Galaxy formation within the classical Big Bang Cosmology

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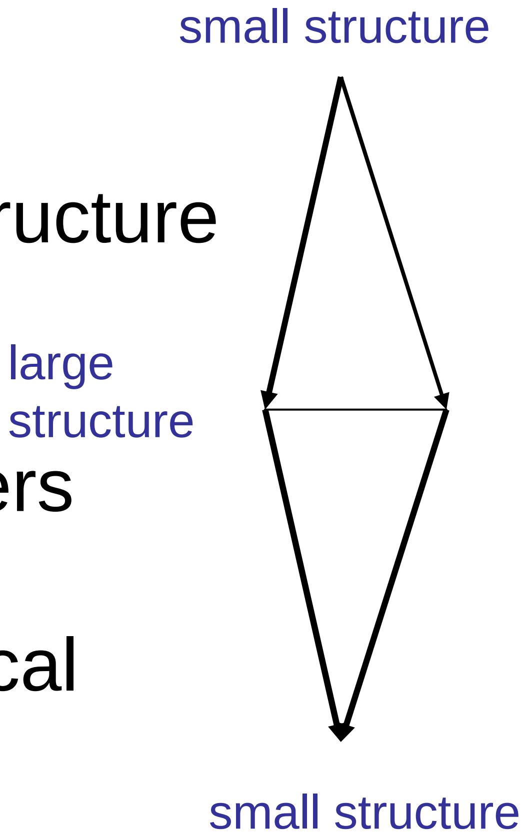
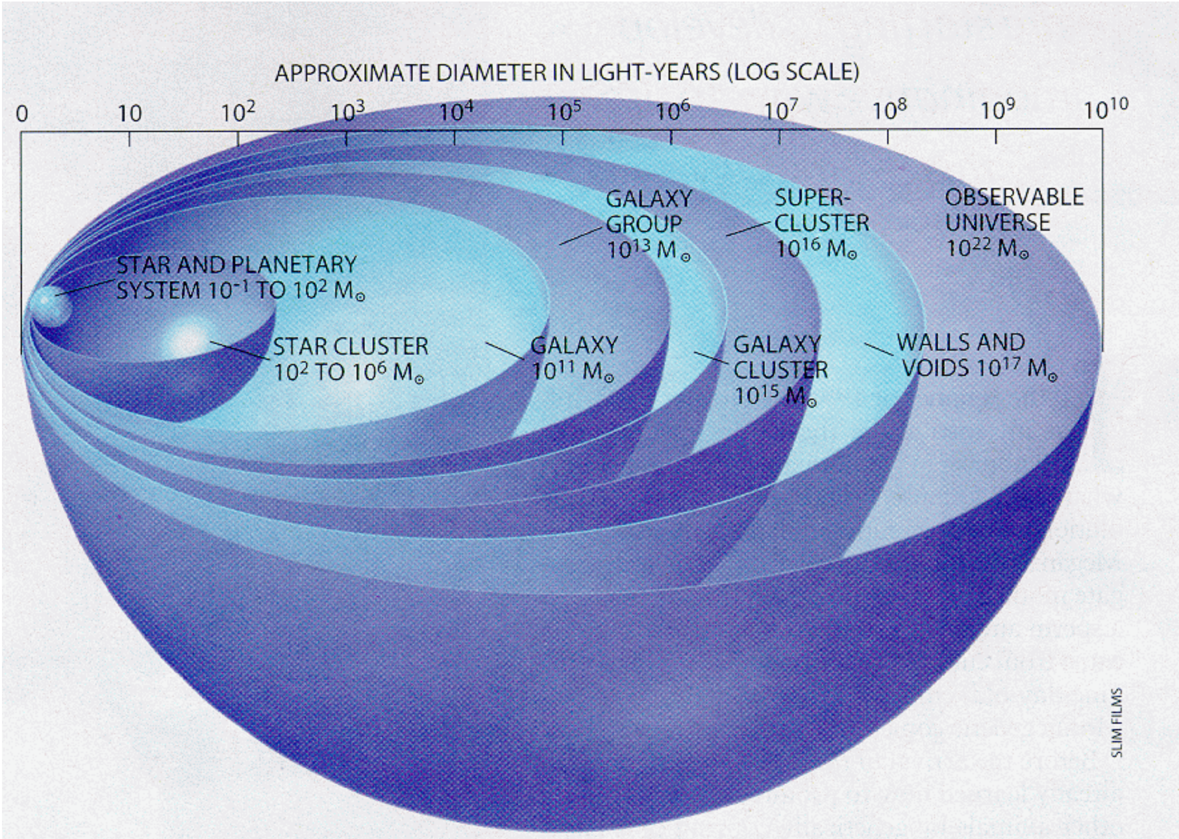
Outline

- some basics of astronomy
- galaxies, AGNs, and quasars
- from galaxies to the large scale structure of the universe
- the theory of cosmology
- measuring cosmological parameters
- structure formation
- galaxy formation in the cosmological framework
- open questions



The architecture of the universe

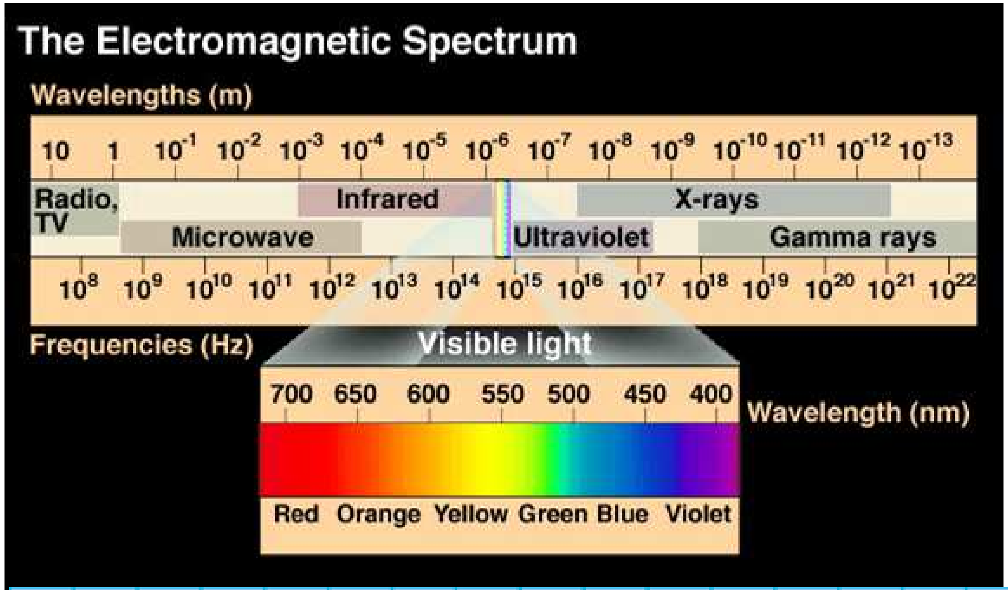
- Earth
  (~10^{-9} ly)
- solar system
  (~6 10^{-4} ly)
- nearby stars
  (> 5 ly)
- Milky Way
  (~6 10^{4} ly)
- Galaxies
  (>2 10^{6} ly)
- large scale structure
  (> 50 10^{6} ly)



HIERARCHY OF COSMIC STRUCTURES ranges from stars and planets to the universe itself. The largest objects held together by gravity are galaxy clusters with masses up to 10^{15} times that of the sun (denoted as $M_\odot$). Although there is a higher level of organization consisting of superclusters and great walls, these patterns are not bound gravitationally. On even larger scales, the universe is featureless. Astronomers think most of these structures form from the progressive agglomeration of smaller units.

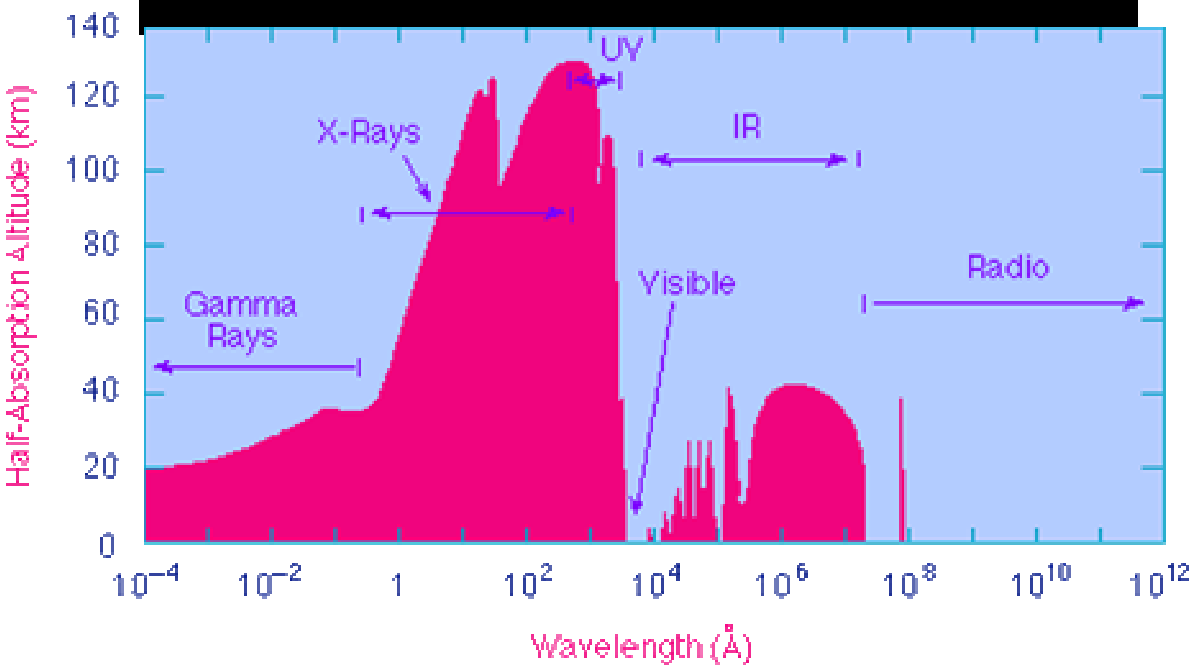
How can we investigate the universe

Astronomical objects emit elctromagnetic waves which we can use to study them.



BUT

The earth’s atmosphere blocks a part of the electromagnetic spectrum.

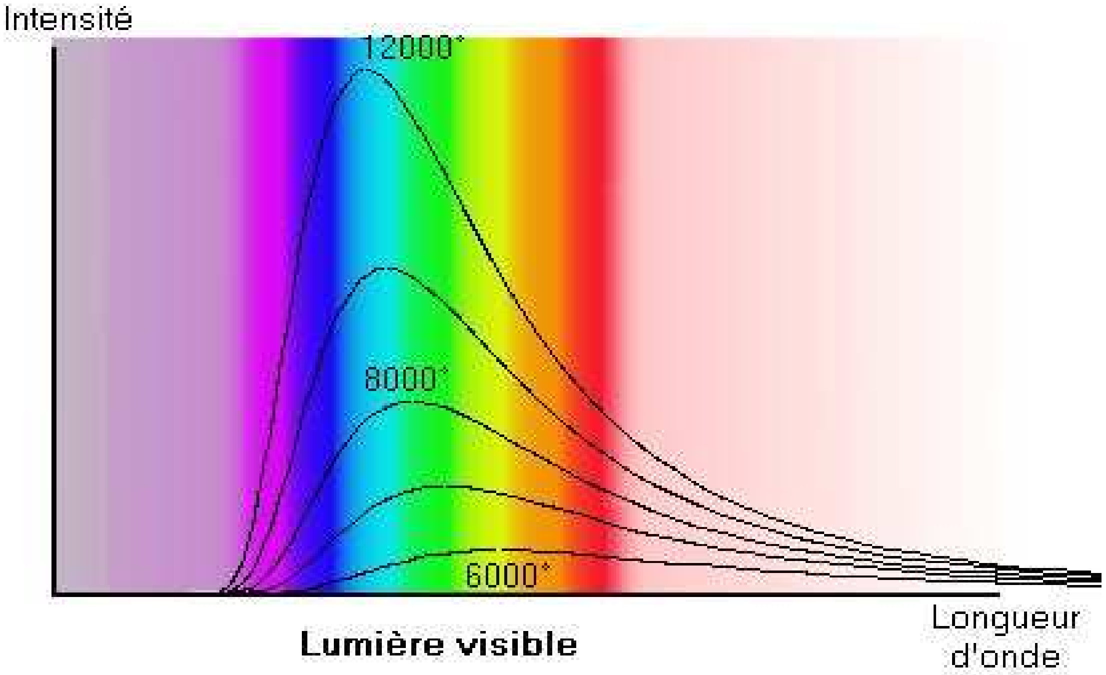


→

need for satellites

Back body radiation

- Opaque isolated body at a constant temperature



Wien's law:

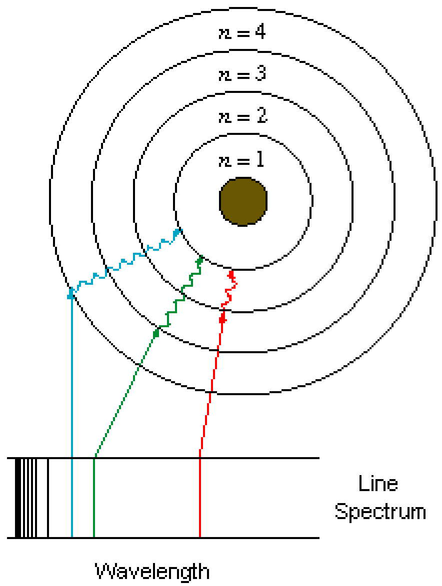
$$\lambda_{max} \times T = 2900 \quad \mu m\ K$$

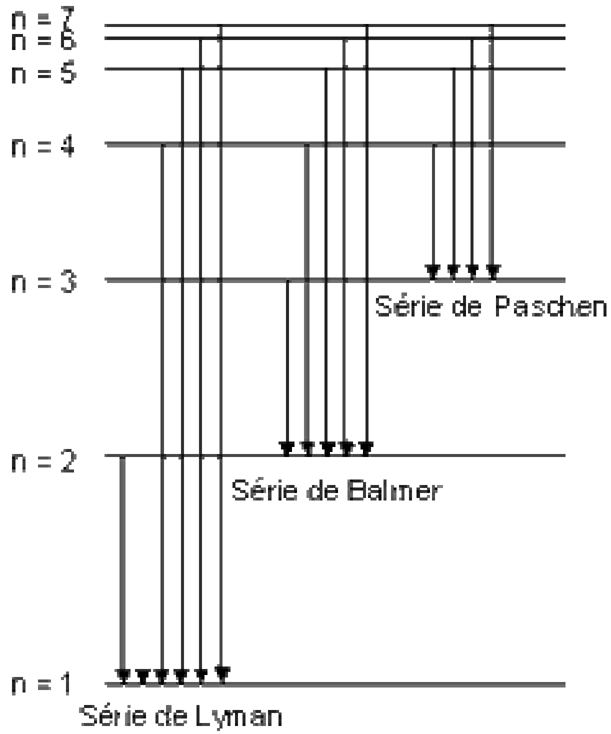
sun/star (5500 K):	0.5 μm	visible
human being (310 K):	9 μm	infrared
molecular cloud (15 K):	200 μm	radio

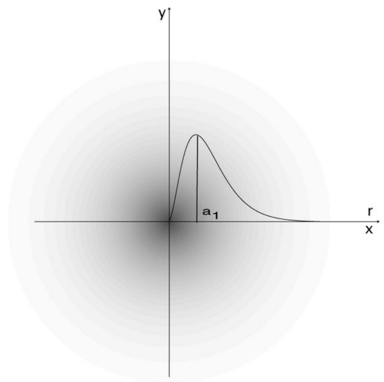
The structure of an atom

Components: nucleus (protons, neutrons) + electrons

Bohr's model: the electrons orbit around the nucleus,
the orbits are discrete



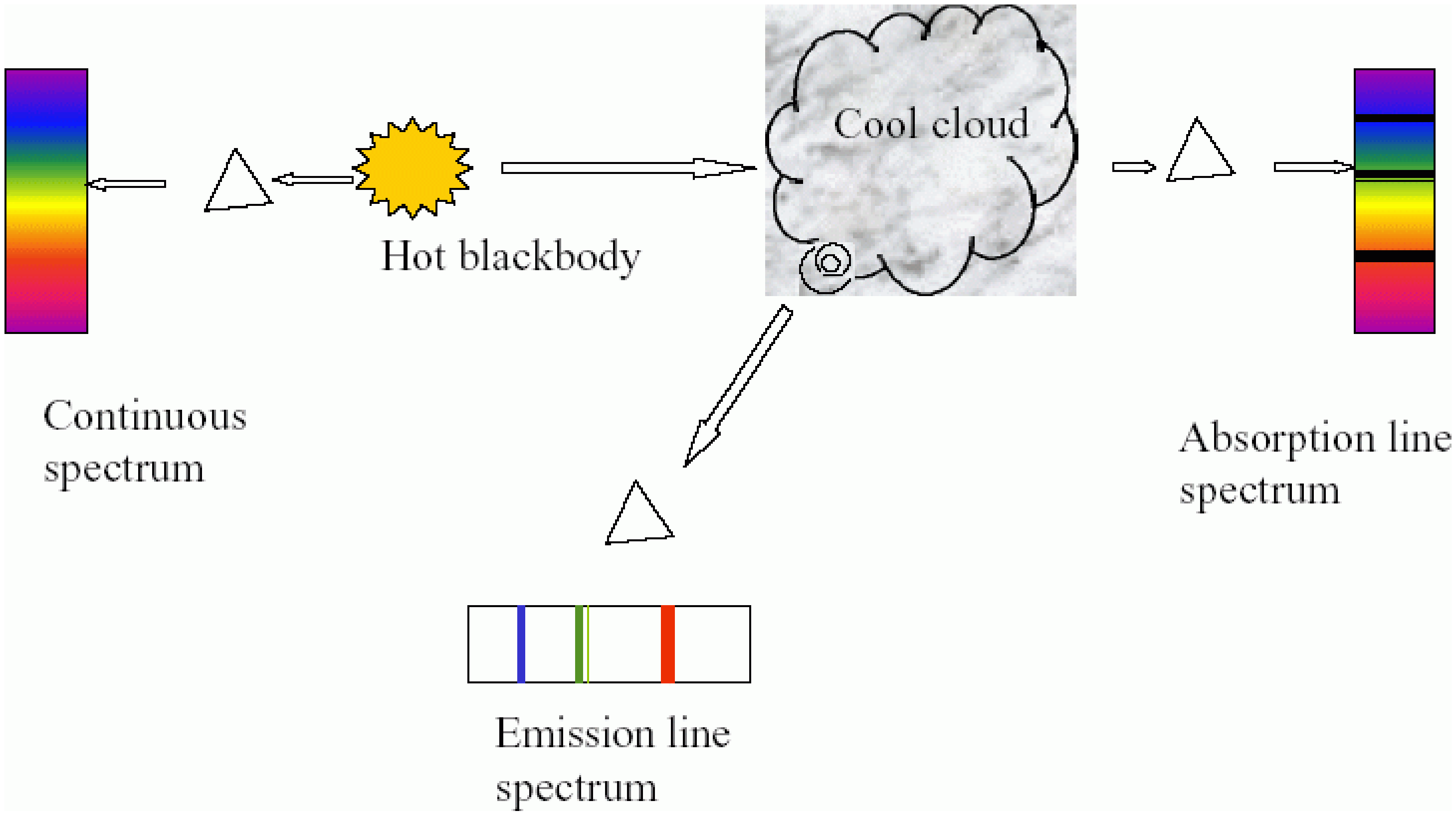




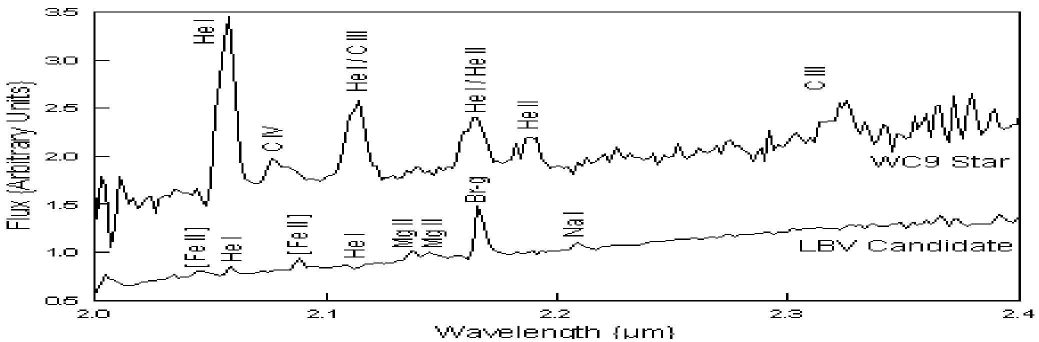
Bohr's model is too simplistic

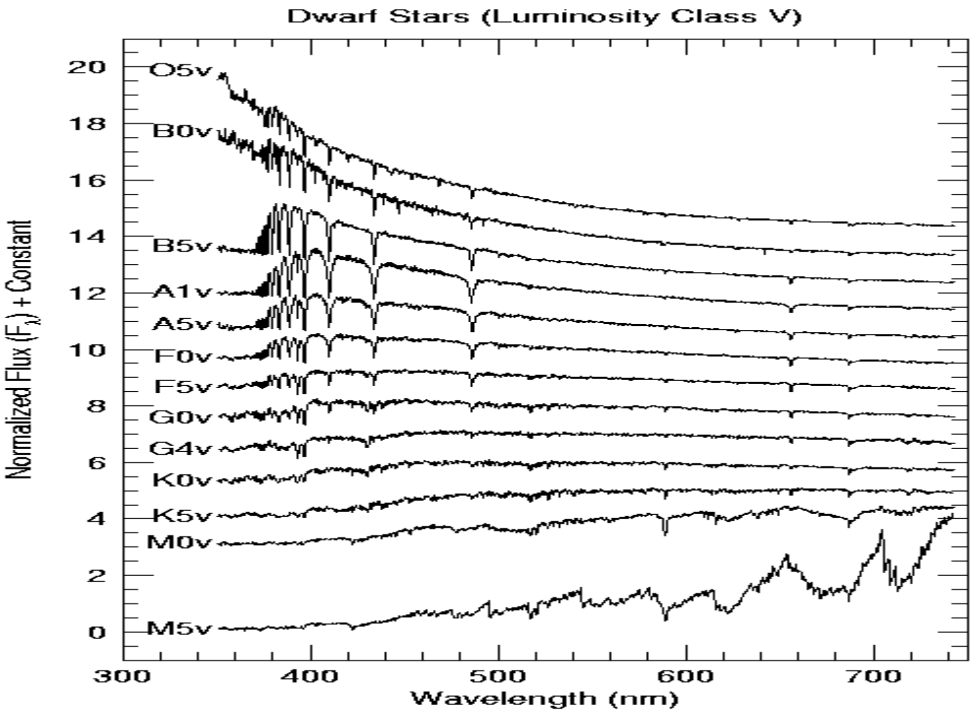
→ *quantum mechanical description*

The emission of an astronomical object has 2 components:
(i) continuum emission + (ii) line emission



Stellar spectra

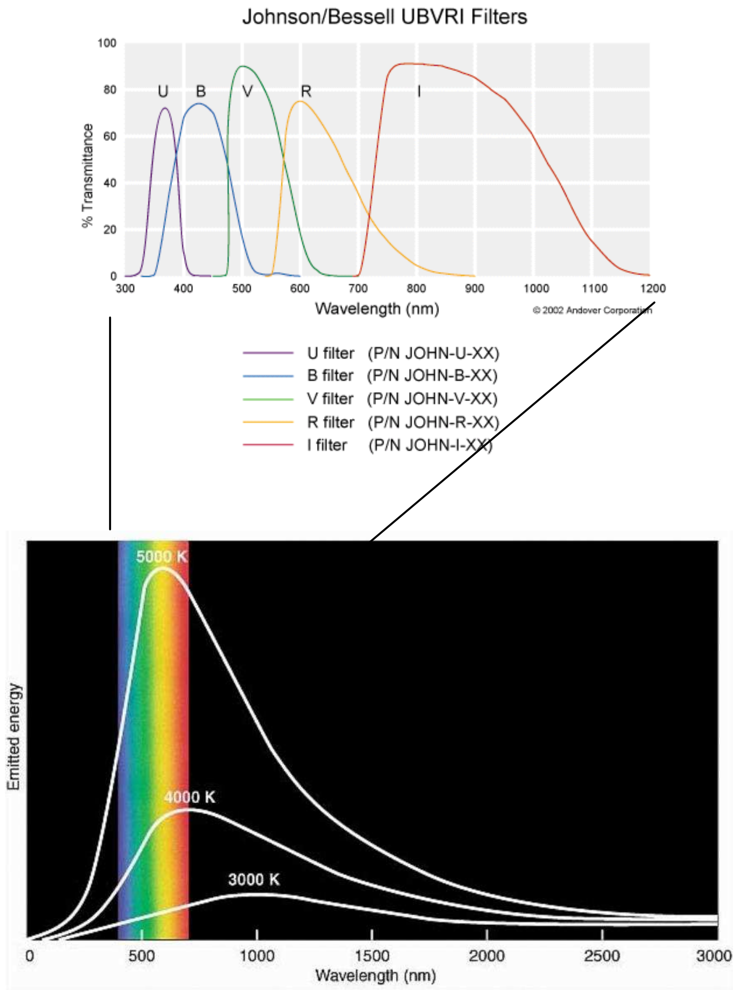




Observing in colors

Usage of filters (Johnson):

U (UV), B (blue), V (visible), R (red), I (infrared)

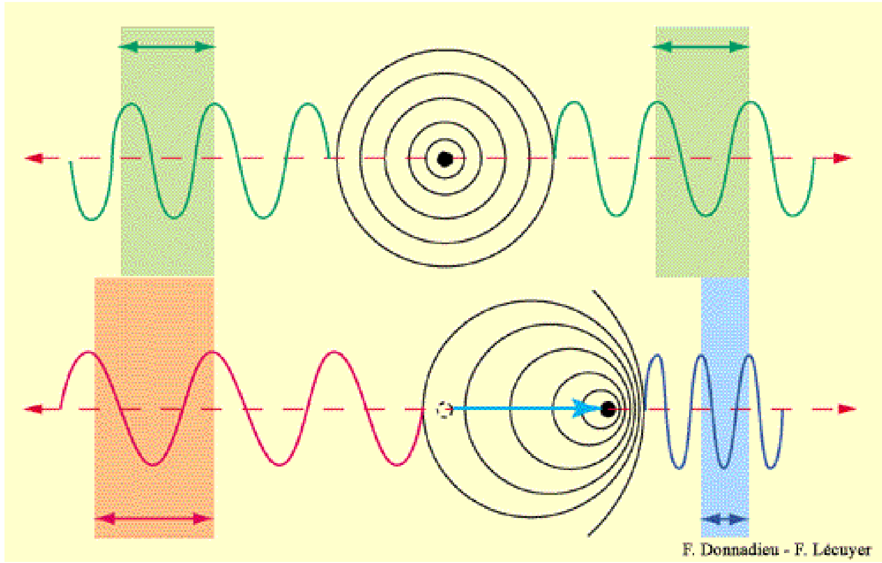


The Doppler effect

- Is the apparent change in frequency and wavelength of a wave which is emitted by a source moving relative to the observer
- For electromagnetic waves:

approaching source: blueshifted emission

receding source: redshifted emission

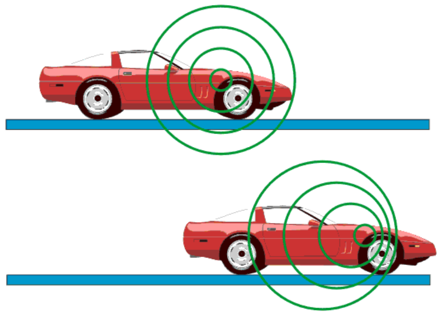


$v/c = \Delta\lambda/\lambda$

λ: wavelength

c: velocity of light

v: velocity of the sourve



The Milky Way galaxy

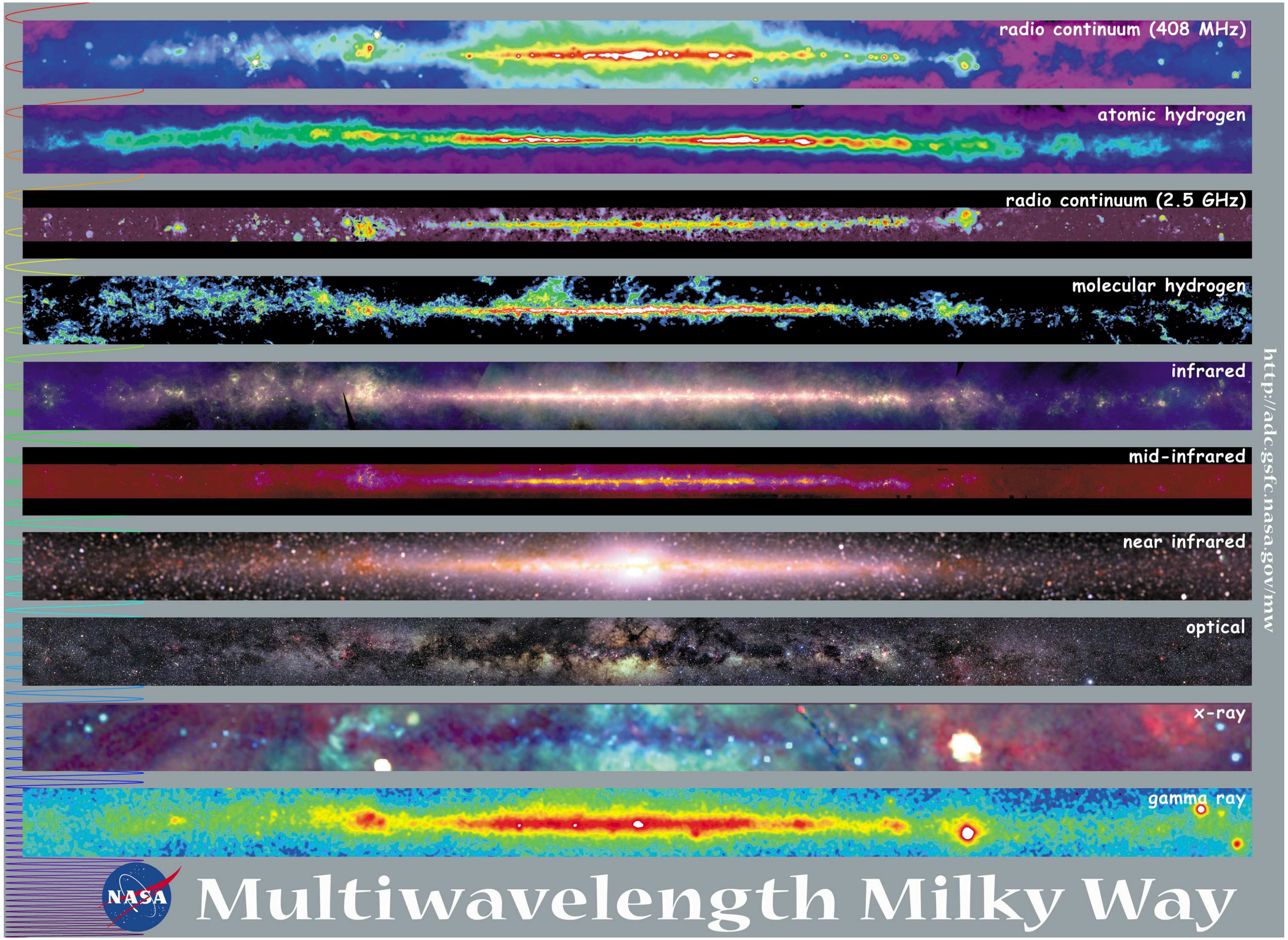
- ~10^{11} stars: halo + bulge + disk

- diameter: ~10^5 ly
- disk rotation velocity: 200 km/s
- Interstellar matter (ionized, atomic, and molecular): several 10^9 solar masses
- dark matter

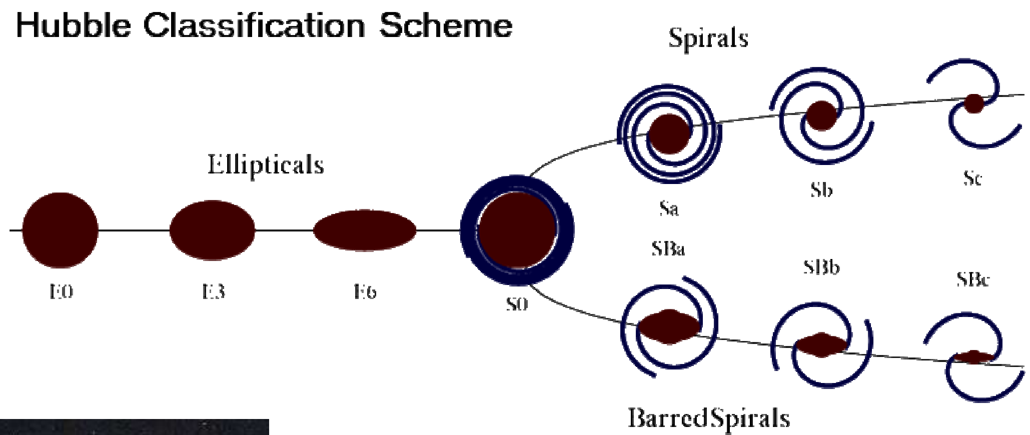
The Milky Way at different wavelengths

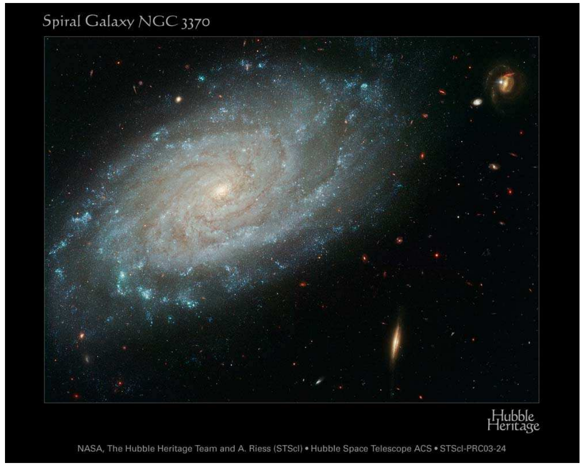
line

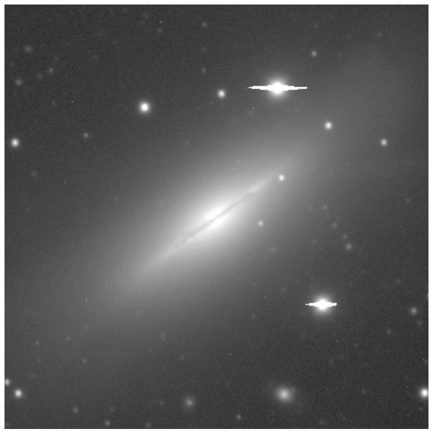
line

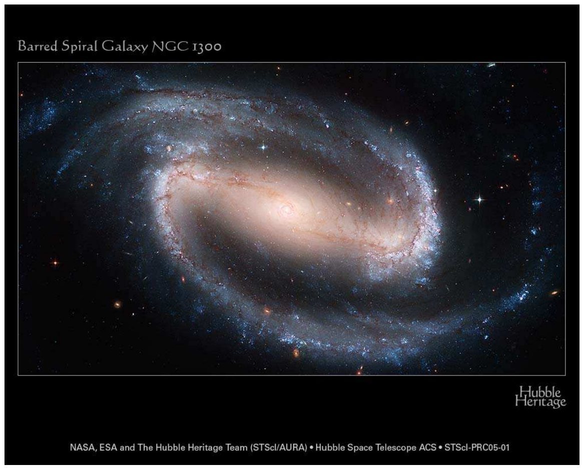


The Hubble sequence





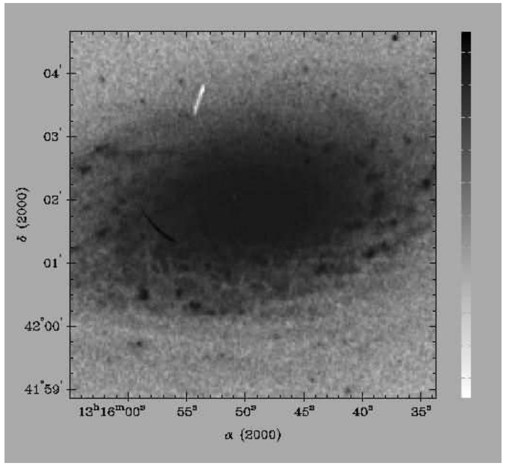




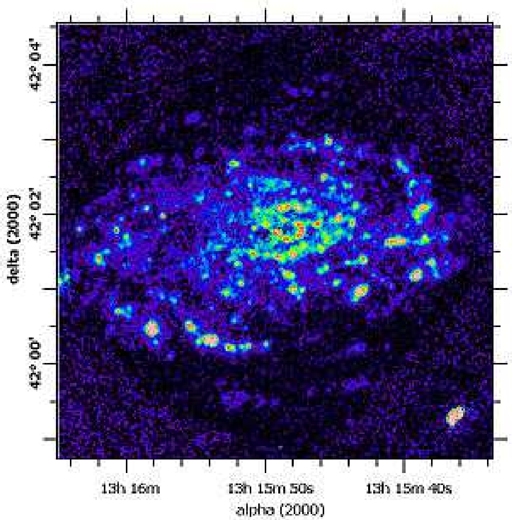
Galaxy dynamics

- Observations of the interstellar gas: optical lines (Hα) or radio lines (mm: CO, cm: HI)
- Doppler effect

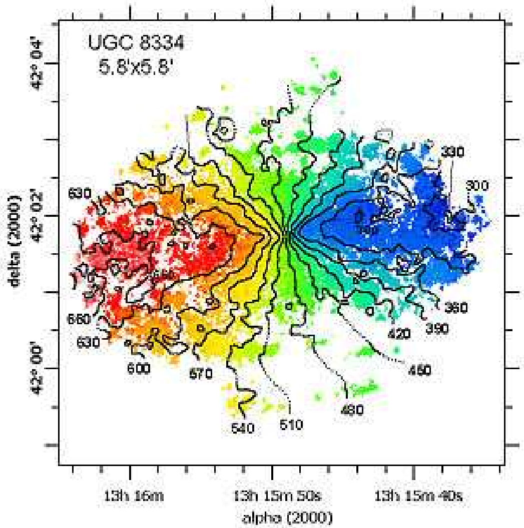
Example: M63



Optical image



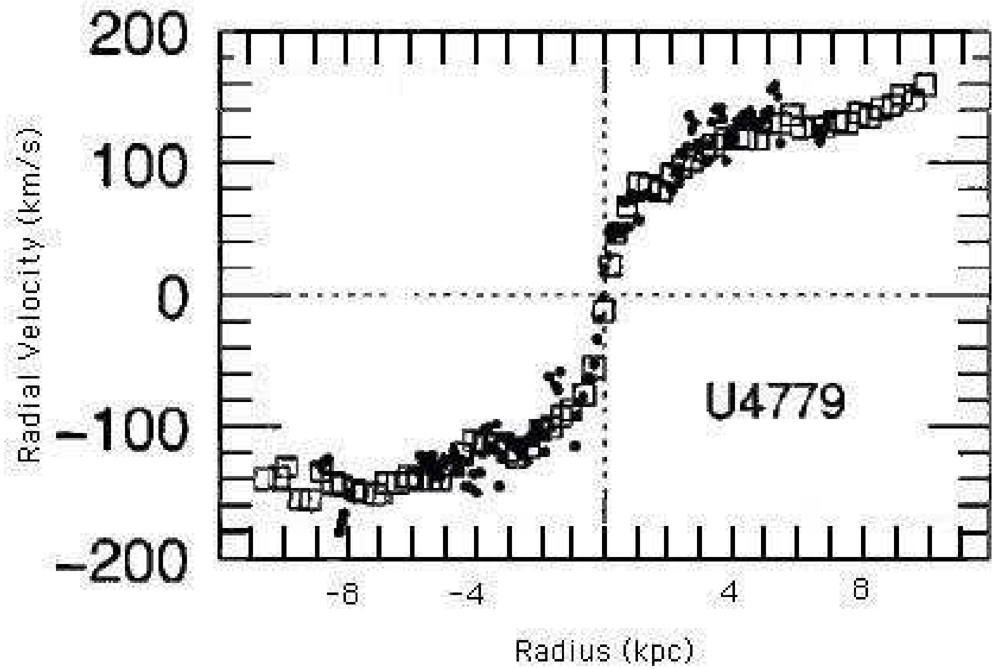
Hα image



Hα velocity field

The rotation curve

- Extraction of the radial velocities as a function of galactic radius
- Correction for the galaxy's inclination with respect to the image plane



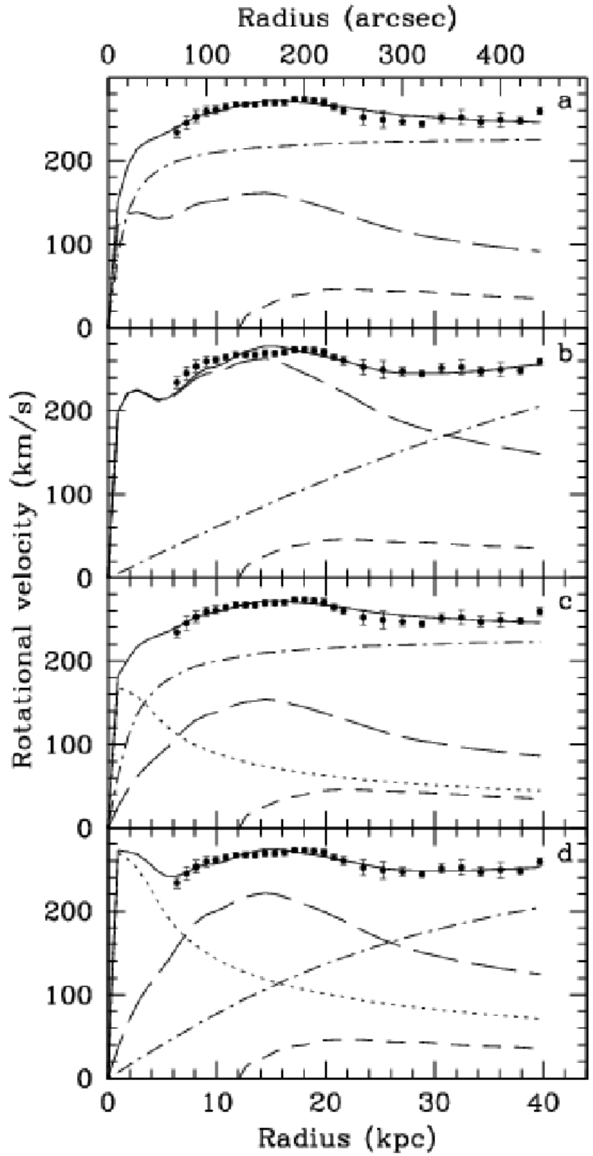
Decomposition of the rotation curve

- $mMv^2/R=mMG/R^2$ -> $v^2=MG/R$

  m: mass of a star, M: mass included within the radius R, v: rotation velocity, G: constant of gravitation, R: galactic radius
- mass components: bulge (…), disc (- - -), gas (-- -- --), dark matter (_._._.)
- mass to light ratio (M/L) for the stars

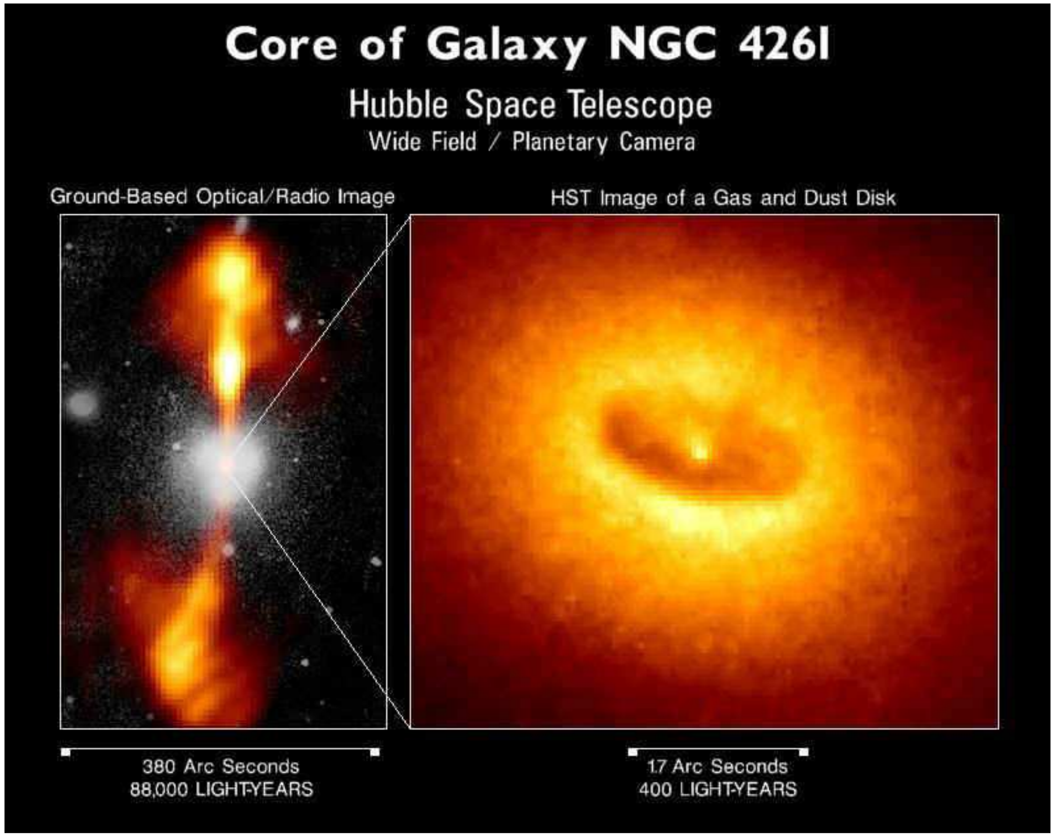
⟶ M/L >1 or the need for dark matter

Typically M/L~10



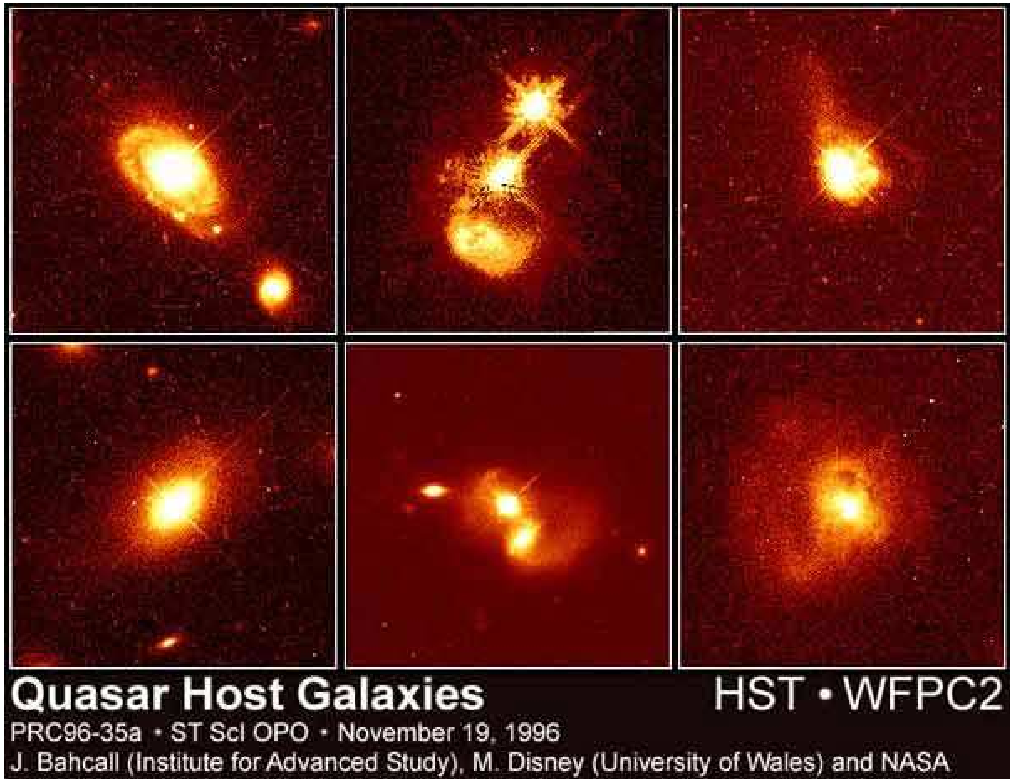
Galaxies with active galactic nuclei (AGN)

- Galaxies whose nucleus is brighter than the whole stellar disk
- Energy source: gravitation (black hole)



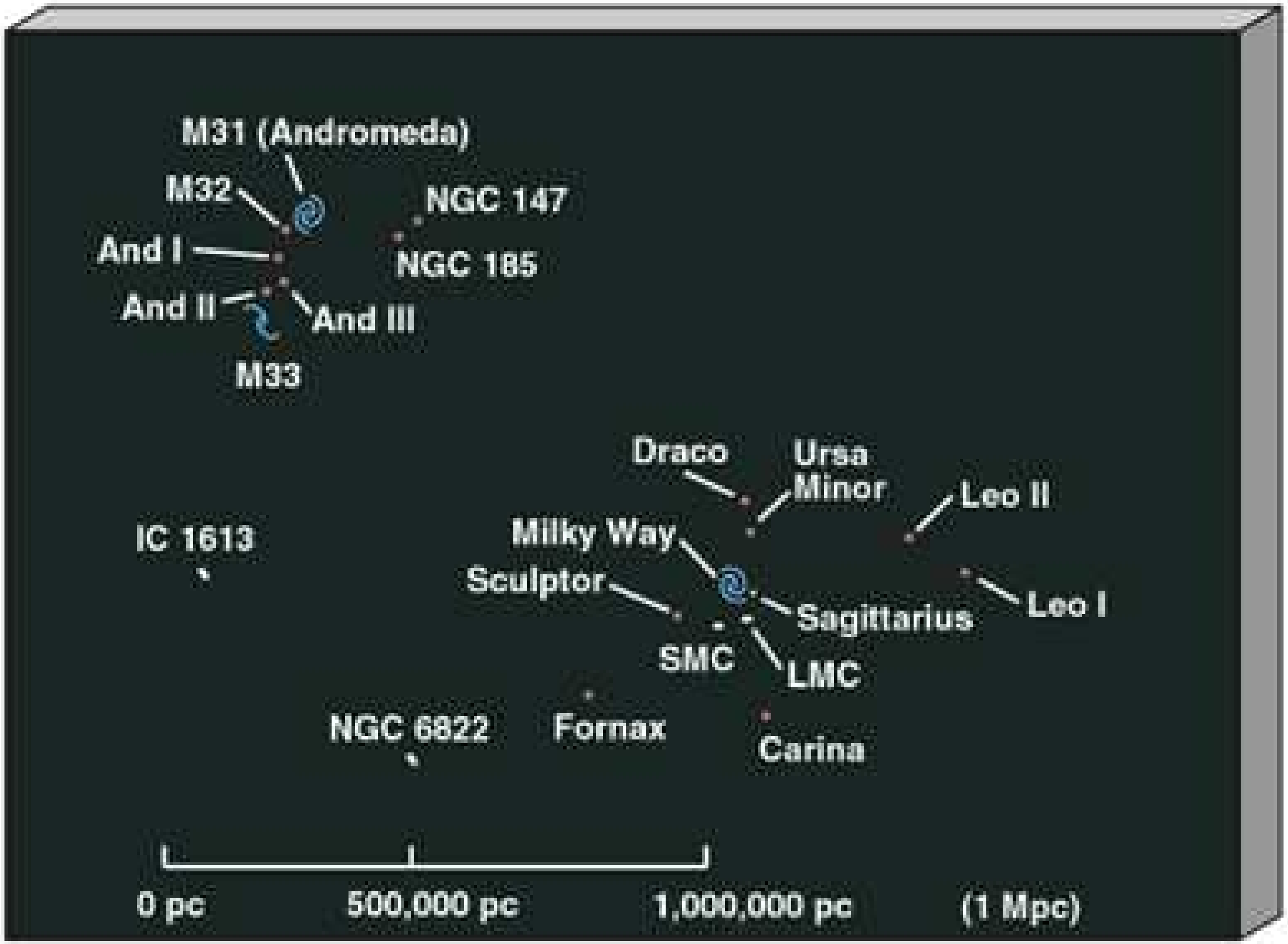
Quasars

- « Quasi stellar objects »
  small compact objects
- very distant sources:
  « light from the edge of the universe »
- Class of AGNs
- Objects with the highest known luminosities



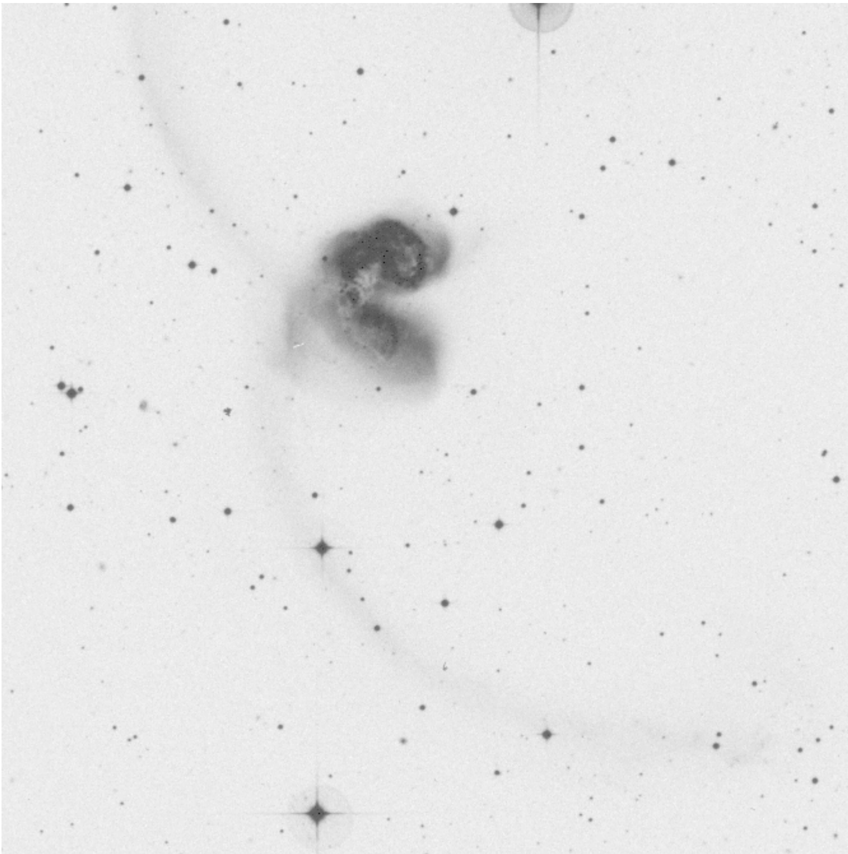
The local group

M/L ~100

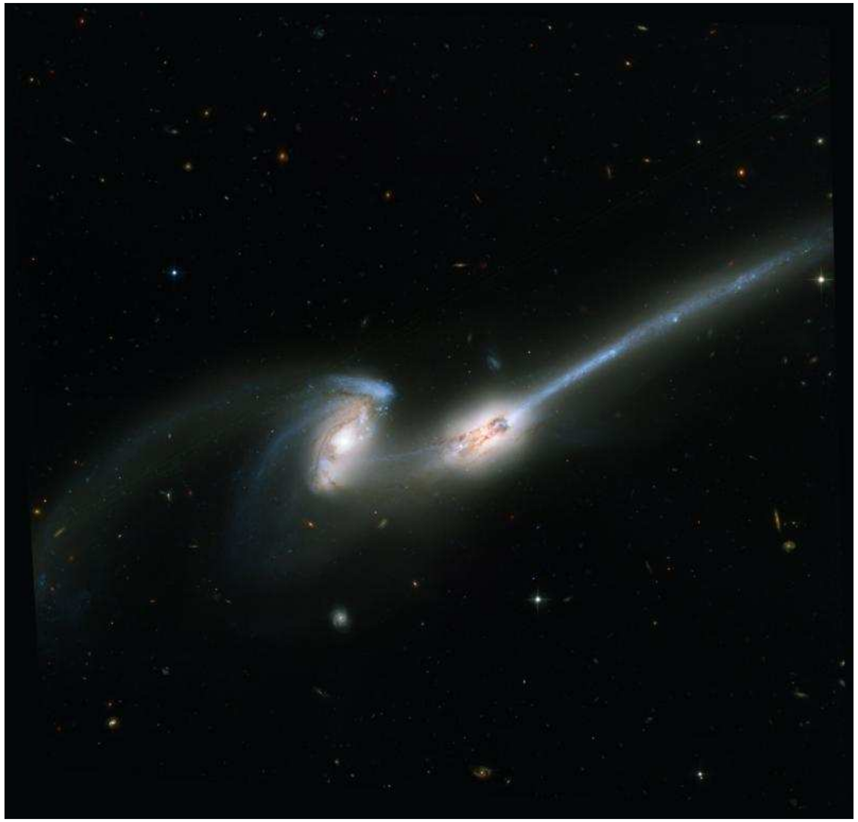


1 pc (parsec) ~ 3 ly

Galaxy evolution via gravitational interactions



The antenna galaxies

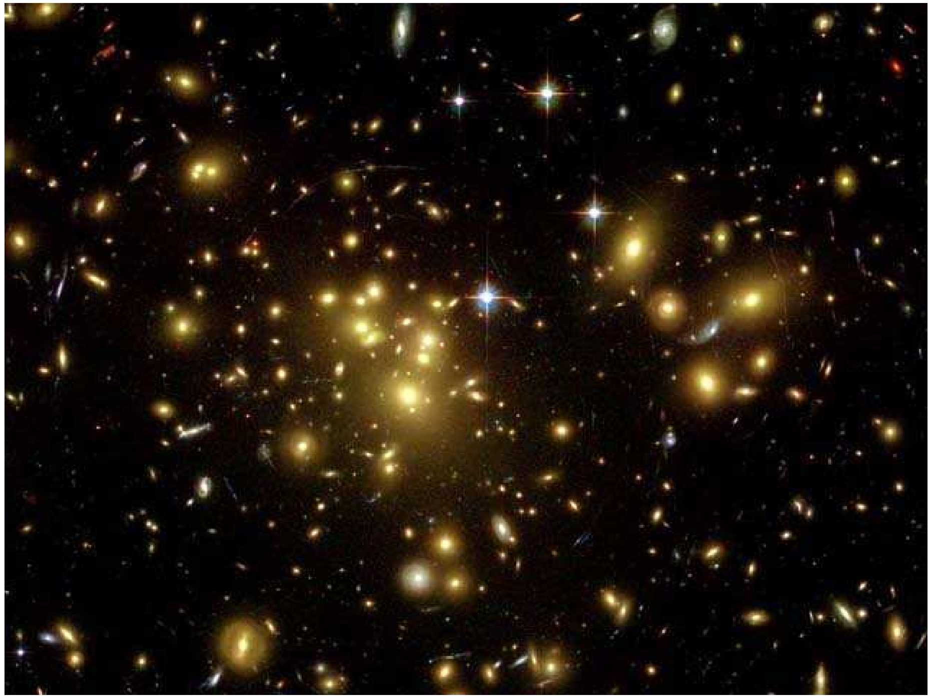


The mice

Galaxy clusters

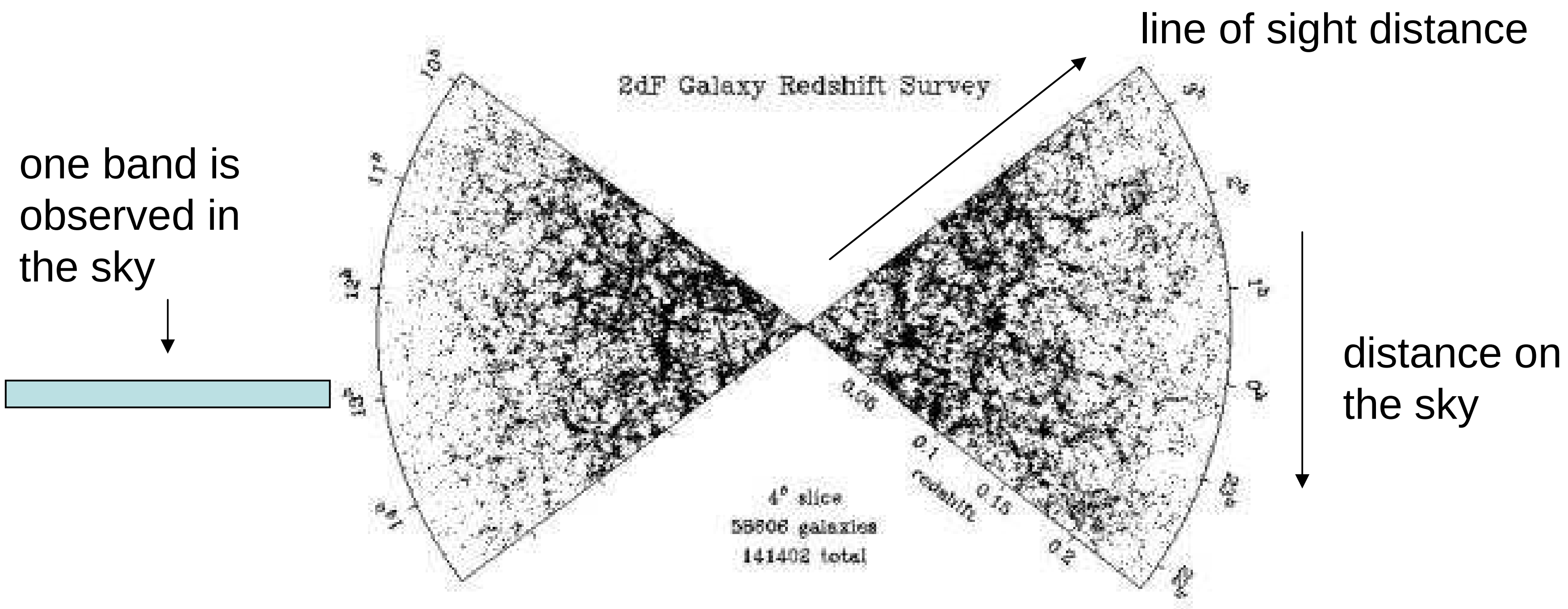
- dimension: ~10 Mly
- more than 100 galaxies
- closest galaxy cluster in the northern hemisphere: Virgo cluster (distance: ~50 Mly)
- determination of M/L: velocity dispersion, X-rays from hot gas + hydrostatic equilibrium + gravitational lenses
- typically: M/L~300

Abell 1689



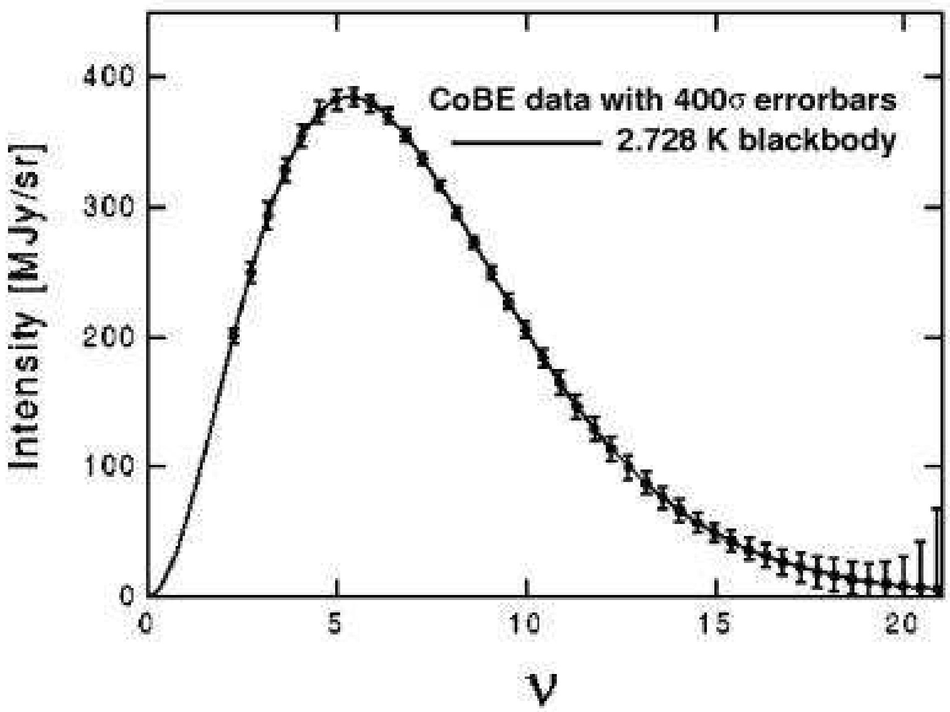
Large scale distribution of galaxys

- distances > 10 Mly
- picture: large scale distribution has a foam or a web structure

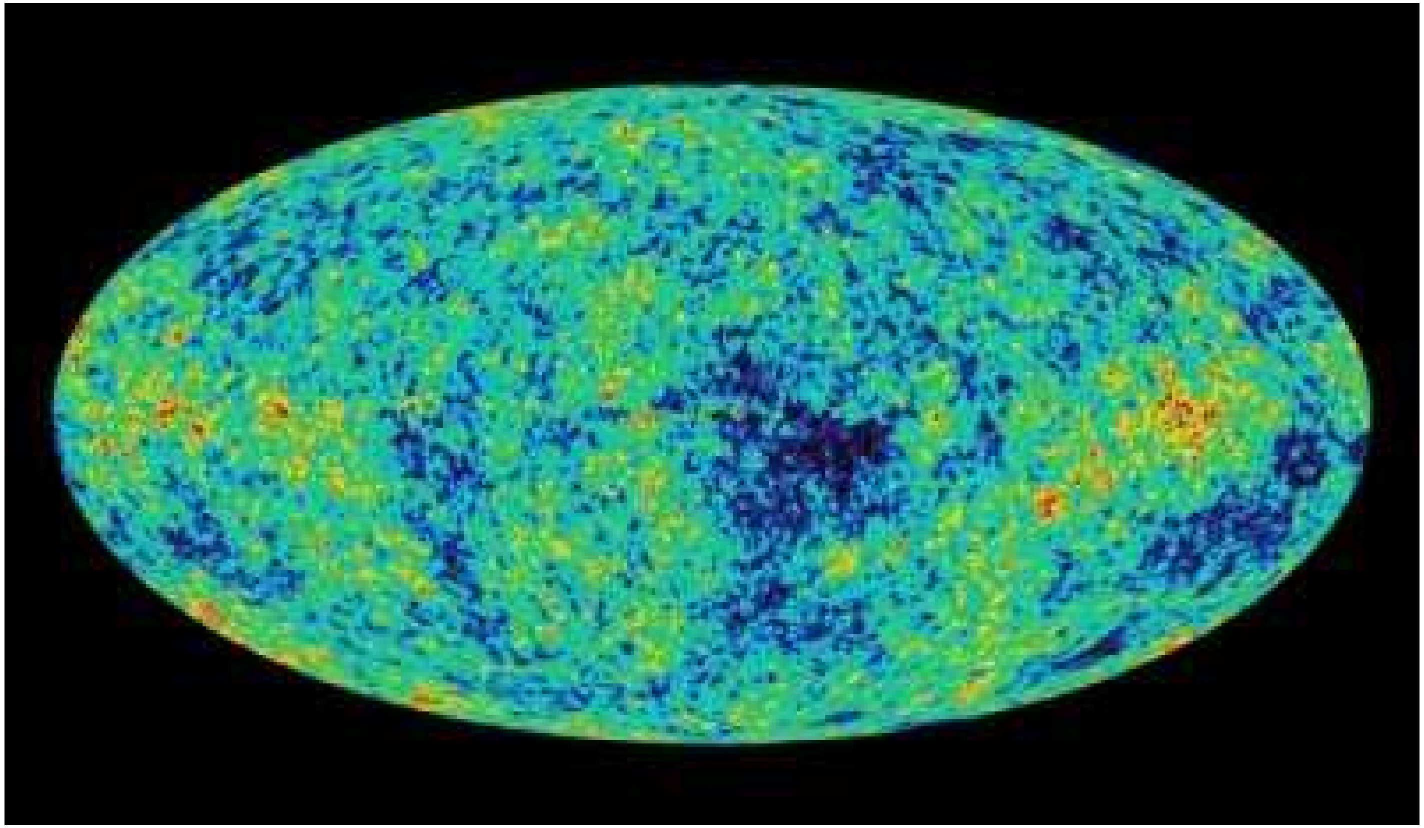


The cosmic microwave background

- 1965: A. Penzias and A.W. Wilson observed an excess emission in the radio independent of position ⟶ Nobel prize (1978)
- Perfect Black Body radiation
- Temperature T= 2.725 K



The 2D distribution of the CMB



WMAP CMB map
Note: the galactic foreground emission had to be removed

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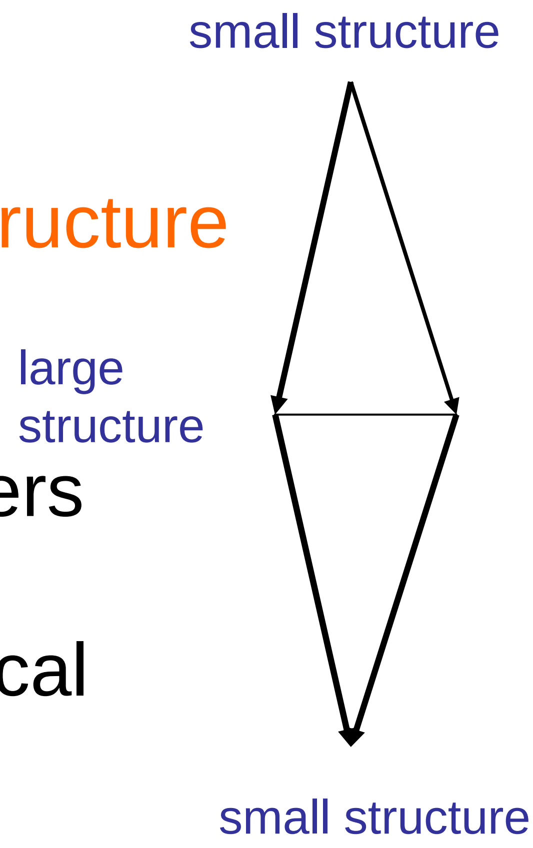


The basis of cosmology

ingredients:

(i) theory of gravitation (general relativity)

(ii) postulats giving rise to a relation between the topology of the universe and its energy-matter content

(iii) cosmological principles

restricted relativity: 4D space-time

distance between two events at (t,x,y,z) and (t+dt, x+dx,y+dy,z+dz):

$$ds^2=c^2dt^2-(dx^2+dy^2+dz^2)$$

which is invariant with respect to coordinate transformations

path of a photon ds=0

without external forces (e.g. gravitation) particle follow a straight line

general relativity:

gravitation is no longer a force, but a property of space-time, which is not necessarily flat, but can have a curvature caused by gravitation

$$ds^2=g_{ij}\, dx^i\, dx^j$$ where g_{ij} is the metric tensor

additional postulats:

1. relation between matter-density and metric
2. energy-momentum tensor T_{ij} only contains first derivations of g_{ij}
3. covariant derivation of T_{ij} is zero

formal

4. at the limit of weak gravitation $\Delta\Phi=4\pi G\rho$ (Poisson's law)

$\longrightarrow$ Einstein's equation

Cosmological principle

1.) there is a universal time such that $ds^2 = c^2dt^2 - dl^2$
2.) the spatial component of the universe is homogenuous and isotropic

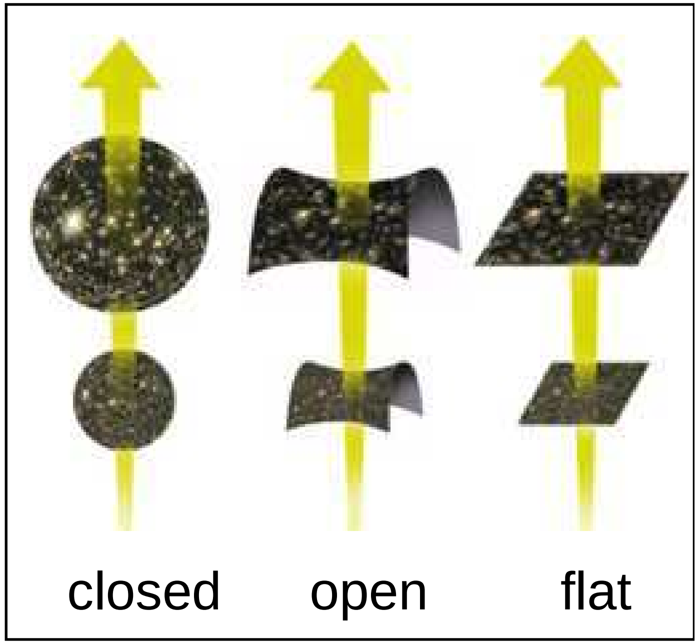
$dl^2 = B(r,t)dx^2$ where $B(r,t) = R^2(t)F(r)$
$R(t)$ is a scale factor

most general expression for $F(r)$:

$$F(r)^2 = \frac{1}{(1+\frac{k}{4}r^2)^2} \;;\quad k = -1, 0, 1$$

$\rightarrow$ Robertson-Walker metric

k=0: flat univers (euklidian);
k=-1: open universe;
k=1 closed universe



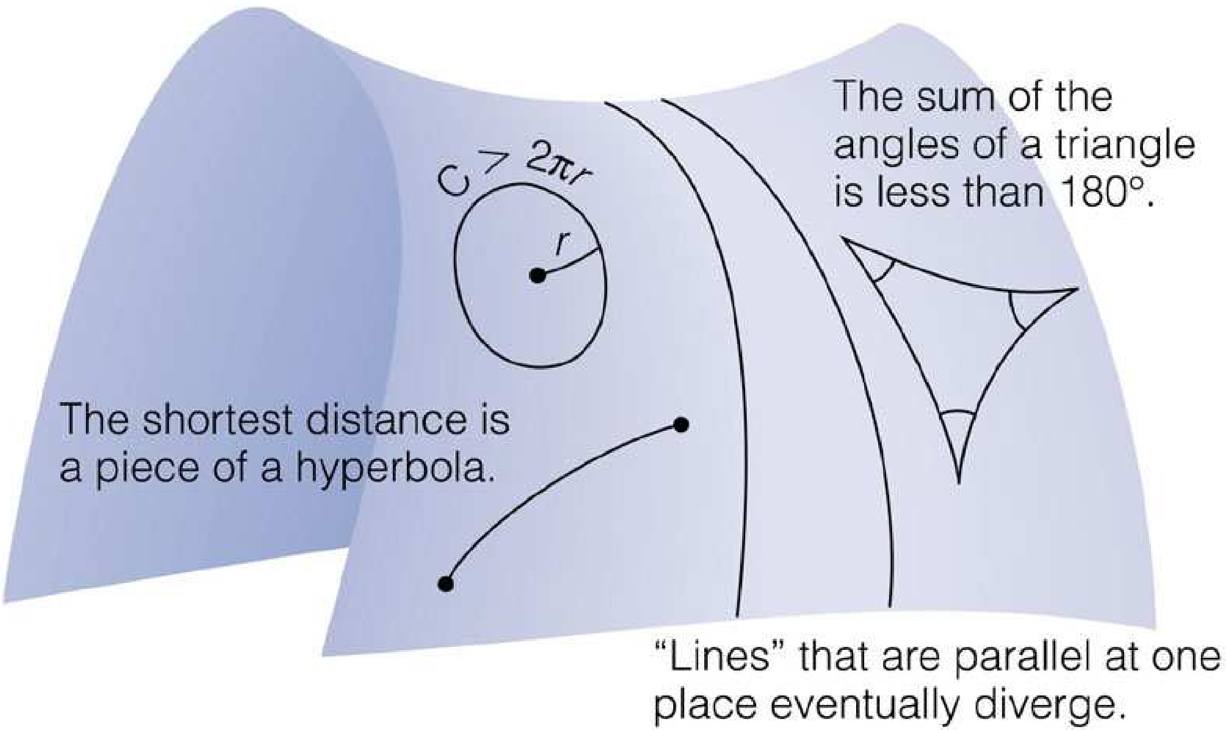
volume:

$$V_{k=0} = \frac{4}{3}\pi(Rr)^3$$

$$V_{k=1} \neq V_{k=0}$$

The Pythagorean theorem ($c^2 = a^2 + b^2$) is only valid for k=0

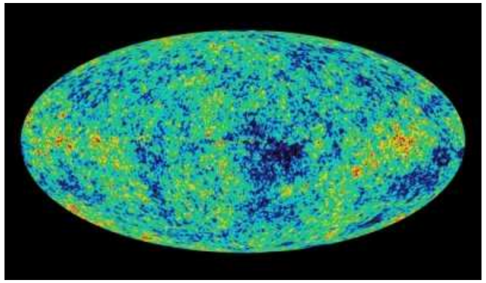
Example: the case of an open universe (k=-1)



Justification of the cosmological principle

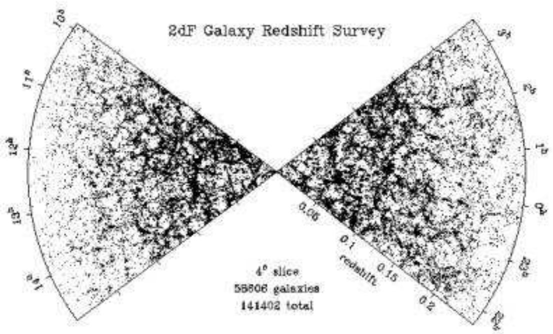
- Isotropy (structure is independent of direction):

  temperature variations in the cosmic microwave background (CMB):
  $\Delta T/T \sim 10^{-5}$



- Homogeneity (translational invariance in 4D):

  quasar distribution, galaxy distribution at distances > 600 Mly



Consequences of the cosmological principle

1.) **Hubble's law:**

let us define a proper distance: $d_{\rm pr} = \int c{\rm d}t = R(t)f(r)$
$\rightarrow$ proper distances change with time

radial velocity:

$$v_{\rm r} = \frac{{\rm d}(d_{\rm pr}(t))}{{\rm d}t} = H(t)d_{\rm pr}$$

this is Hubble's law where $H(t) = \frac{\dot{R}(t)}{R(t)}$ is the Hubble constant.
definition: $H_0 = H(t_0)$

2.) **redshift:**

$$z = \frac{\lambda_0 - \lambda_{\rm e}}{\lambda_{\rm e}}$$

from $ds^2 = 0 \quad \rightarrow \quad$ for two maxima of a wave:

$$\int_{t_{\rm e}}^{t_0} \frac{c{\rm d}t}{R(t)} = \int_{t_{\rm e}+\delta t_{\rm e}}^{t_0+\delta t_0} \frac{c{\rm d}t}{R(t)}$$

one can show that $\delta t_{\rm e}/R(t_{\rm e}) = \delta t_0/R(t_0)$; with $\delta t = \nu^{-1}$

$$z + 1 = R(t_0)/R(t)$$

in words: the redshift corresponds to the ratio of the scale factors

The deceleration parameter

Taylor expansion of $R(t)$:

$$R(t) = R(t_0) + (t - t_0)(\frac{\mathrm{d}R(t)}{\mathrm{d}t})_{t=t_0} + \frac{1}{2}(t - t_0)^2(\frac{\mathrm{d}^2R(t)}{\mathrm{d}t})_{t=t_0} + ... =$$

$$= R_0[1 + H_0(t - t_0) + \frac{1}{2}H_0^2 q_0(t - t_0)^2 + ...]$$

where $\boxed{q_0 = -(\ddot{R}(t_0)R(t_0))/\dot{R}(t_0)^2}$ is the deceleration parameter

Distances

- proper distance: $d_{\mathrm{pr}} = -c\mathrm{d}t = -c\mathrm{d}R/\dot{R}$
- comobile distance: $d_{\mathrm{com}} = -c\mathrm{d}t/R = -c\mathrm{d}R/(R\dot{R})$
- luminosity distance: $d_{\mathrm{L}} = L/(4\pi l)^{\frac{1}{2}}$
  where L is the absolute and l the apparent (measured) luminosity
- angular diameter distance: $d_{\mathrm{A}} = D/\Theta$
  where D is the intrinsic (proper) dimension and Θ the observed angular diameter

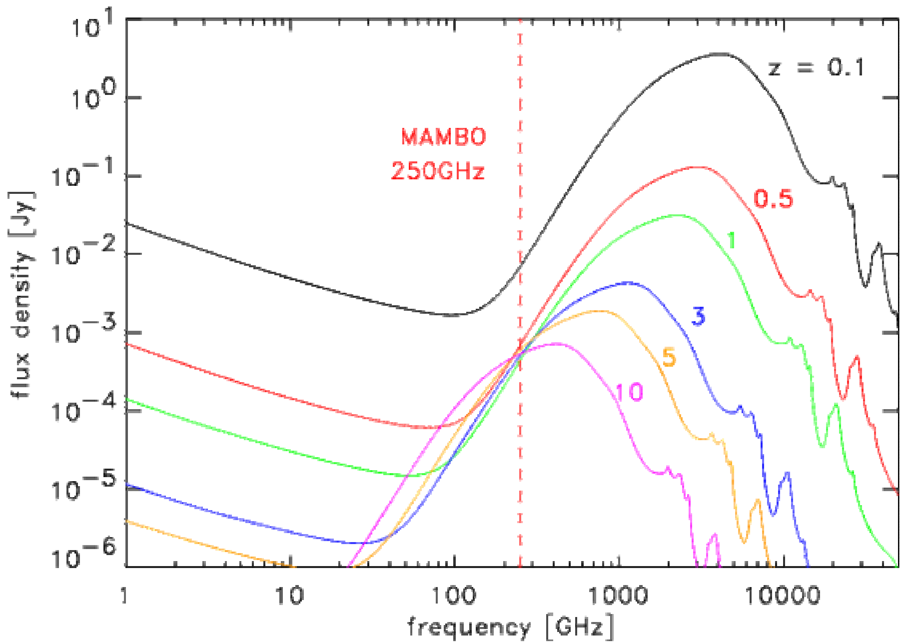
Cosmological dimming factor and K correction

- for resolved sources in the local universe: the surface brightness of a source is independent of distance

  for sources at cosmological distances: the observed surface brightness decreases with $(1+z)^{-4}$ cosmological dimming

- Flux of a galaxy at a redshift z:

  its spectrum is shifted and distorted (recall: observations ith filters)



Friedmann's model of the universe

Robertson-Walker metric + Einstein's equation

assume a perfect fluid:

$$\ddot{R} = -\frac{4\pi G}{3}(\rho + \frac{3P}{c^2})R$$

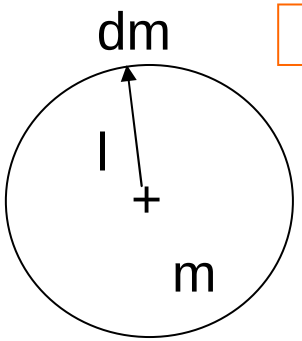
$$\boxed{\dot{R}^2 + kc^2 = \frac{8\pi G}{3}R^2\rho}$$

energy conservation:

$$\frac{\mathrm{d}}{\mathrm{d}R}[\rho c^2 R^3] + 3PR^2 = 0$$

now: assume an equation of state: $P = \omega\rho c^2; \quad 0 \le \omega \le 1$

- $\omega = 0$: "dusty" matter-dominated universe $\rho = \rho_0(1+z)^3$
- $\omega = \frac{1}{3}$: radiation dominated universe $\rho = \rho_0(1+z)^4$



Newtonian view:

consider a sphere of mass m and radius l; acceleration of a particle located at the edge of the sphere:

$$\frac{\mathrm{d}^2 l}{\mathrm{d}t^2} = -\frac{Gm}{l^2} = -\frac{G}{l^2}\frac{4}{3}\pi l^3\rho$$

assume a scaling law: $l/R = l_0/R_0 \rightarrow$

$$\boxed{\frac{1}{2}(\frac{l_0}{R_0}\dot{R})^2 = G\frac{4\pi}{3}\rho(\frac{l_0}{R_0}R)^2 + C}$$

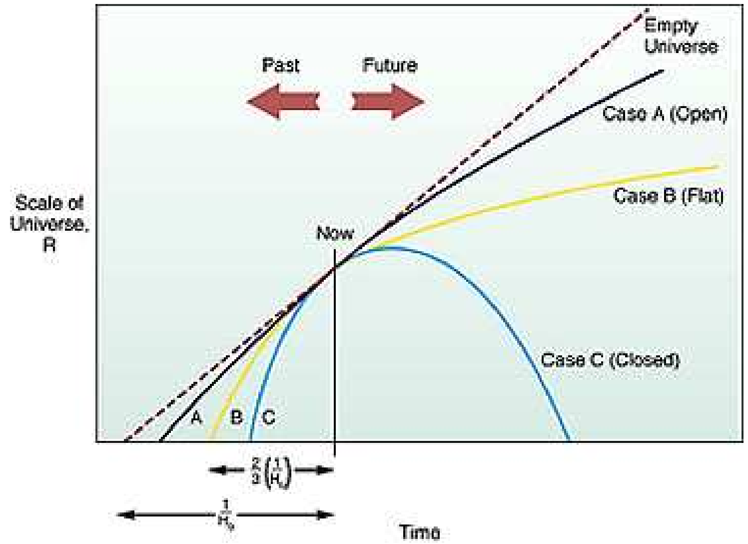
where $C = -K/s(\frac{l_0}{R_0}c)^2$ is proprtional to the total energy

- $K = 1 \rightarrow C < 0$ negative total energy $\rightarrow$ possible collapse
- $K = -1 \rightarrow C > 0$ positive total energy $\rightarrow$ ever lastingexpansion
- $K = 0 \rightarrow C = 0$ zero total energy $\rightarrow$ expansion at the escape velocity ($v = 0$ for $t \rightarrow \infty$)

The existance of a singularity: The Big Bang

- $d^2R(t)/dt < 0$
- $dR(t)/dt > 0$: expanding universe (observed)

→ R(t) is concave
curvature depends on the metric (via k)



singularity: $R(t) \rightarrow 0$ for $t \rightarrow 0$
where $\rho \rightarrow$ infinity → Big Bang
(due to initial conditions of an expanding homogenuous and isotropic universe)

The critical density of the universe

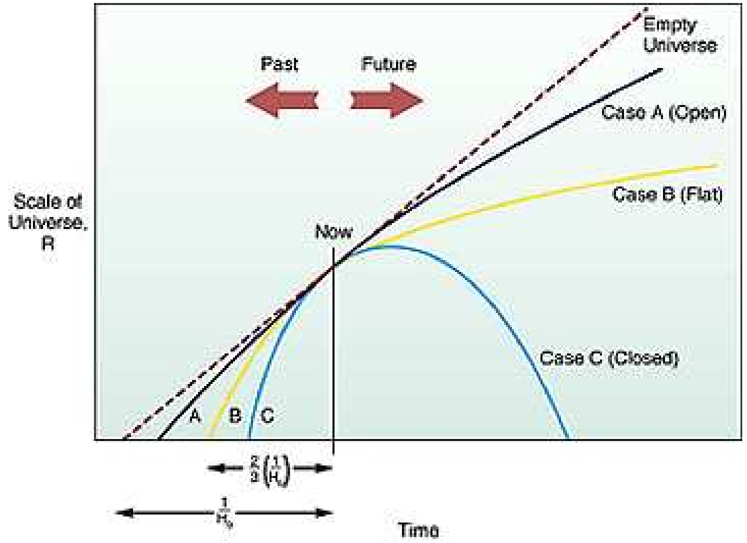
define a critical density: $\rho_{0c} = \frac{3H_0}{8\pi G}$

define $\Omega = \rho_0/\rho_{0c}$

one can show that

$$H_0^2(1-\Omega_0) = -\frac{kc^2}{R_0^2}$$

if $\Omega_0 = 1 \rightarrow k = 0$ (flat euklidian universe)



the curvature of the universe depends on its energy-matter content

The Einstein-de Sitter universe

$\Omega = 1$; $\omega = 0$: flat matter-dominated universe

- $\rho(t) = \frac{1}{6\pi G t^2}$
- $R(t) = R_0(\frac{t}{t_0})^{\frac{2}{3}}$
- $t = t_0(1+z)^{-\frac{3}{2}}$
- $H = \frac{2}{3t} = H_0(1+z)^{\frac{3}{2}}$
- $q_0 = \frac{1}{2}$
- $t_0 = \frac{2}{3H_0}$

The cosmological constant

A. Einstein wanted a stionnary universe
most general form of Friedmann's equations:

$$\ddot{R} = -\frac{4\pi G}{3}(\rho + \frac{3P}{c^2})R + \frac{\Lambda}{3}R$$

$$\dot{R}^2 + kc^2 = \frac{8\pi G}{3}\rho R^2 + \frac{\Lambda}{3}R^2$$

let us define

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

for $\Omega_\Lambda = 1 \longrightarrow$ length scale $L = \Lambda^{-\frac{1}{2}} \sim 5Gly$.
let us define: $\Omega_k = 1 - \Omega_{\rm m} - \Omega_\Lambda$ where $\Omega_{\rm m}$ corresponds to the former Ω_0

effect of the cosmological constant:
additional driving of expansion « dark energy »

The age and size of the Universe

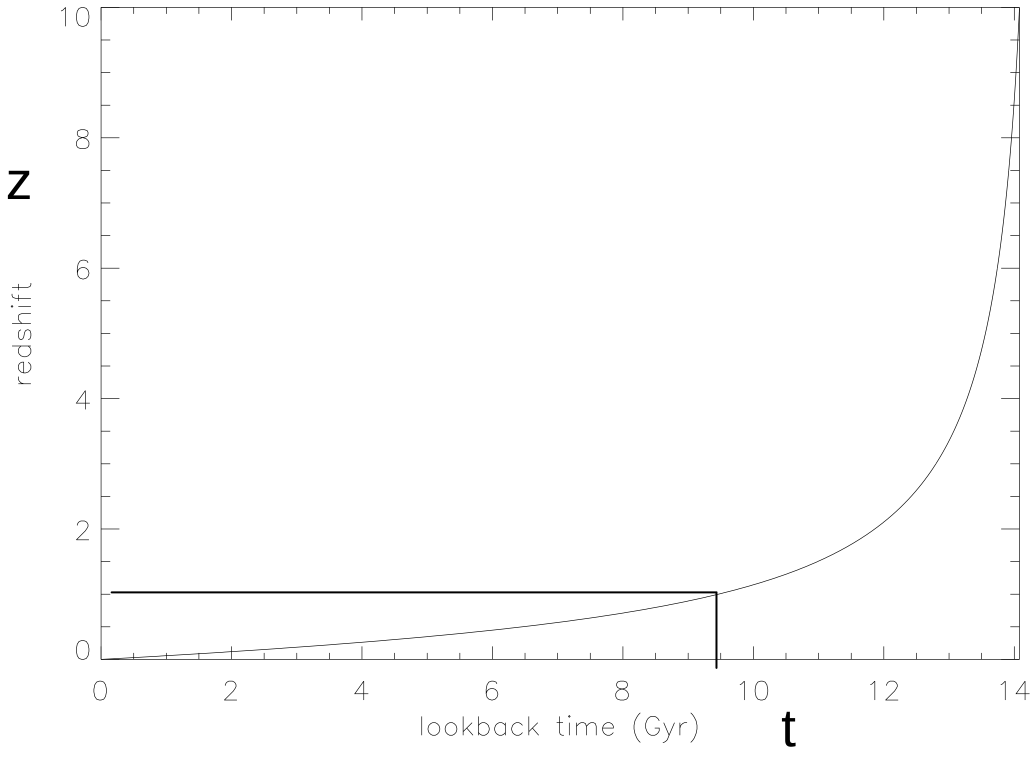
size: maximum distance that a photon can travel

for the Einstein - de Sitter universe:

- age: $t_0 = \frac{2}{3H_0}$,
- size: $d_{\rm H}(t) = 3ct$

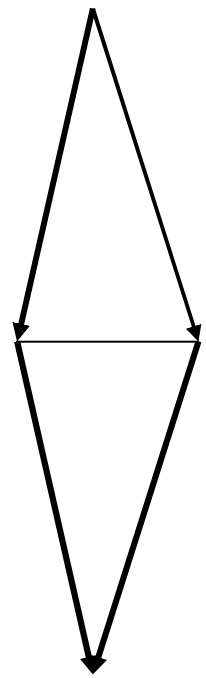
Redshift versus lookback time

- depends on cosmology
- at z=1 the age of the universe is less than half of its present age



Outline

- some basics of astronomy
- galaxies, AGNs, and quasars
- from galaxies to the large scale structure of the universe
- the theory of cosmology
- measuring cosmological parameters
- structure formation
- galaxy formation in the cosmological framework
- open questions



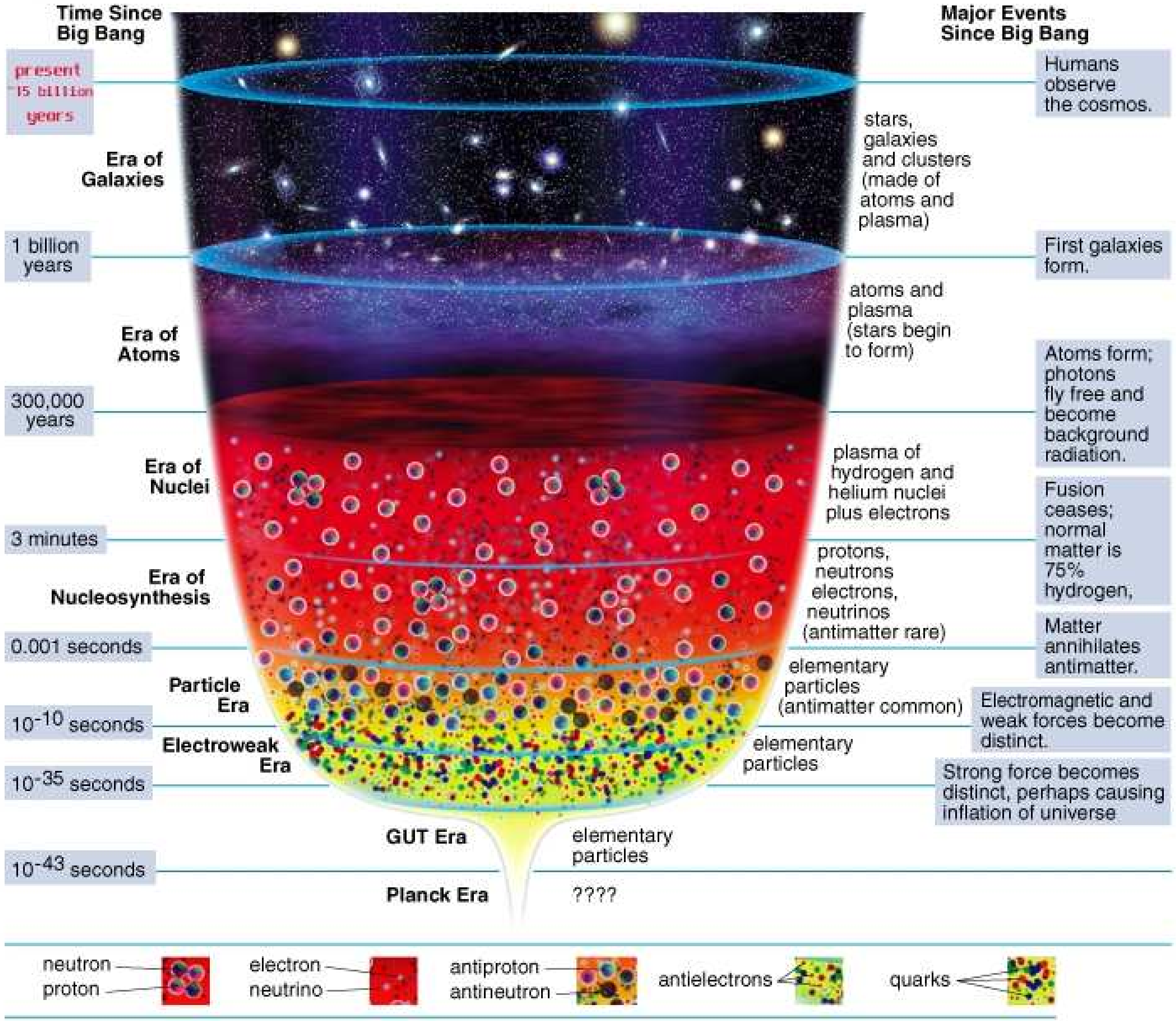
Measuring the cosmological parameters

- H_0: use standard candles (Cepheids, SNIa, Tully-Fisher etc.) and measure luminosity and redshift
- Ω_m: measure M/L (galaxies, groups, clusters)
- Ω_m and Ω_Λ: luminosity and angular distance are affected; CMB => $\Omega_m + \Omega_\Lambda \sim 1$

  SNIa => $\Omega_m \sim 0.3$ and $\Omega_\Lambda \sim 0.7$

The horizon and flatness problem

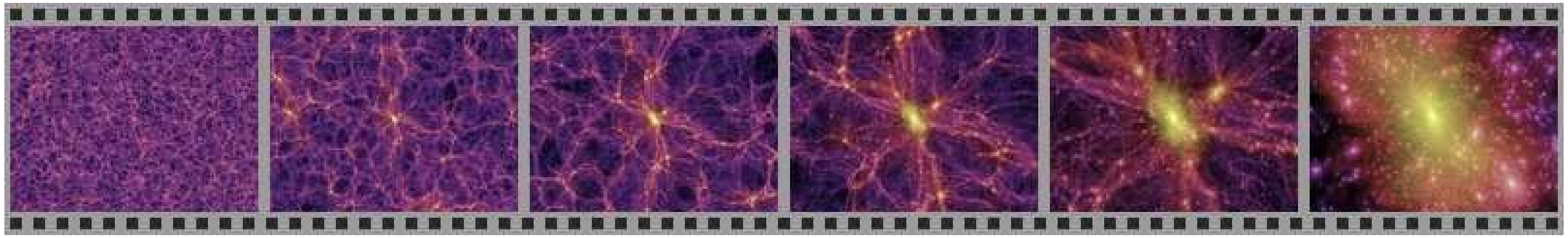
- horizon: the largest causal angular distance is ~2^{o}, but the CMB is isotropic everywhere
- flatness: evolution of Ω(t) shows that Ω(t) had to be exactly one at early times, why?
- solution: *inflation* (Guth 1981) => sudden expansion of the universe shortly after the Big Bang



Time Since Big Bang
present ~15 billion years
Era of Galaxies
1 billion years
Era of Atoms
300,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
10^{-10} seconds
Electroweak Era
10^{-35} seconds
GUT Era
10^{-43} seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons electrons, neutrinos (antimatter rare)
elementary particles (antimatter common)
elementary particles
elementary particles
????
Major Events Since Big Bang
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become background radiation.
Fusion ceases; normal matter is 75% hydrogen,
Matter annihilates antimatter.
Electromagnetic and weak forces become distinct.
Strong force becomes distinct, perhaps causing inflation of universe
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

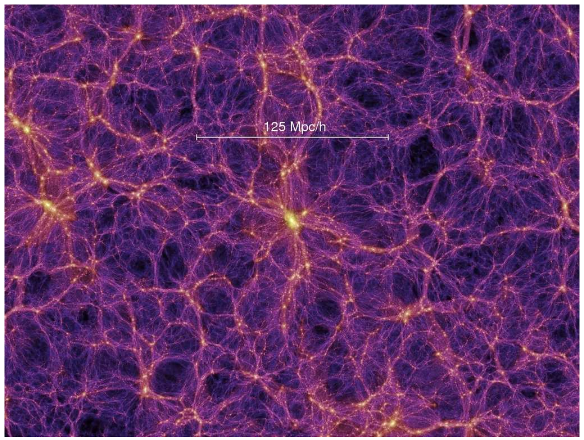
Simulations of the formation of large scale structure

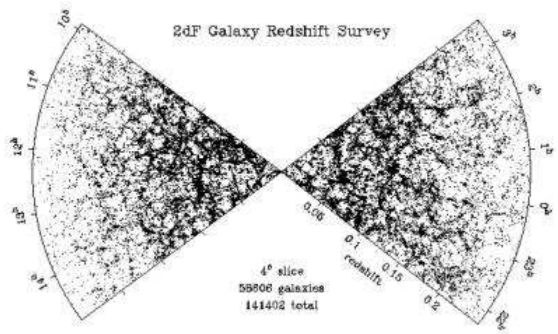
Ingredients: cold dark matter (non-collisional) + initial perturbation (CMB) + cosmology + gravitation (Poisson's equation) + gas/hydrodynamics (optional) + star formation (semi-analytical, optional)



Hierarchical structure formation

- small objects form first (dark matter halos)
- small objects merge to form larger objects
- simulated: dark matter, observed: baryonic matter => observational bias
- can reproduce many observations

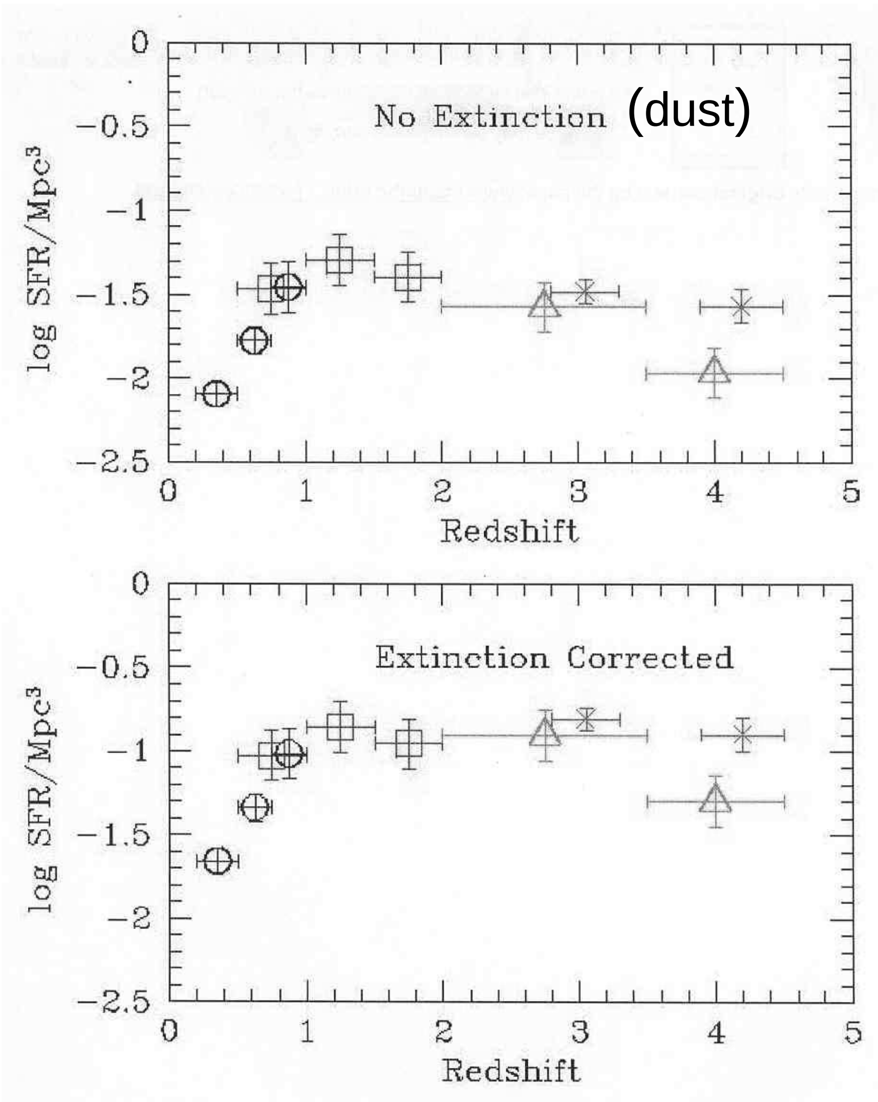




simulations (mainly dark matter)

observations: galaxies

Star formation in the universe



Problems of hierarchical structure formation

- simulated spiral galaxies are too small;

  solution: feedback, e.g. galactic winds
- recent observations: massive galaxies exist already at high z (z>2)

  solution: « downsizing »: at high z the « action » (star formation) takes place in massive objects
- hierarchical structure formation predicts too many small objects (dwarf galaxies?)

  solution: epoque of reionization, feedback

Some open questions

- Quasars have already massive black holes; who was first, the galaxy or the black hole?
- What was the role of the first stars (population 3 stars without metals)?
- How do spiral galaxies form? Why do all spiral galaxies have an exponential disk?
- How does star formation work in detail?

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