Astrophysics & Cosmology
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Lecture – 33
C14 Distances, the Hubble Parameter and Dark Energy (Contd.)

Welcome, let me remind you that we were discussing supernovae and how you can determine distances using supernovae, so supernovae can be used to determine; supernovae of type 1a can be used to as standard candles to determine luminosity distances and these are usually represented as in terms of the distance modulus and the different cosmological models, different predict, the distance modular as a function of redshift.

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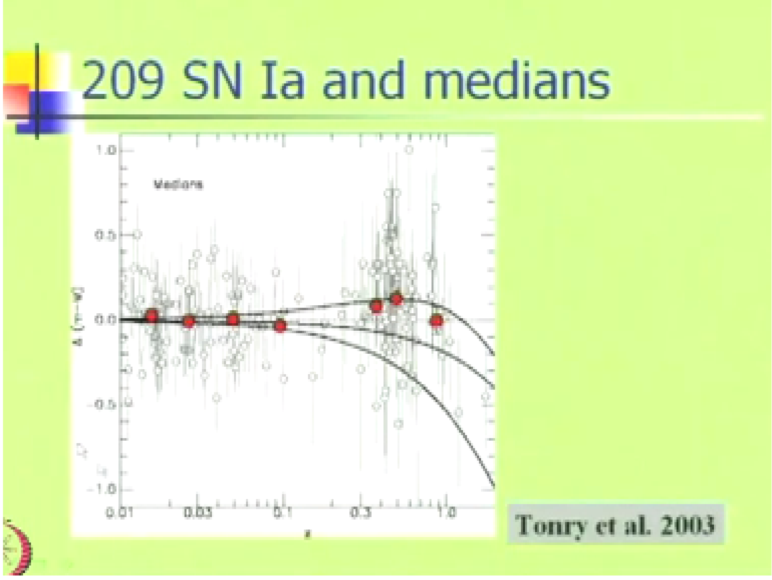

209 SN Ia and medians

Tonry et al. 2003

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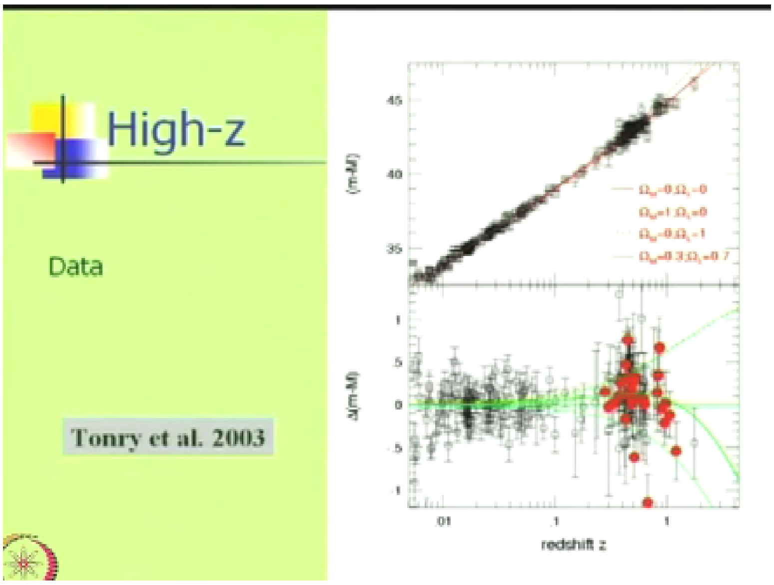

High-z

Data

Tonry et al. 2003

And these come out to be different, they caught to be different; the predictions for different cosmological models.

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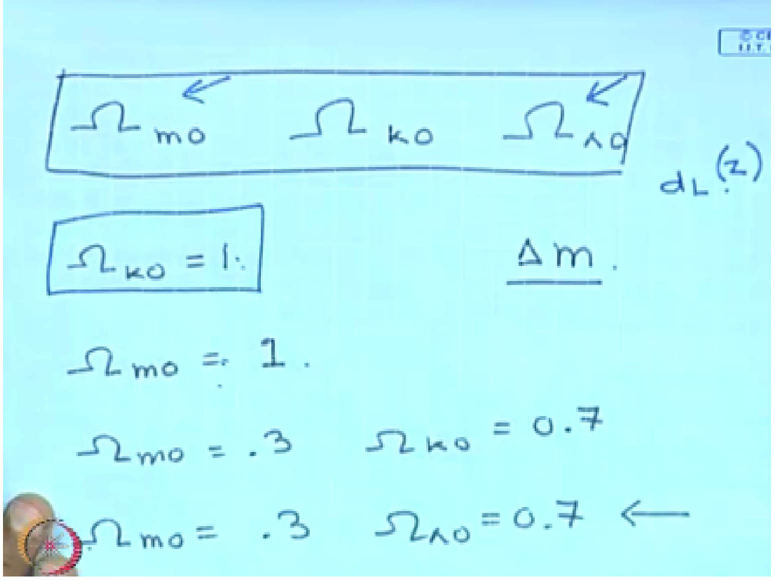

$$\boxed{\Omega_{m0} \quad \Omega_{k0} \quad \Omega_{\Lambda 0}} \qquad d_L(z)$$

$$\boxed{\Omega_{k0} = 1.} \qquad \underline{\Delta m}.$$

$$\Omega_{m0} = 1.$$

$$\Omega_{m0} = .3 \qquad \Omega_{k0} = 0.7$$

$$\Omega_{m0} = .3 \qquad \Omega_{\Lambda 0} = 0.7 \longleftarrow$$

And in this picture; the difference in different distance moduli between various cosmological models with relative to this one has been plotted along the y axis and the redshift has been plotted along the x axis, so the horizontal line through the centre is this model and the upper curve, the lowermost curve is a model which has only matter; omega matter = 1 and the curve over here is a model which has a mixture of matter; 0.3, omega matter is 0.3.

The rest of it is curvature and what this; what the data shows you is that none of these 3 models are able to fit the supernovae luminosity distances as a function of ratio. The distances come out to be larger than predicted by all 3 of these models because the supernovae appeared to be fainter than predicted by these 3 models okay. So, it is necessary to invoke a model which has a constituent with negative pressure this is what we were discussing in the last class.

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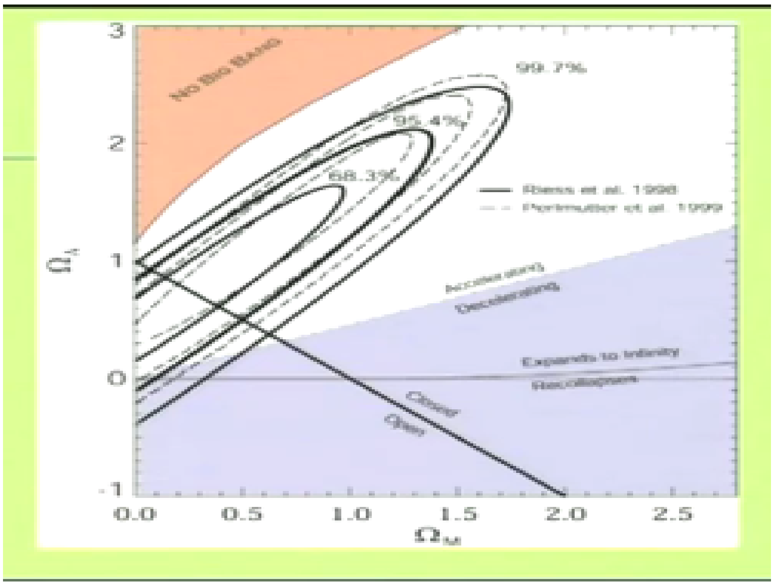

Let me, so, if you introduce allow for a constituent with negative pressure, we call it lambda and negative pressure such that the pressure = - the density *c square.

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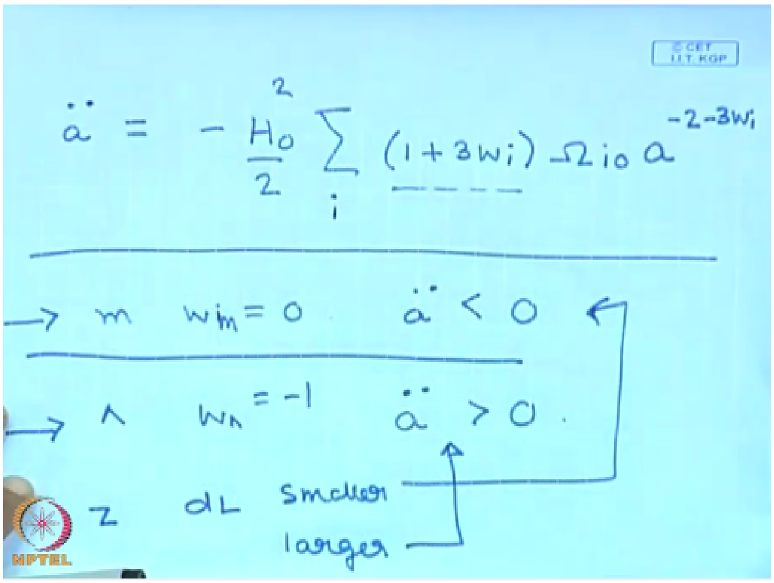

$$\ddot{a} = -\frac{H_0^2}{2}\sum_i \underline{(1+3w_i)}\,\Omega_{i0}\,a^{-2-3w_i}$$

$\rightarrow$ m $\quad w_m = 0 \quad \ddot{a} < 0$

$\rightarrow$ Λ $\quad w_\Lambda = -1 \quad \ddot{a} > 0$

z $\quad d_L \quad$ smaller

larger

The equation of state parameter is -1, if you allow such a parameter and then you allow this, so you have a model where you have 3 parameters; omega matter0, omega curvature0 and omega lambda0, any 2 of these can be vary, the third one is determined from the fact that these sum is the 1 okay. So, the different cosmological models can be our each point represents different cosmological model, okay.

And the solid line are the models which are specially flat okay and the region over here; the line over here demarcates the difference, is a division line between models which are accelerating at present and models which are decelerating at present, so that is the question that we were addressing at the end of last class. What decides this? So, if you look at the equation that governs the evolution of the scale factor, this is the equation.

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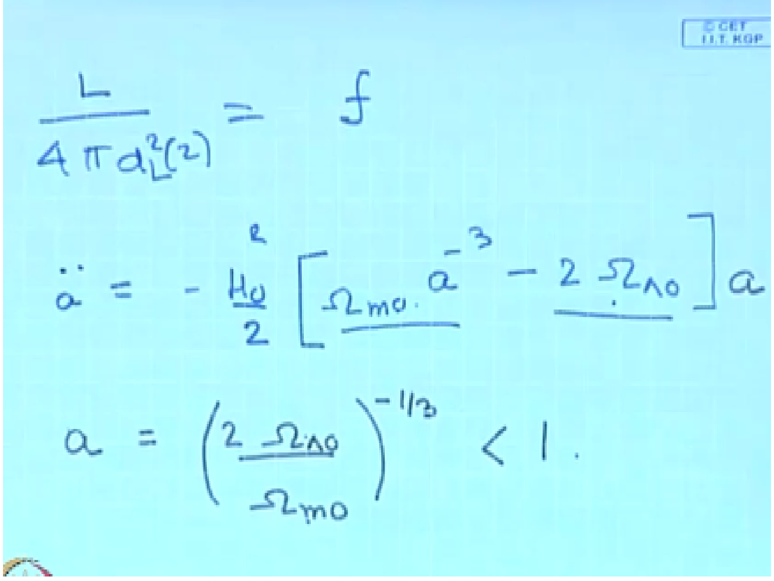

$$\frac{L}{4\pi d_L^2(z)} = f$$

$$\ddot{a} = -\frac{H_0^2}{2}\left[\underline{\Omega_{m0}\cdot a^{-3}} - \underline{2\,\Omega_{\Lambda 0}}\right] a$$

$$a = \left(\frac{2\,\Omega_{\Lambda 0}}{\Omega_{m0}}\right)^{-1/3} < 1.$$

And for a model which has these 3 parameters, this equation then becomes this; the curvature obviously does not contribute to a double dot it is and our interpretation, it is a constant of integration that you encounter when you integrate this, there will be a factor of a here. This is the equation which we have already encountered and integrated hopefully familiar with us by now okay.

So, this equation predicts that the universe will decelerate when this term dominates, so and it will accelerate when this term dominates, so the transition will occur at a scale factor a, which is = 2 omega lambda 0/ omega matter 0 to the power – 1/3, so this number is obviously; if this is 0.7 and this is 0.3, this number will obviously be <1, >0 but <1. Because this ratio is more than 1, okay.

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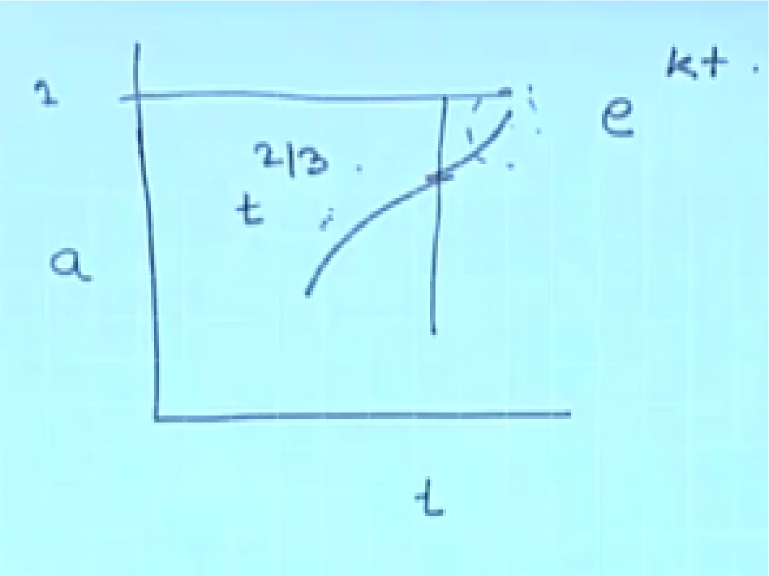

So, at some redshift in the past, there was a transition; the universe went a transition; underwent a transition from a phase of decelerated expansion to a phase of accelerated acceleration okay so, decelerated acceleration means and that if I plot the scale factor as a function of time, the second derivative is positive, if it is accelerated and the second derivative is negative, if it is decelerated.

So, positive second derivative means like this and negative second derivative means like this, so there was a transition here I am just drawing it pictorially, it may not be so dramatic like this and this is the present value a = 1 and once this term dominates, we know that the expansion is going to be t to the power 2/3 matter dominated, okay and it is the universe is approaching exponential expansion e to the power some constant right that is; if we have cosmological constant dominated; this term dominating.

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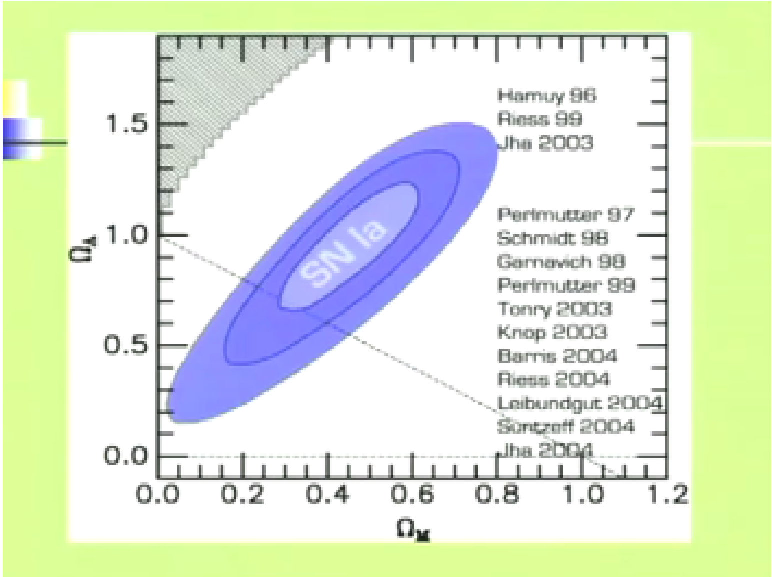

So, we are now in a phase where we have gone over from decelerated expansion to accelerated expansion that is the thing. The question is; what is this thing that is making the universe accelerating? Okay, so we shall come back to this question that is the very important question. Let us go back to the data again, so the data seems to indicate that there is some amount of omega lambda and the supernovae data itself cannot really pinpoint what the value of omega lambda is.

There are regions over here confidence intervals which are shown, so with 99.7% confidence we can say that that data indicates that my cosmological model should lie; our universe lies somewhere inside this region, lesser confidence I can say that it lies within this region this is from supernovae data only but there are other observations in cosmology which I have not mentioned.

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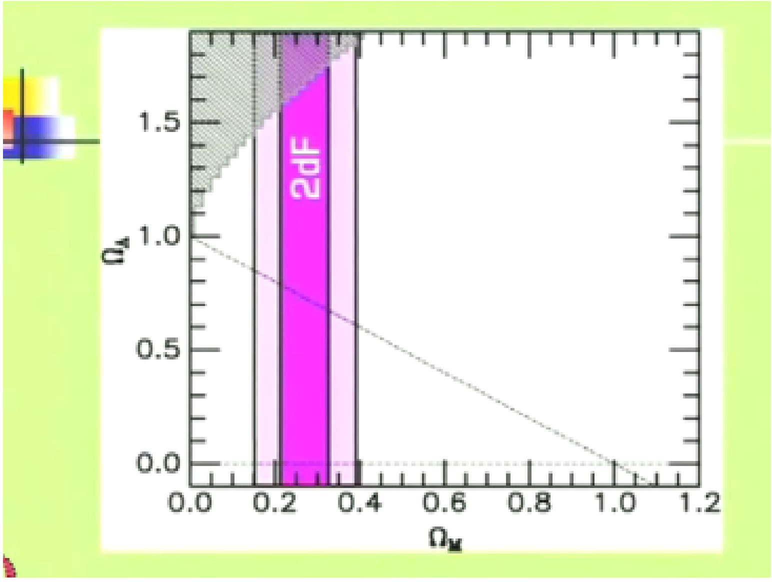

So, let me show you; just show you the results from these observations I will not go into the details of how they are determined. So, these are observations of galaxy surveys okay, galaxy surveys map out the distribution of galaxies in space and these observations can also be used to constraint the value of omega matter and omega lambda, in particular they constrained the value of omega matter.

They could not imposed at low rate shifts, these observations currently exists at low rate shifts and they do not put constraints on omega matters, the observations shown over here; they constrain omega matter not omega lambda and they indicate that omega matter is around 0.3, okay and these observations are observations of peculiar velocities, we have already discussed what peculiar velocities are.

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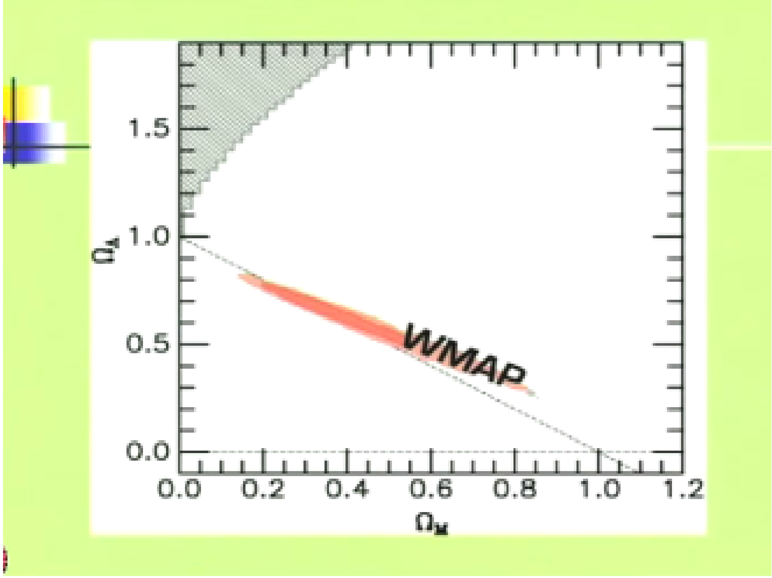

So, these are basically the imprint of peculiar velocities on the galaxy clustering, okay. They indicate that omega matter is around 0.3, so these are the confidence intervals. There are also observations of the cosmic microwave background radiation and I set rupees from a satellite called W map which is now in orbit, even now taking data okay. So, the cosmological parameters which are consistent with these observations, lie somewhere over here.

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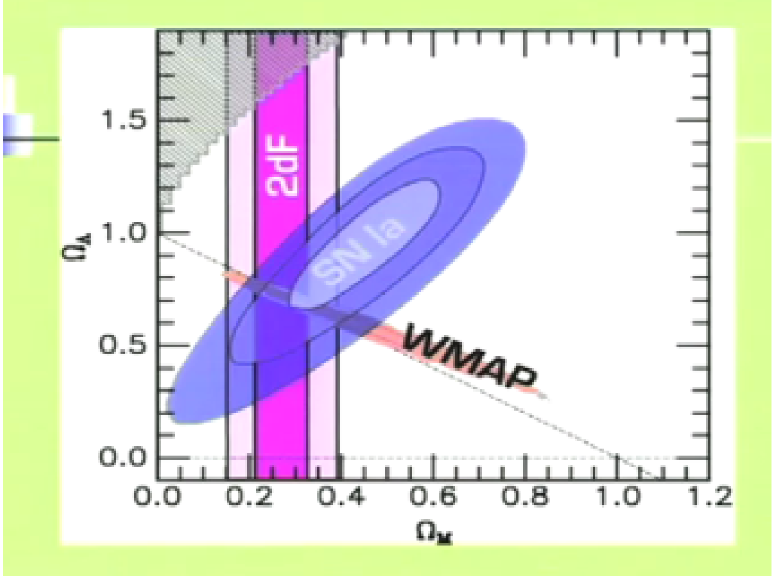

So, W map indicates that the universe is very close to being spatially flat; this is the curve corresponding to a spatially flat universe essentially. So, W map indicates that our universe is very close to being spatially flat that is the allowed parameter space from W map observations of the Cosmic Microwave Background and isotropies. If you put all of them together, you are led to a model, a led to the conclusion that our universe; the parameters of our universe lie somewhere in the overlap of all of these 3, right.

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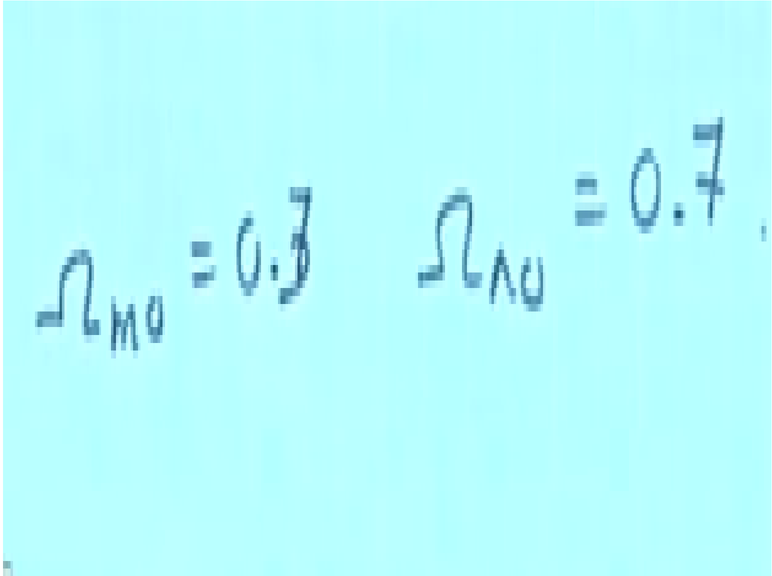

$$\Omega_{M0} = 0.3 \qquad \Omega_{\Lambda 0} = 0.7$$

The universe; that the model that we choose should be consistent with all 3 kinds of observation. So, it has to lie somewhere over here, which is around omega matter 0.3 and omega lambda0; 0.7, okay which you see is where all of these 3 things overlap.

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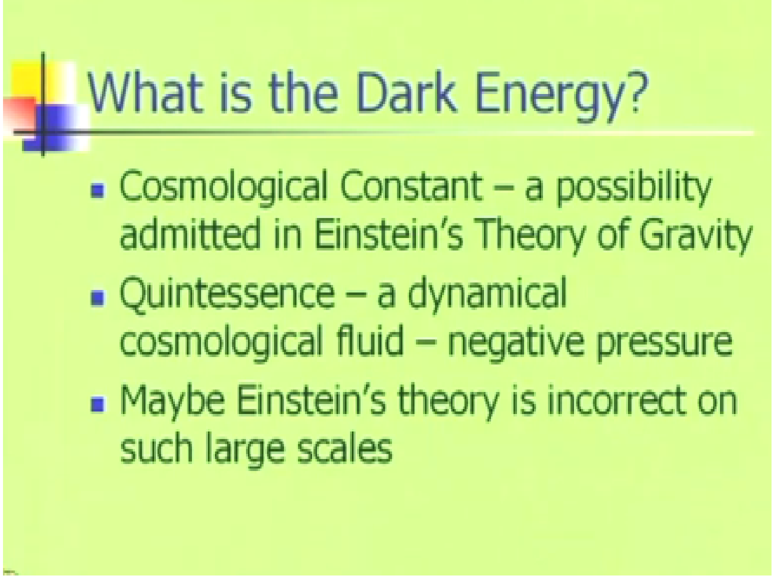

What is the Dark Energy?

- Cosmological Constant – a possibility admitted in Einstein's Theory of Gravity
- Quintessence – a dynamical cosmological fluid – negative pressure
- Maybe Einstein's theory is incorrect on such large scales

So, this component which has got negative pressure this component of the universe which has got negative pressure is referred to as dark energy okay is referred to as dark energy, so we have already learned about dark matter; dark matter is something that exerts a gravitational attraction but you do not see it and we have discussed for example spiral galaxies where the rotation curve indicates the presence of dark matter okay.

So, you do not see the matter but you see that there is something exerting a gravitational attraction and that is given the name dark matter, dark energy is required is put in by hand to make the universe accelerate, so it is some constituent of the universe again which you do not see but it has a property that the net gravitational force acceleration is repulsive. The galaxies are actually accelerating away from us instead of being attracted to us; towards us, right.

A double dot, we calculated remember a double dot by considering the acceleration of a galaxy relative to us and this term lambda makes this acceleration repulsion okay, so this is; so there is evidence that the universe has something like this which has got negative pressure which reverse causes gravity and the gravitational attraction to become repulsive okay. Now, the question, this has been given the name dark energy.

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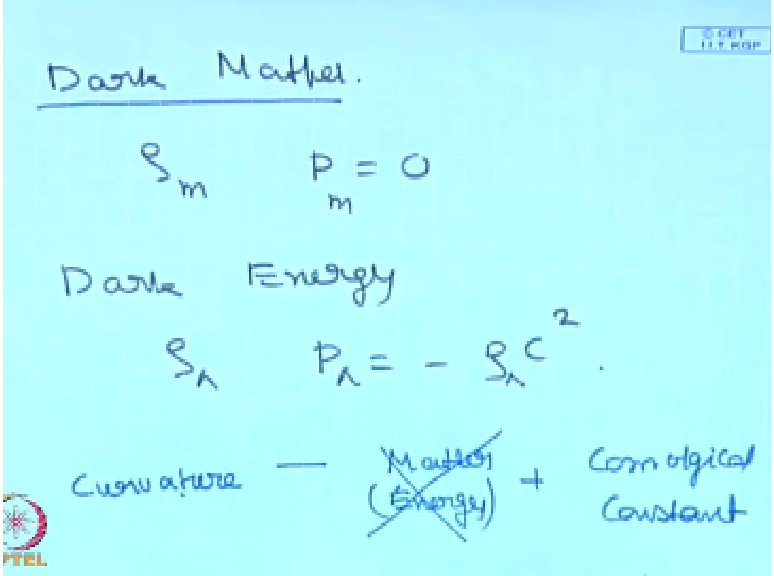

Dark Matter.

$\rho_m \qquad P_m = 0$

Dark Energy

$\rho_\Lambda \qquad P_\Lambda = - \rho_\Lambda c^2 .$

Curvature — ~~Matter (Energy)~~ + Comological Constant

Again this is something you do not see but so dark matter is something which has density which you do not see and pressure is 0; dark energy is again something which you do not see whose pressure is - rho lambda c square okay and this is required to explain the supernovae data for example. Now, question is what is this dark energy? Do we have any physical understanding? Some possible candidates for dark energy.

Well, what are the possible candidates for dark matter for that matter okay, what are the possible candidates for dark matter, what are the possible candidates for dark energy. Well, dark energy there is no dearth of plausible candidates because particle physics theories predict all kinds of particles some of which have not been detected as yet which also do not interact with radiation.

So, it is relatively easier to build models which predict all kinds of particles; massive particles a variety of massive particles which can be candidate for dark matter okay. A dark energy is something which has to have negative pressure massive particles which just hang around in space will be candidate of dark for dark matter okay and there are particle physics models which make such predictions.

Now, what the question that we will we are interested in here is that what is dark energy, what are the plausible candidates? So, one plausible candidate is the cosmological constant; the cosmological constant is a possibility that is admitted in Einstein's theory of gravity okay, so in Einstein's theory of gravity, curvature of space time arises due to matter energy basically but you can also introduce in this equation.

So, with basically a relation between the curvature of space time and the matter energy density, you also have the freedom of introducing a something called the cosmological constant which is basically a constant which is also a source for curvature, so suppose there is no matter, it is not guaranteed that my space is going to be space time will be flat. Einstein's theory of gravity allows the possibility of there being a constant which can also make the universe the space-time curved even in the complete absence of any matter and energy, okay.

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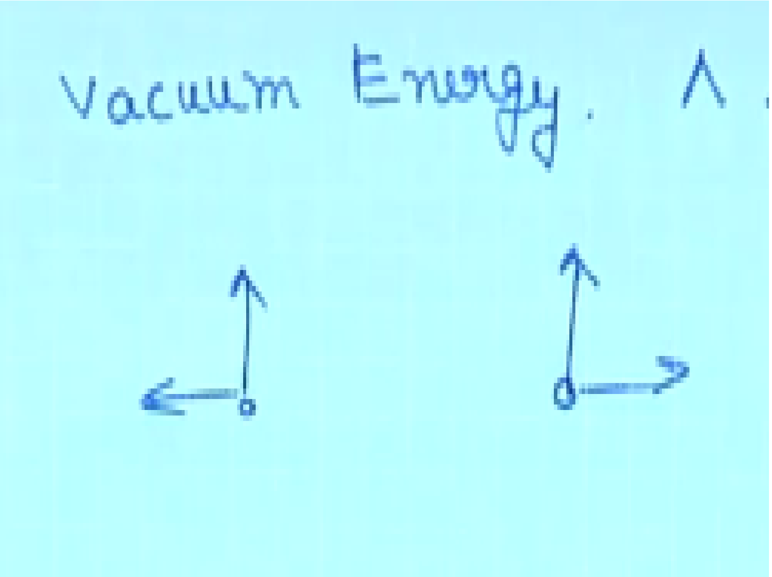

This is a property of the vacuum the cosmological constant, so it is also referred to as vacuum energy okay. The property of vacuum; it is a property of vacuum and vacuum here, so in Einstein's theory of relativity in the Newtonian context, we believe that when there is vacuum when there is no matter, there will be no gravitational attraction or repulsion but in Einstein's theory of relativity it is possible that vacuum itself may produce gravitational attraction or repulsion.

Which is there through the cosmological constant lambda, which are allowed to introduce in 2 Einstein's equations okay and if you have a positive cosmological constant then the curvature is such that it produces it causes inertial observers to basically accelerate away from each other and if you have a negative cosmological constant, it will cause inertial observers to move towards each other.

So, a positive cosmological constant will cause inertial observers who are distant inertial observers; inertial observers they do nothing, they will accelerate away from one another. Basically, that is the property of vacuum if you have a positive cosmological constant that is one possibility okay. Other possibility is that people have; you can have scalar fields which fill our universe okay that is the other possibility.

They go by a variety of names, so one of them is quintessence, so you can have; so basically in this situation, so here it is a constant, here the dark energy is something which is dynamical. It is a cosmological fluid, so just like you have matter spread out all over the universe and you also have another kind of fluid which is spread out all over the universe which has got negative pressure okay.

And such a fluid then has its own dynamics and the scalar field is one example of such a fluid which fills the entire universe by some means you can introduce mechanisms by which it has negative pressure okay. This is one possibility and there are people have also; there has been considerable study and it is still going on into different possibilities; different okay. So, you can change the dynamics, you can do a variety of studies here.

And there is a third possibility that may be Einstein's theory is incorrect at the length scales and the gravitational fields that you are discussing here. I am saying general theory of relativity is mainly tested in the solar system and here we are applying it on scales which are much larger than the solar system also the gravitational forces are much weaker than those encountered in the solar system.

So, it is quite possible that this theory is modified it is not applicable as it is, at those length scales or at those weak accelerations okay, so again this is a field in which people are carrying out research directions okay. The point which I would like to make here is that what is dark energy is one of the biggest problems in cosmology and in physics for that matter; it is something that is still and quite unknown.

We know it is there, it is parameterize by 1 parameter omega lambda0 as far as we are concerned in the simplest cosmological model, we have parameterize it by a single parameter given it a name omega lambda0, so our entire ignorance about this has been parameterized by their parameter omega lambda0, okay. Beyond that, there is not much known then we do not really know what it is going on.

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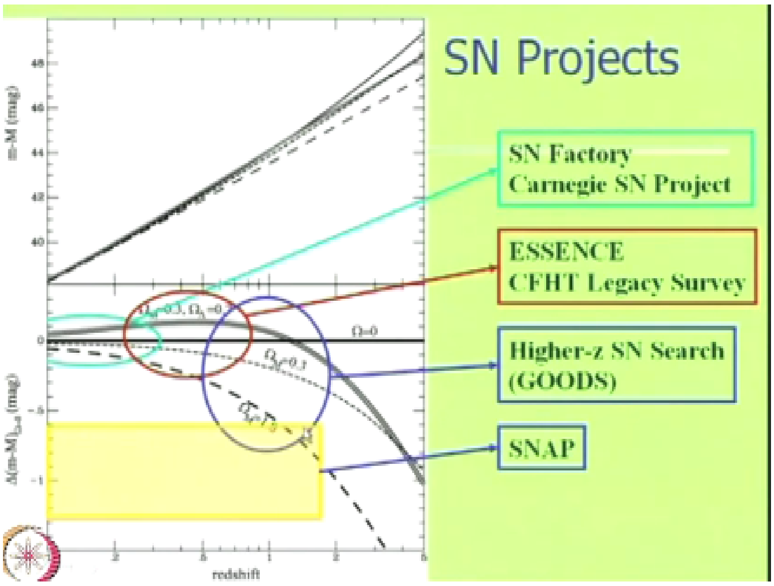

SN Projects

SN Factory
Carnegie SN Project

ESSENCE
CFHT Legacy Survey

Higher-z SN Search
(GOODS)

SNAP

We know that the universe is accelerating but we do not know what is causing it. On the scales of galaxies, we know that there is more matter then that you actually see but again we do not know what it is okay. Now, so this is as I have tried to tell you that this is a topic of tremendous interest in physics and in astrophysics, so there are several observational projects going on to map out this to study this in greater detail.

So, let me briefly show you some of these, so there is a super; they are different names, so there is the supernovae factory cosmology project which is aimed at probing low redshift over here, this is one of the projects. Then there is the another project called essence which is using this Canada Hawaii French telescope legacy survey and this is targeting a redshift range over here and then there is the high redshift search using the goods; the good survey which is started targeting here this red shift range.

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Supernova / Acceleration Probe

Studying the Dark Energy of the Universe

And finally you have this snap which is targeting supernovae in trying to just rule out this part of the diagram okay, so snap is the supernovae and acceleration probe is a satellite which I think will be launched as will study the dark energy of the; to study the dark energy of the universe. So, the basic thing is that you have to measure supernovae, determine supernovae at with more accuracy, so you require more; the better the errors the better we the smaller the error bars and the better you will be able to constrain the cosmological models.

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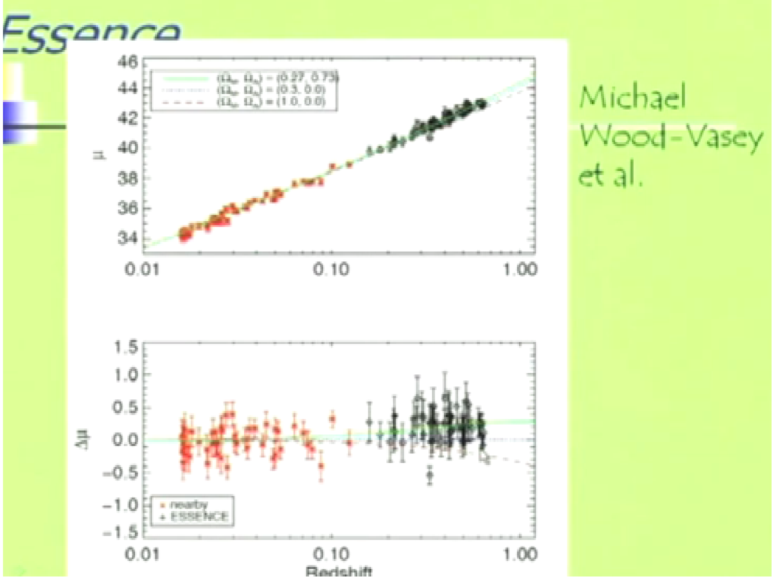

Essence

Michael Wood-Vasey et al.

Further, if you can measure out for higher redshifts, again you will be able to put better constraints on the cosmological models and you might be able to determine what actually makes up this mysterious thing lambda okay, so there is the future is I mean the results are already coming from these, so these are results from the essence which I mentioned.

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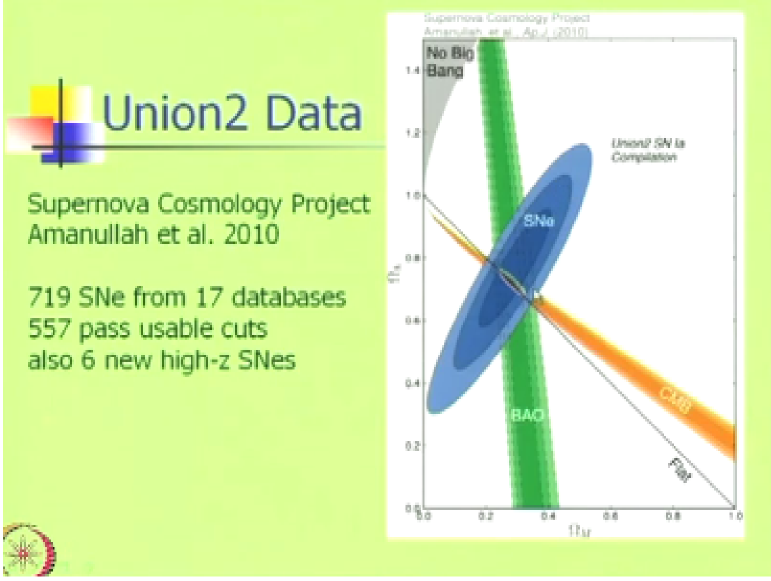

Union2 Data

Supernova Cosmology Project
Amanullah et al. 2010

719 SNe from 17 databases
557 pass usable cuts
also 6 new high-z SNes

And let me show you some other recent data, so the data I was showing you earlier was 2003, this is data from; is the results 2010, so these are results from the supernovae cosmological project, this is a reference and it is called the Union the data that they have considered for the supernovae is called the Union 2 data, it has 719 supernovae 1a from 17 databases of which; 557 pass the usable cuts.

So, 557 of them are usable in addition, it also has 6 new high redshift supernovae and they have combined all of this data and they are able to impose, these are; this is the region of parameter space; omega matter, omega lambda parameter space which they are able to constrain the models 2, so these again are the 68% confidence interval, 95% confidence interval and the 99.7% confidence interval.

This is the line which corresponds to a flat universe, these are the constraints from the CMBR and these are constraints from the baryon acoustic oscillations things which I have not discussed okay but all of these serve to constrain these allowed parameters of the cosmological; allowed cosmological parameter for our universe. Now, something I should mention here that we have been discussing very simple models where we have matter which has got no pressure.

We have this dark energy which has got constant negative pressure and we have the rest of it is in curvature well, these are the simplest models that you can have which has got negative pressure. You could have models where the equation of state itself changes with the redshift. For cosmological constant, this will remain a constant but if you have for example scalar fields quintessence then this w parameter itself becomes a function of redshift, okay.

So, there is tremendous amount of work now going on where people are trying to determine if w is a constant which will indicate that it is most likely a cosmological constant or if you find variation in w it will completely rule out the cosmological constant indicating that there is some physical mechanism which is producing this acceleration okay. So, let me now bring this topic to a close over here and move on to something else.

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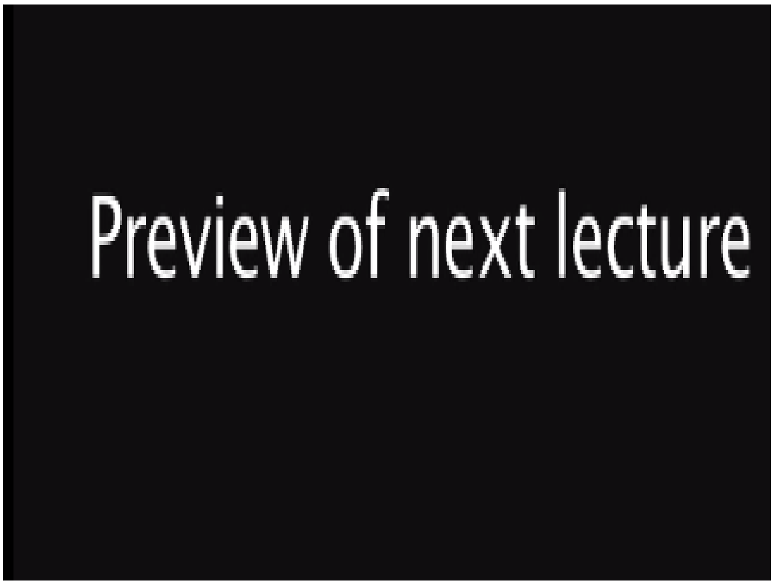

Preview of next lecture

Today we are going to discuss the cosmic microwave background radiation CMBR. We have already learned about its discovery in the 1960s, this is a radiation which is nearly isotropic and it was discovered in 1960s and its spectrum was very precisely measured in 1990s.

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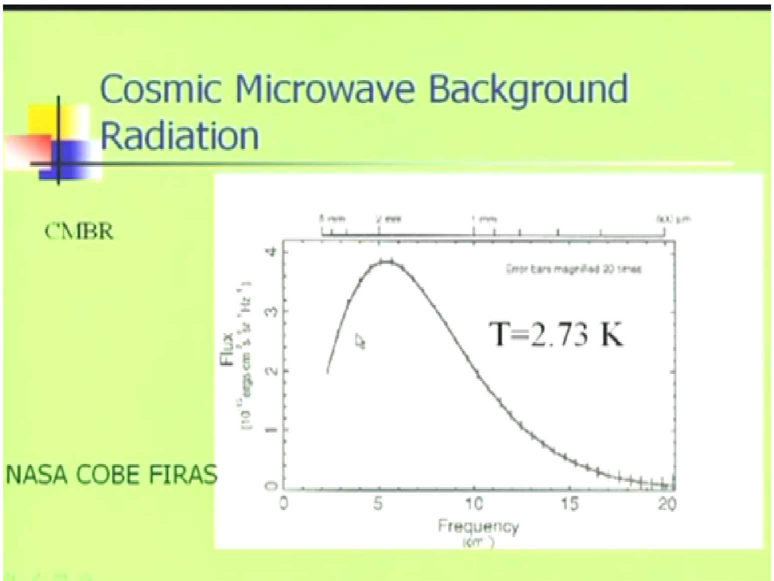

Cosmic Microwave Background Radiation

CMBR

NASA COBE FIRAS

And the spectrum was found to be very well fitted by a blackbody spectrum of temperature 2.73 kelvin. This was a satellite experiment; the satellite was called Cobe and the experiment is called Firas on the satellite. Satellite was launched by NASA in the 90s and this experiment established that this radiation which we see coming from all directions is indeed a blackbody spectrum has a blackbody spectrum with temperature 2.73 kelvin.

This is possibly the best blackbody spectrum that has ever been measured till date anywhere including experiments on earth and the error bars here have been magnified a 100 times, so that they can be seen, there actually they are 1 Sigma errors which are actually 100 times smaller. So, this is a blackbody radiation the peak is in the millimetre and that the bulk of the radiation is in the millimetre and centimetre range of the spectrum.

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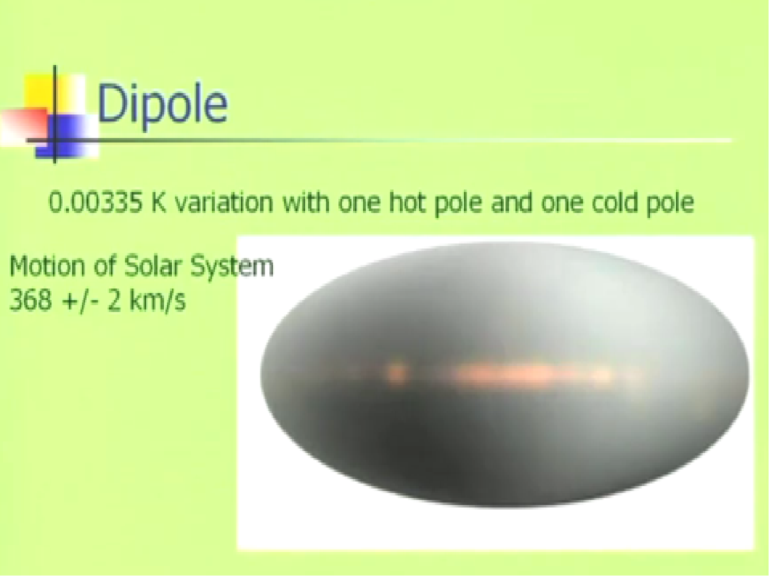

Dipole

0.00335 K variation with one hot pole and one cold pole

Motion of Solar System
368 +/- 2 km/s

And it is quite isotropic; absolutely isotropic, okay. Now, if you look take a closer look, so if you remove an isotropic component, so if you remove a component of blackbody spectrum, so if you remove the radiation corresponding to a blackbody spectrum at 2.73 Kelvin it from all directions, what you have left looks like this. So, there is the next thing that you see once you remove this monopole component, so the isotropic component is a dipole which is quite visible over here.

You see, this part is much fainter and this part is much darker okay, so this is a dipole pattern, the thing that you see in the centre passing through the centre is the image; is the imprint of our own galaxy. After we are seeing the cosmic microwave background radiation through our own galaxy which leaves an imprint this can also be removed by doing observation that over a large number of frequencies.

Anyway, the main point here is that after we remove the isotropic component, the next thing that you see is a dipole and the temperature variation of this dipole is 0.0035 kelvin, so it is around 1% fluctuation, it is a 1% fluctuation, so it is I said 0.1% not even 1%, sorry this is a 0.1 % fluctuation in the temperature and there is a hot one direction in which on the sky in which the temperature is this much hotter and another direction in the sky where the temperature is this much colder okay.

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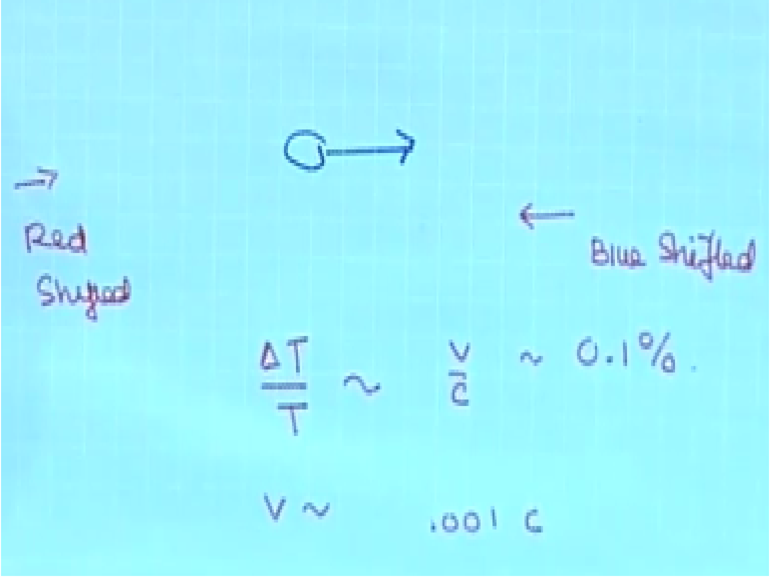

$$\frac{\Delta T}{T} \sim \frac{v}{c} \sim 0.1\%.$$

$$v \sim .001\ c$$

And this dipole pattern in the cosmic microwave background radiation is interpreted in terms of our motion of our solar system, so if the solar system is moving in; this is the solar system, let us see and if the solar system is moving in some direction then the photons from this direction with reference, so we are assuming that there is a frame of reference in which the CMBR is isotropic.

And if the solar system is moving with respect to that then the photons from this direction will be blue shifted and the photons from this direction will be red shifted due to the Doppler shift and the shift is v/c, which is also proportional to equal okay, so the fractional variation in the temperature of the CMBR is directly proportional to v/c, so this is of the order of 0.1%, which straight away tells us that v is of the order of 0.001 * c which is;

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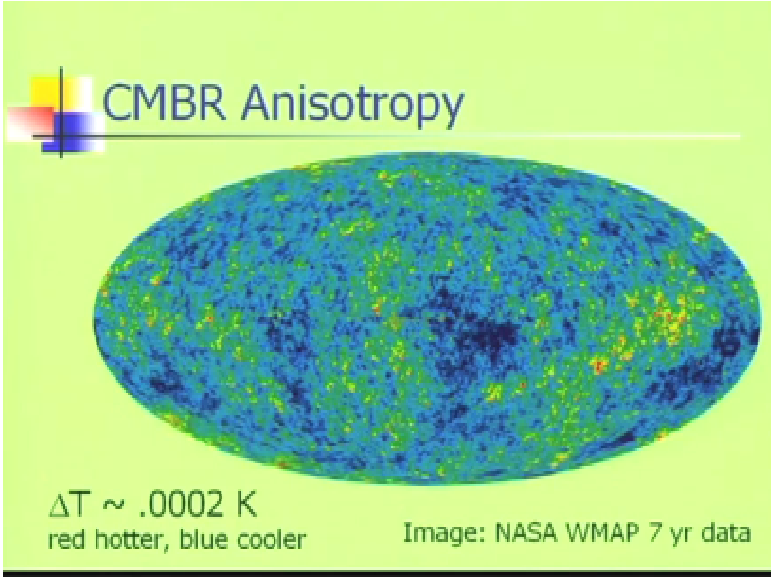

CMBR Anisotropy

$\Delta T \sim .0002$ K

red hotter, blue cooler

Image: NASA WMAP 7 yr data

And so, this dipole can be interpreted in terms of our motion with reference to a cosmological frame of reference where the microwave background radiation will appear isotropic okay. Now, if you look at; if you remove the dipole component also, so if you transform everything to a frame of reference where the CMBR the dipole is not there. The CMBR still has some small and isotropy left so this is a picture of the fluctuations in the cosmic microwave background radiation after you have removed the main dominant isotropic part.

And the dipole as well as the contribution due to our galaxy okay, so this is a picture of the sky have the CMBR and isotropies and isotropies in the cosmic microwave background radiation on the sky after all those things have been removed; the dominant component and the dipole both have been removed. So, the fluctuations that remain you see are even smaller they are of the order of 2 * 10 to the power – 4 kelvin.

And this is an image made by a NASA satellite again called W map Wilkinson microwave anisotropy probe and the satellite is still carrying out observations and this image shows you; this image shows you the result of 7 years of their observation okay and in this image, the redder parts are hotter and the bluer parts are cooler, okay, so it is the cosmic microwave background radiation is isotropic to a very large degree okay.

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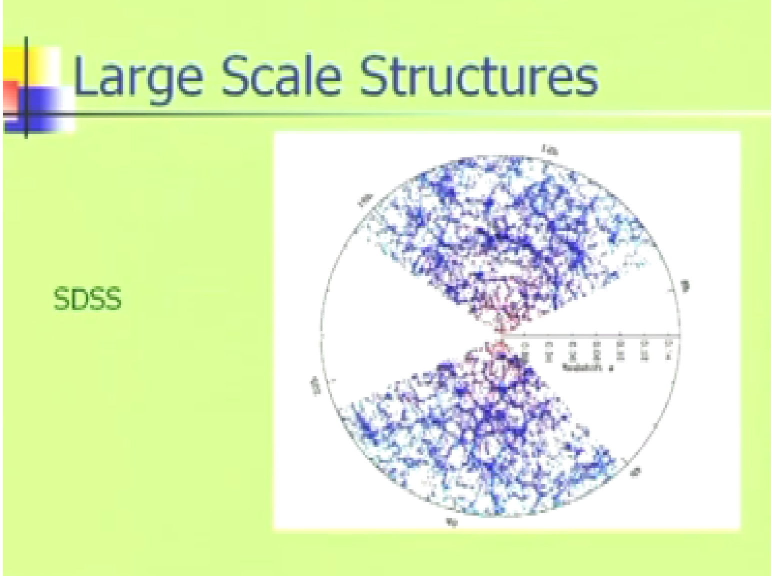

Large Scale Structures

SDSS

It is isotropic to a very large degree but there are minute fluctuations in this radiation and these minute fluctuations are very important for our understanding of the universe and let me explain this to you without going into detail. So, if you look at the distribution of galaxies in our universe for example, I have told you that we expect the universe to be homogeneous and isotropic at least on large scales.

Now, this image shows you the distribution of galaxies in a part of the universe, each point here is a galaxy okay. The distance was measured using red shifts and the red shifts are plotted along this axis, so the largest redshift that you have here is around 0.1, okay, so it is roughly 10% of the horizon size okay, 10 % of the horizon size, few 100 mega parsecs; horizon is few 1000 mega parsecs and the other direction is the angle on the sky.

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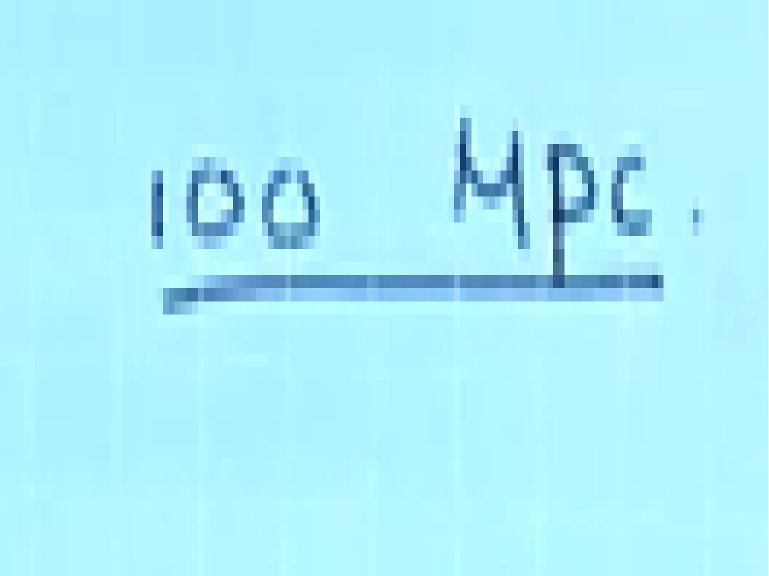

100 Mpc.

So, you have the distance from redshift and you have the angle on the sky, so what you see is; that it really does not look homogeneous and isotropic; homogeneous at least, right. So, the point is that there are large scale structures in the galaxy distribution in our universe okay, they are not perfectly; so there is a length scale, the length scale is somewhere around 100 mega parsecs of the order of 100 Mpc may be somewhat less may be somewhat more, beyond which the universe is homogeneous okay.

But on smaller scale there are considerable amounts of structure and the study of these structures is a very interesting topic itself which we shall not go into in this course, these are referred to as large scale structures and this is showing you the data from the Sloan digital sky service okay, so the question is; how do these things arise in a universe which is largely homogeneous and isotropic.

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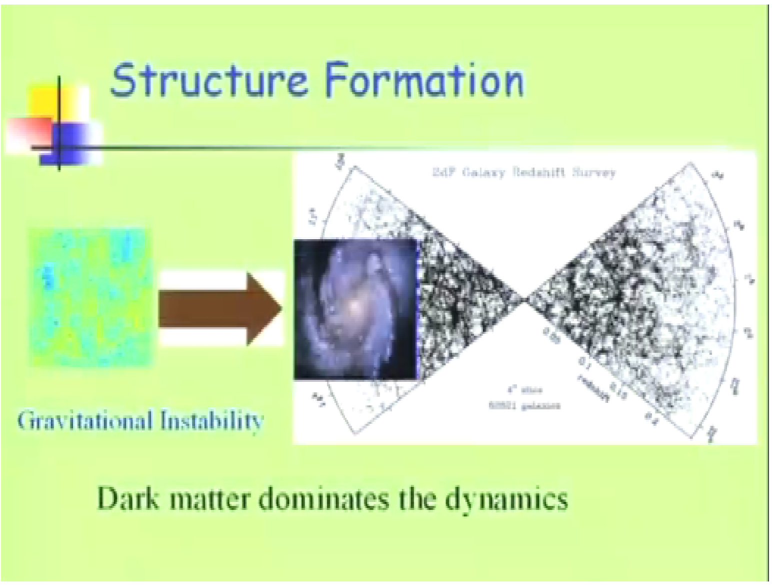

Structure Formation

Gravitational Instability

Dark matter dominates the dynamics

So, the current belief is with the belief is quite also quite well established and well accepted is that they were initially in the universe, some small fluctuations in the density, it is not perfectly homogeneous and isotropic, there were small fluctuations in the density and these small fluctuations in the density grow by the process of gravitational instability. So, what is the process of gravitational instability?

In this process, the regions where the matter density is slightly more than average attract the matter from other places and the region where it is slightly below average, the matter goes out from there and in this process and these fluctuations grow as a consequence of that; it is an instability and as a consequence of this process you form galaxies, the universe in the pass did not have galaxies nothing okay matter was very close to homogeneous and isotropic.

But you had these small fluctuations and the cosmic microwave background radiation is probing these small fluctuations at a redshift of around 1000, that is the basic interpretation okay, so the anisotropy in the cosmic microwave background radiation are probing these small fluctuations at a redshift of around 1000 and these fluctuations grow by the process of gravitational instability to form galaxies and to form this clustering pattern that you see in the galaxies distribution.

This again is another redshift survey; here again the distance is from redshift and this is the angle in the sky. This is another redshift survey called the 2dF redshift survey; 2dF redshift survey, okay. So, the anisotropy in the cosmic microwave background radiation are very important probe of how these structures formed in our universe because they allow you to probe these same fluctuations that grow to give you this at a much earlier redshift.

And the theory should be able to explain that you arrived from here to here, which it does okay. Another point, which I should make, is that the entire dynamics of this process is dominated by dark matter, so it is the dark matter which; so of the matter in the universe, the baryon, the electrons, protons. The protons and the neutrons make a very small contribution, it is mainly dark matter.

So, the fluctuations in the dark matter essentially which dominate the dynamics. The dark energy it is believed; well, dark energy has negative pressure and it is believed that the dark energy is not affected does not participate in this process of structure formation except for driving the expansion of the universe that to beyond a certain only at lower redshifts not in the at higher redshifts okay.

So, this is a brief overview of the cosmic microwave background radiation particularly what are the crucial points in its order; its crucial properties, so it is largely isotropic. There is a dipole component which we interpret in terms of our motion and there are other anisotropies once you remove the dipole and these anisotropies allow us to probe the large scale structure formation in the universe, okay.

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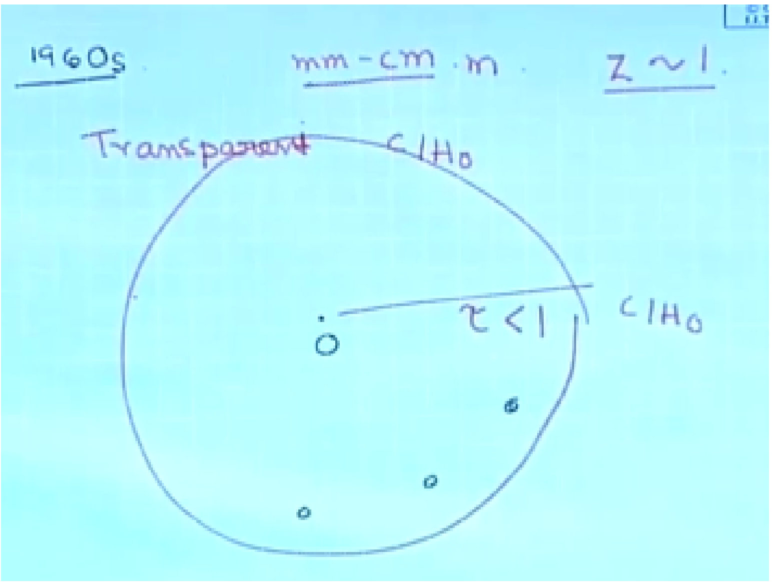

Now, the cosmic microwave background radiation was discovered in the 1960s and its discovery completely revolutionized our understanding of cosmology okay, so let me explain this to you okay. So, we are just imagine an observer sitting over here and we are receiving this radiation which is in, which is a blackbody spectrum. Now, if a radiation has a blackbody spectrum and we know that it originates when blackbody spectrum comes about when radiation is in thermal equilibrium with matter at some temperature t, right.

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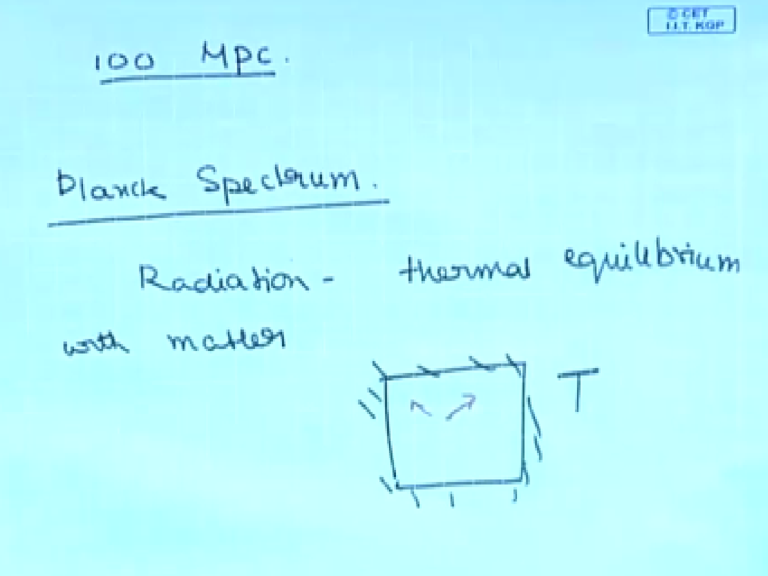

100 Mpc.

Planck Spectrum.

Radiation - thermal equilibrium with matter

This is something that we know, so the Planckian spectrum corresponds to radiation in thermal equilibrium with matter that is the picture that we have. So, we imagine a cavity at a temperature T and if the radiation inside; if the radiation inside comes to equilibrium with the walls of the material inside the cavity, then the radiation has a third Planck spectrum or blackbody spectrum, okay.

Now, this is the observer, we are sitting here and we can see inside, so if you look in the millimetre or centimetre parts of the wavelength or even meter for that matter parts of the wavelength of the spectrum, we can see objects all the way out to a redshift of order unity and even larger. Such objects are visible, so we can identify objects universe till the redshift of order unity which essentially tells us that the universe is transparent optical depth to nearly the Hubble to the horizon c/H0, right.

You are at length scales of the order of c/H0 when you reach a redshift of 1, so the universe; the optical depth all the way to a redshift of length scale of order c/H0 is <1 because we can see objects over here, if the optical depth was >1, the light from those objects would be obscured, so we can see astronomical objects all the way out here, which tells us that the universe is transparent all the way to this distance.

So, the CMBR photons that we are receiving did not; the fact that the optical depth is 1, tells us that the CMBR photons that we are receiving did not interact with matter within the length scale of the order of c/H0. There was no interaction, if there was no interaction how did it come to equilibrium? Right, so this basically tells us that the CMBR that we are seeing did not originate in the nearby universe; the photon.

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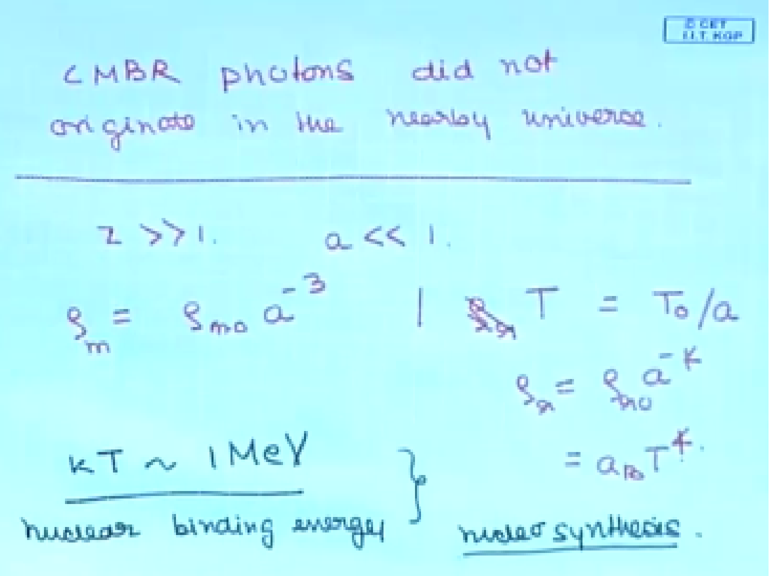

CMBR photons did not originate in the nearby universe.

$z >> 1.$ $a << 1.$

$\rho_m = \rho_{m0} a^{-3}$ | $T = T_0/a$

$\rho_\gamma = \rho_{\gamma 0} a^{-4} = a_R T^4.$

$kT \sim 1 \text{MeV}$

nuclear binding energy } nucleo synthesis.

So, the CMBR photons that we are seeing because these photons have been propagating freely for nearly the horizon nearly not exactly but length scales comparable to the horizon all the way out to redshift of order unity and larger okay, 3, 4, 5, 6 still where you can see discrete objects okay. So, where did the CMBR photons are unite? There were these photons in thermal equilibrium with matter.

So, the picture is that if you go back to high rate shifts, so if you go to z >>1 or a much scale factor <<1, we have seen that the density of matter at those red shifts will be, = rho0; rho matter0 * a to the power -3 because rho*a cube is a constant for matter okay, so the matter density and the high redshift universe was much larger, the radiation density okay or the temperature of the radiation we have briefly discussed this we shall discuss it again.

Also scales as the present temperature by a, so in the high redshift universe, the density of material was much larger, the temperature of the CMBR, if you just take this temperature is proportional to temperature into scale factor is a constant which we have seen by looking at the energy density, we know that the energy density scales as rho r0 a – 4, this we have worked out and we also know that this is =; aB T to the power 4, right.

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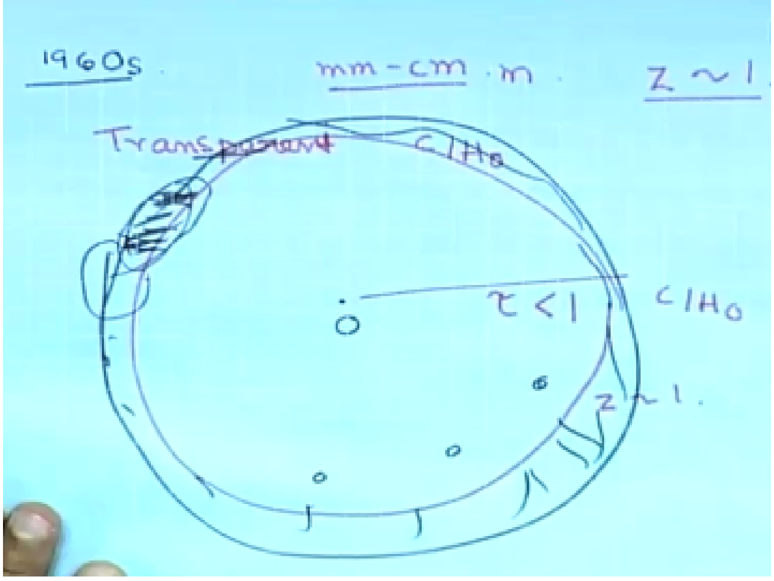

So, from these arguments you can describe clear that the temperature will into the scale factor is a constant, so in the early universe; in these parts in the early universe, the temperature of the CMBR was much hotter and the density was much larger, so sufficiently back in the pass, the CMBR, the universe was hot and dense and the CMBR was in thermal equilibrium with the matter at some high redshift okay.

So, this is the basic picture, so the CMBR was in equilibrium with matter at some high redshift where the density was much more and the temperature was much higher; further if you go back sufficiently into the pass, the temperature will at some stage we of the order of 1 MeV, we know that; so I have told you that the temperature increases as inverse of the scale factor, so if you go sufficiently back in the pass, the temperature will become of the order of 1 MeV.

This is adequate, this is comparable to nuclear binding energy, so all the nuclei will get disassociated okay and so essentially you have the nuclear reactions taking place at those high redshifts and so you can; you can explain the abundances of light elements; light element abundances assuming that they were formed in this high density and high temperature material that was there in the universe at high redshifts, okay.

So, you can also have nucleo synthesis of light elements okay. The heavier elements were made in stars we have already learned about that and the nuclear synthesis; the abundance of light elements are found to be more or less the same all through the universe, so this is a natural explanation for that. Now, what is the significance? Why is the CMBR important? Now that we have this basic picture let us go back to our discussion of the CMBR.

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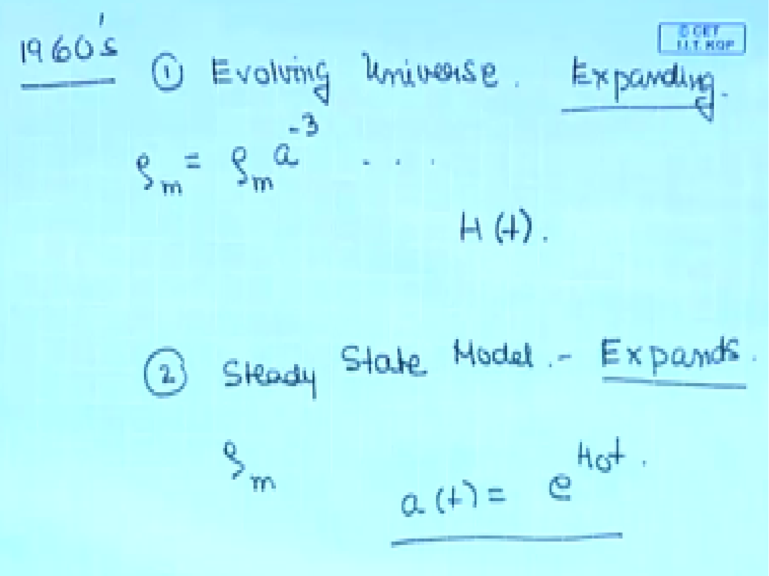

So, I have told you that the CMBR was discovered in 1960s and at that time there were 2 models which were competing in cosmology; one was the evolving universe which is the model that we have been discussing. So, in this model things change with the scale factor, so for example the matter density is equal to the present matter density a to the power -3 etc. Everything evolves with the expansion of the universe okay.

There was another model at that time which was also competing with this model which is the steady state model. In the steady state model, there is no singularity in the past; the density of the universe remains a constant, so the universe expands in this model also that is an observed fact. Both of these models have an expanding universe but in this steady state model, you have to have matter being created and so that the density remains constant okay.

So, nothing evolves in this model. On the average, the universe always looks the same as it does now and the scale factor has an exponential will have an exponential expansion, there is no singularity. If you have an exponential expansion, the Hubble parameter also remains constant. Here the Hubble parameter is a function of time and it was larger in the past okay in the steady state model, you have an exponential expansion where nothing.

It is like our cosmological constant dominated model where you have an exponential expansion. The Hubble parameter remains fixed; the universe looks the same all the time. Now, you see if the universe is.