Episode 81

Titanium Physicists
Episode 81: LISA the Giant Tumbling Space Triangle
Physicists: Dr. Joey Shapiro Key, Dr. Jocelyn Read

Transcribed by Denny Henke

Never be afraid. There's nothing which is known, which can't be understood. And there's nothing which is understood, which can be explained. For over 50 episodes now, my team and I have brought you to the very frontier of knowledge in physics and astronomy. And still, our mission goes on to present you with your birthright, an understanding of the universe. I've traveled the world seeking out a certain type of genius, masters of not only their academic disciplines, but also at explaining their research in understandable ways. And I put stowed upon these women and men, the title of Titanium Physicist. You're listening to the Titanium Physicist podcast, and I'm Ben Tippett.

Music

Ben: So, a student of mine came by the office the other day. Mostly just to chat. She told me about how the geology class had visited a nearby fossil site. One where amateur fossils collectors readily visited and was famous for its plentiful trilobite fossils which predate the fossils in the Burgess Shale, you know, the Cambrian explosion. So wow! I immediately, well, I said goodbye to her, and then immediately ran up to the geology instructors office and asked for directions and instructions and also a rock hammer and if you're it was okay for me to go hit things. And the next day Bethany and I drove down to the site, and it wasn't far from the highway. You turn left onto a small road and then drive past a quarry and a rifle range, then park nearby and walk three minutes up the hill. That was it. And there in a clearing in the forest about the size of a kitchen table were just piles of shale sticking out of the gently sloping hillside. Following the instructions, we picked up a piece of shale and then bonked it on the side with the rock hammer until it split open. And soon enough, one of the rocks we picked up had a fun trilobite fossil in it. It was bonkers. Now, what struck me is worth sharing in this whole affair beyond just bragging about it, was how unassuming it all was. It's just a pile of shale, near the edge of the forest, near enough to the highway, in the middle of everywhere. And here was evidence of great goings on. And once upon a time, a whole bunch of water dwelling bug monsters wandered around in the muck and shed their shells. And then those shells got fossilized as evidence of everything around it happening. But that once upon a time, time is full of them. And the rocks and crust of the earth must be full up of history. Unknown to us, countless stories remain dormant beneath our feet. The deeper you go, the more ancient the story is. And that's an interesting idea to me, because in physics and astronomy, you don't look down to see history, you look up and out. Out farther and farther to the edge of our vision, the universe has laid its history out before us. Surely you're familiar with the idea. Since light travels at the speed of light, it takes time for electromagnetic waves to move across the universe. So stuff that reaches our eyes from far, far, far away, has taken a very, very, very long time to reach us and is carrying information which is billions and billions of years old. The light in the sky holds its own type of geologic record. But what if it wasn't just limited to electromagnetic waves. There are other waves carrying information across the universe like gravitational waves. And in the coming years, the next generation of gravitational wave detectors are going to be able to tell us about sources of gravitational waves all the way back to the earliest moments of the universe. Today on The Titanium Physicists, we're talking about the new detectors, which are going to span the entire gravitational waves spectrum. Speaking of interpreting meaning from ancient signals, our guest today has a notable podcast where he and his co-host comb through old Star Trek episodes on the hit show the Greatest Generation, they've watched, summarized and humorously commented on all the *Star Trek The Next Generation* episodes and are currently working their way through *Star Trek Deep Space Nine*. Also popular, is their podcast *Friendly Fire*, where they analyze randomized war movies with John Roderick. Welcome to the podcast humorist and podcaster. Benjamin Ahr Harrison.

Benjamin: Thank you. Thanks for having me. Thanks for calling me a humorist.

Ben: Well, you are.

Benjamin: That's ah, that's generous of you.

5:14

Ben: Well, Ben, our topic today is tricky and weird. So I found two notable experts to help us through it arise Dr. Joey Shapiro Key.

Joey: Woohooo.

Ben: Dr. Joey got her PhD from Montana State University and she's currently an assistant professor of physics from the University of Washington Bothell, where she studies gravitational wave astronomy. And arise Dr. Jocelyn Read.

Jocelyn: Raaaarrrr.

Ben: Dr. Jocelyn did her undergraduate degree with me at UBC and her PhD from the University of Wisconsin Milwaukee. And she's currently at California State University Fullerton where she studies neutron star mergers. Alright, everybody, let's talk about gravitational waves. Okay, Ben, have you ever heard of gravitational waves before?

Benjamin: I mean, they've got graviton beams in Star Trek. And I don't know what that is, but if it's the same thing...

Jocelyn: If gravity is quantized, then gravitational waves would be made up of gravitons. But we would be detecting like floods of gravitons passing through. So we don't really see any quantum gravity.

Joey: Although we constrained it, right?

Benjamin: It's already over my head, everything, everything is already over my head.

Ben: The long and short of it is, kind of. Okay, let's take our time through this topic, because before we could talk about weird gravitational wave detectors, we need to talk about regular gravitational wave detectors. And before we need to talk about that we need to talk about gravitational waves. Before we talk about that, we need to talk about Einstein's theory of general relativity. Okay, so this is where things get good. Have you ever heard of Einstein's theory of relativity before?

Benjamin: Yes, of course.

Ben: So Ben, like gravity is like a force, right? It's a force that pulls everything down towards the middle of the planet. Benjamin: Right.

Ben: Okay. So that picture of gravity comes from Isaac Newton. And it kind of went out of date around 100 years ago, around now. And the deal is Einstein, this fancy up and comer, he proposed a new way of thinking about gravity that actually fit a lot of experimental and astronomical data a lot better than Isaac Newton's theory. But the weird thing about his theory, is he said that there's this thing called space time, which is all of the space around us, and is somehow stuck to the dimension of time. And they're stuck together into a four dimensional thing, instead of just being time separate from space, space and time are all stuck together. Okay?

Benjamin: Gotcha.

Ben: So Einstein's picture of what caused gravity was that there was curvature in space time. And that's a really weird thing to kind of get your head around. You've probably seen like online, sometimes people show videos of an experiment that they do in science centers where they take a great big rubber sheet, and then they throw like a weightlifting weight in the middle of it.

Benjamin: Yeah, I'm familiar with that image, that that heavy objects kind of draw other objects toward them, because they're lower in the in the sheet.

Jocelyn: So it's more that if you tried to roll a ball on a flat surface, it would just go in a straight line. But once the mass curves the sheet, then you try and roll something in a straight line, and then it ends up rolling around, and it doesn't really need the pull of real gravity, it just needs the curvature to push it in the direction that gravity is making it go. Like it uses real gravity to deform the sheet. But the space time is the curving sheet pushing the balls around.

Benjamin: So is it that heavier things are interacting with gravity more.

Joey: They curve space more. Einstein said mass tells space how to curve and space tells mass how to move.

Benjamin: Wow.

Ben: So heavier things cause more curvature in space time. And that's a really weird thing. Another way to think about it is to imagine like a kid on a skateboard in one of those big skateboard parks that has lots of curved surfaces on it.

Benjamin: I've tended to avoid those but ah...

Ben: Like a skateboard is a really hard thing to turn, you can kind of bank it left and right but seen from above the kids on the skateboards going quite tight circles. And the idea is, it's the curvature that they're traveling over, that's causing their path to turn. And so the idea is that the sun is causing space and time around it to be twisted in this really weird way, to be curved, whatever that means. And in doing so, all the planets are actually traveling the straight lines, but they're traveling in straight lines on this curved surface, which causes them to go in orbits.

Benjamin: Wow.

Jocelyn: Yeah, if you try and explain Mercury's orbit, you need that.

Ben: Yeah, Mercury’s orbit doesn't work unless you include space time curvature corrections to it. That's kind of the introduction to the idea. But essentially, it comes down to, like, the the science experiment that you've seen where the they throw the weight on the rubber sheet. We need to talk very briefly, though, about what it means for space time to curve. And the easiest way to talk about it is to think about, like, distances and time intervals being different depending on where you're standing.

10:05

So in regions of high curvature, like a foot wouldn't look like a foot, it would be longer or shorter by a little bit and one second of time wouldn't be a second of time, it would be longer or shorter by a little bit, when you when you compare the two. So famously on the surface of the earth, where gravity is stronger than way up in space, time is passing at a slightly slower speed than it is way up in space. And so when they built the GPS satellites, the GPS satellites have really, really sensitive atomic clocks in them that are used to tell us exactly where we are on the earth. When they built the atomic clocks, they had to include slight corrections for the fact that time passes at a slightly different rate way out there than way down here.

Jocelyn: So whenever your phone tells you where you are with GPS, it's using Einstein's theory of general relativity.

Benjamin: Wow, you have to believe in the earth being round to for that to work, right? Yes.

Jocelyn: Most of GPS involves that yes, also.

Ben: Yeah. In the global , in the global positioning system, the first word is the... So the idea here is that time is passing at a slightly slower rate down here, then it is way up there because of gravity, because the curvature of space time. It also manifest in terms of like distance scales being different, down lower or up here. A cubic meter down here isn't going to be the same as a cubic meter way up there, it's going to be slightly different. Wait, you guys are mostly American, a cubic foot is going to be slightly different down here than up there. Does that does that make a little bit more sense?

Benjamin: I think the principle holds no matter what...

Jocelyn: Yeah, as soon as you said foot it became entirely clear.

Benjamin: Right.

Ben: Good, good, good, good. So there's a really fun calculation that you can do, which has to do with this spacetime curvature from the Earth. So imagine, like the Borg came to Earth, and it decided to cut up the Earth into one, one mile by one mile cubes. It decided to dice us up like a slice, like a thing of cheese.

Benjamin: Okay.

Ben: And then it decided to count the cubes of cheese to make sure it cut up the whole earth, they would find that there would be like 120 ish too many cubes, then they could account for, for the size of the Earth. When you look at the size of the Earth and you're like, you know, count, calculate its radius, see how big around it is, it's a sphere, right? There is about a five kilometer cube chunk of rock too much inside the earth. And that fits in there, because space is curved by gravity. So the earth is bigger on the inside than it should be because of gravitational curvature. I don't know if that made sense in this context.

Benjamin: I've heard that the matter in black holes is much denser because of the gravitational forces acting on it. Is that the same principle just at way less force?

Jocelyn: See, if you tried to fill up a black hole with stuff, you would just keep putting more and more and more and more stuff in and you wouldn't run out of black hole space?

Benjamin: Sounds like my closet.

Ben: We're going to talk about black holes in a second. But what I'm just talking about is how much stuff can you put in a box? Right? Let's take your closet, for example. Okay, so your closet, it's two meters long, it can hold 50 shirts, okay? You look at the outside of the closet. And you can tell based on the dimensions outside how much room there is on the inside, right?

Benjamin: Sure.

Ben: If you include the possibility that space can be curved, you'll be able to put more shirts in your closet than you should based on the dimensions. So it's like having a closet, it's one meter wide. And then you find out you can put 7000 shirts in it instead of just 50. Like, oh, wow. The deal is that there's more room inside based on how big it is from the outside because of curvature of space time. This is one way that curvature in space manifests. It's bigger on the inside, like a different science fiction, intellectual property that isn't outside.

Benjamin: Oh, is that, is that Doctor Who you're referencing?

Ben: Yeah, maybe. Let's talk about black holes now.

Jocelyn: Sure, yeah. So massive stuff, curves spacetime. And the, the other thing is like the gravitational effects get stronger when you're closer to a massive thing. Right?

Benjamin: Right.

Jocelyn: Like the earth is kind of a big deal. Even though on the solar system scale it's not a lot of mass, but we're right here. So black holes take more than a sun's worth of mass and pack it into few miles or kilometers. And so the gravitational effects are extreme curvature is so extreme, that no matter what you are, if you're inside the horizon of a black hole, your straight line path to escape the black hole just gets curved around back into the black hole so that the horizon is this point of no return once you're inside it. Nothing can follow a path that emerges again, from the black hole, you're lost to the rest of the universe.

Benjamin: I have a question about that. Because I've read that light is susceptible to that, like that's why they're called black holes, that light even falls into them.

15:04

Jocelyn: Yes, not even light can escape.

Benjamin: I've also read that they detect black holes by trying to spot when a star doubles. And that's because of like gravitational lensing that you see the light from the star twice, if it passes behind a black hole. Is that because some of the lights isn't falling in to the black hole?

Jocelyn: Right, exactly. So the horizon, like there's this sort of spherical surface that the, outside of this point of no return. But even outside the black hole's horizon, there's super strong curvature this, I mean, depending on the scale.

Benjamin: Right.

Jocelyn: So, so what you see the effect of a black hole, is the warping of light that goes near the horizon will get curved around a lot as it travels.

Joey: Yeah. So it didn't fall into the black hole and escape, but it got bent.

Benjamin: It just made a close pass...

Joey: Yes...

Benjamin: ... ofthe black hole.

Joey: ...and that's a gravitational lens.Yep.

Jocelyn: Or like the black hole image that was in the news a few months ago. Did you see the snapshot of a black hole from the radio observatories?

Benjamin: Yeah, I mean, it just, it seemed like a rendering to me, so I wasn't really sure what to make of it.

Jocelyn: Well, it's got, like a lot of cool machine learning, to like, put that into a image your eyes understand. But, like, that's not light from inside the horizon, that's light from right around the horizon is the idea. So the horizon where no light can escape is sort of the shadow in the middle of that image.

Benjamin: Gotcha.

Ben: Okay, so. So the deal here is you got these black holes. The universe has a lot of black holes in it, by the way. The black holes are like, hah, what's this, what's the best way to put it? They’re what, it’s what happens when really, really heavy stuff can't resist the force of its own gravity anymore. So like...

Jocelyn: Big stars run out of fuel.

Ben: Yeah, the reason big stars aren't big clouds of gas in space is that this cloud of gas in space collapse down to a star under its own gravity. And so gravity is pulling each and every mote of dust and gas in towards the middle. But the reason it doesn't collapse down to a point is because it's, it's hot. Essentially, the heat and makes the star kind of puffy. But the deal is, as time goes on, stars run out of fuel, and so they can't stay hot anymore. And then they can't really resist the pull of their own gravity, and all of the dust and gas and everything into it collapses down essentially into a point. And what's left is the black hole. So in essence, only really, really big stars do it, the smaller stars, like ours won't supernova and turn into a black hole. But the bigger stars generally do. And so the universe is kind of full of these old dead stars that collapse down to a point and are now black holes. And the interesting thing here is that a black hole is kind of like it's not really an object. As far as we talk about objects as things.

Laughter

Ben: Are usually are made of...

Benjamin: No, I'm against objectification also. So...

Ben: Yeah, objects are usually made of atoms, black holes, there are no atoms, all that's left is kind of a footprint, a sinkhole where the object used to be. Like, imagine you build a big house in Florida, and then it causes a sinkhole and it gets sucked down. Your house isn't there anymore, but the street address still is. And instead, there's just a sinkhole that you interact with. So all that's left is this big hole in the curvature of space time where the object used to be.

Joey: I mean, I do like to think about black holes as astrophysical objects, actually. Even though the atoms that originally were the mass are no longer, the name, black hole is actually a confusing name, because it's not really a hole. It is an astrophysical object, and it has mass. And so therefore, there's gravitational effects that we can observe. Einstein called them gravitationally collapsed objects, which is, just not a very exciting name. So I think, you know, black hole caught on. But you could also call them black stars, or dead stars, or dark stars or something like that, because they are this end state of stars, at least these stellar ones we're talking about so far.

Jocelyn: Yeah, just because they're not made of matter. I mean, there's piles of astronomical things that we don't think are made of matter.

Ben: Well, sorry for being matterist.

Laughter

Jocelyn: Yeah, just cause it's everything around you, Ben, doesn't mean it matters.

Benjamin: I think we've all learned a valuable lesson today about matter availability bias.

Ben: The idea here though, is like Joey said, black holes do have mass, they have the same mass as kind of the star that was there before them, because everything that collapsed into them, that mass is still there. But notably, when you interact with the black hole, when we're talking about a black hole, you describe it in terms of the location of this boundary, Jocelyn was talking about this event horizon. It just kind of like, if you're talking about a sinkhole, you are talking about the boundary where the street ends and the falling begins, right. There's like a rim to it.

20:10

Benjamin: Right.

Ben: We describe black holes in terms of this rim, this event horizon. But the notable thing here is that when all the matter in a star collapses into a black hole, the width of that radius, the event horizon radius, is actually very, very, very, very small. It's like if the sun was to turn into a black hole, the radius of its event horizon would be like a kilometer, a mile, it would be like nothing, just a tiny little thing in terms of space.

Jocelyn: But it would still pull all the planets around with just the same gravity.

Ben: Yeah, it would still have the same gravity the sun did, it's just that the event horizon is much, much smaller than, you know, stars are.

Jocelyn: It's super concentrated gravity.

Ben: Yeah, that's right. And so interestingly enough, we brought this up earlier, when we were talking about GPS satellites, the closer you get to the surface of the earth, for example, the stronger gravity gets, the the more space time is curved, right?

Benjamin: Okay.

Ben: So that's always true. If we took the earth and turn the earth into a black hole, it would be a tiny little event horizon. But if I was...

Jocelyn: Like a ping pong ball.

Ben: Yeah, so if I was like the same distance from the middle of the earth as I am now, but it was a black hole, the effect of gravity that I feel would be the same. The only difference is I can get much, much, much closer to the middle of a black hole than I can to the middle of the earth. Because with the earth, there's a surface there, when it comes to black holes, you can get quite close to them, that event horizon is actually quite close to the middle of them. And so you can reach locations, which have really, really, really extreme space time curvature. So that was a mouthful. The basic idea though, here, is space time curvature manifests in like, for instance, time getting slower if I were to get near the event horizon of a black hole time would almost stop in terms of the rate that it goes I have you ever seen that TV show? What was it *Andromeda* with Kevin Sorbo? Wait, no, have you ever seen *Doctor Who*? Please tell me you've seen *Andromeda*.

Benjamin: You know, I tried to watch it one time, and I just could not get into it.

Ben: The basic premise to that, is that Kevin Sorbo accidentally got too close to a black hole. It only took him a few minutes to go close to the black hole and come back out. But time to the rest of the universe had gone quite quickly compared to his slow downtime. So it was like thousands of years had passed.

Jocelyn: Isn't that other movie *Interstellar*?

Ben: Oh, yeah, *Interstellar*.

Benjamin: Yeah, they come back up. And their scientist buddy has grown a big gray beard.

Ben: Yes. Oh, my God. I don't even need to talk about Kevin Sorbo.

Benjamin: You could have saved yourself a lot of embarrassment.

Jocelyn: Do you know the original draft for that movie started with LIGO detecting gravitational waves?

Joey: Before they had actually been detected.

Ben: But Ben doesn't know we're talking about because we haven't told him what LIGO is yet.

Jocelyn: Do you know what LIGO is?

Benjamin: I do not.

Ben: Yeah, see?

Jocelyn: Okay, so let's tell him about gravitational waves.

Ben: Okay, so here's the really mind bendy thing. Curvature causes change. Your sense of what one meter is to change, for example, right? So for instance, you might have three people standing right next to each other, either each holding a meter stick. Because of gravitational curvature, one of them might have a meter stick that looks really short. And the other might have a meter stick that looks really long.

Benjamin: Depending on their proximity to the center of gravity or whatever.

Ben: Well, yeah, well, like put some near black holes or some stuff, sure.

Benjamin: Right.

Jocelyn Ben, Ben, you have to use yardsticks.

Ben: Oh, right, son of a bun. Okay, so here’s the bonkers thing. The curvature in space time isn't only stuck to black holes, or gravity. The curvature in space time can kind of move around, it can wave like waves on the surface of the ocean. But the important detail here, though, is that when one of these waves travels around, it doesn't like move things back and forth, or up and down. What it does is it kind of changes how long things are, as it passes through them.

Joey: It stretches space time.

Ben: Yeah, it stretches and squishes space time as these waves pass through you. So famously, let's say you had your arms out like a T shape.

Benjamin: Okay.

Ben: And a gravitational wave hit you dead on right in the middle. First off, your arms would get kind of short compared to your legs, and then your legs and head would get stretched compared to your arms, you'd get kind of lowercase t shape.

And then as the wave pass through you, the opposite would happen, you go back to normal, and then your arms would get stretched extra long, and your head and feet would get closer together.

Benjamin: Is that because it's expanding out spherically?

Ben: It's because the wave that is passing through you, is it's kind of changing our sense of exactly how long a meter is.

Benjamin: Uhhuh.

Jocelyn: Like it is expanding out spherically but wherever it hits, it's stretching and squeezing, like all around.

25:02

Benjamin: How bad would this hurt? Just in theory?

Jocelyn: We're not sure.

Joey: Yeah, if you're very close to two black holes colliding, they would make some gravitational waves. And, yeah, if you are close enough, then it would stretch and squish you.

Ben: And maybe kill you.

Benjamin: I mean, it sounds very painful.

Jocelyn: I mean, if you're far away, I mean, there's gravitational waves probably passing through you right now.

Joey: Yes, from space, but they don't hurt.

Jocelyn: They're really far.

Ben: Gravitational waves, as we detect them on earth don't really do much because we're not really in the epicenter of, of one of these gravitational wave sources.

Jocelyn: And the ripples, like, fall off as they go away from this source, like they would in, like, a pond.

Ben: Yeah, they get weaker.

Benjamin: That makes sense to me. I’m formerly a filmmaker. And one thing that you deal with in film production is that light has a rate of fall off. So if you're lighting a huge scene, you need a lot more high power lighting than you’re, you know, shooting something more intimate in a small space.

Joey: Yep. And same with sound, right? If you're far away from someone talking or a jet going by, then it's not as loud. Yeah, and same thing with gravitational waves.

Ben: So if you're really, really close to something generating notable gravitational waves, your head might fall off, but from out here, we're probably fine. But yeah, what causes them? That's the, that's the interesting bit. And the answer is, anytime any mass in the universe accelerates at all, it generates gravitational waves. So if you take a baseball, and you throw it, throwing the baseball will generate some kinds of gravitational waves.

Benjamin: So I probably shouldn't do that.

Ben: Well, I it's not, the deal is that it doesn't...

Benjamin: Should I just try and hold as still as possible.

Ben: Notably, though, gravitational waves you create by throwing a baseball are very, very, very, very, very, very, very, very weak, they don't really do much. So the rule of thumb, though, here is that the more something accelerates, the harder the acceleration is, the more gravitational waves that it will generate. And the heavier the object is, the more gravitational waves it'll generate. So if you take a shotput, and you throw it the same way, you accelerate it the same way you accelerated the baseball, it'll generate a lot more gravitational waves, but still almost none.

Benjamin: Right.

Ben: The deal here is that you can make crazy heavy objects crazy accelerate, if you put them in orbit around each other. So if you have two black holes, black holes are really, really heavy, right? They weigh like, as much as a big star does. And because they're really, really small, they can actually orbit each other very, very closely.

Jocelyn: You can make them orbit like 10 times a second.

Ben: Yeah, those orbits are real fast. They involve tremendous accelerations, because they're going around each other so fast. And because the the black holes are so heavy, that system is going to generate lots and lots and lots of gravitational waves. So functionally, the only things that generate tremendous gravitational waves in our universe is when you have like black holes in orbit around each other, or neutron stars in orbit around each other, or black holes orbiting neutron stars. And most other situations, gravitational waves don't really matter.

Joey: Even those other ones are very hard to detect.

Benjamin: Is that because they're so far away from us, in general,

Joey: Yes, that it's a week effect. That space time is very, stiff. It is hard to shake space time. And so even though these very massive things are moving and accelerating a lot, space time is very stiff. And so they're making gravitational waves, but they are a small effect. They're hard, they're hard to detect. And they're very far away.

Ben: If you want it like an analogy, like the ground is hard to, is also very stiff.

Joey: Yeah, yeah.

Ben: So if a person is walking outside your house, chances are their footfalls will generate little sound waves through the earth, right? Yeah. But it's not like your house shakes when a person walks out front of your house. On the other hand, like if it's like, a bulldozer decides to drive down the street, everything is shaking. Because they're much heavier, so they got more mass, so they’re hitting the ground a lot harder, generating more of these waves.

Benjamin: But a bulldozer two blocks over...

Ben: Yeah.

Benjamin: You might not even here.

Ben: That's right. So let's round out our description of what causes gravitational waves. Because the interesting thing here is, most orbits are kind of what we call stable, at least if there's two objects in orbit around each other. And that system is kind of stable. And by that we mean the two things are mostly going to orbit each other for almost ever, right?

Benjamin: Right.

Ben: The Earth's been going around the sun for billions of years. And it's not like slowing down or anything.

Benjamin: Thank goodness.

Ben: Right? I know, it sounds horrible. One of the reasons for that is conservation of energy. The system doesn't really lose energy when the earth goes around the sun. And so it keeps up that energy, and the planets never spiral into the sun. But notably, if you have a system that's generating a lot of gravitational waves, gravitational waves have energy in them. And so those gravitational waves are carrying energy out of the system.

30:01

So if you have these two black holes that are orbit around each other, and they're close enough together, where they're making lots and lots of these gravitational waves, that system loses energy. And so their orbits are going to decay. And they're going to spiral into each other. What's that going to look like? Well, they get closer and closer together. And one interesting thing is, when two objects are orbiting each other, the closer they are together, the faster their orbital speed is. So instead of slowing down as it loses energy, the two objects get closer together, and they speed up because its gravitational potential energy is being turned into kinetic energy. Never, don't worry about that, they speed up. So when it comes to gravitational waves, you get a really, really specific signal, called a chirp.

Jocelyn: So you have this orbit, right? And it basically stirs up one wave crest every time a black hole sweeps in front of you.

Benjamin: Okay.

Jocelyn: And then as they fall together from emitting the waves, they orbit faster. So the waves come more rapidly with higher frequency. And so you can map that wave pattern to a sound because if they're, say, 10, or 30, or 50 times the mass of the Sun, they do these final stages of orbit in audio frequencies.

Benjamin: Okay.

Jocelyn: And they sound kind of like a (makes sound) because it's really fast. It takes like a fraction a second, in, like, the audio band.

Benjamin: This is like transposing the waveform on to audio, right?

Jocelyn: Yeah. Like, like, you take this wave wiggle that measures the stretching and squeezing of space, and then you like, just take that file and convert it into like, a .WAV file. I don't actually know how to pronounce that.

Benjamin: You just change the file extension.

Ben: Yeah.

Jocelyn: Yeah, yeah.

Ben: It's fun to do. Right before the first detection of gravitational waves, we'll talk about that in a second, a whole bunch of physicists went on Twitter. And they made a hashtag Chirp for LIGO movement where everybody was making the sound we expected to hear. If you actually, if you actually play the sounds, it sounds just like Jocelyn said it's like, (makes bloop sound) but um, slowed down, it sounds like a constant tone that ramps up in frequency and loudness. So it'd be like (makes longer sound going from a low to high pitch).

Joey: Very good.

Ben: And then it peaks off when the two black holes touch each other and merge.

Benjamin: Somebody make that their weird noise when they get introduced on this show.

Ben: Yeah, someone should.

Jocelyn: Just go it (makes the same low to high pitch chirp).

Ben: Essentially, when we talk about gravitational wave astronomy, what we're doing is, we are using gravitational wave detectors to try to, essentially “hear”, these signals, because when you detect one of those chirping signals, it means that somewhere in the sky, two black holes have been spiraling around each other, they lost enough energy and they merge.

Benjamin: Is that where you get supermassive black holes, like over time.

Jocelyn: Maybe, we don’t know where those come from.

Joey: Potentially.

Jocelyn: Potentially.

Ben: When two black holes merge together, they just make a bigger black hole. So you could make a very, very, very large black hole. To answer your specific question about where a supermassive black holes came from, they probably just ate lots of the gas when the galaxy was forming...

Jocelyn: And stars.

Ben: Yeah, and stars.

Jocelyn: And probably merged with other supermassive black holes.

Ben: Yeah.

Jocelyn: From other galaxies in giant galaxy collisions. Because we're going to try and record those sounds too. But they take like years, so it's hard.

Ben: The point of this show is to talk about weird gravitational wave detectors. Let's talk about how you detect them because they're really, really, really subtle.

Jocelyn: Let's start with the supermassive ones.

Ben: Okay.

Joey: So, observed in almost all galaxies, that there's a supermassive black hole in the center of the galaxy, our galaxy. Our galaxy, the Milky Way galaxy, has a supermassive black hole, Sagittarius A*, it's about 4 million times the mass of our Sun. So we think those are in the centers of most galaxies.

Benjamin: That's funny. Sagittarius A* was my rap name in college.

Joey: That's a good one.

Benjamin: Ah, is it a chicken and an egg thing? Like there's a supermassive black hole and a galaxy forms around it? Or vice versa?

Joey: This is a very good question. They seem to know about each other, the size of the galaxy is related to the size of the supermassive black hole. So they probably co-evolve.

Benjamin: Wow.

Ben: Yeah, simulations say that they kind of evolved together. Occasionally, they'll find galaxies without a supermassive black hole in the middle. But usually, it's kind of sad.

Benjamin: That's sad, that’s just sad.

Joey: Poor galaxy.

Benjamin: You hate to hear about that.

Joey: And we also see, we can capture galaxies in various states of merger. Where galaxies merge with each other to form new galaxies, bigger galaxies, all the all the stars, they don't necessarily necessarily collide, but they come together and form a bigger galaxy. In that case, if you had two galaxies colliding, you would expect that eventually, the supermassive black holes in the center of each galaxy would eventually orbit each other.

35:06

So that's now a binary supermassive black hole system, two of them. And when they're close enough to each other, they emit gravitational waves. And those kinds of gravitational waves from these distant galaxies could be traveling through our galaxy. And one way to detect them would be this natural gravitational wave detector, provided to us by pulsars, which are neutron stars, which is sort of similar to a black hole, in that when massive stars die, what can be leftover could be a neutron star, instead of a black hole. And some of them spin really fast and have radio beams that we observe as radio pulses, with radio telescopes here on earth. And if we observe those neutron star radio pulses, we can look for gravitational waves passing between us here on earth. And that array of pulsars out in our galaxy.

Benjamin: Huh.

Jocelyn: Stretches the space time between us. And so it changes, like the time of flight for each little blip of radio.

Benjamin: Huh, wow. Well, it sounds like there's kind of a tempo to that. And when you detect changes in that tempo, you're saying that the reason for that is gravitational waves?

Ben: Yeah. I told you the gravitational waves, if they pass through, say, a meter stick, they will cause the distance between the two ends to change. Right?

Benjamin: Right.

Ben: That's actually really difficult to measure with a meter stick, because the meter stick presumably will stay a meter long. Whatever that is. Like, if the ends of the stick are jiggling, how can you tell the stick is getting longer, shorter?

Benjamin: Right.

Ben: If I took another meter stick and put it next to it, the second meter stick would jiggle in the same way.

Jocelyn: The wave is stretching and squeezing your meter stick. Oh my gosh.

Ben: Right.

Jocelyn: This confused physicists for decades. I mean, not confused, but people are like, can we really trust gravitational waves as a thing?

Ben: Like, how can I tell, whether or not the distance between me and you, for example, is changing a little bit? If a solid object will also change in some way? How can you detect that, and the clever thing here is you can use the travel time of light, okay? Let's say you and I are standing on opposite coasts. And there's somebody drilled a hole through the earth, so we can see each other and wave at each other. And I take a laser and shine a laser beam at you. So usually when no gravitational wave is passing through, it might take I don't know, like half a second to go from one end to the other. If all of a sudden it takes a second for that light beam to go back and forth, or it takes a quarter of a second, we'll know that that that change in travel time for the light beam is because of a gravitational wave.

Benjamin: Gotchya.

Jocelyn: That would be like a whopping huge gravitational wave and we should probably get out of the way from...

Ben: Yeah, we're probably dead. So the idea here is these pulsars, they, I mean, what they do is in the description, they put out a regular pulse. Essentially, it's a spinning neutron star, but the rate it is spinning is really, really regular. And so you always see a steady pulse of these radio beams coming at you. If that neutron stars speeds up or slows down in a way that we can detect and say, oh, it's probably not because there's something going on with the neutron star, it's probably because the distance between us and them is changing because of gravitational wave has passed between us.

Benjamin: Gotcha.

Ben: The sad thing about gravitational waves that we've neglected to really mention so far is that when gravitational waves pass through us, the effects increases with distance. So between us and a neutron star, good, you've got a great big signal. If a gravitational wave passed between us, and Alpha Centauri. So Alpha Centauri is, you know, the stars that are closest to the sun in our neighborhood. But there are several light years away, right? A gravitational wave passed between us, it would only change the distance between us and them by like the width of a human hair.

Benjamin: Pretty subtle.

Ben: Yeah. Super subtle.

Benjamin: Not going to help you get there any faster.

Jocelyn: But we measured them.

Ben: Yeah, okay. Yeah. So long story short, we’ve done it.

Jocelyn: Like, a bunch of times, like there's a public website, you can go to now and see like new candidate black hole mergers getting recorded almost every week.

Benjamin: Wow.

Jocelyn: On the ground, you don't have convenient pulsars sending us little blips of radio. So we use lasers and mirrors. And we take a laser and we shine the light down to different directions. These three or four kilometer long tunnels and it bounces off mirrors and it comes back.

40:00

And then, actually it does like a bunch of bounces back and forth to like, make extra distance to travel. And then the light comes and they compare the light from the two arms. And they see that the travel time and prints a little shift in the light that they can record that the two arms are different.

Benjamin: Wow.

Jocelyn: And we record this overall stream, which in audio frequencies we’re sensitive to we can record these final orbits of merging black holes.

Benjamin: So this is a fairly common place thing galactically speaking.

Joey: Only recently.

Jocelyn: It was done for the first time in 2015.

Benjamin: Wow. But now we can detect them all the time.

Jocelyn: Yeah, we upgraded the machine. We just turned it on on April 1st, which was like a risky decision for sociological reasons. Anyway, but yeah, so we turned it on April 1st. And this this round, we're releasing alerts in real time. So there's, I don't, I’ve lost count.

Joey: It depends on when this conversation is aired also?

Jocelyn: Oh, right. Yes. Yeah. So it's turned on April 1st, 2019. And has been recording for the first couple months, at least roughly a black hole merger every week or so.

Benjamin: Very cool.

Jocelyn: So cool.

Benjamin: That kind of sounds like the tunnel that you described, from one end of the continent to the other, but smaller scale and less costly to build.

Jocelyn: Yes.

Ben: The project is called LIGO, the Laser Interferometer Gravitational-wave Observatory. Also, they didn't want to call it LIGWO, is that it?

Joey: The w is small in wave.

Jocelyn: Gravitational-wave is hyphenated and there's also Virgo in Italy, near Pisa. There's another interferometer. And they're building one under a mountain in Japan to avoid getting jiggled around by seismic noise. So they went underground, and they're making it super cold so they don't get jiggled around by heat.

Benjamin: Wow.

Jocelyn: Anyway, so that one's going to hopefully start recording signal soon, too.

Benjamin: I know scientists love acronyms, and I just want to pitch this you can use this or not. But one of my favorite character actors is in *Interstellar*, John Lithgow. Is there any way to work a TMHW into LIGO so that you can get a little bit more synergy with *Interstellar*?

Joey: Oh, definitely.

Jocelyn: I'm writing this down.

Benjamin: I mean, You talked about the W being small. So I'm just saying.

Joey: We can make the W big, that one’s easy.

Benjamin: Yeah.

Joey: Mm hmm.

Jocelyn: But they may need to add an O in the middle.

Benjamin: And then you'd have a celebrity associated with the experiment like that. There's just a lot that could be done here.

Joey: Scientists love acronyms so much. It is a multi level acronym, because laser is also an acronym,

Benjamin: Right. It's like acronym *Inception*.

Joey: Yeah.

Ben: Notably, there's more than one LIGO station. So as as Jocelyn said, there's Virgo, which is another interferometer and Italy. There's two LIGO stations in the continental United States. And the reason there are kind of its it has an analogy to hearing. So it's like, you know how we have two ears?

Joey: Yes,

Benjamin: Every, everybody but Van Gogh.

Ben: So why do we have two ears Ben?

Benjamin: It gives you three dimensionality in your audio perception?

Ben: Exactly. The reason we've got multiple LIGO stations is because we can use the signal detection times to triangulate exactly where these signals are coming from. So it's not just that we're hearing these chirps and going, oh, something, something out in the universe is chirping, you get the signals at different stations, and then you can say, Oh, look, this signal's coming from that way. And the more of these interferometer stations we build, the better our ability to triangulate exactly where in the sky the signals are coming from gets.

Benjamin: Gotcha.

Ben: So it's an exciting time in terms of gravitational wave detection.

Joey: We already talked about general relativity, and so Einstein, in his theory of general relativity, predicted gravitational waves, but he didn't think they could ever be detected. It is a weak effect, like we said, and he thought it was just too hard to detect them, even though they come from general relativity. And in a way he was right, because it took 100 years after his theory of general relativity for humans to build an instrument capable of measuring these gravitational waves here on earth. And so we have these detectors, these laser interferometers, and they're a big National Science Foundation project. And there's over 1000 scientists in the collaboration that all work on this project together. And it has to be engineers and computer scientists and astrophysicists and data analysis. And it's big science. And in the early 2000s, we had initial LIGO that did science runs, took data, but didn't make any detections.

45:03

And then in 2015, after five years of upgrades to the detectors, we were actually just about ready to turn on for our first observing run for advanced LIGO. And we were still into what's called an engineering run. So we actually weren't quite ready. But we had data from both the detectors. And we just had this crazy loud signal that looked just like the signal we expected for two black holes colliding in a galaxy far, far away. And so it was September of 2015. Just before we were ready to turn on for our first advanced LIGO observing run. And scientists are very skeptical. So at first, we were like, you know, was this a test, we do things called blind injections with somebody put something in the data, we had to check. But it became clear very quickly, that it was a real signal from two black holes colliding very far away, that we just detected. And this was the first ever incident detection of gravitational waves by humans.

Benjamin: Wow.

Joey: So it's very exciting times.

Benjamin: It would be like if you turned on the Large Hadron Collider, and it had a Higgs boson result immediately.

Jocelyn: Yeah, the community even spent decades preparing for like the first signal to be something like really subtle, where you'd have to, like, do careful statistics to just really tease out its significance. And then, wonk. It's amazing.

Benjamin: Wow.

Joey: It was amazing. And so that was September of 2015. And then this big scientific collaboration took a long time. Well took a while anyway, writing the paper that was published.

Jocelyn: Quadrupal checking everything.

Joey: Yes, every word, every sentence written many times, and it was published in February of 2016. And that's when we made the public announcement that we had detected gravitational waves. And this was also the first ever observation of two black holes colliding to make a bigger black hole.

Jocelyn: You know, the clearest signal of black holes existing that we'd ever seen.

Benjamin: Was the thing that was detected that first time a particularly big deal in terms of what you're detecting, on a weekly basis. You said that there's, they're, they're detecting new ones all the time now.

Jocelyn: It's still one of the loudest signals ever, except for maybe what would happen in 2017. So there are a handful more black hole mergers. And then we got a merger of neutron stars. So these are actually the same thing that make the pulsars. We recorded, those merging and they're, they're lower mass, but they also get whipping around each other, like 1000 times a second and crash together. And those were really exciting because we had three interferometers taking data to triangulate the position. And so we were able to send a sky map and a distance frame to observers, who followed up looking at the galaxies in that range and identified a new afterglow signal from the merger. And so we were able to observe both gravity and light from the same collision.

Benjamin: That's gotta be reassuring, right?

It was, it was, like, pretty nice to have this really clear. Yes, this gravitational wave stuff is real, you can see it in other forms of human information.

Ben: That last one was really bonkers significant, because like, no one was exactly sure where all of the gold and platinum and other heavy, expensive metals in our solar system and galaxy come from exactly. So some people thought, well, maybe they come from neutron star mergers. The one Jocelyn was just talking about what it was, was the gravitational wave is a lot louder in terms of its detectable signal than the light it generated. So because they were able to hear it first with the gravitational wave detectors that let them point telescopes at it to see the aftermath of these two neutron stars colliding and see all that good, good Platinum being spewed out into space.

Jocelyn: There, there is actually also gamma ray bursts. So those are super bright. And so there is also a flash of gamma rays, like two seconds after the gravitational waves hit. And there's lots of those gamma ray signals that it's hard to tell exactly where in the universe they're coming from. So we saw the coincident like the thump of the gravitational waves, the flash of light from the gamma ray bursts, and then pointed the telescopes and saw the after, after glow.

Ben: Okay, so overall, the history of LIGO is really cool. To reiterate, for the first decade and a half of it being online, the instrument wasn't sensitive enough, essentially, to detect these black holes, merging. Black holes merging is a really, really rare thing, this chirp signal, this really, really loud in terms of these gravitational waves it generates, that's a fairly rare event.

50:05

And it happens over a fairly short period of time. And so it's kind of like having a microphone, the first LIGO microphone wasn't, wasn't strong enough to hear one of these really rare events. But then after they upgraded the instruments, it was sensitive enough to hear over a much larger distance. And so they could get these very rare events happening occasionally, here and there. Since then, they've upgraded it a second time. And now they're getting these events like every week-ish.

Joey: Right. So you might say that they're, that they're locally rare, right, the close by ones are rare. But we now know that they are common throughout the universe. It's just that we needed to be sensitive enough out to enough distance to be able to hear them.

Jocelyn: And folks are planning now like the gravitational wave detectors on, on earth of like the future where we could identify mergers happening since the beginning of the universe. And it would be, basically, popcorn.

Ben: When Joey said, locally rare, it's kind of like imagining, like winning the lottery. So the first LIGO was like, in your neighborhood, you might wait for somebody in your neighborhood to win the lottery. And you might wait, wait a decade, and no one will have won the lottery. And then the second run was like in your city, what's the likelihood of a much larger area, the likelihood is actually pretty good. So once or twice a year, somebody's going to win the lottery in your city, hurray. And then the last one is like, once you get really sensitive, it's like, what's the likelihood of somebody winning the lottery over the entire Earth? And the answer is, well, that happens like all the time.

Joey: As long as you have lots of lotteries to win.

Ben: Yeah, that's right.

Jocelyn: So obviously, we want to make it more sensitive on earth to see out to the beginning of the universe. But one of the fundamental limitations of gravitational wave detectors on earth comes from the earth being a really noisy place. You know, people, trucks, airplanes, and air, and the ground, and everything is just like moving. So that becomes just intractable background noise, at a certain low frequency. So, so for example, the supermassive black hole mergers that we're trying to observe with pulsar networks, there’s no way to get enough stability on earth to record those tiny changes over years. So one of the things that, that would be really cool would be to make LIGO in space, or LISA, for Laser Interferometer Space Antenna.

Benjamin: So, it would be like, an orbital platform on the Hubble idea.

Jocelyn: It would need to be bigger than that. So it wouldn't orbit the Earth, it would actually trail Earth's orbit, and have like a triangle of three spacecraft firing lasers at each other, orbiting the Sun. And they couldn't track the really high frequency audio band stuff we hear on Earth. But they could measure all sorts of black holes out to the early history of the universe that are on bigger scales. And that would help answer these questions you had about how supermassive black holes form because we would see stuff falling into supermassive black holes that would happen on this frequency band. Joey, do you work on LISA, too?

I do. Yeah, as a grad student, I worked on LISA. And the history LISA is also an interesting one. The science case for LISA is just amazing. Once you're up in space, and doing laser interferometry in space with these long arms, that frequency band is, will be source rich, we will have so many gravitational waves signals all overlapping each other. It's a really interesting data analysis problem that we call the cocktail party problem. Because everybody's talking at once. All the black holes and white dwarfs and neutron stars that are colliding, it's all happening all at once. And you and you get it all at once. And you have to figure out how to draw out those signals. Whereas with LIGO, at least so far, it's mostly been one signal at a time. And you just have to get it above the noise.

Benjamin: Well, I guess if you have a few things like LIGO, you can do triangulation to filter to some extent, right?

Joey: That's right. Yeah, the local sources of noise will be uncorrelated, but the signal from space will be correlated. So yeah, that's how we do some of the LIGO data analysis. That's right.

Benjamin: But you need to you need to have several LISA's to do that, right?

Jocelyn: Well, LISA does a similar thing. It's a triangle. And so each point of the triangle is sort of like its own interferometer.

Ben: So a LIGO, LIGO is pairs of laser beams going down tunnels, okay. So there's two stations of LIGO, like you said, for triangulation purposes, LISA is going to be out in space. And it's going to be huge, what's the distance along the arms of it?

55:02

Joey: Two and a half million kilometers,

Ben: Two and a half million kilometers behind. So there's going to be three little satellites, that the distance between them is so big, that's not even going to orbit the Earth, it's going to orbit the sun, it's going to be kind of in Earth's orbit, but back a little bit, so we don't interfere with it. Millions of kilometers between each of these stations and they're going to bounce, bounce laser beams between them in a triangle shape. So in this triangle shape, they can do your triangulation in the, in a similar way that the two stations on earth can. Because it's going to be a system of lasers bouncing down each arm independently of one another.

Joey: Plus the the constellation of satellites, the triangle, is tumbling as it goes around the sun. And so that also helps triangulate or find out where the signal is coming from in the sky. Because you can picture it sort of cartwheeling around as it orbits the sun behind the earth.

Ben: Physicists are going to make a tumbling equalateral triangle of lasers that orbits the Sun along with the earth. Bananas.

Joey: Yeah.

Jocelyn: And it's going to measure black holes colliding. Like since the dawn of time.

Ben: Yeah, yeah, yeah, yeah. So it's gonna be so much more sensitive, but also it's going to be sensitive to a different domain than LIGO is. So LIGO can get those, those chirps, right. But the idea here is, even before the two black holes orbiting each other, are about to collide, they're still in orbit around each other and still making kind of medium pitch gravitational waves, they're just not very loud. This is going to be big enough to pick those up. So anytime there's two black holes orbiting each other, a little, they'll be making a kind of a little siren sound, Lisa is going to be able to pick it up all the way through the observable universe.

Jocelyn: Well there, and there's also like, black holes that are so big, that they run into each other before they can orbit fast enough for LIGO, to detect them. So there's like a whole new set of black holes out there in the universe, we think, maybe, that that we could never observe on the ground because all the other motion gets in the way. But out in space, we can just see, like how black holes have combined over the history of the universe to form the structure we see today.

Ben: Yeah, supermassive black holes are aren't shrill enough for LIGO to detect, but LISA's gonna be able to hear them. So we also get evidence of supermassive black holes doing things, it's gonna be bananas.

Joey: And we'll answer some of your questions about, yeah, how did the supermassive black holes in the centers of galaxies form? LISA, LISA will help us to astrophysics.

Ben: So you're ready to sign up for a LISA satellite today for your solar system?

Benjamin: Yeah, what's, what's the downpayment?

Jocelyn: It's not even that expensive.

Ben: Yeah.

Jocelyn: As far as space missions go,

Joey: Yeah, it's being led by the European Space Agency, ESA, and NASA is a partner, and is scheduled to launch in in the 2030s.

Benjamin: Cool.

Jocelyn: And in the 2030s, by then, we should have the pulsar timing, like measuring the supermassive black holes, and the, like, scales of years, and LISA will be out in space, measuring them the middle mass supermassive black holes. They're all like bigger and bigger masses, it's hard to, like, use the right adjectives here. And then, and then...

Joey:...super duper.

Jocelyn: Yeah. And then we'll try and build like advanced, advanced LIGOS on the ground that can measure like every neutron star merger in the universe. So stay tuned, this century, we can do it.

Ben: Okay, so let's reiterate this in another way. There's kind of two aspects to detecting these things. One of them is the distance it is from us, the farther it is away, the less of a signal we get, right. The signal gets weaker as it travels through space. But the second aspect is, there’s kind of like, ah, a frequency boundary. Every orbiting system of black holes is generating detectable gravitational waves. But some of them we can't detect with LIGO. So if it's a supermassive black hole, the “sounds” that they're making are too low pitch for us to detect with LIGO. The period is, like, too long for LIGO to detect. When LISA gets up there, it's going to be able to detect them. And then there are some systems that are really, really long. Like if there are two supermassive black holes orbiting each other, the period of those signals is going to be like years. Like it takes years for Mars or Jupiter to orbit the sun, right. So two supermassive black holes orbiting each other are going to take their time orbiting.

1:00:03

So we can't detect those even with LISA, because the amount of time it takes for that signal to change is over years. But we can use the pulsar timing arrays, those are perfect for measuring the third type. And so it's a combination of these different types of instruments, we can essentially detect every type of gravitational wave siren in the observable universe in our lifetimes.

Joey: Yay!

Jocelyn: As long as we eat healthy and exercise.

Ben: That’s right.

Joey: We are going to learn a lot about the black holes that are out there in the universe. How they form, where they are, how many there are, how big they are, we just don't know very much yet.

Jocelyn: What kind of stars would have had to make them. What that means for all the elements and how they've been formed over the history of the universe, how galaxies formed. how star systems formed. It's like the dark universe.

Benjamin: And with any luck will eventually be able to end the scourge of black holes once and for all.

Joey: People might not be as scared about them anymore, when we know more about them.

Jocelyn: We can embrace the black holes. Not not literally though, please.

Ben: Joey, did you want to talk about nanograph specifically at all?

Joey: Yeah, this is a really cool project and, and another really good acronym. So yeah, we definitely should. The North American Nanohertz Observatory for Gravitational Waves, NANOGrav, is using the biggest radio telescopes in North America that Arecibo Observatory in Puerto Rico and the Green Bank telescope in West Virginia, to monitor pulsars in our galaxy over many years, looking for nano hertz, gravitational waves from supermassive black holes in distant galaxies. And so it's lots of radio astronomers, observing pulsars, finding pulsars, using the radio telescopes, and then also gravitational wave astronomers and black hole astrophysicists working together to detect gravitational waves using pulsars. And it looks like there's a good chance in the next decade, that NANOGrav will be able to detect gravitational waves.

Benjamin: Wow, is that just upgrading the equipment as it gets better?

Joey: That's a good question. Yeah, so So finding better pulsars. And monitoring them with good telescopes is important. But also, just, it is really a game for the patient, you have to monitor them for a long time. Because the signals, the wavelengths of the signals are very long, many years.

Benjamin: Right.

Joey: And so you have to observe for many years to to get the signal.

Jocelyn: But they're, they're measuring like stuff like the solar wind. And, like, there's all these amazing, like sources of noise, which are actually really cool physics, and they're all...

Joey: Yes, they’re doing all sorts of interesting astrophysics. And on top of that, will detect gravitational waves in the, in the 2020s.

Benjamin: That's really cool. I got to go visit the Goddard, NASA campus outside DC and the guy I was there with pointed out a, what would look just like a satellite dish to me. And he said it was part of a huge network of dishes that made a giant radio telescope that was, you know, like interconnected dishes that were all over the place. Is that part of this effort?

Joey: That is a really interesting thing about radio astronomy. Is that you can do these synthesised baseline baselines, the very long baseline array and things like that. And actually, the Event Horizon Telescope that Jocelyn was talking about that took an image of the shadow of a black hole also used techniques like that. NANOGrav doesn't need to NANOGrav uses the big radio dishes, because they're monitoring pulsars, that we know where they are, and when to observe them. That doesn't need to do long baseline radio observations. But that is a really interesting way to do radio astronomy.

Benjamin: Do you need to like sign the Arecibo telescope out for a few hours to do this or..

Joey: Yep. The largest cost is the telescope time. And so the Green Bank Telescope is in the national radio quiet zone in West Virginia, out in the hills of West Virginia. And so that telescope and the Arecibo telescope, we have to pay for, for telescope time.

Benjamin: I got one question.

Ben: Yeah.

Benjamin: One time got to go to Switzerland and visit CERN. And we went down into the tunnel where the Hadron Collider is, and I touched it.

Ben: Nice.

Benjamin: And then the guy got really mad at me, that touched it. Would I get in similar trouble if I touched a LIGO experiment?

Laughter

1:05:00

Jocelyn: So depends how close you want to get. Like, so there's like these outer shields that they've been like shot at, which is bad because that's a noise source. But you know, touching it is, no one’s going to be fussed about. We actually, there's a cool, there were these ravens. And one of the cooling systems had like some ice collecting on it. And the Ravens would come peck at the ice. And and that it was like this weird noise source. They couldn't figure out where this like the pecking was like adding this acoustic noise and it coupled in and so it was a problem, they're trying to track down. Where is this peck, peck pecking coming from? And they finally tracked it down to ravens pecking at ice. So they they had to get rid of the ice source. And they assured everyone that the Ravens had other forms of water. So you know, you might get in trouble if you're like knocking on the instrument, but there's also like, downtimes between observing runs. And that's a better time to go to a tour.

Benjamin: Yeah.

Jocelyn: Because stuff will be like, opened up and you can go in and see more of the park.

Benjamin: Yeah, this was during the downtime, nothing, they weren't actually accelerating particles, so...

Jocelyn: Because you still have the hand so...

Joey: You totally should visit LIGO. There's one in Hanford, Washington, Eastern Washington, and there's one in Livingston, Louisiana. And you totally should visit Virgo. It's in, it's in Italy, outside Pisa. There's public tours, school groups can visit. There's public talks. In Livingston, there's a little, there's a science museum, and actually they're going to be building one at the Hanford site as well. So you definitely should visit and they will let you know what you can touch.

Benjamin: Cool.

Ben: Okay, so Jocelyn was talking about the corvids that we're eating the ice. We've been totally underplaying how, like, subtle the LIGO system is. And I told you about how it, like a gravitational wave traveling between us and Alpha Centauri would wiggle the distance between us by like a human hair. Another descriptor is the distance between us and Pluto wiggling by the width of a hydrogen nucleus. But like most of the reasons that the distance, that the travel time for the lasers will change, is because the mirrors are shaking slightly because of whatever reason, a truck drove by. So they have to like isolate it and recognize those signals like sonic vibrations and strip them from the data. And so like the Lygo interferometer, one of the reasons they need to build, Lisa, essentially is, like, ocean waves hitting the continent are a big source of noise in the LIGO data.

Benjamin: Wow.

Ben: Yeah, I think it was probably Jocelyn showed me this one graph that was like, “Oh, I see this blip? Yeah, we couldn't take data that day because a hurricane was hitting North Carolina, and it was generating too much vibration for us to use the LIGO system.” It’s bonkers. Absolutely bananas. Well, that was wonderful. Thank you, Jocelyn. Thank you, Joey. You’ve pleased me. Your efforts have borne fruit and that fruit is sweet. Here is some fruit. Joey, you get a kumquat, the smallest of the oranges.

Joey: Nom, nom, nom, nom.

Ben: And Jocelyn, to represent the supermassive black hole, you get a grapefruit.

Jocelyn: Nom, nom, nom, nom, oh, sour... nom, nom.

Ben: Well done.

Jocelyn: How do grapefruits taste? It’s not sour, is it? It's bitter. Sorry.

Ben: No, it's sour.

Joey: Both.

Ben: The experience is bitter. But it's a sour taste. I'd like to thank our guest, Benjamin Ahr Harrison, host of *The Greatest Generation*. Thank you for coming on our show, Ben.

Benjamin: Thanks for having me. I, my brain is full.

Ben: Oh, no. Well go drink something and watch some television. That's what I always do.

Benjamin: Sounds good.

Ben: Alright, everybody. Well, now it's time for the announcements. Don't forget to listen past the announcements, because there's some good audio that I'm kicking out past the end song. Okay. So first announcement, the hiatus is over, as you've noticed, and now we're in a phase I called the March to 100. I'm going to try to have monthly episodes from now on. I mean, we'll see. But I've got a buffer now. So, here's hoping. We have to get to a hundred before we pod fade, you know. Second, we're going to do a live show in February at the AAAS 2020 general meeting. They have a day or two of live podcasts. So we're going to be attending and participating this year. So if you want to hear us live, come see us there. And third, as always, we live in an era where podcasts are finally going mainstream. And there are so many great shows out there. But it's important when your mom and brother-in-law start listening to podcasts that they know that there's more out there than just shows about celebrities and true crime. There's a show for every interest, even if your interest is black holes and LIGO. And that means spreading the word about us and other shows. I don't know whatever you like, but if you mention us, that's pretty cool.

1:10:00

Review us on the iTunes or iPhone podcast app to help get the word out. Or you can talk about us on social media. We've got a Twitter page and a Facebook page. We're on a whole bunch of different podcasting services. We're on Stitcher, we're on Google Play Music, we're on Spotify, I'm pretty sure we're on Pandora. And I'm pretty sure we have an astounding YouTube page where I just port the audio over. But you know, some people like to listen to podcasts from YouTube while they work. Any way you want to listen to us, that's fine. Fourth announcement, I've decided to start doing the thing where if I can't find a cool guest, or if our guest cancels last minute, I'll choose a listener of the show to sit in the guest chair and chat with us about physics. So occasionally, I'll put the call out on Twitter or Facebook for a guest. So to be a guest, you need three things. First is to follow us on Twitter or Facebook, those are the only places I'm going to make the announcement. The second is that you need to have a fast internet connection and a quiet room in your home or workplace. You've listened to shows since you're a fan and you're listening to announcements, you’ve listened to shows where people have poor audio quality. So if you could, don't sign up if you live with dial up in the honking honk town with geese and car horns. The third point is that you need to be available on the date and time we need to record. But that's it just those three things, follow us on Twitter or Facebook, have a decent chance at recording quality and be around when we're planning on recording. If you do those things and follow us on social media and keep your ears open, you might get lucky. Essentially I'll say, Hey, everybody, you've got an hour and I'm going to check it again and pick from the people who reply in the next hour. So good luck. Final note, we are still humbly soliciting your donations, your donations, go for paying server fees and our episode transcription project and buying our physicists microphones. You can send one time donations through PayPal off of our website. Or you can go through the sweet Patreon site and give a recurring $2 or $5 donations if you give them more than two and supply your address. I'll send you a postcard.

Anyway, this particular episode of the titanium physicists has been sponsored by a collection of generous people. First off, I'd like to thank the generosity of Evan McLeown. And then I'd also like to thank Sharon Bana Geary, Kalin Richardson and JP Rocio, Mr. Aaron Wheeler Sander Boris, A Badger, The Ceptid Baylor Fein, Luke Edwards, Mr. Astro Yuki. Shebang Patel, Mr. Martin Mihalka, Henry Rabum, Peter Scott, Russ Moodsy, Eyush Sing, Matthew Sullivan, a Daniel Lauzen. Patrick Eon, Kevin Forsyth, Yer Panay, Hoynem Duong, Stan Erickson, a TPR Jones, Pascal, a man named Ryan R, Michael Usher, Senior Canada, Adrian Shoning, Sarah Straddler, Louise Pantanella, a guy named Ben, a Mr. Matthew Lambert, a David Myrtle and Mr. Ryan Foster. Janeko Frafenburg, Steve Methers, Magnus Christensen, Bart Gladys and Mr. Stewart Polluck. Our Emperor Courtney Brook Davis, Mr. David Lintels, Mr. Carl Lockhart, our Eternal Friend BS, Randy Dalzell, a miss Tina Rodeo. The Enigmatic Ryan, a gentleman named Crux, Gabe and Evan Weens, David Dee, Dan Vale, Mr. Alex, WTL, Mr. Per Proden, Andrew Waddington, Mr. Jordan young, John Bleesy, a Brittany Crooks, James Crawford, Mr. Mark Simon, Two Songs Gang of One, Mr. Lawrence Leah, Sexton Listen, Mr. Simon, Keegan Eau and Andreas from Knoxville, Cadby, Joe Campbell. Alexandra Zani is great. William Brecht, Eric Deutch, Atien. And a gentleman named Peter Fan, Gareth Easton, Joe Piston, David Johnson and Mr. Anthony Leon, as well as Doug B., Julia, Noah Robertson, Ian and Stu, Mr. Frank, Philip from Austria and Noisy Mime, Mr. Shlomo Delau, Melissa Burke, Yasee Yurasazi, Spider Rogue, Insanity Orbits, Robin Johnson, Sandra Johnson. Mr. Jacob Wick, Mr. John Keys, a Mr. Victor C. Ryan Clause, Peter Clipsham, Mr. Robert Halpin, Elizabeth and Theresa and Paul Car. Mr. Ryan Newell, Mr. Adam K., Thomas Sharay and Mr. Jacob S. A gentleman named

Brett Evans, a lady named Jill, a gentleman named Greg. Thanks, Steve. Mr. James Clawson, Mr. Devon North, a gentleman named Scott, Ed Lollington, Kelly Wiener Smith. Jocelyn Read, a Mr. S Hatcher, Rob Abrosato, and Mr. Robert Stietka.

1:15:00

That's it for Titanium Physicists this time. Remember that if you'd like to listen to scientists talk about science in their own words. There are lots of other lovely shows on our Brachiolope Media Network. The intro song to our show is Tell Balgeary, Balguery is dead* by Ted Leo and the Pharmacists and the end song is *Russia* by Ramona Falls. So Good day, my friends and until next time, remember to keep science in your hearts.

Music

Ben: Any Star Trek questions?

Benjamin: What's a graviton beam, when they shoot a graviton beam out of the ship?

Joey: Good question.

Benjamin: Is that a made up thing?

Joey: Okay, I mean, a light beam, a light beam, is a photon beam. So a graviton beam would, be would be a gravity...

Jocelyn: Maybe it's a beam of? Yeah, a beam of gravitational waves, gravitational radiation.

Joey: So gravitational radiation that's not propagating out spherically. That's somehow a beam. So a jet, a jet of gravitational waves?

Ben: Yeah.

Joey: That's definitely what it is.

Benjamin: Wow.

Ben: I mean, essentially what it is the Star Trek people are like, Hey, what's the sciency word, and ah, for radiation, so they talk neutrinos too which are a real thing. So they're, so far, gravitons are a theoretical particle that has to do with gravity. But we aren't at the point where we can detect them yet, experimentally.

Benjamin: So they're not Higgs bosons?

Ben: No, the Higgs boson is more confirmed than gravitons are.

Benjamin: Wow. Okay. Now, I will have to save that for another episode.

Jocelyn: We know that the gravitons can't be too massive. Because we know gravity and light travel at the same speed. Because we measured from this galaxy moderately far away, a gamma ray burst and gravitational wave that arrived, like within seconds of each other. And that's like, generation time. So, so we know that if if the graviton was massive, then it it can't travel as fast as light does. So it would have to, like, get slowed down as it travels and then, so we can actually say stuff about gravitons without really knowing that they exist.

Ben: I wonder if in Star Trek they imagine the gravitons will like be like gravity where it kind of sucks a thing towards you like a tractor beam, or whether they imagined gravitons to be like, gravitational waves, like a laser where it would cause like the Kardashians or whatever to like, wiggle.

Jocelyn: What do graviton beams do...

Ben: ... heads fall off and...

Benjamin: Hey, all of our all of our rulers are going crazy over here.