DJORGOVSKI: All right. Let's now turn to a more serious pursuit of astronomy as a science. There'll be a lot more history. We will touch upon it as we cover appropriate pieces where we talk about what we know about the universe.

And the problem is that the universe is really, really big. And there are all these metaphorical comparisons. I came up with this one for you just to illustrate the scales we're talking about that you can read yourself. And that's a problem, because we cannot experiment with the universe or anything in it. We can just watch.

So how do we go about this? Astronomy has evolved, first from astrology and mythology to classical astronomy-- which is measuring precise positions of celestial bodies. But then, starting with Newton and Fraunhofer in 19th century, physics started coming in. And though most of the 20th century, astronomy really became a branch of physics.

But in physics, you need to do experiments and test theories, so how they go about this? Well, we can't fly there or take stars in the lab. So we can use the data and math, or together, the scientific method-- which was pioneered by Galileo-- and use physics as an interpretative framework of the things that we see.

So even though we cannot go and bang on stars with a hammer or things like that, we can still measure things and test theories just from observations. So astronomy's strange in that way, and similar to history or geology or paleontology where you have to infer from what you see now, what happened before. And you can't do experiments. Now, there could be extinct species of astronomical objects too.

It's important to distinguish observing and experiments. And typically in most sciences, you do experiments to test some predictions and so on. In astronomy, again, you can just watch. But you can design experiments that can only be done by watching.

Sometimes, it looks like a problem. There is only one universe-- at least, that we can observe. And there is only one cosmic microwave background and so on, so how can you possibly infer general things about them? Well, not all science requires large samples of objects. In a single example of something, if interpreted properly using physics that we know and then predicting new observations-- was just happened with gravitational waves that demonstrate inflation was correct-- that is just as good as anything else.

There are, however, some fundamental limitations of how we can go about this. The first one is that we are essentially living in a moment of a history of the universe. Universe is 13.8 billion years old. Astronomy, as a science, was a maybe 100 years old. This was nothing. So essentially, in four dimensional spacetime that represents universe, we're looking at one tiny slice. And if you've done any special relativity, this is known as the light cone. So the further away you look, the deeper in the past you look because speed of light is finite.

So you have a built-in time machine. If you want to see how the universe was in sometime in the past, all you have to do is look further up. Now, that's not nearly as easy as it sounds. But it's a very convenient way-- that we have this temporal section of the universe that corresponds to the depth.

On the other hand, if you only can see something that happens around the light cone, there could be a lot of stuff that we're missing-- there are certainly regions of the universe that we cannot observe because light never had a chance to come to us since the Big Bang. But we can use some symmetry principles, like Copernican principles of Earth was not special. Sun was special, but then turns out sun was not really special. In cosmology, we use principles that the universe is homogeneous, that means the same everywhere, and isotropic, meaning same in all directions. And that simplifies things enormously. And those are actually testable assumptions.

We also sometimes assume that-- well, we always assume-- that physics that we know and love here on planet Earth will apply everywhere and at all times. That's a pretty reasonable assumption and seems to work. But there are actually ways of testing that. So there are ways to observe light from distant quasars that can give limits on the changes of so-called fine-structure constant. So as far as we can tell, physics that we know here now applied in all of the universe since the Big Bang. And that's very reassuring. If that wasn't the case, we would have little hope of actually having any astronomy or cosmology.

And we can deduce from what we see today-- this fossil record, if you will-- of what happened in the past. When we talk about Milky Way, you will see that there are tracers of past mergers of dwarf galaxies that got torn to shreds and are filling up our halo with stars. So you can infer, just from a snapshot, what happened in the past if you have an interpretive framework like physics.

OK, so astronomy is a branch of physics. And my main goal in this class is not just to tell you about all the fun stuff that's out there. I'm sure there's a lot of fun stuff. But also, mostly, how did we figure it out. Because I think it's a prime example of how correct applications of scientific method can reveal things that are of considerable interest to everybody.

Now, it works both ways. We use physics to explain observed phenomenon in the universe, but you can also observe stuff that implies existence of some new physics. And first, there is physics that we know, but in extreme conditions like extremely dense states of matter or extremely relativistic motions. There are cosmic accelerators that are spewing particles towards us, and stuff that was not expected, like dark matter or dark energy. We'll go through the evidence of those.

And we're getting probably close to understanding what the dark matter is, but it's one of the frontiers of physics. We don't have a blessed clue what dark energy is all about. And it's one of the most outstanding problems of physical science today. Its existence is very solidly established through a variety of different ways. And it pushes theorists to actually try to figure out, and maybe some unification of the standard model of particle physics with general relativity that will give us the answer to what dark energy is all about.

One thing that thing I'd like to point out is that astronomy-- in fact, all sciences-- tend to be driven by this progress in technology. We depend entirely on our detectors and our computers to actually see stuff out there. We have detectors that are vastly better than human eyes. Nobody's looking through telescopes anymore. Silicon can see much better than you can. And this was very obvious throughout the 20th century. I'll show you some of the examples.

But there are limits of what we can do. So it's encouraging that we can apply physics to learn more about the universe, but there are some things that a priori cannot be done. So if you're counting photons from some distant object, there is Possonian statistics, fluctuations, that cannot be overcome. You need to count many more photons, but they don't have any. It's too bad.

Optics that describe how telescopes work on every wavelength has a limit. You can only resolves objects that are bigger than the diffraction limit of the telescope, which is proportional to its diameter. And you can't do any better. So you have to make bigger telescopes or put the telescopes further apart and connect them in a special way in order to see sharper.

And then also, we do not look through a perfectly transparent universe. First of all, planet Earth has an atmosphere. There are good things about it, but it's not so great for astronomy. And the atmosphere absorbs a lot of electromagnetic radiation, which is why we have to send observatories in space. Milky Way has an atmosphere too. There's dust clouds, obscure light. There's also neutral hydrogen that absorbs UV and soft x-rays. So we're kind of in fog of interstellar medium, trying to look through it.

And then, all of that gas that's between us and the rest of the universe is not stationary. There's turbulence in it that tends to smear the images we see. There are magnetic fields. There's all kinds of complications. So we have to slowly de-convolve all of these foregrounds. And we make good progress on that. We talked a little about this.

So when you observe something that's far away-- say, cosmic microwave background like in the latest results here from Jamie Bock's group-- you're looking at a cosmic photosphere when the universe was 380,000 years old.

But you're not looking through empty space. There's all kinds of stuff between you and it that can cause distortions in it-- gravitational lensing and all kinds of scattering, absorption, other sources like galaxies and quasars and whatever. You have to account for all of that before you can actually do precision cosmology. And we have a pretty good idea of how to do it. This is why they do these amazing experiments.

Let me just give you a quick quantitative idea of how good these things are. Here's a cosmic microwave background, which is a 2.7 degree Kelvin thermal radiation. The temperature in this room is approximately 100 times that.

Now, you know from blackbody that the energy density goes as the fourth power of the temperature. So the energy density of the cosmic microwave background is one-hundred millionth of just ambient thermal radiation. And you know, at this scale, it doesn't matter if you're in Antarctica or in Pasadena.

All right. So these fluctuations in cosmic microwave background, which are one part in a million-- and to detect these gravitational waves-- which just made news recently-- you have to go 100 times more precise than that. So it's 0.00001 of 0.00001 of what's around you. This is real precision physics. This is cutting edge of observational experimental physics.

OK. Questions about this? Yes, please.

STUDENT: When you said connecting two telescopes together in a weird way, is that interferometry?

DJORGOVSKI: Yes, the question is connecting telescopes to achieve high resolution, is that interferometry? Yes, that's exactly right. And that applies in any electromagnetic wavelengths. We've done it in radio for a long time. And currently, optical is the frontier of doing that. There are prices to pay. You don't get something for nothing. There are limitations of such techniques, but they sure can give you high angular resolution.