Episode 45

"The Thumbprint of Creation"

Meta

Dramatis personae

- Ben Tippett
- Ryan North
- Katie (Katherine) Mack
- Michael Zemcov

Copyright

The Titanium Physicists Podcast www.titaniumphysics.com
Transcription by Gareth Eason (gareth.eason@signal2noise.ie, who should be blamed for any and all transcription, spelling and grammatical errors.)

Timeline

00:00 - Intro

Ben: Oh! Hello old friend. It's good to see you. Let's talk about this word, "Fascination." It describes an unquenchable urge which compels our hearts to quest and be captivated. As long as there are elegant explanations to complicated phenomena, science will never lose its romance.

Over the years I've travelled the world indulging in my fascination in physics, and now I find that a new hunger has woken within me; a firey need to share these great ideas with the people around me. And so, I have assembled a team of some of the greatest, most lucid, most creative minds I've encountered in my travels, and I call them: My Titanium Physicists.

You're listening to the Titanium Physicists Podcast, and I'm Ben Tippett.

And now... allez physique!

01:10 - Theme tune

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

01:46 - A triumph of theoretical physics

Ben: This is a momentous occasion, so you'll pardon me if I'd like to say a few words. When I started the Titanium Physicists podcast I had two things in mind. The first thing is that fascination - that engrossing feeling you get when you're exploring, where you can't wait to find out what will come next. That fascination is a form of entertainment, just like engaging drama or delightful comedy, learning is definitely a way in which people have fun.

And secondly, that other spacey and sciencey shows didn't give their audience enough credit. They thought for whatever reason, that people only wanted to hear about dramatic science; about the race to the next big revolution in physics. And that's why there are so many documentaries about string theory and so few about superfluid helium. And the tragedy of this kind of thinking is that the dramatic science is often wrong or a dead end. And meanwhile there are so many different topics from well established, verified physics which are honestly fascinating. So I decided to start a show which was as in-depth as I could make it and which covered only topics which were established in both theory and observation.

In 2011 there were three big, sexy topics from theoretical physics which I banned, because they were observationally unverified. There was to be no string theory, no Higgs Boson and no cosmological inflation. Now physicists at CERN announced the detection of the Higgs Boson in 2012, and so - hurrah - we got to do a show on that topic. And it was a huge privilege for me to run a physics show which bridged the areas before and after Higgs.

But let me talk about the last topic I mentioned: Cosmological Inflation. It's a description for what happened in the very very early universe during the first second after space-time emerged from the big bang singularity. And to be honest, I was not, myself, a true believer in inflation. There was circumstantial evidence in favour of it - Titanium Physicists, episode 15 discusses some of them - but I personally had my doubts. So you don't understand how exciting is was for me in March 2014 when the BICEP2 collaboration announced that they had uncovered the thumbprint of primordial gravitational waves in the cosmic microwave background; direct evidence confirming the inflation story for how the universe evolved over its first few moments. It's nothing less than a triumph of theoretical physics. I seriously brought a cake home on the way home from work that day. It's my pleasure to announce that on this episode of the Titanium Physicists podcast, we'll be talking about cosmological inflation and the telltale thumbprint from gravitational waves which the BICEP2 telescope observed.

04:16 - Introducing today's guest, Ryan North

And speaking of beginnings, our guest today goes back all the way back to the beginning of the Titanium Physicists podcast. He was accomplished in 2011 when I started Ti-Phy, but since the last time he's been on the show, he's accomplished even more. Most notably in 2013 he won an Eisner award for writing the Adventure Time comic book, and then late 2012 he made the national news for raising over half a million dollars on a kickstarter to publish his choose your own adventure Hamlet book. In 2014 his sci-fi adventure comic, Midas Flesh, hit the comic book store shelves.

He's the author of the "Adventure Time" comic, "To Be or Not To Be - That is the Adventure", "Midas Flesh", and he's edited both the "Machine of Death" books. His kingdom is witty adventure, his fortress is the "Dinosaur Comics" webcomic and we are all his subjects. Welcome to the show, King of the Internet, Ryan North.

Ryan: Thank you very much.

Ben: So, your highness, for you today, I've assembled two of my favourite Titanium Physicists. Arise Dr. Michael Zemcov.

Michael: [Explosion]

Ben: Dr. Mike did his undergraduate degree at UBC with me. He did his PhD at Cardiff University in Wales, and he's currently a senior post doctoral fellow at Cal. Tech working on experimental cosmology. Now arise Dr. Katie Mac.

Katie: Ta-da!

Ben: Dr. Katie did her PhD in Princeton University in astrophysical sciences. She's currently at the University of Melbourne in Australia where she's currently a postdoc and a Discovery Early Career Research award holder. She studies theoretical cosmology. Alright everybody - it's time to talk about inflation. So, Ryan, the universe is infinitely large, but it's expanding, right?

05:52 - An infinitely large, and expanding universe

Ryan: Wait, wait, wait! Let me stop you right there. Literally infinitely large? I thought it was very big but not infinitely large.

Ben: Well it's probably infinitely large, but we can't see that far back in time, so we can't actually tell. It's not like we can see the edge, but we're pretty sure that it if had an edge, it wouldn't have an edge.

Katie: I mean, it might be infinite, we don't really know. But, you know, it's probably pretty big.

Ryan: I mean, I will accept that the universe is big. I'm with you for that. [laughter.]

Katie: I think, the last episode that I was on, I took issue with the statement that the universe is infinitely large, because we don't actually know.

Ben: You did. It's true! And you were right to do so.

Ryan: Sloppy language, Ben!

Ben: It's true. But, you know, people are so used to thinking of the universe as a little ball of energy that's expanding inside a great big void that I'm always insisting that the universe is infinitely large to hammer in a different paradigm. So yes, but it's true - we don't know what's out there, past a certain point, because we can't see out past a certain point. Let's say we've got pretty good mathematical models of the universe that are fitting all sorts of fantastic data that suggests that, you know, all those models assume that the universe is without bounds at least. So… eugh - so the universe is really, really big.

Ryan: Yes.

07:07 - The Horizon Problem

Ben: And there's a mystery. Some people call this mystery the horizon problem. The deal is that there's this cosmic microwave background. You've heard of it, yes?

Ryan: Remnants from the big bang, right?

Ben: Remnants from the big bang. It's actually remnants from the universe cooling to a certain point where it stops being a plasma, [Right.] because before it's a plasma all these photons and electrons and protons are all bouncing off each other, and then when the universe cools to a degree where everybody decides to settle down, and there's just these lonely photons kicking around from back in the day, with nobody to play with anymore, ever. So, you know, we do these maps of the sky, taking photographs in essence, in the microwave, of what all these photons look like. And something fantastic happened when they mapped the sky, which was: it looks like photons from opposite sides of the sky tell us the temperature that they were emitted at was the same. They have the same temperature, these photons. And it's weird because photons coming to us from, you know, straight up, they come from, you know, 14-billion-ish light-years away, give or take, right? [Right.] And the photons coming to us from the opposite direction - also 14-billion-ish light years away. So, you know, I'm playing fast and loose with the math here, but the difference is kind of astounding. They come from patches of sky that started out 28-ish billion light years away. I mean, the universe has expanded since then - complicated deal - but, you know, really, really, really far apart, and they're the same temperature. Which was weird, because usually the only way you can be sure that things will be the same temperature is putting them right next to each other and letting time pass. You know, you might expect to find a cold patch over here and a hot patch over there. You don't expect to see them, right at the start, being the same temperature.

And so this was a mystery, because nothing's that perfect. The only way they could all be the same temperature is if they started off right next to each other warming each other up so that they were in some kind of equilibrium before they ended up 14-billion-ish light years apart.

Ryan: Right, but they would cool down, presumably, as they travel, right?

Ben: Yeah. The story of these photons, essentially: they have a spectrum. If you map out the spectrum of it, you can read the spectrum to determine the temperature of the universe back when all these photons were emitted. [Right!] I mean, they're really cool right now, because they've cooled as the universe has expanded, but if we do our math to it, play back the tape, we can tell that the universe started off fairly hot, and also the same temperature, even though these patches of sky are really, really, really, really, really far apart.

Ryan: Okay.

Ben: So the mystery was, how did these two patches of sky that aren't in causal contact end up at the same temperature? And the answer that people came up with was this model of inflation which you might have read in the news. People are saying inflation has just been proven by this fantastic observation by the BICEP2 telescope.

Ryan: I've actually purposely avoided reading. It's been quite a feat reading any news on this, just so I could be...

Ben: What a magnificent gentleman!

Ryan: I know. I wanted to be your perfect layman here. So I know the name of it, and that's pretty much all I know.

10:05 - An inflation epoch

Ben: Right. Okay. So this thing announced that, "Hey! We have some confirmation of... that there was an inflation epoch." And the idea behind inflation was, it was thrown in there as an explanation for why these different parts of the sky are all the same temperature. And the idea was, once upon a time, in the early universe but not super, super, super early, just super early, all these different parts of the universe were right next to each other, in causal contact, so they could reach about the same temperature. And then, there was an era where the universe stretched. It stretched really quickly. And we'll talk about the stretching in a second, but it stretched really quickly in a way that these different patches of sky that were once touching each other, end up billions of lightyears apart.

Ryan: Faster even than light, right?

Ben: People say "Hey, the universe is expanding, in this case, faster than light" and that is a complicated statement, because the universe, any time it's increasing in size, there are parts of it that are moving away from us faster than the speed of light.

Katie: I mean if you figure that when you have something that's expanding uniformly, anything that's farther away is moving away faster, and so if the universe is infinite, there's always going to be a region far enough away that it's receding from us faster than the speed of light.

Ben: The universe isn't expanding at a steady rate. The rate it's expanding is changing. And this kinda makes sense, because the thing that's causing the expansion is, in part, the matter that is in the universe. And as the universe expands the matter gets more diffuse, and so the rate of expansion changes.

Michael: The reason you're not worried about the speed of light here is because it's space itself that is stretching.

Ryan: Yeah. It's a way you can get things that apparently move faster than light without having to break any rules.

Michael: Right.

Ben: Yeah, so if we were to imagine that the universe were expanding at a constant rate; a magical universe that doesn't exist but can exist in our head, the rule of thumb with this is if I take my telescope and look out, what I would see is the farther someone was away from me, the faster they would be moving away from me, as the universe expanded.

Ryan: Sorry, is the universe expanding at a set rate, or accelerating at a set rate?

Ben: Expanding. Suppose it's expanding at a set rate - everything's nice and constant [Okay!] The universe is expanding, right... you know, you imagine each metre distance between me and them increasing in size just a little bit, so the farther they are away from me, the faster the distance between us is growing.

Ryan: Ah, okay! The effect gets larger. I'm with you.

Ben: Yeah. The effect gets larger with distance. So even in this universe, a universe where the expansion would be constant, there would be some radius away from us where the distance between us and them would be increasing at the speed of light. And this is the cosmological horizon. And even if our universe were really, really, really old, we wouldn't be able to see all the way across the universe out to infinity, because eventually we would see this cosmological horizon, because nothing further out than that can emit light that will ever reach us. [Right.] So it's its own kind of fence in a causal sense in the expanding universe.

And so the deal is, like I said before, in reality the rate at which the universe is expanding is changing. Okay? Right now the universe is accelerating. The expansion is getting quicker. There was a time when the expansion slowed down. And in all these cases you can describe the different types of expansion in terms of the radius to this cosmological horizon, right? [Okay.] So the faster the universe is expanding, the closer to us the cosmological horizon is.

Ryan: Yes. I'm with you.

13:37 - Exponential inflation

Ben: So the deal is, inflation was an era… there are terms in the equations describing the acceleration of the universe where those terms are exponential, and the way that manifests itself with this cosmological horizon is that… so the faster the universe increases in size, the closer to us this cosmological horizon is. [Right.] And during the inflation epoch, the cosmological horizon was getting closer to use and closer to us exponentially. So it might have started out, you know, 200 million parsecs away, and then the next moment it would be 100 million parsecs away, and the next moment it would be 50 million parsecs away - and the next minute, right - and so the distance between us and this horizon keeps halving.

Ryan: That's pretty terrifying.

Ben: Yeah. Oh yeah it is. Well we talked something about this on the Big Rip episode.

Ryan: We did yeah, with stars going out, and… yeah!

Ben: Yeah, yeah. The big rip happens even faster than that, so in that case the cosmological horizon goes 'Voooop!' [Laughter] But in this case it's only increasing exponentially, so it's getting closer to us - the distance between us and it halves. Well, that's one way to describe what we mean by this exponential growth. So when we say that the universe is expanding faster than the speed of light it's a little bit of a misnomer, but it's certainly a way to describe how violent this acceleration was, [Right] because this cosmological horizon - having it half in size is kind of ridiculous, terrifying even. Okay, so the cosmic microwave background radiation - the one where we say that we can see the big bang. Right. The Universe is currently 14 billion years old. The cosmic microwave background: it comes from about 400,000 years after the big bang.

Ryan: 400,000 - that's not that old…

Ben: Orders of magnitude younger than the universe currently is. We're in billions of years - it was only 400,000 years old when it emitted this cosmic microwave background. But, this inflation era happened less than a second - it was like 10 to the minus thirty…

Katie: Thirty-five

Ben: Thirty-five (10^{-35}) -ish seconds after the big bang, so really soon after the big bang.

Ryan: Is that in terms of duration or just how long the universe existed until it started.

Katie: I think that's when it ended

Ryan: So very quick - very, very powerful.

Ben: Very, very quick, yeah

Katie: Yeah!

Ryan: Traumatic!

15:46 - Perturbations creating temperature variations

Ben: But it had this effect where before it, you know, these patches of sky which we now see have the same temperature, were close together, so they could be the same temperature. And then this crazy violent expansion happened that effectively ripped everything apart and threw different parts of the sky far, far apart, but that's why they have the same temperature. And the neat thing about inflation: people say "Okay, great - maybe this explains this horizon problem - why different parts of the sky are the same temperature." The deal is that it also had a variety of predictions when you looked at how little perturbations would turn into temperature differences that we can see on the cosmic microwave background, so it had some supporting circumstantial evidence that it was a good picture, in that it predicted the different temperatures. So it did have some predictive power beyond this philosophical 'Now we can sleep because we know… we have an explanation for why different parts of the thing,' right? [Laughter.] Katie, tell us more about fluctuations.

Katie: Yeah, so we think that inflation was probably… so there's some kind of field and we call it the Inflaton, and we don't really know what that means but we think there's some kind of field that governed inflation. And that field had quantum fluctuations in it. So every particle, every field, has quantum fluctuations which brings you to the uncertainty principle and all these ideas that there's like fuzziness around everything - there's an uncertainty about where something is, how fast it's moving and so on. And so this Inflaton - this inflation field - had that same quantum fuzziness. And so, the inflation was happening everywhere in the universe, but when inflation ended - when the extremely rapid expansion stopped, it didn't stop at the same time at every point in the universe. It stopped at slightly different times because of this quantum fuzziness, because that Inflaton field was kind of kicked back up a little bit, or dropped down a little bit, or whatever [Right.] and the field was quantum fluctuated around. And because of that, some parts of the universe inflated just a little bit longer than other parts of the universe. And so, the parts that inflated a little bit longer had lower density because they got stretched out a little bit more, and the parts that inflated a little bit less had higher density. [Right.] And so you end up with this situation where you get these quantum fluctuations in density throughout the universe - and they're tiny, right, they're really tiny fluctuations, but the universe expands. And so, these tiny, tiny fluctuations get expanded to now being really, really large fluctuations and over time those fluctuations, collapse through gravity to become the seeds of density fluctuations in the universe and those become the galaxies and clusters of galaxies and so on we see today.

But you can see these initial fluctuations in the cosmic microwave background, and so when you look at the cosmic microwave background it's about the same temperature throughout the whole sky, but there are little tiny fluctuations - at like one part in 100,000 - and those little fluctuations are the quantum fluctuations of this inflation field, and those fluctuations are fluctuations in density and we see them as hot and cold spots on the sky, on the cosmic microwave background, and if you work out the math of the distribution of hot and cold spots that you would expect to have from a field fluctuating in its potential in a quantum mechanical way and laying down density fluctuations like that, that's what the CMB looks like. That's what those spots look like. So statistically they're looking almost exactly like they should for these fluctuations coming from fluctuations during inflation. [Right.]

So that’s one of the things that’s been the biggest piece of evidence for inflation up until now, is that you get these fluctuations in the density that we see in the CMB that have the right statistics to have come from quantum fluctuations from the Inflaton field.

Ryan: Right. That explained it really well.

Katie: Right. Okay.

19:27 -

Ryan: But this brings us up to where we were two weeks ago, right [Yeah.] - before the results that happened, that I’m unaware of because I’ve haven’t read them, showed up. [Right. Yeah.] So we had a pretty good idea that this was at least matching what we were seeing and [Yeah.] and the background radiation looks like what we’d expect after what... if we had these circumstances of inflation generating them.

Katie: Yeah. There were some other theories that could also make these kinds of fluctuations.

Ryan: Right, right.

Katie: One of the big differences between those theories and inflation was that inflation also predicts gravitational waves, and this is where everything gets really interesting. Which is that when inflation is ending; inflation is this very, very energetic process and it puts quantum fluctuations into any field that exists during inflation, including the gravitational field. [Okay.] And so if gravity has quantum properties - which is something that we haven’t seen before - we think that gravity and quantum mechanics have to play nice at some scale, but at the moment all the observations we’ve done, quantum mechanics and gravity just do not work together. We’re like, theoretically we can’t get them to work out together.

But we think that probably gravity is a quantum process at some stage, so we think that if inflation happened it created quantum fluctuations, not only in the density but also in the gravitational field. And these would become gravitational waves. They would be gravitational waves that were created through quantum mechanical fluctuations, and they should give you a distinct pattern in the cosmic microwave background that should happen for inflation and not for a lot of the alternative models.

Ryan: So when you say gravitational wave, gravity propagates faster than light speed, right, [Right.] because otherwise you could use it to send information [Yeah, yeah.] and I’m basically imagining the classic taught fabric that you have a ball in the middle of so that gives you your gravity well, and a wave is waving that sheet. Is that a fair analogy? [Yeah.] Like a Star Trek style shock wave going on? That blows up ships from a distance?

Katie: Sure.

Ben: Yeah, so essentially that’s what’s happening. There’s information that’s propagating outwards at the speed of light, because that’s the rate at which things that have no mass propagate.

Katie: So we've seen evidence for regular gravitational waves in the past. So we've seen evidence from looking at timing of pulsars. Pulsars are rapidly spinning stars [Yup!] , and if a pulsar is orbiting something else then that's a lot of mass moving around quickly, and any time you have mass moving around quickly you make gravitational waves. So it loses some energy through radiating gravitational waves. And so, by watching the timing of pulsars, we've seen evidence for gravitational waves, but those are like classical gravitational waves. [Right.] What we haven't seen before are quantum gravitational waves; so gravitational waves that are not sourced by moving objects around, but sourced by quantum fluctuations in the gravitational field, and that's what inflation should do.

Ryan: Ah!

22:13 - What is a gravitational wave?

Ben: To get the next step you need to understand kind of what a gravitational wave is. It sounds like it's just something waving around, but it's actually a little bit kind of weird and more substantial. Gravity is the manifestation of curvature of spacetime. [Right.] So all that means is if you imagine that the universe is covered in little flags, that, you know, are marking points.

Ryan: That's a lot of flags.

Ben: I know, right? Just little cocktail flags everywhere - that's what I imagine. In a grid of cocktail flags, what gravity does is it dictates distances between these points and time intervals between these points. So that's how curvature manifests itself, in terms of distances between points. So the deal with gravitational waves is, it comes from essentially perturbations that move at the speed of light, like you said, but how do these perturbations manifest themselves? As little changes in distances.

Imagine yourself out in space and you take a marshmallow and you put one marshmallow over here. And then you take another marshmallow and put it kind of next to it. If a gravitational wave moves through, what's going to happen is you're going to see those marshmallows - the distance between them is going to get closer together, and then farther apart, and then closer together and then farther apart. The distance between these free-floating marshmallows is going to wiggle.

Ryan: What?

Ben: In fact, gravitational waves are a little bit weirder than that. Imagine you take a little… you're out in space again… you have a… make yourself a little ring of marshmallows that you put out in front of you, like a steering wheel or something. [Alright, sure.] A ring of them. If a gravitational wave comes through and hits it right, dead on, what will happen is you'll see this ring of marshmallows get squished. So first, the outside edges would get closer and then the up-down edges would get farther apart, so it will smush - like, imagine yourself smushing a water balloon. Smush! [Right.] And then it will smush in the opposite direction, so the longitudinal side of it will get wider and the top will get narrower, and so it will go "Waaaaaaaah!" as it smushes back and forth. [Laughter.] It jiggles like a water balloon or something.

Ryan: And this is like, at the speed of light? Right, like, I wouldn't actually…

Ben: Yeah, okay - so the rate at which it does it depends on the wavelength of the gravitational wave, right? Because it's moving at the speed of light, but the rate at which it happens depends on how long the wave is, right?

Ryan: Right. Like radio?

Ben: Like radio, that's right. So we've got gravitational wave detectors that they're building on earth. They're fantastic things: LIGO is one of them. They're just great big interferometers, because when I say marshmallows getting... it's very vivid, but in actuality it's a fairly subtle thing: less than, what - it's something like - in several kilometers it's less than the width of a…

Michael: Proton!

Ben: or something like that. [Alright.] It's almost undetectable, which is why it's taking them forever to detect these things.

Ryan: That's the piece I was missing. Because it seems like that's pretty easy to detect, smushing marshmallows in space.

Ben: Yeah, yeah - that's right. They're really really subtle, but they make this tell-tale jiggling.

25:06 - Gravitational radiation

Michael: You know, another important thing is that, that particular smushing that Ben's talking about is a signature of gravitational radiation. No other field we know about can do that.

Ryan: And this smushing - let's say the effect is larger than a neutron every twenty kilometers. [Yeah.] Would it actually smush these marshmallows, like physically deform them? I guess it would have to, right, if it's like, bending space.

Michael: Yeah. It's changing the distance of the space between the atoms that it's made up of.

Ryan: So that would be pretty traumatic for the marshmallow, right? If it were a bigger effect. If we want to weaponise this we need to scale it up.

Ben: Yeah, yeah. It's a tidal force so they're really weak and they depend on how big you are. But you know you can use tidal forces to smush up a neutron star and stuff. But you're probably not going to damage anything with gravitational waves any time soon.

Ryan: We'll see about that. [Laughter.]

Ben: But what you can do is, in the early universe you have these things smushing this early universe plasma, and it's causing plasma in some places to become less dense and in some places more dense, periodically. And it's causing plasma in some places to be hotter and some places to be cooler. And so it's one of the effects that causes patches of different temperature on the night sky. But that’s not actually the big smoking gun because there’s more than one type of wave that can cause a manifested density wave in this early universe plasma. In essence, it would cause different patches of temperature in the cosmic microwave background, but other effects, like the one Katie was talking about a second ago, where the Inflaton had perturbations in it are more pronounced. But, it does this other fantastic thing, which is what the experiment measured.

Michael: So in the universe around recombination when you’re making the cosmic microwave background, you know, the cosmic microwave background is made by - you have a plasma, so you have a bunch of basically protons and electrons and photon just banging around in a soup, [Right.] and then the temperature drops to a point where the electrons hit protons and say, you know, “Hey, I want to bind with you” and there are no longer photons around that are energetic enough to dissociate them. And so the CMB is basically all the photons that get released from being in that soup when everything goes neutral again. That’s what you’re seeing in the cosmic microwave background.

So the smoking gun of inflation, which is what the phrase that the B-mode people like to use, is that in the universe around this time, basically, you have a bunch of matter streaming around and it’s going from overdense regions into underdense regions and kind of vibrating and moving around in flows. And that process first of all makes these spots of bright and dark when you make a map of the cosmic microwave background. But what it also does is it makes a slight polarisation to the light, which is that, you know light has basically a direction on which it oscillates, and when you look with something that can differentiate between the different directions you can have you see that, oh, and when you look at a bright spot it prefers one direction and when you look at a darker spot it prefers a different direction, and the field that you map is some combination of all these directional arrows, which is, when you look at the public material, what they show.

Ryan: Right, the same technology used in 3D movies.

Michael: Yes, exactly. Except at wavelengths which heat food.

Ryan: Yeah. [Laughter.] Boil your eyeball 3D movie.

28:18 - Thomson Scattering

Michael: Right, okay! So that’s Thomson scattering and that’s kinda what we were thinking in terms of.

Ben: Do you want to illustrate how Thomson scattering generates polarised light? It’s pretty… I think I can do it in 25 seconds… well… Do you want me to?...

Michael: Do it!

Ryan: Alright.

Ben: Okay, alright. Here’s my stupid explanation.

Ryan: Start the clock!

Ben: Alright. Extend your hands in front of you. We're going to play a hand game. Okay?

Ryan: Done.

Ben: Okay. So, right in front of you, there is a cold region. Cold region. [Right.] And then to the right of you - extend your right just a little bit to the right - there's a hot region over here on the right. Okay?

Ryan: Right, yeah.

Ben: So, photons are going to want to flow from the hot region to the cold region, so they'll be going to the left. [Yep.] Now, each photon has a polarisation. Manifest this... take your hand, karate chop. Make your hand flat. [Okay.] So your hand is coming in from the right to the left. Use your right hand - illustrate, okay. [Right.] Now there's a whole bunch of different polarisations it can have. You can rotate your hand around the same axis and have your fingers pointing in the same direction from left to right, right? [Yep.] So the deal is, each of those photons is going to hit some electron inside the cold region and scatter off it. But the deal is, okay - so if your hand is up-down - you know, if your hand is aligned vertically - it means that the electromagnetic wave is up-down and so it will wiggle the photon up-down, okay. And if your hand is left-right, it means that the electromagnetic wave goes kind of left-right and it will wiggle an electron left-right.

Ryan: I'm with you.

Ben: Okay, so, when the electron wiggles it will emit its own photon. It will emit light, kind of in the direction that it's being perturbed. So if your hand comes in and it's vertically aligned, it will wiggle the electron up and down in our plane of vision, and so the photon that comes towards us will be polarised up-down. [Yep.] And if the original photon came in oriented horizontally, it would wiggle the electron forward-back, and then it would, you know, shoot an electron off in a different direction. We wouldn't see that polarisation. So the net result is, because the electrons are falling from hot to cold in these patches, all of the light coming towards us will be polarised in a certain direction.

Ryan: Right.

Ben: You look at the cosmic microwave background and there are little polarised regions that kind of go from hot to cold.

Ryan: Hmmm. That's cool.

30:28 - Slamming beers

Michael: So that reminded me, Ben, of a friend of mine who said, "Hey! I can slam these two beers in 15 seconds."

Ben: And then he took 15 minutes?

Michael: And like, okay. Yeah right, and we said, “Okay. Fair enough.” And we got out our little stopwatch and we timed him. And he goes, “Okay. How long was that?” And we said, “A minute and a half.”

Ben: That’s pretty good. [Laughter.] It’s only an order of magnitude.

Ryan: This friend of yours sounds great!

Michael: Okay. There’s a secret sauce here. Basically, when you have just regular matter streaming around under the effect of just regular old gravity - not gravitational radiation - just gravity, you can only make E-modes. It only wants to make sort of straight up and down polarisations, relative to other polarisations. This is where the marshmallow, weird, going in and out jello-ness of gravity waves matters. They can actually make the matter move in such a way to kind of ruin that symmetry, and instead of making something that looks like say, you know, when you draw a sun and rays are coming off the sun - right, that’s what kind of normal E-modes would look like - it makes it look more like a pin-wheel, where there’s a kind of curl to it.

Ryan: Right

Michael: And that effect is very small, but the point is with something that’s sufficiently good at measuring polarisation you can go and look for it. And if you see it at the right angular scale… So another thing we’ve missed here is that, going way back to the beginning - Ben’s talking about: I look at a photon in one direction and I see it’s basically the same temperature as something coming from exactly the opposite direction. Except they could not possibly have talked to each other.

Ryan: Right, because they’re out of range.

Michael: Exactly. Right. On big angular scales - that is angular scales where those two photons could not possibly have talked to each other - so on the big scales if you go and you look in the universe, if those scales know about each other and can’t possibly have talked to each other, that’s the signpost for inflation - and it ends up that that kind of; we call them super-horizon fluctuations - that is stuff that is bigger than the cosmological horizon that we know about - you can go and look for that in just regular old temperature in the CMB, and you see it. But the problem is, it can be generated by other things that are sort of more local to us.

B-modes are really hard to fake. There’s not very many things astrophysically that can make them. So if you go out and you measure B-modes on big angular scales, it’s a little bit hard to imagine what possibly they could be but inflation, and that’s why they use this language of “smoking gun.” It’s really hard to make it up.

32:49 - Mimicking B-modes

Katie: I’ve actually, I’ve been kind of asking around what could mimic this, and all I’ve heard is basically, like, there are some maybe-possibilities, but they’re really unlikely and really difficult to get a B-mode polarisation that isn’t gravitational waves. I think it’s a very compelling picture. I mean, I feel like I’m still not 100% convinced, partially because it’s just one measurement and the measurement could be wrong, and because we don't have a fundamental theory of inflation yet and so I'm a little bit nervous about that, but it's not easy to make gravitational waves like this that are not from inflation.

Ryan: If I'm understanding you guys, what was announced earlier last week was one measurement of this pinwheel shape that could only possibly have come from this gravitational wave?

Katie: Yeah.

Ben: Yeah.

Ryan: We've only seen it, so far in human history, once?

Ben: Well our machinery for observing these things is sufficiently good that we can see it now. And this is the first time we saw it, is the argument.

Katie: Yeah, yeah.

Ryan: So we've seen more than one instance of this?

33:47 - Toothpick pinwheel polarisation

Ben: Let me paint you a picture: Imagine that somebody gave you a photograph of a chunk of the sky, and you have it in front of you.

Katie: Delightful!

Ryan: Sure.

Ben: So, take a handful of toothpicks and the deal is that each toothpick represents a polarisation of the light coming at you, right? So you can arrange the toothpicks in a variety of ways in front of you, representing how we might see the polarisation coming from the cosmic microwave background in a variety of ways.

So there's two types of polarisations: the E-modes; it's kind of like, imagine if you took the toothpicks and arranged them so that they're all pointing towards the middle. That's what an E-mode polarization looks like, so when they take photographs of the sky, they see it. And the argument is that lots of different things can make polarisation profiles that look like E-modes.

Another type is, if you take eight or nine toothpicks and you arrange them kind of in a swirly pattern so they're kind of pinwheeling around the middle - so none of them point directly at the middle, but they kind of swirl. [Right.] That's a B-mode. And there's nothing that can generate a B-mode but gravitational waves in the early universe. So what they're seeing is...

Ryan: Smoking gun.

Ben: Yeah. So they look at these early cosmic microwave background and they look at the polarisation map and they see it's covered in these little swirls.

Katie: Okay, wait, wait! Two caveats. Two caveats. One, gravitational lensing also makes B-modes, and that's a big foreground. So that's a big thing that we can confuse these things with, but this collaboration made a very compelling case that what they're seeing is not gravitational lensing, it's actual primordial gravitational waves. But, gravitational lensing B-modes have been detected by other instruments - it's just these gravitational wave B-modes have not been seen before.

Ryan: Wouldn't gravitational lensing ones be less common?

Katie: Actually the gravitational lensing ones come from the gravitational lensing of the cosmic microwave background by all of the matter between us and it. So like, everything in the universe is contributing to the gravitational lensing signal.

Ryan: But, wouldn't that tend to make it more random than that particular pinwheel shape we've been looking for?

Katie: Well, no - because it sort of picks up the biggest sources of gravitational lensing. And the gravitational lensing is stronger for certain distances and separations and stuff. But it shows up at different scales. It has a different behaviour with scale. [Right.] So, the gravitational lensing background is at a smaller scale than these guys. These guys are larger angular scale [Okay.] and so we can distinguish them. And so, like, this is the first time we've distinguished them; that we've seen the primordial gravitational waves, not the gravitational lensing. But you do get B-modes from gravitational lensing as well. [Right.] So, I should just say that.

Michael: The other way that this could potentially get messed up is - I'm not sure that this is very probably, but it's possible - that local dust in our galaxy, because you're looking through a column of dust, you know, when you look out to the distant universe [Right.] and that dust could be polarised - we know that - and you could imagine a situation where because you're looking through this column it has a weird superposition of different polarisation vectors and it can mimic a B-mode. Except that the BICEP guys did a very careful job of - to the extent that they're able, at least - to show that it doesn't look like it could be this dust, based on sort of colour and shape arguments: that you know roughly what that's going to look like, and it doesn't look like that. So you can kind of make an argument that, "Okay - well you have to test it exhaustively, which is why we need more experiments. But, but it could potentially be.

Ryan: It would have to be some really lucky guess that happened to line up just perfectly to give it this shape.

Michael: Right. And I have to say, I've studied the universe for a while now and I do believe that it's more complicated than we give it credit for sometimes. [Laughter.]

Ryan: That's an awesome sentence to be able to say. [More laughter] "I've made a study of the universe myself!" [Yet more laughter.]

Michael: Yeah, well also a collaboration between a bunch of institutions: one of them's Cal. Tech and actually this is where BICEP started, and so my boss was one of the PIs of it and a bunch of guys around here actually are postdocs on it. And I'm actually... I just turned around when we were talking and I'm looking behind me and I actually have the BICEP1 camera sitting behind me. Amazingly enough. Because I'm using somebody else's office.

Katie: Wow! That's cool.

Ryan: That's awesome. And can you take it?

Michael: No, I can't take it, but it's cool. [Laughter]

Katie: Well, you know, primordial gravitational waves are moving through me right now - just so you know. [Laughter.]

Michael: Yeah, that's right. So, this result is really cool. But it's a little bit brighter than we might have guessed.

38:12 - Double the expected strength

Katie: Yeah, so the polarisation signal is stronger than we expected. And there are a couple of reasons for that. One is theoretical and one is observational. The observational reason is that, I think we said at some point that gravitational waves produce B-modes, but they also produce some E-mode polarisation. They also produce the regular sort of asterisk shaped polarisation. [Right.] So other CMB experiments that looked at polarisation and looked at the E-modes, put limits on what we expected to see from gravitational waves, from like looking at the temperature power spectrum and there should have been other effects of these primordial gravitational waves, if they're there, and so we had limits. So there's this number called the tensor scalar ratio which is the ratio between basically the amount of power in, like, just density fluctuations and the amount of power in gravitational fluctuations - the ratio of that: gravitational over density. So tensors are the gravitational fluctuations and scalars are the density fluctuations. So we had that ratio, r, we thought was like less than 0.1 and BICEP measured 0.2. So this is about double what the previous limit was. So we thought we had an upper limit and this was about double what the upper limit was. So, that's weird, and you have to do something a little bit weird with inflation to get that to happen. Like, there are still models of inflation where that totally works but you have to do something a little bit weird with it - or there might be some kind of issue with the measurements, like there have been a lot of complaints about the way they did the dust subtraction - and if you use a different dust model you get a lower value of r and then it's more in line with these other measurements.

So, the magnitude is surprising for that observational reason, just because we thought that we'd already ruled out that magnitude of the effect. [Right.] Or, the other reason we're surprised by the magnitude is that theoretically inflation predicts gravitational waves, but it doesn't predict exactly how strong they should be - like what size this r value should be. So it could have been a lot lower and still been consistent with inflation. And in fact most models of inflation that come out of string theory produce levels of gravitational waves that are undetectable by any reasonable instruments.

Ryan: How convenient.

Katie: So it was… Yeah… So it was surprising because nobody really expected to see this signal so big. I mean, I think there was a quote by somebody on the team or something, saying, "We were looking for a needle in a haystack and we found a crowbar." [Laughter.] Like, it was a much bigger signal than we thought we would see and because it was such a big signal, it means that certain models of inflation have to be more complicated to fit with it because, you know, if it's really this strong… or if it was just overestimated, then we have… then it still means we're ruling out a whole lot of string theory inspired inflation models, and we've cut down the theory space hugely.

Ryan: Which is good, right?

Katie: Which is great, yeah! And as a theorist that's really important. So it's ruled out a whole bunch of inflation models and it's also ruled out some other things. There's a dark matter model that's ruled out by this - it's a kind of dark matter particle called an axion. Not all axion models are ruled out, but certain kinds of axion models are ruled out because of this because basically, they would be a field that was present during inflation, which would mean they would have these quantum fluctuations in them and we would see evidence of that in the CMB and we don't see that. So that model of axions is ruled out.

Ben: You want to hear one crazy one? I wrote part of my thesis based on, it's called the Randall-Sundrum Braneworld model, [Okay.] and the idea is that our universe is a 4-dimensional sheet surrounding, in this case, a 5-dimensional black hole. And so the black hole is making gravitational waves and as the universe expands it gets farther away from the gravitational waves. And so, yeah - you'd see these gravitational waves in the primordial gravitational wave spectrum. [Cool.] And I haven't done the calculation yet, but maybe it gets ruled out. Wouldn't that be great?

Katie: Yeah - it's always… I mean, the best thing that can possibly happen to a theoretical physicist is to rule out a model, because you can't ever prove one, right! [Right.] So the only really solid thing you can do is to rule things out. And this result gives us ammunition to rule out tons of models, and that's awesome.

Ben: Yeah.

Ryan: That is awesome.

42:22 - Antarctica

Ben: Mike, do you want to say anything about Antarctica?

Michael: Okay. Real quick. So I did my PhD on a precursor to this. So, the guys who have been doing this have been doing this for a long time, you know, fifteen years or so. Kudos to them - it's hard. It takes a lot of dedication and the instrumentation is hard. So, you have to build these cameras that get cooled down to 250mK (milliKelvin) or something like that - so very close to absolute zero. So the idea is that you use thermometers to detect these photons because they're really hard to detect. And so you have to cool it to a point where the energy from the CMB is a big change in the energy of your detector, so that's a pretty cold temperature, because the CMB is

2.73K. [Right.] And so you build these big complicated things and from the Earth's surface actually, the water in the atmosphere is the thing that makes it so hard to make these measurements, and the driest place on Earth, or one of them, is the South Pole, in Antarctica, and the US has a big base down there for, you know, 'historical reasons.' [Laughter.]

Ben: Yeah. The thing?

Michael: Yeah. And so these guys have been doing observations for a long time from down there. BICEP2 itself was only observing for three or four years but it's a hard measurement and it takes a lot of dedication and it's kind of cool and they're going to do it for a while longer. I do wonder where the field is going to go, because once you've seen the signal - especially when it's so bright - you kind of measure it pretty quickly, you know, by Moore's law, and then there's not much else to do.

Katie: Well, I mean, the other experiments all have to see it too. In the next couple of years three or four other instruments are going to try and find the same signal and it will be interesting to see if they find the same signal, if they get the same answer.

Ryan: Repeated experimentation: basis of scientific method.

Katie: Yep.

Michael: That's right. Yeah - so, that's the story.

Ryan: That's awesome. And the South Pole is my favourite place on Earth, so I'm totally jealous of these scientists.

Michael: It's fun. We call it "Summer Camp for scientists."

Ryan: I've never been there, because it is very hard to get there. But I made a stuffed T-rex from my comic and someone brought one of those to the South pole and sent me pictures of it at the magnetic, geographic and ceremonial South poles. And I was so jealous that this fictional character is living my dreams.

Katie: So cool!

Michael: Wow! I've been there three times. I got actually, you get… if you're there for a certain amount of time…

Ben: What? You've been to Antarctica?

Michael: Yeah. I've been to Antarctica.

Ben: What?

Ryan: Three times! No big deal.

Michael: Yeah - my job's pretty fun. Anyway, so you get a medal from the US government, which is funny because I'm Canadian so I get to brag to my US friends that I'm a hero now.

44:56 - One last question

Ryan: Actually, I did have one last question on the background radiation.

Ben: Okay.

Katie: Yeah.

Ryan: When I was a kid, and back when you had TVs that you would get static when you turn them on, my Dad always told me that we were watching the background radiation of the universe when we were watching static. And as a consequence to that, I always imagined the early universe being coloured basically as a white, black and grey static screen, which I'm sure isn't accurate. But, is that background radiation to the universe, or is that just noise or what?

Katie: Some of it's background radiation. Yeah.

Ryan: Excellent, excellent! That's super great, because it's this thing that our generation has, but kids today; they don't get static on their TV - they get just that blue screen.

Ben: Yeah - they think the universe is blue. [Laughter]

Ryan: Yes. They don't know the truth.

45:39 - Closing words

Ben: That was wonderful. Thank you Mike. Thank you Katie. You've pleased me. Your efforts have borne fruit and that fruit is sweet. Here is some fruit. Mike: you get a star fruit.

Michael: Yum, yum, yum, yum!

Ben: And Katie: you get a banana.

Katie: Num, num, num!

Ben: I'd like to thank my guest, Ryan North. Thanks for coming on, Ryan.

Ryan: It was my pleasure. Thanks guys.

Ben: It was truly ours. This was amazing. I'm so pumped, and so is everybody. Listen, Ti-phyters, my Ti-phyters, my audience: you guys are called Ti-phyters. Listen: there are four things you need to know.

Firstly, please leave us an iTunes review. Whenever I feel sad I check iTunes and it makes me feel better. Your nice words are giving me power. Please continue to write nice things on iTunes.

Secondly, there's a podcast app call Podiversity for the Android phone. I know that Android doesn't have a native podcast app, so Podiversity: lots of fun. It's a subscription for content based app, kind of like Netflix for podcasts. They pay us cash-money for each episode you download, so if you get the app and listen to our show we get money.

Thirdly, t-shirts: Go to our store off the Ti-phyter website and buy yourself a sweet t-shirt. Some of them were designed by brilliant designer Chelsea Anderson from Calgary. Now, Bethany bought one of these fancy t-shirts two years ago, and she's worn it like every day since and it still hasn't worn out. They're amazing quality t-shirts so, they're very nice. Have a look at them.

Fourthly, if you'd like to contact us or send us an e-mail, my e-mail address is barn@titaniumphysics.com. I forward people their fan mail if you want to write, you know, Katie a nice letter about how fantastic she is, or tell Mike that he sounds like a Hoser - whatever. Also, we're on twitter and Facebook. Get on, even on Tumblr if you can find me.

And remember, if you like listening to scientists talk about science in their own words you might also want to listen to other shows on the Brachiolope Media network. I'm going to rattle off the shows right now: there's "Astrarium" - it's about astronomy. It's with my friend James. Cool! "Science… Sort Of" - it's about science and news and culture. Fantastic! There's "Technically Speaking" - it's about engineering and "The Collapsed Wavefunction" - our newest show, it's all about chemistry. Oh, so, we need a biology show and a geology show and an ecology show and a medicine show and a psychology show - I'm just saying, you guys, start your own podcasts.

The intro to our show is by Ted Leo and the Pharmacists, and the end song is by John Vanderslice. Until next time my friend, good day, and remember to keep science in your hearts.

47:48 - Outro music

[Outro song; Angela by John Vanderslice]

Bonus Material / Cut scenes

{None.}