Episode 62, "Black Bells"
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- Ben Tippett
- Brent Knopf
- Matt Sheehy
- Chiara Mingarelli
- Leo Stein

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

01:11

[Intro song; *Tell Balgeary, Balgury Is Dead* by Ted Leo and the Pharmacists]

01:46

Ben: Let's talk briefly about harmony. I'm no genius at it but here's the premise: you take a note, like C, and you play it on a piano. And then over top of it you play two other notes at the same time. One of them at E, which is 3 notes higher than the first note and then at G, which is 5 notes higher than the first note. You play them all together and you get a major chord. It sounds good, the three notes are in harmony, they sound good together. But why do they sound good together? Part of it has to do with the human brain, which decides which sounds are good and which sounds are bad but it also has to do with frequencies and periodicities. I don't know how much I really want to get into it but a tone is just a periodic pressure wave. And by periodic I mean the pattern of pressure waves repeats itself in time. The frequency of the wave is the number of times the pattern repeats itself every second. So each note has a particular frequency - A440, if you're a musician, is the musical note A and the 440 is the frequency. The pressure pattern of the sound wave repeats itself 440 times per second. Anyway, when you play more than one note at a time, you're hearing both patterns superimposed on each other. And if the frequencies of the two notes sync up regularly, they'll sound like they're in harmony. For instance, if two notes are a perfect fifth apart, say a C and a G, the frequency of the second note will be 3/2 times the first one. In other words in the time it takes the higher note to cycle through three times, the lower note will cycle through two times. So if you superimpose the two pressure waves, you get a new really interesting pressure wave that repeats itself every time the fundamental note cycles through twice. Our ears really like interesting but also repetitious waveforms. The chord I mentioned earlier with its three pitches in harmony also gives a periodic shape - it cycles through every time the foundation note repeats itself four times. So, there's and interesting correspondence between geometry and pitch. If you've had a vibrating string and you half its length, you get a new pitch which is an octave above the original one. So it'll be in harmony. And if you take that original vibrating string and you reduce its length to a third of the original length, you'll get a new pitch which is a musical octave plus a perfect fifth above the original note. So it will be in harmony, too. Pythagoras, the Greek mathematician and cultist recognized these relationships and thought they were really important. He proposed that harmony and geometry were the foundational principles of the Universe. He believed the Earth was at the center of the Universe and the Sun and the Moon and all the planets, like Jupiter, were in orbit around us at distances reflecting and generating some fundamental musical harmony. And he called it the music of the spheres. And he said that we couldn't hear it but that it affected every part of our lives and then stories say that he'd cure people's illnesses with music that were consistent with his model of the Universe. Well, he was wrong about it and the Universe as we understand it is a lot different and a lot more complicated than his Universe of simple harmonies. But that said, it captured people's imaginations. Now that we understand materials and wave propagation we understand very well that there is indeed a connection between the geometry of an object and the sound it'll make when you hit it. You take a little bell and hit it, it'll ring with a high frequency tone, you take a wide, deep bell and hit it, and it'll with a lower frequency tone. So, the thing we're going to talk about today is amazing and it would probably make Pythagoras proud. If you take a black hole and you hit it, it'll ring like a bell and radiate gravitational waves at a very specific frequency consistent with the size of the black hole. So today on the Titanium Physicists podcast, we're going to be talking about black hole perturbation and quasinormal ringing. Speaking of music, I'm reminded of my old friends, two fantastic musicians Matt Sheehy of Lost Lander and Brent Knopf of Ramona Falls. Since we last had them on as guests, Brent has formed a new project called EL VY with Matt Berninger and they put out an album called Return to the Moon. They were even on the Late Show with Stephen Colbert. And Matt, why, Lost Lander has recently put out a killer album called Medallion and it's amazing. Welcome to the Titanium Physicists podcast, my friends! How ya doin'?

Brent: Great. Thanks Ben, how are you?

Matt: Yeah, super good.

06:19

Ben: So, Matt and Brent for you today I've recruited two brand new Titanium Physicists to my team. Arise, Doctor Leo Stein!

Leo: Tu du du du du du du

Ben: Dr Leo did his PhD at MIT and he's currently a postdoc at Caltech where he studies Einstein's theory of general relativity and theoretical corrections to general relativity. Arise, Doctor Chiara Mingarelli!

Chiara: Raaawr!

Ben: Dr Chiara did her PhD at University Birmingham in the UK and she's currently a Marie Curie International Outgoing Fellow at Caltech where she studies gravitational waves. Alright everybody, let's talk about throwing things into a black hole and making them ring.

06:58

Brent: So, I'm/ how do gravitational waves work? I always thought the gravity was just like the curvation of like the fabric of the Universe. But there's actually waves that get like thrown around?

Ben: Good question! Let's talk about gravitational waves. So before then, let's confirm what you know about general relativity. It's Einstein's theory of gravity, right?

Brent: Mhm

Matt: Yeah.

Ben: Yeah, it's Einstein's theory of gravity and the nifty thing about Einstein's theory of gravity that demarcates its difference between it and the precursor Newtonian framework of gravity is that in Einstein's theory distance and time intervals are both dynamic quantities, okay? So, in short you have you and some car. In the Newtonian framework if the distance between you and some car is increasing, it's because either you're running one way or the car is driving the other way. But in Einstein's theory, if the distance between you and the car is increasing it might be that you're running away from the car, it might be that the car is driving away from you or it might be that the distance between you two is dynamic and is increasing. Does that make sense?

08:05

Brent: Mhm

Matt: Yeah.

Brent: For example with like inflation, like the inflating Universe?

Ben: Yeah, just right! The Universe is expanding because the distances between stuff is increasing. It's not that faraway galaxies are moving away from us, it's just that literally the distance between us is dynamically increasing.

Brent: So, is this why, like, girls that I date they always complain that I grow distant after little while? It's just the expansion of the Universe, baby.

Leo: That might have to do with your structure of matter. 'Cause Einstein's equations say that how much distances change are dictated by what matter is in spacetime.

Brent: Mmm

Chiara: It might be something else, to be totally fair.

Matt, Brent: [laugh]

Matt: Are those algorithms in the Tinder app?

Brent: [laughs]

Matt: Is that how that works?

Chiara: That might be your first mistake.

Matt: Yeah.

Brent: Mhm.

08:53

Ben: So, I'm sure that you've heard gravity, general relativity, described in terms of/ there's one fantastic demonstration on the Internet where they say gravity is caused by the curvature of spacetime and so they bring out a big rubber sheet and they put a big bowling ball on it and then they take other balls and they shoot them around and they go on little circles and stuff.

Brent: Yeah.

Ben: Have you ever wondered what the connection between my crazy "distance is dynamic" explanation is and the reason they're doing that with the sheet?

Brent: Yeah.

Ben: It has to do with the mathematics of curvature. So, if you wanna talk about distances being dynamic, the proper mathematical framework to do it in is to talk about it in terms of curvature. And if you're going to talk about a curvature, you have to explain how curvature manifests itself.

Leo: There's this good question of how do you know if you're living just on a flat surface or if you're living on a curved surface, right? Maybe many, many thousands of years ago, before the ancient astronomers, people thought that the Earth was flat. I mean, the Greeks of course knew that the Earth was curved eventually but you could actually measure it nearby, you can tell the difference between living on a flat surface and living on a curved surface. So one way to do it is if you make really, really accurate measures of the angles inside of triangles. So if you took a bunch of triangles, you made a triangle between here and where are you guys? You guys are in Portland?

Brent: Uh-huh.

Matt: Mhm.

10:26

Leo: If you made a triangle from here down in LA and then up to Portland and maybe over to DC and you measured the angles inside that triangle, then the angles would not add up to 180 degrees. In perfectly flat space, then they would add up to 180 degrees. But on the surface of the Earth if you take the straightest lines possible and make a triangle out of it, it's not gonna add up to 180 degrees. So, one way to tell that you're living in a curved space is to do the same thing except not on the surface of the Earth but in spacetime. So if we take lots of triangles arranged in all sorts of different directions and ask what are the angles inside of all those triangles then we would be able to tell if space was flat or curved.

Brent: Wow. Do you get to use lasers?

11:13

Leo: Yeah, we use lasers.

Chiara: Usually.

Leo: Lasers are photons that are moving in the straightest possible lines.

Ben: Another way to think about it/ Sometimes when I go a-travellin' I'll end up in a new city and I'll be like "I'm gonna go for a walk. I don't need a map, I can just count streets." You know, you go north 3 blocks and then you go west 3 blocks and then I'm like "Oh, time to go home. Maybe instead of going the way I came, I'll go south three blocks and east three blocks." Right?

Brent: Uh-huh

Matt: Mhm.

Ben: And arguably that path should close but if I have the misfortune of starting out on a street that's like on a hill, what'll happen is, you know, maybe I walk north three blocks and then west three blocks but uphill and then on the top of the hill my three blocks south and east, that square might not close. And the reason it might not close is because the distance I travelled on one of those legs, because I'm going uphill or downhill might not be the same distance as seen from above as I'm walking. And so because of the curvature of the city under my feet, that rectangle won't close. Does that make sense?

Matt: Absolutely, yeah.

Brent: Good example.

Matt: Horizontal distance versus vertical distance.

12:26

Ben: Yeah, yeah. Versus, like weird diagonal distance.

Matt: Mhm

Ben: Yeah, so the moral of the story is: this is how kind of curvature manifests itself. In things not closing, in straight lines not really being straight, seen from somewhere else, right? So in the example of the triangle inscribed on the Earth's surface and those angles adding up? You might look at it and say "locally it looks like these angles are all straight" but then you go up in the Space Shuttle and you look at this giant triangle you've inscribed and you'll say "Hey, those lines that I sketched, the reason they're not meeting up at, you know, 60 - 60 - 60 is because those lines are bowed because they follow the curvature of the Earth.

Brent: Right.

Matt: Wild.

Leo: So if you were trying to walk in the straightest possible line along the surface of the Earth, eventually you just get back to where you started which is impossible if you were doing that in totally flat space.

Chiara: Mhm. And the same is true for the orbits of the planets, right? So if we now think of General Relativity in that kind of framework like Ben was talking about earlier, this rubber sheet where the curvature of the rubber sheet gives you gravity, it's important to recall that the planets all think that they're travelling in straight lines but actually they're following the local curvature.

Leo: So they're trying to go as straight as they can but they end up basically back where they started.

Chiara: Mhm.

Matt: Is it true that to them they are going straight, essentially?

Chiara: Yeah. Absolutely. And it's the spacetime itself that's curved and that's moving and they're following a straight line but on a curved path.

13:56

Matt: So, those curved lines in space, are those observed only by watching heavenly bodies move around stars or are those curved lines/ are you able to see them like are they sort of invisible and you have some magic way of like looking at them that isn't by just looking up at the sky?

Leo: Here's one pretty direct way. And this was actually one of the first ways that General Relativity was tested. So, in 1918 was one of the first observational tests of General Relativity and that was looking at how light moves close to the Sun. So, if spacetime was totally flat, like in Newton's theory of gravity, then no matter what side of the Sun you were on, if you were looking at some distant stars, you would know where to expect them. They would be in a certain place in the sky. But when the Sun gets really close to the line of sight, then the curvature of spacetime that's generated by the presence of the Sun actually makes those straight lines that the light moves on slightly different than what you would expect in Newtonian gravity. So when you look at certain stars that are very close to the edge of the Sun during the solar eclipse, then they'll end up looking like they're in slightly different places than you would've expected in Newtonian gravity.

Brent: Is that called gravitational lensing?

Leo: Yes, this is exactly gravitational lensing.

15:17

Ben: So imagine that there was a constellation, say, right on the equatorial plane or something called I don't know, Aristophanes the Square. So it's just a nice square shape, right? Right angles, looks nice. At some part of the year, 'cause we go around the Sun, the Sun's gonna be between us and, you know, the Aristophanes Square. Usually you can't see what this square shape constellation looks like because the Sun's in the way. But if there's a solar ellipse, if the Moon comes and blocks out the Sun, suddenly it's not so bright that we can't see the stars behind the Sun and you can tell "hey, look, that square arrangement of stars coming towards us is getting skewed and it won't look like a square anymore". It'll look like, I don't know. I'll look like some kind of weird other shape.

Leo: Yeah, it'll just kind of squish it over in one direction.

Chiara: That's right.

Ben: Yeah, it won't be a recognizable nice little square anymore.

Chiara: And this is true for anything that has mass, right? It doesn't have to be the Sun, it could just be any really dense object that has a lot of mass. It'll curve spacetime around it. And the more massive the object, the more curved spacetime.

Brent: Isn't there like a famous galaxy that gets gravitationally lensed around something that looks/ it looks like this weird kind of warped like Salvador Dali melted spoon or something like that? I'm trying to remember it.

Chiara, Leo: [laugh]

16:26

Leo: Yeah.

Chiara: Well, there's definitely some famous lensing effects. So there's sometimes one of the lensing effects is to create arcs and so sometimes you'll see the pattern reverse itself on the other side, sometimes we see multiple images.

Leo: If we get a perfect alignment then you can get something called an Einstein ring where something that's directly behind the lens gets smeared out into a circle that surrounds the lens.

Brent: Is spacetime kind of curved for all other objects regardless of their mass? For example like if I was on/

Chiara: That's right.

Brent: /the planet Mercury on the equator at like dawn or whatever and I pointed a laser basically right along Mercury's straight line path would the light of that laser curve all way around the Sun in an ellipse and hit the back of Mercury the planet? Or is the laser light like not affected in the same way that the mass of Mercury is.

Leo: That's a great question. So both Mercury's path and the path of the laser are both affected by the fact that spacetime is curved. But they're affected in slightly different ways because light always has to move at the same speed so its path doesn't get bent as much as the path of Mercury gets bent when it's trying to go on a straight line. But there is a limit where what you said is true. So if we could take the Sun and squeeze it down then you could get laser light going closer to the surface of the Sun. So I take the same amount of mass and squeeze it into a smaller space. Then the light will get deflected even more. So you can imagine where this goes. So, if you keep squeezing and keep squeezing it and then again shoot a laser just kind of to skim its surface then it's gonna get deflected more and more and more and more. At some point you'll squeeze the Sun down enough that if you shot a laser so that it skimmed right along its surface, it would just keep going in a circle and light would be in orbit around something in the middle. And we call that a photon ring when light can orbit a central body.

18:25

Brent: Wow. So in other words if the laser that I shot off Mercury was a special laser and the light wasn't going at the normal speed of light, was somehow slowed down and be the same speed as Mercury then the light would curve around. So it basically has to do with like proximity and the speed of light in that relationship, is that what you're saying?

Ben: There's kind of two different types of matter in the Universe. There's stuff with mass and stuff without mass. And they both respond in their own way to the curvature. Their paths both get skewed by the Sun's gravity but they both respond to that curvature in slightly different ways. Any massive object/ if you ask Superman to take Mars and replace it with the baseball travelling at the same speed and the same position, that baseball would travel in exactly Mars' orbit. It would follow exactly the same path because spacetime for it is bent in exactly the same way. Light does something slightly different. But light still feels the curvature of spacetime. So you can make light go into orbit but the types of orbits the light goes into, it requires a lot stronger gravity, a lot more curvature than regular heavy matter.

19:31

Chiara: So we could never be in the photon sphere orbit. Like, that's not an orbit that we could exist in. But if we could, you'd be able to look out and see the back of your head. 'Cause you'd see the light coming back on itself.

Matt: Can we ask why does light behave differently than something with mass? Why does it respond differently to the curvature?

Leo: It's not specific to light. It's actually anything that moves at the fastest possible speed. And the fastest possible speed people like to say that it's the speed of light but actually it's the speed of gravity. Gravity is the thing that's dictating what the maximum speed limit is. And light moves at the fastest speed possible and neutrinos almost move at the fastest speed possible but it turns out that they have a tiny, tiny bit of mass.

Brent: Hm. Awesome. Okay, so can we just talk about gravitational waves? Like, when I think of a wave, I think it takes time to reach somewhere. Does that mean like if the Sun suddenly doubled in its mass that we wouldn't feel that for like 8 or 9 minutes because of the distance it would take for that gravitational wave to reach Earth or is that instantaneous?

Chiara: Gravity also travels at the speed of light. It's/ everything is constrained by/ Leo calls it the speed of gravity but we'll just say this time that it's the speed of light, 'cause that's a bit easier to wrap your head around. And so gravitational waves are ripples travelling in the fabric of spacetime. So, anything that has an accelerating mass will create a gravitational wave. So, Leo and I could get up and start doing a dance, make him swinging around and spinning around, 'cause I'm super strong and that accelerating mass would create gravitational waves. Now, obviously the more mass you have, the more you can perturb the spacetime around you. And the more these ripples of spacetime can travel out and reach further distances. And so the objects which create the biggest - for lack of the better word 'cause they're very small - gravitational waves are things that are very compact and very massive. Like black holes and neutron stars. So, when those are orbiting each other or even merging, these create ripples in the fabric of spacetime. Because now you have these accelerating masses. And those travel in all directions at the speed of light. That's what a gravitational wave is.

21:47

Brent: Wow

Matt: Hm.

Chiara: So again if you take Ben's rubber sheet analogy, if you were to take one of the planets on your rubber sheet and you were to bob it up and down, right, or move it around, it would create little ripples on the fabric of the sheet. And that's similar to what a gravitational wave is.

Brent: Got it. So when I think any type of wave, I think about a crest and a trough, right? So like there's like a compression and rarefaction or whatever. So like, at what frequency are these gravitational waves travelling through the Universe?

Chiara: That's a great question.

Brent: And does that mean that for that moment like the distances get like longer and shorter, they kind of stretch and they come back like a slinky?

Leo: Yesss!

Chiara: They do! They do, they stretch and squash. But in a slightly different way. But yeah, that's very good intuition. Leo and I are very excited, we're like jumping out of our chairs, being like "Yes, yes! That's right!" So, gravitational waves travelling at the speed of light from these compact objects, they have two polarizations. So one is called plus and one is called cross. And all that means is that if you had a gravitational wave travelling through your chest coming out of your chest, that you would be first stretched from your head to your toes so you'd look like a supermodel and then you'd be squashed and so you'd look you know, really small. And then you'd be stretched out the other way so you'd look like a sumo wrestler and then again you would be squashed. And so this stretching and squashing of the fabric of spacetime is how gravitational waves travel and this does change the distance between objects. And so harkening back to what Ben said at the beginning of the podcast about spacetime and distances being dynamic, this is exactly one of those consequences. The fact that spacetime itself can move and so Leo and I right now sitting next to each other could get a little further away and then a little closer and that would be a gravitational effect. So, we're just minding our own business but spacetime itself can move and separate us and then bring us back again.

Brent: Wow

23:48

Matt: Well, that explains a lot of relationship problems I had

Brent, Chiara: [laugh]

Chiara: Okay. So the other point that you touched on that was very important is the frequency of the gravitational waves. So there's gravitational wave frequencies cover the entire spectrum. They can be low frequency, like the gravitational waves that I study which are in the nanohertz regime and these come from for example supermassive black hole binaries and they can also be tens of hertz or even kilohertz which would be audible if these were actually sound waves. So, collaborations like the LIGO scientific collaboration look for tens of hertz to kilohertz gravitational waves whereas different experiments like NANOGrav, the one that I participate in, looks for gravitational waves which are around 1 to a hundred nanohertz. And so gravitational waves at these different frequencies come from different sources. And this is one way that we can explore the Universe, by looking at the gravitational waves from all these different sources.

Brent: And nanohertz is like a million hertz or a millionth of a hertz?

Chiara: A billionth.

Brent: A billionth. Thank you.

Chiara: Billionth, yeah.

Brent: A billionth of a hertz. So like in one billion seconds you get one wave. Is that kind of the idea?

Leo: Yeah.

Chiara: Yeah.

Brent: Okay.

Chiara: Which is like... ten years?

Leo: Yeah.

Chiara: [laughs]

25:05

Ben: Chiara, what is like the energy density of gravitational waves going through us right now?

Chiara: Not very much, actually. What we do when we measure things like a gravitational wave background from the cosmic population of merging supermassive black holes we come up with a number which is a gravitational wave energy density. And this is a really small number. This is like 10^{-10} which is/

Matt: And the source of that energy is like say if you're emitting gravitational waves because you're jetting through the Universe does that mean that some of the energy that you're putting into propelling yourself forward is being converted into gravitational waves and so you're actually losing a little bit of energy because of it? Is that how it works?

Chiara: Pretty much. You guys have a really good intuition. This is really impressive. So, this is how supermassive black holes for example finally merge. So when galaxies merge, their central supermassive black holes merge that only because for their last merger phase when they're orbiting each other, they're accelerating and emitting these gravitational waves and therefore they're losing energy, 'cause you're right - they have to lose energy because they're emitting gravitational waves. And so the closer they get, the more gravitational radiation - we also call it instead of always saying gravitational waves sometimes we call it gravitational radiation - is emitted from the system until they eventually merge and that's how their orbits shrink and they merge.

Brent: Ooh.

Chiara: So definitely you don't get gravitational waves for free.

26:33

Matt: Do photons emit gravitational waves? Or only things with mass?

Leo: I was trying to think about it. But if you could arrange a bunch of photons in a right way, then there would in principle be gravitational waves.

Chiara: How, tell me how.

Ben: Yeah, yeah. Individual photons wouldn't, 'cause their velocity is constant, they're not accelerating. But arrangements of photons will. So you can actually make an arrangement of photons that will make a black hole, right?

Leo: Yeah.

Ben: You just take a lot and lot of photons and aim them all at one point.

Leo: Yeah. Then if the energy density was high enough then it would collapse into a black hole.

Ben: And so you can make the energy density high enough to create two black holes that are really close together and they'll now merge and generate lots of gravitational waves, so yeah.

Leo: That's kind of a cheat.

Ben: Entirely possible.

Chiara: [laughs]

Leo: But even without making/

Ben: It's totally a cheat!

Leo: Without making black holes, if you get enough energy, it doesn't matter what the type of energy is, if you get enough energy together then it pushes on spacetime. In fact any amount of energy pushes on spacetime and makes a curve. So the trick is just to get the right pattern of energy. So for example if you have something that's perfectly spherically symmetric, you know, let's say that we only had a planet and it was a perfect sphere. And then everybody on that planet stood in a perfectly symmetrical arrangement around the outside of the planet and they said "we're all gonna jump at the same time". If everybody just jumped so everything was perfectly symmetrical arrangement then there's no gravitational radiation. But if arrange it so that everybody at the north and south poles jumps at once and then a second later everybody around the equator jumps at the same time, then that does make a gravitational wave. So it depends on how the matter is arranged.

Matt: Wild.

28:13

Chiara: [laughs] I think that's a kind of pathological case. In nature, that's probably not what happens. But you're both right that that it could in principle happen. It's a nice thought experiment.

Brent: Just so we can get a sense for how much these things can affect us. Like the one wave that we are really afraid of in the northwest is, you know subduction zone off the coast of Oregon and Washington. When it slips it'll you know send a tsunami coasting in. So is there anything equivalent you know, to like a gravitational wave tsunami that would like destroy us all?

Chiara: So, you can get different kinds of gravitational waves. So what we've been describing so far have been kind of continuous gravitational wave sources where you have the signal getting bigger and bigger and it's really well described but you could also have bursts of gravitational radiation. But it would be really difficult to imagine gravitational waves destroying the Earth.

Leo: So let's just say that as far as astrophysics is concerned, like the real Universe, you don't really have to worry a lot because gravitational waves come from really far away, gravity is super weak. But if you wanna talk about theory...

Chiara, Brent: [laugh]

Leo: Just in the theory of GR then yeah, you can have gravitational shockwaves. Just like you can have shockwaves in sounds. You can have the pressures getting so high that you make a shockwave you can have a gravitational shockwave.

29:35

Brent: Okay, so in the intro you described like ringing black holes or some sort of quasinormal something? What does quasinormal mean and how do you ring a black hole and like does the black hole have a certain frequency at which it's like fluctuating the gravity?

Leo: Okay, before we talk about quasinormal modes, maybe we should just talk about normal modes.

Chiara: Let's do it.

Ben: Yeah.

Leo: Okay, so one thing that my physics classes taught me was try to simplify problems as much as possible. So physicists I guess always try to simplify all their problems. That's why you've heard of like the spherical cow. So one way of simplifying a problem is to imagine that the energy never leaves the system. So imagine that you've got like a swing set and you're sitting on a swing. If somebody pushes you, you're just gonna keep swinging forever. At the same frequency. However high you started swinging, you're always gonna swing that same height. That's called a normal mode. If you really just have the exact same pattern happening forever.

30:35

Brent: Okay.

Ben: Imagine you have an acoustic guitar. You have an acoustic guitar and you pluck the E string

[E string being plucked]

Brent: That's an E, I think. [laughs]

Ben: Okay, so you pluck a string and it gets quieter, right? Over time. But imagine that you're in deep space. Deep, deep space, there's no gas around you and you pluck the string of your guitar. It'll just keep vibrating, right?

Leo: The energy doesn't have anywhere to go.

Ben: The reason the thing gets quieter is, you've essentially started your guitar vibrating and as it vibrates, it pushes and pulls on the air around it, generating sound waves, pressure waves. And so it dissipates the vibrations inside of it into sound waves, right? And then that's why it gets quieter. And that's the distinction between normal modes and quasinormal modes. Quasinormal modes are modes that decay. But before then we need to talk about modes because that is a very specific thing. If you pluck your guitar string, you're always gonna get the same sound out of it, right?

31:35

Brent: Yeah, depending on how and where you pluck it but yeah, if you pluck it, yeah, in the same place with the same strength, it should be about the same, yeah.

Ben: Fantastic. So that said, the tone you get out of it depends on essentially where you're clamping down on the guitar string, which fret you're pressing because that essentially shortens the string, right? You're essentially defining the wavelength that it's gonna vibrate at.

[Guitar being plucked and tuned]

Ben: But here's the thing, you know what timbre is, right? You've heard the word timbre?

Brent: It's the way something sounds, it's like if its/ the quality of it.

Ben: Yeah, it's the quality of the tone. So the base frequency is the same but when you excite a guitar or a trumpet or a human voice or a saxophone or anything, you end up generating not just the base frequency. And the base frequency is essentially the wavelength of the guitar string. You also generate excitations in the guitar string that are higher frequency. For a guitar string there's a set of different wavelengths that you could generate, all of them fractional lengths of the guitar string, right? If you have one guitar string, you can excite a note whose wavelength is the guitar string or you can excite a note whose wavelength is half the guitar string and you'll get one up and one down on a vibrating string. Or three times the guitar string and then you get three humps on the guitar string et cetera. So, the timbre is how many of those other modes you excite. Because essentially the sound that's coming out of the guitar will be some combination of all of those modes superimposed. Does that kind of make sense?

33:11

Brent: I think so. But real quick, Ben, describing this are you just talking about the different relationships of like the harmonic frequencies above the fundamental? Is that what you're saying?

Ben: Yeah. That's exactly what I'm saying.

Brent: Okay. 'Cause I mean, I'm holding a guitar right now and I can't think of it, like if people don't know what harmonics are like, I could play one right now and like uhm/

Ben: Sure.

Brent: So like if this is the fundamental, an E [plays E]. Then if I rest a finger half way down it, I'll get the next harmonic [plays E octave higher] which is twice the frequency of the fundamental and then if I put my finger like one third way down the string without pressing against fretboard, we're just kind of muting out the other harmonics [plays B], I'll get the third harmonic which is that gone up perfect fifth and then so forth and so forth. In pop music there's a song by Smashing Pumpkins called Zero and you can really hear the harmonics in it 'cause it goes [too - too - too] [plays the notes on the guitar] so it goes [plays intro to Zero]. I don't know if you can hear that but/

Leo: I'm gonna have to listen to Smashing Pumpkins today.

Brent: Yeah.

Chiara: Have you not listened to them recently? I listened to them just the other day. Sorry, I think we may not be from the same generation.

Matt, Brent, Leo: [laugh]

34:20

Brent: So anyway, they're used musically in music all the time. So Ben, what you're saying is like. My understanding of like the way the guitar string when you pluck it way it differs from like a sine wave or a tuning fork is that like the sine wave or tuning fork has just the fundamental vibration, I think. But a guitar string when you pluck it you're not only vibrating the fundamental like vibration. It's also vibrating in kind of a series of different ways, an integer dividers of the length of a string. So like there's a vibration that's like twice the frequency and three times the frequency and four times the frequency. Yeah, those are the harmonics. And then together, all those things together added up is the sound of the guitar string. [Plucks a string]

Ben: Yeah, that's right.

Brent: Yeah.

Ben: So you listen to like old Atari games and sometimes the sound that they make will just be pure sine waves, only one frequency. And it's jarring to listen to. It has just no warmth to it at all. It's that cracking sound. Anyway, moral of the story is yeah, nice warm sounds they're a superposition of all these different harmonics. And the quality of your instrument and the type of instrument you play will determine how many harmonics get excited and the timbre of each note.

Brent: Yeah, totally.

35:31

Ben: Okay, so here's the thing. Let's talk about hitting a cymbal instead. 'Cause cymbals have this great development. You take a cymbal and hit it with something - the first sound is really jarring because there's lots of different weird harmonics that are exciting. It's a little bit more complicated than a guitar string because they're spatial harmonics instead of along a single string. So there's all sorts of different ways standing waves can form over the cymbal. And so a bunch of these will be excited and the sound at first will be jarring but the higher frequency harmonics end up shedding their energy to the surrounding air a lot faster than the lower frequency harmonics. And so you hit a cymbal and it starts off going crash and then eventually they'll just kind of sing a single note, right?

Brent: Let's see... [pshhh] Yeah it sounds like a splash.

Matt: Yeah. It sort of hums after that for a little while.

Brent: Yeah, you're right, yeah.

Ben: So that's called quasinormal ringing. Because essentially there's all these different modes, they get excited when you hit it and then each of those modes decays in time at a different rate until all that's left is the first few fundamental frequencies. And then you end up hearing a really pure note.

Brent: Okay.

Leo: So physicists have some nomenclature we have for the different behavior that these quasinormal modes have. So one of the words that we use is what's the quality or the quality factor of a mode itself. And that basically tells you how many oscillations you'll get before that frequency has either divided by 2 in loudness or usually we like to talk about a factor of *e*. Because of *e*, we love the number *e* a lot more than everybody else.

37:12

Chiara: It's actually my birthday, if you look at the first few digits. Just saying I was born at *e* day.

Leo, Matt, Brent: [laugh]

Chiara: *e* to the power of 1, sorry, I didn't mean to distract you. I just really, I really love *e*. As in Euler's number. [laughs]

Leo: Anyway, so if you hear somebody talk about the quality factor or a quality of some mode then they're saying kind of how long it rings before it's gotten quieter by a factor of 2.

Brent: Is it like radioactive like half-life? It's like how long it takes before half of it goes away or whatever?

Leo: Yeah.

Brent: It's like some sort of decay, it's like the speed of decay.

Leo: That's right. Both of them are exponential decay.

Chiara: Mhm.

Brent: Aaah.

Matt: Hm.

Leo: So if you have like a really high quality glass then you know, you can like run your finger along it then that is tactically very high quality.

Brent: So is something with a high quality that means it decays slower or that means it decays faster?

Leo: It decays slower. It takes longer, so you'll have more oscillations before it gets quieter.

Brent: Cool. So in other words something that/ with a not quasinormal but a normal that would mean like everything is perfect quality, like there's no decay?

Leo: Yeah. It has an infinite quality factor.

38:21

Brent: Cool. So if normal is like you push someone on a swing set and they keep swinging forever based on that one push, that's not actually normal in terms of our normal, everyday lives. In other words, like/

Leo: [laughs]

Brent: Because when I strike a guitar string it decays, it gets quieter. That's a quasinormal behavior but it's normal to me 'cause I'm used to it but it's quasinormal in terms of like physics terminology. Is that kind of what you're saying?

Leo: Yeah, the word normal is one of the most overloaded words in all of physics and math jargon.

Chiara: Preach.

Leo: It's like a million different things.

Matt: Mhm

Brent: [laughs] Got it.

Ben: Yeah, so you can run quasinormal mode evolution backwards. Like you know the old thing with the wine glass, right? Where you take a really high quality crystal wine glass and you ping it and it'll sing a note.

Brent: Mhm.

39:05

Ben: If you sing that note back at it you'll end up exciting the mode and if it's really high quality it won't shed the energy as fast as you're putting energy into it and eventually it'll shake itself to pieces.

Mett: You mean like when the opera singer hits the high note at the end and all the glasses break?

Ben: Yeah.

Brent: Yeah.

Ben: Just so.

Brent: I mean that's resonance, right? I mean that's the same way that you know, the bridges fall apart when the wind strikes them at just the right you know way

Ben: Yeah.

Brent: Stuff like that. So it's, yeah, when something's resonating too much it can actually tear it apart.

Ben: That's right. So the resonance frequencies are the frequencies of the normal modes.

Brent: Okay.

Ben: Or I guess quasinormal modes.

Brent: Mhm.

Ben: So it's quasinormal modes because geometrically it's a normal mode but as it evolves in time it sheds energy.

Matt: Wow.

Brent: Cool. Cool. Okay so are these objects in the Universe are they emitting gravitational waves with them like those waves have lower quality and they decay, is that what's going on?

40:00

Ben: You're gonna start asking about black hole ringing, right?

Matt: Yeah.

Brent: Mhm.

Ben: Yeah, okay. Well, let's start talking about black hole ringing.

Chiara: So just briefly before Leo takes over with ringing black holes. So the black holes can merge by emitting gravitational waves. But then the ringing is what happens after the merger, right? And so this also emits gravitational waves but it's a slightly different concept, right? So whereas before we were talking about two massive bodies merging. You know, black holes, black holes and stars, neutron stars, even neutron stars with neutron stars. All these things can create these really nice way that these merge but the ringing effect in the gravitation of these events is conceptually different. So, Leo can explain that.

Leo: If you guys have any questions about what Chiara just said.

Brent: I feel bad I didn't/ I don't think I follow that one so well.

Matt: Yeah, that was a lot of information.

Chiara: Well yeah. So what I mean is when we're talking about gravitational waves from the beginning of the podcast until now we were talking about the gravitational waves from the merger of black holes. And they're doing this by orbiting each other and emitting gravitational waves. And as in the gravitational waves these carry away energy and so this black hole pair shrinks and shrinks and shrinks until it eventually merges.

Brent: And then when they merge that makes a different type of sound, is that what you were saying?

41:16

Leo: Yeah, there's gonna be a certain gravitational wave form at the end. So if you took two black holes and threw them together at each other. Then if you got them to merge then they would just make a bigger black hole. It would have you know maybe a different mass, different spin. But they'd make a big black hole. So actually the problem of predicting the gravitational waves that come out of two black holes going around each other - that's actually a pretty hard problem. So, like I said physicists try to make their problems as easy as possible so a much simpler problem is just to ask what happens if you just had one black hole that was just sitting there by itself and you just kind of pinged it or just plucked it. So that's kind of more like a guitar string and you just hit it a little bit. So,

Chiara: Then that begs the question what do you hit it with, right?

Matt: Right. You wanna hit it because you wanna create a little acceleration in it?

Leo: Yeah. You make a little bit of energy flowing through the spacetime and that's gonna excite it or perturb it a little bit. And then that whole configuration is gonna ring just like you know you push the swing set a little bit or you pluck the guitar string a little bit.

Brent: Aaah.

42:25

Ben: So first of. They drew a distinction here. They're saying "okay, most of the time when we talk about listening for gravitational waves the source of gravitational waves that we're listening to with like the LIGO facility the source is rotating binary." So, two black holes circling each other and slowly shedding energy in gravitational waves. If you do that, the frequency of the system, the frequency of the gravitational wave will match the rotational frequency of the system, right?

Leo: It will be twice.

Chiara: Factor of two.

Ben: Yeah.

Chiara: [laughs]

Ben: But essentially you've got heavy things spinning around in a circle pushing against the spacetime. And so the rate at which they're moving in a circle is going to determine the rate at which the waves are generated, the frequency. There's another type of gravitational wave source that comes from taking a black hole and pinging it. And what we mean by that. Okay, so like a cymbal or a guitar string, they want to be kind of still and in one shape. And the way you make a cymbal ring is you essentially perturb the shape of the system. So you essentially take a hammer and you ping the shape so that it's curved a little bit and then that curve turns into waves over the surfaces and excites all these other waves that get shedded. Okay? Black holes mostly wanna be spherically symmetric, they wanna be kind of round shaped. The geometry around them wants to be round. And part of the reason for that is because black holes, there's no matter to them, right? Black holes are the gravitational footprint of the star. You know how black holes are often made by stellar cores collapsing after and during a supernova? That leaves behind like a gravitational shoreline, a gravitational footprint. And the thing about it is that you know whatever shape the material is inside the black hole, none of that information about what shape it is, you know, the big clump of whatever matter collapsing down, maybe it's peanut shaped, that information can't escape to the lips of the black hole, to tell the rest of the Universe "hey, I'm peanut shaped". So the horizon of the black hole will want to be round. Nice, round spherical shape. So what happens is, that's an argument about the geometry of the system. And that geometry is determined by the distribution of matter in the system. So if I have a black hole, nice spherical geometry and I take a bowling ball - maybe a really heavy bowling ball, right? - and I throw it in to the black hole, that bowling ball causes curvature in the spacetime and suddenly our system isn't spherically symmetric anymore, 'cause there's the big curvature where the black hole is and there's the little curvature where the bowling ball is. And so when those two curvatures merge, they aren't merging in a spherically symmetric way. There's kind of weird brief peanut shape to it. The system wants to evolve back into being round and spherical. And so the whole thing is going to shed geometry by shedding/ by ringing gravitational waves. And the frequency that it rings is determined by the mass of the black hole. And not, say, the frequency that it's orbiting or anything. Does that, is that too much?

Brent: Yeah.

45:29

Matt: No, totally, that's really fascinating.

Brent: So in other words, like a giant bell, you know, if you ping that, it's gonna sound different than a tiny little bell, well. So in other words you're saying like that size or shape of the black hole when it's pinged is gonna reveal itself.

Leo: Yeah, and the exact gravitational waves that you get out of pinging it can tell you about how massive it is and how quickly it's spinning.

Brent: Ah.

Matt: So how are you guys pinging these black holes that are super, super far away? Like are you guys doing computer models?

Leo: I wish we could.

Matt: Are you guys flying spaceships into them?

Leo: I wish.

Chiara: All the time. That's how we spend taxpayers' dollars.

Leo: Honestly, we have to rely on nature being kind to us and we hope that the nature will ping some black holes out there and that we're listening when that happens. But we can do it on paper, we can do it in the computer and simulate what it'll look like or what it'll sound like. So we understand the properties that the ringing will have.

46:31

Chiara: So I think what's important here with what Leo's saying is that what we'll see on the Earth are the gravitational waves. And if those come from a system which has been pinged or if they come from a system which is *en route* to coalescence, so Ben drew this nice distinction earlier between these two sources, say, of gravitational waves even though the two cannot be simply linked we detect these signatures, these gravitational waves here on Earth and then from these signature what we see we can infer the properties of the source. And so that's how we hope to detect this.

Matt: So by detecting the gravitational waves, I'm imagining you guys knowing that there's a black hole somewhere and noticing that there's a big object that's about to fly into it or something and then you like watch how the stars jiggle around or something like how the path of the light of nearby stars or something gets affected by that, is that what you mean?

Chiara: Not quite. So usually/

Leo: But it's conceptually similar. I mean, we try to set up a local experiment that's kind of like measuring how things jiggle around. So we don't have to rely on stars to measure the jiggling. We use lasers and optics.

47:36

Chiara: But what I was gonna say is that we're not actually looking for candidate sources actively and then saying "oh, that's merging, so we're gonna go look for the gravitational wave signature".

Leo: Right.

Chiara: That would be awesome if we could do that. But actually for most gravitational signatures that are in the LIGO band the signal doesn't last for maybe more than a few seconds.

Leo: A few minutes.

Chiara: Yeah, minutes at most, right? So it's difficult in that amount of time to take these big telescopes and to point them somewhere although this is a project that's being actively worked on.

Leo: We're just waiting for bumps in the night.

Chiara: Exactly.

Leo: It's just always on, always listening.

Chiara: [laughs] So creepy!

Matt: Wow.

Leo: [laughs]

Chiara: But yeah, LIGO's looking for bumps in the night, I guess. You could say that.

Leo: One of the cool things about a black hole's quasinormal modes is that just like a guitar string has all those different harmonics, a black hole has a bunch of different harmonics, too. But there are only two numbers that describe astrophysical black holes. Just the total mass and how quickly it's spinning. So all of the different quasinormal mode frequencies are determined by just two numbers. So that means, if you could measure two of the quasinormal mode frequencies and how fast they decay, then you would know the mass and the spin. And if you could measure more than just two of them then you would be able to test if they were all consistent with our predictions.

Brent: Uh-huh.

Leo: General relativity makes a specific prediction about the timbre of a black hole and maybe nature is slightly different. That's an important thing to test. We wanna know if black holes are really described as they are in general relativity.

49:16

Brent: Right. So far is the data backing up the theory? Are you hearing black holes?

Matt: Can you give us a spoiler?

Brent: Does that sound like Nickelback?

Chiara: There's been rumors on Twitter, right? - It does not sound like Nickelback - Canada apologizes for Nickelback.

Brent: We have Arcade Fire to redeem everybody.

Ben, Leo: [laugh]

Chiara: So the direct detection of gravitational waves will possibly be revolutionary. This is just like when people first started looking at the radio Universe. So looking at the Universe at radio wavelengths. This was completely revolutionary, and we found things that we weren't even looking for. We found weird and wonderful things like pulsars. So, when we do start seeing gravitational waves, not only do we hope to see things that we expect but also maybe things that we never even dreamed of. So this'll be a really important discovery when it happens and so whenever that announcement is made, I'm sure that they're gonna be very sure of their detection.

Leo: Yeah, there was some interesting sociology in this field from back in the day. So before the instruments were nearly as good as they are today, people were making detectors by just trying to have resonance. If you had a bar that had a resonant frequency and there were gravitational waves going through that bar at the same frequency then the gravitational waves would excite the modes of that bar at that resonance frequency. That was the early technology for gravitational wave detection. And people made claims of gravitational wave detection decades ago but they just weren't corroborated. There are a lot of people in the field of gravitational wave detection who were around when that happened and they're very, very careful now to make sure that there isn't a stain on the field by having spurious detections.

Chiara: Mhm.

51:00

Matt: So it's bad that I just tweeted that you guys told us that they totally exist?

Leo: Oh, they exist.

Chiara: Finished.

Leo: They exist for sure because we've seen lots of indirect evidence of gravitational waves.

Chiara: Absolutely.

Leo: But we haven't yet had official, definitive direct detection of gravitational waves.

Chiara: So what Leo's talking about is something called the Hulse-Taylor binary pulsar. What happened is that we found a pulsar in orbit around a neutron star. And a pulsar emits radio waves. So we can time the radio waves that are coming from this pulsar. Now by doing that we can observe how the orbit of this binary shrinks and the scientists who did this found that it shrinks in exactly the same way the general relativity would predict it to shrink if the system were emitting gravitational waves.

Leo: To within something like a tenth of a percent.

51:54

Chiara: And so this won the 1993 Nobel Prize. So we already know that gravitational waves exist. And so now what we're looking for is the actual signature. So we're not looking for a secondary effect like a neutron star and a pulsar slowly merging, we're looking for the real smoking gun. And that's what's really difficult.

Ben: Garbage can is always knocked over in the morning so we know that raccoons exist but we still wanna take a photograph of them.

Chiara: Exactly or you see like a footprint of a moose in the snow and you're pretty sure that it's a moose and it smells bad and there's some fur/

Leo: This is how I know that you're Canadian. [laughs]

Chiara: Ohh yeah.

Matt: Yeah [laughs]

Chiara: There's footprints in the snow and it smells bad and you can hear a weird dying cow noise and you're like "Oh my gosh, I've done everything except for see the moose. But you know that it's a moose.

Leo: It could be a giant cosmic conspiracy but that's/

Chiara: Unlikely.

Leo: Yeah.

Ben: That would be interesting, too. That your neighbors were fabricating the existence of mooses.

Chiara: Is this ancient aliens or... [laughs]

Ben: This would prove that ancient aliens. So that would be neat, if we were wrong. But we're not wrong.

52:58

Leo: You're gonna edit this out, right?

Chiara: We do not in any way endorse ancient aliens.

Brent: Yeah.

Matt: So I just tweeted that you told us that ancient aliens exist.

Brent, Leo: [laugh]

Matt: I hope that's not gonna screw anything up.

Brent: So, LIGO, that's an acronym, right? For Large Interstellar Gigantic Oscillator? Like, what does it stand for?

Leo: Close, pretty close.

Chiara: It's the Laser Interferometer Gravitational-Wave Observatory.

Matt: Next time you guys name really awesome instrument like that you should totally call us up. We're really you know super into naming bands and songs and/ I bet we can come up with something. Don't get me wrong/

Chiara: What are you trying to say? Are you trying to say we didn't get it right?

Matt: I just feel it should be like/

Brent: Like Ziggy Stardust.

Matt: Yeah, yeah. That's a good one.

53:45

Ben: What's that an acronym for?

Matt, Brent: [laugh]

Chiara: Well, there's been this new culture recently, it's backronyms, right? Of like thinking of a cool name and then just really trying to massage the name of your experiment into that. Some people feel very strongly that we shouldn't do that.

Ben: Well, that was interesting. Thank you Chiara, thank you Leo. You've pleased me, your efforts have borne fruit and that fruit is sweet. Here's some fruit. Chiara, you get a calabash melon.

Chiara: Yaaaay! Om om om om om.

Ben: Good, and Leo you get a coconut!

Leo: I am going to stick a straw in it and [slurps].

Ben: Okay, fine, fine.

Chiara: Good call. Good call.

Ben: I'd like to thank my guests, Matt Sheehy of Lost Lander and Brent Knopf of Ramona Falls and EL VY. I hope you guys had fun. Pleas look up their albums and stuff on the Internet. I will of course link to all their stuff on our website.

54:38

Ben: Hey wow, that was fun. Okay so hi everybody, it's time for the after show thing. And don't forget to listen after the song for more fascinating conversation. We talked quite a bit on this episode so it's a bunch of disconnected questions and answers afterwards. Okay, anyway. This episode was so much fun, I'm really proud of it. Now, lots of good news. So, first off, announcement time. Please give us an iTunes review or tell other people about us online. Why? Because people like to keep their love of physics secret until somebody else tells them that they like physics and then they get really, really happy. But they don't usually tell people that they like physics because nobody wants to be the person at the party who thinks about black holes. Anyway, so if you tell them, they'll be happy. And they'll find the show and they'll listen to us. And maybe they'll enjoy us. So, moral of the story is please get the word out anyway you like and the easiest way is the iTunes review. On another note we're still humbly soliciting your donations. Your donations go to pay our server fees and also our ambitious project to get all of the episodes transcribed. You can send one-time donations through the PayPal link off of our website or you can go to our sweet Patreon site and give, you know, recurring two dollar donation or whatever you feel. This particular episode of the Titanium Physicists podcast has been sponsored by a collection of very generous people. First off I'd like to thank the generosity of Mr. Josh S and Mr. Johnatan S for their donation. Thank you, you guys. I'd also like to thank a collection of wonderful people. First off Shlomo Dlal, Melissa Burk, Yaseen Owarzazee, Spider Rougue, Insanity Orbits, Robin Johnson, madam Sandra Johnson, Mr. Jacob Wick, Mr. John Keese, a Mr. Victor C., Ryan Close, Peter Clipsham, Mr. Robert Halpen, Elizabetha Theresa and Paul Carr. A Mr. Ryan Noule, Mr. Adam K, Thomas Shayray and Mr. Jacob S. A gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, Mr. James Clawson, Mr. Devin North, a gentleman named Scott, Ed Lowlington, Kelly Wienersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Aberzado and Mr. Robert Stietka. So, that's it for Titanium Physicists this time except for the stuff after the song. But remember that if you like listening to scientists talk about science in their own words, there are lots of other lovely shows on the Brachiolope Media Network. We're very proud of them. Okay. The intro to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. So good day, my friends, and until next time remember to keep science in your hearts.

57:27

[Outro song; *Angela* by John Vanderslice]

58:16

Brent: Alright, so the Universe is accelerating in its expansion. How do we know that's not just some sort of incredibly giant gravitational wave crest?

Ben: First answer that I can think of is we see the expansion of the Universe as being the same in every direction we look.

Brent: Ah, right.

Ben: And if it were gravitational wave, let's say a really big gravitational wave from a giant space whale at the start of time or something, then we would see stuff getting further apart in one direction preferentially.

Brent: Uh-huh.

Ben: Right? And that's not what we're seeing.

Matt: It's totally homogeneous?

Leo: But it's a really good question because actually physicists worked on this question, too and there's a technical name for it. There's this thing called superhorizon perturbation which is kind of an awesome name, right?

Chiara: It's probably a really good name for a band, guys.

Leo: Yeah. The Superhorizon Perturbations.

Matt: Yeah.

Brent: It's probably taken but I'll make a note.

Chiara, Matt: [laugh]

Leo: Yeah, so you just reinvented superhorizon perturbations.

Chiara: They have really good intuitions, don't they?

Ben: A few years ago, I'm not sure if you remember there was reports that we had detected the evidence of gravitational waves from the early Universe?

Chiara: This was the BICEP2 experiment?

Ben: BICEP2 results. And everybody got really happy, I gave lectures to my class. I gave a lecture about cosmology to my math for elementary school teachers class.

Leo: [laughs]

59:48

Chiara: I organized/

Ben: They were learning how to teach math to elementary school and I was like "okay, you guys are gonna learn about BICEP2".

Chiara: It was really exciting. I even organized a public viewing of the live feed and it was awesome and it was packed and then you well, you know what happened. No one could stream it.

Leo: Our live viewing crashed immediately.

Chiara: Yeah, that's right. Like, I had an auditorium that was packed and I couldn't stream it 'cause/

Leo: I was relying on people retweeting things from live at the presentation.

Chiara: Katie Mack was really good at retweeting things. Like when she saw the paper she tweeted all the key figures and kind of really summarized it nicely.

Brent: So this BICEP2 thing isn't that the like Antarctica like detector which showed polarized patterns in terms of the background radiation which like supported the idea of the inflation theory and then it got debunked? Is that what you're talking about?

Ben: That's exactly what we're talking about.

Chiara: Wow, that's pretty good.

Ben: So those gravitational waves that we thought we were detecting are the superhorizon excitations that Leo was mentioning.

Brent: Okay.

Leo: They were superhorizon during inflation. If they had actually been due to gravitational waves, which they were not.

Ben: They were not.

Chiara: But they're still working on it. There's a BICEP3 now. And they're still working on doing this properly and I think that they're going to be working with the Planck Collaboration more carefully so they can take into account polarization from the dust. Which is what their Achilles' heel was in this case.

61:18

Matt: So they said that the finding actually was inconclusive. It's not like it came back negative.

Ben: That's right. I mean so they thought that all of the signal that the BICEP2 people had come up with was plausibly caused by dust around the Milky Way.

Matt: Gotcha.

Ben: So that the signal strength is that high. So, I mean it's a matter of like subtracting the signal from the Milky Way if you know it and their expectation for how loud that was wasn't accurate because they were working off of old data.

Brent: Haaaa. Did it hurt the reputation of like that particular field much? I mean has there been much blowback? Or is everyone just "oh, that's fine, you tried your best, we'll get it right next time"?

Chiara: The jury's still out. There's/ people have different opinions. So there's one school of thought which thinks that it's really good to expose the public to you know science in action. And that's exactly what this was. Someone had a result and people were like "this is great if you can verify it with another experiment" and when we got more data we saw that you know, this result is inconsistent. And we think that we can explain it in a different way. And so we changed our minds. And this goes a long way to proving that science you know isn't a religion, we don't all have to believe the same thing, we don't have to believe anything. We just have to look for evidence.

Leo: Yeah. Our viewpoints change when we have new evidence. So/

Chiara: But other people think it was a big embarrassment and they shouldn't have had a press conference and they shouldn't have done any of this.

Leo: But this is a sociological question.

Chiara: Yeah, exactly. But that's the thing that physicists are also people and, you know, some people really think that we should always wait before making a big fuss and other people are more optimistic and you know like saying like "look, this is what we've found and this is how we can explain it and yay science". So/

63:06

Brent: I'm gonna say this is why I love science so much. I just love the idea of like that understanding is a work in progress and that when new information comes to light, you know, we have to like modify our perspective. This is so great. It's my favorite thing about science.

Matt: Yeah, I love it too. I wish that more people kind of understood that that's what scientists are doing. Because I think like a lot of people will hear like oh like science is saying something and then later they find out that that science has changed its mind about that or you know has come up with a new theory and since they don't understand that they just think that science lies to them sometimes. You know what I mean?

Chiara: Yeah, it's my personal opinion that you know people are in these days are too used to having black and white answers and the answer is you should be like "this is what we think now". And that changes over time and that evolves over time but it doesn't mean that we don't know what we're doing, it means that we know a little bit better each time and we come up with new models and new ways to think about things and so the whole process is dynamic and ever changing. And I think that that's awesome. It's not something that we should hide.

64:17

Matt: As far as the edge of the visible Universe goes like I think I remember you saying once that we just sort of pretend like that edge of the Universe is/ that actually the Universe is infinite because we know that/ because anything beyond that the edge of the visible Universe doesn't really affect us at all, right? So does that mean that/ so I mean I guess how do you wrap your mind around that as a physicist? I wonder this. I mean, there's all this stuff potentially going on beyond what we can see so do you just like not think about that or do you just/

Ben: No, that's a great question because/ So, there's a conjecture called a Copernican principle that says that everywhere you go in the Universe should be about the same. And this is the one that says that there's other stuff past the horizon of our Universe, the visible horizon of our Universe, so our local Universe area that can interact with us, that there's stuff past it but it's probably all the same stuff, same matter, same trees. I don't know. Book reports.

Leo: Hydrogen has the same mass.

Ben: Yeah, hydrogen has the same mass, the gravitational constant's the same. Same density of material. And so what Leo was talking about is there's one area of physics now, it's a little bit more conceptual, that/ they refer to it as multiverse theory that says that there are patches way past that area where the laws of physics might be different. It flies in the face of this Copernican principle but there's no real reason to believe the Copernican principle aside from "It sounds pretty good". So we don't actually know what's out there. Different physicists, and fairly intelligent ones have speculated about what might be way out past there, and have argued about different consequences of it. But as far as these things go, unless I'm fairly mistaken, most of the stuff way out past our horizon won't be able to ever affect us insofar as we ever observe the outside Universe, 'cause it's just too far away.

Leo: No, you're right.

Ben: 'Cause there's no real way to know or test except for whether it makes philosophical sense or consistent sense with the physical equations that we're dealing with.

Leo: If it is the case that our Universe will continue to expand at an accelerated rate then our horizon will never shrink, it's always going to stay the same distance away. And stuff is going to continue to leave the horizon. So if that scenario was true, then we will never be able to test what's beyond our cosmological horizon.

67:14

Chiara: I just wanna comment on your earlier comment about like how do you wrap your head around that kind of stuff. There's a lot of things which are really amazing all around us. If you look at the Moon, that's a giant space rock that's held in the sky because of gravity.

Leo: It just happens to fall around us at the rate that it's going.

Chiara: Exactly, right?

Leo: So it doesn't hit us.

Chiara: That's totally nuts if you think about that, right? And every day I study supermassive black holes. Like that's totally nuts, those are billion times the mass of the Sun - what does that even mean? Right?

Matt: Mhm. Yeah.

Chiara: So I think as a physicist you have these weird moments of awe where you're just like "what am I even doing? I can't believe that I can even ask these questions."

Leo: I'm so puny compared to this supermassive black hole.

Chiara: Exactly. The supermassive black hole does not give a shit. [laughs]

Leo: But somehow/ I mean we've/ we're living in a time that our civilization has developed enough that we can understand the predictions of, you know, the general relativity, so we know what should happen around supermassive black holes and I just wanna keep trying to understand that.

68:25

Chiara: Mhm. But I think that these moments of awe and sometimes even inspiration that we have are really important to keep us going because sometimes it can get - you know - very difficult to keep that alive and to keep doing a research. Especially if it's, you know, a bit speculative. And hopefully it'll become more concrete in the next few years.

Ben: When we can finally listen for ringing black holes.

Chiara: Absolutely. Or merging ones or/ yeah, merging and ringing.

68:56

Brent: Hey, so isn't Andromeda galaxy and the Milky Way, aren't they on a collision course and if so, are the mega black holes in the middle of each galaxy gonna ping or whatever?

Chiara, Leo: Yeah.

Chiara: Absolutely. The Andromeda galaxy is coming right at us and we will eventually merge with it. And when we merge, our central supermassive black holes will merge and cause the gravitational waves that I like. Which are the [laughs] the ones that I study. And eventually, yeah, so black hole - black hole merger will also have this ringdown effect after the merger. But in this case it's less like having/ I think less than like throwing a stone at a bell but more like smashing two bells together, making a new bell. [laughs]

Leo: Somehow in general relativity, if you took two bells and smashed them together hard enough, you would make a black hole.

Chiara: Yeah, you make a new bell. And then that would ring.

Ben: Yeah, it's kind of like you take two cars and you smash them together and the sound they make, at first there's the collision sound and then after that there's the vibrating pieces of metal that are stuck together sound, and we can listen for them both.

Leo: I think general relativity is much more beautiful than smashing together two cars. Because whatever/

Ben: What do you want to smash together?

Leo: Well, it doesn't matter in GR. If you take two things and smash them together at high enough energy then they'll make a black hole.

Ben: Yeah. It's true.

Chiara: We love black holes over here. I don't know if you can tell.

Leo: They're kind of/ they're the simplest objects that you can imagine in nature.

Chiara: [laughs] Maybe for us. But probably not for the rest of the world. [laughs]

Ben: They don't have any wiggly atoms. They're great.

Leo: That's true.

Ben: There's only two parameters, fantastic.

Chiara: Well, that in our very simplistic way of thinking about them. But if you think about them in an astrophysical sense all shit hits the fan, we have no idea what's happening.

70:51

Matt: Right.

Brent: So, okay, is a black hole simpler than a vacuum?

Leo: Ooooh. [laughs]

Chiara: In what/

Leo: Now we're getting into quantum mechanics, aren't we?

Ben: To the Dyson vacuum or/

Leo: [laughs]

Chiara: No bags!

Brent, Matt, Chiara: [laugh]

Leo: It's definitely simpler than a vacuum cleaner, that's true.

Chiara: The black holes/

Matt: I don't know, I have a pretty nice vacuum cleaner.

Ben: But is it simple?

Chiara: Black holes don't suck, right? Black holes do not suck. You could replace the Sun with a black hole of the same mass and nothing would change, we'd just get really cold.

Leo: Well, we would cold, yeah. And freeze.

Chiara: We would get cold. As a Canadian I feel like I can speak with authority on what cold means.

Matt, Brent: [laugh]

Chiara: But that's the only thing that would change. We wouldn't get sucked in by its magical sucking properties. So, that's a popular myth. Tell your friends.

Brent: No, I more meant like/ my understanding of like a vacuum is that there yeah, there's like fluctuations for like stuff like particles can come out of nowhere and collide with other particles.

Chiara: Oooh. That kind of vacuum. Yeah.

Leo: Right, so you're talking about the quantum vacuum. Okay, so vacuum is another/ sorry, go ahead.

Brent: Oh no, I mean is/ does that kinda stuff not go down inside a black hole? Is a black hole way simpler than that or isn't that kind of (...) maybe?

Leo: So there's so many layers to this question. It's/ this could be an entire podcast in itself. So, first of all/

Chiara: And we don't have any really conclusive answers at the end anyway.

Leo: Yeah, right. So, first of all, vacuum is another one of those words that means multiple things in physics. One of the things that it means is in classical general relativity, it just means that there's no matter around anywhere. So, in that sense, a black hole solution to general relativity is a vacuum solution. So it is just vacuum. That's one answer.

72:44

Leo: But you were talking about the quantum vacuum. So the quantum vacuum means technically the lowest possible energy state you could make a quantum mechanical system. And there's this description that people have/ there's this popular description that people have made that the vacuum is actually this turbulent sea of virtual particles popping in and out. So this is a very strange analogy because the motivation for this analogy came from a very technical place. It came out of a place of the way that people do calculations in quantum field theory. So in theories like the Standard Model. And there are certain calculations that we say "contribute" to the vacuum. And those calculations look like just particles popping out of nowhere, existing for a little while and then smashing back together. But that doesn't happen in the real vacuum. It's just a calculational artifact that we use to make sense of the theory. So, the real vacuum is not actually that place where there's this turmoil of particles popping in and out of existence all the time.

Brent: Hah.

Matt: Wow. I think I understand what you just said.

Matt, Brent: [laugh]

Brent: Yeah, I'm looking forward to listening to this podcast so I can understand better. [laughs]

Matt: Yeah. I mean that/ So, are you saying that sometimes you use descriptions like that because that's what the math is telling you but you don't actually think that's what's happening in reality?

Leo: Yeah. Yeah. So, there are a bunch of calculational tools that people have built because if you do the calculations in a certain way then you get infinities. But if you don't want the infinities there you have to divide by the right thing and the thing that you divide by has all of these diagrams that what they try to mean to you is that these "virtual" particles are popping in and out of the vacuum and annihilating each other. But I don't/ I think it's a very loose interpretation of the math. I don't think that math should actually tell you that.

75:20

Matt: Okay. So, how often do you think/ you know, we hear all kinds of crazy things about quantum physics and the things that it's discovering. Like, what percentage of those really wacky things, you know, like particle existing in more than one place at one time and I'm trying to think of some other ones but like how often is that just an artifact of the math and not what you really think is going on in the world and how often is it really like oh, like you know, the particle really does exist like everywhere until it gets observed or something.

Chiara: So lots of these things are mathematical tools. And even the idea of the singularity that we've presented is largely the mathematical way of looking at it. In reality the black hole probably does have some dense bizarre material at the center that we don't really understand and we probably will never be able to actually look at it to report back and tell anyone what it looks like. And so easiest way to think about is, is just by making some simplifications and that's a lot of the time what we do. And sometimes the simplifications lead us to maybe to simplified versions of reality or not quite accurate ones. They're usually much simpler than what the world really is. So I think that the black hole singularity is probably the best kind of representation of this interpretation if you can follow what I'm trying to say.

Leo: So I have another answer that I wanna add, which is um/ one way that physicists can tell you what's real about the world or what's not and that's just a thing that's going on in the math is they should always be telling you things that are observable. So, you can't observe virtual particles. That's a true statement about quantum field theory. The only types of particles that you can observe are real particles which has a specific definition but you know, so that means that even if the calculations say you need to include all these virtual particles that are in the vacuum the only thing you ever observe are the real ones. So, we always try to do calculations about what can actually be observed.

77:58

Chiara: But just to remember that, you know, a lot of the math that we use is just a tool to understand what the Universe is really like. But you know, the Universe doesn't care what tools we use, it's not gonna change the way that it behaves you know we use math in a particular way. So again this comes back to your comment about string theory, right? In that right now is it useful or is it not? And that's really how we treat maths - to get to these useful answers at the end of the day.

78:31

Brent: How frequent is it that the Moon around the planet will basically always face the planet for example? 'Cause we only ever see like one side of the Moon, right? The Moon is it locked?

Chiara: It's tidally locked. Yeah.

Brent: Tidally locked.

Leo: So, the tidal locking has to do with the fact that it was close enough. So, the closer it is to the planet that it's orbiting, the larger the torque the planet creates on it when it's going around if it's you know, it's not perfectly spherical. So, the torque acts to slow down its rotation until it matches its orbital rotation. Once it becomes synchronous then the torque can no longer speed it up or slow it down. So there are other moons in the Solar System that are also in some of these orbital resonances. This is a type of orbital resonance, it's called the spin-orbit resonance. There are other resonances in the Solar System. The most famous example is the first three Galilean satellites around Jupiter.

Brent: Huh. I didn't know that.

Matt: Are all moons sort of on their way to synchronization?

Ben: Yeah. Yeah, yeah. So think about it this way. So the Earth is applying tidal forces to the Moon - it's kind of squishing the Moon because the back side of the Moon is feeling slightly different amount of gravity than the front side and the sides of the Moon are feeling a slightly different direction of gravity than the front and back. And so it kind of squishes it. So even if the Moon is a sphere, the tides of the Earth kind of deform it in kind of a squished grape shape, okay? So if the Moon is rotating as well then essentially the Moon feels these weird shear forces because different parts of the Moon will feel different amount of tidal forces. And so what's gonna happen is eventually the heating up of the Moon from these tidal forces is going to tidally lock it. It's going to make it so that the Moon doesn't twist under the tidal forces and that way it will stop heating up. And so this tidal locking is gonna be the end stat of all moons eventually.

Leo: So let me say there are some other possibilities. So, Mercury for example is in 3 to 2 spin-orbit resonance. So every time it goes around the Sun 2 times - or is it 3 times? I can't remember if it's 3 to 2 or 2 to 3 - then it rotates on its axis the other number. So it seems to have gotten trapped in a 3 to 2 spin-orbit resonance for some strange reason. It's trapped in a spin-orbit resonance but it's not a 1-1 spin-orbit resonance.

81:18

Matt: Wild.

Leo: There's some interesting history there, too. People used to think that it was in a 1 to 1 spin-orbit resonance. And part of the reason that they thought so/ well, first of all from theoretical bias but second of all because they tried to do radar measurements but they can only have made radar measurements certain times of Mercury's orbit so they were a little bit biased by measurements they were making, too.

Matt: You mean because it was always in the sa/ like it always had it/ the same face to the Sun every time they measured it?

Leo: Right, yeah.

Matt: Interesting.

Brent: Wow.

Matt: Yeah, I feel like where's the news article on that one? I feel like I missed out. When I feel/ I still thought that Mercury was tidally locked.

Ben: Me too.

Matt: Um, interesting.

Brent: Yeah. But it's in retrograde, right? Which is why we're having personal problems?

Leo: Yes.

Matt: [laughs]

Brent: Okay, cool.

Matt: Which is why the distance between Brent and I are/ is increasing.

Chiara: You'll have to forgive Mercury for being slightly eccentric.

Leo: Oh, oh, oh.

Matt, Brent: Oooooh.

Chiara: Zing!

82:24

Matt: I do have one burning question.

Ben: Sure.

Matt: That I wanted to ask a group like yourselves for a long time. Like, a hundred years ago I feel like people were discovering, you know like Einstein came up with this theory that was a real mindblower and they discovered another galaxies around the same time and, you know, quantum physics really got going around that time and we started learning all these really crazy things there. I feel like it's been a while since we've had some sort of major revelation.

Brent: Yeah, stop playing video games, guys.

Matt: [laughs] No, I'm not taking (...).

Chiara: We only play DOTA.

Matt, Brent: [laugh]

Matt: I'm wondering when you guys are gonna get off your butts

Brent: [laughs]

Matt: No. I'm wondering, like, do you guys foresee that happening in our lifetimes? Like, some sort of big, Einstein equivalent discovery?

Chiara: A paradigm shift. A paradigm shift.

Brent, Matt: Yeah

Chiara: Maybe. So, I think one of the things that'll take us forward by leaps and bounds will be quantum computers. I think that before where we were computationally blocked and we can't solve equations that we don't know how to do it fast enough with our given technology that quantum computing will really be a new kind of information revolution. And that will in itself really push science forward.

Leo: But let me just add that there are a lot of things about nature that we know we don't know. There are a lot of known unknowns right now. Like, we don't know what dark matter is. So there has to be something beyond the Standard Model. We don't know if the accelerated expansion of the Universe is because of Einstein's cosmological constant or if it's vacuum energy or if it's some weird other possibilities.

Chiara: Dark energy.

Leo: We think that general relativity has to give rise to some better quantum mechanical theory of gravity at some level but we don't have good ideas for what that should be unless you're a string theorist, if you think that's the right answer. But not everybody agrees. So we know that there are things that we don't know. And they're still out there. So, we could be learning something soon. And maybe the data just have to show us the way. So maybe gravitational waves will give us some surprise about the nature of gravity that we don't understand yet.

Chiara: Mhm.

Ben: And we're right on the cusp of a whole bunch of new crazy data coming in. We're launching all sorts of fantastic new satellites and building new telescopes and LIGO's coming online, right?

Chiara: It is online.

Leo: Advanced LIGO just finished its first observation run this past week or last week.

85:20

Ben: Yeah. And you know, the next/ the upcoming run on in CERN on the Large Hadron Collider may or may not disprove supersymmetry which is kind of the next step in the Standard Model for quantum mechanics, for particle physics. So I feel like the next 20 years will tell us a lot of things in terms of experimental and observational physics that will either confirm or deny a lot of the theoretical advancements that we've made in the last, you know, 40 years.

Leo: Yeah, and maybe the nature will just be kind to us.

Chiara: Nature's never kind to us.

Ben: The time of the great (...) is upon us.

Leo: Nature is subtle but not cruel.

Chiara: So one of the things that I think is most different from a hundred years ago is that 100 years ago people thought that they had a pretty good idea of what was going on and everyone was convinced and they were pretty self-congratulatory in their understanding of nature and I think that now we know that there's lot of things that we don't understand. And so people are ostensibly more open to change. But I think that change will also be very difficult, if there is a paradigm shift. But if there's a paradigm shift it would be absolutely amazing.

Leo: And we'd still be employed.

Ben: General relativity is still right, though.

Leo: [laughs]

Ben: Pardon, what did you say?

Chiara: It might be just that general relativity is a good approximation of some other, more inclusive theory.

Leo: Yeah, that's the new philosophy in physics for the past 30 years. All of our theories are just approximate theories. So we know that they're pretty good within the regimes that we've tested them. So if there's some paradigm shift, then it has to at least recover what we've got right now in the appropriate limit.

Chiara: That's what Einstein did with his field equations. In a weak field limit you had to recover Newton's laws. Because we know that those work. And that's actually one of the ways that you find out what all the constants are that go in Einstein's equations. You have to be able to recover Newton's laws. And so really/

Leo: Yeah, that's always the path forward nowadays. If you have a new theory, it has to at least predict everything that present theories predict and then more.

Chiara: Yep.

Brent: It has to predict the data that we have so far, is that what you mean?

Chiara: Well, you couldn't make a theory that/ and have it be accepted if this theory, you know, claims that you'll never see this effect but you've already seen this effect. Right? Like, that doesn't make any sense. And so in that way new theories just have to be more general versions of their predecessors.

Brent: Right, okay. Got it. And it makes sense. So in other words, it sounds like what you're saying is like, the developments in computation and maybe even artificial intelligence or whatever. Like, those could, you know, propel us to crunch data more to get clearer ideas what's going on?

Chiara: I think so. We have really big machines that are gonna create a lot of data and in order to go through that data and make discoveries is gonna be really tough. I mean, even storing the amount of data that some of these machines produce is requiring, you know, tens of millions of dollars of research.

Brent: Yeah.

Chiara: So, yeah, it'll be really interesting to see how that develops. But I think that'll help with the revolution, if there is one.

Matt: Yeah. I hope you call us when that happens.

Chiara, Brent: [laugh]

Leo: But you can't do physics without doing experiments so you can't just do calculations all day. So, we need LIGO, we need the LHC, we need space telescopes. Otherwise it's not physics, it's just math.