MARKUS KLUTE: Welcome back to the last section of 8.20 Special Relativity. So as we discussed for special relativity itself, also general relativity is a theory which requires experimental evidence to be confirmed. And there's plenty of experimental evidence for general relativity.

We talked about a few examples of them. But let's go through this, one by one. Also, a little bit with an historical context. So one of the first experimental pieces of evidence pointed out by Einstein was the procession of mercury and also of other planets.

This was always this problem that's a procession of mercury, deviates from Newton's prediction was well known and first recognized already in 1859. And it turned out that attempts to correct this failed. You can think about, maybe there's other objects in the solar system which modify the trajectory of mercury around the sun.

But nothing really added up correctly. And then when Einstein calculated the effect of the procession, he found that it's in good agreement with the observation. This was already very strong evidence for general relativity effects. And then there's gravitational lensing.

And here, this was first measured by Dyson and Eddington, 1919, of light passing the sun in a total eclipse. The observation was in Brazil but also at the West Coast of Africa. This wasn't the first attempt to measure this. It was an eclipse, a total eclipse in Argentina in 1912.

But unfortunately, this expedition didn't lead to a result, because it rained out. There was eclipse shortly after in 1914, but that happened during the Second World War, and there's long stories and accounts of how this failed. But basically, one of the expeditions wanted to travel to Crimea in Russia.

And because Russia was in war with Germany, material was confiscated, and people were imprisoned. So this was canceled, if you want, due to the second and first World War. But then in 1919, this led to the observation the data was not as clear. I think there was a little bit more hope than science in the interpretation.

So there was-- there was not a strong evidence, a strong significance of the results. But the evidence, nevertheless, was there. And as I was explaining earlier, that led to the fame or the triumph of Einstein, where really, his fame resulted out of the reporting of those events.

There's more experimental evidence. Light travel time but around or close to massive object is modified. We talked about gravitational time dilation, which can be measured or has been measured. Other tests of the equivalent principle, but also the observation of gravitational waves.

Gravitational waves were predicted by Einstein by the theory of general relativity. And only very recently, we were able to observe those. And then, in addition, there is plenty cosmological tests, which require a precise understanding of general relativity in order to get to agreement between the observations and the theoretical predictions.

But let's talk about-- let's talk about gravitational waves. So those we predicted, as I was saying, but they're very, very difficult to measure. First, indirect measurement was performed by Hulse and Taylor. They were able to study binary neutron star system.

And because the orbits of those two decayed required lots of energy, and that lots of energy needs to happen somehow. And it was theorized or predicted by general relativity that that loss of energy is due to the fact that gravitational waves are emitted. And they received for their findings the Nobel Prize in physics in 1993.

So how are gravitational waves generated? You can ask-- I have a spinning sphere, like our sun. Would that generate a gravitational wave? The answer is no. It's a symmetrical situation. There's no change of the metal distribution. And therefore, spacetime is not modified.

But if you have a sphere with a little bump, that would create gravitational waves. If you have a mass which is moving by, maybe two passing galaxies, that would not directly create gravitational waves. But if you have those galaxies rotating, or two stars rotating, or neutron stars rotating, or black holes rotating around each other, those generate gravitational waves.

And the closer the object, the higher the masses of the objects, the stronger the gravitational waves are. So how can you measure gravitational waves? Very similar to the Michael Smalley experiment. What you want to do is measure differences in arms of your interferometer. And you do this with very powerful lasers and with very precise mirrors.

So it's very clear the very same experiment as Michael Smalley, just much, much bigger. So we're talking about multiple miles of arms and very powerful lasers in order to conduct those experiments. LIGO, which is one of those measurement, of those devices, experiments, measures the change in the length of one arm with a precision smaller than the diameter of a proton.

So that's just really-- it's mind-blowing, the level of precision, the level of understanding needed in order to measure gravitational waves. But nevertheless, they succeeded. So here, you see two experiments. LIGO has actually two experiments, two of those devices in the United States.

And there's other experiments similar worldwide. You see also highlighted here, Caltech and MIT. Those are the leading communities of the leading universities in this endeavor. And then the first observation of gravitational waves happened in September 14, 2015. And this first observation was rather spectacular because it was not just any observation, but it was the observation of two collapsing black holes.

So you have two black holes. They get close to each other, than they circle each other and create a new, heavier black hole. So the collision of those two black holes with masses around 30 times the mass of the sun, it actually took place 1.3 billion years ago. So the gravitational wave was traveling towards us for 1.3 billion years.

The energy of about three times the mass of the sun was emitted as gravitational waves in fractions of seconds. So the huge amount of energy released in form of gravitational waves. The collision happens with both black holes moving with half the speed of light. So this is just a catastrophic kind of event, in our universe. And researchers or faculty at MIT and Caltech received the Nobel Prize in physics in 2017 for this discovery, only two years after the discovery actually happened-- and very deserved, very deserved.

Let me close this lecture by just reminding you of a quote of Einstein, which I use in order to start this very same lecture. It is true that we are living through some difficult times, some turbulent times. But if you think about the bigger picture, I think we're making a lot of progress scientifically but also as humanity. And I like this quote from Albert Einstein a lot.

"It is not the result of scientific research that ennobles humans and enriches their nature, but it's the struggle to understand while performing creative and open-minded intellectual work." I think if there's one thing I want you to take away from this lecture, it is this quote. I want you to be encouraged to be creative, to be open-minded, to question, and to perform high-level intellectual work. Thank you.