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.

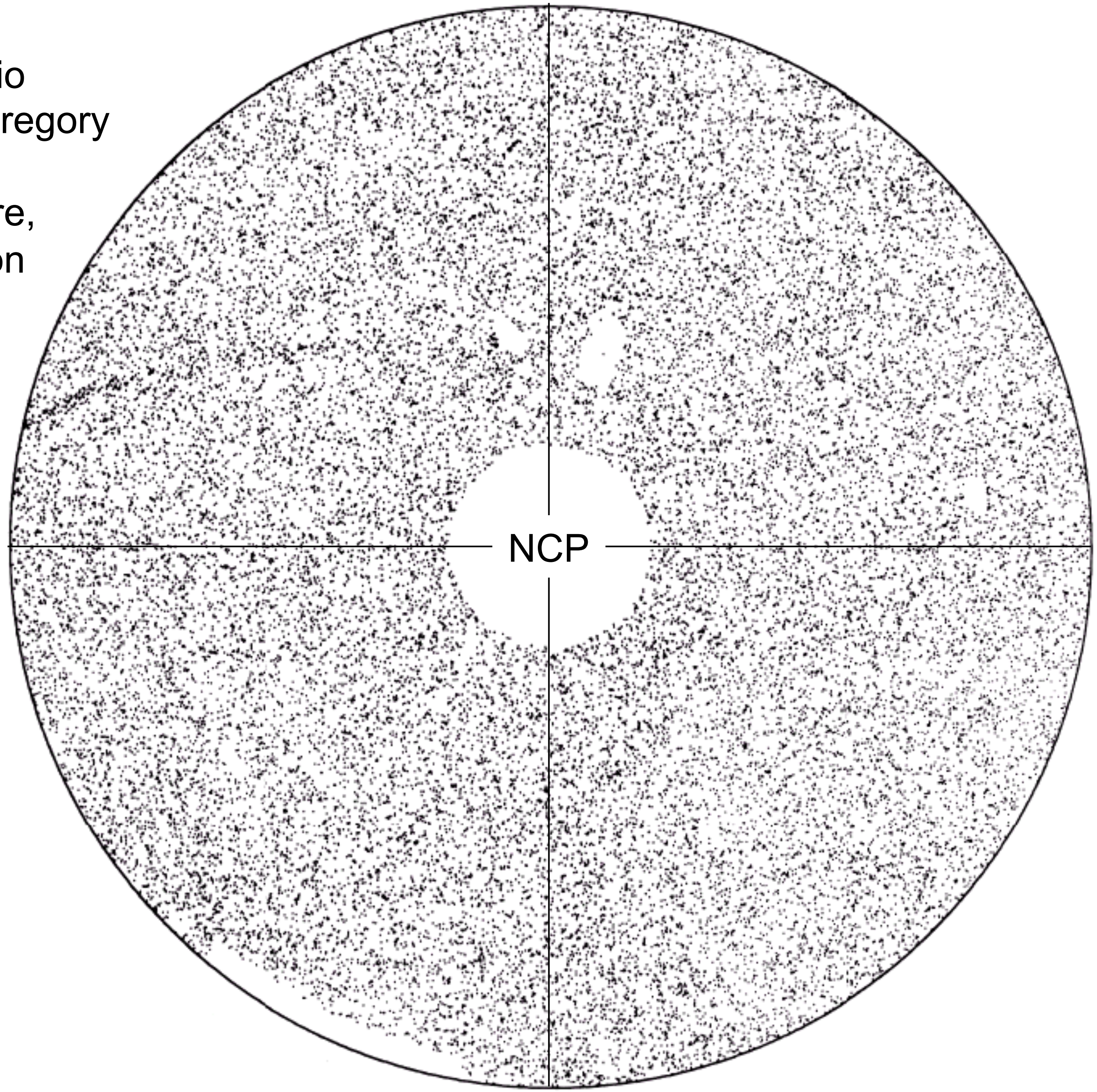
Cosmology

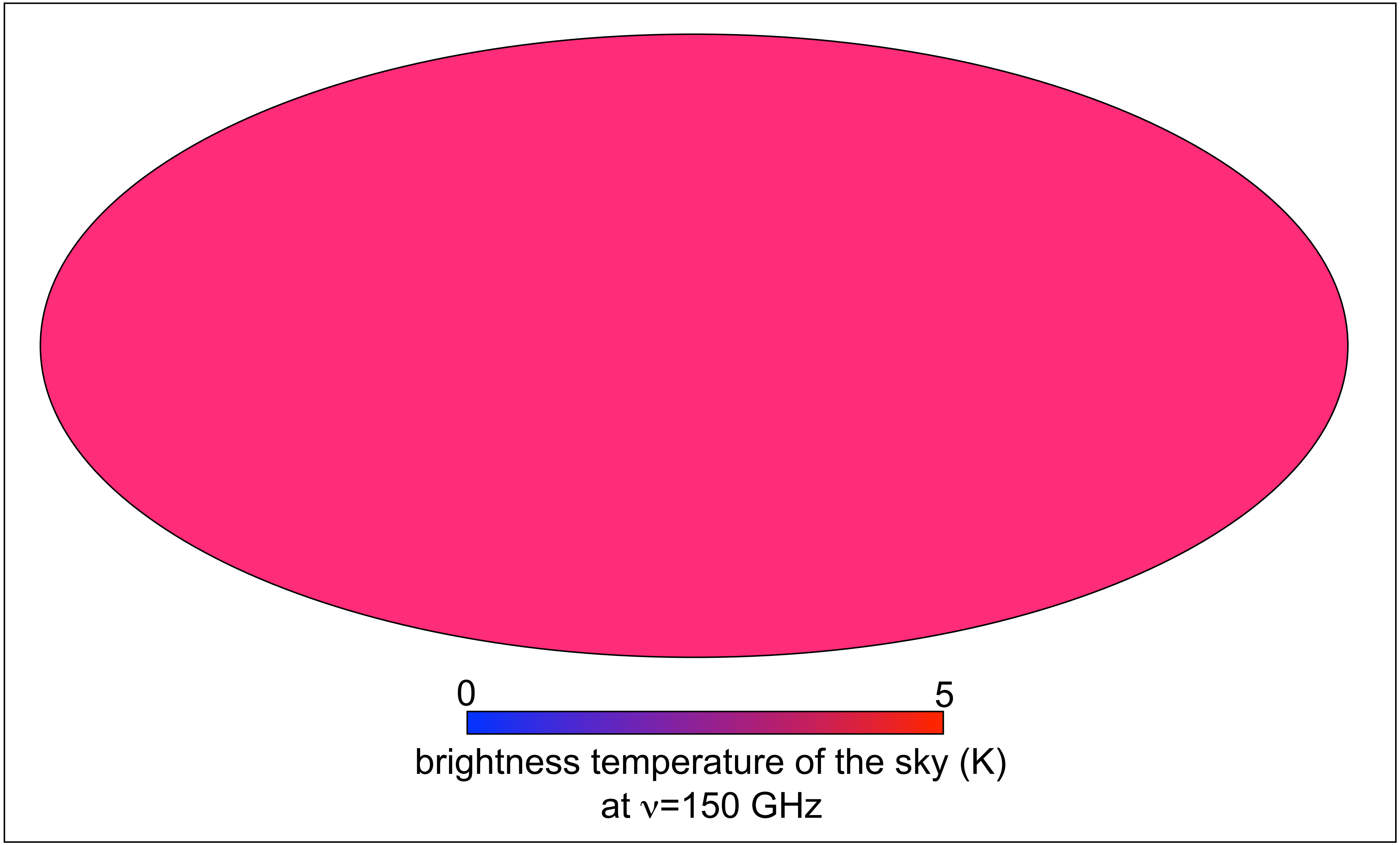
- The aim of cosmology is to describe the universe and its evolution using the laws of physics.
- Overview of *Observational Cosmology*: a paradigm based on observations
- Two levels:
  - background cosmology (the universe at large scales)
  - fluctuations with respect to background (structures in the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

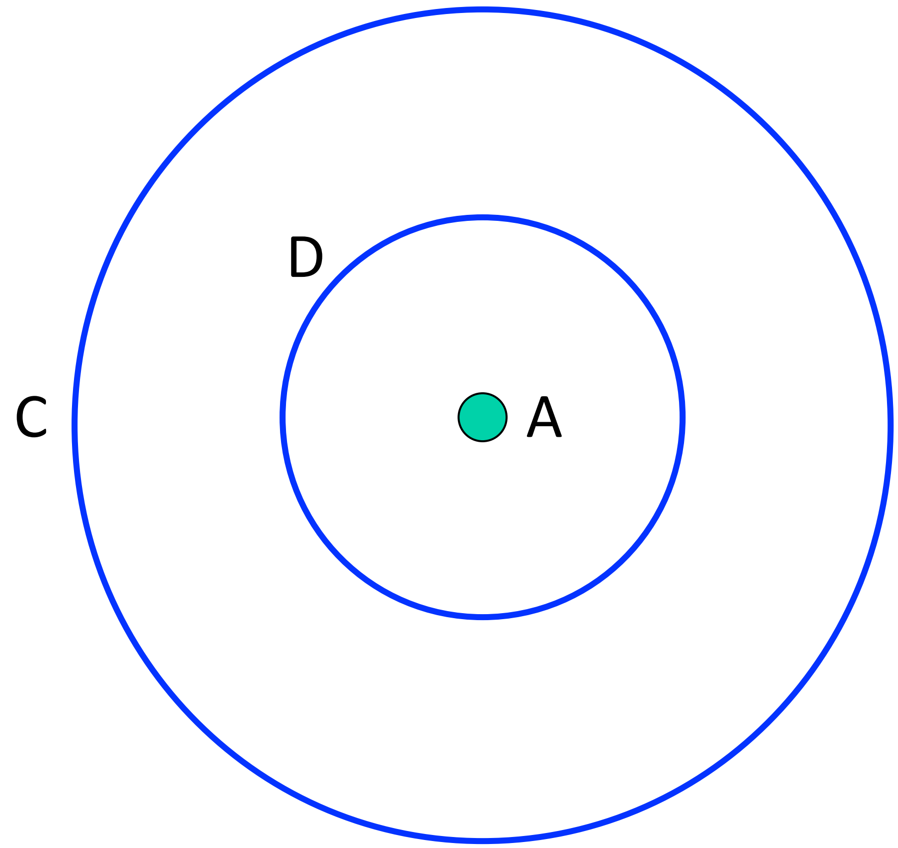
Distribution of the brightest 31000 radio sources (λ=6 cm, Gregory and Condon 1991) Northern hemisphere, equal-area projection



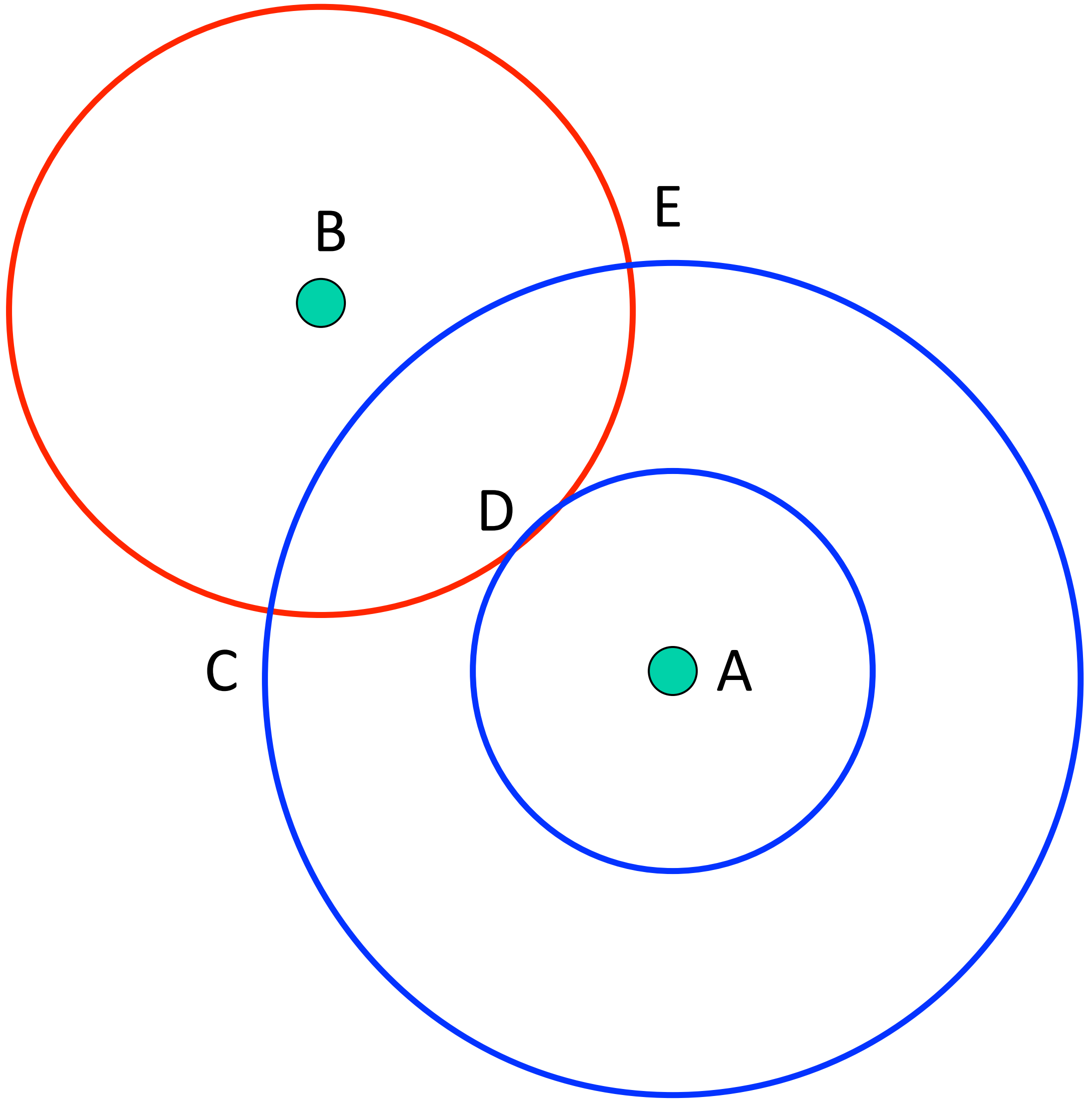


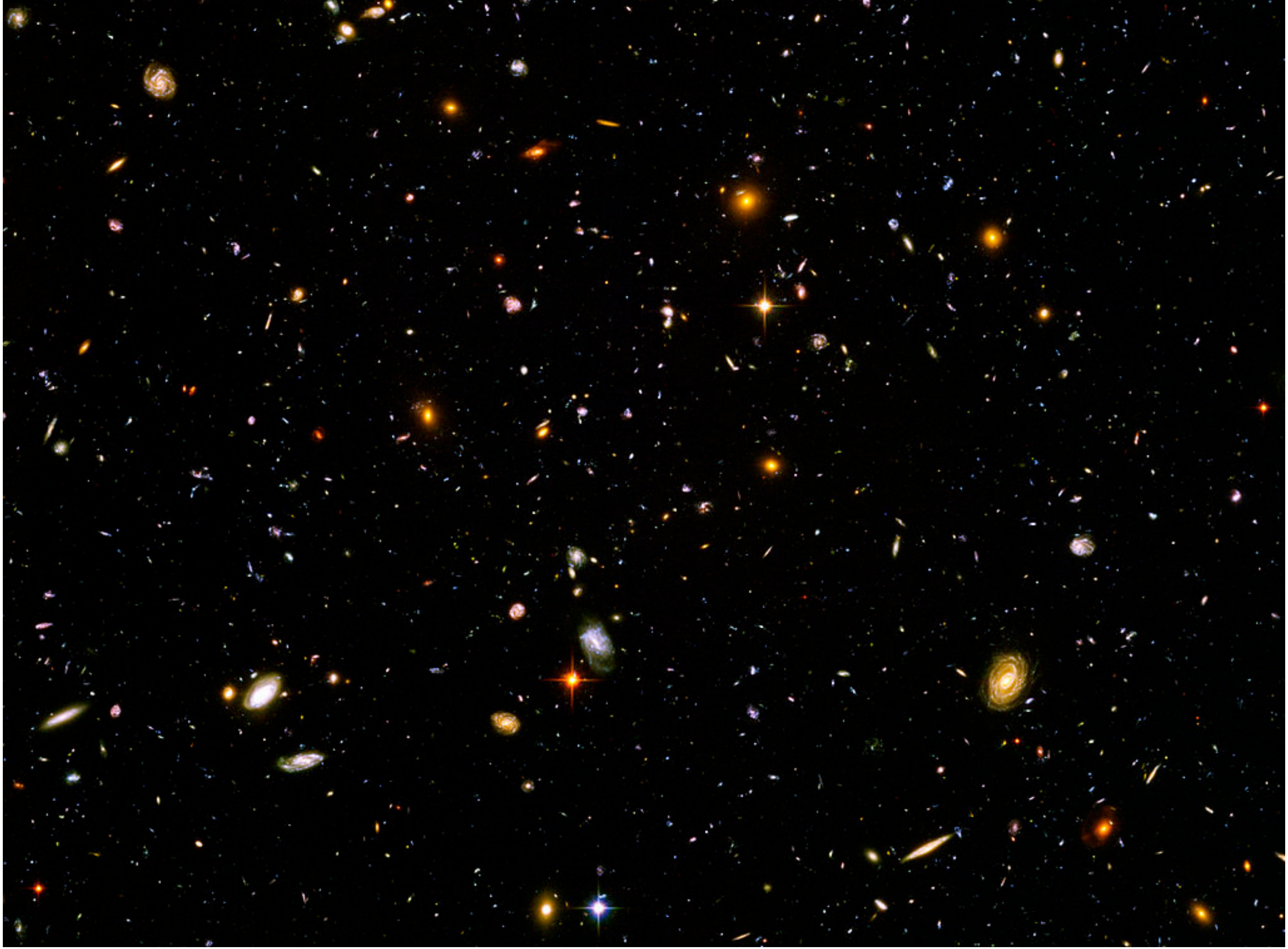
- The CMB dominates the sky brightness at mm wavelengths
- And is very much isotropic: the early universe was very homogeneous
- The most boring picture of the sky ever !

Copernican principle + isotropy = homogeneity

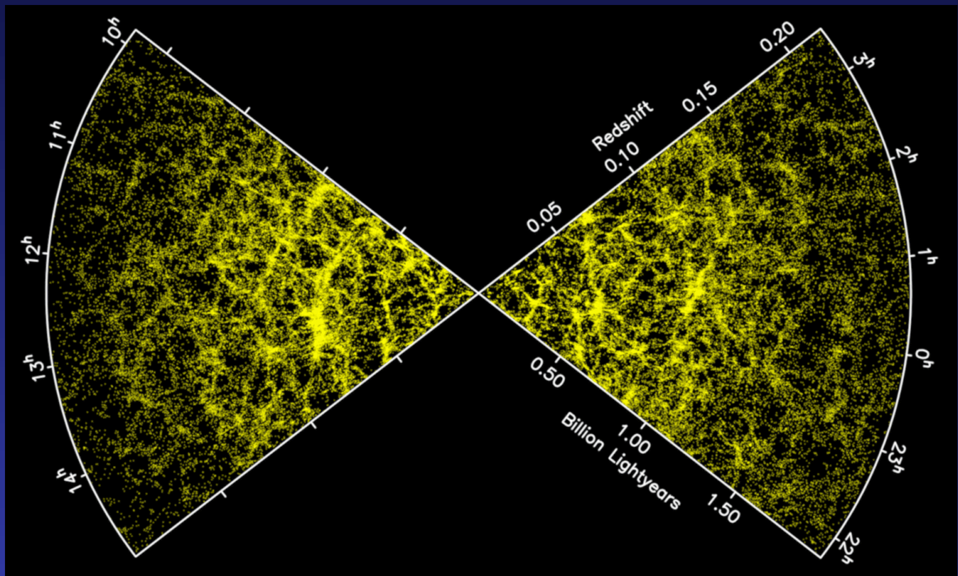


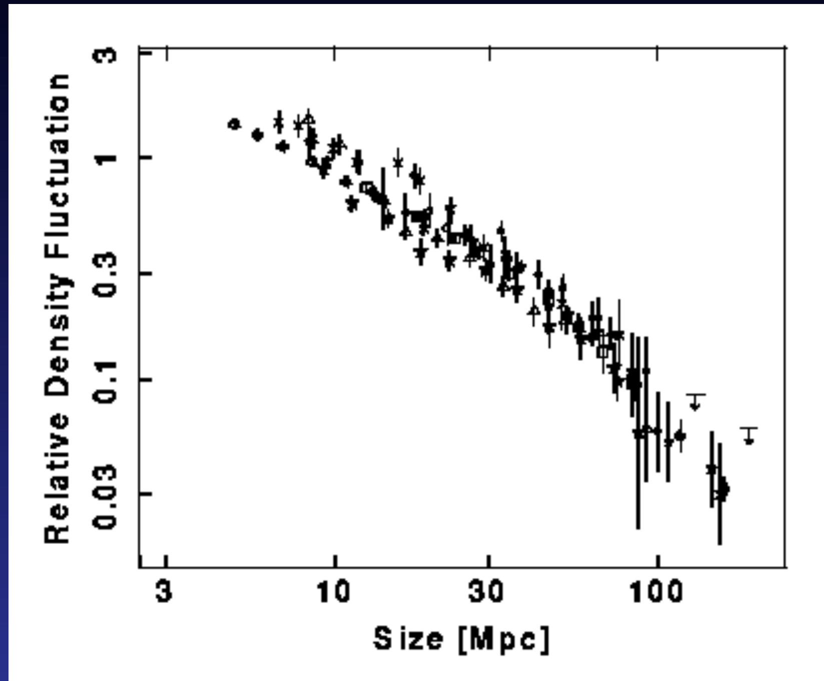
Copernican principle + isotropy = homogeneity





3D galaxy distribution surveys





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

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

Method

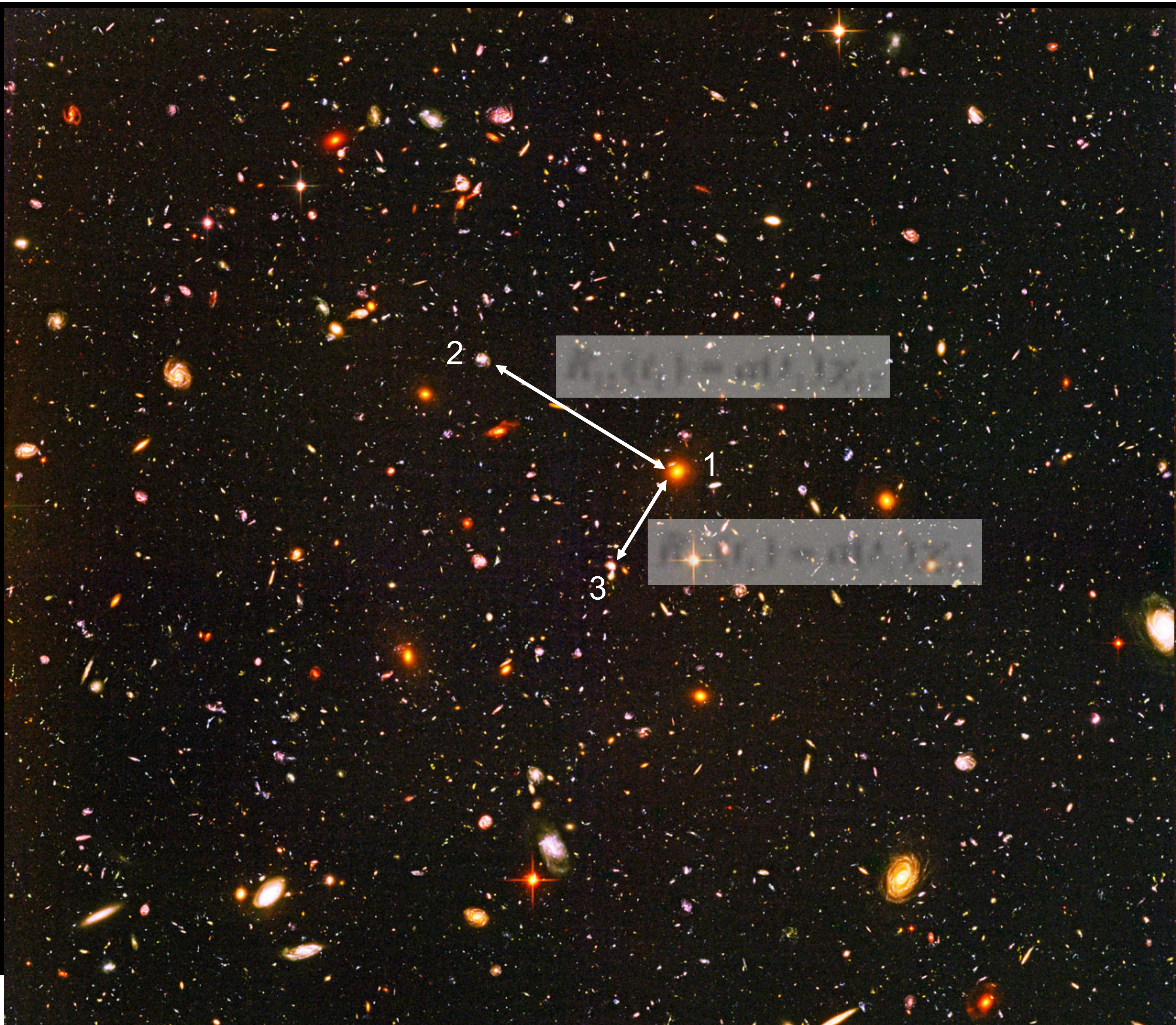
- Simplify the problem :
- Homogeneous and isotropic fluid filling the universe (cosmological principle)
- OK at large scales (background universe):
  - Isotropy of Radiogalaxies
  - Isotropy of microwave, X-rays, infrared Backgrounds
  - Copernican Principle: we are not special in the universe
  - 3D 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: $ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$ $\quad R(t) = a(t)\chi$

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

  - mass-energy content of the universe ?


2
1
3

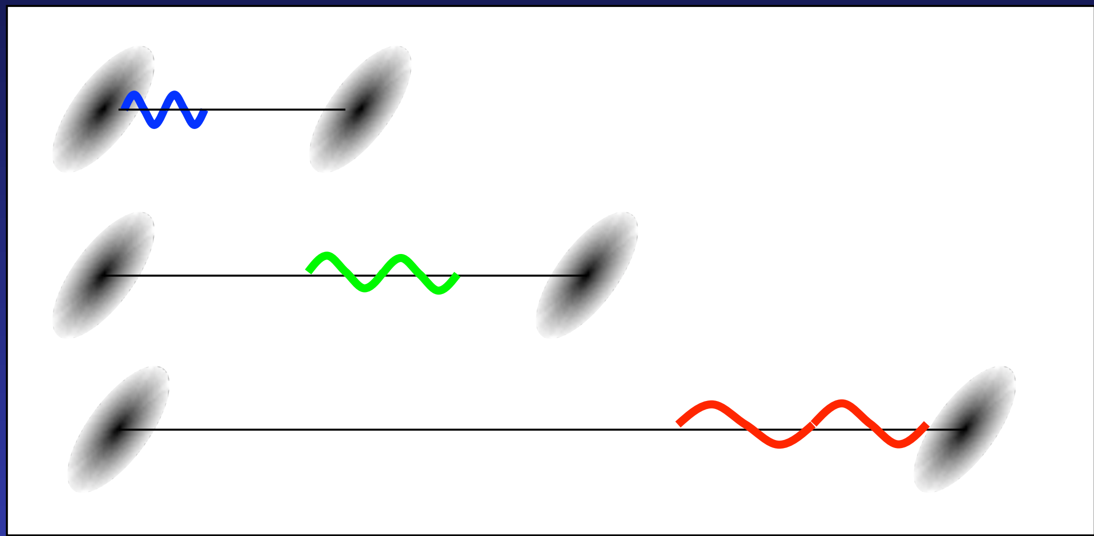

2
1
3


2
1
3

Redshift

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

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



- 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

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

$$z = \frac{\lambda_{\text{det}} - \lambda_{\text{em}}}{\lambda_{\text{em}}}$$

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

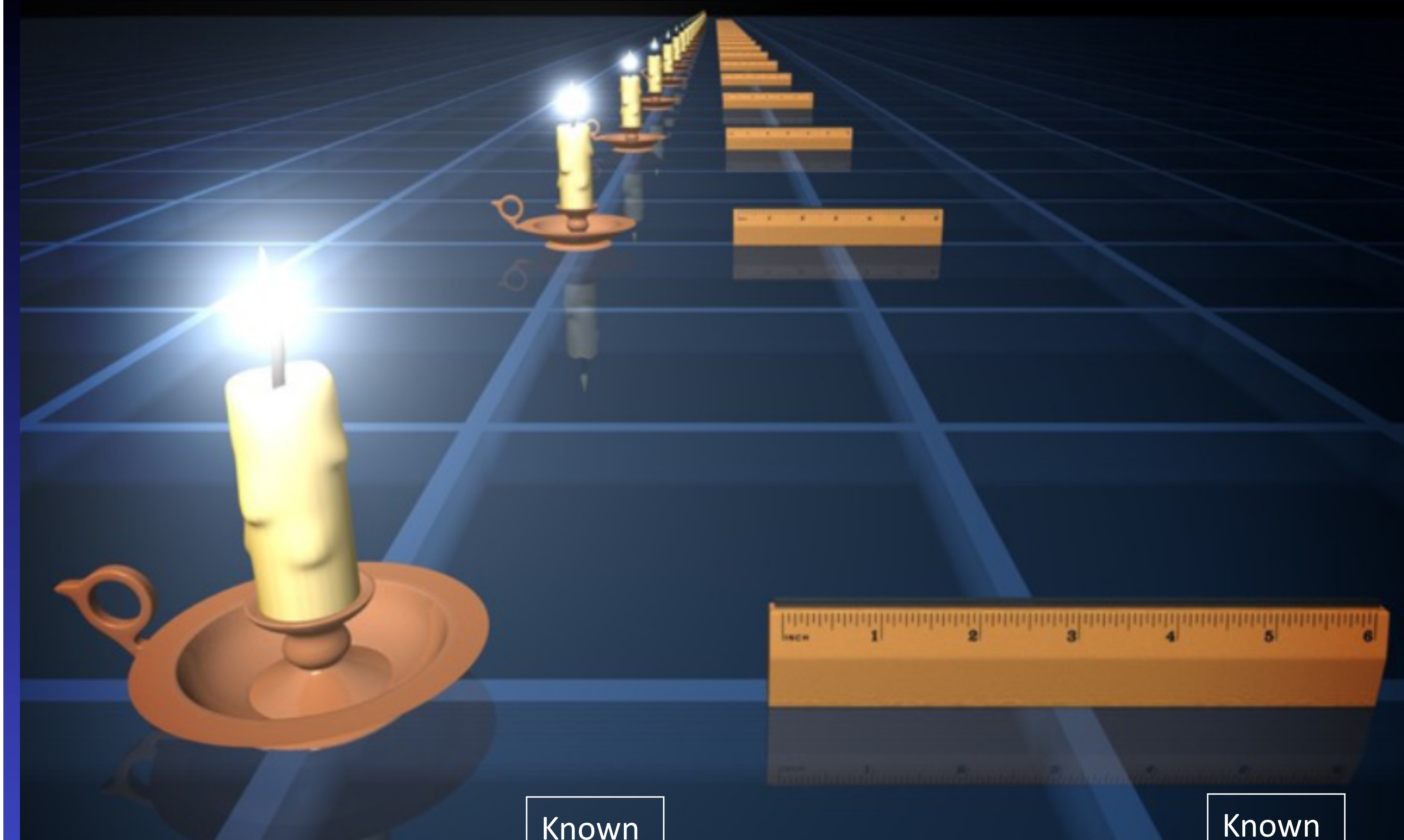
$$z = \left[\frac{H_o}{c}\right] D$$

Measurable (direct measurement with spectrometers) → z

$\left[\frac{H_o}{c}\right]$: A constant

D ← Measurable (indirect, using distance indicators)

Distance Indicators



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

Known *a-priori* (L)

measurable (F)

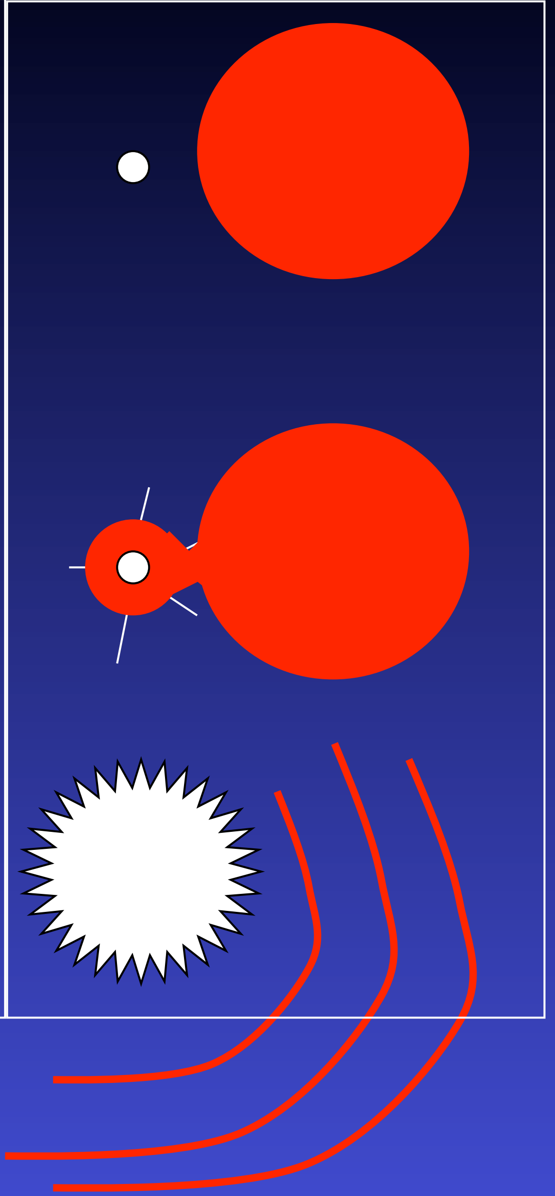
$$\theta = \frac{\ell}{D_A} \longrightarrow D_A = \frac{\ell}{\theta}$$

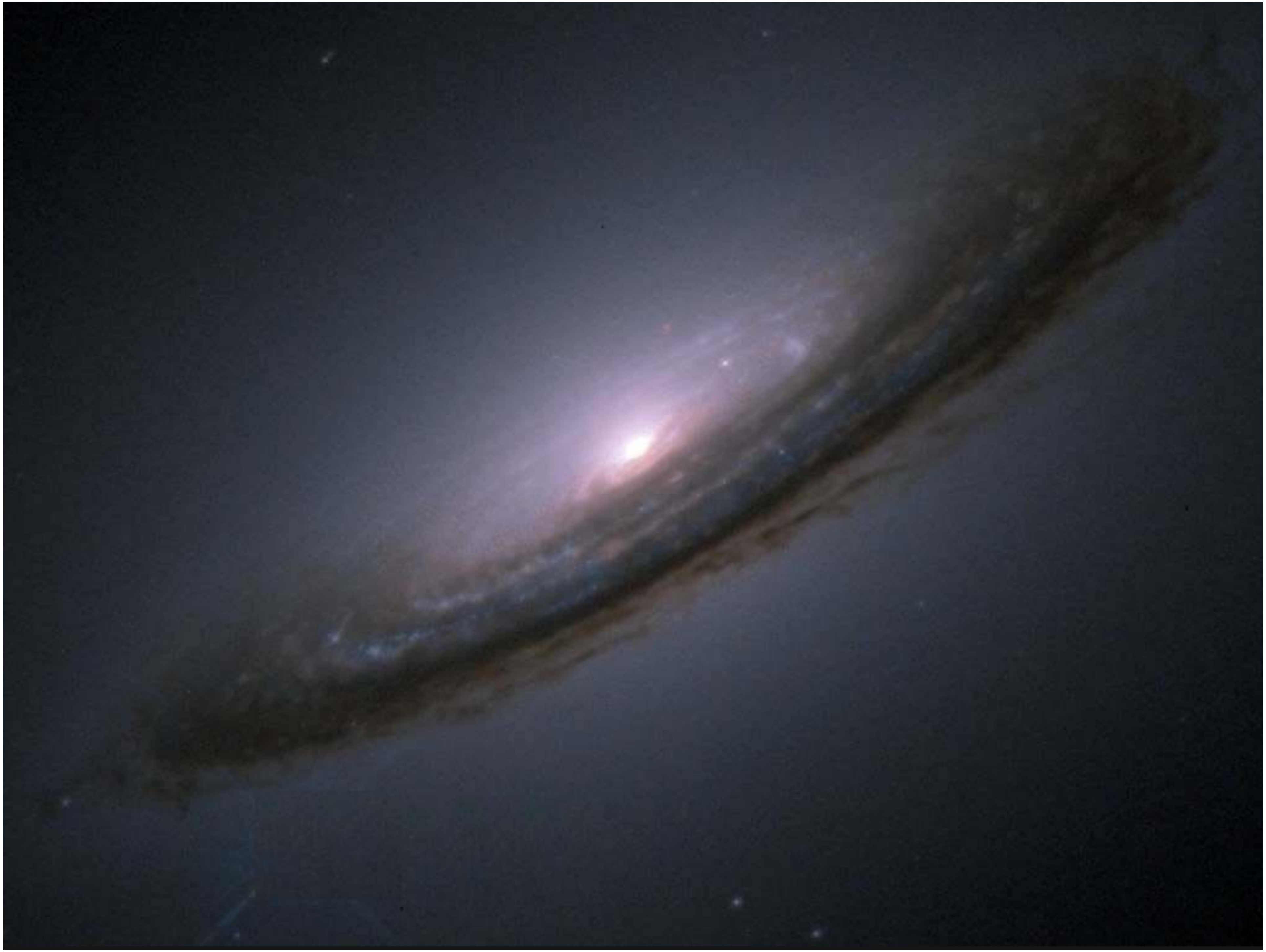
Known *a-priori* (ℓ)

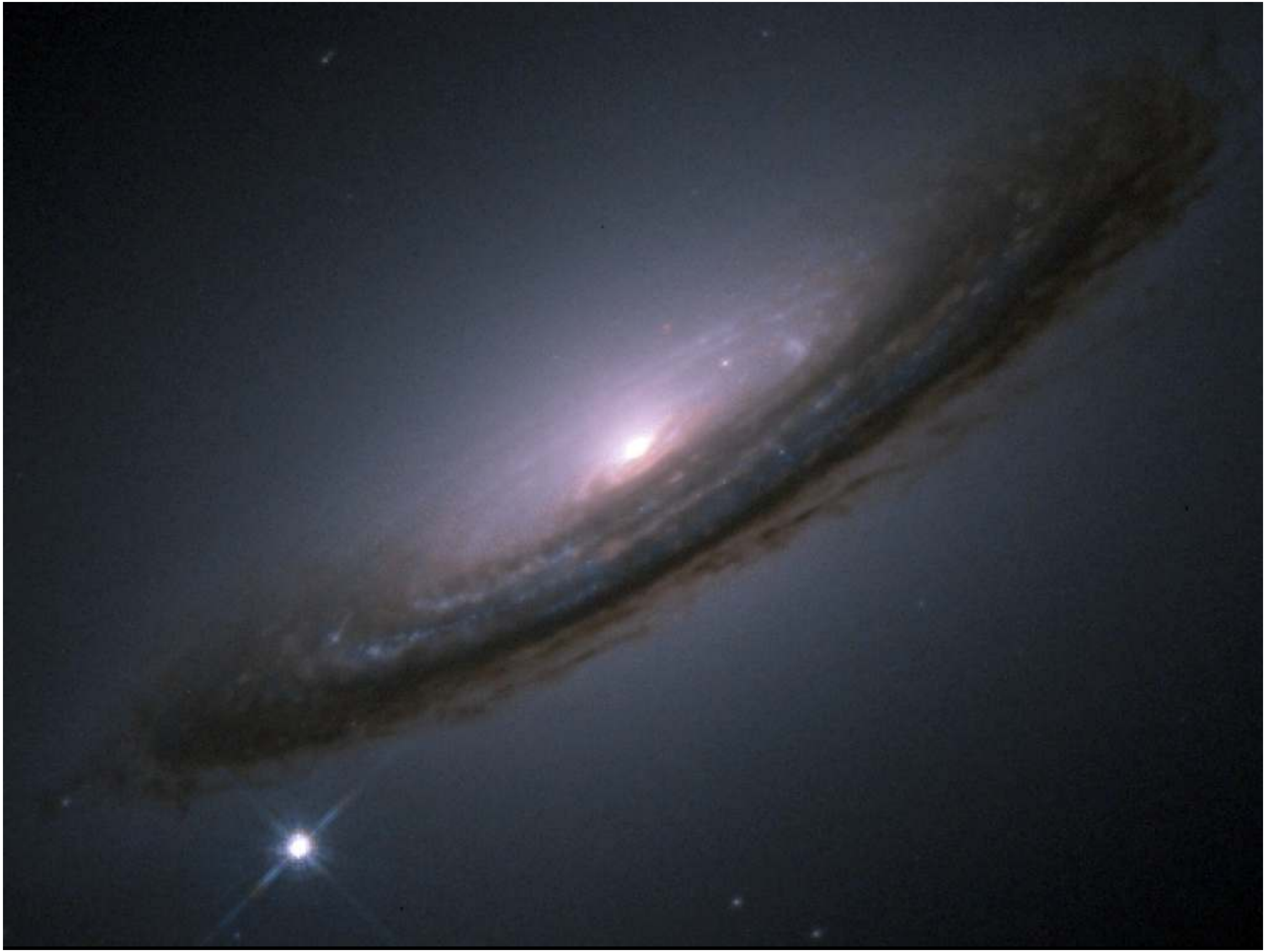
measurable (θ)

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







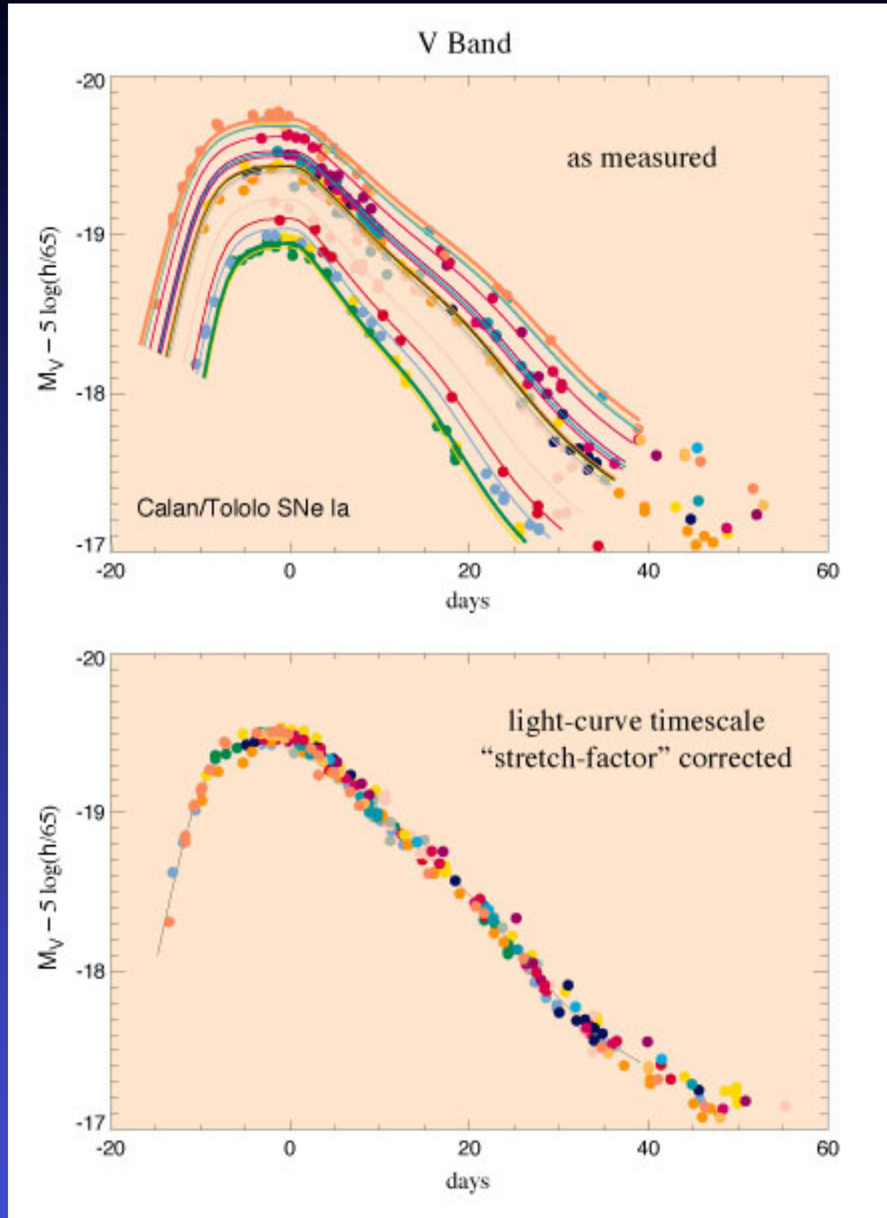
SNe1a

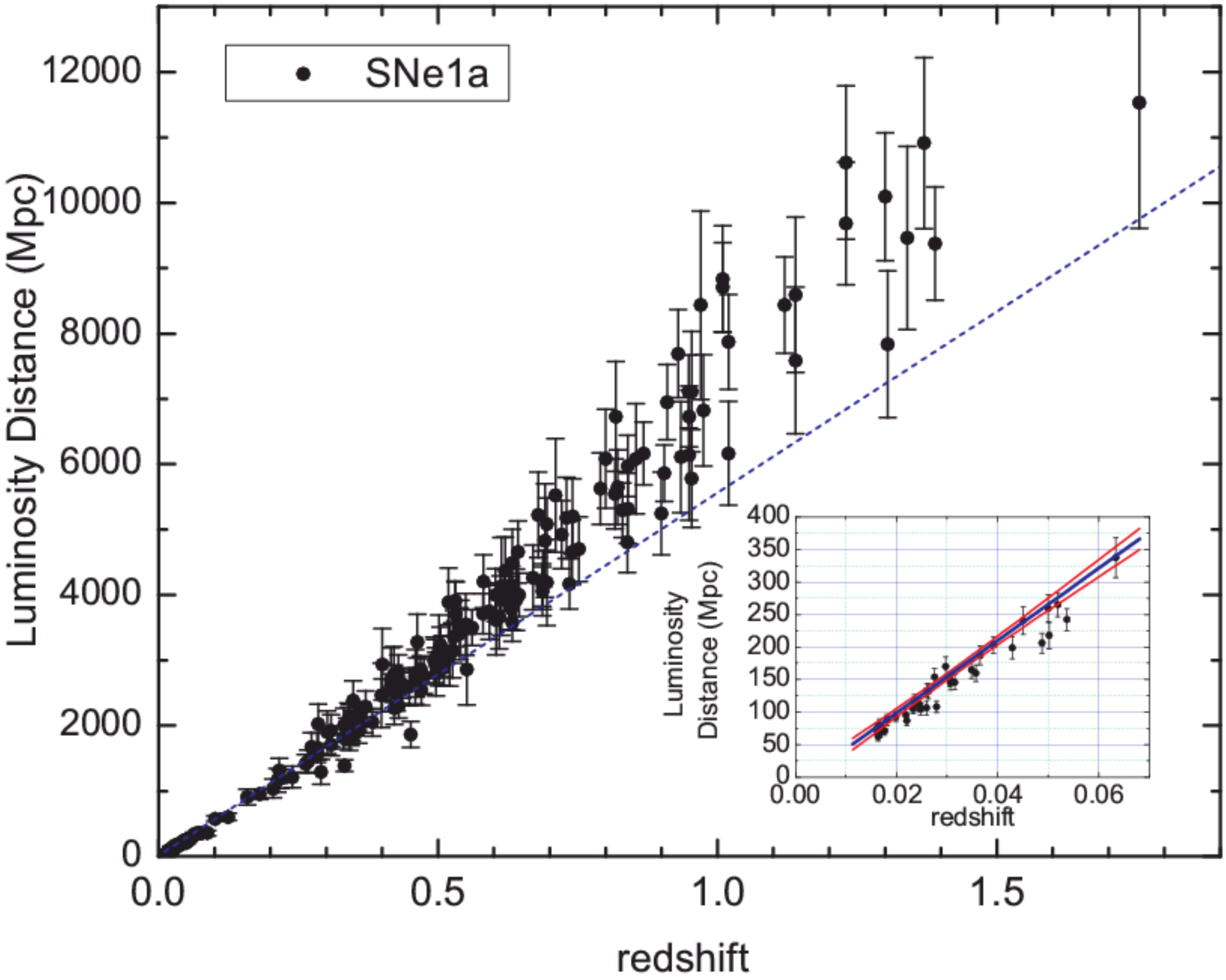
- The luminosity and the light-curve are due to the decay of radioactive nuclei produced during the implosion of the inner part of the star.

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

^{56}Co -> $^{56}Fe + \gamma$ (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





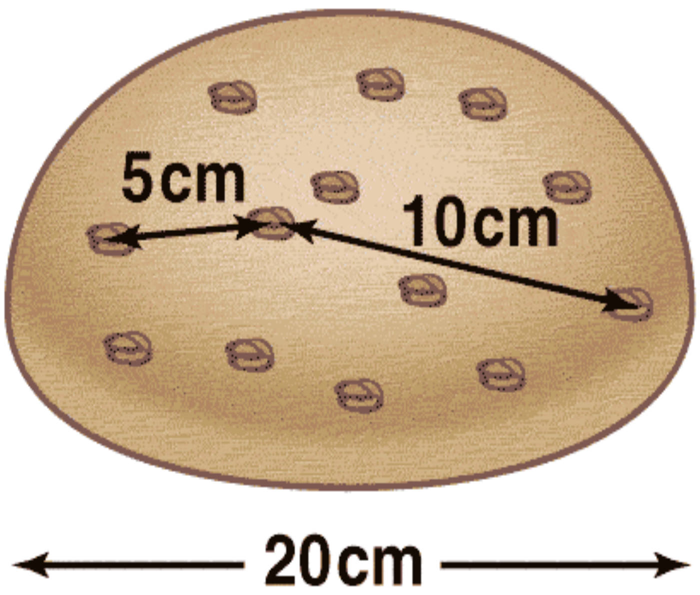
SNe1a
Luminosity Distance (Mpc)
12000
10000
8000
6000
4000
2000
0
0.0
0.5
1.0
1.5
redshift
400
350
300
250
200
150
100
50
0
0.00
0.02
0.04
0.06
Luminosity
Distance (Mpc)
redshift

Hubble's constant

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

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

- 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 $\rho_M = \rho_{Mo} / a^3$
  - Radiation $\rho_R = \rho_{Ro} / a^4 \leftarrow n = n_o / a^3 \quad ; \quad E = h\nu = hc / \lambda \approx 1 / a$
  - Cosmological Constant $\rho_\Lambda = \rho_{\Lambda o}$
- All densities are given in adimensional form, as a fraction of the critical density:

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

$$\Omega_{io} = \frac{\rho_{io}}{\rho_{co}}$$

Friedman's equation

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

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

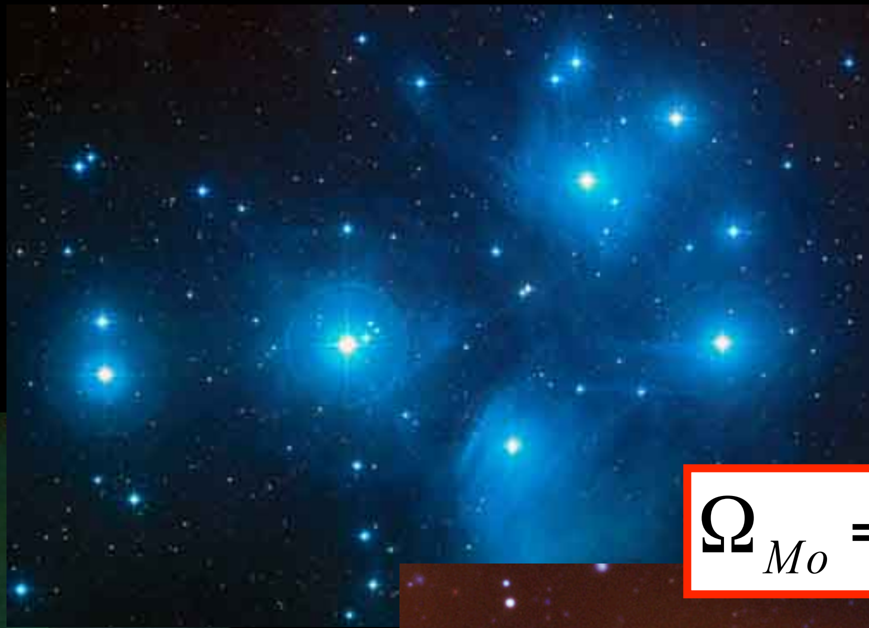
- The solution *a(t)* tells us how all the distances in the universe evolve with time (i.e. how the universe expands).
- To find the solution, we need to find empirically the mass energy densities ρ_{Ro}, ρ_{Mo}, ρ_Λ and from them the parameters Ω_{Ro}, Ω_{Mo}, Ω_Λ

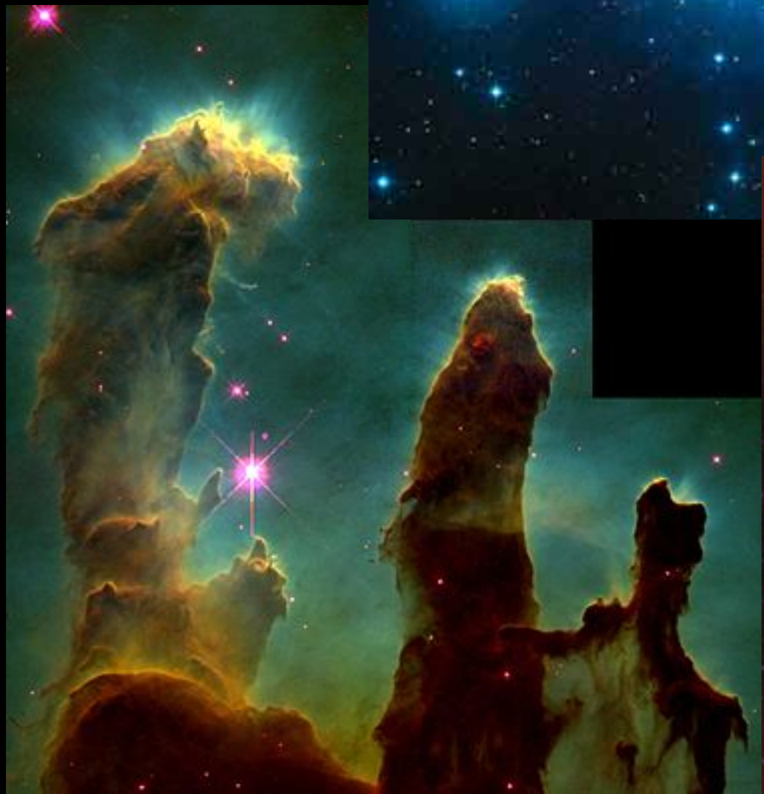
Baryonic Matter

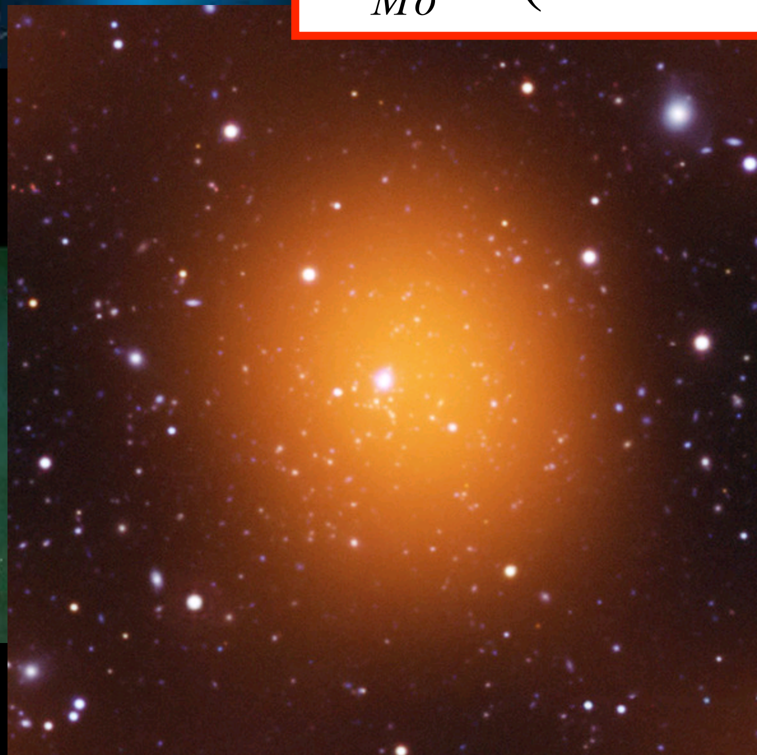
- Baryonic matter interacts electromagnetically
- We can measure it because it emits, or absorbs, or scatters light and electromagnetic waves.
- Us, planets, stars, interstellar matter, galaxies, etc. contain baryonic matter.
- Measuring the luminosity, one can infer the mass responsible for such a luminosity.
- Most recent estimates:

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

- Consistent with primor[…]s.
- A minor component of our universe.







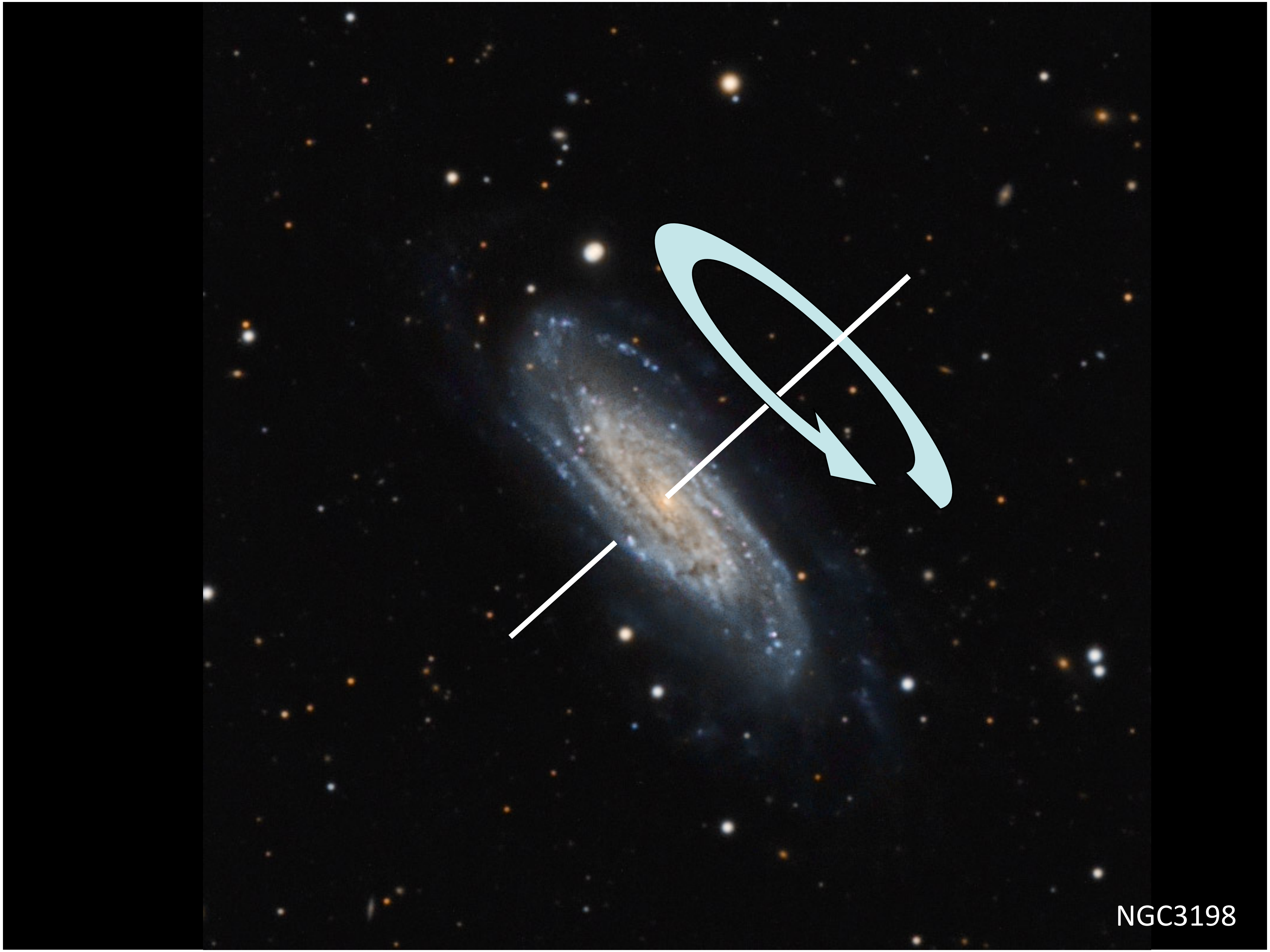
$$\Omega_{Mo} = (0.045 \pm 0.003)$$

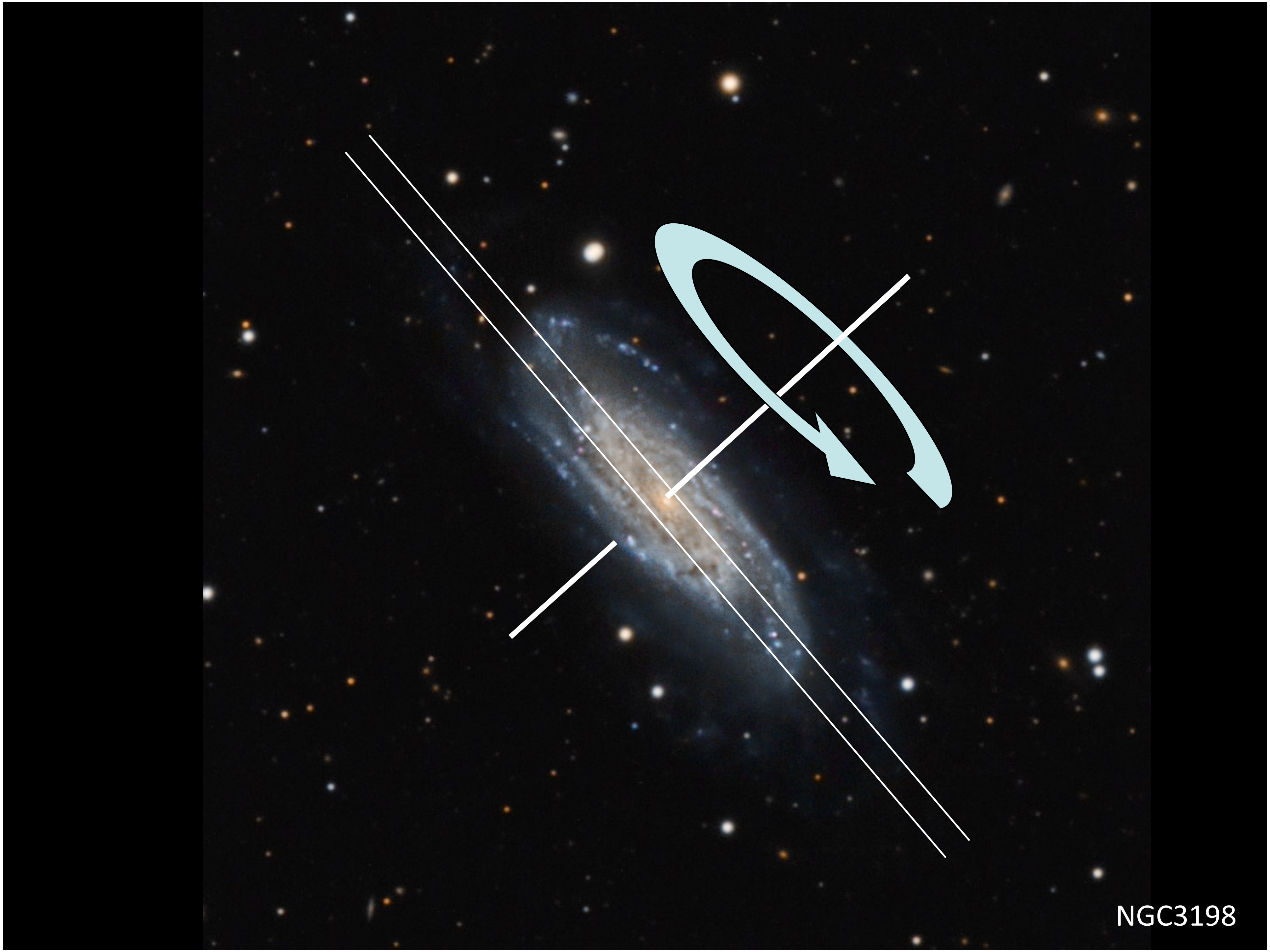
Dark Matter

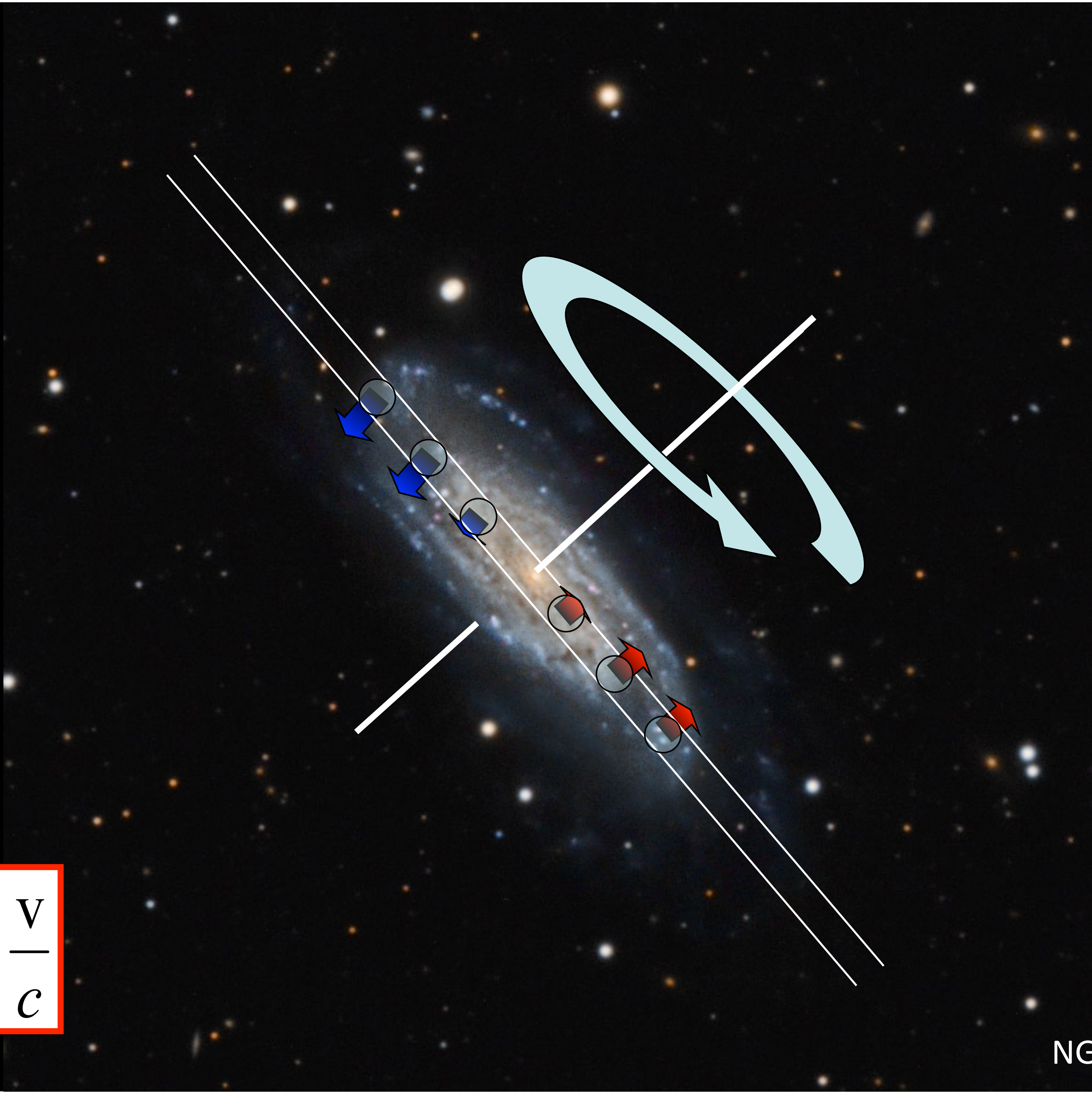
- Dark matter does not interact electromagnetically.
- We can measure it only through its gravitational interaction, which is much weaker than electromagnetic.
- The dynamics of stars in galaxies and of galaxies in clusters of galaxies cannot be explained without the presence of dark matter
- Additional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

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

NGC3198

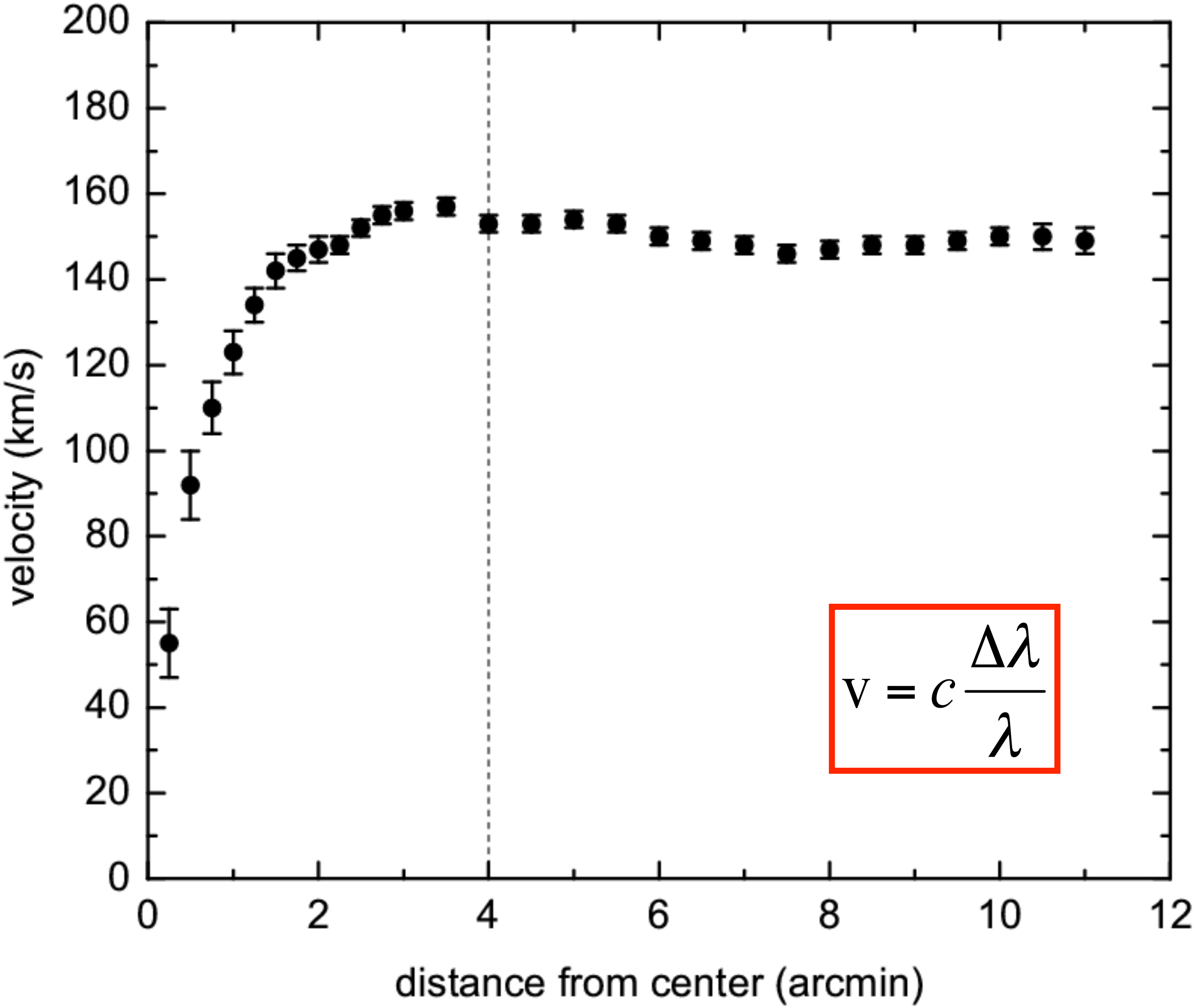

NGC3198

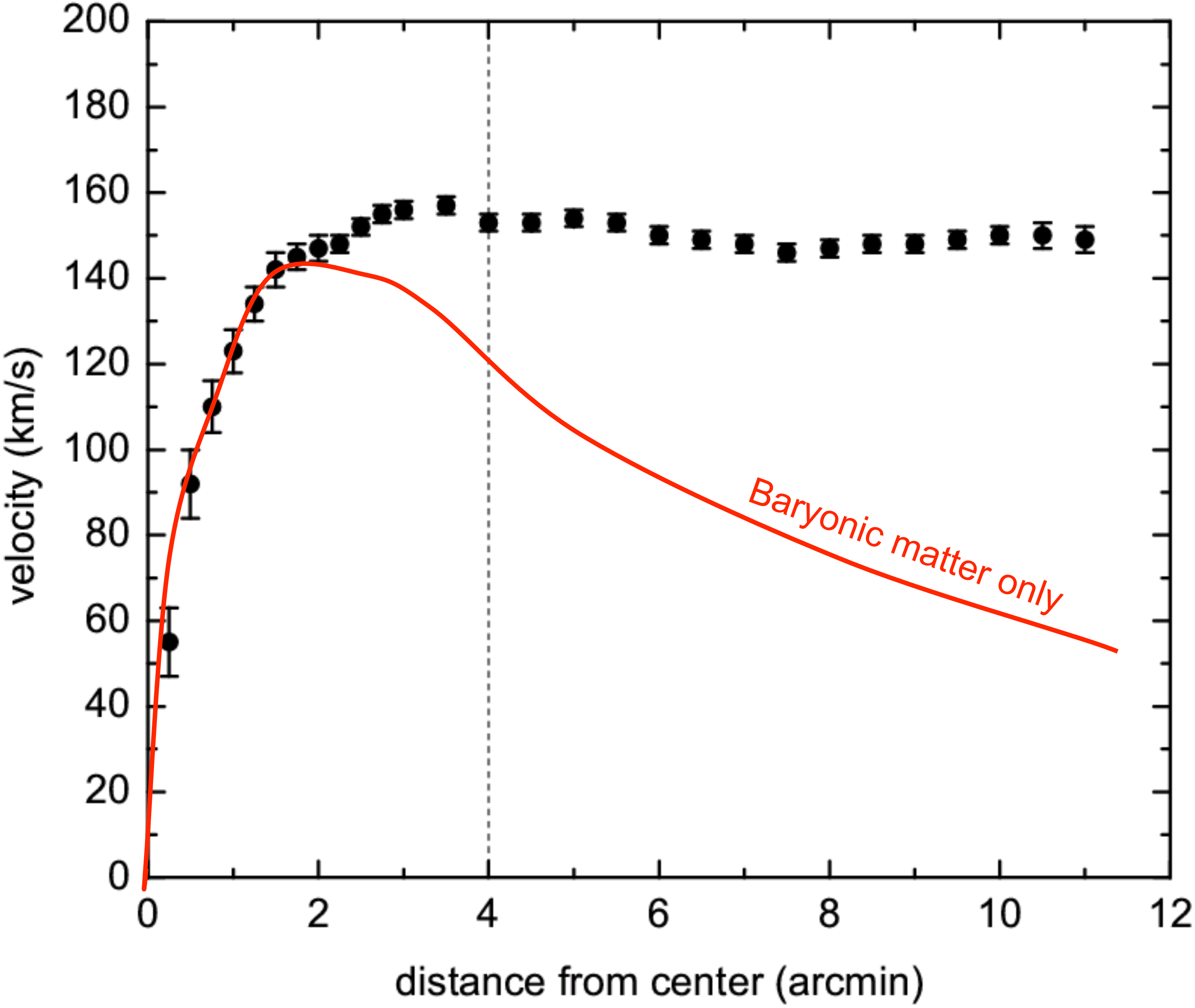

NGC3198



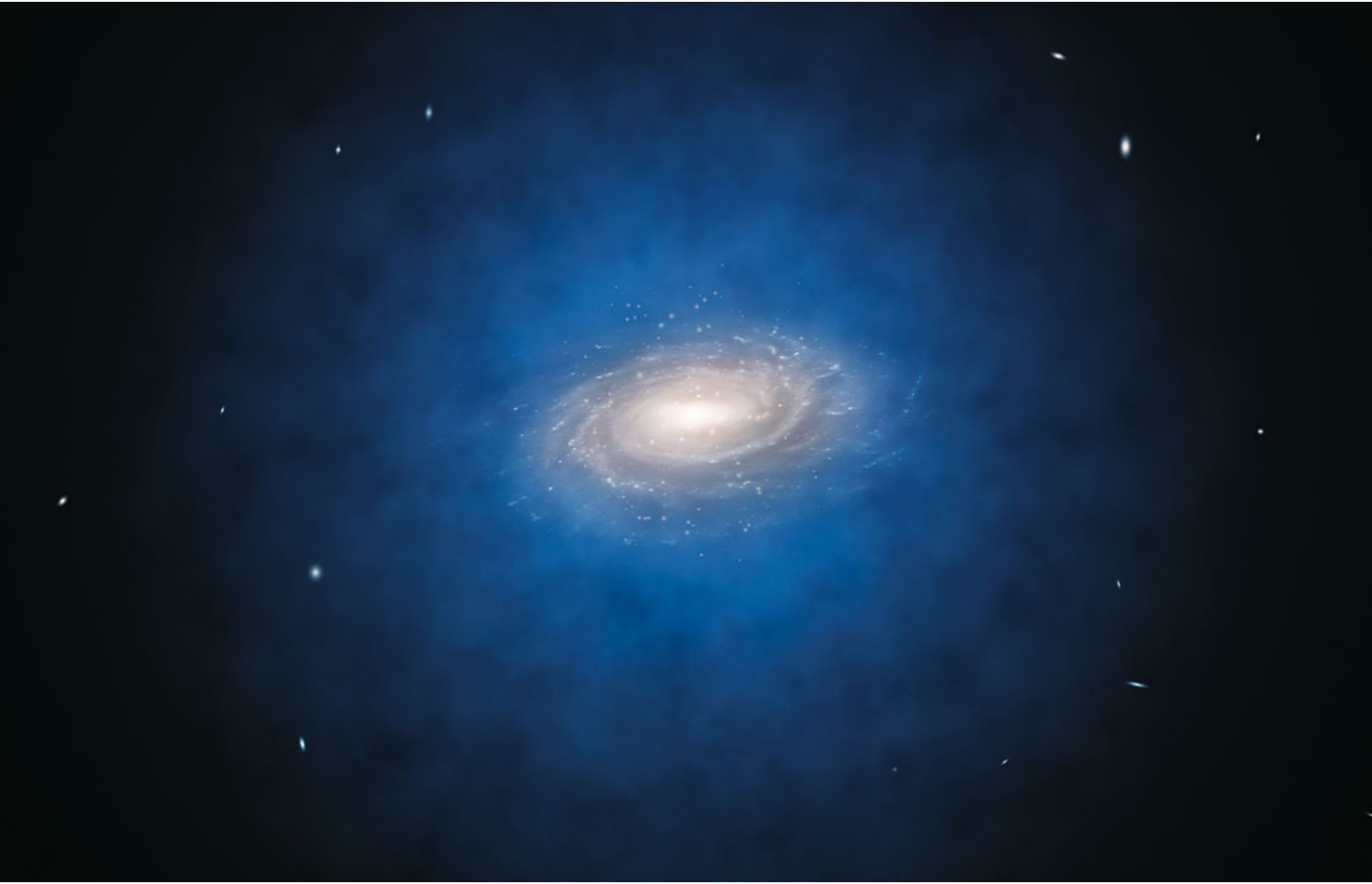
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

NGC3198


200
180
160
140
120
100
80
60
40
20
0
velocity (km/s)
0
2
4
6
8
10
12
distance from center (arcmin)
$v = c\frac{\Delta\lambda}{\lambda}$

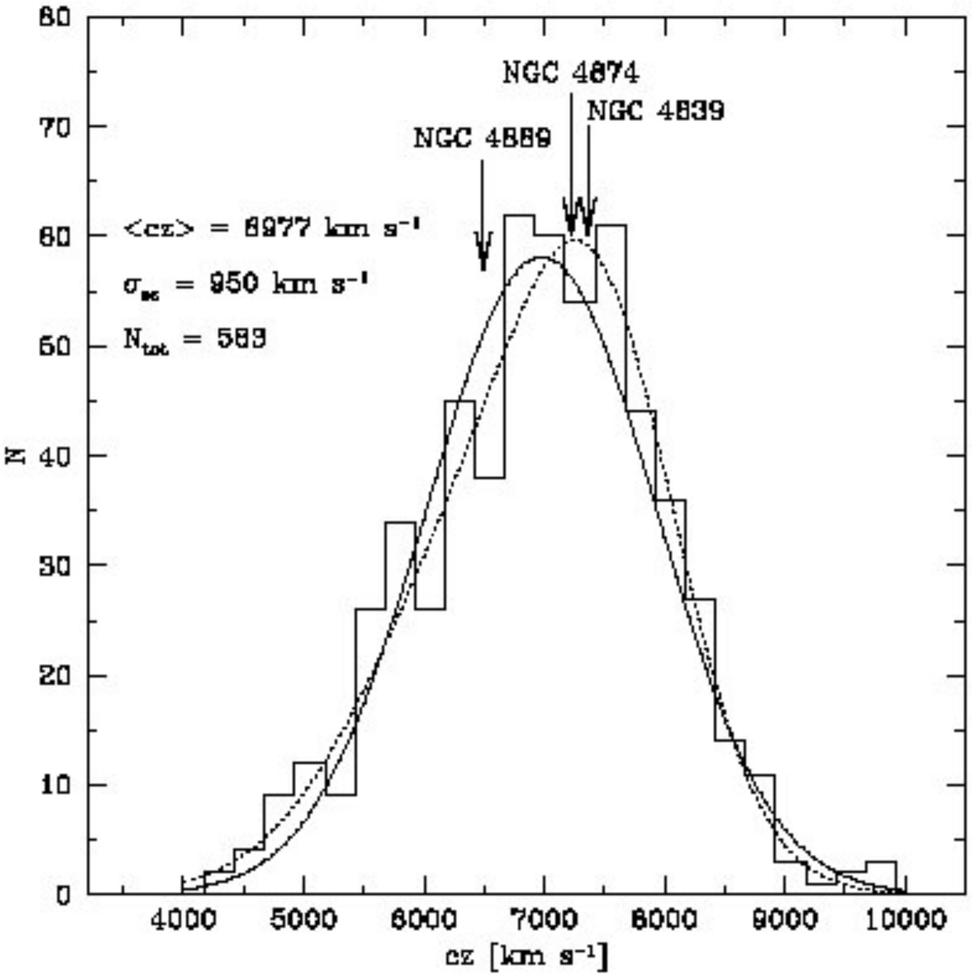


velocity (km/s)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
distance from center (arcmin)
Baryonic matter only



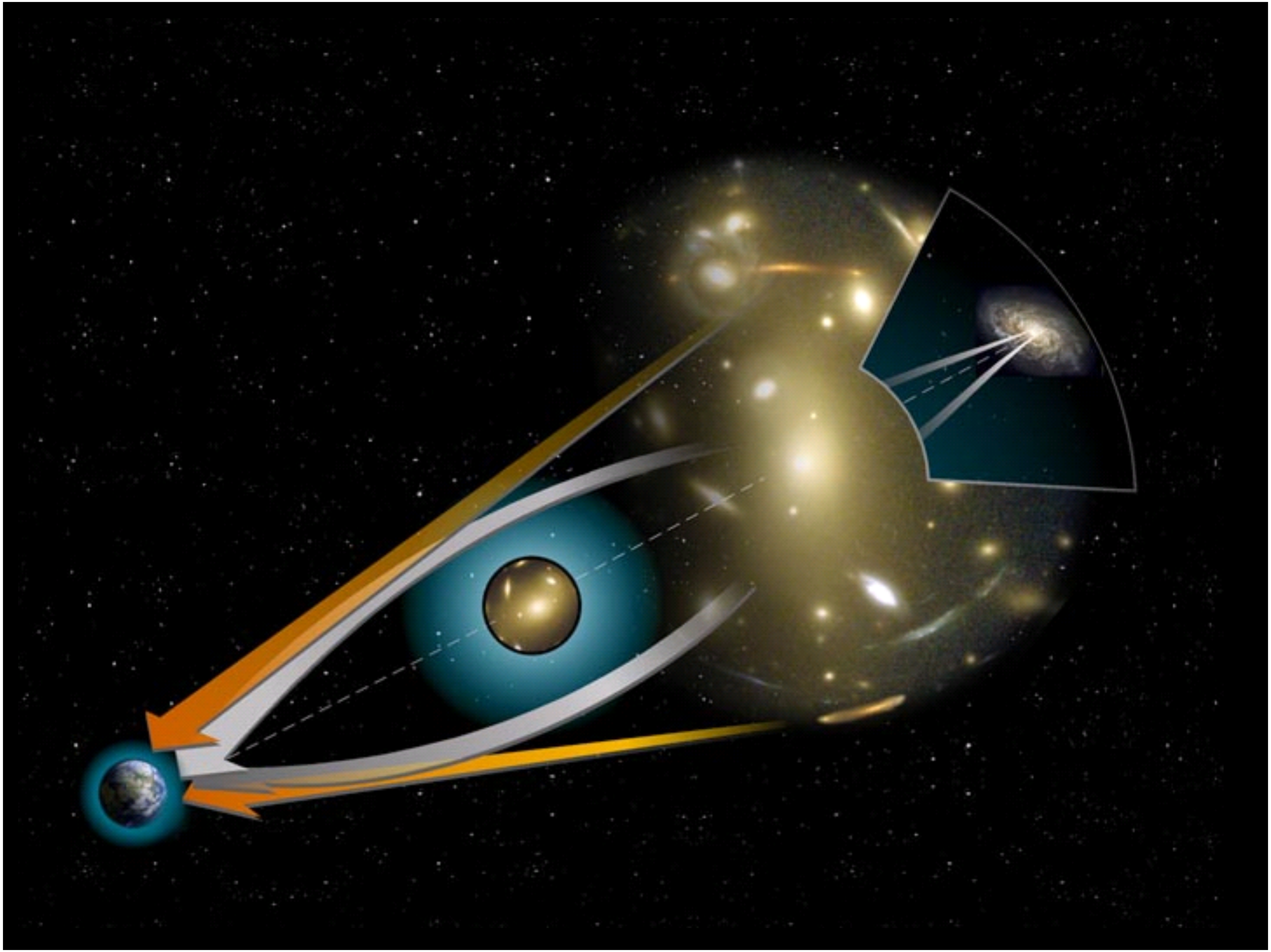

Coma

Figure 4.10— The distribution of radial velocities of all 583 identified Coma cluster galaxies ($4000 < cz < 10000$ km s^{-1}). The solid curve is a Gaussian with mean 6977 ± 53 km s^{-1} and standard deviation 950 ± 39 km s^{-1}. The dotted curve is the sum of two Gaussians with $\overline{cz_1} = 7501 \pm 187$ km s^{-1}, $\sigma_1 = 650 \pm 216$ km s^{-1} and $\overline{cz_2} = 6640 \pm 470$ km s^{-1}, $\sigma_2 = 1004 \pm 120$ km s^{-1} and gives a better fit to the observed distribution. The radial velocities of the three dominant galaxies are indicated.

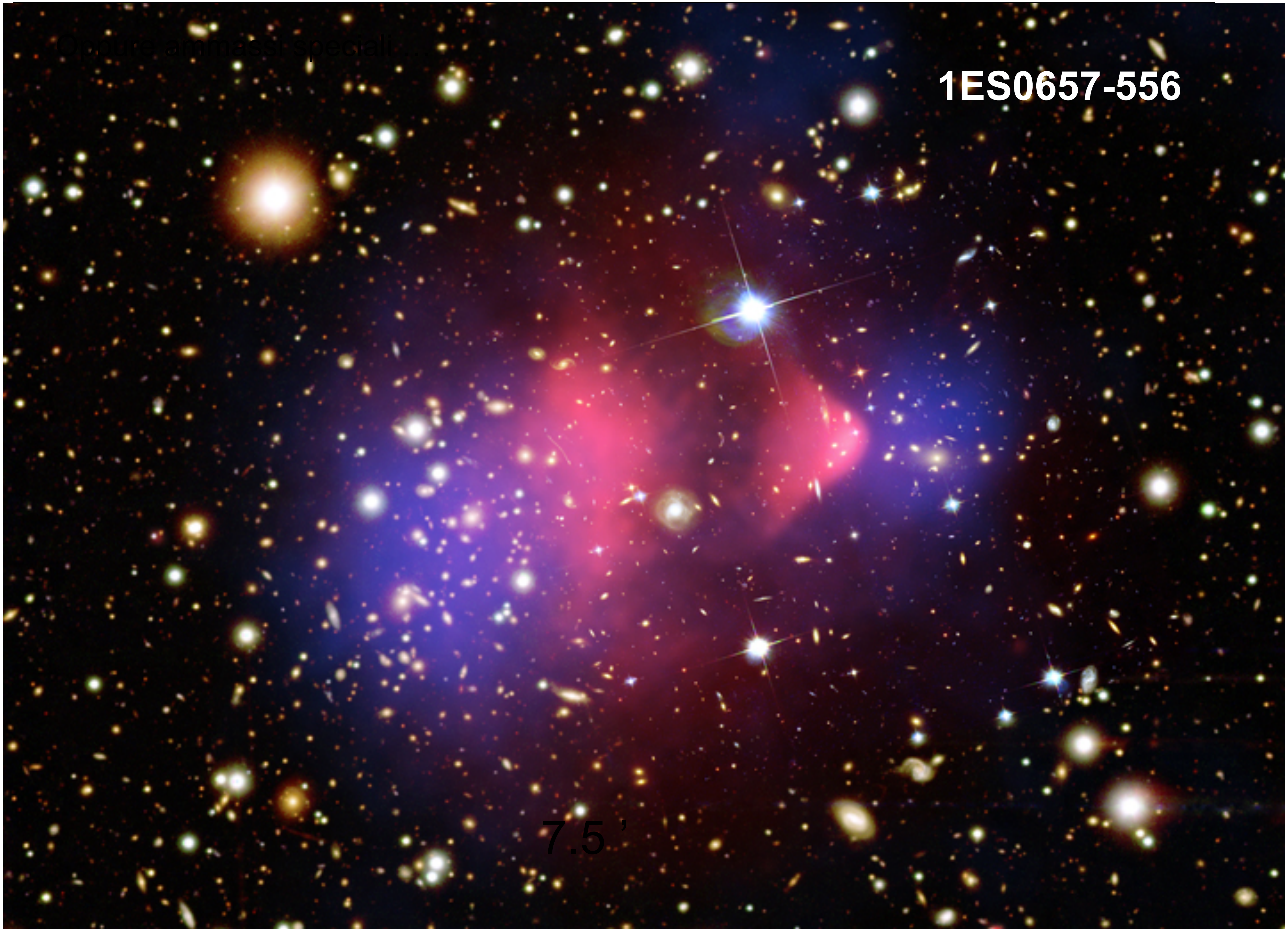


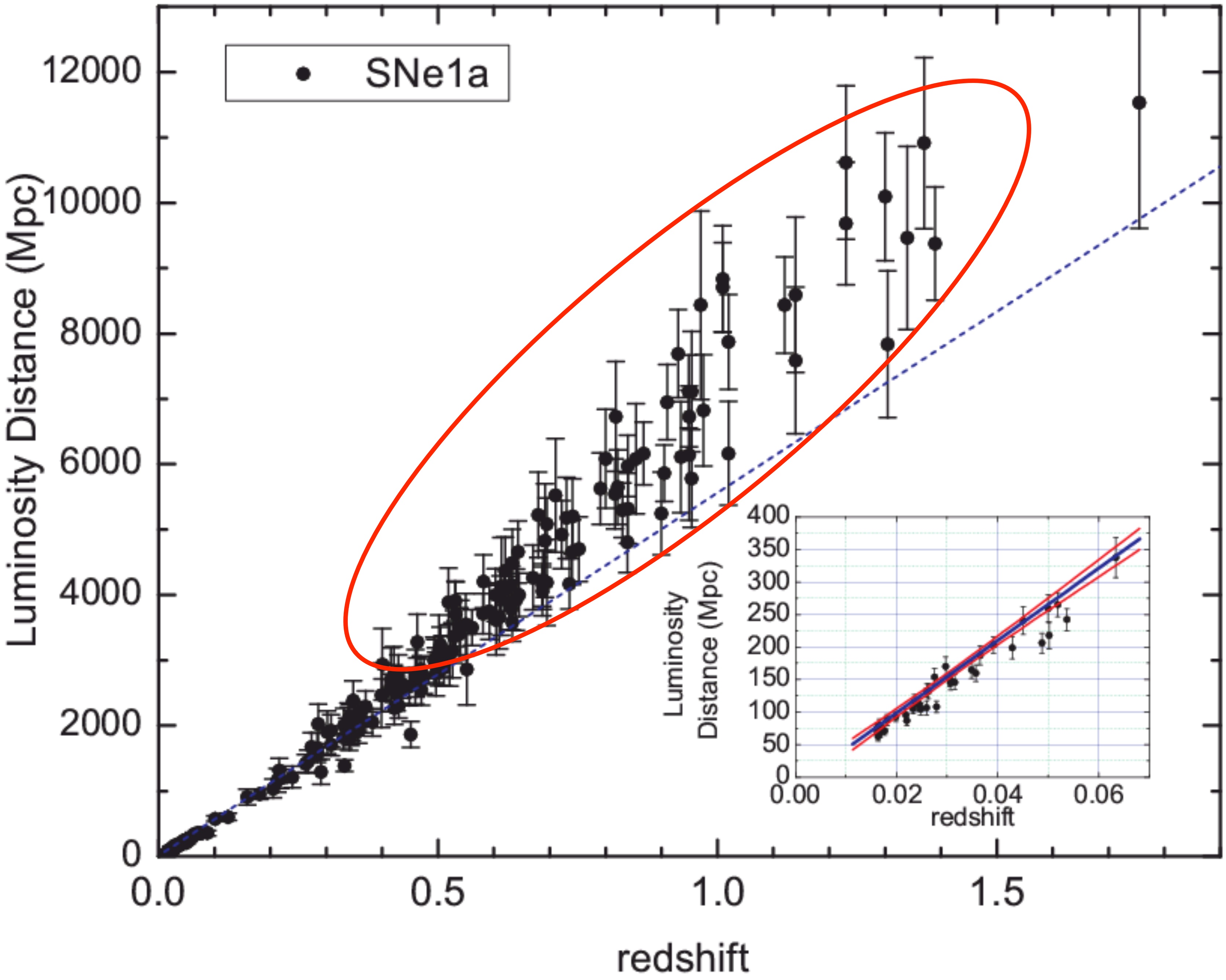
http://www.ub.rug.nl/eldoc/dis/science/m.beijersbergen/c4.pdf

A2218



A1689


Oppure ammassi speciali…
1ES0657-556
7.5 '



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

Dark Energy

- Systematic weakness of distant (high redshift) SNe1a
- Can be explained by an accelerated expansion of the universe, so that they are more distant for a given redshift.
- From Friedman's equation, the only way is to have $\Omega_\Lambda > 0$.

$$\ddot{a} = H_o^2 \left[-\frac{\Omega_{Ro}}{a^3} - \frac{1}{2}\frac{\Omega_{Mo}}{a^2} + \Omega_\Lambda a \right]$$

- The best fit is $\Omega_\Lambda = (0.73 \pm 0.03)$
- This can be obtained from independent measurements as well (CMB, see below)

Radiation

- Light and electromagnetic waves fill the universe.
- Stellar radiation is not the most important radiation field present in the universe, since it dilutes far from stars.
- The cosmic microwave background is a perfect balckbody with a temperature T_o=2.725K filling the whole universe, so dominating over stellar and any other radiation at large scales.
- Its density today is negligible: $\Omega_{Ro} < 10^{-4}$
- However, early in the evolution of the universe, it dominated the energy density. In principle, it was light.

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

Density Parameter

- The total mass-energy density is the sum of all the components analyzed above.

$$\Omega_o = \Omega_{Ro} + \Omega_{Mo} + \Omega_{DMo} + \Omega_\Lambda \approx 1$$

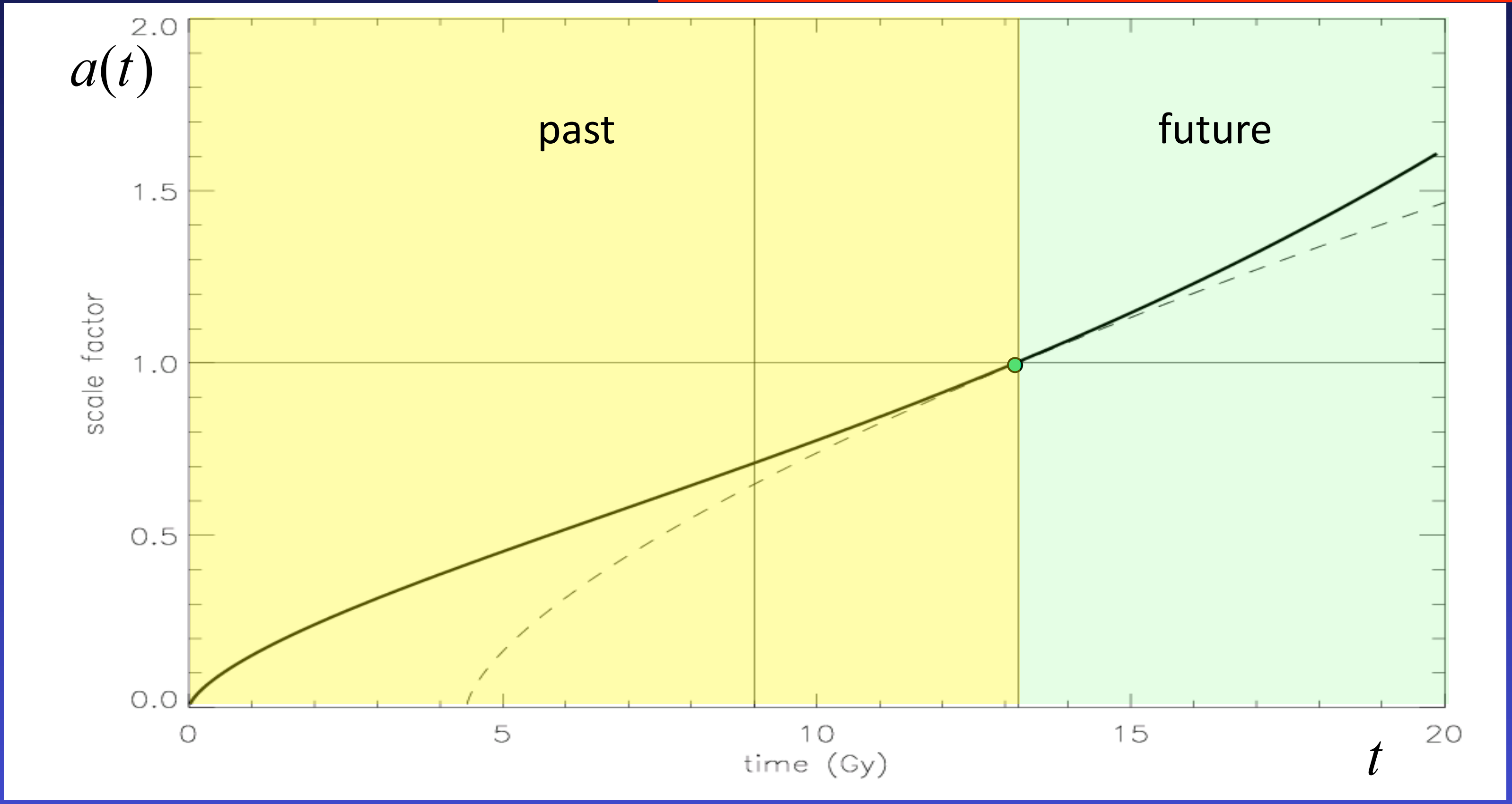
- I.e. the mass-energy density is consistent with the critical density, and there is no curvature of space.
- This result is confirmed and its accuracy is improved by measurements of the causal horizon at redshift 1100, using the cosmic microwave background:

$$\Omega_o = (1.02 \pm 0.02)$$

Friedman's equation

- We know all the parameters, so we can solve the equation:

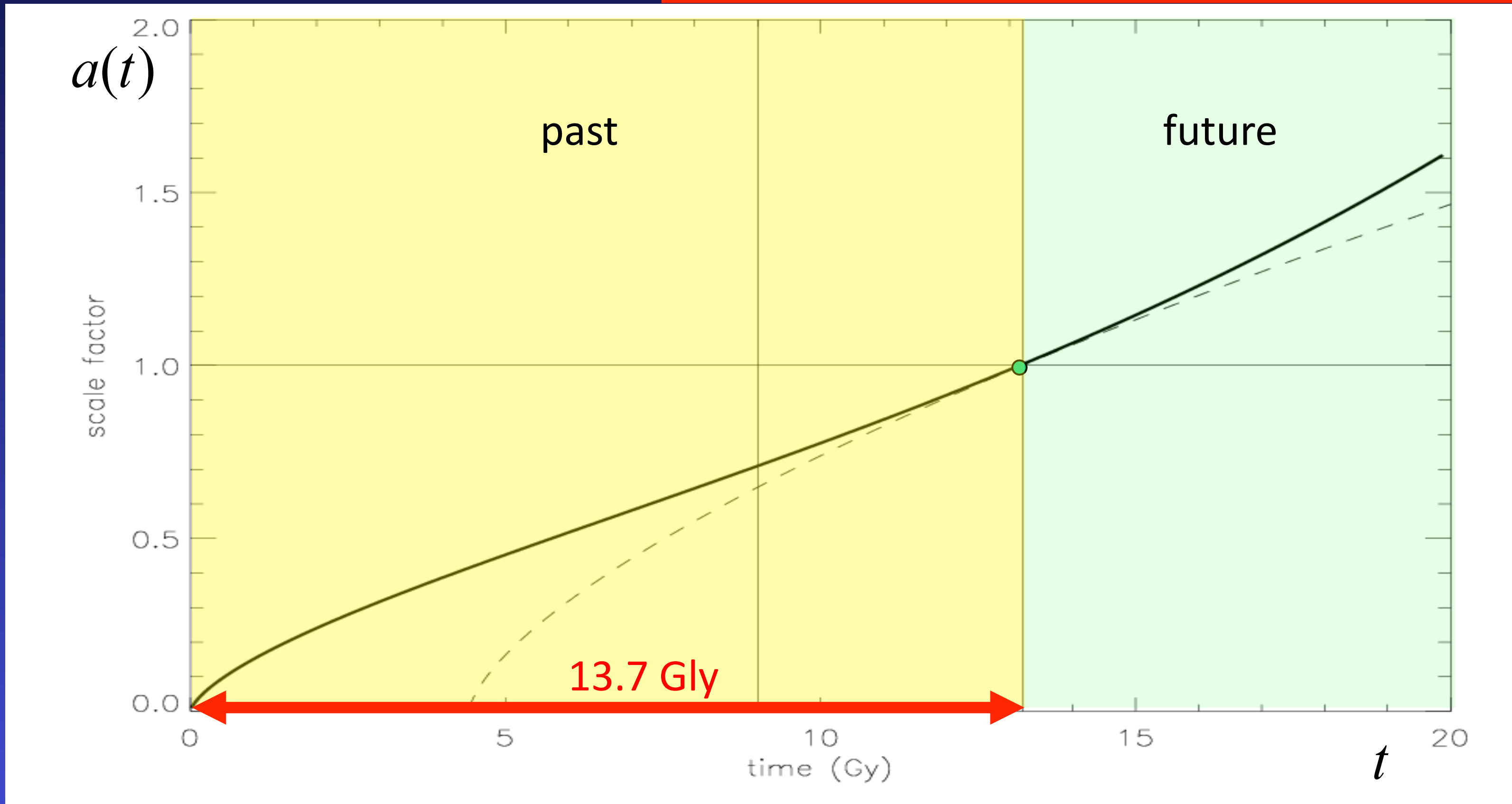
$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4} + \frac{\Omega_{Mo}}{a^3} + \frac{(1-\Omega_o)}{a^2} + \Omega_\Lambda\right]$$



Friedman's equation

- We know all the parameters, so we can solve the equation:

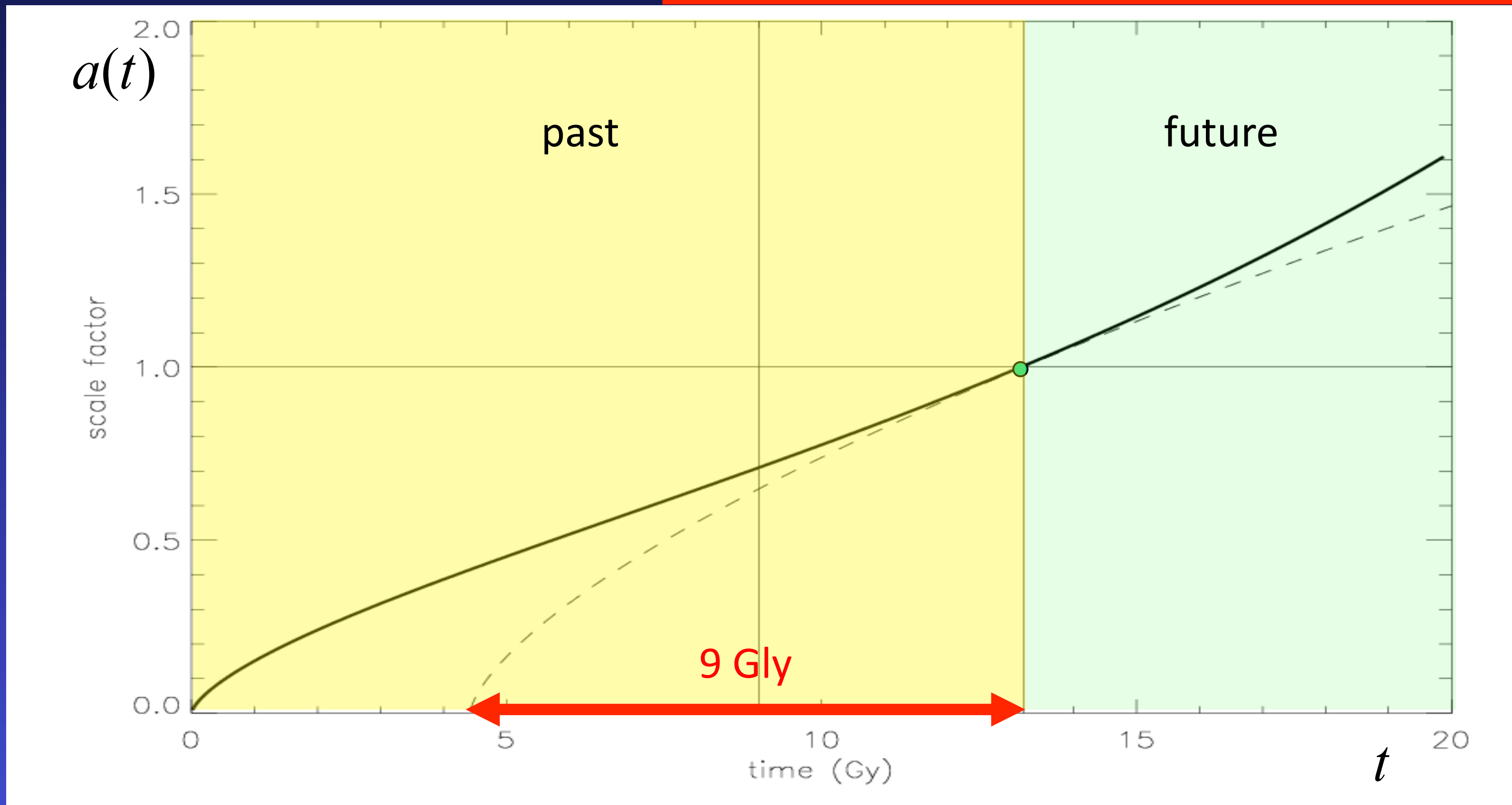
$$\left(\frac{\dot{a}}{a}\right)^2 = H_o^2\left[\frac{\Omega_{Ro}}{a^4} + \frac{\Omega_{Mo}}{a^3} + \frac{(1-\Omega_o)}{a^2} + \Omega_\Lambda\right]$$



Friedman's equation

- We know all the parameters, so we can solve the equation:

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

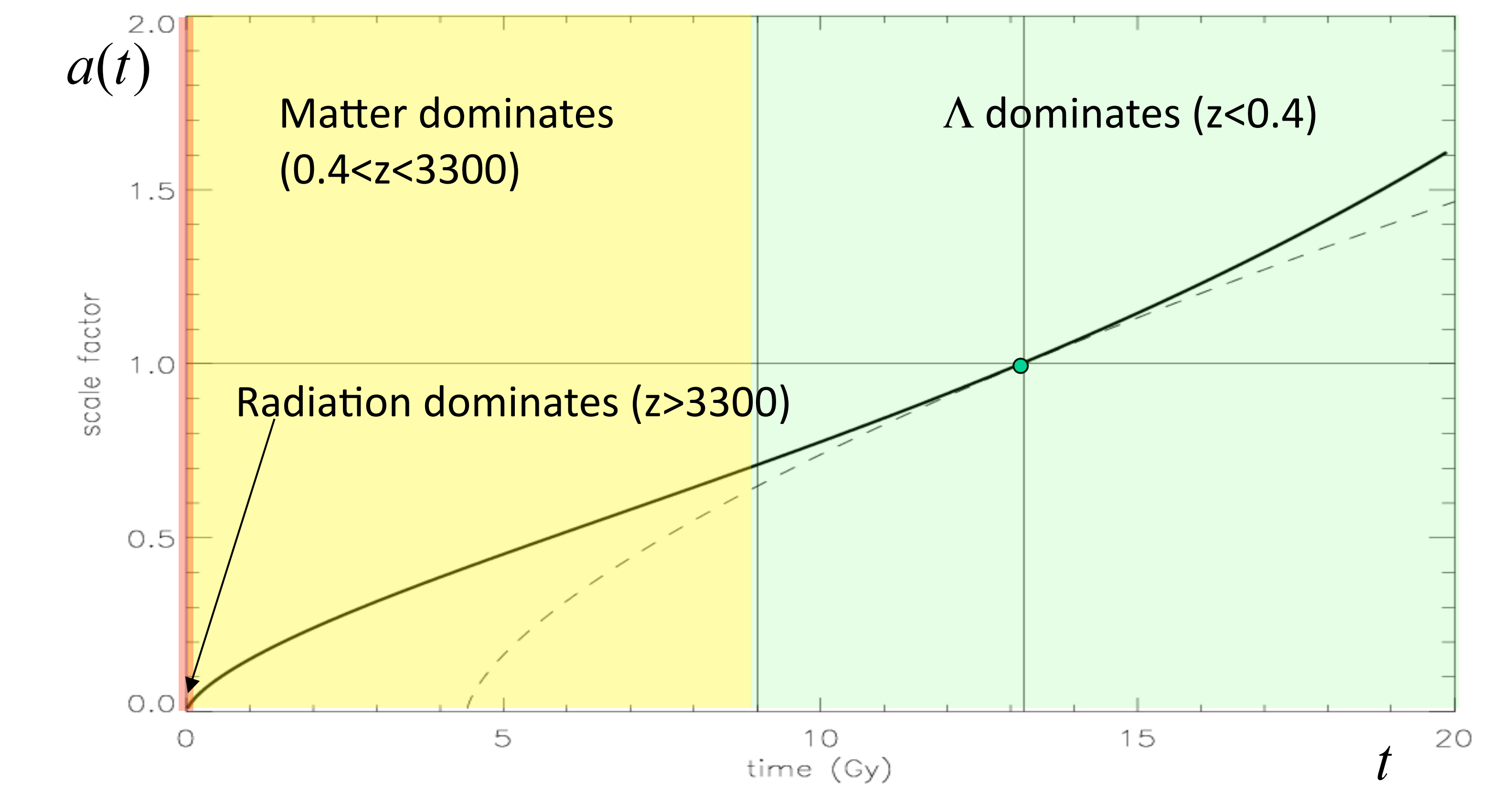



NGC 6397

Friedman's equation

- We know all the parameters, so we can solve the equation:

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



Friedman's equation

- We know all the parameters, so we can solve the equation:

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