Physics Seminar

March 18, 2019

>>: At first I started talking about the beginning, the beginning of the universe and man looking up at the stars. And I talked about the big question where you look at the stars and you wonder where all this stuff comes from. And I talked about the first observatories, and the idea that you want to take data in order to find out more.

And, like I said, you can learn things about the position of the earth and the movement of the sun, the different transitions that the sun goes through. Like you can see here that you've got the solstice, like the winter and summer solstice, where the sun will actually set between certain pillars in Stonehenge. And by doing that, that was a tool back then where they were able to use that in order to figure out when to plant crops and harvest crops and things like that. So it was very useful.

But also it told things like where we were in the solar system, how the solar system moved. And you can see in the bottom picture, there's a guy taking data. So there's actually records coming from this.

Now, this led to more technology, which was needed for even more data. So you've got more accurate telescopes, you've got some telescopes even in space and all of them are meant to study further and further out in the universe so that we can get a better picture of what's really going on in the universe, what's really going on.

So to put it all together, that really comes down to physics, not so much astronomy. So astronomy, a lot of that was based around the idea of these observations, at least classically. The physics part was saying that we're going to make a few assumptions about the universe from these observations and based on that we're going to have a big understanding of the entire universe. And this works at both the large and the small scales.

So of course not everybody understands what the theory is. So as Johannes Kepler would say, you see the orbit of a planet is elliptical. The first guy asks, what's an orbit? The second guy asks, what's a planet? The third guy says, what's elliptical? This is the problem when you're trying to communicate science.

So this is the history of the universe. We start at the top where humans are out looking at the stars and we see all these stars and if we go back a little bit, we see galaxies. And, you know, we see all these distant galaxies. If we look out further, eventually you'll get to the part where there weren't galaxies and there weren't stars. This is 13.7 billion years nowadays. So if you go back about 13 billion years, there weren't even galaxies. They were just starting to form.

You go back a little bit before that, you don't even see stars. You just see gas, like all this plasma bubbling around. And you go all the way back to half a million years after the universe began, and you can't see anything. And that's because everything was so opaque, that you can't see before that.

This is where the cosmic microwave background radiation comes from. And you hear physicists talk about cosmic microwave background radiation as the oldest signals from the early universe, but the truth is it wasn't really that early. The universe was already half a million years old when it came about.

In order to figure out what happened before that, you have to use your physics. You can't observe any further than that because what happened was the cosmic microwave background radiation kind of bubbled out from this opaqueness and we're still seeing it today. And from that we're getting all these ideas about how the universe expanded and -- how the universe expanded, how the inflation happened, all this other stuff, all these other theories about the universe. It all comes from here.

Before that, in order to see what the physics was like, a lot of that comes from physics involving plasma physics and particle physics. So you have this let's say era of nuclei, where you were just starting to form the nuclei for light elements like helium, and there was a lot of electrons floating around. Before that you had nucleosynthesis where you didn't even have these nuclei floating around.

And then you can go back further to where you just had the elementary particles, quarks, electrons. You had this electroweak, which before this the electric and the weak forces were combined into one force. Before that you had these strong force all combined, possibly with gravity, into one grand, unified force, which we don't even understand. And before that, we don't have a clue.

So the only way to even get back here was just going through physics and making some assumptions and just kind of looking at it. And the weakness of that is it's just better to see stuff. And so if we could actually see what happened there instead of doing a lot of guess work, based on what we know about physics and assumptions, then that might be better.

And so that's one of the things that gravitational waves can actually do, because what happens is if you look at this picture of the universe, again you can see the entire history of the universe and you can see that the universe is much smaller back then.

But you can see at the very end there's a light, the light at the end of the tunnel. And right then was what we call inflation. And that was probably in, you know, a lot of ways I'd say the most important event in the history of the universe because that was when, according to our universe, the universe expanded by many, many, many orders of magnitude in a fraction of a second. Like something going from the size of an atom to the size of a beach ball. And we don't know how that happened, but there's signals from it. And we think we can infer some of that from the cosmic microwave background radiation, but we can't see it directly.

And you can't see it here but this is a ball and in an animated gif, this will ripple and that's the gravitational waves going. And so the idea is when this inflation happened, that should have been a source of gravitational waves and that could have been the source that we could even see today, if we had the right tools.

So what are gravitational waves? Well, like anything that starts with relativity, it starts with Einstein. So what happened with is in 1916 he comes up with the theory of relativity. The basic theory of relativity is that the speed of light is the same for every observer. And as a consequence of that, you can actually, as something gets closer to the speed of light, the physics changes. And so, you know, you can end up getting some really interesting effects, like time dilation and link contraction.

The interesting thing to me about the theory of relativity that he first came up with in 1905 was that, at the time, we had Newton's theory of everything. The entire universe. Newton was considered, like, you know, the biggest man on the hill. Practically a god to all the physicists. And you don't question something like that. That's just the way science always seems to work.

So Newton had a theory that worked out pretty much everything in the universe. 90 percent of everything that had been seen or observed could be explained by something Newton wrote.

Then by the time Einstein was born, this guy named Maxwell shows up. He comes up with this theory of electromagnetism. The problem was that Maxwell's theory was not compatible with Newton's theory. And so every sensible scientist on the planet, especially everybody who had a tenure track appointment, was working on ways to make Maxwell's views compatible with Newton's views. Because they knew Newton was right. And Maxwell was new, so he couldn't be right.

Einstein had nothing to lose, so he did the exact opposite. If you read his paper, his 1905 paper was actually on the electromagnetism of moving bodies or something like that he called it. And so that laid down the relativity theory and, you know, that made his -- you know that really created his career.

And so then about ten years later, he wanted to apply that same theory to gravity. And what he came out with was that if you allow space time to curve, then you could basically explain gravity within this context of relativity of a kind of a fluid space time.

And so the way that works is basically if you take a bowling ball -- by the way, a lot of these pictures I did not draw. I stole them from Kip Thorne. So if you take a bowling ball and you put it on your bed, you'll notice it causes an indention. If you take another smaller ball, it will tend to roll towards that bowling ball.

The idea is well, matter curves space time the exact same way. So if you take a piece of matter like a star and you put it somewhere, it's going to curve the space time around it and anything smaller is going to orbit it. So that's the whole basic theory of relativity.

And so basically his theory was that space time is going to tell matter how to move and matter is going to tell space time how to curve and it's going to be a symbiotic relationship between the two. And if you take this matter and you roll it and you move it, what's going to happen is that curvature is going to have to change as you move the object. But that's not going to instantaneously change.

So there's a way you could make ripples in it. So you could make ripples in space time. And when you do that, you create ripples and then waves. Then if you could actually see these ripples, you could learn something about the matter that was moving. So it's a really neat idea.

And then, sometime later, I think it was, like, around the 1930s, Einstein wrote a paper which completely disproved his theory of gravitational waves. And so that was the end of the story. Except for the fact that that paper was never published because it was actually rejected by a physical review. And that was when peer review of journals was new.

And Einstein got the rejection letter for his article, and he responded pretty much how you would think most people would. He said, I'm Einstein. What are you doing? Who are you thinking could review this? And the editors held fast and said, no, we can't publish it. And they ended up not publishing it and he later on figured out this paper was wrong and gave up on it. And never published in that journal again.

But that was one of the things that actually really saved the whole gravitational wave thing. Because if he -- if that paper had been published and people believed it, we probably wouldn't be having this talk right now.

So black holes are this thing that can form as a result of space time. And these things are geographic anomalies. Like we're basically -- geometric anomalies, I guess. You've curved space time to a point so extreme that the diameter is actually greater than the circumference of the circle. In other words to go through the circle is actually further than going around it. And the space time curvature is so weird that it actually works out that way.

And so you can create these objects, which are basically these -- you know, they're extreme curvatures in space time. And they manifest as very, very heavy objects. And so the neat thing about black holes is that when they first came out with the theory of black holes, the response of astronomers was that's the stupidest thing I've ever heard.

And then astronomers realized something very interesting. If you take this phenomena and puts it in the middle of all these things they've observed but can't understand, it makes sense. So they were, like, we love black holes.

So you can see here as an example, this thing called X ray binaries. And what's happening is a black hole is orbiting a star and it's actually -- material from the star is getting sucked off into the black hole and as material falls into the black hole, it goes faster and faster and faster. And the light that it ends up emitting ends up in the form of x-rays.

Another thing you can get are these active galactic nuclei. They would see these jets shooting out of galaxies and wouldn't understand what it was. Until you say, well, there's a supermassive black hole in the middle of it.

Another thing is spinning material, and a thing that causes that is spinning black holes. It picks up so much angle and momentum that it falls out.

And then there were these huge mystery, gamma ray bursts. Nobody knew where they came from, what caused them, why they were existing. All they knew is there would be these huge flashes of gamma rays and if you look at it purely on the gamma ray spectrum, they were shooting out more energy than the rest of the universe combined. But nobody knew what was causing it until about a year ago.

So this is something that was, like, a huge, huge question. And they felt, like, well that's probably got something to do with black holes.

So, what's this have to do with gravitational waves? Well, you've got this black hole which is a really massive thing and if you take a really massive thing and you move it through space time, it has a massive curvature of space time. And as it moves, it twists the space time around and the space time stirs up. And so that is what's causing the waves. So the waves are basically a result of all of this movement, all this space time getting stirred up.

And then -- so if you use black holes, black holes are just a great source of gravitational waves for this exact reason.

Now, I've got to pause and let you know something here. When I was in graduate school, we were working on modeling the source of black holes. The reason why we're modeling black holes was because they were a really strong source of gravitational waves. We had no idea how you could even get two black holes together.

There was a lot of speculation for years about how many of these things can you even see given a really great range on a gravitational wave detector? How many black hole collisions were there actually out there? We don't know. As far as we know, happens once every hundred years and we just missed it. So we couldn't -- so there's a lot of speculation on that. You know, there was no really understanding on why the physics would allow two black holes to be close enough to collide.

So let me see. Hopefully this works. Thank you, Windows. All right. I got -- this is where my flash drive comes in.

Okay. So I think the first one -- movie I want to show you has to do with the collision of two black holes. So you can see here -- whoops, this is galaxies. Not black holes.

Not that one.

>>: (Inaudible)?

>>: Not that one. This is close enough. Well, here, you can see there's two black holes. And what's happening is they're spinning around each other. (inaudible) equal mass. But you can see that as they get closer and closer and closer, the waves keep changing in both the magnitude and the frequency. And then they get faster and faster and then they whirlwind, and then poof. And when they merge, you have a single black hole at the end.

Like I said, I didn't do this simulation myself, but this is pretty fascinating.

Here is a simulation of black holes producing -- this is the one I was looking at before. So here is another one. And again you can see black holes spiraling around each other. And these little arrows are showing how much curvature you can see in the space time. And again at the bottom, this is actually what the waves look like.

So you can actually see the change in the waves and their wavelength. So you can see the wavelength and the amplitude changes as they get to each stage. And as they come together, they move a little faster. And now they slow it down so you can see the merger.

And then at the point where they touch, this is where the merger phase is. And they actually end up forming one odd-shaped black hole for an instant, and then they eventually ring down into just a spherical black hole. And when that merger phase is the higher amplitude phase. That's the part where you can see it the best. So, those are just two examples of black hole mergers.

The other thing that's really massive in the universe that can be a good source of gravitational waves are these things called pulsars. And I think everybody has heard of these. You've got this neutron star. And sometimes the magnetic field is not aligned with the axis of rotation. So you see a changing magnetic field.

And from your electrodynamics class you know that looks like an electromagnetic pulse. So you see this regular pulse from this magnetic field whipping around. And it's just a little changing magnetic field, and that's why we call these pulsars. So these pulsars also can emit gravitational waves if they're close enough, because they are really massive.

Now, the neat thing is in 1974, what happened was Taylor and Hulse actually bound a binary pulsar system where a pulsar and a neutron star and they were close enough together to where they were orbiting around each other. And what he was able to do is by looking at the pulse and the changes in the pulse, you could see that the orbit of neutron stars was changing. And since these are pulsars, not like regular stars, they don't emit optical light. So there's no other way for them to shed energy outside of emitting gravitational waves.

And so what they did was because of the way they were losing energy, they did the calculations and found out that they were losing energy consistent with the emission of gravitational waves. And that was the first indirect detection of gravitational waves. If it wasn't for this detection, they would have probably never funded a gravitational wave detector.

So, this earned them the Nobel Prize in 1993. Now, I want you to take a note here. They made the discovery in 1974. They won the Nobel Prize in 1993. That's almost 20 years. That's usually how long it takes if you make a huge discovery to win a Nobel Prize.

So, now, this is another movie which I think I'm going to have to exit out to show you. This has to do with neutron stars. So if I can show you -- yeah. Equal mass binary neutron star. Come on. Oh. There it is.

So you can see here we've got two neutron stars and they're just kind of spinning around each other. Let me start at the beginning. And you can see that in this simulation, as they get close to each other, they're starting to kind of take material off each other.

But then they're also emitting gravitational waves. So this is kind of what Taylor and Hulse saw but they didn't get to see the waves. They just saw that something else was going on here, and that something else was consistent with the gravitational wave.

One thing you should know about physics is that a lot of what we do is really comes down to probabilities. And the idea is that it just seems more probable that there were gravitational waves than any other explanation.

So here is another one. You can see these two stars, they're rotating around each other. Again they're getting a little bit faster and a little bit closer. They're starting to merge. And when they merge, out come all these waves and this big explosion.

It almost looks like, you know, you're frying two eggs at the same time while you're spinning the pan around. Anybody else do that? No?

>>: They rarely explode like that.

(laughter).

>>: Well, when I make eggs -- (laughter) okay.

And here's another one. This is in spiral of -- whoops. This is two neutron stars, again. And they're inspiralling. And you can see they're -- whoops, they start to touch. Here. And they're merging. And then that's the connection.

And then this is the last one I'll show you on this stuff. These are unequal mass binary neutron stars. So they've been able to do all these different simulations where they just change some parameters. Like they could have two equal mass, they could have one more massive than the other, they could have a neutron star more massive. You can do pretty much any combination of that. The nice thing is once you do a computer simulation, you can see all the data pretty much everywhere in here.

All right. So, that's the simulation I tried to show you. So what are other sources of the gravitational waves? Well first off, we talked about binary black holes. Basically a pair of black holes. We can also have binary neutron stars, which I talked about.

Now, these are things, like I said, the neutron stars we already knew that they could form in pairs since Taylor and Hulse. The binary black holes, they were just a very strong source but we didn't know they could be in pairs until we actually saw them. And then another source is supernova explosions. Every time a star goes supernova, it could send out a pulse of gravitational waves. All you need is mass moving really fasting.

And then there are stochastic, and these would be the background waves in the early universe. They could send out gravitational waves that would still be ringing around in the background of the universe, just like the cosmic background microwave radiation does.

And then we can get into exotic sources and this is where the cool stuff happens. This is all the physics that, like, you have to be really, really in the theoretical side to see. And there are things like cracks in the fabric of space time, like cosmic strings. You can have surface cracks. You can have naked singularities. You know, all this stuff that we don't really know exists. We can't rule it out, we can't say it's there. We just know that in theory, it could exist.

So what do gravitational waves look like? Well this is the interesting thing. When a gravitational wave passes by, you can imagine you have a ring of particles like I show on the board. What happens is as the gravitational wave passes by, the ring can get shorter and fatter and then taller and skinnier and flipping between the two.

So if a gravitational wave hits you, what's going to happen is you're going to get a little bit shorter and a little bit wider and then as it passes you're going to get taller and thinner and keep flipping between those two. And that's assuming the gravitational wave is actually coming right out of the screen.

Or you could have a cross polarization where it forms, like, an X. And so you can see the plus polarization forms a plus like this. And you can even combine the cross and the plus polarization and you'll have an ellipse that'll just be rotating.

And so the neat thing is, you know, just like electromagnetic waves have a polarization, gravitational waves can have a polarization. We might even be able to find some information from what the polarization is.

So the difference between gravitational and electromagnetic radiation is, you can see here on the two columns I have the electromagnetic radiation on the left and the gravitational on the right, where electromagnetic radiation are basically oscillations in the electromagnetic field and they propagate through spacetime. In other words electric and magnetic waves.

Gravitational waves, on the other hand, are oscillations in the fabric of spacetime itself. So it's a completely different phenomena. That means you can't detect them in the same way. The electromagnetic radiation affects different particles differently depending on their charge, and I guess to a certain extent on their mass, where gravitational waves, they affect all matter the same regardless of whether it's positive or negative charge.

The frequencies of electromagnetic waves tend to start at 1 megahertz and go up about 20 orders of magnitude, where the frequency of gravitational waves start at 1 and go down about 20 orders of magnitude. So they're in the same range as, like, your hearing. But it can go much lower in frequency.

And the neat thing about that is that, like, where we can think about astronomy and, you know, as you look and you see the stars, it's almost like there's an analog to hearing here. So it's like you don't see gravitational waves, you hear them. And I think -- I want to say it was Scott Hughes. He had a presentation on gravitational waves where he did the inspiralling of black holes but instead of just modeling on a computer, he hooked it up to speaker and you could hear it.

Also electromagnetic waves can be easily absorbed and scattered. But gravitational waves, you can't really scatter it or absorb it. And also electromagnetic waves, they come from surfaces that are optically thin and gravity is weak. And gravitational waves come from things that are massive, compact, highly dynamical.

So what happens is electromagnetic waves are good for probing the visible parts of the universe and gravitational waves are good for probing the dark parts of the universe. And it just so happens that, like, 90 percent of the universe is dark. You know we look at all the dark energy and dark matter. It's, you know -- this is actually most of the universe you can actually see with this.

And so the astronomy is different. The tools have to be different. But the payoff is that we actually get to see a completely different part of the universe that we could never see before or hear. So conventional astronomy to look at electromagnetic waves, you have to have an electromagnetic telescope. Where you could have electromagnetic waves like light coming in or even a space-based telescope like Hubble or James Webb would have electromagnetic waves it would analyze or you could have a big dish.

But that's not going to work for gravitational waves. For gravitational waves, we're going to use these things about interferometers. So they've been online for a while, although most of that time was spent trying to get them working correctly or get them working and understanding how they worked and proving the machines.

So you can see that here's a map. There's one that isn't on the map and it's down in Australia. But that one, I think, is more of a -- it's more of a scientific test than it is an actual observatory. It's not really expected to see anything.

And you can see that here in the United States, we have the LIGO, which stands for laser interferometers gravitational wave observatory. And we have two sites, one in Hanford, Washington, and one in Livingston, Louisiana.

Over in Europe, there's the GEO600 project which is a collaboration between (inaudible) and Germany, and then VIRGO is a collaboration between France and Italy. And then they're actually -- when they built these LIGO detectors, they actually had three of them. The third one was inside the Hanford, Washington site, and they're planning to move that to India. And then in Japan they're building this gravitational wave detector which is underground and it's cryogenic.

The neat thing about these is you really need to spread these around the world. Because if a gravitational wave comes in and you only have one detector, how do you know if you're reading the signal? If you have two or more, then you can tell where the signal is coming from me and you can also tell things about its polarization. So all these are very carefully planned where you're going to locate them geographically.

So this is a cutaway of LIGO to show you how this thing actually works. The basic way that a gravitational wave does is it creates a strain. And the strain is basically a change in length over a total length. So it's a fraction of your change. So what happens with the LIGO is it shines a laser at this mirror, this beam splitter, and it splits the beam between these two arms. One goes this way and the other goes of a 90 degrees.

And it hits the mirror at the end and it comes back and bounces back and forth between these two mirrors. It actually bounces thousands and thousands of times. And eventually it makes it through, hits this photo diode and gets recombined into a signal here. And the same thing happens along the other arm.

So what happens is if a gravitational wave were to come by, it would cause one arm to get a little bit longer and the other arm to get a little bit shorter. And the difference in the time the laser took to get between these two is going to tell you how much strain there are.

And so the typical signal that we're expected to detect with a gravitational wave from, say, colliding black holes, is on the order of ten to the minus 21. That means the change in length is ten to the minus 21 of the total length. So that means if you want to detect a change of a tenth of a millimeter, you would need arms that are three light years long. Yeah, to get a tenth of a millimeter.

Now I think when they first brought that to NSF, they said, nope.

So if you're ready to settle for say the diameter of an atomic nucleus, that's ten to the minus 13 centimeters, which is pretty tiny. That would require 13,000-kilometer long arms. I mean, I can't think of it off the top of my head, but what's the diameter of the earth?

>>: (Inaudible).

>>: Yeah. So basically that ain't even going to fit on Earth. So that's not going to work. So what they were able to get were 4-kilometer long arms. And with that, the strain that they're measuring, the delta L is one 1,000th the diameter of an atomic nucleus.

This is a single thing that explains why I'm not an experimentalist. Because when I was a grad student, I actually went out to CalTech when I was giving a talk and I visited the LIGO lab and they talked to me about how they have to keep track of all the different sources of noise that can throw this thing off.

You know, like it could be everything from, you know, cars driving on the road, there's seismic noise. We actually did a study of this thing called gravitational gradient noise where they can't even mechanically filter this out because it is gravitational waves that can be generated by the earth because of just the changing densities of the magma within the earth. It can actually throw this off.

And so we looked at -- you know, there's a thing called the microseismic peak, if you study seismic waves, where about every six seconds a wave hits the shore of the United States or any other country. Only surfers and geologists know this because, you know, surfers have to know it because -- to catch the wave.

But the idea, though, is that translates into a frequency of, like, 1.6 hertz or something like that? And what that ends up doing is it would screw up any chance you have of putting a detector on earth which you can actually detect down to that frequency. So because of that, LIGO can't even see gravitational waves below a certain frequency because of all that seismic noise.

And then you've got other noise. When they hang these they can't hang them from ropes because the fibers from the ropes will make noise. The lasers are not continuous. This might seem like a continuous dot but there's a slight variation in the number of photons and that number of photons can actually throw off the signal.

And then this is in a vacuum but it's not cryogenically cooled, and so any impurities in the vacuum can throw it off. If the mirror is not perfect, that can throw it off. People walking by the mirror could probably throw it off. So there's a lot of different noise sources that you can imagine getting from this.

So they built it anyway. This is the LIGO site at Hanford, Washington. And you see the mountains in the background? That's the best way to tell it's not Louisiana. So you can see this is the main building and you can see one of the arms and how long that thing is going off in the distance.

This is the Livingston, Louisiana site, which is a lot more green. You know the interesting thing is with all these trees here, you think about that question, if a tree falls in the woods, will LIGO hear it? And I'm guessing probably yes. But you can see here, this is not a small site. I don't have any pictures of the inside but you could Google them.

This is the VIRGO site in Pisa, Italy. So if anybody wants an excuse to fly to Italy, there's a site there. And it's probably not far from a vineyard, so that's pretty good.

This is the GEO600 in Hanover Germany. And if you look at the central building, this is a lot smaller than these other sites. Like the LIGO sites have (inaudible) arms and VIRGO, it's not even a kilometer. It's, like, 600 meters. But the idea of the GEO600, a lot of that is around developing the technology. Because it took them a long time to develop suspension devices.

Really interesting mechanic engineering problem was how do you suspend this mirror in a way that it's not going to vibrate or shake or anything? And all the minor vibrations of the earth had to be dampened out. Those are the problems they had to address.

This is the one in Japan that is under construction. It's not running yet. But it's built underground, as you can see here. And part of that is, I guess just shield it from different noise sources.

But that's probably going to be one of the next ones that comes online. And then this is what LIGO India is basically going to be. I think this is basically the Hanford site from another view. But you can see what they did was within LIGO, they had built 2-kilometer long arms inside of the facility. So there were 4-kilometer long arms and then next to it 2-kilometer long arms and they're going to take the 2-kilometer long arms and send those to India.

And then this is in Perth, Australia. I believe this is mostly for technology development. I think they're, like, 80-meter long arms or something like that. But you can remember, by sending a laser beam back and forth, you can actually increase the accuracy because it's effectively creating a longer arm.

Now, this is eLISA. The European Space Agency is funding it now. And the idea here is that this is a space-based gravitational wave observatory. And what it is is they have these three satellites and they're flying in formation and are shooting laser beams between them. And they are a distance of 500 kilometers between each arm. So it forms a triangle. Each one is 5 million kilometers.

The nice thing about space is you're not limited by space. You can get more space between them. And so on and also another thing about being in space is you don't have this whole problem with geological noise. So you can have this thing going lower frequencies.

So basically it will track behind the earth by about 20 degrees and it will just follow the sun -- or follow the Earth in the orbit around the sun. And when it sees a gravitational wave, you could basically use any two satellites can form effectively an arm. So you have two arms here and a third arm here. So you can actually create, you know, your interferometers with a triangle as opposed to just, you know, two arms.

So the neat thing about this, like I said, is you can go to lower frequency. So where the LIGO sites and the other terrestrial wave observatories, their sweet spot is around a hundred hertz. ELISA can go up to, like, a hertz. So it's much lower frequency than you could ever get on earth. And the reason why that's an advantage is because the more massive the object you have generating gravitational waves, the lower the frequency of the waves it produces.

So where you could see solar mass black holes with LIGO, this thing could actually see supermassive black holes, like the ones in the center of galaxies.

And this is a new technique called pulsar timing. This is something else that they've been developing for years. The neat thing about this is that they can detect gravitational waves without having to physically build an interferometer. What they're doing is building pulsars as effectively arms at the end of the interferometers.

And what they're doing is they're setting up all of these radio telescopes all around the planet and they happen to sit there monitoring pulsars. And they'll monitor one in this direction and one out in that direction and so on. And what they're waiting for is these pulsars have to be really, really fast. And they just wait for a little glitch in how regular the pulsar is.

Like one of them over here, we get the signal a tiny bit earlier than we're supposed to, and that one we get a little later. And from that we can tell there was a gravitational wave. So the neat thing from here is you can create your interferometer from software and creating all of these different sites around the world.

And then this is a new one they're developing called the Einstein telescope. The basic idea here is they're going to take a lot of the lessons that were learned from LIGO and advanced LIGO and VIRGO and create a gravitational wave interferometer underground.

You can see it's a triangle, not just two arms. And so it can detect the gravitational waves and coordinate its own signal.

By the way, part of the reason why they built LIGO in pairs was because they acknowledged the fact that you could get a glitch in one that would show up as possibly a signal and you could use the other one to kind of coordinate that -- correlate that signal. So if both of them are picking up a signal and they're spread out, then the odds of that being an accident are very low.

So this is what the -- basically the signals look like for each one. And you can see that this is LIGO, VIRGO, advanced LIGO, (inaudible). All of these, this is the noise curve for them. And so you can see that they're pretty much all between ten hertz and a thousand hertz.

And then these are the expected -- how accurate they need to be in order to see different sources. Like the binary black holes and binary neutron stars, pretty much all of them can see. But then if you get more accurate, you can actually see pulsars, you can see supernova. You know, other sources.

And then the eLISA would be able to see a much lower range. It would see -- hundredth of a hertz. It's actually 10,000th of a hertz. And that could see supermassive black holes and other sources from that.

And then the pulsar timing is actually in the nano hertz range. That might actually pick up gravitational waves from the early universe.

So, why we know -- we need to know what these signals look like in advance. And one of the things is that before we can actually get the gravitational wave detectors online, we had to actually calculate what the signals were going to look like. Part of that was to justify the money that was spent on the detectors. Part of it was to understand what the observatories were seeing.

Like we could model all kinds of exotic stuff and then if the detector sees it, we know we were right. But then we can test different theories. We can do science with this. So the idea was if you do the right modeling, then for all these sources, then when you see something on the detector, you can just compare whatever the detector is seeing to that and you know you saw something.

Also another thing is the way LIGO works is that it's constantly getting these signals. And, you know, most of it looks like noise. And it compares that signal not just to the other signals coming from the LIGO sites, but it compares it to templates. And whenever it sees a match, that's when it alerts people, hey, you've got to look at this. And then the scientists jump into action. So the whole idea is we have to create models to the AI knows what to look for.

So the thing about these signals is that few of them can be determined analytically. It's literally too hard of a math problem. We have to do numerical simulations (inaudible). And this is where numerical relativity comes in.

So this is what the gravitational wave looks like for two binary black holes. There's multiple phases. There's a (inaudible) and then there's a ringdown phase where it comes a spherical black hole. And you can see that in each phase, there's a different level of how much gravitational wave is emitted and the frequency and everything. Most of the frequency comes from this merger phase.

Until around 2003, nobody was even able to calculate what this looked like. So it took a while to be able to do that. And this is where you kind of create this template, and then the computer can look at that and say, well, this is what we're seeing.

And so within numerical relativity, what we basically do is we start off with basic conditions of what the spacetime would look like, and it's almost like a movie. We take Einstein's equations and we break it up into the spatial equations and the time equations.

And at each instant, we'll solve what's going on. Move it forward, solve it again. We have the computer continuously solving, and in doing that it moving the movie forward. So we start off with what we know, like what the spacetime around two black holes should look like and we end up with the gravitational waves that that emits.

And so when we break this up, we've got a lot of different equations we have to solve all at the same time. So this is what we do. This is where we solve it.

This guy should look familiar to some of you. This is our singularity cluster. It's located in this building. So, you know, it used to be that in order to solve these equations, you needed a huge super computer which cost, like, $5 million. And now we can solve a lot of this on this machine, which cost closer to $5,000. So, you know, that's progress and that's also just showing you how advanced computers got.

By the way, Chuck, this is what your computer evolved into over time. (laughter).

So, I want to show you another movie before we go. And this has to do with the merger of supermassive black holes. And so what's happening is we actually know that galaxies collide. And we also know from physics that in the middle of these galaxies, there are supermassive black holes. And so the neat thing here is that you put the two of these facts together and you can see that you're going to get supermassive black hole collisions or near collisions from these galaxy collisions.

And also whenever you have matter and it falls into the black hole, it's going to cause it to perturb, and it's going to cause gravitational waves to be released. So you can see a lot of really interesting stuff going on here.

Okay. So I think I've already showed you some of these other movies. Oh, I didn't show you this one. This one was another movie about -- let's see. This is another movie that shows the neutron star mergers in full general relativity. And so you can see that there's simulations, there's a lot of these out there, where some of them are black hole/neutron star and some are neutron star/neutron star.

And you can see here, the two neutron stars, they come together and they -- this one is interesting because you can see they form these bars. So they're forming kind of oblong-shaped neutron stars. And this is emitting a lot of gravitational waves.

One reason I wanted to show you the neutron star collision is because I kind of hinted at this earlier when I talked about gamma ray bursts and how we didn't know where they came from. It turns out that's where a lot of those are coming from, neutron star collisions. And in one observation, LIGO detected a binary neutron star collision, and at the same time they had their partners doing optical astronomy also watching. And they say there was a gamma ray burst and they correlate that together.

They also found out that's where heavier elements like gold come from, from these neutron star collisions. And they were able to also see the gravitational waves, how long it took them to get to us as the electromagnetic waves from the pulse of gamma rays came. And they saw that they move at about the same speed.

So they proved Einstein's theory that gravitational waves move at the same speed as electromagnetic waves is true, or at least as far as we know, which shows that gravitons, as a particle, are massless. Which is another big thing in Einstein's theory. So one observation and they proved three of the biggest mysteries in physics that nobody had any clue to. So that was a good day.

So, I think I already showed you this one. This was actually the binary black hole that they did observe. Oh, not that one. Yeah, this one.

So you can see here, you've got two black holes and they're spinning around. This was actually the first detection of gravitational waves. And so they created this simulation based pretty much exactly on the parameters they observed where they saw two black holes that were roughly 30 solar masses each, and they merged. And they were about -- I want to say they were about 3 billion light years away. And you can see that this is when they merge. And they get heavier and heavier. And sink into a final black hole.

So, this earned them the Nobel Prize in physics for 2017. Now, notice I told you before Taylor and Hulse, they detected that binary neutron star system in 1974 and they got the Nobel Prize in 1993. These guys, they saw this first observation in September of 2015, got the Nobel Prize in 2017. That's not a long wait.

And actually if you think about it, it's actually less than that because even though the first detection was in September of 2015, they didn't tell the public until February of '16. So part of the incredible accomplishment of LIGO was they were able to keep a secret among 500 people for five months. Few people have ever accomplished such a thing.

And so that confirmed -- you know, it was a real confirmation of gravitational waves. It really opened up the field of gravitational wave astronomy. And it was really interesting because these guys have been working on this for 40 years. I mean 40 years of doing the science, begging for money and, nothing. Seeing nothing.

And then there was actually outside of (inaudible) and Kip Thorne, there was another guy who would have been the third guy for the Nobel Prize, but unfortunately he passed away right before -- you know before they actually made the detection. So that's why he lost out on it.

But you can see here that, you know, 40 years, finally made a discovery, and then that was it. And I'm sure the day after they made the big announcement, everybody decided to sleep in.

So, in conclusion, this is an important part of modern physics that a lot of people don't know a lot about because you know the fact that we've only had detections of these for a few years now. It's barely been more than three years since people knew about the first detection and you had a paper to read on it.

There's a large international effort. This is international physics at its best. Because this is literally, just geography involved, you can't have just one country doing this work. And also this is a field where you have theorists, you have computational people, you have the experimentalists working together. So there's a lot of parts to it. And there's also a lot of creative stuff people are doing where they're using observations to test fundamental theories of gravity, to look at the early universe, to be able to test alternative theories of gravity. So, it's a lot of interesting stuff on that.

So, questions? Yes?

>>: So you're talking about the different size detectors being able to detect different (inaudible) can detect much lower frequencies. And those lower frequencies are associated with larger objects.

>>: Right.

>>: So is the idea that those collisions of larger objects are louder, for lack of a better word, so you'd be able to hear them from farther away? So you can increase the amount of space you'd be able to observe?

>>: Yeah. For example, when they look at the range of LIGO, what they used to do was they used binary neutron stars in order to say that the range was so many parsecs or something like that. And they would actually create a value of space and say well, we can detect anything within this range.

Now, when they found out that this binary black hole stuff wasn't just something we made up, it was something that could exist, then all of the sudden they started thinking about the range in terms of binary black holes because you could actually see them further away, even though they are, you know -- they're a little bit more massive. I mean they're not, like, a million times more massive. But you're talking about on the order of maybe 30 -- you know, order of magnitude more massive. So you end up getting that much more range.

And so if you go to super massive black holes like with eLISA -- in graduate school we did a calculation on that and we found that if it meets the specs, it could see as far as any telescope ever made.

>>: (Inaudible)?

>>: Yep. Yeah. So it's really interesting. Yeah.

>>: (Inaudible) if I'm wrong, tell me I'm wrong. But it seemed like after the first detection, then it was suddenly really easy to detect because they made all these detections afterwards. How come it took this one? Did they, like, you know, revamp the way they're doing (inaudible)?

>>: It's actually a more interesting story than that. What happened was in September of 2015, they were gearing up LIGO and they were doing all the engineering stuff and they were getting ready to start their observing run. Because what they do is they test out, they're looking for stuff. And they do engineering runs where they tweak the equipment.

The signal showed up while they were doing an engineering run. So they were completely caught off guard and a lot of people thought, is this a joke? I mean, are you messing with us? Because the signal was too loud and clear to be anything but a joke. And they started looking around -- actually, I teach a class in the fall on this called -- on gravitational waves. And actually use the book called Gravity's Kiss, where it was written by a sociologist who studies gravitational wave physicists. Kind of like Jane Goodall and the apes.

But anyway, it told the inside story of this. They weren't looking for a signal. They spent a lot of time confirming it was the actual signal and not a joke. There were not that many people who were capable of injecting a signal in that would show up on both sites. And, you know, it was -- so there was a lot they had to do to confirm it.

And also they had for the first detection, you had to clear this hurdle of being over five sigma standard, which basically means that the odds of it being something other than a gravitational wave were, like, one in a million. So, what happened was that first detection was clear. And it was loud and it was, you know, unexpected and unbelievable.

And then they had to actually freeze the detector in order to get background information to prove that it was a five sigma accurate. And in doing that, they couldn't actually detect anything else. They didn't want to detect anything else. So they avoided that. And, you know, and all this while they're doing all this stuff in secret and writing the paper and everything.

And so after that, they had a few other candidate signatures -- signals that came in that they sort of dismissed because they weren't at the level of accuracy they wanted. And then later on, when they got to the point after they released the information, that was when other people knew more about what to look for and that's when VIRGO started looking.

But they had basically written this whole protocol where, until they had detected, like, three signals, they were going to go strictly by this protocol where information was very censored and didn't go out to the public. So once they got past the three, (inaudible).

All right, other questions? Yeah?

>>: (Inaudible) the pulsar timing, (inaudible) to detect gravitational waves, you said they can detect a lot lower frequencies than (inaudible) in space.

>>: Right.

>>: (Inaudible) why?

>>: It's because the wavelength is so long. The arms are so long, effectively. In the case of LIGO, to get a tenth of a millimeter, you needed three light year long arms. Well, the distance from here to the nearest pulsar is a lot longer. So if you think about it, you've got a much longer arm.

But also at the same time, if it takes that long for the signal to get between here and there, the wavelength is really long. And because the wavelength is really long, the frequency is really low. So you're naturally tuned to lower frequency. So, like, a high frequency wave with the pulsar timing, it won't even show up as anything. But the low frequency is going to be really loud.

That's the theory on it. They haven't detected anything through pulsar timing yet, so we've still got to see exactly how it's going to work.

Okay. Other questions? yes?

>>: So (inaudible) waves, have we had any luck (inaudible)?

>>: No. Because -- well, like I said, the problem with the graviton is -- assuming it does exist, to detect it is much, much harder than that. The nice thing is with that binary neutron star collision, they were able to find that the graviton, if it does -- you know, if you could write it as a particle, it does travel at the speed of light, which means it is a mathless particle. So we got to learn that about it. But, you know, we're not quite at the level where we can do particle physics with it, because they require much higher energy.

Okay. Yeah?

>>: (Inaudible) anything else? I know, like, (inaudible), like, is there anything else that could come from?

>>: That's a good question. And the truth is that, like, we don't know. I mean the thing, to get that low of frequencies has got to be something, really, really massive. You know more massive than supermassive black hole.

And also another thing that happens is that we know that, you know, as waves travel, you know, like electromagnetic waves travel, they get red shifted. The same thing happens to gravitational waves. So it could be that it's a really low frequency but, like, from the early universe. But it could also mean that it is a really -- it's a higher frequency that was red shifted from being from so long ago.

Like, I mean if we saw something like a supermassive black hole collision from 17 billion years ago, that would be -- okay, wow. We've got to reexamine everything. So, I mean, but could that be out there? Who knows. Older than the known universe? Wow. That'd be interesting. So you never know.

And the thing is that one thing that this really shows is how little we know about the universe. Because the only thing we know about is from looking at stars. And one thing we've learned from looking at the stars is that they only make up about 10 percent of the visible universe, you know, when we start looking at dark matter and dark energy.

So we don't really know much and, you know, we have these dark matter halos around these galaxies. We don't know anything about them. We don't even know what the dark matter is. We don't know what it's made of. We don't know if they're actually made of stuff or if it's just something about gravity we don't know because we don't know the theory well enough.

So, I mean, at the end of the day -- I don't know. I mean, we don't know a lot of stuff. So maybe what this will do is help guide the way.

You had a question, didn't you?

>>: Do gravitational waves still transfer energy like (inaudible)?

>>: That's a good question. Umm, yeah. They can, because in the Taylor Hulse binary system, they actually did take energy out of the system. And in the case of the binary black hole they found, I think it was something like 3 percent of the mass of the black hole was transferred into gravitational energy.

>>: (Inaudible) determining that is happening?

>>: Yeah. I mean, there's probably some other things you can do with that. But yeah.

>>: (Inaudible) just kind of the energy (inaudible) gravitational wave do? I mean, obviously it affects --

>>: Well, yeah, it makes sense, though. Because it is taking particles and (inaudible) moving them. So it's doing something, although, you know, that's the stress and strain of spacetime. And you know from Einstein's theory, we know that -- we can go back up here.

We know from Einstein's theory that the curvature of spacetime depends on this thing on the right-hand side, the stress energy tensor, which is basically energy. So in order to get curvature and spacetime, you have to put in energy. So that has to be in there somewhere.

Yeah?

>>: (Inaudible) space travel?

>>: Not yet. Well, I mean, again like I said, we're still trying to learn a lot because we don't know a whole lot about what else is in the universe. So, I mean, it could be that maybe there's some useful things that we could get out of that. It could be that, you

know, just learning about the universe, it could be that it tells us things about how gravity really works that might be useful in other ways in the future. So we don't know yet.

Stay tuned. (laughter).

But, I mean, the neat thing is that anything you're developing some type of science like this, it always ends up leading to kind of secondary inventions. And we saw that a lot with space travel. So what's happening here is a lot of the things that they needed to develop in order to make LIGO work, like having a suspension system that filters out all of these vibrations could be pretty useful elsewhere.

A lot of the advances we made in developing the computers and the simulations, we've learned things about how to do high performance simulations that other people weren't able to do in other fields because they weren't pushed as far because the amount of data that had to be processed and simulated.

And the way it had to be done, there were things in terms of the artificial intelligence and learning that were state of the art. There were things involving the network in order to communicate to multiple sites in realtime. Secondary stuff, like how do you get your five hundred people on a conference call in a secure way?

That's the interesting thing about science, there's always other stuff that ends up becoming really valuable. Like the whole reason we even have a worldwide web was because physicists didn't want to wait six months to see an article from their colleague. They wanted to see it now. So we got the worldwide web.

So there's almost too many things I could even name. But actually I read a while back that somebody was trying to use basically this code or something similar to this code to try to model the stock market. So it can make people really rich or very, very poor. Probably both (laughter).

All right. Other questions? Yeah?

>>: (Inaudible).

>>: Yeah.

>>: (Inaudible)?

>>: Oh, umm -- polarization, the basic idea is -- all right. When you have an electromagnetic wave, and like let's say you have polarized sun glasses. What happens is they have, like, little filters that go either vertically or horizontally. And what happens is when the light comes in, if the electro part of the electromagnetic wave is vertical, then it goes through the vertical parts. But if it's horizontal, it can't make it through the vertical parts, so it gets stuck. That's why you see about half the light.

And another thing that can do, if you go to a movie theater and you see a 3D movie, what they do with the 3D movies is that they actually polarize the movie on the screen so that your right eye sees one thing and your left eye sees something completely different. And by doing that, they create a 3D effect.

So what's happening here with gravitational waves is that they don't have a vertical and a horizontal polarization. They have a plus and a cross polarization. So this polarization here is like a plus. And this one is like a cross. And what happens is that they actually -- if you actually --

I don't have it on here but there was a picture of the LIGO detectors where they're both basically forming Ls. But they're orientated like this, so they're they're kind of off at different angles. And they did this on purpose. If this one is a plus polarization, this one is a cross polarization. And if a cross, then the other one will see it. And they can use that to determine the polarization of the gravitational waves coming in.

>>: (Inaudible).

>>: Yeah, and also they can determine the direction by looking at when the signals arrive relative to each other. If one arrives a few microseconds later, you can tell that.

Yeah?

>>: (Inaudible).

>>: Yes and no. You can actually get plus -- or you can actually get different polarizations within, like -- I know within turbulence in, like, the early universe you can actually see that there will be different polarizations, the gravitational waves that will come out because of the turbulence. But I think in terms of binary black hole collisions, I think it has to do with the orientation of the plane of the binary black holes relative to each other.

>>: (Inaudible) attractive or repulsive like EM waves?

>>: Kind of. It switches here. So they're being moved around. So when a wave passes by, it will actually cause things to move in either direction. But the thing is every piece of matter is going to respond the same. This is one of the things we found really interesting was because if you can imagine if you have a plasma field where it's all charged particles and it can just be sitting there minding its own business.

If a gravitational wave comes in, what that will do is it will cause the charged particles to move closer together or further apart, and that will generate waves within the plasma and excite the plasma, because it can actually cause the plasma particles to, you know, basically -- they get closer together, they're more magnetically attracted. If they move apart, they're less magnetically attracted.

So it's changing the dynamics. And so one of the tests we did on the plasma was actually injecting gravitational waves in the plasma, having it excite the plasma, and then seeing if how it excited the plasma matches up to how we expected it to. And that was how we could tell that the code actually worked.

So that was also what was interesting to me was that thinking in the early universe, you had these gravitational waves from inflation and they were coming in and hitting the really dense plasma in the early universe and then there was something going on. Okay.

All right. Other questions? Okay. That's it. I guess I'll see you guys next time.

(Applause.)

And if you haven't already, please turn in your papers, turn in the sign-in sheet, and -- let's see. Next week, you know, since spring break is every to, no more breaks in the talks. Next week we are going to have Margaret Cheung here from the University of Houston.

(End of class)