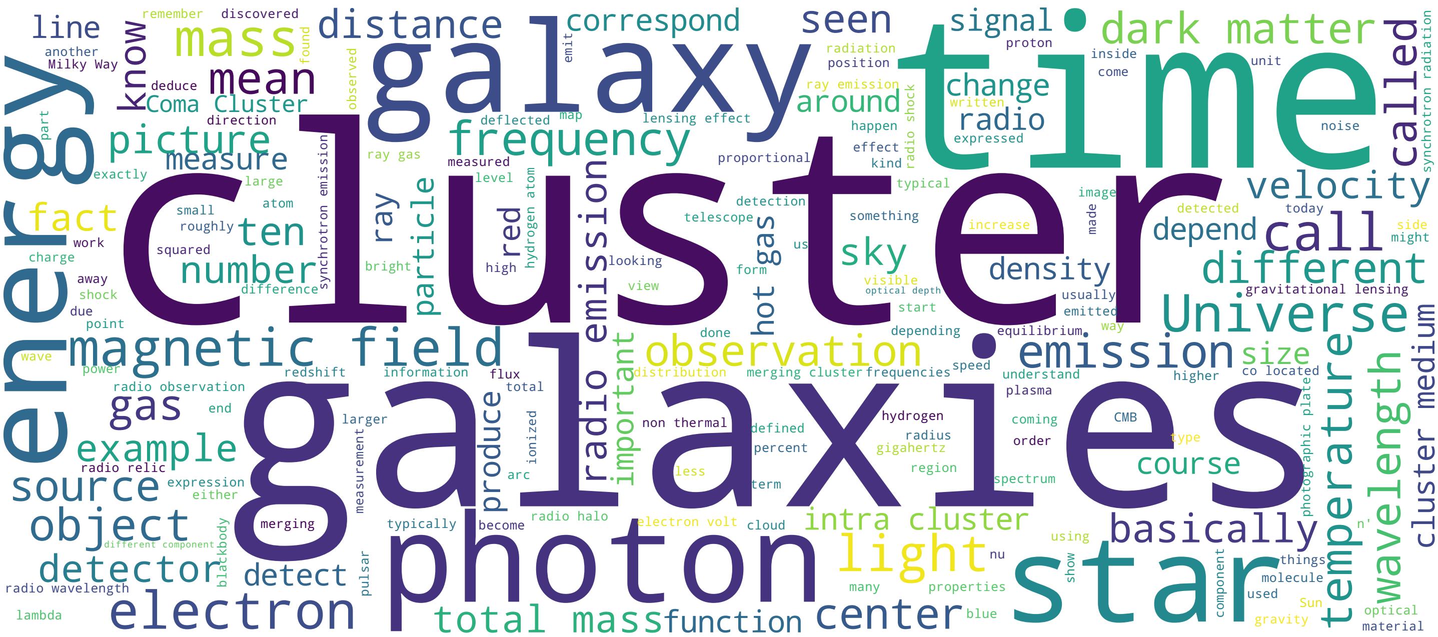
EPFL

Clusters of Galaxies

The Universe At Radio Wavelengths

Jean-Paul Kneib



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Video

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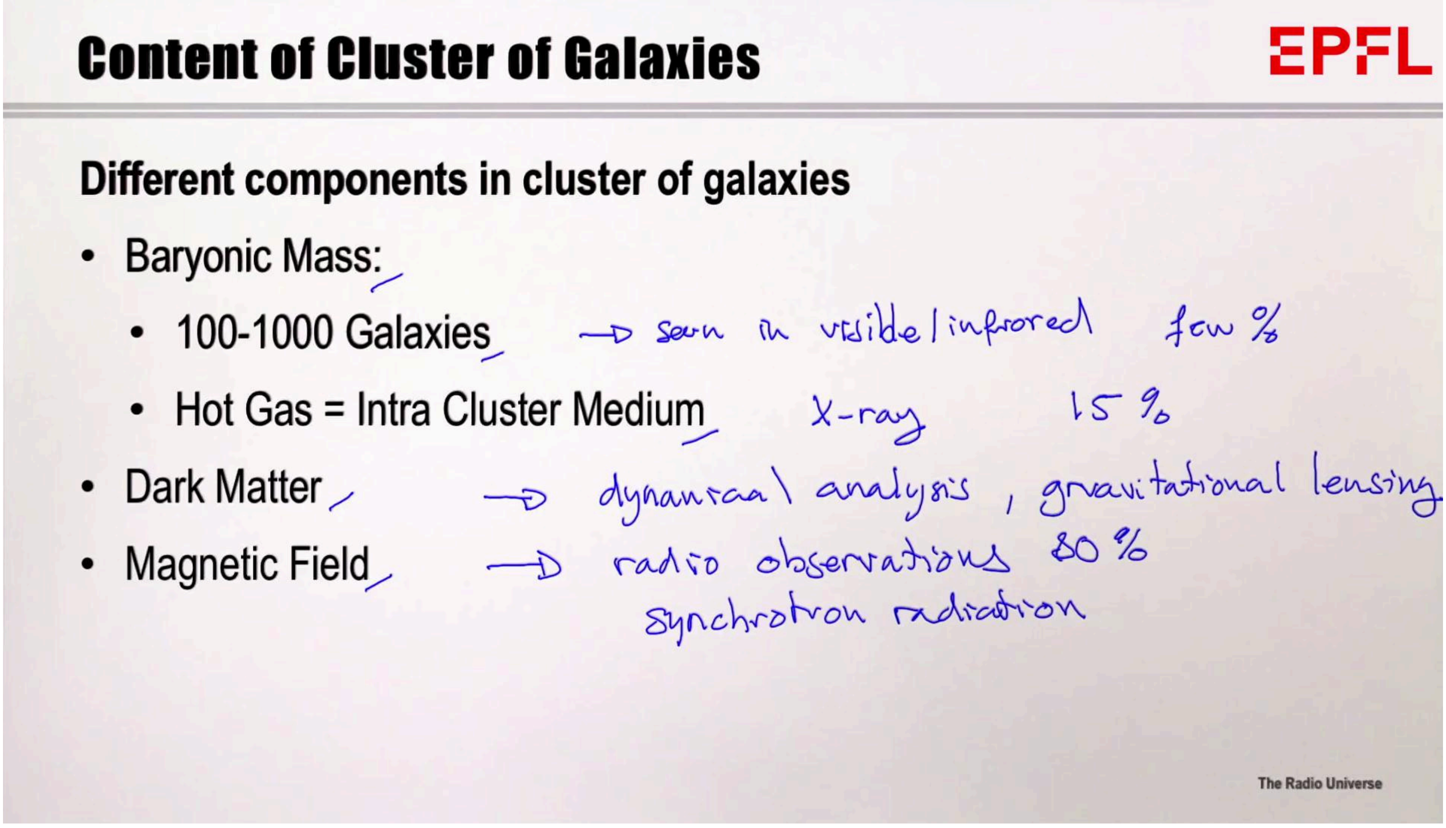
Today we will explore in more detail cluster of galaxies. Cluster of galaxies are the most massive structure in the Universe. They can be as massive as one quadrillion of solar masses. They are located at the crossing of filamentary structure of the cosmic web. Cluster of galaxies were first found through high concentration of galaxies seen the photographic plates covering the extragalactic sky. But clusters are more than just a collection of galaxies. They contain the hot gas also called the intra-cluster medium made of an ionized plasma, of hydrogen, helium and traces of heavier atoms. This hot gas is detected with X-ray telescopes. But the dominant matter contribution of the clusters is dark matter which can be revealed by strong and weak gravitational lensing effects. Finally, another more elusive component is magnetic field. This magnetic field is witnessed through the detection of synchrotron radiation at radio wavelength. Depending of the clusters we can detect radio halos, radio relics, radio shocks and mini-halos. In general, radio halos, relics and shocks are common in cluster mergers as mini-halos are found in relaxed clusters. So let's dive into clusters of galaxies.

Notes

Summary

0m 05s

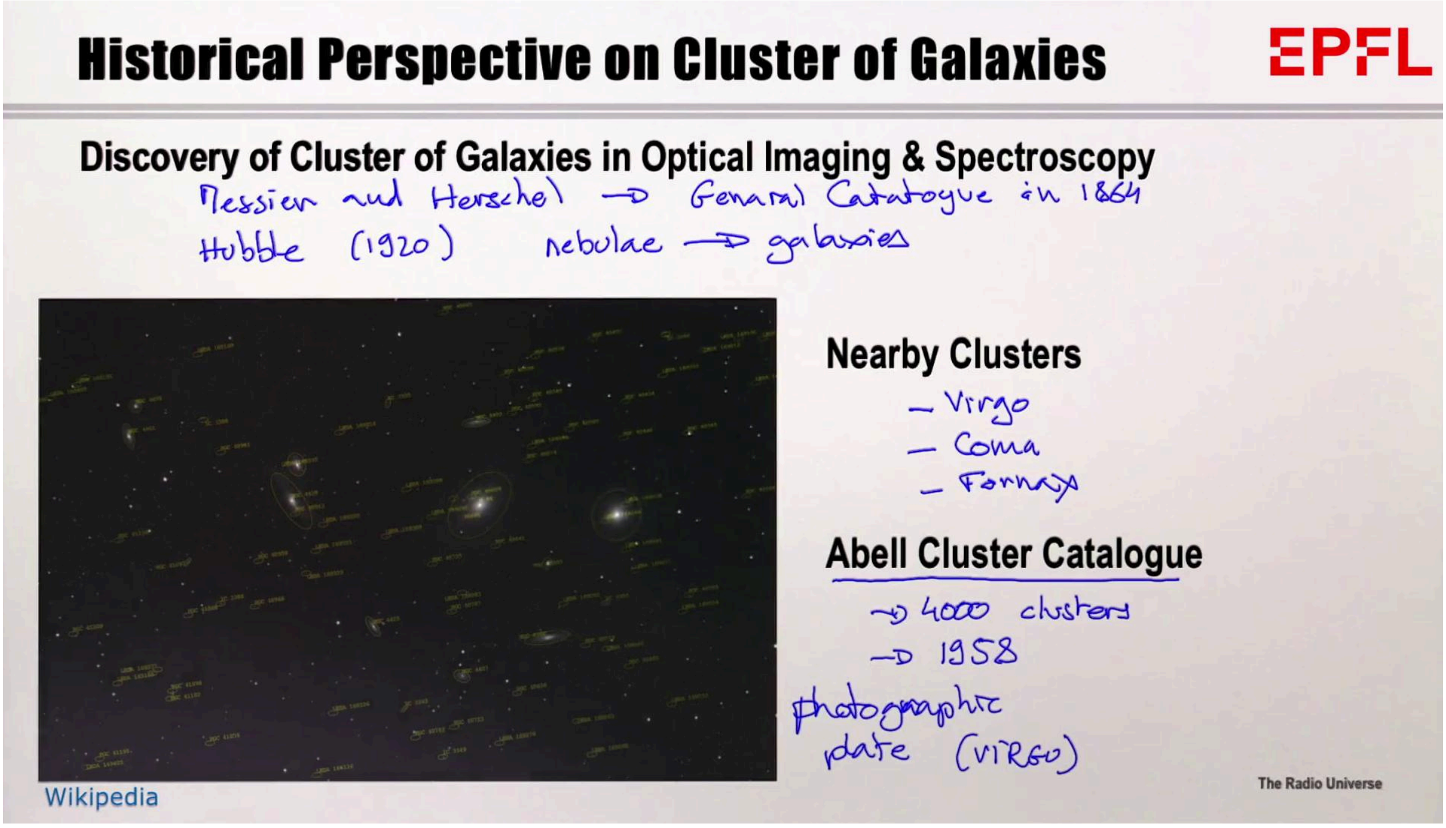


In cluster of galaxy we have different components. We have baryonic mass, dark matter and magnetic field. So let's go and look at these different components. For the baryonic mass we have 100 to 1000 galaxies. Those are seen in visible and infrared wavelengths and they correspond to about a few percent of the total mass. Then we have what we call the hot gas or also called the intra-cluster medium which is a plasma of charged particle like electrons and protons but also heavier ions and those are detected in X-ray. And these are corresponding to about 15 percent of the total mass of the cluster. As for the dark matter we can detect that through dynamical analysis or through the effect of gravitational lensing and the total amount of dark matter represent about 80 percent of the total mass of the cluster. As for the magnetic field we can indirectly detect it through radio observation. This radio emission is due to synchrotron radiation but how did we know about these numbers?

Notes

Summary

1m 49s

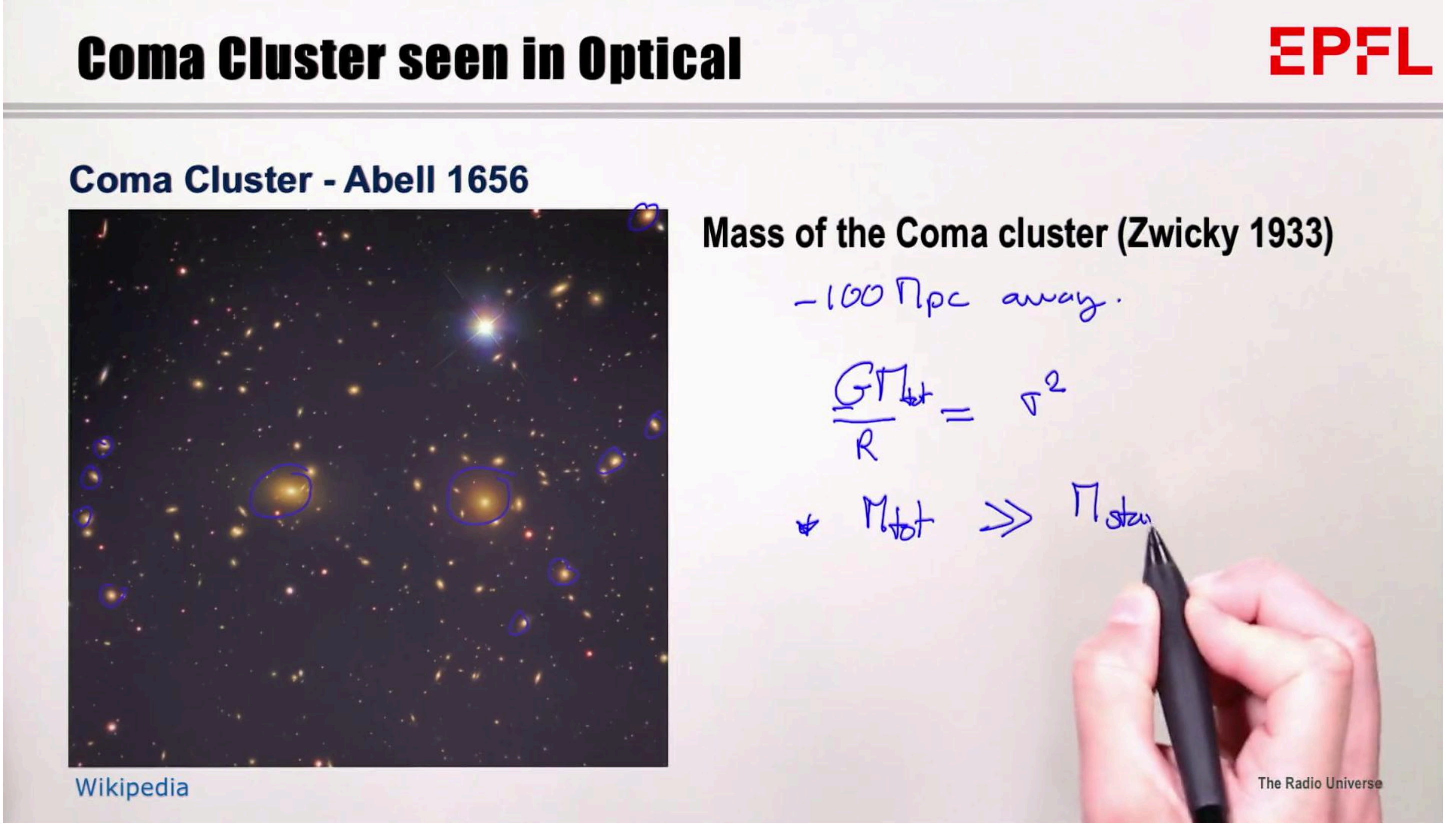


So let's do a little bit of history first. So cluster of galaxies were discovered through concentration of galaxy in the sky. First, remember that Messier and Herschel made what we call the general catalogue in 1864. In this catalogue we had many nebulae. Some of them were clustered were grouped together and later on, Edwin Hubble in about 1920 demonstrated that this nebulae were, in fact, distant galaxies. So nebulae in groups were distant galaxies and those distant galaxy grouped together form what we call clusters. So we have different nearby clusters. We have like the Virgo Cluster, we have the Coma Cluster, and we have the Fornax Cluster. Here is an example of a photographic plate where we record the position of the galaxies and what you see in this particular pictures is the different galaxies that are part of the Virgo Cluster. But we have cluster all over the Universe and the first catalogue of the cluster the first comprehensive catalogue of cluster is the one of Abell. Abell was a scientist and he looked at photographic plate and he found in this photographic plate about 4,000 clusters and this was published in 1958 and there has been revision of this catalogue later on.

Notes

Summary

3m 31s



What we have here is a picture of the Coma Cluster seen at optical wavelength. What you can notice is like we have two big galaxies at the central part of the cluster and then we have many smaller galaxies that can be identified because they have very similar color than the two galaxy at the center. The Coma Cluster has been studied in great detail by Zwicky in 1933. Coma Cluster is about 100 mega parsec away from us. So Zwicky using a spectroscopic instrument measured the distance and the velocities of those galaxies in clusters and then made an assumption that there was equilibrium of those galaxy in the cluster. So we can write the equilibrium between the velocity and the gravity and the equation reads this way. We can write that 'GM' over the radius is equal to the velocity dispersion square sigma. So again ‘G’ is the gravity constant, 'M' is, in fact, the total mass of the cluster and ‘R’ is basically the size the radius of the cluster. And so we have a balance between the kinematics and the potential of the cluster and sigma square is the velocity dispersion of the galaxies in the clusters as seen in this picture. What Zwicky found is that the total mass 'M-tot' was much larger by a factor 10 to 100 than the mass of the stars.

Notes

Summary

5m 36s

Coma Cluster seen in Optical

EPFL

Coma Cluster - Abell 1656

Wikipedia

Mass of the Coma cluster (Zwicky 1933)

~100 Mpc away.

$$\frac{GM_{tot}}{R} = \sigma^2$$

* $M_{tot} \gg M_{stars}$
* extra mass
  ↳ dark mass
  → DARK MATTER

The Radio Universe

That is the mass of all galaxies as measured by the light. So this means that we have some extra mass. So, of course, we know there's some gas today but those first observations were, in fact, pointing to the existence of the dark mass that we call later dark matter.

Notes

Summary

8m 08s

Historical Perspective on Cluster of Galaxies

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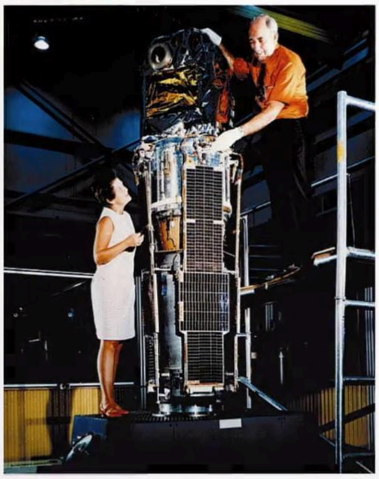
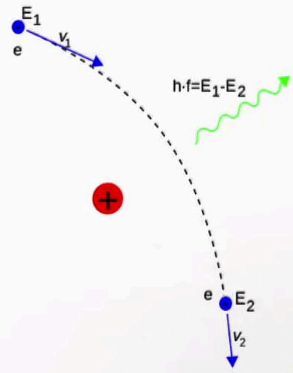
Cluster of galaxies are bright in X-Ray

Uhuru



Wikipedia



Uhuru was the first X-ray satellites (launched in 1970) it detected the Coma cluster

Intra Cluster Medium

Hot gas

$n = 10^{-3}$ atom / cm^3

$L_X = 10^{43} - 10^{45}$ erg/s

e^- passing near an ion

deflected

decellerated

γ braking radiation

Bremsstrahlung

energy → X-ray

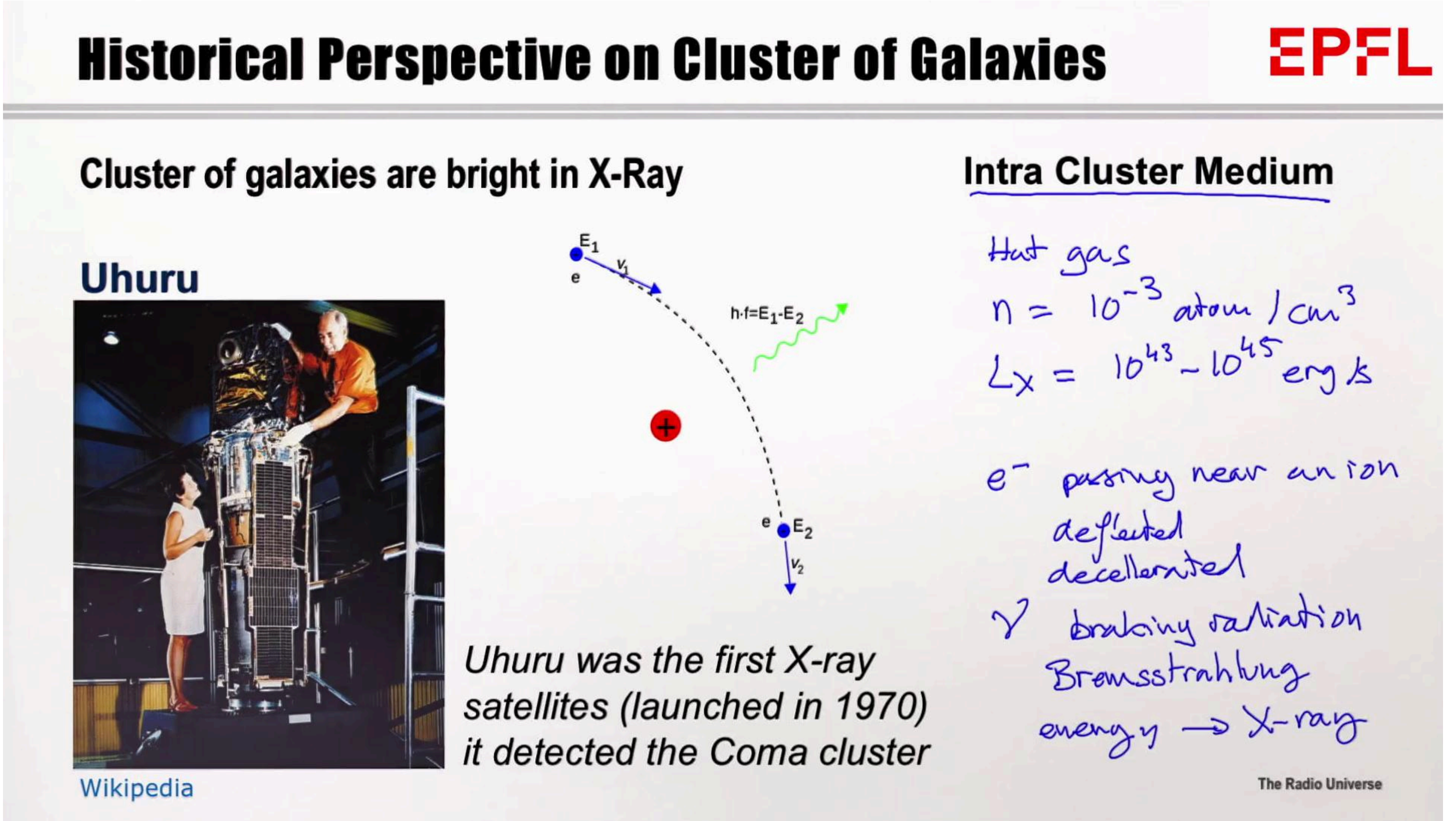
The Radio Universe

Cluster are not only visible at optical wavelength, they also shines at X-ray wavelength. What is the component that is bright in X-rays is what we call the intra-cluster medium. The intra-cluster medium correspond to hot gas in between galaxies. The typical densities of this gas 'n' is about ten to the minus three atom per centimeter cube. Okay. That's the density of the gas and the total luminosity emitted by the intra-cluster medium the total X-ray luminosity is about ten to the 43 to ten to the 45 per second. Okay. That will depend on the size of cluster of course. So what is producing this X-ray emission? As I say, the intra-cluster medium is what we call the hot gas. It's a plasma. So we have electrons and we have protons and the electrons are moving within this plasma and if an electron goes nearby a proton then it will be deflected and decelerated. So the electron passing near an ion will be deflected and decelerated through this effect. There will be a loss of energy in terms of a photon so we will produce a photon and because the electron is decelerated we call this the breaking radiation which was named by a scientist first a German scientist which we call the Bremsstrahlung which is which means breaking radiation and the energy of the photons correspond to the X-ray band.

Notes

Summary

8m 40s



Okay. So what we see here as a picture is the first X-ray satellite Uhuru, which was launched in 1970 and that was able to detect the intra-cluster medium in the Coma Cluster.

Notes

Summary

11m 13s

Coma cluster seen in X-ray

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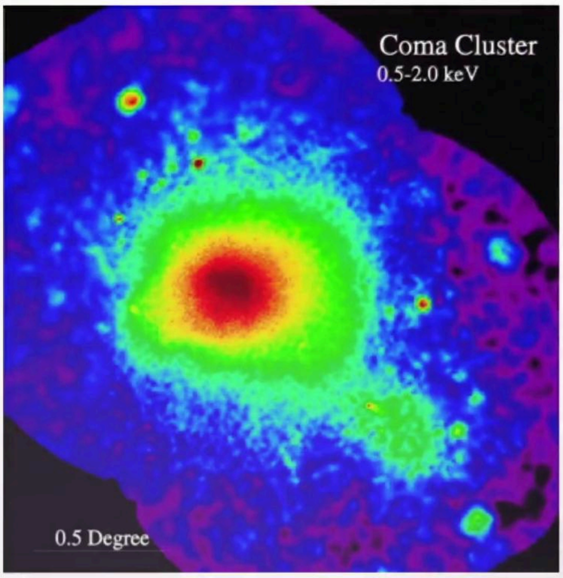

S. L. Snowden USRA, NASA/GSFC

ROSAT 1990

Diffuse emission

point source → AGN

Cluster X-ray gas

$T = 8\text{-}9\ \text{keV} \sim 10^8\ K$

$1\ \text{keV} \sim 1.16 \cdot 10^7\ K$

$B_X \sim n_e^2$

$L_X = 2.6 \cdot 10^{44}\ \text{erg/sec}$

The Radio Universe

There has been many satellite that could detect X-ray emission in the sky. So what we see here is the image of the Coma Cluster seen at X-ray wavelength by the ROSAT satellite which was launched in 1990. What we see here as the cluster is some diffuse emission, diffuse emission of X-ray gas. We do also see here and there some point source but the point source are not exactly the cluster. They belong to the emission of X-ray coming from the Active Galactic Nuclei. The cluster X-ray gas has a temperature ‘T’ equal eight to nine kilo electron volt which correspond to about ten to the eight kelvin. Indeed, one kilo electron volt is equal to 1.16 ten to the seven kelvin. What is important is that what we see here. The brightness of the X-ray emission is proportional to the density square of the electrons in the cluster. And the total luminosity of the X-ray cluster is 'Lx' equal 2.6 ten to the 44 erg per second.

Notes

Summary

11m 32s

Historical Perspective on Cluster of Galaxies

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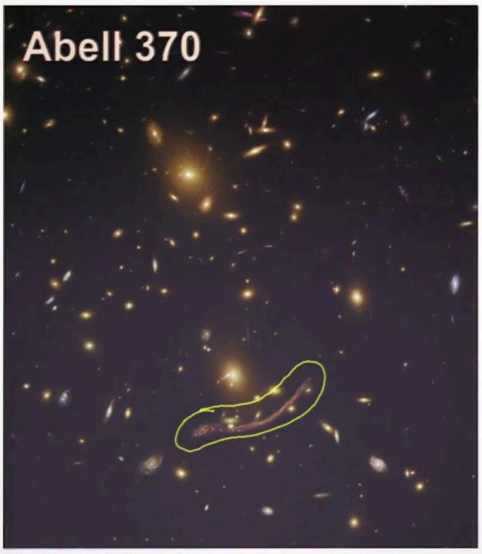
1987: Discovery of Gravitational Lensing effect in clusters



NASA/ESA Hubble Space Telescope

1988 distance of the arc

$z_{arc} = 0.725$ $z_{cluster} = 0.375$

arc 2x cluster.

→ every massive cluster is a lens

. 1 cluster per 10 square degree

→ 2000 cluster lenses

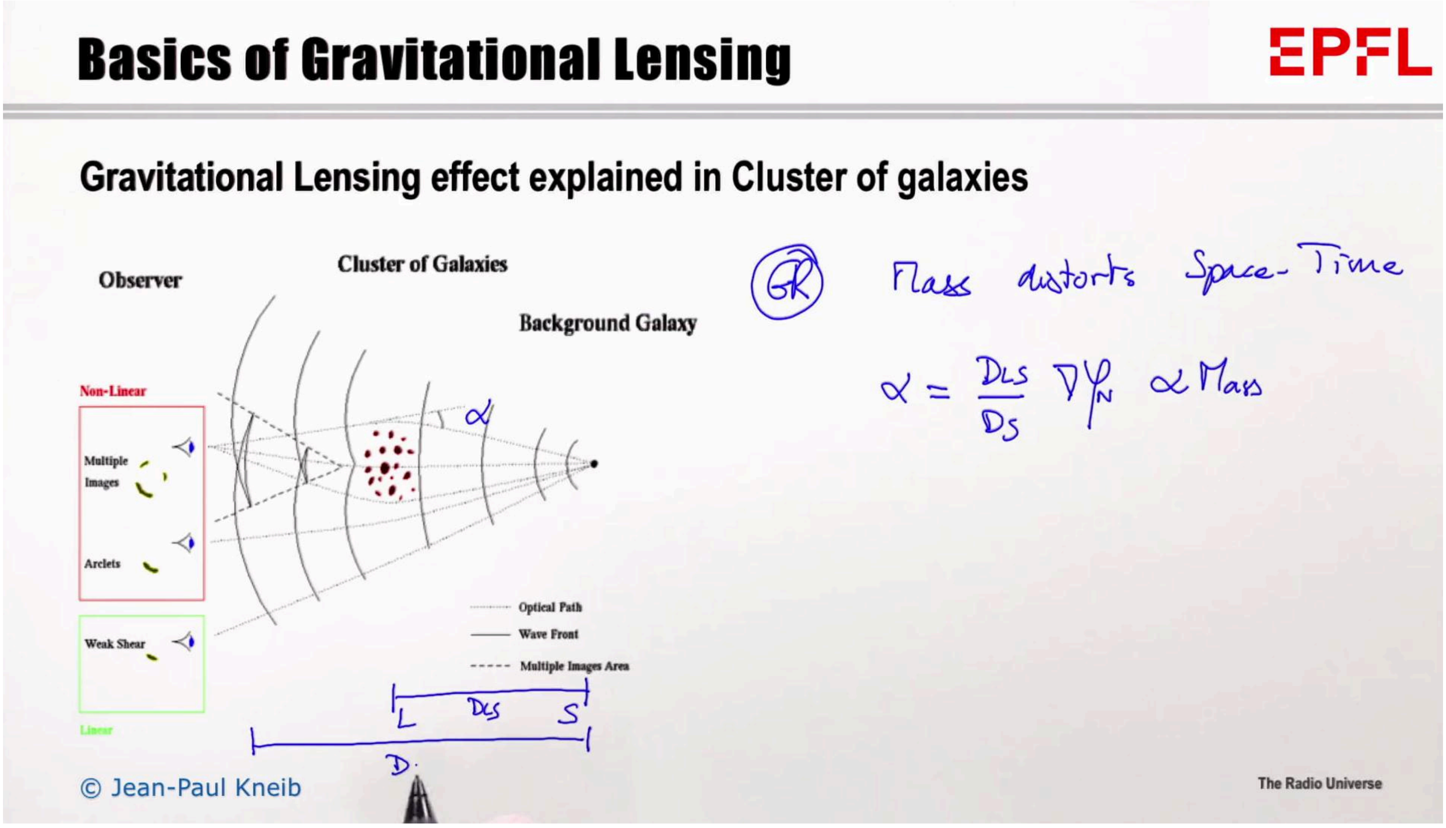
The Radio Universe

More recently we have used gravitational lensing to weigh the mass of cluster, to weigh the total mass of cluster. Here we have a picture of the cluster Abell 370. It's in this cluster that in 1987 we discovered for the first time the gravitational lensing effect in clusters of galaxies. What was found and which was very peculiar is this large and bright arc. Okay. This very long picture is something unusual. In fact, in 1988 there was a measurement of the distance of the arc. This is done by spectroscopy and the what was measured is the redshift of the arc and it was measured to be at 0.725 while the redshift of the cluster is in this case 0.375. So this has proven the fact that the arc is basically a deformation by the cluster of an object which is twice more distant than the cluster. So the conclusion of the first observation is that every massive cluster is the lens. As we have about one massive cluster per ten square degree on the sky and because we have about 20,000 square degree of extragalactic sky it means that there is about 2,000 cluster lenses in the sky. What is important to understand also is that this gravitational lensing effect as best observed from space and in particular, using the Hubble space telescope.

Notes

Summary

13m 31s

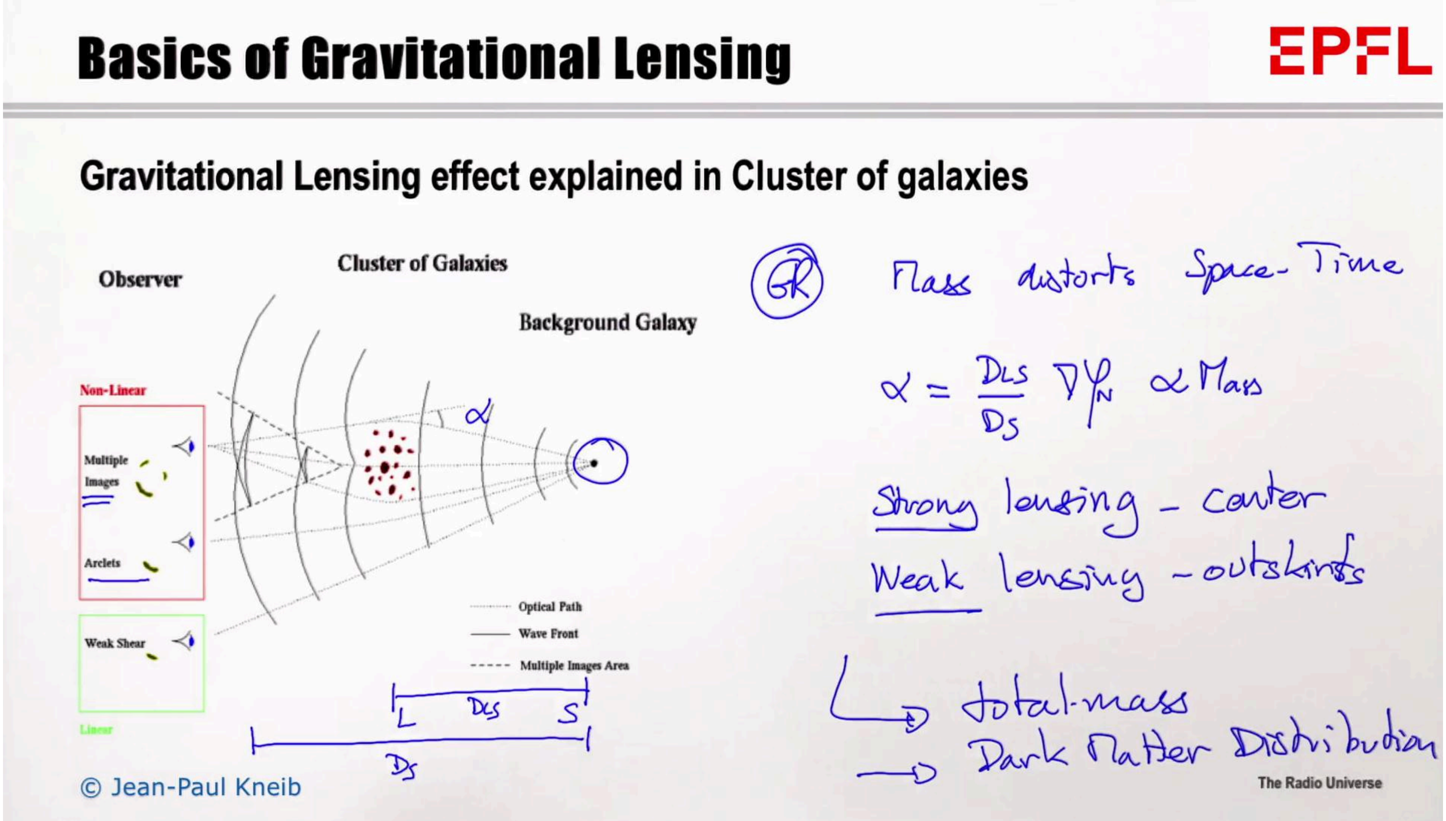


But let's see exactly what is the basics of gravitational lensing theory. How can we explain the fact that cluster of galaxy are producing gravitational lensing effects? We need for that to understand what it means. What is the reason of a gravitational lensing effect in clusters? So let's have a look at this picture. What we see here is a representation of cluster of galaxies. Now we have to also remember that general relativity so the theory of Einstein, the theory of gravity of Einstein tell us that mass distorts space-time. Okay. That's ‘GR’, the theory of Einstein of gravity. So if we assume ‘GR’ and assume that mass distorts space-time then we can show that the light beam coming from the background galaxy which pass nearby the center of a cluster of galaxy, that light pass will be deflected by an angle alpha and the Einstein theory tells us that alpha is equal of 'DLS' over 'DS' times the gradient of the potential, the neutral potential phi of the cluster. And the gradient of phi is, in fact, proportional to the mass of the system. So what we see also in this equation this parameter ‘DLS’ over ‘DS’ which is basically the distance between the lens and the source, that's 'DLS' and the distance between the observer and the source which is 'DS'.

Notes

Summary

15m 59s

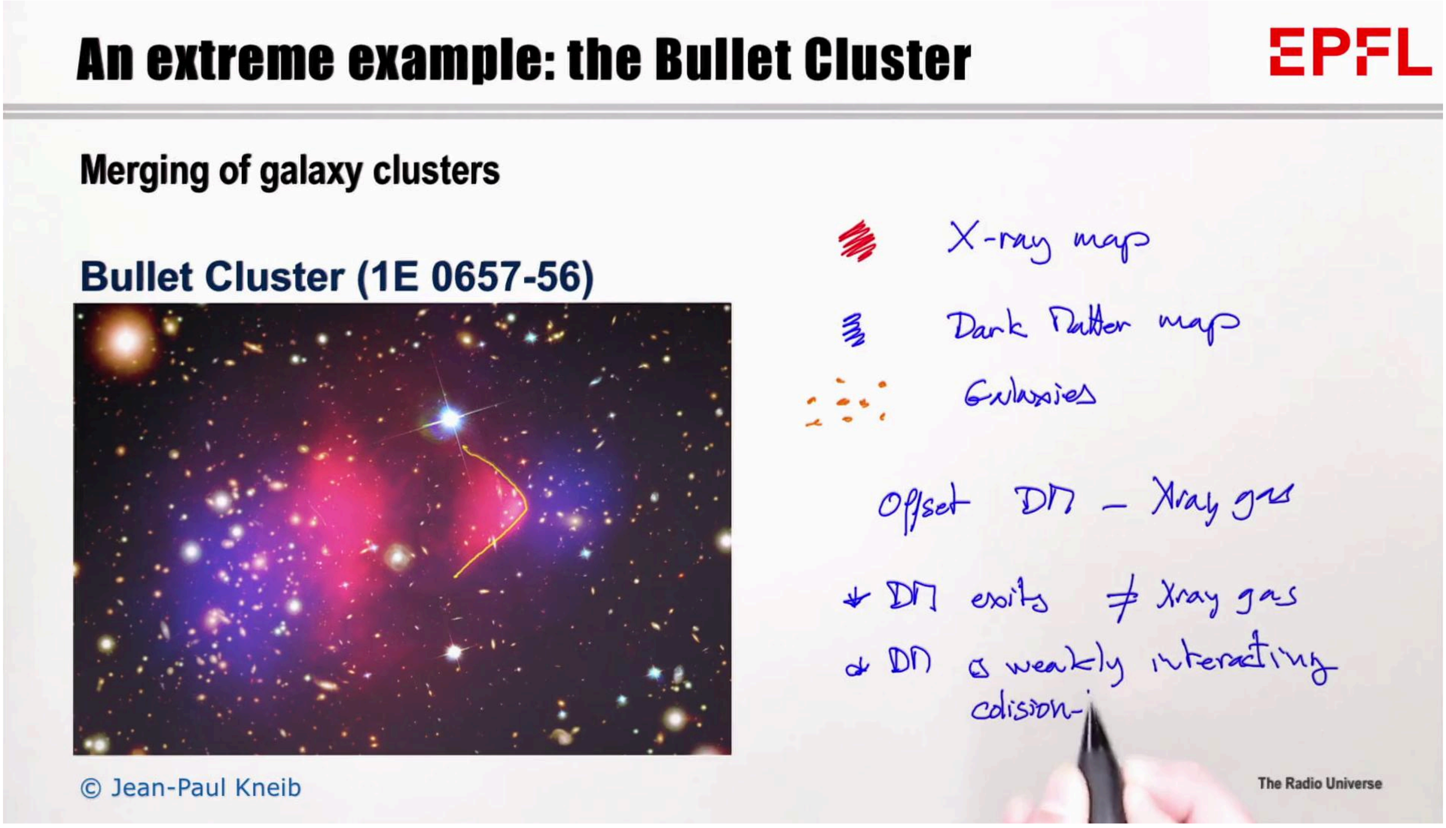


So depending on the importance of the deflection angle alpha, if it's very large then the light beam coming from the distant source can be deflected to your eye in different ways by different routes. Okay. So if this is the case then we will see multiple images of the background sources. If the light beam goes a bit further away from the center then the deflection will be smaller and we only see a distorted object of the background object because of the mass of the system. So we have two regime. We have what we call the central part where you have strong distortion, that's strong lensing and that happen in the center of cluster and we have weak lensing which happen in the outskirts. And we can measure both the strong lensing and the weak lensing and this will give us the total mass of the cluster. And in this way we can deduce the dark matter distribution in cluster.

Notes

Summary

18m 15s

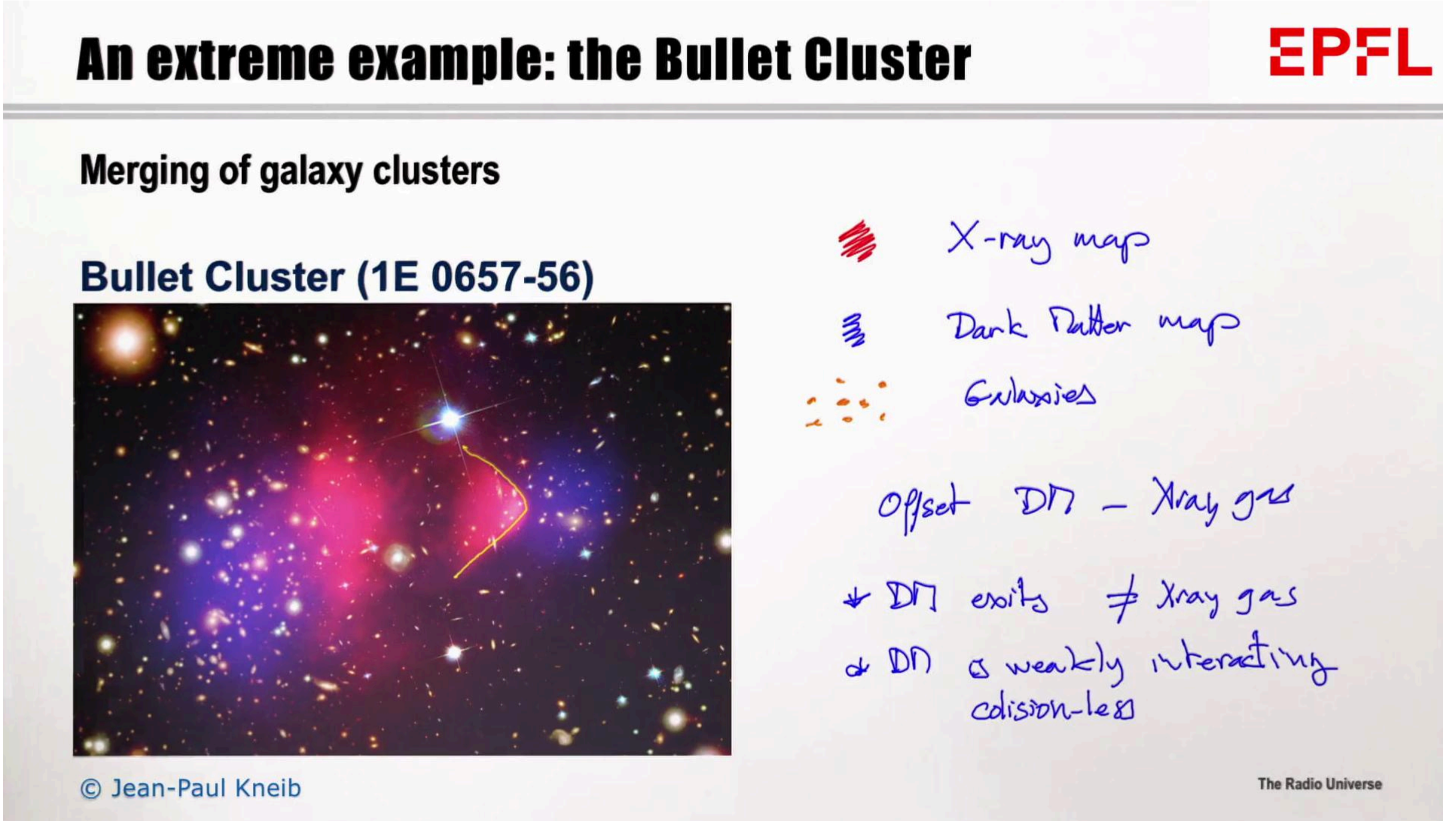


One extreme example of a cluster is the Bullet Cluster. In fact, this is the merging of two galaxy clusters. So let's try to explain this picture. So in red color we have the X-ray map of the cluster, in blue color we have the dark matter map of the cluster and in orange we have the galaxies. What can be seen in the X-ray map is this feature which correspond to a shock when you have like two mass merging together or passing through. When it pass through if it goes at high velocity it will produce a shock like you see here. So in red you have the X-ray gas, in blue you have the total mass or the dark matter and in orange you have the galaxies. What you clearly see is that there is an offset between the dark matter and the X-ray gas. X-ray gas are made of particles that can interact and then they can slow each other. Dark matter is made of an unknown particle and we don't know quite its properties. So from this observation we can deduce that first, dark matter exists. It's different than the X-ray gas because it's located at a different place. And also that dark matter is either weakly interacting or it's not interacting at all and so it could be also what we say collision-less. Okay.

Notes

Summary

19m 54s

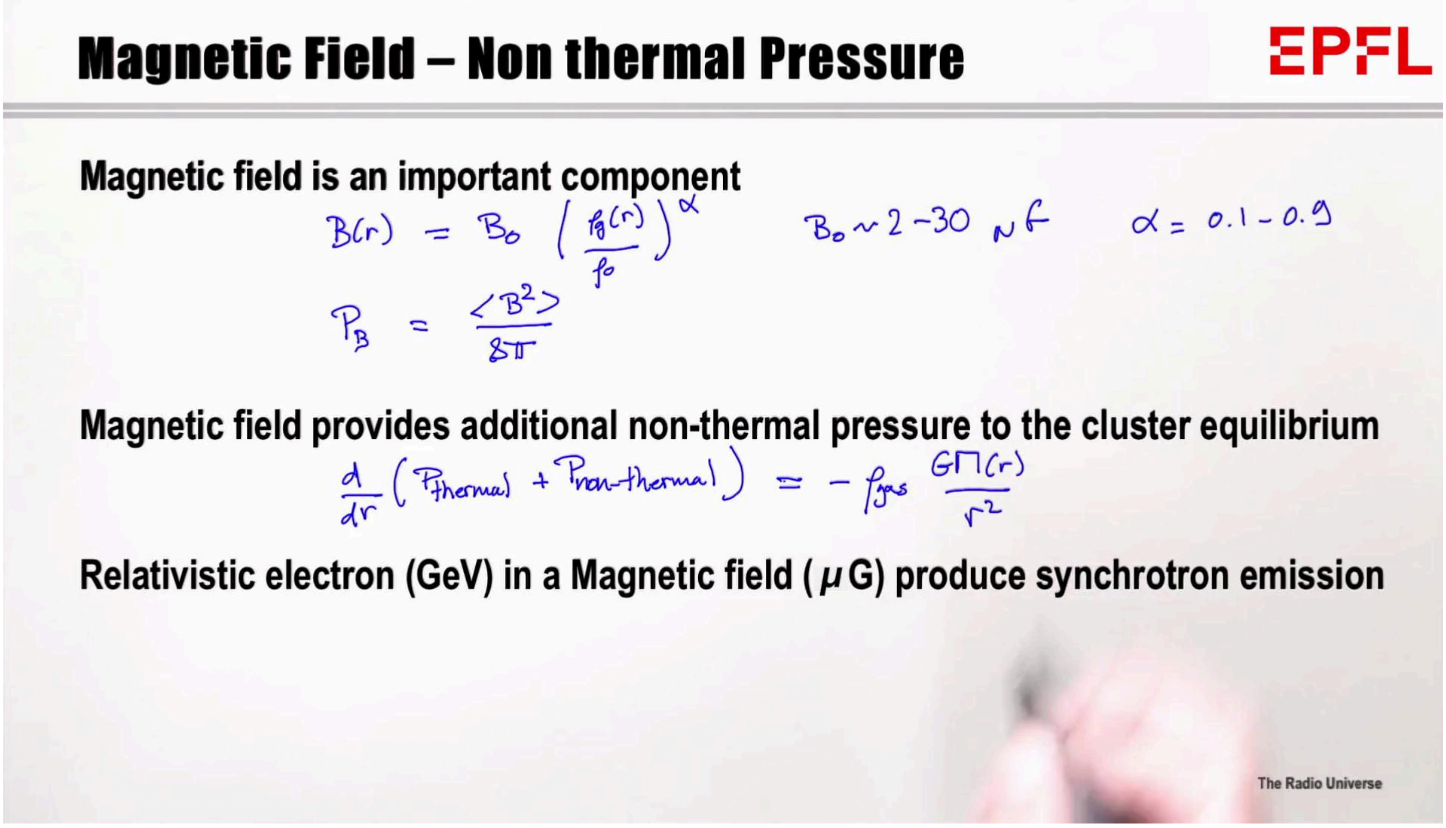


No collision. So this is quite an important observation that makes X-ray, lensing and the position of the galaxies. And that's a case of a merging cluster and we will see there is many merging cluster in the Universe.

Notes

Summary

22m 14s

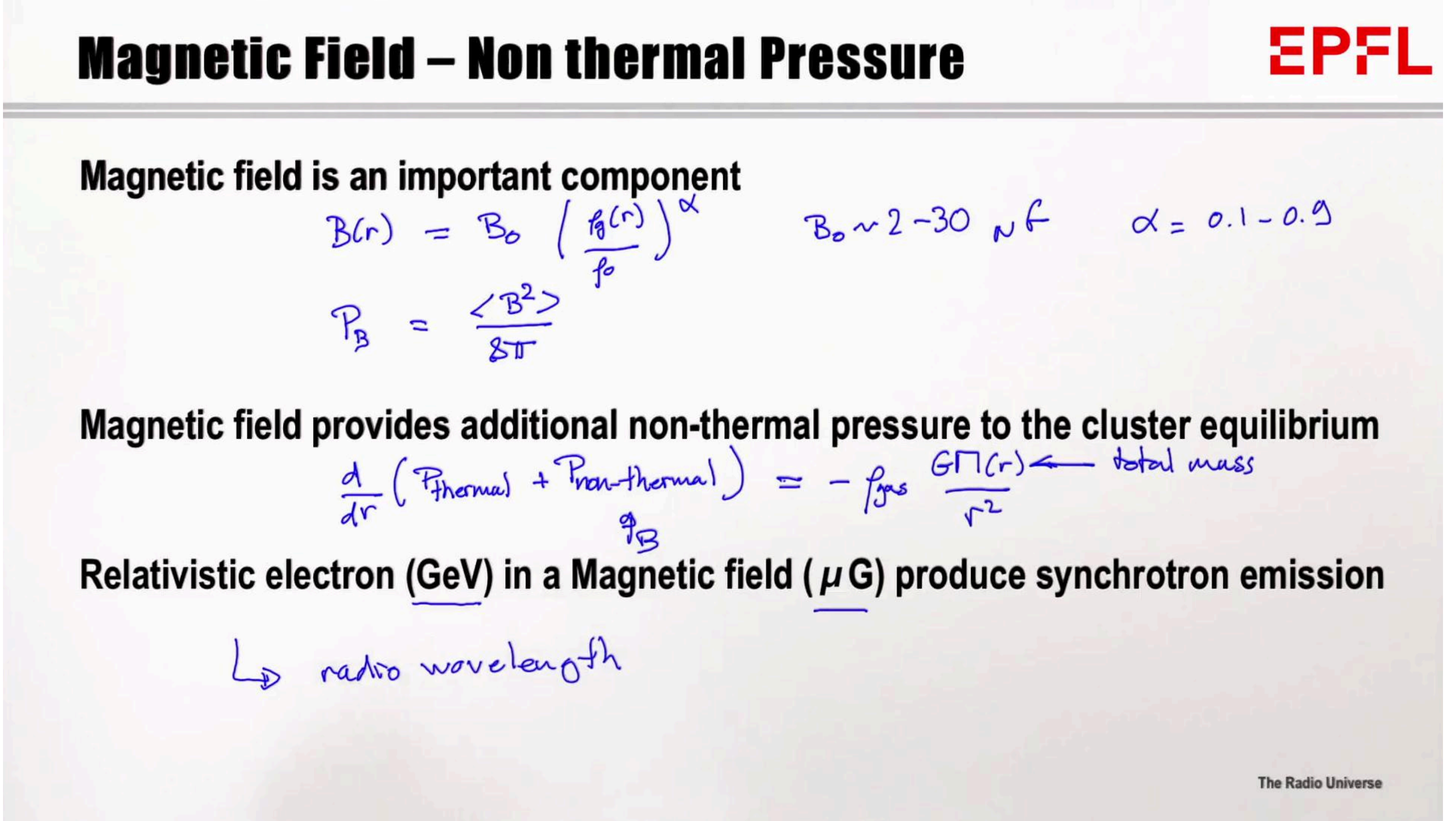


So let's have a look at the last component, magnetic field which produce non-thermal pressure. So magnetic field is an important component that we have to take into account. What we have observed is the magnetic field 'B of r' as a function of radius can be written as ‘B-zero’ basically the magnetic field in the center and it's proportional to the density of the gas at radius 'r' normalize at radius zero to some power alpha. Typically ‘B-zero’ will be of the order of two to 30 microgauss and alpha will be going from 0.1 to 0.9 depending on the clusters. With this magnetic field, we can deduce a non-thermal pressure that we write ‘PB’. Okay. Which is due to the magnetic field and this is typically the average of 'B-square' divided by eight pi. So the magnetic field provides additional non-thermal pressure to the cluster equilibrium. So effectively we need to write 'd' over 'Dr' of 'P thermal', the pressure due to the thermal gas, the hot gas of the cluster plus 'P non-thermal' which is basically for most of it the pressure coming from the magnetic field and this derivative is equal to minus 'rho gas' times G M of 'r' divided by 'r-square'.

Notes

Summary

22m 34s



Here we have 'M' which is the total mass and this is expressed as a function of radius 'r'. So we see that the magnetic field 'B' is important to balance and measure the total mass of the cluster. So how do we detect this magnetic field? Well, we do that by detecting the synchrotron emission and if you have a relativistic electron at giga electron volt and magnetic field which is of the order of microgauss then there will be detection of the synchrotron radiation at radio wavelength. So the higher the energy or the higher the magnetic field, the higher energy of the photons.

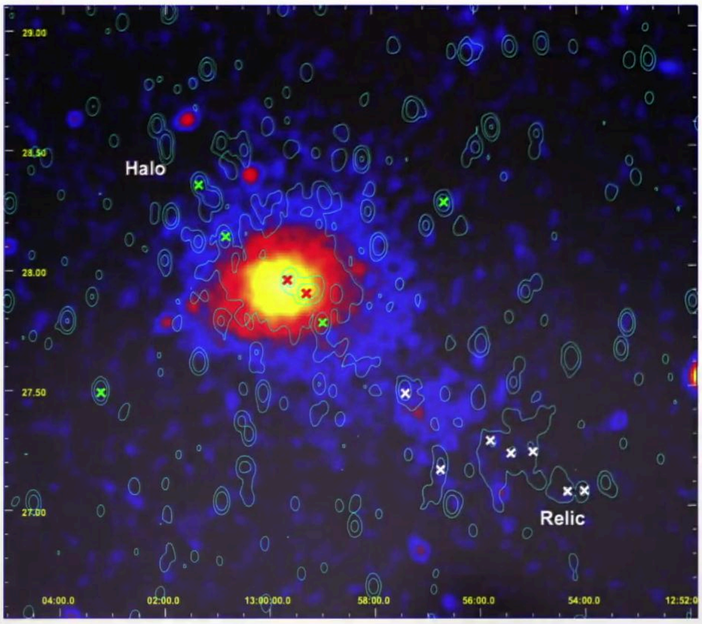
Notes

Summary

24m 54s

Coma cluster seen in Radio

EPFL



Bonafede et al 2013
(ROSAT data + WSRT @325 MHz by Venturi et al 1990)

Radio Halo

co-located with X-ray gas

1959

Radio Relic

not co-located with X-ray

The Radio Universe

So let's see what is the radio emission in the Coma Cluster. So here we have a picture of the Coma Cluster and we have two type of information. In color we have the emission of the hot gas as seen in the ROSAT data so in X-rays. The contours that you see here are measurement done in radio at 325 megahertz. And what we see? We see two things. We see a radio halo. What we call the radio halo is a radio emission which is co-located with the X-ray gas. Okay. So we see here at the center that there is radio emission co-located with the X-ray emission with the ICM. And for Coma, this was discovered in 1959. We also see in this image radio emission over here which is not co-located with X-ray. Okay. So there is a disconnection between the radio relic and the intra-cluster medium. However, the crosses as you see over here correspond to locations of galaxies and you see that the relic is nearby the location of galaxies. So there might be connections between galaxy and the radio relics.

Notes

Summary

25m 55s

Radio emission in *Merging* vs. *Relaxed* cluster

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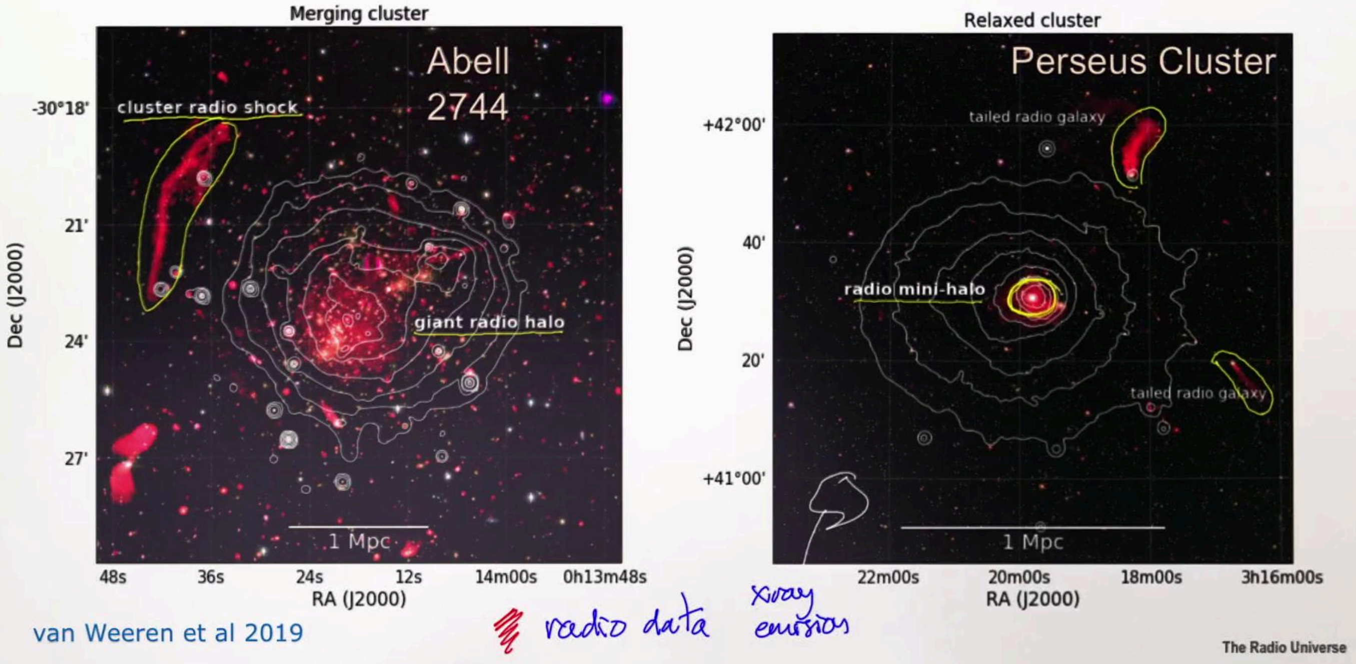


van Weeren et al 2019

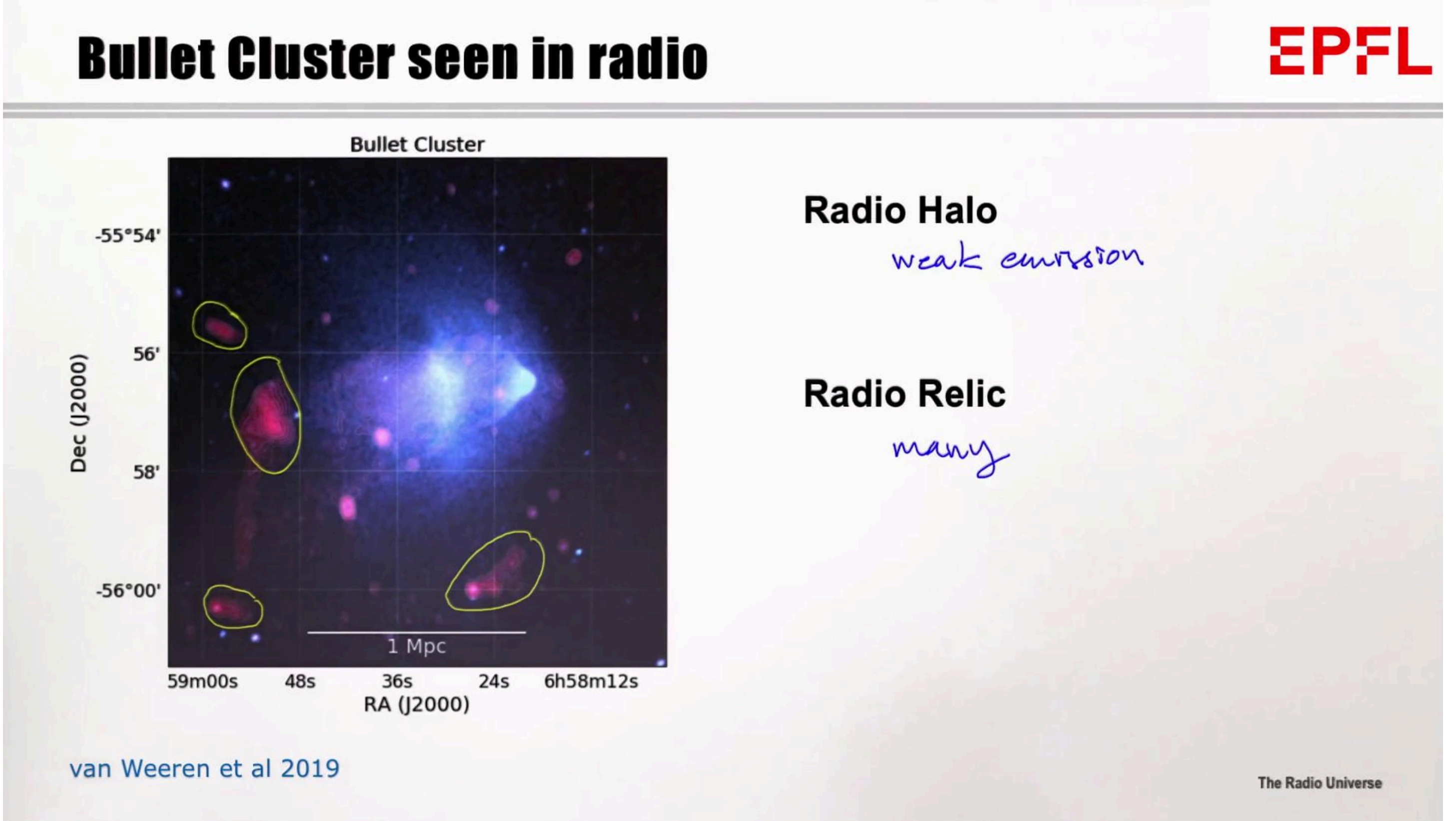
The Radio Universe

These two observations are two very typical radio emission seen in merging cluster and in relax cluster. So here we see the merging cluster Abell 2744 and here we see the Perseus Cluster. So what we have? In red we see the radio data. The white contours are the X-ray emission. So what we have here as witnessed by the X-ray emission? We have basically two cluster that have just been merging or are in the process of merging. And what we see in red over here co-located with the X-ray emission is what we call the giant radio halo. We also see in red over here what we call a cluster radio shock, which is disconnected than the main X-ray emission of the intra-cluster medium. In case of what we call a relaxed cluster so a cluster which has not suffer any merging with a smaller groups or another cluster so something that has been in this position. Quite relaxed, no merging. What we see in this case is a radio mini-halo so we have radio emission but only in the very central part of the cluster. There are also other object radio object in that frame which are two tailed radio galaxies. Okay. Where we have an Active Galactic Nuclei and which produces radio emission.

Notes

Summary

27m 40s

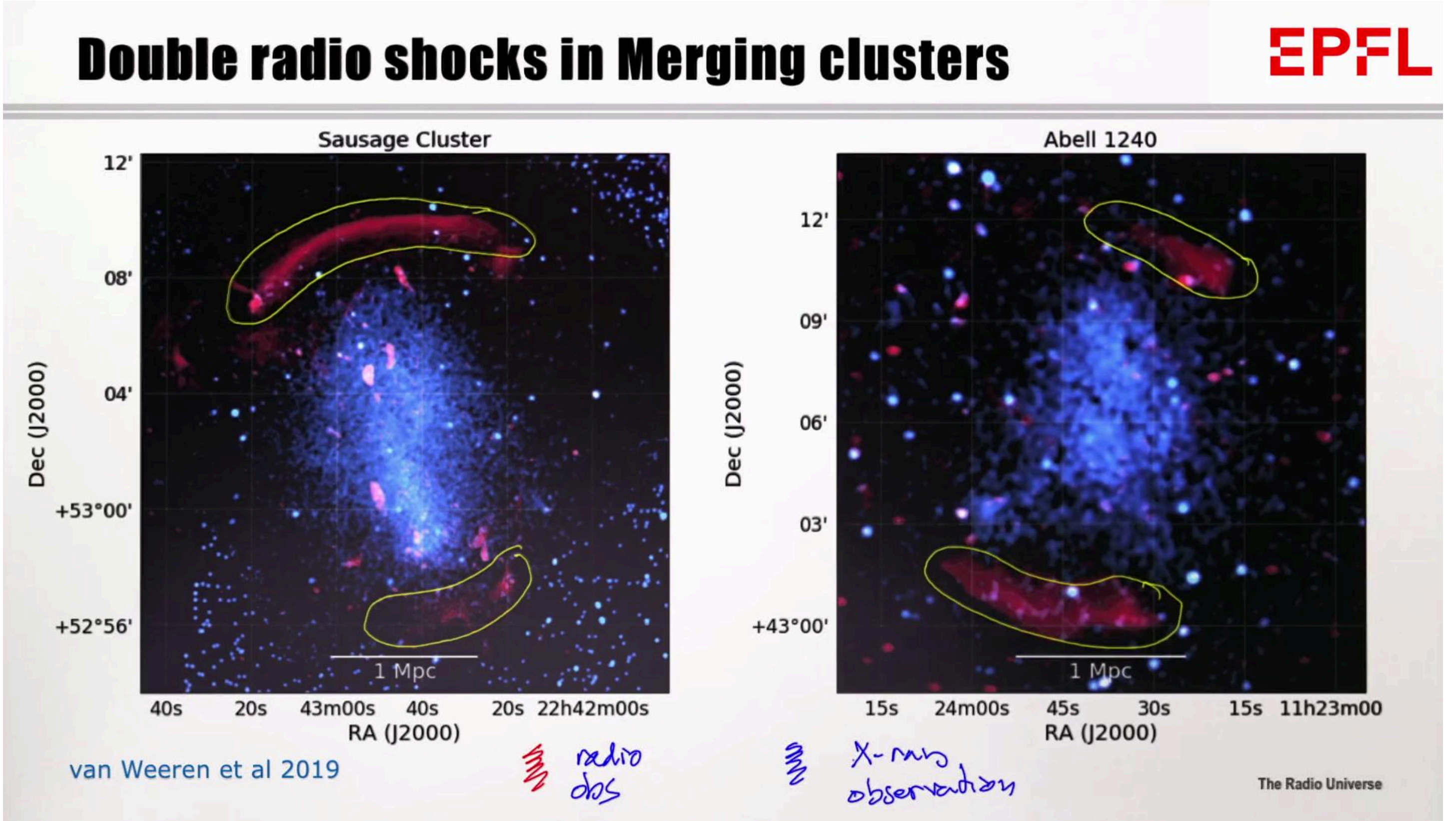


But surprisingly, not every cluster merger are producing a big radio halo. Indeed, here we have observation of the Bullet Cluster seen at radio wavelength and we only see a weak emission as part of the radio halo that, you know, should be much brighter for a cluster merger. However, we see many radio relic in this image as we can see over here, over there, possibly over there, possibly over there. Right. And, of course, we have point sources which are more linked to galaxies in the cluster.

Notes

Summary

29m 55s

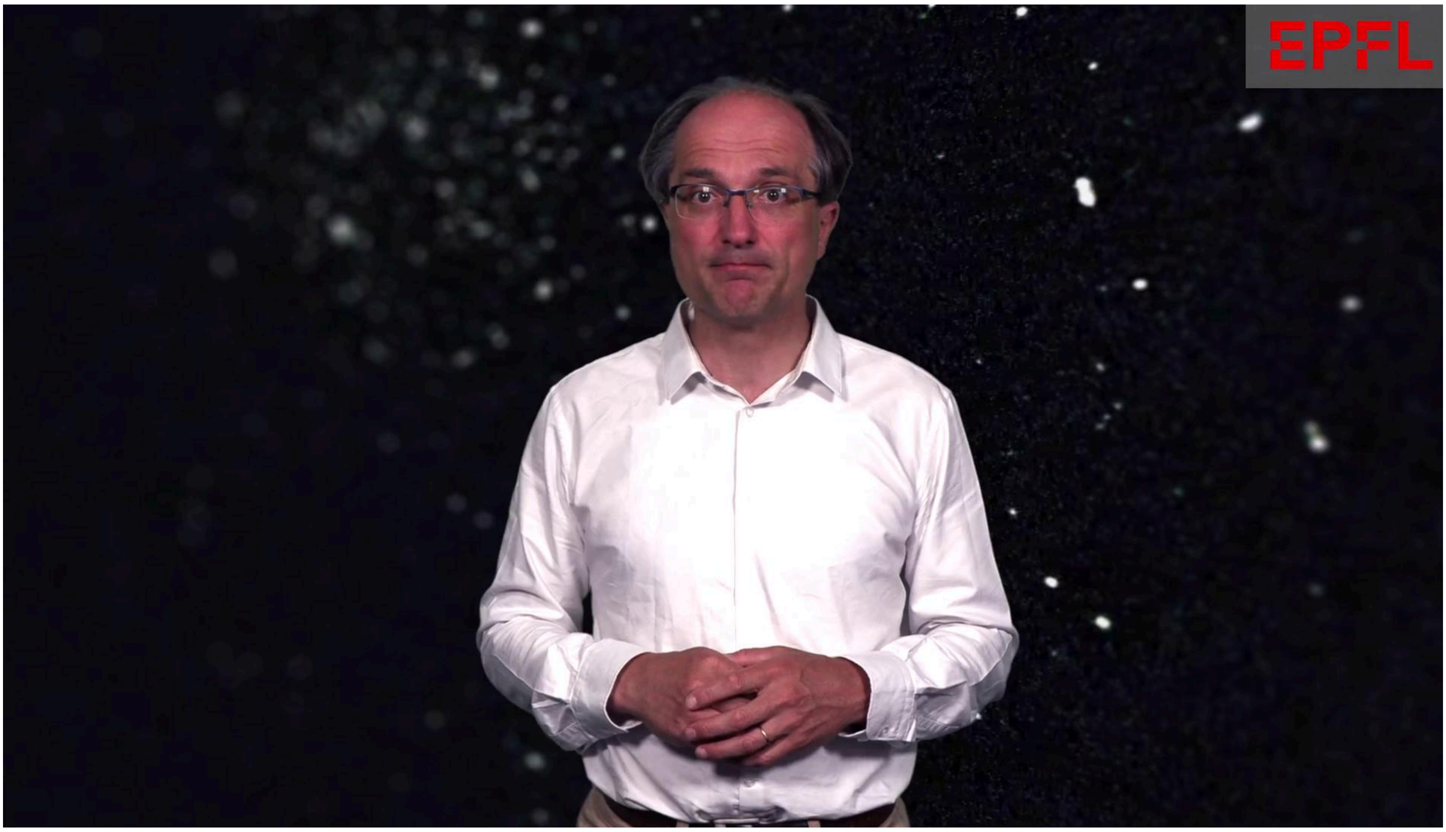


To finish, let's have a look at this two merging clusters. First one is called the Sausage Cluster. Second one is called the Abell 1240. The name of the Sausage Cluster come, of course, from this big picture which has a shape of a sausage seen at radio wavelength. So what you see here in red is radio observation and in blue, it's X-ray observation. So we have diffuse hot gas of the intra-cluster medium here and that it's very very much elongated and that's correspond to what you would see for a merging cluster. So the fact that we see on both side of the cluster here and also here, two radio shocks is a proof of the merging of these clusters.

Notes

Summary

30m 46s



We have seen some of the k properties of cluster of galaxies. This very massive system have different component that can be observed at different wavelengths. With multi-wavelength observations we can thus learn more on the properties of cluster of galaxies. In particular, radio observations are a good way to study merging clusters through detection of radio halos and radio shocks. Some radio observations of cluster are really stunning and surprising such as a Toothbrush and a Sausage. Most of the radio observation of cluster are relatively recent and new spectacular images will be discovered in the near future. So look out for a new discoveries.

Notes

Summary

31m 59s