Delta
Institute for Theoretical Physics

From string to universe

by the creators of
NewScientist

contents

The Dutch school

Being a theoretical physicist is such a great job! You can work on the big bang or quantum computers, on black holes or superconductors, on elementary particles or emergent phenomena of trillions of particles. What binds us all is the language of mathematics, which we use to understand and predict nature. The connection with experimentation is, of course, very important because to measure is to know. Still, nothing is more practical than a good theory!

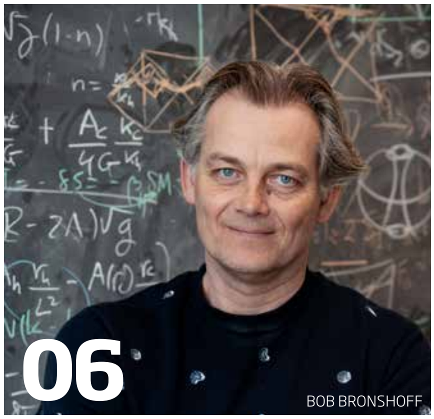
For more than a century, the Netherlands has had a rock-solid tradition in theoretical physics, counting numerous Nobel Prize winners and scientists of world-wide renown. To this day, one can rightly speak of a 'Dutch school'. No wonder the Delta Institute for Theoretical Physics (Delta ITP) was granted funding in the first call of the prestigious NWO Gravity programme ten years ago.

Delta ITP brings together theoretical physicists from the universities of Amsterdam, Leiden, and Utrecht in one large consortium, with the aim of solving major physics problems and making an impact on society. As Delta ITP, we also collectively attract new staff members, and numerous young PhD students and postdocs from around the world. Major challenges are formulated and divided into the three major Delta ITP themes: cosmological matter, quantum matter, and topological matter. You can read about what we have accomplished regarding these themes in this magazine, which includes several great interviews with Delta ITP people, retrospectives, and previews.

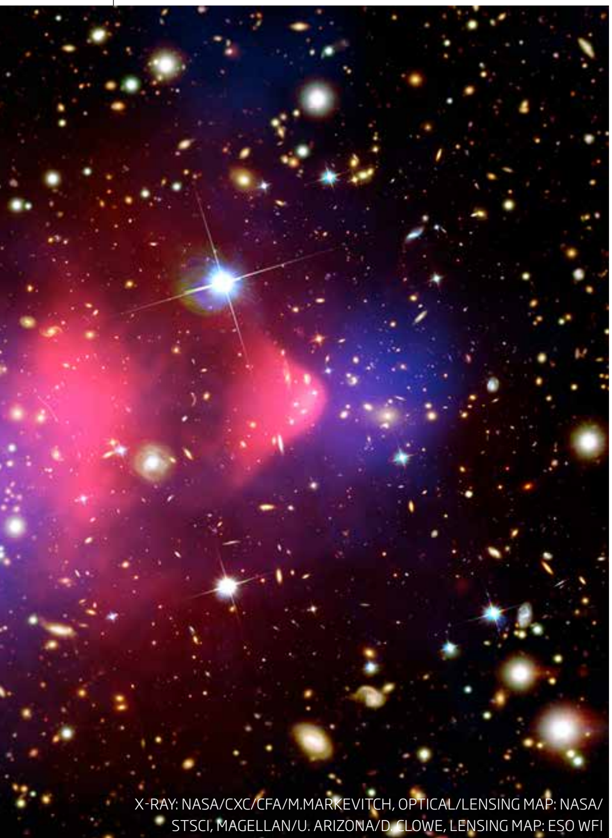
The past ten years have been a wonderful time for Delta ITP. We are now getting ready for a new decade full of great collaborations and hopefully with exciting new discoveries!

Stefan Vandoren
professor of theoretical physics and head of the physics department at Utrecht University, and member of the Delta ITP Supervisory Board

MAAIKE PUTMAN



BOB BRONSHOFF



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BRAM BELLONI

COVER ILLUSTRATION: MANSFIELD & DIEMER **EDITING:** PASCAL TIEMAN

COLOPHON

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Focus

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UP CLOSE

A bridge to the frontier

The Delta Institute for Theoretical Physics – Delta ITP – brings together theoretical physicists from the University of Amsterdam, Leiden University, and Utrecht University. Leiden string theorist Koenraad Schalm reflects on how this collaboration is paying off. 'Because of the enormous achievements of physics in the twentieth century, the level at which research takes place is often quite a bit higher than the level at which you graduate as a physics student. An important part of Delta ITP is teaching joint courses to students from all three universities. These courses bridge the gap between the lecture hall and the research frontier.

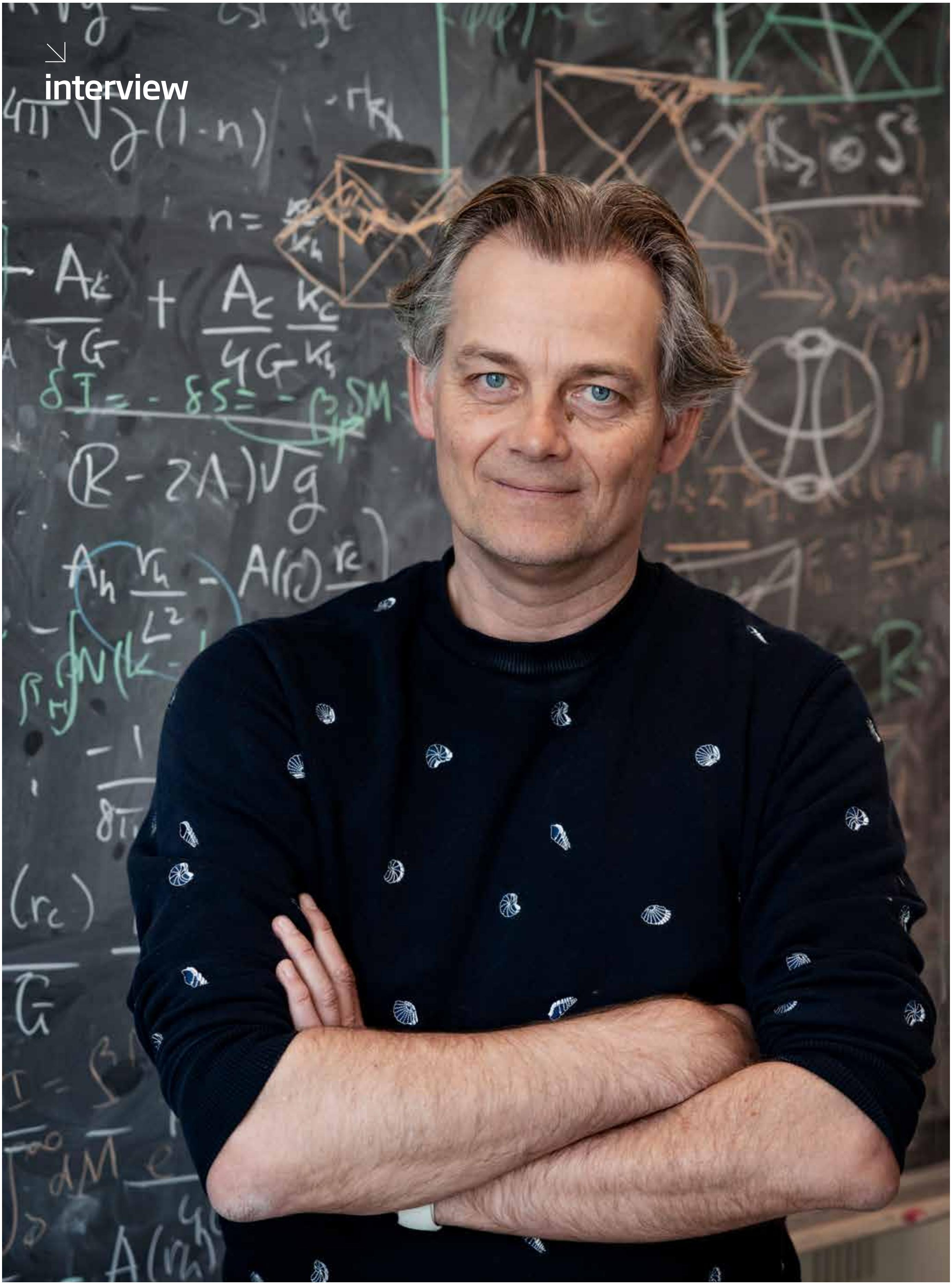
This frontier is not imposed from above. The research questions in a fundamental science institute come from the researchers themselves. What makes an institute flourish is creating an environment in which the interesting questions can be asked. That is the real success of Delta ITP.

I am proud of the fact that, as a small country, we are among the world's best because we have created an environment in which it is easy to work together. Our so-called triangle meetings – meetings between the three institutes focused on a specific topic – are a great example of this collaboration. During these meetings, there is plenty of time for free discussion with confrères. That is when the ideas are born. Theoretical physics is not sitting in your attic room à la Einstein; on the contrary, it is a very social profession. You are only in that little attic room when you are working out the details of your ideas.

What does the future of Delta ITP look like? I don't rule out further expansion, although the geography of the Netherlands would be a challenge. Part of Delta ITP's strength is physical meetings, and because Utrecht, Amsterdam, and Leiden are so close to each other, we have been able to make them happen. On the other hand, the triangle meetings are such a success that colleagues from Groningen and Leuven also participate.'

Text: Wouter Schreuder

MAAIKE PUTMAN



‘Theoretical physics is a team sport’

String theorist and cosmologist **Jan Pieter van der Schaar** is coordinator of the Delta Institute for Theoretical Physics. Responding to eleven keywords, he talks about his roots, work, and dreams.

Text: Jim Jansen
Photos: Bob Bronshoff

Physics
‘I first read about astronomy in primary school. I don’t remember exactly what it was about, but it did get me interested in the subject. A few years later, I built my own telescope. Then, of course, I wanted to study astronomy, and in Groningen that programme was combined with physics. In the end, I liked the latter field much more, because I was interested in the theoretical aspect, among other things. I got my PhD in string theory – very abstract and formal. When I went abroad after my PhD, I got involved in cosmology. And that’s how I came back to astronomy.’

Dreams (1)
‘When I was young, I wanted to be a professional tennis player, but that didn’t work out. I came from Heerenveen, a Frisian village that people call a city. I found that its small size became tedious and the universe was pretty much the opposite of Heerenveen. I wanted to know a lot more about that.’

Delta ITP
‘We safeguard the unity of theoretical physics. In the Netherlands, we have a long tradition in this branch of science, and we are also very good at it, which has to do with a combination of creativity and robustness. The Delta Institute for Theoretical Physics – Delta ITP – is actually unrelated to the funding we received for the institute in 2012. For many years, there had been an idea that the universities of Leiden, Utrecht, and Amsterdam should collaborate much more in this area. Theoretical physics seems a lonely profession because the field is often in the news when a single person has won an award. But make no mistake. It’s a team sport and you can only make progress when collective foundations are laid. Exchange and collaboration are incredibly important.’

Gravitation grant
‘We received 18 million euros, a wonderful amount. We didn’t have to buy expensive equipment and spent hardly anything on overhead, so all that money went to research, often in the form of new research positions, both temporary and permanent. An intensive investment in people, i.e. knowledge. Without the grant, we wouldn’t have been able to do that.’

Cities
‘Amsterdam is a fairly new player within theoretical physics; Sander Bais and Robbert Dijkgraaf have ushered in a period of growth. In twenty years, the Institute for Theoretical Physics at the University of Amsterdam has become the largest and perhaps best group in Europe. Here, we excel at string theory and quantum matter. Utrecht can be seen as the home of Gerard ’t Hooft; a historical place where the focus is on the fundamental questions. Utrecht traditionally focused on the more formal aspects of theoretical physics, but researchers there now also deal with cosmology, gravitational waves, and sustainable materials. Leiden has the Lorentz Institute for theoretical physics, where Albert Einstein was a frequent guest

as an endowed professor. Need I say more? Leiden is different from the other cities; there is a natural collaboration of theoretical physics with astronomy and experimental physics.'

'In a way, I'm following in Stephen Hawking's footsteps'

Stronger together
'Delta ITP is a way to raise our profile as a collective, and I think we have succeeded in showing that the institute is more than just a collaboration between three cities. Internationally, we have put ourselves on the map, in part by establishing exceptional fellowships. These are three-year projects for very good people; postdocs to whom we gave extra money with which they could do whatever they wanted. You couldn't apply; we made a selection. In the end, we linked up with twelve people. They may now call themselves Delta Fellows. Looking back, they all became very successful, which I'm genuinely proud of.'

Einstein
'Every theoretical physicist sooner or later refers to Einstein. At Delta ITP, we focus on topics appropriate to the three institutes. Here in Amsterdam, for example, we do a lot of string theory, and at its core that is about one thing: we want to know what the quantum version is of the general theory of relativity. That's a direct legacy of Einstein.'

Research
'My research focuses on how the universe came into being and the connection to string theory. As a theory of quantum gravity, string theory should play an important role in the extremely early universe. Developments in the field of black holes are also something I keep a close eye on because they can provide a bridge to the origins of the universe. In a way, I'm following in Stephen Hawking's footsteps.'

Curiosity
'I don't do research because it has useful applications, I do it to satisfy my own curiosity. That same curiosity drove people like Einstein and Newton. The applications of their work are taken full advantage of in 2022. Maybe in a hundred years, people will do the same with my findings.'

Manager
'I've had a strange career and am a bit of a jack-of-all-trades. For a while, I found that prohibitive, but things go the way they go. In 2005, I moved to Amsterdam where I was hired by Robbert Dijkgraaf. I ended up in mathematics, where I had no business being. Then I accepted a teaching job at Amsterdam University College. A year later, Delta ITP was started, and Jan de Boer called to ask if I was interested in that. At first, it was a matter of pioneering. It helped that I was able to project myself into the world of the researchers; something that a "regular" manager certainly couldn't have done. Because we had quite a lot of money available, I did feel like a bit of Santa Claus at times.'

Dreams (2)
'There are small dreams and big dreams. In the field of research, I would very much like to better understand de Sitter spacetime. Willem de Sitter was a Dutch astronomer and mathematician who worked in Groningen and Leiden. He was the first to find a solution to the general theory of relativity with a positive cosmological constant. This de Sitter solution describes an accelerating expansion of the universe that probably has properties similar to those of a black hole, with a cosmological horizon that emits Hawking radiation. If we understand how this works in string theory, I expect to learn a lot about the origin of the universe. Another dream is to sail around the world. It has nothing to do with my job, but it just seems like a lot of fun.' ■

CV

Jan Pieter van der Schaar (1972) graduated in theoretical physics from the University of Groningen in 1996 and received his PhD from the same university in 2000. After a postdoc position at the University of Michigan, a fellowship at CERN, and a year as a postdoc at Columbia University in New York, he has been part of the Institute for Theoretical Physics at the University of Amsterdam since 2005. He has been coordinating the Delta Institute for Theoretical Physics since 2013. His research focuses on the interface of cosmology and string theory. He is one of the leading scientists in the national cosmology programme.

BRAM BELLONI

CROWN JEWEL

‘Nature doesn’t know what infinity is’

‘When I was working on my dissertation, there were a lot of major questions in physics about elementary particles and the forces that work between them,’ says Gerard ‘t Hooft, professor of theoretical physics at Utrecht University. ‘It was a great time; every few years, there was a discovery that turned everything on its head.’

With his supervisor, Martinus Veltman, ’t Hooft worked on the rules of one of the forces: the weak interaction. ‘When used in calculation, the calculations were not convergent; outcomes were often infinities. But nature doesn’t know what infinity is, so that meant something was wrong.’ Working with Veltman, he found a solution, which earned the pair the Nobel Prize in Physics in 1999.

Now, elementary particles and their mutual forces are well described by the standard model of particle physics. ‘But we know this isn’t the whole story, because quantum mechanics, on which the standard model is based, doesn’t work well when you combine it with gravity, again resulting in infinities.’ This problem reared its head in the 1970s. ‘At the time, we thought we would solve this in about ten years as well. After all, that’s how it had been with particle physics. But by now we’re fifty years down the road.’

‘Some people think we’ll never figure it out. I don’t believe that. Just look at the history of our field. If we put our heads together, we can work the wrong ideas out of our system. Could it take thousands of years to find the right method? If it does, we’re not giving up. In a thousand years, I will come back with the answers.’

Text: Dorine Schenk

The big and the small of it

The Delta Institute for Theoretical Physics

Whether it is elementary particles, black holes or (quantum) matter, theoretical physics attempts to make sense of all of nature. What is a black hole made of? And how do you change the properties of materials? Following in the footsteps of physics giants such as Albert Einstein and Stephen Hawking, the Delta ITP consortium seeks to answer the most fundamental questions of our existence.

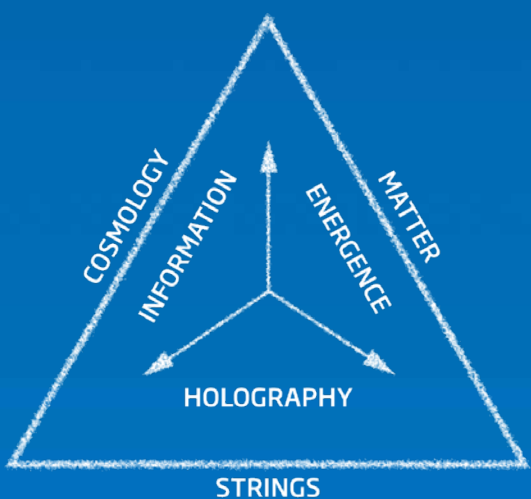
University of Amsterdam

The Lorentz Institute for theoretical physics in Leiden is one of the oldest physics institutes in the Netherlands and has an impressive track record. There, the full breadth of physics is studied, with figureheads such as quantum scientist Carlo Beenakker, cosmologist Ana Achúcarro, and superconductivity expert Jan Zaanen. The nearby Lorentz Center is the ideal venue for hosting workshops and conferences.

Leiden University

INFINITE SUBJECTS

The unique collaborations between the three participating institutes strengthen the unity of theoretical physics. After all, the main research themes – cosmology, matter, and strings – are sides of the same triangle. Within the Delta ITP consortium, the boundaries between physics disciplines are blurred, in order to get to the core of the matter..



DELTA ITP ACTIVITIES

PhD and postdoctoral research projects (41)
Delta Fellowships (12)
Guest researchers (over 100)
Symposia, conferences, and workshops (over 100)
Advanced Topics education courses (17)

TEXT: ELINE KRAAIJENVANGER
ILLUSTRATIONS: PASCAL TIEMAN

The Institute for Theoretical Physics in Amsterdam has quickly gained considerable prestige in Europe. The department is historically known for its pioneering research focussing on string theory and quantum matter. With help from Delta ITP, the department has been able to expand into the full breadth of theoretical physics, with big names like Erik Verlinde and Kareljan Schoutens, and up-and-coming talents like Miranda Cheng and Gianfranco Bertone among its ranks.

Utrecht University

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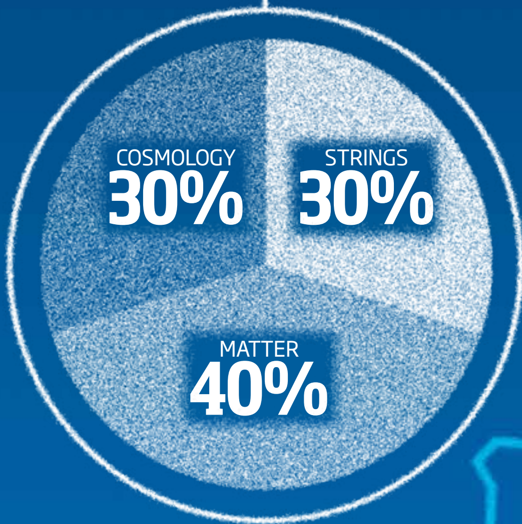
PERMANENT STAFF MEMBERS



Utrecht is the home of Nobel laureate Gerard 't Hooft. Traditionally, research here has focused on fundamental questions, but scientists now also study topics such as cosmology and (sustainable) materials. In addition to figureheads Cristiane de Morais Smith and René van Roij, the new generation – including Rembert Duine and Tanja Hinderer – is making considerable headway. The Advanced Topics education courses are organised from Utrecht.

120+

PHD'S AND POSTDOCTORAL RESEARCHERS

APPROXIMATELY

60%

HAVE A VIDI, VICI OR ERC SCHOLARSHIP

'If I can convince my brother, the rest of the world shouldn't be a problem'

Erik and **Herman Verlinde** on emergent gravity, the cycles of theoretical physics, the increasing number of connections with other fields, and the flood of new experiments. 'When we started, black holes were something very abstract. Now there are actual observations.'

Text: Bruno van Wayenburg

The Verlinde twins are well familiar in Dutch physics. Erik and Herman were born in Woudenberg on 21 January 1962 and shared their interest in the field at an early age. As students and later PhD students under Utrecht professor Gerard 't Hooft, they formed a close-knit club with Robbert Dijkgraaf – currently Minister of Education, Culture, and Science – discussing and focussing on string theory.
Herman Verlinde is now a professor at Princeton University in the United States. Erik Verlinde is a professor at the University of Amsterdam and chair of Delta ITP's Board of Directors. In 2009, he launched a theory of gravity in which thermodynamics, quantum mechanics, and gravity are intertwined in a fundamental way: emergent gravity, based on both the twins' ideas.

Your sparring partner Robbert Dijkgraaf has joined the Cabinet as Minister of Education, Culture, and Science.
Herman Verlinde: 'It happened very quickly, of course, but I thought it was a natural step. He is someone who studies the issues in question from all sides. He was also nearing the end of his time as director of the Institute for Advanced Study, here at Princeton. And he has always remained very involved in the Netherlands.'
Erik Verlinde: 'Actually, I wasn't surprised. I think he is a tremendously strong candidate for such a position and he can contribute a lot. I had emailed him shortly before it happened. I am working on a research project that is very directly related to matrix models that Robbert worked on. I guess it will be difficult for him to respond now.'
Herman: 'Many of the things that the three of us did back in the day are now back at the heart of the research that focusses on how to combine quantum mechanics with gravity. So, I think it would interest him quite a bit.'
Erik: 'The matrix models are a model for what we call emergent gravity. For a century, gravity was described by Einstein roughly as follows: masses deform spacetime, causing objects to move toward heavy objects. We observe this as gravity. Emergent gravity implies that curved spacetime is in turn explained by a deeper, microscopic quantum world, in which quantum entanglement plays a role, the special remote link that connects quantum mechanical particles, and which also plays a crucial role in quantum computers.'

The emergent theory of gravity that Erik put forward in 2009 caused quite a stir, even reaching the pages of the *New York Times*. What is its current status?
Erik: 'That theory built on earlier ideas by Stephen Hawking and Gerard 't Hooft, which had taken a bit of a back seat. They saw connections between black holes and thermodynamics. Black holes have a temperature and entropy, a kind of measure of

disorder. I reversed an arrow, as it were: it is not gravity that is the fundamental phenomenon, but it arises from the microscopic quantum world. It is, as they say, emergent. With this, I wanted to give developments a push. Now you see that other people are finally convinced and thinking in the same direction.'
Herman: 'This field often goes through cycles, from searching for new angles to working out certain issues that arise from them.'
Erik: 'This idea has also been around four times, in different forms. But every time we go around, we learn more."

Erik Verlinde

BOB BRONSHOFF

How did you get into physics?

Erik: 'As high school students in the 1970s, Herman and I became hugely motivated by the television broadcast *The Key to the Universe*, by science writer Nigel Calder. We borrowed books from the library, which we discussed a lot, also with our older brother. Unfortunately, he passed away five years ago. He was more interested in astronomy, whereas the two of us found these kinds of fundamental questions fascinating to discuss.'

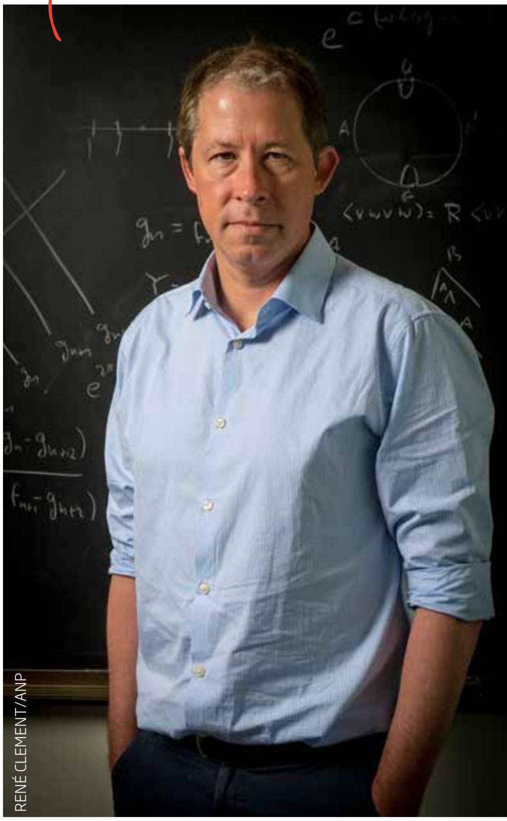
And you never really stopped.

Herman: 'Yes, we'll continue doing so after this interview. Then we'll see how long we can agree with each other (laughs).'
Erik: 'I often think: if I can convince my brother, the rest of the world shouldn't be a problem. But seriously, we were pretty lucky with the people we met during our PhDs in Utrecht, like Robbert. We discussed endlessly and published about it ourselves, which was quite unusual.'
Herman: 'Often, one of us would come up with the original idea and then the other two would start working on it.'
Erik: 'The idea would bounce between us, and we would work it out together in a kind of relay.'

After your PhD, you both left for Princeton University to join one of the top groups in the field of string theory. Erik, what brought you back to the Netherlands in 2003?

Erik: 'That was for personal reasons, but there was also the idea that we could set up a good string theory group in the Netherlands. Physicist Sander Bais had the original idea, but I threw myself into it as well, with Robbert and Jan de Boer. By now, the group has grown tremendously, with many visitors and influx of foreign guests. I think the group is somewhere in the top five in its field, after Harvard and Princeton.'
Herman: 'In Europe, I think Amsterdam is the most established string theory group.'

Herman Verlinde



RENÉ CLEMENT/ANP

Erik: 'Setting up Delta ITP was a logical extension of that. At the time, we saw that with Amsterdam, Leiden, and Utrecht joined together, we could form a kind of nucleus to grow research lines and attract talent. In the developments of the past decade, there are more and more connections with other fields, such as quantum information, cosmology, but also, for example, life sciences. At the same time, we have the first-ever observations of black holes: the detection of gravitational waves by LIGO and the picture of the black hole in the M87 galaxy. When we started out, black holes were something very abstract; now there are actual observations.
The question, of course, is always whether the theories we work on can predict something measurable. That's why these developments are very interesting: can we make connections with possible observations? So much information is being released now, also thanks to all kinds of new satellites, such as the James Webb Space Telescope.... As theorists, we have to take advantage of this. I hope and expect that it will result in a huge turnaround.' ■

New eyes on **the universe**

One does research on black holes, another on distant galaxies. But all four of these young researchers passionately pursue the secrets of our universe.

Text: Peter de Jong
Photos: Bram Belloni

None of them are tied to their home country. Tanja Hinderer is German but lived in the United States during her studies and eventually ended up in Utrecht via Potsdam, Nijmegen, and Amsterdam. Spanish researcher Guadalupe Cañas Herrera settled down in Leiden and teaches Zumba classes in addition to her scientific work. And Evita Verheijden and Jaco de Swart, although Dutch with a strong connection to Amsterdam, are moving to America later this year for new research positions.

The four have another thing in common: each has indicated that their research benefits from the principle of Delta ITP, the exchange of knowledge between Amsterdam, Utrecht, and Leiden. Collaboration is the magic word, because why keep what you know to yourself?

Evita Verheijden

'String theorists know how to party'

Evita Verheijden (1993) is one of the whiz kids at Delta ITP. She graduated cum laude in theoretical physics from the University of Amsterdam. After completing her dissertation later this year, she will move to Harvard to work at the Black Hole Initiative.

'More and more women are studying physics: the intake of female students is now one in five,' she says. 'That's very positive, but there still is a bottleneck higher up the academic ladder: only 10 percent of professors at the University of Amsterdam's Faculty of Science are women.'

Within the string theory research group,

she is working on black holes. More specifically: can you deduce what has disappeared into a black hole from the Hawking radiation it produces? Verheijden is also in search of the holy grail of theoretical physics: the Theory of Everything. She is optimistic: 'I assume we're going to find it during my lifetime. There is fresh determination to take up the issue; more and more good scientists are working on it.'
Leading string theorist Robbert Dijkgraaf has opted for politics. 'He is the right man in the right place,' Verheijden believes. 'He has always argued for more attention and money for fundamental research. As a minister, he can now make a real difference. The fact that he also studied at the Rietveld Academy works in his favour. Art and science are a logical combination; they both require a great deal of creativity.'
On Delta ITP: 'It is a wonderful breeding ground within theoretical physics. We have very good research groups; you would be crazy not to take advantage of them. In addition, it is very nice to meet people from other universities. String theorists may be nerdy, but they also know how to party.'

Guadalupe Cañas Herrera

'I was positive I would be a physicist when I grew up'

Madrid native **Guadalupe Cañas Herrera** (1993) had her first encounter with the Netherlands in 2013. 'I came here to study for a year as part of the Erasmus exchange programme,' she says. 'A fantastic initiative. Later, I did my master's in physics at Leiden University, and this summer I hope to get my PhD in cosmology there.'
The Dutch are nice and direct, she thinks. 'I have become part Dutch by now. My dear parents in Cantabriä had to get used to it a little. In Spain, it is customary to make things clear via something of a detour, with a tactical approach.'
'As a child, I was enchanted by the vacuum and electricity experiments during public Saturdays at the University of Cantabria. I was positive I would be a physicist when I grew up. I am now a cosmologist with the Euclid Consortium, named after the satellite that is expected to be launched in 2023. Euclid looks beyond the Milky Way; it will photograph a million galaxies. With all those data, we will be creating a new catalogue of space, so that we can learn even more about the positions and movements of galaxies, and the expansion of the universe. Super cool.'
In her spare time, she enjoys listening to the music of Bach ('he's a genius!'). And she is a Zumba teacher. Laughing, she says: 'I was quite nerdy as a student; I got tired after only five minutes of running. So, then I started doing Zumba. I love music and dancing. During the lockdowns, I did an online course and now I teach.'
In conclusion: where is the ever-expanding universe going? 'There is nothing to be said about that yet. First, let's learn a little more about dark energy. Maybe Euclid will take us a step closer.'

'Delta ITP is a wonderful breeding ground within theoretical physics'

'I'm Delta ITP's in-house philosopher'

Rock hero and scientist in one: that is **Jaco de Swart** (1989) in a nutshell. In addition to being a PhD student at Delta ITP, he is the bassist for the successful hard rock band X-Raiders. 'Music satisfies my primal urges. On stage, I'm like an animal; I let myself go completely.' That won't stop him from leaving for Boston this summer for two years, where he will work as a postdoc at MIT. 'We'll find a solution for the band. Maybe I'll come back a few times for gigs,' is his down-to-earth comment. De Swart says he was not brilliant at school, but mainly curious. 'I wanted to know how nature works, but I also asked philosophical questions, like "how did discussions

Jaco de Swart

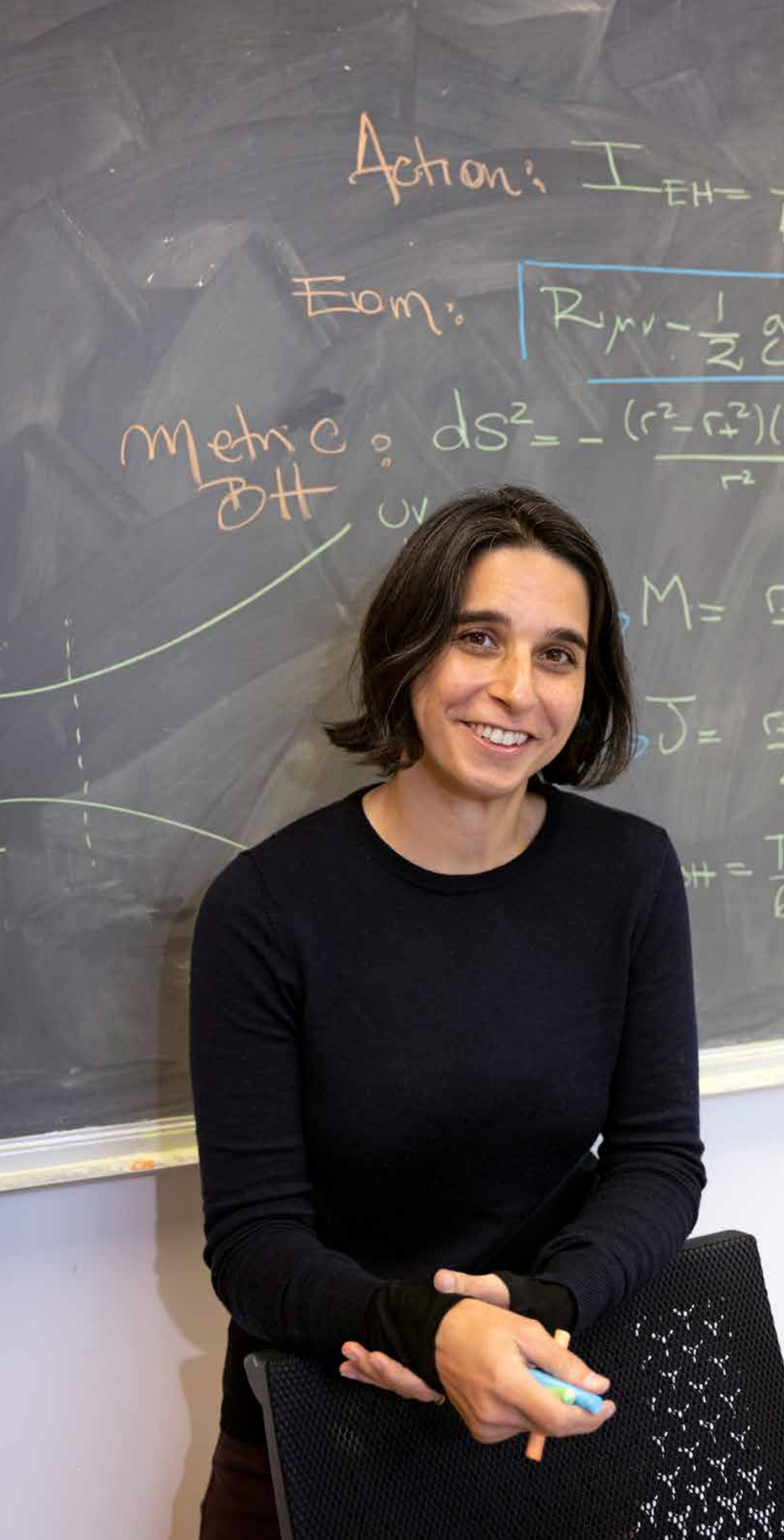
about the Big Bang actually start?" That's why I started studying philosophy alongside physics. I'm Delta ITP's in-house philosopher,' he says, laughing.
His doctoral research on cosmology bridges the gap between philosophy and physics. 'I show that our current way of thinking and acting with regard to cosmology began in the 1970s, influenced by the Space Race between the US and the Soviet Union. A lot of money was put into the development of space travel and new technologies. A new understanding of matter in the universe emerged. It was concluded that 85 percent of the universe was "missing", and, with that, dark matter was born.'
'At MIT, I will be working on developments in cosmology in the 1980s, when astroparticle physics emerged. Is that all? Well, I also like to talk about physics. I will be writing a book about the history of dark matter, and we will soon be recording an episode of *Het Klokhuis* that is also about this mysterious stuff. Great!'

'In science, it's important to exchange ideas; it stimulates new thought'

'Teaching students keeps you on your toes'

Tanja Hinderer (1979), from Hofheim, Germany, is an associate professor of gravitational wave theory at Utrecht University. A globetrotter, you might say. During her physics studies, she moved to the United States, where she received her PhD and later worked as a postdoc at universities in California and Maryland. Via the Max Planck Institute in Potsdam, Radboud University Nijmegen, and the University of Amsterdam, she ended up in Utrecht.
'I am curious and enjoy getting to know new places,' she comments.
'As a university lecturer, I not only do research but also teach students. It's very refreshing. They can be very uninhibited and ask really good questions, which keeps you on your toes.'
'Black holes were already immensely interesting to me at school,' she says. 'They are not normal objects. If you throw something in, it never comes out, not even light. I study the gravitational waves that black holes produce when they collide or move past each other. We are also looking at neutron stars, which contain half a million times the mass of Earth but are only about 20 kilometres across. One teaspoon of a neutron star weighs more than the whole of Mount Everest.'
On Delta ITP: 'In science, it's important to exchange ideas; it stimulates new thought. That's why it's good that the three universities that make up Delta ITP are working together. It only makes us stronger in the search for the answers to the great challenges of modern physics.' ■

Tanja Hinderer



BOB BRONSHOFF

CROWN JEWEL

'I want to see holography in the sky'

'Gravity is like a bad boyfriend. You love it, but it never meets your expectations,' says Alejandra Castro, theoretical physicist at the University of Amsterdam. She researches gravity at a fundamental level. For example, she looks at ideas about quantum gravity, combining quantum mechanics, which describes the behaviour of small particles and light, with Einstein's laws of gravity, which deal with the movements of large objects such as falling apples and stars circling each other.

'Einstein's general theory of relativity is a beautiful and elegant way to describe gravity, but the theory also raises questions,' Castro says. 'One of the things we struggle with is how to apply our understanding of gravity to the quantum world. One successful way of uniting these two important branches of physics is based on the holographic principle.' According to this principle, you can find all the information about a volume in its edges; in the shell around it. Like a hologram, it is a two-dimensional representation of a three-dimensional image. 'The idea is that the shell can be understood with quantum mechanics and the volume with Einstein's theory of relativity. The power of the holographic principle is that it connects the two.'

Anyone researching quantum gravity soon encounters black holes. These objects exert a great deal of gravity in a small space. They force you to combine gravity and quantum mechanics. 'One of my goals is to establish a link between theoretical holographic ideas and observations of black holes by astronomers. I want to see holography in the sky.'

Text: Dorine Schenk

On the shoulders of giants

From the very small to the very large, whether it is the unpredictable behaviour of particles or the heart of a black hole, physics seeks to make sense of all of nature. Great minds such as Albert Einstein, Stephen Hawking, and Richard Feynman paved the way. Delta ITP researchers are now trying to discover what outlooks this path offers, continuing to pioneer where the route ends, and noting what unusual things they encounter along the way.

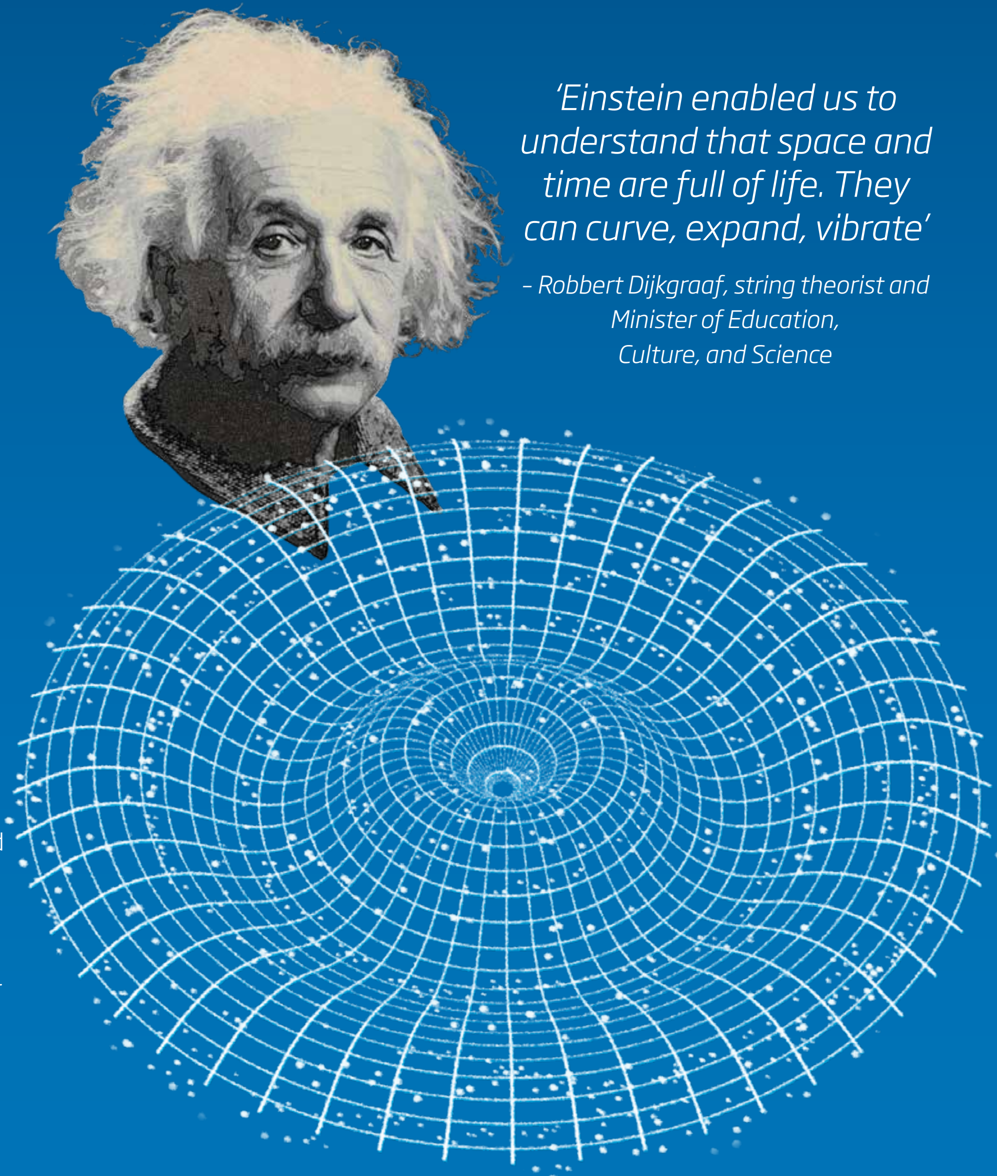
SPACETIME

When Albert Einstein took the stage, it seemed that physicists already had a pretty good grasp of gravity. It is the force by which masses attract each other. For example, a black hole attracts nearby stars, the sun attracts the earth, and the earth attracts people who do not go floating off into space as a result.

But knowing how something works is not the same as knowing why it works that way. Einstein took the theory of gravity a major step further by asking himself that question. He realised that a mass curves the spacetime around it. And everything that moves through space must conform to that curve.

As a result, a star near a black hole inevitably falls in: the star follows the prescribed path of curved spacetime around this dark monster. The earth, in turn, spins around in the curved space-time of the sun.

Spacetime that can be warped opened up a new chapter in cosmology. Einstein realised that space could also vibrate when two black holes collide – a phenomenon he called gravitational waves. In 2015, these waves were measured for the first time, exactly 100 years after Einstein predicted them.



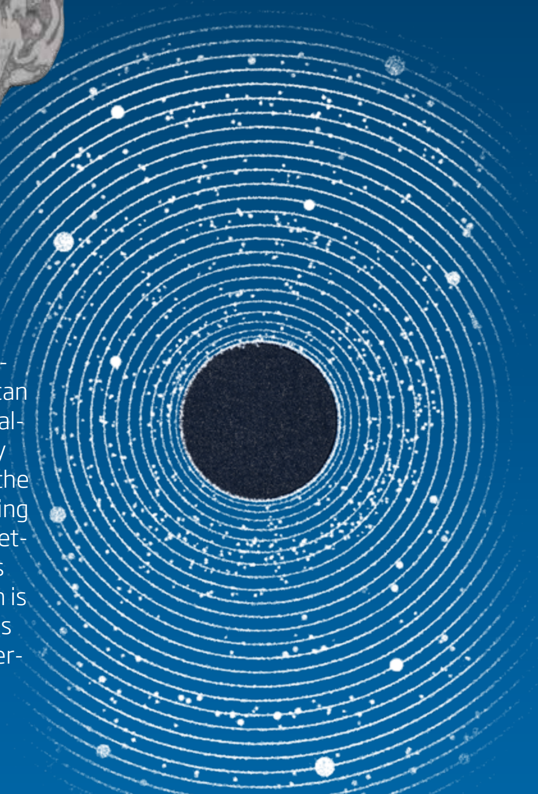
'Einstein enabled us to understand that space and time are full of life. They can curve, expand, vibrate'

– Robbert Dijkgraaf, string theorist and Minister of Education, Culture, and Science

TEXT: ANS HEKKENBERG
ILLUSTRATIONS: PASCAL TIEMAN

'Hawking bridged the – ever mysterious – gap between quantum mechanics and Einstein's spacetime'

– string theorist Jan de Boer, University of Amsterdam



THE EDGE OF REALITY

What happens when you slip over the edge of a black hole? You will be lost forever, that much is clear. Even light cannot escape the extreme curvature surrounding these cosmic heavyweights. But does that also mean that black holes emit nothing but deafening silence? Or can we still pick up a signal from these exciting regions of spacetime? Stephen Hawking asked this question and came upon the greatest insight of his career. Suppose you are looking at the edge of a black hole – exactly at the point that makes the difference between being swallowed up and escaping. There, Hawking reasoned, a particle and an antiparticle can be formed. One of the two can be swallowed, while the other can just barely escape. We should be able to detect the escaping particles as so-called Hawking radiation. So far, this remains a theoretical prediction; Hawking radiation has never been measured. But the search is in full swing. Hawking radiation brings us closer to a message from the underbelly of a black hole than will ever be possible in any other way.

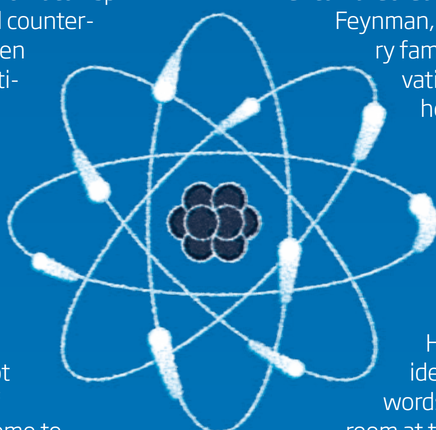
'Feynman connected the fundamental physics of the very smallest with groundbreaking applications'

– Rembert Duine, professor of nanophysics at Utrecht University

MASTERING THE PARTICLE WORLD

From the largest to the smallest: the world of particles is one of uncertainties. For example, a particle can be in two places at once. Or it can spin both clockwise and counterclockwise. Only when you look at the particle (i.e., measure where it is, or how it spins) does it end up in one of the possibe states. Because of this fundamental uncertainty, the world at the smallest scale is not one of facts, but of probabilities. Welcome to the uncertain realm of quantum mechanics.

The path to the smallest was explored by physicists such as Werner Heisenberg, Erwin Schrödinger, and Paul Dirac. A new formulation of quantum mechanics came from the mind of the American theoretical physicist Richard Feynman, who made the theory famous with his observation that he thought he could 'safely say no one really understands quantum mechanics'. Feynman saw that the world of the very small offers unprecedented possibilities. He immortalised that idea with the winged words: 'There is plenty of room at the bottom.' By building with atoms, manipulating particles, and gaining control of quantum laws, physicists hope to master the world down to its deepest foundation.



All that matters

Delta ITP's research focuses on three strange forms of matter: quantum matter, topological matter, and dark matter. A better understanding of these mysterious materials could lead to a revolution in physics.

Text: Yannick Fritschy

Matter. Physics is all about matter. Quantum mechanics, Maxwell's equations, the theory of relativity – wonderful theories have been developed over the past few centuries to describe the behaviour of the matter around us.

Yet there are still many forms of matter that we do not fully understand. They are at the intersection of different fields, like quantum matter. Or they have only been discovered relatively recently, like topological matter. Or they have never even been directly observed, like dark matter.

These three mysterious types of matter are the focus of Delta ITP's research. What has been discovered in this area recently? And what awaits us in the coming years?

Quantum matter

What a rusty piece of copper can't do. In the late 1980s, this material, mixed with lanthanum and barium, was found to be superconducting at 35 degrees above absolute zero. This so-called critical temperature was a lot higher than that of the superconductors previously known. If physicists could raise the temperature at which a material becomes superconducting even further, perhaps all the way to room temperature, the applications would be limitless.

But the more closely physicists studied the new superconductors, the more issues emerged that they could not explain mathematically. Now, over thirty years later, they still can't.

The problem is that the whole is more than the sum of its parts. The behaviour of individual particles in superconducting

The Bullet Cluster consists of two colliding galaxies in which ordinary and dark matter are clearly separated.
X-RAY: NASA/CXC/CFA/M.MARKEVITCH, OPTICAL/LENSING MAP: NASA/STSCI, MAGELLAN/U. ARIZONA/D. CLOWE, LENSING MAP: ESO WFI

materials can be described by quantum mechanics. For example, the theory allows for particles to be entangled. This means that their properties are inextricably linked. But the more particles you have, the greater the complexity of those entanglements. Soon it is impossible to keep track.

This is the case with all matter. But with most matter that we know, you don't have to worry about the entanglement of the individual particles. In large quantities, such quantum properties fall away.

In recent years, it has finally become clear why hot superconductors are so difficult to describe: in such matter, the individual particles are presumably still intertwined. This would seem to represent an entirely new class of matter, argues physicist Jan Zaanen of Leiden University. He calls it quantum supreme matter.

To capture this matter in formulas, you must translate the quantum laws governing individual particles to the macroscale. But the calculations become far too complex. They can only be solved with a computer that itself does calculations with entangled particles: a quantum computer. But that's a long way off.

Fortunately, there is help from an unexpected source: string theory. In the late 1990s, string theorists discovered a link between the field theories used in quantum mechanics and Einstein's theory of general relativity. This isn't the most obvious link: the field theories are related to so-called anti-de Sitter space. In other words, space with an extra dimension and a curvature that is completely different from the space in which we live. But despite these strange properties, the AdS/CFT (anti-de Sitter/Conformal Field Theory) correspondence was also found to apply to quantum matter about ten years ago.

AdS/CFT allows you to investigate the properties of quantum matter without studying the matter itself. Instead, you study phenomena in the corresponding anti-de Sitter space. 'You use postmodern black holes to describe matter,' Zaanen says.

According to Zaanen, a 'quiet revolution' is currently taking place on the way to a mathematical framework for quantum matter. But to complete that revolution, quantum researchers will be forced to delve more deeply into string theory. In addition, it is up to experimentalists to demonstrate that quantum supreme matter is indeed a new class of matter. And hopefully quantum computers will be able to simulate the behaviour of such matter soon.

A quiet revolution is currently taking place on the way to a mathematical framework for quantum matter

Amid all these disciplines, Zaanen sees himself as a bridge builder. 'I'm driven to physics by hedonism – my brain isn't as entertained by anything else,' he says. 'So, I'm extremely promiscuous: I enjoy working with experimentalists, programmers, and string theorists.'

Topological matter

It is possible that research into quantum matter will soon gain momentum thanks to other research by Delta ITP focused on the quantum computer. This computer will be able to perform certain calculations much faster than ordinary computers because it uses the properties of quantum particles. The quantum bits or qubits with which such a quantum computer calculates can not only assume a value of 0 or 1, like traditional bits, but also 0 and 1 at the same time. Moreover, thanks to entanglement, the qubits can directly influence each other remotely.

But it is hard to deliver on the quantum computer promise. There are several materials that can serve as qubits, but they are all very sensitive to outside disturbances. The smallest thing can cause the qubits to lose the quantum properties on which their calculations are based.

To solve this problem, physicists are turning to a type of matter that we have only begun to understand since the beginning of this century: topological materials. The best known of these are topological insulators. These are materials that do not conduct electricity in their interior but do on the surface. The great thing is that electrical conduction on the surface is completely imper-

Notes by Georg Bednorz, who was awarded the Nobel Prize in Physics in 1987 along with Alex Müller for the discovery of high-temperature superconductivity.
ANP

vious to disturbances. 'It's like putting a knot in a rope instead of a loop,' says physicist Kareljan Schoutens of the University of Amsterdam. 'The electrons form a kind of quantum knot, which is not easily broken.'

This robustness makes topological materials the ideal building block for quantum computers. But real life is unruly. Although progress has been made, including by the QuTech institute in Delft, it has not yet been possible to make these kinds of qubits in the lab.

'The physics of other qubits is more familiar. For this, we must first explore a new natural phenomenon,' says Schoutens. However, the promise of robustness is so great that he believes the research will eventually pay off. The only question is when. 'Opinions differ on that,' says Schoutens. 'As a theorist, I find it hard to say. I understand exactly how it should work, but it's proving difficult to implement.'

Dark matter

So new forms of matter are proving difficult to fathom. But what if you don't even have the matter that is to be researched? And what if you have no idea what it consists of? That is the situation in which cosmologists now find themselves. The standard model of cosmology contains several unexplained elements, including dark matter.

> 'I believe dark matter consists of a particle that we will find within five to ten years'

Dark matter is an unknown form of matter that affects the movement of galaxies, among other things. Most physicists are convinced that the stuff exists, but it has never been observed – neither directly nor by creating it with particle accelerators. 'The problem has only worsened,' says cosmologist Daniel Baumann of the University of Amsterdam. 'Ten years ago, we all thought WIMPs were the solution.' WIMPs are weakly interacting massive particles. As their name suggests, these particles are heavy and barely undergo changes when they come into contact with other particles. But WIMPs have never been found, while many experiments could have measured them by now if they existed.

And so, researchers continue to search. The proposed solutions range from extremely light particles to black holes created just after the Big Bang. And then there are physicists who think that dark matter doesn't exist at all and that we should modify our theory of gravity instead. 'So, we don't really know anything,' Baumann says.

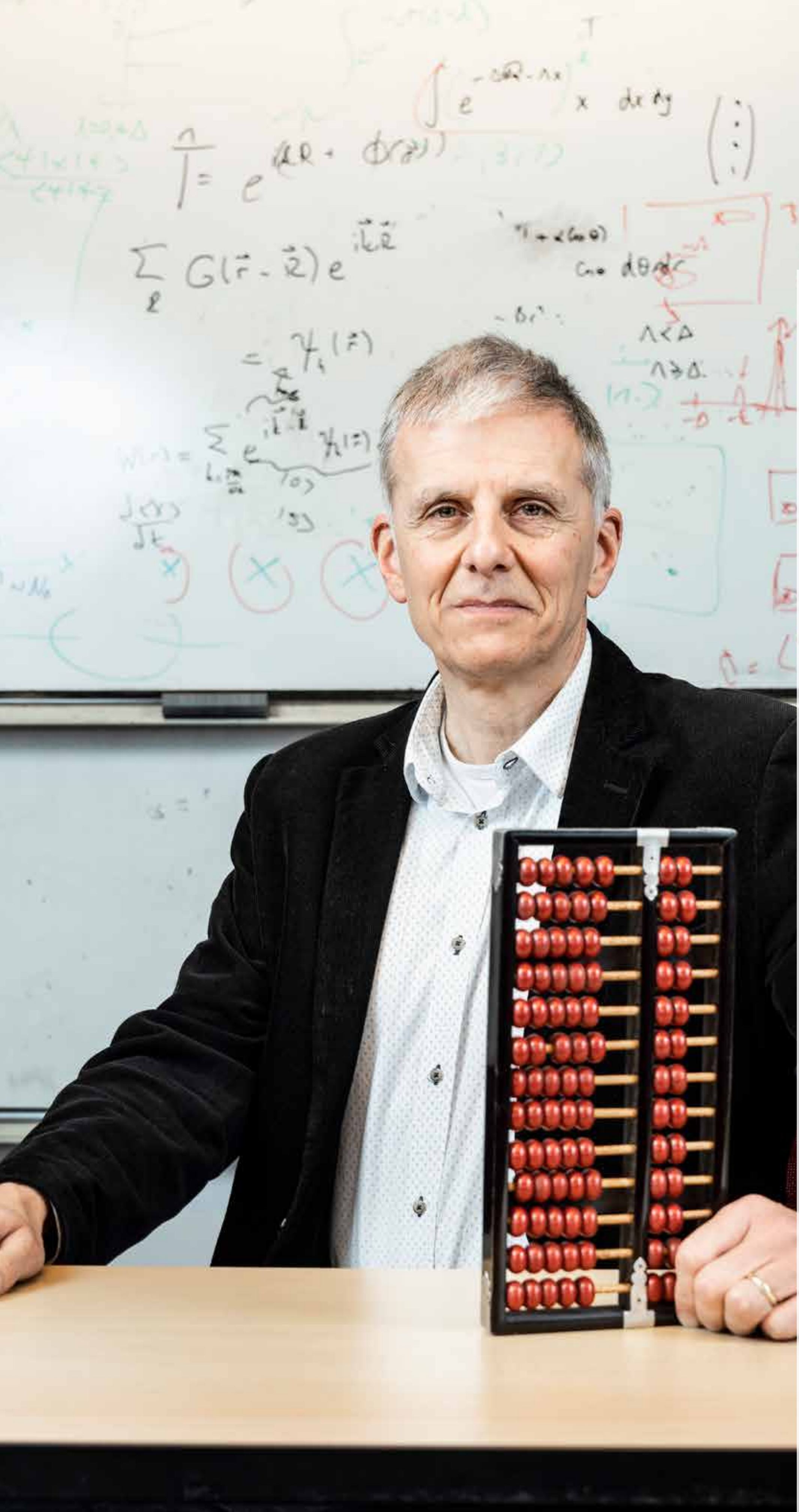
A possible candidate to fix these issues are weakly coupled particles. These are hypothetical particles with masses similar to those with which we are familiar. They are said to interact very little with other particles, which explains why we have never seen them despite their mass. 'We can look for traces of these kinds of particles via gravitational waves,' Baumann says. He expects dark matter to be found within five to ten years despite all the uncertainty. 'I've been saying that for ten years, but still. I believe it's just a particle that we will find.'

String theory

All in all, a lot of new knowledge has been gained about matter, but a lot of new problems have also arisen. What if you had one theory that solves all these problems in one fell swoop? For years, string theory was such an ideal 'Theory of Everything'. Now, it seems that the theory cannot live up to these high expectations. 'When I did my PhD research fifteen years ago, I thought we were further along with string theory than we are today,' says Baumann.

'String theory is especially successful at high energies. In the case of the low energies we see around us, the description unfortunately falls short.' Yet Baumann still sees string theory as the way to go. 'There is no good alternative. Other theories are not even well-defined at high energies.'

Whether through string theory or not, the ultimate goal of physics remains to find a single rulebook describing the behaviour of everything around us. And with their research into strange forms of matter, the Delta ITP researchers are silently taking steps toward that goal – patiently waiting for that one breakthrough that explains everything. ■



CROWN JEWEL

'The quantum world is a magical world'

'The development from abacus to computer seems like a big step. But they calculate in the same way; a computer is just faster,' says Carlo Beenakker, professor of theoretical physics at Leiden University. 'For the last decade or so, physicists have been working on a technique that computes in a radically different way: the quantum computer. It calculates with qubits.' Unlike an ordinary computer's bits, which are zero or one, qubits are a combination of zero and one. Thanks to the quantum properties of qubits, certain calculations can be performed much faster. But because of that, you have to program them completely differently than a regular computer.

'I do research on programming quantum computers as well as on making qubits,' Beenakker says. 'As a theoretical physicist, I don't create the qubits myself; I invent and predict ways to make them. Delft researchers, with whom I collaborate, make them.'

'In terms of programming, the question now is: who will find the killer app for the quantum computer? In the 1950s, no one imagined that, for the computer, it would be the worldwide web – the www. I'm not going to find that killer app, but I've surrounded myself with people who have ideas about it and are looking at, for example, a combination of artificial intelligence and quantum.'

Beenakker, who did not begin quantum research until later in his career, is enthusiastic about the field: 'It's beyond your intuition, which makes it a completely different, magical world in which to explore. And you are dependent on mathematics to avoid going astray.'
Text: Dorine Schenk

BRAM BELLONI

'There are **many ways to help** each other'

Within Delta ITP, scientists can join forces to get a step closer to unravelling the great mysteries of the universe. **Elisa Chisari**, **Alessandra Silvestri**, and **Samaya Nissanke** work together on questions of gravitational waves and the expansion of the universe.

Text: Marleen Hoebe
Photos: Bob Bronshoff

ELISA CHISARI

Cosmologist and lecturer at Utrecht University

'The projects that Alessandra, Samaya, and I are working on are still in the early stages. Alessandra and I started a project with Tomislav Prokopec, cosmologist at Utrecht University. The goal of this project is to research the expansion of the universe using a quantum model that Tomislav has created. Samaya and I are involved with a group of Dutch scientists in the Legacy Survey of Space and Time, a ten-year international study. This will take place at the Vera C. Rubin Observatory in Chile, which is currently under construction. We hope this research will lead us to the properties of the mysterious force that drives the accelerated expansion of the universe.

These days, a scientific article is rarely the work of a single author. Good research requires more than an original idea. The tools to move the research forward are also important. When we talk to each other, we can come up with ideas. And by combining our areas of expertise, we're able to get those ideas started.

We also help each other in other ways. For example, we ask each other questions about our projects to be sure of the robustness of our results. I also see Alessandra and Samaya as role models who can help me on my way in the Dutch academic world. I came to Utrecht two years ago, just before the pandemic. With their help, and thanks to Delta ITP and the contacts I had previously made at Leiden University, I was able to become well embedded in the scientific landscape of the Netherlands.

Collaborating with different research institutes is enriching. First, discussions among institutions stimulate the conception of new ideas that often result in scientific projects. Our monthly theoretical cos-

By combining our various areas of expertise, we can address the very challenging questions that we face in cosmology, and more generally in physics and astronomy. There are many ways to help each other. Through joint group meetings, for example, we learn from each other's styles. And in personal discussions, we can advise each other on many aspects of our work, including the difficulties that we face as young mothers trying to balance scientific careers with family lives. Also, I will never forget the support I received from Samaya when I applied for the Vidi grant from the Dutch Research Council.'

I assumed that once I was hired for a tenure track (a career path leading to a permanent position – ed.) many challenges would disappear. But now I face a new set of challenges. For me – someone who became a mother at a critical point in her career – it has been so helpful to work with women who are in similar phases in their careers and to whom you can vent. In retrospect, the first two years of motherhood were a struggle and that time passed in a blur. But it was also great, and it meant a lot to me to share these experiences with Alessandra.' ■

mology meetings and other seminars ensure that we stay abreast of what each of us is doing. But the human aspect also plays a role; it is enormously valuable that I can share my curiosity for the universe with others. It makes me feel like I'm part of a larger enterprise.'

ALESSANDRA SILVESTRI

Cosmologist and senior lecturer at Leiden University

'Samaya and I were working on a project researching what we can learn about our universe from gravitational waves. With a grant from Delta ITP, we were able to jointly hire a postdoctoral researcher and start this research. This was the beginning of a fruitful collaboration between our two research groups that also attracted good researchers from abroad. We've already published several articles together, but we aren't done yet. Our collaboration has lasted longer than the project that was originally funded. For the project that I recently started with Elisa, we were also able to hire a promising young scientist with the help of Delta ITP.

SAMAYA NISSANKE

Astrophysicist and senior lecturer at the University of Amsterdam

'The physics institutes in Utrecht and Leiden both focus on research areas that we are working on in Amsterdam. As a result, it's not only a pleasure to collaborate, it's crucial. It enables us to develop new ideas and methods and ensure cross-fertilisation.

For me personally, our collaborations are important because I have learned so much from Alessandra and Elisa, both scientifically and personally. Their expertise complements mine and provides new perspectives and insights. It's also a pleasure to work with them; they are inspiring and belong to the new generation of leaders in their field. They're great people. You can see this in their research groups and the fun they have in physics.

I think it's always an advantage to have colleagues who support you. It's a privilege to be part of academia. At the same time, it can also be tough and challenging.

'By combining our expertise, we can address challenging cosmology questions'

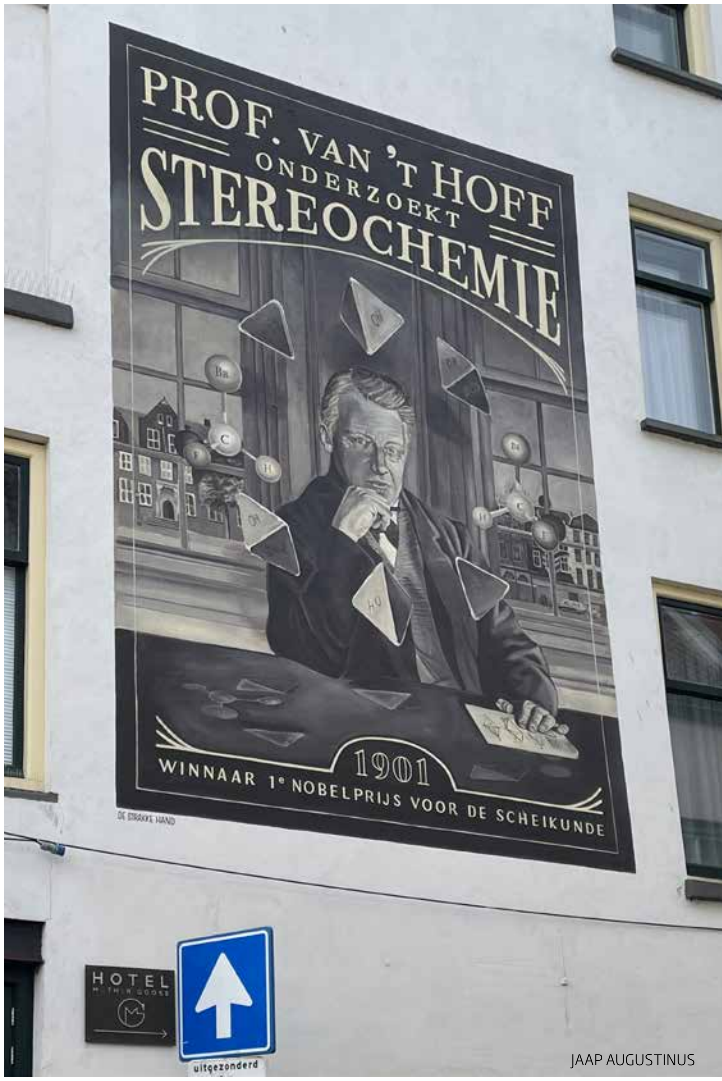
Physics at large

If you stroll through Leiden or Utrecht, you might unsuspectingly stumble across a physics formula. Since 2015, huge murals, each depicting a physical concept, adorn various buildings. For example, the speed of the sun around the centre of the Milky Way as calculated by astronomer Jan Oort (top left), or the Doppler effect: the way the frequency of a tone changes as a sound source passes you by (right). Physicists Sense Jan van der Molen and Ivo van Vulpen initiated the project in Leiden, under the guise of 'the more science in the world, the better'. The initiative was successfully replicated in Utrecht in 2019.

Text: Ans Hekkenberg

INSTITUUT-LORENTZ, UNIVERSITEIT LEIDEN

INSTITUUT-LORENTZ, UNIVERSITEIT LEIDEN



JAAP AUGUSTINUS

JAAP AUGUSTINUS

Beyond the wall **beyond the stars**

Cristiane de Morais Smith is a born pioneer. Flanked by her parrot Yara, she explores the boundaries of reality. Perhaps unexpectedly, Picasso's brush strokes touch her physics heart more deeply than Newton's formulas.

Text: Sebastiaan van de Water
Photo: Bram Belloni

When she was little, Cristiane de Morais Smith was gifted unsolved mysteries by her parents, rather than hard facts. She remembers one night when she was a young girl, when her father took her outside. He pointed up, to the brilliant starry sky that, every night, made their village of Paraguaçu Paulista seem even smaller than it already was. 'Cristiane, what do you think lies beyond those stars?' he asked her. 'I think... more stars, *papai*.' 'And beyond that? 'Even more stars.' 'What about behind those stars?' 'Maybe... a big wall?' 'Ah. And beyond that big wall beyond the stars?' Silently, father and daughter continued to stare upward.

Such moments strengthened the Brazilian village girl's conviction not to keep the large wings of her curiosity hidden, but to spread them fully. She still believes a boundless universe deserves a boundless spirit of discovery. So, she will never fold her wings.

On the bathroom floor

She wasn't called to physics specifically until years later, at age thirteen. A teacher presented her class with a difficult task: calculate the acceleration of objects sliding down a slope without friction. Indeed: Galileo's famous experiment. The teacher enjoyed having his class struggle with this problem, only to surprise them with the counter-intuitive insight that mass has no effect on acceleration.

De Morais Smith can still recall the scene: 'He came to check at my table and suddenly he cried out with joy. All the students looked up in bewilderment, because we knew him to be a very subdued man. He appeared to be over the moon because I had already written down the right equations. I asked him if I could solve more fun puzzles like this. "Then you should become a physicist," he responded.'

'I'm attracted to all phenomena on the edge of the unknown and otherworldly'

From then on, that was her destiny. But, for a long time, the road there seemed to be blocked. 'The Brazilian school system is perverse,' sighs De Morais Smith. 'If you want to study at the university, you have to pass extremely difficult entrance exams. Only students from expensive private schools stand a chance. But I wanted it very, very much.'

She knew what she had to do. 'I knew no boundaries. As long as my body didn't give up, I continued to learn.' Sixteen hours a day. For months. Often at night she would lie on the cold bathroom floor with her textbooks, fighting sleep to keep her dreams alive.

Strange behaviour

'If a path doesn't already exist, I'll create one myself.' That attitude got De Morais Smith to Switzerland as a young twenty-something, for a PhD in theoretical physics. For a long time, she had fantasised about Europe. How different would life be there?

She found that out soon enough. 'Before my first symposium, my professor called me over and said: "You are a woman. So, during your presentation, I don't want you to smile; it distracts the scientists here. I want you to dress simply and act seriously. Be modest. Just like a man." To say such a thing to a Brazilian woman is like denying her right to exist. I responded by saying I would never stop smiling. My smile is my ally, in good moments and bad. He accepted my point of view. Or he probably thought: "Never mind, she's from far away and doesn't understand how things works here." Later, other women in physics told me that my "strange" behaviour also gave them room to behave more freely. So, it was good for something after all!'

Perfect illustration

Today, De Morais Smith is an award-winning professor of physics at Utrecht University. Her research is difficult to summarise. From her medieval home on Oudegracht, where her Amazon parrot Yara provides a Brazilian touch, she reflects on the mystery of human consciousness. In her lab, she plays with the possibilities of the miracle material graphene. She analyses the curious behaviour of atoms at extremely low temperatures. Behind her desk, she calculates what non-existent materials we need to invent for the quantum era to blossom. 'There is a common thread in my research, I think. I'm attracted to all phenomena that are on the edge of the unknown and otherworldly. I feel little for making existing processes more efficient. I dream of new paths to unexplored and misunderstood parts of our reality.'

Significantly, Pablo Picasso's 'deformed' brushstrokes inspire her more than Newton's formulas. 'Take the woman that Picasso depicts with an eye in the middle of her forehead. Completely wrong, correct? Until you realise that the woman was his lover. And that when you see your lover up close, face to face, she would seem to have an eye on her forehead from that perspective. The perfect illustration of the physics concept that all perspectives are equally real. Isn't that brilliant?'

Harmonious zone

As a member of the Delta ITP Board of Directors, De Morais Smith sees an important mission ahead. 'Many brilliant students leave academia. Why? Because their inner spirit of discovery is overshadowed by increasingly fierce competition and more and more bureaucracy. Through Delta ITP, we can create a harmonious space where we can follow our curiosity wherever it leads us.' Beyond the wall beyond the stars, if possible. ■

column **Marcel Levi**

A fundamental difference

NWO chair Marcel Levi helps clear up some of the misconceptions surrounding fundamental and applied science.

Delta ITP is celebrating its tenth anniversary and that's worthy of congratulations. I think you can say without a doubt that this Amsterdam-Leiden-Utrecht gravity consortium is an example of Dutch science at its best. And to think they focus on the incredibly complicated area of dark matter, the Big Bang, and quantum physics. You can hardly imagine science more fundamental.

There are many misunderstandings about fundamental science. One of them is the supposed contradiction to applied research. I think this picture isn't quite correct. Both fundamental and applied science aim to push the boundary between what we don't know and what we do know a little bit further each time. In applied science, this is usually because, for example, a direct societal issue needs to be solved. Fundamental science may lack these questions, but that doesn't mean that it will not eventually lead to solutions to major world problems. But it will probably happen many years later, with more uncertainty and no promises in advance. And with more surprises, because answers are also found to questions that had not yet been asked. Fundamental and applied science are part of the same continuum where knowledge ultimately leads to the solving of questions that make the world a better place, whether it's energy, climate, health or well-being.

You also often hear that there is less and less budget for fundamental science in the Netherlands. This is not really true either. Budgets for fundamental science have remained about the same in recent years. And, fortunately, there is even room for fundamental science in several new impetuses for science with an applied approach, such as the National Growth Fund (from the Ministry of Economic Affairs and Climate Policy and the Ministry of Finance – ed.). It is true, however, that budgets for fundamental science have not grown along with those for applied research. This has led to a lack of balance, and it is important to restore this with the new impetuses for science and knowledge over the next decade.

If you want to do something grand or compelling in the Netherlands these days, the word 'delta' is often attached to it, perhaps inspired by our magnificent Delta Works. For example, we now have a Delta Plan for Dementia, a Quantum Delta, a Delta Plan for Biodiversity, and a Medical Delta. What is 'delta' about Delta ITP? The website suggests a neat triangle connecting Amsterdam, Leiden, and Utrecht but that – for physicists – is a touch imprecise. A perfect triangle would be more likely to be between Diemen, Alphen aan den Rijn, and Maartensdijk. Also, Amsterdam, Leiden, and Utrecht lack an estuary that can lay claim to the description of a delta. But perhaps delta refers to the Greek letter often used to denote 'difference,' and that applies here. Delta ITP is making a difference between what we didn't know before and what we know now, making the institute a fascinating and successful example of excellent fundamental science. ■

Fundamental and applied science are part of the same continuum

Marcel Levi is an internist, professor of medicine, and president of the Dutch Research Council (NWO)

JEROEN OERLEMANS/NWO

column **Marcel Vonk**

How details can disappear into a black hole

Impression of a black hole. But are popular descriptions of this type of object accurate?
NASA/JPL-CALTECH

What is a black hole? It's not the easiest question to ask a physicist. Fortunately, there are several standard answers available. 'A point in the universe where the escape velocity is greater than the speed of light', for example. Not the most exciting phrasing, but one that captures the point.

Although… The underlying idea behind the parallel between light speed and escape velocity is that nothing can go faster than light. So, absolutely nothing can escape a black hole. But does that follow from the above one-liner? Not really. If I were to build a tall tower on the black hole described and climb it, wouldn't I be able to escape from that point with less gravity? If I launch a rocket from my black hole – which then falls back in – would I be able to launch a new rocket from the highest point, and so on until something escapes?

All sorts of solutions seem possible, but you cannot escape a true black hole. To understand that properly, you need the general theory of relativity. Only when you realise that a black hole sucks in space faster than the speed of light and that this does not contradict Einstein's speed limit (which is, after all, about moving through space, not about space moving itself), do you realise that you will never escape, no matter how hard you swim against the tide of space.

> Keep the lines from the scientist to the audience short

The above is an example of a problem that one frequently encounters as a scientist. It's not easy to explain your work to a wide audience without minor inaccuracies creeping in. In the case of black holes, the consequences of a shaky explanation may not be too bad, but if you're researching the spread of viruses or the economic impact of immigration, all kinds of things can go wrong if the public image doesn't correspond to your research findings.

Two things are important for honest communication of science. First, keep the communication lines from scientist to audience short. If a scientist tells his or her story to a communications person who writes a press release that is read by a journalist who writes a piece that is edited by an editor before it reaches the reader, there are four places in the telephone chain where information can be lost. So above all, let scientists who can tell a good story speak for themselves.

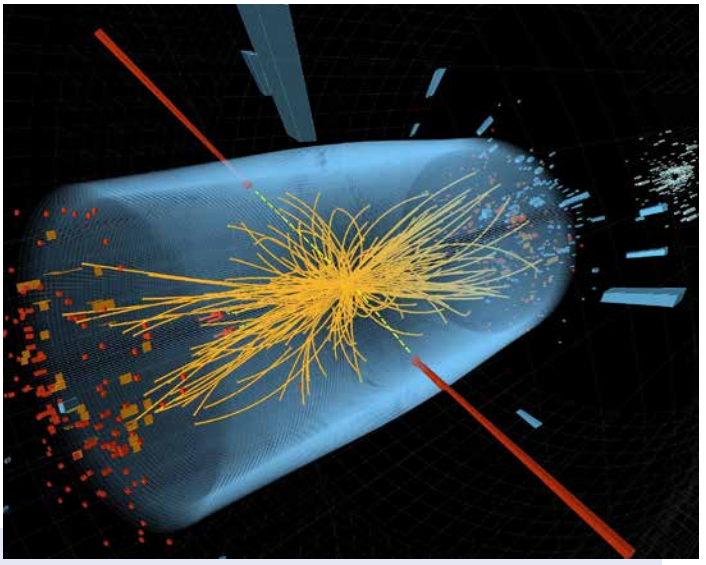
To those scientists, I would say: be honest. Tell your story, but also explain where you're using approximations. This is how we prevent the important details of science from disappearing into a black hole on their way to the public. ■

Marcel Vonk is a mathematical physicist at the University of Amsterdam, and, for Delta ITP, he is editor-in-chief of quantumuniverse.nl, a popular science site about physics. He also provides science popularisation for the Institute of Physics at the University of Amsterdam and has written several books on physics.

No experiment without theory (and vice versa)

A dusty room with a well-stocked bookcase, a chalkboard, and a coffee maker. The stereotypical working environment of theoretical physicists contrasts sharply with that of their experimental colleagues, who work with huge, billion-dollar machines. Yet one cannot succeed without the other. A look at five major experiments, through a theoretical lens.

Text: Dennis Vaendel



A particle collision in CERN's Large Hadron Collider, as observed in the CMS experiment.
CERN

CERN

What would particle physics look like today if CERN had never existed? Wouter Waalewijn, a theoretical physicist at the University of Amsterdam, doesn't dare to speculate. 'But I would probably be working in a different field now.'

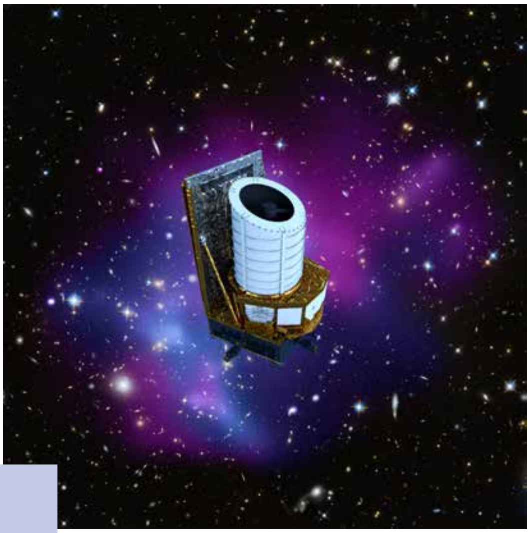
The institute – a 23-country collaboration based in the French-Swiss border region near Geneva – conducts experiments that also figuratively break borders. 'Both the amount of measurement data provided by CERN and its quality exceed that of other experiments in this field,' says Waalewijn. 'Without this data, we can't test our theories about elementary particles.'

A well-known example is the discovery of the Higgs boson in 2012, with CERN's largest particle accelerator, the Large Hadron Collider. The existence of this elementary particle was crucial to the Standard Model, the theory that describes all known particles, and all known forces except gravity. This theory does not hold up without the Higgs boson.

Now this is not to say that particle physicists can sit back and relax since this discovery. The Standard Model is not complete yet, says Waalewijn. 'In recent years, we have seen increasing indications in measurements that particles don't behave exactly as expected. The puzzle pieces of the Standard Model don't quite fit together yet. But it's unclear where exactly we should be looking for answers.'

That is why theorists are calculating how the current Standard Model should behave in certain situations. 'You can use that information to look for anomalies. If a measurement is different than expected, it tells you where something might be wrong.'

In addition, they work out all kinds of different models. Could there be multiple types of Higgs boson or perhaps even completely new families of particles? Do some particles engage in unknown interactions with other particles or with themselves? Their findings can tell CERN researchers where to look for new physics.



'If it were easy to discover the nature of dark matter, my job would be boring'

The Euclid space telescope should shine more light on dark matter and ditto energy.
ESA/ATG MEDIALAB (SPACE TELESCOPE); NASA/ESA/CXC/C. MA, H. EBELING, E. BARRETT (UNIVERSITY OF HAWAII/IFA) E.A./STSCI (BACKGROUND)

Euclid

Whereas particle physicists are busy solving their puzzle, cosmologists first have to figure out exactly what their puzzle pieces look like. Only a few percent of the universe appear to be composed of 'normal' matter, made of particles from the Standard Model. Theoretical models and indirect observations show that the rest consists of dark matter and dark energy. But what these mysterious goodies are made of is still shrouded in mystery.

The Euclid space telescope, scheduled for launch in 2023, will help physicists shine more light on the matter. How? By imaging more than a billion distant galaxies extremely accurately. 'This is because the images of these galaxies can be distorted by dark matter, which acts as a so-called gravitational lens,' says Elisa Chisari of Utrecht University.

By combining the measured distortions of a gigantic number of galaxies, astronomers aim to create a detailed map of the distribution of dark matter in the universe. 'We then compare these with what you would expect to see for the different interpretations of dark matter, to test whether they could be correct,' says Chisari. 'This requires accurate theoretical models. Because the better the measurements, the more precise your model must be.'

Theories that explain dark energy can also be put to the test using Euclid. For example, the telescope can measure how the 'dark matter map' of the universe has changed from the Big Bang to the present, which tells us something about the expansion of the universe, a process that may be accelerated by dark energy. 'This will allow us to test, among other things, the most popular description of the cosmos, the so-called Lambda-CDM model,' says Chisari. 'Recent measurements are already hinting at cracks in this model. So, I look forward to what observatories like Euclid will tell us about this.'

Detectors like ANTARES can detect neutrinos that are an indication of dark matter.
F. MONTANET/ CNRS FOR ANTARES

ANTARES

Gazing at galaxies is not the only way physicists are trying to figure out the true nature of dark matter. Particle physicists are making an attempt as well, using large, undersea neutrino detectors such as ANTARES in the Mediterranean.

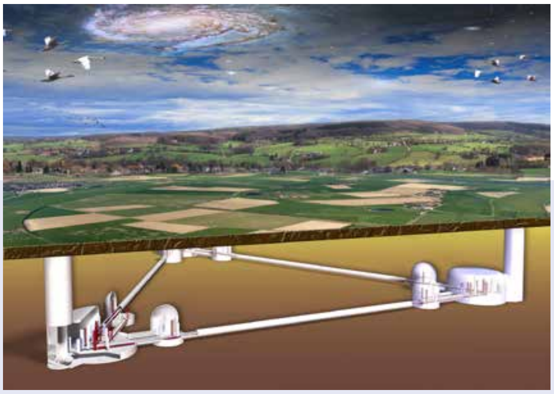
According to theoretical models, some dark matter candidates, including the WIMP (weakly interacting massive particle), popular among physicists, can annihilate each other or decay, releasing highly energetic neutrinos. Detectors like ANTARES can observe these neutrinos. If they turn out to come from the direction of the sun or the centre of the Milky Way, that's a smoking gun for the existence of particles like WIMPs, says Christoph Weniger, a theorist at the University of Amsterdam. 'These are places where there may be a lot of WIMPs.'

In practice, however, the universe remains eerily silent. Although ANTARES has been active since 2008, this detector has not yet detected such neutrinos. Future, more sensitive detectors – such as KM3NeT, which is also emerging on the bottom of the Mediterranean – may be more successful.

Now, the lack of measurements does not mean that the research area is at a standstill. On the contrary. 'Theorists have actually made an awful lot of progress in recent years,' says Weniger. 'Some candidate particles have been dropped, for example, because calculations have shown that they cannot exist. Models have also been developed for completely new particles, including ways to catch them in the act. This, in turn, provides new directions in which observational researchers can search.'

In the meantime, we wait patiently and hope for an actual detection, sighs Weniger. 'But if it were easy to discover the nature of dark matter, my job would be boring.'

Einstein Telescope



The Einstein Telescope, a huge gravitational wave detector, might be built in the south of Limburg.
MARCO KRAAN/NIKHEF

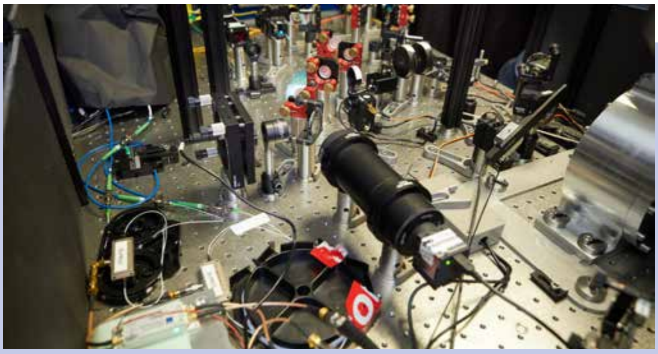
Physicists working on gravitational waves know that patience is a virtue. Using his general theory of relativity, Albert Einstein predicted the existence of these ripples in spacetime as early as 1916. It took another century for physicists to observe them directly.

This was an experimental feat, in which theorists also played an important role. 'The signals from gravitational waves are very weak,' explains Tanja Hinderer, a theoretical physicist at Utrecht University. 'Recognising waves among all the measurement noise and then determining how and where they originated depends entirely on theoretical models.'

Now that it is possible to measure gravitational waves, an entirely new window on the universe has opened. For example, observatories such as LIGO in the United States and Virgo in Italy have already revealed dozens of black hole collisions.

But this is only the beginning. A new generation of detectors is on the way, including the Einstein Telescope. This underground detector, which may be built in the south of Limburg, will look much deeper into the universe, and make measurements ten times more precise than LIGO and Virgo. In doing so, it takes research to an even higher level, says Hinderer. 'There will be many more observations that reveal in detail the properties of merging black holes. This will allow us to test very accurately whether these cosmic collisions behave as the general theory of relativity dictates. Possible anomalies could lead to completely new physics.'

In addition, the detector can uncover completely unknown territory. For example, it is possible to study recently merged neutron stars, in which matter reaches unprecedented densities. 'There is also a whole zoo of exotic, compact objects that theorists suspect may exist,' says Hinderer. 'For example, boson stars, or stars composed entirely of dark matter or energy. The Einstein Telescope is so sensitive that it can measure collisions between these kinds of strange, hypothetical objects. Using their models, theorists will then have to explain exactly what was observed. This can shed light on very interesting physics, from the nature of dark matter to quantum gravity.'



At the QuTech lab, founded by TU Delft and TNO, work is being done toward the quantum computer and the quantum internet.
QUTECH

Quantum computer

Shooting holes in existing theories or discovering completely new physics: those are not every theorist's main goals. Some branches of physics may just be 'complete', says Carlo Beenakker, a theoretical physicist at Leiden University. As an example, he mentions his own field, quantum mechanics, which describes the behaviour of particles and energy at the very smallest scale. 'I'm still working with physics that was developed a century ago.'

So, what do theoretical physicists do? Apply theory to new contexts, to advance technological developments. 'Quantum mechanics is proving to have applications that physicists would have been flabbergasted by a century ago,' says Beenakker. For example, the quantum computer, which can perform certain calculations much faster than ordinary computers. The principle behind this was fully developed by quantum physicists as early as the 1980s and 1990s. First, tentative versions of this computational beast have recently been built by more and more laboratories and companies. The winning design just isn't known yet, Beenakker says. 'Physicists are working on different types of qubits. These are the quantum versions of bits, the information carriers used by computers. To figure out which type of qubit works best, theorists suddenly have to start programming, which works in a completely different way than for a normal computer because you have to take into account the laws of the quantum world.'

You want to make sure that no errors creep into the calculations. Normally, you would do this by checking the value of bits. However, the power of a qubit is that it can have two values at the same time. At least, as long as you don't determine that bit's value. But if that's not allowed, how do you check a qubit? 'Theorists have to find ways to work around this, to prevent the quantum computer from crashing all the time,' says Beenakker.

Whether the quantum computer can ultimately live up to its sky-high expectations? Beenakker is optimistic. 'Although it remains to be seen what the final, major applications will be. Within physics, however, the current generation of quantum computers has already proven its worth. In many fields, their calculations are leading to wonderful theoretical results.' ■

PHYSICAL READING

Delta ITP scholars and topics can also be found in bookshops. Five highlights and a list of further recommendations.

Denken is verrukkelijk

A tragic power couple: that's how you can describe Paul Ehrenfest and Tania Afanassjewa. Ehrenfest was a gifted teacher, one of Einstein's beloved sounding boards, and recogniser of young talent. Afanassjewa was an accomplished physicist in her own right and a progressive thinker in the field of mathematics education. But whereas Afanassjewa was undervalued by society because she was a woman, Ehrenfest failed to value himself, as this double biography shows.

Author: Margriet van der Heijden
Publisher: Prometheus
ISBN: 9789035141902
Price: € 39.99

De race tegen de schildpad

Mathematical physicist Marcel Vonk's *De race tegen de schildpad* (*The Race Against the Turtle*) focuses on thought experiments, from Maxwell's demon to Schrödinger's cat. *New Scientist* chose the book as its Book of the Month in September 2020, judging that, as a writer, Vonk 'measures up to the greatest international names in science books, such as Brian Greene, Carlo Rovelli, Lawrence Krauss, and Stephen Hawking'.

Author: Marcel Vonk
Publisher: Unieboek | Het Spectrum
ISBN: 9789000369843
Price: € 20.99
E-book price: € 12.99

Very Special Relativity: An Illustrated Guide

According to the special theory of relativity, nothing can travel faster than light, and a fast-moving clock ticks slower than a clock that doesn't move. But why is that? In *Very Special Relativity: An Illustrated Guide*, professor of theoretical physics Sander Bais explains Albert Einstein's first great feat to a wide audience using clear diagrams.

Author: Sander Bais
Publisher: Harvard University Press
ISBN: 9789462982789
Price: approx. € 30.-

Het allerkleinste

After Robbert Dijkgraaf introduced television viewers to particle physics and quantum mechanics in his television lecture *Het allerkleinste* (*The Very Smallest*), this book serves comic book readers. Young talent Dirk Ridder turned Dijkgraaf's explanation into an unusual and colourful graphic novel, in which the pair take an imaginative journey past DNA, neutrinos, and more.

Authors: Robbert Dijkgraaf and Dirk Ridder
Publisher: Veen Media
ISBN: 9789085717188
Price: € 14.99

How to Find a Higgs Boson

In *How to Find a Higgs Boson and Other Big Mysteries in the World of the Very Small*, physicist Ivo van Vulpen zooms in on the building blocks of our universe. An accessible, well written introduction to the standard model of particle physics, covering the searches for dark matter, new forces of nature, and extra dimensions.

Author: Ivo van Vulpen
Publisher: Yale University Press
ISBN: 9780300244182
Price: approx. € 25.-
E-book price: approx. € 16.-

Also worthwhile:

In **Fundamentals**, American Nobel laureate Frank Wilczek presents ten fundamentals of physics; in **Helgoland**, Italian physicist Carlo Rovelli explains his take on quantum physics. Those looking for a somewhat more critical biography of Stephen Hawking can turn to **Hawking Hawking** by Charles Seife. Dutch physics heavyweight Hendrik Antoon Lorentz was recently covered in two good biographies: **Hendrik Antoon Lorentz, natuurkundige (1853-1928)** (Lorentz Hendrik Antoon Lorentz, physicist (1853-1928)) by Anne Kox, and **Lorentz** by Frits Berends and Dirk van Delft. And in the **Pocket Science** series, published by *New Scientist*, top science journalists tackle topics such as spacetime, string theory, the end of the universe, and multiverse theories in about a hundred pages each.