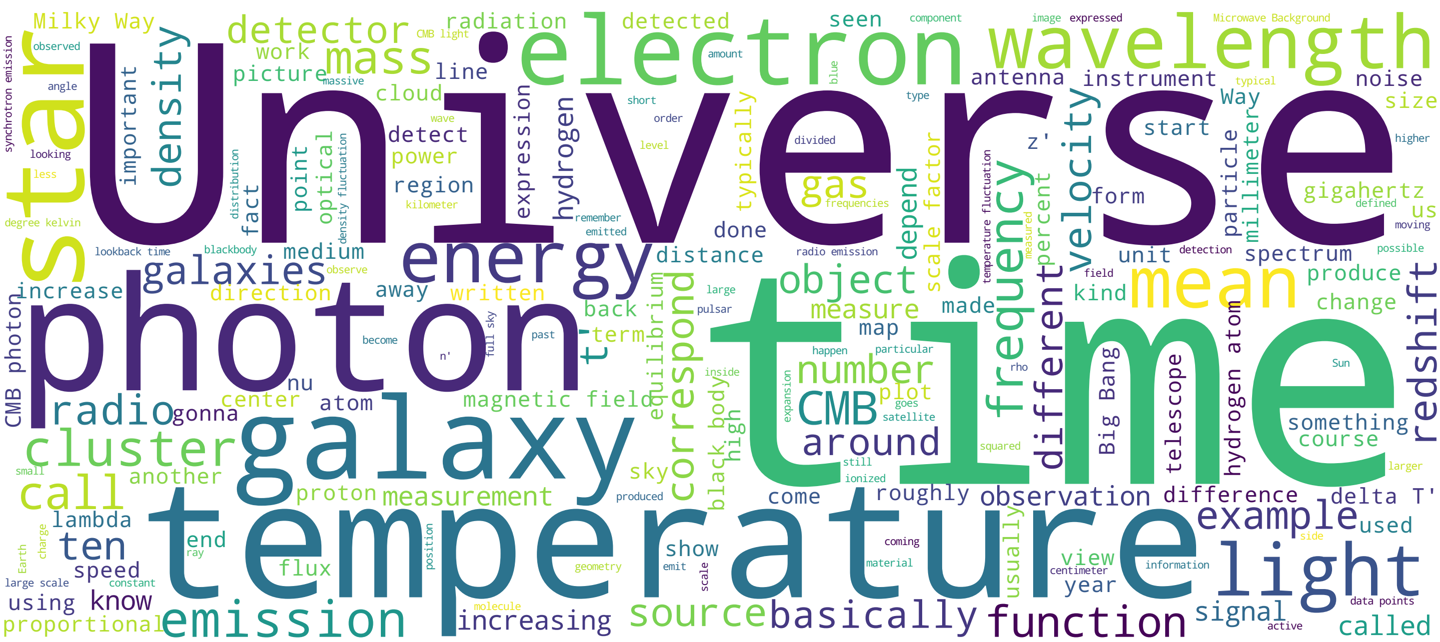
Cosmological Microwave Background

The Universe At Radio Wavelengths

Jean-Paul Knieb



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Video

We have gone through most of the object either galactic or extragalactic that can be detected in the Universe thanks to the radio emission. We will now discuss the diffuse emission of the early Universe also known as the Cosmological Microwave Background or CMB in short. The CMB light corresponds to photons produced at the last scattering surface of the hot plasma made of free electrons, protons, neutrons and ionized atom 380,000 years after Big Bang. Although this emission of photons correspond to black body at roughly 3000 degree kelvin, because of the Universe expansion we detect it in the microwave bands at a temperature of 2.73 degree kelvin. This correspond to an expansion factor of roughly one thousand.

Notes

Summary

0m 05s

The Cosmological Microwave Background

EPFL

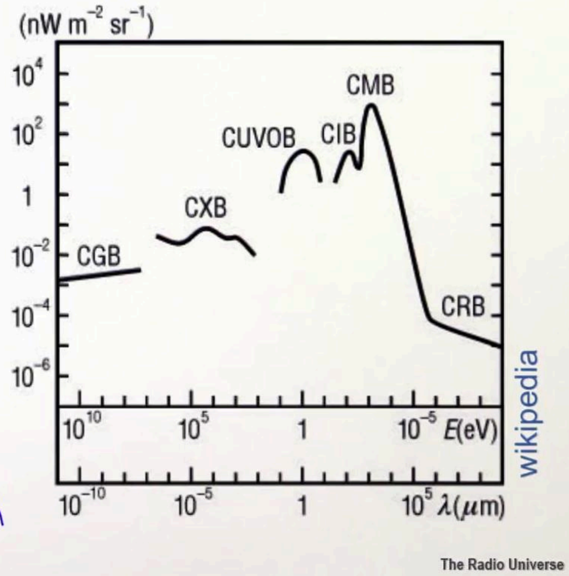
The diffuse extra-galactic background emission:

It corresponds to the diffuse photon fields from extragalactic origin that fills our Universe.

Can be detected at all wavelength.

The *"cosmological microwave background"*
CMB
dominates other backgrounds.

0.5 mm to 20 cm
absorbed by the atmosphere
Seen from the ground



When we survey the extragalactic sky as a function of wavelength we detect what we call the diffuse extragalactic background emission. This is the plot of the diffuse extragalactic background emission as a function of wavelength and this is the amount of energy received. So we have a signal that we see here that will depend on wavelength, here we have the cosmic radio background, here we have what we call the Cosmological Microwave Background, here the Cosmological Infrared Background, here the UV and optical background, the X-ray background and the gamma-ray background. So those backgrounds are produced by different events. Like, for example, the UV optical background is produced essentially by the light of stars. Now we're gonna focus on the Cosmic Microwave Background. We also call it C M B for Cosmological Microwave Background. What we can see from this figure is that it dominates all the backgrounds. And typically it goes from 0.5 millimeter to 20 centimeter. Okay. It's where it's most intense. So at small wavelengths, small lambda this region is absorbed by the atmosphere. The high wavelength part can be seen from the ground.

Notes

Summary

1m 05s

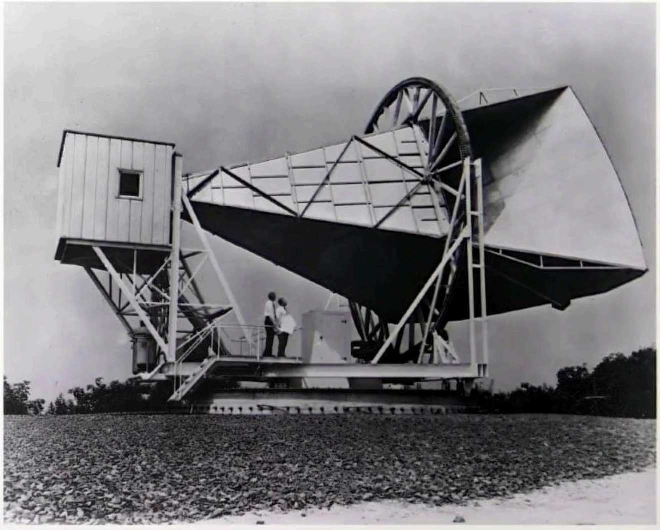
First Measurement

EPFL

In 1964 detection of an isotropic background noise

Measurement used the Holmdel Horn Antenna, equipped with a Dicke radiometer sensitive to microwave (cm wavelengths), developed for satellite communication.

Arno Pensiaz & Robert Wilson, while studying the emission of the Milky-Way, detected an isotropic background noise having an excess of 3.5 Kelvin antenna temperature.



wikipedia

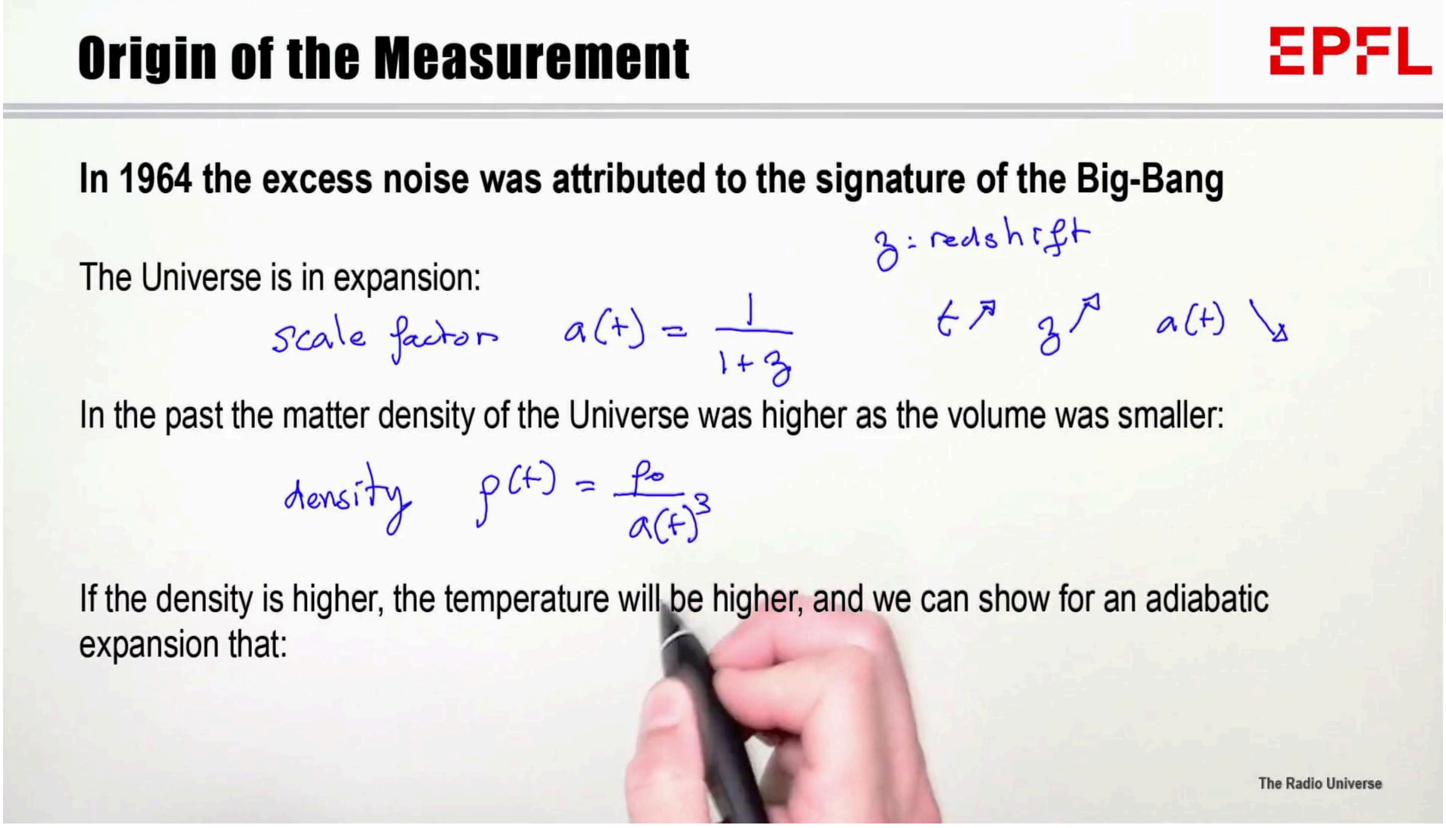
The Radio Universe

So the first measurement and detection of the isotropic background noise at microwave was done with this antenna in 1964. This antenna, the Holmdel Horn antenna, which was equipped with the Dicke radiometer was sensitive to microwave that is centimeter wavelength. It was mainly developed as satellite communication but two scientist two astronomer from the Bell labs, Arno Pensiaz and Robert Wilson, were using this antenna to study the sky and in particular, they were interested in the emission of the Milky Way. While doing the observation of the Milky Way, they detected an isotropic background noise having an excess temperature of 3.5 kelvin.

Notes

Summary

2m 56s

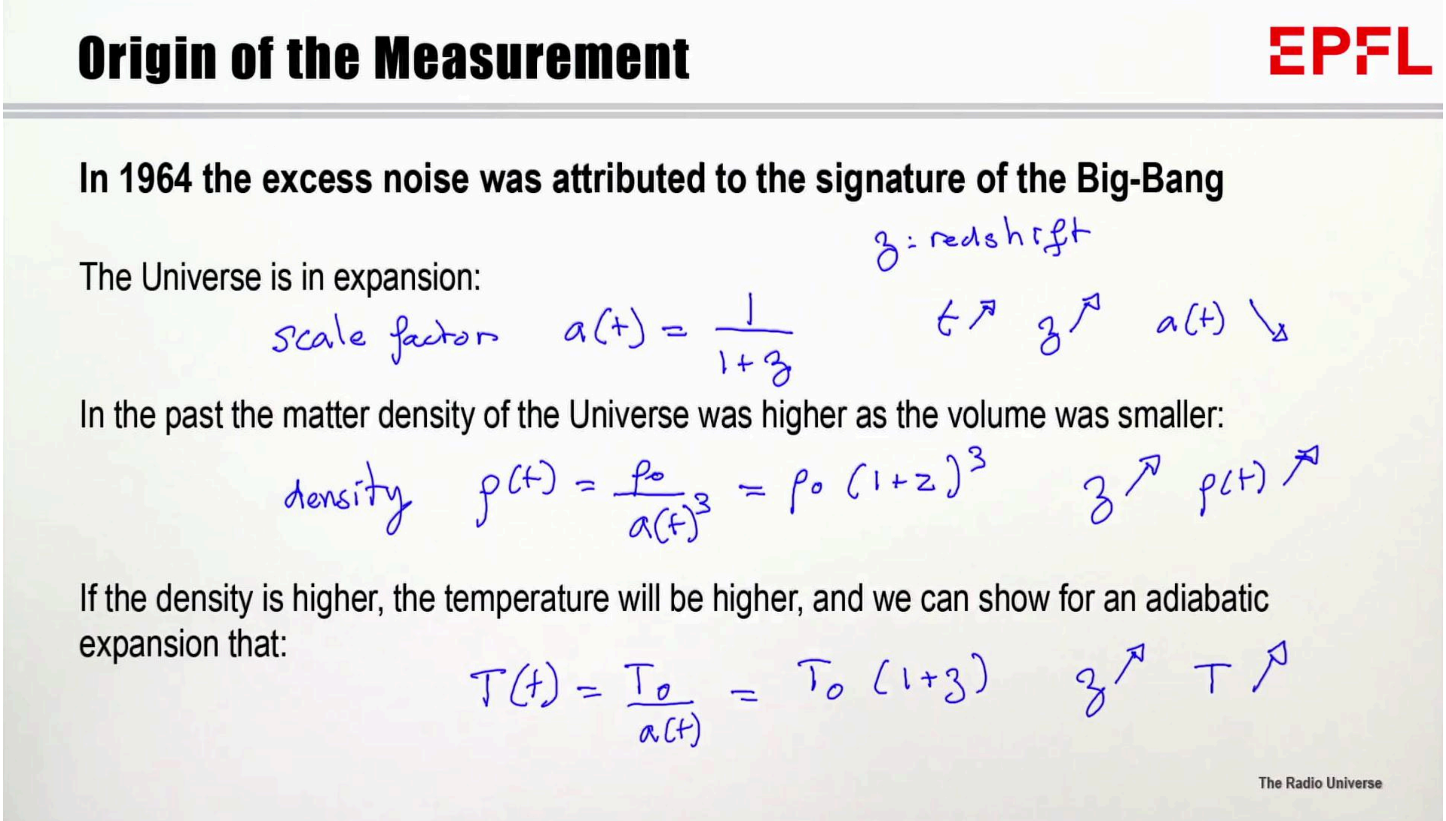


So but how to explain the excess of noise? Many scientists have been working on the Big Bang and on the signature of the Big Bang and in 1964, it was kind of obvious that the detection made by Pensiaz and Wilson was, in fact, the detection signature of the Big Bang. So let's do a bit of math and recall some important expression of the Universe expansion. So the Universe expansion can be characterized by what we call the scale factor. The scale factor ‘a of t’ depends on the lookback time 't' and can be written as one over one plus ‘z’. 'z' is the redshift and it's a way to measure the expansion of the Universe. So when the lookback time is increasing then the redshift is also increasing. So that means also the the scale factor ‘a of t’ will be decreasing. So that means when we go back in time when ‘t’ is increasing then the redshift is increasing and the Universe scale, the typical scale of the Universe gets smaller. So if the scale of the Universe gets smaller the density of the Universe will increase. So we can write the density, the mass density of the Universe as rho of 't' and rho of 't' will be written as rho-zero, the density of today divided by 'a of t' to the power three.

Notes

Summary

3m 53s



Indeed, ‘a of t’ to the power three correspond to a volume. Okay which is basically the cube of a distance cube of the scale factor. So if we express this as a function of redshift then the density rho of 't' can be written rho-zero times one plus 'z' to the cube. So if the lookback time is increasing, looking to the past more and more distant past, then the redshift is increasing and that means the density is also increasing. So if you have a medium where the density is increasing, the temperature will likely increase too and we can show that for an adiabatic expansion of a perfect gas that the temperature of the gas 'T of t' in our case can be written as T-zero divided by 'a of t', the scale factor which means it is also equal to T-zero times one plus 'z'. So again when the redshift is increasing, the temperature will also increase.

Notes

Summary

5m 55s

Origin of the Measurement

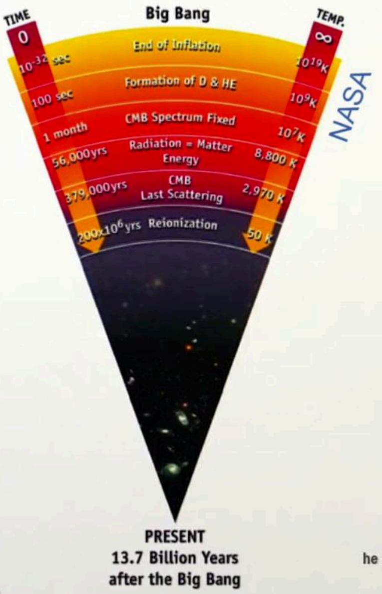
EPFL

In 1964 the excess noise was attributed to the signature of the Big-Bang

At some time in the past, the density/temperature will be so large that the H atoms (corresponding to 75% of the mass in the Universe) will constantly interact with photons forming a plasma in equilibrium:

$$H + \nu \rightleftharpoons p^+ + e^-$$

Photons will be trapped in the plasma, and we can only see the surface of last scattering.



he Radio Universe

So if we look back in time at some point in the past, the density temperature will be so large that the hydrogen atom which correspond to more than 675 percent of the mass in the Universe will constantly interact with photons and they will form a plasma made of ionized particles. To simplify we can say that there will be interaction between the hydrogen atom plus photons and those will basically will be in equilibrium with protons and electrons. So the hydrogen will interact both with photons and will be in equilibrium with protons and electrons. Where you're gonna be in terms of this equilibrium will depend on the temperature. So the higher temperature, the more ionized will be your plasma. The lower the temperature, the more you will be dominated by a neutral hydrogen. So if the temperature is very high, photon will be trapped in plasma. Indeed, there will be constant interaction with the hydrogen forming protons and electrons and because of the constant interaction the photons cannot travel very far. So it's only because the temperature of the Universe is decreasing because of the expansion then that we can see photons escaping from this equilibrium.

Notes

Summary

7m 13s

Origin of the Measurement

In 1964 the excess noise was attributed to the signature of the Big-Bang

At some time in the past, the density/temperature will be so large that the H atoms (corresponding to 75% of the mass in the Universe) will constantly interact with photons forming a plasma in equilibrium:

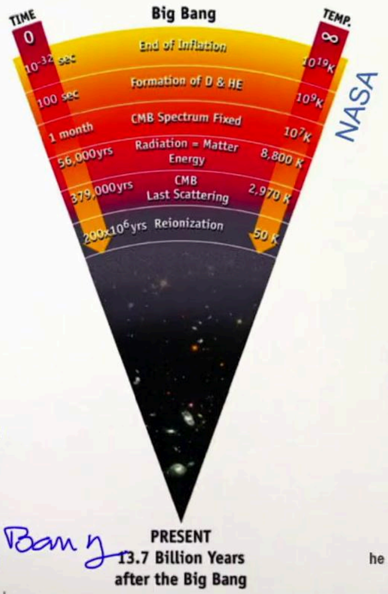
$$H + \nu \rightleftharpoons p^+ + e^-$$

Photons will be trapped in the plasma, and we can only see the surface of last scattering.

$T_{CMB} = 2970\ K \qquad T_0 = 2.73\ K$

$1+z = T_{CMB}/T_0 \rightarrow z \sim 1090$

13.7 billions year   379 000 years after the Big Bang



he Radio Universe

The temperature of this equilibrium at which we can see photons emerging can be computed from plasma physics and it's about 2,970 K. As we observing the CMB temperature today at a temperature of 2.73 kelvin, it means that we can deduce the value of the redshift which is equal to T-CMB divided by T-zero so that means the redshift will be of the order of 1,090. In terms of lookback time it correspond about 13.7 billion years in the past. It also correspond to a time which is about 379,000 years after the Big Bang. We see in the cartoon here the history of the Universe and we see when we go back in time when we get closer to zero time then we have a temperature that also is increasing and here is represented the last scattering surface of the CMB at a temperature of 2,970 K. So we won't be able to see what's happening there. The only thing we can see from the early Universe are photons from the last scattering surface going up to us.

Notes

Summary

8m 58s

The COBE satellite

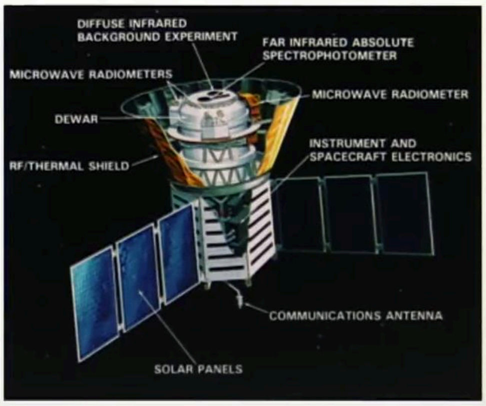
EPFL

The first CMB satellite

Because it is easier to observe milli-meter wavelength above the atmosphere, NASA decided to launch a dedicated telescope to observe the CMB.

The ***CO**smic **B**ackground **E**xplorer* (COBE) spacecraft was launched in 1989.

COBE was equipped with 3 instruments.



The Radio Universe

Because it's easier to observe millimeter wavelength above the atmosphere, NASA decided to launch a dedicated telescope to observe the CMB. That telescope is represented here. It's the COsmic Background Explorer or COBE in short. This spacecraft was launched in 1989 and on the top part here protected by a thermal sheet there was three instrument.

Notes

Summary

10m 34s

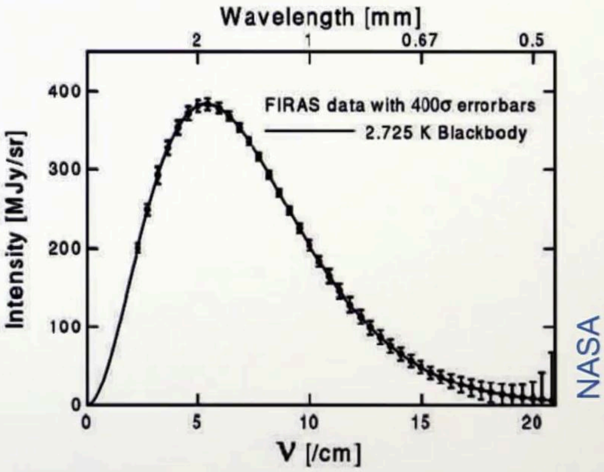
COBE observation

EPFL

Black body measurement of the CMB

The ***F**ar **I**nfra-**R**ed **A**bsolute **S**pectrophotometer* (FIRAS) measured precisely the spectrum of the CMB in the range 0.2<λ<10 mm

Black-body spectrum
2.73 K



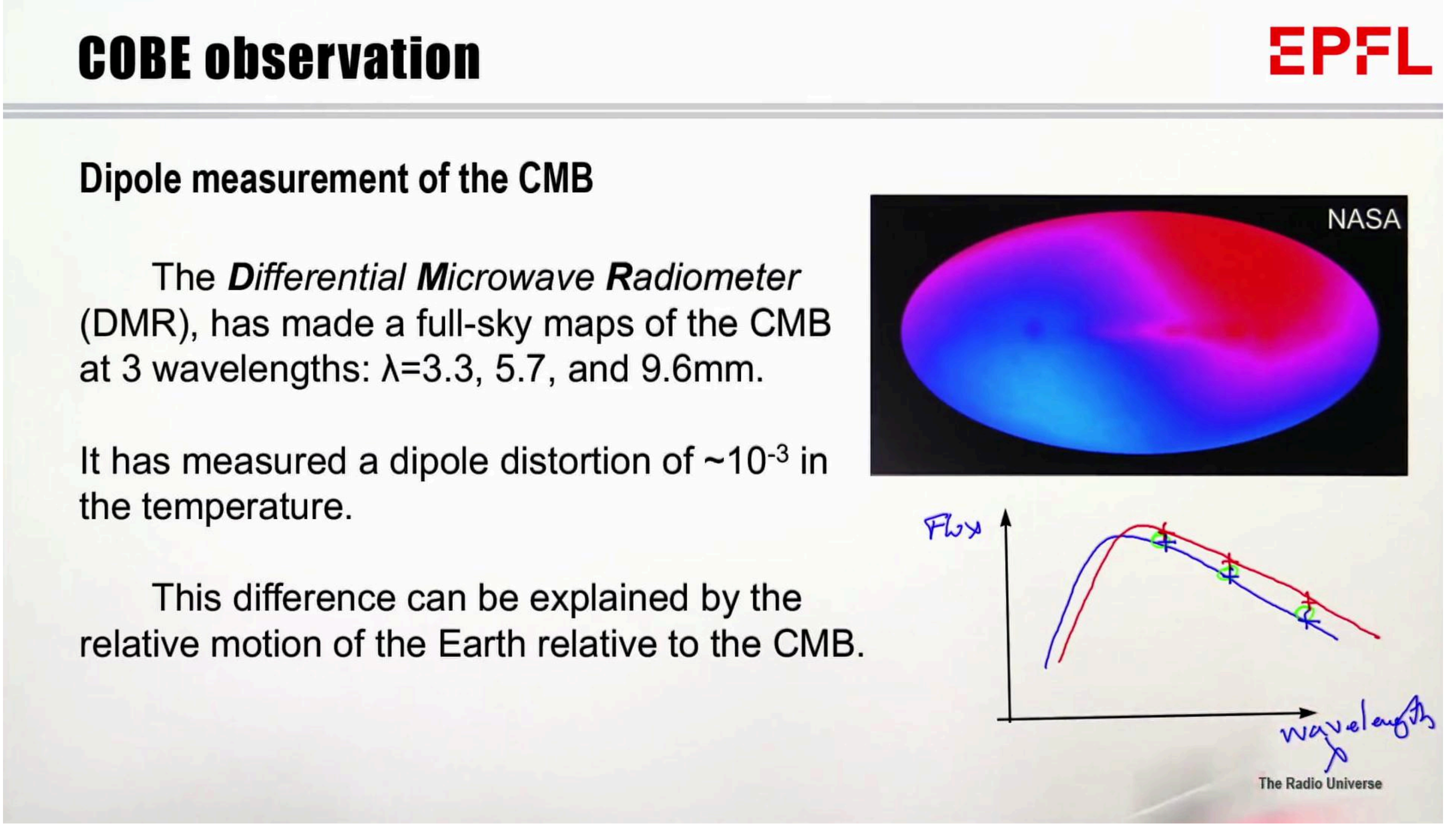
The Radio Universe

One of the three instrument was the Far Infra-Red Absolute Spectrometer also named FIRAS. The role of FIRAS was to measure precisely the absolute flux of the CMB in the range coming from 0.2 to 10 millimeter. What we see in this plot here is the flux as a function of wavelength or as function of frequency here with data points and error bars. Those data points can be fitted by black body spectrum at a temperature of 2.73 degree kelvin. This measurement here is still the best measurement of the CMB black body curve.

Notes

Summary

11m 06s

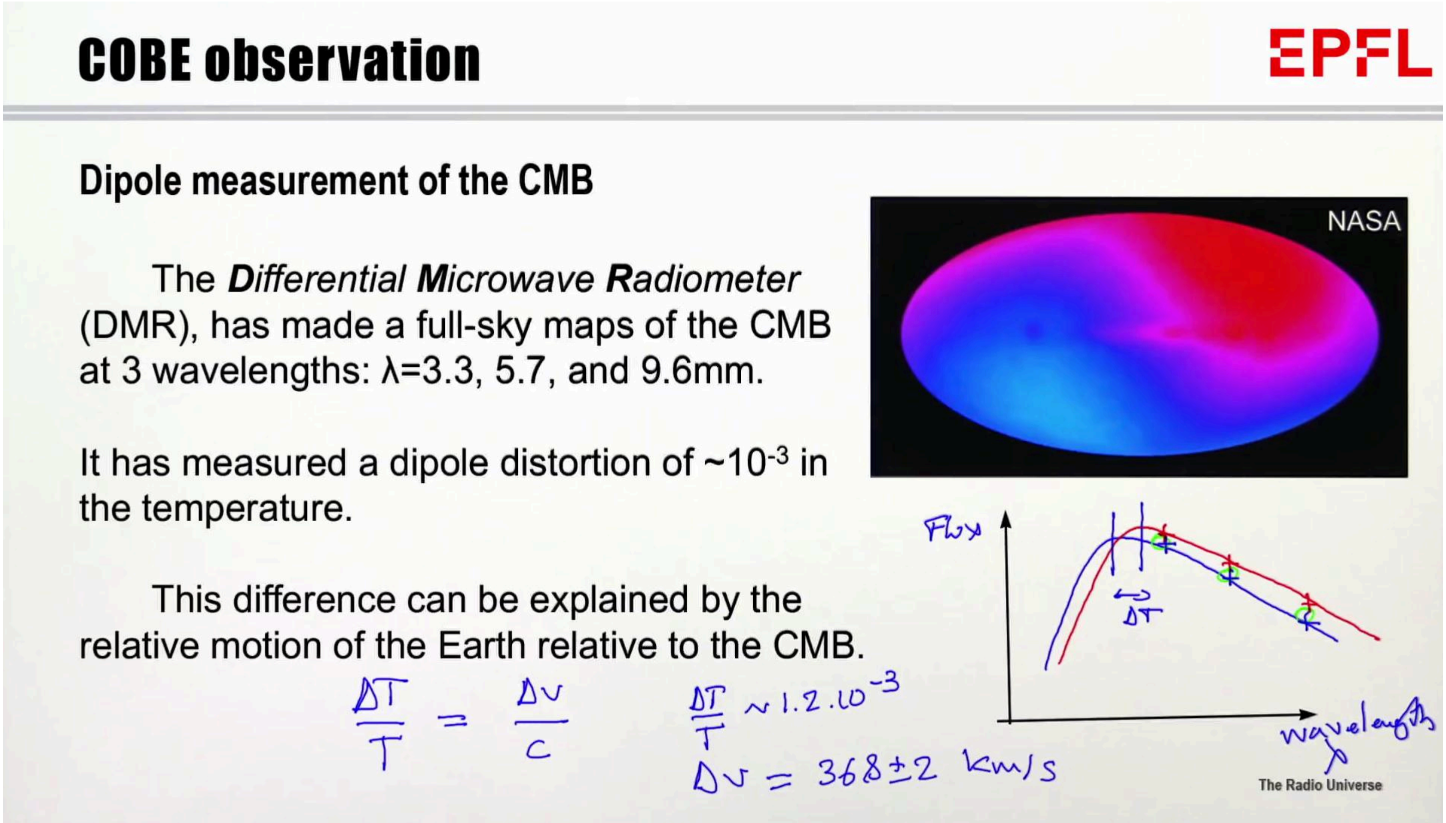


A second instrument that was on the COBE mission was the Differential Microwave Radiometer or DMR. This DMR instrument has made a full sky maps of the CMB at three different wavelengths at 3.3, 5.7 and 9.6 millimeter. What was a bit surprising was that it measured dipole distortion of about ten to minus three in the temperature. As we see here, there was a colder part and a hotter part so how do we do this measurement? So we're going to make a plot where we have the flux here, the wavelength here expressed as function of lambda. The black body curve of the CMB will be looking something like that and if you do this measurement with the DMR so you're basically looking from 3.3 to 9.6 millimeter so you're looking at three data points. One here, one here and one there. If you do the measurement on the blue part of this picture on the red part of this picture, you can find three different data points. So the red part measurement will be here and the blue part measurement will be here. So we find the black body curve that goes through the red point will be looking something like that.

Notes

Summary

11m 59s

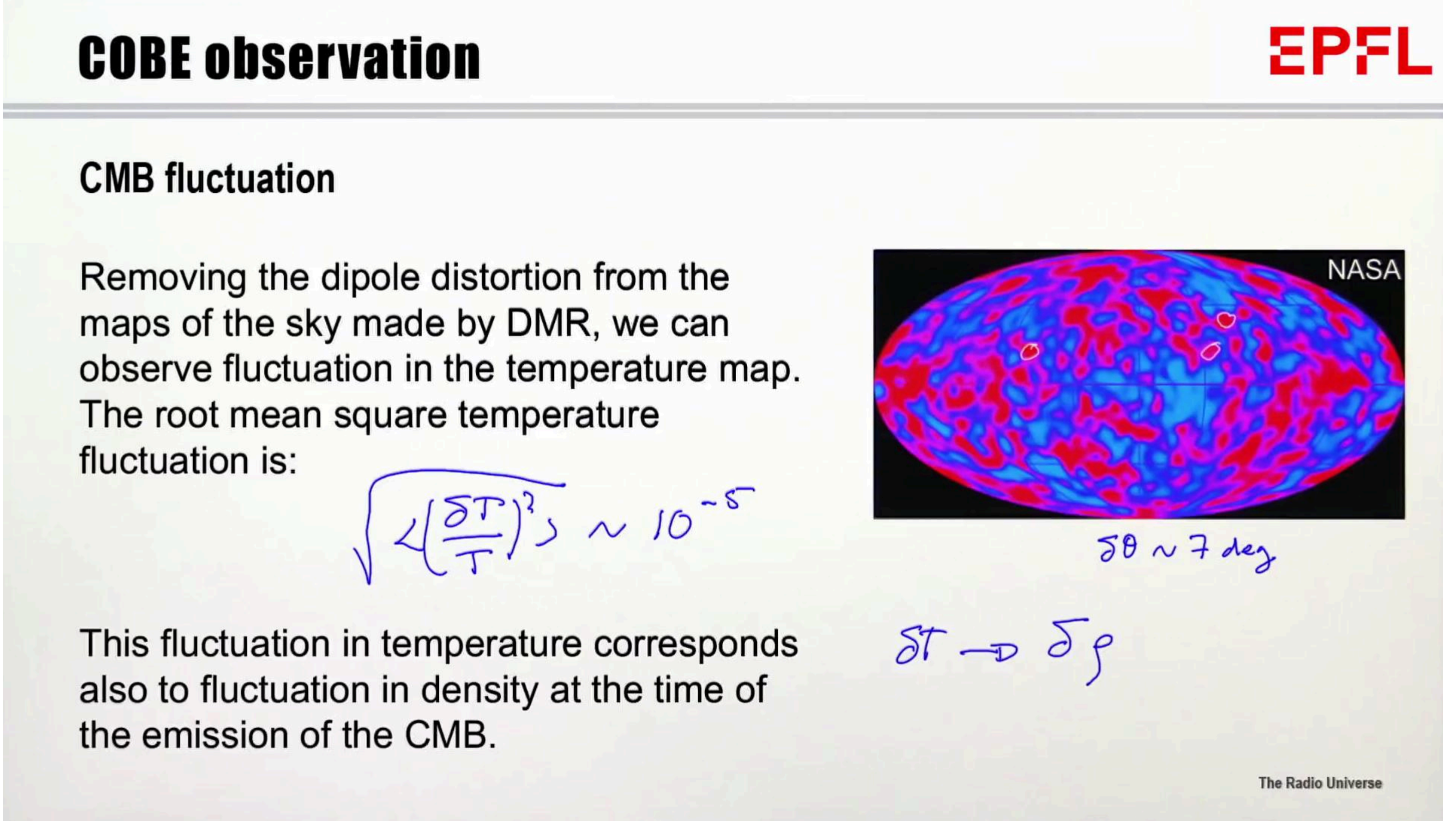


So the difference in the peak will give you a difference in the temperature and the relative distance of the temperature 'delta T' over 'T' can be written as a function of the difference in velocity divided by the speed of light. So this difference in 'delta T', you can explain it by the relative motion ‘delta v’ of the Earth relative to the CMB or the cosmological frame. So in practice, we're measuring a 'delta T' over 'T' of something like 1.2 ten to the minus three which means 'delta v' will be something like 368 plus or minus two kilometer per second. So relative to the CMB light the Earth is moving with a velocity of 368 kilometer per second in the direction of the red spot.

Notes

Summary

13m 42s

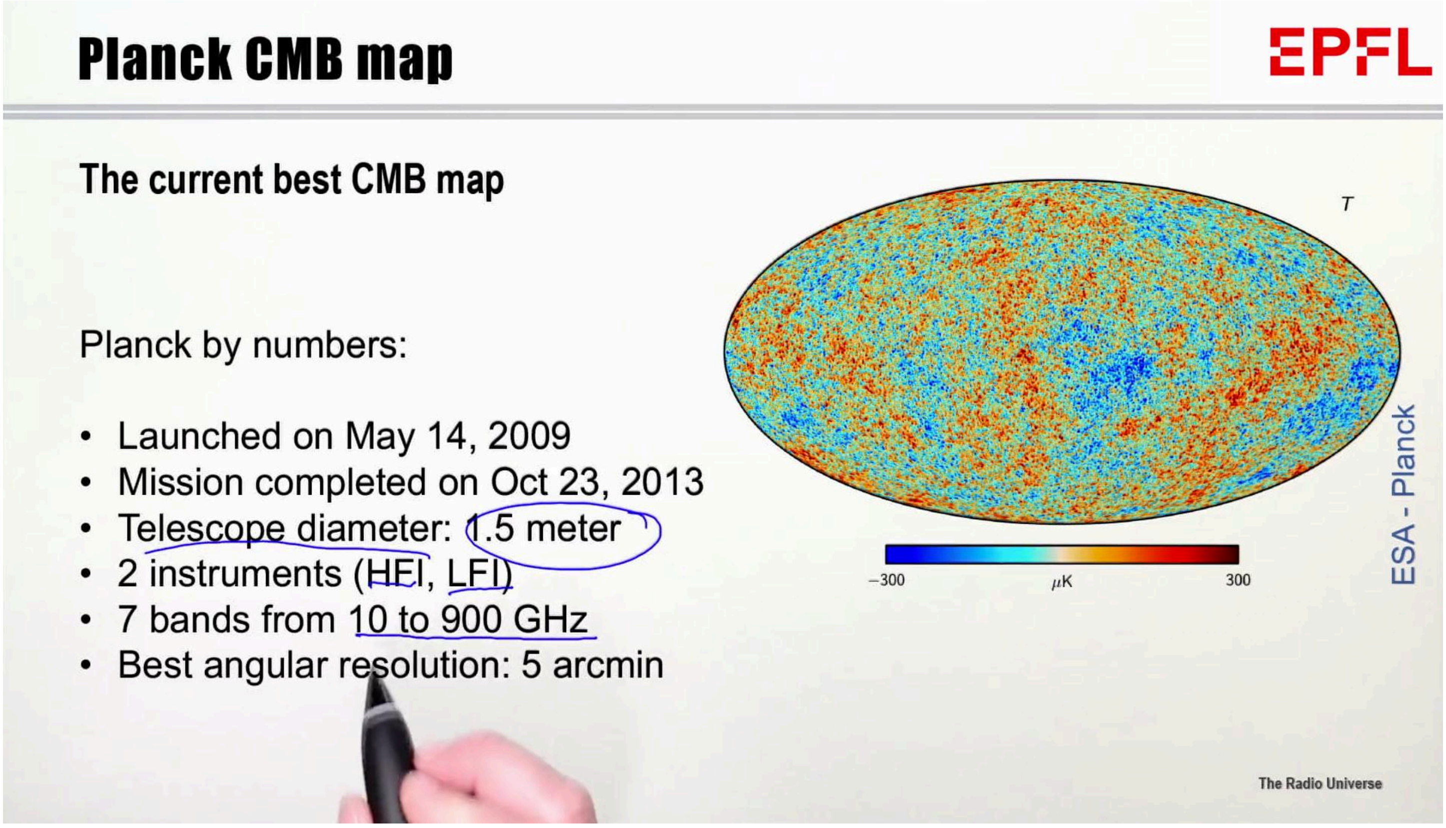


But the DMR experiment has done more than just measuring the dipole. In fact, if you take a model of the dipole and you subtract it to the dipole map then what you'll find is this particular map. It show a fluctuation in a temperature map and if we compute the root mean square temperature fluctuation as written as 'delta T' over 'T' square average and square root of the average, we found fluctuation of ten to the minus five in temperature in relative temperature. So those fluctuation we see in the map are, in fact, fluctuation corresponding to density fluctuation at the time of the emission of the CMB. So our temperature fluctuation can be linked to density fluctuation and those density fluctuation while the Universe will grow will form small-scale and large-scale structure that we see in the Universe. The limit of the COBE satellite was its poor resolution. Indeed, the typical scale that you see in the map are limited to the resolution of the instrument. Those scale is about an angular scale of seven degree. This is relatively large scale in the Universe.

Notes

Summary

14m 44s

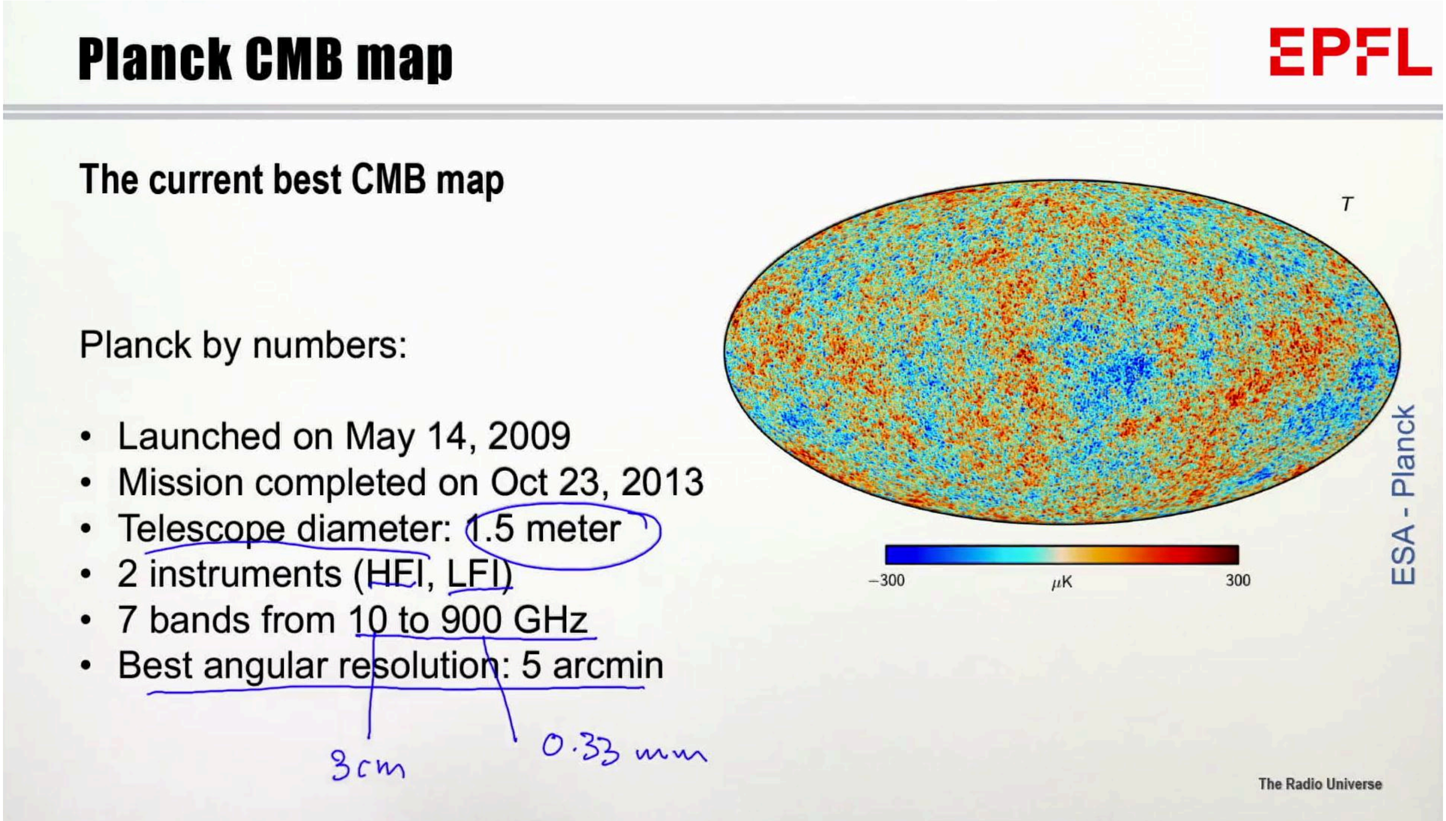


So following the success of the COBE observation there has been a lot of same big experiment trying to reach better resolution images meaning also using larger telescopes. This can be done, of course, using ground-based infrastructure. Here we see the ACBAR telescope which was operational from 2001 to 2008. It's located at the South Pole. It can also be done from balloon-borne experiment and here we have the BOOMERanG experiment also launched from the South Pole and it was active from 1997 to 2003. But better if you manage to launch a spacecraft then you can see the CMB across the full wavelength and get a lot of information. So this was done recently by two satellite The two WMAP satellite that we see here active from 2001 to 2010. And the Planck is a satellite that we see here that was active from 2009 to 2013. The Planck CMB map is certainly the best map of the CMB today. Planck launched in 2009, finish its mission in 2013 so during more than four years it cover the full sky many times. It has done that with a telescope diameter of 1.5 meter. It has two instrument on board. The HFI instrument and the LFI instrument. These two instrument covers with seven bands 10 to 900 gigahertz.

Notes

Summary

16m 24s



This means going from three centimeter wavelength to 0.33 millimeter. So it really cover the CMB light and because of the very small wavelength at which it observe the CMB, it has a very good angular resolution of five arc minute. This is almost hundred times better than the COBE satellite.

Notes

Summary

18m 32s

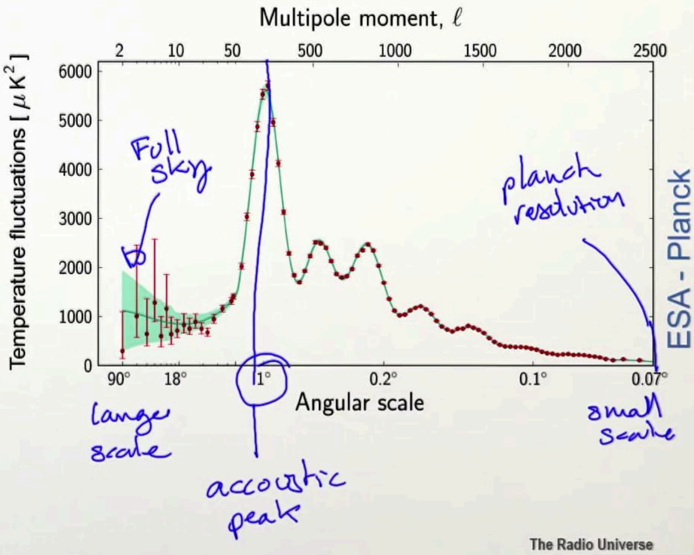
Planck CMB anisotropies

EPFL

The current best CMB map

By measuring the temperature fluctuation on the Planck CMB map as a function of the angular scale, we can probe the cosmological model and constrain a number of physical parameters.

For example, from the angular position of the first peak, cosmological models tell us that the universe is *flat*.



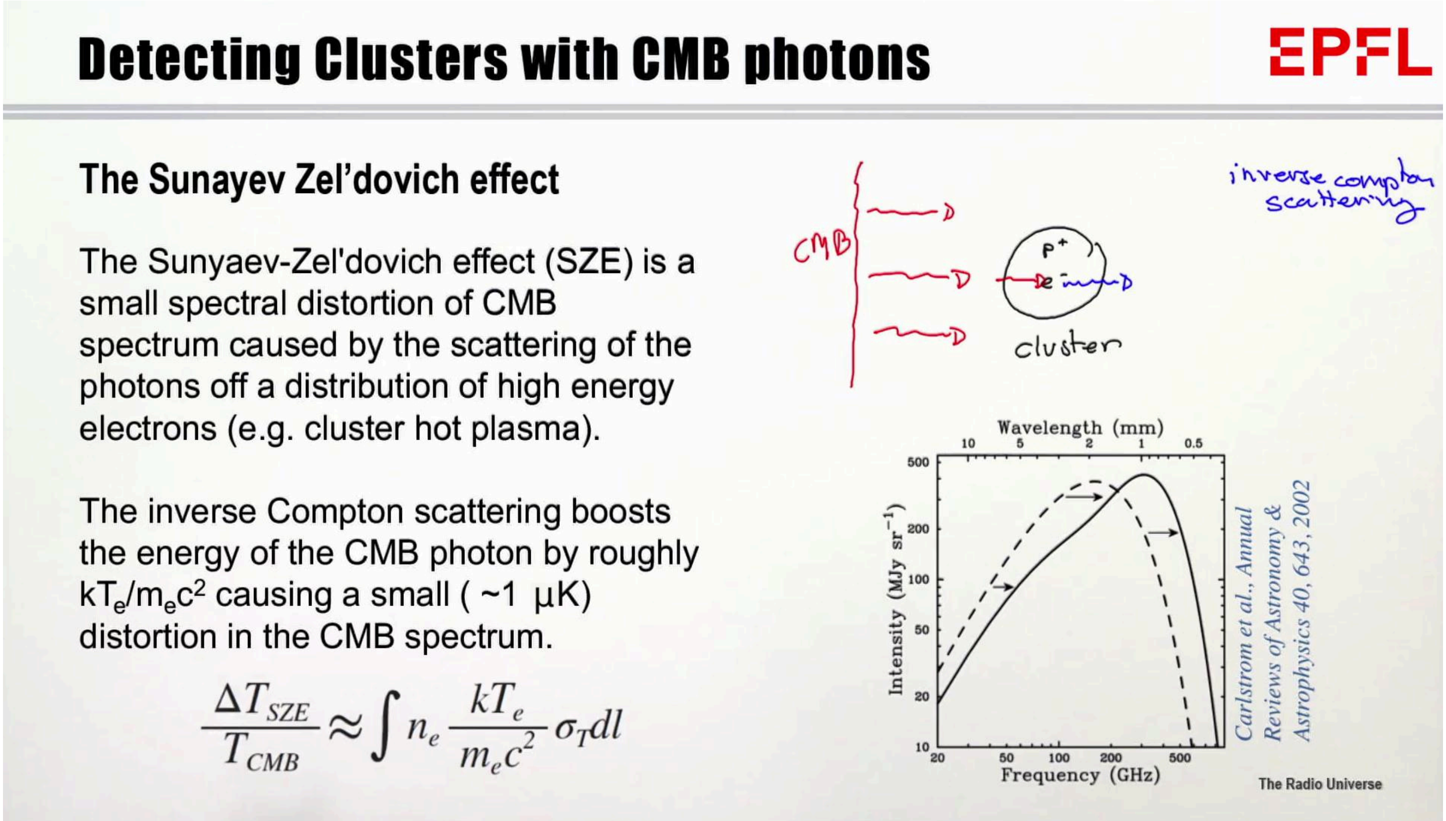
The Radio Universe

So by studying the temperature fluctuation of the Planck CMB map as a function of angular scale, we can probe the cosmological model and constrain a number of physical parameter. So what we have done here, we have converted the Planck map into a curve which express the temperature fluctuation intensity as a function of angular scale. So here we have the large scale and here we have the small scale. Here it's basically the Planck resolution limit and here is the full sky. So what we see here is a number of fluctuation and the main fluctuation that we see here at a scale about one degree is what we call the acoustic peak. This correspond to an acoustic oscillation in the early plasma of the Universe. So the location of the first acoustic peak tells us about the curvature of the Universe and we can deduce from the exact position of that peak that the geometry of the Universe can be considered as a flat.

Notes

Summary

19m 02s



So the CMB observation tell us about the geometry of the Universe, for example. But it can also help us detecting clusters. We can detect cluster of galaxy in the Universe thanks to the CMB photons using what we call the Sunyaev-Zel'dovich effect. So how does it work? Imagine here we have the CMB. So the CMB is emitting some light at some wavelength and let's assume here we have a cluster. The cluster of galaxy is a very massive system. At the center of the cluster of galaxy because it's going to be very hot, we're gonna have a plasma. A plasma made of protons and electrons. When the CMB photons interact with an electron of the hot plasma, it will gain energy and will produce the higher energy photons. This interaction is called the inverse Compton scattering. So the CMB photon interacting with energetic electrons in the hot cluster plasma will gain energy. So that means its wavelength will be shifted to more energetic wavelength so that mean the spectrum of the CMB that we see here in dashed line will be shifted to higher energy which mean smaller wavelength to produce this solid curve here. The gain in energy of a CMB photon will be roughly proportional to 'kTe' divided by 'mec-square'.

Notes

Summary

20m 20s

Detecting Clusters with CMB photons

EPFL

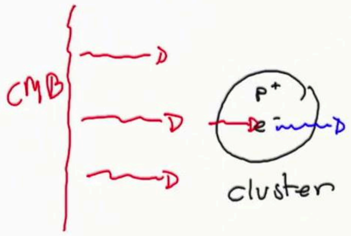
The Sunayev Zel'dovich effect

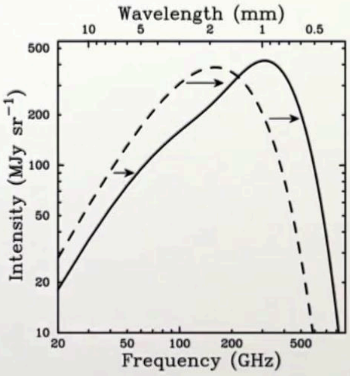
inverse compton scattering

The Sunyaev-Zel'dovich effect (SZE) is a small spectral distortion of CMB spectrum caused by the scattering of the photons off a distribution of high energy electrons (e.g. cluster hot plasma).

The inverse Compton scattering boosts the energy of the CMB photon by roughly kT_e/m_ec^2 causing a small (~1 µK) distortion in the CMB spectrum.

$$\frac{\Delta T_{SZE}}{T_{CMB}} \approx \int n_e \frac{kT_e}{m_e c^2} \sigma_T dl$$





Carlstrom et al., Annual Reviews of Astronomy & Astrophysics 40, 643, 2002

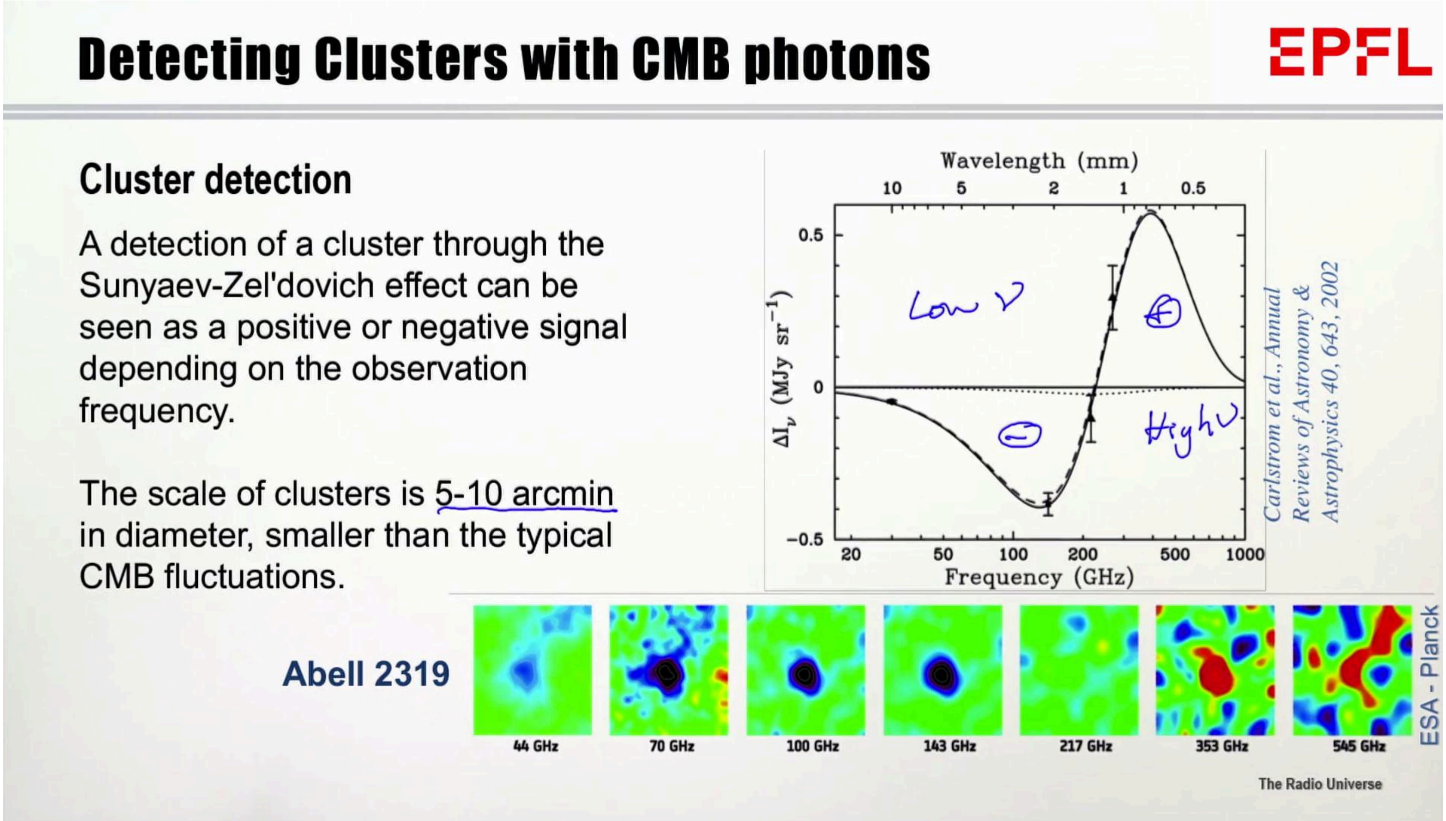
The Radio Universe

That's usually produce a small distortion of typically one microkelvin in the CMB spectrum but the relative temperature change will, in fact, depend essentially on the density of electron in the cluster. So in some way by detecting the SZE effect of the cluster on the CMB photons, we will be able to measure the density of electrons in the cluster which is be proportional to the gas mass of the cluster.

Notes

Summary

22m 06s



So to detect the cluster through the Sunyaev-Zel'dovich effect we're gonna subtract the mean CMB light to the data. So that means we're gonna measure at a position of a cluster a signal that will be different depending on the frequency. At low frequency, we're gonna have a negative signal. At high frequency, we're gonna have a positive signal. Here is an example of the signal measured at different wavelengths for the cluster, Abell 2319. We see the measurement at the seven different bands of Planck going from 44 gigahertz to 545 gigahertz. At low frequency, we have a negative signal. At 217 gigahertz, we have basically a signal close to zero and at high frequency, we have a positive signal detecting the cluster. The detection is possible because cluster size is typically five to ten arc minute which is very small compared to the typical fluctuation seen at the CMB level.

Notes

Summary

22m 44s

In this presentation, we have learned that the CMB is the dominating background amongst the diffuse extragalactic backgrounds observed at all wavelengths. The CMB was accidentally discovered by Arno Penzias and Robert Wilson in 1964 where they were mapping the microwave emission of the Milky Way. Thanks to this discovery they received the Nobel Prize in 1978. The CMB was first observed in details with the COBE satellite which measure a precise black body emission of 2.73 degree kelvin. COBE has also detected a dipole distortion in temperature map of ten to the minus three which can be explained by the relative motion of the Earth against the cosmological frame. Finally, COBE was the first to detect fluctuation of ten to the minus five in the temperature map which correspond to mass density fluctuation that will eventually evolve in the large and small-scale structure of the Universe. Following the COBE results many follow-up observation have been conducted through observation with ground-based telescope, with balloons and with satellites. The most comprehensive recent observation of the CMB was completed with the ESA-Planck space mission. Planck measured the temperature and isotropy to very fine details giving tight constraints on the cosmological model. Finally, Planck has also provided an all-sky catalogue of clusters through their Sunyaev-Zel'dovich effect on the CMB.

Notes

Summary

24m 08s