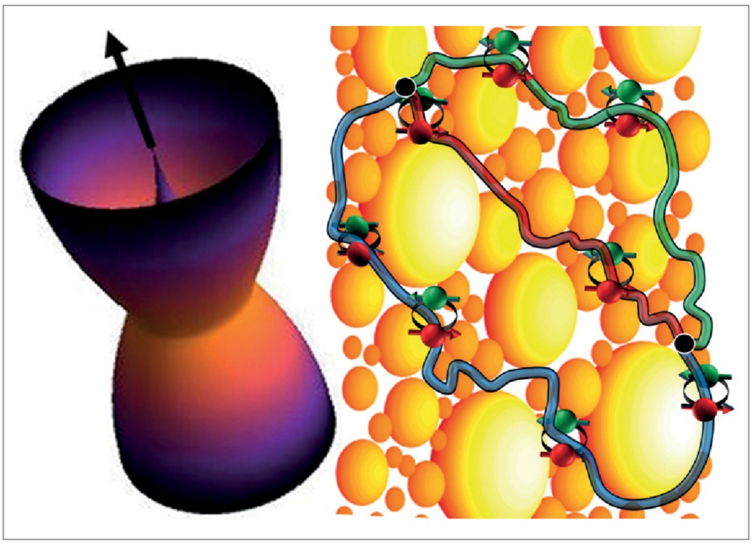
# SUPERSTRIPES 2023



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# SUPERSTRIPES 2023

## Quantum Complex Matter

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# Preface

Antonio Bianconi

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The Superstripes 2023 meeting held in Ischia, (June 26th - July 1st 2023) is dedicated to the memory of K. Alex Muller who discovered high Tc superconductivity in complex perovskite oxides in 1986 [1]. For a century the discovery of new high Tc superconductors (HTS) was driven by material science research using trials and errors method. The BCS theory for superconductivity a Fermi gas in single band in a homogenous symmetric lattice with a very weak electron-electron attraction was not of help for material scientists looking for high Tc superconductivity. Alex opened the roadmap for the research of high temperature superconductivity in in inherently inhomogeneous superconductors made of multiple atomic elements and complex structures, with coexisting local, polarons, and delocalized electronic components where all BCS approximations breakdown.

The Alex roadmap has driven physics to room temperature superconductivity showing experimental evidence that macroscopic quantum coherence in a many body system can occur at room temperature in a complex lattice landscape at nanoscale. Modern band structure theory has been of help in the research for pressurized room temperature superconductors predicting high Tc compounds containing covalently bound H atoms are called hydrides with unconventional strong electron-lattice interaction with high energy phonons. At Superstripes 2015 conference in Ischia the discovery by Mikhail Eremets of $T_c$=203K [2] in pressurized $H_3S$ was first announced at an international conference and he received the 2015 Fano Gold Medal with Lev Gorkov, proposing two component high Tc components, in Rome in December 2015. This discovery has been followed by other hydrides with Tc over 250K [3] showing complex local geometry [4] and evidence for non-BCS unconventional multigap superconductivity at a shape resonance or Fano resonance controlled by the local lattice structure made of a superlattice of atomic hydrogen wires [5]. In these last years fast time resolved using advanced lasers and free electron lasers and local lattice probes like X-ray spectroscopy using synchrotron radiation, anomalous resonant diffraction, X-ray and neutron atomic pair distribution function method, resonant X-ray diffraction. scanning nano-X-ray diffraction, X-ray photon correlation spectroscopy: XPCS, probing local dynamics, terahertz spectroscopy, have changed our understanding of complex quantum matter.
The interest on the new physics of superconductivity in unconventional complex landscape with intrinsic complex quantum geometry at nanoscale, has been grown in these last four years of Covid pandemic. New advances in complex superconductivity and

novel physics in quantum materials appearing for example at interfaces, nanoscale heterostructures, van der Walls flakes, twisted junctions, showing polarons and free particles, complex charge density waves, local charge fluctuations, and advances in theories like unconventional superconductivity at BCS - BEC crossover, quantum fractionalization, Q-balls, advances in DFT theory for complex materials, evidence of quantum critical points at unconventional Lifshitz transitions, theories on the key role of spin orbit coupling [6] and effective topological gauge theories in inherently inhomogeneous superconductors, will be presented at the Superstripes 2023 conference.

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# Floquet generation of topological superconductivity and magnetism in the strong-correlation regime

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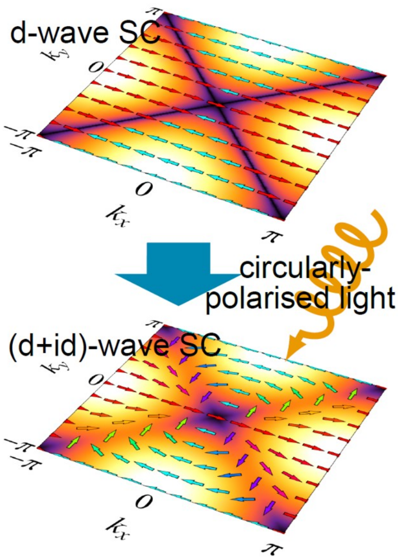
Circularly-polarised light in Floquet engineering stands out because the time-reversal broken modulation (i) facilitates topological transitions, and (ii) can trigger multi-photon-induced cyclic hoppings which is unimaginable from external magnetic fields. These features appear even prominently if we extend the notion to strongly-correlated systems to realise quantum phases that are difficult to attain in equilibrium, e.g. we can modify a Mott insulator to chiral-spin states. We can go even further to convert a d-wave superconductor in repulsively interacting systems into a "Floquet topological superconductor" with *d+id* pairing [1](attached Fig.). I shall describe a perspective of these pathways. Multi-band [2,3] and flat-band [4,5] systems can enhance SC, so that it will be an interesting future problem to explore Floquet topological SC in these cases.

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# Ab initio studies and fractionalization in cuprate high-Tc superconductors

Masatoshi Imada

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Understanding of the microscopic origin of the material dependence of copper oxide superconductors with a diversity of the superconducting critical temperature $T_c$ ranging from 10K to above 130 K is a major challenge in condensed matter physics. We have numerically solved a number of ab initio Hamiltonians without adjustable parameters and reproduced the detailed materials dependence in experiments as well as the common properties, from which the principal component that controls the superconducting amplitude is revealed and a scaling relation to predict the optimum $T_c$ is proposed. The result also shows the connection to electron fractionalization recently revealed by the analyses of spectroscopic data.

# Stripes, superconductivity, and their mutual disappearance in overdoped cuprates

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In layered cuprates, the competition between superexchange coupling of Cu moments and the kinetic energy of doped holes can lead to intriguing intertwined orders [1]. The occurrence of spin and charge stripe orders appears to compete with bulk superconductivity but is compatible with 2D superconductivity. I have recently argued that by viewing charge stripes as hole-doped two-leg spin ladders [2], one can understand both the 2D and 3D superconducting orders [3]. In overdoped $La_{2-x}Sr_xCuO_4$, we have found evidence that superconductivity is driven by stripe-correlated patches of moderate hole concentration, with proximity-induced superconductivity in surrounding weakly-correlated regions [4]. The bulk superconducting temperature drops to zero as the strongly-correlated patches become too dilute to support superconducting order.

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# The curious case of overdoped cuprates: conventional or exotic?

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Underdoped cuprates are without doubt complex and exotic. Several correlated states compete near the Fermi surface including superconductivity, charge ordering and the pseudogap 'state'. But for a long time it was thought that overdoped cuprates represented progressively more conventional behaviour - despite the fact that it has been known since quite early that there is a strong suppression of superfluid densit on progressing deeper into the overdoped state. We know that underdoped cuprates also display a suppression of superfluid density due to the pseudogap so this overdoped behaviour came to be known as the 'boomerang effect'. We have found this deeply puzzling because many other overdoped superconducting properties display conventional behaviour. Amongst these are the scaled BCS ratios for the condensation energy, the specific heat jump and the superconducting energy gap. Collectively they imply that the superfluid density too should remain conventional. Techniques for measurement of superfluid density include muon spin relaxation, optics, susceptibility, mutual inductance and the tunnel diode resonator. We have been involved in a number of these earlier reports. But here we measure the superfluid density using field-dependent specific heat measurements on bulk samples of Ca-doped $YBa_2Cu_3O_x$ and $Bi_2Sr_2CaCu_2O_{8+x}$ and find no suppression of the superfluid density across the overdoped region, consistent with our earlier thermodynamic results mentioned above. Are the overdoped cuprates in this sense conventional after all? And what is the reason for these divergent results amongst so many different techniques? The cuprates continue to fascinate in their curious behaviour.

# Structural changes induced by electric currents in $Pr_2CuO_4$ as an example of a novel control knob of quantum materials

Susmita Roy[1], Feng Ye[1], Zachary Morgan[2], Syed I. A. Jalali[3], Yu Zhang[1], Gang Cao[1], Nobu-Hisa Kaneko[4], Martin Greven[4], Rishi Raj[3], and Dmitry Reznik*[1]

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I will discuss a novel approach to the structural and electronic property modification of oxides and other materials, focusing primarily on $Pr_2CuO_4$, an undoped parent compound of a class of electron-doped copper oxide superconductors. Currents were passed parallel or perpendicular to the copper oxygen layerswith the voltage ramped up until a rapid drop in the resistivity a process refered to as ”Flash” was achieved. Then the current was further increased tenfold in current-control mode. This state was quenched by immersion into liquid nitrogen (LN2). Flash can drive many compounds into different atomic structures with new properties, whereas the quench freezes them into a long-lived state. Single crystal neutron diffraction of as-grown and modified $Pr_2CuO_4$ revealed a $\sqrt{10}x\sqrt{10}$ superlattice due to oxygen vacancy ordering. The diffraction peak intensities of the superlattice of the modified sample were significantly enhanced relative to the pristine sample. Raman-active phonons in the modified sample were considerably sharper. Measurements of electrical resistivity, magnetization and two-magnon Raman scattering indicate that the modification affected only the Pr-O layers but not the Cu-O planes. These results point to enhanced oxygen vacancy ordering in the modified samples well beyond what can be achieved without passing electrical current. Our work opens a new avenue toward electric field/quench control of structure and properties of layered perovskite oxides.

# Adding Depth and Berry Curvature Resolution to Momentum Microscopy Studies of 2D Materials and Heterostructures

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Material platforms based on two-dimensional van der Waals crystals are extremely appealing from a technological perspective because they are both incredibly versatile and sensitive to external stimuli. However, a key requirement for the realization of viable devices based on such materials is a clear understanding of the layer-resolved electronic and magnetic structure, which can vary dramatically as a function of depth and proximity to other materials. Even more importantly, for topologically nontrivial two-dimensional materials, the ability to resolve the spin character of the bands as well as the local (momentum-resolved) Berry curvature is crucial for forming a complete picture of the interactions that are responsible for many of the new functional properties.

We demonstrate the capability to extract depth-resolved electronic structural information from single monolayers of transition-metal dichalcogenides and their heterostructures using standing-wave photoemission microscopy and momentum microscopy [1,2]. Depth-resolved evolution of the valence-band electronic structure and chemical bonding is studied with Angstrom-level depth resolution and sensitivity to different depths within the monolayer. We discuss future possibilities and recent proof-of-principle experiments demonstrating momentum-resolved mapping of the local Berry curvature using momentum microscopy with a combination of magnetic circular dichroism and spin resolution [3].

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# Beyond BCS: An Exact Model for Superconductivity and Mottness

Philip Phillips*, Jinchao Zhao, Edwin Huang, G. La Nave, Luke Yeo

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The Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity described all superconductors until the 1986 discovery of the high-temperature counterpart in the cuprate ceramic materials. This discovery has challenged conventional wisdom as these materials are well known to violate the basic tenets of the Landau Fermi liquid theory of metals, crucial to the BCS solution. Precisely what should be used to replace Landau's theory remains an open question. The natural question arises: What is the simplest model for a non-Fermi liquid that yields tractable results. Our work builds[1] on an overlooked symmetry that is broken in the normal state of generic models for the cuprates and hence serves as a fixed point. A surprise is that this fixed point also exhibits Cooper's instability[2,3]. However, the resultant superconducting state differs drastically[3] from that of the standard BCS theory. For example the famous Hebel-Slichter peak is absent and the elementary excitations are no longer linear combinations of particles and holes but rather are superpositions of composite excitations. Our analysis here points a way forward in computing the superconducting properties of strongly correlated electron matter.

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# Superlattices, bonding-antibonding, Fermi surface nesting and superconductivity

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Raman [1] and synchrotron THz absorption spectral [2] measurements on $MgB_2$ provide experimental evidence for superlattices. The THz spectra show superlattice absorption peaks with low wavenumber, for which spectral density evolves after cooling below the superconducting transition temperature for $MgB_2$ [2]. These observations indicate a direct connection to superconducting properties and mechanisms. Bonding/anti-bonding orbital character is identified in calculated electronic band structures and Fermi surfaces consistent with superlattice structures along the *c*-axis [2]. DFT calculations show that superlattice folding of reciprocal space generates Umklapp processes and substantially enhanced nesting relationships. Tight binding equations are compared to expected charge density waves from nesting relationships [4] and adjusted to explicitly accommodate these linked processes. Systematic analysis of the electronic band structure and Fermi surfaces, allows for direct identification of Cooper pairing and the superconducting gap, particularly when the k-grid resolution of a calculation is adequately fine [5-6]. Thus, we detail a robust and accurate DFT re-interpretation of the BCS superconductivity for $MgB_2$.

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# Experimentally Established Universal and Non-Universal Properties that Define the Physics of Cuprates

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Parent compounds of cuprates are charge-transfer insulators with one charge ($n_{\mathrm{loc}}$) localized within a $CuO_2$ plaquette due to strong correlations. Superconductivity is universally observed in the range of doping between $p\sim$ 0.04 - 0.05 (underdoped) and 0.30 - 0.35 (overdoped) with a maximal value of the superconducting transition temperature ($T_c$) around $p \sim 0.16$. Above $p \sim$ 0.30 - 0.35, cuprates exhibit only Fermi-liquid behavior. This common pattern implies that the origin of superconductivity stems from universal normal-state behavior, while the wide variation, more than an order of magnitude, in observed maximal $T_c$'s is due to more subtle non-universal effects which tune the superconductivity in particular compounds.

Based on now well-established universal transport [1] and optical conductivity [2,3] properties, we show that the phenomenology of cuprates across the phase diagram is fully captured [4,5] by the charge conservation relation:

$$1 + p = n_{\mathrm{loc}} + n_{\mathrm{eff}}$$

with the superfluid density that simply corresponds to:

$$\rho_S = n_{\mathrm{eff}} \cdot (O_S\, n_{\mathrm{loc}})$$

where $n_{\mathrm{eff}}$ is the carrier density, which can be directly determined experimentally [1-5], while $O_S$ is a compound-dependent constant [5]. The Fermi-liquid nature of $n_{\mathrm{eff}}$ is unambiguously determined by two experimentally confirmed scalings [2,3,6], while it was firmly established that the scattering rate and Fermi-velocity are essentially compound- and doping-independent and thus universal [1-7]. The doping and temperature evolution of $n_{\mathrm{loc}}$ reveals a gradual (percolative [8]) delocalization from a value of 1 in the underdoped to 0 in the overdoped regime that is universal for all cuprates [4,5]. As directly obvious from optical spectroscopy, it is $n_{\mathrm{eff}}$ that becomes superconductive, while $n_{\mathrm{loc}}$ provides the glue [3,5]. We attribute the distinction between low- and high-$T_c$ cuprates to the fine-tuning of the p–d–p fluctuation of the Cu-localized hole ($n_{\mathrm{loc}}$) visiting the neighboring planar–oxygen atoms, which is the reason for the material-dependence embodied in the constant $O_S$ [5].

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# Fermion quartets and quartet condensation

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Fermion quartets show up in several areas of physics. Biexcitons, bound states of two electrons and two holes, have been proposed already in the Seventies in semiconductor physics, and their (Bose-Einstein) condensation has been reported a long time ago, leading to a long-lasting controversy. The alpha particle, a bound state of two protons and two neutrons, was already instrumental in the development of the Bohr model at the beginning of the 20th century. More recently, alpha particles as constituents of nuclear matter in the case of equal numbers of protons and neutrons and even their Bose-Einstein condensation has been conjectured. On the other hand, superconductivity involving four-electron bound states appears to be very hard to realise. In this talk a brief review is given on the problem of quartet condensation. Then a simple model of spinless fermions on a square lattice with attractive short-range and repulsive longer-range interactions is introduced [1]. We have studied the model using various methods, including variational wave functions, Exact Diagonalization and a small "zoo of lattice animals". We have established the existence of a tightly bound four-particle state for very small hopping, quite similar to the real pairs in the context of the attractive Hubbard model. Unfortunately, the effective mass of the quartets is very large and Bose-Einstein condensation is unlikely to occur. With increasing hopping the quartets spread and finally decay into delocalised fermions, in a first-order phase transition, quite in contrast to the BEC-BCS crossover reported for the attractive Hubbard model. The addition of spin does not change the phase diagram qualitatively. However, it has been argued that quartets are favoured if in the presence of a second internal degree of freedom, such as isospin (for the alpha particle), the band index for valence and conduction bands in semiconductors ore the valley index in graphene. Work on the SU(4) version of our model is in progress. It will be interesting to see whether large quartets are found in this case, with small effective mass and therefore a propensity towards superconductivity.

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# Epitaxial growth and topological transport properties of Sn-based quantum heterostructures

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Among many topological materials, α-Sn stands out as a unique and promising candidate: It is the only elemental material that shows multiple topological phases, such as topological Dirac semimetal (TDS) and topological insulator (TI), which can be controlled by various means such as strain, thickness, or applying electric field (Fig. 1a) [1]. Particularly, when α-Sn is grown on an InSb (001) substrate, a diamond-type α-Sn thin film experiences in-plane compressive strain, which leads to formation of two Dirac points in the three-dimensional (3D) band structure and drives the α-Sn film into a TDS phase. Furthermore, α-Sn is known to undergo a phase transition to β-Sn upon heating. As β-Sn becomes superconducting at low temperature (< 4 K), this opens a new way to incorporate superconductivity into the already-rich topological phase diagram of α-Sn. In this work, we explore the epitaxial growth and topological properties of high-quality α-Sn thin films and their heterostructures.
We grew single-crystalline α-Sn thin films on non-magnetic InSb (001) (Fig. 1b) and Fe-doped ferromagnetic semiconductor (In,Fe)Sb using molecular beam epitaxy (MBE). The α-Sn thin films grown on InSb show very high quantum mobilities of both the topological surface state (TSS) (30000 $cm^2$/Vs), which is ten times higher than previously reported values, and bulk heavy hole (HH) (1800 $cm^2$/Vs), which is obtained for the first time. Our analysis of the Shubnikov - de Haas oscillations (Fig. 1c) combined with first principles calculations indicate that both the TSS and the HH bands are topologically nontrivial, which unambiguously indicate that our α-Sn samples are in a TDS phase. Furthermore, we demonstrate a crossover from the TDS to a two-dimensional topological insulator (2D-TI) and a subsequent phase transition to a trivial insulator when varying the thickness of α-Sn [2].
We then study magnetotranport properties of an α-Sn thin film (2 nm) grown on a ferromagnetic semiconductor (In,Fe)Sb layer doped with 13.8% Fe (Curie temperature $T_C$ > 300 K) [3]. When an in-plane magnetic field $\boldsymbol{B}$ is applied parallel to the current $\boldsymbol{I}$, the α-Sn thin film shows very large linear magnetoresistances that are odd-functions of $\boldsymbol{B}$ (~ 250%). Furthermore, a nonreciprocal magnetoresistance component $R_{I\mathrm{odd}\_B\mathrm{odd}}$, which is an odd function of both $\boldsymbol{B}$ and $\boldsymbol{I}$, is also observed. The nonreciprocal

component $R_{I\mathrm{odd\_}B\mathrm{odd}}$ increases proportionally to the current $\boldsymbol{I}$, which indicates that it results from a non-linear response in the magnetotransport properties of α-Sn. These novel magnetotransport properties are considered to originate from the breaking of spatial inversion symmetry and time reversal symmetry in the α-Sn/($In_{1-x}$,$Fe_x$)Sb heterostructures.

Furthermore, we investigate the transport properties of superconducting β-Sn nanowires (width 180 ~ 500 nm) embedded in topological Dirac semimetal α-Sn thin films, fabricated by irradiating a focused Ga ion-beam. Upon applying a magnetic field *H* parallel to the nanowire, we observe a large superconducting diode effect, whose superconducting rectification ratio $\eta=$¿, where $I_{C+}$¿¿ and $I_{C-}$ are the critical current values when *I* flows in the positive and negative directions, respectively, reaches a maximum of 35%. We consider a proximity effect between the superconducting β-Sn and the topological Dirac semimetal α-Sn plays an important role in this large superconducting diode effect.

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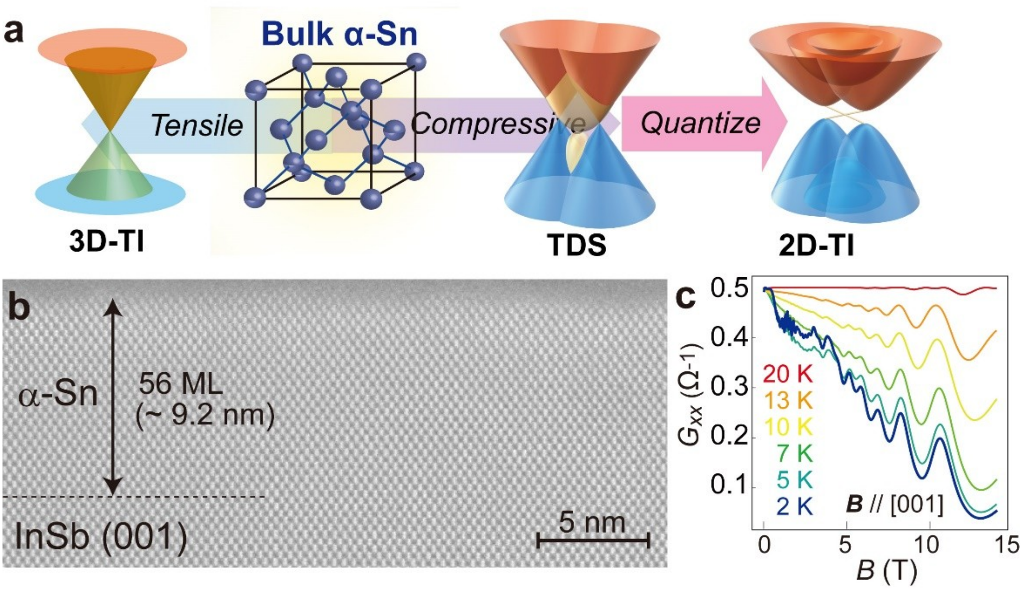


Fig. 1. **a**, Various topological phases that can be realized in the α-Sn platform. **b**, Cross-sectional scanning transmission electron microscopy (STEM) lattice image of our ∼-Sn thin film grown on an InSb (001) substrate: High quality diamond-type crystal structure is clearly observed. **c**, Strong and clear Shubnikov de Haas (SdH) oscillations observed under a perpendicular magnetic field as small as 0.3 T, manifesting the high quantum mobility of our ∼-Sn film.

# Nontrivial gapless electronic states at the stacking faults of weak topological insulators

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Lattice defects such as stacking faults may obscure electronic topological features of real ma- terials [1]. In fact, defects are a source of disorder that can enhance the density of states and conductivity of the bulk of the system and they break crystal symmetries that can protect the topo- logical states. On the other hand, in recent years it has been shown that lattice defects can act as a source of nontrivial topology[2–8]. Motivated by recent experiments on three-dimensional (3D) topological systems such as $Bi_2TeI$ [9] and $Bi_{14}Rh_3I_9$ [10], we examine the effect of stacking faults on the electronic properties of weak topological insulators (WTIs). Working with a simple model consisting of a 3D WTI formed by weakly-coupled two-dimensional (2D) topological layers sepa- rated by trivial spacers, we find that 2D stacking faults can carry their own, topologically nontrivial gapless states. Depending on the WTI properties, as well as the way in which the stacking fault is realized, the latter can form a topologically protected 2D semimetal, but also a 2D topological insulator which is embedded in the higher-dimensional WTI bulk. This suggests the possibility of using stacking faults in real materials as a source of topologically nontrivial, symmetry-protected conducting states.

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# Shedding new light on the parent compounds of nickelate superconductors

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Hole-doped infinite-layer (IL) nickelates are a novel family of superconductors whose similarities and differences to cuprate superconductors are currently under intense debate. For instance, resonant x-ray scattering experiments have revealed a distinct electronic structure of IL nickelates [1], whereas the presence of high-energy spin fluctuations and a charge ordered phase next to the superconducting dome are reminiscent of cuprates [2]. Yet, these insights into IL nickelates were gleaned exclusively from experiments on epitaxial thin films, although the epitaxial strain and the interfaces to the substrate and the capping layer might alter the intrinsic spin and charge degrees of freedom of the material. Here we report the synthesis and physical properties of bulk single-crystals of IL nickelates [3,4], with a special focus on the parent (undoped) compounds of IL nickelates, where the most pronounced spin fluctuations and charge order are expected according to the corresponding thin film studies. Our IL crystals are cleaveable and can be produced in large quantities with millimeter-sizes [4], thus providing a promising perspective for future spectroscopic studies of the intrinsic bulk properties, not only with resonant x-ray scattering, but also for surface-sensitive techniques as well as probes that require samples with large scattering volumes.

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# Strain tuning of the strange metal phase, charge order and superconductivity in underdoped nm scale cuprates

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The "strange metal" phase of High Critical Temperature Superconductors (HTS) is one of the most striking manifestations of the strong electron-electron correlation correlations in these materials. At optimal doping the strange metal manifests as a linear temperature dependence of the resistivity that persists to the lowest $T$ when superconductivity is suppressed. This behavior is fundamentally different from that observed in more conventional metals, where a $T$-linear dependence of the resistivity is found, only at high temperatures, where phonon scattering dominates the transport. For underdoped cuprates this behavior is lost below the pseudogap temperature $T^*$, where Charge Density Waves (CDW) together with other intertwined local orders characterize the ground state. The association between the departure from the $T$-linear resistivity and the occurrence of the pseudogap phenomenon has long been speculated without a general consensus. To address this issue we have tuned the ground state of underdoped HTS by using the geometric modification of the unit cell under the strong strain induced by the substrate. We show that the $T$-linear resistivity of highly strained, ultrathin and underdoped $YBa_2Cu_3O_{7-\delta}$ (YBCO) films is restored when the CDW amplitude, detected by Resonant Inelastic X-ray scattering, is suppressed [1]. This observation points towards an intimate connection between the onset of CDW and the departure from the strange metal behavior in underdoped cuprates. In addition we find that in ultrathin thin films the superconducting critical temperature onset and the upper critical field Hc2 are strongly enhanced compared to single crystals which point towards a competition between CDW and superconductivity [2]. Our results also illustrate the potential of using strain control to manipulate the ground state of quantum materials.

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# Scanning tunneling spectroscopy of the *d*-wave vortex core and periodic conductance modulations in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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The electronic structure of the Abrikosov vortices is one of the outstanding puzzles of high temperature superconductivity (HTS). We present scanning tunneling spectroscopy (STS) of heavily overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) measured at an unprecedented low magnetic field for any HTS material [1]. These experiments clearly reveal the pristine *d*-wave signature (Fig.1a and b) predicted by theory over 25 years ago [2], and confirm our earlier findings of a *d*-wave vortex core in $YBa_2Cu_3O_{7-x}$ [3]. At higher magnetic fields, STS of Bi-2212 shows the unusual electronic features reported previously, including the periodic conductance modulations in the vortex halo (checkerboard – Fig.1c) and the low energy subgap peaks [1]. While this remarkable field dependence is yet to be fully understood, our data show that the checkerboard is not a charge density wave –in agreement with previous experiments on nearly optimally doped Bi-2212. They further question a proposed link between the checkerboard and pseudogap, since there is no pseudogap in heavily overdoped Bi-2212.

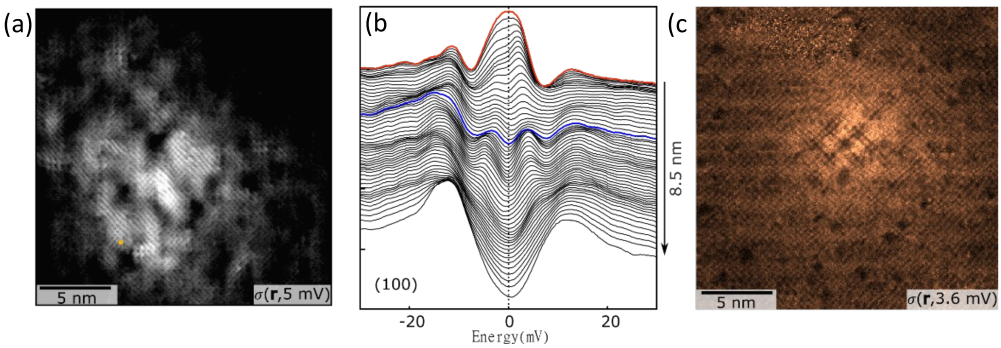


Fig.1. (a) dI/dV(V=5mV, $\vec{r}$) map and (b) conductance spectra measured along the (100) direction at 0,16 Tesla, revealing the d-wave vortex core. (c) dI/dV(V=3,6mV, $\vec{r}$) map revealing the checkerboard in the vortex halo at 2,8 Tesla. Adapted from [1].

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# Tunable unconventional kagome superconductivity in charge ordered $RbV_3Sb_5$ and $KV_3Sb_5$

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Unconventional superconductors often feature competing orders, small superfluid density, and nodal electronic pairing. While unusual superconductivity has been proposed in the kagome metals $AV_3Sb_5$ [1-3], key spectroscopic evidence has remained elusive. We utilized pressure-tuned and ultra-low temperature muon spin spectroscopy to uncover the unconventional nature of superconductivity in $RbV_3Sb_5$ and $KV_3Sb_5$ [4,5]. At ambient pressure, we observed time-reversal symmetry breaking charge order below $T_1^* \approx 110$ K in $RbV_3Sb_5$ with an additional transition at $T_1^* \approx 50$ K. Remarkably, the superconducting state displays a nodal energy gap and a reduced superfluid density, which can be attributed to the competition with the charge order. Upon applying pressure, the charge-order transitions are suppressed, the superfluid density increases, and the superconducting state progressively evolves from nodal to nodeless. Once optimal superconductivity is achieved, we find a superconducting pairing state that is not only fully gapped, but also spontaneously breaks time-reversal symmetry. Our results point to unprecedented tunable nodal kagome superconductivity competing with time-reversal symmetry-breaking charge order and offer unique insights into the nature of the pairing state.

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# Topological order and deconfined criticality in superconductors easy-plane antiferromagnets

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In this talk we review the results of our recent work establishing the existence of a deconfined quantum critical point two versions of two-dimensional easy-plane antiferromagnets, which is in the same universality class of topologically ordered two-dimensional superconductors. In this talk we resolve a number of contradictory findings with regard to whether such a theory undergoes a second-order phase transition. The traditional Landau-Ginzburg- Wilson approach suggests a first-order phase transition, as there are two different competing order parameters. We also establish a bosonization where the bosonic theory is dual to a fermionic one with two massless Dirac fermions, which thus undergoes a second-order phase transition as well.

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# Isotopic effect on the lattice dynamics of yttrium hydrates and oxo-hydrates

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Four hydrogen-rich materials, $H_3S$ ($T_c$ = 203K), $LaH_{10}$ ($T_c$ = 250K), $YH_6$ ($T_c$ = 227K) and $YH_9$ ($T_c$ = 243K) synthesized by research group led by Dr. M. Eremets [1] (Max-Planck Institute, Mainz) at megabar pressures, have revolutionized the field of condensed matter physics providing the first glimpse to the solution of the hundred-year-old problem of **room-temperature superconductivity**. An unprecedented synergy between high-pressure experiments including synchrotron radiation, theoretical methods and computational tools enabled these breakthroughs, which are likely to bring many discoveries in the coming years. Recently we have published results on “Local electronic structure rearrangements and strong anharmonicity in $YH_3$ under pressures up to 180 GPa” [2]. We have used locally sensitive X-ray absorption spectroscopy together with XRD and Raman spectroscopy to get insight into the nature of phase transitions and the rearrangements of local electronic and crystal structure in archetypal metal hydride $YH_3$ under pressure up to 180 GPa.
Here we compared the results of the DFT calculations with the XAFS RDF-data and Raman frequencies to get insight into the nature of phase transitions and the rearrangements of local electronic and crystal structure in $YH_3$ and $YD_3$ under pressure up to 180 GPa. The combination of the DFT calculations with the experimental methods allowed us to implement a multiscale length study of $YH(D)_3$ and yttrium oxohidrates Y-O-H(D): XAFS (short-range), Raman (medium-range), and XRD (long-range). These results will contribute to a better understanding of the hydrogen interaction mechanism with the heavy atom sublattice and high-temperature superconductivity in metal hydrides as well as photochromic effect in Y-O-H.

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# Can the spin polaron concept describe the ARPES of Mott-insulating cuprates?

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Already soon after the discovery of high-*Tc* cuprates, the concept of a spin polaron has been formulated, in order to understand the behaviour of holes in lightly doped cuprates [1]. This idea has gained quite a widespread acceptance, for it could quite well describe the angular-resolved photoemission (ARPES) spectra of Mott-insulating cuprates [2]. Yet, two issues have been raised: (i) the ARPES spectrum on *quasi*-1D cuprates was much better explained using the spin-charge separation picture [3] and (ii) the experimentally observed line shape of the quasiparticles was much higher than the one predicted by the spin polaron theory [4]. Here I address these two issues in detail and, based on the recent works [5], I hope to give a decisive answer on the extent to which the spin polaron concept is still a valid approach.

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# Universal size-dependent nonlinear charge transport in single crystals of the Mott insulator $Ca_2RuO_4$

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The surprisingly low current density required for inducing the phase separation between the Mott-insulating and metallic state has made $Ca_2RuO_4$ an attractive candidate material for developing Mott-based electronics devices. The mechanism driving the resistive switching, however, remains a controversial topic in the field of strongly correlated electron systems. Here we probe an uncovered region of phase space by studying high-purity $Ca_2RuO_4$ single crystals, using the sample size as principal tuning parameter. Upon reducing the crystal size, we find a four orders of magnitude increase in the current density required for driving $Ca_2RuO_4$ out of the insulating state into a non-equilibrium (also called metastable) phase, which is the precursor to the fully metallic phase. By integrating a microscopic platinum thermometer and performing thermal simulations, we gain insight into the local temperature during simultaneous application of current and establish that the size dependence is not a result of Joule heating. The findings suggest an inhomogeneous current distribution in the nominally homogeneous crystal. Our study calls for a reexamination of the interplay between sample size, charge current, and temperature in driving $Ca_2RuO_4$ towards the Mott insulator to metal transition.

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# Resonant Inelastic X-Ray Scattering Study of Electron-Exciton Coupling in High-$T_c$ Cuprates

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Studying the interactions which cause electrons to form Cooper pairs is the first step towards the understanding of the superconductivity mechanism in the high-$T_c$ cuprates. Pairing can be mediated by phonons, the screened Coulomb force, spin or charge fluctuations, excitons, or by a combination of these [1,2,3,4]. An exciton-mediated pairing mechanism has been postulated [4,5], but experimental evidence for coupling between conduction electrons and excitons in the cuprates is sporadic [6].
In this work, we use resonant inelastic x-ray scattering (RIXS) to follow the temperature dependence of the *dd* exciton spectra of $Bi_2Sr_2CaCu_2O_{8-x}$ (Bi-2212) crystals with different charge carrier concentrations. We observe a signature of the superconducting transition on the *dd* exciton spectra: in the proximity of $T_c$ the *dd* exciton peak first moment shows a change of slope in its temperature dependence, which reverses sign as function of doping. We attribute the superconductivity-induced effect and its sign-reversal from underdoped to overdoped to the exchange coupling of the site of the *dd* exciton to the surrounding copper spins.

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# Multi-orbital nature of infinite-layered nickelates

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Since the recent discovery of superconductivity in the infinite-layered phase of Sr-doped NdNiO2, an intense research effort has been devoted to understanding the electronic properties of this class of materials, and in particular the similarities and differences to the cuprate superconductors. A widely debated but still not fully settled question concerns the single- versus multi-orbital nature of these systems. Some groups argue that the Ni 3dx2−y2 orbital is the main player and relevant for the observed super-conductivity, as in the cuprates, while other groups claim that the inclusion of additional orbitals is necessary to accurately describe the low-energy physics.
I will address this issue by analyzing simple model systems [1], and by deriving realistic parameters via a systematic downfolding procedure [2,3]. These investigations show that because the Hund coupling is comparable to the splitting between the different d bands, the multi-orbital nature needs to be taken into account, especially in the hole-doped regime. The implications for the possible local and nonlocal pairing states will also be discussed.

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# Nickelate superconductors – one-band Hubbard model perspective

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At first glace, infinite-layer nickelate superconductors are isostructural and isovalent to their cuprate peers. At second glance, the nickelates appear to be more complicated: Besides the Ni $d_{x^2-y^2}$ band that crosses the Fermi level, there are additional pockets around the A and possibly Γ-momentum that are of predominant Nd character.
At third glance, density functional theory plus dynamical mean-field theory (DFT+DMFT) calculations [1,2] indicate that these additional pockets are merely passive bystanders, electron (hole) reservoirs, while the actual physics is governed by the Ni $d_{x^2-y^2}$ band. This suggests, the most intensively studied model for superconductivity, the one-band Hubbard model to be at the heart superconductivity in the nickelates, albeit with a properly adjusted doping because of the A-pocket. On this foundation, we were able to predict the superconducting phase diagram in nickelates [1] prior to experiments [3,4]. Thanks to recent experimental progress in the form of defect-free infinite-layer nickelates [4], the agreement between theory and experiment has become excellent. This, as well as similar calculations [5] for pentalyer nickleates [6], gives us hope that we are on a good way toward a more thorough understanding and reliable prediction of unconventional superconductors.

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# Charge and Spin excitations in infinite-layer superconducting nickelates

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The discovery of superconductivity in infinite-layer nickelates RNiO2 (with R being a rare-earth) has generated much excitement in the physics community. Many experiments and calculations have been performed to shed light on their electronic structure, in order to establish similarities and differences with respect to (infinite-layer) cuprates, of which they mimic the structure.
Recently, we have carried out RIXS measurements on $NdNiO_2$ thin films with different doping levels, both with and without SrTiO3 capping layers. In the capped films we have established, in agreement with other experiments [1], the presence of dispersing magnetic excitations strongly similar to the ones found in cuprates. At the same time, in the capping-free films we have discovered the presence of charge order with a similar periodicity than in cuprates, although with a different doping and temperature dependence. Interestingly, the capping-free films (which still display superconductivity) show no sign of magnons and also display a stronger hybridization between Nd and Ni atoms, which effectively increases the three-dimensional character of the electronic structure. Our results represent an important step towards the understanding of nickelate superconductors, and show that strain is probably playing a crucial role. They have been recently published on Physical Review Letters [2].

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# Nanoscale off-centering as a path to low thermal conductivity

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Suppression of heat transport is critical to high performance thermoelectricity, requiring the ability to effectively scatter heat-bearing phonons. This can be accomplished either via crystal engineering, or by utilization of materials with intrinsically low lattice thermal conductivity. In the latter case, particularly intriguing are systems exhibiting nanoscale symmetry-broken states that are intrinsic and driven by electronic instabilities. For example, in thermoelectric PbTe such a state emerges on warming and involves Pb off-centering displacements [1] and associated giant anharmonic phonon scattering. The stereochemical activity of $6s^2$ electron lone pairs results in the formation of local dynamic correlated dipoles. A similar emergent state, dubbed emphanisis, was found in $AgGaTe_2$ recently [2], where local off-centering of Ag is driven by a weak $sd^3$ orbital hybridization, resulting in strong acoustic-optical phonon scattering and an ultralow lattice thermal conductivity. These examples show the diversity of electronic instabilities that can lead to hidden nanostructural responses important for applications.
Here we address the binary semiconductor SnSe, a novel high performance high temperature thermoelectric exhibiting ultralow thermal conductivity and high thermoelectric figure of merit ZT. The local atomic structure of SnSe, known to exhibit Sn lone electron pairs and resonant bonding, was characterized across its orthorhmbic-to-orthorhombic (Pnma/Cmcm) structural phase transition using x-ray pair distribution function analysis. Substantial Sn off-centering distortions persist in the high symmetry high temperature phase, with symmetry different from that of ordered distortions below the transition. The analysis implies that the transition is neither order-disorder nor displacive, but rather a complex crossover where the character of displacement coupling changes from 3D-like at low temperature to 2D-like at high temperature. Robust ferro-coupled SnSe intra-layer distortions suggest a ferroelectric-like instability as the driving force. Complex local Sn off-centering, possibly involving nanoscale phase separation, is integral to the ultra-low lattice thermal conductivity mechanism in SnSe [3].

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# Confined quasi-1D superconductivity in envelope description

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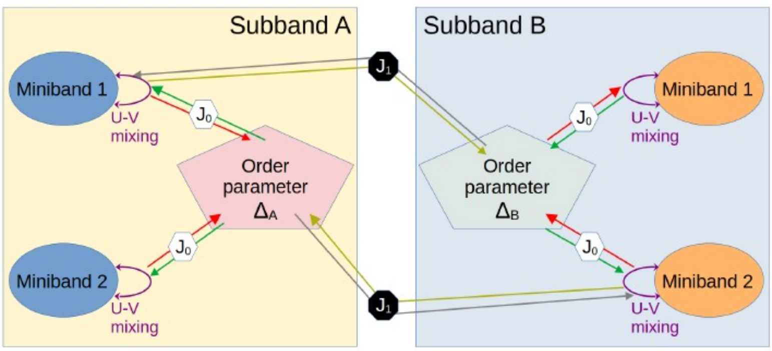
The confined superconductivity in quasi-1D superlattice nanoribbon structures in intrinsically multi-band materials is an arena of the interaction of multiple coupling channels happening simultaneously at different levels: (1) corresponding to the different bands of the bulk material, (2) different subbands resulting from the width restriction to several monolayers, (3) different minibands arising from the 2D → quasi-1D constriction and finally (4) of the different parts in the superlattice Brillouin zone. The envelope approximation approach [1-3] takes advantage of the Anderson approximation of the Bogoliubov-de Gennes equations and allows for the unified parameterized treatment of these mechanisms, while still being able to be informed by the experimental data or more detailed calculation. This method is easily generalisable to a wide class of multiband superconducting systems and makes it possible to describe, among others, the following:
- inter-cell phase difference required to investigate the superconducting current flow,
- pseudogap regions of both inter and intra-subband genesis,
- amplification due to characteristic strongly localised eigenstates – even relatively remote from the Fermi level,
- different character of inter-subband condensate coupling: both the constructive and destructive one.




Schematic general illustration of the model, from [3].

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# Defect bearing hyper-expanded iron-chalcogenides and their robust superconducting state

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Two-dimensional iron chalcogenides offer a rich playground where structural and electronic correlations, tuned by intercalation chemistry promote superconductivity [1]. Here we focus on the $Li_x(C_5H_5N)_yFe_{2-z}Se_2$ ($C_5H_5N$= PyH5) where electron donor molecules, co-intercalated with alkalis in the β-FeSe lead to large Fe-sheet separation (d~16.2 Å) and a five-fold rise of the superconducting critical temperature ($T_c$= 44 K). Chemical insights for maximal $T_c$ have been uncovered by high-throughput, time-resolved synchrotron X-ray total scattering, identifying the different length-scales emerging during the growth of the expanded lattice intercalates. In-situ PDF analysis of the [Li-PyH5-FeSe] reaction pathway reveals local distortions, involving swollen $FeSe_4$ edge-sharing units, as a consequence of the electron donating moieties being accommodated in the interlayer space [2]. Implications on the electronic structure, key to materials-design principles for higher $T_c$, have been investigated by element-specific (Fe & Se K-edge) X-ray absorption and emission spectroscopies, as a function of doping ($0 \leq x \leq 1$), down to 20 K. Raised $T_c$ intercalates carry (a) a low spin state, with somewhat reduced Fe local magnetic moment compared to β-FeSe, and (b) a softer Fe-sublattice at high Li content, corroborating to Fe-site deficiency [3]. DFT calculations on Fe-vacancy baring single-layer $Fe_{2-z}Se_2$, mimicking the strong separation of the inorganic slabs in the intercalants, associate the high-$T_c$ with the presence of electron pockets close to the BZ corners (M point) and the suppression of hole-like Fermi surface near the center (Γ point). The research sheds light on the interplay of electron donating spacers and the Fe-Se layer's tolerance to defect chemistry, a tool to favorably tune the Fermi surface properties for robust superconducting states with widely separated Fe-sheets (d > 8.6 Å).

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# Searching for new electronic properties in ultrathin films of correlated materials via in situ ARPES

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Since the discovery of graphene in 2004, research on 2-dimensional van der Waals materials is at the core of the condensed matter physics research. This is due to the fact that these 2D materials not only show distinct physical properties from those of 3D materials but also can lead to novel properties through stacking. For example, Mott insulating and superconducting states, unavailable in single layer graphene, are realized in twisted bilayer graphene. While these novel 2D systems are built through exfoliation of van der Waals materials, a more conventional way is via thin film growth. In this presentation, I wish to introduce the research efforts to find new electronic properties in a few unit cell (uc) thick thin films by using thin film growth and in situ angle resolved photoemission (ARPES).

We started with ARPES studies on a few thick films of $SrRuO_3$, a prototypical metallic ferromagnet with spin-orbit coupling. It was found that nodal lines and quadratic band crossing points are generic features of ultrathin perovskite films. These symmetry-protected nodal lines and quadratic band crossing points are sources of Berry curvature that causes the sign changing anomalous Hall effects [1]. By using an additional ‘conducting layer’, we were able to obtain the electronic structure of 1 u.c. thick SrRuO3 films. Our results show that 1 uc films are not insulators but remain metallic. Dosing experiments reveal that 1 uc films are correlated Hund metals caused by the high density of states near $E_F$ from the van Hove singularity [2]. We further controlled the strain and octahedron distortion of 1 uc films by using various substates. We demonstrate that the electronic state of 1 uc films can be manipulated from a good metal to a correlated Hund metal, and finally to a Mott insulator [3][4]. I will also briefly touch upon other activities on cuprates[5] and chacogenides [6,7] if time permits.

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# Josephson effect and superfluidity in electron-hole bilayer heterostructures

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We analyze the superfluid characteristics and crossover physics for Josephson junctions [1] in electron-hole bilayer TMD semiconductors [2]. We determine the critical current across junctions of different potential barrier heights [3,4]. We show that the crossover physics in the narrow barrier region controls the critical current throughout. We find that the ratio between the critical current and the carrier density exhibits an observable maximum at the density of the switchover from bosonic excitations to pair-breaking fermionic excitations [5]. This provides, for the first time in a semiconductor system, an experimental measure for the position of the boundary separating the BEC and BCS-BEC crossover regimes.

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# Tunable BCS-BEC crossover, reentrant, and hidden quantum phase transitions in two-band superconductors with tunable valence and conduction bands

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Two-band electronic structures with a valence and a conduction band separated by a tunable energy gap [1] and with pairing of electrons in different channels can be relevant to investigate the properties of two-dimensional multiband superconductors and electron-hole superfluids, as monolayer FeSe [2], recently discovered superconducting bilayer graphene [3], and double-bilayer graphene electron-hole systems [4]. This electronic configuration allows also to study the coexistence of superconductivity and charge density waves in connection with underdoped cuprates [5] and transition metal dichalcogenides [6]. By using a mean-field approach to study the system above mentioned, we have obtained numerical results for superconducting gaps, chemical potential, condensate fractions, coherence lengths, and superconducting mean-field critical temperature, considering a tunable band gap and different filling of the conduction band, for parametric choice of the pairing interactions. By tuning these quantities, the electrons redistribute among valence and conduction band in a complex way, leading to a new physics with respect to single-band superconductors, such as density induced and band-selective BCS-BEC crossover, quantum phase transitions, and hidden criticalities [7]. At finite temperature, this phenomenon is also responsible for the non-monotonic behavior of the superconducting gaps resulting in a superconducting-normal state reentrant transition, without the need of disorder or magnetic effects [8].

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# Superconductivity in superhydrides. New developments

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Since the discovery of superconductivity at ⏶200 K in $H_3S$ [1], similar or higher transition temperatures, $T_c$*s*, have been reported for various hydrogen-rich compounds under ultra-high pressures [2]. Superconductivity was experimentally proved by different methods, including electrical resistance, magnetic susceptibility, optical infrared, and nuclear resonant scattering measurements. The crystal structures of superconducting phases were determined by X-ray diffraction. Numerous electrical transport measurements demonstrate the typical behavior of a conventional phonon-mediated superconductor: zero resistance below $T_c$, the shift of $T_c$ to lower temperatures under external magnetic fields, and pronounced isotope effect. Remarkably, the results are in good agreement with the theoretical predictions, which describe superconductivity in hydrides within the framework of the conventional BCS theory.

Magnetic properties, one of the most important characteristics of a superconductor, have not been satisfactorily defined. Recently, we develop SQUID magnetometry under extremely high-pressure conditions [3, 4] and report characteristic superconducting parameters for $H_3S$ and $LaH_{10}$—the representative members of two families of high-temperature superconducting hydrides. In particular, we determine a London penetration depth $\lambda_L$ of ~20 nm in $H_3S$ and ~30 nm in $LaH_{10}$. These compounds have the values of the Ginzburg-Landau parameter $\kappa$ ~12–20 and belong to the group of “moderate” type II superconductors. We further develop magnetic measurements with the trapped magnetic flux [4]. This technique provides a strong magnetic response and, what is more important, eliminates the huge background of a bulky diamond anvil cell. We will present also new methods and results.

A large part of the report will be a discussion of progress in increasing $T_c$ to room temperature and above at high pressures and substantial superconductivity at low pressures.

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# Orbitals and Nematicity in 1111- and 111-type Fe based Superconductors

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While there is broad consensus that superconductivity in Fe based superconductors is due to an unconventional, most likely electronic pairing, many important aspects of the normal and superconducting state are still unexplored. In particular, the role of orbital degrees of freedom for the normal state electronic properties, nematicity, and pairing is discussed very controversial. In my talk I will present results on a series of large La-1111 single crystals which have been grown for the first time using a method based on anomalous solid state reaction. We have reexamined the phase diagram and studied magnetism and nematic order by means of NMR and strain dependent measurements of resistivity, thermopower, and Nernst effect. The possible formation of polaron-like structures will be discussed and evidence for an unusual state with suppressed long range order and soft nematic fluctuations will be presented. Results will be compared to measurements on LiFeAs where the emergence of nematicity has been observed in the superconducting state only.

# Density wave instability in liquid: From real liquid to electrons

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The pair density correlation functions of liquids show persistent oscillations beyond the first neighbor shell, indicating the presence of the medium-range order (MRO). The MRO has long been considered a mere consequence of the short-range order (SRO) in the nearest neighbor atoms. However, the relation between MRO and the SRO is not direct in supercooled liquid and glass, and the MRO freezes at the glass transition but the SRO does not [1]. We propose that the MRO is driven by collective density wave instability, using the density wave theory with the pseudopotential [2]. In the pseudopotential the strongly repulsive portion of the interatomic potential is removed, because it plays no role at temperatures of interest. The Fourier-transform of the pseudopotential has a minimum at $Q_{min}$, which is close to the position of the first peak in the structure factor $S(Q)$ at $Q_1$, suggesting that liquid is unstable against the formation of the density wave at $Q_{min}$ [2]. The density wave state is not compatible with the SRO, and the competition and compromise results in the MRO. This approach explains various properties of liquid and glass, including the glass transition. This idea of potential-driven density wave instability can be applied to electrons as well, when the kinetic energy is comparable to the electron-electron repulsion in strongly correlated electron systems. We discuss possible contributions to stripe-phase formation and the first observation of the electronic Van Hove function, a density correlation function in space and time, through inelastic x-ray scattering.

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# Dirac magnons in chromium halides

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Bosonic Dirac materials such $CrX_3$ (X = Cl, Br, I) with a honeycomb lattice exhibit topological properties because of quantum confinement. Dirac magnons have been predicted at the crossing of acoustic and optical spin waves, analogous to Dirac fermions in graphene. $CrX_3$ consists of weakly bound van der Waals honeycomb layers, with a hexagonal arrangement of magnetic $Cr^{3+}$ ions with spin S = 3/2. The ground state is either ferromagnetic (FM), as in $CrBr_3$ and $CrI_3$ with an out-of-plane spin orientation, or antiferromagnetic (AFM) with an in-plane FM alignment that alternates in the perpendicular direction, as in the insulating $CrCl_3$. All $CrX_3$ compounds exhibit a structural phase transition driven by shifts in the layers from the high-temperature (HT) monoclinic C2/m phase to the low-temperature (LT) ABC rhombohedral R-3 phase, though this transition is often frustrated. In $CrCl_3$ the magnetic easy axis is in-plane while in $CrBr_3$ and $CrI_3$, the easy axis is out-of-plane with stronger interlayer coupling. From inelastic neutron scattering measurements of the temperature dependence of the magnon excitations in $CrCl_3$, we observed gapless Dirac magnons at the lowest temperature where the dispersion intensity drops to zero at 4.5 meV [1]. $CrI_3$ on the other hand, has a gap at the Dirace point due to Dzyaloshinskii-Moriya interactions. Our recent data indicate that magnetic diffuse scattering is present that is consistent with a model where the spin direction flips across monoclinic-type interlayer boundaries. The presence of the monoclinic phase is associated with AFM order that sets in at low temperatures, below the FM transition of the rhombohedral phase.

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# Magnetic and electronic properties indicating polaron formation in $Eu_5In_2Sb_6$

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Materials crystallizing in nonsymmorphic space groups offer an interesting route to explore new topological properties. Indeed, there are theoretical predictions of nontrivial Fermi surface topology stabilized by nonsymmorphic symmetry [1]. Here we report on our magnetic, thermodynamic and electronic investigations of antiferromagnetic $Eu_5In_2Sb_6$ [2], which are accompanied by electronic band structure calculations.

We find a very large colossal magnetoresistance (CMR) in this low-carrier density material which is linked to the emergence of quasiparticles called magnetic polarons [3]. From our measurements, we provide strong evidence for the occurrence of such polarons in this material. The results of our Scanning Tunneling Spectroscopy (STS) data are in qualitative agreement with the calculated density of states (DOS) [4]. The calculated band structures and resultant DOS for the considered antiferromagnetic and ferromagnetic spin structures in $Eu_5In_2Sb_6$ nicely illustrate how the difference in spin configuration can lead to a reorganization of the small band contributions near the Fermi level. However, at present neither our band structure calculations nor the STS results at low temperature provide any indication for a nontrivial band topology of $Eu_5In_2Sb_6$.

Our experiments reveal highly anisotropic properties despite the $Eu^{2+}$ state indicating complex magnetic interactions [5]. $Eu_5In_2Sb_6$ appears to be a rare example of a material exhibiting polaron formation in an antiferromagnet, likely of anisotropic nature. Such electronically inhomogeneous properties in an intermetallic compound with precise electron count provide a rich playground for possibly new quantum states, specifically in magnetic materials of nonsymmorphic symmetry.

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# Analogies of phonon anomalies and electronic gap features in the infrared response of $Sr_{14-x}Ca_xCu_{24}O_{41}$ and underdoped $YBa_2Cu_3O_{6+x}$

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I will present a comparative study of the phonon anomalies and the electronic gap features in the infrared response of the weakly coupled two-leg-ladders in $Sr_{14-x}Ca_xCu_{24}O_{41}$ (SCCO) and the planar cuprate high-$T_c$ superconductor $YBa_2Cu_3O_{6+x}$ (YBCO) [1]. In particular, I will highlight some surprising similarities of the gap features in the electronic response of these seemingly rather different cuprates and discuss the implications. For SCCO our observations suggests that the local pairing correlations occur within the ladders while a macroscopic superconducting state develops only once the coupling between the ladders is enhanced, e.g. by applying external pressure. For the planar cuprate YBCO it implies that the charges tend to segregate forming quasi-one dimensional structures similar to the two-leg ladders of SCCO, as predicted for the stripe-scenario or certain intertwinned states.

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# Optically driven effective electron-electron attraction in a model with nonlinear electron-phonon interaction

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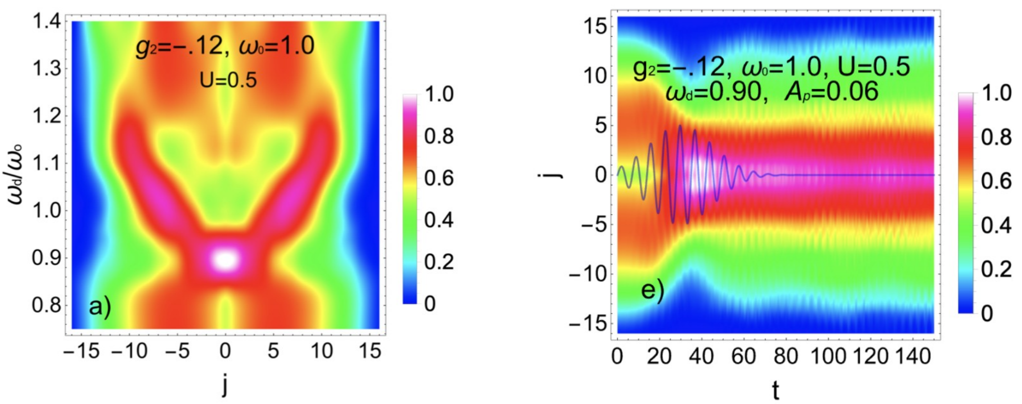
We investigate a Holstein-like model with two electrons nonlinearly coupled to quantum phonons. Using an efficient method based on full quantum approach [1-4] we simulate the dynamical response of a system subject to a short spatially uniform optical pulse that couples to dipole-active vibrational modes. Nonlinear electron-phonon coupling can either soften or strengthen the phonon frequency in the presence of electron density. In the atomic limit, both cases lower the energy of the doubly occupied site compared to two singly-occupied ones [5]. When two electrons are free to propagate on a lattice subject to non-linear coupling to phonons that soften phonon frequency, an external optical pulse with well tuned frequency can induce attraction between electrons. Electrons remain bound long after the optical pulse is switched off. Changing the frequency of the pulse the attractive electron–electron interaction can be switched to repulsive. Two sequential optical pulses with different frequencies can switch between attractive and repulsive interaction [6].




Figures: Left: the time evolution of a density – density correlation function g(j,t) starting from an unbound state at t=0 subcject to an optical pulse. Right: time - averaged g(j) vs. driving frequency ωd.

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# Coupling of lattice and electronic degrees of freedom in mixed-valence rare-earth fullerides

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Rare-earth (RE) metal $C_{60}$ fullerides constitute an intriguing class of strongly-correlated molecular systems as they present the possibility of strong coupling between two electronically active sublattices, the anionic pπ($C_{60}$) and cationic 4f,5d(RE) sublattices both of which are dominated by strong electronic correlations. To date, metal fulleride research has been dominated by work on alkali fullerides, especially those with stoichiometry $A_3C_{60}$ (A = alkali metal). These have emerged as archetypal strongly correlated systems with superconducting transition temperatures, $T_c$ as high as 38 K and upper critical magnetic fields, $H_{c2}$ in excess of 90 T. Nonetheless the electronic properties are entirely dominated by the narrow band behaviour of the $C_{60}$ anion sublattice – the supporting cation sublattice is invariably electronically inactive and only plays a charge-balancing role as a structural spacer. A comparable but exactly reverse situation is encountered in rare earth compounds which represent one of the most fascinating classes of strongly correlated systems that include Kondo insulators and heavy fermions. Here the properties are dominated by the extreme narrow-band behaviour of the rare-earth cation f-electron sublattice with the supporting anion sublattice again playing a charge-balancing structural-spacer role. As electronically active anion solids, the rare-earth fullerides can have properties intrinsically distinct from comparable rare-earth compounds with closed shell anions, and the emergence of novel phenomena such as co-existence of Kondo f-electron behaviour with $C_{60}$-based pπ-electron superconductivity may be anticipated.

To-date our work at high pressure on rare-earth fullerides using a combination of synchrotron X-ray diffraction, partial-fluorescence-yield synchrotron X-ray absorption spectroscopy and Raman spectroscopy has unambiguously established the occurrence of strongly coupled isosymmetric lattice and rare-earth valence transitions leading to insulator-to-metal transitions arising from the simultaneous presence of the electronically-active $C_{60}$ sublattice

# Planckian diffusion in k-(BEDT-TTF)$_2$Cu(NCS)$_2$ ?

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The observation of a linear resistivity ($\rho(T)=\rho_0+AT$) has been reported at low temperature in many compounds such as cuprates, pnictides or even quasi-1D molecular conductors. This linear behavior of the resistivity has been attributed to a Planckian diffusion of the carriers. Such a behavior is not expected at the border of the Mott transition where electron-electron interactions dominate the scattering of the electrons: the resistivity might follow a quadratic behavior at low temperature: $\rho(T)=\rho'_0+BT^2$. The family κ-(BEDT-TTF)$_2$X where X is an anion exhibits a Mott transition in its temperature versus pressure phase diagram. On the metallic side, a superconducting phase is stabilized with a critical temperature of about 10K. On the insulating side, an antiferromagnetic phase is stabilized at low temperature, in competition with the superconducting phase.
We have observed, in a wide range of magnetic field and temperature, an unexpected linear in temperature variation of the resistivity for the compound κ-(BEDT-TTF)$_2$Cu(NCS)$_2$. This behavior is retained under applied pressure (P) and is observed only below $T_{c0}$(P) where $T_{c0}$(P) is the zero magnetic field critical temperature at the pressure P.
We will present a careful analysis of the data in the title compound in the framework of this Planckian mechanism and alternative models including superconducting fluctuations will be discussed [1].

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# New insights from electronic transport in superconducting bound-states

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Majorana bound states are promising building blocks of forthcoming technology in quantum computing. Chains and islands of magnetic impurities in superconductors have attracted considerable attention recently as such systems may host Majorana bound states. However, their non-ambiguous identification has remained a difficult issue because of the concomitant competition with other topologically trivial fermionic states, which poison their detection in most spectroscopic probes. I will theoretically show that the Fano factor, which is the ratio between shot noise and the current, turns out to be a very interesting and distinctive tool in that respect. In particular, the Fano factor tomography displays a spatially constant Poissonian value equal to one for Majorana bound states while it is strongly spatially dependent and exceeds one as a direct consequence of the local particle-hole symmetry breaking for other trivial fermionic in-gap states such as Yu-Shiba-Rusinov or Andreev ones. I will also show how shot noise can be used to reveal coherent and incoherent dynamics of an in-gap bound state associated to the presence of a magnetic impurity in a superconductor which sets the stage for a comparison with experimental shot noise data [2].

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# Structure and Composition of High Pressure Polyhydrides

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Novel polyhydride materials synthesized at high pressure demonstrate unique physical (e.g., high $T_c$ superconductivity) and chemical properties (e.g., polymerization) making them attractive for extensive investigations. Pressure is the critical parameter, which unlocks structural diversity and unique physical and chemical properties. In this talk, I will present the results of investigation of synthetic routes, structure, and vibrational properties of carbon doped polyhydrides of sulfur up to 267 GPa [1,2]. The materials' properties critically depend on the constituent species and doping composition, which are the key elements of this study. The results are discussed in relation to the reported high-$T_c$ superconductivity in these materials. The results of ongoing investigations of other polyhydrides including the ternary ones will be presented at the meeting.
I acknowledge contributions of Maxim Bykov, Elena Bykova, Eric Edmund, Yue Wang, Xiao Zhang, Stella Chariton, Vitali Prakapenka, Jesse Smith, Dmitrii Semenok, Ivan Kruglov, Artem Oganov.

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# High-Pressure Hydrides and Electron-phonon Superconductivity: questions about the Experiments and questions about the Theory

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The high-pressure hydrides represent a pinnacle of achievement for high temperature superconductivity. Or do they? In this talk I will summarize not so much what is known about superconductivity as what is not known, namely, at the time of this writing, there have been no compelling measurements of the Meissner effect. My concern with electron-phonon driven superconductivity at such a high temperature comes not only from experiment, however, and I will also describe some outstanding questions about the efficacy of this mechanism to produce such high Tc's coming from theoretical considerations.

# Probe of Superconducting Order in High-Tc Hydrides

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Magnetic fields enable direct probes of the superconducting order and vortex matter in high temperature superconductors despite the constraints imposed by the megabar diamond anvil. We will review the experimental signatures of the superconducting state, including magnetization and magnetotransport phenomena and the representative superconductive parameters, as well as effective enhancement of electron-phonon coupling. Work at NHMFL-LANL was performed under the auspices of the NSF, DoE, and State of Florida.

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# Eliashberg theory in the uniform electron gas revisited

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The Eliashberg theory with the Migdal approximation has been established as a standard ab initio theory for phonon-mediated superconductor. But there remain challenges concerning accurate treatment of electron-electron Coulomb interaction effects. Historically the electronic Coulomb interaction in nearly uniform superconductors has been of interest in the context of the plasmon superconductivity [1, 2], whereas modern demand has arisen with recent discoveries of high-temperature superconductors. The Coulomb interaction effect especially matters in e.g. pressurized hydride superconductors [3], where the pairing is dominated by phonons but the Coulomb effects may change the Tc by several ten kelvin or more.
To establish nonempirical quantitative estimation of Tc, we study the plasmonic effects that compete for Tc; plasmon-mediated pairing and plasmon self energy effects. The latter in realistic systems has not been investigated thoroughly because of computational cost required. Using the Eliashberg equations with all the Nambu self-energy terms included, we study the effects in the uniform electron gas (UEG) with a modeled electron-phonon interaction, whose properties should broadly apply to various conventional superconductors [4].
We elucidate the spatial and temporal aspects of the plasmon self energy effects and point out a departure of the mass and pairing force renormalizations, which were incorrectly regarded equivalent in the phonon-mediated superconducting context. We thus confirm how the plasmon self energy effects should quantitatively behave in the UEG limit.

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# Electron-phonon interaction in the correlated electron systems revealed by angle-resolved photoemission spectroscopy

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Electron-phonon coupling is one of the fundamental many-body interactions and has been discussed as the key to the enhancement of the superconducting temperature *T*c in a wide variety of materials such as A-15 compounds, high-*T*c cuprates, iron pnictides/chalcogenides, and hydrogen sulfide. The signature of electron-phonon interactions appears in the kink and spectral linewidth of the quasiparticle dispersion and can be investigated by angle-resolved photoemission spectroscopy.

Here we present the signature of electron-phonon interactions observed in the electronic states of $Ca_{2-x}Sr_xRuO_4$ (CSRO) [1] and $BaIr_2Ge_7$ [2]. CSRO shows a metal-insulator transition with a structural phase transition. In the region of small $x$, the bulk of CSRO is in the insulating phase at low temperatures. We have performed angle-resolved photoemission spectroscopy (ARPES) of CSRO ($x = 0.06$) and revealed that the surface is in a metallic state while the bulk is in an insulating state. The observed band dispersion of the surface metallic state exhibits kink structures with the energy scales of 35 and 60 meV. The distinct kink structures suggest a strong electron–phonon coupling compared with $Sr_2RuO_4$.

We also performed ARPES on $BaIr_2Ge_7$ with cage structures and observed the temperature dependence of the ARPES spectra near the Fermi level. We found that the width of the spectral peak shows a concave-downward behavior with temperature similar to the electrical resistivity. Considering the effect of anharmonic phonon modes, this behavior was well reproduced in our simulations. Our results suggest the existence of the weak anharmonic phonon modes in $BaIr_2Ge_7$.

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# Low-energy spin excitations and tunable anisotropy of quasi-2D van der Waals magnets

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Layered van der Waals (vdW) magnetic compounds attract currently large attention as they may display an intrinsically low-dimensional magnetic behavior and as such offer an extensive materials base for exploring fundamental magnetic properties of strongly correlated two-dimensional (2D) electron systems [1-4]. Moreover, the structural and compositional variety of these compounds offers a possibility to realize magnetic ground states with desired types of order and intrinsic anisotropy essential for their application in next-generation spintronic devices [4].
Electron spin resonance (ESR) spectroscopy is an established powerful tool to probe spin-spin correlations, spin dynamics and magnetic anisotropy. In this talk, we will overview our recent ESR spectroscopic results on several members of this family. Particular attention will be given to one prominent representative, $Cr_2Ge_2Te_6$, which is a quasi-2D magnet showing intriguing intrinsic ferromagnetism down to atomically thin films [1]. In a detailed ESR study of high-quality single-crystalline samples of this material we could obtain new important insights into the magnetocrystalline anisotropy of this compound which should be responsible for the stabilization of magnetic order in the 2D limit and find evidence for an intrinsically 2D character of the dynamics of Cr spins even in bulk single crystals [5]. These results are supported by calculations of the electronic structure revealing that the low-lying conduction band carries almost completely spin-polarized, quasi-homogeneous, two-dimensional states [6]. Furthermore, we investigated the possibility to control the magnetic anisotropy of $Cr_2Ge_2Te_6$ and showed that application of a moderate hydrostatic pressure turns this material to the isotropic limit [6].

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# Robust propagating in-gap modes due to spin-orbit domain walls in graphene

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Recently, great experimental efforts towards designing topological electronic states have been invested in layered incommensurate heterostructures. In particular, it has become clear that a delicate interplay of different spin-orbit terms is induced in graphene on transition metal dichalcogenide substrates [1]. We therefore theoretically studied various types of domain walls in spin-orbit coupling in graphene looking for robust one-dimensional propagating electronic states [2]. To do so, we use an *interface Chern number* and a spectral flow analysis in the low-energy theory and contrast our results to the standard arguments based on valley-Chern numbers or Chern numbers in continuum models. Surprisingly, we find that a sign-changing domain wall in valley-Zeeman spin-orbit coupling binds two robust Kramers pairs, within the bulk gap opened due to a simultaneous presence of Rashba coupling. We also study the robustness to symmetry breaking and lattice backscattering effects in tight-binding models. We show an explicit mapping of our valley-Zeeman domain wall to a domain wall in gated spinless bilayer graphene. We discuss the possible spectroscopic and transport signatures of various types of spin-orbit coupling domain walls in graphene heterostructures.

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# Determining the nature and strength of proximity induced spin-orbit coupling in graphene by quasiparticle interference imaging

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Inducing and controlling spin-orbit coupling (SOC) in graphene is key to create topological states of matter, and for the realization of spintronic devices. The most successful strategy to achieve this goal so far is to place graphene onto a transition metal dichalcogenide. However, there is no consensus as to the nature and the magnitude of the induced SOC. In this talk, we show that the presence of backscattering in graphene-on-WSe2 heterostructures can be used to probe SOC and to determine its strength quantitatively, by quasiparticle interference (QPI) imaging using a scanning tunneling microscope. Analyzing QPI images of heterostructures with selected twist angles between 0° and 30°, we find that the induced SOC consists of a valley-Zeeman ($\lambda_{vZ} \approx 2$ meV) and a Rashba ($\lambda_R \approx 15$ meV) term. These results are in excellent agreement with transport experiments, both finding that the Rashba term is an order of magnitude larger than current theoretical predictions. QPI further gives unambiguous evidence that the measured SOC is the result of a modified band structure and demonstrate a viable strategy to determine SOC quantitatively by imaging quasiparticle interference.

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# Optical fingerprints of the electronic band reconstruction in van der Waals magnetic materials

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Understanding the physical mechanism as well as functionalities of van der Waals (vdW) heterostructures and electronic/spintronic devices is at present a central topic of the ongoing solid state physics research activities. We report a broadband study of the charge dynamics in the vdW magnetic materials 2H-$M_x$TaS$_2$ ($M$ = Mn and Co), which span the onset of both long-range antiferromagnetic (AFM) and ferromagnetic (FM) order, depending on the intercalation $M$ and its concentration $x$. We discover a spectral weight (SW) shift from high to low energy scales for FM compositions, while reversely SW is removed from low towards high spectral energies for AFM compounds. This maps the related reconstruction of the electronic band structure along the crossover from the FM to AFM order, which restores an occupation balance in the density of states between spin majority and minority bands of the intercalated 3d elements [1]. Our spectroscopic findings seem to be consistent with dedicated first-principles calculations upon tuning element-intercalation, pressure and/or magnetic field on similar intercalated materials. Finally, the present work demonstrates a feasible route towards understanding magnetism in low dimensions and may help in revealing robust properties, relevant for the development of low-power spin-logic circuits from layered materials.

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# Electron correlation and electron-phonon interaction in cuprate superconductors evaluated by ARPES with machine learning

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Macroscopic physical properties of materials are deeply related to microscopic electronic states. Angle-resolved photoemission spectroscopy (ARPES) is one of the most powerful tools for studying novel quantum materials, such as high-$T_c$ superconductors or topological materials, because it allows us to examine electronic states directly [1]. Furthermore, many-body interactions can be evaluated quantitatively by extracting electron self-energy using high-resolved ARPES [2]. However, such evaluation of many-body effects typically relies on spectral line-shape analysis based on a groundless assumption of a non-interacting band, the so-called “bare band”. On the other hand, machine-learning-based analysis has been recently applied in the research field of X-ray spectroscopic measurements, resulting in improvements in the efficiency/autonomy of measurements and the sophistication of analysis [3].

In this talk, we will present machine learning applications in evaluating the self-energy in high-$T_c$ cuprate superconductors using high-resolution ARPES. In the first application, we utilize numerical optimization for self-energy analysis on a La-based cuprate. We found that quantitative evaluation of many-body interactions becomes possible without assuming the bare band. We will also introduce a novel analysis method enabling quantitative and statistical evaluation of many-body interactions by applying the spectral analysis on a large amount of data from spatially-resolved ARPES on a Bi-based cuprate. In particular, the statistical relationship between electron-electron and electron-boson couplings will be discussed.

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# Anisotropic optics and gravitational lensing of tilted Weyl fermions

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We show that tilted Weyl semimetals with a spatially varying tilt of the Weyl cones [1] provide a platform for studying analogues to problems in anisotropic optics as well as curved spacetime [2]. Considering particular tilting profiles, we numerically evaluate the time evolution of electronic wave packets and their current densities. We demonstrate that electron trajectories in such systems can be obtained from Fermat's principle in the presence of an inhomogeneous, anisotropic effective refractive index. On the other hand, we show how the electrons dynamics reveal gravitational features and use them to simulate gravitational lensing around a synthetic black hole. These results bridge optical and gravitational analogies in Weyl semimetals, suggesting novel pathways for experimental solid-state electron optics.

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# Geometrical nonlinear optical effects of magnons in multiferroic materials

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The responses of materials to high intensity light, i.e., nonlinear optical responses, constitute a vast field of physics and engineering. One of nonlinear optical responses that are attracting a recent keen attention is a bulk photovoltaic effect called shift current which arises from a geometrical (Berry) phase of a Bloch wave function and has a close relationship to the modern theory of electric polarization [1]. While most previous studies of the bulk photovoltaic effects have focused on band insulators of noninteracting electrons, systems of correlated electrons have a potential to support a novel nonlinear functionality.
In this talk, I will present novel nonlinear optical effects originating from magnons in spin systems with broken inversion symmetry. We show that the optical excitation of magnons in multiferroic materials leads to shift current generation due to the electric polarization carried by magnons [2]. We also propose that the linearly polarized light generates nonlinear spin current that we call "magnon spin shift current" originating from nontrivial geometry of the magnon band [3].

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# Geometry-induced spin-filtering in photoemission maps from WTe2 surface states

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We demonstrate that an important quantum material $WTe_2$ exhibits a new type of geometry-induced spin-filtering effect in photoemission, stemming from low symmetry that is responsible for its exotic transport properties [1]. Through the laser-driven spin-polarized angle-resolved photoemission Fermi surface mapping, we showcase highly asymmetric spin textures of electrons photoemitted from the surface states of $WTe_2$. Such asymmetries are not present in the initial state spin textures, which are bound by the time-reversal and crystal lattice mirror plane symmetries. The findings are reproduced qualitatively by theoretical modeling within the one-step model photoemission formalism. The effect could be understood within the free-electron final state model as an interference due to emission from different atomic sites. The observed effect is a manifestation of time-reversal symmetry breaking by the photoemission process. As such, it cannot be eliminated, but only its magnitude influenced, by special experimental geometries.

If time allows we will discuss similar effects in spin-polarized and circular dichroic ARPES maps from $PtTe_2$, $WSe_2$, and $Bi_2Te_3$.

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# High Tc cuprates d-wave insulators

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High Tc cuprates consist of ionic insulator and $CuO_2$ layers. The latter are well described by d-wave insulator whose gap has nodal points at $(\pm \pi/a, \pm \pi/a)$ on Brillouin zone diagonals. In undoped antiferromagnetic (AF) compounds these nodal points are splitted by the finite gap of order 1 ÷ 2 eV due to the strong Hubbard type interaction. Electron removing from, or hole doping of, oxygen sites in $CuO_2$ layers creates first diagonal stripes, which coexist with AF state. Further doping causes formation of crossing stripes, ladder and the two-dimensional grid type structure,

# Pulsed excitations of $2H\text{-}NbSe_2$

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$2H\text{-}NbSe_2$ is a two-dimensional material in which charge density wave (CDW) and superconductive state coexist at low temperatures. While the equilibrium phase diagram of the material has already been well experimentally explored, the nature of the CDW state is yet to be fully understood. We study the material's response to pulsed excitations which gives us further insight into the both equilibrium and out-of-equilibrium physics of the material's quantum states.
An optical pump-probe setup is employed to look at the ultrafast response of the $2H\text{-}NbSe_2$ by measuring the transient reflectivity with 1.55 eV photon energy. Below the transition temperature, we observe a long-lived ultrafast response that is similar to the previously reported response [1], however, the absence of high-temperature background in our experiment allows us to probe the response of CDW to excitation in great detail. In addition, we are able to detect a tiny change in the amplitude of the ultrafast response below the critical temperature for the superconducting state. Similar to Payne et al. [2], we do not observe any coherent oscillations due to the amplitude modes within the explored ranges of temperatures and pump fluences. By means of ultrashort laser excitation of high fluence, no distinct long-lived states are detected.
With a scanning tunneling microscope, we perform a tip excitation with a short electrical pulse of the $2H\text{-}NbSe_2$ surface. After an intensive pulse excitation, we are able to transform a patch of the surface from 2H to 1T polytype which has a $\sqrt{13}\times\sqrt{13}$ CDW.

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# Saturation of the Superconductivity in Maximally Overdoped (p=1) Cuprates???

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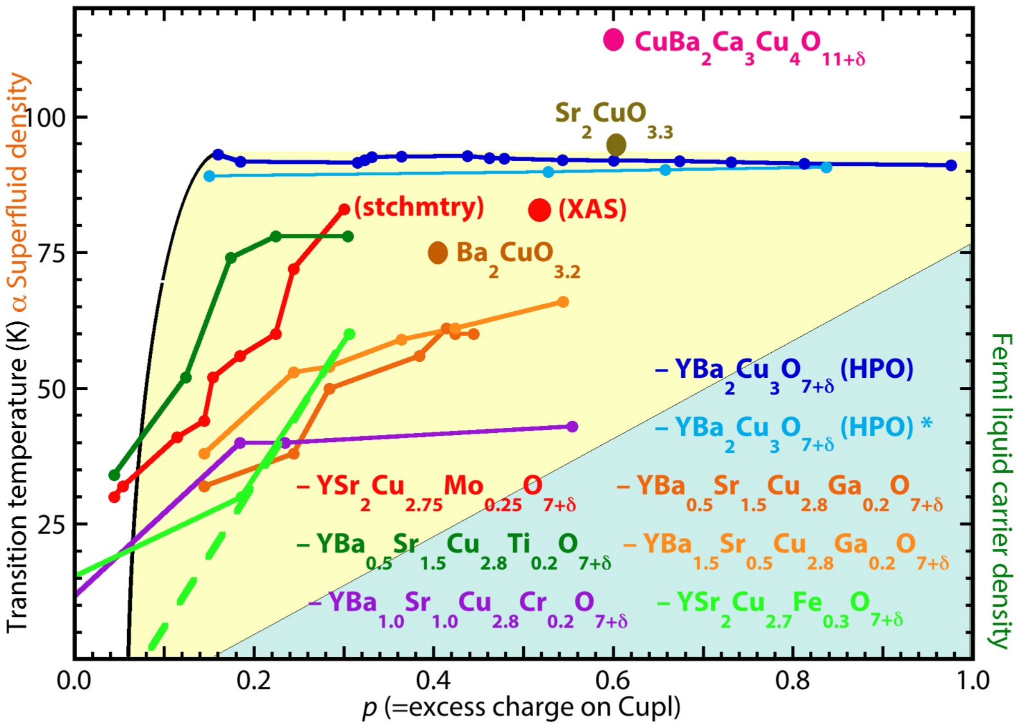
Building on our results from Superstripes 22, the structure of $YBa_2Cu_3O_8$ and the Cu1-substituted compounds of this family in which the excess oxygen is inserted in the spaces between the Cu1 sites to render them tetrahedral demonstrates that the loss of superconductivity on the “overdoped” side of the dome in compounds doped with $O_2$ or by cation substitution is not because of disorder, Coulomb repulsion, fluctuations, or other phenomena used in theories of HTSC but must be an exceptionally subtle effect of SC/electron-lattice coupling. The other unsolved conundrum pointing to novel physics is, of course, the diversion of the excess holes at least partly into Fermi-liquid type carriers, with the remainder going into an unknown electronic phase, and the saturation of the SC as $T_c$ and the superfluid density only shift by small amounts from their optimum values across a six-fold increase in carrier density. Analyses of the EXAFS from 10K past the superconducting transition exhibit the coupling of the dynamic structure of the Cu2-Oap and other Cu-atom pairs to the SC, but with substantial differences between YBCO7 and YBCO8. Exact diagonalization calculations show that the synchronization of neighboring Cu2-Oap pairs – which we have named Internal Quantum Tunneling Polarons – coupled anharmonically through their neighboring divalent alkaline earth cation results in novel phase in which hole density is transferred from the Oap to oxygen ions in the $CuO_2$ plane, which would be significant for the SC.

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# Multi-band superconductivity, polarons and the steep band/flat band scenario

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The basic features of multi-band superconductivity and its implications are derived. In particular, it is shown that enhancements of the superconducting transition temperature take place due to interband interactions which substantially enhance the effective electron-electron coupling. In addition, the isotope effects differ markedly from the typical BCS scheme as soon as polaronic coupling effects are present. Special cases of the model are polaronic coupling in one band as realized e.g. in cuprates, coexistence of a flat band and a steep band like in MgB2, crossovers between extreme cases. The advantages of the multiband approach as compared to the single band BCS model are elucidated and its rather frequent realization in actual systems is discussed.

# Low-energy quasi-circular electron correlations with charge order wavelength in BSCCO 2212

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In the study of dynamic charge order correlations in the cuprates, most high energy-resolution resonant inelastic x-ray scattering (RIXS) measurements have focused on momenta along the high-symmetry directions of the copper oxide plane. However, electron scattering along other in-plane directions should not be neglected as they may contain information relevant, for example, to the origin of charge order correlations or to our understanding of the isotropic scattering responsible for strange metal behavior in cuprates. We report high-resolution resonant inelastic x-ray scattering (RIXS) experiments that reveal the presence of dynamic electron correlations over the *qx*-*qy* scattering plane in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ with $T_c$=54 K. We use the softening of the RIXS-measured bond stretching phonon line as a marker for the presence of charge-order-related dynamic electron correlations. The experiments show that these dynamic correlations exist at energies below approximately 70 meV and are centered around a quasi-circular manifold in the $q_x$-$q_y$ scattering plane with radius equal to the magnitude of the charge order wave vector, $q_{CO}$. We also demonstrate how this phonon-tracking procedure provides the necessary experimental precision to rule out fluctuations of short-range directional charge order (i.e. centered around [$q_x=\pm q_{CO}, q_y=0$] and [$q_x=0, q_y=\pm q_{CO}$]) as the origin of the observed correlations.

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# *Ab initio* investigation of the electronic structure of Weyl semimetal PtBi2

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PtBi2 is Weyl semimetal characterised by strong spin orbit coupling, inversion symmetry breaking and a yet-not-understood superconducting transition at low temperatures [1]. Recently, new experimental data obtained by different techniques (ARPES, QPI, transport measurements) calls for a better understanding of the topological properties of the band structure, considering their possible implication on the superconducting transition. We therefore carried DFT calculations for this system and compared to newly available experimental data, showing extremely good results.

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# Exciton condensation in biased bilayer graphene

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We consider suspended bilayer graphene under applied perpendicular electric field (bias) that is known to generate a single particle gap $2\Delta$ and a related electric polarization P. We argue that the bias also drives a quantum phase transition from band insulator to superfluid exciton insulator. The transition is signaled by the exciton binding energy exceeding the band gap $2\Delta$. We predict the critical bias (converted to band gap), $\Delta c \approx 60$ meV, below which the excitons condense. The critical temperature, $Tc(\Delta)$, is maximum at $\Delta \approx 25$ meV, $Tc\ max \approx 115$ K, decreasing significantly at smaller $\Delta$ due to thermal screening. Entering the condensate phase, the superfluid transition is accompanied by a cusp in the electric polarization $P(\Delta)$ at $\Delta \rightarrow \Delta c$, which provides a striking testable signature.
Additionally, we find that the condensate prefers to form a pair density wave with three unit cell periodicity, offering an additional signature.

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# Vortex motion physics in iron-based and cuprate high-$T_c$ superconductors at microwaves: flux flow, anisotropy, pinning

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Cuprate and iron-based high-$T_c$ superconductors share many important common traits, such as the quasi-2D structure and an unconventional pairing mechanism. On the other hand, distinct features include the single vs multiband superconductivity and a high vs low anisotropy. These various features significantly impact, among the others, the mixed state properties. The experimental study of the high frequency vortex dynamics is particularly interesting for the observation windows that it opens within the mixed state [1]. Indeed, through multi-frequency measurements at microwaves several physical mechanisms involved in vortex motion can be unravelled and disentangled. The individual extraction of vortex parameters such as the flux-flow resistivity $\rho_{ff}$ and the intrinsic (mass) anisotropy allows to separately access the intrinsic properties as opposed to the extrinsic, pinning-dependent quantities, such as the pinning constant and the flux creep factor. For example, the multigap nature of iron-based superconductors makes the definition of anisotropy particularly rich, since various physical quantities allow to evaluate it. Here, we show how the field and angular dependence of $\rho_{ff}$ in Fe-based compounds [2] is found to closely follow the single-band BGL scaling theory [3], with intrinsic (mass) anisotropy values ~2 irrespective of the temperature. We study the $\rho_{ff}$ of Y-based cuprates in pristine conditions and with second-phase additions [4], aimed to improve pinning properties, showing how the added disorder impacts differently the vortex-core quasi-particles scattering time (essentially unaffected) and the pinning strength (appreciably increased). Finally, the analysis of pinning related quantities shed light on possible perspectives for fundamental physics experiments.

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# Mathematical and Physical Properties of Three-Band s+- Eliashberg Theory for Iron Pnictides

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The phenomenology of the iron pnictide superconductor can be described by the threeband s+- Eliashberg theory in which the mechanism of superconducting coupling is mediated by antiferromagnetic spin fluctuations and whose characteristic energy $\Omega_0$ scales with $T_c$ according to the empirical law $\Omega_0 = 4.65k_BT_c$. This model presents the universal characteristics that are independent of the critical temperature, such as the link between the two free parameters $\lambda_{13}$ and $\lambda_{23}$ and the ratio $\Delta_i/k_BT_c$.

# Nodal Multigap Superconductivity in the Anisotropic Iron-Based Compound $RbCa_2Fe_4As_4F_2$

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The $RbCa_2Fe_4As_4F_2$ compound, like all the members of the recently discovered family of 12442 iron-based superconductors, is characterized by a crystal structure that originates from the intergrowth of 122-type and 1111-type unit cells. It is a stoichiometric superconductor (i.e. it does not require any substitution to display superconductivity) because of an intrinsic doping of 0.25 holes/Fe atom, and displays a superconducting critical temperature $T_c \approx 30$ K [1].
Unlike all other Fe-based compounds, 12442 compounds feature double $Fe_2As_2$ layers (with alkali atoms sandwiched) separated by insulating $Ca_2F_2$ layers, making them similar to double-layer cuprates. Moreover, the *c*-axis coherence length is smaller than the distance between adjacent bilayers, that are therefore almost decoupled [2] – suggesting a quasi-two-dimensional superconductivity – and the anisotropy is much larger than that of other Fe-based compounds [3].
The similarity with cuprates seems to be even deeper, according to various experimental evidences of nodal gap – although there is no consensus yet on the number of gaps and on their symmetry. In order to give a contribution to solve this issue, we carried out directional point-contact Andreev-reflection spectroscopy (PCARS) measurements, combined with coplanar waveguide resonator (CPWR) measurements, in $RbCa_2Fe_4As_4F_2$ single crystals [4]. PCARS allows a direct determination of the number, amplitude and symmetry of the gaps, while CPWR provides the temperature dependence of the London penetration depth and of the superfluid density, whose fit gives an independent estimation of the gap amplitudes and information on their symmetry.
The two complementary techniques concur to indicate that $RbCa_2Fe_4As_4F_2$ presents *two gaps*, with clear signatures of *d*-wave-like nodal structures (i.e. with the order parameter changing sign on the same Fermi surface). Owing to the tetragonal symmetry of the compound, the most likely conclusion is that both the gaps are nodal. The PCARS spectra and the superfluid density were indeed very well fitted by a two-band $d - d$ model.
The evidence of nodal gaps persists even upon 5% Ni doping, that reduces the critical temperature from 30 K to about 20 K. This suggests that nodes are more likely to be symmetry-protected rather than accidental, and supports the two-band $d - d$ picture. Further indications in favor of this picture come from the large anisotropy of the

London penetration depth, which is weakly dependent on temperature and fully compatible with the $d - d$ model.

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# Topological Quantum Matter

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Topological matter harnessing long-range effects of interactions between topological excitations is a fundamental paradigmatic constituent of the modern physics of condensed matter. One of the most striking phenomena revealing topological manifestations is a is a widely investigated paradigmatic quantum phase transition, superconductor-insulator transition (SIT). A topological BF gauge theory reveals that the quantum phase structure of the superconductor-insulator transition (SIT) is governed by the competition and topological interactions between three quantum orders: (i) Bose condensate of the Cooper pairs, which is the superconductor with no Higgs field; (ii) the condensate of magnetic monopoles, which is the superinsulator, and (iii) the no-condensate state called Bose- or strange metal. We demonstrate that the Bose metal is a bosonic topological insulator where bulk transport is suppressed by mutual statistics interactions between out-of-condensate Cooper pairs and vortices (i.e., by the large topological mass) and the longitudinal conductivity is mediated by symmetry-protected gapless edge modes. We find that superinsulators realize a single-color version of quantum chromodynamics and establish the mapping of quarks onto Cooper pairs. We reveal that the mechanism of superinsulation is the linear binding of Cooper pairs into neutral "mesons" by electric strings, which emerge from interactions between charges due by the condensate of magnetic monopoles. We construct a unifying effective field theory capturing all universal characteristics of high-temperature superconducting materials (HTS) and explaining the observed phase diagram. The uncovered topological competition between the magnetic monopole condensate and Cooper pair condensate establishes topological nature of the HTS. Finally, we reveal the existence of superconductors where the Anderson-Higgs mechanism of screening of electromagnetic fields must be replaced by the Deser-Jackiw-Templeton topological mass generation. These superconductors are inherently inhomogeneous granular superconductors. This topologically driven superconducting state is a novel type-III superconductivity.

# Complex phase-fluctuation effects and novel vortex configurations in superconducting Nb-based nanostructures

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In the first part of the talk we will present a joint experimental and theoretical inversitagation of complex phase-fluctuation effects correlated with granularity in NbN superconducting nanofilms [1]. Superconducting nanofilms are tunable systems that can host a 3D-2D dimensional crossover, leading to the Berezinskii-Kosterlitz-Thouless (BKT) superconducting transition approaching the 2D regime. Reducing further the dimensionality, from 2D to quasi-1D, superconducting nanostructures with disorder can generate quantum and thermal phase slips (PS) of the order parameter. Both BKT and PS are complex phase fluctuation phenomena of difficult experimental detection. Here, we have characterized superconducting NbN nanofilms thinner than 15 nm, on different substrates, by temperature dependent resistivity and current-voltage (I-V) characteristics. Our measurements have evidenced clear features related to the emergence of BKT transition and PS events. The contemporary observation in the same system of BKT transition and PS events and their tunable evolution in temperature and thickness, has been explained as due to the nano-conducting paths forming in a granular NbN system. In one of the investigated samples we have been able to trace and characterize the continuous evolution in temperature from quantum to thermal PS. Our analysis has established that the detected complex phase phenomena are strongly related to the interplay between the typical size of the nano-conductive paths and the superconducting coherence length.

In the second part of the talk, the focus will be on a theoretical study of novel vortex configurations and prediction of resistive states in superconducting nanostripes, through a numerical solution of the Ginzburg-Landau equations [2]. The importance of confinement in quasi-1D geometries (e.g., superstripes) has been predicted in the pioneering works of Bianconi and Perali [3-5]. Understanding the behaviour of vortices under nanoscale confinement in superconducting circuits is of importance for development of superconducting electronics and quantum technologies. Using numerical simulations based on the Ginzburg-Landau theory for non-homogeneous superconductivity in the presence of magnetic fields, we detail how lateral confinement organises vortices in a long superconducting nanostripe, and present a phase diagram of vortex configurations as a function of the stripe width and magnetic field. We discuss why average vortex density is reduced and reveal that confinement also has profound influence on vortex dynamics in the dissipative regime under sourced electrical current, mapping out transitions between asynchronous and synchronous vortex rows crossing the nanostripe as the current is varied.

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# Test of the mechanism of high Tc superconductivity and strange metal phase controlled by quantum geometry in artificial nanoscale heterostructures at atomic limit

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After 37 years from the discovery first-principles quantum material design of the optimal topology of artificial 2-5 nm heterostructures makes possible to predict high Tc superconductors on demand shedding finally light on the mechanism of high temperature superconductivity (HTS) in cuprate perovskites. We present a theory which predicts the superconducting Tc, multiple gaps and T-linear resistivity in artificial superlattice of quantum wells where quantum geometry controls quantum functionality. Advances in 2-5 nm technology in Stuttgart makes now feasible to verify theory prediction in artificial superlattices of quantum wells. HTS is reached by cooperative interplay of the Rashba spin-orbit coupling (RSOC) due to the internal electric field in interface superconductivity joint with unconventional e-ph interaction at unconventional Lifshitz transitions in nanoscale superlattices of metallic and insulator units [1-4].
We provide a computer code that makes possible to design on demand macroscopic quantum functionality controlling the topological Lifshitz transitions, shape resonances between superconducting gaps in subbands controlled by resonant scattering and quantum configuration interaction between open and closed pairing channels [2,3]. Our results provide a quantitative tool for material design of new high temperature superconductors [4,5] made of particular superlattices of quantum layers at 2-5 nm scale. Finally we show the key role of fine control of the geometry of artificial heterostructures made of quantum wells of undoped insulating units intercalated by metallic units forming a superlattice of 2D interface space charge layers separated by transparent potential barriers. Both the superconducting dome and the T-linear resistivity of the strange metal phase near optimum doping in $La_{2-x}Sr_xCuO_4$ are predicted shedding light on the theory of the high Tc mechanism in cuprate perovskites after 37 years from the discovery.

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# Engineering of Complex Oxide Superconducting Heterojunctions

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Two dimensional (2D) phenomena in complex oxides heterointerfaces attract attention of scientific community during the last ten years due to their multitudinous functionalities and promising applications. The progress in this field has been mostly due to the substantial improvements of the deposition techniques.
One of the perspective method is atomic layer-by-layer (ALL) oxide molecular beam epitaxy (MBE). Compared with other techniques the MBE method has several extraordinary advantages, which allow to achieve a precise stoichiometry and deposition control to synthesis high quality oxide films and different heterostructures, as well as to understand the dynamics of the deposition process itself, what is crucial for the physics and chemistry of the oxide heterointerfaces.
In my talk I present recent results obtained by the oxide MBE synthesis of high temperature superconducting (HTSC) heterogeneous superlattices constructed by repetition of non-superconducting $La_2CuO_4$ and $La_{1.55}Sr_{0.45}CuO_4$ epitaxial layers with different thicknesses. The dependence of the superconducting transition temperature versus layers thicknesses is a subject of our discussion. Different possible scenarios will be considered. In conclusions I present implications of these results on a future work.

# Topological gauge theories of Josephson junction arrays and 2D superconductors

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I will show that Josephson junctions arrays are described by a topological gauge theory [1]. As an immediate consequence, they have three quantum phases at low temperatures, the familiar superconducting phase, but also a dual superinsulating phase [1] and an intermediate (bosonic) topological insulator phase, which is often called anomalous, or Bose metal phase [1]. In this phase the resistance saturates at low temperatures because of transport by edge excitations. In the superinsulating phase, the resistance diverges at a finite temperature, due to magnetic monopole instantons [2,3]. I will further show that all superconductors behave as Josephson junction arrays in the ultrathin, planar limit because of strong infrared divergences [4].

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# Type III Superconductors

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Superconductivity remains one of most fascinating quantum phenomena existing on a macroscopic scale. Its rich phenomenology is usually described by the Ginzburg-Landau (GL) theory in terms of the order parameter, representing the macroscopic wave function of the superconducting condensate. The GL theory addresses one of the prime super- conducting properties, screening of the electromagnetic field because it becomes massive within a superconductor, the famous Anderson-Higgs mechanism. Here I describe another widely-spread type of superconductivity [1] where the Anderson-Higgs mechanism does not work and must be replaced by the Deser-Jackiw-Templeton topological mass generation and, correspondingly, the GL effective field theory must be replaced by an effective topological gauge theory. This superconducting mechanism is realised in planar superconducting films as shown in [2]. These superconductors are inherently inhomogeneous granular superconductors, where electronic granularity is either fundamental or emerging. I will show that the corresponding superconducting transition is a three-dimensional (3D) generalization of the 2D Berezinskii-Kosterlitz-Thouless (BKT) vortex binding-unbinding transition. The binding- unbinding of the line-like vortices in 3D results in the Vogel-Fulcher-Tamman (VFT) scaling [3] of the resistance near the superconducting transition. I report experimental data fully confirming the VFT behavior of the resistance.

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# Possible manifestations of Q-ball mechanism of high-$T_c$ superconductivity in diamagnetic response and X-ray diffraction

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Recently proposed Q-ball mechanism of pseudogap state and high-Tc superconductivity in cuprates [1]-[3] has experimental manifestations [4]. Q-ball charge Q gives the number of condensed elementary bosonic excitations in a CDW/SDW fluctuation of finite amplitude and volume. It is found that attraction between elementary bosonic excitations inside the stable Euclidean Q-balls is triggered self-consistently by condensing Cooper/local pairs below pseudogap transition temperature T*. Euclidean Q-balls charge Q is conserved in Matsubara time due to U(1) symmetry of the effective theory under global rotation of phases of the Fourier amplitudes of the CDW/SDW fluctuations. Conserved Q scales as ~ $TM^2V$, with temperature T, Q-ball's volume V, and fluctuation amplitude M. Simultaneously, Q-ball energy $E_Q$ scales as ~ QT. These leads to inverse proportionality between volume V and X-ray scattering intensity A ~ $M^2$ of the most probable Q-balls at a given temperature. Besides, the theory predicts, that superconducting condensate forms at T* inside the Q-balls starting from vanishingly small superconducting density. Hence, the most probable Q-ball volume should increase when temperature approaches T* from below, since according to Ginzburg-Landau theory the minimal radius of superconducting sphere increases in the vicinity of the transition temperature $T_c$, which for an individual Q-ball coincides with T*. These behaviors are found in micro X-ray scattering experiments [4]. Also, a diamagnetic moment of the Q-ball gas as function of magnetic field above $T_c$ is calculated and favourably compares with experiment in cuprates [5].

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# Electronic structure studies on iron-based superconductor parent compounds via magnetotransport and quantum-oscillation measurements

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We have been studying electronic structures of iron-based superconductor parent compounds by using traditional techniques like magnetotransport and quantum-oscillation measurements. In this talk, I will present recent results on CaFeAsF. which is a variant of 1111-type arsenides [1].
(1) Topological frequency shift. The Fermi surface of CaFeAsF consists of a normal hole cylinder and a pair of Dirac electron cylinders [2]. We have found that the quantum-oscillation frequency due to the latter exhibits a characteristic $T^2$ dependence [3] as is theoretically anticipated [4].
(2) $\nu = 0$ quantum Hall state. The resistivity of CaFeAsF exhibits an anomalous increase as magnetic fields above $B$ = 30 T are applied along the $c$ axis at low temperatures, and the temperature dependence becomes nonmetallic [5]. We have measured longitudinal and Hall resistivities up to 45 T and found that both $\sigma_{xx}$ and $\sigma_{xy}$ approach zero above about 40 T. Our analysis indicates that the Landau-level filling factor is 2 for both electrons and holes. We therefore suggest that the nonmetallic state may be ascribed to the $\nu = 0$ quantum Hall state [6].
(3) In-plane electronic anisotropy. We have measured the interlayer resistivity on detwinned samples under magnetic fields with varying field directions [7]. Counterintuitively, the interlayer resistivity is larger in the longitudinal configuration ($B \parallel I \parallel c$) than in the transverse one ($B \perp I \parallel c$). The interlayer resistivity exhibits a so-called coherence peak under in-plane fields and is highly anisotropic with respect to the in-plane field direction. The magnetoresistance is seven times larger for $B \parallel b_o$ than for $B \parallel a_o$ at $T$ = 4 K and $B$ = 14 T. Our theoretical calculations based on the first-principles electronic band structure qualitatively reproduce these observations but underestimate the magnitudes of the observed features.

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# Coexistence and interplay between superconductivity and ferromagnetism in $EuFe_2(As_{1-x}P_x)_2$: a microwave analysis

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The coexistence of superconductivity (SC) and ferromagnetism (FM) in iron based superconductors containing magnetic rare-earth-metal elements, offers the unique possibility to study the interplay between these two orders in a broad range of temperatures. We report on a microwave analysis of the $EuFe_2(As_{1-x}P_x)_2$ compound that, in a narrow range of composition, shows a magnetic ordering temperature $T_M$ below the superconducting transition temperature $T_{SC}$. $EuFe_2(As_{1-x}P_x)_2$ samples were characterized by a coplanar waveguide resonator technique, giving access to the complex magnetic susceptibility and the London penetration depth [1]. We observed several features in the imaginary component of the susceptibility [2], revealing complex dynamical processes. To discuss this rich phenomenology, we compared these results with those obtained on the same samples by different techniques (MFM, muon-spin spectroscopy, ac susceptibility, …). A focus of the discussion is on the dynamics of superconducting vortices and antivortices influenced by the underlying structure of magnetic Meissner domains, with the identification of intra and interdomain depinning processes [3]. Moreover, we observed the crossover from "ferromagnetic superconductivity" (with $T_{SC}>T_M$) to "superconducting ferromagnetism" (with $T_{SC}<T_M$), driven by P-doping and by disorder induced by 3.5-MeV proton irradiation [4,5], suggesting that SC and FM in $EuFe_2(As_{1-x}P_x)_2$ are two rather independent but competing orders: as the former is suppressed by irradiation, the latter manifests at slightly higher temperatures.

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# Orbital-selective Mott physics in iron-based ladder systems

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Superconductivity in Fe-based two-leg ladder materials under high pressure was discovered [1] opening new directions to improve our understanding of iron-based superconductors. Numerical studies of strongly correlated electronic multi-orbital models can be performed with high accuracy in quasi-one dimension using numerical techniques, such as DMRG. We found exotic states in these systems arising from the Hubbard and Hund interactions.
An ``Orbital Selective Mott Phase'' (OSMP) characterized by the formation of magnetic block states in which a block of N spins up alternate with a block of N spins down [2,3,4,5] was observed in a wide range of Hubbard and Hund couplings and electronic fillings. Neutron-scattering experiments on iron-based 123 ladder materials, where OSMP is relevant, already confirmed our theoretical prediction of block magnetism (magnetic order of the form ↑↑↓↓) [6].
In addition, we found that competing energy scales present in the low-dimensional OSMP induce a new kind of exotic magnetic order, the block–spiral state [4] with magnetic islands forming a spiral propagating through the chain but with the blocks rigidly rotating. The block–spiral state is stabilized without any apparent frustration, the common avenue to generate spiral arrangements in multiferroics. By examining the behavior of the electronic degrees of freedom, parity-breaking quasiparticles were revealed [4]. We also numerically predicted that OSMP could be observed in Ce2O2FeSe2 [7].

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# Conductivity, magnetism and thermoelectric effect by topological excitations in a quasi-1D organic ferroelectric

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The concept of topology has been widely applied to condensed matter, leading to the identification of peculiar surfaces or lines separating topologically distinctive regions in 3D and 2D systems, respectively. In these dimensions, the topological boundaries are immobile ones built in the systems. In 1D, however, the topological boundaries are points, which can be mobile, and their motion may produce emergent phenomena. The quasi-one-dimensional donor-acceptor system, TTF-CA, shows a charge-transferred neutral–to-ionic (NI) transition when pressure is increased. Our pressure study found that the pressure-induced NI transition changes to the NI crossover above 250 K [1]. On the NI crossover, thermally activated NI domain walls with topological (fractional) charges generate high conductivity despite that both neutral and ionic phases are insulators [1]. In the ionic phase hosting a donor-acceptor dimer liquid, charge and spin solitons are thermally excited as mobile defects interrupting ferroelectric dimer orders [2]. On cooling, the solitons exhibit a binding transition to cause inversion-symmetry breaking ferroelectric order [2]. I review the experimental evidence of these mobile topological excitations in TTF-CA [3] and show our ongoing research on the thermoelectric effect and non-reciprocal charge transport in the quest for novel electronic and thermoelectric materials.

The work presented here was performed in collaboration with K. Sunami, R. Takehara, T. Baba, F. Iwase, M. Hosoda, T. Nishikawa, A. Katogi, K. Miyagawa, T. Miyamoto, H. Okamoto, R. Kato and S. Horiuchi.

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# Field control of fluctuation-driven modulated magnetism in the metallic ferromagnet PrPtAl

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Strong electronic particle-hole fluctuations in metals render ferromagnetic phase transitions first order and stabilize modulated magnetic phases at low temperatures. This phase reconstruction can be understood in terms of a fermionic quantum order-by-disorder (QOBD) mechanism: the Fermi surface deformations associated with the modulated order enlarge the phase space of electronic fluctuations, leading to a lowering of the free energy. We will apply this theory to PrPtAl which shows helimagnetic order on the border of ferromagnetism below 5.5K [1]. This helical order is distorted due to a small magnetic anisotropy in the *a-b* plane. As evidenced by magnetic resonant X-ray scattering [2], the modulated magnetism can be controlled by a small magnetic field along the harder *b* direction, resulting in a fan state that extends to zero temperature. Experimental evidence supporting the QOBD explanation is provided by the large increase of the $T^2$ coefficient of the resistivity and the direct detection of enhanced magnetic fluctuations with inelastic neutron scattering, across the field range spanned by the fan state.

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# Magnetic Excitations in the Itinerant Electron Ferromagnet Iron Throughout the Brillouin Zone

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As canonical examples of strongly correlated electron magnetism, the spin dynamics of the transition metal ferromagnets have been addressed both theoretically and experimentally for decades. Understanding of the spin dynamics of these elements is of interest not just because they are the classic examples of itinerant electron ferromagnets, but because they are model systems against which to test and benchmark the latest experimental and calculational tools.
We report the results of a complete measurement of the spin wave excitations and imaginary part of the generalised magnetic susceptibility $\chi(\mathbf{q},\omega)$ in elemental iron throughout the Brillouin zone and at energies up to 0.4eV using neutron spectroscopy. In contrast to earlier triple axis spectrometer (TAS) results [1,2], the lower energy spin waves do not show a marked decrease in intensity above 0.1 eV, a result which had been ascribed to the spin waves entering the Stoner continuum. We discuss this and other experimental differences. We also compare the data with calculations of the generalised susceptibility we have performed using time dependent DFT implemented in the KKR package described in ref. [3], and also in the Questaal implementation [4]. We find that the computational results are robust, and that overall there is reasonable qualitative agreement between the calculations and the data once a scaling factor of ≈ 0.75 is applied to the energy scale in the calculations.

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# Towards the integration of CMOS electronics in the emergent high temperature superconducting phase of twisted bilayers cuprate heterostructures

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Twisted interfaces between stacked van der Waals (vdW) cuprate crystals presents a platform where anisotropic superconducting order parameters interact at high temperature. Employing a novel cryogenic assembly technique, we construct twist vdW Josephson junctions (JJ) at atomically sharp interfaces between $Bi_2Sr_2CaCu_2O_{8+x}$ crystals with quality approaching the limit set by intrinsic JJ and we demonstrate a path to engineered emergent superconductivity at high temperature. Unfortunately, these systems are unstable and degrade quickly when exposed to elevated temperatures, oxygen, water, or organic solvents, limiting their processing in cleanroom and application for quantum hardware components. In the conclusion of the talk, we will show the first steps for the resolution of this problem by introducing a novel methodology to integrate CMOS electronics in these systems, which could be used for on-chip next generation of quantum technologies operating near nitrogen boiling temperatures. We show that electrical contacts can be established through transfer-printable circuits embedded in SiNx nanomembranes. The membrane incapsulates the material shielding it from the environment, while via contacts are used to form the electrical contacts.

# Superconducting microwave circuits with novel superconductors for material exploration and quantum technology

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Superconducting circuits (SCs) are quantum devices that display many of the effects of atomic systems but are made up of macroscopic microwave circuit elements. Their tunability, high coherence, and strong coupling has led to their rapid development as a leading implementation of quantum hardware. Traditional SCs are made using known superconductors such as aluminium or niobium, but the integration of novel superconductors (e.g. heavy-fermions or cuprates) as part of the circuit can lead to new scientific insights and new capabilities. Such hybrid circuits are ideal sensors, capable of measuring the superconducting gap structure of new unconventional superconductors using $\mu m$-sized samples, which have thus far been inaccessible. Once we have good control of the hybrid devices, the unique properties of unconventional superconductors can also be used to make new devices from quantum technology applications. This talk will introduce superconducting circuits and how the can be used as probes of unconventional superconductivity. We will then discuss challenges in combining such materials into devices and fabricating high quality hybrid SCs and how they can be overcome, and present preliminary measurements of hybrid devices.

# Unconventional superconducting quantum devices

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Recent advances in creating van der Waals heterostructures hosting ultrathin electronic states and in the fabrication of hybrid Josephson nanostructures opened new research pathways aimed at understanding and controlling the rich array of exotic electronic properties and functionalities emerging in these hybrid superconducting systems. In this talk, after bird's eye introduction on superconducting quantum devices, we focus on the potentialities offered by the integration of superconducting nanostructures and hybrid Josephson junctions in standard quantum superconducting nanocircuits. We discuss in particular the possibility to exploit conventional superconducting qubits as probes of noise fluctuations generated by these heterostructures [1,2].

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# Elementary interactions in condensed matter analyzed by ultrafast soft x-ray absorption spectroscopy

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Interactions among the charge, spin, and lattice degrees of freedom in complex materials occur on energy scales of few meV to several 100 meV, i.e. on pico- to femtosecond timescales. Extending the element- and site-specificity of soft x-ray absorption spectroscopy into the time domain provides detailed insight into the elementary interactions leading to, e.g., energy transfer dynamics across interfaces in $[Fe/MgO]_n$ heterostructures [1,2] and, in combination with time-dependent density functional theory, into the correlation of local electron correlations and spin dynamics in fcc Ni [3]. While the high soft x-ray flux at x-ray free electron lasers can be a challenge due to sample damage it can also be exploited in the analysis of non-linear effects to analyze elementary interactions [4]. The use of circularly polarized soft x-ray pulses extends these capabilities to studies of the transient magnetization and high frequency spin fluctuations interacting with the crystal lattice. These findings are based on a continuous development of the experimental endstations at the user facilities [5,6] and are currently extended to oxides and organic materials.

These activities were conducted in a large collaboration, involving the SCS beamline at the European X-FEL, Hamburg; the Femtospex beamline at BESSY II, Berlin; the MeV ultrafast electron diffraction facility at SLAC, Stanford; Uppsala University; Konstanz University, University of Duisburg-Essen and many others, see the references below. Funding by the Deutsche Forschungsgemeinschaft through CRC 1242 is gratefully acknowledged.

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# Coherent emission from surface Josephson plasmons in charge-ordered cuprates

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Terahertz emission is observed after impulsive optical excitation only in media in which inversion or time-reversal symmetry are broken [1]. For this reason, in centrosymmetric superconductors this phenomenon is generally not seen, unless a current bias or a magnetic field are applied. Here, we report evidence for anomalous terahertz emission in unbiased cuprates of the $La_{2-x}Ba_xCuO_4$ and $YBa_2Cu_3O_{6+x}$ family [2], in which charge order coexist with superconductivity. A sharp response at frequencies immediately below the bulk Josephson plasma resonance suggests that this radiation originates from surface Josephson plasmons [3], which are generally dark modes but appear to be coupled to the electromagnetic continuum in these materials. We attribute this activated anomalous emission to the fact that charge order breaks inversion symmetry in the out-of-plane direction and folds the plasmon dispersion curve onto the light cone [4].

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# Ultrafast pump-probe spectroscopic study of low-temperature phases in organic Dirac electron systems

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The series of organic charge transfer salts $\alpha$-$(ET)_2I_3$ ($\alpha$-ET), $\alpha$-$(STF)_2I_3$ ($\alpha$-STF) and $\alpha$-$(BETS)_2I_3$ ($\alpha$-BETS) have attracted attention as bulk crystalline topological materials. Recent studies suggest that the Dirac electron system is realized under pressure in the former salt [1] and is theoretically predicted under ambient pressure in the latter two salts[2,3]. At ambient pressure, in $\alpha$-ET, the resistivity steeply increases below $T$ = 135 K due to the charge ordering (CO) transition[4]. On the other hand, the resistivity increases more gradually in $\alpha$-STF below $T$ = 120 K and in $\alpha$-BETS below $T$ = 50 K than in $\alpha$-ET, but the origins of these increases in the resistivity remain unclear[4]. In this study, to obtain further insights into the low temperature electronic phases, the optical pump probe spectroscopy has been systematically carried out. $\alpha$-ET shows a change in the transient signal amplitude and anisotropy for the probe polarization, and divergence in the relaxation time at $T$ = 135 K, which are reasonably interpreted as the CO transition. In $\alpha$-STF, similar dynamics with $\alpha$-ET is observed below $T$ = 120 K but the divergent behavior of the relaxation time is not seen, indicating that a short-range CO is realized. In $\alpha$-BETS, the change in the signal amplitude is observed at $T$ = 50 K, but the anisotropy for the probe polarization and the relaxation time are almost unchanged. The difference in dynamics from the $\alpha$-ET and $\alpha$-STF suggests the appearance of other insulating phases, such as topological insulators, rather than the CO phase.

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# Magnetic flux trapping in high-$T_C$ superconducting hydrides

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Recent discoveries of superconductivity in various hydrides at high pressures have shown that a critical temperature of superconductivity $T_c$ can reach near-room-temperature values [1-3]. However, experimental studies are severely limited by high-pressure conditions, and electrical transport measurements have long been the primary technique for detecting superconductivity in hydrides. We implemented the non-conventional magnetic characterization of superconductors using the phenomenon of the trapped magnetic flux. Contrary to traditional magnetic susceptibility measurements, a magnetic response from the trapped flux is almost not affected by the background signal of the bulky diamond anvil cell due to the absence of external magnetic fields. Therefore, this method was especially successful for study of two near room-temperature superconductors $H_3S$ and $LaH_{10}$ which superconduct under pressure. The specific behavior of the trapped flux generated under zero-field-cooled and field-cooled conditions unequivocally proved superconductivity in these materials. In addition, we determined $T_c$, critical currents and their temperature dependence, the lower critical field $H_{c1}$, London penetration depth, full penetration field, pinning properties and flux creep. This approach can be a powerful tool not only for a routine screening of new superconducting materials at high pressures, but also for studying multiphase samples or samples having a low superconducting fraction at ambient pressure.

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# Coexisting superconductivity and charge-density wave in hydrogen-intercalated $TiSe_2$

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The recent discovery of near-to-room temperature superconductivity in hydrides under pressure has highlighted the potential of hydrogen as a dopant as well as a knob to tune the electronic and phononic spectra of a material. In this talk, we report the non-volatile control of the electronic ground state of octahedral titanium diselenide by means of electric field-driven hydrogen intercalation via the ionic liquid gating method [1]. Based on measurements of electrical transport, dc magnetometry, and muon-spin rotation, we demonstrate that charge-density wave and superconductivity coexist in $H_xTiSe_2$ through most of the electronic phase diagram, with nearly doping-independent characteristic transition temperatures [1]. We will discuss the results of ab initio calculations tackling the unique role of the hydrogen doping in attaining a full reconstruction of the band structure, opposed to a mere rigid electron doping of pristine $TiSe_2$ [1]. Emphasis will be given to the results of our $^1H$ nuclear magnetic resonance measurements, highlighting how the low-frequency dynamical properties of the charge-density wave affect the spin-lattice relaxation of the nuclear magnetization [1,2].

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# Photovoltaic effect in symmetry engineered van der Waals nanomaterials

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Symmetries of two-dimensional van der Waals crystals can be controlled by making curved structures, fabricating heterointerfaces, changing stacking sequences, applying uniaxial strain etc. In such van der Waals nanomaterials with reduced symmetries, unique structures, which are absent in the original crystals, appear and cause exotic physical properties and functionalities. In this talk, I will talk about photovoltaic effect reflecting the emergent electric polarization in symmetry engineered van der Waals nanomaterials [1-4]. We report the giant enhancement of intrinsic photovoltaic effect and focus on its characteristic behaviors. Potential microscopic mechanisms and future perspectives will be also discussed.

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# Multiorbital Mott physics: from models to materials and quantum simulators

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The last decades have provided us with clear evidence that multi-orbital strongly correlated systems display remarkable properties which are not accessible in single-band systems like the celebrated Hubbard models. I will review some of the most important novel phenomena of multiorbital Hubbard systems, ranging from Hund's driven correlations [1] to orbital-selective Mott physics [2], discussing how they have been identified and understood in model systems. I will then address the realization of these phenomena in iron-based superconductors [3], where I will discuss their relation with superconductivity [4] and nematic order [5] and the direct realization of an orbital-selective Mott system in a cold-atom quantum simulator where the SU(N) symmetry is broken in a controlled way [6,7].

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# Resonant X-ray Inelastic Scattering in $FeSe_{1-x}Te_x$

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Reports of superconductivity in few layers of FeSe deposited in $SrTiO_3$ substrates, with critical temperatures reaching Tc = 65 K [1,2] have renewed the interest in Fe-chalcogenide superconductors. The superconducting transition temperature, Tc, in bulk $FeSe_xTe_{1-x}$ under Te substitution presents a maximum for intermediate Te content. This observation suggests phase separation between FeSe and FeTe phases. Also, X-ray absorption near edge spectroscopy (XANES) in this system suggests that astructural phase separation results in an inhomogeneous electronic structure.[3] Resonant Inelastic X-ray Scattering (RIXS) yields additional information about the electronic structure as it probes both unoccupied states above the Fermi level, and occupied states below. We present calculations of RIXS spectra in $FeSe_xTe_{1-x}$ for x= 1,0.75, 0.50, and 0. This calculation method are based on a one-electron approximation that expresses the cross section as the convolution of the x-ray absorption spectra and x-ray emission spectra. For these calculations we have used a Density Functional Theory approach, based on a one-electron approximation, spherically symmetric self-consistent pseudopotentials, previously used in X-ray absorption spectroscopy calculations in Fe-chalcogenide superconductors, based on an local inhomogeneous model of the atomic structure[3]. These calculations show the same trends observed in experimental RIXS spectra.

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# Quantum Monte Carlo study of a bilayer $U(2)\times U(2)$ symmetric Hubbard model

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We carry out a sign-problem-free quantum Monte Carlo calculation of a bilayer model with a repulsive intra-layer Hubbard interaction and a ferromagnetic inter-layer interaction. The latter breaks the global $SU(2)$ spin rotational symmetry but preserves a $U(2)\times U(2)$ invariance under mixing of same-spin electrons between layers. We show that despite the differences in symmetry, the bilayer model exhibits the same qualitative features found in the single-layer Hubbard model. These include stripe phases, whose nature is sensitive to the presence of next-nearest-neighbor hopping, a maximum in the Knight shift that moves to lower temperature with increasing hole doping, and lack of evidence for intra-layer $d$-wave superconductivity. Instead, we find at sufficiently low temperatures inter-layer spin-polarized pairing due to the ferromagnetic interaction. The consequent superconducting state competes with the stripe phases.

# Dynamical study of the origin of the charge density wave in $A V_3 Sb_5$ compounds

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Systems containing the ideal kagome lattice can exhibit several distinct and novel exotic states of matter. An example of such systems is a recently discovered $A V_3 Sb_5$ ($A$=K, Rb, and Cs) family of compounds. Here, the coexistence of the charge density wave (CDW) and superconductivity is observed. We study the dynamic properties of the $A V_3 Sb_5$ systems in the context of origin of the CDW phase. We show and discuss the structural phase transition from P6/mmm to C2/m symmetry that is induced by the presence of phonon soft modes. We conclude that the CDW observed in this family of compounds is a consequence of the atomic displacement, from the high-symmetry position of the kagome net, in the low-temperature phase. Additionally, using the numerical ab initio methods, we discuss the charge distribution on the $A V_3 Sb_5$ surface. The consequence of realization of the C2/m structure on the electronic properties is discussed. We show that the electronic band structure reconstruction and the accompanying modification of the density of states correspond well to the experimental data.

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# Quantized gauge fields with massive Higgs-like boson fields and anomalous properties in high-Tc cuprates

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The relation between superconductivity and the pseudogap is a matter of on going debate. Inelastic x-ray scattering experiments have shown that damped magnetic excitationa are present inside the electron-hole spin-flip continuation (up to ~300 meV) in doped high-Tc cuprates [1]. The frequency-dependent dissipation of the optical conductivity has been interpreted as the coupling of holes to bosonic excitations of high energies ( ~300 meV) [2]. Kanazawa and coworkers [3-5] have introduced quantized massive collective-gauge fields with massive Higgs-like bosons around the doped holes as collective modes, which contain effects of Jahn-Teller fluctuation, charge fluctuation, and spin fluctuation.

In this study, taking account of the interaction between the hole and massive Higgs-like boson, we suggest strongly that massive Higgs-like boson fields, which contain effects of Jahn-Teller fluctuation, charge fluctuation, and spin fluctuation, might be mediating Cooper pairing in high-Tc cuprates.

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# Half-integer combined vortices in incommensurate spin density waves

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Spin density waves (SDW) are commonly observed in low-dimensional electronic systems. They demonstrate such common feature of all incommensurate electronic crystals as a lability to the electric field and a spectacular nonlinear conduction by the collective sliding. Static and transient topological defects emerge mandatory such as space vortices (the dislocations) and space-time vortices (the phase slip centers). This common picture is further enriched in SDWs which possess a high degree of degeneracy corresponding to symmetry and topology of a complex vector. This order parameter admits a formation of an intriguing complex topological object: a half-integer dislocation coupled with a semi-vortex of the staggered magnetization. Splitting of conventional integer vortices into pairs of these objects is promoted by a high cost of Coulomb energy of the charged phase component of the combined vorticity which opposes a confinement force coming from the spin anisotropy. In the sliding state, these objects can appear as a sequence of π- phase slips which should double the rate of the experimentally observed "narrow band noise (NBN)" generation.

Beyond the qualitative picture and analytical results, we present also examples of numerical studies demonstrating the splitting of the conventional dislocation into two half-integer vortices. The results are based on solutions of partial differential equations describing a common evolution of the components of the order parameter, the self-consistent electric potential, and the distribution of normal carriers.

# Emergent quantum critical point for charge-density-wave ordered materials

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Strongly correlated charge-density-wave systems have two forms of gap formation: (i) one is via the ordering of the lattice, which reduces the translational symmetry and (ii) the second is via the Mott transition, which creates a gap without changing the translational invariance.

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# Evolution from charge-order phase to high-temperature superconductivity

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The origin of high-Tc superconductivity (HTSC) of copper oxide superconductors remains one of the most important challenges in condensed matter physics. HTSC can be obtained through doping a Mott insulator or cooling a strange metal, and great efforts have been put forward to understand how Cooper pairs form and condense in the past three decades. However, there is still no consensus on the critical process of the emergence of superconductivity when electron-electron correlations dominate. We have carried out high-resolution resonant inelastic X-ray scattering and scanning tunneling microscopy studies, combining bulk and surface, momentum- and real-space information to address this issue. In this talk, I will present our recent results on Bi2212 [1] and LSCO [2] cuprates. These include: (i) How high-temperature superconductor emerges near the onset of Tc dome [1]; (ii) We reveal a charge order (CO) in overdoped $La_{2-x}Sr_xCuO_4$ ($0.35 \leq x \leq 0.6$) beyond the superconducting dome [2]. Our results suggest that high-temperature superconductivity emerges out of the charge-ordered phase.

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# Recent findings in pressurized high-Tc superconductors

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Pressure is an effective and a clean method to tune the basic structural and corresponding electronic properties of materials without changing the chemistry, and can help to discover new phenomena and understand their corresponding physics. In this talk, I will report our recent new findings from our recent high-pressure studies, including the quantum phase transition from superconducting to insulating-like state [1] and the crossover from two-dimensional to three-dimensional superconducting states in the bismuth-based cuprate superconductor [2]; the observation of breakdown of both strange metal and superconducting states at a pressure-induced quantum critical point in iron-pnictide superconductors [3] and pressure-induced coevolution of transport properties and lattice stability in $CaK(Fe_{1-x}Ni_x)_4As_4$ (x= 0.04 and 0) superconductors with and without spin-vortex crystal state [4].

These works are in collaboration with Profs. GD Gu, CT Lin, XJ Zhou, XG Qiu, HQ Luo, SL Li, Q Wu, T Xiang, N Ni and JR Cava.

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# Local charge dynamics in the amorphous state of 1T-$TaS_2$

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For the last 10 years, the interest in 1T-$TaS_2$ is not fading thanks to its well-known metastable hidden (H) state which can be reached only at non-equilibrium conditions at low temperatures [1]. The charge density wave (CDW) in the material forms domains and domain walls at such conditions. This state is stable for extended periods at low temperatures but relaxes back to the commensurate CDW (C state) upon heating [2]. Except for the most studied H state, 1T-$TaS_2$ can undergo more phase transitions to different states [3], including the amorphous (A) state, which is the topic of this study.
The work is focused on the scanning tunnelling microscopy studies of the local charge dynamics in the laser-induced A-state of 1T-$TaS_2$ in the context of the time-domain phase diagram of the material. Our studies show local dynamical reconfigurations between 1/13, 1/12 and amorphous orders on a timescale of $10^{-1}$ ~$10^3$ s, over length scales 2~10 nm. The origin of the fluctuations is considered to be predominantly thermal.

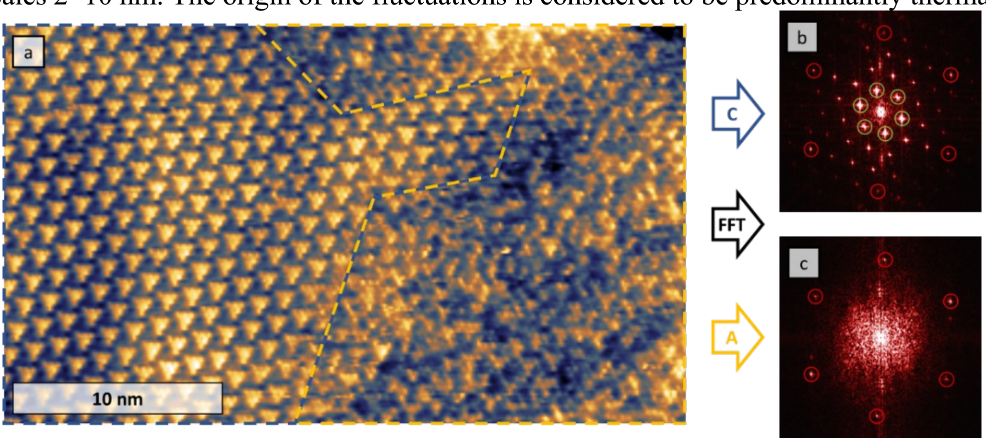


Fig. 1. a) STM image of the border between C (blue dashed line) and A (yellow dashed line) states of 1T-$TaS_2$ after exposure to a laser pulse. b-c) Fourier transform of C and A states, as marked by lines in (a). Polaron positions in FFT are marked with green and atom positions – with red circles.

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# Chaotic fluctuations in the fractionally charged spatial fabric of a polaronic Wigner crystal lattice

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Materials close to the Wigner crystal limit can exhibit very unusual metastable orders. A good example are the layered dichalcogenides which exhibit complex chiral domain states [1] and an amorphous Wigner glass [2], that appear after an external perturbation which forces the system through a symmetry breaking transition. New experimental evidence of characteristic polaronic local structural distortions well above CDW ordering temperatures from X-ray local structure analysis of 1T-$TaS_2$, implies that the complex charge ordering in this material is better described in terms of a polaronic Wigner crystal than a conventional CDW [3]. The application of the Wigner crystal paradigm leads to significant progress in understanding its complex metastable behaviour. In particular, charge injection is shown to lead to the charge fractionalization and entanglement with strong non-local effects that explains the remarkable robustness of the metastable state to local perturbations. The entangled fractionally charged network that results upon charge injection presents a topologically robust gapless space-time fabric for the propagation of single particle excitations that are measured by conventional transport measurements. On the other hand, new fast STM scanning techniques reveal unusual and hitherto unobserved chaotic mesoscopic polaron dynamics.

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# Ultrafast optical polarimetry in magnetic phases of Kondo semimetal CeSb

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The CeSb magnetic phase diagram is one of the most complex among lanthanide monopnictides. It contains at least 16 different magnetic phases in the *H-T* plane [1] comprising different sequences of ferromagnetic, with either up or down spin orientation, and paramagnetic (001) planes stacked along the *c*-axis. The complexity is thought to arise from the interplay of Kondo, spin orbit and crystal field effects. [1, 2] Lattice modulation in the magnetic phases was also observed [3].
The phase diagram [4, 5] and the magnetic excitations [1] were thoroughly studied by neutron scattering. Recently the sensitivity of the electronic structure to the magnetic phase has been demonstrated [6] and additional magnetic excitations were found in the ordered phases [7].
While the main features of the magnetic behavior are understood and successfully modeled using effective interaction approach [8] the microscopic origin of the interactions is still puzzling [2, 7]. An insight into non equilibrium dynamics of different phases might therefore shed some light to interplay of the different degrees of freedom. Here we present and discuss our investigation of the ultrafast non-equilibrium dynamics upon photo excitation in different magnetic phases in CeSb with focus on the magnetic excitations in the weakly nonequilibrium photoexcited state.

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# Advanced light-control of intertwined orders in high temperature superconductors

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Ultrashort light pulses provide new pathways to study and control intertwined orders beyond their equilibrium states. Recently, time-resolved optical and resonant X-ray scattering on $YBa_2Cu_3O_{6.67}$ have shown that the spatial coherence of charge density waves (CDW) can be enhanced nearly two times via photo-induced quenching of superconductivity. The results suggest that Cooper pairs stabilize topological defects within the CDW domains, such as CDW discommensurations [1]. In this talk, I will present a combination of ultrafast X-ray scattering and optical data on YBCO detailing such enhancement dynamics, as well as its reverse process, i.e., the photo-induced CDW melting. I will discuss the limitations of the current approach in terms of lifetime of the photo-induced states and present preliminary results based on tailored pulses designed to overcome such limitations and sustain non-thermal states beyond their intrinsic lifetime, opening new opportunities for light-control of quantum materials.

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# Relaxation of non-equilibrium quasiparticles in a mesoscopic scale superconductor

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Rapid development of micro- and nanofabrication methods have provoked interest and enabled experimental studies of electronic properties of a vast class of (sub)micrometer size solid state systems. Mesoscopic scale hybrid structures, containing superconducting elements, have become interesting objects for basic research studies and various applications, ranging from medical and astrophysical sensors to quantum computing. One of the most important aspects of physics, governing the behavior of such systems, is the finite concentration of non-equilibrium quasiparticles, present in a superconductor even well below the temperature of superconducting transition. Those non-equilibrium excitations might limit the performance of a variety of superconducting devices, like superconducting qubits, single-electron turnstiles and microrefrigerators. On the contrary, in some applications, like detectors of electromagnetic radiation, the non-equilibrium state is essential for their operation. It is therefore of vital importance to study the mechanisms of non-equilibrium quasiparticle relaxation in superconductors of mesoscopic dimensions, where the whole structure can be considered as an 'interface'. At early stages of research the problem was mostly studied in relatively massive systems and at high temperatures close to the critical temperature of a superconductor [1]. Lately various phenomena have been studied in hybrid superconductor-based nanostructures enabling spatial resolution of the relaxation process [2-8]. Here we report our recent experiments indicating presence of coherent non-equilibrium transport in a NIS solid state 'double slit' interferometer-type structures.

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# Magnetodynamics influence on the superconducting condensate in superconducting-magnetic hybrids

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In this work we theoretically studied the influence of magnetization dynamics in two different types of magnetic materials on the superconducting properties of the adjacent superconducting layer, i.e. the static and dynamic inverse proximity effect. Two types of magnets considered in the superconducting (S) bilayer are: a metallic layer of antiferromagnet with a spiral magnetic order of B20-family like MnSi (M); a ferro- or ferri-magnetic insulator (FI) under conditions of the ferromagnetic resonance (FMR).
Magnetodynamics, namely the magnonic relaxation as a result of a pulse magnetic field may change the preferred direction of the magnetic spiral and its orientation to the S/M interface. It changes the conditions of the inverse proximity effect, and respectively the critical temperature of a thin superconducting film. On this base we propose a superconducting spin valve (SSV) of a new type. Another possibility may be bilayer with a helimagnetic metal like Er or Ho magnetized to the saturation in an external magnetic field. Such SSV may be used as an element of superconducting memory for energy-efficient digital and quantum electronics [1-3] and has some advantages.
The influence of magnetization excitations in ferromagnetic insulator on the dynamics of superconducting condensate in the attached superconducting layer is also studied. The system of linearized Floquet-Usadel equations was solved numerically for different precession frequencies. Boundary conditions on the interface between ferromagnetic insulator and superconductor are derived in the limit of small spin mixing angle, the FMR precession frequency is considered to be small in comparison with the superconducting order parameter. We numerically solved the derived Floquet-Usadel equations and calculated non-stationary distributions of spin supercurrent and induced magnetization inside the superconductor in the hybrid structure.
The numerical experiments on spiral magnets were financially supported by the Russian Ministry of Education and Science, Megagrant project N 075-15-2022-1108, calculations of the FMR influence were supported by the Basic Research Program of the HSE University via the Mirror Laboratories collaboration project.

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# Spin-orbital mechanisms for negative thermal expansion

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The phenomenon of negative thermal expansion (NTE) deals with the increase of the lattice parameters and the volume of the unit cell when the material is thermally cooled. The NTE is typically associated with thermal phonons and anomalous spin-lattice coupling at low temperatures. However, the underlying mechanisms in the presence of strong electron correlations in multi-orbital systems are not yet fully established. Here, we investigate the role of spin-orbital entanglement [1] and lattice distortions [2] in setting out the NTE effect, by focusing on the physical case of layered Mott insulator $Ca_2CuO_4$ with $d^4$ configuration at each Ru ion site. We take the realistic Coulomb interactions [3] and employ the Slater-Koster parametrization to describe the electron-lattice coupling through the dependence of the *d—p* hybridization on the Ru-O-Ru bond angle. The evaluation of the minimum of the free energy at finite temperature by fully solving the multi-orbital many-body problem on finite size cluster allows us to identify the regime for which the system is prone to exhibit NTE effects. The analysis shows that the nature of the spin-orbital correlations is relevant to drive the reduction of the bond angle by cooling, and in turn the tendency toward a NTE. This is confirmed by the fact that a changeover of the electronic and orbital configuration from $d^4$ to $d^3$ by transition metal substitution [4] is shown to favor the occurrence of NTE in $Ca_2RuO_4$. This finding is in agreement with the experimental observations of a NTE effect which is significantly dependent on the transition metal substitution in the $Ca_2RuO_4$ compound.

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# Energy-scale phenomenology for condensation, pairing and phase diagrams of unconventional superconductors

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Since the discovery of high-Tc cuprates, we have made MuSR measurements of the superfluid density $n_s/m^*$ of unconventional superconductors (SC), and developed phenomenological discussions by combining / comparing the results with those from other methods and with the case of superfluid He. In particular, we showed: (a) the superfluid density scales with Tc; (b) the effective Fermi energy $T_F$ can be derived from the superfluid density, and the SC systems can be classified in a plot of Tc versus $T_F$; (c) in the Tc versus $T_F$ plot, one finds the actual Tc of unconventional SC's reduced from the hypothetical Bose Einstein Condensation temperature $T_{BEC}$ by at least a factor of 4-5; (d) Tc scales with the energy of the magnetic resonance mode in SC's and the roton energy in superfluid He with the same proportionality constant.

We then realized that $T_{BEC}$ has been detected by actual measurements as the onset temperatures of the vortex Nernst effect and the photo-excited transient superconductivity in the underdoped side of unconventional SC's, including cuprates, $A_3C_{60}$ and organic BEDT superconductors. This can be understood as the result of local and dynamic phase coherence starting to build up among pre-formed bosonic pairs. These observations can be viewed as consistent with expectations from BEC-BCS crossover influenced by the existence of competing order (antiferromagnetic (AF) order for SC and HCP solid order in superfluid He) which reduces Tc from $T_{BEC}$. The BCS condensation, however, apparently does not apply for the overdoped side of the cuprates, where the superfluid density does not follow the normal doped carrier density while Tc still scales with $n_s/m^*$.

In this talk, we present additional arguments related to the pairing mechanism by resorting to the plot of $k_BT_F$ versus the spin fluctuation energy J, and proposing the resonance between the spin and charge energy scales which defines the "optimal Tc" regions. Dynamic charge motion in the environment with AF fluctuations leads to (i) optimization of Tc at the resonating $E_F$ and J, (ii) an energy advantage for the pair formation, and (iii) phase separation / coexistence between bosons and fermions in the ground state of overdoped cuprate SC's. We shall also point out that 2-dimensional supefluid He films on uniform substrates, porous media, and $^4He$-$^3He$ mixture would give us a further insight as examples of condensation which follows Kosterlitz-Thouless theory free from the influence of competing order, and showing the behavior for co-existing bosons and fermions which can be compared with the case of overdoped cuprates.

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# Manipulation of Skyrmions lattice under resonant x-ray conditions: new light on some long standing problems

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The exposure of Skyrmion Lattice (SkL), as realized in CSO, to intense resonant soft X-ray beams evidences unexpected dynamic behavior. This helps to explain a series of phenomenology reported in literature and opens new questions on the fundamental interaction behind these topological magnetic charges. On the other hand, it allows to exclude some hypotheses, and unify some reports appeared in the recent past. We present CSX data and we build a simple interpretations highlighting the role of the electronic interactions underneath these exotic and interesting quasiparticles in the specific material, suggesting some new avenues of investigation in general for SkL.

# Strange metal behavior by overdamped short-range fluctuations in cuprates and elsewhere

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Anomalous metallic properties are often observed in the proximity of quantum critical points, with violation of the Fermi Liquid paradigm. We propose a scenario where, near a quantum critical point, dynamical fluctuations of the order parameter with *finite correlation length* mediate a nearly isotropic scattering among the quasiparticles over the entire Fermi surface [1,2]. This scattering produces a strange metallic behavior, which is extended to the lowest temperatures by an increase of the damping of the fluctuations. We identify one single parameter ruling this increasing damping when the temperature decreases, accounting for both the linear-in-temperature resistivity and the seemingly divergent specific heat [2,3] observed, e.g., in high-temperature superconducting cuprates and some heavy-fermion metals. The challenging issue is also addressed of the mechanisms inducing this seemingly divergent dissipation and local slowing down and its possible relation to a novel type of quantum criticality [4].

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# Coexistence of Charge Density Waves and Superconductivity in Layered $Cu_xTiSe_2$

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Copper-intercalated titanium diselenide ($Cu_xTiSe_2$) offers the possibility to study the interplay between superconductivity and charge density waves (CDW).
The parent compound $TiSe_2$ is a narrow band semiconductor and exhibits a CDW state that has been attributed in literature to either an excitonic mechanism or Jahn-Teller mechanism, both supported by a variety of experiments [1-3]. Furthermore, the CDW in $TiSe_2$ also exhibits chiral properties [4-6].
Scanning tunneling microscopy and spectroscopy of superconducting $Cu_xTiSe_2$ for a variety of doping concentrations reveal coexistence of charge density wave and superconductivity. We find that the amplitude of charge density wave modulation is strongly suppressed with respect to the underdoped case ($x < 0.06$), in agreement with what has been found from specific heat measurements [7] and in analogy to what happens to the charge density wave in $TiSe_2$ under pressure [8]. In our measurements, superconductivity exhibits BCS character . Application of the external magnetic field introduces the Abrikosov vortex lattice that is weakly pinned. The size of the vortex core extracted from vortex images corresponds to the one extracted from the upper critical field. Our results suggest that superconductivity and CDW coexist, and that the superconductivity is consistent with a single s-wave gap with an intermediate coupling strength of $2\Delta/kTc \sim 3.6 \div 3.7$ up to values of $x=0.08$.

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# Micro-Thermoelectric Devices and Nanostructured Topological Insulators

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This presentation introduces the current development of thermoelectric applications with a focus on thermoelectric microdevices [1,2] and tellurium-free thermoelectric modules [3]. Then, the influences of nanostructured topological insulators on the development of highly efficient thermoelectric materials will be highlighted.
In the second half of my talk, I will present thermoelectric transport characterisation using microstructured characterisation platforms on selected model systems such as magnetic nanowires, nanoobjects made of (magnetic) topological insulators and microstrips made of Weyl semimetals [4]. Especially, I will explain the correlations between surface-dominated transport in nanostructured topological insulators and their thermoelectric transport properties.

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# Cooper quartets in hybrid superconducting devices

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The phenomenon of superconductivity is essentially ascribable to the condensation of pairs of electrons in so-called Cooper pairs. Beyond this conventional phase of matter, highly exotic phases in which the condensate is formed by more complex aggregates such as Cooper quartet have been proposed, that remain so far elusive. We propose to engineer charge-4e superconductivity in a semiconductor-superconductor hybrid multi-terminal device beyond already existing proposals, and through engineering of an effective charge-4e condensate in quantum-dot superconductor structure with conventional systems.

# Magnetoelastic coupling in spin-orbit entangled Mott insulators

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Coupling between magnetic and lattice degrees of freedom plays an essential role in the physics of magnetic materials and is important for their applications. In magnets without orbital degeneracy, the lattice vibrations modulate the exchange coupling parameters, but do preserve the spin-rotational Heisenberg symmetry of the interactions. In the late transition metal compounds with unquenched orbital magnetism, however, the lattice vibrations affect the very form and symmetry properties of the effective magnetic Hamiltonians. Through the spin-orbit entanglement, Jahn-Teller orbital-lattice coupling in these compounds is converted into the anisotropic magnetoelastic interactions, whose form is dictated by lattice symmetry and thus can directly be manipulated by the external strains [1, 2]. These interactions have a profound impact on low-energy spin and lattice dynamics. In particular, they lead to a coherent superposition of the spin and sound waves (magnetoacoustic waves), suggesting that the spin-orbit entangled Mott insulators can be useful materials in the emerging field of magnonics.

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# Breaking of spatial inversion symmetry in anti-parallel-stacked transition metal dichalcogenides

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The development of mechanical exfoliation and dry-transfer techniques[1,2] has made it possible to stack two-dimensional flakes dynamically and fabricate new materials that cannot be synthesized through thermodynamic processes. In such composite flakes, changes in the symmetry of the total system lead to a variety of emergent physical properties that would not appear in each component flake alone. [3] Here, we fabricated an anti-parallel-stacked bilayer ReSe2, which is expected to lose the spatial-inversion-symmetry by stacking the centrosymmetric monolayer flakes [4] in the opposite directions. By micro-focused angle-resolved photoemission spectroscopy [5] and second harmonic generation, we successfully observed the band dispersions and the artificially induced spatial inversion symmetry breaking in the anti-parallel-stacked bilayer ReSe2. Our result demonstrates the potential for creating new materials that can exhibit spintronic functions and Berry-curvature-related physical phenomena by controlling the presence or absence of spatial inversion symmetry.

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# Low energy electronic structure in strontium ruthenates: from surface distortions to magnetic-field control of the electronic structure

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The phenomenology and radical changes seen in materials properties traversing a quantum phase transition has captivated condensed matter research over the past decades. Strong electronic correlations lead to novel ground states, including magnetic order, nematicity and unconventional superconductivity. To provide a microscopic model for these requires knowledge of the electronic structure in the vicinity of the Fermi energy. The strontium ruthenates provide a family of ideal model systems to explore this physics using spectroscopic techniques: they exhibit an anisotropic, quasi-two-dimensional electronic structure and occur as single-, double- and triple-layer compounds with similar crystal structure but disparate ground states ranging from unconventional superconductivity via metamagnetism to itinerant ferromagnetism. In the metamagnetic compounds, spectroscopic information about the low energy electronic structure would allow verification of different scenarios that have been proposed to explain their exotic properties. I will present spectroscopic imaging of the electronic structure performed at temperatures down to 100mK[1] and in vector-magnetic fields, and discuss the implications for the low energy electronic structure. Notably, for several of the strontium ruthenates the surface provides a platform to study the properties of the electronic structure under conditions not accessible in the bulk.[2,3]

This work was done in close collaboration with C.A. Marques, L.C. Rhodes, M. Naritsuka, I. Benedičič, as well as colleagues from the University of St Andrews, CNR SPIN, and the Max Planck Institute for the Chemical Physics of Solids.

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# μSR studies of Kagome magnet (Fe, Co)Sn

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Recently, materials with Kagome layers have attracted increasing interest as they were found to be associated with topological behavior and superconductivity. (Fe,Co)Sn, as shown in Fig.1, consists of the stacking Kagome layers of Fe/Co along c axis. It forms a complete solid solution, with a complex magnetic phase diagram [1,2,3]. Novel physics often appears near a critical point, the details of the transitions in (Fe,Co)Sn, such as phase separation and spin dynamic phenomena, are important.

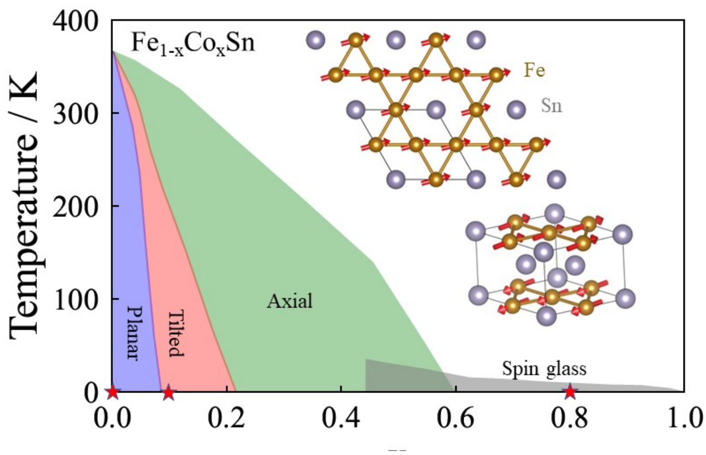


Figure 2: Phase diagram of (Fe,Co)Sn. Insert shows the magnetic structure of FeSn.

We present a detailed μSR study of the Kagome magnet (Fe,Co)Sn with three different concentrations as shown in red marks in Fig.1.

a) For parent compound FeSn, our zero field (ZF) and weak transverse field(wTF) μSR measurements indicate that the local field at the muon stopping site is nearly pointing within the ab-plane in the antiferromagnetic state, which is consistent with the planar spin structure as shown in the insert of the Fig above. In addition to the high-T magnetic transition, we also observed a hidden-order, featured with $1/T_1$ peak, at around 40 K.

b) For Co~0.11 concentration, a full magnetic volume fraction was observed in the ordered state. Our results also follow the magnetic phase transitions with temperatures.

c) For Co~0.8 concentration, with more randomness, our ZF and longitudinal field (LF) μSR measurements show a spin glassy behavior with the dynamic spin fluctuations die away at our lowest temperature, similar to the case of classical spin glasses.
d) We also found that nearly 40 % volume fraction appears to be invisible by μSR in the parent compound FeSn in the magnetically ordered state. Compared with the Co doped results, we suggest that it is most likely from muon site origin due to the local site symmetry.

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# The CDW of $YBa_2Cu_3O_y$: insights from NMR and XRD

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Charge-density waves and superconductivity are electronic instabilities that are found to be competing in a variety of correlated materials, including transition metal chalcogenides or the newly discovered Kagome superconductors. In contrast to these materials, in the cuprate superconductor $YBa_2Cu_3O_y$, charge ordering and superconductivity are apparently competing on equal footing: the onset temperature, $T_{CDW}$, and the superconducting $T_c$ are of the same order [1]. This competition can be tuned by external parameters such as high magnetic fields, hydrostatic or uniaxial pressure. While all cuprates display a propensity towards short-range CDW formation, $YBa_2Cu_3O_y$ stands out due to its long-ranged CDW state that can be induced by high magnetic fields or uniaxial pressure along one of the planar orthorhombic axes [2–4].
In this talk, the signatures of the short- and long-range CDW phases in Nuclear Magnetic Resonance (NMR) and x-ray diffraction (XRD) are discussed. Whereas the competition between SC and CDW is a well-established fact, here I present new evidence for direct competition between short- and long-range CDWs, even at $T > T_c$. This effect is most clearly observed in XRD measurements under uniaxial pressures, because under these conditions the long-range CDW is stronger than what can be reached by applying high magnetic fields [3]. In x-ray scattering or NMR measurements in high magnetic fields where the long-range CDW is reached at temperatures below the zero field $T_c$, it is more difficult to disentangle the competition of the CDW phases from the competing impact of superconductivity [4]. Investigation of these competing effects is potentially relevant for understanding cuprate superconductivity itself.

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# Chiral domains in Tantalum disulfide

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It was recently observed that the nearly commensurate charge density phase in TaS2 hosts chiral domains of commensurate charge order [1]. Here we present a Ginsbourg-Landau theory explaining the emergence of this chirality from a competition between the coupling of the charge order with the lattice and the electronic susceptibility.

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# Correlation-Temperature Phase diagram of Infinite-layer Rare-earth Nickelates

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Novel materials whose properties are influenced by the presence of strongly correlated d- and/or f-electrons have been of sustained interest. Among these, the infinite-layer nickelates, *R*NiO2 (*R* = Nd, Pr, La), that exhibit superconductivity upon hole-doping, have received considerable attention. Based on self-consistent density functional theory (DFT) + embedded dynamical mean-field theory (eDMFT) calculations, we provide new insights into the physics of the low-energy many-body states of the parent compounds of the infinite layer systems. To appeal to a broad audience, we first elucidate the basic ideas underlying the self-consistent DFT+ eDMFT approach. Then we present results of our calcuations in the paramagnetic and magnetic states of *R*NiO2. We depict the emergent many-body states, and the associated correlation (U) and temperature (T) scales in a proposed U-T phase diagram. The key features are a low-T Fermi liquid (FL) phase, a high-T Curie-Weiss regime, and an antiferromagnetic phase in a relatively small U-Tregion.

We associate the onset of the FL phase with partial screening of Ni-d electron moments; however, full screening occurs at lower temperatures. This may be related to insufficiency of conduction electrons to effectively screen the Ni-d moments, suggestive of Nozieres Exhaustion Principle. Consistent with the lack of experimental evidence for long-range magnetic order, and recent observation of magnetic excitations in NdNiO2, our results are suggestive of *R*NiO2 being in the paramagnetic state close to an antiferromagnetic dome, making magnetic fluctuations feasible. This may be consequential for superconductivity.

In the end, we briefly discuss our more recent work on doped nickelates.

# Effect of capping layer on superconducting $Nd_{1-x}Sr_xNiO_2$

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The recent discovery of superconductivity in infinite layer nickelates thin films has spurred a lot of attention in the scientific community [1]. These materials appear to be analog to the cuprates with parent compounds having a single hole in the *d* orbitals that upon hole doping become superconducting. The detection of spin excitations and possible charge density waves [2,3] further corroborated such similarities even if major differences such as the role of rare earth and the balance between Hubbard (U) and charge transfer energies raise questions on their actual similarity. One open question regards the role of the $SrTiO_3$ capping layer which is believed to have effect on the ground state [4].

In my talk, I will present how Resonant Inelastic X-Ray Scattering (RIXS) can unveil the role of the capping layer for the excitations in $NdNiO_2$ and optimal-doped $Nd_{1-x}Sr_xNiO_2$. In uncapped $NdNiO_2$ compound we observe damped spin excitations resembling the one observed in cuprates [2]. The intensity of the spin excitations is however strongly decreased compared to the capped compound indicating a renormalization of magnetism. In superconducting materials, independently of the presence of capping, we see an overall softening of the spin excitations compared to the parent compound. Comparing the capped and uncapped $Nd_{0.8}Sr_{0.2}NiO_2$ we uncover at intermediate momenta a significant difference in the dispersion of the capped sample concomitant with a significant broadening. Overall, the spin excitations spectrum is suppressed in uncapped samples indicating a strong influence of the capping layer on the magnetism in infinite layer nickelates regardless of doping. Remarkably, the spectral weight of the Ni-Nd charge transfer is also highly suppressed.

Finally, I will compare this experimental evidence in relation to previous calculations accounting for the presence or lack of the capping layer. These pieces of evidence uncover the effect of the capping layer on magnetism and Ni-Nd hybridization which has strong implications in the understanding of nickelate superconductivity. This also represents an opportunity for heterostructuring of superconducting nickelates with other materials as a possibility to tune the delicate balance between their electronic properties.

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# Role of Ni-Nd Hybridization in Infinite-Layer Nickelates

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The newly discovered superconductivity in hole doped infinite-layer nickelates (IL-N) have attracted extensive investigation. Motivated by the recent X-ray absorption spectroscopy (XAS) and resonant inelastic x-ray scattering (RIXS) experiments [1], based on Ni impurity calculations [2-3], we explored the nature of the parent compound and hole doped states of IL-N by including the crystal field splitting, the Ni-$3d^8$ multiplet structure, and the hybridization between Ni-3d orbitals and the Nd-5d orbitals that are formally replaced with a totally symmetric orbital Zs based band centered at the missing O in the Nd layer.
For the parent compound, we showed that the spectrum of Ni-$3d^9Zs^2$ state spreads over a large energy range and cannot be represented by a single orbital energy as suggested in other calculations, which is qualitatively consistent with the RIXS measurements showing a broad distribution of the Ni-$3d^9_{z2}$ hole state. For the hole-doped systems, we showed that adding these additional ingredients can still result in the lowest-energy hole-doped state having a singlet character [2-3].
Furthermore, motivated by the presence of a small electron pocket residing in Nd orbitals in the electronic band structure of IL-N, we systematically explored the superconducting (SC) properties of a toy model consisting of a two-dimensional Hubbard model (mimicking Ni-3d orbitals) influenced by an additional conduction band with small occupancy (mimicking Nd orbitals). Our dynamic cluster quantum Monte Carlo calculations demonstrated the unusual impact of this additional dry metallic band, which shifts the SC dome of the correlated Hubbard layer towards the overdoped regime, namely the d-wave SC can be enhanced (suppressed) in the overdoped (underdoped) regime. Our analysis revealed the interplay of the effective pairing interaction, pair-field susceptibility, and antiferromagnetic spin fluctuation in the underlying nonmonotonic physics. We postulate on the physical picture of the SC dome shift in terms of the Kondo-type electron-hole binding in the case of a dry additional conduction band [4].

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# Anomalous Crystal Shapes of Topological Crystalline Insulators

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A topological crystalline insulator (TCI) is a topological phase characterized by crystallographic symmetries. There exist various TCI phases depending on the crystallographic symmetries, such as mirror- symmetric TCIs and glide-symmetric TCIs [1,2]. In these TCIs, whether or not gapless topological surface states appear depends on the surface orientations. Namely, if the surface orientation is mirror/glide invariant, the corresponding gapless surface states appear.

In this presentation, we discuss relationships between equilibrium crystal shapes and topological phases. In the glide-symmetric TCIs, whether a surface supports topological surface states depends on the parity of the surface Miller index, and the surface energy depends on the surface orientation in a singular way. Therefore, the equilibrium crystal shape will change depending on whether the crystal is in a trivial phase or in a topological phase [3] (Fig. 1). If the time allows, we also explain the series of our works on this glide-symmetric TCIs [4-6], particularly on the relationship with multi-helicoid surface states in Dirac semimetals [7].

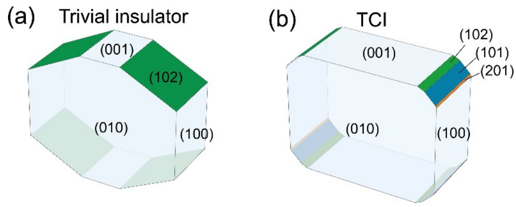


Fig.1. Calculated equilibrium crystal shapes for (a) a trivial insulator and (b) a TCI.

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# Interplay between anisotropy and charge fluctuations in cuprates

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Anisotropic transport properties are well established in a number of cuprate superconductors providing evidence for a nematic state [1,2,3]. Here we analyze recent experimental data for ultrathin YBCO films where nematicity has been induced via strain engineering, leading to a suppression of charge-density wave scattering along the orthorhombic a-axis and a concomitant enhancement of strange metal behavior along the b-axis [4]. It is shown that these experimental features can be accounted for within a model where nematicity is induced via a coupling of the planar copper oxygen electronic system to auxiliary one-dimensional fragments which are associated with nanoscale facet states on an underlying substrate. Based on this model we investigate the scenario of frustrated phase separation and discuss the resulting anisotropy of charge density waves and charge order fluctuations. The scattering of quasiparticles by these excitations can explain the observed transport anisotropies in thin superconducting films.

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# Disorder-robust phase crystal in high-temperature superconductors from topology and strong correlations

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Today there exists a strong research focus on topological effects in condensed matter. Initial studies were only focused on non-interacting electronic systems, but attention is now shifting towards the influence of electron-electron interactions and also the broken symmetry states they can generate. Real-world materials bring disorder as a third important component, as many symmetry broken states are sensitive to disorder. Hence, to understand many materials we need to keep a combined focus on topology, electronic correlations, and disorder. Copper oxide high-temperature superconductors (cuprates) with pair breaking edges host a flat band of topological zero-energy states, making them an ideal playground where strong correlations, topology, and disorder are strongly intertwined. Here, we show that the three way interplay in cuprates generates a new phase of matter: a fully gapped "phase crystal" state that breaks both translational and time reversal invariance, characterized by a modulation of the d-wave superconducting phase co-existing with a modulating extended s-wave superconducting order. In contrast to conventional wisdom, this phase crystal state is remarkably robust to omnipresent disorder, but only in the presence of strong correlations, thus giving a clear route to its experimental realization.

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# Superconductivity in 214-based structural isomers

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The single layered 214 family of high-temperature superconductors has three structural isomers. T'-type RE2CuO4 (RE: rare-earth element) with a CuO4 square planar coordination has been long considered to be a Mott insulator as is the case of T-type La2CuO4 with a CuO6 octahedral coordination. However, superconductivity was reported for RE2CuO4 without element substitution, and the relationship between the oxygen coordination and physical properties has attracted attention. From this point of view, we study superconductivity and spin correlations in T'-type and T*-type cuprate, in which the Cu is in pyramidal coordination, with muon, x-ray and neutron beams. Here, we introduce two topics.

***Distinct annealing effects on the electronic states of T'-type RE2CuO4***

Superconductivity appears in T'-type La1.8Eu0.2CuO4 (LECO) by reduction annealing, while T'-type Pr2CuO4 does not show superconductivity even after annealing. We performed Cu K-edge X-ray absorption fine structure measurements on two compounds and revealed a large difference in the electron concentration (ne) of LECO and PCO after annealing [1]. (ne is 0.40 electrons/Cu for LECO and 0.05 electrons/Cu for PCO.) Our neutron diffraction measurements clarified that the oxygen occupancy in both materials before and after annealing is almost the same at each oxygen site [2]. Thus, the difference in the ground state of the two compounds is not caused by the difference in the oxygen content. The anneal-induced metallic nature with a large value of ne in LECO suggests the self-doping of carriers attributed to the variation of the electronic band structure. The value of ne in annealed PCO is approximately twice of the value of reduced oxygen, suggesting electron doping into Mott insulating state through oxygen deficiency.

***Superconductivity and absence of static magnetism in lightly-doped T*-type cuprate***

We recently synthesized the T*-type compounds, and made a phase diagram by evaluating the actual hole concentration (nh) with x-ray absorption spectroscopy measurement. As a result, we found that the dome-shaped superconducting phase locates in the lower nh region (0.04 $\lesssim$ nh $\lesssim$ 0.18) compared to the T-type La2-xSrxCuO4. Superconducting transition temperature shows maximum at nh ~ 0.09 and decreases with underdoping toward 0 K at nh ~ 0. Futhermore, no evidence of magnetic order was observed by the muon spin relaxation experiment for 0.04 $\lesssim$ nh [3]. These results suggest the presence of the lightly-doped superconductivity in T*-type cuprate.

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# Uniaxial stress control of correlated quantum materials: From superconductors to magnets

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In recent years, uniaxial stress has emerged as an extremely powerful tool to modify the delicate balance between competing ground states in correlated quantum materials. This notion is rooted in the power of uniaxial stress to deliberately control the lattice symmetry of a given quantum material. In this talk, we will provide an overview of the technical advances, that allow for the high-precision control of quantum materials by uniaxial stress. Using specific research examples from the fields of iron-based superconductivity and quantum magnetism, we will illustrate how uniaxial pressure has already and will continue to be a key tool to answer fundamental questions and discover novel phenomena in the area of quantum materials.

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# Theory of Higgs spectroscopy for superconductors in non-equilibrium

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Higgs spectroscopy is a new and emergent field [1-3] that allows to classify and determine the superconducting order parameter by means of ultra-fast optical spectroscopy. There are two ways to activate the Higgs mode in superconductors, namely a single-cycle 'quench' or an adiabatic, multicycle 'drive' pulse, both illustrated in Figure 1. In the talk I will review and report on the latest progress on Higgs spectroscopy, in particular on the role of the third-harmonic-generation (THG) [4-6] and the possible IR-activation of the Higgs mode by impurities or external dc current [7,8]. I also provide new predictions for time-resolved ARPES experiments in which, after a quench, a continuum of Higgs mode is observable and a phase information of the superconducting gap function would be possible to extract [9]. Finally, I show that the Higgs mode can maybe solve the 25-years-old A1g-puzzle in equilibrium Raman scattering on high-Tc cuprates [10].

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# Axial Higgs Mode from Quantum Geometry and a Charge Density Wave

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The observation of the Higgs boson solidified the standard model of particle physics. However, explanations of anomalies (e.g., dark matter) rely on further symmetry breaking, calling for a yet-to-be-discovered axial Higgs mode. In condensed matter, the Higgs mode has been observed in magnetic, superconducting, and charge density wave systems (CDW), and is typically assumed to have a scalar representation. Uncovering the vector properties of a low energy mode is extremely challenging, requiring going beyond typical spectroscopic or scattering techniques to reveal the hidden aspects of their wavefunctions. Here, we discover an unconventional axial Higgs mode of the charge density wave in the GdTe3. The Axial Higgs mode is revealed using the interference of excitation quantum pathways in Raman scattering. I will discuss how the Axial Higgs mode emerges from the combination of the quantum geometry of the Fermi surface and the charge density wave, opening opportunities for new topological - correlated states in 2D systems. Furthermore, this technique can be extended to detect novel topological orders in other CDW and superconducting systems.

# Recent developments in the understanding of superconductivity of $Sr_2RuO_4$

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Superconductivity in $Sr_2RuO_4$ have been recently reinvigorated due to a number to experimental developments providing evidence for an even-parity multi-component time-reversal symmetry breaking superconducting condensate [1,2]. In addition, the superconducting state appears to exhibit nodes [3]. In my presentation I will discuss these recent fascinating developments and provide an overview of recent theoretical progress trying to reconcile the bounds from experiments [4,5].

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# Chester supersolid of spatially indirect excitons in double-layer semiconductor heterostructures

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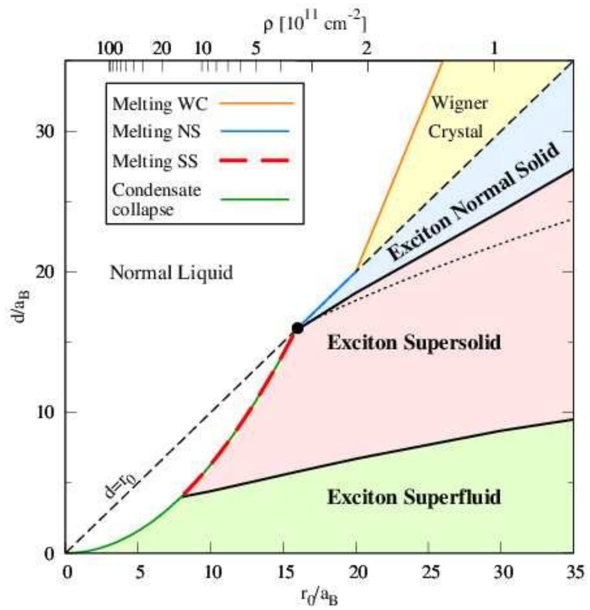
A supersolid, a counter-intuitive quantum state in which a rigid lattice of particles flows without resistance, has to date not been unambiguously realised. Here we reveal a supersolid ground state of excitons in a double-layer semiconductor heterostructure over a wide range of layer separations outside the focus of recent experiments. This supersolid conforms to the original Chester supersolid with one exciton per supersolid site, as distinct from the alternative version reported in cold-atom systems of a periodic density modulation or clustering of the superfluid. We provide the phase diagram augmented by the supersolid. This new phase appears at layer separations much smaller than the predicted exciton normal solid, and it persists up to a solid-solid transition where the quantum phase coherence collapses. The ranges of layer separations and exciton densities in our phase diagram are well within reach of current experimental capabilities.




*Phase diagram at zero temperature. d is the layer separation and $r_0$ characterizes the density r. Effective Bohr radius is $a_B$. Dotted line is the transition to the exciton normal solid predicted in Ref. [1[. Top axis shows densities for a typical double monolayer transition metal dichalcogenides encapsulated in hBN [2].*

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# Unprotected edge modes in quantum spin Hall insulator candidate materials

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The experiments in quantum spin Hall insulator candidate materials, such as HgTe/CdTe and InAs/GaSb heterostructures, indicate that in addition to the topologically protected helical edge modes these multilayer heterostructures may also support additional edge states, which can contribute to the scattering and the transport. We use first-principles calculations to derive an effective tight-binding model for HgTe/CdTe, HgS/CdTe and InAs/GaSb heterostructures, and we show that all these materials support additional edge states which are sensitive to the edge termination. We trace the microscopic origin of these states back to a minimal model supporting flat bands with a nontrivial quantum geometry that gives rise to polarization charges at the edges. We show that the polarization charges transform into the additional edge states when the flat bands are coupled to each other and to the other states to form the Hamiltonian describing the full heterostructure. Interestingly, in the HgTe/CdTe quantum wells the additional edge states are far away from the Fermi level so that they do not contribute to the transport but in the HgS/CdTe and InAs/GaSb heterostructures they appear within the bulk energy gap giving rise to the possibility of multimode edge transport. Finally, we demonstrate that because these additional edge modes are non-topological it is possible to remove them from the bulk energy gap by modifying the edge potential for example with the help of a side gate or chemical doping.

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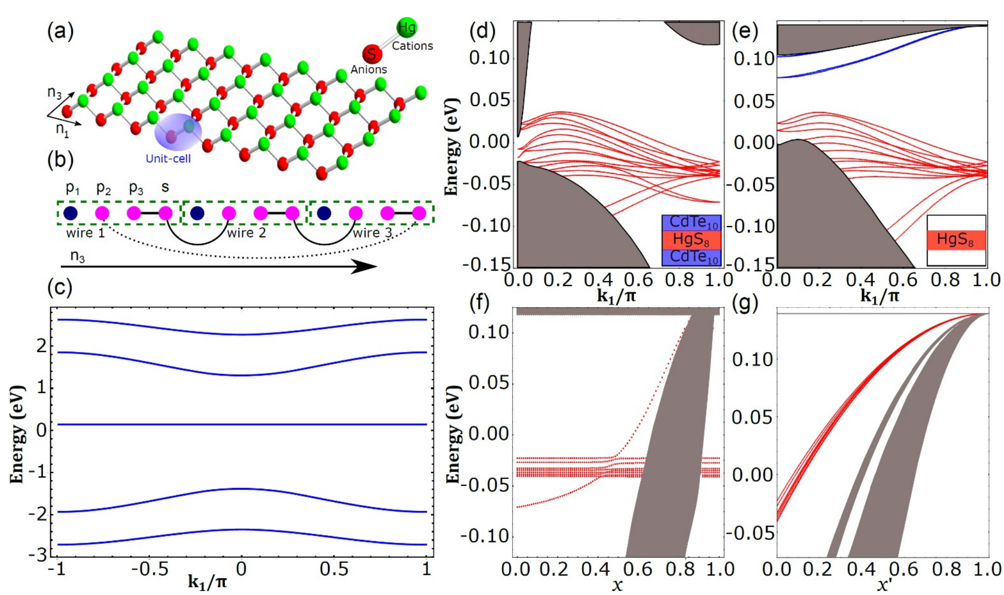


Figure 1: (a) Nanoribbon, a cut throught the HgTe quantum well. (b) Schematic view of the couplings between eigenstates of a single wire within a nanoribbon. (c) Generic spectrum of the nanoribbon of the width W, most of the bands are W-degenerate. (d-e) Edge-states spectra of HgS/CdTe and HgS multilayers. (f-g) Edge-states spectra for $k_1=\pi$ as function of parameter x interpolating between HgS/CdTe and HgS multilayers and parameter x' interpolating between HgS multilayers and minimal model

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# Pair Density Waves in Topological Superfluid $^{3}$He

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The liquid 3He has provided a playground for studying spontaneous symmetry breaking and topology. The most symmetric superfluid phase in the bulk is the B phase which is invariant under joint SO(3) rotation in spin and orbital spaces. Vorontsov and Sauls predicted that 3He under strong confinement undergoes a transition to the stripe phase, that is, the one-dimensional pair density wave (PDW) state [1]. A PDW is a phase of matter defined in terms of broken rotational and translational symmetries and characterized by the order parameter that varies periodically as a function of position [2]. Recently, Levitin et al. have performed NMR measurements in superfluid 3He confined in a nanoscale cavity and observed NMR signals which can be explained by neither the translationally-invariant B-phase nor the one-dimensional PDW [3]. Shook et al. have also reported studies of PDWs using a Helmholtz resonator [4].

Motivated by the experimental observation, we theoretically investigate PDWs in superfluid 3He under planar confinement. Here we find that when the thickness of confinement becomes comparable to the superfluid coherence length, the superfluid 3He spontaneously forms the one-dimensional (1D) stripe order or two-dimensional (2D) crystalline orders with D2, D4, and D6 symmetries. Using the strong-coupling Ginzburg- Landau theory, we examine the thermodynamic and topological stability of 1D/2D PDWs. In contrast to PDW superconductors, which can be stabilized by external fields and strong correlation, the stability of PDWs in 3He is attributed to the intertwining of multiple components of the spin-triplet p-wave Cooper pairs. In addition to the stability of 2D PDWs, we clarify that the polar-distorted B phase undergoes the nucleation-type continuous transition to the PDW phases under strong confinement. In this talk, we will propose a scenario based on the nucleation of 2D PDW orders to understand the NMR signals observed in Ref. [3].

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# Extremely clean doped Mott states in high-$T_c$ cuprates forming small Fermi pockets investigated by ARPES

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The critical temperature of superconductivity ($T_c$) in cuprates is sensitive to the number of $CuO_2$ layers per unit cell. The magnitude of $T_c$ reaches the maximum in trilayer compounds among the homologous series. The highest $T_c$ in cuprates is obtained in $HgBa_2Ca_2Cu_3O_{8+d}$ (Hg1223), which is a trilayer compound. While the intriguing relation between $T_c$ and the number of layers per unit cell was found shortly after the discovery of high-$T_c$ cuprates, its mechanism has not been understood yet and still been under huge debate. In solving this long-standing issue, it is particularly important to clarify the electronic properties distinctive for the many-layered cuprates.
Anomalous features of trilayer $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi2223) were revealed by angle-resolved photoemission spectroscopy (ARPES) using the low energy photons, which allow bulk sensitive measurements [1,2]. While this compound exhibits multibands reminiscent of those in Bi2212, the different bands in Bi2223 show different magnitudes of the superconducting gap. This situation is in stark contrast to that of Bi2212 consisting of the bonding and antibonding bands with the same gaps. The multiple bands of Bi2223 are attributed to be each for the inner and outer planes with different carrier concentrations; that is, Bi2223 has a non-uniform distribution of charges over the triple $CuO_2$ layers, differently from Bi2212 with evenly doped double layers. The charge nonuniformity is a common intriguing feature of the compounds with three or more layers. Furthermore, inner $CuO_2$ planes are protected from the dopant layers, realizing homogeneous electronic state. This is another fascinating aspect of multi-layered cuprates.
In my presentation, I will introduce our recent ARPES studies of multi-layered cuprates $Ba_2Ca_{n-1}Cu_nO_{2n}(F,O)_2$ [4]. These compounds have clean, thus ideal $CuO_2$ planes in the inner layers [3], thus they may reveal the phase diagram, which is inherent for cuprates but has not been unveiled so far. Most surprisingly, we found small Fermi surface pockets around ($\pi/2,\pi/2$) consistently by ARPES and quantum oscillation measurements [4]. The formation of small Fermi pockets has been predicted in the doped Mott state since the discovery of a high-$T_c$ superconductor in cuprates. Yet, this structure had not been detected, even though it could be a key element in relating high-$T_c$ superconductivity to Mott physics. We also find that the *d*-wave superconducting gap opens along the pocket, thus the superconductivity and antiferromagnetic order coexists in the same $CuO_2$ sheet. Our data further indicate that the superconductivity can occur without contribution from the states near the antinodal region, which are shared by other competing excitations such as the charge density wave and pseudogap states. These findings will have significant implications for understanding the superconductivity and puzzling Fermi arc phenomena in cuprates.

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# THz and Pump-Probe Spectroscopy of $Co_2MnGa$ Topological semimetal

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Topological semimetals occupy an important place in the quantum materials family due to the interplay between their bulk and surface states. Depending on their symmetries and band structure near the Fermi level, these materials can be classified into Dirac, Weyl, or nodal line semimetals. The Berry curvature associated with these structures leads to anomalous effects in the electronic transport, such as the chiral anomaly [1], the anomalous Hall effect (HAE) [2], the Nernst effect, and linear and non-linear magneto-optical responses [3,4]. The study of these materials in the thin-film limit is recently being addressed due to the need of characterizing the interplay between the bulk and surface states, while also covering the demand for their exotic properties to produce novel electro-optical devices.

In this context, optical linear and nonlinear THz spectroscopy are key tools for the characterization of the topological features of these semimetals. In this talk, I will discuss recent experimental results concerning the spectroscopic study of a novel topological nodal line semimetal, $Co_2MnGa$, grown as thin films of different thicknesses on a MgO substrate. I will briefly show how the spectroscopic characterization highlights the modifications attained by the electronic band structure at various thicknesses and then focus on the nonlinear THz response of the films. THz emission results, suggesting an interplay between a surface photogalvanic effect and a bulk photon-drag emission, will be presented along with optical pump-THz probe responses, with the latter highlighting a polaronic formation after strong optical illumination.

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# Exploring 2D materials: growth, properties, and applications

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The electronic applications of graphene are constrained by the absence of a band-gap. As a result, there is an increasing demand to investigate alternate two-dimensional (2D) van der Waals materials. Here, we present the growth and physical property measurements of hexagonal boron nitride (hBN), Mg-doped hBN, black phosphorus (b-P) and arsenic-doped black phosphorus (b-AsP) crystals (Fig. 1) [1-5].

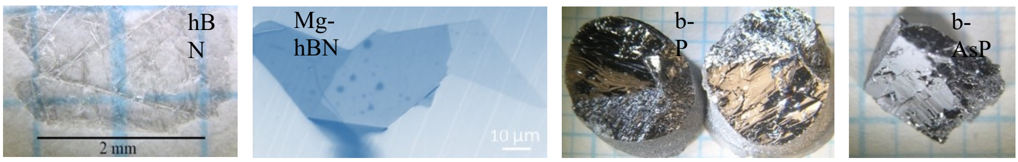


Figure 1. Optical images of hBN, Mg-hBN, b-P, and b-AsP crystals.

Single crystals of hBN and Mg-doped hBN were produced using a high-pressure and high-temperature method from a precursor containing Mg, B, and BN. By altering the growth conditions, we determine the sequence of phase transformations occurring in the Mg-B-N system [1]. Using data from micro-Raman spectroscopy, nano-ARPES, and Kelvin probe force microscopy, we show that the Mg dopants can significantly change the electronic properties of hBN by pushing the valence band about 150 meV toward higher binding energies in comparison to pure hBN [4].

The layered b-AsP crystals were grown at 10 kbar and 1100 °C, and their properties were compared to those of pure b-P. Our study shows that b-AsP has potential for optoelectronics applications that benefits from its anisotropic character and the ability to tune its band gap as a function of the number of layers and As content [5].

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# Charge interactions at buried YBCO interface

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In 2013 Müller and Shengelaya [1] suggested that underdoped ultra-thin layers of copper-oxide high temperature superconductors (HTSs) sandwiched between high-dielectric-constant insulators (HDIs) could provide a potential pathway to increase the critical temperature $T_c$. They proposed to use the concept of ”Coulomb interaction engineering” [2] which consists in an effective change of the dielectric constant of a semiconductor due to the penetration of the electric field from the surrounding insulators with a different dielectric constant. This method applied to heterostructures of cuprate HTSs and HDIs could reduce the Coulomb repulsion between the charged clusters of bipolarons (stripes) formed in the pseudogap phase of the cuprates, and thus resulting in an increase of the superconducting critical temperature $T_c$. Here we present a study of $SrTiO_3/YBa_2Cu_3O_{7-x}$ thin films by means of transport measurements and soft X-ray photoelectron spectroscopy. An increase of $T_c$ was observed in underdoped regime [3] which could be an indication of dielectric confinement into the YBCO layers next to the interface with $SrTiO_3$.

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# Skyrmion-vortex pairs: hybrid topological solitons for quantum information

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Magnetic skyrmions and flux vortices are stable topological excitations in non-collinear magnets and superconductors, respectively. Interactions between these excitations in artificial multilayers are predicted to create skyrmion-vortex pairs, mediated by their stray magnetic fields [1,2] and/or the Rashba-Edelstein effect [3]. The unification of spin and phase topologies within these "hybrid" solitons not only modifies their dynamic properties and magnetoelectric coupling [4], but also offers the possibility to establish a topological superconducting state with localised Majorana zero modes [5,6]. However, there are two significant technical barriers to experimentally realising skyrmion-vortex pairs: the difficulty of stabilizing skyrmions and vortices within the same temperature/magnetic field ranges and the necessity of tuning the superconducting and magnetic lengthscales to maximise the skyrmion-vortex interaction.

I will describe how to overcome these challenges using NbPt/IrFeCoPt heterostructures, where the stray field from Néel skyrmions in a chiral magnet can be engineered to spontaneously nucleate (anti)vortices in a proximate superconductor [7]. Signatures of hybrid solitons emerge in the magnetization and flux dynamics, accompanied by a temperature-dependent Rashba-Edelstein coupling. An increase in the skyrmion radius below the superconducting transition is also discernible via magnetic force microscopy, in line with theoretical expectations [8]. Finally, I will outline the path towards achieving a local topological phase transition in such multilayer systems, with the ultimate aim of braiding individual skyrmion-vortex pairs for quantum logical operations [9].

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# Ergodicity breaking transition in zero dimensions

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If a system is driven far from equilibrium, one usually expects it to return to thermal equilibrium after a sufficiently long time. Currently a lot of effort is devoted to address two open questions: under which circumstances physical systems become nonergodic, and how to describe the transition between an ergodic and a nonergodic state. Recently, by studying the avalanche model of ergodicity breaking transitions, we established certain key properties that can be detected in finite systems in the vicinity of the ergodicity breaking transition [1]. This model can become in the future a toy model of ergodicity breaking phase transitions, since it allows for simple analytical considerations and powerful numerical investigations.

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# Even- and Odd-Parity Density Waves and Superconductivity in Kagome Metals, Nickelates and Other Strongly Correlated Metals

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Exotic quantum phase transitions in strongly correlated metals have been discovered one after another and found to be universal now [1]. The multistage unconventional density-wave (DW) orders in frustrated kagome metal $AV_3Sb_5$ (A=Cs,Rb,K) and its interplay with exotic superconductivity attract increasing attention. We find that the time-reversal symmetric star-of-David bond-order originates from sizable intersite attraction due to the quantum interference among paramagnons [2]. This mechanism is important in kagome metals because the geometrical frustration prohibits the freezing of paramagnons. In addition, we uncover that moderate bond-order fluctuations mediate sizable pairing glue, and this mechanism gives rise to both singlet s-wave and triplet p-wave superconductivity [2]. The obtained impurity-induced change in the SC state is consistent with recent experiments. Furthermore, we discovered that the time-reversal broken charge current order is naturally caused by the bond-order fluctuations [3]. Interestingly, the coexistence of the charge-current order and the bond-order gives rise to a novel nematic state [3]. Thus, both the exotic density waves and the superconductivity in geometrically frustrated kagome metals are explained by the quantum interference mechanism.
We also discuss the interplay between the nematic/smectic bond orders and unconventional superconductivity in nickelates [4] and magic angle twisted bilayer graphene.

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# Nematic quantum critical points and unconventional superconducting states in Fe(Se/S/Te)

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The interplay among magnetism, electronic nematicity, and superconductivity is the key issue in strongly correlated materials including iron-based, cuprate, and heavy-fermion superconductors. Magnetic fluctuations have been widely discussed as a pairing mechanism of unconventional superconductivity, but recent theory predicts that quantum fluctuations of electronic nematicity, which is characterized by rotational symmetry breaking, may also promote high-temperature superconductivity. FeSe-based superconductors are suitable to study this issue [1] because FeSe exhibits a nonmagnetic nematic order that can be suppressed by S or Te substitution for Se. I will review recent studies of FeSe-based superconductors, showing exotic superconducting states. In $FeSe_{1-x}S_x$ superconductors, the nematic order can be completely suppressed at $x$=0.17, above which the superconducting properties change drastically with a significantly reduced critical temperature $T_c$ [2,3]. From recent muon spin rotation (μSR) measurements, we find evidence for a novel ultranodal pair state with broken time-reversal symmetry [4]. In the Te substitution case, however, we find quite different behavior; the suppression of nematic order leads to an enhancement of $T_c$, which is likely associated with quantum critical fluctuations of nematicity [5-7].

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# Superconductivity in hydrides under high pressure: fact or fiction?

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Beginning with sulfur hydride in 2015, approximately 15 different hydrides under high pressure have been claimed to be high temperature superconductors in recent years [1]. However we have pointed out [2] that the few magnetic measurements reported so far for these materials [3,4,5,6,7,8,9] are in conflict with what is expected for standard superconductors. In particular, these materials show no evidence for magnetic field expulsion, the signature property of superconductivity. It has been argued that the absence of a Meissner effect is due to the granular nature of these materials [7]. I will compare the reported observations in hydrides with the behavior seen in other materials known to be granular superconductors, and will discuss the consistency of the various magnetic measurements in hydrides with each other under the assumption that they originate in superconductivity. I will conclude that the totality of magnetic evidence strongly indicates that the observed magnetic phenomena are not due to superconductivity, hence that there is no convincing experimental evidence that hydrides under high pressure are high temperature superconductors. Implications for the theoretical understanding of superconductivity will be briefly discussed.

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# Hybrid Josephson junctions opportunity for quantum hardware and advances in quantum science and engineering

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Superconducting systems are a natural and versatile platform for a variety of applications including quantum technologies and are of undoubtful inspiration also for the development of novel notions in solid state physics. Josephson junctions (JJs) are key structures, because of their unique properties, of their potential to manipulate the macroscopic wave function of a condensate and of their extreme flexibility as circuit elements. Progress in material science and nanofabrication gives opportunities to create unique hybrid JJs which can be *smartly* integrated in complex architectures, paving the way to novel effects and novel avenues for quantum control and detection.
We will review some aspects of the frontiers of the Josephson effect discussing examples of unique solutions to cutting edge problems in condensed matter physics as well as to very advanced applications, including in the emerging field of quantum computing. We will report on special properties of hybrid JJs on how to engineer the macroscopic phase in quantum circuits, which make possible alternative layouts for the superconducting modules inside a more general architecture also through a comparative study of fluctuations and of electro-dynamical properties. These methods can be successfully applied to the emergent van der Waals heterostructures and twistronics structures. The diversity in Josephson junctions opens 'horizons'. Much is happening and partly needs to be consolidated.

# Thermodynamic studies on the Majorana gap of Kitaev material $\alpha$-$RuCl_3$

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The exactly-solvable Kitaev model [1] realizes a quantum spin liquid as the ground state with the 1/2 spins fractionalized into Majorana fermions [2,3]. The low energy excitations of the quantum spin liquid are dominated by the gapless itinerant Majorana excitations at low temperatures with Dirac-type linear dispersion, similar to the electronic structure of graphene. In the presence of the magnetic field, on the other hand, it is theoretically proposed that the bulk excitation spectra exhibit a peculiar excitation gap that depends on the magnetic field direction. The magnetic field dependence is given by the product of the each component of the magnetic field as $h_x h_y h_z$, which can lead to the large anisotropy with respect to the magnetic field direction in the thermodynamic properties.

Experimentally, the high-field paramagnetic phase of $\alpha$-$RuCl_3$ is one of the promising candidates for the Kitaev quantum spin liquid state, where several signatures of the Majorana excitations have been reported including the quantized thermal Hall conductivity originating from the chiral edge mode of the Majorana fermions [4]. However, the bulk state of the Majorana excitations and its relation to the edge mode are still elusive and need to be uncovered. In this talk, I will report on the observation of the Majorana gap in the bulk state of $\alpha$-$RuCl_3$ from precise magnetic-field angle-rotation heat capacity measurements [5]. The field-angle dependence of the gap is in good agreement with the theoretical prediction and provides evidence for the bulk Majorana excitations in this compound.

In collaboration with O. Tanaka, R. Harasawa, K. Imamura, Y. Yoshida, K. Hashimoto, T. Shibauchi (University of Tokyo), S. Suetsugu, K. Ohtsuka, Y. Kasahara, Y. Matsuda (Kyoto University), K. Hwang, P. Noh, E.-G. Moon (KAIST), N. Kurita, H. Tanaka (Tokyo Institute of Technology), S. Fujimoto (Osaka University), J. Nasu (Tohoku University).

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# T-linear resistivity in the strange-metal phase of cuprate superconductors due to umklapp scattering from a spin excitation

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The strange-metal phase of cuprate superconductors exhibits a linear in temperature resistivity [1-3], however, the origin of this remarkable anomaly is still not well understood. Here the linear temperature dependence of the electrical resistivity in the strange-metal phase of cuprate superconductors is investigated from the underdoped to overdoped regimes [4]. The momentum dependence of the transport scattering rate arising from the umklapp scattering between electrons by the exchange of the spin excitation is derived and employed to calculate the electrical resistivity by making use of the Boltzmann equation. It is shown that the antinodal umklapp scattering leads to the linear in temperature resistivity in the low-temperature with the temperature linear coefficient that decreases with the increase of the doping concentration [4], however, the nodal umklapp scattering induces a deviation from the linear in temperature resistivity in the far lower temperature, and then the quadratic in temperature resistivity in the far lower temperature is generated by both the antinodal and nodal umklapp scattering. The theory also shows that the same spin excitation that acts like a bosonic glue to hold the electron pairs together [5-6] also mediates scattering of electrons in the strange-metal phase of cuprtae superconductors responsible for the linear in temperature resistivity and the associated electronic structure [7-8].

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# Quantum Hall liquid crystals

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Focussing on spatially-ordered quantum states that break time-reversal symmetry, I will discuss compressible quantum Hall Wigner crystal, smectics and nematics and their relation via proliferation of corresponding topological defects.

# Multi-length scale X-rays investigation of hierarchically organized supercrystals

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Manipulation of matter at atomic, molecular, and supramolecular levels has reached an extraordinary level of maturity. Hierarchically organized supercrystals, which means µm-scaled 3D supramolecular assembly of nanostructures with material properties dependent on the building nanosystems and their relative positions, are today realized by nanotechnology, with bottom-up or top-down techniques. These supercrystals have emerging functions related to their increased level of structural complexity.
In the aforementioned research field, hard X-rays probes are tools suitable to investigate these smart materials across different length scales, either to evaluate their statical structure or to follow their evolution under external stimuli (temperature, light, electric or magnetic fields, stress, strain ..) [1,2].
In this talk, selected contributions of colloidally synthesized supercrystals will be described which have been investigated with GIWAXS/GISAXS [3], Coherent Diffractive Imaging [4], Ptychography [5,6] and Multilayer Diffraction [7,8,9,10].

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# Topology of chalcogen chains

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We investigate the topological properties of the helical atomic chains occurring in elemental selenium and tellurium. We postulate a realistic model that includes spin-orbit interaction and show this to be topologically non-trivial, with a topological invariant protected by a crystalline symmetry. We describe the end-states, which are orbitally polarized, with an orbital density modulation strongly peaked at the edge. Furthermore, we propose a simplified model that decomposes into three orbital chains, allowing us to define a topological invariant protected by a crystalline symmetry. We contrast this result with recent observations made for the orbital Su-Schrieffer-Heeger model containing a $p$-orbital zigzag chain.

# Higgs-Leggett mode in Kagome Superconductor $CsV_3Sb_5$

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A recent Little-Parks experiment on Kagome-structured superconductor $CsV_3Sb_5$ demonstrated remarkable magneto resistance oscillations with period $\phi_0/3=hc/6e$ [1]. In the present work [2], we perform an analysis based on the Ginzburg-Landau free energy functional involving repulsive Josephson-type couplings between PDW orders at the three reciprocal lattice vectors connecting M points of the hexagonal Brillouin zone of the material. In a ring geometry we unveil that, as a series of intermediate, metastable states, phase of one SC order parameter winds $2\pi$ more or less than the other two ones around the ring, which yields local free-energy minima at magnetic flux of integer multiples of $\phi_0/3$. It is clarified that these intermediate states are stabilized by a Higgs-Leggett mechanism, which induces domain walls (DW) between domains with $Z_2$ chirality [3,4,5]. At low temperatures DW are expelled from the system resulting in free energy minima only at integer multiples of $\phi_0$. Our theory explains successfully the novel 6e superconductivity observed in the recent Little-Parks experiment for Kagome material $CsV_3Sb_5$ and sheds light on rich physics in the Kagome Vanadium-based superconductors.

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# Development of dynamic magnetic pair-density function analysis

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As the intensity of neutron beams increases, the magnetic pair-distribution function analysis mPDF has been developed to study the instantaneous local magnetic structure [1, 2]. Meanwhile, the energy-resolved pair-density function analysis has also been developed for lattice dynamics [3,4]. However, there was no magnetic version for spin dynamics. Here, we developed a program of dynamic magnetic pair-density function $D_M(r, E)$ using the Fourier transform of the dynamic magnetic structure factor $S_M(Q, E)$ in 'Utsusemi' software [5,6]. The real space spin dynamics of an ilmenite $FeTiO_3$ (Fig. 1) powder sample exhibit magnon mode transitions in the spin-spin correlation with increasing energy from no-phase-shift to $\pi$-phase-shift, as shown in Fig. 2 [7]. The mode transition is well reproduced by a simulation using the reciprocal space magnon dispersions. This analysis provides a novel opportunity to study the local spin dynamics of various magnetic systems.

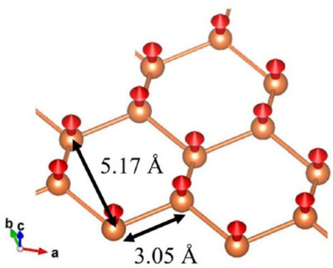


Fig. 1. Magnetic structure of honeycomb lattice in $FeTiO_3$ [5].

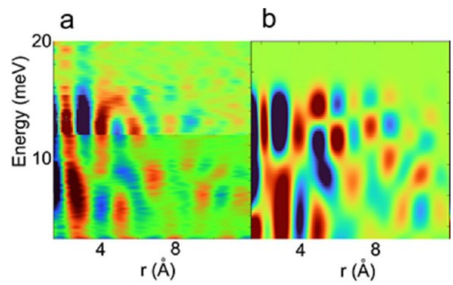


Fig. 2. Dynamic magnetic pair-density function $D_m(r, E)$ of $FeTiO_3$. Experimental $D_m(r, E)$ (a) and simulated $D_m(r, E)$ (b) [5].

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# Investigation of BKT transition under low magnetic fields in NbN thin films

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A comprehensive study of the electronic transport properties in NbN thin films has been carried out under low magnetic field intensities, ranging from $5 \times 10^{-4}$ to $1.6 \times 10^{-2}$ T [1, 2]. We have investigated the properties of the Berezinskii–Kosterlitz–Thouless (BKT) transition, a characteristic 2D topological phenomenon typically occurring in absence of magnetic field and detected in thin NbN films (< 15 nm) [3].
In this work, the two-dimensional nature of the films has been characterized by electrical resistivity analysed using the standard Cooper pair fluctuation model developed by Aslamasov and Larkin (AL) [7] and Maki and Thompson (MT) [8, 9]. The BKT temperature has been extracted in the absence of magnetic field. Upon field application, a large standard deviation was observed in the extracted parameters from cooper pair fluctuation model and $T_{BKT}$, which becomes significantly high at field intensity greater than $10^{-2}$ T.
Similarly, in I-V characteristics, an abrupt change in the α exponent (V proportional to $I^{\alpha}$) at the transition [3, 4, 6], associated with a jump in the superfluid stiffness, confirmed the presence of a BKT transition in our studied system under zero magnetic field. However, in presence of the magnetic field, this effect begins to diminish at field intensity as low as $10^{-3}$ T, then disappearing completely at $10^{-2}$ T. These findings suggest the existence of a threshold in the magnetic field intensity above which the influence of magnetic vortices surpasses any signs of BKT transition [5].
A phenomenological model is under development to explain features experimentally detected in our thin NbN films.

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# Topological order and dynamics in long-range Kitaev chains

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We study a one-dimensional fermionic chain with long-range hopping and pairing [1], we discussing some general features associated to the presence of long-range entanglement and the algebraic decays of the correlation functions. Moreover, we show that the time evolution triggered by a quantum quench between short-range and long-range regions, can be characterized by dynamical quantum phase transitions without crossing any phase boundary. We show, also, that the adiabatic dynamics is dictated by the divergence of a topological length scale at the quantum critical point, clarifying the violation of the Kibble-Zurek mechanism for long-range systems [2]. Moreover we study the combined effects of disorder and range of the couplings, showing that either the range and the on-site disorder can greatly enhance the topological phases characterized by the appearance of one or many Majorana modes localized at the edges, considering both a discrete and a continuous disorder distribution [3].

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# Flux cotunneling and Coulomb drag for quantum phase slips

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Employing charge–flux duality for Josephson junctions and superconducting nanowires,
we predict a novel effect of fluxon cotunneling in SQUID-like nanorings [1]. This process is strictly dual to that of Cooper pair cotunneling in superconducting transistors formed by a pairs of Josephson tunnel junctions connected in series. Cooper pair cotunneling is known to lift Coulomb blockade in these structures at low temperatures. Likewise, fluxon cotunneling may eliminate the magnetic blockade of superconducting phase fluctuations in SQUID-like nanorings, driving them into an insulating state. Yet another interesting and novel effect – Coulomb drag for quantum phase slips [2] – emerges in a system of two electromagnetically coupled superconducting nanowires. We demonstrate that applying electric current to one of such wires one induces a non-vanishing voltage across another one. We evaluate the cross-resistance for such a system which turns out to exhibit a non-trivial power-law dependence on both temperature and current bias.

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# Unconventional Josephson junctions for quantum hardware

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Progress in material science and nanofabrication gives opportunities to create unique hybrid Josephson junctions (JJs), thus providing advanced functionalities in superconducting quantum technologies. We will report on special properties of smart superconducting circuits and of hybrid tunnel-ferromagnetic JJs, which make possible alternative layouts for the superconducting modules inside a more general 3D-architecture for quantum hardware.

We will discuss how the macroscopic phase of a carefully designed superconducting circuit, namely the Josephson Digital Phase Detector (JDPD), can be manipulated to perform digital phase detection of weak coherent radiation, thus constituting a phase-readout protocol for a superconducting qubit [1]. Moreover, we will classify some significant behaviors of tunnel-ferromagnetic JJs [2] through a comparative study of their electro-dynamical properties [3]. The possibility to control high quality hybrid tunnel junctions [4] through different physical means allows for novel tuning mechanisms that are not susceptible to specific noise sources in a transmon configuration [5].

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# Nonlocal Josephson effect in coherently coupled Josephson junctions

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Recently, the coherent coupling between two adjacent Josephson junctions sharing a superconducting electrode has been researched for future application to quantum information technology [1]. The coherent coupling is formed because the wavefunctions of the bound states in junctions penetrate the shared superconducting electrode and overlap. Thanks to the coherent coupling, supercurrent flowing in one junction depends not only on a phase difference of the junction but also on a phase difference of the other junction, producing the nonlocal Josephson effect. In this situation, the symmetries of one junction are easily broken by the other phase difference.

Here we discuss our recent experimental progress in superconducting transport in the coherently coupled Josephson junctions on superconductor/semiconductor heterostructures. First, we have demonstrated the existence of the nonlocal Josephson effect using the InAs nanowires with epitaxially grown Aluminum films [2]. Then we have focused on the symmetry breaking in the coupled Josephson junctions, producing the Josephson diode effect. For the experiments, we used the InAs quantum well with the epitaxially grown Aluminum film. Our results will contribute to establishing the fundamental physics of the coherently coupled Josephson junctions and provide a new platform to seek exotic superconducting phenomena.

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# Dirac cone formation in single-component molecular conductors based on metal dithiolene complexes

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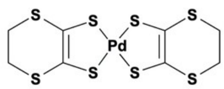
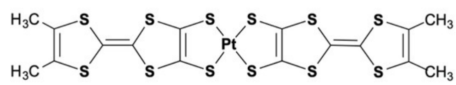
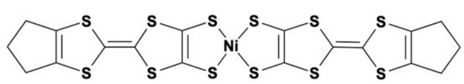
The discovery of the nodal line semimetal state in a single-component molecular conductor [Pd(dddt)$_2$] under high pressure has revealed a significant connection between the single-component molecular conductor and the Dirac electron system [1]. The Dirac cone formation in [Pd(dddt)$_2$] can be understood using a tight-binding model [2]. This mechanism is based on 1) HOMO–LUMO band crossing and 2) node of the HOMO–LUMO couplings, which is favorable for the emergence of the Dirac cones that are located near the Fermi level. After this work, an ambient-pressure nodal line semimetal based on a single-component molecular conductor [Pt(dmdt)$_2$] was reported [3]. Our tight-binding band calculation analysis indicated that this system is a textbook example of the mechanism that we proposed [4]. In this work, we focus on two single-component molecular conductors, [Ni(tmdt)$_2$] [5] and [Ni(btdt)$_2$] [6] that have molecular arrangements very similar to that in [Pt(dmdt)$_2$]. The former is a (semi)metal, and the latter is a narrow-gap semiconductor with a high conductivity at room temperature. We examined the possibility of the Dirac cone formation in these compounds by means of tight-biding models and first-principles DFT calculations.



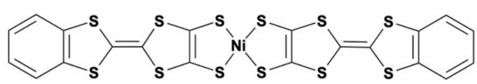
[Pd(dddt)$_2$]



[Pt(dmdt)$_2$]



[Ni(tmdt)$_2$]



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# Focused Ion Beam nanostructuring of superconductors

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Superconducting materials are dissipationless carriers of electric current and provide macroscopic and robust quantum coherence. These properties render them highly valuable as parts for electrical generators, magnetic sensors, and powerful magnets. To achieve the required performance employed in those applications, bulk superconductors often need nanoengineering. Moreover, when these materials are reduced to the nanoscale becoming nano-superconductors, exciting new physical phenomena emerge.

Ground-breaking proposals have taken advantage of the third dimension (3D) for the development of advanced electronic components, opening fascinating novel routes in the fields of material science, physics and nanotechnology. Thus, 3D nano-superconductors could be implemented in future highly-efficient electronic elements. However, their fabrication and characterization remain a challenge.

In this contribution, we introduce a direct-write additive manufacturing method based on focused ion beam technologies to fabricate at-will advanced nano-superconductors.

We have prepared 3D superconducting hollow nanocylinders with controllable inner and outer diameters (down to 32 nm), and nanohelices with at-will geometries, by decomposing a precursor with a $He^+$ FIB [1,2]. These nanostructures become superconducting at 7 K and show large critical magnetic field and critical current density. Remarkably, these nanohelices display superconductivity up to 15 T depending on the direction of the field with respect to the nanohelix axis. This suggest that their helical 3D geometry and their orientation in a magnetic field play a significant role in the superconducting phase transition. Moreover, fingerprints of vortex and phase-slip patterns are also experimentally identified and supported by numerical simulations based on the time-dependent Ginzburg-Landau equation [3]. Additionally, we present an experimental work on the modulation of electric field-induced superconductivity in 45 nm-wide nanowires fabricated using $Ga^+$ FIB [4], theoretically explained using a model based on the GL theory.

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# Tunable topological Dirac surface states and van Hove singularities in kagome metal $GdV_6Sn_6$

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Transition-metal-based kagome materials at van Hove filling are a rich frontier for the investigation of novel topological electronic states and correlated phenomena. To date, in the idealized two-dimensional kagome lattice, topologically nontrivial Dirac surface states (TDSSs) have not been unambiguously observed, and the manipulation of TDSSs and van Hove singularities (VHSs) remains largely unexplored. Here, we reveal TDSSs originating from a $\mathbb{Z}_2$ bulk topology and identify multiple VHSs near the Fermi level ($E_F$) in the magnetic kagome material $GdV_6Sn_6$. Remarkably, using *in-situ* surface potassium deposition, we successfully realize manipulation of the TDSSs and VHSs. The Dirac point of the TDSSs can be tuned from above to below $E_F$, which reverses the chirality of the spin texture at the Fermi surface. These results not only establish $GdV_6Sn_6$ as a fascinating platform for studying the nontrivial topology, magnetism and correlation effects native to kagome lattices, but also open up a new avenue for the potential application of spintronic devices based on kagome materials.

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# Superfluid response of two-dimensional filamentary superconductors

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There is increasing evidence that in several classes of low-dimensional superconducting (SC) systems, the strongly inhomogeneous nature of the electronic condensate appears as a filamentary SC pattern.
While the microscopic mechanism generating the phase separation depends on the specific system under investigation, some properties of the emergent SC condensate are generically related to its filamentary inhomogeneous nature.
So far, several studies have focused on the effect of the mesoscale inhomogeneity on the SC transition above the critical temperature, but only a few studies have investigated the superfluid response of the resulting filamentary condensate [1, 2]. We face this issue by mapping the problem into a random-impedance network (RIN) model that we solve exactly. By studying different RIN realizations, we show how the superfluid response of the system non-trivially depends on its microscopic and macroscopic characteristics. At the same time, by comparing our theoretical results with complex conductivity measurements on $LaAlO_3/SrTiO_3$ interfaces, we show how the different doping regimes can be understood in terms of an intrinsically less or more robust filamentary SC condensate.
In this scenario, we emphasize that in inhomogeneous systems superfluid density and stiffness are highly inequivalent as soon as strong spacial correlations become relevant and despite the fact phase fluctuations are not involved [3].

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# Observation of Kondo lattice behavior in antiferromagnetic metal FeTe

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Finding *d*-electron heavy fermion (HF) states has been an important topic as the diversity in *d*-electron materials can lead to many exotic Kondo effect-related phenomena or new states of matter such as correlation-driven topological Kondo insulator. Yet, obtaining direct spectroscopic evidence for a d-electron HF system has been elusive to date.

In this presentation, I will introduce the experimental observation of Kondo lattice behavior in an antiferromagnetic metal, FeTe, via angle-resolved photoemission spectroscopy (ARPES), scanning tunneling spectroscopy and transport property measurements [1]. The Kondo lattice behavior is represented by the emergence of a sharp quasiparticle and Fano-type tunneling spectra at low temperatures. The transport property measurements confirm the low-temperature Fermi liquid behavior and reveal successive coherent-incoherent crossover upon increasing temperature. We interpret the Kondo lattice behavior as a result of hybridization between localized Fe $3d_{xy}$ and itinerant Te $5p_z$ orbitals. Our observations strongly suggest unusual cooperation between Kondo lattice behavior and long-range magnetic order.

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# High Tc superconductivity boosted by Spin–Orbit Coupling in superlattices of quantum wells

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Here, we present first-principles quantum calculation of superconductivity in an artificial heterostructure of metallic quantum wells with 3 nm period where quantum size effects give two-gap superconductivity with Rashba spin–orbit coupling (RSOC) controlled by the internal electric field at the interface between the nanoscale metallic layers intercalated by insulating spacer layers. The key results of this work show that fundamental quantum mechanics effects including RSCO at the nanoscale [1,2] provide key tools in applied physics for quantitative material design of unconventional high temperature superconductors at ambient pressure. We discuss the superconducting domes where *Tc* is a function of either the Lifshitz parameter ($\eta$) measuring the distance from the topological Lifshitz transition for the appearing of a new small Fermi surface due to quantum size effects with finite spin–orbit coupling and the variable e-ph coupling $g$ in the appearing second Fermi surface linked with the energy softening of the cut off $\omega 0$.

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# Ising superconductivity in a bulk

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New type of superconducting interaction – the Ising pairing – has been discovered in the atomically thin $NbSe_2$ [1]. The lack of crystal inversion symmetry in 1*H* monolayer combined with a strong spin-orbit coupling leads to an effective spin-orbit magnetic field which locks spins in the Cooper pairs out of plane and hinders the spin pair-breaking. This leads to anomalously high in-plane upper critical field strongly violating the Pauli limit. Adding layers to 1*H*-$NbSe_2$ rapidly suppresses Ising superconductivity due to restoration of the inversion symmetry.
Here we study $(LaSe)_{1.14}(NbSe_2)$ and $(LaSe)_{1.14}(NbSe_2)_2$, superconductors with $T_c = 1.23$ K and 5.7 K, respectively, comprised of incommensurate $NbSe_2$ and LaSe layers. Surprisingly, in these bulk single crystals the in-plane upper critical fields exceed the Pauli limit even more that in $NbSe_2$ monolayer Utilizing various complementary experimental techniques, as quasiparticle interference QPI STM, ARPES and transport measurements and DFT calculations it is shown [3,4] that our systems are electronically equivalent to the highly doped $NbSe_2$ monolayer. Also the spin split Fermi surfaces around *K* and *K'* points in the Brillouin zone pointing to Ising superconductivity are observed. Why Ising superconductivity can also reside in a fully three-dimensional crystals will be discussed.

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# Extended Nielsen-Ninomiya theorem in non-Hermitian systems and its application

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The Nielsen-Ninomiya theorem is a fundamental theorem on chiral fermions such as Weyl fermions in condensed matter systems. In this talk, I report an extension of the theorem in open systems, which includes the original Nielsen-Ninomiya theorem in a special limit. In contrast to the original theorem, which is a no-go theorem for bulk chiral fermions, the new theorem permits them due to bulk topology intrinsic to open systems. I will also report applications of our theorem and predict a new type of topological phenomena.

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# Density and pseudo-spin rotons in a bilayer of soft-core bosons

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We study the dynamics of a bilayer system of bosons with repulsive soft-core Rydberg-dressed interactions within the mean-field Bogoliubov-de Gennes approximation. We find roton minima in both symmetric and asymmetric collective density modes of the symmetric bilayer. Depending on the density of bosons in each layer and the spacing between two layers, the homogeneous superfluid phase becomes unstable in either (or both) of these two channels, leading to density and pseudo-spin-density wave instabilities in the system. Breaking the symmetry between two layers, either with a finite counterflow or a density imbalance renormalizes the dispersion of collective modes and makes the system more susceptible to density-wave instability.

# Novel materials with magnetic skyrmions and their three-dimensional dynamics

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Magnetic skyrmion, i.e., a topologically stable swirling spin configuration, has recently attracted attention as a particle-like object potentially suitable for the design of high-density information bits. Previous observations of skyrmions have mostly focused on noncentrosymmetric systems, where Dzyaloshinskii-Moriya interaction plays an important role[1,2]. On the other hand, recent theoretical studies suggest that skyrmions can be stabilized even in centrosymmetric systems by considering different microscopic mechanisms. For example, geometrical frustration of short-range exchange interactions on triangular lattice is predicted to stabilize a hexagonal lattice of skyrmions[3]. Another potential mechanism is the RKKY and four-spin interactions mediated by itinerant electrons, which is expected to favor a skyrmion lattice state for highly-symmetric (such as hexagonal or tetragonal) crystal lattice systems[4].

In this talk, I overview the recent experimental discovery of skyrmions in centrosymmetric systems[5-10]. In particular, we focus on the case of centrosymmetric tetragonal magnets, where the square lattice of skyrmions with extremely small diameter (1.9 nm for $GdRu_2Si_2$, i.e. the smallest value ever reported for single-component bulk materials) has been observed[8,9]. These results demonstrate that skyrmions can be stabilized even without geometrically frustrated lattice nor inversion symmetry breaking, and suggest that rare-earth intermetallics with highly-symmetric crystal lattice may ubiquitously host nanometric skyrmions of exotic origins.

In time allows, I will also discuss the recent experimental observation of skyrmion strings in three-dimensional systems and their excitation dynamics[10,11].

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# Superconducting gap structure and anomalous lower critical field in $UTe_2$

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$UTe_2$ has attracted significant interest because of its paramagnetic spin-triplet superconducting properties [1] and possible chiral superconducting states [2,3]. However, the superconducting gap symmetry is still highly controversial possibly due to the crystal inhomogeneity or the presence of magnetic impurities. Recently, ultra-clean crystals of $UTe_2$ have become available [4], and novel superconducting properties have been revealed in these crystals [5]. In this study, we measured the anisotropic magnetic penetration depth [6] and lower critical field [7] of ultra-clean single crystals of $UTe_2$. We found that the penetration depth follows $T^2$ temperature dependence regardless of the magnetic field directions, indicating that the order parameter consists of multiple components. Furthermore, the penetration depth data show large quasiparticle excitations along the $b$- and $c$-axes, from which we propose that the $B_{3u}+i\,A_u$ state is most plausible in $UTe_2$. As for the lower critical field, we found unusual enhancements for the magnetic field along the $b$- and $c$-axes. We propose the Ising-like ferromagnetic fluctuations detected in NMR [8] and $\mu$SR [9] as the origin of the anomalous behaviors in the lower critical field.

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# Ultrafast magnetometry of (light-induced) superconductors

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Driving certain cuprates and organic materials has been shown to induce THz optical properties reminiscent of superconductivity far above the equilibrium transition temperature [1-4]. So far, nothing is known regarding the magnetic response of these non-equilibrium states. Do they also feature a Meissner effect and expel an external magnetic field? How do they react to a changing magnetic field on sub-picosecond time scales?
In this work, we study the ultrafast magnetic response of these materials, both in static and time-dependen magnetic fields.
We make use of the Faraday effect in a magneto-optical crystal adjacent to the sample to reconstruct its position-dependent magnetic properties with sub-picosecond time resolution.
Starting from the investigation of the distruction of superconductivity below Tc, we investigate signs of the light-induced appearance of superconductivity far above Tc. Studying its dependence on temperature and magnetic field provides new insights on the properties of the non-equilibrium dynamics of these systems.

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# Proximate Deconfined Quantum Critical Point in a Shastry-Sutherland Compound $SrCu_2(BO_3)_2$

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The deconfined quantum critical point (DQCP) describes a continuous quantum phase transition (QPT) beyond Landau paradigm, which takes place between two spontaneous symmetry-breaking states. The DQCP may host novel phenomena such as emergent symmetries and fractionized excitations. Experimentally, however, DQCP has not been realized.
Here I report our high-pressure and ultra-low temperature NMR studies on a frustrated magnet $SrCu_2(BO_3)_2$ which can be described by a Shastry-Sutherland model [1]. When tuned by pressure and field, its ground states transition from dimer singlet (DS) to plaquette singlet (PS) and long-range-ordered antiferromagnetism (AFM) [2,3,4]. We first established microscopic evidences for a pressure-induced DS-PS phase transition at pressures above 1.8 GPa and zero field. At 2.1 and 2.4 GPa, a field-induced weakly first-order PS-AFM QPT is firmly identified with several key observations: the coexistence temperature for two phases is as low as 0.07 K at the transition; the (H, T) phase boundaries of both PS and AFM phases follow the power-law scaling with a single power-law exponent at each pressure; with increasing pressure, the QPT goes toward a continuous type with further suppressed AFM order parameters at the transition; the spin dynamics at 2.4 GPa revealed by the spin-lattice relaxation rates exhibits a quantum critical scaling [5]. These facts can be understood by an approximate DQCP, with a crossover from an emergent O(3) symmetry to an O(4) type with increasing pressure, and offer a concrete platform for studying the long-sought-for DQCP in a real material.

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# Impact of high order of van Hove singularities on the competition of charge and spin degrees of freedom

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Many phases arise in close proximity to each other through the interplay of spin and charge degrees of freedom. The best-known example is superconductivity, which occurs in close proximity to magnetic or charge-density wave phases in high-temperature superconductors and dichalcogenides. In this talk, we address the competition of spin and charge degrees of freedom leading to spin-density wave phases, charge-density wave phases, and topological phases. We come to the possibility of increasing the critical temperature by increasing the density of states. A well-known example is van Hove singularities, where the Fermi surface undergoes a topological transition. Higher order singularities, where several disconnected pockets of the Fermi surface touch simultaneously, can naturally occur at high symmetry points in the Brillouin. Such multicritical singularities can lead to stronger divergences in the density of states than canonical van Hove singularities. As a concrete example of the high order topological transitions at the Fermi surface, we show how they can be used in the analysis of experimental data on Sr3Ru2O7 [1,2]. Understanding the mechanisms involved opens new root in the development of materials for complex quantum phases.

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# Atomic Relaxation in Cuprate Superconductors: The Role of Dynamic Disorder on Charge Density Waves

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Charge density wave (CDW) is an important state in the cuprate superconductors. While a thermodynamic CDW phase transition remains elusive due to the persistence of short-range CDW correlations at temperatures far beyond the superconducting transition, there exists a well-defined, yet much debated temperature $T_{\mathrm{CDW}}$ where the CDW coherence develops a kink. In this work, which combines hard x-ray diffraction, x-ray diffuse scattering and x-ray photon correlation spectroscopy, we show that the atomic relaxation dynamics in $La_{1-x}Sr_xCuO_4$ is determined by the subtle interplay between the dopant-induced quenched disorder and CDW-favored atomic distortions. Such interplay leads to a crossover between cooperative and incoherent atomic relaxation at $T_{\mathrm{CDW}}$, which subsequently changes the CDW coherence properties.

# Flux vortex diode effect in proximity-magnetized superconducting Nb

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The proximity effect in superconductor/ferromagnet (S/F) devices can lead to exotic phenomena, including spin-triplet pairing and spin-valve transport [1–3], as well as non-reciprocal supercurrents [4, 5]. Although non-reciprocal supercurrents (i.e., a superconducting diode effect) have been observed in different superconducting heterostructures with broken inversion and broken time reversal symmetry via an F layer with spin-orbit coupling (SOC), the exact underlying mechanism of the diode effect can be challenging to determine. Here, we report normal and superconducting state electrical transport measurements of Nb/EuS heterostructures and wires in which EuS is a ferromagnetic semiconductor. In the normal and superconducting states, we observe a strong magnetic proximity effect in Nb and a long-range spin-valve effect that is boosted by SOC. We also observe an asymmetric flow of flux vortices in the superconducting state which generate a diode effect.

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# Phase Transitions of Confinement and Aggregation, and Formation of Stripes in Ensembles of Solitons in Quasi 1D Electronic Systems with long range Coulomb interactions.

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Broken symmetries of quasi one-dimensional electronic systems give rise to microscopic solitons taking roles of carriers of the charge or spin (rem. [1] and rfs. in [2]). Discrete degeneracies (e.g. charge- or bonds ordering) give rise to solitons as kinks of a scalar order parameter. Continuous degeneracies (e.g. incommensurate density waves, superconductors) with complex order parameters give rise to phase vortices, amplitudes solitons, and their combinations. The long-range ordering in dimensions above one imposes super-long-range confinement forces upon the solitons, leading to a sequence of phase transitions in their ensembles. The higher-temperature transition enforces the confinement of solitons into topologically bound complexes: pairs of kinks or the amplitude solitons dressed by exotic half-integer vortices. At a second lower temperature transition, the solitons aggregate into rods of bi-kinks or into walls of amplitude solitons terminated by rings of half-integer vortices. With lowering temperature, the walls multiply, passing sequentially across the sample.
Here, we summarize results [2] of a numerical modeling for different symmetries, for charged and neutral soliton, in two and three dimensions. The efficient Monte Carlo algorithm, preserving the number of solitons, was employed which substantially facilitates the calculations, allowing to extend them to very demanding three-dimensional case including the long-range Coulomb interactions.

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# Tc, Pseudogap and other Cuprate Properties from Charge Sharing between Planar Cu and O, Measured with NMR

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The sharing of the charge between planar Cu and O in the cuprates was found to be very different between cuprate families at given doping, with the maximum T_c nearly proportional to the planar O hole content (Tc,max = 200 K n(O)), measured at room temperature with NMR [1]. This was confirmed by cellular DMFT in 2021 [2]. Furthermore, when pressure amplifies the Tc of certain cuprates beyond what can be achieved by doping, a decades old conundrum, NMR showed very recently, that pressure does so by raising the planar O hole content in excess of what follows from changes in doping induced by pressure [3], and according to the relation above. Thus, the importance of the sharing of the charge is central to the cuprate properties, and not how one achieves the required hole contents at Cu and O, whether by doping or other means. More details of these findings will be discussed, as well as new correlations of the charge sharing with the pseudogap that is a temperature independent gap in NMR [4], in good agreement with entropy data. It is proposed that this sharing of charge between Cu and O, which can lead to spatial inhomogeneity, holds information about charge density variations, stripes or nematicity, as well.

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# Third harmonics generation from collective modes in disordered superconductors

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We investigate the third harmonic contribution to the current response when a disordered superconducting system is perturbed by an electromagnetic field. The problem is addressed by exactly solving the time-dependent Bogoljubov de-Gennes equations on a finite lattice where superconducing order is inhomogeneous due to strong local disorder.
Results are presented for both, s-wave systems as e.g. NbN and d-wave superconductors where related experiments have been performed for high-Tc cuprate materials. In the clean system the third harmonic response is driven by the diamagnetic contribution and most pronounced for frequencies corresponding to half of the spectral gap. Already for small disorder the low energy response becomes dominated by the paramagnetic current which has also strong contributions from collective modes. By explicitely analyzing the dynamics with and without the time dependence of amplitude and phase of the order parameter we discuss the relevance of the various collective excitations to the third-harmonic response as detected in recent experiments.

# Superconducting orbitronics: novel effects and quantum phases

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Orbital degrees of freedom play a key role in setting out striking effects when dealing with low dimensional noncentrosymmetric superconductors. A relevant concept in this context is represented by the orbital Rashba coupling. By varying the strength of the orbital Rashba interaction, the superconducting phase can undergo a $0-\pi$ transition with the $\pi$-phase being marked by a non-trivial sign change of the superconducting order parameter between different orbitals [1]. Then, I discuss the physical mechanisms for achieving an unconventional orbital pair-density wave [2]. Breaking of time-reversal and point-group spatial symmetries can have a profound impact on superconductivity. Here, for two-dimensional spin-singlet superconductors with unusually low degree of spatial symmetry content, vortices with supercurrents carrying orbital angular momentum around the core can form and be energetically stable [2]. The orbital vortex has zero net magnetic flux since it is made up of counter-propagating Cooper pairs with opposite orbital moments. Finally, I will discuss the Edelstein effects arising in multi-orbital superconductors that lack inversion symmetry. It is known that the flow of supercurrent can induce a nonvanishing magnetization, a phenomenon which is at the heart of nondissipative magnetoelectric effects. For electrons carrying spin and orbital moments, a question of fundamental relevance deals with the orbital nature of magnetoelectric effects in conventional spin-singlet superconductors with Rashba coupling. Remarkably, we find that the supercurrent-induced orbital magnetization is more than one order of magnitude greater than that due to the spin, giving rise to a colossal magnetoelectric effect [3]. Materials which can exhibit these phenomena as well as orbitally driven transport and topological properties are also presented [1,4].

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# Gate-control of superconducting current

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In modern electronics based on conventional metal-oxide semiconductor (CMOS) technology, the logic state of a device is controlled by a gate voltage ($V_G$), which tunes the density of charge carriers flowing through a device nanoconstriction.
The superconducting equivalent of such effect had been unknown until recently, after several groups have showed that a $V_G$ can be used to tune the superconducting current (supercurrent) flowing through a superconducting nanoconstriction [1-4]. This effect has raised great interest because it can lead to superconducting logics like CMOS logics, but with lower energy dissipation.
In this talk, I will review the different mechanisms that have been proposed to explain the gate-control of supercurrent (GCS) effect, and present results obtained from our group showing evidence for the effect. In particular, I will discuss the importance of parameters like spin-orbit coupling, disorder, and surface states for the observation of the GCS effect, starting from a series of experiments that we have systematically carried out on a variety of gate-controlled devices based on elemental metallic superconductors (e.g., Nb), non-centrosymmetric superconductors (e.g., $Nb_{0.18}Re_{0.82}$) and unconventional oxide superconductors ($Sr_2RuO_4$).

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# Anomalous softening of phonon-dispersion in the under- doped cuprate superconductors

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Cuprate superconductors possess a complex phase diagram with various other phases like charge density wave (CDW) in the underdoped region. Interestingly, the CDW order has become fundamentally important due to growing evidence of its close relation to the pseudo-gap phase. One leading approach to unravel the relation, is to study the phonon-spectrum which couples to electronic degrees of freedom, thus leaving fingerprints associated with the electronic-structure. Several experiments [2] have observed a softening of the phonon-dispersion in the underdoped cuprates at the CDW ordering wave vector, but only below the superconducting transition temperature. The phonon-softening in cuprates is considered 'anomalous' since it is in sharp contrast to the situation in metallic systems [3] where such softening occurs for temperatures below the onset of CDW order. By employing a perturbative approach, we find [1] that a complex interplay among the CDW order, superconductivity and a finite quasi-particle lifetime arising from an unusually connected thermal fluctuations of these orders, can explain the 'anomalous' nature of the phonon-softening, also giving good accounts for other features observed in recent inelastic-Xray scattering experiments.

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# Influence of impurities on the electronic structure in cuprate superconductors

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The impurity is inherently manifest in cuprate superconductors, as cation substitution or intercalation is necessary for the introduction of charge carriers, and its influence on the electronic state is at the heart of a great debate in physics[1-3]. Here based on the microscopic octet scattering model[4-6], the influence of the impurity scattering on the electronic structure of cuprate superconductors is investigated in terms of the self-consistent $T$-matrix approach[7]. The impurity scattering self-energy is evaluated firstly in the Fermi-arc-tip approximation of the quasiparticle excitations and scattering processes, and the obtained results show that the decisive role played by the impurity scattering self-energy in the particle-hole channel is the further renormalization of the quasiparticle band structure with a reduced quasiparticle lifetime, while the impurity scattering self-energy in the particle-particle channel induces a strong deviation from the $d$-wave behavior of the superconducting gap, leading to the existence of a finite gap over the entire electron Fermi surface. Moreover, these impurity scattering self-energies are employed to study the exotic features of the line shape in the quasiparticle excitation spectrum and the autocorrelation of the quasiparticle excitation spectra, and the obtained results are then compared with the corresponding experimental data. The theory therefore also indicates that the unconventional features of the electronic structure in cuprate superconductors is generated by both the strong electron correlation and impurity scattering.

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# Dispersion kink in cuprate superconductors

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The renormalization of the electron in cuprate superconductors manifests itself by the electron quasiparticle dispersion kink [1-4]. However, the nature of this dispersion kink remains controversial. Here, the band renormalization effects are investigated within the framework of the kinetic-energy-driven superconductivity. It is shown that the dispersion kink originates from the strong interaction between the electrons by the exchange of a strongly dispersive spin excitation, and its emergence is always accompanied by the inflection point and well-pronounced peak structure in the real and imaginary parts of the electron self-energy, respectively [5-7]. In particular, as the doping concentration increase, the characteristic energy of the kink decrease monotonously, which is consistent to the superconducting gap coupling strength. Moreover, the peak-dip-heap (PDH) structure in the electron energy distribution curve is dominated by the inverse of the quasiparticle scattering rate, indicating the energy scales of the characteristic energy of the dispersion kink and the dip of PDH are both controlled by the peaks of the quasiparticle scattering rate.

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# Enhancement of Bereninskii-Kosterlitz-Thouless transition temperature in coupled deep and quasi-flat band 2 D system

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A flat(quasi) band is one method that might be used to increase the mean-field critical temperature superconductivity, but it also suppresses superfluid stiffness and the Bereninskii-Kosterlitz-Thouless transition in 2-d systems. [1,2] We address this issue by combining a deep 2D band with a weak coupling strength and a quasi-flat band with a strong coupling strength. This deep band coupling process aids in enhancing the BKT temperature and screening the suppression of superfluid stiffness [3,4,5]. Then, by adjusting the interband coupling between the bands, we investigate the ideal circumstance for achieving a greater BKT temperature. In contrast to the single-quasi flat band scenario, we find a significant amplification of the Bereninskii-Kosterlitz-Thouless transition temperature.

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# Impurity effects on the microwave conductivity of cuprate superconductors

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The microwave conductivity measurements on cuprate superconductors provide the crucial information of the quasiparticle transport in the superconducting state[1-3]. Here based on the microscopic octet scattering model[4-6], the doping and energy dependence of the microwave conductivity in cuprate superconductors in the presence of the impurity scattering is investigated within the framework of the self-consistent $T$-matrix approach[7]. The impurity scattering self-energy is evaluated in the Fermi-arc-tip approximation of the quasiparticle excitations and scattering processes[8] and employed to calculate the electron current-current correlation function by the consideration of the impurity scattering induced vertex correction. It is shown that there is a cusplike shape of the energy dependent microwave conductivity spectrum. At low temperatures, the microwave conductivity increases linearly with increasing temperatures, and reaches a maximum at an intermediate temperature, then decreases with increasing temperatures at high temperatures. In contrast with the dome shape of the doping dependent superconducting gap, the minimum microwave conductivity occurs around the optimal doping, and then increases in both underdoped and overdoped regimes.

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