Numberphile Podcast Transcript
Episode: The High Jumping Cosmologist - with Katie Mack
Episode Released February 25 2021

Astrophysicist Katie Mack discusses Twitter, athletics, mathematics, and the small matter of the fate of the Universe.

Katie Mack's website

And her Twitter @AstroKatie

The End of Everything - Dr Mack's book on Amazon

Direct Download: https://www.numberphile.com/podcast/katie-mack
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[gentle piano music]

Brady Haran [BH]: Today our guest is, the Astrophysicist, Katie Mack. [music fades down and continues] Now when she's not pondering and coding the secrets of space [music fades up] Dr. Mack's well know to many as a popular scientific tweeter at AstroKatie. And she's also the author of a new book about the fate of the universe. [harpsichord and other instruments join in] We'll get to all that later and this being Numberphile you can also rest assured I'm pretty curious about the role of mathematics in the life of a cosmologist. [music fades out]

BH: Can I first ask…

Katie Mack [KM]: Mhm?

BH: Katie or Katherine?

KM: Katie. Katie.

BH: Because you're Katie on your book…

KM: Yes.

BH: …but you're Katherine on your papers.

KM: Yeah, yeah, um… it's been a sort of change over time. It's just because I have the AstroKatie thing, people don't know who Katherine Mack is… profess… you know like… in the general public and…

BH: Yeah.

KM: …with my papers… you know, when I started writing physics paper I was… I would use my full name as seemed appropriate and so… I just… I've diverged into these two different people now.

BH: There's no possibility of switching to Katie on your papers then…

KM: No.

BH: …because then it will cause this kind of disjoin or…?

KM: Yeah, yeah. 'Cause then I would have two different names on my… uh… you know… you wouldn't be able to find all my papers all at once, so I have to… I have to be Katherine on the papers and I have to be Katie in public stuff, it's just… it's all… it's set now. It's like those… you know author's who have

different pen names for different genres, that's where I'm at.

BH: Alright then. We'll go with Katie for now, then.

KM: Okay.

BH: Where are you from? Where were you born?

KM: I was born in Long Beach, California. Just, you know, sort of LA area and… um… I've been… my career has taken me, sort of roughly east, continuously. So I, you know, I did undergrad at Caltech and then grad school at Princeton and then I continued east to Cambridge for… my first postdoc and then wrapped around to Melbourne for my second and then wrapped all the way around back to North Carolina for my… faculty job.

BH: You're just doing laps of the Earth.

KM: Yeah basically. Yeah. I don't know where that suggests I go next but [laughs] I guess we'll see.

BH: If I had been following your childhood at what point would I have said… do you know what? I think that girl's gonna become an astrophysicist?

KM: [laughs] Um… I mean if you'd ask me I would have told you that around ten. So…

BH: [laughs]

KM: Specifically I wanted to be a cosmologist at that time, because that was around when I first started reading stuff by Stephen Hawking and you know, Paul Davies and like, all these… you know, all this stuff about the Big Bang and time travel and… you know, space-time and black holes and that was all

fascinating to me and when I found out that the job Stephen Hawking had was called cosmologist I was like, okay that's what I wanna be. That's my goal now.

BH: Were you a pretty nerdy girl then?

KM: Yeah.

BH: Did you have geeky interests or were you…?

KM: Um… yeah I mean I was… uh… I was super nerdy and super sporty. Um… so I was kind of in both those, those categories. I did track and field and basketball, you know, sort of the whole time growing up. I was always running around doing some kind of sport and then I was also doing things like going to a planetary science summer camp. [laughs] You know, so it was…

BH: Yeah.

KM: I was definitely, you know, very much in both of those categories as a kid. You know I mean, and I was like winning championships in… high jump, stuff like that, I was, you know, I was a pretty serious athlete at the time, but in the end…

BH: Oh?

KM: You know… in the end the physics did win out. Like when I was choosing high schools I was being recruited by the… local high school track team at the same time as I was eyeing this little math and science magnet school… where I could totally nerd out and I ended up going in that direction and… you know, sort of heading toward that side of things in my life.

BH: Was high jump like your… your speciality?

KM: That was the thing that I was sort of best at, but I did all the field events, you know, shot-put and javelin and triple jump and… you know, long jump, all of that stuff I really enjoyed.

BH: What's your personal best high jump?

KM: It's a little bit over five feet.

BH: Okay.

KM: Yeah.

BH: It's in feet then? Not we're not going metric?

KM: No, not in… not in California we weren't. [laughs]

BH: [laughs] So athletics and sport was like a proper option was it?

KM: I don't know, I wonder about that, you know, I wonder if I had… you know gone to a more… sports oriented high school if I would've ended up… getting, you know, super serious about sports but I think I was always enough interested in science and that kind of career that I probably wouldn't have gone too far, although, you know, I mean, when I was at Cambridge, I knew a graduate student who was… while she was doing graduate school in astrophysics was also on the Olympic Diving Team, so, you know…

BH: Right.

KM: People do that. But don't know how far I would've gone with it. But I did love it, you know, and I was, you know, I was pretty good, I think it was, when I was in middle school I won the all city championship for… for high jump which is why I was recruited by the high school but…

BH: When did you last do a proper high jump over a bar onto a bag?

KM: [laughs] Oh… it was a while ago, I think… I did a little bit of practice while I was a postdoc at Melbourne, like I sort of snuck out into the, you know, onto the practice field, but it's hard once you're… once you're not a student, if you do running or basketball or something like that it's very easy to just continue that through your life, but if you do something that involves, you know, heavy duty equipment it's very hard to just casually [laughs] just sort casually high jump.

BH: Yeah. [laughs]

KM: It's not really an option which is unfortunate 'cause I did enjoy it a lot.

BH: So you'd probably like snap your spine if you went out and did one now? [laughs]

KM: Well there's that but also like… I don't have, you know, I don't have like a huge… a huge…

BH: [laughs]

KM: …pad and these giant metal stands and a big pole to put across and like, I just don't have that stuff lying around.

BH: [laughs]

KM: And there's only so much you can do onto like your mattress before you injure yourself so. [laughs]

BH: I was gonna say you don't do the occasionally Fosbury Flop into the bed

or anything?

KM: [laughs] No. No, I don't think that would be a good idea.

BH: [laughs] Alright then, so, through high school and what not then, at school you were like pretty academically sound then? Were you like the, you know...

KM: Yeah.

BH: …near the top of the class, physics, mathsy person?

KM: I was up there.

BH: Yeah?

KM: I did pretty well on that stuff.

BH: What was your attitude to mathematics at this point. I have to ask because it's the Numberphile podcast.

KM: Yeah.

BH: Obvious you've got these physics aspirations.

KM: Yeah.

BH: But mathematics is so intertwined with physics obviously.

KM: Yeah, yeah, of course. Yeah I've always loved math. When I was… middle school I think I was in the math club, you know, and I would do those sort of math… problems for fun, that kind of thing. I never did the competitions.

But…

BH: Yeah?

KM: But I enjoyed the practice of it. It was a little bit harder in high school because the high school I was at, they had this sort of… I dunno experimental math program that was built around… real world word problem kind of things and group work and collaboration and I think that's… that can be very useful but it didn't… it like it didn't get into the kind of math that I really loved which was, you know, sort of the… I dunno, those sort of more technical, more abstract…

BH: Hmm.

KM: …stuff, around you know, proofs and… all of those kinds of things. We didn't really get into that and so my math skills really sort of… faded in high school which was a bummer because I really did love math but it was just… it was just the kind of program that wasn't suited to what I wanted to do and the way I liked to learn, so, that made it a little bit difficult and when I got into… when I ended up at Caltech as an undergrad I really had a lot of catching up to do on the math side of things.

[gentle electronic chimes]

BH: I get the impression from the little bit I've read about you that you had quite a good family for where you wanted to go, like you would probably had parents who were quite… encouraging?

KM: Well my mom is… my mom is super academic. My mom has far too many… [laughs] college degrees. And so… she's… she's retired now but she got her PhD in nursing and spent… a long time working in sort of various aspects of medical things and then became a professor and also at some point got a law

degree and has been teaching things like health law and… you know aspects of that as well, so she's…

BH: Hmm.

KM: …she's very much in the academic side of thing, so she's been sort of in school for most of my life [laughs] most of my life growing up in one way or another.

BH: Right.

KM: And she's always been very encouraging about my… sort of physics and science interests in general and she would like take me to the observatory when I was a kid and we'd… we'd drive out to the desert to watch meteor showers and she would take me to, you know, if Stephen Hawking was giving a talk at Caltech she would drive me out to watch that and you know those kinds of things… she was always very…

BH: Yeah.

KM: You know very encouraging of that.

BH: And what did your dad do?

KM: He was… he was sort of… in a number of different odd jobs, not really… he just did a number of different things but wasn't really into academics at all, so… very different.

BH: I read that your mother encouraged you to watch Star Trek and Star Wars?

KM: [laughs]

BH: Is that true?

KM: Um… she… well she was into science fiction, you know, she's always been into science fiction, so she was into Star Trek a lot, you know, when Star Trek, when the original series was canceled, there was a big… sort of popular protest about it, you know, people were like picketing the studio, trying to get it reinstated, right?

BH: [laughs]

KM: She was part of that.

BH: Yeah.

KM: [laughs] She was very…

BH: Ah yeah!

KM: Yeah, she was very into… Star Trek.

BH: [laughs]

KM: And…

BH: I can see how proud you are. [laughs]

KM: Yeah, yeah, yeah, of course.

BH: [laughs]

KM: Um… you know, when I was growing up she had subscriptions to these

science fiction magazines and I used to take the magazines when she was done with them and read all these science fiction stories so… so… you know, she and I share a love of science fiction, for sure.

BH: Do you have a particular preference here in the Star Wars, Star Trek thing or is that like too hot a subject to even venture into.

KM: [laughs] Uh… you know… there're both fine franchises…

BH: [chuckles]

KM: …I... I like Star Trek a lot. I like the… the sort of utopian vision of Star Trek a lot, so, that's my sort of… the direction I lean in that debate, I think.

BH: Okay then. As an undergrad, you said you went to Caltech, did you?

KM: Yeah, uh… I did physics, just the ordinary physics major, they have an astronomy major there and it's very similar to the physics major. There's a lot of overlap but I wanted to do physics because I thought that it would be maybe a little bit more flexible in case I wanted to go into like particle theory or something like that.

BH: Can you tell me a bit more about the mathematics thing then? It sounds like you said you kind of felt like you were a bit behind the curve to start with 'cause of the alternative education like…

KM: Yeah, yeah.

BH: Was that like… was that dangerous? Did you feel like you were sinking at any point or was it something you always had well in hand?

KM: It was a challenge, you know, when I first arrived at Caltech. There's…

there are these sort of placement tests you take… when you first get there for placement in physics and math. For the mathematics side of things, when you start the first year mathematics is… called… Math 1, right? Like it's the first step…

BH: Hmm.

KM: And there's a special section of Math 1 that they… that they reserve for people who are a little bit behind and need catching up and they… they call it Math point nine. [laughs] So that's where I was.

BH: Right.

KM: I was in Math point nine when I first got there.

BH: [laughs]

KM: It was, you know, so so, there was a lot of catching up to do and when I was taking my physics courses it was… a big challenge was that, you know, we'd have these timed exams and it would just take me a lot longer because I didn't have the sort of mathematical rules just like right at hand in my mind so I would have to sort of rederive everything during the test. [laughs] And… that made it a lot harder to you know, to complete the exams in time, and it just… it was harder to keep up with classes so, you know, if I had to do it all over again, I would've… I would've done… you know a lot more preparation in mathematics before getting into Caltech but… I mean, you know, I got through, like it wasn't… it didn't stop me but it did make things a lot harder.

BH: You said that you did physics because you wanted to keep your options open.

KM: Yeah.

BH: Were you ever… tempted or nearly seduced away from that cosmology, astrophysicist path?

KM: [laughs]

BH: Like were there other things you saw that you thought this might be for me or did you pretty much stay on the straight and narrow throughout?

KM: Well, you know I started in experimental particle physics… in terms of the research that I did, so I did dabble in…

BH: Hmm.

KM: …in other areas of physics.

BH: Yeah.

KM: I was never tempted away from physics as a, you know, broad field but…

BH: Yeah.

KM: …I started doing stuff in particle physics when I was still in high school actually. So I had this very weird and cool opportunity to go work at the Super-Kamiokande Neutrino Detector in Japan while I was in high school. I mean so I went there and just spent some time like running shifts at the detector, not doing anything important but… you know, taking radon measurements and making sure the data… collection was working and everything.

BH: Yeah?

KM: So I…

BH: Is that one that looks really cool inside? Like…

KM: Yeah.

BH: It looks like a art installation? Did you get to go in it many times?

KM: I did. [laughs] I did get to go in it. Um… so the first time I went I was just running shifts at the detector so I was just sorta sittin' in the control room.

BH: Hmm.

KM: But then while I… when I was in college I went again where they were upgrading the machine and…

BH: Hmm.

KM: …and in that instance in order to do the upgrade we had to go in and replace these giant photomultiplier tubes, you know, these things that look like huge lightbulbs basically. We had to go through…

BH: Yeah?

KM: …and replace the wiring on those and so I got to sit in this little boat and… go around…

BH: Yeah.

KM: …replace these things and do, you know, do a bunch of like electronics…

BH: [gasps]

KM: …on the…

BH: I'm so jealous. I so wanna go in that boat.

KM: [mutters]

BH: I've seen pictures and I'm like, ah! That's my dream.

KM: It was very cool. So most of the work we were doing was on the outer detector which is sort of this cylindrical region between the big inside part and the outer wall, so mostly we couldn't see the huge, you know, cool inner detector where… that you always seen in the pictures but I did get to go inside the inner detector at some point so.

BH: Hmm.

KM: I have been inside it.

BH: Very cool.

KM: It is very cool.

BH: Very cool. Alright, so you started with the particle physics.

KM: Yeah.

BH: What happened next? How did you? How… what was the path? Give me the executive summary.

KM: [laughs] Well so I started, yeah I worked on Super-Kamiokande, I worked on this long baseline neutrino experiment, K2K, where… from another

part of Japan, you shoot neutrinos at the neutrino detector and then… observe what happens to them. I was pretty involved in that project and I enjoyed it, you know, it was interesting but… it was also… it's just this huge huge collaboration and the part that I did was just felt like a very very small piece and so I… I wanted to do cosmology because, you know, you could be a little bit more flexible. A little bit more sort of creative. You know, try and answer these big questions in weird interesting ways and you wouldn't have to be stuck on sort of one experiment measuring one number for years and years. And so…

BH: Yeah.

KM: …to me cosmology seemed like a freeing kind of thing, and it was funny because when I first got started in research I was doing this experimental stuff and I had this sort of impression that to be a theorist you had to be like, you know, a super genius, and I thought like I couldn't possibly go into theoretical work because I'm not a super genius. And it took a while of being in physics before realizing that actually you know, like everybody is… everybody there is smart in one way or another [laughs] but it's not like the theorists are the really smart ones and experimental ones are less. Like that's just not how it works. Everybody is doing interesting things in different ways and it's more about what kind of work you like to do, you know, the ways you like to think and the ways you like to approach problems and I started getting into theoretical astrophysics work at the end of undergrad and I just really enjoyed it and you know, it wasn't so inaccessible in this way that I had thought of it as… being and… and so then when I was in grad school I just totally leaned into, you know, cosmology as the thing that I really wanted to do.

[gentle piano music]

BH: Help me understand…

KM: Mhm.

BH: …being a theoretical cosmologist or…

KM: Yeah.

BH: …theoretical astrophysicist because what does your work look like? Take away the teaching…

KM: Mhm.

BH: …take away outreach and all the kind of…

KM: Yeah.

BH: …add-on things and just the pure sort of research doing science part.

KM: Yeah.

BH: What does that work actually look like? ‘Cause to me…

KM: Yeah.

BH: The few people I know who do this…

KM: Yeah.

BH: It seems to me like you just get to sit down and dream up some idea…

KM: [laughs]

BH: …and then do a few sums and think, oh, yeah that could work. [pause] And then then what? [laughs] Like…

KM: [laughs] Yeah so it's… uh… you know… like I spend most of my time in front of a computer. I think that's true for… for people in all areas of physics and astronomy these days.

BH: Hmm.

KM: And I do a lot of coding. And that's also true for most people in my field in any subfield of… astrophysics.

BH: But coding what? Coding…

KM: Yeah.

BH: …coding programs that will run your ideas, or…?

KM: Yeah, so the way it usually works is, first of all the ideas generally come from having conversations with people. So… you know, you go to conferences, you do collaboration visits, you bounce ideas off of people, you sort of… come up with stuff and you come up with like… maybe there's away to measure this particular thing using this particular observation, right? So you try and connect some idea from the theory side, so some, new proposal about, you know, maybe something about how dark matter works, you try and connect that to… an observation that can be made with an actual telescope or an experimental result or something like that.

BH: Hmm.

KM: And then you go through and you start on the theory side and you try and figure out like in a certain environment, in a certain situation what is the theory predict will happen physically.

BH: Hmm.

KM: So that's the phenomenology side of things. Trying to work out what the theory really predicts and so that involves reading a bunch of papers, writing a bunch of equations, you know, sort of… working out the order of magnitude of what's going on in that sort of system… and then you look at what the literature is saying about… the experiments that are gonna happen or the… or the observations that are gonna happen and see what the sensitivities are. See what they can actually observe and you try and make a connection between what the observation can do and what the theory is predicting. And… so… in… this is sort of in my area of theoretical cosmology which is often called phenomenology where you're. You're really sort of in that middle space between the theory and the observation.

BH: Hmm.

KM: And so what you put in the computer… is… uh… [sighs] you know the coding is where you put here's all the parameters of the theory, here's the… you know… here's the relevant equations. If I tweak this parameter this is how this'll all flow through. This is what the prediction will be for the physical property that can actually be measured. You know, and then sometimes you have to do some kind of… random thing where you choose a bunch of… a bunch of possible parameters and try and work out constraints or limits or whatever… so you do a lot of that sort of thing in the code but… yeah… it's mostly the code is for, you know, solving a lot of equations quickly to carry though whatever you've worked out on paper.

BH: What happens if you… are lying in bed one night and you come up with like you know a theory…

KM: [laughs]

BH: … of how the universe is working.

KM: Mhm.

BH: And it's something that… can't yet… be or hasn't been measured and can't be measured or observed.

KM: Yeah?

BH: Do you then have to put that on a shelf, like as scientist say, well if I can't get any measurements to go with it, it's pointless to even think about it.

KM: [laughs] Uh…

BH: Or like what do you do when that happens? What do you do when your idea is something that hasn't… can't be looked at with a telescope yet?

KM: Um… well… so I mean people do write papers about that. I don't…

BH: Yeah?

KM: …usually 'cause I'm not on the model building side. So… um… I tend not…

BH: Right.

KM: …not to come up with the new theories of how things work but I mean you can always… you can always write a paper about, you know, here's a cool new idea, here's how it could be measured in fifty years with a certain, you know, extremely powerful telescope.

BH: Hmm. Yeah.

KM: So…

BH: Yeah.

KM: Like…

BH: And then hope you stay alive long enough to get a Nobel Prize? [chuckles]

KM: Uh… [chuckles] yeah, I mean, or… you know hope that somebody will put together a better telescope sooner, you know, that's also a possibility but…

BH: Yeah.

KM: Yeah, a lot of the work I did, you know, early on my… in my career was about high redshift twenty-one centimeter astronomy which is where we're trying to use low frequency radio telescopes to measure the neutral hydrogen in the epoch of the first galaxies, basically. And… a lot of that work is gonna be done by an instrument called the Square Kilometer Array which is still sort of a decade away from… really producing…

BH: Yeah.

KM: The kind of data that'll be useful. And I've been writing papers about that for years. [laughs] And about like what, you know, what that will tell us. So it's… you know… it's totally permissible to write papers about what future instruments will do and that's often necessary to get those future instruments built so you… you know, it's okay to theorize something that can't be observed at the moment as long as you can express how it will be observed in the future.

BH: It sounds like you've gotta have some decent coding.

KM: Yeah.

BH: How good mathematics do you have to have when you're doing sort… physics at your level? Is it like… is it like super Jedi mathematics…

KM: [laughs]

BH: …that's really good or would mathematicians think what you're doing is pretty basic stuff really?

KM: [laughs]

BH: I have no sense of how good you have to be at mathematics.

KM: Uh… so it depends on what area you're working in, you know, the kind of stuff that I'm doing right now, you know, generally I deal a lot with differential equations but other than that I don't, you know, I'm not doing, like if I were working General Relativity Theory then I would be doing differential geometry, which is complicated, right?

BH: Right.

KM: That's quite sophisticated mathematics. If I were doing String Theory, then I would be getting into a whole lot of really advanced sort of… calculus kind of stuff and differential forms and… a whole lot of more complicated… more sophisticated mathematical stuff and if I were doing data analysis I would have to do a whole lot of statistics [laughs] and I'd have a very deep understanding of statistics.

BH: Yeah.

KM: So it really just kinda depends on what area you're working in. If you do quantum field theory, you're working with path integrals al the time and you know, doing a lot of sophisticated stuff around that.

BH: Yeah.

KM: It's very dependent on the subfield you're in. In a lot of astrophysics you don't do a huge amount of really complex mathematics unless you're doing sort of model building. You're doing the kind of theory where you're coming up with, you know, new models of particle physics or whatever. And then it tends to get more… more abstract but, you know, a lot of us just kinda do a lot of differential equations [laughs] all day.

BH: Yeah.

KM: And we use the computer to do them, so it's not… it's not… day to day it's not always that mathematically complex but it certainly helps to be very conversant in a lot of these ideas just so you can understand what's being written about in the papers. You can kind of visualize the computations. You can understand, you know, even like… even the things that are being plotted are sometimes plotted in a particular way in order to bring out some aspect of the physics and so it's really helpful to just have a good facility with all that stuff.

BH: So you're getting away with your Math point nine at the moment, are you?

KM: [laughs] At the moment, yes, but… occasionally…

BH: [laughs]

KM: Occasionally I have to push myself all the way up to one. [laughs]

BH: [laughs]

KM: Uh, hold on a sec, I just need to pour myself some more tea. Okay. [sound of liquid flowing]

[gentle violin music]

BH: We'll take this quick tea break to remind you that this episode has been sponsored by G-Research a world leading quantitative finance research firm based in Europe. And if you find quantitative easy to say, well, you're a better podcaster than me. Now G-Research is hiring clever people from around the word to tackle the biggest questions in finance. Applying the latest in machine learning, big data, all the top technology. G-Research is always looking to hire the top STEM talent so if you are good with numbers, mathematics, computers, that kind of stuff, well maybe this could be the opportunity you've been waiting for. I know G-Research takes real pride in the culture they've created and they're keen to nurture future talent. To find out more about them, go to gresearch.co.uk/numberphile. G-Research, create today, predict tomorrow.

[gentle strings music]

BH: Can I ask you about Twitter?

KM: Sure.

BH: One of the things you're quite well know for, it's how I first knew of you…

KM: Mhm.

BH: …is for being Twitter famous.

KM: [laughs]

BH: You were kind of the first scientist to become really mega followed on Twitter and you're the person to follow and you're still one of the most followed scientists out there.

KM: [laughs]

BH: Tell me about why you joined Twitter, first. The circumstances under why you're on twitter in the first place and then what happened.

KM: I mean I first got a Twitter account in grad school at some point and I didn't really do anything with it. I just had the account but when I was a postdoc at Cambridge there was a colleague of mine came and gave a talk at some point about, I dunno… active galactic nuclei… whatever he was working on. And on his title slide on the talk he put his Twitter handle and I thought, this was a very weird… I mean this was… this must've been, I dunno, uh… 2010 or something like that. It was a while ago and it wasn't… people were not doing that, like serious people would not include a Twitter handle on a title slide.

BH: Yeah.

KM: That was a very unusual thing. And so I thought this was really intriguing and I looked at his Twitter account and it was all… astrophysics, you know, it was a very… science oriented account and he would tweet about new results or interesting papers or the stuff that he was working on. He would live tweet conferences, you know, this was a thing that people would do a lot at the time.

BH: Hmm.

KM: And I thought well this is an interesting thing maybe I should try this out

and maybe I… maybe this'll be an interesting way to… you know, talk to more people about astrophysics and so you know, I thought, like oh I should do this and… a couple weeks later I was visiting Oxford University for a conference about dark matter and… my colleague was there and he was… he had planned to go to the conference but wasn't gonna be able to… to attend the talks, he was based at Oxford, and so he said, hey can you just live tweet this for me, so I know what I'm missing. I'm like sure, yeah, okay, I'll try that.

BH: Yeah.

KM: And so I just, you know, I did one tweet per talk basically to try and summarize what the talks were about and Phil Marshall my colleague, because he told me to do this, he would then retweet to his followers and he, I dunno, a few hundred or something like that at the time. And so… that sort of got me into his network and so I started to get followers and, you know, I got really excited when I had a couple hundred followers based on…

BH: Yeah.

KM: …based on sort of continuing that and I found that it was just kind of a nice way to get to know other people in astrophysics. To get to know some people who were science writers, interested in astrophysics, and then there were a few people who were just interested in the subject but not at all connected to the field and I really enjoyed being able to talk about science in that way to connect with people who were working on interesting things but not at my institution, you know, so I could, kind of broaden my professional network and then I just kind of carried it on.

BH: All so lovely and collegiate.

KM: Yeah. Yeah, I mean at first it really was.

BH: [laughs]

KM: And… uh… and… uh… you know I got to know a lot of people in a lot of different places and then the Higgs… uh… you know the Higgs boson announcement happened and I was able to tweet about that and that ended up, like, a couple of my tweets were picked up by blogs or newspapers or something about the importance of the Higgs and so that kinda bumped me up some more.

BH: Hmm.

KM: And I just found out… I found it was this really nice… really sort of broad community. I dunno…. that… worked really well for me.

BH: Then what happened, though? I thought you made a couple of clever comments and a couple of smart remarks and things kinda blew up.

KM: Yeah… [laughs] Yeah… so…

BH: [laugh] Let's be honest here.

KM: So, okay, so… a little while later… um… you know, once my following had increased a little bit and I was starting to become like a sort of known voice on Twitter, you know, that point you start to get comments, right? You start to get… uh…

BH: Hmm.

KM: …people… um… trying to say things and get you riled up, right?

BH: Yeah.

KM: And so I would try to… you know sort of address trolls and stuff in

reasonable ways, and… there was a very… specifically impactful [laughs] moment when…

BH: [chuckles]

KM: I guess it was in 2014 or something when… there was a… so… Brian Cox was on a TV show talking about something to do with climate change and I tweeted about it and… I tweeted something about how climate change makes me really sad, you know, because what we're losing because of this process and somebody, you know, just some random person, tweeted back to say, you know, that… this was… you know this is all a scam and, you know, climate change is a scam and I should go learn some science.

BH: [laughs]

KM: And… uh… and so I replied… something along the lines of like, you know, I don't know man, I already went and got a PhD in astrophysics, I feel like more than that would be overkill. And it was just, you know…

BH: [laughs]

KM: It was this reply that was just like… I think I was like walking down a hallway when I saw the tweet and I just sort of…

BH: Yeah.

KM: You know hammered out a reply, just something to be like, yeah whatever, go away. And I sorta chuckled to myself [laughs] while I was typing it but it was just a reply to him…

BH: [laughs]

KM: …I wasn't doing like the whole quote tweet thing or anything, you know, I wasn't trying to make a scene.

BH: Yeah, yeah.

KM: But…

BH: Yeah.

KM: Somehow some people saw it and started retweeting it…

BH: Yeah.

KM: And it just went super viral.

BH: Yeah. [laughs]

KM: You know, suddenly like celebrities were screenshooting it. [laughs] Like this whole exchange…

BH: Yeah.

KM: Um… and it…

BH: [laughs]

KM: And it… it doubled my following in a week. You know…

BH: Yeah.

KM: I went from like forty-thousand to eighty-thousand followers or something like that. Somewhere in the middle of that I got verified. I started

getting messages from people like, you know, saying how much they like my… my uh… my Twitter presence. I got a call from like… Huffington Post… I mean it was just this really bizarre…

BH: Yeah.

KM: …bizarre thing that happened and… that just really got me into this sort of very different category on Twitter.

BH: Do you now feel a kind of pressure or expectation to occasionally be a bit sassy and clever now and sort of…

KM: [laughs]

BH: …and funny? 'Cause, I mean, that's such a great reply.

KM: Yeah.

BH: Is the pressure now on to sort of be that person occasionally, that you know…

KM: Yeah.

BH: …swoops in with the witty remark?

KM: [laughs]

BH: 'Cause you do do it a bit.

KM: Yeah. So… I think there's certainly pressure I think to be funny. I don't wanna make fun of people. I don't want to be, you know, mean. I certainly don't wanna be mean to people who are… you know just kinda minding their own

business or who are not like prominent voices, right? One of the things that that…

BH: Hmm.

KM: …that viral moment showed me very clearly was how… powerful and frightening that sort of attention can be. Because I…

BH: Hmm.

KM: …you know I got a huge amount of attention, and it was almost entirely good attention, right? Like it wasn't, like people were saying nice things for the most part. But it was still just totally out of my hands, you know? This was like… I was getting hundreds and hundreds of messages everyday and… and I was showing up… you know quoted in newspaper articles and stuff and I had no control over that and it's… that's a scary thing to be suddenly thrust into this big spotlight and… at the same time, you know, people were really ragging on this guy who I was replying to.

BH: Yeah.

KM: Tons and tons of messages about how stupid he was or whatever. And you know, he was kind of a jerk so I wasn't… I didn't feel that bad about him, but I still, you know, I realized… like how confronting that must be for him as well and he was just some random dude, you know, not a nice person but not the devil. [laughs] Right? And certainly not a prominent person.

BH: Yeah.

KM: I don't think, you know, he only had a handful of followers. You know, so I'm very aware of the power that having that kind of voice… entails and I'm very aware of how quickly things can go off the rails and I don't want to put

anybody in a position to be harassed, right? So… I do try to be careful to not like attack people or not make anybody sort of the butt of a joke, you know, large context when they're just, you know, just because I disagree with them because, you know, if I sort of call someone out… there's, you know, three hundred thousand people who follow… who choose to follow me who would probably agree with me that that person is wrong and might just be really, you know…

BH: Hmm.

KM: …really abusive towards that person and each person individually saying, oh you're dumb, is not gonna be that big a deal but when you have a huge flood of it, you know, it's a different story. You know, and I've been sort of targeted by… large online mob things in a limited way and… it's terrible. [laughs] Right? So you don't… you don't ever wanna put someone else in that position… so I try to not… I try not to use that avenue of expression too much. So… you know, I will sometimes reply to people in a sarcastic way or whatever and, you know, I will… sort of make my feelings known one way or another but I try to be at least a little bit polite about because… I don't wanna fuel that kind of attack mode.

[gentle string section music plays]

BH: Now one thing you have tweeted about a lot is your book.

KM: Mhm.

BH: I felt like I saw it coming.

KM: [laughs]

BH: There was all this hype and expectation around it.

KM: Yeah.

BH: It's finally out.

KM: Yep.

BH: It's gone down really well, hasn't it?

KM: It has, yeah… um… it's been a… it's been great, you know, the… the response to the book has been better than I could've anticipated. I mean, I'm not really in touch with sales numbers per say, so I don't know. I don't have a good feel for whether it's done well on that side of things but in terms of the reviews, you know, every sort of professional review of it, you know, in magazines and stuff, it's been positive and… the reviews on, you know, Amazon and stuff like that are largely very good so…

BH: Yeah.

KM: It's just been… that's been the thing that I've… I really was worried about, you know? When you're writing a book you want it to sell well, I guess, but once you get the advance… um… it doesn't necessarily make that big of a difference to your life if it sells well or not. [chuckles]

BH: [chuckles]

KM: But you want it to be good, right?

BH: Well it makes a difference to whether you get to write another one. [laughs]

KM: It does get, yeah, yeah… um… certainly, yeah I mean that's an issue and… that's in the back of my mind but my first priority really with this book

was just I want it to be good, right? Like I hope it sells well, sure, but I want it to be something that is, you know, that I can be proud of, and… yeah the reception has been amazing so… I feel really good about that.

BH: Now, it's called the End of Everything.

KM: Mhm.

BH: Do I then say brackets Astrophysically Speaking? Or do I just call it the End of Everything?

KM: Um… either way… so technically the Astrophysically Speaking in parentheses is not a subtitle, it is part of the actual title but I just call it the End of Everything, mostly.

BH: Okay.

KM: The Astrophysically Speaking is in there because… it was important for the publishers that there was something to indicate that this really… like we really meant it. [laughs] That it was the end of everything, that it's not just like...

BH: Yeah.

KM: …you know, metaphorically the end of everything. It's not like a novel about grief or something like that… it is… it is actually about the end of everything.

BH: So it's the end of everything, definitely with a capital E.

KM: Yes, yes, exactly.

BH: And you look at basically how the universe is gonna end. Is that right?

KM: Yeah, so different possibilities for how the universe might end. What they would look like. How we're trying to figure it out in physics and astronomy. What we're gonna learn over the next few decades. But yeah, just… the different possible ends of the cosmos.

BH: This lead… this makes me think about a few things I always think about when I talk to people who do your job.

KM: Mhm?

BH: And one is… what does it feel like to know that… you're probably gonna be dead when all of this stuff happens?

KM: [laughs]

BH: You're probably gonna be dead when all the good stuff happens. All the stuff you think about and write about and research…

KM: Yeah.

BH: …yet alone the end of the universe.

KM: Mhm.

BH: Just… you know… things like the end of galaxies…

KM: Yeah.

BH: …galaxy collisions and stuff. You know, you're gonna miss all that.

KM: Yeah.

BH: What does that make you feel?

KM: I mean it's a bummer, right? [laughs]

BH: [laughs]

KM: I would… I mean…

BH: Yeah!

KM: I want… you know I often wish I could just… I could just fast forward you know a couple hundred years, a couple thousand years… you know, a million years something just take a look, you know? [laughs] Just see what it's gonna…

BH: Yeah.

KM: …what it's gonna be like. And I'm really bummed that I don't get to see that. That, you know, there are astrophysical events that I can anticipate but I can't ever watch like that's… it's too bad.

BH: [laughs]

KM: I mean it's… you know, there's only so much one can do in one's lifetime and you know, you have to kind of accept that, you know, humans are mortal and… and we have these limitations on us and but… we don't have to be happy about it. [laughs] I'm not happy about it.

BH: So if… so if I gave you the magic time machine bubble…

KM: Mhm?

BH: …and you could go anywhere forward, back and also anywhere in space.

KM: Yeah?

BH: And just look at something for an hour or…

KM: Yeah.

BH: You know? Just to watch the sight.

KM: Yeah.

BH: Where would you take it?

KM: Um… I mean… I would have to think about that a lot more, but I mean I would love to see…

BH: [laughs]

KM: I would love to see the collision between the Milky Way and Andromeda. You know, that's gonna be…

BH: Oh yeah.

KM: It's about four billion years from now, right? Um…

BH: Yeah.

KM: That's gonna be really cool looking. Uh… and…

BH: Yeah.

KM: …it'll take a long time, you know, I would probably wanna take my time machine there and then fast forward a while to actually see it carried through but that would be really really awesome.

BH: But if you can only go to one place for an hour, I guess you just wanna catch it like at its peak?

KM: Yeah, yeah.

BH: Like what's the night sky gonna look like from Eart… oh there probably won't be an Earth will there? But what's the night sky gonna look like from around here at that point?

KM: Um…

BH: Like, crazy?

KM: Yeah I mean… the, you know there will just be a lot more… sort of light in the sky. We'll have way more stars.

BH: Hmm.

KM: 'Cause all the stars will be Andromeda will be a lot closer. When the collision occurs, it'll shove a bunch of hydrogen gas together and will make some more stars, you'll get more supernovae for… for… you know a few centuries at least… around that time. I mean, more like millennia I guess around that time. You'll get more supernovae. For the highest mass stars you'll get like sort of millions of years that these things burn so you'll get the collision, you'll get some new stars forming, you'll get new stars blowing up. It won't be a huge amount of star formation, 'cause there's… by that time a lot of the hydrogen will be depleted in both the Milky Way and Andromeda, but you'll get some… some

fireworks. And then… you know when the cores of the galaxies are coming together, the supermassive black holes will coalesce and…

BH: Yeah.

KM: So you might get some really interesting sort of activity… I mean even just at the beginning of the collision, you'll move gas around such that the black holes might become active, so you get… you might get these giant jets coming out of the black holes and, you know, they'll be tearing stars apart and stuff and then, you know, they'll spiral together and that could be really cool. I mean, it's gonna be… fascinating. [laughs]

BH: What about naming rights? What are we gonna call the new galaxy?

KM: Uh… people are calling it Milkdromeda. [laughs] That's the…

BH: Milkdromeda!

KM: Yeah.

BH: No.

KM: That's what… the term I've seen.

BH: That's not good.

KM: I don't know, there might… maybe people will come up with something else but…

BH: I mean even the Andromeda Way is better than Milkdromeda.

KM: Yeah. Yeah. Uh… you know, it's not up to me but…

BH: Not sure about that.

KM: Yeah.

BH: Do you know what. I love space and astronomy.

KM: Hmm.

BH: Like I really love it.

KM: Hmm.

BH: But still if I could have that time machine bubble, d'you know where I think I'd go?

KM: Where would you go?

BH: I wanna see the Titanic hit that iceberg.

KM: [laughs] That's so morbid!

BH: I wanna see that moment. What it sounded like and looked like, as it hit.

KM: Yeah?

BH: Like I'm not happy that the people died, and I wouldn't… I don't wanna see… that's sad and I don't wanna see all that. But I just wanna see that collision.

KM: You don't think that would just be terribly traumatizing and… and horrible?

BH: I don't think the collision would be, like as it sank it would be terrible and traumatizing, you know, what happened afterwards but… just that moment, 'cause no one… well I guess some people down below deck were hurt when that happened, but the actual collision I think was fairly… innocuous.

KM: I mean you could just, you could just go watch an icebreaker… plow around the Arctic Circle if you wanted to see, you know, ships colliding with icebergs.

BH: Yeah it but hasn't got the historic significance.

KM: True.

BH: It hasn't got the historic significance.

KM: True. I know…

BH: I would like go and see a black hole up close as well though.

KM: Yeah. Yeah. I mean… to see a black hole close enough that you can actually see the effects of the gravitational lensing would be very very cool.

BH: Yeah.

KM: Yeah.

BH: The end of the universe, like it's such a fascinating topic, I'm not surprised everyone wants to read your book.

KM: Hmm.

BH: But… is it gonna be a bit boring?

KM: [laughs]

BH: Is it gonna be a whimper? I mean I guess I know you go through all the scenarios but…

KM: Yeah.

BH: …it's gonna be a whimper isn't it?

KM: [laughs] Um… when I was thinking about the book, the structure of the book, one of the things that I considered doing was I thought what if… what if in the beginning of each chapter about each end of the universe I put like a little science fictiony vignette about, you know, like, what it looks like while it's happening and all this stuff and I thought about doing that and then I realized like, none of these are cinematic, you know, none of these are gonna be interesting to watch because… either you have a heat death, which is this very very long slow fading of the universe.

BH: Hmm.

KM: Or you have something that's so sudden that you don't see anything, like vacuum decay where it's just you don't even notice it happening. Or you have something that is dramatic but only on this time scale of like millions of years and… that doesn't make a good story.

BH: Right.

KM: So, you know, each… I mean some of them are more dramatic than others, I mean, a Big Crunch and a Big Rip are both very violent events.

BH: Hmm.

KM: And would be dramatic, but again, on the time scale of sort of millions of years rather than sort of human lifetimes.

BH: So the Big Crunch doesn't have a… a dramatic final few seconds. It hasn't like the Big Bang has a dramatic start?

KM: Well it does…

BH: The Big Crunch…

KM: It does get dramatic at the end it's just by the time it's getting really dramatic… well okay so… so the Big Crunch is an interesting case because you would see it coming.

BH: Hmm.

KM: Right, so if the universe were gonna collapse on itself, you would see it coming because you would see… that galaxies are moving towards you instead of away like they're supposed to.

BH: Hmm. Yeah.

KM: And you would see sort of the universe getting more compact. The part that gets dramatic is that the ambient radiation in the universe would start to head up. Okay, so, so, you know, we have this background light in the universe right now called the cosmic microwave background, which is the, sort of background light from the Big Bang, this light that's left over from when the whole universe was hot and dense when it was younger, when it was smaller, and that light has dissipated through the universe as the universe has expanded, but if the universe is compressing then that light'll be compressed and so the universe will trend more toward that hot dense state again.

BH: Hmm.

KM: But it'll actually be worse than that because in addition to all this background light from when the universe was hot and dense in the beginning, the compressing universe would also compress all of the light from all the stars that have every shone, all of the gamma rays burst and all of the X-ray radiation and all of this other radiation that's been produced in the time since the beginning, all that light gets compressed as well and it gets compressed and it gets shifted to higher frequencies so it gets, you know, it becomes harder radiation. There would be a time when you could sort of watch space heating up and eventually it would get so hot that it would start to actually ignite the surfaces of stars.

BH: Right.

KM: So you get this situation where there's so much hard radiation in the universe that the surfaces of stars start undergoing thermonuclear reactions.

BH: Right.

KM: And… and like exploding basically from the outside in. And… at that point…

BH: Aww yeah!

KM: …it's very dramatic. [laughs] It's very sudden.

BH: That's gonna look amazing.

KM: Yeah.

BH: Do you think… like obviously you don't wanna be around for that.

KM: Yeah.

BH: But…

KM: [laughs]

BH: Do you think there's any chance, any chance whatsoever…

KM: Mhm?

BH: …that humans are gonna be… around for the finale as long as life can be around for the finale?

KM: Um. [sighs]

BH: Do you think like our… our future… we have a chance at all?

KM: I dunno. I mean… the first thing we have to figure out how to do is survive the death of our sun, right? And that's…

BH: Yes.

KM: That's non-trivial. Right? That's a big deal. We only have about a billion years before Earth is no longer habitable.

BH: Yeah.

KM: Because in a billion years the sun will puff up enough to boil off the oceans of the earth and then, you know, in a few more billion years after that the sun becomes a white dwarf and is basically useless, so… so we have to figure out

how to get through that hump, right?

BH: Yeah.

KM: And I kind of feel like if we're able to that, if we're able to find a way to leave Earth and, you know, be sort of free floating in the universe and making use of whatever energy sources we find.

BH: Yeah.

KM: I think that gives us a significant… significantly better chance of making it into some indefinite future, you know, I dunno.

BH: Yeah, 'cause then we can start hedging our bets and going to all sorts of places.

KM: Yeah, exactly, exactly. Um…

BH: Yeah…

KM: But… um…

BH: A billion years seems like enough time to figure it out.

KM: [laughs] You would think so but… [sighs] I dunno, we've had… we've had what… fifty years on climate change and we've done nothing, so I'm not… I'm sure how much…

BH: Yeah. [laughs] Yeah.

KM: I'm not sure much faith I have in humanity on that scale.

BH: Oh don't start me on your climate change, Katie Mack, going and learn some science.

KM: [laughs] Yeah. Sorry.

BH: [laughs]

KM: I'll get right on that.

BH: [laughs] I set it up for you. [laughs]

KM: [laughs]

[gentle violin music]

BH: So I mean obviously the sun won't be around for the end.

KM: Mhm.

BH: Does the Milky Way make it to the end or does the Milky Way turn off before the end as well? Like do we run outta gas and stars here?

KM: Well so it depends on when you think it's happening. I mean so there's the…

BH: Right.

KM: …the heat death is this sort of ultimate end of the universe where that we think we're probably heading to where, you know, it's sort defined by all structures over by then anyway, so it's not… nothing can survive to the end of that because, you know, it's not the end if anything's left.

BH: Yeah.

KM: Other scenario's that could in principle be sooner, I mean, if the… if we're gonna have a Big Crunch, like we probably can't because we're pretty sure the universe is expanding, is going to keep expanding forever, but if it were to stop and turn around, we're pretty sure that could't happen for… you know tens of billions of years at least, but if it were tens of billions and not longer than in principe we could be around for that, but you know again we don't really have a good reason to believe that that could happen or a mechanism for it happening so that's… that's pretty unlikely.

BH: Yeah.

KM: The Big Rip, if the Big Rip were gonna happen then the earliest that could happen and be consistent with current data is about two hundred billion years and in principle, you know, there will be some stars in the Milky Way still around in two hundred billion years so, you know, the universe won't be totally dark and empty by then and something could in principle be around to see that happen. And then there's vacuum decay [laughs] I mean vacuum decay could happen… in principle, at any moment, it's just… if it did you kind of wouldn't… you wouldn't see it coming.

BH: Right.

KM: And it would happen so fast that you wouldn't necessarily really notice it so… that one probably won't happen until long long after everything is kind of fallen apart but, you can't say with certainty that it won't happen sooner.

BH: I don't know much about this vacuum decay 'cause my… the next question… one of the final questions I wanted to ask you is…

KM: Yeah?

BH: Is there like a universe equivalent of, you know, the asteroid that came out of no where and just whacked you in the face? The thing that scientists can't predict?

KM: Yeah totally.

BH: Is that what vacuum decay is?

KM: That's absolutely what vacuum decay is. Yeah, yeah, so vacuum decay…

BH: Right.

KM: …it's this sort of newish idea in the sense that it's gained more popularity recently. The idea behind vacuum decay is, you know, we have… our universe has a Higgs field. So it's this sort of energy field that pervades all of space and the Higgs field is sort of connected with how physics works. Like, it sort of determines the laws of physics, the interactions between particles, just how physics works on a fundamental level and we know that the Higgs field was different in the very early universe, so when you hear about the Higgs boson, the Higgs boson is this particle that's associated with this energy field and discovering the Higgs boson was a big deal because it indicated that our ideas about the Higgs field was correct. That… the Higgs field is this energy field that's throughout all of space. That it did undergo a shift in the very early universe that sort of set up the conditions for particle physics as they are now… and so finding the Higgs boson was an indication that like yes we do live in a universe like that where this… this Higgs field made a change and that change determined how physics works in our universe.

BH: Yeah.

KM: The problem is that measurements of the Higgs boson, our increasingly

better understanding of the Higgs field suggests that the value the Higgs field has now is not necessarily the sort of preferred value that… it suggest that the Higgs field could change again.

BH: Right.

KM: And we don't want the Higgs field to change again because if it did our… we would have totally different laws of physics, our particles wouldn't hold together anymore, we couldn't have atoms and molecules like…

BH: Right.

KM: …it would just… it would destroy…

BH: Yeah.

KM: …all structure in the universe right? [laughs]

BH: Yeah.

KM: So we don't…

BH: Oh that's sounds bad.

KM: Yeah we don't want that to happen.

BH: That would definitely affect my wifi.

KM: Yeah, yeah, yeah. No, it's a problem and the issue that we think that the Higgs field might be metastable in the sense that if it were disturbed a little bit it could… sort of revert to this other value and change the laws of physics.

BH: Oh!

KM: Or, alternatively it could undergo a quantum tunneling event at one point in space where the Higgs field could quantum tunnel to this other value so it would just sort… spontaneously change in one point in space and at that point in space.

BH: Oh gosh.

KM: It would create this bubble of what we call a true vacuum. A different kind of space in which the laws of physics are different inside that bubble and that bubble would then expand out at about the speed of light and destroy everything in it's path and then the space inside the bubble, this true vacuum space, in principle is most likely gravitational unstable and so once you're… once the bubble wall hits you, first the bubble wall incinerates you because it's got a lot of energy in it and then you're inside the bubble and your molecules don't hold together anymore, particle physics is totally different, and then… the space inside gravitationally collapses so you sort of turn into a black hole. [laughs]

BH: Okay. Is there anything we can do to prevent this from happening?

KM: [laughs] No. [laughs]

BH: To stop this event from occurring?

KM: [laughs] No. Not at all. Not at all.

BH: [laughs]

KM: There's nothing we can do.

BH: Right.

KM: And because it's based on quantum tunneling it's a probabilistic event, it's…

BH: [laughs]

KM: ...you know it's based on quantum physics so you can't even predict when it's gonna happen, where it's gonna happen… all we can do is based on our calculations of our understanding… our current understanding of particle physics we can put probabilities on when it might occur.

BH: Hmm.

KM: And we can say that, you know, it's sort of haves a half life, right? We can say that… it's probably not gonna happen within the next, you know, ten to the power of a hundred years.

BH: Hmm.

KM: That's sort of our best estimate at the moment. But we don't know for sure.

BH: Okay. If it happens does it happen at a specific location?

KM: Yeah.

BH: Like…

KM: Yeah.

BH: So it could've already happened like, so far away and be coming towards without us knowing.

KM: Yeah, I mean if it happened… you know next to Saturn right now we wouldn't know for another hour or so, right? Like [laughs] it's…

BH: Okay. [nervous chuckle]

KM: It would… it could just be the bubble could be coming toward us at the moment and we wouldn't be able to see it until it was on top of us. So…

BH: Wow.

KM: So yeah I mean… you know it's very unlikely… for it to happen anytime soon but we can't entirely rule it out.

BH: [laughs] But you're saying there's a chance.

KM: [laughs]

BH: [laughs]

KM: Yep.

BH: Well… on that note I feel like I've better get to working editing this podcast…

KM: [laughs]

BH: …'cause…

KM: You never know, yeah.

BH: I don't know if people are gonna hear it otherwise. [laughs]

KM: [laughs] Yep.

[gentle string section music]

BH: Well that's all for now. You can learn more about Katie's work, her tweeting, and perhaps most importantly her doomsday book, [gentle piano music fades in] in the notes for this episode. Thanks again to G-Research for supporting this podcast. They're also in the notes. And yes, thanks to MSRI, the Mathematical Sciences Research Institute for supporting Numberphile. [music continues] I'm Brady Haran, and you've been listening to the Numberphile podcast.

[music continues and fades out]