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RPPR Final Report
as of 14-May-2019

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Proposal Number: 65675PH **Agreement Number: W911NF-14-1-0379**

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Report Date: 31-Mar-2019 Date Received: 07-Apr-2019
Final Report for Period Beginning 01-Aug-2014 and Ending 31-Dec-2018
Title: Quantum Critical Behavior in Oxide Structures
Begin Performance Period: 01-Aug-2014 **End Performance Period:** 31-Dec-2018
Report Term: 0-Other
Submitted By: Susanne Stemmer Email: stemmer@mrl.ucsb.edu
Phone: (805) 893-6128
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STEM Degrees: 4 **STEM Participants:** 7

Major Goals: The objective of the project “Quantum Critical Behavior in Oxide Structures” was to advance the understanding of quantum criticality involving delocalized electrons in strongly correlated systems. We took advantage of the control afforded by oxide heterostructures and rationally design and manipulate quantum criticality. Different
types of interactions were introduced and have led to an understanding of their relevance in driving quantum critical phenomena and in the promotion of emergent ordered states, thereby enabling the development of a predictive theory.

Accomplishments: Please see attachment and also the publication list.

Training Opportunities: Several graduate students worked on this project. They were trained in advanced many body theory, neutron, synchrotron x-ray, and muon techniques, thin film growth by molecular beam epitaxy and electrical measurements. Results from the project contributed to their Ph.D. theses.

Results Dissemination: Results were disseminated via journal publications (submitted on this site) and conference/workshop talks given by PIs and their students.

Honors and Awards: Ryan Need was the recipient of a postdoctoral fellowship from the National Research Council.
Balents was elected a Fellow of the American Academy of Arts and Sciences.Stephen Wilson received a Hellman Faculty Fellowship
Stemmer received a National Security Science and Engineering Faculty Fellowship (Vannevar Bush Faculty Fellowship)

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Other Professional
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Person Months Worked: 3.00 **Funding Support:**

Project Contribution:
International Collaboration:
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National Academy Member: N
Other Collaborators:

Participant Type: Other Professional
Participant: Thomas Hogan
Person Months Worked: 4.00 **Funding Support:**
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National Academy Member: N
Other Collaborators:

Participant Type: Co PD/PI
Participant: Leon Balents
Person Months Worked: 2.00 **Funding Support:**
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Participant Type: PD/PI
Participant: Susanne Stemmer
Person Months Worked: 1.00 **Funding Support:**
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Other Collaborators:

Participant Type: Co PD/PI
Participant: Stephen Wilson
Person Months Worked: 3.00 **Funding Support:**
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National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Kaveh Ahadi
Person Months Worked: 8.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Kara HEJAZI

Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
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International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Jason IACONIS
Person Months Worked: 4.00 **Funding Support:**
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International Collaboration:
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National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: CHUNXIAO LIU
Person Months Worked: 3.00 **Funding Support:**
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International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Evgeny Mikheev
Person Months Worked: 2.00 **Funding Support:**
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National Academy Member: N
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Participant Type: Graduate Student (research assistant)
Participant: Santosh Raghavan
Person Months Worked: 3.00 **Funding Support:**
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ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: APL Materials
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.5025317
Volume: 6 Issue: First Page #: 056105
Date Submitted: 6/4/18 12:00AM Date Published:
Publication Location:
Article Title: Carrier density control of magnetism and Berry phases in doped EuTiO3
Authors: Kaveh Ahadi, Zhigang Gui, Zach Porter, Jeffrey W. Lynn, Zhijun Xu, Stephen D. Wilson, Anderson Jano
Keywords: Quantum criticality, metamagnetism
Abstract: In materials with broken time-reversal symmetry, the Berry curvature acts as a reciprocal space magnetic field on the conduction electrons and is a significant contribution to the magnetotransport properties, including the intrinsic anomalous Hall effect. Here, we report neutron diffraction, transport, and magnetization measurements of thin films of doped EuTiO3, an itinerant magnetic material, as a function of carrier density and magnetic field. These films are itinerant antiferromagnets at all doping concentrations. At low carrier densities, the magnetoresistance indicates a metamagnetic transition, which is absent at high carrier densities (>6 x10^20 cm♀ ^-3). Strikingly, the crossover coincides with a sign change in the spontaneous Hall effects, indicating a sign change in the Berry curvature. We discuss the results in the context of the band structure topology and its coupling to the magnetic texture.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Applied Physics Letters
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.5016174
Volume: 112 Issue: First Page #: 132407
Date Submitted: 6/4/18 12:00AM Date Published:
Publication Location:
Article Title: Octahedral tilt independent magnetism in confined GdTiO3 films
Authors: R. F. Need, B. J. Isaac, B. J. Kirby, J. A. Borchers, S. Stemmer, Stephen D. Wilson
Keywords: Quantum criticality, magnetism
Abstract: Polarized neutron reflectometry measurements are presented exploring the evolution of ferrimagnetism in GdTiO3 films as they are confined between SrTiO3 layers of variable thicknesses. As GdTiO3 films approach the thin layer limit and are confined within a substantially thicker SrTiO3 matrix, the TiO6 octahedral tilts endemic to GdTiO3 coherently relax toward the undistorted, cubic phase of SrTiO3. Our measurements reveal that the ferrimagnetic state within the GdTiO3 layers survives nearly unperturbed as the TiO6 octahedral tilts in the GdTiO3 layers are suppressed. Furthermore, our data suggest that a magnetic dead layer develops within the GdTiO3 layer at each GdTiO3/ SrTiO3 interface. The ferrimagnetic moment inherent to the core GdTiO3 layers is negligibly (in models with dead layers) or only weakly (in models without dead layers) impacted as the octahedral tilt angles are suppressed by more than 50% and the t2g bandwidth is dramatically renormalized.
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Article Title: Quasistatic antiferromagnetism in the quantum wells of SmTiO3/SrTiO3 heterostructures
Authors: R. F. Need, P. B. Marshall, E. Kenney, A. Suter, T. Prokscha, Z. Salman, B. J. Kirby, S. Stemmer, M. J.
Keywords: Pseudogaps; quantum wells
Abstract: High carrier density quantum wells embedded within a Mott insulating matrix present a rich arena for exploring unconventional electronic phase behavior ranging from non-Fermi-liquid transport and signatures of quantum criticality to pseudogap formation. Probing the proposed connection between unconventional magnetotransport and incipient electronic order within these quantum wells has however remained an enduring challenge due to the ultra-thin layer thicknesses required. Here we address this challenge by exploring the magnetic properties of high-density SrTiO3 quantum wells embedded within the antiferromagnetic Mott insulator SmTiO3 via muon spin relaxation and polarized neutron reflectometry measurements. The one electron per planar unit cell acquired by the nominal d0 band insulator SrTiO3 when embedded within a d1 Mott SmTiO3 matrix exhibits slow magnetic fluctuations that begin to freeze into a quasistatic spin state below a critical temperature T*.
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Date Submitted: 12/4/17 12:00AM Date Published: 11/20/17 8:00AM
Publication Location:
Article Title: A strongly correlated metal built from Sachdev-Ye-Kitaev models
Authors: Xue-Yang Song, Chao-Ming Jian, and Leon Balents
Keywords: Non-Fermi liquids
Abstract: Strongly correlated metals comprise an enduring puzzle at the heart of condensed matter physics. Commonly a highly renormalized heavy Fermi liquid occurs below a small coherence scale, while at higher temperatures a broad incoherent regime pertains in which quasi-particle description fails. Here we study a lattice of complex-fermion SYK dots with random inter-site quadratic hopping. We obtain a heavy Fermi liquid to incoherent metal crossover in full detail, including thermodynamics, low temperature Landau quasiparticle interactions, and both electrical and thermal conductivity at all scales.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Volume: 11 Issue: 4 First Page #: 3760
Date Submitted: 12/4/17 12:00AM Date Published: 3/1/17 8:00AM
Publication Location:
Article Title: Potential Fluctuations at Low Temperatures in Mesoscopic-Scale SmTiO
Authors: Will J. Hardy, Brandon Isaac, Patrick Marshall, Evgeny Mikheev, Panpan Zhou, Susanne Stemmer, Dou
Keywords: Non-Fermi liquids, oxide quantum wells
Abstract: Heterointerfaces of SrTiO3 with other transitionmetal oxides make up an intriguing family of systems with a bounty of coexisting and competing physical orders.Some examples, such as LaAlO3/SrTiO3, support a high carrier density electron gas at the interface whose electronic properties are determined by a combination of lattice distortions, spin?orbit coupling, defects, and various regimes of magnetic and charge ordering. Here, we study electronic transport in mesoscale devices made with heterostructures of SrTiO3 sandwiched between layers of SmTiO3, in which the transport properties can be tuned from a regime of Fermi-liquid like resistivity (? ? T2) to a non-Fermi liquid (? ? T5/3) by controlling the SrTiO3 thickness.
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Journal: Reports on Progress in Physics
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Volume: 81 Issue: 6 First Page #: 062502
Date Submitted: 6/4/18 12:00AM Date Published: 6/1/18 7:00AM
Publication Location:
Article Title: Non-Fermi liquids in oxide heterostructures
Authors: Susanne Stemmer, S James Allen
Keywords: Non-Fermi liquids, oxide heterostructures, quantum criticality
Abstract: Understanding the anomalous transport properties of strongly correlated materials is one of the most formidable challenges in condensed matter physics. For example, one encounters metal-insulator transitions, deviations from Landau Fermi liquid behavior, longitudinal and Hall scattering rate separation, a pseudogap phase, and bad metal behavior. These properties have been studied extensively in bulk materials, such as the unconventional superconductors and heavy fermion systems. Oxide heterostructures have recently emerged as new platforms to probe, control, and understand strong correlation phenomena. This article focuses on unconventional transport phenomena in oxide thin film systems. We use specific systems as examples, namely charge carriers in SrTiO3 layers and interfaces with SrTiO3, and strained rare earth nickelate thin films.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Volume: 93 Issue: 24 First Page #:
Date Submitted: 6/4/18 12:00AM Date Published: 6/1/16 7:00AM
Publication Location: 245151
Article Title: Particle-vortex duality of two-dimensional Dirac fermion from electric-magnetic duality of three-dimensional topological insulators
Authors: Max A. Metlitski, Ashvin Vishwanath
Keywords: Dirac electrons, topological insulators, quantum Hall state
Abstract: Particle-vortex duality is a powerful theoretical tool that has been used to study bosonic systems. Here, we propose an analogous duality for Dirac fermions in 2+1 dimensions. The physics of a single Dirac cone is proposed to be described by a dual theory, QED3, with again a single Dirac fermion but coupled to a gauge field. This duality is established by considering two alternate descriptions of the three-dimensional topological insulator (TI) surface. The first description is the usual Dirac fermion surface state. The dual description is accessed via an electric-magnetic duality of the bulk TI coupled to a gauge field, which maps it to a gauged chiral topological insulator. This alternate description ultimately leads to a new surface theory, QED3, which provides a simple description of otherwise intractable interacting electronic states.
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Volume: n/a Issue: n/a First Page #:
Date Submitted: 9/4/18 12:00AM Date Published:
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Article Title: Singular angular magnetoresistance and spontaneous symmetry breaking in a magnetic nodal semimetal
Authors: T. Suzuki, L. Savary, J.-P. Liu, J. W. Lynn, L. Balents, and J. G. Checkelsky
Keywords: Weyl semimetals, anisotropic magnetoresistance
Abstract: Transport coefficients are incisive experimental probes of the low energy, long wavelength proper- ties of correlated electron systems often useful for mapping hidden phases with distinct symmetries. Here we report a new transport signature of spontaneous symmetry breaking in the magnetic Weyl semimetal CeAlGe in the form of singular angular magnetoresistance (SAMR). This angular re- sponse approaching 1000% radian 1 is confined along the high symmetry axes with a full width at half maximum of less than 1♬, significantly sharper than previously observed in bulk magnets. The SAMR phenomenon is explained theoretically as an effect due to controllable high resistance domain walls, arising as a consequence of magnetic point group symmetry breaking strongly cou- pled to a nearly nodal electronic structure.
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Date Submitted: 9/6/18 12:00AM Date Published: 9/1/18 7:00AM
Publication Location:
Article Title: Resolving interfacial charge transfer in titanate superlattices using resonant x-ray reflectometry
Authors: R. F. Need, P. B. Marshall, E. Weschke, A. J. Grutter, D. A. Gilbert, E. Arenholz, P. Shafer, S. Stemmer
Keywords: Oxide Interfaces, X-ray reflectivity,

Abstract: Charge transfer in oxide heterostructures can be tuned to promote emergent interfacial states, and accordingly, has been the subject of intense study in recent years. However, accessing the physics at these interfaces, which are often buried deep below the sample surface, remains difficult. Addressing this challenge requires techniques capable of measuring the local electronic structure with high-resolution depth dependence. Here,we used linearly polarized resonant x-ray reflectometry (RXR) as a means to visualize charge transfer in oxide superlattices with single unit cell precision. From our RXR measurements, we extract valence depth profiles of SmTiO3 (SmTO)/SrTiO3 (STO) heterostructures with STO quantum wells varying in thickness from five SrO planes down to a single SrO plane.

Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Accomplishments

The objective of the project "*Quantum Critical Behavior in Oxide Structures*" was to advance the understanding of quantum criticality involving delocalized electrons in strongly correlated systems. The project took advantage of the control afforded by oxide heterostructures and rationally design and manipulate quantum criticality. Different types of interactions were introduced and led to an understanding of their relevance in driving quantum critical phenomena and in the promotion of emergent ordered states, thereby enabling the development of predictive theories. Below we summarize the progress in this project over the first year of the project.

A major focus of the experimental and theoretical work in the project was on two-dimensional electron liquids in quantum well structures of type $R\mathrm{TiO_3}/\mathrm{SrTiO_3}/R\mathrm{TiO_3}$ (R = Gd or Sm), which contain a high mobile charge density in the $\mathrm{SrTiO_3}$ quantum well. The $R\mathrm{TiO_3}$ are prototype Mott insulators. These structures were used as a model system to explore questions such as the origins of quantum criticality, and associated phenomena (pseudogaps, non-Fermi liquid behavior,…) and their tunability in oxide heterostructures.

Using molecular beam epitaxy (MBE), the **Stemmer** group grew two-dimensional electron liquids (2DELs) in quantum well structures of type $R\mathrm{TiO_3}/\mathrm{SrTiO_3}/R\mathrm{TiO_3}$ (R = Gd or Sm). A major finding was that the transport data could be modeled using separate transport and Hall scattering rates, also known as "two-lifetime" behavior. This framework gave a remarkably simple and general description of the temperature dependence of the Hall coefficient. We showed that the 0-K Hall coefficient diverged at a critical quantum well thickness, coinciding with a quantum phase transition. We found that the Hall angle follows a T^2 temperature dependence, even when the longitudinal resistance does not. The clear separation the residuals supports the notion of distinct scattering rates in these systems, with different underlying physics that influences them. The data pointed to fluctuations associated with an underlying quantum critical point (QCP), which are reflected in the 0-K Hall coefficient, as the origin of the two lifetime behavior.

We also investigated the influence of disorder on the "two-lifetime" behavior. Disorder can enhance the effects of electron correlations and give rise to non-Fermi liquid behavior. Introducing controlled amounts of disorder can assist in elucidating the transport physics in correlated materials. Disorder was introduced via planar growth defects normal to the quantum wells, which lead to strongly anisotropic transport properties. Using angle-dependent sheet resistance and Hall measurements, the contributions of the defects and those of intrinsic scattering mechanisms to the transport properties and lifetime separation were determined. The residuals in both the longitudinal resistance and Hall angle were found to depend on the relative orientations of the transport direction to the planar defects. The Hall angle exhibited a robust T^2 temperature dependence along all directions, whereas no simple power law could describe the temperature dependence of the longitudinal resistances. Remarkably, the degree of the carrier lifetime separation, as manifested in the distinctly different temperature dependences and diverging residuals near a critical quantum well thickness, was completely insensitive to disorder. We speculated that the robust T^2 behavior of the Hall angle reflects a universal, underlying scattering rate.

One of the key unknowns in driving and ultimately controlling quantum criticality is the nature of the order parameter. To this end, the **Wilson** group focused on directly resolving the nature of the (magnetic) order parameter underlying the QCP of this system. A major activity centered on experimentally interrogating the role of the *spin degree of freedom* in quantum critical magnetotransport behavior. All samples were grown by molecular beam epitaxy (MBE) in the **Stemmer** group.

As a starting point, the **Wilson** group focused on the magnetization density of quantum well heterostructures. Neutron reflectometry was used to directly resolve how magnetization density induced via the neighboring $GdTiO_3$ is distributed across the quantum wells (where the electrons flow in charge transport). The data showed that the entirety of the quantum well is magnetized at low temperatures and charge transport necessarily pushes through a volume of magnetic SrO.

As a next step, the **Wilson** group explored the correlation between the onset of long-range magnetic order or incipient magnetic fluctuations and the appearance of transport phenomena coupled to quantum criticality. Features of particular interest included the emergence of a pseudogap state, discovered by the **Stemmer** group, and divergent carrier mass near a critical quantum well thickness in $SmTiO_3/SrTiO_3$ heterostructures, as well as the underlying coupling between magnetism and octahedral distortions in $GdTiO_3/SrTiO_3$ heterostructures.

The **Wilson** group performed low energy muon implantation measurements on an $SmTiO_3/SrTiO_3$ heterostructure, as well as on a pristine $SmTiO_3$ film. In these measurements, they were able to resolve the onset of antiferromagnetism in both the Ti and Sm sublattices within the isolated $SmTiO_3$ film. These are the first measurements able to detect magnetism within an ultrathin (~20 nm thick) $SmTiO_3$ film—a lingering question given the reduced structural symmetry of the thin films relative to bulk crystals. More importantly, the measurements of a $SmTiO_3/SrTiO_3/SmTiO_3$ trilayer heterostructure revealed that an additional channel of spin freezing appears below $T^* \sim 20$ K after both the Sm and Ti sublattices have ordered in the $SmTiO_3$ layers. This new channel of freezing represents the onset of incipient antiferromagnetic order within the $SrTiO_3$ quantum wells and it coincides with the prior observation of a pseudogap opening in this system. The measurements connect the formation of the pseudogap state in high-density $SmTiO_3/SrTiO_3$ quantum wells with emergence of antiferromagnetic correlations within the wells. More broadly, the work ties the pseudogap formation with previous observations of pseudogaps in carrier-tuned bulk Mott insulating systems such as high-T_c cuprates and manganites.

A second major activity in the **Wilson** group concerned the exploration of the coupling between the octahedral tilts and ferrimagnetism within $GdTiO_3$ layers. As $GdTiO_3$ is interfaced with $SrTiO_3$, the TiO_6 octahedral tilts at the interface are perturbed, and for thin $GdTiO_3$ layers constrained within thicker $SrTiO_3$ layers, these tilts are suppressed toward the undistorted lattice of $SrTiO_3$. As the tilts are relaxed within the $GdTiO_3$ layers, the apparent magnetic moment (as seen via bulk magnetometry) associated with ferromagnetism is suppressed. At the thin layer limit, previous magnetometry work was unable to resolve any ferrimagnetism in $GdTiO_3$, suggesting that the magnetic moment of Ti is substantially renormalized when the $GdTiO_3$ octahedral tilts are relaxed. Our work exploring this effect utilized polarized neutron reflectometry to uncover two key findings. The first is that that this apparent suppression is due to the formation of magnetic deadlayers within the $GdTiO_3$ films once interfaced with $SrTiO_3$. The second is that, once these deadlayers are accounted for, the ferrimagnetic moment of $GdTiO_3$ was found to be unaffected by relaxed TiO_6 tilts in thin $GdTiO_3$ layers. Curiously, this demonstrates that the magnetism is unaffected by the large modifications of the octahedral tilts, and presumably the t_{2g} bandwidth, and suggests that our theoretical understanding of magnetism in this system should be revisited.

The theoretical efforts in the project (**Balents** group) focused on understanding the *origin* of quantum criticality in titanate heterostructures. The experiments of the **Stemmer** and **Wilson** groups pointed to essential differences of the heterostructures involving $GdTiO_3$ and $SmTiO_3$ (in particular with respect to the magnetism and non-Fermi liquid behavior), which suggests that the nature of the Mott insulator is an important ingredient in the types of orders and quantum phase transitions which occur. Pursuant to this idea, the **Balents** group constructed a minimal model of the Mott insulator to band insulator interface. Crucially, in addition to the 2DEL induced by the polar discontinuity inside the band insulator ($SrTiO_3$), the model takes into account the very high density (1 electron per Ti) of *localized* electrons inside the Mott material. While these do not directly contribute to transport, they carry a large amount of entropy and can strongly influence magnetism and quantum criticality.

The model can be *solved* in several regimes in a very controlled fashion, using both analytical approachs and the numerically *exact* method of Density Matrix Renormalization Group (DMRG). The main finding is that the proximity to the Mott layer strongly induces magnetism, which can be either ferromagnetic or antiferromagnetic, depending upon details of carrier density, band offset, etc. The mechanism for these orderings is *kinetic* in nature: electrons which are coupled to the Mott layer move more coherently in a specific magnetic background. Oxide heterostructures might in fact be the first experimental realization of this idea, which was first proposed (in a simpler and rather different context) many decades ago. The model predicts a large range of ferromagnetism and competing antiferromagnetic states at lower electron density.

Theoretical research in the **Balents** group also aimed developing a theoretical description of non-Fermi liquid behavior, especially transport, in strongly correlated metals, such as those arising at quantum critical points. Specifically, they sought a description outside the usual weak-scattering approaches and distinct from Hertz-Millis-Moriya theory, which retains the quasiparticle basis and does not seem to apply to many experimental systems. Furthermore, they sought to understand microscopically how all these phenomena arise from details of electronic orbitals, geometry, and Kanamuri interactions. The main theoretical output was to develop a new approach to non-Fermi liquids starting from what is now called the Sachdev-Ye-Kitaev (SYK) model, which became the subject of intense study as a toy model in which gravity and black hole physics emerges from totally different microphysics: quantum mechanics of many fermions. It has a very simple Hamiltonian involving very complicated interactions that create transitions from two "orbitals" (kl) to another two (ij) in pairs, amongst N total orbitals. The SYK model is one of a very few solvable theoretical models for non-Fermi liquids, which makes it quite valuable. The drawback of the SYK model is that it is "zero dimensional" — every electron in it interacts with every other one, and so there is no built-in locality to the problem.

What the **Balents** group did was to string together these dots as super-atoms, connecting them by one-electron hopping. In this model, there is a competition between the SYK interaction U and the hopping t. For $t \ll U$, we have a strongly correlated system. It remains fully soluble in the large N limit and one can obtain a rich structure. Briefly, at low temperatures and low energy, the system is a Fermi liquid. This allows one to extract the parameters of the Fermi liquid theory: effective mass, Fermi liquid interactions, quasiparticle residue, etc. However, at higher temperatures it is an incoherent metal, and displays properties that are a mixture of those of the pure SYK model and a regular metal. Together, it is striking how many of the properties are similar to those of experimental correlated metals:

Small coherence scale $Ec = t^2/U$

Large effective mass (Sommerfeld coefficient) $\gamma \sim m^*/m \sim U/t$

Small quasiparticle weight $Z \sim t/U$

T^2 low-temperature resistivity with Kadowaki-Woods ratio A/γ^2 = constant

linear in temperature resistivity at high temperature

linear in temperature thermal "resistivity" T/κ at high temperature

Fermi liquid Lorenz number $L = \kappa/(T\,\sigma) = \pi^2/3$ at low T

non-Fermi liquid Lorenz number $L = \pi^2/8$ at high T