MARK HARTMAN: Cluster, from the image, using the distance to the center of the cluster, which was kind of the average of all the redshifts of all the other ones that make up the cluster, we got a linear diameter of 8 times 10 to the 21st meters, which we saw was about 8 to 10 times the size of one galaxy. That makes sense because there's at least 10 to 100 galaxies packed in there.

When we look at the closest galaxy to us using the same prediction from Hubble's law, and we look at the farthest galaxy from us still in the cluster-- and some of you were noticing that some of the galaxies are named Abell 2029, number 55. Those are actual members of the cluster. Some of the other ones may or may not have been.

But then we took the difference between these two to get the linear depth. And these are the numbers that we were coming up. We were saying that from the front of the cluster to the back of the cluster is 10 to the 24th meters-- 9 times 10 to the 24th, 2 times 10 to the 24th, 2 times 10 to the 24th.

How many times longer or deeper are we saying this cluster is compared to how wide it is? What is the ratio between, say, this number and this number?

AUDIENCE: Isn't it almost 1,000 times, about?

MARK HARTMAN: We are saying that this galaxy cluster is 1,000 times deeper than it is wide. That would be like taking a galaxy cluster, stretching it across the room, and having it be about that wide. Does that make sense?

AUDIENCE: [INAUDIBLE]

MARK HARTMAN: Did you actually draw it over there?

AUDIENCE: Yeah.

MARK HARTMAN: All right, so project it.

AUDIENCE: It doesn't fit on one board.

MARK HARTMAN: It doesn't fit on one board.

AUDIENCE: 300 times.

MARK HARTMAN: So that's only 300 times longer. So yeah, if we stretch it across this whole room and it was only that wide, what is going on here? We made a prediction that, yeah, maybe, but how common would that be? If you have just a clump of galaxies that formed from some cloud, you might expect it to be maybe twice as long, or maybe even 10 times longer and it would be like a cigar, but not 1,000 times longer.

This is a prediction that doesn't make sense. How did we get this prediction again? Let's try to figure out whats going on. How did we get the distances to the front and to the back? How did you learn this? That question's going to come back and bite you in the ass so many times.

AUDIENCE: Hubble's law?

MARK HARTMAN: How did we get the distance to the front and the back?

AUDIENCE: Hubble's law.

MARK HARTMAN: Hubble's law. So what did we actually measure using Hubble's law?

AUDIENCE: Distance.

MARK HARTMAN: We predicted the distance. What did we measure?

AUDIENCE: Velocity.

MARK HARTMAN: The velocity. So we're taking the velocities of these guys and turning them into a distance and taking the difference of those distance. So we said that this one is moving away from us because of the expansion of the universe. This one's moving away even further from the expansion of the universe. Jaylen?

AUDIENCE: How do you measure the size of it by the velocity of when it moves?

MARK HARTMAN: That's Hubble's law. We said that if things are further away, we can look at their velocity if they're expanding with the universe's expansion because we're using velocity to get to distance. Why else might these galaxies be moving? Because we took motion, and we turned it into distance. David?

AUDIENCE: Motion within the cluster.

MARK HARTMAN: Maybe they're just orbiting, just like the Earth does around the Sun. Some of these galaxies are going to be moving towards us just a little bit. The whole cluster, yeah, is moving away. But if I'm moving away, and I have something that's orbiting around me-- in this case, I'm orbiting this way. Right here, my galaxy is moving forward. Here, my galaxy is moving backwards.

When it's moving backwards, if Bianca watches it move backwards, it looks like it's moving backwards faster than I'm moving. And if she watches this marker move towards her, it kind of looks like it stayed there for a minute.

[LAUGHTER]

So the motion of these galaxies might not be due to the expansion of the universe just like the motion the Earth is indifferent because we're going around the Sun. It's not like the Earth and the Sun are getting larger. So we get confounded, which means we get confused.

How much of that recessional velocity is due to the fact that the universe is expanding? How much of that is just due to the fact that the galaxies are moving around? There might be a galaxy that's doing this, maybe a galaxy that's doing that. Some galaxies have weird orbits.

So how would you summarize why we might not be able to get an estimate for the distance from the front and the back? Go ahead, Bianca.

AUDIENCE: Because Hubble's law doesn't apply to this model of the [INAUDIBLE].

MARK HARTMAN: Does Hubble's law not apply at all?

AUDIENCE: The theory of expanding universe doesn't apply.

MARK HARTMAN: When you have objects that are orbiting, that are graivationally bound-- I know a lot of you have been using that phrase when you're talking about stuff-- Hubble's law doesn't hold for stuff that's gravitationally bound together. That object might be moving away because of the expansion of the universe. But if there are things orbiting around, it's not that that's expanding too.

So in this case, what we can do, though, and what the galaxy clusters group might do, if you look at how those objects are orbiting, you can actually get an estimate for what is the mass of that whole cluster. And remember, we looked at what's the X-ray luminosity compared to what's the visible light luminosity. We can also get an estimate for what's the visible light mass-

- what mass in galaxies is giving off that light, what mass in X-ray gas is giving off that light.

And then by watching the objects move, we can get an estimate of how much mass is there. And remember, we said that all matter, whether it's regular matter, or dark matter, or anything, causes gravitational attraction. And by watching how things move, you can actually get an estimate of how much dark matter and regular matter there is inside that galaxy cluster.

So even though this motion of these galaxies didn't help us to figure this out, it gave us a clue that the motion then might not be due to Hubble expansion. But instead, it's due to that orbiting. And that orbiting can also tell us something useful.

So in this case, how could we get an estimate of how deep it is? You can't. You can assume that it's about the same depth as it is a width if you assume that it's spherical.

Now, you can look at the distribution of light and try to figure out something about, well, if it was a football shape, then it should be really, really bright in the middle because there's all kinds of stars and galaxies and hot gas there. But essentially, what I wanted you guys to see was by making a prediction from a model that didn't apply to this situation, we got a prediction that doesn't make any sense, which means that you always have to double-check yourself. Always compare it to something else that you have measured or something that you know to make sure, does this number actually make sense. OK.