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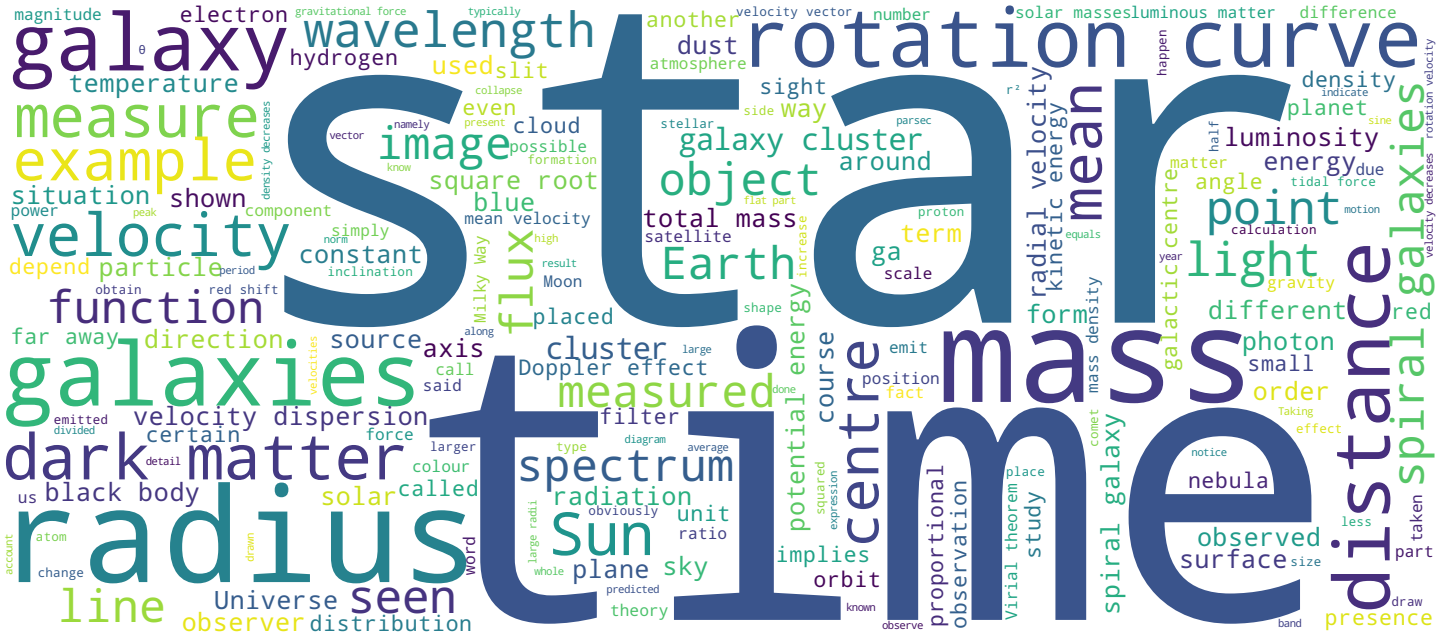
Galaxy cluster MACS J0416.1-2403

Image: ESA/Hubble, NASA, HST Frontier Fields

Dark Matter in Galaxies and Galaxy Clusters

Introduction to Astrophysics; Chapter 6.4

Frédéric Courbin



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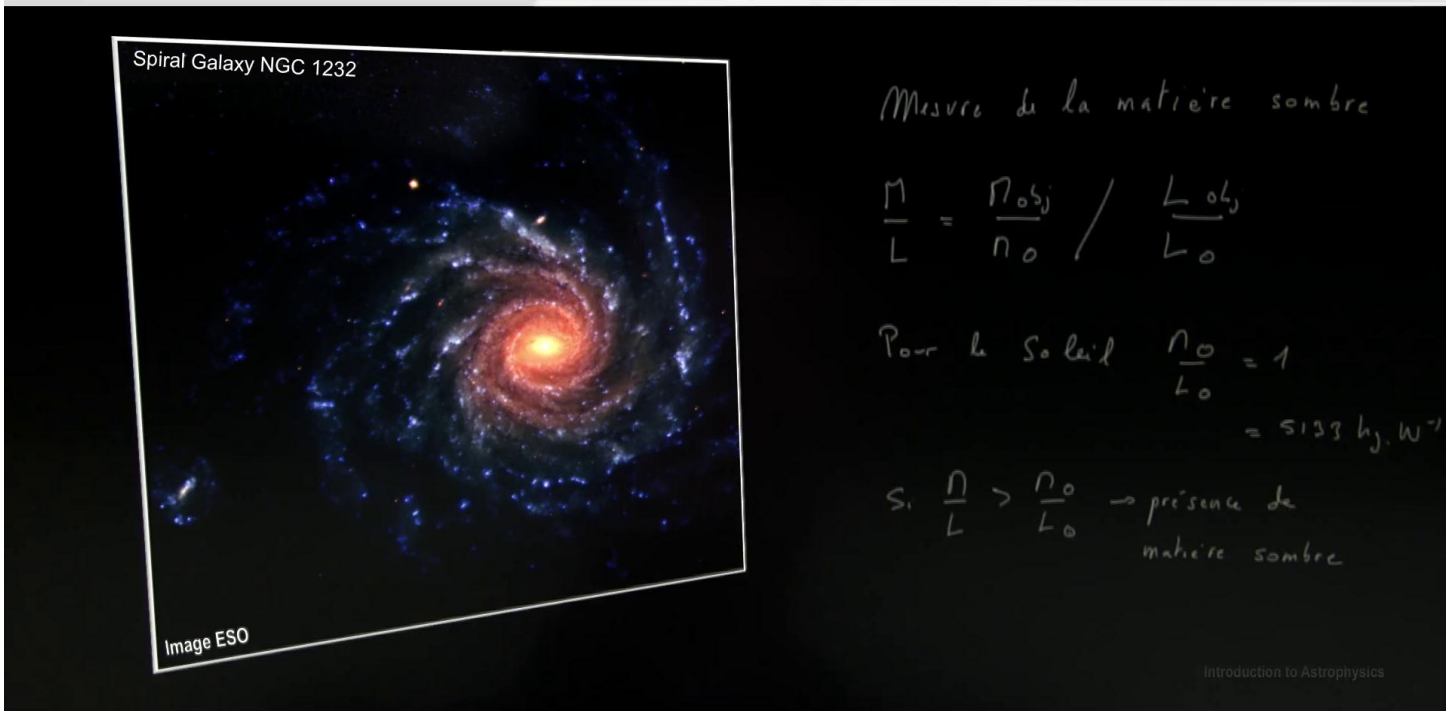
Dark Matter: Units



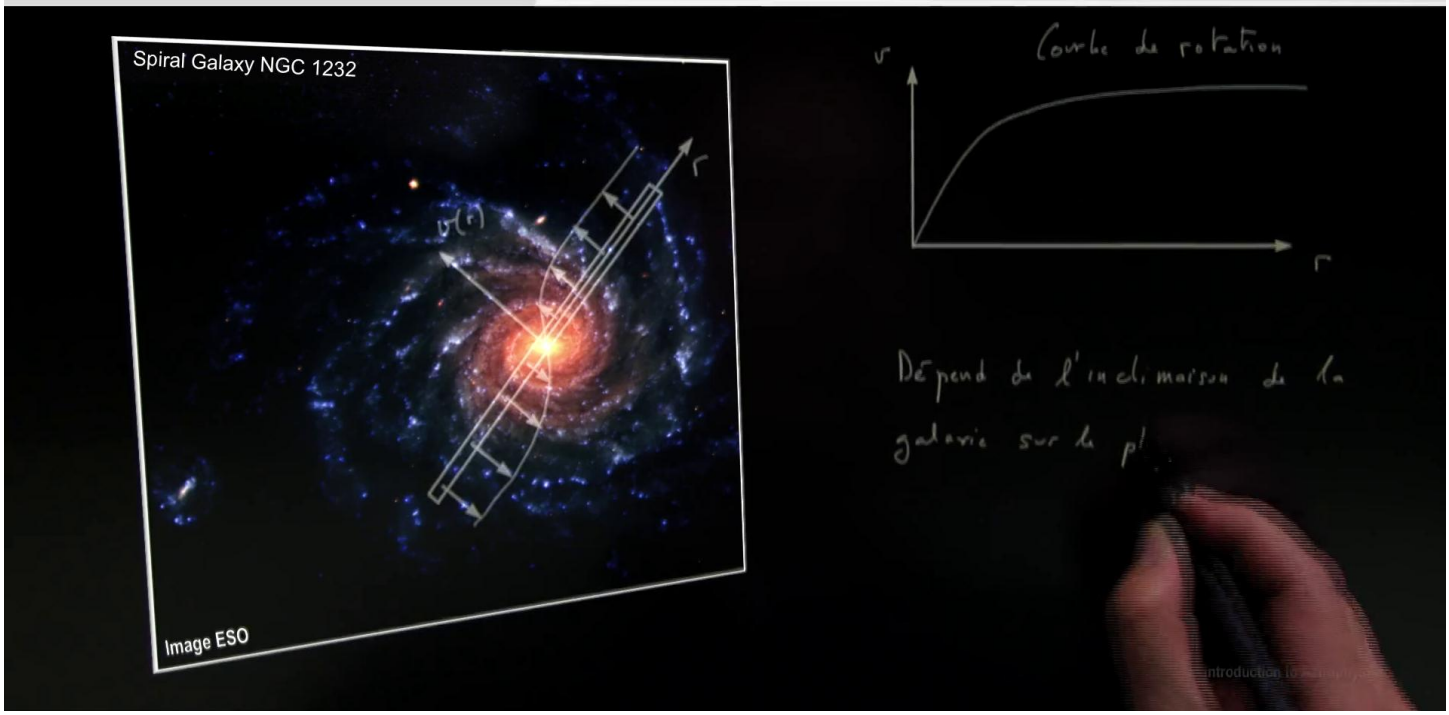
Do we see the whole Univers? In other words, do all massive objects send us light? The answer is no. Now it is known that 25% of the mass of the Universe do not emit any light at any wavelength so it stays unobservable, even for the largest telescopes. However, it is possible to detect the presence of the dark matter in an indirect way, through its gravitational field. It will be shown in this lecture, We will look closer at two examples of indirect detection that are based on the study of the dynamics of spiral galaxies and on the dynamics of galaxy clusters that enabled us to reveal dark matter in the first half of the 20th century. Let's see how to reveal the presence of dark matter in spiral galaxies. Just before that, how dark matter can be measured? How is the mass of a galaxy measured as a function of its light output? In fact, the mass/luminosity ratio will be used expressed in solar units. For example, the mass of an object in solar masses divided by the luminosity of the same object in solar luminosities. Now, for the Sun: in solar units, M/L=1 and in physical units M/L=5133 kg/watt. This means that if M/L of an object is larger than M/L of the Sun, it can potentially contain dark matter so matter that emits less than it does in the Sun. In this way dark matter is measured.

Notes

Summary

0m 05s

Dark Matter in Spiral Galaxies



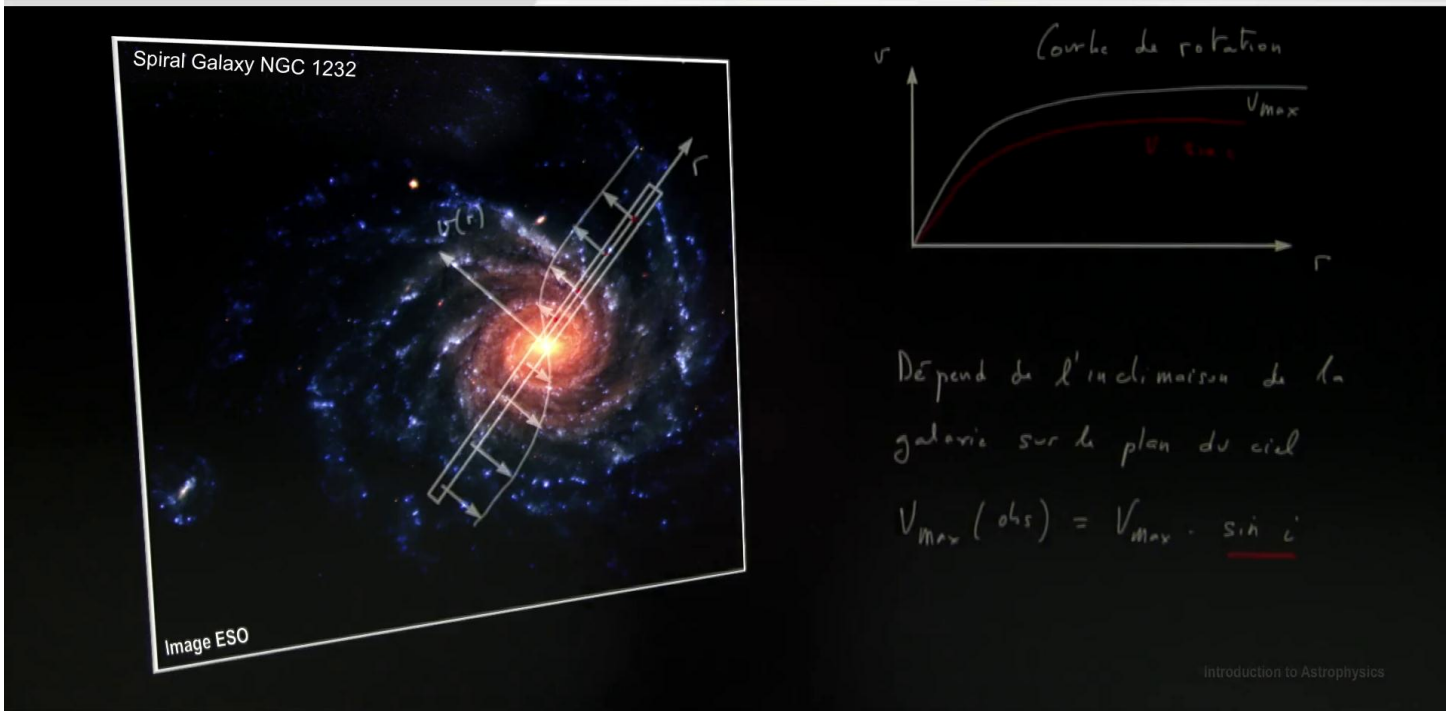
Now, revealing dark matter in spiral galaxies: spectroscopy will be used once again. A spectrum is taken - the slit of the spectrograph is placed in this way on a spiral galaxy - and then a spectrum is taken at all points. An image of the slit in all wavelengths is obtained. as already seen, allowing us to measure the velocity vector at different radii along the slit. We will have here velocity vectors in the opposite direction and the final result is what we call a velocity profile. What you see here is the radius relative to the galaxy centre there and the velocity given as a function of the radius. This is what is called a rotation profile of a spiral galaxy and this is what is used to uncover the presence of dark matter in spiral galaxies. How can that be done? The shape of the rotation curve is drawn here. Taking only half the rotation curve, one has the radius here, the velocity there, and a rotation curve which looks like this. This is what is measured: beware, this velocity is the radial velocity. The rotation curve depends on the inclination of the galaxy with respect to the plane of the sky.

Notes

Summary

2m 09s

Dark Matter in Spiral Galaxies



Here you see that one has a velocity Vmax for a galaxy, if the latter is inclined by an angle i relative to the plane of the sky, then the observed Vmax will be equal to the true Vmax - the circular rotation velocity of galaxies - times the sine of i, where i is the inclination of the galaxy on the plane of the sky. Therefore, the new rotation curve will look like this, which is V times the sine of inclination. Beware, one has to select galaxies which are inclined relative to the plane of the sky. in the picture shown here, for instance, with a face-on galaxy, one would be unable to measure the rotation velocity. I have chosen this picture, just to display a spiral galaxy - it is a nice view of a spiral galaxy - but actually you need a radial velocity component i.e. a component along the line of sight, to measure any Doppler effect. Hence, one can measure only those galaxies that are inclined on the line of sight. Therefore, you need to measure not only the velocities at each point on the slit, with a spectrograph, but also measure the inclination of the galaxy with respect to the plane of the sky. Doing this, one will obtain the observed rotation curve, the one drawn in red, then correct it to get the true rotation curve and study the properties of the galaxy.

Notes

Summary

3m 29s

Dark Matter in Spiral Galaxies

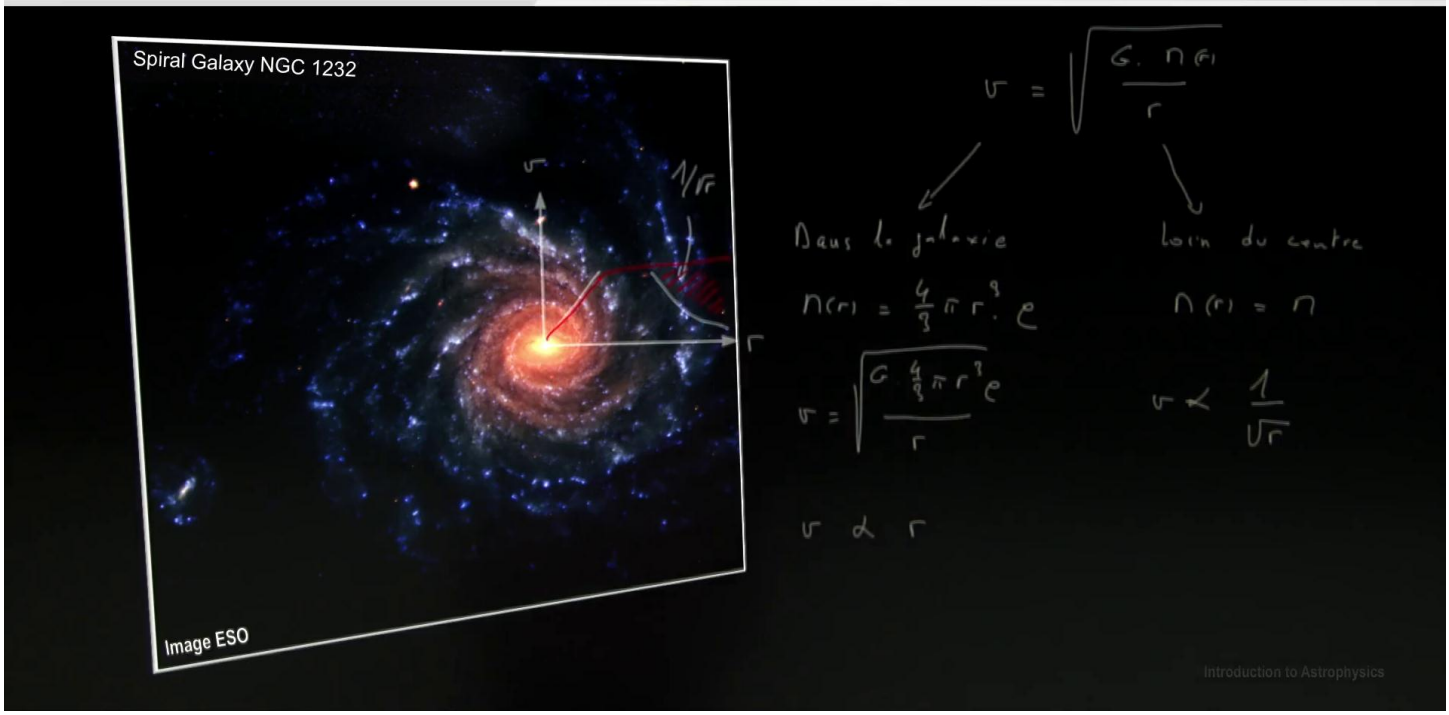
Once we have the observed rotation curve, let's now see how to relate it to theory. The theory is quite simple: one can predict the rotation velocity of the galaxy due to a mass encompassed within some radius r. We have some velocity here; for this specific radius, we have a certain mass and a certain density. The theoretical computation is quick and easy: the gravitational acceleration is equal to the centripetal acceleration, hence G Mr (mass within the radius r)/r^2 equals V squared over r, so that V = square root of G Mr/r. One has somehow predicted the velocity V as a function of radius, actually giving us a rotation curve. Rewriting the calculated velocity: v=square root (G Mr / r). Now, we will consider two situations: we will try to approximate this curve for the vicinity of the galactic centre and far away from the centre. At first, the observer is placed in the galaxy: in this case one uses the approximation made quite often before, Mr = 4/3 π r cube times density. If one places it into this equation, the result will be v = square root (G times 4/3 π r cube times ro / r). This means that v is proportional to r. This is the rotation curve near the galactic centre.

Notes

Summary

4m 53s

Dark Matter in Spiral Galaxies



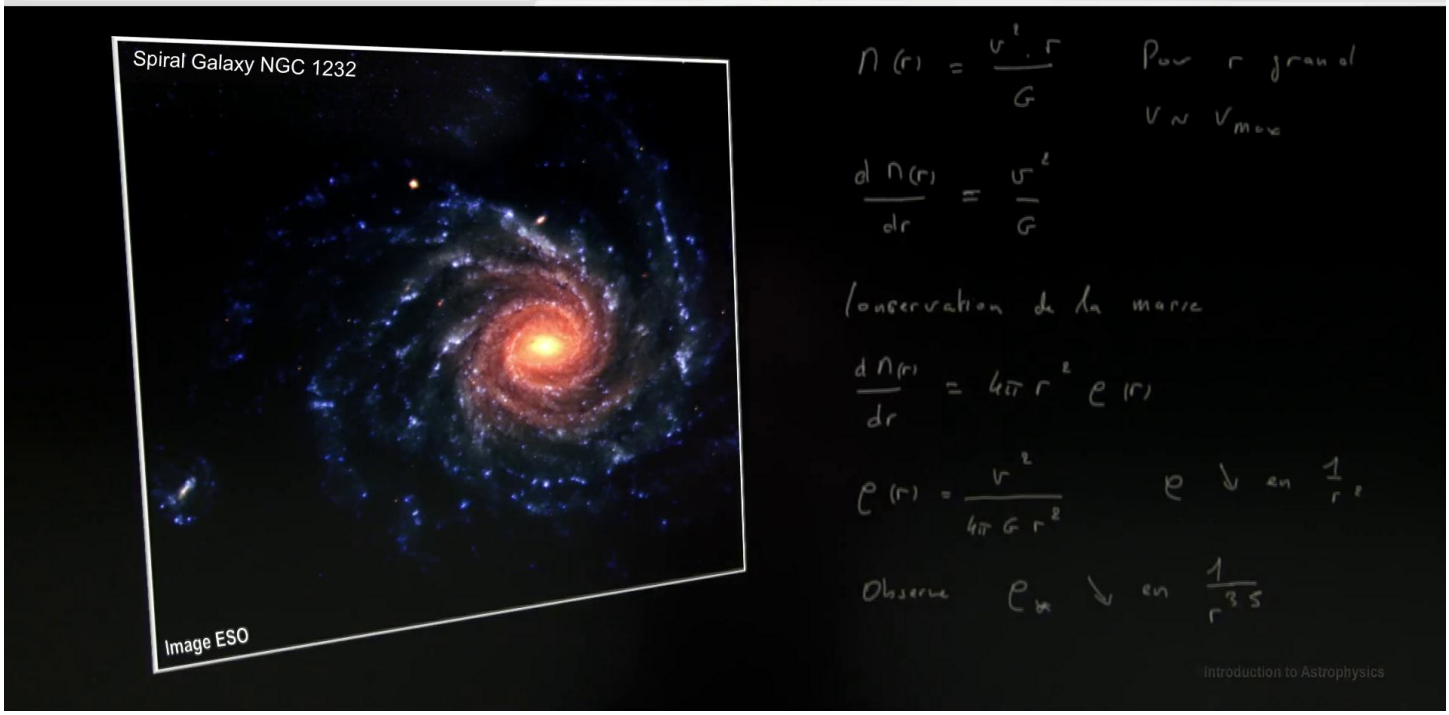
Now, the observer is placed far away from the centre. In such a situation, the approximation we adopt is much more drastic: one squarely considers M as constant and introduces it into this equation. One can immediately see that v is proportional to 1/square root of r. So we have two parts of the rotation curve, near the centre and far away from the galactic centre. Let's draw it: x axis representing the radius, y axis - the velocity. Hence, close to the galactic centre, the velocity is proportional to r - it is more or less a straight line, then something happens here for intermediate radii, then far away from the centre, velocity decreases as 1/square root of r. To some extent we have predicted the rotation curve of galaxies. One also notices that it is quite different from the observed curve, like the one sketched before, where for small r it was indeed proportional to r but then flattened off. What does it mean? It means that, far away from the galactic centre, we have predicted that as long as mass remains constant while we move away from the galaxy, the total mass within the radius r does not increase any more and velocity decreases. But what is observed it that velocity stays constant, meaning that there is more mass at large radius than assumed while making our approximation. Now, we will try to bring this mass out.

Notes

Summary

6m 36s

Dark Matter in Spiral Galaxies



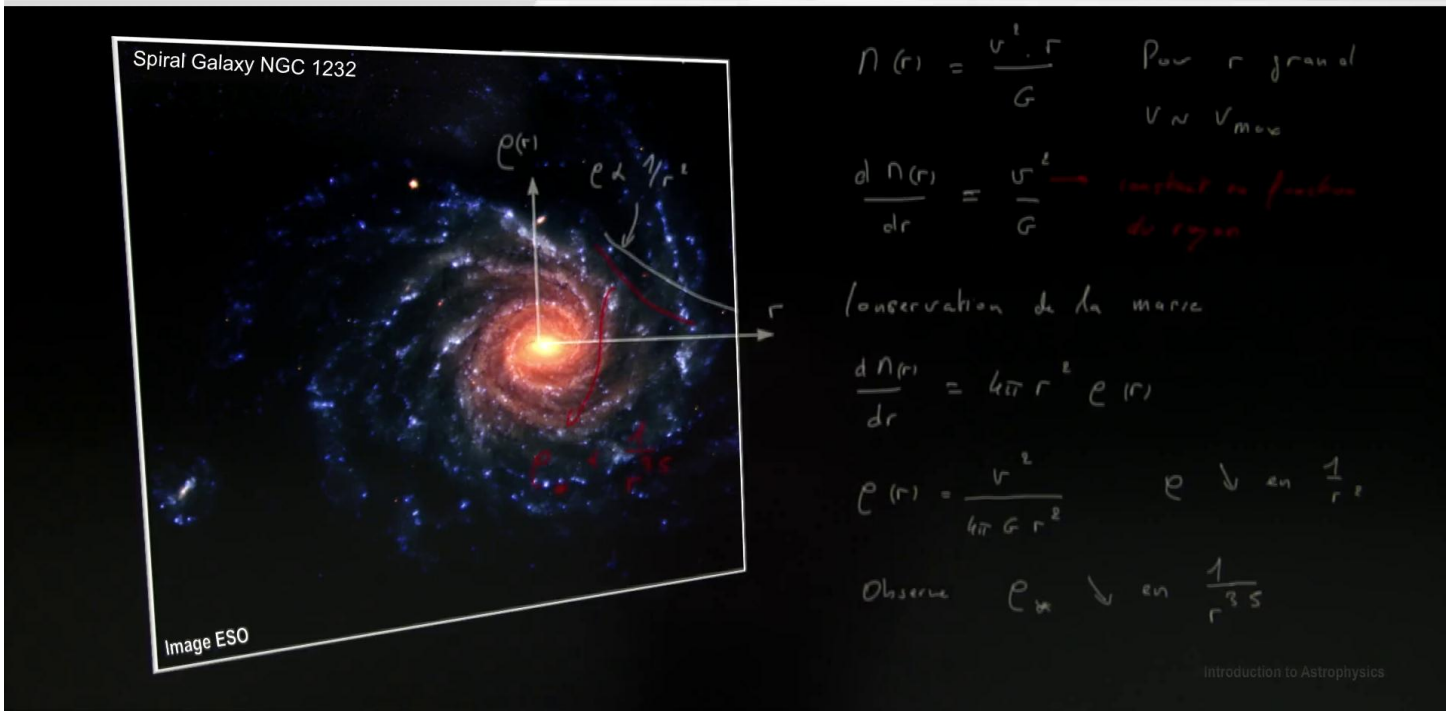
Inverting the problem and writing the equation for the velocity as a function of radius to get the mass Mr as a function of velocity, radius, and G. The equation for the rotation curve was simply inverted, and we have seen that, for observations at large radius, V stays roughly constant. This is observed in the rotation curves of galaxies: Velocity decreases as 1/square root of r in the predicted rotation curve but stays constant according to observations. Taking this into account, one can say that the derivative d M(r) / d r is equal to v^2 / G if v does not depend on the radius. We also have the continuity equation that tells us dMr/dr = $4\pi r^2 \varrho$ r. If both equations are combined, one finds that ϱr is equal to v^2 - a constant velocity as the observations show, / 4π G times r^2. This implies that ϱ decreases with 1 / r^2. What is observed is that stellar ϱ, the stellar mass density, decreases as 1 / r to the power 3.5. One can notice that the density of stellar matter decreases faster than the total density. It means that there is more mass that is not seen under the form of stars and that is needed in order to explain the flat part of rotation curves at large radii.

Notes

Summary

8m 16s

Dark Matter in Spiral Galaxies



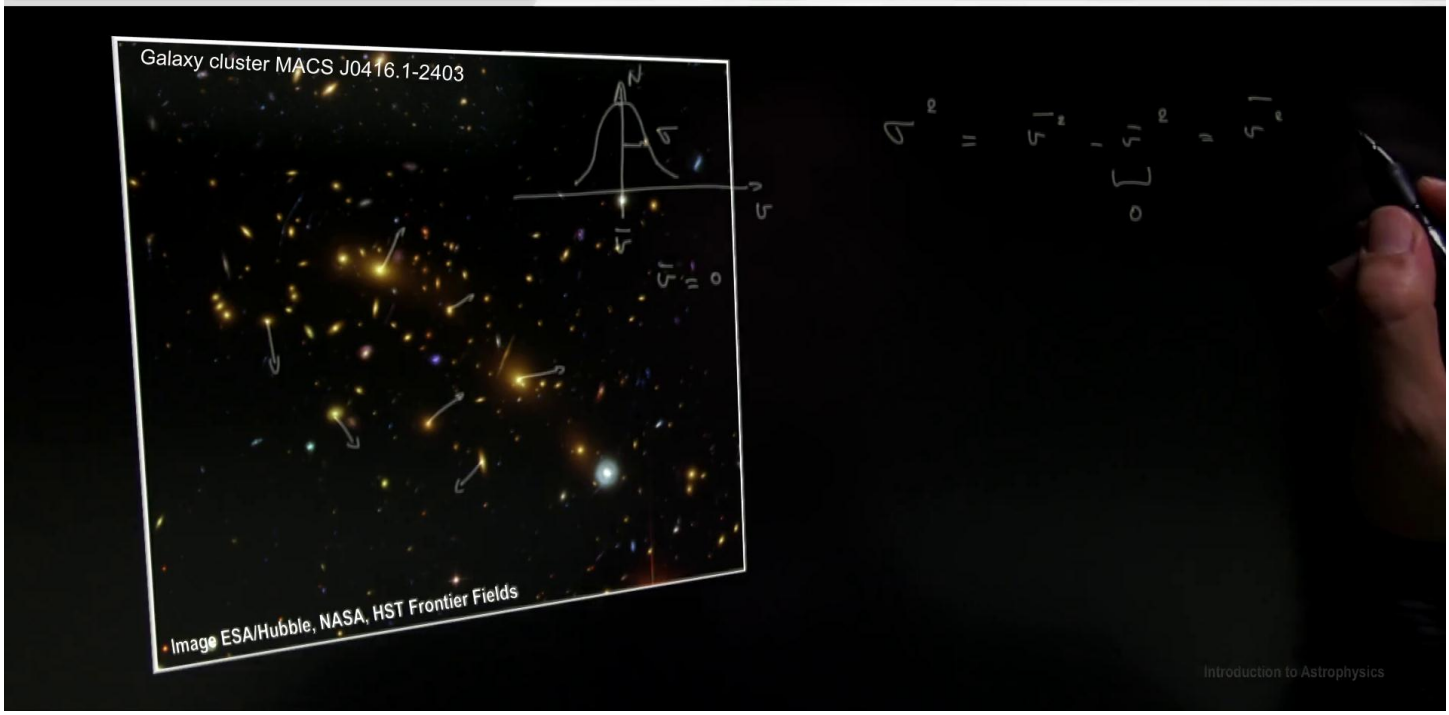
Let's sketch this situation: the x axis represents the radius, y axis the density ϱ. What we have just shown is that there is a decrease in density as 1/ r². Now, the stellar ϱ is proportional to 1 /r to the power 3.5. So the observations imply that the mass density decreases much faster than what is given by the theory which is based on the observations that indicate v constant with radius. Rotation curves of spiral galaxies, showing a flat part at large radii, indicate that the mass density decreases slower (as 1/ r²) than the density of luminous matter. The presence of dark matter was shown thanks to those rotation curves of spiral galaxies.

Notes

Summary

10m 02s

Dark Matter in Galaxy Clusters



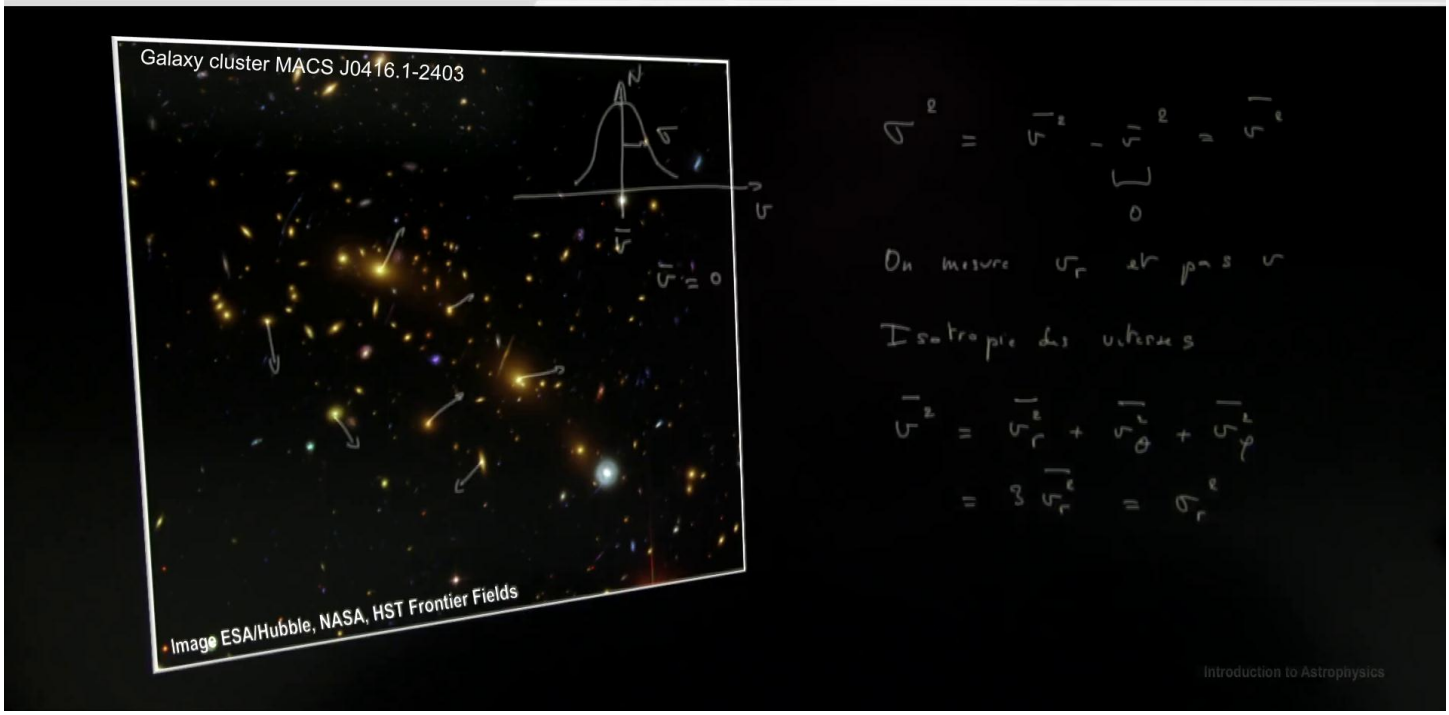
Now, what happens in galaxy clusters? Here the situation is quite different: there are no stellar disks in rotation but there are loads of galaxies, each with the intrinsic velocity. The motions of galaxies are random. All those green points have their own velocity, they rotate about the centre of gravity and so there is a given velocity distribution. There is no longer a rotation curve, the velocity of galaxies is placed here, and the number of galaxies with certain velocity on the y axis - this gives us a distribution that can be approximated by a Gaussian distribution. This distribution has a dispersion and a mean velocity - the mean velocity of the galaxy cluster which can be put as v mean = 0, the mean velocity can be removed from this distribution. There are galaxies rotating about the centre of gravity with some velocity dispersion that characterizes the velocity distribution in the potential well. This velocity dispersion: σ^2 is equal to v^2 mean - v mean^2. This term is equal to zero, as we cancelled the mean velocity of the cluster, so the velocity dispersion is equal to the mean value of velocity squared.

Notes

Summary

11m 17s

Dark Matter in Galaxy Clusters



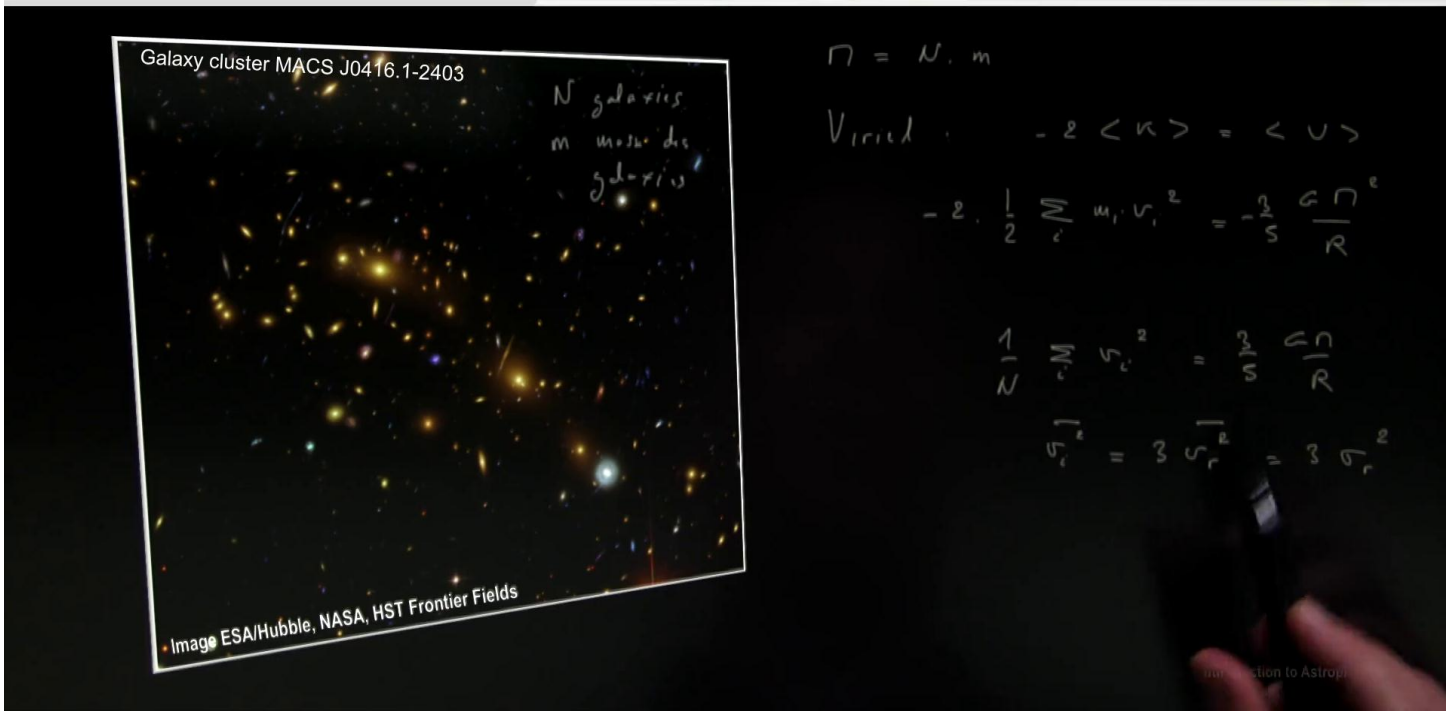
One has to pay attention when considering the spectra of all the galaxies, what is actually measured is the radial velocity of galaxies and not the total velocity v. Of course, if we assume that velocities are isotropic - all the galaxies go, on average, in all directions through the cluster of galaxies - this implies that v^2 mean = v^2 radial mean+ v^2 with respect to the angle θ in spherical coordinates, then v^2 with respect to the third axis in spherical coordinates. On average, those three components are equal, so one has that v squared is equal to 3 vr^2 mean which in turn is equal to the velocity dispersion squared. What was measured was the velocity dispersion, not the total velocity dispersion but the dispersion of the radial velocities measured by the Doppler effect for all the galaxies in the cluster. The width of this distribution, in any case the radial component, is the observable one. How can it be related with the mass? It is again the Virial theorem that is useful, let's see how to use it.

Notes

Summary

12m 54s

Dark Matter in Galaxy Clusters



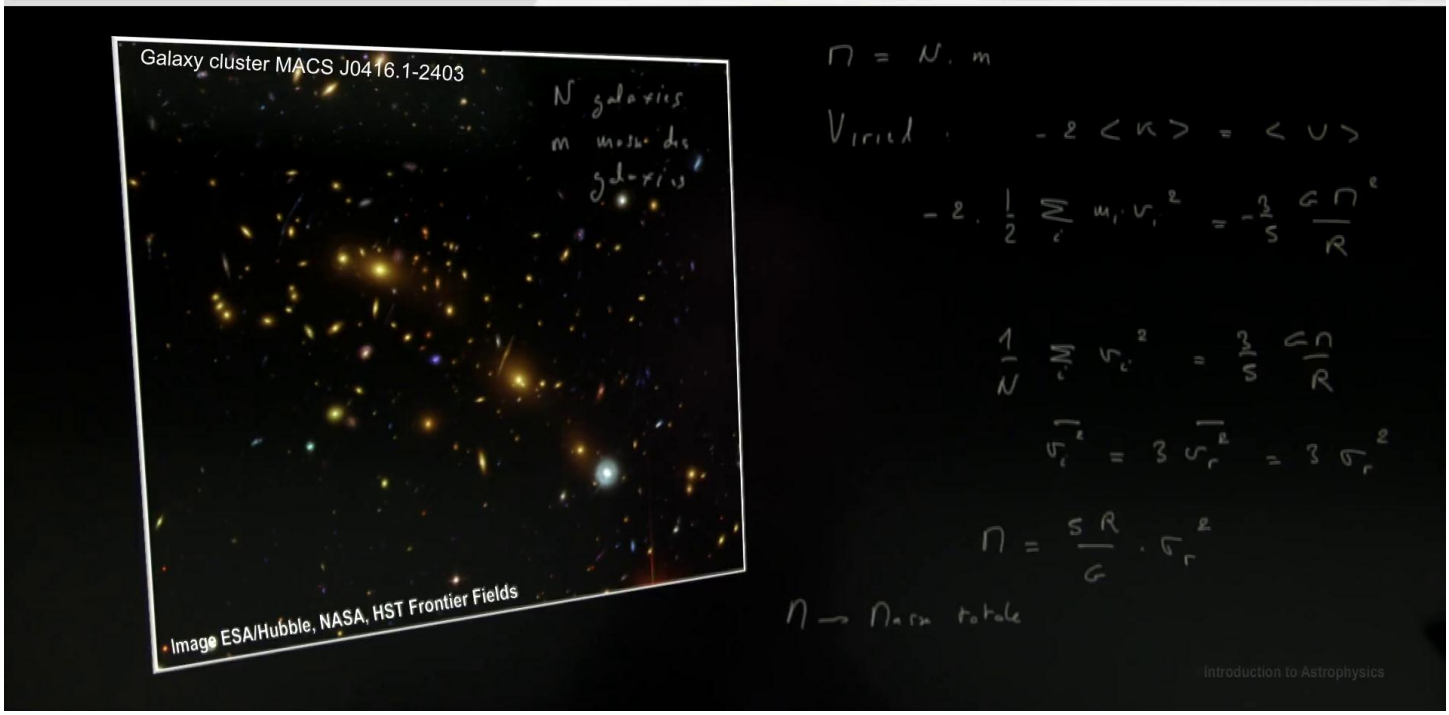
We have, say, n galaxies each of them has a mass m and velocity v. This si the mass of the cluster that is, M = N times m. In order to simplify the calculation all the galaxies are the same. The Virial theorem states that 2 times the mean kinetic energy is equal to the mean potential energy. Developing the expression gives -2 1/2 sum of mi vi ² - i is the index of the galaxies, it goes from 1 to M - this is equal to the potential energy of a sphere: - 3/5 GM² / R which is the total potential energy of the cluster. Now simplifying the calculation and taking into account this expression gives 1/N sum over i of vi ² equals 3/5 GM/R. This term is the mean spatial velocity squared in the galaxy. It was said that this is the mean kinetic energy, the time average, but for a large number of particles, as there are many galaxies in the cluster, the spatial average is equivalent to the time average. This implies that on the left-hand side one has vi² mean = 3/5 GM² / R, but also, as it was seen before, = 3 times vr² mean (isotropy of velocities) = 3 times σr ² which is the radial velocity dispersion of galaxies on the line of sight. Now, all one has to do is to replace this term by this one and solve this equation.

Notes

Summary

14m 23s

Dark Matter in Galaxy Clusters



One obtains an expression giving the total mass of the galaxy cluster. R is the cluster radius, G - gravitational constant, and here one has σr^2. What does it mean? It means that if all the Doppler velocities of galaxies in the cluster are measured, as well as the radial velocity dispersion and the radius of cluster - one can see that here it is possible to measure the radius in an approximate way - then one easily obtains the total mass of the galaxy cluster. M is the total mass. The Virial theorem was used which means that this mass represents matter that is sensitive to gravity: dark matter and luminous matter. Now, one only needs to measure luminous matter, the mass that is in the form of stars, and compare it with the total mass, the difference or the ratio between those two masses will indicate the amount of dark matter.

Notes

Summary

16m 36s

Dark Matter Mass-to-Light Ratio (M/L)

We have just seen that an important observable for galaxy clusters is the radial velocity dispersion that can be measured using the Doppler effect. One measures the radial velocity dispersion, obtains the total mass of the galaxy cluster, compares it with the mass of luminous matter and what typically will be found for galaxy clusters is a mass-to-light ratio of about a few hundreds in units of solar luminosity. This was done for the first time by the Swiss astronomer Fritz Zwicky who in the 30's was working at Caltech, United States. So the clues for the presence of dark matter on the scale of galaxy clusters exist since the 30's, even if there is still no explanation about its nature. For spiral galaxies where it is the rotation curve that is the observable, the rotation curve is flattened at large radii; if you remember, we had the predicted curve in this form, while the observed curve showed a flat part. The difference between those two curves indicates the presence of dark matter. The rotation curves were first measured by Vera Rubin in the 60's and used to reveal dark matter in spiral galaxies. The ratio M/L for spiral galaxies is typically of the order of 2 to 10.

Notes

Summary

17m 39s

The study of dark matter is one "hot topics" in modern astrophysics. What is its spatial distribution? What is its nature and how it influences the formation and evolution of celestial bodies around us? The first detections of dark matter were made in the 20th century, the 21st century is full of important observations and experiments aiming at characterizing it in details.

Notes

Summary

19m 19s