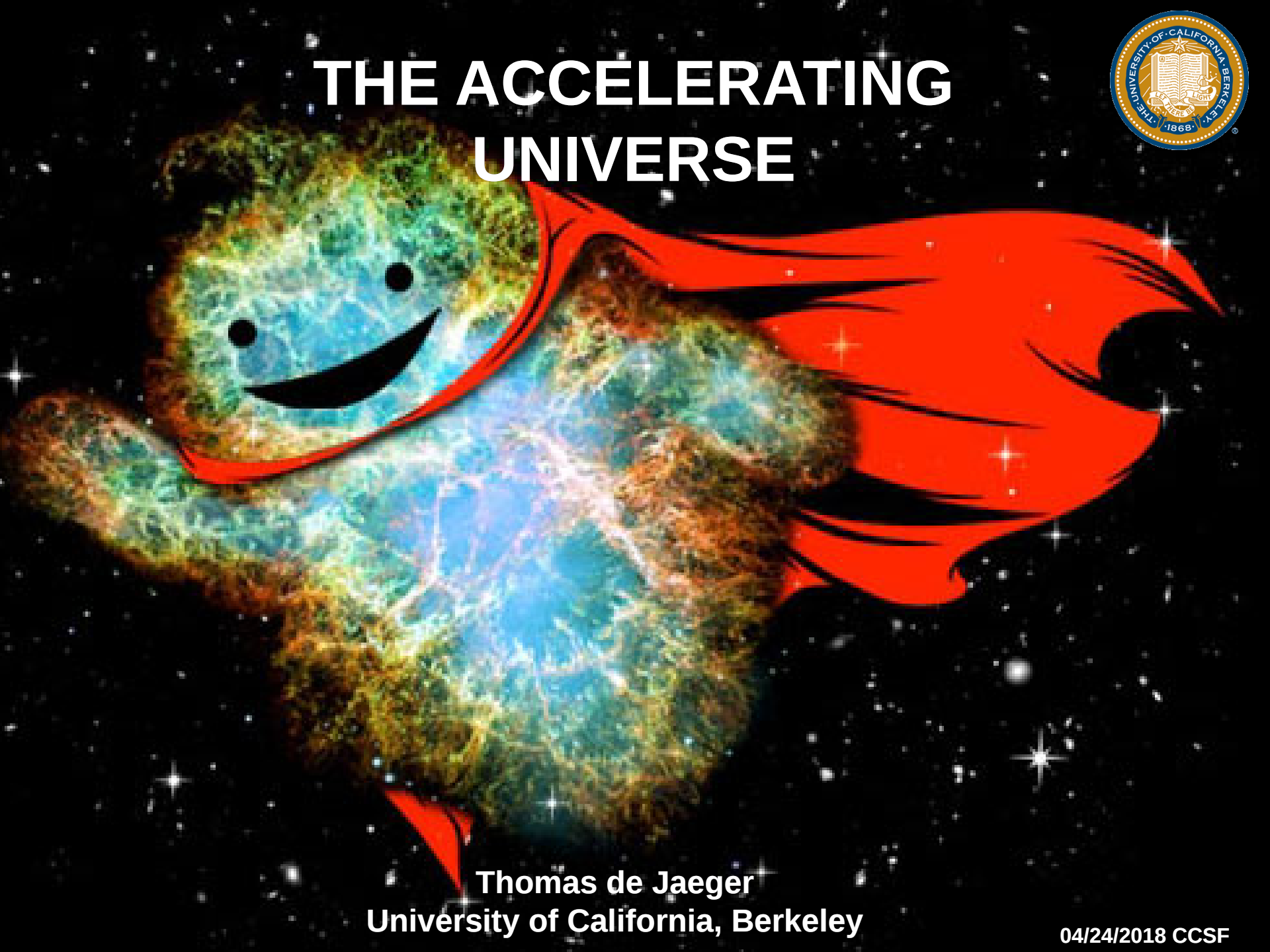
THE ACCELERATING UNIVERSE



Thomas de Jaeger
University of California, Berkeley

Cosmology

Cosmology : from the Greek κόσμος, kosmos "world" and -λογία, -logia "study of"

→ study of the origin, evolution, composition and dynamics of the Universe

Universe scale

Universe scale

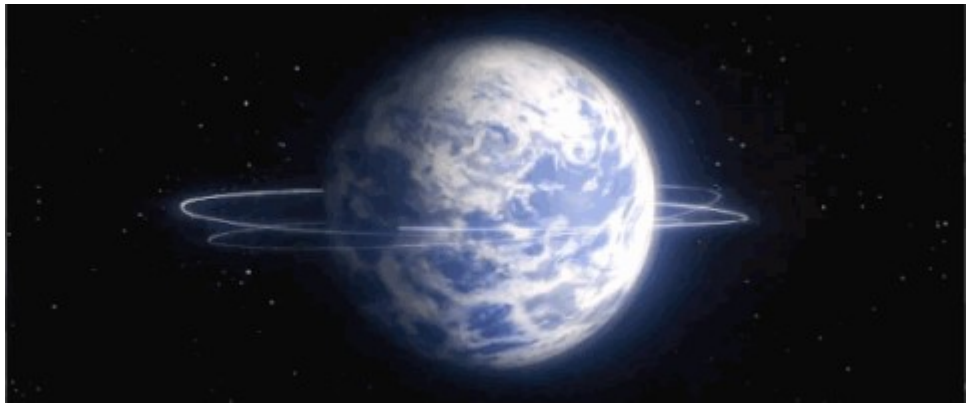
THE UNIVERSE IS

BIG!!!

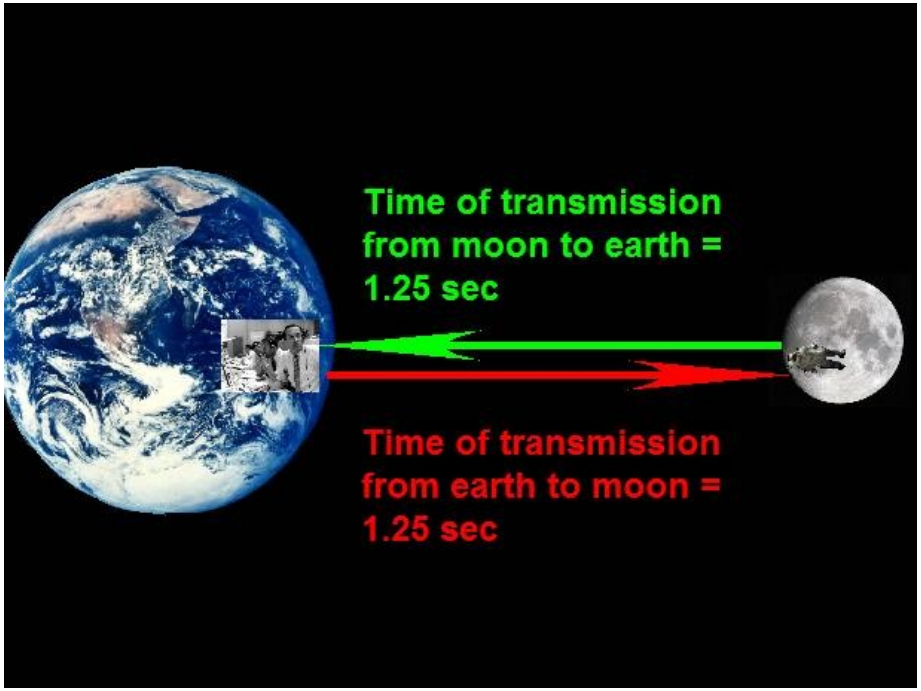
Universe scale

THE UNIVERSE IS BIG!!!

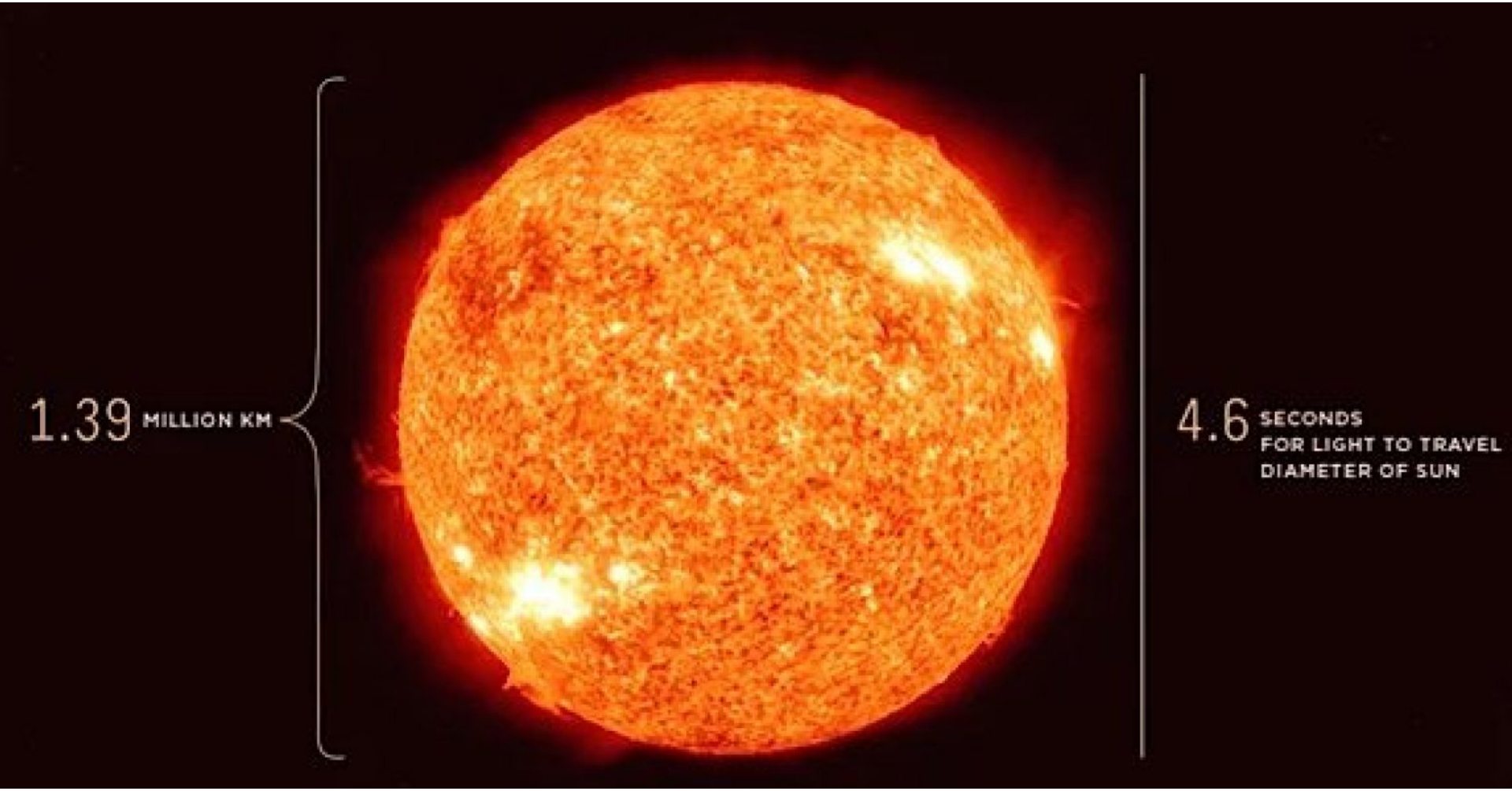
Light travels 300,000 km per sec, that is 7.5 times around the Earth earch sec !



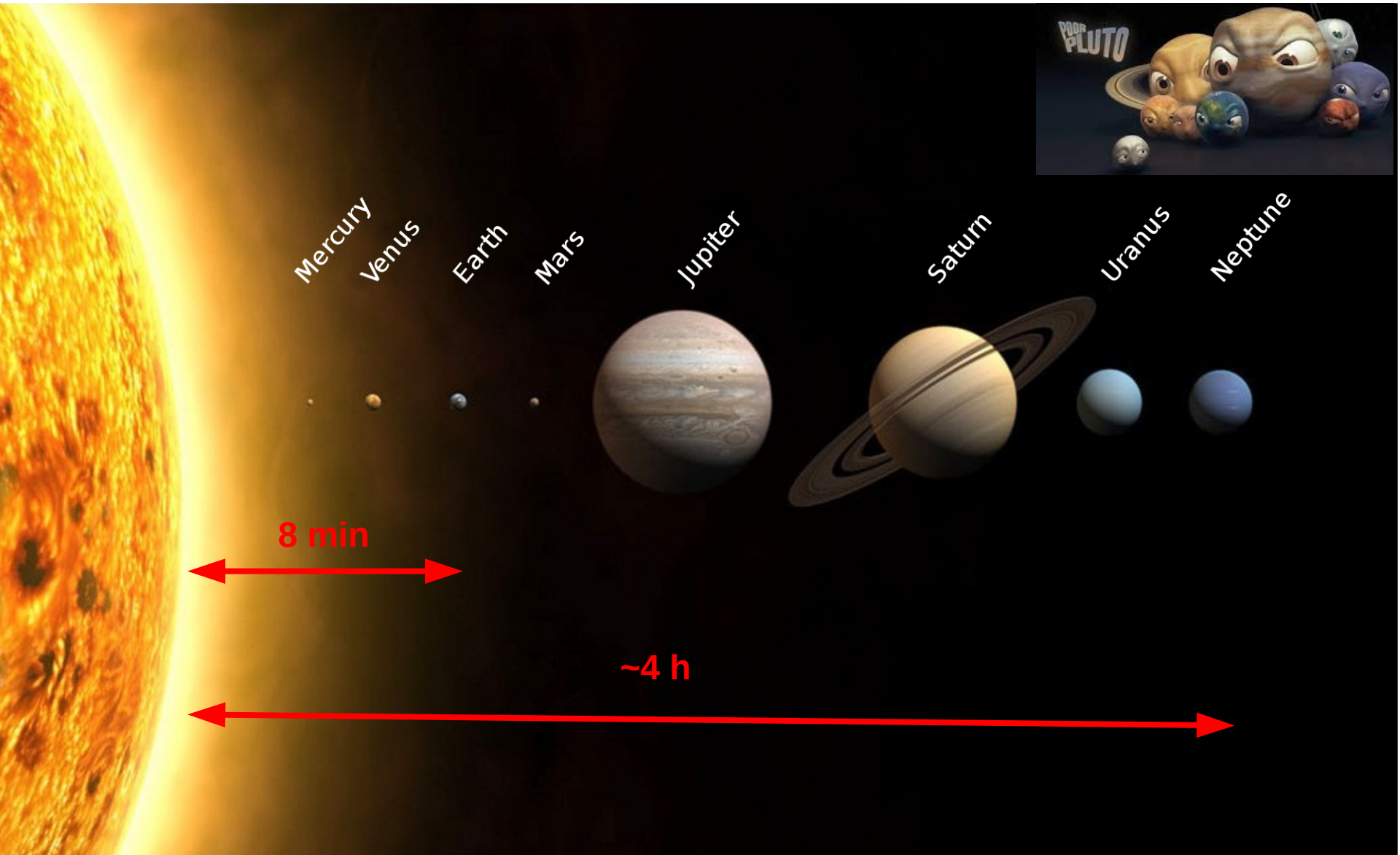
Universe scale



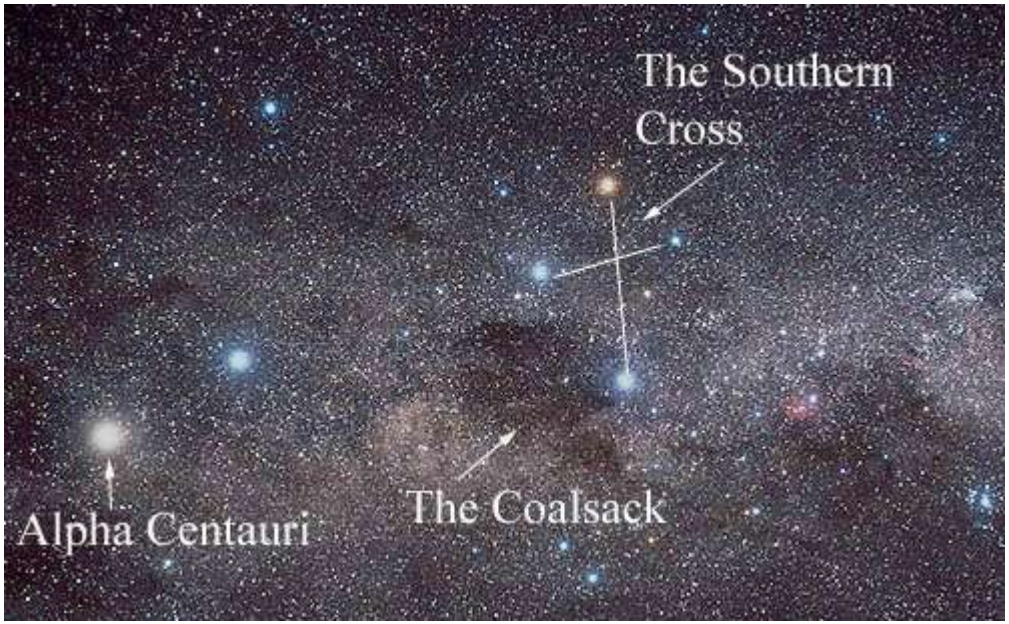
Universe scale



Universe scale

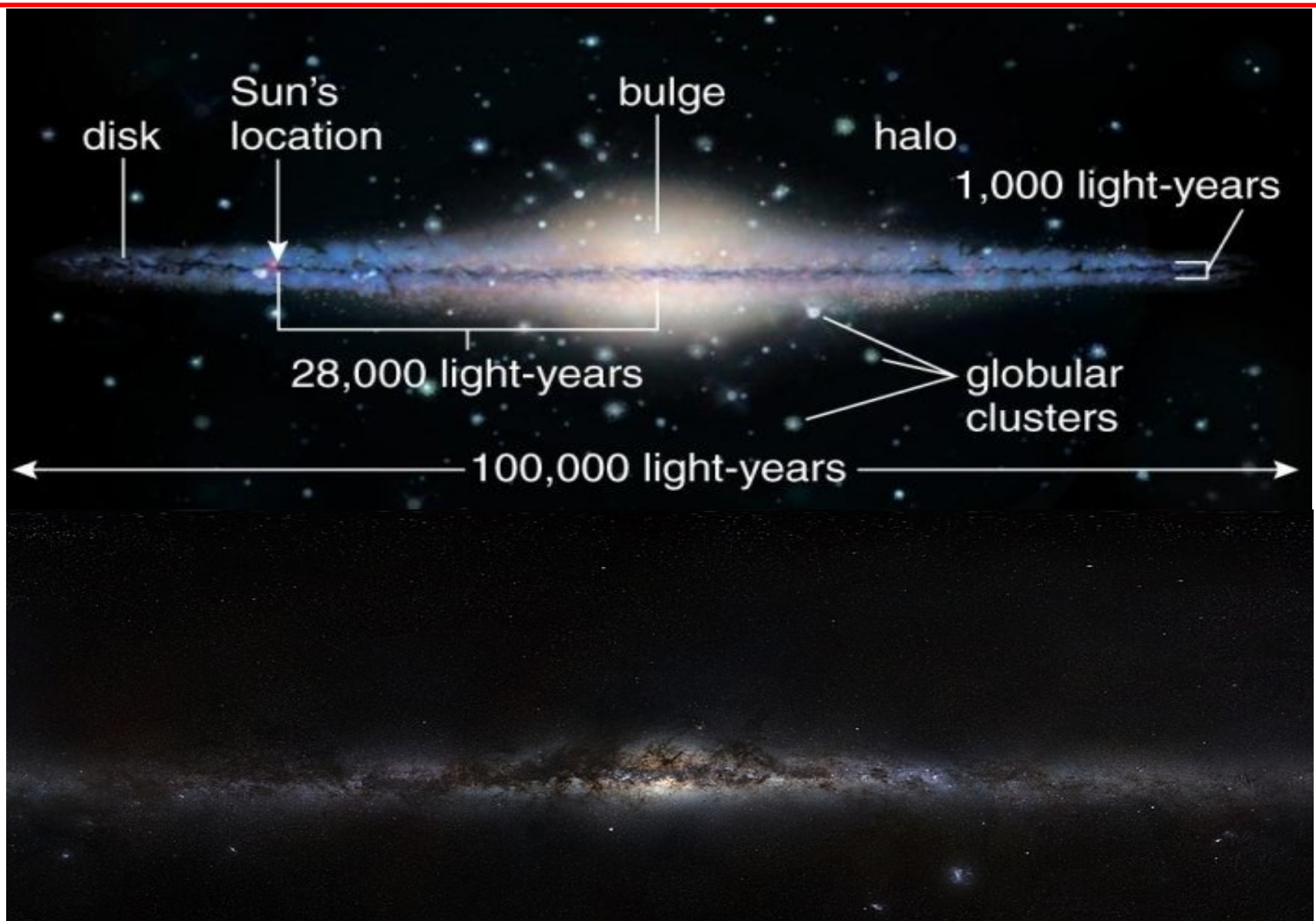


Universe scale

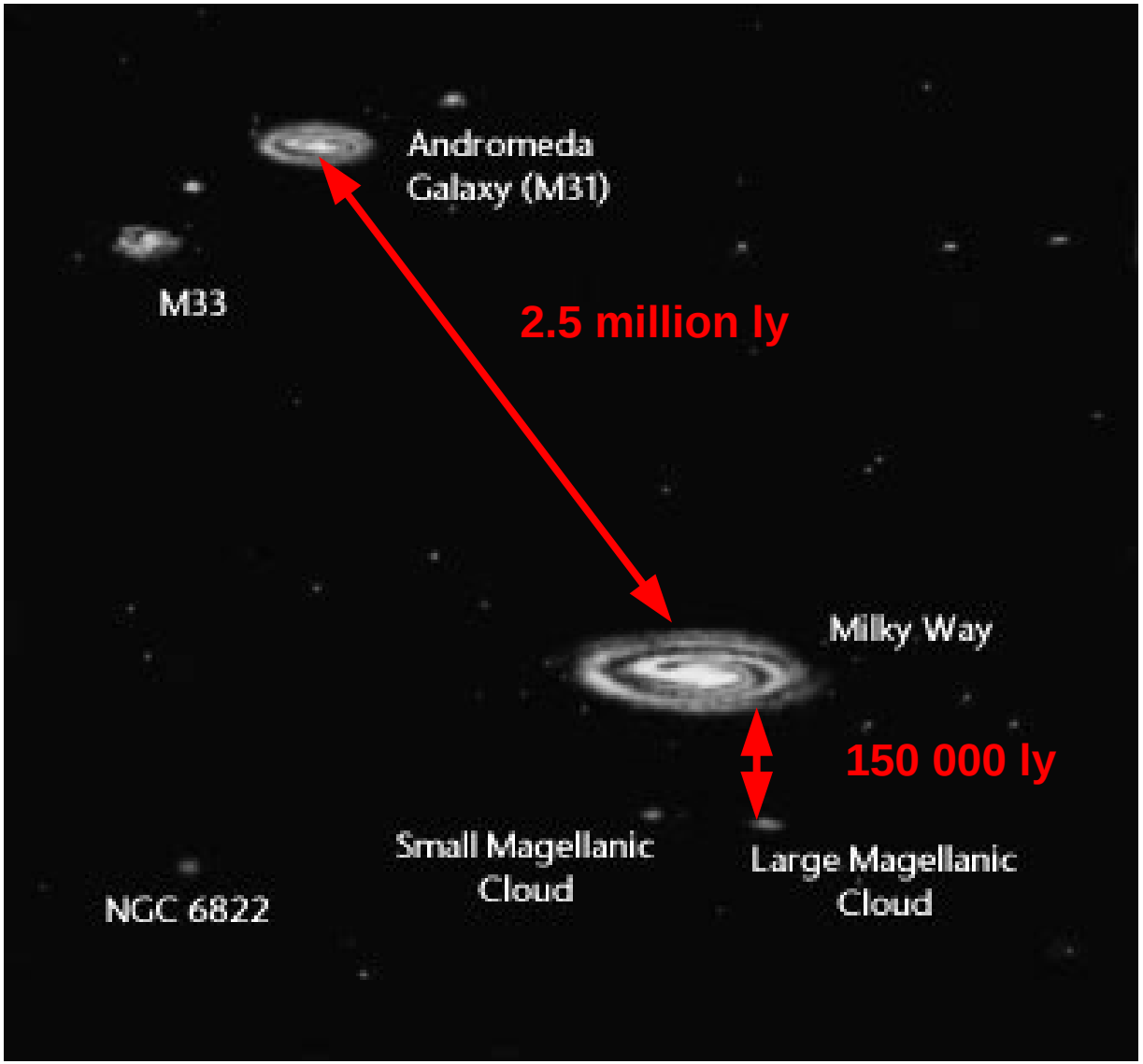


4.4 ly

Universe scale



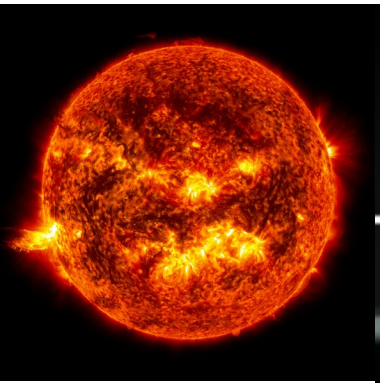
Universe scale

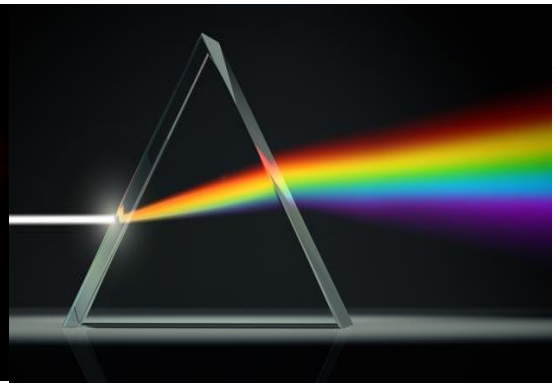


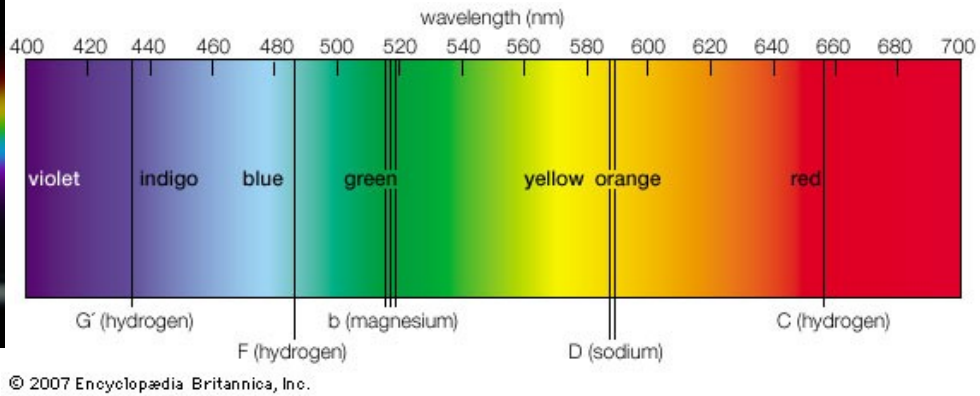

THE MOST DISTANT IMAGE : 12 billions ly !!!

THE MOST DISTANT IMAGE : 12 billions ly !!!

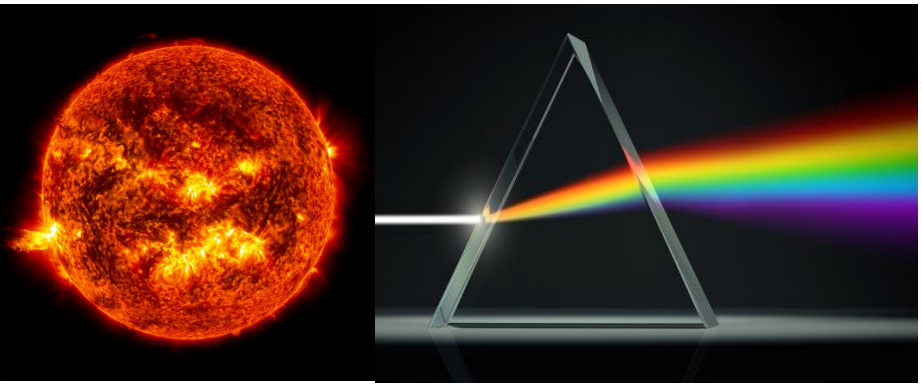
The beginning of cosmology

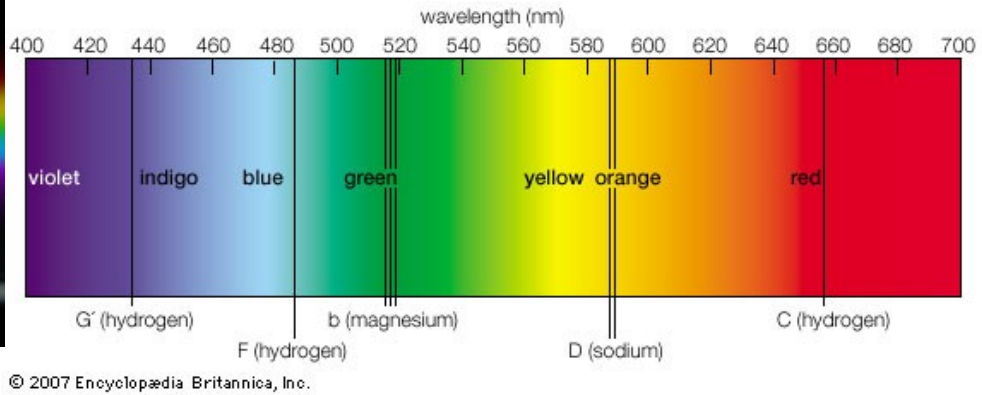




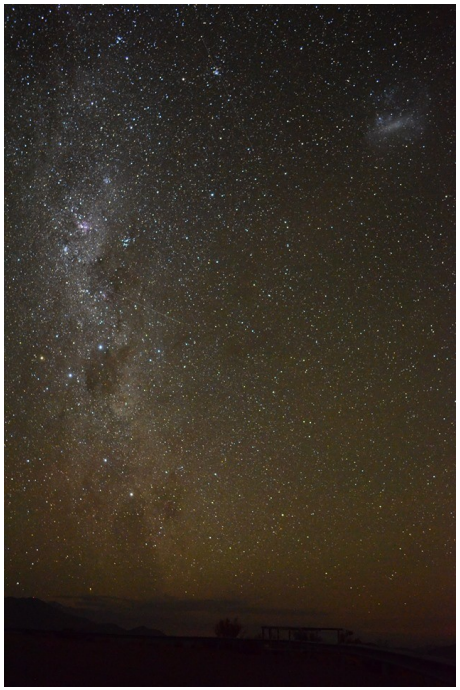


The beginning of cosmology

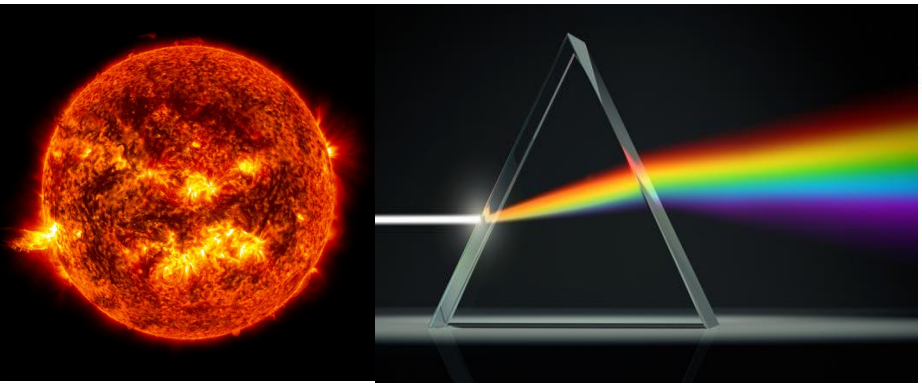


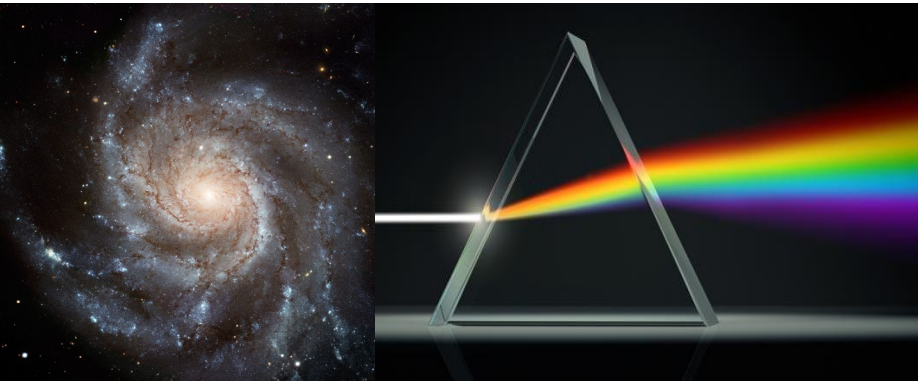


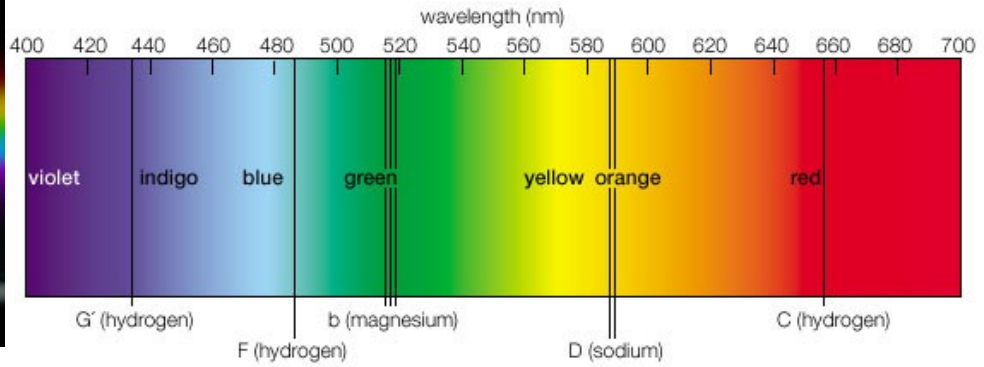
1916 : Slipher

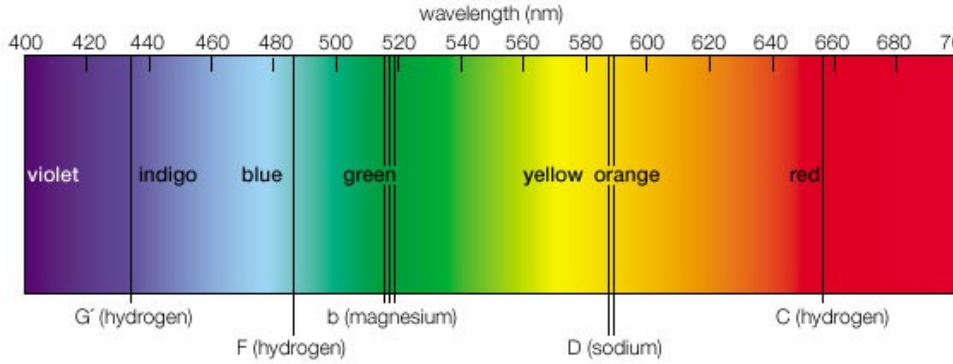


The beginning of cosmology

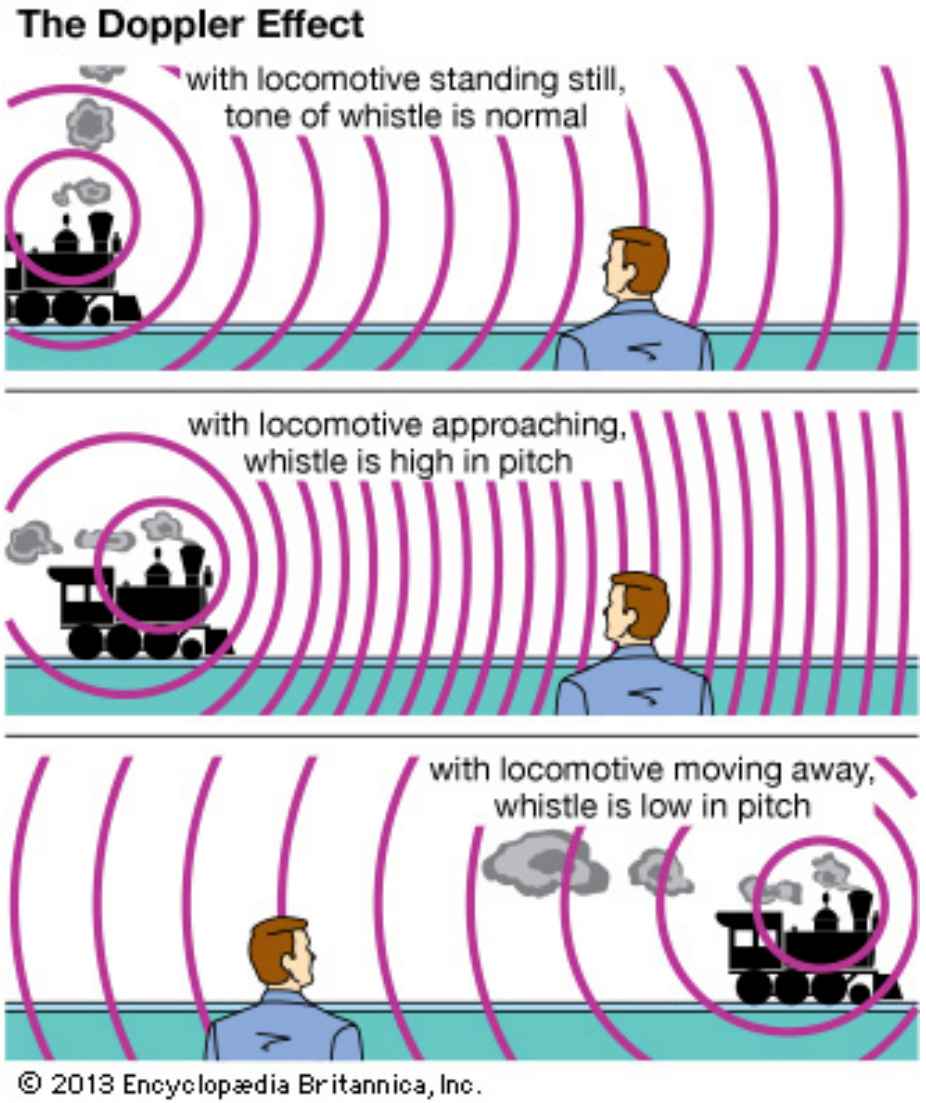




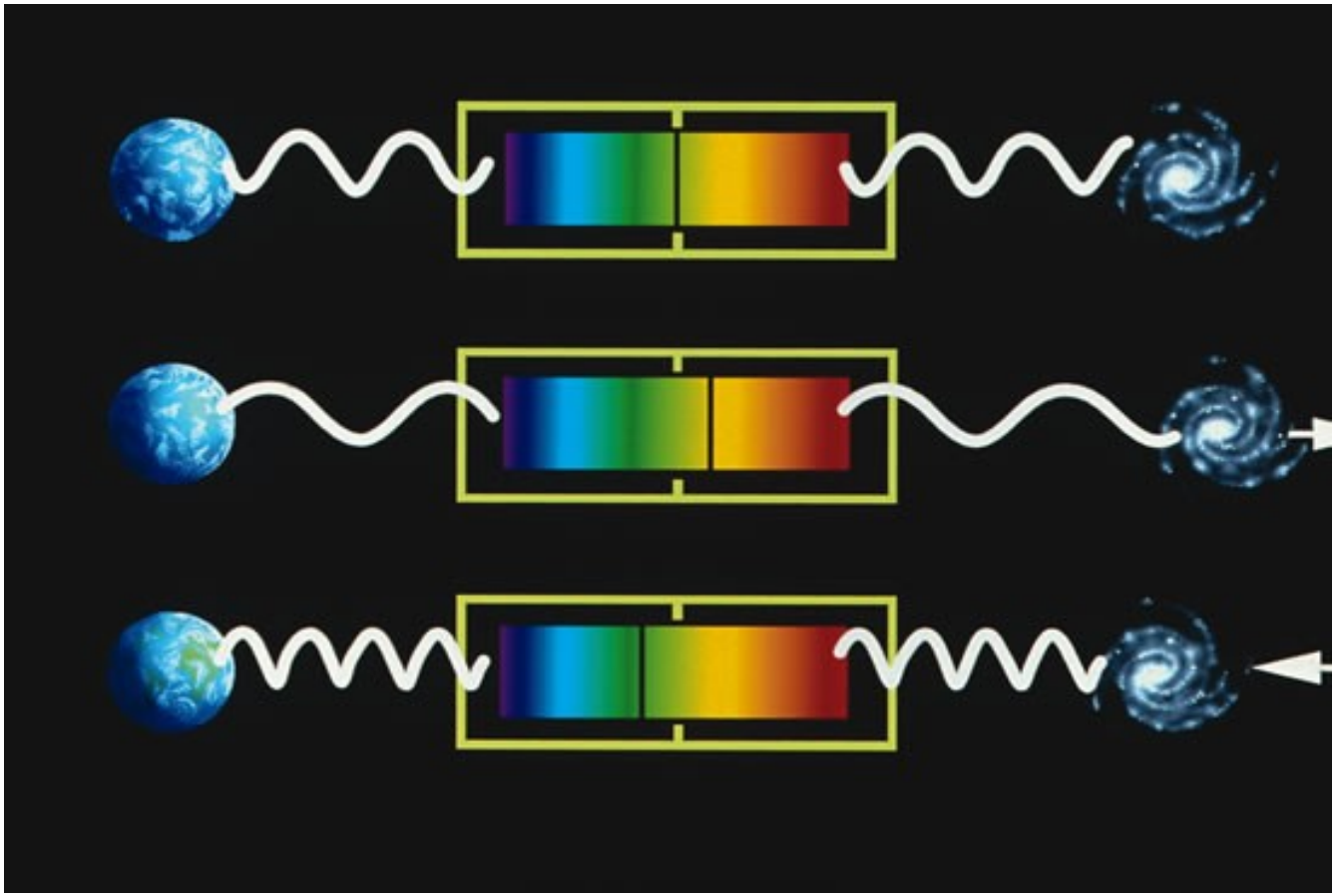




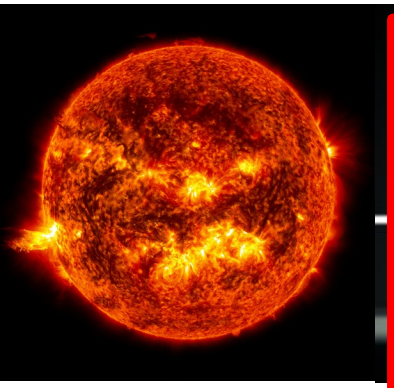
The beginning of cosmology



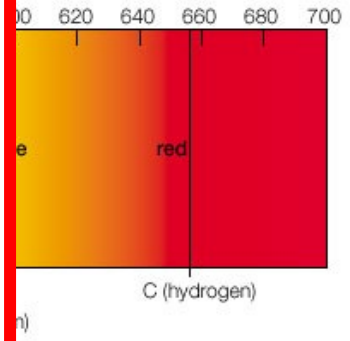
The beginning of cosmology

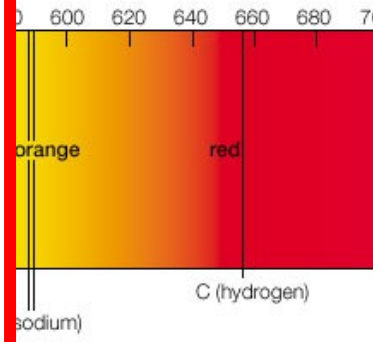


The beginning of cosmology



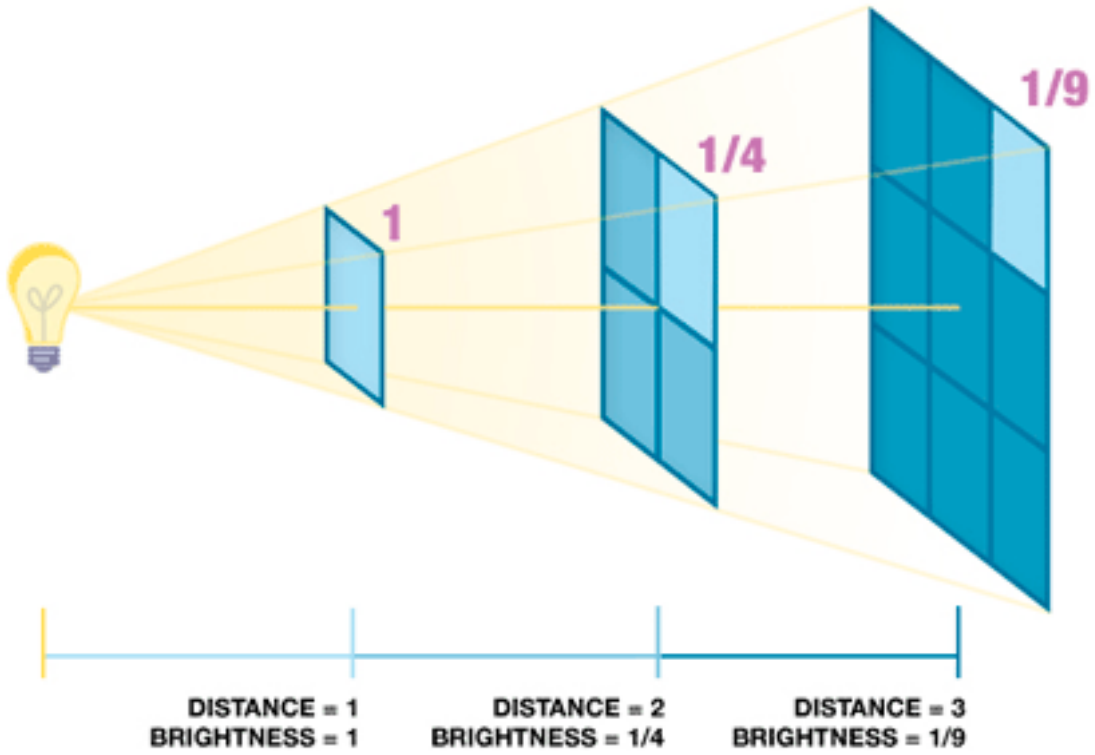
Slipher discovered that all the nearby galaxies are moving away from us.





Distances

Inverse square law

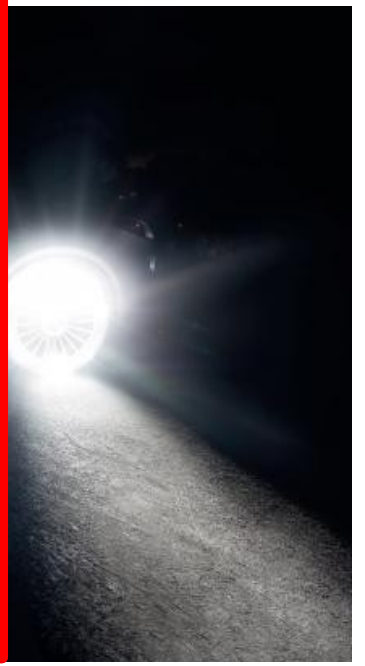


Distances

Distances

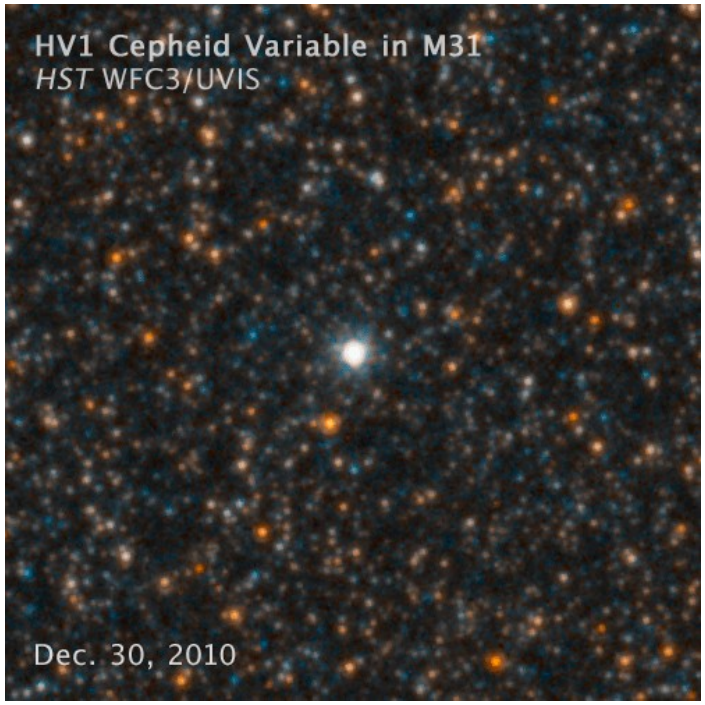
Need to know the intrinsic brightness of the object

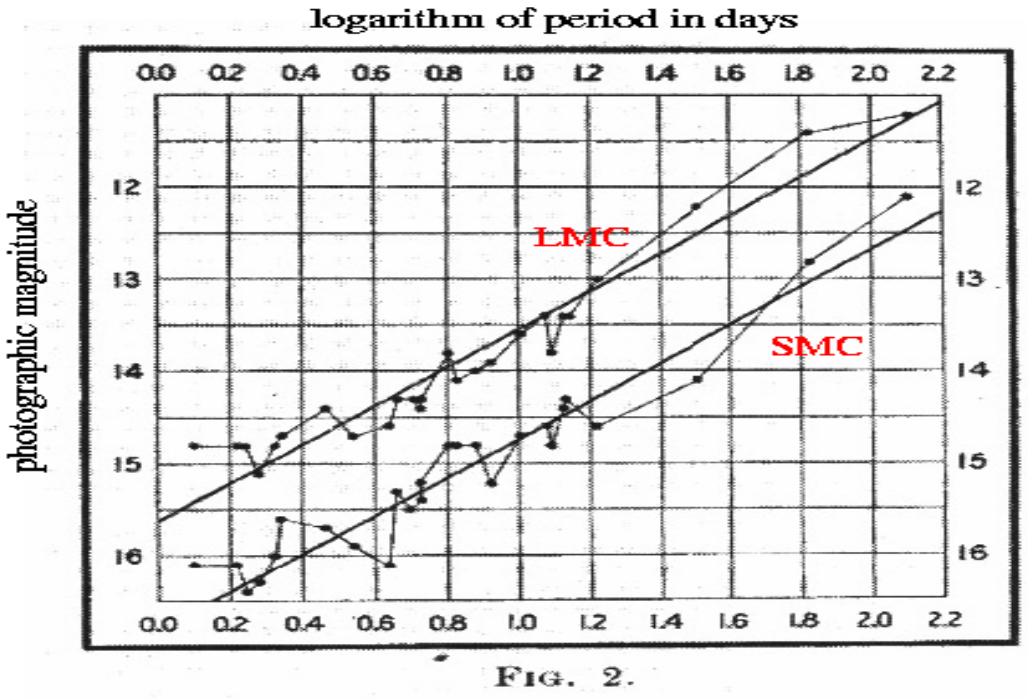
→ **STANDARD CANDLES**



Distances

Cepheids : period-luminosity relation





Leavitt et al. 1908

Expansion of the Universe

Hubble 1929 : **UNIVERSE IS EXPANDING!!!**

→ **More distant galaxies are moving faster away from us!!!**

Velocities measured by Slipher

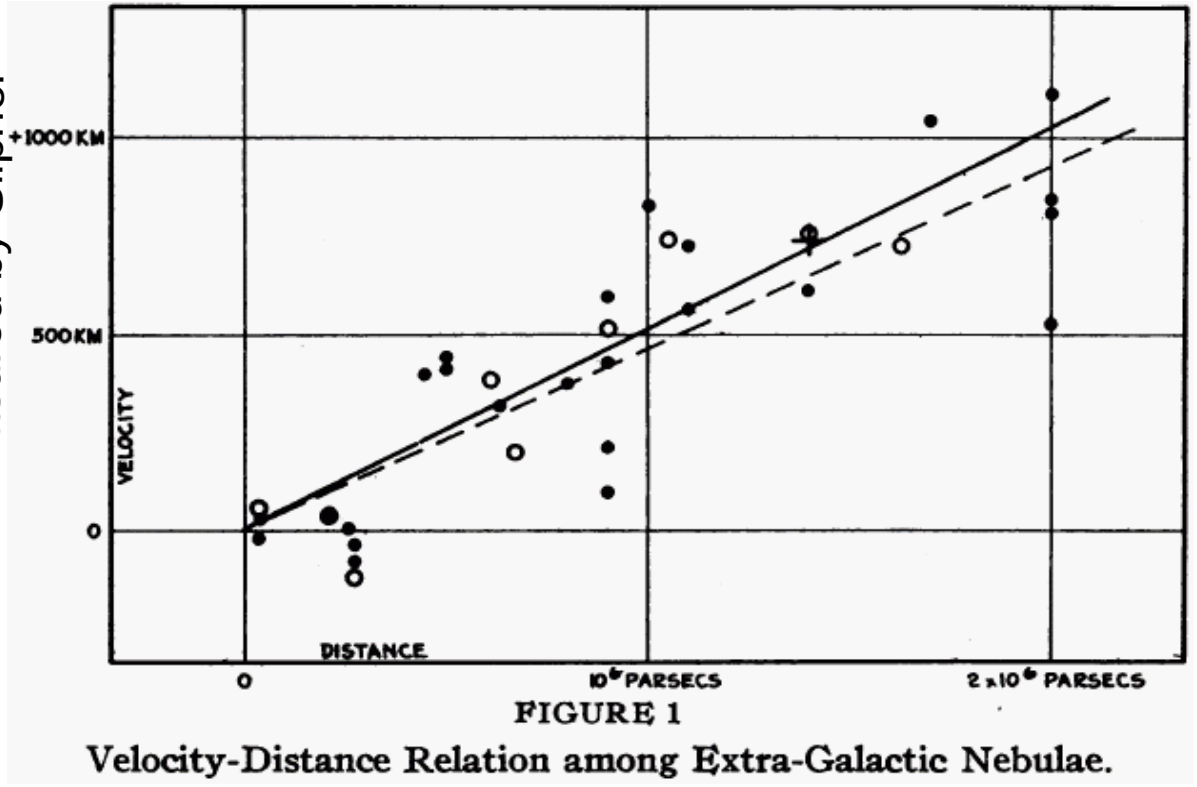


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Distance measured with Cepheids by Hubble

Oops… sorry Hubble

In **1927** : Annales de la Société Scientifique de Bruxelles, A47, p. 49-59

6. Conclusion.

Nous avons obtenu une solution qui vérifie les conditions suivantes :

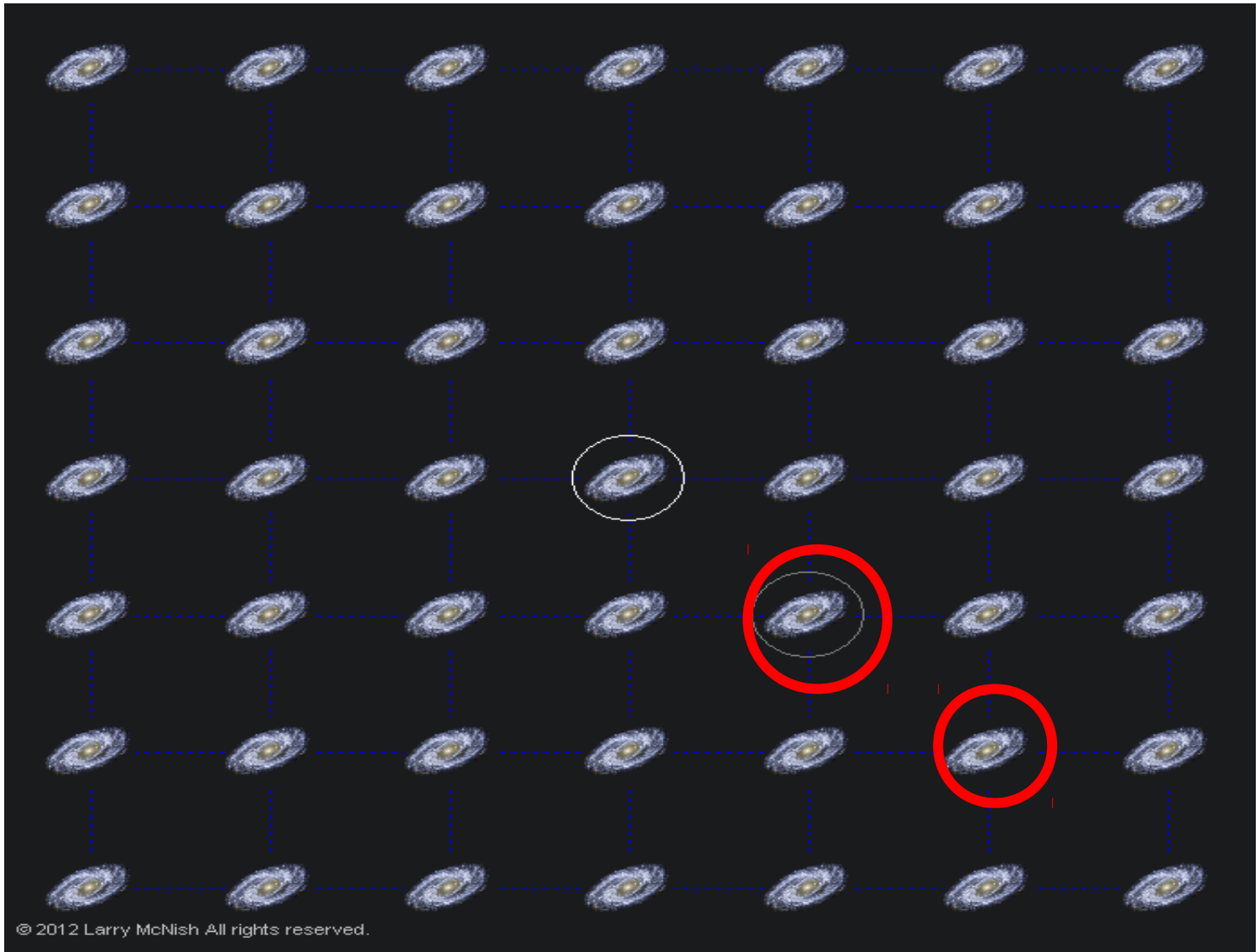
1. La masse de l'univers est constante et est liée à la constante cosmologique par la relation d'Einstein

$$\sqrt{\lambda} = \frac{2\pi^2}{\kappa M} = \frac{1}{R_o}$$

2. Le rayon de l'univers croît sans cesse depuis une valeur asymptotique R_o pour $t = -\infty$.

3. L'éloignement des nébuleuses extra-galactiques est un effet cosmique dû à l'expansion de l'espace et permettant de calculer le rayon R_o par les

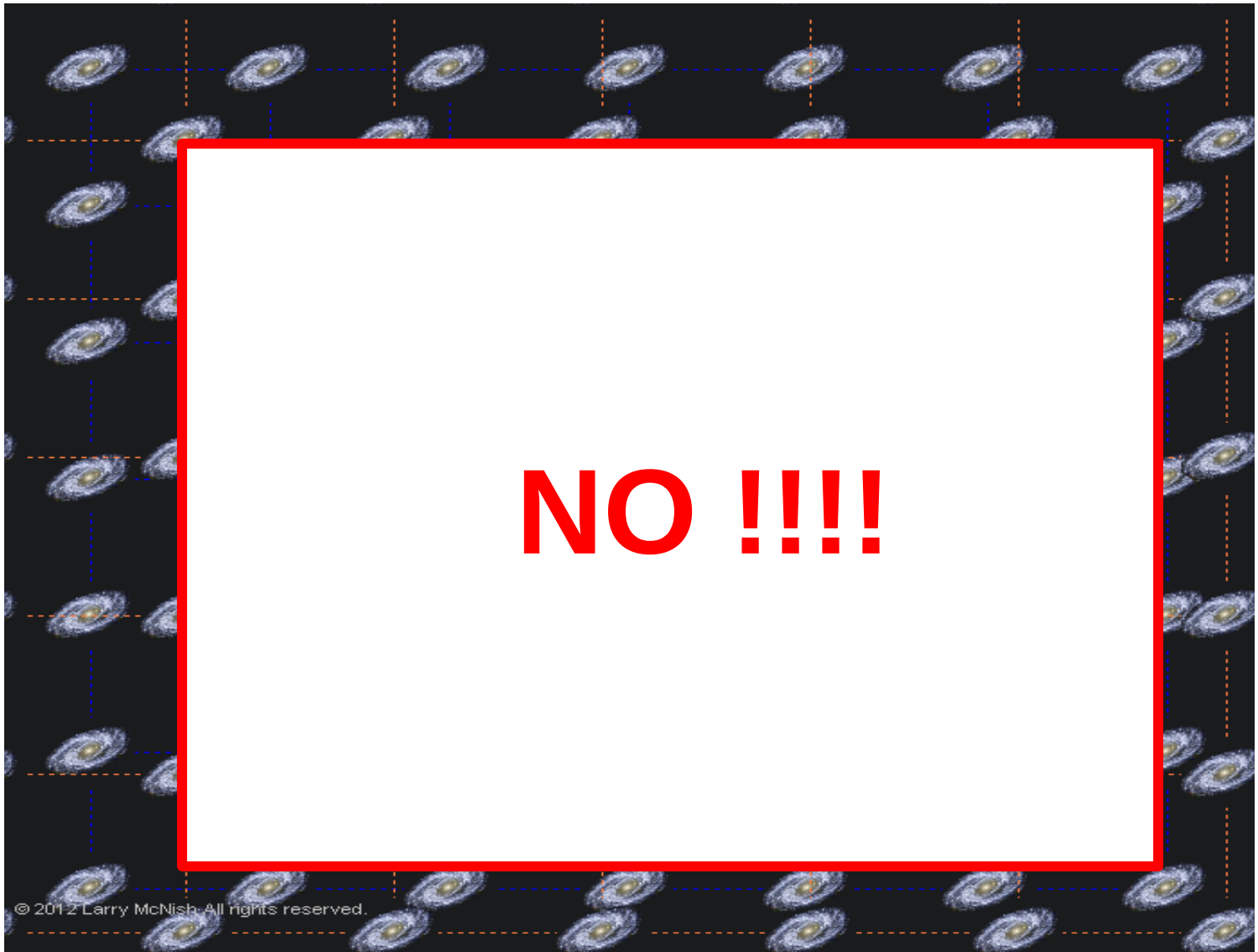
Hubble law



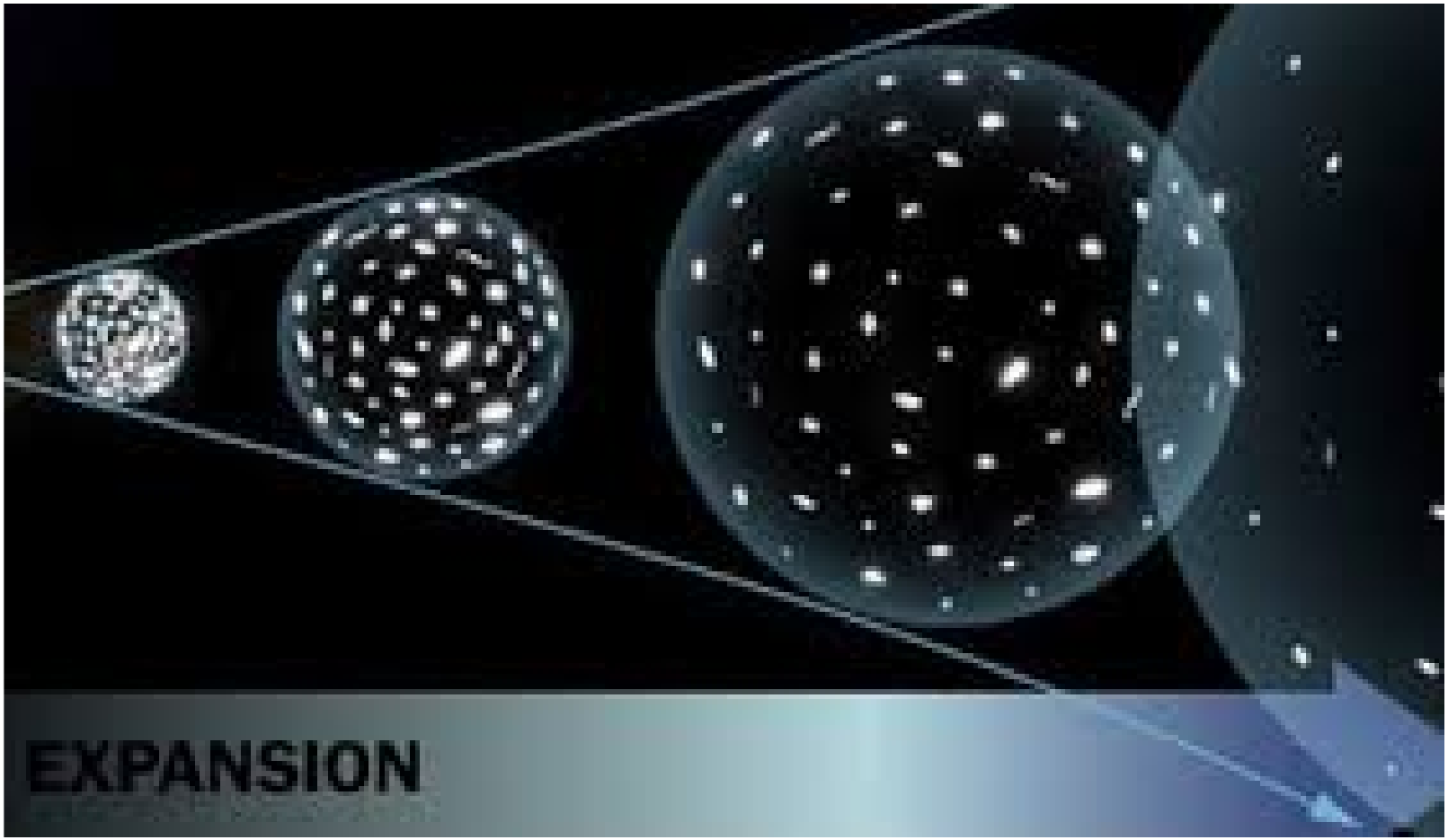
More distant galaxies are moving faster away from us!!!!!

Are we special?

Are we special?



Big Bang



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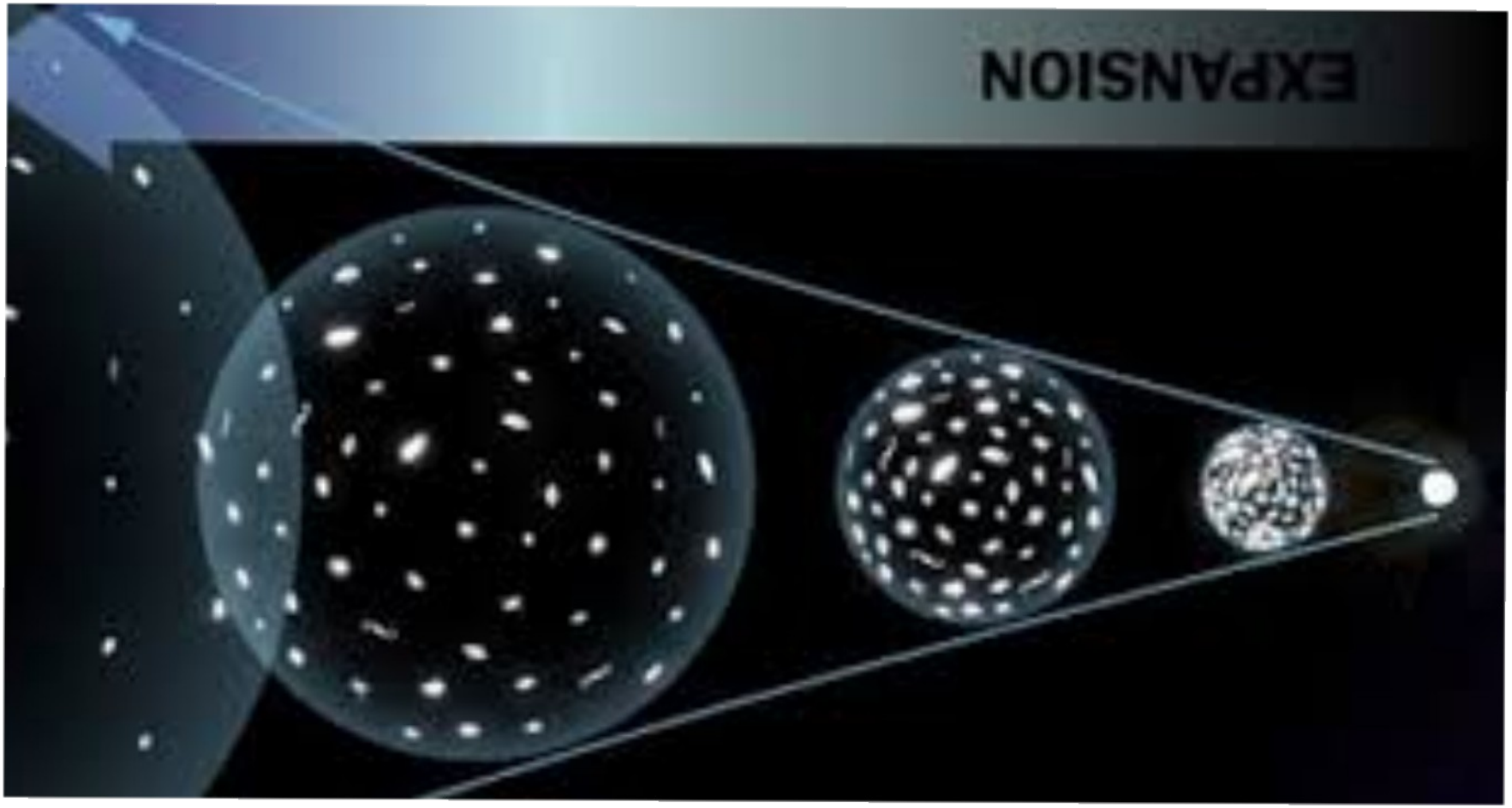
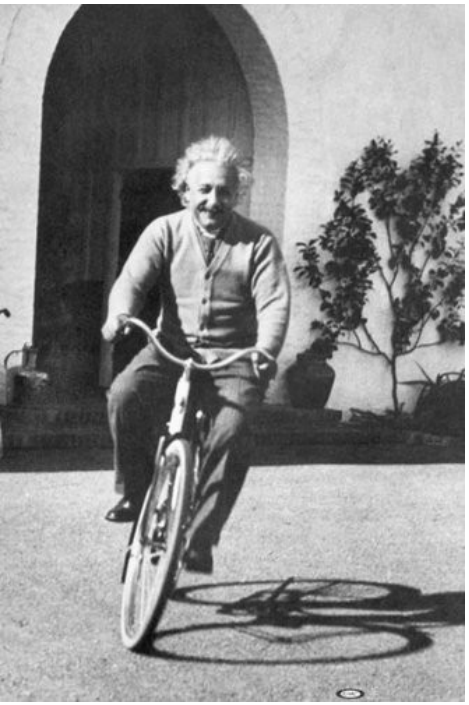


BIG surprise (1915)



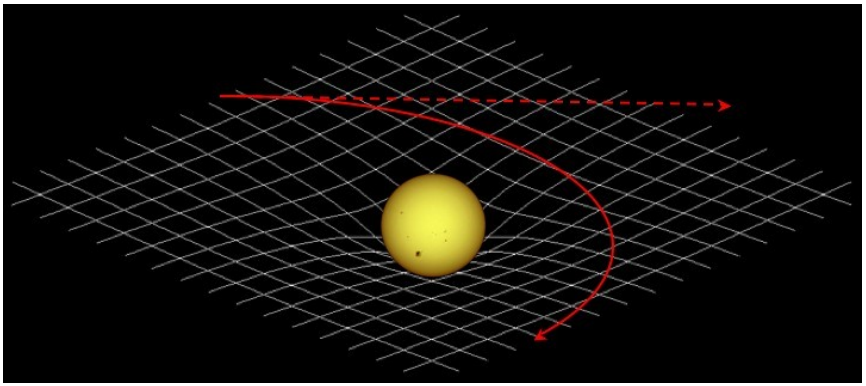
Curvature of spacetime

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Matter/ energy

Only two solutions for Universe : contraction or expansion

Static Universe



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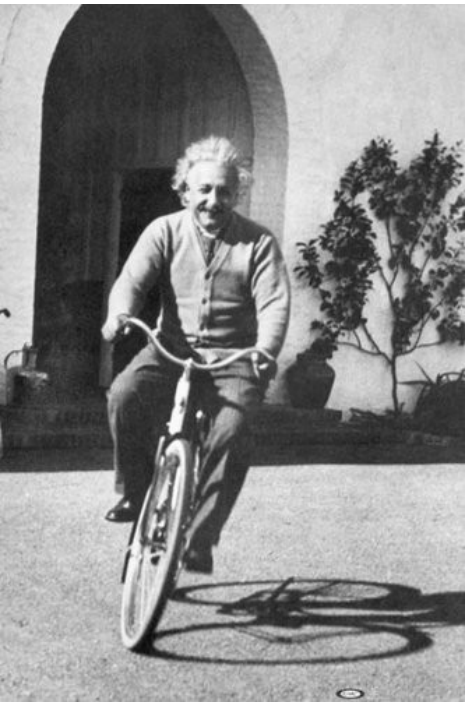

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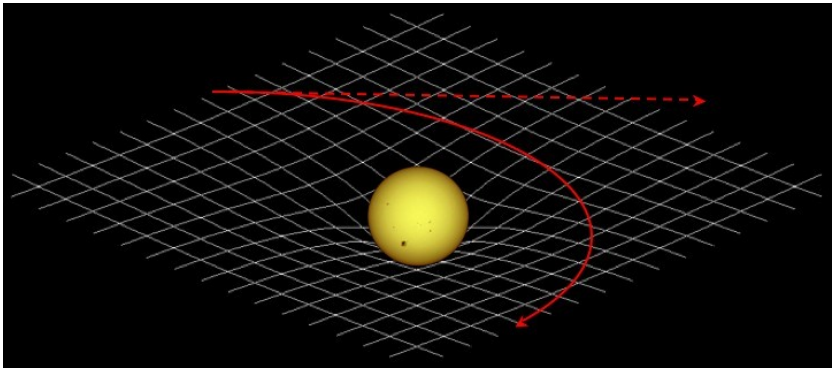
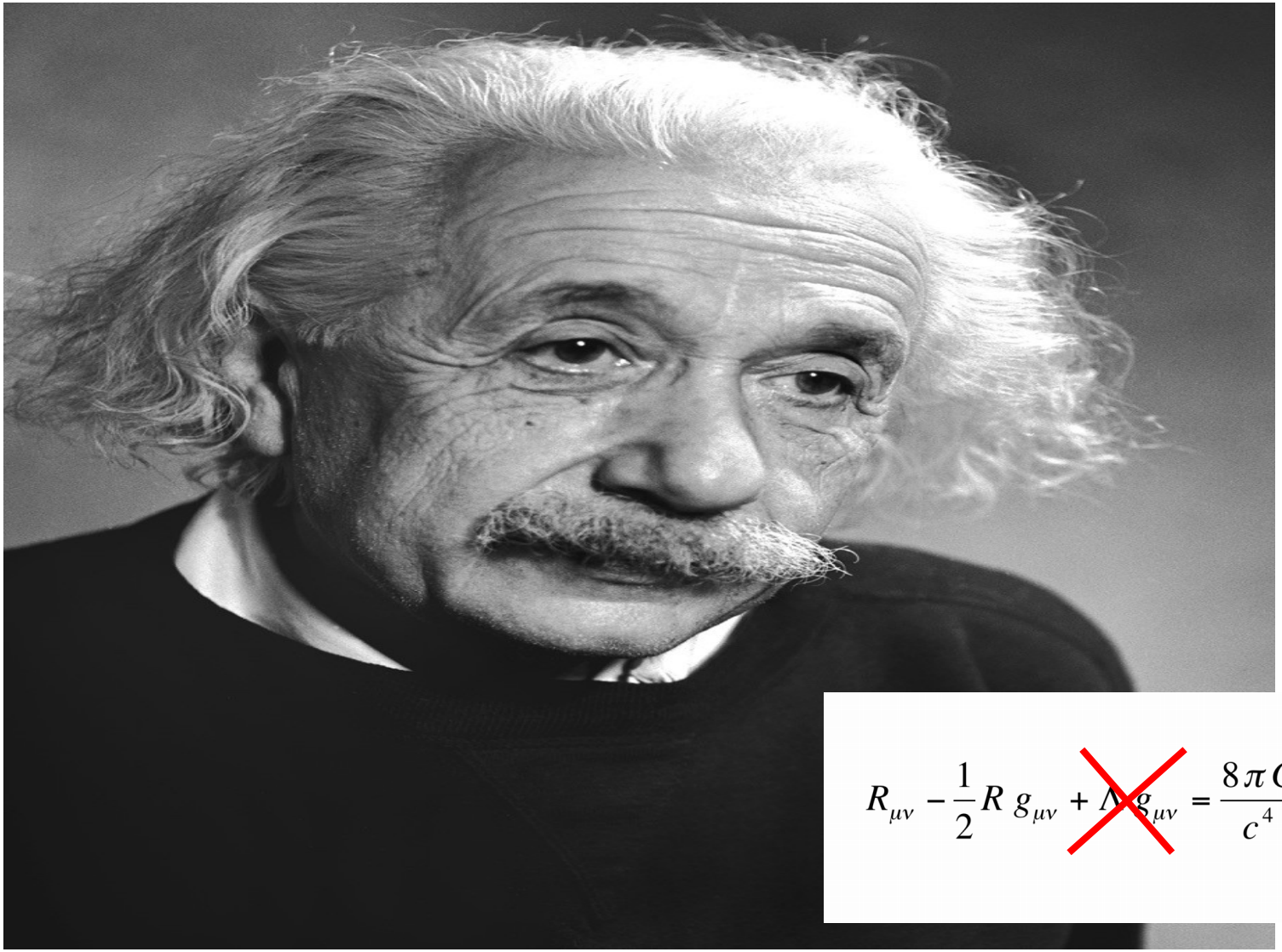


→ **Cosmological constant**

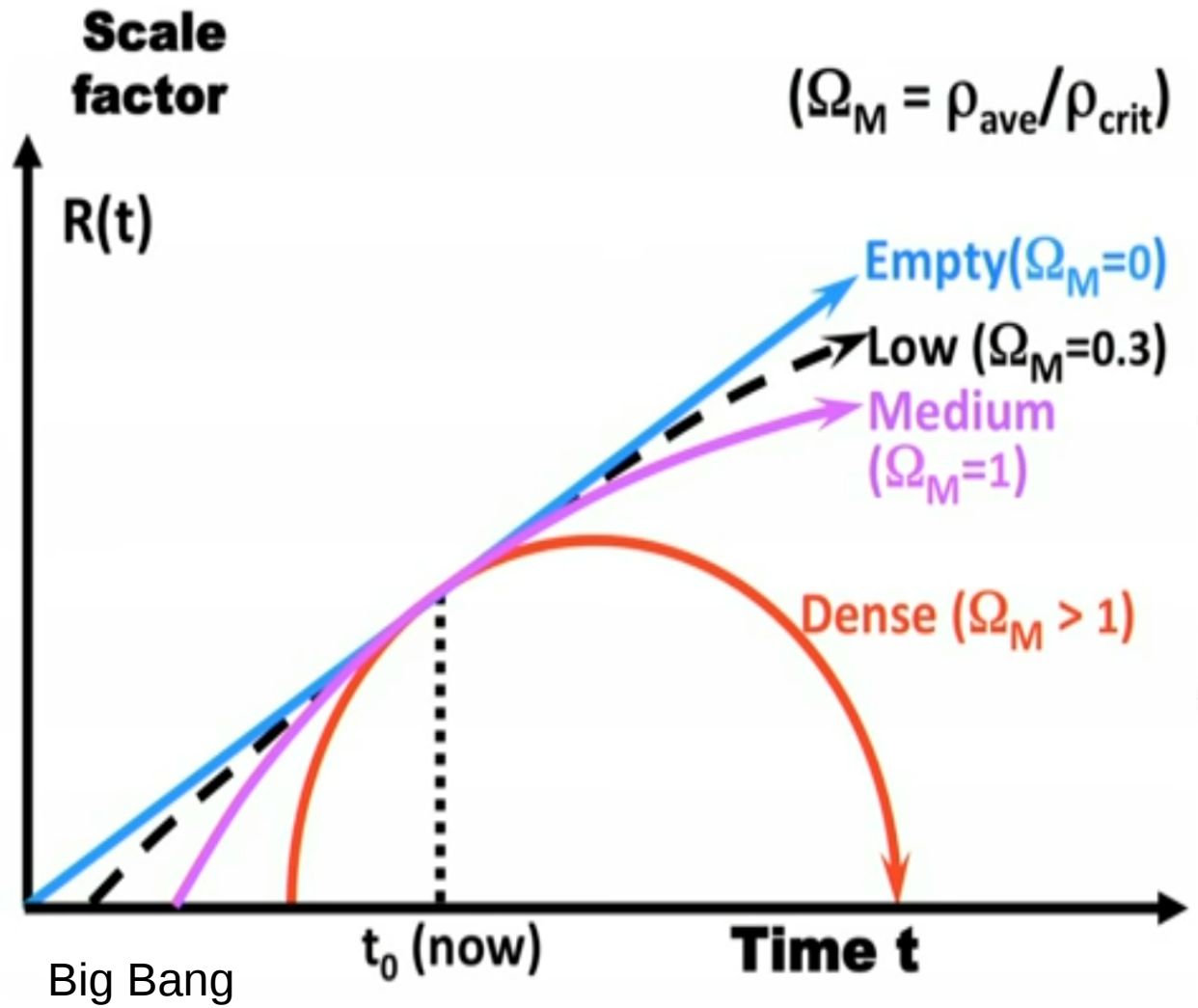
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

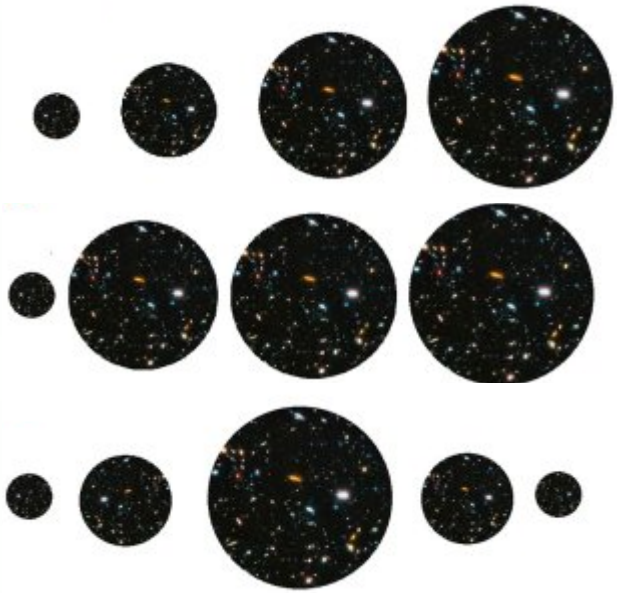
This was my greatest blunder in my life !!!



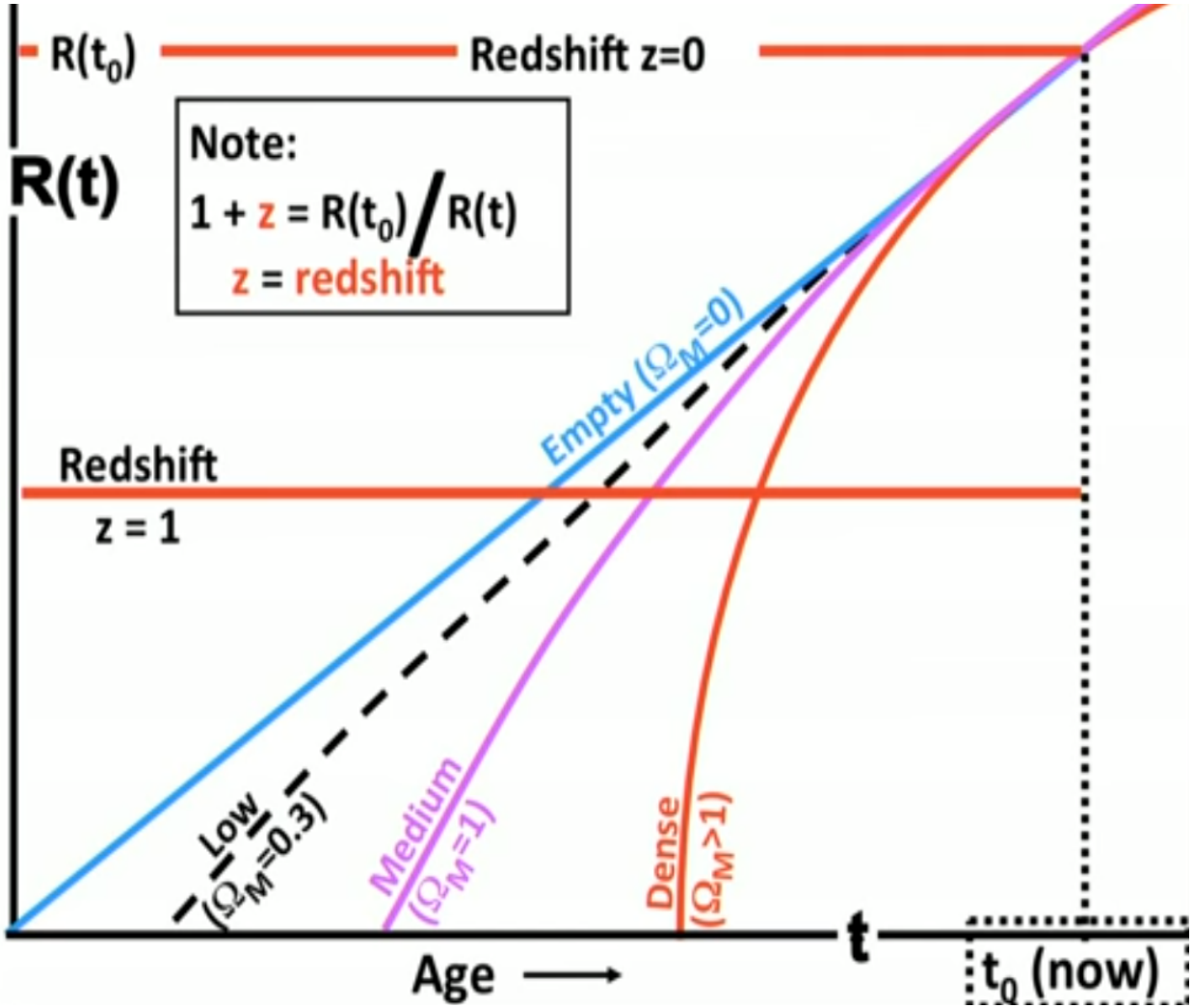
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Universe destiny?



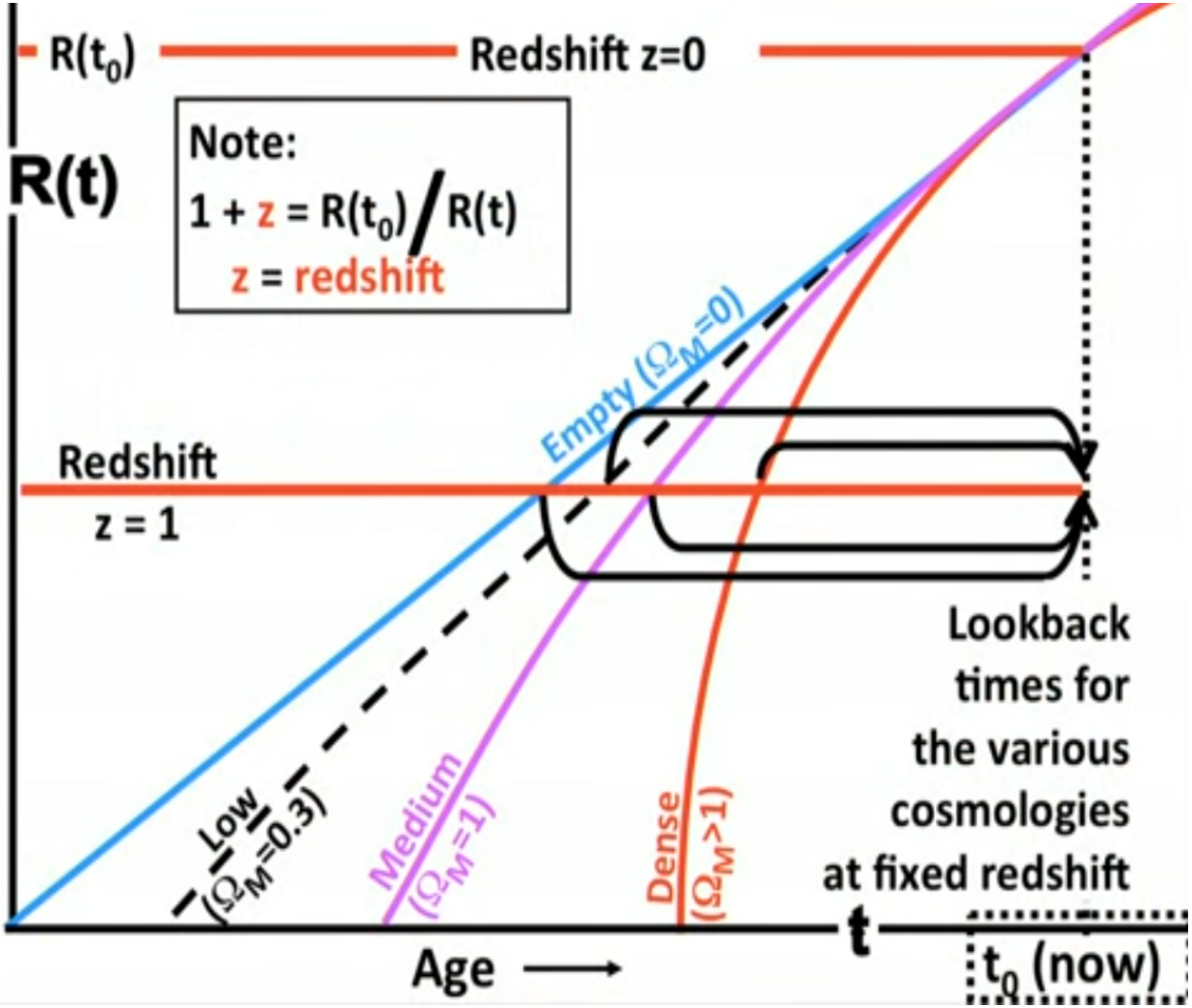


Universe destiny?



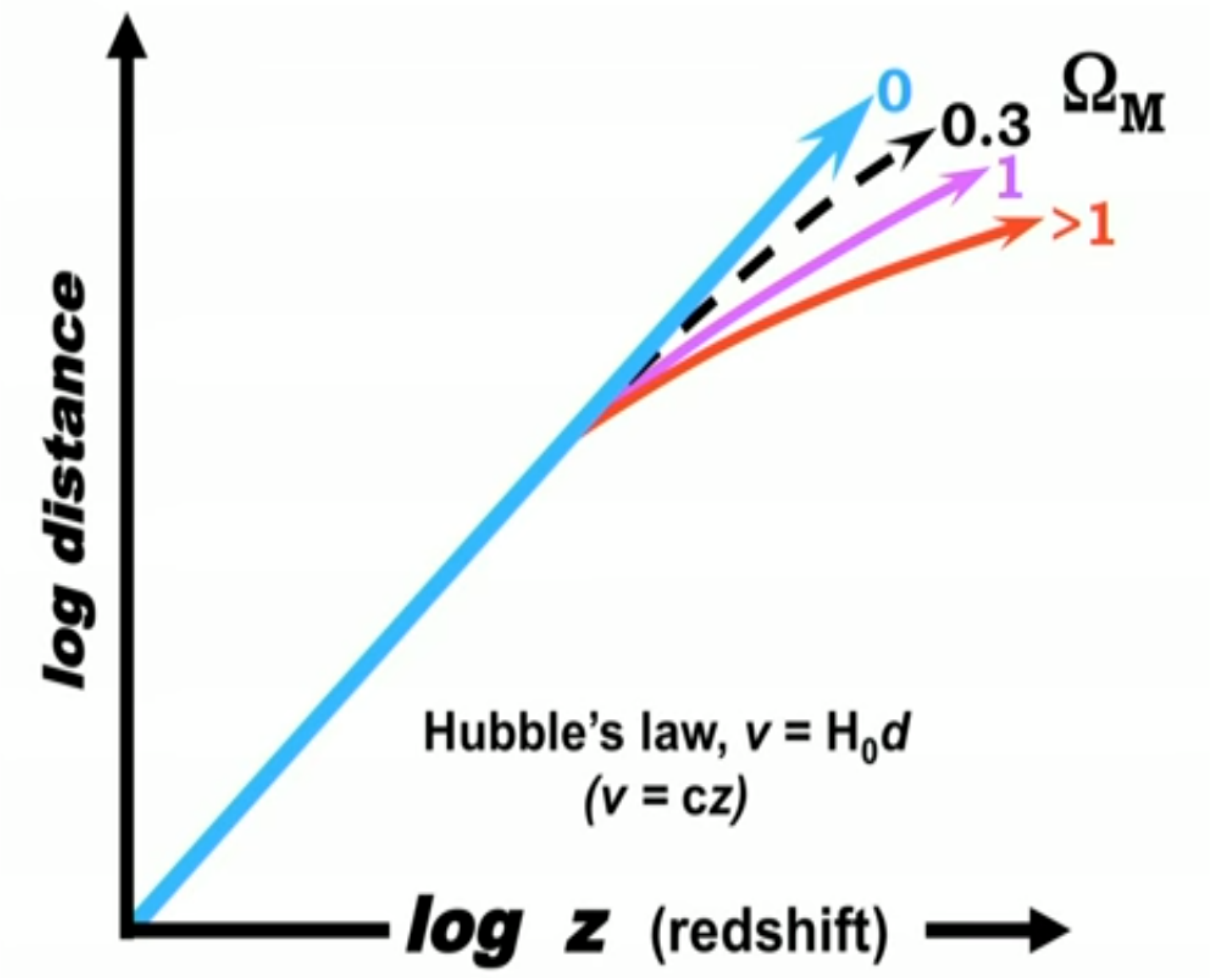
Credit : Alex Filippenko

Universe destiny?



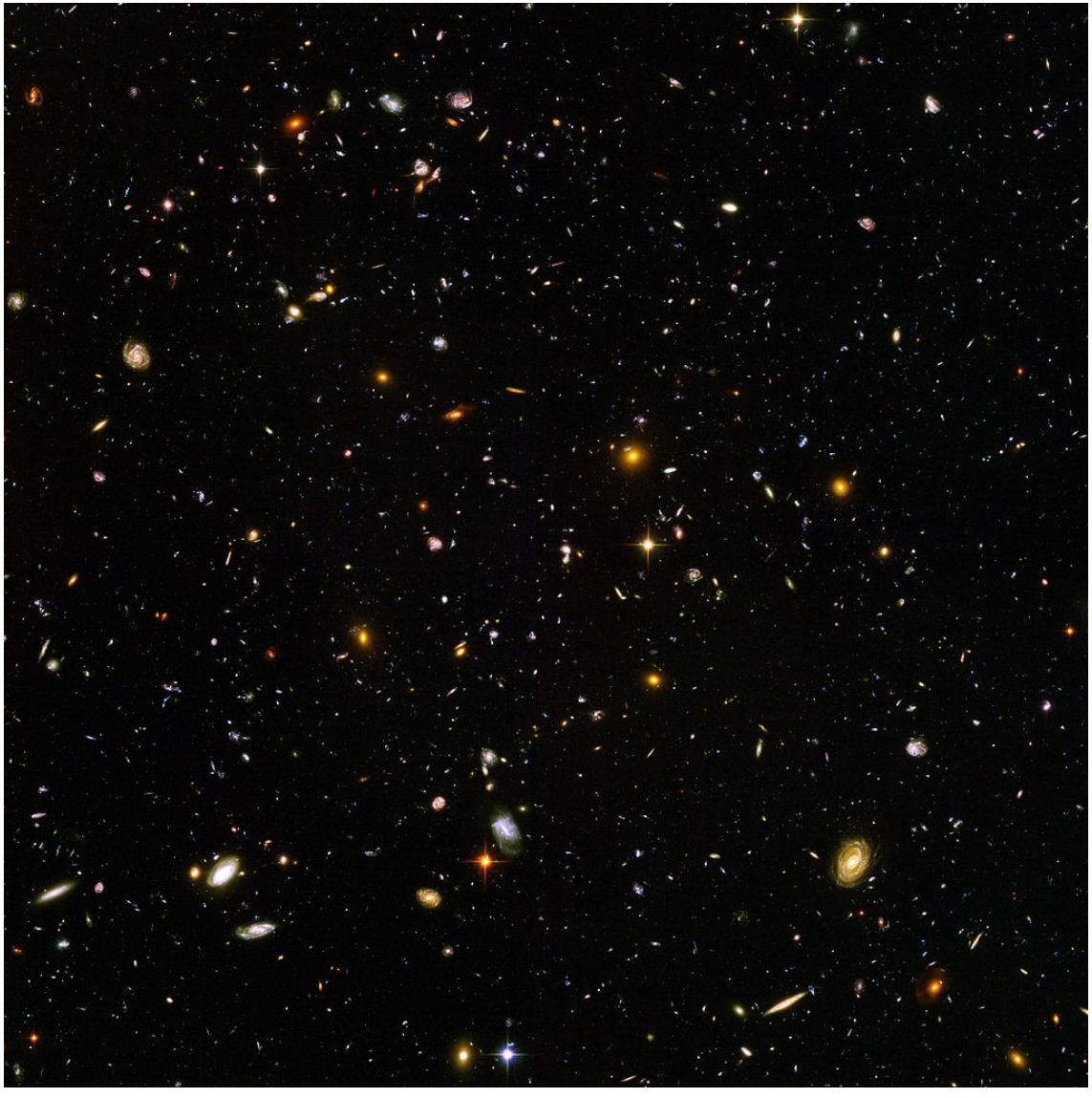
Credit : Alex Filippenko

Universe destiny?



Credit : Alex Filippenko

Measuring great distances



Credit : HST

Supernovae

- A supernova (Zwicky 1931) is a stellar explosion that briefly outshines an entire galaxy (10^9–10^{10} L⊙).

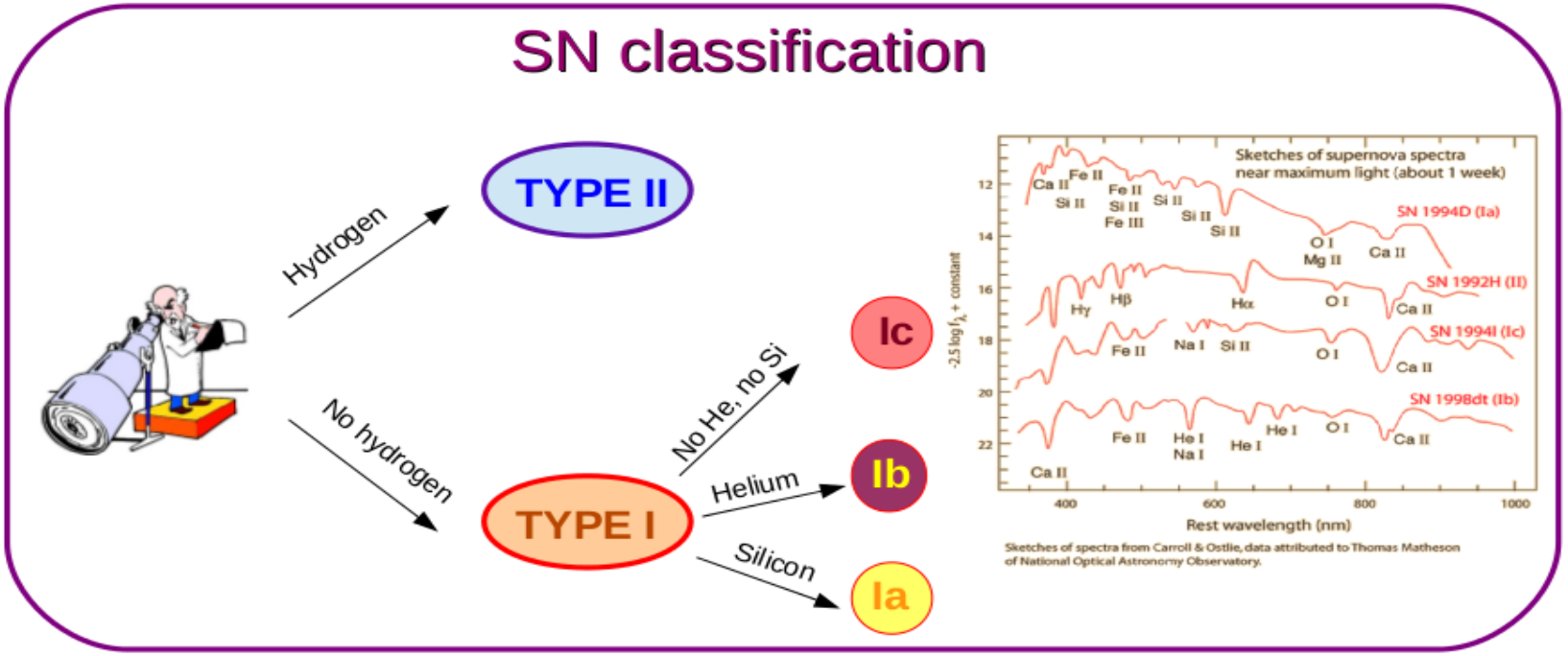
SN 1987A in LMC

Supernovae

Credit :LCOGT BJ Fulton

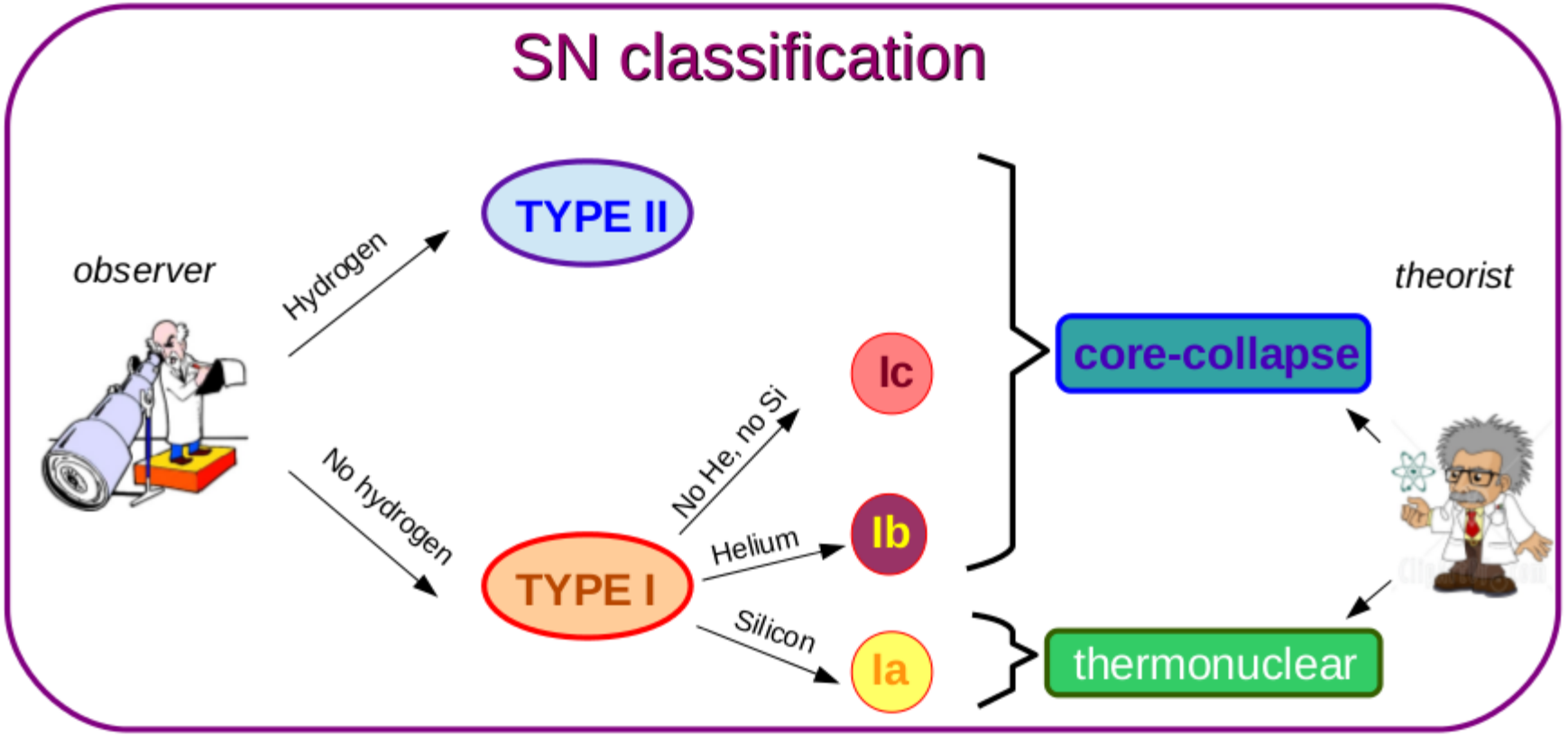
Supernovae

- First SN spectral classification by R. Minkowski in 1941: two SN types based on presence of Hydrogen lines:
  - Presence of Hydrogen lines: **II**
  - Absence of Hydrogen lines: **Ia, Ib, Ic**



Supernovae

- Two different types of progenitors:
  - thermal burning of a white dwarf binary, **Ia**
  - core collapse of massive stars type **Ib, Ic and II**

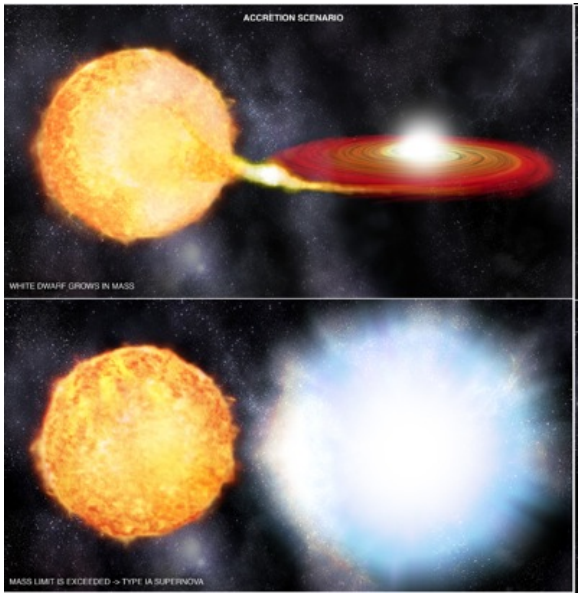


Supernovae (Ia)

- White dwarf (WD) of carbon/oxygen C/O composition in a binary system that undergoes thermonuclear burning (Hoyle & Fowler 1960)

Single degenerate scenario :

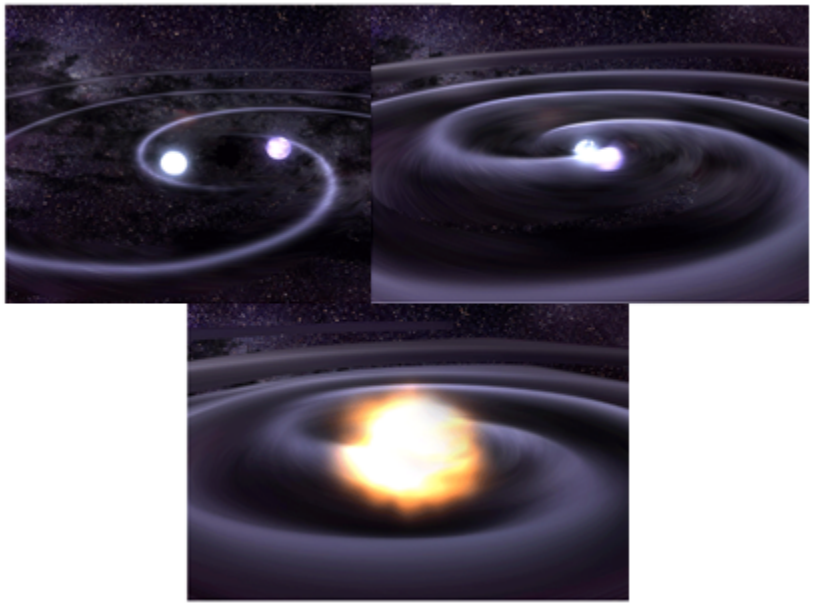
WD exceeds 1.44 M☉ → electron degenerancy does not support weigth



NASA/CXC/M Weiss

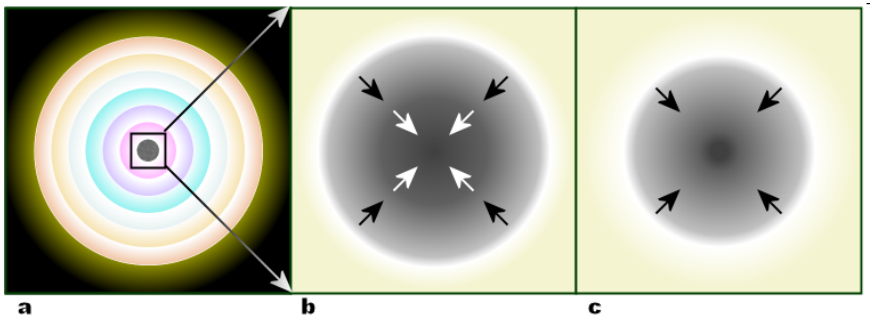
Double degenerate scenario :

Two WD lose energy due to gravitational waves and collide

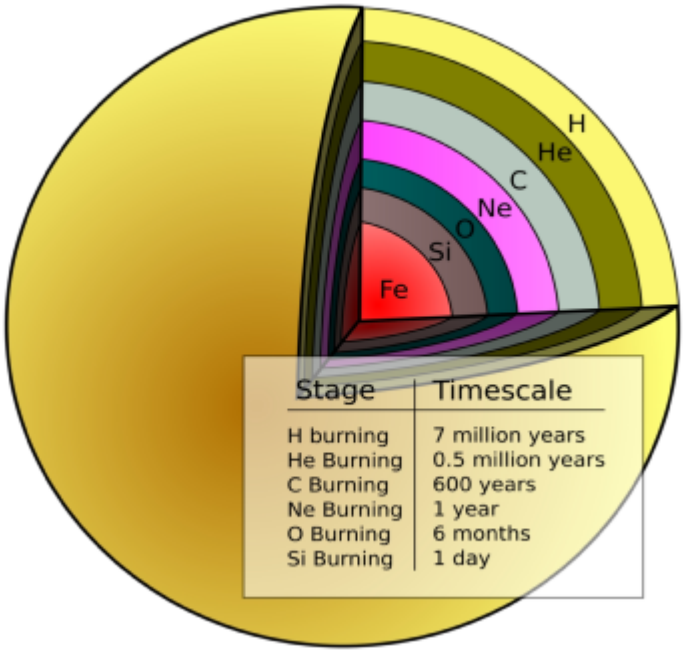


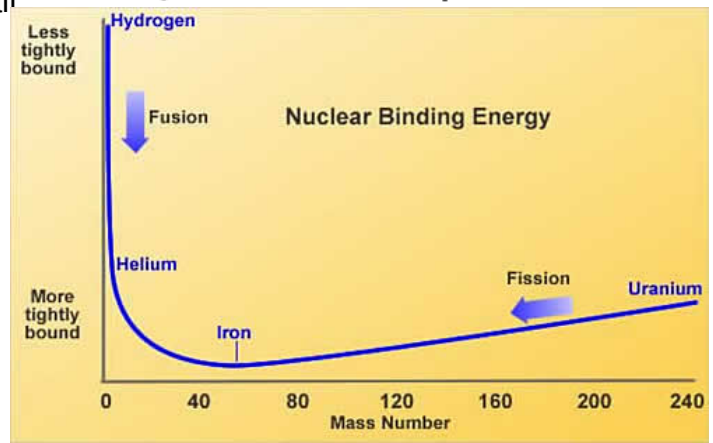
SUPERNOVAE (II,Ib,Ic)

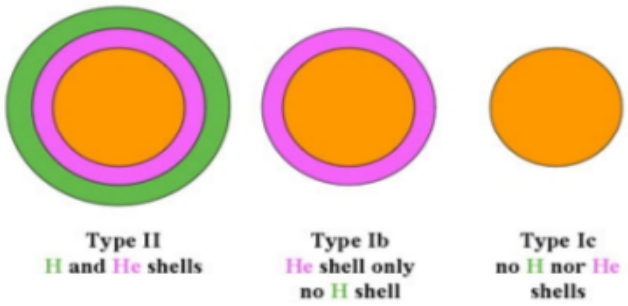
core collapse of massive stars M>8Msol:



R.J. Hall







Observational cosmology

Apparent magnitude

from measurements

Redshift
Measured via SN/host galaxy spectrum

Cosmological parameters
Quantities of interest
Ω_m, Ω_Λ, w, H_0

$$\mu = m - M = 5 \log_{10}\left(\frac{D_L(z, C)}{1\,Mpc}\right) + 25$$

Distance modulus

Absolute magnitude

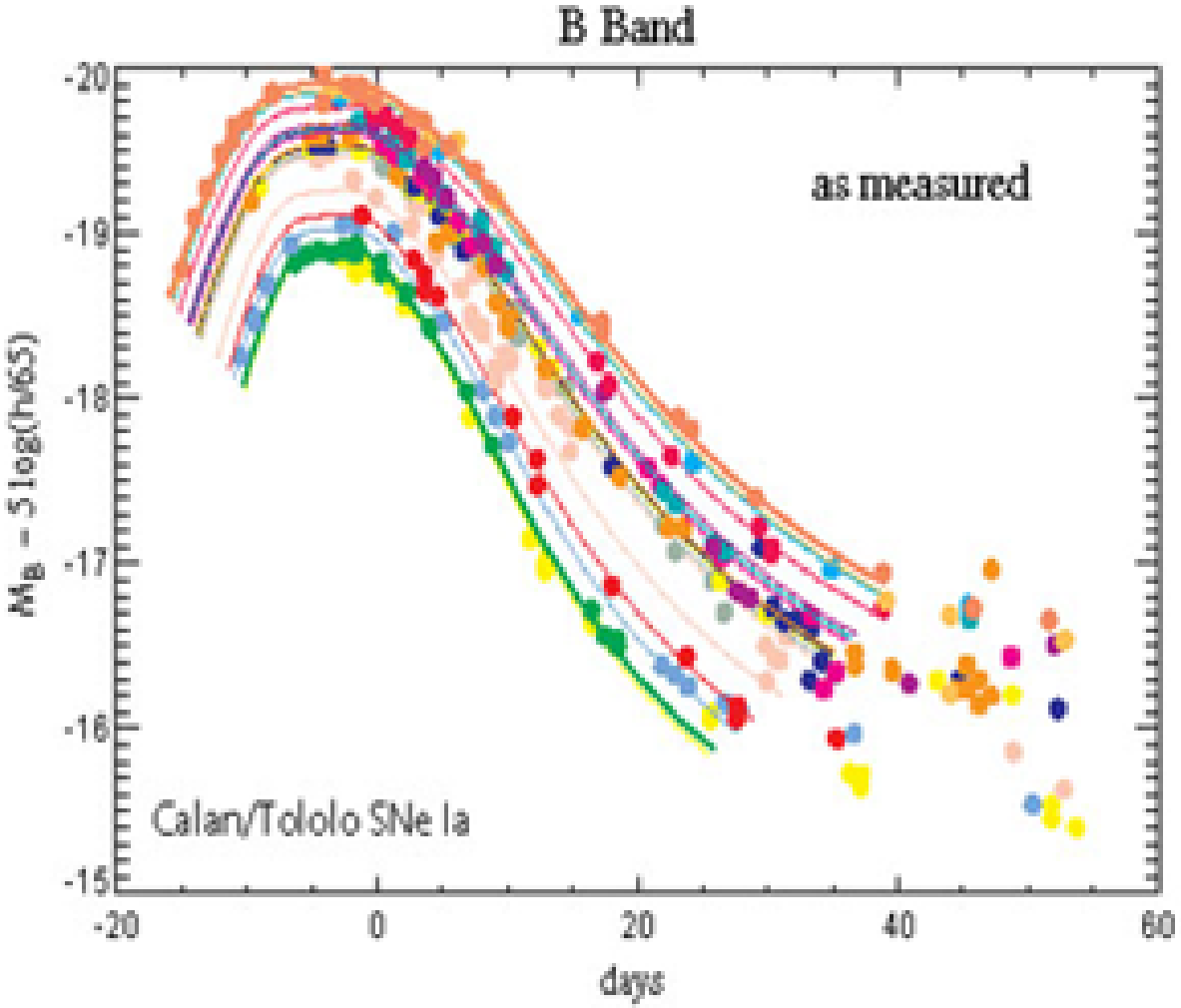
Constant for standard candles.

Luminosity distance

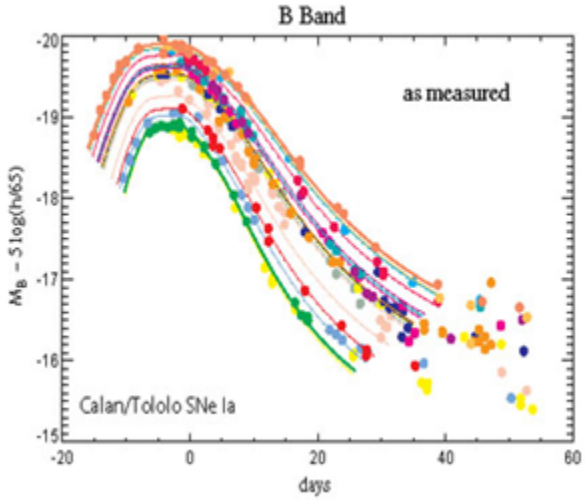
THEORITICAL MODELS

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \Omega_k (1+z')^2 + \Omega_\Lambda (1+z')^{3(1+\omega)}}}$$

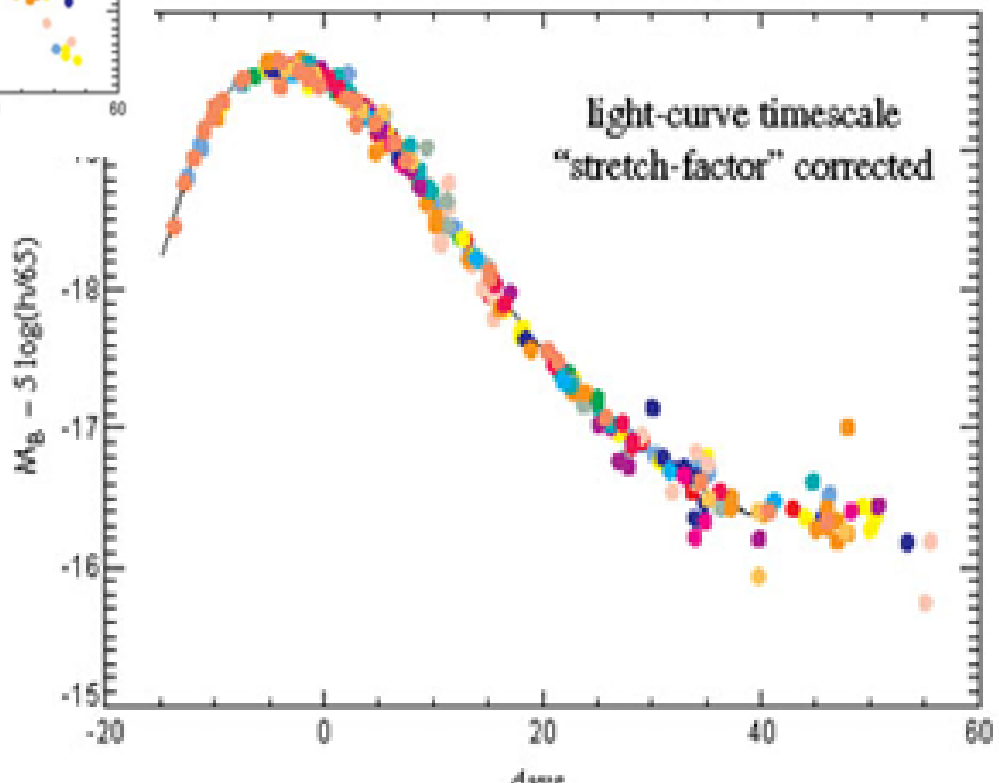
SNe Ia standard candles?

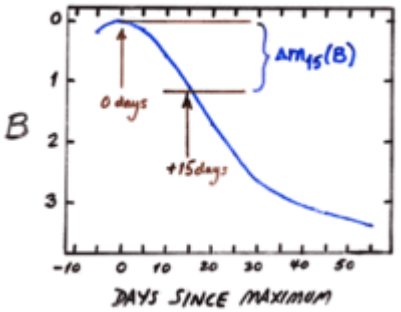


SNe Ia standard candles?



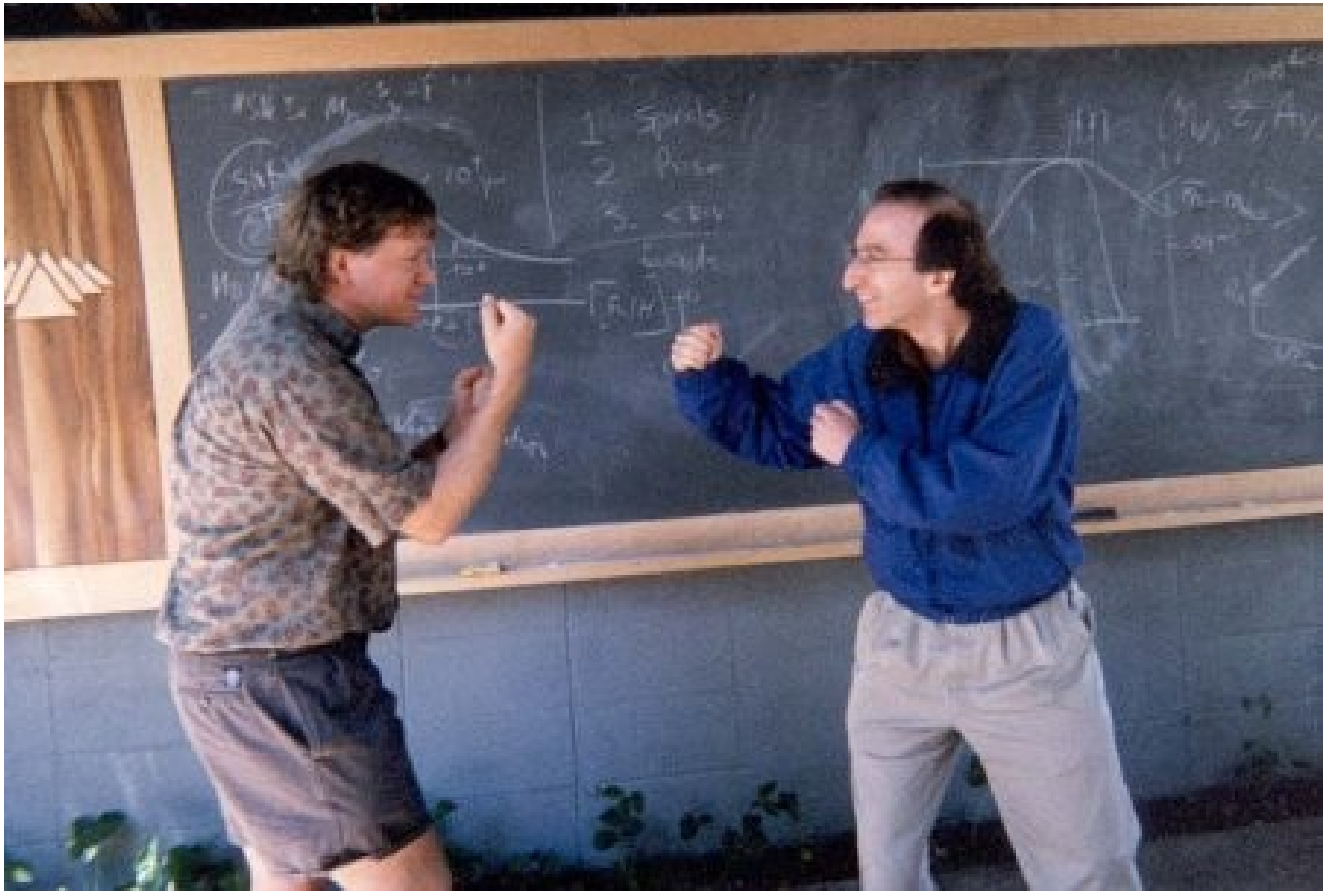
BUT!!!





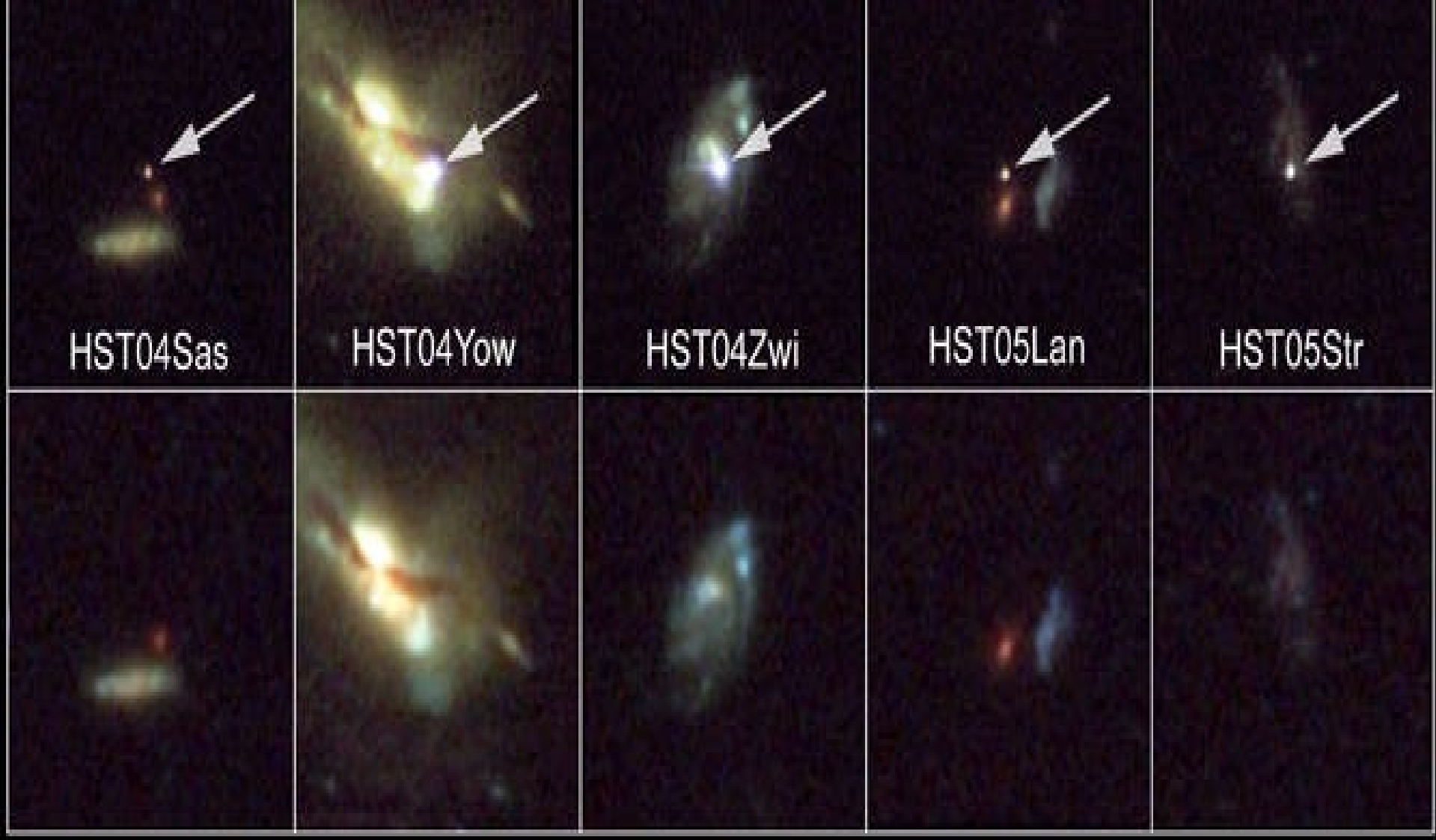
Phillips et al. 1993

2 teams searching distant SNe



On the left : High z supernovae team leads by Prof. Brian Schmidt

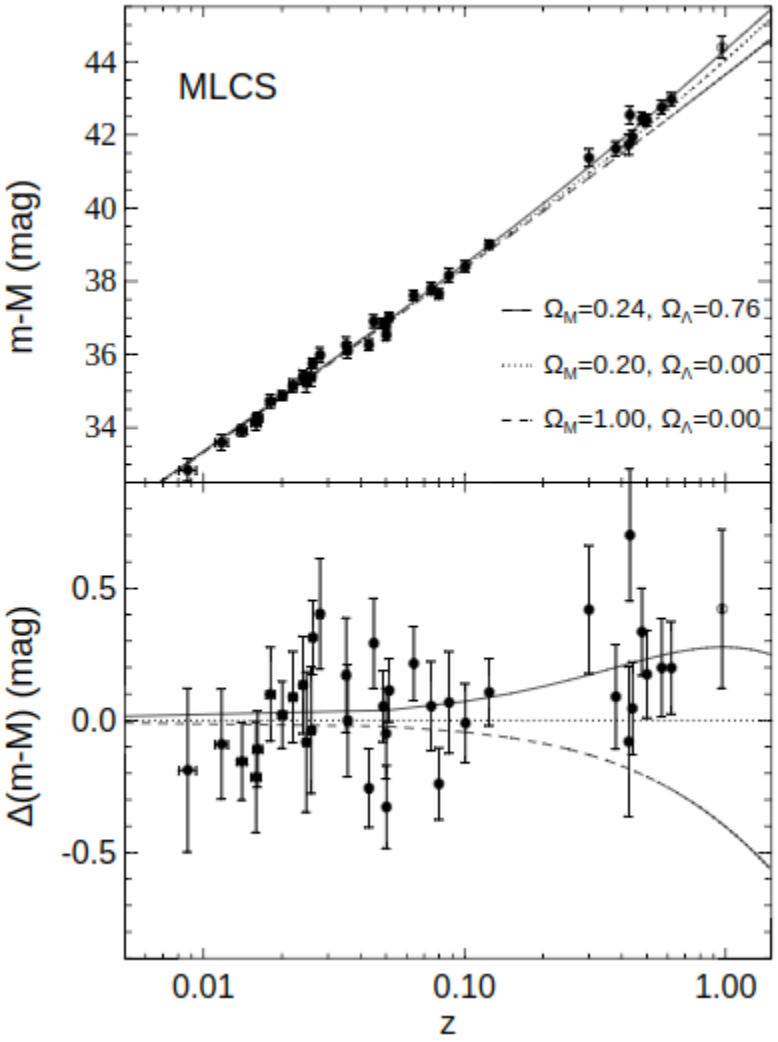
On the right: Supernovae Cosmology Project team leads by Prof. Saul Perlmutter



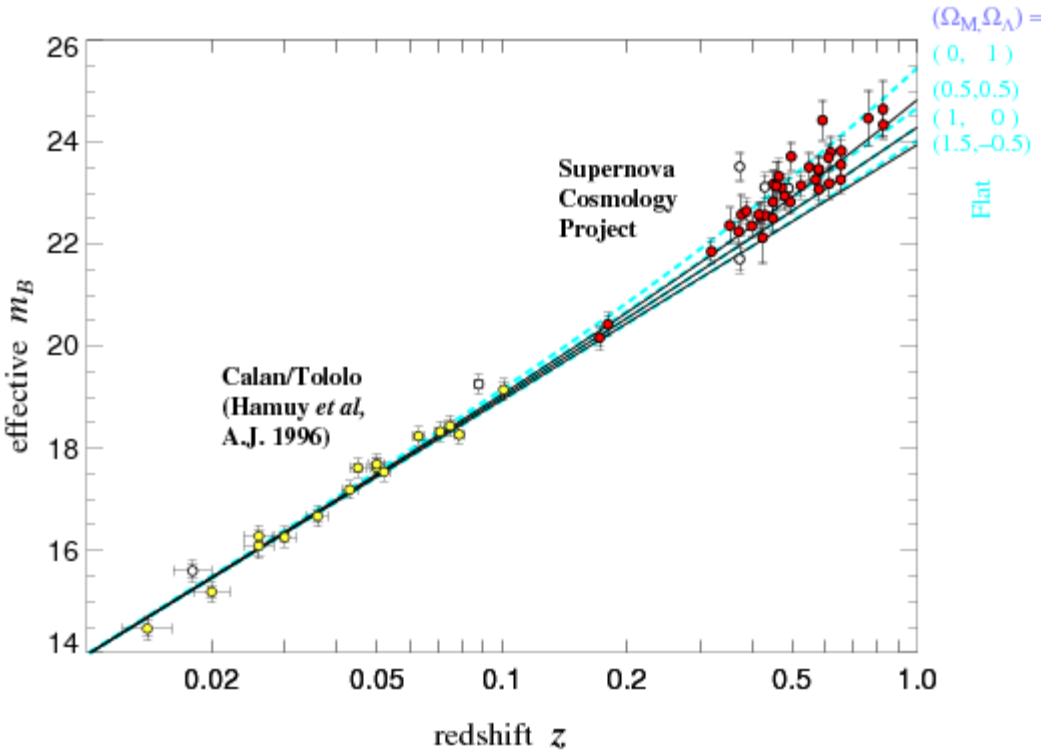
Host Galaxies of Distant Supernovae

Hubble Space Telescope ▪ Advanced Camera for Surveys

1998 : The BIG discovery

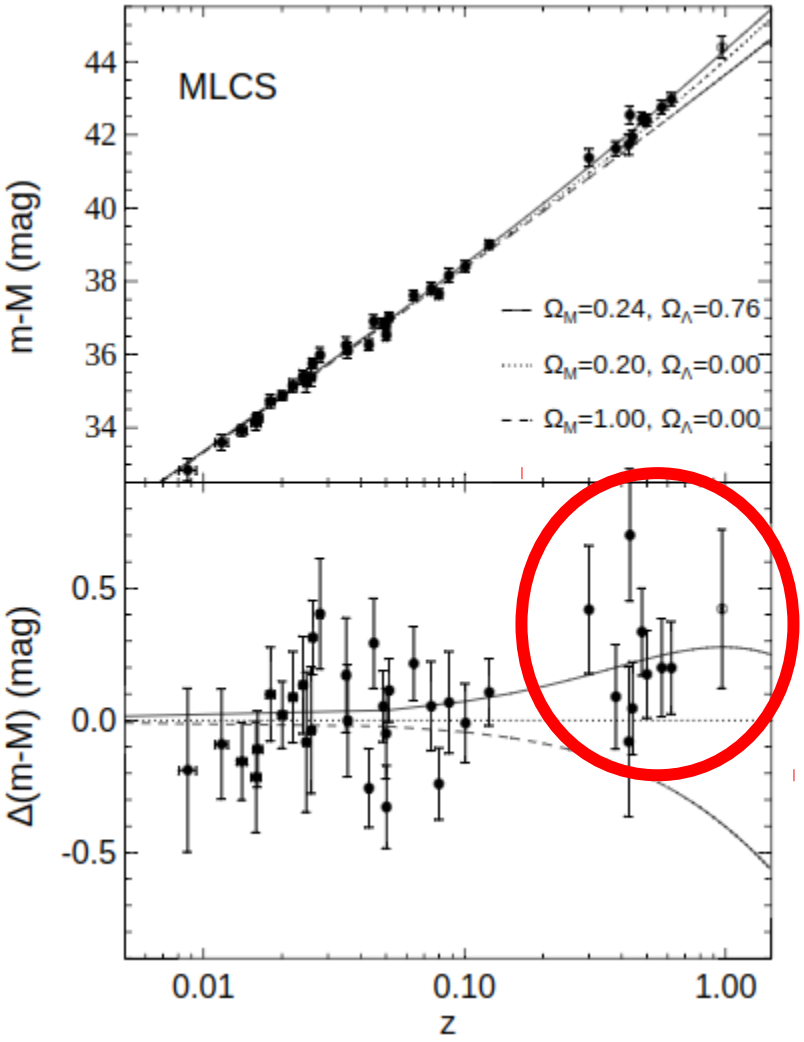


Riess et al. 1998

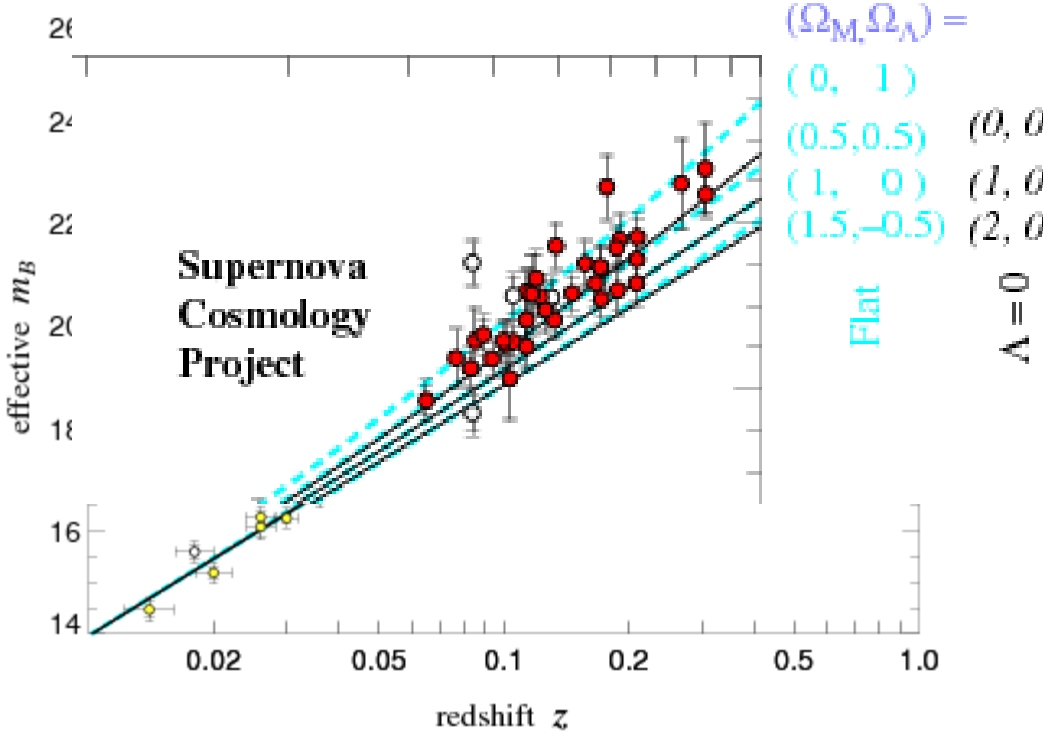


Perlmutter et al. 1999

1998 : The BIG discovery



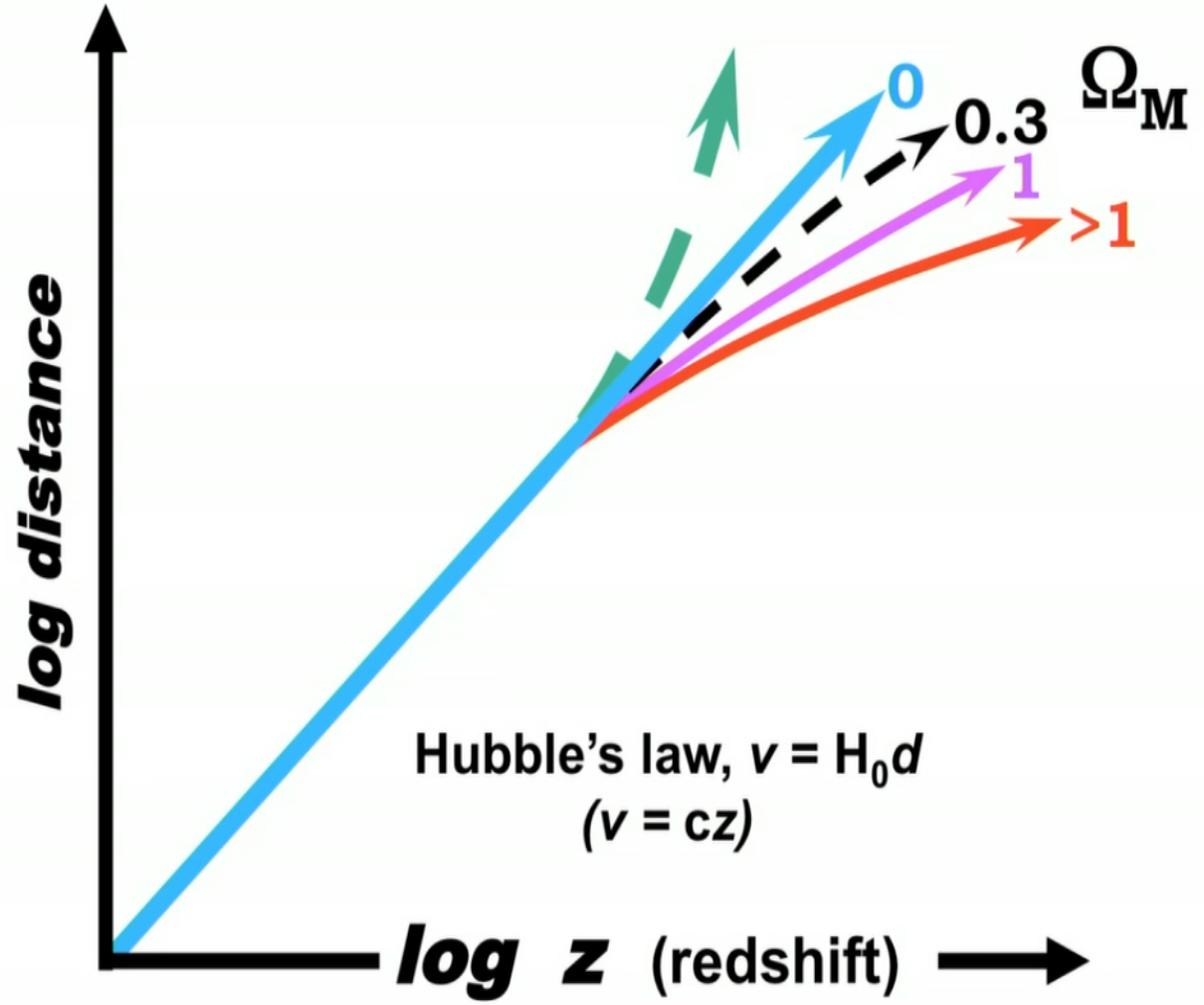
Riess et al. 1998



Perlmutter et al. 1999

DISTANT SNe ARE FAINTER THAN EXPECTED !!!!

Universe destiny ?



Credit : Alex Filippenko

And the winners are ??

2011

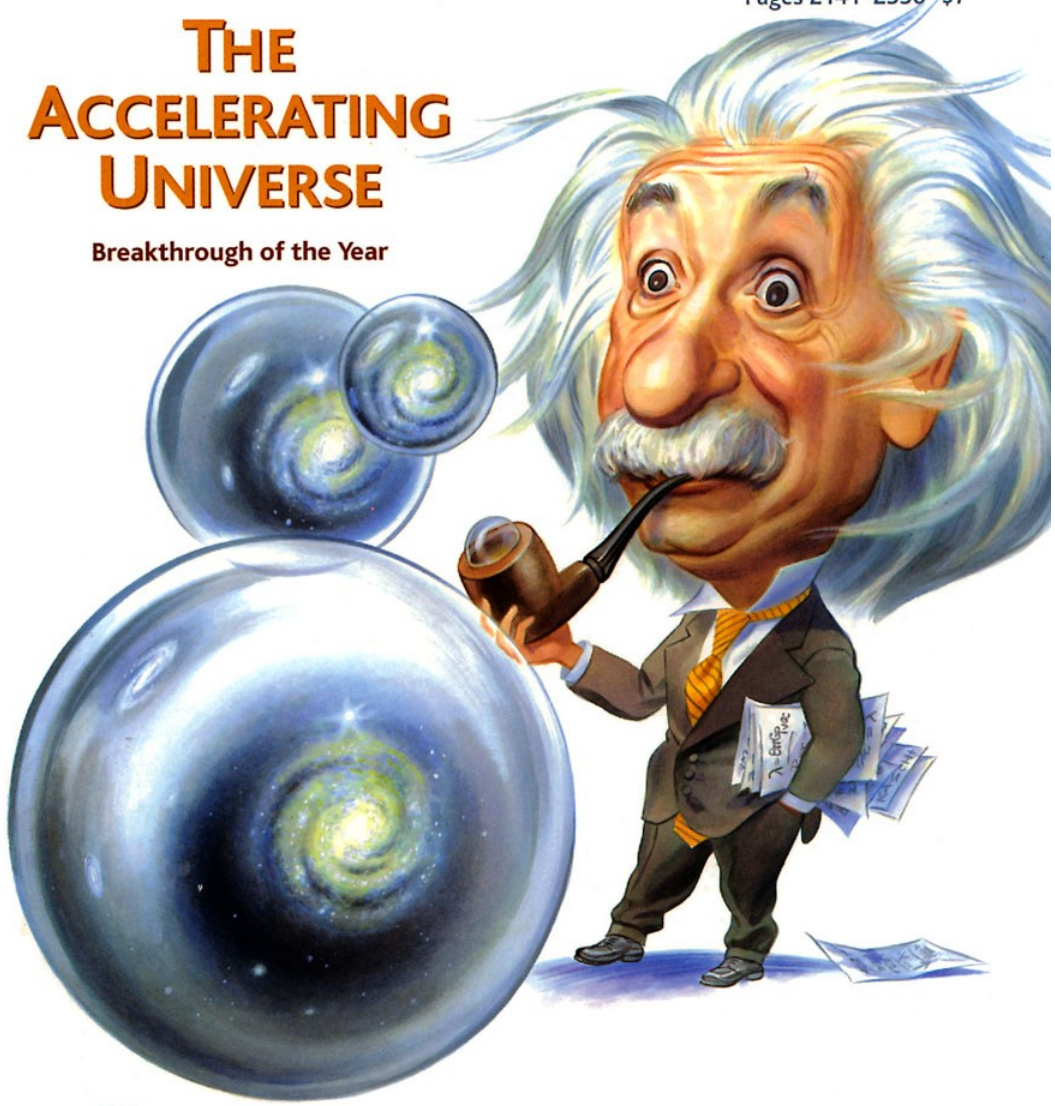
18 December 1998

Science

Vol. 282 No. 5397
Pages 2141–2336 $7

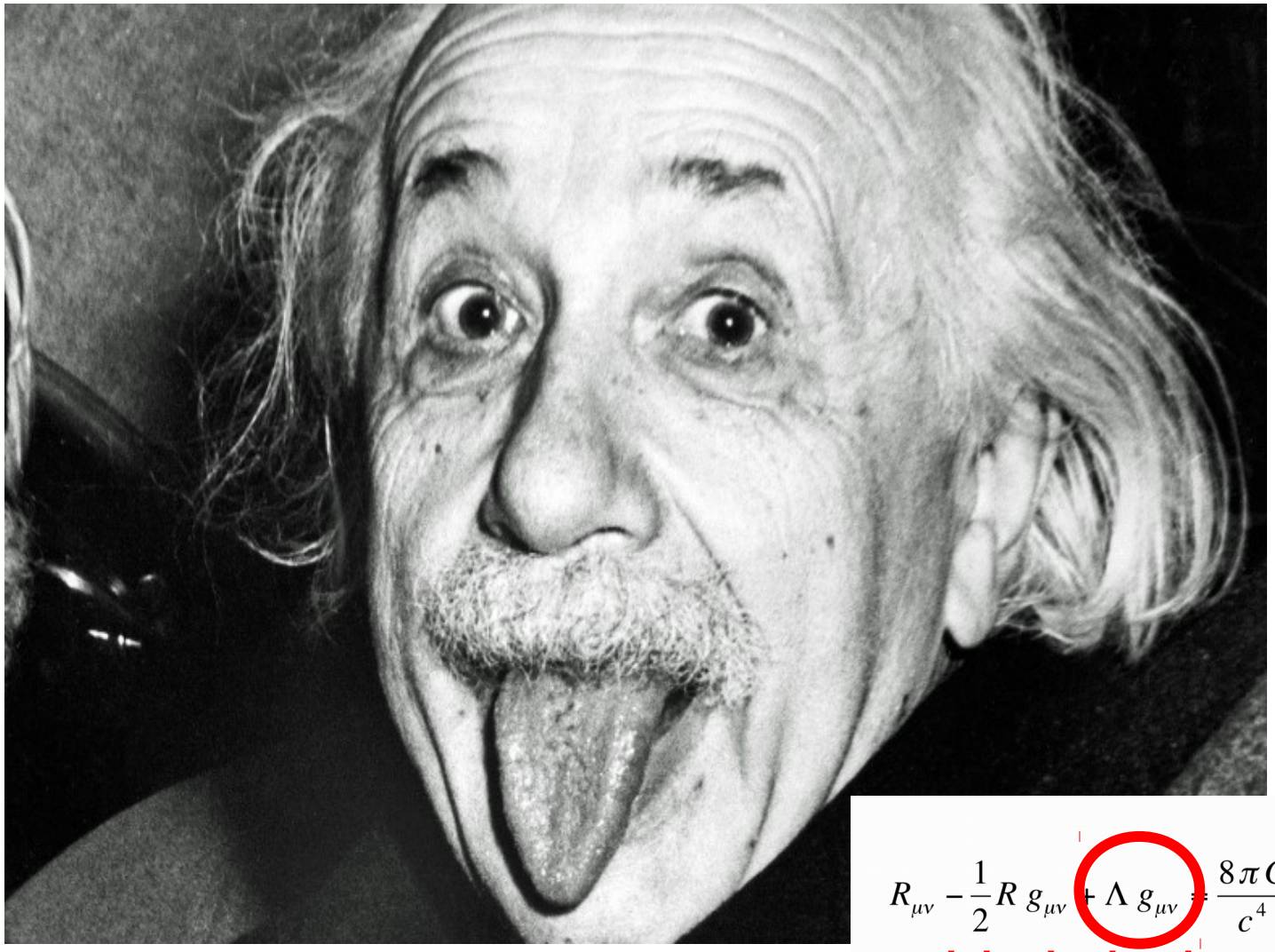
THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

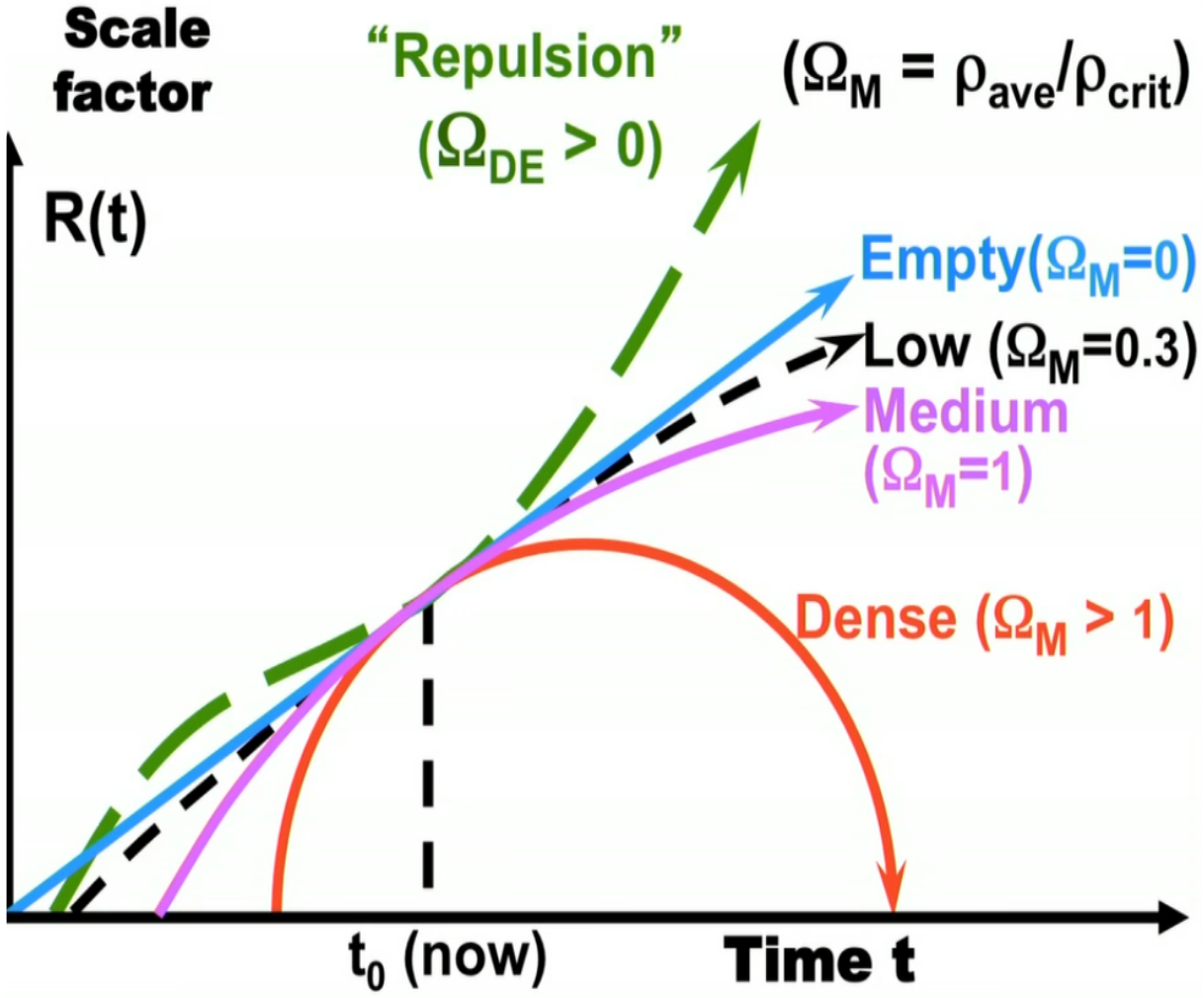
Even when I am wrong I am right



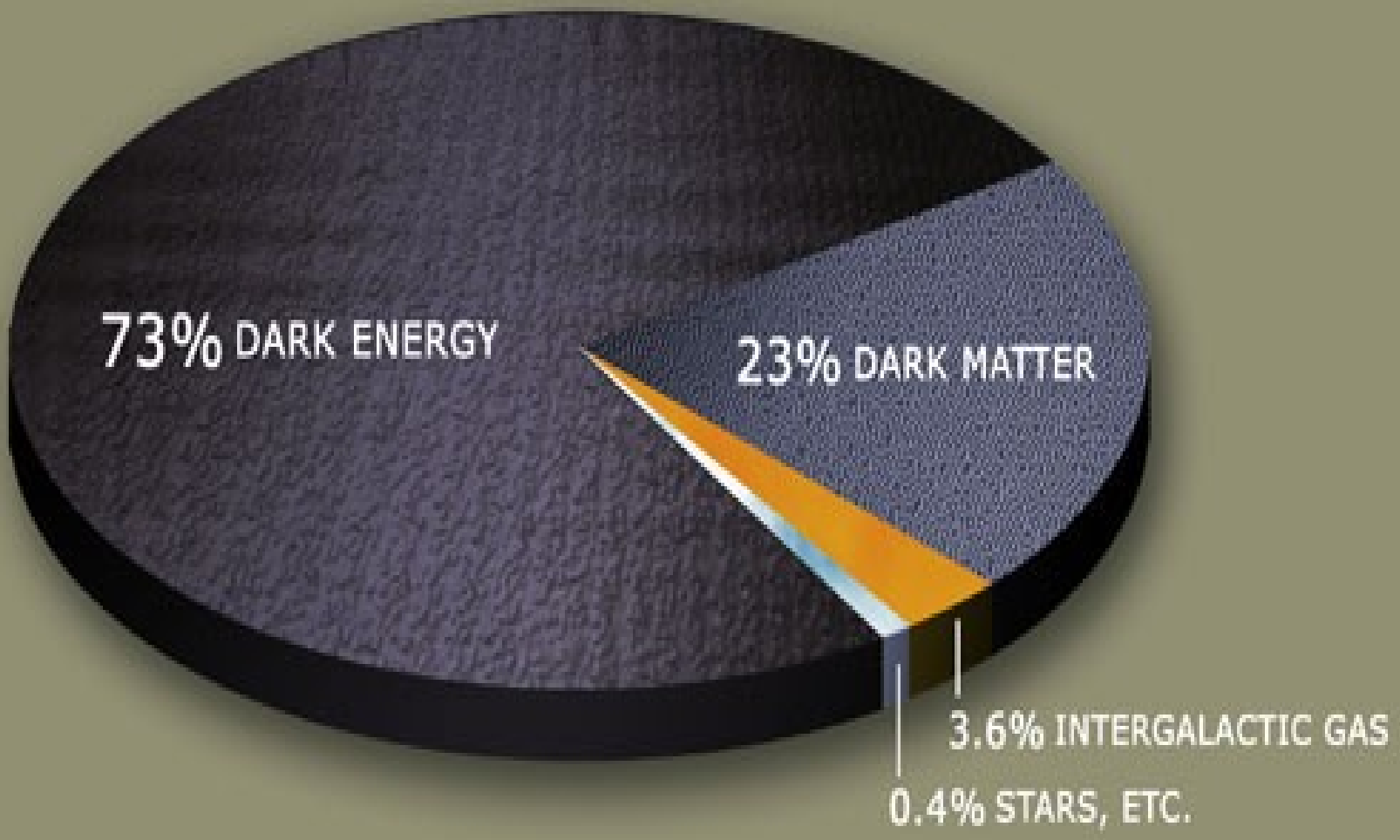
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Back in the business

Universe destiny!!



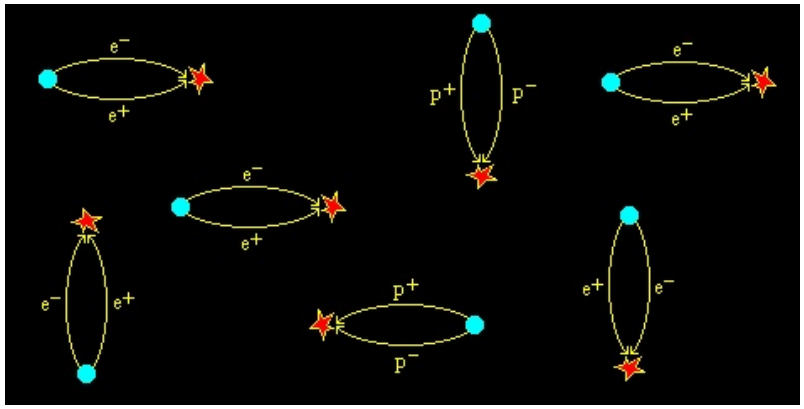
Credit : Alex Filippenko


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

Cosmological constant ?

Energy of the vaccum:

The energy is too big by 128 orders of magnitude:
100,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,000,
000,000,000,000,000,000,000,000,000,000,000,000

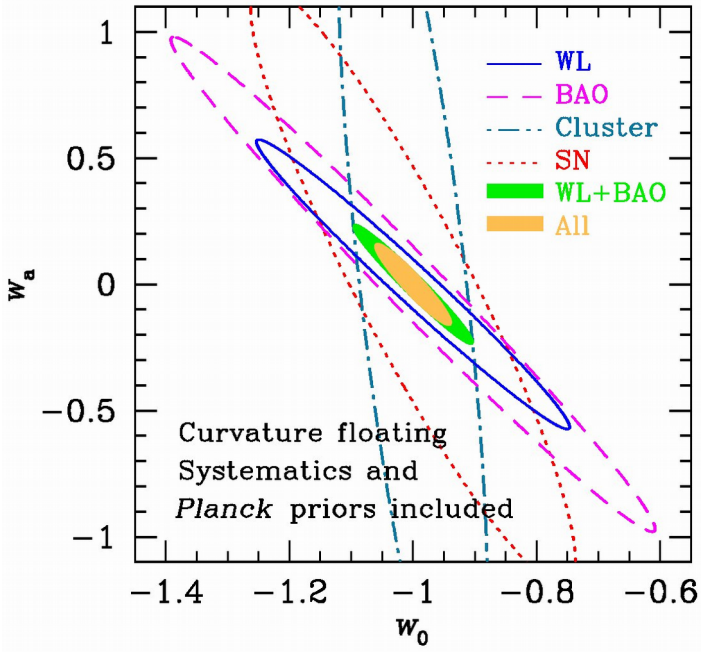


Is constant with time? :

w=p/ρ EoS perfect fluid
w(z) =w0+wa×z/(1 +z)

w=-1 comoslogical constant

0<w<-1 Quintessence model, evolution with time

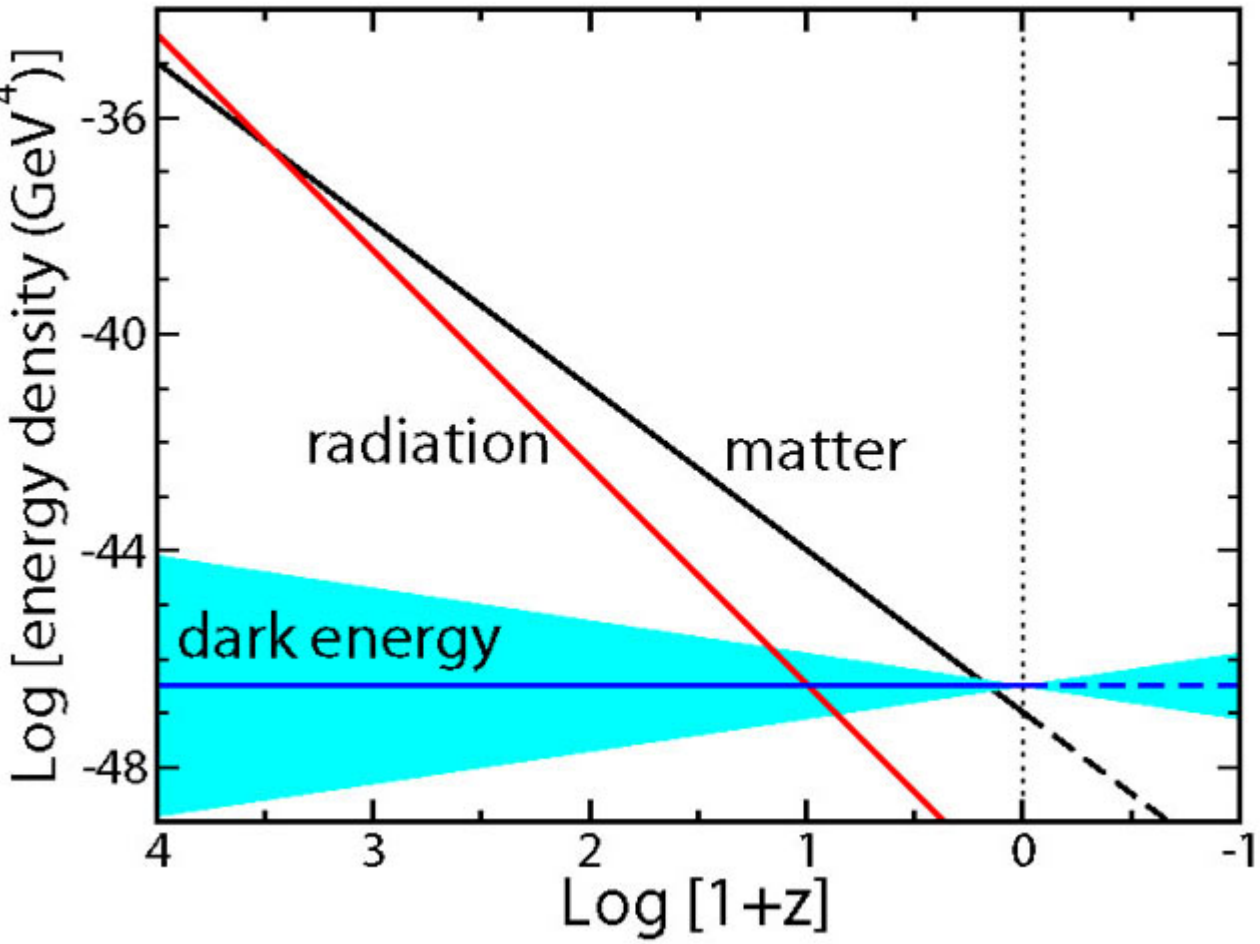


The future of the Universe

t<70 000years :
Radiation dominated

70 000years<t< 10 billions years :
Matter dominated

t>10 billions years :
Dark energy dominated

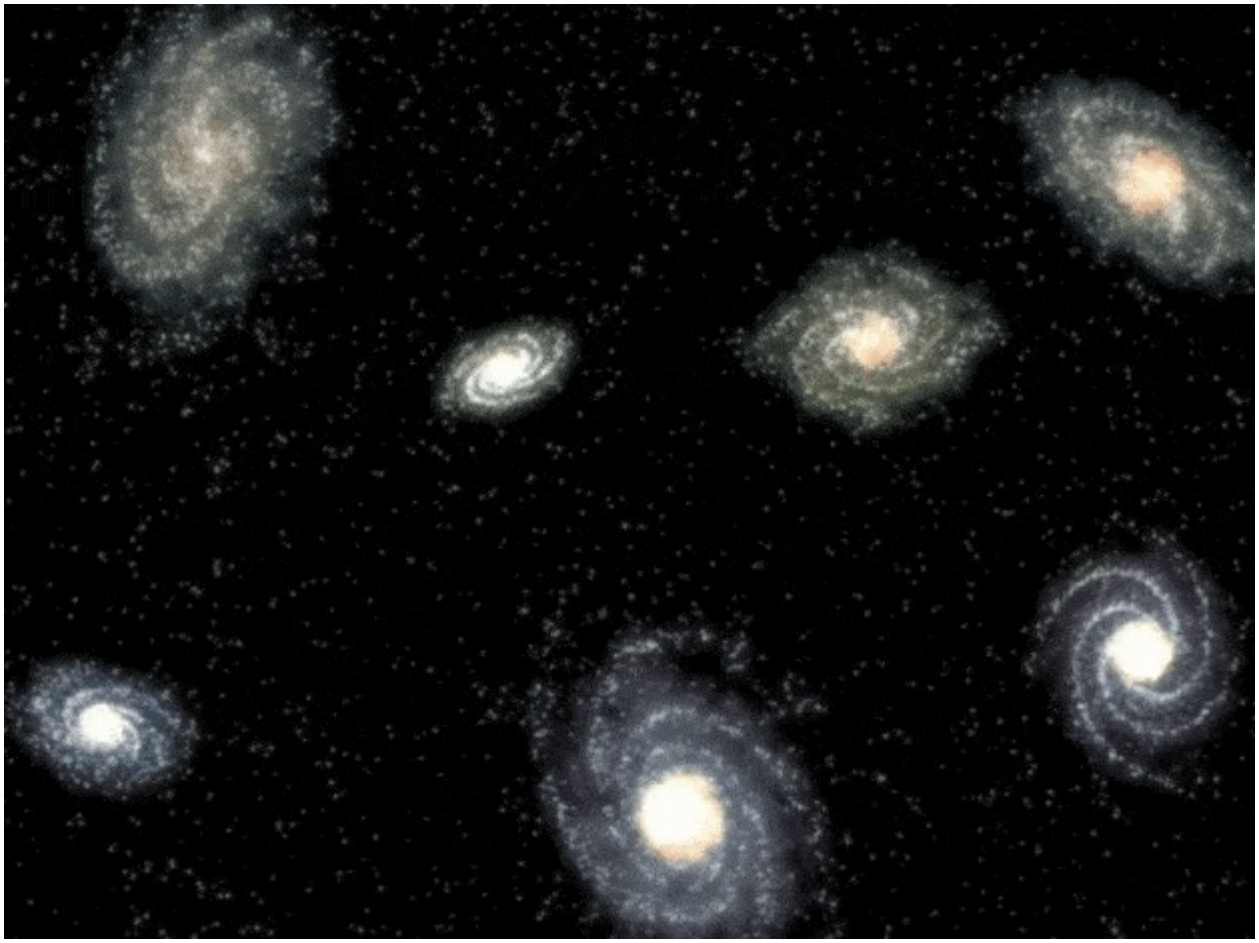


The future of the Universe

Big crunch :

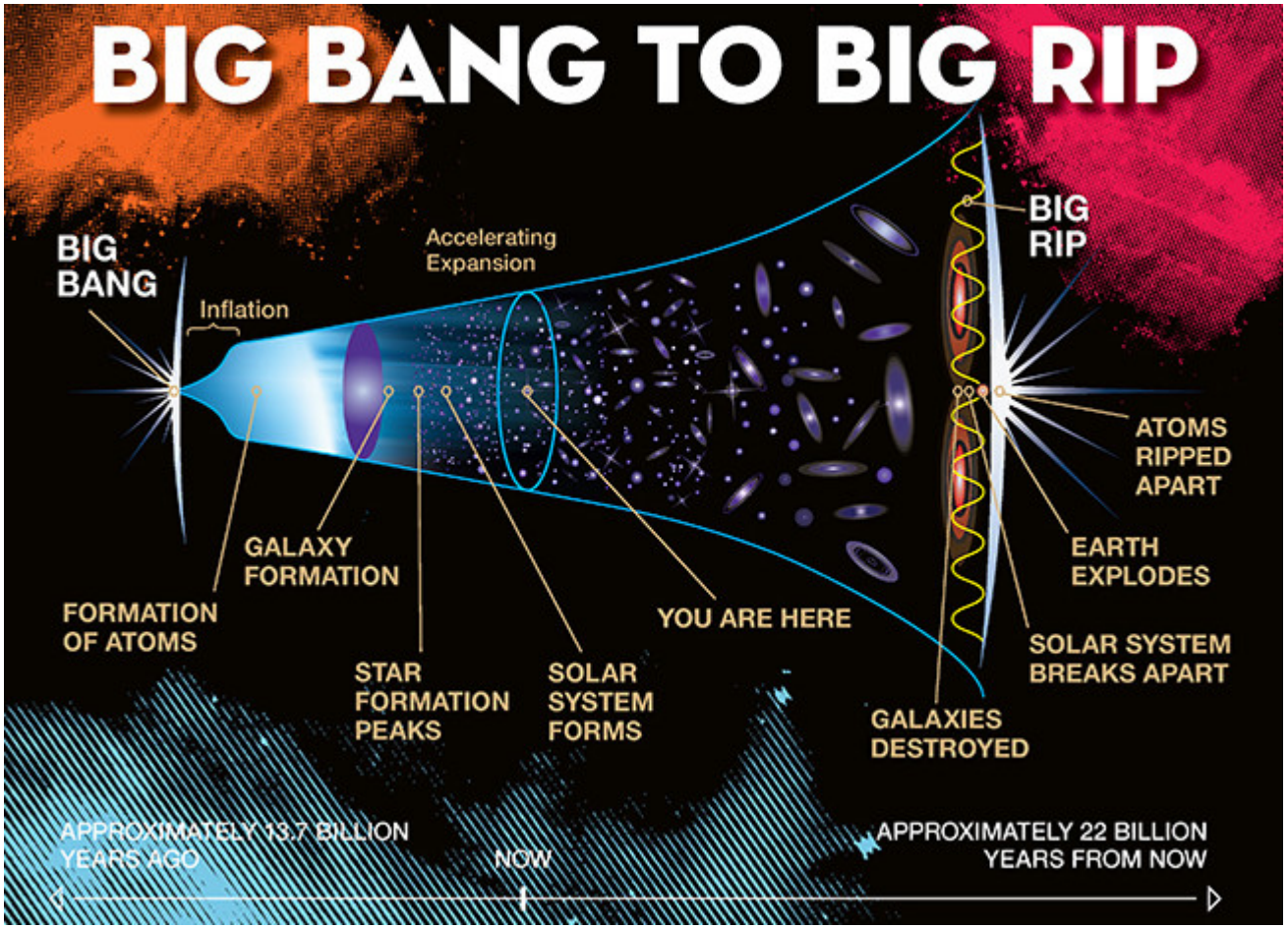
The future of the Universe

Big freeze :

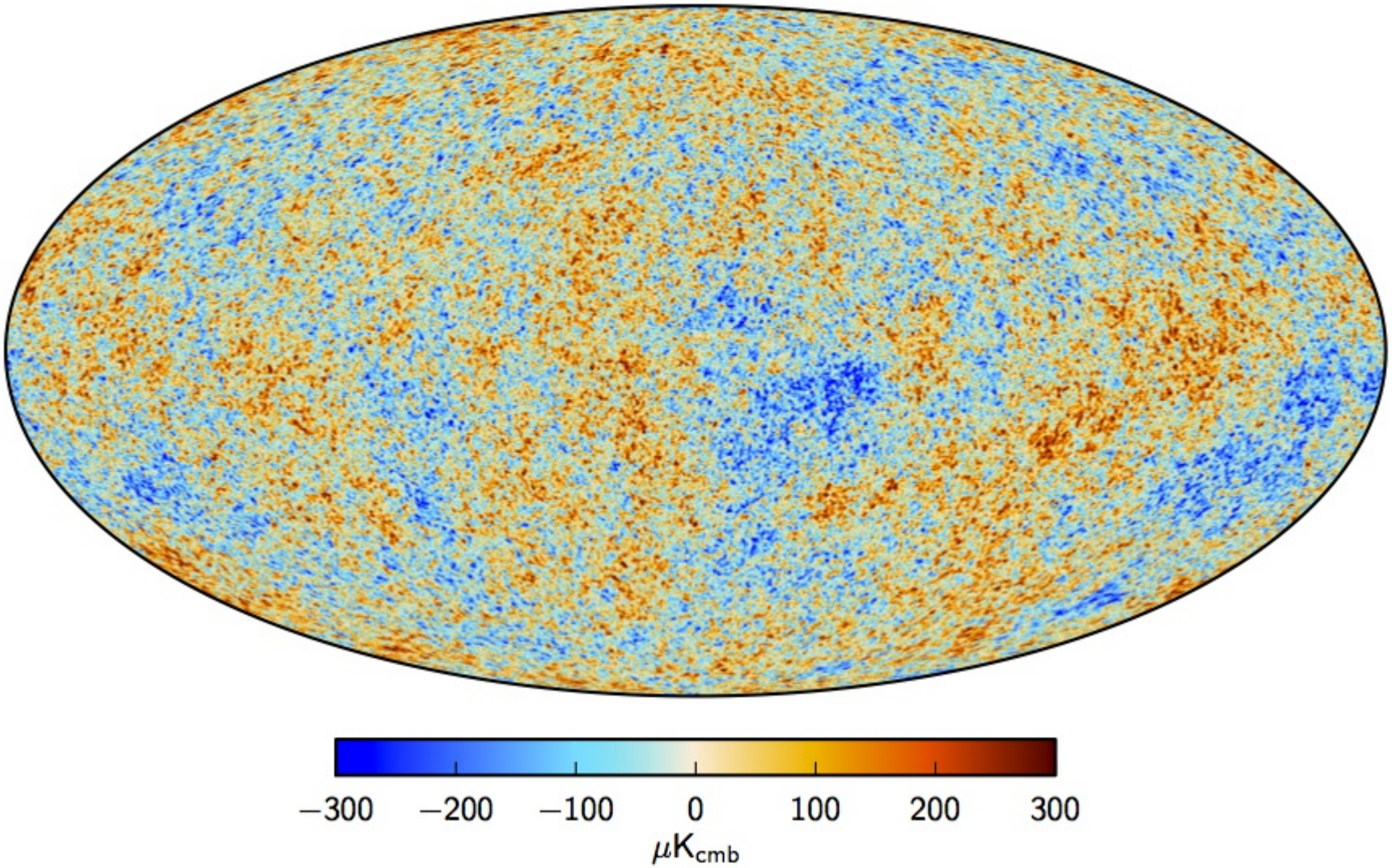


The future of the Universe

Big rip :

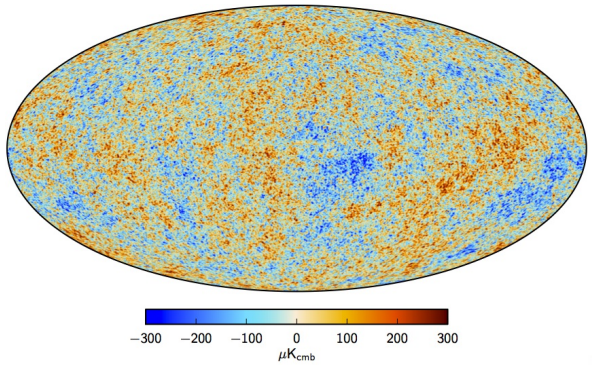


Other probes ?

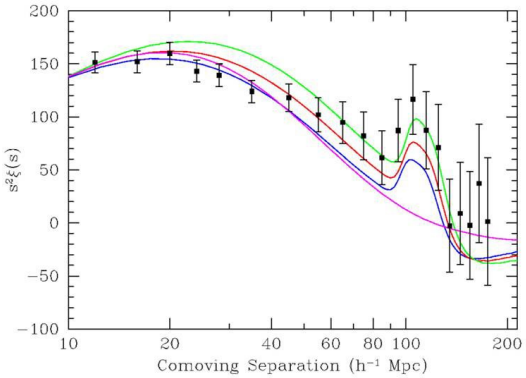


Other probes

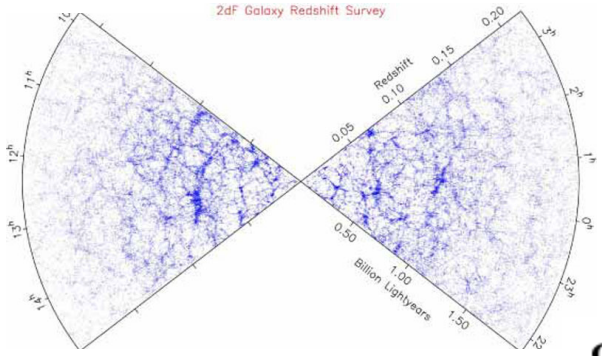
CMB :



Baryonic Acoustic Oscillations :

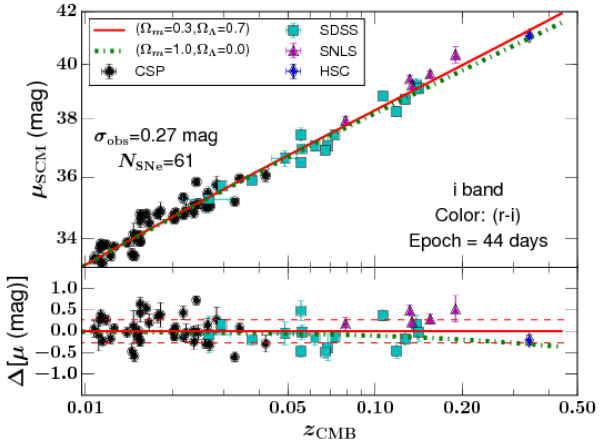


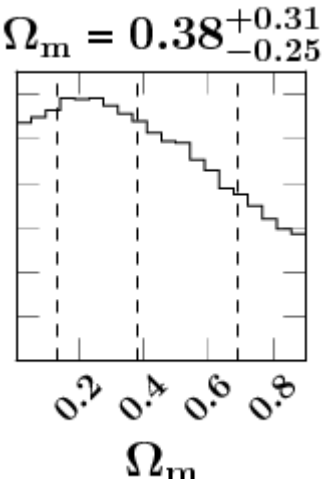
Galaxiy clusters :



Type II supernova? :

My work!!!

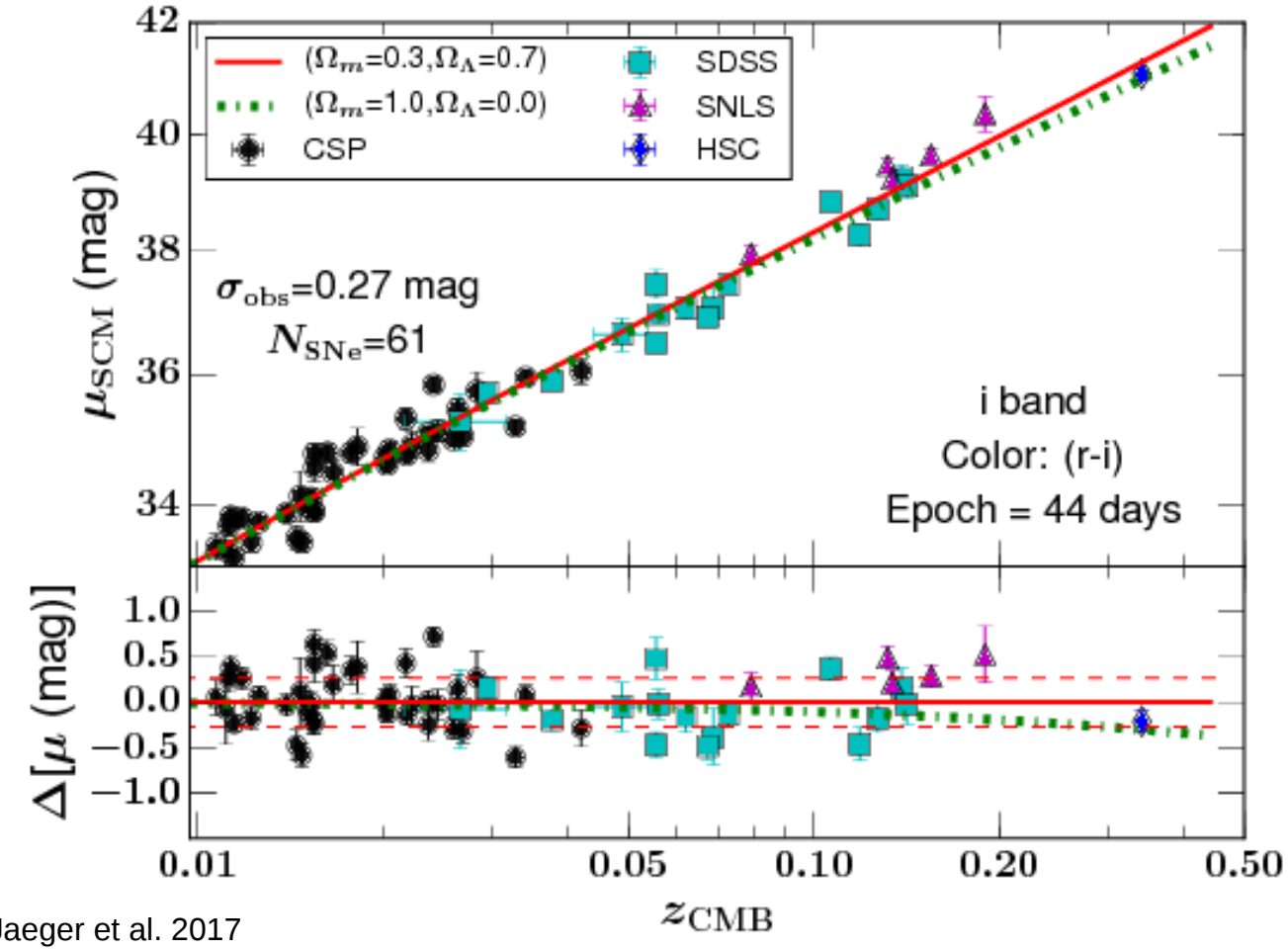


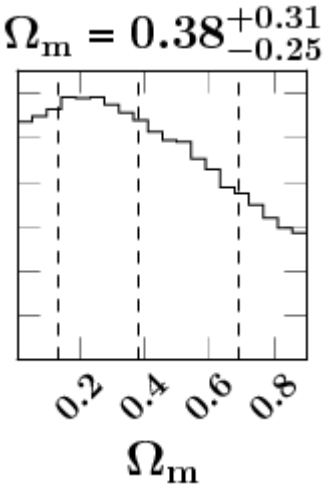


Other probes

Type II supernova? :

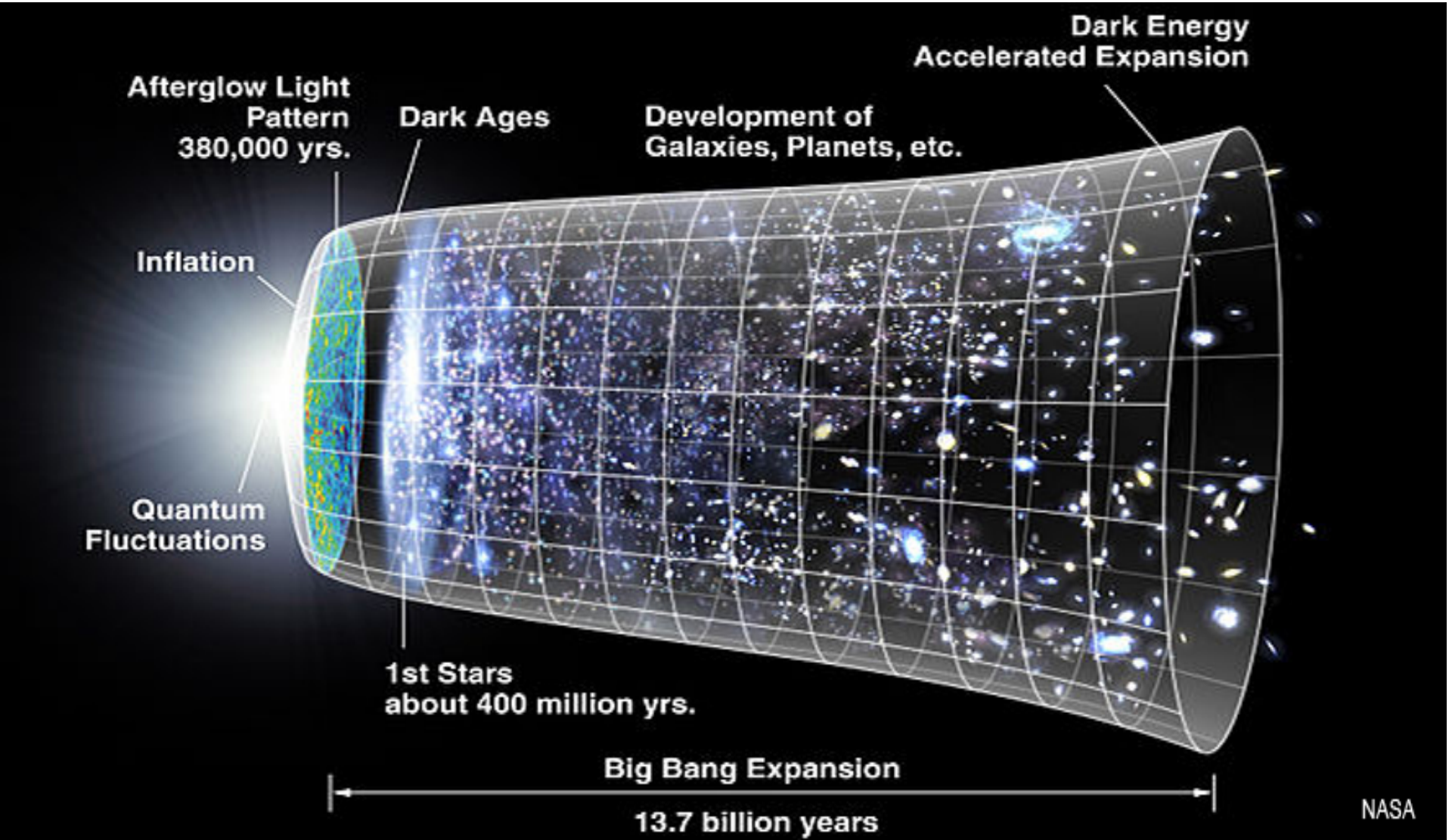
My work!!!





de Jaeger et al. 2017

Thank you !!!!


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA