BLOSSOMS VIDEO MODULE

GALAXIES AND DARK MATTER
BY PETER FISHER

So hello! My name is Peter Fisher. I'm a professor here at MIT and this is a Blossoms module on galaxies and dark matter. In the next hour we're going to talk about what a galaxy is and a little bit about how it works. Then we're going to talk about how, in order to understand how a galaxy works, we need to introduce a new form of matter which is called dark matter. Dark matter is one of the most pressing issues for physicists today because we really don't have any idea what dark matter is. We'll talk a little bit toward the end about dark matter's properties but really the main message is that the shape of our galaxy is really determined by the presence of dark matter.

Many of you probably know that galaxies are large collections of stars but we didn't always know that. Around the turn of the century people looked at images like this one, which shows a cluster of actually 1,000 galaxies called the **Coma** Cluster and they saw that in contrast to the surrounding stars, galaxies were fuzzy, they were extended, whereas stars looked like little light points, and they were different colors. Astronomers referred to them at nebulae. The word comes from the Latin for fog or mist, so they were like these little blobs of mist. And it was some time before astronomers realized, about the turn of the century as I mentioned, that galaxies were really very large collections of stars. One of the people who did pioneering work in this area was this fellow named Fritz **Zwicky** who was an astronomer at **Caltech**.

Here's an image of 1,000 galaxies and stars, and I'd like you to take a few minutes to look at this image and try to look at each object and decide whether you think it's a star or a galaxy. Knowing what you know, that a galaxy is a collection of stars, how does a galaxy in this picture look different than a picture of a star? So let's take four minutes and go ahead and do that.

All right. Welcome back. I hope you learned some things looking at the image. This is a close up of the nearest galaxy to earth, the Andromeda galaxy which is called **M31**. It's about two and a half light years away. I'm sorry, two and a half million light years away. So the light that we see in the Hubble space telescope that took this image took about two and a half million years to get to earth. This galaxy is a little bit bigger than the Milky Way and has about a trillion stars in it. So it weighs about a trillion times, the stars weigh about a trillion times the mass of our sun. And even in this picture, which is the very best picture you can get from the Hubble space telescope, which is the very best telescope there is, you can't really see individual stars inside of the galaxy. What you can see is a very broad, bright region here and then a more diffuse region outside. And that's mostly stars and some gas clouds.

So what makes a galaxy have this shape? Well it's all about gravity. And the matter in the center of the galaxy is exerting a gravitational force on stars on the outside of the galaxy and they're orbiting around the galaxy like this. Now the stars, for example halfway out, are moving at some velocity of about 300 **km** per second, but this galaxy is so huge it's going to take them two hundred million years to go all the way around once. So in the time scale that we've been making observations, these stars haven't moved at all. So if you we want to study the ways stars move within a galaxy, we have to use a different method.

So here's a picture of a galaxy looking at the top. We'll just approximate it as a circle which is a collection of stars, as I said about a trillion stars. And the stars are orbiting around the center. And the question is what causes them to orbit? Here's a star and it's in circular motion just like a planet in our solar system. So as you've learned, if this is our solar system and here's the sun and here's the earth here, the earth has some velocity, our orbital velocity in this direction which is about a few thousand miles per hour. And the thing that's keeping the earth orbiting around the sun is a gravitational force that's pulling the earth towards the sun along this direction. So the force only acts along the line connecting the earth and sun and then the velocity swings the earth around keeping this distance constant just like a ball on a string.

In the next demo you have a ball on a string and swing it around your head and let it go. The string is providing a force like gravity and when you let it go, the ball just goes flying off. So try this and take a few minutes discussing the role of the string, gravity, and why the ball goes straight when you let it go.

So if we come back now that you understand a little bit about how force makes something move in a circle, here's our star and it's moving like this at some radius from the center of the galaxy. And one thing you probably learned in your elementary physics studies is that if we look at this star, it's got a centripetal force acting on it, and that's equal to the mass of the star, times its velocity squared, divided by the distance from the center of attraction. Newton's gravitational law says that the force acting on the star from gravity, in order to make it move at this radius at this velocity, is equal to a constant which is called G or Newton's constant. The mass inside of the radius, which is the mass of the galaxy inside that region, times the mass of the star, divided by the radius squared. This must be equal to this because the centripetal force is balanced by the gravitational force and so we can set these two things equal to each other. And what we see is that we have an M (the mass of the star on both sides) so that cancels out. And we have an R^2 and an R on both sides, so those cancel out. So that we can show that the mass inside of a given radius is equal to the velocity of the star moving at that radius times the radius divided by Newton's constant. So this tell us something very important about observation which is if we can measure of the velocity and radius of a star inside of a galaxy we can measure the total mass of the galaxy inside of that radius.

Here's a little demo using the ball and string again. The force you exert on the string to make the ball go around is like gravity. Swing the ball around ten times slowly paying attention to how much force you need to exert on the string. Now swing the ball around very fast. How does the force you exert change? In gravity the force is related to the mass of the galaxy. So the greater the velocity of the star, the more mass there is inside the orbit of the star. This we showed in the relation $M = V^2 \times R \div G$. In this case R is the same because the length of the string doesn't change. So V goes up and means that the force you exert is much greater.

So what we've shown through the demonstration and the equation is that you can relate the mass inside of the radius of a star with the velocity at which that star is moving. So if you can measure the velocities of stars within a galaxy, then you can determine what the mass of stars at a given radius are and compare that with the amount of light you see. That measurement was first undertaken in the 1970s by the astronomer Vera **Rubin** who observed the Andromeda galaxy which is shown here, this is the one we looked at before. She was able to make use of the Doppler shift of light from a moving object in order to determine its velocity.

Now the Doppler shift is a phenomenon that works with any wave, light, or sound, which is the result of a moving source squishing the wave and making it appear at a high frequency if the source is moving toward you, or a lower frequency if the source is moving away. You might have studied this already in your physics course. If you have, let's take a few minutes to review it. If not, let's take a few minutes for your instructor to explain it to you briefly at the blackboard.

So now that you understand a little bit about how you can use the color of the star to determine its velocity, we can see what Vera **Rubin** has done. Here's a graph superimposed on top of the galaxy with her velocity measurements as a function of radius. She did this by just focusing her telescope at different points along the radius of Andromeda and measuring the color of the star, which as we've just seen tells you the velocity. What you can see is the velocity changes a lot in the center of the galaxy and then becomes constant as you go out further to larger radii. Remember the mass inside of a radius is equal to the velocity squared times the radius divided by Newton's constant. And R is increasing as you go further out. Vera **Rubin**'s data says the velocity is constant so the amount of mass inside the radius must be going up because V is constant and R is going up.

What you can see if you look at the image of Andromeda is that the number of the stars or the amount of visible matter is decreasing as you move out in radius because the image is dimmer. This means that in order to explain this data, which is called the rotation curve, there has to be some component of the mass that isn't visible, that isn't emitting light, and that's called dark matter.

So once Vera **Rubin** had measured the mass inside of a given radius of M31, the next step was to find out what mass you would predict from the number of stars inside of that radius. So what was done is people observed nearby stars, the **Kaptain** stars and measured the total light output inside of the star. And since the star was nearby, by observing its motion inside of our galaxy one could measure the mass of the star. And I'll put a little star on it. So this could be done with our sun or some nearby stars called the **Kaptain** stars. Then in order to compare with what was measured using the rotation curve, one could take the light of M31 inside of the same radius as this mass was measured and then multiply by this ratio. And this is another way of measuring the mass of M31, but this is from light. And this is from velocity.

It turns out that this mass is something like ten times this mass. And that tells us that there must be a significant amount of mass inside of M31 that isn't stars, that isn't emitting light, but that is in fact dark matter. After **Rubin's** measurement in 1972, many people thought that the dark matter inside of the galaxy could be planets, large dust clouds, failed stars, things like that. But measurements of the relic particles from the Big Bang that were made in the 1980s and 1990s systematically excluded all of those things. And now we're left with really only one possibility which is that dark matter is some new kind of particle which could be either very light or very heavy but it's no kind of particle we've ever seen here on earth before and we call it a "WIMP"—a weakly interacting massive particle.

So here's a question for you to discuss. What else could this matter be? We've shown this two different ways now and the question is what do you think it could be?

So one idea for WIMPs is that they are some weakly interacting massive particle. Weakly interacting means they don't interact much with normal matter. So they're called WIMPs. What does it mean to not interact much with normal matter? Well if we take the matter we know about, the particle that interacts the least is called the neutrino. The neutrino was originally postulated by Enrico **Fermi** in the 1930s and first observed in 1956 by **Reines** and Cowan. A neutrino interacts so little that if you wanted a neutrino to interact you would have to line up 200 earths. So here's your neutrino and then you take 200 copies of the earth. And if you sent this neutrino in you could be guaranteed that it would interact, it would hit another particle somewhere in here. A WIMP has an interaction strength that is at most the strength of the neutrino interaction divided by ten million. Now neutrinos are notoriously difficult to detect and people have spent their careers trying to detect them in various ways. They usually require detectors at accelerators that weigh tens or hundreds of even thousands of tons, and even with detectors that big only a few neutrinos interact each day. Here is something that interacts ten million times less. And that makes dark matter very difficult to find.

So the mass of a dark matter particle, our best guess is they weigh between 100 and 1,000 times as much as a proton. And you know a proton is about the simplest nucleus we can have. And their density inside of the galaxy is about one particle per 1,000 cubic cm or about one particle per liter. And they're moving at a velocity of 1,000th the speed of light, which is 300,000 meters/sec. This seems pretty fast but actually by particle physics standards this is very slow. This is not many particles to work with. This is pretty heavy. So the best way to detect such a particle is to look for it hitting a normal nucleus here on earth and giving it some energy. So here's a normal nucleus and the dark matter particle is going to hit it and go off in some direction and then this nucleus is going to recoil with some energy and our job is to detect that energy.

Dark matter particles can hit a atomic nucleus just like these two tennis balls. The stationary ball is the atomic nucleus and it gets some energy from being hit by the moving tennis ball which represents the dark matter particle.

So now we have some idea of one way of detecting dark matter and so a question for you to talk about among yourselves is can you think of other ways that you might detect dark matter?

In this clip, Ezekiel rolls ten tennis balls at a time at a golf ball. Most of the time the golf ball does not get hit. The tennis balls are like the dark matter particles and the golf ball is like a nucleus. The space between the nuclei is very great in comparison with its size, even in a solid. So the dark matter particles do not often hit a nucleus here on earth.

Here's the hallway that you just saw in the video. And that hallway is three meters or 300 cm across. And the golf ball, which measures about 2 cm across, is sitting at rest here. And then from all different directions we rolled tennis balls down the hallway toward the golf ball and those tennis balls are 10 cm across. OK. Now what has to happen for one of these tennis balls to hit the golf ball? Well if the golf ball is here, and the tennis ball comes by on this side, the outer radius or outer edge of this tennis ball has to be at least what the outer edge of the golf ball is. And so if this distance is 5 cm and this distance is 1 cm, then on this side the tennis ball must pass within 6 cm of the golf ball. And similarly on this side. So that's a total of 12 cm. So the probability of hitting is 12 cm. They're all within this 300 cm interval. So then the probability of hitting is 12 cm ÷ 300 cm, which is 0.04, or one in 25.

So in the video you just saw we rolled ten tennis balls five times. I think you saw that one of them struck the golf ball. So you should work out the probability. Now this is on average, so sometimes there will be more or fewer collisions than you would predict from here. And if you do it a large number of times then it will converge to this volume. But this gives a relationship between the probability of an interaction or hitting and the sizes of the objects. And obviously the smaller you make the objects, the lower the probability of an interaction. And that's what we're really getting at with this little demonstration. The dark matter particles are small so they don't interact very much.

So what we've learned is that you can look for dark matter hitting a nucleus here on earth and use that as evidence for dark matter. And in our lab here at MIT we've built a detector to do this and you've just seen a video about that detector. And here are some images from the detector. Instead of dark matter we used neutrons which is a particle that's like a dark matter particle whose property we know very well. And what you see here are images of a fluorine gas nucleus recoiling after being struck by a neutron. The neutrons always come from the left side of the image so you can see the recoil always happens away from the direction of neutrons. And we can use this phenomenon in order to look for dark matter in our galaxy. Now the problem is that there's not very much dark matter. We worked out before that there's about one dark matter particle per quart of volume, or per liter of volume and we've also worked out that the interaction strength of dark matter isn't very strong. So that means we need to build a very large detector and wait a very long time in order to detect dark matter. So we're just at the beginning of a long road of an experiment.

So to summarize what we've discussed in this segment in the last hour, you've learned that a galaxy is a collection of stars, that the gravitation between the stars holds the galaxy together. But there aren't enough stars that we can see to account for the total amount of matter inside of the galaxy. We call this stuff dark matter and it's really not related to any known particle on here on earth. And we look for it by its interaction with normal matter. The problem is it doesn't interact with normal matter very much and that makes the experiments very, very difficult. So I hope you've learned a little bit of physics and a little bit of astronomy and a little bit about what I do and good luck with the rest of your study in physics.

Hello, I'm Peter Fisher. I'm the instigator of this Blossoms video on galaxies and dark matter. And this is the teacher's aid or teacher's materials. And here I will expand on the questions that are given in the demonstration and try to include some additional material that may be helpful in presenting this topic. The topic of dark matter in galaxies is a relatively straightforward one and relies really only on a knowledge of elementary kinematics and Newton's laws. However, I have included a derivation of this centripetal force which is something that many students learn but perhaps I've included the derivation in these materials so that the instructor can go through it with the students again if need be. All of the demonstrations are in some sense optional. I think there's value to doing them but I do realize that it may be difficult because of time or space constraints. So the demonstrations are included in the video and they can simply be used instead of actually doing them yourselves or having the students do them.

So I will discuss the questions and other relevant materials point by point as we go through this. So we introduced the idea of galaxies as the first part of this module and we don't really assume any prior knowledge of what a galaxy is.

The first question is talk to each other about the differences between galaxies in stars. How might these differences show up in an image? Look at the image of the **Coma** Cluster carefully. For each object decide whether it's a galaxy or a star. The idea of this first question is to get students to look at the image and realize that there are two kinds of objects in that image of the **Coma** Cluster. One object is nearby stars, which are typically within a few hundred thousand light years. And the other are galaxies, which are billions of light years away or more.

And really the only goal of this module or this first question is to get students thinking about the two different classes of image and how it may have been very difficult in the very beginning of astronomy up until the 1900s for astronomers to bring themselves to realize that the big, fuzzy, oddly shaped, yellowish or reddish objects are actually very large collections of stars at very, very large distances. The stars which are primarily from our Milky Way are point like or like a little disc. They're circular. They're typically blue in color. So really all that we're after here is for the students to begin to be astronomers and try to classify the objects in that image.

Students should talk about each question for four to five minutes or as you as the instructor feel. But I think four to five minutes is a good start. And it's really best to have the students discuss with each other if that's appropriate because that way they're learning from each other and beginning a dialog. And scientific investigation is inherently collaborative so when they learn to do this they are actually learning how to be scientists.

In the second part we begin to discuss how a particular star is held inside of a galaxy. And the first demonstration of the module is simply a ball and a string and my student Ezekiel just whirls the ball around and lets it go. And there are really two things that are being demonstrated here. The first one is that as he is holding the ball on the end of the string, the force of the string acting on the ball is what's keeping the ball in a circular motion. In this case the string is analogous to gravity and in the same way gravity keeps the object orbiting around the center of the galaxy. When Ezekiel lets go of the string, just like removing the force, the ball flies off in a linear way, in a straight line. Now of course earth's gravity eventually pulls the ball back the ground but the thing the student should observe is that once the string's force is removed, the ball wants to go in a straight line. This is one of Newton's laws which says that an object in rectilinear motion remains in rectilinear motion unless acted upon by an outside force. So what we'd like to do with question two, which is swing the ball around on the end of the string and let it go. Why does the ball move the way it does? In what way does the string play the role of gravity? We'd like the students to begin to have the discussion of the relationship between gravity and the circular motion and Newton's first law.

As far as the demonstration goes, we've included the demonstration on the video and you can simply work from that. You can make your own. All you really need is a string and any sort of object that isn't too terribly heavy. But a small children's toy or a car key or anything that weighs more than the string that you can whirl around and let go, either in your classroom and outside and not do any damage works just fine. Ideally the students themselves would each make one of these if you have the means and the time and do the demonstration themselves because there is really value to as the ball or the object is being swung around feeling the force on the string that you are making it go. And then when you let go feeling that force disappear and seeing the thing fly off in a straight line. But any way would be just fine.

Now in this third part we try to become a little more quantitative in using the relationship between the mass of the galaxy and the force acting on the particle to keep it in a circular orbit. And to do this we bring in the idea of centripetal acceleration and then relate the centripetal acceleration which is the force necessary to make the ball go into a circle to the gravitational force which is the interaction that Isaac Newton first postulated for the gravitational interaction between two masses. Let me show you on the blackboard where the centripetal force comes from and then we'll come back to the question.

So this is a short discussion of centripetal acceleration. It's something that many students have had. Perhaps it's just been stated so this is to give a little more background to it. So what we're thinking about is here is some gravitation body and we're thinking about a star for example that is making a circular orbit at some distance R around that object. So the star is just going around in a circle at a fixed radius. Now we know from observation and kinematics that in circular orbit the velocity is constant. Now the velocity is changing and this time the velocity points in this direction and let's think about a time a little while later at T, the velocity is pointing in this direction. So let's say TE = 0 and this is T = time T. The magnitudes of the two velocities are the same. But their directions are different. So if in this time T this star has gone from here to here, the angle that it makes with respect to its starting point theta is just equal to this distance which is the constant velocity times T ÷ radius R. That's just saying that the angle subtended by an arc of a circle is equal to the length of the arc divided by the radius of the circle.

Now if we look at how the velocity has changed, here's velocity at T = 0, which is just this vector. The velocity at **time** T is a vector of the same length but pointing in a different direction. So the velocity has changed only in direction. The change in direction by similar triangles is this angle theta. So this distance is equal to the magnitude of these sides, which are the same, times theta divided by two. So that's V x T. So the change in velocity is equal to V x theta/2. And that happens in the time T. And the change in velocity in time T is just equal to the acceleration. So now we can say that the acceleration is equal to V ÷ T x R, which is equal to V x T ÷ R. These two cancel out and what we're left with is that the acceleration is V^2 ÷ R. This is called the centripetal acceleration and it's kinematic in the sense that if an object goes with velocity V in a circle at radius R, then this is the acceleration. It doesn't tell you why the acceleration is that; that comes from Newton's force law, which we discussed in the Blossoms video. This just tells you that the circular motion at constant velocity what the acceleration has to be.

Question three reads: "If you swing a ball on a string, the faster you swing the ball the more force you must exert. Try timing how long it takes you to swing the ball around ten times at different speeds and see if you can feel the force difference. If the force you exert on the string represents gravity and gravitational force is proportional to the mass inside the orbital radius, what does this tell you about the relationship between the mass inside the orbit radius and velocity?" This is trying to in a physical way establish the relationship that is shown between mass, velocity, and orbit radius just before the third question on the Blossoms video.

Again I think there's a lot of value in the students actually feeling the force on the string increasing considerably when they try to swing the ball around ten times very fast as opposed to ten times very slow. But really using either the video demonstration by the in-course instructor are both just fine and the materials are exactly the same as for the previous demonstration.

I've given you just a minute ago a little derivation of centripetal force. That's kinematic in nature, meaning it's a relationship between how an object moves and force. There's really nothing more to it than I've shown you. In the video we relate that to the Newtonian force between two objects which of course was worked out by Isaac Newton, and then later Albert Einstein created the general theory of relativity that put this on a much firmer ground. That is something I think you can only just state. First the law, which the force is equal to the Newtonian's constant times the product of the two masses divided by the radius squared. And the fact that the force is directed along the line between the two objects.

Also there are two masses involved, the mass of the orbiting star and then the mass enclosed by the star's orbit. And the fact that you can treat that mass enclosed by the orbit as a single quantity actually comes from Gauss's law, which is a unique law to whatever R^2 force is. Deriving why that is always true for any force as one over R^2 is beyond the scope of this video because it involves vector calculus. But it might be something to talk about and emphasize as I go through it in the video really rather quickly.

So the second part really just gets them to think through the two algebraic steps right before this question was asked. That ends with the relationship between the mass inside the orbit radius, the velocity, the orbit radius and Newton's constant. The algebra is very simple but the consequences profound, and it's this relationship that really led Fritz **Zwicky** to come up with the idea of dark matter and then is behind Vera Ruben's measurement of Andromeda.

In the actual implementation of these measurements there is considerably more advanced mechanics, most of it quite elementary but I think this relationship really captures the essence at a way that's comprehensible for secondary school students.

Vera **Rubin**'s velocity measurements were done using Doppler shift and this is discussed in this section of the video. Doppler shift is one of the most interesting wave phenomenon and I like to take a few minutes to derive it using secondary school level wave mechanics.

So here's a little derivation of the phenomenon of red shift or blue shift which is the changing frequency for wavelength of light or color of light due to the motion of the emitter. So if we have a star here that's at rest and we sit here on earth and observe this star with a telescope, the star emits light which is an electromagnetic wave. And the electromagnetic wave has a wave length which we call lambda, and it has a period or frequency which is the time difference between repetitions of the periodic wave, which is T for the period. So the frequency is equal to one over the period. And also the velocity of the wave, so V wave which we call C is equal to the wavelength times the frequency and that's equal to the wavelength divided by the period, just using that relationship between period and frequency.

So for here, what happens in the light is emitted at some time T = 0 and then at some later time this wave is observed here. This could be, for example, a telescope. The light is collected by the telescope and the color of the light is determined by the spacing or wavelength between the peaks in the electromagnetic wave and that determines the color that an observer at the telescope will see for that light. So this is all fine. This distance and this distance are the same if the object is at rest.

What happens if the object is, for example, moving toward the earth? So here is the case where the star moves toward the earth with some velocity that we'll call V. And at T = 0, let's say there's the wave coming out and at T = 0 that peak in the periodic electromagnetic wave is emitted and begins to move toward the observer down here. So that wave is now moving and at a time T = capital T or one period later, the star has moved a distance equal to V x T, that's just simple kinematics. So now the star is here. This peak has moved a distance equal to the velocity of the **light wave** times T. That's just the motion of the electromagnetic wave. And then at this time, so this t is here now. And after time T, this star is emitting the next peak in the electromagnetic wave.

So what we want to calculate is this distance. This distance is going to be this distance which is C x T- this distance which is V x T and that's equal to T x (C-V). And that's equal to the wavelength, the ratio of the wavelength from the moving star with this wavelength from the star that's not moving, that's T x (C-V) and then from the relationship I had before, this is C x T. I mean just put that again. Remember frequency times period is equal to the velocity and the period is equal to one over time. That's equal to the velocity. So lambda, the wavelength, is equal to the velocity divided by the period. So these two things cancel and what remains is 1-V ÷ C. That tells you the relationship between the wavelength that an observer at the telescope sees, to the wavelength at the emission point of the star is less than 1.

Now if V is very small, for example 200 km/second, and C is something like 3,000 km/second, then this ratio is less than 10%. The change in color is not terribly large, but nonetheless an observable effect. Now the wavelength being shorter means that the light appears bluer and that happens when V is positive, meaning the star is moving toward the earth. If the star is moving away from the earth, V is negative so this quantity is greater than 1, which means the wavelength is longer and that means the light appears redder, hence the term "red shift." There are several places that this is written up in more detail and I'll post them on the website.

The derivation I've shown you is self contained and if your students had some exposure to waves and know about frequency and wavelength in a formal way, it would be perfectly appropriate for them to work through themselves or for you to give them a short lecture on it. Alternatively you can simply state the result and use the qualitative argument about a car of a siren having a higher pitch when the car or siren is moving towards you and a lower pitch when it's moving away and then relating sound as a wavelength phenomenon to light phenomenon. They will have had some experience with this most likely and this is a useful place for them to begin to understand the very important phenomenon of Doppler shift.

In question four, what other ways can you think of to explain Vera **Rubin**'s observations? It's kind of an open-ended question at this point, for the students to try to talk about what other forms of matter might be inside of the galaxy that isn't emitting light. This can be dust, could be plasma, it could be planets or comets or any number of a large number of things. Black holes that don't emit light and this is just an open-ended place to talk about what else might be in the galaxy.

Clearly when we observe galaxies what we're observing are stars which emit light. But inside our own galaxy, inside our solar system we see many, many other things—asteroids, comets, planets, planetary rings. There's credible evidence of a black hole that's quite large at the center of our galaxy. So this is just a place for students to go back and think about this very complex, rich object that they've just learned about really contains.

Question five. Can you think of other ways of detecting dark matter particles? It's kind of an open-ended discussion. The students have learned now that it could be these particles that are flying around and these particles bump into things, presumably atomic nuclei and that's the way we've discussed detecting them in this video. Now is a time for them to perhaps think of what other things could particles that are whizzing around do? Is there some way that they can be collected? Is there some way that other particles can be bounced off of them?

The answer in these cases is really no. And this comes up in the next demonstration and derivation in the video. The fact is that in order to be consistent with our observations dark matter particles must be very, very small, much smaller than nuclei, perhaps even much smaller than electrons. And this means that they don't interact with ordinary matter much. So if you make a bottle out of some normal matter, steel for example, and were able to collect dark matter and put it into the bottle, the dark matter would just fall out. So this is where we have a discussion about what it means for subatomic interactions to happen and that they have relative strengths and that some particles can be very, very penetrating. And that's in distinction to most of the things around us that are a wood desktop or air or things that can be contained. And because of that, in order to contain something you must have an interactive something.

So the derivation of the probably for two objects hitting each other. You may notice that I'm wearing different clothes than in the rest of the video. That's because in viewing the first full cut, Dick Larsen and Elizabeth Murray noticed that I had left out a factor of two in the derivation and I had to re-shoot it. I really appreciate them pointing this out and I'm a little bit embarrassed by it. In any event this is a straightforward mathematical calculation and the word for the quantity which relates to the probability of interaction of a target with incoming projectiles is "cross section."

The demonstration that you'll see in a minute and the derivation are in one dimension, I'm sorry, in two dimensions. In the real world, things move in three dimensions so the cross section represents an area. And it's essentially the size presented to an incoming object by a target object. And hence dimensions of area for length times length or length squared. The smaller the cross section, the smaller the chances of an interaction occurring. And the cross section or size of an object is different depending on what kind of interaction there is.

We're used to seeing things so we associate, for example, the size of the table with the physical dimensions of the table we would measure with a ruler. That's the size of the table for electromagnetic interactions because when we look at something what we're doing is we're detecting light and that's electromagnetic. If you were able to measure the sides of the table using neutrinos it would be much, much smaller than the size of the table you would measure using light. And that's simply because the neutrinos interact much less and consequently the table appears much smaller to a beam of neutrinos of comparable size to beam of light. This is kind of the basic idea behind the smallness of the dark matter interaction is that the dark matter particles only interact via a very weak interaction and consequently their size is small and that's what makes them very difficult to detect because they only interact very infrequently.

Question six is how many total tennis balls did you throw? How many hit the target golf ball? Can you find the probability of hitting from the dimensions of the two balls and compare with your experiment? There's nothing magic about using a tennis ball or a golf ball. It's what Ezekiel happened to have in his backpack. You could use marbles, baseballs, softballs, soccer balls, basketballs. It's good if one of the balls has a different size and you use that as the target.

But if that's not possible, then using balls that are all the same size. Question six asks really that you do the calculation that was just done. If it's more convenient you can simply use the video where Ezekiel throws ten tennis balls five times and you can see that there is only one interaction, so that's 1/50th and that's consistent with the derivation that's given in the demo. Again, this is something where the students can have a lot of fun and spend ten or fifteen minutes rolling balls down the hallway, but it may not be possible or appropriate in some places and so please use the video in lieu of an in-course demonstration.

In the last segment where I talk about the dark matter detector we have, there is mention of a video. That actually refers to the tennis ball rolling video about how the two body interaction works. I didn't include any large questions at the end. Questions you might want to discuss with the students is really recapping what they've learned which is a lot. This is quite a few topics to cover in a one hour session. But what the difference between a galaxy and a star is and how galaxies are collections of stars and possibly other things. How the gravitational force keeps the collection of stars together and makes the stars move at a certain velocity. And by measuring this velocity you can learn something about how mass is distributed within the galaxy. Using the relationship between light and mass derived from the sun or from nearby stars to determine in another way how much mass is in the galaxy leads to a problem that there is more matter when you look at the gravitational dynamics than when you just use the light. And how that has led to the dark matter problem. The idea that dark matter can be particles that don't interact very much and what it means to not interact very much via the simple example with the cross section.

The website will have some additional materials posted on it and please feel free to contact me directly if you have any questions. I have to say it's been a pleasure doing this and I hope you and your students get some thing useful out of this. Thank you very much.

END OF RECORDING