Modern phases of quantum matter

Not adiabatically connected to independent electron states:

many-particle quantum entanglement
“Complex entangled” states of quantum matter in $d$ spatial dimensions

Useful classification is provided by nature of excitations with vanishing energy:

1. Gapped systems without zero energy excitations

2. “Relativistic” systems with zero energy excitations at isolated points in momentum space

3. “Compressible” systems with zero energy excitations on $d-1$ dimensional surfaces in momentum space.
“Complex entangled” states of quantum matter in $d$ spatial dimensions

Gapped quantum matter
   *Spin liquids, quantum Hall states*

Conformal quantum matter
   *Graphene, ultracold atoms, antiferromagnets*

Compressible quantum matter
   *Graphene, strange metals in high temperature superconductors, spin liquids*
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Topological field theory

Conformal field theory

?
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Band insulators

An even number of electrons per unit cell
Mott insulator

Emergent excitations

An odd number of electrons per unit cell but electrons are localized by Coulomb repulsion; state has long-range entanglement
Mott insulator: Kagome antiferromagnet

\[ H = J \sum_{\langle ij \rangle} \mathbf{\hat{S}}_i \cdot \mathbf{\hat{S}}_j \]
Mott insulator: Kagome antiferromagnet

\[ H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j \]

\[ \bigcirc \bigcirc = \frac{1}{\sqrt{2}} \left( |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) \]

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\[ \text{P. Fazekas and P. W. Anderson, } Philos. Mag. \text{ 30, 23 (1974).} \]
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Quantum “disordered” state with exponentially decaying spin correlations.

Mott insulator: kagome antiferromagnet

Quantum “disordered” state with exponentially decaying spin correlations.

Spin liquid with topological features described by a $\mathbb{Z}_2$ gauge theory, or (equivalently) a doubled Chern-Simons field theory.

Entanglement in the $\mathbb{Z}_2$ spin liquid ground state

$|\Psi\rangle \Rightarrow$ Ground state of entire system,

$$\rho = |\Psi\rangle\langle\Psi|$$

$\rho_A = \text{Tr}_B \rho = \text{density matrix of region } A$

Entanglement entropy $S_E = -\text{Tr} (\rho_A \ln \rho_A)$
Entanglement in the $\mathbb{Z}_2$ spin liquid ground state

Entanglement entropy of a band insulator:

\[ S_E = aP - b \exp(-cP) \]

where $P$ is the surface area (perimeter) of the boundary between A and B.
Entanglement entropy of a $\mathbb{Z}_2$ spin liquid:

$$S_E = aP - \ln(2)$$

where $P$ is the surface area (perimeter) of the boundary between A and B.

Entanglement entropy of a $\mathbb{Z}_2$ spin liquid:

$$S_E = aP - \ln(4)$$

where $P$ is the surface area (perimeter) of the boundary between A and B.

Entanglement in the $\mathbb{Z}_2$ spin liquid ground state

Entanglement entropy of a $\mathbb{Z}_2$ spin liquid:

$$S_E = aP - \ln(2)$$

where $P$ is the surface area (perimeter) of the boundary between A and B.

Kagome antiferromagnet

Hong-Chen Jiang, Z. Wang, and L. Balents, arXiv:1205.4289


Friday, June 8, 2012
Kagome antiferromagnet: evidence for spinons

Young Lee,
APS meeting, March 2012
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Spinning electrons localized on a square lattice

\[ H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j \]

Examine ground state as a function of \( \lambda \)
Quantum critical point described by a CFT3 (O(3) Wilson-Fisher)

\[ \lambda = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \]
Entanglement at the quantum critical point

- Entanglement entropy obeys $S_E = aP - \gamma$, where $\gamma$ is a shape-dependent universal number associated with the CFT3.

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- When $A$ is a circle, $e^{-\gamma} = \text{partition function of CFT3 on } S^3$.

Key idea: Implement \( r \) as an extra dimension, and map to a local theory in \( d + 2 \) spacetime dimensions.
For a relativistic CFT in $d$ spatial dimensions, the metric in the holographic space is uniquely fixed by demanding the following scale transformation ($i = 1 \ldots d$)

$$x_i \rightarrow \zeta x_i \ , \ t \rightarrow \zeta t \ , \ ds \rightarrow ds$$
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$$x_i \rightarrow \zeta x_i \quad , \quad t \rightarrow \zeta t \quad , \quad ds \rightarrow ds$$

This gives the unique metric

$$ds^2 = \frac{1}{r^2} (-dt^2 + dr^2 + dx_i^2)$$

Reparametrization invariance in $r$ has been used to the prefactor of $dx_i^2$ equal to $1/r^2$. This fixes $r \rightarrow \zeta r$ under the scale transformation. This is the metric of the space $\text{AdS}_{d+2}$. 
AdS/CFT correspondence

AdS$_4$

$\mathbb{R}^{2,1}$

Minkowski

CFT$_3$
AdS/CFT correspondence

$\text{AdS}_4$

$\mathbb{R}^{2,1}$

Minkowski

CFT$_3$

$r$
AdS/CFT correspondence

AdS$_4$

\[ R^{2,1} \]

Minkowski

CFT3

- Minimal surface area measures entanglement entropy

\[ S_E = aP - \gamma, \text{ where } \gamma \text{ is a shape-dependent universal number.} \]

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• Consider an infinite, continuum, translationally-invariant quantum system with a globally conserved U(1) charge $Q$ (the “electron density”) in spatial dimension $d > 1$.

• Describe zero temperature phases where $d\langle Q\rangle/d\mu \neq 0$, where $\mu$ (the “chemical potential”) which changes the Hamiltonian, $H$, to $H – \mu Q$. 
Conformal quantum matter
Compressible quantum matter
Compressible quantum matter

A. Field theory

B. Holography
The Fermi liquid

\[ \mathcal{L} = f_\sigma^\dagger \left( \partial_\tau - \frac{\nabla^2}{2m} - \mu \right) f_\sigma \]

+ short-range 4-Fermi terms
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- Area enclosed by the Fermi surface \( \mathcal{A} = Q \), the fermion density

- Particle and hole of excitations near the Fermi surface with energy \( \omega \sim |q| \).
The Fermi liquid

\[ \mathcal{L} = f^{\dagger}_{\sigma} \left( \partial_{\tau} - \frac{\nabla^2}{2m} - \mu \right) f_{\sigma} \]

+ short-range 4-Fermi terms

- Fermion Green’s function \( G_f^{-1} = \omega - v_F q + i \mathcal{O}(\omega^2, q^2) \).
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- Fermion Green’s function \( G_f^{-1} = \omega - v_F q + i\mathcal{O}(\omega^2, q^2) \).
- The phase space density of fermions is effectively one-dimensional, so the entropy density \( S \sim T^{d_{\text{eff}}} \) with \( d_{\text{eff}} = 1 \).
Logarithmic violation of “area law”: \( S_E = \frac{1}{12} \left( k_F P \right) \ln( k_F P) \)

for a circular Fermi surface with Fermi momentum \( k_F \), where \( P \) is the perimeter of region A with an arbitrary smooth shape.
Non-Fermi liquids

To obtain a compressible state which is not a Fermi liquid, take a Fermi surface in $d = 2$, and couple it to any gapless scalar field, $\phi$, which has low energy excitations near $q = 0$. 
Non-Fermi liquids

To obtain a compressible state which is not a Fermi liquid, take a Fermi surface in $d = 2$, and couple it to any gapless scalar field, $\phi$, which has low energy excitations near $q = 0$. The field $\phi$ could represent

- ferromagnetic order
- breaking of point-group symmetry (Ising-nematic order)
- breaking of time-reversal symmetry
- circulating currents
- transverse component of an Abelian or non-Abelian gauge field.
- ...
Non-Fermi liquids

- $\phi$ fluctuation at wavevector $\vec{q}$ couples most efficiently to fermions near $\pm \vec{k}_0$.
- Expand fermion kinetic energy at wavevectors about $\pm \vec{k}_0$ and boson ($\phi$) kinetic energy about $\vec{q} = 0$. 
Non-Fermi liquids

$$\mathcal{L}[\psi_\pm, \phi] =$$

$$\psi_+^\dagger \left( \partial_\tau - i \partial_x - \partial_y^2 \right) \psi_+ + \psi_-^\dagger \left( \partial_\tau + i \partial_x - \partial_y^2 \right) \psi_-$$

$$- g \phi \left( \psi_+^\dagger \psi_+ \pm \psi_-^\dagger \psi_- \right) + (\partial_y \phi)^2$$

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Non-Fermi liquids

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• Critical continuum of excitations near the Fermi surface with energy $\omega \sim |q|^z$, where $q = |k| - k_F$ is the distance from the Fermi surface and $z$ is the dynamic critical exponent.

Non-Fermi liquids

- Gauge-dependent Green’s function $G_f^{-1} = q^{1-\eta} F(\omega / q^z)$. Three-loop computation shows $\eta \neq 0$ and $z = 3/2$.

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Non-Fermi liquids

Simple scaling argument for $z = 3/2$.

$$\mathcal{L} = \psi_+^\dagger \left( \partial_\tau - i \partial_x - \partial_y^2 \right) \psi_+ + \psi_-^\dagger \left( \partial_\tau + i \partial_x - \partial_y^2 \right) \psi_- - g\phi \left( \psi_+^\dagger \psi_+ \pm \psi_-^\dagger \psi_- \right) + (\partial_y \phi)^2$$
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Simple scaling argument for $z = 3/2$.

\[
\mathcal{L} = \psi_+^\dagger \left( \partial_x - i \partial_x - \partial_y^2 \right) \psi_+ + \psi_-^\dagger \left( \partial_x + i \partial_x - \partial_y^2 \right) \psi_- \\
- g \phi \left( \psi_+^\dagger \psi_+ \pm \psi_-^\dagger \psi_- \right) + (\partial_y \phi)^2
\]

Under the rescaling $x \to x/s$, $y \to y/s^{1/2}$, and $\tau \to \tau/s^z$, we find invariance provided

\[
\phi \quad \to \quad \phi \ s^{(2z+1)/4} \\
\psi \quad \to \quad \psi \ s^{(2z+1)/4} \\
g \quad \to \quad g \ s^{(3-2z)/4}
\]

So the action is invariant provided $z = 3/2$. 
Logarithmic violation of “area law”: \( S_E = \frac{1}{12} (k_F P) \ln(k_F P) \)

for a circular Fermi surface with Fermi momentum \( k_F \), where \( P \) is the perimeter of region A with an arbitrary smooth shape.

Non-Fermi liquids have, at most, the “1/12” prefactor modified.

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Computations in the $1/N$ expansion

All planar graphs of $\psi_+$ alone are as important as the leading term

Graph mixing $\psi_+$ and $\psi_-$ is $O\left(N^{3/2}\right)$ (instead of $O\left(N\right)$), violating genus expansion


Sung-Sik Lee, Physical Review B 80, 165102 (2009)
Compressible quantum matter

A. Field theory

B. Holography
Consider the metric which transforms under rescaling as

\[ x_i \rightarrow \zeta x_i \]
\[ t \rightarrow \zeta^z t \]
\[ ds \rightarrow \zeta^{\theta/d} ds. \]

This identifies \( z \) as the dynamic critical exponent (\( z = 1 \) for “relativistic” quantum critical points).

\( \theta \) is the violation of hyperscaling exponent.
Consider the metric which transforms under rescaling as

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\( \theta \) is the violation of hyperscaling exponent.

The most general choice of such a metric is

\[
\frac{ds^2}{r^2} = \frac{1}{r^2} \left( -\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)} dr^2 + dx_i^2 \right)
\]

We have used reparametrization invariance in \( r \) to choose so that it scales as \( r \rightarrow \zeta^{(d-\theta)/d} r \). 

At $T > 0$, there is a “black-brane” at $r = r_h$.

The Beckenstein-Hawking entropy of the black-brane is the thermal entropy of the quantum system $r = 0$.

The entropy density, $S$, is proportional to the “area” of the horizon, and so $S \sim r_h^{-d}$.
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Under rescaling $r \rightarrow \zeta^{(d-\theta)/d} r$, and the temperature $T \sim t^{-1}$, and so

$$S \sim T^{(d-\theta)/z} = T^{d_{\text{eff}}/z}$$

where $\theta = d - d_{\text{eff}}$ measures “dimension deficit” in the phase space of low energy degrees of a freedom.
Area of minimal surface equals entanglement entropy

Holographic entanglement entropy

$S_{\text{Ryu and Takayanagi, Phys. Rev. Lett. 96, 18160 (2006).}}$

Emergent holographic direction
The thermal entropy density scales as

\[ S \sim T^{(d-\theta)/z}. \]

The third law of thermodynamics requires \( \theta < d \).

The entanglement entropy, \( S_E \), of an entangling region with boundary surface ‘area’ \( P \) scales as

\[ S_E \sim \begin{cases} 
  P & \text{, for } \theta < d - 1 \\
  P \ln P & \text{, for } \theta = d - 1 \\
  P^{\theta/(d-1)} & \text{, for } \theta > d - 1 
\end{cases} \]

All local quantum field theories obey the “area law” (upto log violations) and so \( \theta \leq d - 1 \).

The null energy condition implies \( z \geq 1 + \frac{\theta}{d} \).
The value of $\theta$ is fixed by requiring that the thermal entropy density $S \sim T^{1/z}$ for general $d$. Conjecture: this metric then describes a compressible state with a hidden Fermi surface of quarks coupled to gauge fields.

\[ ds^2 = \frac{1}{r^2} \left( -\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)} dr^2 + dx_i^2 \right) \]

$\theta = d - 1$

Holography of non-Fermi liquids

The value of $\theta$ is fixed by requiring that the thermal entropy density $S \sim T^{1/z}$ for general $d$.

Conjecture: this metric then describes a compressible state with a hidden Fermi surface of quarks coupled to gauge fields.

The null energy condition yields the inequality $z \geq 1 + \theta/d$. For $d = 2$ and $\theta = 1$ this yields $z \geq 3/2$. The field theory analysis gave $z = 3/2$ to three loops!

The entanglement entropy exhibits logarithmic violation of the area law only for this value of $\theta$!!

The logarithmic violation is of the form $P \ln P$, where $P$ is the perimeter of the entangling region. This form is independent of the shape of the entangling region, just as is expected for a (hidden) Fermi surface!!

$$ds^2 = \frac{1}{r^2} \left( -\frac{dt^2}{r^2d(z-1)/(d-\theta)} + r^2\theta/(d-\theta)dr^2 + dx_i^2 \right)$$

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\[ ds^2 = \frac{1}{r^2} \left( -\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + \frac{r^{2\theta/(d-\theta)}}{d} dr^2 + dx_i^2 \right) \]

\[ \theta = d - 1 \]

- This metric can be realized in a Maxwell-Einstein-dilaton theory, which may be viewed as a “bosonization” of the non-Fermi liquid state. The entanglement entropy of this theory has log-violation of the area law with

\[ S_E = \Xi \frac{Q^{(d-1)/d}}{P} \ln P. \]

where \( P \) is surface area of the entangling region, and \( \Xi \) is a dimensionless constant which is independent of all UV details, of \( Q \), and of any property of the entangling region.

Note \( Q^{(d-1)/d} \sim k_F^{d-1} \) via the Luttinger relation, and then \( S_E \) is just as expected for a Fermi surface !!!!

Gauss Law and the “attractor” mechanism ⇔ Luttinger theorem on the boundary
Holographic theory of a fractionalized-Fermi liquid (FL*)

Hidden Fermi surfaces of “quarks”

Visible Fermi surfaces of “mesinos”

\[ \varepsilon_r = Q - Q_{\text{mesino}} \]

\[ \varepsilon_r = Q \]

A state with partial confinement

S. Sachdev, Physical Review D 84, 066009 (2011)

These are spectators, and are expected to have well-defined quasiparticle excitations.
Confining geometry leads to a state which has all the properties of a Landau Fermi liquid.

Visible Fermi surfaces of “mesinos”

\[ \mathcal{E}_r = 0 \]

\[ \mathcal{E}_r = Q \]

S. Sachdev, Physical Review D 84, 066009 (2011)
Conclusions

Compressible quantum matter

Field theory of a non-Fermi liquid obtained by coupling a Fermi surface to a gapless scalar field with low energy excitations near zero wavevector
Conclusions

Compressible quantum matter

Evidence for hidden Fermi surfaces in compressible states obtained for a class of holographic Einstein-Maxwell-dilaton theories. These theories describe a non-Fermi liquid (NFL) state of gauge theories at non-zero density.
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After fixing $\theta = d - 1$ to obtain thermal entropy density $S \sim T^{1/z}$, we found

- Log violation of the area law in entanglement entropy, $S_E$. 
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- The $d = 2$ bound $z \geq 3/2$, compared to $z = 3/2$ in three-loop field theory.
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- Evidence for Luttinger theorem in prefactor of $S_E$. 