Holography in the lab: are the killer apps around the corner?

Jan Zaanen
“Jan, AdS/CMT needs a killer app, wish you good luck”
Plan.

Reminder: holography is about quantum supremacy.

The Killer App candidates:

- Cuprate ARPES and the unparticles.
- The second sector and the spin-stripes in a large field.
- Planckian dissipation and Geim’s hydro experiments.
The supremacy of the quantum computer.

Sequential one- and two bit operations: engineering pursuit based on well understood parts.
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 $2^{10^{23}}$

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

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

States of matter that we understand are short ranged entangled product!

\[ |\Psi_0\{\Omega_i\}\rangle = \prod_i \hat{X}_i^+(\Omega_i)|\text{vac}\rangle \]

- **Crystals:** put atoms in real space wave packets

  \[ X_i^+(R_i^0) \propto e^{-(R_i^0 - r)^2/\sigma^2}\psi_i^+(r) \]

- **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).

  \[ |\Psi_{FL}\rangle = \prod_k^{k_F} c_k^+|\text{vac}\rangle \]
“Quantum supreme matter”

Are there non-SRE states of matter in nature, where many body entanglement governs the physical properties?

1. Incompressible matter (X.-G. Wen, 1992): macroscopic entanglement underneath the topological order described by topological field theory (frac. quantum Hall, etc). The entanglement is extremely sparse, infinite number of microscopic qubits needed for a topological quantum bit.

2. Compressible matter: by default very densely entangled, little is known. Since the 1990’s strongly interacting CFT’s/”Sachdevian” quantum criticality. Recent developments: SYK and the big AdS/CFT machine.
Fermions at a finite density: the „non-stoquastic“ sign problem.

Imaginary time first quantized path-integral formulation

\[ Z = \text{Tr} \exp(-\beta \hat{H}) = \int dR \rho(R, R; \beta) \]

\[ R = (r_1, \ldots, r_N) \in \mathbb{R}^{Nd} \]

\[ \rho_{BF}(R, R; \beta) = \frac{1}{N!} \sum_{P} (\pm 1)^P \rho_{D}(R, \mathcal{P}R; \beta) \]

\[ = \frac{1}{N!} \sum_{P} (\pm 1)^P \int_{R \rightarrow \mathcal{P}R} DR(\tau) \exp \left\{ -\frac{1}{\hbar} \int_0^{\hbar/T} d\tau \left( \frac{m}{2} \dot{R}^2(\tau) + V(R(\tau)) \right) \right\} \]

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

Fermions:
- negative Boltzmann weights
- „non-stoquastic“: NP-hard problem (Troyer, Wiese)!!!
Are our CM electrons quantum supreme?

General Relativity = Renormalization Group

Extra radial dimension of the bulk \iff scaling “dimension” in the field theory.

Bulk AdS geometry = conformal invariance of the field theory.

\[ dr^2 = -F(r)dt^2 + \frac{dr^2}{F(r)} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \]

\[ F(r) = -\Lambda r^2 + 1, \quad \Lambda < 0 \]
Central charge and quantum complexity of CFT’s

Hierarchical tensor networks (MERA): **pragmatic** approximation scheme “stitching together” the vacuum entanglement CFT’s in terms of local tensors. For a non-integrable CFT this becomes exact only when the bond dimension of the local tensors becomes “$2^N$”.

Evenbly and Vidal (arXiv:1109.5334): to maintain the same accuracy the bond dimension has to increase by $e^c$ with the central charge $c = N^2$. In this sense the large $N$ limit CFT’s are maximally entangled.
The charged back hole encoding for finite density (2008 - ????)

Anti de Sitter universe.

Finite density quantum matter:
- Charged black hole in the middle
- Stripy pseudogap orders
- High Tc superconductors
- Emergent Fermi liquids
- Holographic strange metals
What is a “particle”?

E.g. transversal field Ising model:  

\[ H = -J \sum_{<ij>} \sigma_i^z \sigma_j^z + B \sum_i (\sigma_i^+ + \sigma_i^-) \]

\[ J \ll B: \text{ product state vacuum} \]

\[ \text{Excitation} = \text{inject quantum number(s) (S=1)} \]

\[ \text{“Particle” delocalizes:} \quad G = \frac{1}{\varepsilon_k - \omega} \]

\[ A(k, \omega) = \text{Im } G = \delta(\varepsilon_k - \omega) \]

\[ J < B, \text{ SRE product state } = \text{perturbative corrections:} \]

\[ |\psi_0\rangle = A|\text{product}\rangle + \sum_i a_i |\text{config}, i\rangle \]

“Good” self-energy, at the bottom of the spectrum:

\[ G = \frac{1}{\varepsilon_k - \omega + \Sigma(\omega, k)} \]

\[ G = \frac{A^2}{\hat{\varepsilon}_k - \omega} + G_{\text{incoh}} \]
Quantum supreme matter and unparticle physics.

Given: The vacuum state is infinite party entangled

$$|\Psi\rangle = \sum_{\text{configs}} A_{\text{configs}} |\text{configs}\rangle$$

Inject a quantum-number: this information is now “dispersed” in the whole $2^N$ many body Hilbert space.

The quantum info is no longer “localizable”: there are no particle poles in the spectrum.

Spectral functions are fully incoherent: “unparticle physics” as quantum matter diagnostic!
Strongly interacting “stoquastic” quantum critical states.

\[ S = \int d^d x d\tau \left[ (\partial_\tau \Phi)^2 + (\nabla \Phi)^2 + m^2 \Phi^2 + w \Phi^4 \right] \]

\[ D = d + z < D_{u.c.}(=4) : \quad w \neq 0 \quad \text{at the IR fixed point} \]

“strongly interacting” = NP-hard (critical slowing down in QMC) = densely entangled quantum critical state.

\[ \langle \Phi \Phi \rangle \sim \frac{1}{\sqrt{k^2 - \omega^2}^{2-\eta}} \]

\[ D \geq D_{u.c.} \quad w = 0 \quad \text{at the IR fixed point} \]

Mean-field fixed point: SRE product state characterized by particles in its spectrum:

\[ \langle \Phi \Phi \rangle \sim \frac{1}{k^2 - \omega^2} \]
Fermion spectral functions of quantum critical relativistic (“Dirac”) fermions at small but finite temperature = Dirac quantum mechanics in the AdS-Schwarzschild bulk.

\[ \langle O(\vec{q}, \omega)O(0) \rangle = \frac{1}{(q^2 - \omega^2/c^2)^{D-\Delta}} \]
Finite density: the Reissner-Nordstrom strange metals (Liu et al.).

Near-horizon geometry of the extremal RN black hole:
- **Space directions**: flat, codes for simple Galilean invariance in the boundary.
- **Time-radial (= scaling) direction**: emergent AdS$_2$, codes for emergent temporal scale invariance!


“Un-particle physics”: incoherent excitations, *no poles*.

Non-Wilsonian renormalization property: *local quantum criticality*. 
The cuprate strange metal charge response.

It looks like a holographic QC scaling continuum: \( z \) is obviously infinite.

The factorization in energy and momentum, as well as the marginal energy scaling does not seem to make sense holographically.

We know why: momentum non-conservation due to the lattice potential will play a crucial role and this is still quite poorly understood holographically.
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:

$$\zeta = \text{Dynamical critical exponent}$$

$$\theta = \text{Hyperscaling violation exponent}$$

$$\zeta = \text{Charge exponent}$$
Generalizing the Fermi liquid: thermodynamics.

In d dimensions the FL is characterized by a \textit{d-1 dimensional manifold of massless excitations} (Fermi surface): $\theta = d - 1$

Every point on the Fermi surface \textit{scales like a CFT$_2$}: $z = 1$

$$S \sim T^{(d-\theta)/z} = \left(\frac{T}{E_F}\right)$$ \quad \text{Sommerfeld specific heat}

\textbf{Local} quantum critical (Abbamonte etc.): $z \to \infty \Rightarrow S \sim T^0$

Zero temperature entropy, e.g. Reissner-Nordstrom metal.

\textbf{Top down EMD “conformal to AdS2” metal:}

$$-\theta, z \to \infty, \quad -\theta/z \to 1 \quad \Rightarrow \quad S = \left(\frac{T}{\mu}\right)$$
Entanglement, anomalous dimensions and strange metal instability.

“Quantum critical BCS” (J.H. She, JZ, arXiv:0905.1225)

Densely entangled strange metal: the scaling dimension of the pair operator is anomalous.

\[ \chi_p(\omega) \sim \frac{1}{\omega^{\alpha_p}} \]

\[ 1 - g \chi_p(q = 0, \omega = 0, T = T_c) = 0 \]

If relevant \( \alpha_p > 0 \) \( T_c \) is very high even for a weak attractive glue!

\[ \Rightarrow \Rightarrow \Delta = 2\omega_B \left( 1 + \frac{1}{\lambda} \left( \frac{2\omega_B}{E_F} \right)^{\alpha_p} \right)^{-1/\alpha_p}, \quad \lambda = 2 \frac{g}{E_F} \frac{1 - \alpha_p}{\alpha_p} \]

Holographic superconductivity works this way! J.H. She et al., arXiv: 1105.5377
Plan.

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The Killer App candidates:

**Cuprate ARPES and the unparticles.**

The second sector and the spin-stripes in a large field.

**Planckian dissipation and Geim’s hydro experiments.**
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

Fermions in holographic superconductors.

Normal state: RN strange metal, AdS$_2$.

Deep infrared holographic SC: AdS$_4$, $z=1$
The stoquastic view on scale invariance.

**Scale invariance** is dynamically generated “inside the wedge” anchored at …

... an isolated point in coupling constant space.
The evasive quantum phase transition

When this is the quantum critical wedge.

Where is the quantum critical point?
Doping dependence of antinodal ARPES  

Science 366, 1099 (2019)

Normal state 2212 antinodal ARPES as function of doping.

Strange metal: incoherent

Critical doping \( p_c = 0.19 \)

Reasonable quasiparticles!
From unparticle to particle ..

EDC’s: perfect fit obtained using the industry standard “nodal” self energy for overdoped (Tc = 81 K) metal while the Tc= 86 K metal is completely incoherent.

MDC’s: industry standard self-energies fit well on both sides of p_c.

“The UV first order transition failing in the IR”
The stoquastic view on scale invariance.
The “failed first order” transition in cuprates.

**Stoquastic first order QPT**

- **Energy**
  - SRE-P phase I
  - SRE-P phase II

- **Coupling**

**Cuprates**

- **Energy**
  - Strange metal
  - Less strange metal

- **Doping**

Wilsonian RG principle: discontinuity always amplifies towards IR ("runaway flow")

The only loophole: it is non-stoquastic and thereby quantum supreme!
The nodal-antinodal dichotomy.

The antinodes: the “unparticle responses” at the BZ boundary

In the (d-wave) nodal directions the spectra are much more “particle like”
Holography and the antinodes.

e.g. Balm et al., arXiv:1909.09394

Free fermion Umklapp

"Zero’s eat poles" near the BZ boundary.
Nodal fermion self-energies in the strange metal.

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

arXiv:1509.01611
AdS/ARPES: the RN approaching the Fermi liquid

Bulk: DW fermion gas and the horizon

Boundary: would be fermions decaying in QC infrared

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

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

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

$$2\nu_{k_F} < 1$$  overdamped

$$2\nu_{k_F} = 1$$  Marginal FL

$$2\nu_{k_F} > 1$$  underdamped
Plan.

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Zaanen-Gunnarsson (1987)

Unrestricted Hartree-Fock on 3-band model:

Hole density on oxygen
Su-Schrieffer-Heeger soliton = Jackiw-Rebbi zero mode.

polyacetylene

Domain ‘wall’ (‘soliton’)

mid gap state!
Large S holons

'Hartree-Fock': \[ U \sum_i n_{i\uparrow} n_{i\downarrow} \approx U \sum_i \left[ \langle n_{i\uparrow} \rangle n_{i\downarrow} + \langle n_{i\downarrow} \rangle n_{i\uparrow} - \langle n_{i\uparrow} \rangle \langle n_{i\downarrow} \rangle \right] \]

Uniform:

'Spin bag':

'Soliton':
Zaanen-Gunnarsson stripes

‘Holons on a row’

Mid-gap band
The BIG computational guns (2017).

“Simons collaboration”:
Hubbard model in 2D
$x=1/8$ $U/t = 8$
Science 358, 1155 (2017)
DMRG with huge $(10^4)$ bond dimension:

Like fluctuating, strongly coupled SC stripes.

Like weakly coupled “RPA” d-wave superconductor.
Hartree-Fock Stripes are ubiquitous in doped Mott Insulators (they insulate ..)

Nickelates

Cobaltates

Manganites
A 1995 big puzzle: the “stripy things”.

The ‘half-filled” 214 spin stripes are charge commensurate: they should exhibit a “Mott” (commensuration) gap and activated transport.

But instead they show a slow (log like, small power) diverging resistivity setting in at $T_{SO}$ ..
Why ‘Stripes’?

Xenon on graphite

Discommensurations or ‘stripes’

Commensurate domains
The holographic Mott insulator arXiv:1710.05791

The commensurate case:

- Ionic lattice
- Spontaneous crystal
- Pinned crystal staggered currents
- Pinned crystal “uniform” currents

“Hubbard band”

“super-exchange”
Doping the holographic Mott insulator:

The bulk “RG flow”:

Isolated discommensuration = domain wall in current order!

Discommensuration lattice = (current) stripe phase
The ordering wave vector

arXiv:1710.05791

The doping dependence of the periodicity:

\[ p_0 / k \]

\[ p / k = n_p / n_k \]

\[ \Delta \varphi \]

Lacking charge quantization no preferred density: “Devil’s staircase” behavior with higher order commensurate plateaux.


Mesaros et al, PNAS 113, 12661 (2016)
The insulator is algebraic! arXiv:1710.05791

“Quantum critical infrared sector”:

According to holography even deep in the MI presumably entangled stuff is left behind that is not localizable.

Challenge to experiment: origin of slow resistivity upturns in stripy 214?
Generalizing the Fermi liquid: the two sectors. arXiv:1812.03968

\[ \sigma_{tot}(q = 0, \omega) = \sigma_D + \sigma_{QC} \]

Fermi-liquid

\[ \sigma_{tot}(q = 0, \omega) = \sigma_D = Z\delta(\omega) \]

\[ \sigma_{tot}(q \neq 0, \omega) = \sigma_{QC} \sim \omega^2 \]

Holographic metal

\[ \sigma_{tot}(q = 0, \omega) \sim Z\delta(\omega) + Z'\omega^{\frac{d-2+2\Phi-\theta-z}{z}} \]

\[ \sigma_{tot}(q \neq 0, \omega) = \sigma_{QC} \sim F\left(\frac{\omega}{|q|^2}\right)\omega^{\frac{d-2+2\Phi-\theta-z}{z}} \]
Generalizing the Fermi liquid: the two sectors. arXiv:1812.03968

- The “quantum critical sector”: “Lindhard with anomalous scaling dimensions”.

- It persists at $q = 0$, co-existing with the momentum carrying Drude sector/zero sound.

- It persists in the presence of a “gapping” order parameter, albeit with altered scaling dimensions (e.g. holo-SC)

- It is characterized by a robust emergent charge conjugation symmetry, the Hall effect vanishes (Blake, Donos, PRL 114, 0216001).
The insulator is algebraic! arXiv:1710.05791

“Quantum critical infrared sector”:

According to holography even deep in the MI presumably entangled stuff is left behind that is not localizable.

Challenge to experiment: origin of slow resistivity upturns in stripy 214?
The high field 214 “spin stripes”.

*arXiv:1909.02491*

Non-superconducting “spin-stripe” phase:

- Slowly (logarithmically?) diverging resistivity down to very low T.
- The Hall effect completely disappears!
The high field 214 “spin stripes”
What is to be done?

Theory:

Is the momentum carrying (Drude) sector completely pinned in a full lattice? Is the Hall effect vanishing identically at low T? Compute all properties (thermal transport, ARPES/Tunneling, thermodynamics, optical conductivity, ..)

Experiment:

Magnet lab, throw everything you have at 30 Tesla’s to the spin stripes! You may be the first to nail a quantum supreme T = 0 state, and that will earn you Nobel prizes …
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The second sector and the spin-stripes in a large field.

Planckian dissipation and Geim’s hydro experiments.
Divine resistivity

Nothing happens!!
Strange metal transport: nearly momentum conserving.

Optical conductivity: sharp Drude peak = total momentum is nearly conserved + long “tail” setting in at higher frequency.

The width of the Drude peak is set by the Planckian dissipation time

\[
\frac{1}{\tau_K} \approx \frac{k_B T}{\hbar}
\]

van Heumen
Dissipation = absorption of classical waves by Black hole!

Policastro-Son-Starinets (2002):

Viscosity: absorption cross section of gravitons by black hole

\[ \eta = \frac{\sigma_{abs}(0)}{16\pi G} \]

= area of horizon (GR theorems)

Entropy density \( s \): Bekenstein-Hawking

BH entropy = area of horizon

Universal viscosity-entropy ratio for CFT’s with gravitational dual limited in large \( N \) by:

\[ \frac{\eta}{s} = \frac{1}{4\pi} \frac{\hbar}{k_B} \]
Inspiration: the quark gluon plasma.

- “Fast hydrodynamisation”: within the time it takes a quark to traverse half a proton radius local quark-gluon equilibrium is established.

- “Minimal viscosity”:

\[
\frac{\eta}{s} \approx \frac{1}{4\pi} \frac{\hbar}{k_B}
\]

associated with “Planckian relaxation time”:

\[
\tau \eta \approx \frac{\hbar}{k_B T}
\]
Holographic linear resistivity
(PRBA 89, 2451161, 2014).

“Conformal to AdS$_2$” strange metal: Einstein-Maxwell-dilaton (consistent truncation), local quantum critical, marginal Fermi-liquid (3+1D), susceptible to holo. superconductivity, healthy thermodynamics: unique ground state, Sommerfeld thermal entropy.

Breaking of Galilean invariance (finite conductivities) due to quenched disorder: “massive gravity” = “Higgsing” space-like diffeomorphisms in the bulk !?

David Vegh

Explicit holographic construction explaining linear resistivity!
The secret of the linear resistivity (PRB 89, 2451161, 2014).

**Planckian dissipation = very rapid local equilibration:** a hydrodynamical fluid is established before it realizes that momentum is non conserved due to the lattice potential (not true in Fermi-gas: Umklapp time is of order collision time).

\[
\rho(T) \propto \frac{1}{\tau_{\text{rel}}} = \frac{D}{l^2}
\]

\[
\zeta \rightarrow \infty
\]

Hartnoll

Resistivity due to viscous drag

Einstein relation:

\[
D = \frac{\eta}{m_e n_e}
\]

Stokes

Einstein

\[
\rho(T) = \frac{1}{\omega_p^2 \tau_{\text{rel}}} = A \frac{\hbar}{\omega_p^2 l^2 m_e} \frac{S}{k_B}
\]

\[
\eta = A \frac{\hbar}{k_B}
\]

Planckian viscosity

Sachdev Son
Entropy versus transport: optimal doping

Optimally doped

\[ C = \gamma T \Rightarrow S = \frac{T}{\mu} \]

\[ \rho \propto \frac{1}{\tau_{rel}} \propto S \propto T \]

No residual resistivity since the fluid becomes perfect at \( T = 0 \)!
Scaling of the “Planckian prefactor” with entropy.

Taillefer group, overdoped regime, arXiv:1805.02512

\[ \rho(p, T) = A_p T, \quad A_p \sim S_p \]
Is the momentum relaxation time set by entropy?.

High precision “LHC style” measurement strategy, arXiv:1807.10951

1. Samples over the whole doping range.

2. Measure DC resistivity and establish the linear-in-temperature strange metal regime.

3. Measure optical conductivity, extract Drude weight and Drude width = momentum relaxation rate.

4. Measure the strange metal regime (high temperature) specific heat (‘Loram-Tallon’). Establish whether this scales with the Drude width.
Hi Jan,
Following our own 2019 paper on Hall viscosity in graphene (science.sciencemag.org/content/364/6436/162), we have recently found that this type of measurements is much more robust than the previous approaches (vicinity and point contact measurements of electron viscosity). We tried the latter two on Ivan's material before but saw absolutely nothing.
With the new knowledge about the Hall viscosity, we decided to give another try to the high-Tc material. To my great surprise, the devices show a notable suppression of a local Hall effect with respect to the global one (1/ne), despite the distance to the injector contact is large (~1 um). This is unexpected because the spatial extent of viscous effects should be tiny as viscosity of a strange metal should be minimal. However, the behaviour for this one measured device is quite robust and qualitatively correct. I cannot find any alternative explanation so far, except for speculating that the device had deteriorated after long storage and "somehow produces artefacts".

We still have some material from Ivan and can make better devices. However, before wasting more time on your swan song ;-), it would be good to estimate possible signals in theory. I don't know many parameters (if they are known at all) for Ivan's material (density of states and viscosity). We need B_0 and nu_0 (see Eq. 9 in https://journals.aps.org/prb/abstract/10.1103/PhysRevB.96.195401) to estimate the local suppression of the standard Hall effect.
We work in small B <<<B_0. Can you please advise about expectations for the coefficients.
A

\[
\eta_{ij,kl} = \zeta \delta_{ij} \delta_{kl} + \eta (\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk} - \delta_{ij}\delta_{kl}) + \eta_H (\delta_{jk}\epsilon_{il} - \delta_{il}\epsilon_{kj})
\]

\[
\eta = \eta_0 \frac{1}{1 + (\tau_B \omega_c)^2}
\]

\[
\eta_H = \eta_0 \frac{\tau_B \omega_c}{1 + (\tau_B \omega_c)^2}
\]

\[
\omega_c = \frac{eB}{m_e c}
\]
The unreasonable signal.

Hall viscosity device made from Bozovic-grade optimally doped $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$
What is to be done?

Theory:

The non-topological Hall viscosity vanishes for massless relativistic systems (Yarom), how to get a handle? The signal is understood in the laminar regime, but the cuprate fluid may well be turbulent.

Experiment:

Wish Andre and Ivan the best of luck with the devices …
Planckian dissipation and nanoscale turbulence.

Reynolds number: \[ Re = \frac{\rho v L}{\eta} \]

Turbulence sets in when \( Re > 10^3 \)

Planckian viscosity: \[ \eta = \frac{1}{(4\pi)(\hbar/k_B)s} \]

\[ Re = \frac{\sqrt{2}}{A} \frac{v_{tr}}{v_\mu} \frac{L_{tr}}{l_\mu} \frac{\mu}{k_B T} \quad L_{tr} \leq v_\mu \tau_\hbar \]

\[ \mu \simeq 10^4 K \]  
Turbulent flows on the nanometer scale at low temperature!
The latest on divine resistivity
arXiv:1705.05806

No residual resistivity even in optimally doped 214 (magnetic field/temperature scaling)!

The absence of a residual resistivity by extrapolating from high temperature already observed in the late 1980’s in “clean” 123 etc.

a T=0 metallic state which is a perfect conductor !?
Planckian dissipation, minimal viscosity and the transport in cuprate strange metals.

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arXiv:1807.10951
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The Killer App candidates:

Cuprate ARPES and the unparticles.

The second sector and the spin-stripes in a large field.

Planckian dissipation and Geim’s hydro experiments.
Empty.
Empty.
Near-inviscid fluid flowing through dirt ...

The fluid turns solid: disordering length scale of the stripes $O(10 \text{ nm})$.

Consistent with the measured Planckian momentum relaxation rate

$$\tau_K \simeq \frac{\hbar}{k_B T}$$

Characteristic (zero-sound) velocity cuprates "$v_F= 1 \text{ eV A}$ (plasmon dispersion).

Hydrodynamical flow destroyed "by the trees" at the length

$$L_{hydro} = v_F \tau_K \simeq 1 \text{ micron at } 1 \text{ Kelvin!}$$
Complex horizons: intertwined charge-current-parity-SC order.

Rong-Gen Cai, Li Li, Yong-Qiang Wang, JZ, PRL 119, 181601 (2017), arXiv:1706.01470

Charge and currents

Superconductivity

Charge order intertwined with parity breaking, spontaneous currents and pair density wave order.
Pragmatic Ansatz for the vacuum many-body wavefunction:
- Decompose the amplitudes in local tensors.
- Increasing the “bond dimension” of the local tensors corresponds with wiring in more many body entanglement.
- When the state is quantum supreme the tensor network becomes exact only for bond dimension “$2^N$”!
- The sensitivity of the result to the bond dimension is presently the best measure of many body entanglement that I am aware off!
Typical disorder scales (stripy stuff, STS).
Doping dependence of Planckian relaxation (LBCO).

\[ \tau_K = 2\pi \lambda(x) k_B T \]

Loram-Tallon entropy:
\[ \lambda(x) \sim S(x) = \gamma x_c \frac{x}{x_c}, \quad x < x_c, T > T^*, T_c \]
Magnitude of momentum relaxation.

Given that \( S = \frac{k_B T}{\mu} \), \( \mu = 1 eV \) the RN strange metal has a momentum relaxation rate:

\[
\frac{1}{\tau_K} = \frac{A \hbar}{l^2 m_e} \frac{k_B T}{\mu} = A \frac{l^2}{l^2} \frac{1}{\tau_\hbar}
\]

\[
\mu = \left( \frac{\hbar^2}{m_e} \right) \left( \frac{1}{l^2_{\mu}} \right) \quad \text{compare:} \quad \mu \to E_F, \frac{1}{l_{\mu}} \to k_F
\]

According to the cuprate optical conductivity the momentum relaxation rate at optimal doping is:

\[
\frac{1}{\tau_{\exp}} \approx 2 \frac{k_B T}{\hbar}
\]

It follows for the **microscopic mean free path**: \( l \simeq l_{\mu} \simeq 10^{-9} \text{meter} \)
The problem with good strange metal “=“ bad strange metal.

Upon turning the good strange metal into a bad strange metal by raising temperature it is no longer true that the optical conductivity shows a low energy Drude behaviour:

Delacretaz, Gouteraux, Hartnoll, Karlsson, arXiv:1612.04381
Fluctuating charge order?
Doping dependence strange metal entropy.


\[ x < x_c, \quad T > T^* : \quad S = \gamma x_c \frac{x}{x_c} T \]
Is the viscosity in “covariant” strange metals Planckian?

**Holography:** viscosity is set by the BH horizon area, and is therefore universally Planckian.

**Dimensional analysis:** \[ \eta = f \tau_K \]

\[ \tau_K = A \frac{\hbar}{k_B T} \quad \text{but} \quad f = \mu \quad => \quad \eta \sim \frac{1}{T} \]