Episode 58, "Extraordinary Evidence"
Dramatis personae:
- Ben Tippett
- Kathryn Cogert
- Tim Dobbs
- Katie Mack
- Michael Zemcov

The Titanium Physicists Podcast
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Ben: Never be afraid. There's nothing which is known which can't be understood. 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've bestowed upon these women and men the title of Titanium Physicists. You're listening to the Titanium Physicists Podcast and I'm Ben Tippett. And now... *allez physique*!

01:11

[Intro song; *Tell Balgeary, Balgury Is Dead* by Ted Leo and the Pharmacists]

01:46

Ben: Now that autumn is here and campuses are full of students, it brings to mind the bright days of my own undergraduate education. I recall, in my second year of university, taking course on early Greek philosophy. At the start of the term, the professor said something which has really stuck with me. We were talking about Hesiod, who provided us with stories of the Greek gods and Hesiod said the stories came from shepherds who had nothing better to do with their time than watch sheep and tell stories and talk to the gods. Our professor said that the gods were like humans and like ourselves, the stories they were most interested in were the stories of their own origins. The stories of where they came from. Because, she said, there is nothing more precious to a person than their own story. And when I reflect on it, the problem with my own story is that it has no beginning - it starts midway through the story of two other people, my parents. And their story start midway through other people stories and so on and so on and so on. There seems to be no beginning to this chain of past stories and so it is that people yearn to know how it all began. To know whether or not there is a first story. And if there is, to know the details of it. Every religion on Earth contains a cosmology - an explanation of how the Universe began and thus explaining why things are the way they are. These stories are precious - we treasure them in part because of how they fit in with our own individual stories. In telling us the story of the Universe, they explain how and why we as individuals came to be. And there's nothing more precious to a person than their own story. So it's not surprising that in the early XX century when modern physics claimed its own story of how the Universe began, this new story was not particularly well received in some circles. From some perspectives, the extraordinary story of the Big Bang is more than blasphemous. It's personally offensive, because the physicists are threatening to rewrite their stories. And there's nothing more precious to a person than their own story. But as Marcello Truzzi is famous for saying, "Extraordinary claims require extraordinary proof" and the early evidence in favor of the Big Bang was convincing and unambiguous. As our instruments improved and we acquired subtler data, we are persistently refining our scientific accurate story for what occurred in the first moments of the Universe. So today on the Titanium Physicists podcast, we're going to walk through history and discuss the various instruments that have provided us with the picture how the Big Bang occurred. Now, speaking of living like a shepherd and telling stories, one of my favorite things these days is listening to informative podcasts full of lively discussions and interesting trivia. Of all the podcasts I listen to, my favorite is probably the Encyclopedia Brunch podcast, where two engineers have lively conversations which follow a hyperbolic orbit around a whimsical topic. Welcome to the show, Kathryn Cogert and Tim Dobbs.

Kathryn: Hey, it's good to be here! That was a beautiful introduction, oh my Gosh, I'm all aflutter.

Ben: Yes, my voice went up and down.

Kathryn, Tim: [laugh]

Ben: So, for you two today, I've assembled two of my very favorite Titanium Physicists. Arise, Doctor Michael Zemcov!

Michael: Khhhhhhhhhhhh

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

Katie: Ta-dah!

Ben: Dr Katie did her PhD at Princeton University in astrophysical sciences. She's currently at the University of Melbourne in Australia where she's a postdoc in theoretical cosmology. Alright guys, let's talk about the Big Bang and what we know about it and why.

05:30

Kathryn: [chuckles] So, okay, my understanding of the Big Bang is that something compressed really tightly and then it got too tight, 'cause there was too much energy and then it exploded out but then what was outside of it, if that was all that the Universe was?

Katie: That's, um, very much the popular picture of the Big Bang theory. It's the picture that's always presented as you had a thing that exploded into space and that's really not how we think of the Big Bang theory as cosmologists. There are like couple of different ways to think about it but generally when we say "the Big Bang", we mean the hot Big Bang which is really just the idea that in the past the Universe was hotter and denser than it is today. And that's basically all it is. There was a time in the distant past when the Universe was very dense and very hot and it's been expanding and cooling since then. But that expansion it's the expansion of space itself, not the expansion into space of something smaller, if you see what I mean.

06:32

Kathryn: Mhm.

Tim: Yes.

Katie: So, if you think about the Big Bang as, like, a singularity that then expands, this is how the Big Bang singularity, which is a sort of related concept but not necessarily required by the Big Bang theory. But even if the Big Bang did, like everything started at the single point, that point contained all of space and time and so as that expanded, it created space and time so there wasn't anything outside of it because space and time was all in that sort of singularity.

Ben: The Big Bang singularity it's like the edge point of spacetime. There wasn't any spacetime before it - traditionally speaking - so when we say everything expanded from a point, what we mean is the Universe is full of an infinite number of coordinate points, right? You can move in an infinite direction in any direction you want, right?

Kathryn: Mhm.

Ben: But we can describe the evolution of spacetime in terms of the distance between those points changing dynamically. And that changing definition of what the distance between two adjacent points is, is what we refer to as the curvature of spacetime. And so the idea is, at the Big Bang singularity the Universe was still full of points - infinite number of points in any direction. It's just that at the Big Bang singularity the distance between every point was zero.

07:52

Katie: Like you can have an Universe that's eternal and infinite but it's just that it's becoming more infinite [chuckles] over time. Like, it's becoming bigger. Like, basically it's just becoming less dense over time. So singularity in that sense is like everything was infinitely dense and that doesn't necessarily mean that it was kind all on top of itself. Depending on how you think about it but it does, like/ So the singularity just means that like you go to infinite density but it doesn't mean that there's like a point we can say, like, that's where it all started. That's definitely not the case. If it was all in single point, every point was part of that point [laughs] if you know what I mean.

Ben: "At that point". That's where mathematics totally break down.

Katie: Yeah.

Ben: So what we have to say is: we're pretty sure about the mathematics up until this one point where the math doesn't make sense anymore.

Katie: Yeah. But really when we say "Big Bang" we're almost always just talking about, like, that everything was hotter and denser in the past. And "in the past" is a kind of nebulous concept but it means that there was a sort of you know whole Universe on fire kind of state in the very distant past where everything was sort of this hot dense plasma and it's just been sort of cooling and expanding since then.

09:07

Tim: So, like, the idea is that if we look at trends going backwards in the past from now, we see thing getting denser and those points get closer together and then also sort of general ambient temperature of the Universe, the average temperature of the Universe gets to being hotter and hotter?

Katie: Yes.

Tim: But then we get to a certain point and those trends kind of coalesce to a point that doesn't make sense mathematically and we sort of just shrug and say "well, that's what the math says and we'll never know". Is that right?

Katie: Yeah, more or less. I mean, the problem with getting to actual singularity is that we don't have physics that can describe anything that dense so at a certain point you know you dial back this trend to a stage where you really can't rely on physics that we have to extrapolate back into the past. But, yeah, basically the Big Bang idea comes from saying "well, the Universe is expanding now, I guess it was small in the past". And that's kind of it.

Ben: To illustrate this in another way, we're not sure the details of what happened to the really, really, really early Universe. It might have been that the Universe started out infinitely large and contracting. And then it contracted and contracted until it got so tight together that it bounced. And then everything started expanding everywhere. Or it might be that the Universe started out as a spacetime singularity. Or it might be that our very definition of spacetime and the mathematics of spacetime break down when you get hot enough. We're not quite sure. We don't have experimental evidence or data to tell us which of these descriptions of what happened in the really, really, really, really early Universe is the one that actually generated our Universe that we can see and test experimentally.

10:47

Katie: And to just give you a vague sense of what we mean when we say really, really, really early Universe, like, we're pretty sure back to a time that was about 10^{-10} s after whatever, you know, Big Bang singularity might or might not have happened. Like, the Universe at the age of 10^{-10} s, that's like solid physics. We've got that. We can reproduce laboratory experiments that show us what the Universe looked like at that time. So we can go pretty far back. It's just when we get down to, like, 10^{-34} s after the beginning that things are like uhm...

Michael: So things have moved on since the term Big Bang was coined and it almost like it's not like a good description anymore. So, we have this thing that we call inflation in cosmology, that's kind of a/ it's almost a way to sidestep that question entirely. Which is to say okay, so what happened was – as Katie just said – we can go back to 10^{-10} s and then before that there was this period that looks like there was a huge, rapid expansion of the Universe just mindbogglingly more than you can imagine, you know, as a regular human being in the very, very early Universe down to these very early times. And before that it just looks like it just was some quantum system that looks like a quantum system and we don't need to know much more about it because all that stuff, that information is kind of lost in this process. So now it almost doesn't obtain - at least in my view - you know, what does the singularity mean because that stuff gets erased. So it's almost not well formed question, if you see what I mean. And we're gonna come back to this inflation thing later on.

Kathryn: If we can, like, demonstrate 10^{-10} s after the Big Bang or whatever happened, if we can go that far back then it seems like we have to have a good sense of why the Universe is expanding now and that seems to be/ Like, what's the driving force? It can't have changed that much, like, what that driving force is, right?

12:48

Ben: The thing that's causing the expansion of the Universe right now is an interplay between inertia and how energy gets distributed as matter gets stretched apart. So the Universe started out expanding - stuff moving apart - and different types of matter stretch. The energy gets redistributed as matter stretch differently depending on what type of matter it is, right? It's like some springs when you pull them apart, they stretch, it takes more and more energy to stretch them apart. Sometimes, if you just have like two unattached balls, you can move them as far apart as you want. It's kind of like you have a big ball of dough and you pull it apart and it starts to stretch under its own weight. The dynamics of that stretching will be dictated by the inertia of the strip of dough and also how it's responding to the stretching, right?

Kathryn: Yeah.

Ben: So we have this dynamic system. In this case this dynamic system is being dictated by two things. One is the laws of General Relativity, Einstein's theory of gravity, and the second is the constituent matter making up the Universe and its details. So, what we're seeing is part of the way the Universe is expanding now is dictated by the types of matter. We call it cold dark matter because there's just lots of mass that isn't shining – there's lots of dark matter out there; normal matter -- planets and stars and stuff. And also, in addition to that, there's this weird dark energy force that is for one reason or another, depending on what might be causing it, causing the acceleration. So, what we're talking about in the early Universe is, we know the laws that cause this expansion and we think we know all of the constituents that make up the Universe. Like, we know the various, you know, we've got pretty good handle on electromagnetism. We've got a pretty good handle on, like, how the electrons behave. And so, we say, okay what happens if we take observations of what the Universe looks like now and start playing it backwards? What's the really early Universe going to look like? And the deal is that in the really, really early Universe, there are features that we see when we do observations - we'll talk about that a little bit later today - that kind of dictate that the expansion of the really, really early Universe was dictated by weird types of matter that really aren't around anymore.

15:05

Kathryn: That's/ Wait, that's crazy. [laughs]

Ben: We see like dinosaur footprints of this weird/ this inflationary matter that isn't, you know/

Kathryn: Like extinct matter?

Ben: Yeah.

Tim: Yeah, I feel like you just dropped the bomb here. This is completely/ I've not heard of this.

Ben: Well, like I said - extraordinary claims require extraordinary proof. So, would you like to start talking about how we know all these things are true? Because right now it sounds like BS, right?

Kathryn: Yeah.

Tim: It's been a lot of claims so far.

Kathryn: I feel like I'm a Catholic in like, the Renaissance and would love to execute Galileo right now. That's how I feel right now and I would really like to be enlightened.

Michael: That's a threat, is that a threat?

Ben: That was kind of scary.

Kathryn: [laughs] I'm sorry.

Tim: Ease up, Kathryn, ease up.

Kathryn: [laughs] Ooh, my bad. [laughs]

15:51

Ben: So, this whole picture of a dynamic, expanding Universe started off with a combination of Einstein's theory of relativity (early XX century): Einstein's like "Oh, if we have this very uniform spacetimes full of matter that's just kind of doing its thing, they'll either expand or contract under their own inertia and how the matter interacts with itself. Well, that's interesting but obviously, Einstein said, the Universe isn't expanding. So he made various blunders and added things to his equations and he was very red-faced. But then a guy named Hubble came along and Hubble observed distant galaxies. He observed that they were receding from us in exactly the way consistent with Einstein's theory. And so we started having this picture that the Universe around us was expanding, it was dynamic. It had a start - the Universe wasn't always here. It might have started with one of these Big Bang singularities, we weren't sure - everything was weird. And then, in the 60s, two guys - Penzias and Wilson, they were working for Bell Labs and they were working on this microwave receiver. And it kept getting these weird detections and they were like "What are these detections? I think it's pigeon poop." And so they went out and, sure enough, the thing was full of pigeons and so they kicked out the pigeons out of their big microwave horn and they cleaned it all out and they still received these detections of microwaves.

Katie: It was like static in all directions.

Ben: Yeah, and so it's like what's causing these microwaves? They discovered something called the Cosmic Microwave Background. And what we think this Cosmic Microwave Background is, is really, really in the early Universe, back when everything was really dense and hot, everywhere you went it had the same density and temperature. It was so hot that everything was a plasma, right?

Kathryn: Mhm

17:33

Ben: Plasmas they're really bright because essentially electromagnetic fields are interacting with charged particles - protons and electrons - and everything is bouncing around and then suddenly the Universe cooled. And as the Universe cooled, the protons and electrons stuck together but all those photons from back when it was really hot are still around. And so they kind of just float through space because space is really big and eventually they hit us, or specifically Penzias and Wilson's microwave horn. And that's what they were detecting. Photons from what Katie was describing earlier as the hot Big Bang. The era where everything was really, really hot and really, really dense. And it was fantastic because it was evidence that the Universe at one time was really, really hot and really, really dense because everywhere you look in the sky, has the same kind of temperatures of photons. You see the same type of photons, anywhere you look at the sky, any time of the year you always see the same. And so they must be coming from all directions so they must be ubiquitous. The Universe must be full of these photons that were once, you know, in this really hot soup and then they're still wandering around, looking for something to hit.

Katie: So there's a way to think about this, like, coming from all directions thing. Which is really counterintuitive, I guess. But so if you look at, I don't know, the Sun, you're looking at 8 minutes ago, right? Because light takes 8 minutes to travel from the Sun to you, so when you're looking at the Sun, you're looking at 8 minutes ago, if you look at Jupiter, you're looking at like 45 minutes ago and if you look at another galaxy, you might be looking at billions of years ago. And so it kind of stands to reason that if you look further and further away, you're looking further and further into the past and you get to a point where you're looking so far into the past that you're looking at the time when the whole Universe was this hot Big Bang plasma ball kind of thing, right? And so/

19:22

Kathryn: Oh, that's super clever. [laughs]

Katie: Yes. [laughs] So, like/ So, we're actually looking directly at a part of the Universe that is still in that fireball stage. You know, like if you point in some direction, any direction and you just look far enough in that direction, there's a photon that's just coming out of that fireball state that's been travelling toward you for 13.8 billion years and it's only just getting to you now because that's how long it takes. And so every direction we look, we can look far enough that we're seeing that fireball directly and so that's why in every direction there's this sort of background of the sort of glow of that hot early Universe.

Kathryn: Oh, that makes, like, a lot of sense. That's really cool.

Katie: Good. Cool.

Tim: The way you described it, it sounds like we have to find almost like a blank part of the sky to look at, like shouldn't it hit something along the way?

20:18

Katie: Yeah, that's a great question. And that's one of the big challenges of studying the Cosmic Microwave Background. It turns out that at microwave wavelengths, because those photons are coming to us at microwave wavelengths, there's/ It's actually pretty/ Like, there are other things that are in the way but there's this kind of background and we can subtract out stuff from the Galaxy and stuff like that by understanding how the Galaxy is producing photons of similar wavelengths. Like, it's easier to see if you look away from the Galaxy, like we're in a Galaxy and if you look away from like the plane of the Galaxy, you can see better. It's easier. But even sort of closer to the plane of the Galaxy, you can figure out how to subtract the contribution from our own Galaxy and stuff like that. Interesting thing about the wavelength, which might be too much of a diversion but, these things are microwaves and microwaves are, like, a pretty low-energy kind of radiation. And we're thinking about something that's like a hot, glowing, you know, fireball kind of state, right? So it should be really hot. If we look at like a poker that you stuck in the fire it glows sort of white and red and that's because it's so hot that it's glowing this bright color and the closer the color is to blue, the hotter the flame, right? So you'd expect that this hot fireball state would be a sort of very hot color, you know.

Kathryn: Mhm.

Tim: Yeah.

Katie: And microwaves are pretty cool color, they're cooler than something that's glowing red, they're cooler than something that's glowing infrared. They're cold kind of color. But that's because

Tim: Yeah, what's going on?

Katie: Yeah, so the photons that came from that fireball state have been travelling through the Universe and the Universe has been stretching apart as they’ve gone and so the photons themselves have been stretched out to longer wavelengths.

21:56

Kathryn: Oh my goodness. [laughs] That's really cool.

Ben: There's a critical question you must ask at this point in time. Which is you say - okay so there are these microwaves. How do we know these microwaves came from that particular explanation instead of, you know, some other, weirder.

Tim: I mean, I was really enjoying the explanation for just a minute but /

Kathryn, Katie: [laugh]

Ben: No, no. We gotta talk about the COBE [COsmic Background Explorer] satellite.

22:23

Katie: Okay. So I mentioned like something that's glowing hot from like if you put a poker in a fire, like it glows kind of red. It turns out that's kind of a standard thing in physics that if you heat something up to the point where it starts glowing, the color of that glow is very strongly related to the temperature of the thing. Something can be glowing red, it can be glowing blue. And something that's glowing blue is hotter than something that's glowing red. There's a description of like spectrum of that radiation so like how many photons are at each you know, wavelength. And there's a curve that you can draw that's like intensity of the photons as a function of the wavelength and there's the standard shape of that. It's called the blackbody curve. And I don't know where blackbody comes from, it's like/

Kathryn: It's really reassuring to hear that it doesn't make any more sense to you than it did to me in like freshman physics.

Katie: Yeah, no, I don't

Michael: It's because the emissivity is 1, so that to the human eye at optical wavelengths it's black.

Kathryn: Aaah. Okay.

Katie: Okay. Great.

Kathryn: So like no light is coming through it?

23:24

Katie: Basically, if you take something that's not producing any of its own light but then you heat it up so that it's glowing with heat, that heat glow can be a different color depending on how hot it is. And that curve that describes that is the blackbody curve and everything that's glowing because it's hot follows the same sort of pattern. So like if you stick a hot poker in the fire, you can, you know, take a spectrum of that radiation and it will look like this blackbody curve. It's the same if you take a spectrum of like a star. There's more features in the spectrum of star, 'cause there's sort of elements in the atmosphere and stuff like that but it basically has this blackbody curve and so where, you know, where the peak of that curve is tells you the temperature of the star and the curve just tells you that the star is glowing with heat. So anyway, when the COBE satellite went up to take pictures of the Cosmic Microwave Background, it was able to take a spectrum of the radiation coming from all directions and what it saw was a perfect blackbody curve. Like, an insanely perfect blackbody curve, showing that the radiation that it was getting from all directions was from something that's glowing 'cause it's hot. That explained the entirety of the radiation, it was just glowing 'cause it's hot and it was coming from every part of the Universe so it was saying that every part of the Universe was glowing with heat and that was like a spectacular confirmation of the hot Big Bang hypothesis. And the story goes that when that plot was first shown in the conference, like people actually stood up and applauded. [laughs] Because it was like, "this is showing that the Universe was glowing because it was hot, you know, 13 point something billion years ago and that had never been seen so directly before.

25:02

Kathryn: Oh, that's really great.

Ben: So this was in 1989-ish, this COBE satellite went out.

Kathryn: Oh, wow.

Ben: You know, we've been detecting Cosmic Microwave Backgrounds before then, right? We knew it was there. But we didn't know exactly what the distribution of different colors there was in it, so we couldn't tell whether it was caused by thermal emissions or what. So the satellite went up, it didn't just map where the photons were. It also plotted the spectrum of the Cosmic Microwave in every direction. And what it said was, essentially, the signal we're detecting came from something that was really, really hot and everywhere and also redshifted, you know, 14 billion years or whatever. So, in essence our interpretation of these photons based on this observation of the spectrum tells us that this Cosmic Microwave Background really was photons emitted back when the Universe was really, really hot, which gives us evidence that the Universe was once really, really hot.

Tim: Hey, wait. I feel like I caught a free variable in there. So, you said it was redshifted a certain number of years and also is at a certain temperature. And those two are related, right? Either it has redshifted an unknown amount of time and so we don't know the time and must prove that or it was redshifted, we know the age of the Universe and so we can kind of back calculate how hot it was.

26:23

Katie: Can we just jump in and say what redshift is? Because I don't think we've explained that. Well, the redshift is basically like the stretching of the photons, right? So, what you're asking, I guess, is how do we know that the frequency we see these photons at, this microwave frequency, is because used to be really, really hot and then the photons were stretched out? How do we know it's that and not just like, you know, that it was more recent at a lower temperature or something like that.

Tim: Yeah, yeah. Exactly.

Katie: Yeah, so we can predict when this fireball state happened based on sort of extrapolating back our current expansion and we know sort of when this time period of the fireball should've been. So we can calculate that back and then looking at the temperature of the Cosmic Microwave Background that's consistent with the Universe having been in the fireball at the stage that we predicted.

Tim: I see. Yeah, that makes sense.

Ben: Yeah, 'cause we know that the Universe is expanding right now from observations of distant galaxies. And so we can extrapolate that it was denser and hotter at earlier times and then this is entirely consistent with that picture.

27:28

Tim: Can I ask a much dumber, more basic question before we keep going?

Katie: Sure.

Tim: Um, we talk about the blackbody radiation and, you know, I have an image of a chart in my head and it's got, you know, peaks on it and you said that's oh, we can pick the temperature out from this and then maybe there's other peaks that show certain elements or whatever. What are the axes on that? Like, what are we actually looking at when we talk about, you know, what would be x and y?

Katie: Yeah. So it's intensity of radiation vs like frequency of radiation. So, it's/ a blackbody curve has just one peak and that peak is the sort of frequency where you say that's the frequency of the radiation but it actually sort of extends to other frequencies, too. So like for instance if you have like an incandescent lightbulb, the curve of the glow of that incandescent lightbulb peaks somewhere near the visible part of the spectrum but it has a huge amount of radiation coming out in infrared, which is why they're inefficient. Because they're putting out a lot of heat that we can't see and we can't use as light. Whereas like a fluorescent lightbulb isn't a blackbody, it's radiating in some other way and so you get more just visible light from it.

28:34

Ben: But you can't warm up a baby chick with a fluorescent light.

Katie: That's right, yeah.

Ben: 'Cause it isn't pumping out all that heat radiation.

Katie: Yeah.

Tim: It's their great fault, yeah. That's what they include in all the marketing for the incandescent lights.

Katie, Kathryn: [laugh]

Tim: Sorry to keep harping on the peaks and all that but the other thing that but the other thing that you were talking about, Ben, when you've said that like wow, we know it's a pure blackbody, that this background radiation is just from something hot or glowing heat. What is the radiation coming from if there's something else, you know, there's other weird peaks. Is it like fluorescence? That sort of stuff that I half remember or/

Katie: So like with the Sun we get emission and absorption lines, so there are certain elements or molecules where if you give them a photon of exactly the right frequency, they can have a transition where you get like an electron gets kicked into a higher state or with molecules sometimes like a configuration can change. And so that can show up as an emission or an absorption line where, let's say that you're putting out all your radiation in this nice blackbody but you have an element that really likes to take photons of a particular frequency, then you get an absorption line where you get like a gap in your blackbody radiation that you see because the radiation at exactly that temperature got swallowed up by some molecules or atoms along the way. So that's where you usually get features in spectra is from elements picking up or producing light at very specific frequencies.

29:57

Tim: Wait, so would it be fair to say that okay, so for any given point you point your radio telescope at, there'll just be photons kinda all doing bunch of different energy levels, which corresponds to wavelength, and they'll kind of group around the general heat of that thing but then sometimes that population of energy levels gets all messed up because, say there was a bunch of one particular element that they ran into and that kind of puts a peak or a depression or something into that chart that we were just talking about? Is that like a fair way to describe it or is that way off?

Ben: Yeah, so individual elements will only eat a really specific frequency. So what you see in the actual observation, if there's a cloud of hydrogen gas between where the photon was emitted and us, if you look at the spectrum of photons after it's passed through the hydrogen gas, those specific frequencies will be eaten out of the overall curve. So it'll look like a smooth curve with little jags taken out of it.

Tim: Hmmm...

Ben: Kind of like the hydrogen gas had lunch.

Tim: So if there's no other junk in the way, you'll just see this nice smooth curve, which is just a collection of stuff and that's how we know that this has to be Cosmic Background radiation it's because oh, this is just a super smooth curve it can't have been involved with a bunch of hydrogen eating lunch.

Ben: Yeah. You know, other things we can tell is that it wasn't emitted just by/ You know, after a hydrogen gas eats lunch it'll spit off essentially the same frequency. And this is where I essentially tell where there are say big clouds of hydrogen floating out in space is you look for those specific photons of specific frequency. So one thing we can tell is that this Cosmic Microwave Background wasn't emitted in that type of process because it emits this really smooth curve that has a very specific shape in its spectrum. So you look at that and you go that's clearly a thermal spectrum.

31:38

Kathryn: So how did like the COBE satellite avoid getting interference from something like that or like the Sun? 'Cause that would/ that seems like it would really throw off the spectra.

Tim: Oh, that old thing.

Kathryn: [laughs]

Katie: Well, it had a sort of shield around the detector so it didn't/ to make sure it wasn't looking toward the Sun or the Earth even. And that none of the light could come directly from the Sun or the Earth into the detector so it was definitely always looking not in those directions. But there's always like contamination and stuff. What are the issues, though that helps a little bit is that with this really low frequency radiation, microwaves, there are not a lot of elements that like to gobble up microwaves. Like, a microwave radiation/ microwave photon is so low energy that it can't do a lot. Like it can't kick an electron out of an atom. It's just not energetic enough. So, /

Kathryn: It's like cosmic leftovers.

32:33

Katie: Yeah. So, there are other things that create microwaves but they're very hard to absorb. So, they can pass through a lot of other stuff and get to us reasonably cleanly.

Ben: Kind of like a radar waves pass through fog but regular visual light doesn't.

Tim: Oh, yeah, yeah, yeah.

Ben: It'll just pass through all the crap out there 'cause it's too weak to scatter.

Kathryn: So, now I'm wondering how do we actually collect microwaves, then. If it's hard to make them do anything.

Ben: Well, we put our lunch up…

Ben, Katie, Kathryn: [laugh]

Ben: And then it comes down as puffed pop-corn.

33:08

Michael: There's a couple ways. One is that they're electromagnetic waves, so they like to wiggle electrons around. So if you get a cleverly designed system that has electrons in it, you can measure how the electrons are moving and then that tells you what the waves were. And the other way is to basically put a material that's like a thermometer and to cool it very close to absolute zero. And then to put it in the way of these radiations and say what's the temperature change that I see when I look at it or I don't look at it, basically.

33:39

Kathryn: Oh, that's clever.

Michael: Yeah, so that's hard 'cause, like Katie said, there's these photons don't have a lot of energy so you have to be kinda clever about it but that's how we do it.

Ben: The COBE satellite mapped the entire sky so when you see these maps of what it looked like, you end up mapping what everything is everywhere and it's great because, you know, it's not gonna mask out everything and there are other things that emit microwaves and stuff, like the Galaxy. And so you can see this big, this big band running across it that's essentially the Milky Way galaxy. And I think you can see like Andromeda in it, is it? There's like a/

Michael: You can see various bumps and wiggles but the important part to know here is that if you don't look at the Galaxy, so if you look/ You know, the Galaxy is a disc, it's a pancake. So if you look up or down for a bit even though we're inside it, in the Universe at large, by far the largest energy density in photons is the Cosmic Microwave Background so it's actually very easy to see, relatively. So that's part of why, you know, this measurement was so easy is when you look at the measurement that they did, we're talking about all these effects that can start looking like that. Certainly those are like problems but they're very small compared to how bright the signal is. It's just a fact of how the Universe works.

34:51

Ben: So, let's talk about the satellites again. We put this COBE satellite up, it mapped the spectrum, it told us the temperature of the Cosmic Microwave Background, it said the temperature was 2.73 K and it told us other things. Like, everywhere you look in the sky, where you can detect the microwave background, it's the same temperature. Just like Einstein's theory describes it, the Universe is really, really, it's homogeneous. Everywhere you look, everywhere you go in this early Universe at a specific time, everything, the energy density is about the same. Which is fascinating. But more fascinating is that it's not quite the case that it's the same temperature everywhere. Because in the really, really early Universe there were apparently big pressure waves. I'll talk about that in a second. So Mather and Smoot won a Nobel Prize for the discovery, using the COBE satellite, not just of the spectrum of the background but also they discovered that there are little places where it's slightly hotter and little places where it's slightly colder. And it's fascinating because those little variations in temperature here and there - and they're tiny, compared to the background - it's tiny little variations of temperature. They give us an indication of what happened before the Cosmic Microwave Background. Katie was saying you can look back in time, right? The further out in space you look, the further back in time those photons originated, right? But in this picture of where the Cosmic Microwave Background comes from, it comes from a time when the Universe was so hot and dense that all the matter was in a plasma state. There were lots of free electrons, lots of free protons, light couldn't really travel very far. So this time when the Cosmic Microwave Background was emitted, that was the time when the Universe was most opaque. So we can’t observe the photons that come from before that time.

36:46

Katie: It's kinda like trying to see the center of the Sun.

Ben, Kathryn: [laugh]

Katie: We can't look at the center of the Sun because we can see the outside of the Sun and everything behind the outside of the Sun is just behind this wall of glowing fire and we can't see into it. And the reason that we can't see into the center of the Sun is that the density of the Sun gets less as you go toward the outside and at some point the density of the Sun is so low that photons from, you know, around that point are able to come to us without bouncing off of other things. And so there's a sort of analogous thing in time with the early Universe where with the Sun it's sort of border in space where the density gets lower and the density gets low enough that things can move freely but in the Universe it was like a time transition where there was a time when the density got low enough that stuff could stream freely and we actually call it the last scattering surface, we think of it as a sort of surface in space but it's really a surface in time, it's just that because time and space are so linked with, you know, the time travel of light, we call it a surface. So beyond that surface we can't see with light behind that. But that last scattering surface was 380 thousand years after the beginning, so there's a huge amount of time that we can't see with light.

38:03

Ben: So, I mentioned the guys winning the Nobel Prize for looking at these tiny variations in temperature here and there. Little pockets where it's slightly warmer or slightly colder than everywhere else. And the thing is, those are pressure waves in the plasma. Those come from the pressure waves, 'cause if there's a pressure wave, there's a place where it's slightly denser and hotter and a place where it's more rarified and less dense. And the thing is, if you analyze those pressure waves, you can deduce what happened before this time of last scattering. Absolutely fantastic.

Tim: Ooooh.

Kathryn: That's pretty awesome.

Ben: Part of the march of observational cosmology since then has been to determine more about these waves and get a better picture of whether or not they're actually pressure waves and how much we can use that information to deduce what happened before then. Mike, tell us about the SDSS, the Sloan Digital Sky Survey.

Katie: Can I first jump in with something silly but I think it's cute? So, you know how in space no one can hear you scream?

Tim, Kathryn: Mhm.

Katie: That's true now. But in the hot Big Bang that wasn't true because the space was so dense that sound could travel. Like, pressure waves are just sound. And so if you did scream during the hot Big Bang, [chuckles, Kathryn laughs] it would totally be audible.

Kathryn: And you'd have to. It's so hot!

Katie: Yeah, Yeah.

Tim: [laughs]

Katie: So that scream we would hear and so basically we're looking at the scream of like the early Universe like ripping itself apart with inflation. Like, we're hearing that scream by looking at these pressure waves.

Kathryn: That is both beautiful and horrifying. [laughs]

Ben: (...) Amazing show, one of our earliest episodes was with Ted Leo from Ted Leo and the Pharmacists. And he came on the show and we talked exclusively about this for, like, an hour and a half.

Kathryn: [laughs]

Ben: It’s a great topic. Like it just goes down and down and down. Mike, you're up.

Michael: Oh my goodness, the Sloan Digital Sky Survey. Where to start? So, this is a case of "and now for something completely different".

Kathryn: [laughs]

Michael: So, you could look at the Cosmic Microwave Background, which is what we've been talking about, and that's kind of a snapshot of the Universe's like a teenager, in terms of its evolution.

Kathryn: Sure, yeah.

40:12

Michael: But we're looking at the Universe now as a middle-aged person and there's value in that, right? You can see where that person came from and what's happened to it since then by kind of understanding more about the local stuff. So, Sloan, which is what I'm gonna call it, is this idea of "okay, let's go out and we're gonna map the three dimensional position of bajillions of galaxies. You know, it ends up being millions of galaxies. The idea there is that now you are basically tracing where does matter live in the Universe locally. And when I say locally, I mean out to maybe a third or a half of its current age. So, what you do is you make a bunch of dedicated telescopes that happen to live out in the desert, on top of a mountain and you go out and you take and image and you find where all the galaxies are and then you have a computer program that takes that image and machines an aluminum plate, it puts holes in it wherever all those galaxies are appearing and then you got some poor soul who probably currently are still doing this and you get them to plot fibers into all the holes, so these are little optical fibers that take light and track it somewhere else and then you disperse it somewhere else and basically from that you can look for a different sort of features in the color of these galaxies and you can say "okay, how far is that because of the redshifting?" And so they went along and did this, they've been doing it since 2000 and they're still doing it but they've been releasing, you know, incrementally better results since then. And what you get is this picture of the Universe that is around us that looks a little bit like a sponge where there's a lot of empty bits and matter kind of lives along these sort of walls of the bubbles and they're kind of interlocking and that's kind of what the large-scale structure of the Universe looks like. And, you know, at the present day after 13.6 billion years of evolution. So, why's that interesting? Well, that's interesting because it's telling you a lot about, you know, the same kind of structural properties that we can see in the CMB and in fact what you can do is you can look for these things called baryon acoustic oscillations which is a complicated way to say that what you can kind of try and map out is all these underdensities and overdensities that are causing these anisotropies in the Cosmic Microwave Background we've talked about that are due to pressure waves bouncing around, well what happens is as you evolve the Universe forward, the places that are overdense, remain overdense, right? There's gravity and it's sucking more and more matter in and so you can actually look for the marker of that scale that's been evolved to the current day. And that's a sort of bubble size in the Universe where you can actually go into a picture of the local structure of the Universe and you can say "A-ha! That looks like sort of average bubble size and that corresponds to this feature of what's the preferred size of the features in the Cosmic Microwave Background. So it's telling us a lot about what has happened since the Big Bang but also making us more confident that we understand the models we use to understand how the Universe evolves over time.

43:18

Kathryn: Am I understanding it correctly they say that if not for these like really small ripples in this super hot, dense plasma there probably wouldn't be a ton of mass collected in a way that we know it to be collected? Like, galaxies?

Michael: Yeah, you're absolutely right. So what would happen is if you had a perfectly smooth Universe, there's no preferred place, so you can't start sort of nucleating matter so you can't make galaxies and you can't make stars and you can't make planets and you can't make people, right? It's just some boring uniform particles bouncing around. So, you absolutely need those seeds to start building structure and in fact you need the seeds at about the amplitude they are, otherwise you start making really weird universes, where it doesn't look like anything like what we look around to see around us today.

Ben: Now, now. I think the people in those universes think ours is weird.

Katie, Kathryn, Tim: [laugh]

Ben: Let’s not have any strong anthropic principles around here.

Kathryn: There's no need to be galaxy-normative.

Ben: Okay. So, Sloan's interesting. Do you guys have any questions?

Tim: You know, I've just always/ Not at the level of precision and all these things and I couldn't help but hear metal plates with holes drilled in them measuring/

Ben: I know, right?

Kathryn: [laughs]

Tim: What? Like what's happening? Like, listen. I do experimental work for my job and I can't get precision on like a couple of grams sometimes, let alone like "oh, we'll just measure one of these universal constants".

Katie: The holes in the metal plate were down to, like, micron scale precision. Like, they were really, really carefully drilled.

Tim: What hubris allows practical physicists to think that they can get this level of precision and then do it? But just like, I'm just sort of sitting here astounded (...)

Kathryn: I think you're really jealous, Tim.

Tim: I'm a little jealous.

45:00

Michael: Tim, I invite you to come to my lab and you can learn through the way of pain exactly how we do these things.

Ben, Kathryn, Katie: [laugh]

Tim: Are you asking me to drill some holes in a metal plate?

Kathryn: [laughs]

Michael: If that's what you'd like to do, go for it.

Ben: I wanna try summarizing what happens in these plates. So, if you take a telescope and point it in a certain direction, you know that these various galaxies that you wanna observe are gonna be here and here and here and here and here. Various, specific spots on the image plane. And then you're like "I want to only look at that light". And it's difficult to filter out all the other light so what you do is you take a plate and you drill holes at the exact places you know those photons originating from those galaxies are gonna be. And so you drill holes and you take an optical fiber and stick it in the hole and that way the photon will come, you know, from far away galaxy, pass through this telescope, through all these lenses or mirrors or whatever and then end up at this one hole and go down the optical fiber and then we can analyze its spectrum and color and intensity and stuff. Is that it?

Michael: Yup. Kind of fun, right?

Ben: That's crazy as bananas! Oh, too much work.

Tim: Seriously, what's the reason that it can't just be collected on a photographic plate and then you just pick the part of the plate you want to look at?

Michael: Think of a picture of Hubble in your mind, right? So, if you're gonna do a simple dispersion, let's pick a prism, like Newton would have done, you put that prism somewhere in the optical path and what it does is it takes the light from all those galaxies and it spreads it out and then you can do the dispersion thing. The problem is, for most instruments, galaxies are so dense in the image that the light from one bumps into light from another and you can't disentangle them. So, what this lets you do is this lets you pipe essentially the light from where it's showing up at the bottom of the telescope off somewhere else, where you know, you can do whatever you want to it and you can do that dispersion or whatever, it's not gonna bump into other ones.

Tim: Right, I getcha.

46:53

Ben: So what did the SDSS tell us? It tells us that our interpretation of these slight differences in temperature in Cosmic Microwave Background that those are actually pressure waves. Why? Because if they are pressure waves, then they will essentially guide where the matter's slightly more dense and less dense and if this matter is slightly more dense in one place and less dense in another, then that's where the gravitational collapse will happen. And so there's gonna be a correlation between how wide these pressure waves are and how common they are and also how wide and distributed we see galaxies in the Sloan survey. So, our interpretation of these little differences in temperature as being pressure waves in the plasma from the Cosmic Microwave Background - that's accurate. That's what that tells us.

Kathryn: So, I'm a little bit confused. Why does the temperature differences, like a temperature wave relate to a pressure wave?

Katie: The temperature that we measure is really telling us about the density and the density changes are due to these pressure waves.

Kathryn: Okay, I'm with ya.

Michael: It's the old pV = RT thing.

Kathryn: Ideal gas, gotcha.

Michael: You got it.

Kathryn: [laughs]

Ben: Umm, alright. And now we're onto WMAP.

48:05

Katie: So the WMAP experiment is a satellite that was sent up in, like 2001. WMAP stands for Wilkinson Microwave Anisotropy Probe and the whole point of this telescope was to map out the little fluctuations in density and temperature and stuff in the Cosmic Microwave Background. And the idea was to learn something about whatever put them there which is the stuff that happened before that last scattering. So WMAP was a super big deal when it came up with its first data because the COBE satellite gave us this kind of blotchy picture with like maybe a few dozen sort of blobs of, you know, hot and cold spread across the sky so it was really, really low resolution picture of these fluctuations in the density of the Universe but WMAP gave us this incredibly detailed picture of all these tiny little bits of you know, little bit more dense here, little bit less dense there and just this huge map of the entire sky at just incredibly high resolution. And it was the first thing that let us like really study the parameters of the Universe. So by looking at these fluctuations we can learn about stuff like how much stuff was in the Universe, like we're able to measure whether the expansion was being balanced out perfectly by the matter in the Universe or not; we were able to look at the statistics of how these fluctuations were distributed and use that to rule out other explanations for where these density fluctuations came from. So like there was this idea hanging around at that time that maybe galaxies were seeded by cosmic strings which were these huge strings of energy which might or might not be kind of stretching across space and those could sort of seed structure in some way but they would give you totally different pattern on the Cosmic Microwave Background and so WMAP was able to say that doesn't fit at all, inflation is the thing that really matches this pattern. And basically what they said is that the pattern of these density fluctuations fits really, really well with the idea that these are just quantum fluctuations in some earlier state that were stretched out to the size of, you know, galaxies. So, what that says is that during this inflation time when the Universe is expanding really fast, there are sort of quantum fluctuations in that expansion and those fluctuations lay down these density inhomogeneities and that is what seeded all of structure that we see today. And so WMAP was just really, really consistent with the idea of inflation and gave them a much stronger support to the idea that the inflation happened and the processes that happened during inflation are what laid down these density distributions that gave us what we see now in like the Sloan Digital Sky Survey.

51:07

Ben: So this is fascinating. What we're saying is, WMAP looked specifically in a really high detail at all of the little patches where it was slightly more dense or slightly less dense, Where it was slightly hotter and cooler because it tells us about how many low frequency waves there were, how many high frequency waves there were and we can interpret what happened before based on the relative frequency of these patterns. It was really neat. I mean, if you look into this big noisy picture and you're trying to look for patterns, one group of theorists suggested that a particular ring they saw in the pattern said that the Universe started with a big bounce - earlier in the show I said that the Universe/ one of the possible things that might have happened in the very, very early Universe was that the Universe started out collapsing and then it's rebounded and started expanding and that's what drove that. And so they said "oh, look, these particular ripples tell us that we started with that" and then another group said "oh look, these other particular ripples that means that our Universe started out a brane - 3D spatial surface in a larger set of dimensions. You know, string theory. And our Universe bumped into another Universe at the very start and that's what kicked off the Big Bang. And that's what these waves mean. So there's all sorts of really neat interpretation things you can do to these waves. But the more traditional physicist community analyzed these waves - and the deal is there's a mechanism that relates a quantum oscillations in various fields during this expansion process that preceded the hot Big Bang signal - this Cosmic Microwave Background - there's a mechanism for these quantum waves turning into these larger acoustic waves. And so the question was, the relative frequency of these acoustic waves kind of dictate what the history of expansion of the Universe during the time that we can't see was, right? It's kind of like how, you know, Katie Mack was like "Oh, okay, so it's like how we can't see into the Sun". But we can still tell all sorts of things about what's happening in the middle of the Sun or even in the middle of the Earth by looking at acoustic waves through the Earth or acoustic waves on the Sun. We can look at how the thing's jiggling and that tells us about what's going on in the middle. Similarly, we can look at the jiggles in this Cosmic Microwave Background and analyzing that we can infer information about the history of expansion. And what you're saying is, our interpretation says that it's consistent with this exponential increase in size, this inflationary epoch.

53:39

Kathryn: Okay, I'm with ya.

Ben: You know, it's interesting. Like, last year there was a big announcement and it was that a project called BICEP2 - oh man, cosmology projects, they have the best acronyms.

Kathryn, Tim: [laugh]

Ben: So, the BICEP2 was a telescope in the South Pole and what it was looking for was it was looking for polarizations. You know how light is polarized? You go to a movie theater and you wear polarized glasses and then it filters out some light, it doesn't filter out other light?

Kathryn: Mhm.

Tim: Yeah.

Ben: Right. So, the Cosmic Microwave Background is also polarized. In places. And one explanation for that polarization has to do with gravitational waves in the early, early Universe. Absolutely crazy. So, this BICEP2 project came out and said: "hey, we've detected this signature that's consistent with gravitational waves in the early Universe, isn't that crazy? And this is consistent with this inflationary epoch story. Isn't this crazy? This is fantastic!" And everybody had/ I bought a cake, I brought a cake home to my wife and we ate cake that night.

Kathryn: [laughs]

Ben: I gave a speech to every single one of my class, including the class on mathematics for elementary school teachers. They got a lecture on it. I was very excited. We did a program on it.

Tim: Yeah, I remember that one.

Ben: So, the deal is. The deal is. What's the deal?

54:56

Katie: They were wrong. They were terribly wrong.

Ben: They had made false assumptions based on all of the data they had at the time they were doing analysis. But the deal was we put up a satellite called the Planck satellite. And its job is to do something similar to what the WMAP satellite does. Which is, map out the entire sky, look at the Cosmic Microwave Background. Only it looks at polarization and stuff. And so one of the things people were using the Planck satellite for, was to interpret where the dust in the Milky Way Galaxy was. Because there's dust and it interacts with the magnetic field of the Galaxy and the Cosmic Microwave Background was filtered through this dust and this caused kind of polarizations in the Cosmic Microwave Background signal that we detect. And so the BICEP2 project underestimated the amount of dust. And meanwhile this Planck satellite, this new satellite that's still up and still getting great data, after BICEP2 published their results, the Planck collaboration came out and said "Well, actually, we have better data now and it turns out that everything you think is an actual signal of gravitational waves, that's just dust, probably".

Kathryn: Ow. [laughs]

Tim: Ow. Bummer.

56:05

Katie: Yeah, that was a real bummer.

Kathryn: That's so disappointing.

Ben: Yeah. But I mean it's fantastic. Essentially we're getting better and better pictures of what's happening in the Cosmic Microwave Background and from that we can infer, using various cosmological models, what kind of expansion and what rates of expansion would've caused those particular waves in that particular signal. And so it's absolutely fantastic and this is how we're getting a picture of what happened in the really, really early Universe.

Tim: Right, you just sort of back calculate it.

Ben: Yeah. But I mean, like, we're getting finer data and lets us infer stuff. Okay, so we're up to the present observation. What's gonna happen in the future?

Michael: Okay, I'm very excited to tell you. I'm involved in the project - which is why we're talking about it - which just got selected for what NASA calls Phase A, which means that now you're racing two other instruments in this case. So, the idea of this thing is a little bit like Sloan and it's a little bit like the CMB experiments and it's really super cool. So, it does a bunch of things but just to summarize, the idea is it's a satellite that will go up and over a period of two years it will do measurements of the entire sky between 1 and 5 microns. So that's infrared radiation, a little bit longer than we can see with our eyes. And that has the feature that galaxies emit a lot of light at those wavelengths which is why we tend to look at them at those wavelengths. And what it's gonna do is it's gonna measure basically every galaxy that matters out for more than half of the history of the Universe. So, that's cool 'cause it tells you where all the galaxies are and so it's a little bit like Sloan but on steroids for that reason. Where this ties back into what we've been talking about for the last however long is that this inflationary period that we were talking about it seeds some structure in the Cosmic Microwave Background and we talked a little bit about what that is - it has to do with polarization and we go and look for that. But what it also does is it seeds the initial conditions for the structure formation that happens subsequently to that so where all the galaxies and this sort of spongy structure I was talking about. So by getting a good enough map over a big enough area in the Universe, you can start asking the question "what were the initial conditions of this problem?" Because we understand the physics of what happened later very well. And it ends up that if you map enough of the area and enough galaxies, you can start asking interesting questions about inflation. So this thing, which is called SPHEREx is gonna go out and it's gonna do this experiment and having measured, you know, the positions of billions and billions of galaxies, is going to tell us about how inflation worked and start to, you know, be able to rule out different models for inflation that are kicking around. So this is one of the best ways we have in fact of looking at what happened in the very early Universe way before we can directly measure is by seeing what its repercussions in the structure are.

59:17

Ben: This is kind of like how, you know if you take one person’s DNA it's just some DNA. And if you take 20 people's DNAs you can tell who's related to each other. But if you take, you know, 100 thousand people's DNA and test it and analyze it, you can tell what kind of people lived where and how they moved around in early prehistory, right?

Michael: That is the wickedest analogy I've heard today.

Ben: Thank you.

Kathryn, Tim: [laugh]

Tim: Okay, so. What changed in the past 3 years to go from, you know, the work that we've seen previously to this new and exciting project that’s/ well, we got better at every kind of instrumentation and data management? Is that right? So we can just ask bigger questions? So we're asking about all the DNA instead of a couple bits of DNA?

Michael: Okay, so science is an emergent thing, of course. So as we learn more, we ask better questions. But, you know, with respect to the Cosmic Microwave Background, I'm not sure you're going to see another Cosmic Microwave Background experiment because it's kind of been done. The polarization, you know, that's arguable, and if there's something there, you know, somebody will build something and in fact Japanese people are talking about doing it right now but between COBE and WMAP and Planck you hit brick wall with how much information you can get out and how well you can do the measurement and we're kind of there. So it doesn't make any sense to do any more Cosmic Microwave Background experiments except for maybe in polarization. So, you know, it happens in science. You know, you get so good at something eventually that you've run all you can out of it and there's no purpose in continuing.

60:48

Tim: Sure, like we don't measure the gravitational constant of Earth that much anymore. But that was probably important at some point.

Michael: Exactly. And so SPHEREx is the next step in that evolution. It's saying "okay, well, we've done the CMB which is maybe the low hanging fruit, relatively, so let's try this next thing because we know we can get a really good handle on some of these initial condition type things by doing this measurement.

Tim: Nice.

Ben: Well, that was fascinating! Thank you Katie, thank you Mike. You've pleased me, your efforts have borne fruit and that fruit is sweet, here's some fruit. Mike, you get a persimmon.

Michael: Om nom nom.

Ben: And Katie Mack, you get a banana.

Katie: Nom nom nom nom.

Ben: Nice, now I'd like to thank my guests, Kathryn Cogert and Tim Dobbs from the Encyclopedia Brunch podcast. I hope you guys had fun!

Kathryn: Oh, so much fun! Thank you so much, this was so much fun, it was awesome.

Tim: Yeah, this was great. Thanks all of you.

61:39

Ben: Hey everyone. That episode was pretty fun but it's announcement time. So, it's pretty good. So first, I've had a little bit of success finding people who help us transcribe episodes like I said before, we can pay a fee per episode for your work. If you want to try it, send me an email at barn@titaniumphysics.com and we can talk about the details. So yeah, I'll give you an episode and I'll tell you what you need to do and you can have fun and stuff. Okay, our donation drive is going well. We've got a lot of donations both one-time donations using PayPal, you can find that through our website and through Patreon - we're gonna use all that money to pay people to transcribe our episodes. Things are going very well. On that note, I'd like to thank the various sponsors of our show. So first I'd like to thank generosity of Fred Richardson and Joe Piston. I'd like to also thank Melissa Burk, Yaseen Owarzazee, Spider Rougue, Insanity Orbits, Robin Johnson, madam Sandra Johnson, Mr. Jacob Wick, Mr. John Keese, a Mr. Victor C., Ryan Close, Peter Clipsham, Mr. Robert Halpen, Elizabetha Theresa, and Paul Carr. A Mr. Ryan Noule, Mr. Adam K, Thomas Sharay and Mr. Jacob S. A gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, Mr. James Clawson, Mr. Devin North, a gentleman named Scott, Ed Lowlington, Kelly Wienersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Aberzado and Mr. Robert Stietka. So, that's it for Titanium Physicists this week. Remember, if you like to listen to scientists talk about science in their own words, there are lots of other lovely shows on the Brachiolope Media Network. Try Science... sort of, it's pretty fun. Okay. So, the intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. So, until next time my friends, good day and remember to keep science in your hearts.

63:44

[Outro song; *Angela* by John Vanderslice]

64:39

Tim: Can you expand on weird Universes? (…)

Kathryn: Yeah, please expand. [laughs]

Michael: It's this thing, Katie probably thinks about this more than I do, but it's this thing, I forget. There's like 27 physical parameters about the Universe having to do with like coupling of how electromagnetic radiation works and the mass of things like particles and so on and so forth. And you can show that if you tweak any one of those things by even a small amount, you end up not being able to form stars or everything forms into a black hole very quickly. Or all kind of weirdness like that or you end up having Universe that expands exponentially forever and there's basically no matter in it anymore. So, ends up, you know, aside from Ben's request that we don't do anthropic principles.

Ben: You know it’s hard to say, right?

Michael: Yeah, it is. Especially after a whiskey or two.

Ben, Kathryn: [laugh]

Michael: I mean, it's a directional thing. Either we have the fortune of living in Universe that's conducive to us or we see the Universe we live in because it's conducive to us and I don't care what you pick.

Ben: [laughs]

Katie: Well, I mean there's some things that you can change that don't make life impossible or anything like that. Um, you know if you change enough parameters of our Universe, it's pretty easy to create a Universe in which, you know, we couldn't have happened and then we couldn't be talking about it and so it's a pretty simple thing to say. Like, you know, it's not that the Universe is created just for us to be happy but if we were unhappy enough not to exist, then we wouldn't be talking about universes at all. So, that's kind of the anthropic thing, which/

Ben: Yeah, yeah, yeah. By the way, the first statement is the strong anthropic principle and the second statement is called the weak anthropic principle.

Katie: Yeah.

Ben: Anyway.

Katie: So.

Ben: I had a relativity prof, my Masters' prof who essentially told me not to talk about them, 'cause he was like that's essentially like/ both of them are kind of like shrugging your shoulders at science; they're both reasons that are circular and don't actually lead you to ask any more questions about why thing might be the way they are.

Katie: Yeah.

Tim: Yeah.

Katie: Yeah, I mean in each case you're just like "oh, I guess things are the way they are *shrug*".

Ben: Yeah. You're right. It's just so.

Kathryn: It's a little bit like saying like well I am the person I am because of the mistakes I've made so I'm just gonna be happy that I made those mistakes rather than asking critically like "oh, what mistakes did I make and like should I continue to act in that way in the future?" But you know, on the universal scale.

Ben: Mhm.