Research Statement
Prof. Dr. Jörg Schmalian

Karlsruhe Institute of Technology
Institute for Theory of Condensed Matter and
Institute for Quantum Materials and Technologies
Email: joerg.schmalian@kit.edu | Telephone: +49 721 608 43590 | webpage

My research interest is the investigation of strongly correlated quantum mechanical many body systems. Together with my research team I develop theories for quantum materials with novel electric, optic, or magnetic properties. With my collaborators I predicted the recently observed electron hydrodynamics in graphene and advanced the theory of nematic order and fluctuations in iron-based materials. Using quantum field theoretical approaches to statistical mechanics and many-body theory, I work on phenomena such as unconventional superconductivity, topological superconductivity, quantum phase transitions, hydrodynamic transport, nano-electronics, magnetism, disordered systems and non-equilibrium dynamics. The research activities of my group include:

- Theory of **unconventional superconductivity**, such as superconductivity without quasi-particles, superconducting fluctuations, topological superconductivity, disorder in superconductors.
- **Electron hydrodynamics** and quantum transport with particular emphasis on Dirac systems such as graphene and electron-phonon fluids.
- **Complex order in quantum materials**: nematicity, time-reversal symmetry breaking, vestigial order.
- **Disordered systems and out-of-equilibrium dynamics** and quantum quenches in many-body systems, from quantum Griffiths behavior to self-generated glasses.

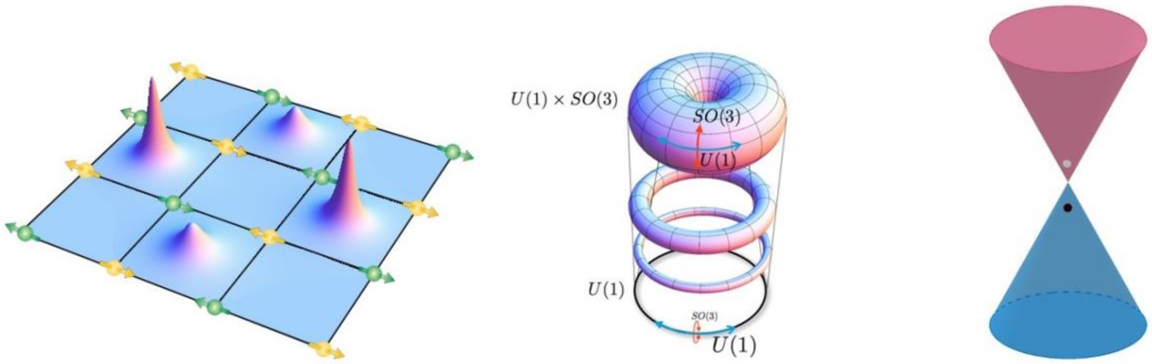

Figure 1 Illustration of major research themes: Left: nematic order in iron-based superconductors, Middle: critical phases in frustrated magnets, Right: Dirac cone of graphene.

1. Unconventional superconductivity

Our research activities in the theory of unconventional superconductivity are partly supported by the DFG transregional collaborative research center TRR-288.

The superconducting state constitutes one of the most fascinating ordered states of quantum matter. Our research activities are primarily concerned with various aspects of unconventional pairing states and with the question of superconductivity without quasiparticles.

Superconductivity is the fate of a Fermi liquid at low temperatures. Since superconductivity occurs in many systems where sharp Fermi liquid quasiparticle excitations are absent, the condition for pairing of incoherent electrons is an important problem in condensed matter physics. Key questions in this context are: Can one form Cooper pairs from completely incoherent fermions? What is the role of quantum criticality for pairing? Are there sharp quasiparticles in such a superconductor? Is the Cooper pair fluid that emerges still an ideal gas of pairs?

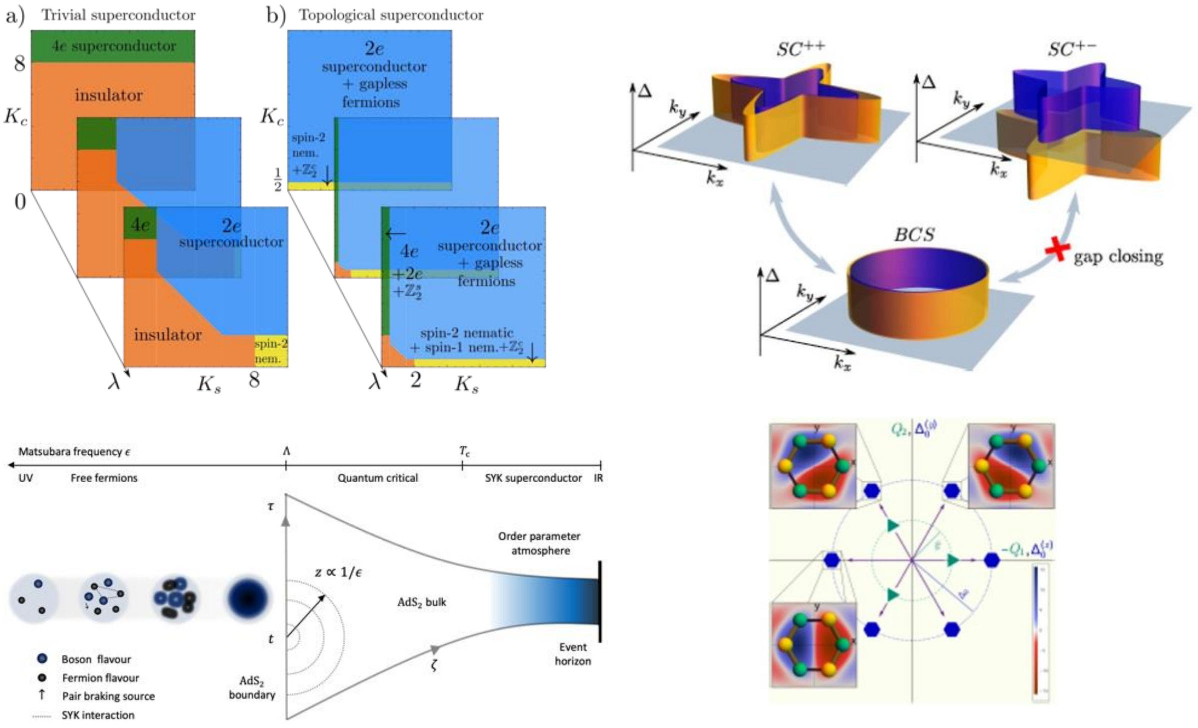

Figure 2; Top Left: Topologically enabled superconductivity where we demonstrated that dynamical zero modes enhance topological superconductivity over otherwise identical trivial superconductivity and yields a topological field theory [1]. Top Right: Analyzing the superconducting instabilities in oxide interfaces we showed that topological superconductivity occurs for an unconventional pairing state while electron-phonon induced pairing is topologically trivial [2]. Bottom Left: We derived the dual holographic gravity theory of a superconductor [3] from a microscopic model of strongly interacting electrons and phonons [4,5]. Bottom Right: We predicted [6] and contributed to the eventual observation [7] of vestigial nematic order due to superconducting fluctuations in the doped topological insulator Bi_2Se_3.

We have addressed these questions by analyzing the pairing problem in electronic systems near quantum critical points, pairing due to valence-skipping charge-Kondo impurities, and the RVB-pairing in doped Mott insulators for organic charge transfer salts and a doped valence bond state. Most recently, we demonstrated that critical and even fully incoherent electrons are undergo superconductivity, yet with reduced weight of the Bogoliubov quasiparticle weight and reduced superfluid stiffness. These results were obtained from the solution of a generalization of the Sachdev-Ye-Kitaev model to systems with strong electron-boson coupling. Most recently we derived from this theory the gravitational theory that was proposed in the context of the holographic description of correlated quantum matter.

We also address a range of problems in the context of the theory of fluctuations in superconductors. We proposed that topological superconductivity serves as indicator for unconventional pairing states in oxide interfaces, determined Cooper pair selection rules in systems with broken inversion symmetry, or showed that the Higgs mechanism in superconductors breaks down for length scales shorter than the superconducting coherence length due to the composite nature of the Higgs field, i.e. due to the finite binding energy of Cooper pairs. The breakdown of the Higgs mechanism inside the superconducting coherence volume is crucial to ensure the stability of the BCS mean-field theory in the weak-coupling limit. We also analyzed the impact of impurity scattering in a number of multi-band superconductors, identifying generalizations of the Anderson theorem to unconventional pairing states. Finally, we demonstrated that in low-dimensional systems topological superconductivity is much enhanced over trivial superconductivity because of change in the ground sate fluctuations of the corresponding topological field theory.

2. Electron hydrodynamics

Our research activities on electronic hydrodynamics are pursued as part of the EU-supported network Hydrotronics, coordinated at KIT.

The fluid flow of liquids is governed by the laws of hydrodynamics. Our research activities are concerned with the question under what circumstances the flow of electrons in solids is governed by hydrodynamic behavior. We proposed in 2008 and 2009 that ultrapure graphene at the neutrality point should be an excellent example for hydrodynamic transport of an electron fluid. By now several exciting experimental observations have been made that demonstrate hydrodynamic flow of electrons in graphene and several other materials of high purity. Our theory for quantum transport in the hydrodynamic regime leads to exotic behavior such as Lévy flights in phase space and non-local transport phenomena, including modified boundary conditions of the electron flow. We also analyzed anisotropic Dirac and Weyl systems, where the much discussed bound for the ratio of the viscosity to entropy density is violated and utilized the duality of quantum field theory and gravity theories to analyze a modified bound.

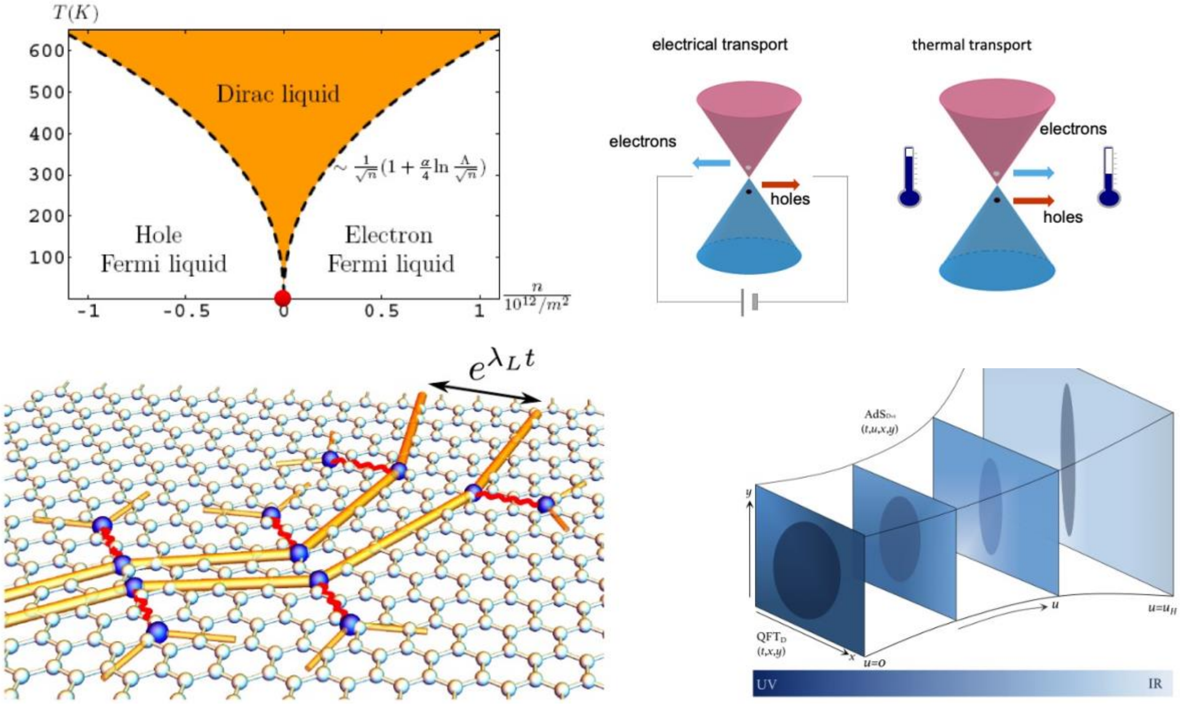

Figure 3 Top Left Temperature and density phase diagram of graphene with Dirac liquid behavior [8] where novel electron hydrodynamics was predicted [9-11]. Top Right: Charge and Heat transport of the Dirac liquid where we predicted the temperature dependence of the electrical conductivity and viscosity and Lévy flight dynamics at the neutrality point [9-12]. Bottom Left: Quantum chaos and scrambling of quantum information of graphene in the hydrodynamic regime where we showed that thermalization and scrambling rates are fundamentally distinct [13]. Bottom Right: We developed the holographic theory [14] and quantum Boltzmann theory [15] of anisotropic Dirac fluids and demonstrated that those violated the much discussed bound for the viscosity-entropy density ratio.

3. Complex order in quantum materials

Our research activities in the theory of complex order in correlated electron systems are partly supported by the DFG transregional collaborative research center TRR-288.

A hallmark of the phase diagrams of quantum materials is the existence of multiple electronic ordered states, which, in many cases, are not independent competing phases, but instead display a complex intertwinement. A particular realization of such intertwined orders occurs when a primary phase, characterized by a multi-component order parameter, gives rise to a fluctuation-driven vestigial phase that is characterized by a composite order parameter. This concept has been widely employed to elucidate nematicity in iron-based and cuprate superconductors. This notion also applied to a variety of phases such as nematic superconductivity or time reversal symmetry of multi-component superconductors. Electronic states with scalar and vector chiral order, spin-nematic order, Ising-nematic order, time-reversal symmetry-breaking order, and algebraic vestigial order emerge from one underlying principle.

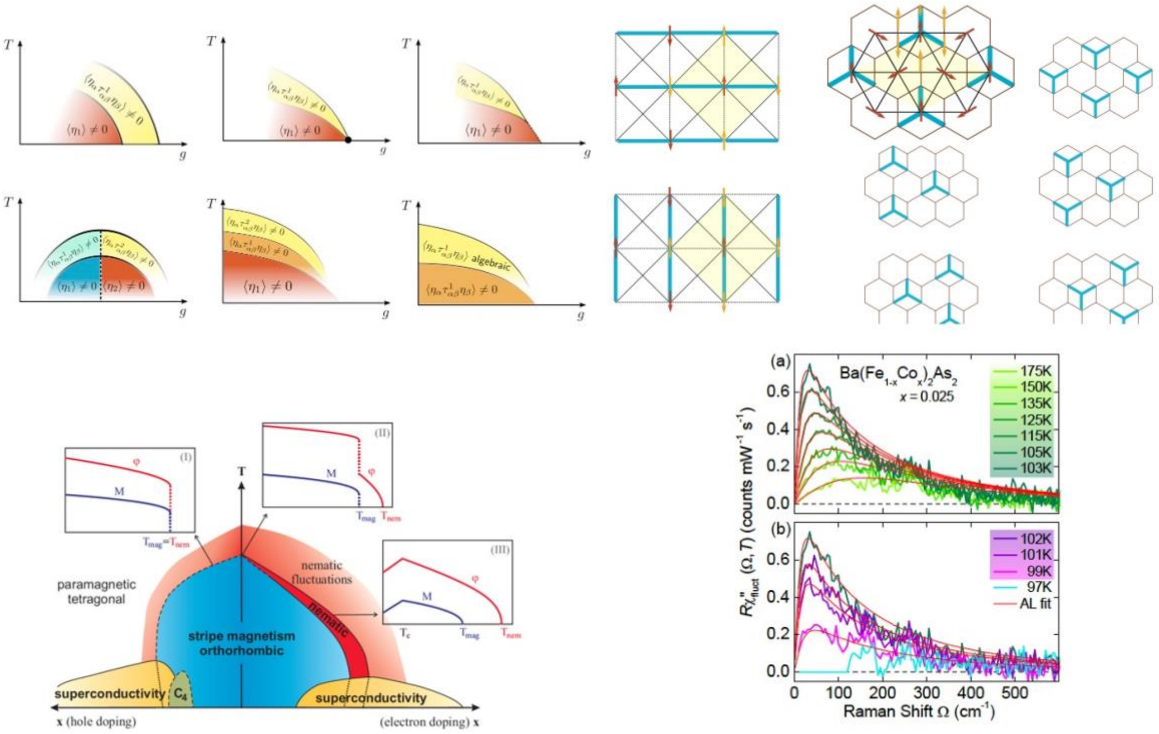

Figure 4 Top Left: We determined complex phase diagrams where multiple phases are characterized by composite, so called vestigial order parameters, i.e. one phase is caused by, not competing with the presence of another phase [16]. Top Right: State of critical vestigial order in a frustrated spin system of coupled triangular and hexagonal lattices [17,18]. Bottom Left: Theoretical phase diagram of iron-based superconductors where we determined spin-induced vestigial nematic order and fluctuations as unique fingerprint of the underlying frustrated magnetic order [19-21]. Bottom Right: Raman response for spin-fluctuation induced Ising nematicity in iron-based superconductors in comparison with experiment [22,23].

4. Disordered systems and non-equilibrium dynamics

Complex materials are exceptionally sensitive with respect to disorder and imperfections. In some cases, they can even self-generate such imperfections. For example, quantum systems in the vicinity of a quantum critical point are exceptionally sensitive to disorder. This gives rise to quantum Griffiths behavior where rare regions give rise to a singular contribution to the thermodynamic response, to novel criticality in percolating systems, to smearing of the transition and to complex-valued critical exponents. We also investigated the possibility of self-generated glass formation in systems with frustrated interactions of different length scales and determined a spectrum of exponentially many metastable states and analyzed the shapes of cooperatively rearranging regions of glass-forming liquids. In addition to the publications that are listed below, we have investigated the issue of disorder in the context of superconductors and other states of complex order. The corresponding references can be found there. We have also investigated several topics in out-of-equilibrium dynamics many body systems. Examples are the universal scaling behavior after a quantum quench to a critical point, the proposal for a two-photon pump based on superconductors, or the population inversion of graphene after an intense Laser pulse. We investigate these systems with quantum non-equilibrium field theoretic approaches, primarily the Schwinger-Keldysh formalism.

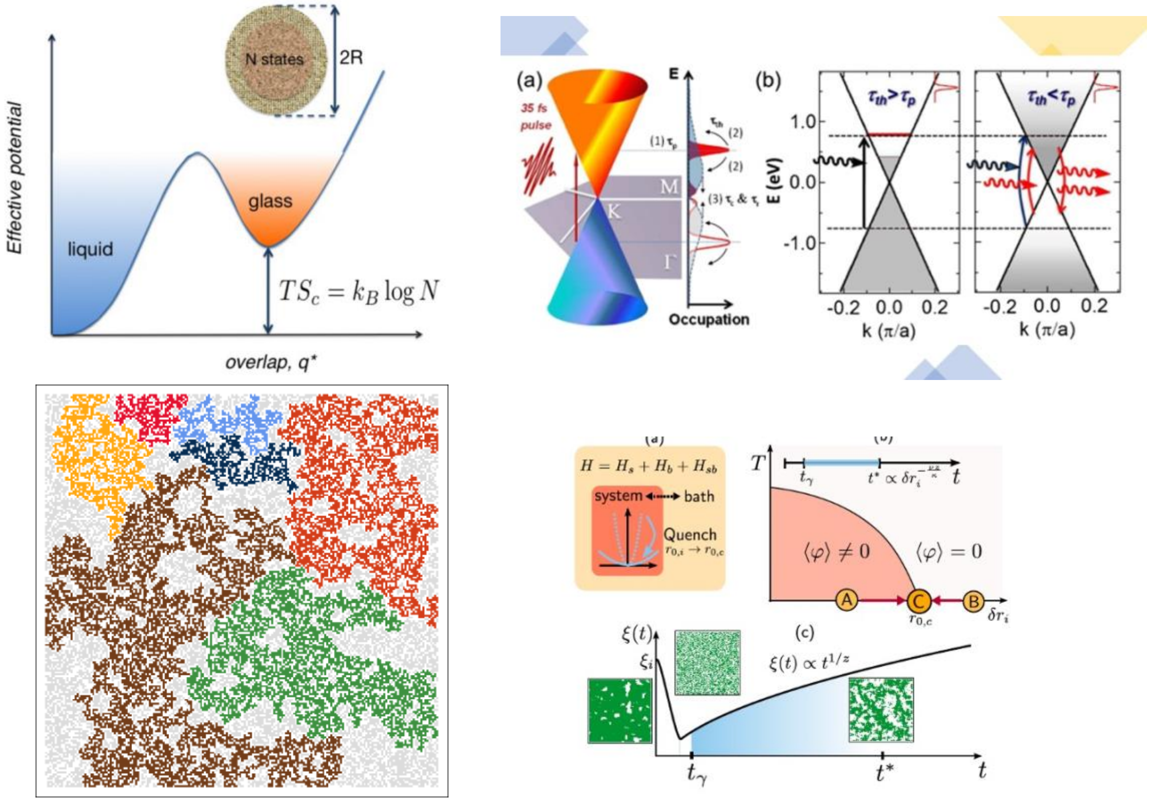

Figure 5 Top left: We predicted a self-generated glassy state in a model for uniformly frustrated phase separation, where an exponentially large number of metastable states, separated by high barriers, emerges at sufficiently low temperatures [24-27]. Top Right: We predicted and modelled a state of Laser-induced population inversion in graphene, stabilized by the unique kinematics of Dirac particles [28]. Bottom Left: We developed the theory of quantum spin systems and Josephson junctions on percolating networks and demonstrated that one can rigorously determine the critical exponents of such a state [29,30]. Bottom Right: We determined the universal post-quench dynamics of an open systems near a quantum critical point [31,32].

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