Episode 63, "E and N (The edges of Einstein)"
Dramatis personae:
- Ben Tippett
- Maya Inamura
- Katie Mack
- Leo Stein

The Titanium Physicists Podcast
www.titaniumphysics.com

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: Physicists tend not to talk about philosophy or how the physics we work with should modify the way humans interact with and describe the world around them. For a variety of reasons. Firstly, it's embarrassing - we're experts at math and experiment and observation and that kind of thing and trained academics tend to dislike saying things in public that might be incorrect. And we're not experts on philosophy or sociology or linguistics so for the most part we tend not to stick out our necks. Second reason is - it's scary. I mean, fighting about string theory and neutron stars can get heated and political but these topics are usually fairly abstract. And it's one thing to argue about mathematics but quite another to talk about politics or religion and nobody likes getting yelled at so mostly we don't talk about these things 'cause we don't wanna get yelled at. Mostly, we keep the deeper, world-changing ideas to ourselves. And thirdly, I think most of us really don't want to deal with how confronting the contradictions might change or redefine our identities. We're scientists - sure - but we're also members of human societies. We've inherited traditions and languages from our parents and friends and questioning the underlying assumptions stitched into our cultures and languages can make us feel like we're pushing away the people we love. And it's bad enough that we have to move all over the world to get an education and do research. And yet, there are contradictions between the physical laws of the Universe as we study it and the way culture tells us things are broken down. And these contradictions run deep. For example, take the concept of simultaneity. In the English language this is one of the fundamental concepts for describing time. We say that two events occur simultaneously if they happen at the same time. Like, imagine a red and blue balloons sitting next to each other and they both pop at the same time, right? Simultaneously. Simultaneity is an important concept because it's fundamental to defining the concept of now. And I'm sure you know what "now" is. It's all the stuff that's happening right now, happening at the same time. But it's also a demarcation between the past and the future. And we put a lot of stock in the existence of a now because the past and the future are very different as we understand them. Lots of different things could happen in the future but the past is wholly unchangeable. And this plugs in all sorts of cultural ideas about free will, justice, human nature - all sorts of things. Now, Einstein's theory of relativity says that simultaneity is not a valid concept. The theory says that if three people watch our two balloons pop, one might say that they happened at the same time, the other might say that the red one popped first, the third person might say that the blue one popped first. And Einstein says all three observers can be right about it. They can all be telling the truth and that the differences in their stories don't amount to problems with their eyes or instruments - they really saw it happen in those different orders. The concept of simultaneity here is what's flawed. And Einstein's theory provides us with the mathematical framework to reconcile these three stories. And this is usually where physics class stops talking about it. Think about why. If simultaneity is a bad concept then the concept of now, the present, must also be an invalid concept. And there's no special line between past and the future. What we call the past, the present and the future are just imaginary countries whose borders are always shifting, lying on a geographic map that Einstein calls spacetime. And therefore the future must already immutably exist, just as much as the past does. And in Einstein's framework, just as you're listening to me say these words right now, somewhere in spacetime, you're still driving to work and stuck in traffic last week. Somewhere in spacetime you're still sitting through your first day of school. And somewhere in spacetime you've already been dead for a million years. The surface of spacetime has everything already written on it, the way an LP record has all the music written on it. There's somewhere in spacetime where the song is already over and another place where it's just about to begin. But hold on - if that's the case does that mean that we don't have any choice in our lives? Are we suddenly talking about free will now? Like I said, if you pick at this scab, you'll end up with some pretty sore questions. So then, we get to the fourth reason physicists don't talk much about philosophy which is that reformatting your entire culture to be consistent with current scientific philosophical frameworks - it sounds cool but isn't it a little bit hasty? I mean, it sounds ignorant when I say it like this but on the scale of history fields of physics changed their underlying philosophical assumptions quite a bit. Shackling language and culture to them isn't fair to our cultural traditions and doing so would probably politicize scientific research. And that's why most of us just kind of stay quiet about these things. But hold/ wait, wait, hold on. All those things I said about relativity - those are pretty radical. How do we even know the theory of relativity is true? I mean, how do we even know that the theory of relativity is true? Today on the Titanium Physicists podcast we're talking about the experimental and observational evidence for Einstein’s theory of general relativity. And speaking of the interface between science and the public's understanding of the Universe, explaining what's new in science and why it's important is the job of the science writer. There is possibly no job more important and more taxing in our very modern times. Welcome to the Titanium Physicists podcast, Maya Inamura, science writer extraordinaire!

07:24

Maya: Hello.

Ben: Hi, Hi Maya. How's it going?

Maya: It's going well, thank you.

Ben: So, for you today I've recruited two fantastic Titanium Physicists and I mixed them together and it's gonna be amazing. Arise, Dr Katie Mack!

Katie: Dun-dun-dunnn!

Ben: Good. Doctor Katie did her PhD at Princeton University in astrophysical sciences and she's currently at the University of Melbourne in Australia where she's currently a postdoc and a Discovery Early Career Researcher Award winner. She studies theoretical cosmology. Now arise, Dr Leo Stein!

Leo: Du du du du du du dud.

Ben: Doctor Leo did his PhD at MIT and he's currently postdoc at Caltech where he studies Einstein's theory of general relativity and theoretical corrections to Einstein's general relativity. What two great people to talk about the tests of general relativity. Alright everybody, let's do it.

08:15

Ben: Einstein's theory of general relativity is one of the most mathematically intricate theories of physics out there.

Katie: Did you know Einstein had to learn a whole new field of mathematics to formulate general relativity? He didn't know it at the time and so he got Marcel Grossmann to teach him.

Ben: Yeah.

Maya: What field of math was that?

Leo: Differential geometry.

Maya: I don't know what that is.

Ben: It's the mathematical analysis of curved surfaces. So it's the math that you use when you're gonna talk about how an ant walks across an apple.

Leo: Maybe we should say why Einstein needed to study differential geometry to formulate theory of general relativity?

Ben: Okay. So, Einstein's theory of relativity is a theory of gravity. It explains why the Earth and the other planets go around the Sun in the way they do, okay? And before Einstein came along, we had a perfectly functional theory of gravity - Isaac Newton's theory of gravity, right? Isaac Newton's theory of gravity, it described things in terms of forces. It said: there's a force of gravity between every object and every other object. And the strength of that force depends on how far those two objects are apart, so it gets weaker with distance, and it also depends on how much mass each object has. And so the Sun has a ton of mass and that's why it pulls everything around it. Because it's got lots of mass, it pulls on the Earth more strongly than, say, Jupiter pulls on the Earth. In terms of predictive power, Newton's theory was just fantastic. You could/ It wasn't just describing how the planets went around the Sun, it would describe the underlying rules that cause the planets to go around the Sun. And so what you could do then, is you could look at, say, how Saturn's orbit change slightly from time to time and you could maybe deduce that there were other planets outside of Saturn's orbit, further out, and you could deduce where they were and how heavy they were and what they were doing. And you could discover those planets with telescopes. And so Newton's theory - its predictive power - allowed us to discover the further out planets in the Solar System - the ones that aren't visible to the naked eye. But that process started to break down when they were analyzing the orbit of Mercury, right? Mercury is the planet closest to the Sun and Mercury's orbit, it kinda had a - I don't know how to describe it. Maybe a wobble? Mercury's orbit isn't a circle. None of the planets orbit in perfect circles, they orbit kind of in ellipse, oval shaped ellipses. And Mercury's orbit - its oval was kind of slowly turning around the Sun in time. It happened at a very, very slow rate and so for the most part Newton's theory was bang on but Newton's theory didn't describe why the oval shape of the orbit would itself turn in time, slowly. And so one of the guesses was that there was another planet inside Mercury's orbit that was affecting it. But, you know, the astronomers pointed their telescopes at the Sun and burned out their eyes, and they're like "Yeah, there's no other planet there". So it wasn't clear why Mercury's orbit was doing that thing it did. Was there another planet that we couldn't see? I don't know. It was a mystery.

11:24

Leo: This measurement was actually amazing feat of astronomy at the time. Because most of Mercury's precession, most of the wobble of the ellipse was explained - most of it was due to the fact that the Sun is not perfect sphere. It's a little squashed 'cause it's spinning. And Jupiter has most of the rest of the mass in the Solar System, after the Sun. So Jupiter going around also tugs on Mercury's orbit a little bit and makes it precess a bit. So, most of the wobble was understood to come from the fact that the Sun is not quite spherical and that Jupiter is out there also pulling on Mercury. But there was just a tiny, tiny little piece of it that was not understood. So, if I had been doing those measurements, I would have thought "Oh, I just got the measurements wrong". But people actually took these measurements seriously enough to think that there's a real physical effect there, it's not just the measurement error.

12:22

Ben: I mean, that was before, like, Facebook and stuff or twitter. You couldn't procrastinate as much back in those days so... there's nothing to do but measure Mercury. So, in comes Einstein. And Einstein had a theory of gravity that was on an entirely different philosophical framework from Newton's theory of gravity and we'll talk about that in a second. But - spoilers - Einstein's theory added corrections to Mercury's orbit, explaining why Mercury was orbiting in that precise way that it was. So, how? That's the million dollar question. So, like I said, it's an entirely different framework. In Newton's theory of gravity, it's all about forces. Everything moves through space, the idea was, and then intervals of distance, intervals of time were all fixed. Everybody could agree at the rate the time was passing, everybody would agree on how long a meter was. You could essentially put a great big clock in space and build yourself a lattice grid and use it to describe the location of all the objects. And it was pretty straightforward like that. And so there's just forces that causes things to move across this grid over time. Einstein's theory was different. Sooo different. In Einstein's theory intervals of time, intervals of distance are now also dynamic quantities. And so you can have objects moving - and that causes their position to change - but also these objects are gonna cause spacetime - intervals of distance, intervals of time - to change depending on where you are, depending on how you're moving, depending on what's moving. Different people would disagree on how long one second takes; different people will disagree on exactly how long a meter is and this was fundamental to it. And now the simplest metaphorical way to describe this, to characterize it, is to say that intervals of distance, intervals of time change depending on where you were standing.

14:24

Katie: It's sort of like you're in this sort of giant grid in space but the grid is not a fixed thing that you're just moving through anymore. Now, when you're moving through the grid, you're changing how the grid lines line up and you're changing, like, the shape of the space around you and you're changing, like, how quickly other things are moving through the grid. Like, you know, it's not just that you can sort of divide everything up and you know, drive straight lines and stuff like that anymore. Now it's like you're moving through some kind of bendable space and the bending of that space is determined partially by how you're moving partially by what's around you, partially by, you know, other things moving around you. And so, you know, you try and make a measurement and you have to take all that into account and it changes how time is moving as well because it's not just space that this grid exists in - it's spacetime. And so both space and time are part of this now bendable fabric that changes based on what's going on and how it's happening.

Ben: It sounds like everything's really up in the air but it's a lot less nebulous than it sounds.

Katie: Yeah.

Ben: The mathematics that we use to analyze this is the mathematics of curvature. This is why Einstein had to learn differential geometry to be able to describe his ideas. In curvature what happens is/ Well, you think about, say, the globe. The globe is curved, right?

Maya: Mhm.

Ben: You can talk about what that means in different terms but/

Leo: If you and your friend started walking in straight lines in the same direction but you started 1 km apart, then eventually you would meet. Which is not possible in flat space. It's just because the surface of the Earth is curved.

15:59

Ben: Yeah. And so in Einstein's theory things come together - you're attracted towards the center of the Earth, the Earth is attracted towards the Sun not because there's a force pushing on it but instead because spacetime - this surface that all these objects travel over - is curved. And if object travels in straight lines over a curved surface and that causes the trajectory to bank. And so things end up moving towards central objects or in circular orbits around heavy thing.

Maya: I'm sorry, can you repeat that? Planets move in straight lines and then what?

Ben: Yeah, planets move in straight lines but it's kind of like if you have, like a bowl, like a cooking bowl and you take a marble. So, marbles roll in straight lines for the most part but if you roll a marble inside this cooking bowl it'll end up rolling in a circle and banking around off the curvature. Planets are doing the same thing around the Sun. The Sun is generating a significant amount of spacetime curvature and so the trajectories of the planets - they wanna move in straight lines but because this surface that they're moving across is curved, they end up banking in circles around the Sun.

Maya: That's the sheet of rubber with the ball in it causing/

Katie: Yeah.

Ben: Yeah, that why they use that metaphor.

Maya: /other balls to spin around, gotcha.

17:12

Katie: Yeah, I mean it's kind of like if you want to run in a straight line on the Earth and you just run in one direction, eventually you'll come back to where you started and you were always running in a straight line but the surface you were moving on was curved. And it's kinda the same with planets moving around the Sun or something like that. They're moving in a straight line through a curved space and so the trajectory they trace out ends up being a circle or ellipse or something like that.

Ben: So, these ideas are bananas.

Maya: [chuckles]

Ben: And it took a lot of experimental and observational evidence to convince people that this new framework was the appropriate one to usurp Isaac Newton's.

Leo: Well, not so much usurp but to correct it. It was very important for Einstein to make sure that the theory of general relativity reproduced Newton's theory. Other people were also trying to work on theories of gravity around the same time that Einstein was that would also make sense in the context of special relativity but Einstein was the one that cracked how to make that happen in such a way that it would be compatible with Newtonian gravity so it would extend Newton. And then he started doing all these other calculations, not just does it reproduce Newton's theory of gravity but what else does it say? And when he found that famous postdiction of Mercury's extra precession he apparently had heart palpitations. You know, he had this exact number that had been measured by observers and then he did his calculation with pen and paper and he saw the same number pop out of his calculations. It was amazing.

18:56

Ben: So, the foundational assumptions of Einstein's theory of relativity are different from Newton's, right? Because in Newton's theory intervals of space, intervals of time don't change from place to place, from moment to moment. But in Einstein's they do - they're dynamic. And so it takes a lot of convincing to convince somebody that things change that way. But we have direct evidence that it happens, so let's talk about that. First off, historically, ordinarily in Newtonian gravity light moves in straight lines. And that's fine in Newtonian gravity but in Einstein's theory of gravity light might want to move in a straight line but if it's moving across a curved surface then the direction light will change, will end up being a curved path. And this was a crazy prediction and everybody was like "well, that's kinda weird" so one of the first dramatic pieces of evidence that Einstein's framework was a good one was in 1918. There was a big solar eclipse happening that year and Arthur Eddington was brought in to do some astronomical photography. The idea is that if the curvature of spacetime will cause light to change direction, will cause light to move along curved lines, then you're only going to see this effect when there's a really strong gravitational field. Like, as close to the Sun as possible. But the problem is, you can't really see what's near the Sun because the Sun is really, really, really bright. And so if there's a solar eclipse, the Moon will block out the Sun almost exactly and you can see the stars that are around and behind the Sun. And so the idea was: okay, we know that there's an eclipse later this year, we're gonna send somebody down to take a photograph of when the Moon is directly in front of the Sun, blocking out the Sun's light because at that moment we can see the stars that are behind the Sun and if Einstein's prediction is right, the light from those stars will have had to kind of bank across the geometry and we will see it as the stars being in slightly different places than we ordinarily do.

Maya: Is that really the only way to take a picture of the stars emitting light that are affected by the Sun's/

Katie: Yeah, I mean the problem is that like in daytime you can't see the stars because the atmosphere is too bright and at night you can see the stars but only when the Sun's on the other side and so what you really want is, like, you want a really big gravitating body and you wanna see the stuff behind it but the only really big gravitating body we had handy was the Sun. And so, you need somehow to be able to see the stuff that's near the Sun during the day. And the only way that's gonna happen is if there's an eclipse so that it's dark during the day. You can see stuff near the Sun and you can see that sort of bending of the light.

Maya: Makes sense.

21:49

Ben: But half a year later our planet will be on the other side of the stars. And so when it's night we'll be facing those stars. We know exactly what those stars look like, we know what shapes the constellations make. So we know which positions those stars should be in. And so during the solar eclipse, we can compare how we know those stars should be arranged with the photograph that we take during the solar eclipse and then determine if those stars have moved positions. And they do. It's something we've seen more accurately since 1918 and this was just the first. But this was the great big piece of evidence that changed everybody's mind on relativity.

Katie: Yeah, this is the thing that made headlines and, like, really got people excited about relativity being a thing. This is what made Einstein famous.

Ben: This effect is called gravitational lensing. This way that the curvature of spacetime causes light rays to skew and splay and bank across the geometry, it's called gravitational lensing. And we see it a lot in astronomy. So the stronger the gravity is, the heavier the thing is, the more this effect will take place. Hubble Deep Field goes like this: they take the Hubble telescope and they point it on this black patch of sky that they know there aren't any stars in. And when they resolve those photographs, they're just full of galaxies. There's galaxies on galaxies. Some of the galaxies in the photograph are between us and galaxies that are further away from us. So they eclipse further away galaxies. And so these further away galaxies - their light will get gravitationally lensed around the middle galaxy and you end up seeing these weird ring shapes.

Katie: It's not just the Hubble Deep Field. I mean, Hubble Space Telescope sees lots of different systems of gravitational lensing and there's some times where it'll look like a cluster of galaxies and that has a lot of mass and the arcs around the clusters of galaxies of the galaxies further away are really impressive. So there's whole bunch of systems like that and then there's this new project called the Hubble Frontier Fields where they have a few big clusters of galaxies and they're studying really carefully all the galaxies behind there to try to find very, very, very distant galaxies whose light is bent around and magnified by this gravitational lens. So they're doing really interesting stuff with these kinds of systems.

24:07

Ben: So, there are other fundamental assumptions in general relativity that there aren't in Newtonian gravity. And the second one - it's really crazy - it's called time dilation. The idea is that different observers, depending on how fast you're moving, time will move slower for you. But the deeper you are inside of a gravitational field, the slower time passes for you. And so we've definitely detected this effect in a bunch of different circumstances since the 60s, since we had the advent of more accurate clocks, like atomic clocks. We can detect, essentially, the differences caused by time dilation, it's called.

Katie: Yeah, this is something that came up with special relativity. So special relativity is the theory that doesn't talk about gravity, just talks about spacetime being this, like, warpable thing. This thing that changes based on how you're moving, what your perspective is. And in special relativity time dilation is a thing that happens when you're moving really fast. So rocket ship that's moving really, really fast, the time will go slower for the people in that rocket ship than the people sitting around on the planet or standing next to the rocket ship as it goes by. But with general relativity there's also this effect where if you're in a gravitational field, the time is going slower than if you're outside the gravitational field. So if you're just floating in space, you know, in the middle of nowhere, your time will go more quickly than for somebody who's standing on the surface of the Earth. And this is something you can test where, like, you can build a really tall tower and put one clock at the bottom of it, one clock on the top of it and the one at the bottom will be ticking a little bit slower than the one at the top. And then you can test the other one - the special relativity version - by putting a clock in an airplane and making the airplane go really, really fast and then bring it back and checking the clocks between the two. And of the things that I think is really cool is that for the astronauts of the space station, both of these things are happening. So, like, not only are they moving really fast, 'cause they're orbiting the Earth, they're also above the Earth. So being above the Earth, they are further from the center of this gravitational field and so there's like this competing thing. Like, would you expect that their clocks would go slower because they're moving really quickly or would their clocks go faster because they're further away from the gravitational field? And it turns out you can calculate the two effects and the fact that they're going fast wins out. So, if you take two identical twins, they're born at exactly the same moment, and you put one of them on a space station for a year, then technically the twin that was on the space station for a year will be a little bit younger when he comes back. And NASA kind of did that, so they have these two identical twin astronauts and one of them is Scott Kelly and the other one is Mark Kelly and Scott Kelly just got home from a year in space. And I mean, you know, twins are never born at exactly the same moment, so you know, that experiment isn't't/ you're better off doing that with clocks but, technically, if you could measure exactly their ages, then Scott would be slightly younger now than his brother.

27:09

Maya: Interesting.

Katie: Yeah.

Maya: And astronaut Mark Kelly is married to former US representative Gabrielle Giffords, it's fun.

Katie: Yeah. We can also see it with GPS. So, the GPS system relies on having a really accurate measurement of your position, your speed on the Earth and the way it does that is it sends signals to a bunch of satellites that are moving around the Earth and it sort of triangulates, right? You have to take into account not only the fact that these satellites are moving and so that gives you some kind of special relativistic effect but also the fact that you're going from gravity situation on Earth to a lower gravity situation in space. And so the signal that you send from the Earth will be redshifted as it goes up to space because it's climbing out of this gravitational well and, you know, sort of do the opposite when it comes down. And so you have to take all that into account and it turns out that if you try and do a GPS system without taking gravity into account, without taking Einstein's relativity into account, you become inaccurate really, really quickly. So the fact that GPS can work and tell us where we are depends on the fact that we understand how gravity and how speed affects measurements of time and things like that.

Maya: So for the GPS system, what is being redshifted and blueshifted/ so it's the signals between the user and the satellites...

28:34

Leo: So each of the satellites has an atomic clock on it. The important thing is that those clocks are running at a different rate than atomic clocks that are down here on Earth. And they're running at a different rate for the same reasons that Katie talked about for the International Space Station. One is that the clocks are moving really fast, 'cause they're in orbit around the Earth and the second is that they're further away from the Earth so they're further out in the gravitational field of the Earth. And both of those effects are important. So the clocks on all of the GPS satellites are ticking at a slightly different rate than all the clocks down here on Earth.

Maya: Are they going faster or slower? Are they going faster?

Katie: I think that they're probably going slower, 'cause they're moving in orbit around the Earth. Although I don't know because the GPS satellites are a lot further away than the International Space Station, so they might be going slower 'cause they're further away. There's a crossover point, I don't remember where that crossover point is.

Leo: Yeah, it's tricky because actually the size of these effects is pretty similar so I don't remember which one is bigger.

Katie: Yeah, so there's some distance out to which, if you're orbiting the Earth at that distance, then your time is going faster 'cause you're further from the Earth but at Low Earth Orbit, where the Space Station is it's the other way around - your time is going slower 'cause you're moving quickly. But yeah, the two effects are very similar in magnitude in the sort of range of the orbits of things that we deal with. And so I don't remember how far away that crossover point is but the GPS satellites are a lot further out from the Space Station.

Leo: I think their orbits are, like, 12 hours maybe? I don't remember what their orbits are. I think it's twice a day. Yeah, that's a lot further than/

Katie: Yeah, the Space Station orbits in 90 minutes.

Leo: 90 minutes, yeah.

30:25

Katie: Both effects are so important that you really have to know both of them really well in order to get everything right.

Maya: It's strange how no one talks about this. Everything feels really meaningless.

Katie, **Leo:** [laugh]

Maya: In the context of time being completely mutable.

Leo: I think I enjoy the Universe more because it's less rigid. You know, it feels very strict in Newton's theory of gravity.

Maya: I think that makes sense.

Ben: So there's a third really weird effect called redshifting that we should talk about. So, the deal with Einstein's theory is that the frequency of light isn't immutable. If you have an object that's moving towards me and it emits white-colored light, because it's moving towards me what it perceives as white-colored light, when it arrives at me, I will see that light as bluish-colored light. And if they're moving away from me, that white-colored light that they see, I will observe it as red-colored light. So this effect is called redshifting or blueshifting, depending on if something is moving towards me or away from me and it's the general relativistic analogue of Doppler shift. You know how Doppler shift works?

Maya: Mhm.

31:44

Ben: An ambulance or a car or whatever moves towards you and the soundwaves come at one pitch and then as it moves away the soundwaves come at another pitch and the deal is that different people disagree on what pitches the soundwaves are because they're all kind of moving relative to those sound waves. Similarly in this case different observers are going to describe color of light differently. The frequency, the wavelength of that light - they'll disagree on it. And so one of the big initial predictions is if I have something that's moving away from me, I'm going to see the color turn more reddish.

Maya: I remember my dad explaining the Doppler effect to me when I was a kid and it ruined me. It was just incredible to me the idea that the same sound would sound different depending on where you were standing and when it was going off. And it's just/ it was such a strange concept to me, you know?

Ben: That's how people felt about Einstein's talking about light. That's why they were like "what?"

Maya: Oh, I can't even imagine. You know.

Ben: So the crazy thing is, you know how we're talking about how you're deep inside a gravitational field, time moves slightly slower for you? Well, if you're in a gravitational field and you shine white light and that light climbs its way out of/ away from the star or whatever and moves off into space, by the time it gets into space, it'll be a different color. It'll start off white and it will end up more reddish. It will lose energy as it tries to get out of the gravitational field. So this is an effect called redshifting that's completely bananas, Newtonian-wise. But Einstein says "yeah, this is definitely different, people are going to disagree on what color this light is". If you're inside a gravitational field, you're gonna see that light as more bluish-colored and if you're outside, that light/ that same light beam is gonna look more reddish-colored - it's gonna have less energy.

33:28

Leo: This one was really hard to measure. People tried to measure it for a while after it had been predicted but it took until 1959 to actually measure it just because the technology wasn't available until then. And it was actually a really, really clever experiment done at Harvard to measure the redshifting of light in the Earth's gravitational field. Okay, so the idea is that you need to be able to measure frequencies of light, or colors of light, really, really accurately. And one way of doing that is to use a nuclear resonance. So what is nuclear resonance? So there are certain nuclei that like to be at different energy levels and the transitions between those energy levels, there's a certain energy difference and that corresponds to a certain color of light. Usually, when a nucleus goes from one energy level to another energy level and emits some light, that light has momentum and so the nucleus gets a recoil and so the light is not always at the same color because there was a little kick. So just like the redshifts, as the nucleus gets a little kick to it, that means that the color of the light is slightly different. So there's a spread in colors. But one way to make that spread in colors really, really narrow is to have this nucleus as part of a crystal lattice. And if it's in a crystal lattice then a fraction of a time the kick that the nucleus will get doesn't go to individual nucleus but it goes to entire crystal itself. And that means that basically the atom doesn't move and so the color of the light comes out almost at just one frequency. So it's very, very narrow. And the opposite is true, too. So that crystal lattice can absorb photons of different energies and usually it'll absorb photons of a range of energies around that special resonant frequency. But when it's the entire lattice of atoms that absorbs the kick, then it's very, very specific. So this experiment that was done in 1959 by these folks at Harvard named Pound and Rebka was they put one of these crystals at the bottom of some sort of shaft and another one at the top of the shaft and one of these crystals is emitting gamma ray photons at that special frequency and the other one is supposed to be absorbing those gamma ray photons. But because of the gravitational redshift that those photons get as they climb up through the Earth's gravitational potential, the photons are gonna be a slightly different color so they'll have moved off of the resonance which means that they're not gonna get absorbed and you could detect them behind the crystal. However, if you're moving the crystal down at just the right speed, then the crystal is gonna see the photons of its favorite color and absorb them. So depending on how fast the crystal is moving up and down, it's gonna absorb those photons at different speeds and you'd be able to detect what favorite speed corresponds to the change in energy from the bottom of the tower to the top of the tower. So it's really complicated experiment but I think it's really beautiful.

36:46

Ben: That makes sense, Maya?

Maya: Honestly, you lost me.

Ben: Okay, so you know about, like, atoms and, like, electrons, right?

Maya: Yup.

Ben: They deal with exact change, right? So, you can cause, like, an electron to jump up to a higher orbital by giving it a precise amount of energy. Like, a photon has to have an exact wavelength to get absorbed, right?

Maya: Yeah. Mhm.

Ben: So, same thing happens inside the nucleus. You need much higher energy scales to cause these transitions but you can cause the internal structure of a nucleus to transition between one state and another and if you do that, it needs exact change.

Maya: Mhm.

Ben: Okay. So, the idea here is: these nuclei will absorb that exact amount of change and they will emit photons at that exact frequency but no other frequency. If it's off by a little bit, they'll just pass through it. So, what they did was they took this tower at Harvard and at the bottom they put a crystal. And the idea behind the crystal is: sometimes when it emits one of these photons, the nucleus will kick back. And if it kicks back, it's gonna move. And if it's moving then, because of this redshift/blueshift thing, the color it emits won't exact change. It'll be off by a little bit, depending on how it moves. And so you can't control for that. But if you put it in a crystal, then sometimes it will emit exactly that amount of change, okay?

Maya: Mhm.

38:04

Ben: So at the bottom of the tower it shoots off these photons and they shoot straight up - well, I don't know, they probably go out into the walls and irradiate undergrads - but some of them shoot up straight up the tower, okay? And at the top of the tower they made a detector made of the same type of crystal. So the idea is that these nuclei are only going to absorb the exact change - the frequency or wavelength are off just by a little bit - it won't interact with it at all. But if it's exactly that - it'll absorb it. And so at the top of the tower, the argument is, if there's no gravitational redshifting, the wavelengths of these gamma rays should be the same at the bottom as at the top of the tower and the block of crystal will absorb them. And it didn't. At the top of the tower the gamma rays passed through. And the reason is, is because they have to climb through Earth's gravitational field and so they redshift - their color changes, it gets more red-colored, it's no longer that exact frequency that the nucleus want to absorb. And so it passes through the thing. And then they said "well, we have this competing effect; if we have an object that's moving we can cause this redshift" and so they took their absorbing block of crystal at the top of the tower and they made it move. And they found that if they move at exactly the speed that Einstein predicted, that would cancel out the redshifting effect, it would absorb it again. So essentially what they're doing is they're using this crystals as really, really, really accurate photon emitters and photon absorbers so you can tell whether or not your photons are exactly the same or slightly changed in frequency. And what they detected was that the change in the energy of the photons as they reach the top of the tower is exactly what Einstein's theory predicts.

Maya: Hm.

Ben: And it's crazy because they did it in a tower. They did it in clock tower, like alchemists! [laughs] Most of the evidence in favor of Einstein's theory of general relativity involves either large scale apparatuses or doing observations of the Universe for stuff really far away. Most of these effects are actually really, really subtle and so it's fantastic that a couple physicists and a tower were able to detect this effect. But they did and it's entirely consistent with what/ But I mean, okay. So we see redshifting and blueshifting and gravitational effects happen astronomically, too, right? So stars shine certain colors, depending on how/

40:17

Katie: How hot they are, mostly.

Ben: How hot they are, yeah. And you know, we were talking earlier about atoms emitting really specific frequencies. You can do spectroscopy on stars and you'll see spikes - emission lines depending/ maybe it's full of hydrogen or whatever. And you can recognize in the spectrum where the hydrogen peaks are. If the stars are moving away from us, those peaks will all be shifted to the red. If the star is moving towards us, they'll be shifted to the blue. And you can use this effect to do all sorts of things, like, you can use it to see if there's a slight wobble if the star's is in orbit around something like maybe a planet? It'll cause the spectrum to wobble a little bit.

Katie: Well, planets orbit around the star, at the same time the star's wobbling because the planet is tugging around. So you get this kind of back and forth motion from our perspective. And yeah, you can see the shifting of those emission lines as the star's alternately redshifted and blueshifted as it's going a little bit away from us, a little bit toward us. And we've discovered tons of planets that way.

41:16

Ben: Hey, do you want to tell that story about the supernovas?

Katie: Oh, yeah, yeah. So, well. Okay, so I have to do the expansion of the Universe real quick. Okay, so the Universe is expanding. As the Universe is expanding, we're in one spot in the Universe and so from our perspective that makes it look like everything is moving away from us. And it's not just, like, that they don't like us. It's that everything is moving away from everything. And so if you're in a different spot in the Universe, it'll also look like everything is moving away from you. I mean, there're nearby things that are not moving away from us but the most distant things, the galaxies, those are all moving away from us. So anyway, we can tell that these things are moving away from us because their light is redshifted. And the further away something is, the faster it's moving away from us because the whole Universe is expanding sort of uniformly, so the further away you are, the more quickly you're receding and so we actually measure distances in cosmology with redshift. By how much these things are redshifted. And so that's an effect that's just because, like, space is stretching and it is messing with how light is stretched out and how light is getting to us. But it also messes with time. Like, basically, something that's moving away from us really quickly or something that's, like, being gravitationally redshifted by the expansion of the Universe, that thing is kind of moving in slow motion from our perspective. For the same kinds of reasons that something that's moving really quickly or something that's in a gravitational field - their time is moving more slowly. Like, one of these consequences of the expansion of the Universe is that things that are further away, that are moving away from us, should seem like their time is moving more slowly. And you wouldn't think that that would be, like, particularly relevant to a lot of different things but it turns out that there are certain kinds of stellar explosions called Type Ia supernovae - these are kind of exploding white dwarf star - and these kinds of explosions happen in very similar ways whenever they occur. So white dwarf gets to a certain mass, it explodes, it makes this explosion where it gets brighter for a bit and then the light sort of fades and there's a characteristic time that it takes for this light to fade after the explosion.

43:29

Leo: How long is that?

Katie: It's something like tens of days. So it takes a few days to rise and then it takes something like 20 days to fall to, you know, sort of normalish levels again. Normalish for like/ I mean, usually we see these things in a galaxy far away and so for a short time the star that just exploded is outshining the whole galaxy and then it sort of fades away into the background of the galaxy again. So it takes, you know, sort of like 20-ish days or something is the sort of normal kind of light curve that you get from this sort of thing. And it turns out that if there are supernovae happening in very, very distant galaxies, the same kind of explosion is happening but it looks like it's going in slow motion. So it takes longer. So if you have a galaxy that's at a redshift of 2, which means that the light is stretched out by a factor of 3, depending on/ So, okay, with one plus Z, Z is the redshift. It's the light is stretched out by a factor of 3 if the redshift is 2, okay? So that's the number that we use. Anyway, if we have a supernova that took 20 days from the brightest point to fading away, if we saw that thing at redshift 2, it would look like it took 60 days. Like, we would see it take 60 days because the light has been stretched out, the time has been dilated and we can actually see these things go in slow motion.

Leo: So everything we see in the Universe is in slow motion.

Katie: Yeah, so the further away the thing is, we can watch it evolve more slowly and it's not that the sup/ Like, if you were near the supernova, which we would not wanna be doing, then it would still take 20 days if we were there. But from where we're standing we watch it happen in 60. And that's like a real thing you can really see. Which is super weird.

45:16

Ben: Yeah, so time is definitely mutable in weird ways.

Katie: Yeah. Yeah.

Ben: Incidentally, let's circle around back and talk about cosmology a little bit more. So in the late 1910s the scientific community was like "okay, maybe we believe this Einstein guy and his theory that says that time intervals and space intervals change, this theory that says spacetime is curved and that's the reason there's gravity; maybe we'll believe you, Mr. Einstein; now what?" And so the scientific progress in this field since then has been informing and informed by astronomical observation in really interesting ways. In ways that are completely/ have nothing to do with Isaac Newton's theory gravity. And one of the first ones involved talking about the behavior of the Universe at the large scale. 'Cause you can talk about how the Universe has gravity, the Universe as a whole will have some general spacetime curvature and this curvature will be dynamic, as the Universe evolves. And so in the early 20s Einstein was like "oh, look; most of these weird solutions describing the Universe describe a Universe that is expanding rapidly or contracting rapidly or maybe collapses down to a point; I don't like that at all". And so he changed the equation, he added a constant into his equation so that everything could sit still and he goes "there, if we do everything right, this is a nice, static Universe - a Universe that doesn't change" and then immediately after that Edwin Hubble announced this crazy finding. He was looking at galaxies that were further away, far away from our Galaxy, in essence. This was before we even had a good enough telescopes to tell that there were other galaxies. We thought they were maybe big, puffy clouds of gas out there.

Leo: Yeah, they still just called them nebulae back then.

Ben: Yeah.

Katie: Spiral nebulae.

47:11

Ben: So Edwin Hubble took his telescope, the one in Los Angeles, incidentally and he measured these galaxies and he could tell based on analyzing stars in them, very special stars, how far away they were from him and how they were moving relative to our Galaxy, say. And he found that essentially there was a law that says the further away from our Galaxy another galaxy is, the faster it will seem to be moving away from us. Now, the galaxies also have a little bit of lateral motion up/down - that's a little bit random but there's this general trend where stuff seems to be moving away from us. And this was mathematically consistent with Einstein's theory of how a dynamic Universe would behave. If the Universe is expanding - even if it's an infinite Universe - if it's expanding, if the distance scales are increasing, then it will look to all observers on it like the whole thing, everything is moving away from you. And so that's what he saw. And when Hubble's like "hey, look we have a Universe that's expanding - it's a dynamic Universe, stuff is getting further away from us" it was entirely consistent with Einstein's theory, except it was entirely consistent with the theory before he added that constant by hand so everything would sit still. So Einstein had accidentally predicted that the Universe could be dynamic, evolving in time. He didn't expect that it was right bit it turned out to be fairly accurate and so since then the study of cosmology studies essentially how the Universe at the largest scale is evolving. And it's a field of study that's entirely enmeshed with Einstein's theory of general relativity. It's a theory that has no classical precursor. Our analytical techniques, the concepts that we use to study these things have no precursor in classical physics.

48:54

Katie: Well, yeah. I mean, as a cosmologist, you know, I deal with the large scales of the Universe and the early Universe and how the Universe is evolving with time and I can't do anything without stuff that is super rooted in Einstein's relativity. I mean, talking about the distances to other galaxies in terms of redshift, like, that only makes sense if the Universe is expanding and the expansion of the Universe shifts light into the red by stretching it out. And it doesn't make any sense with any other model of the Universe. And time dilation, all of these kind of things are just super fundamental to thinking about the large scale Universe. So there's stuff that's just totally weird and is completely enmeshed in this idea that the expansion of the Universe changes light and changes time and everything is dependent on the curvature of spacetime.

Ben: So, the thing is: Einstein's theory has room for a lot more exotic things than just planets going around stars. And as interesting as cosmology is, it predicts a lot of things that are a lot crazier than cosmology. Like black holes, like gravitational waves.

Katie: Black holes are awesome.

50:10

Ben: Modern gravitational physics in part is interested in analyzing, detecting, interpreting to see whether or not those more exotic predictions are there. Because if Einstein's theory fails to describe the theory really well - just the way Newton's theory eventually failed to describe how planets went around the star. If Einstein's theory is gonna fail, it's gonna be in these more exotic situations. Black holes and stuff. Leo!

Leo: Hello. So this is kind of the research that I work on. We wanna learn more about the nature of gravity. And that means that we have to try to find places where general relativity is pushed to its extreme limits.

Katie: Can I interject something, really quick?

Leo: Yes.

Katie: Yeah, so one of things that I really like to stress talking about these kinds of things is that, like, it's all about finding the limits of the theories and the, like, edges of where things are valid. So just the same way that Einstein didn't prove Newton wrong, per se. Like, tests of general relativity, tests of Einstein's theory are also not trying to prove Einstein wrong, per se. What we're trying to do is, say, like, anything you can do in a room by yourself with, like, balls and tables and, like, these inclined/

Leo: Lasers.

Katie: Yeah, like lasers and inclined planes, whatever. All of that works perfectly fine with Newton's theory. Unless you're in, like, in a super fancy lab, you know, with really high-tech equipment, everything that you do in your daily life is gonna be fine with Newtonian gravity. There's no/ you don't have to do anything weird. And it's only when you get to stuff that's stuff that Newton really couldn't even have imagined, then you end up having to tweak the theory to fit better with Einstein's theory. So, Einstein's theory - you can reduce it to Newton's theory and there are regimes where you just don't need to do any of the Einstein's stuff at all and Newton's theory is just fine. And that was really important for making general relativity, like, a valid theory, was that it had to reproduce, as Leo said, had to reproduce all of Newton's predictions, you know, in those regimes. But then there are edges of Newton's theory where it doesn't work anymore. Like if you're trying to move something close to speed of light, you can't deal with Newton's theories. If you're dealing with really, really strong gravity, you can't deal with Newton's theory, you have go to Einstein's theories. And so every theory probably has some range of validity, some regime where it actually makes sense and it actually works and fit the data and then some region beyond that where it stops working and breaks down. And so right now we've got Einstein's theory, it's going great but we're trying to find, like, the edges of where Einstein's theory might have its own breakdowns the same way that Newton's theory had its breakdowns when we start doing really unreasonable things Newton wouldn't have thought of.

53:00

Maya: Have we found any inconsistencies in Einstein's theories? I mean I'm guessing the answer is no because of the gravitational waves stuff.

Katie: Spoiler alert! We've tried everything. We have not yet found the edge of validity of Einstein's theory. We can talk about what we're trying.

Maya: That's okay

Leo: But there's gonna be more and better tests in the future, hopefully in the near future. So let me say that almost everything that we talked about up until now was in the regime where you could think of general relativity as just small corrections to Newton's theory of gravity. But that's not true on cosmological scales where it's the whole Universe that's expanding and it's not true when you get down to the scale of black holes where it's gravity itself that is holding the black hole together - it's only made out of gravity, there's nothing else there.

Katie: Yeah, black holes are awesome because, like, you take a star and you collapse it and it collapses and it's not a thing anymore. Like, once it becomes a black hole, you can't really talk about it as a thing, like stuff. I mean, you can describe a black hole as just, like, a dent in spacetime and kind of not much else. Like they might have a charge, which is like there's some kind of, you know, trapped electric field kind of thing going on, it can spin but, like, spacetime can be/ just have a sort of spin to it in that region. And it has the mass which is just how much spacetime has sort of bent and made this dent there but, like, that's it. That's all a black hole is - it's just a spacetime thing. It's not even mass anymore, it's not even matter anymore. It's just a spacetime thing. It's really cool.

54:39

Leo: Yeah, so if you wanna look for places where general relativity might be pushed to its extremes then you don't really want the places where it's close to Newton's gravity, you want the places where it's as far away from Newton's gravity as possible. So that's why we wanna look at cosmology, we wanna look at black holes, we wanna look at systems where systems are moving very close to the speed of light and that was exactly what the, you know, the most recent test of general relativity was, which was the announcement of the detection of the detection of gravitational waves.

Maya: Pam pam pam!

Katie, Leo: [laugh]

Ben: So. So, the moral of the story is: to put it briefly, we want to talk about analyzing locations that have lots and lots of spacetime curvature because that's where the theory's gonna go wrong. And cosmology is only the tip of the iceberg. So the big one is black holes, right? Black holes are absolutely bananas, 'cause there's nothing there. There's no surface, there's no star. All there is is spacetime curvature. It's gravity gravitating upon itself. There's other stuff, too. Like, the detection of gravitational waves. Which is absolutely fantastic, we heard about it in the news. The deal is the LIGO facility, using kilometer long interferometers managed to detect waves in spacetime. Any ideas that spacetime has a geometry, information in spacetime travels at the speed of light so if you have a system that's rapidly evolving, say you've got two massive stars in orbit around each other that crash together dramatically changing the dynamics of the system, that information will move out at the speed of light and that information will be encoded as a spacetime curvature, as changes in intervals of time, intervals of space. And we can describe those and detect those as gravitational waves. And one of the biggest defects here isn't all that recent. It happened in the late 70s/early 80s. There were two binary pulsars. So two neutron stars in orbit around each other.

56:41

Katie: So one of them was a pulsar. So pulsars are neutron stars that are rapidly spinning and they're spinning in such a way that there's like a jet of radiation and particles coming out of each pole of the pulsar. And the pole of the radiation is not the same as the pole of the spinning. So like it's spinning on a different axis than the radiation and so it means the beam sweeps around/

Leo: Like a lighthouse.

Katie: Like a lighthouse, yeah. And so if there's a pulsar out there where the beam passes over the Earth every once in a while, then we'll see that pulsing. And when I say once in a while, I mean like, within like milliseconds or seconds or whatever. Like, they spin really fast.

Leo: Yeah, the best ones spin - by best I mean the ones that have the best science that you can do with them - spin as fast as possible. Because you can get better precision on the measurements if they're going faster and those spin around once every, say, 5, 10, 20 milliseconds.

57:39

Katie: Yeah, so these things are spinning really fast and the timing of that spinning, they're like extremely accurate clocks. So the jet sort of sweeps out at the same intervals, like really, really accurately and so because they're really accurate clocks, then you can measure how their time is moving. And so if you have a pulsar and another neutron star, they're orbiting each other, you can measure the timing of the orbits and the timing of that clock really accurately. And that allows you to know the system really, really well and so in the 60s and 70s, yeah, the system was discovered where it was a pulsar orbiting a neutron star. So the other neutron star might or might not have been a pulsar but it wasn't facing us so we didn't see any pulses. But these things were orbiting each other/

Leo: Once every 8 hours, think about that.

Katie: Yeah, really quickly.

Leo: These two objects that are each just, like, 20 km across and each of them is about 1.5 times the mass of the Sun, and they go around each other once every 8 hours. That's crazy.

Katie: Yeah, they're really/

Ben: They're really close together to your liking. At closest approach, the distance between them is smaller than the width of the Sun. So they're really close together. Yeah.

58:53

Katie: Yeah, so really extreme system in kind of every possible way. So the scientists were studying, like, how quickly they were orbiting each other and looking at the ticking of the clock and they've found that the orbit was shrinking a little bit over time.

Leo: Before they've found that, they've found some simpler effects. Well, I don't know about simpler but there's a lot of special and general relativistic effects that you can measure from the system. Just like Mercury's precessing, this system's orbit is also precessing. And how much it precesses is a prediction of general relativity and it's basically bang on. You can measure the Shapiro delay in the system. Well, maybe not in the Hulse-Taylor pulsar binary system but in other pulsar binary systems you can measure the Shapiro delay as light from the pulsar goes close to the other massive object, it gets delayed. And finally there's what Katie was talking about.

Katie: Which is the neutron stars are getting closer and closer together so the period of the orbit is getting smaller and they're sort of spiraling into each other and the reason they're doing that is because they're emitting gravitational waves and that's carrying a little bit of energy out of the system over time and the emission of gravitational waves is allowing the system to come together and eventually the two stars are gonna crash into each other.

60:15

Maya: What happens when the stars crash into each other?

Katie: Well, probably a gamma ray burst, which would be awesome. And also we probably see a signal in LIGO, I guess, if it's still around by then. I don't know how long it'll be/

Leo: Yeah, except I think the Hulse-Taylor pulsar binary might/ I mean, we'll all be long dead. I don't know if it's a hundred million years or if it's longer than the age of the Universe but it's super long. But we know about, you know, dozens of these systems/

Katie: Yeah.

Leo: /and at least a handful of them we know will merge within the lifetime of the Universe but none during our life. None of these pulsar binaries will merge during our lifetimes.

Katie: Yeah. But when they do come together, they'll probably make a short gamma ray burst which is like a big burst of radiation and they'll send out even more gravitational waves. But the gravitational waves that they're producing now are the thing that are taking energy from the system and LIGO is capable of detecting gravitational waves from other kinds of neutron stars orbiting each other.

Leo: Ones that are orbiting even faster. So because this Hulse-Taylor system is once every 8 hours, the gravitational waves are at twice the frequency, half the period. So it's a gravitational wave signal that repeats once every 4 hours, about. But LIGO is sensitive to gravitational waves that have frequencies of about 10 hertz to around a 1000 hertz, so that's in audio frequencies. So that means oscillations 10 times a second or up to a thousand times a second.

61:52

Maya: So that's where the chirping comes from?

Leo, Katie: Yeah.

Katie: The chirp is the rapid increase in frequency of the gravitational waves as things are about to merge. So the gravitational waves come at sort of, like, up and down, up and down over time and the time between the sort of waves gets smaller and smaller as the orbit comes together 'cause it's a tighter and tighter orbit. And so as they're about to merge, the waves are coming really, really fast and then they sort of reach sort of crescendo and it makes this high-pitched chirp sound. I mean, it doesn't make a sound, it makes a burst of radiation, of gravitational radiation but if you pretend that that gravitational radiation is actually sound waves, that's what it would sound like. As a chirp.

Maya: So it doesn't actually emit that sound. What would it actually sound like if you were there?

Katie: I mean, it's not/ Like, a sound is a pressure wave in a medium. So like a sound is, like, pressure in the air hitting your ear and gravitational waves don't do pressure waves. What gravitational waves do is they stretch and squeeze spacetime and so if a gravitational wave hits you in the face, then your face gets a little bit wider and a little bit shorter and then a little bit taller and a little bit skinnier. And it does that, it sort of oscillates back and forth like that. I mean, technically if you're really close, you might kinda hear something because it would be messing with, like, the/

Leo: It would be squeezing your ears on the inside.

Katie: Yeah, squeezing your ear and like messing with like how signals are travelling between neurons.

Leo: But you wouldn't wanna be that close.

Katie: Yeah, that wouldn't be good. That would not be a good place to be.

Maya: I just wanted to know what it would sound like.

63:29

Katie: Yeah. It would, I mean, it would/ I mean it would probably/ you'd probably feel it before you heard it. You'd probably feel like sort of tingling 'cause all the little nerves would be kinda stretched out and the nerve signals would take little bit longer to travel and that would feel weird. I've thought a little bit about this.

Leo, Ben: [laugh]

Katie: It's kinda disconcerting.

Leo: So that pattern of squeezing and stretching that Katie described, that's one of the predictions of general relativity. The exact way that things get squeezed sideways and up and down. But that's one of the types of tests that might be possible in the future. Because there are other ways that you can squeeze things and so in theories beyond general relativity some of these/

Katie: Alternative theories.

Ben: Conjectured candidates.

Leo: I don't wanna, yeah, I don't wanna say alternate/ Yeah, I wanna say potential corrections. Different ways that you could think of adding other stuff to general relativity. Then you could change the ways that gravitational waves could squeeze and stretch things. I could make it so that it would, so that if it hit you in the chest, it would make you fatter and thinner and, you know, make your gut grow forward and back instead. Which is not something that's possible in general relativity. So to do those kinds of tests, we would need to wait for future gravitational wave detectors to come online. We would need more than just the two that we have today. Another one of these gravitational wave tests is that general relativity predicts that gravitational waves travel at the fastest speed possible, so the speed of light. But there are other potential changes that you could make to the theory that would make gravitational waves a little bit slower or a little bit faster than the speed of light and that was actually a little bit tested with this the first gravitational wave that was directly detected back in September. Spoiler alert! It's still totally consistent with being massless.

Ben: [laughs]

65:32

Katie: Well, so it's consistent with travelling at the speed of light which is what massless things do. So if whatever is carrying gravitational radiation, if you interpret that as a particle, it's massless particle.

Leo: Yeah.

Katie: I mean one of the things that I think is awesome about the gravitational wave discovery is that it really incorporates every part of Einstein's relativity. Like, you can write down the things Einstein came up with and like you can just check them off on this discovery. Okay, so there's the speed of light as this ultimate speed limit and the gravitational wave travels at the speed of light. And that's like, you know, you can measure the delay between when the gravitational wave hit one of the detectors and then the other and it's just the right delay for light travel time to be that. So, speed of light constant - awesome, we got that. Then there's the whole bending of spacetime being gravity and the ripples in spacetime, gravitational waves, that's what we measured, that was cool. There's the constancy of the speed of light, so one part of special relativity - I mean the thing you can kind of derive everything about special relativity from - is that the speed of light is constant and you need that fact to measure gravitational waves at all because the LIGO detectors rely on that to be able to measure the change in distance of the arms as the gravitational wave comes through. So you've got speed of light being constant that's used in this gravitational wave discovery. And then there's the $E = mc^2$ that comes into it, too - awesomely - so we can use the gravitational wave waveform to measure the mass of each of the black holes before they came together and merged into one black hole. And you can find that there's like 3 times the mass of the Sun left over when you add up the mass of the two black holes and then subtract the mass of the final black hole, there's like 3 solar masses missing, right? And that was converted into the energy of the gravitational wave and so his $E = mc^2$, like you took the equivalent energy of 3 times the mass of the Sun and converted it straight from mass into energy in this merging event. So like every little bit of relativity you could see in this one detection. It's so amazing.

67:43

Maya: That's really cool.

Katie: Yeah.

Maya: Personally I think it's a little strange that time is not constant but light is. That's not something that I would've expected for some reason, I don't know why.

Katie: I know, it's super weird, right?

Maya: I don't know why light is the same but time is not. We can't rely on time but we can rely on light, if that makes sense.

Katie: Yeah, yeah it's just this strange part. I mean, everything in relativity kind of comes out of that fact that light doesn't care what's happening, it travels at the same speed no matter what you're doing to it. I mean, if you make it go through a medium, like glass or something, that slows it down because it's bouncing off stuff but like if you just go through a vacuum and you're like warping the spacetime and you're like doing all these things with gravitational fields and you're moving, going by in a rocket

Leo: Like, flying by in a rocket ship.

Katie: Light doesn't care. It just goes at the same speed. It's like "whatever guys, I'm just doing my thing". And that's where all the weird effects from special relativity come from and that's like part of why you get the sort of stretched out, redshifting. You can interpret that as being like the crests are coming at different times because the time is being dilated but the light is travelling at the same speed. So like super weird but yeah, that's the thing. That's the one thing you get to keep in relativity, that the light speed is constant. And everything else kind of comes out of that being the one thing that's always the same. Oh, yeah, redshifting comes into it too. Like, redshifting affects the shape of the waveform of the gravitational wave and that tells us how far away the black holes were, too. That's also in it. Everything's in it!

69:20

Ben: Hey Maya, are you convinced that general relativity has lots of evidence behind it, even though it's, like, totally gonzo?

Maya: I am, it's pretty satisfying that it all fits together.

Ben: Oh yeah, it's extraordinary.

Maya: I get the hype of the gravitational wave discovery.

Katie: Excellent!

Maya: I do understand. If it had not been discovered I see how everything would have been completely destroyed. I think things would have turned out a lot different.

Ben: Can you imagine going back in time and telling Isaac Newton about it? You'd be like "gravitational waves" and he'd be like "what?" and you like "black holes hit each other" and he'd be like "what?" Just like "energy's carried away" - "wait, what?" and yeah, it'd be fantastic. - "Redshifting" - "What?" Yes, he just wouldn't understand in his infinite genius. Alright, it was fantastic. Thank you Katie, thank you Leo, you've pleased me, your efforts have borne fruit and that fruit is sweet. Here's some fruit! Katie, you get a watermelon!

70:20

Katie: Yum num num num um

Ben: And Leo, you get a cara cara orange.

Leo: Yum yum yum yum.

Ben: Sweet, I'd like to thank my guest, Maya Inamura, the science writer extraordinaire. You can follow her on Twitter [https://twitter.com/mayainamura] and we'll have links to her stuff on our webpage. Did you have fun, Maya?

Maya: I did, thank you.

Ben: Hooray! Alright.

70:41

Ben: First off, please give us an iTunes review or tell other people about us online. The simple reason for that is that lots of people like physics but very few people admit to liking physics in public. And so, when other people come up to them and tell them about things they might like, they'll have a listen. Bring new audiences to our show. If you give us iTunes review, it'll raise our rank in the iTunes ratings and more people will hear about us. Anyway. On a second note our transcription project is still going nicely. If you'd like to try your hand at transcription, send me an e-mail to barn@titaniumphysics.com. On a related note, we're still humbly soliciting your donations. Your donations go to pay for our server fees and also to pay for people transcribing all of our episodes. And you can send one-time donations through a PayPal off of our website or you can go to our sweet Patreon site and give a recurring, I don't know, 2 dollar donation. This particular episode of the Titanium Physicists podcast has been sponsored by a collection of generous and wonderful and intelligent people. I'd like to thank the generosity of Mr Alexander Rin and Mr Etain Callie for their donations. And I'd also like to thank Norah Robertson, Ian Cutler and Stewart Pollock. A Mr Frank Philip from Austria and Nosy Mime. A Mr. Shlomo Dlal, Melissa Burk, 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 as always Mr. Robert Stietka. So, that's it for Titanium Physicists this time. Remember that if you like listening to scientists talk about science in their own words, there are lots and lots of other lovely shows on the Brachiolope Media Network. 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.

73:07

[Outro song; *Angela* by John Vanderslice]

74:09

Ben: Okay, so first off, are there any questions?

Maya: How can I be an astrophysicist?

Ben: Oh. Ah, really? That's a good question. Mostly you go to school, you do an undergraduate degree in astronomy or physics or mathematics or even engineering. And then you go to graduate school until you're tired of graduate school. Right? And then you're just a postdoc until you, yeah

Katie: Until you give up or/

Ben: Yeah.

Leo: Some people are also amateur astrophysicists and they still contribute to the literature, they contribute to observations and/

Ben: It's true.

Leo: Just in their spare time.

Ben: Yeah, I mean there's lots of work to be done from theoretical analysis to data gathering and so, yeah, there's lots of places to fill if you want to. Do you want to become an astrophysicist?

Maya: Um, I'm not interested in being astrophysicist.

Katie: Oooh. [laughs]

Maya: No, I'm not.

Katie: But it's fun.

Maya: I know, I'm/

Ben: That's fine because it means there are fewer people trying to get the one job in astrophysics.

Katie: That's true, yeah.

Leo: How about donating your CPU to contributing to astrophysics?

75:30

Maya: Okay, I'd totally do that. I'm totally a fan of everything you guys do. Especially with the verge of the philosophical stuff. 'Cause that's really what I'm interested in. I mean the reason primarily that I got into science was when I went to college, I went to Columbia and I started off, like many Columbia undergrads do, thinking I was gonna be a political science or philosophy major, so I took a philosophy class my first semester there and I think it was called methods and problems of philosophical thought or something like that and I wanted it to be like an introduction to, like, you know Greek philosophers. I don't know why I selected it but it turned out to a lot of thinking about time travel and a lot of thinking about/

Katie: That's sounds awesome.

Maya: /the future and past and arguments for, you know, what was gonna be possible and all this stuff and I just/ it/ I totally disagreed with the professor's understanding of the future and the past. And he kept talking about time travel to the future or time travel to the past and I kept thinking, you know, "But I'm pretty sure that scientists established that time travel to the past isn't possible, 'cause the past already happened", right?

Katie: Yeah.

Maya: And you can travel to the future and so I thought "why are we spending a semester thinking about what would change if we could travel to the past and change things if it's never going to happen?" And I just could not get myself in that frame of thinking I guess, if that makes sense. I don't know why I remembered this. I guess this was your little soliloquy that (...) had about

Leo: I wanna say that that was really amazing because I took a philosophy class as an undergrad here at Caltech that was called philosophy of space and time. And we also spent a lot of the course talking about whether time travel is possible and how our understanding of the structure of space and time changed from the ancient Greeks to today and what I was thinking when I was taking the class was "but why are we talking about these things from thousands of years ago? Because we already know that their understanding of space and time was wrong". And that was the last philosophy class I took.

Katie: Right.

77:59

Maya: Now, I completely understand that. Especially, what's also really frustrating is spending time reading philosophical texts that their authors have later disavowed and so that was pointless and wrong and there's no reason that you should read them and then you spend time with, like, Wittgenstein. Anyway, that's unimportant because I ended up not studying philosophy because then I bounced around a little bit, did really well in an astronomy class and then I settled on primatology and I/ So I have BA in evolutionary biology of the human species but I ended up studying, like, public health and, like, human adaptation types.

Katie: You've done all of the science. That's awesome.

Maya: I have. And I also was gonna be East Asian studies major for a while so I have, like, some Japanese literature classes under my belt. It took me a while. But I'm happy with what I studied because now I get to learn about things like this from a totally different perspective from my class. So I walked out of that philosophy class just thinking that I need something concrete to latch onto and a world where people establish facts and they stick to them and they will all accept that time travel into the past is not possible and there's no reason to think about it and we can just devote our time to other things that are more productive, in my opinion. So, that's kind of what has inspired me to enjoy observing the world and gathering data and making conclusions about that rather than just thinking about things that would never ever happen.

79:29

Katie: Yeah, sounds cool.

Ben: Fun. Oh man, oh time travel to the past. I love it so much. Anyway, okay, okay, okay, okay. Let's get on track here. Because it's interesting that you say those things because Einstein's theory allows in some cases for weird possibilities where you can travel back into the past.

Maya: Oh geez. Great. Thanks a lot

Ben: Yeah, don't worry, don't worry about it. Because the theory itself is really bananas.

80:04

Maya: Quite honestly right now I'm thinking about how much better I would have done in high school physics if I got them talking about astrophysics. It just makes much more sense. Physics itself makes much more sense if you learn about astrophysics before you learn about Newtonian stuff and like cannonballs and stuff like that. You know, that never made any sense to me, honestly. But it makes much more sense learning about curvature of spacetime and that's why planets move around the Sun and that's the same reasons that rollercoasters have to bank for going around bends and things like that. I think it makes much more sense to me looking back at that curriculum. Understanding the curvature of spacetime before. But that's not the order that you learn about it in.

Ben: No, you learn about wheels for three years and then you get to/

Maya: Right. And they force you to memorize, you know, equations, like it's origin of gravity or whatever but you don't really understand what that means on a grand scale. You just learn what it means for things falling off cliffs.

81:04

Katie: I think one of the nice things about GR, about general relativity, is that this kind of geometrical idea's/ is kind of very visual - you know - it's kind of like you can imagine it, you can kind of have this intuitive picture of, you know, this warped spacetime. But unfortunately the math is lot more complicated than pretty much anything else aside from, like, sting theory in physics. So on the other hand, special relativity is not very complicated mathematically. I think special relativity should be taught in high school 'cause it's awesome and it's really fun and it's not that complicated mathematically. But GR takes, like, a lot of, well, I mean Einstein had to learn, you know/

Leo: Differential geometry.

Katie: /differential geometry, so, you know there's a lot that goes into that. But I do like the idea of using cosmology and relativity as a kind of like "here's the context in which the Universe is happening and let's think about it that way".

Leo: Yeah. That was one of the things that I liked about studying astrophysics, was that at different times at my astrophysics education I had to learn about statistical mechanics, I had to learn about nuclear physics, I had to learn a little bit about chemistry. There are all these different things that I had to learn and I think astrophysics might be the only branch of physics where you have to know a little bit about every other branch of physics.

82:29

Ben: Mhm. I like what you're saying. It's like when you wanna take karate lessons and they're just like "here's a video of, like, a guy punching a tree in half" and you're like "yeah, that's gonna be me" and they're like "okay, pushups".

Maya: Right? I know.

Katie, Leo: [laugh]

Ben: Do pushups for 50 years and then you can punch a tree in half.

Maya: I guess this is why I could never just buckle down in my high school physics classes. 'Cause I always wanted to think about a lot more, I guess what seemed to me important questions of what science could do. I didn't wanna sit there calculating. I just can't get over the cannon balls. 'Cause they just ruined science for me. Sitting there and, like, calculating the/ and it just made no sense to me, conceptually. And I always wanted to think about the bigger questions. And now I get to talk about the bigger questions and it's just lot more fun.

Ben: Yeah.

Leo: I think a lot of it depends on how engaging your lecture is. I mean, honestly I probably ended up studying general relativity because one of the best lectures I had was my general relativity lecture. And then I started to do research for him.

Ben: It's funny, 'cause it's not like general relativity has entirely usurped all of the ideas from Newtonian mechanics. There's a lot of Newton stuff in there still. Like, energy, momentum. There's a lot of people talking about inertia. Inertia is a big thing in Einstein's theory. And these are all inherited from Newton's methods. And it's kind of interesting 'cause if you want to train a physicist and you want to increase the level of complexity but also focus on things that'll be relevant later, you essentially want to drill them on cannon ball questions until they can do the really crazy mathematics. But I see what you're saying. There's not very much carrot there. Mostly stick.

Maya: I guess this is why I thought I wanted to be a philosophy major, so I could think about the big questions. But then I went to philosophy and to me it seemed so froo froo and unrooted in reality. And it's often its own world that I really wouldn't wish of being a part of. So I was a lot happier observing but the/ if we just could have studied black holes in high school, I think I would've turned out a lot better.

Katie, Ben: [laugh]

Leo: Yeah.

Ben: I think they should teach black holes to high school students, too.