Cosmology (THE UNIVERSE) Pt. 1 with Katie Mack
Ologies Podcast
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Heeey. Welcome to Ologies! I'm your Alie Ward, host. Each week I sit down with an Ologist, I ask why do they love what they do, and "what is your deal?" What should we know about it?" and this week: we cover [*echoing*] the Whole Fucking Universe, which has existed, and it's expanding, and you're floating in it, and you're made of particles, and matter, and forces we don't even understand! And maybe there are multiverses. And is this reality? And what are you doing here? And does anything matter? And of course it does. But should you be afraid of wearing bright lipstick or dancing in public? Probably not, no, in the scope of things. And the scope of things is really… It's giant. It's called Cosmology.

If you thinking you listened to this episode already because you learned some stuff about beard care and face wash, think again suckers! That was Cosmetology. This week is Cosmology, the study of the cosmos. So when I say this episode is everything. It's actually everything. It's the whole universe. It's…it's a lot.

It's so much it's a two-parter. It's a twofer. This week, we'll get the nuts and bolts of what astrophysics is. After about an hour, you will walk away cocktail party literate on goddamn astrophysics! Kind of. I don't know. I'm learning here with you. Of all the episodes I've done, this was probably the one I knew the least about, so let's learn together, shall we? Part Two of this, next week, are your questions, submitted via Patreon and the Ologies Podcast Facebook group. Y'all had good ones. Next week we'll address them.

Now the etymology of cosmology: Kosmos with a "k" is the kicky li'l Greek word for world, or order. So cosmology is the study of planets and such, sure, but also WHY? AND WHAT? AND HOW? WHERE? WHAT? HUH? It's the study of Whut?

This week's cosmologist is someone I've had a fawning Twitter fascination with for a while, and I met through a group of science friends I love, known to some as the Nerd Brigade (we're like a gang with a website). I was always kind of intimidated by her because she is, in her own words: "an academic nomad," and she continent hops while studying particle physics, and black holes, and gravitational waves, and she hangs out with Stephen Hawking. So when I met her through friends, I usually just sat at brunch like a barnacle and tried to look away when she caught me staring at her.

I asked her to be on the podcast, she said Yes, and I immediately started perspiring. She came to my apartment, we sat down, and my usual hour interview stretched to almost two (hence the two-parter) hours, before she politely reminded me that we were supposed to be meeting people for a movie and we should stop. I am so, so glad we did this podcast because I got to know her even better as a friend. Which y'all, I'm gonna be cheesy and say it is a true honour.

In this episode you'll learn about the things that make you, you. The stars that exploded to make the things that make you, you. And the scale of our existence in space, and what it feels like to be heckled by Stephen Hawking, and if this is real life, and if astrophysicists are just making bullshit up that the rest of us just accept because we're like, "Man, I don't even know how to read these equations, so okay."

You'll get, at the very least, a loose grasp on, just, the whole of existence. Maybe steel yourself to be the biggest You you want to be. And more importantly, get to know better one of the world's finest voices in cosmology. You know her as @astrokatie on Twitter, aka astrophysicist Katie Mack.

[*Intro Music*]

Alie: So take me back to defining some stuff. Because as a layman, as a laywoman over here… a lay-human, I don't know the difference between a physicist, an astrophysicist, a particle physicist, an experimentalist, a cosmologist, and an astronomer. I don't know what those are. I'm either going to have to Wikipedia this [*Katie laughs*], or I can have you give me a rundown.

Katie: These things are a little bit fluid, these definitions. An astronomer is basically somebody who studies space in some way. Usually when people say astronomer versus astrophysicist, usually astronomer is more on the observational side or, sort of, describing stuff in space. Astrophysicist is more about trying to understand how the physics of the thing in space works. You can be an astrophysicist trying to understand how galaxies form, for example. You're applying physics to this stuff in space.

If you're a particle physicist you're working on how particle interactions work, so atom smashers and things, Large Hadron Collider, Higgs boson. Usually the classic particle experiment is you take two particles and smash them together and you see what comes out. That's what the Large Hadron Collider is doing.

Aside: Now the LHC, that's what you call the Large Hadron Collider when y'all are tight. You've maybe heard of it? You kind of know it's a thing in Europe, maybe? It has something to do with atoms? I looked in to it. The Large Hadron Collider is located near the France-Switzerland border and it's a circular tunnel. It's over 500 feet deep in some parts and is 17 miles around. It is the largest machine in the world.

This thing consists of over 1,200 magnets, and they're cooled to a temperature colder than outer space. The magnets accelerate protons to almost the speed of light and then the protons are bashed together. It's very punk rock. Very expensive.

The LHC was mostly completed in 2008. Over 10,000 scientists and engineers worked on it. In photos it looks kind of like a giant, well-lit subway tunnel. But with less pee. And rats.

If you're like: "I CAN'T REMEMBER WHAT A PROTON IS BECAUSE I'M NOT REQUIRED TO ANYMORE, I'M NOT IN SCHOOL!" Don't worry. Neither did I. I had to Google "how does an atom work." I forgot. So I'll brush you up. Matter is stuff. Molecules are some atoms stuck together. Atoms are made of a nucleus - which is a little cluster of neutrons and protons. Protons have a positive charge – pro. Electrons have an equal negative charge, and electrons are bee-boppin', zooming around, and Whirling Dervish style outside the nucleus. The neutrons and protons, which are the ones that are just cuddling in the nucleus, those are made of smaller particles called quarks. The quarks come in a couple different varieties.

What gives these particles their mass? What are they? Where do they come from? We've got all these tiny things that make up matter. Okay, so I heard it explained that there is a field called the Higgs field. It's named after one alive and well Scotsman physicist named Peter Higgs. How a particle interact with the Higgs field gives it its mass, kind of like drag in water. Higgs bosons are particles that are an excitation of the Higgs field, kind of like a drop of water splashing from an ocean. The Large Hadron Collider smashed protons together to see if they could prove that the Higgs boson exists, and guess what bitches? It does. You're not bitches. Some people call this the God particle because it's so fundamental to all matter in the universe. Does Dr. Higgs like this name? No. He's an atheist and he thinks it sucks. The guy who coined it the "God particle" actually wanted to call it the "Goddamn particle", but his publisher made him change it in a book.

The Large Hadron Collider, one of the things it does: smashes protons together in to smaller things to figure out why matter has mass. There you go.

Also, the Large Hadron Collider accidentally has its name spelled wrong on its own website as "Large Hard-on Collider." Once would be mortifying, but what if they did it more than once? Like twice? Or five times? That's impossible. Is it? Because a search on their site revealed they'd spelled it "Large Hard-on Collider" ONE HUNDRED AND SIXTY FIVE times! Thank God particle for that. That's just precious. So whenever you're like "I don't understand this stuff. Maybe I'm just not smart enough." Just think: someone typed in "Large Hard-on Collider" over 150 times. And they built the thing.

So how else do people figure this shit out about very important things that we can't see?

Katie: Well, there are other ways to do particle physics. Measuring how particles interact with each other, throwing particles at other things, accelerating stuff and seeing what happens, all of that kind of stuff on the experimental side. And on the theory side it's a lot about trying to understand the fundamental forces of nature. How atoms hold together, how particles can change into other particles in certain conditions, how gravity fits into all that (which it doesn't, at the moment, theoretically).

Alie: It doesn't?

Katie: It's very hard to get gravity and particle physics to work together.

Alie: WHAT?!

Katie: Yeah, this may be another topic, but this is the reason string theory was invented.

Aside: Okay. Real quick: what is string theory? Well, in a quark-sized tiny nutshell: The premise of string theory is that basic objects are not point-like, but they're string-like. A quark might be made of a loop that, kind of, vibrates and moves around. Every kind of particle is like a different wiggly string.

Why does anyone care? Why are people so horny for string theory? Well, number one: it's from the '80's and maybe this is like the scrunchie of particle physics, I don't know. More importantly, string theory is a theory that works with both Einstein's general relativity (and that: Mr. Einstein posed that what we perceive as the force of gravity, is the curvature of space and time. More on that in a minute) and quantum mechanics, which is the physics of the tiniest building blocks that exist. Remember those quarks that make up protons and neutrons? What are those made of? Maybe these string-like loops of matter.

Every time I hear string theory mentioned, I think of string cheese. I can't not. When I was writing and researching this episode, I found myself on a website at, like, 2:30 in the morning, learning that string cheese as we know it was invented in Wisconsin in 1976. The way they get it to string is to hear it to 140° F, and that aligns all the milk proteins. Also, the first iterations of string cheese were bigger and chunkier, and served to drunks in bars. Should we get back to physics? Okay, I'm sorry.

Katie: This is the big question in physics. There are a few, sort of, fundamental forces of nature. There's electromagnetism: that's like light, and static cling, and all of those kinds of things, right? And magnetism. Then there's the weak nuclear force, which has to do with how particles decay in radioactivity, that kind of thing, and how particles can change in to other particles under certain conditions. There's the strong nuclear force, and that holds particles together in the centres of atoms. Those all, kind of, make sense together theoretically, like you can write down equations that make those all fit in some way, more or less.

Aside: When Katie says, "you can write down equations that make those all fit," I appreciate her being inclusive with the second person, but I… I cannot write down equations to make those all fit in some way. I cannot do that.

Katie: But then there's gravity, and gravity just doesn't follow any of the same rules. It's very hard to put together a theory that includes the fundamental forces of particle physics and gravity.

Alie: So, is gravity like the bad boy in a teen drama? It's JUST not following ANY rules?

Katie: It's weird. Gravity is all about spacetime. So, the theory of gravity that we have is Einstein's theory of relativity, so general relativity. This is the theory of gravity where…

Aside: Get ready. Heeeeere's Einstein! Here is how the universe, of which you are a part, works:

Katie: The basic picture is that you can think of space as this malleable thing. If you have something that has mass it creates a dent in space – it sort of bends space around it. So other things moving past will respond to that and fall into that dent. That's how gravitational attraction works. You can think of it in this geometric way, and it works really well geometrically to think of it like that. But then there are fundamental principles that happen in that, like the speed of light as a limiting factor, and all sorts of things like that. There's only certain paths that things can follow.

But then, the particle physics stuff, like all the equations of particle physics, are done without thinking about gravity because on those scales, gravity isn't important. It's a really, really weak force. But also, the way that the particle physics is formulated in the Standard Model of particle physics (which is what we use to talk about all these interactions) it doesn't have the same… it doesn't follow the same rules as gravity.

There are ways in which the whole speed of light is violated in one way that you can formulate how particles move around. There's this way of formulating it where a particle going from point A to point B passes through every possible path on the way between point A and point B, and it's only by using that idea that you get the right answer for how that particle is moving in the particle physics point of view, and that doesn't work with relativity.

There are a couple things like that where quantum mechanics and relatively just do not like each other. It gets especially problematic when you get to a black hole. Because a black hole is this very intense gravitational system. It's basically a dent in spacetime that's so deep that everything falls in to it if it gets close enough. But at the edge of a black hole – the event horizon – you have this weird quantum mechanical thing happening, where you can have particles evaporating off of it, and that sets a, sort of, scale of the black hole. That means there's quantum mechanics happening in a strong gravitational system.

And then, just… everything breaks [*laughs*] and just goes totally haywire, because if you look at it from a gravitational point of view, like a relativity point of view, you should see nothing at all interesting happening when you fall into the black hole (aside from you're killed by the gravity). But you don't see… nothing weird happens when you pass the horizon. But from a particle physics point of view, there might be, like, a firewall? Like a boundary of intense radiation there, because of the way you have to think about how the particle physics works. This is a complicated story but basically there's…

Alie: [*laughs*] I mean, astrophysics typically is…

Katie: [*laughs*] Yeah, I'm not explaining it very well, but basically when you get to that point - when you have a black hole that has an evaporation happening, where particles are coming off the edge of the event horizon – one way of looking at it says that means that whatever you fall through in to the black hole you can't ever find out what it was. That information is destroyed. But quantum mechanics, the particle point of view, says you can't do that, so there has to be some kind of loophole. Gravity doesn't like that, and you just end up with chaos. So there's this big problem called the "black hole information paradox" which has been around forever, and every once in a while, somebody is like "Oh, I solved it," and then it's really complicated, and people don't really understand how that works.

Alie: So, has anyone actually solved that?

Katie: I mean, technically I'm not qualified to know that for sure, because it requires understanding quantum gravity in a way that I do not. But there have been some solutions suggested. In general, there's still a lot of discussion, so I don't know.

Aside: Ok wait, so …what does a cosmologist do?

Katie: "Cosmologist" just means you study the universe as a whole. You study maybe the beginning of the universe, the end of the universe, how it changes over time. But you can be a physicist cosmologist, or an astronomer cosmologist, and those are different. It's culturally different. If you're hanging out with particle physics people, and you say you are a cosmologist, then the implication is that you work on the beginning of the universe, and the forces of nature, and maybe the end of the universe, something like that.

If you're hanging out with an astrophysicist and you say you are a cosmologist, then you just study things that are really far away, or you study something more fundamental. But you can be a cosmologist in astrophysics, and you're a cosmologist because you study very, very distant galaxies. The reason that counts as cosmology is because that means you're studying the very distant past of the universe.

Aside: So there are different flavours of cosmology, but they're all kind of linked (at least in my opinion) by "Where are we?" "What are we?" "What are we made of?" a.k.a: it's a branch of astronomy that involves the origin and evolution of the universe. That's a less panicky way to put it.

Katie: So then you're studying how the universe has changed over time. There are kind of different ways of doing it, and I've done all of those different kinds of cosmology, I guess, because I've spent my time kind of bouncing back and forth between the particle physics and the astrophysics communities. I've worked on the Big Bang, and theories of the early universe, and I've worked on distant galaxies and how galaxies form, and I've worked on black holes, and weird stuff like cosmic strings, and just all sorts of things.

Alie: What is a cosmic string?

Katie: A cosmic string is kind of like a line or wiggly line of energy that stretches across the cosmos. It might not exist, probably doesn't exist, but there could be this whole network of strings of like… it's kind of like if you think of a black hole, but you stretch it out across the whole universe. It's kind of like that.

Alie: What does it do?

Katie: Really interesting things. If you have two cosmic strings and they cross each other, they collide, and they can reconnect in a different way. So you can have two cosmic strings that are about to collide, and then they change so that now you have two, sort of, loops of cosmic string that are going into opposite directions. So, they sort of pass through each other by branching off in this weird way.

Aside: So cosmic strings may or may not exist. Now, if they do exist, some theorists have used them to maybe sketch out some stuff about time travel. Please figure that out. Please fix some stuff. Thank you.

Katie: And you can make a loop of cosmic string, and then that loop of cosmic string will wiggle around, and make gravitational radiation, and disappear into nothingness. If you have a cosmic string between you and some distant galaxy, then you might see two pictures of that galaxy because it splits the space, kind of. It's really cool.

Alie: Whaaaat? Now how much do you think about all of this in your day-to-day life? Like, when you're deciding if you should upgrade your rental car? Like, if you should cut bangs? And what happens to your molecules after you die? How much do you let this, kind of, get to your own existence?

Katie: Yeah, somebody asked me that the other day, like, how much do I get, sort of, just overwhelmed by these ideas or whatever. It's not very often, most of the time this is fun stuff to work on. Most of the time it feels more like some kind of combination of science fiction and a fun puzzle, you know? I'm trying to solve a problem, I'm trying to calculate something, I'm trying to come up with a new idea for how to do something. It's like a puzzle. It's like some kind of neat thing to work out. I don't think of it as connecting to my own life or existence, because it's way far away, or way in the past, or you know, or probably doesn't exist or whatever, right?

But then every once in a while, I'll be thinking of this stuff and I'll be like "Oh my god" [*laughs*] like, stuff is out there. I'll be thinking about black holes, or gravitational waves, or the inflation period in the early universe, or something like that, and I'll have to hold on to something, like… "Oh God." [*laughs*] Because these are huge, mind-bendingly intense forces, and massive things. The kinds of energies, and the kinds of force and just… I don't know… the explosions and everything… It's just… we cannot comprehend this stuff. I mean the Earth is really tiny, and really unimportant, in a BIG way.

So… Okay, you know there's this famous photograph, the Pale Blue Dot. Yeah? This is a picture that was taken by the Voyager space craft.

Aside: The Pale Blue Dot photo was taken on Valentine's Day in 1990 as Voyager 1 was leaving the solar system. It was like: "Buuh byyye, I'm out" and astronomer Carl Sagan said "Yo, let's turn that lens around, and let's take a pic of us all far away. What do you say? Might as well." It was 3.7 billion miles away. It's the galaxy's longest-range selfie. This photo itself, it looks like you accidentally took a blurry image of a few Christmas lights, and there was a speck of dust on your lens. Those lights are just a few scattered rays of sun. Someone would have to point out that that dust… is our planet. It is such a tiiiny speck. And I'll let Carl Sagan put this in context, he's the pro here:

[Carl Sagan speaking, with light background music:] That's here. That's home. That's us. On it, everyone you love. Everyone you know. Everyone you ever heard of. Every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologist and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and pheasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every superstar, every supreme leader, every saint and sinner in the history of our species, lived there, on a mote of dust, suspended in a sunbeam. [music swells] The Earth is a very small stage in a vast cosmic arena.

Katie: Sometimes when I give talks about cosmology I'll end with this picture, and I'll be like, you know, just thinking about how vast the universe is, and how really insignificant we are… the insignificance is even deeper than just what you see from that picture because in that picture you see there's a whole lot of empty space, and then there's a little tiny rock. We're on that little tiny rock. There's a lot of space, but it's even worse than that [*Katie and Alie laugh*] because not only are we not the center of the universe, or our galaxy, or solar system, or anything like that, but the matter that we're made of is also really unimportant. [*laughs*] Because the kind of stuff that we are, and that we can understand and interact with - regular matter - is 5% of the universe. So, most of the universe is something called dark energy that we really don't understand, but it is some sort of mysterious stuff that's making the universe expand faster and faster. It's going to take over eventually.

Then there's dark matter, which is some kind of invisible matter that is most of what the galaxy is made of, and what most of all galaxies are made of. So our galaxy, we think of it as this pretty disk of stars, but it's actually embedded in this invisible blob of extra stuff that we can't see, and that blob is WAY bigger than the stuff that we can actually see. So, dark matter is like 85 percent of the matter in the universe, or something like that.

Alie: Oh my god.

Katie: Dark energy is like 70 percent of all of the stuff in the universe. We're this tiny, like 5% size - and that's just the kind of matter that we can understand, that we can do experiments on, that we can see or touch, or interact with in any reasonable way. And then it's like… Not only [*Katie and Alie laugh*] are we a tiny speck of dust on a tiny speck of dust… We are SO insignificant. The universe doesn't even… it doesn't even matter that our kind of stuff is there. You know?

Alie: The best thing about this conversation is, I'm having it with a cosmologist and, like, an astrophysicist, but I could also be having this same conversation with any of my college roommates who had like, [*Katie laughs*] a seven-foot bong in the garage. When astrophysicists and cosmologists get together, is it just kind of like a round robin of stoner existentialism? [*Katie laughs*] Because I feel like there is such a fine line. You're either incredibly, incredibly, smart, and thoughtful, and knowledgeable about this stuff, or you're just like… you've just numbed yourself enough for you to allow yourself to think about it. And then there's this bell curve, this big wide swath of people who are like "I can't even think about it, it's too much." You know?

Katie: So, when I do get together with other cosmologists and we talk shop it's usually very, very technical. We don't get into this stuff at all. Usually we're just talking in a lot of jargon about some measurement or something, and we're throwing out numbers, and we're trying to figure out, like, "is this a reasonable measurement to make?" or, "What kind of plot can we make to illustrate this point?" or, "What kind of calculation should we do?" or "What's the important variable?" It would not be interesting to somebody who was not in the field.

It's really only when I'm talking about people who are not in cosmology where I have these moments of "Oh god". [*laughs*] It's a little bit dangerous to talk about that stuff though, because then sometimes people get the idea that we really are just sitting around making stuff up, you know? Then people think "Oh, I can be a cosmologist. Like, what if the universe is shaped like a football?" I think that the disconnect there is that the ideas themselves, if they're not backed up by the data or by a very rigorous model, are really not that important. Once we have data, and we have some kind of unifying theory that says that this is probably the way things are, then it's super cool. But if somebody had said "Oh you know, maybe the universe is like this," we don't really know what to do with that. It's just not really helpful.

Alie: You can't just spitball?

Katie: Yeah, exactly. It has to be connected to something we can test or write down mathematically, or else it's kind of not helpful, you know? Which is kind of a bummer. But once you do have the mathematical tools and you can speak that language, then you can get really creative and then you can do really fun things. For example: I have a project I'm working on that has to do with… I have a few interesting projects actually, but I have one… Here's one that can be fun. It has to do with black holes and galaxies and the bending of space.

Every time there is a massive object, it bends space around it. That means that light, when it goes past, bends around, like a lens. The massive object acts like a lens for light and so light gets bent around. So there's this way to study what galaxies are made of, by having a very bright light behind the galaxy, REALLY far away, and looking at how that light bends around inside that galaxy, and how the light fluctuates as things move. That's called gravitational microlensing, in this case, the kind of thing I'm working on.

The details aren't important, but the thing that's making the bright light is also a black hole, because it turns out when you have a supermassive black hole, like billions of times as massive as the sun, those things can be pulling matter into themselves, and that matter lights up like a whirlpool of stuff, and it can make this incredibly bright light that you can see across the universe. We use that as a backlight to study the stuff in a more nearby galaxy, to find out how many black holes there are in that galaxy.

Alie: So black holes make light? Is that SUPPOSED to be confusing?!

Katie: Sometime, yeah! It's one of these things… the biggest misconception about black holes is that they are dark. Usually they're not.

Alie: WHAT!?

Katie: The ones we know about are usually not dark. It's because technically the black hole itself can't be seen, but it's doing so much that it affects everything around it. So usually you can see black holes because they're really destructive and the stuff is falling into them. Kind of like if you had a drain at the bottom of the bathtub, you might not be able to see the drain through the bubbles or something, but you can see that there's a whirlpool of stuff falling in at that point.

Alie: Oh man.

Katie: And that's how we see black holes in space usually. We see that they're pulling in a lot of matter, and that matter lights up. Once it goes in to the black hole, we can't see it, but it spends a lot of time whirling around really fast.

Alie: It's like an intergalactic garbage disposal.

Katie: Yeah!

Alie: What!?

Katie: Yeah, and some of the brightest things in the universe are black holes. We call them quasars when they're the supermassive ones, and they're pulling matter in like that. Those are for black holes that are million or billions of times as massive as the sun.

Alie: How far away are those puppies?

Katie: All right. Well… ok, supermassive black holes: the ones I was just talking about, millions or billions of times the mass of the sun, those seem to exist at the centers of pretty much every reasonably sized galaxy we know about.

Alie: At the centers?

Katie: Yes.

Alie: …Including ours?

Katie: Yes.

Alie: Really?!

Katie: Yes. Our galaxy…

Aside: Okay, quick note. Let's do a few cosmological basics. Our galaxy is the Milky Way, right? And this next analogy I got right off of NASA's Night Sky website, which I think is for children, but it's so helpful:

Imagine our sun. It's one star among the hundreds of billions of stars in our Milky Way. If we shrink the sun down to smaller than a grain of sand, our little solar system: Venus, Mercury, Earth, all of those would be small enough to fit the whole solar system into the palm of your hand.

On that scale, with our solar system in your hand, the Milky Way Galaxy would be the size of North America. The Milky Way is big, but our next-door neighbor, Andromeda Galaxy, it's about twice as big as the Milky Way. Scale is important here, I suppose. But at the centre of our galaxy, there's a black hole. So the Milky Way:

Katie: …Is a disk of stars and gas and dust and stuff, and we're sort of out toward an edge. At the centre, there is a bulge of stars and gas and dust, and then in the middle of that, there is a black hole that's four million times as massive as the sun.

Alie: I didn't know that! Do we have a name for it?

Katie: Yeah, yeah, we have a name for it: we call it Sagittarius A-star, [written as "Sagittarius A*], which is a silly name.

Alie: Ok, how did it get that name?

Katie: I think it was a radio source, because it was pulling in some matter it was lighting up in the radio a little bit. Ours is not pulling in very much matter at all. Very occasionally it'll eat a little blob of gas and the astronomers get super excited, [*Alie laughs*] but there's very little happening with it. It is really big, and it's got a bunch of stars orbiting really closely around it. You can actually go online and see data tracing out the paths of some of these stars, and you can see them whip around as they go really close the black hole in their orbit. Some of them have these orbits that are really far away, and then they come in really close and they go *vroom* right around the black hole. So you can figure out exactly how big it is and where it is by watching these stars go around it really quickly.

Aside: I did a little looking, and if you Google "European Southern Observatory" and "S2" you'll find this.

Alie: Oh my god, like a rim shot in a basketball game?

Katie: Yeah, yeah! Like that, except it comes back around in its own orbit. There's stuff orbiting really close to that black hole. That one is, well… 80,000 parsecs away. I don't know how much that is in light years.

Alie: What is a parsec?

Katie: A parsec is about three something light years. A light year is how far light travels in a year. Light moves very quickly, so that's a very long way. For example, it takes light eight minutes to get between the sun and us. There's a rule of thumb actually if you want to know how fast light speed is. It goes about a foot per nanosecond.

Alie: A foot per nanosecond?

Katie: Yes.

Alie: Oh. Well. That's easy to calculate! Just a bunch of zeroes, right? Just put a zero on it!

Katie: Yeah! Yeah! It's easy. But it's kind of cool because then you can say, if somebody is 10 feet away from you, they are 10 nanoseconds in the past.

Alie: [*laughs*] They're 10 nanoseconds in the past? Oh man. I'm going to trip out.

Katie: We're like, 3 nanoseconds apart right now.

Alie: That's so weeeiiiirrrddd! That's so weird!

Katie: [*laughs*] It's great though, you know?

Alie: I learned this recently, and I've already forgotten it, which is embarrassing, the distance between us and the sun is a certain… What is the AU…?

Katie: Oh, that's astronomical unit.

Alie: Yeah, astronomical unit.

Katie: That's the distance between us and the sun.

Alie: I just learned that then completely forgot it all in the span of a couple of weeks. Oops.

Katie: [*laughs*] That's ok. There is no reason to know that stuff.

Alie: I want to know a little bit more about when you were a kid.

Aside: By the time Katie was about 10 years old, she was inspired to pursue some sort of cosmology, and she was already a fan of British cosmologist and theoretical physicist, Stephen Hawking. She was already hip to him. She's like, I know this dude. If you need a quick brush up on him as a person, after this podcast watch the 2014 Eddie Redmayne film *The Theory of Everything.*

[*Audio clip from The Theory of Everything trailer*]

Eddie Redmayne (ER): *I'm a cosmologist.*

Felicity Jones (FJ): *What's that?*

(ER): *I study the marriage of space and time.*

(FJ): *The perfect couple.*

Or you can just watch the trailer and start crying. Like somebody you know.

Now, if thinking about living on a dust mote floating in a sunbeam wasn't inspiration to do what you want to do in life, consider a human who's figuring out the mysteries of the cosmos, doing computations and cracking theories about which I can't even comprehend the first paragraph of the Wikipedia page, also while living with ALS. Katie is one of several billion people inspired by Stephen Hawking.

Alie: What was it that Stephen Hawking did, or how did you become aware of him, and how did you, kind of, absorb what he did?

Katie: I'm not sure how I became aware of him. I think, you know, he's on TV every once in a while and I had *A Brief History of Time*, the book, and I read that, and I was interested in black holes, and I was interested in the Big Bang…

Aside: The Big Bang theory being that the universe began those 13-odd billion years ago, with high temperatures and high density and it's continued to expand. Also note: if you Google "Big Bang Theory" all roads lead to Sheldon. So just be caj and call it Big Bang as far as Wikipedia's concerned.

Katie: I would read about that stuff and Stephen Hawking was a big figure in those areas, and he was doing a lot of science communication. He would visit Cal Tech every once in a while, and I was growing up in L.A., Long Beach and so I would sometimes… my mom would take me to see talks by physicists (because I was super excited about these things). So I remember seeing a talk by him, I remember seeing a talk by Paul Davies, and you know, prominent theorists would give talks sometimes, and somehow my mom would find out about them, and take me along, because she's really into science, and science fiction, and physics, and everything.

Alie: Have you gotten to meet Stephen Hawking?

Katie: Yeah! When I was at Cambridge. I spent a year at Cambridge during grad school, just kind of visiting and working with people on some research, I was mostly based in his Stephen Hawking's department and my office was directly below his. We were in the same research group, basically.

Alie: WHAT?!

Katie: I mean we didn't talk. I wasn't in his research group, but we were in the Center for Theoretical Cosmology. We were both based there. There were half a dozen professors who were involved with that, and he was one of them, and I was a grad student visiting. I would go to all these meetings, and coffee, and shortly after I started being a visitor there, somebody asked me to do one of the lunch seminars.

Aside: Basically, if you're a physicist and you're visiting another department you're kind of obligated to give a talk. That's kind of how it works. Soooo, they say, "Hey, can you give a talk?" She's like "Yeah, I'll give a talk for the Thursday lunch seminar." So, she does it.

Katie: It turn out that it was the lunch seminar that Hawking goes to. I'm getting ready to give the talk, and I see several of my professors in the audience looking expectantly at me, so I'm freaking out - but he wasn't there. Hawking wasn't there so I was like "It's fine, it's fine." And I'm getting ready to give the talk. Then I hear this "Beep, beep, beep."

Alie: [*laughs*] Oh my god. My stomach is cramping just hearing this!

Katie: [*laughing*] Then he shows up… Oh, it gets so much worse… [*Alie gasps*] Oh God. So, I've told this before, but it's still… it still makes me sweat. [*Alie laughs*] So I was getting ready to give the talk. I start the talk, I put up the title slide and the topic was Primordial Black Holes, which is a concept that Hawking came up with along with some other people.

Alie: No pressure.

Katie: Yeah. As I'm starting, after I introduced the title, I hear this this voice say:

[*computerized voice often associated with Hawking*] "Thank you."

Katie: …It was his voice, and I was like… [*Alie sighs sympathetically*] Everybody kind of laughed, and I thought maybe he was thanking me for talking about the thing that he invented? But I don't know, and you can't ask him to elaborate because his speech is very slow. He uses this machine, and it's very slow.

Alie: It tracks his eye movements?

Katie: Yeah. Well, no. Not exactly. There's a little sensor that looks at his cheek. He kind of winks, and that selects words on lists, and it takes a couple of minutes per word sometimes.

Alie: Right. So, you weren't like, "please elaborate."

Katie: Yeah. So, I just kept going, and then eventually I heard it again.

[*Hawking voice*] "Yes."

Or, later on:

[*Hawking voice*] “No.”

Or:

[*Hawking voice*] “I don’t know.”

Katie: Or just random things as I'm going. And every time I would look at him… but he would just look blankly at me. This is a lunch seminar, so the person who is feeding him, she just looked blankly at me, and I had no idea what was going on. I would just pause, then continue. [*laughs*] Because what am I going to do?

Alie: Was he heckling you!? What was happening here!?

Katie: I had no idea, and I was so nervous, and all the professors were there, and already one of the other professors had been asking a whole bunch of really tough questions on the second slide… I was already freaked out.

Aside: JUST IMAGINE BEING IN THIS SITUATION. IT’S A NIGHTMARE. …it’s like the best nightmare ever.

Katie: I answered the questions and he seemed to be okay with it. I finished the talk, and Hawking left, and he hadn't asked any questions. I asked one of the seminar organizers “What was that?” He was like, “Oh, well, when he eats, the machine picks up on his chewing, and it just picks random stuff from the quick select menu.” [*laughs*]

Alie: OOOhhhhhhh NNnnooooooo. OOHHHhh nooooooo.

Katie: [laughing] It had nothing to do with me at all! It was just, like, here’s the most common phrases: Yes, no, maybe, I don’t know, I don’t think so.

Alie: Oh my god! This is the worst deodorant ad EVER! This is THE most stressful situation you could possibly ever be in.

Katie: [*laughs*] It killed me. Oh my god. They could’ve told me!

Alie: Yeah, they could’ve given you a little heads’ up.

Katie: Because this happens every time.

Alie: Ooooh my god. Oh my god!

Katie: They just… they didn’t mention it.

Alie: Any word on whether or not he liked the talk?

Katie: I have no idea.

Alie: Oh my god! Did you ever tell him you went in to cosmology because of him?

Katie: Well… so the first time I met him, when I was 16… well… 14.

Alie: [*baby talk voice*] Just a baby baby!

Katie: I did tell him then that I was a big fan.

Aside: Hawking was at Cal Tech and Katie got her mom to drive her and a friend there to hear him speak. Afterward, they were walking the same way he was going when they were leaving, and she was too nervous to say hi.

Katie: My friend went up to him and said, "My friend would like to speak to you." [*laughs*]

Alie: You had a wing man! [*laughs*]

Katie: I went up to him and said that I was a big fan, and I enjoyed his work, and I thanked him and he said:

[*Hawking voice*] "Thank you very much."

Alie: Awww. What happen to you when YOU get that? Because you're really… I mean, I'm not going to fan-girl right here, I'll do it in the intro, but you're a very big voice in science communication. You're a very well-known astrophysicist/cosmologist. How do you feel when people come up to you and say, "I was inspired to study this" or ,"You've changed my course." What kind of reactions do you get?

Katie: It's not… I'm not like Stephen Hawking. I'm not that level of famous, and I'm not that level of "important" in physics, so it's kind of a different thing. Sometimes people do tell me that they... So, one of the messages I have gotten a couple of times is, like, a teenage girl will say that she didn't think she could do astrophysics, but she really loved it, then she saw what I was saying on Twitter, or she saw me speak, and then she decided she was going to go for it.

Alie: Wow.

Katie: I do get that sometimes, and… my feelings don't know what to do with that. [*Alie laughs*]. But it's really sweet

Alie: [*gruff voice*] Throw 'em in a black hole! No feelings here! [*laughs*]

Katie: I mean, it IS really sweet. It's really rewarding when that happens, and it makes me feel like maybe the stuff I'm doing is worthwhile when people say stuff like that. Or a little kid will sometimes say that they want to be an astrophysicist or something, and they'll be really excited to meet me. I was in Raleigh a couple of weeks ago and I was sitting in a café, and I was wearing my NASA jacket with a little NASA badge on it that I got at JPL.

Aside: JPL, by the way, is NASA's Jet Propulsion Laboratory, and it's nestled in the golden hill of Pasadena, California. It's responsible for things like rovers on Mars.

According to press materials “JPL’s function is to engineer and fabricate cool-ass shit that’s like, so dope.” That’s very bold NASA.

Also, do not fact check that part. It is not true.

Katie: And this little girl came up to me, she was probably 8, and she asked me if I work for NASA. I said I don't work for NASA, but I am an astrophysicist. We talked a little bit and she said that she is really into space and stuff. So I said, “Well I'm giving a talk at the museum in a couple of days, you can come and hear my talk.” She and her mom came to my talk, and she asked a question, and it was just really sweet. And I was like [softly] aww.

Alie: [*Soft squeal*] So what was her question?

Katie: I think her question was about what’s inside a black hole. Which is a good question.

Alie: You’re like, “a bunch of space garbage.”

Katie: Well, yes. I mean, it's not a straightforward answer really, because once stuff goes inside the black hole, it has to go straight to the singularity, and it can't do anything else. So then does it really exist at that point? [*Alie gasps*]. It’s kind of subtle. Anyway, it was a good question. Apparently like she was talking about the talk later on, and I was like “Oooh! I inspired somebody.”

Alie: Ohhh, yay! [*giggles*] She’s going to be in your department later, and give a talk while you’re at lunch!

Dumb question: Explain the singularity?

Katie: Yeah. Singularity comes up in the context of the Big Bang and in the context of a black hole. A singularity is like a point of infinite density. Usually in physics when you have a singularity… A singularity basically means it's a point where something infinite happens, where things diverge in some way. And usually when that happens in physics it means you've done something wrong. It's a sign that the theory is broken, and you just can't deal with that, because none of the theory really works at a point of infinite anything. In the black hole, the way that black holes are defined, and the way that we understand how gravity works, there really should be a singularity at the center of the black hole, and everything has to move toward it. The way you make a black hole… I’m just going to back up a little…

Alie: Yeah, no, back up because I’m like, “Where do they come from?” and “What’s the deal?”

Katie: The way you make a black hole is you take a really massive star, and you wait millions of years, and the star will explode, and the core of the star will collapse on itself if it's massive enough... The reason that the star didn't collapse before was because it had nuclear burning happening, and it was kind of keeping it puffed up. You had this energy source that’s sort of pushing against it. Kind of like if you have a balloon and the air inside is pushing the rubber out, right? When the star explodes, there's nothing to keep it from collapsing under its own gravity. [*Alie gasps*] You get to a point where you can't do anymore nuclear fusion.

Aside: Nuclear fusion is when atoms join to become a different kind of atom, and they give off energy in the process: like two hydrogens becoming helium and giving off energy. This happens with atoms up to the size of iron, at which point that fusion starts to *take* energy.

Katie: You can't get any more energy out of those processes because you've gotten to a point where you've just… the whole center of the star is iron, basically, and it can't go farther than that. Then there's a huge chunk of iron that's not being held up by anything, so it starts to collapse under its own gravity. That stuff just falls in. It has to go toward the center, and it has to keep going toward the center, and it can't go any other direction. So you end up with the singularity. This point of infinite density. Technically.

Alie: What is the shape like? Is it like an ice cream cone that has an infinite tail? Or what does it…??

Katie: You can visualize it that way if you think about it in terms of a 2D analog. Usually when we think of spacetime, the pictures are always a big rubber sheet.

Aside: The rubber sheet visual is so helpful for comprehending spacetime. Also, when I think of rubber sheets, usually the situation is not comfortable. It's either an awkward grade school slumber party explanation or some suburban dungeon kink that sounds exasperating, at best. But for space, rubber sheets: thumbs up.

Katie: You have this big rubber sheet and you put a bowling ball in one spot, and that bends around. Then when you then take your tennis ball and you try and roll it past the bowling ball, it makes a little orbit and falls in. This is the usual visualization for spacetime. But that doesn't have the right number of dimensions because space is three dimensional. You can think of time as another dimension… but that's kind of separate thing.

Alie: I am curious about time as a fourth dimension

Katie: Okay, we can talk about.

Aside: I'm sorry. I HAVE SO MANY QUESTIONS.

Katie: If space is three dimensional, then the way gravity works on it, is that it, kind of, pulls space inward toward itself. So, a massive thing kind of pulls space inward toward itself. In the context of a black hole, it would be like a place where space gets really scrunched up. But it's easier to think about it in the two-dimensional case. It would be like you have your rubber sheet and you pinch a piece of that rubber sheet, and you just pull it down, and just keep pulling it down. And it just goes to a point, forever, and it gets deeper and narrower. You can think about it like that. Then you think about like a three-dimensional analog, and your brain kind of breaks.

So, it's basically a place where space is really super curved and really super bent inward. So there is a point, if you think again about the 2D, the rubber sheet, you can still move past... If you have your little hole where you pulled down on the rubber sheet, you can still take your tennis ball and roll it past that and it'll keep going. But if it gets too close it'll fall in, and there's nothing you can do about it. It'll always go toward the deepest point. There's this horizon, this distance from that singularity, where if you get closer than that, you will fall in, no matter what, and you will just keep going and you can't ever escape.

Light itself will fall in too because light follows the curve of space, so if space is curved enough, then light will just follow that curve all the way down. If you were to throw a flashlight in to a black hole, that light never comes out again. No matter which direction the flashlight is facing, the light beam will bend toward the center.

Alie: And what is that danger zone called?

Katie: The event horizon. You should probably stay farther than the event horizon, [*laughs*] in general. Because other bad things can happen to you if you get close to the black hole.

Aside: If you listened to Ologies Episode 1 Volcanology, and thought jumping into a volcano was intense, like, hang on to your butts right now.

Katie: For one thing, most of the black holes that we've seen directly, with light, are pulling in matter. That means that there's a lot of hot stuff falling into the black hole in the form of a disk, so that'll radiate you to death if you get too close. If you get close, if it's a small enough black hole, then the tidal forces will kill you. Tidal force is where you have gravity pulling stronger on one part of you than another part.

If you imagine you're falling feet first toward a black hole, the gravity - the strength of the gravity - goes up so steeply, because it's such a compact steep thing, that your feet will be pulled on much more tightly than your head, and you'll be stretched out. There's a word for it. It's called spaghettification. It's actually called that.

Alie: [*laughs*] That's the dumbest thing I ever heard in my life!

Katie: So, you have to watch out for spaghettification if you get too close to a black hole.

Alie: [*Breathing hard in from laughing*] Who the hell named that?? [*Alie and Katie laugh*]

Katie: I don't know. I mean, Hawking uses it, and maybe he came up with it? I'm not really sure.

Alie: Oh my god. But all of the things to call it… of all the things!

Katie: Yeah. It turns you into spaghetti. I don't know? What else are you going to call it? It's tidal disruption. But…

Alie: Oh my god… I love it. The most. [*continues laughing*]

Aside: Spaghettification was indeed coined by Hawking in his book *A Brief History of Time.* And if you happen to Google image search this, you will find a bounty of photoshopped images of astronauts being tapered into space noodles by cosmic forces. I'm so impressed by this astrophysical whimsy.

Katie: Yeah there are a lot of there are a lot of really silly names in an astronomy.

Alie: Who gets to name this stuff?

Katie: Whoever comes up with it. People who come up with it name it, but sometimes the community names it. Like the Big Bang, that that was a joke, the word was a joke. The term "the Big Bang." Somebody came up with the idea that the universe started small and has been expanding, and somebody was like, "oh the Big Bang," and that… It stuck.

Alie: No!? it was a throw away!?

Katie: Yeah, it was like, it was mocking.

Alie: Did that person get pissed that it stuck?

Katie: I'm not sure.

Aside: Okay, so English astronomer Fred Hoyle coined the term "Big Bang". It was during a radio broadcast in the late 1940's. It was kind of an accident. The story is that he's so bent that it stuck, but apparently he denies that. Drraaaaama.

Alie: In terms of what in terms of what your output is, you're a professor, you give talks, you travel all over the world. What is your big goal as a cosmologist? Do you want to write an encyclopedia about cosmology? What's your end game?

Katie: So, I'm almost a professor.

Alie: You are?!

Katie: Well I'm going to be an assistant professor starting January 1st [2018].

Alie: Yay!!

Katie: So, I'm not quite a professor yet.

Aside: So, in a matter of days, pretty much, Katie will be an Assistant Professor of Physics at North Carolina State University. Tweet at her and say Congrats!

Katie: What is my goal...?? I mean, I want to figure stuff out, but I don't have… there's not one thing where it's like "I must solve this problem." I kind of like just working on whatever fun stuff comes up, which is not what you're supposed to do. [*laughs*]

Alie: But it's what you like!

Katie: It's always what I like. The big thing I'm working on right now has to do with dark matter. Dark matter is this invisible stuff, and it's possible that dark matter has this weird property, where if you take a dark matter particle and another dark matter particle, and you collide them into each other in just the right way, they'll annihilate and create other kinds of particles. So, that's a possibility. If that's the case, if that's the thing that happens, then it can mess with how the first stars and galaxies formed, because those form in these blobs of dark matter, and the formation of those is kind of delicate, because you have to get the right balance of the gravity and the gas and all this stuff.

So, if dark matter is going and annihilating all the time, then that sort of messes with that balance. It can change the way the first stars and galaxies formed, and then we can look for evidence of that with telescopes. This is the kind of problem that I like, where you have a sort of fundamental particle physics problem, and then you try and figure out how to look for it with telescopes.

Alie: So, what does your work involve? Do you have like a moleskin that's just filled with gobbledygook equations? Or are you working on a computer with data sets? When you get down to work what does that look like?

Katie: Yeah, so I do have my moleskin full of equations, over there. [*Alie laughs*] I brought it with me. So, I have that. I also have a whole bunch of code that I've written to try to solve some of these equations that are in the moleskin. The usual thing is, you talk to people who work on similar things, and you try and come up with: "What is it? How can we answer this question?" or "What is the question we can answer with this observation?" or "What would be a cool thing that might happen that we could find out if it does happen?"

Aside: Then physicists talk to each other and write stuff down, and look at papers, and write down more equations. I was kind of surprised to realize how collaborative this can be. I always imagined physicists needing to be sequestered in a well-appointed lab or a classy den to think clearly. But no, there's a lot of chatting happening.

Katie: Then once you figure out what equations you need to solve, and what things you need to calculate, then you go to the computer and you write code to calculate those things, and to put out numbers and draw graphs. Then you see if you have something interesting or not.

Alie: To see if it all, kind of, clicks?

Katie: Yeah, and you see if, like, does this tell us that this is going to be an interesting technique to test this theory, or not? Because this is all theoretical work, sometimes you find “Well, this is just really uninteresting and nobody’s going to care so I'm not going to write it up.” [*Alie laughs*] Sometimes you find “Well, it turns out you can't measure this thing with this technique, but we should write that down anyway because people might have tried otherwise.” And then sometimes it's “Oh we can measure this thing with this thing, and that’ll be a really interesting result, and we'll get a better answer than anyone has gotten before, so we're going to write it up and be really happy about it.”

Alie: And then you go toward writing it up and publishing it?

Katie: Yeah. Then you write up the paper, then you publish a paper… or you send it to the journal, and the editors or the referees are like “Hey, you should do this differently” and so you do that differently, then eventually it gets published.

Alie: What is the craziest paper that you've ever had published? The title of the craziest paper? Because just looking at paper titles is so funny to me because they're *so* specific and wonderful.

Katie: I guess it depends on what you mean. I wrote a paper called *Known Unknowns of Dark Matter Annihilation Over Cosmic Time*.

Alie: [*laughs*] That sounds like the best Norwegian metal album ever.

Kate: [*laughs*] That was all about what we know we don't know about this problem; I calculated a bunch of stuff. I've had some papers about axions… Those are theoretical particles that are super cool.

Alie: Is there an upper limit to how many words your paper title can be?

Katie: Yeah, you don't want to be... I mean you kind of want it to be punchy right? Like, the whole “known unknowns” thing is because I wanted it to be eye catching.

Alie: It’s good marketing.

Katie: Yeah, so you’ve got to think about marketing to some degree, and you don't want it to be a long title because people are going to be skimming it.

Aside: This part is crazy. It’s like trying to buy Beyoncé tickets.

So, the way that people find papers to read is every weekday the website – it’s arXiv.org - there’s like 100 new papers about astronomy, physics, math and stuff.

Katie: The way that people find papers to read, is every day… Every. Single. Day. Every week day, the archive website arXiv, that’s how it’s spelled, but we call it the “archive,” the archive website displays, like, 100 new papers about astronomy. And there’s just a list, the titles, the authors, maybe the abstract depending on how you read the archive. If you're a responsible astronomer, then every morning you wake up and you read the archive. You skim the papers and the abstracts, and you see which ones are relevant to your work, and then you open those, and read/skim those papers and find out if they tell you something interesting. You get information… This is how you keep up with the field.

Alie: That's so much work.

Katie: It's so much work. It's a lot of work. If you're somebody who maybe does particle theory stuff as well, then there's a whole other archive for particle theory, and then particle phenomenology. Phenomenology is where you try and figure out what you would see in the universe; That's closer to what I do. So then if you're trying to read particle theory, and follow phenomenology and astronomy, you got like 150 papers or something every day.

Alie: It's a black hole.

Katie: It's impossible to keep up. But anyway, because of that you want your paper title to be punchy and eye catching. Then the other thing… this is so totally inside baseball, that there's this ridiculous thing that happens…

Aside: So, the order of the papers as they appear on the website is determined just by what time they were sent in. After not too long, these are LITERAL geniuses, they were like, "duhhh..."

Katie: There's a cutoff time of 4 p.m. - in some time zone, I don't remember which one - where if you get your paper in as close as possible after that time it will appear at the top of the archive.

Alie: Oh my god!

Katie: People have written papers about the spike in submission times. Everybody's trying to get 4 o'clock, 00, one second. They all want to get it exactly at that moment so their paper will be on the top of the list. Because a lot of people, they open the archive and then they just get exhausted by the time they've gone through five papers, and so they don't get to the end of the list. [*laughs*] So there's this ridiculous ritual when you submit your paper to the archive, you watch the clock and you try and hit the submit button at exactly the right moment.

Alie: That makes me so anxious! Like when people comment first on a YouTube video.

Katie: It should be randomized.

Alie: It really should

Katie: Because it's also been shown that it does matter, in terms of citations.

Alie: That's not right!!

Katie: It's not right.

Alie: Oh my god. Oh wait - there was a question that I had right on top of that. It was definitely a dumb one. It was definitely a stupid question.

Katie: I don't think any questions are stupid.

Alie: Are you sure?

Katie: I think these are good questions. These are important questions, because if you're asking questions about something because you're not an expert on that field… You can't be an expert in every field. If I ask questions about entomology, I'm going to have no idea what's going on.

Alie: [*laughs*] Okay, that makes me feel better.

Katie: I'm still trying to remember what the difference is between a bug and not a bug. Right? Like, I don't know!

Alie: I'll give you some clearance on that. But the problem is, is you study the UNIVERSE. So… Could your field be any broader? Like that's…

Katie: No. [*laughs*] No it could not.

Alie: It's literally everything.

Katie: Yeah, and this can be a problem too, when I give talks. I have to be prepared for ANYTHING. That used to freak me out a lot. Now I just feel like I just have to read as widely as possible, and sometimes I'll be like, "I have no idea." But I gave the talk about gravitational waves in Raleigh the other week, and one of the questions was, "Tell me about the Great Red Spot on Jupiter." and I was like "Guuhhh? It's a storm... It's been shrinking... Uhhh…?? There's a spacecraft looking at it….?? You should maybe talk to somebody who studies about that."

Aside: The Great Red Spot, by the way, that's it's actual name. It's a little on the nose. Also, people mix it up sometimes with the "Great Dark Spot," which was near Jupiter's northern pole. Y'all, CALL ME. Let me name some of these things.

Also… how did Katie feel about the detection of gravitational waves? This was the LIGO [Laser Interferometer Gravitational-Wave Observatory] project you may have heard about in 2016.

Katie: The detection of gravitational waves by the LIGO instrument… It was probably the biggest discovery in physics in my lifetime.

Alie: Damn! That's a big deal.

Katie: Yeah, it's a super big deal. The first detection was last year sometime… Well, the detection was at the end of 2015 and it was announced, I guess, during 2016. The announcement was in… I don't remember what time zone it was, but it was such that it was going to be 2 a.m. local time in Melbourne. So, a bunch of us got together and had a party [*Alie squeals "YES!" and laughs*] in a university department. We brought food and booze, and we watched videos, and we took selfies. It was really late. But we were just like "We got to see this live."

There were two people in the room who were part of the collaboration, so they already knew what was going to be done. But the rest of us, we'd heard rumors but we didn't know for sure what was what was going to be announced. Yeah, it was it was just a huge party. We were really excited. Everybody was clapping and stuff when it happened, and I mean, it was a huge deal.

Alie: The way that it was announced was like a press conference from an awesome '80's movie.

Aside: [*clip from the YouTube video of the LIGO announcement*]

David Reitze: "Ladies and gentlemen… We... have detected… [with emphasis] Gravitational Waves. We DID it! [Clapping]"

I mean, how cute is that? That was David Reitze. He's a laser physicist and Director of the LIGO lab. And I love that audio soooo much. It's just pure triumph. Like the last scene of a Schwarzenegger movie or something.

Alie: [*Imitating the clip*] We... have detected… gravitational waves… [*Katie and Alie laugh and clap*] The clapping was, like, the best.

Katie: Yeah. I remember that very clearly.

Alie: Explain to me why the detection of gravitational waves is such a big deal.

Katie: Okay. So first, gravitational waves are ripples in the fabric of spacetime. Space can be bent around massive objects, and when massive objects are moving through space, if they're moving in an accelerated way - which could be in an orbit, an orbit is a kind of an accelerated motion - that creates ripples in this, sort of, spacetime fabric, which is kind of hard to visualize and explain, but it ripples through space. When you have really massive objects moving really quickly, that can make large disturbances relative to other things. I mean, if I wave my hands I'm making gravitational waves, but that is not detectable.

Two black holes orbiting each other make really big, detectable, gravitational waves, especially when they get so close that they're about to merge into one thing. You can have two black holes in a binary orbit, orbiting each other, and then as they get closer and closer, the signal gets stronger and stronger - the waves get stronger and stronger.

Then they merge, and that makes this big, sort of, burst of gravitational waves.

The way that gravitational waves work… They're not like ripples on a pond. Usually when you see a visualization, it's like ripples on a pond, but that's that two-dimensional analogue again, and they're not… if you're standing there, the gravitational wave moves your space that you're in. But it doesn't just move you up and down. What it does, is it stretches and squeezes the space that you're in.

Alie: Whhaaat? [*with curious inflection*]

Katie: So let's say that you're standing there, and a gravitational wave comes and hits you in the face. What that does to you is it stretches your space a little bit so you get a little bit taller, and at the same time a little skinnier. Then a little bit shorter, and a little wider, and it oscillates back and forth. So as the waves are coming at you each wave is giving you that stretch and squeeze, stretch and squeeze. It's actually distorting your shape when this is happening.

Alie: What? Oh my God. This is like a big boi-oi-oi-oi-ing. And it's… Like, for everything that creates gravitational waves, is this doing this to us all the time, on a micro, micro basis?

Katie: Yeah, yeah. The LIGO experiment is built to detect these things. They have two detectors, and each detector is an L-shaped thing. Each arm is four kilometers long.

Aside: If you've seen photos of this, you might think from a distance this is some shit that we built on Mars, because there's just this tree-less, ochre landscape in the desert. It seems to look lonely in every direction. But no, it's just Washington State.

Katie: And they shoot lasers back and forth along these two arms there. They meet at the center. The lasers are just there to measure the length of those arms, basically. When a gravitational wave comes and hits that detector, it makes one of the arms a little longer, while the other one gets a little shorter, and vice versa depending on the direction, and the phase, and everything.

If it does that, then the detector can detect that the length of the arms has changed. And that's the signal, is the changing of the length of the arms. The level on which that happens… So this is four kilometers, right?

Aside: That's about two and half miles, America.

Katie: The first detection, when it was detected… The length of that four-kilometer arm changed in length by a thousandth of the width of a proton.

Alie: Oh my god.

Katie: Yeah.

Alie: That's a teensy tiny…

Katie: That's really small.

Alie: And this was a HUUUGE collision.

Katie: Yeah. This was 1.3 billion light years away, so it was very far. But the black holes were around 30 times as massive as the sun, and they collided. It was a pretty strong signal. A surprisingly strong signal. If you actually looked at the data, the raw data, you could see it. Which is not usually the case in this kind of field. Usually you have to do lots of processing. You can see the signal is very strong. Thousandth the width of a proton. So, your own height is changing much less than that because you're not 4 kilometers long.

Alie: Sure. So I'm getting a little bit not quite as tall, and not quite as skinny, and not quite as short as/fat as… Yeah, not noticeable in a photograph. [*laughs*]

Katie: Yes. It's a really subtle effect. So that's the gravitational wave, the detection of that change in length, that sort of stretching and squeezing of spacetime. Each time the black holes or something collide, you get this… the wiggles will come faster and closer together. The frequency of this changing of shape is going up, and the amplitude is going up, and so it makes this kind of rising sound if you transmit it. If you change it into sound it's sort of like [*ooooooOOUU in a rising pitch*]. And the end part is when they collide.

The reason people change it to sound a lot is because the frequency of these waves coming, how quickly the stretching and squeezing happens, is about the same frequency as sound waves. It is kind of audible. Like, if you change it to sound, it's kind of audible.

Alie: And that was like the "boop" heard round the world, right?

Katie: Yeah, it's called a chirp.

Alie: A chirp!? [*baby talk voice*] Just a little chirp, chirp. A chirp!

Aside: You ready for this? This is the sound of history. [*whooshing sound, similar to a car driving by, with the tail end of the sound rising a little higher and louder*]

Alie: What does that mean going forward for astrophysicists? How many more have we heard since then?

Katie: There have been… oh gosh… I don't even know the number. Something like five seen now. The most recent one was two black holes. But the one before that was two neutron stars. And those were a big deal because those, when they collided, also created a gamma ray burst.

Aside: A gamma ray burst: super energetic explosion. We can't see gamma rays, but they pack a punch in a burst!

Katie: We were able to see the collision from the gravitational waves, but also from light. That was a HUGE deal and I can talk about that for hours. But the whole thing is a big deal for a bunch of reasons. One is that the existence of gravitational waves was kind of known indirectly, because we'd seen systems where you had two pulsars orbiting each other. Pulsars are a kind of neutron star. A neutron star is, like, the core of a dead star.

We'd seen things orbiting each other where the changing of the orbit could only really be easily explained by gravitational waves radiating energy away from the orbit. The orbit got smaller because gravitational waves were pulling energy away and shrinking that orbit. We had indirect evidence that gravitational waves existed but we'd never seen them directly. And directly, like detecting… like, feeling the gravitational wave is a HUGE deal. And gravitational waves were the last prediction of Einstein's relativity to be confirmed.

Aside: Einstein's theory of relativity, remember; our perception of the force of gravity is a bendy spacetime thing. I'm very paraphrasing a lot.

Katie: He [Einstein] predicted them about a hundred years before the first detection was made. So, it took a long time to see these things. It [the waves] confirmed that. It's just this incredible laboratory for relativity, for physics, because by detecting the gravitational waves and looking at the signal we were able to determine that gravitational waves travel at the speed of light, which we didn't know for sure before. That was part of that theory but we didn't know for sure. So, we figured that out.

It told us stuff about how black holes are made… what black holes are made of, the properties of black holes, by examining very closely how they come together and merge. How much energy the gravitational wave bursts creates… a lot of stuff about that. And because now we can watch black holes colliding in the distant universe we can learn about how black holes grow by when they collide with each other. That tells us something about how black holes grow, it tells us something about how galaxies grow, it tells us something about how stars form, because black holes are the end results of stars.

Alie: When you were a kid were you ever hoping that this… that we would be able to detect gravitational waves? Were you like, [*cutesy affected voice*] "I've been waiting since I was a little girl."

Katie: I didn't know a whole lot about gravitational waves when I was a little kid. But there was a really beautiful moment during the detection of the neutron star collisions, when one of the scientists was talking about the neutron star collision. And the neutron stars, when they collide, they make a slightly different kind of chirp sound.

Aside: Here's the sound of the neutron stars boopin' themselves together:

[*electronic humming sound that intensifies and ends with a pleasing 'blip' like a water drop*]

Katie: The black hole one is actually a lot quicker than what I said, but the neutron star one goes like [*imitates neutron chirp with* whoooOOp] It takes a while. There had been simulations of this for years. The scientist who was talking about the discovery said that he'd been waiting to hear that sound from nature for 20 years. [*Alie squeals aww*] And he just did. It was really touching.

For me, I knew about LIGO because it was partly headed by people at Cal Tech, and I was an undergrad at Cal Tech. When I was an undergrad there, people were talking about it a lot. There was a famous bet between Kip Thorne and Stephen Hawking...

Aside: Kip Thorne, by the way, is a theoretical physicist. The 2017 Nobel laureate.

Katie: …about whether or not gravitational waves would be detected by the year 2000. I started Cal Tech in '99. They were not detected by the year 2000, [*Katie and Alie laugh*] so that was lost. But it was a funny thing because when I first got to Cal Tech they were building LIGO, and it was this big deal, and everybody was like, "We're going to detect gravitational waves and it's going to be amazing." LIGO was being built and I was like "Oh, it's any minute now." Then I left Cal Tech, I went to grad school, and after a while I was like: "Hmm, I haven't heard anything about this for a while." And later on I asked about it and they were like: "Oh no it's *advanced* LIGO..."

Aside: There were some upgrades over the years from "Initial LIGO", to "Enhanced LIGO", to "Advanced LIGO." Like the tall, grande, and venti gravitational wave detectors. Just gonna need a 'lil more to get the job done.

Katie: "…Is really going to do the detection." The Initial LIGO was "Maybe it would get lucky, but Advanced LIGO , we'll really see something." For a while I was like "Really? I don't know if I believe that this is really going to happen." But then, as soon as they turned Advanced LIGO on, within a week or something, they saw those things, so they really did it. It's the most precise instrument ever built by humans. I think I read that somewhere. I mean, you're measuring something SO tiny.

Alie: It's crazy.

Katie: It's impossible. It's incredible what went into it in terms of the engineering and the physics. They had to correct for things like how much the photons hitting the mirrors would move them.

Alie: Oh my God! Oh my God!

Katie: That's a big part of the noise in the signal. [*Alie gasps in astonishment*] That's called the photon shot noise. They had to deal with it. I mean it's incredible that they were able to do that.

Alie: Can you get the chirp as a ring tone?

Katie: I believe you can you can. I believe so.

Alie: You Can!? Would you get the neutron whoop, or would you get the…??

Katie: The black hole one you have to speed it up to make it sound cool. You can still hear it, but it's more like [*imitates the noise, makes quick fluttering mouth noise like spitting out a seed*]. In the actual data it's like: [*imitates again but much quicker sound*]. That's kind of what it sounds like. But then when you when you speed it up it goes like [*two quick woops*]. But it's very quick. Whereas the neutron star one is like [*more prolonged wwhhoooooooop! raising in pitch*], which is much cooler.

Alie: Yeah, I feel like that's the way to go.

Let's say someone is interested in cosmology but doesn't know a lot about it and is intimidated by it. What is the best book to pick up? I actually… I don't know if you've ever read this, but I was in Thailand, and I was staying in a hut and there was a free book pile and I picked up a book called *Quantum Mechanics Can't Hurt You*.

Aside: This book was actually called *Quantum Theory Cannot Hurt You*. It's by Marcus Chown and it's delightful. I found my copy. It's still moldy from a monsoon.

Alie: It was good. It was very layperson's terms, but I clearly didn't retain any of it. But is there a book or a documentary or something that's just a good primer? Because in this episode there's no WAY to describe everything, but what's a good go to, like *Astrophysics for Dummies*? What are we talking here? Is there a pamphlet?

Katie: I wish I had a really good answer for this.

Alie: [*laughs*] That makes me feel like you don't. You're wincing.

Katie: The thing is, I don't read a lot of popular level stuff, and there's a couple of reasons for that.

Aside: Number one: she doesn't have much time to read non-papers, because there's a billion papers. When she does, she likes to read about spaceships, okay? Two: when something is written for the general public, astrophysicists have to take that lay-information, and kind of back-translate it to a more technical version in their head. Like, if you were a bartender and someone writes, "She drank a whiskey," but you're distracted wondering, "A whiskey? Well was it like, a bourbon? Is this a single malt scotch? Was it a Rye? Tennessee whiskey? Is this on the rocks? Was it in a cocktail? There's so much detail omitted!"

Katie: I mean Sean Carroll has written several books that are really good. Take a look at those. There's a physicist, Katherine Freese, who's a dark matter theorist like me. She's a dark matter cosmologist, and she's written a book called *The Cosmic Cocktail* and it's all about dark matter, and also some autobiographical stuff. It's really cool.

Alie: What about what about movies? Do you have a favorite, or at least favorite movie about space or cosmology?

Katie: Can I not answer some of these?

Alie: [*laughs*] Yes, yes.

Katie: Favorite… There aren't a lot of movies where I feel like the cosmology… Cosmology is hard to have as a topic of a movie because it's just too big of a topic, and stuff happens on cosmological time scales - which is incredibly long times. So, having something happen within a movie timeframe is really hard. But there's a movie that I really liked for how it portrayed the scientists and it had some cosmology-ish stuff in it. That was *Sunshine*, which, the science is wrong. Just putting that out there. It's about the sun is burning out and they have to fix it, and none of that can happen. All that's false. All that is fake. But it's done really well in terms of, like, they have a physicist who acts like a physicist. They have people who talk like scientists, and I kind of just enjoyed it. Then there's a monster thing. I thought that was done really well.

I really enjoyed *Gravity*. There's also bad physics in *Gravity* in some places, but I thought it was a beautiful movie, and it portrayed space very well.

Alie: How do you feel about *Spaceballs*?

Katie: I think it was funny. It was… it's been a long time. [*Alie laughs*]

Aside: Oh hell yes it was good.

Katie: Other space movies… like, *The Martian* was fun. *Interstellar* had a very pretty black hole in it.

Alie: Okay. You are being very complimentary. And that is duly noted. [*laughs*] You're being. A. Very. Nice. Person.

Katie: [*laughs*] The black hole and the wormhole in *Interstellar* were very beautifully done, and done with proper relativistic equations. It was very clever because what they did is, they had these simulations that are very, very difficult, and take a very long time on super computers, and they gave them to the people who do movie graphics who have really powerful super computers. They're like "No, we need to do this black hole properly." They calculated it and now they got some papers out of it because the result was such a good calculation that they were able to get actual science out of the calculation done for the graphics in the movie.

Alie: Because movies are better funded than… physics. [*laughs*]

Katie: Yeah, yeah. It was a very good move. You should know that the black hole in *Interstellar*, although there are some aspects that are done very faithfully, they did tweak some things so it actually would look pretty different if we saw an actual black hole in real life. There are a couple of things that were tweaked that were a bit different.

Speaking of movies, Katie and I were supposed to go to one after this interview, and we did, but we barely made it because this is all really great information, and we hadn't even gotten to the rapid-fire round of all your questions. I asked her your questions, we raced to the showing, and this poor woman had to smuggle a burrito and eat it in the theatre. I'm so sorry.

By the way: We saw *Murder on the Orient Express*. It features a very bizarre mustache. I will give it that.

Stay tuned - it's the first two-parter in Ologies history - when we resume with your questions. You now have a solid base. Tune in next week to hear Astro Katie address your questions including:

Is there a name for the disorientation and panic one feels when considering the vastness of the universe? There is.

Are any of the sci-fi movie methods to save the planet plausible, or are we basically doomed if an asteroid uses us as a target?

Will the universe expand forever?

What's the deal with multiverses?

Are there aliens?

Speaking of your submissions, I wanted to let you know, I totally see the reviews you write on iTunes, and it's SO appreciated. Rating, reviewing and subscribing is free. It takes very little time, and it helps Ologies stay up there in the science charts so more folks know about it. Thank you so much.

Katie is @AstroKatie on Twitter, where she has approximately one billion, trillion followers. And she is AcademicNomad on Instagram. Thank you to all you Ologites for tweeting, 'grammin', meme-ing at us, and to all the folks on Patreon who make this show possible. It is currently 4 a.m. on a Friday night, and I'm recording this to send it off to Steven Ray Morris. He's going to help edit it, and your funding is making this dream project possible, and putting a lot of facts in a lot of human minds.

You can also keep the show going by stopping at OlogiesMerch.com. We have new pins in stock: horology clock pins and amazing shimmery bird pins, for $8 each, designed by Shannon Feltus with merch help from Boni Dutch.

I also just want you to know that yes, it's super late at night, and I'm recording this partly because the mass of porridge that occupies the space where a brain would be, had to spend a little longer trying to understand and explain these concepts than I thought. Right now, as I record this - middle of the night - my neighbours have been blasting techno Christmas pop songs for four hours, while I was learning about wormholes. The world feels very surreal.

Also: congratulations to anyone who made it do the end of the episode. Man, you're stuck it out, I appreciate that. As a special thanks, I'm going to tell you a secret that no one in the world knows. Earlier tonight I ate cereal I bought from a gas station. And I loved it. If you listened to the end of the episode, feel free to holler at Ologies or Alie Ward. I'm sure I'll have a new secret for you next week, at the very end, when we're back with Katie Mack's Q&A.

Until then, ask smart people dumb questions, because they love it and we're just tiny meat blobs on a dust speck so let's just live. Can we live?

Ok, Berbye!!

[*Outro Music*]

Transcribed by Keely Langford, Vancouver, B.C., Canada, who has a moldy loaf of bread in the cupboard and is pretending it's a science experiment of sorts, and not anything at all to do with procrastination.

Some links that may be helpful:

Spaghettification

Spike in paper submissions

ArXiv.org

Great Red Spot

LIGO

Kip Thorne

Quantum Theory Cannot Hurt You

NASA JPL

Many Worlds

Stars circling black holes

How big is the Milky Way?

Pale Blue Dot

More Pale Blue Dot recording

String Theory in a Nutshell

General Relativity

Peter Higgs interview

Higgs Boson particle

Large Hadron Collider

Large HARDON Collider

For comments and inquires on this or other transcripts, please contact OlogiteEmily@gmail.com