Topology and Geometry: Novel Concepts in 3D Quantum Transport on the Mesoscale

855. WE-Heraeus-Seminar

29 Mar - 02 Apr 2026
at the Digital Hub Logistics Event Location,
Hamburg/Germany

The WE-Heraeus Foundation supports research and education in science, especially in physics.
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Introduction

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Aims and scope of the 855. WE-Heraeus-Seminar:

The Heraeus workshop "Topology and geometry: Novel concepts in 3D quantum transport on the mesoscale" explores charge transport in mesoscale systems where conventional Ohmic scaling breaks down. As device dimensions shrink and materials complexity grows, transport becomes governed by a rich interplay of geometry, topology, and many-body interactions. We aim to unify perspectives across three key areas: (1) topological transport shaped by quantum geometry and Berry curvature, (2) semiclassical and quantum transport under high magnetic fields, and (3) strongly correlated electron dynamics including hydrodynamic flow and quantum criticality. Particular emphasis is placed on identifying how disparate length scales—mean free path, magnetic length, and correlation length—conspire to shape transport in modern materials.

The workshop will foster cross-disciplinary exchange between condensed matter physics, materials chemistry, and device theory. A central focus is to create a platform for junior researchers through integrated poster sessions and networking events. The event will be held at the Krähennest in Hamburg and include an excursion to the Max Planck Institute for the Structure and Dynamics of Matter, showcasing experimental advances in 3D quantum materials.

Scientific Organizers:

Prof. Dr. Philip Moll	MPI for the Structure and Dynamics of Matter, Hamburg, Germany E-Mail: philip.moll@mpsd.mpg.de
Prof. Dr. Raquel Queiroz	Columbia University, New York, USA E-Mail: raquel.queiroz@columbia.edu
Prof. Dr. Tobias Holder	Tel Aviv University, Israel E-Mail: tobiasholder@tauex.tau.ac.il

Introduction

Administrative Organization:

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Venue:

Digital Hub Logistics Event Location (Krähennest)
4th and 5th Floors
Am Sandtorkai 32
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Registration:

Martina Albert (WE Heraeus Foundation)
at the PierDrei Hotel, Lobby
Sunday (12:00 h – 15:15 h)
and
Monday (08:30 – 11:30 h) at the Digital Hub
Logistics Event Location

Program

Topology and Geometry

855th WE. Heraeus Seminar

March 29th – April 2nd | Hamburg, Germany

Sunday, March 29th

12:00	15:15	15:30	16:00	17:00	19:00	21:00
Registration in PierDREI Hotel Lobby	Meet in PierDREI Hotel Lobby	Walk to “Flusi,” Hamburg’s floating church	Opening Talk by Jörg Schmalian	Pick Up by Barge 17:30 Departure	Arrive at Övelgönne & Hoppe’s	End of dinner, return to PierDREI

Time	*Monday, March 30th*	*Tuesday, March 31st*	*Wednesday, April 1st*	*Thursday, April 2nd*
08:00	*Breakfast in PierDREI Hotel – Talks at Event Space: Digital Hub*			
09:00	Talk **Binghai Yan**	Talk **Marco Polini**	Talk **Xavier Roy**	Talk **Jennifer Coulter**
10:00	Talk **Lilia S. Xie**	Talk **Piet Brouwer**	Talk **Roni Ilan**	Talk **Felix von Oppen**
11:00	Poster Discussion	Poster Discussion	Poster Discussion	Talk **Yaojia Wang**
12:30	*Lunch Served in Event Space: Digital Hub*			Closing Remarks & Conclusion Departure
14:00	Talk **Raquel Queiroz**	Talk **Nishchhal Verma**	Talk **Chunyu Guo**	
15:00	Talk **Quansheng Wu**	Talk **Johannes Hofmann**	Poster Flash	
16:00	Coffee Break & leaving for MPI	Coffee Break	Poster Session	
17:00	Welcome to Max Planck Institute	Discussion Session	Poster Session	
18:30	Dinner at Institute & Return to Hotel	Dinner (free for you to plan)	**18:00** Heraeus Conference Dinner on Rickmer Rickmers ship	

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Topology and Geometry

855th WE. Heraeus Seminar

March 29th – April 2nd | Hamburg, Germany

List of Talk Titles

Monday, March 30th

Binghai Yan:	Probing the hidden symmetry by quantum geometry-induced nonlinear transport
Lilia S. Xie:	Superlattice domain effects on transport in a noncollinear antiferromagnet
Raquel Queiroz:	Quantum geometry as a window into bonding and transport in metals
Quansheng Wu:	New Paradigm: Magnetotransport + First-Principles → Electronic-Structure Characterization

Tuesday, March 31st

Marco Polini:	Polariton-induced superconductivity in two-dimensional correlated metals
Piet Brouwer:	Spin-polarized and topological superconductivity in a chiral antiferromagnet
Nishchhal Verma:	Identifying quantum geometric effects in transport
Johannes Hofmann:	Long-lived modes and hydrodynamic transport in interaction-dominated Fermi liquids

Wednesday, April 1st

Xavier Roy:	Quantum complexity in simple materials
Roni Ilan:	Geometry and topology of free and bound excitons
Chunyu Guo:	Many-body quantum coherence in AV3Sb5 Kagome metals

Thursday, April 2nd

Jennifer Coulter:	New Frontiers in Electrical, Thermal, and Thermoelectric Transport Predictions
Felix von Oppen:	Exciton Condensates in quantizing magnetic fields
Yaojia Wang:	Supercurrent interference and its transfer in a kagome superconductor

Important Addresses in Hamburg

- **PierDREI Hotel** Am Sandtorkai 46, 20457 Hamburg
- **Digital Hub / Event Space** Workshop Rooms (4th Floor) & Krähennest (5th Floor),
  Am Sandtorkai 32, 20457 Hamburg
- **Flussschifferkirche** Hohe Brücke 2, 20459 Hamburg
- **Hoppe's Restaurant** Övelgönne 6, 22605 Hamburg
- **Rickmer Rickmers** St. Pauli-Landungsbrücken 1a, 20459 Hamburg

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Posters

Posters

Patricia Almeida	**Kondo, Kagome and strain effects on thermoelectric efficiency in quantum impurity systems.**
Elizaveta Andriyakhina	**Ignition of spin-triplet supercurrent in a ballistic S/F/S Josephson junction with precessing magnetization**
Nitay Ben-Shachar	**Tomographic electron flows in confined geometries**
Sarah Damerow	**Systematic Theory of Real-Time Atomistic Spin Dynamics**
Benshu Fan	**Floquet optical selection rules in black phosphorus**
Viktor Frilen	**Collective modes and transport in d-wave altermagnets: a Fermi liquid approach**
Roemer Hinlopen	**H-linear magnetoresistance due to impeded cyclotron motion in $2H$-NbSe$_2$**
Samra Husremovic	**Fermi surface topology and magnetotransport in corrugated van der Waals semimetals**
Yoshi Iwasa	**Topological surface states of Wey semimetals probed by nonreciprocal transport**
Daemo Kang	**Quantum Printing: Quantum Optical Spanner and Kapitza-Dirac Effect of Higgs mode in superconductors**
Egor Kiselev	**Dynamics of orbital angular momentum in confined geometries**
Viktor Konye	**The non-Hermitian Topology of Transport**
David Alan Krüger	**Kondo impurities coupled to a Chern insulator**
Gal Lemut	**Proximity superconductivity in chiral kagome antiferromagnets**

Posters

Sackarias Lunman	**Lattice Gas Cellular Automaton with Tomographic Dynamics**
Jeffrey Allan Maki	**Tomographic collective modes in a magnetic field**
Pawel Matus	**Interactions and collective dynamics of defects in Wigner crystals**
W. Joe Meese	**Manipulation of ferromagnetism with a light-driven nonlinear Edelstein-Zeeman field**
Johannes Mitscherling	**Quantum geometric origin of P-wave and orbital magnetism in non-collinear magnets**
Raigo Nagashima	**Degenerate Majorana zero modes in a single vortex**
Alexander Nikolaenko	**Sondheimer magneto-oscillations as a probe of Fermi surface reconstruction in underdoped cuprates**
Anatoly Obzhirov	**Constructing Gauge-Invariant Lattice Models for Cavity QED**
Puspita Parui	**Interplay of Spin–Orbit and Exchange Couplings in the Pseudospin-1 Dice Lattice: Effects of Staggered Potentials**
Arpit Raj	**Light-induced pseudo-magnetic fields in three-dimensional topological semimetals**
Bogdan Rajkov	**Electron-phonon hydrodynamics and Viscous Thermoelectric Equations**
Adrien Reingruber	**Quantum Monte Carlo Study of Hydrodynamics in Systems with Particle-Hole Symmetry**
Maximilian Rieger	**Bloch oscillations in a transmon embedded in a resonant electromagnetic environment**

Posters

Oskar Schweizer	**Anomalous Fractional Chiral Currents in Step Edges of Weyl Semimetals**
Veronika Stangier	**Strong-coupling superconductivity near Gross-Neveu quantum criticality in Dirac systems**
Maksim Ulybyshev	**Quantum Monte Carlo simulations of electronic transport in strongly-correlated Dirac materials**
Davide Valentinis	**Quantum critical electronic liquids in strange metals: exact results for magnetotransport from spatially disordered 2D Yukawa-SYK theory**
Yuzhi Wang	**Hall Resistivity Scaling Behavior of Altermagnet CrSb**
Bo Yin	**Topological Anderson Chern Insulator in Monolayer MnBi4Te7/Classical Percolation from Quantum Metric in Flat-Band Delocalization**
Hongbin Zhang	**Medium-throughput calculations on the nonlinear topological transport properties**
Yan Zhang	**Electronic Structure and Effective Hamiltonian Construction for Moiré Superlattices**

Abstracts of Lectures

(in alphabetical order)

Spin-polarized and topological superconductivity in a chiral antiferromagnet

Piet Brouwer

Freie Universitaet Berlin

Cooper pairs in conventional superconductors carry no spin. Spin-polarized Cooper pairs require unconventional forms of superconductivity. 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.

New Frontiers in Electrical, Thermal, and Thermoelectric Transport Predictions

J. Coulter[1]

[1]*Flatiron Institute, Center for Computational Quantum Physics*

Understanding the electrical, thermal, and thermoelectric properties of materials is crucial to the design of efficient devices and the interpretation of experimental observations. Electron and phonon Boltzmann transport equation (BTE) calculations can accurately predict these properties for many materials, but standard methods cannot describe many unique phenomena such as coupled electron-phonon, correlated electron, or beyond-semiclassical effects.

In this talk, I will demonstrate how a combination of high-performance computing and new theory unlocks transport in complex and unexplored cases. These include hydrodynamic materials, where heat and charge transport occur essentially perfectly except at the boundaries of a device [1], ultra-high conductivity transition metal oxides [2], and topological flat-band materials for thermoelectric applications, in which beyond-BTE effects dominate transport [3]. I will close with a new formalism to predict electron-phonon interactions in correlated electron materials, enabling predictions of correlation-enhanced phonon-mediated resistivity and superconducting properties. These developments demonstrate the combined power of computation and many-body physics to revolutionize transport theory, opening new frontiers in device-relevant quantum materials.

References

1. J. Coulter, B. Rajkov, M. Simoncelli. arXiv:2503.07560. (2025)
2. J. Coulter, F. Kugler, H. LaBollita, A. Georges, C. Dreyer. arXiv:2506.10143 (2025).
3. F. Garmroudi, J. Coulter et al. Physical Review X 15, 021054 (2025)

Many-body quantum coherence in AV_3Sb_5 Kagome metals

Chunyu Guo (Mark)[1], Kaize Wang[1], Ling Zhang[1], Carsten Putzke[1], Dong Chen[2,3], Takashi Oka[4], Roderich Moessner[5], Mark H. Fischer[6], Titus Neupert[6], Claudia Felser[3] and Philip J. W. Moll[1]

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[4] *The Institute for Solid State Physics, The University of Tokyo, Kashiwa, Japan*
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[6] *Department of Physics, University of Zürich, Zürich, Switzerland*

Electron correlations significantly modify electron self-organization in quantum materials, resulting in a landscape of competing orders and exotic quantum phenomena. The recently discovered AV_3Sb_5 family Kagome superconductors are an intriguing example of competing correlated orders with robust entanglement, in which electronic correlations give rise to a cascade of charge-ordered phases [1], leading to perturbation-driven symmetry breaking and chiral electronic states [2,3].

Our recent development demonstrates long-range quantum coherent transport manifested by electronic correlations in CsV_3Sb_5 [4]. Magnetoresistance oscillations are observed in mesoscopic pillars for fields applied parallel to the Kagome planes. Their periodicity is independent of material parameters and is given by the number of flux quanta (h/e) threading between adjacent Kagome layers, akin to an atomic-scale Aharonov-Bohm interferometer. Intriguingly, they occur under conditions not favorable for typical interference in solids, at temperatures above 20 K and in micrometer-scale devices well exceeding the single-particle mean free path. The non-analytic field-angle dependence and consistent scaling with other key electronic responses in CsV_3Sb_5 both point to an underlying mechanism that establishes intrinsic coherence. These findings shed new light on the debated nature of correlated order in Kagome metals and establish CsV_3Sb_5 as a platform for realizing long-range coherent charge transport in the absence of superconductivity — opening new directions for coherence in correlated electron systems beyond conventional paradigms.

[1] He Zhao et al., Cascade of correlated electron states in the kagome superconductor CsV_3Sb_5; Nature 599, 216(2021).
[2] Chunyu Guo et al., Switchable chiral transport in charge-ordered kagome metal CsV_3Sb_5; Nature 611, 461(2022)
[3] Chunyu Guo et al., Correlated order at the tipping point in the kagome metal CsV_3Sb_5; Nature Physics 20, 579(2024).
[4] Chunyu Guo et al., Many-body interference in Kagome crystals; Nature 647, 68 (2025).

Long-lived modes and hydrodynamic transport in interaction-dominated Fermi liquids

J. Hofmann[1,2]

[1]Department of Physics, Gothenburg University, 41296 Gothenburg, Sweden
[2] Nordita, Stockholm University and KTH Royal Institute of Technology, 10691 Stockholm, Sweden

There is intense experimental interest in transport in ultraclean (often two-dimensional) materials where electron-electron interactions dominate over phonon and impurity scattering. This gives rise to an effective hydrodynamic description of electron flow with transport coefficients such as the shear viscosity that can be derived from Fermi-liquid theory. While one could think that this framework should be fully understood, it turns out that there are still fundamental aspects of Fermi-liquid theory that remain unexplored.

In this talk, I will review hydrodynamic transport in 2D Fermi liquids and show that Pauli blocking gives rise to excitations whose lifetimes are parametrically longer than conventionally predicted by Fermi liquid theory. These long-lived modes alter the standard hydrodynamic description of electron flow in mesoscopic devices, and in particular lead to extended boundary layers and a strong sensitivity to magnetic fields. I will conclude with an outlook on the extension of these ideas to 3D Fermi liquids and systems with anisotropic Fermi surfaces.

References

[1] E. Nilsson, U. Gran, J. Hofmann, “Nonequilibrium Relaxation and Odd-Even Effect in Finite-Temperature Electron Gases”, Physical Review X **15**, 041007 (2025)
[2] J. Maki, U. Gran, J. Hofmann, “Odd-parity effect and scale-dependent viscosity in atomic quantum gases”, Comm. Phys. **8**, 319 (2025)
[3] N. Ben-Shachar, “Magnetotransport of tomographic electrons in a channel”, arXiv:2025.14431 (2025); “Tomographic electron flow in confined geometries: Beyond the dual-relaxation time approximation”, arXiv:2503.14461 (2025)
[4] S. Musser, S. Das Sarma, J. Hofmann, “Odd relaxation in three-dimensional Fermi liquids”, Physical Review Research, to appear (2026)

Geometry and topology of free and bound excitons

Roni Ilan

Tel Aviv University, Israel

Excitons in quantum materials are shaped not only by electron-hole interactions, but also by the geometry and topology of the underlying electronic bands. In this talk, I will present a framework for describing exciton geometry in terms of quantities such as exciton shift and polarization. Based on a singular-connection approach, this framework clarifies the topological contribution of interactions to exciton structure and identifies the singular connection as a useful tool for analyzing the topology of bound quantum states. It also shows how interacting excitons can acquire geometric and topological properties beyond those inherited from the underlying single-particle bands, and may be applicable more broadly to other classes of bound states. I will also discuss defect-bound excitons in topological materials, where topological in-gap defect states lead to distinctive excitonic wave functions and modified binding energies. Together, these results highlight excitons as sensitive probes of quantum geometry and topology, and suggest new routes for exploring the geometric and topological properties of bound states in quantum materials.

Polariton-induced superconductivity in two-dimensional metals

Marco Polini[1]

[1]Dipartimento di Fisica dell'Università di Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy

The electronic properties of two-dimensional (2D) metals are altered by changes in their three-dimensional dielectric environment. In this talk we will show [1] that superconductivity can be induced in a 2D metal by resonant coupling between its plasmonic collective modes and optical phonons in a nearby polar dielectric. Specifically, we will demonstrate that relatively high-temperature superconductivity can be induced in bilayer graphene twisted to an angle somewhat larger than the magic value by surrounding it with a terahertz polar dielectric. Our conclusions [1] are based on numerical solutions of the Eliashberg equation for massless Dirac fermions with tunable Fermi velocities and Fermi energies and can be understood qualitatively in terms of a generalized McMillan formula.

References

[1] R. Riolo, F. H. L. Koppens, P. Jarillo-Herrero, G. Mazza, A. H. MacDonald, and M. Polini, arXiv:2511.00608.

Quantum geometry as a window into bonding and transport in metals

Raquel Queiroz

Columbia University, New York City, USA

How do we characterize the spatial extent of electrons bound in a solid? In isolated atoms, this is simply the orbital size. In crystals, quantum interference between neighboring sites creates a new length scale, the quantum geometric length, which measures how electrons are shared across the lattice through bonding. This scale, encoded in the quantum metric, enters directly into optical sum rules and governs properties from the dielectric constant to the Drude weight, establishing a transparent connection between transport and wavefunction geometry. In this talk I will introduce the quantum geometric tensor starting from the physical picture of dipole fluctuations and show how the frequency-dependent conductivity acts as a direct probe of the underlying geometry. I will then present a systematic study of the direction-resolved quantum metric across families of metals, revealing how the geometric length varies with orbital character and bonding type. Materials with strong multi-orbital hybridization and lattice frustration develop large quantum metrics that leave clear signatures in their optical response, while simpler bonding environments produce compact wavefunctions with correspondingly weaker geometric effects. This material-specific perspective connects atomic-scale chemistry to macroscopic transport, offering a new lens for understanding why certain metals develop anomalous responses, enhanced superfluid stiffness, or instabilities toward correlated phases at low temperatures.

Quantum complexity in simple materials

Xavier Roy
Professor of Chemistry, C*olumbia University*

In this seminar, I will discuss a new approach for realizing long-sought electronic structures of geometrically frustrated lattice models (*e.g.* kagome and pyrochlore), by "decorating" un-frustrated, primitive lattices with a particular set of atomic orbitals. In the process, we identify the vdW intermetallic compound Pd_5AlI_2 as the first material to realize the electronic structure of the 2D Lieb lattice – featuring Dirac-like bands intersected by a flat band – persisting in ambient conditions down to the monolayer limit. I will discuss how this unique electronic structure gives rise to compact localized states and bound states in continuum (BICs), which could provide a platform for lossless and topologically protected electronic processes.

Nonlocal Transport in Ultraclean Materials

Jörg Schmalian

Karlsruhe Institute of Technology, Karlsruhe, Germany

We discuss the response of a ultraclean Dirac and Fermi fluid to electric fields and thermal gradients at finite wave numbers and frequencies in the ballistic and hydrodynamic regime. We discuss the role of an infinite set of kinetic modes that govern this non-local response and analyze specific aspects such as anomalous, Lévy-flight phase space diffusion [1] or impact of such modes for the skin effect [2,3].

References

[1] E. Kiselev and J. Schmalian, Phys. Rev. Lett. **123**, 195302 (2019).

[2] D. Valentinis, G. Baker, D. A. Bonn, and J. Schmalian, Phys. Rev. Res. **5**, 013212, (2023).

[3] G. Baker, D. Valentinis, D. A. Bonn, and J. Schmalian, Phys. Rev. X **14**, 011018 (2024).

Identifying quantum geometric effects in transport

Nishchhal Verma[1] and Raquel Queiroz[1]
[1]Department of Physics, Columbia University, New York, NY 10027, USA

Quantum geometry offers a powerful way to think about electronic and optical phenomena that are not captured by band energetics alone. In this talk, I will discuss how geometric properties of quantum states appear in quantum transport. Beyond the familiar role of Berry curvature, I will focus on recent theoretical and experimental work showing that the quantum metric can have measurable consequences. In particular, I will describe how it contributes to conductivity [1], stiffness [2], and plasmonic responses [3], even in systems without a topological invariant. I will also review recent progress in probing quantum geometry through transport measurements and point to several material platforms where these effects are expected to be relevant.

References

[1] N. Verma, R. Queiroz, Instantaneous Response and Quantum Geometry of Insulators, Proc. Natl. Acad. Sci. 122(49) e2405837122 (2025)
[2] N. Verma*, D. Guerci*, R. Queiroz, Geometric Stiffness in Interlayer Exciton Condensates, Phys. Rev. Lett. 132, 236001 (2024)
[3] S. Xu*, B. Yang*, N. Verma* et. al., Plasmon dynamics in graphene, arXiv:2601.10493 (2026)

Exciton condensates in quantizing magnetic fields

Felix von Oppen

Freie Universität Berlin, Germany

While theoretically predicted since the 1960s, experimental sightings of exciton insulators have long remained controversial. The situation has changed with recent experiments on transition metal dichalcogenides. In this talk, I will discuss dilute exciton insulators in quantizing magnetic fields and their topological excitations.

Title/Topic:

Supercurrent interference and its transfer in a kagome superconductor

Yaojia Wang[1], Heng Wu[2]

1 Quantum Solid State Physics, KU Leuven, Leuven 3001, Belgium

2 Institute of Condensed Matter and Nanosciences (IMCN/NAPS), Université Catholique de Louvain (UCLouvain), 1348 Louvain-la-Neuve, Belgium

Abstract:

Materials with a Kagome lattice, composed of corner-sharing triangles, have garnered significant interest due to their potential to host strong electronic correlations, exotic magnetism, and nontrivial topology. The AV_3Sb_5 family (A = K, Cs, Rb) has become a focal point of research because of its diverse physical properties, which include cascade charge orders, superconductivity, and topological states, as well as the complex interplay between these phenomena. This presentation will introduce the key physical properties of Kagome family AV_3Sb_5, with a focus on the superconducting properties. Our recent effort has focused on the intrinsic superconductivity in KV_3Sb_5. Supercurrent oscillations have been observed within KV_3Sb_5 itself, demonstrating inherent supercurrent interference. Specifically, we discovered the transfer of supercurrent interference patterns between the superconducting ring and the superconducting flake, which demonstrates the global critical current effect of the superconducting phase coherence. In addition to Kagome materials, the global critical current effect has been observed in various superconducting systems, where the superconductivity of a measured segment can be influenced by other segments along the applied current path. This highlights the broader importance of this effect in understanding superconducting behavior.

New Paradigm: Magnetotransport + First-Principles-->Electronic-Structure Characterization

Shengnan Zhang[1], Zhihao Liu[1], Yuzhi Wang[1], Xu Yan[1], OV Yazyev[2], Zhong Fang[1], Hongming Weng[1], and Quansheng Wu[1]
[1] Institute of Physics, Chinese Academy of Sciences, Beijing, China
[2] EPFL, Lansanne, Switzerland

This talk presents a workflow-style paradigm for **extracting electronic-structure information from magnetotransport** by tightly integrating **first-principles calculations** with a **non-perturbative semiclassical Boltzmann framework**. Starting from density-functional electronic structures, we construct high-fidelity low-energy Hamiltonians and compute magnetic-field-dependent transport tensors in real materials, where **Lorentz-force dynamics, quantum scattering, magnetic-order evolution, and topological band effects** intertwine across multiple scales. The key step is to **translate band topology and Fermi-surface geometry into quantitative magnetoresistance and Hall responses**, enabling a controlled decomposition of contributions from (i) complex Fermi-surface topology, (ii) magnetic order and its field evolution, and (iii) topological features of the bands. The complete pipeline is implemented in the open-source package **WannierTools**, allowing high-accuracy simulations of magnetotransport directly comparable to experiments. We demonstrate that this first-principles-based approach reproduces, with strong consistency, magnetotransport measurements across a broad set of representative systems, including non-magnetic metals/semimetals/semiconductors and magnetic/topological materials such as the altermagnets RuO_2, CrSb, and KV_2Se_2O, the ferromagnetic Weyl semimetal $Co_3Sn_2S_2$, and antiferromagnetic semiconductors $EuSe_2$ and $Mn_3Si_2Te_6$. Overall, the method moves complex magnetotransport analysis beyond phenomenological fitting: it enables **quantitative, material-specific links between electronic structure and transport observables**, establishing a practical route to use magnetotransport as a first-principles-resolved probe of electronic structure.

References

[1]. Magnetoresistance from Fermi surface topology, SN Zhang, QS Wu*, Y Liu, OV Yazyev*, Physical Review B 99, 035142 (2019).

[2]. Z. Liu, S. Zhang, Z. Fang, H. Weng*, Q. Wu*, Phys. Rev. Res. 6, 043185 (2024)

[3]. X. Yan, Z. Song,J. Song, Z. Fang, H. Weng, Q. Wu, SCPMA, 69, 257011 (2026)

[4]. Scaling behavior of magnetoresistance and Hall resistivity in the altermagnet CrSb, X Peng et al., Phys. Rev. B 111 (14), 144402 (2025)

[5]. Universal Scaling Behavior of Transport Properties in Non-Magnetic RuO2, Q Dong, Y. Wang, Q.Wu et al., Communications Materials 6 (1), 177 (2025)

[6]. Colossal magnetoresistance and unusual resistivity behaviors in magnetic semiconductors: Mn3Si2Te6 as a case study", Z Liu, Z Fang, H Weng, Q Wu*, npj Compu. Mater. 2026

[7]. WannierTools, https://www.wanniertools.org/

Superlattice domain effects on transport in a noncollinear antiferromagnet

Lilia S. Xie,[1,2] Shannon S. Fender,[2] Cameron Mollazadeh,[2] Wuzhang Fang,[3] Matthias D. Frontzek,[4] Samra Husremović,[2] Kejun Li,[3,5] Isaac M. Craig,[2] Berit H. Goodge,[2,6] Matthew P. Erodici,[2] Oscar Gonzalez,[2] Jonathan D. Denlinger,[7] Yuan Ping,[3] and D. Kwabena Bediako[2,8,9]

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Superlattice formation dictates the physical properties of many materials, including the nature of the ground state in magnetic materials. Chemical composition is commonly considered to be the primary determinant of superlattice identity, especially in intercalation compounds. Nevertheless, we have found that kinetic control of superlattice growth leads to the coexistence of disparate crystallographic domains within a compositionally perfect single crystal. We demonstrate that $Cr_{1/4}TaS_2$ is a noncollinear antiferromagnet with 120° ordering in which scattering between majority and minority superlattice domains engenders complex magnetotransport below the Néel temperature, including an anomalous Hall effect. We characterize the magnetic phases in different domains, image their nanoscale morphology, and propose a mechanism for nucleation and growth using a suite of experimental probes coupled with first-principles calculations and symmetry analysis. These results provide a blueprint for the deliberate engineering of macroscopic transport responses via microscopic tuning of magnetic exchange interactions in superlattice domains.

References

1. Xie, L. S. et al., *Nat. Commun.* **2025**, *16*, 5711.

Probing the hidden symmetry by quantum geometry-induced nonlinear transport

Yan Binghai

Penn State University, USA

The interplay of magnetism and topology gives rise to exotic transport phenomena caused by the quantum geometry (Berry curvature and quantum metric). I will introduce our recent work where the nonlinear transport sensitively detects the hidden symmetry-breaking in magnetic topological materials such as CrSBr and Ca3Ru2O7 with surprising sensitivity.

Abstracts of Posters

(in alphabetical order)

Kondo, Kagome and strain effects on thermoelectric efficiency in quantum impurity systems

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Understanding thermoelectric transport in materials with strong electronic correlations is crucial for designing high-efficiency devices. At low temperatures, the Kondo Effect drives the formation of the Abrikosov-Suhl Resonance, a sharp peak in the electronic density of states near the Fermi energy level (ϵ_F). This phenomenon is vital for optimizing the Seebeck coefficient (S), a key measure of thermoelectric conversion capacity.In this study, we apply the Single Impurity Anderson Model (SIAM), solved via the highly accurate Numerical Renormalization Group (NRG) method, to analyze the transport properties in a novel system: an impurity coupled to a Kagome lattice nanoribbon. The Kagome lattice, known for its unique geometry and the presence of flat bands, provides an excellent platform to enhance electronic interactions and improve electrical conductivity (σ). Furthermore, we introduce uniaxial strain as an external control tool to tune the electronic energy levels and, consequently, optimize the material's thermoelectric performance.Our results demonstrate that the combination of the Kagome structure, the asymmetric positioning of the impurity level (ϵ_d), and the application of uniaxial strain leads to remarkable improvements in the material's Figure of Merit (ZT). The crucial ability to break electron-hole symmetry, essential for maximizing the Seebeck coefficient, is achieved by carefully tuning the impurity energy level.In summary, the precise simulations performed using the NRG provide clear guidelines for the rational design of highly efficient thermoelectric materials, specifically aiming at the maximization of the power factor ($S^2\sigma$). This work opens up significant possibilities for applications in energy harvesting and solid-state refrigeration systems.

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

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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.

Tomographic electron flows in confined geometries

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Hydrodynamic-like electron flows are typically modeled using the Stokes-Ohm equation or a kinetic description that is based on a dual-relaxation time approximation. Such models assume a short intrinsic mean free path ℓ_e due to momentum-conserving electronic scattering and a large extrinsic mean free path ℓ_{MR} due to momentum-relaxing impurity scattering. This assumption, however, is overly simplistic and falls short at low temperatures, where it is known from exact diagonalization studies of the electronic collision integrals that another large electronic mean free path ℓ_o emerges, which describes long-lived odd electron modes—this is sometimes known as the tomographic effect. Here, using a matched asymptotic expansion of the underlying Fermi liquid kinetic equations that include different electron relaxation times, we derive a general asymptotic theory for tomographic flows in arbitrary smooth boundary geometries. We find that the tomographic effect strongly modifies previous hydrodynamic theories: In particular, we find that (i) an equilibrium is established in the bulk, where the flow is governed by Stokes-Ohm like equations with significant finite-wavelength corrections, (ii) the velocity slip condition at the boundary is strongly modified and not accounted for by the widely-used hydrodynamic slip-length condition, (iii) a large kinetic layer arises near boundaries of width $\sim \sqrt{\ell_e \ell_o}$, which is much larger than in conventional near-hydrodynamic theories, and (iv) all these effects are strongly suppressed by an external magnetic field. We illustrate our findings for electron flow in a channel (see Fig. 1 below). The equations derived here represent the fundamental governing equations for hydrodynamic-like tomographic flows.

Figure 1: *Hydrodynamic-like electron flow in a channel. (a) Schematic showing the flow geometry and expected flow profile. (b) Comparison of the flow profile from the asymptotic theory, hydrodynamic theory and numerical solutions.*

Systematic Theory of Real-Time Atomistic Spin Dynamics

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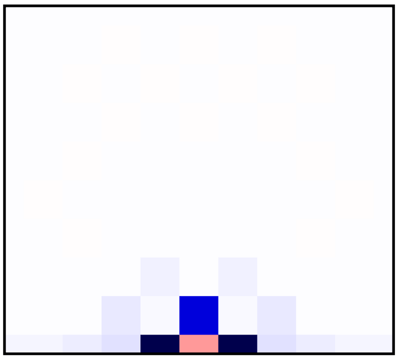

We present a systematic response-theoretical approach for deriving indirect interactions and novel couplings in the effective dynamics of classical spins coupled to generic lattice-fermion models. Via a systematic twofold expansion of the exact time evolution operator, namely in the coupling strength and in the retardation time, one identifies a rich variety of spin-, orbital-, and site-dependent contributions to the equations of motion. These include the familiar Ruderman--Kittel--Kasuya--Yosida and the Dzyaloshinskii--Moriya interactions. Additional anisotropic terms, different types of Gilbert damping and of geometrical spin torques, as well as various spin-inertia terms emerge. While the order of expansion suggests the order of magnitude of the effects, symmetry analysis allows for their classification. The practical feasibility of the approach is demonstrated with numerical results obtained for a Chern insulator.

Floquet optical selection rules in black phosphorus

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Optical selection rules endorsed by symmetry are crucial for understanding the optical properties of quantum materials and the associated ultrafast spectral phenomena. Here, we introduce momentum-resolved Floquet optical selection rules using group theory to elucidate the pump-probe photoemission spectral distributions of monolayer black phosphorus (BP), which are governed by the symmetries of both the material and the lasers. Using time-dependent density functional theory (TDDFT), we further investigate the dynamical evolution of Floquet(-Volkov) states in the photoemission spectra of monolayer BP, revealing their spectral weights at specific momenta for each sideband. These observations are comprehensively explained by the proposed Floquet optical selection rules. Our framework not only clarifies experimental photoemission spectra but also uncovers unexplored characteristics under different pump-probe configurations. Our results are expected to deepen the understanding of light-induced ultrafast spectra in BP and can be extended to other Floquet systems.

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Collective modes and transport in *d*-wave altermagnets: a Fermi liquid approach

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We investigate collective excitations and transport in *d*-wave altermagnets, which are interacting quantum systems in which anisotropic Fermi surfaces lead to unconventional dynamic responses. Using a recently developed Fermi liquid framework, we identify, in addition to the conventional plasmon and transverse modes, two new acoustic collective modes arising from out-of-phase oscillations of the spin-split Fermi surfaces. All four modes depend strongly on the Landau parameters and exhibit longitudinal, transverse, or mixed character depending on propagation direction relative to the elliptic Fermi surface geometry. The mixing of longitudinal and transverse responses arises from the reduced symmetry of the system, for which the conductivity tensor acquires off-diagonal components for generic propagation directions. This poster presents these results and discusses their implications for nonequilibrium response in correlated quantum materials.

H-linear magnetoresistance due to impeded cyclotron motion in 2*H*-NbSe$_2$

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Understanding how strong correlations affect the electronic structure of strange and quantum critical metals is a profound challenge. Over the last decade, linear and non-saturating magnetoresistance (LMR) has emerged in cuprates, Fe-based and heavy fermion. We have proposed the simplest common denominator which could explain this pattern is impeded cyclotron motion (ICM) [1]: Strong correlations affect loci on the Fermi surface which stop cyclotron motion (for whatever reason). However, a detailed explanation of a specific compound was lacking.

Here, we report on a combined theoretical and experimental study of the MR in prototypical charge-density-wave (CDW) compound and Fermi liquid 2*H*-NbSe$_2$, which has been known to host LMR for over 50 years [2]. By invoking ICM where the CDW hybridises the Fermi surface, we capture the MR in 2*H*-NbSe$_2$ using a Boltzmann transport framework as a function of temperature, doping, disorder and magnetic field (see figure). Nonetheless, the simultaneous sign change in the Hall effect remains unaccounted for, even within state-of-the-art models beyond the relaxation time approximation. These findings provide strong evidence that ICM generates LMR in certain correlated metals and the need for computational frameworks beyond the relaxation time approximation.

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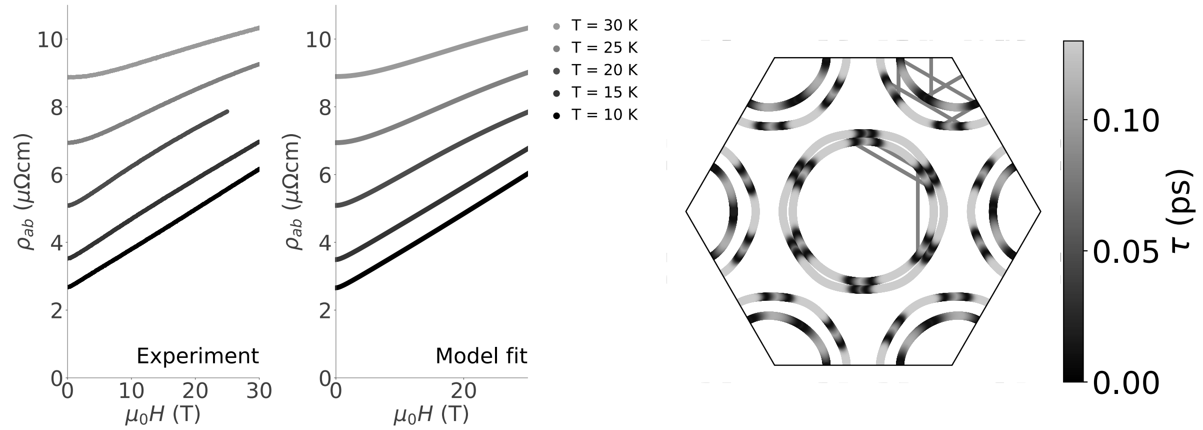

Left: The magnetoresistance of 2*H*-NbSe$_2$. **Right:** CDW impedances (black) at 25 K.

Fermi surface topology and magnetotransport in corrugated van der Waals semimetals

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Gold telluride halides are quasi-two-dimensional crystals with a corrugated crystal structure reminiscent of black phosphorus. Theoretical calculations predict that these materials are topological semimetals, but experimental studies have been limited by challenges in synthesizing large, high-quality single crystals using reliable methods. Here, we develop a chemical vapor transport approach to grow bulk single crystals of these compounds and investigate their anisotropic crystal structure, electron transport, and optical response. These crystals exhibit extremely large magnetoresistance and pronounced Shubnikov–de Haas (SdH) quantum oscillations, which are hallmarks of high-mobility semimetals. Analysis of the SdH oscillations enables mapping of the Fermi surface, revealing potential evidence of nontrivial topology.

Topological surface states of Wey semimetals probed by nonreciprocal transport

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Nonreciprocal transport is known as a powerful probe for symmetry, band parameters, and even topological properties. Weyl semimetals host topologically protected surface states, known as Fermi arcs, which connect bulk Weyl nodes in momentum space. Both bulk Weyl nodes and Fermi arcs are anticipated to be chiral. The chirality of bulk bands has been confirmed through observations of the chiral anomaly and Weyl orbits. In contrast, the chiral nature of Fermi arcs has remained unresolved. We discuss Fermi-arc-induced nonreciprocal transport in the archetypal Weyl semimetals TaAs. Using focused ion beam techniques, we fabricated micro-scale devices that enable simultaneous transport measurements on opposing topological surfaces. While linear transport remains dominated by bulk conduction, nonlinear nonreciprocal transport uncovers surface-specific contributions, including an exceptionally large third-order nonreciprocal response in the magnetic-field expansion that exceeds conventional expectations and highlights the crucial role of the singular arc endpoints. The present findings unambiguously demonstrate the unidirectional nature of Fermi arc transport in TaAs and establish nonreciprocal transport as a direct probe of these topological surface states.

Quantum Printing: Quantum Optical Spanner and Kapitza-Dirac Effect of Higgs mode in superconductors

Daemo Kang, Tien-Tien Yeh, Takahiro Morimoto, Alexander Balatsky

We study how structured light, such as Laguerre–Gaussian beams, can quantum print spatial and topological patterns on superconductors. We describe how light transfers angular momentum to the superconductor ("quantum optical spanner") and predict Kapitza–Dirac–type interference of Higgs waves. Using a time-dependent Ginzburg–Landau equation with an inertial term, we show that structured illumination creates vortex lattices while driving Higgs-mode oscillations. These Higgs waves scatter off light-induced vortex pairs and form diffraction-like interference patterns, similar to electron diffraction in the original Kapitza–Dirac effect. This setting allows amplitude and phase excitations to coexist and interact in superconductors. Our results suggest a "Higgs-wave diffraction" approach to light-induced vortices, and to shape nonequilibrium superconducting textures with structured light.

Dynamics of orbital angular momentum in confined geometries

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Orbitronics deals with the transport of orbital angular momentum in solids. I will discuss several aspects of the orbital Hall effect (OHE) in confined geometries. One key result is that the effective orbital angular momentum decay rate follows a Dyakonov-Perel-scaling and is inversely proportional to the electron scattering rate, even if the latter is small.

Furthermore, I will show that non-Ohmic charge flows with vorticity and shear result in contributions to the OHE which are distinct from the well known intrinsic and extrinsic mechanisms, including non-local and vorticity induced accumulations of orbital angular momentum.

The non-Hermitian Topology of Transport

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Reflection matrices describing waves reflected from the boundaries of topological insulators exhibit non-Hermitian topological signatures [1]. Based on this, we propose ways to realize non-Hermitian topology in the conductance matrix of topological multi-terminal devices [2]. Our work is based on the insight that, in the limit of maximal non-reciprocity, the Hamiltonian for the simplest topological non-Hermitian system – the Hatano-Nelson chain – effectively describes a one-dimensional, unidirectionally propagating mode. This is analogous to the unidirectional boundary mode of a fully Hermitian topological insulator: the quantum Hall system. We show that the multi-terminal conductance matrix of this system exhibits a topologically protected non-Hermitian skin effect. Our approach can be used to construct and study models that go beyond the Hatano-Nelson model, like the non-Hermitian SSH chain. We showed that this system can be used as an ohmmeter with high sensitivity [3].

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Kondo impurities coupled to a Chern insulator

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We study a system consisting of spin-1/2 impurities exchange-coupled to a QWZ Chern insulator. The interplay between the truncated Kondo effect, the truncated RKKY interaction, and the mass parameter m gives rise to a complex phase diagram comprising RKKY singlet and triplet phases, the Kondo singlet, and a partially Kondo-screened phase. Furthermore, we examine how the phase diagram depends on the coupling orbitals and the inter-impurity distance.
The classical limit of the impurities, where the system is known to be topologically classifiable, is implemented through polarization by a strong magnetic field.

Proximity superconductivity in chiral kagome antiferromagnets

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Recent experiments on the chiral kagome antiferromagnet Mn3Ge have provided strong evidence of proximity-induced spin-polarized superconductivity. We introduce and explore a minimal model which exhibits a rich phase diagram as a function of chemical potential and spin canting. We find a valley-singlet superconducting phase for chemical potentials and canting consistent with the experimental system. This phase transitions into a Chern insulator at larger canting and gives way to topological superconducting phases with Chern numbers CBdG=±1,±3 at other chemical potentials. Our results show that proximity-induced superconductivity in kagome antiferromagnets is a promising route towards exotic superconductivity with spin-polarized Cooper pairs, with potential applications in spintronics.

Lattice Gas Cellular Automaton with Tomographic Dynamics

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We study the tomographic effect in lattice gas cellular automata, which are simple discrete models for hydrodynamics. The tomographic effect is predicted in two-dimensional Fermi liquids whenever head-on scattering dominates, which provides inefficient angular relaxation due to Pauli blocking. As a result, odd-parity deformations of the Fermi surface are anomalously long-lived compared to even-parity ones. We find an analogous effect in two-dimensional triangular lattice gas automata, which exhibit a single discrete odd-parity mode. We analyze the relaxation times of the linearized lattice gas dynamics, and find that at low densities, head-on collisions dominate and the odd-parity mode is long-lived, resulting in a two-step relaxation of the system. At increasing densities, three-body interactions set the dominant decay channel and the odd-parity mode becomes short-lived. We then analyze a reduced model of the lattice gas restricted to only head-on collisions, leading to a fully conserved odd-parity mode, and derive the equilibrium distribution via entropy maximization. Using a low-Mach approximation and multi-scale expansion, we derive a set of modified Navier-Stokes equations that incorporate the odd-parity mode. We show that the odd-parity mode couples anisotropically to the momentum, leading to direction-dependent dynamics. Using these governing equations, we solve for the velocity profile in a channel (Poiseuille flow) and compare it to numerical simulations. We discuss the limitations of the model due to its discrete nature and lack of full rotational symmetry.

Tomographic modes in 2D Fermi liquids in the presence of a magnetic field

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Two-dimensional Fermi liquids at low temperatures exhibit an odd-even effect in the collective quasiparticle relaxation rates where even-parity deformations of the Fermi surface decay at a much faster rate than odd-parity ones. A predicted consequence of this effect is a new tomographic transport regime that mixes hydrodynamic and ballistic transport. In the presence of a magnetic field, however, the tomographic regime is expected to evolve towards conventional transport regimes when the cyclotron radius becomes smaller than the dominant odd-parity mean free path. In this poster, we examine this transition from the point of view of collective modes, using a numerically exact solution of the linearised Boltzmann equation within a generalised relaxation time approximation for the odd- and even-parity modes. In the absence of a magnetic field, the transverse conductivity exhibits two diffusive tomographic collective modes. We find that at a critical magnetic field one of these two tomographic modes disappears. The tomographic mode that persists depends on the Landau parameters, and becomes increasingly dominated by hydrodynamic modes at high fields. We corroborate our analysis using a variational approach for the Fermi surface deformation that captures the angular structure of the deformation and the critical magnetic field strength. The collective modes discussed here can in principle be observed by examining the damping of longitudinal and transverse current responses in finite magnetic fields.

Interactions and collective dynamics of defects in Wigner crystals

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I will present a low-energy field theory for electrically charged crystals, which takes into account both the elastic and electromagnetic degrees of freedom. Upon dualization, it takes the form of a gauge theory, in which elastic defects: interstitials, vacancies, and dislocations, are interpreted as point particles interacting with the gauge fields. We then calculate the interaction energy of the crystal defects, with consequences for the melting scenarios of Wigner crystals. Finally, I will show how this gauge theory can be used to describe the long-wavelength collective dynamics of the crystal in the presence of a finite density of lattice defects.

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Manipulation of ferromagnetism with a light-driven nonlinear Edelstein-Zeeman field

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Optical control of magnetization is often symmetry-forbidden because electric fields and magnetization transform differently under inversion and time-reversal. However, through even-order nonlinear response, optical excitation can generate a nonequilibrium magnetic density (the nonlinear Edelstein effect) that acts as an internal Edelstein-Zeeman field coupling to slower magnetic degrees of freedom. Here we demonstrate non-thermal, ultrafast optical control of ferromagnetism in the centrosymmetric van der Waals semiconductor $Cr_2Ge_2Te_6$ via a resonant nonlinear Edelstein effect. Using time-domain THz emission spectroscopy under near-infrared excitation, we directly observe magnetic dipole radiation arising from optically driven magnetization dynamics. The polarization, fluence, and temperature dependences of the THz emission are quantitatively captured by a mean-field description of a weakly anisotropic Heisenberg ferromagnet subject to an Edelstein-Zeeman field. Our results establish a general nonequilibrium route to optical control of magnetism in centrosymmetric materials.

Quantum geometric origin of P-wave and orbital magnetism in non-collinear magnets

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Quantum geometry enables a unifying, quantitative characterization of quantum states and their observable implications in spinful multiorbital systems. By combining a projector formalism for quantum geometry [1,2] with Lie algebra techniques, I provide an intuitive real-space perspective on the unconventional spin polarization of P-wave magnets [3] as arising from the cross product between the non-collinear in-plane magnetic moments [4], contrasting altermagnets [5] with collinear magnetic order. I will show how orbital magnetism arises from the noncommutativity of adiabatic Bloch-state transport in orthogonal directions [6], thereby bridging the gap between Bloch-state geometry and the theory of adiabatic driving. Our theory enables efficient numerical and analytical evaluations for general Bloch Hamiltonians with an arbitrary number of potentially degenerate bands. We predict a large orbital magnetization in a spin-compensated, noncoplanar anomalous Hall magnet with degenerate topological bands, despite vanishing spin polarization and the absence of spin-orbit coupling.

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Degenerate Majorana zero mdoes in a single vortex

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(Dated: February 27, 2026)

We prove that a single vortex with vorticity n in the Fu-Kane-type Hamiltonian with a nonzero chemical potential hosts n-fold-degenerate Majorana zero modes, independent of whether n is an even or odd integer, by constructing the zero-energy solution explicitly. The existence of these zero-energy states is also confirmed numerically [1].

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Sondheimer magneto-oscillations as a probe of Fermi surface reconstruction in underdoped cuprates

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Determining the Fermi surface (FS) volume in underdoped cuprates is crucial for understanding the nature of the strongly correlated pseudogap phase. Conventional quantum oscillation techniques, typically used for this purpose, are inapplicable in this high-temperature regime due to thermal and disorder-induced smearing of Landau levels. We propose Sondheimer oscillations (SO), semiclassical oscillations of in-plane magnetoresistivity in thin films, as a robust alternative probe of FS reconstruction. SO arise from the commensuration between the cyclotron radius and film thickness, do not rely on Landau quantization, and remain observable at moderate fields and elevated temperatures where quantum oscillations are suppressed. Their frequencies depend solely on the FS parameters (e.g., curvature), and not on specific details of scattering mechanisms. SO are also sensitive to the coherence of inter-layer tunneling, allow contributions from individual FS pockets to be distinguished in the frequency domain, and naturally include the Yamaji angle effect (if present in the system) as a prominent feature in the frequency spectrum. We compute SO spectra as a function of the magnetic field orientation for three representative scenarios: (i) an unreconstructed large FS, (ii) a spin density wave reconstructed FS with volume p/4, and (iii) a fractionalized Fermi liquid (FL$*$) with pocket volume p/8 (here p is the hole doping). We show that the SO spectrum offers a wealth of universal features that could be used to differentiate between these scenarios. In particular, we highlight a FS geometry-dependent phase shift between oscillations in longitudinal and transverse conductivities, characterize how the FS curvature can be extracted from SO if the film orientation is perpendicular to the crystallographic c-axis, and analyze the evolution of the SO spectrum with doping.

Constructing Gauge-Invariant Lattice Models for Cavity QED

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We present a rigorous framework to construct accurate and reliable minimal models of cavity QED. We establish the validity of minimal models of cavity Quantum Electrodynamics including Peierls substitution due to projecting matter Hilbert space to few levels. We rigorously show how the long-standing controversy about which gauge to use to study light-matter coupled systems arises from finite-level truncations of the matter system, and present a method to find the gauge that provides maximal accuracy for the energy eigenspectrum. Our method identifies an optimal gauge for a given number of matter levels by optimizing a criterion characterizing completeness of truncated Hilbert space. It can be regarded as a generalization of Power-Zienau-Woolley transformation, and it shows the fundamental limitation that a given set of matter states has to represent the exact solution. We demonstrate our method for a particle moving in a double-well potential and coupled to a single cavity mode. Importantly, our analysis reveals limitations of Peierls substitution in cases where single-band approximation is valid. Finally, we discuss how to construct accurate lattice models by generating a new set of orbitals.

Interplay of Spin–Orbit and Exchange Couplings in the Pseudospin-1 Dice Lattice: Effects of Staggered Potentials

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Abstract.

The Dice lattice is a two-dimensional Dirac semimetal featuring three energy bands - two dispersive bands forming Dirac cones at low energy, similar to the honeycomb lattice, and a non-dispersive flat band at zero energy [1][2]. Owing to its three sublattices, its low-energy excitations are described by pseudospin-1 matrices, placing it among pseudospin-1 systems such as the Lieb and kagome lattices [1]. The presence of the flat band allows additional low-energy states to participate in the system's response to spin–orbit interactions [3]. Here, we investigate the interplay between Rashba spin–orbit coupling and ferromagnetic exchange interaction in the pseudospin-1 Dice lattice. Drawing parallels with Dirac-semimetallic honeycomb-based systems such as graphene and silicene - where such couplings induce quantum anomalous Hall (QAH) phases [4][5], we show that the Dice lattice develops a QAH phase with a quantized Hall conductivity of $2e^2/h$, accompanied by the dispersion of the originally flat band. Introducing a staggered potential (either magnetic or non-magnetic) further modifies the topological phase boundaries and band topology, leading to behaviors distinct from those of the pseudospin-1/2 honeycomb lattice [6].

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Light-induced pseudo-magnetic fields in three-dimensional topological semimetals

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Pseudo-magnetic fields in Weyl semimetals provide a route to realizing axial gauge fields and probing chiral anomaly physics without applying real magnetic fields. Conventionally, such fields are generated through mechanical strain, which limits tunability, reversibility, and spatial control. Here, we propose an alternative approach based on Floquet engineering that enables the generation and control of pseudo-magnetic fields in three-dimensional topological semimetals using spatially structured, linearly polarized light.

Within a high-frequency Floquet expansion, we show that the light field induces an effective axial gauge potential $\mathbf{A}_5(\mathbf{r})$, arising from a position-dependent shift of Weyl nodes in momentum space. The corresponding pseudo-magnetic field $\mathbf{B}_5(\mathbf{r}) = \nabla \times \mathbf{A}_5(\mathbf{r})$ can be directly engineered through the spatial profile of the driving field. This establishes a set of design principles for creating tunable pseudo-magnetic field textures, including nearly uniform fields and domain wall configurations, without requiring material deformation.

We analyze the spectral and transport signatures of these optically induced axial fields. In particular, we compare the Landau level structure generated by real and pseudo-magnetic fields, highlighting qualitative differences that arise from their axial nature. We further compute the linear optical conductivity and nonlinear dc response, identifying clear experimental signatures that distinguish pseudo-magnetic fields from real magnetic fields.

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Coupled electron-phonon hydrodynamics and Viscous Thermoelectric Equations

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Non-diffusive, fluid-like transport of charge and heat has been observed in several materials, and recent experiments suggest that they can emerge simultaneously from electron-phonon bifluids. Here we introduce a first-principles theory and computational framework to quantitatively describe these phenomena from atomistic to continuum scales in nontrivial device geometries. Starting from the microscopic coupled electron-phonon Boltzmann transport equation, we formalize the emergence of composite “relaxon” electron-phonon excitations, showing that they determine the bifluid viscosity tensor, and quantify the impact of electron-phonon drag on thermoelectric transport coefficients. We then demonstrate that the coupled Boltzmann equation can be coarse-grained into a set of mesoscopic Viscous Thermoelectric Equations, formally unifying Gurzhi's hydrodynamic equation for electrons [1] and the recently developed Viscous Heat Equations for phonons [2], while extending them to cover the mixed electron-phonon bifluid regime. We employ this framework to elucidate the conditions under which electron and phonon fluids can coexist and mix, rationalizing pioneering experiments on electron-phonon drag in graphite. Finally, we rely on these findings to predict smoking-gun signatures of non-diffusive behavior such as non-harmonic temperature and electric potential fields, and compressible viscous thermoelectric backflow.

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Quantum Monte Carlo Study of Hydrodynamics in Systems with Particle-Hole Symmetry

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Abstract

The emergence of hydrodynamic behavior in electronic flow within clean, particle-hole-symmetric systems at half-filling is a non-trivial problem. Navier-Stokes (NS) equations describe the momentum flow, while experimental measurements typically capture the current flow profiles. However, in particle-hole-symmetric systems, electric current and momentum flow are entirely decoupled because electrons and holes move in opposite directions with equal distribution functions. This makes it challenging to link NS equations to observed flow patterns. We demonstrate that the hydrodynamic behavior of the charge current at half filling can emerge despite the absence of momentum flow. By combining Boltzmann transport theory with numerically exact Quantum Monte Carlo simulations of clean graphene samples, we show that NS-type equations can be derived directly for the charge current, eliminating the need for any additional mechanism coupling the velocity field and charge current in explaining the experimentally observed hydrodynamic flow profiles in graphene at half-filling. We show that a new transport quantity — the current diffusion coefficient — replaces viscosity and expect this description to be valid for any particle-hole symmetric system. Our results provide new insights into the interpretation of experimental data and demonstrate how Quantum Monte Carlo calculations of exact lattice-models can serve as an alternative to experiments in transport measurements, by delivering unbiased and non-perturbative predictions directly from a microscopic Hamiltonian to verify kinetic theory results within a well-controlled environment.

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Bloch oscillations in a transmon embedded in a resonant electromagnetic environment [1]

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Recently developed Josephson junction array transmission lines (superinductors) implement strong-coupling circuit electrodynamics, compatible with a range of superconducting quantum devices [2]. They simultaneously provide access to probing quantum devices via photons, while also serving as a high-impedance environment which allows for strong quantum phase fluctuations. A simple model to examine the effect of such environment on a superconducting quantum circuit would be a Josephson junction, shunted by a capacitor and a superinductor. Systems of this kind are studied in the context of a predicted dissipative quantum phase transition between a superconducting and an insulating state [3]. Remarkably, in this system, an external current through the junction is accompanied by quasi-charge Bloch oscillations [4], analogous to those in crystalline systems. The frequency of these Bloch oscillations is proportional to the applied current. In this work we examine the interplay between these oscillations and the photons in the superinductor. We consider a transmon qubit, shunted by a short, high-impedance, superinductor with discrete photon spectrum. Importantly, the other end of the superinductor couples to an external microwave circuit, which we model as a transmission line with a continuous photon spectrum. An impedance mismatch at the interface between the superinductor and the transmission line leads to standing wave resonances.

In order to investigate the effect of the impedance mismatch on the interaction of Bloch oscillations and superinductor photon modes, we examine the voltage across the transmon as a function of the external current. We find resonances in the voltage-current relation, i.e. we see voltage peaks, whenever the frequency of Bloch oscillations coincides with a photon mode of the superinductor. Additionally, we calculate the spectrum of photons emitted into the external transmission line and see peaks at the frequency of the Bloch oscillation and at the frequencies of the superinductor photon modes, which become maximal when the former coincides with one of the latter. Finally, we calculate the cross-section of incoming microwave photons that are inelastically scattered at the transmon to energies that are higher by one Bloch oscillation quantum of energy.

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Fractional Chiral Currents at Step Edges of Topological Metals

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In topological matter, the bulk-boundary correspondence guarantees the presence of anomalous surface states and ensures their robustness - a combination that has led to the discovery of various unconventional transport phenomena. Some of the most interesting objects are one-dimensional chiral edge states, which give rise to the robust conductance of ne^2 / h, where e^2 / h is the conductance quantum and n is an integer that is determined by the bulk, independent of local system details. In this work we show that step edges on the surface of topological metals realize anomalous chiral states with a fractional conductance $I< e^2 / h$, wher $I<$ is also fixed by the bulk but assumes non-integer values. We explain this prediction rigorously on the basis of the topology of gapless systems, exemplify it on a lattice model, and connect to recent experimental observations of step-edge states.

Strong-coupling superconductivity near Gross-Neveu quantum criticality in Dirac systems

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Abstract

We investigate superconductivity in two-dimensional massless Dirac fermions at charge neutrality, coupled to bosonic collective modes via a Yukawa interaction. Despite the absence of carriers at zero temperature, we uncover the surprising possibility that such systems can become superconducting near a Gross–Neveu quantum critical point. Remarkably, superconductivity emerges precisely when the fermionic excitations lose coherence—once their anomalous dimension in the normal state becomes sufficiently large. In other words, well-defined quasiparticles fail to superconduct, whereas strongly incoherent ones can.

To capture this behavior, we develop a general framework for four-component Dirac systems and derive explicit algebraic criteria for the onset of pairing. Within this description, different bosonic modes—classified by their transformation under time-reversal and internal symmetries—select distinct superconducting channels. We then apply this approach to Dirac models of spin–orbit–coupled systems with orbitals of opposite parity and extend it to analyze superconductivity in moiré Dirac materials such as double-bilayer WSe_2 and twisted bilayer graphene

Quantum Monte Carlo simulations of electronic transport in strongly-correlated Dirac materials

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Recent advances in the fabrication of high-quality experimental samples have enabled access to regimes in which defects play a minor role in electronic transport compared to electron–electron scattering. This hydrodynamic transport regime is particularly well suited to modeling with *ab initio* Quantum Monte Carlo (QMC) methods, which naturally describe clean systems without disorder. In this framework, all scattering processes are treated non-perturbatively, even when the effective coupling constant is large and perturbation theory breaks down. We present the results of large-scale QMC simulations of the electronic transport in suspended graphene, where the effective coupling constant exceeds 2, making it an ideal platform for studying strong electron–electron interactions. QMC simulations are done on large 102x102 lattice providing sufficient momentum resolution for direct comparison with experiments.

First, we systematically investigate single-particle spectral functions, focusing on the logarithmic renormalization of the Fermi velocity Vf, and compare the coefficient in front of the logarithm with existing analytical and experimental results. We also study composite quasiparticles, with particular emphasis on plasmons. Electronic transport properties are analyzed through the renormalization of the optical and DC conductivities as functions of interaction strength and temperature.

Our results show that freestanding graphene is a strongly correlated system for which even the Random Phase approximation (RPA) is quantitatively inadequate in describing electronic transport. In particular, the temperature-dependent renormalization of the Fermi Velocity exhibits significant deviations from RPA-level predictions, even when perturbation theory is formulated using microscopic tight-binding Hamiltonian. We further demonstrate that lattice effects also play an important role: the Dirac-cone approximation fails to accurately capture both the Vf renormalization and plasmon dynamics, including plasmon dispersion and quasiparticle residue.

Our findings motivate the development of kinetic-theory descriptions of electronic trans port that incorporate both higher-order corrections to the collision integral and the microscopic details of the underlying tight-binding Hamiltonian.

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Quantum critical electronic liquids in strange metals: exact results for magnetotransport from spatially disordered 2D Yukawa-SYK theory

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The two-dimensional (2D) spatially disordered Yukawa-Sachdev-Ye-Kitaev (YSYK) theory offers an exactly solvable platform to analyze non-Fermi liquid states and their associated thermodynamic and spectroscopic phenomenology, microscopically rooted in quantum criticality [1-4]. Here we focus on normal-state transport in the presence of an applied magnetic field B, leveraging on the exact self-consistent disorder-averaged solution of the 2D-YSYK saddle-point equations. We present exact numerical results for the DC magnetoconductivity tensor on a square lattice, at first order in applied perpendicular magnetic field [4]. We calculate the longitudinal and Hall conductivities, the Hall coefficient, the carrier mobility, and the cotangent of the Hall angle, at fixed fermion density. In particular, we find an extended crossover temperature regime, above the marginal Fermi Liquid (MFL) ground state, characterized by superlinear evolution of the Hall-angle cotangent and the inverse carrier mobility with temperature, and concomitant with linear-in-temperature resistivity.

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Hall Resistivity Scaling Behavior of Altermagnet CrSb

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CrSb is a robust altermagnet with a complex Fermi surface hosting both electron- and hole-like carriers, making it an ideal platform for examining multiband magnetotransport and scaling laws [1]. In this work, we investigate the scaling behavior of longitudinal magnetoresistance (MR) and Hall resistivity in CrSb. To capture experimental trends, we employ two complementary Kohler-type scaling relations: the previously established Kohler’s rule for MR and a Kohler-like scaling for Hall resistivity introduced by Quansheng Wu and Shengnan Zhang [2], enabling a unified description of longitudinal and transverse transport. The magnetotransport calculations are carried out using WannierTools [3] based on Wannierized electronic structures. The results obtained for the altermagnetic configuration agree well with experimental observations, exhibiting clear MR scaling and Hall-resistivity scaling. In contrast, calculations using a nonmagnetic structure fail to reproduce the measured behavior. This pronounced altermagnetic vs nonmagnetic contrast provides an additional transport-level consistency check for the altermagnetic electronic structure.

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Topological Anderson Chern Insulator in Monolayer MnBi4Te7

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The interplay between disorder and topology has become a central theme in condensed matter physics. Disorder can not only destroy topological phases but also induce them, as exemplified by the topological Anderson insulator. Here we show that, in close analogy, disorder can drive the clean-limit, time-reversal-broken(T-broken) quantum spin Hall state of ferromagnetic mono layer MnBi4Te7 into a quantum anomalous Hall phase, which was called topological Anderson Chern insulator (TACI), observed in a recent experiment. Using density functional theory and nonequilibrium Green's function calculations in the presence of disorder, we identify disorder induced phases and construct a comprehensive phase diagram. We further use the density of states computed within the self-consistent Born approximation, which in particular distinguishes gapped and un gapped regions. We find that the two effective band inversions of Hamiltonian are suppressed at distinct critical disorder strengths; the survival of a single inversion over a finite disorder window stabilizes the TACI. Remarkably, at strong disorder, we further propose a zero Hall plateau insulating state characterized by an insulating bulk and edge channels subject to diffusive scattering that can coexist with the TACI. The trivial and nontrivial insulating states correspond to the transport signals observed in experiments.

Classical Percolation from Quantum Metric in Flat-Band Delocalization

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The quantum metric is a fundamental ingredient of band quantum geometry and has recently attracted intense interest, with most of its transport signatures appearing in the intrinsic second order nonlinear conductivity. In the clean limit, previous works argued that linear response conductivity is insensitive to the quantum metric. Here we combine analytic derivations with large scale numerics to show that disorder modifies the linear conductivity which is dominated by geometric conductivity determined by the real space quantum metric. Focusing on a two-dimensional multi-flatband model, we identify a delocalized regime sandwiched between flat band localization and Anderson localization. We further map the real space quantum metric marker to the local Wannier spread and construct a square lattice percolation model, the exponent of which supports a classical percolation universality class. These findings suggest that flat band delocalization can be understood as a classical percolation of quantum metric puddles, offering a new route for detecting quantum geometry transport signatures in spin-orbit proximitized moiré heterostructures.

Medium-throughput calculations on the nonlinear topological transport properties

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Quantum geometry gives rise to a wide spectrum of fascinating phenomena, such as nontrivial topological phases characterized mostly by various types of linear topological Hall effects. In this work, going beyond the linear regime, we implement a workflow to perform medium/high-throughput calculations on the nonlinear topological transport properties. To this goal, maximally localized Wannier functions are constructed automatically with the projections and energy windows determined based on in-depth analysis of the electronic structure. Focusing on the shift current as a representative case, it is demonstrated how the nonlinear topological transport properties can be obtained for two classes of emergent materials (a) two-dimensional (2D) perovskites and (b) altermagnets, both dictated by broken inversion symmetry. In the former case, it is demonstrated large above-bandgap photovoltage up to 40 V can be achieved in double perovskite perovskite ferroelectric (cyclohexylmethylammonium)$_2$CsAgBiBr$_7$, which can be attributed to shift current caused by Berry curvature dipoles, enabling future engineering of novel optoelectronic smart devices [1]. Furthermore, we collected the experimentally available 2D perovskite via exhaustive literature survey and performed calculations in order to identify structural/chemical descriptors. In the latter case, we complied the altermagnets (including both the conventional and unconventional (i.e., odd-parity) cases) without inversion symmetry and carried out calculations. It is shown that electric fields can be applied to switch the non-relativistic spin splitting and hence the shift currents.

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Electronic Structure and Effective Hamiltonian Construction for Moiré Superlattices

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Moiré superlattices provide an exceptionally tunable platform where band topology and quantum geometry can be engineered through twist angle, lattice mismatch, and symmetry. A central practical challenge is to construct faithful low-energy effective Hamiltonians that are symmetry-respecting, quantitatively controlled, and transferable across materials and twist angles. In this poster, I present a systematic workflow to derive continuum moiré Hamiltonians directly from first-principles information, emphasizing symmetry-filtered operator bases and controlled truncations that reduce reliance on phenomenological fitting.

Using the resulting continuum models, I compute band-resolved and valley-resolved geometric/topological quantities including Berry curvature, quantum metric, and Wilson-loop diagnostics, and discuss characteristic momentum-space structures that emerge in twisted systems. By bridging first-principles-informed effective theories with quantum-geometric diagnostics, this approach aims to provide a transparent and quantitatively controlled route from microscopic material inputs to effective-model-based characterization of topology and quantum geometry, serving as a foundation for future connections to mesoscale and magnetic-field transport phenomena discussed in this seminar.

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