Lisa Randall. "One challenge today is to see what you can do with large amounts of data, to study fundamental properties, not just questions of how electromagnetism gives rise to certain things. Can we actually see deviations from what you would predict in conventional theories?" *Rami Shllush*

Understanding a warped cosmos

What's the connection between dinosaurs and dark matter? What is the glue that holds the universe together? Is there a fourth – and fifth – dimension? These are just some of the questions that occupy Lisa Randall, the first female physicist to get tenure at Princeton, Harvard and MIT

The CERN facility, near Geneva. "We need higher-energy machines and particle accelerators," says Randall, "but to really see new things, we need even more powerful machines." *Richard Juilliart/AFP*

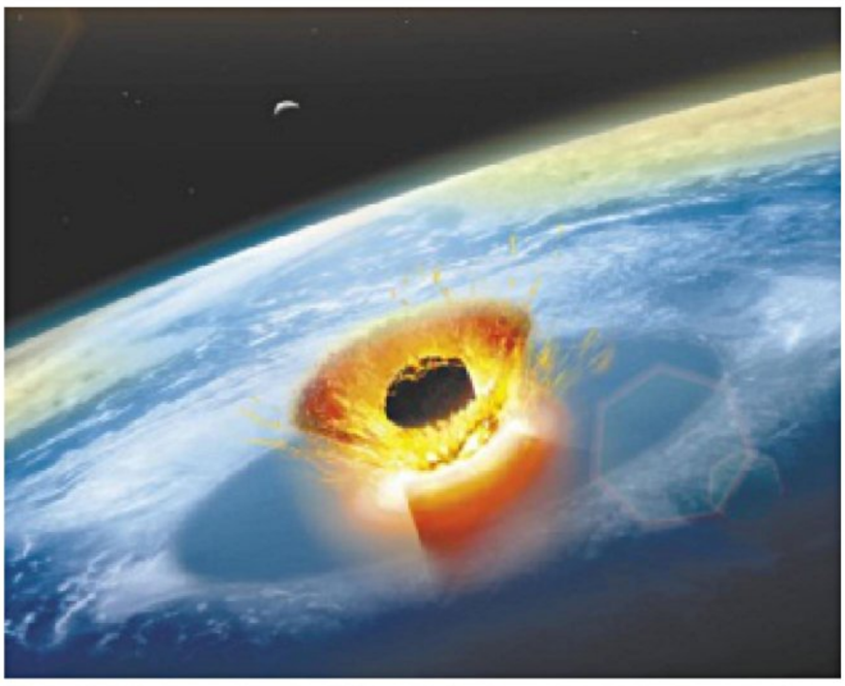


Illustration of a large asteroid colliding with Earth over the Yucatan Peninsula, in Mexico. The impact of such occurrences are thought to have led to the death of the dinosaurs some 65 million years ago. *Mark Garlick/Science Photo Libra*

Ido Efrati

The mystery of the universe, and the many riddles that remain open about it can be exemplified in a myriad ways. One of the most frustrating challenges involves the fact that science is familiar with less than five percent of the matter that makes up the universe. That paltry figure is what you get after adding up all the matter on Earth and outside it – including all the galaxies, solar systems, and such heavenly objects as asteroids, meteors, gas clouds and interstellar dust. Effectively, everything that's made of atoms.

The problem was that science could not explain empirical observations of the universe based on the matter and energies we know about. The baffling conclusion of centuries of observations and calculations is that the matter and energies that have been identified constitute, to be precise, just 4.9 percent of everything in the universe. So what else is out there, that we haven't seen?

Scientists call the mysterious 95.1 percent of whatever is making up the universe "dark matter" and "dark energy." It's called "dark" because it can't be seen, not in the form of celestial bodies or even dust clouds. Nor does it appear to interact with the particles we do know about, including light particles.

It is on dark matter that Prof. Lisa Randall, a physicist at Harvard University, hopes to shed light.

A day before Randall arrived in Israel, this past December, to participate in the annual conference of the Israel Physical Society, U.S. President Donald Trump forbade the Centers for Disease Control and Prevention, a U.S. public health agency, from using the terms "evidence-based" and "science-based" in budgetary documents. Randall opened her talk at the conference, which was held at the Technion – Israel Institute of Technology, in Haifa, on December 17, by saying, "It's nice to speak at a conference in a country where you can still use the word 'science.'"

Her barbed remark reflects the apprehension of many of her colleagues about the future of scientific research in the United States in light of the Trump administration's approach. In the meantime, though, Randall continues to occupy herself vigorously with the big questions of the universe, including, most recently, the nature of dark matter.

If less than five percent of what comprises the universe is even known to science, what can it say about the rest? Scientists estimate that some 26 percent of the universe is dark matter. The search for dark matter began in the 1970s. The idea of its very existence arose in an attempt to explain the speed at which galaxies rotate around their axes in the cosmos. The measurements, which didn't correspond to the known effects of gravity, led scientists to postulate the existence of additional matter, not visible to the eye or measuring devices, that exercised gravitational influence, and could in part explain the speeds that were calculated.

(In an uncanny coincidence, this week saw a dramatic development in the study of dark matter. In an article in the prestigious journal Nature, Prof. Rennan Barkana, head of the astronomy department at Tel Aviv University, described how the EDGES radio telescope in Australia had picked up a radio wave dating back to a much earlier period in the history of the universe. The signal serves as the first direct evidence of dark matter's ability to interact with regular materials. It provides new testimony about the mysterious period shortly after the universe came into being, a period described as the era of "the cosmic dawn," meaning the period when the first stars were formed, some 200 million years after the Big Bang (which, according to current understanding, took place about 13.8 billion years ago). The findings are still preliminary, and require extensive analysis, but if they can be confirmed, they can be seen as evidence that dark matter interacted in some way with hydrogen atoms, thus leading to the lowering of the temperature of the dark matter. Physicists responding to the article in nature suggested that the discovery could open a new direction into the study of dark matter and the universe.)

The remaining 69 percent of the "explanation" for the observed behavior of the universe is the postulation that there is some sort of energy out there that researchers called "dark energy."

This force did not enter the theoretical picture until the end of the 1990s, on the basis of surprising observations of supernova events (the explosion of stars), which revealed that the universe is not only expanding and spreading, but is constantly accelerating the speed with which it does so. (The assumption had been that the expansion was decelerating, because of the effects of gravity.) The basic argument for the existence of dark energy is that there must be a hidden force that is pushing the galaxies away from one another.

When I met Randall, the Frank B. Baird, Jr. Professor of Science at Harvard, I asked why she chose to focus her physics research on dark matter. Our interview took place at the Dan Carmel Hotel, in Haifa.

"I think that dark matter is just at a very interesting juncture right now, because we know it's there, but we don't know what it is. And, depending on what it is, there can be different ways to look for it. My research is being conducted in areas that others haven't looked at."

But are you certain that it exists?

"I would say yes. There are many different pieces of evidence that point to its existence. We see how stars move in our galaxy; we see how galaxies move in galaxy clusters. We also see evidence in cosmic microwave background radiation, left over from the earliest moments of the universe." (Randall is referring to radiation that is a kind of remnant of the Big Bang, the event that brought the universe into being nearly 14 billion years ago. The radiation is an artifact that serves as something like a photograph of the state of the universe at its genesis, and its existence is one of the proofs that the Big Bang occurred.)

"In contrast to dark energy, dark matter is, after all, matter, which means it can interact, it can clump differently, it could take on certain shapes and sizes and exist in different concentrations in galaxies. So there's a lot of research to be done – to figure out what we can really predict from these models, and understand what we hope to see.

"People often ask me, 'You haven't seen it, so how do you know it's there?'" Randall says, in response to which she usually compares the investigation of dark matter to an unidentified celebrity who comes to town for a visit. "You know that a celebrity is there because you see people gathering around, and there are cameras, but you don't necessarily know who it is. It's the same with dark matter: We see its gravitational effects on other matter, on visible matter, so we know it's there, but we're still trying to figure out what it is."

Falling stars

In her Technion lecture, Randall explained that the existence of dark matter was first postulated on the basis of the rotational speed of stars in our galaxy. In certain cases, she said, the motion of the stars in their orbits is so rapid that, without hypothesizing the existence of dark matter – that is, without the existence of a gravitational force in addition to that of regular matter – we would expect these stars to lurch out of those orbits. Today it's clear that without dark matter, galaxies and galaxy clusters would not even have come into being.

Over the years, studies have mapped the presence of dark matter in various places in the universe, including in the center of our galaxy, the Milky Way. In her most recent book, "Dark Matter and the Dinosaurs: The Astounding Interconnectedness of the Universe" (HarperCollins, 2015), Randall takes dark matter and its possible effects one step further, linking its presence in our solar system with the extinction of nearly all of the dinosaurs some 66 million years ago.

The unusual connection between dark matter and dinosaurs proved irresistibly intriguing on the lecture circuit and TV talk shows. Her research on this subject began with a survey of all the known craters on Earth with a diameter of more than 20 kilometers and which are no more than 250 million years old. There are 26 such monster craters, all created, according to the geological evidence, by large objects that slammed into the planet. Randall found a consistent cyclicality in the formation of the craters, with a new one having appeared approximately every 30 million years. The reason for this recurring cycle, she argues, is to be found in the cyclicality of the solar system's circumnavigation of the Milky Way – once every 30 million years.

'I believe there's life on other planets. I don't believe we'll find it or know about it, necessarily, but I do think it's there. Every time we've decided we're unique or that we're the center, we've been wrong. I don't see why we should be the only example of anything.'

The cyclical blow to Earth is related to two phenomena, Randall believes. One is a familiar concept from space research known as the "Oort cloud." . The second is Randall's theory of the existence of the "double-disk dark matter."

The Oort cloud, named for the 20th-century Dutch astronomer Jan Oort, is thought to consist of billions of blocs of ice that are the source of many of the meteors, the long-tailed icy bodies that look like falling stars as they hurtle across the galaxy.

Randall's double-disk dark matter is postulated to be a large expanse of dark matter in the center of the Milky Way galaxy that possesses immense gravitational attraction. According to her theory, once every 30 million years – that is, once during the solar system's orbital cycle around the galaxy – a situation forms in which the gravitational pull of the dark matter disk causes large meteors to be "wrenched" from the Oort cloud, some of which then proceed to collide with Earth. That, Randall says, is the "season" in which the large craters are created.

One such crater, called Chicxulub, which was discovered in the 1970s by employees of the Mexican oil company Pemex, on the edge of the Yucatan Peninsula, was studied and dated. The crater was created by an impact with Earth very close to the time of the great dinosaur die-off, Randall says.

Fourth dimension

Lisa Randall was born in Queens, New York, in 1962, the second of three children, to a father who was a salesman and a mother who was a primary school teacher. Her impressive memory and interest in mathematics were evident from an early age. She attended the prestigious, public Stuyvesant High School in Manhattan, which specializes in the sciences. In a 2016 interview with The New Yorker, she related that in her teens she had frequent confrontations with her mother, who was reluctant to let her leave for school before dawn so she could arrive in time for the early-morning meetings of the school's math team, of which she was captain (the first girl to serve in that capacity).

At age 17, Lisa finished first in the prestigious Westinghouse Science Talent Search (as it was then known), a nationwide science competition for high-school seniors.

She entered Harvard in 1980, and by 1987 had obtained a doctoral degree in particle physics there. She was the first woman to receive tenure in the physics department of Princeton University and the first female, tenured theoretical physicist at Harvard. She also served as a tenured professor at MIT.

Her research deals with diverse aspects of theoretical physics and with the study of the universe (cosmology), covering the gamut from elementary particles – the minuscule, basic matter of which the materials of the universe are constituted – to understanding space itself.

The "standard model" of particle physics, formulated in the 1970s, describes the structure of matter on a small scale. The model refers to the reciprocal relations between the different atomic particles, which are divided into particles called "bosons," which carry the forces that act on matter, and "fermions," from which all the particles of matter are made, along with the forces that act on them. The model, which describes the basic interactions in nature, contains three forces: They are known as the "strong nuclear force," the "weak nuclear force" and the "electromagnetic force."

According to Prof. Yael Shadmi, a theoretical physicist at the Technion, who has worked with Randall, "As of today, we have a beautiful theory called the 'standard model,' which describes all visible matter and its interactions, with the exception of gravity, in terms of a very small number of elementary particles. We understand the strong, weak and electromagnetic forces as stemming from symmetries. The weak force is related to broken symmetry."

Shadmi: "The Higgs boson, which was discovered in 2012, is responsible for this symmetry breaking, and its mass determines the strength of the weak force. But there are fundamental problems with the theory – in addition to the fact that it doesn't explain dark matter. Randall investigated various extensions of the standard model in order to contend with these problems. One of the major questions they raise relates to the strength of the weak force. The weak force is many times stronger than gravitation, and we have no explanation for this hierarchy."

Randall's best-known research work – a theoretical model she developed with the physicist Raman Sundrum, known as the "Randall-Sundrum model," and published in 1999 – hypothesized that a hierarchy of this kind is created because space actually possesses four dimensions. The extra, fourth, dimension is warped, and is responsible for the vast difference between the weak force and gravitation.

"The Randall-Sundrum model is one of the most influential works in particle physics, and has important theoretical implications. A great many other works were published in its wake," Shadmi says.

It's difficult to explain the model in plain language – or, for that matter, in complex language. Generally speaking, it describes a world in which another dimension exists (a fourth, or a fifth, if the time dimension is included), which generates spatial warping and non-uniformity. Its existence, though, can explain at least some of the problems and contradictions that engage physicists as they try to describe regularity in nature's behavior with different criteria.

"The extra dimension is very small," Shadmi says. "It's like a narrow pipe which, if looked at from afar, will appear to be a thread; we will not see its thickness. But an ant that walks along the pipe sees that it also possesses circumference. The warped character of the extra dimension can be likened to a pipe whose thickness changes. If you were to walk along the pipe you would see different scales of energy. The Higgs is located at the far end of the pipe, where the energy scale is lowest. That's what creates the large differential between the basic energy scale, which is characteristic of gravitation, and the Higgs mass, which determines the weak force. It sounds very abstract, but the extra dimension has measurable implications."

The model stirred considerable interest in the scientific community and served as a catapult for Randall's reputation and career. Between 1999 and 2004, she was the most quoted scientist in articles about theoretical physics; in 2007, she was included in Time magazine's list of the 100 most influential people in the category of scientists and thinkers.

We are barely getting along with the four existing dimensions, and you had to add yet another dimension. How do you arrive at these kinds of ideas and conclusions?

Randall: "That's the great thing about doing physics: You can think in ways that allow for a fifth dimension. It's not obvious that it's there. In this case, it could be particles that carry momentum in another dimension."

Momentum is defined as mass multiplied by speed, and it expresses the intensity of motion of a particular body or particle. What Randall is referring to is that the extra dimension might be

'Dark matter is, after all, matter, which means it can interact, it can clump differently, it could take on certain shapes and sizes and exist in different concentrations in galaxies. So there's a lot of research to be done – to figure out what we can really predict from these models, and understand what we hope to see.'

manifested in the existence – alongside the familiar particles, such as the electron – of another whole family of particles with greater masses, which impart to the fifth-dimension particles their power.

She continues: "The challenging question for a physicist is to identify the subtle clues that indicate the existence of this type of matter, which we never anticipated. And that to me is very interesting."

A man's world

What Randall and her colleagues are looking for in this case are singular particles that look and interact like typical particles, but are heavier. "We haven't seen them yet, because we haven't yet achieved high enough energy to produce these particles," she notes. "But maybe at the Large Hadron Collider [at CERN, the European Organization for Nuclear Research, in Switzerland], or a machine like it, we will be able to reach the energy where you can see these things."

In addition to being a research scientist, Randall is a successful author of popular books on science. Her books "Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions" (2005) and "Knocking on Heaven's Door: How Physics and Scientific Thinking Illuminate the Universe and the Modern World" (2011) both made the New York Times list of notable books of the year. "Warped Passages" also served as the basis for the libretto wrote for the opera "Hypermusic Prologue: A Projective Opera in Seven Planes," with music by Spanish composer Spaniard Hèctor Parra.

How do you go about writing books of popular science about such complex subjects? I don't even know how I will be able to make our conversation accessible to readers of Haaretz.

"It's a lot of work, to be honest; I mean, it takes years. Honestly, I sometimes look back and think, 'How did I do that?' But I guess there are a few reasons I want to do it. One is that it is very easy to look at books and say, 'I don't like the way this is written.' But I thought, 'Can I actually do it better?' I wanted to write books for people who really want to understand what's going on. Many science books are a little condescending, or they talk very authoritatively but don't actually let you know why we're asking what we're asking or what we're doing.

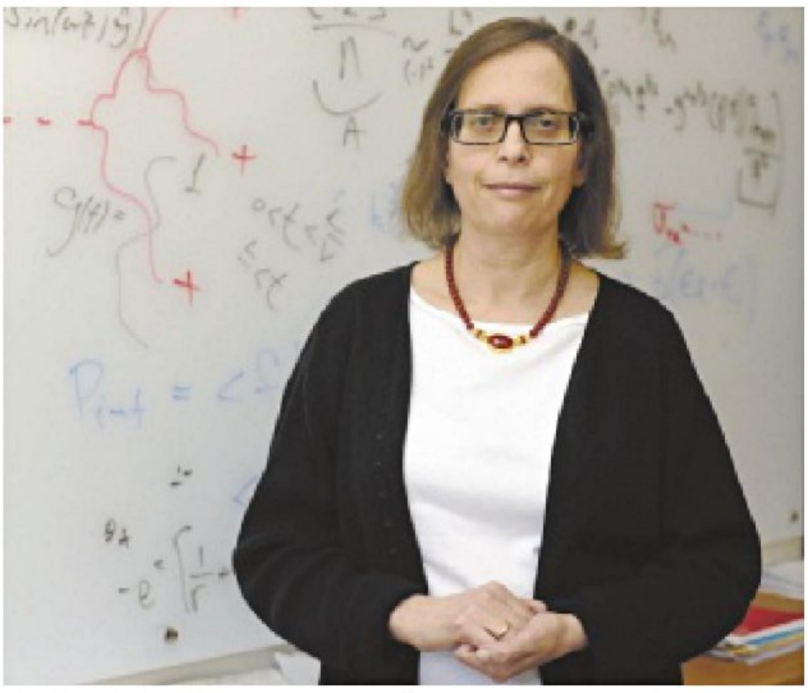
"It was fun for me to think creatively about how I can explain these ideas and tie them together in different ways, and come up with different analogies. In each book I wanted to say something a little bit different, too, about how we do science. Especially in the United States, where there is so much confusion about what science is and how it works."

Her latest book, "Dark Matter and the Dinosaurs," she explains, "is about the question of how we got to where we are. I wanted to tie together the evolution of the universe, the evolution of the galaxy, the evolution of our solar system, and even life. This was a good opportunity for doing that. It's not just making sure people can understand the ideas, but also making them want to read about them."

These days, however, says Randall, she is not working on a new book, but rather is focusing on her research.

The prevailing feeling in many circles is that we are in a new and exciting era of cosmology, witnessing a milestone in the technological developments in these realms. In 2012, physicists finally succeeded in identifying the Higgs boson, the particle whose existence had been predicted half a century earlier, in the LHC particle accelerator at CERN. Since 2015, the existence of the gravitational waves postulated by Albert Einstein a century earlier has been verified by means of specially designated facilities possessing unfathomable sensitivity, in the United States and Europe. Science has greatly developed its ability to observe the depths of the universe and to analyze behaviors and traits of objects, planets and various phenomena. Within a short time, a list has been formed of more than 5,000 planets that possess features similar to those of Earth.

Have we reached the stage where science has the technologies that will allow it to confirm or refute different theories about the universe? Is this the era of answers to the basic questions about the universe?



Yael Shadmi, of the Technion. "The extra dimension has measurable implications."
Rami Shllush

"The answer is yes and no. The launch of the Large Hadron Collider and the discovery of the Higgs boson were magnificent. The discovery of gravitation waves is fantastic. But those theories had been around for 50 years and more. What's different today, I think, is that data processing is improving, which means that, if before we were always looking for clean, precise measurements – which are still absolutely important – one of the challenges today is to see what you can do with large amounts of data, to study fundamental properties, not just questions of how electromagnetism gives rise to certain things. Can we actually see deviations from what you would predict in conventional theories? So a lot of my research today is devoted to that kind of question.

"In regard to the discovery of new particles, I think we need higher-energy machines and particle accelerators. Some things are improving all the time, like precision measurements. But to really see new things we need even more powerful machines. There are constant new developments, but we might have to wait [longer] for those that will be most meaningful."

What is the greatest challenge in cosmology today?

"The challenge is to figure out which are the best research opportunities. Theoretically, we can make progress on many fronts, but the question is where we can make progress both in understanding and in verifying. We have finite resources, so how do you best dedicate them to really making progress?"

How much of a role does technological ability play here?

"There's definitely a sense that we're close, but there's a big difference between being close and reaching the goal. As a theorist, I'm not conducting experiments. The best I can do is say, 'This is the way things are. Are there things that we're missing? Are there ways that we can interpret the data so that we can learn more than we thought we could?' That's how the discovery about gravitational waves was finally made, but it took 50 years. We could do the same for particle physics: talk about what we'd like to see in the future, but at the same time talk about what information we can extract from the measurements we already have. It's a combination of those two: how to disperse our research resources optimally, but also how to analyze the existing information and learn more."

If resources were unlimited, would we be able to get all the answers to the big questions about the universe and the emergence of life on our planet, or are there other objective – human – limitations?

"There are definitely ways in which we could make progress if we had infinite resources. Would we be able to answer all the questions? I don't have an answer to that."

Do you believe that intelligent life exists elsewhere, too?

"Yes. I believe there's life on other planets. I don't believe we'll find it or know about it, necessarily, but I do think it's there. Every time we've decided we're unique or that we're the center, we've been wrong. I don't see why we should be the only example of anything. But that doesn't mean we have access to it."

It's impossible not to refer to the gender issue in your case. You're the first female physicist to be tenured at three top universities, and that's a detail that's always mentioned in connection with your activities. Why are there so few women in theoretical physics, and what does that tell us about the status of women in this area?

"It's a good question. It's hard to imagine that in the best of all possible worlds, the imbalance would be so great. But it's also hard to say it's due to any one particular thing. I do think that we tend to give guys the benefit of the doubt a lot more than we give women. I mean, we've seen this in politics. No woman could say things as stupid as Donald Trump said and be elected. We don't realize it, but there are many subtle effects going on. I think people judge men and women differently without realizing it. In conferences I attend, most of the participants are men. I mean, there are a few more women than there used to be, but it's not progressing as quickly as you might think it would."

Why is that, do you think?

"There are major, fundamental differences all through society in the way men and women are treated, and I think that just filters down. So there aren't many women in theoretical physics. Even if there are some specific problems that might exist in this regard, I think it's part of a larger cultural issue that needs to be addressed. I have to say that one of the reasons I've written popular books is to show what women, as well as men, have done in the field."

Do you think that women with your standing should work to change the situation?

"No. I think we should be allowed to do whatever we want, because it's so hard to do physics in the first place. The best thing is to do physics the best I know how, and to write good books. I don't think there should be any extra demands on women."