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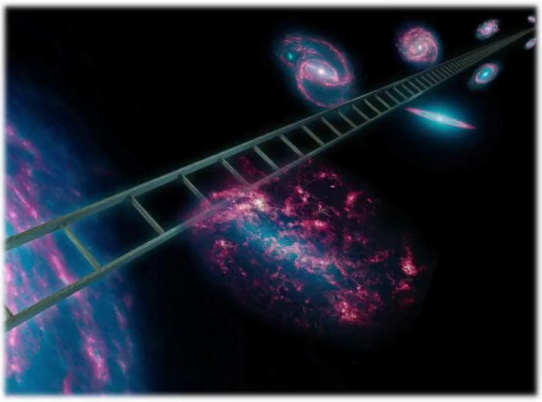


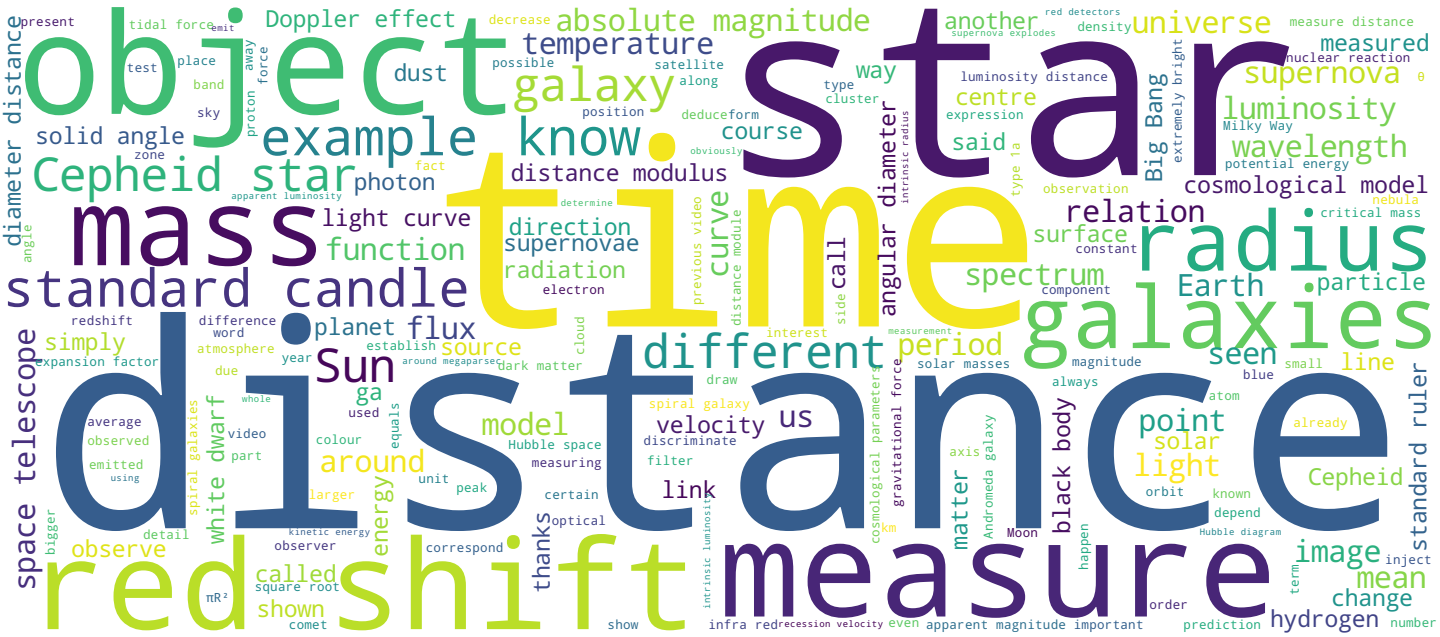
Cosmic distance ladder

Illustration: NASA/JPL-Caltech

Distance Ladder

Introduction to Astrophysics; Chapter 7.2

Frédéric Courbin



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Video

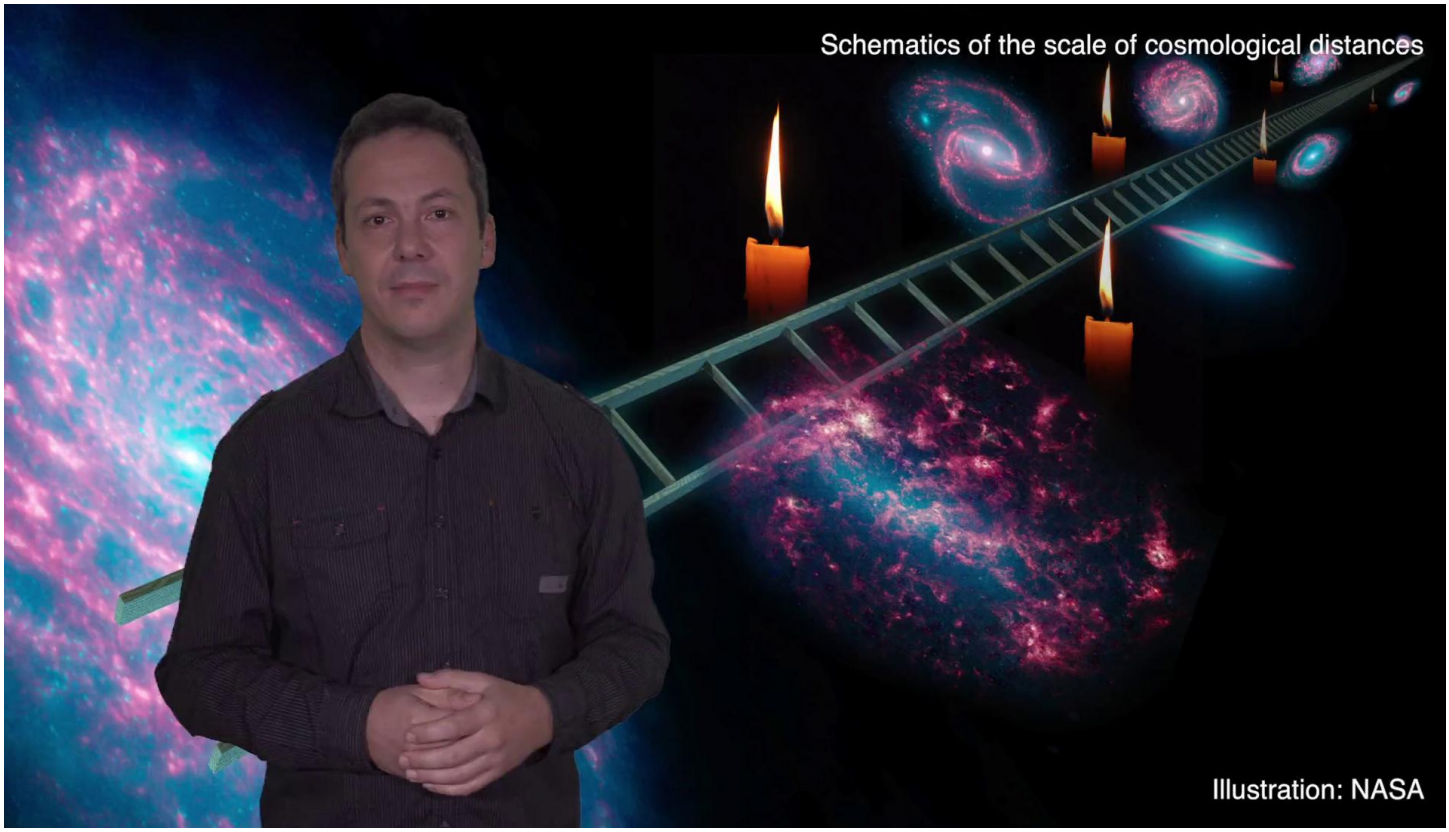
EPFL

In the previous video, we introduced some basic cosmology notions and we tied the notion of red shift to the expansion factor of the Universe. The challenge is now to link redshifts to distances because they can be calculated or predicted by comological models. If we can measure distances, we can test cosmological models by confronting the predictions of the models to the observations and by looking at models which are best capable to predict the measured distances. We will see in this video how to measure the distances and what the signification of these distances are. We will see that there are essentially 2 available methods for this : one is founded on what we call standard rulers and the other on standard candles. In the case of the standard ruler, the principle is to measure how the angular size of an object varies with the red shift. If also know the physical size of this standard object, we know its distance. It's what is drawn here where we see a galaxy with an intrinsic size and an apparent size. The intrinsic size will not change with the distance, but the measured size, the angular size of the sky will change and it's like this that we will be able to measure the distance.

Notes

Summary

0m 06s



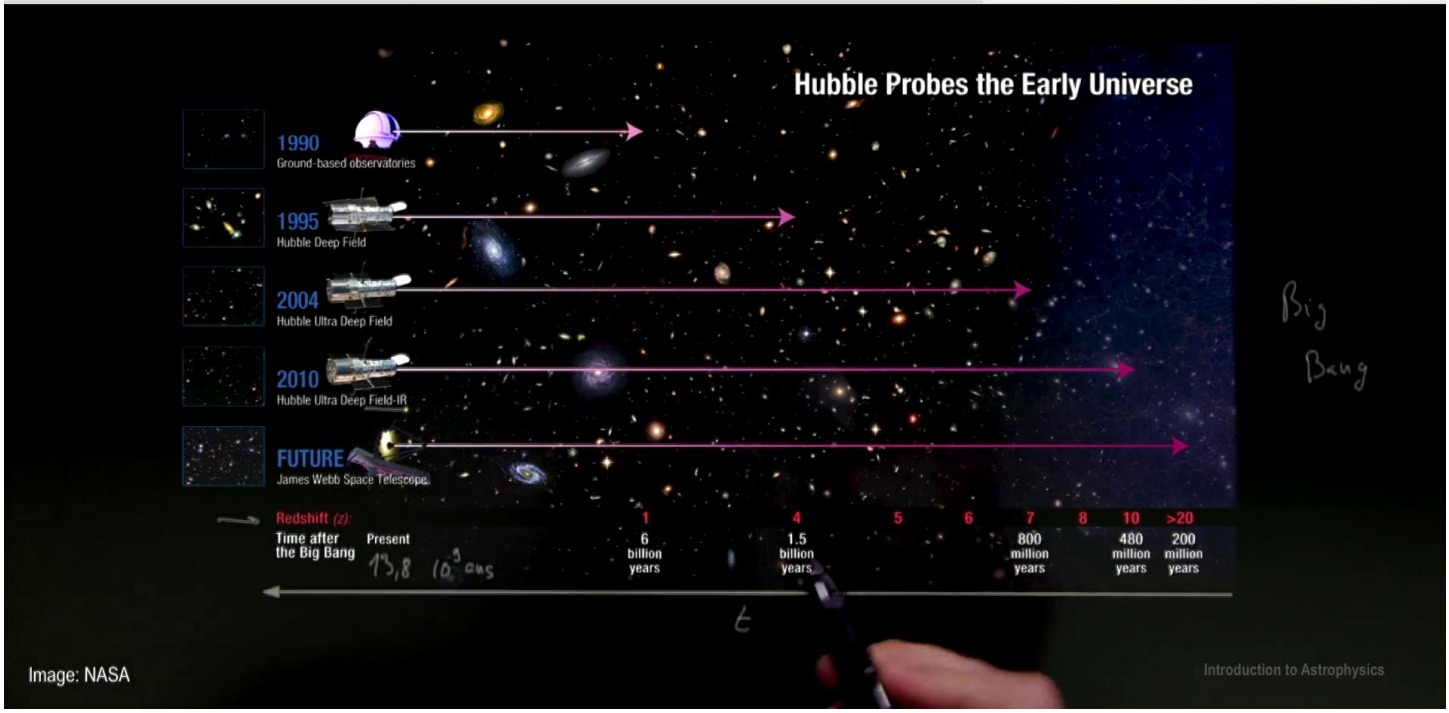
We can hold the same logic and measure the apparent luminosity of an object of which we would know also the intrinsic luminosity, i.e., the absolute magnitude. It's what is shown here: a standard candle with a well defined intrinsic luminosity whose apparent luminosity will diminish with the red shift and the distance. It's thanks to these standard rulers and standard candles that we can link the red shifts to the distances and make cosmological measurements.

Notes

Summary

1m 22s

Redshift and Distance



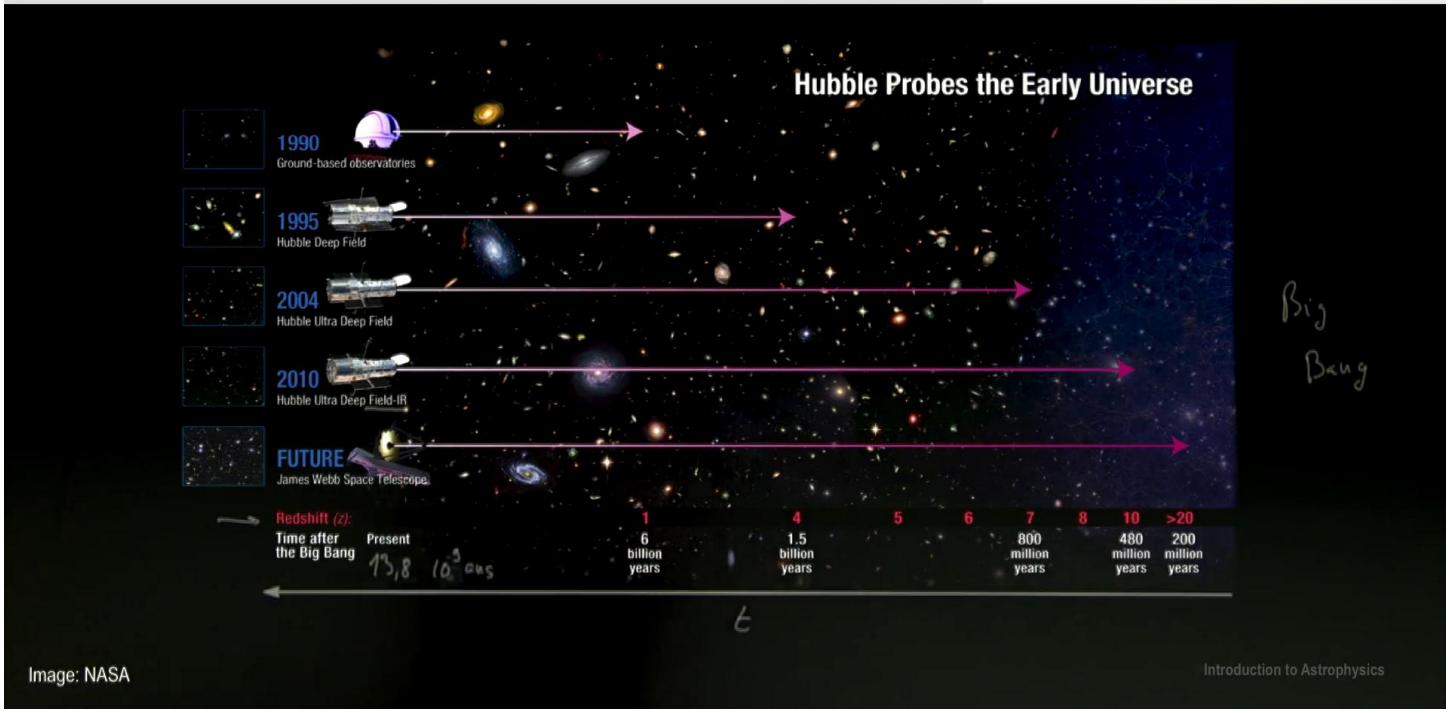
What are we searching for in cosmology ? We are trying to establish a connection between redshifts and the time that passes after the Big Bang. So the time after the Big Bang is summarized in this slide : we have here the time beginning at time "zero". The beginning of time is the Big Bang, which is around here. and then time passes after the Big Bang : we arrive here for example at a red-shift of 4 which corresponds to 1,5 billion years after the Big Bang. So time flows in this direction. At present time, we are around 13,8 billion years and we will try to establish a connection between the redshift and time after the Big Bang, so the distance. To do that, we need more and more powerful observatories So here we have the evolution in time of different observatories. Here's the Mount Palomar observatory with a 5m telescope in diameter which allowed to reach redshifts of the order of 1 with cameras that had the sensitivity of the 90s. Then from space with more and more sensitive cameras, as more and more servicing missions to the space telescope allowed to replace the cameras that were used with the telescope. We were able to go to ever greater distances. Here, we see that we added the infra red.

Notes

Summary

1m 51s

Redshift and Distance



Why? Simply because the spectrum of the galaxies we try to observe, will be more and more red shifted to the point of reaching the infra red domain. We therefore need infra red detectors if we want to observe at extremely large distances. That is the actual space telescope with optical and infra-red detectors. and then there is the next generation space telescope, the James Webb space telescope, which will have only infra-red detectors. It will be able to see extremely distant galaxies. The diameter of the James Webb telescope is also much bigger, three times the actual space telescope diameter which has a diameter of 2,4 meters.

Notes

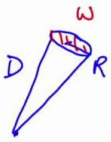
Summary

3m 19s

Relation fondamentale $1+z = \frac{1}{a(t)} = \frac{\lambda_{obs}}{\lambda_{em}}$

$D = f(z, \text{paramètres cosmologiques})$ → H_0, densités des différents composants de l'univers.

Mètres standards : R



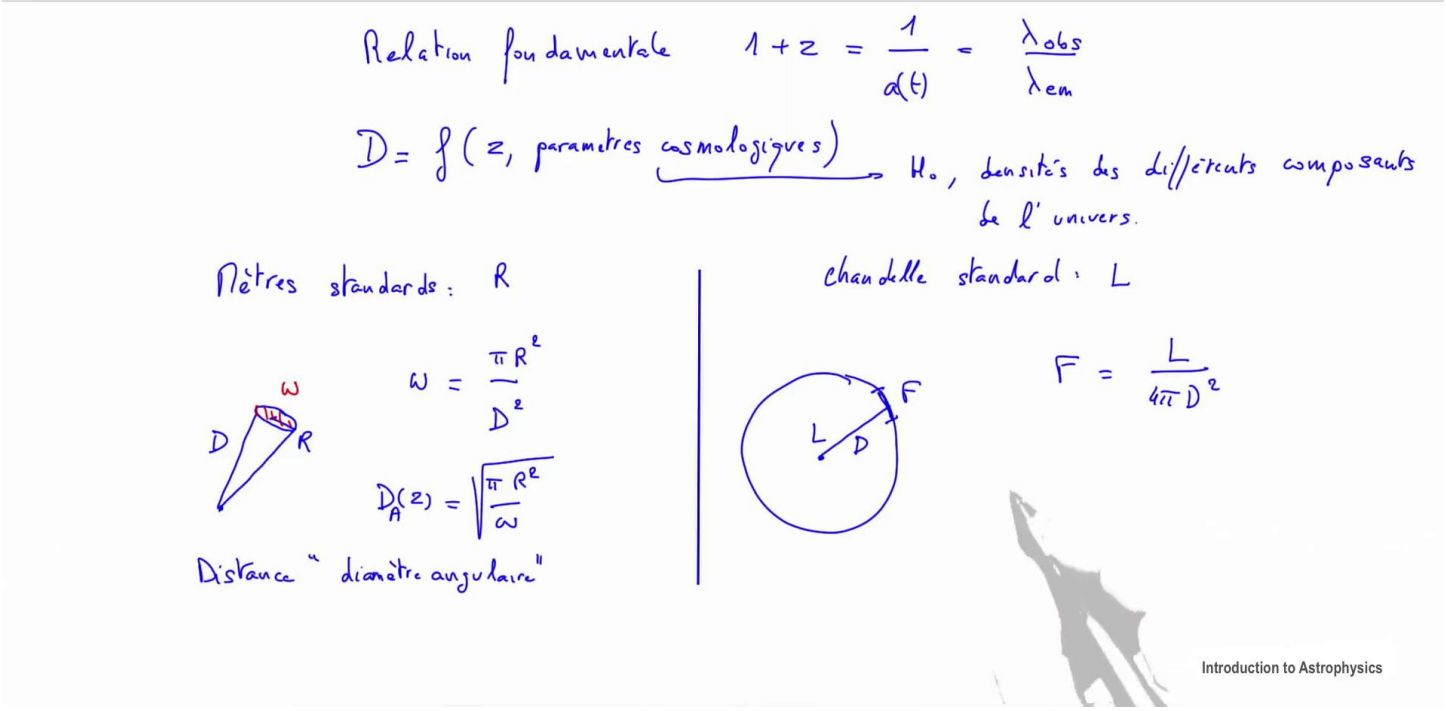
What we try to do in observational cosmology, is to use the fondamental relation we established in the previous video. between the redshift z or actually 1+z and the expansion factor of the universe α(t) and what we can measure: the cosmological red shift measured by Doppler effect. That is the wavelength of an object as we would observe it and that is the emission wavelength of a signal in the object's frame of reference that emitted the signal. The cosmological models give us the possibility to determine the distance to the objects, which will be a function of the red shift or the expansion factor, and the cosmological parameters. These cosmological parameters will be essentially H zero but also the density of the different components of the universe. These components will include the repulsive dark energy which is responsible for the accelerated expansion of the universe and dark matter. Now how to define the distances ? I said that we have standard rulers and standard candles. For standard rulers, we will suppose that we have an object of which we know the intrinsic radius and then we observe this object at a given distance d from us and this object will underlie a solid angle, the object has a given radius, which underlies a certain solid angle ω it is at a given distances from us, and that is of interest and we will have a relation between these three quantities.

Notes

Summary

4m 00s

Distance Ladder

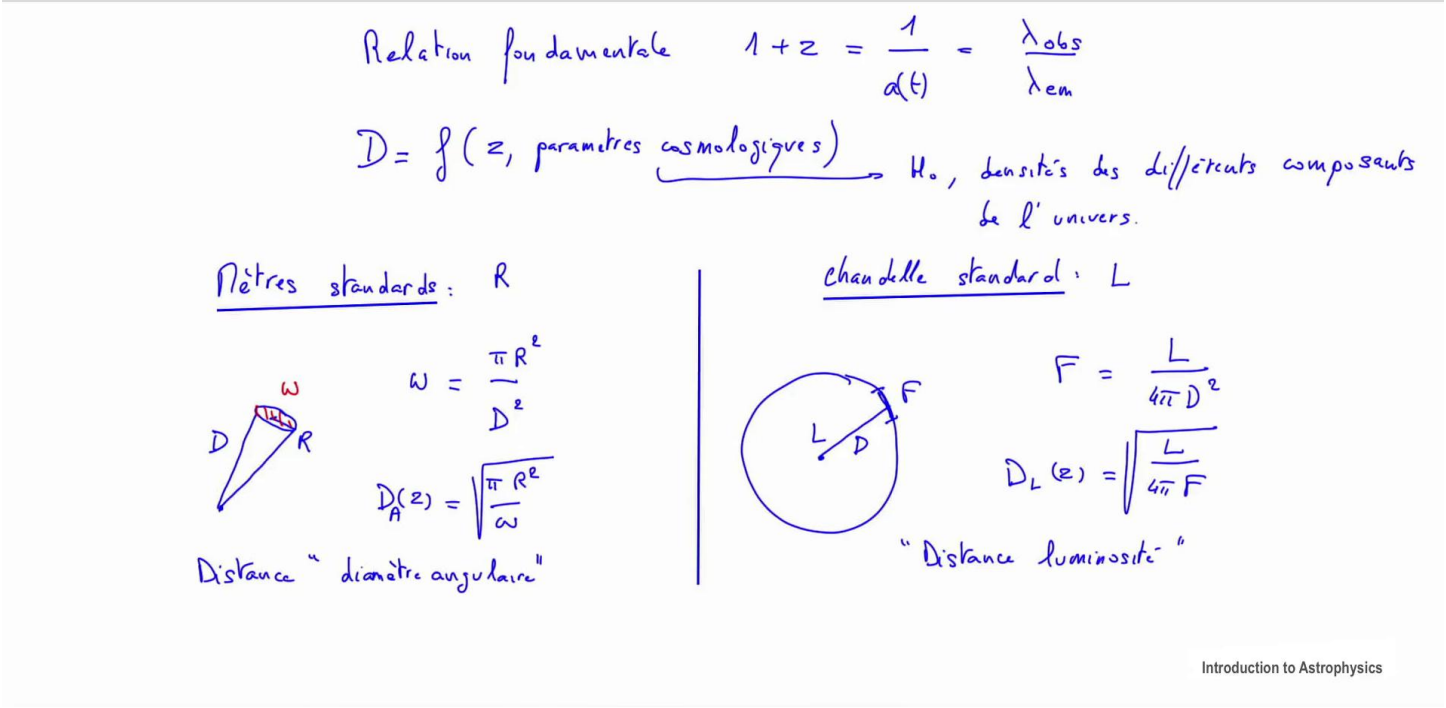


It's simply the relation between the solid angle and the radius of the object : ω (the solid angle) will be equal to πR² (R is the radius of the star) and D is the distance that we are interested in. So by measuring the solid angle, if we know the intrinsic radius of the object, we get the distance we will call the angular diameter distance, DA(z) will be equal to the square root of πR² over w (w is an angle). This is what we call angular diameter distance. We also said that we have standard candles. If we look at what happens at the level of the standard candles, how we will define the distance? If we have a standard candle, we do not have anymore a stellar object with a well known, well callibrated, well determined radius but we have a certain luminosity which will be the standard luminosity. We have already seen how to measure the flux of an object with a certain well known luminosity L the object has an isotropic radiation at a certain distance D from itself and sends us a flux diluted over a sphere like this and the flux is simply F is equal to L / (4πD²) This allows us to define a second distance. If we measure the flux of an object, we know its intrinsic luminosity.

Notes

Summary

6m 00s



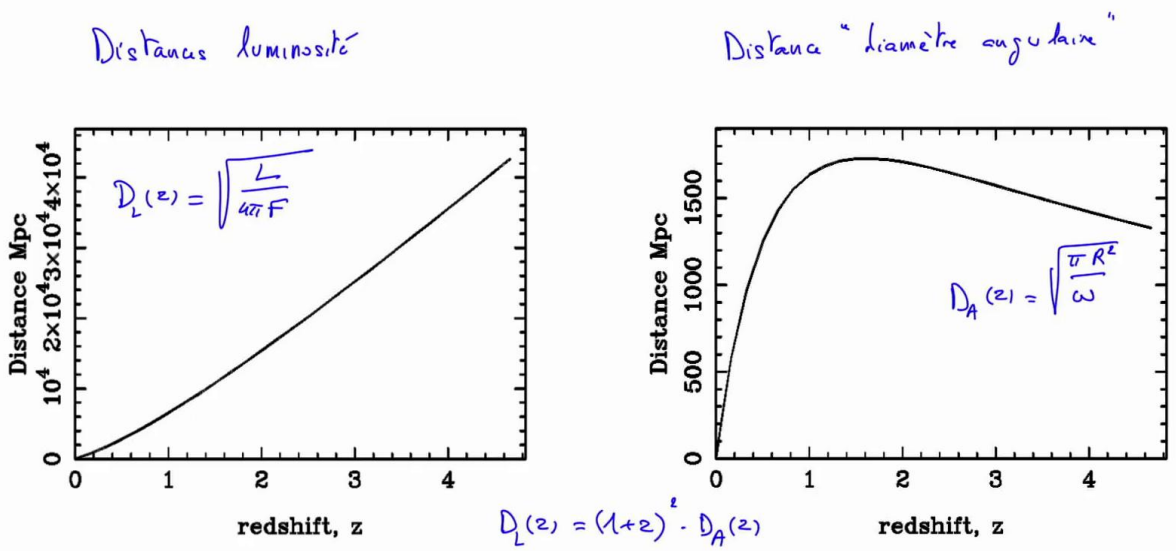
We deduce from it the distance we call the luminosity distance which depends on z (red shift) measured by the Doppler effect, so we will have D equal to L over 4π times the measured flux. This is what we call the luminosity distance. So we have two possible definitions of the distance, one based on standard rulers, and the other on standard candles. So objects that have either a well known size or a well known luminosity. It's like this that we will define distances.

Notes

Summary

7m 38s

Distance Ladder



Graphiques: Refregier et al. (2011, Astronomy & Astrophysics, 528, 33) et http://www.icosmo.org

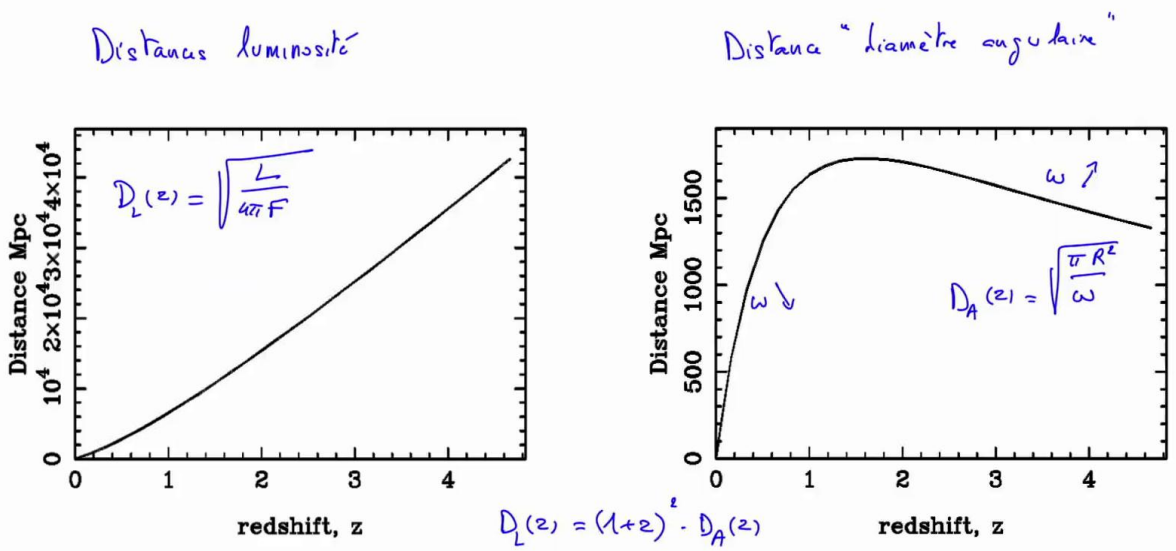
So let's see how the models (we use a given cosmological model without giving the details of this model), here the curves that link the redshifts to the distances in this case luminosity distances and in this case angular diameter distances. We have two types of distances. In the case of luminosity distances we have DL(z) equal to the square root of L over 4πF If we know an object of luminosity L and place it a different redshifts, we will measure a given flux and deduce a given distance. This is the predicted distance by a certain cosmological model. We have the angular diameter distance on one side, which will be equal to πR², so the intrinsic radius, which we are supposed to get by an independent method, and the solid angle which underlays the object. We see that we do not have the same relations, we do not have the same curves. We have in fact a relation between the different distances, we have DL(z) = (1 + z) ² times DA(z) it's for this that the curves are different. They are different but not incompatible. We just have two ways of defining distances. It's important to define how we look at distances : either with angular diameter distances, or with luminosity distances.

Notes

Summary

8m 18s

Distance Ladder



Graphiques: Refregier et al. (2011, Astronomy & Astrophysics, 528, 33) et http://www.icosmo.org

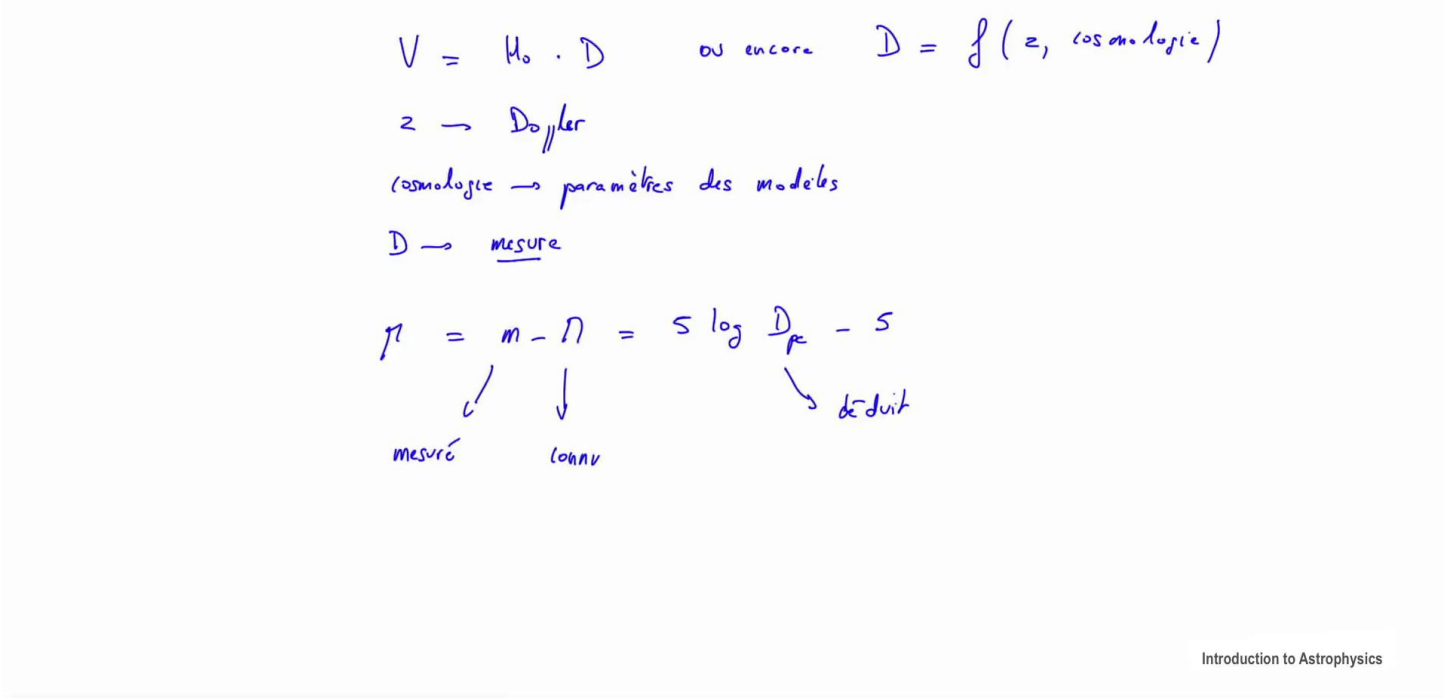
In both case, we have to confront the correct observations, to the correct theoretical predictions. Here we have models that predict luminosities or apparent fluxes. Here we have models that predict apparent solid angles for reference objects. It's important to know what distance we are talking about. There is also something that might seem counterintuitive : in the case of luminosity distances, an objects gets fainter and fainter as the red shift gets higher. Here when the red shift goes up, the angular diameter distance to an object will get to a peak and then go down. This means in practice: ω the apparent diameter or apparent radius of an object in the sky, when its red shift gets higher the apparent diameter will first go down ω goes down, and then goes up in this part here of the curve. An object that we will put further and further will have the tendency of getting bigger and bigger in appearance. However, its apparent luminosity will continue to diminish. and the distances are linked by this equation here.

Notes

Summary

9m 59s

Standard Candles



Now we will concentrate on the standard candle methods to measure distances. We will link the velocity to the distances, with Hubble's law, valid for small shifts up, small z or in other words we will try to link the distances to a function of cosmology (z) and cosmological parameters. Here z is measured by Doppler effect. Cosmology are the parameters of a model and when we change these parameters, we change the prediction of these models. D is what we try to measure with standard candles. We have a very useful tool for that: the distance module μ the difference between the apparent magnitude and the absolute magnitude of an object which is equal to 5 times the log to the distance/sec minus 5 So the method is very simple from here on: if M is known, (for a standard candle) and if m is measured, then we can deduce the distance. The standard candle method is extremely simple : we use the distance modulus we measure it by measuring the apparent magnitude of a celestial body of which we know also the absolute magnitude and we get the distance.

Notes

Summary

11m 19s

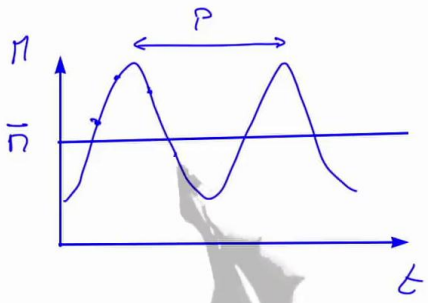
Cépheid Stars

Supergeantes , brillantes , pulsantes

$L = 4\pi R^2 \sigma T^4$

$\bar{M} = f(P)$ L ↗ avec P

$\bar{M}_V = -2{,}43\,(\log P - 1) - 4.05$



There are a series of objects which we can consider as standard chandles. The most famous are the cepheides stars and we will also see the supernovae. First the Cepheid stars : are gigantic stars that are extremely bright, so we can them from far away and they will be pulsating. If they pulsate, their radius varies periodically. We have the famous relation L = 4πR²σT4 If the radius varies, the temperature also varies a little bit but it's the luminosity in the end that will vary. There is a relation between the period and the luminosity of the Cepheid stars. If I show you this on a graph : here is what could be the absolute magnitude of a Cepheid star, the time is here, and the light curve of the Cepheid star. We have a given mean value, we have a mean m, we also have a period and the Cepheid stars also have a link between their absolute average magnitude and the period. So we have an average m which is equal to a function of the period. Also the luminosity grows with P So M decreases with P because it's in magnitude and the exact relation is m average in the v band is equal to minus 2,43 times (the decimal logarithm of the period - 1) minus 4,05 This means that if we measure for example observational points, on a curve like this.

Notes

Summary

12m 48s

Céphéid Stars

Supergeantes, brillantes, pulsantes

$L = 4\pi R^2 \sigma T^4$

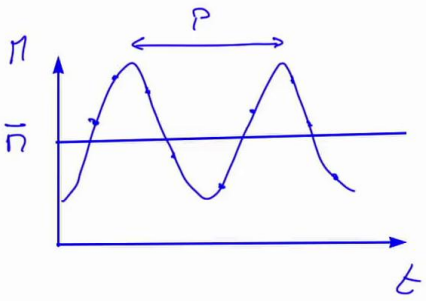
$\bar{m} = f(P)$ L ↗ avec P

$\bar{m}_V = -2{,}43\,(\log P - 1) - 4.05$

$m - \bar{m}_V = 5 \log D - 5$

δ Céphée → archétype

Etoile polaire → céphéide



Henrietta Leavitt

v 1910 - 1920

Introduction to Astrophysics

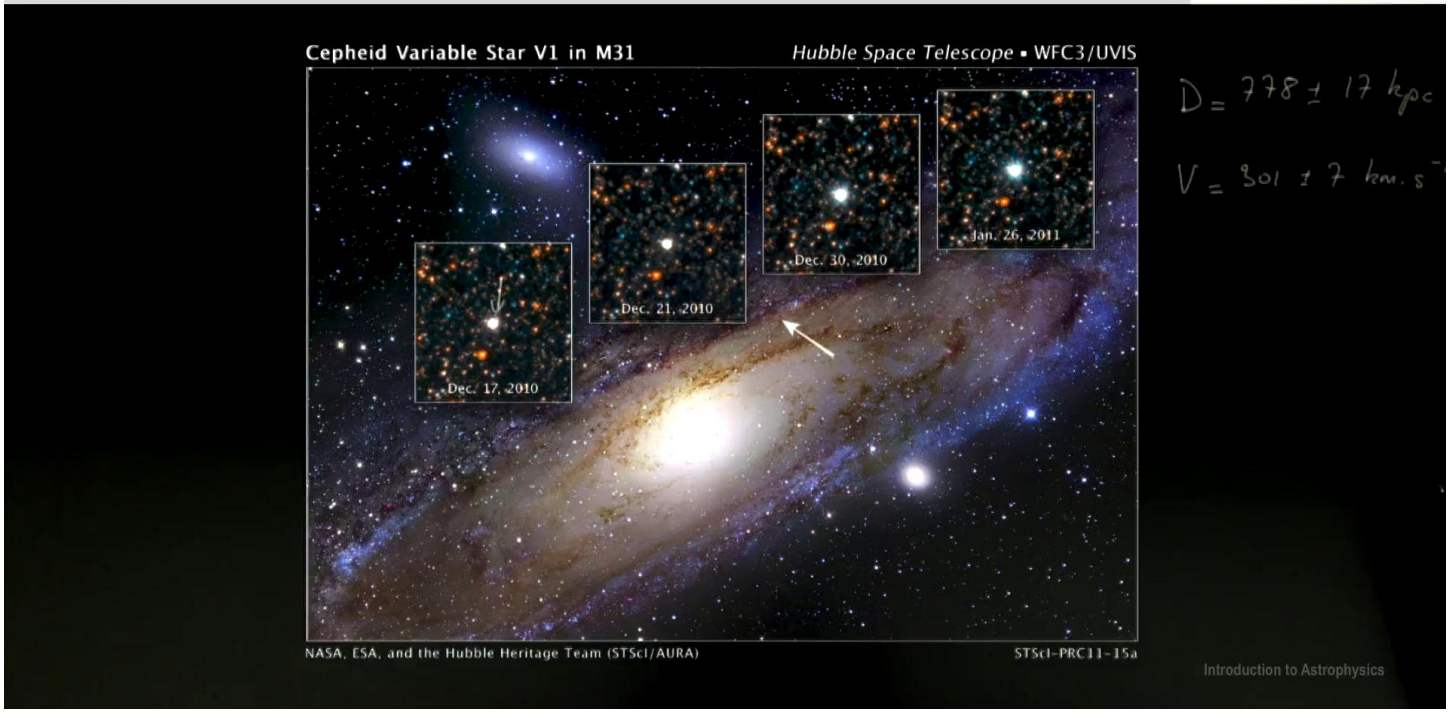
I take a galaxy in which there is a Cepheid star, I regularly measure its photometry and then I will have what I call the light curve. I will be able to measure the period and so have the absolute magnitude that I will be able to inject in the distance module. Here is again the formula of the distance modulus: we will be able to inject m average here in the formula of the distance modulus and get the distance. It's a relation that was first measured by Henrietta Leavitt, in the years 1910-1920. It's not something recent but it's only recently that we could apply this method with the Hubble space telescope to measure distances to galaxies to around 40 - 50 megaparsec from us. There are some very well known stars that are Cepheid stars : obviously the δ Cephei star which is the archetype of Cepheid stars but the polar star is also a Cepheid star The star towards which the rotation axis of the earth points, the polar star, is a pulsating Cepheid star.

Notes

Summary

14m 52s

Cépheid Stars in the Andromeda Galaxy



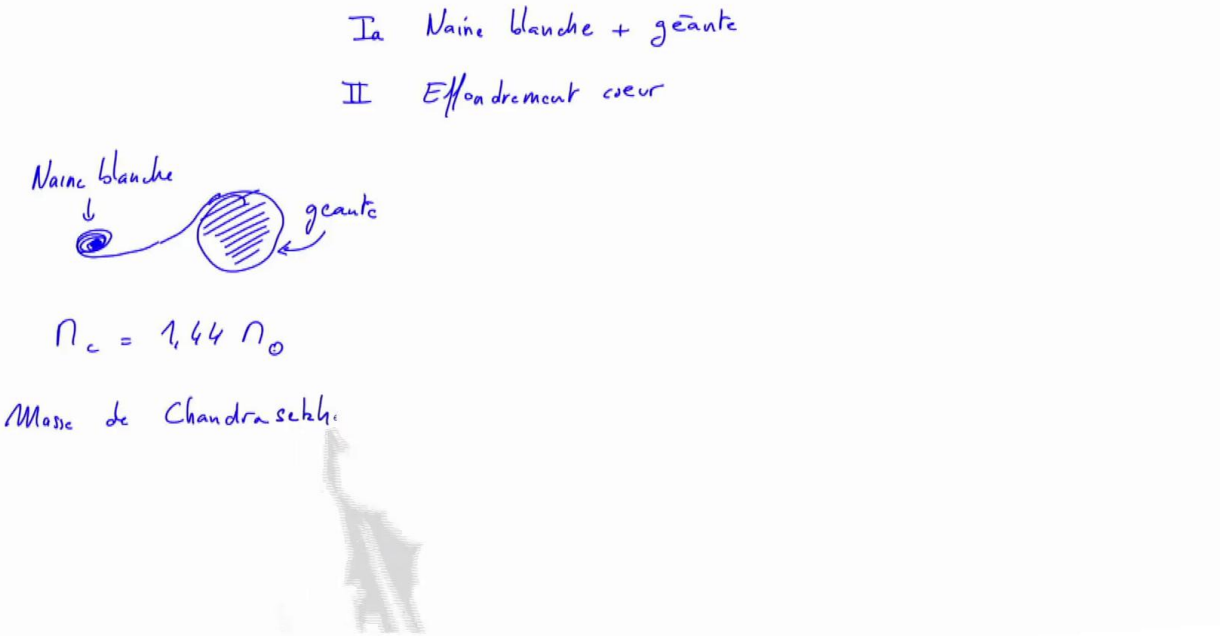
As I said before, we used the space telescope to observe the Cepheid stars. We also need to separate the stars in the Messier 31 galaxy in this case here, to distinguish between the Cepheids and other stars. I said that Cepheid are very bright, here is one If we measure the luminous flux of that Cepheid star in time, we see that from here to here the star has grown in brightness. We measure the light curve, we measure the period, and we deduce the absolute magnitude. For the Andromeda galaxy, the measured distance is 778 +/- 17 kg/sec and the recession velocity measured by Doppler effect is around 301 +/- 7 km/s, so the Andromeda galaxy flees from us at an approximate velocity of 300 km per second.

Notes

Summary

16m 09s

Type Ia Supernovae



We know other standard candles which will be even brighter, so we will see them from even further away : which will be type 1a supernovae I'll skip the details here on how supernovae work. They are two types. Type 1 supernovae stars : those are white dwarfs which are in orbit around a common gravity centre with giant or super giant stars. Matter will go from the giant to the white dwarf and matter will accrete. After some time, we will have a sufficient critical mass for a supernova explosion. This is a type of supernova i haven't talked about in the previous videos. What we had until now, were type 2 supernovae which we call core-collapse supernovae. We have seen that for massive stars we have nuclear reactions up to the iron fusion reaction which takes place from here on, the iron reaction being endothermic the core of the star collapses and we have a supernova explosion. This is what we saw in the previous chapter. chapter 5 on stellar evolution. The supernovae of interest for us are type 1 a supernovae, which are fact white dwarfs, so binary stars, white dwarfs, around a giant and matter will fall, attracted by the white dwarf, spiral around the white dwarf and so accrete matter After some time, we will reach the critical mass of the white dwarf, the critical mass is 1,44 Solar Mass also called the Chandrasekhar mass.

Notes

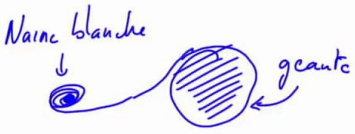
Summary

17m 02s

Type Ia Supernovae

Ia Naine blanche + géante

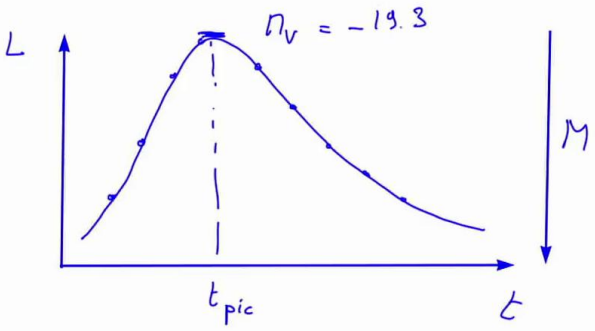
II Effondrement coeur



$M_c = 1,44 . M_\odot$

Masse de Chandrasekhar

→ explosion → toujours la même luminosité



Introduction to Astrophysics

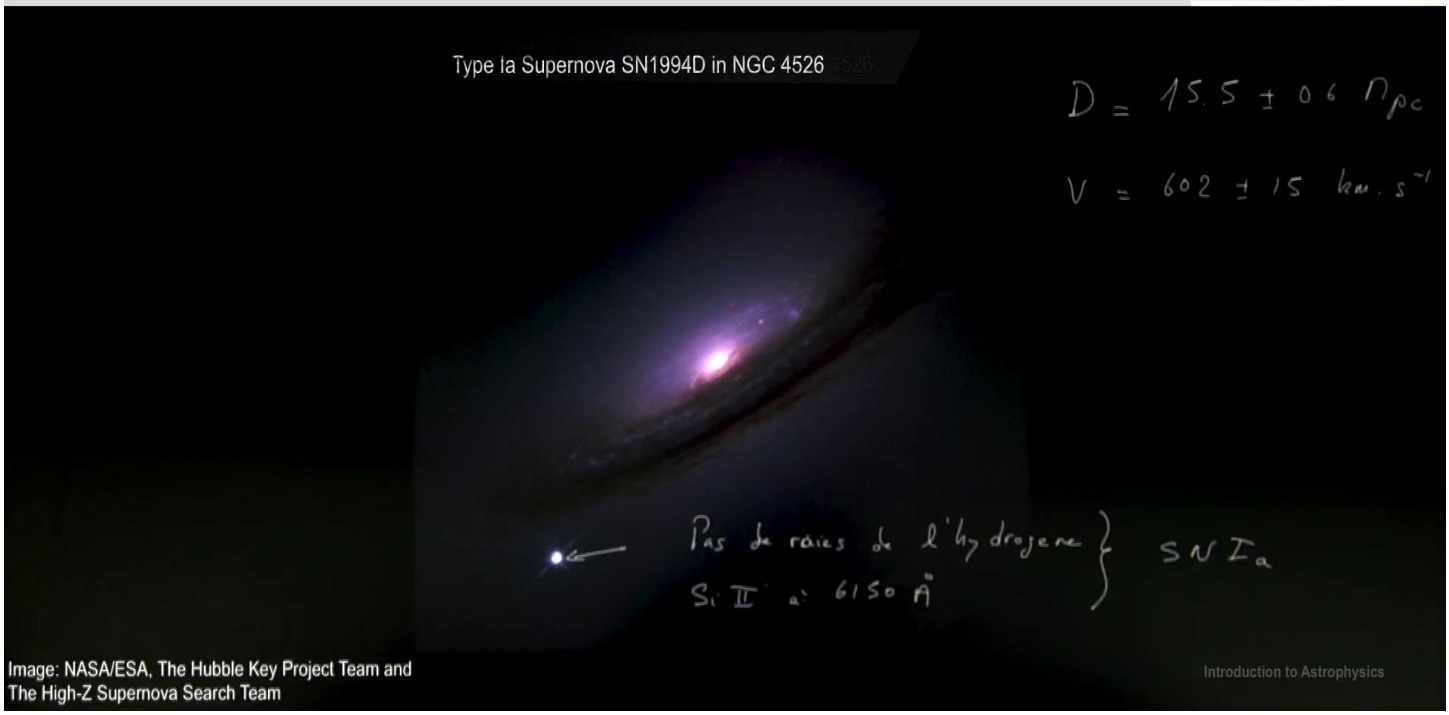
Each time the white dwarf has accreted enough matter, that is 1,44 times the mass of the sun, we will have a supernova detonation. Since the critical mass is always the same we will always have the same luminosity. Actually it's the explosion peak that will always have the same luminosity. What is of interests here is what we call the light curve of the supernova as in the Cepheid stars case. But this time on the axes we have the time here the luminosity here, and also the absolute magnitude that would be here. When the supernova explodes, it will grow in luminosity, reach a peak and then go down. If we calibrate this curve, we will see that at a given moment, we have a luminosity peak that will correspond to an absolute magnitude in the v band of -19,3 So when a supernova explodes, we take some measurement points, we have a light curve, we make the adjustment by least square over the light curve, we measure the peak and that gives us the absolute magnitude in the v band another time, that is what we will inject in the distance modulus to determine the distance to the supernova.

Notes

Summary

19m 05s

Type Ia Supernovae



Here are some supernovae examples : here we have a spiral galaxy at a relatively short distance. We have here the distance C measured through supernovae of 15,5 +/- 0,6 megaparsec that is already a lot further away than the Andromeda galaxy. We would not be able to see Cepheids in a galaxy like this. The recession velocity here is much larger : 602 so exactly twice that of Andromeda so 602 km per second and if we take a spectrum of that supernova we will find that there is no hydrogen line. Instead we will have silicium II, i.e., silicium ionized once, that can be found at the wavelength 6150 Å It's these two caracteristics that are the spectral signatures of type 1a supernovae. When a supernova explodes, we can do two things : we take a spectrum, we look if there is no hydrogen and if there is silicium and we measure the light curve to get the apparent magnitude of the supernova, which will worrespond to a given absolute magnitude. So we will have the distance modulus and the distance to the galaxy where the supernova is.

Notes

Summary

20m 37s

Type Ia Supernovae

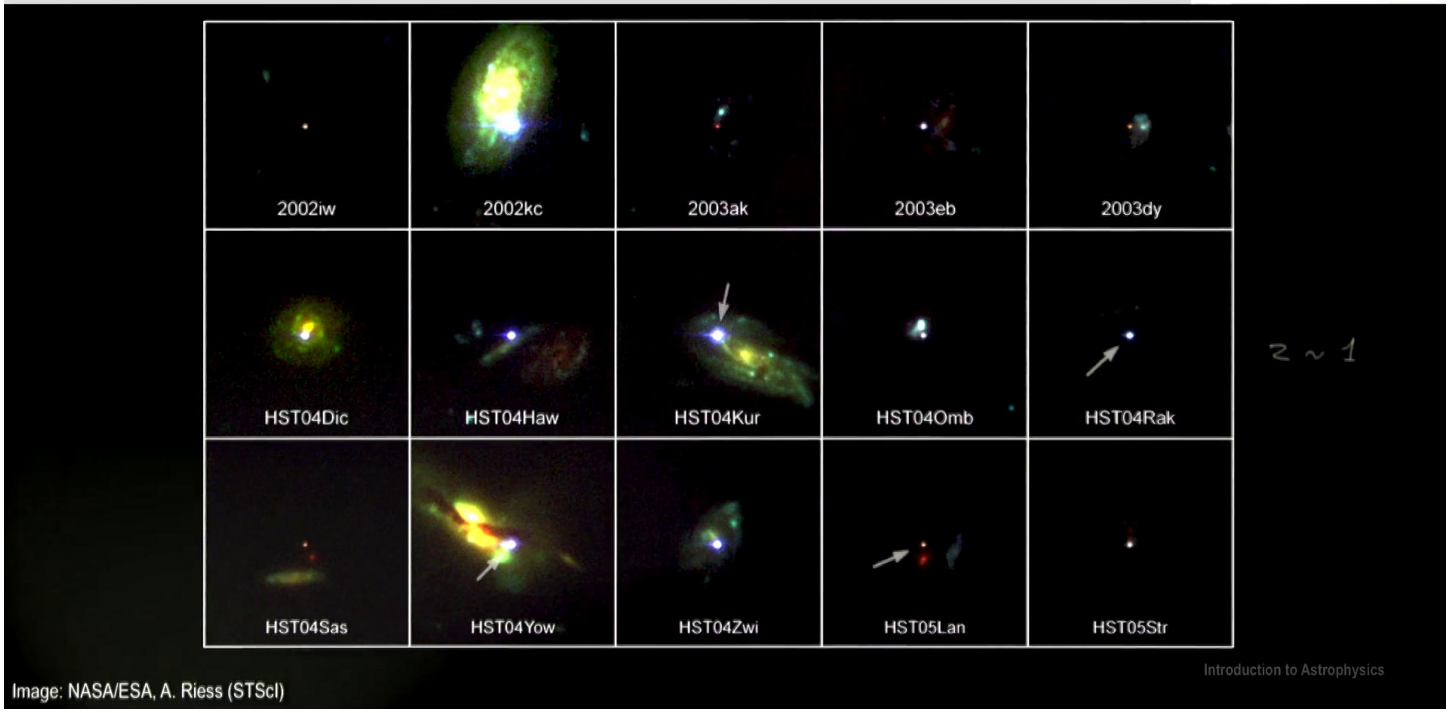
Here is another galaxy NGC 3370 The distance is beginning to be a bit higher : we have a distance of around 30 megaparsec We have here an observation taken by a ground telescope, with a supernova that exploded, and an observation taken with the spatial telescope with the supernova before or after the explosion in any case not present on the image.

Notes

Summary

22m 02s

Type Ia Supernovae



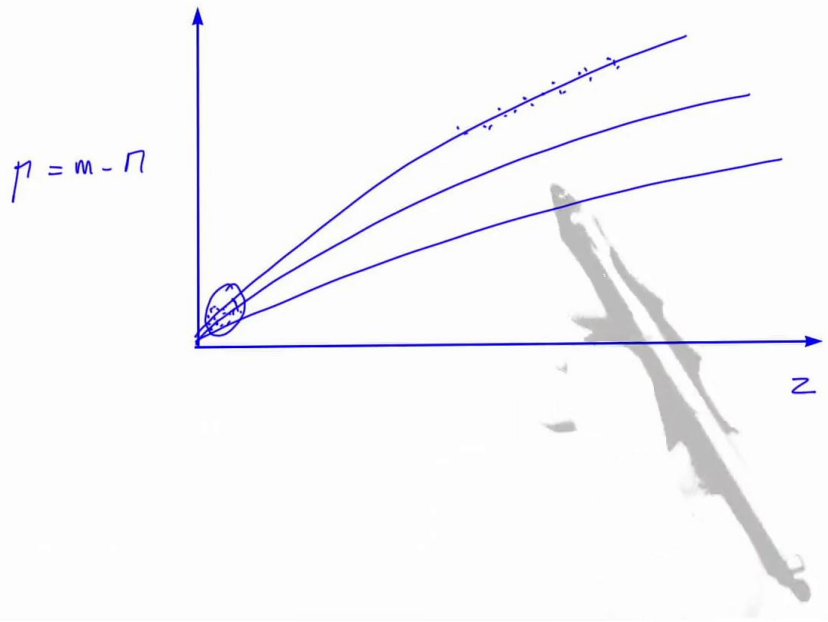
The recession velocity of this galaxy is even higher than the others : 1279 km per second for this one Now if we go even further, we'll be able to see the true usefulness of the supernovae tool We have galaxies at a red shift of around 1, the red shift is around 1 and we have different supernovae here : we see an extremely bright one here. In fact many times brighter than the galaxy in which the supernova is, which we barely see. We have another here which is in an interacting galaxy. Another one here, with a relatively blue supernova spectrum. And here another one. So thanks to these supernovae we will be able to measure the distances to all these galaxies. The further we go, the better we will test the cosmological models.

Notes

Summary

22m 37s

Hubble Diagram



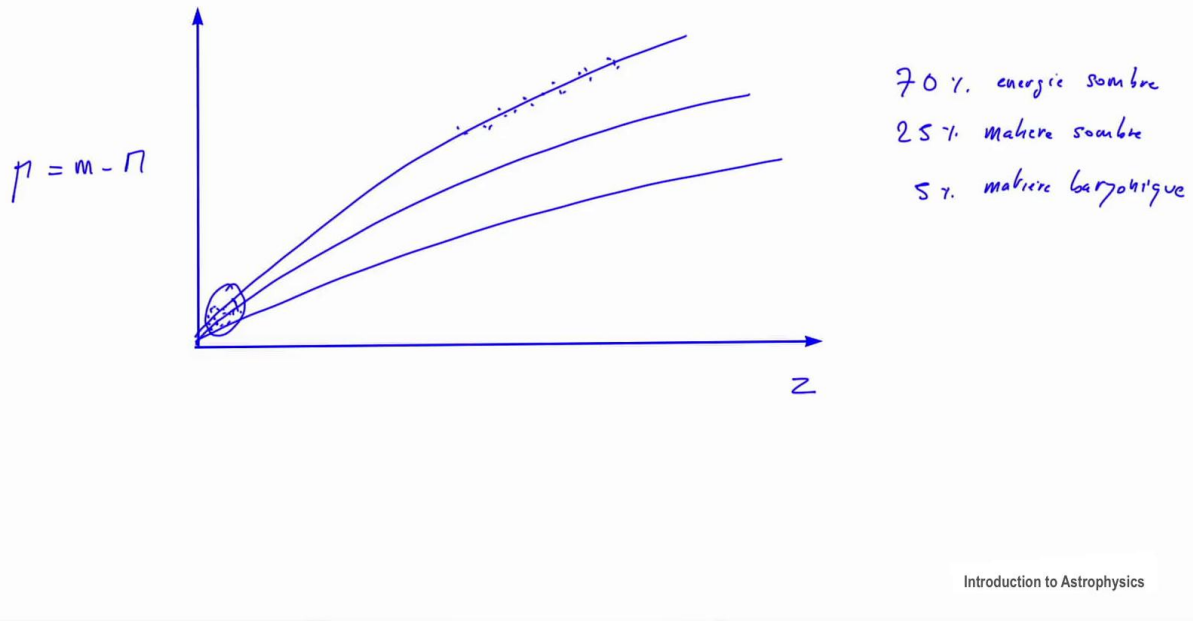
What will be important here, thanks to the Cepheids or supernovae, is to construct what is called a Hubble diagram. This Hubble diagram links the distance modulus to the red shift. Here is how one of these diagrams looks like : these are not observations or predictions. It's just a qualitative schematic. We will have here a red shift. Here the distance module m minus M So for the Cepheids, we measure the mean apparent magnitude and we know, thanks to the period-luminosity relation, the absolute magnitude. For a supernova, we know the absolute magnitude of the luminosity peak at the explosion. We measure the apparent magnitude of the explosion peak and obtain the distance modulus. Now we of course have theoretical predictions. I draw like this, theoretical models which link the red shift to the distance modulus. Then, we have to take sufficiently precise observational points to be able to discriminate between the different cosmological models. We can already see here that the further one goes in red shift, the more one will be able to discriminate between the different models. If I take points too close to us we will not be able to discriminate between the cosmological models, while there we can do it.

Notes

Summary

23m 21s

Hubble Diagram



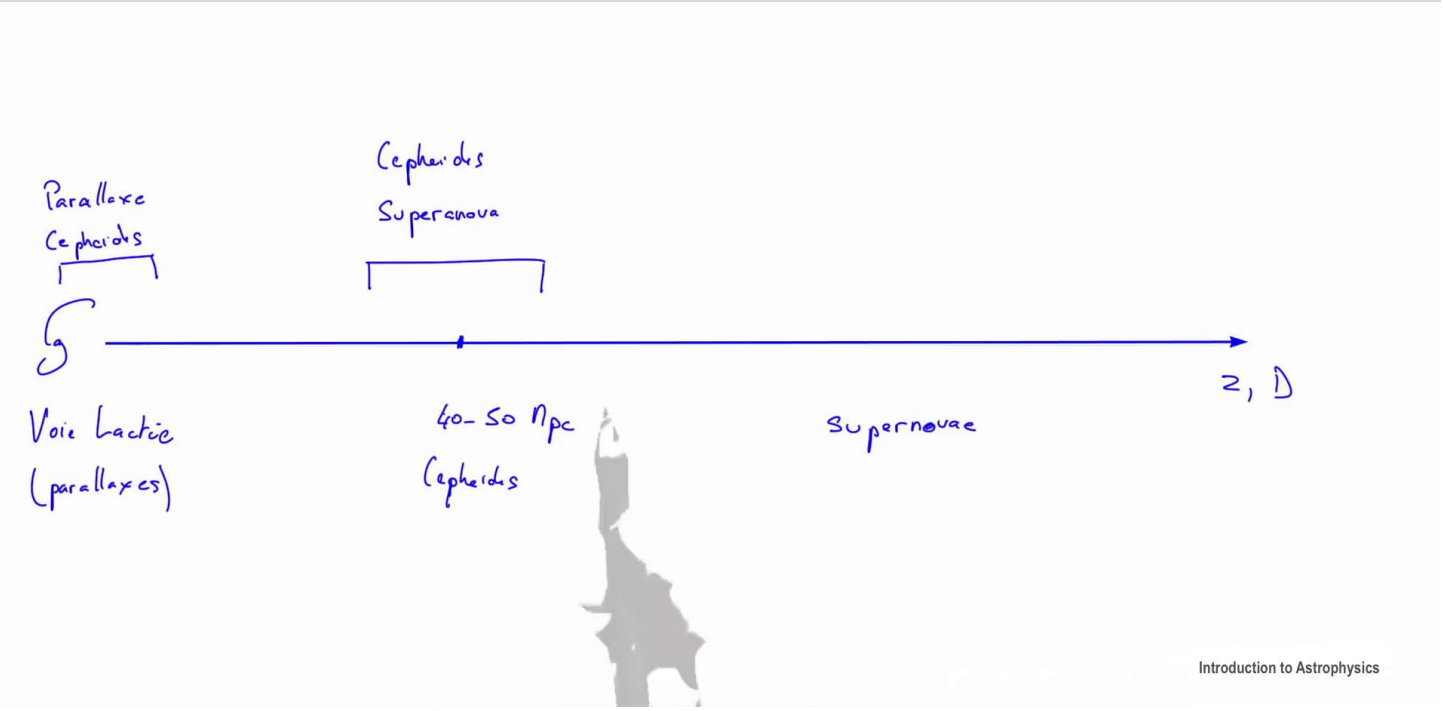
Of course it is harder to measure distant points since we need bigger telescopes but we also test the cosmology better. The prediction of the models, the difference between the curves, will be the cosmological parameters so H zero but also the different energy density parameters. 70% dark energy, 25% dark matter and 5% baryonic matter or normal matter. So the difference between these models here, are the proportions of these different densities. If we manage to measure μ and z, we can differentiate between the different cosmological models. Since the years 2000, we know that we live in an universe in accelerated expansion, so we were able to discriminate between the different curves in these Hubble diagrams.

Notes

Summary

24m 57s

Building the Distance Ladder



A word about what we call the distance scale : we have seen that we have different methods to measure distances. The goal is to go to high red shifts. We have high red shifts, large distances here We are somewhere in the Milky Way. Then we can measure parallaxes in the Milky Way. We will be able to go to distances of around 40-50 megaparsec. We will be able to use Cepheids. and then further, we will use supernovae We have a certain number of inter calibration zones, let's say : for example here a zone where we have measured parallaxes for Cepheid stars. So we will be able to establish a period liuminosity relation for Cepheids by measuring their distances with parallaxes. Then we have a zone here where we have galaxies in which we have Cepheids. From time to time these galaxies will have a type 1a supernova These are very rare, each galaxy has around one type 1a supernova per century. So these objects are extremely rare, we know of approximately 10 at the present time. It's thanks to this that will be able to correctly calibrate the relation between the supernova luminosity at their peak and the distance. Further away we use only supernovae as distance indicators.

Notes

Summary

25m 53s

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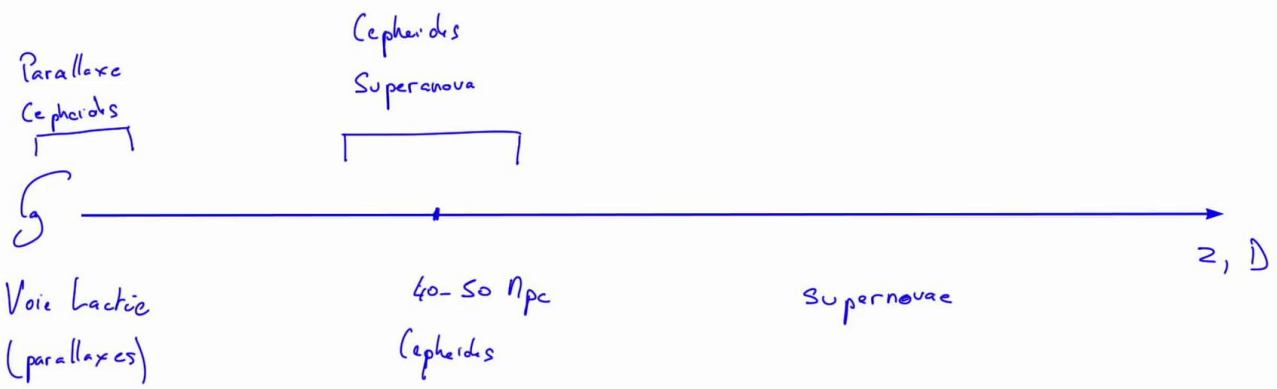

Introduction to Astrophysics

We have three essential indicators : parallaxes, Cepheids, supernovae which will be calibrated between each other in some zones where we have two different indicators available at the same time and then at a larger red shift, we only have access to extremely bright supernovae allowing us to go very far in our distance measurements.

Notes

Summary

27m 43s

We have seen how crucial, it is important to measure distances in the universe. it's one of the rare methods in fact the only one we have at our disposition to test the cosmological parameters, the parameters of the models which describe the relation between red shift on the one hand, measured by the Doppler effect, and the distance on the other hand, so what we predict through cosmological models. there are a given number of obstacles to this but fortunately they are not insurmountable. What we need in practice are bigger and bigger telescopes to capture as much light as possible and so see further and further standard candles, standard candles which will send us less and less photons due to their distance. That is not all, we also need ultra fine images, at very high resolution, as shown here, a galaxy taken with the Hubble space telescope. In these images, we will be able by zooming, to isolate interesting objects from the surrounding objects. For example we will be able to see the image of standard Cepheid candles a crowded stellar neighbourhood. In this sense, the Hubble space telescope is absolutely crucial for cosmology.

Notes

Summary

28m 04s