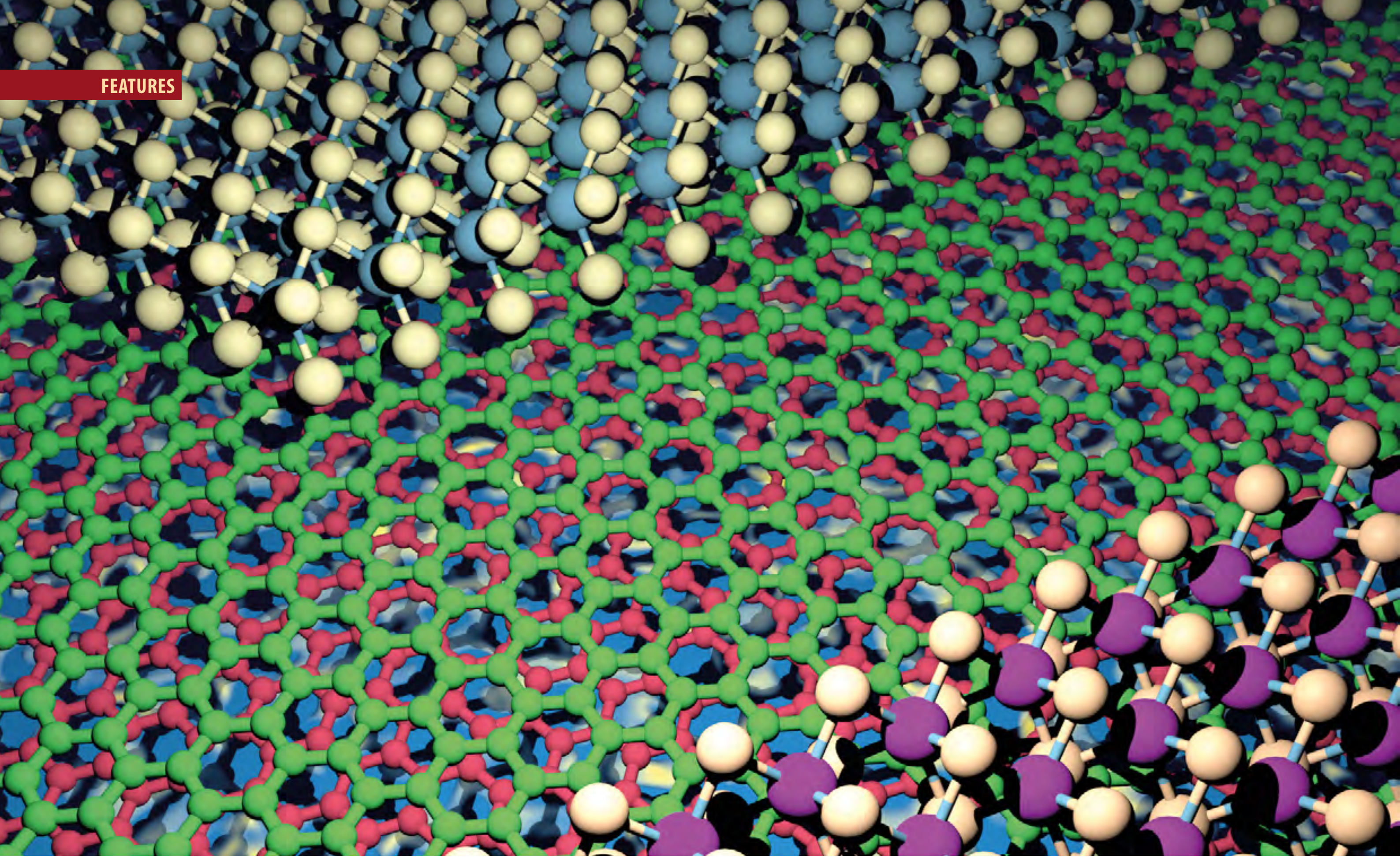


ENGINEERING EXOTIC QUANTUM MATTER IN TWISTED VAN DER WAALS MATERIALS

Jose Lado – Aalto University, Finland – DOI: https://doi.org/10.1051/epn/2024408

Pushing the boundaries of knowledge in quantum matter requires having a controllable platform to engineer quantum phenomena. Twisted van der Waals materials have risen as a highly flexible platform to engineer exotic states of matter, enabling creating quantum matter with a degree of control beyond conventional bulk materials [1].

Such flexibility stems from the weak van der Waals forces between materials, which allow for a simple yet incredibly powerful knob to create controllable quantum matter. Two-dimensional materials with widely different different competing electronic properties can be combined with nearly complete freedom. Furthermore, the weak van der Waals forces allow changing the rotation angle between materials, giving rise to a new length scale known as the moiré pattern, hosting a new electronic structure. Within these new crystals, electronic states feature propagation and interactions that can be widely different from the original materials, enabling the emergence of new quantum states. Ultimately, these features open a pathway to explore quantum matter not observable in any other naturally occurring materials.

In this feature article we will highlight some of the recent demonstrations in twisted van der Waals materials that have widely expanded the scope of their emergent quantum phenomena. In particular, we will address recent demonstrations of spin triplet superconductivity, heavy-fermion Kondo phenomena, unconventional twisted magnetism, fractional Chern physics, twisted ferroelectricity, and super-moiré physics.

Van der Waals spin triplet superconductivity

In most superconductors, Cooper pairs are conventionally formed by electrons with opposite spins, one up and one down, leading to a so-called spin singlet state. Conventional superconductors such as lead and unconventional superconductors such as cuprates belong to this class. However, Cooper pairs can be formed by electrons with the same spin, namely one spin up and another spin up, leading to a so-called spin-triplet state [2]. Artificial spin-triplet superconductivity arises in topological superconductors, as demonstrated by combining magnetism and superconductivity in a $CrBr_3/NbSe_2$ van der Waals heterostructure. However, spontaneous spin-triplet superconductivity is incredibly rare and is often realized in materials hosting rare earth elements with f electrons. Spin triplet superconductivity has the unique characteristic that it can be enhanced with an external magnetic field, in stark contrast with spin-singlet superconducting states. Twisted graphene trilayers have been shown to feature a spontaneous spin-triplet superconducting state enhanced by an in-plane magnetic field, the unique feature of spin-triplet superconductors. These findings establish the potential of finding elusive superconducting states in two-dimensional materials. Ultimately, this shows that the superconducting states realized in twisted van der Waals materials go well beyond those of most correlated superconductors, and may allow us to expand the types of superconductivity observed in nature.

Van der Waals heavy-fermion Kondo matter

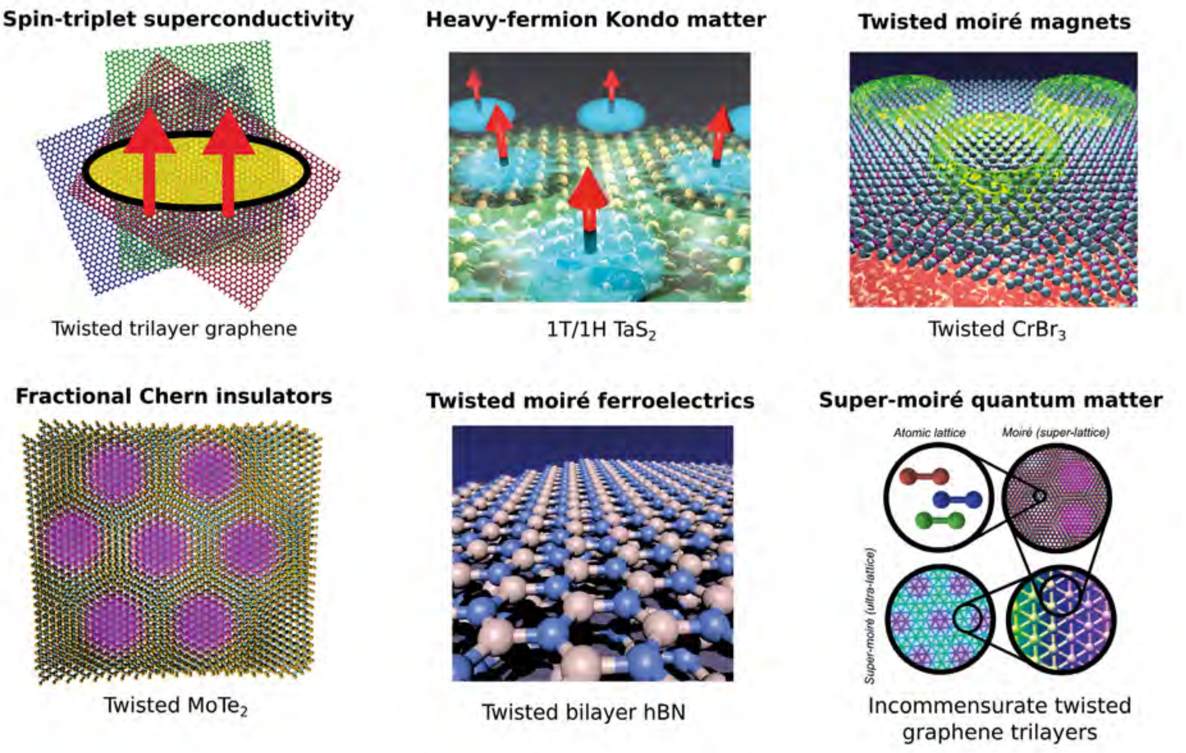
Heavy-fermion Kondo phenomena arise in systems featuring both extended states and localized magnetic moments, leading to a state dominated by quantum magnetism. The interaction between localized magnetic moments and metallic states leads to quantum entangled singlets that create a macroscopically entangled state. Conventionally, Kondo lattice phenomena have been mostly restricted to compounds with rare earth elements with f-electrons. In van der Waals materials, both localized magnetic moments and delocalized states can be naturally engineered, providing a unique platform to explore heavy-fermion phenomena. Such materials have been realized [3] both by combining different monolayers featuring the two ingredients, as in the case of 1T/1H TaS_2, as well as emerging from moiré bands as realized in twisted dichalcogenide $MoTe_2/WSe_2$ heterostructures. Heavy-fermion materials feature a widely rich set of unconventional phenomena, including screened entangled states, rich symmetry broken states, hidden order and spin-triplet superconductivity. Twisting, gating and van der Waals materials engineering provide unique strategies to explore the phase diagram of Kondo lattice models, potentially allowing us to gain deeper understanding of the physics of heavy-fermion Kondo matter.

Unconventional twisted van der Waals magnets

Classical magnetism, namely not dominated by quantum fluctuations, provides a complementary platform for emergent matter in moiré materials. The emergent length scale in twisted materials provides a new geometric knob to control magnetism, enabling magnetic structures with widely different length scales. A paradigmatic example is the case of twisted $CrBr_3$ bilayers [4]. While $CrBr_3$ monolayer is a ferromagnetic insulator, when forming a bilayer, the magnetic alignment between monolayers goes from ferromagnetic to antiferromagnetic depending on the stacking. In a twisted bilayer this leads to different regions of space have opposite magnetic alignments due to the change of local stacking. This moiré magnetism gives rise to non-collinear magnetic textures, and can ultimately lead to van der Waals-based skyrmion devices. Skyrmions are topological magnetic textures that have been intensively investigated for their potential for information processing, and twisted van der Waals magnets provide a potential 2D platform to realize such strategies. Another type of unconventional magnets are orbital magnets as realized on twisted graphene bilayer on hBN [5]. In this system magnetic order stems from spontaneous orbital currents instead of the spin of the electrons, further realizing a topological state known as Chern insulator.

Moiré fractional Chern insulators

Chern insulators are materials featuring quantized transverse conductivity in the absence of an external magnetic field, realizing a quantum Hall state without requiring the application of an external magnetic field. Strong many-body effects allow to create its fractional counterpart, a system featuring fractional transverse conductivity and emergent anyons at zero magnetic field. Creating a fractional Chern insulator requires two basic ingredients, a topological Chern band that is as similar as possible to a Landau level, and the existence of strong electronic interactions when partially filled. These two conditions can be often found in twisted van der Waals materials [6], making them ideal platforms for fractional Chern physics. Recent experiments have demonstrated the emergence of fractional Chern insulators in twisted bilayer $MoTe_2$ and pentalayer graphene/hBN moiré multilayer. The demonstration of fractional Chern physics in van der Waals materials establishes a new state of matter never observed in any other material in nature, a finding likely to have far-reaching consequences. Fractional Chern states at zero magnetic field would enable to explore quantum states emerging from the combination of fractional Chern physics and superconductivity. This was before nearly impossible, as fractional quantum Hall states require large magnetic fields, and superconductors ●●●



Spin-triplet superconductivity

Twisted trilayer graphene

Heavy-fermion Kondo matter

1T/1H TaS_2

Twisted moiré magnets

Twisted $CrBr_3$

Fractional Chern insulators

Twisted $MoTe_2$

Twisted moiré ferroelectrics

Twisted bilayer hBN

Super-moiré quantum matter

Incommensurate twisted graphene trilayers

▸ **FIG. 1:** Some of the emergent states in twisted van der Waals heterostructures, including from graphene, dichalcogenides, trihalides and boron nitride van der Waals twisted multilayers.

● ● ● are destroyed by it. This combination can enable new forms of quantum matter never observed so far, including exotic quantum excitations such as parafermions, and Fibonacci anyons. These excitations would enable creating topological qubits, providing a platform for quantum computing that could be scalable and free from decoherence, potentially overcoming the limitations of all current quantum computing architectures.

Twisted ferroelectricity in van der Waals materials

Moiré physics is not only restricted to electronic degrees of freedom, but also structural moiré physics can have wide impact. Ferroelectrics are materials featuring electric dipolar order spontaneously, and such degree of freedom can be used as a memory device, in close analogy with magnetic memories. Twisting allows creating van der Waals ferroelectrics from materials originally not ferroelectric, with twisted hBN a paradigmatic example [7]. In a twisted bilayer hBN the change in local stacking arising from the twist gives rise to spatially dependent structural relaxations. This gives rise to an emergent electric dipole following the moiré that can be externally switched with an electric field. Phenomena is twisted van der Waals materials often happens at low temperatures on the order of a few Kelvin. Interestingly, ferroelectricity in twisted hBN appears all the way up to room temperature, turning it into one of the first phenomena that can have a wide impact on next-generation nonvolatile memory technologies. Ferroelectricity can be used to control other emergent states in van der Waals materials, including correlated and superconducting states [8]. Ultimately, ferroelectrics may have an instrumental role in controlling quantum states in van der Waals heterostructures, a key component of a variety of future van der Waals quantum technologies ranging from detectors to qubits.

Super-moiré van der Waals heterostructures

The demonstrations described above rely on the emergence of the moiré length scale. However, recent breakthroughs have demonstrated that it is possible to reach the next level, creating van der Waals heterostructures featuring a moiré pattern of a moiré pattern, called super-moiré phenomena. In super-moiré systems, the electronic phenomena associated with the moiré pattern are itself modulated in space [9]. Such phenomena appear in twisted van der Waals materials featuring two different moiré length scales, such as twisted graphene trilayers and twisted bilayers on twisted bilayers. Super-moiré physics opens a whole new direction in van der Waals materials, enabling creating states where superconductivity and correlated states coexist in the same twisted van der Waals heterostructure. Super-moiré physics represents an instrumental strategy to create new quantum states that require as starting point phenomena only appearing in twisted multilayers, such as those required to build topological qubits by combining fractional Chern states and superconductivity. Ultimately, super-moiré materials open a whole new pathway for unconventional phenomena, turning all findings in moiré physics into new building blocks for an unexplored family of exotic quantum materials.

Twisted van der Waals heterostructures have become a highly successful platform to realize an astounding variety of unconventional quantum phenomena, and providing even states of matter never observed before. Moiré materials have become a widely interdisciplinary area in physics, bringing together the theoretical and experimental communities of two-dimensional materials, strongly correlated physics, magnetism, and topological physics, among others. The controllability and tunability of twisted heterostructures provides one of the most powerful strategies for quantum materials engineering, where the property of a quantum state can be externally tuned and engineered in a highly controlled manner. The richness and controllability of van der Waals materials provide a realistic strategy to harness exotic quantum phenomena for new quantum technologies, potentially enabling reconfigurable quantum devices [10] leveraging quantum states found in these materials. At a fundamental level, moiré materials provide an exciting pathway to push the boundaries of knowledge of emergence in quantum materials, and ultimately in physics. Twisted van der Waals materials have become a mature field, every year providing new breakthroughs enabling deeper and more exciting control of quantum matter, and breaking boundaries that just five years ago we would have considered many decades away, if not utterly impossible. ■

About the Author

Jose Lado is an Assistant Professor at Aalto University in Finland, working on the theory of quantum materials. He focuses on engineering artificial quantum materials featuring exotic quantum matter, combining materials science, quantum many-body physics, and machine learning, often in collaboration with experimental groups.

References

[1] Eva Y. Andrei *et al.*, *Nature Reviews Materials* **6**, 201 (2021)

[2] Shawulienu Kezilebieke *et al.*, *Nature* **588**, 424 (2020) ; Yuan Cao et al, *Nature* **595**, 526 (2021)

[3] Viliam Vaňo *et al.*, *Nature* **599**, 582 (2021) ; Wenjin Zhao et al, *Nature* **616**, 61 (2023)

[4] Tiancheng Song *et al.*, *Science* **374 6571**, 1140 (2021) ; Hongchao Xie *et al.*, *Nature Physics* **19**, 1150 (2023)

[5] M. Serlin *et al.*, Science, **367 6480**, 900 (2019)

[6] Jiaqi Cai et al, *Nature* **622**, 63 (2023) ; Zhengguang Lu *et al.*, *Nature* 626, 759–764 (2024)

[7] Kenji Yasuda *et al.*, *Science* **372 6549**, 1458 (2021) ; Kenji Yasuda *et al.*, *Science* 385, 6704 53 (2024)

[8] Dahlia R. Klein *et al.*, *Nature Nanotechnology* **18**, 331 (2023)

[9] Simon Turke *et al.*, *Science* **376 6589**, 193 (2022) ; Aviram Uri *et al.*, *Nature* **620**, 762 (2023)

[10] Folkert K. de Vries *et al.*, *Nature Nanotechnology* **16**, 760 (2021) ; Daniel Rodan-Legrain *et al.*, *Nature Nanotechnology* **16**, 769 (2021)