Episode 68: The Shadows of Creation
Physicists: Michael Zemcov, Danica Marsden

Transcribed by Denny Henke

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

[1:49]

Ben: People often think that when something is gone, you'll never have a chance to know its nature. Like a book. Go into a library, take a book off the shelf and throw it in the fire. There, you're warm and no one will ever be able to know what the book says ever again. But it's not quite true. Even when it's gone what it leaves behind tells a story. Even if what it leaves behind is nothing at all. I mean, in the book example you could probably guess at the book's size by looking at the hole it leaves behind on the shelf. You can guess it's topic by looking at the topic of the books around it. Let's see, um, good job, you destroyed the World Book Encyclopedia Letter H from 1993. It's generally true that you can tell a lot about something by the hole it leaves behind. The empty dog bed surrounded by little chewed up pieces of fluff. The seat at the end of the bar farthest from the television that no one is allowed to sit in. The missing tooth that your tongue can't help but poke at or the hole in the pumpkin pie that is shaped exactly like my fork. I mean, think of footprints. What are they except the absence of mud in a very specific way which tells you about the shape of the foot that displaced it and also the shape and the weight of the animal that stood there. And so it is that in physics we often use the conspicuous absence of the thing to deduce things about the object or material that caused the absence. How do we, for instance, know what kind of atoms compose the sun? If you take the light emitted by the sun and pass it through a prism and then study the breakdown of the colors you'll see dark bands in that spectrum. Those are absorption lines. Every type of atom will absorb a characteristic collection at very specific frequencies and the argument goes that the sun should emit a continuous spectrum of light. Light at every visible frequency and thus the atoms in the sun's atmosphere are backlit by this light and as they absorb their specific frequencies they're going to leave shadows behind at those colors. The Fraunhofer absorption lines from the sun are exactly these shadows. Think about it, wouldn't it be great if everything in the Universe were backlit? Then, even if you had some material that was dark or cold or weird gas that doesn't emit light we could still see their shadows. Well, it is and we can. Rashid Sunyaev and Yakov Zel'dovich first predicted that we would be able to in the later half of the twentieth century. The source of this backlighting is the Cosmic Microwave Background. A type of light emitted before any galaxies or stars were formed, back at the start of the Universe. And a type of light that's been traveling for longer and thus from farther away from us than anything we can see. Today on the Titanium Physicists Podcast we're talking about the Sunyaev Zel'dovich effect. Speaking of things from back in the beginning, today's guest is returning to the show for a second helping of physics. He wrote and sang the song for the start of every episode of our podcast. He's the front man for his band Ted Leo and the Pharmacists and he's also in a hip band called The Both with Aimee Mann. Welcome back to the show Ted Leo.

Ted: Thank you, very glad to be here.

Ben: Okay Ted, I've assembled two of my old friends to greet you. Arise Michael Zemcov!

(Strange noise)

Ben: Dr. Mike did his undergraduate degree at UBC with me. He did his PhD at Cardiff University in Wales and he's currently an assistant professor at the Rockchester Institute of Technology working on experimental cosmology. Now, arise Dr. Danica Marsden.

(Whhhiiiiishhhhhhhh)

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

Alright everybody, let's talk about shadows. Let's start talking about the Cosmic Microwave Background. The argument is this effect is what happens when shadows are formed in the Cosmic Microwave Background and to understand why and how that works you need to know about this light that's getting filtered out. So, Ted Leo, we've talked about the Cosmic Microwave Background before, do you remember anything about it?

Ted: I do, yeah. That's one of those things that um, I think, it's out there in the ether for anybody to have a sort of, you know, tourists, you know, basic grasp on, is it not?

Ben: Right. So the Cosmic Microwave Background is our best evidence that the Universe started with a Big Bang. Okay? And essentially it's light that was emitted from a time when the Universe was really, really hot and really, really dense. And so, talking about the story of that light kind of illustrates why this Sunyaev Zel'dovich effect is so useful. Primarily the idea is that because of the nature of the Cosmic Microwave Background light we can see Cosmic Microwave Background radiation in every direction we look. And that's why this is helpful. It's literally backlighting all of the structures in our observable Universe.

[6:45]

So, quick refresher, the easiest way to explain Cosmic Microwave Background is to talk about, ah, the Universe's dynamics on a large scale and the easiest way to do that is to talk about what would happen if the Universe evolved backwards. Um, so what if somebody had taken a video of the Universe from the very beginning up to now and then started playing that in reverse, what would you see? Um, so what you'd see is, um, there's galaxies everywhere, structure, clusters of galaxies, galaxies flying all over the place, blackholes, stars. What you'd see if you played the thing in reverse, is the stars would turn back into clouds of gas, very exciting. And then the clumps of gas that make up the galaxies would kind of spread out. At the large scale, observationally we know that currently the galaxies in the Universe are getting farther and farther apart so if you play that backwards you'd see the galaxies over reverse time would get closer and closer together, right? So, these clouds of dust that make up all the galaxies now, they get closer and closer together until they merge into one big dusty, gassy soup. And in this backwards video you would say, what's causing all these galaxies and all these bits of elements to get closer together, it's got to be gravity. Your model for the Universe would say that all of the dust and gas has kind of collapsing down onto itself. Not to a point but you would say that the density of matter is getting higher and higher and higher. It's not collapsing down to a point because the Universe is infinite in every direction. So, instead what you see is, as the distance between every atom gets smaller and smaller, the rate of collisions increases, the gas will heat up and eventually you just get this really, really hot soup of gas. So, that was the backwards picture. And the argument is that gravity is causing this evolution. Einstein's theory of gravity predicts, essentially, the same type of dynamics will happen the way it has in our Universe. Where it starts out as an infinitely wide, tall, long density of gas that gets rarified, that spreads out, that gets cooler as the Universe expands. And so the important thing to note here is that when gas gets really, really dense and really, really hot, it does what has happened on the sun which is it gets so hot that the electrons get knocked off of the protons. And so, what you end up with is instead of a whole bunch of neutrally charged atoms you have a whole bunch of positively charged protons bouncing around in soup with negatively charged electrons. So, early in our Universe there was such a soup. There was a plasma, charged particles bouncing everywhere. And the thing about a plasma is that photons can't go anywhere in a plasma because an electromagnetic wave, when it tries to move anywhere, will immediately get absorbed and scattered off of all the charged particles around it. So, the moral of the story is, as our Universe cooled all of the protons and electrons eventually stuck together in pairs and the gas went from being ionized to being neutrally charged. And a neutrally charged gas lets light pass it by just fine. Because when an electromagnetic wave comes by and tries to wiggle it the electron will go one way and the proton will go the other and the thing won't move in response to the electromagnetic wave. So, the Universe went from being a dense, hot plasma to being neutrally charged and as soon as it was neutrally charged all of the atoms stopped interacting with the photons, the electromagnetic waves. And so those electromagnetic waves stuck around, they're still around today. They just never got absorbed. And so, they're still just kind of wandering the Universe. As the Universe got larger these electromagnetic waves lost energy. So, they went from being really, really hot, bright, you know, white colored mix of photons to a really, really cold mix. But, they're still everywhere. Okay? The moral of the story is the Universe is full of these ancient, dinosaur photons that are really, really cold that are just wandering around in every direction. Does that make sense?

Ted: Yes.

Ben: So, that signal, those photons, as a collection are called the Cosmic Microwave Background. Ah, Cosmic because it's cosmological in origin, microwave because they are microwaves now, that's a really cold type of photon, and background because they are everywhere you look. Everywhere in space has these photons wandering around from them. But there's an interesting point here. The surface of last scattering that is the the source of the Cosmic Microwave Background happened when the Universe was something like 100,000 years old as opposed to, like, the 14+ billion years it is now. So, it was a very, very long time ago. So, the neat thing here is if we look out into the sky there are photons from the Cosmic Microwave Background that are hitting us, hitting the Earth, hitting our eyes, hitting our instruments from every direction. But those individual photons, the photons that hit us, all, right now, they have spent their entire lives moving in straight lines.

[11:41]

So, there's a straight line from where they were emitted, you know, 14 billion years ago minus 100,000 till now. And they travel at the speed of light because they're light and so, what it means is that, there is the Cosmic Microwave Background photons that are hitting the earth right, right now. They all originated on a sphere, on a spherical shell that's like, pretty much, give or take, 14 billion light years in radius. So, in other words, there was a shell of photons that were destined to hit the Earth all 14 billion light years away from us and they've spent the entire transparent age of the Universe wandering from really, really far out, to us.

Ted: Do we know this because of the effect that we're going to discuss in this episode or is this a theoretical proposition or just an assumption based on the fact that we know they are arriving on a straight line. In other words, if we know that they are arriving on a straight line, why do we know that they originated from a sphere.

Ben: Oh, that's good. Ah, a circle is a mathematical object where all the points on the circle are the same distance away from the middle. Right? Same thing with a sphere. A sphere is a mathematical object that's composed of points that are all the same distance from the middle. So in this case, we, I suppose, it's maybe an inference that they spent their entire lives traveling in a straight line. Ah, we know this for a variety of reasons, it is consistent with a lot of the other data that we are taking. So, the argument is, light usually travels in a straight line. This light, in particular, is consistent with a model where we say this light is about 14 billion years old so it must have started 14 billion light years away from us. So, you look at all the points in space that are 14 billion light years away and that's a sphere.

Ted: Right. So, if they're hitting our sphere at the same moment, they must have originated at a similar shape at a particular point in the past. In other words they wouldn't be coming from a flat...

Ben: Yeah, that's exactly right.

Michael: Ted, you've done this before haven't you?

Laughter.

Ted: Not much, not much. No. Just purely as a point of interest.

Ben: So, to put a cap on the CMB, the moral of the story is the CMB is everywhere because the Universe is expanding in every direction in the same way. The Universe is super, super uniform. Everywhere you go it's kind of the same at the large scale. But, the particular photons that we're seeing, when we detect Cosmic Microwave Background photons, all originated on a great big spherical shell that's like a little, less than, give or take, 14 billion light years wide and that particular width, because structures formed in the time since that, all of the things that we can see stars, galaxies, they all formed since then, ah, the light from distant galaxies is at a smaller distance away than these Cosmic Microwave Background photons. If a particular galaxy formed 4 billion years into the age of the universe the photons we get from it might be 10 billion years old but that means that they come from 10 billion light years away and that's still not as far away as the particular CMB photons. And so, these Cosmic Microwave Background photons are traveling through and past all of the different structures that have formed since then to reach us and that's the idea. Everything in the Universe is being backlit by these CMB photons.

Ted: And we can read them because they have a different wavelength or some kind of different structure or...

Ben: Well, they have a very characteristic, aw shoot, what's the, ah, spectrum!

Ted: Yeah, yeah.

Ben: So, they have a very specific mix of frequencies.

Ted: That would be different from what we would see coming from something else.

Ben: Yeah, they are a lot colder than everything, you know, regular matter, the stars and stuff.

Danica: They have a particular signature and when that signature passes through a cluster of galaxies it gets distorted.

Ted: Right. Okay. I'm with you. I get it.

Michael: Okay, so galaxy clusters, what the heck is that? So, we know what a star is, a star is like the sun. And then if you put, like a gajillion stars together and kind of have them orbiting around, that's called a galaxy. And then, what you can do, is you can imagine putting a bunch of galaxies together and they're kind of all orbiting a kind of common center of mass which, in the case of galaxies, is basically dark matter not actually real, baryonic matter than makes up, you know, stars and galaxies and you and me and stuff like that.

Ted: That exerts, ah, some sort of force that creates the cluster or that keeps the galaxies in the cluster.

Michael: Ah, yeah, so dark matter is this weird stuff that is defined by the fact that it interacts solely through gravity on cosmological scales. So, it doesn't do anything except for make other matter want to go there basically.

Ted: Wow, I did not know that, okay. Interesting.

[16:42]

Michael: Yeah. So, on like solar system scales, dark matter doesn't matter, doesn't really factor into it. But on galaxy scales, because the volumes are huge...

Ted: Sorry, sorry, can I, do you mind if I use that line "dark matter doesn't matter" in a song at some point?

Michael: Go nuts.

Danica: I think you should. You really should.

Ted: Alright, sorry, so, okay, so...

Michael: We were at dark matter clusters. Okay, so, you've got the picture. There's a bunch of galaxies and they are all kind of bees in a hive, kind of buzzing around. You know, the buzzing takes millions of years but, whatever, we've got time because we're cosmologists. So, there aren't just galaxies there. What happens is galaxies are like dynamic systems and one of the things that happens in a galaxy is supernova. So, that's when you have a big star, bigger than the sun, by a lot. And it reaches the end of its life and it blows up, basically. And so, ah, supernova are like, messy, they're really messy. There's a lot of energy that gets put into them and the thing at the center that eventually becomes a black hole or whatever end state it's going to be, has some of that mass but a lot of it gets lost as hot gas basically. And it's very hot gas because it was, you know, I forget the number but it's something like the whole brightness of a galaxy happens in a supernova in a short time. So, you get these really violent things and what happens is you make a lot of hot gas and that hot gas kind of blows out of the galaxy. Think like boiling water with the bubbles rising through it and eventually stuff kind of ends up as this diffuse hot gas just hanging out in the middle of the cluster in between the galaxies. And when we say hot we mean really hot. So, let's see, 10 million degrees Celsius and when you're talking 10 million degrees Celsius, it doesn't matter if you mean Fahrenheit because it's first order it's the same number. So that happens and so you've got his really hot gas and it's basically just electrons just kind of banging around out there. So what happens is you get your, I like Ben thing of like old dinosaur photon, it's like, you know rinkydinking along, it's cold, it's tired, it's been going for a long time. And you get a hot electron and it hits it and it gains a little bit of energy from that electron.

Ted: Ah, okay.

Michael: And the electron loses a little bit of energy so that's called inverse Compton scattering for those who are keeping score. Okay, so, run the picture forward. The photon's bumbling along and eventually it ends up in a telescope somewhere. And we're talking here about photons that have a wavelength of like a millimeter which is roughly the wavelength that your microwave oven works at. So, what you're doing is you're making a picture of the Cosmic Microwave Background. And I was using this analogy before, imagine you're looking at a white wall. Boring, kind of featureless thing, let's call that the Cosmic Microwave Background. It's not really, there's a lot of structure, but let's just pretend it's white. Um, and, what you can imagine is, the photons that went through the cluster that I see have a little bit more energy than they should. So, what you can imagine seeing is that blue, at least to our eyes, blue means more energy. So, what you see is a little blue spot. And then if you get your filters out of your handy filter set you could imagine looking at it in a red filter and a green filter and a blue filter. And what you'd see, at this longer wavelength of course, but what you'd see is that in red you've lost some photons. So, it's little bit fainter in that spot. What's happened is those photons have been scattered up so in the green filter you probably don't see any difference, it looks like the white wall but in the blue filter you see something that's a little bit brighter. And through that we can actually learn a lot of things about how the Universe works.

Ted: Yeah. So, my first question about that is what you're telling me is that change can lead you back to understanding where it passed through that hot cloud of gas...

Michael: Yes!

Ted: And eventually create a picture of it which is sort of the effect that we're ultimately talking about, here, right?

Danica: Yeah, so if your white wall is your CMB backdrop and you make a picture of it, the frequency of light where you don't notice a change is in what's called the null of the Sunyaev Zel'dovich effect which occurs at about 220GHz where the wavelength of this light is close to a millimeter as Mike had said. But then if you go a little bit over to a slightly different frequency, if you go to, say, a 150GHz all of the sudden all of these red dots pop out on your wall. Or if you're looking at your CMB map you see a bunch of what look like holes and all of the sudden what's popped out of this map is the location of clusters of galaxies. And you have found them in a way that is not limited by how bright they are. It's only limited by how big they are, the mass of them...

Ted: Okay.

Danica: As far out as they exist.

Ted: Now, my only question about that is, so, could a photon with a similar signature appear to you that just originated somewhere else and therefore, retain this little bit more energy in this area and, you know what I mean?

Ben: Yeah.

Ted: Like, ah...

Ben: Yeah, yeah. You can get false positives

Ted: Can you get false positives, yeah.

[21:40]

Ben: So, what we're talking about is kind of like population statistics . Imagine if the backlighting, the CMB backlighting gave off three, three different colors. Characteristically, suppose it gave off, I don't know, seven red photons, four yellow intermediate energy photons, two high energy blue photons. Okay? So, you could look at any patch of sky and say yeah, 7-4-2, that ratio, that's the Cosmic Microwave Background. So, it's not just counting the photons and saying where does this photon come from? It's like comparing one color population to the other. So, what we're saying is if a packet of photons on the Cosmic Microwave Background passes through one of these clouds of really, really, really, really hot gas, some of those red photons are going to turn into blue photons. So, instead of 7-4-2 you would end up with, I don't know, 6-4-3 or something, right? So, you just compare the ratios and you'd be like there's more of this than there should be, there's less of this than there should be.

Ted: Right, I see. So you could have 30 6-4-whatever's hit on someplace but if you had 3,000 hit in another place you would look where the 3,000 went, came from.

Ben: Yeah. Yeah. So you could say, oh, wow, there's a lot more blue photons than there should be so this effect is probably getting washed out by some cloud of gas or something in front of it. So this isn't the only effect that's generating photons, but when we look specifically at the

Cosmic Microwave Background signal this is an effect that modifies the Cosmic Microwave Background signal.

Danica: In a lot of the intervening structure between us and the CMB is sort of tiny compared with you know, the overarching whole sky, so, you know, their impact is relatively small.

Ted: So, like the ratio of those that have been changed is actually pretty small compared to the type of photon that you would normally expect the CMB to just be feeding you all the time.

Ben: Yeah, most of the CMB signal doesn't pass through these galaxy clusters.

Michael: Yeah, you need a fair amount of this hot gas to cause it. And another thing I was going to mention is what Danica touched on, which is that, the whole secret here, why this is clever, right, and why people spend effort doing this, is that lots of things in the Universe look hot. Stars, galaxies, they all look hot, right. They are all emitting photons. Nothing looks like a hole. So, by looking for the hole, you are kind of automatically rejecting a lot of things that aren't the thing you're looking for. Um, which is kind of the secret to success here.

Danica: Yeah, it's really unique because it's the one thing where you're not limited by your ability to capture photons that come from that particular source. So, like a star. The further away a star gets the harder it gets to see. But with this effect, as long as, you know, the cluster of galaxies is big enough, it can be super far away and it, in this effect, it still looks as bright.

Ted: Right, I see. Yeah, yeah. You know, is there a point at which something will get so far that we're never going to see the photons that are being...

Danica: No, that's the great thing. Because those photons are the CMB photons so...

Ted: Oh, right.

Danica: So, they come to us no matter what, the same number of photons. And it's really all just limited by how big that blob of galaxies is in between us and them. So, it turns out that, you know, as luck would have it, most of these clusters of galaxies live in a certain distance, at a certain distance between us and the CMB. And so they, on average, tend to be about the same size, which is...

Michael: They're like, ah, like an arc minute, so like the size of a small crater on the moon kind of thing.

Danica: So, they all tend to look about the same size though, right.

Michael: Yeah and like Danica said, you see them all the way back except you go so far back that eventually that there were no galaxy clusters and then you kind of run out of gas.

Ted: And even though we talk about the Big Bang, like, it's hard to not think of the space around us, you know, as a lay person, it's hard to not think of the space that surrounds us as it emanates from the Big Bang, as just sort of like an ever increasing cone size. But, of course, you know, it's not. But, in thinking of it, ah, four dimensionally, is there any, I don't know what I would call it other than an event horizon, where the CMB photons like, "end" at this point?

Danica: Um, sort of. It's like you're in the middle of a beach ball and that beach ball is the wall of CMB photons that left 14 billion years ago are just hitting you now.

Michael: And the that, and the CMB is that horizon, right. The horizon you're talking about is defined by the CMB, that's how far a photon came since that epoch and further back you cannot see, right?

[26:42]

Ben: Yeah, because the Universe was opaque before then because it was all made of plasma. So, photons couldn't travel anywhere before then.

Michael: And what's really cool about the CMB is if you could live forever and you sat and watched it, that horizon is moving right. So, you know, in a million years or 10 million years it's going to look different than it does today.

Ted: Right, because it's still expanding.

Ben: Yeah. But there is an effect that you might be thinking of called the cosmological horizon where, essentially the distance between us and another object far away is increasing, right. Because the Universe is expanding. And so, the farther away an object is the faster it will be moving relative to us. Eventually as the Universe continues to expand and accelerate its expansion, in billions and billions of years, when you look out, and you try and see the CMB, those CMB photons will be of... the idea is that they won't be moving fast enough to reach us given the expansion of the Universe and so the effect is that of an event horizon.

Ted: Right. Interesting. Yeah, okay, that's, I didn't even understand what I was asking bit that is exactly what I was trying to...

Ben: Yeah. So we're not, the Universe isn't old enough for us to see that attribute yet. In our current Universe there is a cosmological horizon, at least theoretically. But, the news that we're getting from around that area is too old for us to be able to see it or observe it or interact with it.

Ted: Right. Is it fair for to say that if, one were looking to make a visual representation that was not at all scientifically accurate, of, like, one of the these CMB photon waves that when it reaches us, the signature that it carries, in understanding where it came from and in understanding how it has been affected by these bodies and these gasses that it has potentially passed through, ah, is almost like actually reading the wave backwards as if it had been visually printed in space.

Ben: Ah, yeah, that's kind of the idea. Right? So, the photon, it passed through this cluster of galaxies billions and billions of years ago. So, what we're reading as the distribution of photons in the CMB is, essentially the history of the entire Universe in structural information along that line through history.

Ted: This is not dissimilar to what we discussed last time in the way that sound waves operate. You know, you can see the paths of these things but they really only represent that exact moment when it hits your ear drum, in a way. But it tells the story of all the air that it's moved...

Michael: Yes. I like everything about that.

Ted: Alright, cool.

Ben: Okay, so, to summarize, the CMB exists. It's backlighting everything. The photons that we are absorbing now have passed through everything in the observable Universe on their journey from when they were emitted billions of years ago to when we detect it and in doing so we're getting a history of structure formation. Some pass through galaxies and those clusters of galaxies, some of them have really, really hot gas around them and if the gas is really, really, really hot it will change the light distribution in this Cosmic Microwave Background signal. And we can interpret that change, compare it to the photons around it and, say hey look this particular group of photons passed through a cluster of galaxies. And we can use this as an astronomical device.

Ted: Sounds good!

Ben: Okay, so, um, um...

Ted: Well, what about the actual discovery of the Sunyaev...?

Ben: Sunyaev Zel'dovich effect.

Ted: Yes, thank you, that's what...

Michael: They were two Russian fellows. One of them is still alive but quite old. But he's a real sweetheart if you ever get the chance to meet him.

Ted: I certainly hope to now.

Laughter.

Michael: And Zel'dovich passed away a long time ago but I'm told he was a complete A-hole so, I don't know. Anyway, ah, they were doing this work in the early 70s. And then claims of measurements stretch back, oh, to the early 80s. I'd say. But it wasn't really generally accepted. Ah, it wasn't till, kinda like, 95 I'd say that people were saying oh, you know, we think we saw this thing in real life. And then I think the transformation's been pretty profound where, like, what is that, 20 years ago? So, there was ten years of like search around the darkness which was kind of like when I was an undergrad... and Danica, and then I'd say for the last ten years it's become like a real workhorse. Um, there's a bunch of telescopes that just kind of do this routinely now which is amazing to me. You know I was alive and working when it was hard. And that makes me feel old.

Danica: Right. So this effect was predicted in like the 80s and then they knew okay, these are the frequencies where we need to go and look. But it turned out that in that point in time there weren't detectors that could see that light yet, really developed well. And so there were, in particular, a couple of telescopes where the whole design of the telescope was built around trying to see this light at these frequencies that would reveal these structures.

[31:49]

So they used bolometer detectors which we discussed in a different podcast. But they sort of detect all the light and then you put filters in front of them just like with your camera to throw out all the photons you don't care about at the frequencies you don't care about. And then you collect the photons that you do care about and make your picture with them.

Ted: I get it. From the perspective of Earth, is there and advantage to geographical location, would it be better if we could encase the entire planet in one big...

Michael: Oh my god, I'm so glad you asked that.

Chuckles.

Danica: That's a very good question.

Michael: So, the general rule of thumb is that anywhere there's plants is bad because plants mean there is moisture and at these wavelengths the thing that kills you is actually water vapor in the atmosphere.

Ted: Uhhuh.

Michael: Which drives us to go to crazy places like the top of volcanoes in Hawaii or the deserts in Chile or the South Pole, because the South Pole is very dry. It's the biggest desert in the world.

Ted: Right, right.

Michael: So, a lot of the submillimetery type instruments that do this are in weird places.

Danica: Yah, you don't think of the South Pole as being dry do you but I guess it's all that moisture just freezes out.

Ted: Yeah, it's frozen. And then, this is specifically, we're talking about light, what do they read, for example, at Arecibo. I know it's up high but is it that dry up there in the rainforest in Puerto Rico?

Danica: No, Arecibo is in the radio wavelengths, the long wavelengths which cut through a lot of stuff. But, in fact, there's another thing that's going on which is that if you sort of look in the ring that is in the plane of where our Milky Way galaxy lies, the Milky Way galaxy gets in the way.

Ted: Ah, of course, right. Interesting.

Danica: So, it's better if you can look up, out of the pancake of the Milky Way or down. So, that's the other thing, the confluence of dry places and looking away from the Milky Way.

Ted: This just occurred to me, is our visual frequency light pollution any problem with this?

Michael: Nope.

Ted: No, okay.

Michael: So, you could do this in the middle of a city if there wasn't a million cell phones and radio stations and whatever the hell else...

Danica: And wifi and things, right.

Michael: So, one story I have is way back in the Stone Ages when I was a kid I was observing at a telescope that doesn't exist anymore called the Caltech Submilimeter Observatory, there was an instrument called SuZIE, which stood for the Sunyaev Zel'dovich Infrared Background Experiment, something like that. Um, and, you know, we were observing with this thing and, 9 o'clock at night, suddenly there was all kinds of noise and we're were like, for two minutes, and we were like what the hell is this? And it kept happening and happening and then eventually we put two and two together and realized, you know, that Brad was going downstairs at 9pm and microwaving a burrito...

Laughter

Michael: And the microwave was leaking right, and we were picking it up on the instrument because it's the same kind of wavelengths.

Ted: Right, Yeah that's...

Michael: That was the end of microwave burritos

Laughter:

Ted: Aw Brad. It's always Brad man.

Laughter

Ted: So, I think I have a pretty good picture of how it works, ah, how you know, broadly is the study of it being deployed, and like, have we found anything...

Danica: So, what is it good for? Why do we care? Well, okay, so, it turns out that if you, you know, map out where all these clusters of galaxies are and you sort of count them up it can tell you about what ingredients went into your pumpkin pie of the Universe. So, how much dark matter, how much dark energy, how much radiation, how much baryons. And the proportions of those things will impact how many clusters you'll see in the sky. So, if you see a thousand in a particular patch versus 10,000 that means something. The more dark energy you have, kind of spreading everything out, the fewer clusters you'll see in a given patch of sky. So, they act as the buoys on the ocean of darkness.

Ben: So, the deal is that depending on what's on what's around, galaxies will form in different ways at different rates. Ah, right? And it's kind of like a computer modely thing. It's like, you say, hey, grad student, you've got this big fancy computer, throw this much dark matter, throw this much baryonic matter, ah, see how long and what types of galaxies you get if you do a really long simulation. Ah, okay, so, then they'll say, well if we throw this ratio of dark matter to regular matter we get this distribution of galaxies and if you do it this way you get pancake galaxies like this, right? Whatever. The argument is, that this data that we're getting using the SZed effect lets us compare, contrast, ah, judge those simulations. To say, okay, so we think we know the baryon density, we think we know how much dark matter ratio that particular patch of galaxies had.

Ted: Ah, are you saying that like, you can run, like an infinite number of simulations get potential, things to look at and if you notice something coming back at you, you know from the actual CMB, you could like, literally just consult some simulated models and say this looks a little bit like this, let's explore a little further?

[36: 52]

Ben: Yeah, you know, its kind of like, you know how America's test kitchen, I think, did this like, cookie study where they're like hey, if we put this much flour and this much butter in the cookies or this much sugar at this temperature, how do the cookies come out? And they ended up with a big table of different shapes and sizes cookies. They were mushier if you put, right, you know, and then essentially this is a photograph of all the cookies in the Universe.

Michael: That is the analogy of the night Ben. I know I...

Laughter.

Ted: All the cookies in the Universe.

Ben: Those galaxies had this ratio, these galaxies formed this way...

Michael: Yeah, yeah, yeah, you simulate the Universe with different inputs, and, well, not the whole Universe but you simulate, starting at some point and you just ask, is what I see consistent with the model.

Right.

Ted: Okay, and let me ask you this, when you're asking that question, are you running what you are observing like in real time against your database of simulations or are you a human detective having to study the databank of simulations and assess yourself if they, you know, match up with something that you are seeing.

Michael: Well, we have statistical, you know, mathematical framework for how to judge how well one thing agrees with the other and the simulation part is not the easy part but it's the part where it's kind of deterministic, right. Like, you know how to turn the crank and sausage comes out the back end of it. The hard part is with real data where real instruments have all kinds of crud in them, like, say microwave ovens that Brad's making a burrito and you have to figure out...

Ted: Fuckin' Brad, man.

Michael: Yeah, this guy, I'm telling you.

Ted: Sorry.

Laughter.

Michael: Ah, you know, the hard part about real data is you have to figure out, like, okay, there's all kinds of extra junk in here, what is it? Where did it come from, which parts do I have to throw away because they're complete trash, you know.

Ted: Right, right.

Michael: That kind of stuff.

Ben: Okay, well, lets talk about what other things you can study with this because it's a great topic. And there's lots of details that come out of this.

Michael: Okay, so, we talked about finding galaxy clusters because they tell you about where mass is in the Universe. So, if your question is, where is mass in the Universe and how does that trace the large scale filamentary structure of dark matter. That's a good question and that's one thing that this can do so we talked about that a little bit. Another thing you can imagine is that clusters themselves are interesting astrophysical objects that can teach you various things about this that and the other. So, people sort of study clusters for their own right. So, if you imagine that the gas in the galaxy cluster, it has weather, right? It has temperature variations, it's hotter here, it's colder here, it has pressure variations because gas is moving from one place to the other, it's sloshing around. So, studying that can tell you various things and so that's a big thrust and something that I've spent some of my career on is understanding like, what can understanding like the spectral details of the SZ effect tell us about what's happening in galaxy clusters, where does this hot gas come from, and so on and so forth. And so that's one thing you can use it for. Another thing is this gas emits X-rays, it's hot, so just like at the doctors office with the X-ray that goes through you you have similar wavelength light that can get made by these very hot photons and basically by comparing the X-ray and the SZ maps you can tease out what must be the distance through the cluster that the photons traveled and that is a way to understand, basically, how the Universe is expanding. Because you map out, basically, what is that distance do as a function of distance from us. Ah, so, that's been another, you know, you asked earlier, like, what is it good for, what have we learned? So, you know, we've learned about cosmology with a capital C, or some people call it Cosmography, which means like there is a few fundamental numbers that describe the Universe. What are they and how big are the, that kind of thing. There's sort of weather in galaxy clusters, there's the cosmic distance ladder which is, you know, how far apart are things and how far are we from them. Which is, you know, a fundamental interest, it calibrates a bunch of things we do.

Ben: So, wait, wait, hold on. When you said that last one, are you saying that, okay, so, the gas is a certain temperature. We know because it is doing the SZed effect, we know what temperature this gas is and so we also know that this gas at this location should be emitting X-rays.

Michael: Okay.

Ben: And then we absorb the X-rays and see how much they've red-shifted. Is that what you're telling me?

Michael: So, it's actually the other way around which is you know that it emits X-rays because you go out and observe and X-rays are being emitted. You go out and you measure SZ and there it is, it's the same thing. But basically the X-rays go as the density of the gas squared whereas SZ goes just as the density of the gas. So, by computing their ratio and taking the square root and things like that you can basically work out what must be the line of sight through the cluster. So, it's a kind of measuring two different brightnesses and then taking their ratio kind of argument.

[41:49]

Ben: But how do we use that to determine the red shift profile of the Universe? I thought you said...

Michael: So, basically the free parameter, when you take that ratio, is the Hubble constant. Which, the Hubble constant is how fast the galaxies recede away from us as a function of how far they are away from us.

Ben: Okay, so, what you're saying is the density of the gas determines how much SZed effect there is?

Michael: Mmhmm.

Ben: And then in a different way it determines how much X-rays get emitted.

Michael: Right.

Ben: And then the difference between the two also depends on how fast it's moving away from us.

Michael: Right.

Ben: And so we can compare the two signals, the SZed effect and the ah, so, how many photons get switched around as the, as the Cosmic Microwave Background photons travel through the gas and compare that to the profile of the X-rays and in doing so we can learn information about how fast the galaxy is moving away from us. How fast the Universe is expanding.

Michael: Bingo.

Ted: That's interesting. Because it sounds like on paper that becomes a pretty, not complicated equation. To determine each of those variables that you're talking about in there?

Ben: Yeah Mike.

Michael: Well I've suppressed a lot of information there Ted.

Ted: Right, no, well, I know, I mean...

Laughter.

Ted: I mean like what you ultimately, you know, the ultimate, you know, variable that you end up with is not going to be more than a few, you know... I'm not talking about what goes into actually figuring out each of those elements. But like, you really are only talking about, sort of these three things that interact and give you a vast wealth of information.

Michael: Yeah, right, yeah, right. Ah, well, I mean, we should do a show, someday, Ben, about the difference between reality and mathematical models.

Ben: That sounds boring. I vote no.

Michael: Ah. So, when you write down an equation that describes a physical system, so that equation has, I don't know, ten, different variables in it. Some of them are fixed like the value of pi. Some of them, you are safe assuming or just at least saying I'm going to basically claim ignorance on that and just assume it's a two. And then you get numbers that you get to basically fit as part of the model. You get to constrain from the data. And, you're absolutely right. So, h is ultimately the thing that gets constrained but the way that people do it there is a couple of other things that get constrained at the same time and it's kind of mushy so.

Ted: To h is a whole process... got it.

Michael: Right, you got it. Okay. So those are, those are, let's see, three things we got up to. Another one is, we talked about dark matter, it's what makes up galaxy clusters at some level. How do you make a galaxy cluster? Well, you take the little galaxy clusters and you bang them together and you get a big one. Or, you take a big one and you add a little one. So, people go out and they make measurements of dark matter as it's passing, well no, you can't see dark matter. That's the first statement.

Laughter.

Ted: Dark matter has no signature whatsoever.

Michael: Only indirect. Okay, so picture like this, ah, dark matter has a bunch of fans that are baryonic matter that is like you and me, stuff that interacts with photons. And, so, dark matter, you know is going out to clubs and stuff, and it's got the baryonic matter it just can't shake, right? And so, let's say it wants to go to the cluster party, it will, you know, gravitationally attract and it will go into the bigger cluster and that baryonic matter is just going right along with it. Until the baryonic matter hits the atmosphere, basically, of this galaxy cluster at which point the dark matter is still going to go at the same speed, right? It's not interacting with anything, it's just going to go straight through, out the other side and then come on back because it's just going purely through gravity, there's no pressure. But the baryonic matter, first of all, was following it, but then it sees that atmosphere and it goes aw crap, I'm going way to fast and it has to kind of brake. Basically think of it as a shock. There's actually pictures of shocks of matter going through cluster atmospheres that look like a bullet, basically. It looks like a shock front, And you can do a calculation. You can basically say, well, you need dark matter to make this baryonic matter go that fast because the baryonic matter on its own doesn't have enough mass to be that attracted to this bigger cluster. So, it must be that there is some slug of dark matter that this thing was following and then it hit the atmosphere, splat, and it makes the shock and we can go on and measure that. And, it ends up that measuring the SZ effect is a good way to do that. It's kind of a hard measurement but people are doing it nowadays.

Ted: Ah, dark matter has mass?

Michael: Yes.

Ted: Okay. So, you know what it is sort of before it hits and that's how you can determine that it is, that it is the only thing that passed through.

Michael: You see how fast the baryonic matter is going and how much there is and then you back out how much mass there must have been.

Ted: Got it.

Michael: And then the final thing that I can think of was, there was this funny thing called the kinetic Sunyaev Zel'dovich effect. Now we're really getting down the rabbit hole. The Sunyaev Zel'dovich effect that we've been talking about so far is, I haven't talked about things moving with respect to each other, just photons hitting electrons and bouncing off kind of thing.

[46:49]

Michael: Here you can imagine the galaxy cluster as moving with respect to the Cosmic Microwave Background. So, that means that photons coming from one direction have more energy than photons coming from the opposite direction. Just from Doppler shifting.

Ted: Right. Okay.

Michael: And so what that means to us is that when we look at these clusters we see a little bit of the signal having to do with the fact that the cluster itself is moving along the line of sight in some way. And basically that lets you measure not only the position of the cluster but also how fast it's moving. And if you know both of those things you can constrain these cosmological models we were talking about earlier in a way that is kind of new information. Like, you're not measuring the same thing, it's like, going to let you measure some other parameters really well. So, that's something that's just coming online now.

Ted: Is that better for measuring the size of something, like the sort of overall dimensions of something?

Ben: Okay, so, what he's saying is, you take a picture of the Universe. You know where all the galaxies are, hurray! You don't know, necessarily just based on that, which direction each galaxy is going. Is one moving away from the pack? Are they all collapsing towards the middle? What's going on, right? Because it's just a moment in time. We're just getting a snapshot of where they are. So, Mike's saying that because, if it's moving quickly relative to this Cosmic Microwave Background, we can detect a signal that tells us which direction and how fast that the piece of the galaxy, that clump of gas, is moving relative to the, ah, well, us. And so we can get a picture, we can say, here is, not just where the galaxies rest, but which direction they're going. How fast they're all heading. And that can inform our models for how these galaxies formed dynamically.

Ted: I think I get that.

Michael: Okay, okay. Let me, I just thought of an analogy and maybe it's terrible but I'll try it. Okay, so, I have a pool and I have a bunch of balls. And I chuck the balls in the pool and then I take a photo. The photo tells me where the balls are now and by knowing where the balls are now and maybe some simple assumptions, how they were arranged when I chucked them in. I could back out what the initial conditions are and also where they're going to go. But that's really uncertain, right? You don't really know where they're going to go so if I could measure not only where they are but where their velocity is headed I can actually figure out where they came from and where they're going. So, it's basically that.

Ted: Yeah. Okay, that makes sense, yeah.

Michael: Good.

Ted: Yeah. Yeah, um, what's the future. Like what are you, like hoping for, what are people looking for, you know?

Michael: What are people looking for... Well, so the KSZ effect that I was talking about is a big deal. And I'm interested, myself, for example in learning about very hot gas in galaxy clusters. So, it ends up, this is another complication, but it ends up the SZ effect has this shape but the shape depends on the temperature of the gas. And at very high temperatures you get weird, special relativistic Einstein kinda stuff happening. And we're at this point now where we can actually start probing that and using it to kind of understand the dynamics of plasmas at very high energy. Much higher energy than we can achieve in a lab at home. So, that's another future direction. And I think people are going to still use it for cosmology although things have kind of moved on from that I'd say. Oh, and here's a cool one, you can actually measure the temperature of the Cosmic Microwave Background as a function of distance. So, everybody assumes oh, well the temperature just varies smoothly with the distance away. So as you go back it goes back as some, you know, simple function. Um, it doesn't have to be and if it didn't you'd go, oh my god, something's really wrong with our understanding of how the Universe works. People look for that as well.

Ben: To summarize, when we talk about how the Universe has evolved as a picture, various questions come up, right. You could talk about what the Universe is made of, how it evolved, how galaxies formed, at what scale is the Universe expanding? Ah, how that profile depends on position, how that's changed over time. And the information that we are getting from this technique provides a lot of good details that we can use to understand our models and which picture is right overall.

Ted: I dig it. I like it, I'm very interested. I'm going to read more.

Ben: Okay. Well, that was fun. Thank you Mike, thank you Danica. You have pleased me. Your efforts have born fruit and that fruit is sweet. Here's some fruit. Mike, you get a persimmon.

Munching sound.

Ben: Nice. And Danica, you get a tangerine.

Slurping sound.

Laughter.

Ted: That's good. You peeled that very quickly too.

Laughter.

[51:48]

Ben: It was very ripe. Well, I'd like to thank my guest Ted Leo, thank you Ted, that was lots of fun.

Ted: Thank you, it was really fun.

Ben: Alright! Well, it's announcement time! That was a super fun episode. First, please give as an iTunes review or tell other people about us online. Why? Because people keep their deep love of physics and astronomy secret. They want to know that there's a show like ours online for them to listen to but they don't know that we exist. So, a subset of your friends and family will be really, really happy for you to tell them about us. And then you'll have someone to talk to about all the physics you learned.

Alright, on another note, we're still humbly soliciting your donations. Your donations go to paying the server fees and our project to transcribe the episodes as they come out and a new project where we buy everybody fancy new microphones. Did you hear how good Mike sounded this episode? That's right, that's because we bought him a microphone with your donations.

Aright, so if you want to donate some money, 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 donation. This particular episode of the Titanium Physicists podcast has been sponsored by a collection of generous people. I'd like to thank the generosity of Jordan Young for his donation and then I'd also like to thank Sixton Linason, Laurence Lee, Mr. Simon, Keegan Ead, Adrian Shonig, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein, 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, Robin 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 Scot, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, a Mr. Robert Stietka. So, that's it for Ti-Physicists this time.

Remember that if you like listening to scientists talking about science in their own words there are lots of other lovely science shows on the Brachiolope Media Network. The intro song is by Ted Leo and the Pharmacists, oh yeah, that was today's guest, and the end song is by John Vanderslice. Good day my friends and until next time remember to keep science in your hearts.

[56:08]

Ted: When was the Cosmic Microwave Background identified as such?

Michael: Ah, what was it, 65? It was Penzias and Wilson and they won a Nobel Prize for it so it's kind of a big deal.

Danica: That's when it was first observed and um, what's sort of funny is that it was either the CMB that they were seeing, which had been predicted, or it was pigeon poop on their antenna.

Ted: Wow.

Danica: Those were the options.

Ben: The story was like, they were working for Bell Labs and they had a great big microwave antenna telescope, right? So, it was a horn that was pointed in a certain direction. And I think they were trying to tune it, so they were trying to, you know, make sure no strange signals were coming from it. They were trying to prep the instrument to do, I don't know...

Michael: Echo balloon satellites.

Ben: Echo balloon satellites. Oh, okay.

Michael: Who knows what that is, I don't know.

Ben: Yeah. And then, and so when they turned it on it had a listing, oh, like there's this buzz and they figured out where that buzz was coming from. Maybe a screw was loose or whatever...

Ted: Right.

Ben: Ah, and then they were like man, there is a buzz that we can't get rid of.

Ted: Okay.

Ben: There's a signal that we can't get rid of and so they went up and they said, oh, it's all this pigeon poop in the horn and so they cleaned it out. And then the signal stayed and it was the first detection of the Cosmic Microwave Background.

Ted: Right. Okay, because I feel like that's kind of famous, like that, that, ah, you know, me without knowing the details and the year and the people, that's sort of a famous story in the snow that we hear or see on our various antennas on the radio or whatever, is related to this?

Michael: Yeah, so there's some statistic that you and I are probably old enough to old antenna tvs.

Ted: Yes.

Michael: Um, you know how you used to tune it between channels and there was like snow.

Ted: Yes.

Michael: That, that, like 1 in 400 of those or 1 in 100, something like that, of those noisy things was because of a CMB photon.

Ted: Interesting. Okay. Wow. I feel like the sort of, you know, popular lore on that is that that's all CMB. Oh, yeah...

Michael: No...

Ted: Tune between stations and you're hearing the Big Bang man, you know.

Laughter.

Ted: I feel like that was the line I got growing up. You know, its good to, now I know.

Michael: Well, I still, I still am blown away, like, CMB photons interact with your body once in the while too. But I'm like, I'm still blown away that this poor photon just propagated itself for 14 billion years, you know, across the Universe, and it ended up hitting my TV or something, like...

Ted: Right. Depends on what you're watching.

Michael: Yeah. Right, right.

Ben: I mean, you, alright, I'm probably going to delete my saying this but like, some of them hit, like dog poop, right.

Michael: Right.

Ted: Sure.

Ben: At least it hit your TV antenna.

Laughter.

Michael: It could be worse.

Ben: There are worse places...

Ted: I have one more question based on where we've gotten to so far. As you guys were describing the, you know, reverse action of the Big Bang. And objects that we think of relatively solid, you know, in space, be that planet, or galaxy, expanding into gas as we go into reverse, ah, while the larger picture is actually collapsing into a near singularity, so like, so, in the Big Bang you have mass expansion but localized congealing and compacting into the bodies in space that we know. Is that correct?

Ben: That's correct, yeah. That's the general, at the large scale of the Universe is getting bigger but at the smaller scale things are collapsing. You know, matter is collapsing into galaxies. The dust and stuff in galaxies is collapsing into stars and planets.

Ted: Is that just because things cool and attraction increases, like, what's the...

Ben: I think the answer is because it's getting cooler. You know, there was a time when it was, you can think about the energy density of the Universe is decreasing. Um, and then you can also think of structure as only being able to form once the system is cool enough, right. So there's a time when it's so hot that electrons have too much energy to stick to protons.

Ted: Right.

Ben: And once the Universe has cooled past that point they'll stick together. Ah, similarly, dust won't collapse down into a point unless it's moving slowly enough, then that happens as the Universe kind of stretches out all of the energy.

Ted: The energy from the initial bang decreases as gravity eventually draws slowing and cooling things toward each other because that attraction becomes more powerful than what was actually the overall expansion.

Ben: So, the overall expansion gets larger, the larger a volume you have. But, um, things will collapse down into smaller structures uh, at a, at, depending on how big those structures are locally. Uh, I don't know how to say that right.

Ted: No, no, yeah, I get it. Okay.