Episode 76: Neutron Stars Smash Together in Space!
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Transcribed by Denny Henke

Ben: Never be afraid. There's nothing which is known which can't be understood. And there's nothing which is understood which can't be explained. For over fifty 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've bestowed upon these women and men the title of Titanium Physicist. You're listening to the Titanium Physicist Podcast and I'm Ben Tippett, and now allez physique!

1:45

Ben: One question which dogs human thought is where does wealth come from? How can I feel like my resources are abundant and that I have power and influential status in my community and that these will continue into the future. I have to tell you that I don't know the answer to this question and I would question why you might think that I would. But some people think that it can only come from dominating others and insuring that they'll work to your benefit today and in the future. Others say that it can only come from establishing a community of people and family around you who can hold you up in hard times. Others think that it can only come from government, formalizing cooperation that we owe to others and which is owed to us in turn. And others think that wealth is a zero sum game, that the only way to get it is to build a metaphorical wall and then take it away from other people. Other people notice that wealthy people seem to have a lot of gold. So, instead of focusing on where wealth comes from, they ask the question, where does gold come from? And this, this is a question we can answer. Ancient philosophers wondered a lot about it. Ancient alchemists worked a lot at it. And all of them figured that there must be some reason why the Earth has lots of gold, that gold is under the surface of the Earth. Some people thought that gold was solidified sunlight, the way that ice is solidified water vapor. Others thought that you could only get it through transmutation, that's the alchemists word for what we'd call a chemical reaction. But, transmutation involving a rare and unachievable object called the philosopher's stone. Or, if you're in America, the sorcerer's stone. But after all this trying, no one managed to make it work because it takes more than chemistry to transmute lead into gold. It takes the death of stars. In modern terms the word is nucleosynthesis,the combination of atomic nuclei. And gold and all the precious metals we see on the Earth were transmuted into being on some of the most violent processes in the modern universe. And so it was to my delight that the LIGO interferometer, an international collaboration of astronomers announced in October, that they had witnessed an example of this process earlier this year. The process which sprinkled the galaxy in gold and precious metals, the collision of two neutron stars. Today on the *Titanium Physicists* podcast we're talking about smashing two neutron stars together. Speaking of pure gold, I've been a fan of this guest for many years. He's a stand-up comedian and famialar voice on Canadian television and radio. He frequently performs on CBC's radio's *The Debaters* and he even has a podcast, *The Well Reads* which is a monthly left-wing book report show. The first book in his curated humor imprint, Robin's Egg Books, has just been released and it's called *What I Think Happend: An Underresearched History of the Western World * by Evany Rosen. And also, good news, he just released a comedy album. It's called *Fatherland* and can be purchased off of iTunes. Welcome to the show Charlie Demers.

Charlie: Thank you so much for having me.

Ben: Oh Charlie, I have a real treat for you today. My two oldest and favorite physicist team for the auspicious start of our seventh year in podcasting, I present to you the A-Team. Arise Dr. Tsang.

5:09

David: Mmmmwwwwaaaawwwaaahhhhhaaahaha.

Ben: Dr. Dave did his undergraduate degree with me at UBC and his PhD from Cornell University and he's currently at the University of South Hampton, UK where he studies theoretical astrophysics. And now, to much acclaim, arise Dr. Jocelyn Read!

Jocelyn: Raaaarrrrrraaaarrrrr.

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 smashing stuff together.

Alright Charlie, did you hear the news about these neutron stars smashing together?

Charlie: Is this a set-up? I feel like a punchline is coming.

Jocelyn: Two neutron stars walk into a galaxy.

Charlie: Yeah, yeah. Um, so, no, I have not heard this one.

Jocelyn: Have you heard about gravitational waves at all?

Charlie: I mean, I've definitely heard about gravity and I've definitely heard about waves. I'm not so positive about the combo. So, like, theoretically if I had forgotten what they were...

Jocelyn: Hypothetically, if we were going to explain from scratch...

Charlie: Yeah.

Jocelyn: As if you might not have known what they were...

Charlie: Yeah. Like pretend I'm a guy that doesn't know about science.

David: So, there was this guy with hair and a mustache.

Charlie: Stalin?!

Ben: Yes!

Laughter

Jocelyn: Bigger hair.

Charlie: Oh, Einstein! I know this because there's a, ah, my dad had an Einstein poster, you know, because my dad was a teacher in the 80s and 90s and you were required by law to have a lighthearted Einstein poster in your classroom. And in this poster my dad looked exactly like Einstein.

David: Is it the one with his tongue out?

Ben: Is it the one where he rides a bike?

Jocelyn: Or is he saying imagination is more something, something knowledge?

David: Or is he sticking his tongue out?

Charlie: Imagination sounds right. I feel like that's the one. Right next to a poster of Garfield telling you to read.

Ben: That's right. Let's start talking about gravitational waves.

Jocelyn: The big thing about how Einstein changed the way we think about gravity by saying it's not, you know, two things pulling each other with forces, but it's this influence on the background fabric of space and time, warping and stretching around stuff. And that causes things to do, you know, fall.

Charlie: Is that what he said?

Ben: That's what he said.

David: Exactly those words.

Ben: Yeah.

Charlie: So, when you say it's like a background thing that is warping around things, I mean, I know that was pretty specific but um, is there any, like, what kinds of things wrapping around what kinds of things?

Jocelyn: So, like, the distance between things stretches and if something tries to go in a straight line, the warped spacetime curves it around into say, like, the orbit of the moon around the Earth.

David: Do you know those, um, old mattress commercials?

Charlie: With the bowling ball?

David: Yeah, with the bowling ball. Think about the bad mattresses.

Charlie: And with Stalin, right?

David: And Stalin, yeah…

Charlie: Yeah, okay, yeah.

David: Yeah, and good old uncle Joe is, like, dropping a bowling ball while you're trying to sleep.

Ben: This commercial is very Vancouver specific, I don't know if everybody else is going to get our Stalin, bowling ball, mattress commercial reference.

David: I don't, I don't think Stalin ever came to Vancouver.

Charlie: Yeah, that's what they named the Georgia viaduct after.

Jocelyn: Stalin is pretty widely known, he's not only famous in Vancouver guys.

Ben: He's only famous, but, Vancouver specifically, he's only famous for mattresses right? So, and the Georgia viaduct.

Laughter

Charlie: You're talking about the commercial where there's bowling pins set up and then the bowling ball drops on the other side?

David: So, we're talking about a bad mattress here, where if you put the bowling ball down, the mattress sinks around it, right?

Jocelyn: So, Einstein said the universe is like a bad mattress.

Charlie: Right, and so, physics is the quest to find the pee underneath it.

Jocelyn: Yes.

David: Right, yeah. Physics is like the black light you are shining on the mattress.

Laughter

Ben: Oh, Jesus Christ.

Laughter

Charlie: Oh Jesus. I stay in too many hotels not to be disturbed by that.

David: So, for instance, the mass of the Earth, you can imagine space and time as this mattress. The mass of the Earth pushes down into that mattress. And if I took a little marble and I tried to roll it around on that mattress, instead of just rolling in a straight line it would curve around because of the indent that mattress has made. And, just like if I took a little asteroid and threw it at the Earth, it would sort of come around. Maybe, enter into an orbit.

10:00

Charlie: So, before Einstein, people thought of the universe more as a pool table.

Jocelyn: Yeah.

David: It had, sort of, invisible strings or invisible springs that sort of held things together.

Jocelyn: Connected things.

Charlie: Nice.

David: Invisible, these sort of invisible distant forces, was the picture that Newton had.

Charlie: And Einstein said that was not the case. How did he know that?

Jocelyn: One of the things that Newton gravity has is that if something changes where it is, across the universe the pull of gravity changes instantaneously. And now, Einstein is like no, if something moves, that change kind of has to ripple out through the mattress.

David: Right. One of the things that led Einstein to develop his theories of special and general relatively was the observation that the speed of light was constant. It didn't sort of, matter, how you were moving, you would always measure the speed of light to be the same. And so, one of the consequences of this is that information can't actually travel faster than the speed of light. So, if I took some mass and I shook it around, that information can only travel at the speed of light. So, it sort of ripples outwards at the speed of light. And so spacetime also carries out this information at the speed of light.

Ben: It's like your bad mattress analogy. You're on your bad mattress with your like, ah, fat, ugly husband and your fat ugly husband rolls around in his sleep.

David: How dare you?

Ben: ...bad mattress, you've got like fractions of a second before you're thrown to the floor by the shifting mattress because it takes time for the wave, the information that your fat ugly husband has rolled around to travel to the nice side of the bed.

Charlie: So, how come the speed of light being constant means that's true.

Jocelyn: That, more led to the idea that there's this thing called spacetime. That space and time can stretch and squeeze and aren't just a background thing. So, to make the speed of light be constant no matter how you are moving, space and time need to kind of shift around.

Ben: I feel like your question kind of asks, kind of the history of experimental and ah, astrophysics, up until the development of Einstein. So, what would happen is, we thought Newton was right up until the end of the 1800s. But, slowly there were a bunch of observations and there were a bunch of experiments that suggested it was wrong. So, one of these experiments said hey, it doesn't matter which way we are going around the sun, the earth goes in a circle around the sun, right?

Charlie: Yeah. That I was 100% unaware of.

Ben: If light was traveling through a medium, like, if we were in water and we were talking about waves moving through the water, depending on the direction the earth was traveling around the sun, ah, the sound, soundwaves through the water would be different. And similarly , we'd expect the lightwaves to travel at different speeds depending on how we were moving around the sun. And the answer is, no, it doesn't depend where we are on the sun, light is always traveling at the same speed and everybody was like what, that doesn't make any sense. And then, in addition to that, there were some astrophysical observations talking about what Mercury was doing in its orbit and it wasn't quite orbiting in the way Issac Newton would have predicted it. And so the table was set for a new physical framework to describe gravity in. We knew that Newton's theory wasn't quite right because it didn't predict the right stuff. And also, we had all these other new pieces of information, like, light always travels at the same speed regardless of how fast you're traveling relative to it. That's weird. And so, Einstein put all these different pieces together into his theory of gravitation which involves the curvature of spacetime. Does that make a little bit more sense?

Charlie: Mmmhhmmm.

Jocelyn: One of the big implications of all this spacetime wibbly wobbly stuff was that if stuff is moving around really fast it can stir up gravitational waves. Although, Einstein was like, but they are way too tiny that it's totally irrelevant.

David: So, one of the implications of the Theory of General Relativity is that spacetime is dynamic, it responds to matter and it warps and changes. And the result of, sort of, wiggling around that matter can be the sort of waves that propagate outwards from where the matter is moving. And those are gravitational waves.

Charlie: So, the idea is that the universe is more like a smoothie than a salad. It's all, like, mixing and moving around, it's more like a slurry than like a kind of, you know, a crystallized constellation of things.

Ben: Yeah.

Jocelyn: It's more like Jello than a chocolate bar.

Ben: Oh.

Charlie: Right. Mine was healthy but.

Laughter

Jocelyn: A smoothie is good too but I think the salad confused me.

David: The smoothie is just too viscous.

Charlie: Okay, okay.

David: If you try to shake it around, just, sort of, and then, you know. The Jello will keep shaking.

Charlie: And there's always room for it.

Ben: Yeah, so, let's reiterate what David just said because it's philosophically bonkers.

15:00

Ah, a person should, rightly, kind of loose their mind when they hear it. We're used to thinking of distance as a kind of mutable quantity, right? So, like, the distance between me and the door is three meters. Right now. And we're used to the idea that that three meters is just kind of set in stone. It's just because where the door is and where I am relative to the door. And the only way for that distance to change is if I get closer to the door or somehow the door gets closer to me. Einstein takes that idea and goes well, not quite. Because in Einstein's theory of General Relativity, and his theory of gravity, gravity is caused by space and time warping. Distant scales, in this case, are dynamic. So, what Einstein says is well, you know, the distance between me and that door might be three meters now, but you never know. Some weird gravity thing might come in and make that distance two meters. You stay in place, the door stays in place, it's that the distance between you and the door is now a dynamic quantity. And the thing that makes it change is, essentially, the presence of mass and what mass is doing because mass spacetime to warp. But it's weird. And so what these gravitational waves are, is they are waves carrying information about how objects have moved around, shifted positions. But the form that these waves take is, it’s a wave of changing distance scales. In other words, if one of these gravitational waves were to pass between me and this door that’s three meters away, suddenly the door might be, because of this wave, the door might go from three meters to one meter away and then…

Charlie: Whoa!

Ben: Then back to three meters then up to five meters. You never know. I mean, that’s pretty bonkers.

Jocelyn: That’s basically, like black holes are merging like…

David: Yeah, I think we’d be dead.

Jocelyn: Yeah, you would be stretching and squeezing along with the door in this scenario.

David: Yeah.

Ben: Yeah, no, it’s the principle of the thing. That distance scales are dynamic and these gravitational waves carry information about gravity but because they’re essentially dynamic distance scales they pass through you and suddenly the distances around you kind of change.

Charlie: It sounds like the distance scale is still, because you‘re saying the door would now be two meters away but, like, a meter is still the same amount, right? Or…

Ben: Well, no, that’s…

David: Yeah, if you had a ruler and you tried to use that wooden ruler to measure the distance the ruler would also shrink and so you wouldn’t be able to tell.

Jocelyn: Although it would…

David: But because…

Jocelyn: Resist it.

David: Yeah, that's true. Because it's solid it would try to push against it.

Jocelyn: The way we measure this is we use, lasers and as each laser travels it, well, it's a lightwave packet thing. But it's got a little clock going tick, tick, tick, tick. And it's traveling at the speed of light. And so when it travels it bounces, it comes back and you can kind of calibrate by what state it's in, how long it has traveled. And then a gravitational wave comes in and it stretches the distance and now we send another little packet of light through and it has to travel a little extra so it's clock has gone a little bit further by the time you, you know, compare it again.

David: By using these light pulses you can measure distance in a way that's sort of not in reference to ah, something that has physical separation.

Jocelyn: I mean, that is a part of the challenge, is like, how do you measure the distance changing when that stretching and squeezing affects everything.

Charlie: Is there any marker outside of this fluid process by which you can measure?

Jocelyn: I mean, there's a lot of debate about this and like, one of the early thought experiments was if you had two beads on a really stiff rod the gravitational wave would kind of slide them back and forth and then that would mean that they could rub and make heat and that would pull energy out. So, it was like a real physical thing happening here, it could do stuff. The beads on a stick which was from, like, a famous conference in 1957 where this guy called Pirani came up with this and everyone tells the Richard Feynman story and gives him all the credit.

David: Yeah.

Ben: So, Jocelyn mentioned that the most efficient way to measure these changes in distances is to use light. Unlike a meter stick that might get squished or stretched as a gravitational wave passed through it and throw off your ability to measure it. Light, you know, if you take two mirrors and you bounce a pulse of light between them, ah the amount of time it takes for the light to go down the mirror and come back will depend on, essentially, the pure distance between them. And so, if a gravitational wave passes through, ah, it will either take more or less time than usual.

Charlie: So, the light is affected still by all the bending and pushing, it's not outside of it.

Ben: It's traveling through a background that's being stretched and skewed.

Jocelyn: The light is getting stretched too but we're always, like, sending in new photons and each photon goes in and bounces and comes back with its report and then we send in a new little bit of light and it goes out and measures the distance and comes back with its report. So they're all getting stretched and squeezed by the gravity too but we can still figure out what's going on.

20:05

Ben: So, we use light to, essentially, measure distances in this case. Um, but the problem here is that light goes really, really, really, really, really, really, really, really, really, really, really, really, fast.

David: The speed of light, if I'm not mistaken.

Ben: It's not like we can say, okay, laser, we're going to shine you down this, ah, this hallway and we're going to measure when you leave and we're going to measure when you come back because that time interval is teeny tiny. Even if we, like, made a hundred kilometers long tube it would still take an unmeasurable amount of time to get back. So, we do something really clever. We take two, essentially, mirror corridors, long tubes with a mirror on one end and we put them perpendicular to each other, 90° angles. Um, so, we set one going north and make it, you know, four kilometers long. And then we set one going east and we make it four kilometers long. And then instead of measuring how much time each photon takes to go down the tube and bounce back, what we're doing is we're sending photons down both of them at the same time, and if a gravitational wave comes through, it's going to change the two perpendicular arms in different ways. It will stretch one and shrink the other or shrink one and stretch the other. Because they are perpendicular to each other, they are at 90°, they'll feel different affects from the gravitational wave that passes through them. And then we compare the two photons when they come back home, we can combine them in a process called interference. We can figure out if they've taken the same amount of time to go back and forth down these hallways. Or different amounts of time and if it's different amounts of time we can be like, sweet, we can measure that by comparing the two photons using interference. And then we can say yes, a gravitational wave is passing through here.

Charlie: So, it's like triangulation.

Ben: Ah, kinda.

Charlie: But, like, where are these tubes? Like, where is the light going out?

Jocelyn: Well, they're in Washington and Louisiana. So, the light is generated at the central b station from ah, like, a laser system. And then it hits a mirror that's half transparent. So, part of it gets reflected and part of it keeps going and they go off at 90° from each other, bounce against these big chunks of mirror really far away, come back and then they get recombined at the central station. And, so, light travels as a wave so it's, you know, cresting and trough and crest and trough and they come back together and they see whether the crests and troughs line up or not.

Charlie: Wow.

Jocelyn: To blow your mind a little bit, the precision of this is so much that we detect the relative change of distance from one arm to the other arm is the same fraction as a human hair compares to the distance to the nearest star.

Charlie: Jesus. That ah, yeah, that's really wild. And so these gravitational waves are not, they're not just constant background. Like, they happen?

Jocelyn: Well, we think there might be a constant background but it's really, really low level. Stuff that's kind of brighter in gravitational waves or stirs up distances more, are these sort of infrequent, transient things. So, the thing that's caused the strongest gravitational waves that we've measured is black holes crashing together.

Charlie: Black holes crashing together?

Jocelyn: They start out orbiting each other and then the gravitational waves make them fall together so they orbit closer and faster which stirs up more gravitational waves so they fall together. And that keeps on happening until they crash together. Except they are black holes so they don't have surfaces so they don't really crash together. They just kind of like get really close to each other and then fwoop, there's a bigger black hole that's all wonky and then it settles down.

Charlie: Whoa.

David: So, basically, any big chunks of matter that are sort of moving relative to each other will emit gravitational waves. Ah, if they're sort of, imagine, like, a dumbbell that's rotating. That's sort of, the simplest thing you could have that will emit gravitational waves.

Jocelyn: So, you can wave your hands around and it will make gravitational waves,

Charlie: Should I do that for the show, like, for the sake of the episode, should I make some gravitational waves with my hands?

Jocelyn: We can all do it and now we're creating a background of gravitational waves fluctuating though the universe.

Charlie: So different thing are putting out, like, there are myriad sources of gravitational waves at any given time.

David: So, the bigger the masses…

Charlie: Mmmmhmmmm.

David: And um, the faster they move, the more they emit gravitational waves.

Charlie: So, with Donald Trumps hands, they would be smaller gravitational waves.

David: Yes

Ben: That's right.

David: Exactly.

Charlie: Like, you know, stubby little...

Jocelyn: Very beautiful gravitational waves though.

Charlie: Yeah.

Jocelyn: The best gravitational waves so. The best gravitational waves.

Ben: Right.

David: Huge. Huge gravitational waves.

24:57

Ben: The name of the game here is acceleration. The more a massive object accelerates the more energy that is going to go into gravitational waves. And so, you end up with a process that Jocelyn was just talking about called binary inspiral. It's when you've got two objects that are orbiting each other. Both of those masses, to go in a circle, they have to be accelerating. So, the closer they are to each other in orbit, the faster their orbit is going to be and the larger the acceleration you'll need in order to stay in orbit, right? So, I mean, the moon is far away from the earth and it has an orbital period of a month whereas the International Space Station is much closer and has a much, it's got an orbital period in the hours. So, long story short, the narrower the orbit is the faster the object is going to go, the more acceleration you need and the more acceleration you have the more gravitational waves you're going to produce. And so, um, in Einstein's theory of gravity, you can't have two objects in orbit around each other forever. In Newton's theory of gravitation you can get orbits that last forever. So, you could say, oh, well, the moon will orbit the earth forever. In Einstein's theory of gravity though, orbits loose energy to gravitational waves. The affect is really, really small usually but it's measurable. This was the first evidence that anybody had of gravitational waves was, you could look at systems that were orbiting each other and check to see if that orbit was changing. And it was changing, due to, essentially, the system loosing energy to gravitational waves. So, if you have two objects that are in orbit and they are loosing energy to gravitational waves, their orbits will get closer together. Their orbits will decay. And the closer they are together the more acceleration they need, they radiate more and more intense gravitational waves. And so, in a black hole binary scenario what you can get is, once they get fairly close to each other they are radiating a ton of energy in terms of gravitational waves and their orbits are decaying faster and faster and faster. And this generates a ton of gravitational waves in a really, really recognizable signal. Because as they get closer together the period of their orbit decreases, the frequency is going to go up and up and up. And they'll go faster and faster and faster and the amplitude of that signal is going to increase because they are orbiting closer and so they are going to lose more and more energy. And so you get a ramping up, tell tale signal called the chirp.

Charlie: A chirp?

Ben: Yeah, a chirp.

Charlie: This is like what hockey players do to each other. Like, it's kind of a chippy, confrontational kind of signal.

David: More of the bird.

Jocelyn: It depends on the mass of the objects.

Charlie: Oh, okay. Okay.

Jocelyn: So, the black holes, like, they come into the audio band, these waves are coming in and it turns out they are the same frequencies as human hearing can hear a sound so we can just map the waves into sound. And if it's black holes, it's just like this, thwump, kind of thing, because by the time you can hear them they orbit around each other a few times and then thwump together and so it's just thwump, just a few cycles of sound. While there are things, 10 times to 30 times the mass of the sun are swinging around each other at a third of the speed of light.

David: So, this merger, um, of these two black holes gave off 3.6×10^{49} watts, that's ah, imagine a lightbulb, instead of ah, a 100 watts, you know, a one with two zeros behind, a 1 with 00, it's a 1 with fifty zeros behind it and that's sort of the amount of energy it gave off. So, during that brief second, when it gave off these gravitational waves it was releasing more energy than every single star in the entire universe.

Jocelyn: Right before they, ah, collide into each other, that's when they are going around the fastest and stirring up the spacetime the most and they loose huge amounts of energy that goes out into the universe so if you could measure the energy of gravitational waves the same way that you measure light energy it would outshine all of the stars in the universe.

Charlie: Wow.

Jocelyn: Just for a fraction of a second and then it's one black hole and it just settles down to darkness. And then nothing.

David: So do you recall Einstein's famous formula about $E=MC^2$?

Charlie: Ah, I'm not familiar with it, no, I'm not.

Ben: From the poster!

Charlie: Ah, yes, from the poster.

Laughter and cross talk.

Charlie: I don't know, in fairness, I've heard it 7 million times in my life.

Jocelyn: But what does it really mean?

Charlie: And I have no idea what it means.

David: So what it means is that to figure out how much energy you would get by converting pure mass to pure energy you you just multiplied by the speed of light^2.

Charlie: Oh, okay.

David: And in this case three entire suns of mass disappeared and shot out as energy.

Jocelyn: Yes, that's right.

Charlie: And what happened to all that energy?

Ben: It just turned into gravitational waves.

David: It ripples off.

Charlie: And then does it just keep bouncing around or does it eventually kind of peter out.

Jocelyn : It just spreads out through the universe. So it's going off mostly in all directions in kind of a peanutty shape actually. But it's sort of radiating out from the system.

30:02

And so the system collides and you get this sort of bright ripples going out in most directions and as they travel they kind of get weaker and weaker, right? And so like you imagine plunking a rock into a pond and as it ripples out the ripples get smaller and smaller as it moves out, away from the central plunk. And so by the time it reached us, a billion years later, it's just this faint wiggle in our space time fabric that is much weaker than it would have been, you know, near the dramatic explosion itself.

Charlie: So the gravitational waves that we see, um, is it like the light from stars, like we're not experiencing it in real time, like it something that happened, potentially eons ago and we are just measuring it now. Or is this something like if we have these big gravitational waves it means that something is happening right now in the universe.

Jocelyn: It is exactly like light.

Charlie: Okay.

Jocelyn: It travels at the speed of light to get to us.

Charlie: So, measuring a gravitational wave is the same as seeing the light from a distant star, like, they could be potentially, be measuring something that happened millions and millions of years ago.

David: Yes, that's right.

Charlie: So then, what's the earliest or the soonest we could see something? Like, so is this something where like, something like, if something happened much closer to us we would find out much sooner?

Jocelyn: If for example something happened in a galaxy 140 million light years away, it would only take 140 million years to reach us.

Charlie: Right.

Ben: I guess the thing to note here is, you asked a couple of minutes ago, if we were always being bathed in gravitational waves and the answer is yes and no. We are, but most of the ones we are being bathed in, aren't detectable. It's these really, really strong gravitational waves that are generated by binary merger that are strong enough for our instruments to detect. But we can only detect them if they are within range of the sensitivity of our instrument.

David: We've only really just turned on this microphone to the universe. Like it, it's sort of like, just the crudest mic. We can only pick up at the very, very loudest things. And so we are still deaf to, or we still can't hear, basically, most of the noise that's out there.

Ben: Yeah gravitational waves, ah, that are detectable come from events that don't happen very often.

Jocelyn: Well if you go through the entire observable universe we think that they happen every seven minutes.

Ben: Yeah, so that is the notable thing, is that they are common enough if we listen to a broad, a wide enough stretch of space. Like, if we can listen over a region of space that is billions and billions of light-years wide, then these things will happen frequently enough that we will be able to detect them with our instruments. And so it's kind of like, ah, a size game, right? Based on your instrument's sensitivity you're going to hear them more frequently because even though it is a fairly rare event, it's sure to happen somewhere. It's like somebody winning the lottery, right? So, nobody in your neighborhood is going to win the lottery. But if you extend your your population size to the size of Canada or the size of North America then hey, every week somebody wins the lottery.

Charlie: Right, right.

Ben: Even though that event is fairly improbable.

Charlie: But you are saying every seven minutes two black holes collapse into each other somewhere in the universe?

David: Yeah.

Charlie: Wow.

David: Only some of them are close enough so that they are loud enough for us to hear.

Charlie: I don't know what to do with this information.

Joslin: That's a lot of where we are with this kind of science. I mean, it's new enough that, people, it's kind of like, well you know, people are like well how does this affect my day today life. I'm like, (crazy sounds) we're hearing black holes across the universe, I mean, it's so cool!

David: But one thing to realize is that these detections only happened two years ago.

Joslin: Yep.

David: And...

Charlie: The very first ones?

David: The very first ones. And that is the first time we've ever measured anything with gravitational waves.

Charlie: What was the lag time between Einstein proposing gravitational waves and the first time we were able to measure them?

David: The lag time was almost 100 years.

Charlie: Oh wow!

Joslin: Yeah, yeah it was like on the 100 year anniversary.

Ben: Yeah.

Charlie: But then, that's kind of like poetic because in the same way as you see the light from from a star that has maybe been extinguished, afterwards, he says gravitational waves, then dies, and then we get to see it almost like an echo after he's dead.

Ben: Yeah the news hasn't reached the scientific community that Einstein is dead.

Charlie: Yeah, yeah.

David: It's basically like we have built a radio that can listen to the universe, all of the sudden.

35:02

We've built this receiver that can suddenly listen, you know, right now, kind of only to the loudest things, but we have suddenly sort of been able to turn on our hearing.

Jocelyn: Yeah we have developed an entirely new sense.

Charlie: That's cool. See that's really neat. You guys, this is like an accelerating strength of metaphor going on here. Where I am more and more able to see, there is such a tremendous gulf between specialists and turnip truck rubes like myself, that we don't even know enough to be excited by some of these things. But that sound sounds very cool. The idea of being able to listen to the universe, or having another sense and suddenly being able to tell, and it feels like early enough to be excited about it...

Joslin: Oh definitely.

Charlie: On the ground floor.

David: Well it's definitely the beginning of being able to listen and see the universe.

Jocelyn: Yeah and we just had another cool development in August so you can be even more on the cutting edge. If you ask us about that.

Charlie: Wow.

David: So the black holes that we talked about, that we detected a few years ago, those made a really loud noise that we heard in gravitational waves. But we didn't really get to see anything from it, our telescopes didn't catch anything that's because black holes themselves unless they have some matter around them, they don't make any light.

Jocelyn: So two black holes can stir up space-time and fall together and emit three masses of suns worth of energy and be just, this completely dark event, from the perspective of all our previous telescopes.

David: Right. So if you have some matter around that can interact and emit light, then you have a chance of seeing some event on your telescopes.

Charlie: So, we're like Tyrannosaurus rex in *Jurassic Park* where we needed them to move to see them.

David: Exactly, so um, you can think of sort of old long exposure astronomy. Like you know just taking pictures of the static sky that is, like, you know, a photograph, right? And then more recently, you know, in the last few decades we have been developing the ability to look at transients, things that sort of go flash in the night. And we have sort of been able to get better and better pictures over time. So we are now starting to be able to see movies, you know animated GIFs of whats up with...

Charlie: Mhhhmmmmm.

David: What the night sky sort of looks like so we're discovering all sorts of neat things that sort of, you know, pop up off. Sort of like, supernovae and different kinds of transients and sort of all different parts of the electromagnetic spectrum.

Jocelyn: Whoa. Animated gifts are like the silent movies of today. That's really deep.

David: Yeah, yeah. But if you could see something that comes from the merger of two really heavy objects, to really heavy dense objects, um, that are emitting gravitational waves then all of a sudden, it's like we are in the talkies.

Jocelyn: So we started out with, like, just the black holes with no light associated with them. So we are sitting in the car, in *Jurassic Park*, and we just see like this thump, ripple. Period.

Ben: Oh, cool.

Jocelyn: Thump, ripple. But now we are going to start combining the new transient, like moving picture astronomy and the soundtrack at the same time.

Charlie: That's really neat.

David: Yeah. So, in fact, in August, there was a simultaneous detection of a merger of two neutron stars that was caught in the electromagnetic spectrum with light and with gravitational waves.

Charlie: So, for the very first time we heard and saw something like that happening at the same time.

David: That's right.

Jocelyn: Yeah, we got this unprecedented, multi-channel view of an astronomical event with like 70 observatories around the world all joining forces to try and observe it with whatever astronomical techniques were possible. Including like five space-based satellites all getting, independent views in all kinds of light and gravitational waves of this one dramatic event.

David: It was the most observed event ever, I think. In terms of astronomy.

Charlie: It replaced the Justin Timberlake/Janet Jackson, um, halftime show.

Laughter.

Um, how did they know that event was coming. Like how did they everyone prepare like it started happening and then people realized it was happening? Or...

Jocelyn: Yeah, yeah, so it's like this astronomical alert network and for the last gravitational waves set of observations this was done by people who had signed up ahead of time and agreed to like, to not talk about things because we weren't really sure if we were going to do it right on the first tries.

Charlie: Mmmmhmmm.

39:57

Jocelyn: So we had this basically like, I don't know, Twitter platform for gravitational waves stuff. And every once in a while, I think there were five things that we talked about, where like, oh something interesting, ah, gravitational wave with these properties from this patch of sky.

Charlie: Mhmmm. And so all of that added up to, there was going to be this big thing happening.

Jocelyn: Well, so a bunch of these had gone out and telescopes would follow up to see if they could see anything and there hadn't been anything particularly exciting. Until this one event came in. And the really amazing thing was that the gravitational waves signal came in and then, at basically the same time, a gamma ray observing satellite said I saw a flash of gamma rays.

David: So, gamma rays, so there is this history of…

Jocelyn: Famous for creating the Incredible Hulk.

Charlie: Yeah.

David: Right.

Charlie: Yes so that's what I know them from.

David: Right, right. So there's actually a really interesting history of, they are called gamma ray bursts which are literally bursts of gamma rays from out in the universe. Um, in that we had no idea they existed until the US put up a satellite to monitor nuclear testing. They were trying to, basically, look for hidden gamma rays from hidden nuclear testing. And then, they turned it on and then…

Jocelyn: They were like, a bunch of these things a day.

David: Yeah a bunch of these things, like, bursting out in the universe somewhere and the Russians were not all the way out there. So we accidentally discovered the fact that there are these big bursts of gamma rays that are…

Charlie: Aw, that's, that's just what the Russians wanted you to think.

David: That's right, that's right.

Jocelyn: And for ages we have no idea where in the universe things were even coming from. Like are they in our own galaxy? Are they across the universe?

David: So it is thought that they come from sort of two main things. The longer lived ones probably come from the collapse of massive stars. So big massive stars that sort of collapse in on themselves and then shoot out jets, sort of up and down. And if we happen to be sort of staring down the barrel of that jet then we see these gamma rays, these big bursts of gama rays.

Charlie: Mmmhhhm.

David: And then, it is thought that when you have two neutron stars that merge and smack together that they will also do something similar but it is a little bit more short lived. It is a burst of gamma rays that only lasts a couple of seconds.

Charlie: Um, how would you describe what a neutron star is?

Jocelyn: So a neutron star is is basically as close as you can get to collapsing into a black hole while matter makes its last stand against just, like, being crushed to a singularity. So it is the densest kind of matter that we know of in the entire universe. And it is something that is like one and a half times the mass of our sun that started out as a big massive star that ran out of energy and went supernova and collapse down until it got to this strange form of matter that halted the collapse at the density of a nucleus and about the size of the city.

Charlie: Wow.

David: It is the most extreme matter in the universe.

Charlie: And it stays like that?

Jocelyn: Yeah it is supported by quantum pressure. So, pressures of particles not wanting to be in the same quantum states, keeps it from collapsing any further for as long as you can imagine.

David: So these neutron stars are, you can think of them as, sort of, like giant nucleuses. There is so much matter crammed in that everything is as tight as the nucleus is in an atom. Do you remember the sort of science class picture of what an atom looks like? There is, you know the protons and the neutrons at the center and then the electrons sort of floating around?

Charlie: Vaguely.

Jocelyn: The idea is like all of the mass in an atom is in this tiny little nucleus in the middle. What is it like a basketball in a football stadium or something like that.

Charlie: Do they mix up the ball in the stadium from disparate sports on purpose?

Ben: Yes.

Jocelyn: Ah, it could just be that I am bad at distinguishing my sports.

Laughter.

Charlie: No, it's okay, I just thought, like, having a basketball in a football stadium was just like one extra level of confusion for me...

Jocelyn: Oh, here we go, oh I was totally off the atom is a pea in a football stadium.

Charlie: Oh wow, okay.

Ben: The way it goes is, regular matter, the stuff around us, solid matter, it comes from electrons in different adjacent atoms interact.

Jocelyn: So, like you are prevented from falling towards the center of the earth because the thin layer of electron clouds on your feet is bumping up against the thin layer of electron clouds on the ground and they are repelling each other.

45:00

Charlie: Really?

Ben: Yeah so at regular energy scales different atoms interact by their electron clouds, pushing up against there each other. And so the the size scale, it's like saying, hey, you can't build these two adjacent stadiums next to each other. You know, your one stadium bumps into another stadium, I guess you put you put your stadiums on wheels so that you can smash them together.

Charlie: Mmmmhmmm.

Ben: That gives you a sense of the size scales. It's not like the nucleuses are the peas in the middle of the stadiums are touching each other. Inside a neutron star what happens is, it's all peas, all the time. Everything is made of peas.

Charlie: Yeah

Ben: It’s much, it’s a tinier size scale then we are used to here on earth because the crushing gravity allows these nuclei to interact, and so essentially, like Dave said, everything is the density of a nucleus. It’s tiny.

Jocelyn: Neutron stars are really weird and extreme. So they are massive enough and compact enough that they can stir up gravitational waves. But there is this weird stuff there which, as it turns out, turns into mostly neutrons, hence the neutron star name. So this really neutron rich, wacky matter of all nucleus like particles at super high densities. And so two of these things crashing together, it ripples out gravitational waves and then they crash together and then it sends out this jet of gamma rays really soon afterwards. And both of those were just detected.

Charlie: Okay.

David: We also see something called kilonova or macronova and what this is, is, all of the neutrons, imagine two neutron filled piñatas, and you are sort of swirling them around and smacking them together and you know, some of the piñata’s stick and form some object, maybe a black hole. But a lot of the candy sprays out. All of the neutron rich candy sprays out and that neutron rich material is basically a whole bunch of heavy heavy atoms and a whole bunch of neutrons. And what happens is what’s called the rapid nuclear process which is all the neutrons can smack into those atoms and get absorbed and that generates really heavy elements. In fact that is one of the few ways of generating really heavy elements in the universe. And so we think that this is actually where most of the really heavy elements come from. Elements like gold, elements like platinum.

Jocelyn: So these two neutron stars crashing together, threw off what turn into, like between 1 and 10 earth masses of gold along with a bunch of other heavy elements.

David: A lot of heavy, radioactive elements. So the atoms in the neutron star were squeezed so much all of the neutrons popped out of them and then when they are flung off, they are suddenly decompressed. They were no longer squished down by the gravity of the neutron stars. And it gets flung out and they all sort of run back into the atoms and they swell these atoms up really really heavy and make really heavy elements, and really heavy radioactive elements. And this radioactive cloud decays into things like gold and platinum and that decay, that radioactive heating and the energy given off of that is what we see as a kilonova or a macronova in the infrared. And there is also some evidence of it being in the optical as well.

Jocelyn: So we actually observed all of this but we were only able to find this because the gravitational waves allowed us to triangulate where in the sky this was. And also told us this that it was kind of close by so we were able to point telescopes at the right galaxies to find this new scenario happening.

Charlie: How recent was it?

Jocelyn: We are observed it on August 17th.

Charlie: But when do we think it actually happened?

Jocelyn: So because we are able to pin down the galaxy that it happened in we know pretty precisely that it was, oh gosh, and can I remember, it was 140 million years ago.

Ben: Dinosaur times.

Charlie: Wow. In a different galaxy.

Jocelyn: In a galaxy far far away.

David: Not that far.

Charlie: But would any of our gold, would any of the gold that we have potentially have come from that event?

Jocelyn: Not this one. A similar one in our own galaxy. So the gold probably stays in whichever galaxy it is produced in. But this suggests that some...

Charlie: Oh, so like, in the local economy.

Ben: Right.

Charlie: So, supporting local small business, yeah.

David: Most of the gold on earth came probably came from some event like this. And then it gets distributed out in the galaxy and those eventually swirl around and form into stars and planets and then we get the gold that is mixed into our planet.

50:05

Charlie: So after World War II...

Jocelyn: So, it would have to be something in our galaxy that happened before the sun formed.

Ben: Um,do you want to get a better idea of how this formation of gold happened? How you go from smashing neutron stars to gold because I've got some pretty stupid analogies. Okay, so before we go, we need to understand the problem of where gold comes from. The idea is you know how earlier in the show we were like $E=MC^2$? The the deal is that, that's essentially the mechanism that stars use to burn and to stay puffed up. Is they take two hydrogen atoms and they combine them and the resting mass of one helium atom is less than two hydrogen atoms alone. And so if you combine two hydrogen atoms there is an excess mass energy that then becomes heat. And so in combining two atoms into a heavier atom you get energy back out. That works you can do that up until the atom iron. Anything heavier than iron you can't combine in this way to get new atoms. And so one question here is okay, all of the elements on earth: carbon, oxygen, things lighter than iron, they came from essentially, heavy stars are combining two elements into a heavier one. Up until iron. But then passed iron, it's like where did all of that stuff come from and the answer is really, really violent processes like a supernova, sometimes generate them. But a huge candidate for where they come is from neutron star mergers. And issue here is what neutrons do when left unattended. If you have a proton and it's just sitting on its own, or an electron and it's just sitting on its own, they are stable. A proton is not going to do anything it will just sit there forever. An electron will just sit there forever. But if you take a neutron because nucleuses in atoms have have protons and neutrons, if you take a neutron and just leave it outside of a nucleus on its own it will decay. It will turn into something else, it will turn into a proton and electron. And so you don't see any neutrons wandering the wilderness alone. So the neat thing here is, how do you get a neutron? You essentially take an electron and you squeeze it into a proton and that's fun. So, in the cores of these neutron stars, it's covered in neutrons. Almost everything is made out of neutrons because the gravity is so strong that it's crushing all of the electrons into the protons making just a ton and ton of neutrons. So when these things collide they kind of pop like grapes being squeezed as they are about to collide, and they spew neutrons everywhere.

I want you to imagine, like, you are out at sea, there is nothing but two rafts full of survivors of a big shipwreck, okay? So, it's just like, they're living on crappy flotsam that they have tied together and it's just a two masses of them. The flotsam, that's like protons. Your neutrons need to hold on to some of them to stay neutrons. Your neutrons are the people, these flotsam ships are just covered in people. There are people everywhere. And imagine if that these two rafts made of flotsam covered in people, they hate each other. So they are going to ram each other. And so they ram each other, what do you get?

Jocelyn: This seems unproductive for a ship.

Ben: Yes. But that is human nature, right? Um so you get these big collisions, you get detritus, flotsam, flying everywhere, and people flying everywhere into the ocean. So most of the people in the ocean just drown and turn into fishes and flotsam. But, if there are people near little bits of, maybe there are a little bit of a barrel floating there or another, you know, piece of garbage, something floatable, a proton, the neutrons around it will kind of glom onto it and grab it. If they can grab it they will be stable. And so you end up with these patches. Whatever, you know, any free protons flying around or going to suck up the neutrons around it. Like the people gathering at whatever bits of flotsam they can. And so you'll end up with one bit of flotsam which is like a barrel covered in lots and lots and lots of people which is like neutrons. So you'll end up with these clumps of, essentially, atomic nuclei that have way, way, way too many neutrons in them. But it's kind of stable. And so, from the those you will get a little bit of radioactive decay maybe it will throw couple people into the ocean until you get a stable mass. But in the end, or maybe, I guess in this metaphor, some of the will people die. Some of the neutrons will turn into protons again and then they will be used to make a new raft. And so you'll end up with, essentially, new smaller rafts that have way more people on it then you would expect which are gold atoms, polonium, palladium. Yeah, some of the people get turned into garbage and get used to add to the raft of stability that all of the other neutrons are clinging to you. Yeah, so that's where all of the gold in the world comes from.

Charlie: Wow. So, at the end of World War II when, you know, the international, sort of financial system moves to the Brettonwoods system where currencies are pegged to the US dollar and the US dollar is pegged to gold.

55:03

You had at the end of a conflict that was ended with the first use of, like nuclear power, nuclear explosions in the atomic bomb. You then had the whole world go to an economy based on these heavy elements created by colliding neutron stars billions of years ago.

Ben: Can you think of anything more precious?

Charlie: That's wild, that's crazy.

David: What that tells you is that it's not actually a philosopher stone it's two of them and they are neutron stars.

Charlie: Right that was the big problem with alchemy.

Ben: That's right.

Charlie: Was that they thought it would...

David: Harry Potter should have been crushed by the philosopher stone's gravity.

Ben: Yeah, the tides. Harry Potter and the impossible tides, Harry Potter and spaghettification.

David: Tidally ripped apart.

Charlie: That's like, that's incredible. Also it feels like a hilarious analogy that in our wedding ceremonies when we're bringing two people together, we exchange these gold rings that are basically the product of...

Ben: That's true.

Charlie: Two hyperdense buddies colliding violently.

David: In fact they are the only things to escape the fate of those two bodies being thrown together.

Laughter

Charlie: That's amazing.

Ben: Well, that was amazing. Thank you Dave. Thank you Jocelyn. You please me, your efforts have born fruit and that fruit is sweet. Here is some fruit, Dave David you get a golden delicious apple

Munching sounds

Ben: And Jocelyn for your services here is a mango.

Munching sounds

Ben: All right I'd like to think my guest, Charlie Demers. Hero of the radio and the podcast, go buy his album, *Fatherland* which can be purchased on iTunes as we speak. Thank you Charlie!

Hey everybody let's do the announcements. First please give us a iTunes review or tell other people about us elsewhere online. Why? Because people keep their love of physics as a deep secret and they want to know that there is a show like ours online but they don't know that we exist. Your friends and family will be happy to hear about us and will have someone else to talk to you about physics. Secondly, thanks to your donations that we have received over the last few years I was able to hire professional to redesign our website. It looks great and it should work on your phones and tablets just as well as on your computers. Why don't you mosey on over to titaniumphysicist.com and have a look. I need to rewrite some of the things on it in the new style so I'd be happy to get your feedback about what you think could use a bit of work. On another note, that's related we are still humbly soliciting your donations. Your donations go to pay our server fees and our project to transcribe the episodes as they come out. Thanks for your support we have transcribed the entire back catalog of the *Titanium Physicist* podcast. You can send one time donation through PayPal off our website or you can go to our sweet Patreon site and give a recurring $2 donation. This particular episode of the *Titanium Physicist* has been sponsored by collection of generous people. First I would like to thank the generosity of Stian Hendrickson and Steve Hargrive for their donations. I'd also like to thank Adrian Shonig, Sandra Stradler, Louise Pantalina, a guy named Ben, a Mr. Mathew Lombare, a fellow named Aioosh Singh, a David Murtle and Mr. Ryan Foster, Janetco Fifenberg, Steve Smetherst, Magnus Cristisen, Bart Gladys, and Mr. Stewart Pollack. Our emperor Courtney Brook Davis, Mr. David Lindells, Mr. Carl Lockhart, our eternal friend B.S. and Randy Dazel. A Miss Tina Roudio, the enigmatic Ryan, a gentleman named Crux, and Gabe and Evan Weans, David D and Dan Vale, a Mr. Alex, WTL, Mr. Per Proden, Andrew Wattington, Mr Jordan Young and John Bleasy. A Brittany Crooks, James Crawford, Mr. Mark Simon, Two Songs Gang of One, Mr. Lawrence Lee, Sixton Linason, Mr. Simon, Keegan Ead, Adrian Shonig, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein Raymond, and a gentleman named Peter Fan, Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia, Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Insanity Orbitz, Robert Johnson, Madam Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka.

So that's it for *Titanium Physicists* podcast this time everyone. Remember that if you like listening to scientists in their own words there are other lovely and new shows on the Brachiolope Media Network so go drop by the BMN and check them out. Ah, the intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Good day my friends and until next time remember to keep science in your hearts.

1:01:58

Ben: Alright.

Jocelyn: I forgot my rarrrr sound. I think it was rarrrrr.

Ben: Ah, yeah, I don't know. I can't remember. I am sure it will be fine.

Jocelyn: Yeah.

David: Maybe it was a bit more mutant enemy, rarrr.

Jocelyn: Yeah, yeah, I think I, well, I was influenced by children's television.

Charlie: Sorry, am I allowed to say Jesus?

Ben: No, not on this podcast.

Charlie: Sorry, sorry, ah geez Louise. Um, wow, so that is wild, so like...

Jocelyn: Holy moly, yeah.

Ben: Not holy, what's the word, Nondenominational.

Jocelyn: You can't say holy moly?

Ben: Holy nondenomination I think is the phrase.

Charlie: Holy moly.

Jocelyn: Jinkies.

Charlie: Holy moly. I'm sorry, I said holy again.

Jocelyn: Jinkies.

Ben: Jinkies. I've got that out.

David: If you, no these things don't typically...

Laughter

Jocelyn: We need a list of approved, ah, is it ejaculation, no that sounds even worse. Um...

Ben: Alright, here's ejaculations that you can't use. You can't use ejaculations talking about god or Jesus or any reference to the existence of any organized religion whatsoever.

Jocelyn: Do…

Laughter

Charlie: Well, I mean, sorry go ahead…

Jocelyn: Beans and rice.

Charlie: I was…

Ben: I'm being silly, ah, I don't care, get back to work Jocelyn.

David: Right, no ejaculations of the cloth.

Laughter.

Ben: We have lots of material and we have covered everything on my list of things that are worth covering. Have you got any questions Charlie before we end the show?

Charlie: I've got 20 million questions but I am afraid that they would all…

Ben: You can ask a few of them.

David: No, absolutely.

Charlie: No, no I mean I, like they are not even, they're not even fully questions yet, like I feel like now I have this, you know, child like awe that might, that might crystallize into a question, you know in the coming days and weeks. But I, it's just neat, my daughter she is about to turn four in January and she is just learning about planets. And so she has been excitedly explaining to us about Venus and Jupiter. And this is like, you know this is the order of magnitude of things, you have to learn about, to go back to having that kind of feeling of just, kind of total wonder and partial understanding like, but it is a really neat.

Jocelyn: Yeah.

Ben: That is what our show is all about.

Jocelyn: Yeah, that's what's fun about science you can just be like a four-year-old forever, going what!?!

Charlie: Yeah.

David: That's actually why we do what we do.

Charlie: Ben, if your podcast it's about teaching me the glory of god's creation then you have done it.

Laughter and crazy sounds.

Charlie: Thank you guys so much, that's really...

David: You have gone and ejaculated again.

Laughter

Ben: Alright.

Laughter