RESEARCH STATEMENT

INTRODUCTION

These days there are much reason for optimism: the discovery of the first 'designed' high-Tc superconductor in twisted bilayer graphene, realization of the Majorana zero modes in nanowires and possibly in the vortex core of Iron-based superconductors, detection of the Majorana edge modes in $\nu = 5/2$ fractional quantum Hall regime and the confirmed realization of a Kitaev spin-liquid from thermal conductivity measurements are just some of the milestones we have passed recently. However, while the possibility of high temperature superconductivity, and topological protected quantum computation, two long-sought dreams of the strongly correlated condensed matter research community, appear tantalizingly closer than at any previous time, there are major problems, both conceptual and technological, to overcome. What is undeniable, even to the most hardened sceptic, is that out of this great ferment there are will be major spin-offs, with major implications for the future of the field and its applications. These factors make it a very inspiring time to begin a research career.

The community has long sought designing new materials and systems in which the interplay between many-body quantum effects, spin-orbit and Coulomb interactions create exotic phases that enable new applications. However, an important aspect of such design, is the development of new creative ideas - such as Bistritzer and Macdonald's [1] creative idea of Moire tuning of Graphene bands - or the development of new solvable models, by Kitaev [2]. These approaches provide the bedrock for paradigm shifts in our understanding and materials development. The study of simplified interacting models, e.g. frustrated Kondo systems (Fig. 1), using state of the art tools is a promising direction which is expected to influence both our fundamental understandings and help us get closer to realizing these applications.

There have already been numerous analytical and numerical works on these problems, but they have remained difficult, and the progress has been slow and saturated. So, why in the age of the topological revolution, many-body localization and non-equilibrium physics, one would still be interested in such classical problems? One reason is that we have recently succeeded in developing a new theoretical tool that allows us to tackle exactly these kind of problems. Also, as I explain here, these interacting systems serve as vital toy-models that not only help us understand new emerging physics in unconventional superconductors, but also provide a route towards topological quantum computation.

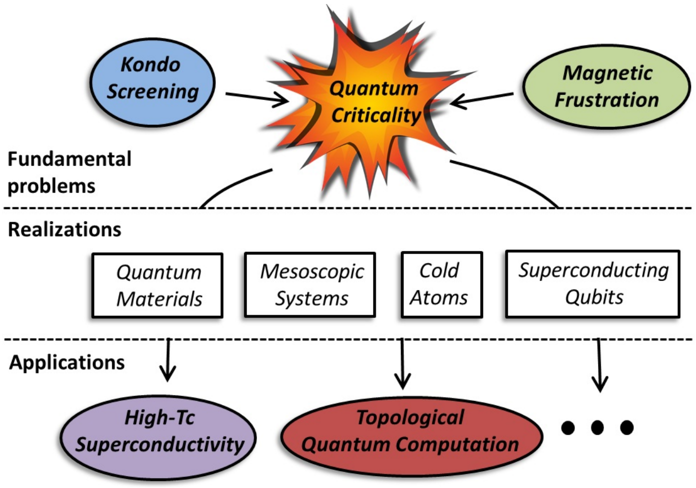

FIG. 1: The basic philosophy that I advocate here. Fundamental problems, e.g. interplay between Kondo screening and frsutration, can be used to realize quantum criticality, out of which many applications can be realized in different platforms.

About me - I have had a rather unusual carrier path; I did my PhD as an experimentalist at ETH Zürich where I did low-temperature quantum-transport experiments on quantum dots and point contacts and developed my cryogenic and cleanroom skills. Afterwards, I climbed a steep learning curve by doing two postdocs in theoretical condensed matter physics, one at UBC with Ian Affleck and one at Rutgers working with Piers Coleman, Gabriel Kotliar and Natan Andrei, which prepared me for a theoretical carrier on topics that are in close connection to experiments.

Against the common flow, and perhaps to some extent unwisely, I have chosen to take my time to focus on difficult theoretical problems which involve deep concepts and advanced techniques. While it has taken me some time to build an interdisciplinary background, this has brought me a unique perspective to condensed matter physics and an ability to study a wide range of problems and bridge between experts across the field from both experiment and theory.

PAST RESEARCH : QUANTUM TRANSPORT IN MESOSCOPIC SYSTEMS

Very briefly, this is a list of my main experimental and theoretical projects in the past (more on my website).

- *Experiment*: The 0.7 anomaly and g-factor anisotropy in p-doped GaAs quantum point contacts
- *Experiment*: Time-resolved charge detection and full counting statistics in p-doped GaAs quantum dots
- Decoherence due to inelastic scattering off Kondo impurities - Transport in Aharanov-Bohm-Kondo rings
- Quantum transport in junctions between topological superconductors (Majoranas) and Luttinger liquids
- Orbital Kondo effects of Laughlin quasiparticles in fractional quantum Hall regime

PRESENT RESEARCH : STRONGLY CORRELATED QUANTUM MATERIALS

Quantum criticality and emergent slow charge fluctuations in YbAlB$_4$ - Quantum critical points (QCPs) happen when a second order phase transition is tuned to zero temperature. They act as nexus between various phases (fixed points), which may be used to stabilize a desired (perhaps a superconducting) phase. Some of the open questions that I have helped to resolve are: What is the origin of Fermi-surface (FS) reconstruction? Is there new emergent mode at the QCP? Is there any residual entropy?

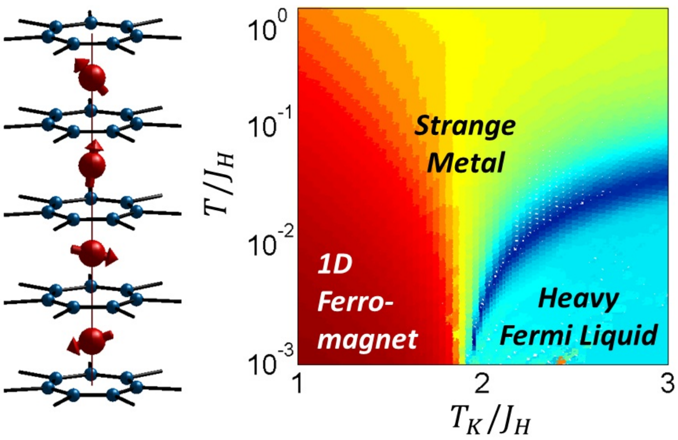

FIG. 2: The heavy-fermion β-YbAlB$_4$ consists of weakly coupled quasi-1D chains of Yb moments (left). We studied a simplified model of that using our method. The calculated phase diagram (right) includes a Fermi liquid, and a 1D ferromagnetic phases separated by a QCP [3]

Heavy-fermions are miniature high-T$_C$ superconductors in which many of these questions can be studied with controlled approximations. An example is the heavy fermion material YbAlB$_4$ which is mysteriously critical over a wide range of pressure around the ambient pressure. Motivated by this and the recent neutron scattering experiments indicating ferromagnetic correlations in the quasi-1D β-YbAlB$_4$, we have recently studied the possibility of a ferromagnetic QCP (Fig. 2) in this material. Using a combination of analytical and numerical tools, we have demonstrated spinon deconfinement (fractionalization of spin) [3] and that Kondo-reduced moment enhances quantum fluctuations of the spins stablizing criticality over a finite range near QCP.

Another feature of YbAlB$_4$ is that Mossbauer spectroscopy has seen slow charge fluctuations in the critical regime. We have recently shown that such critical charge fluctuations are natural consequences of Kondo breakdown between a heavy Fermi liquid and a spin-liquid [4]. We discovered a new emergent zero mode which describes formation/destruction of Kondo singlets and gives rise to a residual entropy (due to entanglement entropy) at the critical point. Such a naked singularity is expected to be concealed beneath a dome of exotic phases, e.g. superconductivity. In spite of all the progress, there are still many open questions. My personal list is:

- Is there any topological (or other quantum) order in thse systems? There are indications [5] (also see below).
- Do mixed valence and disorder play an active or passive role in the strange metal phase?
- Can noise measurement reveal more about the nature of transport in the strage metal phase?
- If the transport is incoherent, what is the source of the decoherence? My thoughts are influenced by [6].

New types of order parameters - The Landau-Ginzburg-Wilson paradigm of phase transitions has proven to be insufficient due to a number of phases that cannot be captured as a symmetry-broken bosonic order parameter, their prime example being the deconfined criticality, but even the Mott and heavy Fermi-liquid phases. Our contribution to this has been to use numerical renormalization group (NRG) calculations and large-N path integral aproach to identify a new class of order parameters [7] in which the ordered state is characterized by emergent fermions which are bound states of an odd number of fermions or a fermion and a spin, very much as a proton is an emergent bound-state of three quarks. The new order parameters, represent new collective phenomena, transform as spinors and can in principle be measured in pump-probe experiments.

Spin impurities coupled to quantum critical systems - We have recently studied the effect of having few trapping potentials in the Bose Superfluid-Mott transition [9]. This is described by an spin-S XY Bose-Kondo model with a critical bath. We have discovered an even-odd effect, showing that for $2S$ even the impurity is fully screened whereas for $2S$ odd we have partial screening, an effect that can be observed in ultracold atoms.

Orbital selective Mott transition We have recently used slave-particle mean-field methods to study this interesting effect in which Mott localization is orbital dependent. We studied low-lying excitation on top of the ground state, including a novel bound state between doublon in one orbital and holon in another orbital and in some cases we obtained very good agreement with dynamical mean-field theory [8]. Open question:

- Is this phase stable against fluctuations around the mean-field and the emergent gauge fields?

---

[1] R. Bistritzer and A. H. MacDonald, PNAS **108** 12233 (2011).
[2] A. Kitaev, Usp. Fiz. Nauk **171**, 131 (2000); Annals of Physics **321** 2 (2006).
[3] Y. Komijani, P. Coleman. Phys. Rev. Lett. **120**, 157206 (2018).
[4] Y. Komijani, P. Coleman. ArXiv: 1810.08148, submitted to Nature Physics.
[5] M. S. Scheurer, S. Chatterjee, W. Wu, M. Ferrero, A. Georges, S. Sachdev, PNAS **10**, 1073 (2018).
[6] G. Kotliar, Q. Si, Phys. Rev. B **53**, 12373 (1996).
[7] Y. Komijani, A. Toth, P. Chandra, P. Coleman, in preparation; A. Wugalter, Y. Komijani, P. Coleman, in preparation.
[8] K. Chen, Y. Komijani, ArXiv:1810.12812, submitted to Phys. Rev. lett.
[9] Y. Komijani, G. Kotliar, Phys. Rev. B **96**, 125111 (2017); Y. Komijani, K. Hallberg, G. Kotliar, ArXiv: 1808.06680.