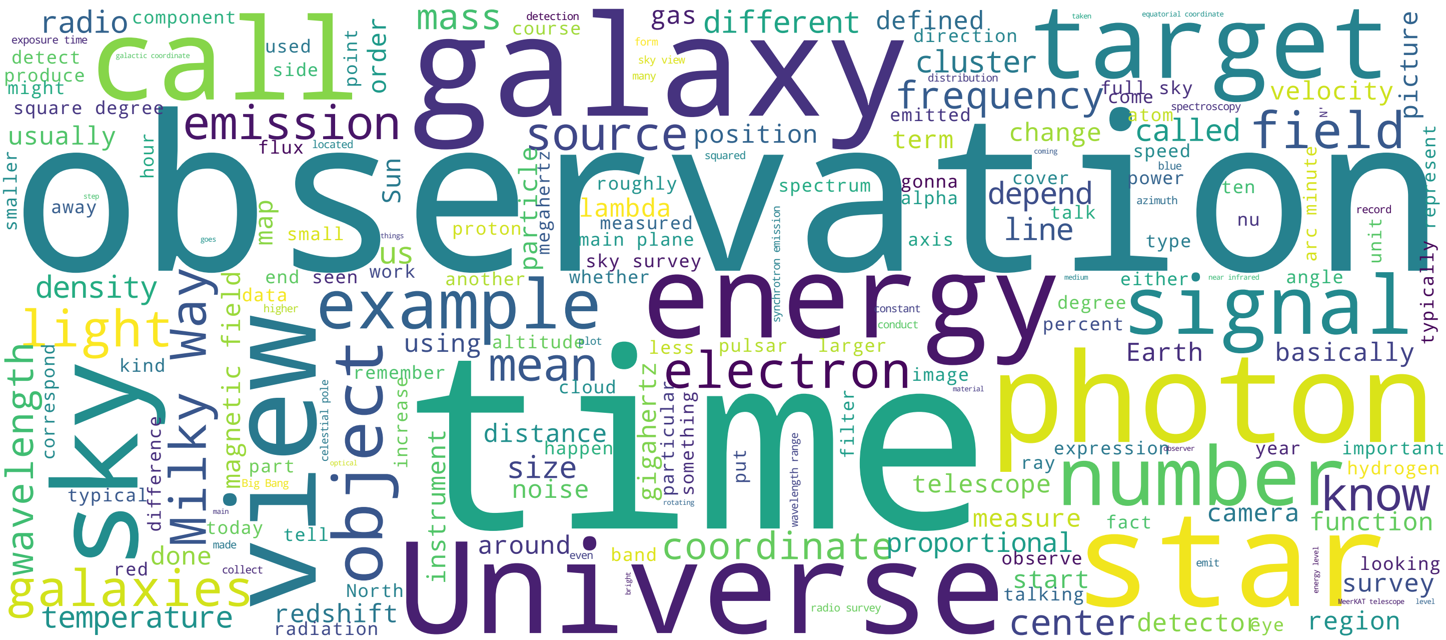
Sky Surveys

The Universe At Radio Wavelengths

Jean-Paul Kneib



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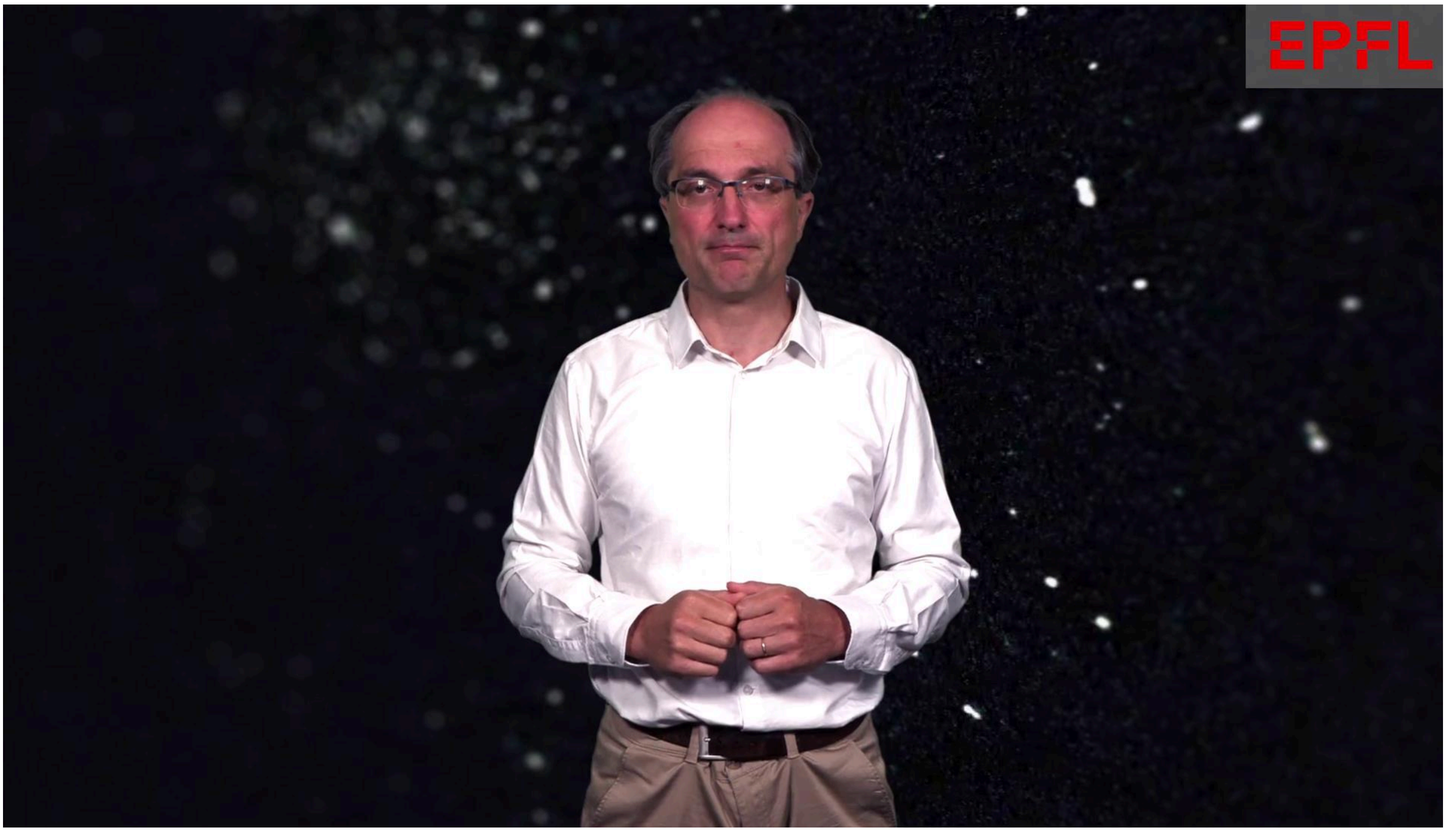
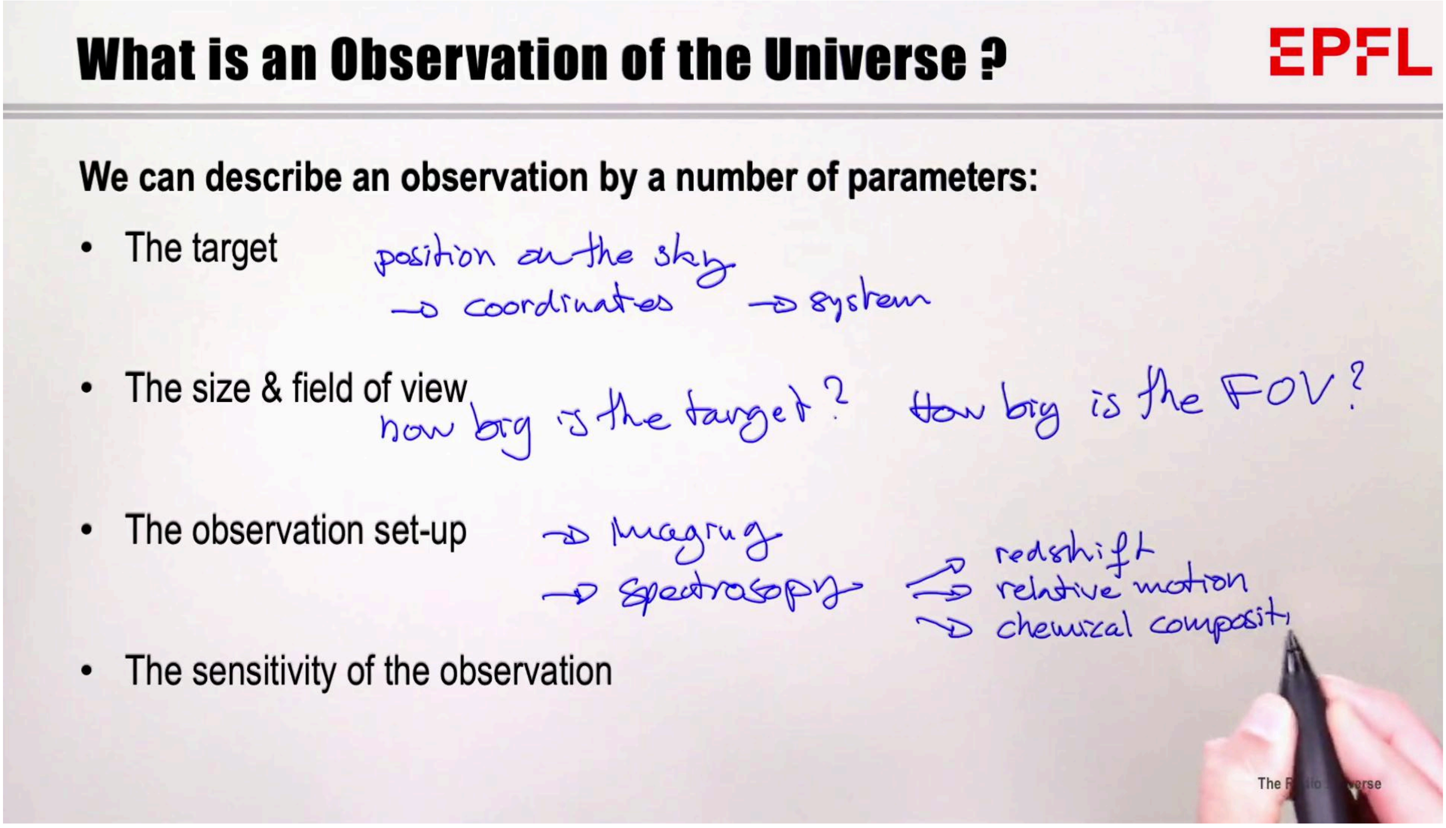


Today we will complete the week with some observational concepts to survey the sky. As the sky is huge, the first step to define is the target of the observation. The target can be located with two angular coordinates on the celestial sphere. The choice of the coordinate system on the sphere depend on the type of the object whether it belong to our solar system, to the Milky Way or whether it's far outside the Milky Way. The second step is to define how big is the target and depending on the instrument and telescope just a single or multiple observation will be needed to complete the survey of the target. The third step is to define which mode of the instrument and telescope we will use to acquire the data. Whether we just take an image or whether we aim to do spectroscopy. The fourth step is to define the exposure time which should be large enough to enable the detection of the target with adequate signal to noise. To conclude, I will present a number of sky survey projects.

Notes

Summary

0m 04s

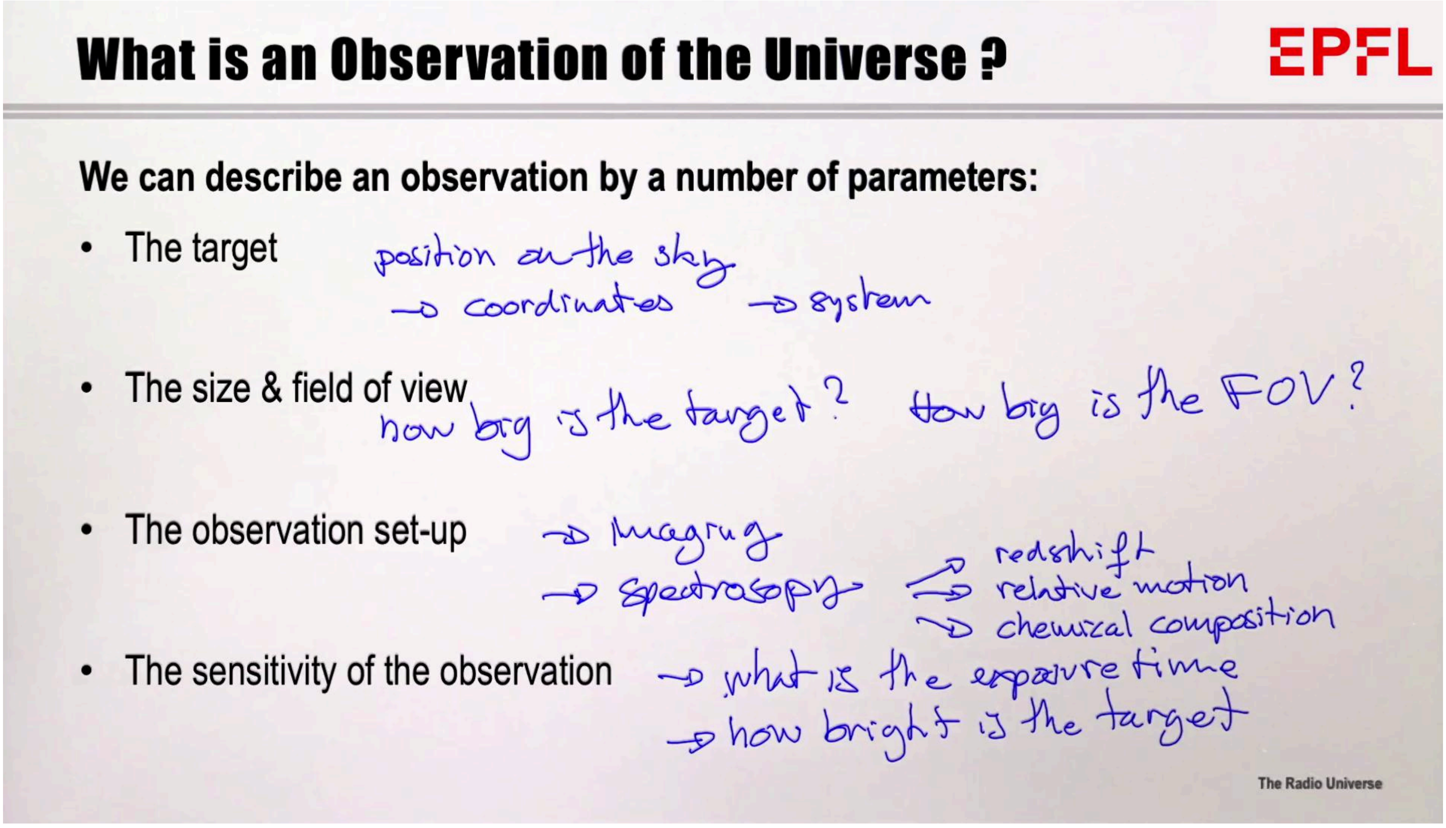


When we want to survey the sky we need to conduct some observation with a telescope. So how do we define an observation of the Universe? Well, we can describe an observation by a number of parameters which will help, plan and organize the observation. To start with, we have to define the target. The target is the purpose of the survey or the observation. The target will be defined by its position on the sky. That means we have to define the coordinates of the targets and that will depend on which system coding system that we're gonna use. The second point is to know about the size of the target and the field of view of the camera or the telescope. So we have two question. How big is the target? And how big is the field of view of the camera? Then we have to define what we call the observational setup of the observation. Okay, so we can do either imaging that is, we are recording the energy of the source of the target in a given frequency on a given wavelength range or we do spectroscopy and here we not just record the position on the sky but we also record the energy level of the photons we received. So if we do spectroscopy we want to either measure the redshift, the relative motion or the chemical composition.

Notes

Summary

1m 26s

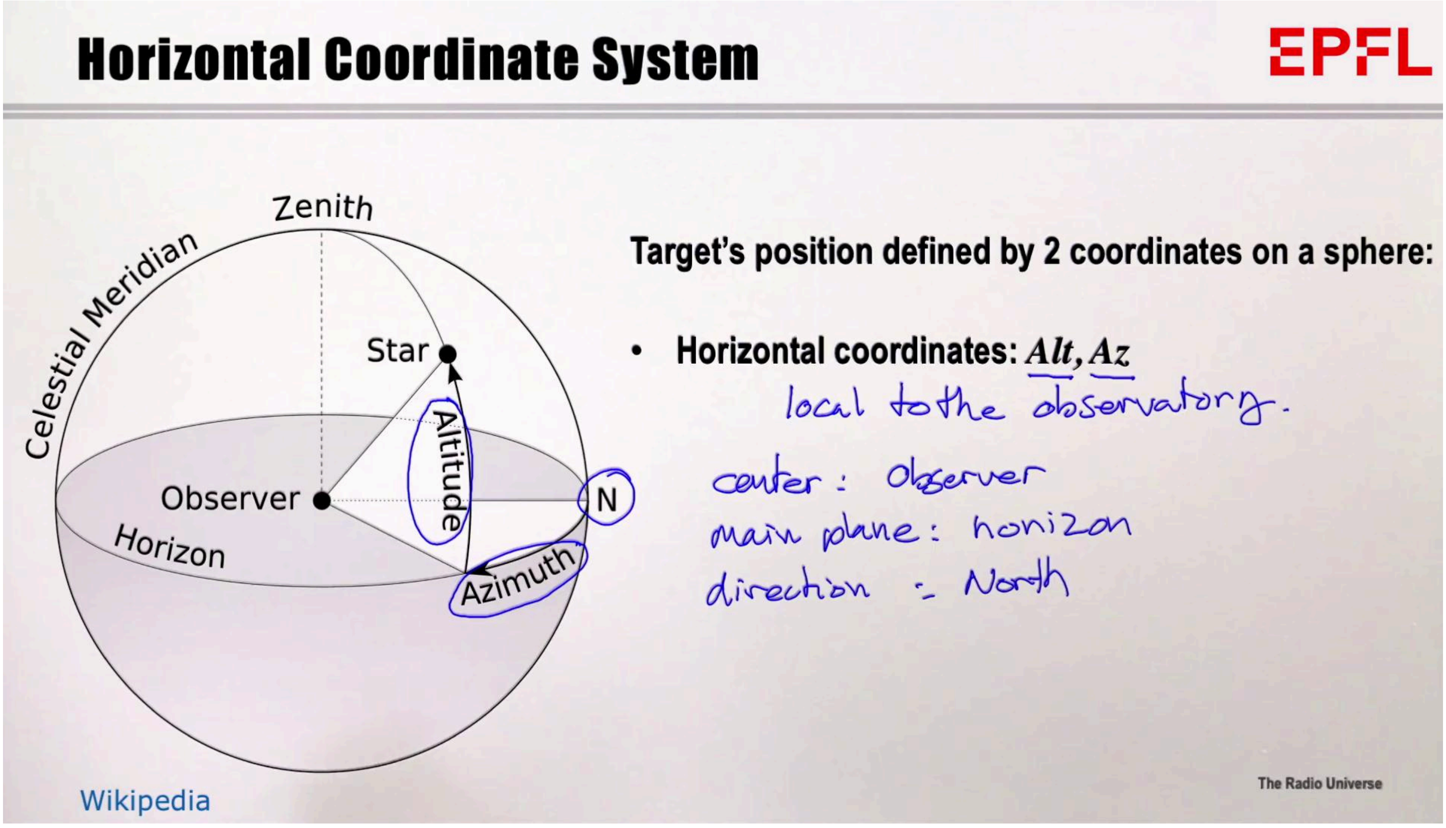


So the last point has to do with the sensitivity of the observation and the question to answer is what is the exposure time. So that will depend on how bright is the target.

Notes

Summary

3m 23s

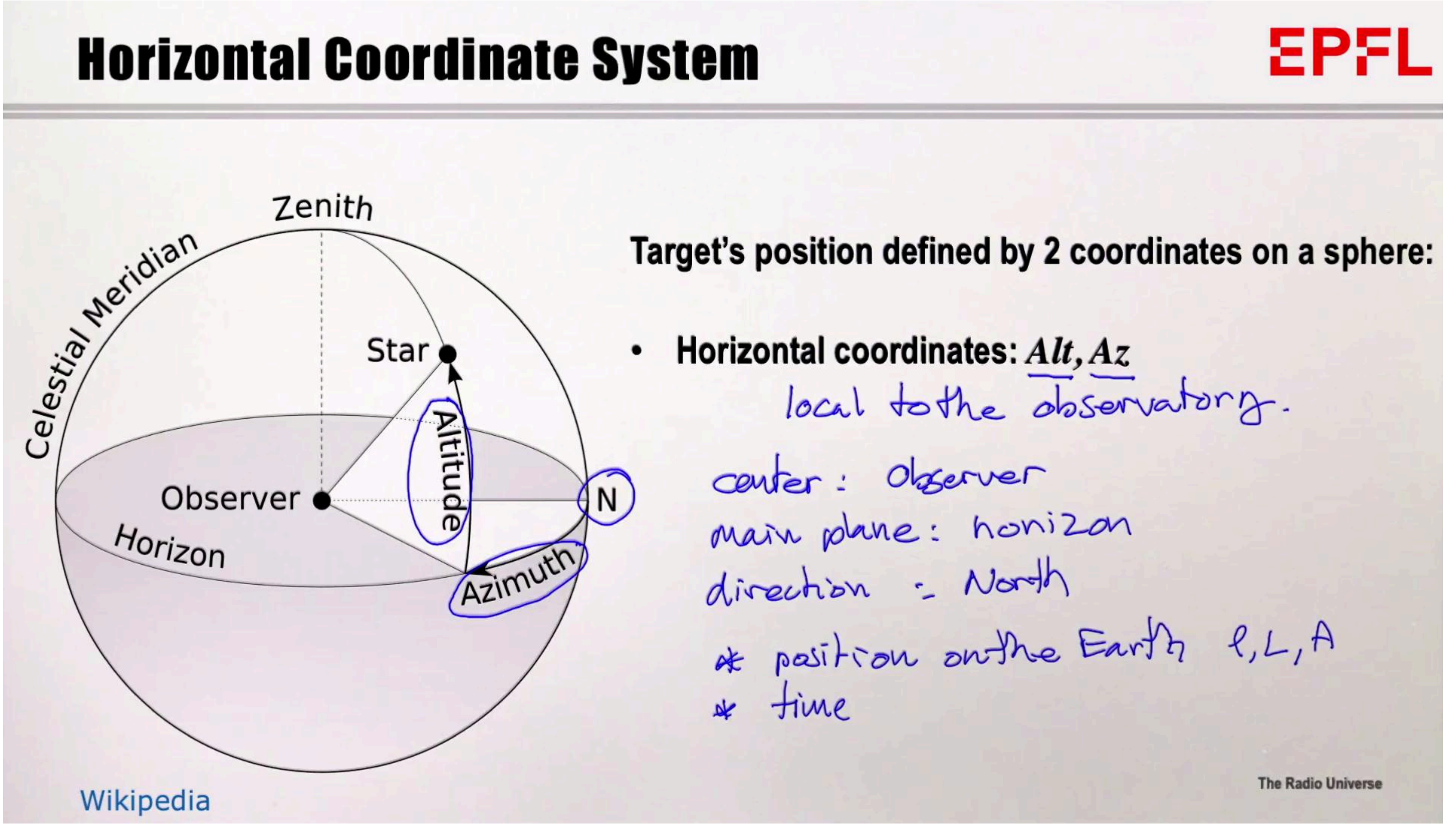


So how do we find the target in the sky? Well, it's relatively simple. Okay. Here we have the sky view. Okay. We are on the observer here at the location, say, of a telescope and we are looking at a star, for example. And so you see that the location of the target on the sky on the celestial sphere can be defined by two coordinates. In this case, we have the azimuth and the altitude. The altitude is written 'Alt' and the azimuth is written ‘Az’. That correspond to what we call the horizontal coordinate system. This coordinate system is local to the observatory. So we can define the center. The center is the observer. We can define the main plane. So the main plane is the horizon and we can define the direction, the main direction which is the North direction. So when we have this system, the horizon which is the main plane does then it give us the perpendicular to the main plane, the North direction and then we can define the two angle; the azimuth and the altitude. We also define here in this picture what we call the Celestial Meridian which basically that line that goes from the North to the Zenith back to the South.

Notes

Summary

3m 37s



So this local coordinates system will depend first on the position on the Earth, that is the latitude, the longitude and the altitude of the place. And the other important aspect is the time. Because objects are moving over the sky so we need to know, once we define the altitude and the azimuth to connect to our target, we need to know the latitude, the longitude and the altitude of the observatory and we need to know the time at which we do the observations.

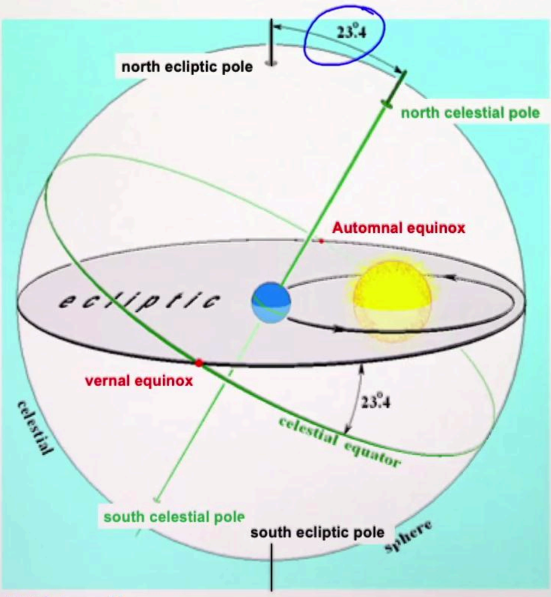
Notes

Summary

5m 21s

Celestial Sphere

EPFL



Wikipedia

Target's position defined by 2 coordinates on a sphere:

- **Equatorial coordinates:** α, δ RA, DEC
- **Ecliptic coordinates:**

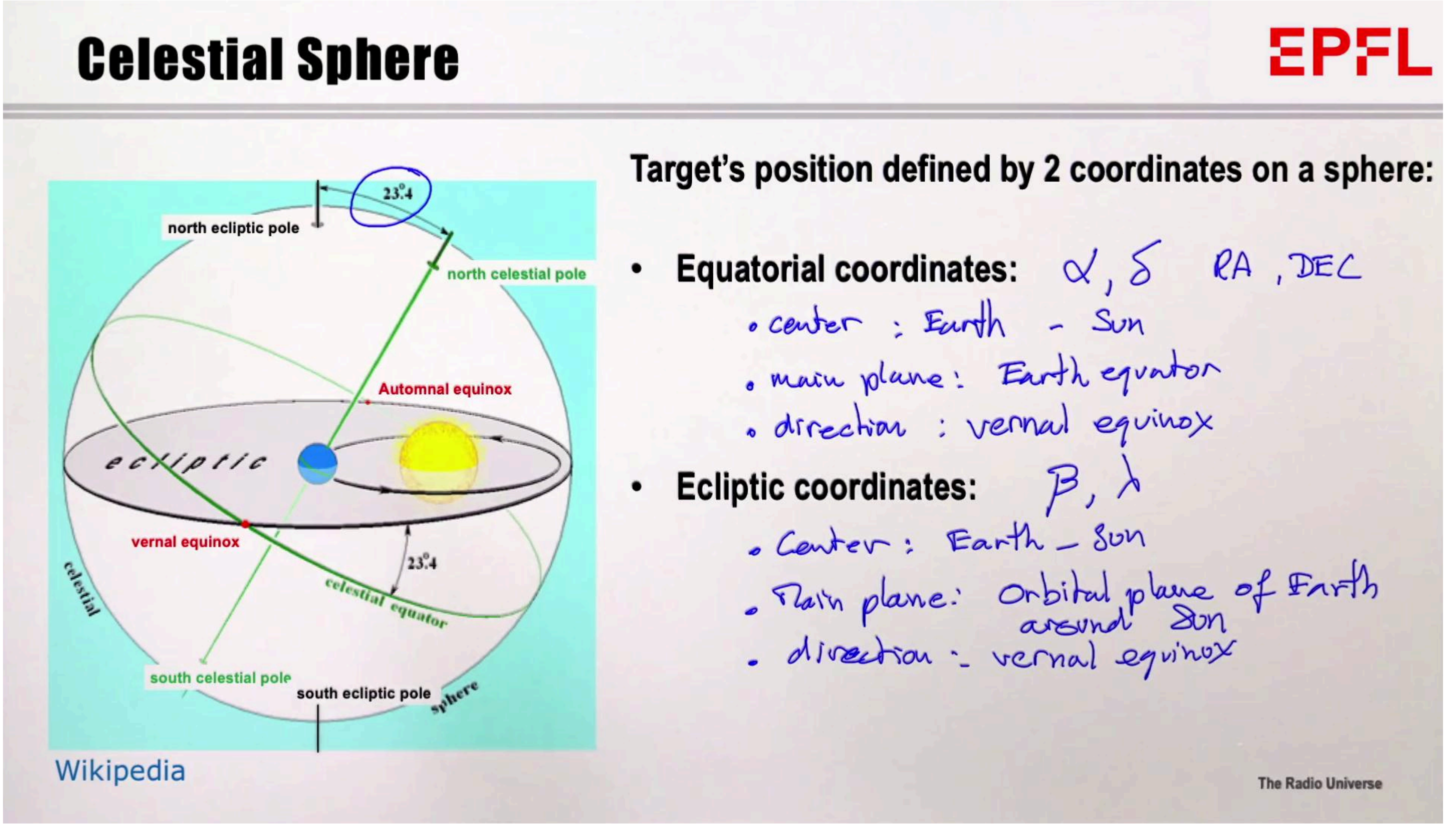
The Radio Universe

The other type of coordinate system which is more linked to the target itself on the celestial sphere are twofold. Either we can use the equatorial coordinates or we can use the ecliptic coordinates. So we have two different systems. So let's try to explain what are those two different systems. So here we have picture which try to represent the two different system. What we see in this picture is the position of the Sun, the position of the Earth. So the Earth is orbiting around the Sun and it's orbiting in a plane that we call the ecliptic plane but also the Earth is rotating and it's rotating on an axis which is not exactly align with the axis of the North and South ecliptic pole. Okay. It's rotating around the axis that we call the the North and South celestial pole. Okay. And there is a difference between these two axes of 23.4 degree. So there's an offset and that's why we have this two different coordinate system. So how do we define the equatorial coordinate system? First, we can name them those coordinates. We call them alpha and delta for alpha is also called the right ascension and delta is called the declination. We also write them RA and DEC.

Notes

Summary

6m 09s



So the center of this coordinate system is either the Earth and then we talk of a geocentric system or the Sun and then we talk about the heliocentric system. The main plane is the Earth's equator. Okay. We also call that the celestial equator and it's basically perpendicular to the North celestial pole and the South celestial pole so the axis of rotation of the Earth. The reference direction it's what we called the vernal equinox, which is defined by the time of the year and in more particularly, the 21st of March which is the start of the spring. The second coordinate system is the ecliptic coordinates. So the ecliptic coordinates that we write beta and lambda are basically in the frame of the ecliptic plane. Okay. And perpendicular the North and South ecliptic pole. So the center of this coordinate system again can be either the Earth or the Sun. The main plane is the orbital plane of the Earth around the Sun. This is also the plane of the constellation. The main direction, it's the same. It's the vernal equinox. So because there is a little precision of the this angle between the North ecliptic pole and the North celestial pole which is due to the precision of the Earth, there is also some variation of those coordinates as a function of time.

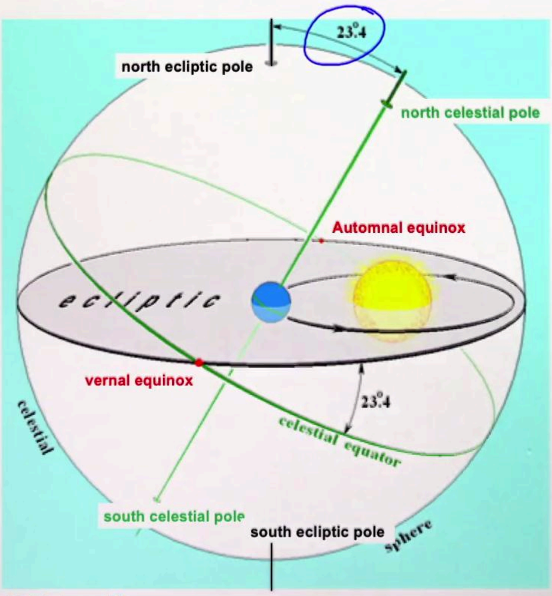
Notes

Summary

8m 08s

Celestial Sphere

EPFL



Wikipedia

Target's position defined by 2 coordinates on a sphere:

- **Equatorial coordinates:** α, δ RA, DEC
  - center: Earth – Sun
  - main plane: Earth equator
  - direction: vernal equinox
- **Ecliptic coordinates:** β, λ
  - Center: Earth – Sun
  - Main plane: Orbital plane of Earth around Sun
  - direction: vernal equinox

- precession Earth → ~50 arcsec/year
- year of reference: J2000

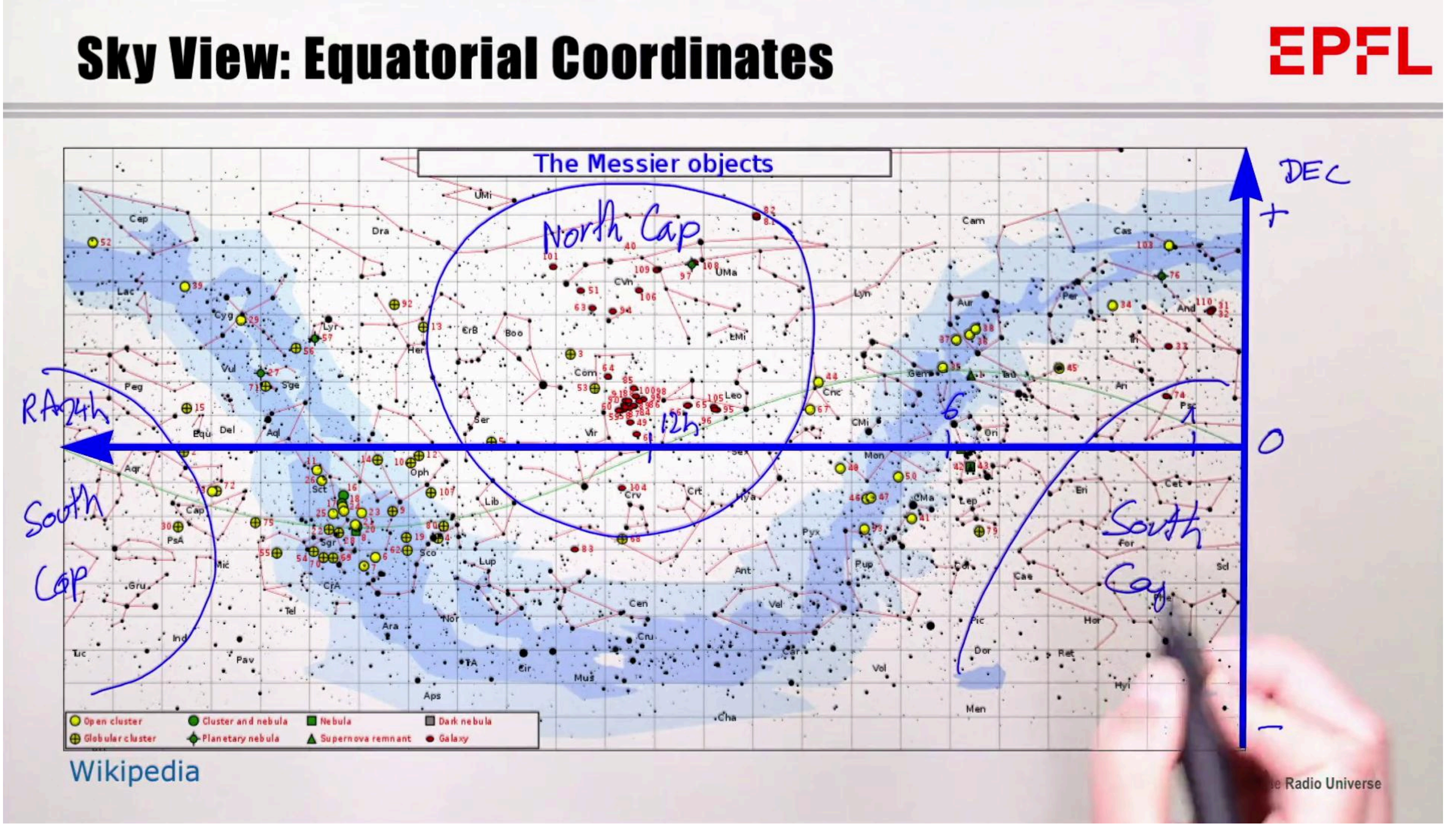
The Radio Universe

So the precision of the Earth is leading to change which are of the order of 50 arc second per year. So when we give the coordinates in this different system, in particular, in the equatorial coordinates, we need to precise the year of reference at which the coordinate system is attached. And today the current system is what we call the system J2000.

Notes

Summary

10m 35s

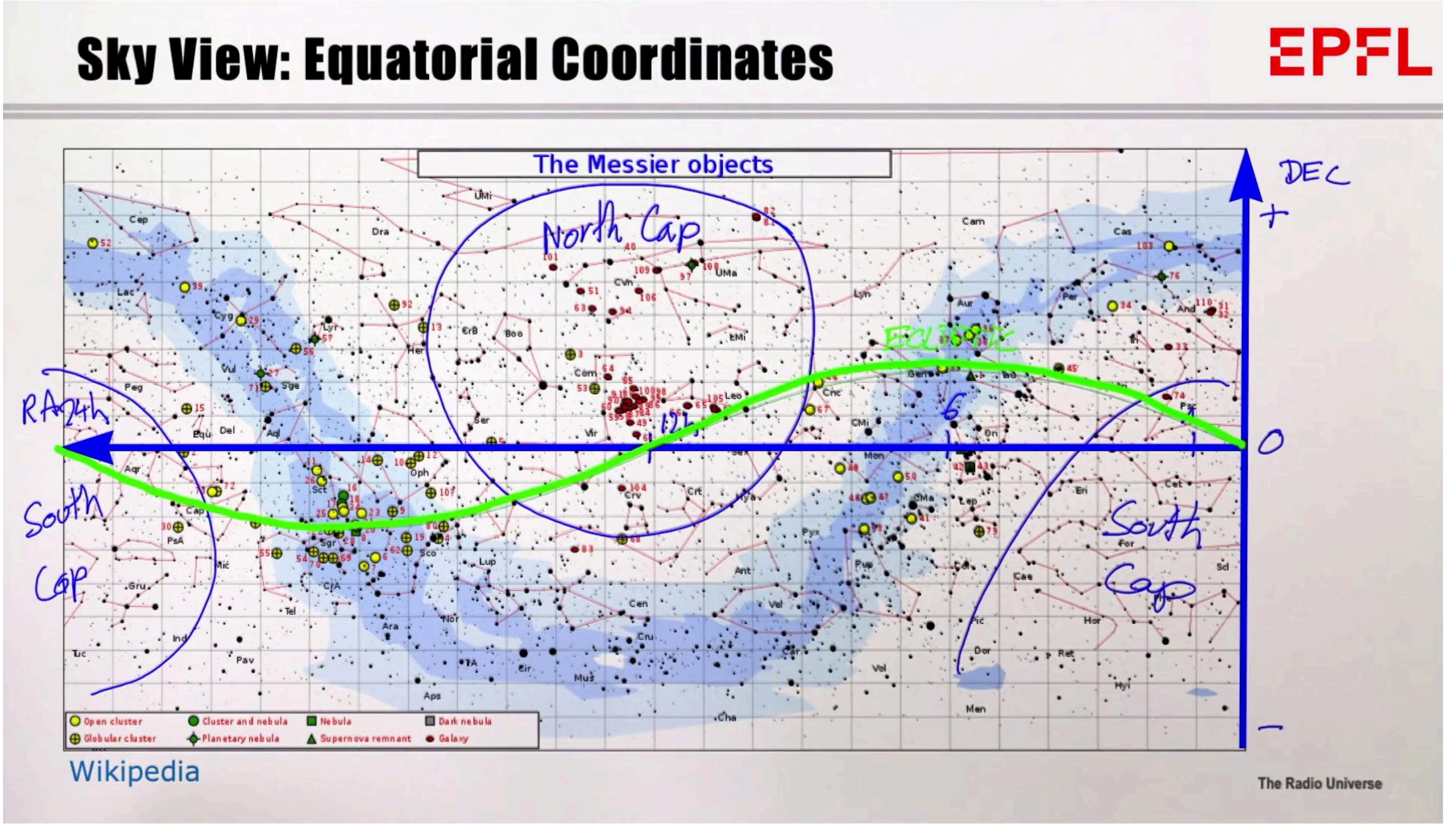


So the view of the sky would be shown differently in the different projection depending on which coordinate system we use. This is the sky view using the equatorial coordinates. In this view of the sky, which represent the full sky that can be seen around the Earth, we have located the different messy objects and a different constellation that you see in red with those different lines. What you see also is the trace of the Milky Way over here which obscure almost half of the sky. So where are the coordinates here? So let's put the coordinates. Over here we have the declination. Over here we have the right ascension. Here we have the zero. So here we have positive declination. Here we have negative declination. Over here is the North pole. Over here is the South pole. And the right ascension is either expressed in degree or in hours. So here this plot is for every hour. So this is one hour two three four five six. Okay. Here we have 12 hours and here we have 24 hour. What we also see is extragalactic region where we have no basically no many stars from the Milky Way. So this region here, it's called the North Cap and this region here, it's called the South Cap.

Notes

Summary

11m 11s

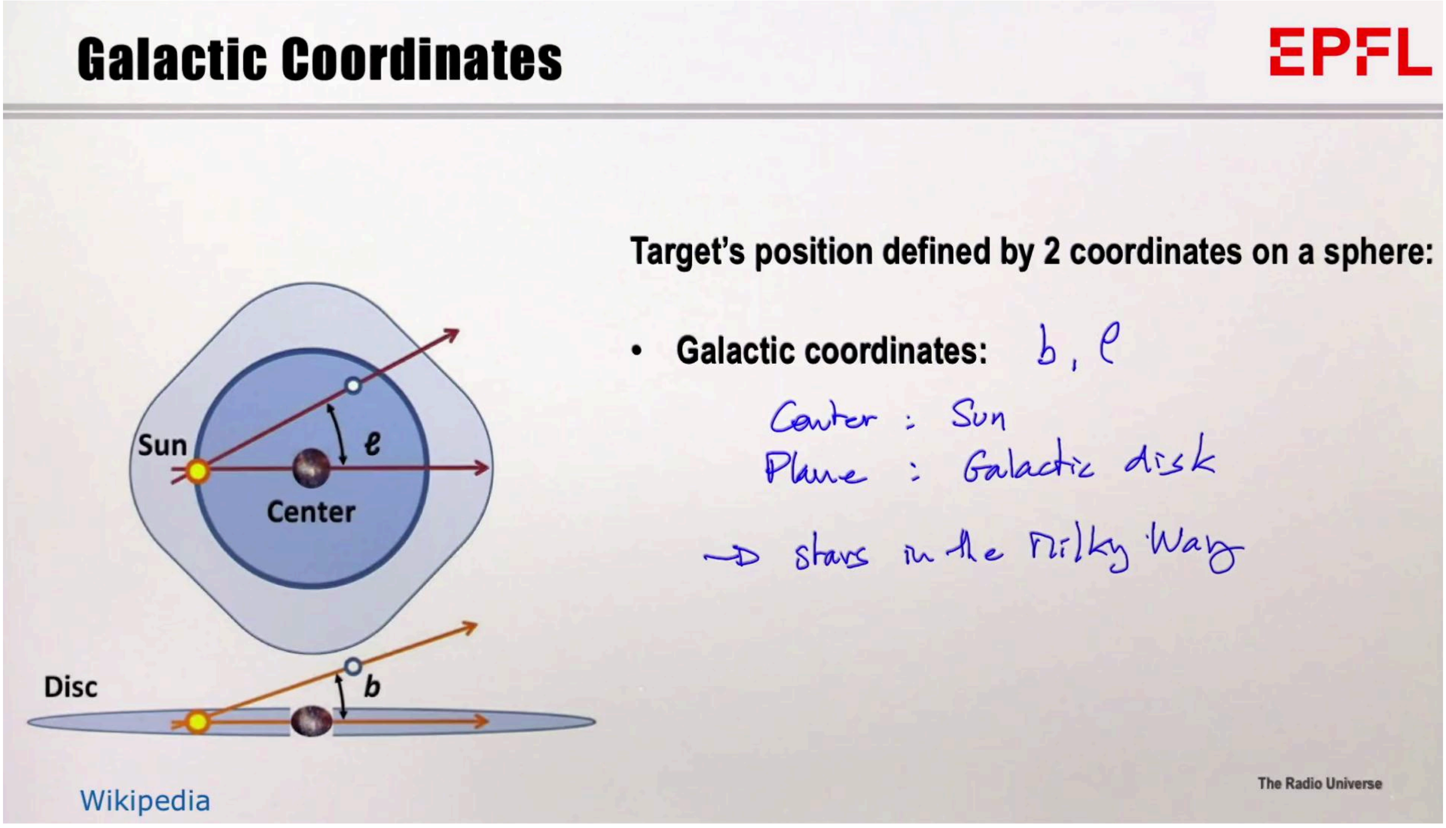


This line over here that I trace in stronger signal in green, it's what we call the ecliptic. So the Sun will follow this line on the sky as well as the different planets of the solar system. And it's along also those line this line that we have the various constellation from the astrology.

Notes

Summary

13m 10s

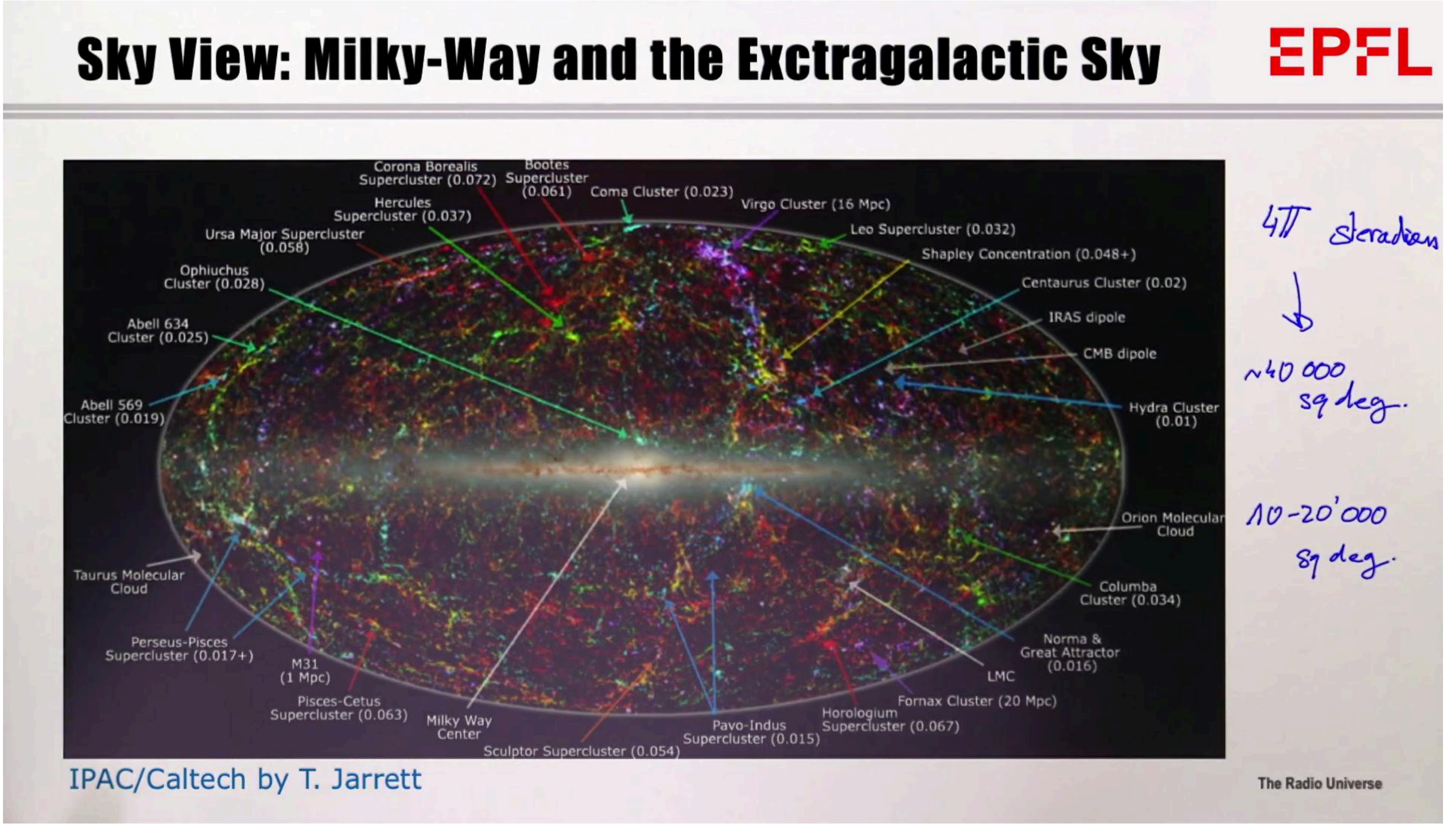


Finally, the other coordinate system that is used and particularly used for stars in our Milky Way, is what we call the galactic coordinates. Here is a representation of the galactic coordinate system. Again it's defined by two angle on the sphere. Those angle are the galactic coordinates and they're written 'b' and 'l'. 'b' correspond to the elevation of the star compare to the main plane where we put the center as the position of the Sun so the center of this coordinate system is the Sun and the main plane is the galactic disk, the Milky Way disk where is the highest density of stars. So here we have the center of the Milky Way, we have the Sun position and an object to target will be defined by this two angle. The 'b' and the longitude ‘l’. So this coordinate system is essentially used for stars in the Milky Way but it's also used to define like the density of dust around the Milky Way center.

Notes

Summary

13m 41s

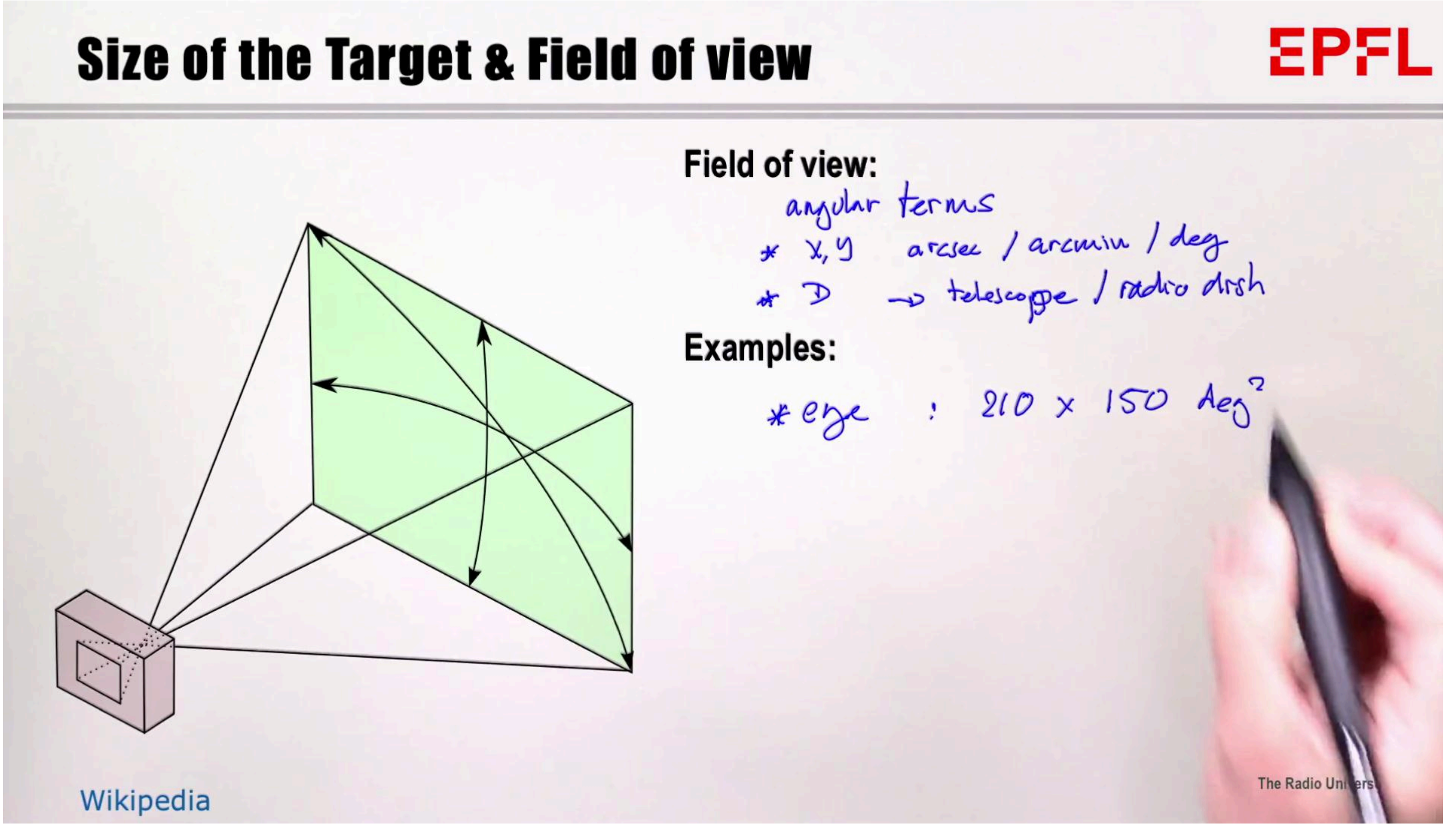


So this is the sky view of the Milky Way and the extragalactic sky. Again we are seeing here the full sky. What we see in the middle here is the Milky Way and we see the center of the Milky Way here this diffuse light. What we see also and that's an image taken in near-infrared are the density of galaxies with a color code which depend on the distance. The bluer are the closest. The redder are the most distant object. The closest big galaxy is Andromeda M31 which is located at one megaparsec and what you see also is a famous cluster, up North over here is the Coma Cluster at redshift 0.023. So the full sky in terms of area, it's four pi steradian. That correspond to about 40,000 square degree. So you see the sky is really huge, 40,000 square degree. The Milky Way occupy between ten and twenty thousand square degree depending on the wavelength and depending to where you put the boundary of the Milky Way.

Notes

Summary

15m 13s



So now we have defined the target and its location using the different coordinate system. Now the second step when we conduct an observation is to have an idea of the size of the target and the field of view of the instrument that will collect the data. So we need to define what is this field of view of our camera. So here we have our camera and this is basically the size of the picture that can be taken with our camera. So usually the field of view will be defined by the size and it will define in angular terms so we using angles and we usually define it by two number 'x' and 'y' expressed either in arc seconds or in arc minute or in degree and that will give us the two dimension of the side of the field of view. Sometimes we are using a diameter of a circle if the field of view is a circle and that's usually more used for telescope or using a radio dishes. So let's give us some example to have an understanding of what it means. Let's start with the eye. Well, we have two eyes. Right. So we gonna have basically a larger extent in a horizontal direction than in a vertical direction. So our eyes field of view, our two eyes field of view it's about 210 by 150 degree square.

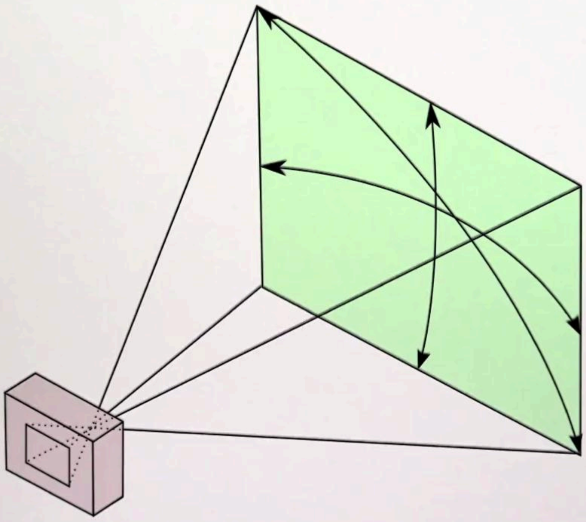
Notes

Summary

16m 58s

Size of the Target & Field of view

EPFL



Wikipedia

Field of view:

angular terms

* x, y   arcsec / arcmin / deg
* D → telescope / radio dish

Examples:

* eye : 210 x 150 deg^2
* HST / ACS : 3 x 3 $arcmin^2$ ~ 10 $arcmin^2$
* Pan-STARRS optical telescope ~ 7 sq deg
* MeerKat @ 1420 MHz ~ 1 sq deg

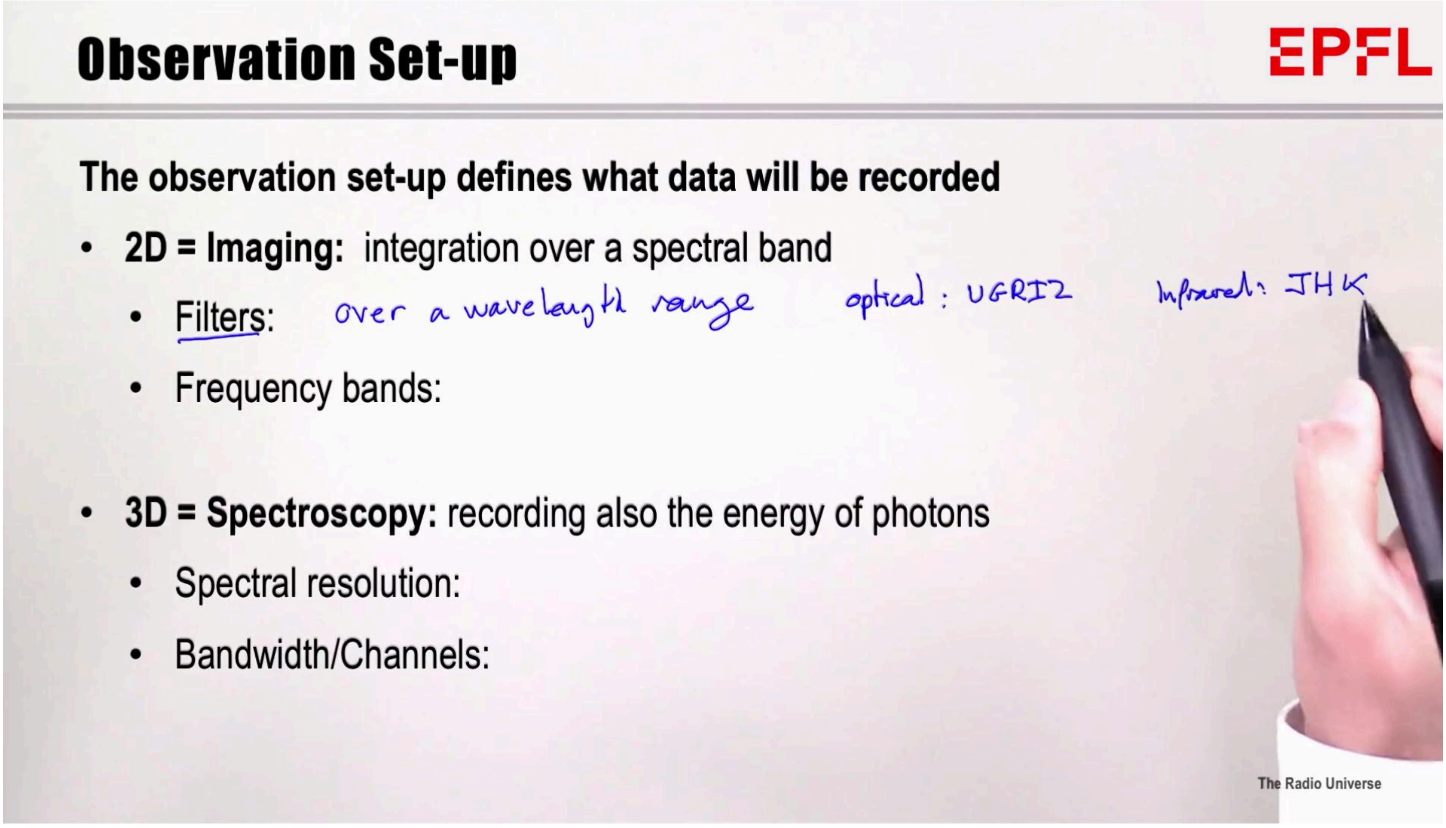
The Radio Universe

So with our eyes we're having a very large field of view. In comparison, if we take the Hubble Space Telescope with the ACS camera, it has a very small field of view. The field of view is only like three by three arc minute square which is roughly ten arc minutes square. Okay. So very very tiny. Very very small If you take off one of the largest optical camera on Earth, part of what we call the Pan-STARRS experiments, so the field of view of the Pan-STARR optical telescope is of the order of seven square degree. So quite big. Not as big as your eye but in a couple of exposure you can cover quite big surface of the sky. Now let's have a look at a radio telescope and let's take one of the newest radio telescope which is the MeerKAT telescope and this will depend the field of view will depend on the frequency at which the observation is done. And so at 1,420 megahertz, the field of view of the MeerKAT telescope is the order of one square degree. So again MeerKAT can do a quite large observation although, you know, to cover basically half of the sky 20,000 square degree would require quite a number of observations.

Notes

Summary

18m 57s

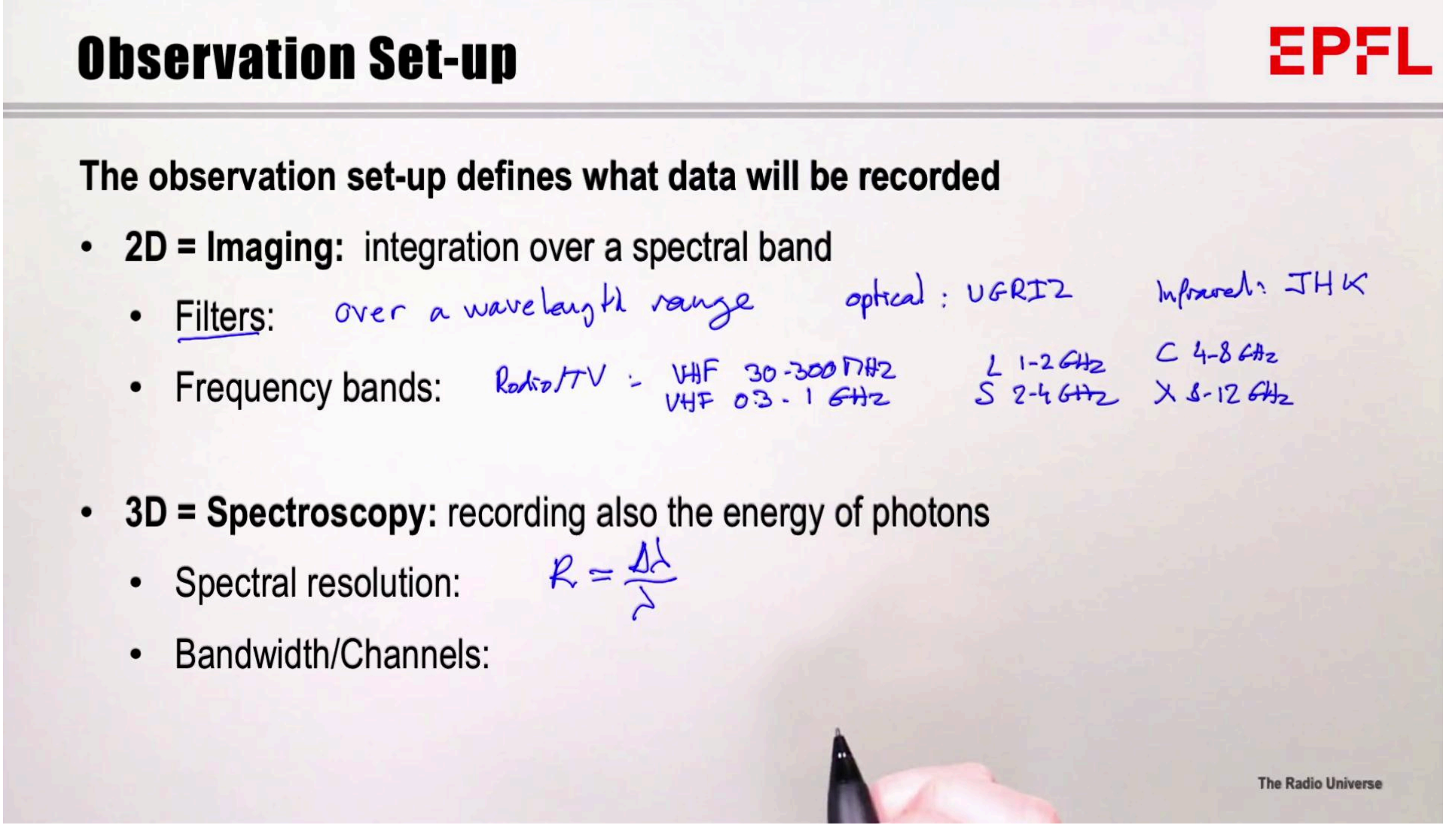


So when we conduct a survey and we want to do this observation, we need to define as a third step, you know, what is the setup of our instrument and telescope. What do we mean by the observation setup. The observation setup defines what data can be recorded by our camera or by our instrument. So either we do imaging, that is a 2D recording and we do an integration of a spectral band or we do a 3D recording which is usually done by what we call spectroscopy when not only we record the position but we also record the energy of the photons. So let's have a look at first at the imaging. And we will talk differently whether we do optical infrared observation or whether we do radio observation. So, for example, if we do optical observation what we be using is the term of filters. We will integrate over a wavelength range and those filters will have a certain wavelength range and filters might be different depending whether we observe in optical and the usual set, a very famous set of filters is the U G R I and Z that goes from ultraviolet to near-infrared. Okay. Five filter to cover the optical band or if we work in near-infrared we usually use the set of filter which is called J H and K.

Notes

Summary

20m 47s

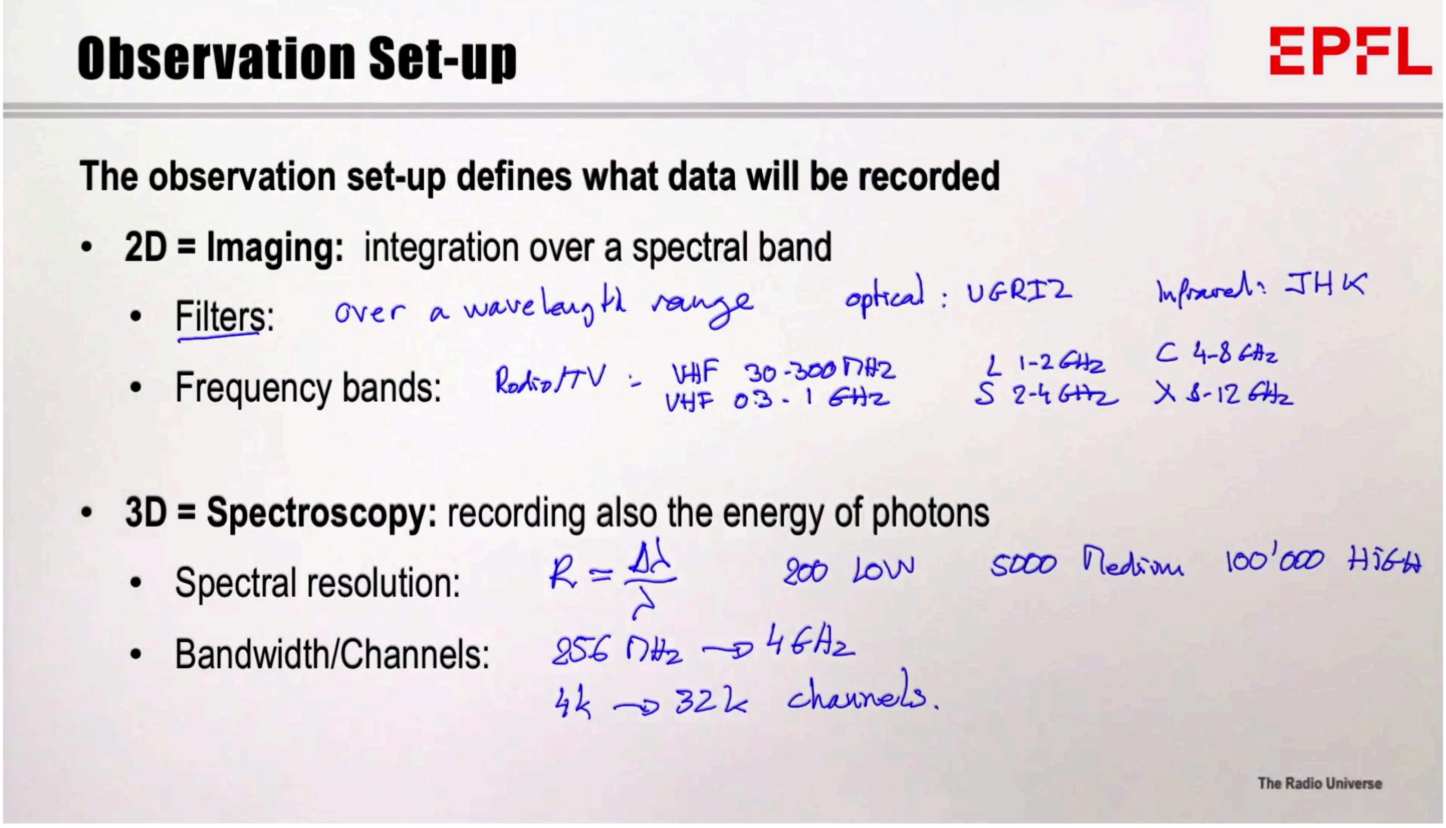


When we work in radio, we're more talking about frequency band than wavelength range and so, for example, those frequency band are quite common in communication so, for example, for radio and TV we have, you know, we've been using VHF band which go from 30 to 300 megahertz or UHF bands that go from 0.3 to one gigahertz and then there's more recent and modern frequency band for communication which have higher data rate that are quite common. We're talking about the 'L' band which is one to two gigahertz or the ‘S’ band from two to four gigahertz or also we use sometime the 'C' band from four to eight gigahertz and the 'X' band from eight to twelve gigahertz. Okay and there are other bands like the KU band or K band or KA band which go to even higher frequencies. So that's for the imaging part and what about the spectroscopic part. Here we record data not only as a function of position but as also a function of the energy of the photons. So in optical and infrared we're talking about spectral resolution. The spectral resolution is defined by 'R' which is delta lambda over lambda, lambda is the wavelength. Delta lambda, it's the element of the smallest element of the energy recording and lambda, it's the mean wavelength at which the observation is done.

Notes

Summary

22m 39s

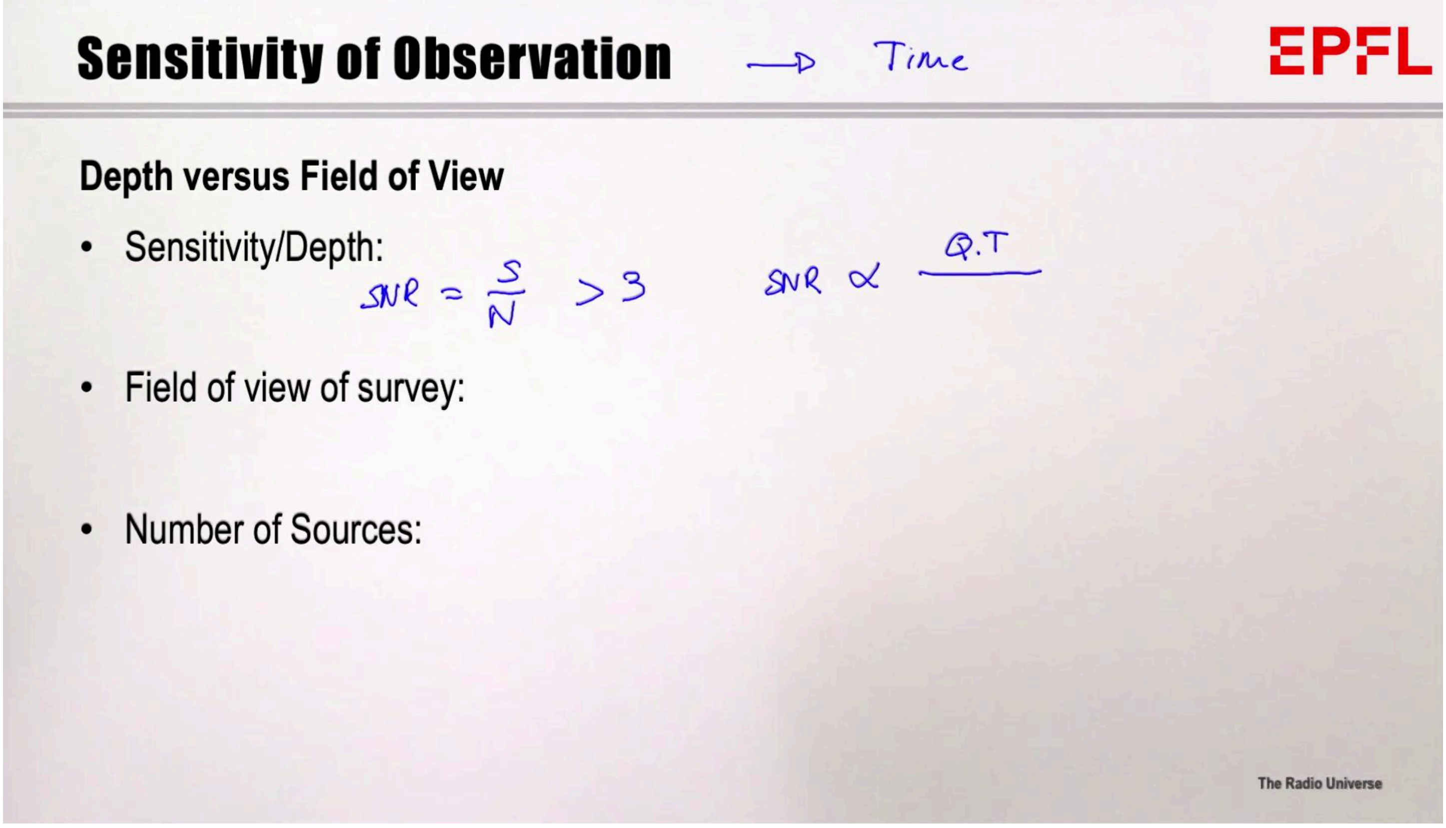


So the typical value for the resolution 'R' is 200 for low resolution or 5000 for medium resolution or things like 100,000 for high resolution high spectral resolution. When we go to radio bands then the terminology is more like, you know, what is the bandwidth and what are the number of channels available. So the bandwidth can basically goes from 250 megahertz up to maybe four gigahertz and maybe sometime eight gigahertz even and then you define the number of channel to cover this bandwidth and typically today we're using 4k channels up to 32k channels.

Notes

Summary

24m 44s

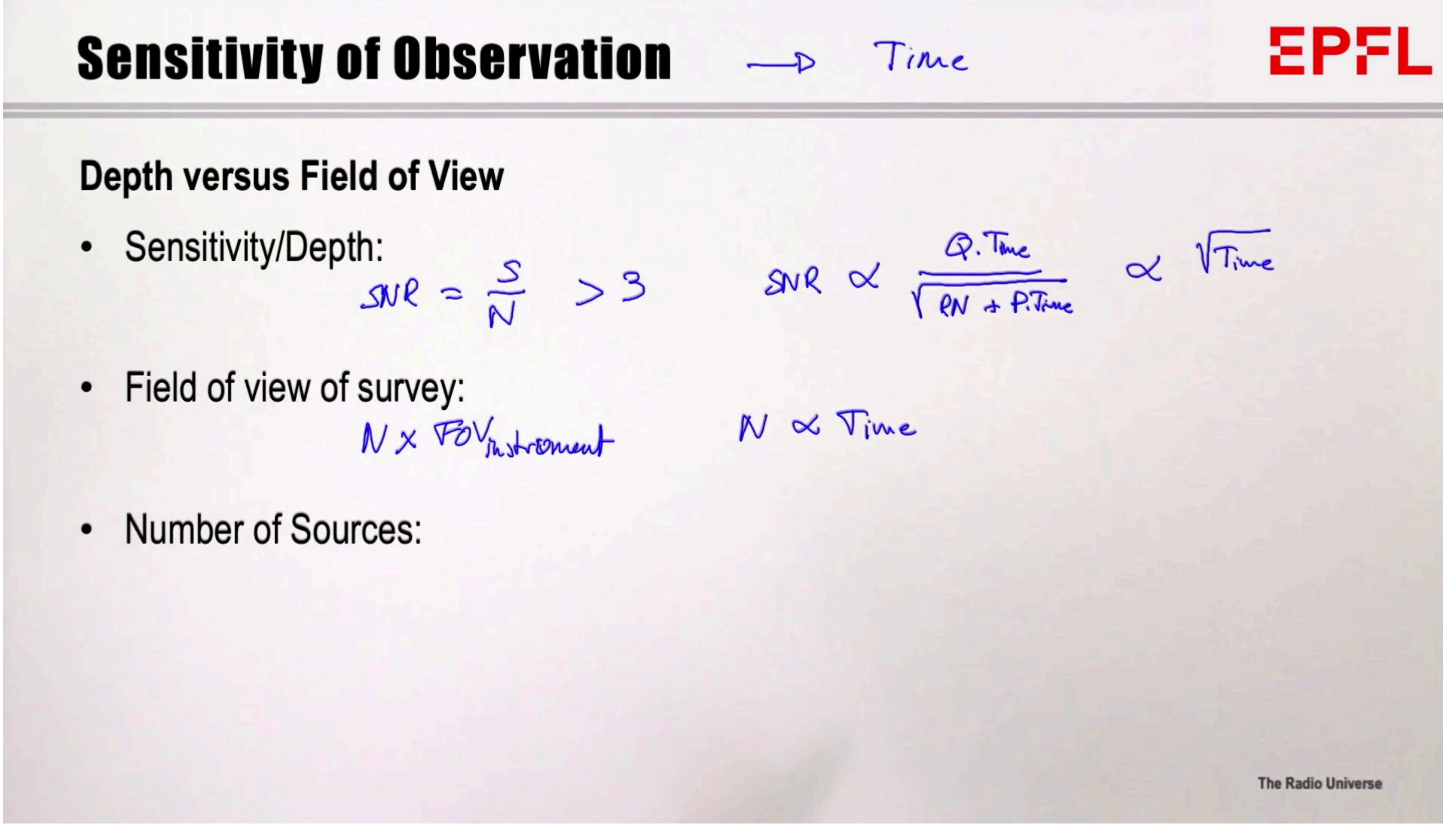


The final step in order to conduct an observation of a target is to be careful at the sensitivity of the observation. In other terms what we want to determine is the time of observation. How long we can observe our object? So that has to do with the sensitivity of our instrument and that has to do of how deep we want to do the observation. A way to define the quality of the observation is by defining what we call the signal-to-noise ratio. Okay. It's the signal divided by noise and we want, of course, to our signal a number of time higher than the noise term otherwise we will not detect our object. Okay. If our signal is comparable to noise or smaller to the noise then there will be nothing to see. So we want to have a signal-to-noise which is larger, say, than three. That would be the minimum for detection of something. But typically you can also want to have a quite high signal-to-noise ratio in order to have a very good detection. Then we will talk about signal-to-noise of 10 or 100. So the signal-to-noise is proportional to two term so the signal the signal will be proportional to the time because we just are collecting photons so the longer the observation, the longer the total number of photons.

Notes

Summary

25m 53s

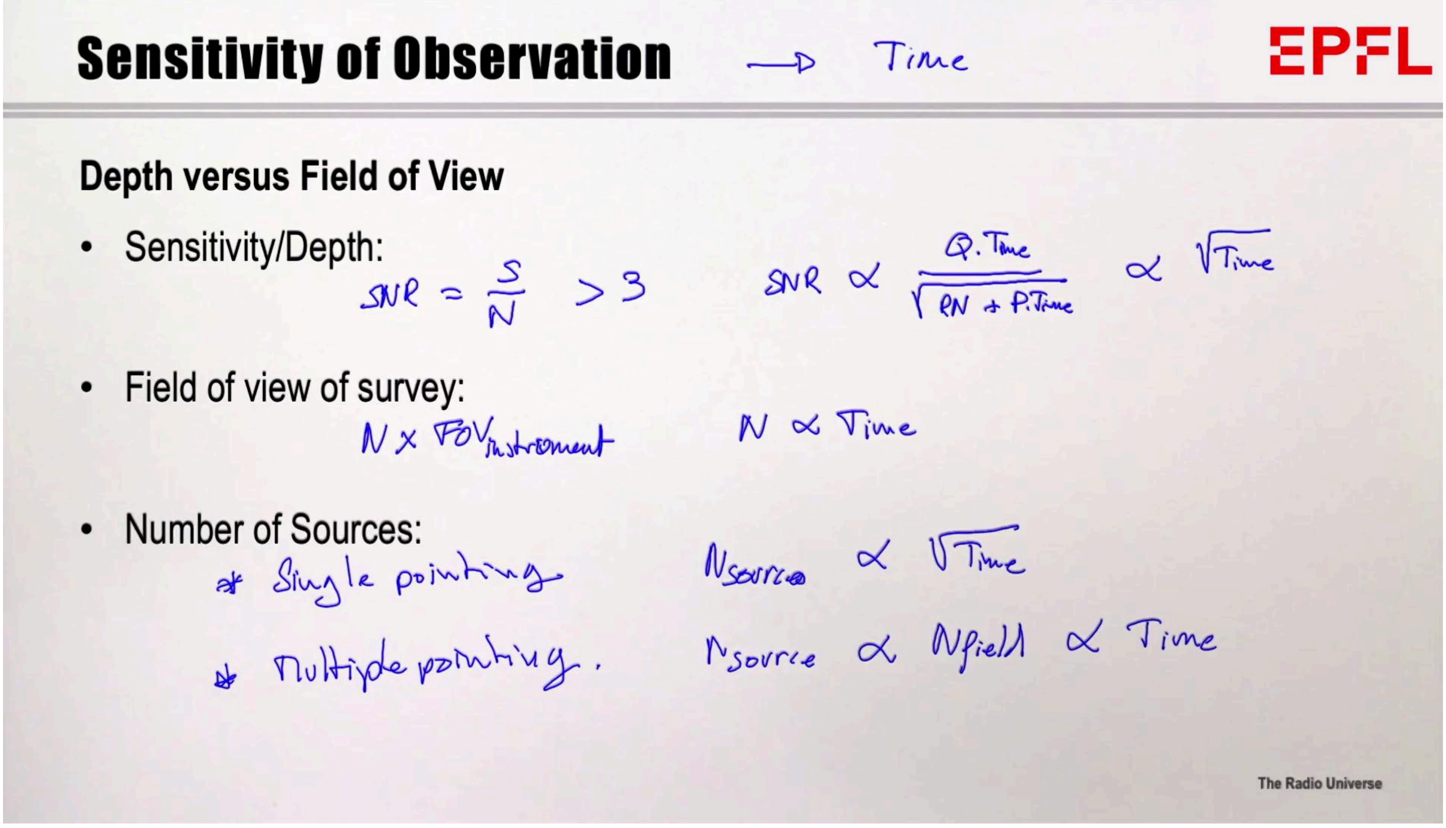


So the signal will be proportional to the time of the observation. Okay. As for the noise, there might be two component. We will submit the noise in quadratic terms and you will have usually some readout noise, something which is constant that is due to just the acquisition of your observation and then there might be a second term which will be then proportional to the time, for example, because you will collect some noise and that noise term will be proportional to time. So overall the signal-to-noise generally will go like the square root of time. So you will improve your signal-to-noise ratio as a square root of time. The other important part, it's the field of view of the survey and whether you have to have just a single observation or multiple observation to cover your target. So you might have to do 'N' times the field of view of your instrument to cover your target. Okay. And, of course, 'N' will be directly proportional to the time of observation. Okay, because if you have to collect at the given exposure time ‘N’ times the field of view then, you know, the total time will be proportional to 'N'. So what about you expect if you are doing like a survey and you want to count the number of sources?

Notes

Summary

27m 42s

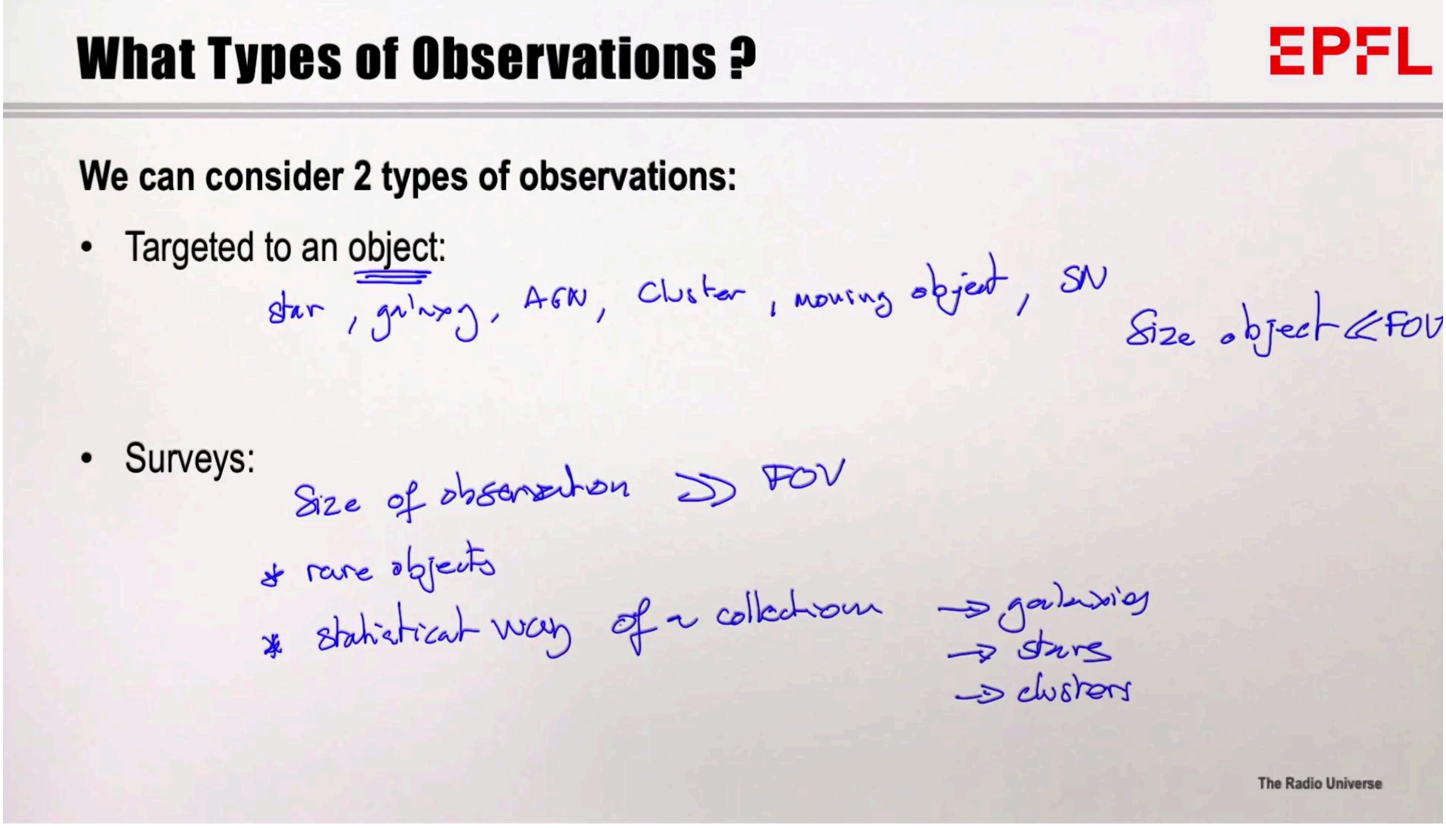


So I think there will be two cases. One is if you have a single pointing. Okay. Or the other case is if you have multiple pointing. So if you have a single pointing and you assume that the density of sources does not evolved and that in the Universe which is not evolving then the number of sources will be, you know, proportional to the square root of your integration time. Okay. This is just have to go because your this object will be more distance and the flux you will receive will be proportional to the inverse of the distance square. Now if you have a multiple pointing, okay, the number of sources will be effectively proportional to the number of pointings or number of fields of observations and then this will be just proportional to time. Okay, because the each field will be observed for a given time but then because you have 'N' field to observe then it would be basically proportional to the total time.

Notes

Summary

29m 34s

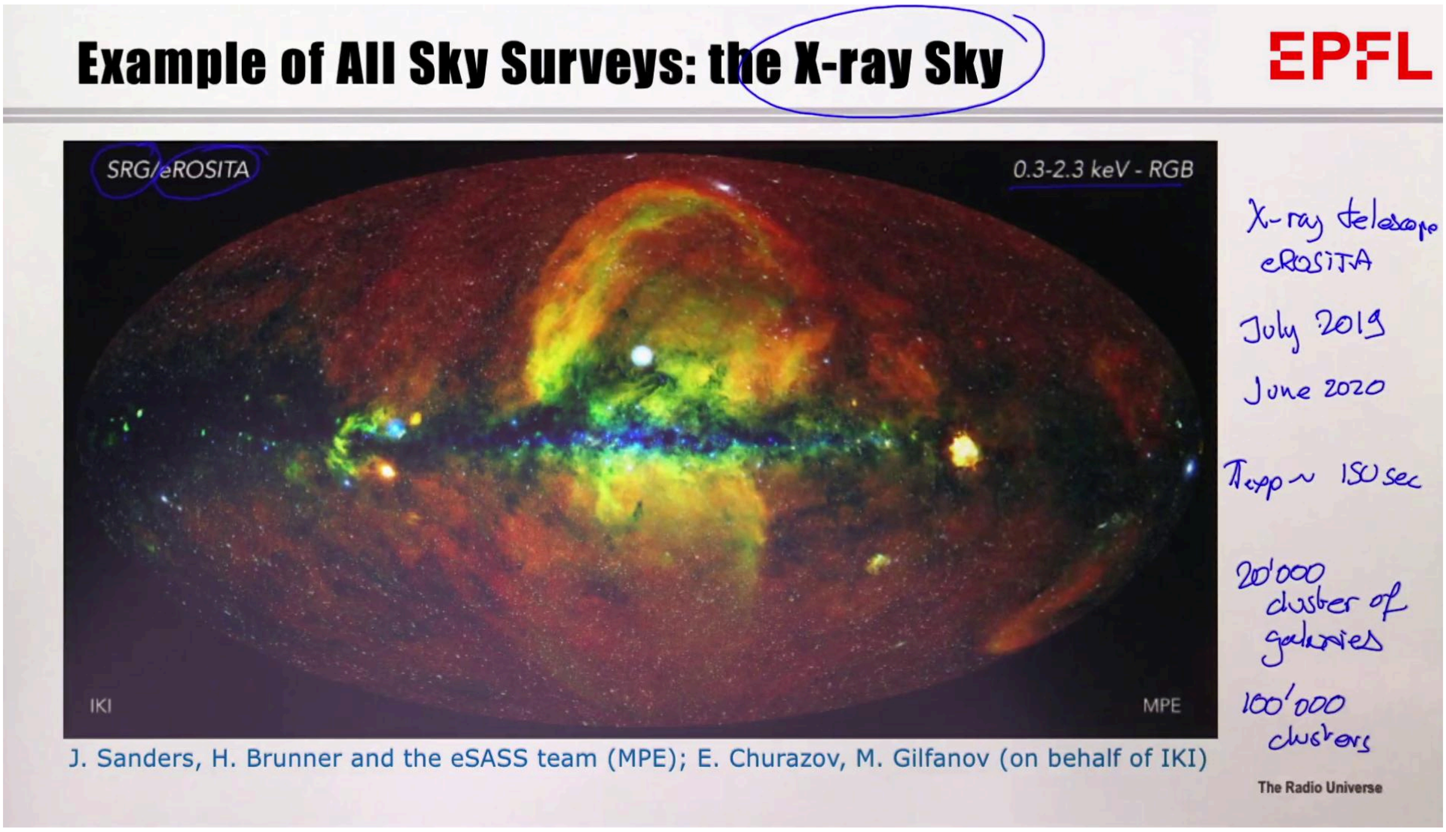


So we have defined the observational parameters but then we want to class the different type of observation we can do. Either we are doing an observation which is targeted to an object. So, for example, if your particular interest in by a star or by a galaxy or by an AGN or by a cluster or even if we're interested by a moving object or even supernova or transient, here we know very well the object. Okay. And usually the size of the object, it's much smaller than the field of view of your camera. Okay and that's the main, you know, one of the main observation. It's when it's targeted to an object. We talk of surveys when generally the size we want to observe is much bigger than the field of view of the camera. This can be done for two cases, for example. If you're looking for a rare object. Okay. And you're just trying to discover these rare objects so we want to cover a big field of view and then you will find within this big field of view these rare objects. The other purpose of doing a big survey is because you want to look in a statistical way of a collection, a large collection of objects like galaxies or stars or clusters. There you need a very big field of view. Okay and that's you'll be then doing a survey. You're not looking at particular one like a targeted observation but you will be doing a survey. You'll collect a lot of data.

Notes

Summary

30m 54s

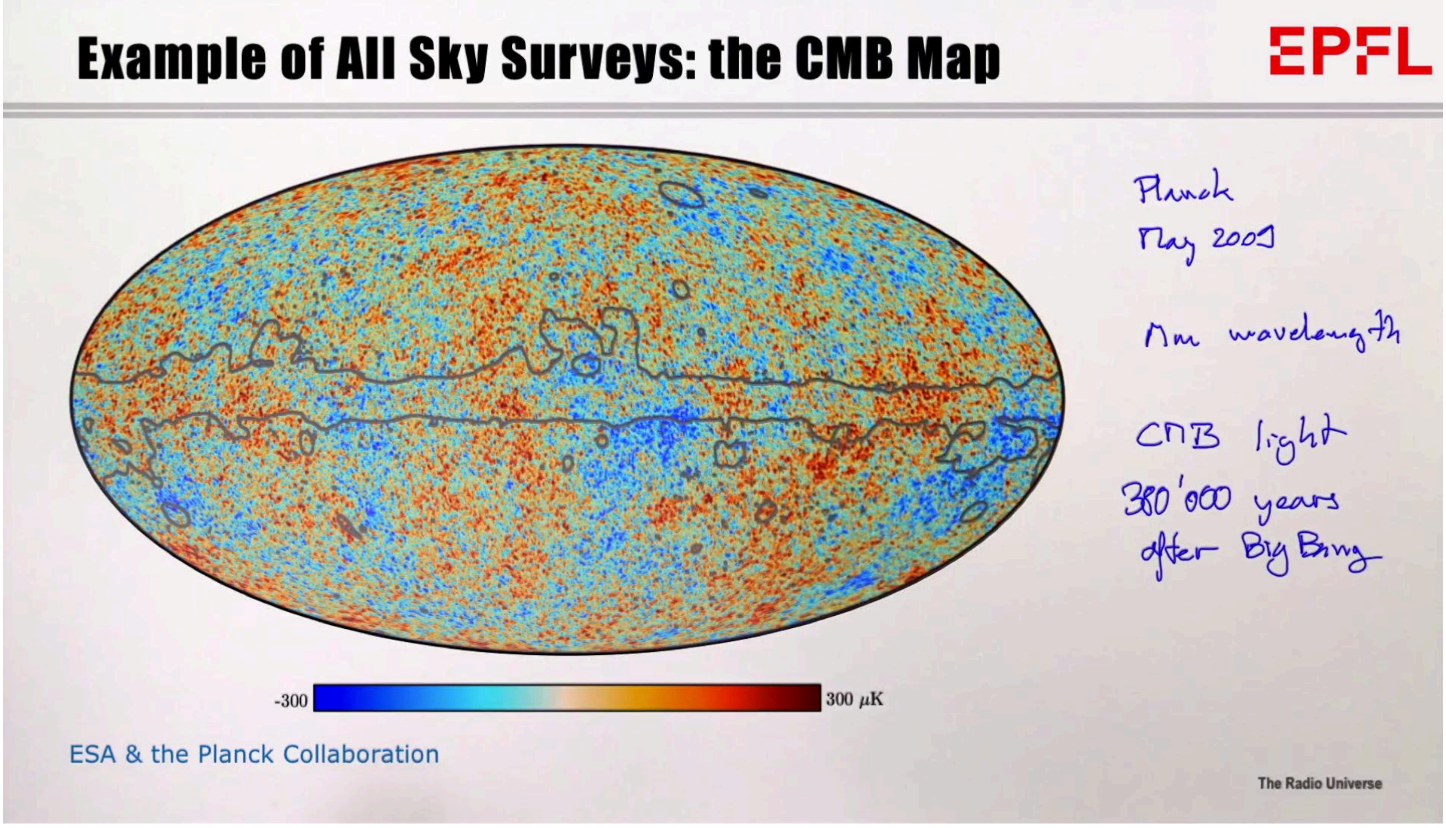


So let's have a look at some different example of surveys of the sky. Here we have a sky view in the galactic coordinates where we see the galaxy over here. This, you know, plane of the galaxy. The center of the galaxy here and this data has been recorded in the X-ray. So we're talking about X-ray sky here. Those observation were conducted recently by the eROSITA satellite using the SRG instrument. So eROSITA is an X-ray telescope. It was launched in July 2019 so quite recently and this picture was released in June 2020. It's the full sky observation at X-ray band between 0.3 and 2.3 kilo electron volt. The typical exposure time is about 150 second for each position recorded. What you see here are, you know, diffuse X-ray light but you see also a number of sources which can be either Active Galactic Nuclei or X-ray cluster. Like over here we detect the Coma Cluster and we find in this picture 20,000 cluster of galaxy. The eROSITA is gonna cover the sky many more times and so the integration time per position will increase and then the total number of cluster will also increase. At the end of the mission of the eROSITA mission we will be detecting about hundred of thousand clusters of galaxies.

Notes

Summary

32m 55s

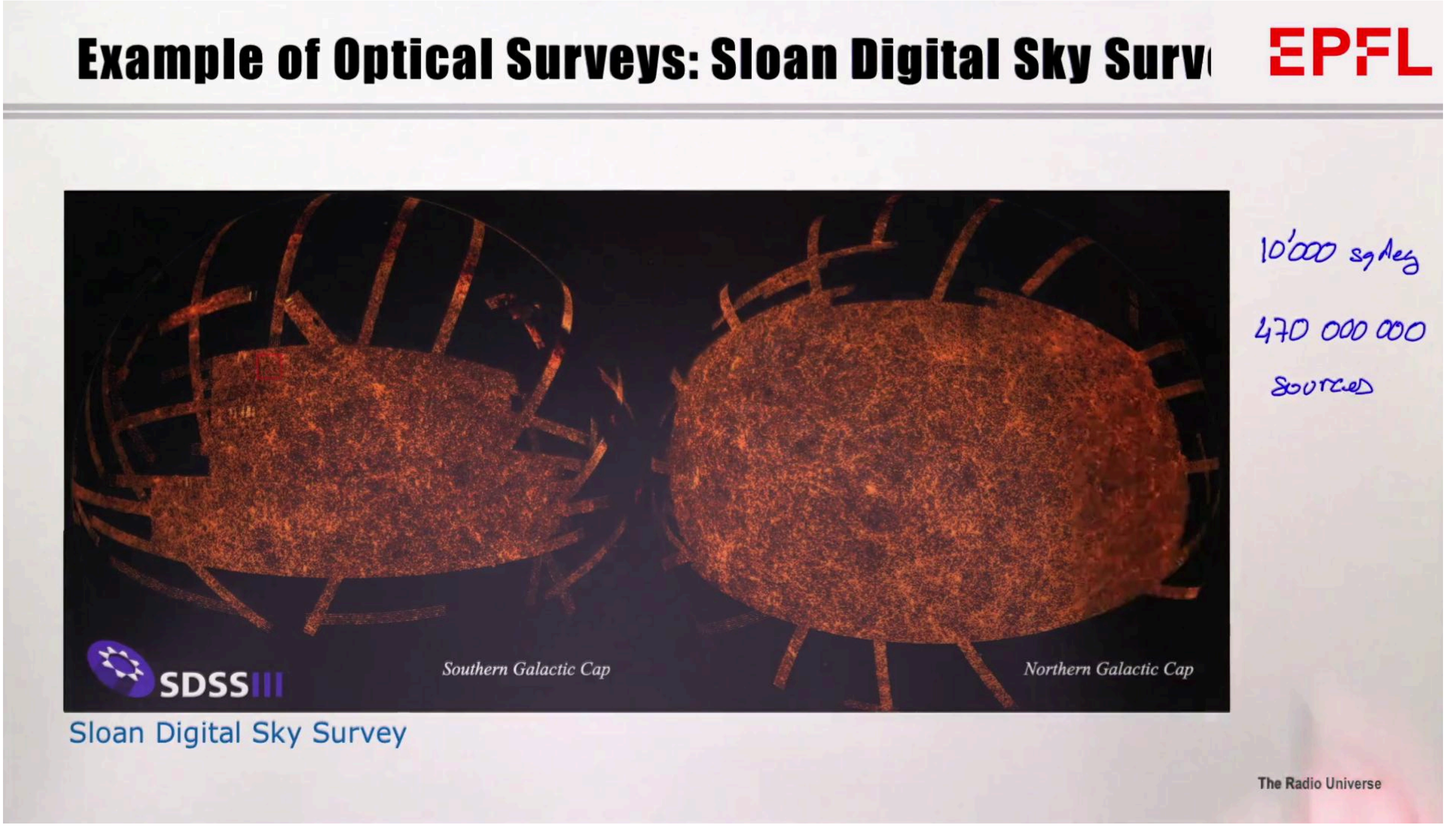


This is another example of all-sky survey the CMB map. This map was done by the Planck satellite. The Planck satellite was launched in May 2009. What we see here is the map of the sky at millimeter wavelength but more precisely, it's not exactly what is seen directly but what is corrected when we have remove a number of signal. In particular, there is a strong signal from the Milky Way and we have over printed here the location of the Milky Way but the signal is so strong from the Milky that you have to remove it in order to see the background sky and what you see effectively is what we call the Cosmic Microwave Background light and that light correspond to the Universe when it was only 300,000 years after Big Bang. So the imprint we see are fluctuation in density and in temperature of the microwave background. So that's give us a picture of the Universe when it was very young and on the density mass density of the Universe so the redder spot are the more dense and the blue region are empty region.

Notes

Summary

35m 09s

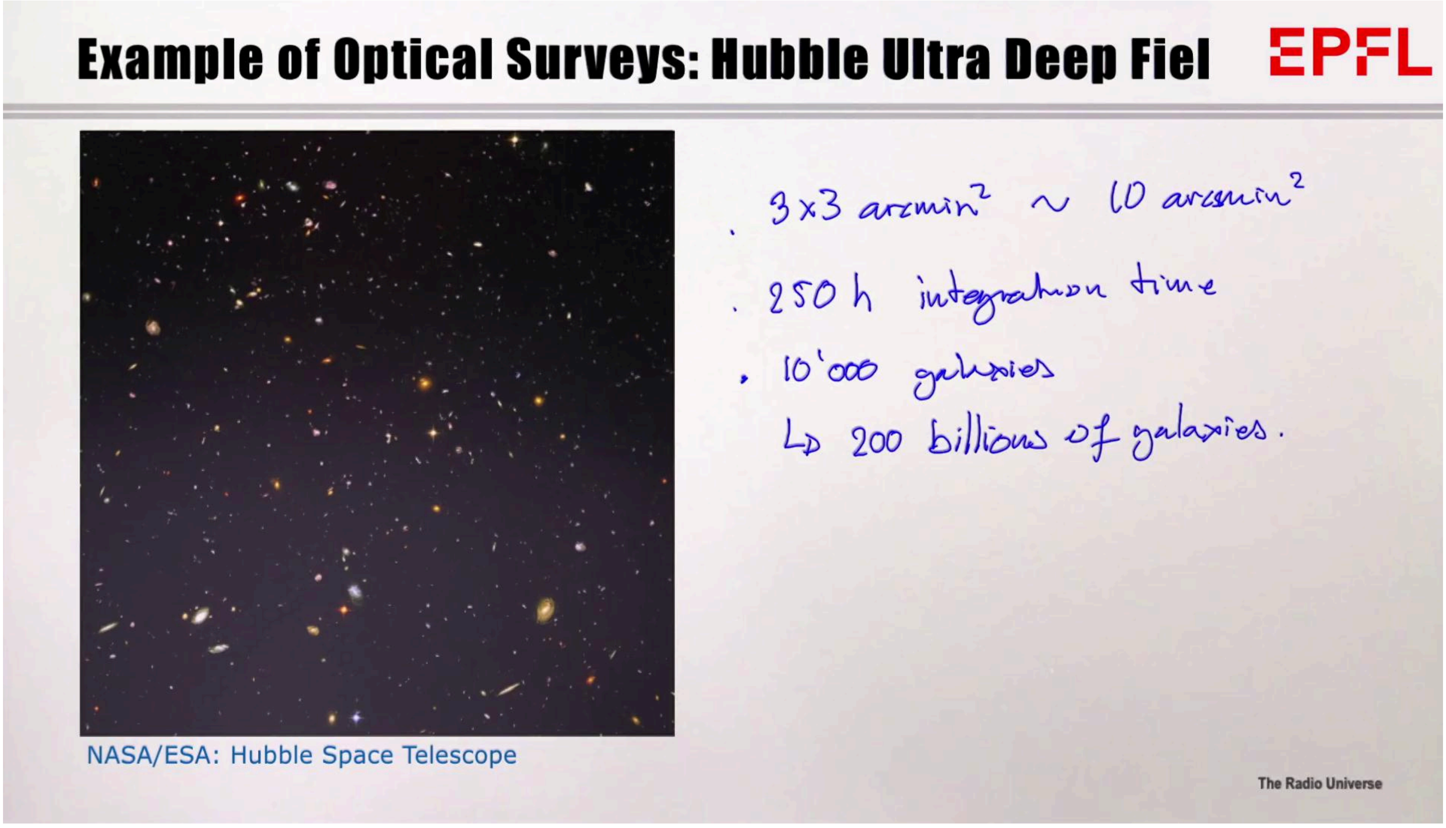


Here is another example of optical survey. The Sloan Digital Sky Survey. What we see here are two region of the sky, the Northern Galactic Cap and the Southern Galactic Cap. What is represent here is the density of galaxies and stars detected in optical imaging. So the higher the density, the higher number of galaxies seen in this map. So the total field of view of these two maps is of the order of 10,000 square degree and the total number of galaxies detected in those maps are 470 million objects.

Notes

Summary

36m 40s

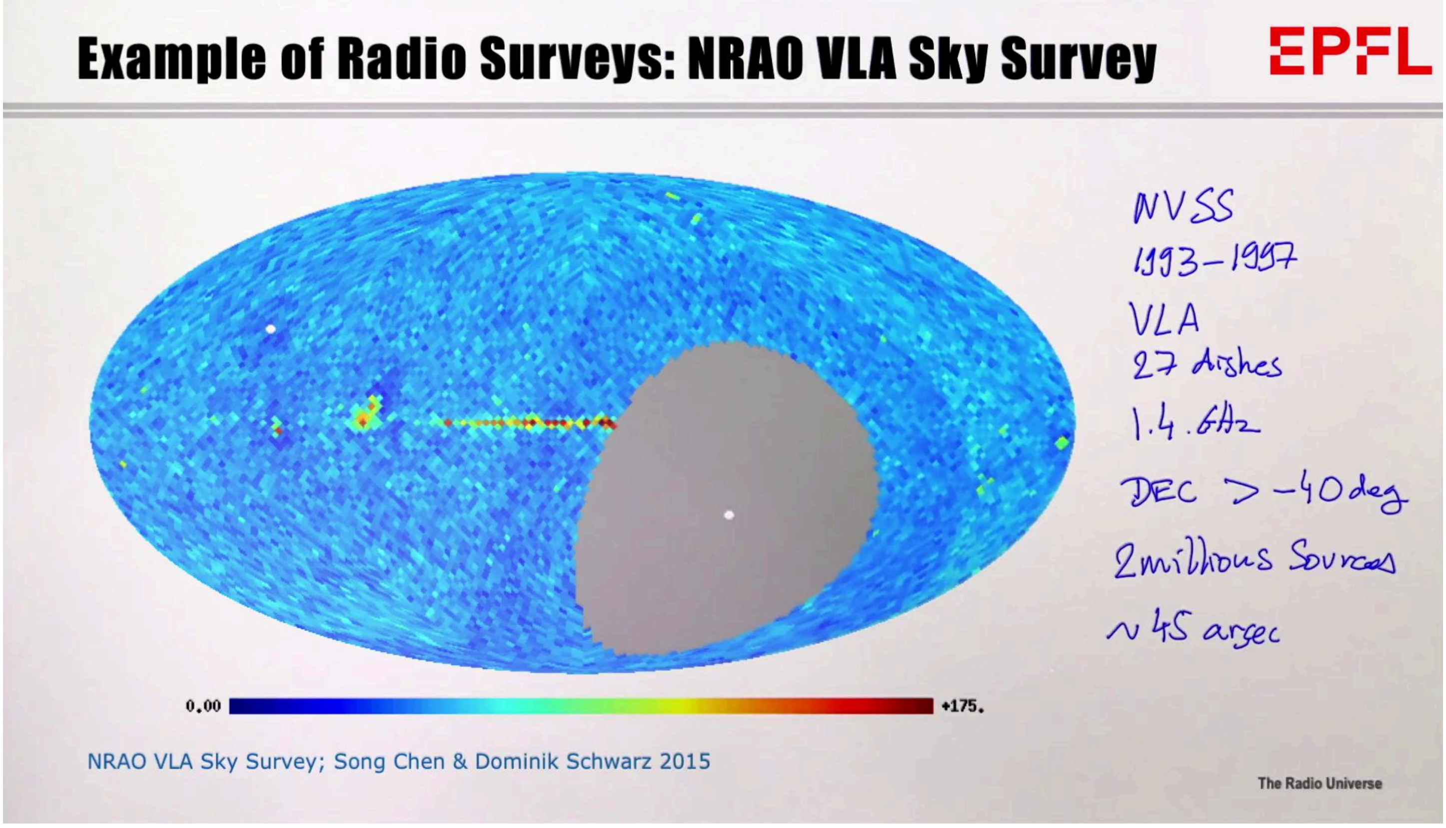


At the opposite this is another example of an optical survey. This is the Hubble Ultra Deep Field so you see it's a square. That square is about three by three arc minute so roughly ten arc minute square. And this is the deepest image taken with the Hubble space telescope. It has a total of 250 hours of integration and in this little piece of the sky we are detecting of the order of 10,000 galaxies. Okay and because this is a tiny part of the sky if you assume that this tiny part of the sky is representative of the full Universe then it would means that there is about 200 billions of galaxies in the Universe. So you see these 200 billions of galaxy are much larger than the 470 million sources detected in the Sloan Digital Sky Survey. It's because here we're going much deeper. We've seeing much fainter sources than we see in the SDSS survey.

Notes

Summary

37m 35s

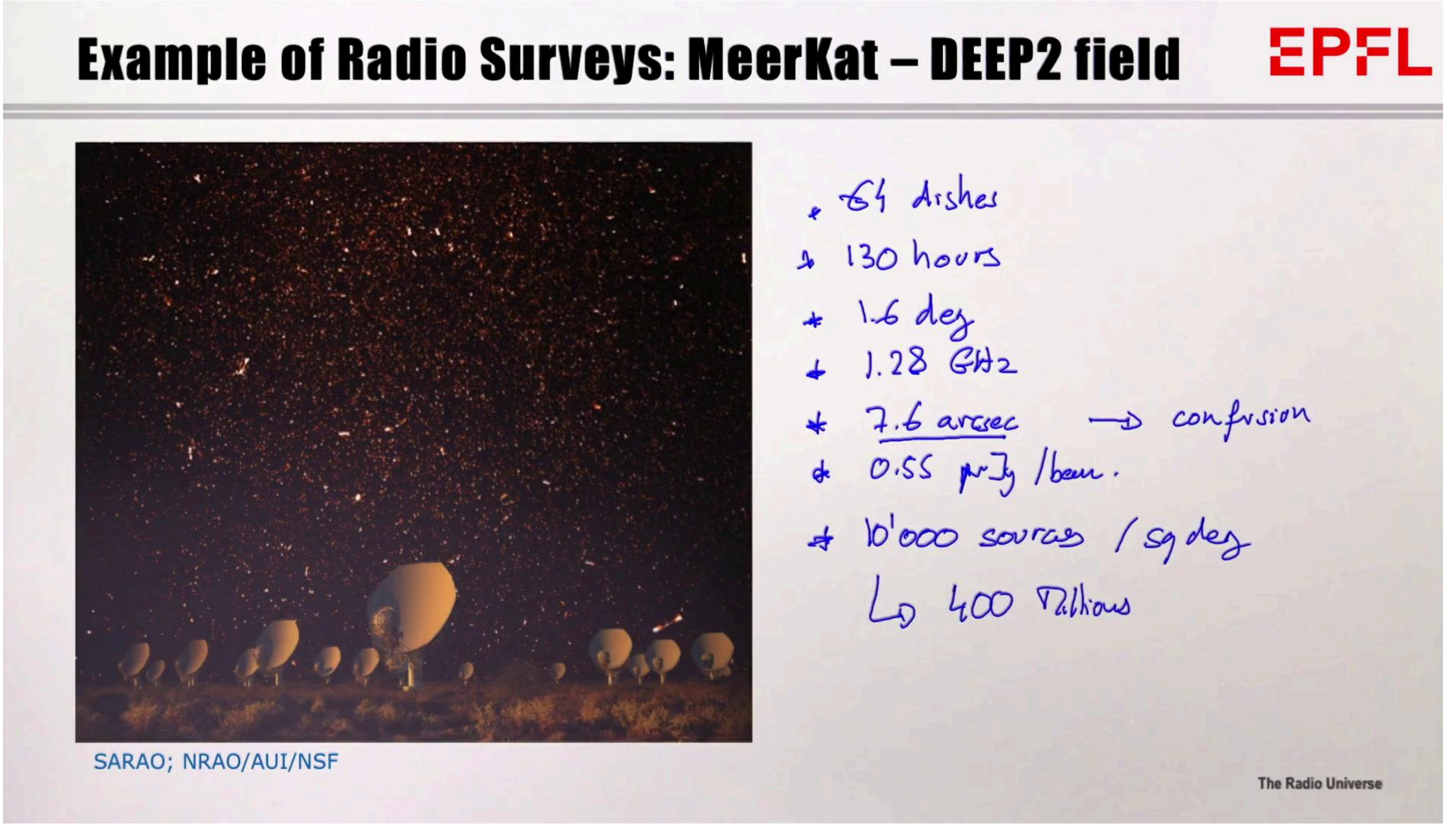


Now let's turn to some radio survey and the first example of a radio survey is the NRAO VLA Sky Survey also known as NVSS. It's a wide survey of the sky that was taken between 1993 and 1997. This was done with the VLA radio telescope which has 27 dishes and it was obtained at 1.4 gigahertz. Okay. Another aspect is that here you see there's no data. All the observation were done with declination which is larger than minus 40 degree. Okay and so that's the South pole and so you don't see this region because the telescope cannot see beyond minus 40 degrees. What you see here again it's the density of sources. Okay. And overall what was detected is two million sources. The image resolution was relatively poor. The beam size was only like 45 arc second. Okay. When a galaxy is probably smaller in size than the one arc second. So this map doesn't resolve the faintest object but just give you the signal of the strongest object.

Notes

Summary

39m 08s

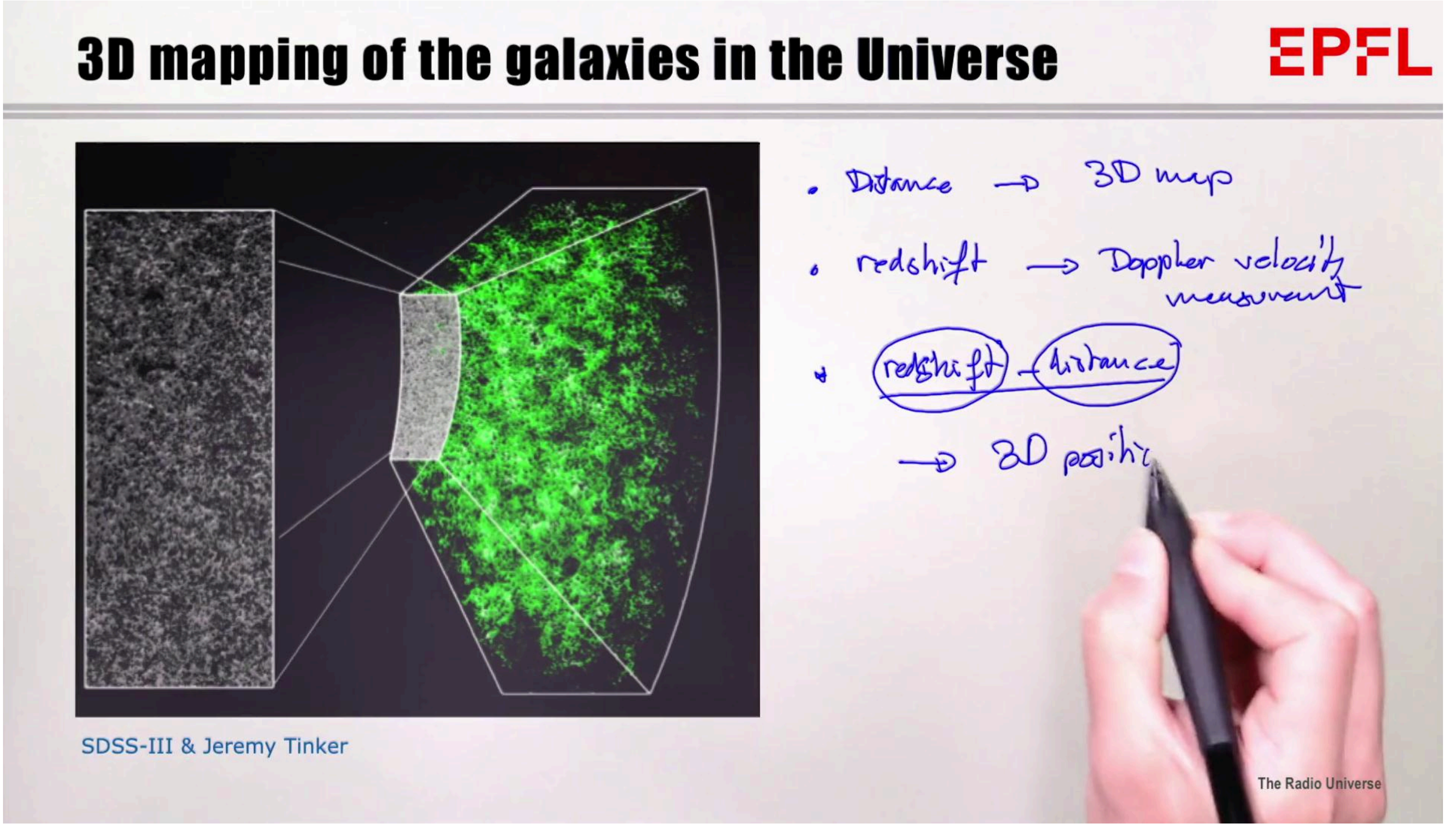


At the opposite here is an example of a radio survey using the MeerKat telescope looking at the DEEP2 field. So this observation that you see here was taken with the MeerKAT telescope. The MeerKAT has 64 dishes so much more than the VLA and that particular image last 130 hours of observations. The size of the field of view the diameter is 1.6 degree in diameter. The mean frequency recorded was 1.28 gigahertz and the image resolution is about 7.6 arc second so much better than NVSS. And for the expert the depth of the images was 0.55 micro Jansky per beam. What is recorded in this observation is about 10,000 radio sources per square degree. Okay. So if you extrapolate over the full sky then this mean about 400 million sources over the full sky. Okay. So 400 million is less than these 200 billions optical sources but again here with a image resolution of 7.6 arc second, certainly there will be some confusion of sources that are faint and are very small so you don't detect them so you will need to have a different setup of your telescope to be able to have a better resolution and see more sources.

Notes

Summary

40m 51s



To finish up, I would like to say something about the 3D mapping of the galaxies in the Universe. So when you take an image of the sky we have it projected on the sky. So we don't know whether that galaxy or that galaxy are close to us or very distant from us. Okay. So what you want to do is have a 3D picture so you want to tell be able to tell that that galaxy is close to us or whether it's far from us. So through that you need to compute distance, distance in the third dimension and then you can do a 3D map. So to measure a distance the proxy to measure the distance is to measure the redshift. The redshift is just measured by looking at, for example, the frequency of a particular line over the wavelength of a particular line. So the redshift measurement is just a Doppler velocity measurement. Then once we have the redshift we can use the redshift distance relation. This redshift-distance relation is given by the fact that the Universe is in expansion and, of course, it will depend on the properties of our Universe but now as we measure the redshift through spectroscopy we can deduce the distance and then we have the 3D position of the galaxy in the sky.

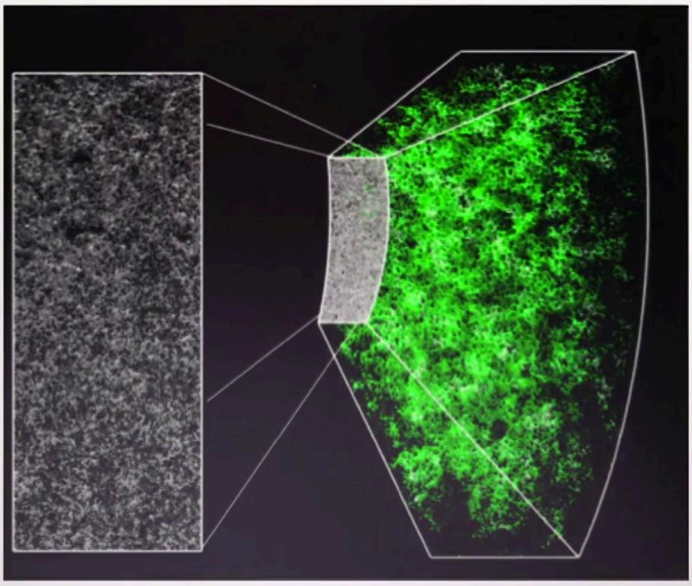
Notes

Summary

43m 03s

3D mapping of the galaxies in the Universe

EPFL



SDSS-III & Jeremy Tinker

- Distance → 3D map
- redshift → Doppler velocity measurement
- redshift – distance

→ 3D positions

TODAY : • optical

FUTURE : HI line radio

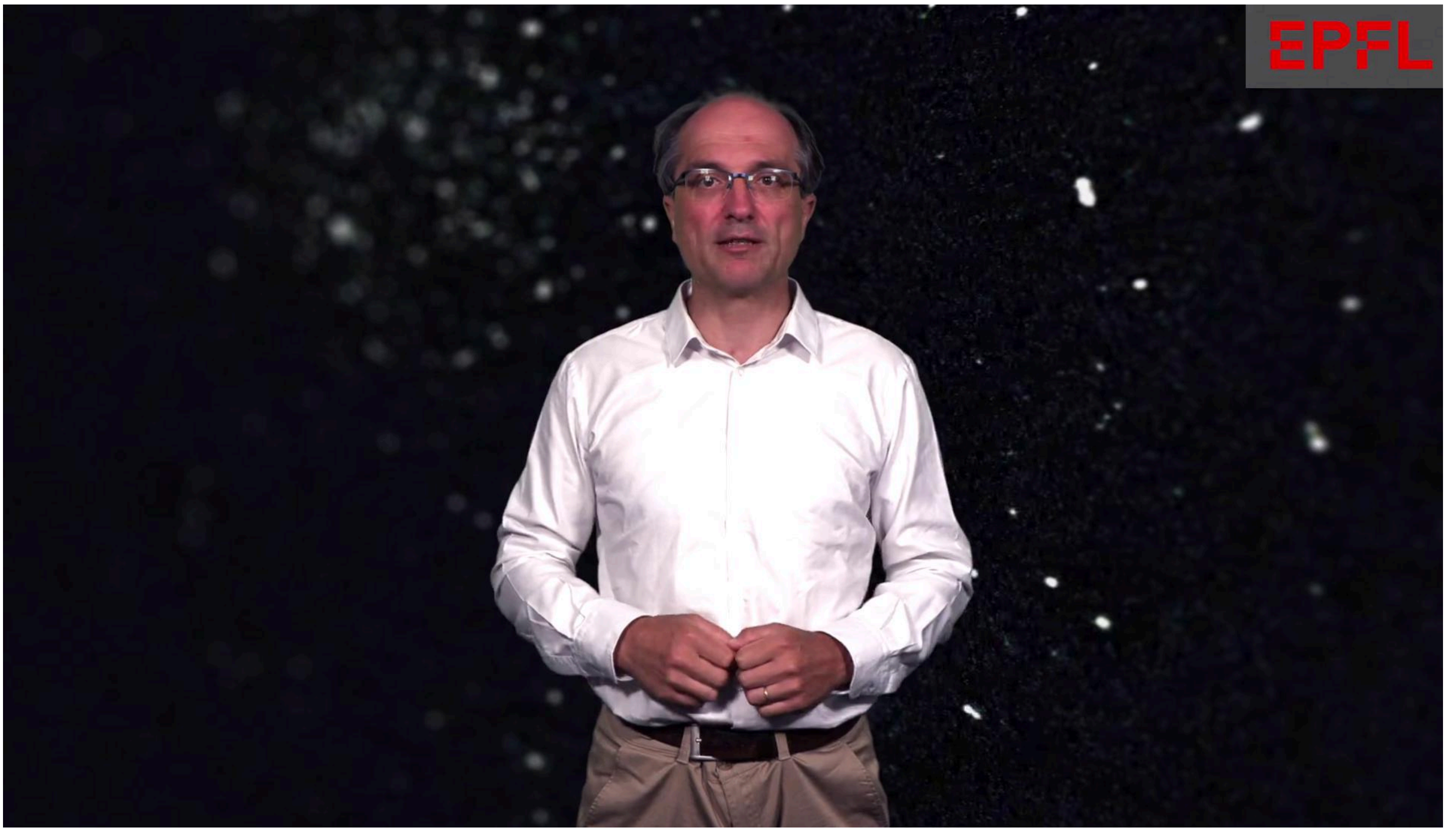
The Radio Universe

So today these galaxy redshift measurement are done with optical data. In the future tomorrow the redshift measurement will be done using the H1 line using the radio data. So today we can construct the 3D map of the galaxy in the Universe with optical data but in the future we will be much better in doing that with radio data using the H1 line.

Notes

Summary

44m 42s



We have seen some of the basic concept of conducting a sky survey. We also explored a few important sky surveys conducted at different wavelengths. These surveys inform us on the number of stars, galaxies and cluster in the Universe as well as the evolution of the Universe since the Big Bang. By using spectroscopic information we can also deduce the third dimension and produce 3D maps of the Universe. In short, sky surveys are gold mine to explore our gigantic Universe. Today optical survey are already well advance but the next frontiers is radio surveys. So let's keep exploring.

Notes

Summary

45m 23s