Episode 41: The Light Which Pushes Back The Darkness
Physicists: Vicky Scowcroft, Mike Zemcov

Transcribed by Denny Henke

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 traveled the world indulging in my fascination with physics and now I find that a new hunger has woken within me. A fiery need to share these great ideas with the people around me so I have assembled a team of some of the greatest most lucid, most creative minds I have 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!

[1:49]

Ben: Hi everyone. Everything I'm about to say comes from a podcast series I half listened to about five years ago so pardon me for any inaccuracies. The way it happened was this, 2,000ish years ago the Romans conquered all of Europe and with it they brought governments and commerce. They built roads, they unified the language. People interacted with each other and there were technical revolutions, aqueducts and stuff. People took baths! Then the western Roman Empire collapsed. Several countries and kingdoms formed and the languages started to diverge. Education was rare. Literacy was rare. Communication was difficult. It was a mud and dust time, it was a time of plagues and superstitions. It was a time for trolls and witches and elves. And then Galileo was born. He borrowed jewels from Isaac Newton and hired Christopher Columbus to discover America. And then Galileo dropped the one ring into Mount Doom and brought about the Renaissance. Those were the Dark Ages in Europe. And did you know there was a time when the Universe was in a dark age? It was an era between the time we call Recombination and a time we call Re-ionization. It was a time when nothing was emitting light. Today we're going to be talking about the dark ages of the Universe. And it's funny, the dark ages in the beginning come about not from the actions of great and powerful forces, they come about from the actions of the smallest individuals. You can't get an era of light if all of the atoms aren't shining. Who then is better to discuss these events with us than Dr. Corey Olsen, the Tolkien Professor! Hi Corey!

Corey: Hello.

Ben: Corey is the only person I know to have ever have started his own university. The Mythgard Institute is an online center for the study of J.R.R. Tolkien and other fantasy and science fiction literature. You can take online courses there with lectures. Anyway, it's a part of the Signum University which is in the process of being made where you can take all sorts of courses and get actual degrees. Hurray!!!

Corey: Hurray!

Ben: Corey, for you today I've assembled two of my proudest Titanium Physicists. Arise Dr. Michael Zemcov! Dr. Mike did his undergraduate degree at UBC with me. He did his PhD at Cardiff University in Wales. He's currently a senior post-doctoral fellow at CalTech working on

experimental cosmology. Now, arise Dr. Vicky Scowcroft. Dr. Vicky did her PhD in Liverpool at John Moores in the U.K. She's currently a postdoc at Carnegie Observatories where she works on the Carnegie Hubble program. She has a new knitting podcast called *One Starry Knit* and we'll have a link to it on our website if you'd like to watch a thing about knitting.
Okay everybody, let's start talking about the dark ages.

Ben: Okay, Corey.

Corey: Yes.

Ben: Do you know how the universe began?

Corey: Um, no. Not very well. The main thing that I know about it is that in the beginning was Eru the One and then he propounded a theme of music to the Ainur who were the offspring of his thoughts. And they took up the music and adorned it with themes after their own imaginings and there from the mighty music of the Ainur came and based upon that pattern the Universe was formed.

Ben: That's right.

Vicky: That's basically it.

Corey: Yeah. That was pretty much where I thought we were getting to. That is, of course, Tolkien's cosmological story, ah, in the beginning of the *Silmarillion*.

Ben: Yes. So at the very start there were these weird elf god things and they just played music and then the Universe formed. Now the Universe formed, as a result, it's infinitely large. People like to imagine the Big Bang as there's space and then there's an explosion somewhere in space and then stuff comes out of that explosion. And that's not the case. What happened is the Universe started out, immediately after its birth the Universe was infinitely large and everywhere you went it was full of stuff. And the stuff was distributed in a really uniform way. It was just gas. In essence, well, it was really, really hot gas. So, stuff was happening. Details, details. But the moral of the story is that everywhere you went the density of the gas was about the same. So, you could go a million jabillion light years in one direction and you'd see gas in the same density as you did where it started. And anywhere you went it would be pretty much the same as anywhere else you would go.

Corey: Okay, Gotchya. How did the stuff get a million bajillion light years away so quickly.

Ben: Oh, it started out a million jabillion light years away.

Corey: Okay. So, when we talk about the Big Bang we're not actually talking about a localized event then?

Ben: No, that's right. The word Big Bang is kind of a misnomer.

Corey: Well, I understand that it started as kind of a joke. That the phrase, Big Bang, wasn't that name given derisively to the theory when it was first, that was my understanding.

Vicky: Yes. Then we were like, well actually, this is right.

Corey: So, the Big Bang is not as often understood, you know, a ball of matter which has exploded. So, at the beginning, the infinitely sized Universe was... Because infinite is a big number.

Ben: Yes. It's a very big number.

Cory: Yeah... Yeah.

Vicky: So, the thing is the Universe isn't expanding into anything, it's just expanding itself. So, it's always kind of infinite.

[6:47]

Corey: If it's infinite in what sense could it be said to be expanding?

Ben: Yeah, the distance between any two points in it is increasing. Let's say you travel back in time, ah, you're Zeus or something, and you take two planets and you put them, you know, ah, 30 light years apart in the very early Universe. Planet A over here, planet B over here. In time they, the distance between them, they won't feel like they are moving apart from each other, they're just sitting still, but the distance between them will be increasing over time. So, it's like, it's the very concept of distance itself that's expanding. Spacetime itself that's expanding. Not everything moving in anyway.

Corey: So, if we say that things aren't expanding, but that spacetime is expanding, um, what is the thing that is expanding? Because, if we say, you know, on the one hand over here we've got all the things and over here on the other hand we've got, you know, the spacetime continuum. What is that over there? I mean, I'm just trying to understand then, what exactly, it is that is expanding if it's not stuff that's expanding.

Ben: There's an ambiguity here, in our language, when it comes down to it.

Corey: Right.

Ben: Um, so when we talk about something that's moving away from you. Let's say, you're standing on the street and somebody on a bicycle is moving away from you...

Corey: Right.

Ben: You're describing motion, it's true. You're saying if I was on that bike I would feel wind against my face, you know, whereas if I'm standing still I'm not feeling any wind, things like that. But, this is how our language is built, but when you start doing the physics of it, when you describe this type of motion you're not talking about wind on your face or anything like that. You're saying that the distance between you and the bicycle is increasing.

Cory: Right.

Ben: All the way up through Newton, until Albert Einstein came along. And Albert Einstein said, what's up with gravity? Which was an interesting question. Isaac Newton had a theory of universal gravitation. It works really well when you're describing the motion of the planets around the Sun, things like that.

Mike: As long as things don't start moving to close to the speed of light we're fine with Newton. Or, as long as the gravitational fields aren't too intense.

Ben: Kind of. Yeah, so Mercury doesn't quite obey Newton's laws...

Cory: Okay.

Ben: As much as it should. There's a tiny precession in Mercury's orbit that can't be explained using Newton's laws. But for the most part where Newton works really, really well. And what Newton assumed is the concept of distance wouldn't change. But Einstein said well there's some mysteries here. He invented Special Relativity that said time dilates and length contracts and stuff like that. And from that came the abstraction of spacetime. And so, somebody said, hey what if we can talk about things moving around down on the surface called spacetime. But Einstein said, oh, that's a nice abstraction of the work I've done. What if this spacetime surface was curved itself?

Corey: Right.

Ben: What if there was some curvature, what if there was some dynamic to it. And so Einstein's picture, the Earth doesn't orbit around the Sun because the Sun is pulling on the Earth using an invisible cord. The Earth is going around the Sun because spacetime, the surface describing distances and times between events itself is curved. So, the spacetime is like a curved surface, the Earth is always moving in a straight line but because it's a straight line on a curved surface it closes in on itself and you see the Earth going around in a loop.

Mike: And that's General Relativity, essentially.

Ben: Yeah, Yeah. So, Einstein introduced this idea that spacetime, this idea that distance itself, was a dynamic quantity. And so what happened was, you could apply Einstein's theory to talk about this universal set-up where everything starts out pretty uniform, undifferentiated matter. There's no difference between one point and another. And when you apply these equations to it the distance between two points that aren't moving, feel no motion, none of them have rockets, none of them are on bicycles, but the distance between them can be dynamic even if they're not properly moving. And so this is what's expanding in the Universe, it's like ah, it's like if you take two ants and you put them on a squished up sponge and then you let the sponge go so the sponge expands. The ants will say oh, we're moving apart from one another. But really what's happening is the sponge underneath them is expanding.

Corey: Right. So they don't feel that they are moving relative to the things that are immediately surrounding them.

Ben: Yeah, that's right.

Corey: And yet the distance is expanding.

Ben: They're like I'm stuck to this point on the sponge and the other ant is like I'm stuck to this point on the sponge but they see the distance between each other increasing.

Corey: So, this is essentially a mathematical construction designed to explain, or show the patterns, of these kinds of motion. Because it sounds like the thing that is explained in a different way is how these things can be moving differently apart without any impetus of motion for any one of them. As you say, they don't any one of them have a bicycle and yet they are moving apart. Why are they moving apart?

[11:22]

Ben: The way you state it, it's kind of backwards to how it happened in history. What happened was, the people applied the mathematics to these very simple models. The assumption that the Universe is initially full of undifferentiated matter where it's not denser in one point than another. It simplifies the mathematics a great deal, right. So when Einstein first proposed his theory they applied this symmetry to it just to make the equations be much easier to solve. And they saw these dynamical universes. So, these mathematical models described a Universe that expanded and collapsed and Einstein saw them and was like, that's B.S. No way is that possible. And so he introduced this term, the Cosmological Constant. He's famous for saying it was his greatest blunder. He introduced this special term into the equations that would keep everything still. And then he said there, the Universe is obviously sitting still. We don't need to deal with it. And then immediately after the astronomer Hubble discovered that the Universe itself was actually expanding and so these models describing the Universe expanding, that we're talking about actually fit the data to a remarkable degree.

Corey: The data being the modern astronomical data.

Ben: That's right. So, what we have here is a picture where the Universe starts off undifferentiated. Everything is really, really hot. If you take a gas and you put it in a cylinder and then you compress the cylinder the air inside of it heats up. And the reason for that is that the temperature is kind of a description of the energy density

Corey: Right.

Ben: How much energy is there per volume. And so if you squish the volume smaller and smaller and smaller the energy density goes up even though the particles themselves don't feel like they are moving any faster. They are bumping into each other a lot more. And so the temperature itself goes up and if you increase a gasses temperature hotter and hotter and hotter what happens is they start bumping into each other enough that they start knocking off electrons. And so in the very early Universe there was a time when there was just a soup of hydrogen, a little bit of helium, it was so dense, so hot, back then because the Universe was smaller than it is today so everything was so much and denser, that the hydrogen was all ionized, it was all a plasma. Yeah, you got a question?

Corey: I do. What happened to infinite.

Ben: It was still infinite. It's just...

Corey: Wa, wa, wa, wa, wa, wait.

Ben: Yeah, yeah. Okay.

Corey: How can one thing be infinite and smaller than another thing that's infinite?

Ben: Ah, so, you're absolutely right, the complaint, that's an old Greek philosopher complaint, and I appreciate it. So, what we're saying here, is, I mean, we do, we describe it as increasing in size the way the ants on the sponge would. They say, aw, the volume, ah, the sponge is increasing, right. But what we actually describe in terms of things increasing and decreasing is, we talk about the density of matter increasing and decreasing. Because the density, as the ants on the sponge, as you squish up the sponge, as they get closer together, more ants are going to fit inside of a box that you draw on the line.

Corey: Right, right.

Ben: And so, the density of ants on the sponge, inside your little box, is increasing and decreasing, even if you can't talk about the volume of the Universe increasing and decreasing...

Corey: The density increases and decreases. Okay. So, essentially, it sounds, if I'm understanding, then, it sounds like the question which would say, is the Universe actually infinite or finite in size, is a question in which you're not particularly interested. Because, as you were saying, if it were infinite we wouldn't be able to know it. Is that right, so, basically we're you treat it mathematically as if it's infinite but in fact we just sort of confess ignorance on that question?
Ben: Yes, very good.

Corey: Okay.

Mike: You can come up with very strange topologies to the Universe, right. Where it looks infinite but it's not. Like, picture a donut, where...

Corey: Right.

Mike: You can go around it in different ways and you end up on different spots but it is a finite thing. So, it's a hard question and people try to figure out ways to determine the answer to it but I would say that it's considered part of esoteria.

Corey: Okay. So, basically you feel fairly confident that the Universe is, at the very least, larger than we could possibly measure and so therefore it might as well be infinite.

Vicky: Yes.

Corey: Yeah. Okay.

Ben: And that mathematically it's described by a model which says it's infinite.

Corey: Okay. I'm willing to let it go but that's a little bit of a stumbling block to me because, again, mathematic infinity, like what infinity does to equations, it seems to me, not necessarily to describe. Again to say that it is bigger than we can measure is, mathematically, not to mention philosophically, a very different thing from saying it's infinite.

Ben: Yeah.

Corey: It kind of seems to me that to actually use mathematical infinity in your equations to describe the universe, seems to me like at least potentially introduces some hand waving into things and inaccuracy. Because again, if it's not actually infinite but just really, really big, even bigger than we can measure, then the equations, in fact, might come out very, very differently if you have a finite versus an infinite number because that's a very significant difference.

Ben: Yeah, well I mean, physics is a really local thing. You need to do some pretty bonkers things to have... What happens is infinity entering into your equations because...

Corey: Right.

Ben: ... information will only propagate at the speed of light. If we assume a very, very large patch of around us, larger than we could ever measure, has the same consistent density then we would say it might not be infinite but mathematically we can't tell the difference between this and infinity. And it's not like infinity enters into the equations, really, all it does is the equations become very simple and there's no edge to anything.

Corey: Okay.

Ben: So, it's not quite as spooky as we make it sound when we say infinite. We just mean it's the same everywhere you go and there's no edge.

[16:48]

Mike: And to be fair the, everything we're going talk about today is completely agnostic to that kind of question.

Corey: Fair enough. So, we're expanding, we've got the ants on a sponge and this is a description of the way that the stuff in the Universe actually moves apart from the rest of the stuff.

Ben: Yeah. Essentially the early Universe is a gas, and a really, really hot gas. And so, essentially, what it's made up of protons and electrons. Protons have a positive charge. Electrons have negative charge and photons, light. And, you know light interacts really strongly with protons and electrons and so everything is bouncing around like crazy . A photon comes in, smashes an electron, sends it flying in different direction. A proton and an electron might try to join together to make a neutral atom and in doing so they'll shoot off a photon but then before too long another photon comes in and breaks them up, okay?

Corey: Okay. Yeah.

Ben: So, everything's dynamic and crazy and really, really fuzzy.

Corey: Yes.

Ben: And this was bright. It emitted a lot of light. It was like the color of a hot gas.

Corey: And this is understood this to be, more or less, universal. So, we're talking about an enormously bright sponge.

Ben: That's right. Well, everywhere you go it was the same amount of bright.

Corey: Gotchya.

Ben: That's right, a gaseous sponge. Like I keep saying, the Universe underfoot was expanding and so the distance between all these atoms on the sponge are getting bigger and that cools down the gas and the photons are going to, it's called red shifting, the expansion of the Universe makes the photons redder in color, their energy decreases as time goes on. And so what happens is the Universe, as it expands, the photons cool, the photons on average won't be energetic enough to knock the electron and the proton apart.

Corey: Okay. And there would be, presumably, fewer of those collisions as they separate.

Ben: Yeah, that's right.

Corey: Right, so, yes.

Ben: Right. And so you have all these photons suddenly around that aren't blue colored enough to knock apart the protons and electrons and so they're not really interacting with anything. We call this era recombination.

Corey: Recombination. Is there a net decrease in the number of photons or is it that they interact less frequently with other particles?

Ben: Well, these photons, they're kind of, ah, they're kind of like lost dogs left behind after the party. They ah...

Vicky: That's so sad.

Ben: They don't, yeah, they make up something called the Cosmic Microwave Background. Ah, because they stopped kind of interacting that strongly with matter but they're still kicking around and the Universe is full of them. As the Universe expanded, they got cooler and cooler, more red, red color until now they are microwaves. And essentially the Universe is just kind of full of this microwave background bath of radiation.

Corey: And the uniformity of this is the reason why you are suggesting no localized center of a Big Bang at the beginning. Because that's not the pattern we would expect to see if things had started from one point radiating outward.

Ben: That's right.

Corey: So the uniform background radiation is what suggests that that's not, in fact, how it happened.

Ben: Right, so, this recombination happened 400,000 years after t=0.

Corey: So, we had the really hot glowing sponge for 400,000 years?

Ben: Mmmmhmmmmm. That's right.

Corey: Okay. Recombination in question, the things that are combining are protons and electrons?

Ben: That's right.

Corey: Into hydrogen atoms rather.

Ben: Into hydrogen atoms.

Corey: Primarily. It's called recombination because they used to be combined?

Ben: Apparently, that's a misnomer. They just ah, there's another type of radiation in the Universe called recombination only it happens around stars and stuff.

Corey: Awesome. That's the kind of thing that drives physics students absolutely crazy.

Ben: Oh isn't it horrible?

Mike: That piece of nomenclature is no friend to public explanations.

Ben: No friend.

Laughter

Corey: Alright, so it's called recombination even though they'd never combined before and so t=400,000 years. What is the threshold that we have crossed that makes us say "and now begins the recombination period?" Is it, when the photons drop down to a particular energy level?

Ben: Yeah, when they, when the photons, on average, can't ionize the gas anymore.

Mike: We consider that epoch to be the time when the CMB was released because we're saying the same thing. The technical definition is the time at which photons and matter are decoupled from one another

Corey: Okay.

Mike: So those are all saying the same thing.

Corey: So, whereas, before they were just in this sort of chaotic mix and hydrogen atoms forming and being unformed and photons flying all over the place and dying and being born. And so now we've reached a more stable state of hydrogen atoms which now by and large, ah, with fewer exceptions are able and content to remain hydrogen atoms. And the photons have now calmed down and are no longer disrupting so many atoms and therefore we have a stable population of hydrogen atoms and a more calm level of photons floating around and nobody is colliding with each other nearly so much as they used to be.

[21:47]

Ben: The party's over. Everybody's gone home with their partner.

Corey: Yes. Exactly. It really does sound, ah, yes, that was actually something very much like what I had in my head right there. Yeah.

Mike: To go back to Ben's analogy, this is the time when the Goths were sacking Rome.

Ben: Then what happens is, essentially, the Universe is still very uniform, everywhere you go the density of matter is still about the same but it's not emitting light anymore. And the Universe is full of neutral hydrogen gas.

Vicky: Right, so you've got all this neutral hydrogen that's like, everywhere. But then as the Universe, because the Universe is continuing to expand and cool, this hydrogen doesn't have as much energy anymore. And eventually gravity will pull these atoms together and the same with dark matter. So, dark matter is just there hanging around but it doesn't interact with the protons anyway. So, the dark matter is starting to form clumps. The hydrogen starts to fall in there too, now you're starting to get structure.

Corey: Can I ask two questions? Okay, question number one, what is it that makes the hydrogen atoms join together? Doesn't that require energy?

Vicky: So, you've got your dark matter that doesn't interact with light. And the dark matter, basically only interacts with itself. So, the gravitational attraction of the dark matter particles will start to clump them together. And then your hydrogen atoms can also interact through gravity with dark matter and they join in the clumps. Does that make sense?

Corey: I think I have to ask, first, my second question which is, what is dark matter made of?

Vicky: We don't know.

Corey: We don't know, by definition because it's dark and therefore...

Vicky: By definition...

Corey: doesn't interact with light.

Vicky: It only interacts by gravity, that's all we know about it.

Corey: So, we know about it basically by calculating total mass and subtracting the mass of the stuff we can see and saying...

Vicky: Yeah.

Corey: ... Gosh, there's mass left over, that is all I know about dark matter.

Vicky: Yeah. That's it, so...

Corey: Okay.

Vicky: Like they measured galaxies and then they were like that's not right.

Corey: Right, there's something that is monkeying with the numbers there.

Vicky: Yeah.

Corey: Now what then leads us to believe that it forms clumps in some sense?

Vicky: We see the affects in galaxies, like it tends to form these halos around galaxies...

Corey: Okay.

Vicky: So you've got these huge dark matter halos and that's how we kind of see it interacting so we know that it interacts by gravity and that it will clump together.

Corey: Okay. We can see it's gravitational affects on other things.

Vicky: Yeah. Yes.

Corey: Okay. So, by watching the patterns of movement of the things we can see we can say, gosh, this looks like it has some kind of orbital interaction with something else that we can't see. Or rather its orbital pattern would be explained by a massive object or some sort of mass which we can't see so then therefore dark matter does interact gravitationally with stuff.

Vicky: Yes.

Corey: It is only dark inasmuch as it doesn't interact with light.

Vicky: Yes.

Corey: With photons? Okay.

Vicky: So, this started happening around 500 million years after t=0. Yeah, so, this is a like a long time ago...

Corey: Oh my goodness. So we've totally left the bright sponge in the dust. I mean it's like ancient history...

Vicky: Yeah, the bright sponge is gone...

Corey: Absolutely. So the bright sponge lasted for 400,000 years and then it's been now 499,600,000 years since then.

Vicky: Yes. I'm glad you can do maths in your head, I can't do it.

Laughter.

Corey: Okay, I just trying to make sure I'm understanding the scale properly.

Vicky: Yeah, so this is like a super long time later...

Corey: Yeah, absolutely.

Vicky: It's just like now we're starting to form structure and we're getting the first stars. So, these first stars are like proper weird because they're only made of hydrogen. So, like the stars you see today have hydrogen and helium and like all these other elements. But these first ones are just hydrogen so they're really massive. They're literally huge, giant balls of hydrogen. They're like a hundred times more massive than the sun and they're really, really hot, so they emit tons of UV light. They're just insane, these weird stars.

Corey: So, I'm trying to make sure that I understand why this is happening.

Vicky: Okay.

Corey: We're getting cooler and more spread apart and so, of course, one would think that in theory things would clump together less not more as time goes on. Basically the reason they're clumping together now where they didn't before is that before you had those super energetic protons agitating everything and so nothing could settle and so even when things were colliding nothing was coming of it. And so when finally, like, you know, we've put the kids to bed and we have peace and quiet, ah, now, like they, although they interact less frequently, the hydrogen atoms, because they're further apart. They do still occasionally, by chance, hit each other and when they do they now can gravitationally form up together. So, and that's why also it would take so much more time because they're spread apart...

Vicky: Yeah.

Corey: ...and getting further apart...

Vicky: Yeah, they're even further apart then when they do clump together there's not going to be a photon comes along and kicks them apart again. It's...

Corey: Right, exactly.

Vicky: They just... So now you've got, you've got these gravitational structures and they can collapse further and they can like make the first stars...

Corey: And like the dark matter, we don't have any idea how the dark matter is interacting with the actual star formation?

[26:49]

Mike: The dark matter is important because it's providing the seed for the other, baryons we call them, stuff that makes light, basically, that interacts electromagnetically. Um, they're providing a seed for that, because, just to go back a couple steps. A definitional difference between dark matter and baryons is that dark matter is defined by the fact that it only interacts gravitationally and then baryons is kinda like everything else.

Corey: Okay.

Mike: So what's happening is dark matter sees a bunch of dark matter and where there's over-dense regions and under-dense regions it starts to fall down and get denser and denser and then other parts of the universe you know, more and more under-dense. And baryons are more complicated, right, because they can talk to each other through all these different mechanisms. And so they have a kind of property where they both want to attract and they want to repulse each other and it gets complicated.

Corey: Right.

Mike: With dark matter's function...

Corey: With gravity going on as well as the...

Mike: Exactly. Gravity...

Corey: Electromagnetic forces.

Mike: Those are the dominant things. So, basically dark matter is giving a place that the baryons can live preferentially closer together. That's it's function.

Corey: Okay. The way that it provides this place is gravitationally, right? So it, by being gravitational stuff it helps gravitationally to attract hydrogen atoms together...

Vicky: Yeah.

Corey: And then those hydrogen atoms interact with each other in these ways so even though none of them are actually interacting with the dark matter in any way other than gravitational. So, it's like, so the dark matter is basically sending out the invitations as, see the metaphor of seed, ah, was troubling to me for a second because that suggests that the dark matter is in someway going going to turn into the other stuff... or something.

Ben: So, it's like, imagine you have a gymnasium full of people, right. And there's two types of people. There's posers and there's cool dudes.

Corey: Ok, cool dudes, yeah.

Ben: So, the cool dudes don't care what the regular people are doing. They don't talk to each other, they don't talk to the regular people.

Corey: Right, they are far too cool to even interact with each other.

Ben: That's right. Well, no, they don't interact with anybody else. But they have their own, they're cool, everybody... So, the deal is, they kind of clump up at first. They're like hey man, that's the cool place to stand in the gymnasium.

Corey: Right. Right.

Ben: And then all the rest of the people who interact with each other, they're calling each other back and forth and they're moving around a lot. They go, oh, maybe there's something going on in the cool places that those little clumps and so they start to gravitate and the more people that go to those places the more other people around them are like oh look, that's the place to be. And so you end up with everything collapsing down around these centers that were started by the cool people.

Corey: So, the cool people, who are cool but entirely misanthropic and don't...

Mike: Yeah.

Corey: ... in fact interact with anybody...

Ben: They're cool.

Corey: ...but still have this magnetic sense of coolness which draws other people to them. And the other people, when they're there are like hey, you like this cool person, I like this cool person, let's get together. Got it.

Vicky: Yeah.

Corey: Yeah, okay.

Vicky: So, that's like forming your first, like, proto-galaxy stars.

Corey: Okay, proto-galaxy, alright, and I've always been a little shaky on star formation. Ah, but if enough of this matter gets together in the one place and forms a gravitational center then these things are going to, ah, you know, a large enough gravitational clump then this stuff is going to start interacting in this way.

Vicky: We've got this clump of stuff and then once it gets enough mass in a concentrated space then it will collapse gravitationally. Like the gravitational energy will collapse it and then it becomes so dense that the hydrogen can interact and fuse. And then that's what's going to release your energy.

Corey: Right. So then that's when, you're now talking about star formation and you were talking super massive stars.

Vicky: Yeah, these are huge stars where they are only hydrogen. There's no other elements in the Universe at this point so these are just hydrogen, they're massive, they're really, really hot and they live for a really, really short time. And this is happening at like a billion years after t=0.

Corey: We were at 400,000, at the end of the bright sponge phase and with the beginning of the combination phase which we call the recombination phase for some reason. And then, that was at 400,000 and that lasted until 600 million?

Vicky: So, the dark ages goes to like 500 million.

Corey: 500 million.

Vicky: And that's when the gravitational effects start to happen and then you're starting to form structure... And then at a billion years your stars start to appear.

Corey: Okay. Alright, so from 500 million to 1 billion the gravitational clustering and the stars are finished forming at about a billion.

Vicky: Well, they're not finished forming. They're still forming. This is the...

Corey: No, of course, they're still in process, yeah.

Vicky: First population of stars is when they're forming.

Corey: Okay.

Mike: Just to go back another step. The gravitational collapse is happening the whole time. It's kinda like, it takes that whole 500 million years to go from this kind of pretty uniform soup of neutral stuff to the point where you actually have these nucleated things that can start, you know, lighting their furnaces so to speak.

Corey: Right.

[31:45]

Mike: So, that evolution is happening the whole time. And okay, so, we have a definition and I hate to do this to you because recombination was the first one that's bad. We have another crappy astronomy definition here which is...

Corey: Awesome.

Mike: Astrophysicists call metals to mean anything that isn't helium and hydrogen. Anything heavier than that is a metal.

Corey: Right!

Mike: So, I introduce that because if I don't I'm going to say metals and you're going to think of, you know, steel and I don't mean that.

Corey: Yeah, exactly, right. Okay. Oxygen is a metal, got it.

Mike: Okay, so, when you have these stars that are just helium and hydrogen, helium doesn't participate. Hydrogen is the thing that matters. The point is that in the local Universe, when we look around us and we ask, how do stars form, you have to get this huge massive gas into a fairly compact region. You know, what's the density of the sun? It's like the density of water, right? Something like that. So, you need to get pretty dense in order for the hydrogen to want to fuse. So, in the local universe there are...

Corey: Can you define local, please, based on how you're using it here.

Mike: Local means our galaxy and galaxy we see around us, in this context.

Corey: Okay.

Mike: So, you know, when guys go out and they look at beautiful star forming regions like you see with Hubble and stuff, I'm thinking of that process.

Corey: Okay.

Mike: So, in that process there is a thermal dynamic problem which is that as you pack stuff together, you know, with gravity, it gets hotter and when things get hotter they expand back out again. So, you need some way to shed that heat in star formation. And so, in the local Universe, I guess, by local here I'm expanding my definition to mean anytime there are metals. Because, in, sort of normal star formation what happens is the metals have a bunch of, you know, complicated quantum level transitions that they can do with electrons and other atoms and things like that. Chemistry basically. They can inject energy that way, they can emit photons in all different wavelengths and basically it comes out in the infrared and sub-millimeter. But basically they can shut that heat very efficiently which leads them to be able to make small stars like our sun, or even smaller. Now, when you take the metals away and you're stuck with just hydrogen, there's only really one cooling mechanism and it's very inefficient. So, the property of that is that it takes a lot of mass to get everything kind of close enough together to start fusing in the center and turning it into an actual star. So, these early stars, we call them population III, it's the first generation of stars in the Universe. Um, and they're cool to understand.

Corey: And it's called Population III

Vicky: Population I is now and then Population II is the ones before now and we thought that was it but then we were like oh no, there's Population III as well.

Corey: I see, so we're counting backwards in time in the population. Okay. I see.

Vicky: Yeah.

Corey: Can I also just say that I find the metals thing is way more excusable than the recombination thing.

Ben: I know, that one's bananas.

Corey: Like, that doesn't make a lick of sense at all. But the metals thing, one could say that perhaps the place of the word metal was a little unfortunate but I can certainly see from a chemical and a quantum physics standpoint why you would want a category which was all elements that are not hydrogen and helium. I mean the difference between hydrogen and helium on the one hand and all the other elements on the other hand, that distinction, from like an astrophysics standpoint, makes perfect sense. That you would want to have the two categories. But to call that second category metals, that's the really dumb thing.

Mike: It's a little bit more wieldy than the elemental products products of nucleosynthesis, right?

Corey: Right. Though even an acronym is better than the name of another category that already exists and call something else. Maybe it was designed, actually, to foment discord between astrophysicists and chemists.

Mike: Astrophysicists love to make up completely nonsensical names for things so this won't be the last time you think that.

Corey: Yeah. Okay, so anyway, we were saying we'd gotten so far as the formation of these super-massive hydrogen only stars which are now beginning to fuse and to emit light. Okay.

Vicky: Yeah, now we're starting to get light again.

Corey: And it's about a billion years.

Vicky: Yeah. So, now we've got these stars That, that by the way, we've never actually seen, nobody's ever seen one, but we know they're there. So, they're starting to emit light again. We also have quasars. So, quasars are like super bright galaxies with black holes in the center which are also ionizing. So now you've got these two sources, the first galaxies and the first stars that are starting to emit light. And now these are emitting light that is much more energetic than what was left over before in the microwave background. You've got, like this big clump of gas and that starts to fragment and make your first group of stars.

Corey: Right

Vicky: So, they're kind of already in a cluster if you get what I mean. And then as time evolves then those first stars are going to go supernova, they're going to explode. And that's going to happen pretty quickly because they're so big they don't live for very long. And that's going to send out a lot of radiation. Now you're going to start to get metals.

[36:44]

Corey: I was going to say, now we're going to get metals all over the place. With stars going supernova.

Vicky: So, now your new lot of stars can form which is what we call Population II which are the oldest stars we see today. And they do have a bit of metal in them. But now you're going to start to see things that look more like galaxies do today.

Corey: Did Population II stars begin to form then I assume the Population II stars that are still around...

Vicky: Yes.

Corey: ... are, must be small. Right? If they're still around, presumably. Right?

Vicky: Yeah, we still see them today. We still see them in things like globular clusters. We do still see the Population II stars. But it is this process of like the very first stars forming from this hydrogen that starts to begin to re-ionize the universe.

Corey: Right. We still have our old tired photons out there forming the microwave background and minding their own business now. But now, because of the fusion that's going on in the cores of our super massive, weird hydrogen stars, we now have new much more energetic and thus interfering photons which are going out and energizing stuff.

Vicky: Yeah.

Corey: And thus we have the end of what, of what you're calling the dark age because now we have light again with the...

Vicky: Yeah, that's the very start of it, is when these stars start to form I think.

Mike: Right. So, we're at the stage, we're giving way to some nice baroque music in the background and we're starting to form little galaxies and things like that. Um, so, the big question is, we have this fairly uniform soup of neutral hydrogen and helium in the early universe and then we have the Universe we see today and one property of hydrogen is that it absorbs photons, right. So light can't go very far through it. So, on the other hand the Universe we have today, we can essentially see billions of years into the past. Which means that at some point the Universe has gone from this neutral absorby thing to a transparent non-absorby thing and what is that process? So, the answer is that process is re-ionization and it's because of the kind of objects we were just talking about with Vicky. And one property of these objects is that when you have a super massive star it puts out a lot of ultraviolet photons which are exactly the kind of photons that cut like a knife through this neutral stuff and start to basically bump electrons off the protons and make the Universe transparent. So, if you picture it, you have a little proto-galaxy in the center of this dark matter potential in this uniform soup of neutral hydrogen, and you're going to just burn that away so you have this little light bulb in the middle. I told Ben earlier, it's like if you have a candle or a thing of wax and you took a Christmas light and you put it in the wax. It just starts melting slowly, slowly, slowly through that medium turning it so it's transparent.

Corey: Okay, so Deionization? That's what you called it?

Mike: No, Re-ionization because...

Corey: Re-ionization, re-ionization, okay.

Mike: Because if you remember we've gone from an ionized Universe back...

Corey: So, we're returning the hydrogen atoms back into ions again.

Mike: Yeah, exactly.

Ben: This, this Re, the prefix Re is meaningful this time.

Corey: Right, right, exactly.

Laughter.

Corey: Right. Right. Okay.

Mike: The process, basically, looks like a bunch of bubbles, like Swiss cheese and so the bubbles get bigger and bigger and start meeting up.

Corey: Bubbles forming around stars...

Mike: And eventually, exactly. And that's how we get the Universe we see today. So, that's interesting and it's interesting because it's the one part of cosmic evolution that we don't know very much about and we would like to understand more, most of cosmic evolution. Specifically this transition from the dark ages to sort of the transparent Universe is a very hot topic in astrophysics these days. And it's because of all the weird processes that are involved that there are no local analogs to.

Ben: Can I try a Lord of the Rings metaphor now?

Corey: Hey, let's do that.

Ben: Okay, so like, okay, so, you've got this battlefield right?

Corey: Yeah.

Ben: And it's covered in orcs. Orcs! They're shooting arrows and stuff.

Corey: That happened several times, yeah.

Ben: The deal is an arrow can't travel very far on a battlefield without hitting an Orc.

Corey: Which is an advantage if you're opposing the Orcs.

Ben: That's right. But, you know, let's say you want to send a message to somebody by tying a note to an arrow and shooting it over at your friend.

Corey: A mechanism which can easily be misconstrued during a battle, I have to point out.

Laughter.

Ben: It's true.

Laughter.

Corey: But anyway, yes, carry on, carry on.

Ben: I was thinking about doing this in terms of throwing hobbits at each other but let's stick with orcs for now.

Corey: That also could be misconstrued.

Vicky: Nobody tosses a dwarf.

Corey: Right. Exactly. Yeah.

Ben: Um, so, oh, dwarves, that would be good. Anyway, we'll keep going with arrows though, right. So, essentially you've got these clumps of elves, surrounded, surrounded by, ah, orcs. And what they do is they shoot a whole bunch of arrows out. They're just shooting arrows out, pushing the Orcs back turning them into stuff that doesn't absorb arrows, specifically dead bodies lying on the ground.

Corey: Corpses lying on the ground.

[41:42]

Ben: Right. Until these clumps of elves have pushed back all of the orcs so that all of them are either pushed back into clumps or blown away and not absorbing arrows anymore. And you can send your nice arrow message over to Legolas and say hey, what kind of conditioner do you use.

Corey: Right. Um, that is indeed a grim picture of this process.

Corey: If we're re-ionizing things why don't we get the return of the bright sponge? Because the atoms that are being ionized are further apart from each other than they were before?

Mike: So, it's this thing that can absorb photons just like orcs can absorb arrows. Once the arrow is gone it's out of play.

Corey: Right. But back in the good ol days, you know, before we started recombining, photons would come in and they would hit a hydrogen atom and they would ionize it and they would fly off. So, basically, they're not bumping. So the photons are absorbed by the hydrogen, so that process of the ionization of the hydrogen doesn't release energy.

Mike: It's an energy balance thing. It's that in the early Universe you had a whole bunch of energy and then at recombination you've released a lot of that energy in the form of photons that are no longer coupled to the matter.

Corey: Right.

Mike: And then the Universe expands and so those original photons that got released through that process are out of play now.

Corey: They're background infrared photons that are now old and cranky and don't... Okay.

Mike: Exactly, exactly. And now you're using different photons from sort of a different bank to do the re-ionization and so they are enough to re-ionize the Universe but not enough to fill it with a uniform bath of photons like there used to be.

Corey: So, just thinking individually, I'm thinking of one photon hitting one hydrogen atom and the hydrogen atom is ionized. This does not release energy?

Mike: It liberates the electron from the proton but it doesn't actually cost energy.

Corey: So, no photon would be emitted from that process.

Mike: Correct, it's absorbed.

Ben: And then the electrons out in space. The Universe has gotten bigger since then...

Corey: They're much less likely to run into another proton and reform a hydrogen atom.

Ben: Yeah, it's going to die alone.

Mike: Or maybe get bound up in a galaxy later on and be happy. Who knows?

Mike: Okay, so we don't understand that process so there are several questions that would help us understand. So one is, exactly in detail, is how do these Population III stars work? We don't know, we've never seen one. We can kind of guess but eh, you know. One is, and this is a hot topic right now, what were the galaxies or proto-galaxies responsible for this re-ionization process. What did they look like, how do they compare with the stuff we see around us today. They're probably very low mass and low mass means faint so hard to see so we're going to have to hard time studying them. But, that's a big question right now, is, how did the metals, for example, get put into the other stars, to make Population II stars, what was that process?

Corey: Right.

Mike: So, these are things we're just starting to maybe understand, a little bit about observationally but definitely there's a lot more work to do. Um, how do we know anything about this, right? Ah, so you can make measurements three different ways. Basically you can look at the light that would have been, if the Universe was neutral and the photons were getting absorbed, you could look at the wavelengths where that process would be happening and say okay, I see it now or I don't see it now. So, we're having a lot of success there. We're seeing kind of midway back into this process where we're looking at very distant, very faint galaxies and saying, ah, I see that guy and it's at whatever distance and so at least I can see that far back and you can study, basically the area around it and ask questions about what are the metals there, what's the gas doing, all these kinds of things.

Corey: Right.

Mike: There's a second way which is kind of complicated and we can spend time on it if you want. Which is that the Cosmic Microwave Background, I've been, we've been kind of fibbing to you a little bit, right?

Corey: Okay.

Mike: We said, it's not coupled...

Corey: I knew it! Sorry, go ahead.

Mike: It is a little bit coupled. So, you actually get a couple different affects where that uniform soup of photons that's old and tired now is still a little bit talking to the matter now that it's got ionized again it can talk to the electrons. And so we can look at, you know, microwave frequencies today and look for various distortions. The recombination Cosmic Microwave Background is very simple. The physics is understood. You can write down the equations and do some math and say ah, it looks like this. But the lower redshift stuff is not simple and it's nonlinear and it's kind of ugly. So, what you basically do, is you're going into the Cosmic Microwave Background and you're saying, where is all the ugly bits that I can't explain with a simple picture. And so from that we know that re-ionization happened, we're kind of certain it was sort of happening at this sort of 500 million years ago mark. You know, and then what happens, a span of, you know, a few hundred million years. But that's a picture that's just now emerging. And then, finally, you can study the neutral hydrogen.

[46:42]

So, what happens is hydrogen in the early Universe is kind of banging around but you can actually form molecular hydrogen which is two hydrogen atoms that are molecularly bonded by sharing electrons. So, you may remember this from earlier studies but the hydrogens actually have a quantum way to talk to each other called hyper fine splitting that emits photons at very long wavelengths and very low energy. So, we can actually take radio telescopes and look for that very low energy, very rare form of emission. And you can see that in the local Universe, right, in our own galaxy. It's very bright at this wavelength. But that emission of course is happening in the distant Universe. It's just it's very far away and very faint. So, the new thing that people are talking about doing is you build a telescope that works at this 21 centimeter but now redshifted to about a centimeter because of the distance from you to where it's coming from. And you can actually use that to make, basically, X-Ray scans or, actually, X-Ray is the wrong analogy. Actually MRIs. By tuning the frequency you can basically take slices of what's the neutral hydrogen doing at those high redshifts and you can sort of take pictures of the Swiss cheese of the Universe at that time and it's going to tell you a lot about structure, how the structures formed.

Corey: Huh.

Mike: So, there's a lot of excitement in astrophysics these days. It's a big new direction that people are building a bunch of instruments for and it's very difficult so the new instruments may or may not see something, who knows. But you'll hear over the next decade they are building this telescope called the Square Kilometer Array. It's one kilometer of collecting area.

Corey: Okay, can I just say that the nomenclature, this is the thing that really gets to me about astronomy. Is that when astronomers and astrophysicists go to name objects or forces or parameters for bodies or anything like that they are over inventive sometimes with names. And then they go to name telescope arrays and completely make fools of themselves. Can I just say that like...

Vicky: Did you see, like, the video a week ago, there was an XKCD comic about the naming of telescopes.

Corey: Yes, I did, I did. I'm a big fan of XKCD and he's dead on about the name of the telescope arrays which are just as dumb as they could possibly be. And so can I just say that the Square Kilometer Array is not helping. Um, really not.

Mike: I'm sorry. There's actually a website you can go look up called dumb astronomy acronym or DAA and you go in and it will describe, and there are some spectacularly bad ones in there.

Corey: Yes, I can easily imagine this. But, anyway, okay, so, Square Kilometer Array...

Mike: I apologize for the Square Kilometer Array

Corey: That's okay.

Mike: The behind the scenes is all these things get a working title until they are built and then they get named after some rich benefactor.

Corey: Yeah, well, and that's, you know, understandable. Hey, but you know like I'm still pleased anyway that the astronomical community as a whole decided to stick with the mythology theme, you know, when they started naming new planets and stuff. I thought that was cool. I was glad that they, because, you know, the astronomers who are naming the new planets were, you know, in a very different place, culturally from the astronomers who named the other planets.

Ben: Do you mean like Sedna?

Corey: Yeah, yeah. Like the little sort of semi-planets or whatever.

Ben: The dwarf planets, the planets that the dwarves live on.

Corey: Yeah, see, this is why I object to the phrase dwarf planet.

Mike: So, actually, in astrophysics there's a big, everybody's a Tolkien fan, right. So there's a very big trend in naming instruments after, you know, all and sundry. So, there's an instrument called Sauron. I think there is an instrument called Melkor, things like that.

Corey: Really.

Mike: Yeah.

Corey: That's pretty cool though, I have to say, they named an instrument after Melkor?

Mike: I think, you'll have to look it up. But they're naming instruments after various...

Vicky: Yeah. It's really hard because they'll think of the cool acronym, like Sauron, and they're like, how do we make that...

Corey: Right, and then they have to bend over backwards to make it fit the acronym, yeah. That's okay, you know, that I think is fine, I actually fully applaud that. Which is better, to think of the acronym first and then put in some stupid words that no one is going to remember or ever say anyway to fit it. Or to think of some kind of sensible phrase that describes it for which the acronym is really stupid and hard to remember. So, clearly, that's obviously the way to go. But I'm just saying that I don't think I would name an instrument after Melkor. I just wouldn't. I think you're begging for problems, um, to...

Mike: He's supposed to be out there somewhere, right, maybe he'll come back?

Corey: Well, yeah, see, that, I would, this is one of the problems. Ah, you know, one of the undesirable events one, in fact, would not want to hurry along, um, according to Tolkien's mythology. But, um, yeah.

Ben: Well, that was fun. Thank you Mike, thank you Vicky. You've pleased me, your efforts have born fruit and that fruit is sweet. Here is some fruit! Mike, you get an apple.

Mike: Nom, nom, nom nom.

Ben: I fished it out of a barrel that was floating around. Okay, Vicky, you get some fruit from the Tree of Valinor.

Vicky: Nom, nom, nom, nom.

Ben: Nice. I'd like to thank my guest.

Corey: I'd be careful biting into that because you could be biting into the Sun. So, you know, you have to be, you have to be cautious with that.

Ben: Come on Vicky! Alright, I'd like to thank my guest Corey Olsen, the Tolkien professor. Thanks Corey!

Corey: No problem, thanks for having me, that was fun.

Ben: That was super fun! Alright. Hey Ti-Phyters, listen, I know you love the show and I love it too. But for every listener of the show I know there's a hundred other people who would love to listen but don't know how. Here's how you can spread the word. First, iTunes. It's still the biggest place to find new podcasts, please give us a review if you haven't. It increases our rank and more people will see us when they go looking for science podcasts. The second is to teach people how to listen to podcasts. Everyone has a smart phone or tablet these days. It's just around the holidays and a very low percentage of them know how to listen to podcasts. So, if you have somebody who might like the show ask them if they know how to listen to podcasts and if they don't know how point them to the Stitcher app or the Podiversity app which is a fun podcast app which carries our show. The third way, is, of course, to spread the word about us online. The Internet is full of weird explanations about physics, most of them are not very good. So, if you see someone on the Internet talking about a topic that one of our episodes covered post a comment telling them about the show. It would be nice if people started treating podcasts like they actually had something to say instead of just four nerds around a table talking about what they ate for lunch. That's it. I hope you'll help us out and point new listeners in our direction. That's it for the main part of today's show. 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 like the Weekly Weinersmith or Science Sort Of, like Astrarium. Fine, okay! The intro song is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Until next time my friends good day and remember to keep science in your hearts.

[54:04]

Ben: (over end music) Alright, so, hey, Corey, can you give me two Tolkien related fruit?

Corey: Tolkien related fruit... Um, well, um, the only fruits that are described as being eaten in Tolkien are the fruits that you would normally find. Like, you can find apples and plums and things like that in the Shire and elsewhere. The only other things, the only other fruits I would describe as being unique to Tolkien are like the, particularly, the fruits of unique trees, like the fruits of the trees of Valinor and that kind of thing. But they're not classified.

Ben: Okay, so ah, alright, I'll give ah, Mike an apple.

Mike: Nom nom nom.

Ben: Hold on! I'm not doing it yet!

Laughter.

Vicky: Didn't give it to you yet!

Ben: What, Valinor? Val-i-nor. Okay.

Mike: Ben, can I jump in?

Ben: Yeah, go ahead. Mike, you take it.

Mike: Okay, so in modern cosmology we have this concept of the light horizon which is if I stay in my spot and I fire a photon in one direction, how far, can that photon, if it doesn't interact with anything, how far does it get? Because we have this concept in physics of causality, right? You can't go faster than the speed of light and so, the causality means that, um, the only thing I care about in my "Universe" is the distance that light can have traveled since t=0, since the Big Bang.

Corey: Okay.

Mike: So, when we say infinite, you know Ben, Ben's right, and you know, the jury's kind of out, I don't think this is the sort of metaphysical kind of question. I don't think we have a good answer to it which is, you can call the Universe infinite or you can call it, you know, finite but for the purposes of the discussion, what we care about is how far can light travel. Because what happens past that we don't care. That's a causal to us.

Corey: Right. Ah certainly, I mean, I agree, it would be theoretically unknowable by the same, ah, reasoning that you just gave, um. But I guess, it leads me to the question, what then are we calling t=0.

Ben: Right, okay, so, um, so, the deal is that the conceit here is that, is that we're playing with infinity. It's kind of tricky if you're, um, if you're not used to the mathematics of dealing with infinity. Um, you're like, how can you compare, if one thing is infinite and another thing is infinite how can you say that one is bigger than the other?

Corey: Right.

Ben: And how can something shrink to zero? And it does have to do with the equations, right. So, we say that, um, recall that what we're talking about is the things aren't moving apart from one another, what we're talking about is, ah, kind of the sponge moving, expanding out under the feet of the thing, right.

Corey: But they are still moving apart from each other in the sense that like, those ants on the sponge are further apart from each other.

Ben: That's right, yeah.

Vicky: Yeah, they each of them are moving apart from each other.

Ben: And that's the sense with which we talk about, about the Universe expanding or contracting sometimes, depending on the model. But in this case the ants would say, well, um, you know, the sponge under our feet keeps stretching us apart. The Universe is getting bigger. Now, that doesn't mean that the sponge ever has any edges, all it means is that the distance between any two points keeps getting larger. And that's the sense in which we mean that the Universe is expanding.

Corey: But in which case we can't use the word infinite.

Ben: Oh, well, in the case of the sponge it's difficult for me to talk about an infinitely large sponge that I've smushed up with my hands.

Corey: Sure.

Ben: Mathematically, ah, that's essentially what we're describing. And one can ask, well, how do we know that the matter doesn't just end somewhere if you walk 14 billion light years in one direction or the other.

Corey: Right.

Ben: And that's an entirely good question. And in fact there are physicists interested in those types of questions. Um, but, for the matter at hand we kind of apply Occam's Razor, right? Um, the Universe is certainly consistent like, okay, so the light we see coming at us from the north, in the direction of the North Pole, you look up north, the light from the very, very early Universe, 14 billion years oldish, ah, that light tells us the temperature, ah, the energy density of the Universe at that time, 14 billion yearsish ago. If we look to the south, that light has come to us from 14 billion years, the opposite direction. And so, what we're seeing is, we're seeing regions of the Universe that are spread where the monstrous distances between them are about the same temperature. And so it's, the data itself is fitting a description of this remarkable uniformity. Ah, and we don't know that the ah, that the Universe beyond what we can see is like the Universe that we can't see, but we know that the mathematic... The data we see is consistent with our mathematical models and our mathematical models describe a Universe with this uniformity.

[59:23]

Corey: Right. But if we're even talking about the universe beyond which we can see it's not infinite, it's just very big...

Ben: Well, we...

Corey: I mean, really big.

Ben: Yeah, yeah, so the models say infinite, um...

Corey: But now, they say infinite mathematically?

Ben: Yes.

Corey: Because that's the problem that I have because mathematical infinity is really quite a large number and, and, and there can't be anything beyond that. This is, this is my...

Vicky: Exactly, that's the whole point.

Corey: But, but we were just suggesting that there might be things beyond that in which case we couldn't confidently call it infinite.

Ben: Oh, right.

Corey: We just have to say it's very, very big.

Ben: We aren't saying that there's anything beyond that, we're saying that it's turtles all the way down. We're saying that no matter how far you go, it's the same stuff.

Vicky: What he's saying is that we can't, like, it's, we're presuming it's the same everywhere. We can only see as far as we can see...

Corey: Which is fine.

Vicky: But we have no reason to expect that anything else is different because our model that predicts the infinite being the same predicts everything else so well, why would it suddenly change at the point we can't see anymore.

Corey: So, but, but again, if we're talking about it's getting bigger...

Vicky: It's the space that is getting bigger.

Corey: Right. Then it wasn't infinitely large if it can increase. This is the thing that I keep...

Mike: It doesn't expand into anything.

Corey: It doesn't expand into anything.

Vicky: Yes.

Mike: No, there's nothing that isn't the Universe.

Corey: Right.

Mike: The observation is, it's a very, it goes back to what Ben was saying before, it's the simple observation that the distance between things is getting bigger.

Corey: Yes.

Mike: And, but that doesn't necessarily, this is where the sponge analogy breaks down. That doesn't mean that you need space in which the sponge can, that it needs to take up more volume. It just is getting bigger. There's no need for it to have some space that it, that isn't the Universe.

Corey: Sure, yeah, no, it's not that I'm thinking of... that the problem I'm having is that if the Universe is getting bigger it must, therefore, by definition be displacing something else or something like that. Um, again, I'm just struggling with, I can, I can conceive of two things. I can conceive of an imaginary mathematical grid which proceeds outward to infinity in all directions. Um, bit that's not a thing. It's an imaginary mathematical construct, it's not a thing. It's not stuff. Okay. And then I'm imagining the stuff, ah, the howsoever like or unlike a sponge in fact, but anyway, nevertheless it is stuff which is, which fits within this infinite grid but inasmuch as the mathematical, the imaginary mathematical grid may go on out to infinity and however far you go you can continue you can carry on imagining, ah, a grid that goes out further past that. I have a hard time imagining that the, ah, the possibly like or unlike a sponge Universe is ah, in fact, if it's getting larger than it must now be larger than it used to be.

Ben: Right.

Corey: In which case it didn't used to be infinite.

Ben: Oh, I see.