Episode 65: New Ways of Looking
Physicists: Danica Marsden, Suresh Sivanandam

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 50 episodes now my team and I have brought you to the very frontier of knowledge in physics and astronomy. And still our mission goes on. To present you with your birthright, an understanding of the Universe, I've traveled the world seeking out a certain type of genius. Masters of not only their academic disciplines but also at explaining their research in understandable ways. And I have 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!

[1:46]

There's something universally appealing about a picture of stars. Now, think about social media. Photos of stars are literally everywhere. It might just be selection bias talking but anytime someone wants to write an inspirational quote to share on the Internet there's a respectable chance that they are going to put it over a star field. Anytime you want people to feel humility or awe or encourage a kid to study math, stars. Pictures of stars. Anytime you want to encourage people to think aspirationally, stars. Or Michael Jordan. I mean, some of the oldest images and charts drawn involve plotting the location of stars. It predates paper even. A lot of people might explain that these old maps of constellations are there for navigation or time keeping or astrology, sure, maybe, I don't know. But, I'm willing to argue just for the sake of argument, that a good deal of the motivation behind it is just that people like looking at stars. I mean, they like it even more if they can do it in the daytime when it's warm, without hurting their necks. Incidentally, did you know that our eyes are not such bad instruments at gauging how bright a star is? I'm couching my argument here because I don't want to give you the impression that we're robots. But I would have guessed that our eyes' ability to quantify how bright a star is would be somewhere between terrible and not worth trying. It seems unbelievable to me that you can use the human eye with all the subjective experience involved looking at something and then trying to describe it and turn it into a number that has scientific value. But Hipparchus, an astronomer 2,000 years ago came up with a numerical scale for describing how bright tars are. Numbers between 1 and 6 where a really bright one is a 1 and a really barely visible star is a 6 and the numbers you get judging by the eye are actually pretty good and consistent. You can actually use these numbers to meaningfully describe the actual brightness that you would measure with a bonafide instrument. Modern astronomy has even inherited this numerical system of describing how bright things are. We call the number the magnitude. Anyway, mapping out the stars by hand is tiring and no one can tell which dots are actual stars and which dots came from you sneezing on the paper. So, stellar photography is the thing. You take a photograph of the stars and then you don't have to do all that drawing. And photography is, in principle, an easy thing even if you haven't invented it yet. You find a chemical that gets darker when you expose it to light and then you smear it on a piece of glass or wood or something and then you expose it to the image and then parts of the light will turn dark. Badaboom, badabing. I mean, there's a lot of chemistry in finding the right chemicals and the right materials and in developing the images afterwards so you can look at it without the whole thing turning black and all that stuff but this isn't the Titanium Chemistry Podcast. See, it's pretty straight forward. But, even then, the history of stellar photography is absolutely bananas and mostly because it was so hard to get everything right. Old fashioned photographic techniques like daguerreotypes require that things stay still for a really long time and stars are pretty dim and they're always turning. Well, I mean the Earth is turning technically but it just meant that it didn't work, it didn't work very well at all. And so it was around the 1870s and 1880's when the technology finally became advanced enough to photograph pictures of stars. And it wasn't just motivated by laziness either. In 1883 the amateur photographer Andrew Ainslie Common took the first photographs of stars too dim for the human eye to see. See, there's some cleverness here. Photography allows astronomers more sensitivity than the human eye and furthermore it provides you with a physical record of what you're looking at at night so you can study it. For instance you might make your graduate student count the number of stars in a galaxy or you might take a photo of the same star once a year then compare photos over the years to see if that star moves around. Astrophotography has become a wonderful research tool and that's allowed us to better qualitatively and quantitatively study what stars are doing, what they're made of. But we don't do it using photographic plates anymore. Just like we don't really take photographs using film anymore. And the reason is simple. We've developed light sensitive imaging tools which are more responsive and practical than just using light sensitive chemicals. But how do they work? I mean, how do we take light, and turn it into electronic signals that can then be processed into a picture? It's a big question. Today on the Titanium Physicists Podcast we're talking about how our fancy, digital light detectors work. Now, speaking of compelling images, I've decided that the very person for this topic would be one of my favorite authors. She writes in all genres of speculative fiction from steampunk to science fiction. And she's won the John W. Campbell award for best new writer as well as more Hugo awards than I can count. Welcome back to the show Elizabeth Bear! Hello!

[6:40]

Elizabeth: Hi, how are you?

Ben: I'm great. So, Bear, for you today I built a brand new team. Two experts in building detectors. Arise Dr. Suresh Sivanandam!

Suresh: Beboop.

Ben: Dr. Suresh is an astronomer who did his undergraduate with me at UBC and then a PhD from the University of Arizona. He's currently an assistant professor at the University of Toronto where he works at the Dunlap Institute and is an expert in the design and construction of imagers and spectrographs. Now, arise Dr. Danica Marsden.

Danica: Aaaaawwwwwwwwwwaaaaaa.

Ben: Dr. Danica is an astronomer who did her undergraduate degree with me at UBC and then a PhD from the University of Pennsylvania. Afterward she was a postdoc at UC Santa Barbara where she did research on MKID detectors and she's currently a project manager working for D-Wave systems.

Alright everybody, let's talk about how technology works.

Elizabeth: It's elves. It's all elves.

Suresh: Little elves turning cranks.

Elizabeth: Yes, it's like little people inside your television.
Danica: It kind of is magic, actually.

Elizabeth: Well that's why actors have to be so much thinner now, because television screens have gotten much skinnier.

Laughter

Ben: Ah, so, let's start by talking about telescopes, specifically. The imaging technology that we're going to be talking about today. We're going to talk about different types of light detectors that we use to take in light and turn it into electronic signals somehow. And all of these have applications beyond just telescopes but telescopes are a good way to talk about it because they are pretty much just that, right. I mean, if you want to talk about the one in your cell phone then you have to be like, well, okay what about usability and... No. We just want a thing where you shine an image in it, take a picture. Simplify the discussion just a little bit. Okay? Even though things like CCDs for instance get used in all sorts of applications now and days, not just the Hubble Space Telescope.

Suresh: Yeah, so, in fact it's nice to think of the history of CCDs, ah, which became the first real mass produced image censor.

Elizabeth: Okay, now, what's a CCD? What does that stand for?

Danica: Charge-Coupled Device.

Elizabeth: Thank you.

Ben: Isn't that descriptive?

Elizabeth: No.

Ben: I know, right?

Laughter.

Ben: For the first time ever ...

Elizabeth: What a useless piece of information.

Ben: ... Telling people what a euphemism stands for.

Danica: Well, no, but once you hear Suresh's explanation then it will all be clear.

Ben: It's true.

Suresh: So, there was research going in Bell Labs where they were trying to design new forms of computer memory and then they discovered that, you know, it was actually sensitive to light.

And then they did a little bit more research related to that and they actually came up with this new device that could actually record images electronically. And it was called a Charge-Coupled Device which sounds very esoteric of course and the reason it is called a Charge-Coupled Device is the way this particular sensor reads out. So it's got lots of pixels, ah, arranged in a grid so that when the light hits this device it generates electrons. So, every photon of light that hits the device it can generate an electron and then it is stored in the pixel and the way that they can get the electrons out of the pixel is that they basically shift the charge from pixel to pixel until it gets out on the other end of the sensor where you have a little amplifier that reads it out. And that's why it's called Charge-Coupled Device because each pixel is coupled and you shift the charge across it.

Elizabeth: Like a fire bucket brigade.

Suresh: Yes, that's the perfect analogy for it.

Danica: And how it creates the electron is that each of those pixels is a teeny tiny little slab of silicon with little atoms of germanium or some other element in there. And so when the photon comes in and hits the germanium atom it knocks an electron off.

Ben: Thereby creating a free-roaming electron.

Elizabeth: Thereby creating a free-roaming electron. Okay.

Ben: So, the idea here is that you have this, you have this plate of silicon. You want a way to record where the light is hitting it. And so you specially make this crystal so that it has the type of atomic properties when a photon comes in, if it has enough energy it will knock free one of these electrons. And then you'll get kind of like a free roaming electron where the photon hit the plate.

Suresh: And then you want to trap that electron otherwise it might roam away.

Elizabeth: And then you won't know where it belongs.

Ben: Yeah, so, how do you turn this plate covered in distributions of elections into an image. How do you keep, how do you figure out where on this plate the electrons are free? And so that's what Suresh is saying. Ah, they use electromagnetic fields to trap the electrons into little squares, pixels. Yeah, well, little regions so if you partition up the whole plate into little pixels and then all of the electrons that got knocked free in any pixel will just kind of stay inside that pixel. And then we collect them all later.

Elizabeth: And from the concentration of electrons you can tell how many photons hit that area of the plate. Okay.

[11:40]

Danica: Right. So if the first square has three electrons and the second has zero and the third has ten and then that tells you how many photons hit those pixels.

Elizabeth: I'm kind of a ringer, um, I took four semesters of dark room photography back in high school, back when it was actual darkroom photography. And ah, this is not too different from how a silver plate works except you're using crystals of silver and reading the result with your eye instead of using electromagnetic fields.

Ben: Yes and no.

Elizabeth: Okay.

Ben: This is the cool part. So, the principle is the same. In your film photography light comes in, it causes a chemical change in that little pixel. Right? And in this case, light comes in knocks an electron free in that little pixel and then there's a free wandering electron. So, essentially the exposure is the same. You take your sheet, you expose it to the light, you close your camera's shutter just like in regular photography and then you have a distribution, in this case of electrons over the things. And then we need to parse that into electronic signals. And, like Danica said, we're going to kinda count up the electrons in each square. But how do we do that? This is the...

Elizabeth: How do we do that?

Ben: ...coolest thing. Okay, so the idea here is that every pixel is, it's like a electromagnetic well. So what they have is, on the side of every pixel there are these three electrodes. Okay? There's one on the top, one in the middle, one on the bottom. They're metal electrodes. We can use batteries, say, to change the amount of charge on them, change the electric field through them so we could make the middle electrode really, really positive and then the up and down ones really, really negative. And then the electrons, the free roaming electrons, will say hey, I want to here you hang out by that big positive one in the middle because electrons are negatively charged. So we can use these electrodes to partition up the sheet into these pixels. These electrodes are what produce these electromagnetic wells that trap each of these collections of electrons. Kay. So, then, what they do is, once the sheet has been exposed they start shifting around the electric fields generated by the electrodes so that all these wells of electrons start shifting up the sheet and there's collecting amplifiers along the top of the sheet and so it just kind of pushes them up off the top of the sheet in order. So, there's only one row of collectors and we're shoving all of the electrons through the collectors at the top and so the order that these collectors receive the signals dictates how far down the, ah, sheet the electron wells started. Does that kind of make sense?

Elizabeth: I think so. Are you talking about like the ah, what would be, you know, like scan lines on an old 300 baud modem, kind of?

Ben: Yeah. I guess in the modems they do it, they do it, there's a dot scans around, right? And in this case you, each detector at the top tabulates one column at a time. So, all of the electrons in one column are going through the same one at the top. So, you're doing it line by line instead of one point shifting back and forth. But similar to that, yeah.

Elizabeth: Okay.

Suresh: One point I want to make is the reason these things are so great is compared to film they are about a 100 times more sensitive. These days the sensors that you can get are almost 100% effective at detecting individual photons of light.

Elizabeth: That's pretty magical.

Suresh: Yeah, we're pretty much at the limits of physics now. We can't do much better than that.

Danica: I beg to differ but yes, okay.

Elizabeth: Fight, fight!

Ben: No, no, no, don't fight yet, don't fight yet.

Laughter.

Suresh: I'm just saying, in terms of detecting a photon. So we're very close to the limits of, I mean, we can't detect more than one photon for every photon.

Ben: Before we go on, do you guys want to hear a crazy analogy that I came up with for how these things work?

Suresh: Go ahead.

Ben: So, have you ever been in an airport where there's like a big glass partition down the length of the hallway, where it's like American boarding gates on one side and Canadian boarding gates on the other and you're not allowed to cross this wall.

Suresh: And the restaurant that I want to go eat at is on the other side of the wall.

Ben: Yeah yeah, you know exactly what I'm talking about. Imagine we've got that scenario where there's this big terminal and then imagine that a bunch of airplanes have all landed all at the same time and these airplanes are full of little kids. So, one airplane has like 5 kids on it, one airplane has 15, whatever. And so, we want all of these kids to move down, out through the end of the terminal where they can be collected and counted, that kind of stuff. But we want to keep track of which kids came off of which airplane. So, we don't want to mix them up. And, for some reason, because they're still on American soil or whatever we're not allowed to cross that barrier so we're stuck on one side of this barrier. We're stuck on the glass side and all the kids are on the other side. So, what do we do? We set-up adults. Haha! We set-up a row of adults running down the length of the wall. And, each adult will have two things. A handful of broccoli in one hand and a teddy bear in the other. And we know that children love teddy bears and they hate broccoli, right?

[16:49]

Ben: So, what you're going to do is outside each terminal you're going to have one adult holding a bear and then the adults on either side of them are going to hold broccoli. Alright? And what this is going to do is as the kids come off their plane and they don't know where to go so they pile up on the glass near the bear. They don't go anywhere near the broccoli. Right. So then you get these parcels of children along the glass wall, right. And then what you do is you have the adults switch hands in a really coordinated way so close to the end you have one person with the broccoli change their hand and show the bear and the kids shift down to the right and then that person with a bear holds up a broccoli and shuts off all the kids and you can shunt all the children down through the exit in the order that they arrived on their airplanes without mixing them up and without interfering with them directly.

Danica: That's such a great analogy.

Suresh: Yeah, that's very elaborate. You will have a problem if one of those kids likes broccoli.

Ben: Well, we know that that's impossible.

Danica: So, getting back to, ah, what Suresh was talking about, whether or not you see the kid in the first place. Ah, I believe that's known as quantum efficiency, is that what you were referring to? Suresh?

Suresh: Yes, yes. That's right.

Danica: Okay. Because you can loose kids sometimes.

Elizabeth: Well, that's an ongoing problem. Especially when the Airbus shows up full of unattended children and sort of dumps them in the going to America exile section of say, you know, Pearson Airport.

Laughter.

Elizabeth: Where there's nothing but a terrible bagel place.

Suresh: So, I can stretch this analogy a little bit more. There is this thing called charged transfer inefficiency in CCDs. So when you shift the electrons from one pixel to the next there's a small probability that you loose some of those electrons so I guess to stretch your analogy there's always a small probability that one or two kids decide to stay on the aircraft because it's just much more interesting.

Danica: Or they swapped positions in the lineup or something.

Ben: Or they're running around on the tarmac. I think CCDs are pretty well explained at this point in time. Do you want to rattle off some trivia about like what kind of awesome telescopes use CCDs? I guess like everything.

Suresh: Pretty much any astronomical telescope that's looking in wavelengths that we can see or close to is...

Danica: With our eyes.

Suresh: With our eyes are using CCDs. So, the largest telescopes in the world like the Keck telescope in Hawaii.

Danica: The Gemini telescopes, there's one in Chile and one in Hawaii.

Suresh: Right, and including the Hubble Space Telescope uses these devices.

Danica: And Kepler the planet finder...

Suresh: Has many of these devices. Kepler has just got a very giant CCD consisting of something like tens of these detectors that are very, very efficient at detecting light. So, one of the other characteristics of these things, is very stable and well behaved so if you're trying to look for a planet that's orbiting a star you know, tens of hundreds of light years away, you need to find minuscule changes in the brightness of the star as the plant transits in front of the star. Thanks to these devices and how stable they are, you can actually see an Earth-like planet orbiting around a star hundreds of light years away.

Danica: So, the majority of the known extra solar planets have been found with telescopes using CCD arrays.

Ben: So, here's one question . You mentioned that we use this for light that we can see, optical light. Well, what about, like, I don't know, infrared.

Suresh: Ah, that's a pretty loaded question. Because infrared is very broad and there's near infrared, there's mid-infrared, there's far infrared, it all depends on which part of the infrared spectrum you're looking at and I'm guessing you're going to ask, near-infrared which is where I do a lot of my work.

Ben: That sounds good.

Suresh: So, near infrared is um, so, for example, our eyes are sensitive to a wavelength range of about 400 nanometers which is blue, the sun is about yellow-green which is around 550 nanometers and then the edge of what we can see is about 650 to 700 nanometers which is red. And then CCD detectors are made out of silicon and so silicon is actually sensitive to about 1,000 nanometers or one micron. That's very near infrared and actually, in a lot of cameras they actually put a special filter, SLR cameras, called infrared blocking filters, so that the sensor inside won't see light past red. You can actually take that out and actually see some of the near infrared. So in astronomy a lot of work right now is being done in the near infrared which is around the range of a thousand nanometers to 5,000 nanometers. And that's because a lot of, a lot of objects in the night sky emit their light at those wavelengths. And especially very distant galaxies which are moving away from us very fast.

[21:43]

Suresh: Unfortunately silicon-based CCDs don't work for looking at this range of wavelengths. And so there needed to be a new technology that can address this and so you need to make a whole different kind of material that is sensitive to infrared light and the current material that's very good is made out of three metals: mercury, cadmium and tellurium. And in short it's called MerCad Telluride. So, it's a weird alloy and it's sensitive to these wavelengths of light. Now, the other problem is the physical process of how you detect infrared light is the same as we described for CCDs where a photon comes in, hit's one of these atoms and then it ejects an electron that we then try to save and measure. So, the technology used for this is what's called a CMOS sensor, complimentary metal oxide semiconductor. So, what these devices are, are basically every little pixel has a little amplifier so it's called an active pixel. Unlike the CCD where you have to push all the charge to the very end of the device and then amplify it, now you can amplify each individual pixel and in the case of infrared detectors you have this MerCad Telluride layer which is actually detecting the light but then you need the electronics, the amplifiers and readout electronics which given our current technology can only be made in silicon. So what you do is you build millions of these little amplifiers for each pixel and then you sandwich and electrically connect the MerCad Telluride layer which detects the infrared light. And then you get out your signals from that process.

Danica: So, I was going to ask, just as a brief aside, what, what sort of things in the sky are more easily seen?

Suresh: Well, there are so many things. So, the most exciting thing I would think for a lot of people is exoplanets. One of the big things going on right now in terms of developing new instruments for astronomical research is developing these cameras that can actually image exoplanets orbiting around nearby stars and this is all done in the infrared.

Danica: Right. And what about brown dwarfs?

Suresh: Yes, they are capable of seeing brown dwarfs. So, the exoplanets that they are trying to take pictures of are basically scaled down versions of brown dwarfs so they emit mostly light in the infrared.

Ben: Alright, so, Bear.

Elizabeth: Yeah.

Ben: Let's talk shop here. Essentially, the idea here is there's this whole spectrum of light, right?

Elizabeth: Right.

Ben: And different objects will emit electromagnetic waves depending on a few different things but one of the things that determines it is how hot they are, right?

Elizabeth: Right.

Ben: I mean, if fire is red it's hot. If the fire is blue it's really, really, really hot. Right?

Elizabeth: Yes.

Ben: So, there's a temperature dependence on this. And so what they're talking about right now is they are saying there are things in the Universe that aren't stars. Stars go, they're white hot or red hot, they're kind of visual hot.

Suresh: Or blue hot.

Ben: Or blue hot, yeah.

Elizabeth: Blue hot.

Ben: But people also emit infrared radiation. Things that aren't as hot as a star but can still be pretty hot. Maybe it's hot because it's a planet near a star. You know, the planet has a temperature because the nearby star is cooking it and so it's radiating at a less than stellar hot, but still a pretty hot temperature.

Elizabeth: Right.

Ben: Maybe it is a great big object, you know a brown dwarf is a...

Danica: It's a star that didn't quite turn on.

Laughter.

Elizabeth: It's a fizzled star.

Ben: Yeah, so it's hot like ashes but not hot like a star. So, the idea is if we can look into these parts of the electromagnetic spectrum, these features will become more apparent to us. They'll really pop out. There's a few things here. Suresh was saying that essentially silicon is essentially transparent to these wavelengths so our CCDs, you shine it at it, it just goes through. It doesn't catch any of the light. It doesn't cause the electrons to pop out, nothing happens. So, the idea is that these CMOS detectors, they are made with a material that will absorb that spectrum of light and will kick off an electron that we can then measure. Does that make sense?

Elizabeth: Yeah. Absolutely.

Danica: And sometimes, I mean, different types of detectors or wavelengths are complimentary. Just as you know, you approach a foreign object and you might, well, you look at it, to try to understand what it is. But you might also poke and prod it and sniff it and maybe taste it and in that way sometimes using a bunch of different types of detectors that can see all of the different parts of the spectrum that this object might be emitting or absorbing the light from ah, you can learn about it.

Elizabeth: So, what percentage of the electromagnetic spectrum do we have the technology to detect with these various types of detectors.

Suresh: Everything.

Elizabeth: Excellent.

Danica: Well, no, that's not quite true actually. There's still large swaths of the spectrum that we don't have detectors that work very well.

Ben: Yeah, where's your Planck length photon detector Suresh?

[26:43]
Suresh: Okay, maybe... I mean, we have gamma ray observatories, we have X-Ray observatories, ultraviolet observatories, optical, that's passé... Infrared...

Elizabeth: Nobody cares about eyes anymore.

Suresh: No, I think we got, as long as you go into space we can cover most of the electromagnetic spectrum.

Danica: Enough that we don't really care about the remaining bits until something new comes along to convince us otherwise.

Suresh: Right.

Ben: That's another interesting point they make. As far as, that, once you go into space, the deal is, the atmosphere, I mean, okay, global warming, let's talk about that. How does it work? There's gasses in our atmosphere that interact very strongly with infrared radiation.

Suresh: Yeah, so that's, that's bad for astronomers.

Ben: Yeah, yeah. So the atmosphere isn't transparent at a lot of these different frequencies. It's transparent in the visual which is why we can look out and see the sun and the stars and all the fancy things that, you know, deer that are a kilometer away. You can see pretty far. Individual, radio, it's transparent but they're most of the things in between, the atmosphere will scatter the light. And so it's kind of like, I don't know, imagine it looking really foggy, the light signals stop being sharp. They get really blurred, splayed out and so we can't use infrared detectors usually, from ground based observatories because the atmosphere is radiating in that spectrum and it will outshine the stars that we are trying to look at. It's kind of like being in the city on a really bright night where there's lots of light pollution and you can't see the stars. Yeah, so you can't usually see the stars in the infrared from the ground because the atmosphere is outshining the brightness of the stars.

Suresh: Well, the nice thing is, we have actually found little windows in the infrared where there isn't an atmospheric molecule that is absorbing all the light so a lot of astronomy is done in these small windows where we can actually look through the atmosphere.

Danica: But it is no coincidence that the window that is let through our atmosphere coincides with the wavelength that our eyes can see.

Elizabeth: Okay, now, you say that that's no coincidence. I mean, obviously, our eyes would evolve to, um...

Danica: Yeah.

Elizabeth: Say we lived on Titan or some place where there's a different atmosphere...

Danica: We would likely have evolved to be able to see...

Elizabeth: Right. We would have evolved to different...

Danica: Other parts of the spectrum.

Elizabeth: Yes.

Ben: So, Danica mentioned something earlier that's absolutely fantastic. She mentioned that it's helpful when we're doing these things to look at different colors. Because you look at an object in one color and compare it in what you see in another color and it gives you more information about what might be going on inside that star say. Based on our description, both CMOS's and CCD's and even like, black and white photography, they don't really care, I mean, there's a threshold, a frequency, but past that, red light, blue light, it's all going to cause an electron to register, right?

Suresh: Right.

Ben: So, a question we might ask is how do we use, say, a CCD telescope to see in color? How do we use a black and white plate photography telescope to see in color?

Suresh: Well, there are many ways of doing it. So, the crudest way is you use a filter that lets only certain color of light go through onto your sensor. And so you basically throw away all of the light that's not let through and so then you get the color information by using different filters and you take an image with a filter at a given time. So, actually, our cameras have filters in them too. The image sensors they have, they have this thing called a Bayer pattern, where you have a red green and blue filter put on individual pixels and then later on when you take the image it interpolates the color information from the different pixels and gives you the overall color of the image. The other way you do it is you build a spectrograph and the spectrograph has a prism or some sort of element that spreads the light as a function of the frequency and then you take a picture of that.

Danica: So, it spreads the light into rainbow constituents and then you detect that spread out light with your CCDs.

Ben: So, is that clear Bear? So, you're like, I want to know if this traffic light is red, green, blue or what and so you take multiple photographs of it with different filters in front of them and then compare them and then you're like well this one has all red light because when I put on the green filter it disappeared completely.

Elizabeth: Well, I want to know where you're finding the blue traffic lights.

Laughter.

Elizabeth: Sorry. Under the bus Ben.

Ben: You did throw me under the bus.

Elizabeth: I did.

Ben: For a speculative fiction author you should be taking the hints I've given you and be running with them.

Elizabeth: Basically what you're describing is identical to some tricks that one would use in old fashioned film photography. Or, the reverse of that is how four color process printing works. You have a yellow, red and a blue and black ink and you layer them over one another to get the full spectrum of colors.

[31:53]

Ben: Yeah. Yeah.

Elizabeth: So, you're doing that in reverse. You're subtracting color.

Ben: Yeah. Right.

Danica: And that's why you always run out of cyan.

Elizabeth: Always. Always.

Laughter.

Danica: Right. So, Suresh has informed us very nicely about what I would classify as the bread and butter detectors. And now and days bleeding edge is making use of another revolution in materials science and condensed matter physics which is to use superconductors. Superconductors are metals that when you cool them down very cold, almost absolute zero, essentially all of their resistance goes away. So now we're experimenting with detectors made out of these materials and I worked on what are called MKIDS or microwave kinetic inductance detectors. What they do is, rather than, these poor little photons that are traveling, you know, billions of light years to get to you and then you just chuck them in the garbage. You know, because it's not the red one and it's not the green one. Instead, we make pixels of these MKIDS where every single little photon gets detected. And each pixel can tell what that photon's energy was without any filtering. So, how do we do that? There's, similarly, this underlying sea of silicon doped with something like phosphorus or you could use sapphire. We're still experimenting with materials. This is cutting edge stuff and we're still optimizing but then you can lay down a circuit of this super conducting metal. It could be titanium nitride, it could be tungsten and you make a little resonate LC circuit. So, you have an inductor and a capacitor together and it resonates at some particular frequency which you specify by design. How you design the inductor and the capacitor. And then when a photon comes in and it gets focused using a lens array onto the inductor. When it hits the inductor metal, this super conductor, it blasts apart a bunch of pairs of electrons that are known as Cooper Pairs which exist in superconductors. And all the Cooper pairs being blasted apart changes the inductance of the inductor and then what you see is your signal is the resonance will shift the whole circuit's resonance frequency to one side and the amount is proportional to the energy of the incoming photon. Does that make sense?

Elizabeth: And the energy of the photon is...

Danica: That's the color.

Elizabeth: That is the color. Okay, so it's the wavelength.

Danica: Right. So, if it's a red photon it shifts this resonate frequency a little bit and if it's green it shifts it a bit more and if it's blue it shifts it a lot.

Ben: So yeah, it's a system that responds not just to the intensity of the light but also its frequency. But I bet we can explain all the other stuff in there because it's fantastic. Okay, so, she just said something called an LC circuit. Have you ever heard of one of these before?

Elizabeth: Nope.

Ben: Okay. That's fine. L stands for inductor and C stands for capacitor. Okay, so, it has to do with kind of geometry and charges moving through a wire. Okay. Now, the idea is this super conductor that they have, it is in essence just a really complicated wire. The way that it's laid out on this chip is really, really complicated but in essence it's a wire. And there are electrons that are moving around through this. So, there's two things to keep in mind here. There's the capacitor and the inductor and together they have a certain affect called a resonate frequency and we'll talk about that in a second. The idea here is that, okay, usually when we teach electromagnetism to kids, in high school, we imagine that the response to the circuit is at the speed of light. But it's not.

Danica: I think the current of water in a river is a very good analogy to the current of electrons flowing along the wire.

Ben: Yeah, exactly. Because it takes time and stuff can build up and slosh around. And essentially what we're talking about here is the electrons end up sloshing around in the system.

Elizabeth: At some point in their life everybody should get doped up on cold medication and have somebody explain electrical engineering to them.

Laughter.

Elizabeth: There are no words small enough for me at this point.

Ben: So, here's the thing. A piece of wire is neutrally charged. Right? There's the same number of protons as electrons in it, right?

Elizabeth: Right.

Ben: And so, if you drive all of the electrons to one end, one end will be negative and the place they left behind will be positive.

Elizabeth: Right.

[36:35]

Ben: Right. And positive and negative things attract each other, right. Well, what you can do is you could bend the wire into a kind of u shape so that if you drive all the electrons to one side and that leaves positive charges on the other the two ends of the wire that are almost touching really close together, those will feel each other pulling across the gap. The positive and negative ends will interact with each other in a way called the capacitance.

Elizabeth: Okay.

Ben: So, it will kind of stick. Electrons hate each other so they don't want to hang out together but they'll be like oh man we're really close to a whole bunch of positive charge, we kind of like being on this end. Only a little bit. And the other thing is something called inductance. It has to do with magnetic field. If you have charges moving in a spiral shape, ah, it will generate a magnetic field through it. And so there are these things called inductors which it's an electronic component shaped like kind of a spiral. And what happens is if you drive a current through it it will generate a magnetic field but that takes a little bit of effort. And so this object will resist changes in the magnetic field. It will resist changes in the current. So it will be like I like how much current we have right now, I don't want to change it. And so, what happens in the system is you're hooking up a wire, a capacitor, the two ends are really close together with one of these inductors, a spirally shape then you're driving all the electrons to one end. And what happens is the electrons all go to one end and they go, ah, we don't like being really,really close together. We kinda do but not much, we're going to spread back out. And so they spread out and that becomes a current moving down the wire and then the inductor goes hey, you're not allowed to change.

Elizabeth: I've been in that relationship.

Ben: What you end up with is the electrons end up sloshing back and forth and back and forth through the circuit. It's kind of like when you're a kid, when you're in like the bathtub and you start kicking back and forth with that wave, pumping it, making it bigger and bigger.

Suresh: That's the best explanation I've heard for a resonate circuit.

Laughter.

Ben: So there's a timing involved here. Ah, depending on the geometry of the system, it will take more or less time for the electrons to cycle back and forth through the system and so forth. The moral of the story is, these things are determined by the geometry of the system. Okay?

Elizabeth: Okay.

Danica: So, for a whole array of these things you can design them such that they're all slightly different and therefore they all have a slightly different resonate frequency. And then you can read them all out at the exact same time.

Ben: Okay, so the idea here is that I can figure out what the resonance frequency of one of these LC circuits is by interacting with the electromagnetic field that it it generates. Pretty much the magnetic field right. I said that the coil is going to generate a magnetic field.

Elizabeth: Right.

Ben: And so what you can do is you can take another external magnetic field and you can switch it back and forth at a certain frequency and if you tune it just right so that the driving frequency matches the resonating frequency then you're going to see the oscillations inside the circuit, their response is going to be huge. Like the system is just going to resonate. Like, ah, it will sing like a wine glass when you sing its harmonic frequency right? So what they're looking for is that singing back affect when they... Okay, so, in this case the system is made out of superconducting wire. And that's difficult to make but superconducting wire has a really useful property which is that the reason it is superconducting is that the electrons inside of it are all paired up. Boy, I mean, we've done whole episodes on superconductivity.

Danica: Yes.

Ben: Um, do you want to know more about how superconductivity works?

Elizabeth: Sure, why not.

Ben: Aw, it's the cough syrup talking.

Laughter.

Ben: Okay, so, have you ever hear of the Pauli exclusion principle?

Elizabeth: I don't think so.

Ben: Well, I'm sure you've talked, in like high school chemistry, about how, like, an atom has electrons in shells right?

Elizabeth: Yes.

Ben: And all of the electrons aren't all in the lowest energy stage shell. Instead they're kind of stacked out. Right?

Elizabeth: Yes.

Ben: And the reason for that is called the Pauli exclusion principle. No two electrons can share the same orbital shell. And this particular property applies to a type of particle called a fermion. Fermions have one half spin. But there's another type of particle called a boson and boson's have integer spin. Spin 1, spin 2... don't worry about that. But the moral of the story is if you cool down a material cold enough all of the electrons will couple up together and each individual electron is a fermion. But when they're interacting in this way they effectively become a couple and that couple acts as a boson. And so, this bosonic state is what allows superconductivity to happen. So what happens when your photon comes in it interacts with your detector in this case is, the photon comes in and it breaks up some of the electrons. And so, they stop being coupled up and so the system stops being superconducting in a few places.

Danica: Right. Electrons are like siblings who are like get away from me. And the, ah, Cooper pairs, these paired electrons, act like a romantic couple who want to be, occupy the same place.

[41:36]

Ben: So, the moral of the story is, your once superconducting wire now has all sorts of patches in it where it's not superconducting. And that changes the inductance, it changes the timing of the resonate frequency and so if the system has just been hit with a photon it's going to ring at a different frequency and we can detect that change is resonate frequency and that's what we're detecting and that's how we can detect when one of these has been hit by a photon. And it's response, how it's resonate frequency has changed in response to it depends on what color the light was. And so we can use exactly how much it's resonate frequency has changed to figure out what color of light hit it.

Danica: Exactly.

Ben: So, these detectors are bananas. I, I didn't believe it when I saw it. So, what you have is a whole array of these little wirey, spirally superconductor things and each one will have its own resonate frequency and so you can use them to detect not just light hitting it but also what color it was and you can do it without having throw away all of the photons that you would just by using filters.

Elizabeth: Fascinating.

Danica: They're very efficient.

Elizabeth: Yeah.

Danica: All these little photons and you can really wring a lot of information out of what's coming from the sky.

Suresh: Well, one thing you want to know about astronomers is we are absolutely greedy about collecting photons. As many as we can get, we want to get. So if there's any way of doing that we want to do it. Because every photon is precious.

Danica: So, the last type of detector that we are going to talk about is a Transition Edge Sensing bolometer, so TES bolometer. And, ah, this pertains to a very different part of the frequency spectrum. Um, it's over in the radio part of the spectrum and we wanted to see wavelengths about a millimeter long. And the reason is that two Russians back in the 80's predicted that we would see a particular effect. Their names were Sunyaev and Zeldovich. So, the effect is called the Sunyaev-Zeldovich Effect. If you look out in the Universe, the very furthest, oldest thing that we can see is the Cosmic Microwave Background. And, essentially, this is just the afterglow of the Big Bang. And this light peaks in the microwaves which is why it's called the Cosmic Microwave Background and it travels 14, roughly, billion light years, all the way to us. And on its travels it passes through and around all the intervening things that have formed over the life of the Universe such as galaxies, clusters of galaxies and so on. And as it passes through a cluster of galaxies the hot gas in the middle of this cluster of galaxies will actually absorb some of those photons. And so what happens is that when we map, make a map of this background light, we, at particular frequencies, will see these, what look like, holes where these clusters of galaxies have essentially swallowed up those photons. And what's really cool about this is that normally when we want to try and see something out there in the Universe we have to collect its photons but in this case we're doing the opposite. We're looking at the absence of photons and because it doesn't matter how bright it is we can see these objects as far out as they exist. So, it took awhile for us to develop detectors that could see this radiation. It took a few decades, um, to get it right. And we finally came up with an idea which was to, again, we're using superconductors. So, you take an absorber, could be silicon doped with phosphorus for example, pixel and you couple it to a superconducting circuit. And in the case of the Atacama Cosmology Telescope that I worked on which is in Chile. There's another one in Antarctica called the South Pole Telescope that uses the same affect. So, you can take a molybdenum gold resistor which is a superconductor and when a photon hits the bath it heats it up. And the reason they are called Transition Edge Sensing bolometers is that you set them on the transition between their superconducting cold state and their normal higher temperature state when they are warm. And so you set them on this sort of knife edge between those two states and they are very sensitive to temperature changes. So, the resistance of the circuit, the molybdenum gold circuit, changes a lot when the photon comes in. It heats up this absorber and the whole thing shifts off of its transition. And that is the detection of those photons.

[46:32]

Elizabeth: So, one photon is enough to cause this transition.

Danica: So, as with the CCDs, right, you sit there and you integrate for awhile and you look at one patch and you let the signal build up.

Ben: Okay, so this is a bolometer which means it measures temperature. It's taking advantage of physics on a much simpler scale than all of the other detectors that we've talked about. But it's absolutely very, very clever. And the idea here is, okay, let's say we got a photon. It's really difficult to make one of these really, really fancy machines that absorbs just that photon and reads all sorts of information about it. But it's a little bit less difficult to just have something that absorbs the photon and gets warm. And so the idea is what we do is we make a system that's really, really, really sensitive to temperature change. Now, superconductors, we talked about how there are these Cooper Pairs that couple up, that effect is a real sudden thing. It's like a high school dance where there's all these, you know, all thee teenagers don't want to dance with each other. They're just hanging around, milling around, bobbing their head to the music, and you're like, no, I want them to couple up. And they won't. They won't, they won't, they won't. So, you turn the temperature down. And what happens is, there's this special temperature where the gymnasium is just cold enough that they're like, it's too cold and they'll grab their date, right. They couple up. So, it's a really, really, really sudden transition between the two. They, in fact, the transition between superconducting and non-superconducting is something people studied for years and specified this is one really special type of transition. So, it's a really, really sensitive transition. So, what they do is they tune their machine so that there are superconducting elements that are each, each superconducting element is embedded in a material that will absorb the heat from some photons and they tune its temperature so it's just on the edge of superconducting. So, right now it's superconducting but if it gets any warmer all those teenagers will split up, and will stop superconducting. And so, each of these blocks that the superconducting material is embedded in, you expose it to light, it heats up just a little bit and then the ones that heat up those stop being superconducting. And you can measure the degree to which they're not super conducting and figure out how much the temperature has changed and deduce from that how many photons hit it.

Elizabeth: So, this is not something that measures Asiatic bears.
That would be a boloometer.

Danica: Bolometer.

Elizabeth: Yes. Yes. I said it. I said it too fast and my nose is stuffed up. It was nearly a joke.

Laughter.

Ben: It's not a machine that measures intake of cereal in children either. That would be a bowlometer.

Laughter.

Danica: When we were talking about the Atacoma Cosmology telescope which I spent some time operating in Chile, it always sort of puzzled people when they would ask me, okay so when you go down to your telescope in Chile and you look through it what do you see? And I'd say nothing, you can't look through it. And even if you could, you're eyes wouldn't see anything because they don't see these wavelengths. I always seem very disappointing to people but in fact it even gets worse. So, you take this data, you make your electronic picture, whatever. And you combine it using your computer but for us it could take weeks before you saw the picture on the other end, so, you know. Definitely no selfies, instant selfie where you can take a picture and go oh, I need to fix my hair and then take again.

Elizabeth: No instant gratification here.

Ben: Well, that was really fun. Good work everybody. You've pleased me, your efforts have born fruit and that fruit is sweet. Here's some fruit. Thank you Danica, that was wonderful. Here is a Mango.

Danica: Slurp.

Ben: Suresh, you get a durian.

Suresh: MMMMmmmmm. Nom, nom, nom.

Ben: Alright.

Elizabeth: Just don't hit me with it.

Laughter.

Ben: I'd like to thank our guest, author Elizabeth Bear. Thank you for coming on the show!

Elizabeth: Yaaayyyyyy!

Ben: Would you like to tell your audience about your most recent books?

Elizabeth: I do not actually have a book in 2016 because I had two books out last year. The first one is a Wild West steam punk adventure novel staring heroic saloon girls versus disaster capitalists. Um...

Ben: That makes sense.

Elizabeth: Yeah, if you imagine like leverage with hookers that's basically it in the Wild West. With gigantic sewing machines that you can drive like tanks.

Danica: Nice.

Elizabeth: It's called *Karen Memory* and the other one is a book called *An Apprentice to Elves* which I wrote with Sarah Monette which is a high mud Norse companion animal fantasy. Imagine, like the Pern books meet *Game of Thrones*. Telepathic wolves and Vikings, what more could you want from life.

[51:25]

Ben: Right. Alright. Well, that's it! Hi Everybody. Well that was fun. Let's get to some announcements. First, again, please give us a review on iTunes because that's where all the rankings of the podcasts go. Or, you can tell other people about us online through various online communities with your Facebook and such. You can follow us on Facebook, incidentally, if you want, follow us on Twitter. On another note, we're still humbly soliciting your donations. Your donations go towards paying server fees and also to our ambitious project to get all the episodes transcribed. You can send one time donations through our PayPal off our website or you can go to our sweet Patreon site and give a recurring $2 donation. This particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I'd like to thank the generosity of Mr. Patrick Knightenson and Mr. Jordan Young for their donations. I'd also like to thank Doug Bee, Ms. Julia, Ms. Nora Robertson, Ian and Stu, a Mr. Frank Phillip from Austria and Noisy Mime, Mr. Shlomo Delow, Melissa Burke, Yesem Wursase, Spider Rogue, Insanity Orbits, Robin Johnson, Madam Sandra Johnson, a Mr. Jacob Wick, Mr. John Keys, Mr. Victor C., Ryan Claus, Peter Clipsham, Mr. Robert Halpin, Elizabethan Teresa, Paul Carr, a Mr. Ryan Newl, Mr. Adam Kay, Thomas Shyrae, a Mr. Jacob S., a gentleman named Brent Evans, a lady named Jill, a gentleman named Greg, thanks Steve, Mr. James Clauson, Mr. Devon North, a gentleman named Scott Allowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Abersado, a Mr. Robert Steatka.

So, that's it for Titanium Physicists this time. Remember that if you like listening to scientists talk about science in there own words there are lots of other lovely shows on the BrachioMedia 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 the next time remember to keep science in your hearts.