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

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 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.

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

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.

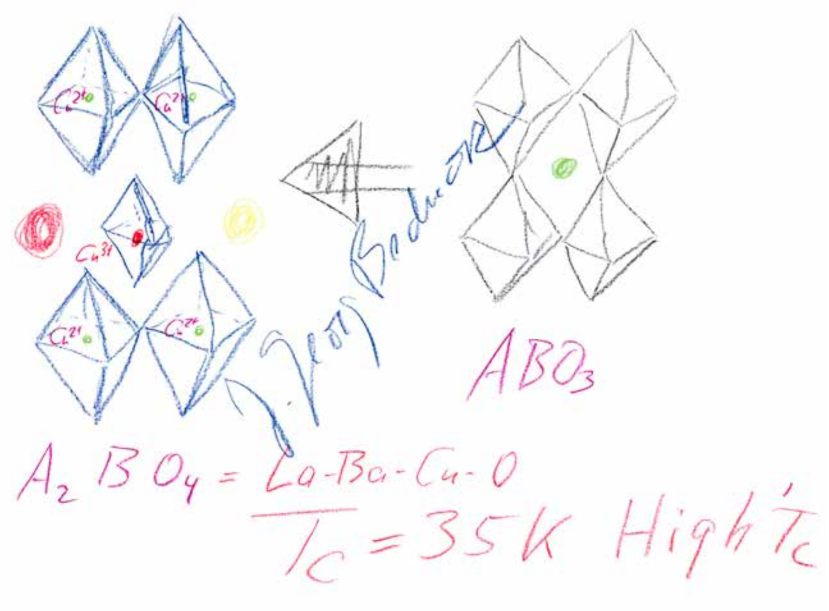
Amid all these disciplines, Zaanen sees himself as a bridge builder. 'I'm driven to physics by hedonism – my brain isn't as entertained by anything else,' he says. 'So, I'm extremely promiscuous: I enjoy working with experimentalists, programmers, and string theorists.'

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

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

now find themselves. The standard model of cosmology contains several unexplained elements, including dark matter.

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.

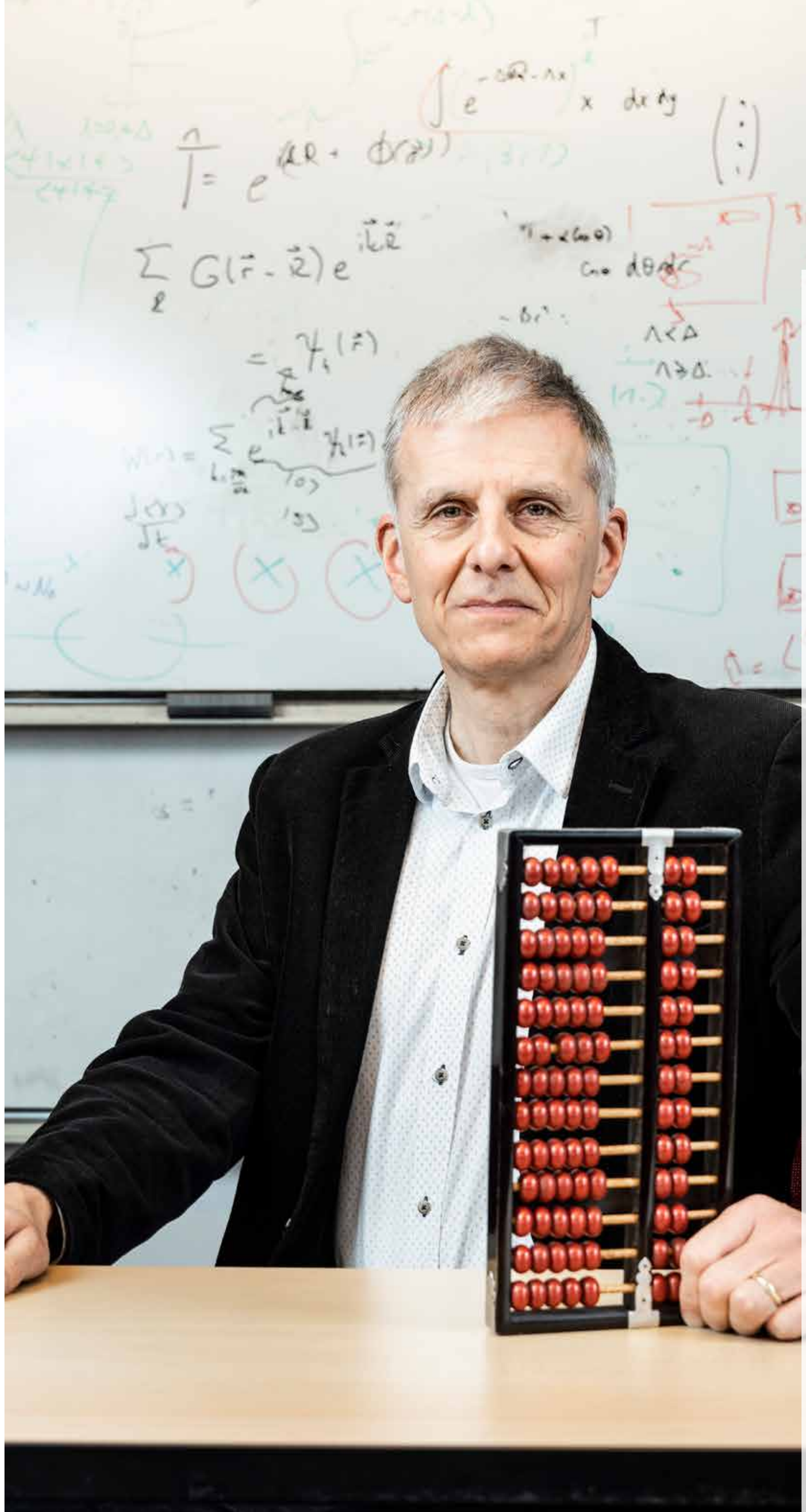
A possible candidate to fix these issues are weakly coupled particles. These are hypothetical particles with masses similar to those with which we are familiar. They are said to interact very little with other particles, which explains why we have never seen them despite their mass. 'We can look for 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

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