Superinsulators: The Hideout of Magnetic Monopoles

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Scientia

SUPERINSULATORS: THE HIDEOUT OF MAGNETIC MONOPOLES

Magnetic monopoles have long been dismissed as impossible by many physicists, but their existence has nonetheless been theorised for many decades. Through their extensive research, scientists at Terra Quantum AG, the University of Perugia, and SwissScientific Technologies, show that the end could soon be in sight for this conflict. The team's investigations into superconducting materials not only show that magnetic monopoles must be real – their discoveries also set the stage for exciting technological advances.

Single or Matched?

The concept of single electrical charge is ubiquitous in physics. Whether they are protons, electrons, or quarks, particles carrying either positive or negative charges are crucial to understanding many fundamental aspects of our universe.

Meanwhile, however, magnetism appears to operate under a different set of rules. Instead of being single, magnetic charges come in inseparable pairs – like the north and south poles in a bar magnet – which are connected by looping field lines. If such a magnet were broken in half, their two poles would not simply separate. Instead, they would each re-form an opposing pole – creating two new bar magnets.

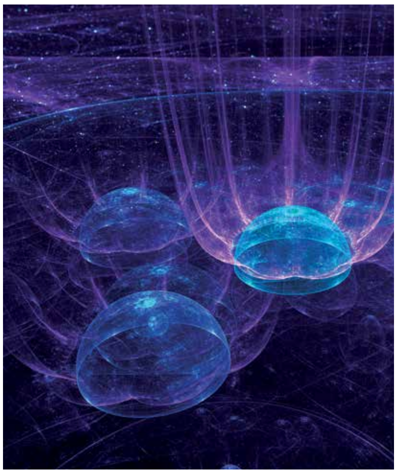
This principle is at the centre of the theory that isolated magnetic charges, named 'magnetic monopoles', cannot possibly exist. The idea was even expressed in the foundational equations of electromagnetism, first set out by James Clerk Maxwell in the 1860s – and stood unopposed for many decades afterwards.

However, this situation didn't last. In the 1930s, Paul Dirac expressed doubt in the idea of a fundamental difference between the properties of electrical and magnetic charges, whose resulting fields are otherwise treated in similar ways in Maxwell's equations. Through ground-breaking theoretical calculations, he showed for the first time how magnetic monopoles could exist after all.

Dirac's Case for Monopoles

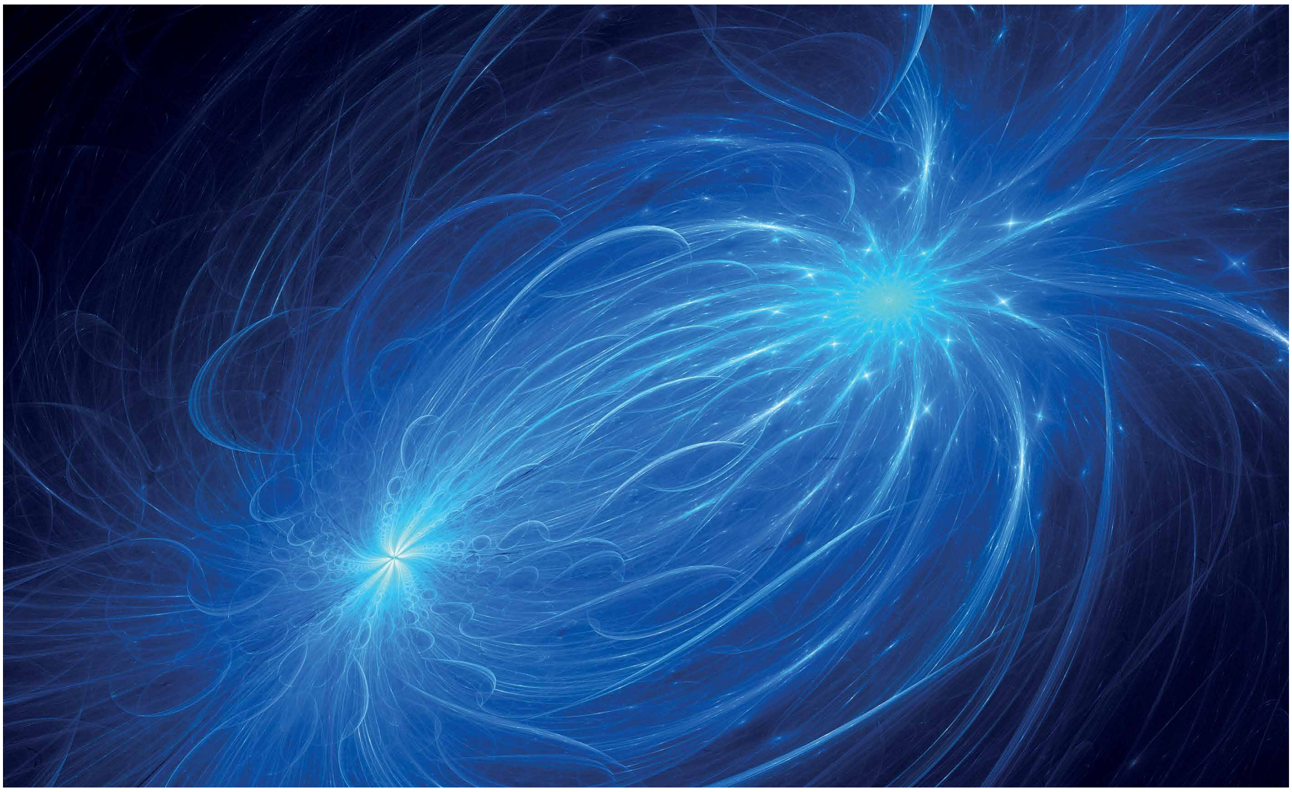
Dirac's ideas did not appear intuitive at first, but lead to a perfectly consistent quantum theory of electromagnetism, including both electric and magnetic charges. Magnetic charges cannot exist, because they lead to unacceptable singularities. However, if the product of the magnetic and electric charges is an integer multiplied by 'the Planck constant', these singularities become unobservable. The Planck constant is an important value in physics demonstrating that quantum mechanics underlies our world.

Crucially, Dirac's idea removes the inexplicable asymmetry between the properties of both charges within



Maxwell's equations. Furthermore, if combined with other fundamental forces – namely the strong and weak nuclear interactions – a theory emerges for the formation of magnetic monopoles shortly after the Big Bang, when temperatures across the universe were vastly hotter than they are today.

Despite the robust reasoning and elegant outcomes of Dirac's theory, researchers have still found no experimental evidence for such fundamental magnetic monopoles to date, even after many decades of searching. So far, several studies have



offered tantalising glimpses of the effects predicted by his ideas, but hard evidence for them still remains elusive.

Now, through extensive research, Dr Maria Cristina Diamantini at the University of Perugia, Dr Valerii Vinokur at Terra Quantum, and Dr Carlo Trugenberger at SwissScientific Technologies, predict that this long-standing deadlock could soon be about to change, by pointing out that magnetic monopoles should be searched for in materials in the laboratory rather than in the cosmos.

Advances in Superconductivity

The team's theories originate from an effect that appears at first to be unconnected to the search for magnetic monopoles. First discovered as far back as 1911, superconductivity is a phenomenon that allows electrical currents to flow through some materials with zero resistance. It arises in certain materials at ultra-cold temperatures, where pairs of oppositely-spinning electrons couple together through the effect of exchange by lattice vibrations called 'phonons'. The result is a 'Cooper pair' of electrons, which can flow through the material without dissipating any of their energy in the form of heat.

Superconductivity is a key example of a quantum effect that can be observed on macroscopic scales. It contrasts with the common misconception that quantum laws can only apply to small groups of particles, or over minuscule distances. The effect has now been known and studied for well over a century, but several of its aspects remain a mystery to physicists. Superconductors can be homogenous materials or synthetic arrangements of superconducting granules, called 'Josephson junction arrays'. In Josephson junction arrays, Cooper pairs exhibit quantum tunnelling between adjacent superconducting granules, mediating an electric current with no energy loss.

Superinsulators: The Hidden Face of Superconductors

In 1996, theoretical studies of regular Josephson junction arrays led Dr Diamantini and Dr Trugenberger to a new discovery: under certain conditions, the superconducting properties can switch around entirely, and a Josephson junction array can fall into a new state, which they called a 'superinsulator'. At ultra-low temperature, they predicted that these materials have an infinite electrical resistance, making it impossible for Cooper pairs to flow through them. As a result, superinsulators are 'twin mirror images' of superconductors in terms of their physical properties.

In their study, Dr Diamantini, Dr Trugenberger and a colleague demonstrated that superinsulating states could emerge close to the point of transition between superconducting and insulating states within Josephson junction arrays. Further to the insulating side, Cooper pairs would less readily tunnel between different granules, but would not be stopped entirely. At just the right point, however, they predicted that the material's conductivity would drop straight to zero.

Such an idea implied the need for a duality between the properties of electrical and magnetic charges: a principle that itself relied on the existence of magnetic monopoles. The team's discovery was so unexpected at first that it didn't receive much attention following its initial discovery. As a result, their findings remained largely unvisited for over a decade.

Rediscovery and New Understanding

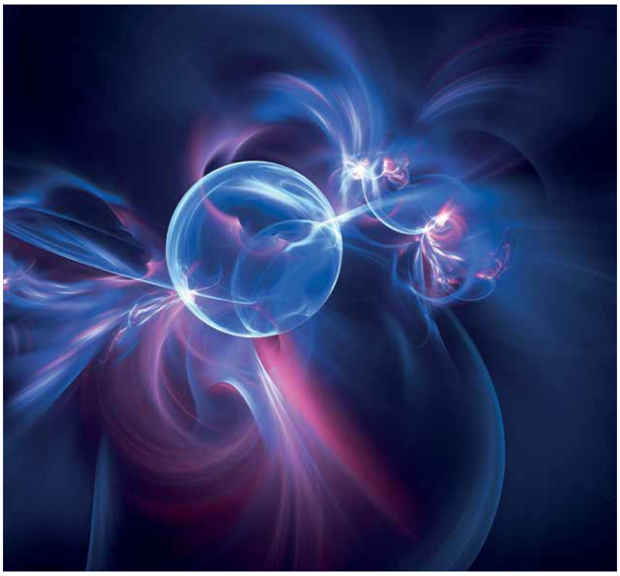
In 2008, exploring superconductor-insulator transitions in a seemingly unrelated physical system, strongly disordered thin films, Dr Vinokur and his research team discovered that upon cooling, the conductivity of an insulating film suddenly drops to zero at a certain temperature – decreasing its magnitude over a million times. This drop is the opposite to superconducting behaviour: when taken across the superconductor-insulator transition onto the superconducting side, the same film displayed a drop to zero electric resistance at superconducting transition temperature. Having followed in Kamerlingh Onnes footprints, Dr Vinokur's team also independently termed this newly discovered state with zero conductivity a 'superinsulator'. Dr Vinokur and his colleagues conjectured that close to the superconductor-insulator transition, the films self-organise into arrays of superconducting droplets coupled by Josephson tunnelling. Indeed, they demonstrated that near this transition, these disordered films behave exactly as regular Josephson junction arrays, as if there was no disorder whatsoever.

Dr Vinokur's team has built a solid understanding of the origin of a superinsulator on the foundational concept of quantum mechanics: the Heisenberg uncertainty principle. This principle states that it is impossible to measure two conjugated variables of a quantum system (for example, the position and the momentum of a particle) with absolute precision. The more accurately we know one of these variables, the less accurately we can measure the other.

Josephson junction arrays host two conjugated entities: Cooper pairs, representing electric charges, and superconducting vortices that impersonate magnetic charges. In superconductors, Cooper pairs form quantum fluid called a 'Bose condensate' that manifests quantum properties on macroscopic scales.

The basic experimental fact about superconductors is that the number of 'magnetic charges' is always known and fixed. This means that the number of Cooper pairs in the Bose condensate is fully uncertain and they move without scattering (otherwise one could have counted them), and hence, without resistance.

By reversing the uncertainty principle, Dr Vinokur and his colleagues ruled that fixing electric charges implies that magnetic vortices arbitrarily fluctuate around and become indistinguishable, forming a Bose condensate of magnetic charges. According to fundamental law of superconductivity, the 'Josephson effect', moving vortices create finite voltage. And finite voltage in the absence of current implies infinite resistance, hence formation of a superinsulator.



Characteristics of Quantum Fluids

Using the Heisenberg uncertainty principle brought about an understanding that is now supported by experiments, whereby the effect of infinite resistance at finite temperatures observed by Dr Vinokur's team at the insulating side of the superconductor-insulator transition stems from formation of the Bose condensate of magnetic charges.

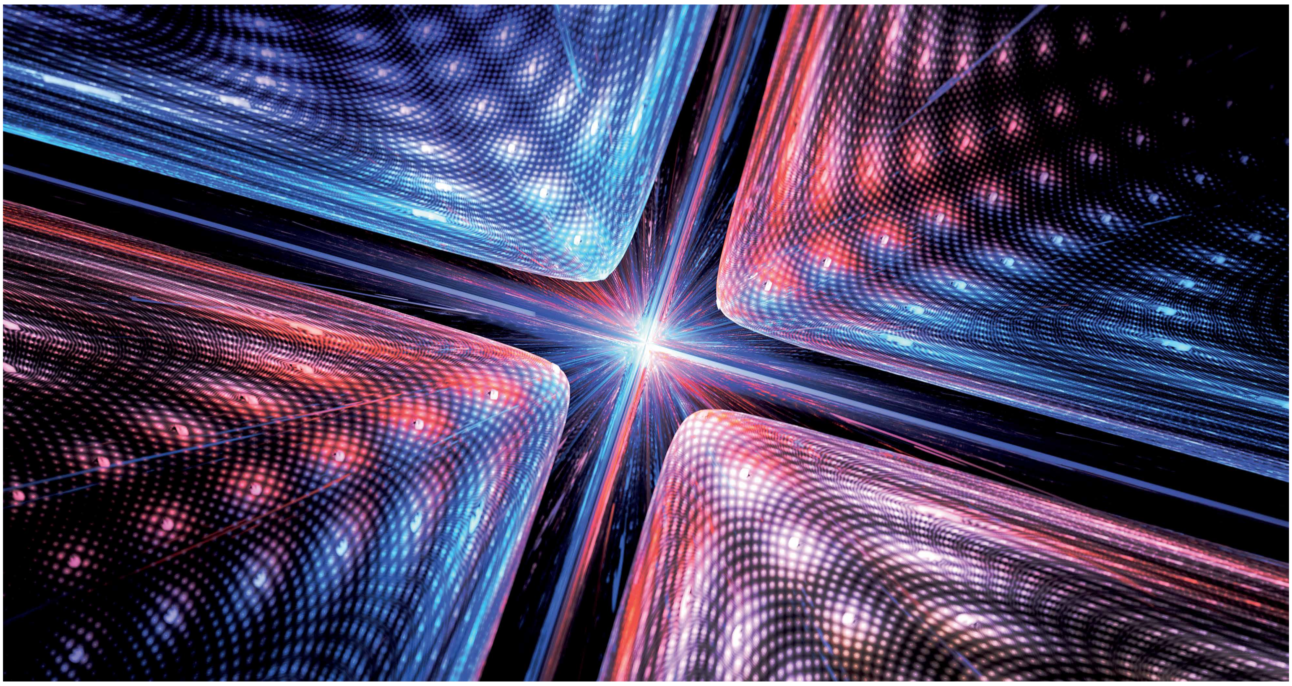
This Bose condensate is a mirror twin of the Bose condensate of paired electrons that is characteristic for the superconducting state. Therefore, duality between electrical and magnetic charges emerged again – now as a consequence of the most fundamental concept of quantum mechanics – and was strongly evidenced by experiment.

Squeezed Magnetic Filaments

The second fundamental effect characteristic to superconductivity to stem from Bose condensates of paired electrons emerges when superconductors are penetrated by magnetic fields. According to Maxwell's laws of electromagnetism and the hydrodynamics of charged superfluid liquids, this causes superfluid paired electrical charges within a material to move in circular paths around the magnetic field lines.

In turn, the magnetic fields created by these circularly moving charges will squeeze the external magnetic field lines into extremely thin filaments. These circling currents are known as 'Abrikosov vortices', and are a key demonstration that homogeneous superconductivity and homogeneous magnetic fields cannot coexist. Superconductors that allow for the penetration of a magnetic field in the form of Abrikosov vortices are called 'type II superconductors'.

Josephson junction arrays host a slightly different kind of magnetic vortices, which can exercise quantum tunnelling in



the grainy Josephson junction arrays observed in Dr Vinokur's experiments. This behaviour mirrors the Cooper pairs' tunnelling between superconducting granules and supports the picture of duality between the properties of electrical and magnetic charges. According to Drs Diamantini and Trugenberger's earlier theories, perfectly mirrored processes should also play out on the superinsulating side of the transition – demanding the presence of magnetic monopoles.

Until then, such effects had gone almost entirely unexplored – but this was about to change through the combined research of Dr Vinokur, Dr Diamantini, Dr Trugenberger, and their colleagues.

Parallels in Superinsulators

After more than a decade of repeating and improving on this initial experiment, the team has now gathered indisputable proof of this effect. Through their observations, they have discovered a necessity for magnetic monopoles to exist on the superinsulating side of Josephson junction array transitions.

Moreover, these singular charges must behave just like quantum particles – forming Bose condensates at ultra-low temperatures, which flow in circular paths around any electric fields that penetrate the material. In the same way that superconductors expel magnetic fields, this process squeezes electric fields into thin filaments, which tightly bind positive and negative charges together. In turn, any free flow of current is completely eliminated, resulting in an infinite resistance in the material.

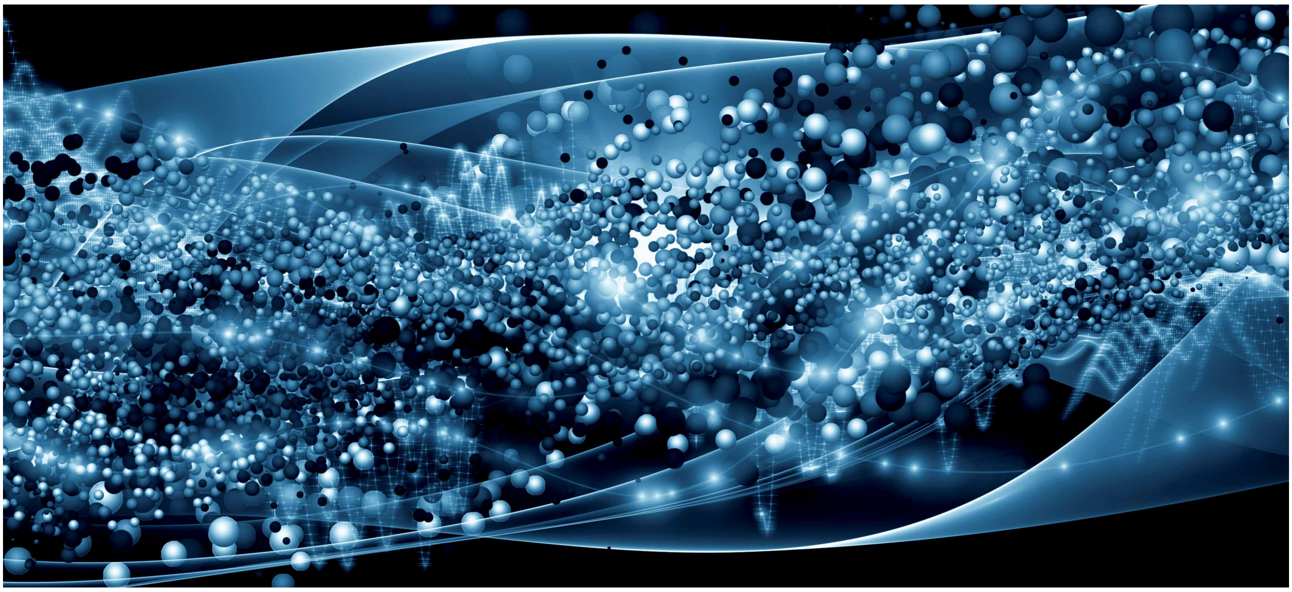
Clearly, this behaviour perfectly mirrors that of the magnetic filaments that form on the other side of the transition – fully realising the duality between electrical and magnetic charges first put forward by Dirac. In addition, the electric filaments display a remarkable similarity with pions – bound states of quarks. These fundamental particles are described by the Standard Model of particle physics, and form the basis of hadrons: a family of particles including protons, neutrons, pions and a diverse range of other, more exotic particles.

Pion-like Strings

Because of the strong nuclear force, a quark can never be observed outside of a hadron. If a physicist ever attempts to isolate a quark, other quarks will be generated spontaneously to ensure the laws of physics are not broken. As a result, the mechanisms used by quarks to bind together into hadrons can only be studied indirectly through high-energy collisions, and are still poorly understood. Such a property is notably comparable with the impossibility of separating the magnetic charges in a bar magnet – and according to the researchers, this is no coincidence.

Previous studies have given rise to theories involving a property named 'colour'. They suggest that quarks interact via the strong force by exchanging three possible colours – whose exact physical nature is still far from clear. In their research, Dr Diamantini, Dr Vinokur and Dr Trugenberger noted remarkably similar roles in the electric filaments observed in their superinsulators.

In particular, the Cooper pairs bound by the filaments have the same electrical properties of particles named 'pions': hadrons containing one of either an up or a down quark, and one of either of their antimatter counterparts. Moreover, this behaviour can be modelled using just one colour – avoiding the need to make any assumptions about unknown aspects of fundamental physics. Such a clear analogy could soon shed new light on a difficult problem in particle physics.



Generalising the Picture

Up until this point, Drs Vinokur, Diamantini, and Trugenberger had only studied the properties of superconductor-insulator transitions in 2D. To gain a full picture of the physics involved, they would need to extend their predictions to a more generalised, 3D case. From their earlier descriptions of electric filament confinement as a mechanism for superinsulation, alongside previous theories of the quantum fields that underly the universe's fundamental particles, the team has now made this step in their latest research.

Through these studies, they have found that magnetic monopoles can display even more exotic behaviours in 3D materials. In particular, they discovered clear evidence for electrical charges being carried on top of magnetic monopoles: particles named 'dyons' by theoretical physicists. Furthermore, these particles can also settle into Bose condensates when cooled, giving rise to even further intriguing properties.

These observations have now improved physicists' understanding of the once mysterious effect of high-temperature superconductivity, which enables current to flow with zero resistance at above ultra-cold temperatures. The researchers have now clearly shown that this behaviour can arise from the interplay between Cooper pairs and dyon condensates – once again, showcasing the key role of magnetic monopoles.

A New Mechanism for Attraction

Through this improved understanding, Drs Diamantini, Trugenberger and Vinokur were next able to shed new light on the mechanism that allows electrons to become paired in the first place, through interactions within their host materials. Previously, this mechanism was thought to be particle-like vibrations named 'phonons', which travel through solid atomic lattices. However, this would no longer work in high-temperature superconductors, where pairing mechanisms would need to be far stronger.

Instead, the researchers have suggested an entirely different route to Cooper pair formation, based on the attraction provided by magnetic monopoles. Unlike phonons, monopole-based mechanisms would allow electrons to become paired even when higher temperatures introduce more vibrations to atomic lattices – which would otherwise drown out the information carried by individual phonons.

This insight could soon be exploited by engineers to design new materials specially tailored to display superconductivity at room temperatures: now one of the most widely pursued goals in materials physics.

Unifying Two Charges

For nearly a century since Dirac's initial theories, the very idea of a symmetry between singular magnetic and electrical charges has been either heavily doubted, or dismissed entirely by many physicists. Yet through their ground-breaking discoveries of the crucial roles played by magnetic monopoles in providing a full picture of the duality of superconducting materials, Drs Vinokur, Diamantini, and Trugenberger are rapidly transforming this picture.

Not only do the team's ideas hold the potential to unify the physics of magnetic charges with those of electrical charges – the technological implications would also be profound. Through new ways to produce high-temperature and even room-temperature superconductors, researchers could soon produce technologies ranging from extremely high-performance sensors, to electrical circuits in which no energy is lost to heat. In turn, such discoveries could pave the way to tackling some of the newest and most exciting technological challenges emerging today.



Meet the researchers

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Dr Maria Cristina Diamantini completed her PhD in theoretical physics at the University of Perugia in 1995. She then held positions at both CERN and the University of Oxford with a fellowship of the Swiss National Science Foundation, while becoming a Humboldt fellow at the Free University in Berlin. She now teaches Theoretical Physics and Statistical Mechanics at the University of Perugia, and is part of the Noise in Physical Systems Laboratory in Perugia and of Italy's National Institute for Nuclear Physics (INFN, Perugia's section). Dr Diamantini has now been part of a wide variety of exciting research projects across Europe.

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Dr Carlo Trugenberger obtained his PhD in theoretical physics at ETH Zurich in 1988, and then pursued an international academic career, eventually becoming an associate professor of physics at the University of Geneva. He then went on to found two artificial intelligence companies – one of which he continues to manage today. Dr Trugenberger's research interests lie in both theoretical condensed matter physics and quantum gravity, and he continues to be an active part of both research communities.

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Professor Dr Valerii Vinokur completed his PhD in theoretical condensed matter physics at the Institute for Solid State Physics of the Academy of Sciences of USSR in Chernogolovka in 1979, where he worked until 1990. In 1990, he assumed an appointment at Argonne National Laboratory, USA. In 2021, he retired from his position of Senior Scientist and Argonne Distinguished Fellow, to join Terra Quantum AG as its Chief Technology Officer in the US. Professor Vinokur is a Foreign Member of the National Norwegian Academy of Science and Letters and Fellow of the American Physical Society. He has won numerous awards for his groundbreaking research, including the International John Bardeen Prize in 2003, the Alexander von Humboldt Research Award in both 2003 and 2013, and the Fritz London Memorial Prize in 2020.

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