Strange metals and black holes

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Talk online: sachdev.physics.harvard.edu
Strange metals:
no quasiparticles

Ordinary metals:
quasiparticles

Black holes
Ordinary metals: quasiparticles

Strange metals: no quasiparticles

Black holes
Ordinary metals are shiny, and they conduct heat and electricity efficiently. Each atom donates electrons which are delocalized throughout the entire crystal.
Almost all many-electron systems are described by the quasiparticle concept: a quasiparticle is an “excited lump” in the many-electron state which responds just like an ordinary particle.
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 \( e_\alpha \)

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

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 lead to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time. In a Fermi liquid, this time diverges as

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

where $U$ is the strength of interactions and $E_F$ is the Fermi energy.
What are quasiparticles?

- Quasiparticles eventually collide with each other. Such collisions eventually lead to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time. In a Fermi liquid, this time diverges as

\[ \tau_{eq} \sim \frac{\hbar U^2 / E_F}{(k_B T)^2} , \text{ as } T \to 0, \]

where \( U \) is the strength of interactions and \( E_F \) is the Fermi energy.

- Similarly, a quasiparticle model implies a resistivity

\[ \rho = \frac{m^*}{n e^2} \frac{1}{\tau} \sim T^2 \text{ with } \tau \sim \tau_{eq} \]
• These times are much longer than the ‘Planckian time’ $\hbar/(k_B T)$, which we will find in systems without quasiparticle excitations.

\[ \tau \sim \tau_{eq} \gg \frac{\hbar}{k_B T}, \quad \text{as } T \to 0. \]
Ordinary metals: quasiparticles

Strange metals: no quasiparticles

Black holes
Twisted bilayer graphene

Cao et al., Nature 556, 80 (2018)
Twisted bilayer graphene

Cao et al., arXiv:1901.03710
High temperature superconductors

$\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$
Universal $T$-linear resistivity and Planckian dissipation in overdoped cuprates

A. Legros$^{1,2}$, S. Benhabib$^3$, W. Tabis$^{3,4}$, F. Laliberté$^1$, M. Dion$^1$, M. Lizaire$^1$, B. Vignolle$^3$, D. Vignolles$^3$, H. Raffy$^5$, Z. Z. Li$^5$, P. Auban-Senzier$^5$, N. Doiron-Leyraud$^1$, P. Fournier$^{1,6}$, D. Colson$^2$, L. Taillefer$^{1,6}$ and C. Proust$^{3,6}$

Planckian dissipation and scale invariance in a quantum-critical disordered pnictide

Yasuyuki Nakajima$^{1,2}$, Tristin Metz$^2$, Christopher Eckberg$^2$, Kevin Kirshenbaum$^2$, Alex Hughes$^2$, Renxiong Wang$^2$, Limin Wang$^2$, Shanta R. Saha$^2$, I-Lin Liu$^{2,3,4}$, Nicholas P. Butch$^{2,4}$, Zhonghao Liu$^{5,6}$, Sergey V. Borisenko$^5$, Peter Y. Zavalij$^7$ and Johnpierre Paglione$^{2,8}$

Strange metal in magic-angle graphene with near Planckian dissipation

Yuan Cao$^1$, * Debanjan Chowdhury$^1$, * Daniel Rodan-Legrain$^1$, Oriol Rubies-Bigordà$^1$, Kenji Watanabe$^2$, Takashi Taniguchi$^2$, T. Senthil$^1$, † and Pablo Jarillo-Herrero$^1$, †

Bad metallic transport in a cold atom Fermi-Hubbard system

*Peter T. Brown$^1$, Debayan Mitra$^1$, Elmer Guardado-Sanchez$^1$, Reza Nourafkan$^2$, Alexis Reymbaut$^2$, Charles-David Hébert$^2$, Simon Bergeron$^2$, A.-M. S. Tremblay$^{2,3}$, Jure Kokalj$^{4,5}$, David A. Huse$^1$, Peter Schauß$^1$, Waseem S. Bakr$^{1,6}$

*Corresponding author.
†Present address.
§Further information and author contributions are available in the Supplementary Information.
Remarkable recent observation of ‘Planckian’ strange metal transport in cuprates, pnictides, magic-angle graphene, and ultracold atoms: the resistivity, $\rho$, is

$$\rho = \frac{m^*}{ne^2} \frac{1}{\tau}$$

with a universal scattering rate

$$\frac{1}{\tau} \approx \frac{k_B T}{\hbar},$$

independent of the strength of interactions!
A comparison of the measured slope of the linear resistivity vs Planckian limit in seven materials.

\[
\frac{1}{\tau} = \alpha \frac{k_B T}{h}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>(n) ((10^{27} \text{ m}^{-3}))</th>
<th>(m^*) ((m_0))</th>
<th>(A_1 / d) ((\Omega / K))</th>
<th>(h / (2e^2 T_F)) ((\Omega / K))</th>
<th>(\alpha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi2212</td>
<td>(p = 0.23)</td>
<td>6.8</td>
<td>8.4 ± 1.6</td>
<td>8.0 ± 0.9</td>
<td>7.4 ± 1.4</td>
</tr>
<tr>
<td>Bi2201</td>
<td>(p \sim 0.4)</td>
<td>3.5</td>
<td>7 ± 1.5</td>
<td>8 ± 2</td>
<td>8 ± 2</td>
</tr>
<tr>
<td>LSCO</td>
<td>(p = 0.26)</td>
<td>7.8</td>
<td>9.8 ± 1.7</td>
<td>8.2 ± 1.0</td>
<td>8.9 ± 1.8</td>
</tr>
<tr>
<td>Nd-LSCO</td>
<td>(p = 0.24)</td>
<td>7.9</td>
<td>12 ± 4</td>
<td>7.4 ± 0.8</td>
<td>10.6 ± 3.7</td>
</tr>
<tr>
<td>PCCO</td>
<td>(x = 0.17)</td>
<td>8.8</td>
<td>2.4 ± 0.1</td>
<td>1.7 ± 0.3</td>
<td>2.1 ± 0.1</td>
</tr>
<tr>
<td>LCCO</td>
<td>(x = 0.15)</td>
<td>9.0</td>
<td>3.0 ± 0.3</td>
<td>3.0 ± 0.45</td>
<td>2.6 ± 0.3</td>
</tr>
<tr>
<td>TMTSF</td>
<td>(P = 11 \text{ kbar})</td>
<td>1.4</td>
<td>1.15 ± 0.2</td>
<td>2.8 ± 0.3</td>
<td>2.8 ± 0.4</td>
</tr>
</tbody>
</table>

Slope of \(T\)-linear resistivity vs Planckian limit in seven materials.

The Sachdev-Ye-Kitaev (SYK) model

Pick a set of random positions
The SYK model

Place electrons randomly on some sites.
The SYK model

Place electrons randomly on some sites
The SYK model

Place electrons randomly on some sites
The SYK model

Entangle electrons pairwise randomly
Entangle electrons pairwise randomly
The SYK model

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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))

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

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

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

$U_{ij;kl}$ are independent random variables with $\overline{U_{ij;kl}} = 0$ and $|U_{ij;kl}|^2 = U^2$

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

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

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))

\[
H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} U_{ij;kl} c_{i}^{\dagger} c_{j}^{\dagger} c_{k} c_{\ell} + e \sum_{i} c_{i}^{\dagger} c_{i}
\]

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\]

$U_{ij;kl}$ are independent random variables with $\overline{U_{ij;kl}} = 0$ and $|U_{ij;kl}|^2 = U^2$

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

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

The large $N$ limit is given by the sum of “melon” Feynman graphs

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

There is a one-parameter family of critical solutions with varying $e/U$, yielding different $0 < Q < 1$.

For long (imaginary) times $\tau > 0$

$$\langle c_i(\tau) c_i^\dagger(0) \rangle \sim e^{-2\pi \varepsilon T \tau} \times \left( \frac{T/U}{\sin(\pi T \tau)} \right)^{1/2}$$

In a Fermi liquid,

$$\langle c_i(\tau) c_i^\dagger(0) \rangle \sim \frac{T}{\sin(\pi T \tau)}$$

S. Sachdev and J. Ye,
PRL 70, 3339 (1993)
A. Georges and O. Parcollet
PRB 59, 5341 (1999)
The complex SYK model

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For long (imaginary) times $\tau > 0$

$$\langle c_i(\tau)c_i^\dagger(0) \rangle \sim e^{-2\pi\mathcal{E}T\tau} \times \left( \frac{T/U}{\sin(\pi T\tau)} \right)^{1/2}$$

Characteristic Planckian time scale $\sim \hbar/(k_B T)$ for ‘dissipation’ of excitations.

A. Eberlein, V. Kasper, S. Sachdev, and J. Steinberg, PRB 96, 205123 (2017)
The complex SYK model

There is a one-parameter family of critical solutions with varying $e/U$, yielding different $0 < Q < 1$.

For long (imaginary) times $\tau > 0$

$$\langle c_i(\tau)c_i^\dagger(0) \rangle \sim e^{-2\pi\mathcal{E}T\tau} \times \left( \frac{T/U}{\sin(\pi T\tau)} \right)^{1/2}$$

The exponential pre-factor determines the particle-hole asymmetry, and $\mathcal{E} = 0.41(e/U)$ from a numerical solution.
The SYK model

\[ -\text{Im} G^R(\omega) \left\{ \mathcal{E} = 0 \right\} \]

\[ \mathcal{E} = \mathbb{C} \frac{e}{U} \]

Planckian dynamics with peak width \( \sim k_B T / \hbar \) and independent of \( U \)

A. Georges and O. Parcollet PRB 59, 5341 (1999)
S. Sachdev, PRX 5, 041025 (2015)
The SYK model

There are $2^N$ many body levels with energy $E$. Shown are all values of $E$ for a single cluster of size $N = 12$. The $T \to 0$ state has an entropy $S_{GPS} = Ns_0$, where $s_0 < \ln 2$ is determined by integrating

$$\frac{ds_0}{dQ} = 2\pi\varepsilon .$$

At $Q = 1/2$,

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

where $G$ is Catalan’s constant.
The SYK model

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\[ \frac{ds_0}{dQ} = 2\pi E. \]

At $Q = 1/2$,

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

where $G$ is Catalan’s constant.
All electrons in the (flat band) SYK model have the same $e$

In a more realistic metal, the electrons have a dispersion $e_k (k$ is momentum), and $e_k = 0$ is the Fermi surface.
Flat band metal

All electrons have the same \( e \)

\[
\mathcal{E} = \mathbb{C} \frac{e}{U}
\]

\(-\text{Im} G_R^R(\omega)\) \( \mathcal{E} = 0 \)

\( \mathcal{E} = -0.26 \)

Planckian dynamics with peak width \( \sim k_B T/\hbar \)

and independent of \( U \)

A. Georges and O. Parcollet PRB 59, 5341 (1999)
S. Sachdev, PRX 5, 041025 (2015)
Planckian metal ansatz with some dispersion

Electrons ‘remember’ their momentum, and have a SYK spectral function according to their $e_k$

$$\mathcal{E}_k = C \frac{e_k}{U}$$

Planckian dynamics with peak width $\sim k_B T / \hbar$ and independent of $U$

A. A. Patel and S. Sachdev, PRL 123, 066601 (2019)
Planckian metal ansatz with some dispersion

Electrons ‘remember’ their momentum, and have a SYK spectral function according to their $e_k$

\[ \mathcal{E}_k = \mathbb{C} \frac{e_k}{U} \]

\[ \mathcal{E}_k = -0.26 \]

Planckian dynamics with peak width $\sim k_B T / \hbar$ and independent of $U$

Flat band metal

For a dispersionless SYK model

\[ \langle c_i(\tau) c_i^\dagger(0) \rangle \sim e^{- (e/U) 2\pi C T \tau} \times \left( \frac{T/U}{\sin(\pi T \tau)} \right)^{1/2} \]

S. Sachdev and J. Ye, PRL 70, 3339 (1993)
A. Georges and O. Parcollet, PRB 59, 5341 (1999)
Planckian metal ansatz with some dispersion

For a strongly-interacting metal with underlying quasiparticle dispersion $e_k$ ($k$ is the momentum)

$$\langle c_k(\tau)c_k^\dagger(0) \rangle \sim e^{-(e_k/U)2\pi\mathcal{C}T\tau} \times \left( \frac{T/U}{\sin(\pi T\tau)} \right)^{1/2}$$
Planckian metal ansatz with some dispersion

For a strongly-interacting metal with underlying quasiparticle dispersion $e_k$ ($k$ is the momentum)

$$\langle c_k(\tau)c_k^\dagger(0) \rangle \sim e^{-(e_k/U)2\pi\Omega T\tau} \times \left( \frac{T/U}{\sin(\pi T\tau)} \right)^{1/2}$$

At $e_k = 0$ we have a ‘remnant Fermi surface’ with a particle-hole symmetric spectral function.
Planckian metal ansatz with some dispersion

For a strongly-interacting metal with underlying quasiparticle dispersion \( e_k \) \((k \text{ is the momentum})\)

\[
\langle c_k(\tau) c_k^\dagger(0) \rangle \sim e^{-\frac{(e_k/U)2\pi C T \tau}{\sin(\pi T \tau)}} \times \left( \frac{T/U}{\sin(\pi T \tau)} \right)^{1/2}
\]

No free parameters—everything is determined by the (underlying) quasiparticle dispersion \( e_k \), and the interaction strength \( U \).
Resistivity of a Planckian metal as $T \to 0$

From the Kubo formula, we obtain the resistivity

$$\rho = \frac{m^*}{ne^2} 2.71\mathcal{C} \frac{k_B T}{\hbar}$$

where the Fermi surface is defined by $e_k = 0$, $v_F = \nabla_k e_k$ on the Fermi surface, and

$$m^* = \frac{dV_{FS}}{\int_{FS} |v_F|}$$

with $d$ the spatial dimensionality, and $V_{FS}$ is the volume enclosed by the Fermi surface. For a circular Fermi surface, this is the usual $m^*$.

Note that all explicit dependence on $U$ has cancelled out!

Choosing $\mathcal{C} = 0.41$ as in the SYK model, we have the prefactor $2.71\mathcal{C} = 1.11$. 

A. A. Patel and S. Sachdev, PRL 123, 066601 (2019)
Resonant SYK model

\[ H = \frac{1}{(2N)^{3/2}} \sum_{k_a} \sum_{\alpha, \beta, \gamma, \delta = 1}^{N} U_{\alpha \beta; \gamma \delta}(k_a) c_{k_1 \alpha}^{\dagger} c_{k_2 \beta}^{\dagger} c_{k_3 \gamma} c_{k_4 \delta} \]

\[ + \sum_{k \alpha} e_k c_{k \alpha}^{\dagger} c_{k \alpha} \]

\[ U_{\alpha \beta; \gamma \delta}(k_a) \text{ is a random function of } \alpha \beta \gamma \delta \]
\[ e_k \text{ has a bandwidth } W. \]

A model with weaker \( W \lesssim U \), but with a resonance condition (supported by a RG argument).
This leads to a solution which obeys the Planckian ansatz as \( T \to 0 \).

\[ U(k_1, k_2, k_3, k_4) U^*(k_5, k_6, k_7, k_8) = U^2 \left[ \delta(k_1 + k_2 - k_3 - k_4 - k_5 - k_6 + k_7 + k_8) \right] \]
\[ \times \left[ \delta(e_{k_1} + e_{k_2} - e_{k_3} - e_{k_4}) + \delta(e_{k_5} + e_{k_6} - e_{k_7} - e_{k_8}) \right] \]

This implies off-site interactions with correlations which decay with a power-law in space.
Ordinary metals: quasiparticles

Strange metals: no quasiparticles

Black holes
Black Holes

Objects so dense that light is gravitationally bound to them.

In Einstein’s theory, the region inside the black hole horizon is disconnected from the rest of the universe.
Quantum Entanglement across a black hole horizon
Quantum Entanglement across a black hole horizon
Quantum Entanglement across a black hole horizon
Quantum Entanglement across a black hole horizon

There is quantum entanglement between the inside and outside of a black hole.
Hawking used this to show that black hole horizons have an entropy and a temperature (because to an outside observer, the state of the electron inside the black hole is an unknown).
Quantum Black holes

- Black holes have an entropy and a temperature, $T_H$
- The entropy is proportional to their surface area.

J. D. Bekenstein, PRD 7, 2333 (1973)
• The ring-down is predicted by General Relativity to happen in a time $\frac{8\pi GM}{c^3} \sim 8$ milliseconds.
The ring-down is predicted by General Relativity to happen in a time \( \frac{8\pi GM}{c^3} \sim 8 \text{ milliseconds} \). Curiously, this happens to equal \( \frac{\hbar}{k_B T_H} \), so the ring down can also be viewed as the approach of a quantum system to thermal equilibrium at the fastest possible rate!
• 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 Planckian time $\sim \hbar/(k_B T_H)$.
Holography: Quantum black holes “look like” quantum many-particle systems without quasiparticle excitations, residing “on” the surface of the black hole.

- 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 Planckian time $\sim \hbar/(k_B T_H)$.

Work with a theory of Maxwell’s electromagnetism and Einstein’s general relativity. Include a negative cosmological constant, and examine black hole solutions with a net charge.
Work with a theory of Maxwell’s electromagnetism and Einstein’s general relativity. Include a negative cosmological constant, and examine black hole solutions with a net charge.

Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space and one time dimension.
The near-horizon region of a charged black hole has the geometry of (1+1)-dimensional anti-de Sitter spacetime. By holography, this should map to a zero-dimensional quantum system: this turns out to be the SYK model.
SYK model and charged black holes

\[
\text{AdS}_2 \times S^2
\]

\[
ds^2 = \frac{(d\zeta^2 - dt^2)}{\zeta^2} + d\vec{x}^2
\]

Gauge field: \( A = \left(\frac{\mathcal{E}}{\zeta}\right) dt \)

\[
\zeta = \infty
\]

\[
\mathcal{S}^2
\]

\[
\vec{x}
\]

Bekenstein-Hawking entropy of \(\text{AdS}_2\) horizon at \( T = 0 \) $\Leftrightarrow$ \( N s_0 \) entropy of SYK model.

\[
\frac{ds_0}{dQ} = 2\pi \mathcal{E}
\]
can be obtained from the Einstein equations for the black hole, and the quantum theory of the SYK model, and \( \mathcal{E} \) determines identical fermion spectral functions.

Remarkably, the correspondence between charged black holes and the SYK model also holds for the leading fluctuations at higher temperatures: both are described by a ‘Schwarzian’ theory with emergent SL(2,R) and U(1) gauge symmetries. For the black hole, the Schwarzian describes the fluctuations of the boundary between AdS$_2$ and AdS$_4$. 

\[
    ds^2 = R_2^2 \frac{(d\zeta^2 - dt^2)}{\zeta^2} + R_h^2 d\Omega_2^2
\]

Gauge field: \( A = \frac{\mathcal{E}}{\zeta} dt \)
Main result

A. Kitaev (2015)
J. Maldacena, D. Stanford, and Zhenbin Yang, PTEP 12C104 (2016)
J. Engelsoy, T.G. Mertens, and H. Verlinde, JHEP 1607 (2016) 139
P. Chaturvedi, Yingfei Gu, Wei Song, Boyang Yu, arXiv:1808.08062
S. Sachdev, arXiv:1902.04078
Main result

SYK model of fermions with random interactions of mean-square-value $U$, with total fermion number $Q$, at temperatures $T \ll U$
Main result

SYK model of fermions with random interactions of mean-square-value $U$, with total fermion number $Q$, at temperatures $T \ll U$

and

Charged black holes in 3+1 dimensions of radius $R_h$, with total charge $Q$, at temperatures $T \ll 1/R_h$

are described by a common low energy quantum theory in 0 + 1 dimensions
**Main result**

The common low $T$ path integral is $\mathcal{Z} = \int \mathcal{D}f \mathcal{D}\phi e^{-I}$. This can be exactly evaluated, and the action is

\[
I = -s_0 + \int_0^{1/T} d\tau \left\{ \frac{K}{2} \left( \frac{\partial \phi}{\partial \tau} + i(2\pi\mathcal{E}T) \frac{\partial f}{\partial \tau} \right)^2 - \frac{\gamma}{4\pi^2} \text{Sch}[\tan(\pi T f(\tau)), \tau] \right\},
\]

where $f(\tau)$ is a monotonic reparameterization of the temporal circle with

$f(\tau + 1/T) = f(\tau) + 1/T$,

$\phi$ is a phase conjugate to the charge density with

$\phi(\tau + 1/T) = \phi(\tau) + 2\pi n$, $n$ integer,

$\text{Sch}[g[\tau], \tau]$ is the Schwarzian derivative of $g(\tau)$.

The couplings are related to the entropy $S(T, Q)$ and the chemical potential $\mu$ via

\[
S(T \to 0, Q) = s_0 + \gamma T, \quad K = \left( \frac{dQ}{d\mu} \right)_{T \to 0}, \quad 2\pi\mathcal{E} = \frac{ds_0}{dQ}
\]
Main result

- Closely related to, but not the usual AdS/CFT correspondence, which involves only neutral black holes at $T > 0$.

- Unlike the AdS/CFT correspondence, both sides of the duality are fully solvable. This has enabled numerous recent studies of black holes quantum information.
Quantum matter without quasiparticles

- Planckian dynamics (i.e. fastest possible local thermalization in a time $\hbar/(k_B T)$) is realized in the ‘solvable’ SYK models.

- Planckian SYK ansatz yields resistivity $\sigma \sim (m^\ast/ne^2)(k_B T/\sim)$; this ansatz is realized by a ‘resonant’ SYK model in momentum space.

- Black holes thermalize in a Planckian time $\sim \sim/k_B T_H$, where $T_H$ is the Hawking temperature.

- A Schwarzian theory of a time reparameterization mode, with SL(2,R) symmetry, (along with a phase fluctuating mode) describes the quantum dynamics of
  - the SYK models
  - black holes with near-extremal AdS$_2$ horizons
Quantum matter without quasiparticles

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Quantum matter without quasiparticles

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