Episode 71: NeutriYES or NeutriNO
Physicists: Ken Clark, Tia Miceli

Transcribed by Denny Henke

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

[1:49]

Ben: I want to talk today about the news. Well, specifically about the news and its relationship to the truth. I live in a country where the news media, like newspapers and radio and television programs and now websites are, overall, a healthy thing for our country's governance. Ah, they let the voters know the "truth". But these news organizations, for the most part, they are companies whose duty is to make a profit doing business and their business is selling the news. Not, the truth, the news, it's there in the title. Things that are new. Now, I don't mean to insult the journalistic trade when I say this nor do I mean to oversimplify the issues of the day but the thing about the business of selling the news is that it runs the risk of falling into a trap. Which is that people often enthusiastically buy newspapers that are exciting even if the news isn't true. And so your newspaper or radio station or website will make lots and lots of money and gain a devoted audience in spite of the fact that what they're all excited about isn't something thats actually happening. Take for instance, science news. There's a huge audience of people who are big fans of science and technology and they want to know more about it. And they're super excited to hear about a world changing discovery. So, in recent history we've heard in the news about the Ebola vaccine, and the detection of gravitational waves, Germany's new fusion reactor, people want to hear about it when it happens. But here's the thing. Big, groundbreaking science announcements are pretty rare. I mean, there are science journals like *Science* and *Nature* and *Physics Review D* that every month publish articles written by scientists about their discoveries, isn't that news? Well, no, it's not. Science isn't a book of facts that we're always updating. It's more like an ongoing conversation that the scientific community has with itself. And the science papers that people publish with their results, they're being published so that other scientists can look through them to see if they make sense. So, the results they are publishing aren't necessarily "the truth", not yet. Each science paper is more like a sentence in a much longer conversation. And so, when science journalists try and write amazing news stories based on these science papers, well, it's news but it might not be the truth. Take, for example, a story you might have heard of. In 2011, the OPERA experiment in Italy measured neutrinos traveling faster than the speed of light. This result made international headlines. In this story, a beam of neutrinos, which are small neutral particles that barely touch anything, they were created in CERN and they traveled under the Alps and then they were detected in Gran Sasso Italy. Using atomic clocks and GPS we could tell when they were created and when they arrived and boom, the result was in. They moved faster than the speed of light. Man, that story went gangbusters. My mom and cousins and uncles and aunts and students and people on the streets were asking me about it. What fantastic news. But, here's the thing, it doesn't make sense. Those results don't make any sense according to everything we know about modern physics. Neutrinos have mass and so they shouldn't be able to travel at the speed of light, let alone faster. And these results threw a lot of other results and experiments and observations into question. The OPERA group wasn't wrong in publishing their results. They analyzed their data to the best of their abilities and now they wanted to hear what the rest of the scientific community thought. So, in the ensuing months the rest of the scientific community got back to them and said hey, your results are bonkers. They don't make any sense. And then it turned out that there was a problem with the OPERA experiment's equipment. A plug was loose and the error this generated was the reason the data was flawed. When they fixed the plug and redid the experiment their re-analysis nullified their original result. And that's fantastic. That's how science works. But here's the thing. Because the science journalists needed to jump on the original and in the end, incorrect result, the general public got all excited over nothing, in the end. I don't think there's anyone to blame in these stories. I think everyone does their best and acts as professionally as they can. It's just that in our culture we've learned to value what's new over patiently waiting to learn about what's true and it's hurting us. Well, anyway, bummer city, right? No, no. Because today we're going to talk about something totally bananas. Because you missed a question in that last story I told you about the OPERA experiment. Which is, neutrinos pass through everything. Right? Effectively, nothing can touch them. How do you make a beam of something you can't touch or poke or shape or herd. And why was there a beam of neutrinos being shot from CERN to Italy anyway? Today on the Titanium Physicist Podcast we're talking about neutrino beams. Now, I didn't mean to disparage science and technology journalism just now. Because frankly, longer form documentary journalistic pieces where the maxims are "is it true" and "is it interesting", where the focus is on the process instead of the headline, that's where the most mind blowing, fascinating work is done. Thats what gets people into science as a career and that's what keeps everybody we know in love with science and technology. And there are thousands of people out there doing amazing work.

[6:45]

And as the tools of the internet media are becoming more and more sophisticated the work they're doing is becoming amazing. Today's guest is a science and technology journalist. One of the founders of the tested.com website. His work has made science interesting, assessable and friendly. And more recently he has endeavored to a broader and more ambitious project. He's Kickstarted the world's first virtual reality tv talk show. *The Foo Show* is the first 3D rendered virtual reality talk show that brings you video games and science experiments and welcome to the show Will Smith!

Will: Well thanks for having me Ben.

Ben: Oh, I'm so excited. So Will, today, for you, I have assembled a fantastic team of physicists. Arise Ken Clark!

Ken: Whoooooshhhhhh!

Ben: Dr. Ken did his masters degree with me at Queens University and he finished his PhD at Queens and then he was a postdoc at Oxford and Penn State and a professor at U of T and now he's working as a research scientist at SNOLAB where he's looking for dark matter. Now, arise Tia Michelli!

Tia: Boing, boing, boing.

Ben: Dr. Tia did her PhD at UC Davis and she's currently a postdoc at New Mexico State University working at FERMI Lab where she's an expert in neutrino experiments.

Alright everybody, let's talk about neutrinos!

Will: Everything I know about neutrinos I think I learned from old X-Men comics so I feel like I'm ready for this. Let's...

Ben: Well, what did you learn from old X-Men comics about neutrinos?

Will: Well, let's see. They went faster than the speed of light...

Ben: Oh no...

Will: And if enough of them hit you you turned into a mutant and um, that's probably it. I don't know.

Tia: The second one might be true.

Ken: Yeah, that's it.

Will: So, perfect. How many neutrinos are in me right now? That's the first question I have. Are they everywhere? Is this just one of those things, just, everywhere in the world all the time and we never notice?

Ken: Yes.

Tia: Just in your thumb, right now, there is probably three billion of them.

Will: That's a lot of anything.

Ben: They pass through us all the time like rain made of ghosts. It's fantastic.

Will: Okay, so, in the deep past I went to college and got a biochemistry degree and took intro physics all the way up to PChem and stuff like that. What are these things made of? What are they? At the base level? Is that a good place to start? I don't know.

Ben: They're fundamental particles. They're not made of anything. They're just wee little particles.

Will: But I thought everything was made of something, eventually, right?

Ben: Well, I mean, electrons aren't made of anything.

Ken: Well, they're made of something. They're just fundamental. They're made of themselves.

Ben: They're made of themselves.

Will: Okay.

Tia: Well, as, this is as best we know. It could be some string theory vibrating strings deep down.

Ken: Booooooo.

Will: Wait, when you say deep down, you mean like in deeper dimensions or...

Ben: Yeah, I think she means in deeper, more untested physical frameworks, right? So there's the forefront of physics which is, why is everything doing anything. And then there's the tested but still under experimentation realm of physics which is, you know, particle physics where we're saying, "What happens if we mash these two particles together?" It's less foundational mathematically but it's also a lot more experimental. Okay?

Will: Okay.

Ben: So...

Will: So that's like what's happening at the large hadron collider and...

Ben: Yeah.

Will: And any particle accelerator, basically everywhere.

Ben: Yeah, that's right.

Will: Okay.

Ben: So, a neutrino is a basic type of particle. There's only a few basic types of particles. They're not made of anything. You can't cut a neutrino in half. It's not made of two smaller things, unless, like Tia just said, into some, more, higher level physics. Different people might explain it in different ways but as far as we can tell it's just a point like particle that's made of itself.

Will: Okay. No quarks or anything in there...

Ben: That's right. It's a lepton like an electron is in that it's not made of quarks.

Will: I've already learned something guys.

Tia: Quarks are, themselves, fundamental particles.

Will: Yeah. Okay. But, I mean, at some point we thought atoms were fundamental particles, right. Like, we just need to keep drilling down getting smaller and smaller.

Ben: That's the hope, right. I mean, everything we say here is with an asterisk that within a hundred years time people are going to listen to us and say well, for one thing they're not all speaking with strange accents. And then for the other thing everything they're saying is way outdated because this is before everybody discovered the neutrolino that (funny sound) So....

Will: Look, I took my science classes 20 years ago, I'm old enough to have done that. So, literally, everything I know at this point is 20 years out of date and thus, you know, ancient history in your alls terms so...

Ben: Okay, so, it's a fundamental particle but it's different from most of the fundamental particles. Um, most particles have electric charge. Ah, electrons have negative charge. Protons which are made of quarks have positive charge and that's why they are attracted together. And electromagnetic fields are the reason you can't smush one surface through another surface. The reason rigid objects are rigid, you know?

Will: Mmmm hmmmm.

Ben: So, neutrinos don't interact with the electromagnetic field at all. They're neutrally charged and that means that if there is a positive charge over here a neutrino will just pass right by it without feeling any push or pull.

Will: So, does that mean that it's like an electron that has no charge? Is that the same kind of...

[11:38]

Ben: That's a starting, to think about it. Neutrinos have mass too. We discovered in the late 90s that neutrinos actually have mass as well. Their mass is so small and the energies that they're formed at are usually so high that they are usually traveling very, very close to the speed of light as far as we can measure. So, we didn't know until fairly recently that they had mass but it turns out they have mass. So, they're tiny and they only interact with other matter through the weak force.

Will: Okay.

Ben: So, they are four fundamental forces. There's gravity, there's the electromagnetic force, most of the phenomena that we see in the macroscopic world is some combination of gravity and the electromagnetic force. Gravity is a very, very small force so in particle physicists it doesn't usually do anything. Ah, and then these neutrinos don't interact with the electromagnetic force, so it's not feeling the push and pull that most of the regular matter is feeling. The other two forces are the strong force which binds nucleons together. It binds quarks together.

Will: Okay. So thats why protons and neutrons are big...

Ben: Yeah.

Will: And electrons are relatively small.

Ben: And it's also why protons and neutrons stick together. And then there's a fourth force in there which is the weak force which causes repulsion between the nucleons in an atom that's too big. So, you know how some isotopes are too large and they're unstable and those atoms will break apart.

Will: Oh, everything on the high side of the number and the stuff on the right side of the periodic table.

Ben: Yeah.Yeah.

Will: Okay

Ben: If they have too many neutrons...

Will: Well, not all the way on the right I guess.

Ben: Right. If they have too many neutrons they fall apart and that's because of the weak force. It's a very small effect. It only shows up in very specific circumstances. And thats' the only force that these neutrinos feel. So, they need to get really close to other things to feel any push or pull. So mostly they just travel though solid objects. So, one of the places they are generated is in the Sun and so we're continuously being rained on by neutrinos from the Sun and those just pass right through the Earth.

Will: Okay, so, when you say they pass through the matter, what you mean is, they're basically, shooting the gap between the protons and the electrons or are they even, like, passing straight through the protons. Like, if a neutrino hits a proton does something happen or does it just go through?

Ben: Mostly it goes through.

Will: Wow.

Tia: So, most of solid matter is just empty space anyway. So, usually when a neutrino passes through it's just passing through empty space. But, there's some very small probability that even if it passes though the actual proton or the quark within the proton itself, it may just keep on going. It, there's a possibility that it will interact and that's what we all bank on for our experiments. So, the answer is really both. It goes through that empty space in between and it can also just go through other particles itself I think.

Will: Wow. So, that means if you dug a theoretical hole through the center of the Earth. Or, I guess, a better way to do it is go on the far side of the planet from the Sun. So if you're on the dark side of the planet and you have a sensor on the light side of the planet and they're both measuring neutrinos coming from the Sun, they're going to see, essentially, the same number of neutrinos even though there's a whole planet between one of the sensors and the other sensor.

Ken: That's pretty close. I mean, one of the experiments I work for, IceCube, we look at neutrinos, we're at the South pole. But we mostly look at neutrinos that traveled through the Earth from the North Pole to the South Pole and we look at them there.

Will: So, are we getting bombarded by neutrinos from other stars all the time too?

Ken: Yes. But of course those are pretty far away and they don't give us very much. The sun is the main source for, like ones generated by stars.

Will: Can we make neutrinos in a lab? Can we make a beam of neutrinos like we can make a beam of protons or electrons or something.

Ken: What a great question! Yes.

Will: Like, do you just go out with a mosquito net and catch a bunch and dump them in a big hooper and then fire them in a gun and shoot them at whatever you want to shoot them at? Or like, I'm getting my Maker background out here but, how do you make a beam of neutrinos?

Tia: So, that's a great question Will. We will back to that but first we need to introduce how neutrinos are made in general. Because, you know, there's all kinds of different sources of them. So we mentioned a couple. Ken mentioned the Sun and stars but there's a couple other ones. So with any cosmic rays that come into our atmosphere, like high energy protons traveling through space. And when they interact in our atmosphere they create particle showers and in those showers the proton will interact with a proton or neutron in the atmosphere and out of that will come a spray of pions which are smaller particles made out of quarks. And those guys decay to other particles including muons and muons decay to neutrinos. And there's also other paths to create neutrinos also.

Will: So, high energy protons randomly hits stuff up in the sky, up in the atmosphere, and those beget pions and the pions beget muons and the muons beget neutrinos?

Tia: Yep.

Will: That makes it sound really easy and I think that there's probably more there.

Ken: Also, makes it sound really Biblical.

Ben: Yeah.

Laughter.

[16:38]

Ben: The thing about neutrinos is that they are fundamental particles and that means that they can be created in nuclear reactions. So anytime the energy in a system is high enough you can have particles being created out of nothing.

Will: Really?

Ben: Yeah, yeah. Like...

Will: I didn't know that, that's new.

Ben: Like the Higgs Boson. That's how it works. What you do is you smash two really, really heavy, well, nuclei, hadrons, together. And the energy density where they've collided is so high that, you know, nature rolls a set of dice and just says alright, we can just change this energy into a Higgs Boson or we can change this energy into two protons or we can change this energy into 16 pions or whatever, right?

Will: But, it's really a roll of...

Tia: But there's certain rules.

Ben: Yeah. Well, yeah. It is a roll of the dice. It's governed statistically. There's no way to predict what you're going to get except that what things can turn into are governed by very specific rules, conservation laws. So, one of the conservation laws is conservation of electric charge. So, the total charge of your system has to be the same at the end as it was at the beginning.

Will: Okay, I remember that, makes sense. Right.

Ben: So, if the system starts out neutrally charged and you make one electron then you also have to make something with the same amount of opposite charge, the total stays the same.

Will: Okay.

Ben: Okay, right?

Will: That makes perfect sense to me. And one of these types of conserved charge involves, a kind of, electron flavor. So, the electron has two cousins. One of them is called the muon and it's kind of heavier. And the other is called a tau and it's much heavier. And they just look like electrons, they're just more massive. They require more energy. And they're also a little bit unstable. So, if one hangs out too long it will fall apart and turn into an electron which has less mass and isn't unstable.

Will: Okay. And something else, presumably, then.

Ben: Right. Exactly, because there's another conservation law that says the total amount of electroneness, the total amount of muoness, the total amount of tauoness, in a system has to be conserved. And so, if you have a muon and it wants to turn into an electron it's got to produce two neutrinos because neutrinos can also carry that lepton flavor. Um, so, you can have an electron neutrino and an anti-electron neutrino which is the anti-matter of an electron and a muon neutrino. So, each of these different types of electron cousins has an associated neutrino and so any time you have one of these conversions between, say, muons decaying into electrons, it also generates these neutrinos that accounts for difference in the the missing flavor. And so one very common byproduct of one of these nuclear decays is it generates just a bunch of different neutrinos. It's kind of like changing money. So, the total value, in dollars and cents needs to stay the same before and after you make change. Neutrinos are like pennies.

Will: Oh, okay.

Ben: Once they show up they have so little energy that they don't really turn into anything and they interact so weakly. And so, in these showers that Tia was talking about, heavy radiation hits the upper atmosphere from space, the energy density is that high that it generates a shower of unstable particles. And often when those particles decay, ah, they'll generate these neutrino particles which then, you know, they're like pennies, they just accumulate. You can never spend them. And so what we end up with is a shower of different neutrinos.

Will: So, is the same thing happening inside the Sun to generate the neutrinos or is it like just a byproduct of atoms fusing?

Ken: Yeah, that's exactly it, yeah. It's all nuclear reactions in the sun and like Ben said, all these nuclear reactions generate neutrinos. But it's pretty cool because neutrinos are basically the only thing that makes it out of the center of the Sun.

Will: Oh.

Ken: Everything else gets trapped and neutrinos actually make it out of there which is neat.

Will: Oh. So, do they carry information or anything with them from inside of the sun or is that something, is that a crazy science fiction question?

Ken: No, they carry a lot of information about the processes going on in the Sun.

Will: So, are there different kinds of neutrinos?

Ken: Exactly. That is exactly right. There are different kinds of neutrinos.

Will: Is this a flavor thing? Like, just so you know, when I talked to particle physicists in the past I always reach a point where I think that they are pulling my chain. So, I feel like with all this flavor stuff we're getting a little close to that. But um, they carry stuff out of the sun that then you look at and tell about things that are happening in the depths of the Sun.

Tia: Yeah, that's right. You can make images of the Sun and check on the health of our greatest fusion ball of energy in there.

Will: So, does that mean if we ever get fusion working here in a reasonable way we're also going to be creating a ton of neutrinos that blast out from wherever that reactor happens to be?

Tia: Yeah, it will be a really awesome neutrino source to set up some detectors.

Will: So does this mean you can also have, like, a neutrino, I know it wouldn't be a telescope, but a, like, neutrino astronomy? Look at stars and tell stuff about, like, what kind of information do you get from the center of the Sun, I guess, is what I'm trying to get at.

Ken: So, your phrase is exactly right. In fact, Ice Cube, this project I work for, is basically a neutrino telescope. We learn a lot about stars by looking at the neutrinos that come from them. So, we do astronomy looking at the neutrinos

Will: How do you tell whether a neutrino comes from a star or from the Sun?

[21:36]

Ken: It can be challenging but we get directional information. So, we can pretty much rule out the stuff from the Sun pretty quickly. After that it gets much more tricky trying to figure out where these things came from.

Will: Because, presumably, if they go through everything it's not like you can just make a metal tube that you aim at whatever star you want to look at and wait for a neutrino to hit right?

Ken: That's true but one of the really great things about neutrinos is what Ben said earlier. As they travel, from, like some distant star they go in exactly a straight line right to our detector.

Will: Oh.

Ken: So, if we can trace that backwards, they point exactly where they are. They are the only source of information that we have that doesn't bend. Like light bends, and you know, gamma rays bend, etc.

Will: Interesting. Okay, so, what do we learn from neutrino telescopes that we point at suns. Like, do we know, like, how long the stars have or like what the composition of the inside is or?

Ken: So, the first big neutrino experiment was called Homestake where, basically, there's this guy, Ray Davis, went to a mine in South Dakota and set up the most crazy sounding neutrino experiment I've ever heard of. What he wanted to do was look at neutrinos from the Sun and figure out how many neutrinos were coming out and how healthy or how long the Sun had. The problem was his experiment used a reaction, he only saw one flavor of the neutrinos. So when he actually did his experiment, he only saw about a third of of the number of neutrinos that were expected from the Sun. So everybody lost their minds and said the Sun is burning out, it doesn't have the right number of neutrinos, we're all going to die, etcetera, etcetera. But then these other two experiments SNO and Super-K came along and said, no, no, it's all cool. The problem isn't that we only have a third of the neutrinos, the problem is you only saw a third of the neutrinos. If we look at all the flavors, all the neutrinos are there, the Sun is going to live, everybody's going to be happy and they just got the Nobel prize a couple years ago for doing that.

Ben: I want to emphasize the details to that story. The Homestake experiment was there measuring how often neutrinos bombard his experiment, right? The rate that neutrinos are passing through his experiment refers directly to the rate that they are being made inside the Sun, right?

Will: Yeah.

Ben: And the rate they are being made inside the sun is a direct reflection of the rate that fusion is happening. Right?

Will: So, how much hydrogen is being converted to helium. Basically.

Ben: Yeah, yeah. Exactly. But Ken just said it, that neutrinos are really the only thing that makes it out of the Sun in a reasonable amount of time. So, if fusion at the center of the Sun shut off it would still take a long time. Long, like millions of years, it's just this monstrous timespan for heat to make it out from the center of the Sun, um...

Will: Geologic scale is what you're saying.

Ben: Yeah, geologic scales. So if the Sun is shut off we would have no indication of it based on how bright it was.

Will: Oh, wait, I saw this documentary. We build this space ship, we fly right up to the Sun then everybody goes crazy and then the guy from the other ship comes and they try to restart the sun with nuclear bombs and it doesn't work out.

Ben: Yeah

Will: Or maybe it does, yeah, yeah, it's good.

Ben: Exactly.

Laughter.

Ben: So, in the Seventies, physicists thought that the sun had gone out because, ah, the rate that neutrinos were bombarding this guys experiment were measured to be a third of what was predicted to keep the Sun going. So, we said, oh no, the Sun has gone out, we're doomed.

Laughter.

Ben: The sun went out a long time ago...

Will: Yeah, that seems bad, it seems like that would be on the news.

Ben: The fusion rate is really low. I know, well, mostly physicists just kind of kept it under their hat. And so the explanation was that this guy's experiment was only measuring one of the three different flavors of neutrino and in between them being produced inside the Sun and reaching his experiment the neutrinos changed flavor. So, they mixed up the types they were. There were three flavors they could be so once they were all properly mixed up there was only a third of the detectable neutrinos.

Will: So, he was embezzling neutrinos, right? He was only recording one out of three and the other two went in his pocket. I see how this is.

Ken: That's right.

Ben: Oh man.

Ken: Um, can you indulge me for thirty seconds about this experiment. So, basically what this guy had was he went to down into the mine and he had a tank that had a bunch of chlorine atoms in it. Every so often a neutrino would come in and what would happen is it would interact with the chlorine atom and it would turn into argon. And then he would drift this single atom out of his tank and count it and that was how his experiment worked. Which is insane to me.

Will: How did he drift it out?

Ken: He circulated it out and then he had this filter, basically, that just counted single atoms of argon in there.

Will: Wow.

Tia: Well, he actually collected them all in a test tube, like, because argon is neutral. So he would filter out all of the chlorine you know, travel in an airplane with this little vial.

Will: Wow, wow.

Ken: Anyway...

Will: Like that's something that doesn't seem like it's real, right?

Ben: Yeah, yeah.

Will: Like, it's... Yeah. Okay, so, so it seems like the neutrinos must be pretty stable once they blast out of the Sun. And then they just keep going forever and ever and ever.

Ken: In fact, one of the things that we see from neutrinos is the background from the neutrinos that were created like, around the time of the Big Bang.

[26:35]

Will: Wow. So, okay, I have two questions and I don't know which order you want to do these in. I want to know more about the flavor stuff. Is this just like a normal quantum thing where it's like top and bottom and fuzzy and all the nerd jokes that physicists do on naming quantum flavors or is it something else.

Ben: No, it is like top and bottom, and charm and strange and...

Will: So, it's just picking up elements of the quantum state from whatever it degraded from.

Ben: Yeah.

Will: Okay.

Ken: There's three flavors of neutrinos and they match the three flavors of leptons that Ben talked about. There's electron neutrinos, muon neutrinos, and tau neutrinos that all correspond to one of the other particles.

Will: Okay, so, when the neutrinos hit the chlorine and start turning into argon were there other neutrinos hitting the chlorine and making some other kind of gas or, like, what happened to the other two thirds of the neutrinos that went through that tank.

Ken: Well, the reaction that happened with the chlorine, you could really only see one type of neutrinos. The other ones just didn't go that reaction. So, this detector was just completely blind to them.

Will: Oh, so they just didn't, they just passed through and nothing happened.

Ken: Yeah. They just went through it like any other day I guess.

Tia: Yeah. But the thing that was so weird about the Homestake mine experiment was that when you do the nuclear physics, there should really only be one type of neutrino coming out of the Sun. So, they thought it was really weird, hey, we only see one third of the number that we expected. But, the thing is that those electron flavored neutrinos were switching into the other flavors, muon flavor or tau flavor.

Will: Oh, and that was unexpected.

Tia: Yeah, we had no idea that that happens. And that's why some people were like oh my god the sun has shut off, we're all going to die. But there were a lot of other scientists who were like Ray Davis I think that you're just not counting your argon atoms correctly. You have this little vial full of them, how sure are you?

Will: Well, you can just weigh them and divide by by Avogadro's number or something right?

Tia: I think it was less than that. I think there were so few.

Will: Okay, so, they're generated by the Sun, they blast out all over the place. If I want to aim at a star, if I want to aim at, say, Alpha Centauri and see what it's neutrino spectrum looks like, like how do I tell which direction they come from? Do you just set up two detectors far apart and time them and hope that you've got the same neutrinos or are there more of a...

Tia: Go Ken.

Ken: So, the way that a lot of the detectors do it is they cover a lot of space. So, what you can see is the neutrino comes into your detector, it interacts to create a particle and then those particles are all scattered along, generally, along the path that the neutrino came in on. So, what we do is we put all those particles, we look back to where they started from and then we, essentially, project where they came from using that.

Will: And presumably you know what the material that the neutrino hit was, right?

Ken: Yeah.

Will: So you can then kind of model out what happens and see what direction the impact came from?

Tia: Yeah.

Ken: That's exactly right. Yeah. And these are pretty relatively high energy, I mean, depends on your definition of high energy, but, in the 10s or 100s of GEVS. So, they create quite a few particles that go along the path of the neutrino.

Will: Okay. And we can set up detectors for those other types of particles relatively easily?

Ken: Exactly. Those ones are pretty easy to detect. Neutrinos are hard but once they interact we can see what they make pretty easily.

Will: So then, can you look at those particles that come off the collision and tell stuff about the neutrino from that?

Ken: You certainly can. That's exactly right.

Will: Wow, this seems like it's really inferential and, seems like the kind of thing that would require a lot of weird, like, mental gymnastics to get, I mean, let me ask a meta question first. When you're doing this stuff as an undergraduate, a lot of it is so far and complex and terrifying, it's like it's impossible to visualize because it's all so tiny and the scales are so infinitesimally small, like, as you spend more time with it I assume you like build a mental picture and it kind of gets easier to manage, right?

Tia: Yeah. At least for me. I don't know about you guys.

Ken: Maybe? I mean, to some extent, as you get more and more specialized you learn more and more about a smaller and smaller area. So, someone like Tia probably knows a lot about this because it's exactly her area.

Will: So, it's funny because one of the things that we're doing for FOO, one of the upcoming episodes is with a biophysicist who builds nano machines out of DNA. It's been interesting talking to him because we do this in VR where we're able to make these things that are normally these nanomachines that he builds that are normally impossibly small that you can see under an electron microscope but that's it. And we're able to make them tangible and big so that you can hold them and kind of turn them around in your hands and look at them and experience them in a way that you experience things in the real world. He said it's changed a little bit about the way that he looks at it as he's been doing this. But I wonder if you take something like the output from one of these detectors and get it to a position where you can look at it hold it and kind of interact with it like a thing in the real world if that makes it easier or harder?

Tia: So, yeah, yeah, so actually it's really exciting on the experiment that I'm on right now, it's called MicroBooNE.

[31:35]

And we have an augmented virtual reality kind of picture of our detector and we can view it through all kinds of different platforms. And you know, we have members of our experiment that show the former Department of Energy Secretary, our virtual reality of our detector and what events look like in there, so, yeah, I mean, it is useful. It's a lot of fun to see too.

Will: It makes it a little more accessible too I guess. Okay, so what haven't I asked? I feel like I have a pretty good idea where these things come from. So, mostly from suns and the Big Bang. Are these something that, like, come out of black holes and stuff like that? Or is this primarily main line stars.

Ben: Anywhere where the collisions between atoms are high enough for, like, fusion. Nuclear reactions.

Will: So, does fusion produce them too?

Ben: Yeah. Fusion, fission, both them.

Ken: Yeah. In fact, that's another source of neutrinos, is, reactors give off lots of neutrinos.

Will: Okay.

Ben: Yeah, can't you use, um, neutrino detectors to see if somebody's testing atom bombs.

Tia: Yeah, there's a lot of research right now in looking into kind of non-proliferation, we use neutrino detectors to make sure other folks don't have nuclear material that they shouldn't have.

Will: Oh, so it's not, it doesn't have to be an active reactor it can just be fissile material that's kind of hanging out.

Tia: Yeah.

Will: So, are the detectors, like small enough, and usable by normal people enough that we can like, use them for port security and stuff like that? Things that are traditionally kind of hard.

Tia: So, they're usually pretty large detectors and you usually need a source that has a lot of neutrinos in order to see a few of them. Right now I think they are doing research, or maybe they even have prototypes of, just like you mentioned, port security. So, you know, shipping containers come in and they want to pass it through this little garage and the garage is actually a neutrino detector. And so, you know, if you see too many neutrinos coming out of this shipping container, you're like, hey, please open that and show us what's inside.

Will: And then they are like, it's just a bunch of bananas.

Tia: But yeah, exactly. So, we were talking about the main ways that you get neutrinos, so it's all through the weak force. So, bananas have radioactive decays that they undergo. You get neutrino's out of those, you get neutrinos coming out of fusion, you get neutrinos coming out of fission, so the Sun and nuclear reactors are sources. But, we can also make beams of neutrinos. We have proton accelerators all around the world at different laboratories and what you do to make a neutrino beam is you speed up these protons really, really fast and then you shoot it onto a target. For example, at FERMI Lab, for the MicroBooNE experiment we shoot it onto a target of beryllium and we just picked beryllium because it has nice properties that can stay cool. You can cool it off quickly. Because when you're shooting this proton beam at it, you know, it heats up really fast. And so, if it gets too hot that can be dangerous.

Will: When you say protons, you mean you're firing like hydrogen atoms with the electrons stripped off by the accelerator and it's just a massive number of them?

Tia: Yup, a massive number of them.

Will: Like, what's a massive number of hydrogen atoms?

Tia: Like, 10^{12}.

Will: Oh, okay, that is a really massive number.

Laughter.

Will: It's either really tiny numbers or really huge numbers. It's yeah, okay.

Tia: Yeah, there's no middle ground.

Laughter.

Tia: So, so in the beryllium target, you know, these protons hit the beryllium atoms in that target and they create a spray of particles. So, just like we were explaining earlier, when high energy cosmic protons come to our atmosphere and you know, hit a molecule in our atmosphere and then they start this shower of particles which I think is as simple as proton begets pion begets muon and then you got a neutrino. And that's exactly how we make beams of neutrinos too. But the really cool thing is that if you're thinking about one of these showers, you know you have this spray of charged pions and muons coming out and, you know, they just kind of go in every which direction. So, those are charged, so what we do is we focus those to go forward and we do that using a special magnet that we call a horn.

Will: Is it like a big giant electric magnet or something?

Tia: Yup. It's shaped like a horn.

[36:36]

So, imagine, like, the end part of a tuba and...

Will: Okay.

Tia: And that's what it looks like. So we make electric current flow through the inside and back through the outside of the horn and this creates a magnetic field that goes circumferentially and it has the effect of bending all of the charged particles in a forward direction.
Will: So, it's like throwing balls into one of those things at science museums that they run around the outside edge and then just shoot through the middle basically?

Tia: Yeah, exactly. Or those coin donation, you know, funnels.

Will: Yeah. The coin vortex thing.

Tia: Yeah, I love those.So, once you get those particles projected forward then you just wait for a really long time. You put a lot of material in and you cause all of those charged particles to decay and by the end you're left with a beam of neutrinos that can travel through the Earth and onto your detectors.

Will: So, now we're back to Rome and firing through the base of the Andes.

Tia: Yeah.

Will: Okay, so, I know that if I stand in front of a beam of protons of a particle accelerator it's going to be, depending on how lucky I am, from bad to really, really, really bad. What happens if you stand in front of the beam of neutrinos?

Tia: Nothing.

Will: Nothing.

Tia: We do it all the time. There's no radiation hazard.

Will: This is a much more fun version of particle physics than most of the particle physicists I've talked to. They all are always like you can't go down in the hole while the things running, so. So, once you have the beam of neutrinos what can you do with them?

Tia: Yeah, so, the beam of neutrinos, so, earlier we were talking about neutrino oscillations and how they saw oscillations from solar neutrinos. So, solar neutrinos are primarily electron flavor but when you make a neutrino beam they are primarily muon flavor. So...

Will: Just because of the way the hydrogen particles, is it beryllium particles that is just decaying when they get slammed into or the hydrogen particles, I guess both, or does everything explode?

Tia: Yeah, it's a destructive interaction for the beryllium and sometimes it's just the proton that will decay.

Will: Okay.

Ben: Ah, so, the question here is why would we want to make a neutrino beam in particular. And the answer is that neutrino beams allow us to make a certain pure type of neutrino.

Ken: If you use a beam you know the energy and the path length and those are the two really important parts.

Ben: Right. We want to make pure muon neutrinos to see how they mix as they are passing through matter. That's the deal, right?

Tia: Yeah.

Ken: And in a beam you know how much matter they passed through, precisely.

Will: So, what happens to it when they pass through matter? Sorry, this is, this is, I feel like we missed something someplace.

Tia: Yeah, so the cool thing about some of these neutrino experiments is that even if you have an imaginary pure source of say, tau flavored neutrino and that neutrino travels through a vacuum to your detector you will not only measure tau neutrinos, it will mix to other neutrino types. And that's just neutrino mixing.

Will: Is that just because there are sources on the other side of whatever thing you're looking at that are shooting out different kinds of neutrinos?

Tia: No, no.

Will: Or just something that happens when they hit things?

Tia: Nope, it's not because they hit things, it's as they are traveling they are quantum mechanically allowed to switch around and right now we don't really understand how that happens and we want to quantify all of the variables that describe and can predict those oscillations and the prediction changes based on path length, so, how far did it travel? And also what energy does it have.

Will: Okay, so, they all have different amounts of energy, they go in a specific direction to infinity basically. And if you fire one out and check on it every half light year, or whatever, I don't know what distances we're talking about here, 3 feet, half light year, it's one or the other, right?

Tia: It changes based on the energy actually.

Will: Wow. And is it predictable? Like, the same energy always changes in the same way or does it change, is that...

Tia: Yeah, it's predictable. There's a probability, so, you know, everything in quantum mechanics is a probability. But we understand those probabilities and what we do with the experiments is try to refine our model to get better predictions.

Will: So, like, what kind of scales are we talking about here? Do you measure them at three feet and then shoot them through the planet at a different lab and see what they look like on the other side too?

[41:21]

Tia: Yeah so the scales are all different for different energy neutrinos. So, for example, at my experiment at FERMI Lab, our experiment is located less than a kilometer from the production point of the neutrinos and we're looking for oscillations there. But there's also other experiments with different energy neutrino beams that are hundreds of kilometers from the detection point and they are able to make different measurements of neutrino oscillations. How many are electron flavor, how many are muon flavor, etc.

Will: So we understand how it happens, we measure it, we have a statistical model but we don't understand the why of how it happens?

Tia: I think that's accurate. Ken, do you want to add anything?

Ken: No, I think that's right. I mean, as, exactly what Tia said. We can predict probabilities with these things but the kind of how it happens is not exactly understood.

Will: And is the hope that if we can figure that out it will unlock some more of the underlying fabric of the Universe?

Tia: Yeah, that's right. We hope to kind of narrow down on that...

Will: How stuff works.

Tia: Yeah. I mean, some models, they make some predictions and if we make a measurement and are like hey, we don't see that prediction, your model sucks go make a new one for me. That's how we keep the particle theorists, ah, we give them job security.

Ken: I think, just to kind of say what Tia was saying, I guess, I mean, neutrinos, as we said, are a fundamental particle and not knowing how they actually operate is just vexing. So, you know, this is kind of a fundamental knowledge thing.

Will: Let me put on the science journalist hat and say, is this one of those last great mysteries, is this one of those things, like, how much stuff do we not know about particle physics still?

Tia: Yeah, so, this is, actually, one of the last great mysteries of particle physics. There's a worldwide rallying around this. There's big international collaborations forming to, you know, try to answer the couple final questions about oscillations and make the final measurements. One of those is called the DUNE experiment. So, they'll make a huge beam of neutrino particles starting at FERMI Lab outside of Chicago and aim them at the DUNE detector in South Dakota.

Ken: So the cool history part here. DUNE is going into the same Homestake lab where they did that experiment.

Will: How much of these experiments end up, like, in the bottom of some incredibly deep mine someplace?

Ken: A lot. That's where I work, at the bottom of an incredibly deep mine.

Will: That's really cool.

Tia: Most of them. And the reason is because there's so much cosmic muons coming from the sky that if those were going through our detectors all the time we might not ever be able to see these neutrinos in our detector.

Will: So, you go in the deep holes to avoid false positives.

Tia: Yeah. We use the Earth to filter out as much of these charged particles as we can.

Will: Are there other subatomic particles that are like this that can penetrate almost everything or is it pretty much neutrinos.

Tia: Oh, that's a good question.

Ken: Pretty much just neutrinos. Well, I mean, unless we're going to talk about dark matter, if it exists, could also get into these deep underground mines.

Will: But we haven't seen it yet. Or we just don't know how to look for it.

Ken: Probably, yeah. I think both statements are true. Somewhat.

Laughter.

Will: Seems very ambiguous for science guys.

Tia: There have been many tens of dark matter experiments not seeing dark matter.

Ken: I work for one right now and we're very good at not seeing it.

Will: Well, I mean, it's doing its job. It's supposed to be dark right?

Ken: That's right.

Will: Science. This stuff seems really easy guys, I don't know what the whole deal is here but...

Ken: You just found secret number one about being a scientist.

Tia: Ken, how do you, kind of, existentially, like deal with the fact that your experiment is all about putting limits on measuring nothing.

Ken: The way I really, honestly deal with it, is, you have to believe that at some point we will probably see something and even if we don't we're advancing science by not seeing it.

Will: You're making little steps on the path to discovery, right?

Ken: Exactly.

Will: Is how this works.

Ken: Isn't this like the Edison thing. You know, I found out a thousand ways not to make a light bulb first.

Ben: But I mean like, there are candidates for dark matter particles that people have proposed and arguably if Ken doesn't see one for long enough it will rule out some of these candidates, right?

Ken: That's right.

Tia: So, actually one of the dark matter candidates is a super symmetric neutrino which...

Will: Explain.

Tia: Yeah, so, these are called neutralinos and so far they don't exist, so.

Will: Okay, we can make beams, we can use the beams to find out underlining truths about neutrinos which will help us understand things like the Sun and other stars.

[46:29]

Tia: Oh! The really cool thing about neutrino beams is that, ah, well, two things. You can shut them off.

Will: What, just like, pull the plug?

Tia: Yeah. Just don't supply energy to the accelerator. So, if you turn them off that means that you can understand your backgrounds better. So, like on Ken's experiment, he cannot shutoff...

Will: You can't turn off the Sun.

Tia: Yeah. He can try but.

Ken: We just can't stop that so. We have to work very hard at understanding what neutrinos are from the atmosphere and what is just a background in our detector. Whereas with Tia's, well, you want to find out you just turn off the source. Bang. Whatever's left is not a neutrino that you're looking at.

Will: So, it's like removing the room audio from an audio recording.

Ken: Exactly.

Tia: Yeah, removing background. And then the other super cool thing about neutrino beams is that you can very simply make them into anti-neutrino beams.

Will: I feel like your idea of very simply might be very different from mine but I'm interested.

Tia: Okay, you remember the horn I was talking about? The tuba horn that you cut off and you send current through it to creat our magnetic field.

Will: Mmmmhmmm.

Tia: If you reverse that current and you send the magnetic field going the other way instead of focusing positive particles you focus negative particles and then you get the opposite flavor of neutrino coming out of those.

Will: But I thought you said neutrinos didn't have charge?

Tia: Yeah, so, that's a weird part. We think they still have a particle and an anti-particle but that doesn't mean that one has positive charge and one has negative charge. It means that one has a positive electron flavor neutrino and the other one is an anti-electron flavor.

Will: Wow. Okay, so that actually makes sense to me. I don't know what you guys have done but that makes total sense. Okay, so is this a thing we can actually understand, that we can actually learn? Can we get to a point that we understand the mechanics of the oscillation?

Tia: I think so.

Ken: Yeah, I believe, that's the goal. I think it's achievable.

Tia: Yeah.

Will: That's really cool.

Tia: But it does take funding to make the experiments to get that to happen though.

Will: So, once we understand that what can we do with that knowledge? Will it make us able to build a, you know, a neutrino x-ray machine, you know, like, are there obvious spin offs for this or is that something that's to, kind of, concrete for where it's at right now.?

Tia: Yeah, so that's a really great question. Kind of, what are the applications of this knowledge? And I think a lot of the scientists would agree that this is really in the baby steps. We don't know what's possible in the future.

Ben: There's one avenue that we haven't really gone down. So, when Tia was like, so you can make these anti-neutrinos, the question is, why do you care about seeing anti-muon neutrinos?

Ken: Yeah, that's a good question.

Will: Oh, I just assumed they were interesting in some way.

Tia: We're getting into the really cool result that everybody is kind of waiting for because it could have potentially science fiction like devices in our future if it...

Will: Teleporters and phasers and all that stuff?

Tia: Depending on how that turns out. Maybe not teleporters but...

Will: This sounds great. I would love to know about science fiction applications of real world technology.

Tia: Okay, okay. So, if we are able to study how the anti-neutrino oscillations are different from neutrino oscillations that can lead us to uncover a deeper understanding of why we have this imbalance in the Universe between matter and anti-matter. If you look around, everything is made out of matter. It's not like, oh, I think instead of regular milk today I'm going to have anti-matter milk.

Will: That seems like it would be bad for me from everything I learned from Star Trek.

Tia: Yeah you might just, you know, explode.

Will: I mean, it wouldn't be that big an explosion, right?

Tia: I'm pretty sure you would die.

Will: Okay, I just assumed. I mean, I like, all I know is Scotty yells about stuff and makes them go faster than the speed of light. So, what you're telling me is if we figure this out we can travel faster than the speed of light.

Tia: Well...

Ben: No...

Tia: So, what are some cool things we could do if we could be able to understand matter versus anti-matter better? So, I don't have a good source on this, but I imagine, I think it was in Harry Potter, they were like, able to make this bag where...

Will: Is this one of those things, it's like having access to a way to make anti-matter is something we don't have right now and most people don't know that?

[51:26]

Ben: We can, we can make anti-matter. You know how at the start of the show we were talking about how neutrinos are created in like, collisions?

Will: Yeah.

Ben: When the energy density of something is high enough then random particles will be generated as long as the energy is conserved and that there were other conservation laws that held. And so, one aspect of this is that usually if you make an electron you also have to make an anti-electron.

Will: Okay.

Ben: So, you have to make a positron. Or, if you make a muon you have to make an anti-muon or if you make a quark you have to make an anti-quark. And usually, when you generate new particles you'll also be generating their anti particles. And the issue here is that there are some fine details on this but for the most part the laws of physics should be about the same for regular matter as for anti matter. And, um, it seems like they should be created in equal amounts when the energy is really high. And so the argument is that in the early Universe matter was created but for every electron an anti electron should have been created, right? So, why is there matter here, right now, instead of anti-matter. Or instead of an equal mix of both? And nobody knows the answer to that. Because, we wouldn't be here right now if there were an equal mix of both. All of the anti-electrons would collide with our own electrons, it would be hell. So, somehow there must be some subtle physics involved in making matter act and evolve in a different way than anti-matter.

Will: I thought after the Big Bang all the anti-matter went left and the matter went right and we're just on the right side of the Universe.

Ben: We don't know. We don't know. And so one of the things particle physicists are looking for are slight differences in how regular matter behaves differently from anti-matter. So, the deal with these neutrino beams is you can make a beam of pure, regular neutrinos and you can make a beam of pure anti-neutrinos and then you can compare how those two different states will mix into their you know, neighbor neutrinos. And if they mix in different ways its telling about the differences between how regular matter acts and anti-matter acts. And so it's really kind of cutting edge pushing us past the standard model of physics.

Will: Huh.

Ben: Tia's right insofar as once we push really far past the standard model who knows what useful things we'll discover.

Tia: Yeah, but what could we do.

Ben: I mean, who knows? There might be some hook where you twice as much regular matter and none anti-matter or twice as much anti-matter and none regular matter.

Ken: Yeah, and then we can use that to generate energy. I mean, who knows what we can do with this in the future. It's all up there, it's like astronauts and Tang, we just don't know how this can be applied.

Will: That one's actually a myth, the Tang thing.

Ken: It'll be like astronauts and Velcro.

Will: The ah, yeah, when you talk about, when you go to the kitchens at Johnson Space Center and start and start talking about Tang they get a little testy. So, um...

Ken: Whoa. Well, I apologize to all of the Johnson Space Center employees.

Will: They'll show you Space Lab food paste all you want though so, I prefer not to do that. Yeah, Velcro and smoke detectors, those are the big ones from NASA. That's pretty much, that and that Mylar sheeting stuff.

Ken: Oh yeah, that's good stuff.

Tia: Ah, I didn't know that smoke detectors came from NASA?!

Will: I think the ones that are actually, particle decay ones that they used on Apollo and SkyLab are, ah NASA.

Tia: Oh, okay. Wow. That's cool.

Ben: Well, that was fantastic. Thank you Ken, thank you Tia, you've pleased me. Your efforts have borne fruit and that fruit is sweet, here is some fruit. Ken, you get a dragon fruit.

Ken: Nom, nom, nom. Dragony.

Ben: Tia, you get a kiwi.

Tia: Nom, nom, nom, nom.

Ben: Aw, fantastic. I'd like to thank my guest, Will Smith, host of the FOO Show, the first VR television talk show. Will, how do we watch your show?

Will: So, if you would like to watch the show now and you have a set of VR goggles, either Oculus Rift or an HTC Vive you can go to the respective stores and search for the FOO Show and the first episode that was released last year will pop up. We actually take people into the thing that we're talking about so sometimes it's video games, the first episode is about Fire Watch. Our next episode is about Quadrilateral Cowboy which is a cyber punk game about a, you know, childhood friends who rob people, who are bad. Ah, and then we have some upcoming science episodes where we're going into UCSF Lab that has been recreated so that it's easier to record and train postdocs and graduate students as well as look at things that are infinitesimally small like nano machines that are in our DNA. Um, and you can find us, ah, we will have a 2D client really soon that will work kind of like, a video game. So you can walk around and see the avatars and explore the world and pick stuff up and interact with it. Even if you don't have an expensive VR headset. And that will be on STEAM, probably by the time you hear this. Soon, I will say.

Ben: Alright, fantastic!

[56:14]

Ben: Hey everybody! That was a pretty fun show. Sorry it took so long for me to edit it but it's all edited and now its all online. So, it's announcement time. First, please give an iTunes review to our show because it helps us climb the iTunes rank and more people will come across our show naturally and sometimes I read them to make me feel better. And, second announcement, this month, March, it's a big push called Trypod where people tell people who don't know anything about podcasting to listen to some podcasts. So, grab your friend the one you know who spends a lot of time listening to talk radio and tell them hey, there's something more fun you could be listening to and then choose them a podcast that you like and you think they will like. And then, tweet all about it on Twitter or wherever using the #trypod.

On another note, we're still humbly soliciting your donations. Your donations go to paying our server fees and our project to transcribe all the episodes as they come out. And, thanks to all of your past donations we have successfully transcribed all of our episodes in our back catalog. So, our newest project is to buy everybody microphones so maybe we won't have to listen to, ah, the dog in the backyard barking at the airplane that's passing by anymore. Alright, you can send us one time donations through PayPal off of our website or you can go to our sweet Patreon site and give a recurring, I don't know, $2 donation.

On that note, this particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I would like to start by thanking the generosity of Rastislov Kissel, Daniel Gruber, Harris Ashkar, Ampere Cacarativ for their donations. I'd also like to thank Evan Weens, David D and Dan Vale. A Mr. Alex, W.T.L, Mr. Per Proden, Andrew Waddington, Mr. Jordan Young and John Bleesy. A Brittany Crooks, James Crawford, Mr. Mark Simon, Two Songs Gang of One, Mr. Lawrence Lee, Sixton Linason, Mr. Simon, Keegan Ead, Adrian

Shonig, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein, and a gentleman named Peter Fan, Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia, Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Insanity Orbitz, Robert Johnson, Madam Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka. So, that's it for Ti-Phy this time.

Remember that if you like listening to shows with scientists talking about science in their own words there are 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.