International Workshop on

„Flat Bands and Unconventional Superconductivity”,

Bochum, Germany, October 1-2, 2025

PROGRAM AND USEFUL INFORMATION

Organizing Committee

Ilya Eremin, Ruhr Universität Bochum, Germany,
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Ruhr- Universität Bochum

LOCATION AND DATES

The workshop will be held from October 1 – 2, 2025 in the campus of Ruhr University Bochum, Germany.

REGISTRATION

The registration desk will be open on Wednesday, October 1st, from 09:30 to 10:00.

TRAVEL INFORMATION

The workshop will take place at the International Convention Centre, room Shanghai of the Ruhr-Universität Bochum, Beckmannshof.

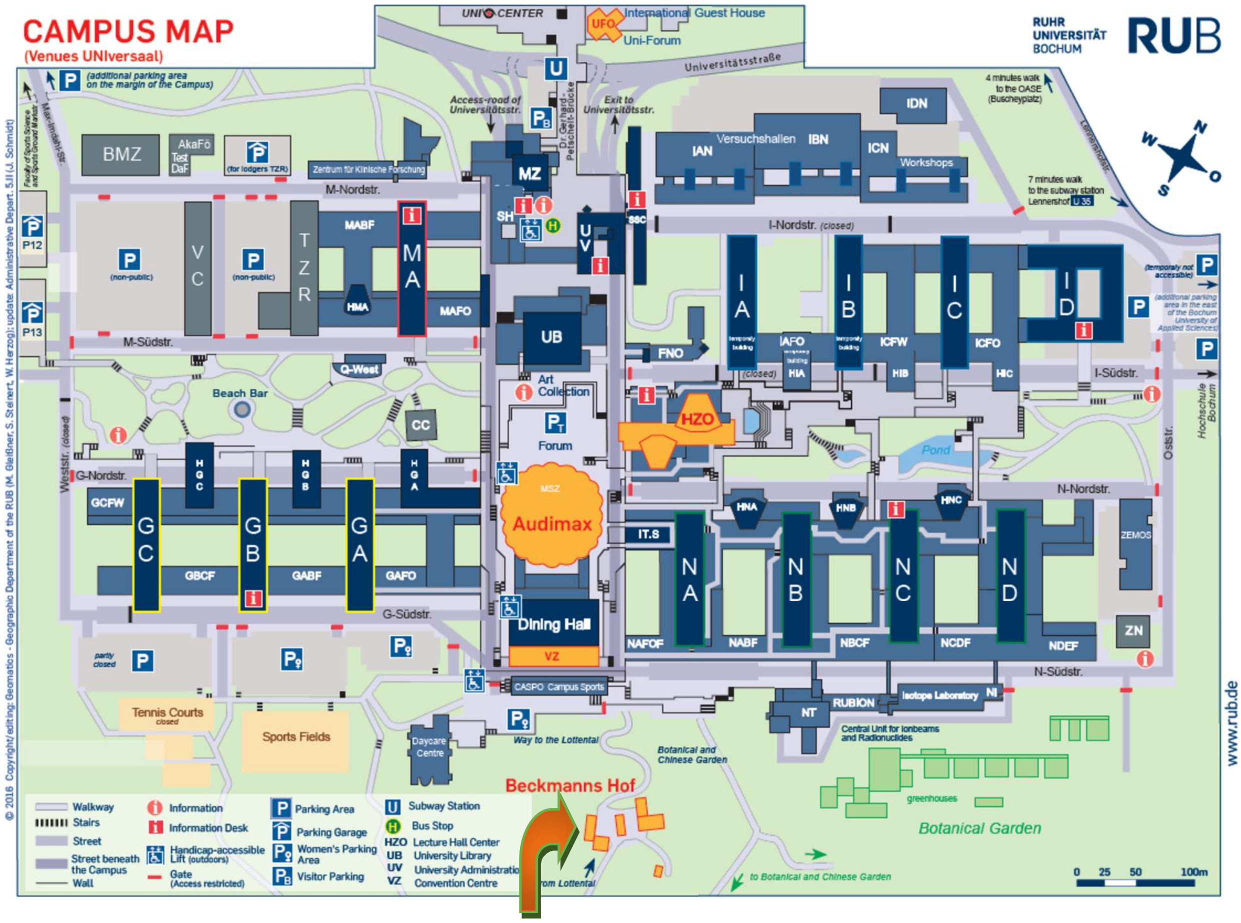
https://www.ruhr-uni-bochum.de/universaal/raumuebersicht/beckmannshof.html.en

The center is located at the edge of university campus, close to Botanic Garden.

The easiest way to reach the Beckmanshof is to use line U35 from the Bochum Hbf (main station) (or from Rathaus Nord, depends which one is closer to your accommodation) in the direction of Hustadt till the station 'Ruhr-Universität'.

The campus will be located on your right (do not be confused with Uni Center, which is on the left). Once you reach the campus just continue straight through the campus (passing by the Audimax, you should also see the big construction hole on your left) and then take either stairs or elevator towards the ground. Once on the ground (for orientation it should be Frauenparkplatz) look to your left, there should be a sign pointing towards the Beckmanshof and then just follow this sign.

Map of the Ruhr-Universität Campus



CONTACT INFORMATION

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SCIENTIFIC PROGRAM

Invited speakers will be allotted 45 minutes plus 15 min. questions, contributed talks are 20 minutes plus 10 minutes questions.

Program

Wednesday October 1st, 2025

09:30-10:00 Arrival, Registration & Opening and Coffee

Session 1
Chairperson: Miguel Marques

10:00-10:45 **Päivi Törmä (Aalto University)** *"Quantum Geometric Superconductivity and Transport in Flat Bands"*

11:00-11:45 **Dmitri Efetov (LMU München),** *"Revealing electron-electron interactions in graphene at room temperature with the quantum twisting microscope"*

12:00-12:20 **Maximilian Buthenhoff (Institute of Science, Tokyo)** *"Superfluid weight beyond the minimal metric in flat bands"*

12:30-14:00 Lunch (Buffet)

Session 2
Chairperson: Michael Scherer

14:00-14:45 **Franck Lechermann (Ruhr-University Bochum)** *"Correlated flat-band physics in the $La_3Ni_2O_{7-y}$ system"*

15:00-15:20 **Joshua Althueser (TU Dortmund)** *"Secondary Collective Excitations in Intermediate to Strong-Coupling Superconductors"*

15:30-15:50 **Steffen Bötzel (Ruhr-University Bochum)** *"Superconductivity in bilayer nickelate $La_3Ni_2O_7$"*

16:00-17:00 Coffee break and Discussions

Thursday October 2nd, 2025

Session 3
Chairperson: Ilya Eremin

09:00-9:45 **Sergey Borisenko (IFW Dresden),** *"A-approach in ARPES and recent results on $PtBi_2$"*

10:00-10:45 **Brian Andersen (NBI Kopenhagen),** *"Unconventional superconductivity hidded as conventional superconductivity on the kagome and Lieb lattices."*

11:00-11:30 Coffee break and Discussions

11:30-12:00 **Simon Moser (Ruhr-University Bochum),** *"Moiré-assisted charge instability in ultrathin RuO_2."*

12:00-13:30 Lunch (Buffet)

Session 4
Chairperson: Miguel Marques

13:30-14:15 **Andrei Bernevig (Princeton University),** *""Some" Progress in Superconductivity Outliers"*

14:30-15:15 **Roser Valenti (Uni Frankfurt),** *"Complex orders in Moiré systems: a playground for flat bands and heavy fermion physics "*

15:30 Coffee break, discussions and closing

Abstracts

Quantum Geometric Superconductivity and Transport in Flat Bands

Päivi Törmä

Aalto University, 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]. The quantum transport in flat band shows unique behavior [4]: 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 [5]. While most of the mentioned work is for on-site interactions, in a recent study [7] we found that nearest-neighbor pairing at flat band and van Hove singularities of the kagome and Lieb lattices is strongly influenced by the geometric properties of the eigenfunctions, and it is crucial to determine the superfluid weight of the superconducting and pair density wave orders as it may contradict the predictions by pairing susceptibility. We have also studied the connection of quantum geometry and the superconductivity in the flat surface bands of rhombohedral graphite [7].

[1] S. Peotta, P. Törmä, Nature Commun. **6**, 8944 (2015); K.-E. Huhtinen, J. Herzog-Arbeitman, A. Chew, B.A. Bernevig, P. Törmä, Phys. Rev. B **106** , 014518 (2022).

[2] P Törmä, Phys. Rev. Lett. **131**, 240001 (2023); J. Yu, B.A. Bernevig, R. Queiroz, E. Rossi, P. Törmä, B.-J. Yang, arXiv:2501.00098 (2025).

[3] A. Julku, T.J. Peltonen, L. Liang, T.T. Heikkilä, P. Törmä, Phys. Rev. B **101**, 060505(R) (2020); X. Hu, T. Hyart, D.I. Pikulin, E. Rossi, Phys. Rev. Lett. **123**, 237002 (2019); F. Xie, Z. Song, B. Lian, B.A. Bernevig, Phys. Rev. Lett. **124**, 167002 (2020); P. Törmä, S. Peotta, B.A. Bernevig, Nat. Rev. Phys. **4**, 528 (2022).

[4] V.A.J. Pyykkönen, S. Peotta, P. Törmä, Phys. Rev. Lett. **130**, 216003 (2023).

[5] P. Virtanen, R.P.S. Penttilä, P. Törmä, A. Díez-Carlón, D.K. Efetov, T.T. Heikkilä,

arXiv:2410.23121, to appear in Phys. Rev. B Letter (2025).

[6] E.O. Lamponen, S.K. Pöntys, P. Törmä, arXiv:2502.20911 (2025).

[7] G. Jiang, T.T. Heikkilä, P. Törmä, arXiv:2504.03617 (2025).

Revealing electron-electron interactions in graphene at room temperature with the quantum twisting microscope

Dmitri K. Efetov

Ludwig-Maximilians-Universität München, Germany

The Quantum Twisting Microscope (QTM) is a groundbreaking instrument that enables energy- and momentum-resolved measurements of quantum phases via tunneling spectroscopy across twistable van der Waals heterostructures. In this work, we significantly enhance the QTMs resolution and extend its measurement capabilities to higher energies and twist angles by incorporating hexagonal boron nitride (hBN) as a tunneling dielectric. This advancement unveils previously inaccessible signatures of the dispersion in the tunneling between two monolayer graphene (MLG) sheets, features consistent with a logarithmic correction to the linear Dirac dispersion arising from electron-electron (e-e) interactions with a fine-structure constant of alpha = 0.32. Remarkably, we find that this effect, for the first time, can be resolved even at room temperature, where these corrections are extremely faint. Our results underscore the exceptional resolution of the QTM, which, through interferometric interlayer tunneling, can amplify even subtle modifications to the electronic band structure of two-dimensional materials. Our findings reveal that strong e-e interactions persist even in symmetric, nonordered graphene states and emphasize the QTMs unique ability to probe spectral functions and their excitations of strongly correlated ground states across a broad range of twisted and untwisted systems.

Superfluid weight beyond the minimal metric in flat bands

M. Buthenhoff[1,2], T. Holder[3], M. M. Scherer[2]

1-Department of Physics, Institute of Science Tokyo, Japan

2-Theoretical Physics III, Ruhr-University Bochum, Germany

3-School of Physics and Astronomy, Tel Aviv University, Israel

In flat-band superconductors the critical temperature scales with the interaction strength, making dispersionless bands good candidates for strong pairing. This talk presents a general BCS-level expression for the superfluid weight of isolated flat bands with unconventional spin-singlet pairing. The result separates the minimal quantum metric term from additional nonlocal quantum-geometric contributions that arise beyond conventional pairing. Consequences for identifying pairing symmetries in flat-band materials will be highlighted.

[1] M. Buthenhoff, T. Holder, and M. M. Scherer, Functional approach to superfluid stiffness: Role of quantum geometry in unconventional superconductivity, arXiv preprint 10.48550/arXiv.2505.09249 (2025).

Correlated flat-band physics in the $La_3Ni_2O_{7-y}$ system

Frank Lechermann, Steffen Bötzel, J. Gondolf and Ilya M. Eremin

Theoretische Physik III, Ruhr-Universität Bochum, 44780 Bochum, Germany

In recent years, the condensed matter community has witnessed the discovery of superconducting properties of layered nickel oxides. In fact, these systems have been in the focus since the early days of cuprate high-Tc superconductivity, as possible additional representants of unconventional superconductors with a high transition temperature. But only 2019, a stable electron-pairing phase has been identified in thin-films of Sr-doped $NdNiO_2$ with a formal $3d^{9-x}$ valence on Ni was found by by Li et al. [1]. In 2023, the bilayer nickelate $La_3Ni_2O_7$ with formal $3d^{8-x}$ valence was detected superconducting under pressure [2]. These two findings provided the seed for a growing number of superconducting systems associated with either of the two nickelate families.

The advanced combination of density functional theory (DFT), self-interaction correction (SIC) and dynamical mean-field theory (DMFT) provides unique access to this novel playground of realistic interacting electrons prone to superconductivity in a competing Mott-Hubbard vs. charge-transfer scenario. In this talk, we will focus on the second family of superconducting nickelates. It will be shown that the whole bilayer $La_3Ni_2O_{7-y}$ system shares intriguing correlation physics [3,4], building up from a Ni-e_g multiorbital low-energy regime, where flat-band characteristics play an essential role. These findings open up possibilities to eventually connect both so far distinct superconducting families.

[1] D. Li et al., Nature 572, 624 (2019).

[2] H. Sun et al., Nature, s41586-023-06408-7 (2023).

[3] F. Lechermann et al., Phys. Rev. B 108, L201131 (2023).

[4] F. Lechermann et al., arXiv:2412.19617 (2024).

Secondary Collective Excitations in Intermediate to Strong-Coupling Superconductors

Joshua Althüser, and Götz S. Uhrig

Condensed Matter Theory, TU Dortmund University, Otto-Hahn Straße 4, 44227 Dortmund, Germany

Considering systematically derived, energy-transfer dependent, effective electron-electron interactions entails the appearance of secondary phase and amplitude modes in isotropic superconductors in the intermediate to strong-coupling regime, even in the presence of the Coulomb repulsion [1]. We study the implications of such interactions on Bravais lattices by computing the corresponding response functions using the iterated equations of motion (iEoM) approach. We find that the secondary modes emerge largely independently of the underlying lattice and the specific Fermi level. Intriguingly, the amplitude and phase modes couple if the system is not particle-hole symmetric.

[1] J. Althüser, G. S. Uhrig, Collective modes in superconductors including Coulomb repulsion, SciPost Physics 19 (3) (2025) 067. doi:10.21468/SciPostPhys.19.3.067.

Superconductivity in bilayer nickelate $La_3Ni_2O_7$

S. Bötzel[1], F. Lechermann[1], J. Gondolf[2], T. Shibauchi[3], I. E. Eremin[1]

1-Theoretische Physik III, Ruhr-Universität Bochum, D-44801 Bochum, Germany

2-Niels Bohr Institute, University of Copenhagen, DK-2200 Copenhagen, Denmark

3-Department of Advanced Materials Science, The University of Tokyo, Kashiwa, Chiba, Japan

The bilayer nickelate $\mathrm{La_3Ni_2O_7}$ hosts high pressure, high temperature superconductivity with critical temperatures up to 80 K [1]. $\mathrm{La_3Ni_2O_7}$ has a complex low-energy electronic structure which is ruled by strong interlayer and multiorbital physics. Furthermore, a flattish band with Ni-$3d_{z^2}$ character likely crosses the Fermi level. Many theoretical works suggest a spin-fluctuation-mediated $s_{\pm}$-superconducting gap structure that exhibits a sign change between the bands with bonding and antibonding character with respect to the bilayer structure. In this talk, I will elaborate on what kind of spin fluctuations that can naturally explain such a gap structure and how it is connected to interlayer pairing. Furthermore, an orbital anti-phase gap structure may enforce accidental gap nodes. Additionally, the footprint of magnetic excitations in such a superconducting state is analyzed, which can be measured by inelastic neutron scattering or resonant inelastic x-ray scattering [2]. Moreover, the suppression of T_c due to impurity scattering is discussed [3]. The suppression rate depends on the asymmetry of the bonding and antibonding subspaces. For the predicted electronic structure, the $s_{\pm}$ gap structure exhibits a convex-to-concave transition reflecting the crossover to s_{++} gap structure as impurity concentration increases.

[1] Sun, H., Huo, M., Hu, X., Li, J., Liu, Z., Han, Y., et al., Nature, 621(7979), 493-498 (2023)

[2] Bötzel, S., Lechermann, F., Gondolf, J., & Eremin, I. M., Physical Review B, 109(18), L180502 (2024)

[3] Bötzel, S., Lechermann, F., Shibauchi, T., & Eremin, I. M., Communications Physics, 8(1), 154 (2025)

A-approach in ARPES and recent results on $PtBi_2$

Sergey Borisenko

IFW-Dresden, Germany

I will start with a comment on the different approaches of the ARPES technique and then move on to our recent results on the trigonal Weyl semimetal $PtBi_2$. There we observe unconventional superconductivity at the surface. We investigate the electronic structure of the Fermi arcs and try to understand the reasons for this exotic state.

[1] S. Borisenko, The Role of A in ARPES, http://dx.doi.org/10.2139/ssrn.5356192

[2] A. Kuibarov et al. Measuring superconducting arcs by ARPES, https://doi.org/10.48550/arXiv.2505.09347

[3] S. Changdar et al. Topological nodal i-wave superconductivity in $PtBi_2$,

https://doi.org/10.48550/arXiv.2507.01774

Unconventional superconductivity hidded as conventional superconductivity on the kagome and Lieb lattices

Brian M. Andersen

Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark

I will report on our recent theoretical investigations of fully momentum-compensated unconventional superconducting order on the kagome and Lieb lattices. Both these geometries feature three atoms per unit cell, flat bands, and nontrivial momentum structure of the Bloch weights on some of the bands. The latter has consequences for superconductivity. In particular, unconventional superconducting order becomes robust to point-like disorder and exhibit Hebel-Slichter peaks in NMR, despite their order parameters summing to zero over the whole Brillouin zone. Normally, such properties are characteristics of conventional superconductivity. I will explain these surprising outcomes and attempt to expose the generality of the results to other systems.

Moiré-assisted charge instability in ultrathin RuO_2

Philipp Keßler, Andreas Feuerpfeil, Armando Consiglio, Hendrik Hohmann, Ronny Thomale, Jonas Erhardt, Bing Liu, Vedran Jovic, Ralph Claessen, Patrick Härtl, Matteo Dürrnagel, and Simon Moser

Physikalisches Institut and Würzburg-Dresden Cluster of Excellence ct.qmat, Universität Würzburg, 97074 Würzburg, Germany

Ruthenium dioxide (RuO_2) has been in the focus of contemporary condensed matter research as a prototypical candidate material for altermagnetism. In the face of daunting evidence for bulk magnetic order despite promising theoretical predictions, it naturally suggests the focus on thin films where Coulomb interactions are dimensionally quenched and may yield a more strongly correlated environment prone to magnetic ordering. Here, we combine scanning tunneling microscopy (STM), density functional theory (DFT), and density matrix renormalization group (DMRG) methods to investigate atomically ordered ultrathin RuO_2(110) grown on Ru(0001). Contrary to predictions of magnetic order, we observe a nonmagnetic charge density wave (CDW) instability that is driven by Fermi surface nesting within the flat-band surface state, and stabilized by the incommensurate moiré stacking with the substrate. We further identify a nonmagnetic and metastable 2×2 surface reconstruction that breaks in-plane mirror symmetry and can be reversibly toggled via STM tip manipulation. Our spin-polarized STM measurements find no sign of any magnetic instability at the RuO_2 surface. As much as our findings refute proposals for either bulk or surface magnetism in RuO_2, we establish ultrathin RuO_2(110) as an intriguing platform for exploring Moiré-assisted electronic surface order.

“Some” Progress in Superconductivity Outliers

B. Andrei Bernevig

Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

We report work done on understanding superconductors which are outliers (MgB2, others) and new bounds on wannier states. We also report incipient machine learning work on laves phases and their properties (to be extended to other materials), with the scope of obtaining an understanding of what machine learning teaches us about the physics of materials

Complex orders in Moiré systems: a playground for flat bands and heavy fermion physics

Roser Valenti

Institut für Theoretische Physik, Goethe Universität Frankfurt, Max-von-Laue-Strasse 1, 60438 Frankfurt am Main, Germany

In magic angle twisted bilayer graphene, transport, thermodynamic and spectroscopic experiments pinpoint to a competition between distinct low-energy states with and without electronic order, as well as a competition between localized and delocalized charge carriers. In this talk I will discuss these observations in the context of a heavy fermion-like description. We will show [1-4] through a combination of Hartree-Fock and Dynamical Mean Field Theory that such a heavy fermion picture is able to describe in a unified way many of the experimentally observed complex orders in these materials.

[1] Hu et al. Phys. Rev. Lett. 131, 166501 (2023)

[2] Rai et al. Phys. Rev. X 14, 031045 (2024)

[3] Kim et al. arXiv:2505.17200

[4] Crippa et al. to be published (2025)