Condensed matter physics and string theory

Talk online: sachdev.physics.harvard.edu
Comfort zone of string theory

One, two, three.... particles
(quarks, gluons, gravitons....)
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Can have strong interactions during scattering events
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(near black holes)
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Works at critical points where particle spectrum changes
(AdS/CFT correspondence)
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Infinite numbers of particles (non-zero density) with weak interactions: electrons, trapped cold atoms
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Quantum phases with universal low energy properties, independent of most interaction details:
  Fermi liquids, solids, superfluids
In momentum space, Fermi surface separates occupied and empty electron states.
Ultracold $^{87}\text{Rb}$ atoms - bosons
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Fermi liquid theory (and its cousins) allow adiabatic continuation to strong interaction regime
Move out of comfort zones, and use tools developed in both fields
Strong coupling problems in condensed matter

1. Electrical resistance at non-zero temperature near quantum critical points

2. Zero temperature quantum phase transitions of Fermi liquids
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Superfluid-insulator transition

Ultracold $^{87}\text{Rb}$ atoms - bosons

CFT at $T > 0$

Quantum critical

$T_{KT}$

Superfluid

Insulator

$g_c$
Quantum critical transport

Quantum "perfect fluid" with shortest possible relaxation time, $\tau_R$

$$\tau_R \gtrsim \frac{\hbar}{k_B T}$$

Quantum critical transport

Transport co-efficients not determined by collision rate, but by universal constants of nature

Electrical conductivity

\[ \sigma = \frac{4e^2}{h} \times [\text{Universal constant } \mathcal{O}(1)] \]

Requires long-time limit of correlations at non-zero temperature.

Cannot be obtained numerically by computers even for the simplest quantum problems. Is the sum of an exponentially large number of terms which oscillate in sign.
AdS/CFT correspondence

The quantum theory of a black hole in a 3+1-dimensional negatively curved AdS universe is holographically represented by a CFT (the theory of a quantum critical point) in 2+1 dimensions.

Maldacena, Gubser, Klebanov, Polyakov, Witten
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Kovtun, Policastro, Son
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Quantum criticality of Pomeranchuk instability

Fermi surface with full square lattice symmetry
Quantum criticality of Pomeranchuk instability

Spontaneous elongation along $x$ direction:
Ising order parameter $\phi > 0$. 
Quantum criticality of Pomeranchuk instability

Spontaneous elongation along $y$ direction: Ising order parameter $\phi < 0$. 
Quantum criticality of Pomeranchuk instability

Pomeranchuk instability as a function of coupling $\lambda$

$\langle \phi \rangle \neq 0$

$\langle \phi \rangle = 0$

$\lambda_c$

$\lambda$
A $\phi$ fluctuation at wavevector $\vec{q}$ couples most efficiently to fermions near $\pm \vec{k}_0$.

Infinite set of 2+1 dimensional quantum-critical field theories, one for each pair of points on the Fermi surface. Ward identities ensure consistency of redundant description.
All planar graphs of $\psi_+$ alone are as important as the leading term

Conformal field theory in 2+1 dimensions at $T = 0$

Einstein gravity on AdS$_4$
Conformal field theory in 2+1 dimensions at $T > 0$, with a non-zero chemical potential, $\mu$ and applied magnetic field, $B$

Einstein gravity on AdS$_4$ with a Reissner-Nordstrom black hole carrying electric and magnetic charges
Examine free energy and Green’s function of a probe particle

Green’s function of a fermion

\[ G(k, \omega) \approx \frac{1}{\omega - v_F(k - k_F) - i\omega \theta(k)} \]

See also M. Cubrovic, J. Zaanen, and K. Schalm, arXiv:0904.1993


Green’s function of a fermion

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Similar to non-Fermi liquid theories of Fermi surfaces coupled to gauge fields, and at quantum critical points


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