Episode 78: The Heat Death of the Universe
Physicists: Katie Mack, Robert McNees

Transcribed by Denny Henke

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

Music

Ben: When I was an undergraduate I took a course in pre-Socratic Greek philosophy. It was really fun and it began with the poet Hesiod and Greek myths and the professor said something that really stuck with me during one of her lectures. She said that there were goat herds back in the day with nothing to do so they talked to the gods because the gods loved listening to stories. And the Greek gods, my professor explained were a lot like people and just like people their favorite stories were the ones that explained where they came from. So, the goat herds would tell them their own stories, about how it began, the family trees, and how the present set-up of the Earth came to be. That gods, just like people, are obsessed with where they came from. it stuck with me because it had never occurred to me before that people might be obsessed with hearing their own stories but it seems to be a universal thing to hear old stories, to hear where our parents came from and how they met and to hear how our grandparents met and made our parents and back and back through history. Our stories don’t just include our own family line though. They go back to the gods and the creation of the Earth and the creation of the universe itself. The word for these explanations is cosmology and every religion that I’ve ever heard has a cosmology. An explanation for the actors and the acts that built the world around us as well as an explanation of how it all will end. So, it’s both surprising and obvious that science should endeavor to find similar explanations. It’s obvious because we are human and our favorite stories are the ones that tell us where we came from. But it's surprising because and how the universe came to be and how it will end are questions of a scope far beyond the evidence we can gather along shorelines and walking through forests and in laboratories. And yet, we have. In so many ways, in so many fields, we're filling in the blanks with the story of our own cosmology. And the clues to answer the biggest questions seem subtle at first. And come from humble origins like studying show pigeon breeds eventually becomes an explanation for what and where humans came from on the Earth. Or, an explanation of how life can exist in our universe and how it can stop might originate with studying engineering of water pumps in coal mines or the temperatures in brewing beer. In fact, from the study of thermodynamics comes the field of statistical mechanics and the concept of entropy. And then the idea that the complexity and structure in our universe might slowly, slowly be winding down. Like a pocket watch run with a giant spring that can never be wound up again. Today on the Titanium Physicists Podcast we're going to talk about the heat death of the universe. And speaking about the end of the universe our guest today knows as much as anybody does because he's the author and translator of *Knownt* . He's responsible for bringing Liu Cixin's world shaking novels, *The Three-Body Problem* and *Death's End* to the English language. But he's a notable author in his own right. His 2011 story, *The Paper Menagerie* was the first ever work of fiction to win the *Nebula Award* and the *Hugo Award* and the *World Fantasy Award* and it made me cry. I'm halfway through his 2015 silk-punk epic fantasy series, *Grace of Kings* which is just the first of the *Dandelion Dynasty* series and is the reason I can't sleep at night these days.

5:05

He's written, more recently, a sci-fi story in the *MIT Tech Review's Anthology* called "Twelve Tomorrows", welcome to the show Ken Liu.

Ken: Hi, thanks for having me.

Ben: Oh, this is going to be so much fun. Now Ken, today's show is going to be magnificent because of the physicists I've brought together for you today. Arise Katie Mack!

Katie: Tadaaaa.

Ben: Dr. Mack got her PhD from Princeton and did postdocs at Cambridge and Melbourne University and she's currently an assistant professor in membership of the Leadership in Public Science Cluster at NC State. Now, arise Robert McNees.

Robert: (Whistle sound)

Ben: Dr. McNees got his PhD from the University of Texas at Austin. He did a postdoc at Michigan and Brown in the Perimeter Institute and he's currently a professor at Loyola University Chicago where he studies relativity and quantum gravity. Alright everybody, let's talk about heat death.

Hey Ken, have you ever heard of the heat death of the universe?

Ken: I think so, I've heard the term.

Ben: Alright. Well, do you want to start Katie because you wrote a book about it.

Katie: I haven't finished writing a book about it but I have finished the heat death chapter. So, I'm writing a book about different ways for the universe to end and the heat death is a really interesting one partially because it's the most likely based on our current understanding of the universe and where it's going and how it's evolving. And so the heat death is an end-state of the universe where, basically the universe doesn't go away, it just stops being able to have anything interesting happen in it ever again, basically. It's a sort of end-state of the universe that is destruction in the sense of everything we think of as being part of the universe as being an interesting thing, is ah, finished.

Ben: It's the boringest of all apocalypses.

Katie: Yeah, it is sad, because, you know, it's just kind of a fade out of structure, of order, of useful things. It's a fadeout of life and intelligence, and if that doesn't exist in the universe it's just like everything just kind of ends in this darkness that's almost at absolute zero temperature and just persists forever as far as we can tell in this totally useless, finished burned out state.

Ben: Instead of ending in ice and fire, our universe ends in like an interminable waiting room.

Katie: Yeah, yeah.

Ken: The sad, deflated balloon of possible endings to the universe.

Katie: There are some little caveats that I guess we might get to later where you can have kind of temporary reprieves in certain localized regions but basically, as far as we can tell, the universe that we live in is evolving toward a state where it is completely uniform and boring and cold and utterly lifeless and without structure.

Ken: I guess that's my first question here. So, in the heat death state, there literally will be no structure whatsoever. So, no brown dwarfs, no nothing. So, everything is just uniform, no atoms even?

Katie: Yeah, everything decays and I guess we'll go through how that all happens. But we think that probably every kind of elementary particle and certainly every kind of composite particle is unstable if you leave it alone long enough. And it will decay and so basically everything will decay into radiation after a sufficiently long time and then that radiation will just be spread out by the expansion of the universe such that you have a very uniform, extremely cold state where it has a theoretical temperature, um, but it's almost absolute zero.

Robert: Yeah, so small that it almost doesn't mean anything different than zero. You just have this very scarce population of, like, maybe there are leptons left that, you know, can't decay or something like that. Really light leptons and photons but nothing else really.

Ben: So, how we get there is an important thing. It's not just physicists are like, man, wouldn't it be great if nothing was left.

Robert: Wouldn't it be great if the universe was just done.

Ben and Katie: Yeah.

Ben: This particular circumstance comes about from arguments about thermodynamics. So, the heat death of the universe as a possible ending for our universe is something that we've been thinking about since the 1800s. Thermodynamics was kind of the study of engines. Engines and temperature. We wanted to know how heat moved around. I mean, it's in the name, heat death. So, the way to think about this is like, one of the first concepts that we get in thermodynamics is the conservation of energy. So, the total energy in your closed system. Let's say you have an engine in your engine room and it's got a bunch of coal next to it, the total energy of that system is constant. Sometimes it's in potential energy energy, like in the coal and sometimes it's in like, useful, working energy like when your pump is running and turning and things are moving. And so, thermodynamics was concerned with how one energy turns into another type of energy. But the overall idea is the total amount of energy in your system is going to be a constant, right?

10:04

Ken: Yep.

Ben: Early engineers sorted energy kind of into two piles. You can think of it as useful energy and useless energy. So, useful energy is the class of energy that you can use to do something useful like pump water out of a mine or drive a locomotive forward and then useless energy was energy that you can't do anything with. So, like, thermal energy is usually kind of a useless energy. So, like, the ambient temperature of the air in your room, we can't harness that energy to do anything useful.

Katie: Well, and this is something that's kind of intuitive, like, if you have some kind of machine or whatever and it's heating up, you know, that heat, where you're just heating the machine up, if it's more inefficient then there will be more heat in the machine and you can't use that energy. Kind of like with, ah, a traditional incandescent lightbulb, it produces light but it also produces a lot of heat and that heat is not useful for what you're trying to do with it. And, so a lot of times, friction or, like, some kind of inefficiency in a machine will distribute some of the energy as heat and that's like a less efficient machine if you're loosing a lot of energy by heat.

Ben: So, when the energy turns into heat you can't do anything anymore with it in your box. So, the idea here is, a room in a box, once you've burnt all your coal and you've turned all that coal energy into heat energy, it's not coming back. You can't turn it back into coal energy to run your machine again.

Ken: Is that always true? Is it ever possible to reverse the process and turn the energy that's being dissipated into heat, back into a useable form by applying more energy somehow?

Katie: I mean, not without making more heat somewhere else.

Robert: They can't be perfectly efficient.

Katie: Yeah.

Robert: You always come out with a little less.

Katie: Yeah. So, like, a steam engine, you know, you're heating up water and then that's expanding and that's driving a piston and stuff and so, so in some sense you're using the heat from, the, you know, the burning of the coal but it's also creating more heat as it all escapes and so, in the total system there is more heat in the end.

Ben: This waste heat, in a specific system, it goes by the name of entropy, you've heard the word entropy before, right?

Ken: Yup.

Ben: And the second law of thermodynamics says that in a closed system the entropy, or this waste heat, is always going to increase. So, the amount of useable energy in an enclosed system is only going to decrease over time. Because, over time, no matter how careful you are, because there's no such thing as a perfectly efficient way to change one energy into another, any process you use, any type of motor you use, is always going to make heat and that heat is always going to be useless so it just piles up until all of the energy in the box is going to be heat and you can't do anything useful.

Ken: Can we talk a little bit about entropy a bit more because entropy I've heard generally defined as a measure of the system's disorder.

Ben: Right

Katie: Mmmhmmm

Ken: It's kind of hard to get a sense of it because the very words order and disorder seem to me somewhat subjective but obviously in science we have to have an actual definition for what disorder means that is not subjective. For example, if you drop a little bit of chocolate syrup into milk, initially when the chocolate syrup is a dot swirling around in the milk that looks to me like disorder and when you actually stirred it all up and it's uniform I would say that's actually more orderly but obviously it's actually the reverse. Right, I mean the completely mixed up state is actually more entropic, right. So, how do we get a better intuition of what entropy actually means.

Robert: So, I think one of the things there that kind of interferes with how you think about it is that there's the notion of order and disorder and there's also the notion of complexity. Right, and ah, they're not necessarily the same things. So something can be disordered but it can have a very low level of complexity. Like, I would say that the description of the chocolate syrup in the milk, once it's all stirred in, I only need one word to describe it once it's stirred in. In any volume there is x amount.

Katie: So, when you talk about.

Robert: So, the complexity is very low.

Katie: Yeah, so we talk about it in terms of like, the number of possible states, kind of. There are only a few ways for the chocolate syrup to be, making a particular shape in the milk. You know, like, there's a, you'd have to describe the path of all of those little particles of chocolate and you have to describe this very complex path and there's a lot of different things that you have to specify. Ah, but, there's only kind of one way for the chocolate to be all around in that shape but once it's mixed in, you know, you can swap individual chocolate particles all over the place and it really doesn't make a difference to the total, you know, what it looks like. And so as Bob said, you only need like one sort of parameter to describe that. Um, but there are so many different ways for it to happen cause, you know, switching the particles around in lots and lots of different places in the milk is totally fine, you get the same answer. Does that make sense?

Ken: Ah, yeah, I get the complexity versus the not complex distinction.

15:01

Katie: Mmmhhmmm.

Ken: It's still not totally clear, I guess maybe, entropy is sort of the measure of a kind of set of many different states that are now meaningfully distinguished from each other?

Katie: Yeah.

Robert: That's a really good way of putting it.

Katie: Yeah.

Robert: So, for instance, if you take that glass of milk and you dissolve the chocolate syrup in it then you could characterize what you would call the macro state of the milk by saying, like, okay it is kind of pleasing light brown color and that's basically all you need to tell me for me to know that the syrup has been dissolved in the milk, right? But there are many, many, many, what you would call micro-states. Like, actual configurations of here's this molecule of chocolate syrup and here's this molecule and there are lots of different ones that would all correspond to, essentially the same macro description. It's this pleasing brown color.

Ken: Okay.

Robert: So, there are so many more states consistent with this pleasing light brown color than there were for the way that it was organized previously which was essentially just this kind of dollop as it falls into the milk. So, in that sense there are lots more states and so that's the notion about order and disorder that we're talking about.

Ken: Okay. I think, I think the reason why I think it might be hard for someone who has not, you know, gone through the math rigorously to understand it, is that the, the idea of entropy here is, we're saying that there is a bunch of, many, many, many possible states here not meaningfully distinguished from each other and the meaningful part here is an empirical, objective measure. Meaning the system can be in any of a billion different states but empirically we don't see these differences as mattering in any sense. Whereas when there is less entropy in the system the different states are in empirically different, that is, they manifest their differences in some physical way that we can measure. Is that one way to think about it?

Katie: Well, sort of. I mean, one way I might think of it is, let's say that you take this glass of chocolate milk and you make a sort of three dimensional grid and for each, in each cell you say whether it has a chocolate particle or not or like, what particle is there, you know.

Ken: Yeah.

Katie: And in the state where you've just dropped the chocolate in and it hasn't mixed in fully, then, for the cells that have the chocolate in it, you have a large number of particles in that cell and for the other ones you have none. But then for the fully mixed state all of the cells kind of look the same so if you swap them around it doesn't make any difference. Whereas with the more ordered state, with the chocolate making this particular path, if you swap a whole bunch of those cells around it will look totally different. So, it's kind of a matter of how evenly populated this sort of space is versus not.

Ken: That makes sense to me, um, intuitively. But, if you zoom into a very, very, very, very, very tiny part of the milk you would see, actually, quite a bit of differences, right? Because each moment there may be a section with two chocolate milk particles then the next second there will be only one and the second after there is three or something like that. Like, if you set your scales small enough, wouldn't you see a whole bunch of very random local variations?

Katie: Yeah, yeah, which is really important because when we define entropy we're defining of a large system and it matters whether that's a closed system or an open one. So, how you measure the entropy in a closed system is very different from how you measure the entropy in a smaller part of the system or an open system.

Ken: Okay.

Robert: Yeah, I think you're talking about actually distinguishing the different, what we call micro-states a second ago. Um, and, you know, if you can do that, if you can resolve the states, then there's really no ambiguity about what's going on. If you can zoom in and say this molecule is here and this molecule is here then you know everything that is going on. But when you step back and you only make these macro observations, um, when the entropy is really big, that's essentially saying, like, wow, there could be, like, any one of a number of things going on consistent with what I'm seeing which kind of connects with the idea that they are very disordered. Whereas when you zoom in and can say something specific then it's not as essential a concept.

Ken: Okay, gotchya.

Ben: Let's take a step back here and put things in context.

Robert: Yeah.

Ben: So, the idea here is, um, when we think about thermodynamics we're kind of conflating two different kind of historical theories. There was the original, classical thermodynamics it's often called. Ah, people didn't know what atoms were or that atoms existed. They knew what fluids were and so they were pretty sure, all they could do was measure the macroscopic properties of a system. So, there was this idea that there was, kind of, two types of energy, useful energy or useless heat, entropy energy and nobody knew kind of why they behaved that way but we developed fairly sophisticated arguments about how to analyze your evolving system. So, if you take your material in a box, you take an ice cube and hot cup of coffee and a lump of coal and a whole bunch of oxygen and a lit match and you put them all in a box and you close the door, eventually, as the system evolves on its own the entropy is going to increase in the box, ah, the useful energy is going to decrease until eventually the entropy in your box will reach a maximum.

20:00

And so that, essentially, was what the argument system, we had no idea what entropy was, we had a vague idea about what energy was, but this is the series of arguments that led us to the idea of heat death. Which is to say, the universe as a whole is kind of a closed system. You can't get stuff from outside the universe and so, over time the useful energy in the universe, say, all the coal under ground because you're like, an English engineer, so all the coal, all I care about is coal, coal and maybe charcoal, the amount of coal in the universe is finite. You burn all the coal, goodbye, there's no more useful energy in the universe, eventually we're going to run out and our steam locomotives won't be able to run anymore. And that's kind of the framework that we use to talk about heat death. Is that you say, well, there's more than coal in terms of energy. There's light from the sun that can make trees and you're like yeah but eventually the sun is gonna go out so the total amount of energy is always, or, the total amount of useless energy is always going to increase. Okay, so, that's classical thermodynamics and the deal was at the turn of the 1900s, just before then, like, ah, theories of atoms, ah, started to emerge describing what matter was and what that allowed physicists to do at the time is develop a new theory called statistical mechanics which said, hey, what if everything is made of these little atoms and they're just jiggling and wiggling around? But, you know, if you've got a cup of hot water, you can't track where each and every atom or molecule in it is. But you can talk about, statistically, where they should be. You're like, each individual atom of water is just bouncing around at random inside this cup of water but statistically we can describe where it might be. And in describing statistically what the matter is doing, the different compositions of matter, you end up with a description of the universe that explains all of the laws we came to in thermodynamics. So, your picture that you were asking us questions about is a statistical, mechanical picture of entropy. All we had is this idea that for who knows why reason, the useless energy always increases in a system until you reach some maximum and then you can't do anymore work. Ah, the statistical mechanics picture was really cool because, you know, it said things like, oh, the kinetic energy of vibrations of atoms is what heat is, what temperature is. So, thermal vibrations, little atoms bouncing around, that's what heat is. It also came up with a really interesting explanation of what entropy was. It introduced entropy as, like what we've been saying, statistical ensembles. This is a bonkers concept and let's walk through what, what we've talked about. The idea here is you've got a glass of milk, where is the milk atoms going to be, they can be anywhere inside the glass of milk. They're just going to bounce around at random. And then you introduce a dollop of chocolate syrup. At first all of the chocolate syrup is in a lump, it's like a micro-state. We know where all the chocolate syrup is in there but you think about it overtime, diffusion happens, right. Overtime the atoms bump into each other and knock each other about and they get more and more spread out over time. And so, after a long, long, long time each of those, each molecule of chocolate could be anywhere inside the glass. And so, statistically speaking the chocolate will be described as, ah, being diffused through the glass of milk. It could be anywhere which generates your, um, picture of a completely mixed up glass of milk. But, the interesting bit here is that we do actually have a method for talking about how the entropy changes. We have a method for describing entropy as a number in terms of this disorder.

Ken: Okay, let's hear it.

Ben: It's kind of complicated, you have to take a logarithm. But essentially what we're talking about, is, all you know about the system are kind of like, macroscopic descriptors. All the chocolate is over here, all the milk is over in this region. You don't know where each individual molecule of chocolate is in the overall lump of chocolate but you know, kind of, that all the chocolate is over here. And so, you enumerate, you add a, you count up all the different possible ways you can get the same picture and you go oh, well, there's 700 billion different ways we can rearrange the atoms of chocolate when they are in this big lump. Ah, but if they're all in this lump there's only 700,000 different ways or whatever, right? You just...

Ken: Right, because there's a smaller space for them...

Ben: That's right.

Katie: Mmmhmmm.

Ben: And then you say, after a long time after diffusion has happened those chocolate atoms could be anywhere. How many different ways could I arrange these chocolate atoms into, oh god, I'm just going to stick with it, these chocolate atoms inside the milk to get this overall diffuse picture. And there's a hundred kabillion of them. There's just so many more because it occupies so much larger space...

Ken: That, that's really helpful, Okay, go on.

24:55

Ben: Yeah, so statistically speaking you're like, well, at the start of it I know that the chocolate is, can be in one of 100 billion, the micro-state, the state of all the atoms at one particular time. I don't know which one it is but I know it's one of these 100,000, some number. And then you say, after the diffusion has happened and the chocolate has bounced around and is now occupying the whole cup, there is a hundred kajillion different possible ways. And so the probability that it is going to be one particular state of this is 1 in 100 kajillion, right, it's a much bigger number.

Ken: Right.

Ben: And so the idea here is that over time, as your milk, like you mentioned, the micro-states in the milk are always evolving. If you look at any little droplet of milk in there sometimes it's going to be one atom of chocolate, sometimes there's going to be four atoms, right, it will change over time. But then statistically speaking the probability that all of those atoms of chocolate are going to go from all mixed up down back into the corner is, there's a probability associated with it but it is exceedingly, exceedingly small.

Ken: Okay, got it.

Ben: And so the numerical descriptors of entropy, which is how much useable energy there is the system, stops being one of an energy accounting game and starts, interestingly enough, becoming a game of statistics. What's the probability compared to, of all of the atoms of chocolate being in this one place, compared to the probability that they are everywhere. It's much smaller so chances are, your system won't evolve to one where it has a low entropy compared to one where it has a high entropy. The entropy corresponds to the probability that your particular atoms are going to be in a particular configuration.

Ken: So, let me ask a follow-up question that I think will clarify this. So, so, let's take two situations. One situation is you have the totally mixed up milk with chocolate and it's close to the freezing point of water so all the molecules are moving a little bit, not as, not a very vigorously. The other one is where the milk is heated near the boiling point so that every atom is jumping around up and down. The second state has more total heat energy in it and if I'm understanding this correctly, the two systems actually have the same entropy measure, is that right?

Katie: Ah, no, I mean, entropy also is connected to heat. So, so when the particles are moving around faster there is higher entropy. Kind of because they can be in lots of different places more quickly, I guess you could think of it that way...

Ken: That's the part, I'm confused why because, statistically speaking, right, the two states seem to have the same number of states or the same probability but your point is if they're moving faster then it actually makes the probability even less.

Robert: Yeah, if all we wanted to keep track of was how many where the chocolate atoms there are you know, in a volume, then that would seem to disconnected but there's really, kind of, no way to ignore the other thing that is going on which is, as Katie says, it's heating up, things are zipping around faster. Um, and in the statistical description of what's going on and how you, how, kind of, how the state evolves, ah you have to keep track of all that stuff.

Ken: Okay, that makes sense.

Robert: Did we cover open and closed?

Katie: So, it is important if the system is open or closed because, then, a closed system you know how the entropy is going to evolve. In an open system, sort of, the heat energy can go somewhere else and so you can't keep track of it in the same way.

Robert: Yeah, I think that the important thing is like, in a closed system we expect the entropy to increase.

Katie: Yeah.

Robert: In an open system, because you can move things around, send someone to some, you know, thing you're connected to that, you know, you can have entropy go down and there's no...

Ken: Well, I guess open refers to the fact that you can put energy into the system and take energy out.

Katie: Yeah.

Robert: That's right, it's in contact with something that you can kind of exchange with.

Katie: Yeah.

Ben: For instance, like, you imagine, like, instead of chocolate milk we were talking about, like, salt. You add salt to water. In terms of entropy we would say you can't get that salt back out of the water. But you can, you can boil away the water, evaporate the water and the salt will all accumulate back into crystals at the bottom, right?

Ken. Right, it's just that you can't wait around until the salt spontaneously becomes a crystal because that doesn't happen.

Ben: Yeah. So, in the second example where you're boiling it off you're essentially in an open system. You're giving the system energy and you're letting the water molecules leave and through that process you can return the salt to a low entropy state.

Katie: Yeah, it's, I mean, it's sort of about when you're actually keeping track of stuff versus when you're not. If there's, if you let particles leave and you don't keep track of exactly where they're going and what they're doing then it's an open system. Or, if you let energy come in that you weren't keeping track of before then it's an open system.

Ken: Ah, here's a point that may be a little bit of pushing it, but the probability that the salt will spontaneously crystallize is very low but it is not zero, right? I mean, if you, if you had a glass of water with salt in it sitting there for the age of the universe and beyond, at some point there is a probability that the salt will spontaneously crystalize right?

Robert: That's right.

Katie: Yeah.

30:04

Robert: Like, if it was a closed system, like, if you really weren't letting any energy come in or out and you just had the salt dissolved in the water then there is a chance that the salt just kind of spontaneously turns into some well organized salt crystallized sitting on the bottom. But you look at the entropy associated with that macro state, and the entropy associated with the salt dissolved in the water and the difference is enormous and it's something, like, there's a factor that tells you how likely it is to get the less likely thing and it has to do with taking that difference in entropy using, doing the number e to that power and it's a huge number and that kind of suppresses it and that kind of tells you how unlikely it is.

Ben: Hey...

Robert: And because that's such a huge number you wait, you know, however many lifetimes of the universe and you know, aren't very likely to ever see it happen. In principle it could, it's just not very likely.

Ken: Right.

Ben: And that's a fascinating concept right? Because in classical thermodynamics it's not going to happen. The entropy is always going to stay high. But if you introduce, kind of, statistical mechanics as an underlying explanation for thermodynamics, you can start to say, well, it could happen, it's just really, really, really, really, really, really, really, really, really improbable.

Ken: Well, actually, that sort of thing is, is catnip for a science fiction writer because with the heat death of the universe, right, as you were talking about, I mean, I could, I could envision that if you just let the universe sit in that completely entropic state. But if you wait long enough it might spontaneously get back to the Big Bang, right, and then we could start over again.

Katie: This isn't just science fiction, this is actual research in cosmology as well. Once you allow quantum mechanical fluctuations into the picture you can do lots of things and people do talk about a possibility of the heat death creating a new Big Bang or our Big Bang coming from a fluctuation of a heat death universe. I think we were going to talk about that a little later as we get more into the topic but yeah.

Ken: We'll get there, yeah.

Ben: It's a pertinent thing to mention because...

Katie: Yeah.

Ben: All we've talked about so far, well, pretty much, is statistical mechanics and thermodynamics and entropy. So, apply it to the universe is a fascinating thing because if you think about it, the argument is, over time, you start out with an aquarium and it's sealed and covered styrofoam or whatever, it's a closed system. You take an ice cube and you throw it in, you take a glass of hot water and you throw it in, eventually everything's going to end up the same temperature and you'll get uniform distribution of molecules and it's very boring, right?

Ken: Yup.

Ben: Okay, we want to apply this to the Big Bang. The argument is okay, so, at the end of our universe is going to be this state where all of the coal is now just random carbon atoms and everything goes away and you don't get any interesting structure anymore because of the increasing ratchet of entropy has dissolved all the interesting parts of the universe and everything is really boring and the same everywhere. When we look at our universe, our information from the Big Bang comes from us starting large, large scale structure universe and the Cosmic Microwave Background. But when we look at the Cosmic Microwave Background which is a record of the temperature of all the different parts of the sky. The idea is that a long, long time ago when the universe was much hotter than it was, you had all these atoms floating around, bumping into each other, creating heat. There was a temperature, they were generating photons and then it cooled to the point where all these photons just kind of got left alone. And so when we map the Cosmic Microwave Background we're mapping those photons from the early, early hot, hot universe. But the photons I'm mapping come from different parts of the sky. They're like 14 billionish years old. The photons I get from looking at the North Pole and the photons I get looking at the South Pole come from entirely different parts of the universe. One is 14 billion light years up and the other one comes from 14 billion light years down. So they come from completely different parts of the sky but when you do that, the temperature from all these parts of the universe is pretty much the same. Which tells you something weird. It tells you that the early universe was kind of a uniform soup where everything was the same temperature and everything was made up of pretty much the same stuff. Shouldn't that be a really high entropy state?

Ken: Yeah, that sounds like it.

Ben: Why in your universe do we start out with a hot soup and...

Ken: Yeah, that’s not intuitive.

Ben: Right.

Ken: You would expect something completely different. You know, the highly, highly ordered state at the beginning, right. That’s what you would expect.

Ben: Yeah.

Robert: Again, ordered vs simple, kind of sneaks in, right? Because we say that we would expect something highly ordered but in fact it was really simple. You don’t need much to describe what it was like. So, in that sense it is highly ordered.

Ken: ... intuition of this, it was highly ordered but simple. How is that different from the chocolate milk example where it’s highly disordered but also simple. Like, what is the difference between these two.

Katie: I mean, it comes down to the fact that gravity is a factor and gravity interacts with entropy in really strange ways.

35:00

So, this is not an easy thing to explain because this is something that’s not, sort of, well quantified within physics, but, um, basically, so, the early universe was a very dense state but a very uniform state and it had little tiny fluctuations of density and over time those fluctuations of density collapse and became, you know, galaxies and clusters of galaxies and so on as the universe expanded. And for reasons that are very complicated, a gravitationally collapsed system like a black hole is higher entropy than the equivalent mass of just, like, gas in a cloud. So when you bring things together by gravity that actually sort of increases the entropy in some sense. So a sort of smooth, uniform universe with a lot of mass but not a lot of, sort of,]fluctuations is like a lower entropy state than a universe with a whole bunch of galaxies and stuff in it. And then as you go on over time you get into a situation where you just go through a state where there’s a whole lot of blackholes and things and then those decay and the particles decay and then you get to the highest entropy state so...

Ken: Yeah, that is really unintuitive to me, I mean…

Katie: Yeah.

Ken: Because that feels to me like the key to understanding this.

Ben: One way to think about this isn't terms of the temperature distribution of one type of particle. It's also, you have to include the possibility that you can change into different genus's material in the universe. So, early in the universe there were atoms. Lots and lots and lots of atoms. Right, and it was very interesting. But, you can have other types of stuff out there, you can have photons, you can have weird, heavier particles. So, let's just imagine like, a cloud of gas and space. So, a cloud of gas and space in the middle of nowhere, it's pretty uniform, just imagine this is just a big spherical boring cloud of gas. The temperature everywhere is about the same. It's just made up of hydrogen atoms floating around in straight lines, occasionally bumping into each other. Okay?

Ken: Mmmmhmmm.

Ben: We know that that is going to gravitationally collapse, because, gravity. So, it collapses down to a thing going from a big cloud to a ball, a planet in space, it's reversible, right? I mean, you could take a whole bunch of dynamite, you could blow it up and turn it back into a cloud of gas, right?

Ken: Okay.

Ben: But why in our universe does the collapse go one way? The answer has to do with photons. The gas collapses, as it collapses the temperature of the gas increases, right?

Ken: Mmmmhmmm.

Ben: There's thermal radiation, those hot photons, they get radiated out into space. One way to talk about it is this collapsing ball of gas isn't in a closed system, it's in an open system and it's turning things into photons. You're changing the number and different types of particles in there. You've got a whole bunch of new photons in there as it collapses and heats up and those photons stay photons. They go out into space.

Ken: Right.

Ben: And then the system doesn't have enough energy to go back to being a cloud. Another way to talk about this though is as a closed system. Just imagine you've surrounded your ball of collapsing gas with a great big thermos. You've seen styrofoam balls and mirrors and stuff like that, right?

Ken: Okay.

Ben: It collapses down. We go from a system that's made entirely of atoms to a system that's made of a mix of atoms and photons. The entropy increase means that it can't go back from the material being a mix of types to being all of one type.

Ken: Is that, in some sense, because the photons represent useless energy in the classical term so that…

Ben: Yeah, that's kind of one way to think about it. But you could think about it in terms statistical mechanics too. It's just like, how many different ways can my energy represent itself. At the very start it has to only be a particle. That particle can be anywhere inside the box, high entropy, right? But, we know what type of particle it could be. As it collapses it turns, you know, to thermal radiation. Now it can be one of a whole bunch of different, it could be a hot photon, it could be a cold photon…

Ken: Ah, okay, got it. So your state space has become bigger.

Ben: Yes!

Katie: You're also creating, like, space-time curvature too. So, like, the gravity is, is warping the space and so the sort of shape of space is no longer a kind of smooth, flat space. Now you have this kind of dent in space from the gravity and you can kind of think of that as another way of encoding what is happening.

Ken: I think I get it. I guess my question is then, why wouldn't the heat death of the universe be similar given that you have lots of local gravitational structures and matter being all sorts of different states. Wouldn't that be a bigger total state space than everything being uniform and smooth?

Robert: There's one more factor that we kind of left out with this discussion of the Big Bang. We start, you know, with this hot state and it seems kind of counterintuitive. Um, so, imagine we took our glass of chocolate milk and we got it pretty hot.

40:00

Hot enough that, like, normally, if it was uncovered it would boil out. But we keep it in a small volume. Okay, so, it's got an entropy and its entropy is higher than it would be if it was cold. And now imagine it kind of letting it take up a bigger space, you know, even maybe evaporating and being this chocolate milk gas that fills up the room. It's temperature goes down but the volume it has access to has gone up dramatically. Um, and so, the number of states accessible to the system, micro-states that kind of correspond to the same macro-state of this fairly dilute chocolate milk gas is so much bigger that the entropy has still gone up. So, you all know the original state of the system, you know, seems, you know, it's hot, you know, very hot, it seems like it should be high entropy. This other thing that is happening that is kind of the growth of the universe of the volume means that there's lots more states that the system has access to.

Ken: Okay.

Robert: Okay?

Ken: Yeah. I get that.

Ben: Earlier, to answer your question, earlier, I was talking about how, you know, you get genuses of particles and as the number of genuses of particles can increase you can get an increase of entropy in your system even though it corresponds to the matter all collecting at one point, right? So, if you think about it, ah, stars for example, they don't just turn stuff into photons, they can take your hydrogen atoms and combine into heavier, different types of atoms.

Ken: Right.

Ben: So, the stars, ah, the reason they can be hot and radiate heat out into space is because they are, essentially, great big entropy engines. The entropy in the system is always increasing as the stellar furnace combines different atoms. The more material you pile onto the system the more entropy it's going to have. Because the more different types of things you can make in your stellar furnace. If you follow this argument the solar system would have more entropy if all the planets in it, instead of orbiting the sun, ended up inside the sun.

Ken: True.

Ben: Arguably, the heavier your object is the more concentrated all the material is at the center of it, the higher entropy of the overall system is able to evolve into. But, in terms of classical celestial mechanics, if there were just two planets orbiting each other, their orbits wouldn't decay. But in Einstein's general relativity there's another type of particle you can kind of generate. You can generate gravitational waves. You can think about gravitational waves as another genus of thing that the energy can go into.

Ken: Okay.

Ben: And so over time, if you have two things orbiting each other, some of the energy in the system is going to turn into gravitational waves and it's not going to turn back.

Ken: Right, it just dissipates.

Ben: Right, yeah, it just goes out to the universe...

Katie: Yeah.

Ben: ...right. And so, in modern physics lots of the energy sustaining the Earth's orbit around the sun is eventually going to change into gravitational waves and then the Earth is going to end up in the sun and then the Sun is is going to have a higher entropy.

Ken: Yup, okay.

Ben: And so one of the arguments is that over a large, large, large, large, large, large scale of time everything in the galaxy is going to end up in the center. The entropy is going to increase as some of the energy turns into gravitational waves, that's not going to come back and everything's going to collapse down. And that's why heat death isn't a whole bunch of different orbiting, blackholes orbiting the center of the galaxy, it's everything in one glob.

Katie: But then, what happens to blackholes is important too, to this picture.

Ken: Right.

Katie: So, I want to say just a brief thing about Hawking radiation. So, you've heard of Hawking radiation...

Ken: I've heard the term, yes.

Katie: ...or blackhole evaporation. Yeah, so, so Hawking radiation is this idea, it's due to Hawking and a couple of other people worked on it and the idea is that if you leave a black hole alone and nothing's happening to it, it will slowly, kind of evaporate. It will produce high energy particles and photons that will kind of come off of the blackhole. It will kind of glow with a low level of radiation that will, over time carry away mass and the blackhole will shrink and shrink and it will evaporate completely. It will eventually kind of blowup and so that's a way to convert a black hole into a whole bunch of particles and radiation and this is called Hawking radiation. And kind of the way that this came about was this sort of thought experiment where, okay, you have the second law of thermodynamics that says that the entropy has to be increasing over time in any system. Right, and you also have this fact that you have a blackhole, if you throw something into the blackhole that black hole is going to get a little bigger and so there's this kind of idea that the area of a blackhole and the mass of a blackhole can't go down, it's always going up.

Ken: Right.

Katie: But, okay, this is going to be a complicated analogy but I need to have a system that takes entropy out of and sort of put's it somewhere else. Okay, so, one of the things that people talk about for entropy is you can't unscramble an egg. Okay, so, right, like, you scramble an egg, that's increasing the entropy of that little egg and you can't put it back together. But let's say you had a machine that very, very carefully, took every particle of that egg and aligned it perfectly and eventually created your egg again. You know, so...

45:05

Ken: A reprinted egg, yeah, sure.

Katie: Yeah, yeah. So you have this egg unscrambler but of course because of the second law of thermodynamics, like, that will increase the total entropy of like, the room in which this is happening. It will heat it up, basically. Um, so, let's say that you, you create this egg unscrambler in this box, right and you unscramble your egg and then you snatch the egg away and then you throw the whole room into a blackhole then you had a scrambled egg, you reduce the entropy in that egg and then you hid all of the extra entropy behind the horizon of this blackhole. And so now you seem to have violated the second law of thermodynamics. You've reduced the entropy in something and you've hidden the extra heat waste energy, the extra entropy, behind the horizon of the black hole.

Ken: I see. So we keep…

Katie: So that's a contradiction… okay.

Ken: Right, okay.

Robert: Yeah, it goes back to John Wheeler. He posed this thought experiment. In physics, when something is hot, we think of it as radiating. If something has a temperature then it radiates. Classically, blackholes are perfectly cold because they don't radiate anything, right. They just swallow things and that's it. And so if you imagine this scenario that Katie described which is, you know, you take something with entropy, something hot and you toss it in there and now it's in this perfectly cold thing. Where has all the entropy gone?

Ken: Right. You've somehow magically reduced the entropy in the universe just by shuffling all that mass into the blackhole which is…

Katie: Right.

Ken: Kind of nice but it doesn't work.

Katie: Yeah. Yeah. So, that's not allowed and so that was the idea that led to the idea that black holes have to have some radiation because there has to be some way for the entropy of you threw in there to come back out again. And, in addition to that, whatever the entropy of the blackhole is it has to be, kind of the maximum entropy you can have for any object of that mass because otherwise you might have something that is way hot or something that has a really high entropy, throw it in a blackhole and that reduces, right? So, a radiating blackhole has to be the kind of maximum entropy state of any, sort of collection, of that mass. So, what you get from that is that anytime you have a collection of matter it strictly increases in entropy when you put it into a blackhole. And as that blackhole is evaporating, that strictly increases the entropy of the universe. And so that way you can have this path through to higher and higher entropy all of the time.

Ken: Yeah, it's sort of like conservation of increasing entropy...

Katie: Yeah.

Ken: So you don't have disappearing entropy, magically, okay.

Robert: That's right, it's maintaining the second law of thermodynamics which is that the entropy has to be increasing.

Katie: The evolution of the universe is one in which, you know, first you have, sort of, gravitationally collapsing objects and then those will increase in entropy by turning into blackholes and then those blackholes will evaporate and other things that maybe are not in the blackholes will sort of decay. And so you're evolving towards this state where the universe is full of this disordered radiation either from the decay of particles directly or the evaporation of blackholes. So, can we go through like, just the chronology of the heat death...

Ken: Yeah, stage it.

Katie: Okay. So, we start with the, some kind of Big Bang and we're not going into the details of what that is or how that happened. But you start with this extremely low entropy state, relatively, of a pretty uniform but extremely dense universe that is in some sense smaller than the universe we are in today. And over time that universe is expanding and within that universe there are little fluctuations in density are collapsing in on themselves and creating structure, stars and galaxies and things like that. And those structures have higher entropy than a bland, uniformish distribution of very dense matter. And the universe is expanding and so there is more and more space and these objects are getting farther and farther and evolving and you know you're using up the gas and creating stars and the stars are burning out and polluting the universe with heavier elements and then you get, you know, people and stuff. And then, over time, the stars will burn out and because things in the universe are getting farther and farther apart, because the universe is expanding, and the fact that it is expanding in an increasing way, so it's accelerating in its expansion due to something we call dark energy. It's expanding, it's expanding and increasingly things are getting farther and farther and farther apart from each other and so the kinds of processes that happen to create new stars like clumps of gas running into each other and heating up and stuff like that, um, that happens less and less often because galaxies are not colliding with each other anymore and so each galaxy, the stars within it are burning out, everything is kind of fading away. And as the the stars are burning out and evolving with, you know, gravity and gravitational radiation and all that you're getting a universe that is, in each little patch of the universe where there's some matter, that matter is evolving more into blackholes or kind of decaying in some way. And so each part of the universe that has some matter is getting more and more isolated from every other part because the dark energy is increasing the expansion so much that things are carried away so far that they can't be observed anymore and they don't interact anymore. And so each part of the universe becomes a little isolated island of this sort of decaying matter and blackholes. And then those blackholes are evaporating over time and so each part of the universe is becoming more, just this, very empty part of the universe where it's got a little low level radiation that's diluting over time as the universe gets, continues expanding. And so eventually you have a space where it's just this very, very low level of radiation that's been diluted. And it hits a temperature floor so there's a lowest temperature that you get to at the maximum entropy state.

51:00

And that has to do with the fact that this state of spacetime that you get to toward the end has a kind of entropy associated with it. It has a cosmic horizon and that horizon has an entropy associated with it in a sort of similar way that a blackhole has a horizon associated with it and there's an entropy associated with that horizon. But, in any case, that leads to a kind of minimum temperature at the maximum entropy state and that's a space called de Sitter Space where it's really just expanding universe with almost no, anything, almost no radiation. And that sort of just persists forever in this sort of useless state where there's only disordered energy, just waste heat and nothing else and nothing can ever happen again because there is no structure and you've reached the maximum entropy state and you can't do anything with that.

Ken: But it continues to expand even in that state?

Katie: Yeah, it keeps expanding but in the sense that is kind of meaningless because there's no marker on the expansion anymore.

Robert: There's no one to observe the expansion, there's no variation in what's there where you would see some change caused by the expansion. So, it's uniform, it's dark and uniform and lonely and that's it. The temperature that Katie is talking about is phenomenally low. Like, if you take, kind of our best cosmological measurements right now and use that to pin down, kind of, the dark energy driving this expansion, the temperature that comes out for this, kind of, long term future, is on the order of 10^{-30} Kelvin.

Katie: Or maybe even 10^{-40} or something like that.

Robert: It's so low that it almost seems meaningless.

Ken: Wow.

Katie: Yeah.

Ken: So, what's left in the universe at that point. I mean, what is the, what is this um, what kind of radiation or anything is left?

Robert: Extremely long wavelength radiation, the occasional lonely lepton that hasn't decayed.

Katie: Yeah, but it's basically extremely cold radiation and that's it.

Robert: Wow.

Ben: Hurray.

Ken: The funny thing is it actually looks a little bit like the beginning of the universe only, you know, much, it's uniform, it's just...

Robert: Yeah, it's like we were saying before. So, at the beginning at the universe we think it is comparatively low entropy but also complexity level is very simple. And then, kind of, all of existence as we know it and life and all the interesting stuff, is this detour into high complexity as the entropy gets bigger but then eventually it ends up back in this state where the entropy is very high but the complexity is very low again. So you don't need much to describe that final state.

Ken: Yeah. I mean, one way I think about it, I mean, I'm sure this is not right but it's kind of how I like to think about it which is that at the beginning, you know, when there are no possibilities really, I mean that one state is all you can be, the entropy is very, very low because there are no possibilities of being other particles of being other things, of bigger space to do things. And then you go through this stage were there are lots of possibilities and entropy goes up because there are just so many more things to do and at the very end you still have this huge space, this state space of potential but you have nothing left at that point. It's a high...

Katie: Yeah.

Ken: It's a high entropic state, the possibilities have all been expanded and there's all this stuff out there but you actually don't have those possibilities, you just have this one dead, cold thing.

Katie: Yeah.

Ken: It's kind of like, a metaphor for life.

Laughter.

Katie: It might be worth saying something about life. Because people do, sometimes, talk about life as a violation of the 2nd law of thermodynamics.

55:00

It’s not but, but they talk about it that way because life is a kind of process that reduces the entropy of a particular life form, right. So, so, it’s a process of creating order, right. So, a, a life form is more ordered than a pile of chemicals. But because it’s, you know, these are not closed systems, the entropy does go up in building a life form. Ah, because a life form produces its own heat and it produces waste products and all this kind of thing, so, the entropy will still be increasing all the time even when life is happening. But one of the other ways that this is a relevant issue is that one thing you do need for life is that you need an energy gradient. So you need to be able to move energy from one place to another. So this is something that comes up a lot in talking about extraterrestrial life, you know, you need like, a sun to produce energy that goes from the sun to the planet or you need, like, a hydrothermal vent to take energy from the bottom of the ocean up. So, you have to have some kind of energy difference in order to have, you know, something that can create life, that can build something, some energy that you can work with. There has to be a gradient, it can’t be uniform all around you and this is the same problem we run into with heat death is there is energy but it’s so uniform, there’s no gradients, so you can’t do anything with it.

Robert: It’s worth mentioning that, you know, we’re talking about, kind of, the heat death of everything in the really, really far future and we’re talking about time scales that are like, really colossal. Time scales that make astronomical time scales look like nothing, right? But, it’s kind of worth pointing out that in most of the universe as it is right now heat death has kind of already happened. Most of the universe is empty and just has cold CMB photons, the Cosmic Microwave Background and that’s radiation that, you know, is like 2.7 Kelvin and that’s pretty cold and so there’s not much that can be done with that, right. For something to be done useful with that it would have to, you know, be cooled down below that so that you know, it could bind some energy from it. And that’s kind of the overwhelming volume of the universe as it exists today. Alright, so, we always talk about the heat death as something in the future but kind of in a practical sense in a lot of places it’s already pretty close to heat death, right, and we’re just kind of this rare phenomena on these little corners of the universe where interesting things are still happening.

Katie: Yeah, yeah, and as you go on that’s just more and more true because the universe is expanding, increasing the distances between interesting places. And you can define an observable universe as sort of the radius of the horizon, you know. And if you count up all of those sections of observable universe then most of those are pretty empty and will just increasingly become so.

Ken: Yeah, that's depressing.

Robert: It's a very bleak future…

Katie: Yeah…

Robert: And also kind of a bleak present for, kind of the only thing here that can make you feel better is that at least you're in one of the parts of the universe where interesting things are still happening.

Katie: Yeah.

Ben: Katie, did you want to mention Boltzmann brains?

Katie: Oh, gosh, we've totally glossed over Boltzmann brains. Alright, so the heat death, ah, state, the maximum entropy state of the universe, you have this, this totally uniform universe with no useful energy and nothing happening. But, as always, things get much more interesting when you factor in quantum mechanics. And so, one of the things you have to think about is that quantum mechanics is, like, you know, spontaneous, weird stuff happens in the universe and if you're just sitting around in this maximum entropy universe forever once in the while something weird is going to happen and that weird thing that is going to happen is that you get a fluctuation of part of your universe into a lower entropy state and that lower entropy state can then do stuff, can have processes happening, can have stuff evolving or whatever. And you can have these sort of spontaneous rearrangements of this tiny amount of radiation or the sort of energy of the vacuum even into objects, into, like, ah, matter. And so people have talked about this as we sort of alluded to before, as a way of restarting a universe or starting a universe as you have this, you know, this heat death state and you have a little fluctuation, of part of that space into a Big Bang, into sort, of…

Ken: A smaller one, sure.

Katie: ...the beginning state, yeah, a beginning state of the universe and then that sort of expands and you know, evolves, and it sort of evolves back into this maximum entropy state and sort of rejoins this soup of nothingness, right? So people talked about that like, okay, maybe we can have a fluctuation into the Big Bang and then that, that's a great, you know, way of starting up the universe. But then other people were like, well, okay, if it's possible to fluctuate into a Big Bang state, it's even more likely to have a much smaller fluctuation where you create just one galaxy. But then it's actually even more likely to create just one planet.

1:00:07

Ken: Hmmmmhhmmm, sure.

Katie: Um, and, in fact, it's even more likely that instead of creating a whole planet full of people who are observing the universe, you just create a single brain, like, the brain of one person and that person just happens to have the memory of the whole universe and imagines that they have observed the Cosmic Microwave Background. That state is much less complicated, like, you have to do less to create a brain that thinks that the universe exists.

Ken: Right, I follow you.

Katie: Than to recreate the universe itself. So, this is called the Boltzmann brain problem. Um, which is a generic problem you get with any universe that you try to create out of quantum fluctuations from a heat death state is that in some ways, in some ways of calculating, you're more likely to just produce a brain that thinks it's a universe that came out of a heat death state and, in fact, will immediately spontaneously decay back into the sort of quantum soup.

Ken: And so, we could, theoretically be figments of such a brain's imagination.

Katie: Yeah, like, right now, you could be that.

Robert: Yeah, Ken, what we're trying to tell you is that none of this was here a second ago. You were in heat death and there was a spontaneous fluctuation that produced your brain and all your memories which didn't exist a second ago.

Katie: Yeah.

Ken: That is pretty cool. And I assume it will flutter out of existence as soon as we stop recording.

Robert: It could, or it might just wind down. You'll never know.

Katie: Yeah, it's hard to say. Like, there are different ways of measuring what it takes to do that fluctuation and so there are ways of measuring where it's more likely to produce a Big Bang than to produce a brain. Um, there's sort of complicated accounting because this is a sort of very weird state. Um, but there are a lot of fun things you can do with the possibility of fluctuations, like, for example, you get Poincaré recurrence. This is a really cool topic, I really enjoy talking about this because it goes back to some kind of really bizarre, sort of philosophical thought experiments. There was a book that Nietzsche wrote and in this book he brings up the idea of eternal return. And eternal return is this idea that, what if, every moment of your life you live over and over again an infinite number of times and like, wouldn't you just be like, screaming in agony if this were the case, right? And this sort of dystopian thought experiment of this, you repeat your life over and over again but in the sort of quantum mechanical system, like a heat death universe, any state that the universe could have been in in the past or any state that's possible or that did happen can happen through fluctuations and in fact will happen an infinite number of times. So, like, a universe that is arranged exactly as the universe is exactly at this moment, because it's possible, in a heat death universe, you will, in principle, fluctuate randomly to this moment again and again and again forever, just at a long sort of time scale. So, like the time scale...

Ken: Yeah, nothing like us...

Katie: ...fluctuations will happen and so this is called a Poincaré recurrence. So in some sense, Nietzsche's idea is plausible in this cosmological sense that every moment of the universe repeats infinitely many times over and over again with just long times in between in a heat death universe. Which is a really fun thought.

Ken: Yeah, that is. Let me ask a follow-up question on this. So, if it's possible, however unlikely, that a heat death universe we can spontaneously have a recurrence of a galaxy or this whole or even a brain, why isn't that a violation of the second law of thermodynamics. Why, because, spontaneous, we did in fact decrease the entropy of the system.

Ben: Didn't you say it yourself, that like, when you're talking about a glass of chocolate milk there was some finite but very very small probability that not all the chocolate milk particles…

Ken: It is right. So, I'm trying to understand, so, why wouldn't that be considered a violation if that could spontaneously happen.

Ben: Because you're dealing with infinite amounts our time.

Katie: And quantum mechanics which sort of messes with this whole picture and usually only matters on a microscopic scale but in this case could matter on a much larger scale. So that makes everything more difficult to align with this idea.

Robert: The, the second law is, you know, essentially, is, as Ben was saying earlier, is a statistical statement. That you're overwhelmingly likely to increase the entropy. But there are times scales associated with that. Um, you know, you're always overwhelmingly likely to increase the entropy on time scales short enough that these other phenomena don't happen. The odds of a fluctuation to take you back to a low entropy state, you know, are suppressed by huge numbers. You can estimate the rate of that and then, based on that, you can figure out roughly how long it would take. On time scales much shorter than that that are always overwhelmingly likely to increase the entropy. But once you stretch things out into this very, very long, dark bleak future you kind of move beyond that and there's always the possibility of a fluctuation causing something extremely unlikely. Although some physicists will argue that in fact this final state of the universe is different and our intuition about these fluctuations are wrong and we shouldn't expect that and it is just bleak and ends and that's it.

1:05:03

Katie: And you know, discussions about this continue in the literature and among cosmologists. It's a fun topic and it's definitely not one that is all tied up in a bow. We're still trying to figure out exactly what to do about the low entropy state of the early universe and the high entropy state of the late universe and how that all fits together. As far as we know the second law of thermodynamics is super solid for every kind of system that we ever really deal with and for anything where we're not looking at the quantum mechanical fluctuations of the very, very smallest scales. But quantum mechanical fluctuations will affect macro-scales if you have an infinite amount of time and so then it gets a little bit fuzzier.

Ken: Yeah. I mean, this is just so interesting because now, now you can even imagine some crank saying that well, perpetual motion machines are very possible all you have to do is give it infinite time scale and wait for the fluctuations to come. Right, I mean, the system will reset so there you go.

Ben: Yeah, pretty much. Well, that was great. Thank you Katie, thank you Bob. You've pleased me, your efforts have born fruit and that fruit is sweet, here's some fruit! Dr. Katie Mack, you get the highest, no, the lowest entropy fruit. An apple.

Katie: Nom, nom, nom, nom, nom.

Ben: And Dr. Bob McNees you get the highest entropy fruit, it's a raspberry.

Robert: Mmmmhmmhmmhhh.

Ben: I'd like to thank my guest, Ken Liu. A list of the different novels of his and short stories will be on the website for you to link. And buy and read, they are absolutely fantastic. Thank you very much Ken Liu for coming on the show.

Ken: Thank you very much for having me.

Ben: Alright. Hey everybody, ah, it's time for announcements. That was a really good episode. By the way I read Ken Liu's books since we finished recording and they are amazing. So, ah, announcement time. One of the reasons we've had so few episodes lately is that I've been moving cities and changing jobs. So, there's this episode and the episode following this that I've recorded before the move but then after that I won't have any new content to release until who knows when because I have to get set-up. I'm thinking a month or two. Anyway, ah, so first announcement. Please give us an iTunes review as always. Or tell other people about us online. Your iTunes reviews help other people find the show and even if we're on kind of hiatus we have a very deep back catalog they can listen to an episode a week for a year and still have more of it to listen to. Second, I'd like for you to follow us on Twitter at Titaniumphysics. I do make announcements about what's going on on that account once in a while. But also, sometimes, we are in the lurch for a guest. Maybe we'll book a show and everything will line up and our guest will have to cancel at the last minute. I'm going to start using Twitter to find a replacement guest. So, if you're on Twitter you might find yourself on the show. And finally, we're still humbly soliciting your donations. Your donations go to paying for our server fees and our project to transcribe episodes as they come out. So, if you'd like to donate please follow the links on our website. Please give us a donation through Patreon which allows me to take a payment every time I make an episode but if I don't make an episode for four months you don't have to pay for it. Or, alternatively if you want to make a one-time donation there is a PayPal link.

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Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka.

1:10:45

So, that's it for Titanium Physicists this time. Remember, if you like listening to scientists talk about science in their own words there are lots of other lovely shows on the Brachiolope Media Network. The intro to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Good day my friends and until next time remember to keep science in your hearts.

Music

1:12:00

Robert: We're lucky.

Katie: Yeah, seize the day man. You know.

Ken: Yeah, I, you should totally trademark that. That's good.

Katie: I do have, I do have a motivational poster I made about seizing the day that has to do with the sun is going to burn out in a few billion years and, or, it's going to engulf the Earth, or at least engulf Venus and the Earth will fall in in some way because of like dissipative forces and so, you know, you should seize the day before it kills us all.

Robert: Talking about kind of the the fate of life and how life needs energy gradients, one of my favorite speculative physics papers is called "Time Without End" written by Freeman J. Dyson in like, the late 70s, like, 1979 or something and it was a response to this book that Stephen Weinberg wrote called *The First Three Minutes* and in Weinberg's book, he was looking at the early universe and what happens and Dyson said, well, you know, what about the field of eschatology, like why doesn't that get any love. Let's talk about the end of the universe and how long we can stretch things out. And so, you know, he talks about physics as it was understood at the time. Like, how far out can we forecast, what is the really the fate of the universe and it's built on assumptions that we know now probably are not right. In particular, you know, it was before we suspected that there was dark energy but it really sits almost at the intersection of physics and sci-fi. Ah, because, so many ideas, you know, are there in the paper that kind of made their way into stories but also he borrowed things from like Fred Hoyle's *Black Cloud* because he examines how long you can stretch out life in a universe like that. As the universe gets colder and more dilute what can you say about the physical principles that underlie life and then how far can you push them and still call that thing life. It's a fantastic read even if you don't, like, understand all the physics that goes into it, it's kind of one of the more fun speculative things that you can read. And it's got a great timeline of all the things that happen in the far future from things that we understand to things that you might not ever expect. We have a pretty good idea of like, how the lowest mass stars work and how long they can burn for and it's, it's like 10 to a 100 trillion years or something like that. Then, you know, we can estimate how long it takes for planets to be pulled away from their stars by close encounters with other stars or for orbits to decay by gravitational radiation and also, like, as things get really cold, you know, quantum fluctuations making matter loose its shape or even kind of spontaneously, just kind of spontaneous long term radioactivity of regular matter as quantum fluctuations turn it into other elements, you know, everything kind of turning into iron in the form, in 10^{1500} years or something like that and you know everything collapsing into black holes and black holes evaporating and things like that. It's a tremendously fun read.

Katie: Yeah I…

Robert: If you like bleak futures