The distance scale

Topic 7

Material from
Chap. 20 “The cosmic perspective”, by J. O. Bennett, M. O. Donahue, N. Schneider & M. Voit
And Chap. 3 “Extragalactic Astronomy and Cosmology”, by P. Schneider, 2nd edition

Distance scale

- Parallax
- Standard candles
  - Cepheids
  - Supernovae

Hubble law

- Redshift
- Expanding Universe

Distance scale



Bright and big because they are close

Faint: they are close but not very bright,
or distant and brighter?

To answer, you need to know the distance
of the sources

Brightness, or flux
(Observed property)

Luminosity
(Intrinsic property)

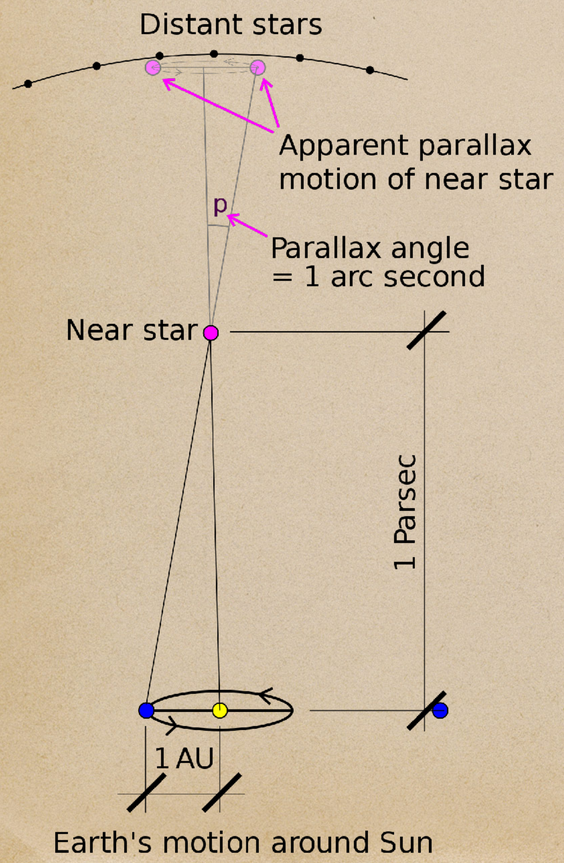
$$F = \frac{L}{4\pi D^2}$$

Distanza

$$L = 4\pi D^2 F$$

Distance scale

The measurement of distances in astronomy is based on a chain (scale, ladder) of measures that allow us to reach ever greater distances

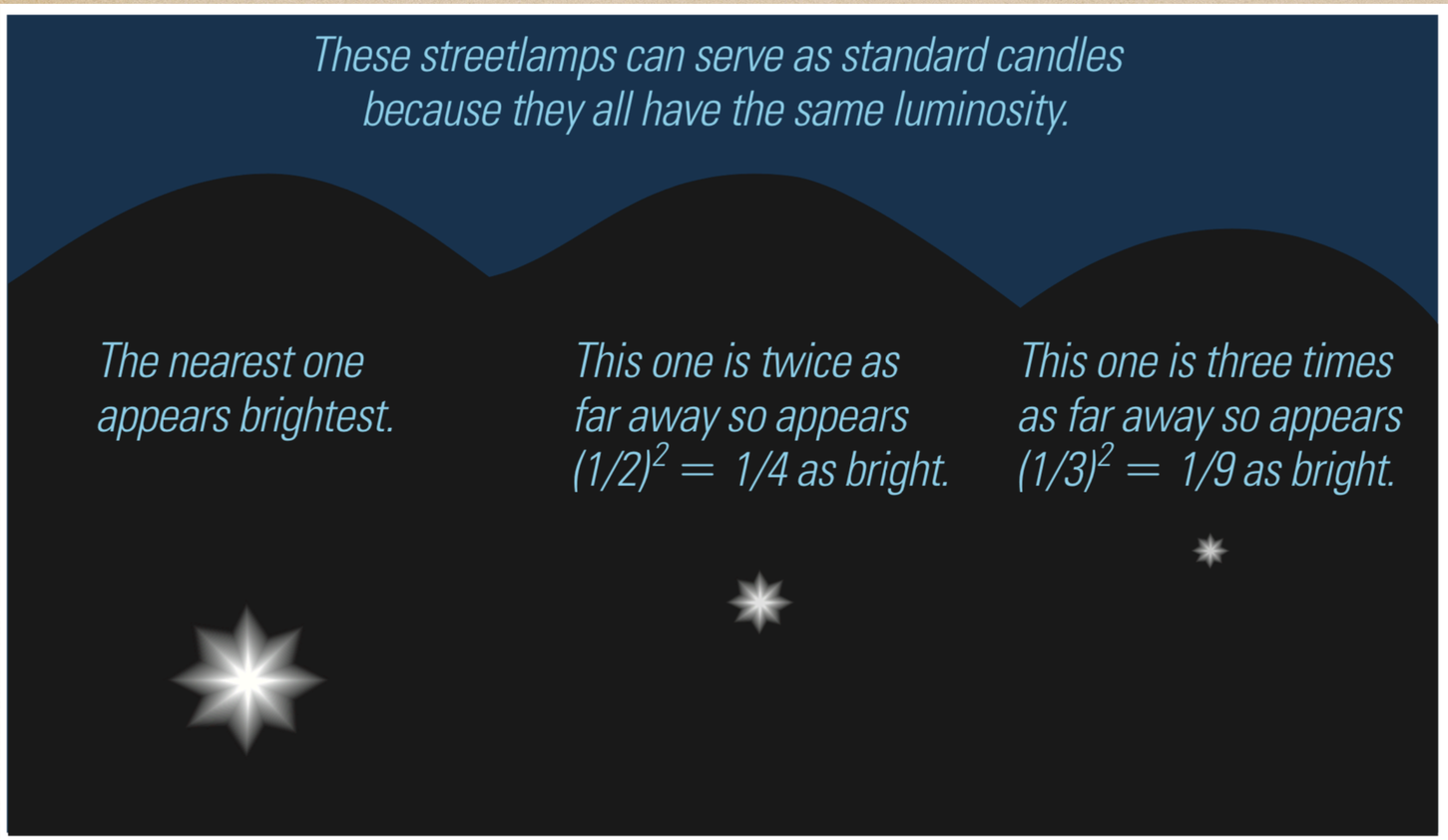


1. Measurement of the AU (Astronomical Unit)
   - With the radar you measure the distance of Venus
   - With Kepler's laws the distance of the Sun is obtained

2. The AU is the basis for determining the distances with the parallax
   - I measure the parallax angle
   - I get the distance in parsec

The parallax allows me to measure the distance of nearby stars

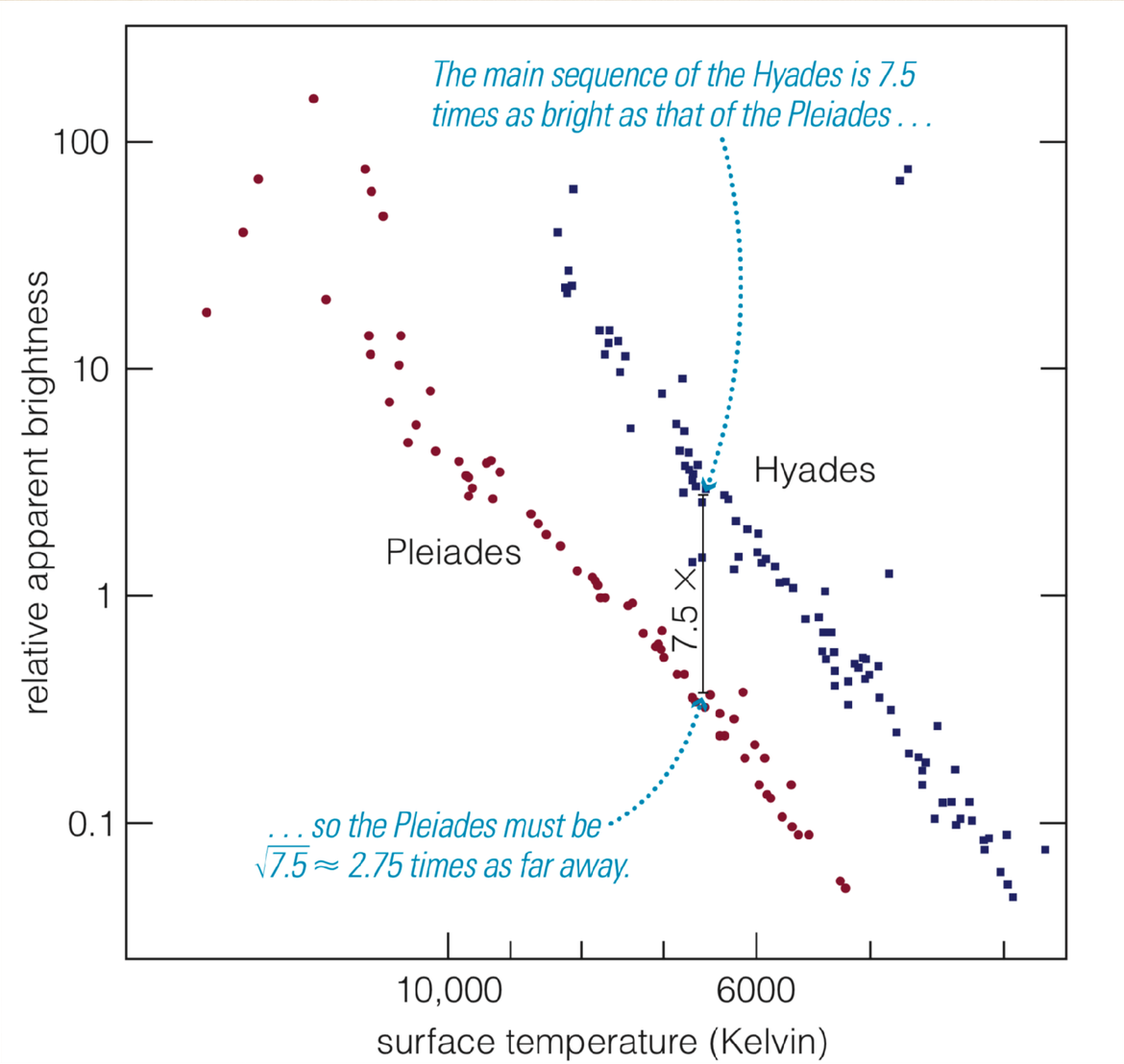
Standard candles



If I know the intrinsic luminsity of an object, I can calculate its distance by measuring its flux

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

Main-sequence fitting



Unfortunately, most astronomical objects do not have known intrinsic luminosity

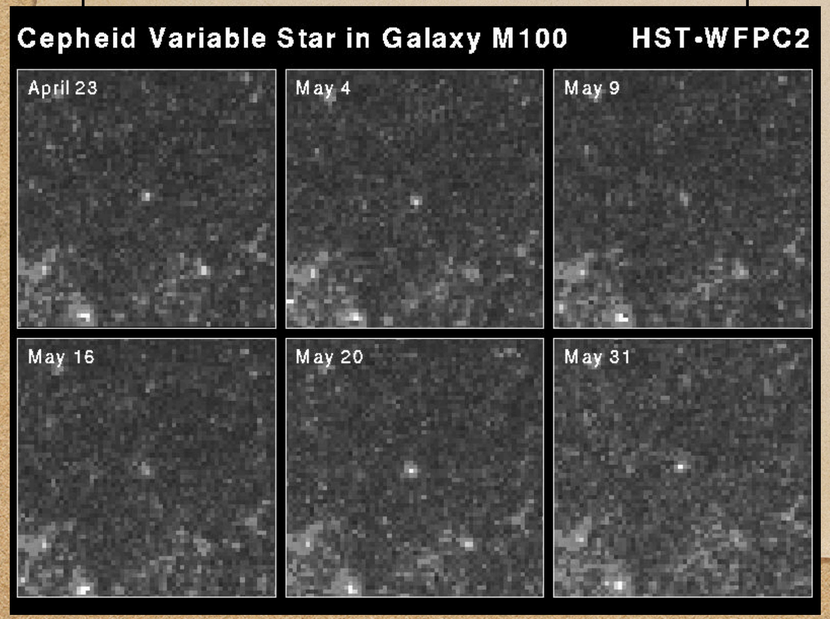
But for example I know the intrinsic brightness of solar stars

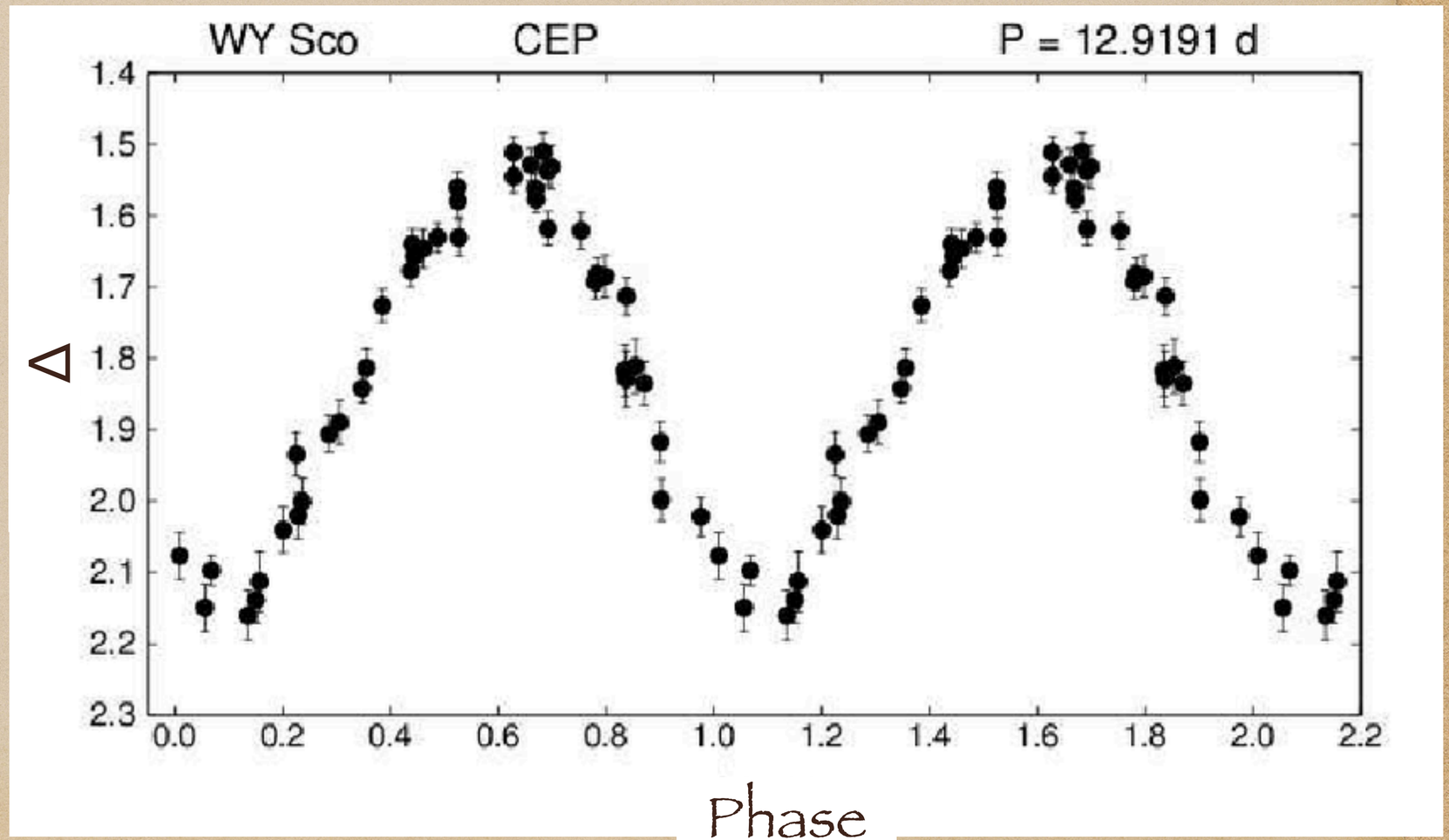
If I recognize the spectral type of distant stars, I can derive their distance

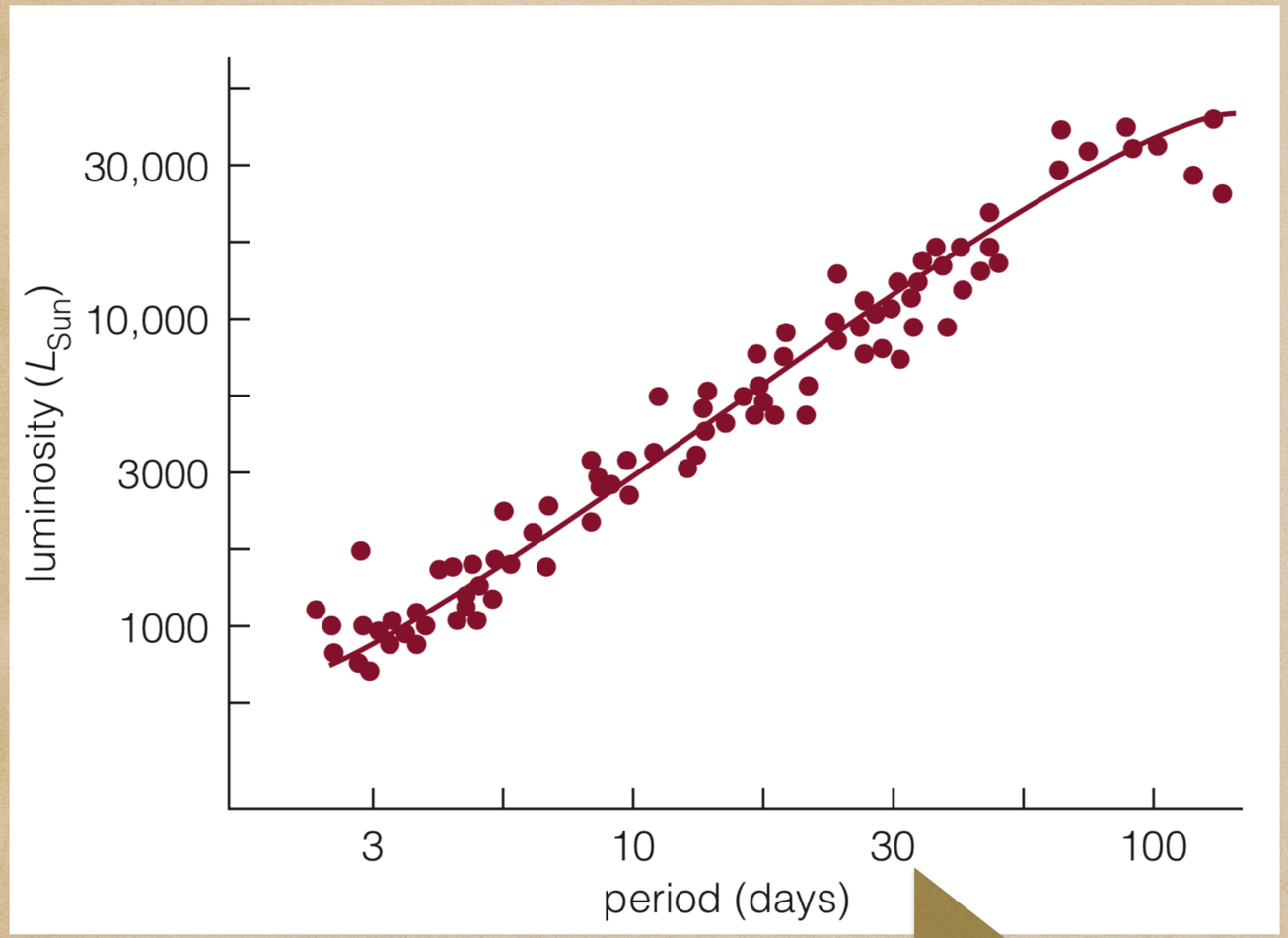
Cepheids

Cepheids are variable stars

The luminosity of the Cepheids varies periodically as a function of time







Henrietta Leavitt in 1912 discovered that the period of the Cepheids is linked to their luminosity

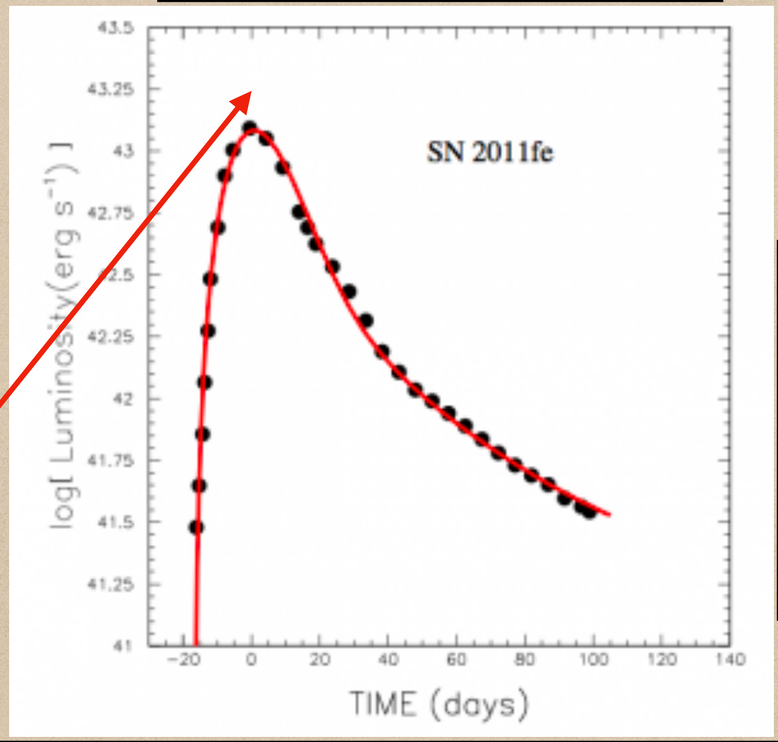
Just calculate the period to have the Luminosity

Cepheids are excellent standard candles

Distant standard candles

Distant supernovae are excellent standard candles





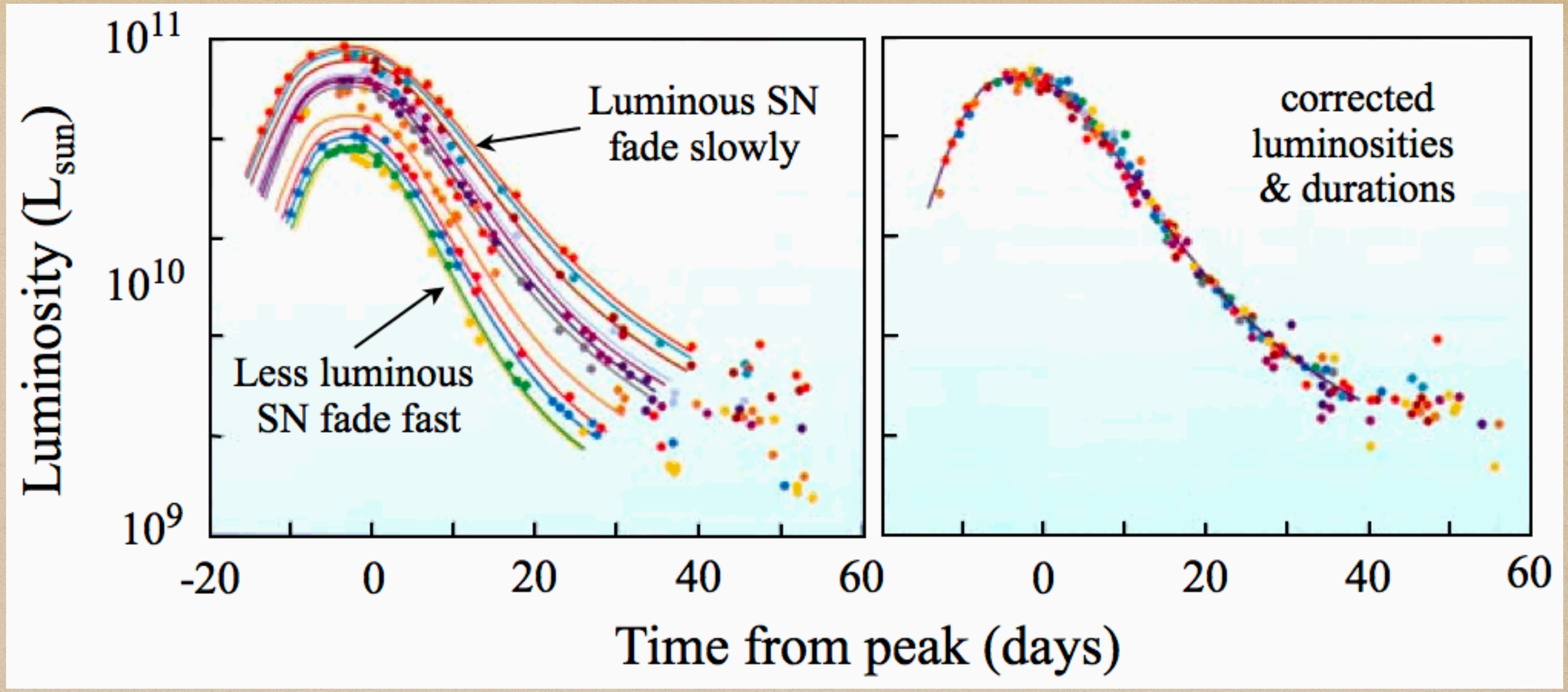
type Ia Supernovae are the final phase of the evolution of a binary stars system

$L_{peak}=10^{43.25}$ erg/s ~ 2×10^{43} erg/s

$L_{sun}=3.8\times10^{33}$ erg/s

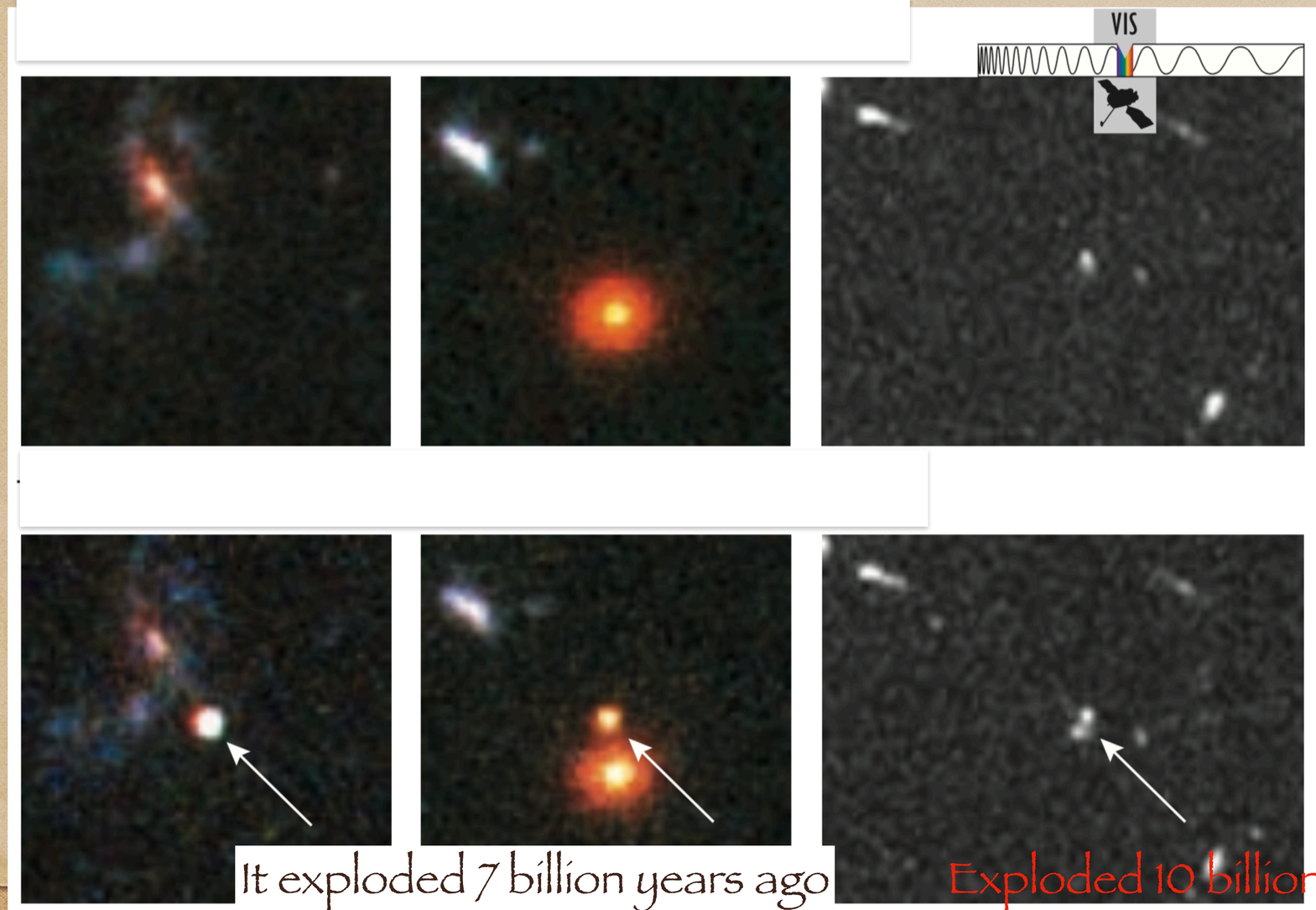
$L_{peak}=5\times10^{9}\ L_{sun}$!!!

Supernovae at the peak reach luminosities of 5 billion Suns: also visible from galaxies billions of light years ago, in the primordial Universe



In reality, the light curves of supernovae are a little more complex: the luminosity of the peak correlates with the speed of the flow decline

However, it is sufficient to correct for this correlation between brightness and duration so that all the curves overlap

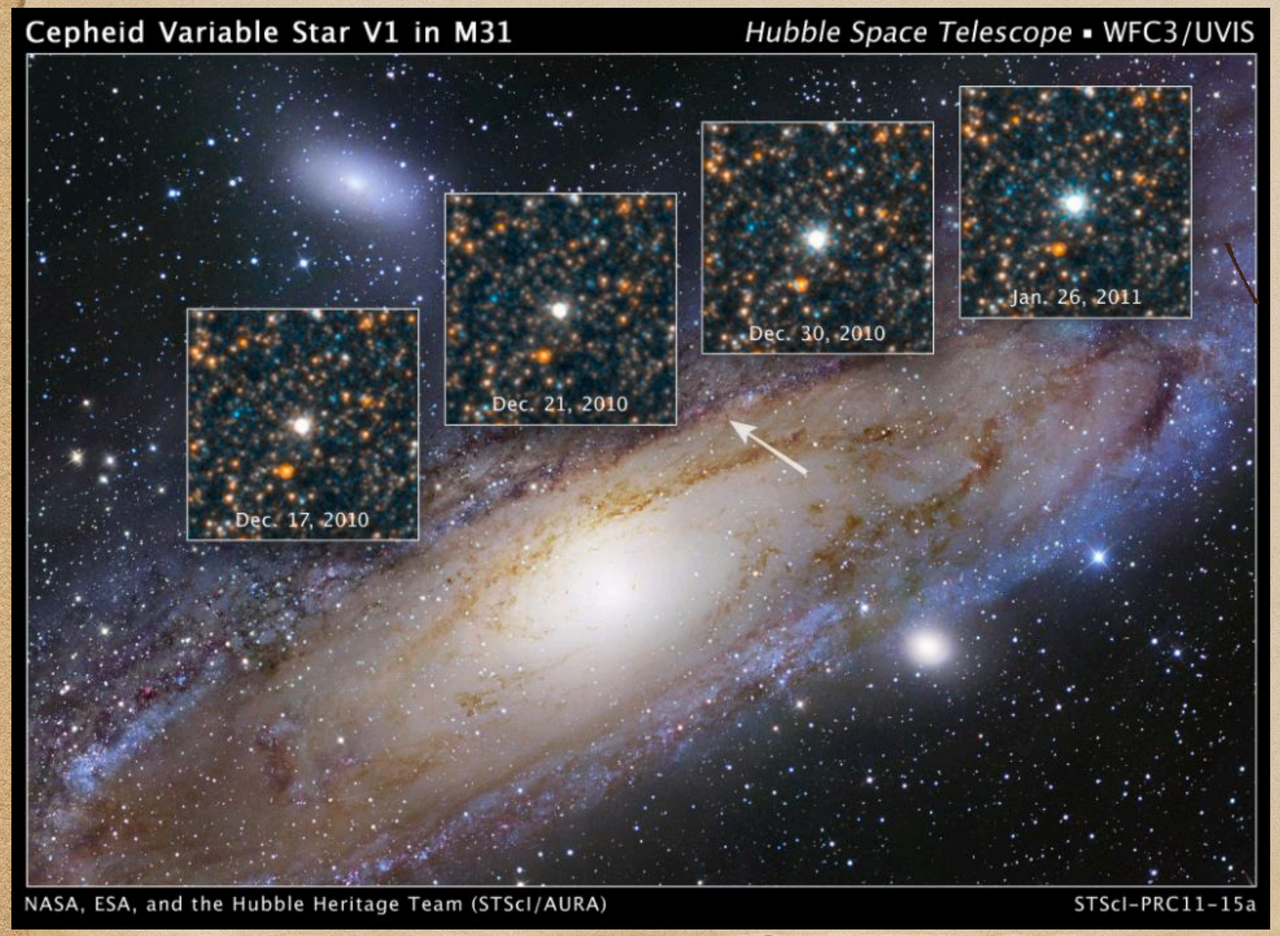


Distant galaxies before the supernova

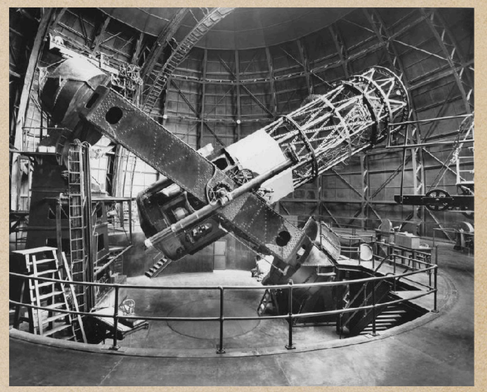
Same galaxies during the supernova

Distance from Andromeda

Until a century ago, it was not known if the "nebulae" that today we know to be external galaxies were objects external to our galaxy



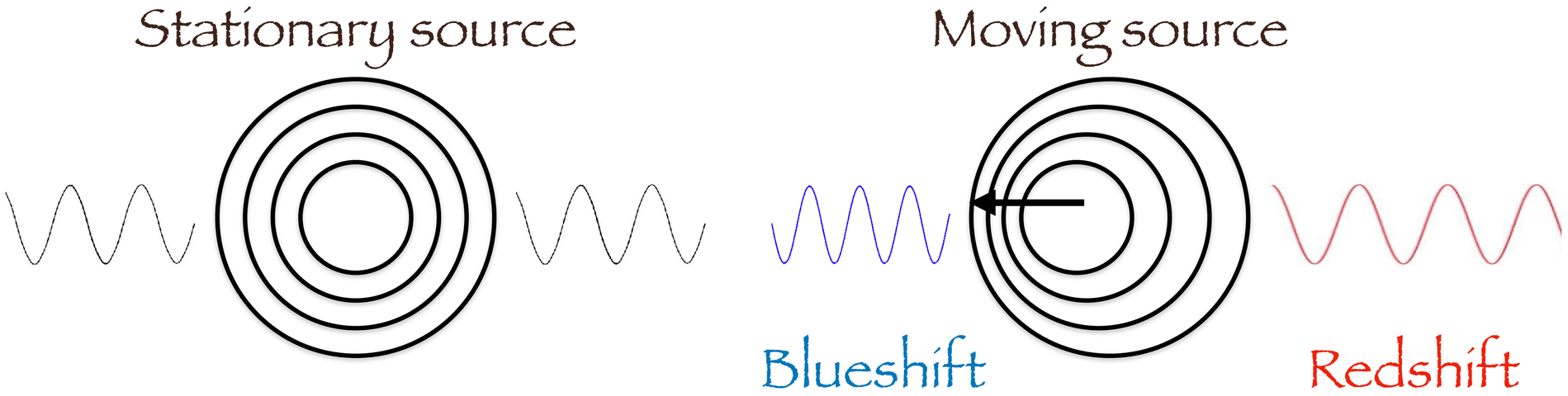




Everything changed in 1925 when Edwin Hubble observed individual stars in the Andromeda galaxy: it was proof that that was a galaxy like the Milky Way

Hubble realized that some of these individual stars were variable; he recognized that they were Cepheids and calculated their distance

How to measure the speeds of external galaxies



Through the Doppler effect

Even before Hubble there were speed measurements for nebulae, but it was still not known that they were external galaxies; most of them move away from us

THE HUBBLE LAW

The change in the wavelengths of photons as a result of the relative motion between source and observer is established, based on the Lorentz transformation, to be

Observed wavelength

Emitted wavelength

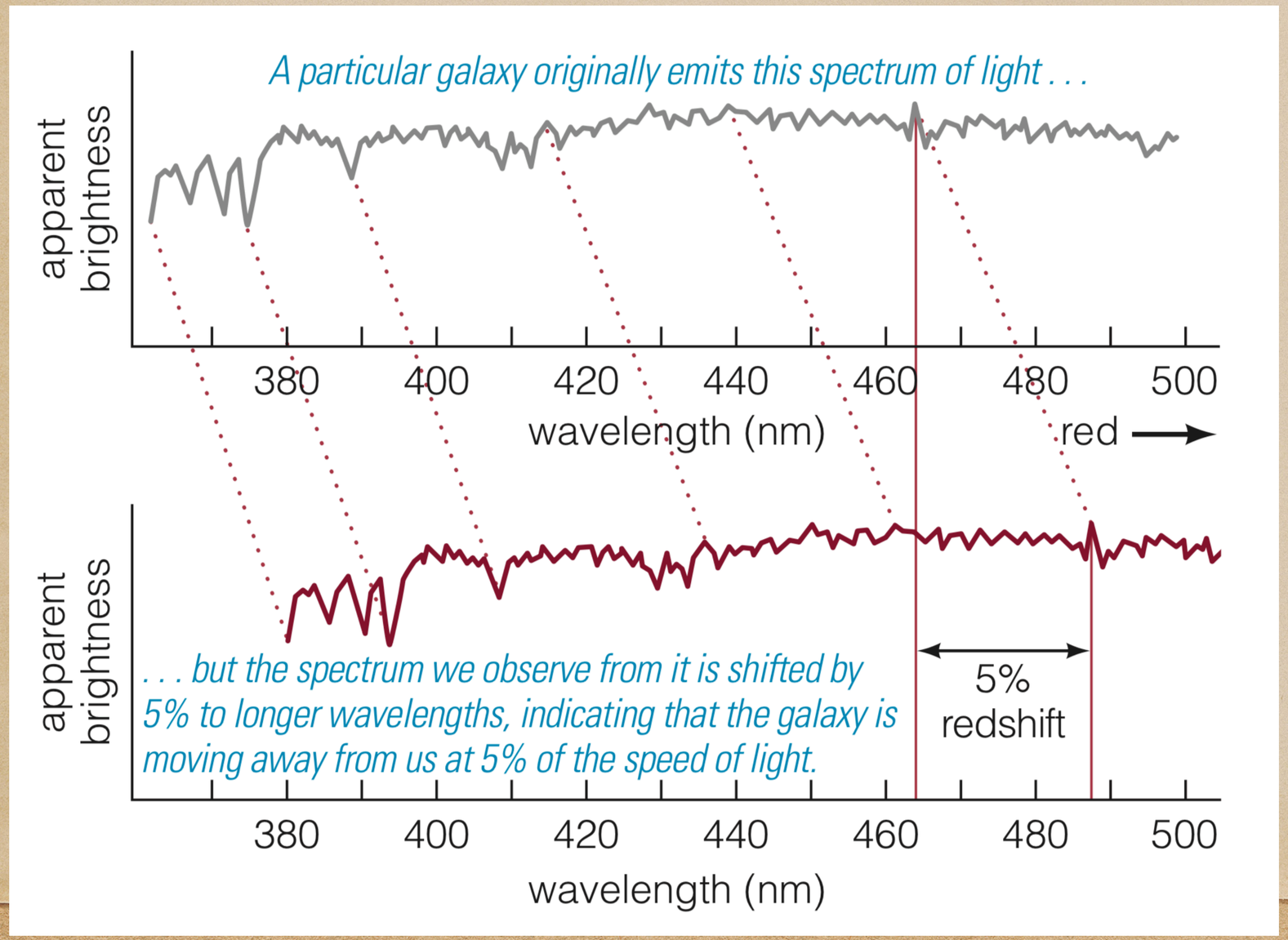
$$\lambda_o = \sqrt{\frac{1+v/c}{1-v/c}}\lambda \qquad [1]$$

If v<< c:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_o - \lambda}{\lambda} = \frac{\nu_e - \nu_o}{\nu_o} \equiv z = \sqrt{\frac{1+v/c}{1-v/c}} - 1 \simeq \frac{v}{c} \qquad [2]$$

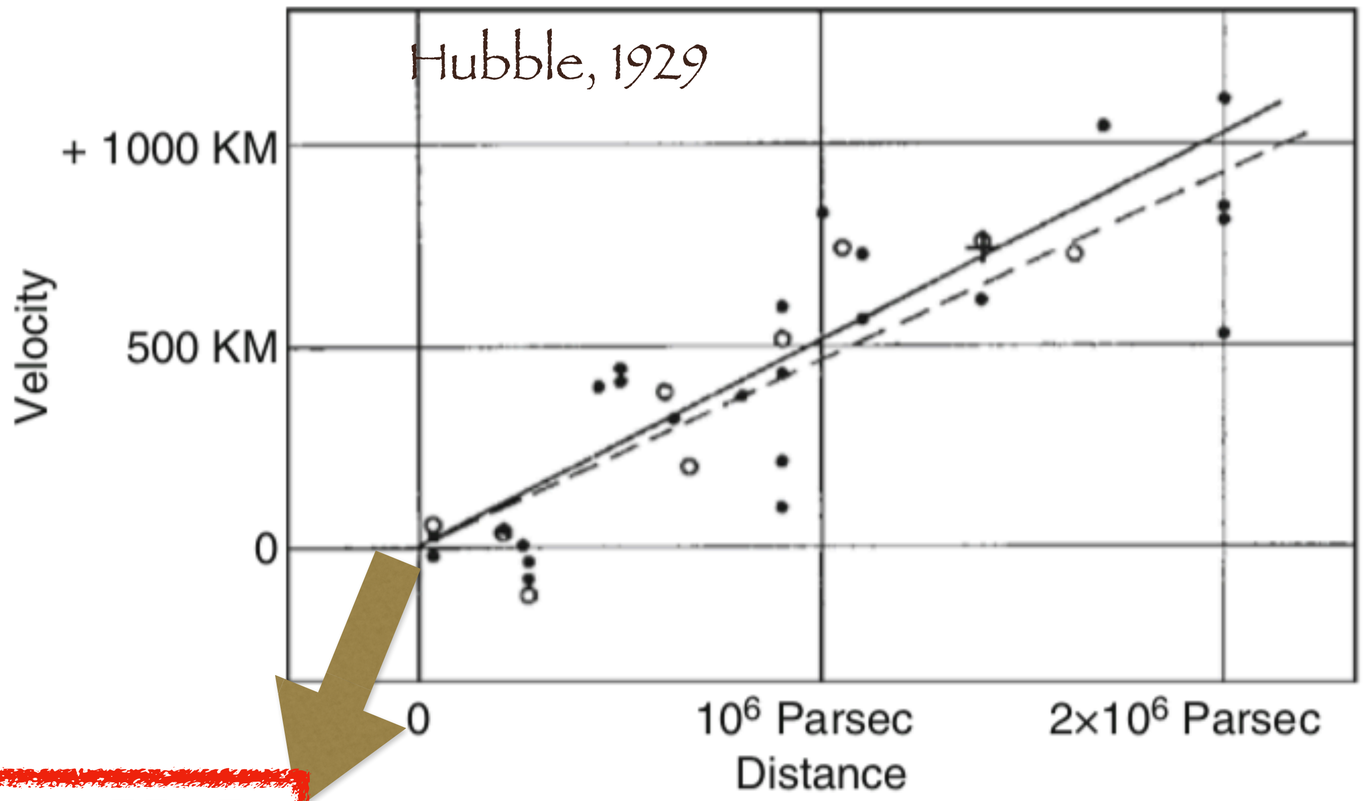
H0 is the so called Hubble constant, usually expressed in units go Km/sec/Mpc

Redshift



$$\Delta\lambda/\lambda = z = 0.05$$

$$v = z \cdot c = 0.05 \cdot c$$



The original version of the Hubble diagram shows the radial velocity of galaxies as a function of their distance. While the radial velocity is easily measured by Doppler displacement of spectral lines, accurate determination of distances is much more difficult.

$$v = H_0 D$$

$$H_0 = (71 \pm 4)\,\mathrm{km\,s^{-1}Mpc^{-1}}$$

H_0 Hubble constant

Hubble had considerably underestimated the distances, thus obtaining too high a value for the Hubble constant. Only very few very close galaxies show a blueshift, that is, they move towards us; one of these is Andromeda (M31).

Historical note: Lemaitre



Already in 1927, 2 years before Hubble, the Belgian priest Georges Lemaitre published the discovery of the distance-speed relationship of recession, therefore the expansion of the Universe

He put together the distances calculated and published by Hubble with the recession speeds published by Slipher
Unfortunately he published the result in a little-known magazine in French, and the result then went unnoticed (even to Hubble, who published his law without knowing about Lemaitre's publication)

In 2018 in Vienna, after almost a century, the International Astronomical Union voted to change the name of the law on the expansion of the Universe to:
Hubble-Lemaitre's law



$$z := \frac{\lambda_{\rm obs} - \lambda_0}{\lambda_0}\,, \quad \lambda_{\rm obs} = (1+z)\lambda_0$$

Definition of redshift

For small redshift z<<1

$$v \approx zc$$

I use the Hubble law

$$v = H_0 D$$

$$D \approx \frac{zc}{H_0} \approx 3000\, z\, h^{-1}\mathrm{Mpc}$$

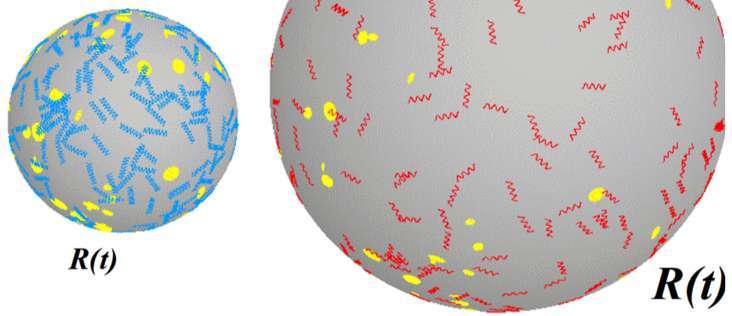
$$H_0 = h\, 100\, \mathrm{km\,s^{-1}Mpc^{-1}}$$

Parameterize our "ignorance" on H_0

Dimensions of the Universe are proportional to a function of time R(t): the scale factor

del

solo tempo ***R(t)*** (fattore di scala)



$$\frac{r_1(t_2)}{r_1(t_1)} = \frac{r_2(t_2)}{r_2(t_1)} = \ldots\ldots \frac{r_n(t_2)}{r_n(t_1)} = \alpha = \cos t \qquad [6.0]$$

If the expansion is uniform, the quantity alpha does not depend on the position (but it could depend on time). The recession velocity from the origin of galaxy 1 is then:

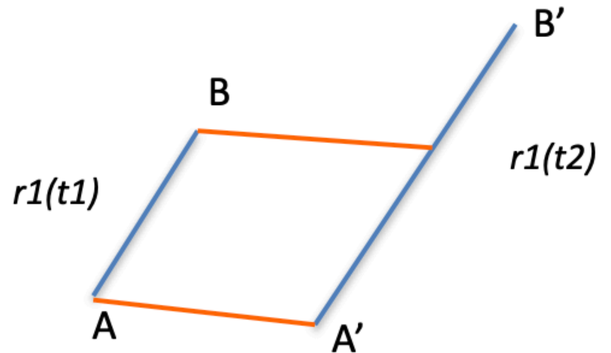
$$\mathrm{v}_1 = \frac{r_1(t_2) - r_1(t_1)}{t_2 - t_1} = \frac{r_1(t_1)}{t_2 - t_1}\left[\frac{r_1(t_2)}{r_1(t_1)} - 1\right] = \frac{r_1(t_1)}{t_2 - t_1}[\alpha - 1] = H_0 r_1(t_1)$$

Having set in H0 all the constants that do not depend on the position. The is valid for any point, we can thus write:

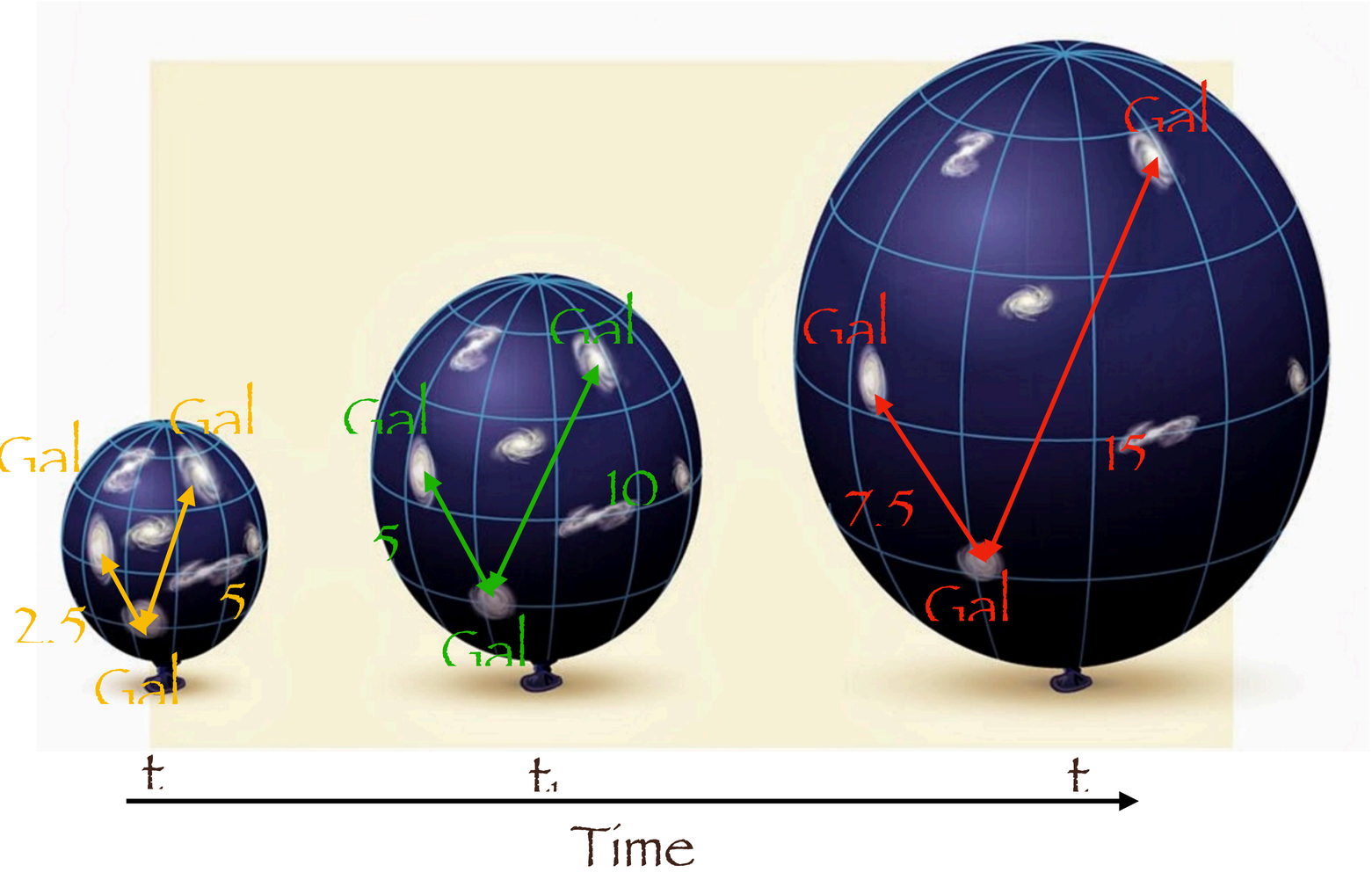
$$\mathrm{v}_n = \frac{r_n(t_1)}{t_2 - t_1}[\alpha - 1] = H_0 r_n(t_1).$$

A uniform expansion turns automatically into a velocity-distance relation:

$$\mathrm{v} \propto r\,.$$



Expansion of the Universe: Hubble's law



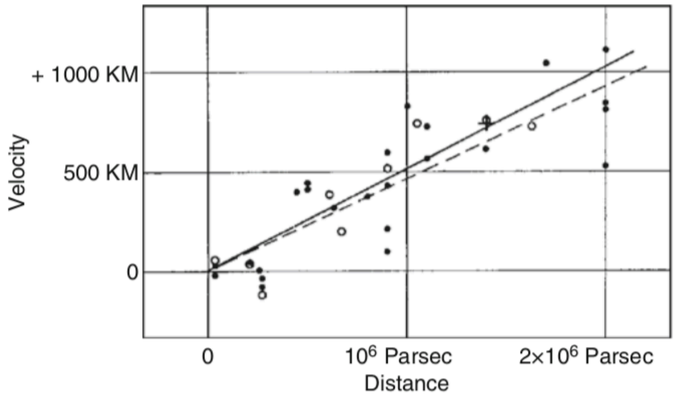
We put ourselves on galaxy 1:

d_{12}=2.5 Mpc

d_{13}=5 Mpc

v_2=2.5 Mpc/yr

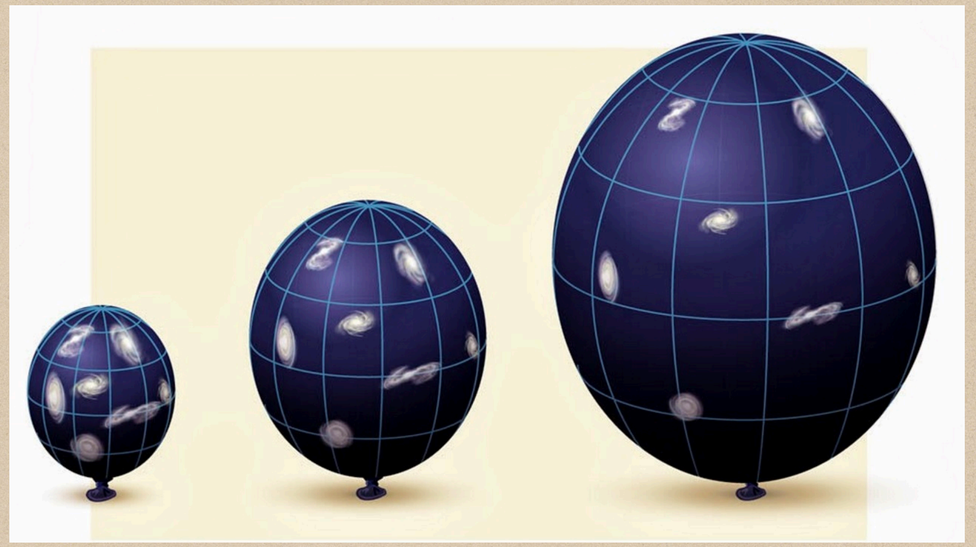
v_3=5 Mpc/yr



Hubble's law implies the expanding Universe

Expansion of the Universe: Hubble's law





Extrapolating the expansion on the contrary...

The Universe, in the past, was smaller; if we go back we meet the

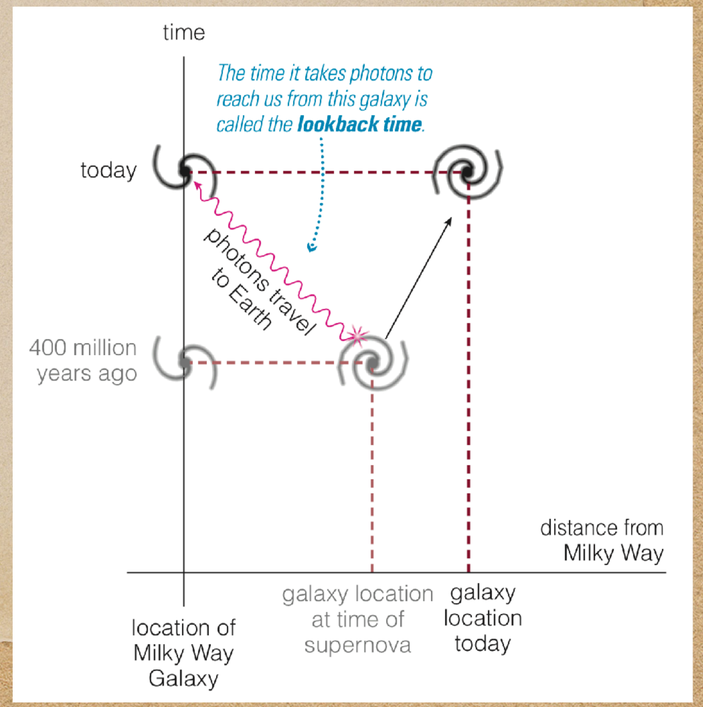
Big Bang

Effect of expansion on the measurement of distances

- The expansion of the Universe leads to a complication in the discussion of distances
- Since the speed of light is finite, the light coming from a supernova in a distant galaxy will take a significant amount of time to reach us
- This implies that from the moment the light of the supernova started, the galaxy moved, so the distance the light traveled does not directly indicate to me how far it is from us

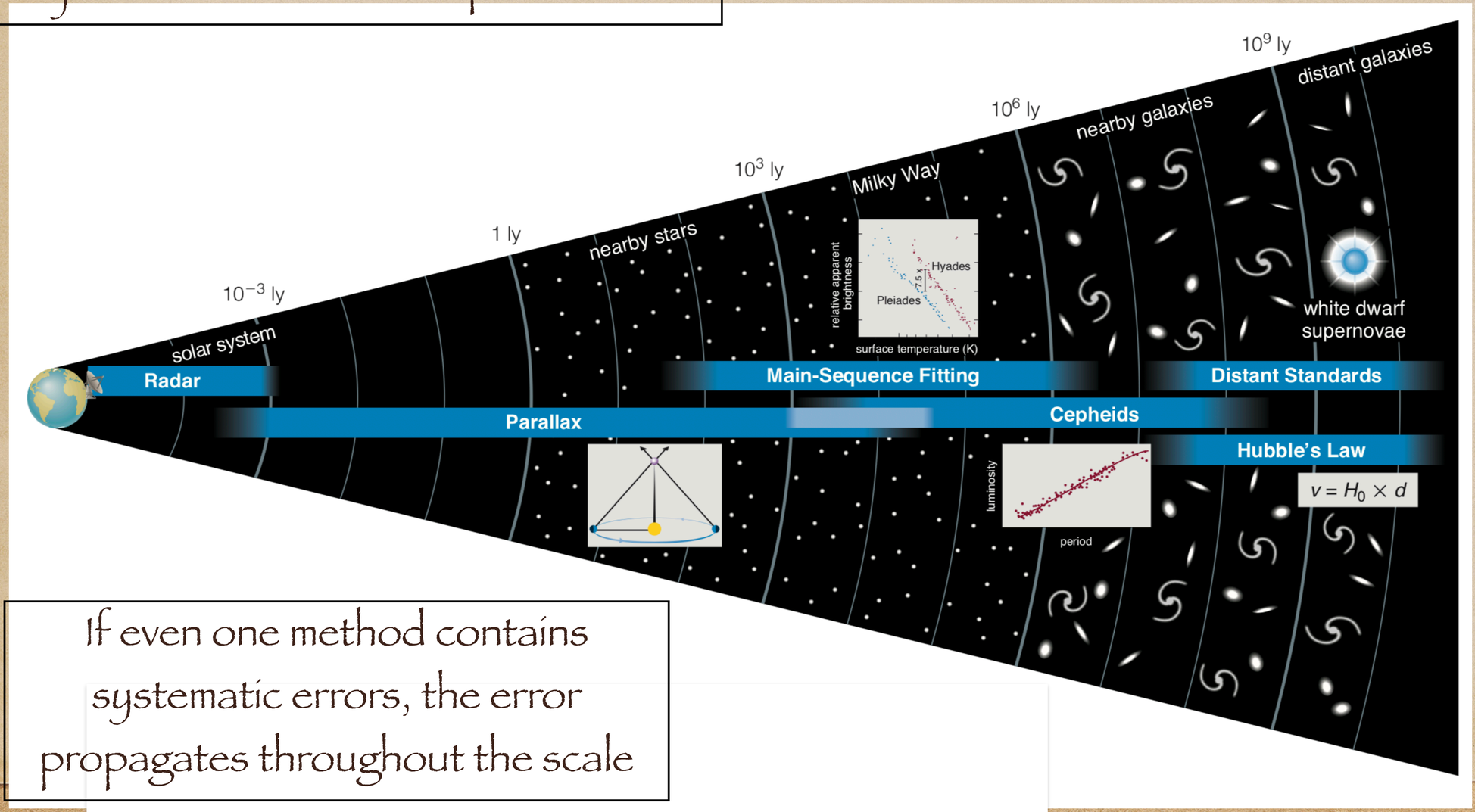
- (It is also understood that the concept of present in cosmology is very empty: it makes no sense to ask where the galaxy is now of which we only now receive the light)

- This reasoning also implies, among other things, that by seeing distant galaxies we are seeing them as they were in the past; the further we look, the more we see them back in time: this is very convenient in the study of the evolution of galaxies because by studying galaxies at different distances from us I can see them in different phases of their evolution



Distance scale summary

- The distance scale is a chain of methods
- Each one works at longer distances
- "Adjacent" methods overlap



If even one method contains systematic errors, the error propagates throughout the scale