Abstract book of the mini workshop

Towards strong correlations in van der Waals heterostructures and 2D materials

25th of March, 2021

Contents

Aims and Scope

The COST Action nanocohybri develops groundbreaking research in superconducting hybrid nanostructures. Recent experimental breakthroughs in building nanostructures out of 2D materials have lead to the observation of correlated insulating and superconducting states in structures with twisted layers, particularly in bilayer graphene. This provides a new opportunity to harness strong correlations and study its influence on superconductivity, which might impact our understanding of electron correlation driven high-temperature superconductivity. This workshop aims to gather Action participants with world-wide experts to address the overarching open questions, regarding both theory and experiment, in the establishment and characterization of strong correlations in hybrid nanostructures.

This miniworkshop is part of a series, which will be organized within an agile format, consisting of virtual half-a-day mini-workshops on a thriving new research results in the field of the Action. There will be three 25+5' talks and several 15+5' talks, by invitation after consultation to the COST MC. Poster sessions will be also organized on demand. We particularly welcome the participation of young students and follow excellence and inclusiveness strategy of COST.

Organizers of the series of mini-workshops

Yonathan Anahory, Floriana Lombardi, Milorad Milosevic, Jovan Mirković and the COST Action Management Committee.

Supporting team:

Irene González and Rafael Álvarez.

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Invited Speakers

NAME	ORGANISATION
Plenary session	
Dmitri EFETOV	*ICFO – The Institute of Photonic Sciences, Spain*
Eli ZELDOV	*Weizmann Institute of Science, Israel*
Chun NING LAU (Jeanie)	*Ohio State University, United States*
Invited session	
Yuval RONEN	*Harvard University.*
Jana VEJPRAVOVA	*Charles University. “*
Lucian COVACI	*University of Antwerp.*
Peter MAKK	*Budapest University of Technology and Economics*
Devidas TAGET	*The Hebrew University of Jerusalem*
Tobias WOLF	*ETH Zürich*
Sara CONTI	*University of Antwerp.*

Schematic Program

25 March 2021, from 14h00 to 18h00 CET

Plenary session

14h00-14h30: **Dmitri Efetov**, ICFO – The Institute of Photonic Sciences, Spain. "Competing phases of correlated Chern insulators in Superconducting Twisted Bilayer Graphene"

14h30-15h00: **Eli Zeldov**, Weizmann Institute of Science, Israel. "Imaging topological currents and twist-angle disorder in magic-angle graphene"

15h00-15h30: **Chun Ning Lau** (Jeanie), Ohio State University, United States. "Tunable Helical Edge States in van der Waals Materials"

15h30-15h45: Break

Invited session

15h45-16h05: **Yuval Ronen** – Harvard University. "Induced superconductivity in a fractional quantum Hall edge"

16h05-16h25: **Jana Vejpravova** – Charles University. "Topographic states of graphene – chemistry meets physics"

16h25-16h45: **Lucian Covaci** – University of Antwerp. "Flat Bands and Correlated States in Buckled Graphene Superlattices"

16h45-17h05: **Peter Makk** – Budapest University of Technology and Ecnomics. "Tuning the band structure of twisted double bilayer graphene with hydrostatic pressure"

17h05-17h25: **Devidas Taget** – The Hebrew University of Jerusalem. "Spectroscopy of barrier defects coupled to superconductors in van der Waals tunneling devices"

17h25-17h45: **Tobias Wolf** – ETH Zürich. "Valley Spirals in Magnetically Encapsulated Twisted Bilayer Graphene"

17h45-18h05: **Sara Conti** – University of Antwerp. "Three-dimensional electron-hole superfluidity in a superlattice close to room temperature"

Abstracts

Competing phases of correlated Chern insulators in Superconducting Twisted Bilayer Graphene

Dmitri EFETOV

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Flat-bands in magic angle twisted bilayer graphene (MATBG) have recently emerged as a rich platform to explore strong correlations, superconductivity and magnetism. Here we use magneto-transport and Hall measurements to reveal a rich sequence of wedge-like regions of quantized Hall conductance with Chern numbers $C = \pm1, \pm2, \pm3, \pm4$ which nucleate from integer fillings of the moiré unit cell $\nu = \pm3, \pm2, \pm1, 0$ correspondingly. We interpret these phases as spin and valley polarized many-body Chern insulators. The exact sequence and correspondence of Chern numbers and filling factors suggest that these states are driven directly by electronic interactions, which specifically break time-reversal symmetry in the system. In addition, we observe correlated Chern insulator in zero magnetic field in hBN non-aligned MATBG, which manifests itself in an anomalous Hall effect around a filling of one electron per moiré unit cell $n = +1$ with a Chern number of $C = 1$ and has a relatively high Curie temperature of $T_c \approx 4.5$ K. Slight gate tuning away from this state exposes strong superconducting phases with critical temperatures of up to $T_c \approx 3.5$ K. In a perpendicular magnetic field above $B > 0.5$ T we observe a transition of the $n = +1$ Chern insulator from a Chern number $C = -1$ to a higher $C = 3$, which is characterized by a quantized Hall plateau with $R_{yx} = h/3e2$. These observations show that interaction-induced time-reversal symmetry breaking in MATBG leads to a zero-field ground state which consists of almost degenerate and closely competing Chern insulators, where the B-field always couples strongest to states with higher Chern numbers. Our study is also the first demonstration of a system which allows gate-induced transitions between magnetic and superconducting phases, and hence marks a major milestone in the creation of a new generation of quantum electronics.

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Imaging topological currents and twist-angle disorder in magic-angle graphene

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Utilizing a scanning SQUID-on-tip, we develop a method for direct imaging of the ground state currents flowing in the quantum Hall regime in graphene. We reveal that the edge states, which are commonly assumed to carry only a chiral downstream current, in fact carry a pair of counterpropagating currents, in which the topological downstream current in the incompressible region is counterbalanced by a non-topological upstream current flowing in the adjacent compressible region [1]. In twisted bilayer graphene, the emergence of flat bands and of strongly correlated and superconducting phases crucially depends on the interlayer twist angle upon approaching the magic angle. The scanning SQUID-on-tip provides a tomographic imaging of the Landau levels and renders nanoscale high precision maps of the twist-angle disorder in high quality hBN encapsulated devices, which reveal substantial twist-angle gradients and a network of jumps [2]. We show that the twist-angle gradients generate large gate-tunable in-plane electric fields, unscreened even in the metallic regions, which drastically alter the quantum Hall state by forming edge channels in the bulk of the samples. The correlated states are found to be particularly fragile with respect to twist-angle disorder. We establish the twist-angle disorder as a fundamentally new kind of disorder, which alters the local band structure and may significantly affect the correlated and superconducting states.

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Tunable Helical Edge States in van der Waals Materials

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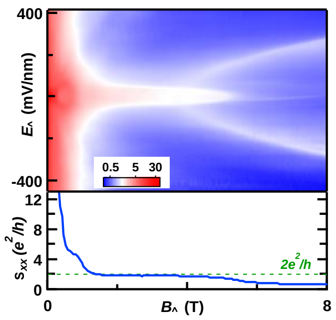
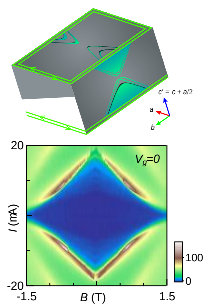
Helical conductors, systems that have no bulk conduction but support dissipationless conducting states at their edges, may be engineered to realize Majorana statistics for quantum computation. Underlying these remarkable systems are the non-trivial topology of electronic structure in the bulk, arising band inversion in the bulk and crossing of conductance and valence bands at the system boundary. In helical conductors, these counterpropagating states carry different spin quantum numbers, protecting the crossing and preventing a gap from opening in the spectrum of edge states. Traditional helical conductors, such as those achieved in topological insulator systems, are typically not tunable in situ, and helical conduction is only achieved over a narrow range of parameters.

Here we show that helical edge states are achievable and tunable in few-layer van der Waals materials. In Bernal-stacked trilayer and tetralayer graphene, we observe helical edge states at moderate and strong magnetic fields, respectively, arising from the competing effects of inter-layer coherence, electrostatic polarization and exchange interaction. As the interlayer potential and magnetic field varies, we observe a series of quantum transitions among the phases that host 2, 1 and 0 helical edge states on each edge. Our work highlights the complex competing symmetries in few-layer graphene and the rich quantum phases in this seemingly simple system[1, 2]. Lastly, in thin exfoliated Bi_4I_4 samples, which is a quasi-1D topological insulator and candidate for higher order topological states, we observe gate tunable magneto-transport and Josephson current. Our combined transport, photoemission, and theoretical results indicate that the gate-tunable channels consist of novel gapped side surface states, a 2D TI in the bottommost layer, and helical hinge states of the upper layers[3].





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Induced superconductivity in a fractional quantum Hall edge

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Topological superconductivity, realized as an intrinsic material property or as an emerging property of a hybrid structure, represents a phase of matter where topological constraints and superconductivity coexist. The exchange-statistics (braiding) of its quasiparticles is not bosonic nor fermionic but is rather non-Abelian. Due to their exchange-statistics as well as non-locality these excitations offer a promising route towards fault-tolerant quantum computation. The simplest non-Abelian anyon is the Majorana zero mode with an Ising order. However, since braiding of Ising anyons does not offer a universal quantum gate set, theoretical studies have introduced *Parafermion zero modes* (PZM), an array of which supports universal topological quantum computation. The primary route to synthesize PZMs involves inducing superconductivity on a fractional quantum Hall effect (FQHE) edge.

In this talk, I will introduce high-quality graphene-based van der Waals devices with narrow superconducting electrode (NbN), in which superconductivity and robust FQHE coexist. We find crossed Andreev reflection (CAR) across the superconductor separating two counterpropagating FQHE edges. Our observed CAR probability of the integer edges is insensitive to magnetic field, temperature, and filling, thereby providing evidence for spin-orbit coupling inherited from NbN enabling the pairing of the otherwise spin-polarized edges. FQHE edges notably exhibit a CAR probability higher than that of integer edges once fully developed. This FQHE CAR probability remains nonzero down to our lowest accessible temperature, suggesting superconducting pairing of fractional charges. These results provide a route to realize novel topological superconducting phases with universal braiding statistics in FQHE–superconductor hybrid devices based on graphene and NbN.

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Topographic states of graphene – chemistry meets physics

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Graphene is a prototypic two-dimensional material, featuring many unique properties due to its intrinsic flatness. Nevertheless, by introducing the topographic corrugations in a controlled manner, manifold modifications can be achieved. The strategies include the transfer of the graphene on substrates decorated with nanoparticles [1–3], fullerenes [4], and nanopillars [5], or count on different thermal expansion of the graphene and the supporting substrate [6,7]. Consequently, spatial modulation of the strain and doping is achieved. Both the curvature of the graphene and the position of the Fermi level are the key factors influencing its local reactivity. In this vein, we achieved nanometer resolution for hydrogenation and fluorination applied to single-layer graphene with carefully controlled topography [8]. The wrinkles can also serve as an ultra-small prison for the confinement of various molecules. We succeeded in capturing tiny amounts of water molecules between a silica substrate and monolayer graphene, structured into a net of small wrinkles [9]. The confinement caused a drop of the water melting point by ~ 30 K. The wrinkled graphene also served as an extremely sensitive probe for monitoring the phase transitions of the nanowater *via* graphene-based spectroscopic monitoring of the underlying water structure.

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Flat Bands and Correlated States in Buckled Graphene Superlattices

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It is well known that applying inhomogeneous strain to graphene has a similar effect to an effective pseudo-magnetic field, with the use of which one has been able to experimentally quantize the electron spectrum into Landau levels corresponding to a magnetic field as high as 500 Tesla. We have recently shown that the strain fields induced by periodically buckled graphene result in a periodic pseudo-magnetic field that transforms the linear electronic band structure into a series of mini bands [1]. Furthermore, we have shown that experimental evidence of the appearance of correlated states warrants further scientific inquiry in these systems. By changing the geometry, amplitude, and period of the periodic pseudo-magnetic field, we determine the necessary conditions to access the regime of correlated phases by examining the band flattening [2]. As compared to twisted graphene the proposed system has the advantages that: 1) only a single layer of graphene is needed, 2) one is not limited to hexagonal superlattices, and 3) narrower flat bandwidth and larger separation between flat bands can be induced. Periodically strained monolayer of graphene can become a platform for the exploration of exotic many-body phases.

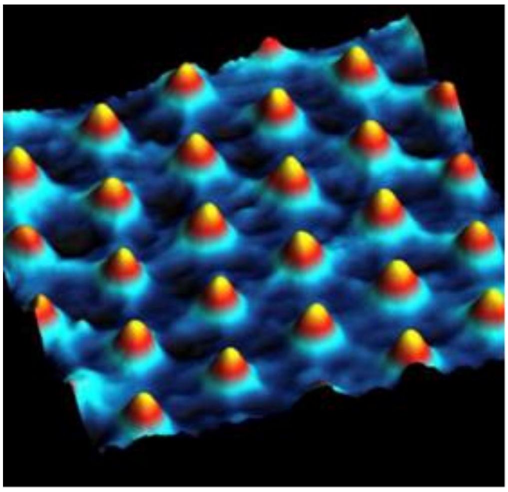

Figure 1. STM topography of the zeroth pseudo-Landau level in the buckled superlattice.

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Tuning the band structure of twisted double bilayer graphene with hydrostatic pressure

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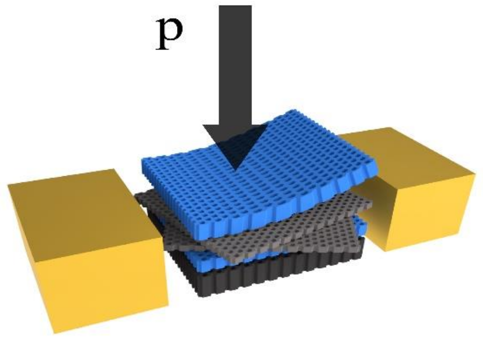
In van der Waals heterostructures the twist angle between 2D materials strongly affects the bandstructure allowing the formation of novel phases of matter. In twisted double bilayer graphene (TDBG) the electric displacement field allows for control of layer polarization and gives another control on the band structure [1-3].

Here we investigate a twisted double bilayer graphene heterostructure encapsulated in hBN under hydrostatic pressure using our recently developed unique setup. By applying pressure on TDBG the layer distances and interlayer hopping parameters can be tuned, resulting in changes of the band structure. To study these changes we extracted the band gaps from thermal activation measurements at the electron and hole side and at the neutrality points in zero and in finite D. We have observed a strong modulation of the gaps with pressure. We performed calculations based on the continuum model, which are in good agreement with the experimental findings.



Artistic image of our device showing the tuning of TDBG with pressure.

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Spectroscopy of barrier defects coupled to superconductors in van der Waals tunneling devices

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Superconductor-Quantum Dot (SC-QD) coupling is a subject of an intense research effort. In the van der Waals (vdW) family of materials, atomic defects in insulating/semiconducting materials play the role of Quantum Dots, allowing their easy integration into vertical vdW tunnelling heterostructures. Based on the strength of coupling between the QD and the superconductor, one can observe a multitude of ground states. In the present work, we study a vertical stack of graphene-MoS_2-$NbSe_2$ vdW tunneling heterostructure. The use of graphene as a source electrode allows for energy tunability of the QD present in MoS_2, via an electric field through an electrostatic back-gate. The Coulomb blockade characteristics of the QD indicate an asymmetric SC-QD coupling. The QD is further observed to serve as a very sensitive tunneling spectrometer. Scanning the dot potential across the superconductor Fermi energy, we map the $NbSe_2$ density of states which exhibits a well-resolved two-gap spectrum [1]. An interesting observation is that of the dot-assisted tunnelling current being dominated by the lower of the two $NbSe_2$ gaps, possibly due to a selection rule which favours coupling between the dots and the orbitals which exhibit this gap.

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Valley Spirals in Magnetically Encapsulated Twisted Bilayer Graphene

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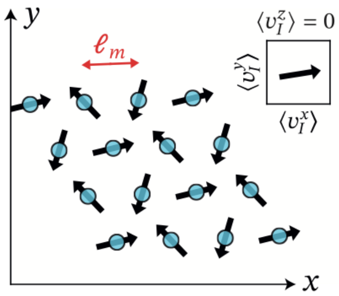

Fig. 1. Illustration of an interaction-induced valley spiral state on the moiré length scale ℓ_m. Each moiré unit cell (blue circle) develops an in-plane valley polarization (black arrow) in the valley spinor (inset).

Van der Waals heterostructures provide a rich platform for emergent physics due to their tunable hybridization of layers, orbitals, and spin. In this presentation, we show that a heterostructure formed by twisted bilayer graphene sandwiched between ferromagnetic insulators features flat bands stemming from the interplay between twist, exchange proximity and spin-orbit coupling. We demonstrate that in this flat-band regime, the spin degree of freedom is hybridized, giving rise to an effective triangular superlattice with valley as a nearly-degenerate pseudospin degree of freedom. Incorporating electronic interactions at half-filling leads to a spontaneous valley-mixed state, i.e., a correlated state in the valley sector with geometric frustration of the valley spinor, see Fig. 1. We show that an electric interlayer bias generates an artificial valley–orbit coupling in the effective model, controlling both the valley anisotropy and the microscopic details of the correlated state, with both phenomena understood in terms of a valley-Heisenberg model with easy-plane anisotropic exchange. Our results [1] put forward twisted graphene encapsulated between magnetic van der Waals heterostructures as platforms to explore valley-correlated states in graphene.

References

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Three-dimensional electron-hole superfluidity in a superlattice close to room temperature

Sara CONTI [1], Matthias VAN DER DONCK[1], Andrea PERALI[2], Alexander R. HAMILTON[3], Bart PARTOENS[1], Francois M. PEETERS[1], and David NEILSON[1,3]

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Bound pairs of electrons and holes in semiconductors may condense into a superfluid and the electron-hole coupling is predicted to be much stronger than in conventional superconductors, when the electrons and holes are confined in separated layers [1].

Although there is strong theoretical and experimental evidence for electron-hole superfluidity in bilayer system at low temperature [2, 3], the two-dimensional superfluid transition is topological, and so the transition temperature is limited by strong 2D fluctuations and Kosterlitz-Thouless effects [4].

We show this limitation can be overcome and that high-temperature superfluidity can be generated in a three-dimensional superlattice of alternating electron-doped and hole-doped semiconductor monolayers.

The transition temperatures are not topological and can approach room temperature when the superfluid gaps are very large. As a quantitative example, we present results for the properties of an electron-hole superfluid in a superlattice of transition metal dichalcogenide monolayers in which the critical temperature can reach 270 K [5].

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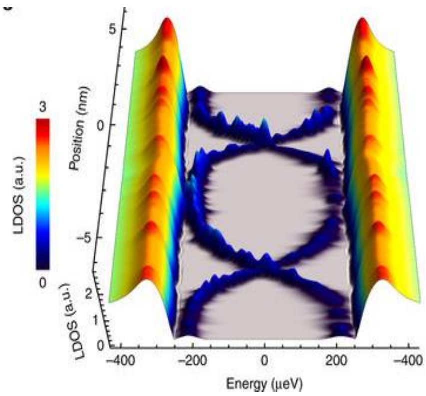
The COST Action Nanocohybri

The COST Action Nanocohybri is open to scientists from 27 European countries and collaborators all over the world. Nanocohybri kicked-off in November 2017 and will likely last until end of April 2022. Nanocohybri organizes networking activities aimed to fulfil the objectives of the Action. Nanocohybri organizes meetings, promotes exchanges through short term visits and provides opportunities for young researchers to present work related to the Action in other meetings. The Management Committee approves activities following COST excellence and inclusiveness policy. All details, including time and budgetary frames as well as eligibility issues are available at the Action's webpage.

The next major meetings of the Action will be, "Nanoengineered Superconductors – NES21 Young Investigator's online workshop, May 10-12, 2021" and "Superconducting Hybrids @ Extreme, 28th June – 02nd July 2021".

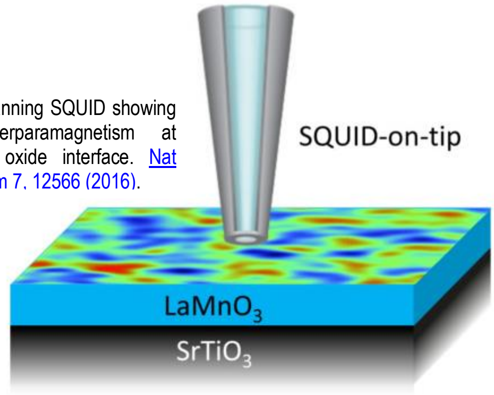
Nanocohybri is triggered by the amount of fundamental knowledge obtained in superconducting systems and the recently acquired ability to control magnetic flux, electron charge and spin in devices. Much of the topical research in this area is being carried out all over Europe in the subfields of low dimensional systems, hybrids between superconductors and magnets or semiconductors, and nanoscale engineering for current carrying applications. The scientific and methodological approaches in these fields are similar and there is an important potential for cross-fertilization. The challenge is to use the understanding achieved and control the main superconducting parameters in devices to produce radically new behaviour. The Action has three working groups:



Topological superconductivity in monolayer of Pb covering Co-Si islands, see Nat Comm 8, 2040 (2017).

- Working group 1 (WG1). Low dimensional and hybrid systems. WG1 deals with two-dimensional and ultra-thin film superconductors. Nanofabrication techniques include lithography, controlled constrictions, exfoliation and systems capable to produce devices composed of layers of different materials. Characterization is made through photoemission spectroscopy, tunnelling microscopy, micro-Raman, quantum transport or ultrafast optics. New imaging techniques available at large-scale infrastructures (such as X-ray holography at synchrotron radiation sources) are also used. Theory analyses quantum transport from numerical studies using standard systems for superconductivity and ab-initio calculations. WG1 is lead by Brigitte Leridon.

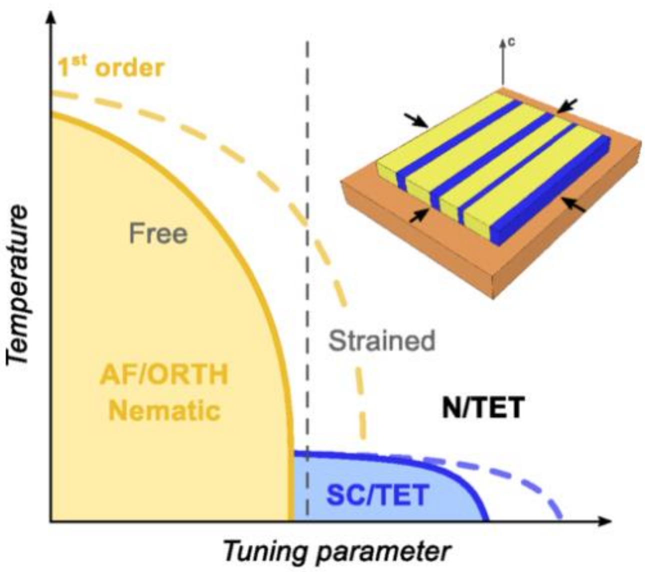
Scanning SQUID showing superparamagnetism at an oxide interface. Nat Com 7, 12566 (2016).



- Working group 2 (WG2). Novel devices from hybrid interfaces. The involved groups aim to integrate materials where the Cooper pair wave function has a sign change into devices, for example cuprates or topological insulators and other materials with topologically non-trivial surface states into Josephson junction circuits. We also study superconductor/ferromagnetic hybrids in detail, looking at novel modulated phases. Techniques include microscopic bandstructure calculations and measurements of the Josephson effect using transport experiments. We use advanced microscopies, including SQUID-on-a-tip and magnetic force. WG2 is lead by Alexander I. Buzdin.

- Working group 3 (WG3). Hybrids with nanoscale vortex pinning and nanofabrication for high magnetic fields. We explore vortex pinning and current transport at low temperatures and high magnetic fields, in cuprate as well as in pnictide superconductors. We control fabrication techniques allowing to make pinning on demand and to study the collective behaviour of the vortex lattice in presence of patterned arrays of nanostructures. We also address the influence of structural or electronic distortions (such as

Strain induced normal and superconducting stripes in a pnictide superconductor, Phys Rev B 97, 014505 (2018).



nematicity), particularly close to quantum criticality, in the enhancement of superconducting parameters. Working methods include microscopy, correlated with transport calculations in superconductors, three-axis nanoSQUID and vortex manipulation. WG3 is lead by Dieter Kölle.

Quantum fluctuations near criticality. [Nat Phys (2018)]