Nordic-German Wilhelm and Else Heraeus-Seminar 2026: Quantum Condensates and Quantum Geometry (QCQG)

Quantum Condensates and Quantum Geometry

Tutorial 1 Engineering artificial correlated quantum matter in 2D van der Waals materials

Jose Lado, Department of Applied Physics, Aalto University School of Science, Finland

Van der Waals materials provide a flexible platform to engineer exotic quantum matter, thanks to the ability to combine different 2D materials with competing orders. Understanding emergent quantum states in quantum materials requires capturing topology, spin-orbit coupling effects, impurities, strain, magnetism, superconductivity, and electronic correlations, among others. Here, we will present the theoretical background and computational demonstrations showing how to engineer emergent quantum matter in 2D materials and van der Waals heterostructures. Specifically, we will address the emergence of topological states, conventional and unconventional superconductivity, criticality, moiré electronic states, and conventional and frustrated magnetism. First, the tutorial will provide an introduction to the different phenomena addressed, and discussing how these unconventional states of matter can be engineered by combining specific orders in 2D materials, by leveraging proximity effects and twist engineering. Second, the tutorial will demonstrate the emergence of these quantum states using the Python computational library pyqula [1] using real-space tight-binding models, exemplifying how the different concepts discussed can be studied with computational models. The computational demonstrations will be accompanied by hands-on exercises using Jupyter notebooks, enabling real-time experimentation on how those electronic states can be engineered. The tutorial will provide an introduction and hands on demonstration on a computational tool to rationalize different form of 2D quantum matter, aimed both for theorists and experimentalists.

[1] https://github.com/joselado/pyqula

Tutorial 2 Quasiclassical theory

Mattias Eschrig, University of Greifswald

Colloquium

Stuart Parkin, MPI-Halle

Keynote talks

K 1) Spin-polarized and topological superconductivity

Piet Brouwer, Freie Universitaet Berlin

Cooper pairs in conventional superconductors carry no spin. Spin-polarized Cooper pairs require unconventional forms of superconductivity. I'll review how such spin-polarized superconductivity and topological superconductivity can arise in superconductor-magnet heterostructures with non-collinear magnetizations. Recent experiments on the chiral kagome antiferromagnet Mn3Ge have provided strong evidence of proximity-induced spin-polarized superconductivity. I introduce and explore a minimal model which exhibits a rich phase diagram as a function of chemical potential and spin canting, which has various topological and non-topological forms of spin-polarized superconductivity.

K 2) Topological superfluid ^{3}He under confinement in engineered nanofabricated geometries

J. Saunders, Department of Physics, Royal Holloway University of London, Egham, UK

Superfluid ^{3}He is the paradigm for topological superconductors, which require unconventional, odd-parity, spin-triplet pairing states. The order parameter of superfluid ^{3}He can be engineered by confinement in a nanofabricated cavity of height comparable to the superfluid coherence length. An alternative approach has been to embed a network of scattering centres. The surface scattering conditions can be tuned *in situ*; we can create ideal specular scattering by plating the atomically flat surfaces with a superfluid ^{4}He film. And the ^{3}He itself is pristine, free of impurities. The spin degrees of freedom of the superfluid Cooper pairs are the ^{3}He nuclear spins. Therefore nuclear magnetic resonance (NMR) provides a direct and non-invasive probe to both fingerprint the superfluid order parameter, and the surface bound states. Confinement as a control parameter allows order parameter sculpture, and the engineering of hybrid nanostructures and superfluid meta-materials [1].

The relative stability under confinement of the chiral A-phase and time reversal invariant B-phase has been determined [2,3]. Furthermore, under such conditions new phases emerge; the polar phase [4,5], pair density wave states [6]. The quasi-2D chiral A-phase [7] has already been identified, and the gapless chiral phase is in prospect. This has required the demonstration of the fragility of surface states to surface scattering conditions [8]. The stepped confinement, essential for the engineering of hybrid nanostructure, has been applied to create isolated volumes of superfluid [9]. In conjunction with powerful computer simulations [10], this has led to a "table-top" demonstration of cosmological Kibble-Zurek phase transitions in a system with multi-component order parameter [11].

The talk will also give an overview of the current focus of our research: the investigation of topological surface, edge and interface states, as a benchmark for topological superconductivity. Objectives are: to identify dispersing Majorana fermions, predicted at the surface of the time-reversal-invariant superfluid ^{3}He-B phase; to apply thermal transport in new superfluid devices to investigate interface states, the thermal Hall effect and detect chiral edge currents in the fully gapped quasi-2D chiral state; to create quasi-1D channels of polar phase as analogues of hybrid topological superconductor nanowire structures.

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K 3) Quantum Geometry and Transport

Päivi Törmä, Department of Applied Physics, Aalto University School of Science, Finland

We have found that superconductivity and superfluidity are connected to quantum geometry [1,2]: the superfluid weight in a multiband system is proportional to the minimal quantum metric of the band. The quantum metric is connected to the Berry curvature, which relates superconductivity to the topological properties of the band. Using this theory, we have shown that superconductivity is possible also in a flat band where individual electrons would not move. These results may be relevant for explaining the observation of superconductivity in twisted bilayer graphene [3], and rhombohedral graphite [4]. The quantum transport in flat band shows unique behavior [5]: while supercurrent can flow, quasiparticle transport is highly suppressed even in non-equilibrium conditions. This may have important consequences for superconducting devices. We have predicted that flat band systems as part of Josephson junctions can lead to behavior distinct from the dispersive case [6]. Our recent results show that superfluid weight in a flat band is robust to disorder, which can be explained by intra- and interband localization functionals [7].

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K 4) Hubbard models for unconventional magnetism and superconductivity

D. Agterberg, University of Wisconsin - Milwaukee

Unconventional superconductivity is traditionally understood from a single-band perspective. However, many newly discovered superconductors do not naturally fit within this paradigm. Unconventional magnets, such as altermagnets and odd-parity magnets, have recently emerged as important classes of magnetic materials for spintronics due to their vanishing net magnetization and large, strongly momentum dependent, energy splittings between opposite spin electronic states. Here I present recent progress on sublattice-based Hubbard Hamiltonians for both unconventional magnetism and superconductivity. These Hubbard models provide insight into the origins of non-relativistic spin splittings in unconventional magents [1,2,3] and odd-parity superconducting states [4].

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K 5) Controlling Cuprates' Ground State with Designer Substrates

Floriana Lombardi, Chalmers University of Technology

Despite decades of intense research, the microscopic mechanism of high-temperature superconductivity in the cuprates remains unresolved. A central obstacle is the limited tunability of these materials: unlike many two-dimensional systems, the charge carrier density in cuprate superconductors is fixed during synthesis, making it difficult to continuously access and manipulate competing electronic phases using conventional gating approaches.
In this talk, I show that substrate engineering provides a powerful alternative route to control the electronic ground state of cuprates, enabling access to new phases and reshaping their interplay with superconductivity. Focusing on nm thick $YBa_2Cu_3O_{7-x}$ films, I demonstrate that substrates with a nanofaceted surface morphology, formed by high-temperature surface reconstruction induce electronic nematicity and a unidirectional charge-density wave, stabilizing a novel ground state distinct from that of thicker films and bulk crystals.
Remarkably, these interfacial effects lead to a strong enhancement of superconductivity: the onset temperature increases by more than 20 K, and the upper critical magnetic field is enhanced by more than 50 T at fixed doping. Together, these results establish substrate engineering as a

powerful strategy for tuning quantum phases in cuprates and for designing high-performance superconducting materials.

Topical talks

T 1) Chrisroph Strunk, Uni Regensburg

T 2) Topological i-wave superconductivity in trigonal $PtBi_2$

Carsten Timm, Technical University of Dresden

Trigonal $PtBi_2$ is a noncentrosymmetric Weyl semimetal with topologically protected surface bands forming six Fermi arcs at each (001) surface. Recent angular resolved photoemission (ARPES) experiments suggesting the presence of unconventional, nodal superconductivity in these Fermi arcs with a critical temperature of about 10 K [1] have created quite a bit of excitement. After reviewing the experimental evidence, I will argue that the nodal superconducting state has angular momentum 6 (i-wave). The six point nodes at one surface are characterized by the same winding number and are predicted to be associated with topological hinge states.

[1] S. Changdar et al., Topological nodal i-wave superconductivity in $PtBi_2$ Nature 647, 613 (2025).

T 3) Spin and pair density waves in 2D altermagnetic metals

Laura Classen, Technical University of Munich

Altermagnetism, a recently proposed and experimentally confirmed class of magnetic order, features collinear compensated magnetism with unconventional spin split bands. Here, we show that in a metallic 2D d-wave altermagnet with [C2||C4] symmetry, secondary instabilities can arise. Using an unbiased functional renormalization group approach, we analyze the weak-coupling instabilities of a 2D Hubbard model with a preexisting altermagnetic order inspired by our ab initio electronic structure calculations of realistic material candidates from V2X2O (X = Te, Se) family. We identify two distinct spin density wave (SDW) states that break the underlying altermagnetic [C2||C4] symmetry. Additionally, we find spin-fluctuation-induced instabilities leading to a singlet d-wave superconducting state and an unconventional commensurate pair density wave (PDW) state with extended s-wave and spin-triplet symmetry. We analyze the pairing mechanism and characterize their excitation spectrum, which exhibits Bogoliubov Fermi surfaces or nodal points depending on the gap size.

T 4) Single-atom Josephson junctions: diode-like behavior and interaction with high-frequency radiation

Katharina J. Franke, *Fachbereich Physik and Halle–Berlin–Regensburg Cluster of Excellence CCE, Freie Universität Berlin, Germany*

The scanning tunneling microscope (STM) is a powerful tool for atomic-scale spectroscopy of normal and superconducting materials. By using superconducting tips, Josephson junctions can be formed when approaching a superconducting substrate. A fingerprint of the Josephson junction is a zero-bias peak in voltage-biased differential-conductance spectroscopy. However, an applied bias destroys the phase coherence of the junction.

Replacing the conventional voltage bias with an effective current bias, phase coherence can be longer preserved in the superconducting state. Here, we first investigate the phase dynamics in Pb-Pb junctions. We identify switching and retrapping currents that mark the transitions between superconducting and normal states. Adding magnetic adatoms to the surface of a superconductor leads to Yu-Shiba-Rusinov states inside the superconducting gap. Using Josephson spectroscopy, we find that the switching currents are significantly reduced compared to the pristine junction, indicating a local reduction of the superconducting order parameter. Even more interestingly, the retrapping current shows an asymmetric behavior with respect to the biasing direction [1]. This implies that a supercurrent can flow without dissipation in one direction while experiencing resistance in the opposite direction. We attribute this diode-like effect to the electron-hole asymmetry of Yu-Shiba-Rusinov states [1,2]. When then expose the junctions to high-frequency radiation where we find Shapiro steps, signifying the coherent absorption of photons, although phase diffusion is enhanced at the same time [3].

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T 5) **Classification of Topological Phases in Multiterminal Josephson Junctions**

Julia Meyer Université **Grenoble**-Alpes

Multiterminal Josephson junctions are of interest both as probes of the topological properties of the superconducting leads and as synthetic topological matter. Using the superconducting phases of the terminals in n-terminal Josephson junctions as variables, one may realize topological band structures in d = n-1 dimensions. For example, it has been shown that a 4-terminal junction may realize the analog of a Weyl semimetal, whereas a 3-terminal junction may realize the analog of a Chern insulator. Extending the analogy to more terminals opens the possibility of realizing topological phases in arbitrary dimensions, not accessible in real materials. As the superconducting phases act as "anomalous" variables, the symmetry-based classification of topological phases in multiterminal junctions differs from the usual table. Here we classify possible phases and provide an example for a gapped 3-dimensional topological phase characterized by a Z2-invariant in symmetry class C using 5-terminal junctions.

T 6) Yasmine Sassa, Royal Institute of Technology, KTH

T 7) **Exotic spin physics in disordered superconductors**

Tero Heikkilä, University of Jyväskylä

The interplay of spin physics with superconductivity has been studied for decades, with the emphasis varying between exotic spin-dependent order parameters to the spin responses in superconductors. One effect of particular recent interest that brought this interplay into highlight has been the superconducting diode effect originating from this interplay. Until relatively recently it was quite difficult to make precise predictions about the size of this diode effect, driven by a combination of the spin-orbit coupling and exchange field, in the usually realistic setting of disordered superconductors. This changed with the extension of the quasiclassical Usadel equation framework to include the suitable ingredients for the diode effect, primarily by Virtanen, Kokkeler, Tokatly and Bergeret. In my talk I will describe this extension and highlight its implications via the quantitative theory for the diode effect, a prediction for a previously unexplored anomalous vortex, and showing a calculation of an ac spin Hall and spin splitter effects in superconductors.

T 8) The role and influence of antiferromagnetic correlations in electron doped cuprates

Oscar Tjernberg, Department of Applied Physics, KTH Royal Institute of Technology

The role of antiferromagnetism in high Tc cuprates remains at the center of understanding the superconductivity in these systems. During this talk I will present some of our recent results on electron doped high Tc cuprates and show the dual role that antiferromagnetic fluctuations seem to play in the electron doped cuprates*. An intriguing link between electron-phonon coupling and the strength of antiferromagnetic fluctuations will also be elucidated. As an outlook, the ongoing work on directly detecting and characterizing Cooper pairs using 2e-ARPES will also be briefly described.

* Bogoliubov quasiparticle on the gossamer Fermi surface in electron-doped cuprates, Nat. Phys. 19, 1834 (2023)

T 9) **D-vector spectroscopy in triplet superconductors**

Andreas Kreisel, Uppsala University

The heavy-fermion compound UTe_2 is a candidate for hosting intrinsic spin-triplet superconductivity. At present, however, the type of triplet Cooper pairing realized in UTe_2 remains unknown, which calls for further experimental and theoretical investigations. Using a microscopic minimal model for the superconducting phases, we examine which imprints of the superconducting order parameter occur on the surface spectral function. Crystalline symmetries determine the properties of the topological surface states allowing to discriminate superconducting order parameters transforming differently under remaining symmetries of the surface.

From the perspective of the bulk superconductivity, it turns out that the relative direction of the d-vector that parametrizes the triplet order parameter can be detected in data from quasiparticle interference. We show that beyond the enhanced density of states close to the nodes, one is able to distinguish the allowed superconducting ground states B_{2u} and B_{3u} as proposed for UTe_2.

Technical complications of these investigations are the body-centered orthorhombic structure allowing a number of pairing contributions leading to accidental nodes on the Fermi surface, the nature of the electronic states exhibiting strong spin orbit coupling and the fact that atomically flat surfaces suitable for scanning tunneling microscopy can only be achieved on a (0-11) cleaving plane.

T 10) **Atomistic Spin Dynamics: From Microscopic Theory to Topological Textures and Magnons**

Anna Delin Department of Applied Physics, Royal Institute of Technology, KTH, Stockholm

Atomistic spin dynamics provides a powerful framework for simulating magnetization dynamics on the fundamental length and time scales where quantum mechanics, exchange interactions, and thermal fluctuations all play essential roles. In this talk, I will introduce the core ideas behind atomistic spin-dynamics theory, and how the parameters entering the Hamiltonian can be computed from density functional theory so that the theory becomes independent of experimental input. I will then show some examples of how this approach enables quantitative predictions for topological spin textures—such as skyrmions, antiskyrmions, and their interactions. Finally, I will discuss atomistic spin dynamics in relation to topological magnons. Together, these examples illustrate how atomistic spin dynamics bridges microscopic physics and emergent topological phenomena in modern magnetic materials.

Contributed talks

C 1) Ignition of spin-triplet supercurrent in a ballistic S/F/S Josephson junction with precessing magnetization

Elizaveta Andriyakhina, Freie Universität Berlin

We develop a theory for a ballistic Josephson junction with a ferromagnetic (including half-metallic) interlayer whose uniformly precessing magnetization generates a controllable equal-spin (triplet) supercurrent. In a co-rotating frame, the driven junction maps to an effective static problem that can be treated with a scattering-matrix approach to obtain Andreev bound states and the dc Josephson current. A key result is that steady precession produces a spin-dependent non-equilibrium occupation in the rotating frame, yielding a finite dc supercurrent. In the half-metal limit the junction is "off" without precession, but becomes "on" when a finite precession angle induces phase-sensitive Andreev levels and a triplet current. For small precession angles, the induced current is approximately sinusoidal in phase and the critical current scales quadratically with the precession angle (and with drive parameters), enabling microwave-controlled switching via ferromagnetic resonance.

C 2) Quantum Geometry and Fractionalization

Emil Bergholtz, Stockholm University

I will discuss the key role of quantum geometry in fractionalisation, in particular in the context of fractional Chern insulators and moiré materials. Theorems regarding ideal geometry conditions, flat curvature, symmetry breaking and density algebras will be discussed along with heuristics for finding novel states of matter such as Hall crystals and non-Abelian liquids.

C 3) Diamagnetic Meissner response of odd-frequency superconducting pairing from quantum geometry

Ankita Bhattacharya, Uppsala University

We investigate the role of quantum geometry in the Meissner response of odd-frequency superconducting pairs in multiband systems. Odd-frequency pairing is commonly associated with a paramagnetic Meissner response, raising questions about the stability of the superconducting phase, particularly in multiband systems where such pairing is ubiquitous. Using analytical calculations in a general two-band model, we show that the quantum geometric contribution from odd-frequency pairs is always diamagnetic for interband processes, while intraband processes remain paramagnetic. Since odd-frequency pairing is generated by interband pairing, an overall diamagnetic response is often expected. We support these results with numerical calculations for both flat and dispersive band models. In flat-band systems, where geometric effects dominate, the diamagnetic odd-frequency contribution can exceed the even-frequency response. These findings demonstrate that quantum geometry stabilizes odd-frequency superconductivity and identify flat-band materials as promising candidates for realizing a diamagnetic Meissner effect from odd-frequency pairs.

C 4) Quantum Geometry of Time-Reversal Symmetry Breaking in Flat-Band Superconductors

Aaron Dunbrack, University of Jyväskylä

Typically, the connection between quantum geometry and flat-band superconductivity is derived in the presence of time-reversal symmetry. In the absence of both time-reversal and inversion, it is possible to have a term in the free energy that is linear in phase gradient (called the Lifshitz invariant); this term gives rise to a helical modulation of the superconducting order parameter. In a flat band, this term is dependent on "mixed quantum geometry" that combines k-space and parameter-space.

C 5) Cosmological Kibble-Zurek-driven phase transitions in superfluid helium-3

Petri Heikkinen, Royal Holloway, University of London

The extremely pure liquid helium-3 at millikelvin temperatures, with its cosmological analogues, is an ideal test bed to study the early-Universe phase transitions in laboratory. In helium-3 both the first and second order phase transitions are accessible, with the mechanism of the phase transition between its topological superfluid A and B phases having been a fundamental problem in the condensed matter physics, evading explanation despite decades of both experimental and theoretical work. Whereas the models for an intrinsic first-order phase-transition - homogeneous nucleation via thermal fluctuations or quantum tunnelling - predict a timescale for such a phase transition to take place far longer than the age of the Universe under relevant experimental conditions, in laboratory they are routinely observed to take place within seconds to hours, often facilitated by the sample container construction. Here we show that confining helium-3 inside five nanofabricated well-isolated atomically smooth phase-transition chambers protects against any obvious spurious sources of phase nucleation. Only remaining external trigger is ionising radiation, effect of which is also suppressed by the tiny volumes of the chambers. We extensively study this over a wide temperature and pressure range and discover a rich non-monotonic dependence of the lifetime of the supercooled metastable A phase on both temperature and pressure. Our SQUID-amplified nuclear magnetic resonance experiments are supported by high-performance computer simulations to understand the nonequilibrium superfluid dynamics, revealing the vital role played by the Kibble-Zurek mechanism. In the future, this strengthened understanding of the radiation-triggered phase transitions will give the elusive intrinsic mechanisms a chance to become detectable.

C 6) Dirty Superconductor Magnet Hybrids

Tim Kokkeler, University of Jyväskyla

The field of superconducting spintronics has recently evolved from a focus on the interplay of superconductivity with ferromagnetism and various types of spin-orbit coupling, to include also unconventional types of magnetism such as altermagnetism and p-wave magnetism. Like spin-orbit coupling, these unconventional magnets have a momentum-dependent spin-splitting that vanishes after averaging over the Fermi surface. However, unlike spin-orbit coupling, the underlying mechanisms break time-reversal symmetry. As discussed in this talk, this difference leads to qualitatively different transport responses in hybrid structures, both in equilibrium and out-of-equilibrium. To show this, first the transport equations for unconventional magnets with superconductivity are discussed, including the influence of the spin-dependent diffusion constant on Cooper pairs and an unconventional Larmor precession. Then, several effects are presented that are unique to hybrid systems with superconductivity and unconventional magnetism, and they are compared with effects that appear due to the interplay of superconductivity with spin-orbit coupling. With this we provide predictions for transport signatures of altermagnetism and p-wave magnetism.

C 7) Unconventional gap structure in kagome superconductor coupled to hybrid microwave resonators

Yejin Lee, Max Planck Institute for Chemical Physics of Solids

Kagome superconductors provide a rich platform to explore strong electronic correlations, superconductivity, pair density wave features and nontrivial band topology. Identifying a pairing symmetry is essential to understand the intertwined quantum phases. Despite numerous experimental efforts, focused on bulk crystals, there is no consensus for microscopic origin so far. Additionally, van der Waals flakes show distinct phases that are hard to probe with conventional methods due to the micron-size. We employ hybrid microwave circuits in which van der Waals kagome flakes are noninvasively coupled to superconducting resonators with preserved interface. This method enables microwave measurements with high coherence and low loss for the superconducting electrodynamic response at ultra-low temperatures. Using this technique, we resolve the temperature evolution of its superfluid response. A linear decrease in the temperature dependent resonance frequency is observed, inconsistent with a fully gapped state and instead indicative of nodal superconductivity. Our finding provides a crucial insight into the microscopic pairing mechanism in kagome superconductors, and establishes microwave resonators as a powerful probe of pairing symmetry in low-dimensional superconductors.

C 8) Josephson diode effect in junctions involving strongly spin-polarized magnetic materials without spin-orbit.

Danilo Nikolic, Institute of Physics, University of Greifswald

Long-range equal-spin triplet supercurrents induced by nontrivial spin textures are of fundamental importance both for the understanding and the applications of superconducting spintronics. Considering the interface between a conventional spin-singlet superconductor and a ferromagnetic material, the creation and control of equal-spin correlations is allowed due to two fundamental processes. First, the spin-mixing (or spin-dependent-phase-shift) effect due to the spin polarization of the interface converts spin-singlet pairs from the superconductor into mixed-spin triplet correlations in the ferromagnet. Second, if a noncollinear spin arrangement is present in the ferromagnet, the spin-rotation mechanism turns the short-range mixed-spin pairs into the long-range equal-spin pairs. Therefore, the noncollinearity of the spin texture is necessary for the existence of equal-spin triplet correlations. However, if the spin texture is not only noncollinear but in fact noncoplanar, new functionalities, such as an effective decoupling of the Josephson phases in the two spin bands, may appear. Consequently, junctions involving such materials can exhibit the spin-resolved Josephson diode effect. In this context, such an effect has been predicted in various setups, including strongly spin-polarized ferromagnetic trilayers with noncoplanar magnetization profiles, intrinsically noncoplanar magnetic materials such as conical magnets, and ferromagnetic trilayers involving altermagnets.

In this talk, we will present the necessary conditions for the appearance of the Josephson diode effect in junctions involving strongly spin-polarized magnetic materials without spin-orbit. As we will show, such an effect emerges if the Josephson current-phase relation (CPR) possesses no phase-inversion center, and, in what follows, we will examine the conditions under which this

regime is realized. First, we will comment on the essential role of the noncoplanarity of the spin texture, which breaks the spatial inversion symmetry and gives rise to quantum geometric phases, $\Delta\varphi'$, that enter the Josephson CPR similarly to the superconducting phase difference, $\Delta\chi$. Second, we will show that both spin bands in themagnetic material have to contribute to transport, i.e., the effect is absent in half-metallic junctions. Third, different band-specific densities of states are required, and this condition is ensured by the strong spin polarization of the magnetic material. Finally, higher harmonics in
the Josephson CPR are necessary, i.e., the effect is absent in the tunneling limit. However, even in this case, the Josehson CPR must not have a phase-inversion center, which is ensured by the restriction of the quantum geometric phase to values $\Delta\varphi' \neq k\pi/2$, $k \in \mathbb{Z}$. Finally, we will illustrate our theory by formulating a simple phenomenological model that incorporates the abovementioned points and exhibits the spin-resolved Josephson diode effect.

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C 9) Multiterminal Josephson Junctions: Reflectionless modes and Quantum Geometry

David Christian Ohnmacht, Universität Konstanz

In multiterminal Josephson junctions (MTJJs), the Andreev bound state energies depend on multiple phase differences, enabling band structure engineering with external flux control. MTJJs are predicted to host non-trivial (non-Hermitian) topological phases and associated Weyl nodes in the synthetic Brillouin zone spanned by these superconducting phases [1,2]. In Ref. [3], spectroscopic measurements were performed on four-terminal Josephson junctions with phase control over all three superconducting phase differences, unveiling the presence of a tri-Andreev molecule, compatible with a topologically non-trivial model.

We predict that reflectionless scattering modes in MTJJs are a source of topological phase boundaries [4]. Our work provides an effective bulk-boundary correspondence by demonstrating a relationship between unity transmission modes and boundaries between topologically trivial and non-trivial regions, like in quantum Hall systems. Further insight into these systems can be provided by quantum geometry, where the so-called quantum weight [5] establishes bounds on the topological gap and existence of flat bands in MTJJs [6].

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[6] D. C. Ohnmacht, et. al. (in preparation)

C 10) Moiré fractional Chern insulators from topological bosons and trivial fermions

Raul Perea-Causin, Stockholm University

Recent realizations of fermionic fractional Chern insulators (FCIs) and anomalous Hall crystals have established moiré systems as a powerful platform for exploring correlated topological phases. Here, we predict the emergence of robust bosonic topological order arising from long-lived interlayer excitons consisting of holes in twisted bilayer WSe_2 and electrons in an additional $MoSe_2$ layer. In particular, exact diagonalization reveals that realistic long-range interactions stabilize Laughlin and non-Abelian Moore–Read states at filling factors 1/2 and 1 of the exciton Chern band present in this system. In parallel, we uncover Laughlin-like fermionic FCIs in topologically trivial bands of twisted multilayer graphene, where a strongly inhomogeneous quantum geometry drives topological order independent of band topology. Together, these results highlight the extraordinarily rich landscape of moiré quantum matter, encompassing both bosonic and fermionic topological order shaped by quantum geometry.