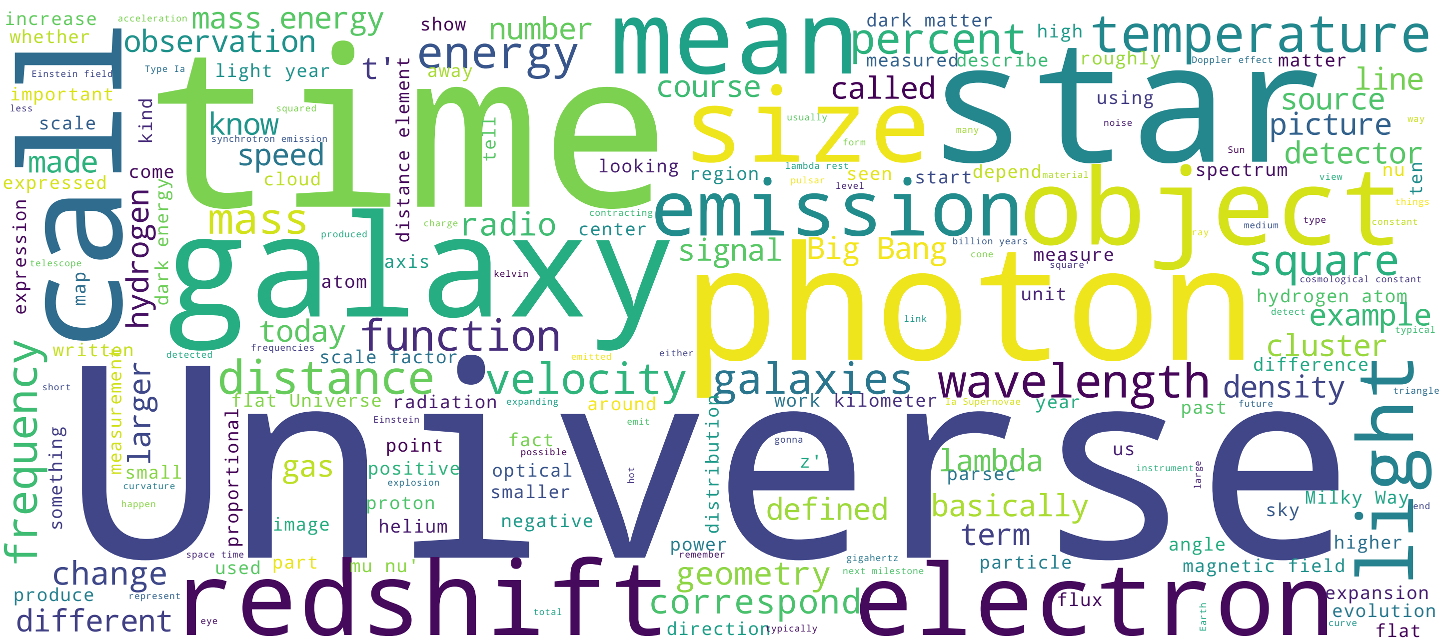
EPFL

The Cosmological Context

The Universe At Radio Wavelengths

Jean-Paul Knieb



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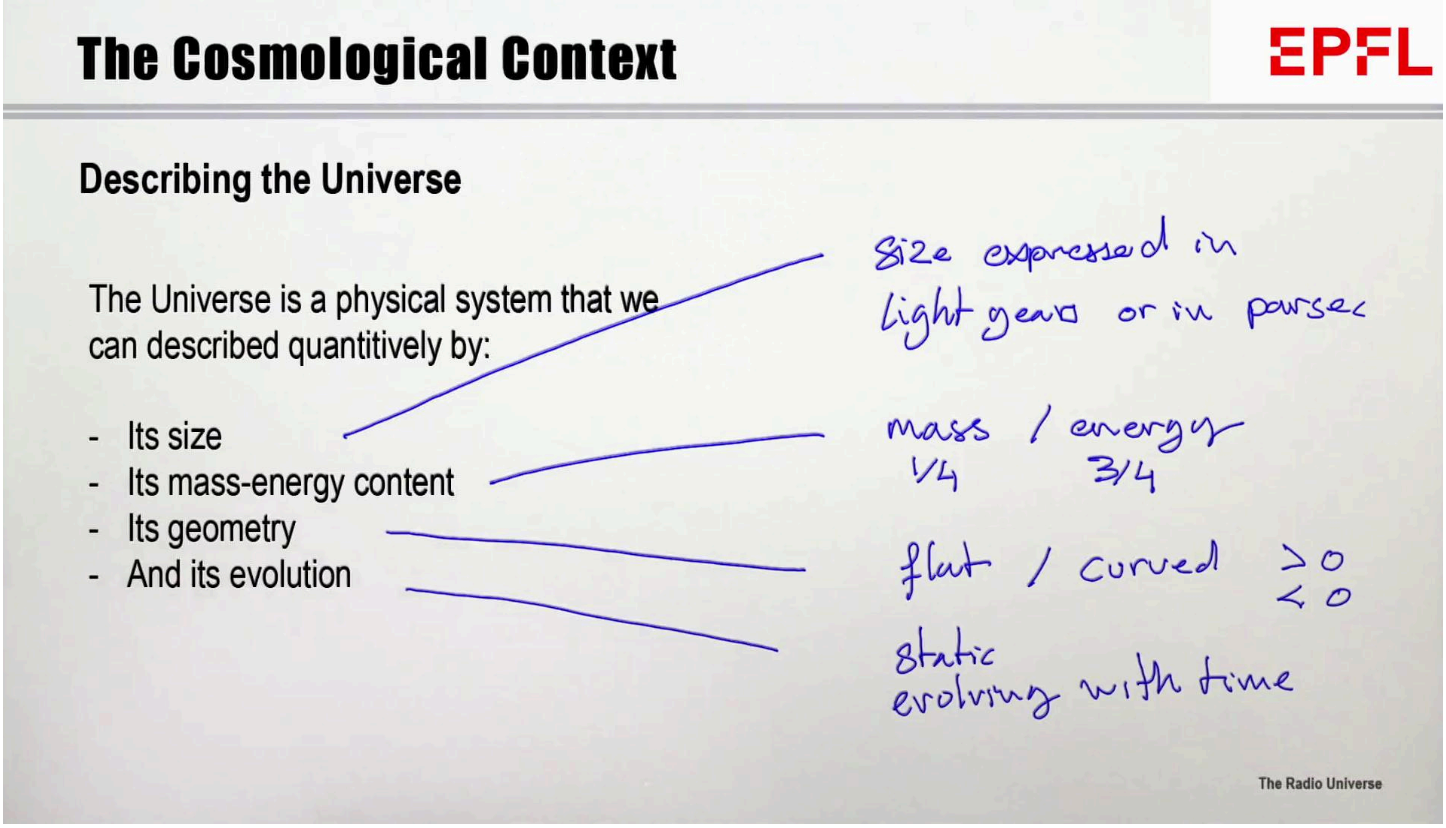
Today we will set up the framework describing the Universe. The physical study of the Universe has been possible only recently and it is based on the Einstein theory of general relativity developed one hundred years ago. General relativity is the theory that makes the link between the force of gravity and the geometry of the Universe. Einstein showed that a massive body in the Universe will curve the space-time. This is why the Earth is orbiting the Sun. In fact, the Earth is just going straight ahead in the locally curved space-time. But there is more than matter in the Universe. Let's explore this.

Notes

Summary

0m 05s

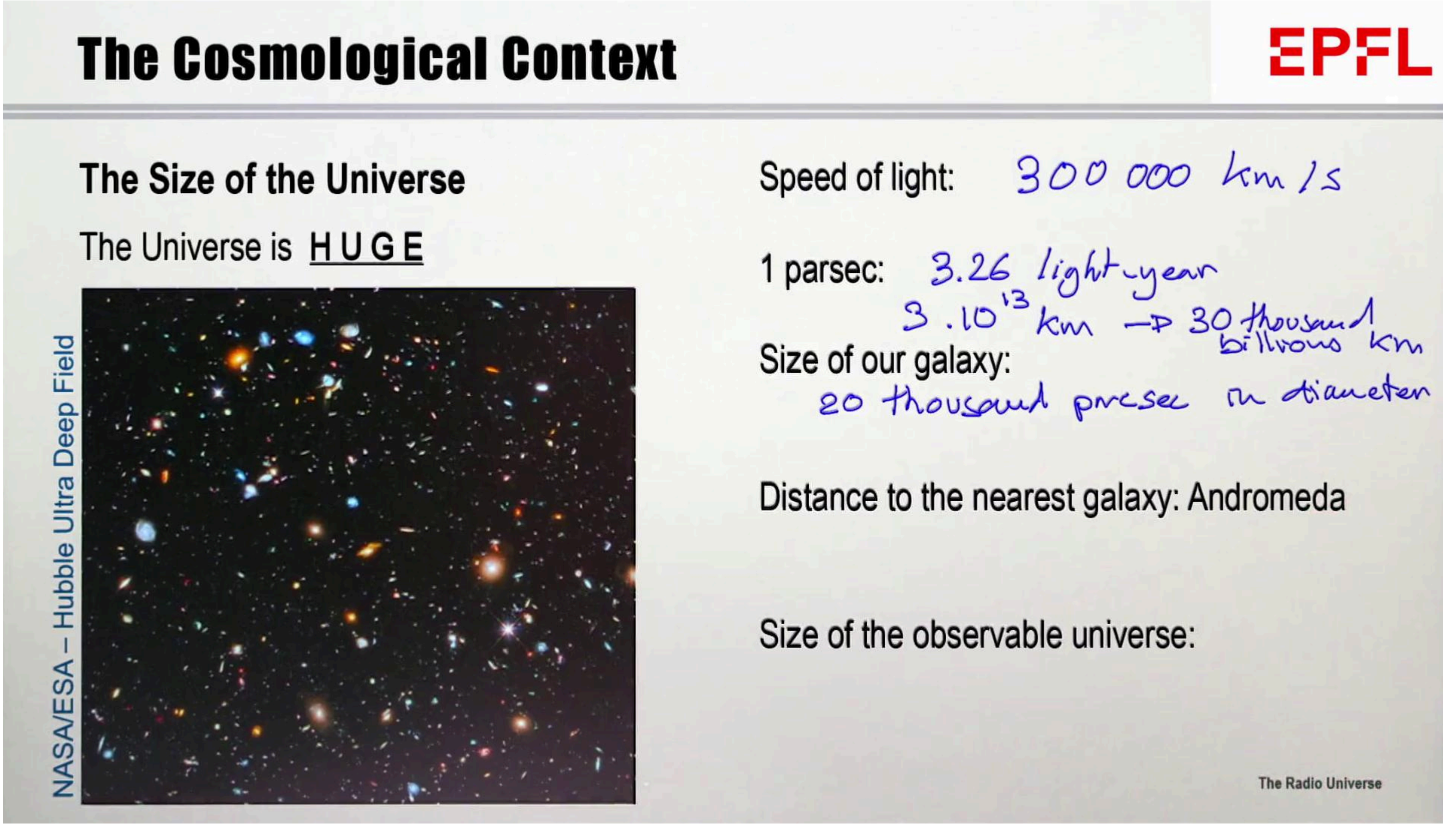


Today we're gonna talk about the cosmological context. The context in which we are going to conduct our radio astronomy observation. The point here is to describe the Universe. The Universe is a physical system that we can describe quantitatively by its size, its mass energy-content, its geometry and its evolution. Size will be expressed in light-years or in parsec. As for its mass-energy content, we're gonna check whether there are some mass and whether there are energy in the Universe. We will show that mass is about one-quarter of the total content and three-quarter is about the energy content. As for the geometry of the Universe, what is important is to know whether we have a flat Universe, an Euclidean Universe or a curved Universe, and then whether the curvature is positive or is it negative. As for the evolution, then the question is whether the Universe evolution doesn't change its static whether it's evolving with time and whether it's expanding or contracting.

Notes

Summary

0m 57s

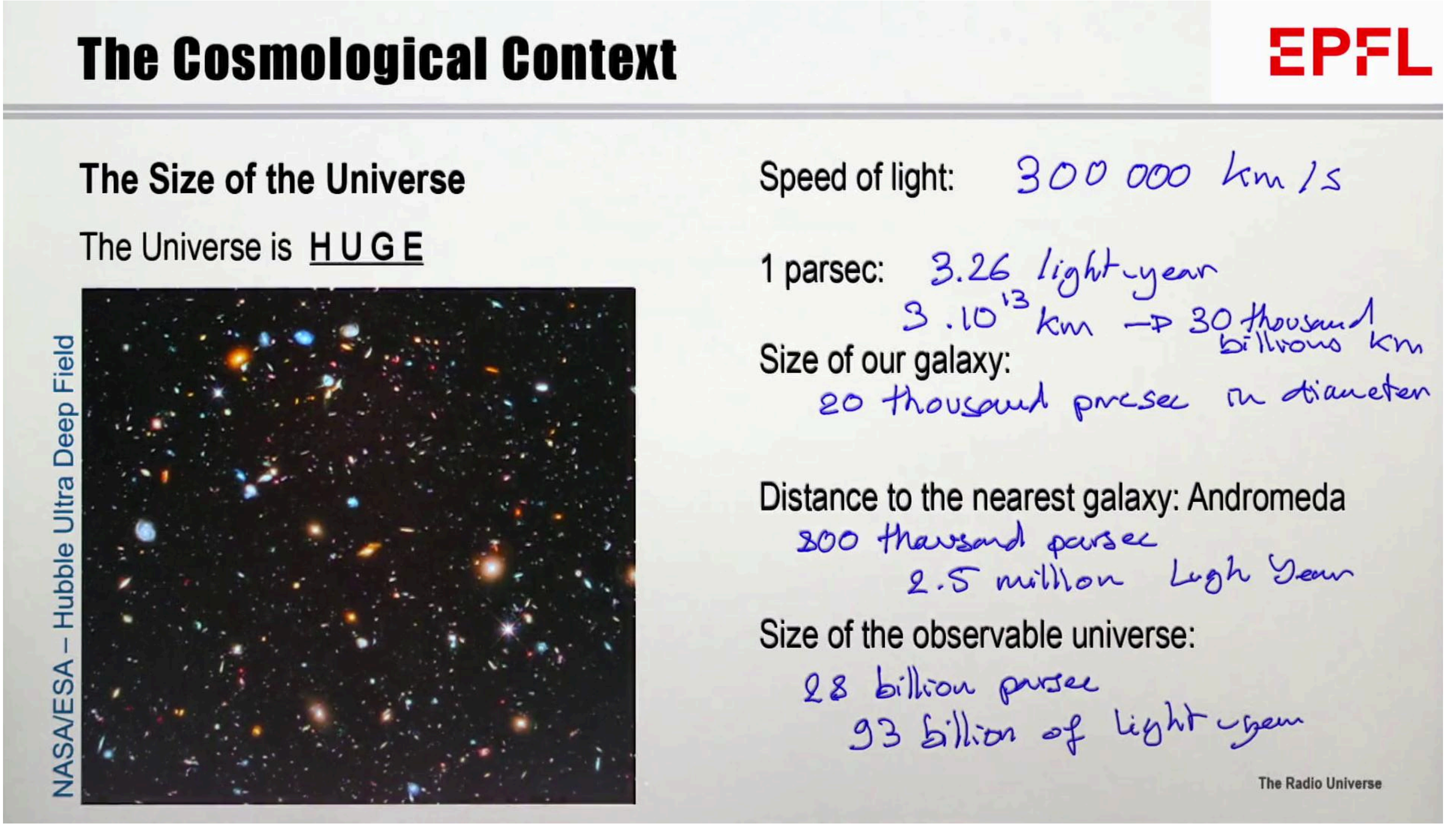


First thing is about the size of the Universe. What you have to realize that's the Universe is really huge. Here we have a picture of one of the deepest image of the Universe. What you see, each punch of light is basically a galaxy and we believe from that image that there is more than hundred billions of galaxies in the Universe and for each galaxy typically you have a hundred billions of stars. So all together it's made a lot and lot of stars. What are the limiting quantity? The limiting quantity is basically the speed of light. The light travels at about 300,000 kilometer per second. This is quite a limiting factor as if you go and look further into the distance, it means the light travel time takes a long time to come to you because we're talking of very large distance and so that means we're gonna set distance in terms of typically light-years, as we were saying before, parsec. One parsec is 3.26 light-year. Okay. So one light-year is distance that is covered by the light during one year. Okay so one parsec is 3.26 light-year. It also correspond to three 10 to the 13 kilometer which means 30,000 billion of kilometers. Okay that's one parsec. The size of our galaxy is about 20,000 parsec in diameter.

Notes

Summary

2m 28s

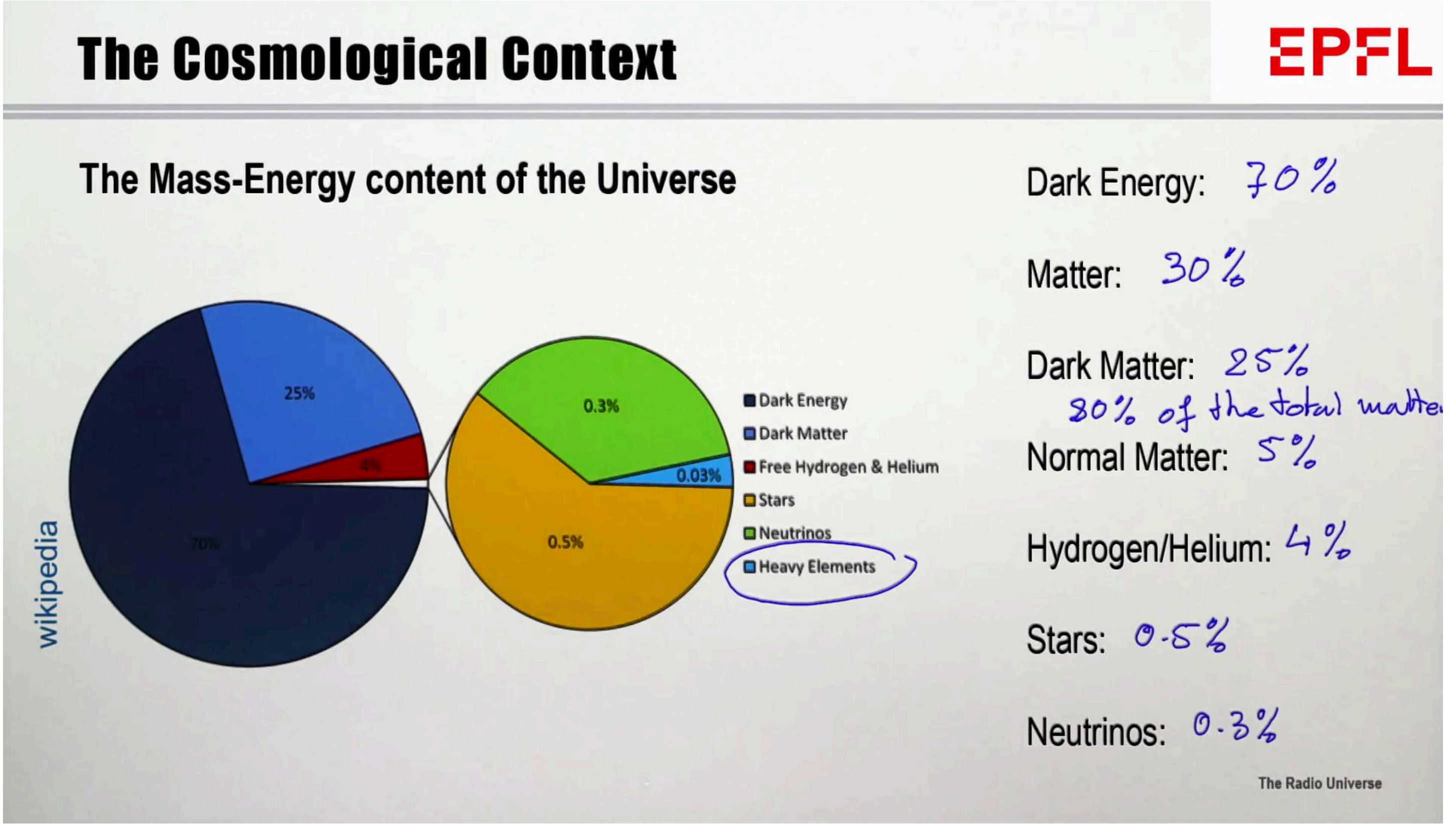


Okay so that's 20,000 times 30,000 billions of kilometer. The distance to the nearest galaxy, the Andromeda galaxy, is about 800,000 parsec. This is about 2.5 million light-year. And what about the size of the observable Universe? Well, this is maybe something difficult to quantify. We can estimate it to be about 28 billion parsec. That's about 93 billion light-year in diameter.

Notes

Summary

4m 31s

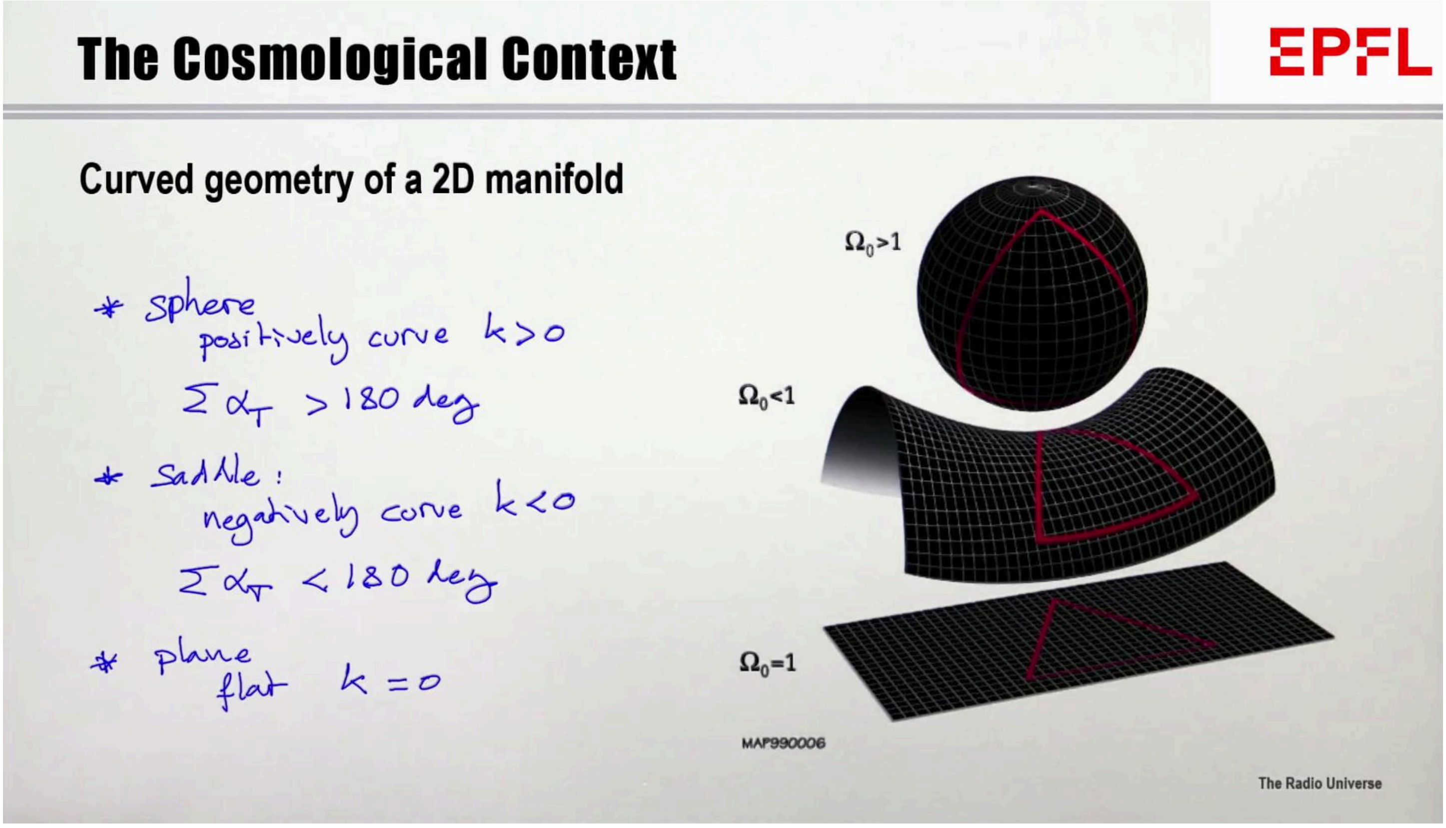


Now we have some hint about the size of the Universe. We want to look at the mass-energy content of the Universe and this mass-energy content is something that was only very well measured in the last 10 to 20 years. Here we have a pie chart trying to represent the net mass-energy content in the Universe. So the very dark blue here is what we call dark energy and this is about 70 percent of the mass-energy content of the Universe. The other part here we see is the matter content of the Universe. The matter content of the Universe is about 30 percent. The light blue part is what we call the dark matter. This is about 25 percent of the total budget and the part you see here, the normal matter, is about five percent of the mass budget, mass-energy budget of the Universe. 25 percent compared to five percent. That means the dark matter is thus 80 percent of the total matter. Now if we zoom out on this five percent, what we find? We find that four percent is made of hydrogen and helium and the remaining one percent is about 0.5 percent of stars, 0.3 percent of neutrinos and then we have a little bit of heavy elements like iron or silicons. Those elements that will be produced when stars explodes.

Notes

Summary

5m 09s

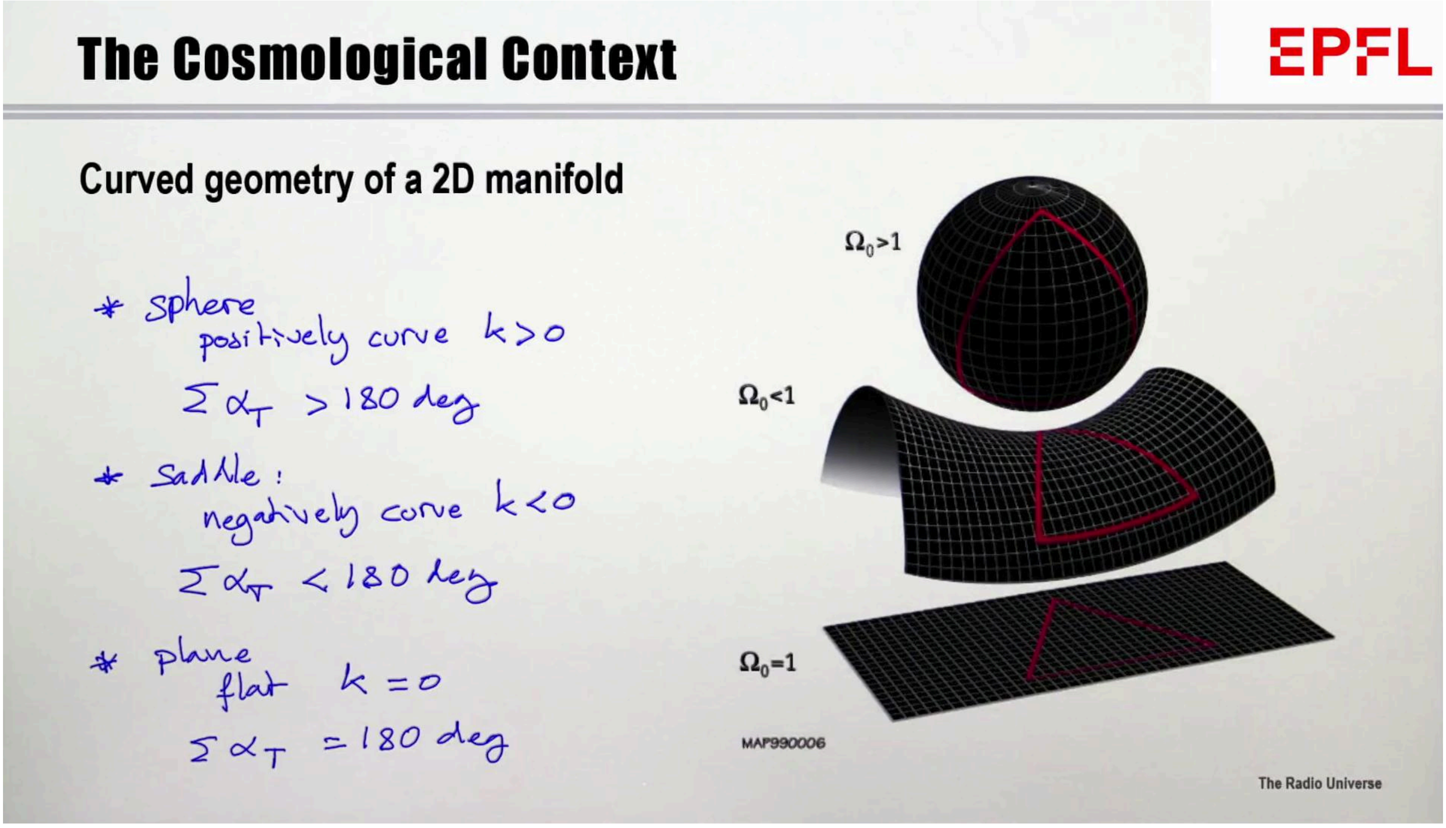


So we've been looking at the size, we've been looking at the mass-energy. Another key element is the geometry of the Universe. So, of course, it's quite difficult to represent ourself the geometry of a 3D manifold but let's start to look at what is the curved geometry of a 2D manifold. So here we have some picture of 2D manifolds. The first example is the case of the sphere. It's a 2D manifold which, you know, occupied a three geometry. What you see is you have a certain curvature which is constant and what we can say, it's positively curved. Okay and we define a value 'k' which is positive which defines the curvature of the sphere. In a curved space which is positively curved then the sum of the angles of a triangle will be larger than 180 degree. Second example is the one of what we call a saddle. A saddle is negatively curved and it has a 'k' which is negative which means it's negative. In case of a saddle if we draw a triangle then the sum of the angle of the triangle will be less than 180 degree. Now let's look at the third case. The third case is the case of a plane and we can say the geometry is flat which means ‘k’ equal zero. That's the case of the Euclidean space.

Notes

Summary

7m 09s

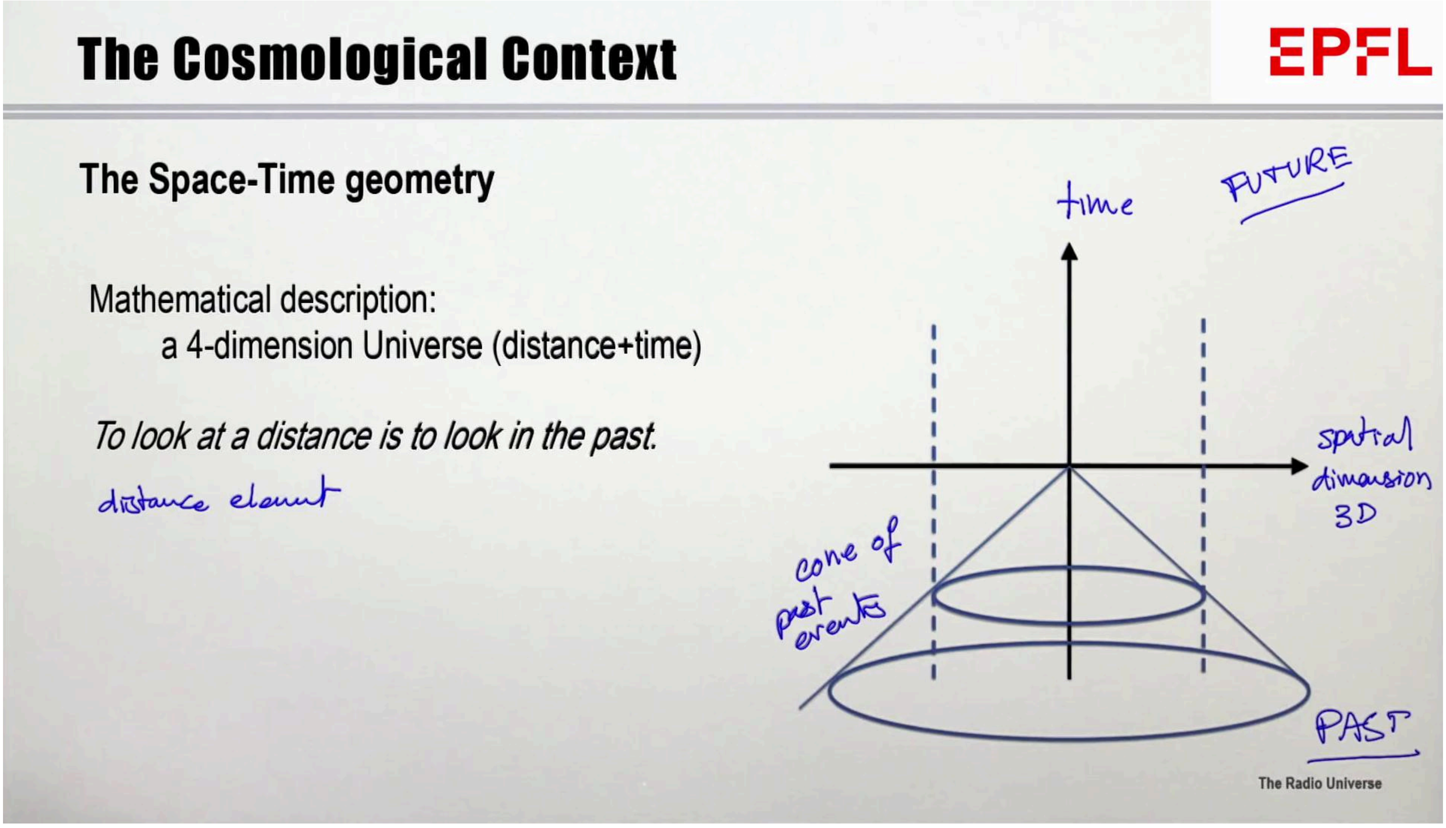


And then the sum of the angle of the triangle on such a manifold will be exactly 180 degree. So it would be the same for the space in 3D. We can define some curvature which is either positively or negatively curved or alternatively, we are in a flat Universe where we can apply the Euclidean geometry.

Notes

Summary

9m 09s

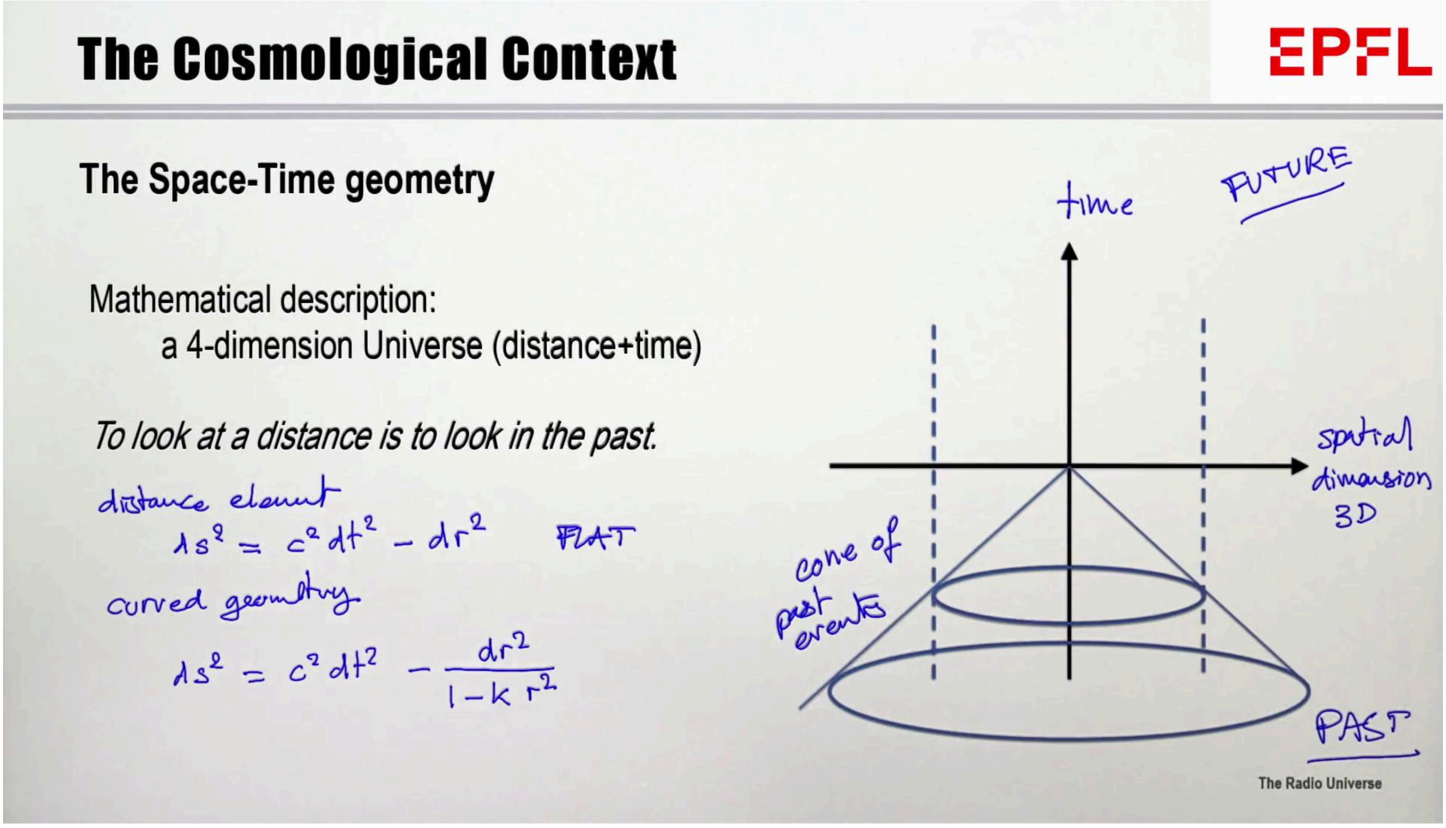


The next detail is that we need to define the geometry of the Universe to consider the space-time. Not only the spatial dimension but also the time dimension. So we need to have a mathematical description of a full dimension Universe which include both distance and time. So here is kind of a picture of what we want to represent here. Here we have two axes; one is the axis of the time, one is the axis of the spatial dimension. Here we have only one axis but, in fact, we have the 3D dimension in X, in Y and in Z. So, of course, because of the limited speed of the light, when we look at a distance we looked at something that happened in the past. So in this picture here we can define the future over here. Okay because it goes into the positive side of time and in the negative side of time, it's what we call the past. We can define a cone of past event. That's the cone we see here and this is just a representation of a cone in two-dimension but effectively we have to face a cone of three-dimension in reality. So because of this four-dimension Universe having both distance and time, we need to define a distance element which encapsulate both the time direction and the spatial direction.

Notes

Summary

9m 40s

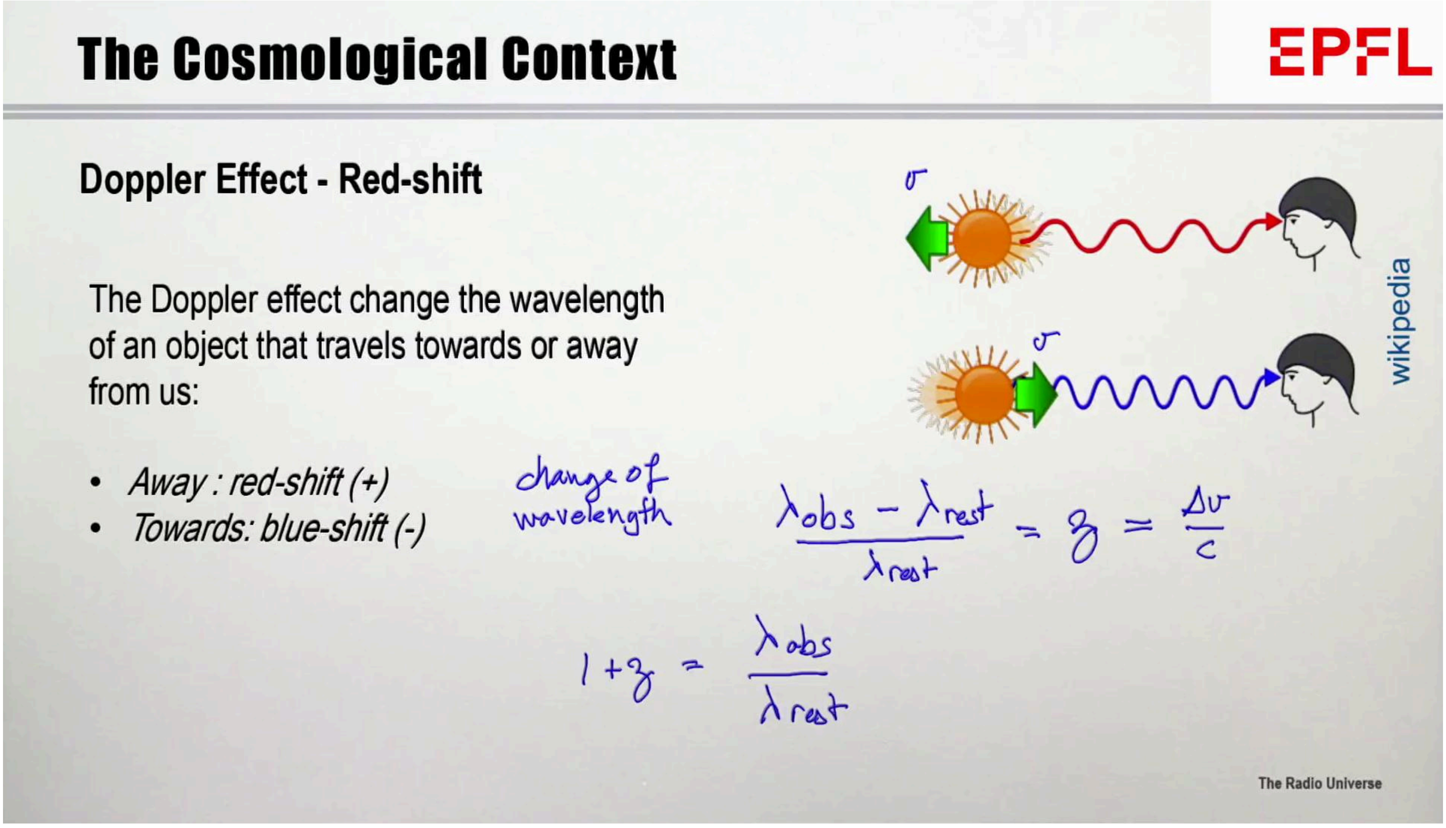


So we can define 'd s-square', ‘s’ being the distance element in the 4D dimension as 'c-square d t-square minus d r-square'. 't' is the time, 'r' is the geometrical distance, spatial distance and the fact that we have a c-square just because of the speed of light, what is really relevant in terms of distance is 'c' times 't'. That would work for flat geometry but in case we have a curved geometry, the distance element would write ‘d s-square equal c-square d t-square minus d r-square' divided by one minus ‘k’, the curvature, r-square. Okay so if 'k' equals zero then we're finding the flat Universe equation and if ‘k’ is positive or negative then we have to do this correction.

Notes

Summary

11m 49s

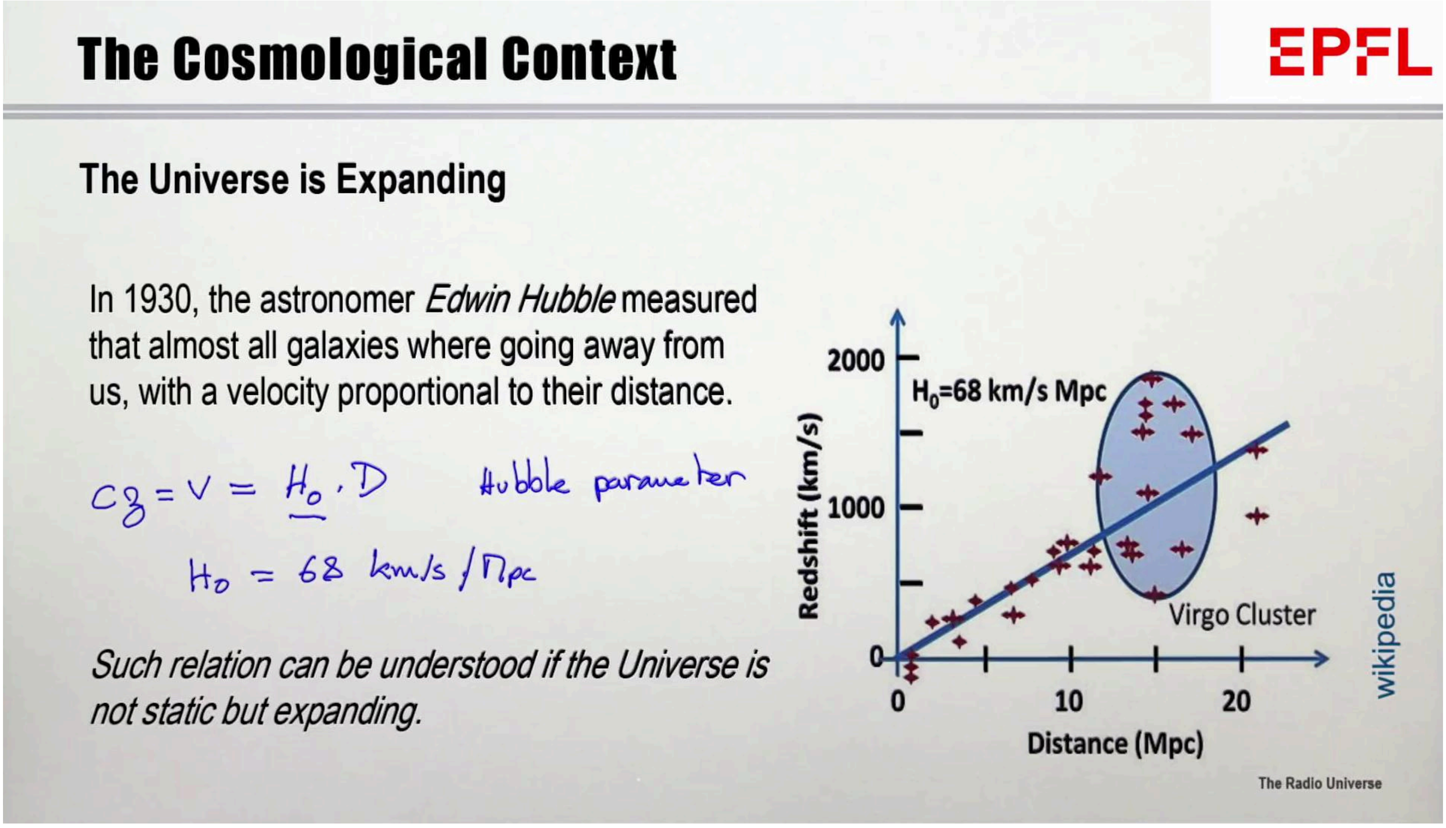


So before going into more details, we need to define the redshift. The redshift is defined by the Doppler effect. So let's consider we're looking at some object and thus those object here, they can move with a certain velocity in one direction or in another direction going away from us or going toward us. Because of the Doppler effect there will be a change in the wavelength of that object and the wavelength will be redshifted if the object is going away from us and the wavelength will be blueshifted if it's going towards us. So we can define the change of wavelength by the redshift following this equation. Lambda-obs is the wavelength we observe from that object at a distance. Lambda-rest is the wavelength emitted by that object. So now if we do the difference of lambda-obs minus lambda-rest divided by lambda-rest, it's how we define the redshift that we write 'z'. This is also equals to delta v, the velocity of that object divided by the speed of light. So 'delta v' will be positive if the object will go away from us, it will be negative if the object is going towards us. Another way to define the redshift is to write one plus 'z' as a difference of lambda-obs divided by lambda-rest. This one plus 'z' just give the change of scale that has been suffered by the wavelength due to this velocity.

Notes

Summary

12m 58s

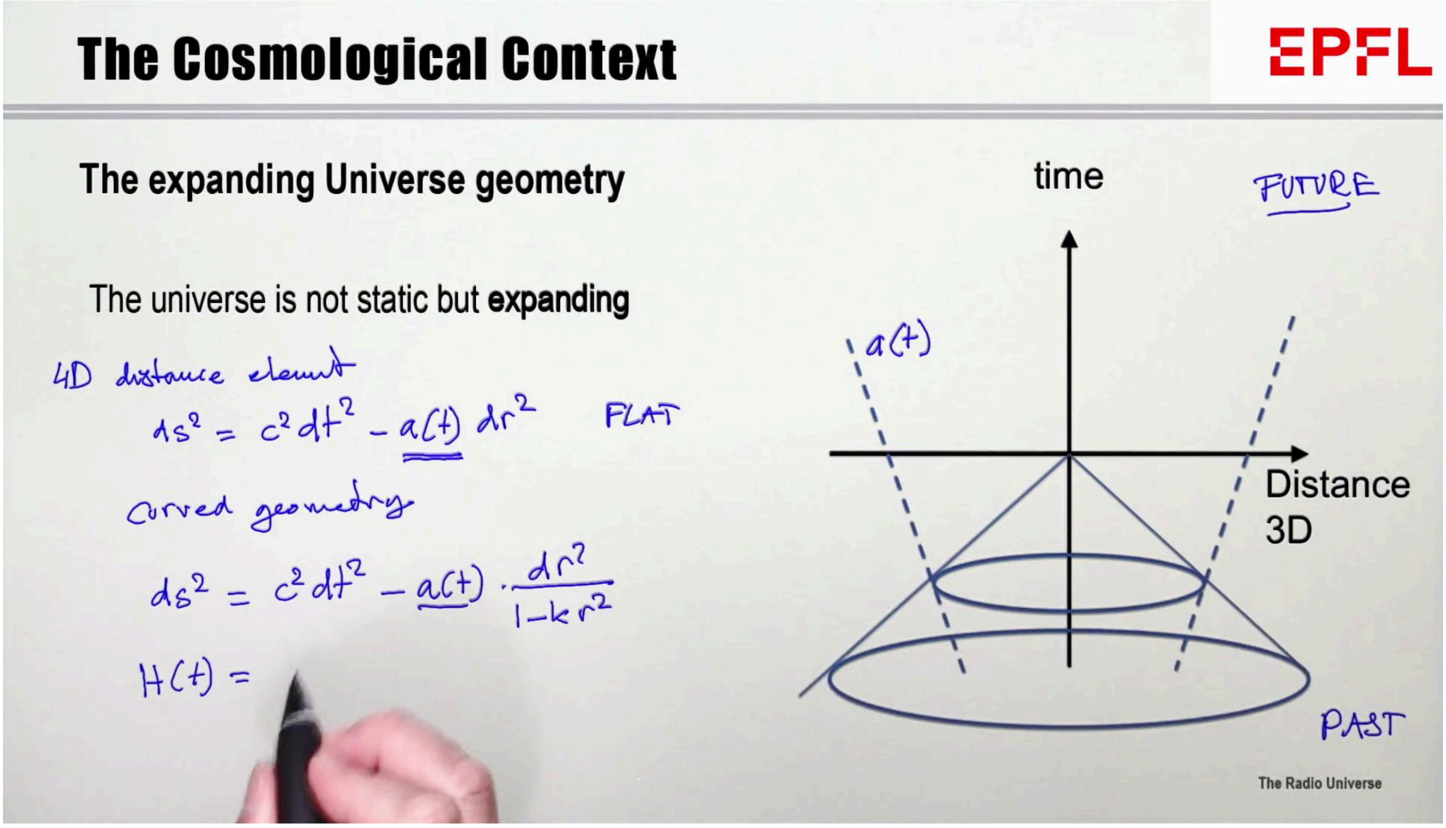


Now we have defined the redshift, we can say something about the expansion of the Universe. Indeed in 1930, the astronomer Edwin Hubble measure that almost whole galaxies around us were going away from us and he has measured the redshift of those galaxies as a function of distance from the galaxies. The redshift is basically 'cz'. It's just measuring the velocity by the Doppler effect of those object and Edwin Hubble has found that the velocity is, in fact, proportional to the distance. So the further the larger away is the object, the larger the recession velocity or the redshift is measured. So we have the velocity that we'll scale with the distance 'D' by a factor which is called 'H-not' which we call also the Hubble parameter. The Hubble parameter ‘H-not’ is measured today to be 68 kilometer per second per megaparsec, that is, if you take two galaxy separated by one megaparsec, the relative velocity between those two galaxy is 68 kilometer per second and this is due to the change in the geometry. This is not real velocity. It is really a change of the size of the Universe. So if we have this relation it can only be understood if the Universe is not static but it's expanding.

Notes

Summary

15m 14s

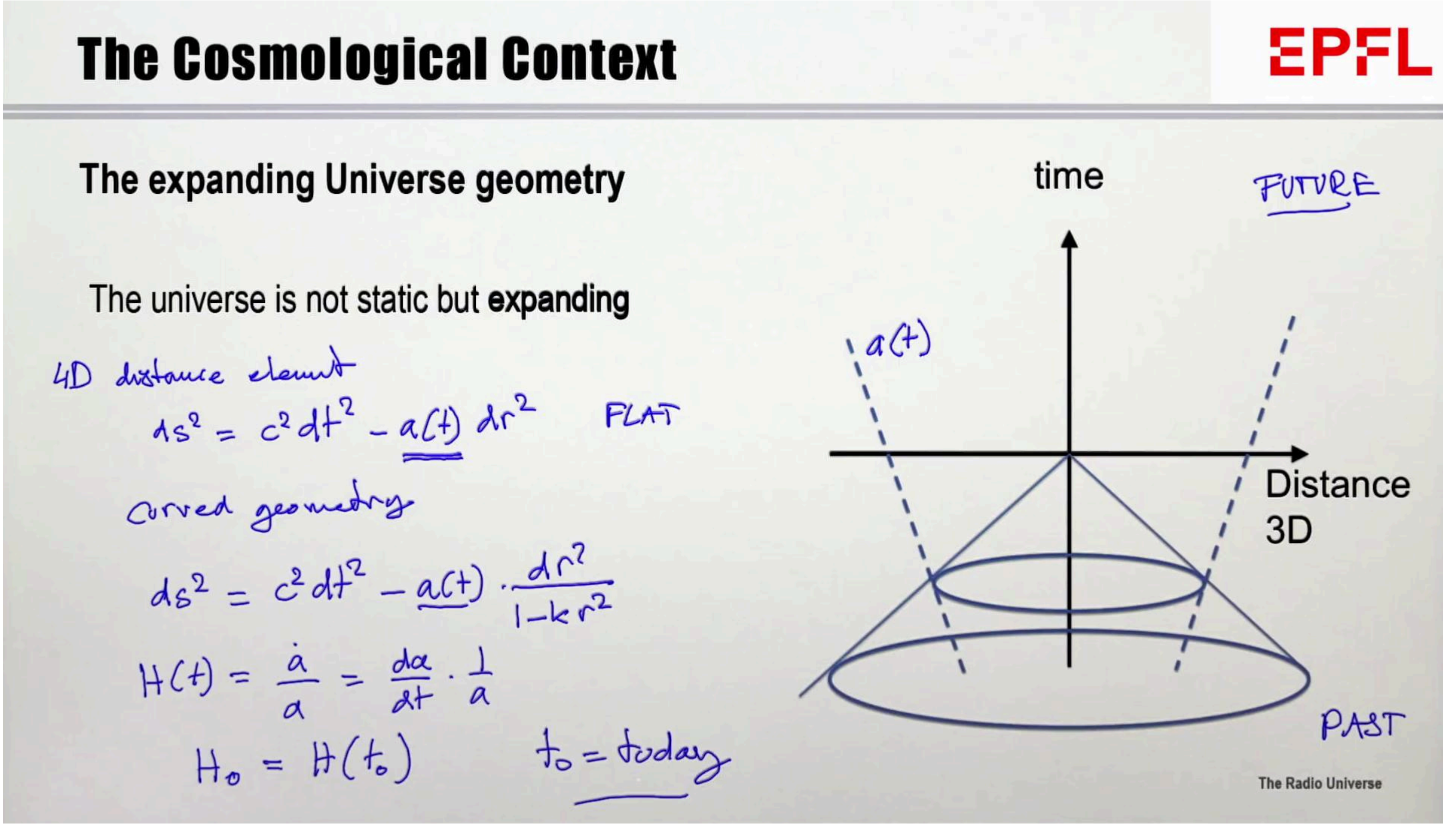


So what does it mean in curves of the Universe geometry if I come back to my previous plot that I had here? So here again we have time. Here we have the distance in 3D. Here we have the future when we go in this direction and here going down we are in the past. Okay and here basically the dashed line here correspond to how the Universe is changing in size. So I can define a curve that tells me that the Universe is expanding. So I can define a size which I will call 'a of t' which give me the scale of the Universe at a given time. So the 4D distance element can then be written 'd s-square equal c-square d t-square minus a of t d r-square' and again this is for flat Universe. Okay so I have introduced here a scale factor that basically adjusts the size of my Universe as a function of time so it encapsulate the expansion or the contraction of the Universe. Now if I have a curved geometry, my 4D distance element would write ‘d s-square equal c-square d t-square minus a of t times d r-square divided by one minus k r-square'. Okay so I re-find back my distance element in a curved space. So what is the relation between 'a of t' and the Hubble parameter? We can show that 'H of t' is basically 'a-dot over a'.

Notes

Summary

17m 29s



Okay. Where 'a-dot' is 'd a over d t times one over a' and the value of the Hubble constant 'H-not' that we've been defining. 'H-not' is basically 'H' at time zero, t-zero is equal of the time of today. So now I have a link between my size of my Universe and how I can measure it by looking at the velocity, the recession velocity of the galaxy around me.

Notes

Summary

19m 51s

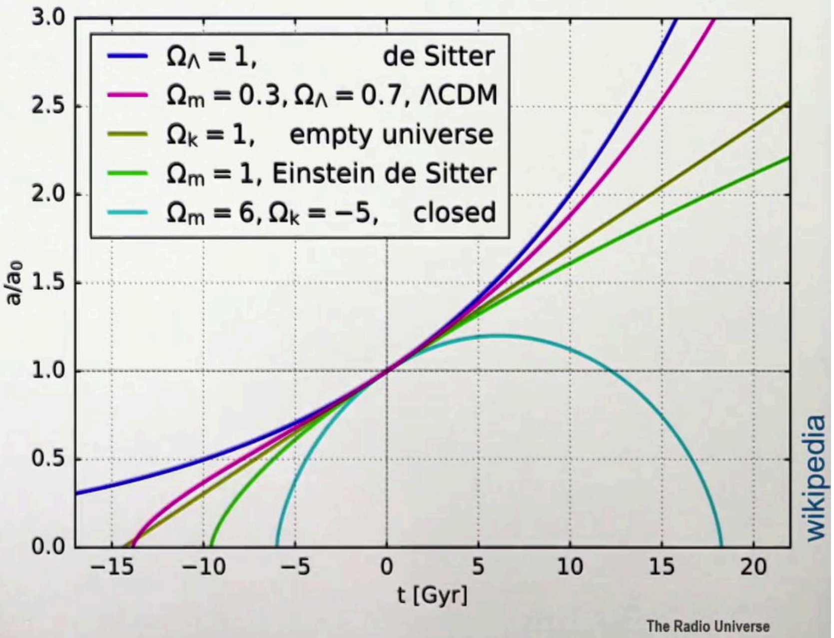
The Cosmological Context

EPFL

Different evolution model of the Universe

expanding today

future? past?

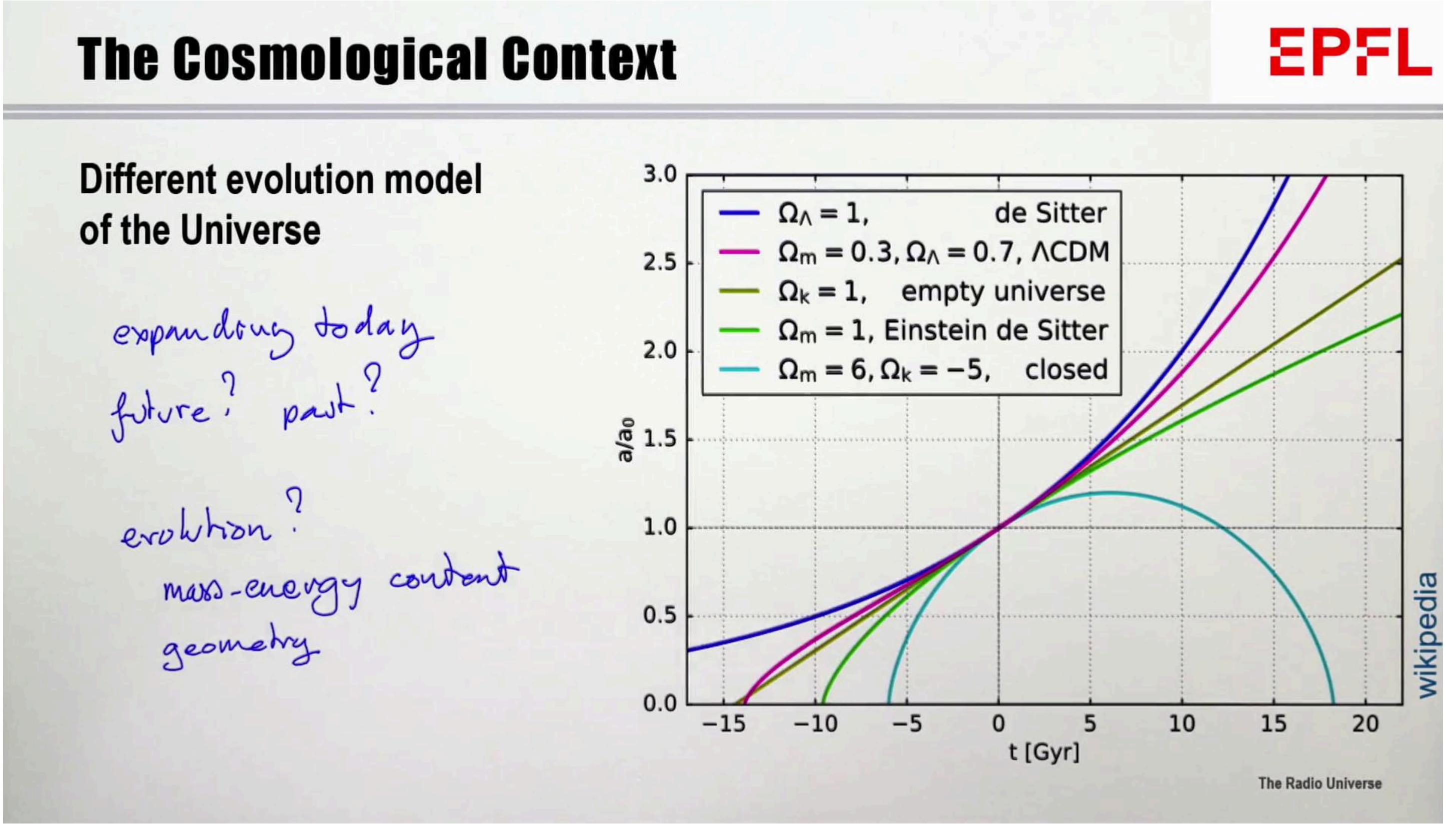


So here I have a picture of the scale factor of the Universe as a function of time. Here I have time of today defined as 't' equal zero and here my scale factor 'a' of today. We can rescale it by 'a-zero' which is the scale of the Universe today. So 'a over a-zero' at time zero as defined of today is equal to one. My Universe is expanding so as time goes along, it will increase. My size will increase with time. So the question is, now I know the Universe is expanding today but what about the future? What about the past? So, of course, you could see that here I put different curves. Those different curves correspond to different models of the Universe whether it's a de Sitter Universe, a lambda CDM Universe, an empty Universe, an Einstein de Sitter Universe or the closed Universe. Those Universe model are defined with different values of omegas and that will have a different evolution with time. In that closed Universe at some point in the future, the Universe will stop expanding and it will be contracting again. In the de Sitter model, the dark blue curve that expansion will continue to accelerate. In the Einstein de Sitter model, the model the Universe will expand but slower and slower.

Notes

Summary

20m 24s

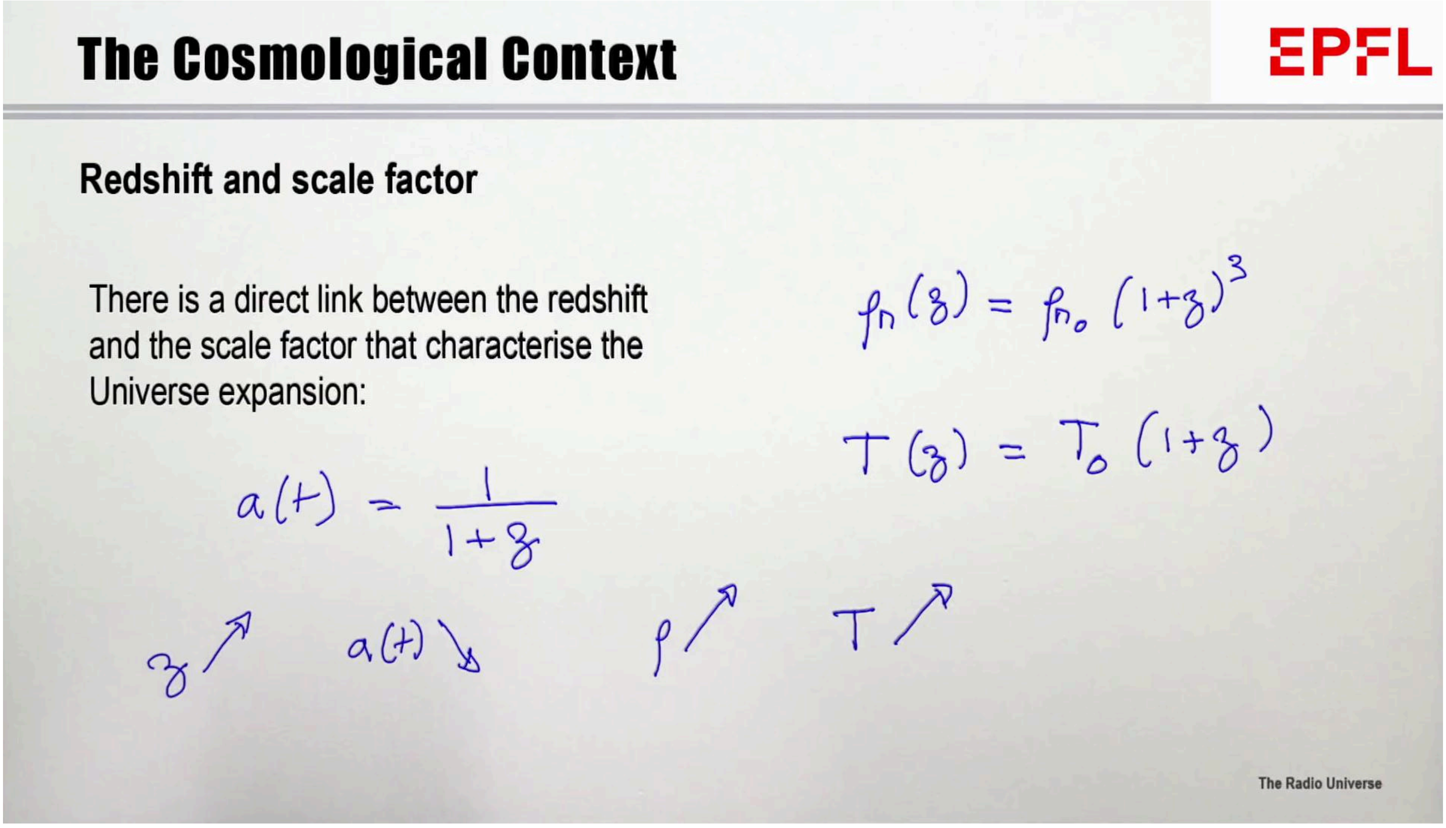


So what the evolution depends on? The evolution depends on these many parameters. These many parameter are depending on the mass-energy content of the Universe and it also depend on the geometry of the Universe whether it's flat or curved.

Notes

Summary

22m 25s

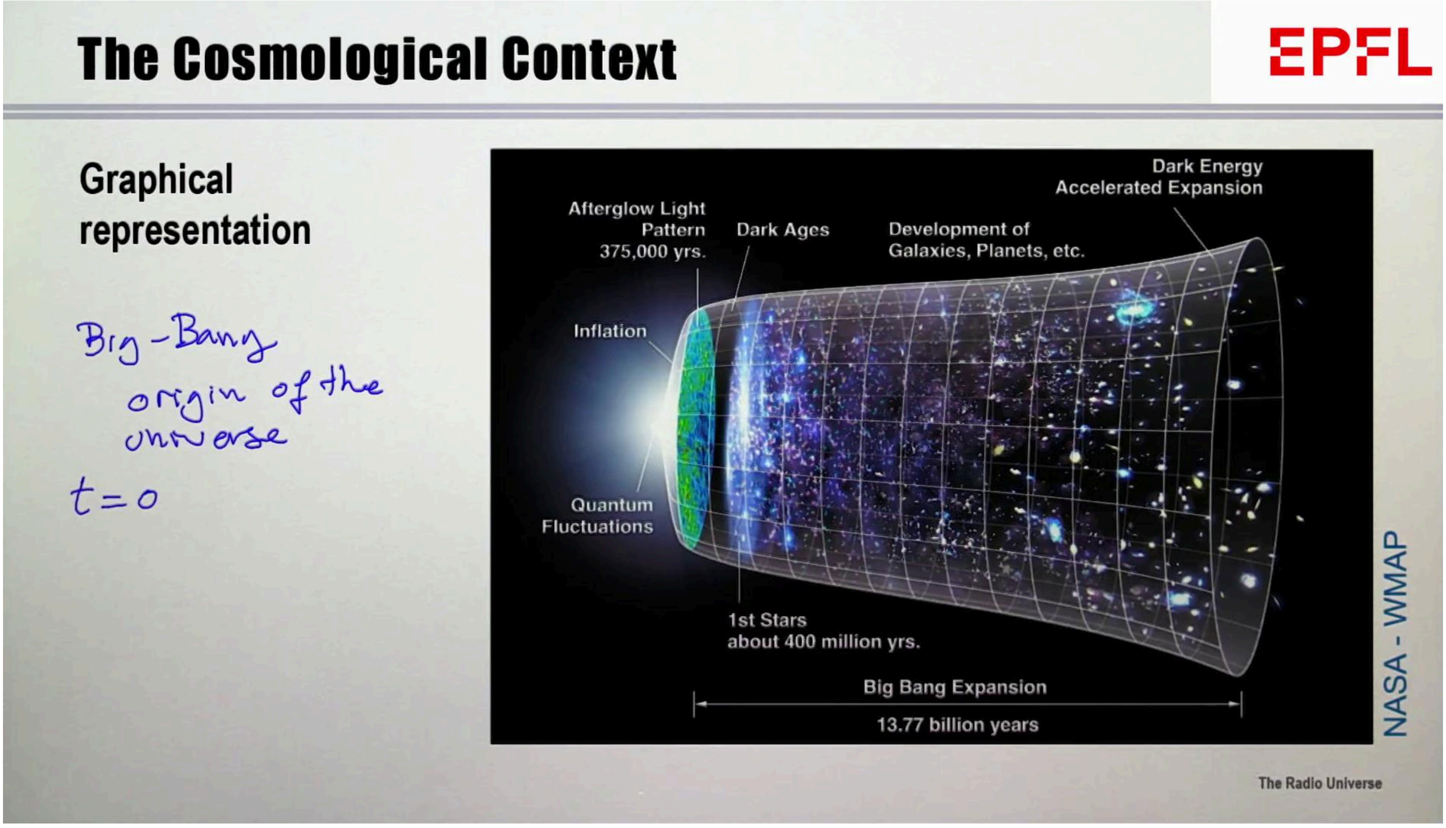


Here I want to make a link between the redshift and the scale factor. The scale factor is this ‘a of t’ function that define the size of my Universe and I can show that 'a of t' is basically scaling as one over one plus 'z', the redshift. So the larger the redshift, the smaller is 'a of t' and I can show also that my mass density of the Universe 'rho m' which is a function of time or redshift is scaling as the matter density of today with the index zero times one plus ‘z’ to the cube. Similarly the temperature in my Universe as a function of time or as a function of redshift is scaling as the temperature of today times one plus 'z'. So if 'z' gets larger, that is, we're going towards the past, that is, we go earlier in time, the size of the Universe is contracting. The density of the Universe is growing and the temperature of the Universe is also increasing. So if ‘z’ gets very large, the density and the temperature will get very large and the size will be very small. So the Universe will contract quite a lot. By contracting, of course, the density will get higher and the temperature will get higher.

Notes

Summary

22m 49s

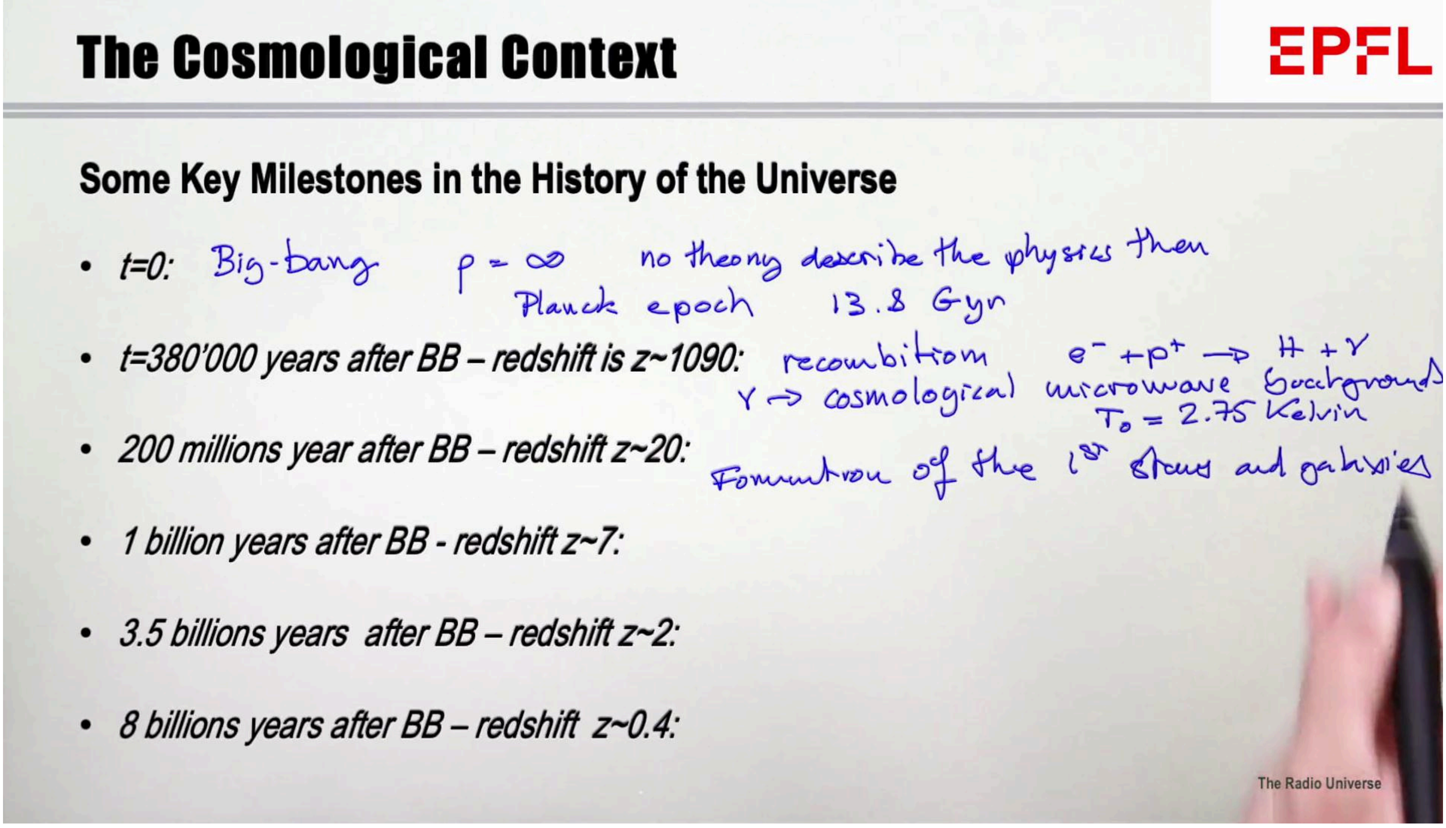


So we now have this graphical representation of the Universe. We are here today and when we're going back toward the past, we see a different Universe that was smaller in size. It was smaller but denser and it was very hot at the beginning. It was very small also and people have linked the early Universe which is very hot and very dense as kind of an explosion but that's really like an image because there has not been any explosion but we have defined the Big Bang as the origin of the Universe and we have defined the Big Bang as the time zero at the beginning of the Universe. About 380,000 years after Big Bang, we have the first glow of the Universe we can see with our eyes. Well, effectively with instruments that we can read with our eyes. At that time the Universe was essentially made of hydrogen and helium and there was no stars. We had to wait about 400 million years, 200 to 400 million years to see the first stars and those stars have evolved from galaxies more larger and larger galaxies and that's what we see around us and we have we are at about 13.77 billion years after what we call the Big Bang which is really the origin in time of the Universe.

Notes

Summary

24m 55s

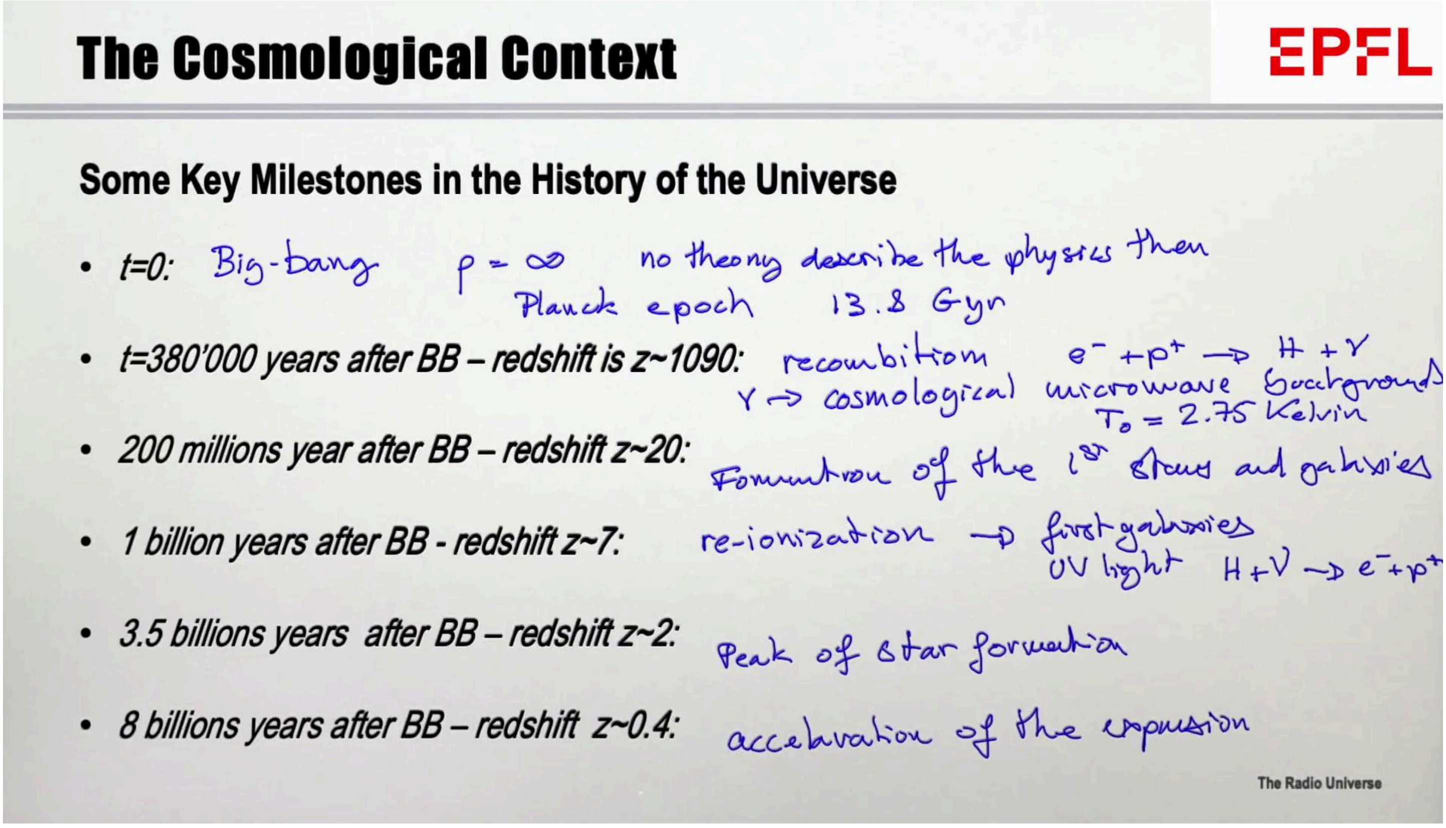


We can define some key milestone in the history of the Universe. So 't' equal zero is really what I call the origin of time and that's what we call also the Big Bang. The density of the Universe is then basically infinity. In short, it means that there's no theory that can describe the physics. We also characterize this time as the Planck epoch and it correspond to a lookback time of 30.8 billions of year. The next milestone we have in the beginning of the Universe is what we call the recombination. It's the time when the electrons plus the protons are forming the hydrogen atom. They're forming the hydrogen atom and this will produce an emission of photons. These photons are free to travel through the full Universe and they can be detected by our instrument. These photons can be detected today and they produce what we call the cosmological microwave background. These photons are detected in microwave and they correspond to a temperature of today measured today of 2.75 kelvin. The next milestone is about 200 to 400 million year after Big Bang corresponding to redshift about 20 and is corresponding to the formation of the first stars and galaxies.

Notes

Summary

26m 53s

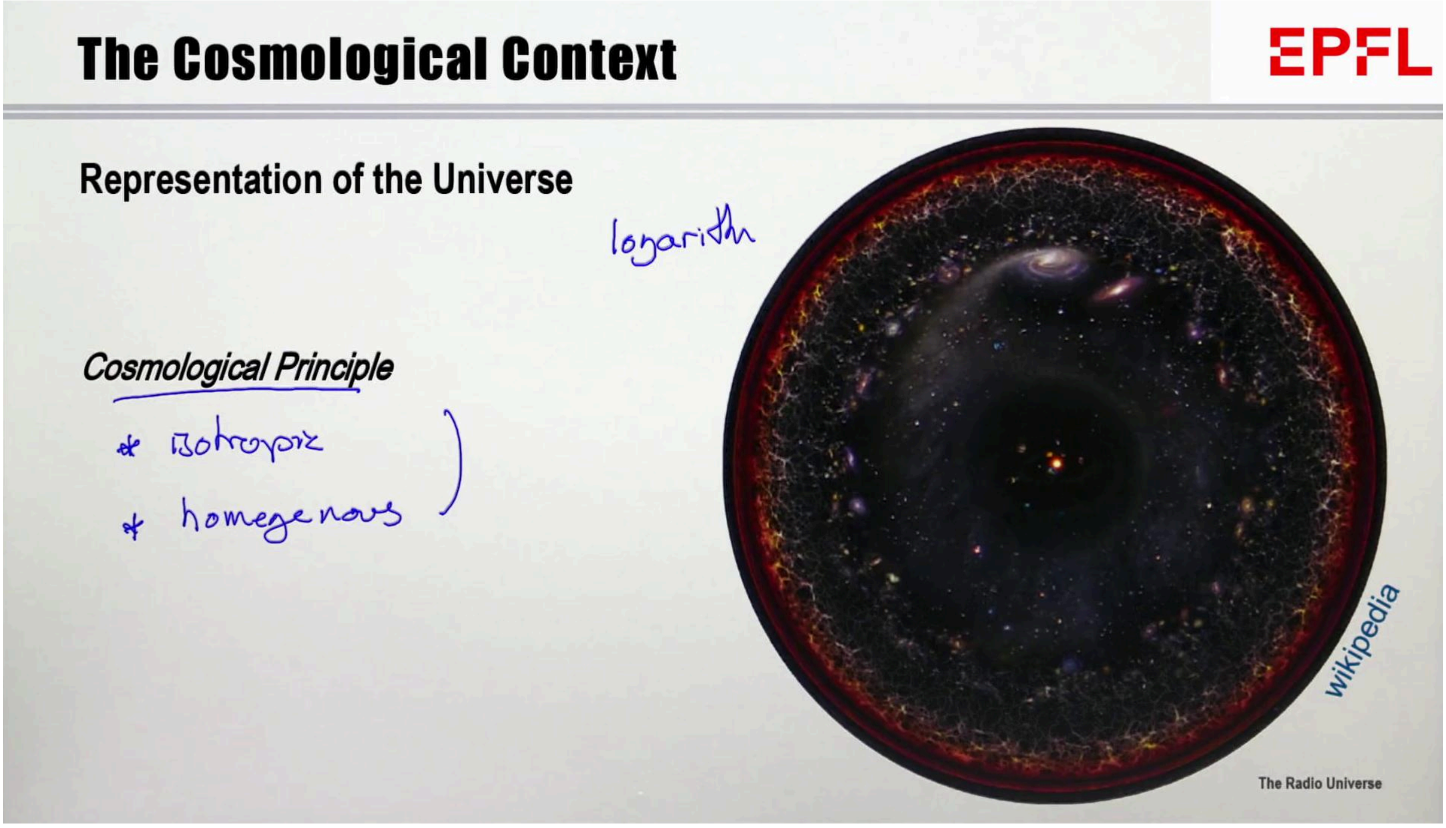


Next milestone is about one billion years after Big Bang at redshift about seven. It correspond to what we call the re-ionization. It correspond to the time when the first galaxies which are producing a lot of UV light are going to break the hydrogen atom and ionize them again so that's what we call re-ionization. So the hydrogen atom plus the photons coming from the first galaxies will ionize the Universe again and they will produce a plasma made of electrons and protons. The next milestone at 3.5 billion years after Big Bang which correspond to redshift about two. It's the peak of star formation in the Universe. Last milestone at about eight billion years after Big Bang corresponding to redshift about 0.4 is the acceleration of the expansion of the Universe. It correspond to the time when dark energy dominates in the Universe.

Notes

Summary

28m 40s

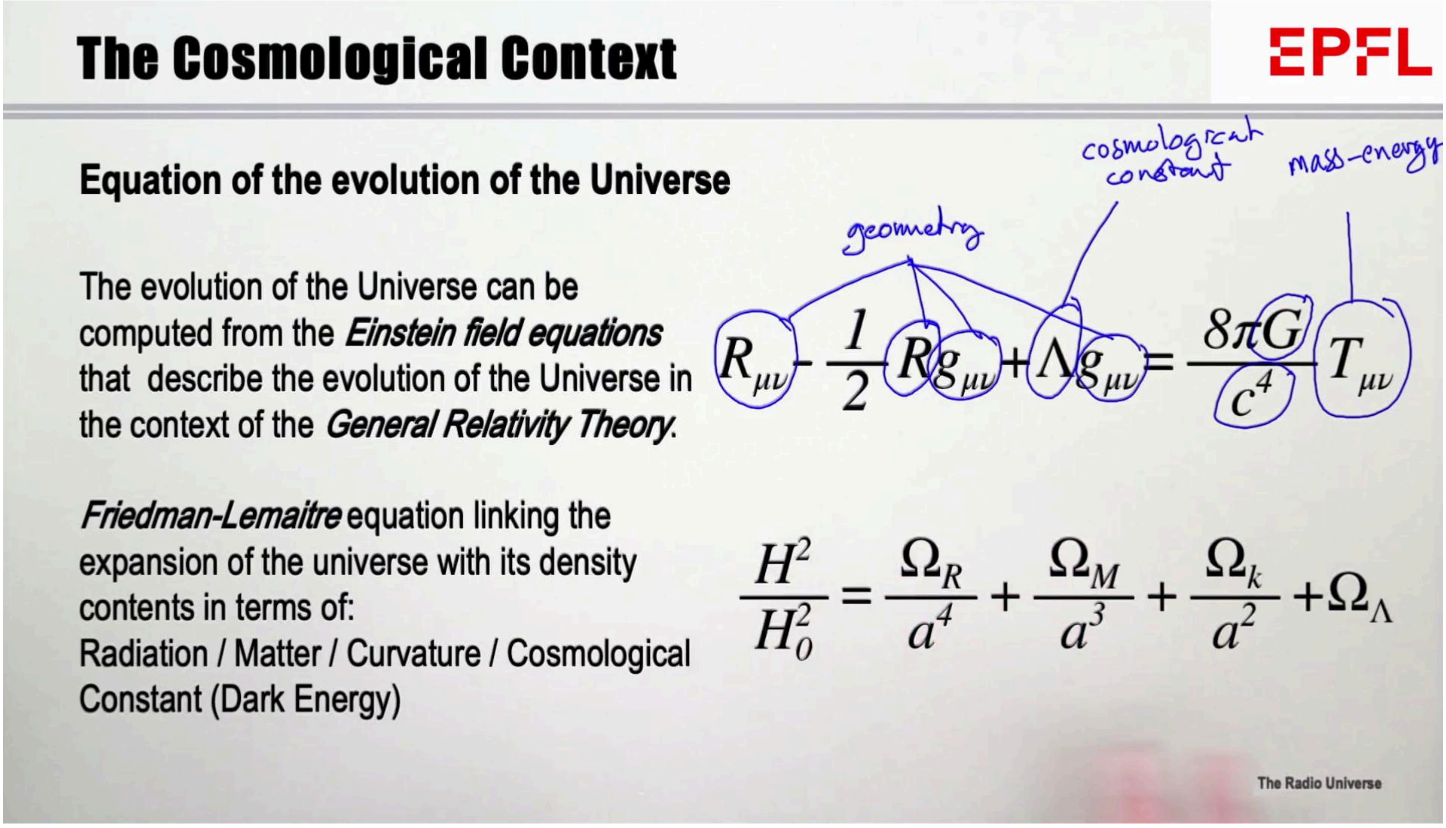


Here we have a representation of the Universe where distance are expressed in logarithm. Here at the center we see the Sun surrounded by planets. Around it we have some stars and then we have the diffuse light coming from the Milky Way. Further along, you have set of galaxies around us and those galaxy are then distributed along filamentary pattern that describe what we call the cosmic wave. In this picture, we see two things. We see that the Universe is isotropic. That means it's the same in all direction. Now if we average the mass distribution in the Universe, we can also show and demonstrate that the Universe is homogeneous. Those two concept of isotropy and homogeneity is what we call the Cosmological Principle and based on this Cosmological Principle we can turn the equation of Einstein into the equation of the evolution of the Universe.

Notes

Summary

29m 58s

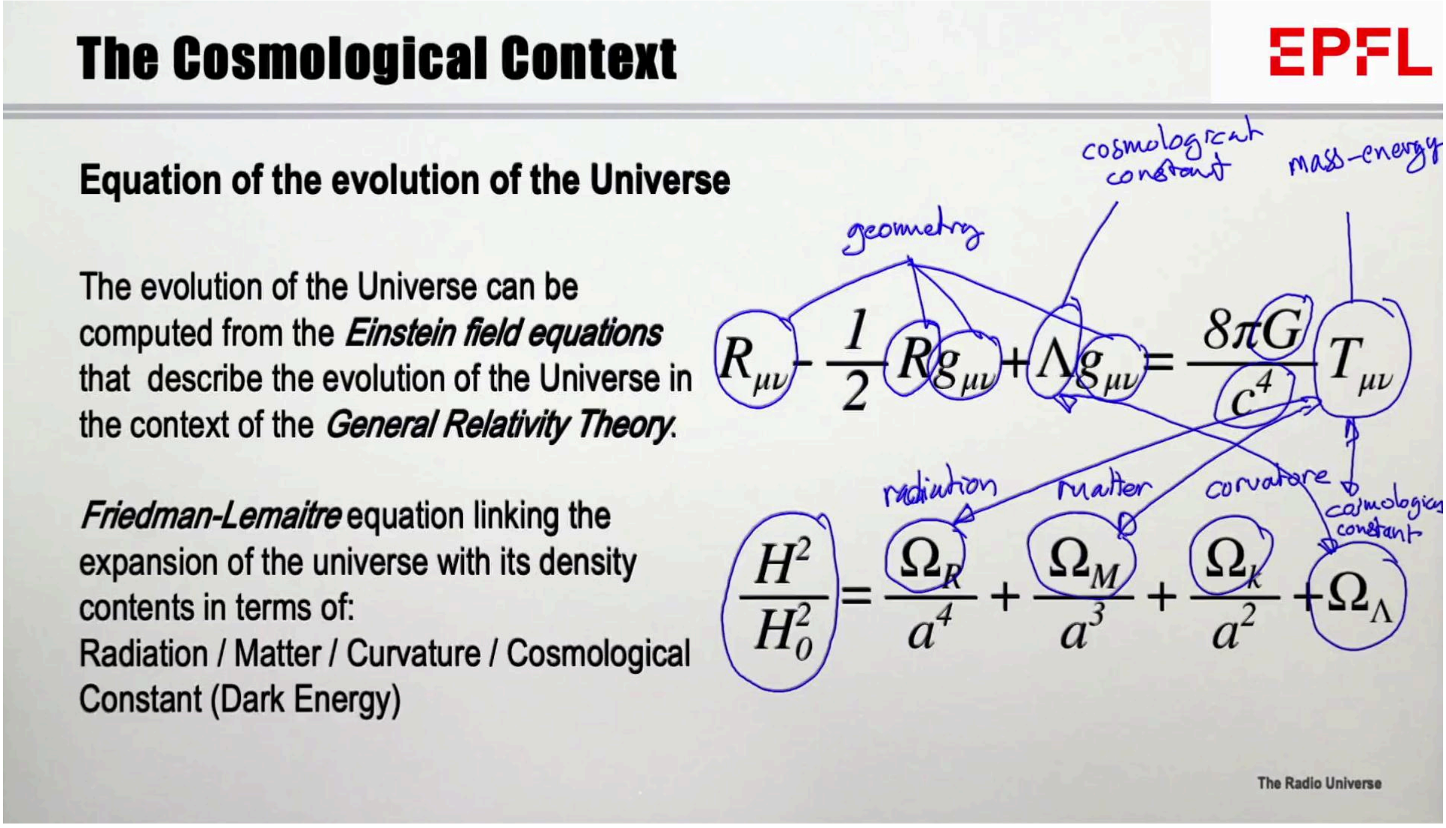


So in short, the evolution of the Universe can be computed from the Einstein field equation. Here we have written the Einstein field equation that describe the evolution of the Universe in the context of the general relativity theory. What is important in this equation is the following. We have different component. We have 'G' which is the constant of gravitation. We have ‘c’, the speed of light which is important that we define our four-dimension geometry of space-time. We have a number of parameter 'R mu nu', capital R, 'G mu nu'. All of them are characterizing the geometry of the Universe whether it's local or global. Whether we have a Universe which is flat or whether we have a Universe which is curved. The geometry of the Universe will basically depend on two parameters. We have lambda, what we call the cosmological constant and we have a tensor 'T mu nu' which is a tensor of mass-energy distribution in the Universe. So 'T mu nu' tells you how much mass and how much energy there is in the Universe and what is the distribution as a function of position in the Universe. You can go from this Einstein field equation, process it making some assumption like the Cosmological Principle and you can derive what we call the Friedman-Lemaitre equation that we have written here.

Notes

Summary

31m 18s

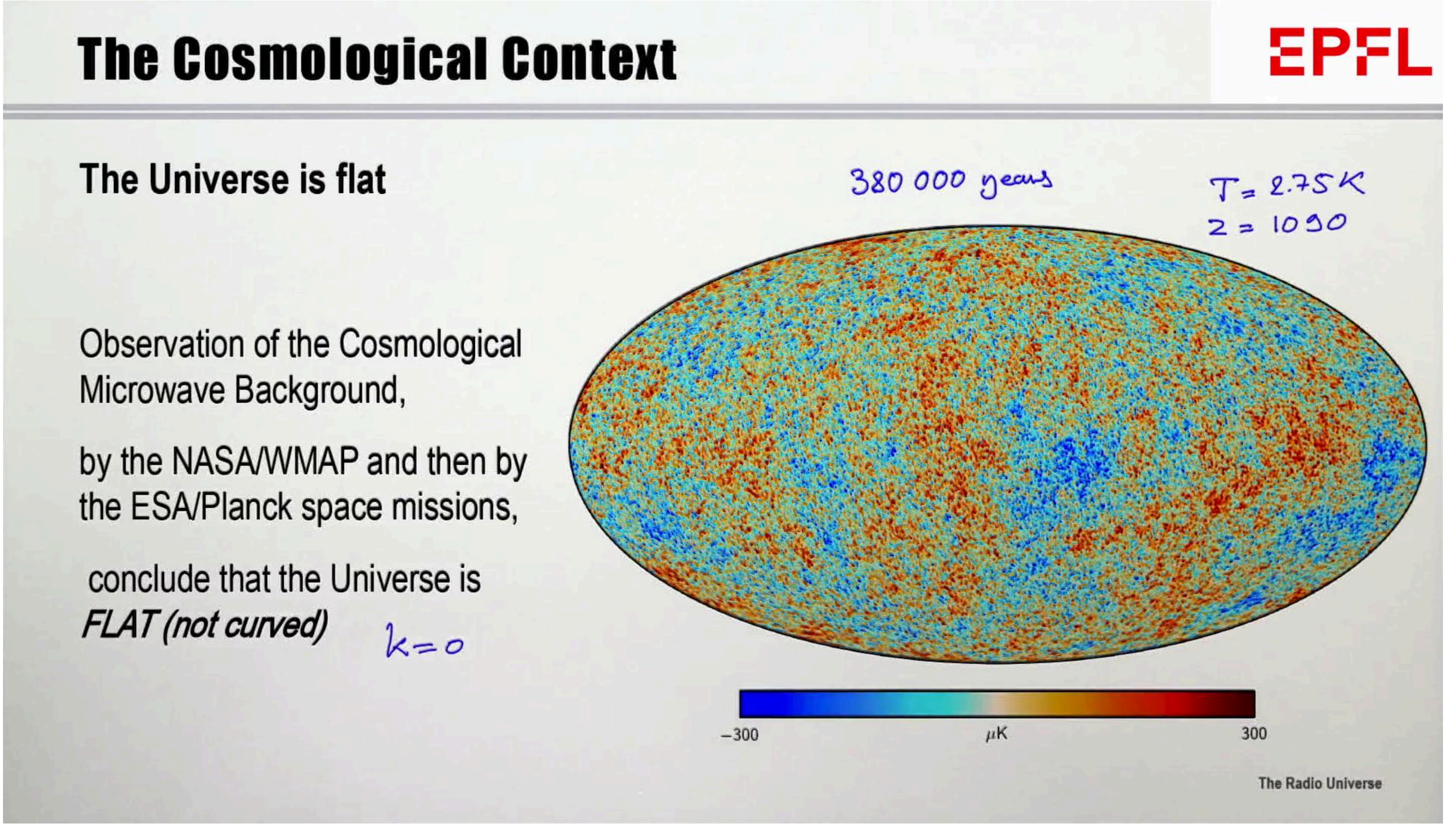


The Friedman-Lemaitre equation is linking the expansion of the Universe as a function of its content in terms of radiation, in terms of its matter, in terms of its curvature whether we have a flat or curved Universe, and in terms of the cosmological constant. So the cosmological constant is basically linked to the lambda in the Einstein field equation. The matter, it's linked to the mass-energy budget as well for the radiation and there could be also a representation of the cosmological constant parameter or the dark energy parameter that is expressed in the energy part of the 'T mu nu' transfer.

Notes

Summary

33m 20s

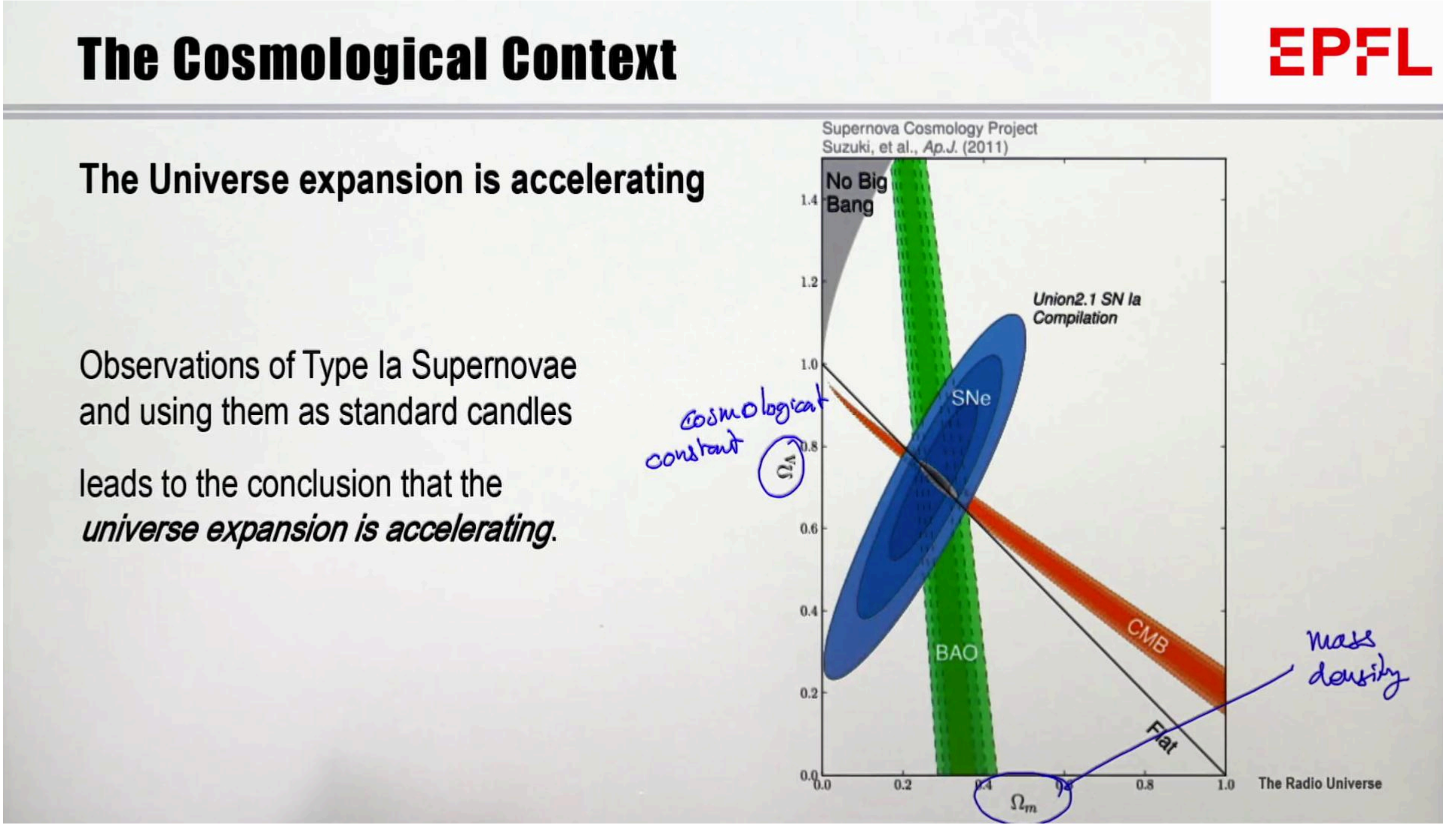


So what tells us the observation of the Universe? One key observation of the Universe is the observation of the Cosmological Microwave Background. So this is the light emitted by the Universe when it was 380,000 years after time zero after the Big Bang. This is a map of that emission in different direction across the sky. The mean temperature is measured at 2.7 kelvin today but because it correspond to redshift of emission of 1,090, it correspond to a temperature originally which was one thousand time larger so about 3,000 kelvin. This map was made by the ESA Planck space mission and previously, we had a similar map not as accurate made by the NASA WMAP space mission. Those two space mission concluded from the analysis of this map that the Universe is flat and it's not curved. So we can basically assume that 'k' in my equation is equal to zero.

Notes

Summary

34m 20s

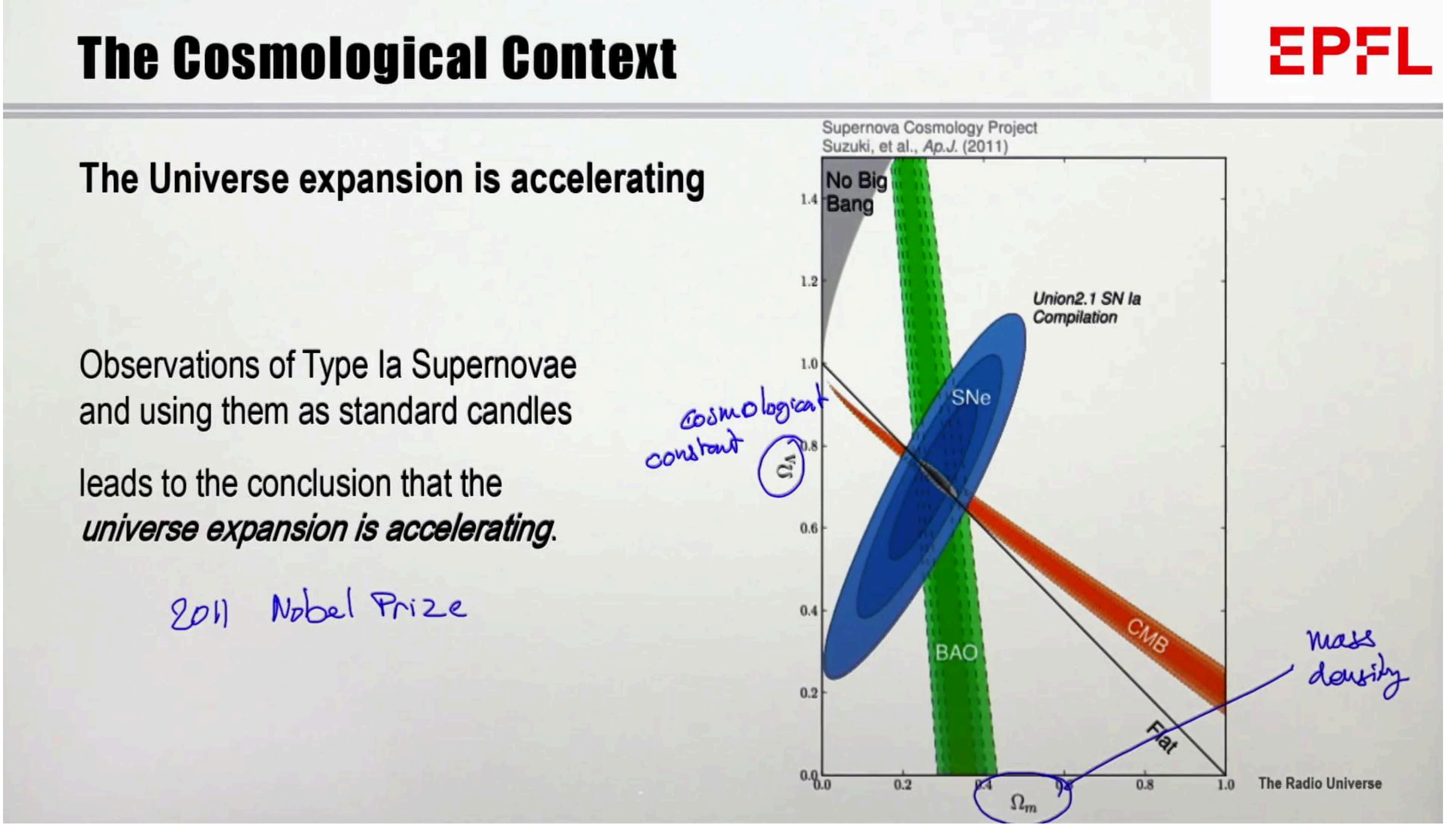


The other more recent observation of the Universe was the observation of Type Ia Supernovae and we're using this Type Ia Supernovae as standard candles. So that means if your supernovae is a standard candle it means it will emit the same amount of light irrespective to its distance so the flux you will receive from that object can tell you about the distance of that object. So by observation of Type Ia Supernovae you can make a direct link between the redshift and the distance and then you can measure the expansion of the Universe. Here we have a summary plot of the supernovae measurement and the CMB measurement as a function of two parameter. 'Omega-m' is the mass density in the Universe and omega-lambda, it's the cosmological constant parameter in the Universe. The ellipses give you the confidence at which an experiment is measuring these two numbers. The curve here in black tells you about whether the Universe is flat or not. If you are on that line you have a flat Universe. The CMB measurement is very close to a flat Universe. And the measurement of the supernovae are basically when combined with the CMB information tells you about what is the value of 'omega-m' and what is the value of omega-lambda.

Notes

Summary

36m 02s



Those two measurement have also been confirmed by more recent observation that we call the BAO, Baryon Acoustic Oscillations. But it's really the observation of Type Ia Supernovae and the combination with the CMB earlier measurement that are basically proving that the Universe expansion is accelerated. The discovery of the accelerated expansion of the Universe was made about 20 years ago and we had to wait 2011 to have this discovery awarded the Nobel Prize.

Notes

Summary

38m 08s

In this presentation we have seen that the content of the Universe is made of mass and energy. 95 percent of this mass-energy budget is made of two unknown component; dark matter and dark energy. The content of the Universe is driving its evolution so measuring precisely the Universe evolution is a good way to learn about the two dark components. In 1929, Edwin Hubble was among the first astronomers to characterize the expansion of the Universe and in the last 20 years, modern measurements have shown that the Universe expansion today is accelerating. This acceleration could be explained by lots of dark energy but its nature remain a mystery so more is to be discovered.

Notes

Summary

38m 48s