The following is a conversation with Anna Furbel, an astrophysicist at MIT, studying the oldest stars in the Milky Way galaxy in order to understand the chemical and physical conditions of the early universe and how from that our galaxy formed and evolved to what it is today, the place we humans call home. And now a quick few second mention of each sponsor. Check them out in the description. It's the best way to support this podcast. We've got Hexclad for well designed and well engineered cookware, Numeri for the world's hardest data science tournament and house of academia for delicious snacks. Choose wisely, my friends. Also, if you want to work with our team, world was hiring, go to lexfreedman.com slash hiring. And now onto the full ad reads. Never any ads in the middle. I tried to make this interesting, but if you skip them, please still check out the sponsors. I enjoy their stuff. Maybe you will too.

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in quotes, hybrid cookware. I don't know what that means. All I know it looks badass. I got it a couple of weeks ago. I already cooked a couple of steaks on it. It's just perfect. My goal for this weekend actually is to cook an omelet on it. But it works perfect for steak, non-stick. I don't know how they do it. But as they say, it has the performance of stainless steel, the durability of cast iron, and it has non-toxic and non-stick coating. The steaks, in case you were wondering, were delicious. I like it about medium rare. And there's probably a lot more to be said about how I like to cook steak in different conditions when I'm traveling, when I'm at home, all that kind of stuff. But steak is the simple meal I return to time and time again for a source of simple happiness and fulfillment. Almost exclusively, I've been eating one time a day. And so it's steak, big steak, with a bunch of veggies on the side if I'm going keto and just steak if I'm going carnivore. Anyway, go to hexclad.com and use code LEX to get 10% off your entire order. That's hexclad.com and use code LEX for 10% off your entire order. This show is also brought to you by Numari, a hedge fund that I've talked a bunch about in the past. It uses machine learning to make investment decisions. And it's the tournament that challenges data scientists from all over the place to construct predictive models for financial markets. And then it uses those models to help people make financial decisions. If you're a data scientist and you want to be involved, this is an amazingly interesting, complex, difficult, and impactful machine learning tournament and challenge. I think too often in the machine learning community, the problems will work with the toy problems. And so I really love the idea that Numari is creating this problem, this giant problem that is not at all a toy. It's working with real markets and real money. That's to me, super exciting. Head over to numari.com slash LEX to sign up for a tournament and hone your machine learning skills. That's numari.com slash LEX for a chance to play against me. Yes, me. And for a chance to win a share of the tournament's prize pool.

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at the bottom. And you know, so much of my life I've wasted on peanuts when I could have been spending all this valuable time with macadamia nuts. Anyway, if you want some more delicious nuts in your life, go to HouseOfMacadamias.com slash LEX to get a free box of their best seller, the Namibian Sea Salted Macadamia Nuts. They're delicious. Plus 20% off your entire order. That's HouseOfMacadamias.com slash LEX. This is the Lex Friedman podcast. To support it, please check out our sponsors in the description. And now, dear friends, here's Anna for Bell. Let's go back to the early days. What did the formation of the Milky Way Galaxy look like? Or maybe we want to start even before that. What did the formation of the universe look like? Well, we scientists believe there was the Big Bang, some big beginning. But what is important for my work, and I think that's what we're going to talk about, is what kind of elements were present at that time. So the Big Bang left a universe behind that was made of just hydrogen and helium and tiny little sprinkles of lithium. And that was pretty much it. As it turns out, it's actually quite hard to make stars or any structure from that. That's fairly hot gas. And so the very first stars that formed prior to any galaxies were very massive stars, big stars, 100 times the mass of the Sun. And they were made from just hydrogen and helium. So big stars explode pretty fast after a few million years only. That's very short on cosmic time scales. And in their explosions, they provided the first heavier elements to the universe because in that course, all stars fuse lighter elements like hydrogen and helium to heavier ones. And then that goes all the way up to iron. And then all that material gets ejected in these massive supernova explosions. And that marked a really, really important transition in the universe because after that first explosion, it was no longer chemically pristine. And that set the stage for everything else to happen, including us here talking today. So what do you mean by pristine? So there's a whole complex soup of elements now as opposed to just hydrogen, helium and a little bit of lithium. Yeah. So after the Big Bang, just hydrogen and helium, we don't really need to talk too much about lithium because the amount was so small. And after these very first stars formed and exploded,
they, the heavier elements like carbon, oxygen, magnesium, iron, all of that stuff was suddenly present in the gas clouds, tiny amounts only, very tiny amounts. But and that actually helped especially the carbon and the oxygen to make the gas cool. These atoms are more complicated than hydrogen. That's just a proton. And so it has cooling properties, can send out photons outside of the gas cloud. So the gas can cool. And when you have gas that gets colder and colder, you can make smaller and smaller stars. So you can fragment it and clump it and turn it into stars like the sun. And the cool thing about that is that when you have small stars like the sun, they have a really long lifetime. So those first low mass stars that formed back then are still observable today. That is actually what I do. I try to find these early survivors, because they tell us what the gas looked like back then. They have preserved that composition of these early gas cloud, the chemical compositions until today. So I don't need to look very far into the universe to study all the beginnings. I can just chemically analyze the oldest stars. And it's like unpacking everything that that happened back then. That's very exciting. So to just reiterate, so in the very early days in the first few million years, there was giant stars that's mostly hydrogen helium, and then they exploded in these supernova explosions. And then they made these clumps. Yeah, so the first not pristine clumps. Yeah, pretty much fun. So it took a few hundred million years for the first stars to emerge.

And then they exploded after a few million years. Kaboom. And then it's like, I always consider the universe like a, you know, a nice soup. And then these first supernova explosions kind of provided the salt, you know, just a little sprinkle of heavier elements. And that made it really tasty. It's just changed it completely, right? And that changed the physics of the gas. So that meant that these gas clouds that were, you know, surrounding the former first stars, they could now cool down and clump and form the next generation of stars that now included also little stars. And as I just mentioned, the small stars have these really long lifetimes. The sun has a lifetime of 10 billion years. Any star that is even less massive will have an even longer lifetime. So that gives us a chance to still observe some of the stars that formed back then. So we are testing the conditions, the chemical and physical conditions of the early universe, even before the galaxy formed. So what's the timeline that we're talking about? What is the age of the universe? And what is the earliest time we've got those salty, delicious soup, clump soups with heavier elements? Well, the universe is 13.8 billion years old. Legitly, yeah. Okay. When I was in high school, the universe was 20 billion years old. Do you think that estimate will evolve in interesting ways or no? Is that pretty stable? I think we have mostly converged, yes, because the techniques are very different now, much more precise. The whole business of precision cosmology by mapping out the cosmic microwave background, that's a marvelous feat. Maybe the digits will still move around a little bit, but that's all right. Plus the gravitational waves and all that, all the different sources of data mapping out this detailed picture of the early universe. Totally. And so we think the earliest little stars formed, I don't know, maybe half a billion years after the Big Bang, again a few hundred million years for the first stars to emerge and then took some time. So give or take half a billion years. And that was the time when sort of the very first proto-gallaxies formed early stellar structures, stellar systems from which the Mickey way eventually formed. So the Mickey was probably a slightly bigger one. And we know today that galaxies grow hierarchically, which means they eat their smaller neighbors. So if you're the bigger one and have a few friends around, you're just going to eat them, absorb them, and then you grow bigger. And so all these little early stars kind of came into the Mickey way through that kind of process. And that's why we find them in the outer parts of the galaxy today, because they're just kind of deaf and just left there since.
So the old stuff is on the outskirts of the galaxy and the new stuff is in closer to the middle? Is there? Broadly speaking. Yes. So that's where you would look for it. So maybe just to step back, like what is a galaxy? What is a proto-gallaxy? I love that question. So the galaxy is a huge assembly of stars. The Mickey way contains something like 200 to 400 billion stars. And most of the material and the stars are in the disk. And when we look at the night sky, what we see as the Mickey way band on the sky, that is actually the the inner the next inner spiral arm, because we actually live in a spiral disc galaxies on the Mickey way as a spiral disc galaxy. And we're looking actually depends a little bit in the northern hemisphere, we're looking out of the galaxy. So we're seeing the next outer spiral arm. And as you can imagine, there's only dark space behind that. So we don't see it all that nice on the sky. But if you travel yourself to the southern hemisphere, let's say South America, you see the Mickey way and it looks so different on the sky, because that's the next inner spiral arm. And that's backlit by the galactic center. The galactic center is a very big puffy, you know, region of gas, there's a lot of

star formation that the galactic party is happening there. So it's very bright. And it makes for this very beautiful Mickey way on the night sky that we see. So actually, if you if you ever get the chance to experience that, I encourage you to almost like close your eyes while seeing this and imagining that you're sitting in this kind of disc in this pancake, and you're just kind of looking right into it. And you can you can really feel that we're in this 2d disc. And then you can imagine that there's a top and a bottom and that that we really part of the galaxy, you can really experience that we're just not not just lost in space somewhere, but we're really a part of it. And, you know, knowing a little bit about the structure of the Mickey way really helps.
Do you feel small when you think about that? When you look on the spiral on the inside of the Milky Way, and then you look out to the outside? How are we supposed to feel?
I don't know. I don't feel small necessarily. I feel in awe. And I feel I'm a part of it, because I can really feel that I'm a part of it. I think for many people, they think like, oh, there's just the planet, and then there's nothing. And that's almost a little bit sad, but that's really not the case, right? Because there's so much more. And I really like to imagine how I'm sitting in this big galactic merry go around and we're going around the center and I can see the center above me, right? And I can almost feel like we're going going there. Of course, we can't really feel that. But the sun does circle the galactic center.
But there's a kind of sadness to like looking pictures of a nice vacation place.
All we get is that light, an old light. Do you feel like sad that we don't get to travel or you and I will not get to travel there? And maybe humans will never get to travel there?
Yeah, I always wanted to travel into space and see the earth and other things from up there. There's certainly that. But I don't know, it's also okay. It would just be at our vantage point and see it from here. With the sensors, with the telescopes that we have and explore the possibility. Yeah. I mean, there is a kind of wonder to the mystery of it all. What's out there? What interesting things that we can't possibly imagine. There could be all kinds of life forms, bacteria, all this kind of stuff. I tend to believe that it depends on the day. I tend to believe there's just a lot of very primitive organisms just spread out throughout. And they built their little things like bacteria type organisms. And just to think what kind of worlds there are, because they're probably really creative living organisms. Because the conditions, I guess the question I'm wondering to myself when I look out there to the stars, how different are the conditions on the different planets that orbit those stars? It will definitely be very different. I mean, the variety out there is huge. We know now that I think it's about every other star has at least one planet. I already mentioned the number of stars in the galaxy. I mean, it's a huge number of planets out there. So who knows what that looks like. All we know is that there is, there is a lot of variety. We don't quite yet understand what drives that, what governs that, why that is the case. Why is it not all one size fits all?
We mean the dynamics of planet formation, like exoplanet formation or star formation?
All of it. Star formation remains a much researched topic. We kind of, we definitely know that it works because all the stars are there, same for the planets. But the details are so varied per gas cloud, right? It's very hard to come up with very detailed prescriptions. Broadly, we have figured it out. You need a gas cloud, you need to cool it, something clumps and fragments, and somehow it makes a star with planets or without.
But the dynamics of the clumping process is not fully understood.

No, no. And the local conditions are so varied, right? I mean, it's the same with,
all people look like people, but individually, we look very different.
So even the subtle diversity of the formation process creates all kinds of fun.
We just don't know how this turned out in an individual case. And it's kind of hard to
figure it all out and to take a look certainly with planets, right? The chance for ever,
to ever actually take a picture of a planet is miniscule because they don't shine. So they're
really dark. So I'd say there's, there's, there's a lot of possibility out there.
But we have to be a little bit more patient before we come up with technologies where
patients becomes less necessary by extending our lifetimes or, or increasing the speed of
space travel, all the kind of stuff. Humans are pretty, pretty intelligent. They're pretty,
most part. I hope when I'm on the optimistic days, well, maybe just to linger on the, on the,
what a galaxy is. What should we know about our understanding of black holes in the formation?
Is that an important thing to understand in the formation of a galaxy? Like,
so all the orbiting, all the spiraling that's going on, how important is that to understand?
All of the above. That's what makes astronomy really hard, but also really interesting, right?
No day is like another, because we always find something new. I want to come back to the,
the idea of the proto galaxy, because it actually matches or, you know, relates to,
to the black hole formation. So most large, well, pretty much all large galaxies have a super massive
black hole in the center. And we don't actually know, don't, we don't really know where they come
from. Again, we know that they are there, but how, how do we get there? So we go back to the,
to the early universe, right? We had a, a little galaxy that just sort of, you know,
I don't know, had some small number of stars. It was the first gravitationally bound structure that,
that was held together by dark matter, because dark matter actually kind of structured up,
you know, first before the luminous matter could, because that's what dark matter kind of does.
And it, it started to hold gas and then stars sort of together in his first very shallow,
what we call potential well, so these gravitationally bound systems. And then the Mikiway grew from
absorbing neighboring smaller, even smaller systems. And somewhere in that process,
there must have been a seed for one of these super massive black holes. And I'm, I'm not actually
sure that it's clear right now, kind of what was their first, the super massive black hole or the
galaxy. So lots of people are trying to study that. And of course, the black hole wasn't as
massive back then as it is these days. But it's, that's a, it's a big area of research. And the
new James Webb, the JWST, the telescope, the infrared telescope in space is, is working on,
many people are working on that to, to figure out exactly what, what happened. And there are some
surprising results that we really don't understand right now. So.
So to solve the chicken or the egg problem of, do you need the super massive black hole to
form a galaxy? Or does the galaxy naturally create the super massive black hole?
Yeah, yeah. I mean, I think to some degree, we, we can answer that because there are lots of
little dwarf galaxies out there. The Mickey way remains surrounded by many dozens of,
of small dwarf galaxies. I have studied a bunch of them. And to the extent that we can tell,
they do not contain black holes. So they are certainly were gravitationally bound structures.
So either you can call them proto galaxies or dwarf galaxies or first galaxies,
they were definitely there. But there must have been bigger things,
like the proto Mickey way, where something was different, right? What made them more massive so

that, you know, they would gravitationally attract these smaller systems to, to integrate them. So we'll have to see.
How do we look into that, the, into the, the dynamics of the formation and the evolution of the proto galaxies? Is it possible that they shine? I mean, what, what are the set of data that we can possibly look at? So we've got gravitational waves, which is really insane that we can even detect this light. What else can we?
So that, that would fall into the category of observational cosmology and the, the JWST is, is the prime telescope right now to, and it promises big, big steps forward. This is in its early days because it's only been online like a year or so. But that collects the infrared light from the farthest, like literally proto galaxies, earliest galaxies that light has traveled some 13 billion years to us. And they're observing these faint little blobs.
And folks are trying to, you know, again, study the early, the onset of these early supermassive black holes, how they shape galaxies. So they're, they're seeing that they are, they were there, you know, surrounded by already bigger galaxies. Ideally, I'd like for, for my colleagues to push a little bit further, hopefully that will eventually happen. In terms of looking towards older and older. Yeah. Yeah. More and more sort of primitive in terms of the structure. But of course, as you can imagine, if you make your system smaller and smaller, it becomes dimmer and dimmer. And it's further and further away. So we're reaching the end of the line from a technical perspective pretty quickly. But it's dimmer and dimmer means older and older.
Yes, in a sense, because it all started really small, right? Because it's smaller and smaller, which correlates to older and older. In that phase of the universe, it would, otherwise it, it doesn't. Yeah. Just to take a small attention about black holes and, you know, because you do quite a bit of observational cosmology and maybe experimental astrophysics. What's the difference to you between theoretical physics and experimental?
So there's a lot of really interesting explorations about paradoxes around black holes and all this kind of stuff. About black holes destroying information. Do, do those worlds intermix to you? When you, especially when you step away from your work and kind of think about the mystery of it all? Well, at first glance, there, there isn't actually much crosstalk.
Personally, I mostly observe stars. So I don't usually actually think too much about black holes. And stars is a fundamentally kind of chemical, physical phenomena that doesn't.
That's right. The physics is, is kind of different. It's not extreme. I mean, you know, you could consider a nuclear fusion sort of be perhaps extreme. You need to tunnel.
That there's some interesting physics there. But it's just a different flavor. And I don't, I don't do these kinds of calculations myself either. I, I very much like to talk with my theory colleagues about these things though, because I find there's always an interesting intersection. And often it's just, I've written a number of papers with colleagues who do like simulations about galaxies. And so they're, they're not quite as far removed as let's say the, the black hole, you know, pen and paper folks. But even in those cases, we had the same interest in the same topics, but it was almost like we're speaking two different languages. And we weren't even that far removed, you know, both astronomers and all. And it was really interesting just to take that time and really try to, to talk to each other. And it's, it's amazing how, how hard that is. You know, even amongst scientists, we already have trouble talking to each other. Imagine how hard it is to talk to non scientists and other people to try, you know, to, we're all interested

in the same things as humans at the end of the day, right? But everyone has sort of a different angle about it and different questions and way of formulating things. And sometimes it really takes a while to, to converge and to, to get, you know, to the common ground. But if you take the time, it's so interesting to participate in that process. And it feels so good in the end to say like, yes, we tackled this together, right? We overcame our differences, not, not so much in opinion, but just in expressing ourselves about this and how we go about solving a problem. And these were some of my most successful papers. And I certainly enjoyed them the most. It can also lead to big discoveries. I mean, there's a, I think you put it really well and saying that we're all kind of studying the same kind of mysteries and problems. I mean, I see this in the space of artificial intelligence. You have a community, maybe it seems very far away, artificial intelligence and neuroscience. You know, you would think that they're studying very different things, but one is trying to engineer intelligence and in so doing try to understand intelligence. And the other is trying to understand intelligence and cognition in the human mind. And they're just doing it from a different set of data, different set of backgrounds and the researchers that do that kind of work. And probably the same is true in observational, cosmology and simulation. So it's a, it's like a fundamentally different approach to understanding the universe. Let me use for simulation, let me use the things I know to create a bunch of parameters and create some, just play with it, play with the universe, play God, create, create a bunch of universes and see in a way that matches experimental data. It's a fun, it's like playing Sims, but at the cosmic level.
And then probably the set of terminology used there is very different and maybe you're allowed to break the rules a little bit more. Let's have, you know, yeah, it's like the Drake equation. Yeah, you don't really know, you kind of come up with a bunch of values here and there and just see how it evolves. And from that kind of intuit the different possibilities, the dynamics of the evolution of a galaxy, for example. Yeah, but it's cool to play between those two because we, it seems like we understand so little about our cosmos. So it's good to play. Yes, it's like a big sandbox, right? And everyone kind of has their little corner and they do things, but we're all in the same sandbox together at the end of the day. But in that sandbox does have super powerful and super expensive telescopes that everybody's also, all the children are fighting for the resources to make sure they get to ask the right questions using that big cool tool. Well, can we actually step back on the big field of stellar archaeology? What is this process? Can you just speak to it again? You've been speaking to it, but what is this process of archaeology in the cosmos? Yeah, it's really fascinating. So I mentioned the lesser the mass of the star, the longer it lives. And again, for reference, for the next dinner party, the sun's lifetime is 10 billion years. So if you have a star that's 0.6 or 0.8 solar masses, then its lifetime is going to be 15 to 20 billion years.
And that's an important range for our conversation because again, if you assume that such a small star formed soon after the Big Bang, then it is still observable today. You mentioned old light before. Yeah, that light is like a few thousand years old, but compared to the age of these stars, it's nothing. So to me, that's young. It comes straight from from our galaxy. Oh, you know, it's not far. These stars are not far away. They're in our galaxy in the outskirts. They probably did not form in the galaxy because again, hierarchical assembly of a Milky Way meant exactly. They formed in a little other galaxy in the vicinity. And at some point, the Milky

Way ate that, which means absorbed all the stars, including, you know, these little old stars that are now in the outskirts of the Milky Way that I used to point my telescope to. So what can we learn from these stars? Why should we study them? Now, these little stars are really, really efficient with their energy consumption. They're still burning for the experts, just burning hydrogen to helium in their cores. And they have done so for the past 12, 13 billion years, however old they are. And they're going to keep doing that for another few billion years, same as the sun. The same sun also just does hydrogen to helium burning and will continue that for a while, which means the outer parts of the star, well, pretty much actually most of the star, that gas doesn't talk to the core. So whatever composition that star has, you know, in its outer layers is exactly the same as the gas composition from which the star formed, which means it has perfectly preserved that information from way back then, all the way to today and going forward. So I'm a stellar archaeologist because I don't dig in the dirt to find remnants of past civilizations and whatnot. I dig for the star, for the old stars in the sky because they have preserved that information from this first billion years in their outer stellar atmosphere, which is what I'm observing with telescopes. So I'm getting the best look at the chemical composition early on that you could possibly wish for.
What kind of age are we talking about here? Are we talking about something that's close to that, you know, like a 13 billion, 12, 13 billion age range?
That's what we think. Now, there's a small caveat here. We cannot accurately date these stars, but we use a trick to say, oh, these stars must have formed as some of the earliest generations of stars, because we need to talk about the chemical evolution of the universe in the Milky Way for a second. So I already mentioned the pristineness of the universe after the Big Bang, right? Just hydrogen and helium, then the first stars formed, they produced a sprinkle of heavier elements up to iron. Then the next generation of stars formed, that included again massive stars that they would explode again, but also the little ones that keep on living, right? So, and then the massive ones again explode as supernova, so they provide again another sprinkle of heavier elements. And so over time, all the elements in the periodic table have been built up. There have been other processes, for example, neutron star mergers and other exotic supernovae that have provided elements heavier than iron all the way up to uranium from very early on. We're still trying to figure out those details, but I always say pretty much all the elements were done from like day three. So iron is where, like once you get to iron, you got all the fun you need, most of the fun. Yes, I know. I really like the heavier elements, you know, gold silver, platinum, that kind of stuff. For personal reasons or for star formation?
Well, both. What's the importance of these heavier metals in the evolution of the stars?
So they're the spice of life, right? So every supernova gives you elements up to iron. That's cool, but at some point it gets a little bit boring, because that always works. But that's the baseline. We need that. And that's certainly what came out of the first stars and then all the other supernova explosions that, you know, followed with every generation. And it took about a thousand
generations, give or take, until the sun was made. So the sun formed from a gas cloud that was enriched by roughly thousand generations of supernova explosions. And that's where the sun has the chemical composition that it has, including, you know, and somehow the planets were made from that as well. So the supernova explosions, the many generations are creating

more and more complex elements? No, it just goes all the way up to iron. And then it just, it's a little bit more of all of these elements. Just more. Yeah, it's one sprinkle, then another, and it just kind of adds up, right? Now, the heavy elements form in very different ways. They're not fusion made. They are made typically through neutron capture processes, but for that you need seed nuclei, ideally, you know, iron or carbon or something. So the supernova made elements are very good seed nuclei for other processes that then create heavy elements. And because they cannot be made everywhere, they, when you, when, you know, so I, some of my stars
have huge amounts of these heavy elements in them, and they tell us in much more detail, something really interesting happened somewhere. Well, wait, I thought the really old ones we would not have. So what does that mean if the old? Yes, important clarification. So the stars that we are observing today, these old ones, they formed from the gas. And the question is what enriched that gas? So it could have been just a first star dumping their elements into that gas all the way up to iron. And we have found some stars that we think second generation stars, second generation stars, so they form from gas enriched by just one first star. That's super cool. Then we find other old stars that have a much more complicated heavy element signature. And that means, okay, they're probably formed in a gas cloud that had a few things going on, such as maybe a first star, maybe another more normal supernova, and maybe some kind of special process like a neutron star merger that would make heavy elements. And so they created a local chemical signature from which the next generation star then formed. And that is what we're observing today. So all these old stars basically carry the signature from all these progenitor events. And it's our job then to unravel, okay, which processes and which events and how many may have occurred in the early universe that led to exactly that signature that we observed 13 billion years later. Is it possible to figure out the number of generations that resulted in these stars? Well, we think we can sort of say, okay, this was like second generation or third, because the amounts of heavy elements in the stars that we observe is so tiny. One normal supernova explosion is actually already basically too much. It would give us too much of it. And the thing is, you can never take away things in the universe. You can only add, there's no cosmic vacuum cleaner going around sucking things away.
The black holes are probably the closest to that, but they would have taken the whole star.
Yeah, they would have taken the whole thing, not just a little bit.
They wouldn't have taken stuff out of the gas. So we have maybe 10 stars or so now, where we are saying that they contain so little of these heavy elements, that there must be second generation, because how else would you have made them? And again, I want to stress that the elements that we observe in these stars were not made by the stars themselves that we observe. That's just a reflection of the gas cloud. So we don't actually, I had to say that, because I love stars. At the end of the day, we don't really care for the stars that we're observing. We care for the story that they're telling us about the early universe. Yeah, so the stars are kind of a small mirror into the early universe.
And so what are you detecting about those stars? Can you tell me about the process of archaeology here? What kind of data can we possibly get to tell the story about these heavy elements on the stars? Yeah, it depends really on what star you find. There are many

different chemical signatures. We actually pair up these days our element signatures with also kinematic information, how the star moves about the galaxy. That actually gives us clues as to where the star might have come from. Because again, all these old stars are in the galaxy, but they are not off the galaxy. That's a small but important distinction. So they all came from somewhere else. So you can rewind back in time to kind of estimate where it came from. Yeah, so we kind of say, oh, it came from that and that door of galaxy. But interestingly enough, I just a few days ago, I submitted a paper with three women undergrads. It was so good to work together. And we found a sample of stars that have very, very low abundances in strontium and barium. So very heavy elements. And I had a hunch for a while that these stars would probably be some of the oldest. Because as I said, heavy elements give you extra information about special events. And again, finding something that's really low means that must have happened either really early on or in a very special environment, because we can only ever add. So if you find something that's incredibly low in terms of the abundance, maybe just one event contributed that max. So we looked at the kinematics, how are these stars moving? And they're all going the wrong way in the galaxy. How is that possible? Well, it is possible because consider, and I would come back to the proto galaxy, the proto galaxy was like a beehive. It just didn't really know what it was or what it wanted to become when it grew up. So and it was absorbing all these little galaxies to grow fast. Some galaxies, some absorbed galaxies were thrown in going the main way. And some came in the wrong way. Happens. Yeah, happens. But this could only happen early on
when, you know, there wasn't left and right and up and down. So stuff would come in from always. So now 13 billion years later, we're still doing it. Yeah, they're still doing it. And B, we just looked for stars that have low strothium and barium abundances. And then we look at the kinematics and lo and behold, they're all at hundreds of kilometers per second, going the wrong way. It's like, dude, you must have come in really early on from somewhere else. So we call this retrograde motion. That's a clear sign of accretion. So something that has come in to the galaxy. And because they're so fast, and it's really all of them, that that must have happened early on, right? You can't throw a galaxy into the Mickey Ray right now the wrong way. It eventually will turn around. Can you actually just a small tangent speak to the three women undergrads, like this little it's pretty cool that you were able to use a hunch to find this really cool little star? Yeah, what's the process of like, especially with undergrads, I think they'll be very interesting and inspiring to people. Yes, it was a wonderful little collaboration that actually emerged in the fall. So I really like working with undergrads and grad students, postdocs. And I came up with a new concept for a class at MIT, where I wanted to integrate the research process into the classroom. Because sometimes people find it really hard to call email a professor, hey, you know, I'm this and that person, and I'm interested in your research could have possibly, you know, come. And I wanted to streamline that and give, and not just trial, how it would work to provide a sort of the safe confines of a classroom where you just sign up and do research in a very structured way. And I developed it was a lot of work, a little bit more than I thought, to map up an entire research project basically from scratch in 10 worksheets, so that they could do it again in a very structured and organized fashion. So you created this whole framework for it to do the whole thing. But the promise was, you come sign up for my class in teens of two, you each get your own old star that has not been analyzed before. I don't know

what the solution is, because in research, we don't look up the solution at the end of the book, we do not know what we're going to find. Our job is to do the work and then to interpret the numbers, because our job as scientists is to find the story. Anyone can crunch numbers. Anyone. It's complicated sometimes, but it's doable, right? But coming up with a story, when you only have three puzzle pieces, what does the puzzle look like?
You have to be a little bit bold, you need to have some experience, and you need to kind of see the universe in 3D, you just need to kind of go for it. And that's the beautiful thing, I really love that. And so this was a story of weird kinematics going the wrong way, combined with this particular weird signature in terms of the elements.
Exactly. And you have to come up with a story about that.
And so the story of that paper is now, usually I don't say I find the oldest stars. When I talk to my research colleagues, I talk to them about we find the chemically most pristine stars, because that's actually what we measure, the chemical abundance that tells us, okay, it must have been second or third or fifth generation of stars, right? But these low strontium stars that go in the wrong way, like they're getting paid for it, they must be the oldest stars that came into the galaxy because they formed before the galaxy was the Mickey way, right? And this is so cool. And it was so wonderful. So this class, it went so well in the fall, I had nine people sign up that that's not unusual for a class, a specialty class at MIT, so small number. It was eight women and they were so into it that I said, okay, let's use this opportunity. You're going to do some extra work with me. And we're going to publish this. Try to publish. Yes. I also like that you're using the terminology of chemically more pristine. When I'm talking to younger people, I'll just say that I'm more chemically pristine than them. I like the description of age. So there's this term of metal, poor stars. So most of these old stars are going to be metal, poor. Yes. I search for the most metal, poor stars. And what is that? Can we just define? Yeah, what does it mean? I don't know who came up with this. I would love to know, but the universe is a complicated place. So many decades ago, someone clever came up with the idea to say, let's simplify things a little bit. Let's call hydrogen X, helium Y, and all the other elements combine metals, Z. When I give public talks, I always ask, is there a chemist in the audience? Let me just tell you, neon is a wonderful metal. And they're like, oh my God, what's he saying? I'm an astronomer, I'm not a chemist, so I'll get away with it. So if you just roll with it for a moment, all the elements except hydrogen and helium are called metals. Now, if we look again at the concept of chemical evolution, it means more and more off all the elements, everything higher than hydrogen and helium gets produced slowly but surely by different types of stars and events. So that's a monotonously increasing function. And so we look for the stars that have the least amounts of heavy elements in them because that means we are going further and further back in this process, in that function, almost all the way to the very beginning, and that is the first stars. They started that process. That's why I said it was such an important transition phase because we call the post-Big Bang universe pristine, just hydrogen and helium, and after that the mess started. If you soon as you add elements to it, things kind of get a little out of hand. That ends in this beautiful variety that we have everywhere these days.
And you're looking at the very early days of the introduction of the variety.
Yes, exactly, when it was still a little bit more organisable. But the variety of different types of metal-poor stars, we have a stark, many different types of stars,

many patterns we have sort of identified, but they are still crazy ones out there
that we're still trying to kind of fit in. So what kind of stars have been discovered? So you've already a while ago helped discover the star H.E. 1327, 2326. Great name.
And H.E. 1523, 0901. What can you say about these stars and others that have been found?
I love them. They're my baby stars. What do you call your baby stars?
Well, I'm probably the only one who can spit out these names without cheating.
Are there nicknames? Are there nicknames? No, that's not allowed.
Well, some colleagues at conferences have just called them Anna's Star or Freeble Star, because they didn't want to learn the phone number. These numbers are actually based on older sets of coordinates for these stars. So the minus in the middle means that they are in the southern hemisphere. So negative is in the southern hemisphere, positive is in the northern.
And then 13 and 15 means they're sort of observable in the middle of the year.
Okay, so that's the deal with the observation and where was observed?
Yes, yes, yes. But they have very different stars, both absolutely significant career defining actually for me, but really pushed the envelope in very different ways. So H.E. 1327, the first one that you mentioned, that was the second second generation star that we found.
And usually people say like, oh, the first one is a big one and the rest is nobody cares.
But to us, it proved that yes, we can do it because one astronomers live in this sort of way of, you know, there are a lot of serendipitous discoveries and we, that's really great.
But we need to show that we can do it again. Because then we're on to something and it's not just some kind of weird quirk and there are a lot of quirks in the universe. But we want to know is that a real thing? Does that happen regularly? Is there something that we can learn? Is that a piece of the story? And so finding the second one that was even a little bit more extreme than the first one really showed, yes, our search techniques work, we can find these stars.
They provide an important part to the story in the sense that if we had more than two stars, and by now we have about tarnish or so, what do they tell us about the nature of the very first stars? And what we found, again, working with the theorists, of course, who run these supernova models is that, so actually, let me before I get into this, these two stars had huge amounts of carbon relative to iron. So we usually use iron as a reference element for what we call the metallicity. So the overall metal content, the overall amount of heavy elements in it.
So that's why it's called iron deficient. That's right. So these stars are incredibly iron deficient, which means there must be of the second generation, because there was, and interestingly enough, there was this discrepancy, a normal supernovae. Until then, we thought would
get us so much iron, and you would distribute that in the gas cloud, and then you would form this little star that we're observing. But the iron abundance that we measured was actually much lower than that. And I already mentioned, you can't take things away. That must mean these early massive pop three, we call them population three, the first stars, they must have exploded in a different way than we previously thought. They can't output as much iron, because they just can't. Otherwise, it wouldn't match our observations. And so that's when we started to work with several theory groups on supernova yields. So what comes out of-
From the explosion of the supernova? That's cool. Supernova yields. And so this one was not yielding much iron. Well, we needed to concoct a theoretical supernova that made less. And it's actually

surprisingly difficult, because you can always add more in the universe, right? But you can't take stuff away. So Japanese colleagues kind of came up with the idea of a fainter supernova that just doesn't have enough oomph when it explodes. So somehow there's less iron coming out. But at the same time, then these stars showed huge overabundances of carbon, a thousand times more carbon. So how do you now get a thousand times more carbon out of these poor first supernovae, right? That was the theoretical challenge. And because we didn't have just one star, but two, that really spurred the field to think about what was the nature of the first stars? How did they explode? What are the implications? Because if they are not as luminous and bright and energetic, that has consequences for these early proto galaxies in which they must have been located in terms of blowing the gas out, let's say, and disrupting the system. So much higher chance for the earlier system to stay intact for longer, right? So there's a whole tale of consequences. And this is what I mean with we need to find the story, because you one thing, and it's like the dominoes, the consequence is everywhere. And suddenly you have a different universe, right? What could possibly be a good explanation for something that yields a lot of carbon and doesn't yield a lot of iron?
Well, it's not so much an explanation, more like finding a mechanism for what happens in supernovae
and the official term, what was sort of, as I said, cooked up in order to explain the observations. And we have, by the way, found a whole bunch more of these stars, so that holds. And it's called a fallback mechanism. So actually in the supernovae, during the supernova explosion, a massive black hole emerges. And so some of the material falls back onto the black hole. So here is a vacuum cleaner now plopped into the middle, right?
Like a temporary one that just cleans up some of the elements.
Sort of, right? Because if you think of the, we haven't talked about this yet, but if you know what a massive star looks like in its interior before it explodes, you have hydrogen helium still on the outskirts, and then you have your layers of heavy and heavy elements all the way up to iron. So you have an iron core in the center. And because you can't get any energy out of iron when you want to fuse to iron atoms anymore, right? That's when the supernova explodes, occurs really. It's actually an implosion first. And then you have a bounce of the sort of neutron star phase that occurs in the process. And then it gets disrupted. Yeah. It's like this giant basketball. And then it all goes up. So implosion first, explosion after.
And so in the process, right, if you make your black hole basically big enough, it will suck away some of the iron because that's the closest in terms of the layers. You hold on to it. You don't let it escape. And carbon is much further out. You let it all go. And so. So that explains why you can have a big oomph and not much iron yield.
Yes. Yes. So is this explained the HE-1327?
Correct. And others like it? Yes. So there's a well established now that the lower the iron abundance of the stars are, the higher the carbon sort of gets. And carbon is such an interesting element in that regard. If we come back to the formation of the first low mass stars, right? So we had the hotter gas, just hydrogen and helium that made the first stars. They were 100 solar masses or so because the gas couldn't cool enough. So they were big and puffy. Carbon then coming from the first stars probably led to enough cooling in these gas clouds that enabled the formation of the first low mass stars.

So think about what happened if there wouldn't have been any carbon or the properties of the carbon atom would be different. It would not have cooled the gas in such significant ways, perhaps. There wouldn't be any low mass stars. We wouldn't be here today, right? And we're carbon based. And so I think carbon is really the most important element in the universe for variety of reasons because it has enabled this whole evolution that we're now observing and literally seeing in the sky. And it's really fascinating. So combined with the fact that you have the iron deficient. So all of that is probably important to creating humans. Yeah. We need all the elements, but if you don't have stars like the sun, small stars that can actually host planets, that have long lifetimes, you need long, long lifetimes if you want to have a stable planet and develop humans. Carbon is kind of important in many ways. Yes, yes.
This is perhaps a interesting tangent. If I could just mention that you interviewed a military Dresselhaus, a carbon queen, the remarkable life of the nanoscience pioneer.
Is there something you could say about the magic of carbon and the magic of Millie?
Well, Millie was certainly magic. She was a professor at MIT for many decades.
I met her a number of times. Her photograph, actually a young and an older Millie is still on the wall. Every time I step out of the elevator in one of the buildings, I see it.
She pioneered all sorts of carbon nanowork, so she was a material scientist, very far removed from what I do on a daily basis. But yes, carbon has amazing properties when you study it. And again, that's indeed another aspect of why carbon is so fascinating, not just in the cosmos, but also for us, making us, creating us in the way that we can use it.
It's wonderful. Just sometimes think about this chemical evolution in this big philosophical way that we're the results of that chemical evolution. We're made of this stuff. We're made of carbon. Yes, we're made of store stuff. Yeah, and it came-
We can go right. I mean, it's almost like a cliche statement, but it's also a materials, a chemical, a physics statement that came from hydrogen and helium. And then somehow this formation has created this interesting complexity of soup that made us. What are we supposed to make of that? Like what, did we just get really lucky? Why did we get all this cool stuff?
Yeah, that's a good question. I don't think it's a question as an answer. I keep just asking why.
But it's just this incredible mystery. So much cool stuff had to happen. So much, sorry, hot stuff had to happen to create us. Right, and so much could have gone wrong and there would have been another outcome. And it's actually amazing how many things kind of fell in place. I mean, maybe that's all sort of self-deterministic in some ways, right? We are who we are, because that was the path. Maybe we would have ended up being robots, I don't know.
But it's certainly wonderful to assign this for us to help contribute unraveling our cosmic history. I always say the biological evolution on Earth was absolutely facilitated by the chemical evolution of the universe, right? And one doesn't go without the other from a human perspective.
That evolution seems to be creating more and more complexity. The kind of interesting clumping of cool stuff seems to be accelerating and increasing. And it's hard not to see as humans that there's some kind of purpose to it, like a momentum towards complexity and beauty, you know?
Well, beauty is in the eye of the beholder. But yes, everything gets more complicated.
Well, there's also a beauty to the chemically pristine universe in the early days.
Yes, yes. I love the desert with its nothingness. It has so much aesthetics and appeal.
We came from nothing, we'll return to nothing. So what about H.E. 1523? What's exciting?

What's exciting? A red, a red giant star. Yes. That's another one of your babies.
Yes. 13.2 billion years old. Yeah. So that one isn't quite as iron deficient as the other one.
So probably not a second generation star, but easily second, third, sorry, third, fourth,
fifth or so. We can't really pin it down. But that's also not super important for us.
What is important is that that star has a very different chemical composition in a sense that,
yes, we have all the elements up to iron there. They have sort of normal ratios,
which means kind of the same as most other old stars and not too different from the sun or at
least different in quantifiable ways. But it has this huge overload of very heavy elements.
And what was so nice about that star in particular was that I could measure
the thorium and the uranium abundance. And again, that was the second of its kind.
But the uranium abundance could be more well determined. So we had a better grasp on that.
Now, why are thorium and uranium interesting? They are radioactive elements. They decay.
Thorium has a half life of 14 billion years, I believe, and uranium of 4.7,
which, you know, two folks on us on earth is a really long time. But those kind of timelines
are really good when you want to explore the early universe. So there are two questions now that
kind of come to mind. Where do these elements come from? And what do they tell us, right?
And these, as we know, these heavy elements are made in a specific process. It's a neutron capture
process, usually referred to as the R process for rapid neutron capture process.
We talked about seed nuclei before, right? So we still don't exactly know where this
process can occur. So you have, let's say, a lone iron atom somewhere. And it is in an
environment where you have a strong neutron flux, which means there must be lots of neutrons
around.
And again, when we talk about the site, we can surmise and ponder where that might be the case.
But you have this iron atom and you bombard it with neutrons and you do it incredibly fast.
Now, what happens in the process? That iron atom, you know, you collect lots of neutrons,
it becomes really big and unstable. So it's a heavy neutron rich nucleus that wants to decay
because it's not stable, it's way too big. And so let's say you add only one neutron to it,
that would already make it unstable. So it will then, it has a characteristic decay time that's
called the beta decay timescale. So it will decay to a stable nucleus. So the neutron will convert
to a proton and that makes it stable. If you know bombard lots and lots and lots of neutrons
onto that seed nucleus within that timescale of the beta decay, that's how you get to this huge
fat neutron rich nucleus that then wants to decay, right? So the are the rapid processes,
you have your seed nuclei, they get bombarded, you create these these really heavy neutron rich
nuclei, they're heavier than uranium even, the neutron flux stops, and then all these heavy
nuclei, they decay and they make all these stable isotopes that we know of,
all the way up to thorium and uranium. So that rapid nuclei decay is what creates all the fun.
Correct. And the whole thing is done within two seconds. So just to add to the rapid here,
and literally the snapping on my hand, it's all there. In my talks, I often, I have this
nice simulation that illustrates, you know, this creation of these wrap of these heavy
nuclei. And I always say, this is the only simulation you will ever see that slower than
real time because in astronomy, you know, we show, oh, this is how a galaxy forms 13 billion years
in 30 seconds. Really short, right? This is the opposite. Me showing you this, the element's
already long, long made. So where and when does this happen? Does this process happen? So you

need the strong neutron flux. That's the clumping of the, the neutrons. Yes, that's right. And so there are not that many options, right? So where do you find lots of neutrons in the universe? So it's neutron stars, right? Neutron stars form in the making of supernovae, of the explosions. Okay, so maybe some of this heavy material gets sort of made in the making of the supernova explosion
and then gets expelled. Or you have neutron stars. So the, you know, if the neutron star survive, I mean, usually that's the leftover of the supernova. If you have two from a binary pair, so stars usually actually show up in pairs. And so it's not too unusual to create a pair of, of neutron stars that will still orbit each other after both of their progenitor stars have exploded. And those two neutron stars will orbit each other diligently. But as we know now, thanks to LIGO, the gravitational wave observatory, I mean, we know already that before, but now it's been measured by LIGO is that these two neutron stars, they will orbit each other for like forever. But in the process, they will, they will lose energy. So that, that orbit is what we call the orbit decays. And eventually, the two neutron stars will merge. And that results in a, in an explosive event that has roughly the energy of a supernova. But the process is completely different. And the cool thing is, when these two neutron stars collide, they produce a gravitational wave signature, because neutron stars are super dense objects, they're like giant atomic nucleosys. So there's a lot of interesting physics happening already. And so if you basically form a super neutron star, by smashing two into each other, more interesting physics happens. And that means that there's this ripple sent out, you know, into the space, the, you know, the spacetime continuum, basically, you know, the, what do people say, the, the ripples of spacetime, you know, it's like, it's like you drop a rock into water, right? You see the waves coming. So that's exactly what happens when two, two neutron stars merge. And this is neutrons galore, right? It's really violent to smash two neutron stars, you know, so that are so dense already into each other. And they in 2017, one of these events occurred and the LIGO and Virgo gravitational wave observatories, they detected that. And then the astronomers pointed their telescopes in that direction. And they indeed observed what we call the electromagnetic counterpart. So there was something seen in the sky that faded over the course of two weeks. And that light curve, that light was exactly what you get when you create all these heavy neutron rich nuclei in the R process. And then the neutron flux stops. And then it takes about two or three weeks for most of them
of these nuclear to decay to stability. So we saw the astronomers saw in this electromagnetic counterpart, the nuclear synthesis of heavy elements occurring. And that's, that's just, that's amazing. Awesome. So that that's electromagnetic counterpart to the gravitational waves that were detected with two neutron stars colliding aggressively, violently to create a super neutron star. And that's where you get all the neutrons and neutron flux somehow. And then that the whole shebang that happens in two seconds and creates a bunch of.
So that confirmed that one of the sites for sure is for the R process to occur is neutron star mergers. Interestingly enough, I have to mention this year, a year prior in 2016, my former grad student, Alex G and I, we discovered a small dwarf galaxy that is currently orbiting the Milky Way, it's called reticulum two, that was full of ancient iron deficient stars that also had a strong signature of these heavy

elements, exactly like AG 1523. We weren't looking for that. I actually wanted to prove that they had really low levels of heavy elements, because that's what we had seen in all the other dwarf galaxies. And I was dead set on showing yet that that is yet the case again, and that that is a typical signature of early star formation. We already talked about low strontium and barium abundances and the oldest stars, right? This is what we had seen anecdotally in the ancient dwarf galaxies that are surrounding us. So that's an ancient dwarf galaxy that dwarf galaxy has a bunch of ancient stars in it. Yes. And so now we find reticulum two and it has these, the stars show the signature of the rapid neutron capture process, the R process, and we are like, okay, these stars are located in a dwarf galaxy right now, we have environmental information, they are not lost in the galaxy where we don't know where they actually came from.
No, we know these stars were formed in that galaxy because they're still in it.
And that we already deduced from that, that it must have been a neutron star merger that went off in reticulum two at early times, that polluted the gas from which all our little stars formed. Can you speak to what a dwarf galaxy is? Can you speak to what this reticulum two dwarf galaxy is that is orbiting the Milky Way galaxy? It's going to be eaten by it, presumably. It totally is going to be eaten. I can't tell you exactly when.
Yeah, the Milky Way remains surrounded by dozens of small dwarf galaxies.
They're collections of stars. Some of them, we call them ultra faint dwarf galaxies because they now only contain, I don't know, a few thousand stars, very, very faint.
But still detectable?
Yes, because they're fairly close and we detect actual individual stars in them. So I've observed some of the faintest stars you possibly observe with current telescopes in these dwarf galaxies because I was like, I need to know what the chemical composition is because there are leftovers from the early universe. They did not get eaten. So they're still in their native surroundings. It's like getting the lions in the wild, right? I got to study those and compare to the counterparts that got eaten and are now in the Milky Way.
So presumably most of those stars, it's not all of those stars in that dwarf galaxy, they're really ancient. They're all really ancient because actually, as it turns out, if you have a small galaxy, there was a process early on in the universe called reionization that heated up everything. And together with some supernova explosions in early shallow bound system, all these little systems lost their gas. It was sort of blown out or it simply evaporated or both, probably both. And so these systems have been unable to continue to form stars since. So it's the best for astellar archaeologists that you could hope for because it's a whole bunch of stars still sitting there. It's not just one, it's a whole bunch of them still sitting there ever since and literally nothing has happened to them. They have just been waiting there for us. So from the stellar archaeology perspective, what is juicier and more interesting? The old stars in the outskirts that have been eaten, are the outskirts of Milky Way or the stars in the dwarf galaxies? Of all the things you love about the world, you said you love stars, so which do you love more?
That's a hard one. I love them all, of course. They serve different purposes. The stars in the Milky Way, I can get much, much, much better data for them because they're brighter, they're closer,
so they're brighter. And that tickles my fancy. And they have interesting kinematics,

yes, and we can get that. And so HG1523, for example, that one is really bright, only it's a red giant, so it's intrinsically bright and it's fairly close. And so the data I got for that was insanely good and that yielded this uranium detection and thorium detection. I can never get that kind of data for dwarf galaxy stars. So that's a big trade-off. But the environmental information that we get along with the basic information over these stars in each dwarf galaxy is really, really valuable in establishing, for example, these site information, right? Because the galaxy is still there, so nothing crazy could have happened. So it should to close that loop. Probably some heavy elements come out of supernovae here and there, but somehow my theory colleagues tell me that a normal supernova just doesn't have enough oomph to really get an R process going and doing it, doing it all. So you need these orbiting supernovae? We need probably the neutron star mergers or we need a special kind of supernova that's maybe extremely massive or heavily rotating or does something else funny, right, to really kind of get that particular process going. But the normal supernovae don't do it, right? So only a little bit comes up. But you could come along and say, Anna, why don't you just take 100 supernovae together to build up the yield, right? But then I come along and say like, look, this dwarf galaxy is still intact today. If you would have plugged in 100 supernovae into this little system early on, it would have blown apart. It would have blown apart past five supernovae or 10. So that's a really important constraint that we have that these systems are still alive, right? So it helps us to pin down where certain processes could have possibly happened. And so it's just a different type of information that we get. It'd be amazing if we could talk about the observational aspect of this, the tools of observation. So what telescopes have you used? Do you use? And what does the data look like? And I think I've read a few interesting stories about the actual process of day-to-day observation, a bunch of probably late nights. Well, yeah, astronomers are doing it all night long. So we have lots of late nights. Can you explain the all night long aspect of it? Well, let me start by saying I mostly these days use the Magellan telescopes in Chile. They are 6.5 meter telescope, which means the mirror diameter is 6.5 meter. That's not the largest that is out there, but it's among the largest. And I use a spectrograph because I'm a spectroscopist. I don't take pictures. And that particular spectrograph at that telescope is actually unusually efficient. So it kind of makes up for the fact that the mirror isn't as large in, let's say, the eight meter telescopes from the Europeans or so. So I'm very happy with that. Efficiency meaning? How many photons get collected sort of per time unit? Because we, that's always the limiting factor. Prior to the pandemic, we would travel to Chile to do our observations. Those telescopes are the, that's the last observatory where people were sort of supposed to travel there and take their own observations. Most other observatories basically have staff there by now who take the observations for you. So there's the directly, the scientists are specifying where to point the telescope and sitting there and collecting the data, making sure the data is collected well, the cleaning of the data, the, what are offloading of the data, all that kind of stuff. Yeah. So it's mostly done for them. Obviously that's super convenient, but it also takes, takes away a central part of what the work of an astronomer is, which is data collection, right? We don't have an experiment in the basement where we can go day and night or whenever we please and ask a certain question

of the apparatus, right? Let's turn this knob and see what happens. Let's turn that knob and see what
happens. No, you know, we, we only have one experiment, which is the universe. And we, what we see is what we get. And I think it's, it's so important to, to take an active role in that. So I really loved going to the observatory. I've taken many students there over the years to, to teach them and to just show them what it means to, to be an astronomer because you, you go to the, these remote mountain tops and it's such a magical environment and you wait there, you know, for the sun to go down and then you get ready and you look outside and it's, it's such a serene environment. It's, it's a little bit out of this world.
You're sitting there. So the sun goes down, it's evening, late evening. And what does it look like? What are some of the most magical experiences of that process? Well, you know, when you're on
top of a mountain, you know, climbers, I guess, get to see that probably otherwise.
It's, it's very calm and the colors are so beautiful. And I always become much calmer when I'm there. I'm just a, because I'm just there for one purpose only. That's data collection. I can say no to my emails. I can say no to everything else because I'm observing. So there, there's literally less, less distractions because, you know, you're just there to do one thing. And also the emails somehow seem less significant. Yeah. Yeah. It's just, you can afford to focus on this one thing and you, it just kind of does something to you. It's, it's, it's a little hard to describe, but you know, if you then fast forward, maybe I can speak a little bit about that. And I have done a lot of astrophotography there as well. So, and, and I observing feint or galaxy stars, you know, these are like 45 minutes, 55 minute exposures. So you actually have a lot of time. So I would run outside and just lay on the ground under the southern Milky Way, beautiful right up, you know, there. And I would just lay there like the snow angel, and just stare up there and just kind of let my thoughts sort of pass through my brain and just like, I'm, I'm one of it. Right. We talked about this in the beginning. This is when I personally have the feeling that I'm a part of it. I belong here rather than feeling kind of small. Yes, I'm small, but there are many other small things and lots of small things make one big hole. And we're part of that big hole. And so that's looking at the inner spirals of the Milky Way galaxy. And just, you know, this, this dark sky with the, with the bright stars. And I have described this in my book years ago. If the Milky Way is all bright above you, you don't need a moon or anything. You can walk in the starlight and you will find your way. There are no trees there for safety reasons, but you wouldn't even run into a tree, right? I mean, you can see, you can almost see the shadow, you know, from, from the starlight because it's such a dark site and, and the stars are so bright. And these are kind of moments that, that kind of change you a little bit.
And you see the unity of it all. Yeah. And it's just you and nature and,
and, you know, with modern civilization and all of that, we, I think we often try a little bit too hard to be removed from, from nature, you know, to, to be independent of it and figuring it all out. But at the end of the day, we're just a part of it. And, and that really helps me to remember that, that, you know, we're one in the same. Well, that fills me with hope that I tend to think of I tend to think of us humans as in the very early days of whatever the heck we are.
And so that makes me think thousands, tens of thousands, hundreds of thousands of years from now, that will be reaching, will be, whatever we become, will be traveling out there to explore

more and more and more. So we're, what you're doing is the early days of exploration with the tools we have. Yes, the early seafarers looking at the sky for navigation. Coming up with different theories of what, what's on the other side that the earth is starting to gain an intuition that the earth may be around. And then we might be able to navigate all the way around to get to the financial benefits of getting spices from India, whatever the reason, whatever the grant funding process is all about, but ultimately actually results in a deep understanding of the mystery that's all around us. And I mean, just to travel out there. I mean, to me, the discovery of life in the solar system, I really hope to see that in my lifetime, some kind of, some kind of life, bacteria, something maybe dead, because that means there's life everywhere. And that, that just the kind of stuff that might be out there, all the different, all the different environmental conditions, chemically speaking, that are out there. And it just seems like when you look at earth, life finds a way to survive, to thrive in whatever conditions. And so maybe that process just kind of humbles you as a super as exciting to know that there is life out there of different forms. And of course, that raises the question of what is life even would have to have a very human-centric perspective of what is a living organism and what is intelligence and all this kinds of stuff. And all the work in artificial intelligence now is starting to challenge our ideas of what makes human beings special. And I think we're doing that through all kinds of ways. And I think you're working some part doing that as well, like the unity you feel is realizing where we're part of this big mechanism of nature, whatever that is, that's creating all kinds of cool stuff from the humble, pristine origins to today. So what is, if you could just kind of linger on the process of the data, what does the data look like? And how does the raw data lead to a discovery of an ancient star? Well, as a spectroscopist, we have to, I guess, talk for a brief moment about what a spectrum is. Everyone, I hope, has seen a rainbow in the sky. That is basically what we're doing. We don't send the starlight through a raindrop that then gets bounced around and splits up the light into the rainbow colors. We do it with a spectrograph, so basically a prism. So we send the starlight through a prism of sorts, and that splits it up. And then we record exactly that. So it's a little 2D picture, actually, of a spectrum. Now, it's not going to look colorful. It's just black and white. Different colors have, of course, different energies. That's what we record. More specifically, we record it as wavelengths, so wavelengths and frequency and energies all the same at the end of the day. We process that little image in the sense that we do a crosscut and then sum up a few columns so that we get all the data that we recorded. And what we see is a, it's a bit funny to describe just with words, but a wiggly line with lots of dips. So the 2D process spectrum, we call it continuum. So it's just a flat line, basically, and then there are dips. So the interesting things are the dips. If you think back of the rainbow, what we actually see in our stars is not just a rainbow, but it would be a rainbow with lots of black lines in it, which means certain little pieces of color have been eaten away by a certain amount. And so we can no longer see it as well. We're not at all. Why is that happening? So if we come back to our stars, what we're observing, we're observing the stellar surface. We can actually never peer with our telescopes inside. We only ever go, can go after the surface. And the surface contains, the surface layer contains different kinds of elements. Every one of those types of atoms, so elements are just different types of atoms, they absorb different photons that are coming from the hot core where the fusion is occurring. And so that means that if you were the observer, you know, with a

spectrograph
or without, you will see the starlight, but certain frequencies, certain energies of that light will have been absorbed by all the different atoms in the gas. So you see less of them. And so those are the dips. And the strength of the dips tell us, you know, which element was it, and how much of that element was or is in the star. So we have many, many, many dips. The solar spectrum for reference, you know, all the dips are overlapping because the abundance of all the elements is so high. It's actually a very complicated spectrum. My spectrum, I really look like a straight line, and then there's a dip here, and then the straight line again, there's a dip there. The sun doesn't have straight lines. I mean, it's just all absorbed in some form or another. But the old stars have so little of all the elements that they're only occasionally these, these dips that then indicate, okay, that one at that wavelength was iron. And here we have carbon, and there's magnesium and sodium. Oh, there's a little strontium line here. So we have a much easier way to map out this barcode that the spectrum, you know, pretty much is at the end of the day. And to then measure the strength of these, we call it absorption lines, to then calculate with existing codes that mimic the physics of the stellar atmospheres, like how much was absorbed, how many, what, what kind of elements were, were present
in, in the stellar atmosphere. And so this is how we get to our abundance measurements. And then all together that gives us the, the, the chemical composition and, and that particular signature in that stuff. If you, do you ever look at like the raw spectrograph and the absorption line, and they're able to see into it some interesting non-standard outlier kind of patterns? Or do you, does this have to do heavy amount of processing?
We actually process our, it's fairly straightforward to, to do our processing. We do it at the telescope. So I often take a shorter exposure first, let's say 10 or 15 minutes. So mostly when I do discovery work, we would just take a quick look spectrum, then we process it while we observe the next star. Then we take a quick look. We have what I call the summary plot. It's, it's a collection of little areas in the spectrum that have the key positions, the positions of the key elements in it. And it's kind of like reading the tea leaves. I have stared at so many spectra. I just need to know, I just need to see our summary plot and I can tell you exactly what the numbers are going to be. Also, and also to tell if it's going to be promising to look at further. Exactly. And so that's it. Thumbs up, thumbs down. Are you worth my time or not? In most cases, it's not, or it's good enough. We can do a basic analysis, maybe publish this as part of a larger sample, just so, you know, we output that we have observed the star and their basic nature, that that's an important part to publish as well. And yeah, I had a run. So now we do remote observing. I do all of this now from my home, from my living room all night long. And I often work with colleagues. So we do it over zoom, and we process the data, we look at it same thing still. And we just found a star that had a very low iron abundance. And then we decided, okay, that looks interesting, we're just going to keep exposing. So we took more data on it on the spot and we're writing up the paper right now. How do you know where to point the telescope?
It's not random. There's a lot of work that goes into that. I began my career by answering, trying to answer that question as in like doing the search process. That's why I called my book that I've written some time ago, searching for the oldest stars, because searching is one thing, it's very time consuming. And then on top of that, not everyone finds, right? And I often don't find.

But I keep searching, because, you know, techniques have established that, yes, we can do it if we're just patient enough and keep going because it's a numbers game. And that's often the case in science.
And that's something that not enough is talked about, how tedious it is and how long it takes to get to that one discovery, right? That moves the field further.
And how difficult it is to believe that there's a thing to be discovered?
Yes, yes. We have the saying, I learned this, I think from my supervisor. One star is a discovery, two is a sample, and three is a population. So as soon as you found three of roughly the same kind, you're done. But you need to get there. Probably the first is the hardest, right?
Yes. But it kind of remains really hard. But the thing is then at past three, many of us are, okay, we solved that problem. We've done it three times, we can do it. That's a thing, right? That's a population, three iron deficient stars, let's say, right? That's one puzzle piece. Now we can move on to the next thing. That's an indicator that there's many more of them potentially.
Yes, yes, yes. So to cut a long story short about the searching, we started early on with what's called low resolution spectroscopy of many stars. So for example, my thesis work almost 20 years ago was piggybacking off a quasi survey that had collected, so quasi's basically giant supermassive black holes that are really far away. So you only see one big bright light point. So it looks like a star, but it's actually just a giant supermassive black hole that outshines its own galaxy. And people had been trying to study those, and they had taken little spectra of all things in the sky. And it turns out, oh, you can fish out the actual stars from that and look for certain signatures that might indicate low metallicity stars, so stars with low abundances. And so it was painstaking work to then take medium resolution spectroscopy to get a little bit more information and to use approximations and to kind of get candidates that we can then eventually take to the big class like Magellan to get a high resolution spectrum. So we really see the dips of all the individual elements that then give us a final answer. Is it yay or nay? These days, with another grad student, I just I developed a new technique to use images actually of all the stars in the sky taken with very narrow filters. So it's like you're wearing very specific glasses that only let so much light through. And so we can do similar things through having several narrow band filters, what we call it, to fish out things that have, you know, no absorption over here. So just the straight line and then a little dip here, so a little something there. And that has proven fairly successful in recent years.
So looking at the entire, looking at a broader regions of space.
That's right, because these stars are a little bit like the needle in the haystack, right? They're not that many left over. And there's certainly the galaxy has made plenty of stars in between. We need to comb through all of those to get to the goods. So we always start with millions
and then work our way down. And in the end, we have like three good candidates.
I wonder how those ancient stars feel that they were noticed. They probably know that nobody pays attention. I'm just kidding. We're all special, right? It's good. It's inspiring. Even if you're the outcast, in your pristine nature, you still might nevertheless be noticed. I'm hoping the same about humans if somebody's observing us. Is there something else you could say that's about the challenges of this kind of high precision measurement that you're doing?

So this kind of collection of data looking, trying to pull out the signal from the noise out there.
Well, that's literally what we're doing in multiple ways, actually. We're trying to find the needle in the haystack, and then we find something. And then it turns out it's just a little bit too faint to actually get the kind of data quality on it that we would like or that would be warranted given the potential of the star, right? So there's always noise. There's always a little bit of noise and you have to try to say how special it is when you're looking at the absorption line.
So the most iron poor stars, their iron lines are so tiny that they're literally almost in the noise. So you need incredibly good data to make detections. And the funny thing is we're looking for the nothingness of, let's say, the iron lines, but then we don't want nothing because if there's nothing in the spectrum, we can't measure anything. We can only get an upper limit.
But we'd really like a measurement. So we are looking for the last little bit that you could possibly detect. And that's the strong function of the brightness of the star, because the telescopes have the size that they do. That's not going to change for a while. Hopefully eventually it will, but it's going to be at least 10 years out. And so, yes, we're often literally stuck in the noise because we can't make the measurement. So actually the record holder for the most iron poor star only has an upper limit. We can't get enough data on this to actually pinpoint a measurement to then take it to our theory colleagues and say like, give me this little iron out of your first star. So it's a bit frustrating, but also super exciting at the same time.
So let's go to both sides of that spectrum. What's like the most exciting discovery to you personally? Is there a moment you remember that you saw a piece of data and your heart skipped a bit?
Yeah, yeah, of course. Is it HEE 1327? That was definitely one of those moments. I wasn't actually present at the telescope, but we were sent the data immediately from our colleague. And we just looked at it and our eyes got really wide and was like, oh my God, this is this really what we think it is. So we had to run some numbers and it was and these are magical little moments.
The thing is, often we have false positives and so there's always this kind of period and often it's, I don't know, 10, 15 minutes where you need to make some tests to kind of make a decision.
Is this really something I should keep observing now? Is this really as good as I think or am I being fooled by something? So actually if you take a spectrum of a white dwarf, a white dwarf is the leftover core of a star like the sun that has gone extinct. And white dwarfs have lost all their outer atmosphere. So it's just a hydrogen helium core. So they look like a metal poor star because that's only hydrogen helium left, right? But the hydrogen lines that you can see in the spectrum of our stars and of the white dwarfs are a little bit wider than normal. So you need to have a good eye just to check, you know, does this look a little bit wider than us? Is this a white dwarf who's fooling me here, right? And so it's like this moment, it's like, oh my god. It's just minutes of nervousness. Yes, yes. And sometimes, you know, it's it's a dud and sometimes it's not.
What's been, what's been a big, that you remember, heartbreak, like a painful low point?
Is it all leading up to the first? Is it all about HE 1327 again, just the leading up to it? Or has there been like a yeah, has there been like low points in the search? That's a good question.
I mean, you know, it starts with mundane things as in like, you you want your telescope time, you travel there, and the weather is completely cloudy, it rains, and you had three nights, which is a lot, and you go home empty handed. So that's definitely a low point.
Probably not what he was thinking of. But there is a certain occupational hazard to it.

Which requires a kind of resilience and a patience.
Yeah, and you just got to learn to to live with it. Coming back to reticulum too, actually, you know, that little dwarf galaxy, that was a run that we had, and the weather was incredibly bad. And I had sent my student there. And I was at home, and he calls me at 2am. And he was like, I think I observed the wrong star. I'm so sorry. There is this line there, this European line. And it looks like a metal rich star. And I was like, it's cool. We all make mistakes. Send me the data, send me that summary plot. And so I look at it, you know, I was like, super tired. It's like, I can't really tell it doesn't look wrong. But I can't tell you right now that it's right either. So why don't you go to the next target? And he calls me back an hour later, you know, it looks just the same. What am I supposed to do? And then I joked, well, maybe we found an R process galaxy. Let's go to the next one. And the weather was degrading. And so to cut a long story short, we had to come. So he was observing the right stars. It was an R process galaxy. The first one we had ever discovered totally uns, I mean, unpredictable. We had no idea that this was a thing. I mean, you know, of course, we thought that, you know, such a thing might possibly exist because why not, right? Newton's summer just happened somewhere. Crazy supernovae probably too. But we were not prepared
in that moment to find this thing. And in the end, the weather was getting worse and worse. And we wanted to see how many R process stars are in this galaxy. So we managed by a hairline to observe the nine brightest stars, but the data quality was atrocious.
And the weather affects the data quality. Yes, absolutely. Because these were really faint stars. And so we were really lucky by making a very tight strategy of getting the absolute bare minimum for all the stars. So we could at least take a very crude look. Is it a yay or a nay? We couldn't even say yes or no, just to get an idea, because we needed to know.
Why was that important? Because we could only observe this system again nine months later. So there's always a window of observation. Yes, it was setting. This was our chance. And it was going away with the clouds, you know, that was super high stakes. But we just made it. Like really, it was almost impossible. And it was just the thing is, this is such a serendipitous moment in a serendipitous moment. The enhancement of these heavy elements was so strong. That even in this really crappy data, we could still see the enhancement, right? The absorption was so strong that it stuck out of the noise. If that enhancement wouldn't have been as strong, we would not have been able to say anything because we wouldn't have been able to tell. But because it was so extreme, it lend us a hand, despite the weather and all, to say like, yes, this is it. So that was quite the night.
Luck. I mean, a lot of this is just luck. So that was the first our process galaxy discovered. Yes, I didn't sleep all that much.
Do you have hoped, are you excited about James Webb Space Telescope and other telescopes in the future that increase the resolution and the precision of what can be detected out there? Absolutely. JWST is fantastic already. I am not planning to use it personally, although I think I'm on one or two observing proposals, actually, because similar to what we already spoke about, we're interested in the same thing. We're just kind of looking at at different sides of the fence, right? I have my old surviving stars and I concoct these little stories about what the earliest galaxies may have looked like, what the objects were that

contributed, you know, energy and elements and all these things. And my JWST colleagues, they try to detect some of these earliest photons from these earliest systems to look at the energetics and other things, you know, what was there, how many these kinds of things, right? So together, we're trying to explore this first billion years, but we do it in very complementary ways. And so I'm very excited to see what they can come up with and how that helps me
to inform my stories better and more comprehensively.
What do you think is the future of the field of stellar archaeology? How much can we, maybe what are the limits of our understanding of this first billion years of our universe?
Well, obviously, lots of limitations in the sense that I always say, I have a metal poor star for any of your questions, because there are so many different kinds out there. And we still find new patterns sometimes, right? And there needs to be an explanation, the question is, is it ultimately just one quirky star or is it two or is it three, right? Is it a sample? Is it a population? So we haven't concluded that kind of work yet.
So every metal poor star is a kind of data point that you can use to improve the quality of your model of how the evolution of the early universe. Yes, yes. And I would say we've made huge progress
over the last 20 years. When I joined that field, it was in its infancy. And there was this serendipitous discovery of that first second generation star. And we have filled in the canvas a great deal since then. And this is what I have greatly enjoyed about doing so, because there was so much discovery potential. And it's been, it's been dying down a little bit because of all the progress. It's gonna, it's gonna, it's on, on the up and coming again, because there's so many large spectroscopic surveys in the works now that will just provide a different level of data that we haven't had before. I'm sort of of these older generation. I have only very few colleagues, I work in small teams, and I observe every single star myself, that, you know, whatever I can, I do myself. I don't generally take other people's data, at least not certainly not in the end stage. And, and, you know, I'm not a big data kind of person, although we all headed that that way. I certainly use data from the Gaia astrometric satellite for the kinematics, for example. But that's personally a new thing for me to, to use sort of big sky surveys that are available. So it's still very sort of hand grown field, you know, where we do our individual observations. I have enjoyed that a lot, but that's about to change. So one start at a time. Yes. I mean, there's power to that, to build up intuition of the early universe by looking one start at a time. Yeah. And this is how you can really drill down on the questions that you have, right? Because you control what data you get.
Otherwise, you have the data that you have, right? You get what you get and you don't get upset. I don't like that. I'm a little bit snobby. I really like to formulate my questions, go to the telescope and then come what may, I will try to get it. And also develop the intuition of where the data can be relied upon and where it can't and all the different quirks of the data and all that kind of stuff. Yeah. Sometimes a lot is lost in the aggregation of the noisy data.
Yeah, yeah, yeah. And, and that's always the danger if you have someone else's data that you just don't really understand the, you know, the limitations and completeness things, how certain things were set up and, you know, you get out what you put in. So I'm really particular about that. And it certainly paid off for me. That's one of the main notions that I try to teach in my classes

and to my, my students that you need to be able to formulate your question really well, because otherwise you're going to get an answer to a different question, but you won't notice that it had, that the goalpost has shifted in the meantime, right? So your interpretation can only be as good as the question. If you need to change your question, that's cool. Do it. But then, you know, it needs to pair up with your interpretation again. And so knowing, really being in the know about every step of what happens, that relates to quality results, I think. That's why I have sometimes little trouble with, with sort of big data and statistical analysis. Yes, on average, that's true. I'm not debating that. But I, I'm the kind of person I like to look at the outliers or not the bulk, but, you know, the special ones. And they just need to be treated in a different way. And there needs to be an acknowledgement of that different ways for different things. So big data can look at divorce rates. And perhaps you and I are more interested in the individual love stories. Yes. That works for me. So I don't know if it's possible to say, but what do you think is the big discoveries that are waiting? Is it on the different dynamics of the yield? The common narrative, the common story of how some of these metal poor stars are formed? Is it where the discoveries in this field that you think will come? I think the individual discoveries are actually, we've made most of those, certainly through individual stars. Finding yet another second generation star is incredibly important for me, but isn't, isn't really going to move the needle. Finding 50 of them or 100 of them, that would move the needle, but that's in a word or two magnitudes up. And new search techniques and new surveys may enable that. But would you still call that a discovery? Right? So that's just a scale. This is scale. Yes. So I think about it more like literally of the puzzle. Let's say you have a thousand piece puzzle and you have 900 pieces in there. If you're a person like me, I want to get to the last ones. I'm not going to leave it. It's like, okay, I see broadly what this is going to look like. I'm done now. No, I want to get to the last one. Is the picture globally going to change? No. Are we going to figure out all the details and how it really works? Yes. Right? So really carefully getting into it. Getting into it. The ancient, the ancient stars of our universe. Yeah. Because I think that's what many of our scientists are a little bit detailed, obsessed. But I think that's our job too, right? To really kind of make it airtight, to really walk away saying, I fully understand this, not just broadly, but we really know now. And so more and more of that is going to happen. And so I think this is probably true across astronomy. These individual 10 sigma discoveries become less and less. If they were easy, we would have made them already, right? Which means we have made many of them. But really filling in the details is the next level of discovery. Maybe we need to find a new word for that. The hopes and expectations that go along with the word discovery are so enormous, we may not always be able to live up to that. But it doesn't mean that we're not finding out new things. It's just a different kind of quality because the questions have shifted. You close one door, suddenly there are 10 new open doors that we want to explore and march through. And that's finding these last puzzle pieces here and there that really make it airtight. And so there's a lot of value, a lot of power and beauty to the discovery in the big picture of our universe and in the details. Yes, we need both, absolutely. Perhaps drifting into the philosophical, let me ask about the Big Bang as we kind of encroach onto it. So your work is kind of taking steps back through time in a weird way.

Do you think we'll get to deeper and deeper understand the really, really early days of the Big Bang and the philosophical question, do you think we'll be able to understand what was before the Big Bang or why the Big Bang happened? Do you think about that stuff?
Not with stars, for better or for worse, because stars only probe the time when they were formed and the Big Bang is surely before then. I mean, I often talk to my students about the difference between math and physics. Let me give you an example. We talked earlier about 1815-23 and I was happy to share with you that I measure thorium and uranium, but I actually didn't quite close that loop. So we did this to try to attempt to calculate an age for these stars. But they rely on us knowing how the R process works, how these elements are created,
where it happens and then how those elements get dispersed into the gas and end up in the next generation star. So quite a few question marks. So that's how we got to the age of 13.2 billion years. This is probably not accurate, but this is the best calculation we could do. And the reason why I'm bringing this up is that that was actually the average of multiple elemental ratios that each gave a certain age and then we averaged that because for better or for worse, this is the best we can do. So some of these numbers said, oh, this star is 15 billion years old. And then others said, oh, this is 10 billion years old. And so I often use that in my class to say like, what's the good news and what's the bad news here? Some ratios say 15, something 10, right? Is 15 correct? And then I asked them and some people will say something. And so the thing here is that it's an absolutely correct calculation given the mathematical and physical model that we constructed. But does it make sense? No, it doesn't. If we believe the universe is 13.8 billion years old, 15 is ridiculous. Yet it is correct. Isn't that interesting? Correct from a mathematical perspective. It is not incorrect because this is what I calculated. Nobody made a mistake. Now, we can question whether that's a good model, but that's a separate issue.
So you're saying physicists are much closer to truth than mathematicians?
Well, it depends. Sometimes yes and sometimes no, right? So what our job as physicists is, is to take the mathematical model, calculate our numbers, and then ask the question, does this make sense, right? Now, in the case of 15, it doesn't, but we took the average anyway because that was the best we could do, right? So, all right, let's put that aside. Let's apply the same sort of thinking to the Big Bang, right? Math can tell us things that we as physicists cannot grasp because it doesn't make sense to us. Now, in the case of the Big Bang, the Big Bang, that's a special case because we don't actually know what's supposed to make sense. And this is where things
get interesting. But this is where math will ultimately be the winner because we can no longer say this makes sense or this doesn't make sense because the physics is broken down.
But math breaks down too at the singularity of things.
Well, depending on who you ask.
Sure, this is the current question, right? How far, how much further can we push math, let's say, to the front of the Big Bang if there is such a thing?
What's the front in the back? Well, before the Big Bang.
Oh, before the Big Bang. Okay.
To clarify, all the doorways and the entrances.

So, how far can we let the math go before that stops to make sense, right? And I don't know what the answer is to that. But it's really cool that because math is not limited by our physical nature, it can probably go a little bit further than the physics, right?
And math can go into more dimensions than four dimensions comfortably.
And it's judgment free because it just calculates things on its own.
Well, as physicists, we are so judgmental. This makes sense. This doesn't make sense, right?
It doesn't get any worse. It's such a beautiful dance. It's so amazing that through this dance, you can explore the origins of the universe. Like, doesn't the Big Bang just blow your mind that this thing has just started from a point? Yeah. And now we're here.
Yeah, yeah, yeah. Hydrogen and helium. And then all the stuff you're studying,
I mean, this evolution of chemistry created humans. And we're here talking.
And there's a lot more to the story. It's amazing. Yeah, yeah, yeah.
And this kind of march that you're doing is observing data. And is there,
you're looking at old light and old data. But only a few thousand years, right? Just a few thousand years. That's the difference between me and my JWST colleagues. Yes.
Their objects, that light has traveled 13 billion years or whatever it was to us,
and they're observing that now. My light has only traveled a few thousand years.
It's nothing. So whatever you observe now is likely still going on.
Yes. These stars are alive and kicking and having a blast.
Thousand years. Just a few thousand years. It all it takes. If we can travel at the closest speed of light, maybe we can reach out there.
We wouldn't have any planets around those stars, though.
So that's, is that a definitive intuition?
Well, what are planets made of? Elements, right? To take the earth as all heavy elements, right?
The universe needed to reach a certain stage first to have produced enough of all these elements to actually make a planet. So on average, you're okay, right?
So that took quite a few billion years. So they're not going to have a mechanism for forming planets.
You could have visitors probably, but the kinematics of that are unlikely.
Yeah, I would say so. Okay.
So they're interesting in that they reveal the early chemical evolution of the universe.
Yes.
Not that there could be good vacation spots, but not...
Well, it'd be like a worm.
Just no planet islands to go to to chill.
In your book, you highlight the major contributions in the field by many women.
Some of these women were not, as you describe, immediately credited for their discoveries.
So for me, from computer science perspective, the story also tells Harvard computers.
Who were these women and what can you just say about the nature of science and humanity?
Discovering things is part of the human nature, right?
And so it has happened for the longest time, not just by men, but also by many women.
The field of stellar astronomy, which is my field, has particularly benefited from many discoveries made by women. You mentioned the Harvard computers.
That's a term used for women who worked about 100 years ago at the Harvard College Observatory,

and they were hired for their low wages and willingness to do diligent and patient work
to comb through the big data of the day.
So the Observatory Director, they were carrying out large sky surveys at the time,
and they needed that data needed to be processed and looked at and analyzed.
And so many women, or several dozens, or one or two dozen women over the years,
were hired to do this work. And in the process, because they were looking at the actual data,
and they were smart, even though they had often no formal education,
they made a lot of discoveries simply by being in tune with what they were doing.
So they weren't robots, as the term computer would perhaps let on, lead on.
So Annie Jump Cannon classified thousands and thousands of spectra and found out that
you can, you know, stars have different temperatures and their spectra look according.
We still use that classification sequence today. Cecilia Pena-Poshkin later on in I think 1925 was
one of the first women to obtain a PhD in stellar astronomy, and she figured out,
she calculated that the Sun is mostly made of hydrogen and helium.
That seems normal to many of us these days, but at the time, it was thought that celestial objects
are made of the same thing as the Earth. That's a gutsy amazing discovery.
Yes, it was later termed the most important thesis of humankind or something like that.
What a revelation to realize that stars are made of hydrogen and helium, right?
And this was exactly the time when people figured out why stars are shining,
namely because of nuclear fusion and that it's protons and, you know,
the tunneling effect that leads to the actual fusion. Otherwise, you know,
the protons repulse each other, they don't come together.
And so what an incredible time it was back then. And so stars and nuclear physics were very closely
related and it remains, now it's called nuclear astrophysics. And so many women had many
contributions to that. Of course, prior to that, Marie Curie discovered two new elements.
Ah, so awesome.
Radium and polonium. Lisa Meitner discovered nuclear fission. That is the basis for
understanding the R process. This is exactly what happens in the R process.
You know, the heavy nuclei, let's say uranium, if you bombarded with a neutron,
we talked at length about it, it will decay, it will, well, not decay, actually,
it will fission, it will split into barium and krypton, let's say. So two lighter elements.
That's exactly what we observe. I have always a higher abundance of barium than the heavier
elements because of this fission cycling that she calculated in 1938, 1939. So many,
many contributions and it's just so remarkable. If you just take that body of work, that changed
how we do things, how we see the universe, how we understand things has led to so many
subsequent discoveries, good ones and bad. Well, all of it is taken together. That's
progress. It's science is what it is. We have to decide what we do with that knowledge. We can
always use things for good or for bad. That's part of the human endeavor as well.
And also part of the human endeavor and the human nature is the issues with corruption and credit
assignment and all these kinds of things that make this whole ride so damn interesting about
what's right and wrong and about the nature of good and evil. And that seems to surface itself
in all kinds of places all the time. Yes, yes. Lisa Meitner was nominated for the Nobel Prize 40
times, more than that even. It's amazing. She holds the record for that. She never received it.

Case in point. Yeah, and of course, the Nobel Prize is as complex as it is. One is the credit assignment, but two, even in astronomy, sort of assigning credit to a handful of folks when so many more contributed. That's a complicated story also. Yeah, it's very complex.
Okay, sorry for the romantic question, but what do you use the most beautiful idea in astronomy, in stellar astronomy? Well, so early on, when I was in high school, I was thinking like, okay, what do I want to do when I grow up, right? I knew I wanted to do astronomy, but I was a little bit torn because my interests were definitely stars, stellar astronomy, but also chemistry. I always had a fascination about the elements, so Marie Curie was a big role model. My friend actually made a beautiful, produced a beautiful movie about the discovery of of the elements. This is a theater play, but digitized, where when I saw it, I could actually kind of relive the sort of discovery moment that Marie Curie had. It sent shivers down my spine. It was fantastic. I mean, this is the kind of thing that I wanted to experience.
But yeah, so nuclear physics and element creation and formation was really interesting to me. Chemistry, the elements, stars and all of that. And I was like, I don't know if I ever find something that combines all of these things. And then I ended up in Australia, and I met this person, and he was working on old stars. And as I was sitting in his talk, hearing about this for the first time, it kind of, it clicked all over my head and was like, oh my God, it all fell in place because we can use these old stars to study the elements, to learn how they're formed.
We can get these clean signatures that help us inform the nucleosynthesis processes.
I know, of course, I need to know a lot about stars too. So it's like all together. And that was sort of a moment of magic. And then the fact that I have now done that for 20 years, it's just like I won the lottery. It all clicked into place.
And so in some sense, it's an ongoing love story for me, if I could say it like that, where I found my stars, my thing, and I am fortunate enough to be able to keep doing that.
And I'm happy to see where it will take me. It's an evolution, as with every relationship.
You have to, if you don't march forward, you move backwards. I'm not interested in moving backwards. So I'm, I'm letting the field and the discoveries and the findings lead me to, you know, and I'm often, it's not hard for me to follow sort of my hunches. And sometimes, even at the telescope, it's like, let's take a look at this one. I have a good feeling. And then usually something good or, you know, not bad pops out at the end. And I really like that, A, that I have the freedom to do that, that I'm allowed to follow my hunches. Too many people, I think, are sort of boxed in with their job or their life, that they don't have that kind of freedom, that that's really important to me. And I certainly try to make use of that. I also try to teach that to others, to trust them, to learn, you know, you need to learn your things, but then you need to also trust that knowledge and that you have a grasp on it, right? You get out what you put in. And being able to contribute in meaningful ways to our knowledge about our cosmic ancestry, cosmic history, that's a wonderful thing. And in this way, your personal love story with the stars evolves. What advice, you've already spoken to it a little bit, but what advice would you give to young people that are trying to find the same kind of love story in their career, in their life? It seems increasingly hard for folks to find that. Sometimes I feel that, you know, young people have all the opportunities these days, and that's wonderful. But it's almost like that leads to some, what's the right word? They're a little bit too tired to make all the decisions because at some point, you need to put your eggs in a basket and you need to be okay with

that. We can't do all the things, even though we're often told you can be president too. And I think that's really important to convey. But at the end of the day, we can only have sort of one job or one type of profession. I'm not saying, you know, you need to be locked in, but it's hard to change 180 degrees. And so lots of people, I think, are often afraid to really dig in, at least for some time and get their hands real dirty and really learn from the bottom up. On one thing. On one thing, because they're afraid they're missing out on 99 other things. But life is a little bit missing out on 99 other things because we only have 24 hours in a day. I have that feeling very often. There are so many things I would like to do, many things I would like to try to be good at. Sometimes I wish I had a different job. You know, because I have other interests too, but I realize, okay, I can only do one thing. So I have no regrets. But this is a general feeling that I think I would think most of us have. But if it stops you from really digging and drilling down on one thing to become an expert on one thing, to become really good at one thing, that you call your own, then it just makes it difficult. And so a fulfilling life is in part likely to be discovered in a singular pursuit of a thing, of one thing. For at least for a time. Yeah, for some time with your heart and your hands. Because I think most people long to own something. You know, we all, I think, want to leave some legacy of some sorts, you know, for our children, for humanity, for this planet. And I think it's really important for young people to strive for that and not lose sight or trade that for all the opportunities, because an opportunity is nothing if you don't do anything. You need to, you need to do something at the end of the day. So I chat with lots of people about this. And I often start by just saying, Hey, tell me what you don't like. Because it's often much easier to, to, you know, let out what, what's not on your plate. And then this way we get a little bit closer. And then it's like, well, why don't you take a risk and just sign up for something for three months. But that's what it feels like. That's what it feels like. And it is that is a risk. Commitment is a risk. Yes. Because it's, you're basically sacrificing all the other possible options. But then I guess you have to trust the magic you noticed in that thing. Yes. If you notice one thing, just stick with it. And then, and then maybe there's something there. Right, right. And, and this moment of kind of feeling it in your entire body and mind that this is the right thing, you know, getting there is, is probably really hard. But if you don't try, you won't find out. The hard stuff is the fun stuff. That's also another thing you find out. And then there's that. Somehow, it doesn't make sense. You also mentioned that you've taken a little stroll into the artistic representation of yourself. Can you speak to that for a little bit? Yes. Well, I already just mentioned. Sometimes I wish I, you know, had more time to do other things. So I find little, little sideways, I guess, to, to pursue things that, that I like besides astronomy, or at least I try to find connections. And so some years ago, I, again, with the help of, of my friend who made this Marie Curie movie, she and I wrote a one woman play where I actually portray Lisa Meitner, who was an Austrian German physicist, nuclear physicist from Germany. So I have the right accent for that. And we wrote this play about this moment of discovery of nuclear fission. Again, this is an absolutely critical piece that explains my work today. And we all stand on the shoulder of giants. She was one of those giants. And in some ways, it's, it's of course a way for me to acknowledge other people's work that have come before me. It's a wonderful way to highlight the contribution by a prominent woman.

And the way I, I do it is it's a 25 minute play in costume, where I relive for people
the moment of discovery. Then I turn into myself. And then I give a 30 minute presentation
on the art process and the creation of heavy elements, because the audience can now perfectly
understand that the public audience, given the historic backdrop of this discovery that they
just lived through my presentation. And it's, it's a wonderful compliment that almost spends 100
years from one woman to the next, passing on the torch. And, you know, when we write up our results
in, let's say, you know, in magazines like Nature and Science, it's always about the results on the
golden platter, perfectly prepared. It's the discovery is never described, only ever the results.
You asked me beforehand, right? What does it feel to be at the telescope in this moment, right?
I'm happy to talk about this, but it's nowhere written ever. Nobody, nobody really talks about it.
And so having a form of, you know, theater of the arts to bring this, this exciting moment that,
that is what we all want to experience as scientists to a wider audience is so profound
and so rewarding. And they all love it because everyone can understand a moment of discovery.
I was looking for something and then I found it. It's like you misplace car keys, right?
Or love. Yes, yes. It everyone can understand.
With the glorious experiences, yes.
The implications and the findings, that is much harder to understand for the, for anyone.
This is where the scientists work truly lies. This is our job. But the moment of discovery is easy.
And it's beautiful. And it needs to be said. And so taking my audience on this journey,
what is the perils? What are my worries? And then, oh, here is the moment of discovery.
Let me tell you about it. It profoundly transformed me. And here, here's how it went, right? It's so good.
And art is a way to reveal this fundamental human side of science.
Yes. It's the problem with science is that's people doing it.
That's also not a problem, but that's also what makes it beautiful, right?
Humans are fascinating and that we're able to come up with these ideas
through all the struggle, through all the hardship, through all the hope, through all the search.
And so the art is a great way to, to portray that and to broadcast that, right?
I think this is how the audience really should be interacting with scientists,
much less about the findings, but really more about this yearning for answers, right?
I need to find these khakis. I need, I need it because I need to go, right? It's like now, now.
And then, oh God, here it is. Now I can go my, my merry ways. It's, it's so relatable.
We just need to find more and better ways to, to do that. So I hope to turn this into
also a digitized version at some point to again, make it more accessible.
I hope so too. So far I'm just doing it in person, but it's, I would love it.
I think a lot of people would love to see it. So I hope you do just that.
Let me ask you a big, ridiculous question. You look up at the stars, you look up at the
early, early, early stars. So let me ask the big question that we humans often ask
and struggle to answer. What's the meaning of this whole thing?
Why, why are we here?
We talked about, you know, the biological evolution requires the chemical evolution
for all of this to kind of play out and carbon play this important role.

And, you know, in some sense, we're, we're just a consequence of all of these things being the way they are, right? So maybe this is just where we are supposed to be. Because, you know, the, the laws of physics sort of work the way they do. And we talked much about the variety of, of everything really in certainly, you know, from over here to over there. And things in the vicinity of where the sun and the solar system formed, they were the way they were. And life maybe wasn't necessary consequence of that. In some sense, I like to believe that because then it becomes reproducible and we can apply that same argument elsewhere.
If it's total chance, right, that makes it harder. And that's not, not truly satisfying to, to a scientist.
So it's a, it's a consequence of psychological evolution, which is a consequence of biological evolution, which is a consequence of chemical evolution, consequence of physical evolution, whatever, whatever disciplines, it's turtles on top of turtles.
Turtles all the way down. Yes.
I, yeah. You have studied some of the most ancient turtles at the very bottom of the thing.
That's right. They live for quite a while.
Yes, they do. Well, thank you for your incredible work. Thank you for highlighting both the human side and the deep scientific side. It's just, I'm a huge fan of your work. And thank you for everything you do. I thank you for talking today. This is awesome.
Of course, it was wonderful. Thank you.
Thank you. Thanks for listening to this conversation with Anna for Bell.
To support this podcast, please check out our sponsors in the description.
And now let me leave you with some words from Douglas Adams and H Hikers guide to the galaxy.
Far out in the uncharted backwaters of the unfashionable end of the Western spiral arm of the galaxy lies a small unregarded yellow sun orbiting this at a distance of roughly 92 million miles is an utterly insignificant little blue green planet whose a descendant life forms have so amazingly primitive that they still think digital watches are a pretty neat idea.
Thank you for listening. I hope to see you next time.