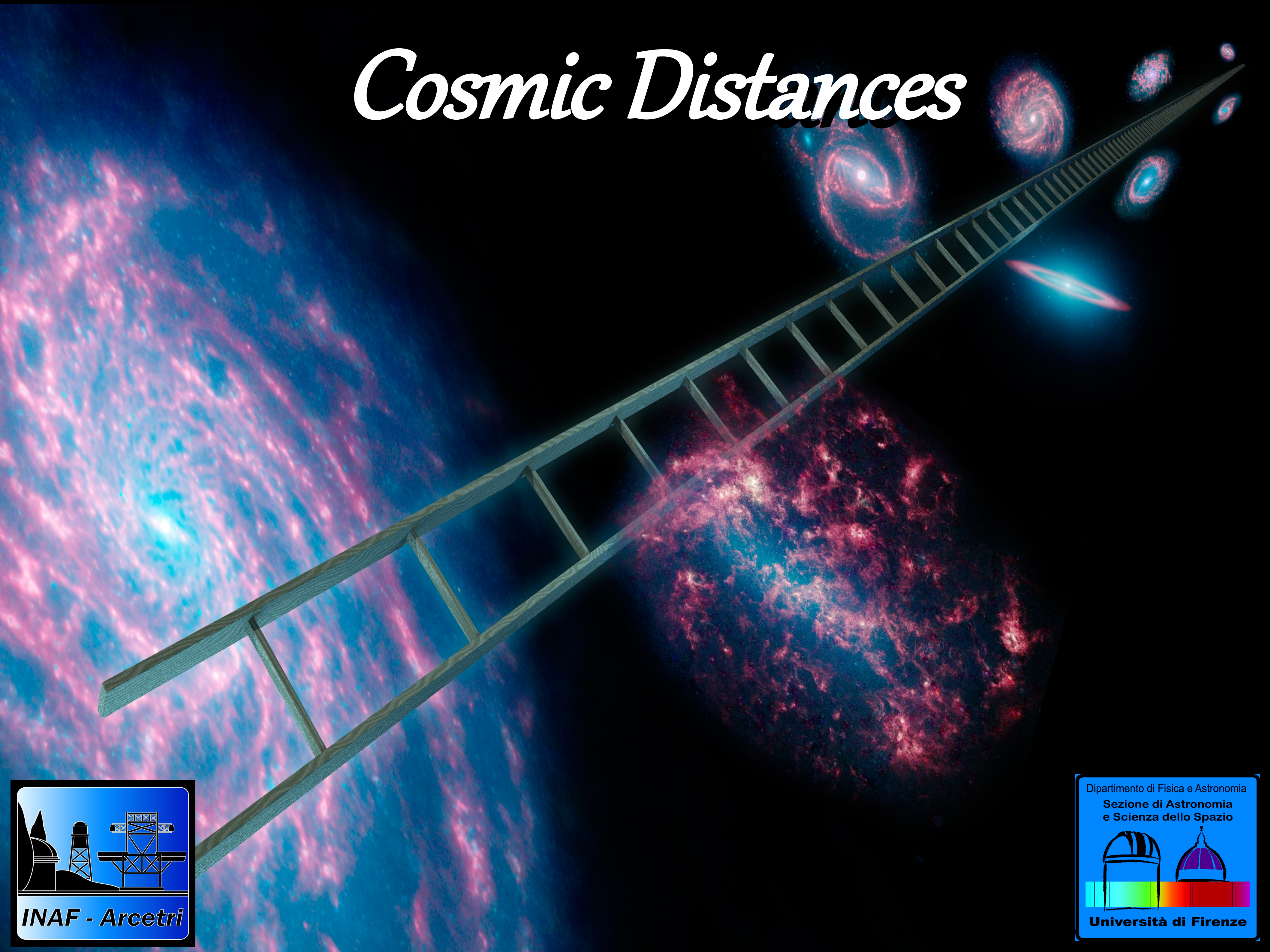
Cosmic Distances



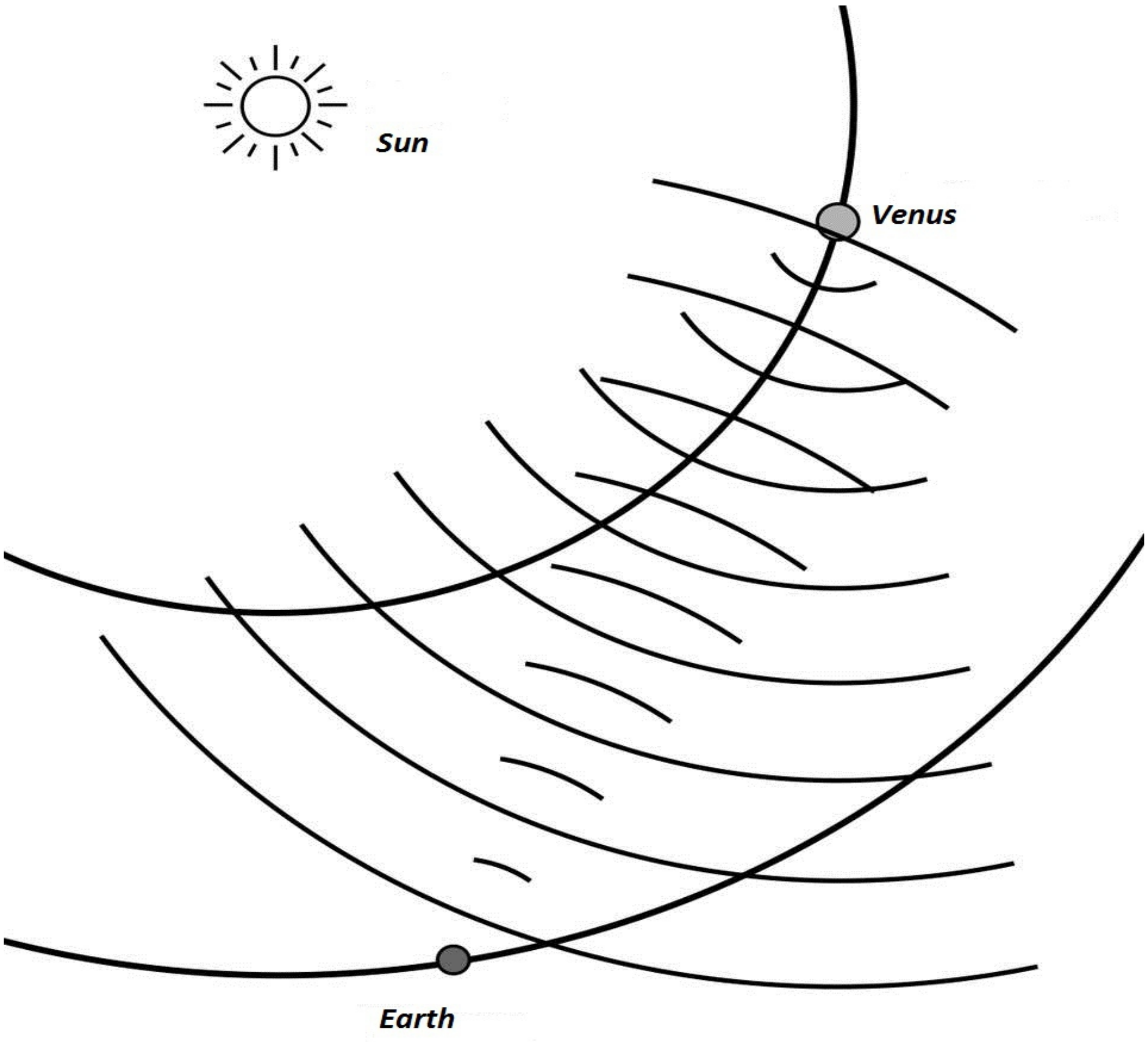
INAF - Arcetri

Dipartimento di Fisica e Astronomia
Sezione di Astronomia e Scienza dello Spazio
Università di Firenze

The Cosmic Distance Scale

It's the set of methods used to determine the distances to objects in the Universe.

Radar Ranging



It is based on the measurement of the round-trip time ("t") of a powerful radio signal (with speed "v") that is reflected on the atmosphere of Venus

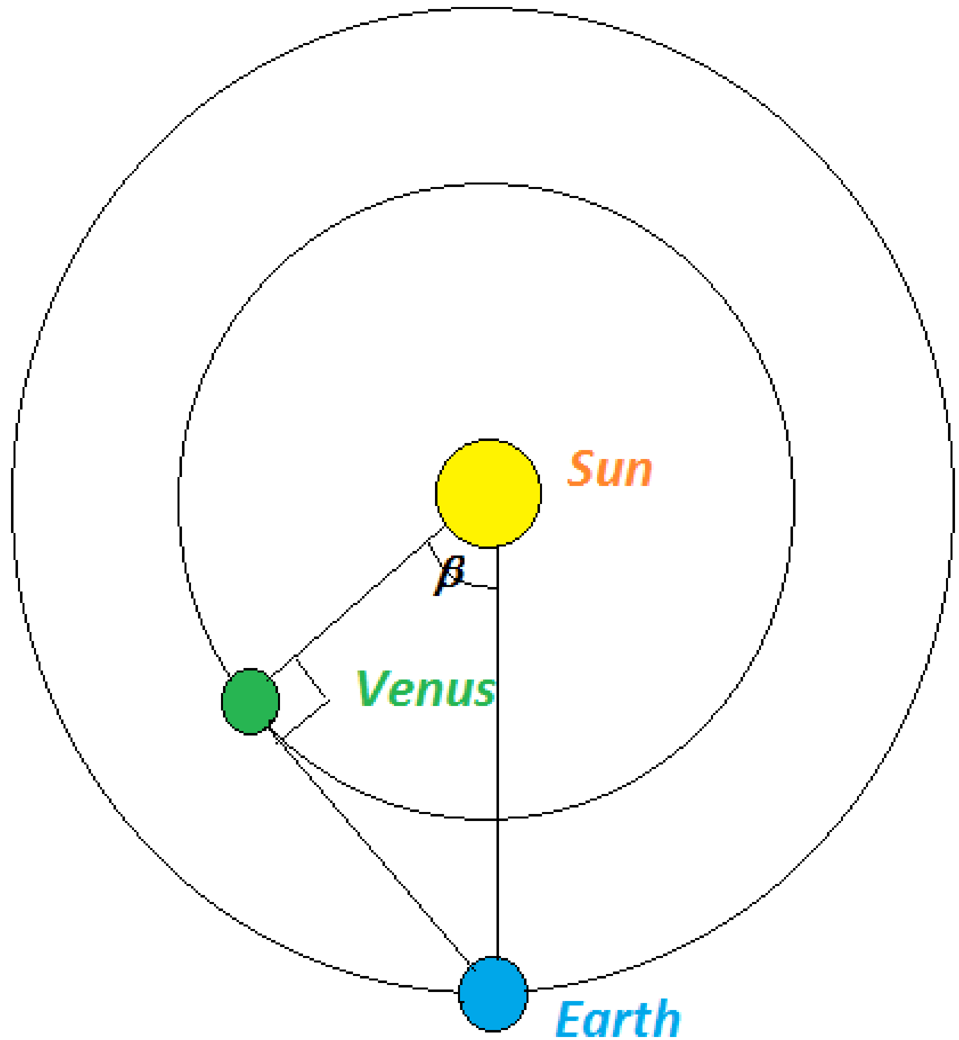
$$D_{E\text{-}V} = v\,(t/2) =$$
$$= 42 \times 10^{6}\ \text{km (average)}$$

Using this method we can obtain the value of Astronomical Unit

Astronomical Unit is the average Earth-Sun distance

Since D_{E-V} is known, so it's possible to determine the distance Earth - Sun trigonometrically

The maximum apparent distance of Venus from the Sun (as seen from Earth) varies between 45° and 48 °.
For simplicity, we take an average value between these : 46 °



$$D_{S-V}/D_{S-E} = \sin 46° = 0{,}72$$
$$D_{S-V} = 0{,}72\ D_{S-E}$$

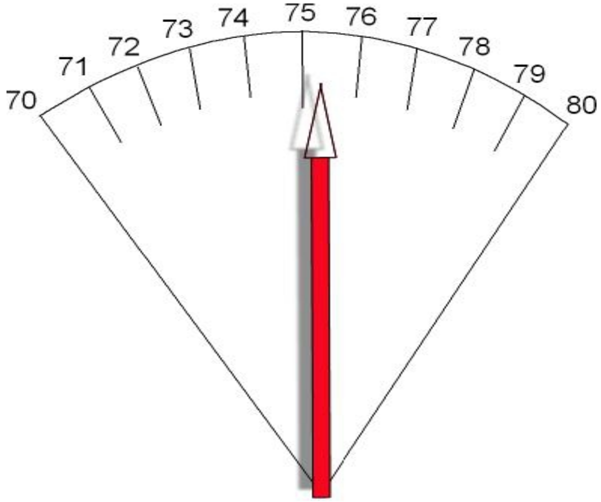
$D_{S-E} = 1\ AU$ $D_{S-V} = 0{,}72\ AU$ $D_{E-V} = 0{,}28\ AU$

$$\mathbf{1\ AU} = D_{E-V} / 0{,}28 = \mathbf{1{,}5 \times 10^8\ km}$$

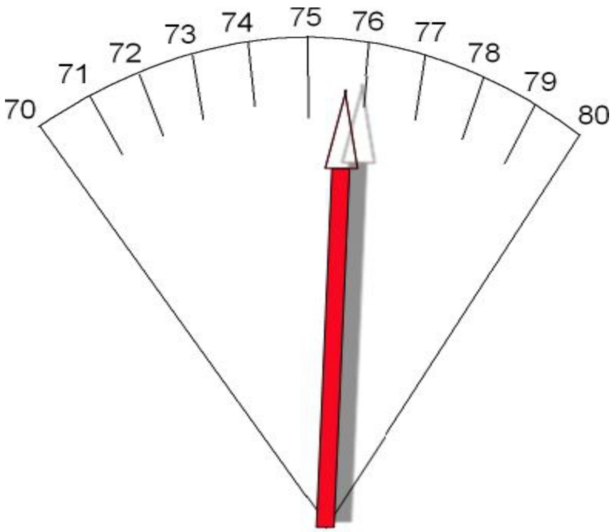
Parallax

When we want to determine the weight with a scale, we may note that the needle varies position each time we move our head: if we move it

to the right, we will project the needle to the left



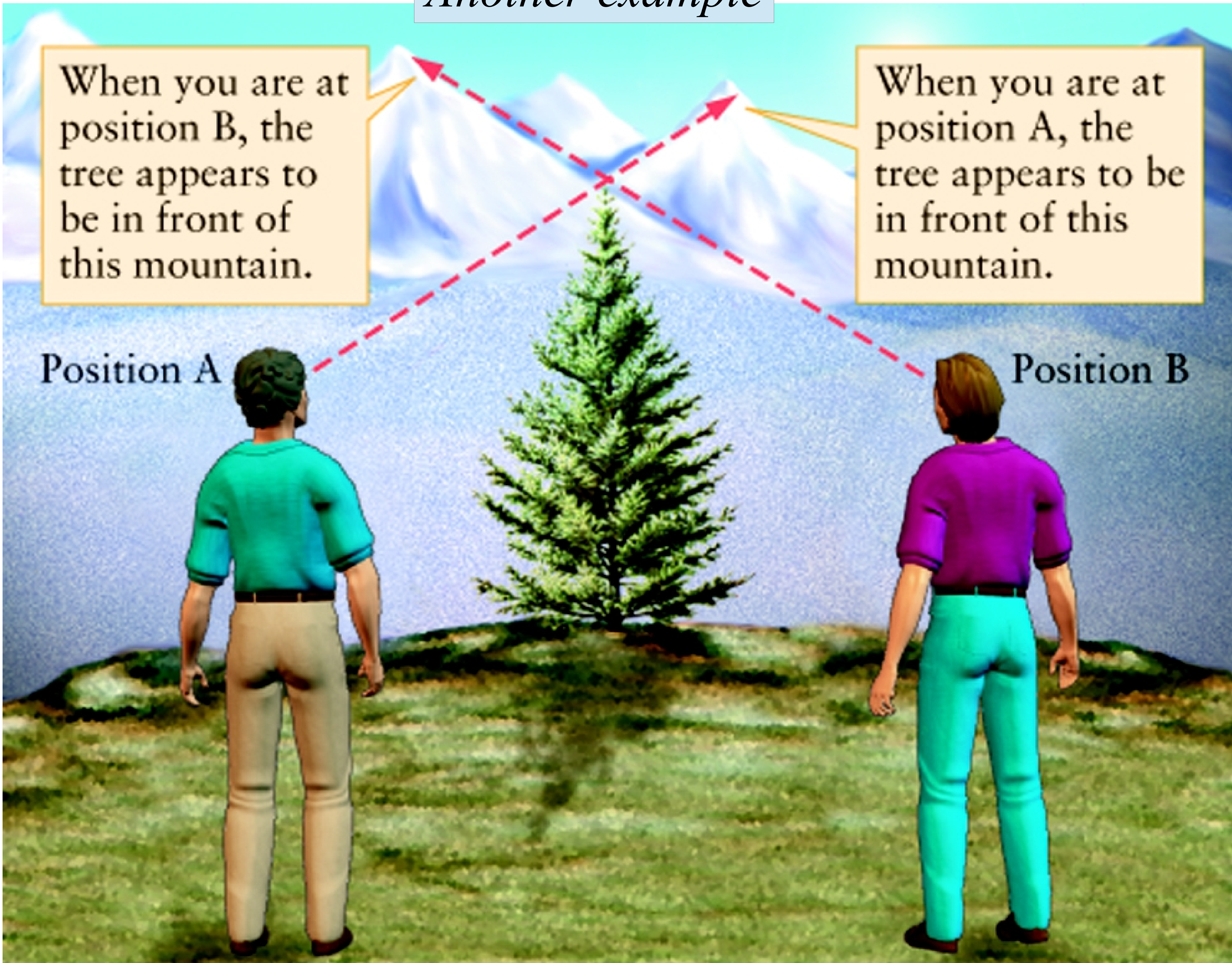
to the left, we will see the needle projected to the right.



The shift of the object is only ***apparent*** *and it is caused by a change of the position of the observer.*

This effect is called PARALLAX

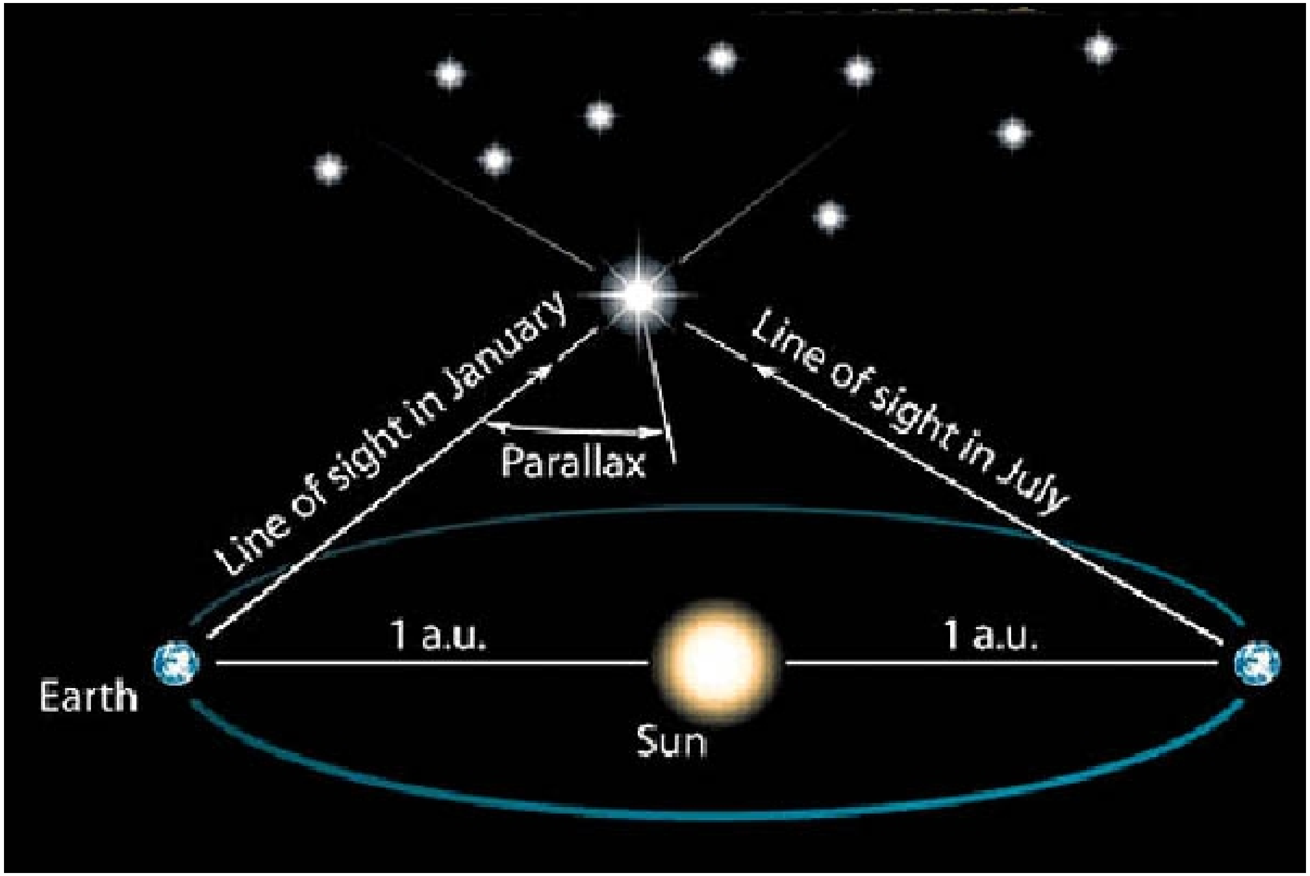
Another example



The stars have a parallax effect, annual parallax, caused by the motion of the Earth around the Sun.

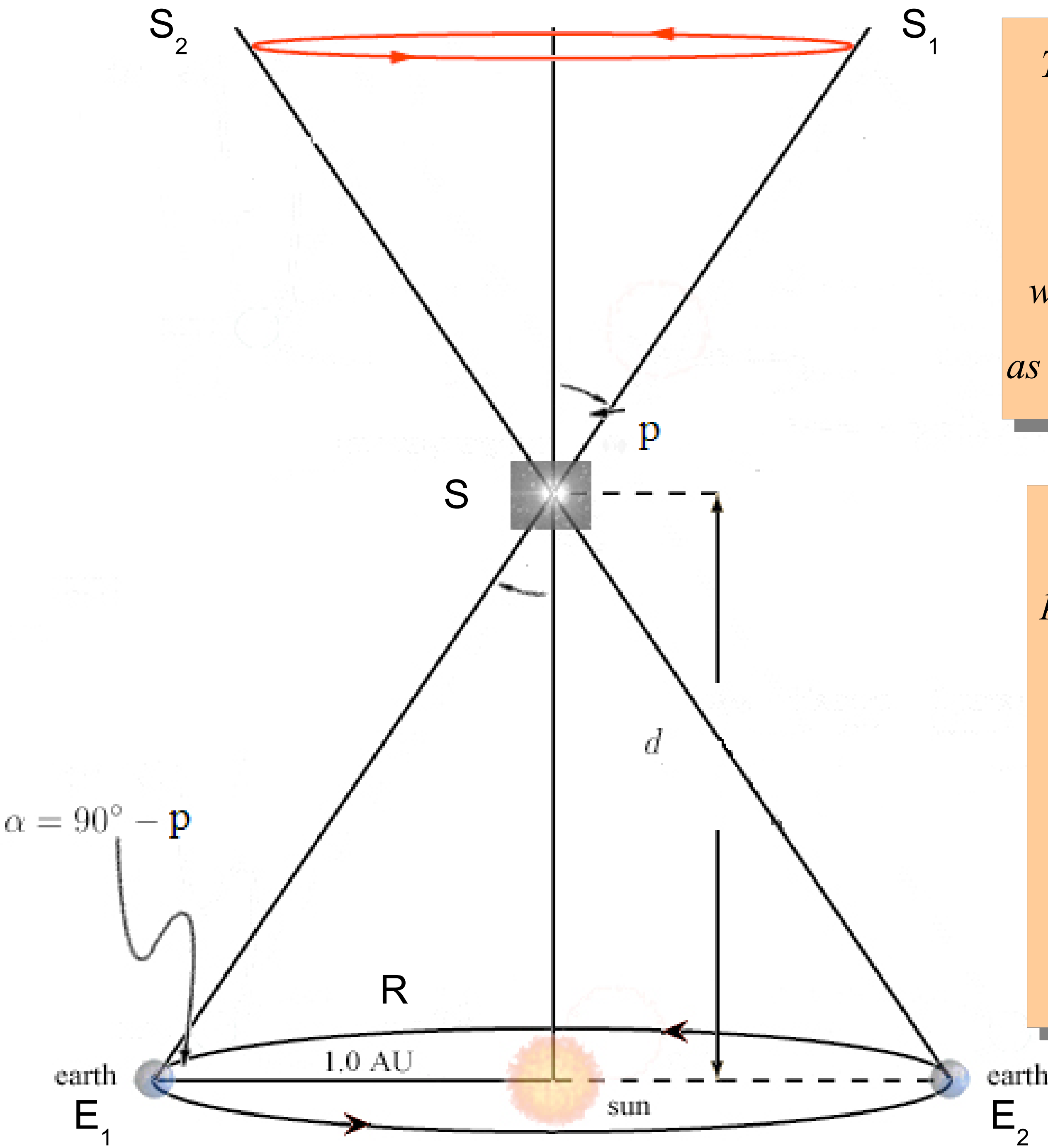
The Earth revolves around the Sun drawing an ellipse whose major axis is about 300 million km.

The position, from which we observe the sky, changes over the course of the year.



Let us fix the position of a star and let repeat the observation from the same place on Earth after six months when the Earth is in the opposite point in the orbit around the Sun, we will note a small change in the star's position.

In the course of a year, a star describes a small ellipse in the sky.



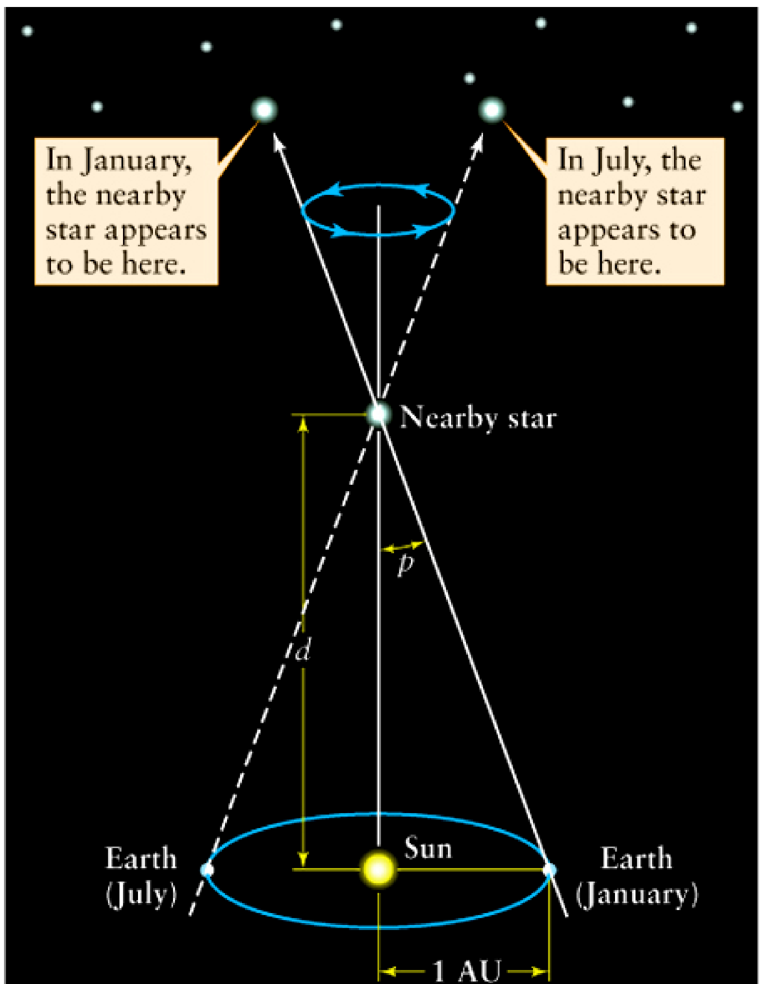
The parallax method is a method similar to the triangulation. In fact, if we join the point E_1 with S_1 and S_2 with E_2, we define a triangle, which the major axis as base and the distances S-E_1 S-E_2 as sides.

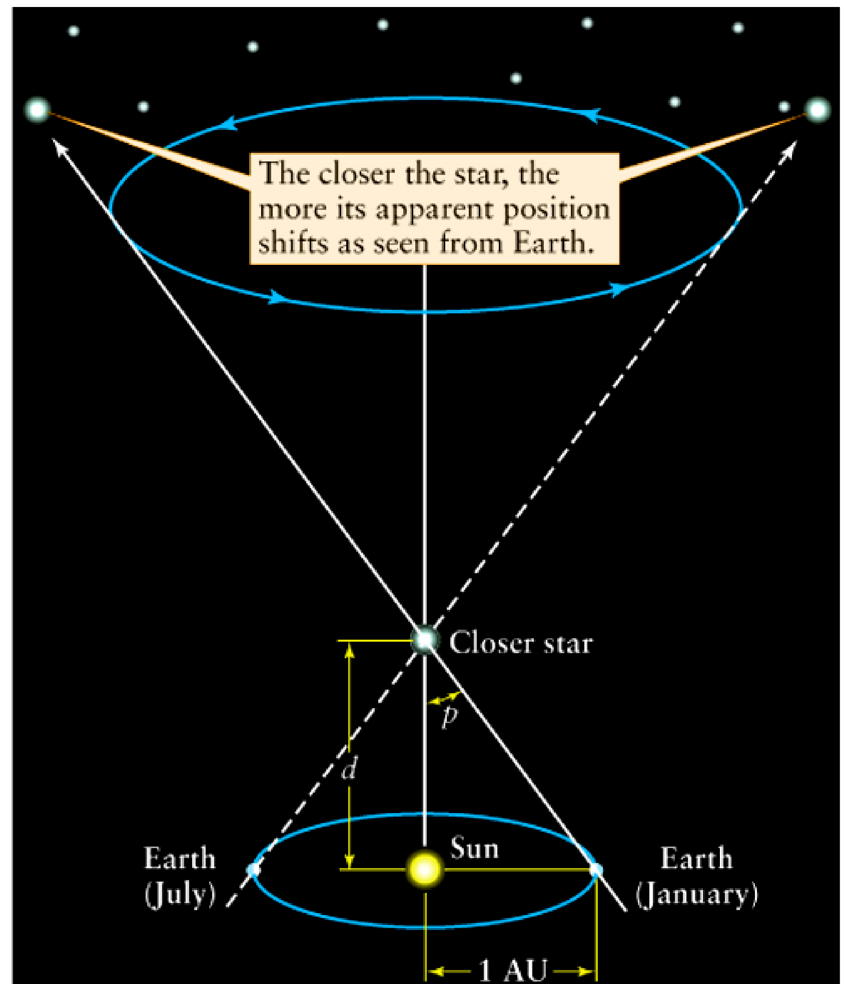
By convention, the angle of the annual parallax (p) is equal to half the apparent angular shif of a star in 1 year, and corresponds to the vertex of the triangle which is based on the semi-axis of Earth's orbit around the Sun (R = 150000000 km) and has vertex the star.

The parallax of a star decreases with distance and it has always very small values.

The nearest stars to Earth have a value of the parallax a little less than 1 second of arc.

As the distance increases, the measurement of the parallax angle becomes more difficult, as the annual change in position decreases significantly. For this reason the more distant stars maintain a fixed position and do not exhibit apparent shifts.





To derive the distance to a star directly from the value of the parallax, it is convenient to adopt a particular unit of measurement: parsec (pc).

1 parsec is the distance at which a body subtend a parallactic angle of 1'' of arc.

If we express the distance in parsecs and assign the value 1 to the distance Sun-Earth = "R", "d" is d=1/p

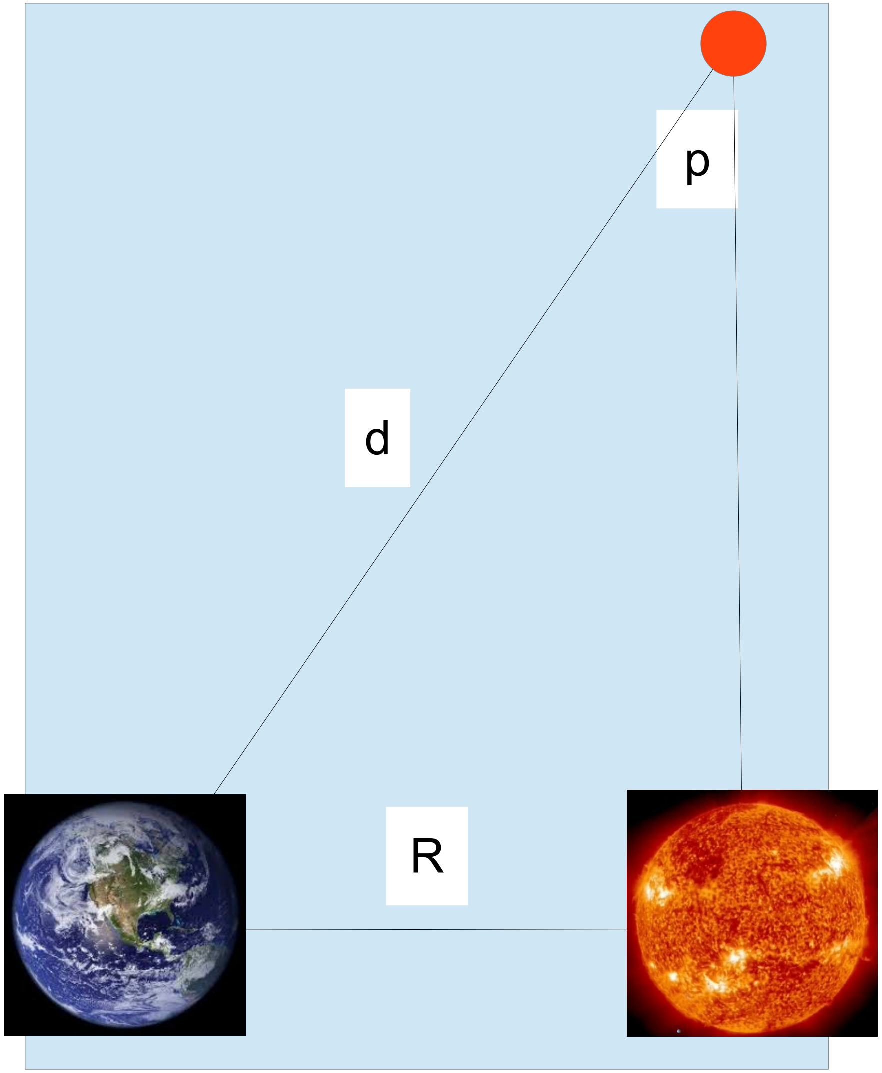
To obtain it we use trigometric ratios :

$$d = R / \sin p = 1 / \sin p$$

Since the angles with which we deal are very small, we use the approximation

$$\sin p \sim p$$

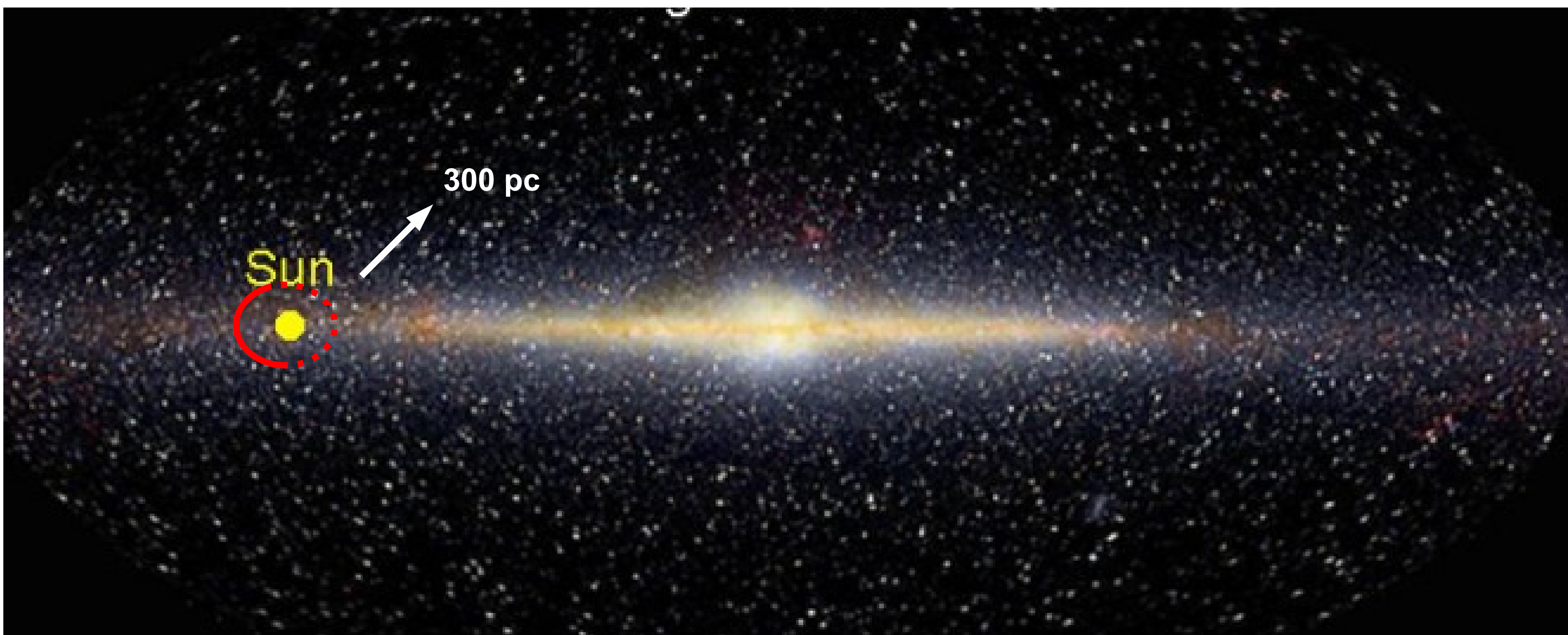
d (pc) = 1/p



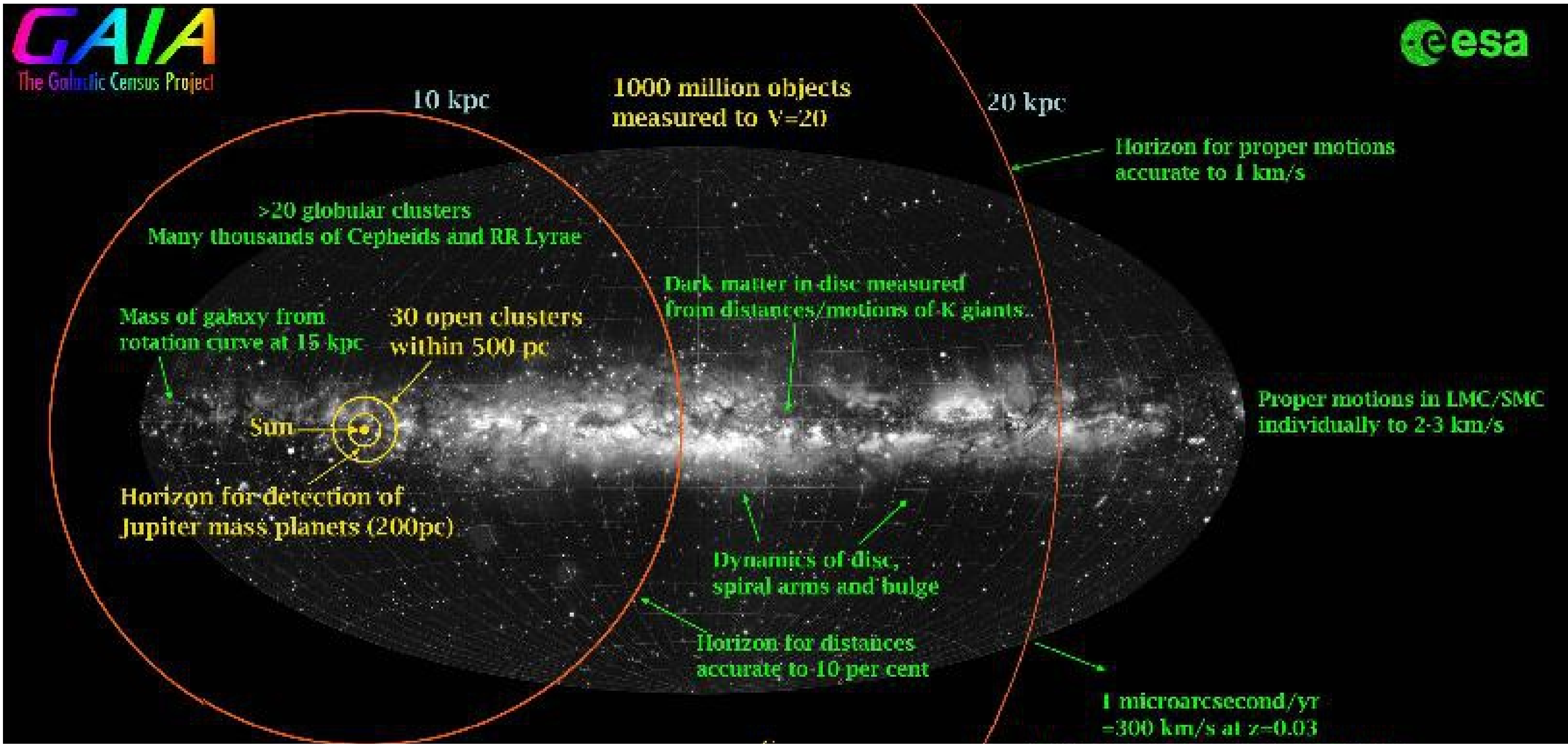
By studying the annual shifts in the positions of the stars, we are able to measure parallaxes corresponding to a maximum distance of 50 pc.

The measurement of parallax seems very easy, but in reality it is necessary to use tools that reach accuracies much greater than those of a "normal" telescope, that does not reach the required accuracy.

With the Spacecraft Hypparcos we can measure parallaxes up to 300 pc.

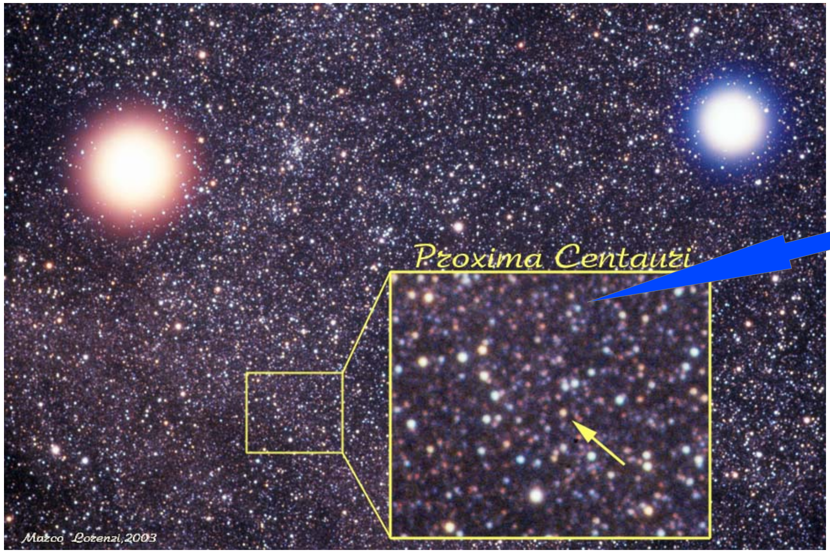


By the end of 2013 the Spacecraft Gaia will be launched and it will be able to measure parallaxes up to 10000 parsec

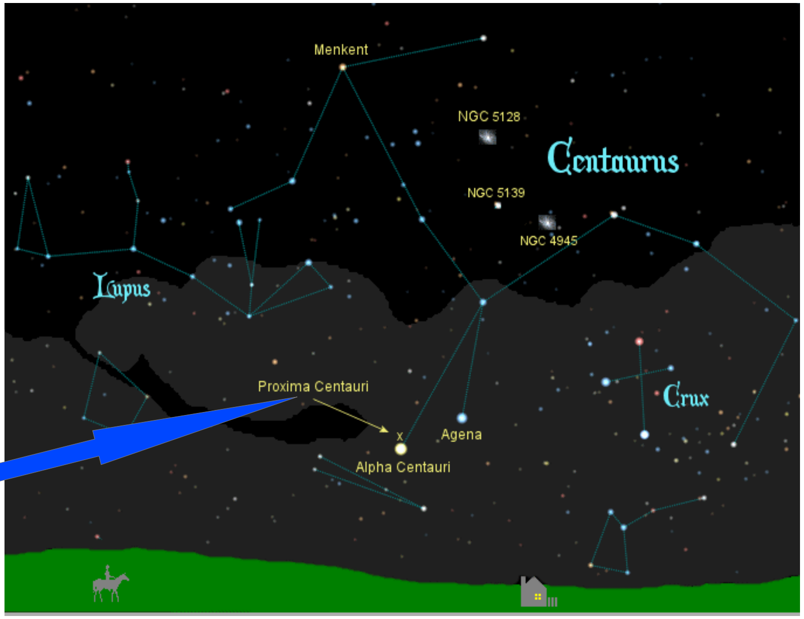


Exercises

Proxima Centauri

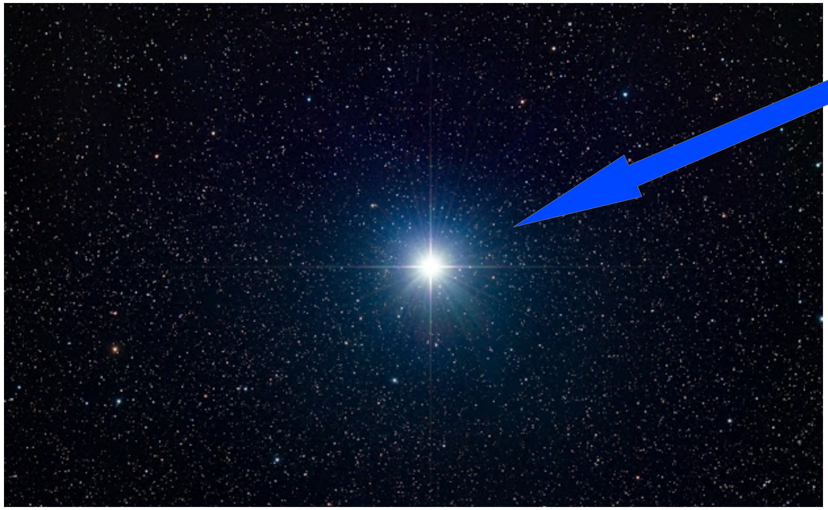


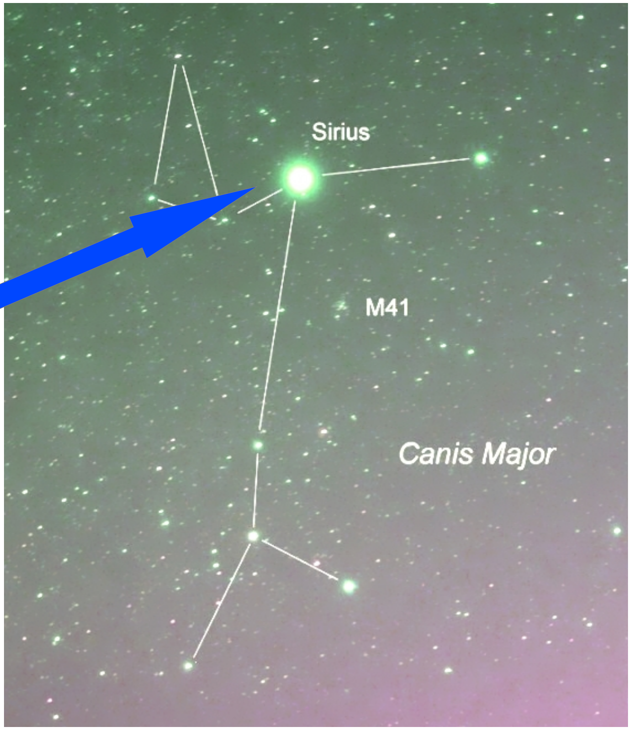
Proxima Centauri is the nearest star to the SolarSystem. It has a parallax of 0,775"; so its distance is 1 /0,775 = 1,295 pc



Sirius

Sirius is the brightest star in the night sky. It has a parallax of 0,380”; so its distance is 1/0,380 = 2,632 parsec





Unit of Measurament

Conversion Factors

Astronomical Unit (au): average Earth-Sun distance (149 600 000 km)

Parsec (pc): the distance from the Sun to an astronomical object which has a parallax angle of one arcsecond (1/3,600 of a degree).

Light Year (l.y.): the distance that light travels in a vacuum in one year with a speed of ~ 300 000 km/s

1 au ≈ 4.85×10^{-6} pc ≈ 15.81×10^{-6} ly

1 light-year ≈ $63{,}24\text{x}10^{3}$ au ≈ 0,31 pc

1 parsec ≈ $20{,}62\text{x}10^{4}$ au ≈ 3,26 ly

CAUTION!

LIGHT YEAR is NOT a unit of measurament of time.

It is correct to say that the image of celestial body, which is far a certain number of light years, shows us that celestial body as it was the same number of years ago, and not at this time.

The distance Earth - Andromeda is 2 million ly, so if an observer could see the Earth from Andromeda, he would see the Earth today as it was 2 million years ago.

Main – Sequence Fitting

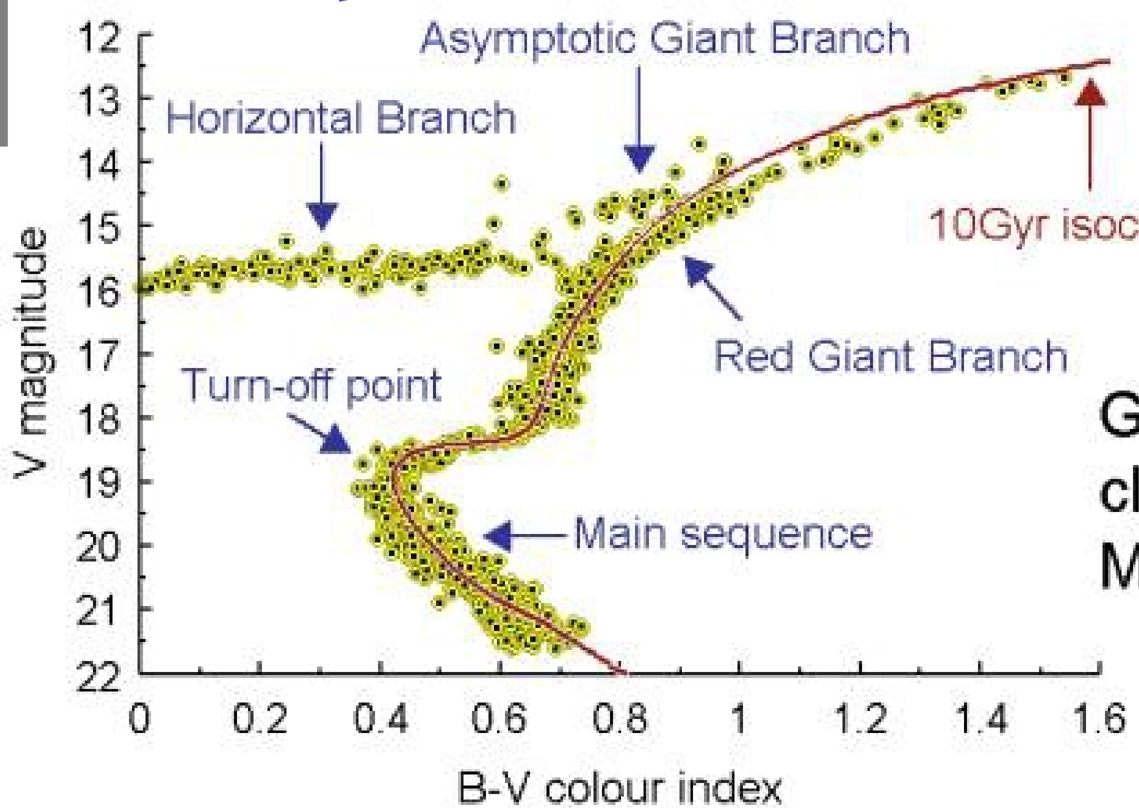
Both the temperature and the brightness of a star can be derived from the analysis of its spectrum.

*The knowledge of these parameters allows us to locate a star in the HR diagram and then to derive the absolute magnitude (**M**).*

*Knowing **M** and the apparent magnitude (**m**) we can obtain the value of the distance **d** :*

$$M - m = 5 - 5 \log d$$

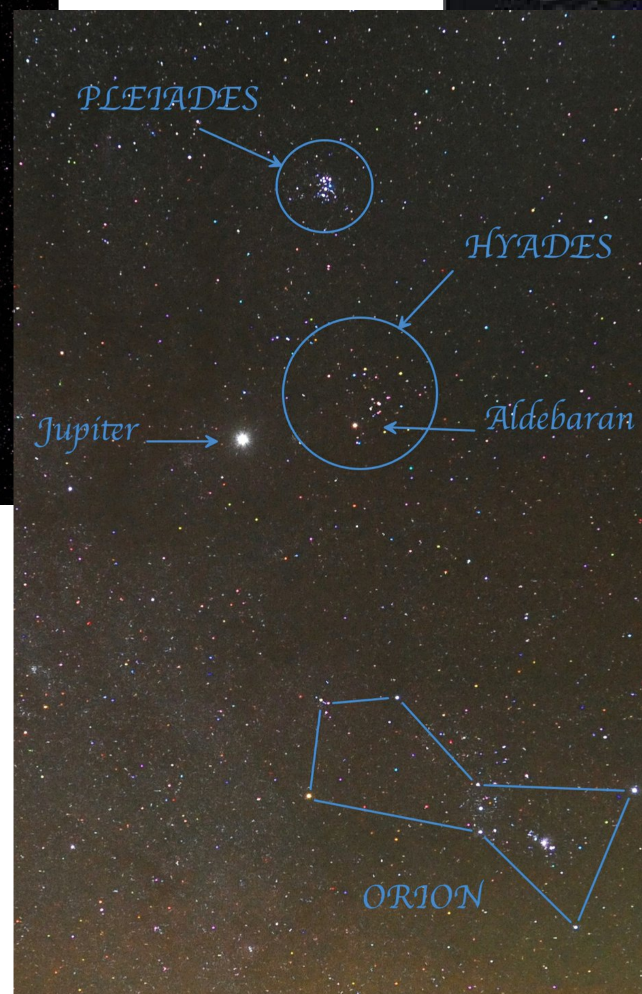
*This method is called **spectroscopic parallax**.*



Globular cluster M3

The determination of spectroscopic parallaxes is particularly useful to determine the distance of the stars that belong to a cluster.

The star clusters are generally far away, so the direct determination of the distance of their individual stars is very uncertain.

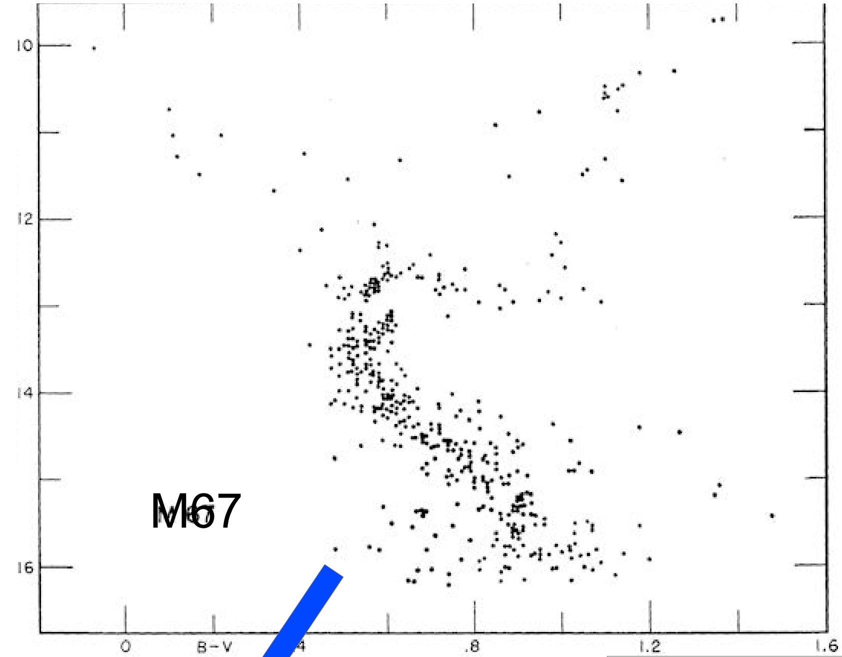


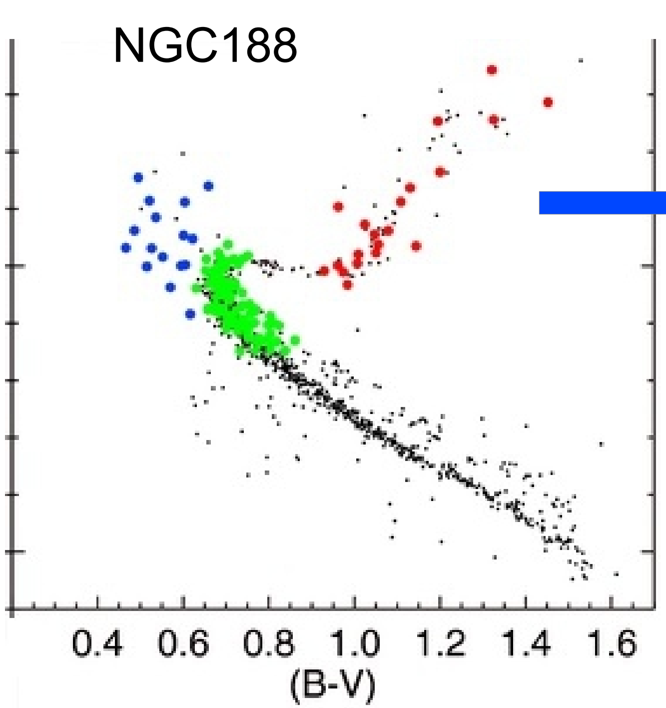
Almost all clusters have a small angular diameter; therefore they are aggregates of stars of modest size compared to the great distance that separates them from us.

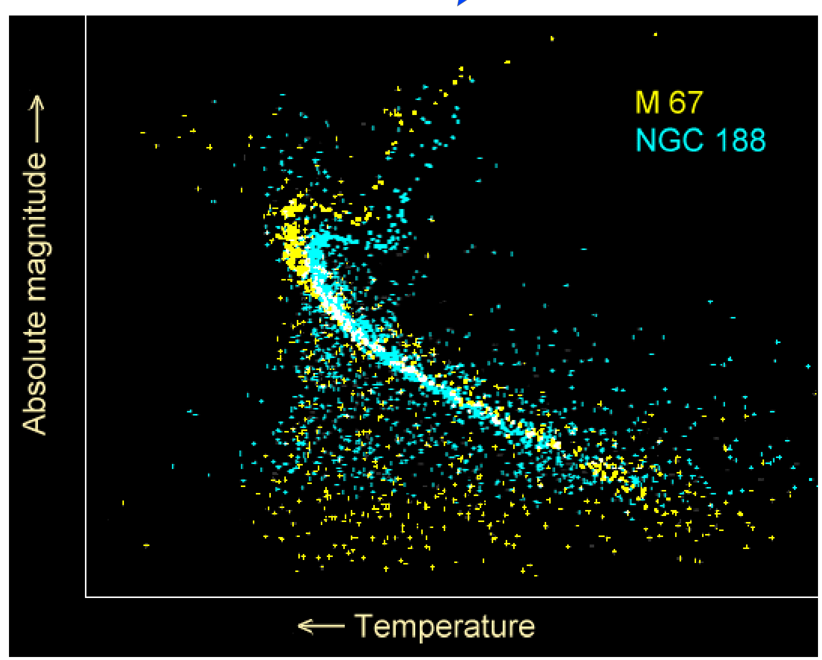
Then we can assume that the member stars are at the same distance from Earth.

Using the apparent magnitudes instead of absolute ones, we can build the HR diagram of the stars in the cluster

The main sequence of the unknown cluster, thus obtained, differs from that of a known cluster for the different scale on the y-axis.

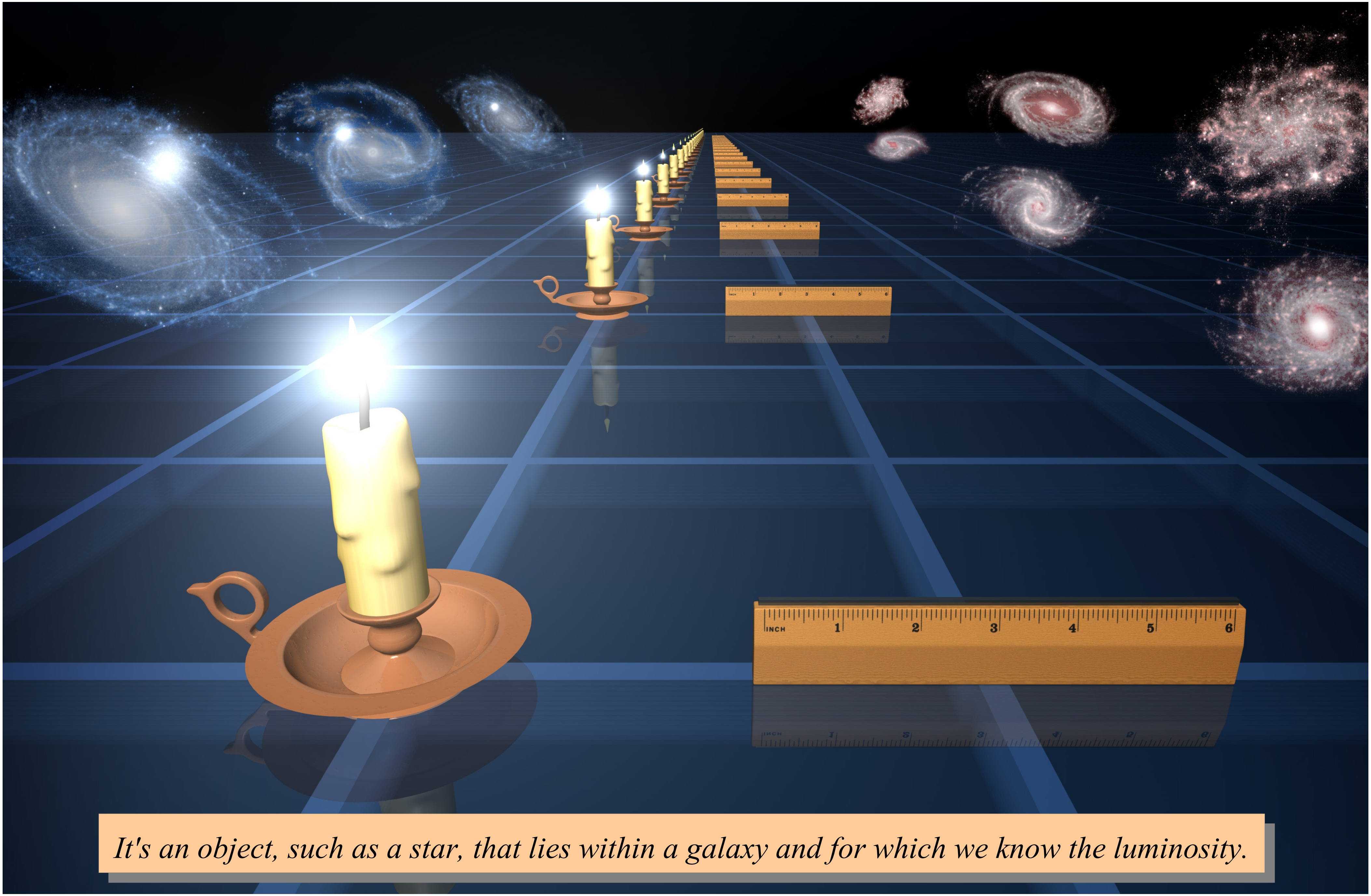






From the traslation that must be introduced in order to obtain the overlap of the two sequences, we can determine the value of the average distance of the stars of the cluster from Earth.

Standard Candle



It's an object, such as a star, that lies within a galaxy and for which we know the luminosity.

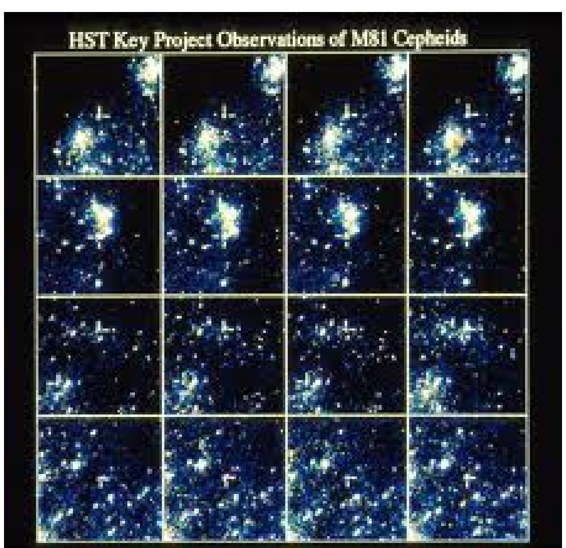
*Comparing the known luminosity with the observed luminosity (apparent magnitude), we can calculate the distance (**d**):* $\boldsymbol{M - m = 5 - 5 \log d}$

To be useful, standard candles should have the following properties:

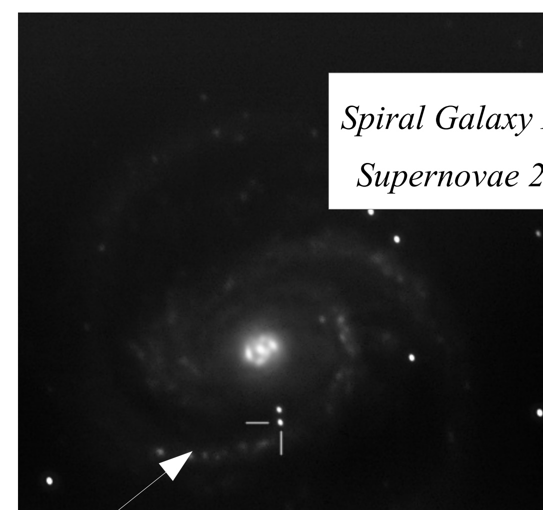
- *They should be luminous, so we can see them out to great distances.*
- *We should be fairly certain about their luminosities.*
- *They should be easily identifiable.*
- *They should be relatively common, so we can use them to determine the distances to many different galaxies*

Type of Standard Candles:

Cepheids



Type Ia Supernovae



Spiral Galaxy M-100
Supernovae 2006X

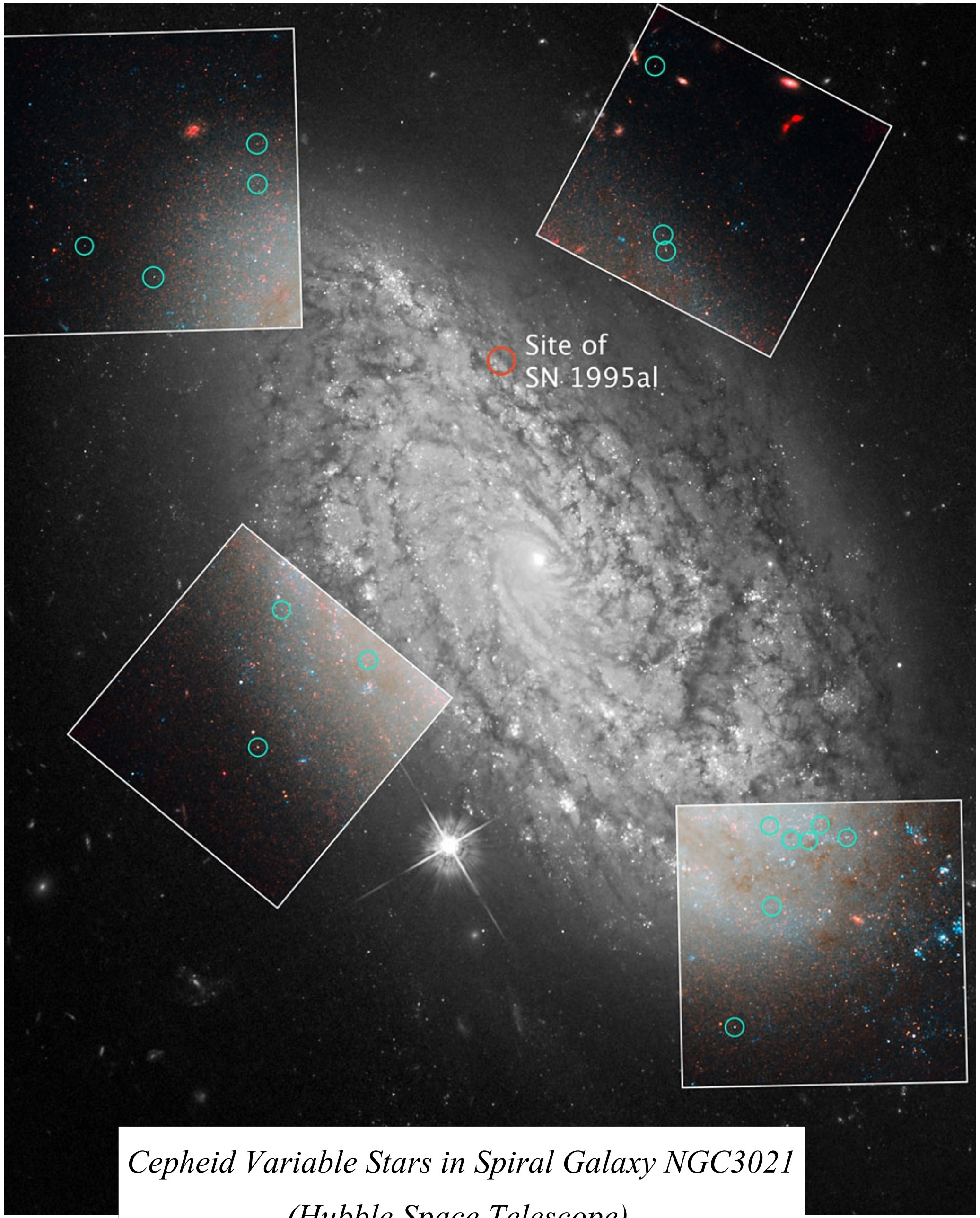
Cepheids

Cepheids are variable stars; stars showing variations of luminosity in the course of their existence.

*The period of pulsation (**P**) is related to the luminosity of the star. The longer is the period, the higher is the luminosity.*

A Cepheid with a three-day period has a brightness equal to 800 times that of the Sun; a Cepheid with a period of thirty days is 10000 times more luminous than the Sun

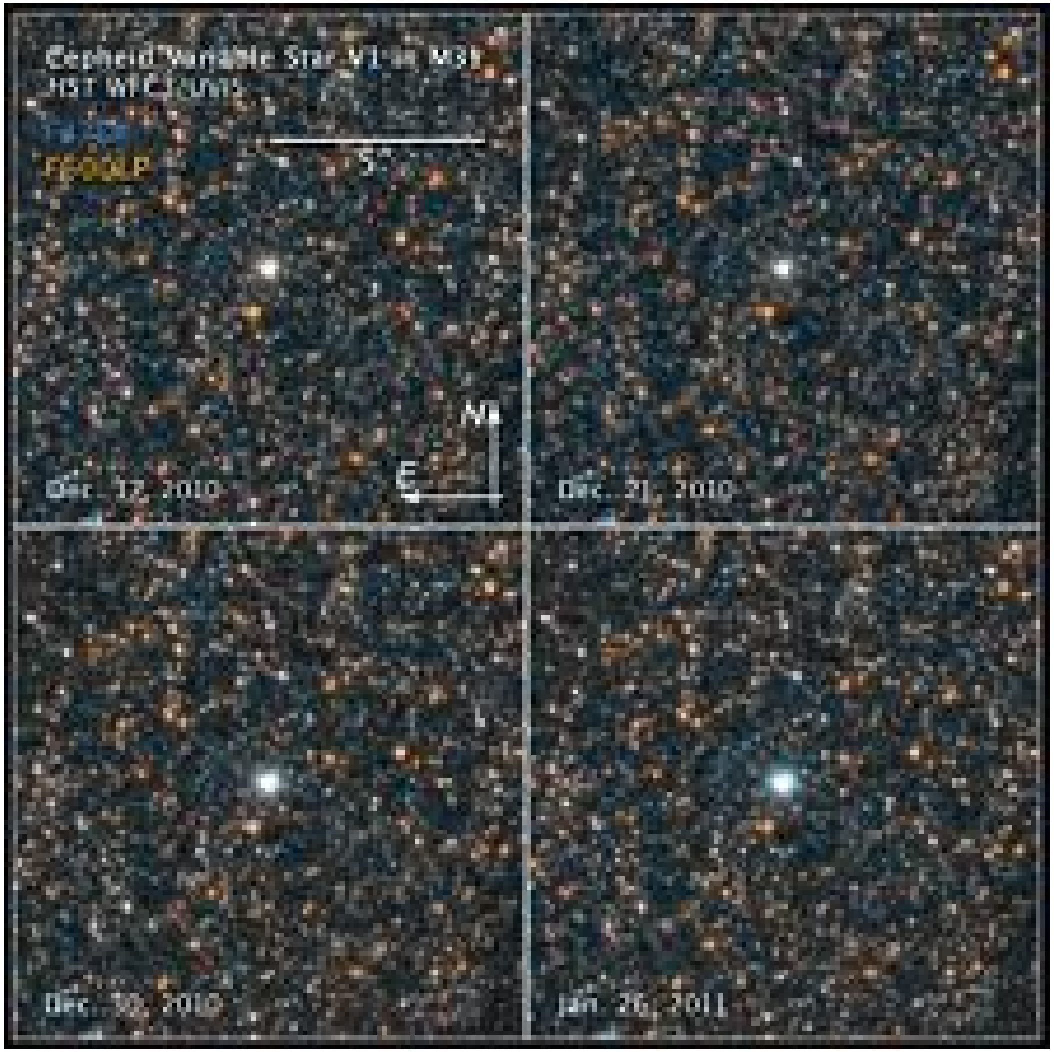
If you analyze the spectrum of a star, you can determine its temperature and its color. From these parameters we derive the luminosity.



Cepheid Variable Stars in Spiral Galaxy NGC3021
(Hubble Space Telescope)

*Through the period – luminosity relation one can determine the absolute magnitude of a Cepheid: (**M = -1,43 – 2,81 log P**)*

*Comparing **M** with the apparent magnitude **m**, we can determine the distance **d**:* ***M – m = 5 – 5log d***



Owing to the great accuracy of the measurement of the pulsation and of the period-luminosity relation, Cepheids can then be used as standard candles to determine the distance of globular clusters and the galaxies in which they are contained.

Cepheids in particular are very important because, due to their high luminosity, they can be easly observed in nearby galaxies.

In 1912, Henrietta Leavitt discovered that the periods of Cepheides variable stars in the Small Magellanic Cloud are related to their luminosity.

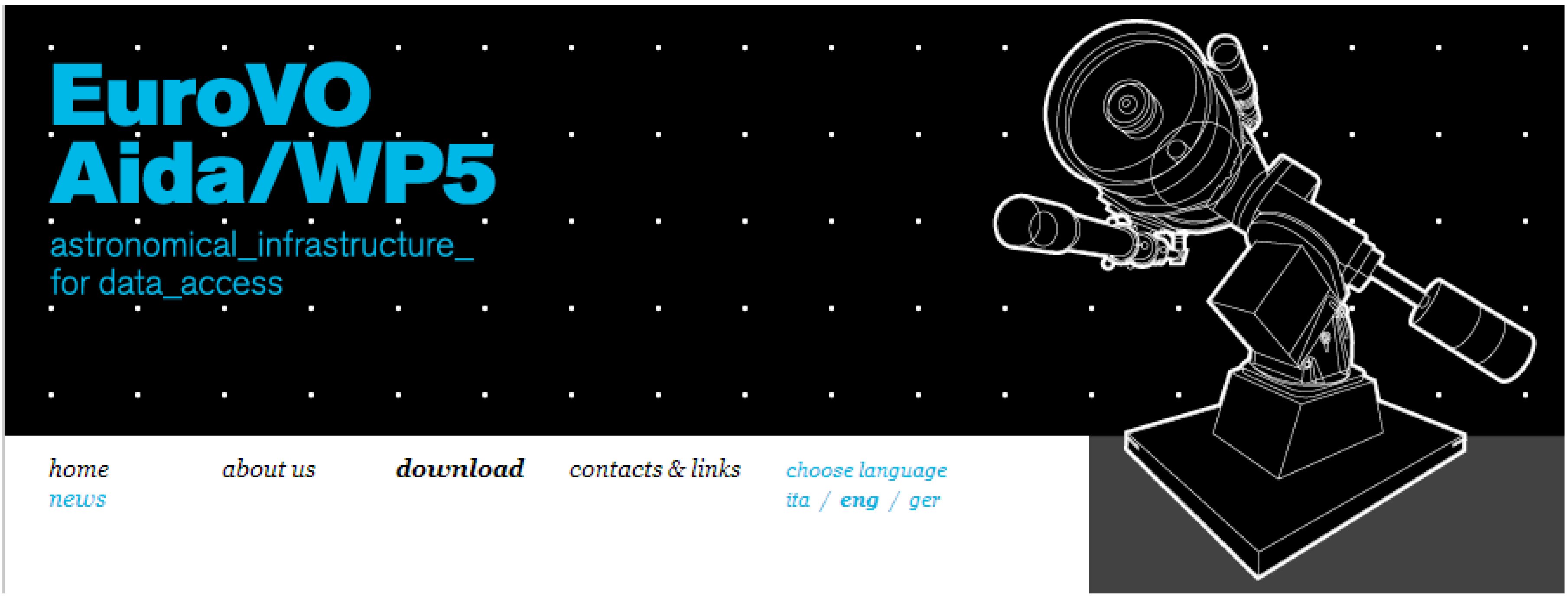
More recently, the Hubble Space Telescope was able to identify some Cepheid variables in the Virgo cluster, at a distance of ~ 20 Mpc.

With Cepheid variables we can estimate the distance of the nearest galaxies up to 30 Mpc. Therefore, they are the main step connecting galactic and extragalactic distances.

EuroVo

To experience the emotion of the scientific research and of the astronomy, we can use a free tool available on the Internet:

EuroVo → a project developed within the European Virtual Observatory which has as goal the diffusion of data and software EuroVo to the public.



This project provides examples, teaching modules and semplified professional software.

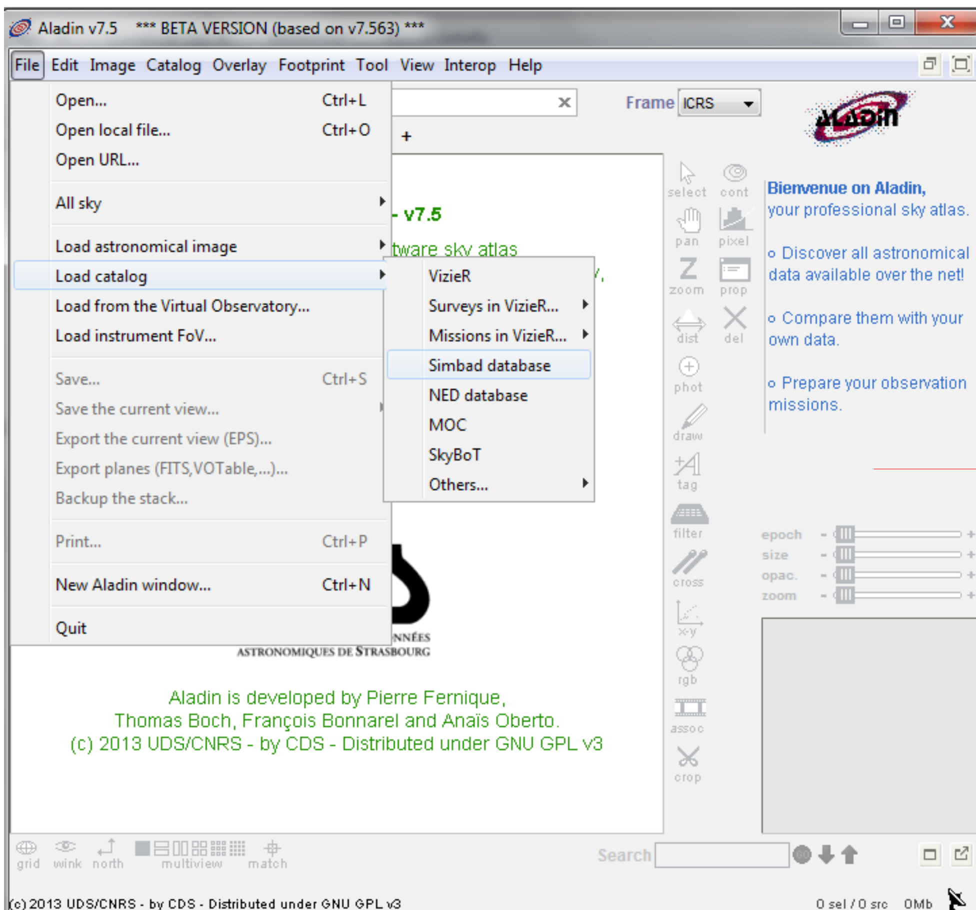
To download it: http://wwwas.oats.inaf.it/aidawp5/eng_download.html?fsize=medium

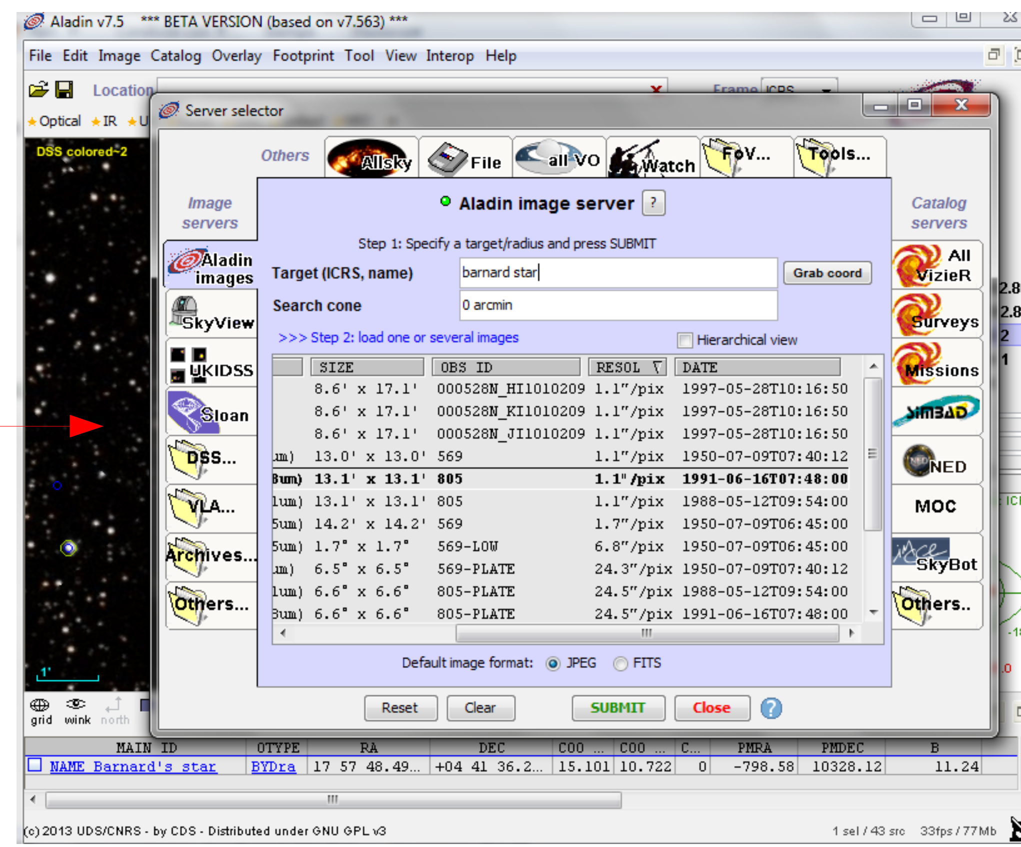
Worth of mention is Aladin that has several built-in functions that allow the image handling and a quick analysis.

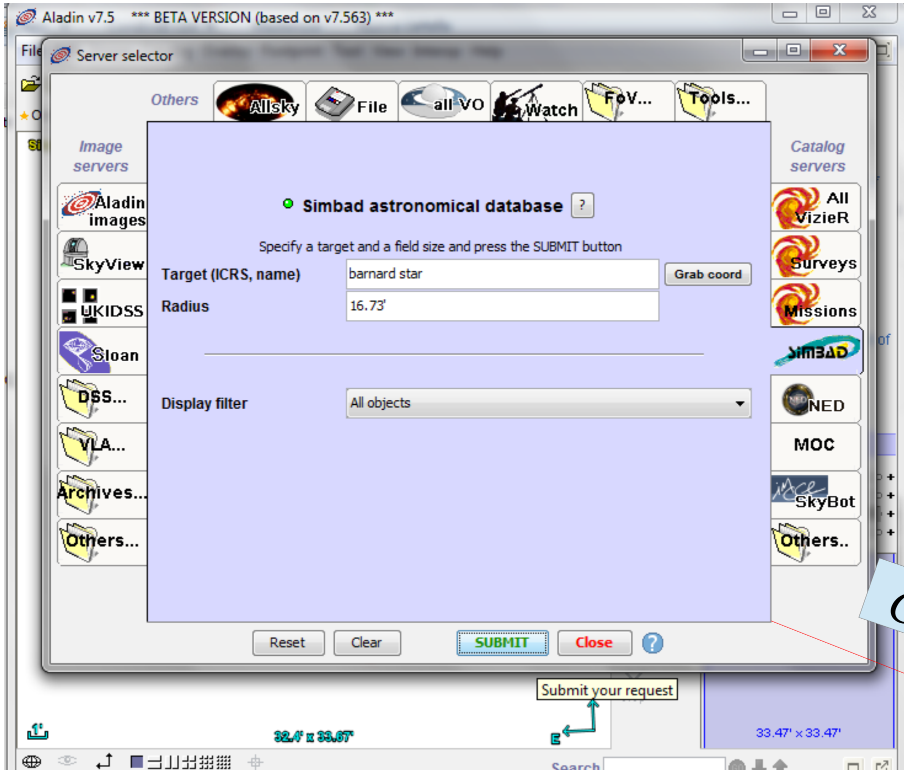
We can see two possible applications of Aladin on cosmic distances

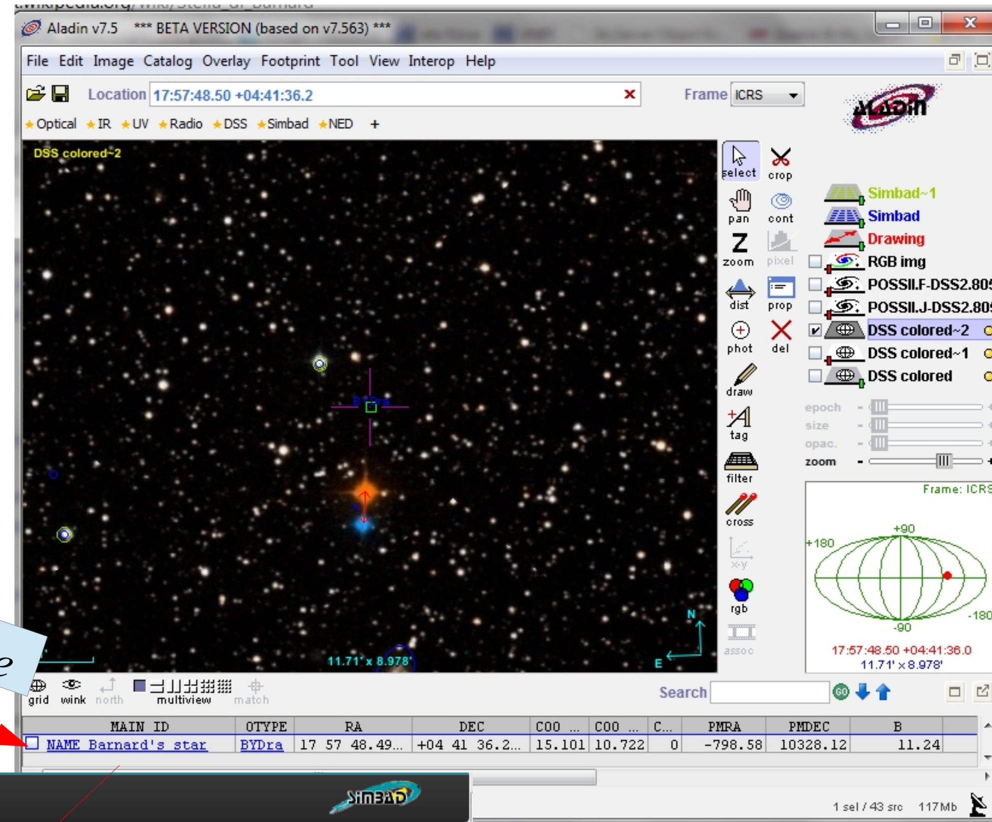
Distance of Barnard Star

Star Aladin









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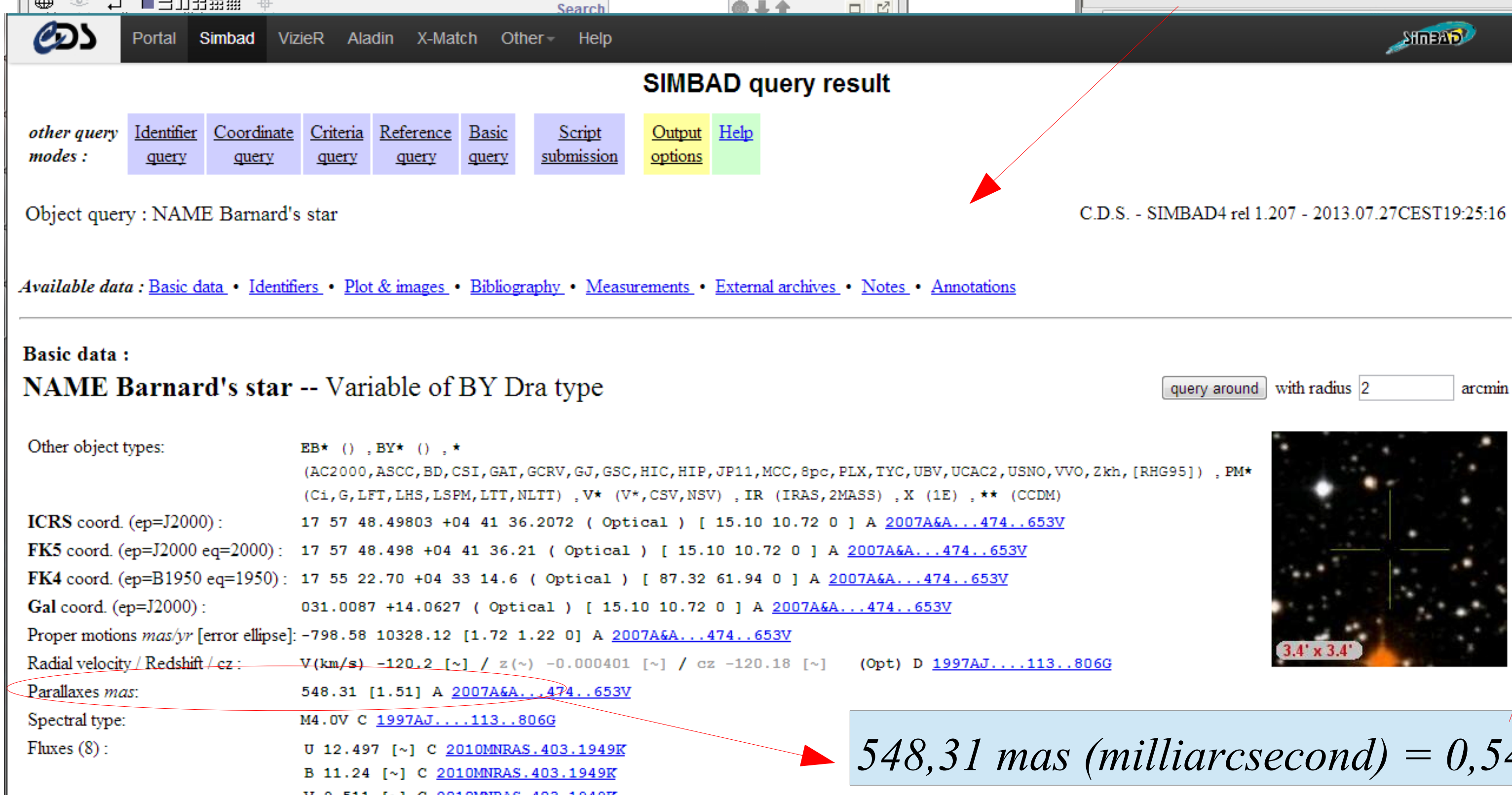


Portal Simbad VizieR Aladin X-Match Other Help

SIMBAD query result

other query modes : Identifier query | Coordinate query | Criteria query | Reference query | Basic query | Script submission | Output options | Help

Object query : NAME Barnard's star

C.D.S. - SIMBAD4 rel 1.207 - 2013.07.27CEST19:25:16

Available data : Basic data • Identifiers • Plot & images • Bibliography • Measurements • External archives • Notes • Annotations

Basic data :

NAME Barnard's star -- Variable of BY Dra type

query around with radius 2 arcmin

Other object types:	EB* () , BY* () , * (AC2000,ASCC,BD,CSI,GAT,GCRV,GJ,GSC,HIC,HIP,JP11,MCC,8pc,PLX,TYC,UBV,UCAC2,USNO,VVO,Zkh,[RHG95]) , PM* (Ci,G,LFT,LHS,LSPM,LTT,NLTT) , V* (V*,CSV,NSV) , IR (IRAS,2MASS) , X (1E) , ** (CCDM)
ICRS coord. (ep=J2000) :	17 57 48.49803 +04 41 36.2072 (Optical) [15.10 10.72 0] A 2007A&A...474..653V
FK5 coord. (ep=J2000 eq=2000) :	17 57 48.498 +04 41 36.21 (Optical) [15.10 10.72 0] A 2007A&A...474..653V
FK4 coord. (ep=B1950 eq=1950) :	17 55 22.70 +04 33 14.6 (Optical) [87.32 61.94 0] A 2007A&A...474..653V
Gal coord. (ep=J2000) :	031.0087 +14.0627 (Optical) [15.10 10.72 0] A 2007A&A...474..653V
Proper motions *mas/yr* [error ellipse]:	-798.58 10328.12 [1.72 1.22 0] A 2007A&A...474..653V
Radial velocity / Redshift / cz :	V(km/s) -120.2 [~] / z(~) -0.000401 [~] / cz -120.18 [~] (Opt) D 1997AJ....113..806G
Parallaxes *mas*:	548.31 [1.51] A 2007A&A...474..653V
Spectral type:	M4.0V C 1997AJ....113..806G
Fluxes (8) :	U 12.497 [~] C 2010MNRAS.403.1949K B 11.24 [~] C 2010MNRAS.403.1949K V 9.511 [~] C 2010MNRAS.403.1949K

3.4' x 3.4'

548,31 mas (milliarcsecond) = 0,54831 as

The distance of the Barnard star from Earth is :

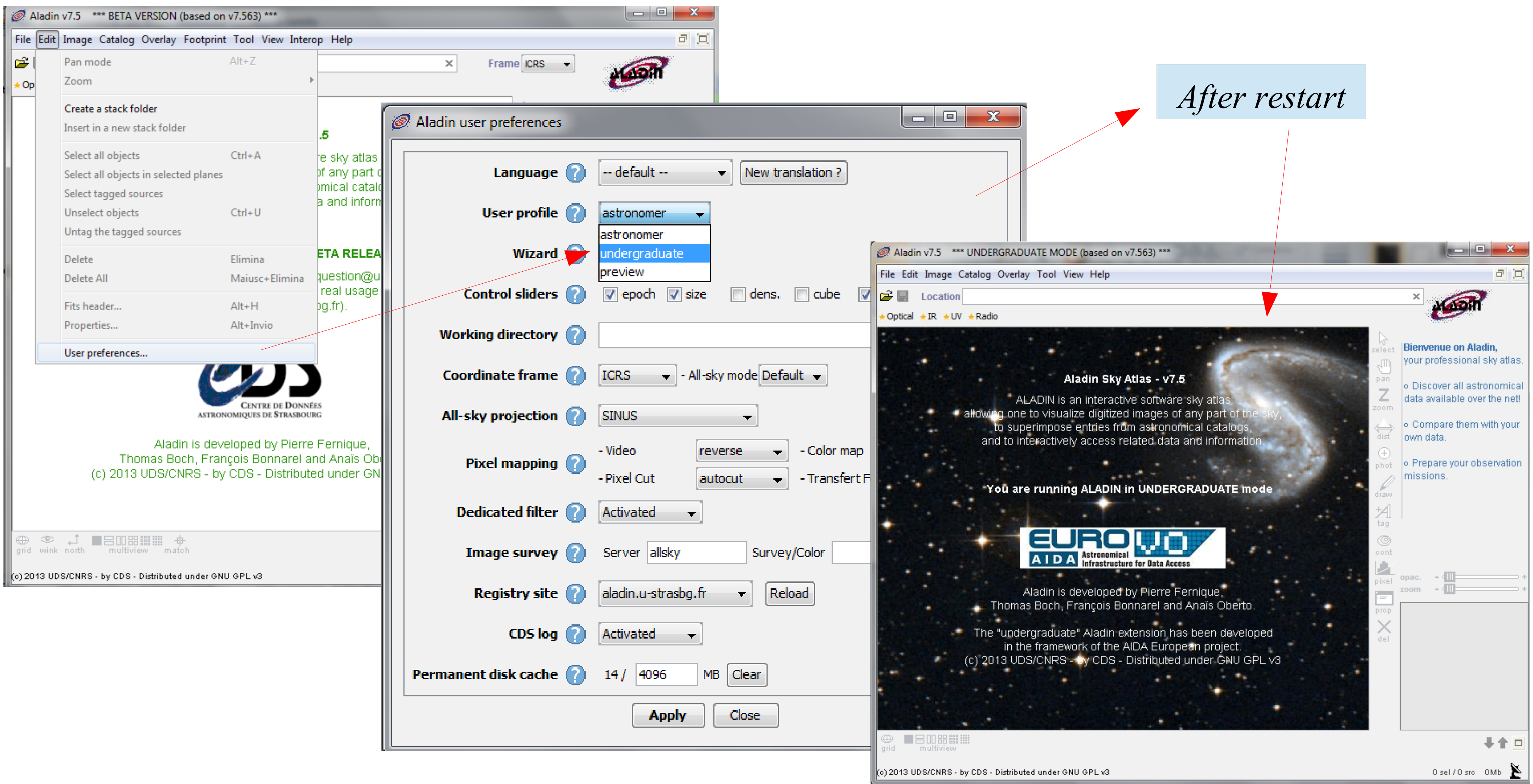
d = 1 / 0,54831 ~

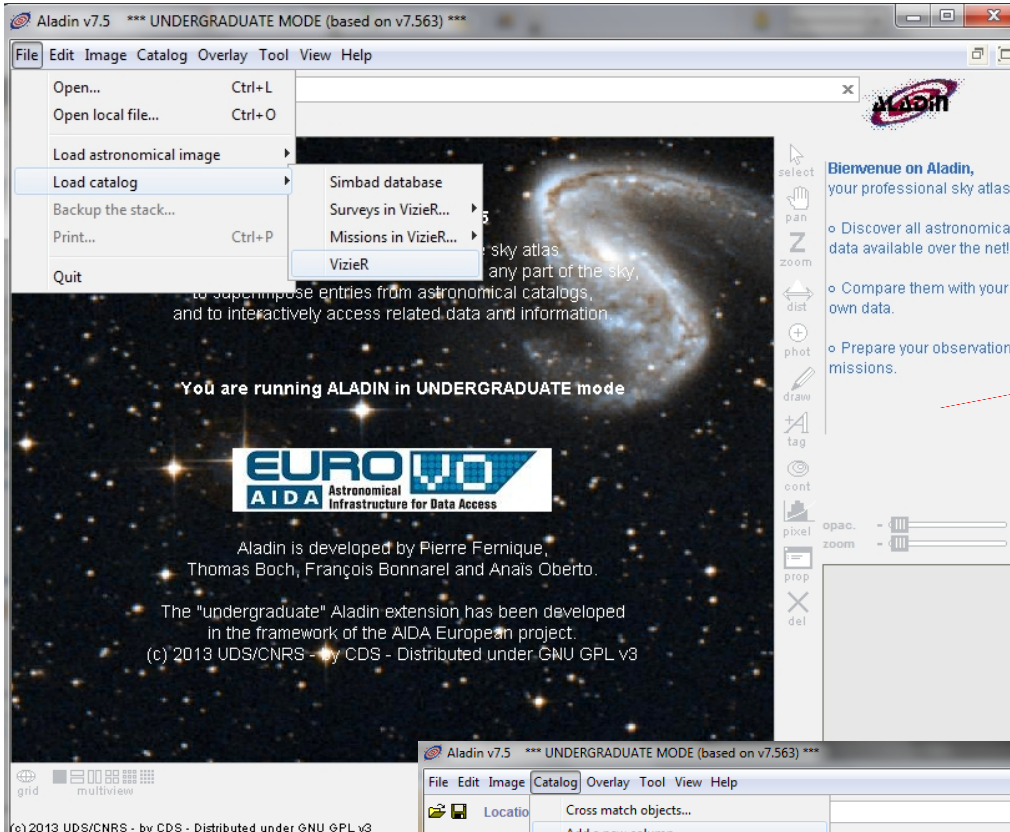
~ 1,82 pc

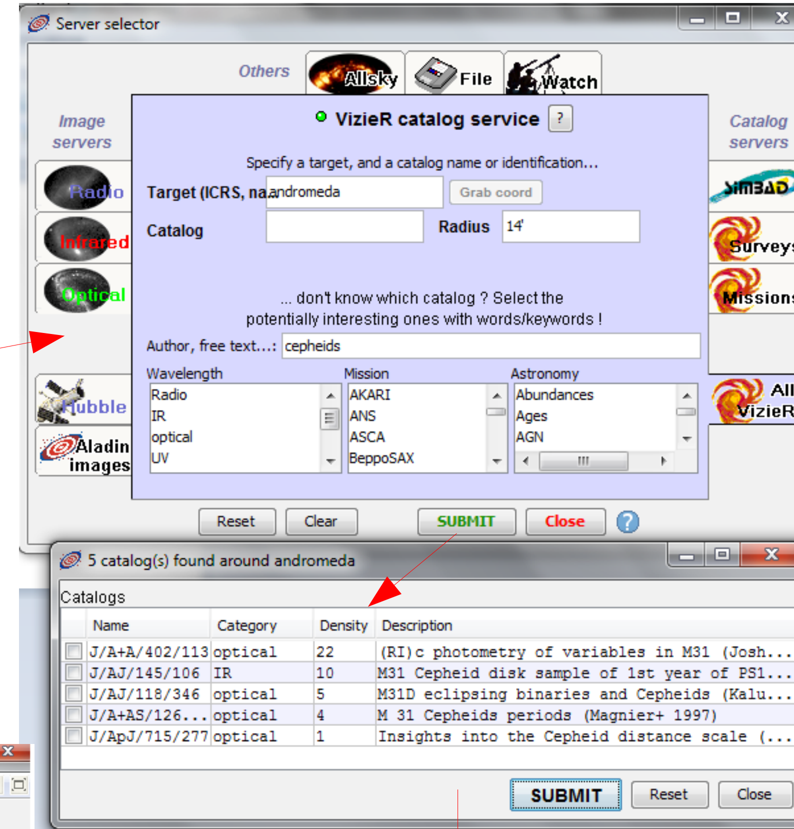
Distance of Andromeda Galaxy

In 1924 Edwin Hubble identified some Cepheids in the Andromeda Galaxy; he concluded that it was located far away from our Galaxy.

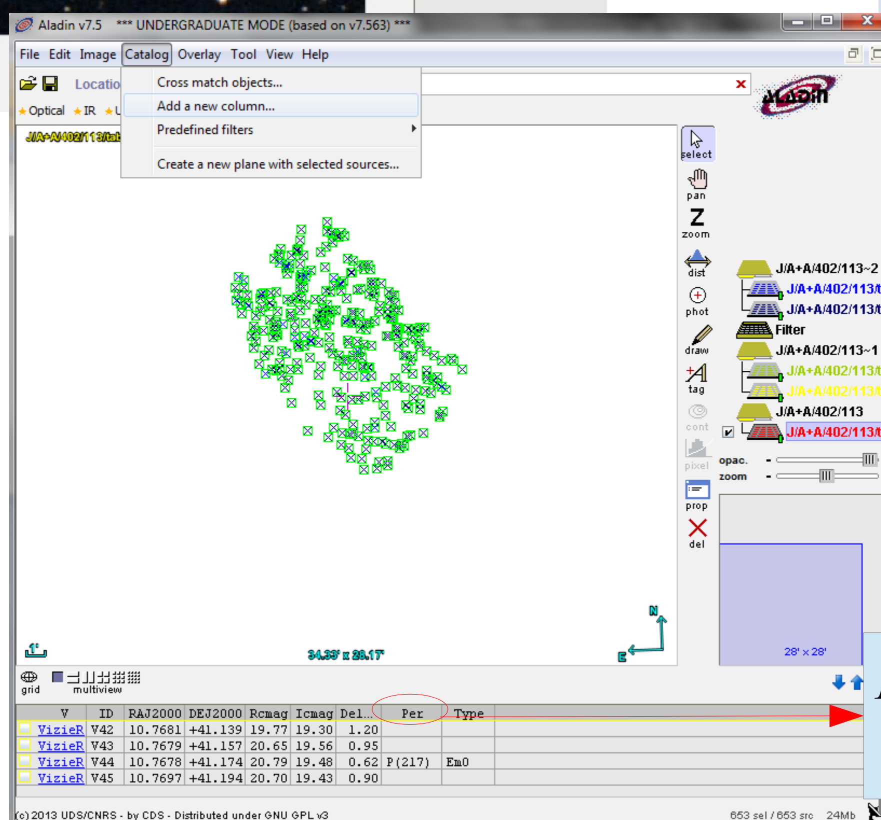
Start Aladin







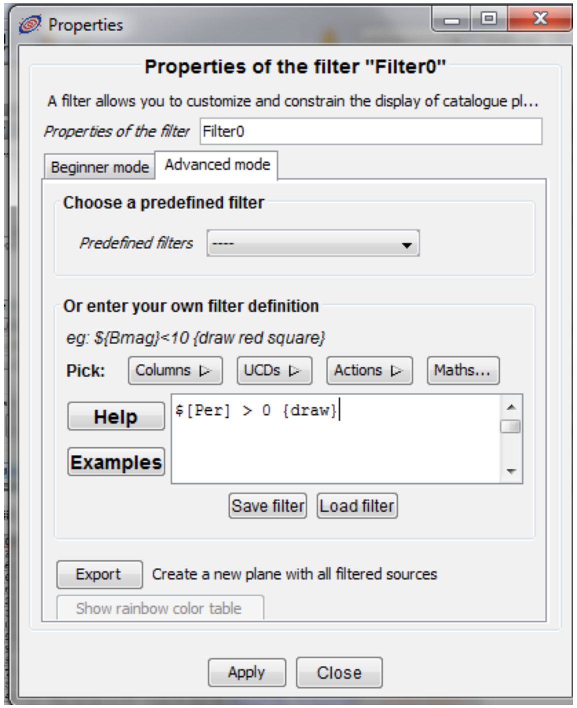
We choose the most recent catalog



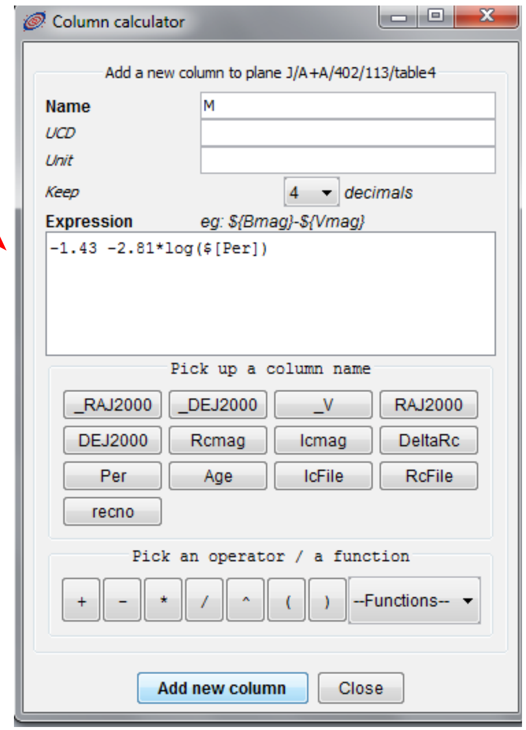
It means the period of the stars,

but not all have it shown.

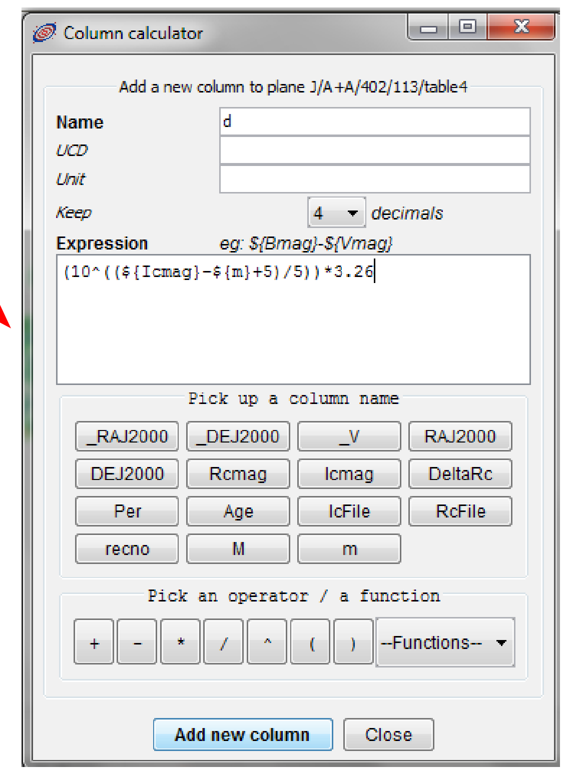
To see only the stars of which the period is indicated, we create a filter.



To calculate absolute magnitude



To calculate the distances



grid multiview

	V	RAJ2000	DEJ2000	Rcmag	Icmag	Del...	Per	Ag	IcFile	RcFile	m	d
☐	VizieR	10.9321	+41.1970	20.48	19.98	0.27	7.459	75	lc/iv1.dat	lc/rv1.dat	-3.[illegible]	Click for sorting, clic
☐	VizieR	10.8469	+41.1737	20.17	19.69	0.15	8.566	69	lc/iv2.dat	lc/rv2.dat	-4.[illegible]	[illegible]...
☐	VizieR	10.8669	+41.2320	20.61	20.28	0.22	8.836	68	lc/iv3.dat	lc/rv3.dat	-4.0889	2437797....
☐	VizieR	10.9366	+41.2503	20.28	19.54	0.11	9.160	67	lc/iv4.dat	lc/rv4.dat	-4.1329	1769284....
☐	VizieR	10.9721	+41.2128	20.56	20.04	0.19	9.790	64	lc/iv5.dat	lc/rv5.dat	-4.2140	2312158....
☐	VizieR	10.8736	+41.2367	20.42	20.27	0.28	10.500	61	lc/iv7.dat	lc/rv7.dat	-4.2995	2673730....
☐	VizieR	10.7500	+41.1426	19.89	19.55	0.17	11.170	59	lc/iv8.dat	lc/rv8.dat	-4.3750	1987090....
☐	VizieR	10.8594	+41.2004	20.21	19.60	0.26	13.773	52	lc/iv9.dat	lc/rv9.dat	-4.6306	2287376....
☐	VizieR	10.9290	+41.1715	20.77	19.84	0.48	14.420	51	lc/iv10.dat	lc/rv10.dat	-4.6866	2621425....
☐	VizieR	10.9255	+41.2489	19.57	18.87	0.16	15.260	49	lc/iv11.dat	lc/rv11.dat	-4.7557	1731241....
☐	VizieR	10.9576	+41.2227	20.84	20.08	0.32	15.460	49	lc/iv12.dat	lc/rv12.dat	-4.7716	3044651....
☐	VizieR	10.8259	+41.1386	19.82	19.46	0.40	15.760	48	lc/iv13.dat	lc/rv13.dat	-4.7951	2313330....
☐	VizieR	10.9049	+41.2419	19.93	19.58	0.22	15.900	48	lc/iv14.dat	lc/rv14.dat	-4.8059	2456957....
☐	VizieR	10.9115	+41.2396	20.79	19.91	0.30	15.950	48	lc/iv15.dat	lc/rv15.dat	-4.8097	2865217....
☐	VizieR	10.9775	+41.2348	20.28	19.74	0.40	16.380	47	lc/iv16.dat	lc/rv16.dat	-4.8422	2689413....
☐	VizieR	10.9069	+41.1868	20.12	19.60	0.39	16.600	47	lc/iv17.dat	lc/rv17.dat	-4.8585	2540490....
☐	VizieR	10.9853	+41.2176	19.47	19.09	0.21	17.730	45	lc/iv18.dat	lc/rv18.dat	-4.9388	2084383....
☐	VizieR	10.9839	+41.2374	19.83	19.60	0.32	17.830	45	lc/iv19.dat	lc/rv19.dat	-4.9457	2644585....
☐	VizieR	10.9526	+41.1540	19.20	18.99	0.35	20.090	42	lc/iv20.dat	lc/rv20.dat	-5.0913	2135391....
☐	VizieR	10.8379	+41.1514	19.74	19.31	0.39	21.440	40	lc/iv21.dat	lc/rv21.dat	-5.1707	2566596....
☐	VizieR	10.8272	+41.1071	20.01	19.19	0.29	26.990	35	lc/iv22.dat	lc/rv22.dat	-5.4516	2763997....
☐	VizieR	10.9059	+41.2379	19.78	18.92	0.34	28.780	33	lc/iv23.dat	lc/rv23.dat	-5.5300	2530565....
☐	VizieR	10.9002	+41.1823	20.55	19.57	0.23	35.120	30	lc/iv24.dat	lc/rv24.dat	-5.7730	3817838....
☐	VizieR	10.9293	+41.2475	18.89	18.35	0.31	43.530	26	lc/iv25.dat	lc/rv25.dat	-6.0349	2455826....
☐	VizieR	10.9183	+41.1856	19.36	18.82	0.22	56.020	22	lc/iv26.dat	lc/rv26.dat	-6.3428	3513804....
☐	VizieR	V27	10.7264	+41.158	20.16	19.25	0.50					
☐	VizieR	V28	10.7357	+41.166	18.38	17.91	0.17					
☐	VizieR	V29	10.7393	+41.167	20.27	19.25	0.59					

It's the distance of all Cepheids

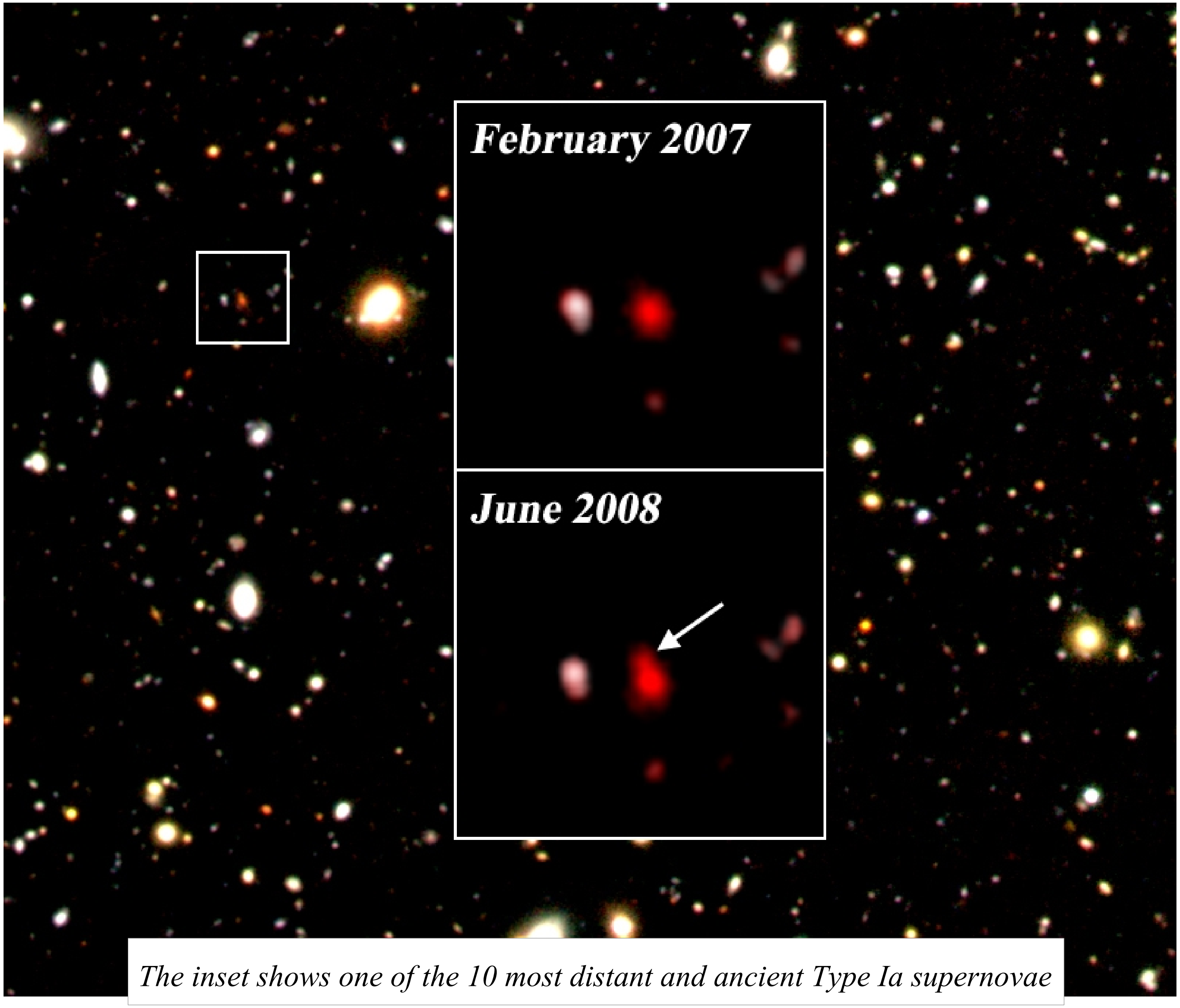
By averaging, we find the approximate distance to the Andromeda Galaxy: (2,52 ± 0,14) 10^6 ly

Type Ia Supernovae

To extend the distance scale even further, we need brighter objects but just as reliable as standard candles, and the best candidates are the Type Ia Supernovae.

These are used beyond 30 Mpc and occur when a white dwarf in a close binary system accretes enough matter from its companion to blow itself apart in a thermonuclear explosion.

If a Type Ia supernova is seen in a distant galaxy and its maximum apparent brightness measured, we can find the galaxy's distance.



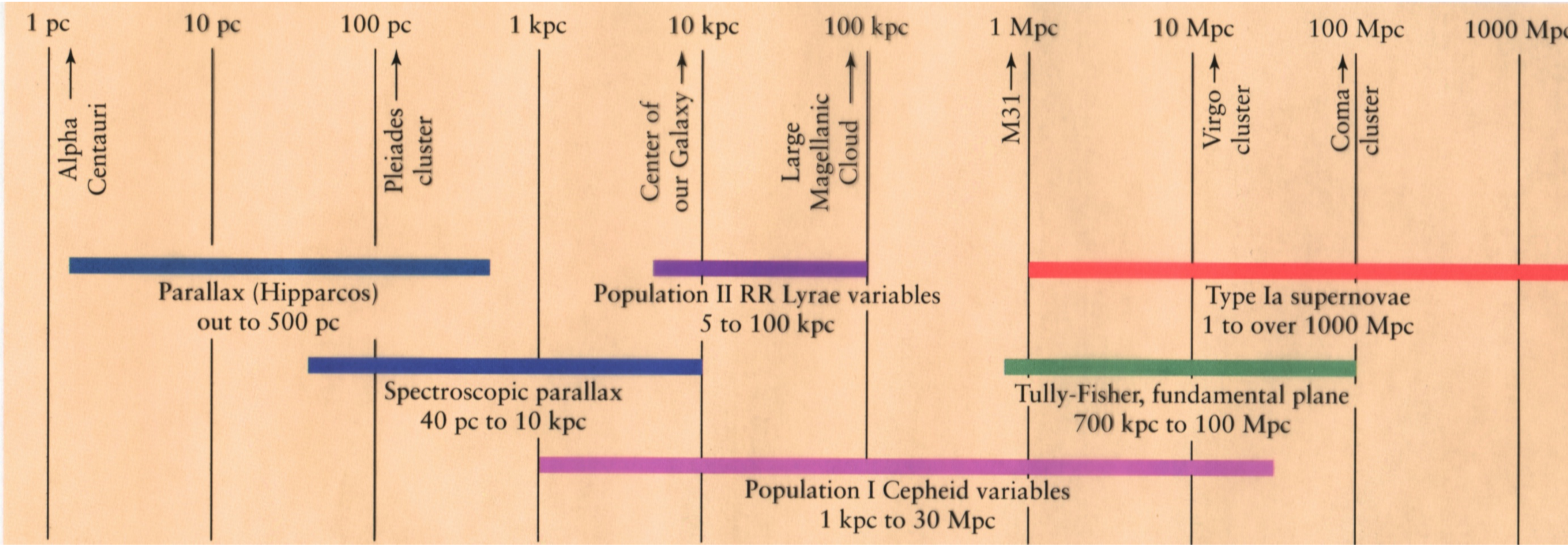
The inset shows one of the 10 most distant and ancient Type Ia supernovae

Not all Type Ia supernovae are equally luminous, but a simple relation holds: the slower the brightness decreases, the more luminous the supernova.

Using this relationship, we have measured distances to supernovae more than 1000 Mpc from Earth.

This technique can be used only for galaxies in which we happen to observe a Type Ia supernova. Now we are able to identify many dozens of these supernovae every year, so the number of galaxies whose distances can be measured in this way is continually increasing.

The distance scale

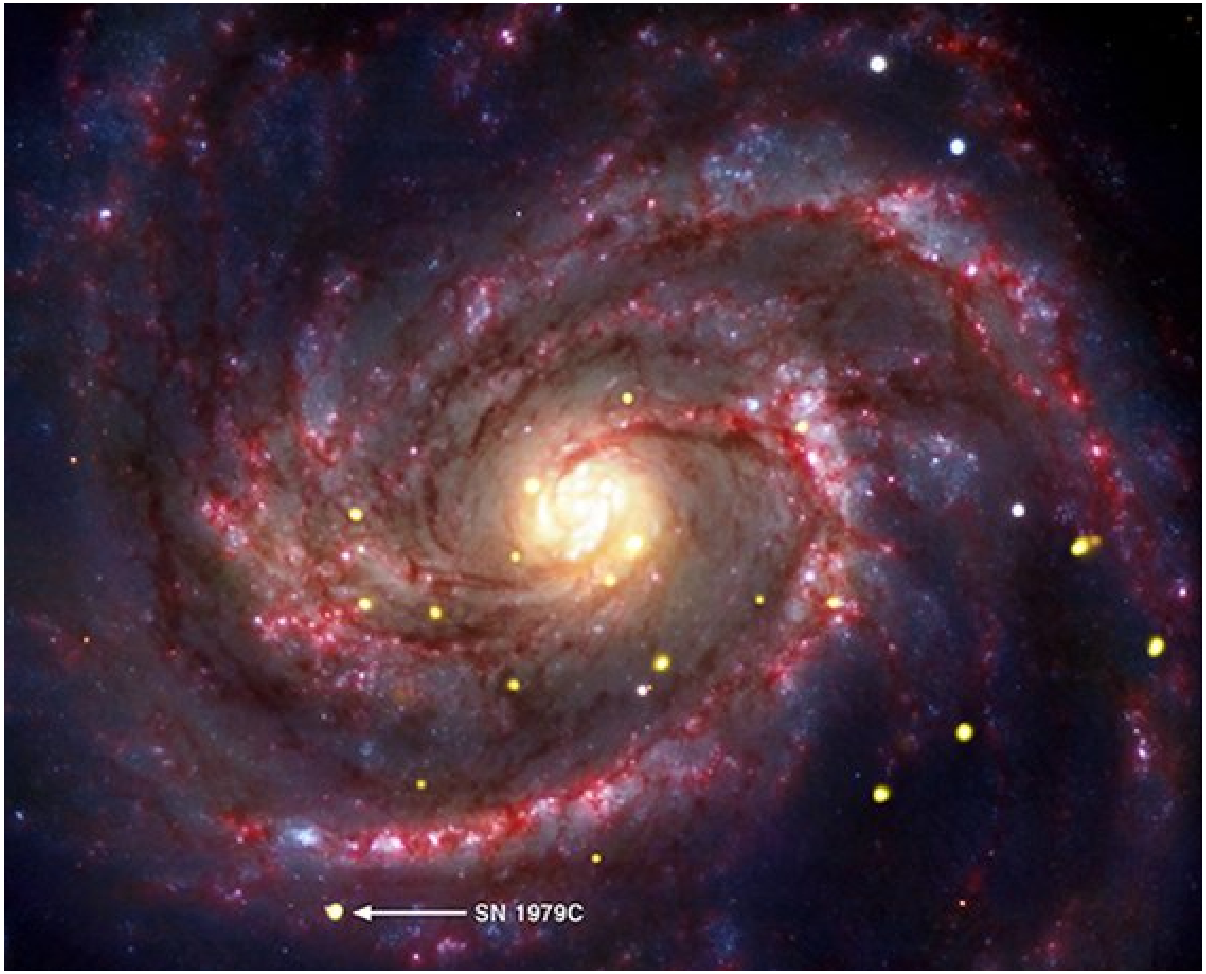


The figure shows the ranges of application of several important methods for the determination of astronomical distances. Because these ranges overlap, one technique can be used to calibrate another.

For this reason, we go to great lengths to check the accuracy and reliability of our standard candles.

A change in distance-measuring techniques used for nearby objects can also have substantial effects on the distances to remote galaxies.

As an example, the distance to the galaxy M100 shown in the figure is determined using Cepheids. A Type Ia supernova has been seen in M100, as the figure shows, and its luminosity is determined using the Cepheid-derived distance to M100. Any change in the calculated distance to M100 would change the calculated luminosity of the Type Ia supernova, and so would have an effect on all distances derived from this.



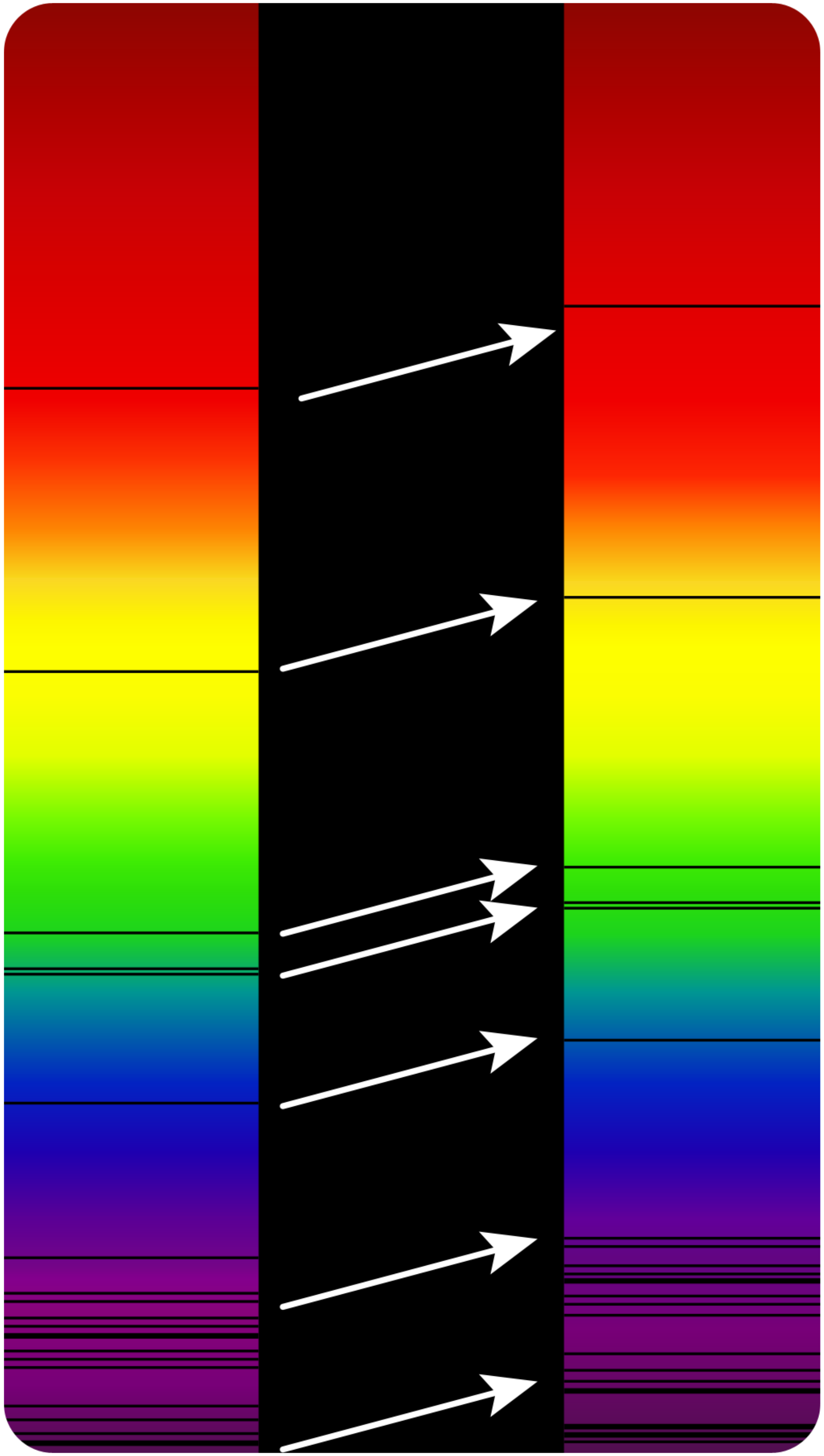
Because one measuring technique leads us to the next one like rungs on a ladder, the techniques shown in the figure of the previous slide, are referred to collectively as the distance ladder.

Hubble Law

During the 1920s, Edwin Hubble, by observing the luminosity and pulsation periods of Cepheid variables in many galaxies, was able to measure the distance to each galaxy.

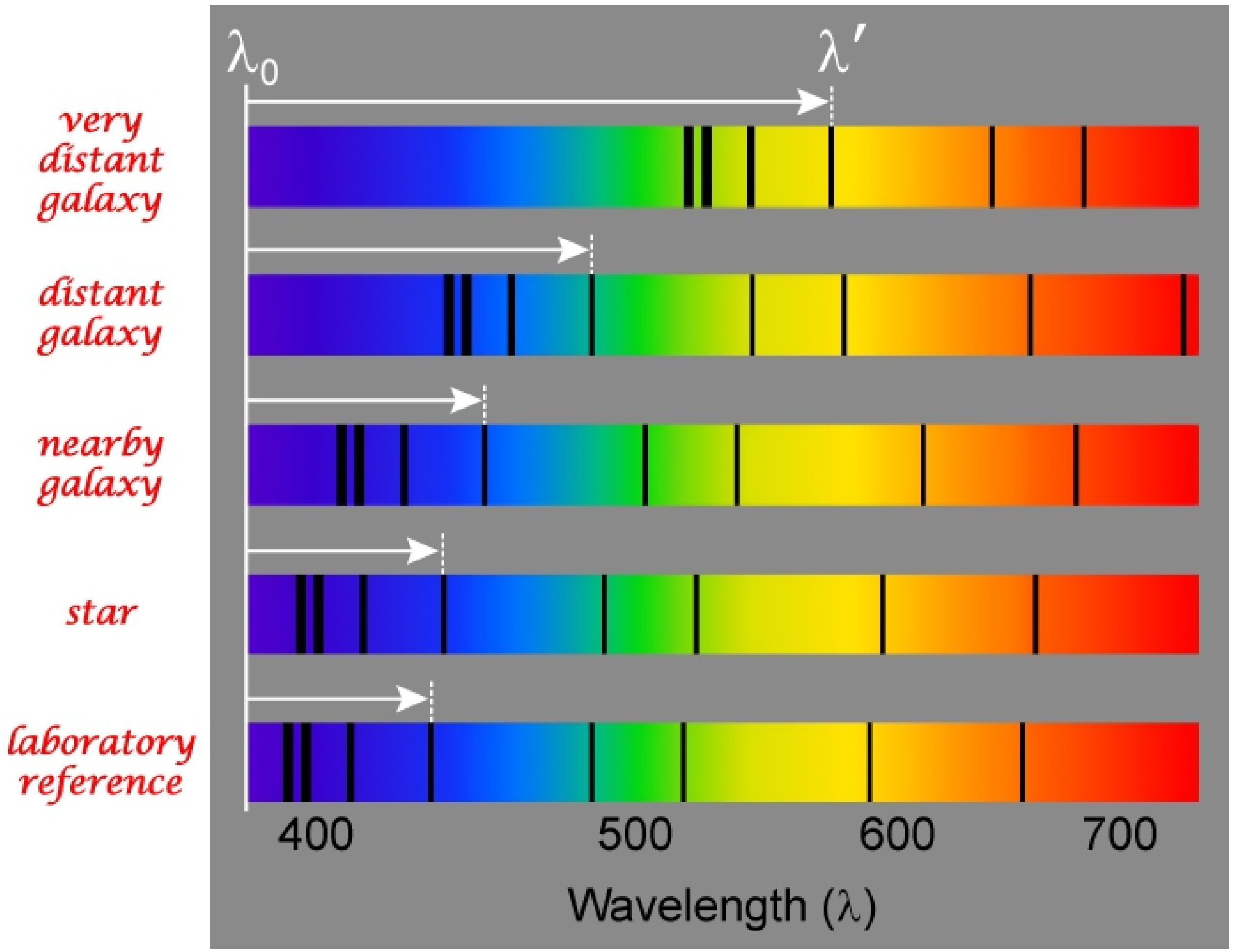
Many spectral lines emitted by chemical elements similar to those present in the Sun are found in the light emitted by distant stars.

Analyzing the spectra we can notice that the lines produced by the distant stars correspond to those emitted by known elements only with a systematic shift towards longer wavelengths.



Hubble found that most galaxies show a shift toward the red portion of the spectrum.

The redshift (z) is found from the ratio: $z = (\lambda - \lambda_o) / \lambda_o$



λ is the wavelength of the line of the spectrum emitted by a star in motion and the corresponding wavelength λ_o of the same line of a reference spectrum, usually the solar one.

Hubble found a correlation between the distance to a galaxy and its redshift: nearby galaxies are moving away from us slowly, while more distant galaxies are rushing away from us much more rapidly.

CAUTION!

The redshift is similar to a Doppler effect, but in reality its physical nature is different.

It is the basis of the most shocking cosmological theory:

<u>the expansion of the Universe</u>.

It creates new space between source and observer, "stretching" the wavelength.

The movement away from our of the other galaxies is called reccession motion. The relation between the recession velocity $\mathbf{v}$ *and distance* $\mathbf{d}$ *of a galaxy from Earth is expressed by the Hubble law:* $\mathbf{v = d\, H_0}$

$\mathbf{H_0}$ *is the Hubble constant and its value is constantly revised. It is costant because if at this time we repeat its measure, again, in any other point in the universe, we would get the same value of* $\mathbf{H_0}$*; but it varies over time. The evolution of* $\mathbf{H_0}$ *is due to the effects of the gravitational force of the matter in the Universe that tends to slow the expansion, and the so-called dark energy, which instead tends to speed it up.*

Measured by	*Hubble* 	*Hubble Space Telescope* 	*Space Infrared Telescope Spitzer* 	*Planck Spacecraft* 
H_0 *(km/s/Mpc)*	*500*	*73,8 ± 2,4*	*74,3 ± 2,1*	*67,15 ± 1,2*

From these measurements continuously updated, we can conclude that the sequence of measurements of the Hubble constant is converging to a value more accurately.

CAUTION!

The use of the Hubble law has some limitations. We can not use it when:

- ***the distances are less than a few million light years, because the gravitational effect would occur due to the proximity.***

- ***the distances are very large, in excess of several billion light years, for two reasons: on one hand the uncertainties increase with distance; on the other hand, the proportionality speed - distance requires knowledge of the developmental characteristics of the galaxy, to as the Hubble parameter that has characterized the expansion of the universe in the distant past (cosmological parameters were measured using the Type Ia Supernovae as standard candles).***

Finally, it should be noted that this law expresses a situation existing at a given moment and not as the velocity of an object changes when it moves away.

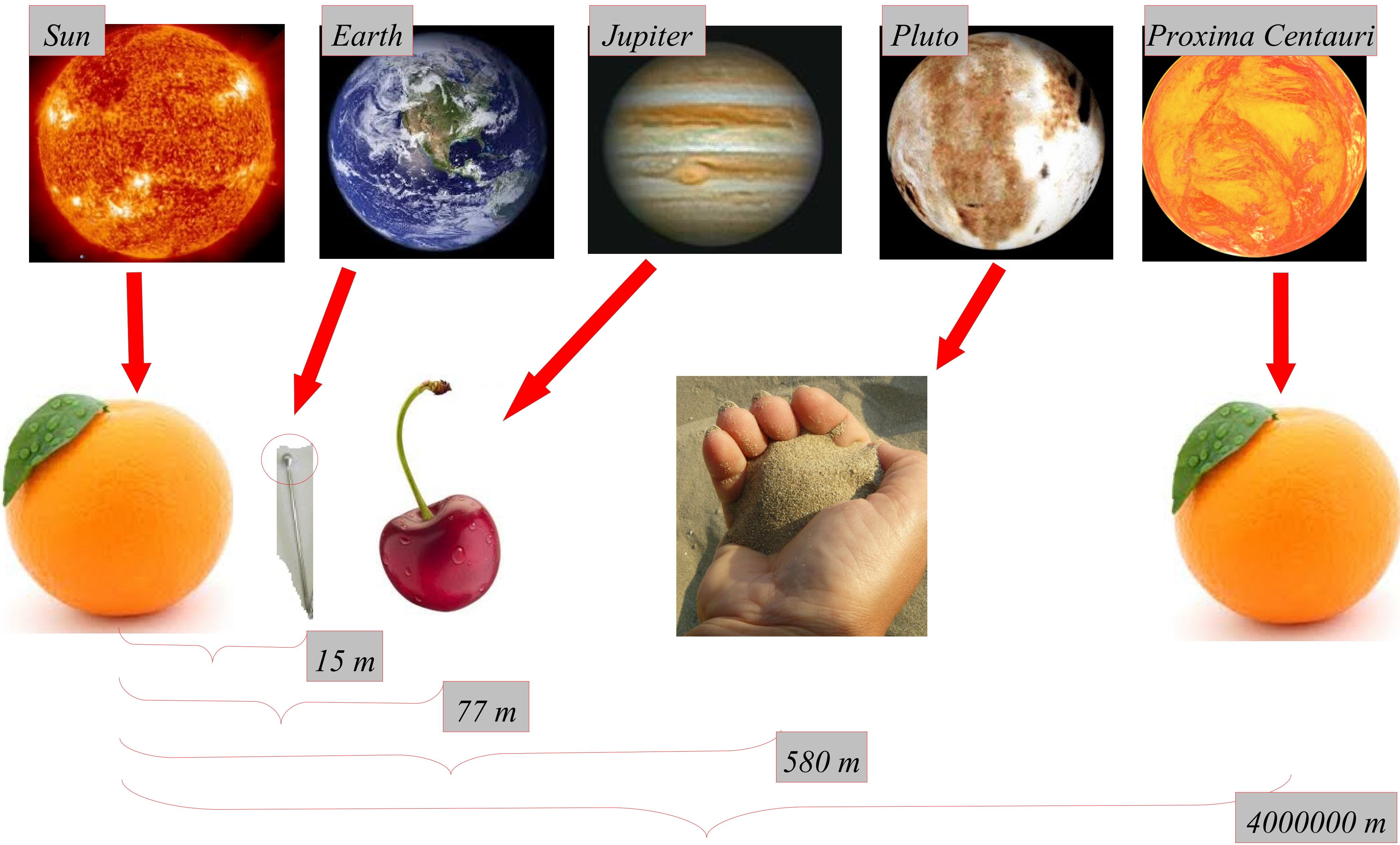
Given the value of $\boldsymbol{H_0}$*, we can use the Hubble law to find the distance* **d** *to the galaxy if we know how to determine the recession velocity v from the laws of the Doppler effect.*

If the redshift and recession velocity are not too great, we can use the following equation:

$\boldsymbol{v = c\,z}$ *, where c is the speed of light.*

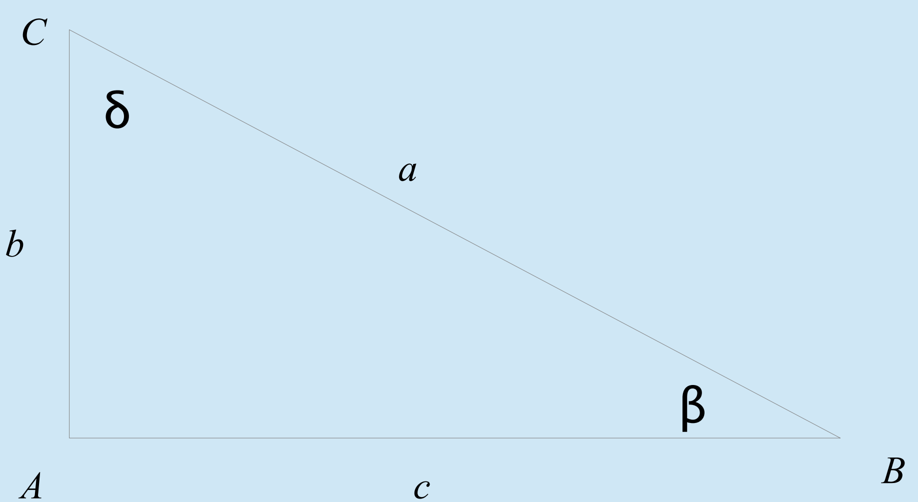
Not all galaxies are moving away from us! Some of the nearest galaxies, including Andromeda Galaxy, are actually approaching us and have blueshifts rather than redshifts.

Let's take an example, for us closer, to understand the orders of magnitude with which we deal in the distance scales: if the Sun was an orange, the Earth would be the head of a needle turning 15 meters away around the orange, Jupiter was a cherry, turning around 77 meters, Pluto a grain of sand at 580 meters and Proxima Centauri another orange at 4000 km!



Appendix A: Knowledge Required

Trigonometric Ratios



$b = a \sin b$

$c = b \operatorname{tg} g$

$b = a \cos g$

$c = b \operatorname{cotg} b$

$c = a \sin g$

$b = c \operatorname{tg} b$

$c = a \cos b$

$b = c \operatorname{cotg} g$

Brightness and Luminosity

Brightness is the amount of light received by an object.

Luminosity is the amount of light emitted from the star in the unit of time. Its unit of measurement is "candela".

Magnitude

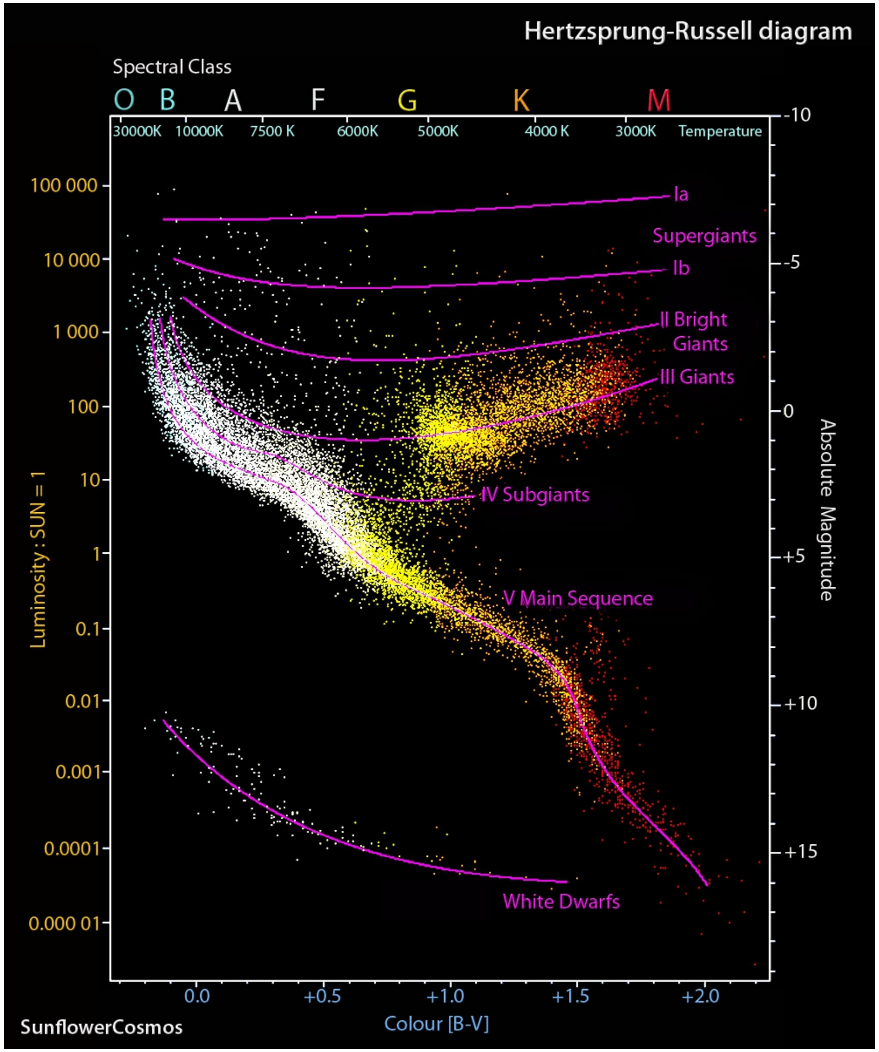
*The apparent magnitude (**m**) of a celestial body is a measure of its brightness as seen by an observer on Earth, adjusted to the value it would have in the absence of the atmosphere.*

*The absolute magnitude (**M**) is the measure of a celestial object's intrinsic brightness.*

$\boldsymbol{M - m = 5 - 5\log d}$ *The difference (**M – m**) is called distance modulus*

HR diagram

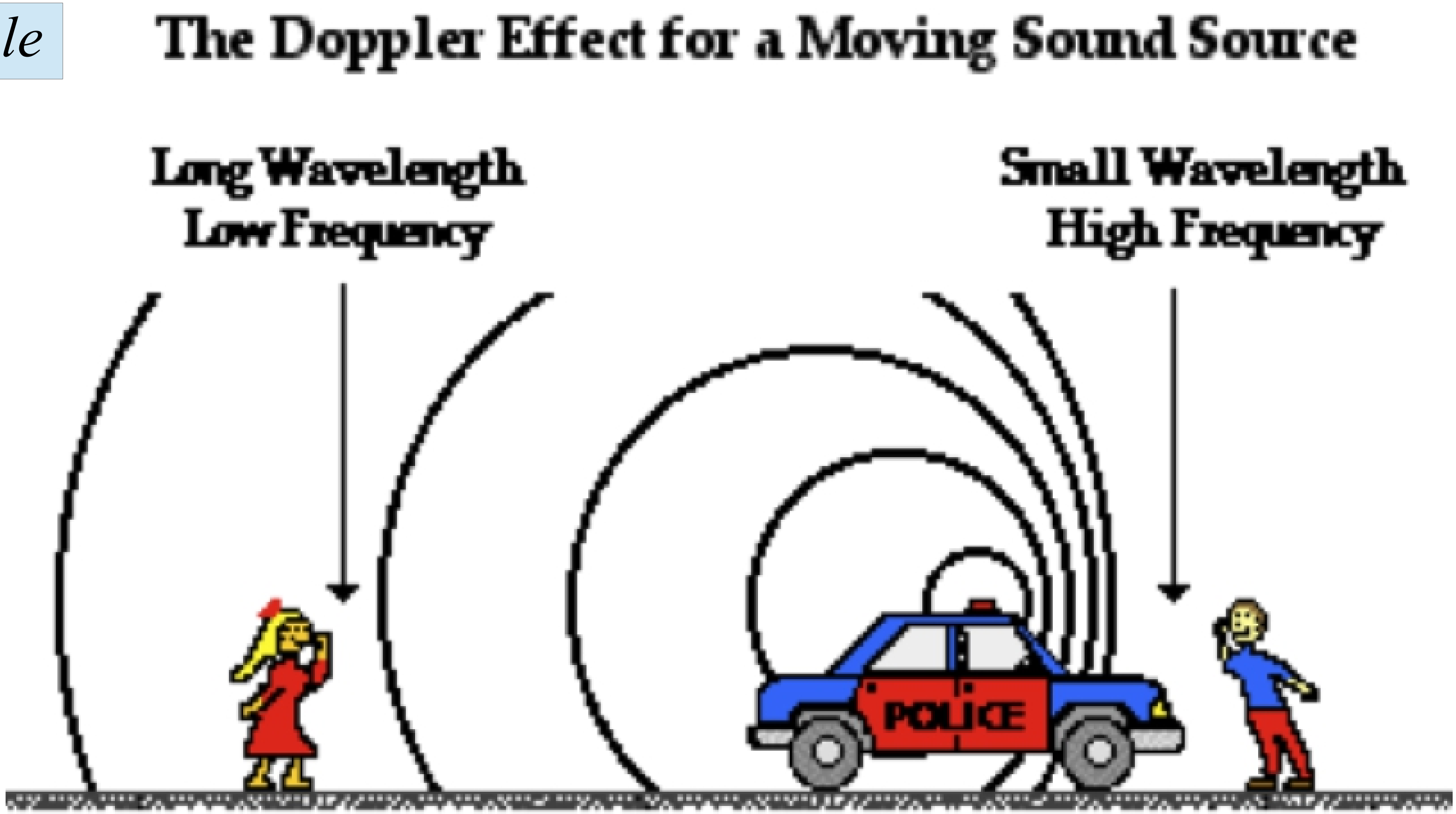
The HR diagram collects key information on stars.
Each star is identified by two coordinates:
in the x-axis is the spectral type,
in the y-axis the absolute brightness.
The spectral types indicate the surface temperature of the star, they are arranged in the upper x-axis in order of decreasing temperature.
The central area of the diagram, that extends diagonally from top left to bottom right, is called the main sequence.
It collects the highest number of stars in the diagram.



Doppler Effect

It is a physical phenomenon which consists in the apparent change in frequency or wavelength of a wave perceived by an observer who is in motion or at rest relative to the source of the waves, also in motion or at rest

Example



If the car with siren is approaching us, we hear an higher sound than the same one issued by the source when it is stationary; when it goes away it appears lower.