with ambient gas contributes. Finally, the first detection of astrophysical high-energy neutrinos by IceCube was another breakthrough in the path toward identifying the sources of cosmic rays. This wealth of data now challenges theories of cosmic-ray emission scenarios to properly describe all observables.

Fang and Murase went beyond the state of the art by presenting a model of cosmic-ray emission from active galactic nuclei that takes local and global propagation into account. Active galactic nuclei are thought to be typically embedded in galaxy clusters — a medium that strongly differs from the general intergalactic medium in magnetic field strength and density. Both magnetic field and density are significantly higher, leading to larger diffusion and interaction effects. The interaction of cosmic rays with photon fields in the cluster results in the production of photons and neutrinos in the local cluster medium and therefore contributes to the measured photon and neutrino fluxes on Earth.

In a second step, the authors propagated cosmic rays through the intergalactic medium to Earth. The model properly reproduces both the energy spectrum and composition of cosmic rays. It also predicts that the dominant part of the fluxes of high-energy photons and neutrinos observed at Earth must originate from the clusters. The entire two-step propagation scenario is sketched in Fig. 1 for one active galactic nucleus located in a cluster.

This article certainly represents a novel theoretical approach that offers many paths for future research, in terms of both observations and theory. It needs to be emphasized, however, that the article does not provide a full statistical treatment, but rather qualitatively discusses that it is possible to describe the multimessenger picture of cosmic rays, photons and neutrinos consistently. In a quantitative statistical study, a parameter scan providing best-fit regions for the parameters would need to be provided — including, for example, a prediction of the strength of the cluster magnetic field and the spectral behaviour of cosmic rays at the source. Only then can it be determined whether the parameters needed to properly fit all the data are in a range that fits the general astrophysical picture.

Nevertheless, the paper presents a novel approach to describing all multimessenger data, which gives the field an important incentive to dig deeper by extending the model and testing it with observational data. A necessary future test is the modelling of cosmic-ray propagation in a three-dimensional magnetic field through the intergalactic medium. In this way, the prediction of arrival direction patterns of cosmic rays can be compared to cosmic-ray (an)isotropy level as measured by the Telescope Array and the Pierre Auger Observatory, something that is still missing in this paper. It is a challenge, because detailed magnetohydrodynamic-based models of the magnetic field structure of the Universe are only available for the local Universe — that is, up to around 100 Mpc.

Fang and Murase have paved the way to more detailed studies of a full treatment of propagation and interaction from the acceleration site in active galactic nuclei to Earth. The model can further be tested by looking for a possible correlation of the arrival direction of neutrinos with low-mass clusters, as predicted in this theoretical modelling. Future neutrino observatories such as IceCube-Gen2 and KM3NeT will be able to perform dedicated searches to verify or falsify the hypothesis of active galactic nuclei being the sources of the highest energy cosmic rays.

The authors predict that one source class can explain the entire non-thermal energy budget of hadronic photons, neutrinos and cosmic rays. If this scenario can be strengthened, models favouring sources such as gamma-ray bursts or starburst galaxies for parts of these detections could be proven wrong and we would need to rethink the role of cosmic rays in those environments. ❒

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TOPOLOGICAL SUPERCONDUCTIVITY

Quantized, finally

Quantized Majorana conductance is a hallmark of topological superconductors, but its fragility has made it difficult to observe. Device improvements have now enabled its measurement, making everyone eager to see the next step — topological qubits.

Marcel Franz and Dmitry I. Pikulin

Topological states of matter exhibit quantized physical observables. For example, in quantum Hall liquids the transverse conductivity can only assume values that are rational multiples of the conductance quantum e^2/h. In the case of one-dimensional topological superconductors, the physical observable theoretically predicted to exhibit quantization is the tunnelling conductance between the topological superconductor and an external normal lead[1–3] — known as Majorana conductance. This quantization, expected to be exact only at zero temperature, is more fragile than in the case of the quantum Hall effect, and has eluded observation so far. Writing in *Nature*, Hao Zhang and colleagues[4] have now reported robust quantized Majorana conductance in a semiconductor nanowire that hosts topological superconductivity due to a combination of spin–orbit coupling, induced superconductivity and Zeeman splitting created by a magnetic field[5,6].

Majorana fermions, particles that are indistinguishable from their antiparticles, have been theoretically predicted some 80 years ago by Ettore Majorana[7] in the context of high-energy particle physics. To this day they remain unobserved

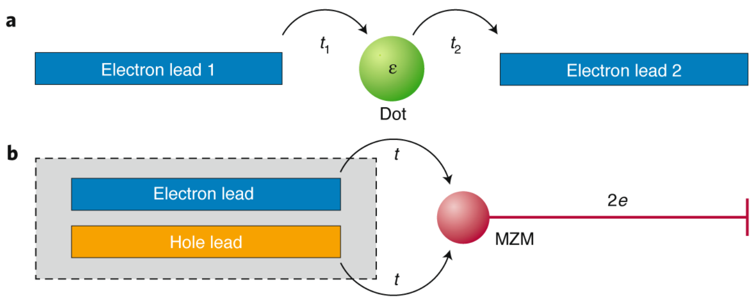

Fig. 1 | Resonant transmission and Andreev reflection. a, Two leads are attached to an island, which we model, for the sake of simplicity, as a single electron level with energy ε. An electron can hop on and off the island from the two leads and the respective tunnelling amplitudes are t_1 and t_2. **b**, A lead is attached to the Majorana-harbouring device, such as the Al-covered InSb wire employed in the experiment of Zhang and colleagues[4]. An electron or a hole from the lead can tunnel into the Majorana zero mode (MZM) with equal amplitude.

in that realm. However, a special instance of such a particle can exist as a collective manifestation of topological superconductivity in certain solids[1,5,6,8] — a quasiparticle known as Majorana zero mode. Signatures of these modes have indeed been reported in several condensed-matter systems, including semiconductor quantum wires[9], magnetic atom chains on superconducting substrates[10] and vortices in the so called Fu–Kane superconductor[11].

Many improvements in the device quality were necessary before the system was clean enough to observe the predicted conductance quantization. This is the achievement of Hao Zhang and co-workers, who finally demonstrated quantized Majorana conductance in indium antimonide semiconductor nanowires, covered with an epitaxial aluminium superconducting shell, by placing them in an external magnetic field of approximately 0.8 T. They have tested the robustness of the quantization to changes in the magnetic field, global gate voltage and tunnel barrier. This report comes on the heels of an earlier work by the group of Charles Marcus from Copenhagen[12], who observed scaling of the conductance consistent with quantization (but not the persistent quantized value itself).

So why do we expect Majorana zero modes to give rise to quantized conductance? The answer lies in the phenomenon of resonant Andreev reflection. To understand this, it's helpful to first consider the simpler problem of conductance through a quantum dot in a set-up as illustrated in Fig. 1a. According to the seminal work by Rolf Landauer in the 1970s, the conductance in this situation depends on the quantum-mechanical probability of an electron with a certain energy being transmitted from one lead to the other. Computing this probability is an undergraduate-level exercise in wavepacket scattering, yielding a conductance of e^2/h provided that the amplitude corresponding to the electron hopping between the first lead and the dot equals that of hopping from the dot to the second lead, and that the electron energy is resonant with the localized level. Under these conditions, perfect transmission is achieved independently of the hopping amplitudes — as long as they remain equal and non-zero.

Resonant Andreev reflection into a Majorana mode can be understood from similar considerations. The mathematical properties of these modes, due to the fact that a Majorana fermion is its own antiparticle, constrain the form of the most general Hamiltonian describing the tunnelling between a normal lead and a topological superconductor (Fig. 1b): the tunnelling amplitudes of an electron or a hole into a Majorana zero mode have to be equal. When, in addition, the energy of the incoming electron is matched with that of the mode at zero energy, a condition known as zero bias, tunnelling becomes a resonant process in which the incoming electron is reflected with certainty from the Majorana zero mode as a hole, leaving behind charge $2e$, which is converted into a Cooper pair. The conductance in this case is $2e^2/h$ because the charge transferred in each such event is $2e$. This is the essence of resonant Andreev reflection. Crucially, the condition of equal hopping amplitudes, which had to be imposed externally in our quantum dot example, is in this case automatically satisfied due to the unique property of Majorana zero modes. The conductance is thus quantized and requires no fine tuning of the hopping amplitudes.

In the paper by Hao Zhang and colleagues[4] the experimentally measured conductance is shown as a function of the tunnel-gate voltage, which can be thought of as controlling the tunnelling amplitude. At zero bias the conductance is mediated by the zero mode and shows a well-developed quantized plateau at $2e^2/h$ in accordance with the theoretical prediction. At higher bias no quantization is observed. This gives a glimpse of the impressive stability of the quantized peak with respect to the changes in the tunnelling amplitude, magnetic field and global chemical potential, observed in the current experiment and calculated using the accompanying theory.

The theoretical considerations predicting the quantized conductance are very hard to attain in actual experimental realizations of Majorana zero modes. Disorder in the contact between the normal lead and the topological superconductor, finite temperature, imperfections and soft gap in the superconducting part of the sample all lead to corrections to the quantized value. It took a heroic effort to fabricate a device where these problems would be overcome — making such a device a new standard in Majorana research.

Having achieved the milestone of quantized Majorana conductance, what is the next step? The long-term goal is to exploit the special property of Majorana zero modes — their non-Abelian exchange statistics — in topological quantum computation. For this, one must first build a Majorana qubit. Theoretically, such a device would be almost immune to decoherence — the bane of regular non-topological qubits. Several different designs for building a qubit out of Majorana zero modes are currently being tested in labs around the world. The next big milestone is to verify the non-Abelian exchange statistics by performing braiding or fusion operations[13]. Given the latest progress, this goal might just be within our grasp. ❐

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TURBULENCE CONTROL

Peace in the pipeline

Turbulence in pipe flows causes substantial friction and economic losses. The solution to appease the flow through pipelines might be, counterintuitively, to initially enhance turbulent mixing and get laminar flow in return.

Mitul Luhar

Vast networks of pipes crisscross our cities, suburbs and rural areas. These pipe networks are often invisible, buried underground or tucked away in uninhabited areas. Yet they serve as essential circulatory systems that keep our society going, transporting water, oil, natural gas and other goods (Fig. 1a). Operating these networks is expensive, not least because a tremendous amount of energy is required to overcome the frictional losses generated by fluid flow in large-scale pipelines[1]. Generating this energy costs tens of billions of dollars each year globally. Given the scale of the problem, even a small reduction in friction has the potential to yield substantial economic and environmental benefits. Writing in *Nature Physics*, Jakob Kühnen and colleagues[2] demonstrate an elegant approach for reducing frictional losses in pipes, and hence pumping-power requirements, by as much as 90%.

More specifically, Kühnen et al. have found a general method for suppressing turbulence in pipe flows. Compared to ordered laminar flow, turbulent flow generates, at a given flow rate, significantly more friction at the pipe walls. Ever since Osborne Reynolds's landmark studies in the late nineteenth century[3,4], it has been widely accepted that pipe flows transition from an ordered laminar state to a disordered turbulent state once a dimensionless quantity known as the Reynolds number exceeds a critical value. Most pipelines operate at Reynolds numbers far above this critical threshold. The real question then is how turbulence can be suppressed at these high Reynolds numbers.

It turns out that one must take a step back to move forward. In numerical simulations and experiments, Kühnen et al. show that turbulence can be suppressed over large sections of pipes by initially enhancing turbulent mixing. This counterintuitive measure leads to a more uniform flow across the pipe cross-section, which in turn causes the turbulence to die away (Fig. 1b).

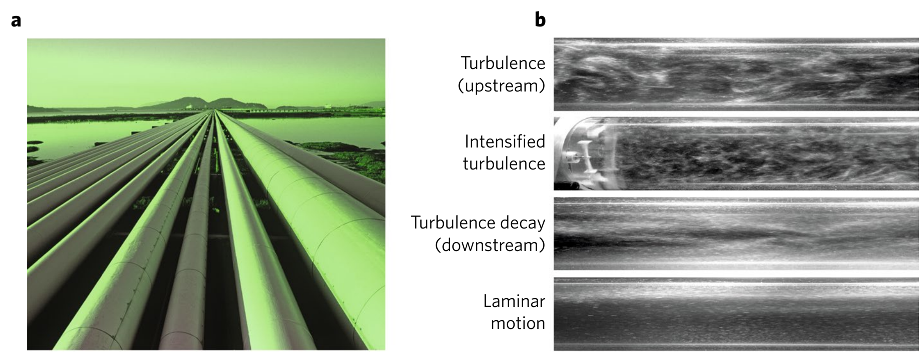

Fig. 1 | What a drag. a, Turbulence increases friction in pipelines. **b**, The counterintuitive solution proposed by Kühnen et al. involves initially enhancing turbulent mixing to get laminar flow in return. Credit: Alan Kearney/Getty Images (**a**); reproduced from ref. [2], Macmillan Publishers Ltd (**b**).

To fully grasp why this procedure works, one must understand what fuels turbulence in the first place. The energetics of turbulent flows are perhaps best explained with a decomposition of the flow field into an average mean component and a fluctuating turbulent component. This decomposition is known as Reynolds-averaging[4]. In the Reynolds-averaged version of the governing Navier–Stokes equations, the turbulent fluctuations are sustained by energy transfers from the mean flow. This energy transfer arises due to interactions between the turbulent eddies and the gradient in mean velocity. In other words, the variation in the mean flow across the pipe cross-section fuels turbulence. For a more uniform mean flow field, this gradient disappears and the energy transfer pathway from the mean flow to the turbulence is closed off. And without a sustained energy input, the turbulence decays away.

To demonstrate this effect in numerical simulations, Kühnen and co-workers included an artificial forcing function in the governing equations that made the mean velocity profile more uniform. For appropriately chosen forcing, the turbulent fluctuations disappeared completely — the flow relaminarized. At the highest Reynolds numbers tested, the friction coefficient dropped by nearly 95% as a result.

In accompanying laboratory experiments, Kühnen et al. showcased how such turbulence suppression systems could be implemented in practice. To enhance turbulent mixing and create a more uniform mean flow profile, they employed multiple techniques, including stirring using rotors (Fig. 1b), injection of small jets of fluid from the wall and abruptly moving a small section of the pipe wall. In each case, a complete collapse of the turbulent flow was observed downstream of the forcing location. Also, this new laminar state persisted for a long distance, more than a hundred pipe diameters. The ensuing reduction in