Condensed matter physicists need Einstein!

Jan Zaanen
Benchmark …
String theorists need Eddington!

Jan Zaanen
Holographic gauge-gravity duality

Einstein Universe “AdS”

Quantum field world “CFT”

‘t Hooft-Susskind holographic principle

Classical general relativity

Uniqueness of GR solutions

Extremely strongly coupled (quantum) matter

“Generating functional of matter emergence principle”
“It from Qubit.”

Dear Qubitzers,

GR=QM.

Leonard Susskind

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Abstract

These are some thoughts contained in a letter to colleagues, about the close relation between gravity and quantum mechanics, and also about the possibility of seeing quantum gravity in a lab equipped with quantum computers. I expect this will become feasible sometime in the next decade or two.
Welcome to Hell

Matrix Large N
UV INDEPENDENCE
A universe of mysteries as analogue quantum computer …

Is this controlled by holographic strange metal principle?

“Fermi liquid with anomalous scaling dimensions” rooted in dense many body entanglement.

Natural explanations for transport (“Planckian dissipation”, ETH), “unparticle physics” spectral functions, …. 

Intertwined order in pseudogap regime as “BCS-like” instability of the strange metal: “Black hole with dreadlocks.”
Phil Anderson: “The only meaning of theory is to demonstrate possibility. It is about learning to think differently, be it on basis of flawed solutions to wrong problems.”

Case in point: “Anderson-Morel” for p-wave superconductivity.
Koenraad’s cloverleaf ....
Quantum field theory = Statistical physics.

\[ Z = \sum_{\text{configs.}} e^{\frac{-E_{\text{config}}}{kBT}} \]

Path integral mapping

"Thermal QFT", Wick rotate:

\[ Z_h = \sum_{\text{worldhistories}} e^{\frac{-S_{\text{history}}}{\hbar}} \]

But generically: the quantum partition function is not probabilistic: "sign problem", no mathematical control!

\[ Z_h = \sum_{\text{worldhistories}} (-1)^{\text{history}} e^{-\frac{S_{\text{history}}}{\hbar}} \]
Fermions at a finite density: the sign problem.

Imaginary time first quantized path-integral formulation

$$\mathcal{Z} = \text{Tr} \exp(-\beta \hat{\mathcal{H}})$$
$$= \int d\mathbf{R} \rho(\mathbf{R}, \mathbf{R}; \beta)$$
$$\mathbf{R} = (\mathbf{r}_1, \ldots, \mathbf{r}_N) \in \mathbb{R}^{N_d}$$

$$\rho_{B/F}(\mathbf{R}, \mathbf{R}; \beta) = \frac{1}{N!} \sum_{\mathcal{P}} (-1)^{\mathcal{P}} \rho_{\mathcal{D}}(\mathbf{R}, \mathcal{P}\mathbf{R}; \beta)$$
$$= \frac{1}{N!} \sum_{\mathcal{P}} (-1)^{\mathcal{P}} \int_{\mathbf{R} \rightarrow \mathcal{P}\mathbf{R}} d\mathbf{R}(\tau) \exp \left\{ -\frac{1}{\hbar} \int_0^{\hbar/T} d\tau \left( \frac{m}{2} \dot{\mathbf{R}}^2(\tau) + V(\mathbf{R}(\tau)) \right) \right\}$$

Boltzmannons or Bosons:
- integrand non-negative
- probability of equivalent classical system: (crosslinked) ringpolymers

Fermions:
- negative Boltzmann weights
- non probablistic: NP-hard problem (Troyer, Wiese)!!!
Fermions: the tiny repertoire ...

Fermiology

BCS superconductivity

\[ \Psi_{BCS} = \Pi_k \left( u_k + v_k c_k^+ c_{-k}^+ \right) |vac. \rangle \]
Solving the sign problem: the Troyer way.

The ground state is densely entangled: I need a quantum computer!
Bell pairs and the “spooky action at a distance”.

Classical computers live in tensor product space:

\[ |\text{product}\rangle = |0\rangle_A \otimes |1\rangle_B \text{ or } |1\rangle_A \otimes |0\rangle_B \]

Quantum computers exploit entangled states capable of “spooky action at a distance” (EPR paradox).

\[ |\text{Bell}\rangle = \frac{1}{\sqrt{2}} \left( |0\rangle_A \otimes |1\rangle_B - |1\rangle_A \otimes |0\rangle_B \right) \]
Many body/bit Hilbert space.

Two qubits: Hilbert space dimension $2^2 = 4$

$|00\rangle, |01\rangle, |10\rangle, |11\rangle$

Three qubits: Hilbert space dimension $2^3 = 8$

$|000\rangle, |001\rangle, |010\rangle, |011\rangle, |100\rangle, |101\rangle, |110\rangle, |111\rangle$,

Physical world $10^{23}$ “qubits”: Hilbert space dimension $2^{10^{23}}$

$$|\Psi_n\rangle = \sum_{\text{config.}i} C^n_i |\text{config.}i\rangle$$

Overwhelming amount of quantum information.
“The classical condensates: from crystals to Fermi-liquids.”

States of matter that we understand are product!

\[
\left| \Psi_0 \left\{ \Omega_i \right\} \right\rangle = \Pi_i \hat{X}_i^+ (\Omega_i) \left| vac \right\rangle
\]

- **Crystals**: put atoms in real space wave packets
  \[
  X_i^+ (R_i^0) \propto e^{(R_i^0 - r)^2/\sigma^2} \psi^+(r)
  \]

- **Magnets**: put spins in generalized coherent state
  \[
  X_i^+ (\vec{n}_i) \propto e^{i\varphi_i/2} \cos (\theta_i/2) c_{i\uparrow}^+ + e^{-i\varphi_i/2} \sin (\theta_i/2) c_{i\downarrow}^+
  \]

- **Superconductors/superfluids**: put bosons/Cooper pairs in coherent superposition
  \[
  X_{k/i}^+ \propto u_k + v_k c_{k\uparrow}^+ c_{-k\downarrow}^+ , \quad u_i + v_i e^{i\varphi_i} b_i^+
  \]

- **Fermi gas/liquid**: product state in momentum space (mod Pauli principle).
  \[
  \left| \Psi_{FL} \right\rangle = \Pi_k c_k^+ \left| vac \right\rangle
  \]
Black holes as “fermion sign quantum computers” !?
Holography and quantum matter (0)

Holographic duality (AdS/CFT): the “mean field theory of maximal infinite party entanglement” (??)

Nature as analogue quantum computer: strange metals in cuprate superconductors etc. ruled by holographic principle?
Quantum criticality and entanglement.

Strongly interacting zero density ("bosonic") quantum critical state: irreducibly infinite party entangled vacuum state.

Equivalent to strongly interacting stat phys critical state: configuration space spanned up by globally different configurations (cf. critical slowing down), no local unitaries that can map it on a product state.

Quantum number localizable in short range entangled product vacuum: particles in the spectrum

\[ G(\omega, k) = \frac{Z_k}{(k - \omega)} + \cdots \]

Quantum number non-localizable in long range entangled QC state, no particles but "unparticle" branch cut spectrum.

\[ G(\omega, k) = \frac{1}{(k - \omega)^\Delta} \]
\[ \chi''(q, \omega) = \chi_0(q) \tanh \left( \frac{\omega_c^2}{\omega^2} \right) \]

- Temperature-independent down to \( T = 20K \)
- No propagating excitations.
- Local criticality.
- Not a Fermi liquid
- Inconsistent with “soft mode” criticality
Unparticle physics in high Tc superconductors.

Photoemission spectra at antinodes:

Blue: Bogoliubov quasiparticles deep in the superconducting state.

Red: birth of Fermi-liquid quasiparticles in the normal state

Shen group Stanford (unpublished)

J.C. Campuzano

FIG. 1: Spectra at constant temperature as a function of doping. (A) Dots indicate the temperature and doping values of the spectra of the same color plotted in (D-F). (B) Schematic phase diagram for a quantum critical point near optimal doping. (C) Schematic phase diagram for a doped Mott insulator. (D) Spectra at $T \sim 300$K for several samples measured at the antinode, where the $d$-wave superconducting gap below $T_c$ is largest. The spectra are normalized to high binding energy and symmetrised in energy to eliminate the Fermi function. The doping values are indicated by the top row of dots in (A). (E) Same as in (D), but at $T \sim 150$K, with the dopings indicated by the middle row of dots in (A). (F) Same as in (D), but at $T = 100$K, with the dopings indicated by the bottom row of dots in (A).

FIG. 4: Electronic phase diagram of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ versus hole doping, $\delta$. Brown dots indicate incoherent gapped spectra, blue points coherent gapped spectra, green dots coherent gapless spectra, and red dots incoherent gapless spectra. The brown double triangles denote $T^*$, and the green double triangles $T_{coh}$. $T_c$ denotes the superconducting transition temperature.
AdS/ARPES: the RN approaching the Fermi liquid

Bulk: DW fermion gas and the horizon

Boundary: would be fermions decaying in QC infrared

$$G_f(\omega, k) = \frac{1}{\omega - \nu_F(k - k_F) - \Sigma(k, \omega)}$$

$$\Sigma(k, \omega) \sim e^{i\phi k_F} \omega^{2\nu k_F}$$

$$2\nu_k \sim \sqrt{\frac{1}{\xi^2} + k^2}$$

Boundary: $2\nu k_F < 1$ overdamped

Marginal FL $2\nu k_F = 1$

underdamped $2\nu k_F > 1$
Nodal fermion self-energies in the strange metal.

\[
\Sigma''_{PLL}(\omega) = \Gamma_0 + \lambda \left[ \frac{(\hbar \omega)^2 + (\beta \k_B T)^2}{(\hbar \omega_N)^{2\alpha-1}} \right]^{\alpha}
\]
Nodal fermions and their scaling collapse ...  

Optimal doped nodal ARPES:  
\[ A(k, \omega) = \frac{1}{v_F k} A(\omega'), \quad \omega' = \frac{\omega}{v_F k} \]

“generalized MFL” is not scaling!  

Branch-cut is scaling:  
\[ G(k, \omega) \sim \frac{1}{(\omega^2 - v^2 k^2)^{\Delta/2}} = \frac{1}{(v k)^{\Delta}} \frac{1}{((\omega')^2 - 1)^{\Delta/2}} \]
The “first law” of holography: the compressible metallic phases of matter at finite density are “self-organized quantum critical”.

Is this a principle? “Irreducibly infinite party entangled, compressible states of matter have to be emergent scale invariant.”

Experimentalists: are strange metals ruled by a quantum critical point or are they “intermediate temperature” quantum critical phases?
Fermi-liquids can be viewed as “ordered states breaking symmetry spontaneously.”

But they may also be viewed as a fermionic version of a Gaussian critical “phase”, characterized by covariance instead of invariance under scale transformations.

Can the holo strange metals be viewed as “strongly interacting critical” generalizations of the Fermi liquid? “Fermi liquids with anomalous dimensions.”
“Scaling atlas” of holographic quantum critical phases.

Deep interior geometry sets the scaling behavior in the emergent deep infrared of the field theory. Uniqueness of GR solutions:

1. “Cap-off geometry” = confinement: conventional superconductors, Fermi liquids ….


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

$$x_i \rightarrow \xi x_i, \quad t \rightarrow \xi^z t, \quad ds \rightarrow \xi^{\theta/d} ds$$

Quantum critical phases with unusual values of:

- $$\zeta$$ = Dynamical critical exponent
- $$\theta$$ = Hyperscaling violation exponent
- $$\zeta$$ = Charge exponent

Kiritsis
Holographic transport: relaxation times are generically “planckian”,

\[ \tau \sim \frac{\hbar}{k_B T} \]

Is the high Tc strange metal “nearly hydrodynamical” due to very fast thermalization even in the presence of microscopic quenched disorder?

Experimentalists: can you device “hydro-test experiments? Is transport highly collective, detached from single electron properties?
Planckian dissipation = ETH (?)

Are the Planckian dissipation and the “rapid hydrodynamization” ubiquitous consequences of quantum thermalization involving very densely entangled states, perhaps in combination with scale invariance?
“Unparticle physics”: macroscopic entangled matter.

Conjecture I: All strongly interacting quantum critical states are long ranged entangled. Support: dynamical critical scaling down in Euclidean signature, branch cut propagators.

Conjecture II: Fermion signs are “stabilizers” of long range entangled vacuum states. If compressible these have (?) to form quantum critical phases.

Conjecture III: this dense entanglement implies that such states are maximally efficient entropy generators = Planckian dissipation.