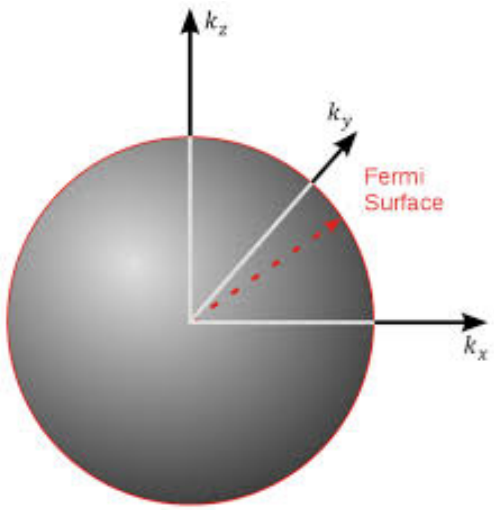
Gapless ultra-quantum matter



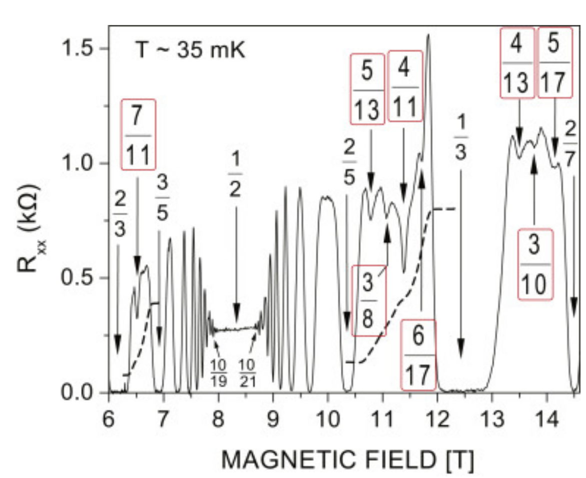
Shamit Kachru (Stanford)

Simons UQM collaboration kickoff meeting

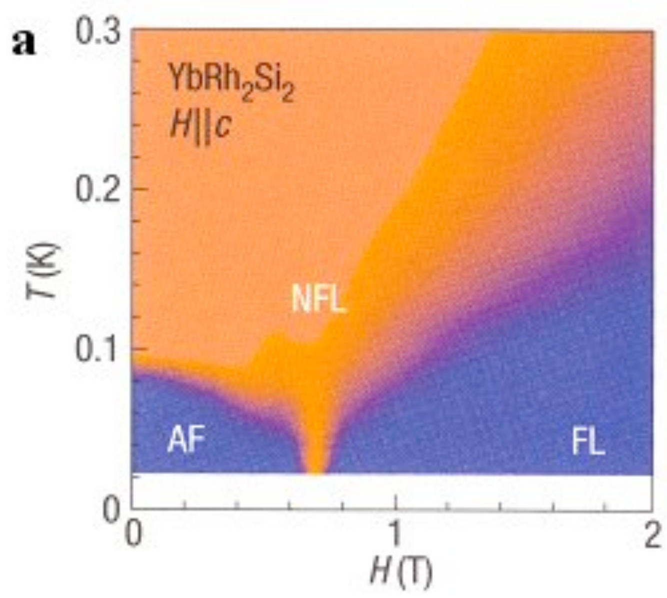
Some of the most intriguing phases of quantum matter — motivating much of the research carried out by members of the collaboration — involve gapless theories.

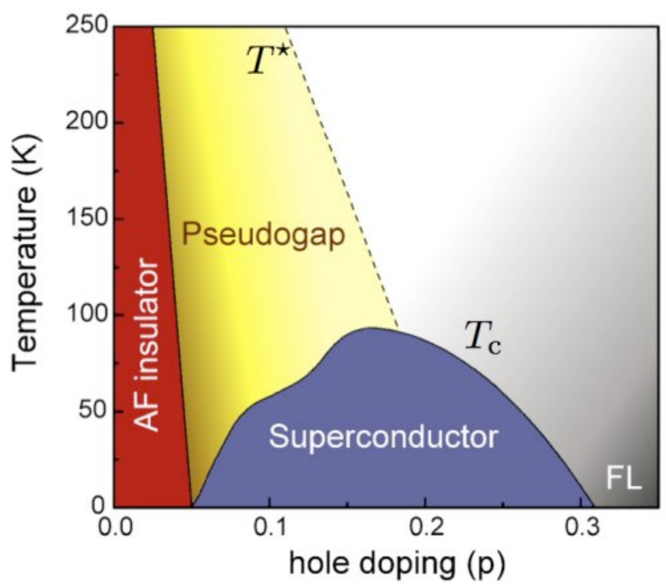
Two prototype sources of related questions in Nature:

— 2DEG at even denominator filling fraction:



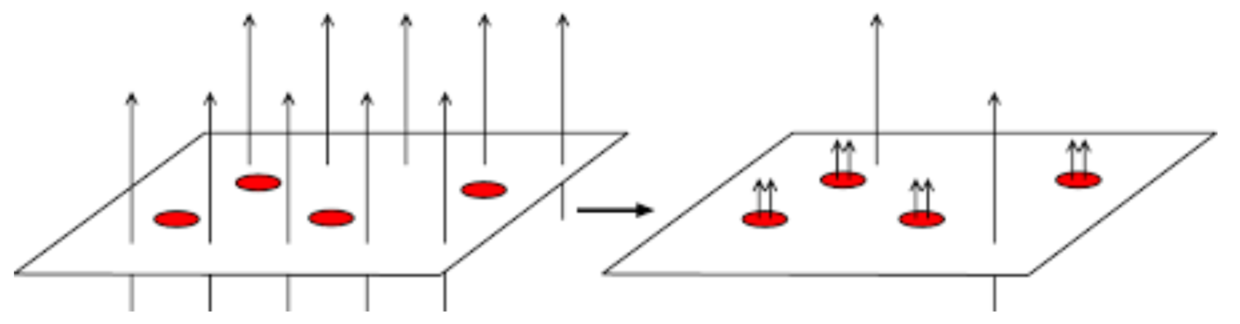
— (normal state of) unconventional superconductors:





I can briefly describe idealized theorists' versions of both systems.

The first problem starts with electrons in a plane subjected to a magnetic field.

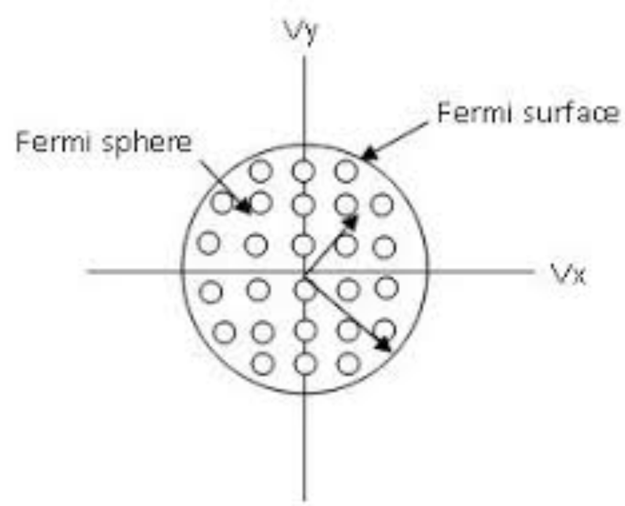


Flux attachment suggests that we try to reinterpret a state at filling fraction

$$\nu = \frac{1}{2}$$

by attaching two units of flux to each electron.

This new quasiparticles still have fermionic statistics, but move in a vanishing effective magnetic field.



Naively these “composite fermions” fill out a Fermi surface.

Interactions can have various interesting effects:

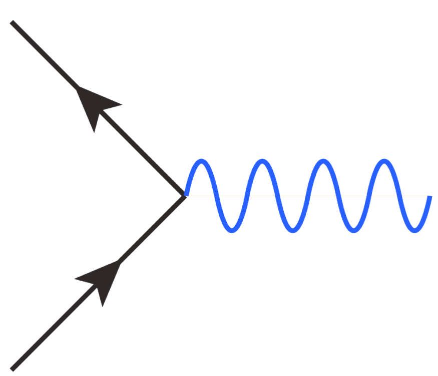
$$\nu = 1/2 \rightarrow \mathrm{non-Fermi\ liquid?}$$

$$\nu = 5/2 \rightarrow ??$$

$$\nu = (2k+1)/2 \rightarrow \mathrm{stripes?}$$

Obtaining a precise understanding of these states remains a problem of significant interest.

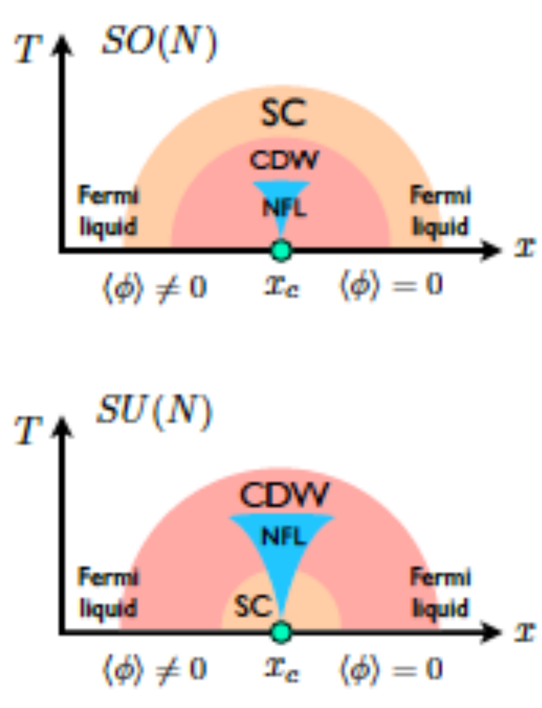
The second problem suggests a different theoretical question. One starts with a metal, but in candidate theories, the Fermi surface interacts with an (emergent) order parameter mediating a second order transition.



A theorists' idealization of the problem — solve for the dynamics of this quantum field theory:

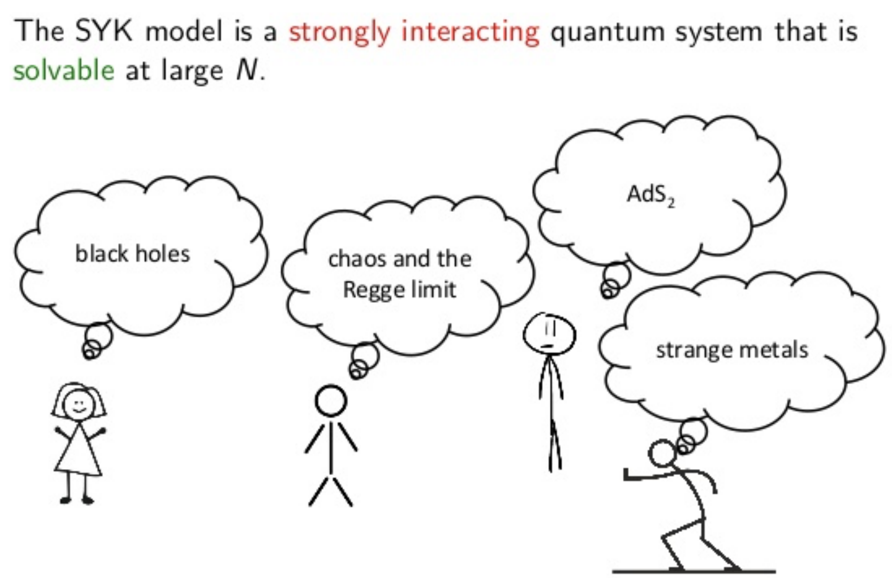
$$\mathcal{L}_\psi = \bar{\psi}_\sigma \left[\partial_\tau + \mu - \epsilon(i\nabla)\right] \psi_\sigma + \lambda_\psi \bar{\psi}_\sigma \bar{\psi}_{\sigma'} \psi_{\sigma'} \psi_\sigma$$

$$\mathcal{L}_\phi = m_\phi^2 \phi^2 + (\partial_\tau \phi)^2 + c^2 \left(\vec{\nabla}\phi\right)^2 + \frac{\lambda_\phi}{4!}\phi^4$$



Various large N solutions give various answers to questions about low-energy dynamics.

Other approaches might be illuminating!



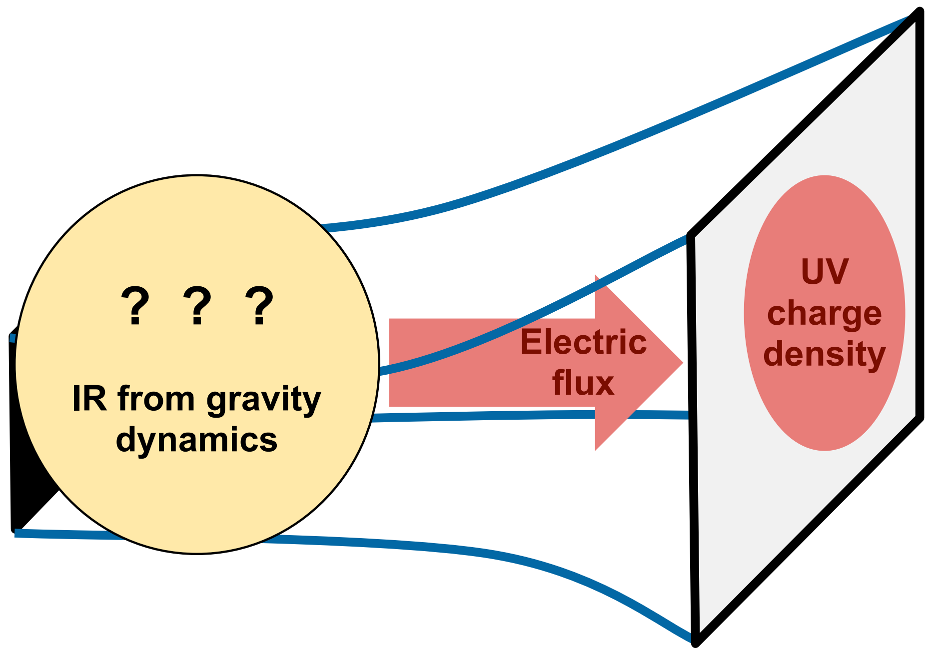
I've been thinking a little bit about a different way that AdS2 may enter into related stories, in discussions with various people…

DMFT is an influential approach to understanding dynamics of correlated electron systems.

I have little idea what it is, but the central step seems to be an approximation where one works at large d and replaces a coupled many electron system with an impurity model.

There is lore that at large d, the regime of energies where this impurity model emerges to control dynamics is quite broad.

With this in mind, we decided to explore the behavior of holographic non-Fermi liquids at large d.



Finite chemical potential in AdS/CFT often leads to an IR emergent AdS2.

Via the analysis of Faulker/Liu/McGreevy/… and others, the way to think about this for fermions at finite density is probably as follows.

$$S = S_{\text{strong}} + \sum_{J,J'} \int dt\ c_J^\dagger \left(i\delta_{J,J'}\partial_t + \mu\delta_{J,J'} + t_{J,J'} \right) c_{J'}$$

$$+g \sum_J \int dt\ c_J^\dagger \mathcal{O}_J^F + (\text{Hermitian conjugate})\ .$$

The resulting fermion self-energy

is purely frequency dependent at very low energies.

This is somewhat reminiscent of DMFT results:

— impurity model vs emergent AdS2
— purely frequency dependent self-energy

What does large d add to the story?
(Large d black holes have been of independent interest in our community for various reasons.)

Take a toy bulk theory in d dimensions

$$S = \int d^{d+1}x \, \sqrt{-g} \, (R + F_{\mu\nu}F^{\mu\nu} - 2\Lambda)$$

The charged black hole solution is known…

$$ds^2 \equiv g_{MN} dx^M dx^N = \frac{r^2}{R^2}(-f dt^2 + d\vec{x}^2) + \frac{R^2}{r^2}\frac{dr^2}{f}$$

$$f = 1 + \frac{Q^2}{r^{2d-2}} - \frac{M}{r^d}, \qquad A_t = \mu\left(1 - \frac{r_0^{d-2}}{r^{d-2}}\right) .$$

Work in progress: at large d, there is a parametrically enhanced regime of validity of the results derived in the IR AdS2 region.

Blatant ad: See Milind's poster.