# *Cosmology*

Master NPAC

*Lesson 1 (Introductory lesson) :*
*History and Observational facts*
*Measuring distances in the Universe*
*Universe dynamics*
*What is the Universe made of ?*

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2016-11-07

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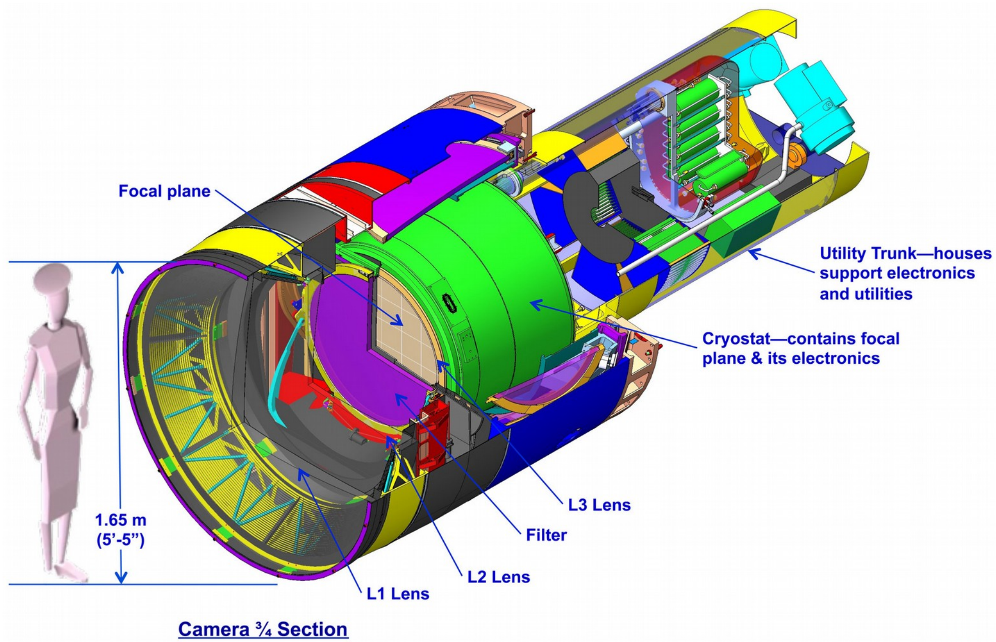
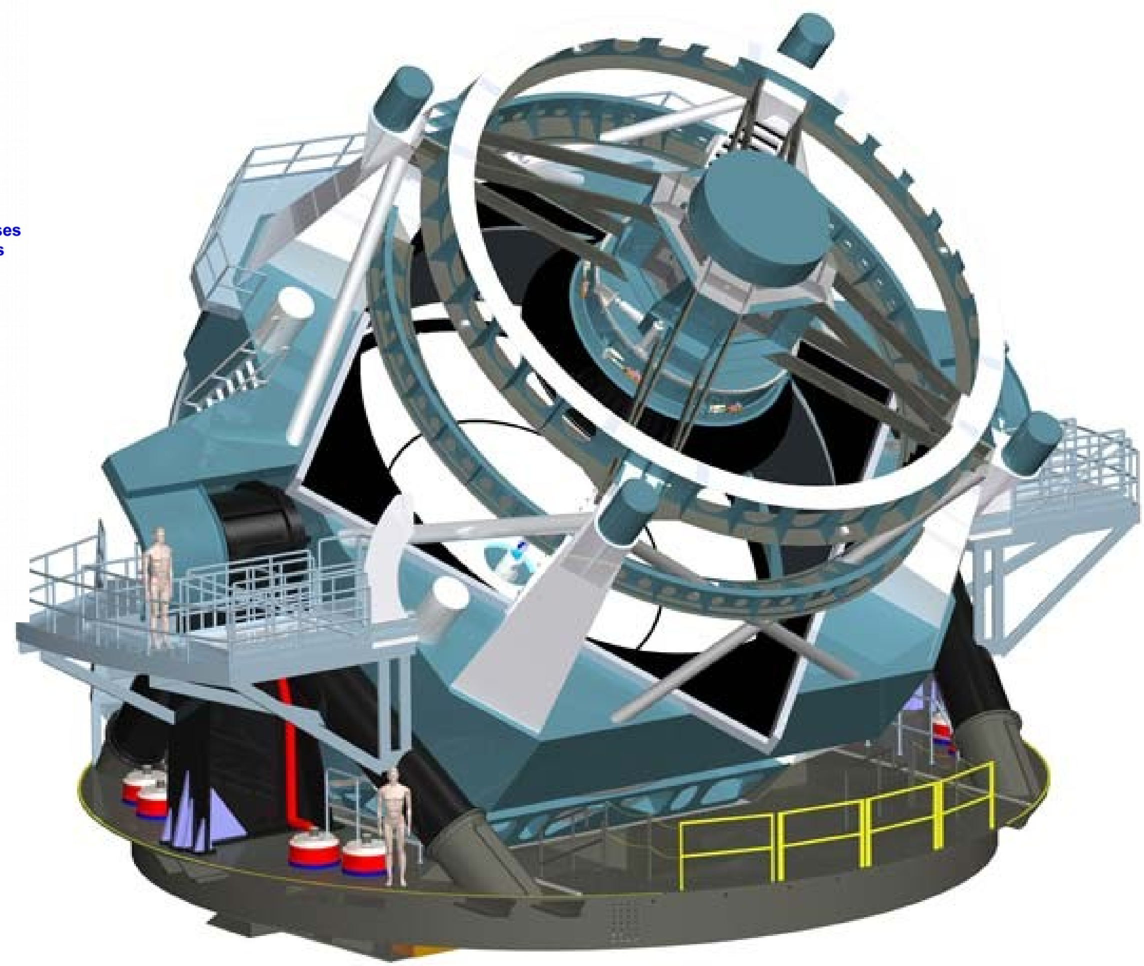
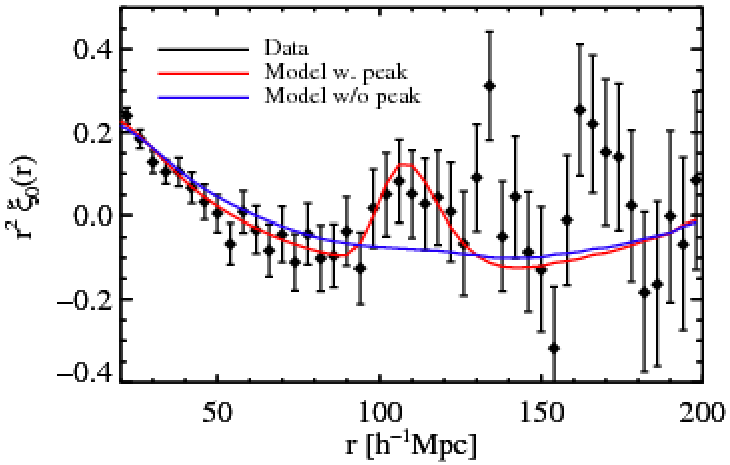
(14 faculty/CNRS, 4 postdocs, 3 PhD students)
Cosmology with SNIa, BAO, instrumentation, calibration.

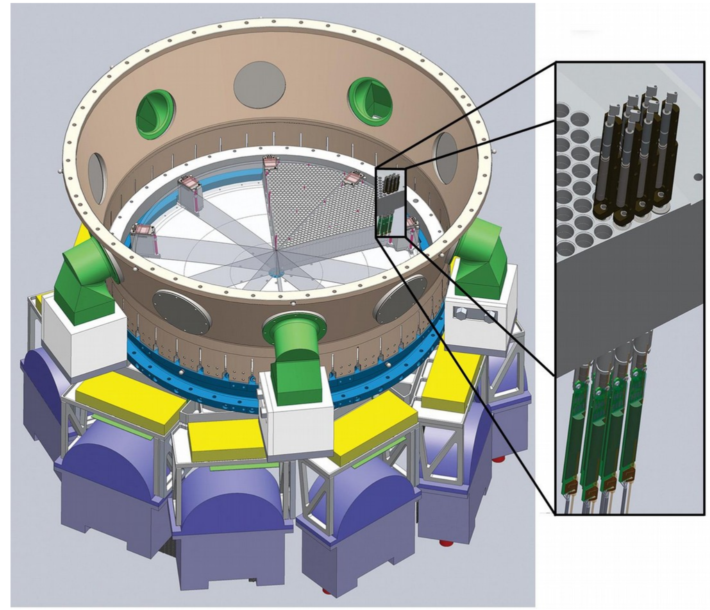
Research: Instrumentation for Cosmology (LSST), Instrumental Calibration (DICE), SN observations, Baryonic Acoustic Oscillations (DESI)

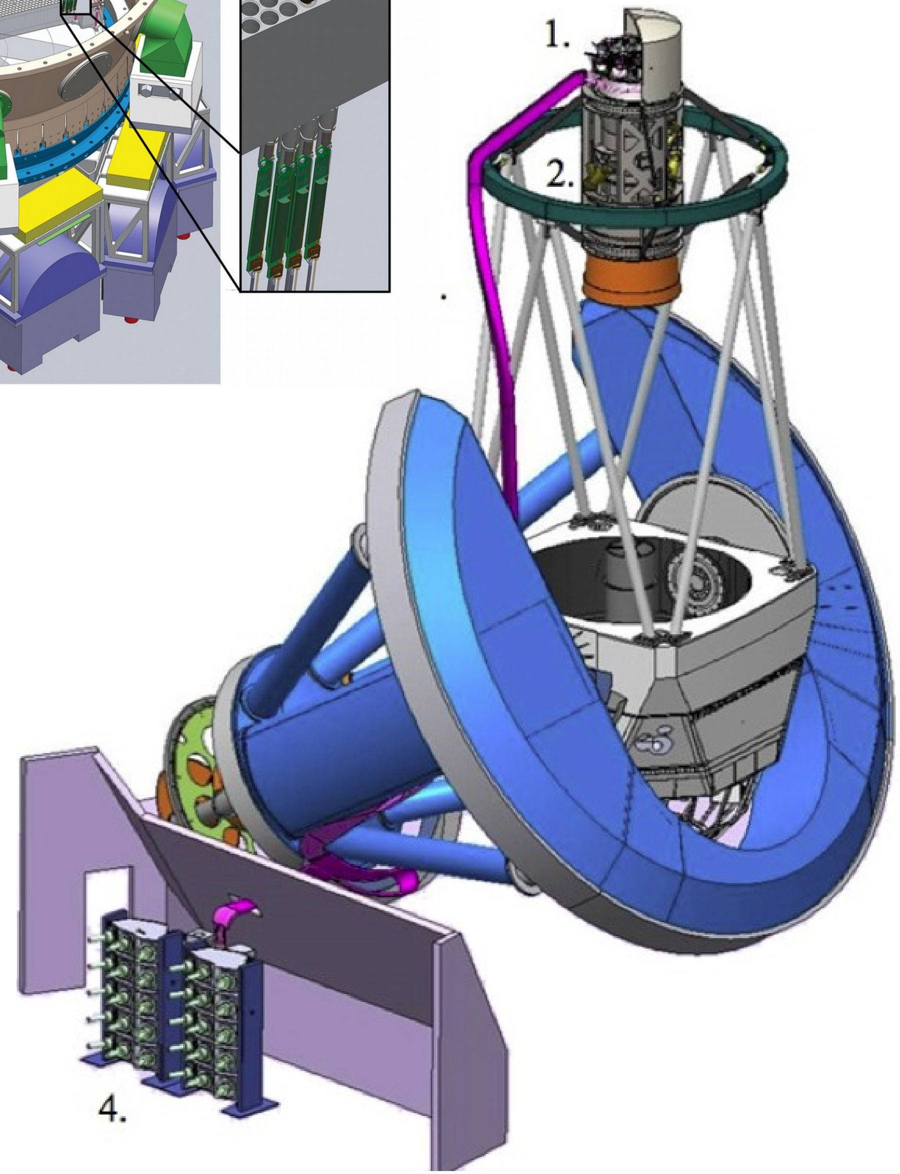


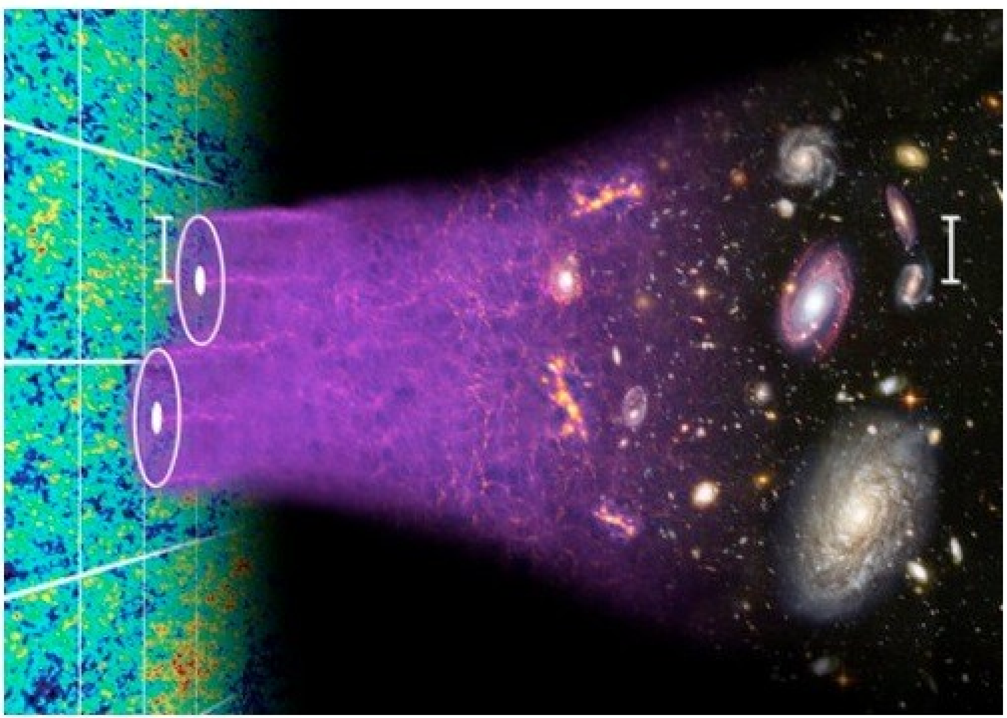

**LSST**, 8.4-m, 9.6 deg$^2$
Chile, Cerro Pachon
First light ~ 2022
20000 deg$^2$, 1000 visits in 10 y







Scales of certain physical processes, imprinted on the CMB, survive to the late-time universe and can be see in the clustering signal of galaxy positions

**DESI (Mayall)**, 4-m, 3.2 deg$^2$
Arizona, US, Kitt Peak (KPNO)

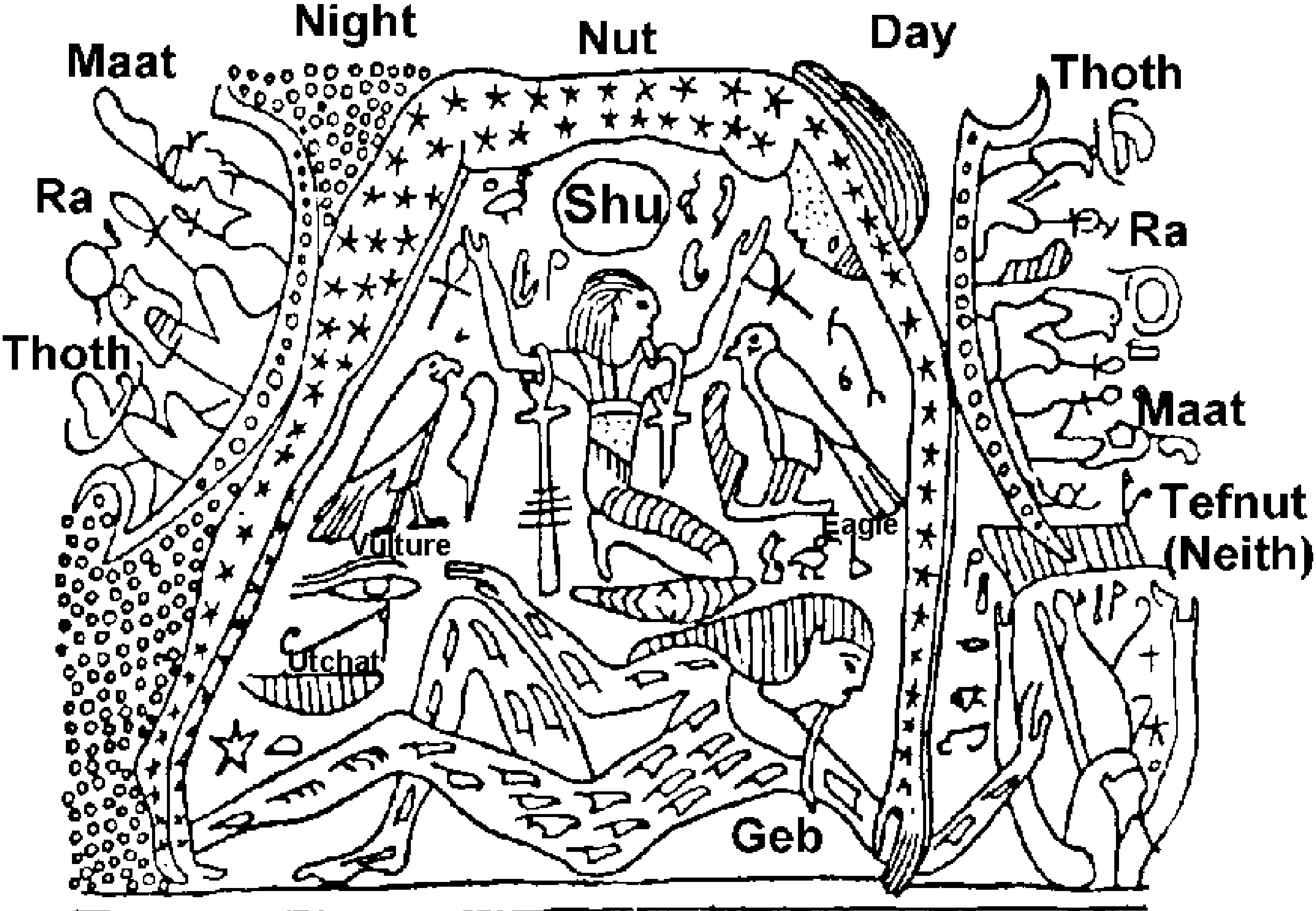
# *Contents*

1.1

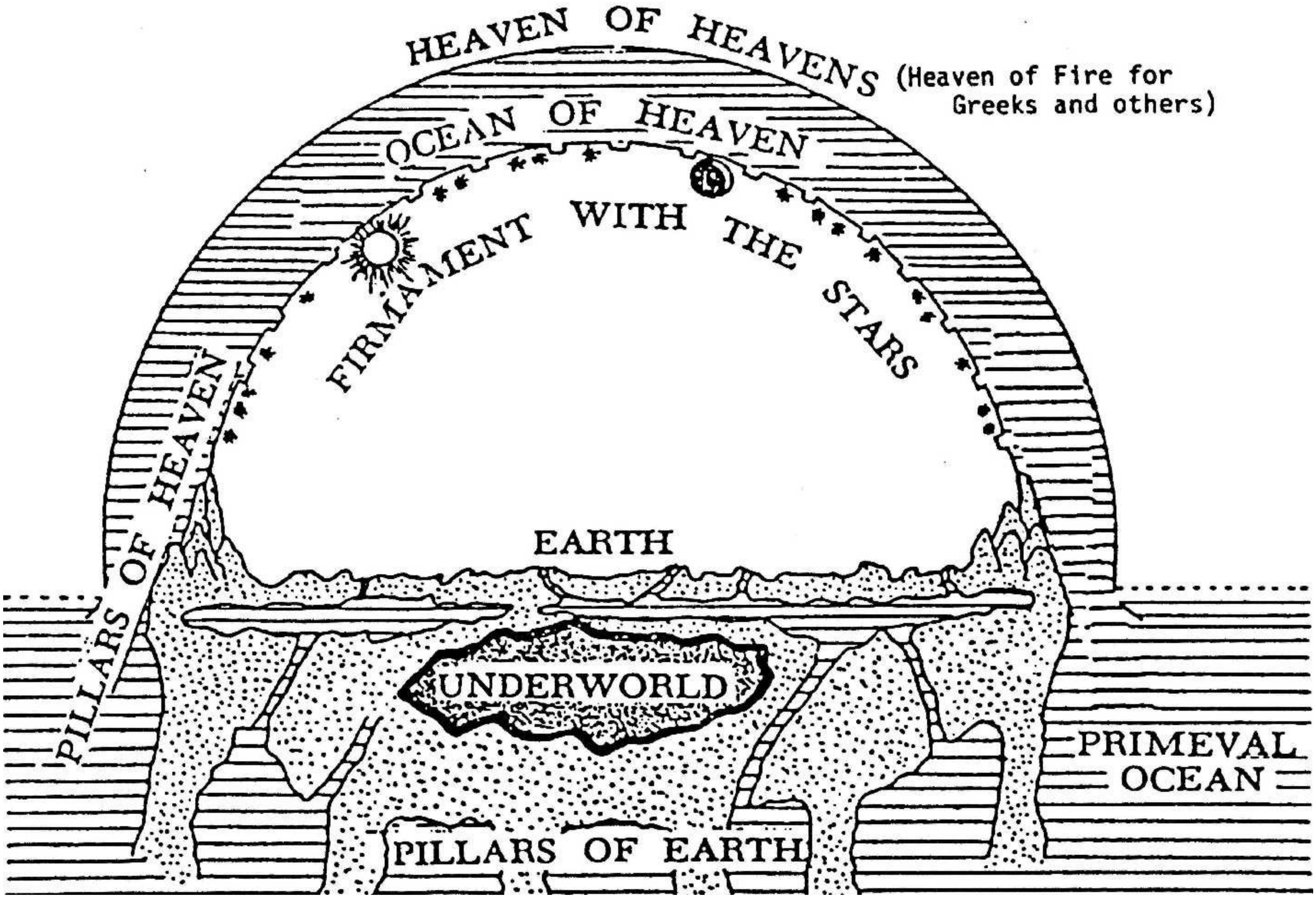
# *A (brief) history of Cosmology*

*Worldviews across the ages*
*Origins of Modern Cosmology*

# *Egyptian Cosmology*



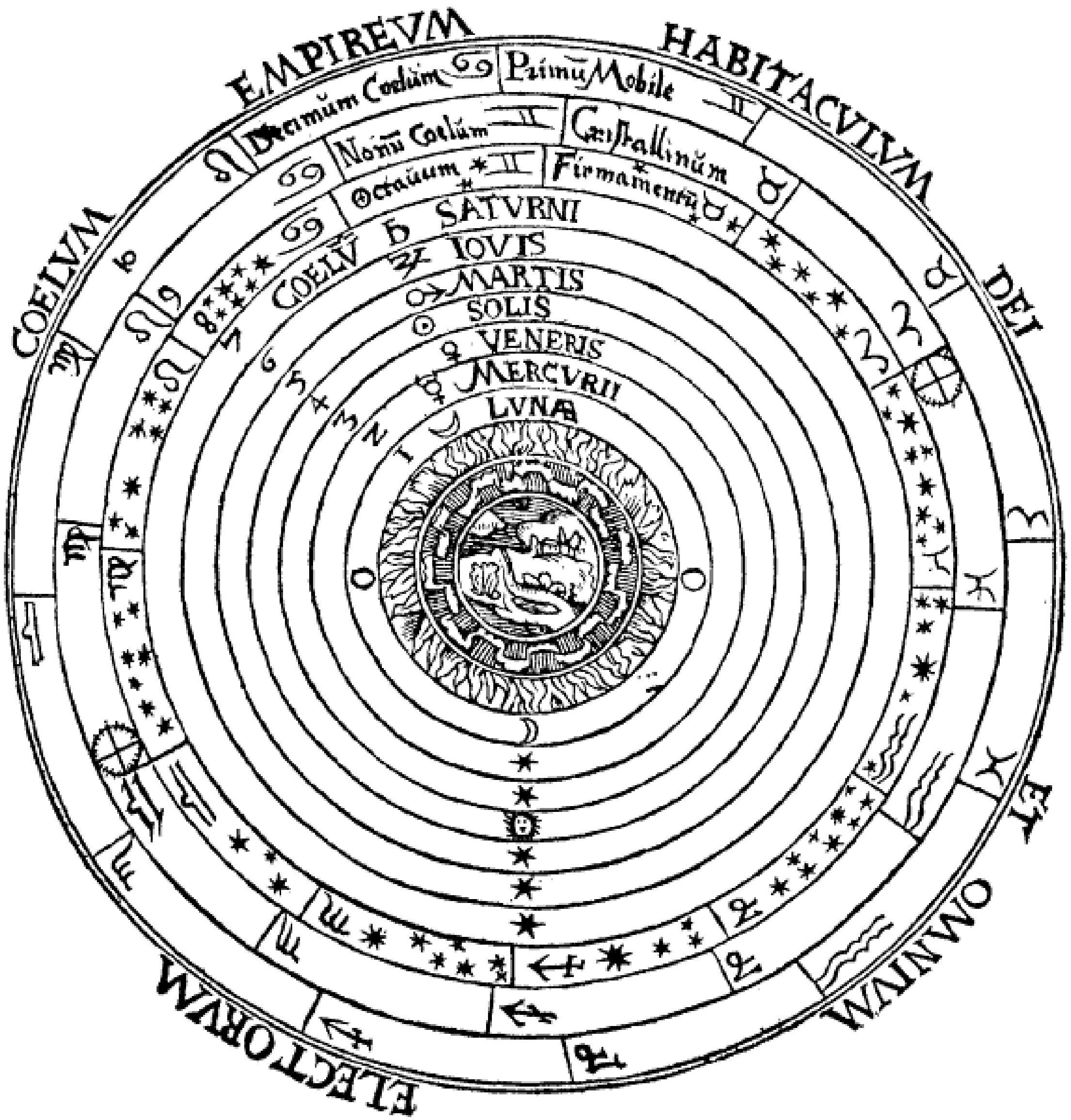

Duat of Osiris

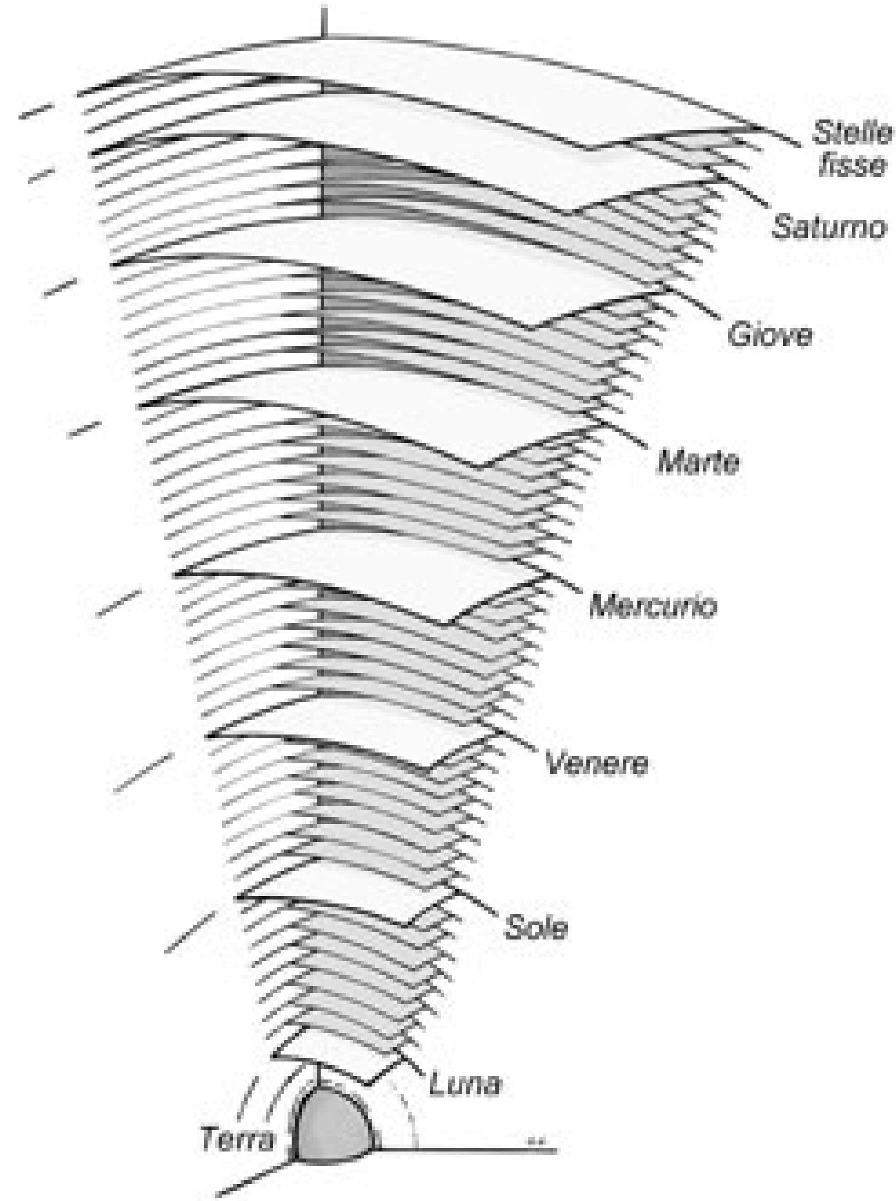

HEAVEN OF HEAVENS
(Heaven of Fire for Greeks and others)
OCEAN OF HEAVEN
FIRMAMENT WITH THE STARS
PILLARS OF HEAVEN
EARTH
UNDERWORLD
PRIMEVAL OCEAN
PILLARS OF EARTH

# Celestial spheres

*Eudoxus of Cnidus (IV century B.C.).*

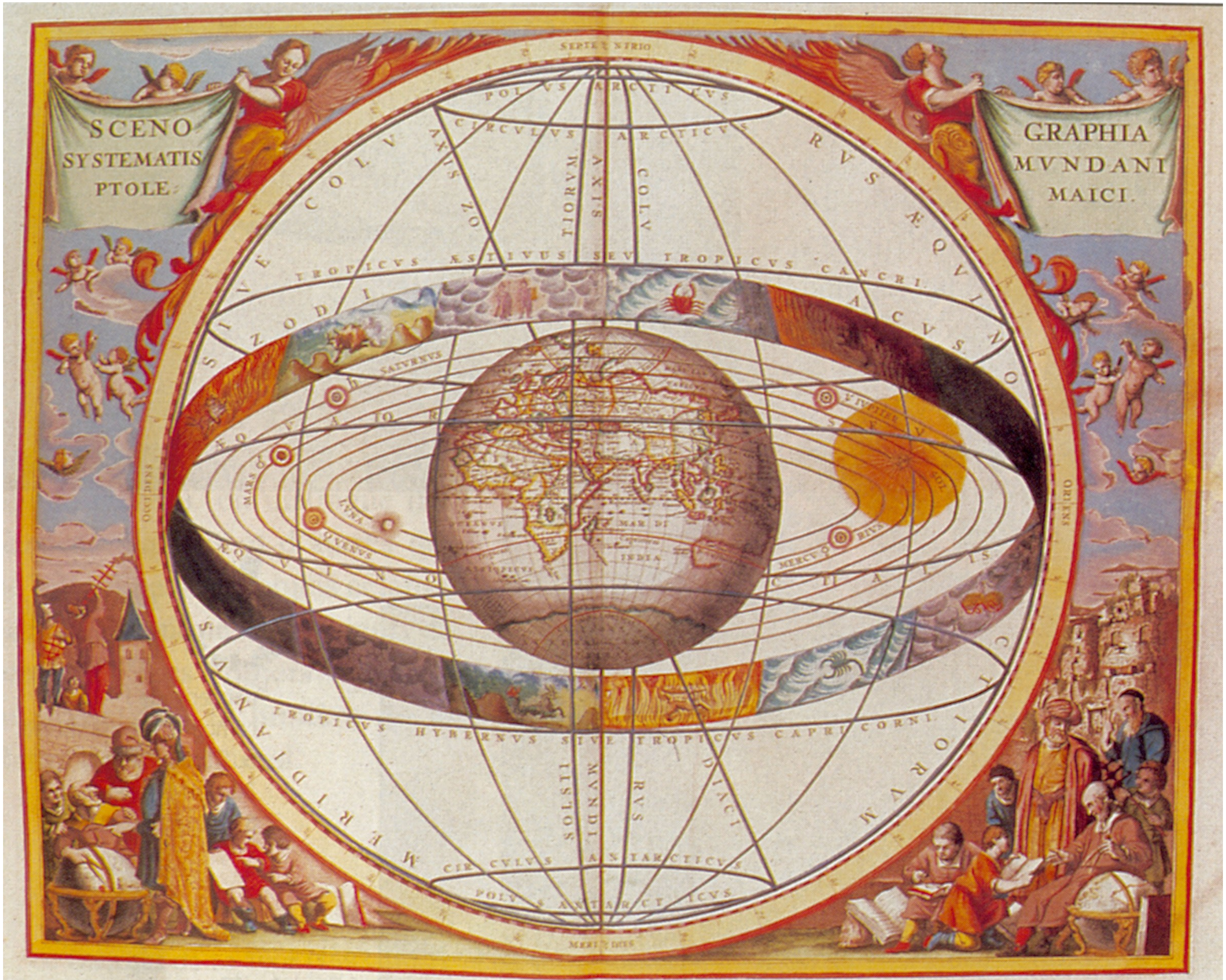
Schema huius præmissæ diuisionis Sphærarum .



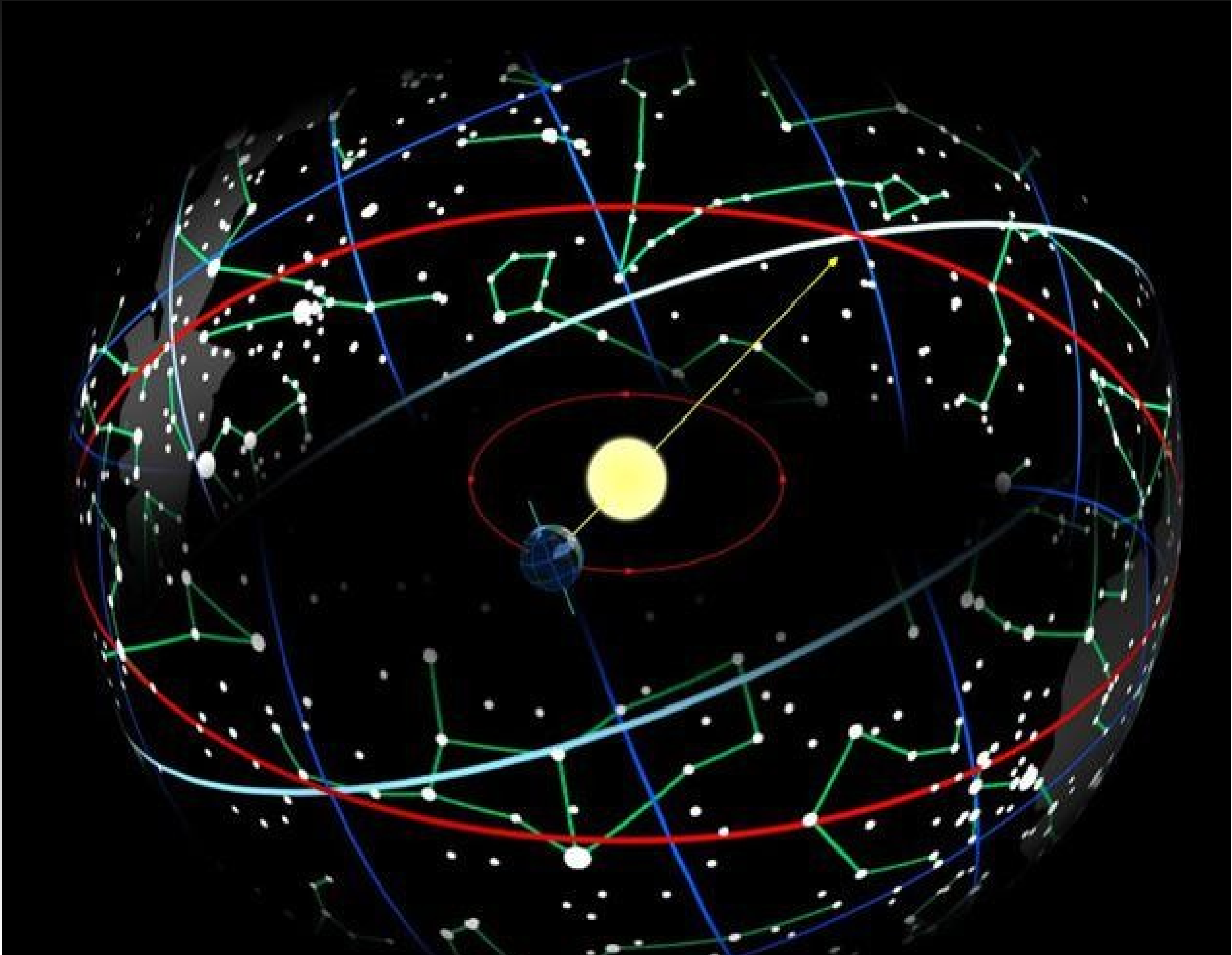



# *Sphere of fixed stars*

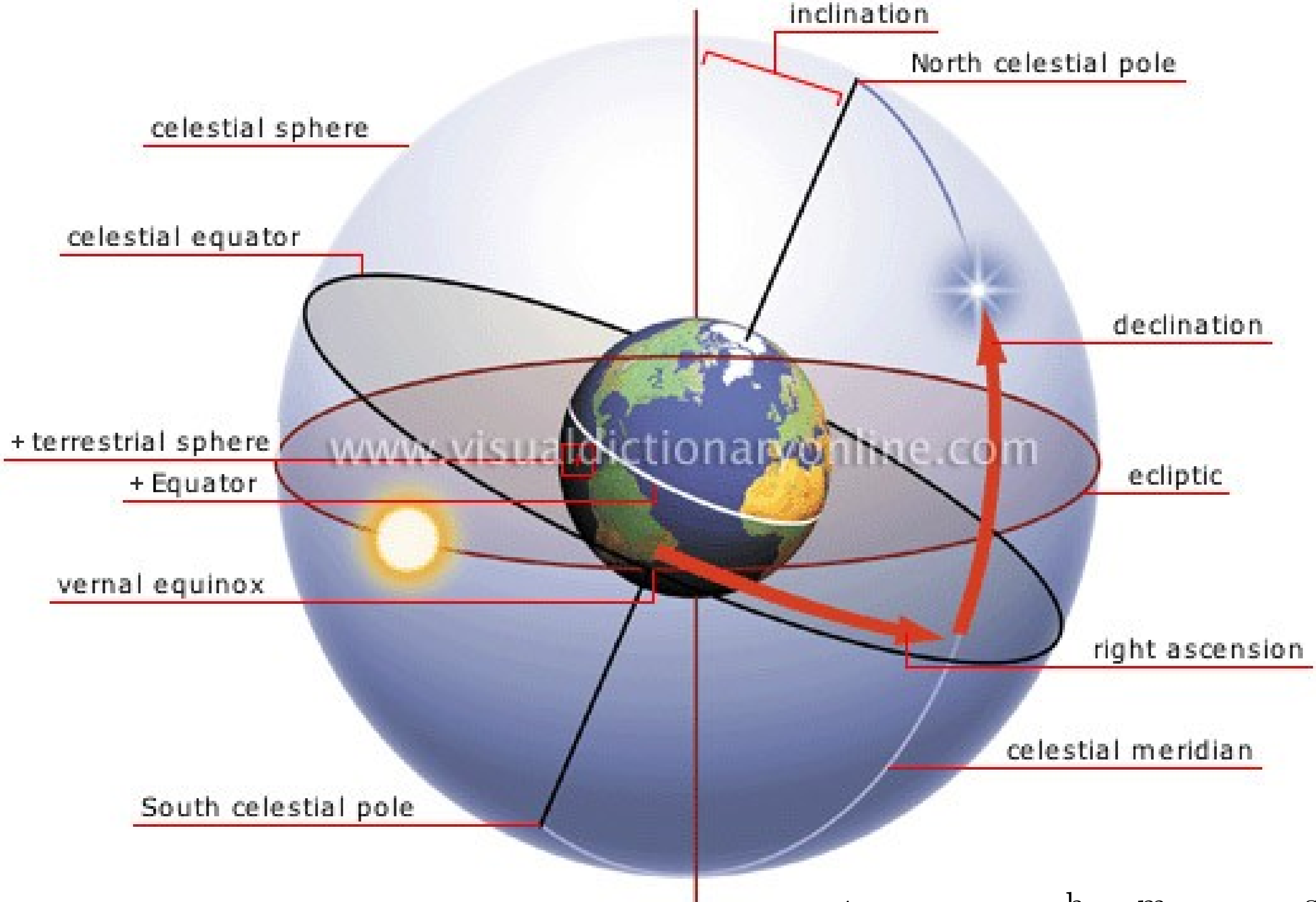
# *Ancient Greece (Ptolemy)*



# *The Sphere of the « fixed » stars...*



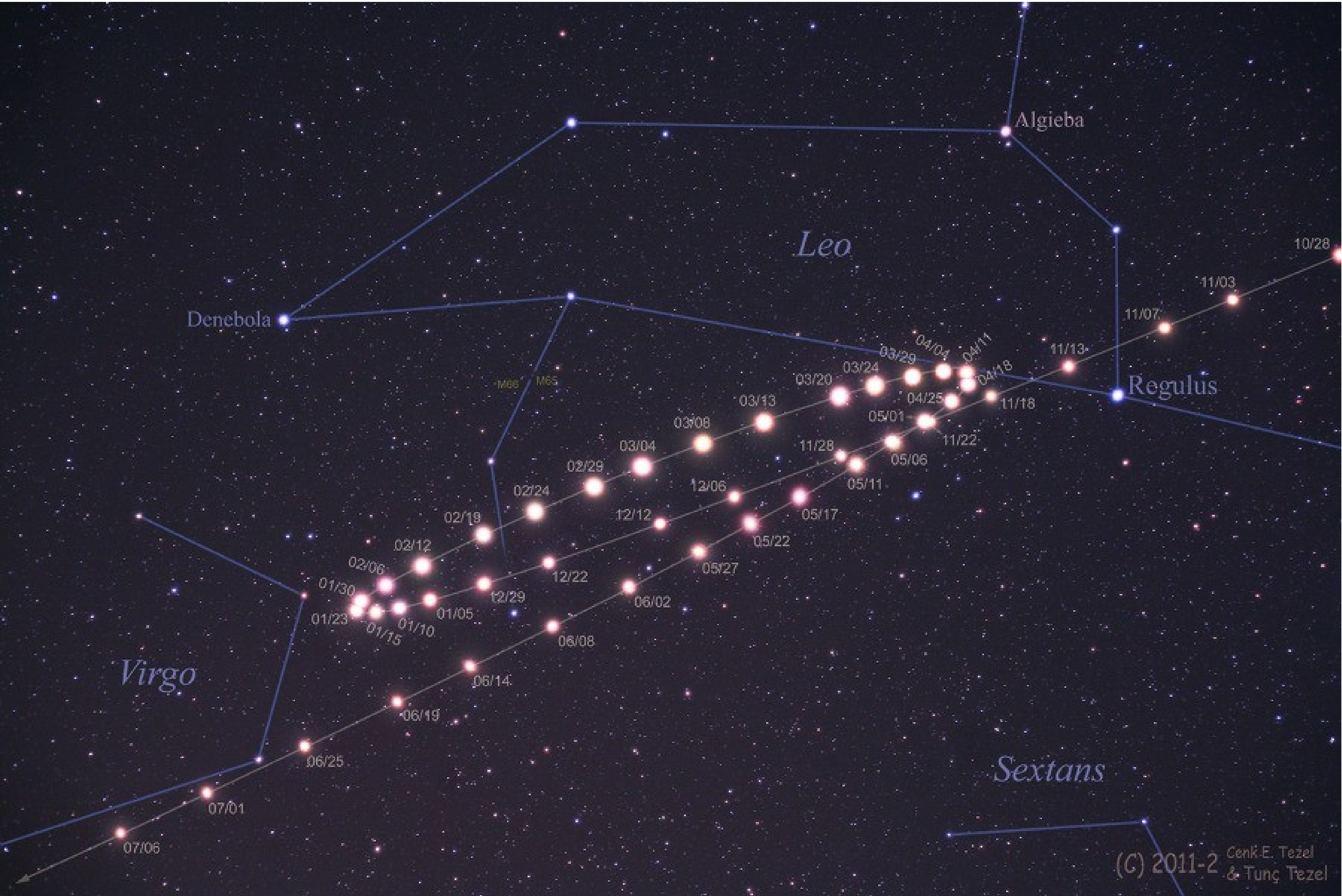
# *Celestial coordinates*

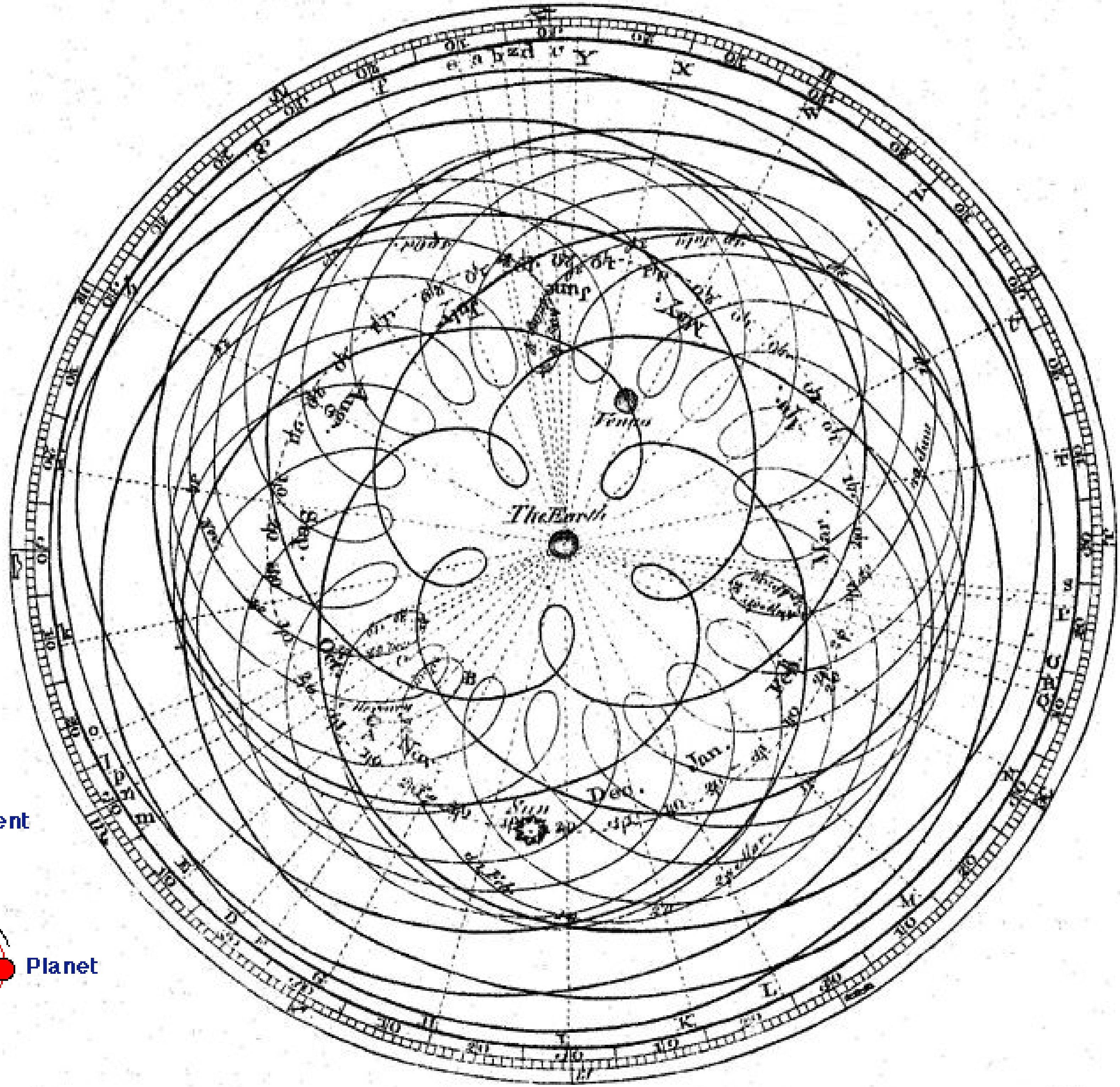


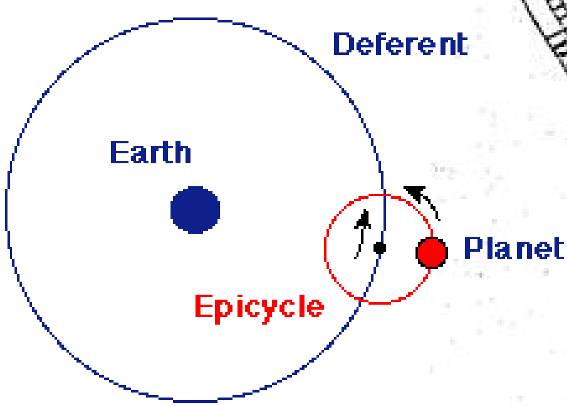

(M31) Andromeda :

$$RA = \alpha = 00^{\rm h}42^{\rm m}44.330^{\rm s}$$
$$DEC = \delta = +41^{\rm o}\,16'\,07.50''$$

# *Retrograde movement of Mars*




The Earth
Venus
Sun
Jan.
Dec.

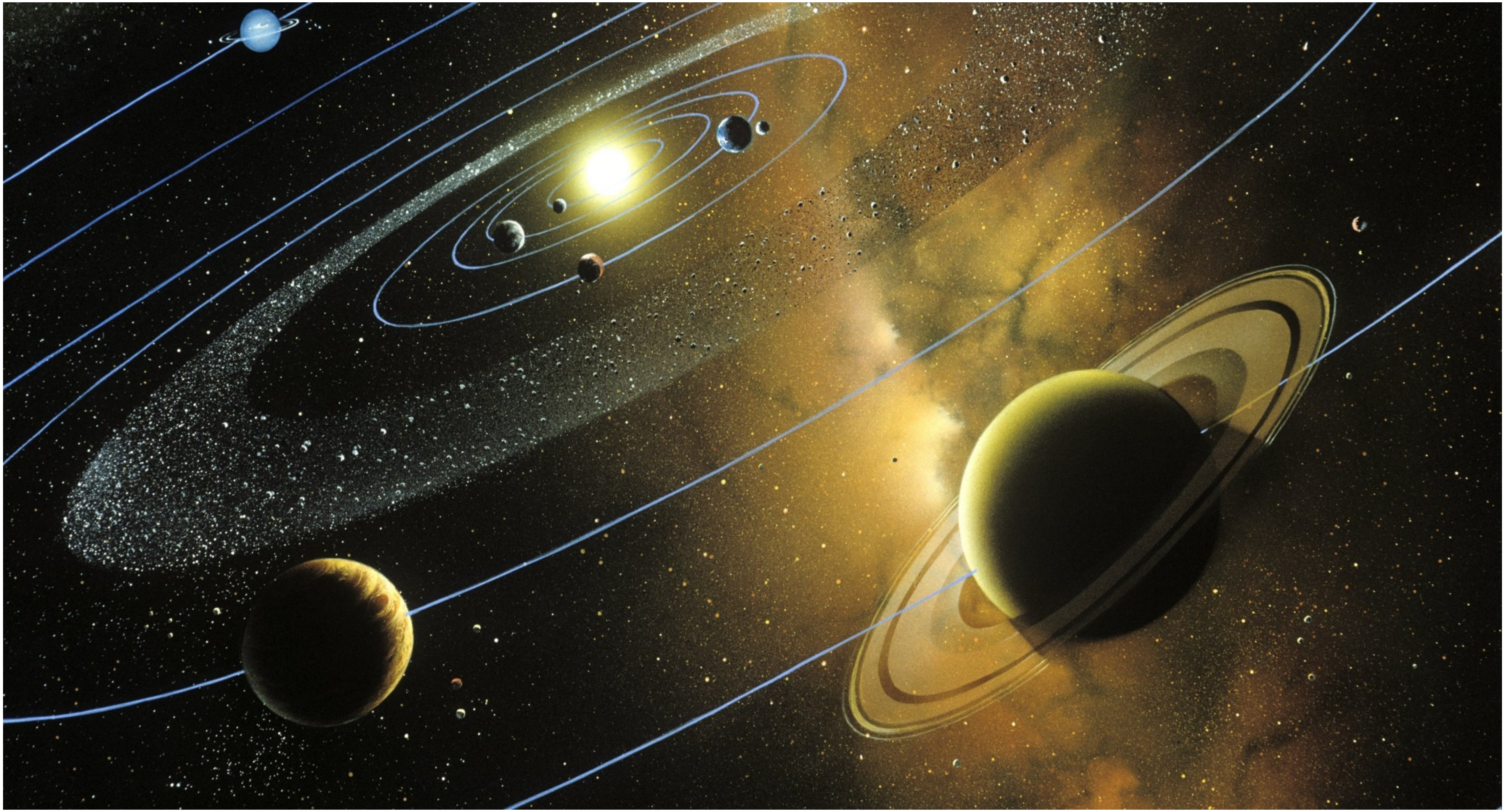

Deferent
Earth
Planet
Epicycle

# *Copernician revolution*

*Nicolaus Copernicus (1473 – 1543), J. Kepler, ...*

# *The Solar System*

*A modern view*

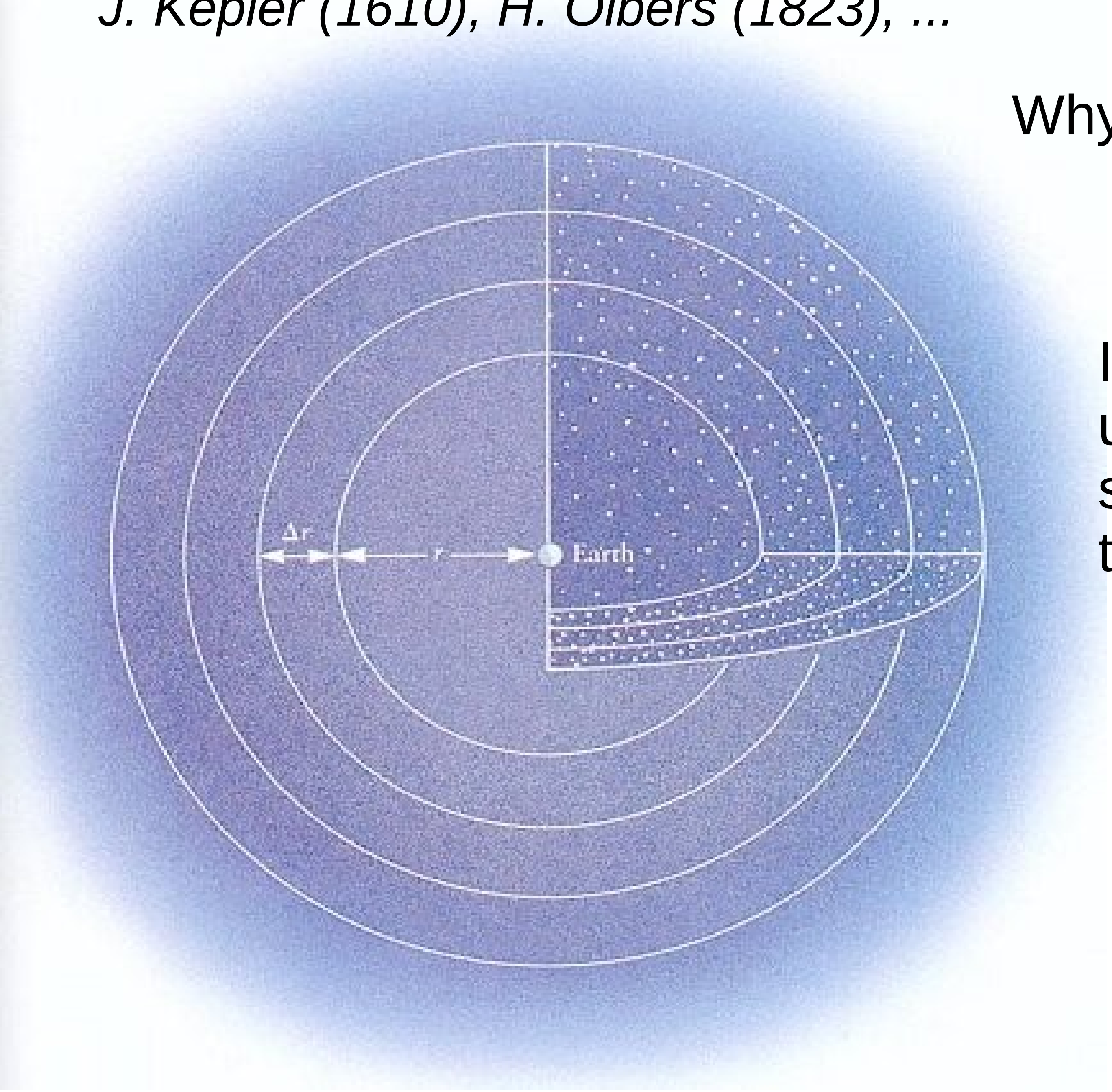


*7 planets + Uranus (Herschel, 1781) + Neptune (Galle/Le Verrier 1846) + Pluton (1930)*

Cassiopeja.
PERSEUS.
Camelopardalus.
Andromeda.
Auriga.
Triangulum
Majus.
Minus
Musca.
Taurus
Aries.
Fig. W.
Longitudo
Latitudo
Via
Lactea

# *Olbers paradox*

*J. Kepler (1610), H. Olbers (1823), ...*



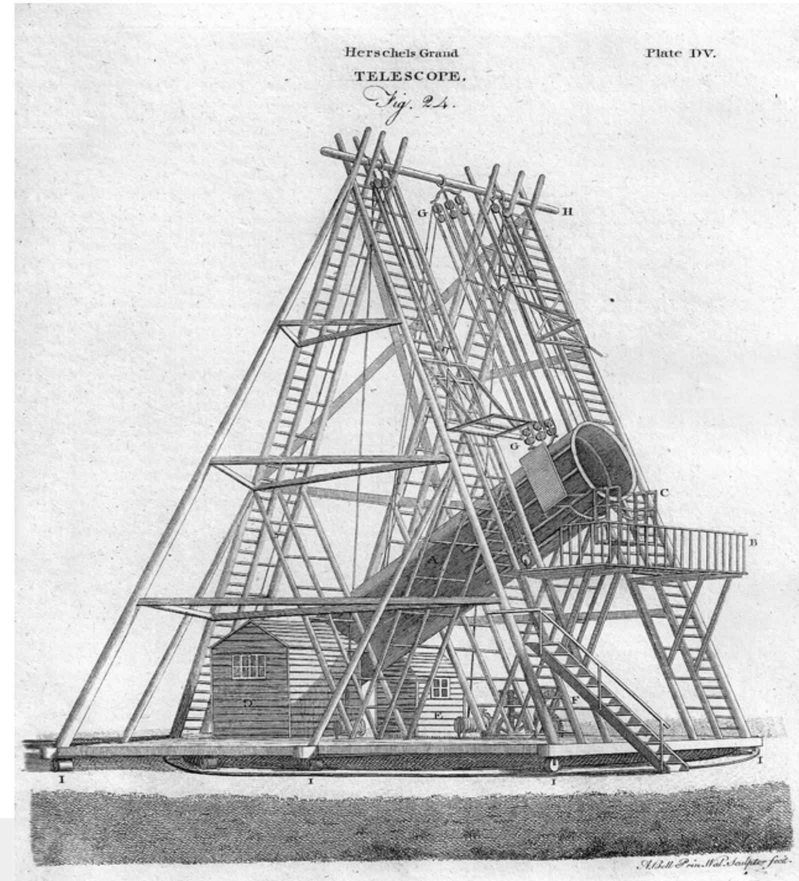

Why is the night sky dark ?

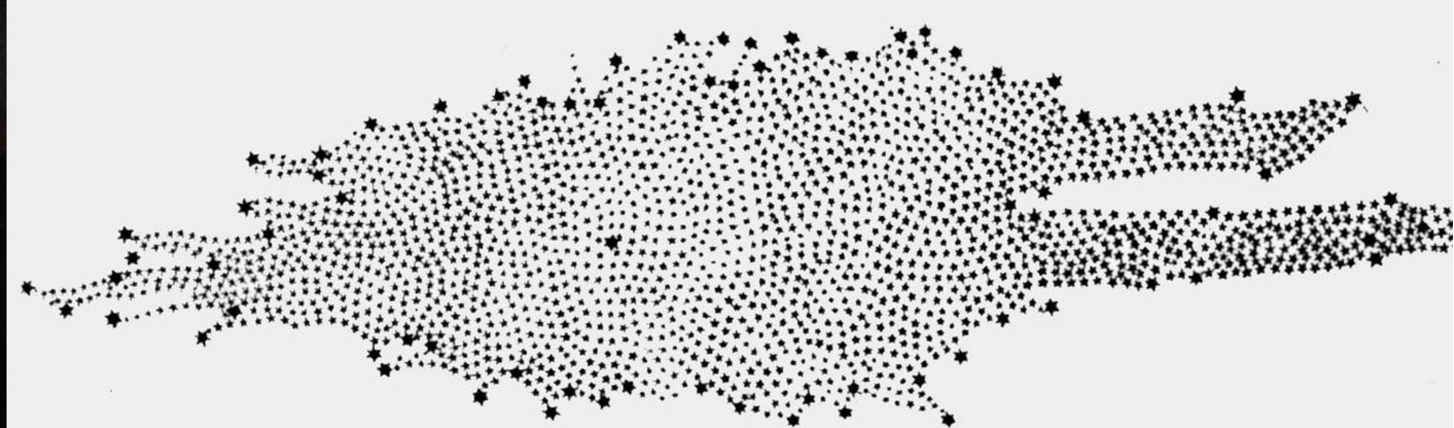
In an infinite and static universe, the sky should be as bright as the sun surface

# *Our « galaxy »*

W. Herschel suggests (1781) from star counts that the shape of the « universe » may be lenticular.

First hints about our own galaxy,
and extra galactic objects (« nebulae »).

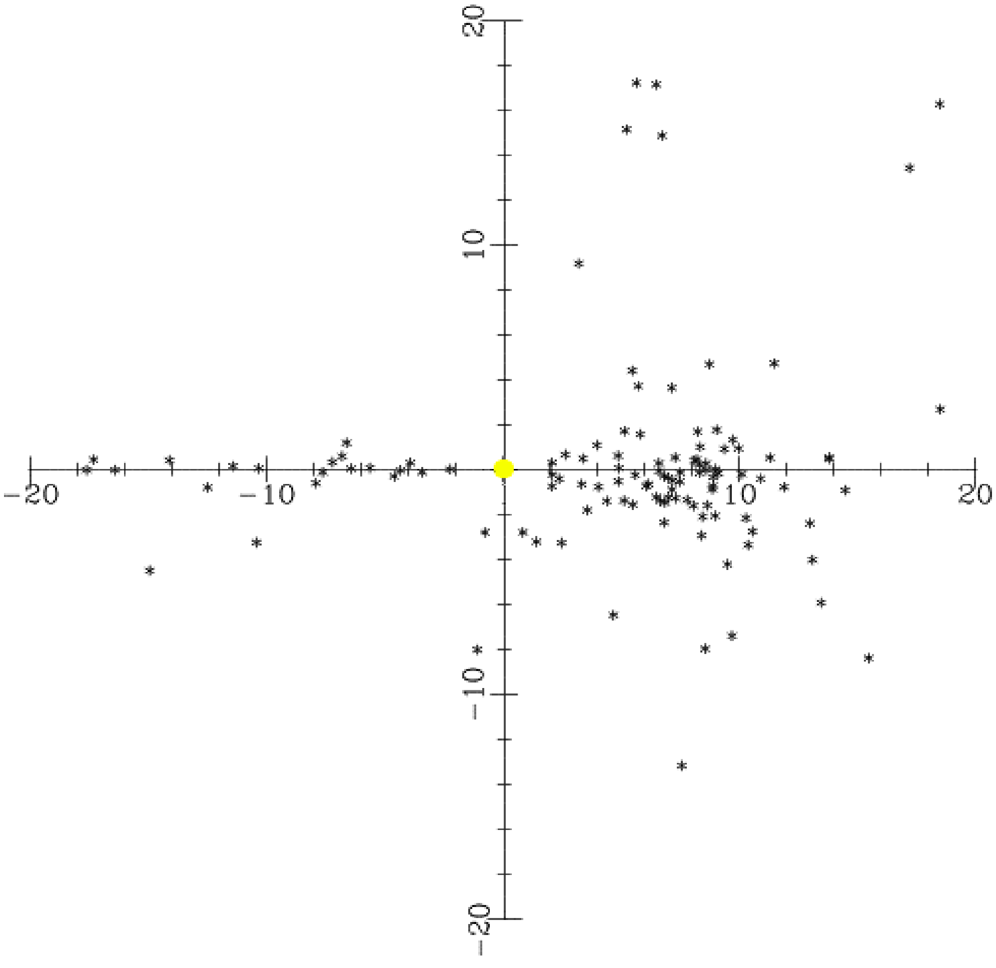


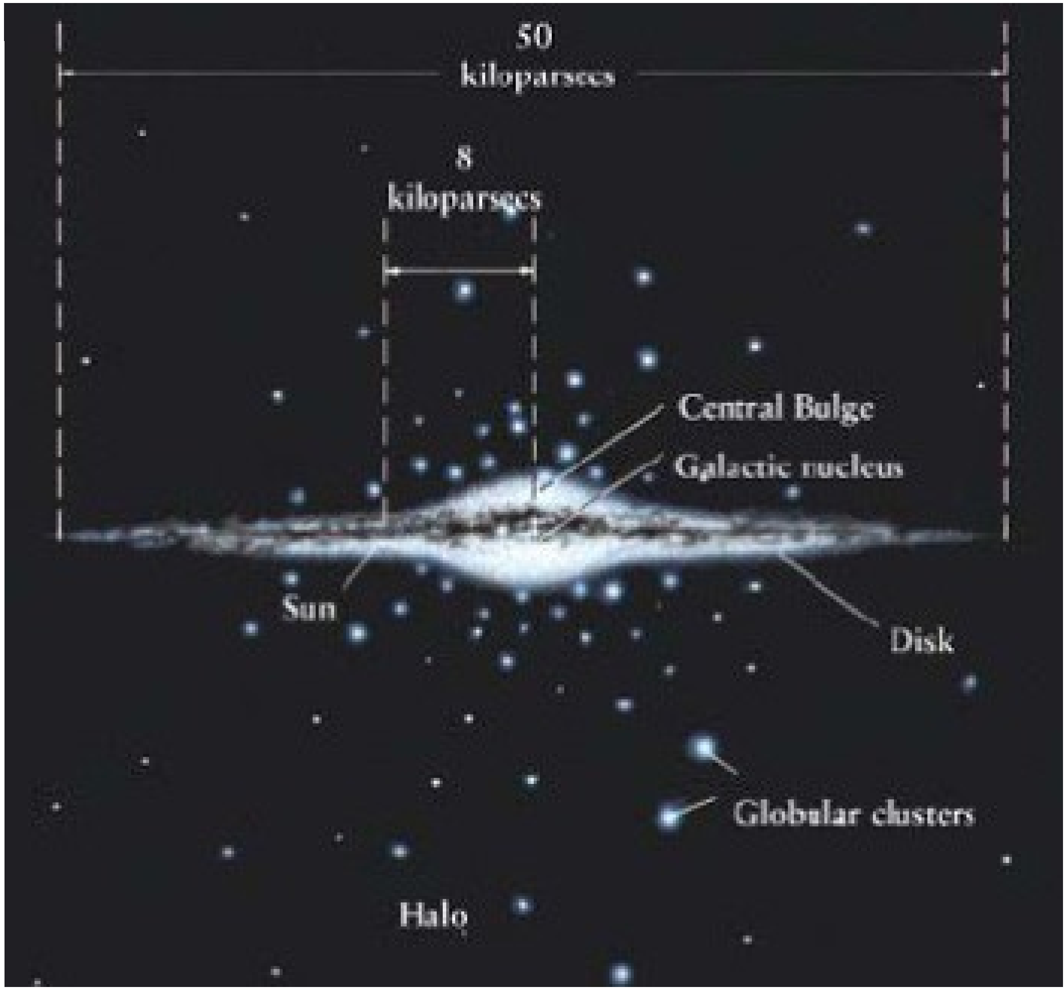



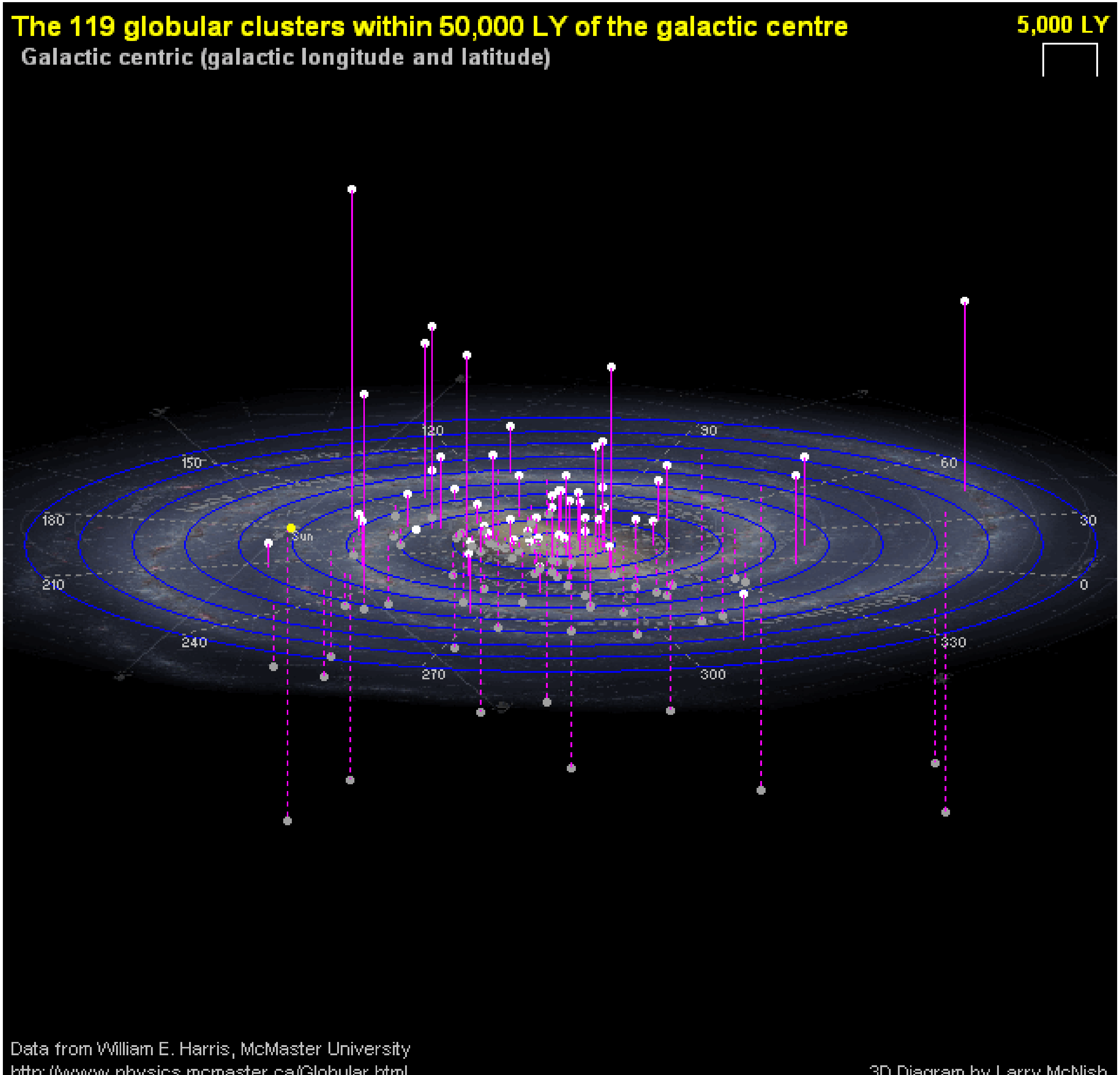
# Our position in the Galaxy

*H. Shapley (1885 – 1972)*

*From the distribution of the globular clusters (distances from RR Lyrae / cepheids)*

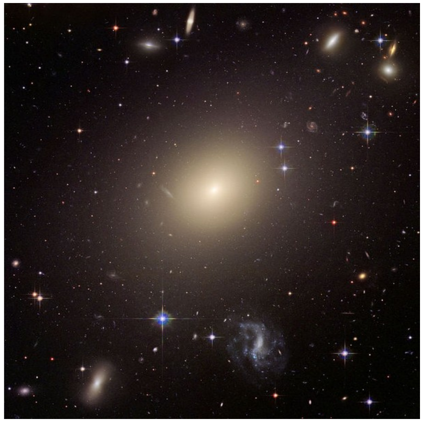



The 119 globular clusters within 50,000 LY of the galactic centre
Galactic centric (galactic longitude and latitude)
5,000 LY
120
90
150
60
180
30
210
0
240
330
270
300
Sun
Data from William E. Harris, McMaster University
http://www.physics.mcmaster.ca/Globular.html
3D Diagram by Larry McNish

# *The Great debate (1920)*

*H. Shapley (1885 – 1972) – H. Curtis (1872 – 1942)*



Are the fuzzy faint « nebulae » extra galactic objects ?
Are they « island-universes » similar to our own ? (Shapley)

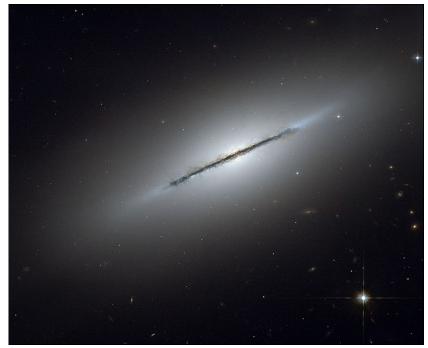
Or are they objects close to us ?
Does the « galaxy » constitute the entire Universe ? (Curtis)

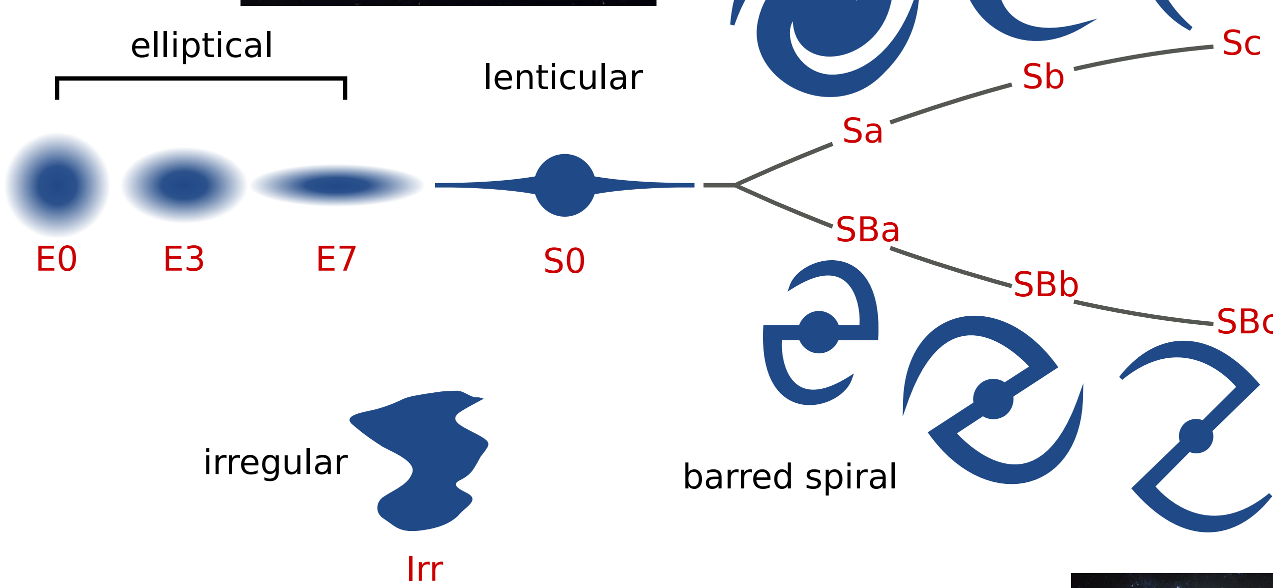
Mid-1920s → Hubble measured the distance to M31 using Cepheids

*Conclusion : the Universe is much bigger !*

# *Classification of the galaxies*

*E. Hubble, M. Humason*






# *Hubble's law*

Redshift z :

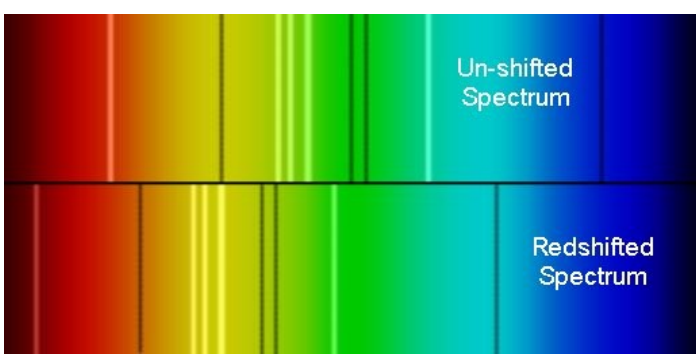
$$\lambda_{\text{obs}} = \lambda_{\text{emit}}(1+z)$$

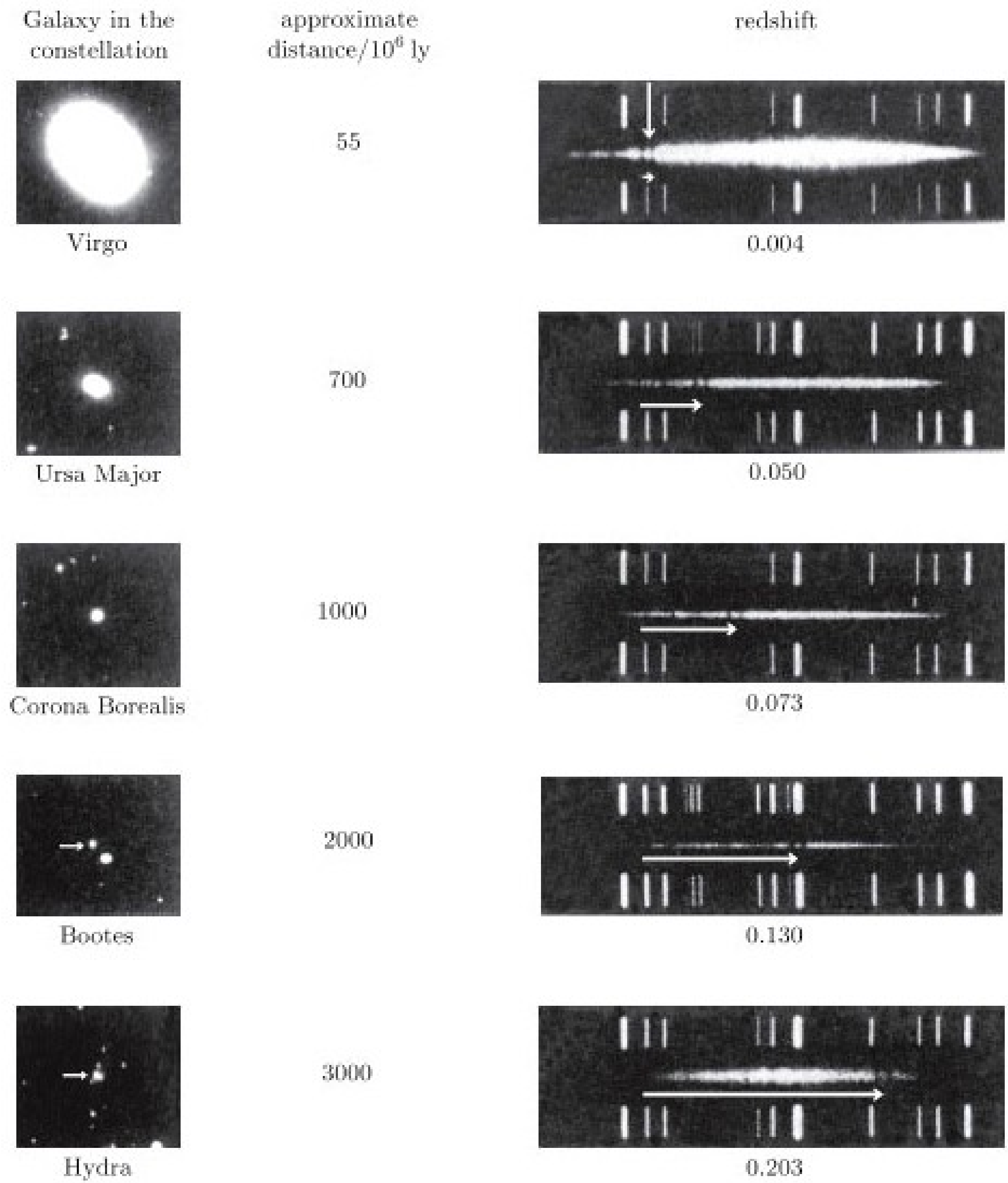
$$z = \frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} - 1$$

« Doppler » effect :

$$\frac{\lambda_{\text{obs}}}{\lambda_{\text{emit}}} = \sqrt{\frac{1+\beta}{1-\beta}} \simeq 1+\beta$$

$$z \simeq \beta \qquad v \simeq cz$$



# *Hubble's law* $v = cz = H_0\, d$

*(1929)*

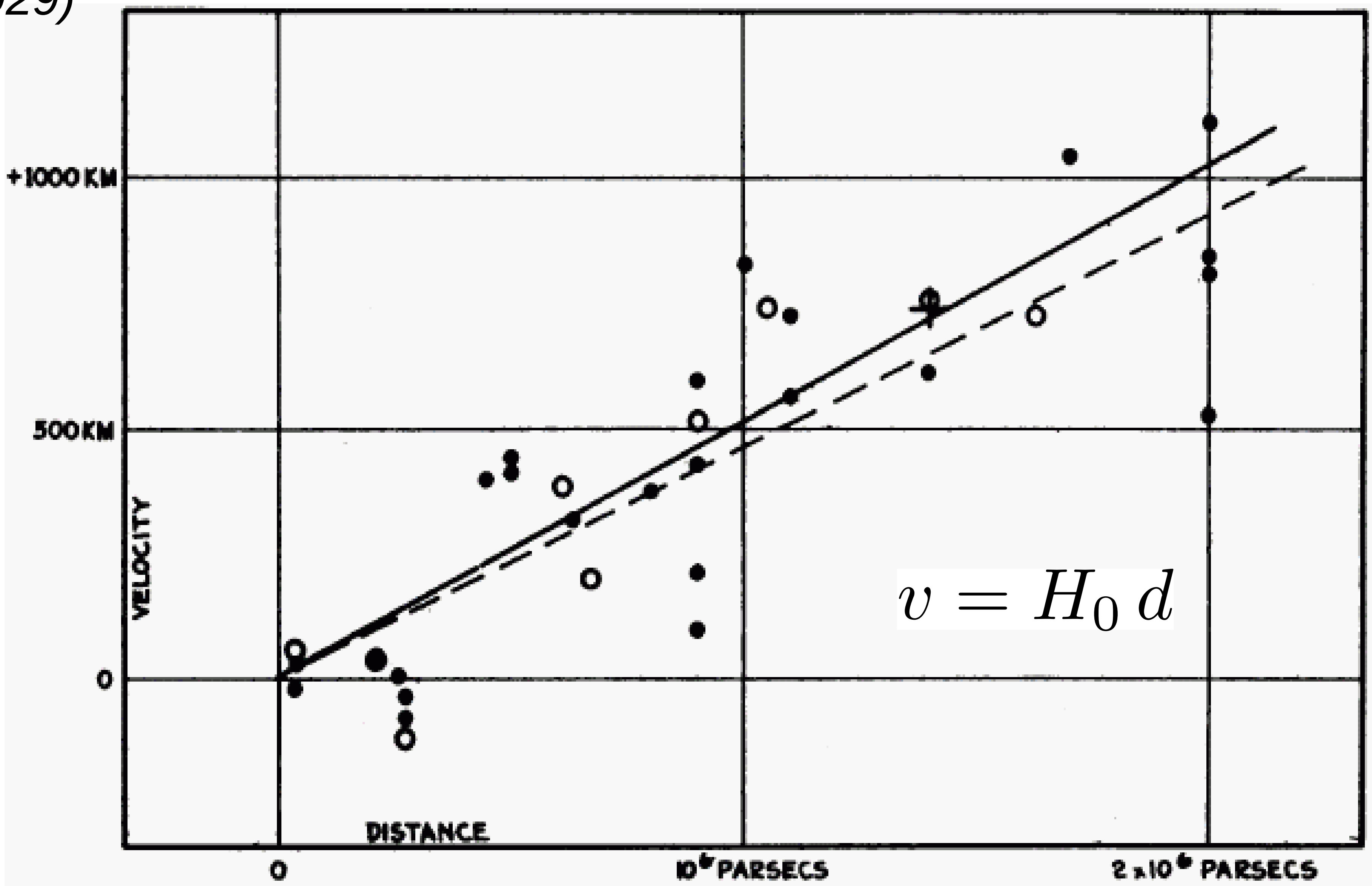
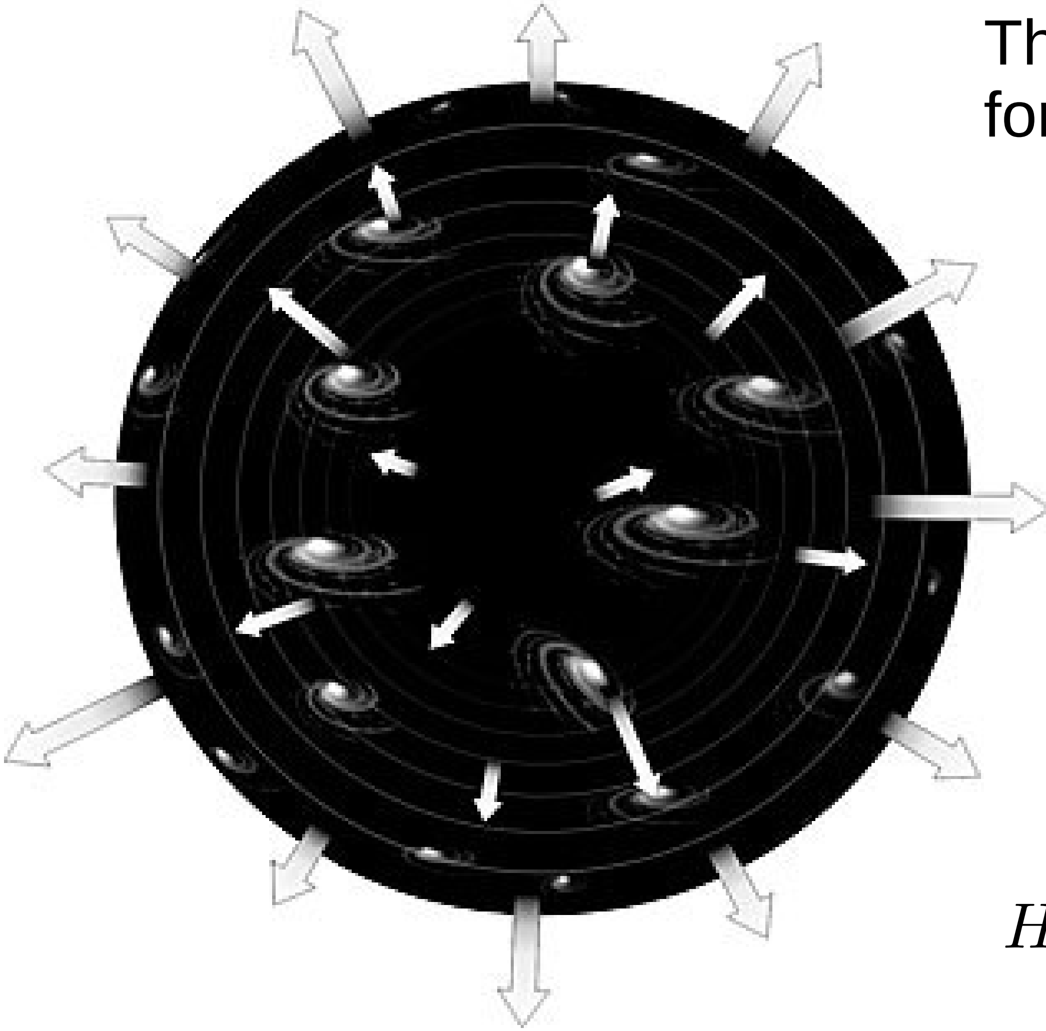



FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

# *The Universe is expanding !*

*E. Hubble, G. Lemaître, A. Friedmann, ...*



The point of view is the same for any galaxy : no center

Isotropy and homogeneity at large scale

Typical age of the Universe : *Hubble time* :

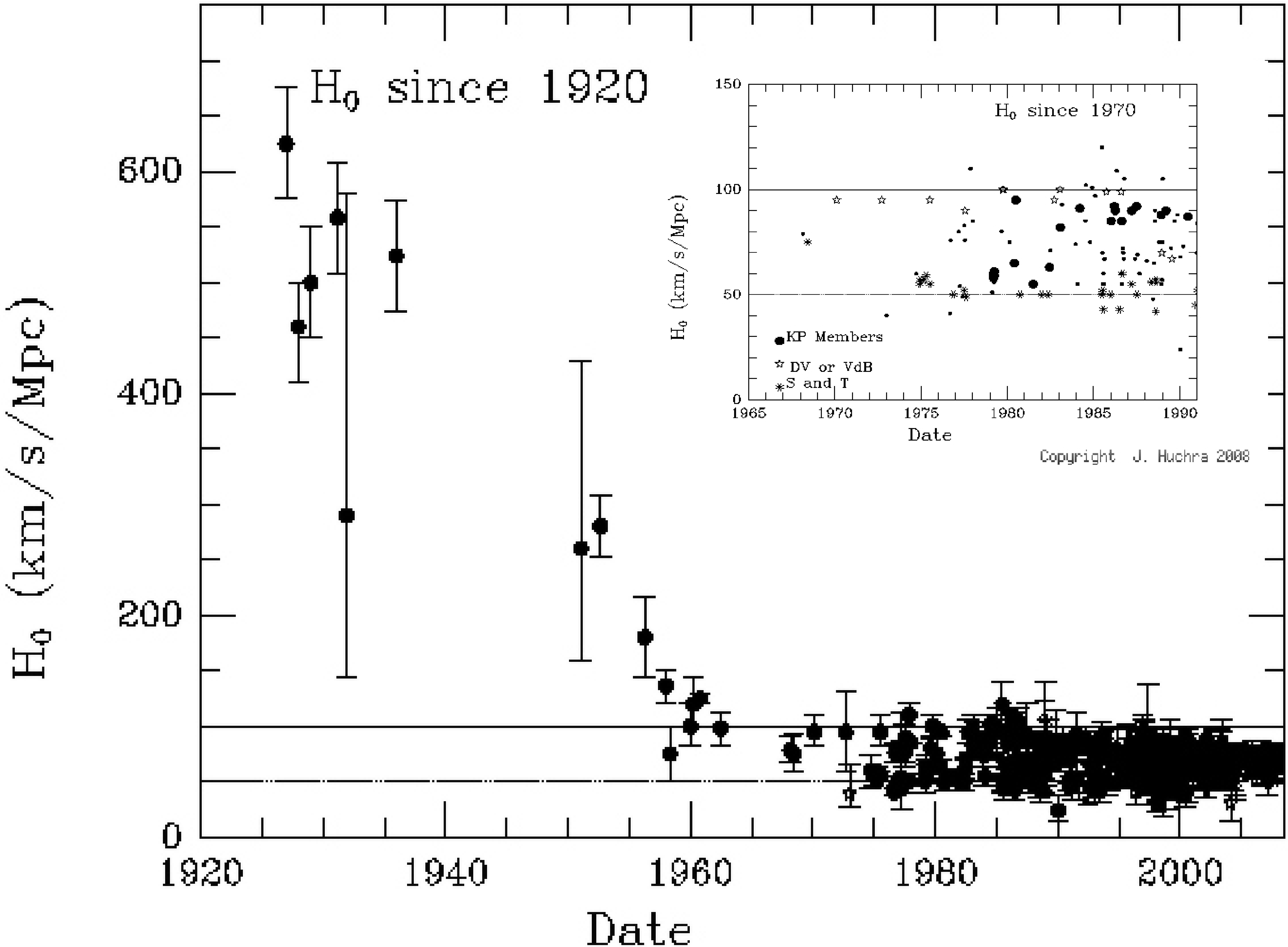
$$t_0 = 1/H_0$$

Hubble initial value was much too high :

$$H_0 \simeq 500\,\mathrm{km/s/Mpc} \qquad t_0 \simeq 2\,\mathrm{Gy}$$

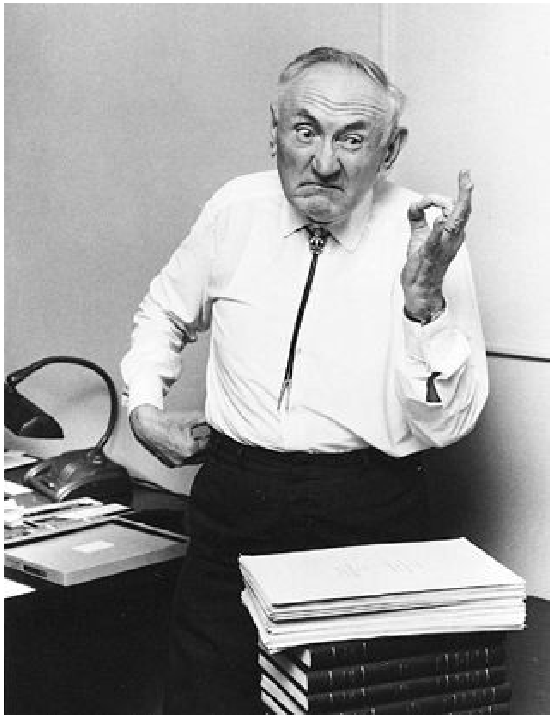
***Expanding Universe : The Universe should have been more compact and warmer in the past.***

*One answer to Olbers' paradox : the age of the Universe is finite*



H0 since 1920
H0 (km/s/Mpc)
600
400
200
0
1920
1940
1960
1980
2000
Date
H0 since 1970
150
100
50
0
1965
1970
1975
1980
1985
1990
KP Members
DV or VdB
S and T
Copyright J. Huchra 2008

# *Alternative theories* *(« Every good story needs a villain »)*



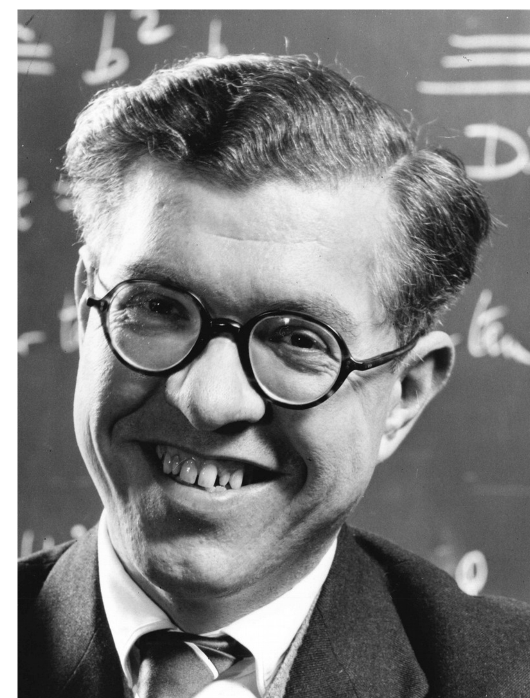
*F. Zwicky (1898 – 1974)*

Theory of the « *tired light* » to explain redshift from far away objects

Prediction of neutrons stars, discoverer of many supernovae.

Original mind, hard to work with...

*F. Hoyle (1915 – 2001)*



First papers on nucleosynthesis in stars. Predicted the triple alpha reactions.

Strong detractor of the « Big Bang » theory. Alternative theory of matter creation to compensate expansion (« *steady state* »).

# *Cosmic Microwave Background (CMB)*

## *A. A. Penzias & R. W. Wilson (1965)*

Black Body spectrum (microwave)

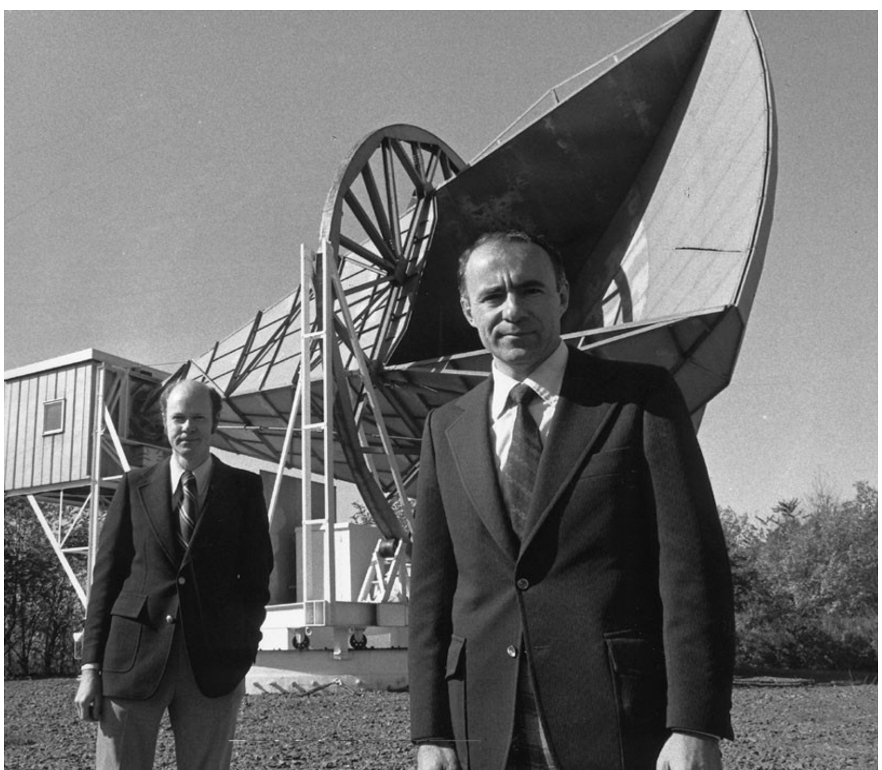
T ~ 2.73 K (BB spectrum up to $10^{-5}$)

Predicted by the « hot Big Bang » model

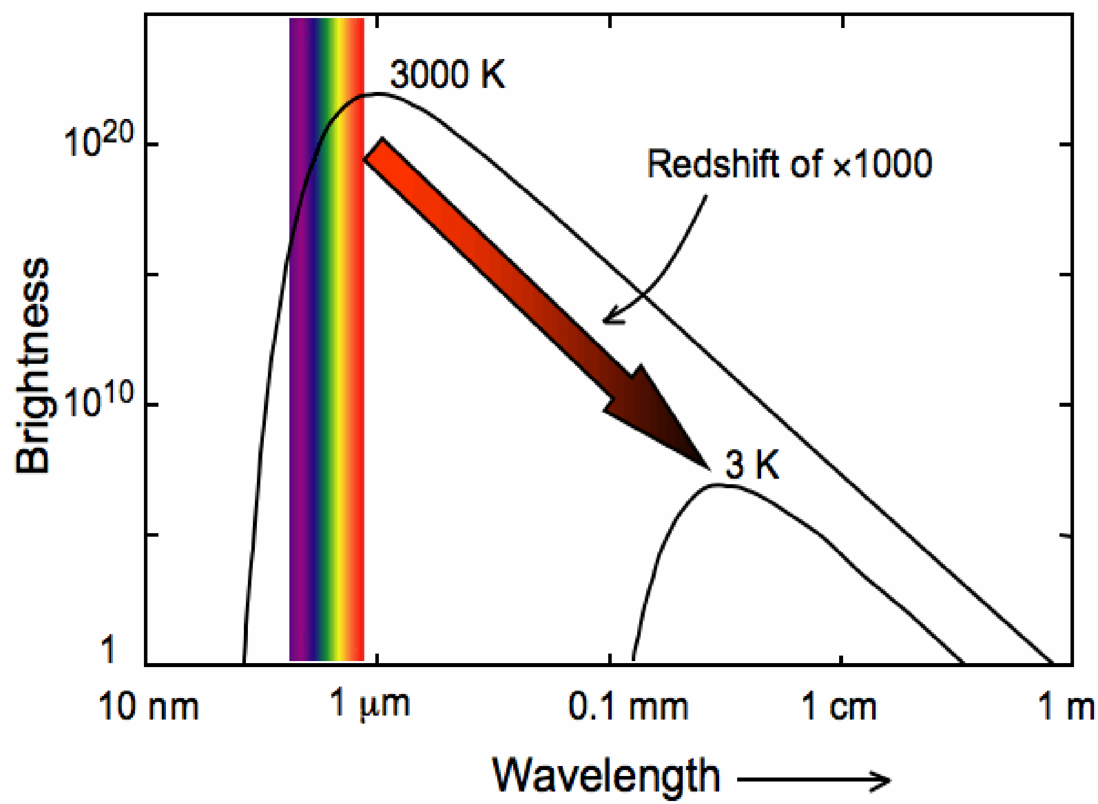
Hot Universe in the Past

Black body spectrum emitted at the time of last ionizations (decoupling of photons and matter)

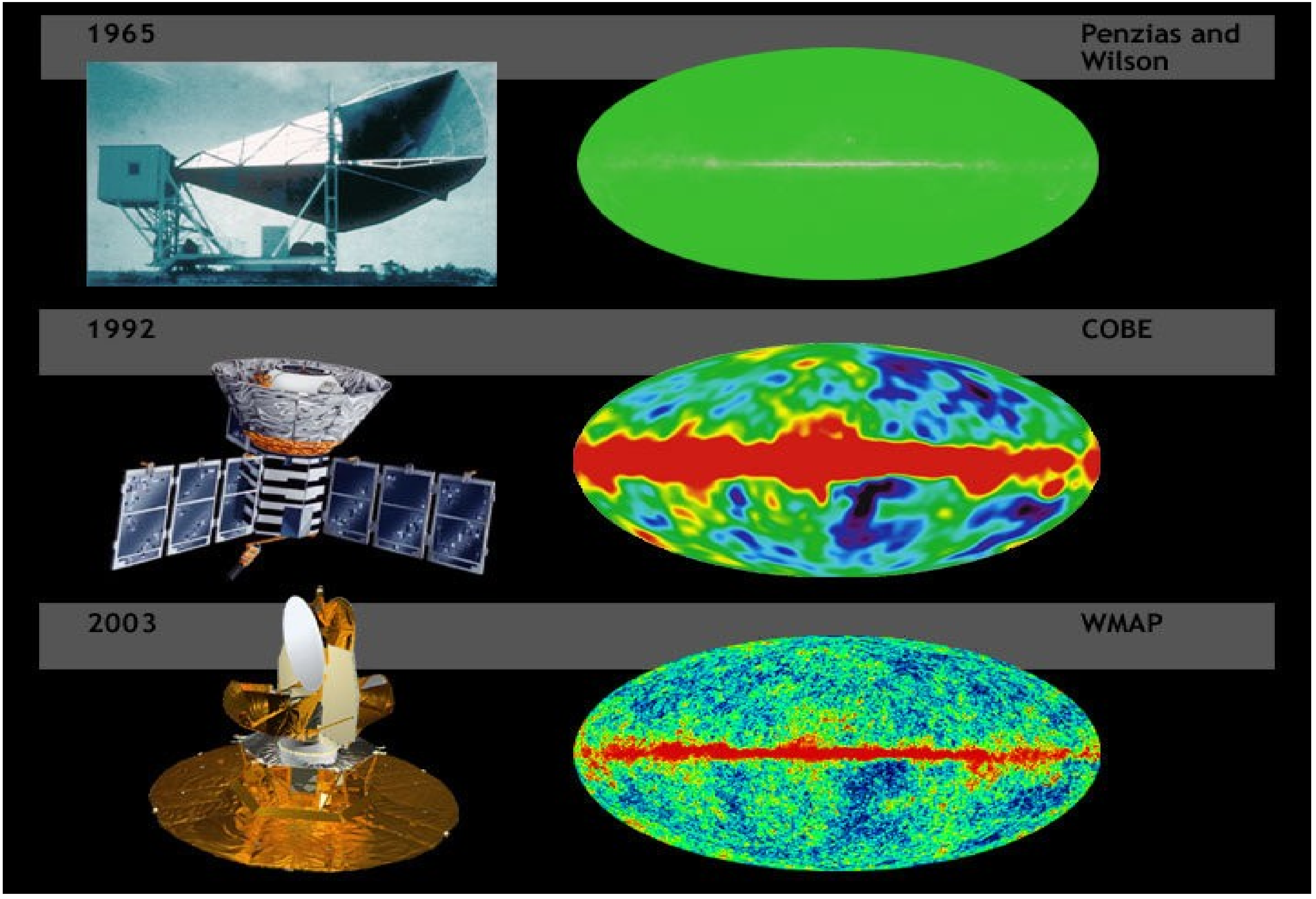
T ~ 2.73 K implies a redshift of ~1100







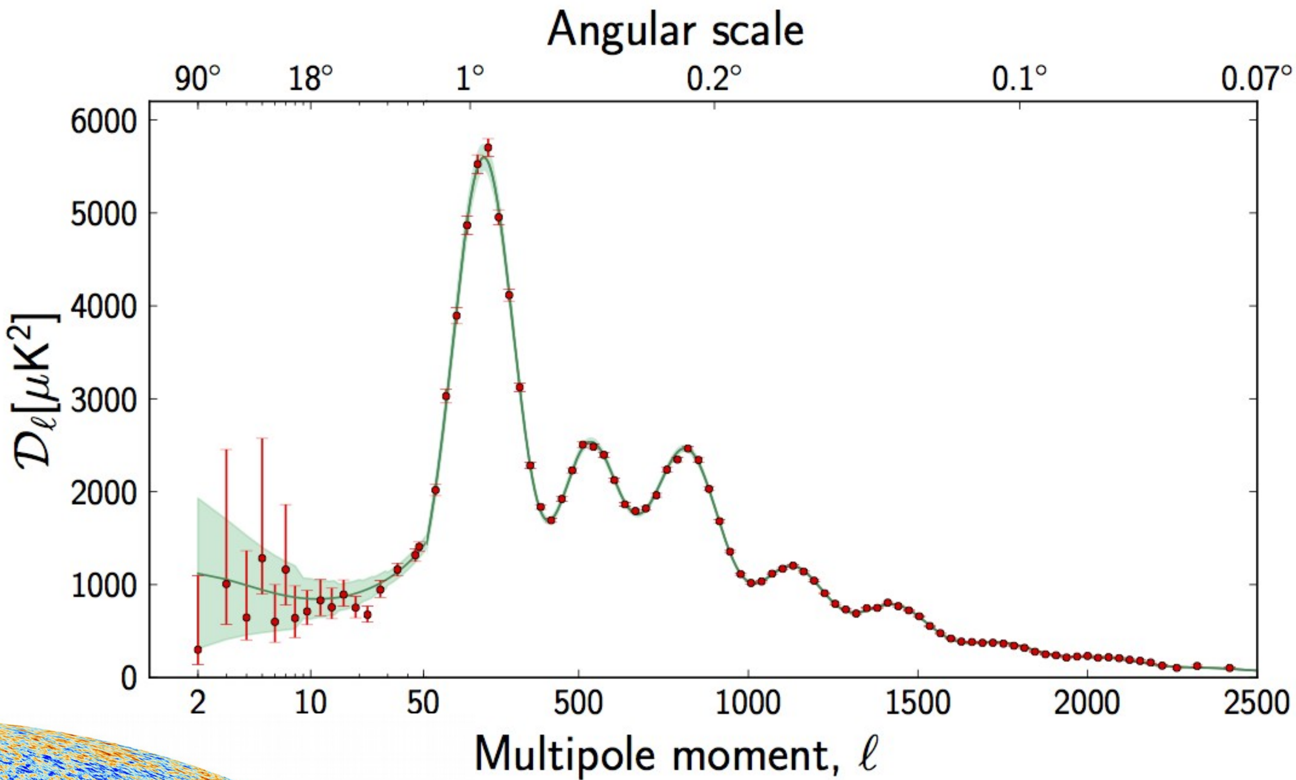
# Cosmic Microwave Background (CMB)

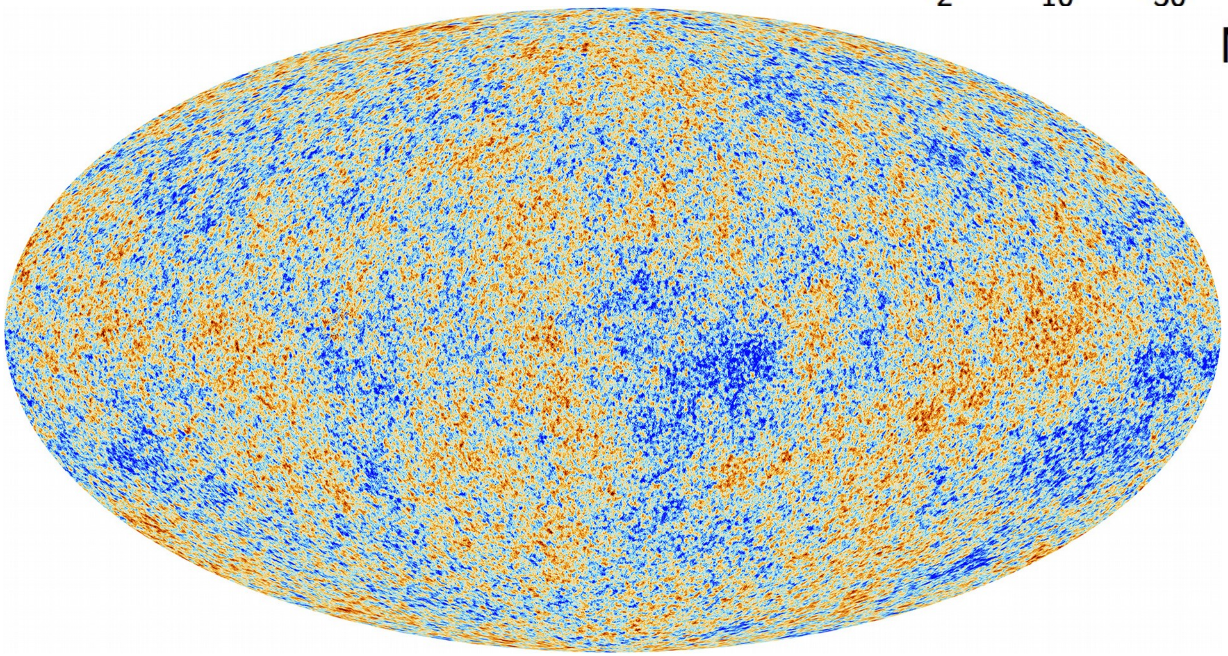


# *Cosmic Microwave Background (CMB)*

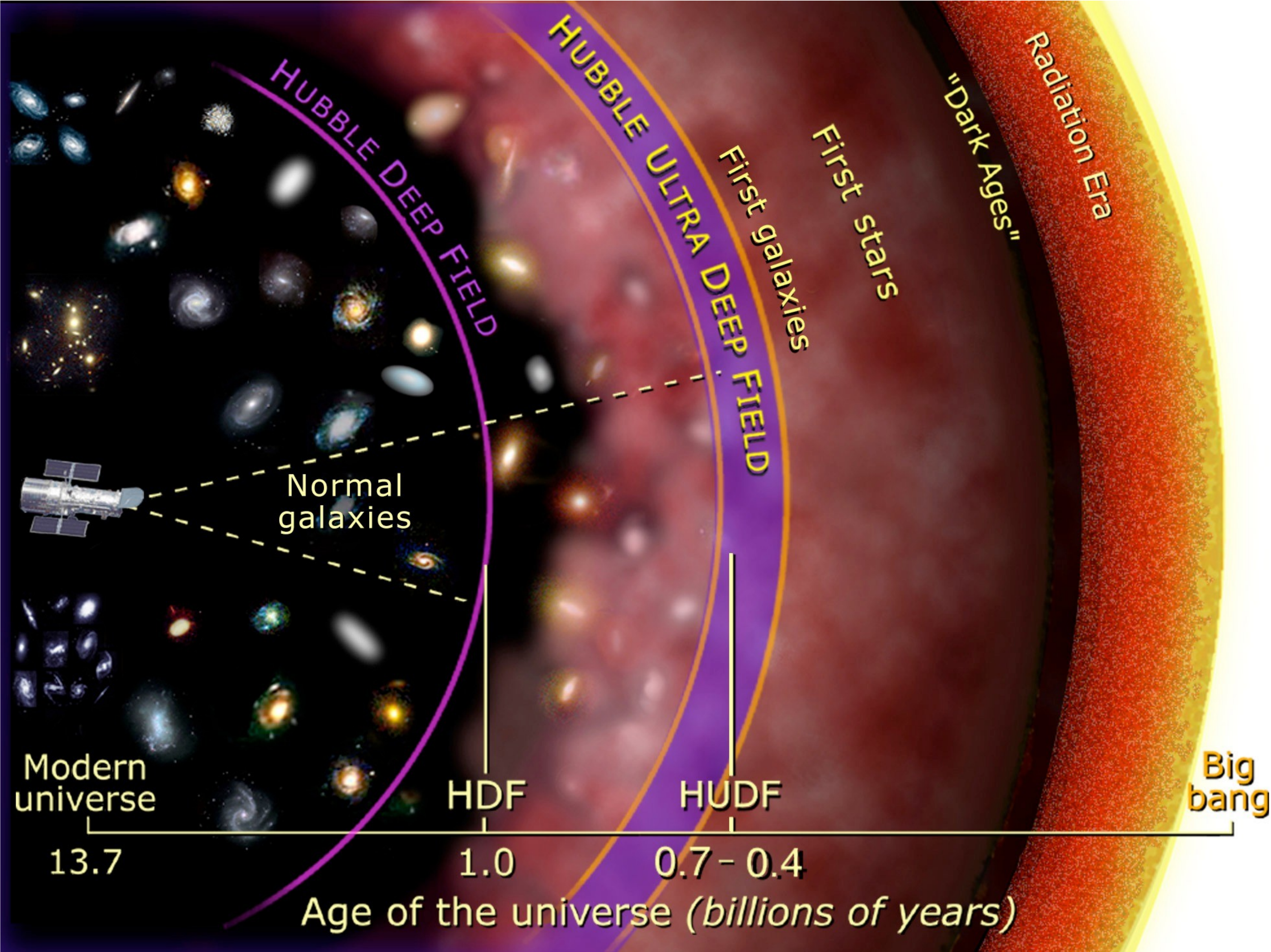
Anisotropies reveal densities fluctuations at the time of emission of the CMB

z~1100
Age ~ 370 000 y



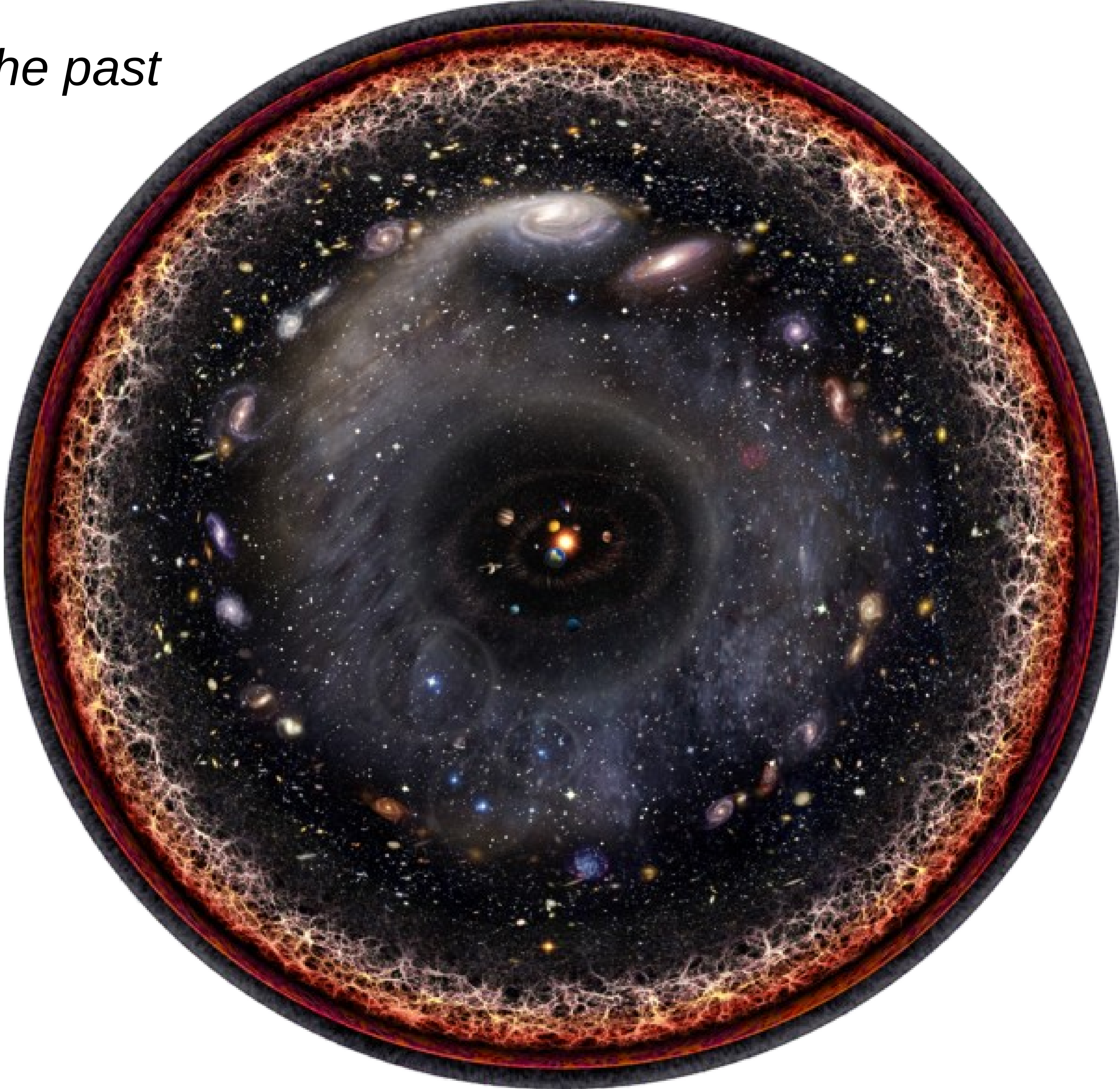



Planck
2009-2012



HUBBLE DEEP FIELD
HUBBLE ULTRA DEEP FIELD
First galaxies
First stars
"Dark Ages"
Radiation Era
Normal galaxies
Modern universe
HDF
HUDF
Big bang
13.7
1.0
0.7 – 0.4
Age of the universe (billions of years)

*Looking into the past*



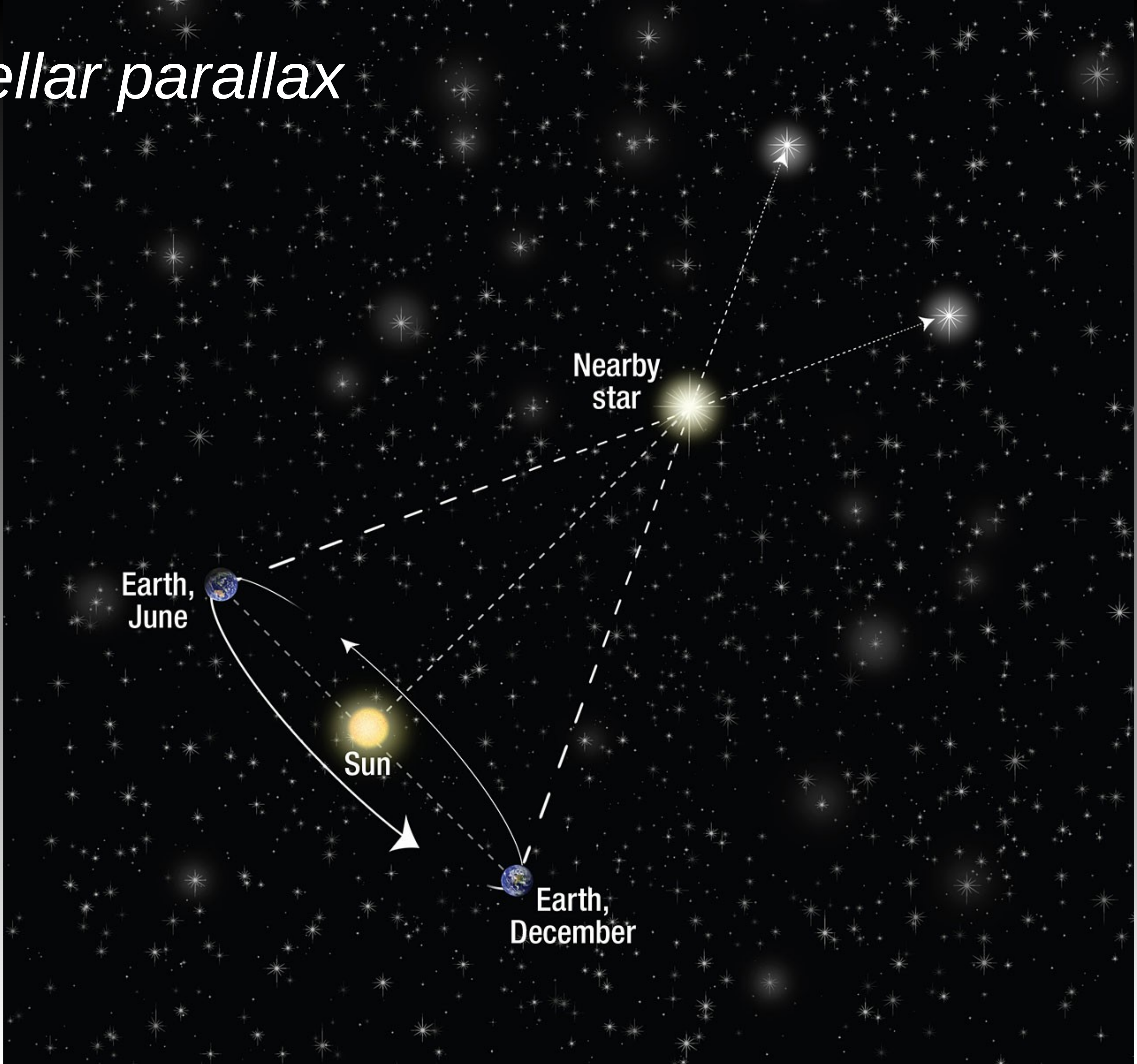
*1.2*

# ***How do we measure distances in such a big Universe ?***

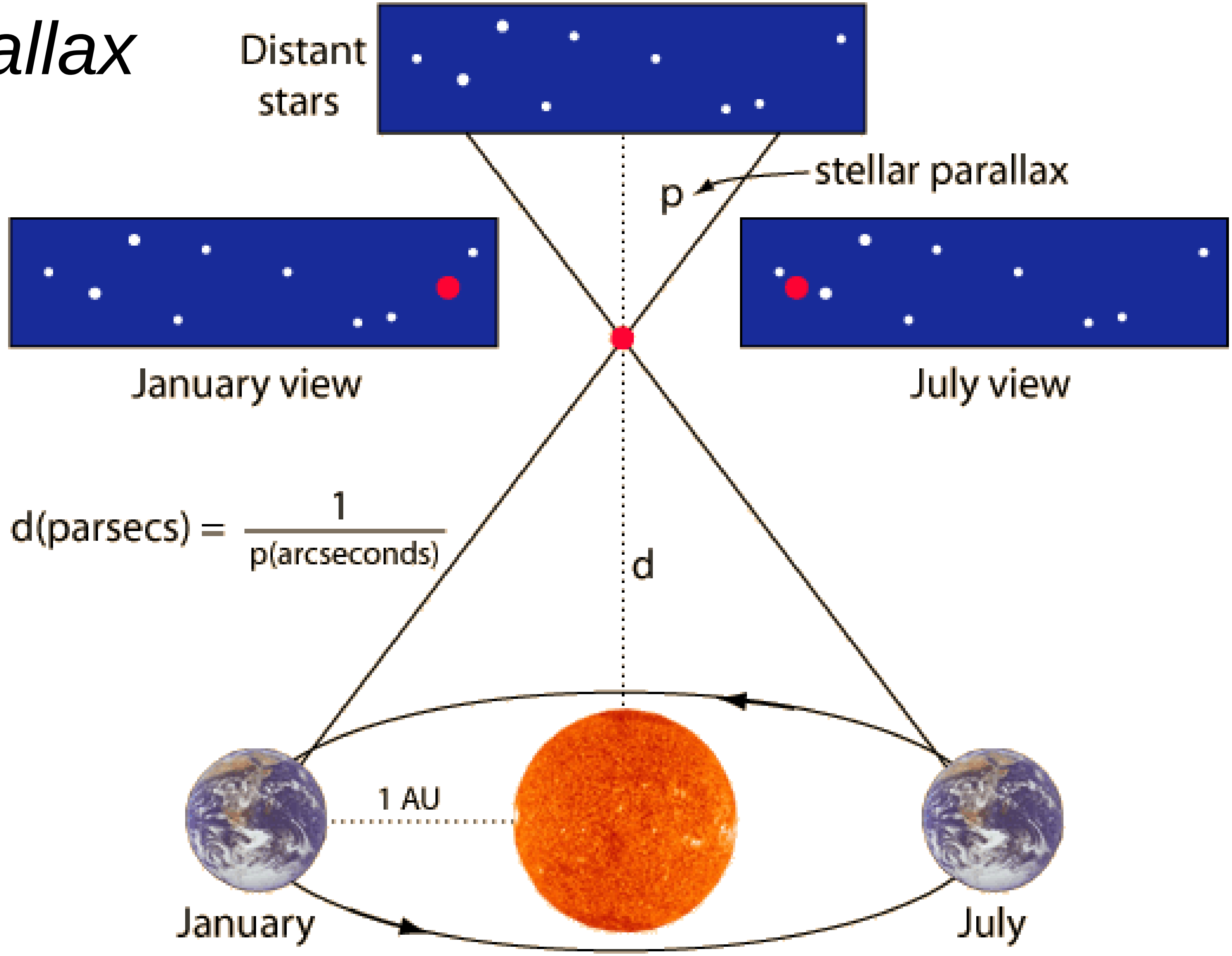
*To do Cosmology we often need to measure distances to objects sitting very far away...*

*The « Cosmic ladder »*

# *Stellar parallax*



# *Stellar parallax*




$$1\,\mathrm{pc} = 3.26\,\mathrm{ly} = 3.09 \times 10^{16}\,\mathrm{m}$$

# *Stellar parallax*

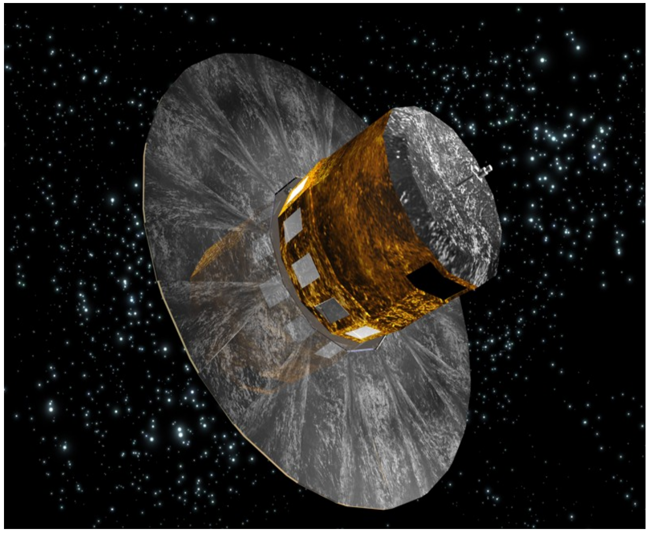
- Only nearby stars (19-20th century)

  ~ 1000 stars, up to ~100 pc

- **Hipparcos** (1989-1993)

  ~ 100 000 stars, 0.001 arcsec,

  distances up to ~500 pc

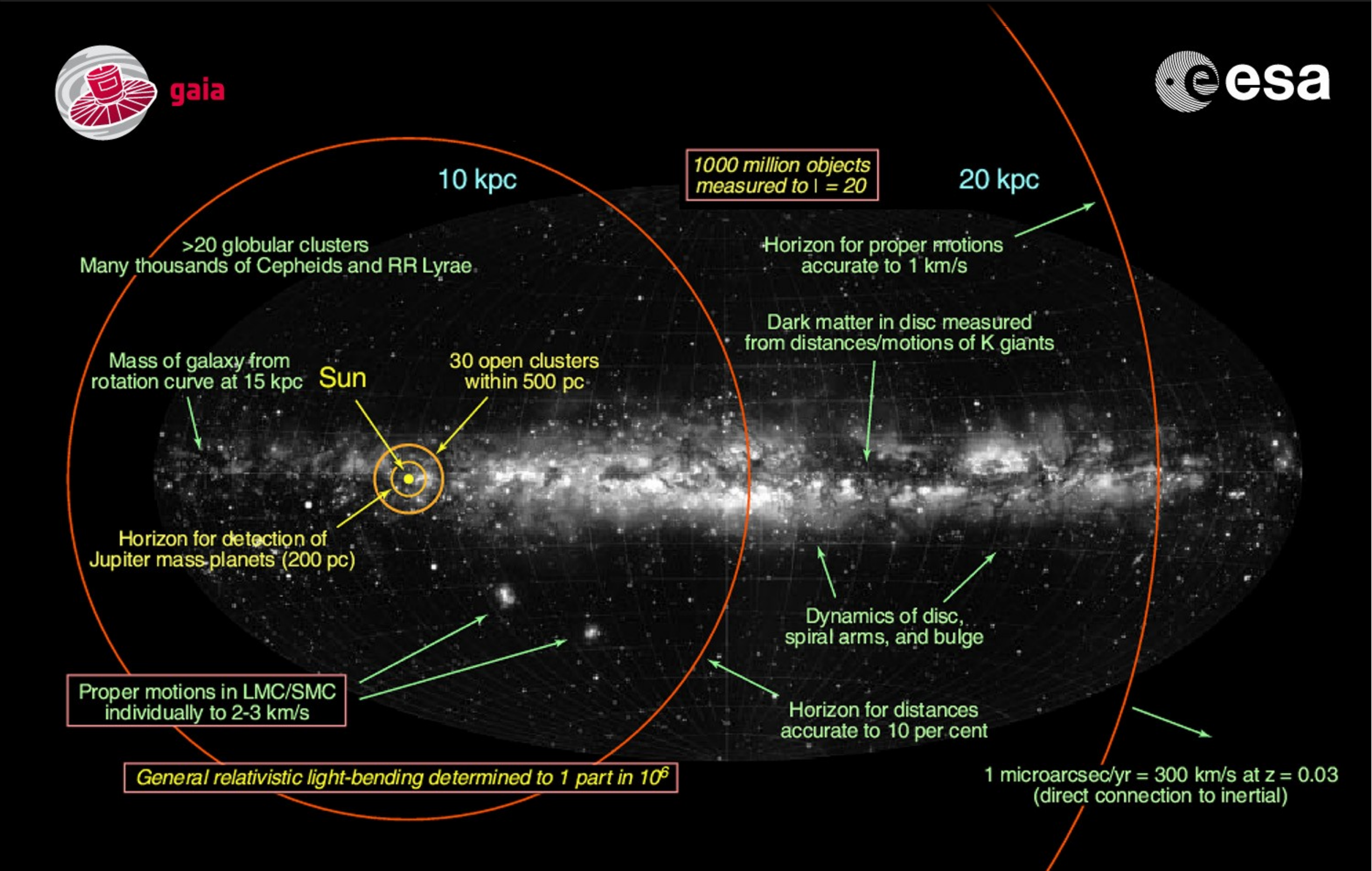


- **GAIA** (2013-)

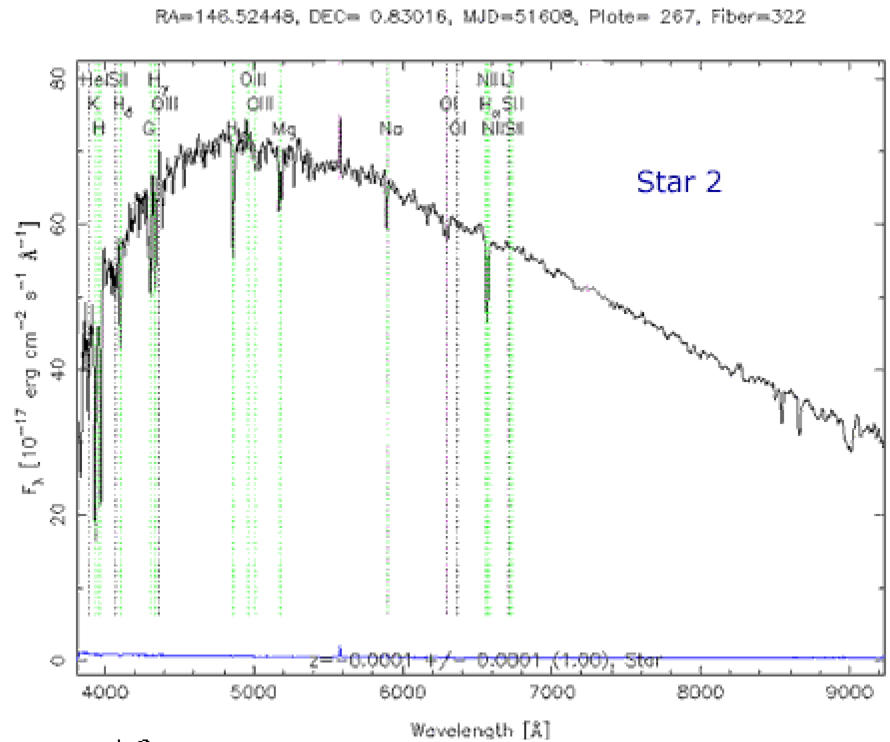
  3D catalog of ~ $10^9$ stars

  reliable distances up to ~10 kpc

# *Stellar parallax*



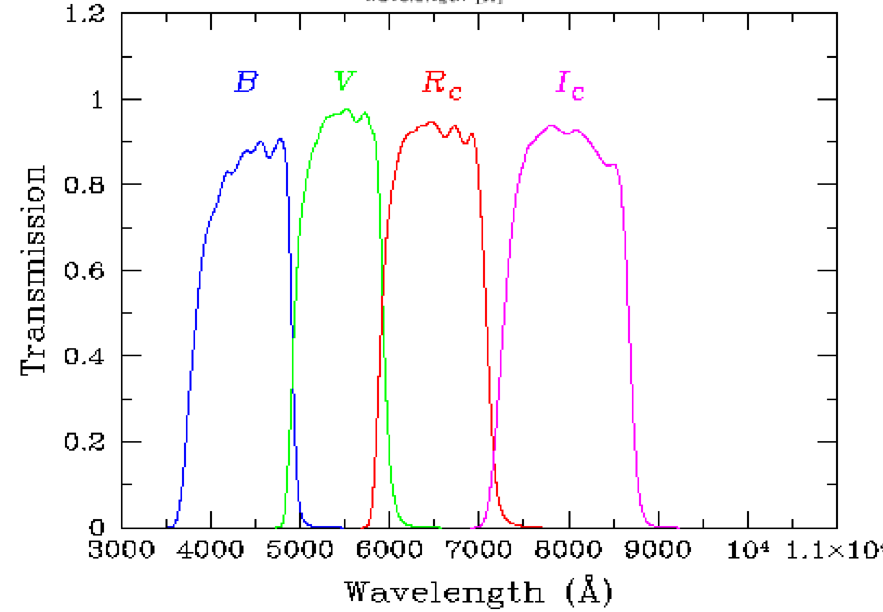
# *Stellar properties*




Stellar spectrum : a black body → T°
+ emission/absorption lines

Spectral classification : OBAFGKM

Temperature, Color and Luminosity




Stellar apparent magnitude (in filters)
(ref = ref star, Vega) :

$$m_x - m_{x,\mathrm{ref}} = -2.5\log_{10}\left(\frac{I_x}{I_{x,\mathrm{ref}}}\right)$$

Absolute magnitude M : magnitude
of the same object seen at 10 pc

Distance modulus μ :

$$m - M = \mu = 5\log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right) = 5\log_{10} d - 5$$

*Exercise*

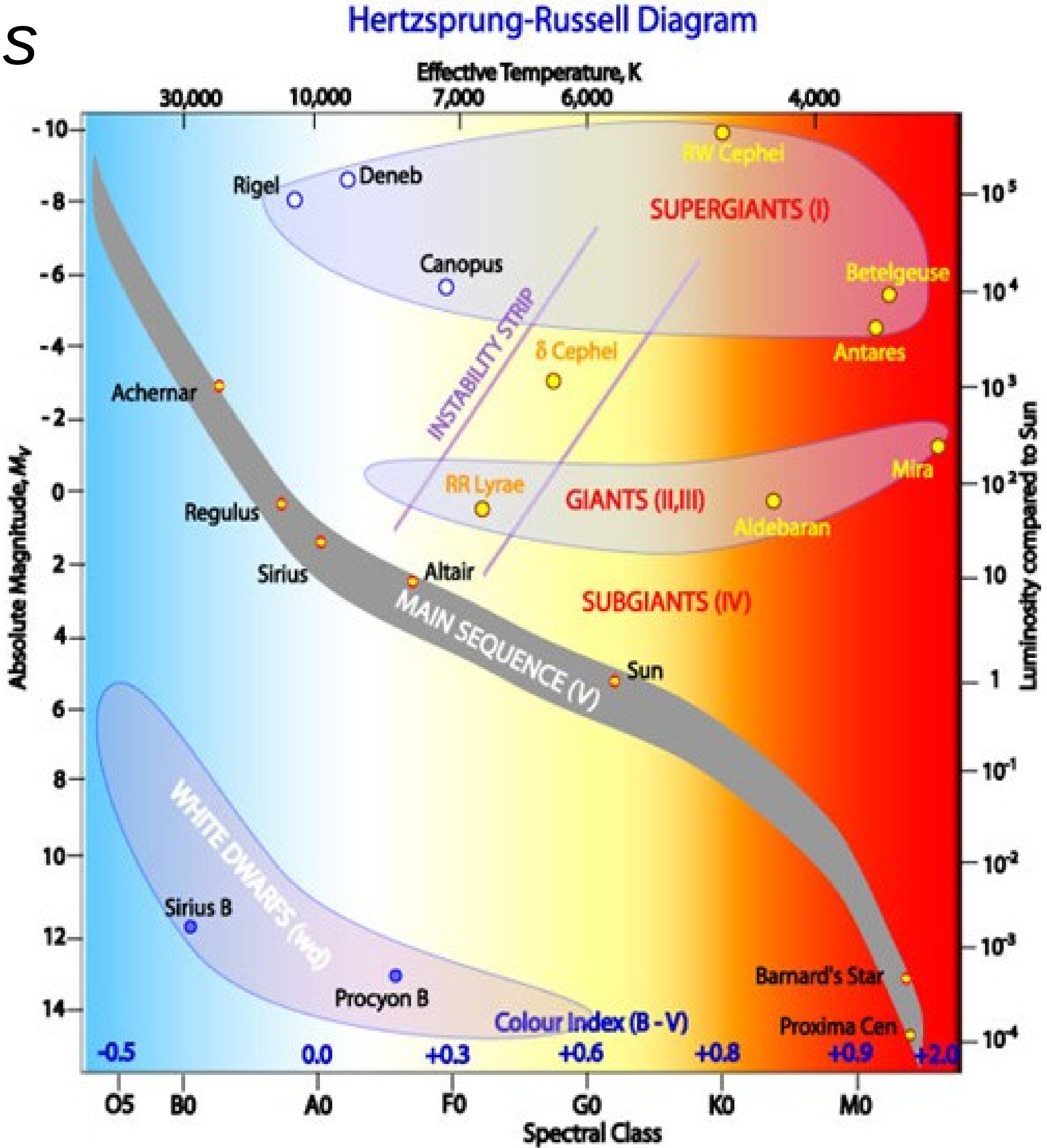
# *Stellar properties*

Absolute Mag.
Temp° & color

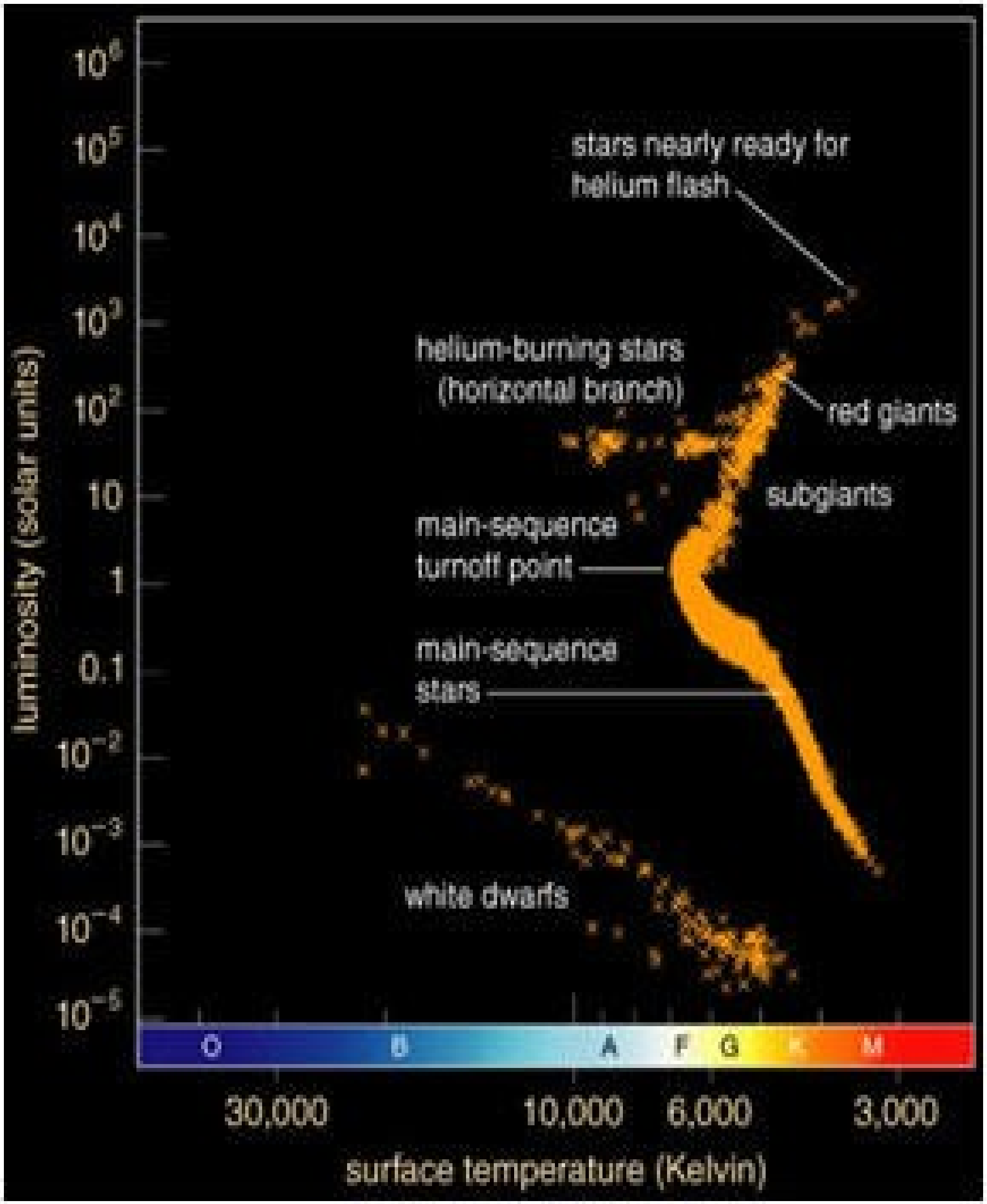
Stellar classes

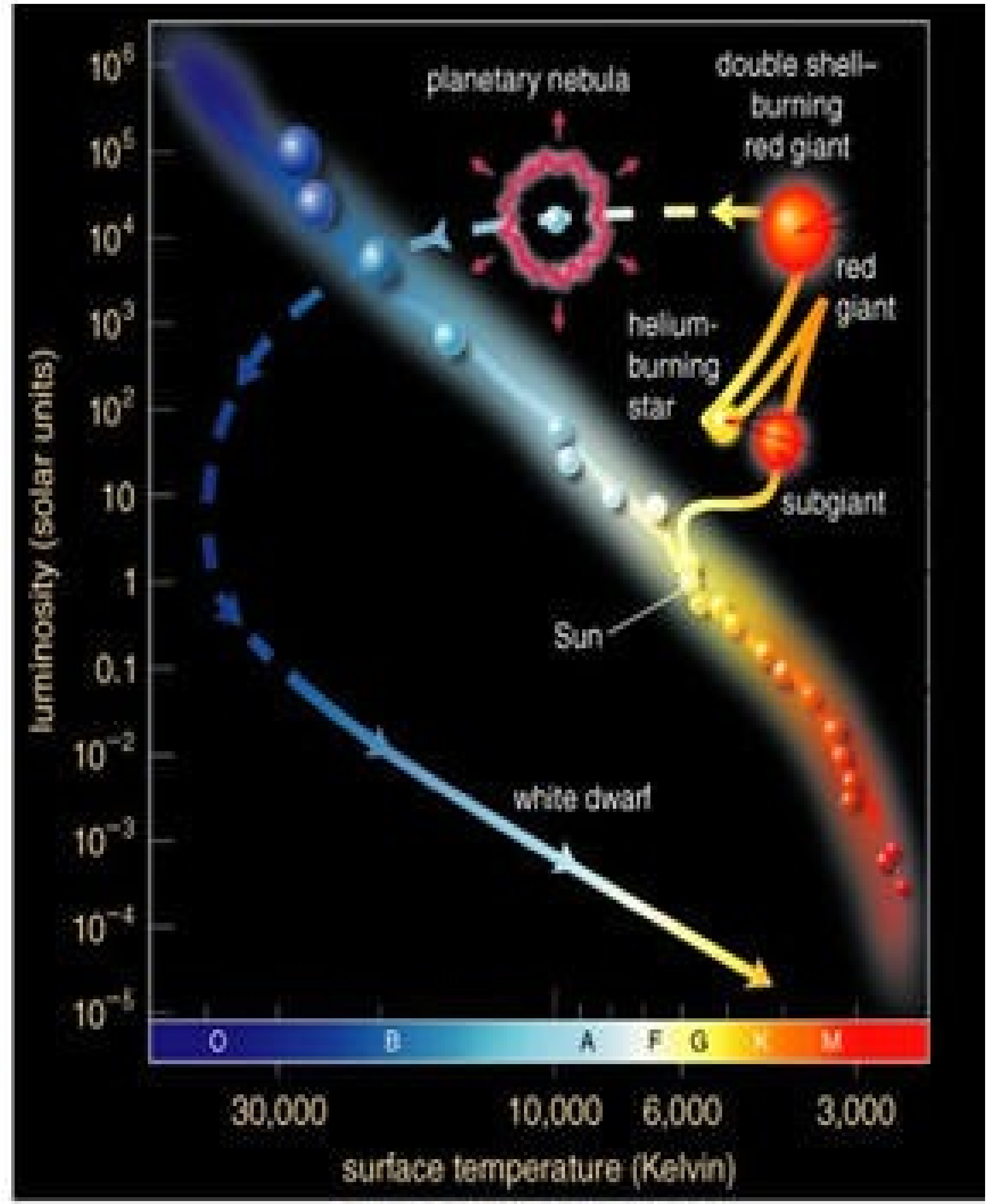
Stellar Evolution

H-R diagram can be build for stars at the same distance (clusters)



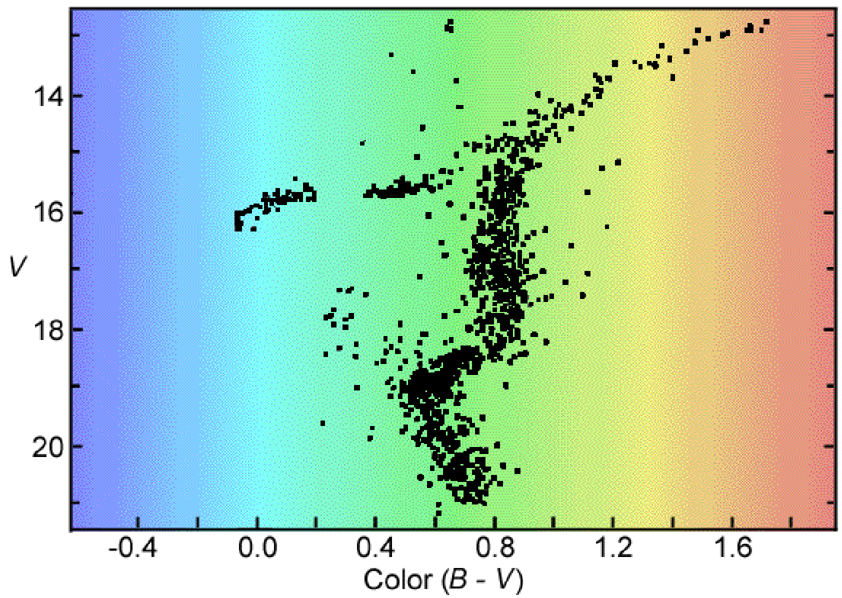
# *Stellar evolution*

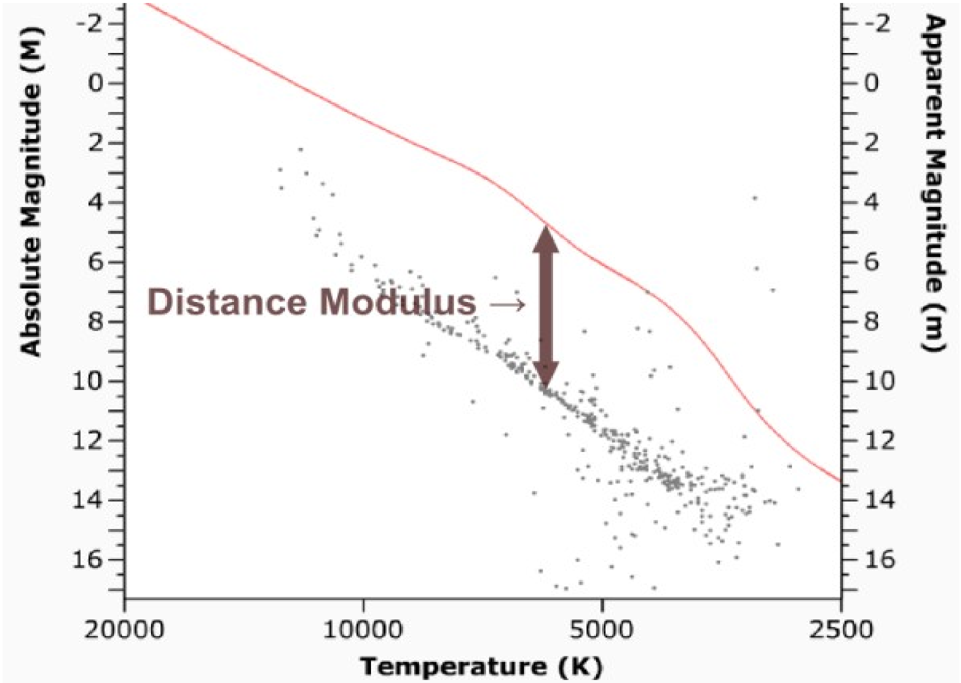


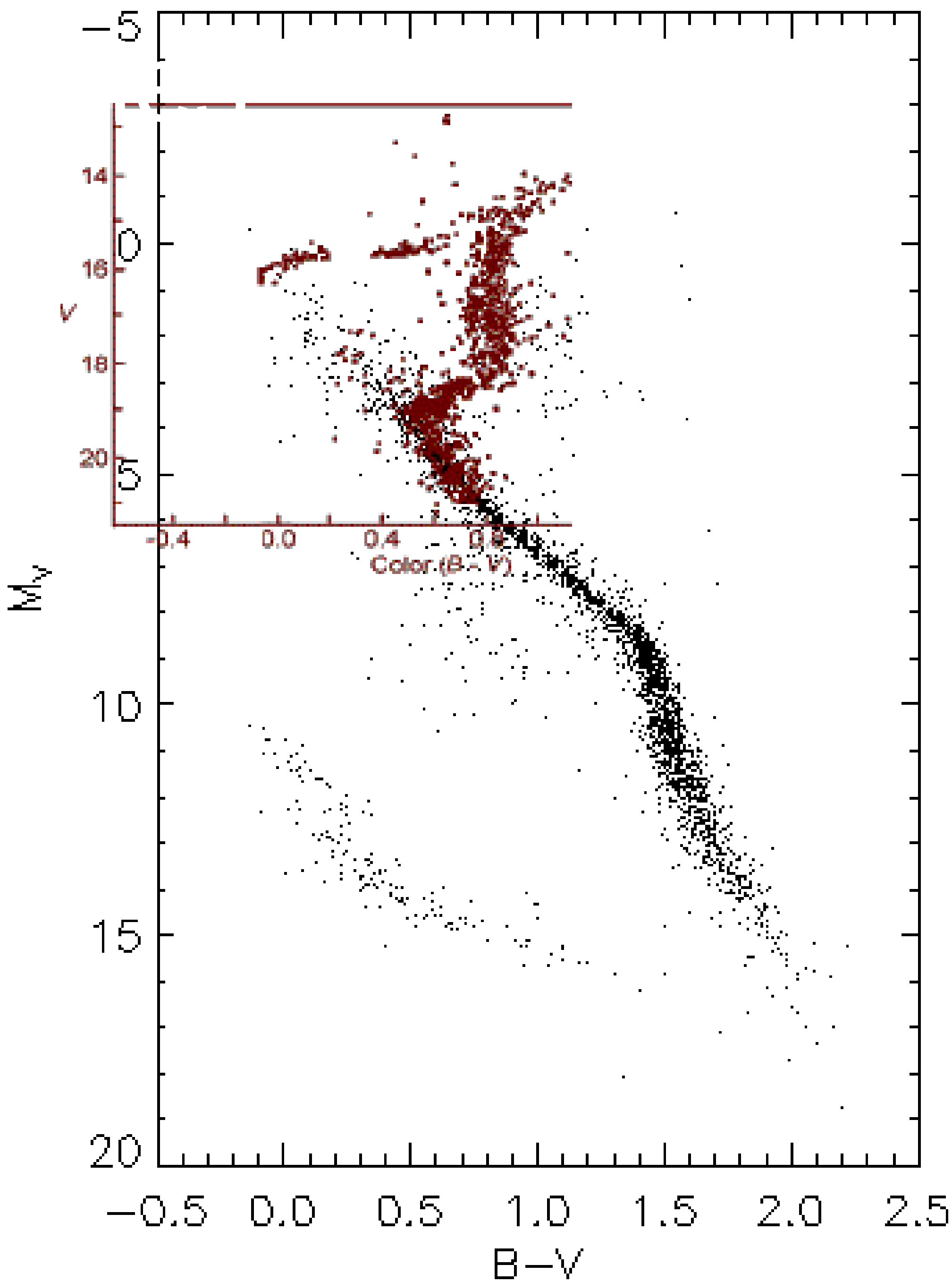



# *Main sequence fitting*

Stars from M3 (cluster)



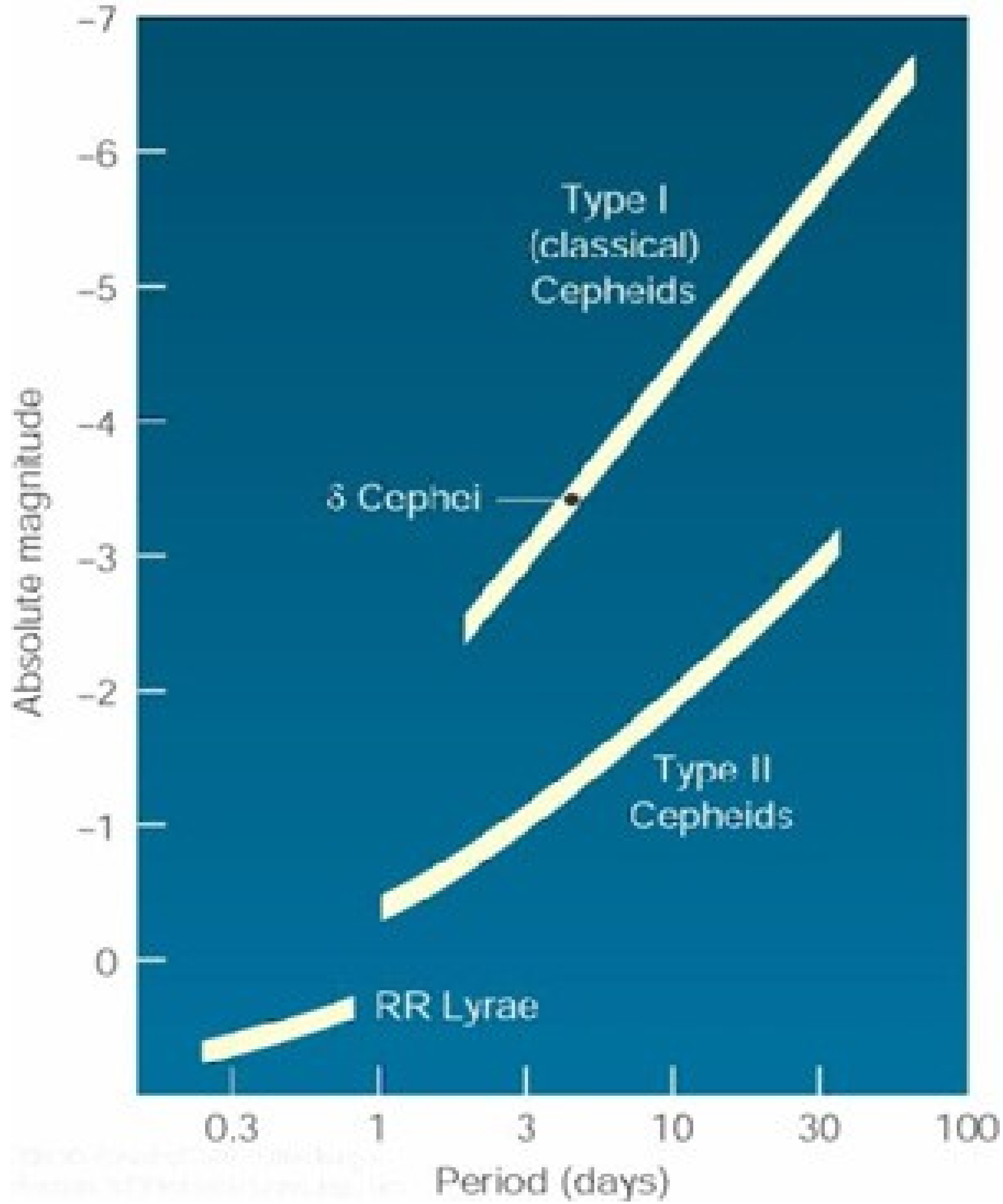



# *Variable stars*

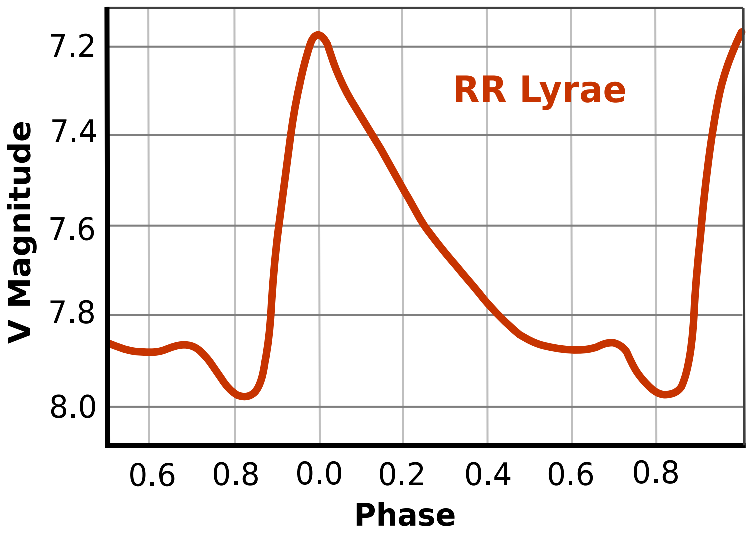
« Standard candles »

Objects with a known absolute luminosity

Distance modulus and distance may be deduced



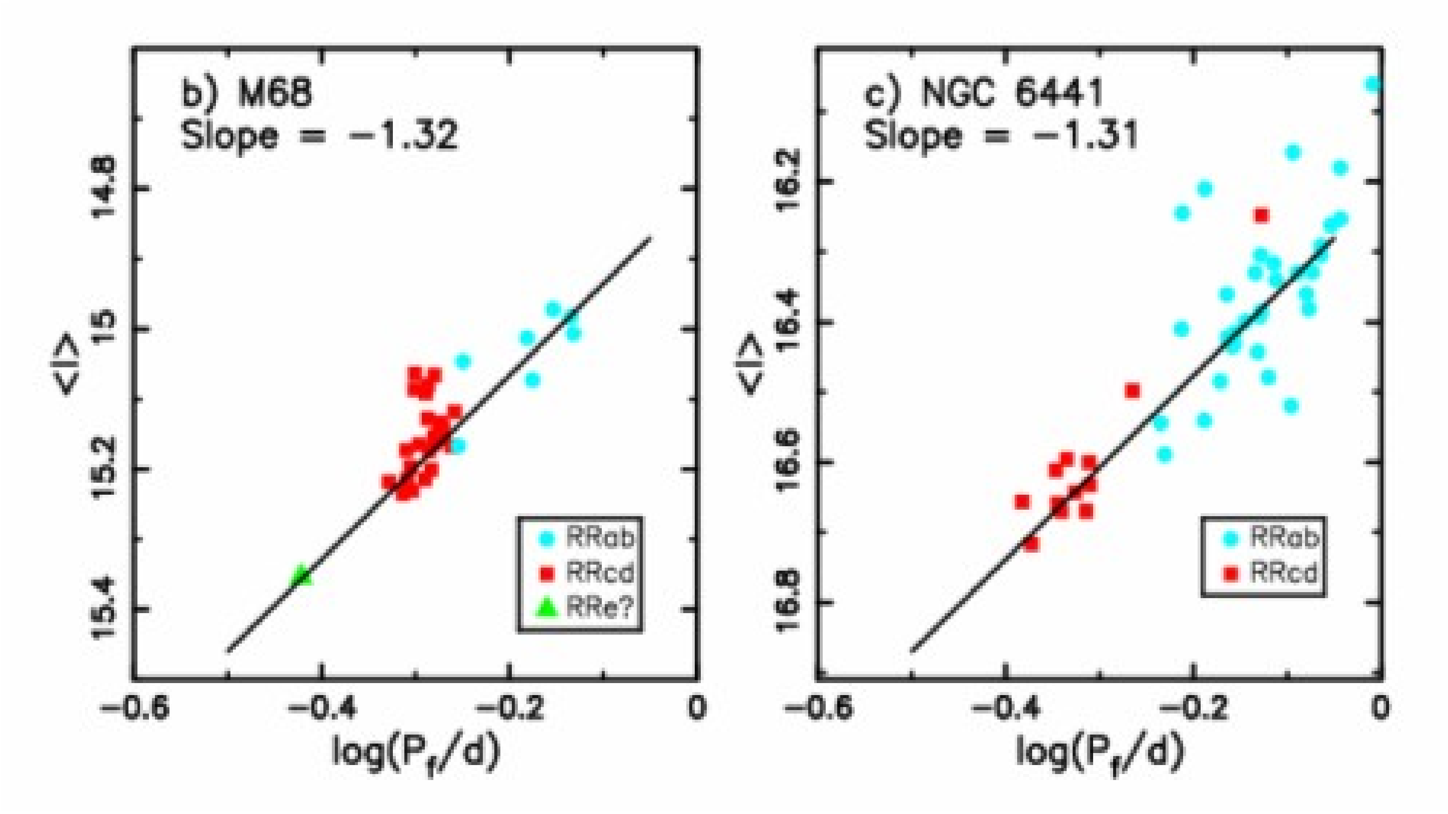
# *RR Lyrae*



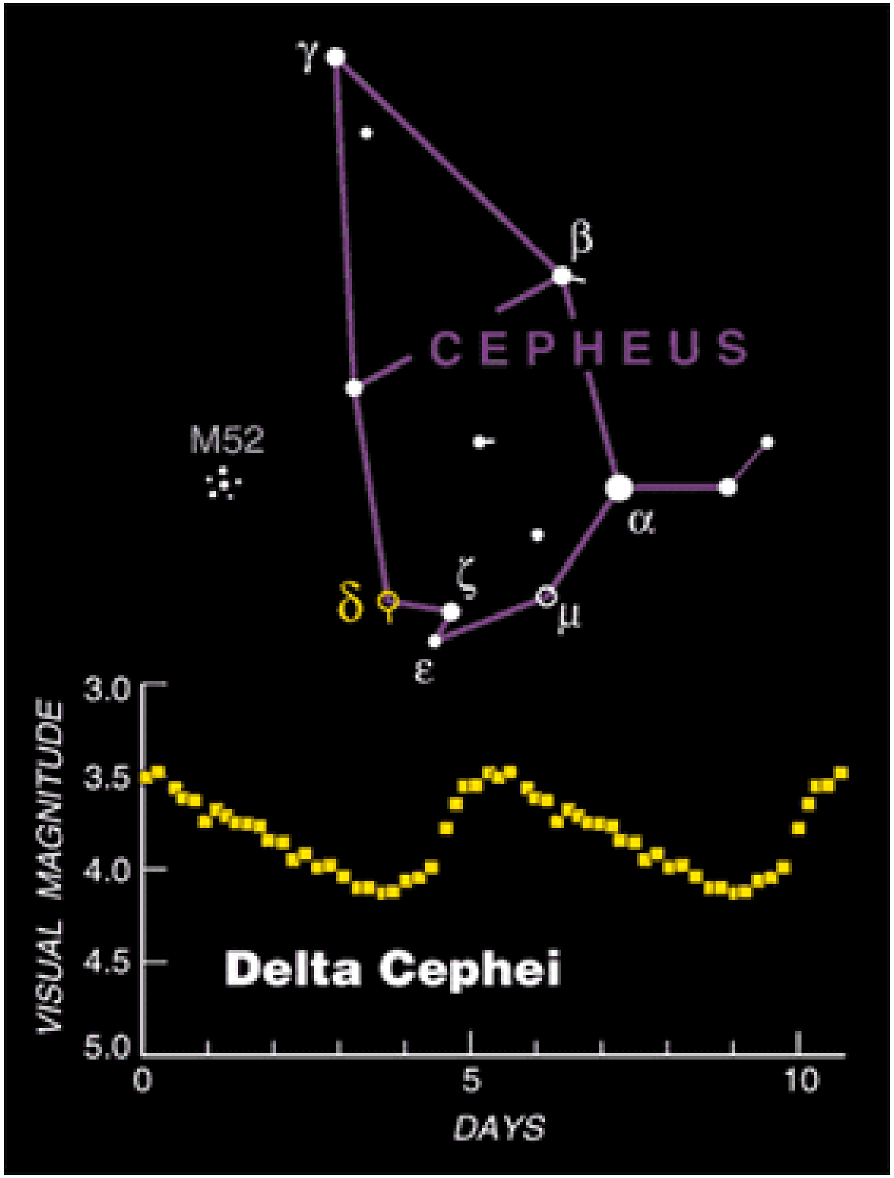

Pulsating variables
P ~ 0.1 – 1 day

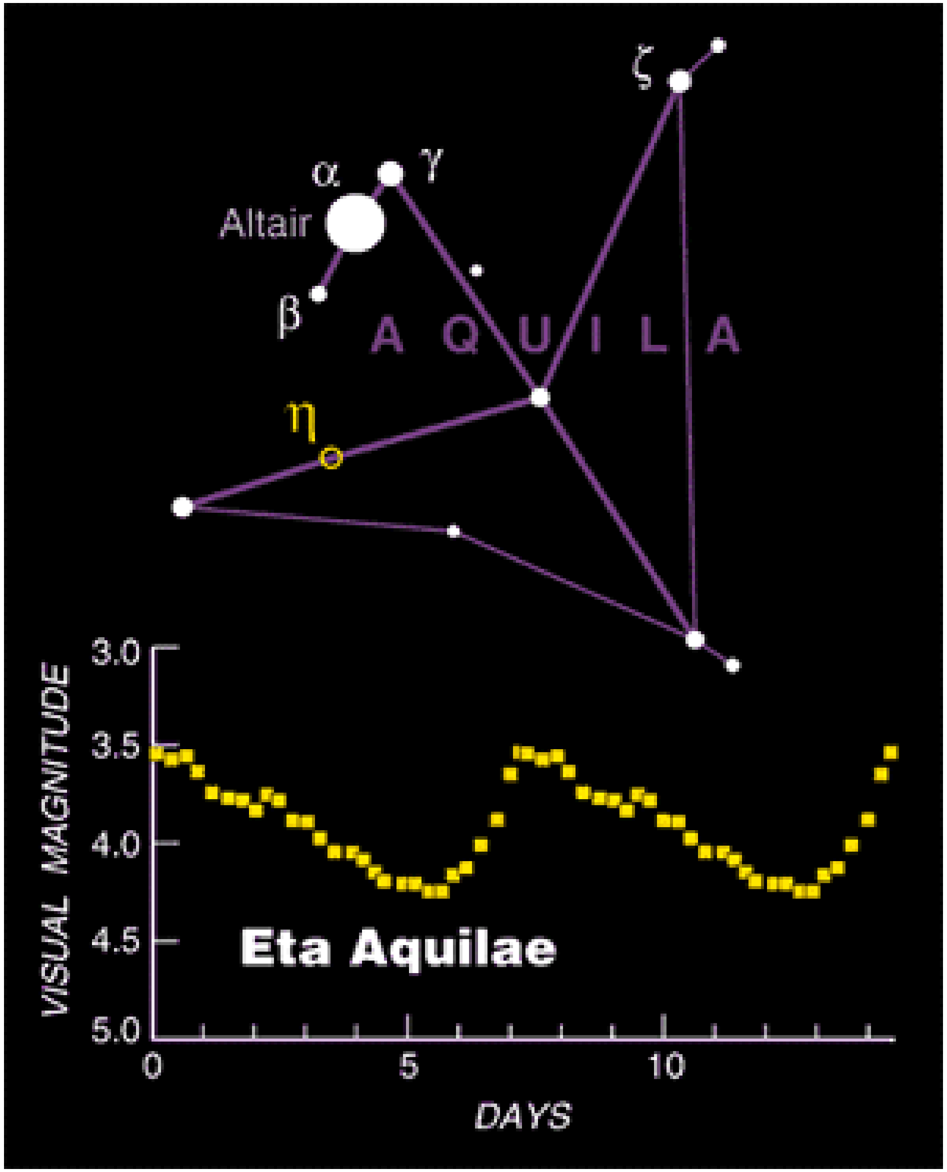
Period-luminosity relation
Abs Mag ~ +0.75

Distance indicator inside the galaxy / local group



# *Cepheids : pulsating stars*



# *Cepheids : luminosity-distance relation*

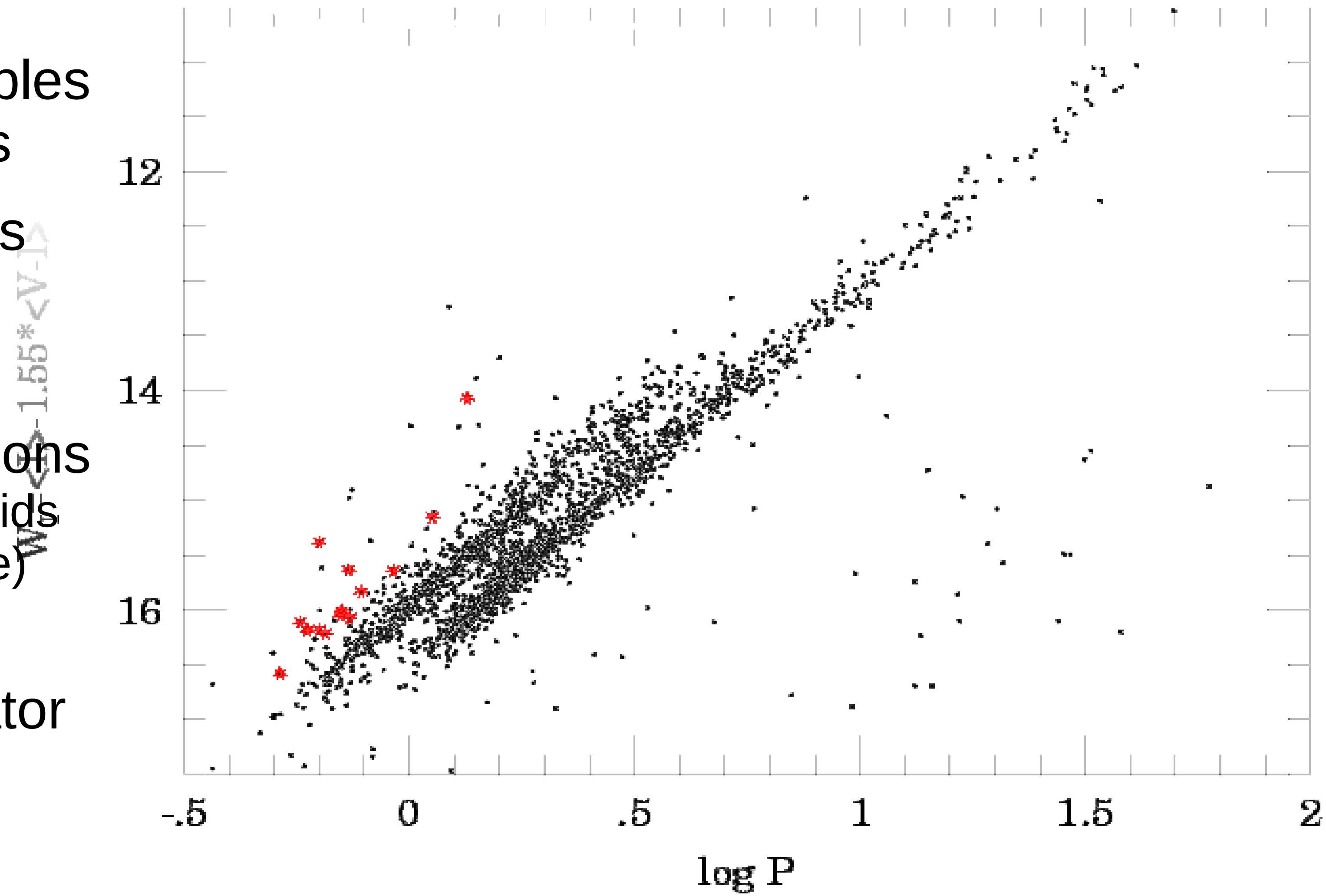
Pulsating variables
P ~ 1 – 50 days

Very bright stars

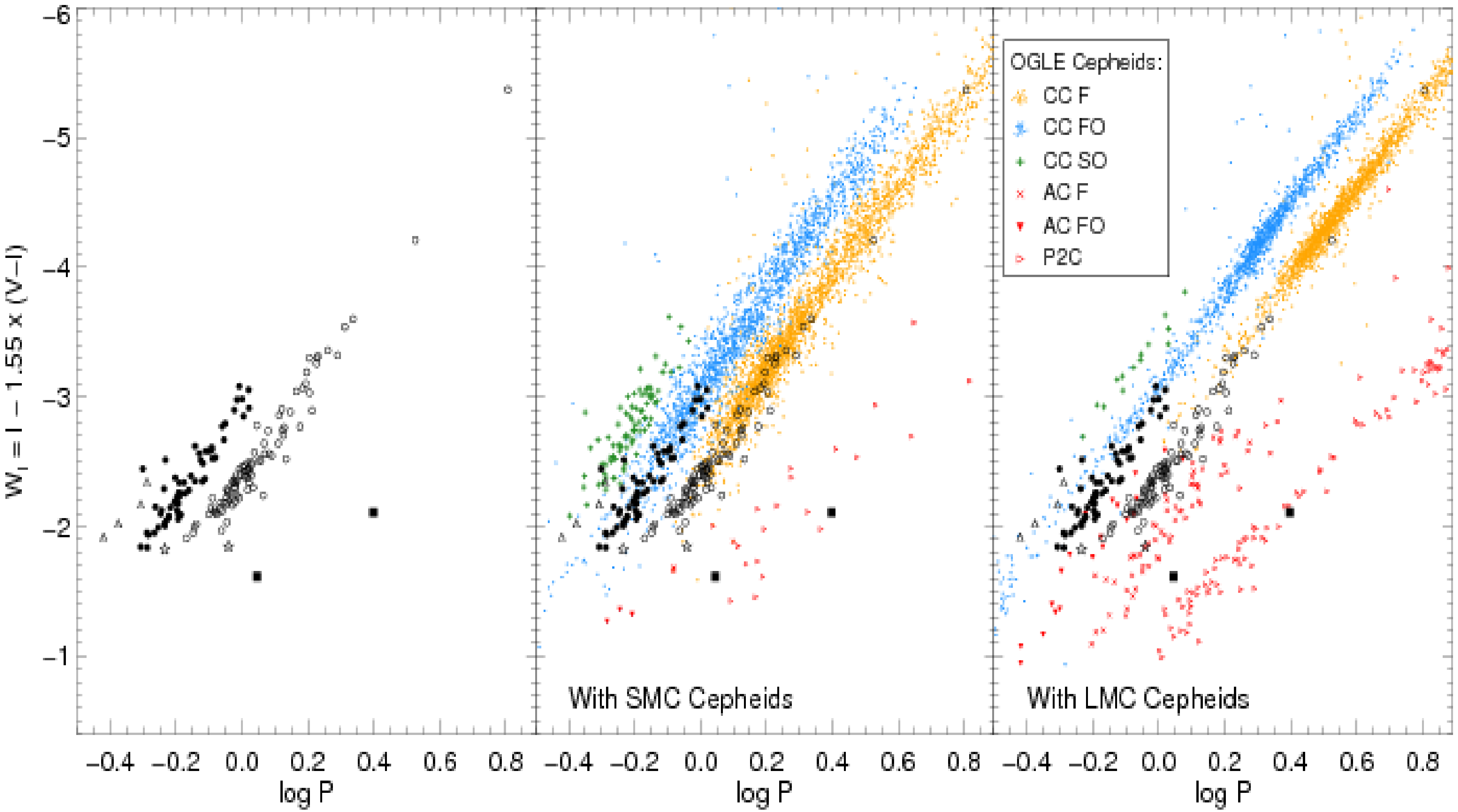
Rare objects

2 main populations
– Classical Cepheids
– Type II (overtone)

Distance indicator
Up to ~30 Mpc

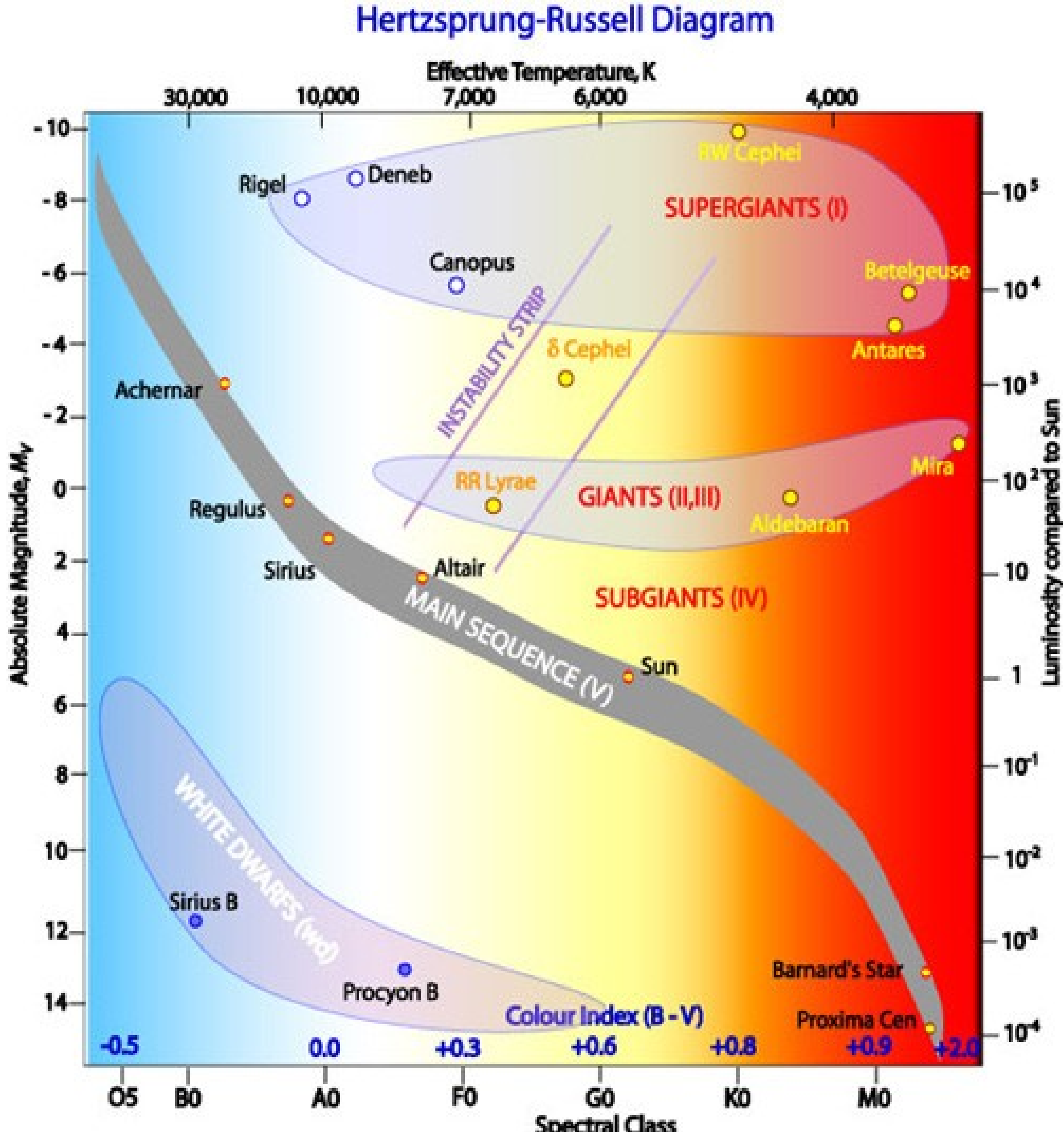



$$M_v = (-2.43 \pm 0.12)(\log_{10}(P) - 1) - (4.05 \pm 0.02)$$



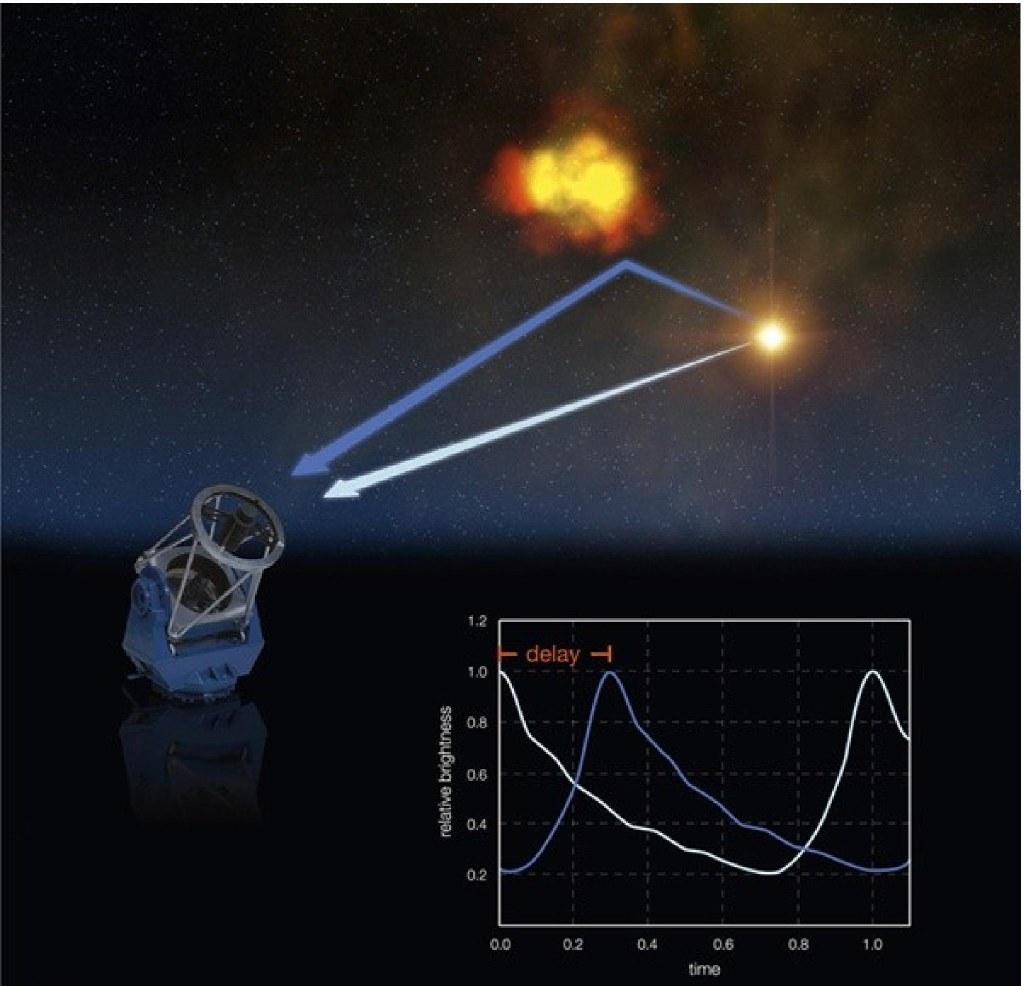
−6
−5
−4
−3
−2
−1
$W_I = I - 1.55 \times (V-I)$
−0.4 −0.2 0.0 0.2 0.4 0.6 0.8
log P
With SMC Cepheids
With LMC Cepheids
OGLE Cepheids:
CC F
CC FO
CC SO
AC F
AC FO
P2C

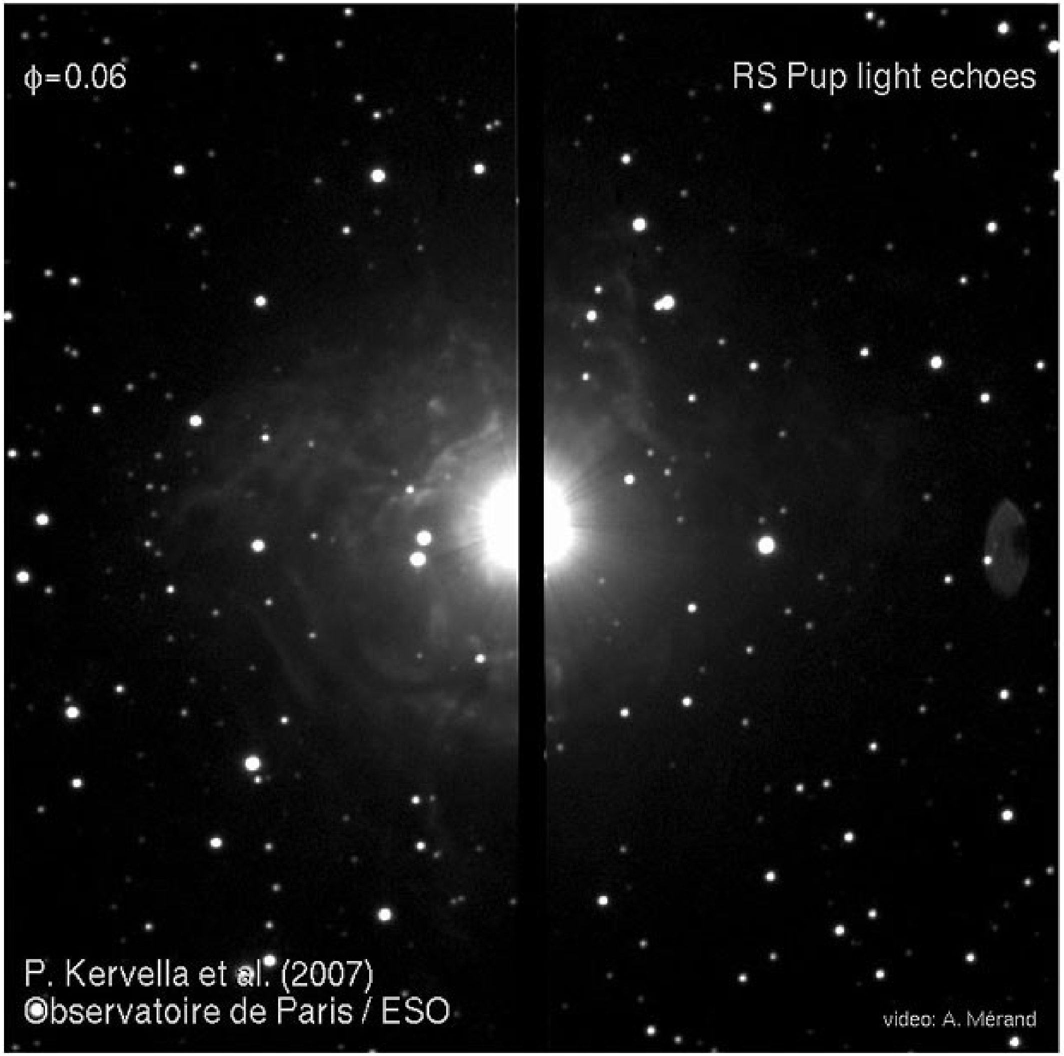
# *Cepheids*



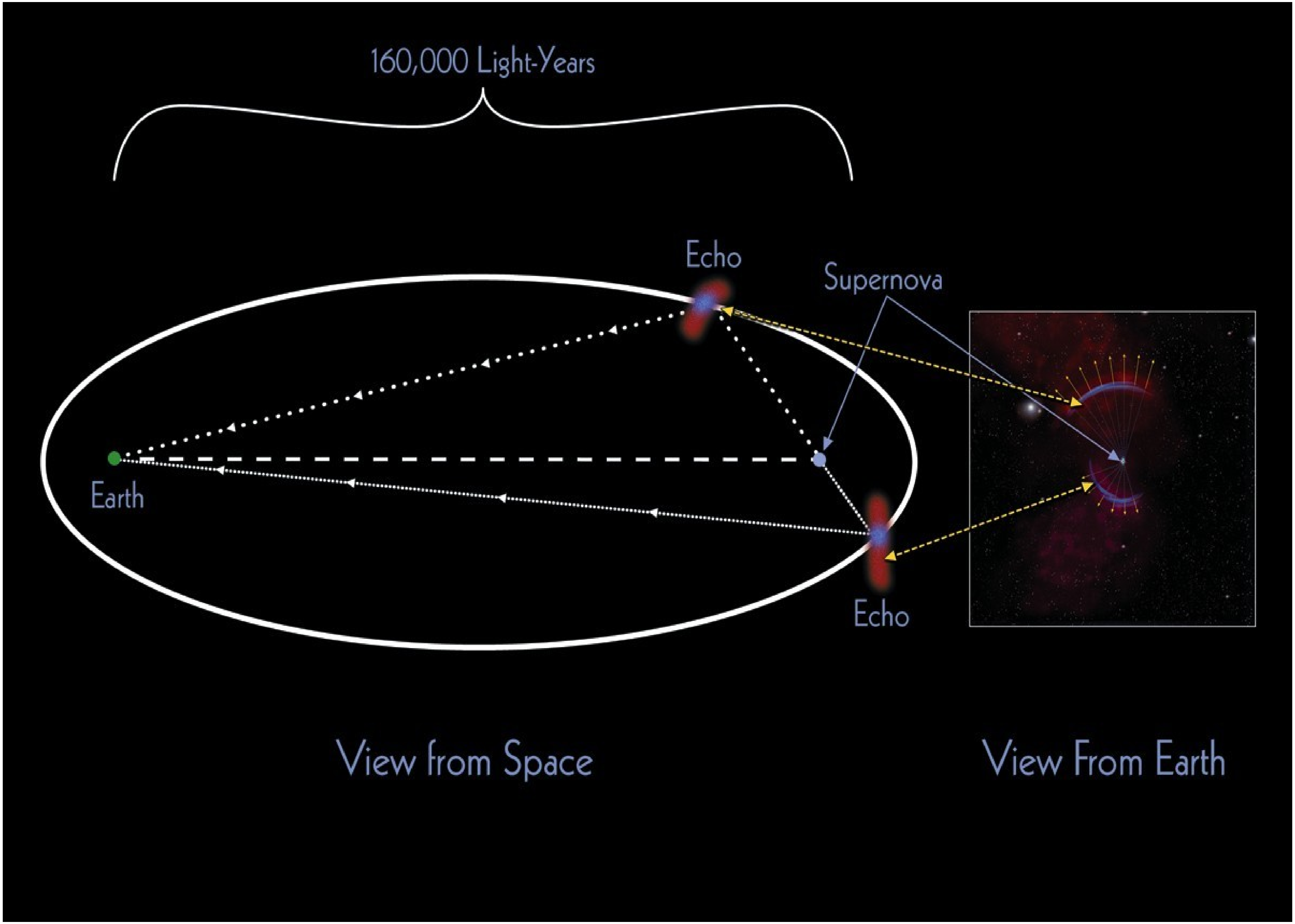
Hertzsprung-Russell Diagram
Effective Temperature, K
30,000
10,000
7,000
6,000
4,000
Absolute Magnitude, $M_V$
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14
Luminosity compared to Sun
$10^5$
$10^4$
$10^3$
$10^2$
10
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
RW Cephei
Rigel
Deneb
SUPERGIANTS (I)
Canopus
Betelgeuse
Antares
INSTABILITY STRIP
δ Cephei
Achernar
Mira
RR Lyrae
GIANTS (II,III)
Aldebaran
Regulus
Sirius
Altair
SUBGIANTS (IV)
MAIN SEQUENCE (V)
Sun
WHITE DWARFS (wd)
Sirius B
Procyon B
Barnard's Star
Proxima Cen
Colour Index (B - V)
-0.5
0.0
+0.3
+0.6
+0.8
+0.9
+2.0
O5
B0
A0
F0
G0
K0
M0
Spectral Class

# *Light echoes*



# *Light echoes*



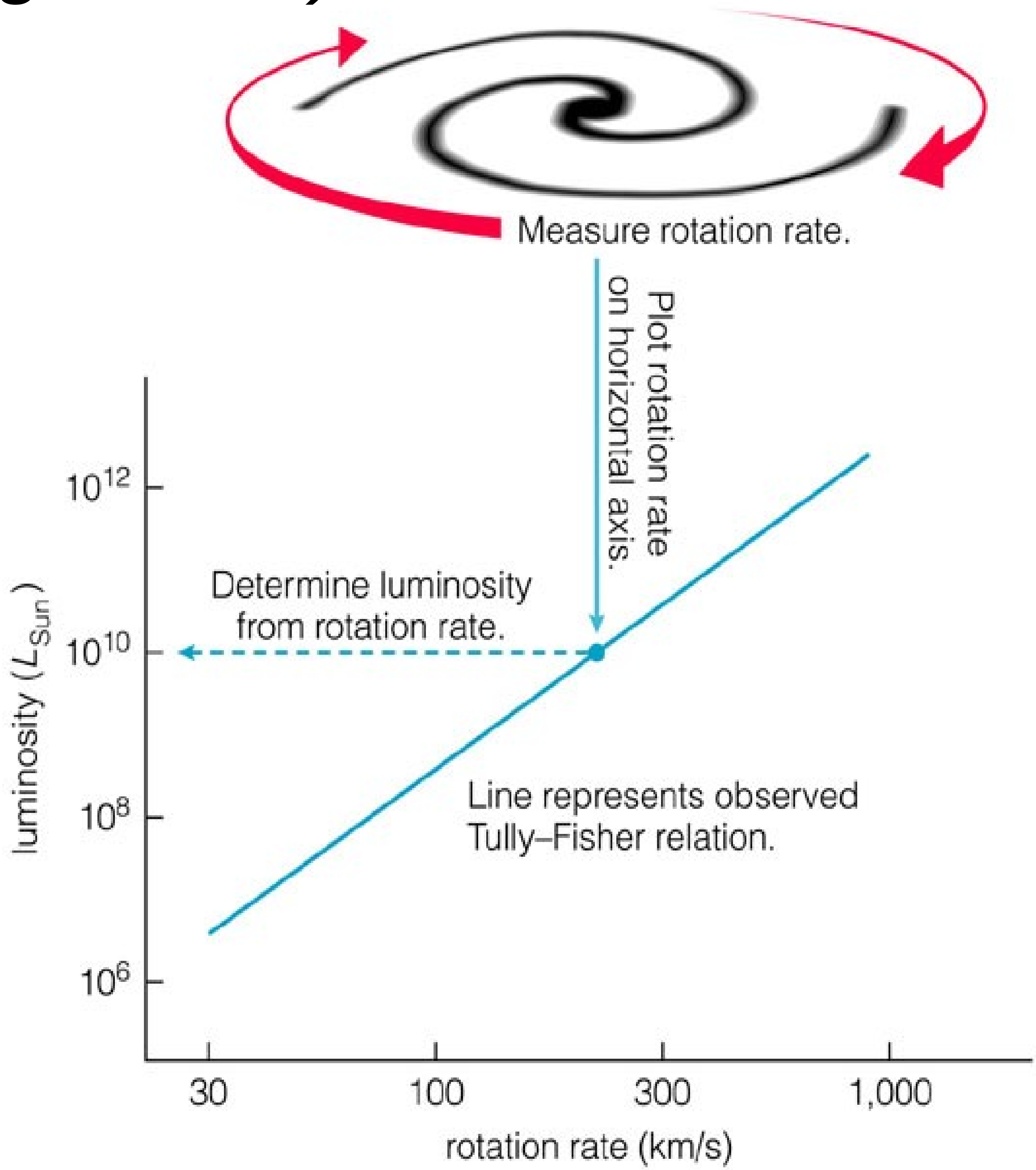
# *Tully-Fisher (spiral galaxies)*

*R. Tully & J. Fisher (1977)*

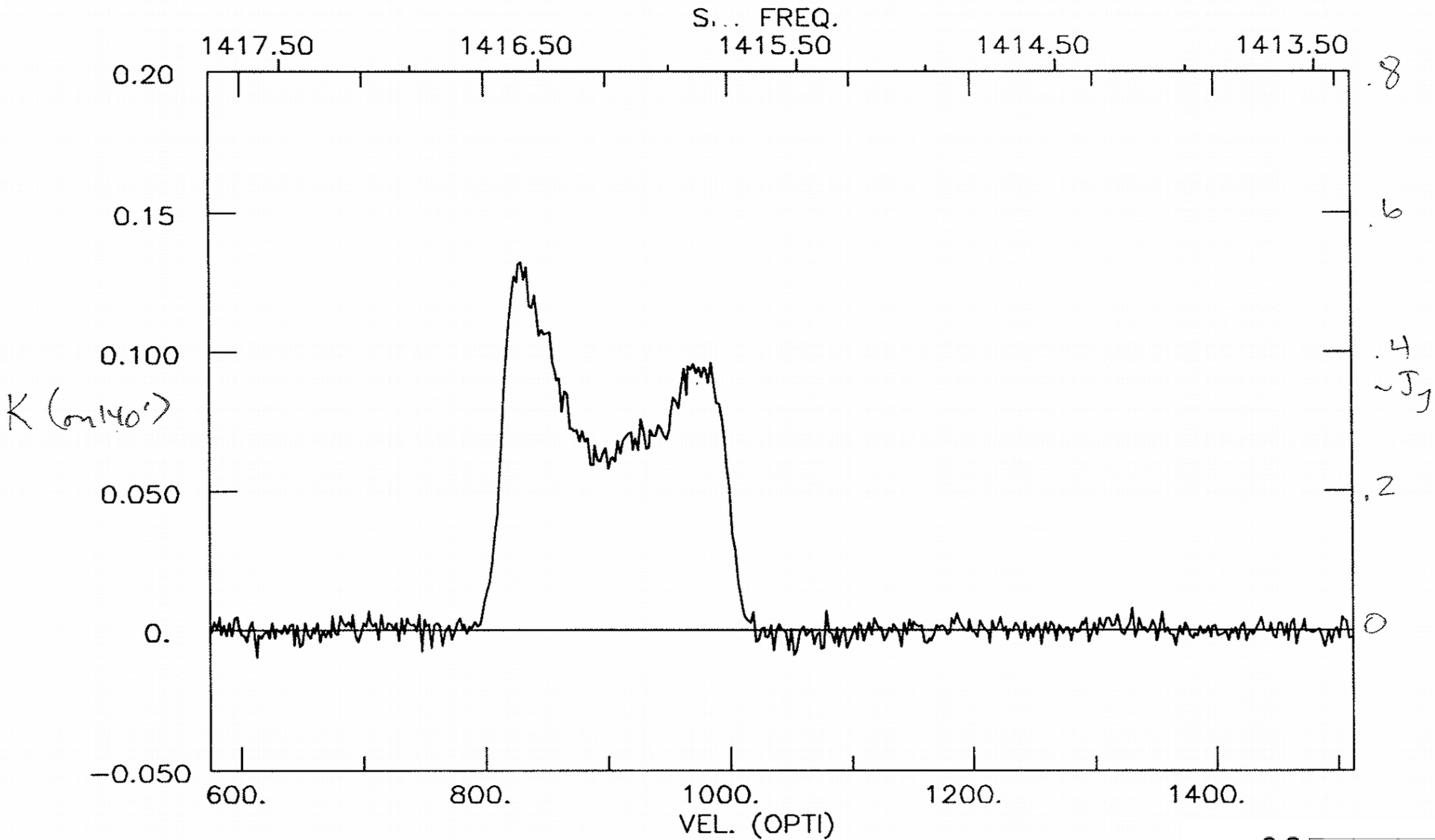
Relation between the rotation velocity of a galaxy (deduced from the width of its emission lines) and its absolute magnitude

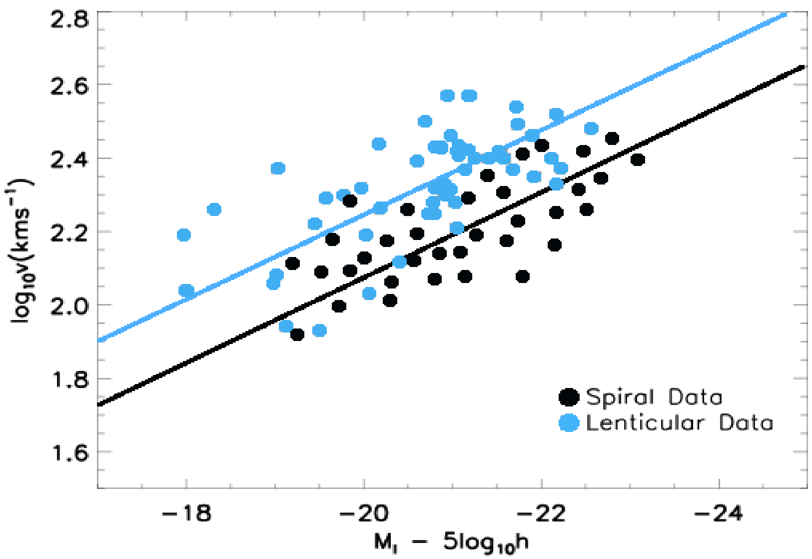
By comparing with the apparent magnitude, gives the distance modulus

Similar relations for elliptical galaxies (Faber-Jackson,
Fundamental plane)



# Tully-Fisher



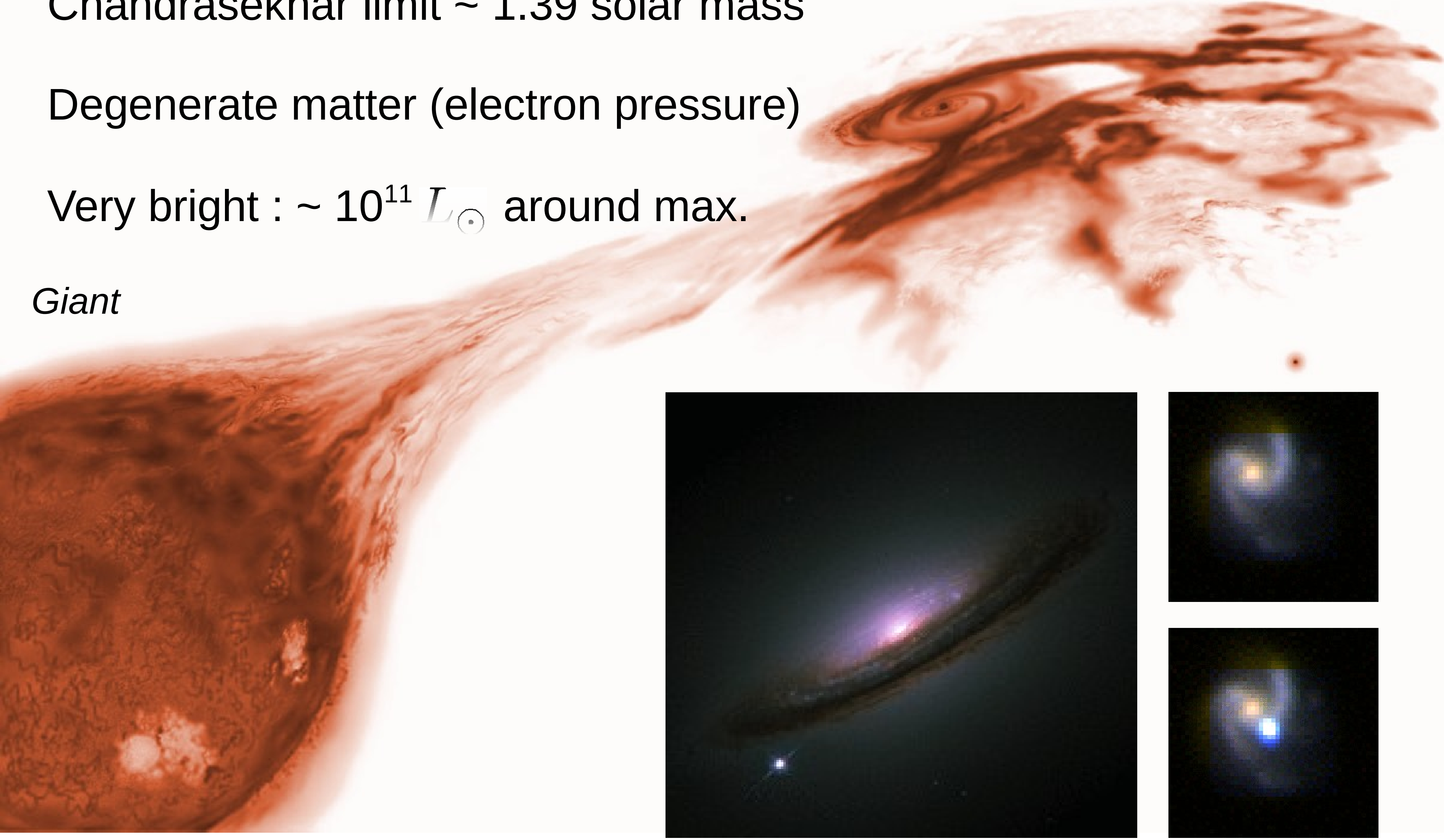



# *Type Ia supernovae : standard candle*

White dwarf accreting mass from its partner
Chandrasekhar limit ~ 1.39 solar mass

Degenerate matter (electron pressure)

Very bright : ~ $10^{11}\ L_{\odot}$ around max.



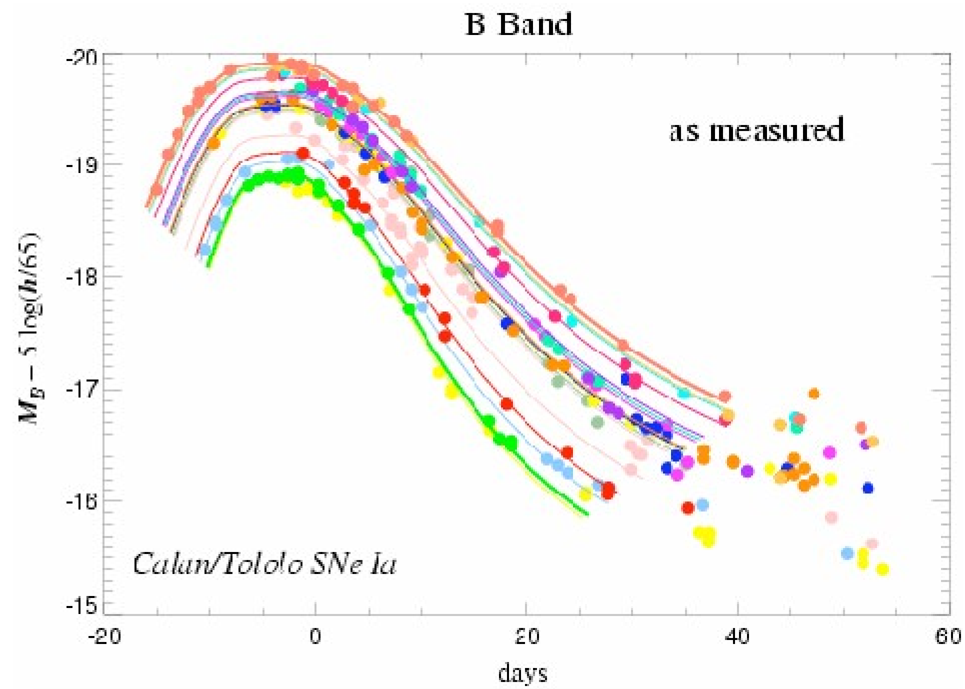
# *Type Ia supernovae : standard candle*

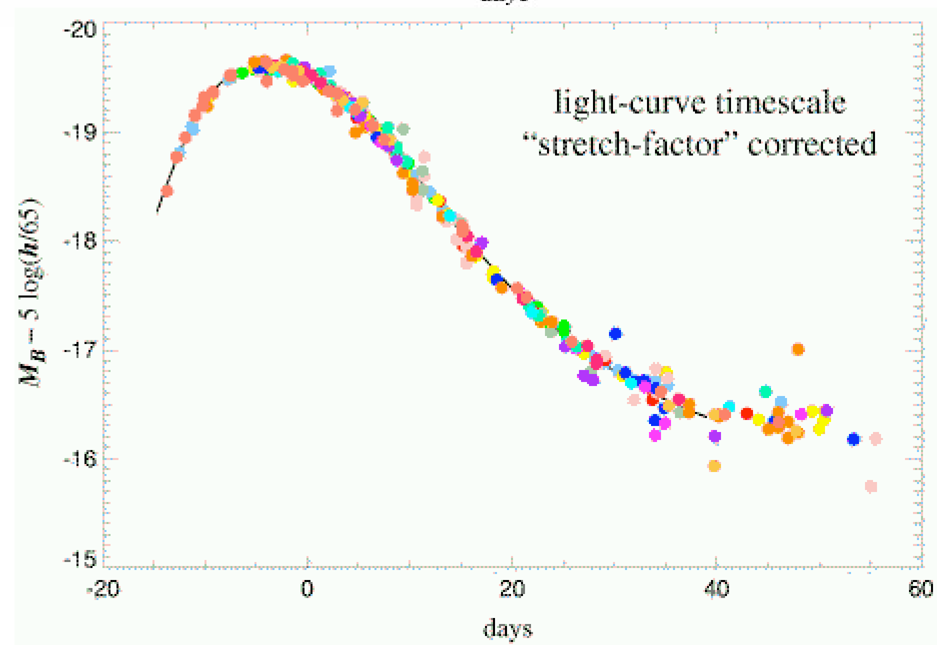
SNIa = standard candles

Raises in a few weeks, decreases in a few months

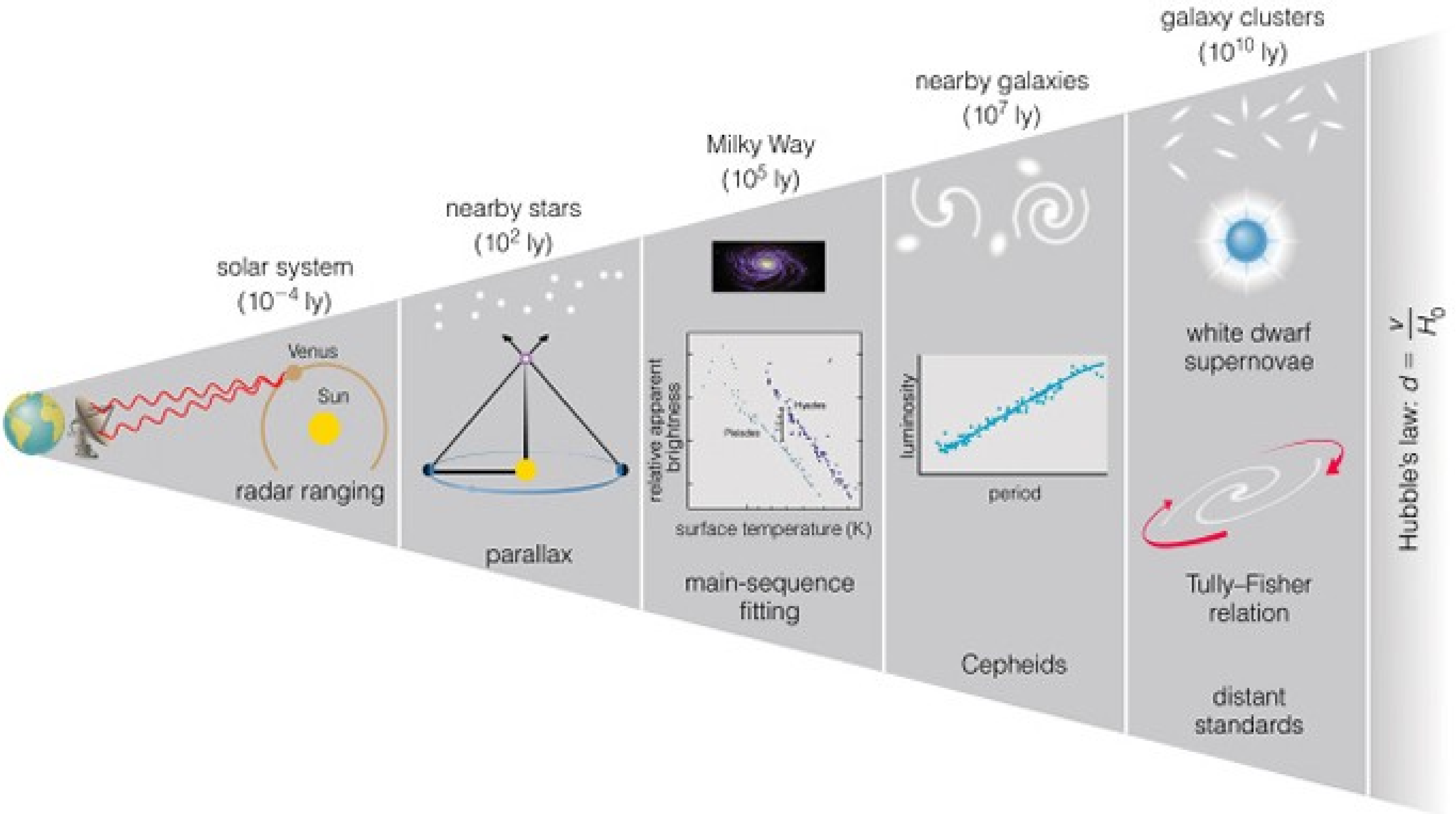
« Standardization » : Correlation of the peak luminosity with the decay (« stretch ») and the color.

Distance estimator up to z~1 and beyond.

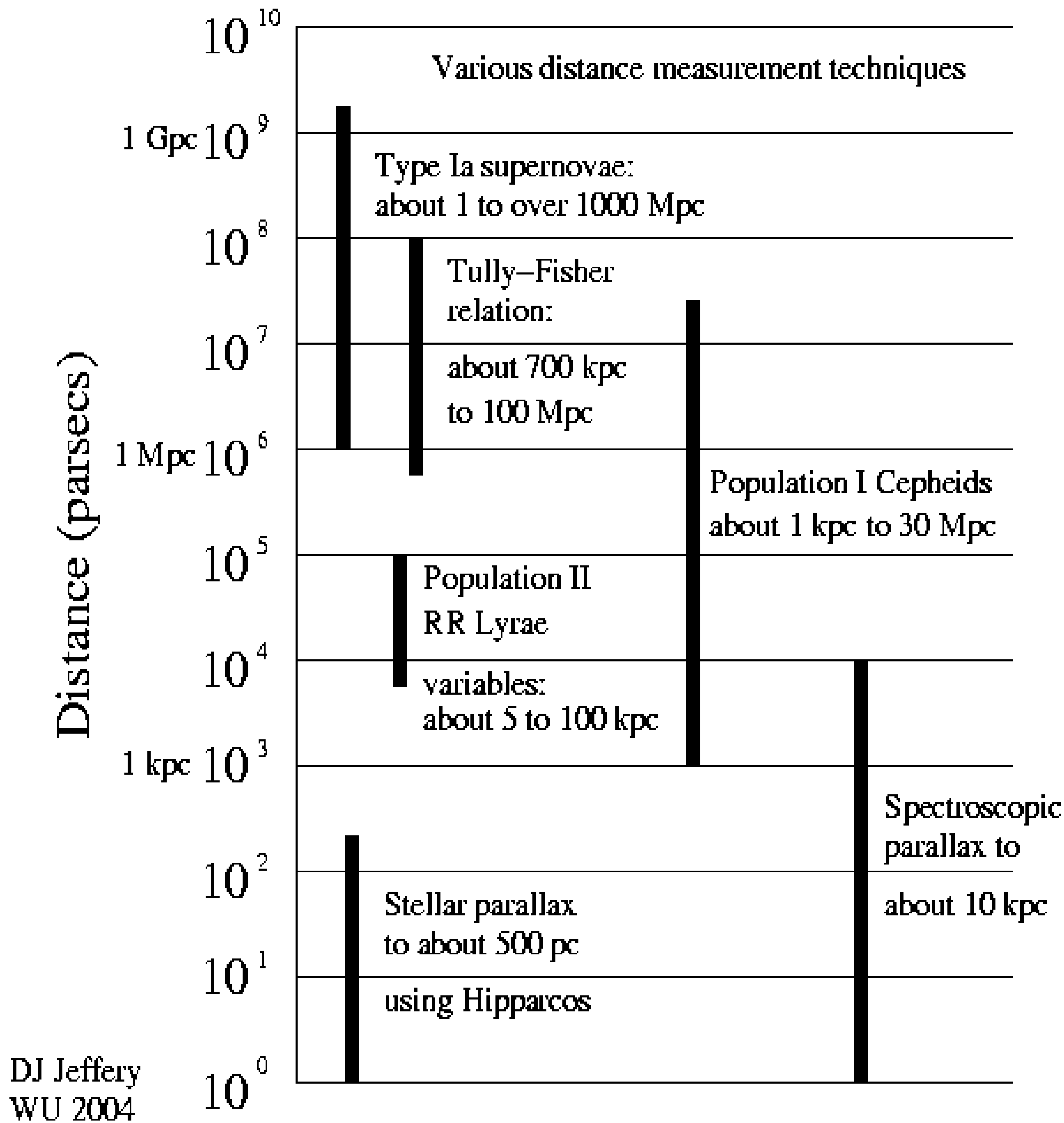


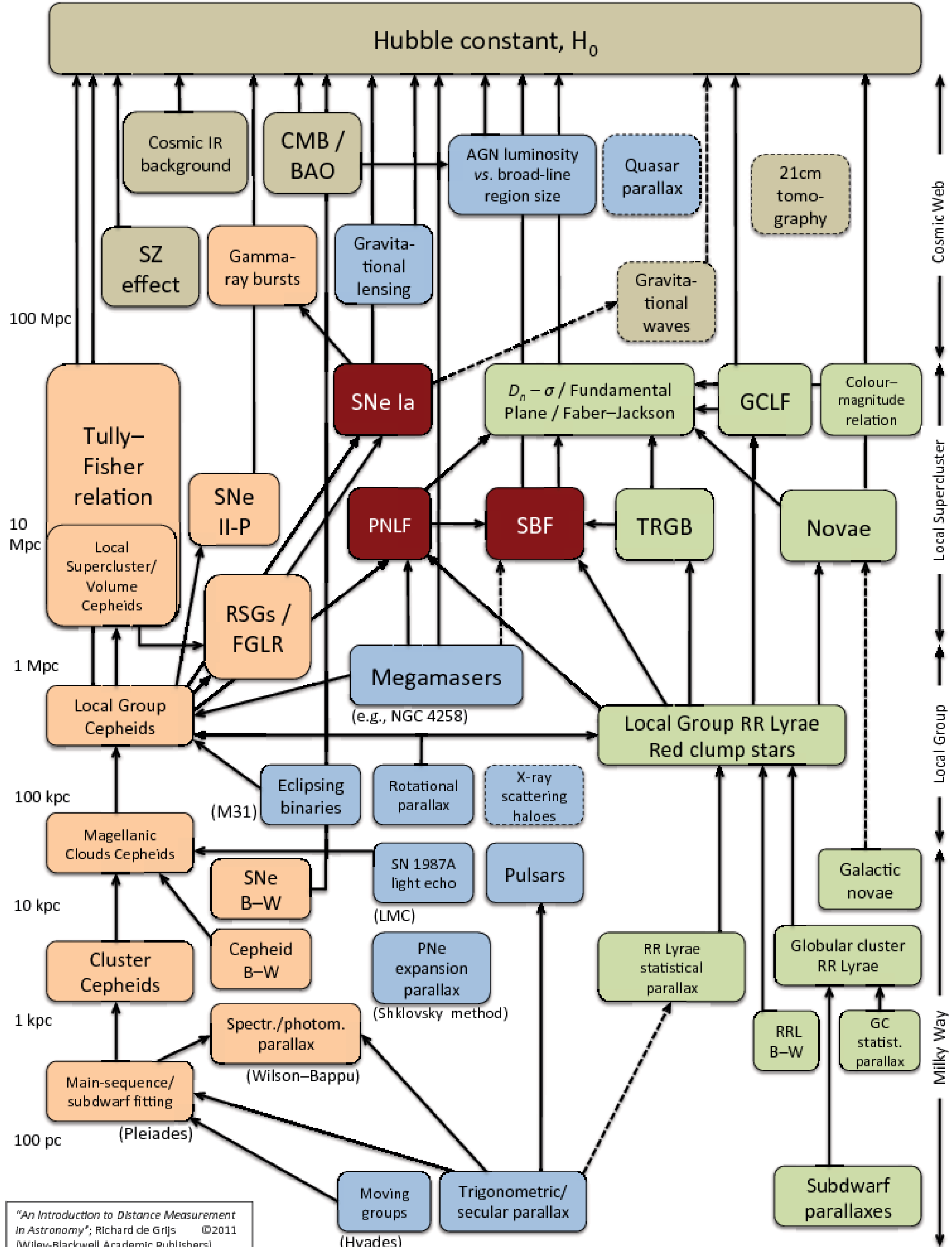



# *Cosmic distance ladder*



A Cartoon of the Distance Ladder





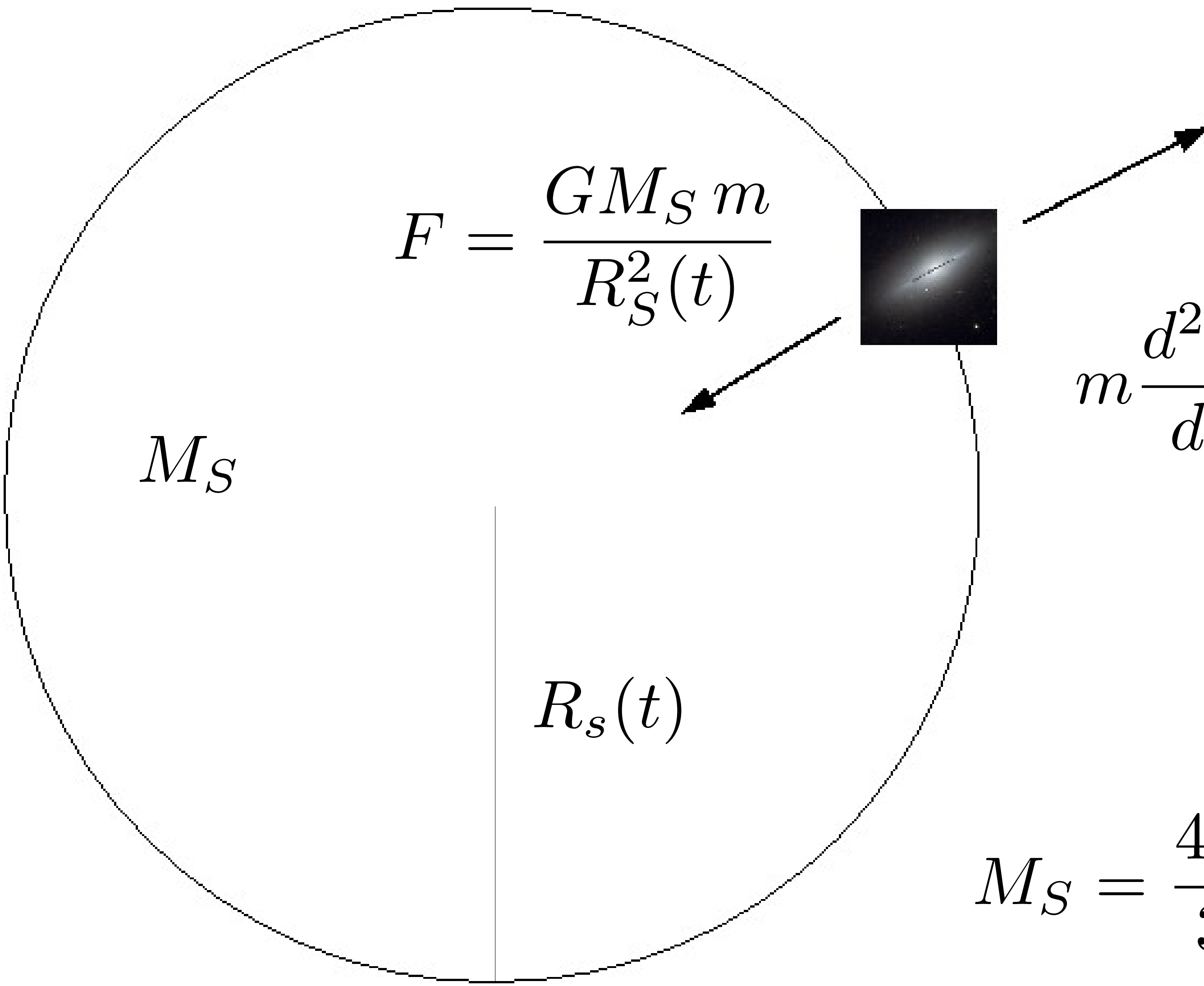
Hubble constant, $H_0$
Cosmic IR background
CMB / BAO
AGN luminosity vs. broad-line region size
Quasar parallax
21cm tomo-graphy
SZ effect
Gamma-ray bursts
Gravita-tional lensing
Gravita-tional waves
100 Mpc
Tully–Fisher relation
SNe Ia
$D_n - \sigma$ / Fundamental Plane / Faber–Jackson
GCLF
Colour–magnitude relation
10 Mpc
Local Supercluster/ Volume Cepheids
SNe II-P
PNLF
SBF
TRGB
Novae
RSGs / FGLR
1 Mpc
Megamasers
(e.g., NGC 4258)
Local Group Cepheids
Local Group RR Lyrae Red clump stars
100 kpc
(M31)
Eclipsing binaries
Rotational parallax
X-ray scattering haloes
Magellanic Clouds Cepheids
SNe B–W
SN 1987A light echo
(LMC)
Pulsars
Galactic novae
10 kpc
Cepheid B–W
Cluster Cepheids
PNe expansion parallax
(Shklovsky method)
RR Lyrae statistical parallax
Globular cluster RR Lyrae
RRL B–W
GC statist. parallax
1 kpc
Spectr./photom. parallax
(Wilson–Bappu)
Main-sequence/ subdwarf fitting
(Pleiades)
100 pc
Moving groups
(Hyades)
Trigonometric/ secular parallax
Subdwarf parallaxes
Cosmic Web
Local Supercluster
Local Group
Milky Way
"An Introduction to Distance Measurement in Astronomy"; Richard de Grijs ©2011 (Wiley-Blackwell Academic Publishers)

1.3

# *Dynamics of the Universe*

*How a simple (and wrong) Newtonian description may (partly) capture the Universe dynamics*

# *A very simple (and wrong) model*




$$F = \frac{G M_S \, m}{R_S^2(t)}$$

$$m \frac{d^2 R_s}{dt^2} = -\frac{G M_S \, m}{R_S^2(t)}$$

$$M_S = \frac{4\pi}{3} \rho(t) R_S^3(t)$$

# *Newtonian dynamics*

$$R_s = r_s \, a(t)$$

$$\ddot{a} = -\frac{4\pi G \rho(t)}{3} \, a(t)$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G \rho(t)}{3} + \frac{2C}{r_s^2 a^2(t)}$$

If C > 0 : expansion will never stop.

If C < 0 : expansion stops at $a^2_{\mathrm{max}} = -GM_S/Cr_s$
Followed by contraction

C = 0 : limit case (expand forever but $\dot{a} \longrightarrow 0$ )

Analogy with the dynamic of a ball bouncing on Earth

# *From Newton to General Relativity*

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho(t)}{3} + \frac{2C}{r_s^2 a^2(t)} \quad \longrightarrow \quad \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho(t)}{3} - \frac{kc^2}{R_0^2}\frac{1}{a(t)^2}$$

$$\frac{2C}{r_s^2} \quad \longrightarrow \quad -\frac{kc^2}{R_0^2}$$

$$k = -1, +1, 0 \qquad\qquad R(t) = a(t)R_0$$

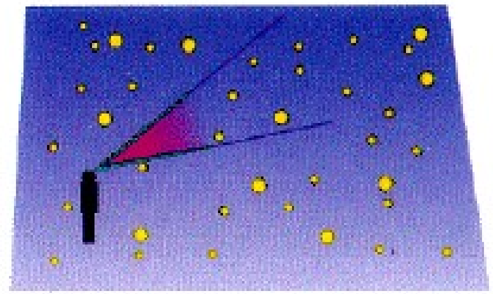
If k = -1 (C > 0) : negative curvature
expansion will never stop.

If k = +1 (C < 0) : positive curvature
expansion stops, contraction follows

If k = 0 (C = 0) : flat universe (limit case)

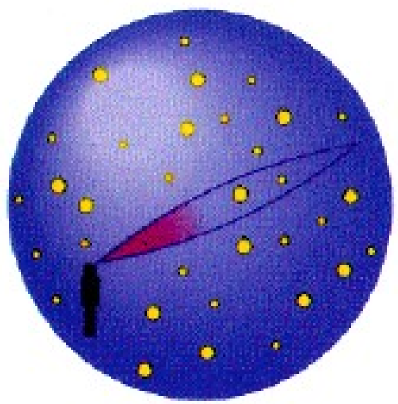
*[GR, dynamics...]*

$k = 0$



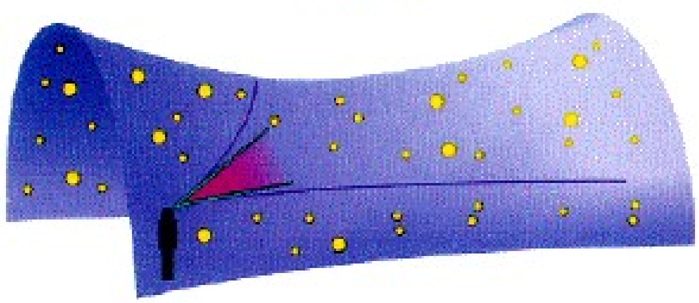
Flat universe

$k = +1$

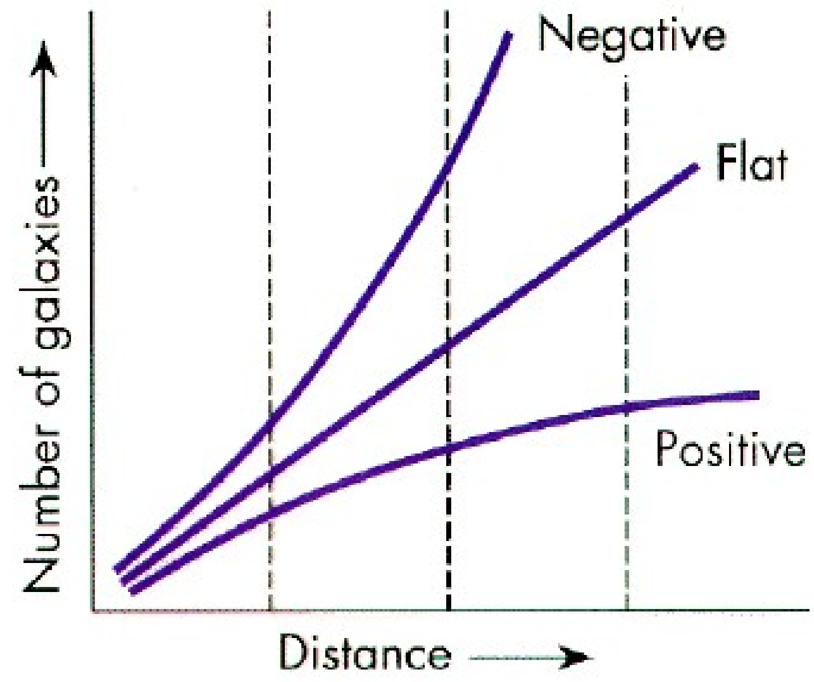


Positively curved universe

$k = -1$



Negatively curved universe



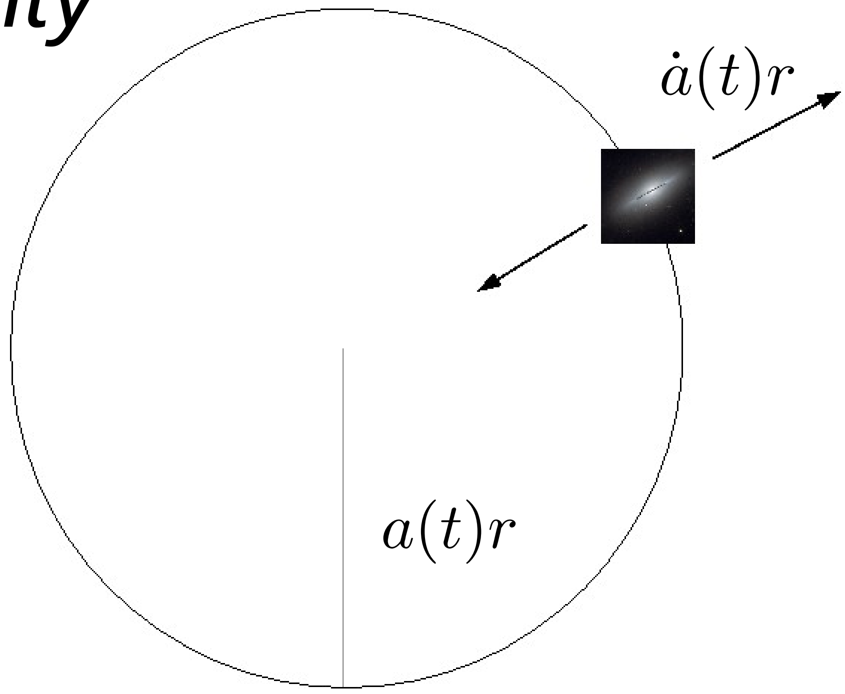

[Curvature, General Relativity...]

# *Hubble rate and critical density*

$$H(t) = \frac{\dot{R}(t)}{R(t)} = \frac{\dot{a}(t)}{a(t)}$$

$$z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} - 1$$

$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = \frac{a(t_{\rm obs})}{a(t_{\rm emit})} = \frac{1}{a(t)}$$




$r$ comobile distance
$a(t)$ scale factor

$$H^2(t) = \frac{8\pi G}{3}\rho_c(t) = \frac{8\pi G}{3c^2}\varepsilon_c(t)$$

$$H_0 = H(t_0) \simeq 70\,{\rm km/s/Mpc}$$

$$a(t_0) = 1$$

$$\rho_c(t) = \frac{3}{8\pi G}H^2(t) \qquad \varepsilon_c(t) = \frac{3c^2}{8\pi G}H^2(t)$$

$$\rho_{c,0} = \rho(t_0) \simeq 9 \times 10^{-27}\,{\rm kg\,m^{-3}} \simeq 1.4 \times 10^{11}\,{\rm M_\odot\,Mpc^{-3}}$$

$$\varepsilon_{c,0} \simeq 5200\,{\rm MeV\,m^{-3}} \quad \text{5 protons per m}^3$$

# Friedmann Equation

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{R_0^2 a^2}$$

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\varepsilon - \frac{kc^2}{R_0^2 a^2}$$

$$-\frac{kc^2}{R_0^2 a^2(t) H^2(t)} = 1 - \frac{\rho(t)}{\rho_c(t)} = 1 - \Omega(t)$$

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)} = \frac{\varepsilon(t)}{\varepsilon_c(t)}$$

$$\Omega_k(t) = -\frac{kc^2}{R_0^2 a^2(t) H^2(t)} = 1 - \Omega(t)$$

# *Fluid equation*

Adiabatic expansion : $\delta Q = dU + pdV = 0 \quad \text{i.e.} \quad dS = 0$

Fluid equation : $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3p)$

Friedmann equations :

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\varepsilon - \frac{kc^2}{R_0^2 a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3p)$$

$$\dot{\varepsilon} + 3\frac{\dot{a}}{a}(\varepsilon + p) = 0$$

Needed : equation of state : $p = w\varepsilon = w\rho/c$

# *Equations of state*

Non-relativistic matter : $p_m \ll \varepsilon_m = \rho_m / c^2 \qquad w_m \simeq 0$

Light, relativistic matter (photons, neutrinos, ...) :

$$p_r = \frac{\varepsilon_r}{3} \qquad w_r = \frac{1}{3}$$

Density evolution with time :

$$\dot{\varepsilon} + 3\frac{\dot{a}}{a}(\varepsilon + p) = 0 \qquad \varepsilon(t) = \varepsilon(t_0) a(t)^{-3(1+w)}$$

$$\varepsilon_m(t) = \varepsilon_m(t_0)/a(t)^3$$

$$\varepsilon_r(t) = \varepsilon_r(t_0)/a(t)^4$$

*Eras ! Light era, matter era, ...*

*[Dynamics, Thermal history...]*

# *Friedmann Equations*

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\varepsilon - \frac{kc^2}{R_0^2 a^2}$$

$$\dot{\varepsilon} + 3\frac{\dot{a}}{a}(\varepsilon + p) = 0$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3p)$$

Describe an evolving, non static Universe (scale factor *a*(t))

Einstein → How to stabilise it to get a static Universe ?

# *Friedmann Equations (with $\Lambda$)*

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2}\varepsilon - \frac{kc^2}{R_0^2 a^2} + \frac{\Lambda c^2}{3}$$

$$\dot{\varepsilon} + 3\frac{\dot{a}}{a}(\varepsilon + p) = 0$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\varepsilon + 3p) + \frac{\Lambda c^2}{3}$$

$$\Lambda = \frac{8\pi G}{c^4}\varepsilon_\Lambda = \frac{8\pi G}{c^2}\rho_\Lambda \qquad p_\Lambda = -\rho_\Lambda c^2 \qquad w_\Lambda = -1$$

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c}$$

# *Universe driven by its contents*

Non-relativistic matter : $$\Omega_m = \frac{\rho_m}{\rho_c} = \frac{\varepsilon_m}{\varepsilon_c}$$

« Curvature » : $$\Omega_k(t) = -\frac{kc^2}{R_0^2 a^2(t) H^2(t)} = 1 - \Omega(t)$$

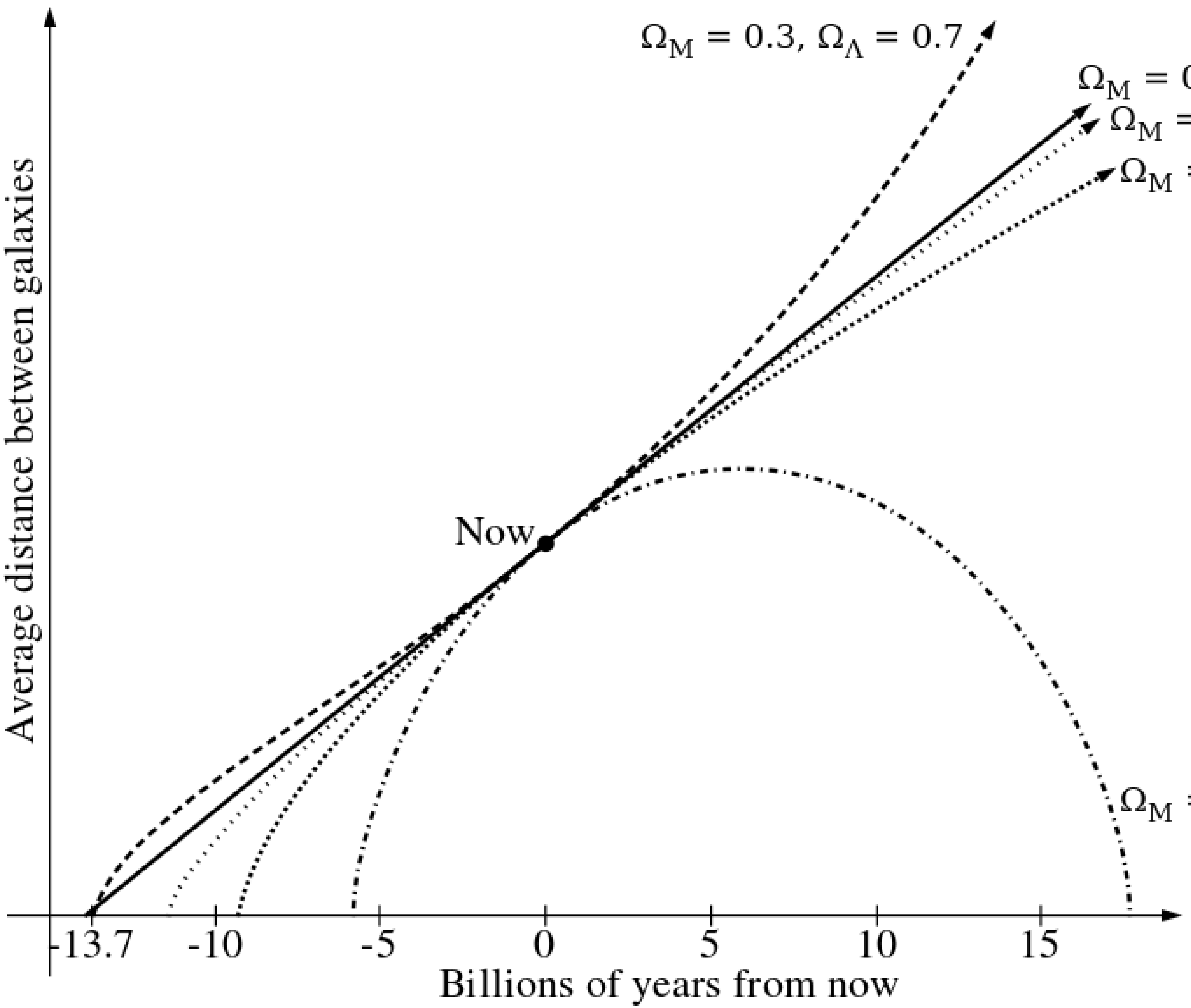
Photons : $$\Omega_\gamma = \frac{\rho_\gamma}{\rho_c} = \frac{\varepsilon_\gamma}{\varepsilon_c}$$

Neutrinos : $$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\varepsilon_\nu}{\varepsilon_c}$$

$$\Omega_r = \frac{\rho_r}{\rho_c} = \frac{\varepsilon_r}{c}$$

« Cosmological constant » : $$\Lambda = \frac{8\pi G}{c^4}\varepsilon_\Lambda = \frac{8\pi G}{c^2}\rho_\Lambda$$

Exotic fields...




[Universe Dynamics...]

1.4

# *Contents of the Universe*

*The dynamics of the Universe*
*is driven by its contents.*

*So, what is the Universe made of?*

# *Stars*

Typical luminosity in a few hundreds Mpc :

$$j_{\star,B} \simeq 1.2 \times 10^8 L_{\odot,B}/\mathrm{Mpc}^3$$

In the vicinity of the Sun (1kpc) :

$$< M/L_B > \simeq 4 M_\odot / L_{\odot,B}$$

If typical,

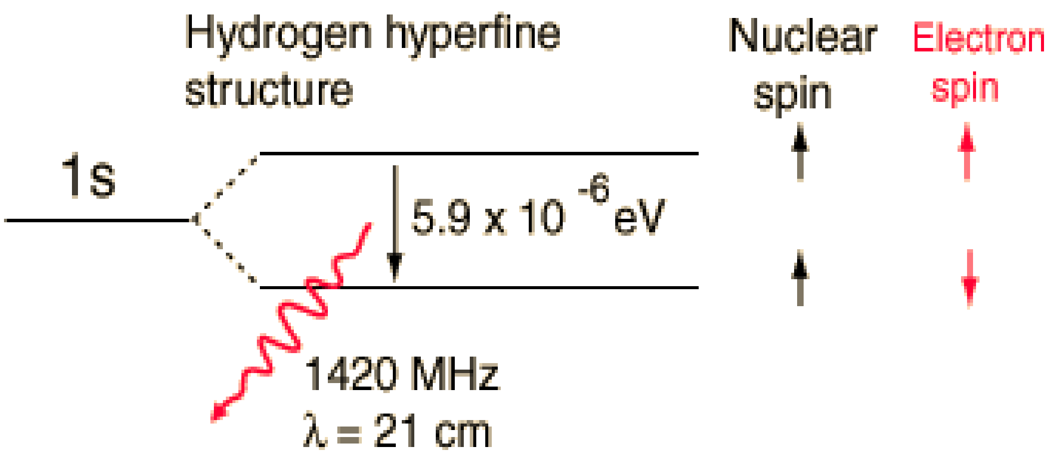
$$\rho_{\star,0} = j_{\star,B} * < M/L_B \simeq 5 \times 10^8 M_\odot/\mathrm{Mpc}^3$$

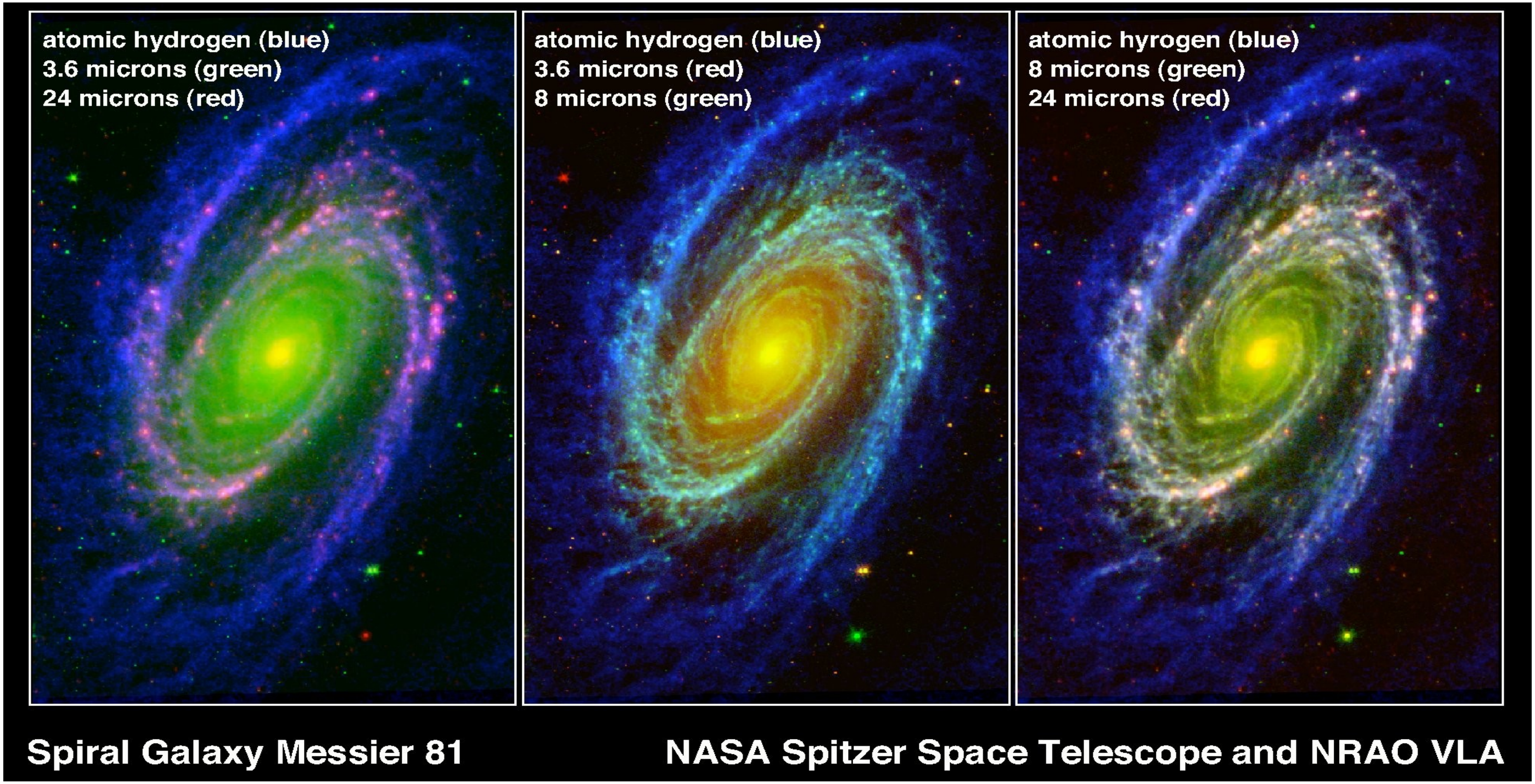
$$\Omega_\star \simeq 0.003 - 0.004$$

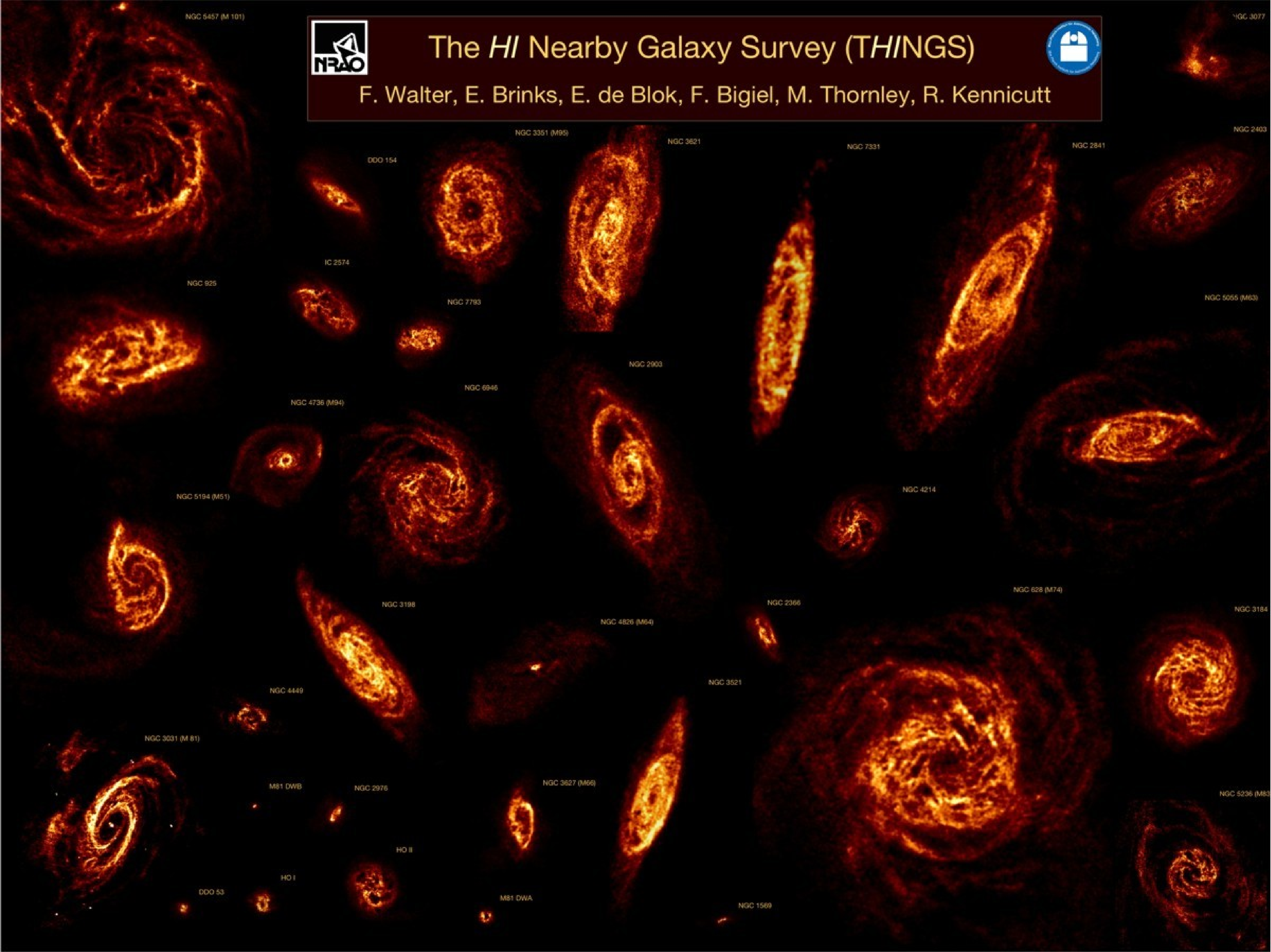
# *Gas (HI, $H_2$, ...)*

HI : 21 cm line (radio)

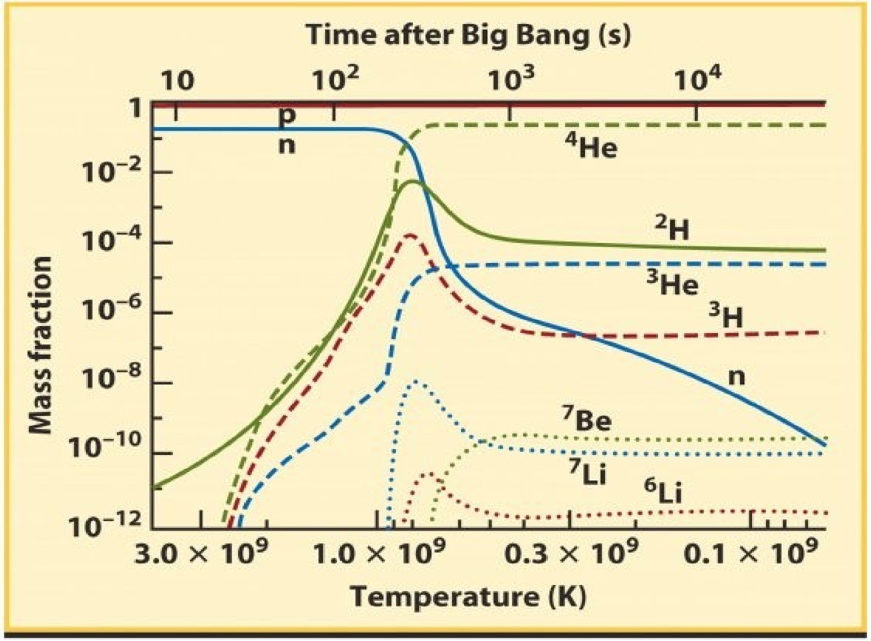
$$\Omega_{\rm HI} \simeq 3 \times 10^{-4}$$
$$\Omega_{\rm H2} \simeq 2 \times 10^{-4}$$

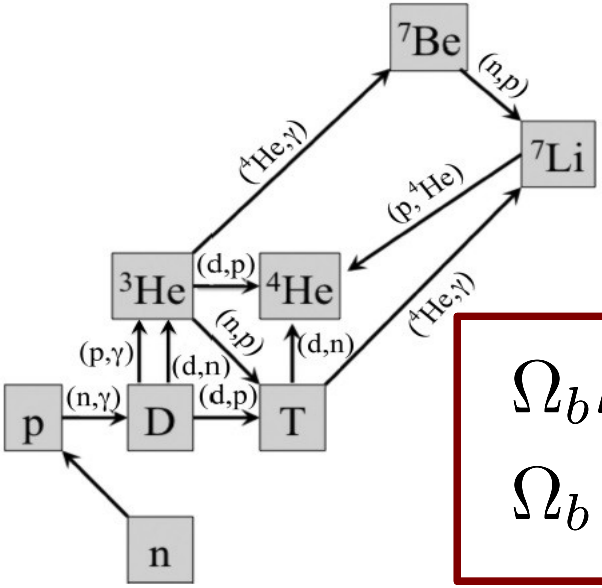



The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NGC 5457 (M 101)
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
NGC 2403
DDO 154
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 5194 (M51)
NGC 4214
NGC 628 (M74)
NGC 3198
NGC 2366
NGC 4826 (M64)
NGC 3184
NGC 3521
NGC 4449
NGC 3031 (M 81)
M81 DWB
NGC 2976
NGC 3627 (M66)
NGC 5236 (M83
HO II
HO I
DDO 53
M81 DWA
NGC 1569

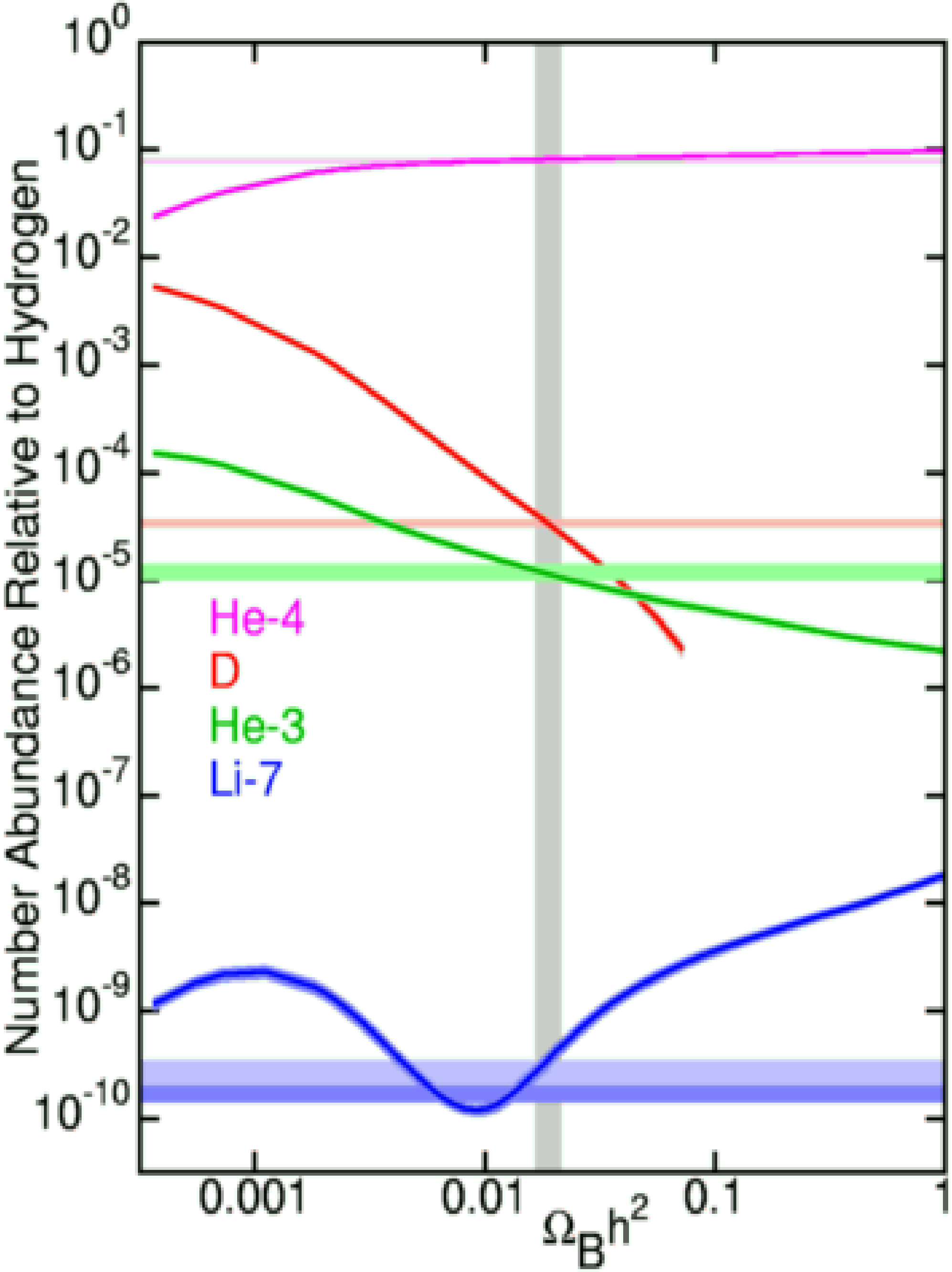
# Baryonic matter : primordial nucleosynthesis



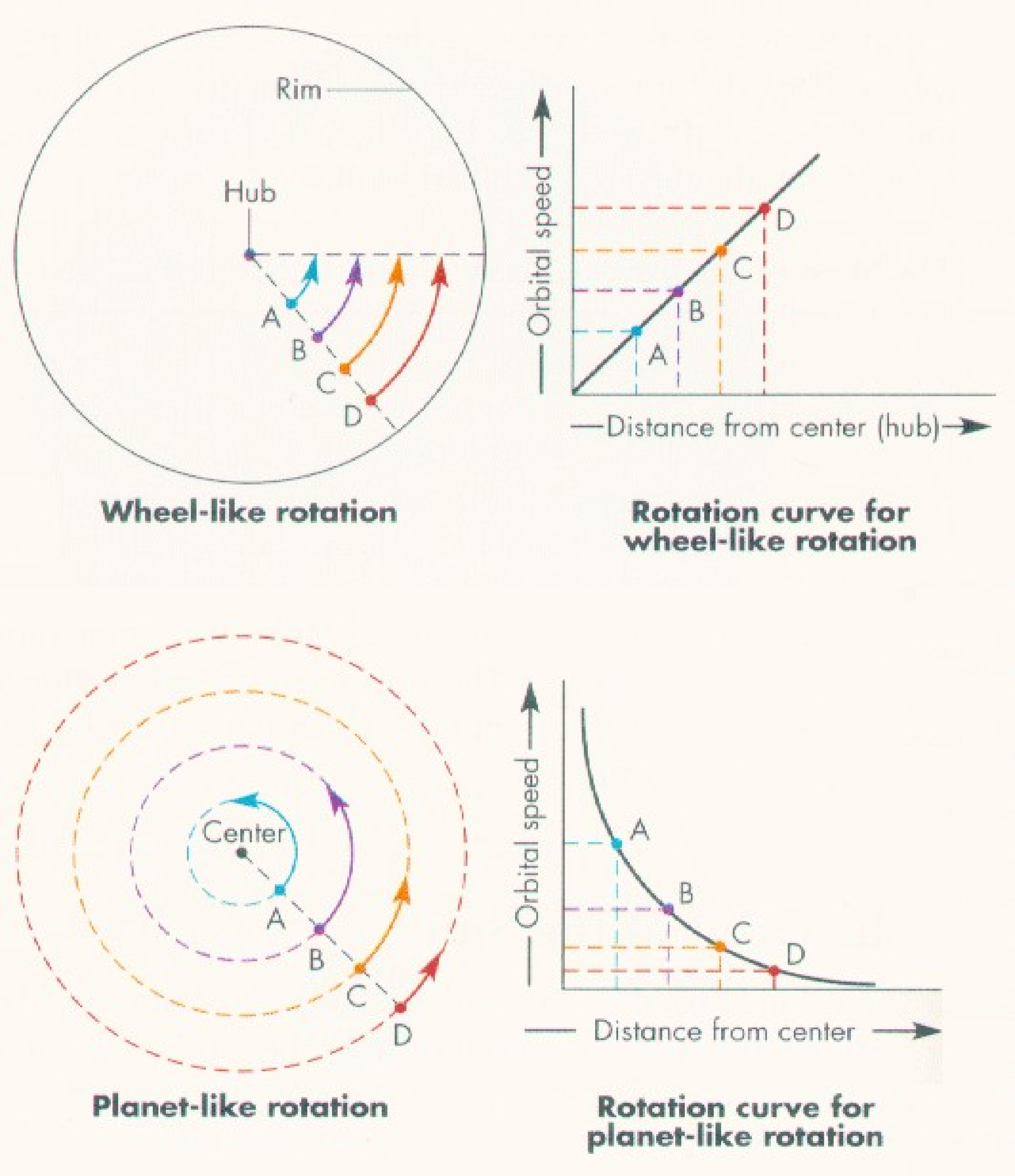




$$\Omega_b h^2 \simeq 0.022$$
$$\Omega_b \simeq 0.045$$

(CMB : Planck, 2014)



# Galaxies : rotation curves

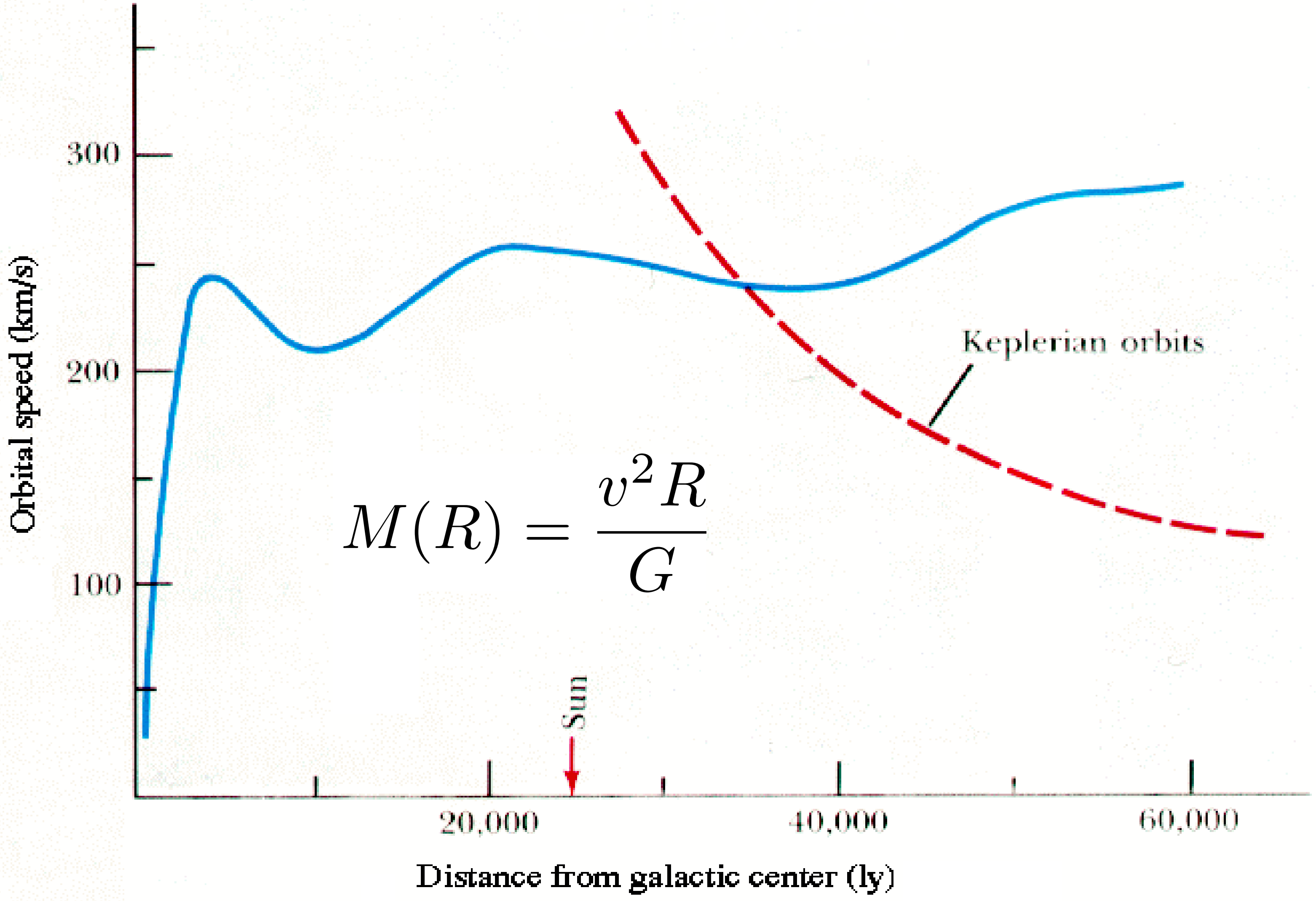



$$\frac{GM(r)}{r^2} = \frac{v^2}{r}$$

$$v = \sqrt{\frac{GM(r)}{r}}$$

$$M(R) = \frac{v^2 R}{G}$$

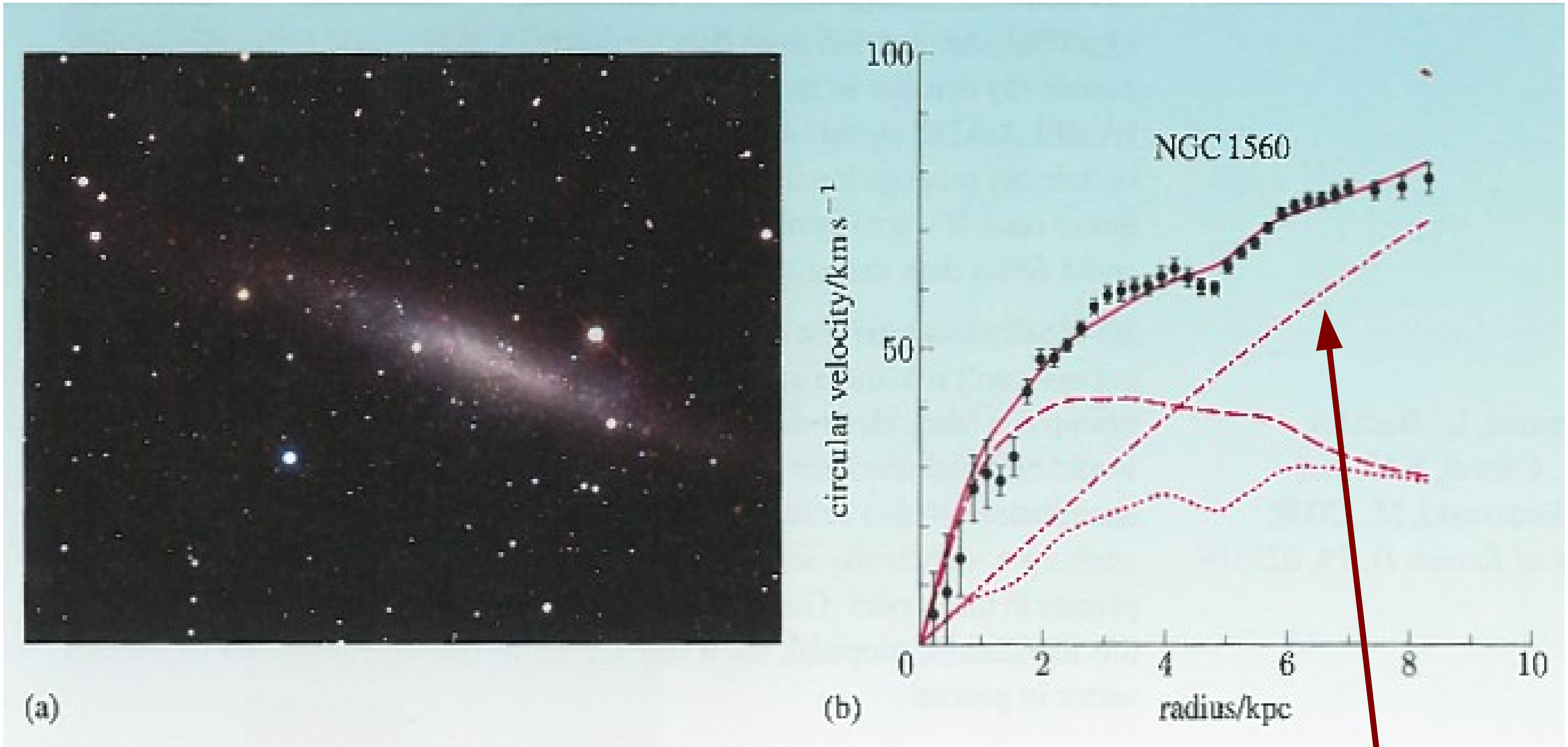
# *Galaxies : rotation curves*




$$M(R) = \frac{v^2 R}{G}$$

$$M(R) \simeq 10^{11}\, M_\odot \left(\frac{v}{220\,\mathrm{kms}^{-1}}\right)^2 \left(\frac{R}{8.5\,\mathrm{kpc}}\right)$$

# *Galaxies : rotation curves*




$$\Omega_{\rm gal} \simeq 0.04 \text{ to } 0.16$$

**Dark matter halo !**

# *Galaxy Clusters*

Virialized objects $V + 2T = 0$

$$\frac{1}{2} M < v^2 >= \frac{\alpha}{2} \frac{GM^2}{r_h}$$

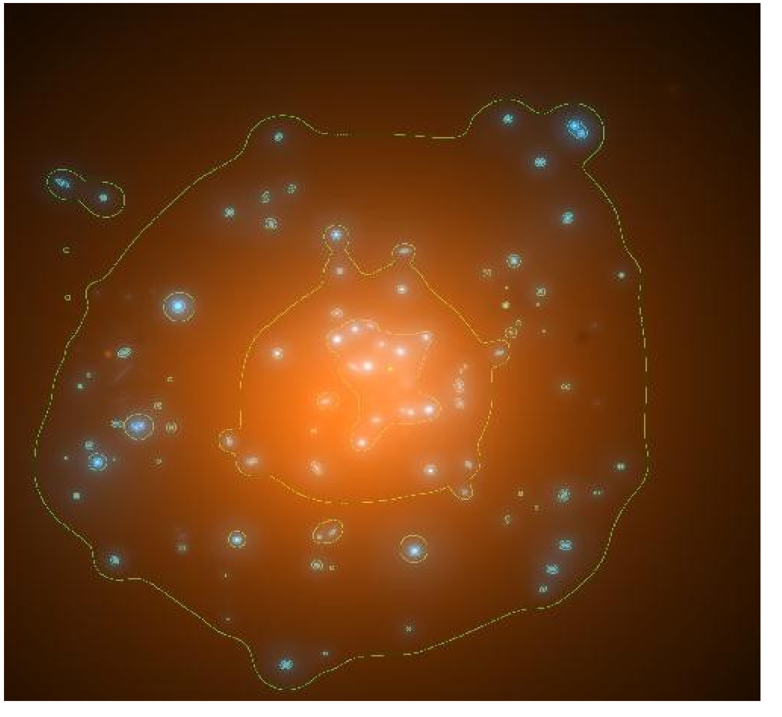
Mass may be deduced from velocity dispersion :

$$M = \frac{< v^2 > r_h}{\alpha G}$$

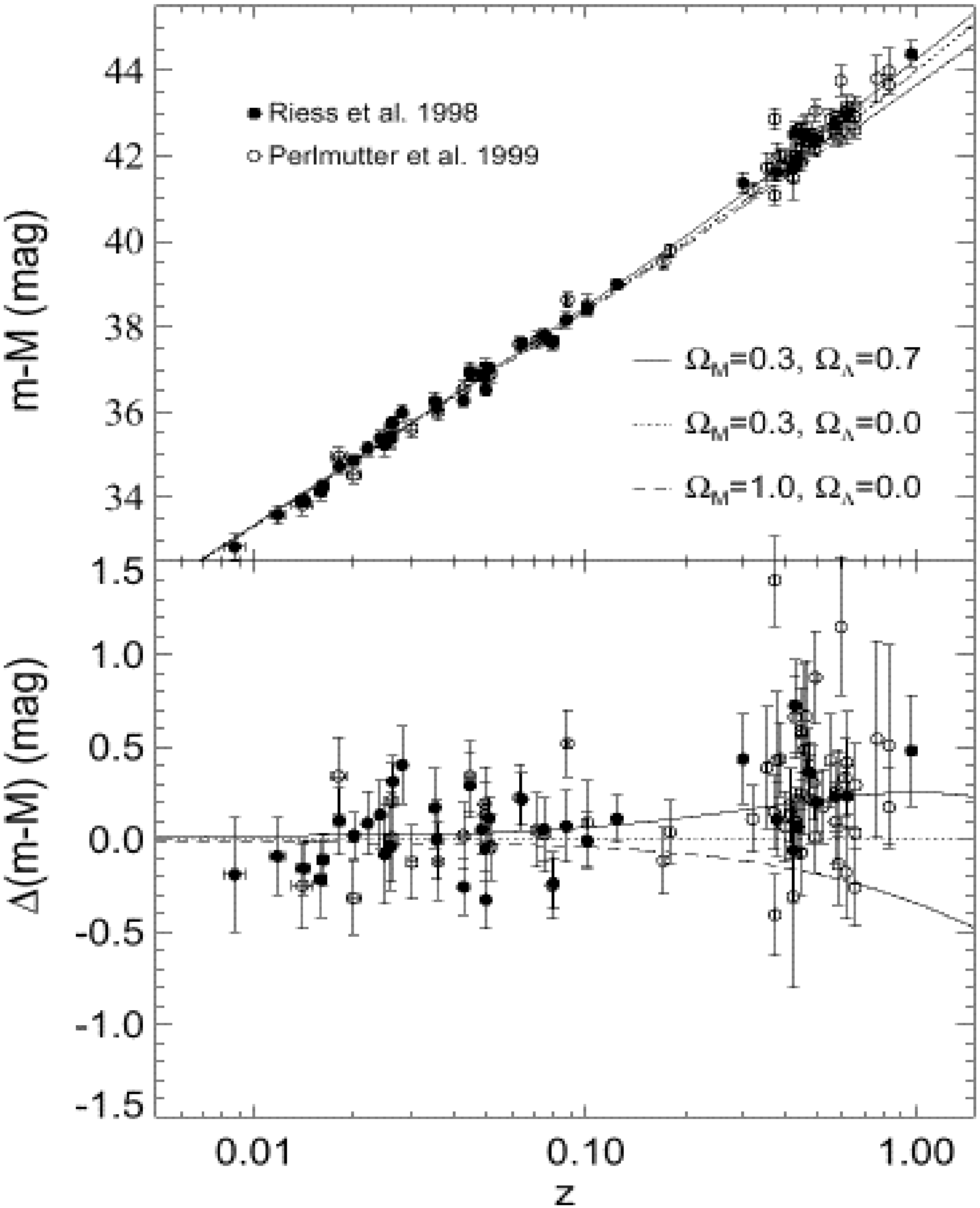
Hot X-ray emitting gas under hydrostatic equilibrium

$$\Omega_{\text{clusters}} \simeq 0.2$$

**« Dark » matter again !**



# *Type Ia Supernovae and Dark Energy*




Expansion is accelerating!

Best model :

$$\Omega_m \simeq 0.3 \quad \Omega_\Lambda \simeq 0.7$$

The cosmological constant is back!

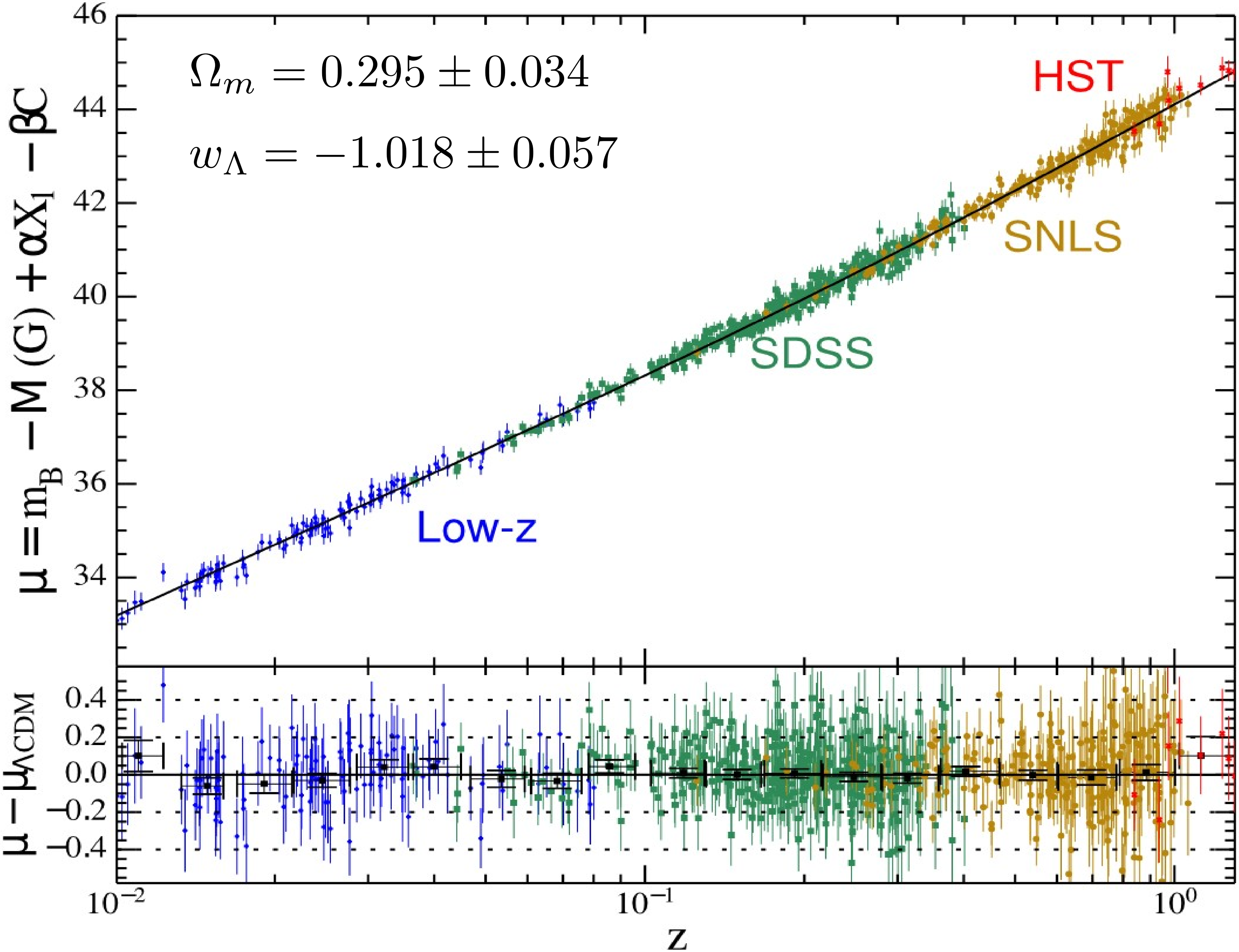
May be seen as an dark energy with

$$p = w\rho = w\epsilon/c^2$$

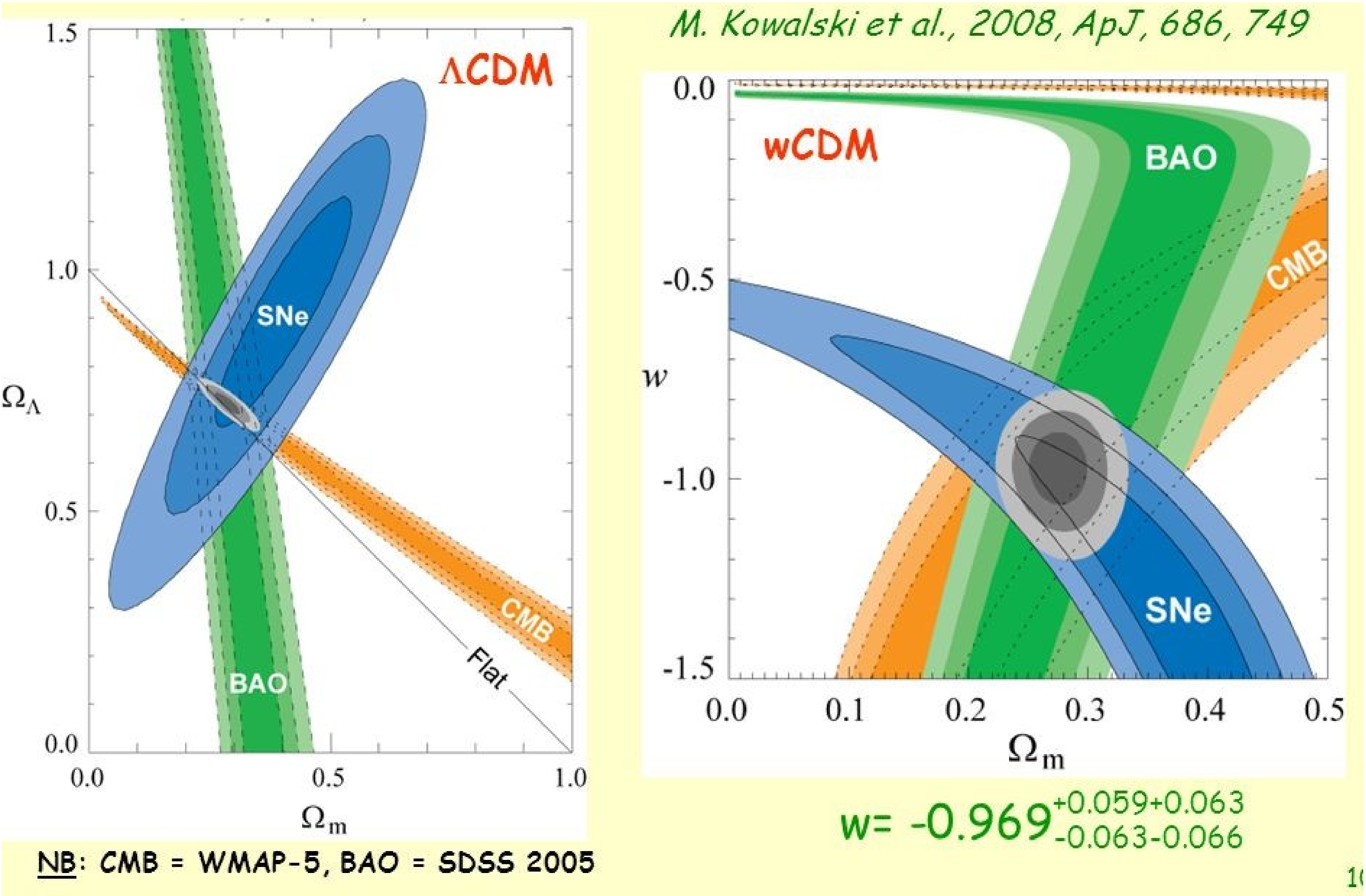
$$w = -1 \qquad p = -\rho$$

# *Supernovae and Dark Energy*

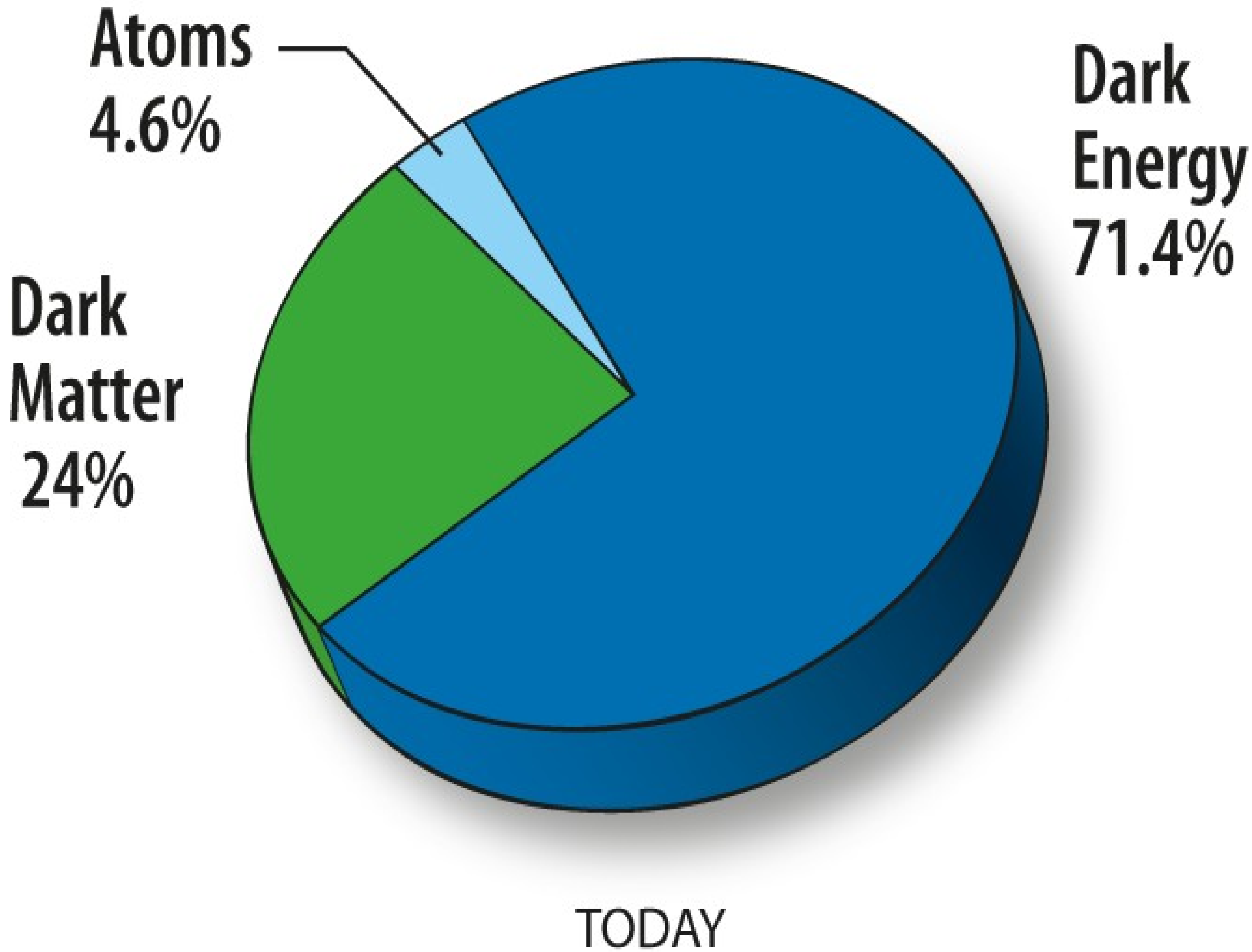
Betoule et al., 2014



# Concordance Model



*A strange Universe...*



# A short history of the Universe