The 16th Capri Spring School on Transport in Nanostructures 2022

	Sunday 08.05.2022	Monday 09.05.2022	Tuesday 10.05.2022	Wednesday 11.05.2022	Thursday 12.05.2022	Friday 13.05.2022	Saturday 14.05.2022
Chair		Schönenberger	Tagliacozzo	De Martino	Egger	Egger	
9:00-9:55		Ilani (1)	Andrei (1)	MacDonald (3)	Efetov (1)	Vishwanath (3)	
10:00-10:55		Fabrizio (1)	Fabrizio (3)	Andrei (2)	Vishwanath (1)	Efetov (2)	
11:00-11:30		Coffee Break & Poster Session					
11:30-12:25		Ilani (2)	Ilani (3)	MacDonald (4)	Andrei (3)	Efetov (3)	
13:00-16:00		Lunch Break					
Chair		Egger	Bercioux		De Martino	Bercioux	
16:00-16:55		Fabrizio (2)	MacDonald (2)		Vishwanath (2)	Vishwanath (4)	
17:00-17:30		Coffee Break & Poster Session			Coffee Break & Poster Session		
17:30-18:25	Registration Hotel Senaria	MacDonald (1)	Cantele	Free Afternoon	Participant talk	Participant talk	
18:30-19:30	19:30-20:00	Participant talk	Participant talk		Participant talk	Concluding remarks	
20:00 Dinner	Le Arcate	Le Arcate	Le Arcate		Le Arcate	Le Arcate	

School excursion to Pompeii/ Sorrento (if weather permits) Start at 9 am, Capri Harbour Return by 6 pm

Eva Andrei	Graphene viewed through STM: atomic collapse, Kondo screening and flat bands.
Giovanni Cantele	First principle approach to MATBG
Dmitri Efetov	Plethora of Many-Body Ground States in Magic Angle Twisted Bilayer Graphene
Shahal Ilani	1) Visualizing electron hydrodynamics. 2) Flavor symmetry broken states and the Pomeranchuk effect in MATBG. 3) The Quantum Twisting Microscope.
Michele Fabrizio	Jahn-Teller effect and topological Jahn-Teller Mott insulators in magic-angle twisted-bilayer graphene
Allan MacDonald	1) Moire Patterns and Moire Materials. 2) Properties of Twisted Bilayer Graphene - Magnetism and Superconductivity. 3) Properties of TMD Moire Materials - Magnetism and Wigner Crystals. 4) Outlook for Moire Materials.
Ashvin Vishwanath	Topology, quantum geometry and the strong coupling approach to magic angle graphene.

Participant Talks

Monday Session (12+3)	Anushree Datta	Tight-binding model for twisted bilayer graphene
	Bert Jorissen	Describing strain in TMDs using Tight-Binding models
	Florie Mesple	Effect of heterostrain on the flat bands of magic-angle twisted graphene layers
	Rupini Kamat	Controlling graphene-hBN rotational alignment - a critical parameter for graphene-based moiré heterostructures
Tuesday Session (12+3)	Gunda Kipp	On-chip THz spectroscopy of gate-tunable graphene heterostructures (pt. 1)
	Hope Bretscher	On-chip THz spectroscopy of gate-tunable, graphene heterostructures (pt. 2)
	Alaa Mohammed Idris Bakhit	Electronic structure of stable facets in the 2D material hBN/Pt system
	Nikita Astrakhantsev	Critical behaviour of variational ground-state preparation on quantum devices
Thursday Session (12+3)	Alexina Ollier	Giant energy dissipation on twisted bilayer graphene at the magic angle twist
	Miguel Alvarado	ϕ_0-Josephson junctions in TBG
	Tim Kokkeler	SNN junction with mixed superconducting potential
	Andrea Maiani	Nonlocal transport in hybrid semiconductor-superconductor systems
	Ahmed Abouelkomsan	Quantum Geometry and Particle-hole duality in Moire superlattices
	Natasha Kiper	Investigating correlated electronic states using photon correlations
	Josefine Enkner	Modifying the integer quantum hall effect with cavity vacuum fields
	Dmytro Oriekhov	Bloch oscillations in the magnetoconductance of twisted bilayer graphene

Participant Talks

Friday Session (12+3)	Nisarga Paul	Moiré Landau fans and magic zeros
	Balint Szentpeteri	Tailoring the band structure of twisted double bilayer graphene with pressure
	Tymoteusz Salamon	Quantum simulation of Twistronics with ultracold atoms
	Jacob Steiner	Quantum Magnetism in Yu-Shiba-Rusinov Chains
	Jorge Vallejo-Bustamante	Graphene's divergent orbital diamagnetism at the Dirac point
	Giulia Zheng	Fabry-Pérot Cavities Using Different Dispersions in Twisted Double Bilayer Graphene
	Davide Valentinis	Non-local electrodynamics and skin effect in anisotropic metals: kinetic theory and microwave experiments on PdCoO$_2$
	Dario Bercioux	Information regarding the excursion to Pompeii & Sorrento

Abstract short talks: Monday Session

From 18:30 to 19:30

Anushree Datta (Instituto de Ciencia de Materiales de Madrid - CSIC) — *Tight-binding model for twisted bilayer graphene*

Observations of correlated phases in twisted bilayer graphene (TBG) indicate the importance of electronic correlations in this flat band system. A first step toward treating correlations is to construct a Wannier function-based model. The construction of such a model in TBG is under debate due to the topological character of the bands. We discuss the validity of the Wannier description for the widely-used Bistritzer and MacDonald model for a range of twist-angles and values of relaxations. Our findings provide a starting point for studying interactions in TBG.

Bert Jorissen (University of Antwerp) — *Describing strain in TMDs using Tight-Binding models*

Monolayers of Transition-metal dichalcogenides (TMD) are 2D semiconductors with rich opto-electronic properties. Experiments on TMDs have found interesting phenomena, like localized excitons in strained or twisted multilayer structures. These systems are too large to handle with ab-initio methods. In order to tackle large systems with adequate accuracy, tight-binding implementations of available models from literature are used, implemented within the open-source library Pybinding. I will first show a review of these tight-binding models and asses their performance under uniaxial strain. I will also show results for 1D periodically buckled structures and compare these with DFT results for small scale superlattices.

Florie Mesple (PHELIQS/CEA Grenoble Alpes University) — *Effect of heterostrain on the flat bands of magic-angle twisted graphene layers*

In twisted bilayers of graphene (TBLG), the interference of two rotated atomic lattices results in a moiré pattern. Previous research has shown that the moiré and its electronic structure are not only controlled by the rotation between the layers but also by the relative strain between them (heterostrain). Scanning Tunneling Microscopy (STM) is the ideal tool to probe the electronic properties on a nanometer scale while deducing the exact stacking arrangement of the graphene layers including heterostrain. In this context, we performed a meta-analysis of the prolific STM data available in recent literature from the perspective of heterostrain. We used commensurability analysis of experimental data combined with tight-binding calculations to explore the effects of strain magnitude and direction on the electronic properties of TBLG systems near magic angle. Our analysis demonstrates that heterostrain dominates twist in determining the flat-bands near the magic angle as theoretically anticipated.

Rupini Kamat (Stanford University) — *Controlling graphene-hBN rotational alignment - a critical parameter for graphene-based moiré heterostructures*

Stacks of van der Waals materials can be engineered to have nearly-flat electronic minibands, yielding a variety of novel correlated electron states, but some such states have proven challenging to reproduce across devices. For example, ferromagnetism in twisted bilayer graphene (TBG) requires not only a narrow range of graphene-graphene twist angles, but also crystallographic alignment between graphene and a hBN cladding layer. Rotational alignment between two different materials is difficult to engineer and to verify, limiting reproduction and further exploration of ferromagnetic TBG. By optically characterizing flake orientation prior to stacking and twist angle in heterostructures after stacking, we have taken a key step toward reproducing ferromagnetic TBG and exploring the effects of varying the graphene-hBN twist angle.

Abstract short talks: Tuesday Session

From 18:30 to 19:30

Gunda Kipp (Max Planck Institute for the Structure and Dynamics of Matter) — *On-chip THz spectroscopy of gate-tunable graphene heterostructures (Part 1)*

Graphene-based van der Waals (vdW) heterostructures host a plethora of topological and strongly correlated quantum phenomena that can be tuned in situ using electrostatic gates. However, current experimental probes are limited in their ability to investigate these phenomena on small samples, at millikelvin temperatures, and in the meV energy range. What is especially needed to complement current experimental probes are spectroscopic probes on the relevant scales capable of measuring buried interfaces. In this talk, I will motivate the development of on-chip THz spectroscopy with bandwidth from ~30 GHz – 1.2 THz and discuss the design, construction and measurement of our sophisticated devices.

Hope Bretscher (Max Planck Institute for the Structure and Dynamics of Matter) — *On-chip THz spectroscopy of gate-tunable, graphene heterostructures (Part 2)*

Using our current platform of on-chip THz spectroscopy we find that we generate plasmon standing waves. As the carrier density of the graphene is varied, the resonance frequency shifts and the spectral weight transforms, consistent with the expected changes in the plasmon dispersion. In a superlattice of graphene aligned to hBN, we see evidence of gaps opening both at the primary and secondary Dirac cones. These measurements illustrate the potential for this technique to bring near-field optical spectroscopy to millikelvin temperatures and strong magnetic fields, into the realm traditionally reserved for quantum transport.

Alaa Mohammed Idris Bakhit (Materials Physics Center) — *Electronic structure of stable facets in the 2D material hBN/Pt system*

We present the study of hexagonal boron nitride (hBN) grown on a curved crystal substrates c-Pt, reporting the electronic structure properties of the stable facets. We encountered (111), (110), (221) and (441) as stable facets, studied by low-energy electron diffraction (LEED) and scanning tunnelling microscopy (STM). The electronic structure was characterized by Near Edge X-ray Absorption Fine Structure (NEX- AFS) spectroscopy and X-ray photoelectron spectroscopy (XPS). We observed that the hBN/Pt(111) system is the weakest interacting overlayer system, in contrary to the side facets which are strongly bound to the c-Pt substrate. Additionally, we determined using angle-resolved photoemission measurements (ARPES), a $\pi*$ band energy shift around (1.3 eV) due to the changed hBN/c-Pt interaction between the electronic bands at (111) and (110) facets.

Nikita Astrakhantsev (University of Zurich) — *Critical behaviour of variational ground-state preparation on quantum devices*

In this work, we study how the fidelity of variational state preparation on a quantum computer depends on the number of circuit "shots" N_s used for the gradient estimation. We observe critical behavior of fidelity as the function of N_s.

Abstract short talks: Thursday Session

From 17:30 to 18:30

Alexina Ollier (Swiss Nanoscience Institute) — *Giant energy dissipation on twisted bilayer graphene at the magic angle twist*

We report on low temperature (T=5K) energy dissipation measurements of twisted bilayer graphene (TBG) at the magic angle twist – a system with flat electronic bands and highly correlated insulating phases. P-AFM showed giant dissipation peaks attributed to different filling (ns/n) of the energy bands. The constant height tip imaging allows to map the twist angle distribution of TBG.

Miguel Alvarado (Universidad Autonoma de Madrid) — *ϕ_0-Josephson junctions in TBG*

Recent experiments in superconducting Twisted Bilayer Graphene (TBG) point toward a non-conventional superconducting order parameter [1]. We study the effect of the topological nature of normal TBG in the current phase relation of Josephson junctions. We observe non-zero valley currents at zero phase bias that become spontaneously uncompensated when the topological nature of normal TBG is taken into consideration, giving as a result phi0-junction behaviour in direct Josephson junctions only when chiral superconducting order parameters (p+ip or d+id) are considered. This result could thus be used to identify the exotic order parameter in TBG. [1] Oh *et al.,* Nature **600**, 240 (2021).

Tim Kokkeler (DIPC/University of Twente) — *SNN junction with mixed superconducting potential*

The proximity effect in SNN junctions containing a non-centrosymmetric superconductor is studied using the Usadel equation.

Andrea Maiani (Copenhagen University) — *Nonlocal transport in hybrid semiconductor-superconductor systems*

Nonlocal tunnelling spectroscopy of multiterminal semiconductor-superconductor hybrid devices is a powerful tool to investigate the Andreev bound states. We examine how to exploit microscopic symmetries to extract information on the normal and Andreev transmission probabilities from the electric and thermoelectric differential conductance matrix in ideal devices, finding a number of symmetry relations on the conductance matrix. Next, by considering a numerical model of a proximitized semiconductor wire with two normal contacts, we show how such symmetries can be used to identify the direction and relative strength of Rashba versus Dresselhaus spin-orbit coupling. Finally, we study how a voltage-bias-dependent electrostatic potential as well as quasiparticle leakage break the derived symmetry relations and investigate characteristic signatures of these two contributions.

Abstract short talks: Thursday Session

From 18:30 to 19:30

Ahmed Abouelkomsan (Stockholm University) — *Quantum Geometry and Particle-hole duality in Moire superlattices*

I will discuss how the particle-hole asymmetry of projected interactions in a flat band could have dramatic consequences on the possible phases of Moire systems at fractional band filling. Such asymmetry results from the non-trivial quantum geometry of the bands. The phases (eg. Fermi Liquids, fractional Chern insulators and charge density waves) obtained at fractional band filling in systems such as trilayer graphene and twisted bilayer graphene, both aligned with boron nitride could be then understood from the correlation of the momentum occupation with the quantum metric fluctuations. [1] arXiv:2202.10467. [2] Abouelkomsan Phys. Rev. Lett. **124**, 106803 (2020).

Natasha Kiper (ETH Zürich) — *Investigating correlated electronic states using photon correlations*

Moiré heterostructures of transition metal dichalcogenides (TMDs) have emerged as a promising material platform to study correlated electronic states. Optical signatures of strong correlations in the form of Mott-Wigner states have already been observed in TMD monolayers and twisted bilayers. In this work, we introduce a new technique, photon correlation spectroscopy, to gain new insight into the dynamics of the electronic state. In a device consisting of two TMD layers separated by a monolayer hexagonal boron nitride spacer, we study interlayer electron dynamics by measuring the second-order correlation function of the reflected photons.

Josefine Enkner (ETH Zürich) — *Modifying the integer quantum hall effect with cavity vacuum fields*

We observe how vacuum cavity fields modify magneto-transport in the integer quantum Hall effect. In particular, odd filling factors loose their quantization, while fractional states remain intact. We quantitatively describe this loss of quantization as vacuum field-induced resistivity. In our interpretation the interaction with vacuum fields adds a long-range perturbation to the system, making it possible for electrons to scatter in between edge and bulk states via an intermediate state containing a virtual particle. This process ultimately breaks the topological protection of the edge states.

Dmytro Oriekhov (Lorentz Institute, Leiden University) — *Bloch oscillations in the magnetoconductance of twisted bilayer graphene*

We identify a mapping between two-dimensional (2D) electron transport in a minimally twisted graphene bilayer and a 1D quantum walk, where one spatial dimension plays the role of time. In this mapping, a magnetic field B perpendicular to the bilayer maps onto an electric field. Bloch oscillations due to the periodic motion in a 1D Bloch band can then be observed in purely DC transport as magnetoconductance oscillations with periodicity set by the Bloch frequency.

Abstract short talks: Friday Session

From 17:30 to 18:30

Nisarga Paul (Massachusetts Institute of Technology) — *Moiré Landau fans and magic zeros*

I discuss the energy spectrum of moiré systems under a uniform magnetic field. The superlattice potential generally broadens Landau levels into Chern bands with finite bandwidth. However, these Chern bands become flat at a discrete set of magnetic fields or "magic zeros". By developing a semiclassical quantization method and taking account of superlattice induced Bragg reflection, I show that magic zeros arise from the simultaneous quantization of two distinct k-space orbits. The flat bands at magic zeros could provide a new setting for exploring crystalline fractional quantum Hall physics.

Balint Szentpeteri (Budapest University of Technology and Economics) — *Tailoring the band structure of twisted double bilayer graphene with pressure*

In van der Waals heterostructures the layer distance strongly affects the interaction between the layers. Therefore, pressure is an ideal tool to engineer their band structure. Here we demonstrate the strength this method on magic-angle twisted double bilayer graphene, a fascinating and versatile system with correlated and topologically non-trivial phases that are also tuneable with displacement field. We show by transport measurements, that the band structure can be drastically changed by pressure, in good agreement with our simulations. Furthermore, our measurements suggest that the pressure can also tune the strength of correlation effects [1]. [1] Szentpeteri *et al.* Nano Lett **21**, 8777 (2021).

Tymoteusz Salamon (ICFO) — *Quantum simulation of Twistronics with ultracold atoms*

We present the overview of our recent results on quantum simulators of twisted bi-layer materials. These 2D systems with a primary example of Twisted Bi-layer Graphene (TBG) host many strongly correlated phases [1, 2] due to the slight rotation of one of the layers resulting with generation of Moiré patterns and emerging quasi-flat bands at the Fermi level. Ultracold atoms in 2D optical lattices thanks to their ground-state manifold allow to generate a synthetic bi-layer lattice [3]. From that being a starting point we present the methods of effective twisting of a bilayer lattice without a need of physical rotation[4], generation of the quasi-flat bands in the unit cells orders o magnitude smaller than in actual TBG, topological properties of the system (QAHE) [5] and the effect of twisting on the system of interacting fermions together with analysis of the relation between the quasi-flat bands and superconducting properties. [1] Cao *et al.,* Nature **556**, 43 (2018). [2] Cao *et al.,* Nature **556**, 80 (2018). [3] Boada *et al.,* Phys. Rev. Lett. **108**, 133001 (2012). [4] Salamon *et al.,* Phys. Rev. Lett. **125**, 030504 (2020).[5] Salamon *et al.,* Phys. Rev. B. **102**, 235126 (2020).

Jacob Steiner (FU Berlin) — *Quantum Magnetism in Yu-Shiba-Rusinov Chains*

Chains of magnetic adatoms on superconductors have been discussed as promising systems for realizing Majorana end states. Here, we show that dilute Yu-Shiba-Rusinov (YSR) chains are also a versatile platform for quantum magnetism and correlated electron dynamics, with widely adjustable spin values and couplings. Focusing on subgap excitations, we derive an extended *t-J* model for dilute quantum YSR chains and use it to study the phase diagram as well as tunneling spectra. We explore the implications of quantum magnetism for the formation of a topological superconducting phase, contrasting it to existing models assuming classical spin textures.

Abstract short talks: Friday Session

From 18:30 to 19:30

Jorge Vallejo-Bustamante (Laboratoire de Physique des Solides) — *Graphene's divergent orbital diamagnetism at the Dirac point*

The singular orbital magnetism of undoped graphene, a fundamental signature of the characteristic Berry phase of graphene's electronic wave functions, has been challenging to measure in a single flake. Using a highly sensitive GMR sensor, we have measured the gate voltage-dependent magnetization of a single graphene monolayer encapsulated between hBN crystals. The signal exhibits a diamagnetic peak at the Dirac point whose magnetic field and temperature dependences agree with theoretical predictions. Moreover, we present magnetization measurements in a wide range of Fermi energy for two other stacks with a moiré potential. Besides the diamagnetic peak at the Dirac point, we could also detect the diamagnetic peaks at the satellite peaks surrounded by paramagnetic peaks.

Giulia Zheng (ETH Zürich) — *Fabry-Pérot Cavities Using Different Dispersions in Twisted Double Bilayer Graphene*

The rich and electrostatically tunable phase diagram exhibited by moiré materials has made them a suitable platform for hosting single material multi-purpose devices. To engineer such devices, understanding electronic transport and localization across gate-defined interfaces is of fundamental importance. Little is known, however, about how the interplay between the band structure originating from the moiré lattice and electric potential gradients affects electronic confinement. Here, we electrostatically define a cavity across a twisted double bilayer graphene sample. We observe two kinds of Fabry-Pérot oscillations. The first, independent of charge polarity, stems from the confinement of electrons between dispersive-band/flat-band interfaces. The second arises from *p-n* junctions between regions tuned to the flat band regime, giving a lower bound for the coherence length of electronic transport in such a strongly interacting regime.

Davide Valentinis (Karlsruhe Institute of Technology) — *Non-local electrodynamics and skin effect in anisotropic metals: kinetic theory and microwave experiments on $PdCoO_2$*

Electron motion in new-generation ultra-pure materials deviates from the usual diffusive response, with consequences like viscous and ballistic flow. We develop a kinetic theory of non-local electrodynamics, due to spatial correlations among the motion of electrons, in 2D and 3D and for an arbitrary Fermi-surface shape, based on the Boltzmann equation. For polygonal Fermi surfaces. The theory is compared with a new technique developed for broadband microwave spectroscopy of the delafossite metal $PdCoO_2$. The surface resistance for three distinct sample geometries shows differing power laws in the ballistic regime. Our work permits a novel symmetry-based diagnostic for non-local electrodynamics.

Dario Bercioux (Donostia International Physics Center) — *Information regarding the excursion to Pompei² & Sorrento*

Important information for the excursion on Saturday to Pompeii and Sorrento.

Poster session

From Monday to Friday in parallel to the coffee breaks

1. Ohad Antebi (Weizmann Institute of Science) — *In-plane orbital magnetization as a probe for symmetry breaking in strained twisted bilayer graphene*
2. Isidora Araya Day (QuTech, TU Delft) — *Topological defects in a double-mirror quadrupole insulator displace diverging charge*
3. Matan Bocarsly (Weizmann Institute of Science) — *Imaging Chern mosaic and Berry-curvature magnetism in magic-angle graphene*
4. Andres Diez-Carlon (ICFO) — *Magnetic Josephson Junctions and Superconducting Diodes in magic-angle twisted bilayer graphene*
5. Giovanna Feraco (University of Groningen) — *Nano-ARPES investigation of twisted bilayer WS_2*
6. Lasse Gresista (University of Cologne) — *Moments and Multiplets in Moiré Materials from Functional Renormalization*
7. Rajashree Haldankar (ICFO) — *Probing superconductivity and measuring effect of strain in suspended twisted bilayer graphene*
8. Rounak Jha (University of Basel) — *Superconducting interference in twisted bilayer graphene junctions*
9. Miguel Angel Jimenez Herrera (Material Physics Center) — *On the corner modes of the breathing kagome lattice: origin and robustness*
10. Aprem Joy (University of Cologne) — *Dynamics of visons in perturbed Kitaev models*
11. Bert Jorissen (University of Antwerp) — *PyBinding: modeling electronic structures with Tight-Binding*
12. Duy Hoang Minh Nguyen (DIPC) — *Synthetic Weyl semimetal in trilayer photonic grating*
13. Ida Nielsen (Niels Bohr Institute) — *Readout of parafermionic states by transport measurements*
14. Simone Traverso (RWTH Aachen) — *Edge dependence of the higher order topological phase in a quasicrystalline system*