Novel electronic properties of two dimensional materials (NEP2DM)

July 11-15th San Sebastian, Spain

Full Program

Monday 11/07

8:15 - Registration
9:00 - **S. Nadj-Perge:** Superconductivity, correlations, and symmetry-broken states in (un)-twisted graphene multilayers.
9:45 - **C. Rubio-Verdú**: Twisted graphene: nematic order and topological edge states.
10:30 - Coffee and discussion
11:30 - **D. Basov**: Shedding Nano-light on quantum materials
12:15 - **H. Ochoa**: Phasons in moiré superlattices
13:00 - Lunch
15:00 - **D. Parker**: Quantum Geometry and Fractional Chern Insulators
15:45 - **C. Repellin**: Fractional Chern Insulators in Magic Angle Twisted Bilayer Graphene
16:30 - Poster session with coffee

Tuesday 12/07

9:00 - **M. Koshino**: Topological quasicrystals in twisted 2D systems
9:45 - **L. Bascones**: The “normal” state of graphene based moiré heterostructures
10:30 - Coffee and discussion
11:30 - **A. Berdyugin**: Novel electric properties of Dirac plasma
12:15 - **A. Imamoglu**: Optical spectroscopy of strongly correlated electrons in two-dimensional materials
13:00 - Lunch
15:00 - **J. Cano**: Designer meron lattice on the surface of a topological insulator
15:45 - **J. Jung**: Electronic structure of lattice relaxed alternating twist tNG multilayer graphene
16:30 - Poster session with coffee

Wednesday 13/07

9:00 - **J. Park**: Magic-Angle Twisted Graphene Family
9:45 - **K.Ensslin**: Insulating and superconducing states in twisted graphene layers
10:30 - Coffee and discussion
11:30 - **Jeanie Lau**: Experimental investigation of non-trivial band topology and quantum geometry in graphene
12:15 - **D. Efetov**: Plethora of Many-Body Ground States in Magic Angle Twisted Bilayer Graphene

13:00 - Lunch
15:00 - **P. Törmä**: Quantum geometry and flat band superconductivity
15:45 - **A. Bernevig**: Flat Bands, Quantum Geometry, Many-Body Spectra and Topological Heavy Fermions
16:30 - Poster session with coffee

Thursday 14/07

9:00 - **E. Zeldov**: Imaging the Local Band Topology and Chern Mosaic in Magic-Angle Graphene
9:45 - **X. Xu**: Magnetism in moiré superlattices
10:30 - Coffee and discussion
11:30 - **E.-A. Kim**: Fractionalization in fractionally filled Moiré systems
12:15 - **N. Bultinck**: Kekule spiral order at all nonzero integer fillings in twisted bilayer graphene
13:00 - Lunch (and free afternoon)
16:00 - Visit to Santa Clara island.
20:45 - Conference dinner at Ni Neu

Friday 14/07

9:00 - **O. Yazyev**: Novel structural and electronic phases of 2D transition metal dichalcogenides
9:45 - **L. Classen**: Topological superconductivity in moiré transition metal dichalcogenides
10:30 - Coffee and discussion
11:30 - **Y. Oreg**: Phenomenological theory of correlated insulators and superconductivity in twisted bilayer graphene
12:15 - **P. Pantaleon**: Band Structure and Topological Properties of Graphene Multilayers
13:00 - Final remarks and closure

Monday 11/07

Superconductivity, correlations, and symmetry-broken states in (un)-twisted graphene multilayers

Stevan Nadj-Perge
California Institute of Technology, USA

Following the discovery of magic-angle twisted bilayer graphene, the family of graphene-based superconductors has expanded considerably in the last year. In this talk, I will briefly overview superconducting systems explored recently in our lab, highlighting their striking similarities and differences. In particular, we will focus on magic-angle twisted trilayer graphene measurements using scanning tunneling microscopy that reveals several signatures of unconventional superconductivity, including the possible transition between BEC and BCS phases, alongside many similarities to twisted bilayers. In the second part, we will discuss the role of auxiliary tungsten diselenide monolayer in stabilizing the superconductivity in Bernal bilayers and twisted multilayers, as well as the intimate connections between superconductivity and interaction-driven symmetry broken parent states in these systems.

Twisted graphene: nematic order and topological edge states

Carmen Rubio-Verdú
Department of Physics, Columbia University, New York, New York 10027, USA

Atomically thin van der Waals materials stacked with an interlayer twist are an excellent platform towards achieving gate-tunable correlated phenomena linked to the formation of flat electronic bands. We demonstrate the formation of emergent correlated phases in twisted double bilayer graphene (tDBG) in two regimes of twist angle: minimally twisted (<0.1°) and 1.1°. Minimally twisted tDBG hosts large regions of uniform rhombohedral four-layer (ABCA) graphene where scanning tunneling spectroscopy reveals unprecedentedly sharp flat band of 3-5 meV half-width [1]. We demonstrate that, when this flat band straddles the Fermi level, a correlated many-body gap emerges. Moreover, under certain experimental conditions, topological helical edge states appear at the natural interface between rhombohedral and Bernal graphene domains. On the other hand, scanning tunneling microscopy on tDBG at a regime of twist angles (~1.1°) at which moiré physics play an important role, reveals the presence of van Hove singularities whose spatial distribution within the moiré unit cell is determined by the inequivalent stacking sites [2]. Tuning the electron filling as well as the displacement field reveals broken C_3 symmetry that emerges when the Fermi level is brought in the flat band. This symmetry breaking is manifested as long-range commensurate stripes along a high-symmetry moiré crystallographic direction, distinctive of nematic correlations of electronic origin. Comparing our experimental data with a combination of microscopic and phenomenological modeling, we show that the nematic instability is not associated with the local scale of the graphene lattice, but is an emergent phenomenon at the scale of the moiré lattice, pointing to the universal character of this ordered state in flat band moiré materials.

[1] Kerelsky*, Rubio-Verdú* *et al., Moiréless correlations in ABCA graphene*, PNAS **118** e2017366118 (2021)

[2] Rubio-Verdú *et al., Moiré nematic phase in twisted double bilayer graphene,* Nature Physics **18**, 196 (2022)

Shedding Nano-light on quantum materials

Dimitry Basov
Columbia University, USA

Phasons in moiré superlattices

Héctor Ochoa
Donostia International Physics Center, San Sebastian, Spain

In this talk I will argue that the long-wavelength lattice dynamics of moiré patterns is more akin to an amorphous solid than to a crystal. The reason is the existence of soft collective modes, called phasons, associated with the sliding motion of one layer with respect to the other [1]. At finite temperature this motion necessarily involves friction, microscopically, due to anharmonic coupling with optical phonons. Consequently, phasons are overdamped at low frequencies, reflecting that in this regime the moiré pattern relaxes via internal diffusive processes rather than by collective oscillations. This reflects, more broadly, that the "acoustic phonons" of the moiré superlattice are not protected by a conservation law [2]. I will discuss physical consequences of this observation for twisted bilayer graphene, including the widespread presence of “twist angle disorder”. This is governed by the collective pinning of stacking domain walls caused by lattice relaxation. The phason spectrum acquires then a gap, which displays a universal dependence on the twist-angle variance.

[1] H. Ochoa, Phys. Rev. B **100**, 155426 (2019).
[2] H. Ochoa and R. M. Fernandes, Phys. Rev. Lett. **128**, 065901 (2022).

Quantum Geometry and Fractional Chern Insulators

Daniel Parker
Harvard University, USA

In contrast to the fractional quantum Hall (FQH) effect, where electron density fixes the applied magnetic field, fractional Chern insulators (FCIs) can realize FQH states in comparatively weak or even zero magnetic fields. Previous theoretical work highlighted magic angle graphene (TBG) as a promising FCI platform, satisfying the twin requirements of flat bands and lowest-Landau-level-like quantum geometry. Indeed, recent experiments have demonstrated FCIs in magic angle graphene with weak magnetic fields.
In the first part of this talk I will discuss how the humble position operator naturally leads to ideal (holomorphic) quantum geometry and present the generalization to many bands and higher Chern numbers.

In the second part, I will combine ideal geometry with numerics and the Hofstadter butterfly to answer three practical questions about the FCIs observed in TBG:1. Why do FCIs appear in TBG? 2. Why have they only appeared at finite magnetic field so far? 3. What are the experimental parameters required for FCIs at zero magnetic field?

Fractional Chern Insulators in Magic Angle Twisted Bilayer Graphene

Cécile Repellin
CNRS

Layered moire systems have become an outstandingly versatile platform for the study of strongly correlated quantum phenomena, due to the possibility to tune the band structure to obtain a flat band. Topological properties are also expected in many moire systems: for example, aligning magic angle twisted bilayer graphene with a substrate of hexagonal boron nitride (hBN) creates flat valence and conduction bands with Chern number +/- 1. A nearly flat Chern band can host an analog of the fractional quantum Hall effect in the absence of a magnetic field, a fractional Chern insulator. I will discuss which microscopic ingredients are necessary for this phase to arise, and show that these conditions may be found in magic angle twisted bilayer graphene aligned with hBN. Based on the results of exact diagonalization, I will show that both a spin singlet and spin polarized fractional Chern insulators are possible depending on the fine details of the band properties of this material, and discuss how this theoretical analysis applies to recent experimental results.

Tuesday 12/07

Topological quasicrystals in twisted 2D systems

Mikito Koshino
Osaka University, Japan

When 2D materials having different periodicities are overlaid with each other, an interference pattern of the lattice mismatch often gives rise to unusual electronic properties. In a twisted bilayer graphene (TBG) with a small twist angle, a long-range moiré pattern gives rise to a flat band formation, where the electronic structure can be well described by the effective continuum approach. In larger twist angles (> 10 deg.), however, the atomic scale and the moiré period are no longer separable, and the system becomes quasiperiodic, i.e., the conventional Bloch theory breaks down.

In this talk, we present our recent theoretical works on electronic properties of quasiperiodic twisted 2D systems, including twisted bilayer graphene and hBN/graphene/hBN system [1]. We show that the electronic spectrum against the twist angle generally exhibits fractal minigaps like the Hofstadter butterfly, where each gap can be characterized by a set of topological numbers associated with area of a quasi Brillouin zone. These numbers can be expressed as second Chern numbers by considering a formal relationship between an charge pumping in interlayer sliding and quantum Hall effect in 4D space. [2]

[1] H. Oka and M. Koshino, Phys. Rev. B 104, 035306 (2021).
[2] M. Koshino, H. Oka, Phys. Rev. Research 4, 013028 (2022).

The “normal” state of graphene based moiré heterostructures

Leni Bascones
Instituto de Ciencia de Materiales de Madrid (ICMM), Spain

The plethora of symmetry breaking transitions in twisted bilayer graphene, ABC/hBN and other graphene based moiré heterostructures give clear evidence of the importance of correlations in these systems. While the effect of correlations is more easily identifiable when they produce a phase transition to an ordered state, research in other strongly correlated electron systems has shown that the non-ordered, so-called “normal”, state can be also strongly modified by such correlations. Specifically a notable spectral weight reorganization can produce highly anomalous temperature and doping dependencies in transport, optical or STM measurements and even control the phase transitions which take place. In the talk I will show that graphene based moiré heterostructures suffer from a significant spectral weight transfer at experimentally relevant interactions, not only in the ordered phases but also in the metallic “normal” state. The “normal” state of graphene moirés is everything but normal.

Novel electric properties of Dirac plasma

Alexey Berdyugin
University of Manchester, UK

The most recognizable feature of graphene's electronic spectrum is its Dirac point around which interesting phenomena tend to cluster. At elevated temperatures, thermal excitations can overcome the background disorder caused by charge inhomogeneity and create an electron-hole plasma of Dirac fermions. This relativistic-like plasma has recently been shown to exhibit unusual properties, including quantum critical conductivity and hydrodynamic flows, which are driven by strong electron-hole scattering. Little remains known about behavior of the Dirac plasma in magnetic field. In my talk I will present our recent findings of unconventional and intriguing behavior of Dirac plasma in a low and high magnetic field. In low fields, the plasma exhibits giant quadratic magnetoresistance, reaching >100% at 0.1 T even at room T. This is orders of magnitude higher than in any other metallic or semiconducting system at this temperature, including bilayer and multilayer graphene. The record-high magnetoresistance translates into a surprisingly high carrier mobility, exceeding 100,000 $cm^{-2}\ V^{-1}\ s^{-1}$ at room temperature, despite frequent electron-hole collisions. With the onset of Landau quantization in a few T, the room-temperature Dirac plasma develops a giant linear magnetoresistance. The latter can be attributed to the two-dimensional version of the so-called quantum linear magnetoresistance.

Next, I'm going to discuss an out-of-equilibrium transport in graphene and its superlattices. Surprisingly, non-linear transport in those systems in closely related to the Dirac plasma. In thermodynamic equilibrium, current in metallic systems is carried by electronic states near the Fermi energy, whereas the filled bands underneath contribute little to conduction. However, under applied electric field the carrier distribution in graphene and its superlattices can be shifted so far from equilibrium that the filled bands start playing an essential role, leading to a critical-current behavior. The criticalities develop upon the velocity of electron flow reaching the Fermi velocity. Key signatures of the out-of-equilibrium state are current-voltage characteristics that resemble those of superconductors, sharp peaks in differential resistance, sign reversal of the Hall effect, and a marked anomaly caused by the Schwinger-like production of hot Dirac plasma.

Optical spectroscopy of strongly correlated electrons in two-dimensional materials

Atac Imamoglu
Institute for Quantum Electronics, ETH Zürich, Switzerland

In this talk, I will describe recent experiments in atomically-thin transition metal dichalcogenides (TMDs) where Coulomb interactions between electrons dominate over their kinetic energy. Our measurements provide a direct evidence that the electrons at densities $< 3 \cdot 10^{11}\ cm^{-2}$ in a pristine $MoSe_2$ monolayer form a Wigner crystal even at $B = 0$ [1]. This is revealed by our low-temperature ($T = 80$ mK) magneto-optical spectroscopy experiments that utilize a newly developed technique allowing to unequivocally detect charge order [2]. This method relies on the modification of excitonic band structure arising due to the periodic potential experienced by the excitons interacting with an electronic lattice. Under such conditions, optically-inactive exciton states with finite momentum matching the reciprocal Wigner lattice vector $k = k_W$ get Bragg scattered back to the light cone, where they hybridize with the zero-momentum bright exciton states. This leads to emergence of a new, umklapp peak in the optical spectrum heralding the presence of periodically-ordered electronic charge distribution.

Twisted bilayers of TMDs in turn offer a wealth of new phenomena, ranging from dipolar excitons to correlated insulator states. Another striking example of qualitatively new phenomena in this system is our recent observation of an electrically tunable two-dimensional Feshbach resonance in exciton-hole scattering [3], which allows us to control the strength of interactions between excitons and holes located in different layers. Our findings enable hitherto unexplored possibilities for optical

investigation of many-body physics, as well as realization of degenerate Bose-Fermi mixtures with tunable interactions.

[1] T. Smoleński, P. E. Dolgirev, C. Kuhlenkamp, A. Popert,1 Y. Shimazaki, P. Back, X. Lu, M. Kroner, K. Watanabe, T. Taniguchi, I. Esterlis, E. Demler, and A. Imamoglu, arXiv:2010.03078 (2020).
[2] Y. Shimazaki, C. Kuhlenkamp, I. Schwartz, T. Smolenski, K. Watanabe, T. Taniguchi, M. Kroner, R. Schmidt, M. Knap, A. Imamoglu, arXiv:2008.04156 (2020).
[3] I. Schwartz, Y. Shimazaki, C. Kuhlenkamp. K. Watanabe, T. Taniguchi, M. Kroner, A. Imamoglu, arXiv:2105.03997 (2021).

Designer meron lattice on the surface of a topological insulator

Jennifer Cano
Department of Physics and Astronomy, Stony Brook University, USA
Center for Computational Quantum Physics, Flatiron Institute, USA

We present a promising new route to realize spontaneous magnetic order on the surface of a 3D topological insulator by applying a superlattice potential. The superlattice potential creates tunable van Hove singularities, which, when combined with strong spin-orbit coupling and Coulomb repulsion give rise to a topological meron lattice spin texture. The periodicity of this designer meron lattice can be tuned by varying the periodicity of the superlattice potential. We characterize the magnetic order using Ginzburg-Landau theory and show that the magnetic transition temperature reaches experimentally accessible values. Our work introduces a new direction to realize exotic quantum order by engineering interacting Dirac electrons in a superlattice potential, with promising applications to spintronics.

Electronic structure of lattice relaxed alternating twist tNG multilayer graphene

Jeil Jung
Department of Physics, University of Seoul, Seoul 02504, Korea
Department of Smart Cities, University of Seoul, Seoul 02504, Korea

In this talk I will introduce a real-space atomistic approach to study the interdependent electronic and atomic structure of twisted bilayer and multilayer graphene where we calibrate the interlayer tunneling to fit the experimental magic angle at 1.08 degrees in order to resolve the indeterminacy of other system parameters such as the Fermi velocity, interlayer tunneling and lattice relaxation scheme. Our approach is used to study tNG multilayer systems where we assess the evolution of the magic angles with layer number N that shows a non-monotonic evolution towards the alternating twist graphite limit when using open surface boundary conditions for the atomic relaxation. Due to the moire pattern strains, we show how the lattice relaxation helps to stabilize the AA'AA'… interlayer stacking configuration and works towards the reduction of the magic angles with respect to rigid system's predictions. When the magic twist angles are evaluated from density of states considerations their error bars are shown to expand

progressively from 0.05 degrees of t2G up to 0.2 in the limit of large N. Our work shows routine applicability of real space atomistic approaches for addressing the physics of twisted graphene systems involving multiple moire patterns or systems interfaced with hexagonal boron nitride substrates.

Wednesday 13/07

Magic-Angle Twisted Graphene Family

Jane Park
MIT, Boston

Since the discovery of magic-angle twisted bilayer graphene (MATBG), new moiré systems have been explored to study strongly correlated and topologically nontrivial phenomena. Multiple interesting states, including but not limited to correlated insulators, quantized anomalous Hall states, ferromagnetism, and correlated Chern insulators, have been observed in various moiré materials. However, during the first few years, superconductivity was reproducibly seen only in MATBG. More recently, magic-angle twisted trilayer graphene (MATTG) has shown robust superconductivity and correlated states with an additional knob for electric displacement field tunability. Is it a coincidence? Interestingly, MATBG and MATTG, which are the only robust moiré superconductors known to date, are part of a hierarchy of magic-angle graphene systems, which exhibit a series of twist angles for different number of twisting layers. We experimentally realize magic-angle twisted 4-layer and 5-layer graphene structures, and show that they also exhibit robust superconductivity, therefore establishing alternating-twist magic-angle multilayer graphene as a family of moiré superconductors. With the application of electric displacement and magnetic fields, we find interesting similarities and differences between the members that help us understand the underlying physics behind these systems. In this talk, I will discuss the key data and our current understanding of the magic family, as well as some of our most recent progress.

Insulating and superconducting states in twisted graphene layers

Klaus Ensslin
Department of Physics, ETH Zürich, Switzerland

The electronic properties for twisted single and bilayer graphene, at the magic angle, as well as for larger angles are experimentally investigated. We observe novel insulating states, prepare quantum devices in superconducting devices such as Jospehson junctions and SQUIDs, and investigate novel quantum oscillations related to the peculiar energy landscape at Lifshitz transitions.

Experimental Investigation of Non-trivial Band Topology and Quantum Geometry in Graphene

Jeanie Lau
Ohio State University

The interplay between quantum confinement, non-trivial band topology, symmetries and electronic interactions gives rise to a rich variety of correlated phenomena and topological phases in van der Waals heterostructures. Here I will present our recent works on this topic, focusing on emergent magnetism in rhomohedral-stacked few-layer graphene, and strongly renormalized band velocity and experimental evidence for strong-coupled superconductivity that is enabled by quantum geometry in twisted bilayer graphene.

Plethora of Many-Body Ground States in Magic Angle Twisted Bilayer Graphene

Dmitri K. Efetov
LMU Munich, Germany

Twist-angle engineering of 2D materials has led to the recent discoveries of novel many-body ground states in moiré systems such as correlated insulators, unconventional superconductivity, strange metals, orbital magnetism and topologically nontrivial phases. These systems are clean and tuneable, where all phases can coexist in a single device, which opens up enormous possibilities to address key questions about the nature of correlation induced superconductivity and topology, and allows to create entirely novel quantum phases with enhanced interactions. In this talk we will introduce some of the main concepts underlying these systems, concentrating on magic angle twisted bilayer graphene (MATBG) and show how symmetry-broken states emerge at all integer electron fillings [1]. We further will discuss recent experiments including screened interactions [2], Chern insulators [4], magnetic Josephson junctions [4], quantum criticality [5], re-entrant correlated insulators at high magnetic fields [6] and discuss some of the avenues for novel quantum sensing applications [7].

[1] Nature, 574, 653 (2019).
[2] Nature, 583, 375–378 (2020).
[3] Nature Physics, 17, 710 (2021).
[4] arXiv:2110.01067 (2021).
[5] arXiv:2108.07753 (2021).
[6] arXiv:2201.09260 (2021).
[7] arXiv:2111.08735 (2021)

Quantum geometry and flat band superconductivity

Päivi Törmä
Aalto University, Finland

We have discovered that superconductivity (superfluidity) has a connection to quantum geometry [1]. Namely, the superfluid weight in a multiband system has a previously unnoticed component which we call the geometric contribution. It is proportional to the quantum metric of the band. Quantum metric is connected to the Berry curvature, and this allows to relate superconductivity with 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. We and other groups have shown [2,3] that these results are relevant for explaining the intriguing observation of superconductivity in bilayer graphene and may eventually help realize superconductors at elevated temperatures. Recently, we have shown that the superfluid weight is proportional to the minimal quantum metric [4]. Moreover, we show in [4] that to benefit from flat band effects, an isolated flat band is not needed, in contrast, band touchings are beneficial for higher transition temperatures. This widens the class of systems available for high critical temperature flat band superconductors. We have also explored the effect of quantum geometry on Bose-Einstein condensation [5].

[1] S. Peotta, P. Törmä, Nature Commun. 6, 8944 (2015); A. Julku, S. Peotta, T.I. Vanhala, D.-H. Kim, P. Törmä, Phys. Rev. Lett. 117, 045303 (2016); P. Törmä, L. Liang, S. Peotta, Phys. Rev. B 98, 220511(R) (2018)

[2] 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)
[3] P. Törmä, S. Peotta, B.A. Bernevig, Nat. Rev. Phys. (2022) https://doi.org/10.1038/s42254-022-00466-y
[4] K.-E. Huhtinen, J. Herzog-Arbeitman, A. Chew, B.A. Bernevig, P. Törmä, arXiv:2203.11133 (2022)
[5] A. Julku, G.M. Bruun, P. Törmä, Phys. Rev. Lett., 127, 170404 (2021)

Flat Bands, Quantum Geometry, Many-Body Spectra and Topological Heavy Fermions

Andrei Bernevig
Princeton University, USA
Donostia International Physics Center, Spain

We review and enhance the strong coupling (projected) theory of flat bands with nontrivial quantum geometry/topology. We show - in exact solutions - that the charge edification and collective mode spectra above the interacting ground-states (with both repulsive and attractive interactions) are intimately related, both in dispersion as well as in their topology, with the quantum geometry of the initial flat bands. We then apply this to twisted bilayer graphene to obtain the strongly interacting dispersions on top of the projected ferromagnetic ground states obtained by Kang and Vafek. Lastly, we show how an exact map of the TBG flat bands into a topological heavy fermion model allows for a natural emergence of all these strong coupling properties and more.

Thursday 14/07

Imaging the Local Band Topology and Chern Mosaic in Magic-Angle Graphene

Eli Zeldov
Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel

Topology is a key element governing the electronic and magnetic properties of 2D moiré materials. The topological electronic bands are classified by their Chern number C, which is considered to be a global topological invariant. The Chern number is governed by the Berry curvature that leads to orbital magnetization. Utilizing a scanning superconducting quantum interference device on a tip (SQUID-on-tip), we image the Berry-curvature-induced equilibrium orbital magnetization in magic-angle graphene, thus providing new means to resolve the local band topology on the nanoscale [1]. At integer filling $\nu = 1$, we observe a zero-field Chern insulator, which rather than being described by a global topologically invariant C, forms a Chern mosaic of microscopic patches of $C = 1$, 0, or 1, the boundaries of which carry chiral edge states. Upon further filling, we find a first-order phase transition due to recondensation of electrons from valley K to K', leading to irreversible flips of the local Chern number and magnetization, and to the formation of valley domain walls giving rise to hysteretic anomalous Hall resistance. The findings shed new light on the structure and dynamics of topological phases in moiré devices.

Magnetism in moiré superlattices

Xiaodong Xu
Department of Physics, Department of Materials Science and Engineering, University of Washington, Seattle

Moiré superlattices of 2D materials is an emerging platform for studying new physical phenomena with high tunablity. In this talk, I will present emergent magnetic interactions in two distinct types of moiré superlattices. I will firstly present the observation of magnetic textures in small angle twisted 2D magnet chromium triiodide (CrI_3). Employing single-spin quantum magnetometry, we directly visualize nanoscale magnetic domains and periodic patterns, a signature of moiré magnetism, and gain quantitative information on domain size and magnetization. The observed AFM and FM domains with periodic patterns are in good agreement with the calculated spatial magnetic structures arising from the local stacking-dependent interlayer exchange interactions in CrI_3 moiré superlattices. Then I will present the drastic tuning of spin-spin exchange interactions in WSe_2/WS_2 moiré superlattices by optical excitation, which results in ferromagnetic order over a small range of doping at elevated temperatures. This discovery adds a new and dynamic tuning knob to the rich many-body Hamiltonian of moiré quantum matter.

[1] S. Grover, M. Bocarsly, A. Uri, P. Stepanov, G. Di Battista, I. Roy, J. Xiao, A. Y. Meltzer, Y. Myasoedov, K. Pareek, K. Watanabe, T. Taniguchi, B. Yan, A. Stern, E. Berg, D. K. Efetov, and E. Zeldov, arXiv:2201.06901

Fractionalization in fractionally filled Moiré systems

Eun-Ah Kim
Cornell University, USA

Abstract: The best-established example of fractionalization starts from the partially filling flat kinetic energy dispersion, namely the fractional quantum Hall effect. The opposite starting point of strong Coulomb repulsion is expected to give a Wigner crystal state in the continuum. We will show that moiré systems present new platforms for arriving at fractionalization from melting the Coulomb repulsion-driven crystalline states. We propose distinct fractionalized quantum states for 1/3 filled transition metal dichalcogenide (TMD) moiré systems and n\pm 1/3 filled twisted bilayer graphene (TBG) moiré systems. For the 1/3 filled TMD, the crystalline state triples the unit cell by electrons occupying every third site. Upon introducing hopping, our density matrix renormalization group studies show the system to first transition into a featureless insulating state that does not break symmetries. This featureless insulating state still shows logarithmic growth of the bi-partite entanglement entropy. Given the charge gap, the low-energy excitation should have a fractionalized nature in this phase. For the 1/3 filled TBG, we predict the incompressible crystalline state to be a novel state with a uniform 1/3 charge per AA site based on the extended fidget spinner-shaped Wannier orbitals [1]. Holes in this crystalline state can fractionalize into charge 1/3 objects with restricted mobility. The restricted mobility limited to sub-dimension gives fracton-like character to the charge 1/3 excitations. We conjecture quantum melting of the crystalline state to result in a quantum lemniscate liquid state with resonating figure-8 shaped lemniscates.

[1] Zhang et al, arXiv:2105.13371

Kekule spiral orders at all nonzero integer fillings in twisted bilayer graphene

Nick Bultinck
Oxford University

Friday 15/07

Novel structural and electronic phases of 2D transition metal dichalcogenides

Oleg V. Yazyev
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Layered transition metal dichalcogenides (TMDs) of chemical composition MX_2 (M = transition metal; X = S, Se, or Te) represent a broad family of materials with diverse electronic properties, including metals, insulators, as well as more complex states such as the charge-density-wave (CDW) and superconducting phases. More recently, the possibility of realizing single- and few-layer TMDs has brought the two-dimensional (2D) forms of these materials into the spotlight of prospective application in electronics, optoelectronics and beyond [1]. In my talk, I will review the "periodic table" of TMDs attempting to reveal systematic trends and develop chemical intuition across this family of 2D materials. Using a Wannier function approach, I will address the relevance of the crystal and ligand fields in determining the relative stability of 1T and 1H polymorphs as a function of the filling of the d-shell in 2D TMDs [2]. Then, I will present a unified picture of lattice instabilities in metallic TMDs that describes both the CDW phases and the strong-coupling scenario resulting in the formation of metal-metal bonds (as e.g. in the dimerized 1T' phases) [3]. In the rest of my talk, I will focus on topological and magnetic phases of TMDs. The 1T'-phase of Mo and W TMDs that have recently been shown to host the topologically non-trivial quantum spin Hall (QSH) insulator phase. The robustness of the QSH phase as well as the topological edge states [4] and interface states at the well-ordered 1T'-1H lateral heterojunctions will be discussed in conjunction with recent experiments on 1T'-WSe_2 [5]. I will also cover our recent discovery of magnetic ordering and magnetoresistive switching in metallic few-layer and insulating single-layer $PtSe_2$ [6,7].

[1] S. Manzeli, D. Ovchinnikov, D. Pasquier, O. V. Yazyev and A. Kis, Nature Rev. Mater. **2**, 17033 (2017)
[2] D. Pasquier and O. V. Yazyev, 2D Materials 6, 025015 (2019)
[3] D. Pasquier and O. V. Yazyev, Phys. Rev. B **100**, 201103(R) (2019)
[4] A. Pulkin and O. V. Yazyev, J. Phys. Chem. Lett. **11**, 6964 (2020)
[5] M. M. Ugeda *et al.,* Nature Commun. **9**, 3401 (2018)
[6] A. Avsar *et al.*, Nature Nanotechnol. **14**, 674 (2019)
[7] A. Avsar *et al.*, Nature Commun. **11**, 4806 (2020)

Topological superconductivity in moiré transition metal dichalcogenides

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Homo- or hetero-stacks of transition metal dichalcogenides (TMDs) have enriched the opportunities for analysis and utilization of correlations in moiré systems. Theoretical predictions and experimental observations confirm the relevance of many-body interactions in these systems, and demonstrated the importance of their extended range. Since the interaction, its range, and the filling can be tuned experimentally by twist angle, substrate engineering and gating, we explore Fermi surface instabilities and resulting phases of matter of moiré bilayer TMDs. They are describable by extended triangular-lattice Hubbard models, which we study via an unbiased renormalization group approach. We establish in particular that hetero-bilayer TMDs are unique platforms to realize topological superconductivity with

winding number |N| = 4. We show that this state reflects in pronounced experimental signatures, such as distinct quantum Hall features.

Phenomenological theory of correlated insulators and superconductivity in twisted bilayer graphene

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We introduce and analyze a model that sheds light on the interplay between correlated insulating states, superconductivity, and flavor-symmetry breaking in magic-angle twisted bilayer graphene. Using a variational mean-field theory, we determine the normal-state phase diagram of our model as a function of the band filling. The phase diagram includes robust insulators at even integer fillings, occasional weaker insulators at odd integer fillings, and a pattern of flavor-symmetry breaking at non-integer fillings. Adding a phonon-mediated inter-valley retarded attractive interaction, we obtain strong-coupling superconducting domes, whose structure is in qualitative agreement with experiments. Our model elucidates how the intricate form of the interactions and the particle-hole asymmetry of the electronic spectrum determine the phase diagram. It also explains how subtle differences between devices may lead to experimentally observing different behaviors. A similar model with minor modifications is suitable for describing other systems, such as untwisted and twisted trilayer Graphene.

Band Structure and Topological Properties of Graphene Multilayers

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The emergence of flat bands in moiré superlattices leads to an enhancement of interaction effects, and thus to highly correlated phases at low temperatures. In particular, for twisted and untwisted graphene multilayers placed over hexagonal boron nitride (hBN), a periodic variation of the interlayer interaction in the form of a moiré pattern appears due to the lattice mismatch. Here, the resulting periodic perturbation acts over the multilayer graphene charge carriers and leads to multiple minibands and the generation of narrow bands with a rich band topology.

In this talk, I will describe the emergence, tunability and topological transport properties of narrow bands in moiré superlattices arising from the interaction of monolayer, bilayer and trilayer graphene with a hBN substrate, as well as the case of twisted multilayer graphene.