DJORGOVSKI: Now let's talk about the kinematics of the Milky Way and its rotation and how that provides compelling evidence for the existence of dark matter. This is, of course, just artist conception. The dark halo is suddenly blue. The important thing about the rotational galactic disc is it's a differential rotating disc, meaning the angular velocity is a function of radius. It's not like a solid body disc that will have constant angular velocity everywhere. Inner parts are spinning faster. Now, that has a number of interesting consequences.

One of which is that wherever you are, they'll be things passing you by or lagging behind you on either of the radii, and if those things are say, giant molecular clouds with a lot of mass that provides nice title shocks with which to dissipate freshly made clusters. But it also changes other things like enables spiral density waves. So, as I mentioned we use normally, mostly, H1-21 centimeter line, although we can also use now molecular lines to map the kinematics. The problem is we're just sitting in the plane and we have just radial look out.

So, when you look at this, they'll be some spinning discs, they'll be some spiral arms, but you're looking along the given line of sight, so you'll be seeing gas, or range of different philosophy, that will be piled up, gas when you say crosses spiral arm, or some giant cloud or something like that. But without knowing how far that is, there isn't much you can do. So, we have to measure distances, and the way that's done is we can't tell the distance to H1 cloud, but if we can say well there is a big composition of hydrogen over there, and I also see star cluster in the same direction, so chances are pretty good that they are close to each other because stars are born inside clouds, and we know how to measure distances to star clusters, like from HR diagram fitting of the main sequence.

So you have to make these assumptions that you see something that's associated with the given blob of gas. And sometimes it's vastly wrong, and we find out sooner or later, but most of the time it's OK. And so what radial telescope gives you is a plot like this. You go around in galactic longitude. Each longitude you have a spectrum of neutral hydrogen, Doppler shift response to velocity, and different intensity of different velocity. So they look like this, they're called LV diagrams, and you can actually see there's some systematic things that correspond to spiral arms.

So after doing this in great and gory detail, then associating distances to particular spots in it, you have radii, you have velocities, you know there is a differentially rotating disc, you can solve it and find out what the rotation as a function of radius is. And here it is. This is what the observed rotation curve of the Milky Way looks like. Rotation curve meaning it's linear velocity, in this case tangential velocity, as a function of radius. And there is more in the middle. There's a lot more mass. Then it kind of goes down, but then flattens out with some bumps and wiggles.

To a good approximation, outside the very middle, it's roughly flat. Now, if you had purely Keplerian motions, it'll be dropping dramatically with radius because gravitational potential will be declining. And therefore kinetic energy has to go down. And so, right away there is going to be an issue here. So, if all the mass was squished in the middle, it will be just like solar system, every star will be zipping around a gigantic black hole, but that's not the case. So when you actually decompose this, you add up all the stars and gas that we see, and ask OK, there is this much mass.

I'm now going to compute gravitational potential as a function of radius. And you do that. And you ask, what will be the velocities needed to balance the gravity of the stuff that we see? And you'd come up with the prediction that's shown here as the blue line, which is vastly wrong. So, the only way to bring the velocities up to what's observed is to add some mass that you haven't seen. And so this is the origin of the dark matter defections. Now this is commonly seen in essentially every spiral there is, and also in elliptical galaxies except it's not rotation, it's random motions.

So, a couple things to note here, our first is that the importance of the dark halo made up of some mysterious substance increases with radius. Near the middle, regular stuff, stars, gas, dominate galactic gravitational field. The further out you go, the stars thin out exponentially, but this dark material, probably the flying stuff, gets to be dominate. And one thing that we can tell is that it couldn't possibly be all into this because if you were to smush it all in the disc, say make it out to block all flying around or something, then that will cause dynamical heating of stars.

The discs would puff up because there'd be all this mass in the disc to be compensated with random motions. This is not observed, so this is why we're pretty sure it's some kind of spherical, or almost spherical, distribution. Well the interpretation of this is pretty straightforward, it's the usual centrifugal force equals centrifugal force, and so if you measure velocity, and remember it's circular motion, so it's just one variable radius. If you measure velocity as a function of radius, you can tell how much mass is inside of that radius in order to create a centripetal force needed to balance it.

And the mass in for constant enclosed mass will be like this. But now, if you were to assume that say density of the total material goes as a power wall, turns out to be a good assumption. So it goes as a radius to some power minus alpha. And then plug this in. You ask, in what circumstances, what value of alpha is v of r equal constant? And the answer is if density goes as a minus second power off radius. Now, if it were pure power law, from 0 coordinate the infinity, then that will imply infinite density in the middle, which is clearly not the case.

So, this idealized model of pure parallel density distribution is called singular isothermal sphere. Singular because it's got singularity point of infinity in the middle. Isothermal because velocity is constant, meaning kinetic energy is constant. And it's a reasonable approximation except right in the middle, and a really large radius. So now, if you put this in a formula, you find out that oh, because mass goes as 4 pi r squared, density of radius times the r, and the density as goes radius with my second power, you find out that mass is linearly proportional to radius as we integrate it.

So the further out you go, more mass you get. And the question is where does it stop? And the answer is, nobody actually knows, but we're pretty sure it stopped by about 100 kiloparsecs radius. Because as that point, you start running into halos of other galaxies and so on. So what is this mysterious stuff? How do you know this is actually true and it's not just that say we got something measured something wrong, or maybe Newtonian gravity doesn't work. I mean, there are proposals to do that as well.

And it turns out, there's several independent lines of evidence that give us the same result. You can do the same thing as you've done this galaxy for elliptical galaxies, except use random motions, not rotational. But then if you look at clusters of galaxies, turns out they're filled with hot gas, x-ray gas, temperatures of millions or tens of millions of Kelvin. If you ask, what are the kinetic energies off those protons and electrons, and how much mass there has to be in order to keep the cluster together, you get, again, huge amounts of dark matter.

This is actually how Fritz Zwikcy first discovered dark matter, but he used galaxies as test particles, not x-ray gas. A completely different method using gravitational lensing; you remember mass bends light rays. And so, if you look behind the massive cluster of galaxies, you'll see the galaxies in the background distorted into little arches and stuff. And so you can invert this and that tells you how much mass, of any kind, is there inside that radius that requires you to make this gravitational optics. Completely different physics. Completely different measurement.

And amazingly enough produces the exact same results as measurements from x-ray gas or galaxy motions. A modern thing is looking at cosmic microwave background fluctuations, which is arena of precision cosmology too which we'll come later in the class. And that too implies that there is a large amount of some non-baryonic mass. Mass that's not the regular protons and electrons and stuff. And again, in exactly the right amount.

Finally, there's one more argument, and this is that kinematics and evolution of large scale structure and universe are also implying presence of dark matter in order to account for depth dynamics, and how the large scale structure forms because if you have more dark matter it's going to accelerate the collapse of structures, and so on. That too matches everything. So we have several different approaches based on different physics, completely different measurements, and they all agree. And this is why we're really convinced that there really is such a thing as dark matter. That's OK. That's not complete fabrication.

Already there are things that very much exist, like neutrinos but do not interact with electromagnetic field. So this is some other kind of particles. Well, we don't know what is. Turns out that the standard model particle physics does not predict existence off suitable particles to account for dark matter. So since physics beyond the standard model, which is why physicists are all excited about it, and there is some hope that this will be seen in accelerators. But they're also super precise measurements in the lab deep underground that try to capture dark matter particles scattering of the atoms.

And after many years, and hundreds of different possibilities for what it could be, things have now narrowed down to essentially two types of hypothetical particles. One it's called weakly interacting massive particles, or WIMPs. And the other one is called axioms. And it's most likely WIMPs. And WIMPs probably have masses of 100, 200 gig electron volts, something like that. And there is every expectation that they too will be seen in large pattern collider, just like Higgs particle was. So, my guess is that before too long, we will actually know what dark matter is. And need not be one kind of dark matter, it could be 92 different kinds of dark matter, but at least this is a start.