TSINGHUA RESEARCH HIGHLIGHTS

SELECTED CONTRIBUTIONS TO FUNDAMENTAL SCIENCE AND SCHOLARSHIP

Hydrazide-Enabled De Novo Chemical Protein Synthesis: Unlocking Access to Beyond-Biology Proteins

Hardware and Algorithm Advances Tackle the Grand Challenges of Fault-Tolerant Quantum Computing

Decoding Dengue Transmission: Linking Host Signals, Vector Infection, and Symbiont-Based Control

Tsinghua Fluorescence Lights the Way to Efficient and Stable Blue OLEDs

CONTENTS

At the core of a great research university lies a sustained commitment to the pursuit of knowledge and to the deeper understanding of nature and the world.

This volume presents selected research contributions from Tsinghua University in recent years, spanning physics, chemistry, engineering, life sciences, and medicine. While diverse in discipline and methodology, these contributions are united by a common intellectual aim: to elucidate fundamental principles, open new directions of inquiry, and extend the boundaries of existing understanding.

Together, they reflect a research culture grounded in rigor, curiosity, and long-term intellectual commitment.

This volume offers a glimpse into that continuing endeavor.

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Decoding Dengue Transmission: Linking Host Signals, Vector Infection, and Symbiont-Based Control

A fragmented understanding of how mosquitoes locate infected hosts and support viral transmission has limited effective control strategies. Integrated insights into host-derived signals, extracellular vesicle–mediated infection, and symbiont-based interference now provide a mechanistic framework for system-level intervention.

> Implementing an environmental intervention using a naturally occurring symbiotic bacterium represents an eco-friendly biocontrol strategy with promise for controlling dengue transmission in endemic regions.

Mosquito-borne diseases such as dengue continue to impose a substantial global health burden, infecting hundreds of millions of people each year. At the heart of these diseases lies a deceptively simple but highly efficient biological cycle: a mosquito bites an infected person, acquires the virus, and later transmits it to a new host through another bite. This "host–mosquito–host" transmission cycle underpins the global spread of dengue and other arboviruses.

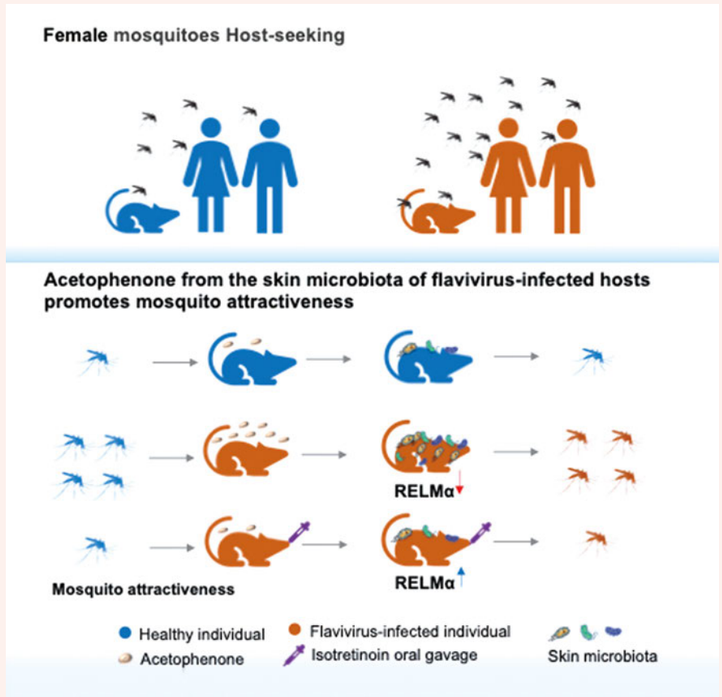
Mosquitoes play an active and highly selective role in determining whether a virus can spread. First, mosquitoes locate infected hosts within large populations. After ingesting infected blood, the virus replicates and disseminates within the mosquito before it can be transmitted again. Importantly, not all mosquitoes can transmit all viruses. For example, *Aedes* mosquitoes efficiently spread the dengue virus, whereas other species, such as *Culex* mosquitoes, cannot transmit the dengue virus. This species specificity has long been recognized; however, its underlying biological basis remains unclear.

These complexities point to two fundamental questions: how mosquitoes preferentially target infected individuals and what determines whether a mosquito becomes a competent vector? Addressing these questions is essential, as they represent the key bottlenecks that control transmission efficiency. Recent advances from

three complementary lines of research now provide a more complete and mechanistic view of this process.

Dengue virus enhances host attractiveness to promote mosquito targeting

The first breakthrough reveals that the dengue virus actively enhances its own transmission at the host level. Infection alters the skin microbiota, leading to increased production of volatile compounds such as acetophenone, a microbiota-derived metabolite. This compound strongly stimulates mosquito olfactory systems, enabling mosquitoes to preferentially locate infected individuals—even when they are rare within a population. This finding explains a long-standing epidemiological puzzle: how mosquitoes efficiently identify infected hosts during the early stages of an outbreak. By biasing mosquito feeding behavior toward infectious individuals, the virus effectively increases its chances of being acquired and transmitted.



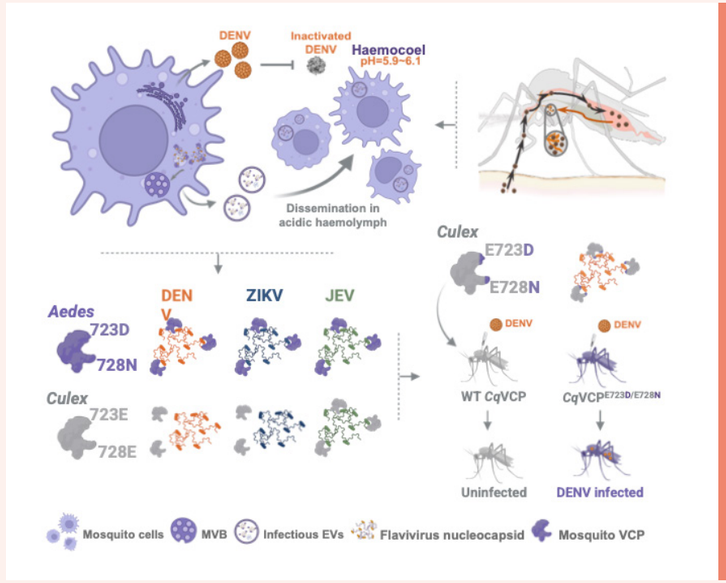
Dengue virus enhances host attractiveness by altering skin microbiota-derived volatiles, acetophenone, thereby promoting mosquito targeting of infected individuals. Designed by a team at Tsinghua University. Credit: Tsinghua University

Dengue virus establishes systemic infection in mosquitoes despite the acidic internal environment

The second advance addresses what happens after the mosquito takes an infectious blood meal. Inside the mosquito, the virus encounters a hostile environment: the hemolymph is acidic (pH ~6.0), a condition that can inactivate free viral particles. This challenges the traditional view that viruses spread as intact particles within the vector. Instead, the dengue virus uses a non-classical strategy. It hijacks extracellular vesicles (EVs) to transport its genetic material in a protected form. This process depends on a specific interaction between a mosquito protein, VCP, and the viral capsid. Notably, this interaction varies between mosquito species, providing a molecular explanation for why only certain mosquitoes can transmit the dengue virus. This work redefines how viruses survive and disseminate within the mosquito and reveals the molecular basis of vector specificity.

Symbiont-based strategies effectively block dengue virus transmission

The third line of research translates these mechanistic insights into a practical intervention strategy. Researchers identified a naturally occurring symbiotic bacterium, *Rosenbergiella sp. YN46*, that colonizes the mosquito gut. This bacterium acidifies the gut environment during blood feeding, lowering the pH to levels that effectively inactivate the dengue virus before it can establish infection. Semi-field studies show that introducing this bacterium into mosquito breeding environments significantly reduces viral infection rates in mosquito populations. Because the bacterium is naturally occurring and environmentally stable, this approach represents a promising and scalable strategy for dengue control. As noted by the researchers, "Implementing an environmental intervention using a naturally occurring symbiotic bacterium represents an eco-friendly biocontrol strategy with promise for controlling dengue transmission in endemic regions."

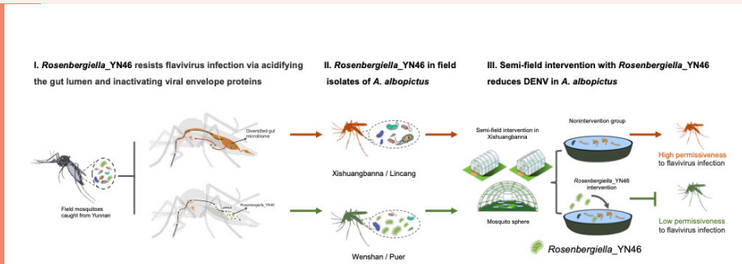


Dengue virus establishes systemic infection in mosquitoes through an extracellular vesicle–mediated mechanism that protects viral components from the acidic hemolymph environment. Designed by a team at Tsinghua University. Credit: Tsinghua University

Future directions

Together, these three lines of work establish a coherent, multi-scale framework for understanding dengue transmission: host-derived signals enhance mosquito attraction, EV-mediated mechanisms enable viral survival and dissemination within the mosquito, and symbiotic bacteria can disrupt infection at the earliest stage. This integrated perspective shifts the paradigm from isolated interventions to system-level control strategies. Future efforts should focus on integrating these strategies into coordinated intervention programs, evaluating their effectiveness across diverse ecological settings, and assessing long-term evolutionary responses. By targeting multiple rate-limiting checkpoints within the transmission cycle, this integrated framework provides a foundation for next-generation, system-level strategies to achieve sustainable control of dengue and other mosquito-borne viruses.

The naturally occurring symbiotic bacterium Rosenbergiella_YN46 inhibits dengue virus transmission by acidifying the mosquito gut during blood feeding. Designed by a team at Tsinghua University. Credit: Tsinghua University



Breaking the Limits of In Vivo Imaging: RUSH3D Unveils 3D Biological Dynamics at the Mesoscale

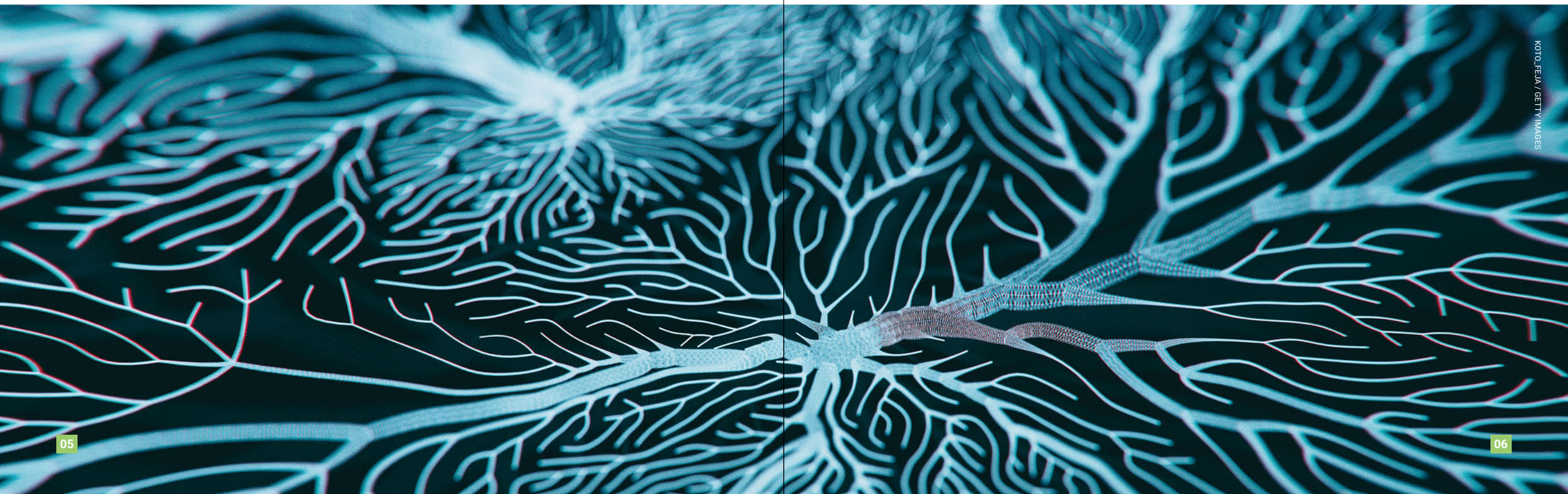
A new mesoscale imaging paradigm integrates digital adaptive optics, scanning light-field microscopy, and deep learning to capture 3D cellular behaviors and functions across whole organs with unprecedented fidelity.

> Modern AI and computational imaging modelscan fundamentally change the way we observe the complexity of life," says the research team. "By combining hardware innovation with deep learning,we can now monitor panoramic biological processes that were previously invisible.

For decades, biological imaging has been defined by a fundamental struggle between two axes: resolution and field of view. While breakthroughs like cryo-EM and super-resolution microscopy have pushed the boundaries of biological imaging to see individual molecules, they are typically limited to a few cells.

Conversely, medical imaging such as CT and MRI can visualize entire organs, yet they lack the single-cell resolution necessary to understand complex cellular interactions.

It represents a significant gap in the technical landscape. Capturing both a large field of view and high resolution to analyze large-scale intercellular interactions at the organ level is known as mesoscale imaging. Bridging this gap is essential for understanding how large-scale intercellular dynamics govern life. Now, a research team at Tsinghua University has developed RUSH3D, a next-generation mesoscale intravital fluorescence microscopy.



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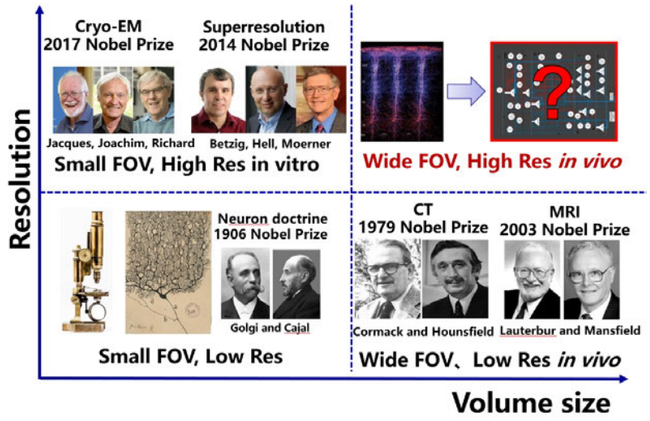


Tradeoff between resolution and field of view for biomedical imaging. Credit: Tsinghua University

A breakthrough in mesoscale computational imaging

At the core of RUSH3D is a transformative approach to digital adaptive optics (DAO), which overcomes the fundamental challenge of spatially nonuniform optical aberrations. While traditional microscopes sacrifice resolution as the field of view expands, the team implemented a wave-optics DAO framework capable of performing tiled, high-speed aberration corrections across the entire imaging volume. This innovation allows the system to maintain near-diffraction-limit resolution even at a centimeter-wide mesoscale, an essential requirement for capturing fine cellular details throughout whole organs. The aberration correction capability is seamlessly integrated into a scanning light-field imaging framework, further enhanced by axially elongated line-confocal illumination to suppress background fluorescence. By removing complex aberrations digitally rather than through bulky hardware, the RUSH3D provides the unprecedented fidelity for long-term, high-speed 3D observation in native intravital environments.

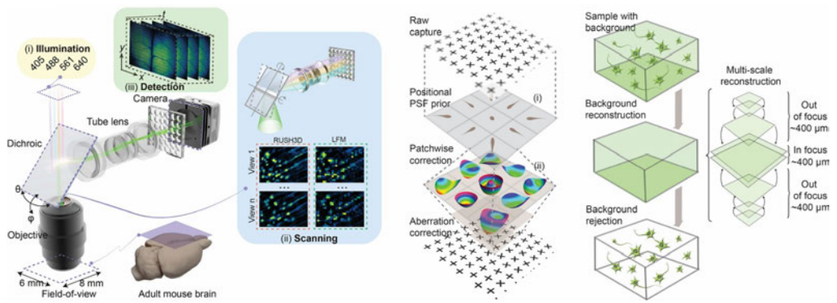
AI-powered image processing and analysis

To handle the vast volumes of data generated at the mesoscale, RUSH3D leverages cutting-edge deep learning algorithms. The team implemented DeepCAD-RT for real-time noise suppression, enabling high-sensitivity imaging even under low light to minimize phototoxicity. Furthermore, the DeepWonder framework supports the rapid, automated extraction of cellular signals from thousands of cells simultaneously. The integrated pipeline ensures that mesoscale big data is translated into clear biological insights with minimal manual influence.

Visualizing cellular dynamics within the living organs

By integrating these novel technologies, RUSH3D allows for long-term, high-speed 3D imaging at a centimeter-scale field of view, which is a “game-changer” for observing intercellular dynamics across a mammalian organ.

The RUSH3D framework. An illustration of the system architecture (left) highlighting the wave-optics DAO (right) for large-scale aberration removal, enabling high-fidelity 3D imaging across mesoscale biological volumes. Credit: Tsinghua University

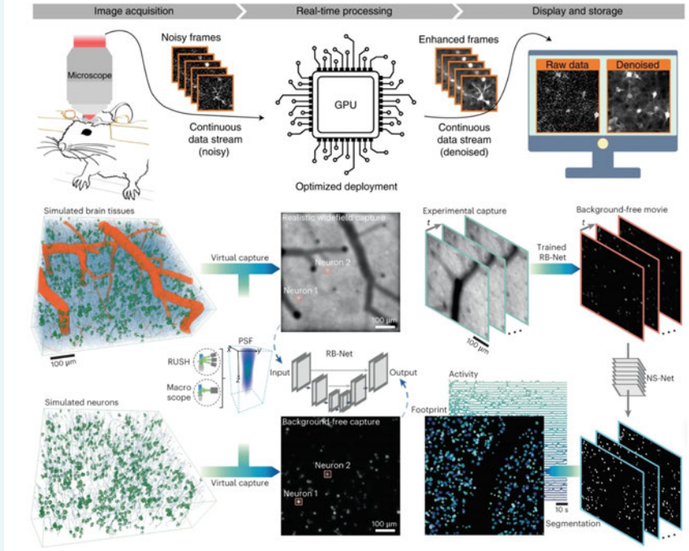


“Modern AI and computational imaging models can fundamentally change the way we observe the complexity of life,” says the research team. “By combining hardware innovation with deep learning, we can now monitor biological processes that were previously invisible.”

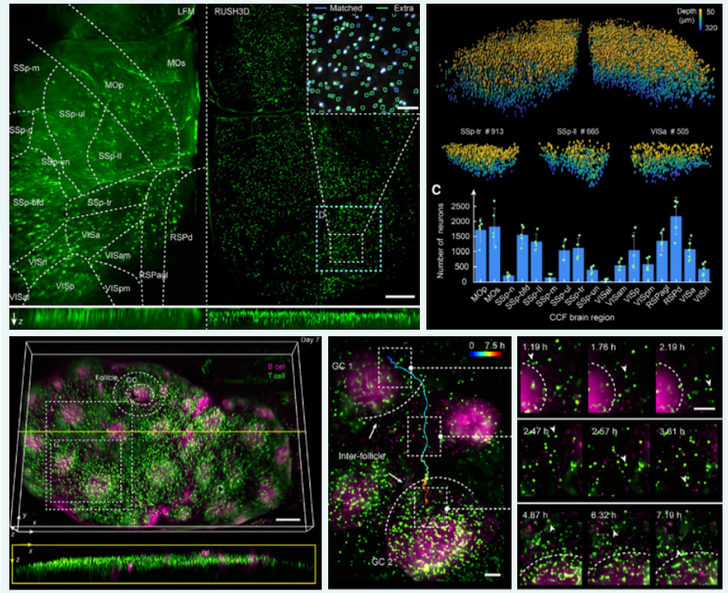
The team has successfully recorded the activity of over 10,000 neurons simultaneously across multiple cortical areas in mice. Furthermore, they observed the formation and progression of multiple germinal centers in lymph nodes, capturing the real-time interactions between T cells and B cells during an immune response over several days.

Future frontiers for advancing drug R&D

The development of RUSH3D marks a pivotal shift in how we observe the complexities of life at the mesoscale, opening doors to previously unreachable research frontiers. By capturing intricate interactions in native physiological environments, RUSH3D will offer researchers unprecedented visual evidence to evaluate therapeutic efficacy and safety during drug R&D, moving beyond barriers to offer a much clearer window into the performance of next-generation therapeutic candidates.



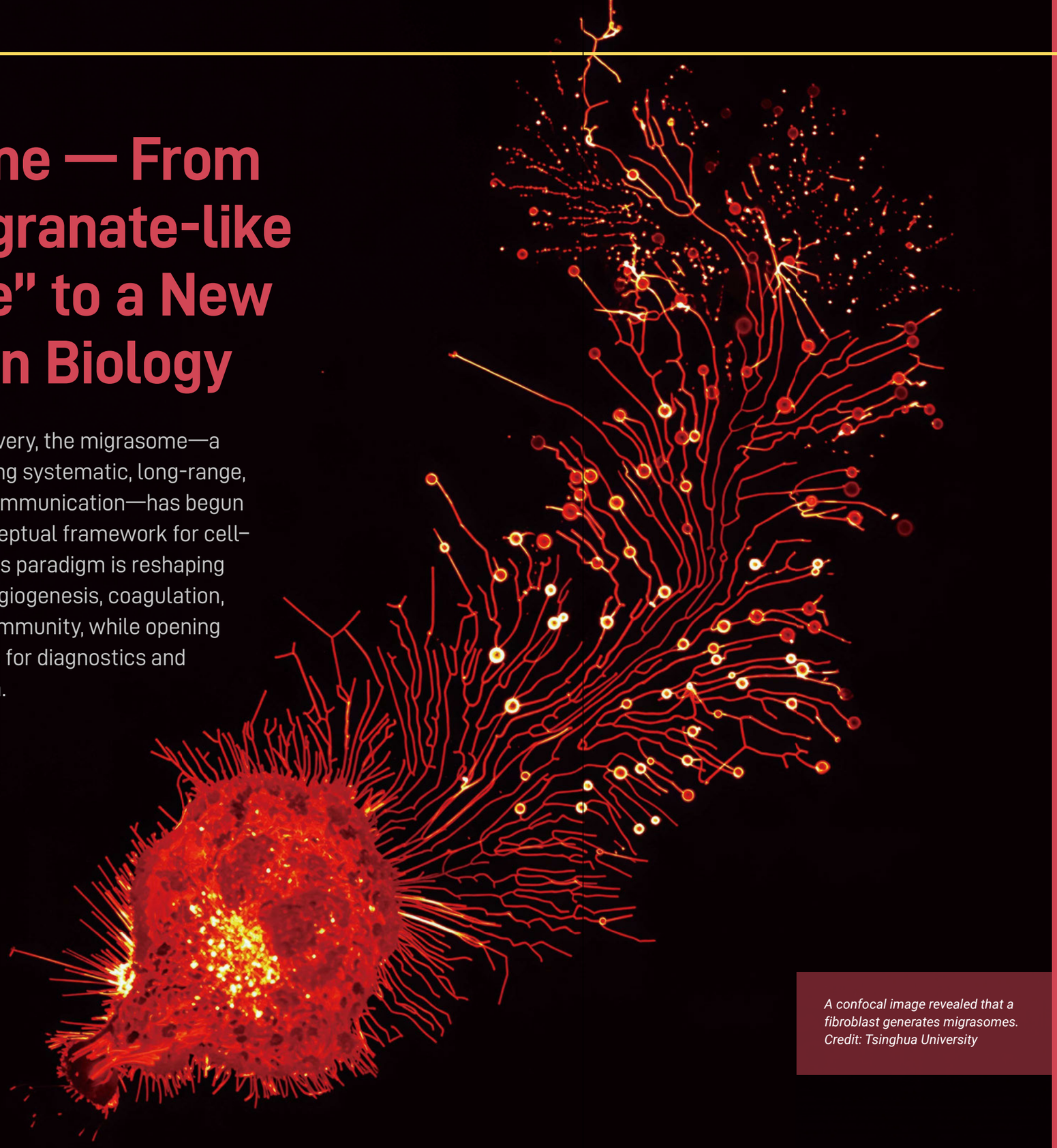
AI-powered image processing pipeline for denoising (top) and neural activity extraction (bottom). Credit: Tsinghua University



Mesoscale Intravital observations. (Top) Cortex-wide 3D neural recording in a behaving mouse. (Bottom) Long-term tracking of intercellular dynamics and B cell clustering within lymph node germinal centers. Credit: Tsinghua University

Migrasome — From a "Pomegranate-like Structure" to a New Frontier in Biology

A decade after its discovery, the migrasome—a unique organelle enabling systematic, long-range, and targeted cellular communication—has begun to establish a new conceptual framework for cell–cell communication. This paradigm is reshaping our understanding of angiogenesis, coagulation, tumor metastasis, and immunity, while opening unprecedented avenues for diagnostics and therapeutic intervention.



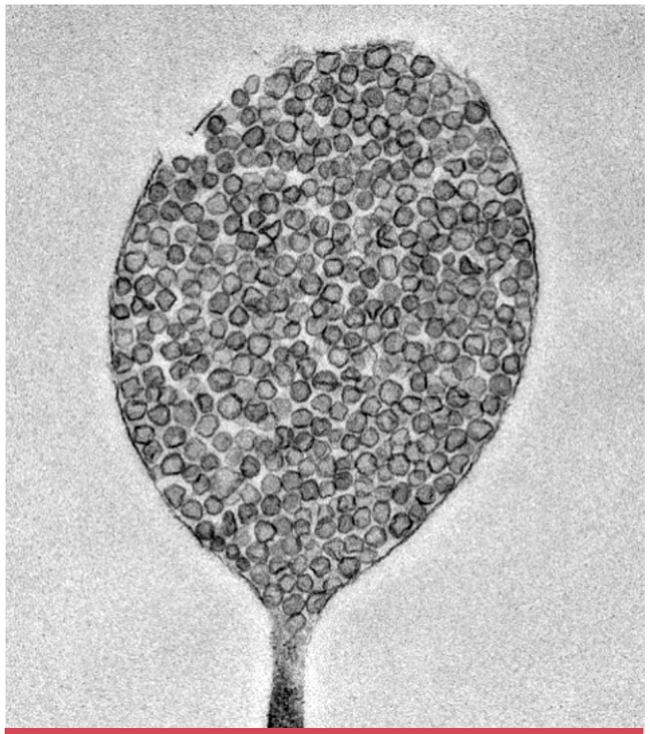
A confocal image revealed that a fibroblast generates migrasomes. Credit: Tsinghua University

> "Migrasomes act as central mediators of system-level, targeted communication."

The Missing Theory in Cell-Cell Communication

For decades, scientists have recognized two principal modes of intercellular communication: direct cell–cell contact and the secretion of soluble signaling molecules. The latter is largely explained by gradient theory, in which signaling molecules diffuse to form concentration gradients that guide cellular responses. Yet a fundamental question has persisted: soluble signals are inherently unstable—particularly in dynamic flow environments such as the circulation—so how do cells, especially those in distant regions of a complex organism, exchange information that is both stable and precisely controlled in space and time?

In 2014, a discovery at Tsinghua University provided an answer. While examining migrating cells, Li Yu and colleagues observed long membrane tubules bearing vesicle-like structures at their tips and intersections. Under electron microscopy, these structures resembled opened pomegranates. Because their formation depended on cell migration, they were named migrasomes.



Transmission electron microscopy image reveals that migrasomes are packed with numerous small vesicles. Credit: Cell Research

Over the past decade, research has revealed that migrasomes function as signaling platforms left behind by migrating cells. A defined combination of signaling molecules is selectively transported into migrasomes and released in a highly controlled manner, enabling the delivery of combinatorial signals with spatial and temporal precision. In this way, migrasomes provide a long-sought mechanism for cells to dispatch packaged, location-specific information to distant or neighboring targets—bridging the gap between direct contact and diffusive secretion, and resolving a longstanding puzzle in cellular communication.

A New Theory of System-Level Targeted Communication

Migrasomes are far more than just another class of extracellular vesicle. These single-membrane organelles, typically 0.5–3 μm in diameter, carry a rich and selective cargo—chemokines, cytokines, growth factors, and other signaling molecules—while their surface can recruit factors such as components of the coagulation cascade, thereby directly influencing local blood clotting.

What distinguishes migrasomes is their functional versatility. While still tethered to retraction fibers, they act as spatially defined secretion platforms, releasing signals locally to generate linear gradients that guide neighboring cells. Upon detachment, they enter the extracellular milieu or circulation and serve as long-range delivery vehicles, transporting their molecular cargo to sites of injury or inflammation with remarkable precision.

This dual functionality—combining localized secretion with systemic transport—establishes a previously unrecognized, system-level communication network. In doing so, migrasomes offer a new conceptual framework for how cells achieve long-distance, high-precision information transfer beyond the limits of classical diffusion-based signaling.

Researchers have begun to uncover the elegant molecular machinery behind migrasome formation. The process happens in three stages: first, nucleation, triggered by the assembly of SMS2 spots; second, maturation, controlled by the PIP5K1α-Rab35-integrin axis; and third, expansion, driven by the formation of tetraspanin-rich microdomains. The coordinated action of these three steps ensures that migrasomes are built at the right time and place — laying the structural foundation for system-level targeted communication.

Beyond secreted proteins, the cargo carried by migrasomes is remarkably diverse, encompassing mRNAs, growth factors, coagulation factors, entire secretory vesicles, and even damaged mitochondria. Notably, cargo selection appears to be tightly regulated, underscoring migrasomes as highly versatile organelles. This breadth of cargo underlies their central role in cell physiology and highlights their potential importance in health and disease. A wide range of functions has emerged from recent studies. In zebrafish embryos, migrasomes act as chemotactic cues that guide dorsal forerunner cells to form Kupffer's vesicle, a structure essential for establishing left–right asymmetry. In developing chicken embryos, they promote angiogenesis, while in adult tissues, they contribute to vascular stability. Migrasomes can also initiate rapid clotting at sites of injury by presenting and releasing coagulation factors, enabling precise, spatiotemporally controlled hemostasis. In another line of work, damaged mitochondria are selectively packaged into migrasomes and expelled from migrating cells, representing a previously unrecognized mechanism of mitochondrial quality control.

These seemingly diverse functions converge on a unifying principle: migrasomes act as central mediators of system-level, targeted communication. They can sense tissue states, localize to sites of injury or inflammation, and deliver signals in a directional and coordinated manner, thereby orchestrating collective cellular behavior to maintain physiological homeostasis.

Future Directions

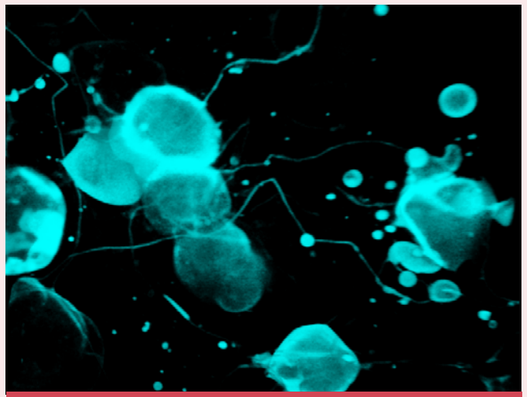
What began as a single observation in one laboratory has evolved into a globally recognized field. Migrasomes carry profound academic significance, revealing an entirely new mode of cellular communication.

Understanding how cells choreograph the formation, cargo loading, and release of these organelles may uncover fundamental principles of spatiotemporal signaling—principles that could ultimately be harnessed to tackle some of the most challenging diseases in medicine. Indeed, migrasomes already show broad translational promise: they can serve as therapeutic targets, function as thermostable vaccine platforms, and enable the targeted delivery of therapeutic cargo.

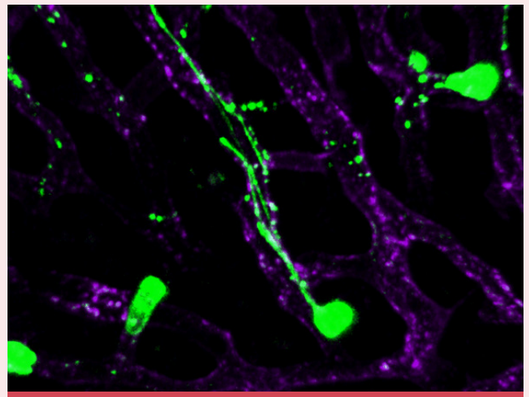
As Li Yu reflected in a recent interview: "As the work progressed, migrasome research accelerated rapidly—not because of any single breakthrough, but because of the sustained efforts of students, postdocs, and collaborators working in parallel. Experiments ran continuously, ideas were tested and discarded quickly, and progress emerged more from persistence than inspiration. The pace of discovery reflected a shared commitment: many people pushing together, often quietly, toward the same uncertain goal.

If migrasomes exist today as a field rather than a curiosity from a single TEM image, it is not because of individual effort. It is because of this collective network. I was fortunate to be present at the beginning; it was the community that carried the work forward."

Looking ahead, the continued growth of this field will depend on contributions from diverse disciplines, and broader engagement of the scientific community will be essential to fully realize the potential of migrasomes.



A three-dimensional confocal image shows that zebrafish embryonic cells generate migrasomes. Credit: Nature Cell Biology



Intravital imaging of mice shows that neutrophils generate migrasomes within blood vessels. Credit: Nature Cell Biology

Quantum Anomalous Hall Effect in an Antiferromagnetic Topological Insulator

Gate voltage and magnetic fields reveal complex spin-driven topological phases in $MnBi_2Te_4$, offering new insights into quantum anomalous Hall physics.

Introduction

Topological quantum materials have opened new frontiers in condensed matter physics by enabling dissipationless edge transport and exotic quantum phases. Among them, magnetic topological insulators are particularly intriguing, as their electronic topology is intimately coupled to magnetic order. As the first intrinsic antiferromagnetic topological insulator, $MnBi_2Te_4$ has attracted extensive attention in recent years. This interplay between topology and magnetism provides a unique platform for controlling quantum states using external parameters, including magnetic fields, electric gating, and temperature.

Although the quantum anomalous Hall (QAH) effect has been realized in thin $MnBi_2Te_4$ devices, the microscopic mechanisms governing its evolution under external conditions—and how competing magnetic interactions shape the phase diagram and topological transport—remain poorly understood. These knowledge gaps continue to limit the broader application of $MnBi_2Te_4$-based quantum devices.

> “Using the optimized device, the team systematically maps out a rich phase diagram under combined electric and magnetic control.”

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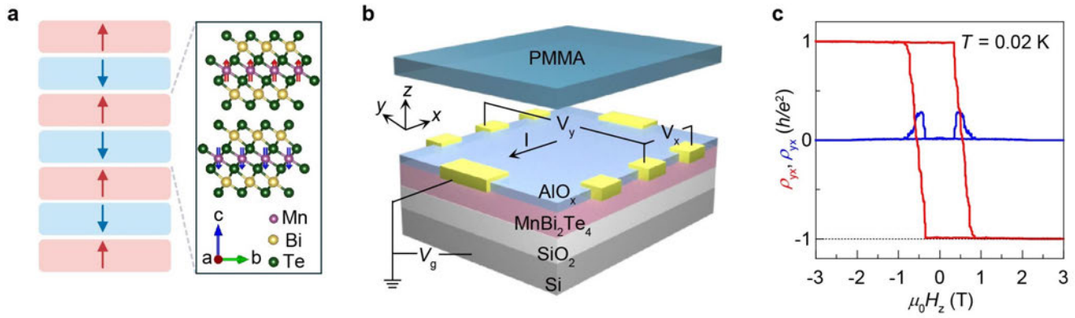
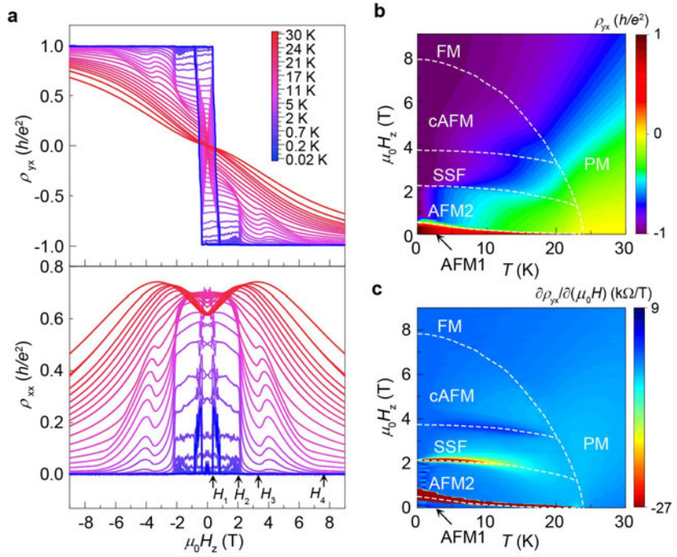


Crystal structure, illustration of device, and quantum anomalous Hall effect in $MnBi_2Te_4$. Published at Nature, 641, 70 (2025). Credit: Tsinghua University

Method and Key Results

In this work, the researchers introduce a 3 nm aluminum oxide (AlO_x) capping layer during device fabrication. This encapsulation not only physically isolates the topological surface states from contamination during processing, but also significantly enhances the perpendicular magnetic anisotropy at the surface. Enabled by this robust design, high-quality 7-septuple-layer $MnBi_2Te_4$ devices exhibiting well-quantized zero-field Hall resistance plateaus are realized, providing an ideal platform for precise transport measurements.

Using the optimized device, the team systematically maps out a rich phase diagram under combined electric and magnetic control. The measurements reveal a cascade of quantum phase transitions driven by evolving spin configurations, arising from the competition among interlayer exchange coupling, magnetic anisotropy, and Zeeman energy. These transitions involve multiple magnetic states, including antiferromagnetic (AFM), surface spin-flop (SSF), canted AFM, and ferromagnetic (FM) phases, each of which modifies the band structure—particularly the gap of the topological surface states—and thereby strongly influences quantized edge transport. A one-dimensional antiferromagnetic spin-chain model quantitatively reproduces the experimental results, establishing a clear link between spin configurations and topological transport properties.



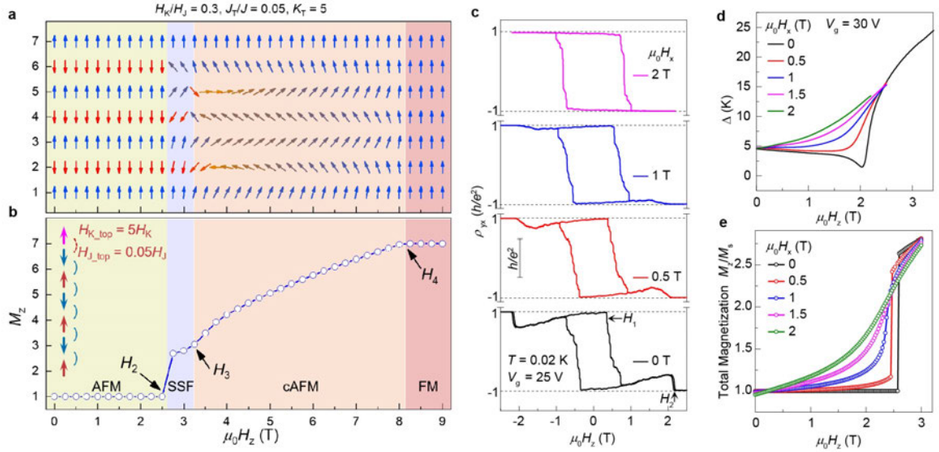
(a) Experimental evolution of Hall resistance and longitudinal resistance with magnetic field at various temperatures. (b, c) Colour maps of Hall resistivity and its derivative as functions of magnetic field, revealing rich spin configurations corresponding to the transport data. Published at Nature, 641, 70 (2025). Credit: Tsinghua University

A particularly striking finding is the unconventional response of the QAH effect to in-plane magnetic fields. In contrast to ferromagnetic topological insulators, where in-plane fields typically suppress quantization, the application of an in-plane magnetic field in $MnBi_2Te_4$ significantly enhances the coercive field. At the same time, it improves the quantization quality and broadens the QAH plateau, while also increasing the thermal activation gap of the surface states. These counterintuitive yet robust behaviors are well captured by the spin-chain simulations, highlighting the unique spin physics of $MnBi_2Te_4$ and demonstrating that Hall transport serves as a highly sensitive electrical probe of complex antiferromagnetic order.

Impact and Outlook

This study provides a comprehensive and experimentally validated framework for understanding how magnetic interactions govern topological quantum phases in $MnBi_2Te_4$, advancing the fundamental understanding of antiferromagnetic topological insulators. By elucidating the relationship between spin configurations and transport behavior, it opens new avenues for controlling topological states through combined electric and magnetic tuning—an essential step toward next-generation low-power electronics and spin-based quantum devices.

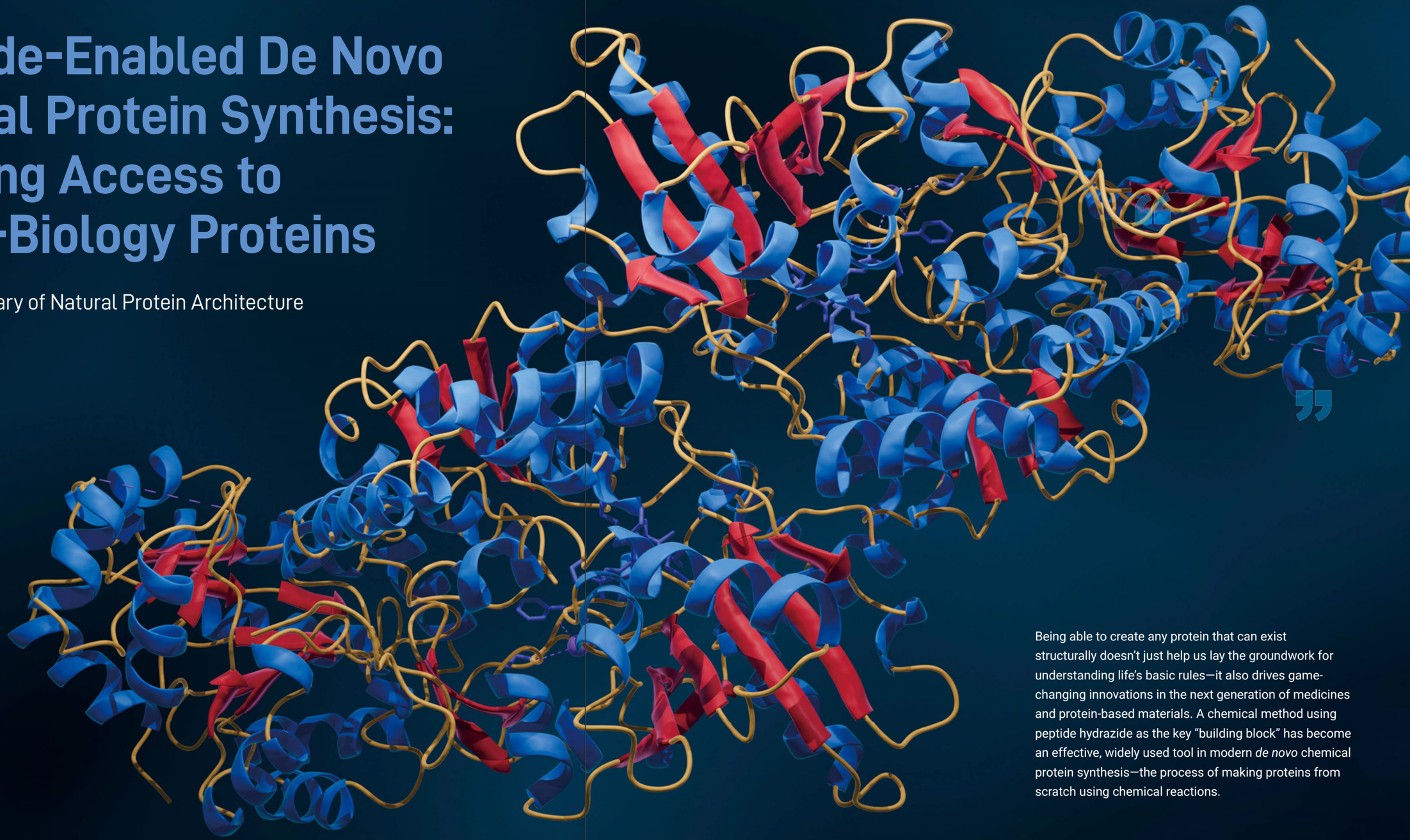
Looking ahead, the ability to probe and manipulate complex spin configurations offers exciting opportunities to explore emerging phenomena such as current-driven phase transitions and quantum critical scaling. More broadly, the device fabrication and characterization strategies developed here can be extended to other magnetic topological materials, paving the way for deeper insights into correlated quantum matter and accelerating the translation of topological physics into practical applications.



(a, b) Simulation results of spin configurations for the 7-septuple-layer device under different magnetic fields, based on the antiferromagnetic spin-chain model. (c) Enhancement of QAH effect with in-plane magnetic field. (d) Thermal activation gaps obtained from experimental data under different in-plane magnetic fields. (e) Simulation results of the antiferromagnetic spin-chain model under different in-plane magnetic fields, which are qualitatively consistent with the experimental data. Published at Nature, 641, 70 (2025). Credit: Tsinghua University

Hydrazide-Enabled De Novo Chemical Protein Synthesis: Unlocking Access to Beyond-Biology Proteins

Crossing the Boundary of Natural Protein Architecture



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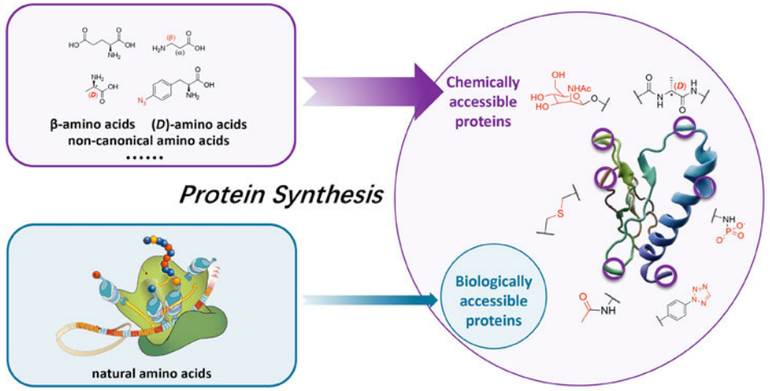
Being able to create any protein that can exist structurally doesn't just help us lay the groundwork for understanding life's basic rules—it also drives game-changing innovations in the next generation of medicines and protein-based materials. A chemical method using peptide hydrazide as the key "building block" has become an effective, widely used tool in modern *de novo* chemical protein synthesis—the process of making proteins from scratch using chemical reactions.



Chemical protein synthesis versus biological protein synthesis. Credit: Tsinghua University

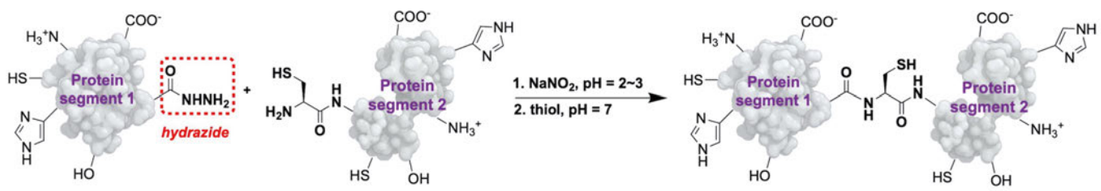
The Rising Need for "Beyond-Biology" Protein Synthesis

As the fundamental molecules that support all life on Earth, proteins are closely tied to human progress in biomedicine and advanced materials. While AI-driven *de novo* protein design has ushered in a revolutionary era for studying natural proteins, our next big challenge is to design and develop functional proteins that break free from the structural limits of biological systems. To do that, we need a key technique: *de novo* chemical protein synthesis. For a long time, though, this technique was only possible for a small group of experts—mostly because there was no easy-to-use building block for making proteins chemically.

Peptide Hydrazide Ligation: A Robust Core Technology

To build a comprehensive, widely accessible platform for *de novo* chemical protein synthesis, researchers from Tsinghua University invented a method called peptide hydrazide ligation. Here's how it works in simple terms: a fully unprotected peptide hydrazide connects specifically with another matching peptide to form a longer peptide chain. By repeating this step over and over, scientists can build an entire, full-length protein. The biggest upside of this method is that peptide hydrazide is cheap and easy to obtain—it can be made in small amounts (just a few milligrams) or large batches (up to kilograms)—and it's simple to handle. This makes chemical protein synthesis reliable, practical, and easy to use for more people.

Building on peptide hydrazide ligation, Tsinghua researchers developed a complete, powerful "toolbox" for *de novo* chemical protein synthesis, eventually creating a full technological platform.



Peptide hydrazide ligation. Credit: Tsinghua University

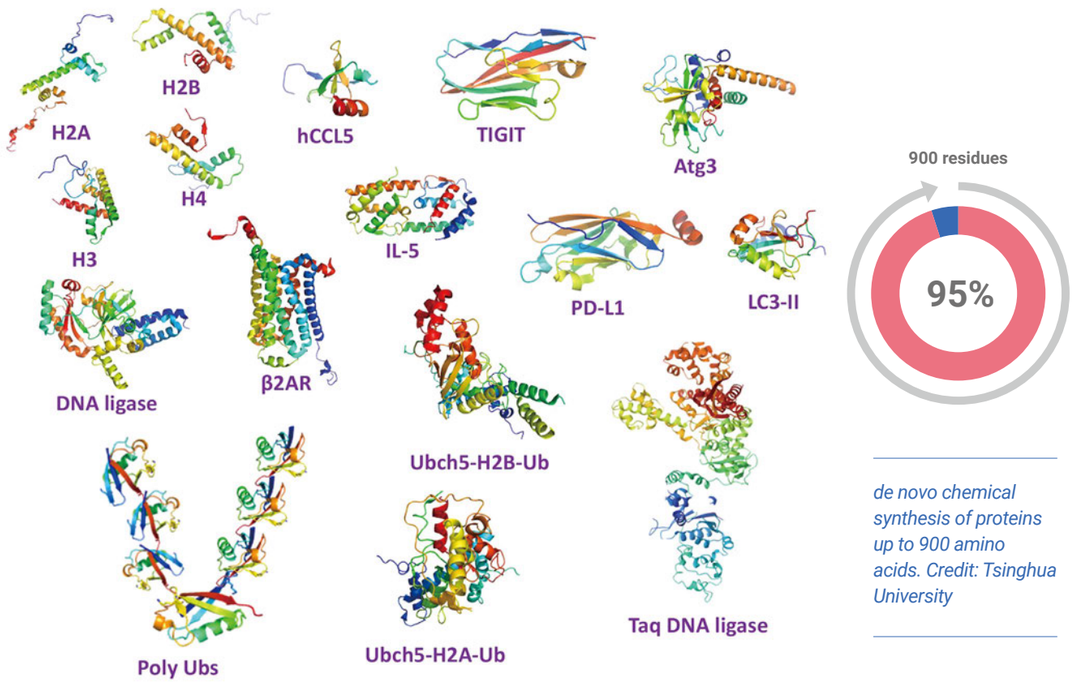
This innovative breakthrough has completely expanded what's possible with total chemical protein synthesis: today, it can make proteins with around 900 amino acids, covering nearly 95% of all known proteins. Most importantly, it has made chemical protein synthesis accessible to more researchers—turning it from a specialized skill into a widely used technology.

> "Today, it can make proteins with around 900 amino acids, covering nearly 95% of all known proteins."

Increasing Applications of Hydrazide-Driven Chemical Protein Synthesis

Using peptide hydrazide ligation, Tsinghua researchers have shown its value in many areas: studying how proteins are modified after they're made (known as post-translational modifications), developing biocatalysts, and creating therapeutic drugs. Today, peptide hydrazide ligation has become a go-to method for chemical protein synthesis, helping it spread from specialized expert labs to research and industrial fields all over the world.

Looking ahead, combining hydrazide chemistry with automated synthesis robots will make *de novo* chemical protein synthesis faster and more efficient. Artificial intelligence (AI) will use data on the structure and properties of chemically synthesized proteins—including those with non-natural parts—to help design peptide or protein drugs and materials that work even better than natural ones. These chemically made "beyond-biology" proteins are opening a new chapter in how we use proteins to improve human health and well-being.

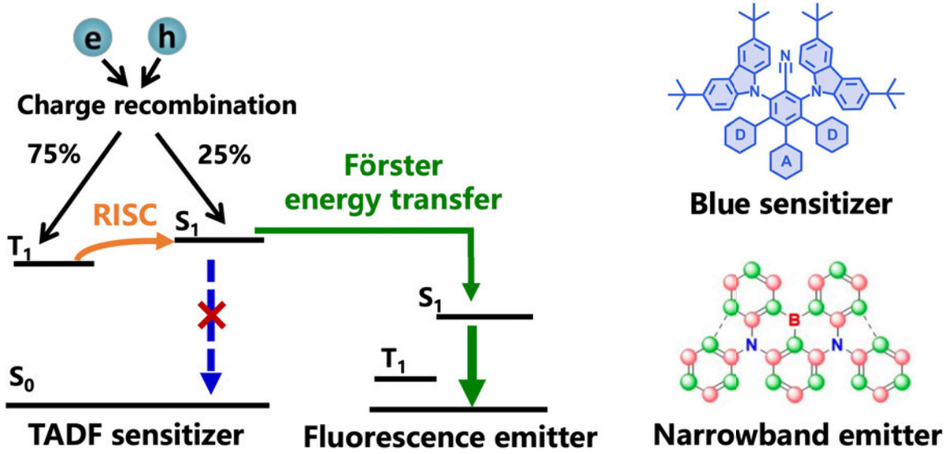


de novo chemical synthesis of proteins up to 900 amino acids. Credit: Tsinghua University

Tsinghua Fluorescence Lights the Way to Efficient and Stable Blue OLEDs

The sensitized fluorescence approach decouples the harnessing of triplet excitons from the radiative decay of singlets within a single molecule, thereby overcoming the long-standing efficiency–stability trade-off in blue OLEDs for practical applications.

DIYUN ZHU / GETTY IMAGES



The energy transfer process of the TSF process, as well as the scheme for the molecule structure for the sensitizer and narrowband emitter. Credit: Tsinghua University

Blue organic light-emitting diodes (OLEDs) have long represented the most stubborn bottleneck in the development of energy-efficient, long-lasting displays. The pursuit of stable and efficient blue emission has been hampered by a fundamental trade-off: materials that achieve high efficiency tend to degrade rapidly, whereas stable emitters often lack sufficient brightness. This conflict arises because triplet harvesting and radiative decay are intrinsically incompatible processes on a single molecule, which prolongs the excited-state lifetime and leads to exciton annihilation. This compromise has limited the performance and longevity of consumer electronics, from smartphones to large-screen TVs.

A research group led by Professor Lian Duan at Tsinghua University has now pioneered a solution with the introduction of a fourth-generation OLED technology: TADF-sensitized fluorescence (TSF). Moving beyond conventional fluorescence, phosphorescence, and thermally activated delayed fluorescence (TADF) mechanisms, the TSF approach cleverly separates the processes of triplet exciton utilization and light emission. Here, a TADF molecule acts as a "sensitizer" to harvest triplet excitons, then efficiently transfers the energy to a separate fluorescent emitter that radiates light. This elegant decoupling of triplet harvesting from singlet emission within a single molecular system simultaneously overcomes the historic efficiency-stability trade-off. Moreover, when a narrowband final emitter is adopted, TSF could provide high color purity emission that satisfies the requirement of BT.2020, a color gamut standard for the ultrahigh-resolution displays.

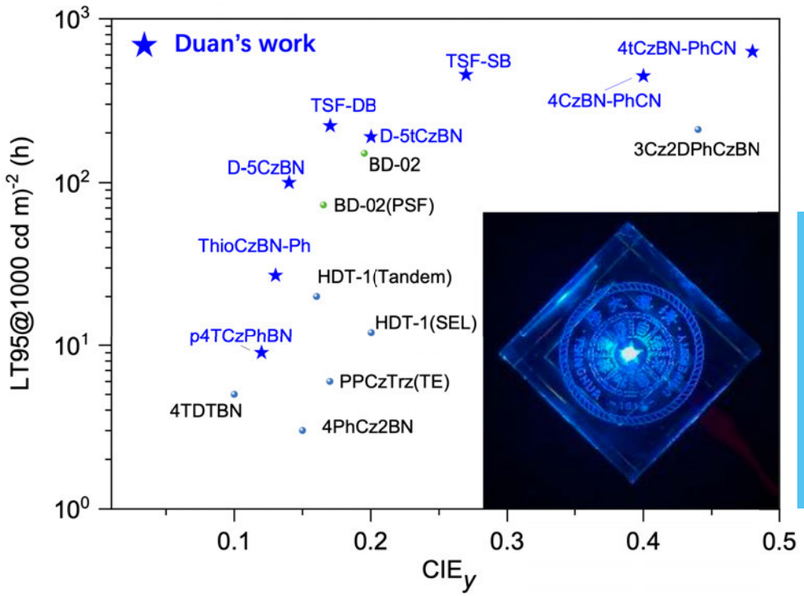
Building upon this TSF architecture, Prof. Duan's team engineered two key components: highly stable blue TADF sensitizers and novel narrowband fluorescence emitters. The sensitizer ensures efficient triplet-to-singlet conversion, while the specialized fluorescent emitter delivers pure, saturated color. This synergistic combination has yielded

> **By separating the functions, we can independently optimize stability and color purity without compromising one for the other. This marks a decisive step from laboratory innovation toward industrial application.**

blue OLEDs that set new performance benchmarks, achieving the longest operational lifetime reported for blue devices alongside high efficiency, thereby paving a concrete technological pathway toward real-world application.

"TSF also stands for Tsinghua Fluorescence. The strategy fundamentally changes the design rules for blue OLEDs," explained Prof. Duan. "By separating the functions, we can independently optimize stability and color purity without compromising one for the other. This marks a decisive step from laboratory innovation toward industrial application."

Looking ahead, the researchers suggest that future work will focus on further broadening the color gamut, pushing the stability limits for deep-blue emission, and integrating these materials into large-area, flexible display prototypes. The successful demonstration of TSF technology is expected to accelerate the development of the next generation of displays that are not only vivid and energy-saving but also exceptionally durable.



A summary of the stability of blue OLEDs in literatures. Credit: Tsinghua University

Unveiling the Dark Universe: Tsinghua's AI-Powered MUST Telescope Set to Decode Dark Matter and Dark Energy

The integration of advanced artificial intelligence with a next-generation spectroscopic survey telescope will help scientists map the cosmos and solve the universe's greatest mysteries.

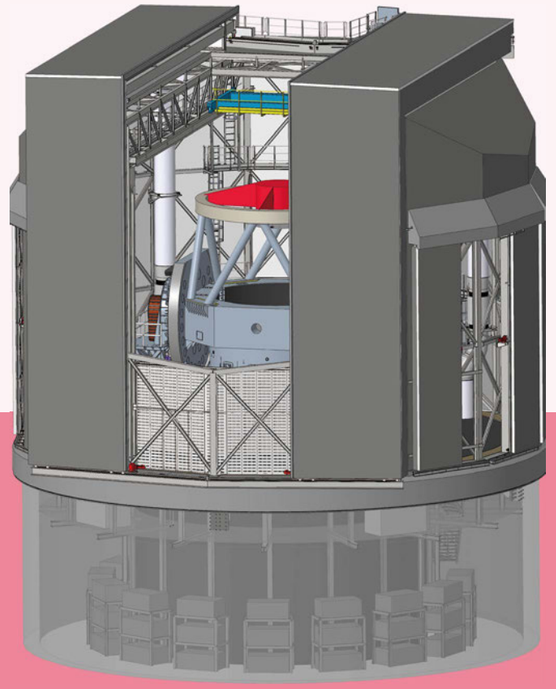
MULIANY / TUCHONG CREATIVE

The Cosmic Bottleneck

The universe is predominantly composed of dark matter and dark energy, yet their fundamental nature remains one of science's most profound enigmas. Understanding these invisible components is critical for modern physics, but traditional observational tools are hitting a plateau. To map the universe accurately, astronomers must process petabytes of complex, noisy astronomical data—a challenge that classic data processing pipelines struggle to handle efficiently.

To address this monumental challenge, Tsinghua University is pioneering a bold scientific engineering endeavor: combining cutting-edge artificial intelligence with the construction of the Multiplexed Survey Telescope (MUST).

> MUST is more than just a telescope; by merging this world-class spectroscopic hardware with sophisticated AI, we have built a highly reusable engine of discovery that will help us bring the hidden physics of dark matter and dark energy into the light.



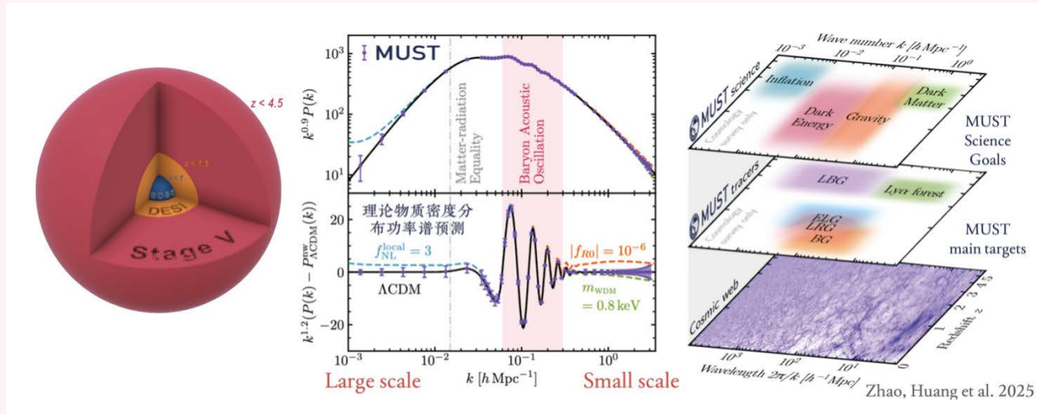
An illustration of the Multiplexed Survey Telescope (MUST) facility, currently under construction and set for completion in 2030. Credit: Tsinghua University

Next-Generation Cosmic Mapping

Scheduled for completion in 2030, the MUST project represents an unprecedented large-scale scientific exploration led by a Chinese university. As a top-tier international spectroscopic survey telescope, MUST is designed to capture the light spectra of tens of millions of galaxies, creating a highly detailed three-dimensional map of the cosmos.

To make sense of the overwhelming volume of data that MUST will generate, Tsinghua researchers have developed novel AI algorithms specifically tailored for high-dimensional cosmological datasets. By utilizing advanced foundation models trained on extensive simulated universes, the AI can automatically identify the subtle gravitational lensing effects and cosmic expansion signatures hidden within the noise.

This machine-learning approach evaluates complex structural variables exponentially faster than traditional computational methods. Because the underlying AI framework is adaptable and does not need to be constantly retrained from scratch for different observation sectors, it dramatically increases the efficiency of the entire optimization and discovery process.

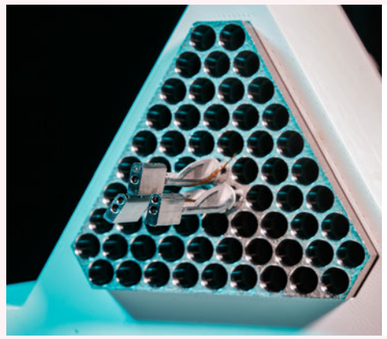


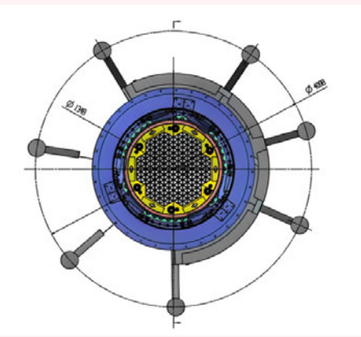
A data visualization of a simulated dark matter halo network, optimized and processed using the team's advanced AI foundation models. Credit: Tsinghua University

Illuminating the Unknown

The synergy of the MUST telescope's optical hardware and innovative AI software will position Tsinghua at the forefront of global astrophysics. This ambitious initiative promises not only to push the boundaries of large-scale engineering but also to trace the distribution of dark matter halos and measure the repulsive force of dark energy with unparalleled precision.

"Modern AI and machine-learning models can fundamentally change the way scientists analyze complex cosmic systems," says a lead astrophysicist at Tsinghua University. "MUST is more than just a telescope; by merging this world-class spectroscopic hardware with sophisticated AI, we have built a highly reusable engine of discovery that will help us bring the hidden physics of dark matter and dark energy into the light."





EPFL joined MUST as a founding partner and will be responsible for the MUST fiber positioner. Credit: Tsinghua University

A Two-Dimensional Trapped-Ion Quantum Simulator Exceeds Classical Computing Capabilities

Researchers have built a two-dimensional trapped-ion quantum simulator that can perform quantum simulations beyond the reach of classical computers. This breakthrough paves the way for scaling up the number of controllable qubits to hundreds — a critical step for both quantum simulation and quantum computing — with potential applications ranging from fundamental physics to information security.

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Trapped ions hold a special place in quantum computing history: the very first two-qubit quantum logic gate was implemented in this platform. Today, trapped ions remain one of the most promising candidates for building a universal quantum computer. The main challenge, however, lies in scaling up the number of physical qubits without sacrificing the fidelity of quantum operations.

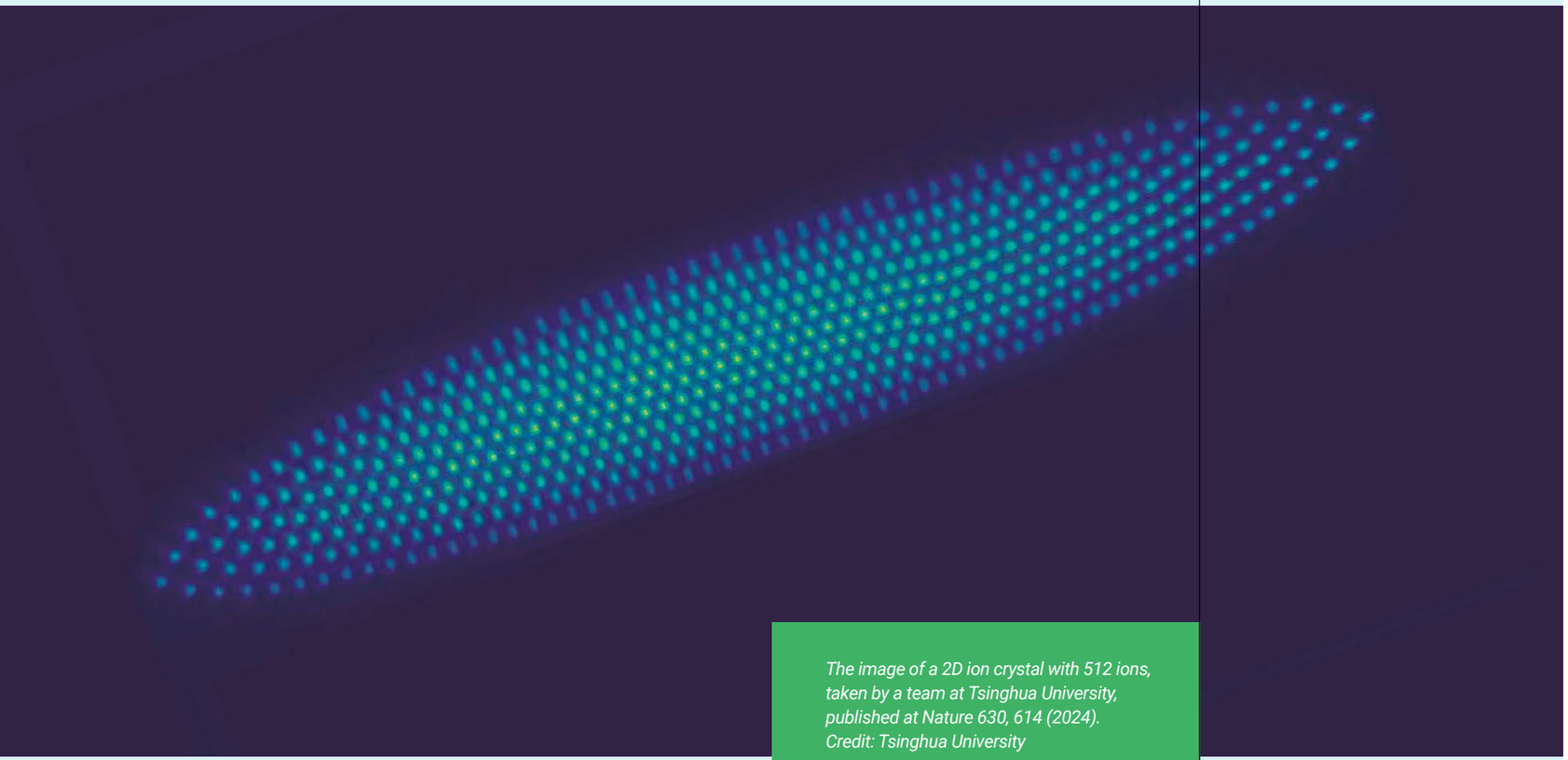
In room-temperature systems and conventional one-dimensional ion chains, scaling is severely limited by collisions with background gas and by the achievable radio-frequency pseudopotential before reaching the breakdown voltage between electrodes. Over the past decade, the largest ion crystals used for quantum information processing in Paul traps have contained only about dozens of qubits.

A quantum simulator with 300 ions performs site-resolved simulation of many body physics model

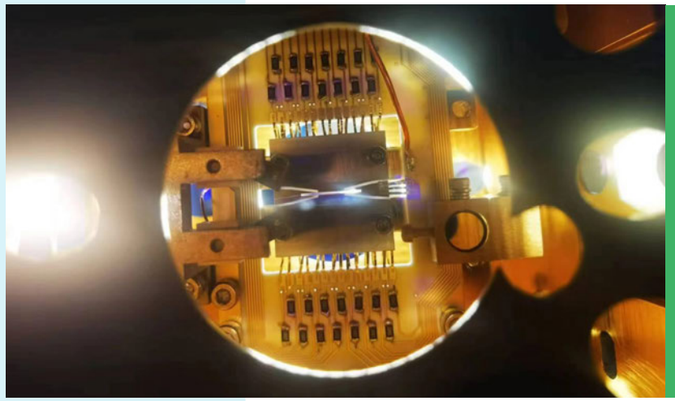
Now, a team of researchers at Tsinghua University has developed a new approach. Using a monolithic three-dimensional ion trap operating at cryogenic temperatures (around 6 kelvin), they have successfully trapped a two-dimensional ion crystal consisting of 512 ions. After Doppler cooling and sideband cooling, the entire ion crystal can be initialized to its ground state.

By applying counter-propagating off-resonant laser beams together with a global microwave field, the researchers performed quantum simulations of the long-range Ising model using 300 ions. They further achieved Hamiltonian learning for the all-to-all coupled Ising model — all with global manipulations and single-qubit-resolved state detection.

Because the Hilbert space grows exponentially with the number of qubits, simulating quantum dynamics and verifying simulation results are notoriously difficult for classical computers. This new quantum simulator platform overcomes that barrier. By dynamically tuning coupling strengths and patterns, the researchers



The image of a 2D ion crystal with 512 ions, taken by a team at Tsinghua University, published at Nature 630, 614 (2024). Credit: Tsinghua University



The 3D monolithic ion trap installed inside vacuum chamber, taken by a team at Tsinghua University. Credit: Tsinghua University

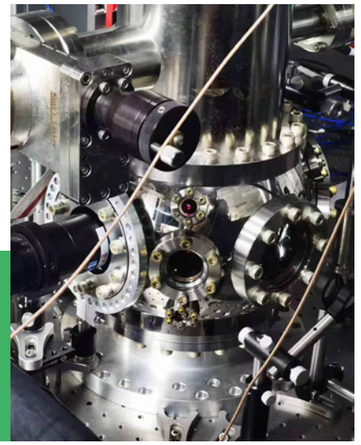
> **Simulating quantum dynamics and verifying simulation results are notoriously difficult for classical computers. This new quantum simulator platform overcomes that barrier.**

can prepare the ground state of the Ising Hamiltonian or observe dynamical phase transitions. With hundreds of qubits and single-site detection, many-body dynamics become clearly visible through measured spatial spin-spin correlation patterns.

thousands or even tens of thousands of ions. Moreover, by integrating a two-dimensional individual addressing system, high-fidelity two-qubit quantum gates could be implemented, offering a promising architecture for a future universal quantum computer based on trapped ions.

Future Directions

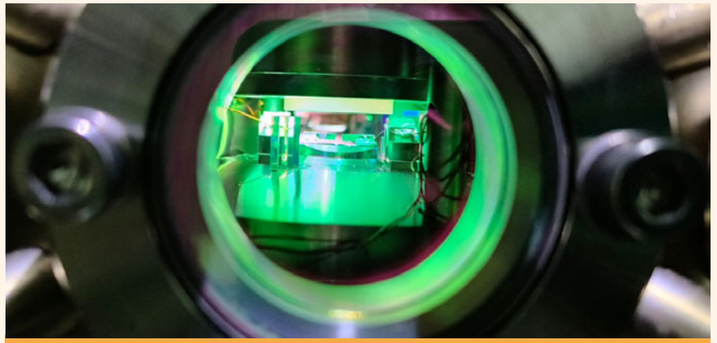
The current use of a 300-ion two-dimensional crystal is limited only by available laser power for strong couplings — not by any fundamental constraint. With more precisely fabricated monolithic ion traps and better vacuum pressure, this approach could scale to



The vacuum chamber of cryogenic ion trap, taken by a team at Tsinghua University. Credit: Tsinghua University

Hardware and Algorithm Advances Tackle the Grand Challenges of Fault-Tolerant Quantum Computing

Metasurface-generated tweezer arrays trapping atom arrays with 10,000 atoms, a millimeter-scale high-cooperativity optical cavity, and an efficient atom rearrangement algorithm – with these three breakthroughs, Tsinghua takes on the challenge of universal fault-tolerant quantum computing using atom arrays.



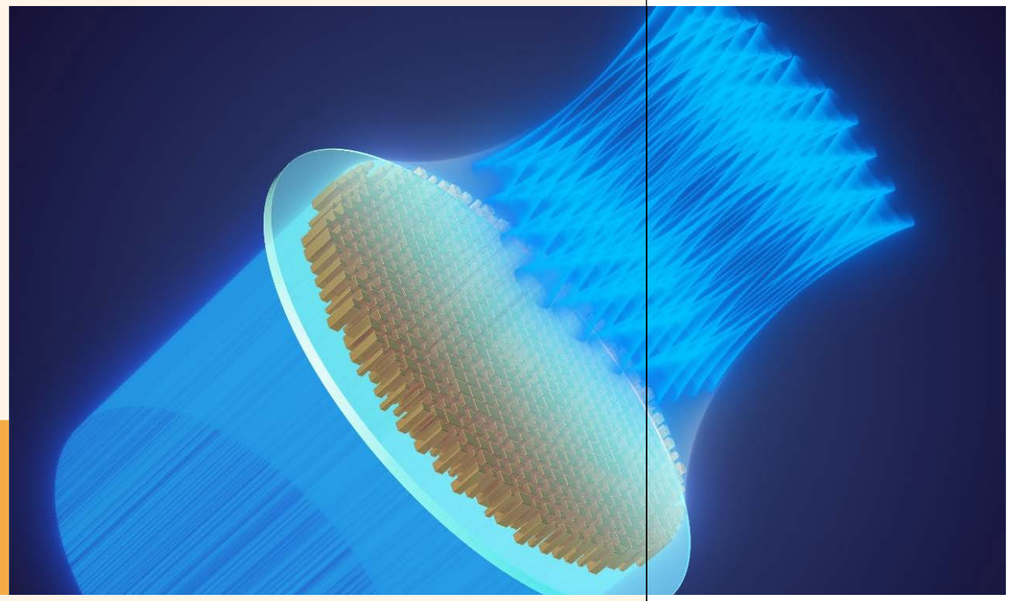
An optical cavity with a 1.66 mm cavity length and cooperativity greater than 100 was installed in the vacuum system. Credit: Tsinghua University.

Universal fault-tolerant quantum computing is widely considered the most formidable challenge in quantum technology. Among the many hardware approaches now under development, atom array quantum computing, building on decades of progress in cold atom physics, has emerged as one of the most promising routes toward scalable, fault-tolerant quantum machines.

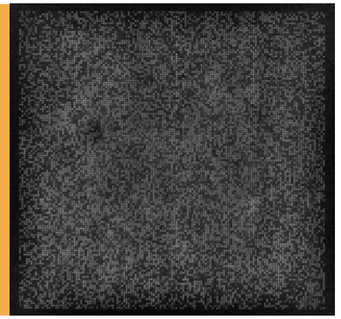
Now, a team at Tsinghua has reported a series of advances that could help move this platform significantly closer to that goal. The researchers have recently achieved single-qubit and two-qubit gate fidelities of 99.95% and 99.5%, respectively. These results surpass the threshold required for quantum error correction and place the team among the world's leading teams in the field. They have also developed the world's only millimeter-scale optical cavity system that can simultaneously accommodate more than 100 atomic qubits while maintaining a cooperativity greater than 100, enabling fast and accurate readout of multiqubit quantum states.

The team has also developed a set of hardware and software innovations to scale up the system. They have projected a few tens of thousands of high-quality optical tweezers with a single metasurface, laying the hardware foundation for an atom array containing more than 10,000 atomic qubits. This capability enables them to capture 10,064 individual atoms recently, the first time to reach 10,000-physical-qubit scale among all quantum computing platforms. The work was highlighted by *Physics World*, a leading publication of the Institute of Physics in the United Kingdom. They have also developed AI-based control algorithms that enable rapid manipulation of atom arrays at the 10,000-atom scale, including defect-free rearrangement and the encoding of large qubit error-correcting codes.

"With this series of hardware and software innovations, we can achieve high-fidelity computation and measurement, and are now able to trap and control atomic qubits on the 10,000 scale," says Professor Hui Zhai. "These capabilities give us confidence to tackle quantum error correction on the atom array platform, which is arguably the hardest step in quantum computing. It is also the final barrier on the road to practical quantum computing."

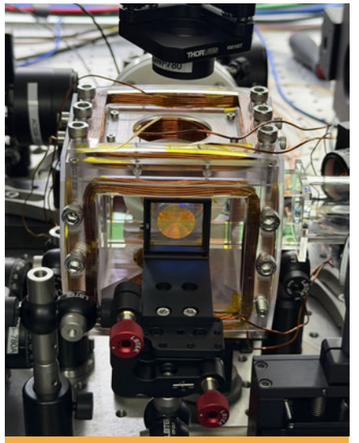


Single metasurface generates up to 78,400 optical tweezers. Credit: Tsinghua University.



Generating large-scale optical tweezers and trapping 10,064 single atoms with a single optical metasurface. Credit: Tsinghua University.

> **These capabilities give us confidence to tackle quantum error correction on the atom array platform, which is arguably the hardest step in quantum computing. It is also the final barrier on the road to practical quantum computing.**

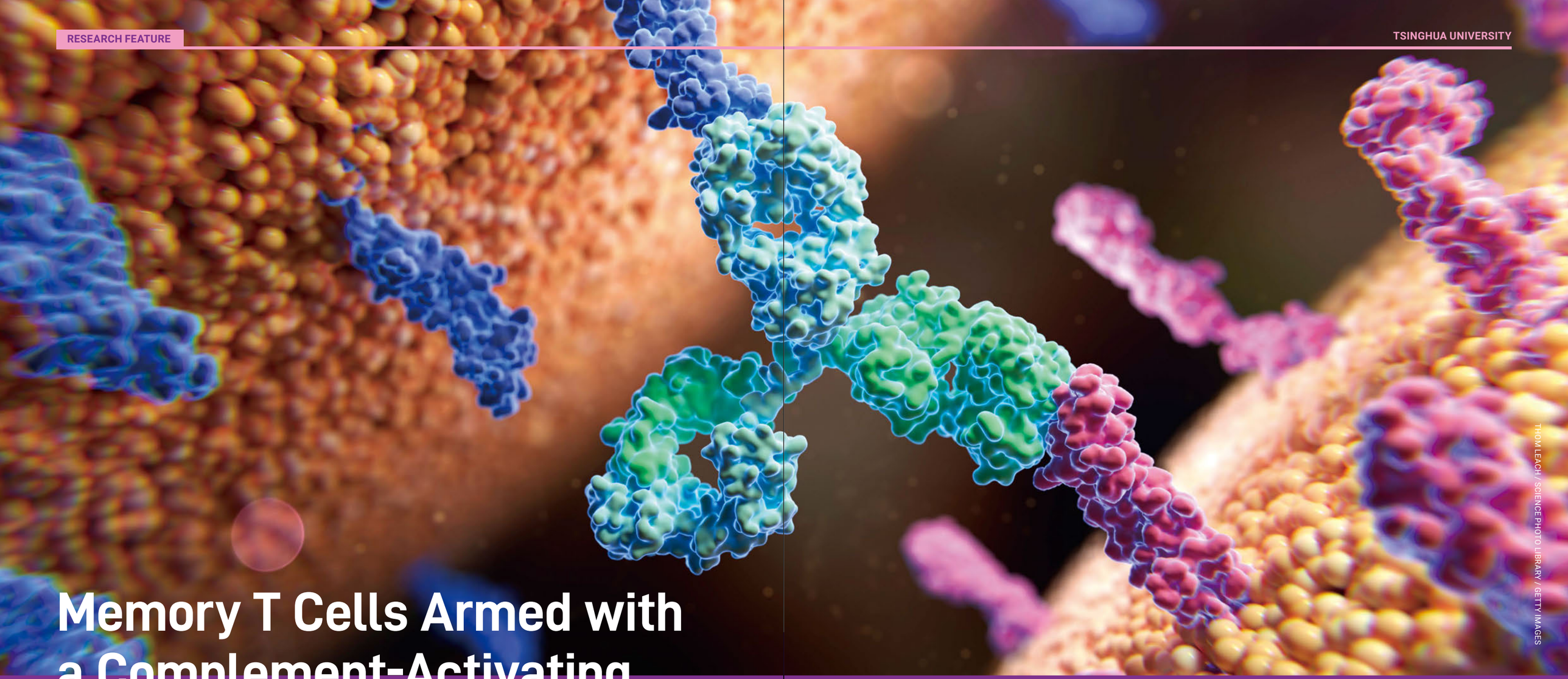


Optical metasurface mounted on the vacuum system, demonstrating the loading of atom arrays at the 10,000 scale. Credit: Tsinghua University.

The Tsinghua team's ability to achieve these breakthroughs in a relatively short time is rooted in more than a decade of sustained work in fundamental cold atom physics research. Professor Zhai has made several internationally recognized contributions to cold atom theory, and his book *Ultracold Atomic Physics*, published by Cambridge University Press, has been well received by researchers in the field.

Beyond academic efforts, the group has also incubated the quantum computing startup *Qosmos*, which focuses on system-level engineering and the development of upstream components and downstream applications. Together, the Tsinghua team and Qosmos have established a full-stack research and development chain spanning basic science, technological innovation, and engineering translation, with the shared goal of advancing universal fault-tolerant quantum computing.

As quantum computing moves from proof-of-concept demonstrations toward practical implementation, the ability to combine large-scale qubit generation, high-fidelity gate operations, intelligent control, and efficient readout will be critical. The Tsinghua team believes that its integrated advances across these areas position the atom array platform as a strong contender in the global race toward practical, fault-tolerant quantum computing.



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Memory T Cells Armed with a Complement-Activating Enzyme Drive Recurrent Airway Diseases

A Tsinghua University–led team identifies a long-overlooked population of $CD8^+$ T cells whose effector molecule, Granzyme K, fuels chronic rhinosinusitis and asthma — and points to it as a new therapeutic target.

Why some airway diseases keep coming back

Chronic rhinosinusitis affects more than one in ten people worldwide, and roughly a quarter of those patients develop nasal polyps — soft, inflamed growths that often require repeated surgery and that travel hand-in-hand with asthma. Even after the polyps are removed, they tend to grow back. Even after symptoms quiet down, the next flare-up is rarely far away. Current therapies calm the inflammation but do not erase its source.

Immunologists have long suspected that an "immune memory" of the disease itself — a small reservoir of cells that remembers and re-ignites the inflammation — may explain why such diseases relapse. But the precise identity of those cells and the molecular weapon they wield have remained elusive. A new study in *Nature* from researchers at Tsinghua University and Beijing TongRen Hospital, Capital Medical University, identifies both.

> Targeting GZMK, or the memory CD8+ T cells that produce it, offers a novel therapeutic strategy—one aimed at not only the inflammation but also the source of disease recurrence.

A pathogenic memory uncovered

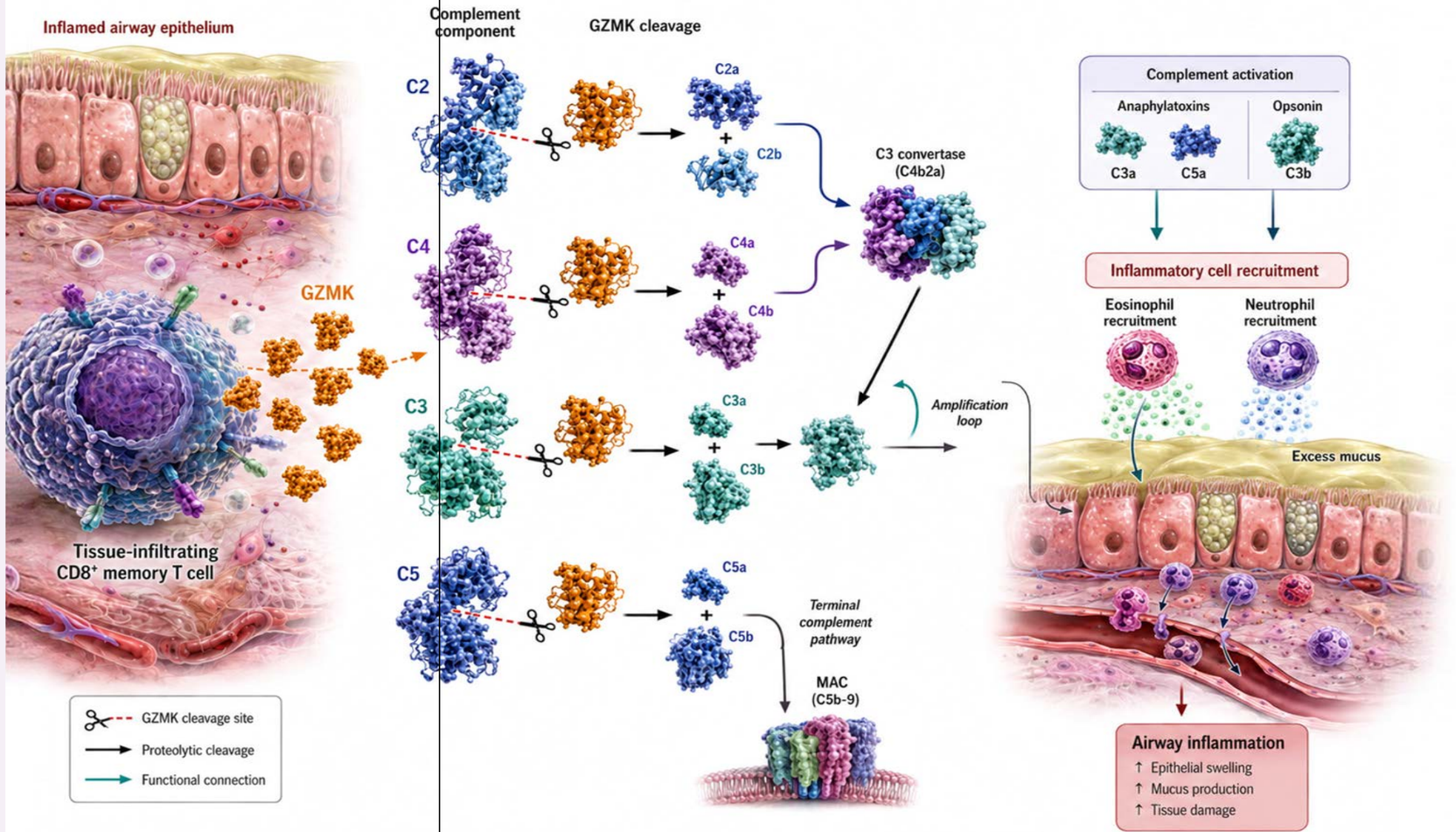
By pairing surgical samples taken from the same patient across multiple polyp recurrences — some separated by more than three years — and combining single-cell RNA sequencing with T cell receptor repertoire analysis, the team found that the very same CD8+ T cell clones repeatedly re-colonize the diseased tissue. These persistent cells carry the hallmarks of effector memory T cells, and, distinctively, express high levels of a protease called Granzyme K (GZMK).

A protease that activates the complement cascade

Granzymes are best known as the assassins inside cytotoxic T cells, with Granzyme B famously killing infected or cancerous cells after being delivered into those cells by perforin, a hole-punching protein. GZMK, by contrast, had no widely accepted job description. To find out what it does in inflamed tissue, the authors purified active recombinant GZMK, used a catalytically inactive mutant as bait to pull down its targets from polyp lysates, and validated the hits enzymatically. They discovered that GZMK directly cleaves multiple components of the complement cascade — C2, C3, C4, and C5 — generating the potent pro-inflammatory fragment C3a and amplifying complement activation. In a cohort of 148 patients, tissue GZMK levels predicted disease severity and asthma comorbidity better than established biomarkers such as eosinophil counts or interleukin-5.

From mechanism to therapeutic potential

The team then tested the hypothesis in mouse asthma models. Mice lacking GZMK in their T cells, or treated with the GZMK inhibitor PPACK after disease onset, showed sharply reduced eosinophil infiltration, less goblet cell hyperplasia, and substantially restored lung function. Adoptive transfer of GZMK-overexpressing CD8+ T cells worsened airway inflammation — but only when the recipient mice had an intact complement C3, confirming that the GZMK–complement axis is the critical pathogenic engine.



Implications and what comes next

Because GZMK+ CD8+ T cells have also been described in rheumatoid arthritis, lupus nephritis, Sjögren's syndrome, IgG4-related disease, and aging-associated "inflammaging," the findings have implications well beyond the airway.

"Targeting GZMK, or the memory CD8+ T cells that produce it, offers a novel therapeutic strategy—one aimed at not only the inflammation but also the source of disease recurrence," says Hai Qi, professor at Tsinghua University and a corresponding author of the study. "We are particularly excited about the possibility that a single approach could benefit patients across multiple chronic inflammatory conditions that share this mechanism."

The authors also caution that translating the mouse results to humans will require selective, well-tolerated GZMK inhibitors and a deeper understanding of GZMK-expressing cells. Still, the work reframes a long-overlooked enzyme as a promising target — and offers a molecular explanation for why so many inflammatory diseases insist on coming back.

Schematic illustration of how GZMK released by tissue-resident CD8+ memory T cells cleaves complement components C2, C3, C4 and C5 to drive airway inflammation. 8. Credit: Laboratory of Dynamic Immunobiology, Institute for Immunology, Tsinghua University

Single-Atom-Site Catalysis: A New Driving Force for Advancing Energy, Environment, Materials, Chemistry, and Chemical Engineering

To enhance catalytic efficiency and reduce catalyst cost through uniform and maximized metal-atom utilization, Professor Yadong Li's team at Tsinghua University has developed a series of synthetic technologies for metal single-atom-site catalysts. These advances have established a versatile and expandable toolbox of metal single-atom-site catalysts, enabling the field to move from fundamental research toward real industrial application scenarios, including petrochemicals, energy catalysis, automotive exhaust purification, and environmental remediation.

Practical Challenges

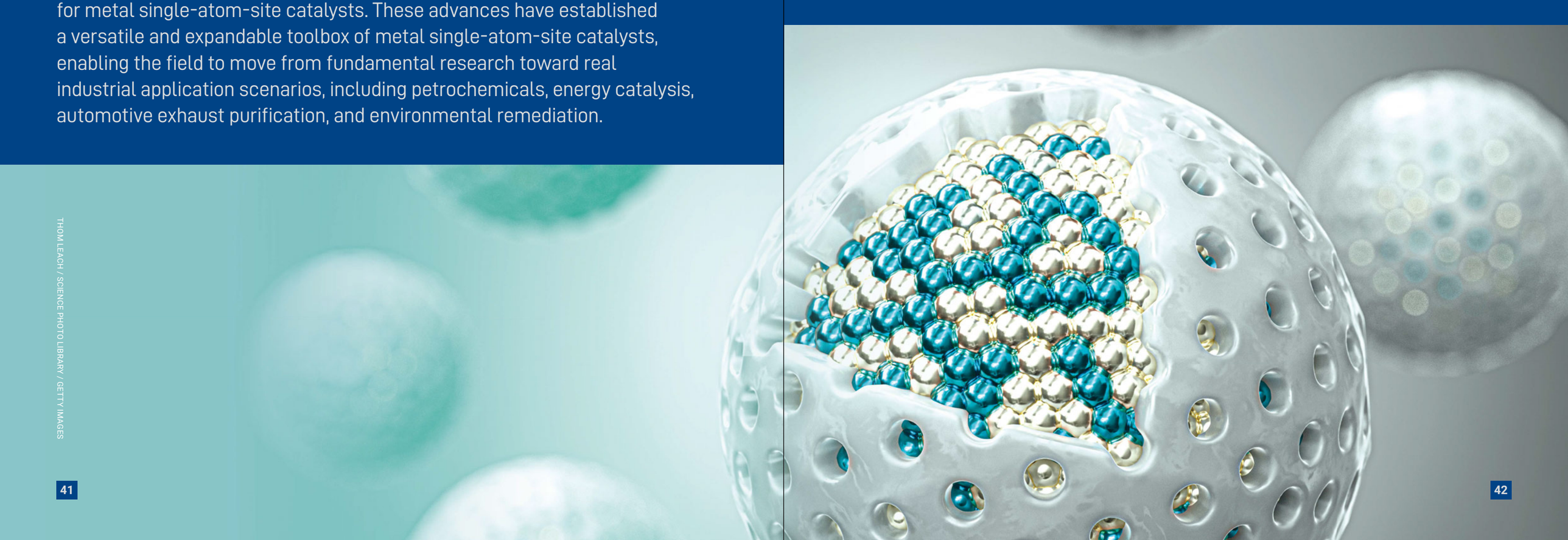
Catalysis is the soul of chemistry and the engine of the chemical industry. It underpins key processes in modern chemical manufacturing, energy conversion, materials production, and environmental remediation, and has become a foundational technology for building a sustainable, green, and low-carbon industrial system. However, many established industrial processes in petrochemicals, energy, materials, and environmental technologies still rely heavily on scarce and precious metal catalysts, such as platinum, palladium, and rhodium. How to use these limited noble-metal resources more efficiently in industrial catalysis remains a major challenge for sustainable development.

Metal single-atom-site catalysis offers a new pathway to address this bottleneck. By anchoring isolated metal atoms onto defects or surface sites of solid supports, single-atom-site catalysts feature atomically dispersed and structurally identifiable catalytic active centers, theoretically approaching 100% metal atom utilization. This concept combines the advantages of homogeneous catalysis—well-defined active centers and precise reaction regulation—with the merits of heterogeneous catalysis, including facile separation and recyclability. It therefore provides an important route for reducing noble-metal loading and replacing precious metals with earth-abundant alternatives, while also opening broad opportunities for discovering new reactions, developing new processes, and heterogenizing homogeneous catalysis.

From Controllable Nano-Synthesis to a Toolbox of Metal Single-Atom-Site Catalysts

Since 1996, Professor Yadong Li of Tsinghua University has devoted his research to the design, controlled synthesis, and structure–property relationships of inorganic functional nanomaterials. His work has established key principles and methodologies for preparing nanomaterials with tailored composition, structure, morphology, and functional properties, making important contributions to nanomaterials chemistry and nanocatalysis.

In 2012, Professor Li discovered that monodisperse Pd nanocrystals could generate highly active Pd



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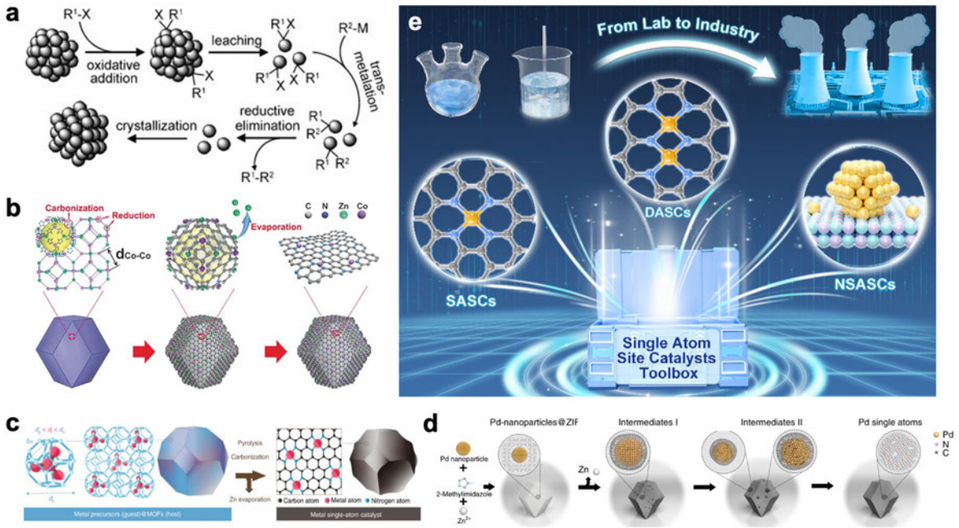


(a) Schematic illustration of the dissolution of Pd NPs to Pd mononuclear species during Suzuki coupling catalysis; Credit: WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim (b) Schematic illustration of Co single-atom-site catalyst (SASC) derived from Co-Zn-ZIF. The first report of carbon-supported SASCs prepared through a ZIF-derived route; Credit: WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim (c) Scheme of the general host–guest strategy for the fabrication of metal SASCs; Credit: The Author(s), under exclusive licence to Springer Nature Limited (d) Schematic illustration of the atomization process from Pd NPs to Pd single-atom sites; Credit: The Author(s) (e) Schematic illustration of the single-atom-site catalyst toolbox, encompassing three classes of catalysts and bridging the gap from laboratory research to industrial application in single-atom-site catalysis. Credit: American Chemical Society

single-atom-level sites during catalytic reactions, opening the way to this highly challenging frontier. In 2016, his group developed the first carbon-supported metal single-atom-site electrocatalyst through a ZIF-derived route, a breakthrough that marked an important turning point in the transition of single-atom-site catalysis from fundamental research toward application-oriented development. Building on this foundation, his team further developed a class of landmark, generally applicable, and controllable synthetic methods for metal single-atom-site catalysts, including the direct transformation of nanocrystals into single-atom-site catalysts. These advances have provided the international research community with a rich toolbox of metal single-atom-site catalysts. The toolbox is compatible with diverse supports, including metal oxides, zeolites, and porous carbons, and covers multiple types of catalytic active structures, such as isolated metal single-atom sites, dual-metal single-atom sites, and synergistic single-atom–nanocrystal catalytic sites. Collectively, these contributions have propelled metal single-atom-site catalysis into a new stage of development.

From the Laboratory to Industrial Application

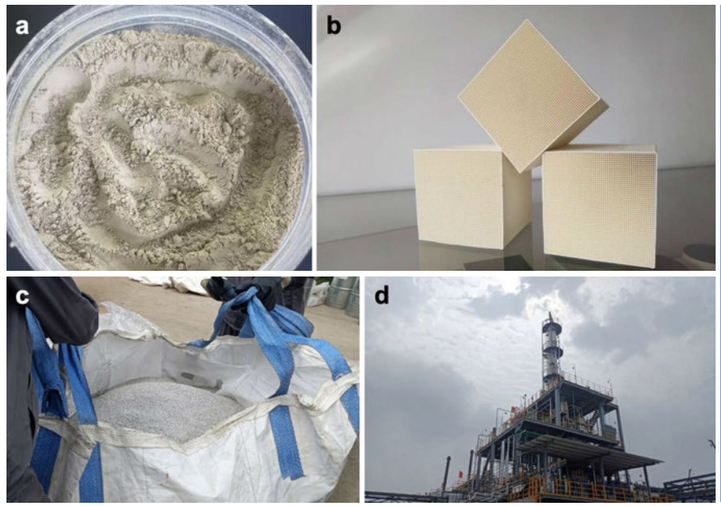
Professor Li's team has continuously expanded the boundaries of metal single-atom-site catalysis, extending the concept from conventional thermocatalysis to electrocatalysis, photocatalysis, and enzyme-mimetic catalysis. Their research covers a wide range of industrially important catalytic processes, including alkane dehydrogenation, olefin hydroformylation, Fischer–Tropsch synthesis, selective C_2 hydrogenation, and hydrosilylation. In energy catalysis, their work spans the oxygen reduction reaction, oxygen evolution reaction, hydrogen evolution reaction, CO_2 reduction, and N_2 reduction. In environmental catalysis, their studies include CO oxidation, automotive exhaust purification, and flue-gas treatment in the steel industry. They have also extended metal single-atom-site catalysis into photocatalysis and biomimetic enzyme catalysis, creating new opportunities for sustainable energy and resource-conversion systems.

Professor Li has also achieved notable success in translating scientific discoveries from fundamental research into industrial applications. In 2019, with support from private investment, he founded Beijing Single-Atom Catalysis Technology Co., Ltd., the world's first R&D-oriented enterprise dedicated to metal single-atom-site catalyst technologies. Under his leadership, metal single-atom-site catalysts have been implemented in multiple industrial scenarios. For automotive exhaust purification, metal single-atom-site three-way catalysts have reduced noble-metal usage by more than 30% while achieving scale preparation at the 1,000 kg level, honeycomb monolith coating, bench testing, vehicle-matching validation, and road testing. These catalysts have entered the supply chains of mainstream automobile manufacturers, including Chery and JAC. For petrochemical applications, high-performance single-atom-site catalysts for hydroisomerization in premium lubricating-oil production have completed 10,000-ton-scale industrial pilot validation at Hebei Feitian Petrochemical. Under continuous feeding, high space velocity, high pressure, and fluctuating real-feedstock conditions, these catalysts demonstrated strong activity, selectivity, and stability. In addition, related technologies are being extended to fixed-source air-pollution control processes, such as catalytic CO oxidation treatment of sintering flue-gas in steel plants. These achievements are comprehensively advancing metal single-atom-site catalysis toward industrial catalytic applications.

> "These advances have provided the international research community with a rich toolbox of metal single-atom-site catalysts."

Impact and Future Outlook

Looking ahead, metal single-atom-site catalysis is expected to play an increasingly important role in advancing the sustainable and green development of fundamental chemistry, chemical engineering, energy technologies, advanced materials, and environmental process engineering. As more metal single-atom sites, dual- or multi-metal single-atom sites, and single-atom-site-nanocrystal synergistic catalysts are applied to complex reaction systems, metal single-atom-site catalysis is poised to become a core industrial catalytic technology for high-efficiency, low-cost, and sustainable development in petroleum, chemical manufacturing, energy conversion, and environmental protection, including VOC purification and conversion. More broadly, this field is expected to open new pathways for discovering new reactions, developing new processes, heterogenizing homogeneous catalysis, and promoting deeper integration between chemistry and chemical engineering. By maximizing metal utilization, enabling precise active-site design, and bridging fundamental catalysis with industrial implementation, metal single-atom-site catalysts will provide critical scientific and technological support for green chemical manufacturing and clean energy development in the pursuit of a sustainable future.



Representative images related to the industrialization of SASCs. (a) Single-atom-site three-way catalyst powder for automotive exhaust aftertreatment; (b) honeycomb ceramic-supported SASC for steel sintering flue-gas purification; (c, d) kilogram-scale SASCs and the 10,000-ton-scale industrial pilot unit for lubricating-oil hydroisomerization. Credit: Tsinghua University

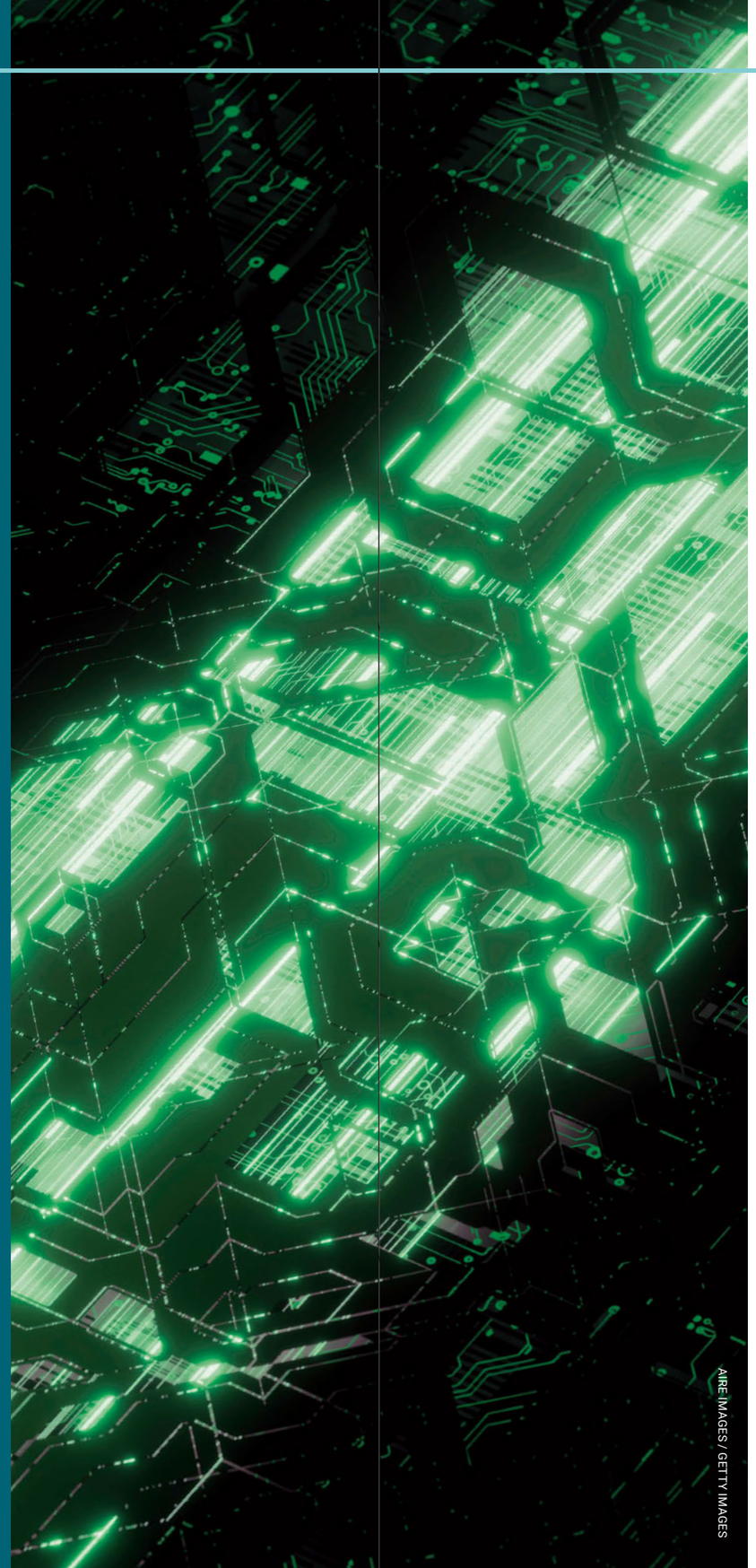
The Experimental Realization of the Quantum Anomalous Hall Effect

The quantum anomalous Hall effect—a quantized Hall effect that exists even without an external magnetic field—remained a theoretical dream for 25 years. In 2013, a team led by Qi-Kun Xue at Tsinghua University realized it in an engineered magnetic topological insulator thin film, opening the door to practical applications of the exotic dissipationless quantum Hall edge states.

The integer and fractional quantum Hall effects (the discoveries that won Nobel Prizes in Physics, in 1985 and 1998, respectively) require strong magnetic fields, making them impractical for low-energy electronics. A zero-field version—the quantum anomalous Hall effect (QAHE)—would allow dissipationless edge currents without bulky magnets. However, realizing it in experiment requires a material that simultaneously satisfies three stringent conditions: a topologically nontrivial band structure, spontaneous long-range ferromagnetic order, and an insulating bulk. Meeting any one of these properties is already a major challenge for materials science; fulfilling all three seemed nearly impossible.

Starting in 2009, a team at Tsinghua set out on a remarkable journey towards the experimental realization of the quantum anomalous Hall effect. They chose the newly discovered Bi_2Te_3-family topological insulators as the matrix materials and employed a whole range of powerful experimental techniques, including molecular beam epitaxy, scanning tunneling microscopy, photoemission spectroscopy, and low-temperature transport measurements.

They first established the molecular beam epitaxy growth kinetics of Bi_2Te_3-family topological insulators and obtained ultrathin films with unprecedented quality. Carefully scrutinizing the effects of chemical composition, magnetic doping, film thickness, and surface morphology on the electronic and magnetic properties of a wide variety of composite topological insulator materials, they found a complex quaternary compound Cr-doped $(Bi,Sb)_2Te_3$ as the optimal material system for realizing the QAHE.



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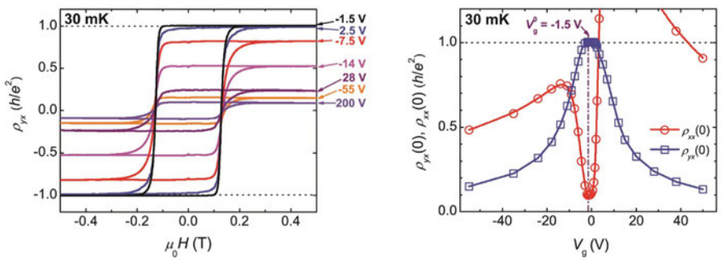
> “It concluded a 25-year search for the zero-field quantum Hall effect and resolved half-century-old debates about the intrinsic anomalous Hall effect.”

Eventually, in late 2012, they observed the quantized Hall resistance (h/e^2) (~25.813 kΩ) at zero magnetic field for the first time in history. The discovery, published in *Science* in 2013, was later confirmed and repeated by several groups worldwide, which unambiguously confirmed the discovery. It concluded a 25-year search for the zero-field quantum Hall effect and resolved half-century-old debates about the intrinsic anomalous Hall effect.

In *The Scientific Background for the 2016 Nobel Prize in Physics*, the Royal Swedish Academy of Sciences states that “this phase of matter described by Haldane is now called a Chern insulator, and twenty five years later, in 2013, a quantized Hall effect was observed in thin films of Cr-doped $(Bi,Sb)_2Te_3$ at zero magnetic field, thus providing the first experimental detection of this phase of matter.” It highlights the discovery as the main experimental support of the theoretical contribution of F. D. M. Haldane, the Nobel Prize laureate this year.

In recent years, rapid progress has been made in the exploration of higher temperature QAHE and quantum metrology applications of QAHE. QAHE has been achieved in intrinsic magnetic topological insulators, ultracold atom systems, and several moiré superlattice systems. Fractional QAHEs have been observed in recent years. These following advances have made QAHE one of the most rapidly growing fields in condensed matter physics, which would drive novel quantum Hall states from a puzzle of fundamental physics to practical applications in electronics, metrology, and quantum information.



Transport measurement data exhibiting the quantum anomalous Hall effect. Credit: Science 340, 167 (2013)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