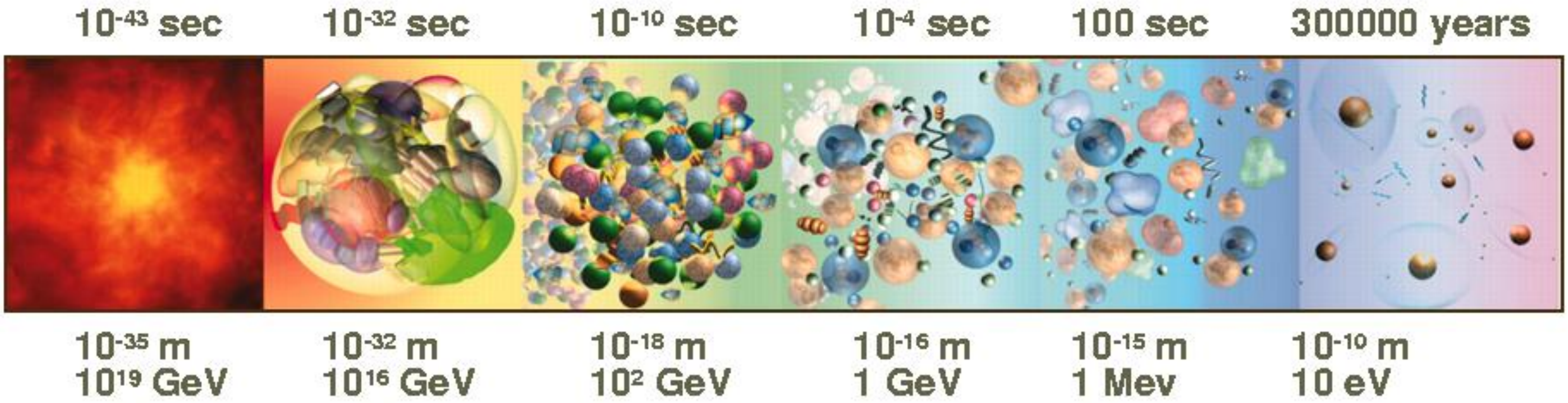
COSMOLOGY I



M. Mezzetti

Anno accademico 2012-2013

mezzetti@oats.inaf.it
tel.: 040-3199-126

Content

Introduction: ***General Relativity and Astrophysics.***

Theoretical Cosmology**: *Cosmological principle; Robertson and Walker metric, redshift, horizons; Friedmann equations, cosmological models with matter, radiation and cosmological constant.***

Observational cosmology**: *luminosity distance, K correction, angular diameter distance, number counts, specific intensity and redshift, radiation absorption.***

Early universe**: *the Standard Big Bang, energy scales, thermodynamics, neutrinos, nucleosynthesis, baryogenesis, recombination.***

Inflation**: *problems of the Standard Big Bang, outline of field theory, relation between mass-energy and pressure, phase transitions, old and new inflation, inflaton dynamics, slow roll and reheating.***

Dark Energy**: *Cosmological constant and related problems, quintessence, other models of dark energy.***

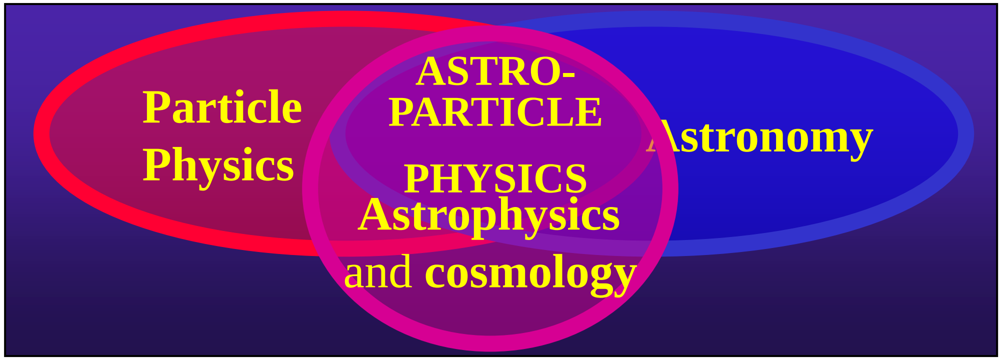
Textbooks

- ***Notes of the lectures***
- ***Gravitation and Cosmology*** – S. Weinberg – Wiley 1972
- ***Introduzione alla Cosmologia*** – F. Lucchin – Zanichelli
- ***Cosmology, The Origin and Evolution of Cosmic Structure*** – P. Coles, F. Lucchin – Wiley
- ***Structure Formation in the Universe*** – T. Padmanabhan **-** Cambridge
- ***The Early Universe*** – E.W. Kolb, M.S. Turner - Perseus Books
- ***Cosmological Physics*** – J.A. Peacock - Cambridge
- ***Particle Physics and Cosmology*** – P.D.B. Collins, A.D. Martin, E.J. Squires – Wiley
- ***Cosmologia e cosmologie*** – S. Bonometto - Zanichelli 2008
- ***Cosmology*** – S.Weinberg – Oxford 2008
- ***Galaxy Formation and Evolution-*** Mo, van den Bosch, White - Cambridge University Press 2010

Cosmology

- studies the **Universe** (= ***all that exists***): its physical properties and evolution. **But** we have access to only a ***finite*** part of it**.**

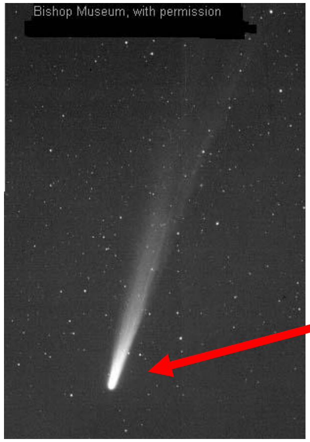
- it's an **applied** science, it doesn't make experiments from Galileo's point of view. But it places constraints to physical theories (e.g.: ***astroparticle physics***).



- The finiteness of the speed of light ($c \sim 3 \times 10^{10}$ cm s^{-1}) allows us to observe the universe at different epochs (farther = younger) and then follow the time evolution of its constituents and their properties. Increasingly sensitive tools allow us to collect information from more and more distant and weak objects.

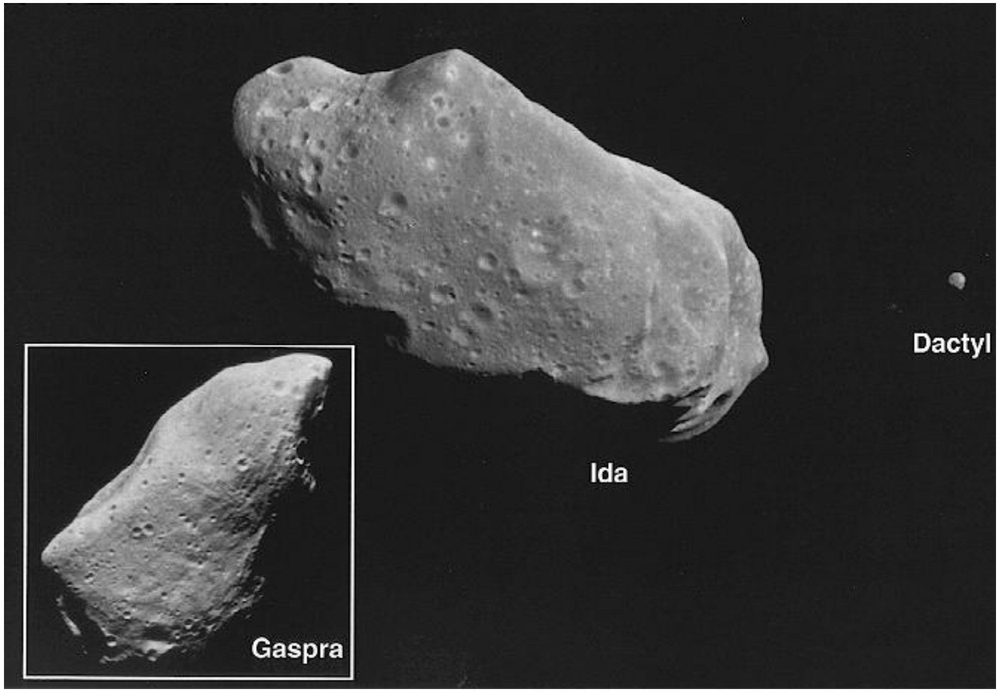
Cosmic Objects

Comets and asteroids



Halley comet

nucleus seen by ***Giotto*** probe



Asteroids

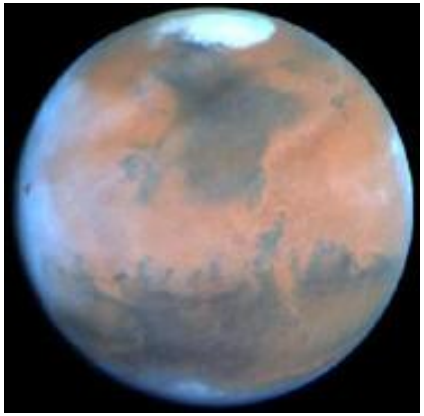
~ 10 km

Planets and satellites

Earth

and

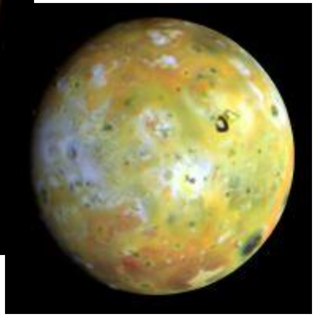
Moon



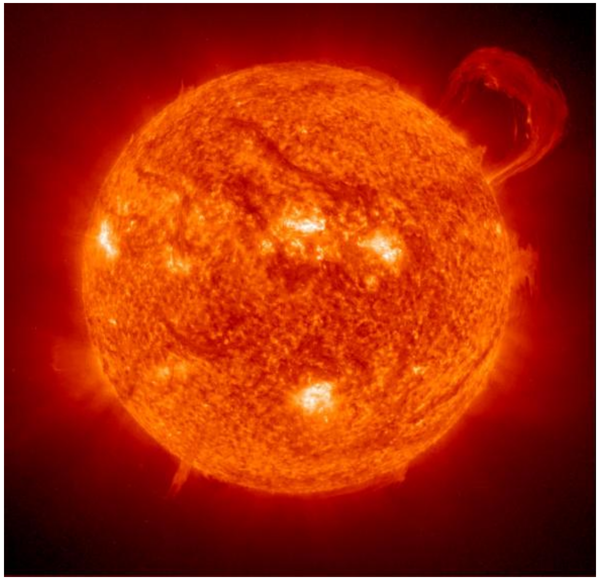
Mars

and

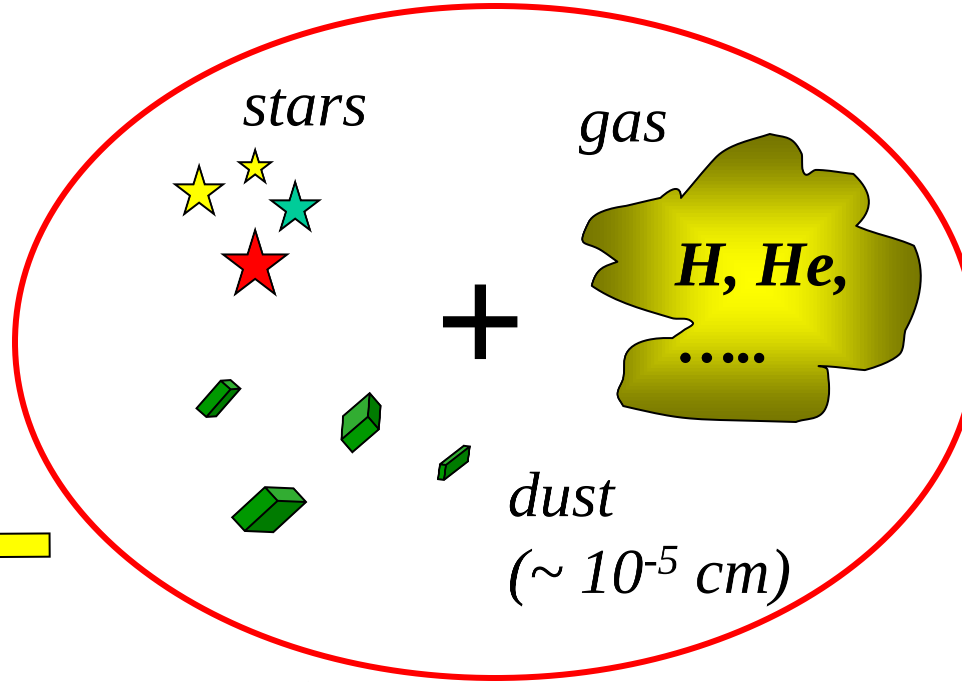
Juppiter + Io

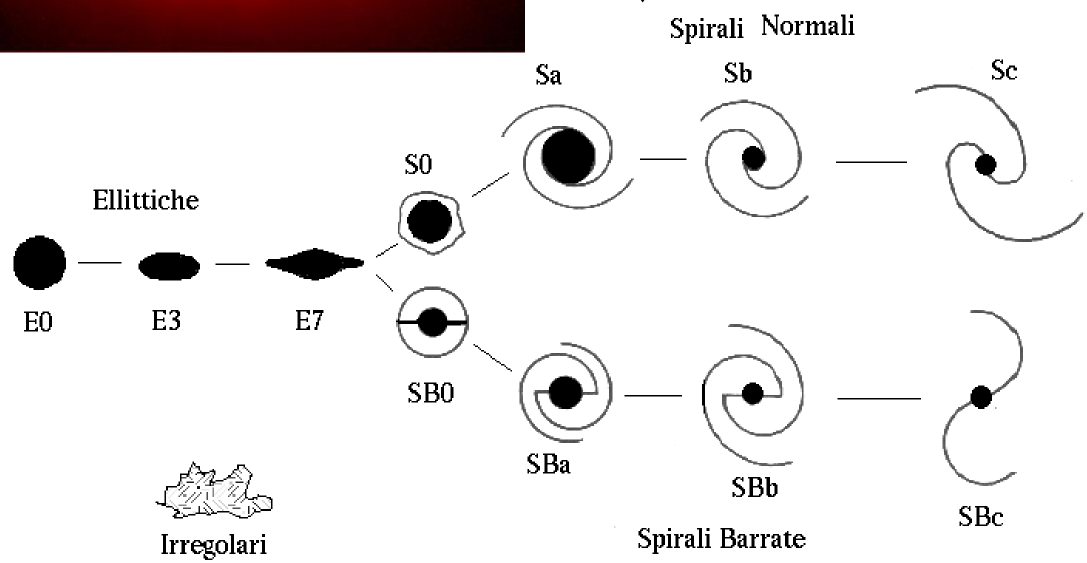


Stars and galaxies



Sun





Hubble's
"Tuning-fork diagram"
for
galaxies

Gas e disc increase

For cosmology galaxies are the "*building blocks*" of the universe







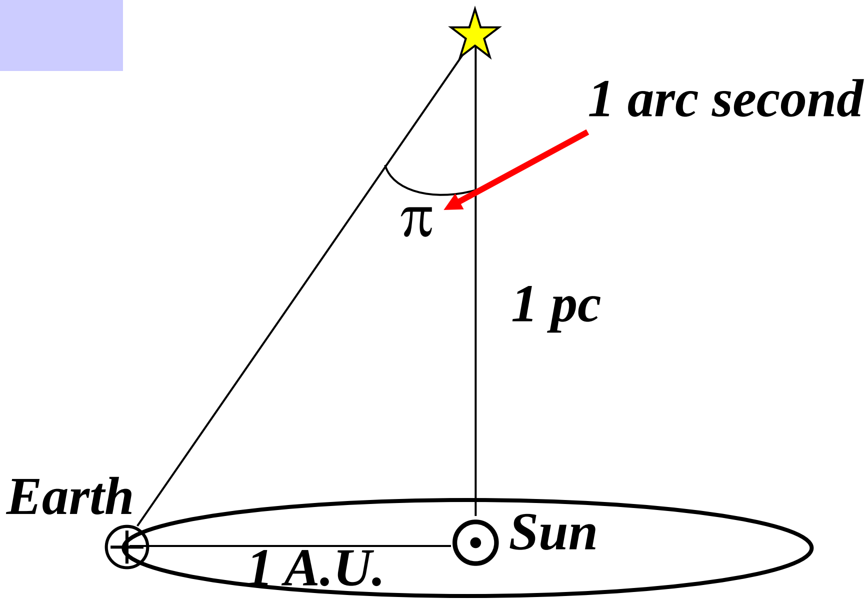
Astronomical units

Distance

light year $1\ ly = 9.5 \times 10^{17}$ cm $(= 3 \times 10^{10}$ cm/s $\times 3 \times 10^{7}$ s$)$

Astronomical Unit $1\ AU \sim 150 \times 10^{6}$ km
= mean distance Sun - Earth

parsec (pc) $= 3.26\ ly \sim 3 \times 10^{18}$ cm
(= parallax second)
mean distanza between stars
Multiples:
$1\ kpc = 10^{3}$ pc
size of galaxies
$1\ Mpc = 10^{6}$ pc
distance between galaxies and
size of galaxy sistems



1 radiant = 57°.29578
= 206265"

1" :  @ 5 km

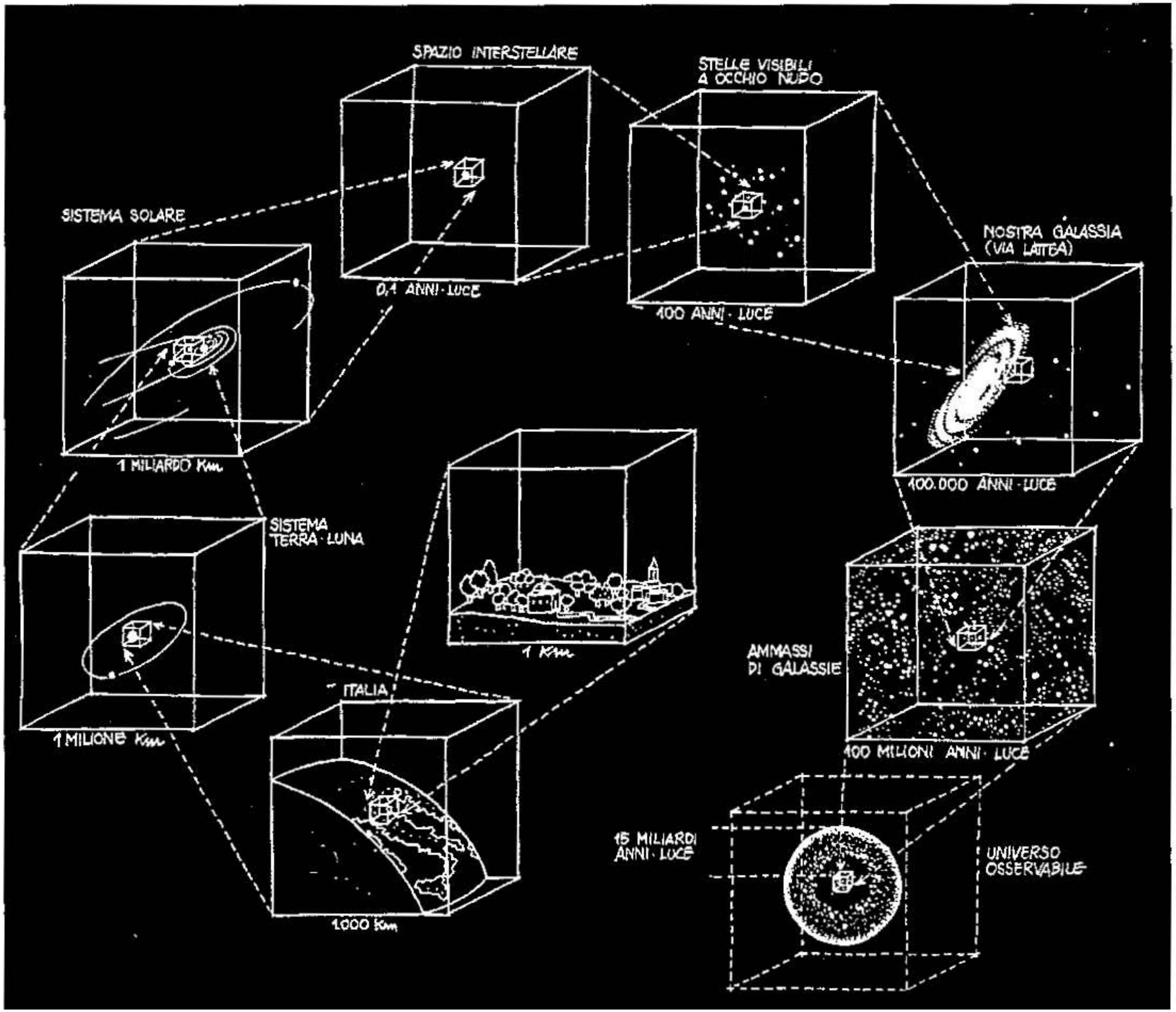
Mass

Solar mass $M_{\odot} \sim 2 \times 10^{33}$ g

Luminosity

Solar Luminosity (bolometric) $L_{\odot} \sim 4 \times 10^{33}$ erg/s

Cosmic Scales



From an object with luminosity L, at a distance d, we receive a <u>flux</u> F:

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

magnitude (m) (apparent)

logarithmic measure of F (C = constant dipending on λ):

$$m = -2.5\, Log_{10} F + C$$

defined in such a way that if the ratio of fluxes is 100, Δm = 5; m ⬆ se F ⬇

*In general we don't measure the bolometric flux, but within a **spectral band** (e.g.: visual **V** λ~ 5500 Å = 550 nm, blue **B** λ~4400 Å, Δλ ~ 0.2 λ)*

Absolute Magnitude (M)

M = m se d = 10 pc

m = -2.5 Log L + 5 Log d + const.

M = -2.5 Log L + 5 Log (10 pc) + const.

*<u>Distance modulus</u> : **m – M = 5 Log d (in pc) -5***

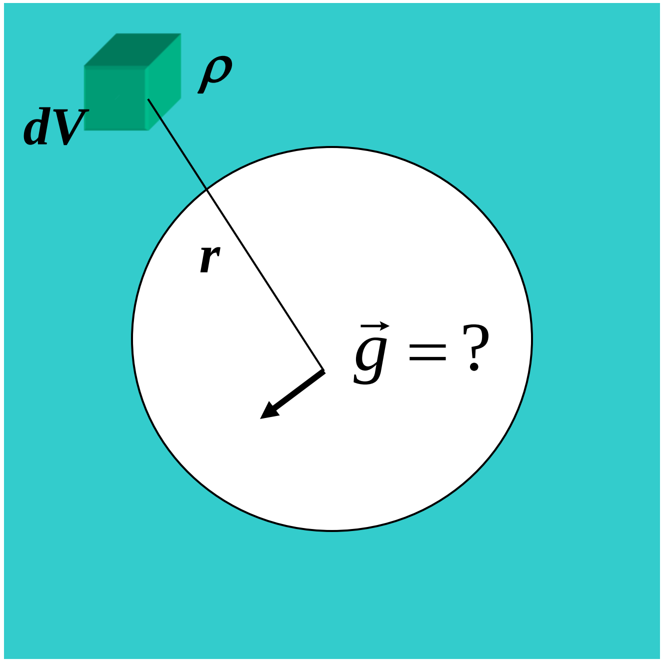
from m and M ⇨ d
(standard candles, e.g. Cefeids)

*If there is **extinction**, F ⬇ and m ⬆: m = M + 5 Log d – 5 + A(λ)*

*interstellar dust ⇨ **A(λ) ~ 1/ λ ~ 1 mag/kpc** in the visible region*

Historical background

▶ ***<u>1692-93</u>*: Newton tried to build a model of homogeneous and isotropic universe, but static (unstable). A finite universe would collapse in its center, forming a single spherical mass. But if the matter was distributed in an infinite space, a part of it would collect on a mass, a part on another mass and so on, forming the Sun and the fixed stars. And the universe would be static because, by symmetry, the resultant forces on each star would vanish and there would be no movement. … But....**



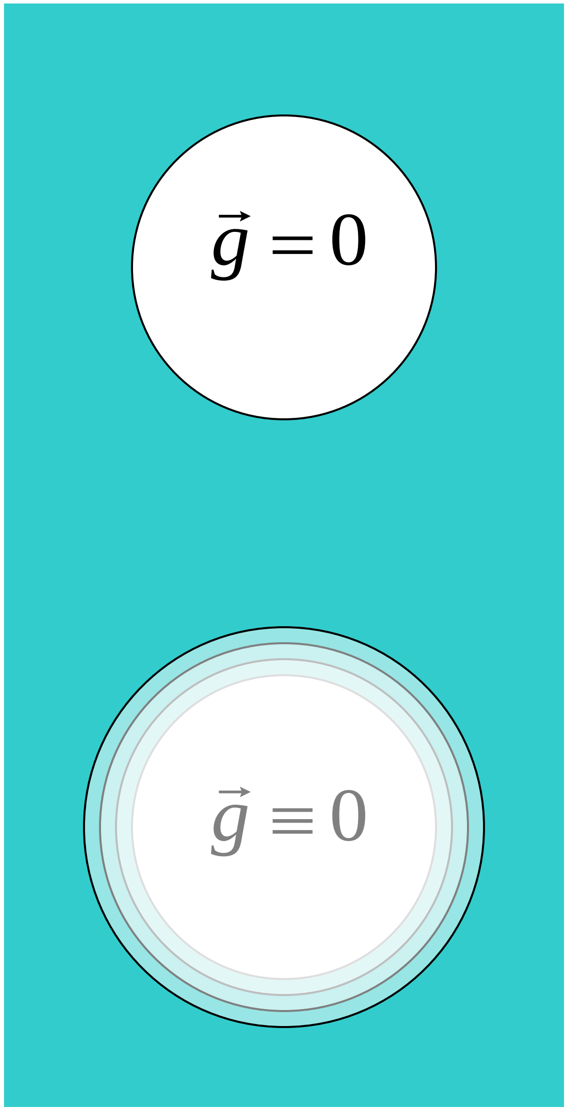
$$\vec{g} = -\nabla \varphi$$

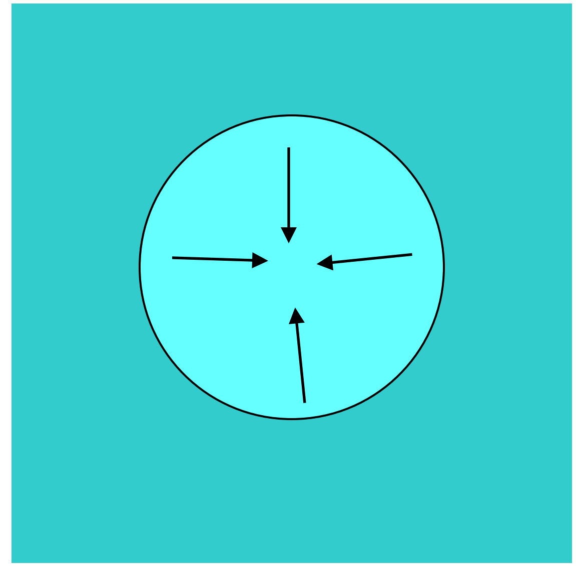
$$\varphi = -G \iiint_V \frac{\rho \, dV}{r}$$

$$\varphi \rightarrow \infty$$

Suppose we remove a ball of matter from an infinite universe. What would be the field in the cavity? If we calculate the potential, this diverges!

If the field within the cavity is equal to zero, reintroducing the matter this collapses due to self-gravity (or the external universe must provide some kind of centrifugal force).





But when we integrate the field due to an infinite number of spherical shells around the cavity we get exactly ***zero.***

At the originof the problem is the fact that
<u>Poisson equation</u> $\nabla^2\varphi = 4\,\pi\,G\,\rho$
does not admit a constant solution

Idea (Neumann 1896): *modify the Newtonian potential*

$$\varphi = -\frac{G\,m}{r} \quad \rightarrow \quad \varphi = -\frac{G\,m}{r} \cdot e^{-r\sqrt{\lambda}} \qquad (\lambda = \text{cost} \approx 0)$$

Poisson equation becomes:

$$\nabla^2 \varphi - \lambda \varphi = 4\pi G \rho$$

which admits the constant solution

$$\varphi = -\frac{4\pi G \rho}{\lambda}$$

Einstein *will do something similar by introducing the* ***cosmological constant*** Λ

$$\nabla^2 \varphi + c^2 \Lambda = 4\pi G \rho$$

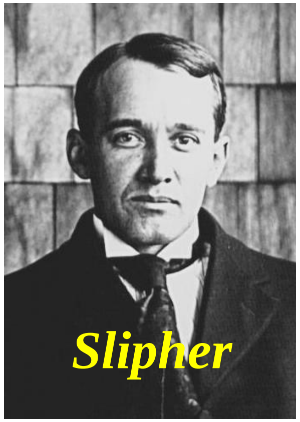
In this form Poisson equation admits the solution $\varphi = 0$ *as long as*

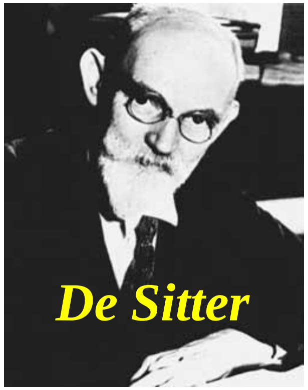
$$c^2 \Lambda = 4\pi G \rho$$

But the problems arises from the idea of a static universe, linked to absolute space. If we give up the idea of absolute space, a global, homogeneous contraction of an infinite universe induced by self-gravity could be possible: no star would move preferentially <u>compared to the others</u>.

▶ ***<u>1914:</u>* Slipher** *and others begin to find generally a redshift in the spectra of nebulae.*

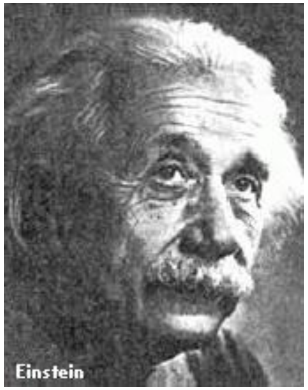
▶ ***<u>1915</u>:* Einstein**, ***General Relativity Theory***; *gravitation is related to the geometry of space and time.*

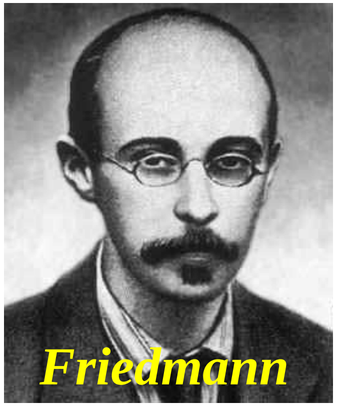




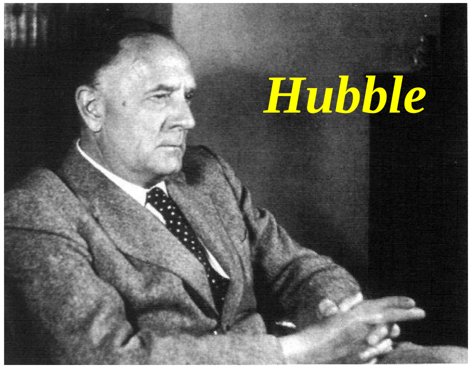
▶ ***<u>1917</u>:* Einstein** *builds the* ***first model of the universe****, but to get a static model he adds to his equations a term containing the cosmological constant. With the same equations* **de Sitter** *proposes a model empty but expanding.*

▶ ***1922 – 24: Friedmann*** *gets models of the universe in* ***expansion without cosmological constant.***





▶ **<u>1924</u>: Hubble„** *using Cepheids as distance indicators, states that the* ***Andromeda Nebula*** *is so far that it must be* ***extragalactic****.*



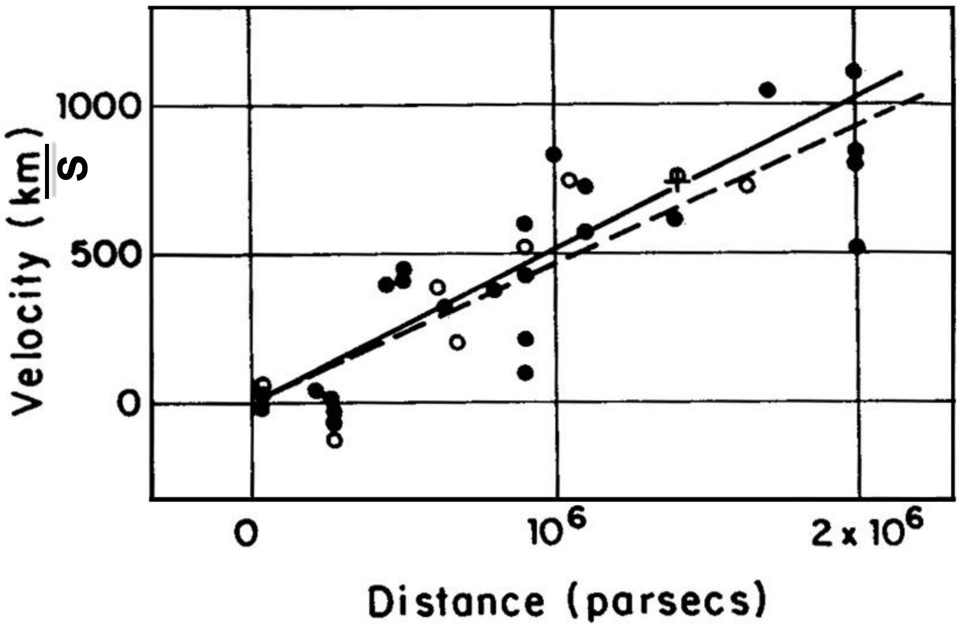
▶ **<u>1927</u>: Lemaître** *(independently) gets models for an* ***expanding universe without cosmological constant****. He also predicts a* ***linear relationship between speed and distance****.*

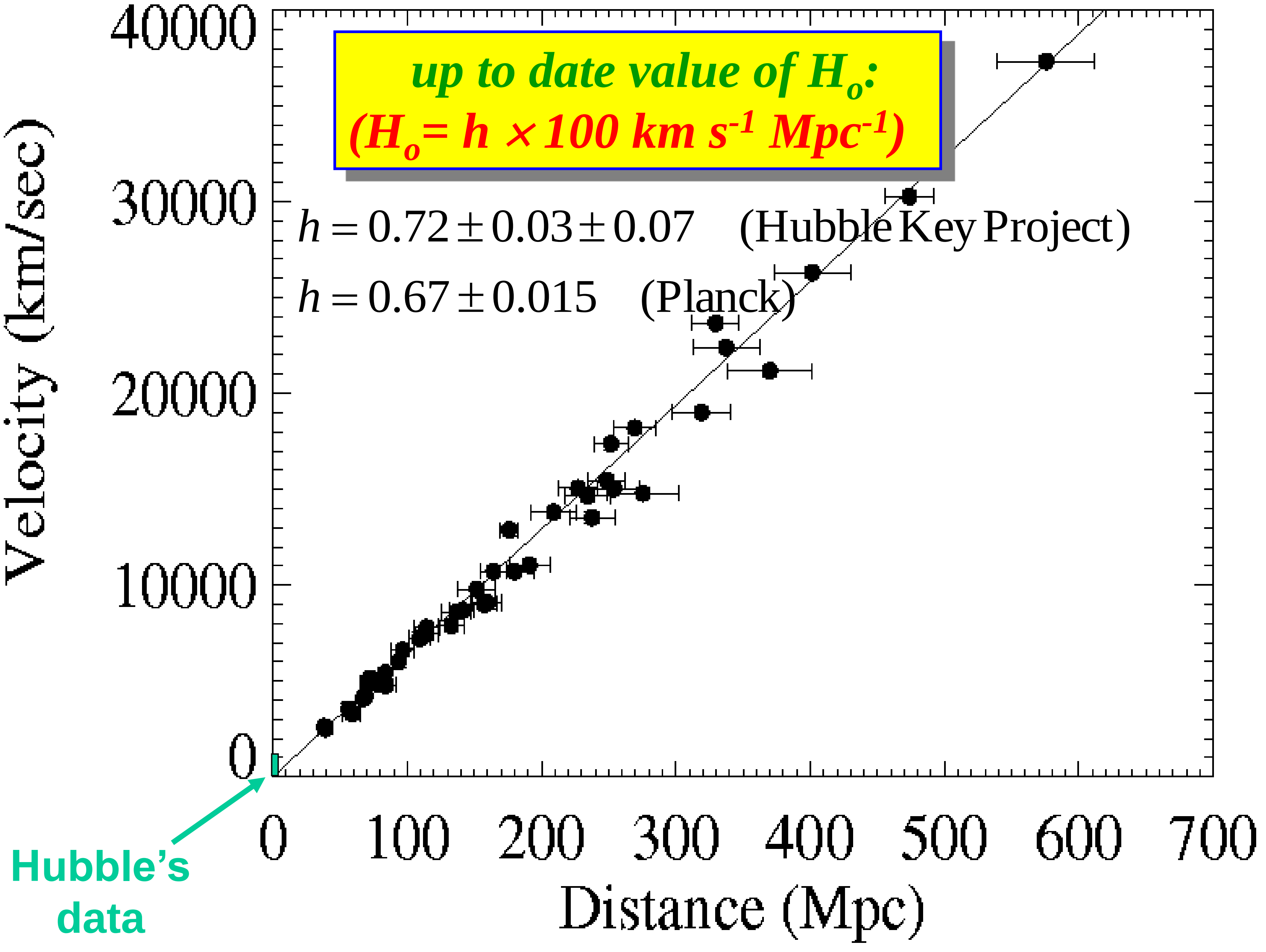
▶ **<u>1929</u>: Hubble** *announces the discovery of a* ***velocity - distance relation for extra-galactic nebulae.***

$$v = H_0\, d$$

(Hubble's law):

$$H_0 = 540\ km\ s^{-1}\ Mpc^{-1}!!!$$



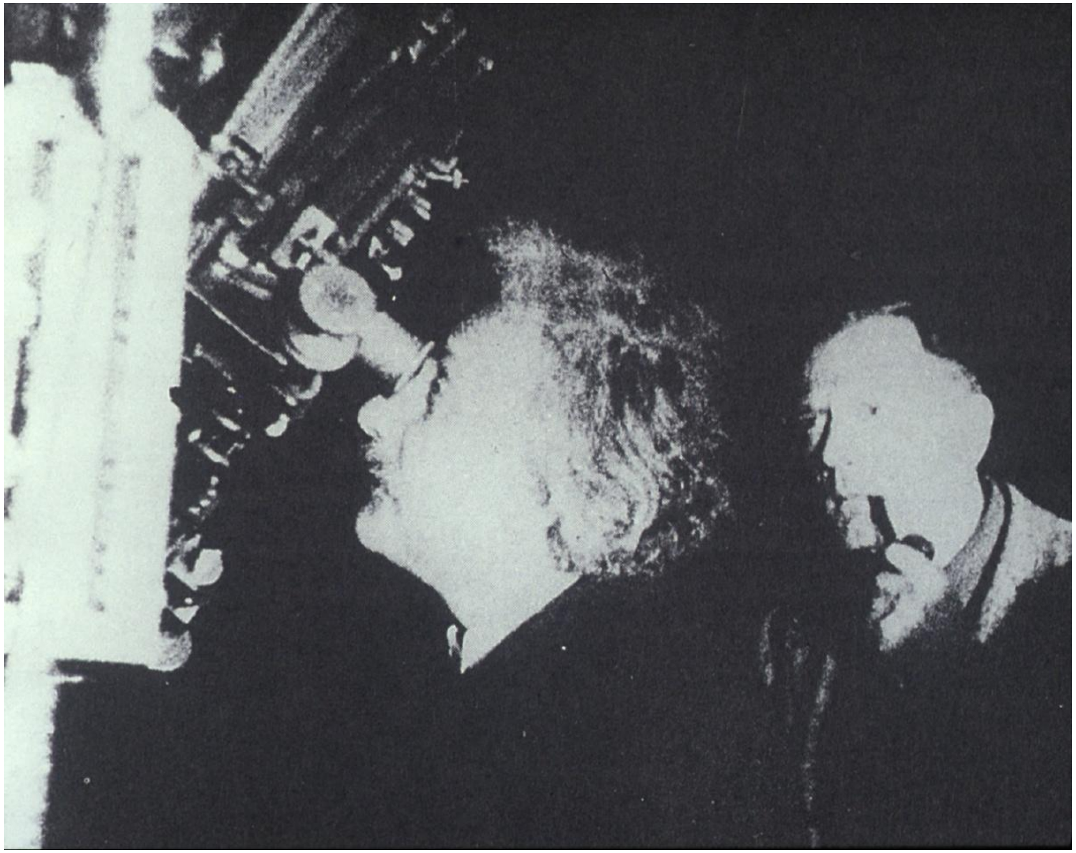


up to date value of H_o:
(H_o= h × 100 km s^{-1} Mpc^{-1})
$h = 0.72 \pm 0.03 \pm 0.07$ (Hubble Key Project)
$h = 0.67 \pm 0.015$ (Planck)
Velocity (km/sec)
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
Distance (Mpc)
Hubble's data

▶ *After Hubble's law was accepted, Einstein considered no more realistic a static universe and abandoned the cosmological constant, considering it the biggest blunder of his life.* ***But*** *...*

… at the end of the second millennium, in our galaxy :

The cosmological constant strikes back



Stellar Parameters

Masses, Luminosities and Radii

$R_\odot \sim 7 \times 10^{10}$ cm
$T_{e\,\odot} \sim 5800$ K

$0.08 < M/M_\odot < 100$

$10^{-4} < L/L_\odot < 10^{6}$

$0.01 < R/R_\odot < 1000$

$1/3 < T_e/T_{e\,\odot} < 20$

Effective Temperature T_e

Temperature of a black body of radius R having the same luminosity L of the star

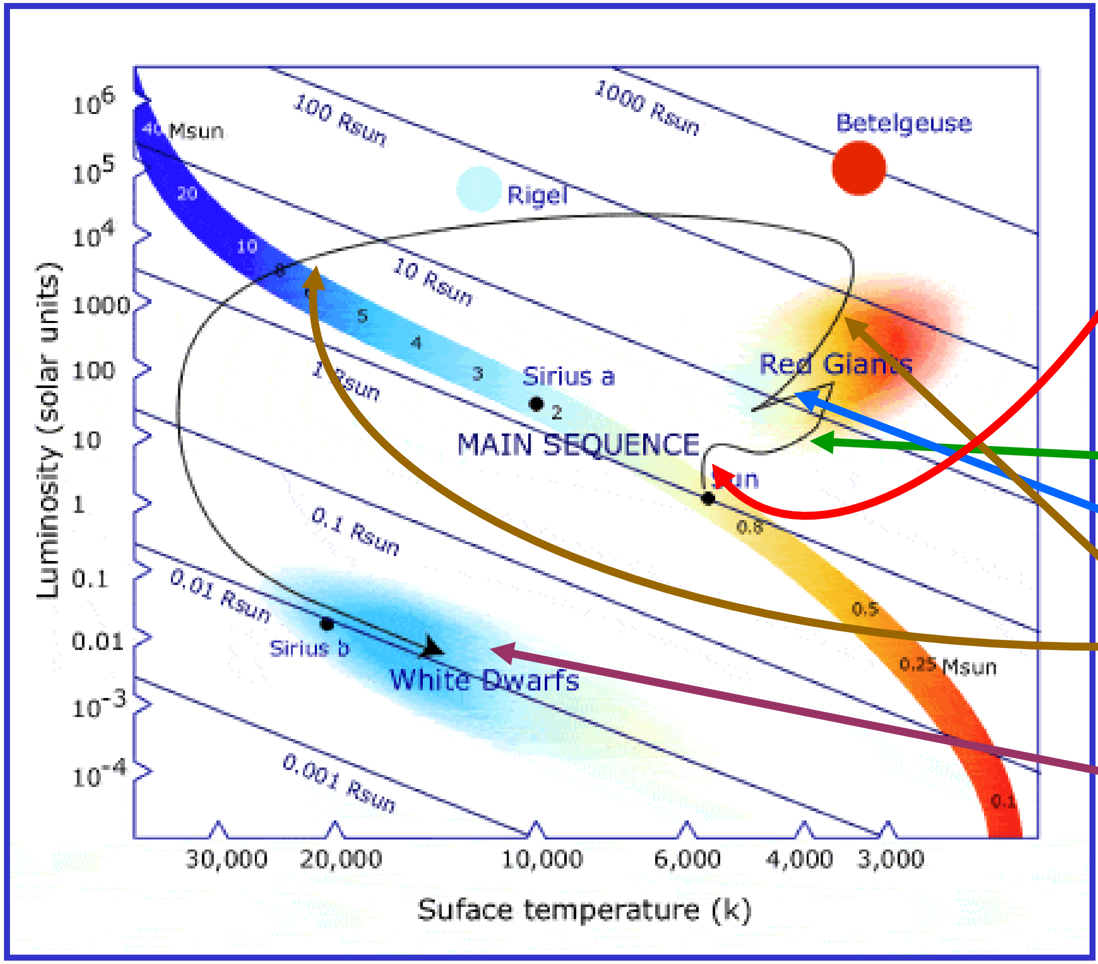
Relation among L, R e T_e :

$$L = 4\,\pi R^2\,\sigma T_e^4$$

$$\sigma = 5.67 \times 10^{-5} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ K}^{-4}$$

The HR diagram

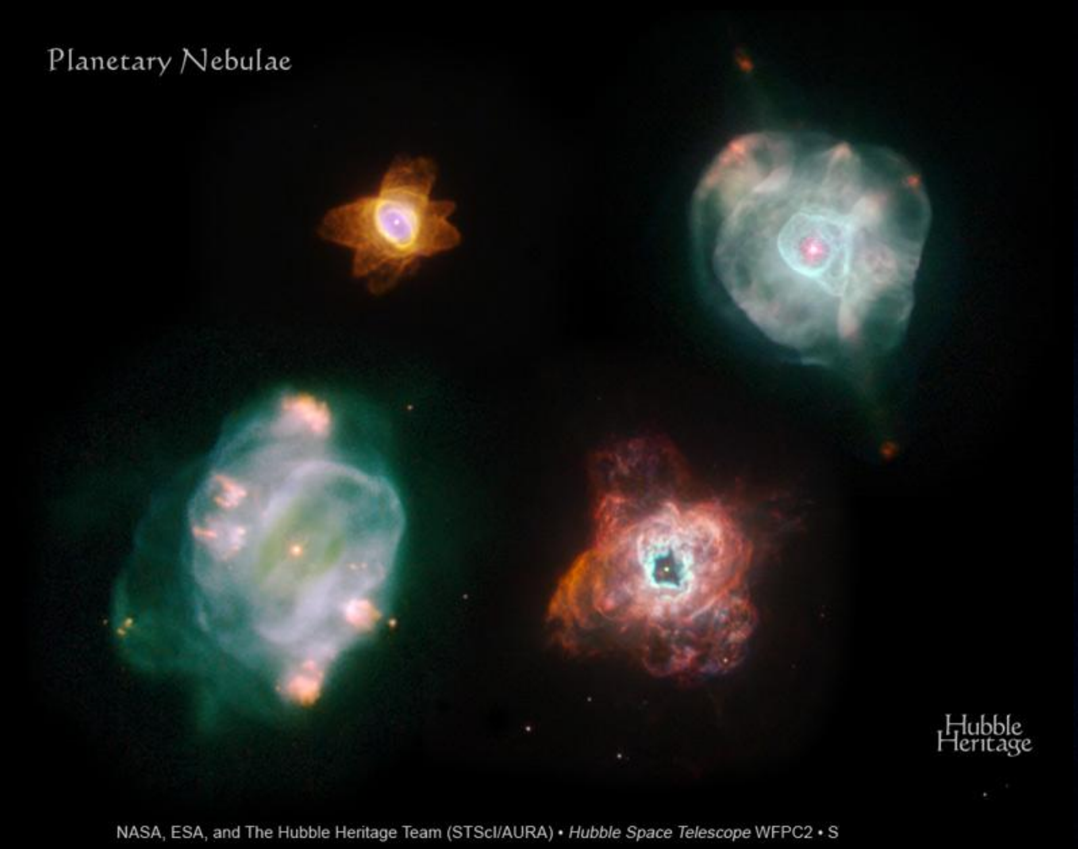
In the L-T_e plane (Hertzsprung-Russel diagram) stars are not randomly distributed



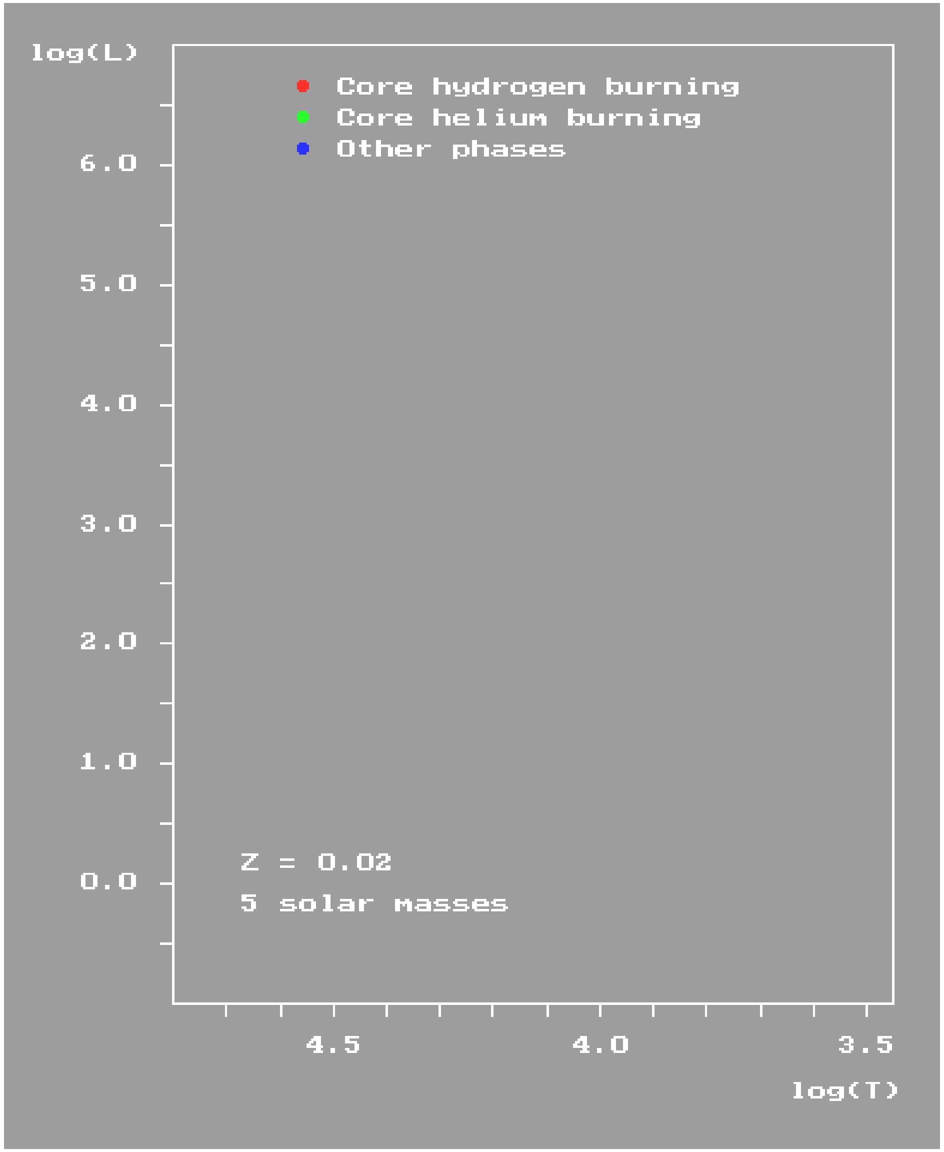
90% of stars lies on the ***Main Sequence****, where:*
H ➩ He in the core

Other phases:
H ➩ He in shell
He (flash) ➩ C,O in core
H,He ➩ C,O in shell
Instability - Planetary Nebula (10^3 yrs)
Core C,O degenerate (White Dwarf)

Evoluzion of the Sun *(and of stars with $0.08<M/M_\odot<2$)*


Planetary Nebulae
Hubble Heritage
NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • *Hubble Space Telescope* WFPC2 • S

Evoluzion of a 5 $M_\odot$ star



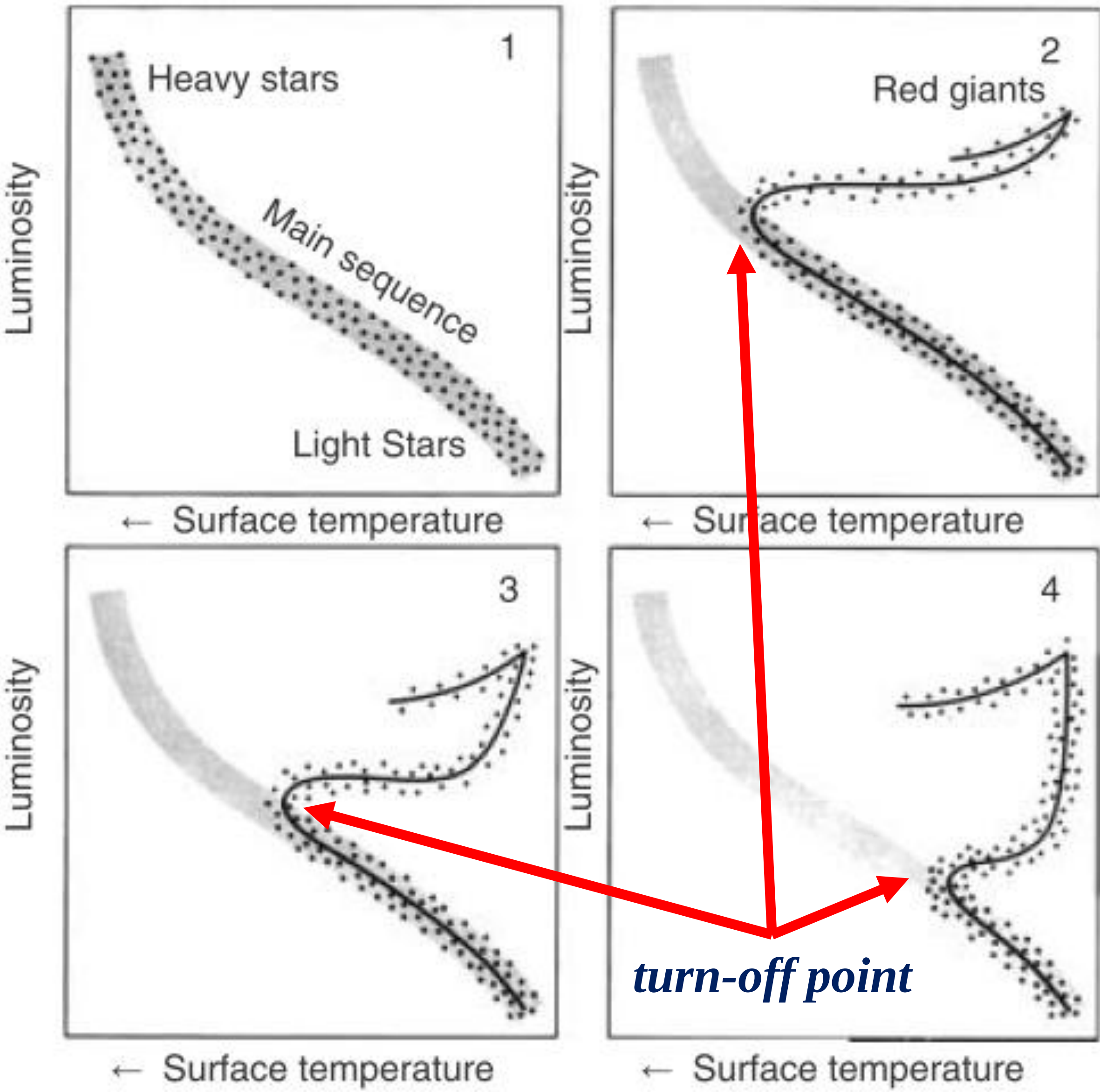
2 < $M/M_\odot$ < 10:

He ⇨ C,O in core (not degenerate)
C does not turn on
Instability - Planetary Nebula
C,O core degenerate (White Dwarf)

10 < $M/M_\odot$ < ~50:

C ⇨ ⇨ ⇨ core of Fe (~ 100 yrs)
Core contracts, T↑, Fe dissociates
$e + p \rightarrow n + \nu_e$
Collapse stops when $\rho \sim \rho_{nucl}$
Shock + ν ⇨ espulsion of envelope
SNII (SNIb/c)
Core:
- ***M <~2 $M_\odot$ ⇨ NS (pulsar)***
- ***M >~2 $M_\odot$ ⇨ BH***

Evolution in time of HR diagram



Massive stars have shorter life:

Fuel stock ~ M

but

$L \sim M^3$

so

$t_{MS} \sim M/ M^3$

Life-time on MS:

$t_{MS} \sim 10^{10}\ (M/M_\odot)^{-2}$ *year*

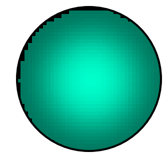
The death of stars

$M < 0.08\ M_\odot$ — *H doesn't burn* ⇨ **brown dwarf (degenerate matter)**

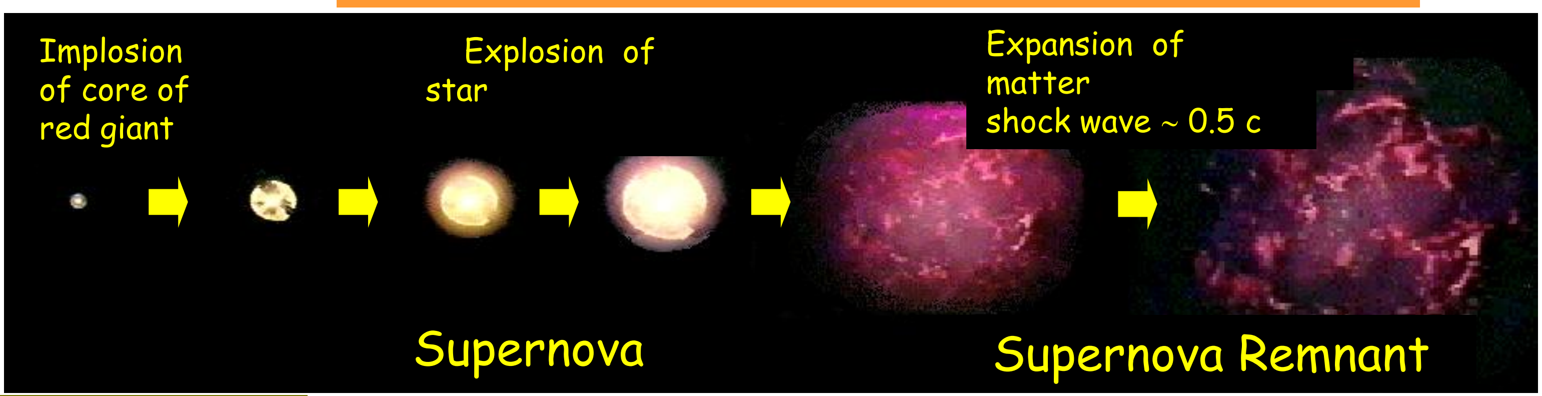
$M < \sim 10\ M_\odot$ — ⇨ *White dwarf made of C-O; degenerate matter density ~ 10^6 g/cm^3*

Planetary Nebula

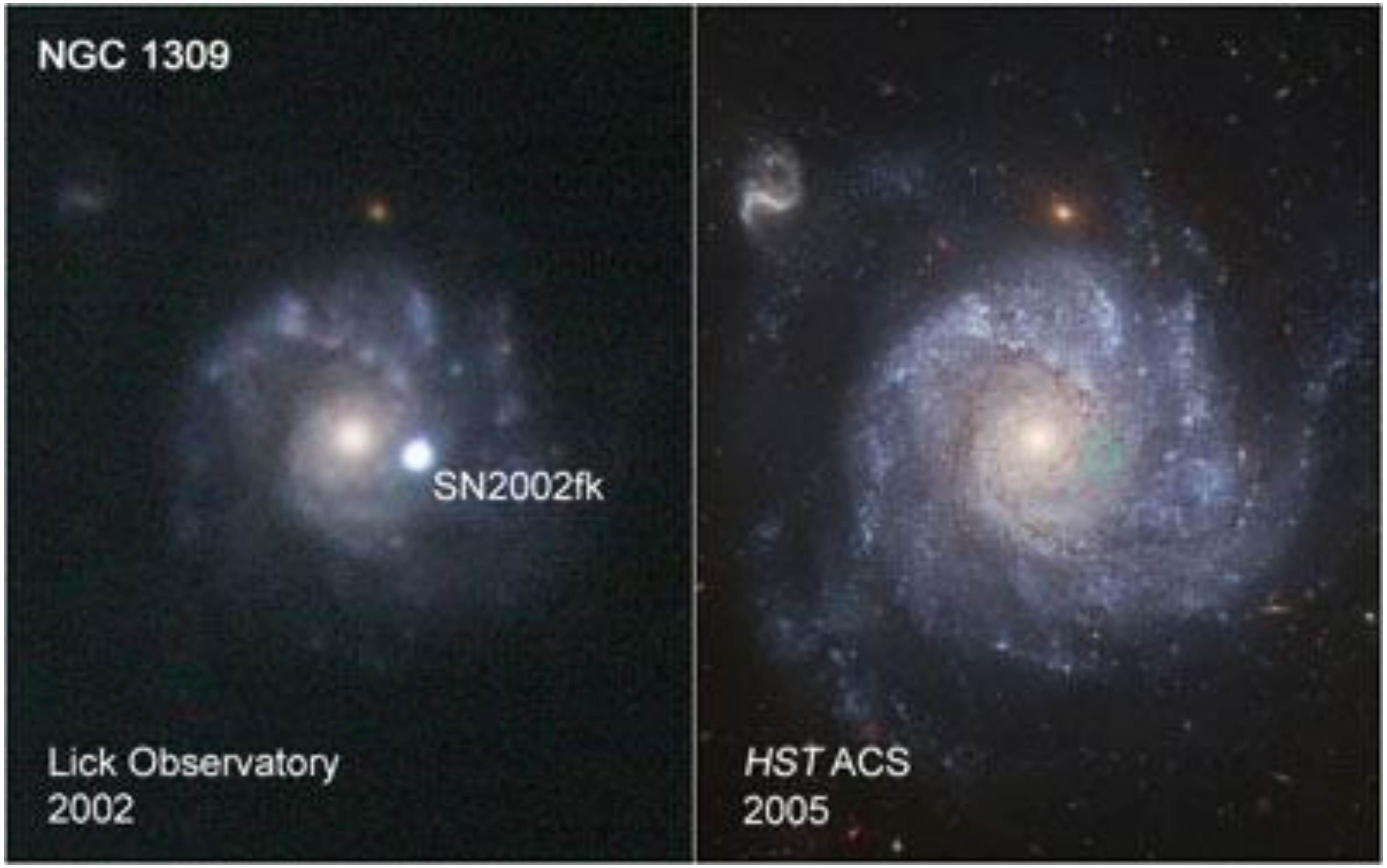
White dwarf



$M > \sim 10\ M_\odot$ — *Core collapse* ⇨ **neutron star** *(10^{14} g/cm^3)*
Envelope ejection ⇨ *Supernova* **SNII** *(10^{51} erg)*

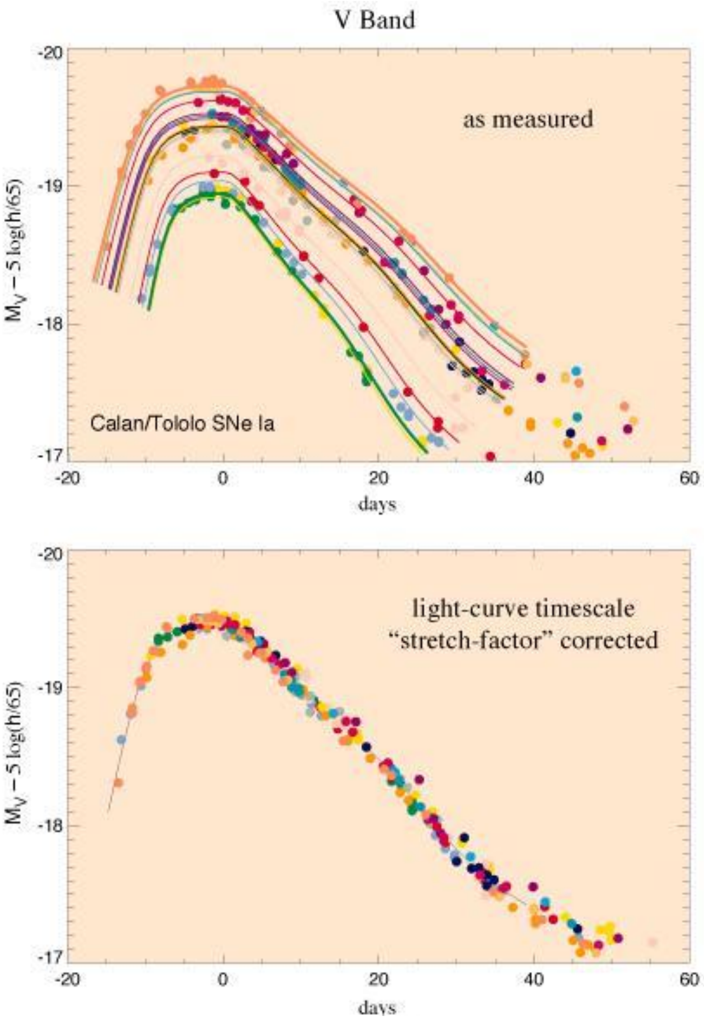


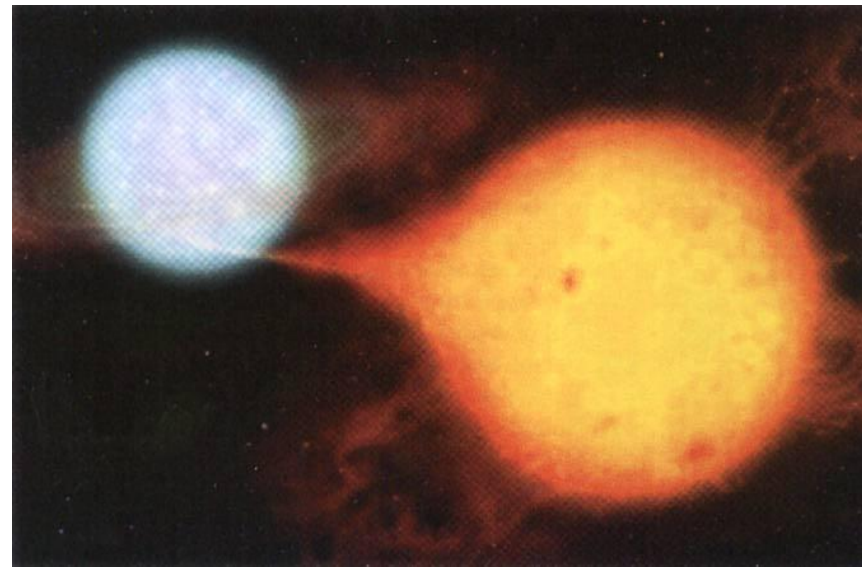
$M > \sim 50\ M_\odot$ — *Collapse* ⇨ *Black Hole (no SN) ??*


NGC 1309
SN2002fk
Lick Observatory
2002
HST ACS
2005

Supernovae Ia (SNIa)

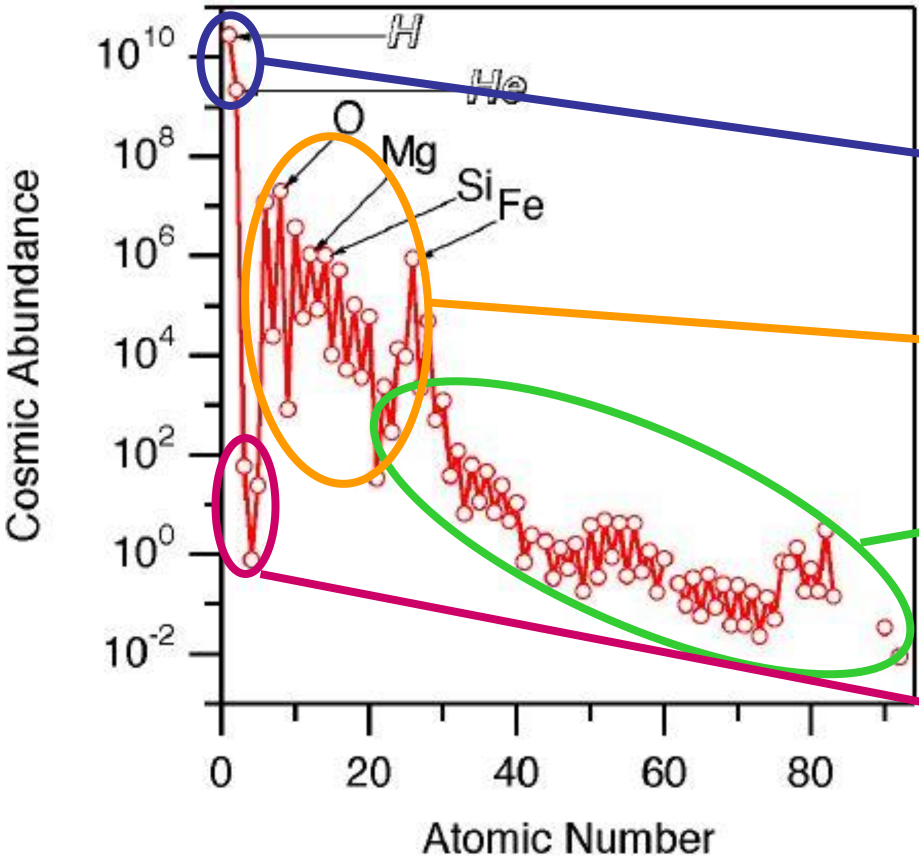
Are formed in binary stars in which one component is a white dwarf of CO with mass ~ 1.4 $M_\odot$ (Chandrasekhar mass). If the mass, by accretion by his partner, exceeds this value ⇨ explosion ⇨ SNIa





SNIa are standard candles
Visible at very large distance

Cosmic Abundancies



origin:

Big Bang Nucleo-synthesis

Hot Stars

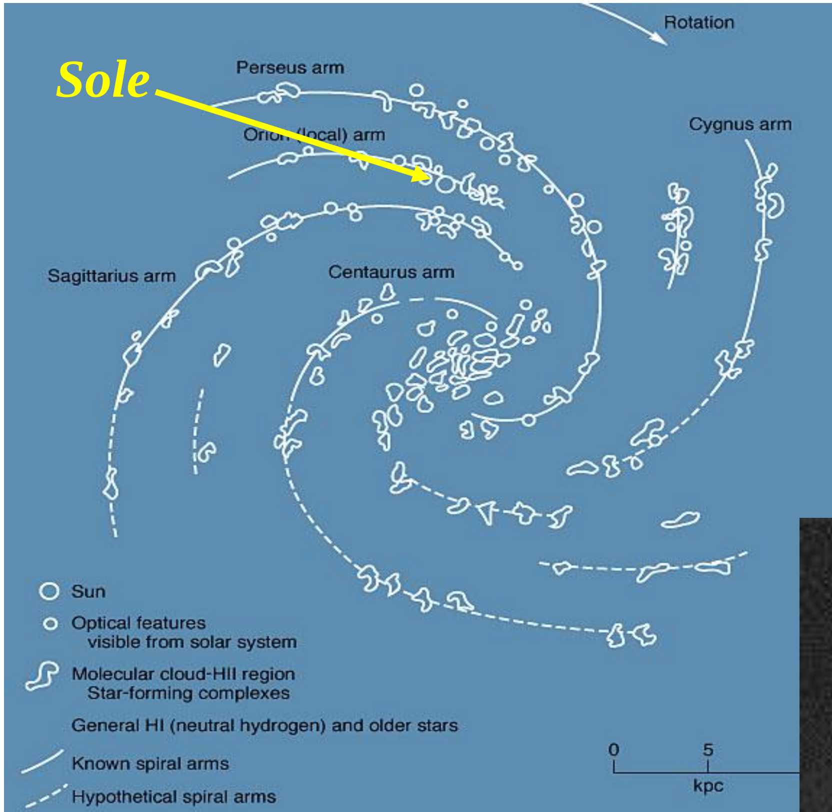
Supernova explosions

Interactions with cosmic rays

Fraction in mass: X (H), Y (He), Z (metals = not H and He)

Young stars, metal rich (Pop I): Z < ~ 0.04 (SNII)
Old stars, metal poor (Pop II): Z > ~ 0.003 (SNIa)
Sun: Y=0.27 Z=0.02 X+Y+Z=1

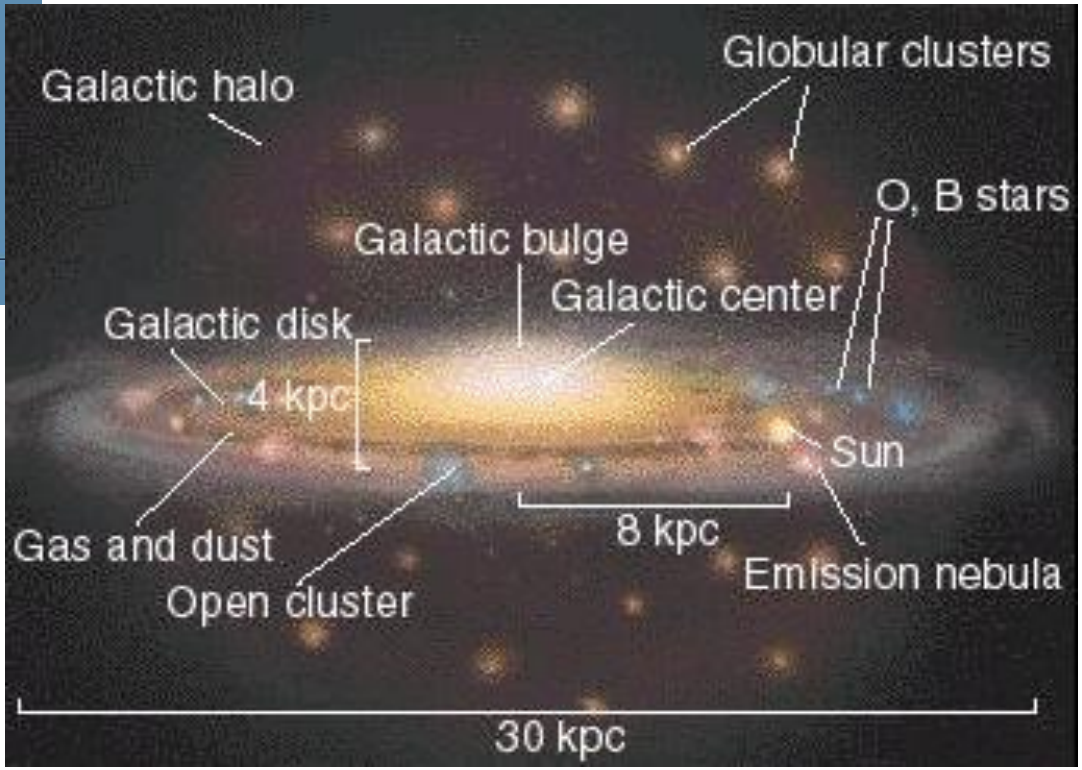
Our galaxy



Disc: gas, dust, young stars, open clusters, Pop I

Bulge: old stars, Pop II

Halo: old stars, globular clusters, PopII



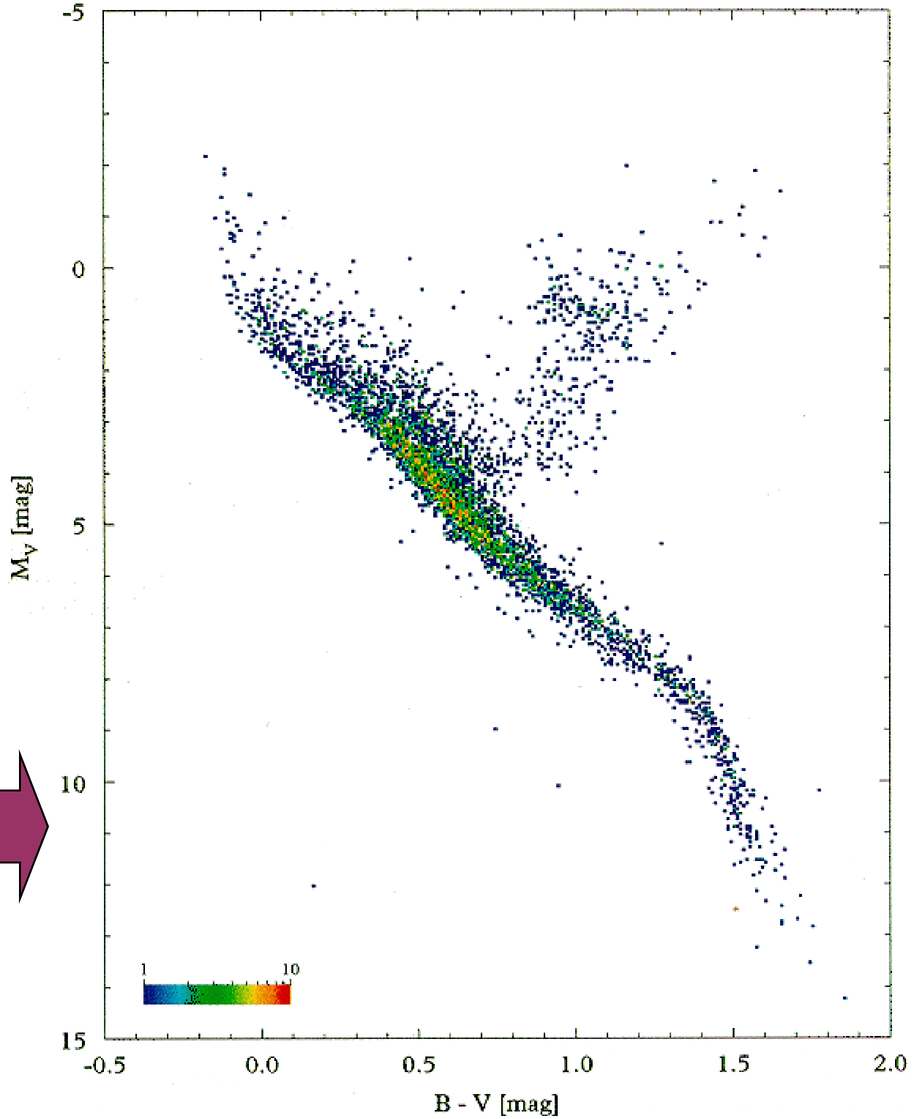
Open clusters

Color: $m_B - m_V = M_B - M_V = B - V$ (linked to T_e)

Young, massive stars

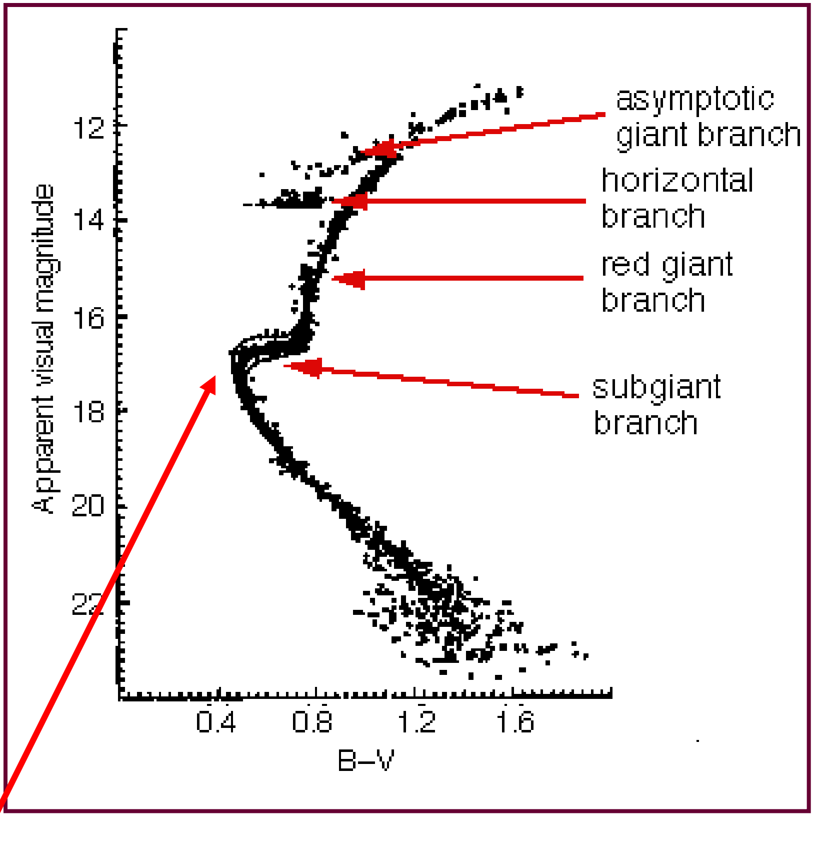
HR diagram of nearby stars (Hipparcos satellite)

Galactic disc population also with young stars



Globular Clusters

~ $10^5 – 10^6$ old stars- Pop I



Turn-off point : deviation from Main Sequence ⇨ age of the cluster

The age of the Universe

Lower limit to the age of the Universe: age of very old objects (plus 0.5-1.0 Gyr to take into account the formation time):

Globular Clusters

From the position of the turn-off point ⇨ age > ~11.5 ± 1.3Gyr

White Dwarves

From the cooling time of the coolest white dvarves ⇨ age (globular cluster M4) ~ 12.7 ± 0.7 Gyr

Nuclear Cosmochronology

From the radioactive decay of nuclei with lifetime ~ 10 Gyr

$$U = U_0 \exp(-t/\tau)$$

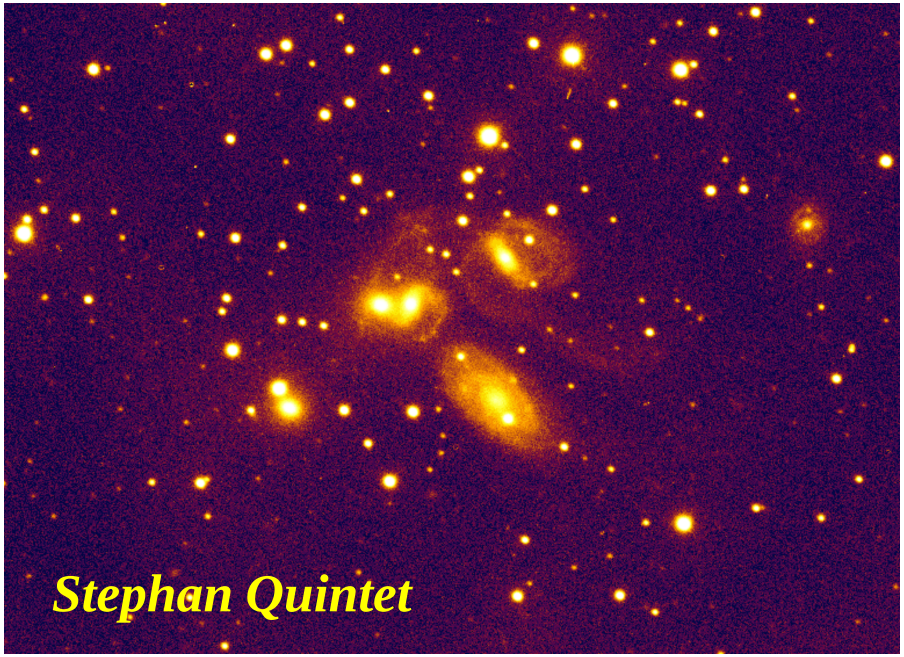
$^{232}Th \rightarrow {}^{208}Pb$ ($\tau = 20.27$ Gyr) $^{238}U \rightarrow {}^{206}Pb$ ($\tau = 6.45$ Gyr)

From the comparison between theoretical and observed values of the ratios between unstable and stable elements ⇨ age (Cayrel star) 14.0 ± 2.4 Gyr

The Large Scale Structure of the Universe

Galaxies are not randomly distributed in space, but they tend to cluster into:

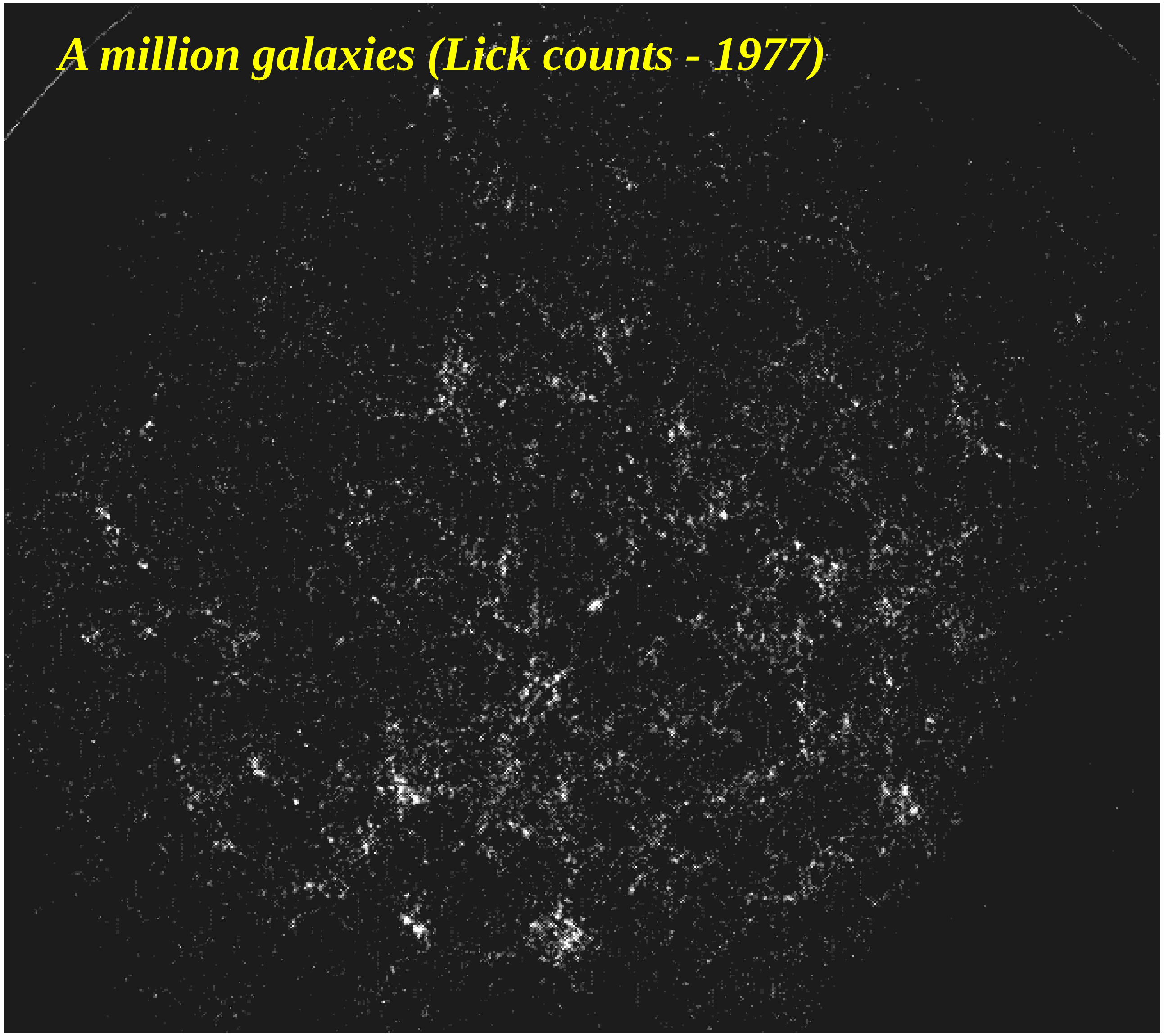
Binaries



Groups

Clusters

The distribution of galaxies on the celestial sphere



We do not see the third dimension, but already you can see filaments, voids, clumps of galaxies.

To know the true spatial distribution we need the third dimension: the redshift z, from which:

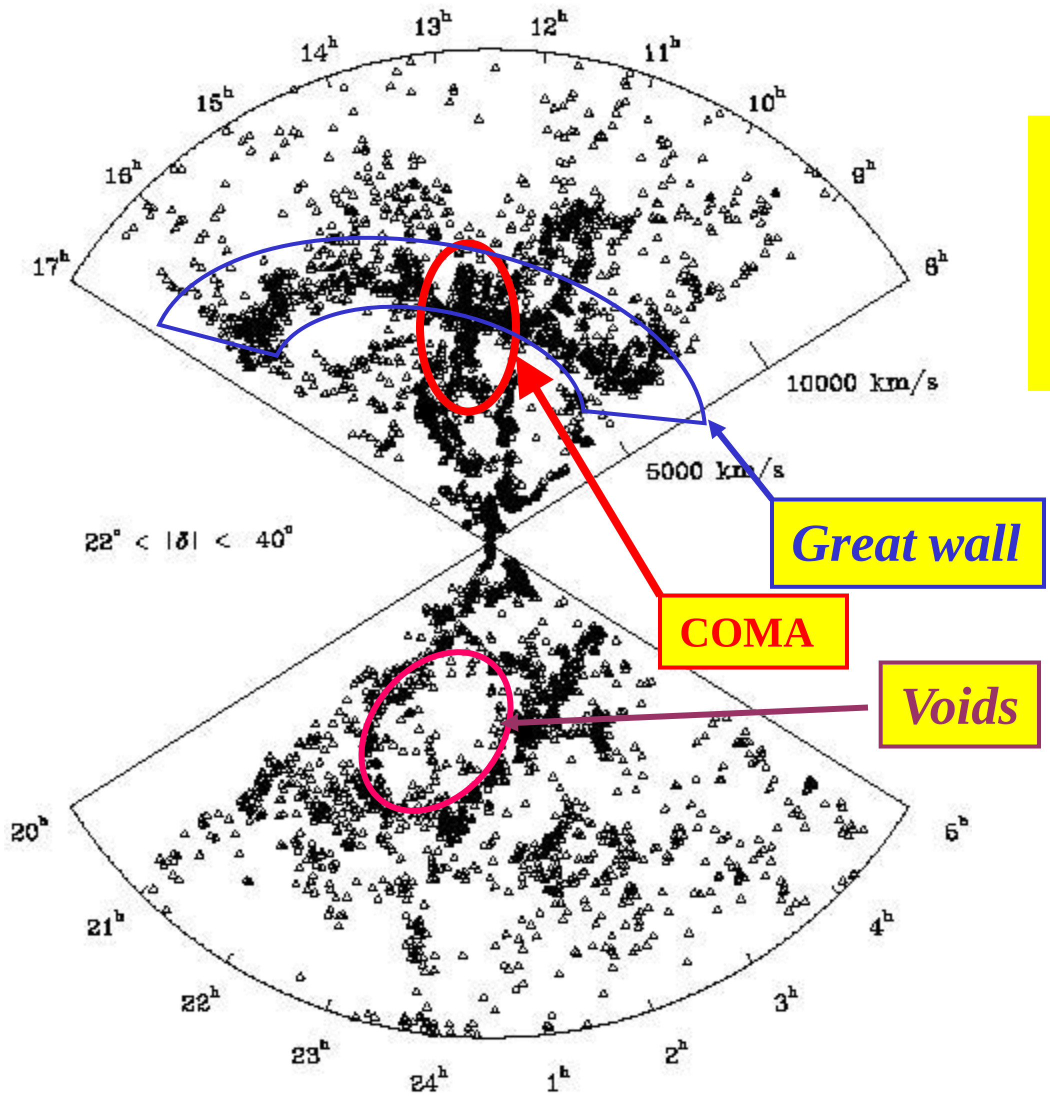
$$z=(\lambda_{obs}-\lambda_{em})/\lambda_{em}$$

$$V=c\,z$$

$$D = V/H_0 = c\,z/H_0$$

The 3D distribution of galaxies

Since the 70s : extended redshift surveys ⇒ 3-D samples of galaxies



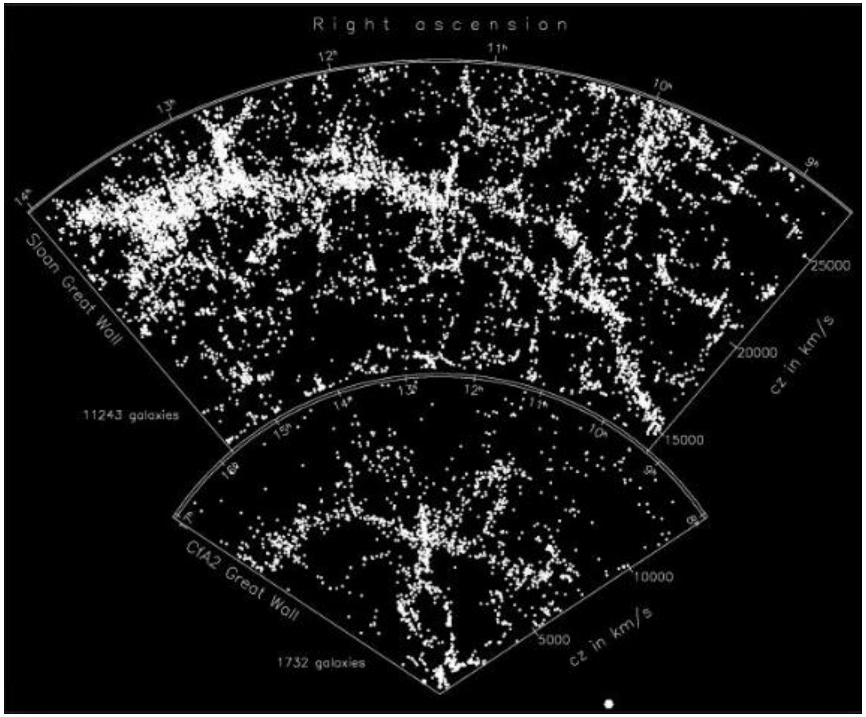
"Slices" of the Universe from:

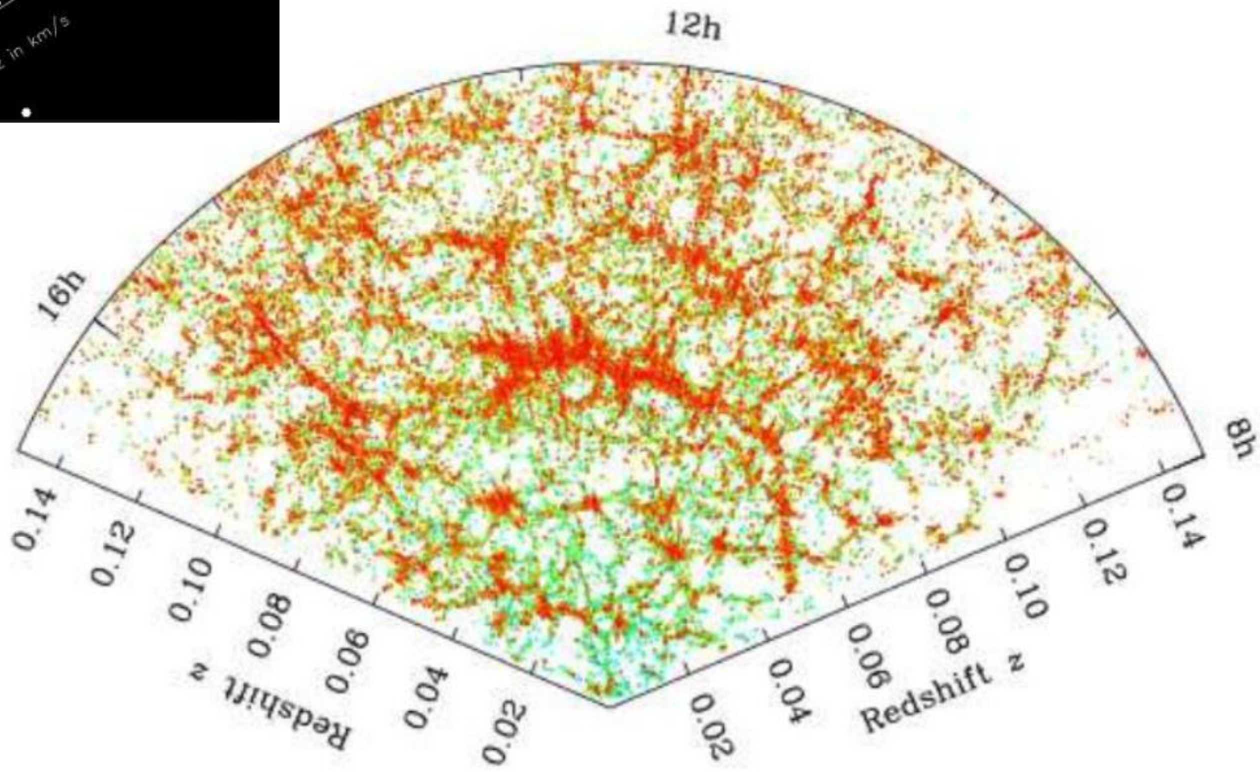
- ***CfA1, CfA2 (~15000 gal., B limit 15.5 mag, cz<7000 km/s)***
- ***SSRS, SSRS2 ~5000 gal., B_j limit 15.5 mag***

- ***Fingers of God***
- ***Great wall***
- ***Voids (5000 - 10000 km/s)***

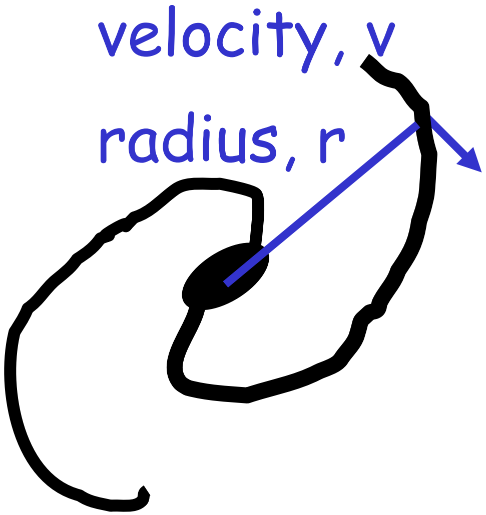
This confirms the impression of 2D maps: the galaxies are distributed to form a kind of "cosmic foam" or cosmic web, with empty bubbles and galaxies along the walls

Deeper Surveys confirm these results
2dF Survey
Sloan Digital Sky Survey



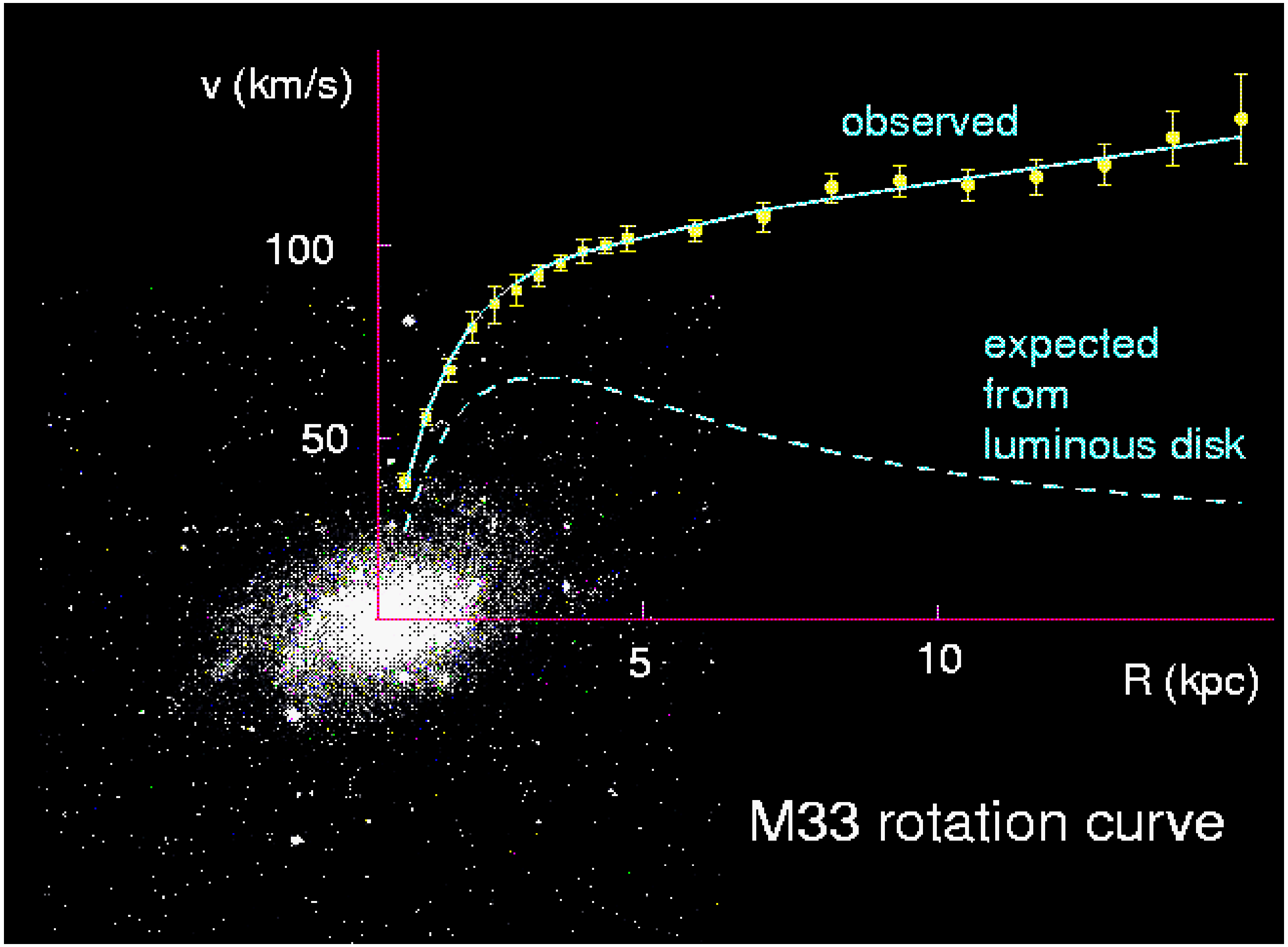


Dark matter in galaxies



Gravity:
$G\,M(r) / r^2 = v^2 / r$

Mass within r:
$M(r) = v^2\,r / G$
Density ~ $1/ r^2$

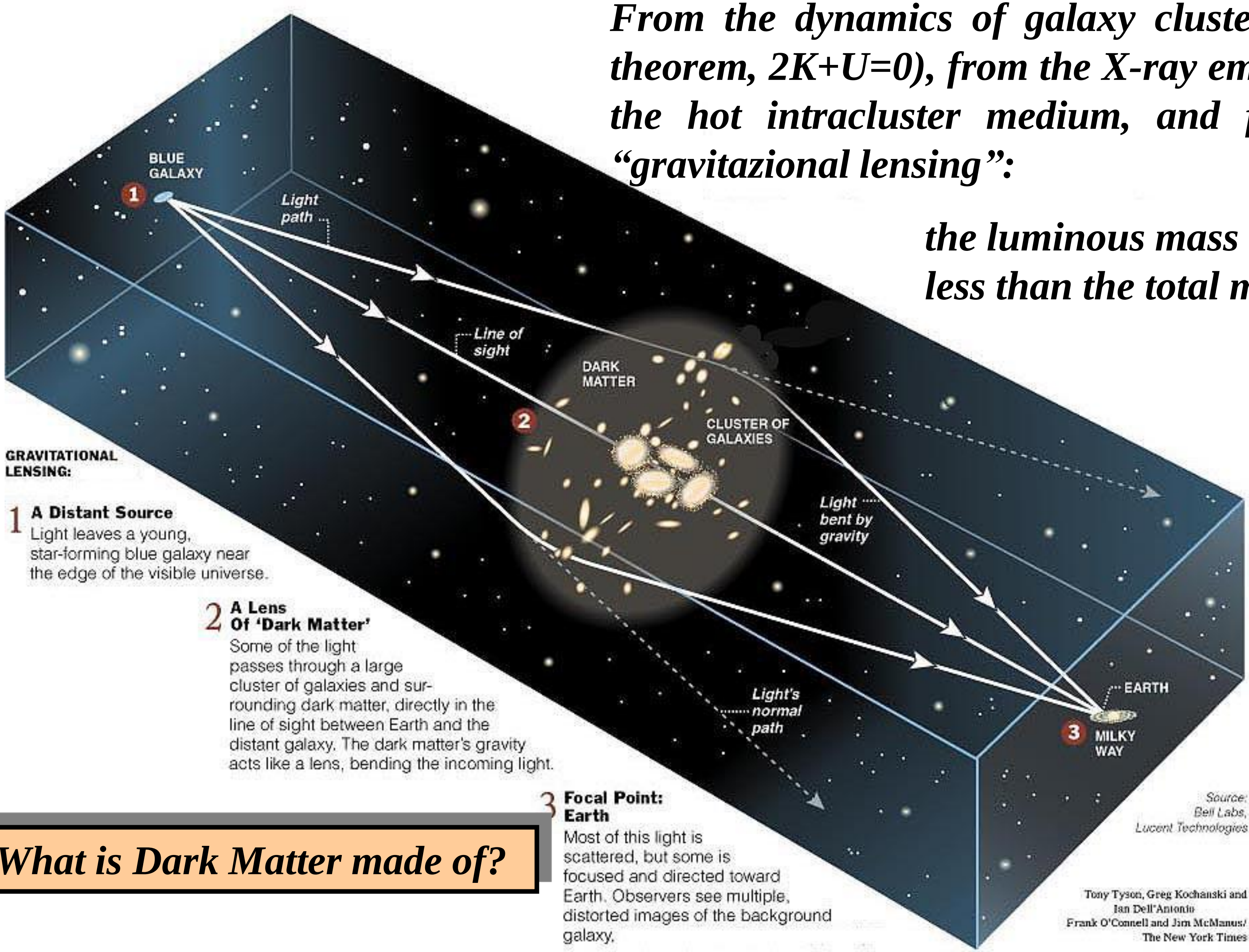


The luminous mass (stars) is only a small fraction of the total mass of galaxies

Dark matter in galaxy clusters

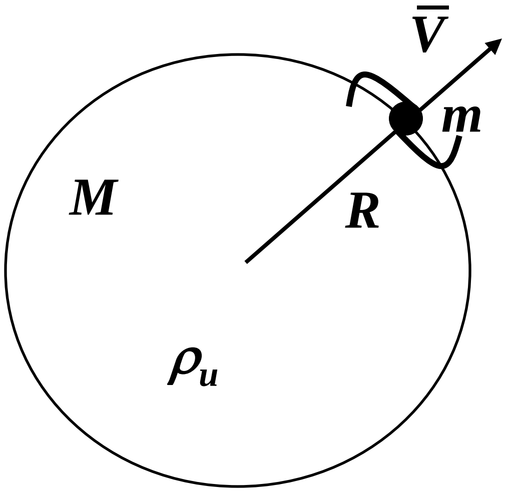
From the dynamics of galaxy clusters (virial theorem, 2K+U=0), from the X-ray emission by the hot intracluster medium, and from the "gravitazional lensing":

the luminous mass is mach less than the total mass



What is Dark Matter made of?

The mean density of the Universe



Homogeneou Universe with density ρ_u

A galaxy on the sphere containing the mass

$$M = 4/3\ \pi\ \rho_u\ R^3$$

Will have a velocity sufficient to continue expansion if its velocity V (=H_0 R) is larger than the escape velocity V_f

$$\tfrac{1}{2}\, m\, V_f^2 = G\, M\, m/R \Rightarrow V_f^2 = 2\, G\, M/R$$

$$H_0^2 R^2 \geq \frac{2G}{R} \cdot \frac{4\pi}{3} \rho_u R^3 \Rightarrow \rho_u \leq \frac{3H_0^2}{8\pi G} = \rho_{cr}$$

$$\rho_{cr} \cong 2 \cdot 10^{-29} g\ cm^{-3}$$

ρ_{cr} : *critical density of the Universe*

$$\rho_u \equiv \Omega \rho_{cr}$$

Ω *Density parameter*

From observations: 0.1 < Ω < 1

The mass of the Universe

(We mean: the mass of the Universe accessible to observations)

Within the sphere whose surface expands at the speed of light c:

$$c = H_0 R_H \Rightarrow R_H = c/H_0 \quad (R_H\text{: Hubble radius})$$

$$R_H \sim 3000\ h^{-1}\ Mpc \sim 10^{28}\ h^{-1}\ cm$$

$$M_u \approx \frac{4\pi}{3} R_H^3 \Omega \rho_{cr} = \frac{4\pi}{3} \cdot \frac{c^3}{H_0^3} \cdot \Omega \cdot \frac{3H_0^2}{8\pi G} \approx \frac{\Omega}{2} \cdot \frac{c^3}{H_0 G}$$

From $V = H_0 R \Rightarrow R/V = 1/H_0 \sim t_u$ ***age of the Universe***

$$H_0 = 100\ km\ s^{-1}\ Mpc^{-1} \sim 3 \times 10^{-18}\ s^{-1} \Rightarrow t_u \sim 10^{10}\ \text{anni}$$

$$M_u \approx \frac{\Omega}{2} \cdot \frac{c^3}{H_0 G} \approx \frac{\Omega}{2} \cdot \frac{c^3}{G} \cdot t_u \approx \Omega \cdot 10^{56} g \approx \Omega \cdot 10^5 \left(\frac{t_u}{1\,s}\right) M_\odot$$

$$0.1 < \Omega < 1 \Rightarrow M_u \sim 10^{22}\ M_\odot$$

$$M_{gal} \sim 10^{11}\ M_\odot \Rightarrow M_u \sim 10^{11}\ M_{gal}$$

The mass of the Universe must be "great" because the age of the Universe must be such as to allow the existence of physicists, made of C, N, O.
These elements are produced in stars in different generations and require times of the order of a few billion years.

This is an aspect of the so-called (weak) **Anthropic principle** *:*
"The observed values of all physical and cosmological quantities are not equally probable, but can assume only values that satisfy the demand that there are places where carbon-based life can evolve and that the universe is old enough to allow that this already happened".
(J.D. Barrow & F.J. Tipler, **The Antropic Cosmological Principle)**
"strong" version: "The Universe must have properties that allow life to develop during its history"

The nearby Universe

Video downloadable from:

http://www.ifa.hawaii.edu/~tully/outreach/movie.html

Thanks to its progress, Cosmology allowed man to ask new questions about the Universe

Cosmology

as seen

by Snoopy