Episode 79

Episode 79: MiniBooNE or Giant Curse Physicists: Erica Caden, Ken Clark

Transcribed by Denny Henke

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!

Music

1:46

Ben: Earnest Rutherford is one of the most important characters in modern physics. He’s a New Zealander who’s also claimed by England and also, for some reason, Canada. He’s known as the father of particle physics and he lived, ah, I don’t know, over a hundred years ago. Okay, so Rutherford is also famous for a really important quote. He said: “All scientific disciplines are either physics or stamp collecting. I think by this he means that most other scientific disciplines have a large component of cataloging and categorization. Try to recognize and classify the different types of rabbits or the different types of chemicals, right. Whereas physics is interested in the fundamental laws of the universe. Real important stuff. Okay, but here’s the thing, Rutherford was wrong for two reasons. One, it’s a really rude thing to say about other scientific disciplines because if it weren’t for other sciences we wouldn’t know about dinosaurs, and then where would we be? And two, it’s a really ironic thing to say because particle physics, the field of physics that he helped found is, at it’s heart, just like stamp collecting. Now, let me elaborate before you get your nose out of joint. Ah, imagine you’re a stamp collector. You live in, I don’t know, Vancouver, Canada and you’re trying to collect all the stamps in the world. Now, imagine that you don’t have anything like a catalog of world stamps. There’s no way to know what stamps are out there. So, you have to use cleverness and patience and deductive reasoning. Not just to try to figure out what stamps are out there in circulation but also how to get your hands on them. For instance, like, in your home in Vancouver, there are lots of inexpensive Canadian stamps in circulation so it's easy to collect the 1 cent and 5 cent and the 25 cent stamp. And you think, maybe at first, that those are the only stamps in existence. But then you reason that maybe there are higher denomination ones so why wouldn't you have seen them? You have to reason that through. Well, maybe, maybe you don't know anybody who can afford to send anything that's higher price. So, you decide to go look for one by rooting through the garbage in rich neighborhoods and then you use that garbage to inform your further expectations. You see? Or like, look, it's an American stamp. I guess that means that Americans have stamps too. This stamp is a 10 cent stamp so maybe there is an American 5 cent stamp or maybe a 25 cent stamp. So you go to the American consulate and root through their garbage. You see how it works? Particle physics is about learning about the different types of elementary particles out there and then looking for patterns in the types of particles which might lead you to strategically design an experiment to see them. So, for instance, you know that electrons have a related particle called an electron neutrino, maybe the particle called the muon has a related particle called the muon neutrino so you go look for that. Now, before you think I'm belittling particle physicists, this knowledge is incredibly subtle and incredibly useful when trying to answer the bigger questions in the universe. For instance, like, is the sun going out. There was a thing in the latter half of the 20th century called the solar-neutrino problem. We did a show on it actually, episode number 4 if you want to listen through our archives. Anyway, the deal is that the sun makes all of its heat using nuclear reactions and that these reactions should also produce a particle called a neutrino.

5:00

And when we measured the rates that neutrinos were coming in from the sun the rate was 66% lower than it should have been which told us that maybe the sun was going out. Maybe that was too much information too quickly. Imagine it in terms of our stamp collector. Our stamp collector, you, just discovered a good source of stamps from England. The dumpster behind the bank in downtown Vancouver. You reason that the rate you are finding British stamps in the garbage is related to the rate that England is sending out mail. Which is related to the amount of commerce happening in England. Which is related to the English GDP. It's a statistical relationship but you reason that if the GDP of England were to double, for instance, so would the quantity of mail and the quantity of stamps from this far off place.

Now, imagine the drama you would feel when you looked up the GDP and then tallied up the rate that you were collecting English stamps and you were receiving the rate at 1/3 you expected to find. Either something is wrong with your reasoning or the English economy has just collapsed and nobody knows about it yet. Right. So, the English economy hasn't collapsed just like how the sun hasn't gone out. But what you didn't know until you discovered that there's this conflict is that English stamps, I guess, as trains of mail pass through Germany and France, they get randomly replaced with German and French stamps. So, the quantity of mail you are receiving from England is just right, what you expect based on the GDP. But you get the third number of stamps that you expect because a third of them have turned to French stamps and a third of them have turned to German stamps. Right? Stamp collecting is a great way to learn about international mail laws as well as a fun pastime. Anyway, just like that, our sun hasn't gone out. The neutrinos that we were detecting from the sun are of one type, electron type. But there are other types of neutrinos. Muon and Tau type. Consider more in depth analysis of the mail from England, what that might tell you. Maybe you should count all the English and and French and German stamps on these English letters. If you still came up a little bit short it would tell you more than just that some of the stamps are turning German and some of them are turning French. Maybe it could tell you about the existence of other countries, maybe that you haven't heard of or can't recognize. Today on the Titanium Physicists Podcast we're going to talk about the most elusive of endeavors. The possibility that neutrinos are turning into an undetectable type of neutrino called the sterile neutrino. Speaking of things turning into other things, our guest today has really done it all. She's a musician and an author and an opera composer and a television producer and a journal editor. She currently pays her way as an author of young adult novels, comic books and graphic novels. In 2007 she won the Schuster award for the best Canadian comic book writer for her graphic novel, *The Plain Janes*. Her latest young adult novel, *Don't Cosplay with my Heart* is out this year. Welcome to the show Cecil Castellucci.

Cecil: Hi!

Ben: Hi Cecil!

Cecil: I'm very excited.

Ben: This is going to be great! So, Cecil, today's show is going to be fantastic. An old friend is returning and he's brought a new colleague with him to join our crew. Arise Ken Clark!

Ken: Whoosh!

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

Erica: Blblblublbl (Bubble sounds)

Ben: Alright, Dr. Caden got her PhD from Drexel University and she was a postdoc at Laurentian University and she's currently a research scientist at SNOLAB where she studies neutrinos. Alright everybody, let's talk about sterile neutrinos. Cecil, have you ever heard of neutrinos before?

Cecil: Yes, I have. Sometimes don't they slice through the Earth. I feel like when I was at Banff we went up a mountain and there was a neutrino catcher there.

Ken: Yes, at Banff there is a cosmic ray observatory station.

Cecil: Yes.

Ken: Way up on one of the mountains. I don't remember which one. But yeah, they had studied, that one they had studied, started studying cosmic rays and those are cosmic rays that produce neutrinos that then go through the Earth, exactly like you said.

Cecil: I've heard of them!

Ben: That's fantastic! Okay, so neutrinos are a type of elementary particle. Okay, so, let's walk our way down the size ladder in terms of particles, right. You've got molecules, everything is made of molecules. Molecules are made of atoms, you know that, right?

Cecil: Sure!

Ben: Atoms are like the smallest thing as far as chemists are concerned.

Cecil: I have heard of all of these things but which order they go in, didn’t know that. Now I do.

Ben: Yeah, molecules are made up of atoms the way houses are made of trees. No.

Erica: The way that houses are made of bricks.

Cecil: Thank you Erica!

Ben: So, ah, so, atoms are made of smaller particles. They are made of electrons and they’re made of protons and they’re made of things called neutrons.

Cecil: Right.

Ben: And the protons and neutrons are inside the middle, in the nucleus. And the electrons go around the outside. So, at the start of my monologue I talked about Earnest Rutherford. He was the guy who was like “I think there is a nucleus inside this and the electron goes around it.

10:00

So, particle physics has advanced since those days. What people started doing is smashing particles together and seeing what happens. And, you see a lot of very interesting things at the subatomic level. So, when we’re talking about electrons running into each other or neutrons running into each other or neutrons running into protons, that kind of thing, when smaller things than atoms collide, you see some really interesting things. And the biggest interesting thing is that particles pop in and out of existence.

Cecil: Oh.

Ben: So, if you collide two electrons together and if there is enough energy in the, or, if you’ve heard of Einstein’s $E=MC^2$ equation?

Cecil: Yes. I’ve heard of that.

Ben: Yeah. So, what that tells us is that energy which, you know, can involve things moving really quickly, can turn into mass.

Cecil: Right.

Ben: So, if you, if you ram two electrons together and they have enough energy you might get any other type of weird particle. And there is a whole zoo of other particles that you can create by ramming things together with enough energy. Okay?

Cecil: Yep.

Ben: So, this is has led to a smaller series of lego bricks that things like atoms are built of. So, like protons and neutrons, there are so many other different weird particles you can make by colliding them at high energies that we had to develop a whole other, kind of, structure, it’s called the standard model, of smaller particles that make up these larger, more familiar subatomic particles.

Cecil: Okay.

Ben: So, there’s three ones that we want to talk about today, right, right now. But the idea here is that if you smash them together or, there’s something called radioactive decay, ah, particles can break up into smaller pieces and shoot out other weird particles. So, we want to talk about things called leptons. That comes from the Greek word meaning really light weight. So,the electron is a lepton and it has two siblings that have higher mass. We don’t see them very often because they fall apart really quickly and they turn into other types of particles but one of them’s called the muon and one is called the tau particle. And they look just like electrons they’re just heavier.

Cecil: Got it.

Ben: So, there’s also, when you have a nuclear reaction, another type of tiny little particle called a neutrino.

Erica: When particle physicist’s were smashing beams of electrons into everything they could find, they were looking at different kinds of particle decays and looking at this thing called beta decay. So, beta was the early term for an electron. And in looking at a beta decay you expected to have one particle coming out but you would think that particle would have one energy and every time it got hit by a particle of a known energy. But it turned out that wasn’t the case. The particle coming out had this really broad spectrum of energies. And they could come out in crazy directions that didn’t make sense compared to the direction where the beam of particles was coming from. So, what it turned out, is that you thought that, did we not understand these really fundamental laws of physics, that energy is conserved and this property called momentum is conserved. The weirdness of beta decay was really screwing with particle physicists’ understanding of things at the time. And Wolfgang Pauli came up with this idea that, hey guys, what if there is this particle called the neutrino, what if this neutrino was taking away the energy so that we still had energy conservation. And what if it was flying away in the opposite direction so that we still had momentum conservation. What if all of our well beloved, well treasured physics laws were saved by this neutrino. I mean, it’s going to be really light, it’s not going to interact with almost anything or else, we would have found it already. I know, I know this is crazy he said. I’ve done a terrible thing, I have predicted a particle that could never be detected. But, it’s this mathematical fudge factor of the equations that all of the sudden you put in this neutrino and everything works out again and physics makes sense and everyone goes to sleep happy. And it took 26 years for scientists to finally say, oh, this neutrino, it’s not just math, it really exists. We’ve actually found it.

Cecil: So,the neutrino that they couldn’t see because everything was going in strange directions but if you had the neutrino then it made the strange directions make sense?

Erica: Yes, yes. Then all of the directions added up together made perfect sense.

Cecil: Okay, got it.

Ken: Yeah, it was basically like, they could see two pieces of this puzzle but they couldn’t set the third and you needed the third in order to make the two pieces make sense.

Cecil: I understand. Okay, and so then they found the neutrinos, so what happened?

Ben: Well, in brief, there is an interesting aspect to neutrinos which is they often get made in nuclear reactions and kind of the reason is there is a conservation law called flavor conservation. You remember how I said there were three different types of leptons, ah, I don't know if you remember.

15:00

Cecil: Yes.

Ben: There's electron...

Cecil: Yes...

Ben: And electron's brother muon, right?

Cecil: I'm taking notes by the way.

Ben: That's brilliant. So, those three brothers, sometimes they go away, like, a muon will stop being a muon. And you can smash an electron into something and it will just disappear from the universe. But there is an aspect to each of those, the electroniness or the muoniness or the tauaniness of each of those brothers needs to stay in the universe according to the conservation laws. And so the idea here is there are three different types of neutrinos. There's an electrony neutrino that tastes like an electron. And a muony neutrino that tastes like a muon and a tau neutrino that tastes like a tau particle. And so, if the universe ever wants to get rid of a muon it will have to make a muon neutrino to carry away its flavor. Or, if the universe ever wants to create a tauon it needs one of these tau neutrinos to come in and give the new particle its flavor.

Cecil: Okay, should we be worried though that things are popping in and out of the universe?

Ben: No, it's the way the universe works.

Cecil: Okay.

Ken: Yeah, the universe is not nearly as stable as everyone gives it credit for.

Ben: Yeah.

Ken: There's stuff appearing and disappearing all the time.

Cecil: Okay.

Ben: There are conservation laws governing the universe, like, conservation of energy and so...

Cecil: Mmhmmm.

Ben: You can't get a muon popping into existence unless there is enough energy in that region to make one, to afford one. Because, you know, $E=MC^2$, there's a certain amount of mass associated with that particle so you can't build the particle out of nothing. You need that energy to pay for the mass that's going to exist when the particle pops into creation. So, they don't exist until enough energy is concentrated in a place and then they might pop into existence and be like, hey everybody I'm a muon. And similarly, if they pop out of existence they'll have to release a whole bunch of other particles that can carry that energy away. So, the energy is always there, it just takes on different forms.

Cecil: Ah, is that why dark matter is so interesting? Because there is a lot of stuff there but it's also, we don't know what it is.

Ken: You have hit the core of why dark matter is interesting in that we know that there is something there that exists but we don't know what it is. You know, we think that it can interact with regular matter and that kind of thing and so, yeah, I think that's one of the reasons why it's pretty fascinating.

Ben: So, the story goes that, an electron neutrino is only going to come into existence if an electron has died. And a muon neutrino is only going to disappear from the universe if it has to go create a muon. If its flavor needs to be donated to the existence of a muon. Does that kind of make sense?

Cecil: Yeah, the cycle of life...

Ben: Yeah.

Cecil: With electron neutrinos.

Ben: Yeah. That’s right. Okay. So, we could detect neutrinos, you can detect their existence but it’s really, really hard.

Ken: One of the properties of neutrinos and one of the reasons that people like to study them is that they really hate interacting with anything. It is incredibly rare that they interact with any other particles. So, when we try to make detectors to look for neutrinos, generally we have to make them incredibly big so that there’s lots of neutrinos going through them all the time and then those one in 10 million or something actually interact inside your detector. And then you can see what happens. But you can never see the neutrino, you can only see what the neutrino interacts with inside your special container. They remain invisible. We never see the neutrino itself, we only see its influence on the stuff that’s there.

Cecil: Got it. That makes sense to me. So, it’s like, you can’t see it but you can see the reaction to it, that’s how you know that it’s passed though or that it’s there doing it’s thing.

Ken: Exactly. It’s like wind. We can’t see the wind but we can see the trees moving and, you know, houses blowing away or whatever else the wind does.

Cecil: Got it.

Ken: There are different ways to look for neutrinos so I will talk about an old way and then Erica can talk about news ways because she does these things. But, the old way that people look for neutrinos, they actually had, underground, they had big tanks of cleaning fluid.

Erica: Like, dry cleaning fluid.

Ken: Yeah. And this is an incredible experiment. So, this guy was looking for a neutrino to come in and interact, and basically have a nuclear reaction, an interaction with one of the atoms in this dry cleaning fluid, change it from chlorine to argon and then detect that atom of argon and say that you saw a neutrino

because of that atom that was detected. It blows my mind that there are experiments, or there were experiments that actually worked on, you know, looking at detecting single atoms of things.

Erica: And this was in the 1970s.

Ken: Yeah.

Erica: And 60s, I think.

Ken: Yeah.

Erica: This was technology from that era and they were able to do this.

20:00

Cecil: Why did they choose dry cleaning fluid?

Ken: Because they needed, basically, something that had a lot of chlorine in it. Because, what happens is the neutrino comes in and causes this change in the nucleus of the chlorine, it changes it to argon.

Cecil: Oh, I see, okay.

Ken: And then you're able to, basically, pick up the argon, take it out of the dry cleaning fluid and then you can see that oh, here's this argon atom. This must have happened inside this big tank of fluid that, you know, that this nuclear reaction happened. So, that's, just, pretty amazing.

Cecil: Got it.

Ken: But that's not how we do it now.

Erica: No, now, one of the most common ways, is to use a material called scintillator. So, it's a mineral oil with a bit more chemistry to produce a bunch of light. So, a neutrino or an anti-neutrino, it's a proton. And produces a positron and a neutron and you see a lot of light when the charged particles pass through your scintillator. So, that's one of the new ways and you can see neutrinos of much lower energies than you could with the chlorine or water was another way that people used. People still have water Cherenkov detectors.

Ken: I still work for a Cherenkov water detector, in fact.

Erica: Well, you work for an ice detector.

Ken: Well, that's true. But ice is water.

Erica: But scintillator is one of the cool things now. People use liquid argon as well for similar reasons. There is more light produced. So, different neutrino detection methods are better for neutrinos of different energies.

Cecil: Is it very pretty, the new kind. Like, can you actually see, like, light. Does it like, leave like a thing that you can see.

Erica: So, it's not enough light that can see with your eye. But all of these detectors, or these scintillator ones, or the water ones, are covered with these photo sensors. So old school would call photomultiplier tubes, new detectors use newer kind of photo detection devices but they see light. So, whether it is light that you can see in the right wavelength of your eyes or enough for our eyes, not so much. But, there are small amounts of light that are produced and we have ways of detecting that light. So, that light tells us how much energy the neutrino had and we can figure out where in the the detector the neutrino interacted. And the little bits of light can tell us a lot.

Cecil: Got it. And I forgot that there's a big spectrum of light so thanks for reminding me of that.

Ken: But actually, I think that's a really good question and you can see, for example, if you look around nuclear reactors, you can often see them glowing blue which is actually the same kind of light that these detectors detect, it's just that there's so much going on that they produce a lot of this light in the water pools around them.

Ben: You want to know some fun trivia?

Cecil: Mmmhhhmmm.

Ben: You ever watch Godzilla movies?

Cecil: Of course.

Ben: When Godzilla is under water the water around him glows blue. It pretty consistently happens because Japanese people think a lot about radiation.

Cecil: Yeah.

Ben: The story is that if you have a charged particle and it moves through, say, water, a liquid, it will kind of bump into the stuff as it goes through and that will make a pretty persistent kind of bluish light. Like Ken said, we often associate nuclear reactors as glowing and they don't really. Like, if somebody brought up a nuclear reactor, just in the air because, I guess we're going to die of radiation poisoning and you looked at it, it would look pretty normal. It would probably get very hot very quickly. Ah, if you put it under water though, it will make the water go blue, characteristically. And the process that generates that light is called Cherenkov radiation. And essentially, it's just, you have these charged particles that are made inside the nuclear reactor that shoot off into the water and bounce around in the water and generate this blue light. So, in the neutrino detectors in the scintillators, what's happening is, like Erica said, the neutrino comes in and it kicks something, generates a little bit of an electron. The electron's traveling pretty fast and so as it bounces around, as it moves through the, ah, tank of really, really clear water, it will generate this Cherenkov radiation. But not very much. It will generate, like, one particle of light. Almost undetectable and then we use, essentially, amplifiers to detect the signal.

Cecil: Okay. I get it. I understand how we capture these things.

Ben: Awesome.

Ken: Nice. Now we're getting somewhere.

Ben: So, I want to tell you something about, it’s called the solar neutrino problem. I mentioned it in the introduction. The solar neutrino problem is totally amazing. So, the first type of detector Ken was talking about, it relies on a nuclear reaction happening and then kind of chemistry happening after that, right. So, your neutrino comes in, it’s an electron neutrino, and it‘s going to interact, it’s going to kind of get absorbed by the nucleus of one of these chlorine atoms and it will kind of make an electron that will kind of do other things inside the nucleus and it will change the nucleus from one type of atom to another type of atom.

Cecil: Mmhhhm.

Ben: The deal is that only electron neutrinos are going to do that. So, like, tau neutrinos or mu neutrinos, the other flavors of it, won’t make the same thing happen in the cores of these atoms. So, it won’t, it won’t create the same signal. These old detectors can only detect that one type. Okay, so…

Cecil: Okay.

Ben: So, inside the sun, the sun is hot because there is nuclear fusion going on inside the middle of it, right?

Cecil: Right.

25:01

Ben: So that nuclear fusion, it’s a type of nuclear reaction so it often generates these neutrinos, and they are electron neutrinos. And so we are constantly being showered in electron neutrinos that are made in the core of the sun.

Cecil: Right.

Ben: So, this was called the Homestake Mine Experiment because it took place in the Homestake Mine. The guy with the big bath of dry cleaning solution, he went in and he tried to measure the neutrinos coming from the sun. And we know how bright the sun is so we know the rate that the sun is making heat and so we can predict the rate that nuclear reactions are happening in the middle of the sun. He put out his detector and when he came back a couple weeks later and counted the number of argon atoms there was about a third of the number there should be. In other words, according to this, these electron neutrinos should be coming in three times more than he was detecting. There's a couple things you can guess from that but the easiest conclusion you can draw is that the nuclear reaction inside the sun was happening at a third of the rate that we would expect. And the bonkers thing about that is that happens inside stars. It happens inside stars when they are running out of fuel.

Cecil: Right.

Ben: So he and the scientific community had to guess that the sun had gone out.

Cecil: Oh my god, that is so scary.

Ben: If the sun went out like that we wouldn't feel it for tens of thousands of years, right? Like, it takes the sun awhile too cool down before something terrible happens. So, maybe the sun ran out of fuel...

Cecil: Right.

Ben: ...and we don't know when.

Cecil: That's like the stuff of nightmares.

Ken: And people were really, like, terrified. Can you imagine if somebody today said, oh, by the way, the sun is going to go out pretty soon.

Cecil: So, what happened. So that happened and then, you know, I, when was this, in the 70's you said? So...

Ken: Yeah.

Cecil: So, did he use his rotary phone and call somebody and just be like, hey, I think there's a problem.

Erica: Yeah, so, the theorists who predicted what happened in the sun, they say, you sir, no you don't know how to make an experiment. You have it all wrong. Our calculations are right and the guy, Ray Davis, and some other people working on some other different experiments, but they were also getting the wrong number of neutrinos. They said, you theorists, you have no idea what you are talking about. How do you claim to know what's happening in the sun. I know how to catch a neutrino. Because we just learned how to catch neutrinos twenty years ago. So this went back and forth for a long time. Until an experiment in Sudbury Ontario called the Sudbury Neutrino Observatory, solved the solar neutrino problem. They had not chlorine, not water, but heavy water. So, water that has an extra neutron in it.

Cecil: Oh, okay.

Erica: Heavy water is very commonly used in nuclear reactors in Canada so Canada has a lot of heavy water. So, the people that came up with the idea for this experiment said hey Canada, do you want to have an awesome neutrino experiment? We could use some heavy water please. And they put this giant ball of heavy water deep underground in an active nickel mine and looked for neutrinos coming from the sun to interact in the heavy water. So they saw the same reactions that everybody else was seeing. That when they were looking for electron type neutrinos they only saw one third of the number that was predicted. But the cool thing about the heavy water is that there was a reaction that was sensitive to all flavors of neutrinos. So, like Ben said, there's the electron, the muon and the tau type of leptons so there's electron and muon and tau type of neutrinos.

Cecil: That means that they got like a bunch of them so then they were like oh, there are the missing two thirds of neutrinos.

Erica: Exactly

Ben: Exactly. Yes.

Erica: Yeah.

Cecil: Yay!!

Erica: So they could detect those neutrinos coming from the sun were changing what flavor they were as they traveled through space from the center of the sun into the Earth, into their detector.

Cecil: That is pretty cool. Also...

Erica: It is super cool.

Cecil: I like, because I've been to that, the big nickel in Sudbury so, put it into the, into the nickel mine, that makes so much sense. It makes me like Sudbury so much more.

Ken: And in fact Sudbury is where both Erica and I are right now.

Erica: Yes.

Cecil: Excellent. Well, will you say hello to the big nickel for me?

Erica: I will.

Ben: Just for keeping things tidy, they had to put it deep inside the mine in Sudbury because neutrinos barely interact with anything, right? But everything else in the universe sure as heck runs into things. So, if you put your detector up on the ground there's all sorts of fast moving charged particles that might pass through it and trigger your experiment.

Cecil: Ah.

Ben: And you don't care about fast moving electrons.

Cecil: Right.

Ben: So, by putting it deep underground you're shielding it from all these other sources of radiation. But the neutrinos will just pass through the Earth like it's nothing. So, the ground isn't filtering out any neutrinos but it's filtering everything else out. Ah, so, yeah, the solution is that the sun is only making electron neutrinos

but then as they travel, as they become more worldly, as they move through the universe, they say I'm tired of being an electron neutrino, I'm going to switch my type.

30:06

Ben: I'm going to go from being an electron to a muon. I'm going to switch from being a tau to an electron. They just switch around. And so, by the time they get here they are all mixed up. And that explains why...

Cecil: Got it.

Ben: Why there were two thirds missing.

Cecil: I really do find that very fascinating and I like the fact that things in the universe can change their flavor. You know, that they don't always have to be one thing. I like that.

Ben: There's a few issues with this that you need to kind of understand. One of them is like, why didn't we notice this mixing happening a lot earlier? Ah, the first neutrinos we detected were us putting big dry cleaning boxes next to nuclear reactors. Because you have real control over a nuclear reactor so you can say I'm making neutrinos at exactly this rate because that's the rate the nuclear reaction's happening. And then you can use it to calibrate your machine and tell how sensitive it is and things like that, right. So, why didn't those early detectors, why weren't they missing 2/3 of the neutrinos? And the answer is, it takes awhile for a neutrino to change from one type to another. They kind of cycle through their different possible types as they move through the universe. So, if you're right up close to a nuclear reactor as it's doing it's thing, the electrons that come out, all the electron neutrinos, they're not going to mix up very much by the time they get to your reactor. So, if you put your old fashioned detector right next to your nuclear reactor, you're going to see all electron neutrinos and you're going to say, okay the number of electron neutrinos we're getting is exactly what we predicted. So, the reason we saw them get mixed up so much on the way from the sun was because they had the time to change their flavor.

Cecil: They were changed by travel.

Ben: That’s right.

Ken: Exactly.

Ben: Like the rest of us.

Cecil: Yeah.

Ken: Like Erica said, these are neutrinos on a gap year.

Laughter

Cecil: Would those neutrinos change flavor again, like, once they got to Jupiter...

Erica: Yes.

Cecil: Or, to, like, Pluto?

Erica: Yes, so, they don’t decay into a new flavor, they are constantly oscillating. So, a neutrino that is born an electron type neutrino will just keep changing, electron, muon, tau, electron, muon, tau until it finally hits something and gets detected or, in that flavor, interacts with another particle. They just keep going forever and are constantly changing flavor.

Cecil: That’s pretty cool.

Erica: It is insane.

Ben: Imagine that it is like rolling dice on a table. So, you take, like a 20 sided dice and you roll it on a table. While it’s moving it’s changing.

Cecil: Mmhmmm.

Ben: So, as long as it’s moving it’s going to keep switching between what number it is.

Cecil: Right. But then when it lands, so that’s when it interacts with something or it hits something, that’s when it’s changed to the new thing, whatever it is.

Ben: Yeah…

Cecil: … like the water turns to argon because the neutrino got attached, like, it reacted with something.

Ken: That’s exactly right. Once it interacts that kind of defines the flavor it was at that point.

Erica: Yes.

Cecil: Got it.

Ken: But yeah, these neutrinos, they interact so rarely, it will just keep going for, basically, ever and ever until it, once in a 10 million shot it actually interacts with something.

Cecil: So, when it interacts with something, and it changes, it becomes that, then is that it for that neutrino. That’s, now it’s this new thing? Or does it continue to keep going?

Erica: Both can happen. So, like it can bounce off something but generally it, that’s the end of the neutrino’s life.

Cecil: Ah, okay.

Erica: It transforms some particle into something else, that it has produced light so we can then see the other particles.

Ken: We talk about an example of both I guess because the chlorine to argon, the neutrino is gone, right, it is, it has become part of this. But when you were talking about neutrino scattering, which we sort of talked about, that, in that case, the neutrino keeps going. It's just deposited some energy.

Erica: Yeah.

Cecil: Oh, okay, got it. But you said, Ben, that there's another kind, the sterile kind, right?

Ben: Well, yeah, well...

Erica: Whoaa.

Ken: Well done.

Ben: That's the mystery.

Cecil: I'm taking notes!

Ben: Great! Okay, before we say anything about that, the next thing we need to note is that it's hard to detect neutrinos. So, another reason that the early neutrino detectors didn't really recognize and solve this mystery is because the error bars on their data are big. Because neutrinos, like, they barely interact with anything. Right.

Cecil: Right.

Ken: For example, when the detector in Sudbury was built, it's sphere that is basically the height of a ten story building and it takes, you know, that size of detector to actually detect these. Or, I work for an experiment at the South Pole where we actually have a cubic kilometer of ice that we instrument and we need to have our detector that big because it's so rare that we need a giant detector in order to see ah, you know, a reasonable number of these interactions.

Cecil: That's incredible. Is it easier to see neutrinos at the South Pole than it is, like, in Sudbury?

34:59

Ken: That's a very good question. It's different to see neutrinos. So, in Sudbury, for example, they have, you know, it goes down in this mine and you're in kind of these controlled conditions where you can make everything dark and you can actually, you know, look for the tiny flashes of light that come from the neutrinos interacting whereas at the South Pole we just put our sensors down into the ice and we rely on all of this other stuff to happen for us to see these little flashes of light. So, the difference is in the neutrino detector in Sudbury they can see much more faint flashes of light. So, much less energy. Whereas at the South Pole we need more energy deposited in our detector in order see the affect of the neutrinos.

Cecil: Got it. Okay.

Ben: Okay, so now let's talk about sterile neutrinos. Up until now what we've been talking about is pretty standard modely stuff. I mean, they revised the standard model as we get new information but nothing is too strange. There are three different types of leptons: electrons, tau, muons. And three different types of neutrinos. This whole thing about neutrinos changing types, that's really interesting and new. But why are there three different types of neutrinos?

Ken: I would just like to interject a few points. To say that it's very standard modely stuff, I think that we should say that there is a standard model of particle physics that is, kind of, the description that we use to talk about all the particles that we know about. So, that's kind of an important thing to say. Saying something is outside the standard model may not make a lot of sense until you know that physicists have been working on building up this standard model for decades in order to try and understand all the particles that exist.

Erica: And it describes 99.9% of what we see. It is a beautiful model and almost everything agrees with the standard model except for neutrinos. They're like the black sheep cousin of the standard model of particle physics family. They do their own thing and we don't quite understand it all yet.

Cecil: Well, can you do like that guy and just, like, come up with another thing and then, like all the math will make sense for that .1%?

Erica: That is very close to what we might be trying to do actually.

Laughter

Erica: So, Ben talked about, we get neutrinos from the Sun, we get neutrinos from a nuclear reactors. Ah, another source of neutrinos is particle accelerators. So, you can take a beam of protons and smash it into a carbon target and end up getting out a beam of neutrinos. Neutrinos that you've made on your own with whatever energy you want and then you can then build your detector at whatever distance you want from your beam's target.

Cecil: That's what that CERN thing is?

Ken: Very close.

Erica: Very similar.

Ken: So, CERN, they aren't necessarily trying to make a beam of neutrinos. They're just trying to smash, you know, protons and things together and then they look at the pieces that come out, basically. The one that Erica is talking about, it's a specific bespoke detector, artisanal detector or whatever that they, that you specifically try to create neutrinos with it.

Cecil: Okay, got it. Okay. But it's the same idea. You're using some kind of thing to make neutrinos

Ken: Yeah, it's exactly the same idea. You're speeding some particles up really fast and then you're either smashing them or you're trying to make neutrinos with them. So, it's very similar.

Cecil: Okay.

Ben: I think we want to clarify it. So, the deal is that neutrinos get made in nuclear reactions, right.

Cecil: Right.

Ben: And nuclear reactions take place, weird things pop into existence when the energy is high enough in a certain region. I mean neutrinos will get made anyway, at, like, CERN, but in this place you want a beam of neutrinos.

Cecil: Right.

Ben: So, what you're doing is you're making a really specific nuclear reaction. You're ramming two things together in a certain way so that it makes a culminated beam of neutrinos because that's really useful. Neutrinos will mix their type the farther along they go, right. So you can make this beam of neutrino and then measure the types of neutrinos in one spot and then measure it a hundred kilometers away to see if they've changed how they're mixed up.

Cecil: Got it. Also it seems like since you said that they are very elusive that it would be better to have a beam because then you have a lot to work with.

Ken: Exactly, that is exactly the point. And also, I was going to say just that neutrino beams are good for very little else. Other than counting neutrinos. There's almost nothing you can do with them.

Erica: The sun is really good for other things than producing neutrinos. Nuclear reactors power the world. Neutrino beams make neutrino beams.

Cecil: I'm sure some superhero will be able to use neutrinos is some fancy way, somewhere.

Ben: Yeah, we're probably messing up the stuff on another planet far, far away.

Laughter

Ben: They are jut like, setting up a very expensive piece of equipment and our neutrino beam will just pass right through it and they'll be like, whoa, we've got a weird spike of data and we don't know why.

Cecil: Maybe that's what we're seeing whenever we see those news articles, it's like, mysterious burst from somewhere. Maybe it's just them doing their neutrino beams.

Ken: That's maybe a topic for a different show but that's very interesting, if people would choose to communicate with these things.

39:59

Erica: I mean, right now we bounce signals, like through satellites around the Earth. If we could just send neutrino beams to each other that would be way more convenient.

Cecil: Alright guys, I'm going to put it in a book. Just wait.

Ben: Okay, so…

Cecil: So you're doing these beams, intentional beams of neutrinos.

Erica: Right, so, there are people of different experiments that use neutrino beams. There was one in New Mexico awhile ago. There is one currently running in Japan that is shooting a neutrino beam to a detector underneath a mountain in Japan. There's one that's shooting a neutrino beam from Chicago up through northern Minnesota and it's actually the same facility that produces the neutrino beam to an experiment called MiniBooNE. So, MiniBooNE, it is a detector that uses a scintillator, so this is the detector technology that doesn't need a lot of energy to produce a lot of light. So, it's a somewhat recent detector technology. And, the MiniBooNE experiment confirmed the results of a previous experiment called LSND. They both saw an excess of electron neutrinos in a muon neutrino beam. So, this is really weird because we didn't expect to see this excess. We were looking and trying to understand at different energies how the neutrinos oscillate from one to another. So we think we understand these oscillation parameters from multiple other experiments as well. But these experiments saw even more neutrinos oscillating into electron neutrinos than they had expected. So, this is weird, I mean, we're scientists, we just keep taking data and we think these statistical anomalies are going to go away. But they didn't go away. And they didn't go away. And they kept not going away. So, this originally happened in the 1990's with this experiment called LSND. So, that was at an accelerator New Mexico. And the MiniBooNE experiment was built to test the results from the LSND. Because LSND thought, well, if we have an excess of neutrinos and we're pretty sure we understand our detector and we're pretty sure we understand, at this point we understand oscillation physics, could it be that the muon neutrinos that we're creating are oscillating into some kind of neutrino we don't see? And then oscillating into an excess of electron type neutrinos? And then everyone thought maybe, but you're kind of, that's a little nuts. So, I mean, obviously the people working on the experiment didn't think it was nuts. But it's a bit of a far fetched idea to explain your

data. Maybe you just don't understand your detector response. Maybe you don't understand your beam as well as you think. So, maybe there's some other world somewhere and their neutrino beam is making neutrinos and you're detector in that one specific spot. So, the MiniBooNE experiment was built so this is using a different beam of a different energy and a detector at a different distance but the same relative existence and energy to make the experiment match. And everyone thought oh, MiniBooNE is going to show what LSND didn't understand. Sterile neutrinos, that's a joke. And it turned out MiniBooNE saw the same excess. Again, they took very careful data for many, many years and they just keep seeing more electron type neutrinos than you would expect for their muon neutrino beam. So, this is a lot of the same people but not entirely the same people. And different beam, different detector, same result.

Cecil: So that's how they decided that then, there must be another flavor of neutrino.

Ken: Well...

Erica: That is the the one idea they have to explain their data.

Ken: Well, the problem is that there are a lots of other experiments that have looked to see if they can see any affect of these new type of neutrinos. And other than those two, no other experiments really have. I mean, there are a few, maybe, that have some small discrepancies in their data but nobody has seen the same effect. And other experiments have looked. So, this created a big battle royale in the scientific community. If you can imagine a bunch of nerds throwing down at a conference. That's what happens here.

Cecil: I can 100% picture that. Yep.

44:55

Ken: Because there are experiments like the experiment I work on, the IceCube experiment, we actually look to see if we can see anything happening. So IceCube has the advantage that we look at neutrinos traveling through the Earth. So as both Ben and Erica have said, you need some length, you need some time for neutrinos to change and so IceCube looks at them as they come through the Earth and we didn't see any evidence of anything funny going on. It looked to us like we understand neutrino oscillations perfectly the way we are.

Cecil: So you didn't have any excess electrons on your muon neutrinos.

Ken: Exactly, we didn't see anything like that and if this were really a sterile neutrino the chances are that we should have seen something. We should have seen a discrepancy in our data which we don't see. And I'm only using that because I'm on it. There have been other experiments also that have looked and haven't seen this difference in the neutrinos.

Cecil: Well, I have a question. Because they're using, in their, in their MiniBooNE and their LSND thing, they're using a stream right, like a stream, like a bunch of, bunch of bunch but when they are slicing through your ice or through the nickel mine, isn't it, it's like, not that many right?

Erica: So, one of the cool things about a beam experiment is that you have bunches of protons hitting your target. So it's not a continuous stream the way a, like you would think of a stream of water. It's like a blurp and then a blurp and than a blurp and so you can, you know when, because you understand your beam timing, you know when you should expect to look for data. We call it a neutrino beam but maybe it's not a...

Cecil: A beam the way that I think of it. Right.

Erica: Yeah.

Ben: It's like pulses instead of a steady hose.

Erica: Yeah.

Cecil: Call it a neutrino blurp then and that makes much more sense.

Ken: It does make more sense. But you bring up one of the big points that these groups fight back and forth on. Which is in the experiments such as Erica was talking about with the neutrino beam or reactor, you have some chance to turn off your source of neutrinos and look at your detector on its own and figure out how it works. Whereas if you are using neutrinos from the sun or from the atmosphere, you can't turn that off. So you have to be much more careful about how your detector works. So, one of the argument points that come between these groups is well you just don't understand your detector because you haven't been able to figure it out. You know, that's one thing that goes back and forth. Of many. And then it just goes into name-calling, eventually.

Cecil: Okay.

Ben: The obvious question here is, okay, so, you know why the solar neutrino problem was there, there was one type of neutrino detector that was only sensitive to one type of neutrino. And then we developed these detectors that should be sensitive to all the different types, right?

Cecil: Mmhmmm.

Ben: Why wouldn't we be detecting this fourth type, if it exists? Like, why would there be any mystery about it? So, this is why they call it a sterile neutrino. The deal is that this thing doesn't have any electron flavor or muon flavor or tauon flavor. In particle physics the type of charge you have kind of indicates what kind of forces you'll feel from other things. If that makes any sense. So, like, the electron neutrino is going to feel the types of forces and interact with things kind of in the same way that an electron would. Which is why it can cause that reaction in the dry cleaning detergent, right? And the other two don't interact with the other atoms that way and so they can't cause that reaction. The sterile neutrino, it has nothing that it can interact with in our universe made of regular matter. It doesn't have like a companion lepton that it can kind of interact with the universe. The only way to make one arguably is if you have a neutrino of another type that could shift into this fourth type and it will cycle back and fourth. And so the idea here is that, like, we wouldn't see any indication of this particle except for in its absence. So, you'd make like, a whole bunch of electron neutrinos in a beam and you'd be like look at this nice beam of electron neutrinos and you'd be like, I'm missing some. And so you'd tally up the other, the other muon and tauon neutrinos and you're like, I'm still missing a small numbers of neutrinos in this pile. The idea is that maybe those switched into that fourth category. But we'd never know it because when they're in that fourth state they can't touch anything in our universe.

Cecil: Wow.

Ben: Right. Isn't that bonkers? And so like, remember earlier how I was like, the error bars on neutrino experiments are pretty big. That's why this is a huge, a huge deal. Right. Because it's just like, maybe your signal is bad, maybe you're not interpreting all the statistics correctly.

Ken: Just to step in briefly, when you were talking about the error bars earlier that was on, kind of the first generation, right? So, you could see, it was tough to tell that we weren't detecting all three flavors because the error bars were so big on those first experiments because they were crazy experiments. Now the error bars have gotten smaller, we're able to see that we're detecting all three flavors but now maybe we're still missing something else because the error bars are still big enough that that tiny little fraction, it doesn't, we can't tell whether it is there or not.

50:01

Erica: Right. So, many sterile neutrinos are, again, crazy fudge factor to make all the math work. Maybe we just don't understand our detectors. Maybe there really is something in the experiments that don't see anything, aren't looking in the right way. Maybe we need better models to predict what we should be looking for. Maybe, it's some other solution that we haven't even thought of yet.

Cecil: I have a question. Remember, before, you were talking about how, you know, it's like the death and birth thing, where, it's like the muon, like, you know, has to swap spaces with the other thing in order to make space for it. Like, it pops in and out, like, is that a possibility with the sterile neutrino, that it's just switching out with something that we can't see?

Ken: Yeah, I think, I thank that's, I think what you're suggesting is the idea, right. That we have this neutrino that's going along and it's ready to interact with either an electron or a muon or a tau, and then it, suddenly, for whatever reason, changes into something that can't interact with anything. So it's stuck in this lonely land where it doesn't have any friends that it can interact with. Of course the reverse also happens where we get things that are in this land and they, they oscillate back and they get into where they can interact with an electron, muon or tau. So, it's like they get banished in some ways to the...

Cecil: Yeah, phantom zone, phantom zone.

Ben: Phontom zone, ha, ha, ha, ha, ha!

Ken: These neutrinos go off into the phantom zone where, you know, they can't do anything and then they sometimes come back and so that's what Erica was describing earlier. Either you're missing some neutrinos because they went off into the phantom zone or you have an excess because some came back and have interacted with the neutrinos that were in your beam.

Cecil: Got it. It's the statement that we don't know what it is so right now it's just sort of like, it's just sort of like the big mystery.

Ken: Yeah.

Erica: Yes. And it's not even just the mystery, it's a controversy too because it's not that everyone is seeing this thing that we don't understand, it's that only half or some fraction of the experiments are seeing this thing that we don't understand.

Cecil: Right.

Erica: So, is it the science that we don't understand or is it the detectors or the beams that we don't understand. It's so much fun.

Ken: It is pretty fun and in fact, two of the physicists on this call disagree strongly about whether sterile neutrinos exist or not.

Ben: I'm not one of them.

Laughter

Cecil: I think that’s really cool. It’s very exciting to thing that there are things that, you know, are understood and then not understood and then understood again and then a new mystery opens up once something is understood. That’s pretty cool.

Ken: I completely agree and the other thing is, I mean, this is ongoing, this is a hot topic. It was at a conference that Erica was at, like, three weeks ago or something that this got presented, that they came out and said, no, we still think there are sterile neutrinos. So…

Erica: Yeah.

Ken: Yeah, it’s the talk of the town in the neutrino physics community.

Cecil: Well, I’m going to make sure to pay more attention whenever I see anything about particle physics, now, in my science feed, whenever it comes by.

Ben: Well, that was wonderful, thank you Erica, thank you Ken, you’ve pleased me. Your efforts have born fruit and that fruit is sweet, here is some fruit! Erica, you get a cherry.

Erica: Nom, nom, nom, yum, yum.

Ben: And Ken, you get a strawberry.

Ken: Oh, slurp, slurp, slurp.

Ben: I’d like to thank my guest, Cecil Castellucci. Thank you Cecil!

Cecil: Thank you, thank you scientists, you’re amazing.

Ken: Thank you!

Erica: Thank you!

Ben: A link to Cecil and her numerous achievements can be found on our website and remember her latest young adult novel *Don't Cosplay with my Heart*.

Alright, hey everybody. That was fun. Okay, so, big time announcement. Pay attention everybody. Ah, first, please give us an iTunes review as always because if people hear about us on the iTunes or wherever else people who are interested in listening to podcasts can, they might try us and they might discover that they've always wanted to know how a neutrino works and finally somebody has explained it to them. Now, in addition to iTunes, we are also on Google Play Music, Spotify and YouTube. So now you can enjoy us in whatever way you enjoy podcasts. Now, second, I'm sure you've noticed that we've been on hiatus. Actually, to be honest, we're still on hiatus. We recorded the episode you just listened to in May 2018. So, the reason is, I got a new job, we had to move to a new city and buy a house and my hands have been totally full. But I'm taking this time off to fix up a lot of things about the show behind the scenes including getting this episode edited and out finally.

55:03

Plans are in the works for new episodes so you can expect them in a few months time. In the spring of 2019. Anyway, sorry about the delay for this one. But soon enough we'll be back to recording episodes on our endless march to episode 100. Third point, I decided to start doing a thing where if I can't find a cool guest or maybe they cancel at the last moment but all the physicists are there, I've decided to start filling the seat in with whoever I can find on social media. So, if you're a fan on the show and you want to maybe want to possibly sometime be a guest follow us on social media and maybe keep your eyes open and you might see a call for people to volunteer to come on the show. Okay, finally, we're still humbly soliciting your donations. Your donations go to paying our server fees and our episode transcription project and buying our physicists microphones. Ah, you can send one-time donations through PayPal off of our website or you can go to our sweet Patreon site and give a recurring $2 or $5 donation. You get billed every time we make an episode. If you give $5 or more and supply an address to us I'll send you a postcard.

This particular episode of the Titanium Physicists Podcast has been sponsored by a collection of generous people and it's time to hear the listing of the names. I'd like to thank the generosity of Mathew Sullivan, Simon Lunt, Joshua Riker, Tom Corbin and Tom Hall for their donations. I'd also like to thank Mr. Astro Yuki, Shebank Patel, Mr. Mike Mihoka, Henry Rabum, Peter Scott, Russ Mutzi, Iesh Sing and Mathew Sullivan, a Daniel Lason, Patrick Yong, Kevin Forsyth, Yer Panet, Hoynim Dwong, Stein Henrickson, Atiper Jones Pascal, a man named Ryan R. and Michael Usher, Senor Canada, Adrian Shonig, Sarah Stradler, Louise Pantanela, a guy named Ben, a Mr. Mathew Lambert, a fellow named Aioosh Singh, a David Murtle and Mr. Ryan Foster, Janetco Fifenberg, Steve Smetherst, Magnus Cristisen, Bart Gladys, and Mr. Stewart Pollack. Our emperor Courtney Brook Davis, Mr. David Lindells, Mr. Carl Lockhart, our eternal friend B.S. and Randy Dazel. A Miss Tina Roudio, the enigmatic Ryan, a gentleman named Crux, and Gabe and Evan Weans, David D and Dan Vale, a Mr. Alex, WTL, Mr. Per Proden, Andrew Wattington, Mr Jordan Young and John Bleasy. A Brittany Crooks, James Crawford, Mr. Simon Sing, Two Songs Gang of One, Mr. Lawrence Lee, Sixton Linason, Mr. Simon, Keegan Ead, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein Raymond, and a gentleman named Peter Fan, Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia, Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Insanity Orbitz, Robert Johnson, Madam Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka

So, that's it for Titanium Physicists this time. Remember, if you like listening to scientists talk about science in their own words there are lots of other lovely shows on the Brachiolope Media Network. The intro to our show is provided with permission by Ted Leo and the Pharmacists and the end song, with permission, is by John Vanderslice. Good day my friends and until next time remember to keep science in your hearts.

Music

Ben: Ken, how come, why can't we say that the dark matter in the universe is just sterile neutrinos that are too low energy to interact with anything?

Ken: The dark matter in the universe could be maybe, potentially, be made up of partially of sterile neutrinos but they don't fit on some of the other qualities that we expected dark matter to have.

Erica: Yeah, part of the difficulty with the sterile neutrinos is it's not just these two accelerator experiments that have discrepancies. There's experiments at nuclear reactors that are just the right distance away from the nuclear reactor to make one neutrino measurement but they don't quite see the right number that they think that they're supposed to see depending on your calculations of what's happening inside the nuclear core. So, maybe we don't know how to understand nuclear fission which is quite possible, it is rather complicated and maybe we don't understand those detectors either. Or maybe there's a different kind of sterile neutrino that is also interacting because the properties of the sterile neutrino that the the reactor experiments or that they predict, are different than the properties of the sterile neutrino that the accelerators predict so maybe we just don't know anything at all. Which is totally possible.

Ken: You're just making up new stuff.

Erica: Isn't that what we do?

Ken: I mean, sort of.

Ben: I mean, you started the neutrino thing introducing neutrinos as a fudge factor that people are introducing to be like, well, we're not sure where the energy is going so...

Erica: Let's see...

Ben: So, essentially the tradition continues.

Erica: It could be all crazy, it could make sense later. We have a whole career to figure this stuff out.

Cecil: Well, one day I will probably have millions of questions about dark matter too because, you know, that’s very interesting as well.

Ken: If you have questions about dark matter, I’m happy to answer them. That’s what I spend most of my time doing is dark matter stuff.

Cecil: Yeah. I’m interested in learning.

#TitaniumPhysicists