



In this very last video, we will see a natural phenomenon which is extremely useful to astrophysicist and cosmologist, the gravitational lensing phenomenon. It's a phenomenon also known as gravitational "mirage" by analogy with the optical mirages observed in the desert. As the name suggests, it is about the deviation of light not due to a changing refraction index in the propagation medium, but due to a strong gravitational field, as the one created by a galaxy, a star, a cluster of galaxies. As it passes near a massive object in the foreground, the light coming from a distant body will be deviated so that the background object will be distorted by the foreground object, and by studying the manner in which the object is distorted, we can deduce the matter, visible or not, in the foreground object which is then called a gravitational lens. We have already seen gravitational lenses during this class. For example in the galaxy cluster here with a Redshift of 0,397 with a mass of 10^{15} solar mass, this is an excellent gravitational lens.

Notes

Summary





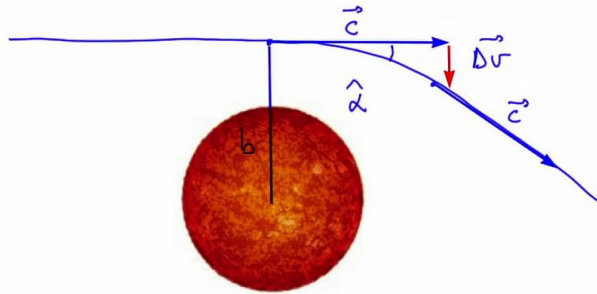
By zooming on the external parts of the cluster, we can see that there is a whole series of blue arcs which are the distorted image of distant galaxies by gravitational lens effect in the background of the galaxy cluster, which you see here and which is shown in greenish colours. So we will see in this class how the gravitational lens effect works and why it's such a precious tool for an astrophysicist.

[illegible]

Summary



Deflection Angle



$$\hat{\alpha} = \frac{\Delta v}{c}$$

Introduction to Astrophysics

We have seen that the gravitational lens effect is essentially a light deflection effect. We will see how to draw this. So a light ray arrives in the proximity of a mass, here the Sun, which I represent arbitrarily. The ray will be deviated, we have for example here a velocity vector which will be the light velocity. The ray will be deviated, and to get that deviation we will have an acceleration. So acceleration does not mean we will have velocities faster than light, but we will have a deviation of the light ray, we will have a changing velocity. We will have a photon that arrives with the velocity of light. We will have a photon leaving, after deflection, with the velocity of light and then we will have a velocity difference vector. So the photon will be accelerated for a while. We will get back later on this "for a while" the photon arrives with a certain impact parameter that we will call B , relative to the Sun or any mass that deviates light. What we intend to compute is the deflection angle we call α here. So this deflection angle, if we do some trigonometry we see that $\alpha = \frac{\|\Delta v\|}{c}$.

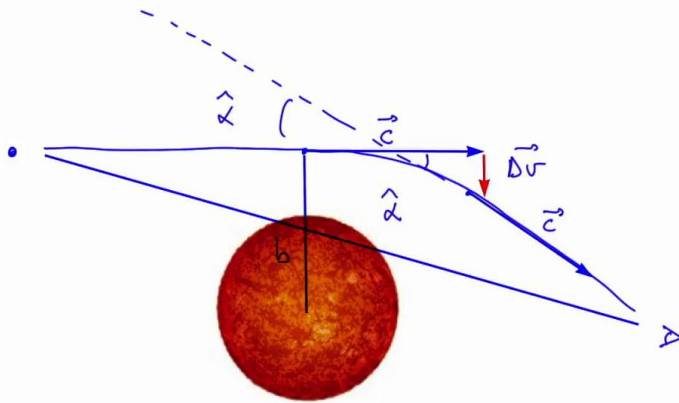
Notes

Summary



1m 44s

Deflection Angle



$$\hat{\alpha} = \frac{\Delta v}{c} \quad \hat{\alpha} \text{ petit}$$

$$\Delta v = \frac{GM}{b^2} \cdot \Delta t$$

$$\Delta t = \frac{b}{c} \quad \text{ordre de grandeur !}$$

$$\hat{\alpha} \sim \frac{GM}{c^2 b} \quad \hat{\alpha} \text{ ne depend pas de la longueur d'onde}$$

Introduction to Astrophysics

Keeping in mind that α^{\wedge} is always very small, of the order of a few tenths of an arcsecond, or of one arcsecond in the strongest cases. Now ΔV , what is it? It's the acceleration of the photon due to the Sun in this case here. So GM/b^2 during some time Δt . So this, is the acceleration during some time, it is indeed a velocity. Now the "some time" is just an order of magnitude here. We can say that the photon feels the acceleration, will be under the influence of the gravity field of the Sun during "some time" which will be of the order of magnitude b/c . Beware, this is simply an order of magnitude. Now if we take all these equations together, we will find that α is proportionnal to $GM/c^2 b$. But what we especially see is that the deflection angle depends only on the lens mass, the impact parameter and physical constants and in particular, α does not depend on wavelength. rather α^{\wedge} , sorry. So, counterintuitively, the deviation of a light ray does not depend upon energy or wavelength. In this case here, the result is that, if we put an observer here, instead of seeing the source where it was without the Sun, namely in this direction, we will see the light source so if we had a light source here, one would see it in the direction of this ray here, hence in this direction here. Here we also have α^{\wedge} .

Notes

Summary



3m 20s

Solar Eclipse and General Relativity (1919)

- Newton
 - Einstein (1912)
 - Observation
- Arthur Eddington



Introduction to Astrophysics

The deflection angle of light by a massive object was measured for the first time in 1919 during a Solar eclipse. Note that these ideas are not new. Actually, Newton had already raised the possibility of light deviation by mass. But it is in fact Einstein who predicted the phenomenon for the first time in unpublished notes in 1912. However, the observation only came later on. The observation, which actually provided evidence for Einstein's general relativity theory, was made in 1919 by Arthur Eddington, an English astrophysicist, during a solar eclipse. Note that the measurement principle is simple: we choose a stellar field. So, if we observe it during the night, we will of course see stars at certain positions relative to the Sun. So this is a moment when the Sun is not in the field of view. The white points are the positions where the stars would be if we observed them during the night. Now we put before the stars a certain mass, but since the Sun is bright, we will only see the stars during a solar eclipse. So here, during the eclipse, light rays coming from the stars will be deflected by the Sun and what we will see are stars fleeing the sun radially like this.

Notes

Summary



5m 27s

Solar Eclipse and General Relativity (1919)



- Newton
- Einstein (1912)
- Observation
- Arthur Eddington



$$\hat{\alpha}(\text{Newton}) = \frac{2GM}{c^2 b}$$

$$\hat{\alpha}(\text{Einstein}) = \frac{4GM}{c^2 b}$$

$$\hat{\alpha} = 1.75'' \left(\frac{M}{M_\odot} \right) \left(\frac{b}{R_\odot} \right)^{-1}$$

Introduction to Astrophysics

I'm drawing arrows of different lengths and the length of each arrow is inversely proportional to the impact parameter B , namely the projected distance on the sky between star and sun. So here is the deviation angle of light, each time in the radial direction. So the new star positions with the sun present in the field of view, will be the new positions indicated by red dots. Now, how far does this validate general relativity? If we measure, or rather predict, the $\hat{\alpha}$ angle using Newton's theory, namely the little demonstration we made earlier, we would predict $2GM/c^2b$ but $\hat{\alpha}(\text{Einstein})$, using the general relativity theory gives back twice that value, that is $4GM/c^2b$, where M is the Sun's mass and b the Sun's radius and if we took a star which would lie just at the edge of the Sun, assuming that we can perfectly measure a star at the edge of the Sun. Otherwise we would need to rescale by the factor b that we have here. So now the numerical values we have, are that $\hat{\alpha}$ is 1,75 arcseconds in solar mass units. Therefore, if we put solar masses here, $b / (\text{solar radius} - 1)$. That, provided we express b in solar radius units.

Notes

Summary



7m 12s

Solar Eclipse and General Relativity (1919)

- Newton
- Einstein (1912)
- Observation
Arthur Eddington



$$\hat{\alpha}(\text{Newton}) = \frac{2 G M}{c^2 b}$$

$$\hat{\alpha}(\text{Einstein}) = \frac{4 G M}{c^2 b}$$

$$\hat{\alpha} = 1.75'' \left(\frac{M}{M_\odot} \right) \left(\frac{b}{R_\odot} \right)^{-1}$$

$$\hat{\alpha}(\text{mesure}) = 1.75''$$

Introduction to Astrophysics

The measurement taken by Eddington gave 1.75 arcseconds, which is actually the numerical value predicted by general relativity. So the fundamental difference between $\alpha(\text{Newton})$ and $\alpha(\text{Einstein})$ is that, using Newton's theory of gravity, we have photons following curved trajectories in an Euclidean space. In the framework of the general relativity theory we find that photons travel along straight trajectories in a curved space, in other words trajectories that minimise the travel time of photons, so what we call geodesics; and these trajectories are those of shortest travel length in a curved space. So we have two radically different interpretations of gravitation, and this is what is crucial, and has given all the legitimacy to the general relativity theory, since we construe gravitational fields as acceleration fields and not anymore as forces that masses feel. So here we have a beautiful confirmation of the general relativity theory, simply because the angle measured by Eddington is exactly equal to the angle predicted by the general relativity theory.

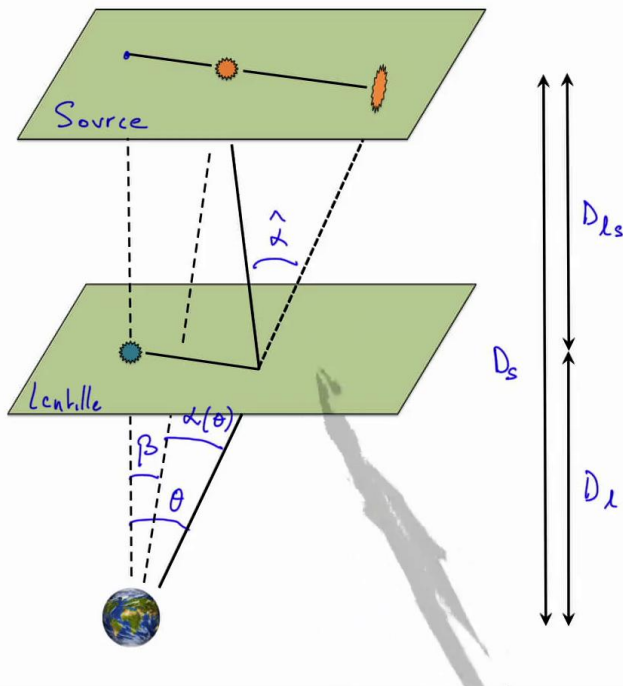
Notes

Summary



8m 55s

Lens Equation



$$\beta = \theta - \alpha(\theta)$$

Introduction to Astrophysics

So now let's see how all this works in more details. We have three important planes, if we draw the situation simply. We have a source represented in orange which is affected by the lens effect, here on the lens plane. This lens can be anything: a star, the sun or another star, a galaxy, a cluster of galaxies, or even, as we shall see, the great structures of the universe. So the source can be imaged. So light will be deviated by an angle α that we computed earlier and the source will be displaced and distorted by the gravitational lens effect. Now the source is located on the sky by an angle β relative to an arbitrary position. We will take here a reference point. The position of the images on the sky, as seen from Earth, is located by an angle θ and then, we also have an angle α which of course depends upon θ . We also have different distances here. We have the distance from observer to source, the distance from lens to source and the distance of the lens. And these distances are angular diameter distances. Now we have a very simple relation between those three angles. That is the lens equation. We have $\beta = \theta - \alpha(\theta)$. That is what we call the reduced deflection angle.

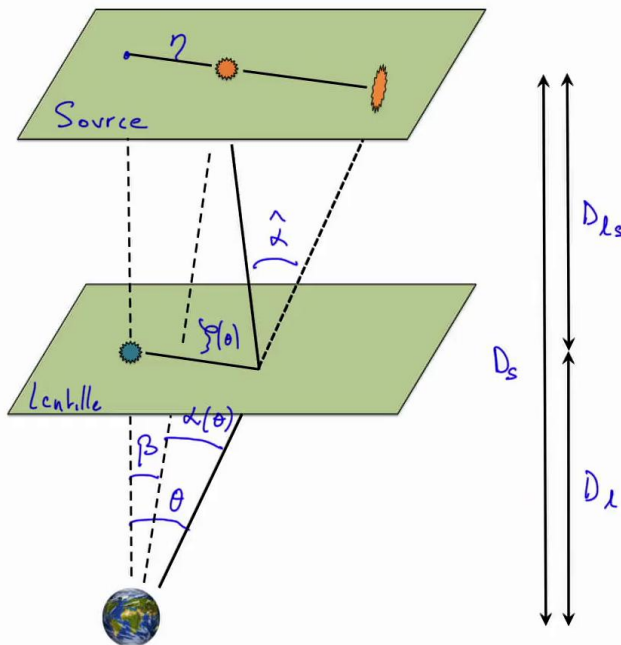
Notes

Summary



10m 17s

Lens Equation



$$\beta = \theta - \alpha(\theta)$$

$$\eta = \frac{D_s}{D_l} \zeta - D_{ls} \hat{\alpha}(\zeta)$$

$$\alpha(\theta) = \frac{D_{ls}}{D_s} \hat{\alpha}(\zeta)$$

Introduction to Astrophysics

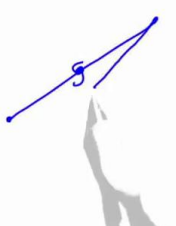
Beware, it's α , not α^\wedge . It is of course related to α^\wedge , we will see that later. Now we can also express things as a function of linear distances in the different planes. we will put η here and ζ there, which will depend upon θ , because if θ changes, ζ changes accordingly. We can even rewrite the lens equation. So here we have angles, there linear distances, and playing a bit of trigonometry, we will find this : $\eta = \Delta l / \Delta l \zeta - \Delta l s \alpha^\wedge$, so there, the α^\wedge appears. Thus, the relation between $\alpha(\theta)$ and α^\wedge , again by doing some trigonometry in the similar triangles here, we get $\alpha(\theta) = \Delta l s / \Delta s * \alpha^\wedge(\zeta)$. So there are some different forms of the very simple equation that is called the lens equation and which relates the different angles, or angular positions. Let's consider the angular positions of the various objects on the plane of the sky, β for the source, θ for the images, and α , the reduced deviation angle. we can also relate the linear distances to the different planes, but for that we have to know the angular diameter distances between the different objects.

Notes

Summary



Einstein Radius



$$\beta = 0 \Rightarrow \theta = \alpha(\theta)$$

$$= \frac{D_{ls}}{D_s} \hat{\alpha}(\zeta) \text{ avec } \zeta = \theta \cdot D_l$$

$$\theta = \frac{D_{ls}}{D_s} \cdot \frac{4G\eta}{c^2 \zeta} = \frac{D_{ls}}{D_s} \cdot \frac{4G\eta}{c^2 \theta \cdot D_l}$$

$$\text{Rayon d'Einstein} \leftarrow \theta_E = \sqrt{\frac{4G\eta}{c^2} \cdot \frac{D_{ls}}{D_s \cdot D_l}}$$

Introduction to Astrophysics

An extremely important, characteristic quantity is Einstein's radius. If the source, lens and observer are aligned, then we have $\beta = 0$, where the β angle represents the position of the source on the sky. So, if everything is aligned, we have $\beta = 0$, which means that the lens equation is greatly simplified. So we have $\theta = \alpha(\theta)$. It's a simplified version of the lens equation. So now $\alpha(\theta)$, we have seen that it was $\Delta l_s / \Delta s * \alpha^\wedge(\zeta)$. with ζ , if we look at the earlier figure again, and if we do some trigonometry, we have that ζ is linked to θ through the distance to the lens, from Earth to the lens. What does it mean exactly? It implies that $\theta = \Delta l_s / \Delta s * GM/c^2 \zeta$. that is $\alpha(\theta)$, which we linked to α^\wedge . So all that will be equal to $\Delta l_s / \Delta s * GM / (c^2 \theta \Delta l)$. Here, we have a θ here, a θ there, This θ on the other side, i will have a θ_e which will be Einstein's radius equal to $\sqrt{(GM / c^2) - M \text{ is the lens mass - and we will have a distance ratio } \Delta s / \Delta l}$. So θ_e is Einstein's radius. that means that, if we have a source aligned with the observer and then we have a lens, a small spiral galaxy for example, then the light will be able to go through the lens.

Notes

Summary



13m 20s

Einstein Radius



$$\beta = 0 \Rightarrow \theta = \alpha(\theta)$$

$$= \frac{D_{ls}}{D_s} \hat{\alpha}(\xi) \text{ avec } \xi = \theta \cdot D_l$$

$$\theta = \frac{D_{ls}}{D_s} \cdot \frac{4G\eta}{c^2 \xi} = \frac{D_{ls}}{D_s} \cdot \frac{4G\eta}{c^2 \theta \cdot D_l}$$

$$\text{Rayon d'Einstein} \leftarrow \theta_E = \sqrt{\frac{4G\eta}{c^2} \cdot \frac{D_{ls}}{D_s \cdot D_l}} \quad \eta = \eta(\theta_E)$$

Introduction to Astrophysics

Since we have a totally symmetric situation, we have a cylindrical symmetry and this angle here, is the Einstein radius θ_E . That means that the image of the source, seen from Earth, when we have a situation where $\beta = 0$ so where all objects are aligned, the lens equation has an infinity of solutions which are distributed over a circle with a diameter $2\theta_E$ and so the source has an image taking the shape of an annulus around the lens galaxy. As an example, here is a real object which is precisely in that case. The mass indicated here, M , is the Mass within Einstein's radius. So we see immediately that in this particular configuration, one can measure the mass of a lens galaxy included in the Einstein radius which is materialised by a circle; the latter is the shape taken by an object affected by the lens effect in case of perfect alignment between source, lens and observer. It turns out that θ_E , is also a characteristic quantity that gives an idea of the separation between the images of a source in a gravitational mirage, even if β is not exactly zero.

Notes

Summary



Solution for a Point-like Lens

$$\begin{aligned}\beta &= \theta - \alpha(\theta) \\ \alpha(\theta) &= \frac{\theta_E^2}{\theta} \\ \Rightarrow \beta &= \theta - \frac{\theta_E^2}{\theta} \quad \Leftrightarrow \quad \theta^2 - \beta\theta - \theta_E^2 = 0 \\ D &= \beta^2 + 4\theta_E^2 \\ \theta_{\pm} &= \frac{1}{2} \left(\beta \pm \sqrt{\beta^2 + 4\theta_E^2} \right) \\ \frac{\theta}{\theta_E} &= \frac{1}{2} \left(\frac{\beta}{\theta_E} \pm \sqrt{\left(\frac{\beta}{\theta_E}\right)^2 + 4} \right)\end{aligned}$$

Introduction to Astrophysics

Now let's consider again the lens equation and look at a simple case where we can solve it. So we have $\beta = \theta - \alpha(\theta)$. We see that $\alpha(\theta)$, if we look at the previous slide, can also be expressed like this as a function of θ_E . I said that θ_E is a characteristic quantity of lenses. One can simply rewrite the lens equation in a different way so that here one will have: $\beta = \theta - (\theta_E)^2/\theta$. Here, we are solving it in one dimension. One could of course have 2-dimensional angles. For example in x and y, if we want to thoroughly represent everything. Anyhow, for a point mass lens, we have cylindrical symmetry even spherical. So the choice of coordinates does not matter much. Now this is equivalent to a second degree equation in θ . If we solve this equation here, we will get a discriminant which reads $\beta^2 - 4\theta^2 * (\theta_E)^2$. So $\beta^2 + 4(\theta_E)^2$ this is a positive quantity, so we have two solutions and the solutions -- We will call them + and - and they will be equal to $1/2 (\beta \pm \sqrt{\beta^2 + 4\theta_E^2})$. So now, we can also divide everything by θ_E to have everything in θ_E units. since we said that it was a characteristic quantity of lenses, so we have the angles as a function of the Einstein radius.

Notes

Summary



16m 56s

Solution for a Point-like Lens

$$\beta = \theta - \alpha(\theta)$$

$$\alpha(\theta) = \frac{\theta_E^2}{\theta}$$

$$\Rightarrow \beta = \theta - \frac{\theta_E^2}{\theta} \quad \Leftrightarrow \quad \theta^2 - \beta\theta - \theta_E^2 = 0$$

$$D = \beta^2 + 4\theta_E^2$$

$$\theta_{\pm} = \frac{1}{2} \left(\beta \pm \sqrt{\beta^2 + 4\theta_E^2} \right)$$

$$\frac{\theta}{\theta_E} = \frac{1}{2} \left(\frac{\beta}{\theta_E} \pm \sqrt{\frac{\beta^2}{\theta_E^2} + 4} \right)$$

$\underbrace{\hspace{10em}}_{d_{\pm}}$

Introduction to Astrophysics

There, one has $1/2 (\beta \pm \sqrt{\beta^2 + 4\theta_E^2})$ we are not forced to do that, but it is common practice. So now this, I can call it d . We will write d_{\pm} for the signs here. That is a displacement vector which will be slightly bigger than this one here. What does that mean? It means that if I have a lens somewhere in the sky, and I have the Einstein radius which is like that... Here I show the Einstein radius, that does not mean that the source takes the shape of a circle, but it is the characteristic quantity associated with a lens of mass M . If I place my source somewhere β/θ_E , if we measure everything in arbitrary Einstein units, so if I take an arbitrary β , it will be β/θ_E , which can be found again here. If I add d_+ to this quantity here. I will have a mirror image that will form here, this is d_+ , that will be the θ_+ image, θ_+/θ_E since we measure everything as a function of the Einstein radius and then, so my source is here, I will write a quantity d_- equal to the norm in the other direction, so on the other side, so I will get somewhere around here, I have d_- . This will be the second mirage image of the source, that I will call θ_- .

Notes

Summary



Solution for a Point-like Lens

$$\beta = \theta - \alpha(\theta)$$

$$\alpha(\theta) = \frac{\theta_E^2}{\theta}$$

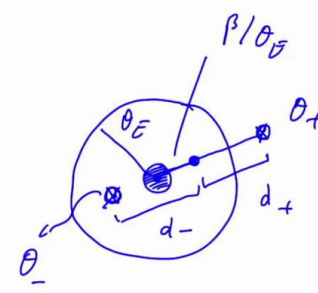
$$\Rightarrow \beta = \theta - \frac{\theta_E^2}{\theta} \quad \Leftrightarrow \quad \theta^2 - \beta\theta - \theta_E^2 = 0$$

$$D = \beta^2 + 4\theta_E^2$$

$$\theta_{\pm} = \frac{1}{2} \left(\beta \pm \sqrt{\beta^2 + 4\theta_E^2} \right)$$

$$\frac{\theta}{\theta_E} = \frac{1}{2} \left(\frac{\beta}{\theta_E} \pm \sqrt{\frac{\beta^2}{\theta_E^2} + 4} \right)$$

$\underbrace{\hspace{10em}}_{d_{\pm}}$



Introduction to Astrophysics

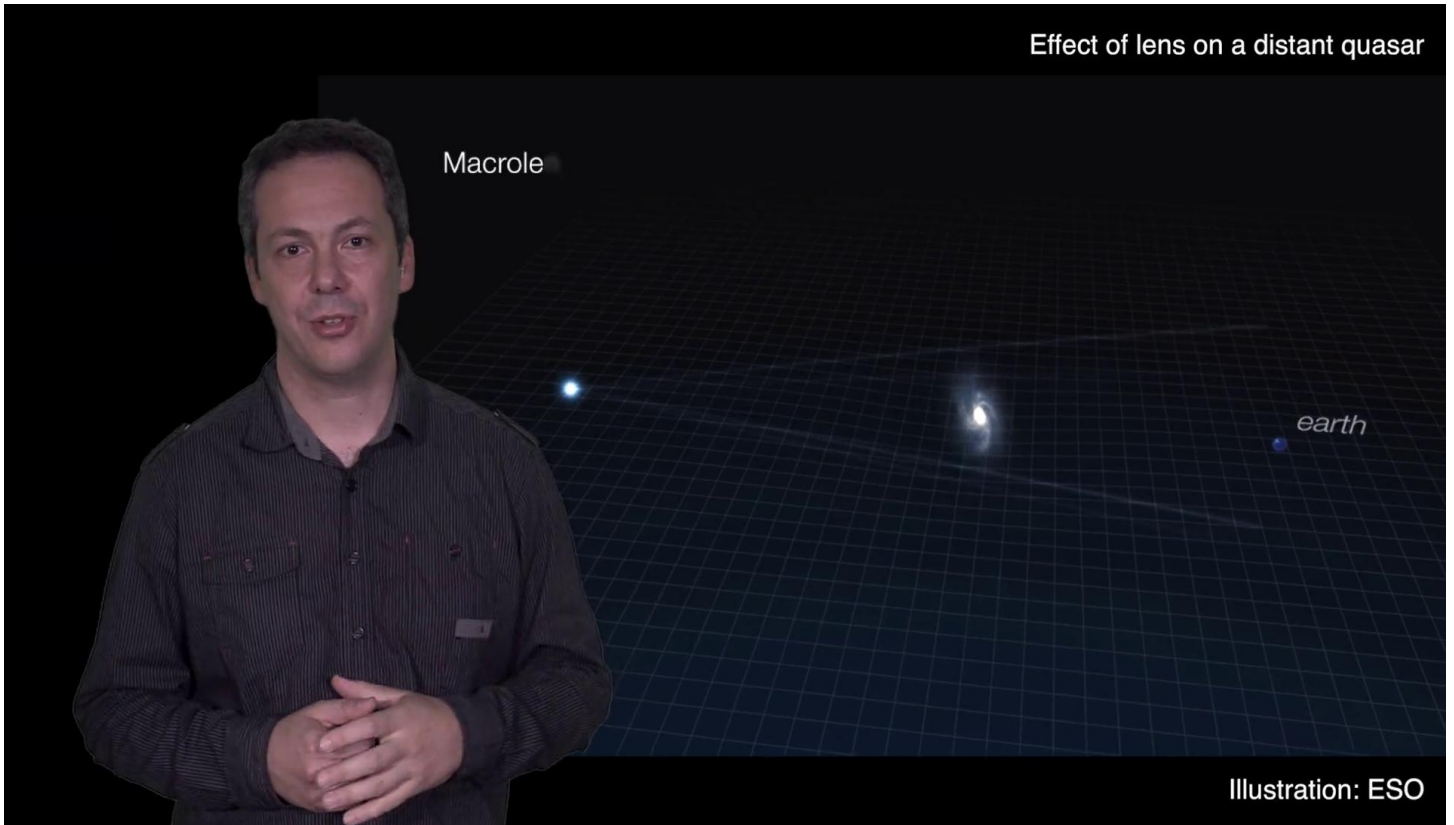
So we see here that in the case of lenses, we have a point lens, which means that the whole mass is concentrated in one point. M is constant as a function of the radius θ . If the lens is a point-mass, we'll have two mirage images on either side of the source. So, these are the two mirage images of the source which was here originally, and this is where was the object that is the lens.

Notes

Summary



20m 39s



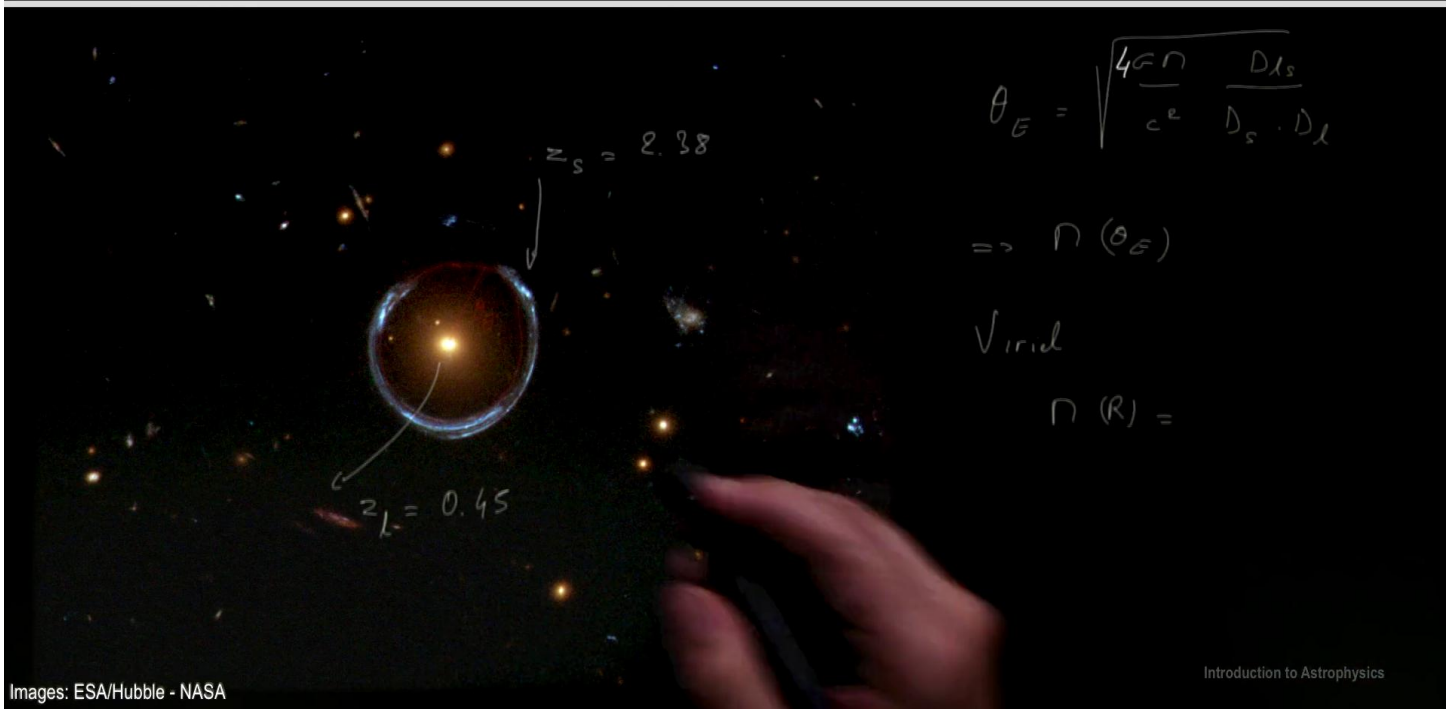
As we have just seen, photons can be deflected by gravitational fields. So on this figure we see a gravitational lens effect on a distant quasar, the very bright bright nucleus of a distant galaxy, hosting a supermassive black hole. When light rays from the quasar pass near the lens galaxy, the foreground galaxy, they are deflected, and the image of the background object - the quasar - is modified. We have seen in the previous slides that in the simple case of a point-mass lens, we predicted two mirage images of the background object, the quasar in this instance. But actually, when the models are a bit more realistic, we predict that we always get an odd number of images, 3 or 5 depending on the shape of the foreground lens. In the animation shown here, one sees in fact 4 images of the quasar, the fifth image lying between the 4 images distributed around the lens galaxy; and the lens galaxy, because of its brightness, masks the fifth image.

Notes

Summary



Application to Galaxies



So we talked earlier about Einstein's rings we have just seen in the video, in the previous animation, 4 mirage images of a quasar. Now what happens if instead of a point like source, the latter is slightly extended and if the source is perfectly aligned with the lens? We obtain in that case of a situation like this, a perfect Einstein ring. Here is a lens galaxy with a redshift z_l of 0.45. We have a source, the red shift of which, z_s , is equal to 2.38 in this case. And we see at once, here, the Einstein ring materialize. I'm drawing it here in red but it is already very well-defined by the blue background galaxy at $z=2.38$ which appears as a very distinct Einstein ring. What we see here is the Einstein ring. Now, we have said that $\theta_E = \sqrt{((GM / c^2)(D_{ls}/D_s \cdot D_l))}$ and we have a distance ratio here. So we have distances, and we need to convert the red shifts into distances using a cosmological model. So if we have that equation here then we inverse the equation and we deduce from it the mass inside the Einstein ring. Now it's the mass inside θ_E but the Virial would also give us the mass within a certain radius R that can be chosen arbitrarily.

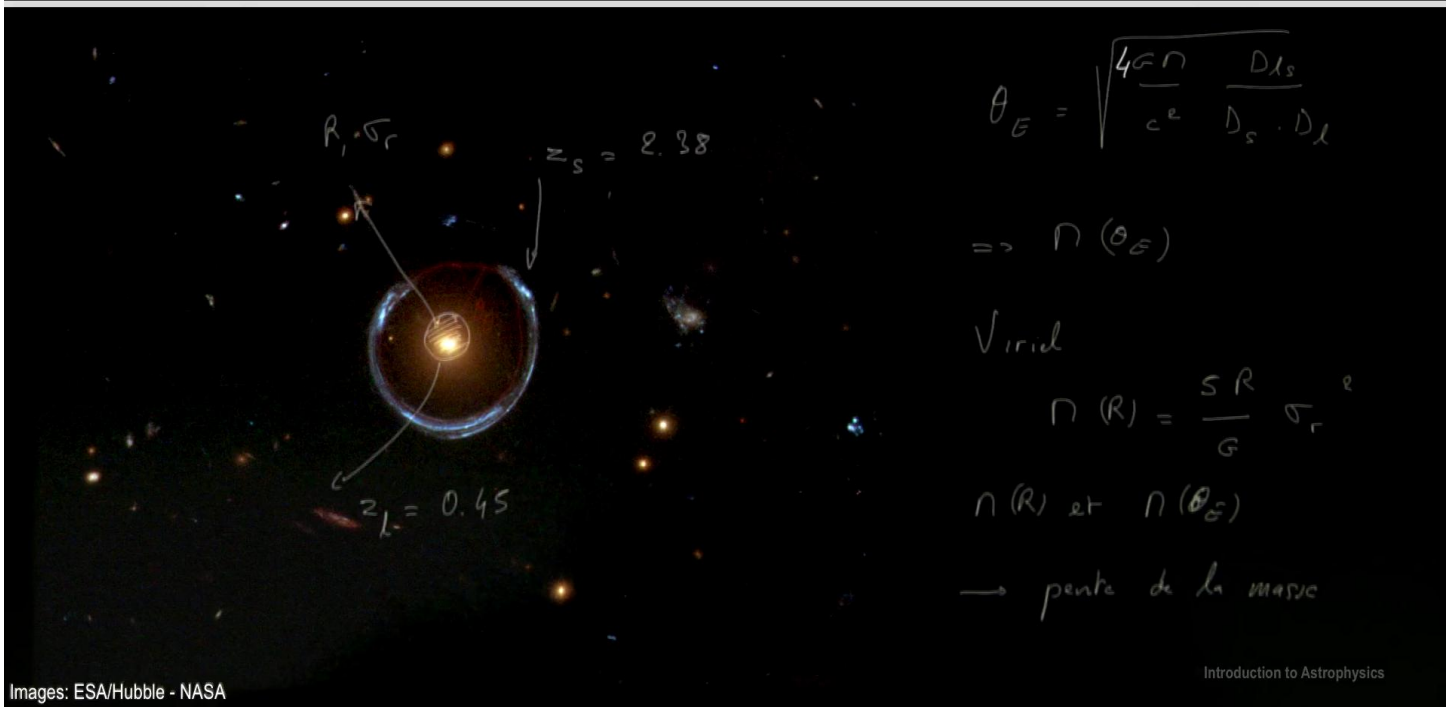
Notes

Summary



22m 21s

Application to Galaxies



So, if we measure the velocity dispersion of the stars within a certain radius R , we have seen in the chapter about dark matter that mass is related to the dispersion of the radial velocities in this way here. This means that if we measure σ_r through the Doppler effect, in an aperture as shown here, here we have a certain radius, a certain σ_r measured by Doppler effect. We'll have the mass within a certain radius and the mass inside the Einstein ring which is here. So we'll get two mass estimates inside different radii meaning we'll have access to the mass gradient. It's extremely important to constrain the models of galaxy formation that are produced through numerical simulation. The mass gradient measurement is possible partly through this gravitational lens effect combined with the velocity dispersion in well chosen apertures. We already see that the strong gravitational lens effect, strong because it produces large mirage images of background objects; we see that the gravitational lens effect is an extremely powerful tool to measure mass as a function of radius and we can measure the luminous mass and the total mass thanks to this phenomenon of gravitational lensing, since it only depends on gravitation. We do not need to see the mass to measure the effect it has on background objects.

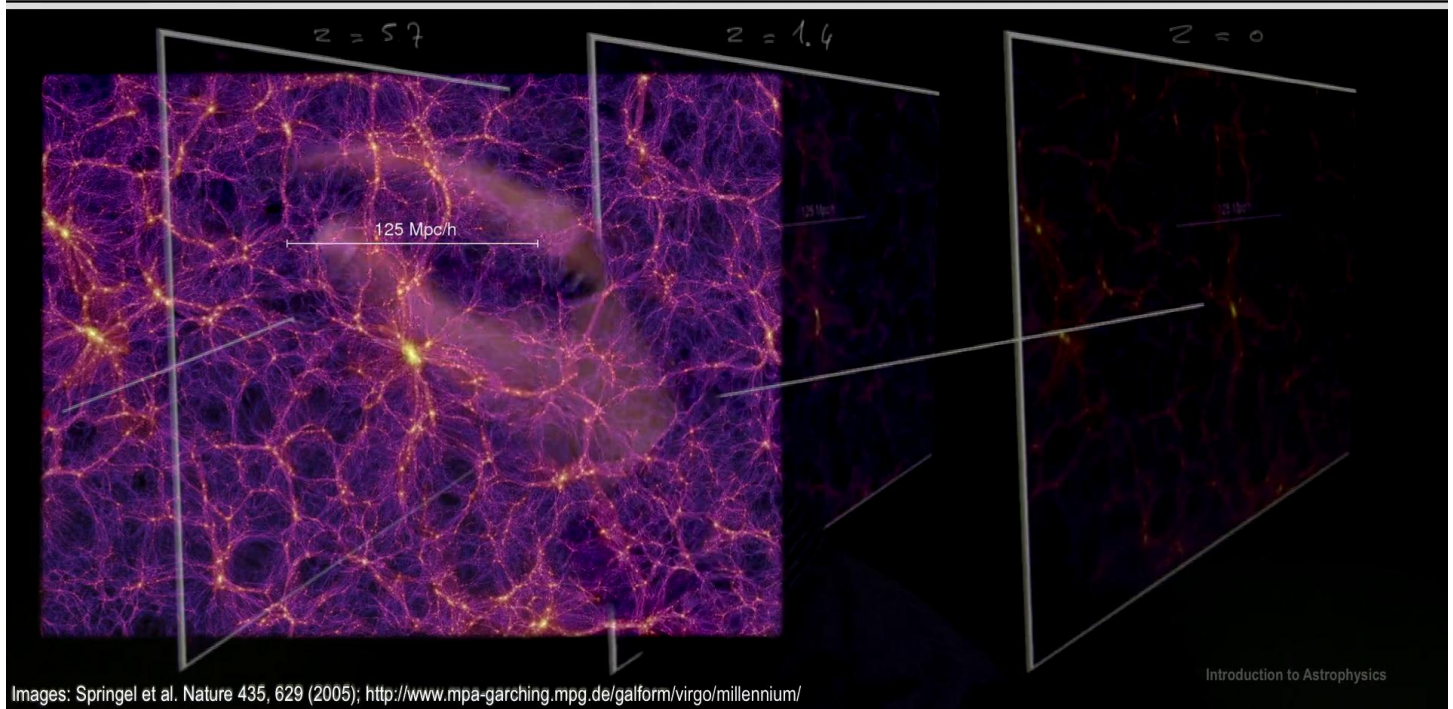
Notes

Summary



24m 07s

Application to the Whole Universe



Last example, there are in fact multiple applications of the gravitational lens effect, we will not describe them all here. We have seen the strong gravitational lens effect, which produces multiple images of background objects, namely Einstein rings. Now we'll see the weak gravitational lens effect. it's an effect which causes weak deformations of background objects, but it is also present everywhere in the Universe. Here we see a slice of the Universe, it's a numerical simulation. We see different slices of the Universe at different red shifts. We see evolving structures. We have a red shift of 0, this is the present epoch. Here we have a red shift, it's a numerical simulation. In the numerical simulation, the red shift was of 1.4. And here we have a red shift of 5.7. Now if we take some light rays coming from far away. The light rays will intercept each plane. We'll have a deviation of light which arrives for example here in this plane here. It will be deflected again by a mass lying, for example, here. It will arrive at the plane, around the present epoch. If we have the image of a background object here, for instance, we'll see its distorted image by lens effect and we'll see it distorted at its arrival, hence at the present time where we observe the background source.

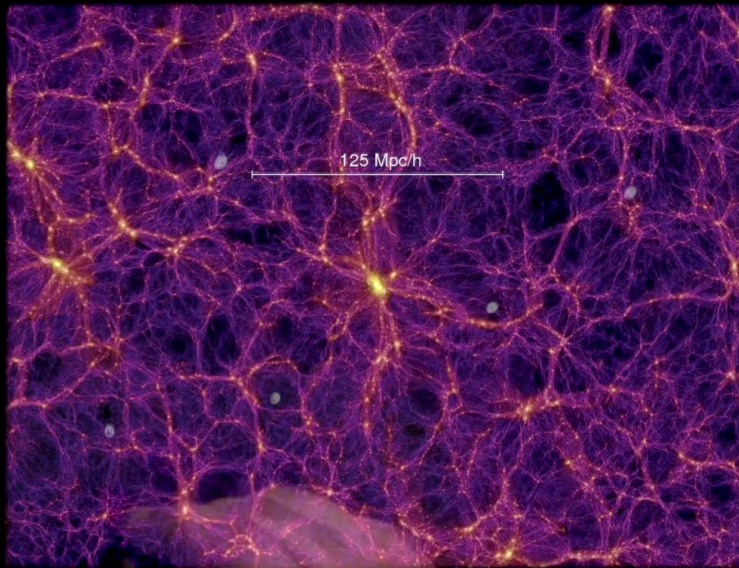
Notes

Summary



25m 46s

Application to the Whole Universe



Images: Springel et al. Nature 435, 629 (2005); <http://www.mpa-garching.mpg.de/galform/virgo/millennium/>

Introduction to Astrophysics

So this effect is very weak, we need to measure it on a lot of galaxies and take an average to see it, but it is something detectable. Of course the effect will change as a function of what we put in the different slices of the universe. The deformations predicted by the cosmological models will change as a function of H_0 , of the composition of the Universe, of the composition in terms of dark energy and dark matter. We will not have the same predicted universe and so will not predict the same deformation. The point here, the goal will be to measure the distortions of these extremely distant galaxies, using this mirage effect, which is weak. We of course exaggerated the light deviations to be able to constrain the cosmological models. In practice, how will we proceed? We take a slice of the present universe. This is a simulation, in practice we do not see the simulated filaments. Actually, the galaxy clusters, here we have gigantic scales, the galaxy clusters can be found at the connections between the filaments. But filaments are essentially composed of weakly luminous matter and dark matter. Now, assuming that the background galaxies are round like this. I'm placing them like this.

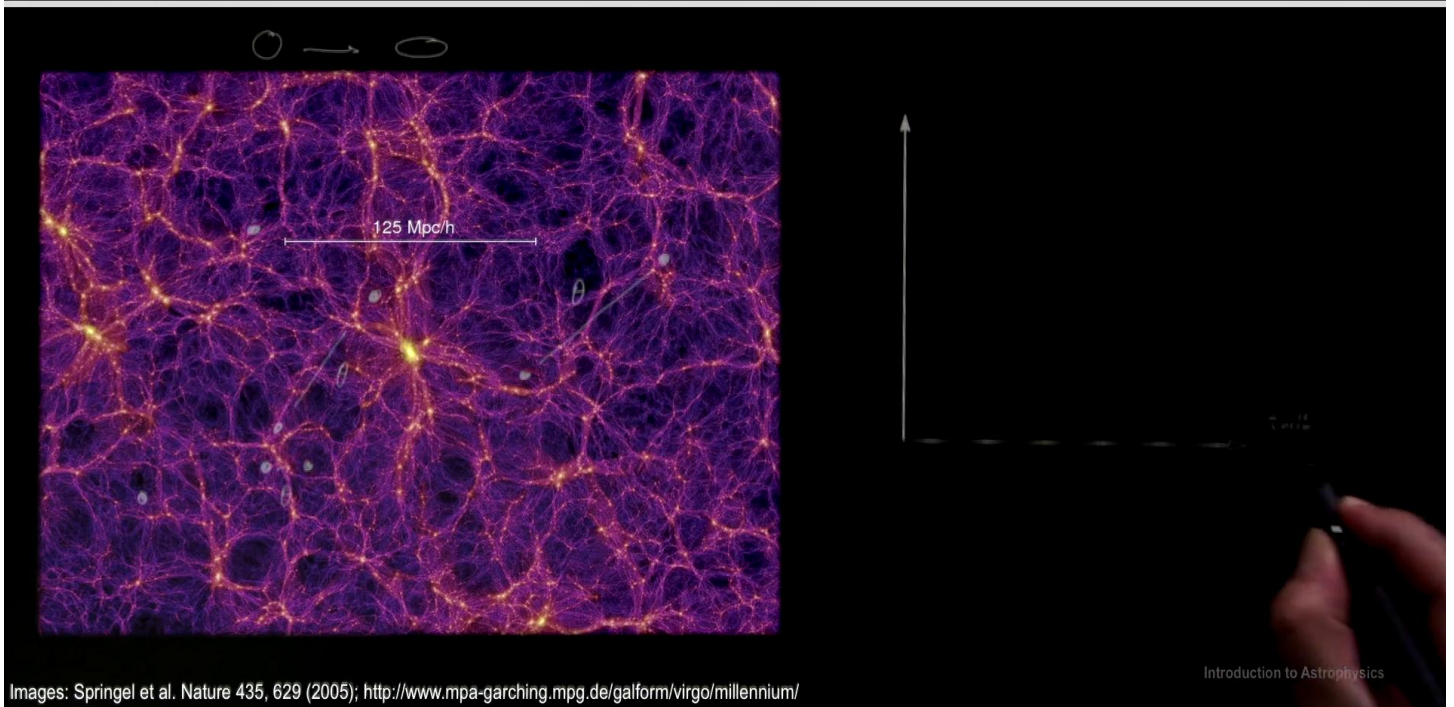
Notes

Summary



27m 17s

Application to the Whole Universe



They are of course billions, I only have a few. Some of them are near each other, others are far away from each other; each time the rays are deflected, what will happen is that a circular galaxy will be distorted into a small ellipse by the lens effect. The distortion will be tangential with respect to the direction of the mass. A round galaxy, and some mass here, it will be distorted by lensing effect, I'm exaggerating the deformation a lot but in this manner Here, if we have a massive filament going through here, the distortion will be like this. Here the distortion will be like this. We can draw a lot of others, I cannot show them all. But here for example, we have several galaxies distorted by approximately the same filaments. Here, there is another like this. We can see that the shapes of galaxies which are affected by the same filament, will obviously be more correlated than galaxies distorted by filaments lying very far away, angularly on the sky. So here, between two galaxies, we have an angle θ , there another angle θ , what we'll be able to measure in practice is what we call the 2-points correlation function of the shapes of the galaxies.

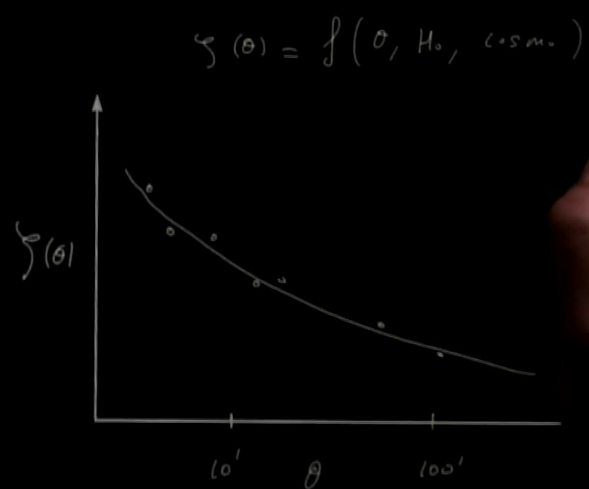
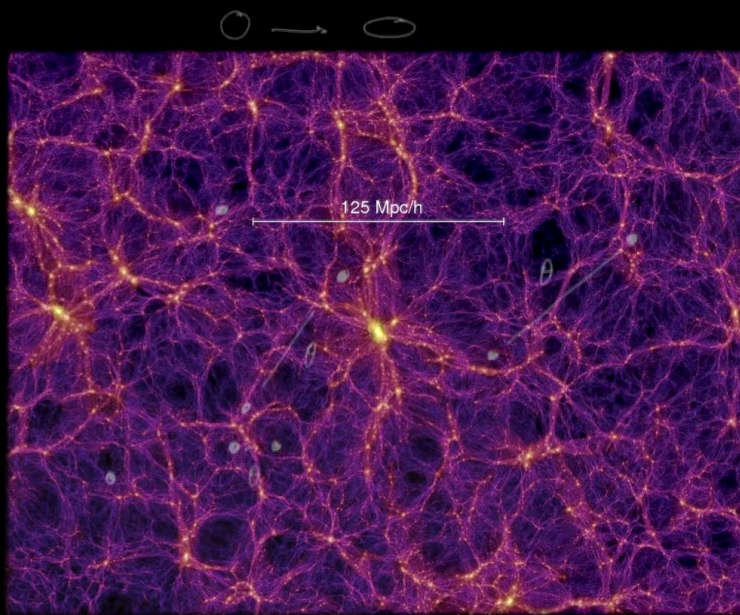
Notes

Summary



28m 41s

Application to the Whole Universe



Images: Springel et al. Nature 435, 629 (2005); <http://www.mpa-garching.mpg.de/galform/virgo/millennium/>

Introduction to Astrophysics

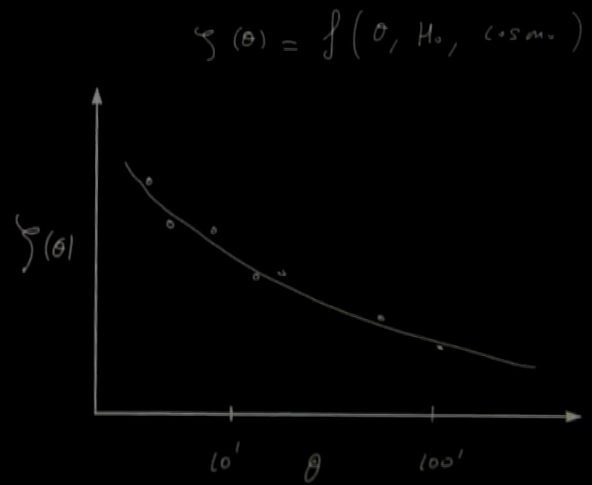
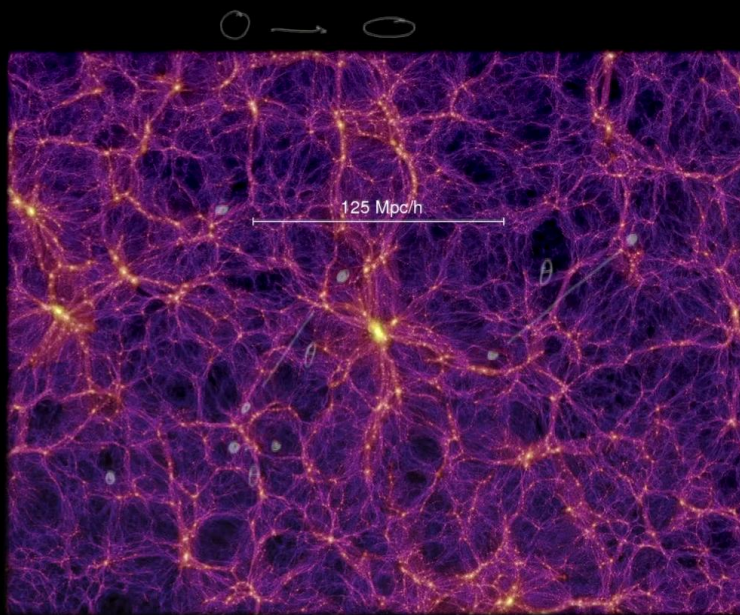
This correlation function, we'll omit the details here, we'll call it $\zeta(\theta)$. We have here the θ angle, the typical scales are 10 arcminutes to 100 arcminutes on the sky, hence the importance of taking wide field images. We want to measure the correlation function over very large scales; so for small angles, we look at the correlation of the shapes of galaxies which are separated by a certain angle θ . Then, of course, the galaxies that lie close to each other feel a lens effect due to the same filaments, so the correlation is very strong. Galaxies lying far away from each other, hence at high θ , will be much less correlated. What we expect to see is a correlation function that will decrease like this. The goal is to measure the distortions of all galaxies over the whole sky and to measure the shapes of all galaxies over the whole sky and to measure the correlations at every scale. The idea is to take the most precise measurement points, here, to discriminate between the different curves, the different correlation functions here, which are predicted by the cosmological models. The cosmological models will predict a correlation function or a power spectrum which will be a function of θ of course, of H_0 , and then of cosmology.

Notes

Summary



Application to the Whole Universe



Images: Springel et al. Nature 435, 629 (2005); <http://www.mpa-garching.mpg.de/galform/virgo/millennium/>

Introduction to Astrophysics

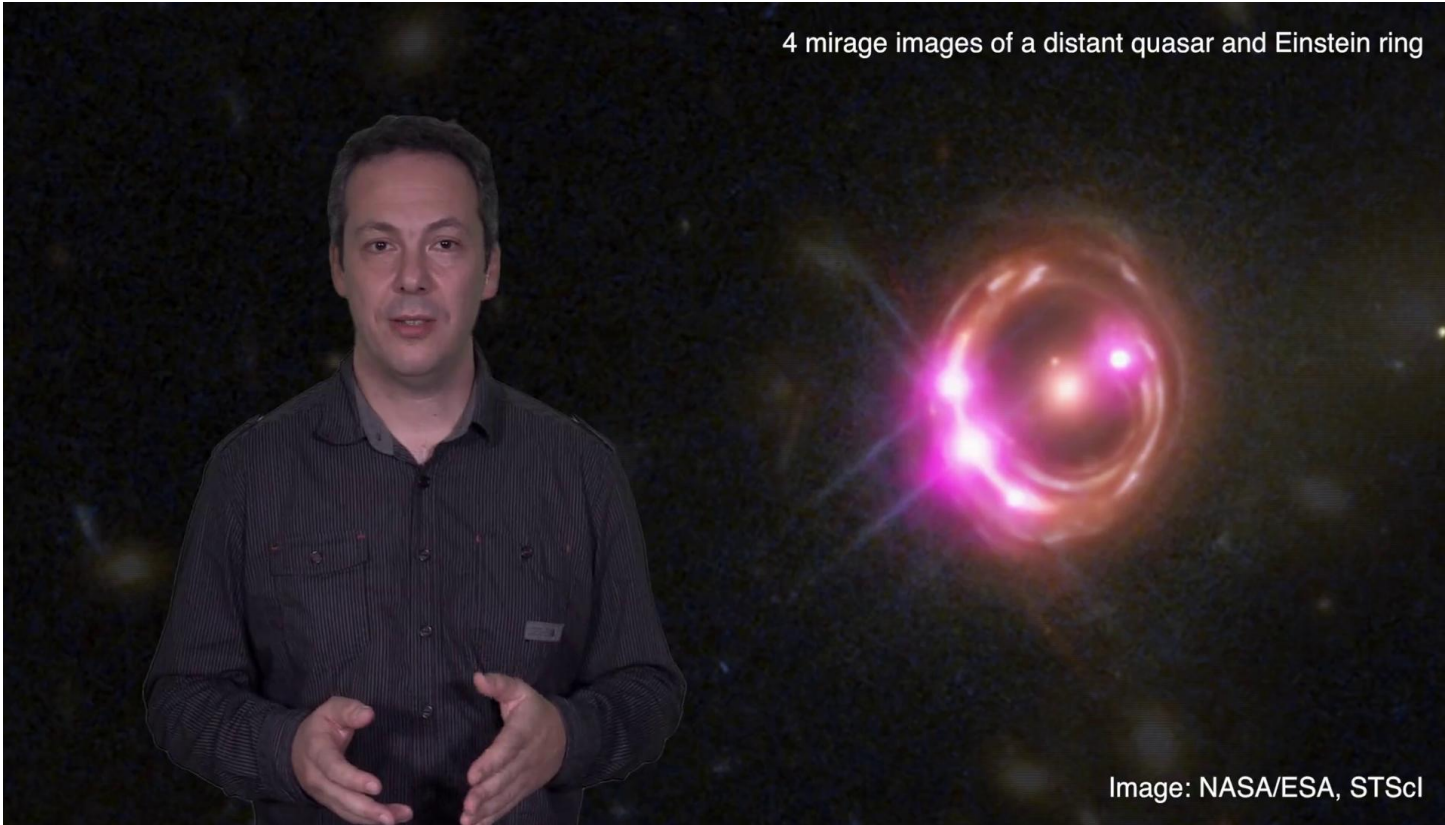
Cosmology is, among other things, H_0 , but also the densities of the different components of the universe namely dark matter, dark energy. Thanks to these measurements of weak gravitational lensing and of the correlation function of galaxy shapes everywhere in the universe, we can constrain cosmological models, provided we have, as far as possible, a map of the whole sky with a very high spatial resolution.

Notes

Summary

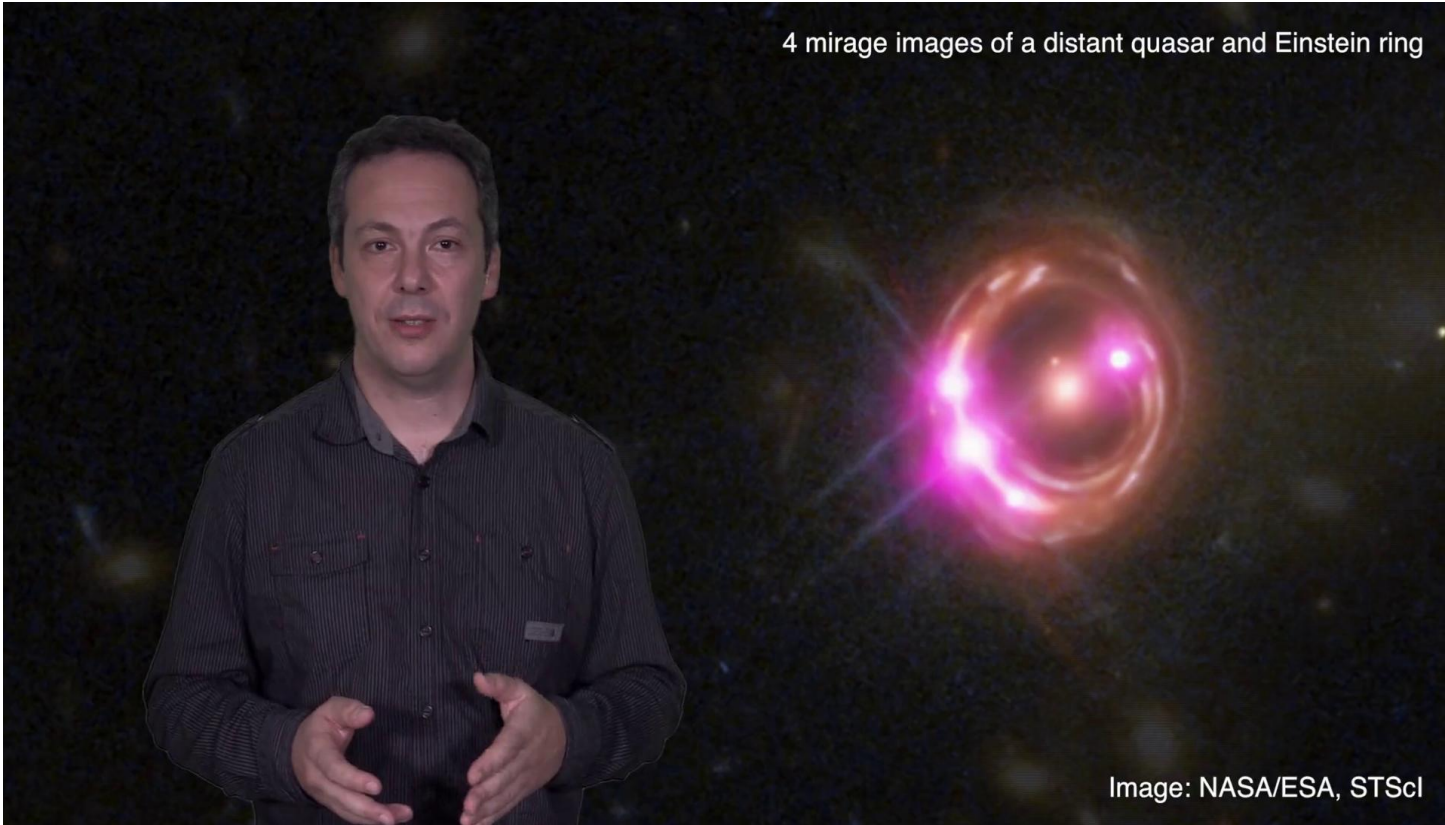


31m 29s



4 mirage images of a distant quasar and Einstein ring

Image: NASA/ESA, STScI




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The gravitational lens effect manifests itself at all mass scales and at all spatial scales : from stellar scales or even planetary ones, to galaxies or even galaxy clusters. We have even seen that the largest structures in the universe, the cosmic filaments, produce a weak but measurable lensing effect and that these measurements allow us to determine the cosmological parameters, the parameters which describe how the universe is evolving and what its composition is.

[illegible]

Summary







So for now the future of cosmology depends on our ability to map the whole universe and not just some well targeted areas as we were able to make until now. This concludes this week of lectures and our MOOC of introduction to astrophysics. We have introduced a large variety of topics and described physical concepts hiding behind astronomical observations and their interpretations. The goal has been to understand the principles, rather than the detailed mathematical developments.

- Notes

Summary





I hope this goal has been achieved. But I especially hope that you took as much pleasure in following this course as we had preparing it.

- Notes

Summary

