ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

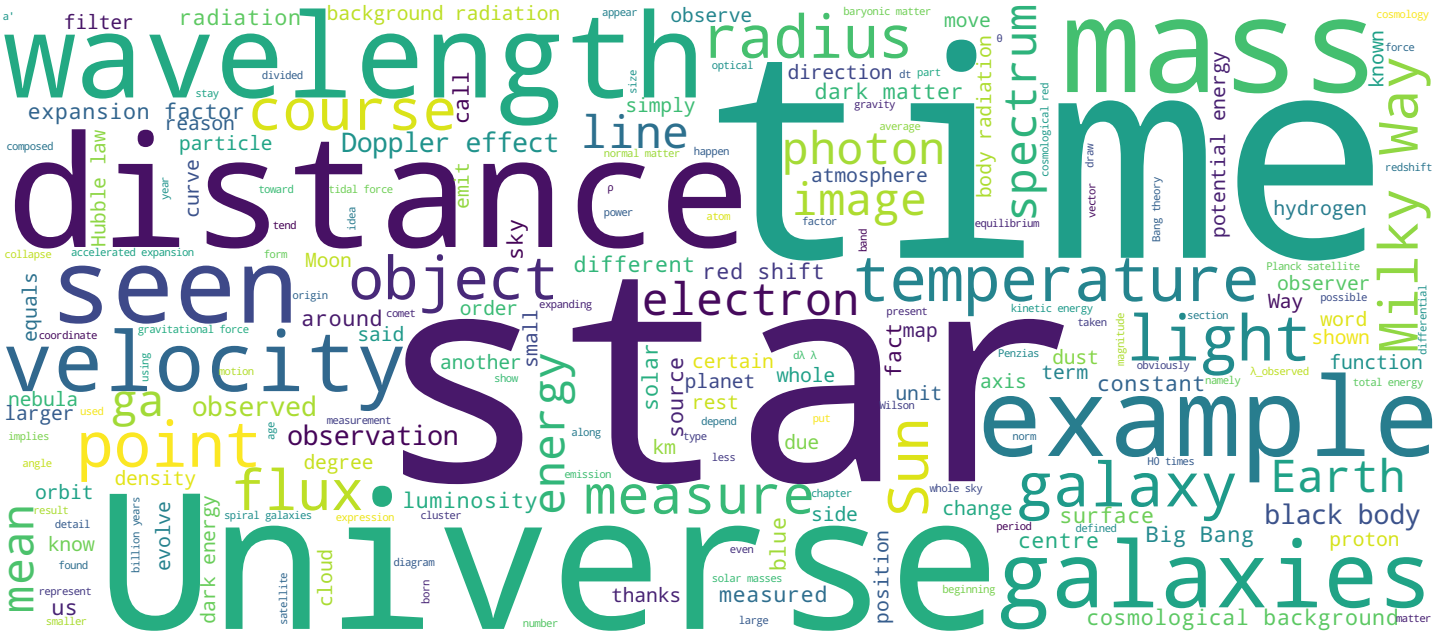
Brief Overview of Cosmology

Introduction to Astrophysics; Chapter 7.1

Frédéric Courbin

Cosmologie: «science des lois générales par lesquelles l'univers est gouverné»

Illustration: Camille Flammarion, «Atmosphère: météorologie populaire» (wikipédia)



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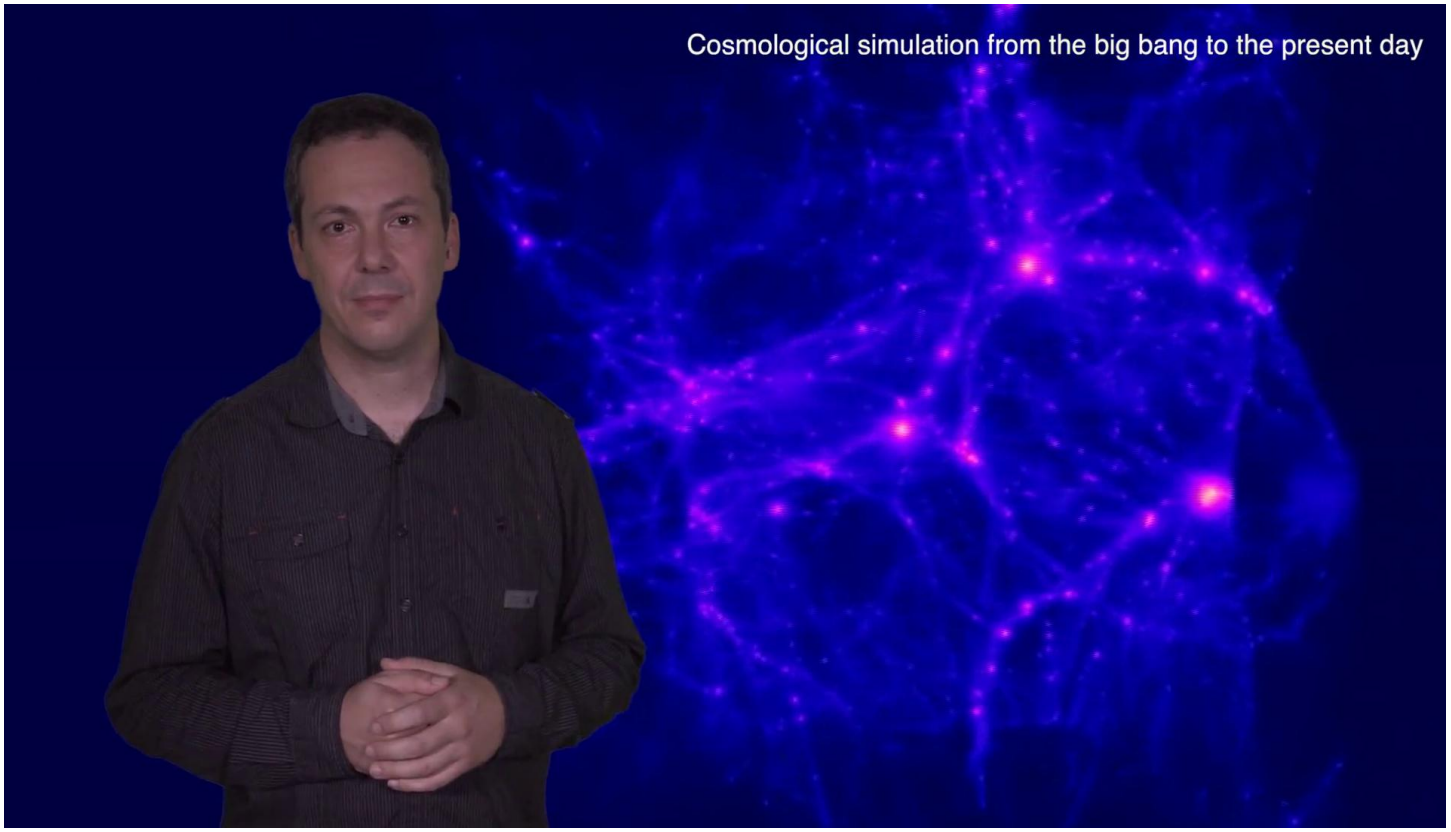


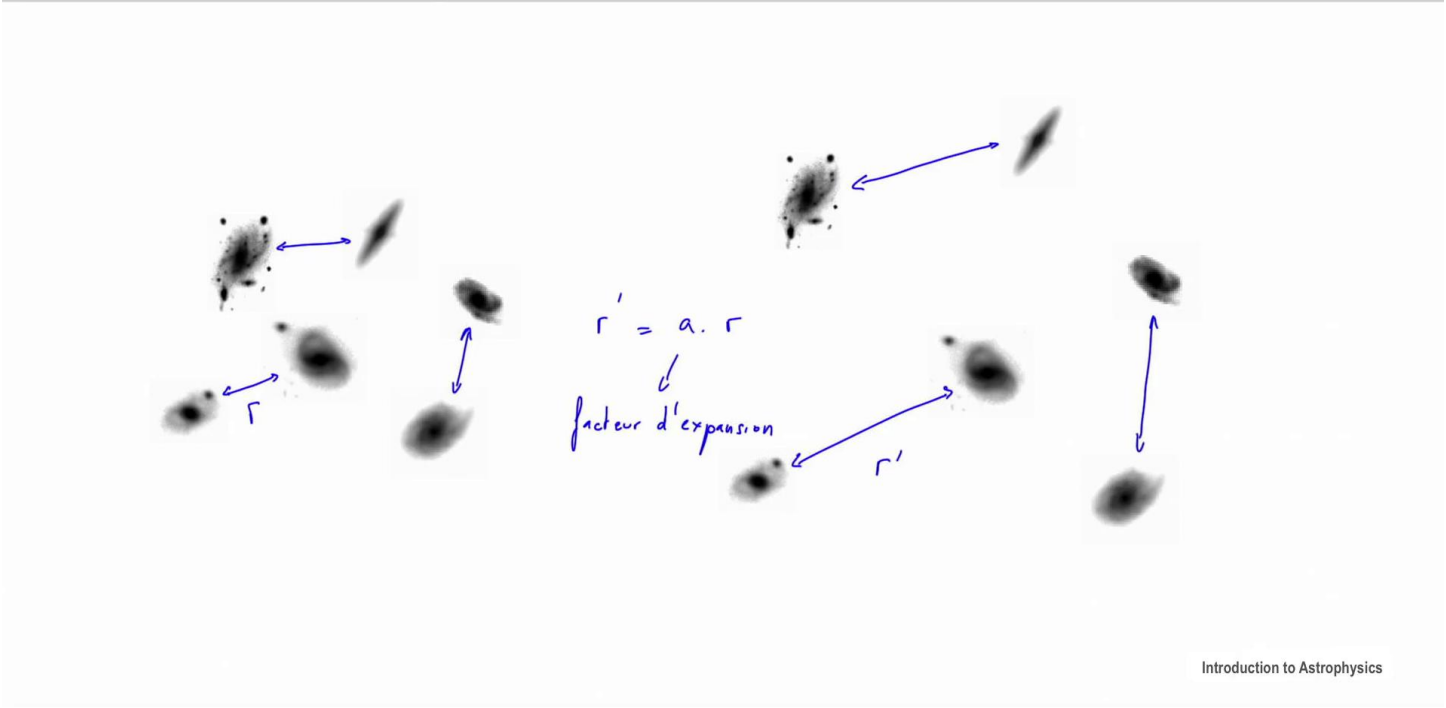
Up to now, we have seen how are formed celestial bodies that compose the universe, how they evolve and what are the physical phenomenons which give them their mass and luminosity. But what for the Universe as a whole ? What is its origin? How does it evolve with time? What will become of it ? What is his global composition ? All these question are closely linked, and belong to the field of cosmology. The theory which currently best explains all observations that are at our disposal is the Big Bang theory, where the Universe was born of one initial explosion, some 13, 8 billion years ago, followed by an extremely rapid expansion, called inflation, then, a slower expansion, as was found in twenties-thirties. Since the years 2000, we know that this expansion is accelerated, but the reason for this remains completely unknown. This can be explained only by invoking the existence of a repulsive force, due to some unknown form of energy called dark energy, and that would counteract the gravitational force, which tends to make the Universe contract itself.

Notes

Summary

0m 05s

Expansion of the Universe



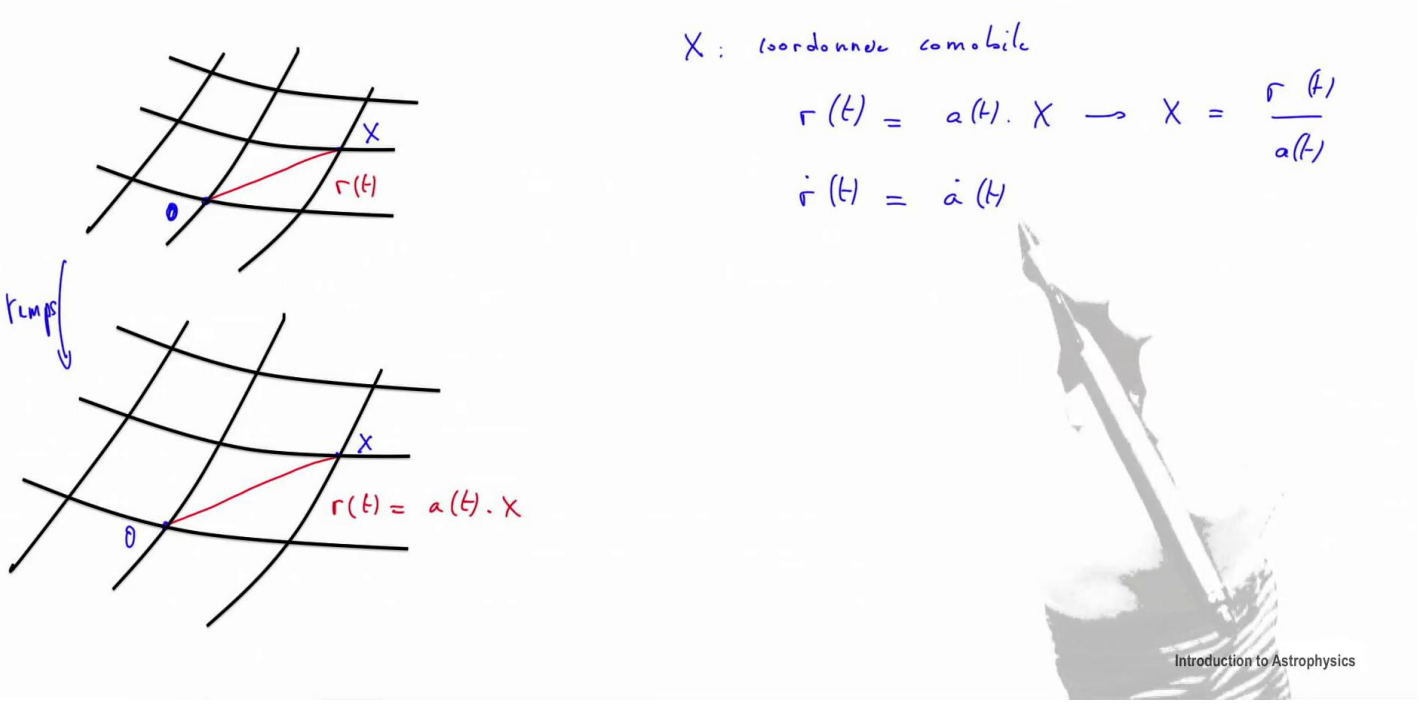
So we said that the Universe is expanding, that doesn't mean that the Universe was born in one point and is expanding like a spherical ball. But it means that all points are growing further apart from each other with some factor, called the expansion factor. So for example, here, we have a certain distance which becomes longer as the Universe is growing. We have another distance here, which also becomes longer by a certain factor, etc, etc. and the same for the distance here. and if we call r' the distance here and r the distance here between two points, we have r' = a * r, where a is what we call the expansion factor.

Notes

Summary

1m 14s

Expansion and Hubble Law



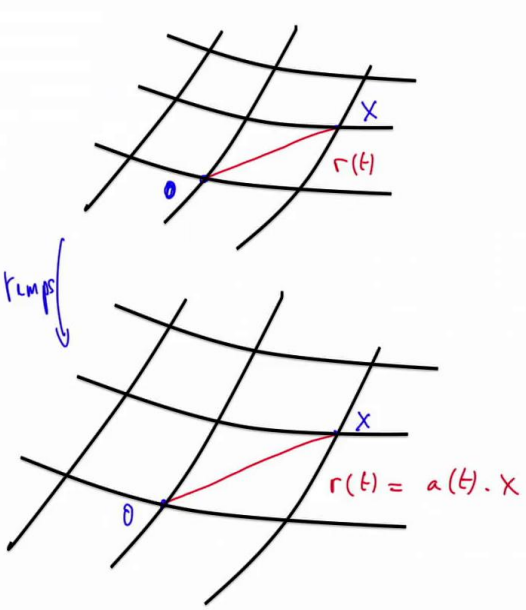
So lets look at this expansion in more details. So here we have a grid representing the metric defining how we measure coordinates in the Universe. and this grid will evolve with time, so time flows like this. and we can localize objects on this grid in various ways. For example, we put an origin here so the origin will be here, at an instant t later We take an object at a coordinate X. And when we let the system evolve with time, the X coordinate hasn't changed, for example, we take a section here and a section there to go to X. And we take a section here, a section there, to go to X. So X is what we call the comobile coordinate, which moves with the reference grid. We can also localise objects in a different way. We can say that the distance from O and X is the distance r, which is here. so r(t). and then, a moment later, the distance r(t) has grown. so this r(t) will be equal to a certain expansion factor times the co-mobile coordinate. So a(t) is the expansion factor of the Universe. Now we will see how all this evolves. So, as we said, r(t) is equal to a(t) times X. Of course we can also write that X = r(t) / a(t). Then, if we derive the expression to get the velocity, we will try here to recover Hubble's law.

Notes

Summary

2m 01s

Expansion and Hubble Law



X : coordonnée comobile

$r(t) = a(t) \cdot X \rightarrow X = \frac{r(t)}{a(t)}$

$\dot{r}(t) = \dot{a}(t) \cdot X$

$v(r,t) = \frac{\dot{a}(t)}{a(t)} \cdot r(t)$

$\frac{\dot{a}(t)}{a(t)} \rightarrow H(t)$

Taux d'expansion

$v(r_0,t_0) = H(t_0) \cdot r(t_0)$

$V = H_0 \cdot D \rightarrow$ Loi de Hubble

Introduction to Astrophysics

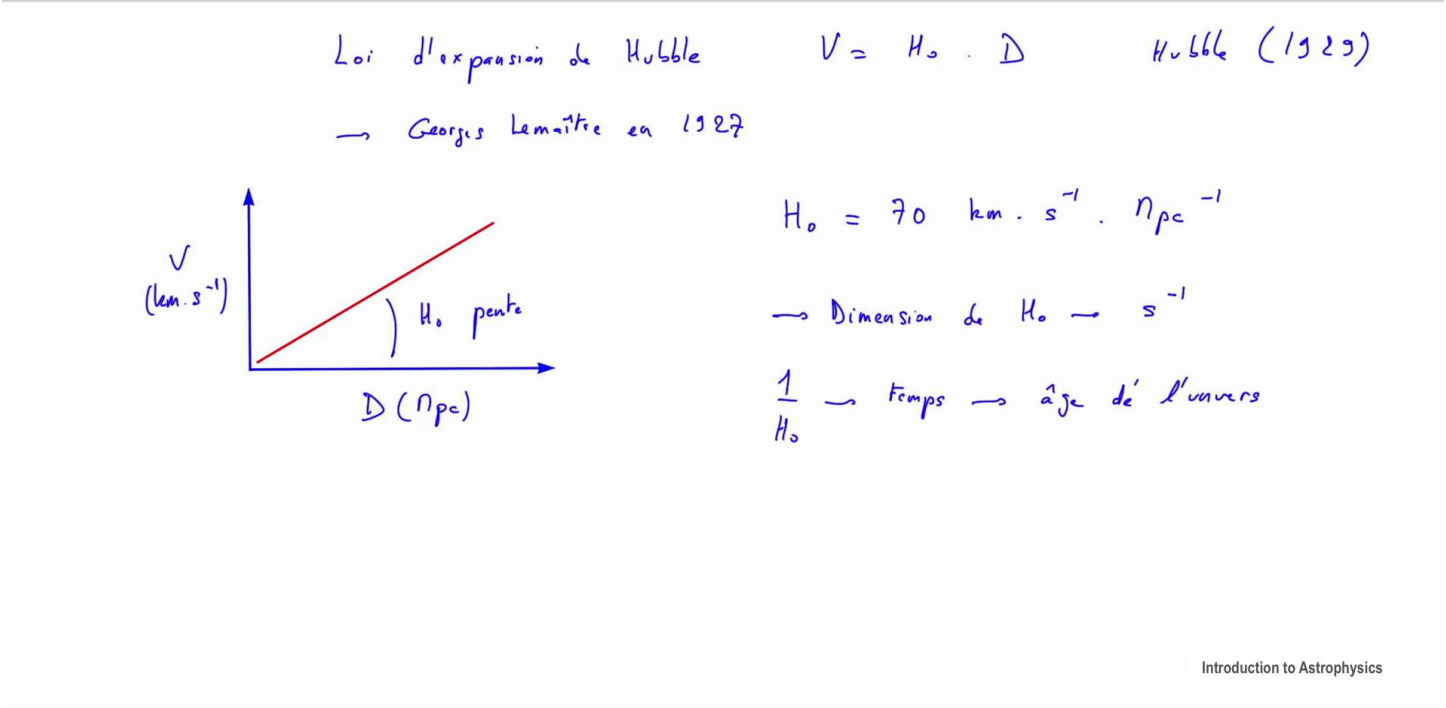
We will have here da/dt times X because X doesn't change with time. So if we input X here, we will have, that r', that is V(r, t), will be equal to a'(t)/a(t), I just introduced X here, times r(t). And what we will do here, we will write that this, is H(t), and this is the expansion rate of the Universe. So we had an expansion factor, a(t), while this is a ratio a'/a, that is an expansion rate. So now, we can also write that V(r0, t0), is equal to H(t0) times r(t0). In other words, we have here Hubble's law. Namely, V = H0 times r, that is to say, times the distance that separates us from an object. So what we wrote here, is nothing other than Hubble's law.

Notes

Summary

3m 52s

Hubble Constant



Then, this Hubble expansion law, we will write it again here: V = H0 times D. That was Hubble in 1929. But actually, the idea was also proposed by Georges Lemaître, a belgian astrophysicist, in 1927. Drawing this law, as we have already seen, it connects the distance, long distances indeed, measured in mega parsecs (Mpc), to the velocity, also large velocities, measured in km per second (km/s). That is what we call the recession velocity of galaxies. And we have a linear law between velocity and distance. and what H0 measures, is the slope of this line. The present value of H0 isn't very well known. To date there is a 10% error margin on the exact value, perhaps a bit better in the more optimistic cases. it amounts to 70 km/s per Mpc. Right, these units may seem strange but they are indeed km/s per Mpc that are measured. Now, the units can be simplified. The true dimension of H0, is in fact the inverse of a time. Thus, 1/H0 belongs of course to the time dimension. and is actually the age of the Universe. So why? Becase if we know the distance and the velocity of a point, we can find the time needed for that point to be in contact with us. So, we have an expanding universe, all points were in contact at the beginning, at the Big Bang. and 1 / H0 later, 13,8 billion years later, the Universe has its present shape, its present size.

Notes

Summary

5m 06s

Cosmological Redshift

$$\frac{d\lambda}{\lambda} = \frac{dr}{c} = \frac{H(t)\cdot dr}{c} = \frac{\dot{a}}{a}\frac{dr}{c} = \frac{\dot{a}}{a}\cdot dt$$

$$\Rightarrow \frac{d\lambda}{\lambda} = \frac{da}{dt}\cdot\frac{dt}{a} = \frac{da}{a} \longrightarrow \lambda(a) = K\cdot a$$

A l'époque actuelle $a = 1$ $\quad \lambda_{em}(1) = \lambda_{obs}$

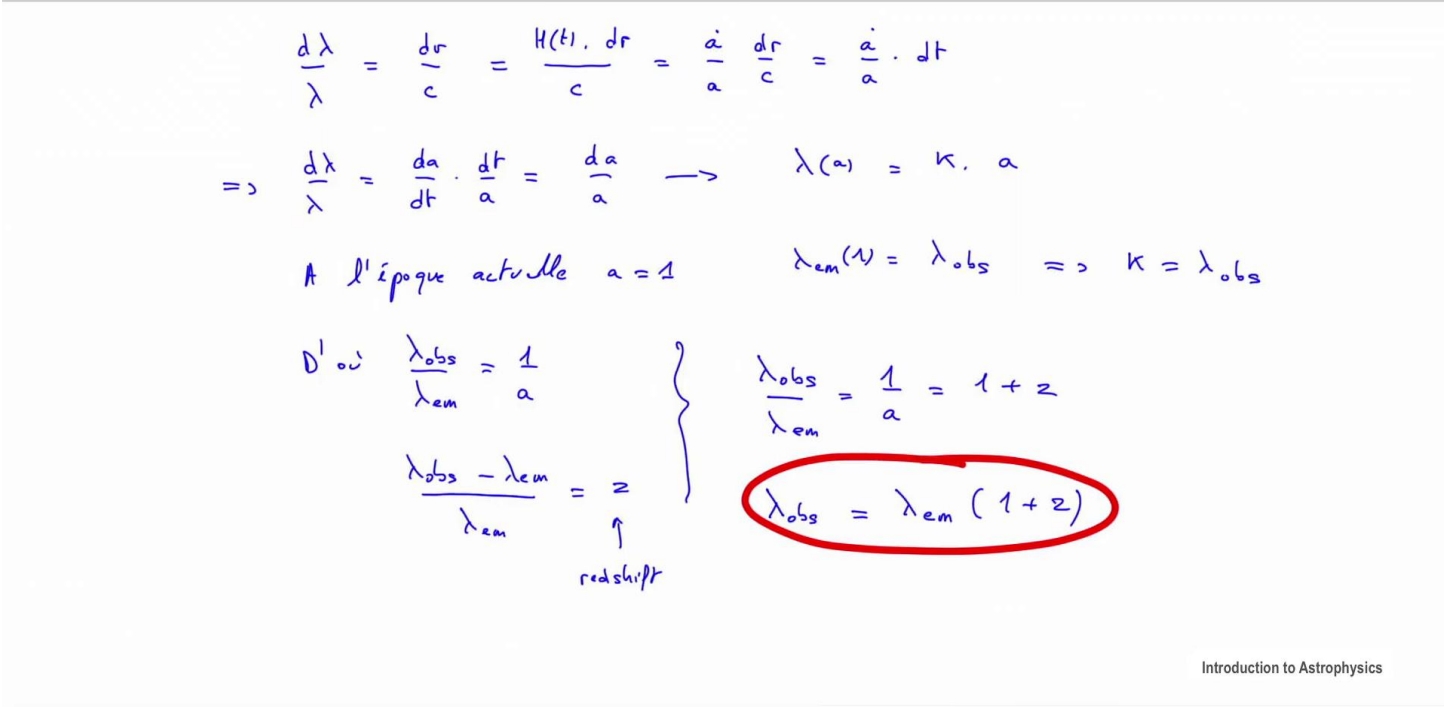
So we have an expanding universe; now, what is the link with what is called the redshift, the cosmological red shift? We can write the Doppler effect, namely the ratio dλ / λ. This is λ observed minus λ emitted divided by λ emitted, which is equal to dv/c, that is the Doppler effect, that we had seen in Chapter 3.2. Now we have seen that following Hubble's law, that V equals H times distance, so here, we have a differential hence we also have a differential there. We have the constant c which stays here. H, as we said, is a'/a, and we have dr / c which stays here. Now a certain time dt is needed to travel the distance dr with the velocity c. So we could write that as: (a'/a)*dt. Now, what does this mean? Re-arranging these two terms here, it means that dλ / λ is equal... remembering that a' is da/dt, and then we have dt/a left. So in the end, we obtain dλ /λ = da/a. This is a differential equation of the first order. The solution to this, is λ(a) equals a certain constant K times a. Thus, at the present epoch, we have a = 1, so we have that λ_emitted (1) is equal to λ_observed. Because at present, the wavelength, with an expansion factor of 1, the emission and observation wavelengths are the same.

Notes

Summary

6m 59s

Cosmological Redshift



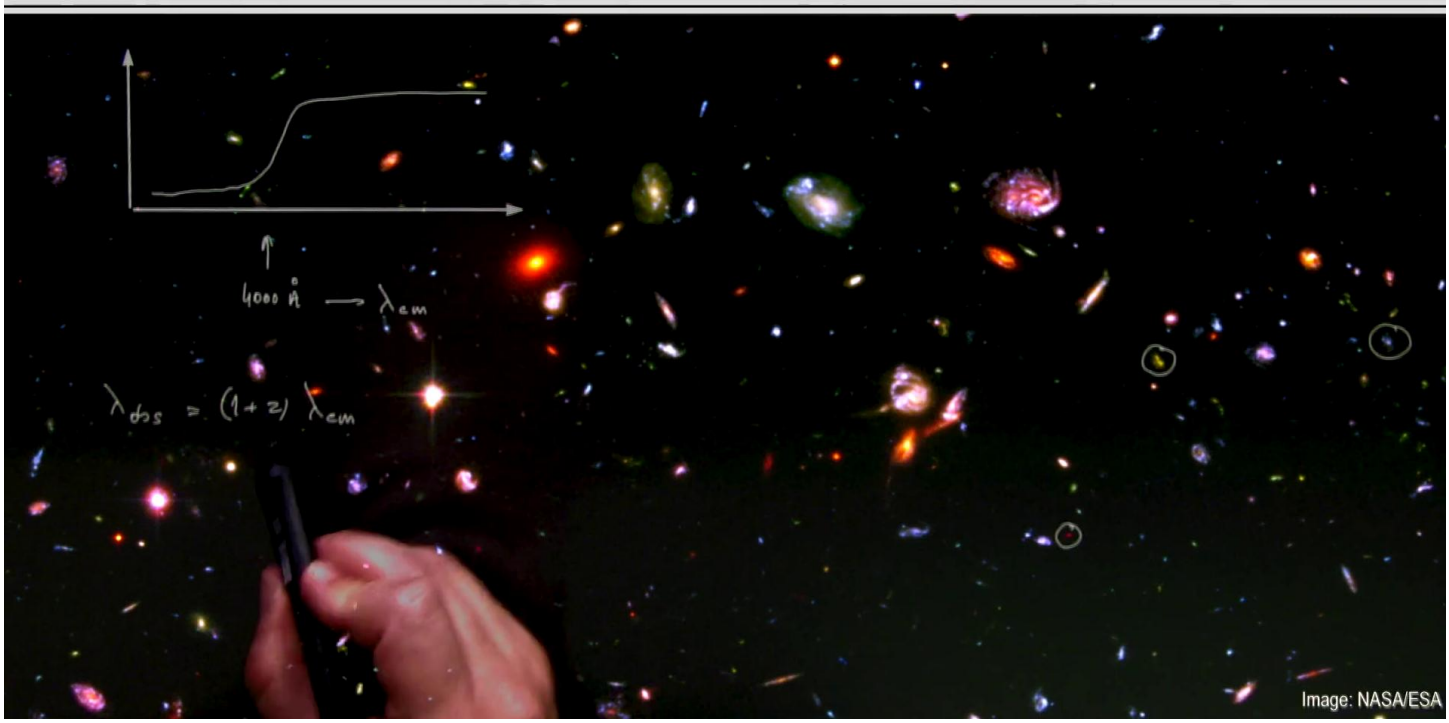
So we have a = 1 here, and this implies that the constant K is equal to λ_observed. This is simply the Doppler effect. For a universe with an expansion factor of 1. Now, if we re-arrange the results here, what we will get is that λ obs / λ emit is equal to 1/a. It is exactly this equation once we have replaced the K constant by λ_obs. We also have the Doppler effect formula, telling us that (λ_obs minus λ_emit) / λ_emit is equal to V/c, as we have seen, and we will set this as being equal to z. and this will be, by definition, the famous red shift. Now, if we gather these two equations, we see that we will have : λ_obs / λ_emit = 1/a, namely the inverse of the expansion factor. But it is also equal to 1 + z. This implies that, if we want to know the red shift of an object, we measure a given observed wavelength. let's take for example a line in a spectrum: if we know its wavelength at rest, in other words the emission wavelength, the intrinsic wavelength of the line, then we can find the redshift z. That is the well known equation of the cosmological Doppler effect.

Notes

Summary

8m 48s

Cosmological Redshift



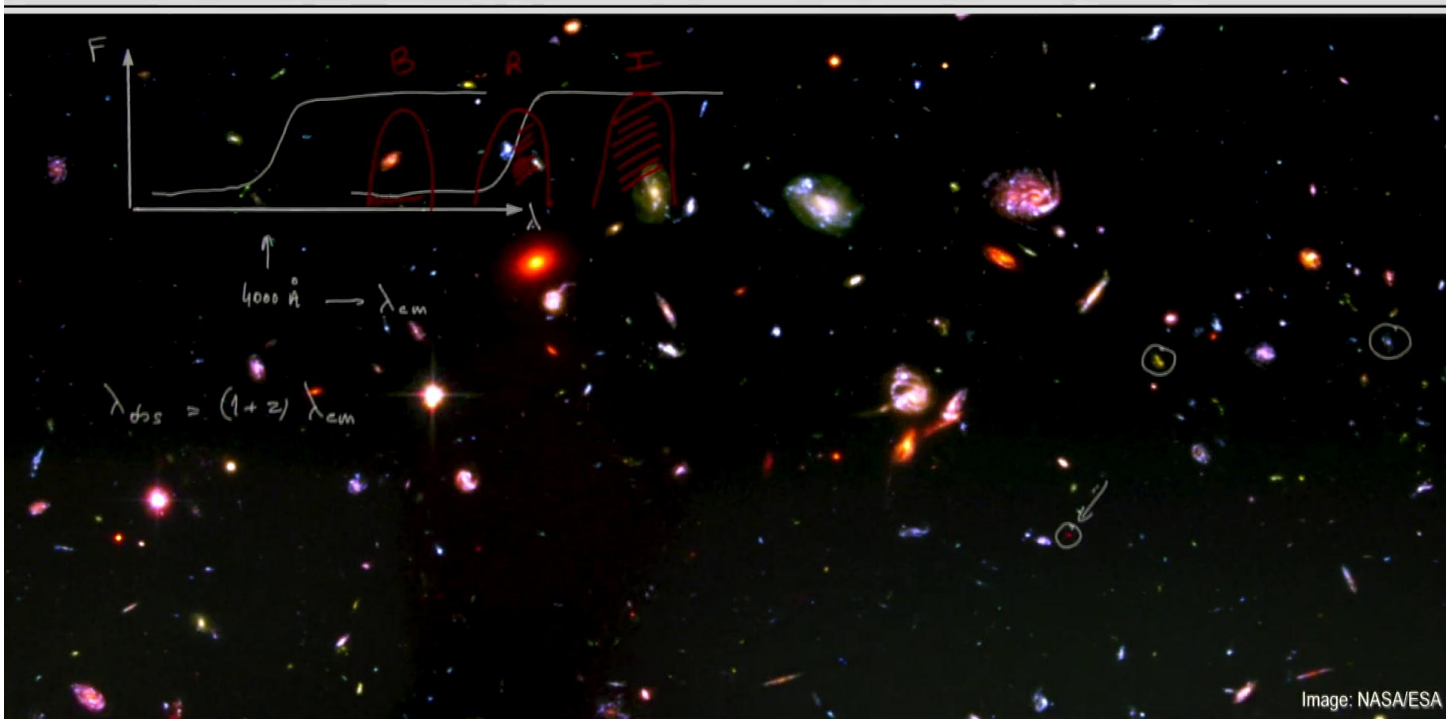
Now an example. Lets take the Hubble Deep Field, as we did several times before in this class. We see that there are many galaxies of all colours. Some are blue, others are rather green, yet others are red, like here, and there are two reason for that. First of all, galaxies have intrinsic colours. Some have blue and hot stars, just born. Such galaxies have an intrinsic blue colour. Others will have for example a lot of dust making their colour redder, or contain a population of old stars, with low masses. So there are multiple reasons for the observed colours of galaxies. But one additional reason is the cosmological red shift. For that we can draw the spectrum of a galaxy in a schematic way. So a galaxy spectrum resembles this. There are stars in a galaxy, so we will have the Break at 4 000 angströms, Balmer's Break, that we had already seen in the chapter dedicated to hydrogen. So here, we have a typical feature at 4 000 angströms, if the galaxy is at rest, without any cosmological red shift. Now this is the wavelength, of λ_emission when at rest. And λ_observed will be equal to (1 + z) times λ_emitted. So, if we have an object with a very high red shift, 5 for instance, we will multiply 4000 by 5+1 or 6.

Notes

Summary

10m 25s

Cosmological Redshift



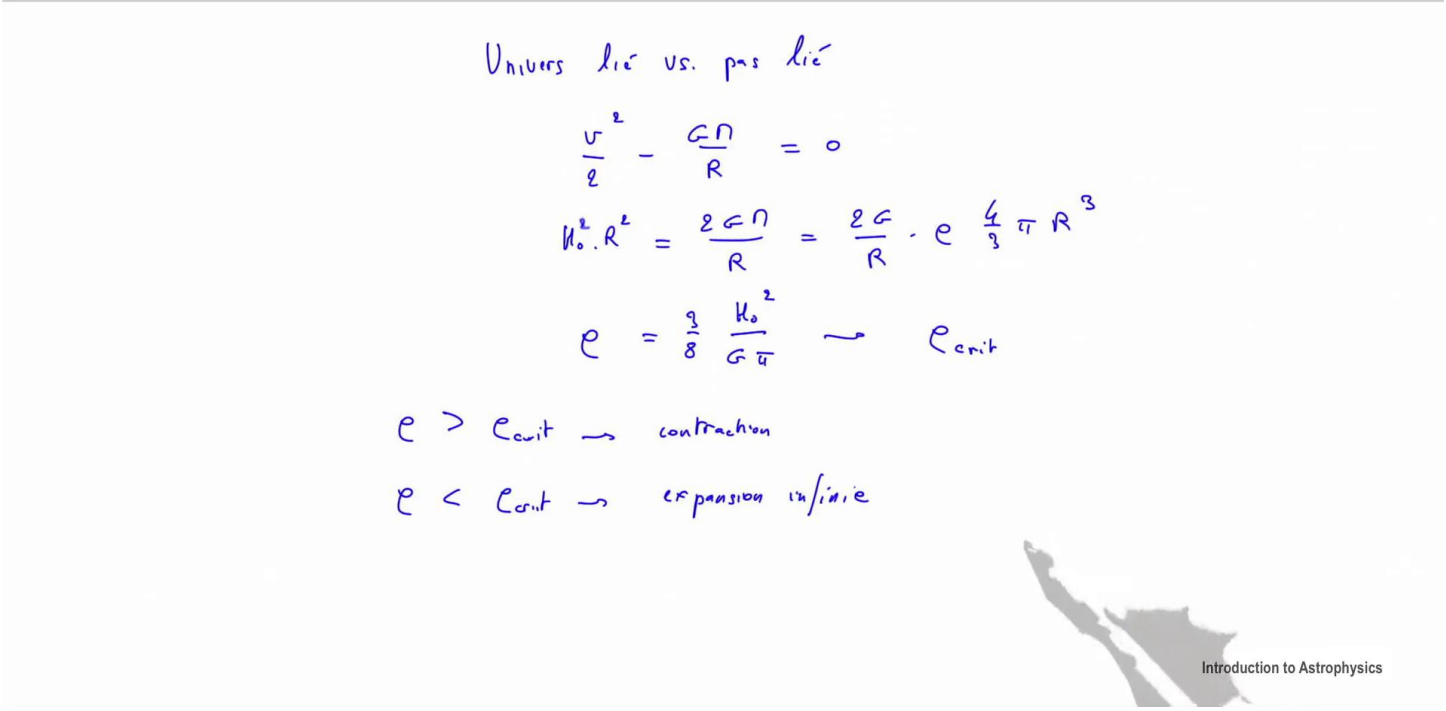
So we will have wavelengths that will move like this, far into the red. I will put here again the wavelength, and there the flux, since we have a spectrum, so we will multiply the whole spectrum by that factor (1 + z). So we will find here again the break, that was seen before at rest, but now (1 + z) times farther. and the spectrum will be stretched by a factor (1 + z). So everything is stretched by a factor (1 + z) in cosmology. So now, if I add filters to this, for example a filter here, and a filter there, and one here, and then I integrate the light as we did before in the first chapters of this course, i will have a lot of flux here in an infrared filter for example. Here, considering the red filter, I will have a moderate flux, and then almost no flux at all in the blue. Now if we make a true colour image of a galaxy, with this spectral distribution, we will have typically, a galaxy, as we can see here, which will appear very red in a true colour image. Of course, all intermediate situations occur. In images like these, you can find galaxies with any colours. First, because they have an intrinsic colour, and second, because they have a certain cosmological red shift.

Notes

Summary

11m 53s

Critical Density



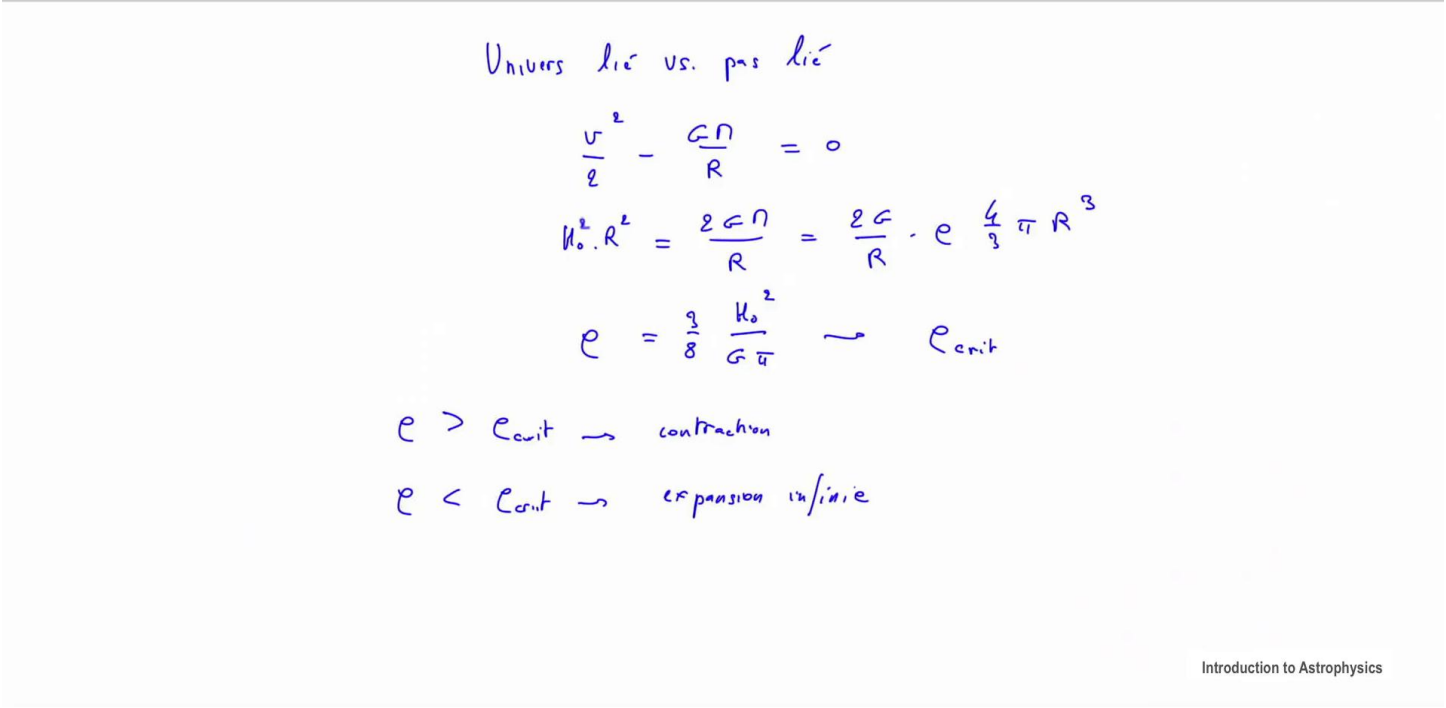
Remember, the universe is expanding. and a simple way to determine whether it will expand forever or not, is to see whether the system is bound or not, I mean the universe as a whole. So, is the universe bound or not? Is it a gravitationally bound system? So we write the equilibrium between the kinetic energy and the potential energy. Here M is the mass of the Universe. R is its radius, or characteristic radius, V the velocity of a test particle in the Universe. This is 0, so it would be the total energy of the Universe. Now, we have seen that V is H_0 R, namely H0 times a distance, squared here. We move the 2 to the other side of the equation. thus obtaining 2 G M / R. and this, if we assume a constant density, will equal 2 G / R times ρ times 4/3 π R³. This allows us to define a density, which can be defined as a critical density, the value of which is 3/8 (H0²/Gπ). So this ρ is what we call the critical density of the Universe. it is such that, if ρ is larger than ρ_critical, then the potential energy is larger then the kinetic one and we have a contraction, or at least a fading expansion. And if ρ is smaller than ρ_critical, then we have an everlasting expansion.

Notes

Summary

13m 16s

Critical Density



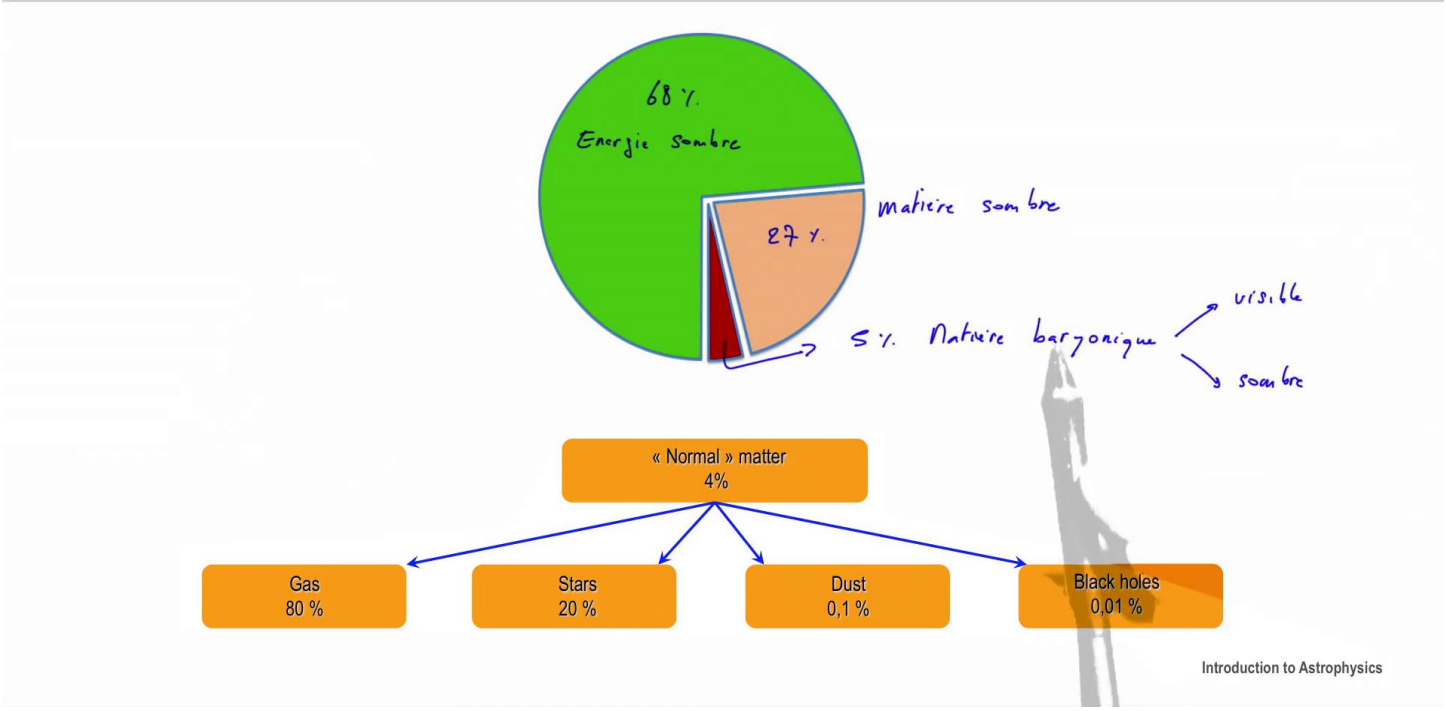
So we can see that the density of the Universe is of crucial and far-reaching importance regarding the future of the universe. For that reason, it is extremly important to understand the energy balance, the different density contributions, of the different components of our universe.

Notes

Summary

14m 52s

Composition of the Universe



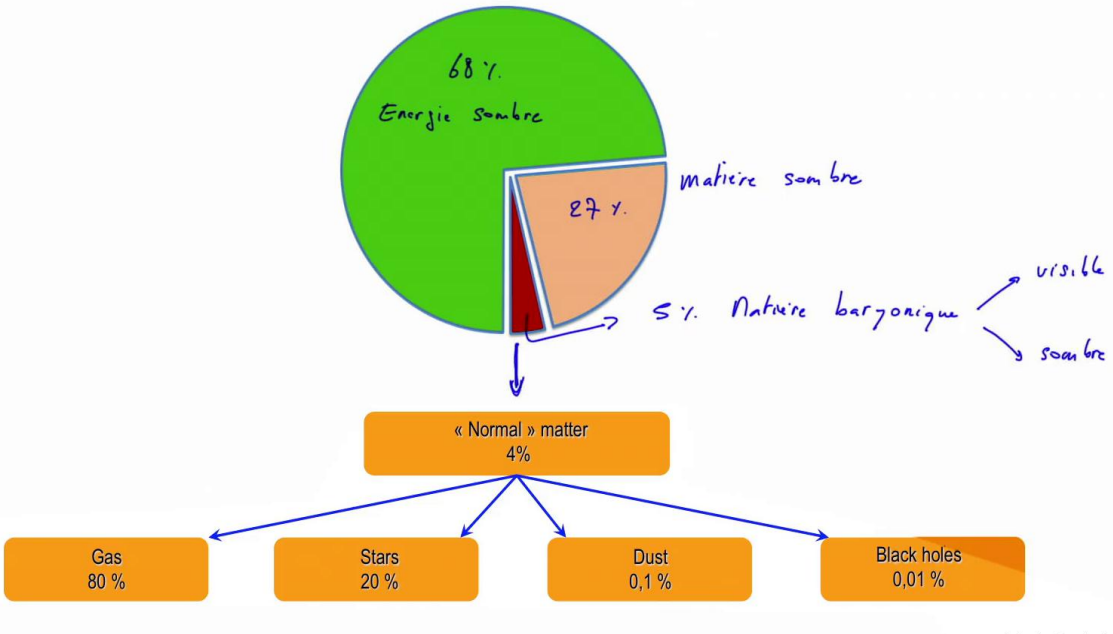
Currently, the very fact that the Universe is undergoing accelerated expansion implies, within the framework of the Big Bang model, that we have 68% of dark energy; that is the energy balance of the Universe. This dark energy is repulsive, and explains or mimics a Universe undergoing accelerated expansion. On the other hand we have 27% of dark matter, which is subject to gravity, and as such, tends to make the universe contract; and the proportions we have here result in a universe in accelerated expansion. And than, we have a very small fraction of the total energy content, 5%, which is normal matter, called baryonic matter. So this baryonic matter includes the proton and neutrons, and by extension the electrons that are not baryons but actually leptons, but are associated with normal matter, which is called normal, or baryonic. Some of this matter Some of this matter which emits radiation, is fact the subject of all this course, so "normal" matter, but that doesn't emit light or light at the wavelengths we can observe. And there is also dark matter that does not emit any light at all, at any wavelength, we have no idea of what it is.

Notes

Summary

15m 10s

Composition of the Universe



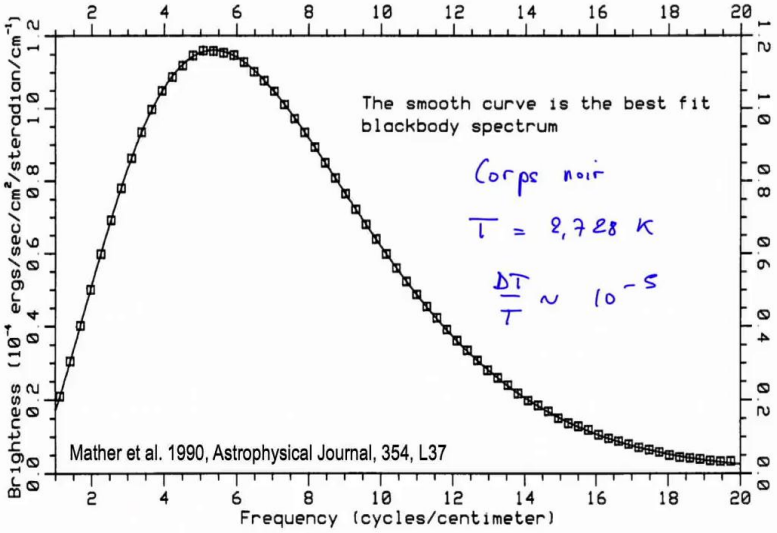
So if we talk about dark matter, it can be two things : either dark matter, here of which we have absolutely no idea, or normal baryonic matter but which we cannot see because either it doesn't emit enough light, or it emits at wavelengths we do not observe. So now, these 5 % of baryonic light, has a mass distribution as follows: 5 % of "normal" (baryonic) matter, which are composed 80% of gas, only 20 % of stars, and 0.1 % of dust, you remember these dark lines that absorb the light in galaxies, and dark holes, even if they are very compact objects, they are very few of them, and represent only 0.01% of the energy or the mass.

Notes

Summary

16m 36s

Cosmological Background Radiation



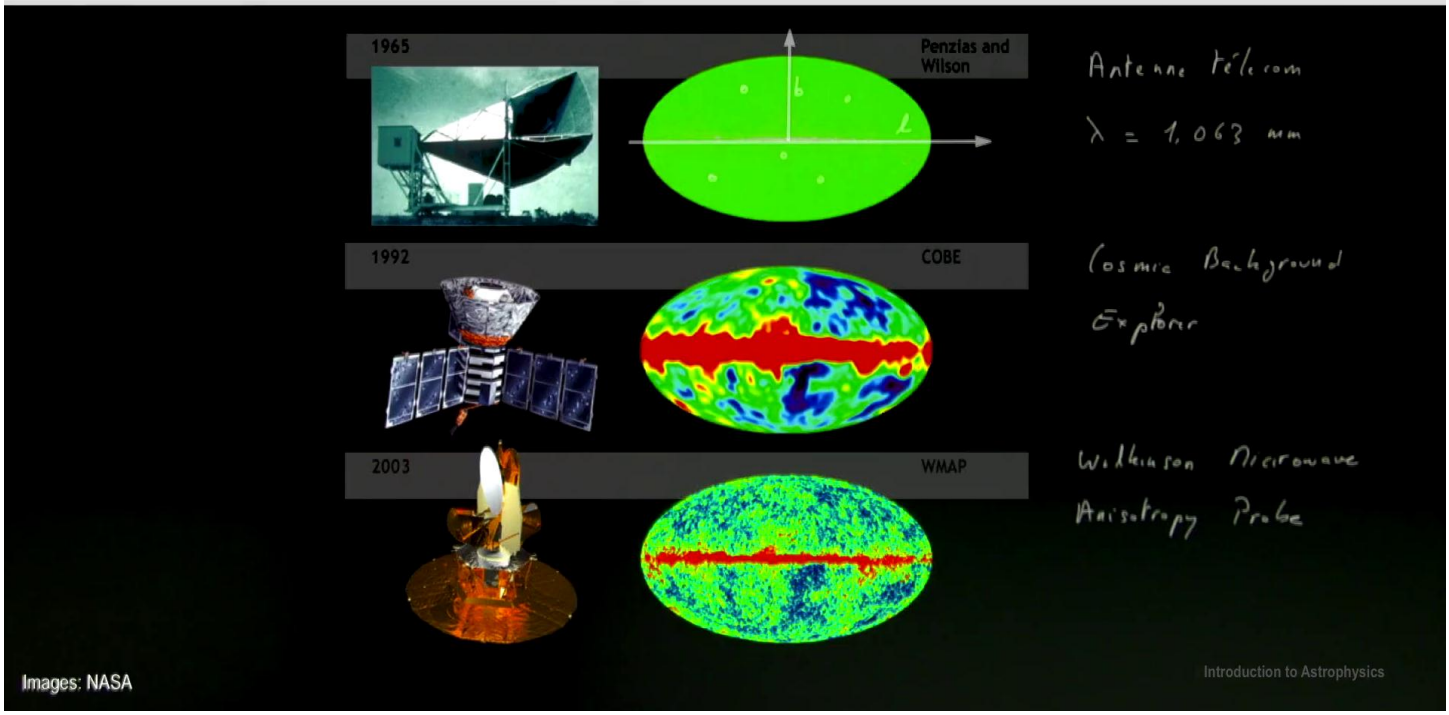
So these numbers are taken from observations of the Cosmic Microwave Background (CMB) radiation. What's it is all about? First of all it's a black body radiation whose temperature is 2,728 degrees K and there are small spatial variations of temperature of around 10 to the power -5. Now if we take the mean temperature over the whole sky we will find a perfect black body, which is represented by this curve here, measured by the COBE satellite, which stands for the « Cosmic Background Explorer ». Its an American satellite, from NASA, which has measured for the first time the temperature of the cosmological background. So the black body radiation is a radiation at 2, 728 K. We measure the temperature of the sky background everywhere, in all directions of the universe isotropically, equals to 2, 728 degrés K, with small variations of 10-5. At the beginning, just after the Big Bang the Universe had a much larger temperature temperatures of course, that cooled down due to the expansion and at the present time, the temperature is 2,728 degrees K.

Notes

Summary

17m 21s

Discovery



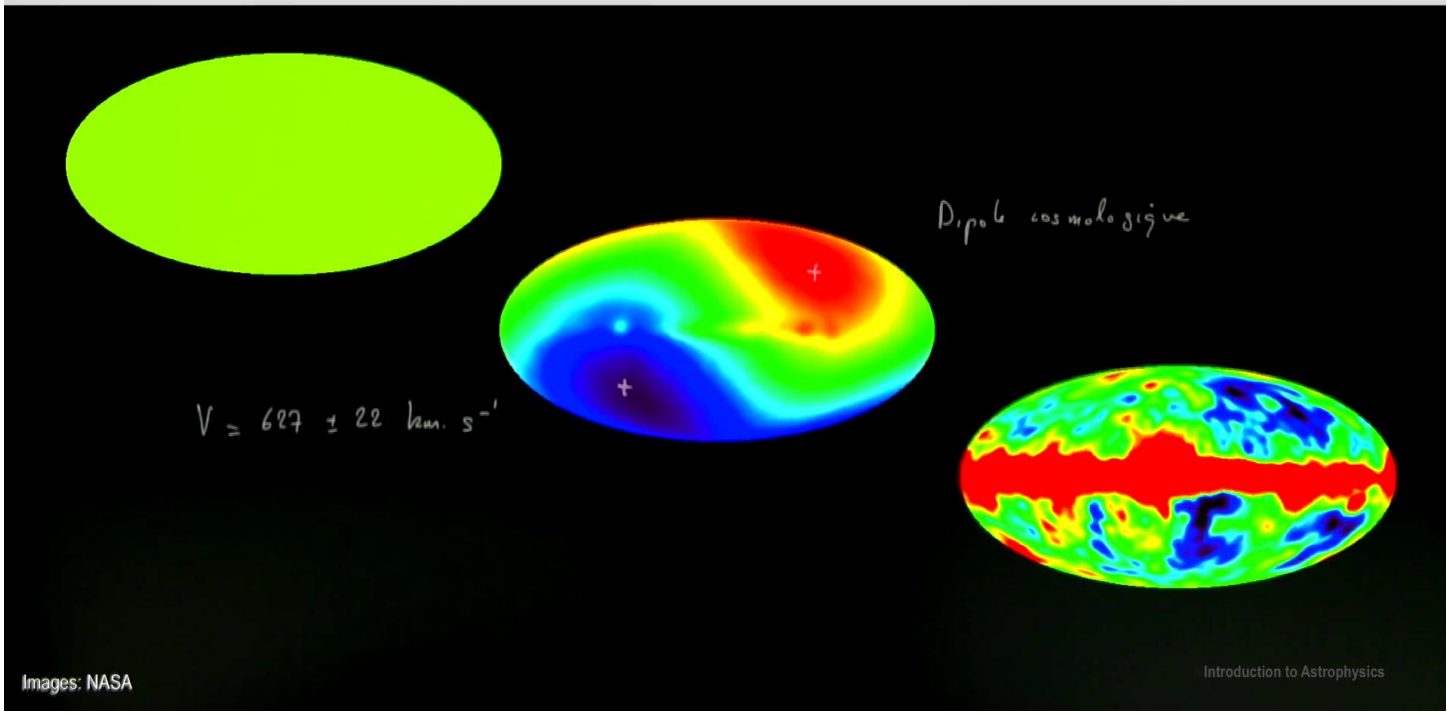
So, what is the history behind the discovery of the cosmological background ? First of all, come the first observations by Penzias and Wilson, who observed with a telecomunication antenna at a wavelength of 1,063 mm, so in the micro waves, They observed in different directions on the sky and each time, observed a background noise corresponding to a black body radiation at 2,728 degrees K. So they observed with an antenna that didn't permit them to construct a map of the sky, but they observed that wherever they did the measurement on the sky background, if they observed here, here or here or anywhere, they were measuring 2, 728 degrees K. So these maps, that we see often represented like this in an oval shape, they are in galactic coordinates. So we have here, the galactic longitude and latitude we already saw in the chapter about the Oort constants. We have the whole sky map here, as seen by the antenna of Penzias and Wilson, then seen by the COBE satellite. Its the « Cosmic Background Explorer », which measured and obtained the first sky map in 1992. What you see here is the millimeter image of the Milky Way. By improving the observations with the « Wilkinson Microwave Background Anisotropy Probe », we can see more and more details in the map of the cosmological background radiation. There are still around 30 years each observation.

Notes

Summary

18m 39s

COBE (Cosmic Microwave Background Explorer)



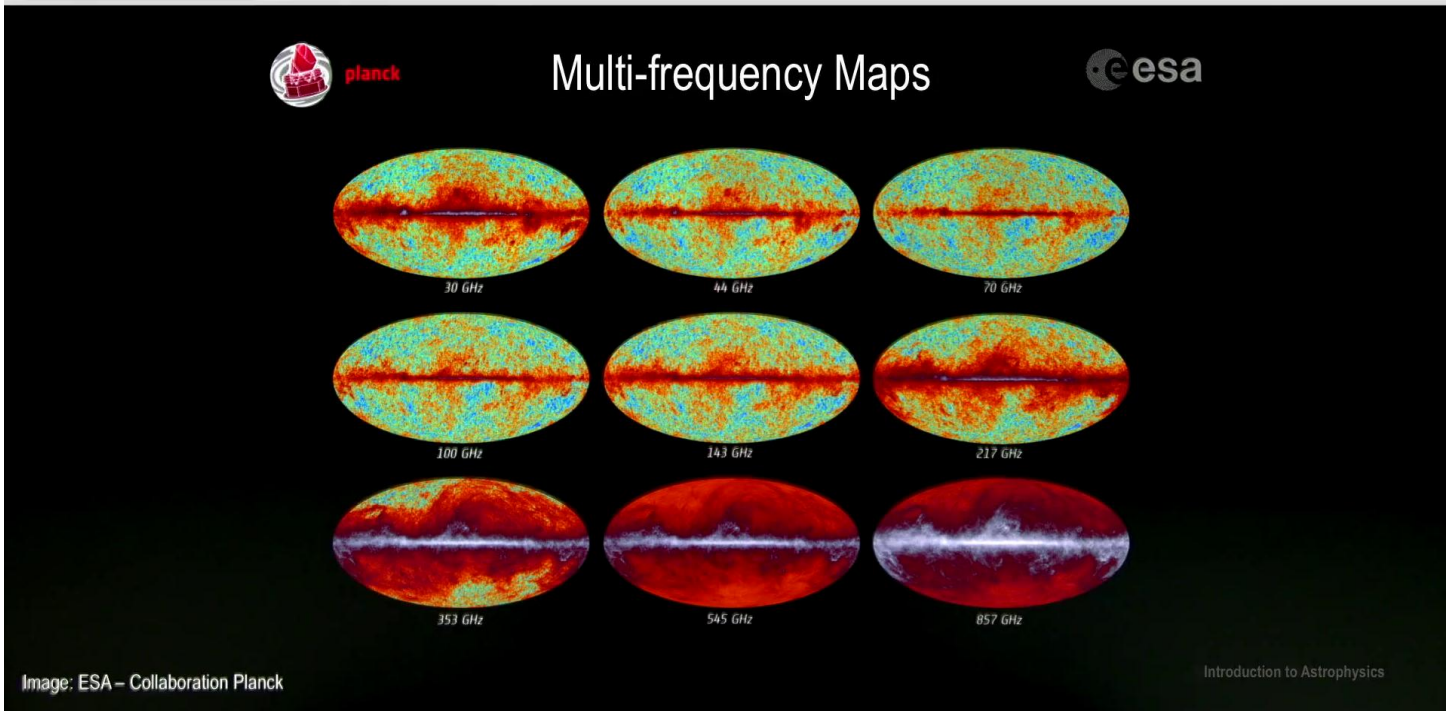
So this cosmological background radiation is not observed easily. The observation of Penzias and Wilson, is a constant over the whole of the sky. but we have to take into account that the Milky Way is moving in the sky, and so we go towards a point that can be found here. Of course, if we look in the direction opposite to the movement, we find ourselves here and so we see a "bluer" sky, a bluer wavelength in the direction of the motion, and redder in the opposite direction, due to the Doppler effect, So what we see here is what we call the "cosmological dipole", because they are two poles like this. and this is simply due to the movement of the Milky Way, with respect to the cosmological background radiation. Now the velocity of the Milky Way, with respect to the cosmological background radiation, measured through the Doppler dipole, is V = 627 ± 22 km/s. Thanks to the Doppler effect, we have some sort of absolute referential here, that allows us to measure the proper motion of the Milky Way in the Universe. So now if we substract this Doppler effect we finally obtain the map of the cosmological background radiation with also here the image of the Milky Way. The cosmological information is of course hidden by the Milky Way.

Notes

Summary

20m 26s

Map from the ESA Planck Satellite



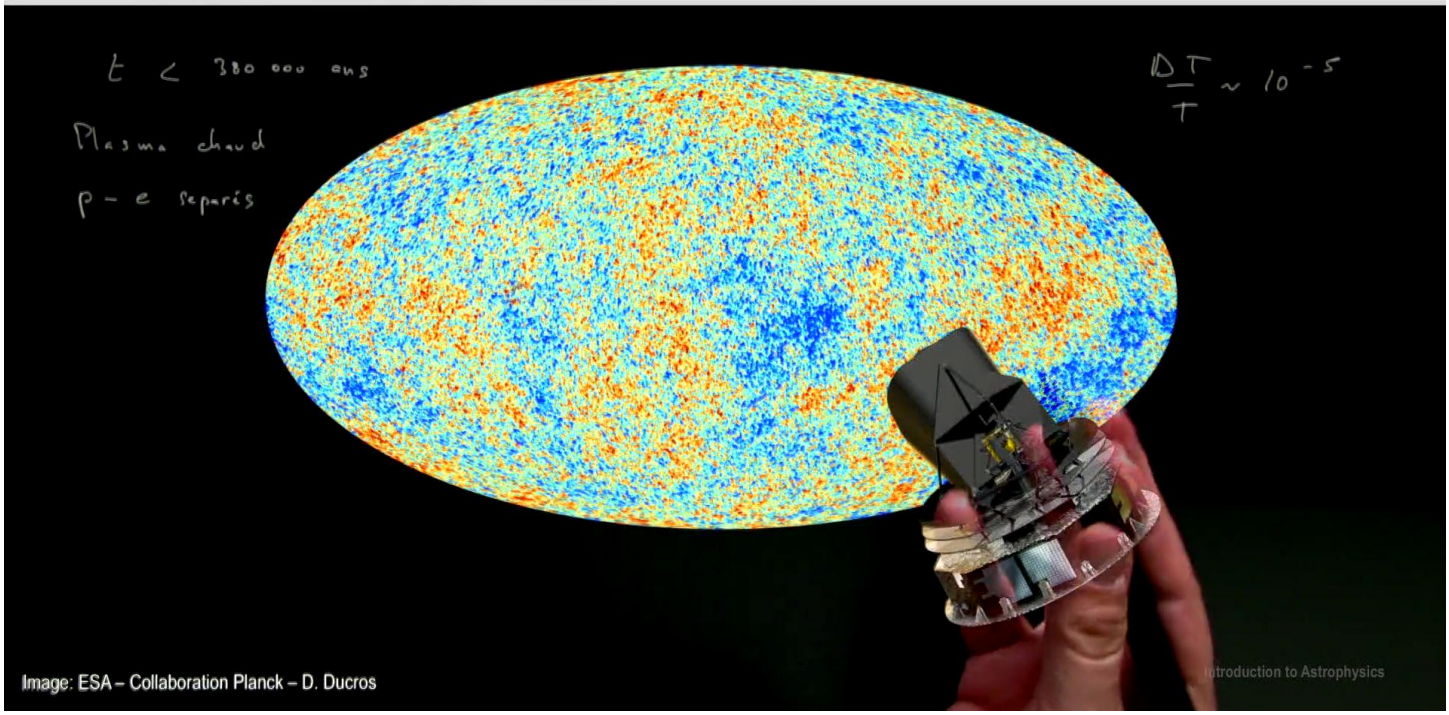
But the Milky Way can be removed thanks to multi frequency maps, obtained here with the Planck satellite, which is the last satellite to have taken CMB measurements. So this is recent, 2013-2014. By taking multi frequency maps of the sky we can, thanks to the apparent change of the Milky Way shape, substract it to get the final image, which is here.

Notes

Summary

21m 49s

Map from the ESA Planck Satellite

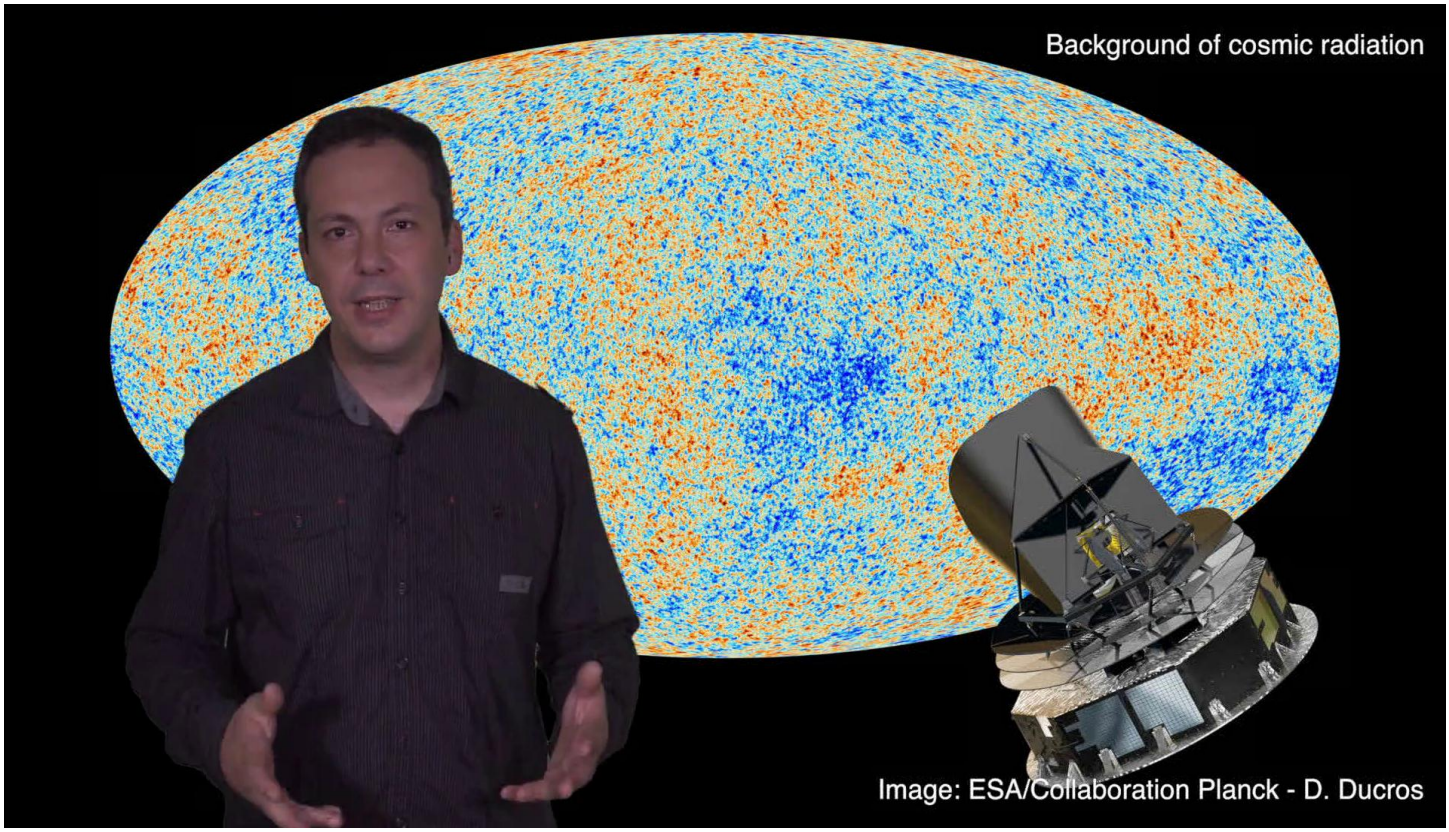


So this is the map obtained by the Planck satellite, it's a temperature map of course, the average of the temperatures is 2,728 degrees K. and there are small fluctuations around it. So this red points here are slightly hotter than this, and the blue points slightly colder, with variations of temperature that are Δt/t, as we have already said around 10 to the power -5. The cosmological information is contained in fact, in the statistical distribution of these small points and this is what we want to measure very precisely at small scales, but also at large scales. Because this is what the Big Bang theory predicts. So we will try to make observations that we will confront to the theory. Or in other words, we will confront the theory to the observations. So what is the cause of the fluctuations? When the Universe was born it was extremely hot, then the temperature decreased and while the Universe was younger than 380 000 ans, we had a hot Plasma. So hot that photons and electrons were seperated.

Notes

Summary

22m 12s

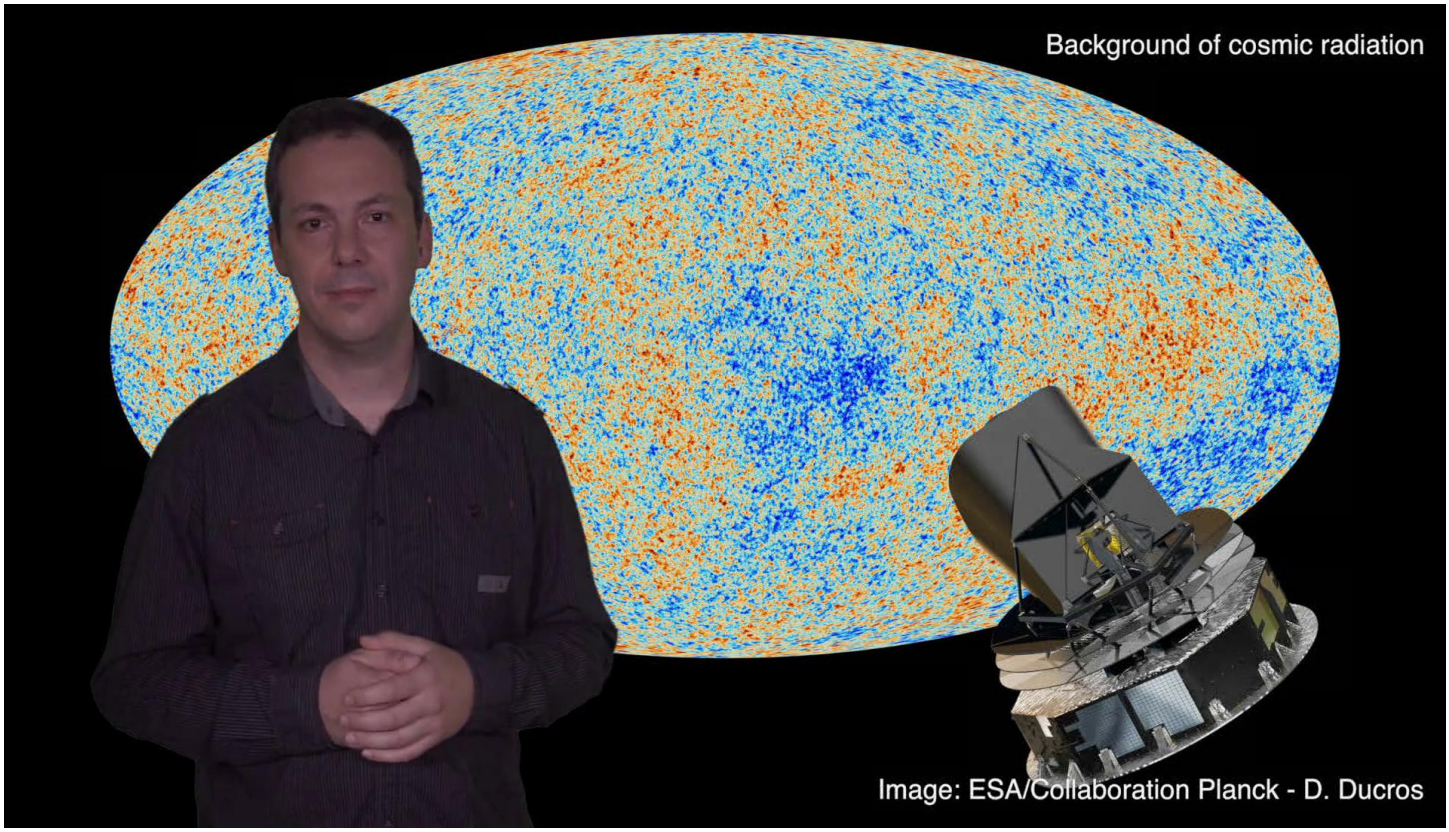


The gas was totally ionized So now the photons present in the gas at that time, were constantly in interaction with the electrons, they were in fact all the time scattered by electrons, until the moment where, due to the decreasing temperature of the Universe, because of the expansion, so when t dimishes, this intervenes at a time t = 380 000 years after the Big Bang So a that moment, we have what the recombination between protons and electrons. So now, if protons and electrons recombine, this produces hydrogen, with the consequence that photons cannot anymore be scattered by electrons. So photons propagate straight through a Universe that is completely transparent to light and reach us. So what we see here is what we call the surface of last diffusion, or last scattering the last time photons and electrons could interact with each other before the electrons recombined with protons. and it is for that reason that we say that the milimeter map, the microwave map of the sky, is the map of the cosmological background radiation, also known as fossil radiation, because it bears the imprints of temperature fluctuations and so the density of the Universe as they were, only 380 000 years after the Big Bang.

Notes

Summary

23m 27s



The best description of the world in which we live is provided by the Big Bang theory. Far from being perfect, it still explains a large number of concrete observationnal facts like the expansion of the Universe, but also the cosmological background temperature and its spatial fluctuations throughout the sky. Still, to date, the accelerated expansion of the Universe, is 68% dark energy and 27% dark matter We still cannot find a fully satisfying explanation. The solution of the problem will be found through the characterisation of large scale structures, and so by multi-wavelength observations of the whole sky. That has been done here by the Planck satellite, in the microwave wavelengths, to see the cosmological background radiation. But the sky will soon be mapped in optical and the infrared by the ESA Euclid satellite and by ground-based telescopes.

Notes

Summary

24m 55s