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Welcome to IFL Science – The Big Questions, the podcast where we invite the experts to explore the biggest mysteries of science with your host, Dr Alfredo Carpineti.

I: **It is very human to wonder about the end of things. What conclusion as an author, written for the fantasy series? What happens at the end of our lives? Will the earth survive the death of the sun? It is hardly surprising to know that scientists have looked even further afield into the biggest curtain call that can be found in the cosmos: the end of the universe itself. I am your host, Dr Alfredo Carpineti, IFLScience Senior Science Writer. The big question for this episode is how will the universe end? To help us answer this query and provide context we are joined by Theoretical Astrophysicist, Dr Katie Mack, the Hawking Chair in Cosmology and Science Communication at Perimeter Institute.**

Dr Mack, it is a pleasure having you with us today. Could you please introduce yourself and tell us what you do?

R: Yep, my name is Katie Mack. I am a Theoretical Astrophysicist and I study Cosmology, the study of the universe from beginning to end on the smallest and largest scales.

I: **Wonderful. The question we are tackling this time is about the universe and how it's going to end. You wrote a fantastic book about it, so can you briefly explain that to us?**

R: Well, there are several possibilities for what will happen in the far future of the universe and in the book, I go through five different possibilities. The most likely thing seems to be that the universe will continue to expand forever and just kind of eventually cool down and die out. So right now, we know that the universe is expanding. It's getting bigger, the spaces between galaxies is getting bigger. The galaxies themselves are not getting bigger, you know, Earth is not getting larger but the universe is expanding in the sense of all the empty spaces getting bigger and that process seems to be set to continue indefinitely and as that goes on the universe just gets more and more diffused, more and more empty, colder, darker, lonelier and it looks like it will eventually end in what we call a heat death, where everything just fades away and dies. It's not the most cheerful thought but that's the one that most cosmologists point to as the likely future, but there are some other interesting possibilities where something more violent could come in and change that story.

I: **So, out of morbid curiosity, what are the scientific reasons for being interested in the end of time?**

R: Well, part of it, I think is curiosity and not necessarily morbid curiosity but just the question of, what is our story? What is the narrative of existence? Everybody has got curiosity about the beginning, where did we come from? How did it all start? I think the natural thing is to then also ask, okay, where are we going? How does it end? What's in the future for humanity, for existence, for matter itself, for the universe? So, I think it is partly just that we want to know what the story looks like, what is the end of this story and where are things going? But then, in a scientific sense, as a physicist I am interested partially because a lot of the questions about the end of the universe really tie back to the beginning as well because different ideas about the beginning of the universe set the scene for different kinds of evolution, different shapes of the cosmos in some sense. Are we part of a larger system of universes? Are we something that will go through cycles? Does our cosmos go through cycles from beginning to end and then a new beginning? What set up the conditions for the beginning of the universe? How does that relate to how the universe evolves in the future? So, there are a lot of ways in which those two questions are very much connected in a physics sense, and so that's particularly interesting to me. Then another part of it is just when you start to ask these questions it leads you to other interesting questions in physics and astronomy. It leads you to think about what kind of physics drives the universe and what the extreme cases can be when you tweak some of the parameters and there are a couple of instances in the book where I get into some really fun things that can happen if you take a standard theory and say, "well, what if I just change this number a little bit? Where does that go?" Sometimes it goes to, "Well, the universe has just ripped itself apart." So, you can really find some fun things when you start to ask these questions.

I: Fascinating, this is so fascinating. I personally find it such a rush trying to think about how it all might end up. I think I also like this sort of mirroring in our search for answers between trying to understand how the universe started and how it might end. You mentioned the importance of numbers and that by tweaking them we end up in very different scenarios. To what degree do we need to understand the universe today to predict how the universe will evolve in the future? Is there something crucial and maybe big that we have to determine to work out which scenario is correct?

R: One of the things that we really need to understand if we want to understand the future of the cosmos is something called dark energy. The universe is currently expanding, and that expansion is speeding up. That acceleration is something that was not predicted by standard theories of physics when it was discovered, and it seems to be due to something that we call dark energy. We don't know what dark energy is, there are a number of possibilities for what it could be. It could just be a property of space that we call a cosmological constant, where space has a kind of stretchiness built into it as something that just shows up in the equations and it's a property of the universe, and that could be the dark energy. But dark energy could also be something that is a new component of the universe or a previously unknown component of the universe, that is a field of energy of some kind that would change over time, would maybe take on different characters over time. If its that dynamical thing, if its something that changes then that could lead to something like a big rip, where the universe tears itself apart in the future if this dark energy gets more powerful. Or it could lead to something like a big crunch where the universe collapses on itself if dark energy changes from something that is causing expansion to something that's causing contraction. There are models that people have put together that

could cause those different activities. So, understanding what dark energy is, is a really important question and right now we are doing a lot of observations to try to pin down what dark energy is, what it will do in the future, how its acted in the past. And right now, everything is consistent with dark energy being just a cosmological constant, a property of space that will lead us to a heat death in the future. But we're still following different possibilities, still taking more and more detailed observations, looking into different theories, doing laboratory experiments that might connect to different kinds of energy fields that could exist in the universe. That's one of the really big questions where we're kind of at this point now where the data are all balancing in a particular direction but if you go a little bit to either side of that, things change. So, we're trying to figure out how precisely we can measure that number, essentially. The other thing that is really important here is understanding the physics of the very beginning of the universe because that can tell us something about the other two possibilities I talk about in the book. One where you have a cycling universe, a universe that goes from beginning to end to new beginning, and that could arise from certain theories of cosmology where we might find clues about that in studying the beginning of the universe because we might see a clue that suggests that there was a previous cycle. Then the final possibility is something called vacuum decay, which is what happens when this energy field that exists in all the space called the Higgs Field changes character and does so in a way that ends up being disastrous to the cosmos. That might be possible, it might not, we're not sure. But the way to figure that out is to understand how the Higgs Fields changed in the early universe because we know that it did. So, that's another case where trying to understand the beginning is going to potentially tell us something about the end. That one is one where it's really particle physics experiments that are teaching us the most about that. So, studying the Higgs Boson, this particle that is associated with the Higgs Fields in things like the Large Hadron Collider, that's giving us clues about the Higgs field and then potentially about both the beginning and the end of the universe.

I: That is absolutely enthralling. So, we have five scenarios. Can I ask you which one is your favourite?

R: I do have a favourite. Vacuum decay is 100 percent my favourite of these ideas. It's not one that I think is particularly favoured by Cosmologists – as I said, Cosmologists generally think that the universe will end with a heat death – but vacuum decay is just such a fascinating possibility because it involves something that happens on the quantum level, sub-atomic physics. Basically, there is a quantum tunnelling event, a particle goes from one place to another in some sense and when that happens is triggers a cascade that destroys the cosmos. I think that's just such a fascinating possibility where something that's so tiny and so obscure and so unpredictable as a quantum event could destroy macroscopic objects and galaxies and the universe. So, it's fascinating to me for that reason, it's fascinating because it does rely on an unpredictable event, something that's governed by quantum physics, by this fundamental uncertainty. So, if it were going to happen, we would not be able to say where or when it would start, and when that event occurred it would create a bubble of a new kind of space that would expand throughout the universe and destroy everything at roughly the speed of light, is the expansion rate for that bubble, so you wouldn't see it coming either. That is a sort of scary notion and I know that a lot of people have contacted me saying that they find vacuum decay

terrifying, and they want me to tell them that it can't possibly happen, and I can't tell that it can't possibly happen. What I can say though is that our current understanding is that if it is possible then the timescale on which it would occur, the earliest time we would expect it to happen would be something like ten to the power of a hundred years from now, which is a very, very long time from now. It could potentially happen sooner but it's extraordinarily unlikely to happen any time soon. Then the other thing I can say is that the whole notion that vacuum decay is possible is based on assuming that our very limited current understanding of particle physics is the last story; that no new physics will ever appear to change that picture and we have very good reason to believe that's not true, that there are holes in our standard model particle physics. We're seeing hints of that all the time these days with experiments and so we're pretty sure that something will change, we just don't know what and because we are pretty sure that something will change, we have a pretty good reason to believe that vacuum decay is not something we should take super seriously as an end of the universe scenario. But as a physicist and a cosmologist I think it's super fun to think about. So, of the five scenarios I talk about in the book, that's the only one that I have actually done professional physics research related to.

I: Wonderful. Yes, it is my favourite too. I absolutely adore that scenario if one can adore the idea of the death of everything.

R: Excellent.

I: Thank you very much for taking the time to speak to us today.

R: You're very welcome. Thank you for having me.

I: One day the universe will end. We're not certain how. Long after the last star has shone its last light, the cosmos will be no more. And while this finality seems dreadful, it is extraordinary that humans have the ability to ponder such a big question and even find a reasonable answer to this great mystery. Let's keep wondering.

Thanks for listening to IFLScience The Big Questions. Head over to iflscience.com and don't forget to sign up to our newsletter so you don't miss out on the biggest stories each week. Until next time.

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