Microcosmo e Macrocosmo

Paolo de Bernardis

Dipartimento di Fisica

Sapienza Università di Roma

Lezioni della Cattedra Fermi

23 Gennaio 2014

Dipartimento di Fisica

Sapienza Università di Roma

Microcosmo e Macrocosmo

- Le proprietà *globali* e *locali* dell' universo dipendono dalle particelle che lo compongono, e dalle loro interazioni.
- Per questo si possono usare le leggi della fisica per prevedere struttura globale ed evoluzione dell' universo (Cosmologia) e delle sue strutture (Astrofisica).
- Viceversa, spesso le osservazioni astrofisiche e cosmologiche danno indicazioni di grande interesse per la fisica fondamentale.
- Inoltre, i cosmologi e gli astrofisici hanno sviluppato le più avanzate metodologie sperimentali, sfruttando le interazioni tra i vettori di informazione (la luce, i fotoni) e i sistemi di rivelazione (materia microscopica) per indagare i dettagli più elusivi del cosmo.

Microcosmo e Macrocosmo

- Prima lezione: Come con la fisica si può descrivere l’ universo a grande scala e la sua evoluzione

- Seconda lezione: le misure sull’ universo primordiale e le grandi domande ancora aperte.

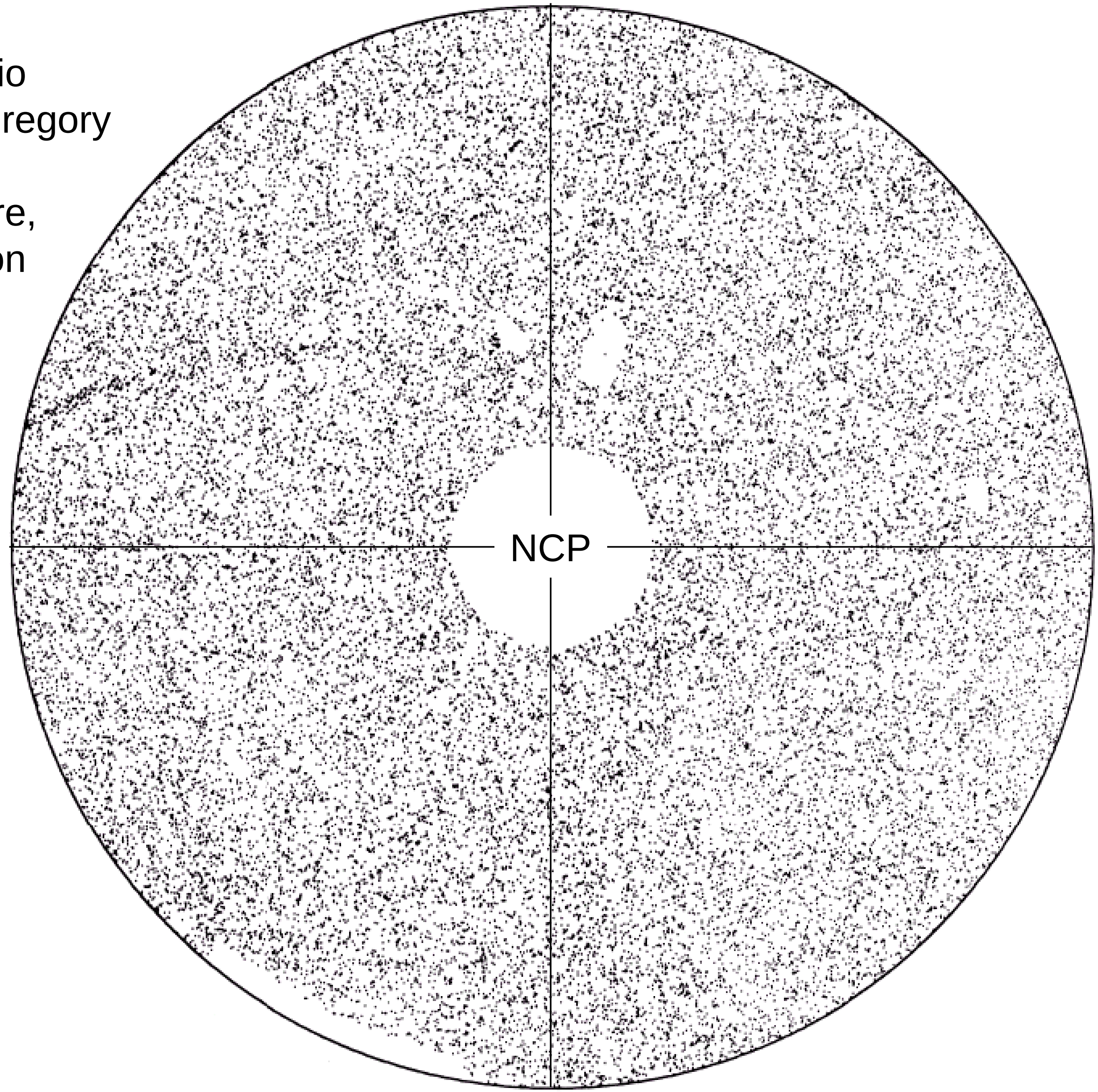
Cosmology

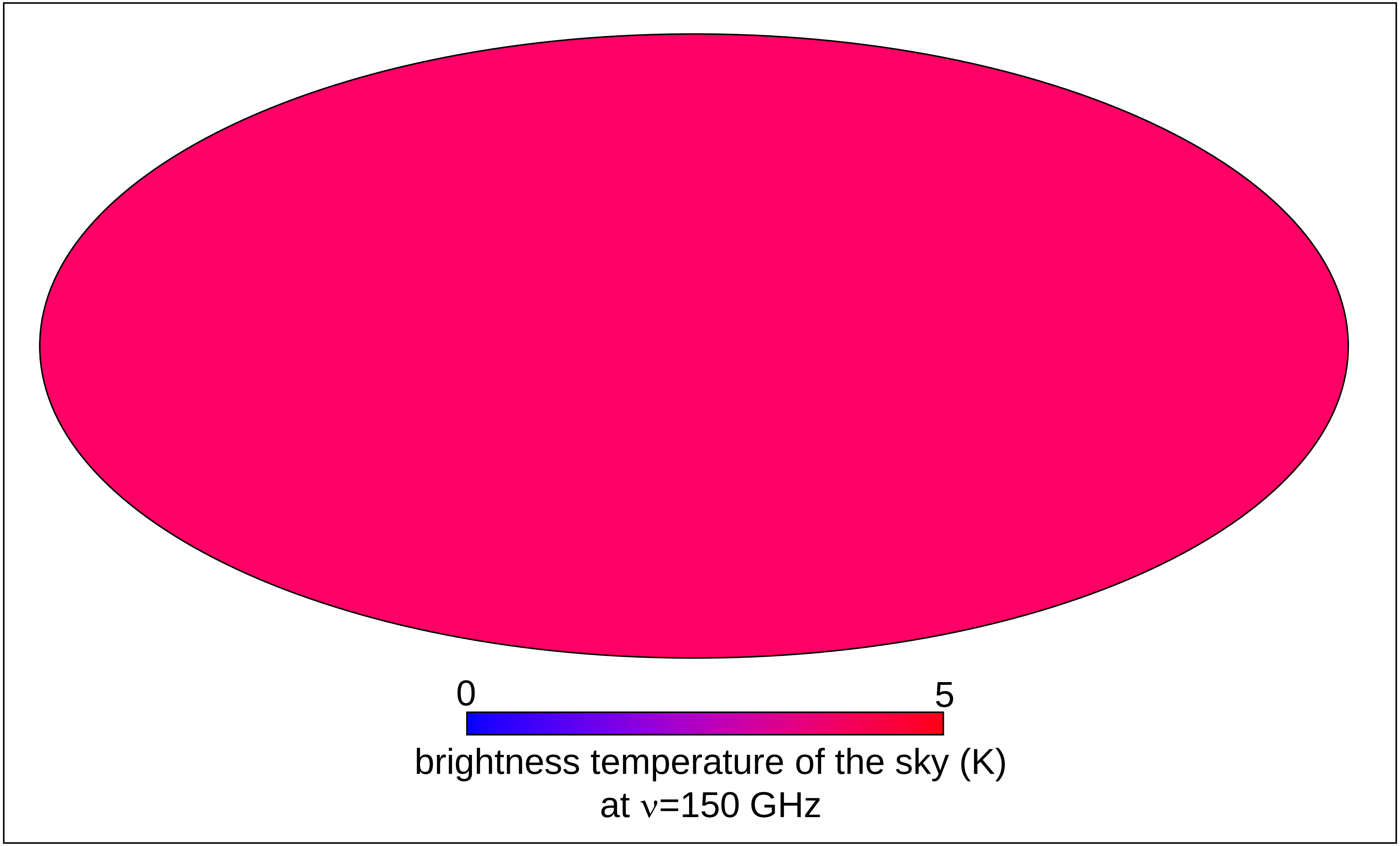
- The aim of cosmology is to describe the universe and its evolution using the laws of physics.
- Overview of *Observational Cosmology*: a paradigm based on observations
- Two levels:
  - background cosmology (the universe at large scales)
  - fluctuations with respect to background (structures in the universe, including clusters of galaxies, galaxies, stars, planets …. us)

Method

- Simplify the problem :
- Homogeneous and isotropic fluid filling the universe (cosmological principle)
- OK at large scales (background universe):
  - Isotropy of Radiogalaxies
  - Isotropy of microwave, X-rays, infrared Backgrounds
  - Copernican Principle: we are not special in the universe
  - 3D galaxy distribution surveys
- Applied forces: gravitation
- Theory: General Relativity (GR)

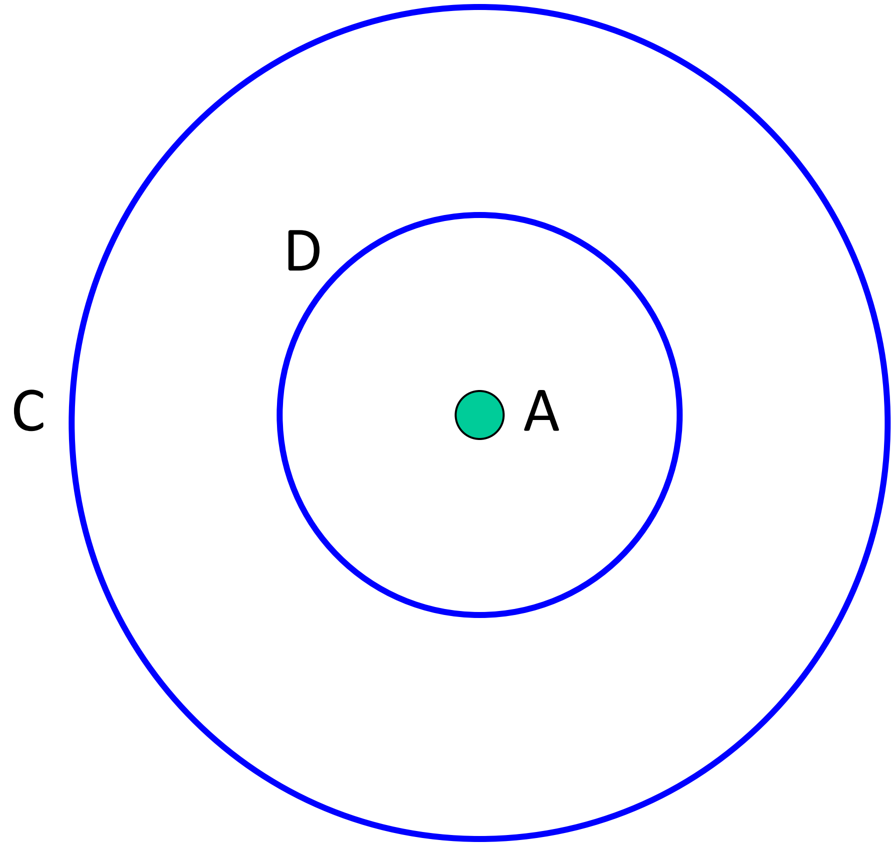
Distribution of the brightest 31000 radio sources (λ=6 cm, Gregory and Condon 1991) Northern hemisphere, equal-area projection



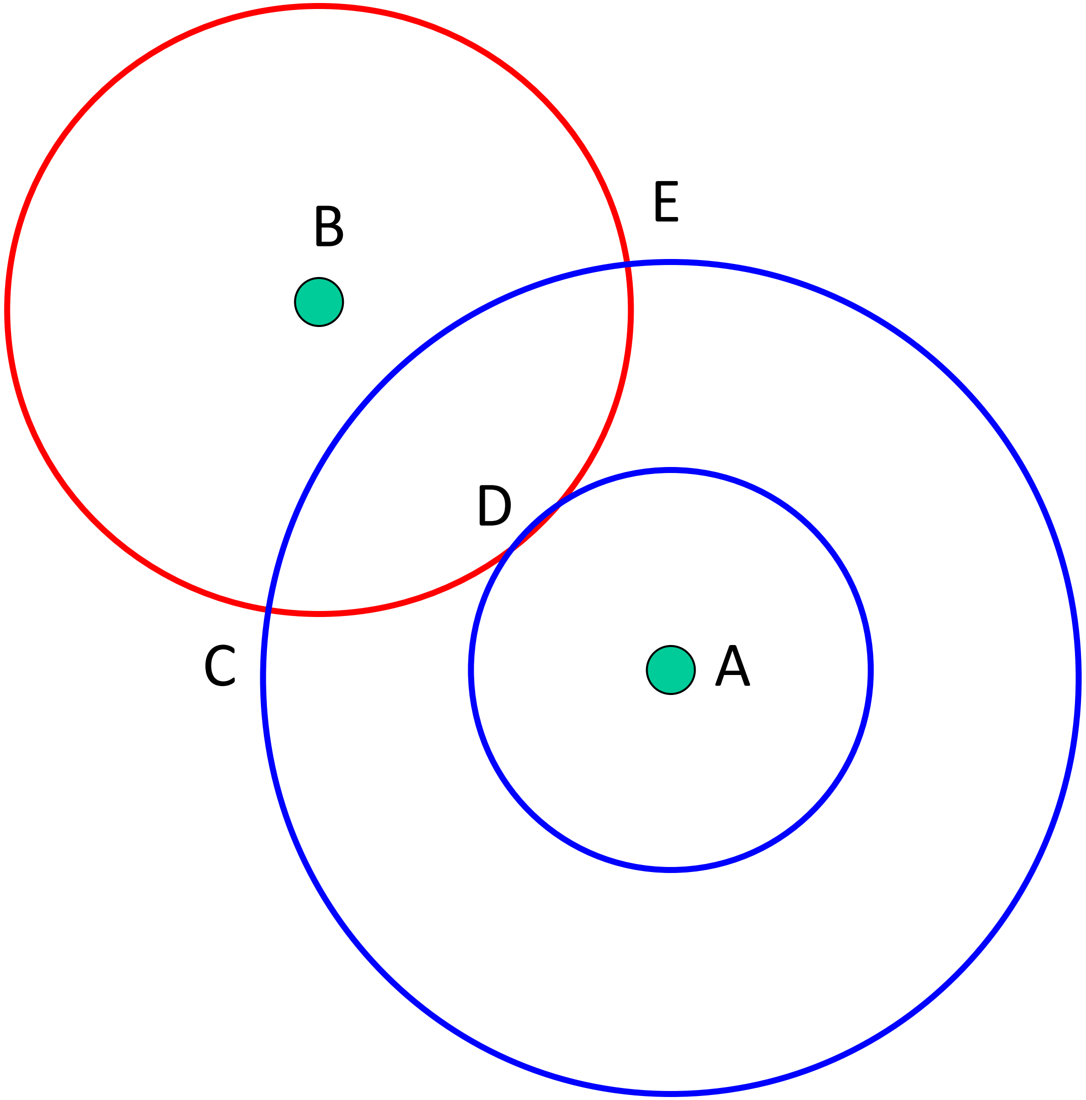


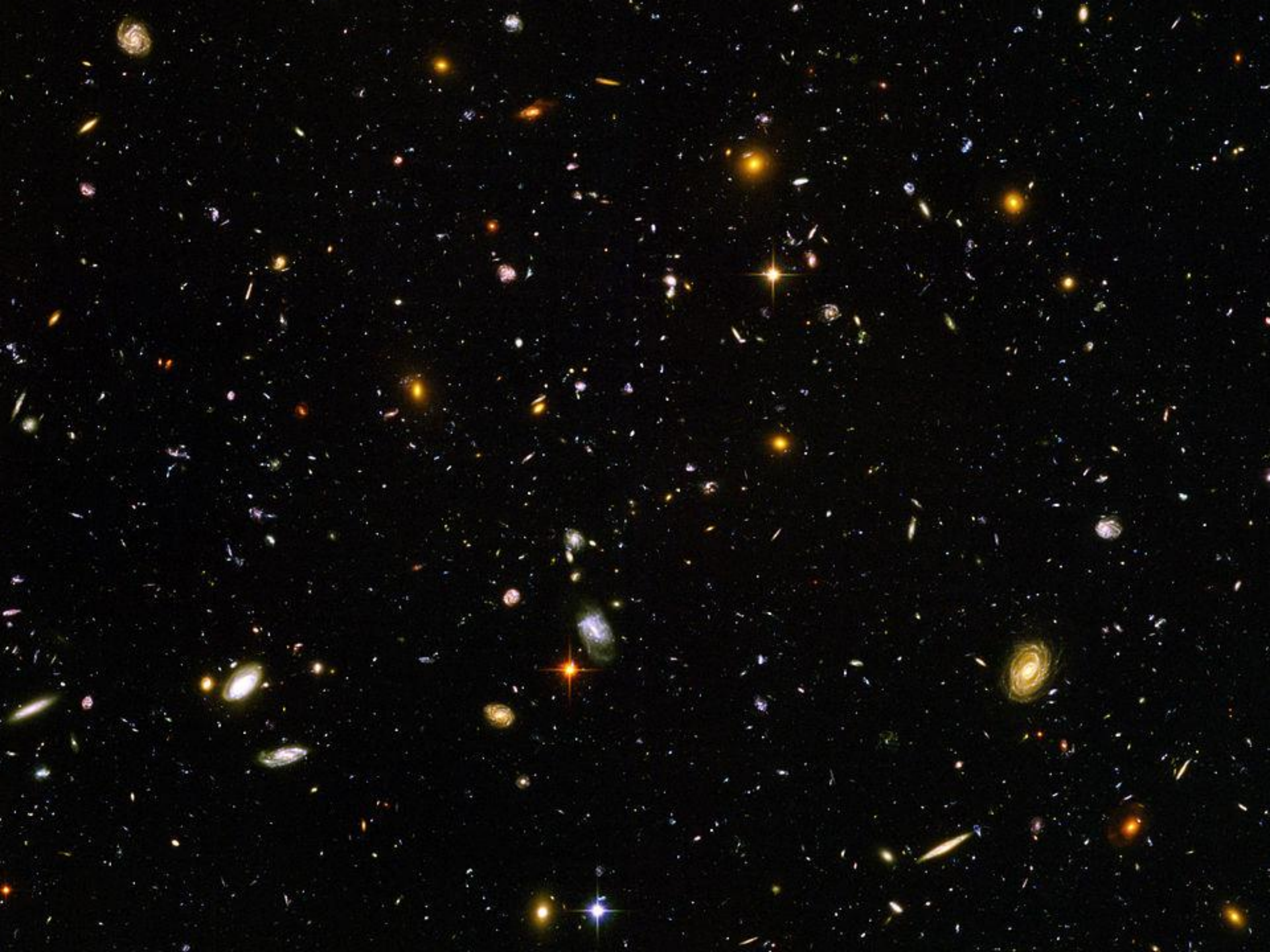
- The CMB dominates the sky brightness at mm wavelengths
- And is very much isotropic: the early universe was very homogeneous
- The most boring picture of the sky ever !

Copernican principle + isotropy = homogeneity

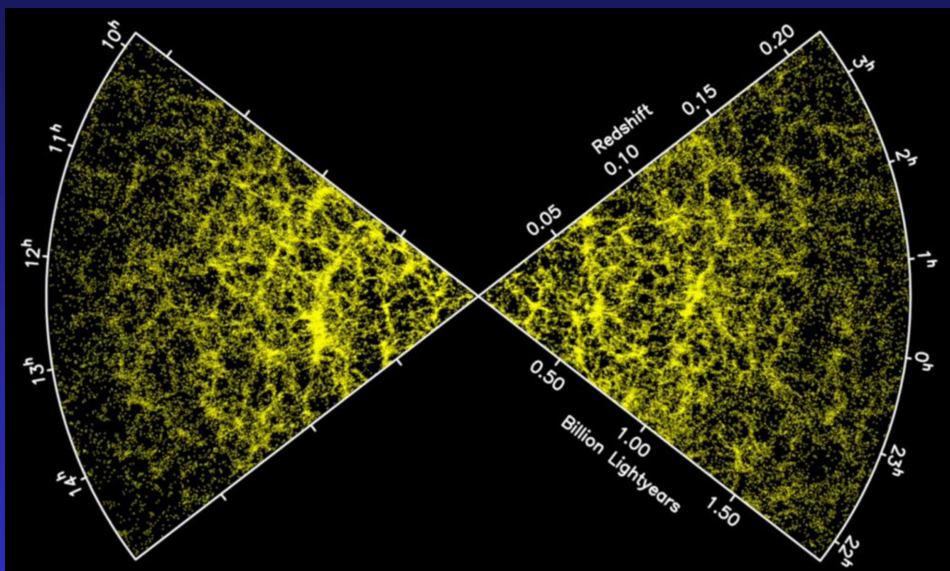


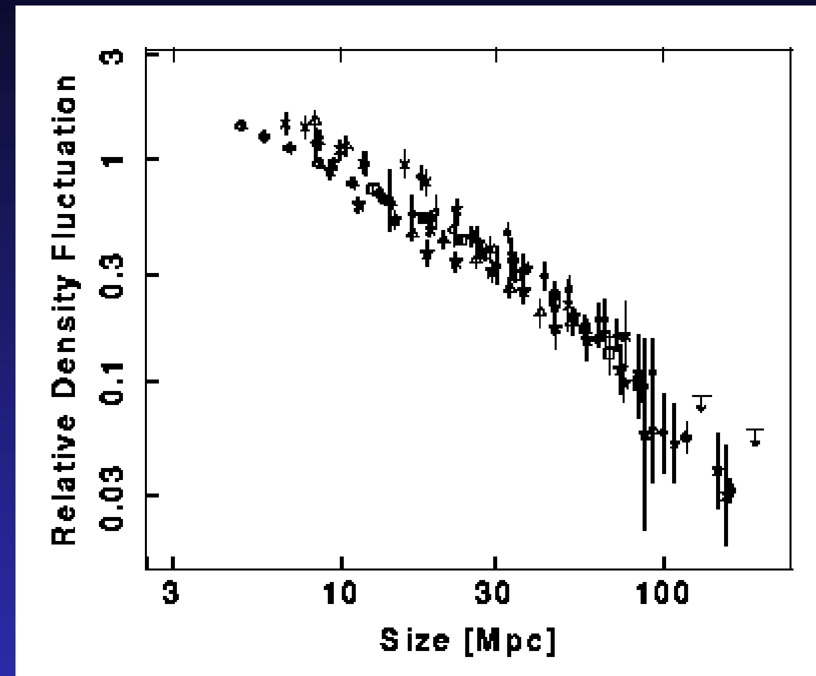
Copernican principle + isotropy = homogeneity





3D galaxy distribution surveys





Peacock and Dodds
(1994, MNRAS, 267, 1020)

- The Universe is homogeneous and isotropic at large angular scales (>100 Mpc)

Method

- Simplify the problem :
- Homogeneous and isotropic fluid filling the universe (cosmological principle)
- OK at large scales (background universe):
  - Isotropy of Radiogalaxies
  - Isotropy of microwave, X-rays, infrared Backgrounds
  - Copernican Principle: we are not special in the universe
  - 3D galaxy distribution surveys
- Applied forces: gravitation
- Theory: General Relativity (GR)

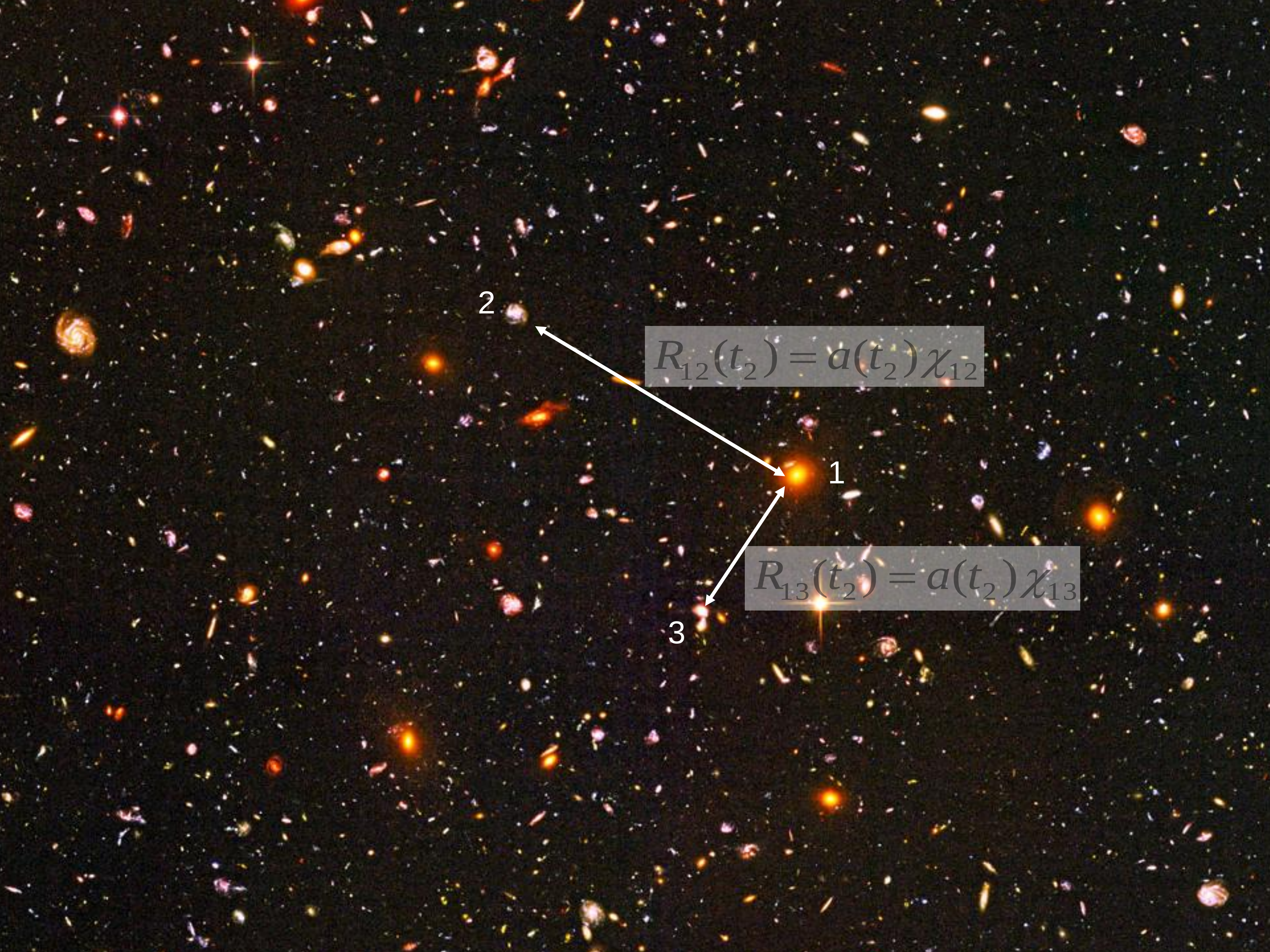
GR prescription

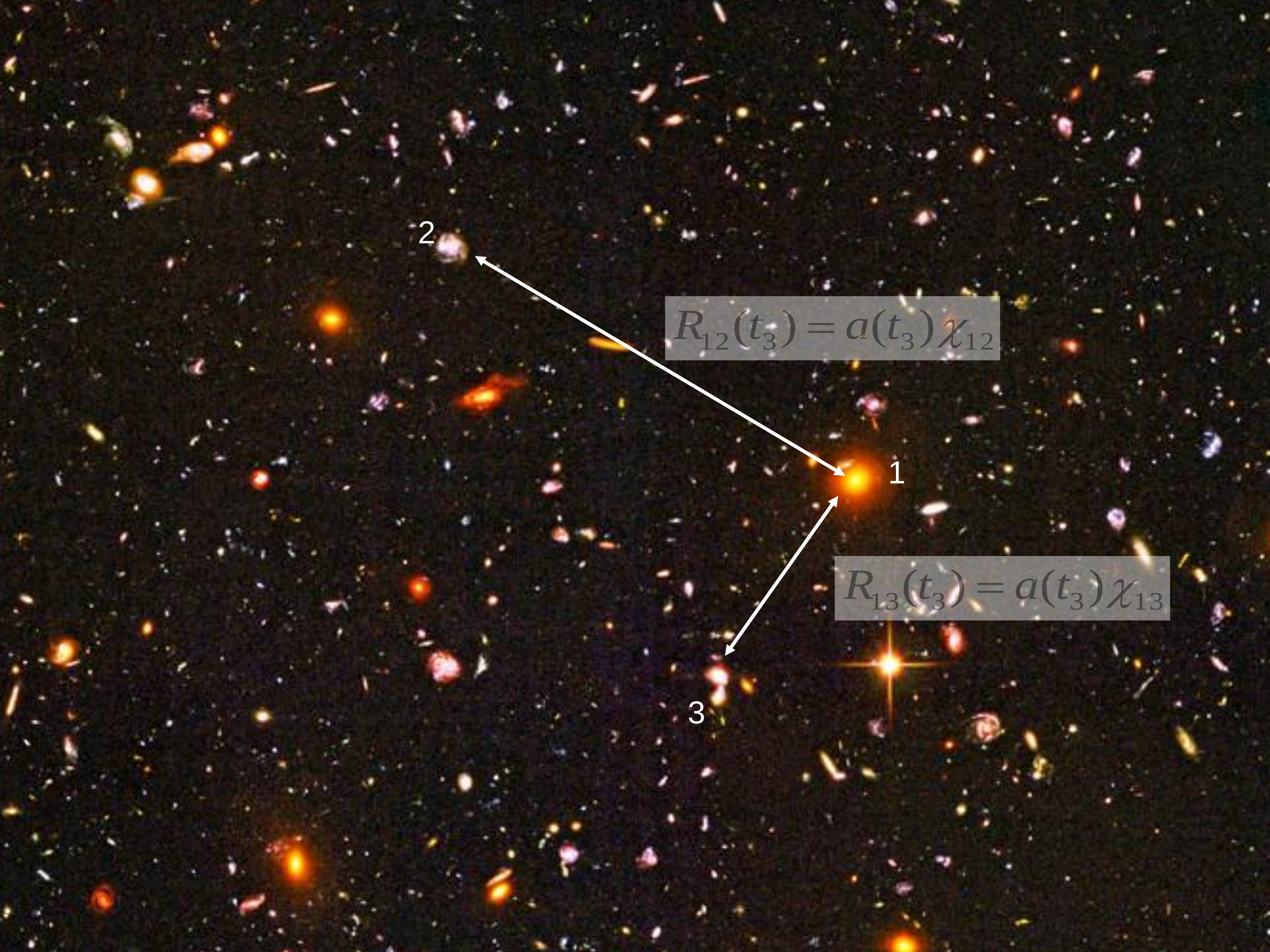
- Specify the geometry (metric), write down the mass-energy content, and Einstein's equations will do the rest for you.
- In our case (4D=3D+ict):
  - metric: $\boxed{ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2}$ $\boxed{R(t) = a(t)\chi}$

$$\boxed{ds^2 = c^2dt^2 - a^2(t)\left[\left(\frac{d\chi}{\sqrt{1-k\chi^2}}\right)^2 - (\chi d\theta)^2 - (\chi\sin\theta d\varphi)^2\right]}$$

  - mass-energy content of the universe ?


2
$R_{12}(t_1) = a(t_1)\chi_{12}$
1
$R_{13}(t_1) = a(t_1)\chi_{13}$
3

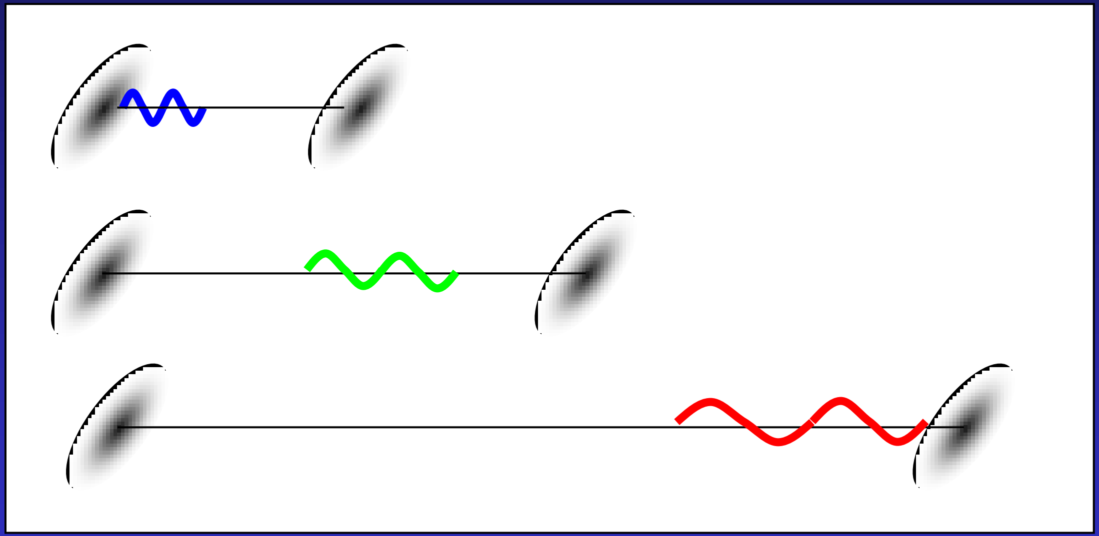

2
$R_{12}(t_2) = a(t_2)\chi_{12}$
1
$R_{13}(t_2) = a(t_2)\chi_{13}$
3


2
$R_{12}(t_3) = a(t_3)\chi_{12}$
1
$R_{13}(t_3) = a(t_3)\chi_{13}$
3

Redshift

- If the universe is not static [*a*=*a*(*t*)] the wavelength of light changes when travelling in the universe:

$$\boxed{\frac{\lambda_{\mathrm{det}}}{\lambda_{\mathrm{em}}} = \frac{a(t_{\mathrm{det}})}{a(t_{\mathrm{em}})}}$$



- Cosmological redshift in an expanding universe

Hubble's law

- The farther a galaxy
- The longer the travel time of light (photons)
- The larger the expansion of the universe meanwhile
- The larger the wavelength increase
- The largest the redshift

$$\boxed{\frac{\lambda_{\mathrm{det}}}{\lambda_{\mathrm{em}}} = \frac{a(t_{\mathrm{det}})}{a(t_{\mathrm{em}})} > 1}$$

$$\boxed{z = \frac{\lambda_{\mathrm{det}} - \lambda_{\mathrm{em}}}{\lambda_{\mathrm{em}}}}$$

- **z increases with distance**.
- For small distances (z<<1): Hubble's law:

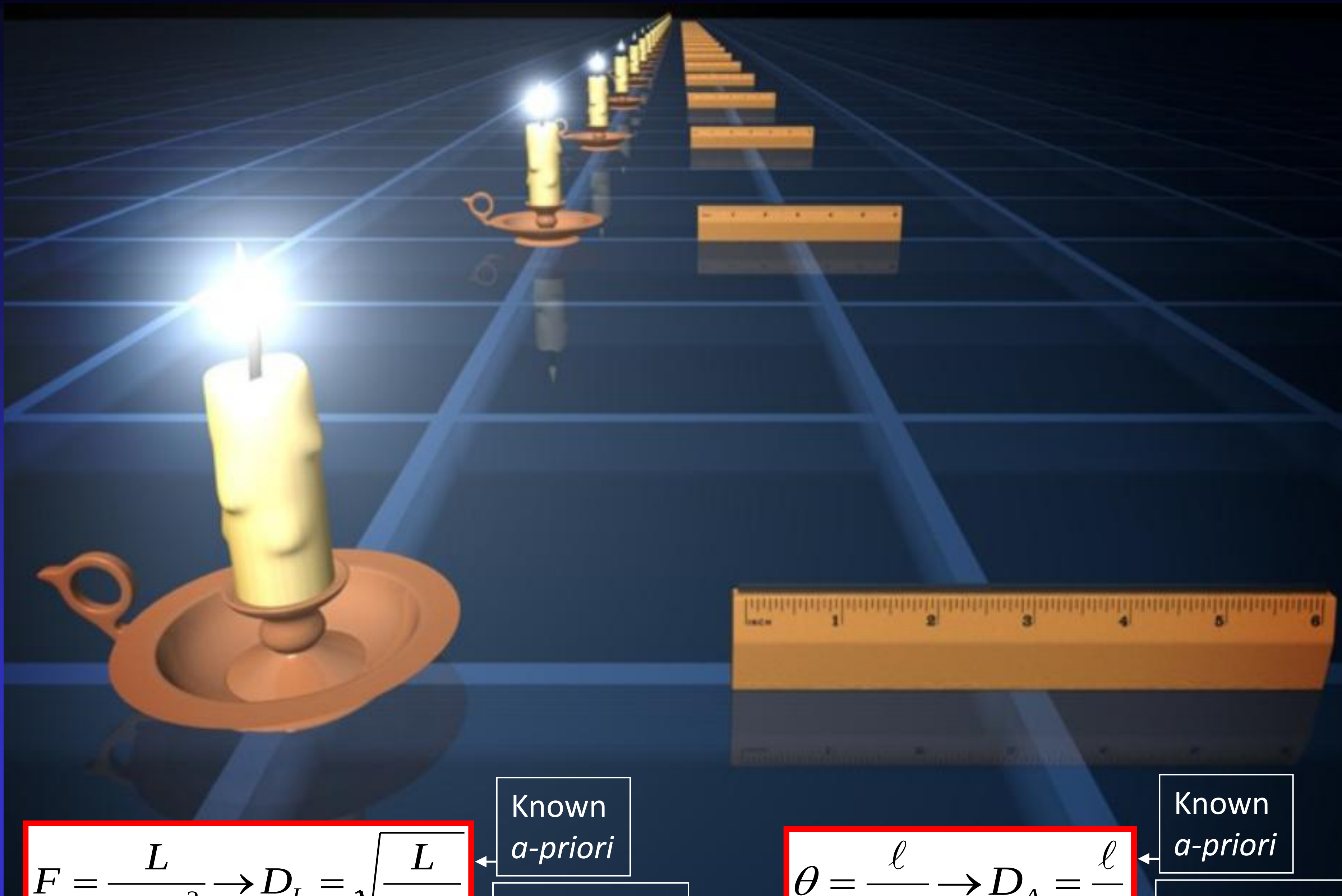
Measurable (direct measurement with spectrometers) →

$$\boxed{z = \left[\frac{H_o}{c}\right] D}$$

← Measurable (indirect, using distance indicators)

A constant

Distance Indicators



Known *a-priori*

$$F = \frac{L}{4\pi D_L^2} \rightarrow D_L = \sqrt{\frac{L}{4\pi F}}$$

measurable

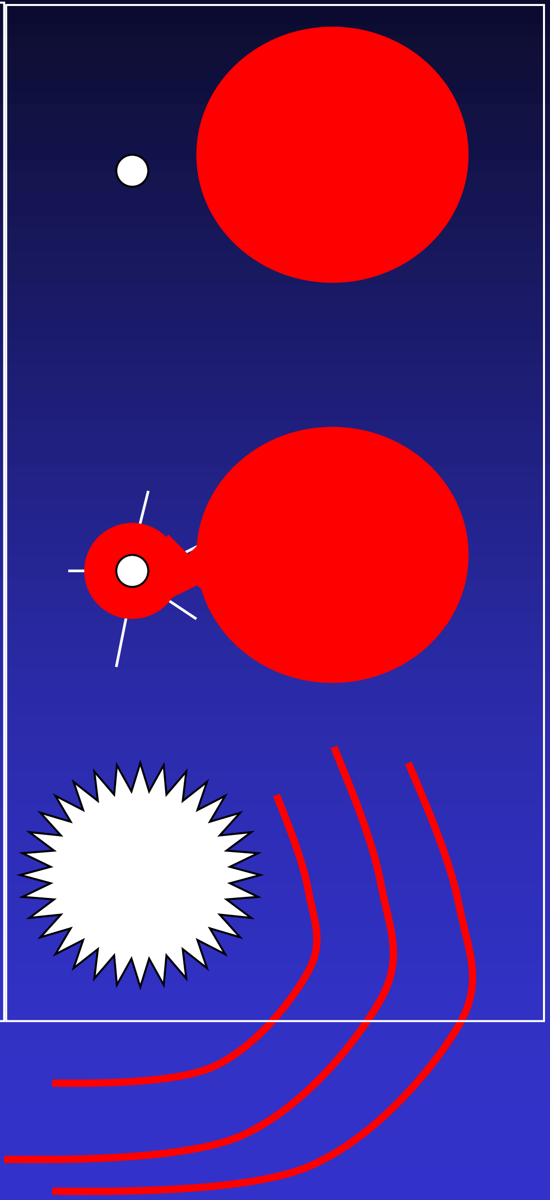
Known *a-priori*

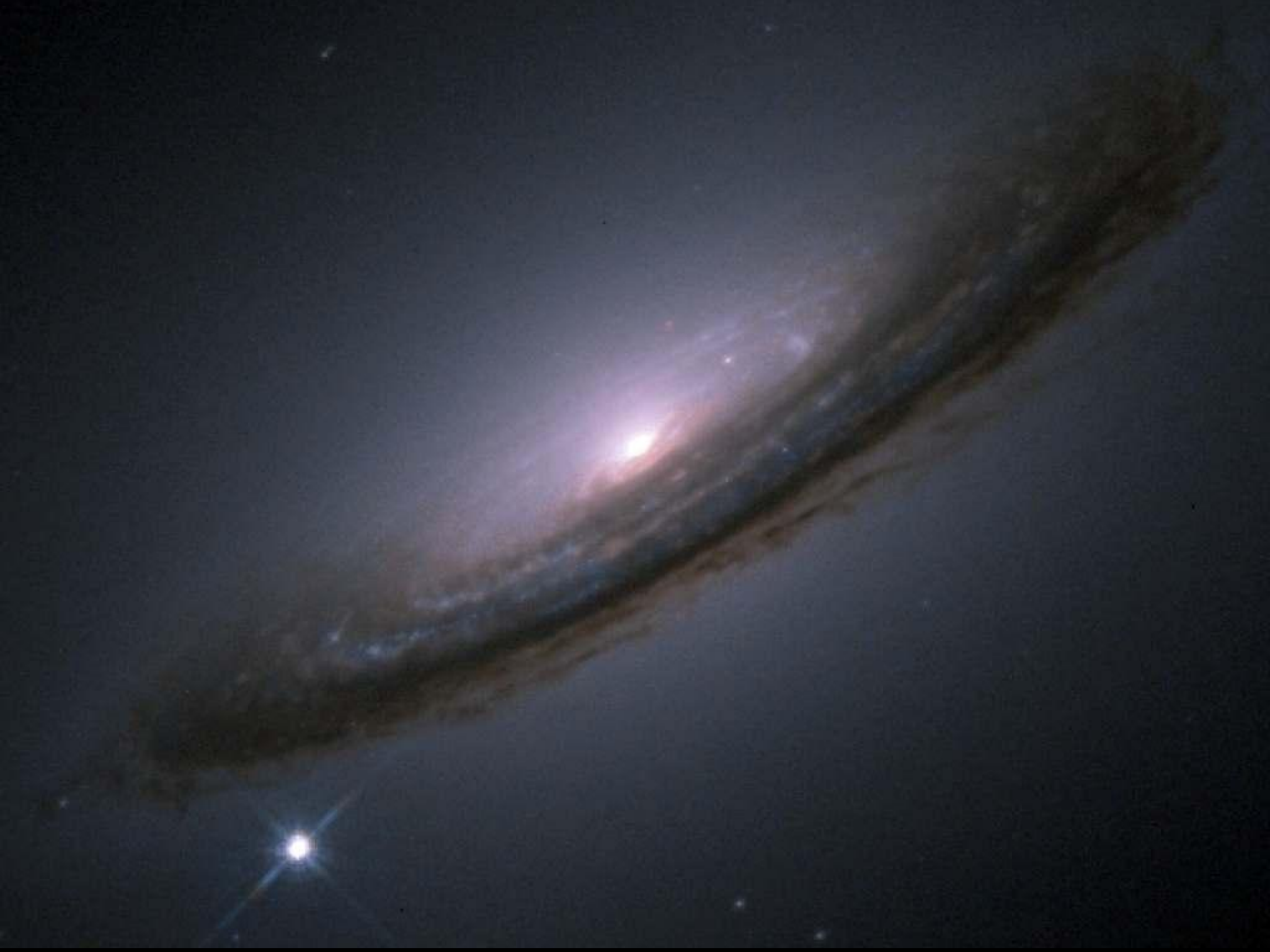
$$\theta = \frac{\ell}{D_A} \rightarrow D_A = \frac{\ell}{\theta}$$

measurable

SNe1a

- A rare phenomenon
- Double system : red giant + white dwarf
- Accretion of red giant material on the white dwarf
- When the mass of the WD approaches Chandrasekhar’s mass ($1.4M_{sun}$), internal pressure cannot withstand self gravity anymore, and the star explodes





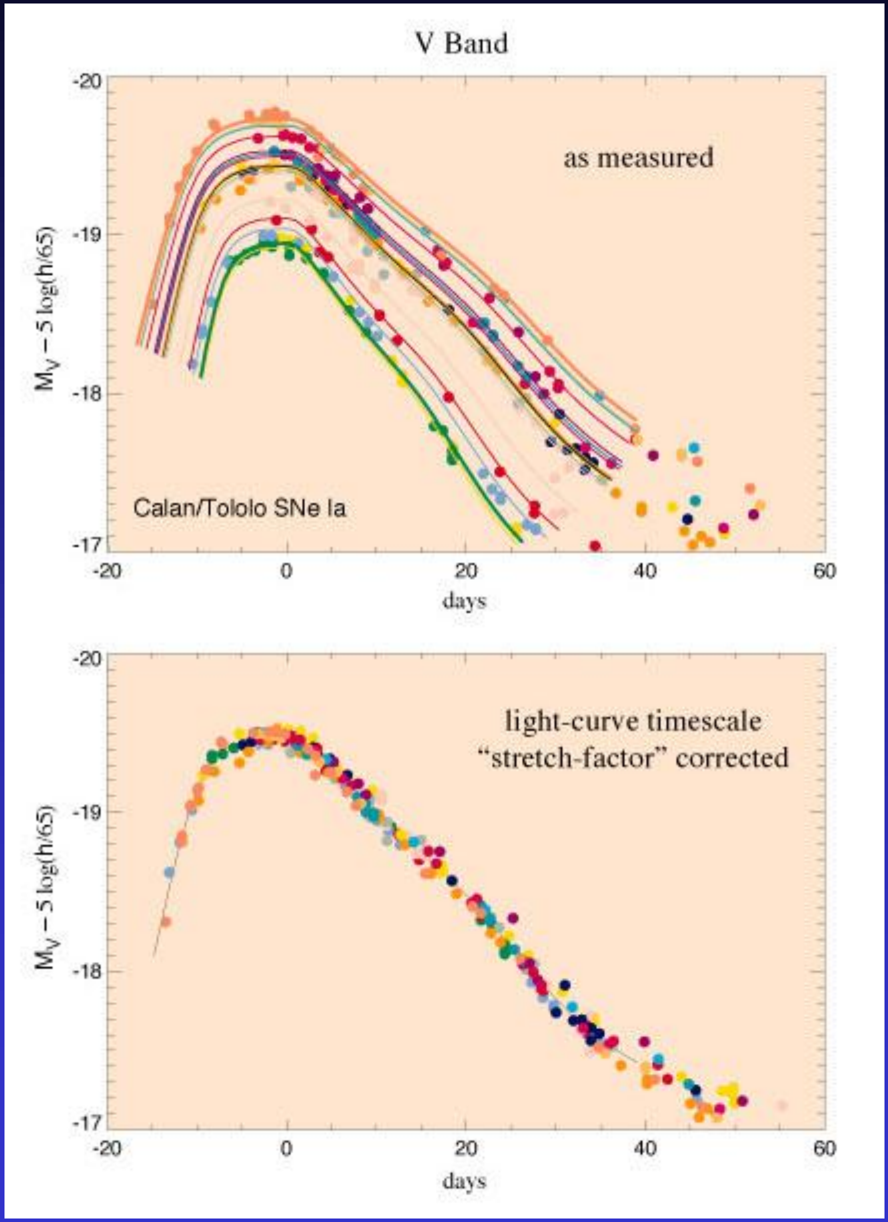
SNe1a

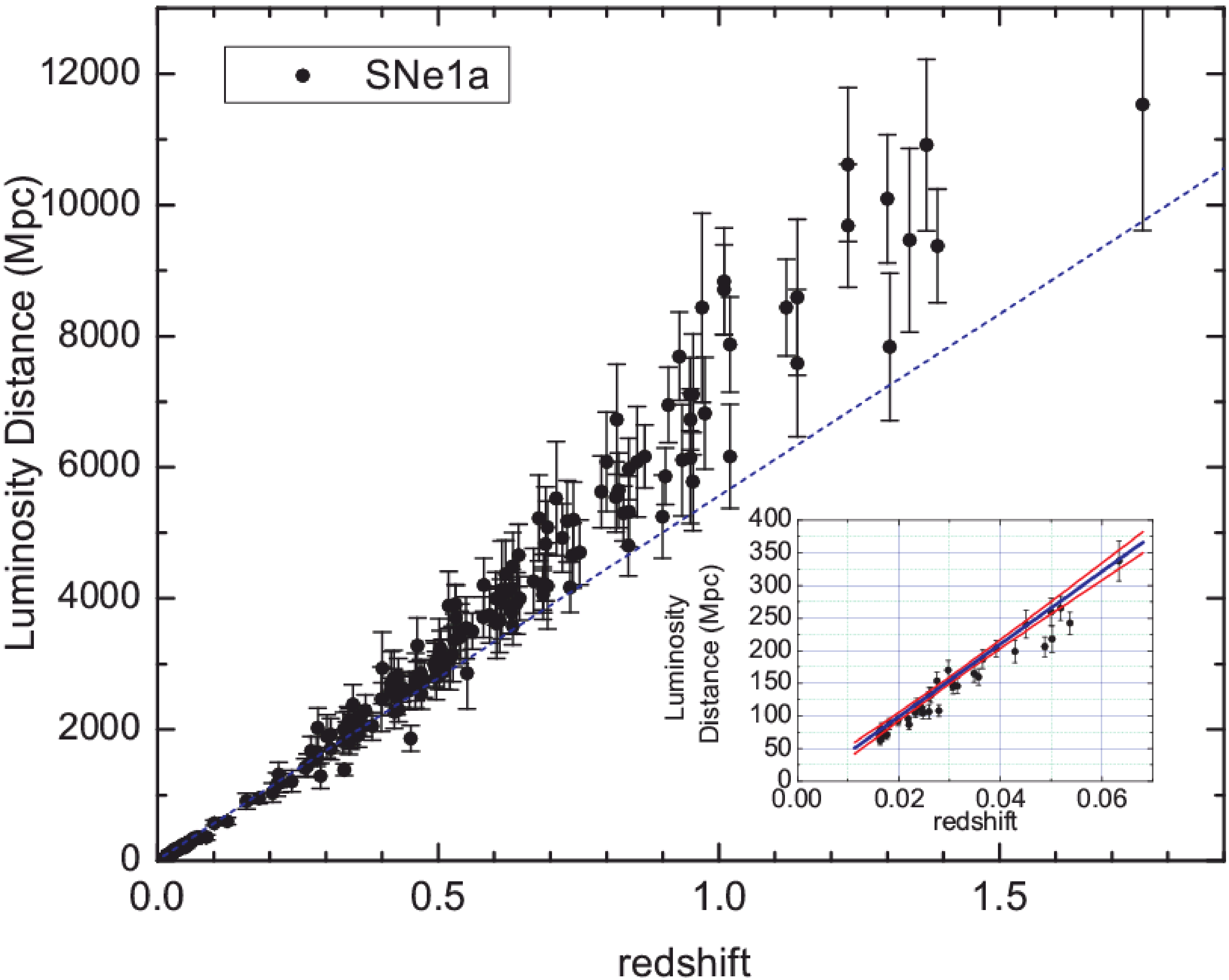
- The luminosity and the light-curve are due to the decay of radioactive nuclei produced during the implosion of the inner part of the star.

$^{56}Ni \rightarrow {}^{56}Co + \gamma$ (5.6 days)

$^{56}Co \rightarrow {}^{56}Fe + \gamma$ (79 days)

- Since the composition and the initial mass are all about the same, the absolute luminosity is about the same for all SNe1a.
- Corrections can be applied using the correlation between maximum luminosity and duration of the light-curve





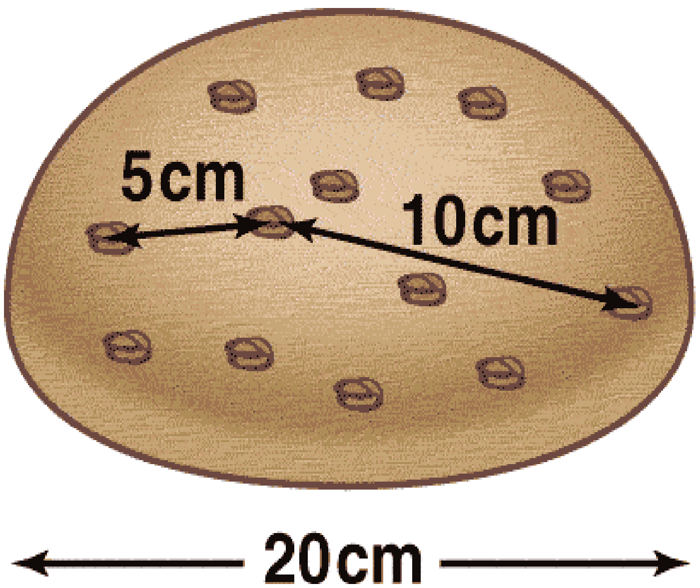
SNe1a
Luminosity Distance (Mpc)
redshift
0
2000
4000
6000
8000
10000
12000
0.0
0.5
1.0
1.5
Luminosity Distance (Mpc)
redshift
0
50
100
150
200
250
300
350
400
0.00
0.02
0.04
0.06

Hubble's constant

- Using standard candles (SNe1a, but also Cepheids) it is found that Hubble's law is valid, and Hubble's constant is:

$$\boxed{z = \left[\frac{H_o}{c}\right] D} \Leftrightarrow \boxed{H_o = (74.3 \pm 2.1)\,\mathrm{km/s/Mpc}}$$

- A galaxy at a distance of 1 Mpc (3 million light years) recedes from us at a speed of 74 km/s.
- A galaxy at a distance of 10 Mpc (30 million light years) recedes from us at a speed of 740 km/s.
- There is no center for this expansion.



MAP990404

Friedman's equation

- At this point we are in a position to write half of Einstein's equation (metric part) for an homogenous isotropic universe.
- To write the other half, we need to specify how much of the different possible forms of mass-energy densities is present in the universe, and how each contribution scales with the expansion of the universe:
  - Matter $\boxed{\rho_M = \rho_{Mo} / a^3}$
  - Radiation $\boxed{\rho_R = \rho_{Ro} / a^4 \leftarrow n = n_o / a^3 \quad ; \quad E = h\nu = hc/\lambda \approx 1/a}$
  - Cosmological Constant $\boxed{\rho_\Lambda = \rho_{\Lambda o}}$
- All densities are given in adimensional form, as a fraction of the critical density:

$$\boxed{\rho_{co} = \frac{3H_o^2}{8\pi G} = (1.04 \pm 0.07) \times 10^{-29} \mathrm{g/cm}^3} \qquad \boxed{\Omega_{io} = \frac{\rho_{io}}{\rho_{co}}}$$

Friedman's equation

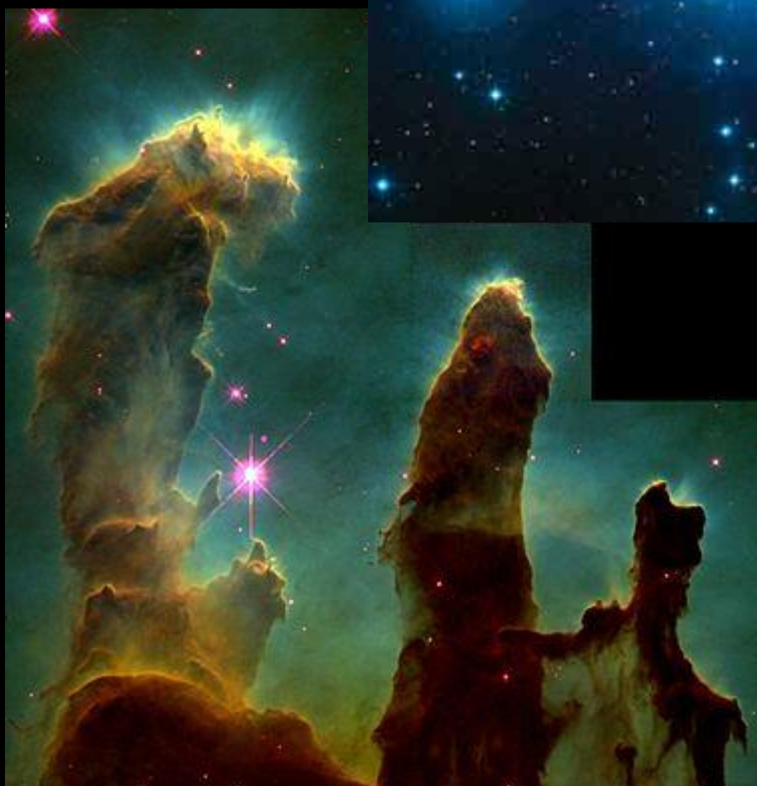
- Einstein's equation, in the case of a homogenous isotropic universe, gives

$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4} + \frac{\Omega_{Mo}}{a^3} + \frac{(1-\Omega_o)}{a^2} + \Omega_\Lambda\right]}$$

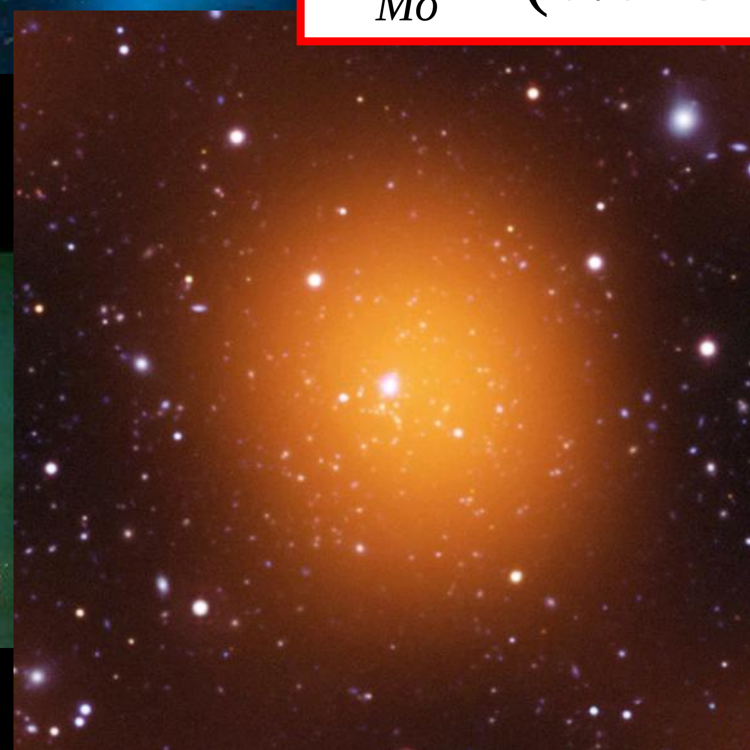
- The solution *a(t)* tells us how all the distances in the universe evolve with time (i.e. how the universe expands).
- To find the solution, we need to find empirically the mass energy densities ρ_{Ro}, ρ_{Mo}, ρ_Λ and from them the parameters Ω_{Ro}, Ω_{Mo}, Ω_Λ

Baryonic Matter

- Baryonic matter interacts electromagnetically
- We can measure it because it emits, or absorbs, or scatters light and electromagnetic waves.
- Us, planets, stars, interstellar matter, galaxies, etc. contain baryonic matter.
- Measuring the luminosity, one can infer the mass responsible for such a luminosity.
- Most recent estimates: $\boxed{\Omega_{Mo} = (0.045 \pm 0.003)}$
- Consistent with primordial nucleosynthesis.
- A minor component of our universe.



$$\Omega_{Mo} = (0.045 \pm 0.003)$$



Dark Matter

- Dark matter does not interact electromagnetically.
- We can measure it only through its gravitational interaction, which is much weaker than electromagnetic.
- The dynamics of stars in galaxies and of galaxies in clusters of galaxies cannot be explained without the presence of dark matter
- Additional evidence comes from gravitational lensing and other effects.

$$\boxed{\Omega_{DMo} = (0.22 \pm 0.02)}$$