Quantum matter without quasiparticles: strange metals and black holes

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A quasiparticle is an “excited lump” in the many-electron state which responds just like an ordinary particle.
Quantum matter with quasiparticles:

The quasiparticle idea is the key reason for the many successes of quantum condensed matter physics:

- Fermi liquid theory of metals, insulators, semiconductors
- Theory of superconductivity (pairing of quasiparticles)
- Theory of disordered metals and insulators (diffusion and localization of quasiparticles)
- Theory of metals in one dimension (collective modes as quasiparticles)
- Theory of the fractional quantum Hall effect (quasiparticles which are `fractions’ of an electron)
Strange metal

Entangled electrons lead to “strange” temperature dependence of resistivity and other properties.

Quantum matter without quasiparticles

Figure: K. Fujita and J. C. Seamus Davis
Quantum matter without quasiparticles

Resistivity \( \sim \rho_0 + AT^\alpha \)

Superconductivity in Bad Metals

V. J. Emery and S. A. Kivelson
Phys. Rev. Lett. 74, 3253 – Published 17 April 1995

Beyond YBCO

$D^{-1} (s/cm^2)$

$T[K]$

No resistivity available to compare

Thermal diffusivity measurements by the group of A. Kapitulnik in $(Sm_{1.839}Ce_{0.161})_2CuO_4$
Quantum matter with quasiparticles:

- **Quasiparticles are additive excitations:** The low-lying excitations of the many-body system can be identified as a set \( \{ n_\alpha \} \) of quasiparticles with energy \( \varepsilon_\alpha \)

\[
E = \sum_\alpha n_\alpha \varepsilon_\alpha + \sum_{\alpha,\beta} F_{\alpha\beta} n_\alpha n_\beta + \ldots
\]

In a lattice system of \( N \) sites, this parameterizes the energy of \( \sim e^{\alpha N} \) states in terms of poly(\( N \)) numbers.
Quasiparticles eventually collide with each other. Such collisions eventually leads to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time. In a Fermi liquid, this time diverges as

$$\tau_{eq} \sim \frac{\hbar E_F}{(k_B T)^2}, \quad \text{as } T \to 0,$$

where $E_F$ is the Fermi energy.
Quantum Ising models

Qubits with states $|\uparrow\rangle_i$, $|\downarrow\rangle_i$, on the sites, $i$, of a regular lattice.

$$\sigma^z |\uparrow\rangle = |\uparrow\rangle \quad , \quad \sigma^z |\downarrow\rangle = -|\downarrow\rangle$$

$$\sigma^x |\uparrow\rangle = |\downarrow\rangle \quad , \quad \sigma^x |\downarrow\rangle = |\uparrow\rangle$$

$$H = -J \left( \sum_{\langle ij \rangle} \sigma^z_i \sigma^z_j + g \sum_i \sigma^x_i \right)$$

For $g = 0$, ground state is a ferromagnet:

$$|G\rangle = |\cdots \uparrow\cdots \cdots \rangle \quad \text{or} \quad |\cdots \downarrow\cdots \cdots \rangle$$

For $g \gg 1$, unique ‘paramagnetic’ ground state:

$$|G\rangle = |\cdots \rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\cdots \rangle$$

where

$$|\rightarrow\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle) \quad , \quad |\leftarrow\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle - |\downarrow\rangle)$$
Quantum Ising models

- In one dimension, quasiparticles exist even at the quantum critical point: there is a non-local transformations from the qubits to a system of free fermions.
In two dimensions, the “quantum critical” region provides us the first example of a system without a quasiparticle description. This is described by a strongly-coupled conformal field theory (CFT) in 2+1 dimensions, and dynamic properties cannot be computed accurately.
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Quantum matter **without** quasiparticles:

- If there are no quasiparticles, then

  \[ E \neq \sum_{\alpha} n_{\alpha} \varepsilon_{\alpha} + \sum_{\alpha, \beta} F_{\alpha \beta} n_{\alpha} n_{\beta} + \ldots \]
Quantum matter without quasiparticles:

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- If there are no quasiparticles, then
  \[ \tau_{eq} = \# \frac{\hbar}{k_B T} \]
Quantum matter without quasiparticles:

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- If there are no quasiparticles, then

\[ \tau_{\text{eq}} = \# \frac{\hbar}{k_B T} \]

- Systems without quasiparticles are the fastest possible in reaching local equilibrium, and all many-body quantum systems obey, as \( T \to 0 \)

\[ \tau_{\text{eq}} > C \frac{\hbar}{k_B T} . \]

- In Fermi liquids \( \tau_{\text{eq}} \sim 1/T^2 \), and so the bound is obeyed as \( T \to 0 \).
- This bound rules out quantum systems with e.g. \( \tau_{\text{eq}} \sim \hbar/(Jk_B T)^{1/2} \).
- There is no bound in classical mechanics (\( \hbar \to 0 \)). By cranking up frequencies, we can attain equilibrium as quickly as we desire.
A simple model of a metal with quasiparticles

Pick a set of random positions
A simple model of a metal with quasiparticles

Place electrons randomly on some sites
A simple model of a metal with quasiparticles

Electrons move one-by-one randomly
Electrons move one-by-one randomly

A simple model of a metal with quasiparticles
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A simple model of a metal with quasiparticles

$$H = \frac{1}{(N)^{1/2}} \sum_{i,j=1}^{N} t_{ij} c_i^\dagger c_j + \ldots$$

$$c_i c_j + c_j c_i = 0 \quad , \quad c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$$\frac{1}{N} \sum_i c_i^\dagger c_i = Q$$

$t_{ij}$ are independent random variables with $\overline{t_{ij}} = 0$ and $|t_{ij}|^2 = t^2$

Fermions occupying the eigenstates of a $N \times N$ random matrix
Let $\varepsilon_\alpha$ be the eigenvalues of the matrix $t_{ij}/\sqrt{N}$. The fermions will occupy the lowest $N_\mathcal{Q}$ eigenvalues, up to the Fermi energy $E_F$. The density of states is $\rho(\omega) = (1/N) \sum_\alpha \delta(\omega - \varepsilon_\alpha)$.
A simple model of a metal with quasiparticles

There are $2^N$ many body levels with energy

$$E = \sum_{\alpha=1}^{N} n_{\alpha} \varepsilon_{\alpha},$$

where $n_{\alpha} = 0, 1$. Shown are all values of $E$ for a single cluster of size $N = 12$. The $\varepsilon_{\alpha}$ have a level spacing $\sim 1/N$. 

Many-body level spacing $\sim 2^{-N}$

Quasiparticle excitations with spacing $\sim 1/N$
A simple model of a metal with quasiparticles

Let $\varepsilon_\alpha$ be the eigenvalues of the matrix $t_{ij}/\sqrt{N}$. The fermions will occupy the lowest $NQ$ eigenvalues, up to the Fermi energy $E_F$. The density of states is $\rho(\omega) = (1/N) \sum_\alpha \delta(\omega - \varepsilon_\alpha)$. 

\[ \varepsilon_\alpha \text{ level spacing } \sim 1/N \]
A simple model of a metal with quasiparticles

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Many-body level spacing $\sim 2^{-N}$

Quasiparticle excitations with spacing $\sim 1/N$
The Sachdev-Ye-Kitaev (SYK) model

Pick a set of random positions
Place electrons randomly on some sites
The SYK model

Entangle electrons pairwise randomly
The SYK model

Entangle electrons pairwise randomly
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Entangle electrons pairwise randomly

The SYK model
The SYK model

Entangle electrons pairwise randomly
The SYK model

Entangle electrons pairwise randomly
This describes both a strange metal and a black hole!
The SYK model

(See also: the “2-Body Random Ensemble” in nuclear physics; did not obtain the large $N$ limit; T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. 53, 385 (1981))

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell} c_i^\dagger c_j^\dagger c_k c_\ell - \mu \sum_i c_i^\dagger c_i$$

$$c_i c_j + c_j c_i = 0 \quad , \quad c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$$Q = \frac{1}{N} \sum_i c_i^\dagger c_i$$

$J_{ij;k\ell}$ are independent random variables with $\bar{J_{ij;k\ell}} = 0$ and $|\bar{J_{ij;k\ell}}|^2 = J^2$

$N \to \infty$ yields critical strange metal.

S. Sachdev and J. Ye, PRL 70, 3339 (1993)
The SYK model

There are $2^N$ many body levels with energy $E$, which do not admit a quasiparticle decomposition. Shown are all values of $E$ for a single cluster of size $N = 12$. The $T \to 0$ state has an entropy $S_{GPS} = Ns_0$ with

$$s_0 = \frac{G}{\pi} + \frac{\ln(2)}{4} = 0.464848\ldots$$

$$< \ln 2$$

where $G$ is Catalan’s constant, for the half-filled case $Q = 1/2$.

GPS: A. Georges, O. Parcollet, and S. Sachdev, PRB 63, 134406 (2001)

W. Fu and S. Sachdev, PRB 94, 035135 (2016)
Many-body level spacing \( \sim 2^{-N} = e^{-N \ln 2} \)

Non-quasiparticle excitations with spacing \( \sim e^{-N s_0} \)

There are \( 2^N \) many body levels with energy \( E \), which do not admit a quasiparticle decomposition. Shown are all values of \( E \) for a single cluster of size \( N = 12 \). The \( T \to 0 \) state has an entropy \( S_{GPS} = N s_0 \) with

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where \( G \) is Catalan's constant, for the half-filled case \( Q = 1/2 \).

No quasiparticles!

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W. Fu and S. Sachdev, PRB 94, 035135 (2016)
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- Low energy, many-body density of states
  \[ \rho(E) \sim e^{Ns_0} \sinh\left(\sqrt{2(E - E_0)}N \gamma\right) \]

  A. Georges, O. Parcollet, and S. Sachdev, PRB 63, 134406 (2001)
  D. Stanford and E. Witten, 1703.04612
  A. M. Garica-Garcia, J.J.M. Verbaarschot, 1701.06593
  D. Bagrets, A. Altland, and A. Kamenev, 1607.00694
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- Low temperature entropy
  \[ S = Ns_0 + N\gamma T + \ldots \]

A. Kitaev, unpublished
J. Maldacena and D. Stanford, 1604.07818
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- Low temperature entropy
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- At zero temperature, the fermion Green's function
  \[ G(\tau) \sim \tau^{-1/2} \]
  at large \( \tau \).

S. Sachdev and J. Ye, PRL 70, 3339 (1993)
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- \( T = 0 \) fermion Green’s function
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- \( T > 0 \) Green’s function has conformal invariance
  \[ G \sim (T/\sin(\pi k_B T \tau/\hbar))^{1/2} \]

A. Georges and O. Parcollet PRB 59, 5341 (1999)
The SYK model

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- The last property indicates \( \tau_{eq} \sim \hbar/(k_B T) \), and this has been found in a recent numerical study.

A. Eberlein, V. Kasper, S. Sachdev, and J. Steinberg, arXiv:1706.07803
The basic features can be determined by a simple power-counting. Considering for simplicity quantum criticality governs the entire low temperature "SYK cluster interaction of strength $10^{-18}$ has been generalized to SYK Prominent systems like the high-$T_c$-fermion interactions. Subsequent works have shown the system has a coherence temperature and random inter-cluster interactions.[10–18] We show the system has a coherence temperature and both electrical and thermal conductivity at all scales. We find study. The Sachdev-Ye-Kitaev (SYK) model describes a Landau quasiparticle interactions, and both electrical and thermal conductivity at all scales. We find study. The Sachdev-Ye-Kitaev (SYK) model describes a $0 \leftrightarrow 1$ transition metal to incoherent metal crossover in full detail, including thermodynamics, low temperature of quasi-particles. Here we study a lattice of complex-fermion SYK dots with random inter-site interactions between many "orbitals". We obtained in a double limit of infinite dimension and large $N$. This model is simpler, and does not require infinite dimensions. We and an incoherent metal. For $\bar{t} > t_c$ we are in the quasiparticle description. The Sachdev-Ye-Kitaev (SYK) model describes a heavy Fermi liquid to incoherent metal regime and the resistivity of a non-Fermi liquid

$$H = \sum_x \sum_{i<j,k<l} U_{ijkl} x c_{ix}^\dagger c_{jx}^\dagger c_{kx} c_{lx} + \sum_{\langle xx' \rangle} \sum_{i,j} t_{ij,xx'} c_{i,x}^\dagger c_{j,x',x'}$$

$$|U_{ijkl}|^2 = \frac{2U^2}{N^3} \quad |t_{ij,xx'}|^2 = \frac{t_0^2}{N}.$$
Title: A strongly correlated metal built from Sachdev-Ye-Kitaev models
Authors: Xue-Yang Song, Chao-Ming Jian, Leon Balents

Low ‘coherence’ scale

\[ E_c \sim \frac{t_0^2}{U} \]
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Low ‘coherence’ scale

\[ E_c \sim \frac{t_0^2}{U} \]

For \( E_c < T < U \), the resistivity, \( \rho \), and entropy density, \( s \), are

\[ \rho \sim \frac{\hbar}{e^2} \left( \frac{T}{E_c} \right), \quad s = s_0 \]
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Low ‘coherence’ scale

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For \( T < E_c \), the resistivity, \( \rho \), and entropy density, \( s \), are

\[ \rho = \frac{h}{e^2} \left[ c_1 + c_2 \left( \frac{T}{E_c} \right)^2 \right] \]

\[ s \sim s_0 \left( \frac{T}{E_c} \right) \]
Black holes have an entropy and a temperature, $T_H$.

- The entropy is proportional to their surface area.
The Hawking temperature, $T_H$, influences the radiation from the black hole at the very last stages of the ring-down (not observed so far). The ring-down (approach to thermal equilibrium) happens very rapidly in a time $\sim \frac{\hbar}{k_B T_H} = \frac{8\pi G M}{c^3} \sim 8$ milliseconds.
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- Black holes have an entropy and a temperature, $T_H$.
- The entropy is proportional to their surface area.
- They relax to thermal equilibrium in a time $\sim \hbar/(k_B T_H)$. 
AdS/CFT correspondence at zero temperature

Quantum gravity in 3+1 dimensions

Maximally supersymmetric Yang-Mills theory in 2+1 dimensions

\[ ds^2 = \left( \frac{L}{r} \right)^2 \left[ dr^2 - dt^2 + dx^2 + dy^2 \right] \]

Maldacena, Gubser, Klebanov, Polyakov, Witten
AdS/CFT correspondence at zero temperature

Quantum gravity in 3+1 dimensions

Minkowski

Maximally supersymmetric Yang-Mills theory in 2+1 dimensions

This spacetime is a solution of Einstein gravity with a negative cosmological constant

\[ S_E = \int d^4x \sqrt{-g} \left[ \frac{1}{2\kappa^2} \left( R + \frac{6}{L^2} \right) \right] \]

Maldacena, Gubser, Klebanov, Polyakov, Witten
There is a family of solutions of Einstein gravity which describe non-zero temperatures.

\[ ds^2 = \left( \frac{L}{r} \right)^2 \left[ \frac{dr^2}{f(r)} - f(r)dt^2 + dx^2 + dy^2 \right] \]

with \( f(r) = 1 - \left( \frac{r}{R} \right)^3 \)

AdS/CFT correspondence at non-zero temperatures

AdS\(_4\)-Schwarzschild black-brane

Maximally supersymmetric Yang-Mills at a temperature

\[ k_B T = \frac{3 \hbar}{4\pi R} \]

Maldacena, Gubser, Klebanov, Polyakov, Witten
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AdS$_4$-Schwarzschild black-brane

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Maximally supersymmetric Yang-Mills at a temperature $k_B T = \frac{3\hbar}{4\pi R}$.

Black hole horizon at a Hawking temperature $T_H = T$

Maldacena, Gubser, Klebanov, Polyakov, Witten
AdS/CFT correspondence at non-zero temperatures

AdS\(_4\)-Schwarzschild black-brane

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with \( f(r) = 1 - \left( \frac{r}{R} \right)^3 \)

Maximally supersymmetric Yang-Mills at a temperature

\[ k_B T = \frac{3\hbar}{4\pi R}. \]

Black hole entropy = Entropy of Yang-Mills theory

Maldacena, Gubser, Klebanov, Polyakov, Witten
Is there a holographic quantum gravity dual of the SYK model?
The leading low temperature properties of the Einstein-Maxwell theory holographically match those of the SYK model. The mapping applies when temperature \( \ll 1/(\text{size of } T^2) \).
The SYK model

- Low energy, many-body density of states
  \[ \rho(E) \sim e^{Ns_0} \]

- Low temperature entropy \( S = N s_0 \)

- \( T = 0 \) fermion Green’s function \( G(\tau) \sim \tau^{-1/2} \) at large \( \tau \).

- \( T > 0 \) Green’s function has conformal invariance
  \[ G \sim (T/\sin(\pi k_B T \tau/\hbar))^1/2 \]

- The last property indicates \( \tau_{eq} \sim \hbar/(k_B T) \), and this has been found in a recent numerical study.
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All these properties of the SYK model match those of the AdS\(_2\) horizon on Einstein-Maxwell theory.

S. Sachdev, PRL 105, 151602 (2010)
The SYK model

• Low energy, many-body density of states
  \( \rho(E) \sim e^{Ns_0} \sinh(\sqrt{2(E - E_0)N\gamma}) \)

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  \( G \sim (T/\sin(\pi k_B T \tau / \hbar))^{1/2} \)

Schwarzian theory of quantum gravity fluctuations also matches these corrections

D. Stanford and E. Witten, arXiv:1703.04612
Many-body quantum chaos

- Using holographic analogies, Shenker and Stanford introduced the “Lyapunov time”, $\tau_L$, the time over which a generic many-body quantum system loses memory of its initial state.

  S. Shenker and D. Stanford, arXiv:1306.0622
Many-body quantum chaos

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- A shortest-possible time to reach quantum chaos was established
  
  $$\tau_L \geq \frac{\hbar}{2\pi k_B T}$$
  
Many-body quantum chaos

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  S. Shenker and D. Stanford, arXiv:1306.0622

- A shortest-possible time to reach quantum chaos was established
  
  $\tau_L \geq \frac{\hbar}{2\pi k_B T}$


- The SYK model, and black holes in Einstein gravity, saturate the bound on the Lyapunov time
  
  $\tau_L = \frac{\hbar}{2\pi k_B T}$

  A. Kitaev, unpublished
  J. Maldacena and D. Stanford, arXiv:1604.07818
Quantum matter without quasiparticles:

- No quasiparticle decomposition of low-lying states:
  \[ E \neq \sum_{\alpha} n_\alpha \varepsilon_\alpha + \sum_{\alpha,\beta} F_{\alpha\beta} n_\alpha n_\beta + \ldots \]

- Thermalization and many-body chaos in the shortest possible time of order \( \hbar/(k_B T) \).
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- No quasiparticle decomposition of low-lying states:

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- These are also characteristics of black holes in quantum gravity.
Graphene
Graphene

$T(K)$

Quantum critical
Dirac liquid

Hole
Fermi liquid

Electron
Fermi liquid

$\mu < 0$

$\mu > 0$

$\sim \sqrt{n} (1 + \lambda \ln \Lambda \sqrt{n})$

$T(K)$

$n / 10^{12} m^{-2}$

M. Müller, L. Fritz, and S. Sachdev, PRB 78, 115406 (2008)
M. Müller and S. Sachdev, PRB 78, 115419 (2008)
Graphene

Predicted “strange metal” without quasiparticles

$T(K)$

Quantum critical Dirac liquid

Hole Fermi liquid

Electron Fermi liquid

$\mu < 0$

$\mu > 0$

$\frac{n}{10^{12}/m^2}$

M. Müller, L. Fritz, and S. Sachdev, PRB 78, 115406 (2008)
M. Müller and S. Sachdev, PRB 78, 115419 (2008)
Strange metal in graphene

Measurements of the Lorenz ratio $L$, between the thermal and electrical conductivities

Wiedemann-Franz obeyed

Strange metal in graphene

Measurements of the Lorenz ratio $L$, between the thermal and electrical conductivities

Wiedemann-Franz violated!
Two-terminal to keep a well-defined temperature profile

Nitride (hBN) \([\text{atures set the experimental window in which the DF and the electron-electron scattering rate. These two temper-}

Channels. This high temperature limit occurs when the potential, and even when the sample is globally neutral, it

Ritaries cause spatial variations in the local chemical po-

Tential, so that the thermal energy be larger than the local chemical po-

Neutrality point.

**FIG. 1.** To minimize disorder, the monolayer graphene samples –

\(r\) Elec. Conductivity (4 e

\(50 K\) (B)

\(10^{-10} \text{cm}^{-2}\)

\(\text{Thermal conductivity (red points) as a function of (C) gate voltage and (D) bath temperature}

All measurements are performed in a cryostat controlling

\(\Delta V (V)\) measured at various fixed temperatures for a

\(\text{representative device (see SM for all samples). From this, versus }

\(\text{ph}\)

\(\text{imp}\)

\(\text{dis}\)

\(\text{e}\)

\(\text{B}\)

\(\text{H}\)

\(\text{C}\)

\(\text{ Vladimir H. Istrate, M. Müller, and S. Sachdev, PRB 76, 144502 (2007) }

\(\text{S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB 76, 144502 (2007) }

\(\text{J. Crossno et al., Science 351, 1058 (2016) }

\(\text{Lorentz ratio } L = \kappa/(Ts) \)

\(= \frac{v_F^2 H T_{\text{imp}}}{T^2 \sigma_Q} \frac{1}{(1 + e^2 v_F^2 Q^2 T_{\text{imp}}/(H \sigma_Q))^2} \)

\(Q \rightarrow \text{electron density; } H \rightarrow \text{enthalpy density} \)

\(\sigma_Q \rightarrow \text{quantum critical conductivity} \)

\(T_{\text{imp}} \rightarrow \text{momentum relaxation time from impurities} \)