

*Dave Eicher:*

Welcome to the Superstars of Astronomy podcast, from *Astronomy* magazine. I'm Dave Eicher, editor-in-chief of *Astronomy*. Each month I will share the thoughts and research of the world's greatest astronomers, astrophysicists, cosmologists and planetary scientists, with you in these hourlong chats. Superstars of Astronomy is brought to you by Celestron. From your first telescope to precision observatory-grade instruments, Celestron has the perfect telescope to suit your experience level and budget. You can find out more at [Celestron.com](http://Celestron.com).

And I'm very excited this time to have an important guest for our fourth show, Abraham Loeb. Avi is a Frank B. Baird professor of science at Harvard University, chairman of the department of astronomy, and director of the Institute for Theory and Computation. He is an accomplished astrophysicist, having authored more than 400 research articles on astronomy, and he's written three books. They are *How Did the First Stars and Galaxies Form*, *The First Galaxies in the Universe*, and *First Light in the Universe*.

Avi has researched and written on a broad range of subjects, including the formation of the first stars, the formation of black holes, the future of extragalactic astronomy, gravitational lensing, gamma-ray bursts, and much more. Of course, one subject he's gained notoriety with has been his research on the future of the Milky Way, which will see our galaxy colliding and merging with the Andromeda Galaxy.

Honors that Avi has received include the Kennedy Prize in 1987, the Guggenheim Fellowship in 2002, the Salpeter Lectureship at Cornell University in 2006, the Bacall Lectureship at Tel Aviv University in 2006, and many others. He's written several times for *Astronomy* magazine and has been profiled or had his research discussed in *Time* magazine, *Discover* magazine, *Science* magazine, and in many other outlets. So without further adieu, Avi, thank you so much for joining me today.

*Abraham Loeb:*

My pleasure.

*Dave Eicher:*

It's a great pleasure to have you, and there's a lot to talk about because you're a fellow who has his research hands in many, many interesting places. So let's start with a discussion of how did you first get interested in astronomy as a young man, and how did you grow up, where did you grow up. Where did this idea that you wanted to be an astronomer hit you?

*Abraham Loeb:* Well, things could have turned out differently. I grew up in a small farm in Israel, in a village. And I used to collect eggs every afternoon, and then I was mostly interested in philosophy. So I read many philosophy books on existentialism, by Jean-Paul Sartre, in particular.

And then when I got to the age of 18, I was obligated to serve in the military; there is obligatory service in Israel. But there were two options available to me. One was to work in physics. They recruited me to a special program that allowed me to work in physics. And the second alternative, which appealed much less to me, was to run in the fields like a regular soldier. And so doing physics was closer to my interest in philosophy, and so I did that, but it was temporary. I always wanted to go back and study philosophy.

And then I finished my Ph.D. during that program, and I also initiated a project that was funded by the Strategic Defense Initiative in the U.S., and that brought me to Washington quite frequently. In one of my visits, I also visited Princeton, the Institute for Advanced Study. I met Freeman Dyson, who introduced me to John Bahcall, and it was quite embarrassing, because I didn't know how the Sun shines, I didn't know anything about astrophysics, and how the Sun shines was the main focus of John Bahcall's career.

Nevertheless, he invited me again for a visit, and at the end of a monthlong visit, he offered me a five-year fellowship at the Institute for Advanced Study, under one condition — that I switch to astrophysics. And I of course accepted that because of the prestige of the place and the fact that it was once-a-in-a-lifetime opportunity to pursue research at the frontier, I started doing astrophysics without much knowledge. And that was quite difficult because the environment was very competitive. There were a lot of postdocs around me that knew astrophysics for many years, and I didn't really know the vocabulary. So I was learning it.

*Dave Eicher:* Yes, and you were quite young at this time. This was in 1988 when you first there; you were in your 20s.

*Abraham Loeb:* Yes. I completed my Ph.D. at age 24, and then I was still in the military at that time. But once again, this new interest in astrophysics, since I didn't know much about it, I did it just because of the opportunity, and I thought of it as a compromise for the time being, that would eventually go away and I would go back to either doing philosophy or going back to work in the farm that

my parents owned. And then I was offered the junior faculty position at Harvard. Once again, this position was not particularly — was not considered by many as a long-term position. People thought that the likelihood of getting tenured at Harvard is very small. In fact, the position was offered to someone else before me, but he turned it down. He thought that it's just another postdoc position that doesn't lead anywhere because the last time that Harvard tenured someone was 20 years earlier.

And so I accepted it because I could always — I had job security; I could always go back to the farm and work there. And I wasn't particularly stressed out being in such a position that does not have any guarantees for the future.

But then three years down the line, I was offered a position elsewhere, and Harvard decided to tenure me. And then at that point, it became clear to me that astrophysics will be my lifetime occupation, and I also realized that it closes a circle for me, because in astrophysics, we're able to address very fundamental questions that were previously in the realm of philosophy or religion, and we do that with scientific tools. So in a way, I did return to my old love of philosophy, but in a different way, in a scientific way. And it made me somewhat different than my colleagues, who were interested in science from a very young age, and that was the main focus of their career all along.

So there is actually an advantage coming from a different background, looking at things differently than many other people. And that's one of the reasons that I nowadays promote diversity. I think that the scientific endeavor can be very successful if we have a diverse set of people, from different backgrounds, different — you know, both males and females, different genders, and that can only strengthen our research. And so nowadays, as the chair of the astronomy department at Harvard, one of my goals is first of all, to help young people fulfill themselves because I realize that there might be many Loeb's out there, people just like me, with the same skills, similar interests, that didn't have, that were not as fortunate to get the opportunities that I got.

*Dave Eicher:*

Yes. That was quite a rare sort of coming together of circumstances to give you the career path that you have there.

*Abraham Loeb:*

Yes, and I'm grateful for that because on many occasions, it was either a matter of being in the right place at the right time, or a matter of pure luck, that someone else turned down a position that I accepted. But given this, I feel obligated first to justify the

opportunity that was given to me and work to demonstrate that it was worthwhile, but also enable others to achieve similar success. For example, out of the seven graduate students that I have, six of them are women. I feel very strongly in terms of promoting both minorities and women in science.

And the people that come from other backgrounds, one of my main criticism of my colleagues, some of my colleagues, not all of them, is that they look — they take a snapshot of a young person, and then by that, they basically express, evaluate that person and express their opinion of that person, without updating it at later times. And in my view, people should be evaluated routinely because we should pay more attention to the growth of people than to the initial conditions from where they start from. And I think a single snapshot does not give us a true assessment as to the abilities of a person. So I'm very much opposed to evaluating people based on their academic ancestry, for example, based on who they worked with, because there are some people that didn't have the fortunate circumstances to work with good advisors, good mentors, and we should pay more attention to the way they grow during their career.

*Dave Eicher:*

And don't we, Avi, sometimes think the scientific process, of discovering things, of thinking of things in a certain way that allow discoveries or research on certain kinds of objects, as almost an inevitable machine that lurches forward? But as you've talked about some of the insights that allow for thinking of things in a new and different way, really are so subtle, that as you said, the maximum diversity of different ideas, different backgrounds, different opinions, might allow some of those new ways of thinking or new approaches that could be the difference.

*Abraham Loeb:*

This is exactly right. The reason I promote the diversity is practical, because on many occasions — well, first of all, it allows you access to a bigger pool of people, so that you can harvest the talent that is out there. But more importantly, on many occasions, the mainstream of the research is wrong, and it's important to have different matches in your matchbox, so that not all of them will be duds. So that there will be different opinions, different ways of looking at the problem. And one of them, one of these matches, will light up and show us the way forward in the dark.

And then there are many — I actually wrote an essay about many examples where the mainstream view was wrong. Obviously, I mean, we all know about the fact that, you know, for many centuries, people thought that the Sun moved around the Earth

because it sounds obvious. But also, people thought that a heavy object falls faster than light objects until Galileo decided to test it. And there are more recent examples. People thought that ... thought that the Sun has the same composition as the Earth, and Cecilia Payne-Gaposchkin did her Ph.D. dissertation on the composition of the Sun and concluded that at least the surface of the Sun that she was observing, analyzing, appears to be made mostly of hydrogen.

And Henry Norris Russell, who was the director of the Princeton University observatory, at the time one of the most prominent astronomers, he was on her thesis review committee, and he tried to convince her to take away that statement from her thesis because everyone knew at that time that the Sun is made of the same elements as the Earth. And she did take it out, and later on, a few years down the line, he himself studied the same spectrum of the Sun and concluded that she was right. There are many more examples that I can mention, that illustrate that even luminaries, people that thought that the establishment, the thought leaders in science, are often wrong. And so I think diversity of opinion is extremely important for the healthy development of science.

*Dave Eicher:*

Mm-hmm, very good. Before we get into the many interesting areas that you're involved with with astrophysical research, would you mind talking briefly a little bit, what's the state of affairs at Harvard? Because Dean Lee, department chair and one of the key people at arguably the greatest educational institution in the United States, in many ways, one of the premier astronomy departments, what is sort of an overview, how is astronomy going at Harvard these days?

*Abraham Loeb:*

Oh, when I came to Harvard, which was 22 years ago, the situation was not great, especially in theoretical astrophysics. A decade earlier, Harvard tried to recruit the very best theoretical astrophysicists. They went after the people, the senior people, without success. And so they had — at that point in time, they didn't have much choice but to hire younger people, like myself and a few others, trying to establish theoretical astrophysics from the bottom up.

And this turned out to be a blessing, because there were no strong personalities around, and so slowly, we built up a group in theoretical astrophysics that is currently very successful, I mean, objectively speaking, one of the most successful worldwide. We have the Institute for Theory and Computation, that brings together about 30 postdocs, 35 graduate students, and about 15 senior

people, and we have 200 visitors a year coming through. There is even an urban legend that unless you become a postdoc at the ITC, at the Institute for Theory and Computation, you have a hard time getting a faculty position, which I heard from a number of outside people.

So altogether, it took a lot of work, because at the very first stage, we had to establish the reputation of the place. We had to convince people to send their best students, best postdocs, to us. And that took awhile, but through hard work, we were able eventually to establish reputation. And given the resources at Harvard, we had also to convince the higher administration at Harvard to do so, to invest in theoretical astrophysics. And I'm happy to say that we succeeded on both fronts.

In terms of the astronomy department, again, the department had a long history before that required some work, in particular in the area of diversity. And I'm doing my best to attract a diverse group of people to our faculty. In terms of the students we get, somewhere between 30 to 50 percent women among the graduate students that we admit. Among the faculty, I try to bring both minorities and at the same time women. I'm trying to promote that as much as possible, and I get a lot of support from the higher administration at Harvard. So far I haven't had any instance where I asked the higher administration at Harvard for something and they said no, and I've been in this position for four years. And I don't ask them for things that I don't think are appropriate.

One thing about diversity that is extremely important is that one should strive for excellence because if one is just trying to improve the statistics of having a diverse group of people, without putting an excellence bar, then people would argue — people would say, oh, you're just bringing people that are not necessarily good, and it justifies prejudice against diversity. However, I do think that there is excellence out there, and it's quite possible to fulfill both tasks at the same time. So diversifying a group, while at the same time maintaining excellence, is the real way forward. And businesses, you know, outside the academic world, businesses that are open to diversity are often more successful, so we should adopt the same approach in academia.

*Dave Eicher:*

And aren't we sort of more or less, at least potentially on a fairly significant tipping point in astronomy? Of course, senior professors we know are not a terribly diverse group at this point in time, but in waltzing through the poster sessions at AAS meetings,

the young generation of fresh Ph.D.s, of postdocs, extremely diverse.

*Abraham Loeb:* Yes. I'm very hopeful for the future. I hope that we're going in the right direction. And I haven't encountered much resistance within my department or from other places when I move forward in that direction. So either people agree that this is the right thing to do, or they are afraid of speaking out against it. Both ways, it doesn't matter. We can move forward.

*Dave Eicher:* Yes, yes. Well, let's talk about the research because you are involved in a lot of different areas, in very interesting ways. And as you talked about your early interest in philosophy, it sort of crystallized in my mind why you're doing some of the things you're doing because a lot of what you've looked into and written your books about and know a lot about really harks back to a philosophical question, if you will. How did the first stuff in the universe form; the first matter, the first stars, black holes, galaxies? That's an important area of interest to you, is it not?

*Abraham Loeb:* Yes, it is. It's the first chapter of the Bible, the Old Testament, it has the words let there be light, and we are now able to address this biblical story in scientific terms. In fact, a few months ago, I was interviewed by the BBC about the first stars. They're producing a program. And then at the break, we went to a YMCA nearby to warm up, because the place where the filming took place was quite cold. And at the reception there, there was a person that asked us, "What are you filming? I'm very curious to know, because I might want to watch it when it comes out."

And the producer tried to explain that we are investigating the first stars and galaxies and tried to explain why this process scientifically is of great interest. And the guy said, "Well, it's above my head. I cannot really follow what you're talking about." So I approached him and said, "Are you familiar with the first chapter of the Bible?" And he said of course. And I said, "Well, what we are doing, what we are discussing, is the scientific version of that story." And he said, "Now I get it."

So when I came back, I mentioned it to the director, and he said, "Well, now we have to ask you some questions about the grading of the first chapter of the Bible. What kind of a grade would you give it? If a student came to you with such a story?" So I said, "Well, perhaps a B+," because there are some elements of truth in the story, and it's quite impressive that there was — in the biblical story, there was a beginning in time, and also, everything that was

created, that appeared, appeared in a sequence. There was a sequence of events.

I mean, one could have thought if the story were everything was created at the same time. But there was actually a sequence, and that's more or less the scientific approach, sequence of events. However, the order of events is wrong, and the story needs to be revised. But it's quite remarkable that without any data, thousands of years ago, someone came up with this story.

So the scientific version of the story is that the universe is expanding; therefore, if we go back in time, we get to a state of extreme density and temperature. And that point in time when the density was infinite is called the Big Bang, and that's when everything started. We can't really tell what happened beforehand, and after the Big Bang, the universe expanded and cooled. And there was a time when it cooled enough for matter to start clumping into clouds — the first gas clouds — that eventually fragmented into the first stars.

And so in my research over the past two decades or so, I tried to understand how the very first stars formed and how the very first galaxies formed, at a time when the universe was dark, after the radiation that was left over from the Big Bang cooled off.

And of course, all of this relate to our cosmic origins because we are made of heavy elements. Life as we know it requires water, so water has oxygen, and also requires carbon. And both oxygen and carbon were not produced in any significant quantities in the Big Bang. They would produce tiny quantities in the Big Bang, but really completely insignificant. And so the only way to make them is in the cores of stars. And so if we trace back our own existence, we would find that the carbon and oxygen atoms that we are made of came from the interiors of stars, and these stars started forming at some point in the evolution of the universe, about 50 to 100 million years after the Big Bang.

*Dave Eicher:*

Now, we really don't know the details yet of how the first normal matter formed, and the sequencing and whether black holes seeds came first or galaxies formed and stars within them, or stars, and then they gravitationally created into galaxies. I mean, we really don't know the details yet of the sequence of formation of the first stuff ...

*Abraham Loeb:*

Yeah, we don't know for sure, but we know the initial conditions that the universe started from quite precisely. So by now, there is a

standard model of cosmology, and we know the parameters of the universe, to percent level of precision. And we can see the computer simulation with the initial conditions of the universe, which we can read off from the cosmic microwave background, the radiation — the relic radiation leftover from the Big Bang.

So the universe was filled with radiation, when it was hot and dense, and then about 400,000 years after the Big Bang, the electrons and protons in the universe combined to make hydrogen atoms, and at that point, the cosmic fog disappeared because the electrons, the free electrons, were scattering the radiation, and the universe was opaque. If you were an astronomer back then, less than 400,000 years after the Big Bang, and you used your telescope, you wouldn't see very far. You wouldn't be able to see very deeply into space because there were these electrons that scattered the radiation, free electrons.

But these electrons disappeared into hydrogen atoms at that time, 400,000 years after the Big Bang, and at that point, the universe became transparent. And so the cosmic microwave background started permeating through the universe, streaming freely through it, and we can see it today. About 90 percent, 92 percent of the particles fly, the photons that we receive, came from the time when hydrogen formed. About 12 percent of these photons were scattered once along their path to us. And then we see these photons and we can read off the conditions in the universe that were back then.

The situation is similar to looking at the surface of the Sun. Actually, the temperature of the universe at that time was very similar to the temperature on the surface of the Sun, several thousands of degrees. And we are looking at the photosphere of the universe which surrounds us. So it's sort of like a star, but from the inside out. We are looking at the photosphere of the universe, and we can read off the conditions back then, and from that, we can feed those initial conditions. The universe had almost the same conditions everywhere, but there were small ripples, small differences, in the density of matter from one place to another. And we know the statistics of how big those differences were on different scales, different partial scales.

And we can generate in the computer initial conditions that are similar to that, and then let the law of gravity act on these initial conditions. And so what gravity does is amplify the small differences in density. A region that is slightly denser than average attracts more matter into it. And density grows, and eventually that

region collapses to make a bound object, like a galaxy or a cloud of gas.

Most of the matter in the universe is dark. It doesn't seem to be the same as ordinary matter that we are made of. And we can put dark matter, we have to put dark matter into the simulation in order to make the very first objects. In fact, if there was no dark matter in the universe, we wouldn't exist. You wouldn't be able to make galaxies because there were no density inhomogeneity on small scales in the ordinary matter. These were washed out by the radiation. The only density differences on small scales, the seeds for galaxies, existed because of the dark matter that didn't interact with the radiation. It was not smoothed out by the radiation like the ordinary matter was. And so in a way, we owe our existence to dark matter. Without dark matter, galaxies like the Milky Way would never form, and stars like the sun would never form.

And so all of this can be fed into a computer simulation, and then we can follow our nose and just see what happens, and these computer simulations generate clouds of gas with dark matter about 50 to 100 million years after the Big Bang. These are the very first objects of the universe. And then we can follow the behavior of the gas, the cooling and eventually fragmentation of the gas into the first stars. But as soon as we get to forming the stars, the computers that we have right now are too slow. They're not strong enough, they're not powerful enough, to follow the formation of the first stars and to see their impact on the surroundings. We can sort of get very close to the formation of the first stars, but not go through it accurately.

So you're right. There are many details that are left for us to explore. But we know more or less what the parameters of the first objects were. We think that the stars formed first, then some of collapsed to make black holes, and then these black hole seeds grew to become very powerful quasars with later times. And then the galaxies like the Milky Way were made of building blocks, just like a building made of blocks of concrete. A galaxy like the Milky Way has a million building blocks from those early times that came together to make the Milky Way as we see it today.

*Dave Eicher:*

Merger after merger after merger, repeated mergers of tiny protogalaxies.

*Abraham Loeb:*

Exactly. And then these mergers took place over cosmic time, since the time when the universe was 100 million years old, to the present time, 13.8 billion years after the Big Bang.

*Dave Eicher:* Yes. How do you see, Avi, the coming in the next few years, both with respect to the increasing complexity and power of supercomputing simulations, and also what we know now about the first matter in the universe, relative to coming observations from the Webb space telescope, how those might impact our overall ...

*Abraham Loeb:* Yeah. So we can in principle try to generate the universe in the computer, generate those early times, and for that, we need powerful computers. And as computers evolve to become more powerful, we are able to do better and better. So we are able to — under some simplifications, we are able to produce galaxies like the Milky Way without getting into the details of how the stars formed on the small scales. So there are gaps in our understanding right now, but as computers get better, these gaps narrow and a more consistent picture emerges. There is no crisis at the moment between what the computer simulations produce and what observers are telling us.

And then the second approach is to observe the sky and to compare observations to those theoretical predictions. And right now we can see galaxies all the way to when the universe was 500 million years old. So starting around that time to the present time, we see plenty of galaxies, and we can compare notes between the observers and the theories and see if there are any discrepancies. So that's an exciting process by which in a way — you know, I wrote a number of books on the first stars. So one way to think about the future comparison between data and theory is to say, well, I should be happy if there is agreement because then I don't need to revise my book in the next edition. But actually, I would be happier if there would be a discrepancy between theoretical expectations and observations because that would teach us something new. If there is agreement, we would not know anything new.

So, for example, in particle physics, the Large Hadron Collider recently, two years ago, confirmed the existence of the Higgs boson that was predicted 50 years earlier. And in a way, it's a triumph of physics that you get agreement, but then it's quite disappointing, because at the same time, it didn't reveal any new physics, and so we are back to where we were. And so the way physics makes progress is by anomalies, by something unexpected being discovered. So I very much hope that the observers will teach us something new.

*Dave Eicher:* But it's incredible though that although the details at a fairly fine level are yet to be worked out, as you said, we know the basic story now, which is astonishing.

*Abraham Loeb:* Yes.

*Dave Eicher:* I mean, isn't it incredible in this respect that we've learned in the last generation more than, you know, we had learned in count the number of previous centuries. I mean, this is a really special, magical time.

*Abraham Loeb:* It is remarkable. You know, whenever I hear the president of the United States give a State of the Union address, I wonder whether he, or hopefully in the future she, will make a statement about the state of the universe that surrounds the Union. Whenever we make a significant advance in our understanding of the universe, and such an advance was made, for example, recently, about the way that the universe expands. Astronomers realized that the expansion is not slowing down, but instead accelerating. Sort of like throwing a ball up in the air and seeing it move faster and faster as it goes away from you. And that is quite remarkable. Particle physicists expected the cosmological constant of the energy density of the vacuum to either be extremely large, much larger than would allow our universe to exist, by 120 orders of magnitude or they said, well, if it appears to be as small as required by astronomers, it should probably be zero.

But now when we see this accelerated expansion, it looks like it's not zero, and it's quite small, and that vacuum energy density, according to Einstein's theory of gravity, is causing the accelerated expansion. Einstein introduced the cosmological constant, or the vacuum energy density, because he thought back then that the universe is not expanding. So he wanted to have a term in his equations that counteracts the attractive effect of ordinary matter. And so he put a constant that gives a repulsive force that can in principle balance the attractive force of ordinary matter.

So the universe as the whole was the Milky Way back then. But then he realized that he was wrong, because a small perturbation, a small change in the matter of density would make it — would make such a universe unstable. It so happens that the universe has a cosmology constant, has a vacuum energy density that is small. We are expanding and the expansion is accelerating right now.

The expansion — most people that study the universe, most cosmologists, think that the universe also started with a phase of

accelerated expansion, called cosmic inflation. So we are realizing now that both at the very beginning there was accelerated expansion, that phase ended and then the standard expansion followed, where the universe was dominated by matter and radiation. And very recently, just when the universe was roughly half of its current age, the vacuum density started dominating, simply because the matter was diluted enough for the vacuum, who doesn't get diluted by the expansion, to show up and accelerate the universe expansion.

And that has enormous implications for the future because it means that if you think about any source of light that you're looking at outside of our galaxy, distant galaxies, they're being pulled away from us at the speed that keeps increasing. And so eventually, each of these distant galaxies will reach the speed of light relative to us, and even light will not be able to bridge the gap that is being opened between us and those distant galaxies.

So, for example, if you had a friend waving his hand or her hand or sending you a text message, eventually you won't be able to know about the whereabouts of that friend, because even light will not be able to propagate from the cellphone of that friend to you, simply because the friend is pulled away from you at a speed that exceeds the speed of light. This sounds a bit paradoxical because we know that nothing can move faster than light, but that's true locally. You know, if you consider the motion of the particle, then obviously, locally the particle cannot move faster than light.

But space itself can separate points at a speed, at an arbitrary speed, and the situation is similar to imagining ants on the surface of the balloon. So the ants can walk at a certain speed, and they are the analog of the particles of light and they propagate at the speed of light. So the ants walk at some speed on the surface of the balloon, but then if you blow the balloon fast enough, the ants will not be able to visit a significant fraction of the surface of the balloon. They will have a limited region on the surface that they can walk around. But since the balloon is expanding faster than their speed, they are very limited in terms of the region that they cover. And the ants can be separated from one another such that they will never see each other again or walk to each other again.

And this is exactly the same situation that we face as the universe is accelerating its expansion. Those distant galaxies will be separated from us faster than light propagates. And then that has important ramifications for the future of astronomy. And my conclusion from that, from studying that, and by the way, I should

say most of my colleagues, they are sort of down to Earth. They want testable predictions within their lifetime.

So they just want to think about the past, and I'm sort of unusual in that regard. I'm willing to think about the future because I'm very curious to understand what the standard model of cosmology — we have this amazing accomplishment of developing a standard model of cosmology, accurate to a few percent. What does it predict for the future? To me, it sounds like a very natural question, and I don't really care if people find it practical or not practical. I would like to know the answer.

And so I thought about this question, and I realized that, you know, once the universe will age by about a factor of 10 to 100, we won't be able to get information about distant galaxies. In fact, once it becomes a trillion years old, once the universe ages by a factor of 100, even the cosmic microwave background, the radiation left over from the Big Bang, will — right now it's in the radio, it's in the microwave wavelengths, so it has characteristic wavelengths of a couple of millimeters, a few millimeters. But because of the accelerated expansion of the universe, the wavelengths of the photon of a particle of light will be stretched — within a trillion years, will be stretched to be as large as the universe, as the horizon of the universe, 10 billion light-years across.

And so there would be no sense of thinking about the cosmic microwave background because even one photon will be stretched to cover the entire universe. You wouldn't be able to measure it, irrespective of how good of an instrument you're developing. There would be no trace of the Big Bang.

And so I was quite depressed to realize that because, well, obviously it means that we have to fund astronomy in the next few billion years, collect as much data as possible, because this data will not be accessible in the future. But you then realize that, for example, the books that I wrote, they will tell a story about the Big Bang, but nobody would be able to test this story to verify by looking at the sky. The sky would be completely dark, except for our own galaxy. And so nobody would be able to test the story of cosmology, of the Big Bang.

*Dave Eicher:*

We're really living in the golden age of cosmology now because of the interstitial expansion of space. Ultimately, we will know nothing but remains of our own galaxy, plus Andromeda.

*Abraham Loeb:* That's exactly right. There will be no evidence of the Big Bang. We will have at our possession — I mean, future generations will have at their possession books that tell a story, but they won't be able to verify the story observationally. And the situation is similar to cosmology becoming a religion —

*Dave Eicher:* A faith.

*Abraham Loeb:* A story being told in books, without any ability to test it, verify it. So that's a depressing thought. However, every now and then we have a very major snowstorm in New England during the winters, and actually this winter it was quite frequent.

*Dave Eicher:* Oh, boy, yes.

*Abraham Loeb:* And I love these storms because Harvard is closed, I have no interruption, all of my appointments are canceled. I have a lot of time that I can allocate to myself to thinking about these problems. So in one of these snowstorms, I realized that, you know, even a trillion years from now, it will be possible to do cosmology, and the reason is, well, first of all, most of the stars are not like the Sun. Most of the stars in the Milky Way are lower-mass stars, and a star that is, for example, a tenth of the mass of the Sun, 10 percent of the mass of the Sun, has a lifetime of 7 trillion years. So the Sun right now is roughly at the middle of its life. It has about 5 to 7 billion years to go. And a star that is a tenth of the mass of the Sun will live for 7 trillion years. So it has a thousand times more time left than the Sun does.

And these stars will still be shining a trillion years from now, and it so happens that the Milky Way is ejecting one star every 100,000 years from its center, from the vicinity of the black hole at the center of the galaxy. And if this process continues, then we will have these stars ejected from the Milky Way, and once they are far away from the Milky Way, the cosmic acceleration will take over and will carry them at an ever-increasing speed. So future astronomers, a trillion years from now, would be able to watch these stars and see them accelerating, just like Hubble, Edwin Hubble, looked at distant galaxies and inferred the expansion of the universe. The same will be possible a trillion years from now. You could look at these stars that are escaping from the Milky Way and do cosmology with them.

*Dave Eicher:* Oh, that's an amazing realization. Wow.

*Abraham Loeb:* By the way, speaking about stars that escape from galaxies, a few months ago, we wrote a paper with a postdoc, James Guillochon, actually we wrote two papers, where we predicted a new population of stars that should be out there. These are stars that are ejected from the centers of galaxies by a pair of black holes. So when two galaxies come together, for example, the Milky Way and Andromeda will collide, they're on a collision course. When two such galaxies come together, the black holes at their centers make a pair. And this pair, when it becomes tight enough, can eject or accelerate stars, just like a slingshot.

And we calculated that this mechanism, this process, can produce stars moving almost at the speed of light. So there are stars in the universe that are moving through the universe at a speed that approaches the speed of light. This is quite remarkable. It would be fantastic to be on a planet close to such a star and go for the journey because you are not confined to one galaxy and you go through space in a spaceship that nature provided you with.

*Dave Eicher:* Wow, that's incredible. And it has to be a co-rotating binary black hole in a merger to produce this dynamical effect.

*Abraham Loeb:* Yes. In fact, not just a binary black hole system, but the expectation is that when you put a binary black hole, a pair of black holes in a sea of stars, that the pair of black holes tends to develop an eccentric orbit, where the two black holes get very close to each other and then farther away. And in such an eccentric orbit, stars that are bound to one of the black holes can get slingshot out of the system at very fast speed, up to the speed of light.

*Dave Eicher:* That's amazing.

*Abraham Loeb:* Yeah. So that's — these papers we just submitted a few months ago, and it's a new population of objects that can transmit information. So in principle, we can look for those stars in our neighborhood near the Milky Way. If we detect fast-moving stars with future telescopes, we — these stars may have come to us from the edge of the universe. So far, all of astronomy is based on photons, particles of light, detecting — using telescopes, detecting particles of light. Here you have a way of learning about distant forces by looking at a material object, a star that traversed a big chunk of the universe, a significant fraction of the universe, during the age of the universe. And so that opens a new window into cosmology.

But since we mentioned collision of galaxies, I should say that in the future, we would not stay within just the Milky Way Galaxy. As I mentioned, there is the Andromeda galaxy approaching us, and within two or three billion years, it will collide with the Milky Way.

*Dave Eicher:*

And for those who don't know, we've had a lot of press about this, because it's so intriguing, but you coined the term for the resulting galaxy merger Milkomeda.

*Abraham Loeb:*

Yes. In fact, I thought about trying to focus the collision dynamics between the Milky Way and Andromeda already when I was a postdoc at Princeton, around 1990, 1991, and I spoke about it with a postdoc that used to be — that used to make numerical simulations of galaxy mergers. That person told me that yes, he would like to work on it, but after a decade where he put it on his pile of to-do list but never attended to it, I realized that he's not really into this project. And then I met a postdoc in our group, T.J. Cox, that also did his Ph.D. on simulating galaxy mergers, and I suggested this project to him.

And so around 10 years ago, we started simulating the collision between the Milky Way and Andromeda, and we realized that the first passage of Andromeda will take place within 2 billion to 3 billion years from now, so that will be when the Sun is still shining, and potentially, there could be future astronomers in the solar system that would launch this process. It would be quite remarkable, because right now, Andromeda, the luminous part of Andromeda, is a relatively small smudge in the sky. Andromeda is just like the Milky Way. It's a disk galaxy, and it has roughly the same — within a factor of two — the same mass as the Milky Way. It's sort of the sister galaxy of the Milky Way, and it's approaching us at a speed of about 100 km/s. And it will come very close to us within 2 billion to 3 billion years. At that time, it will cover a fair chunk of the sky.

I remember visiting Australia, actually the island of Tasmania, near Australia, and usually in the evening, I'd check my email and check the papers, the new papers that appeared on the archive where all the astronomers post their papers. But when we got to this island, Tasmania, there was no Internet connectivity, and I had nothing better to do than to just walk out of the cabin and look at the sky. And it was quite remarkable, because there were no city lights, and I could see the Andromeda Galaxy, and I could imagine what it would be like when Andromeda approaches us because then the night sky will change completely. Eventually, the two

disks will mix together, stars in both disks will scatter, and the final product will be an elliptical galaxy. We see many elliptical galaxies, some of which resulted from collisions between spiral galaxies or disk galaxies. And so our night sky will look very different after this collision.

I should mention that even though Andromeda, the luminous part of Andromeda, looks quite small right now, when we look at it, the dark matter halo of Andromeda is huge. It actually covers almost half of the sky, if we could only see it. The two galaxies, the dark matter halos of the two galaxies are touching each other right now.

*Dave Eicher:* That's incredible.

*Abraham Loeb:* Yes, it's quite remarkable. But unfortunately, we can't see the dark matter. That's why we don't really know what it is.

*Dave Eicher:* Yeah. But we'll end up — is it fair to say, very approximately, we'll end up, for the amateur astronomers who are galaxy nuts, with something like a train wreck elliptical galaxy, and more or less in the mold of Centaurus A?

*Abraham Loeb:* Yeah. So this would be — there would be an intermediate phase, where, for example, the black holes that make a tear at the center of the galaxy, they might be fed with gas, get active galactic nucleus. Not as powerful as Centaurus A because our black holes are not very massive, and also this process will take place a few billion years from now, when the gas in both galaxies was mostly consumed already in making stars. If the collision would have taken place a few billion years in the past, then it would have resulted in much more activity at the center of the galaxy because there would have been more gas available to fuel the starbursts and to feed the black holes.

But then eventually, the center of the galaxy will quiet down and the galaxy as a whole will relax into an elliptical galaxy. And this will be the only galaxy that will be observable in the very distant future. We as astronomers will be able only to look at Milkomeda, the merger of the Milky Way and Andromeda, in the distant future. And by the way, this term Milkomeda that I mentioned, when we wrote the paper with T.J. Cox, we many times, on many occasions, we had to refer to the merger product of the Milky Way and Andromeda, so I was looking for an abbreviation to save space, and that's the name I came up with. I remember checking the Internet whether it has any other meaning or bad connotation, and I didn't find any.

*Dave Eicher:* Well, I think it's a term that's already beloved by amateur astronomers, astronomy enthusiasts everywhere. They love the concept. And the fact that Milkomeida eventually will become the entire universe, from a visibility standpoint, is quite an incredible thing.

*Abraham Loeb:* Yeah. In a way, if you think about it, in a way that's the kind of universe that Einstein thought of, that our galaxy is the entire universe. But that will turn out to be in the distant future our situation.

I should mention there are two other subjects that I'm mostly working on. One of them has to do with black holes. So, for example, I'm engaged right now in a project that is attempting to get an image of a black hole. When gas falls into a black hole, it shines. It keeps up and shines, and then the radiation that is emitted, the light that is emitted from behind the black hole, gets swallowed by the black hole. And so the black hole appears as a shadow on the wallpaper of shining gas, and in principle, one can go after imaging this shadow as a test for the existence of black holes, or event horizons around black holes.

*Dave Eicher:* But how does one achieve such incredible resolution to go after that from an imaging standpoint?

*Abraham Loeb:* That's right. So in fact, this is very challenging. There was a student who did his senior thesis back in 1965 with John Wheeler on the question of whether it's possible to image the shadow. And he concluded that it's not practical because you need to build a telescope as big as the Earth to do that. And then this student became a professor of physics and went on to work on something else. I actually contacted that professor and told him that he made the wrong career move because we currently can do that.

You might ask how can we build a telescope with an aperture as big as the Earth? The answer is using interferometry. You just place observatories at wavelengths of one millimeter across the globe, and you detect the electromagnetic radiation that is impinging on each of these telescopes, and you correlate it. And by that, you can in principle combine all these different observatories, as if they were part of a very large aperture, a telescope as big as the Earth. This is called very large baseline interferometry.

And if you do that at wavelengths of one millimeter, then if you calculate the resolution of the telescope with a size as big as the

Earth and a wavelength of one millimeter, you find that the resolution is tens of microarcseconds. So it's 100,000 times better than the resolution of an amateur astronomer telescope in the optical band. And at that resolution, one is able to image the shadow, the silhouette of the black hole at the center of the Milky Way galaxy, for example, Sagittarius A\*, which is the biggest one in the sky. So we are working on that.

The other very exciting project that we're working on with respect to black holes, for example, how does a star get shredded when it comes close to a black hole, like Sagittarius A\*. What will happen to the Sun? It turns out the Sun will become a filament of gas, sort of like spaghetti, when it comes within 10 times the horizon of the black hole at the center of the galaxy. And observers are finding evidence for these tidal disruption events. In fact, I actually gave a short talk on black holes at the class of my daughter, who is 9 years old, and I told the kids about the dangers of getting close to a black hole and the fact that you can get ripped apart and it's quite dangerous. At the end of the presentation, I asked them who would like to take a field trip to a black hole, and half of the class raised their hand.

*Dave Eicher:* Really?

*Abraham Loeb:* I was really surprised.

*Dave Eicher:* Wow.

*Abraham Loeb:* So I asked one of the boys, I said, "Why would you do that? I just explained that it's very dangerous." He said, "I would like to become spaghetti."

*[Laughter]*

*Abraham Loeb:* So for some reason, young kids and I guess the public as well, are fascinated with black holes.

*Dave Eicher:* Absolutely, absolutely. And maybe they also saw the movie *Interstellar* and thought that they'd survive, perhaps.

*Abraham Loeb:* Yeah, that might be possible. There is more to it. And there are many other interesting topics on black holes. It's also of interest to physicists because it represents break down of Einstein's theory of gravity, where quantum mechanics must play a role. And we don't have a theory that unifies quantum mechanics and gravity. So I

think the study of black holes will continue to be fascinating for the public and for physicists alike in the coming years.

Another subject, in fact, the subject that I think is the most exciting, the most interesting in astrophysics, is whether we are alone. Are we alone or is the universe teeming with life? Everything that I spoke about before in this conversation has to do with lifeless objects. So when cosmologists talk about the universe, about galaxies, they often think about those galaxies, those stars as lifeless objects that have no life, that life had no significance in shaping the way we see the universe. But in reality, it may well be that the universe is teeming with life.

We could be on the verge of a Copernican revolution, where we would realize, just like Copernicus realized that, you know, the Sun is not moving around the Earth, that we are not at the center of the solar system, we might realize that we are not at the center of the biological universe, that in fact we are not special in any sense. And life is everywhere, and the reason it may happen is because life doesn't produce a lot of energy. It's very difficult to see evidence for life. Last summer, I tried to calculate what would happen if you had a nuclear war on a planet, how easy would it be for us, for astronomers to see it, using our best telescopes. Turns out, it would not be observable. It's extremely difficult to detect this signal. With the best telescopes we have, we can't do it, even for the nearest star. And so we are talking here about full-fledged nuclear war. So obviously, primitive life, or even intelligent life that is not particularly hostile or particularly bright, obviously may exist without us noticing it.

*Dave Eicher:* Well, because the cosmic distance scale is so incredibly large, even to the nearest stars.

*Abraham Loeb:* That's right.

*Dave Eicher:* The inverse square law's in effect, and even if they're at least something on the order of 10,000 billion, billion star systems in the universe, and maybe much more than that, you know, I mean, the odds of us being the only life are pretty absurd.

*Abraham Loeb:* Yes. Given all the planets which were found recently, we can calibrate how many planets should be out there, how many habitable planets should be out there. Turns out there are more habitable planets in the observable universe than there are grains of sand on all beaches on Earth. And if you think about emperors or kings that in the past used to get an ego boost by conquering a

piece of land on Earth, the situation is similar to an ant hugging a grain of sand on a huge beach and being very proud of itself.

I mean, obviously, we are insignificant in this big picture, and the practical question is how to find evidence for life. And I wrote one paper in which I showed that even a city like Tokyo could be visible all the way to the edge of the solar system with a modern telescope. So one possible way to look for a spaceship or intelligent life is to look for light, artificial light, coming to us. We can do that out to the edge of the solar system.

But beyond that, the way to do it is by looking for planets that are transiting in front of their parent star, and when they transit in front of it, a fraction of the light from the star passes through the atmosphere of the planet, if it has an atmosphere. And we can look for the fingerprints, the spectroscopic traces of the molecules that provide evidence for life, such as oxygen or methane. Oxygen, for example, would disappear from the atmosphere of the Earth within a million years if there was no life on Earth. So we can do this, for example, with the James Webb Space Telescope. That would be a very interesting challenge to try and look for the fingerprint of oxygen in the atmospheres of habitable planets.

I also wrote a paper last summer about looking for industrial pollution. Just like one can search for oxygen molecules in the atmosphere of a planet, by the same token, one can look for more complex molecules, like those molecules that we produce artificially. And this would be evidence for an industrialized civilization, not just primitive forms of life. So there are plenty of opportunities for us to observe the existence of life in the distant future, with better and better telescopes.

*Dave Eicher:*

And of course, as the census of nearby exoplanets continues to explode, there will be more and more and more and more places to look for transits.

*Abraham Loeb:*

That's right. And we should also think of it as potential real estate for us, if we decide to expand beyond the solar system.

*Dave Eicher:*

Fantastic. Well, it's really incredible, and thank you for the time, Avi, today, to talk to you about all these things. And I think we could talk all day, you're involved in so many areas of research that we didn't even get to. But fascinating career that you have, and it's really been an honor to have you today in this series. I thank you very much for joining us, and we'll look forward to having you back, and also, of course, in print in the magazine, with

your contributions from time to time. It's great to talk to you, and good luck with everything that you're working on at Harvard.

*Abraham Loeb:* Thank you very much. It was my pleasure.