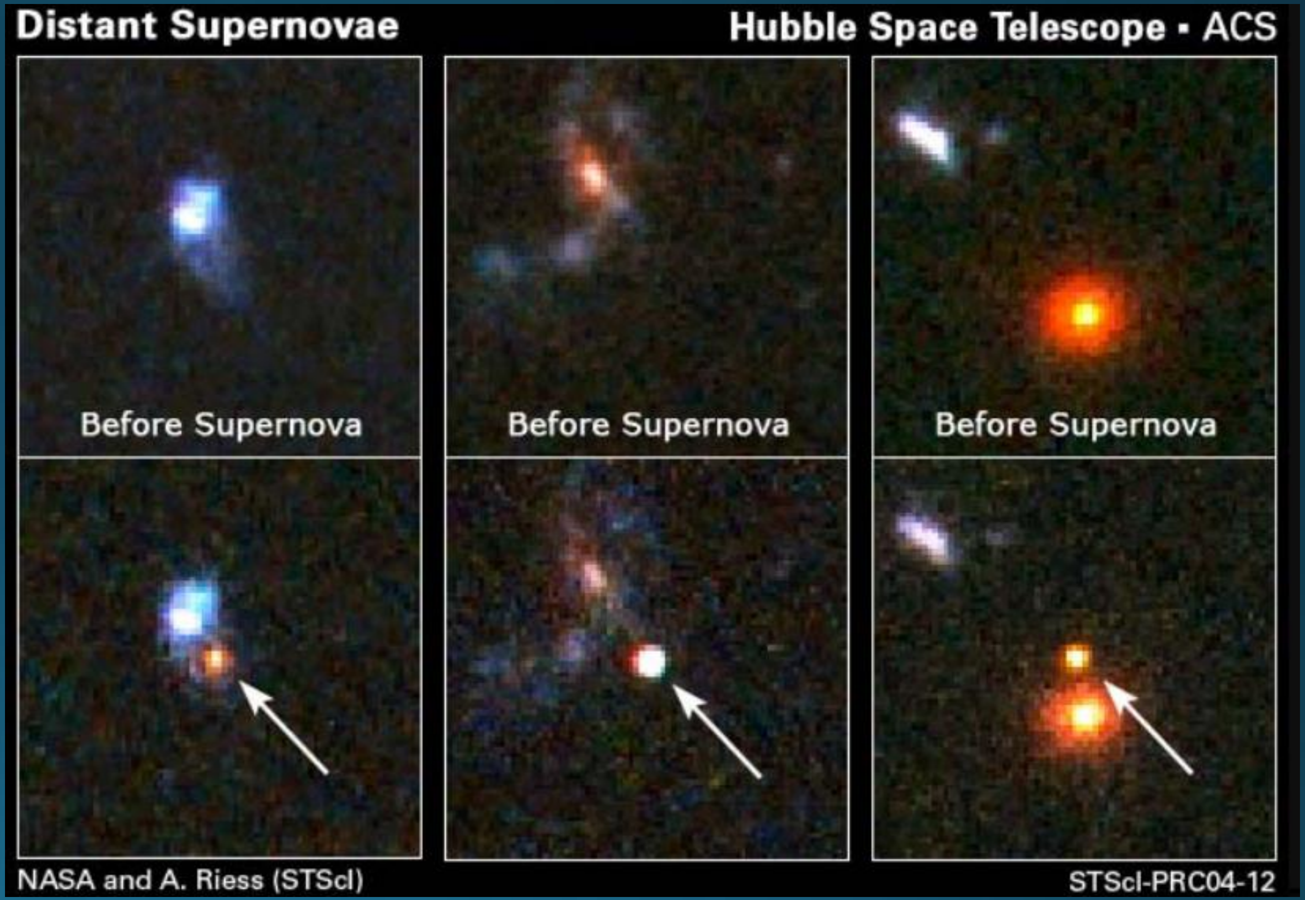
Where sin *n* is equal to *sinh* when $\Omega_k > 0$; it is equal to *sin* when $\Omega_k < 0$ and when $\Omega_k = 0$ (Euclidian case $\Omega_m + \Omega_\Lambda = 1$) sin *n* and Ω_k disappear.

Supernovae Type Ia

Advantages:

- *High luminosity at maximum ($M_B \sim -19.5\, mag$);*

- *Phillips relation (1993) between the peak of luminosity and the rate of luminosity decrease in time.*

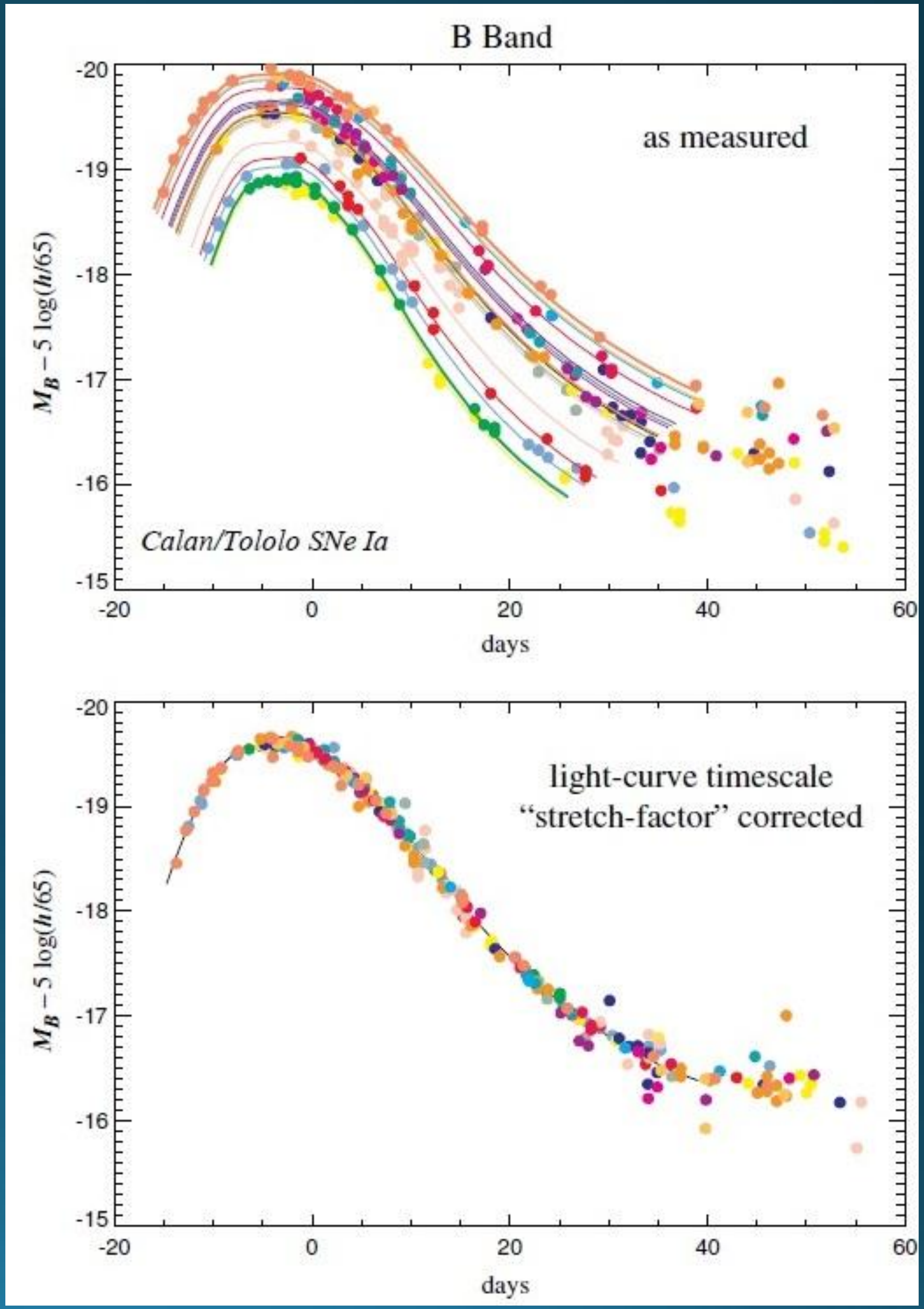


Using the Phillips' relation it is possible to calibrate the light curves

↓

Standard Candle

The distance of SNe at high redshift was, on average, 10-15% (0.25 – 0.28 mag) bigger than the predictions of distance in a Universe with low density $\Omega_M = 0.2$ and without a cosmological constant.



Estimation of cosmological parameters

$$m(z) = M + 5\log d_L(z;\Omega_\Lambda,\Omega_M,H_0) + 25$$

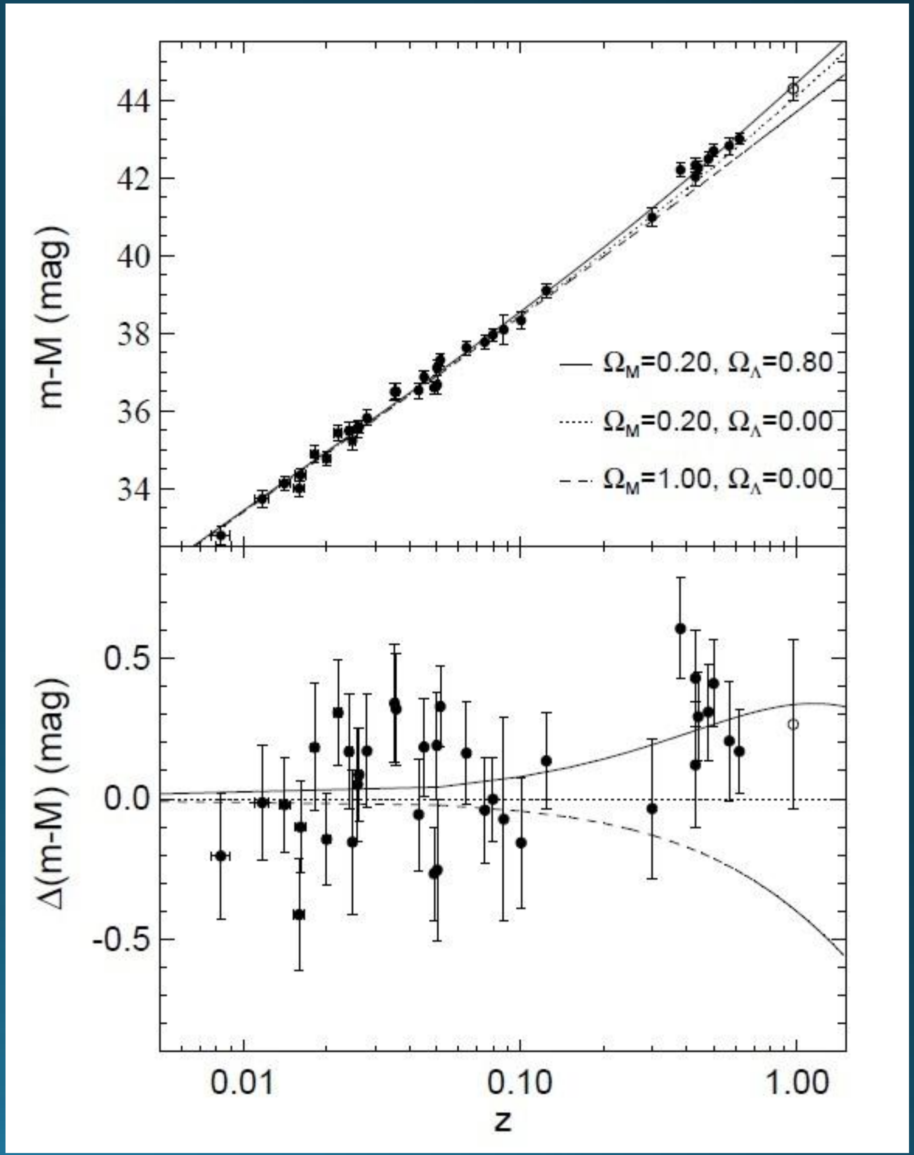
In the limit of low redshift:

$$m(z) = \mathcal{M} + 5\log cz$$

$$\mathcal{M} \equiv M - 5\log H_0 + 25$$
$$D_L \equiv H_0 d_L$$

The parameter $\mathcal{M}$ can be determined using SNe at low redshift. The best fit of the parameters can be found resolving the following equation:

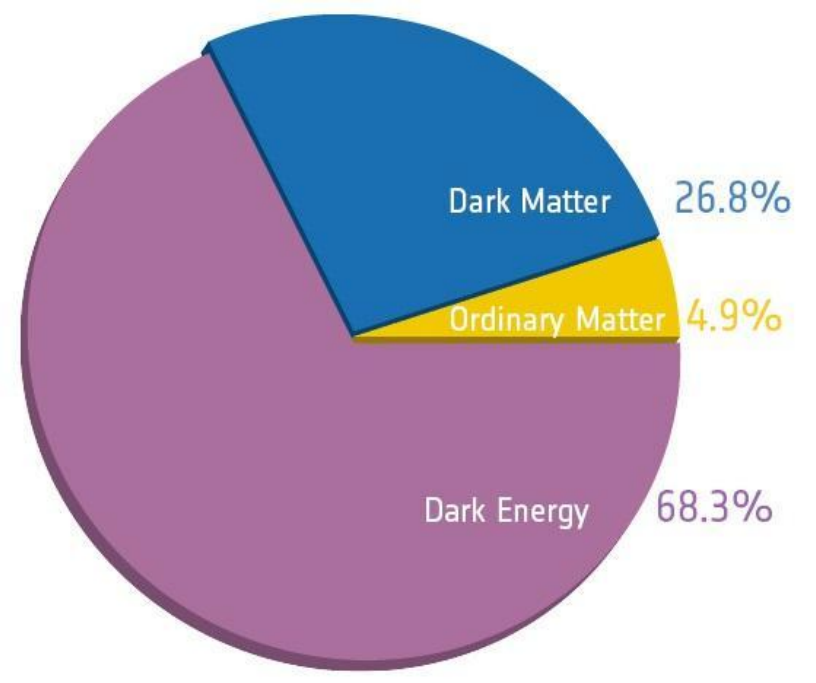
$$m(z) - \mathcal{M} = 5\log D_L(z;\Omega_\Lambda,\Omega_M)$$

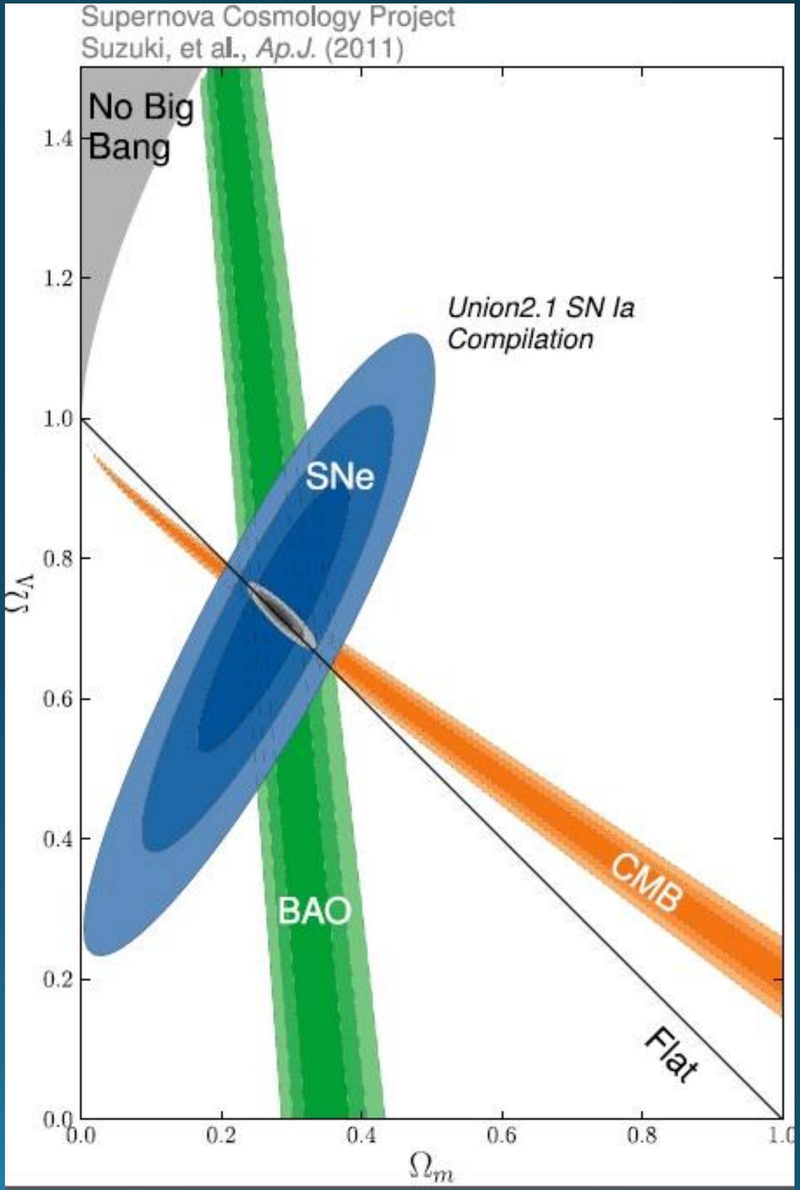


Riess et al. 1998

Results

- Evidence of $\Omega_\Lambda > 0$ responsible for the accelerating expantion $q_0 < 0$;
- Flat Universe $\Omega_M + \Omega_\Lambda = 1$;
- Age of the Universe $14.2 \pm 1.7\ Gyr$.



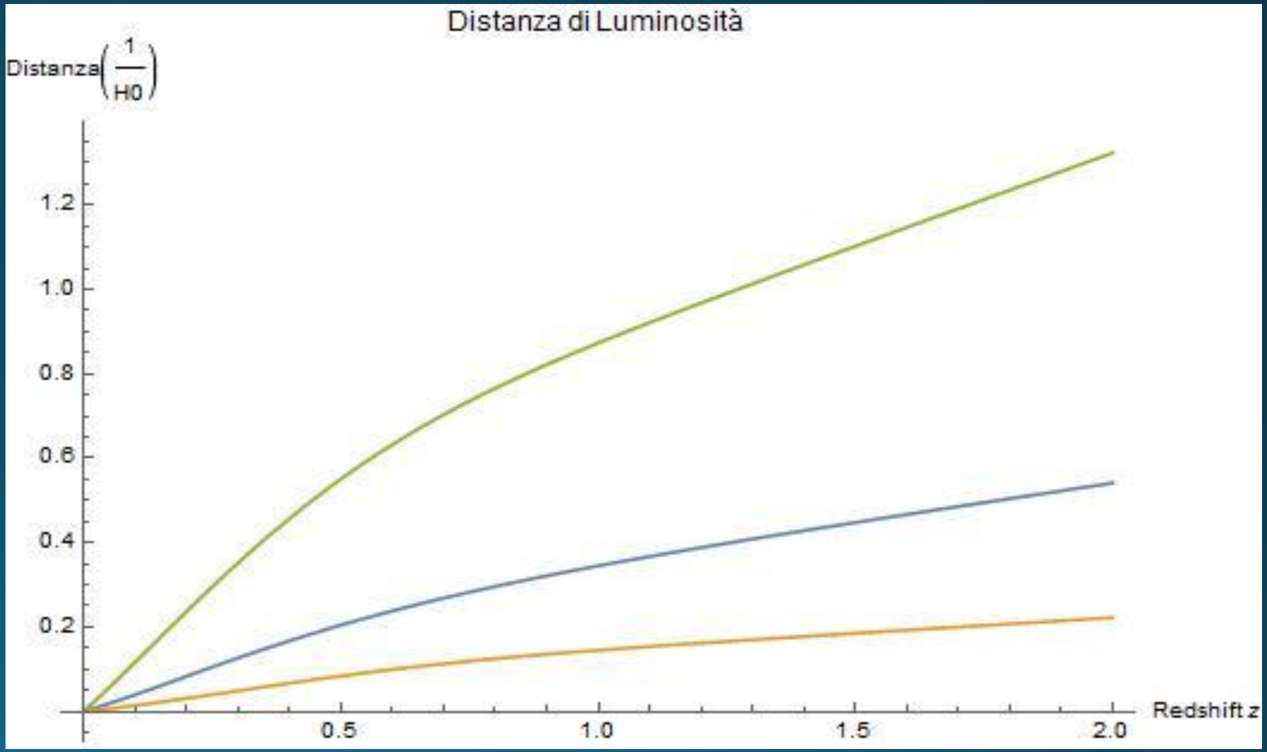


Luminosity Distance and Parameterizations of Dark Energy

Equation of state $p = \rho w$*. The w parameter gives a phenomenological description of the Dark Energy. The parameterization w= -1 is interpreted as a cosmological constant.*
From the continuity equation: $\dot{\rho} + 3H(p+\rho) = 0$

$$\downarrow$$

$$\rho_{DE}(z) = \Omega_{DE,0}\exp(3\int_0^z(1+3w(z'))\,d\ln((1+z'))$$



Blu line : $w(z) = w_0 + \frac{w_a z}{1+z}$
Green line: $w(z) = w_0 + b\ln(1+z)$
Orange line: $w(z) = w_0 + w'z$

$w_0 = -1 \quad w' = b = 1.67 \quad w_a = 3.3$

Dark Energy

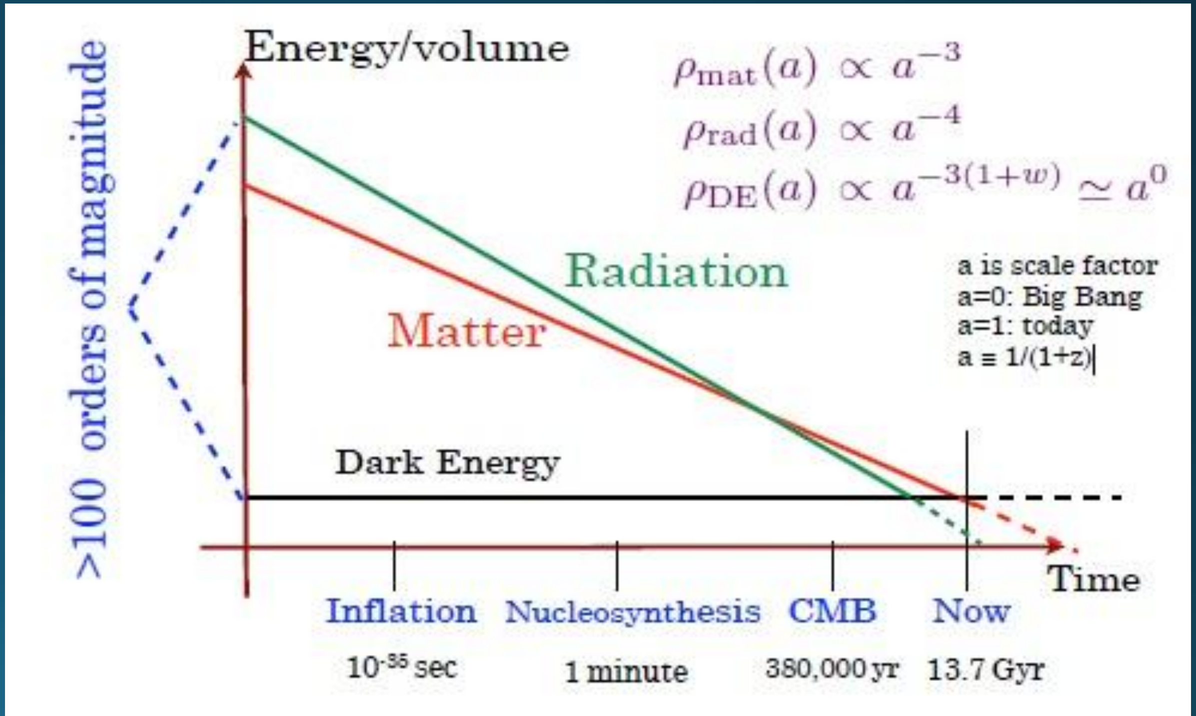
Evidences
- CMB
- Large Scale Structures (LSS)
- Weak Gravitational Lensing
- Integrated Sachs-Wolfe effect (ISW)

In the ΛCDM model it is interpreted as the quantum energy of the vacuum (w = -1). The value of the vacuum energy density is:

$$\rho_{vac} = \frac{1}{2} \sum_{fields} g_i \int_0^{\infty} \sqrt{k^2 + m^2} \frac{d^3k}{(2\pi)^2} = \infty$$

COSMOLOGICAL COSTANT PROBLEM

COINCIDENCE PROBLEM

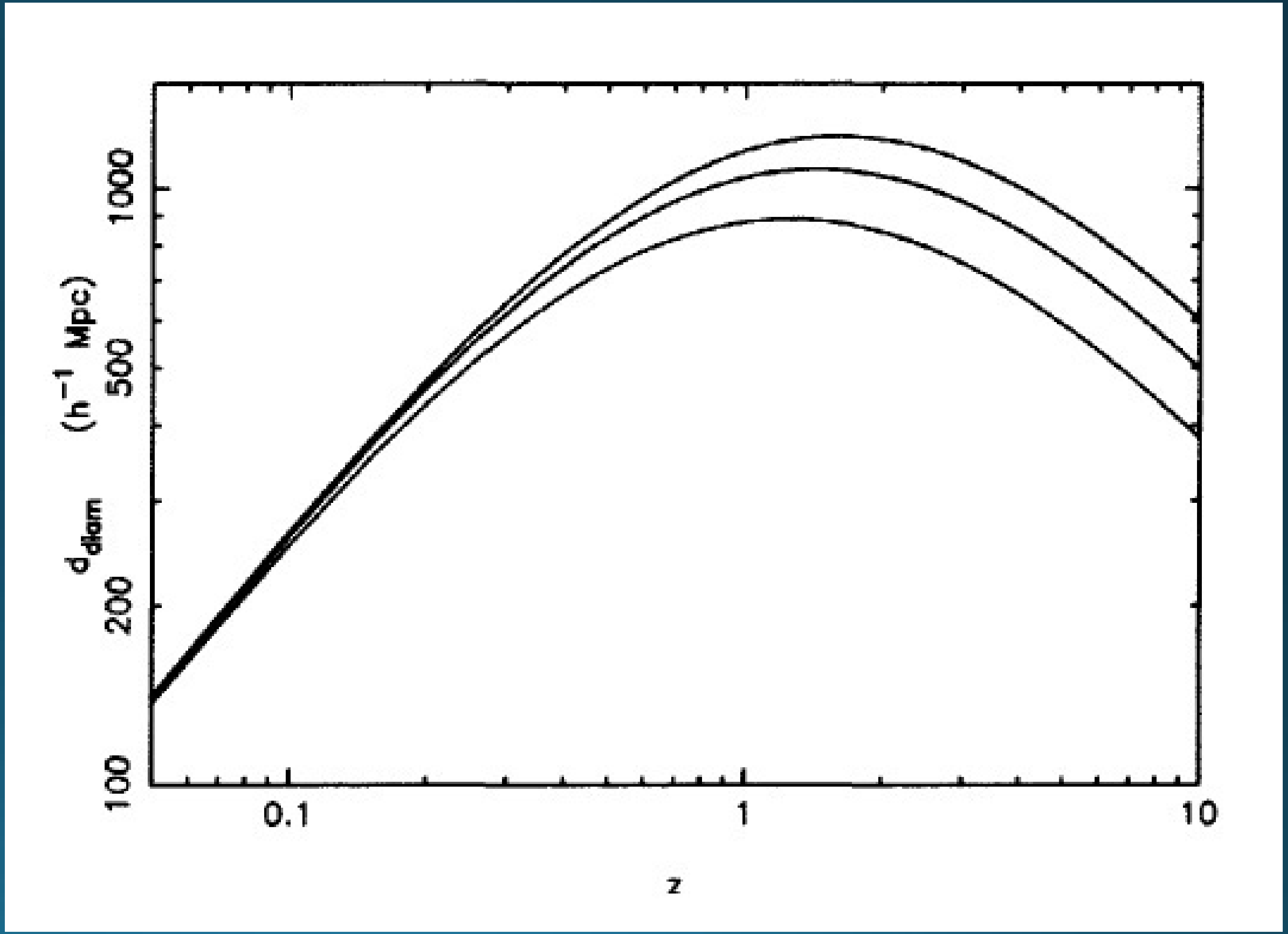


Angular Diameter Distance

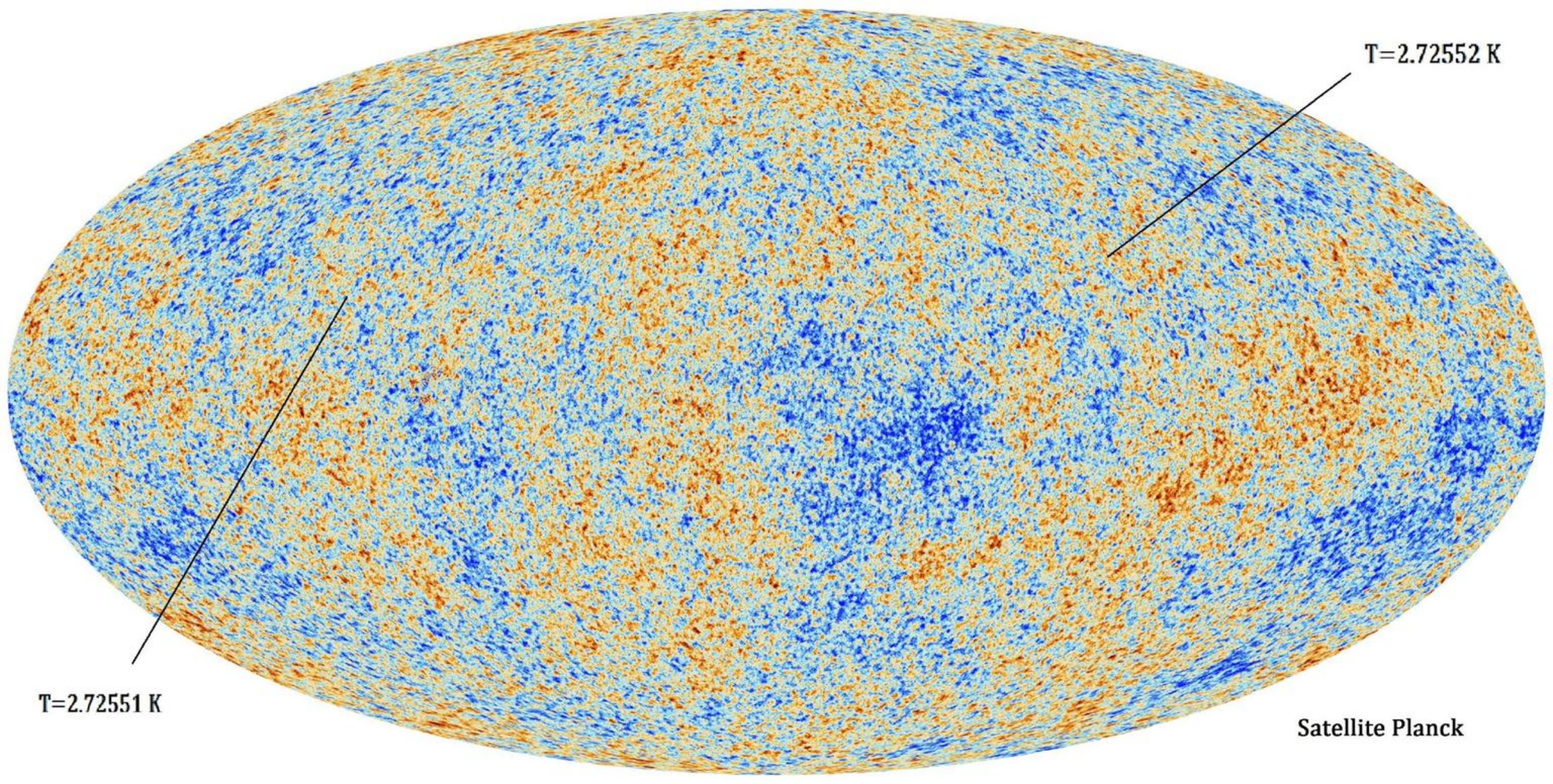
$$d_{diam} = \frac{l}{\sin\theta} \approx \frac{l}{\theta}$$

For an object at radial distance r:

$$d_{diam} = \frac{a_0 r}{1+z}$$



Cosmic Microwave Background



Anisotropy in temperature equal to $\frac{\Delta T}{T} \sim 10^{-5}$

Angular Diameter Distance and CMB

The CMB is sensible to cosmological parameters. Before the Last Scattering, the photons' and baryons' fluid fell down into the gravitational potential's holes due to the Dark Matter.

Increasing of density

(it corresponds to higher ΔT)

Formation of structures

Acustic peaks attributable to the print of the waves sound propagated in the photons' and baryons' fluid

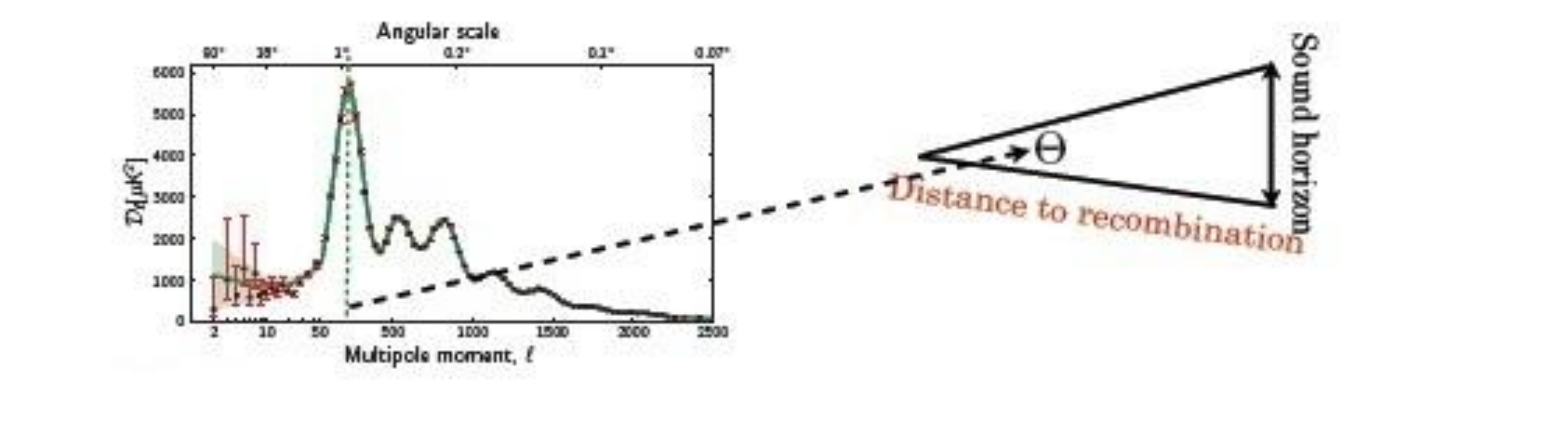
Angular Diameter Distance and CMB

Sound horizon :

$$r_s = c_s \int_0^{a_{rec}} \frac{da}{a^2 H(a)\sqrt{1+\frac{3\Omega_B a}{4\Omega_\gamma}}}$$

Angle of the first acustic peak :

$$l_{peak} = \pi \frac{d_{diam}(z_{rec})}{r_s}$$



Conclusions

- It's possible to estimate some of the cosmological parameters using the luminosity distance and the angular diameter distance on the SNe and CMB;

- The results show a Universe dominated by Dark Energy which controls the acceleration at present time;

- Dark Energy is described by the equation of state $p = w\ \rho$ (where in the ΛCDM model w = -1); it shows that luminosity distance is sensible to the parameterization of w;

- We briefly saw some problems linked to the Dark Energy such as the Cosmological Constant Problem and the Coincidence Problem.

Thanks for your attention

There are these two young fish swimming along, and they happen to meet an older fish swimming the other way, who nods at them and says, "Morning, boys, how's the water?" And the two young fish swim on for a bit, and then eventually one of them looks over at the other and goes, "What the hell is water?“

-David Foster Wallace, This is Water -