Holographic quantum matter

4. Planckian dynamics

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More quantitatively, holographic methods lead to straightforward computation of *dynamical* response, such as conductivity $\sigma(\omega, k)$, in strongly correlated metallic phases.

$\sigma \sim T^{\alpha}$ is *not* universal in finite-density holographic matter.

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In a nutshell, we expect

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where m is effective quasiparticle mass (not generally well-defined), n is electron density, and

$$\frac{1}{\tau} = \frac{1}{\tau_{\mathrm{el-el}}} + \frac{1}{\tau_{\mathrm{el-ph}}} + \frac{1}{\tau_{\mathrm{el-imp}}}$$

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is the **momentum-relaxing** electron scattering rate.

In an ordinary metal, we expect that:

$$\frac{1}{\tau_{\text{el}-\text{el}}} \sim T^2 \qquad \frac{1}{\tau_{\text{el}-\text{ph}}} \sim \begin{cases} T^{d+2} & \text{low } T \\ T & \text{high } T \end{cases} \qquad \frac{1}{\tau_{\text{el}-\text{imp}}} \sim T^0$$

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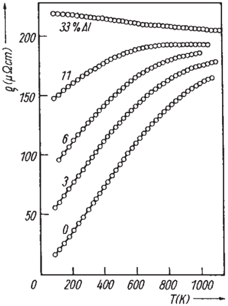
In e.g. alloy $Ti_{1-x}Al_x$, MIR bound works!
[Mooij; *Phys. Stat. Sol.* **A17** 521 (1973)]

$$\rho \lesssim \frac{m}{ne^2}\frac{v_F}{a} \sim \frac{p_F}{k_F^d e^2 a} \sim \frac{\hbar}{e^2}\frac{1}{k_F^{d-1} a}.$$



Why does nature care about applicability of kinetic theory? 🤔

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$$\tau \gtrsim \frac{\hbar}{k_{\mathrm{B}}\,T}.$$

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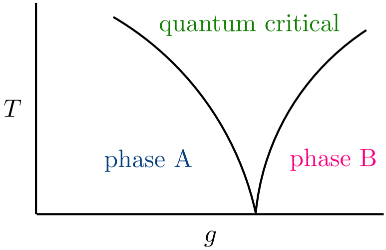
In a metal, there are other energy scales (E_{F}!). This is a non-trivial conjecture about many-body quantum systems.

Many strongly correlated metals appear to have a **quantum critical fan** in the phase diagram:



In the quantum critical fan, one often finds

[Hartnoll, Mackenzie; *Rev. Mod. Phys.* **94** 041002 (2022)]

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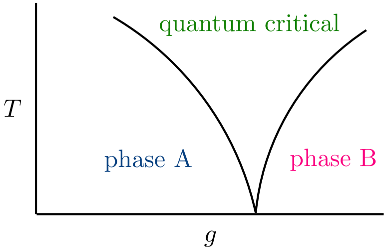

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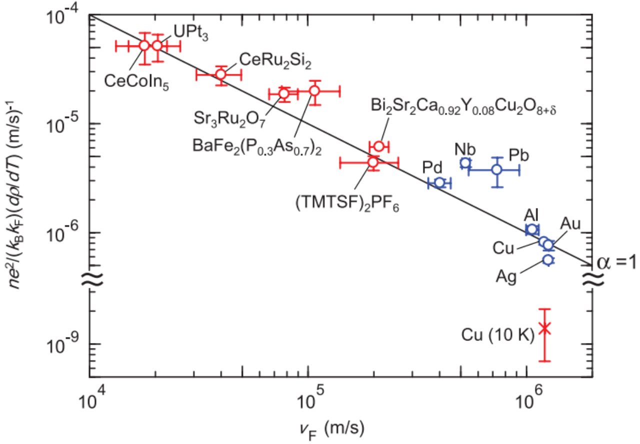
Similar scaling also holds in 2d semiconductors.

[Ahn, Das Sarma; *Phys. Rev.* **B106** 155427 (2022)]

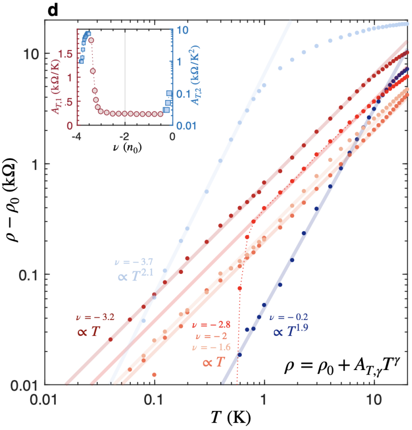
Planckian dynamics in experiments

This Planckian scaling is highly universal across different materials, with very likely different microscopic origins for resistivity.



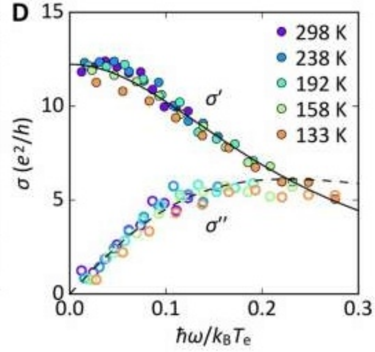
[Bruin, Sakai, Perry, Mackenzie; *Science* **339** 804 (2013)]

Subtracting off impurity scattering (T-independent contribution), one finds Planckian resistivity to *very low* temperatures in magic angle twisted bilayer graphene. Unlikely that phonon scattering can explain.



[Jaoui++; *Nature Phys.* **18** 633 (2022)]

A Planckian time scale also arises in *optical conductivity* of charge-neutral graphene. [Gallagher++; *Science* **364** 125 (2019)]



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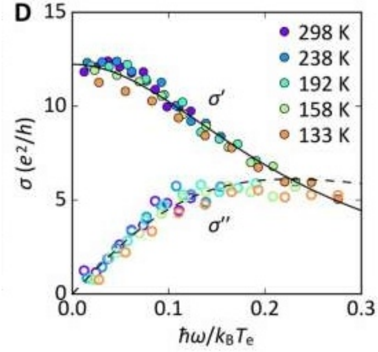

This case is not as mysterious – system is (a little) analogous to charge neutral CFT, where Planckian time scale is by default the only one that can show up.

Non-holographic Planckian dynamics

Some non-AdS/CMT theoretical observations of Planckian scaling:

- 1+1d CFT
- 2+1d CFT

[Witczak-Krempa, Sorensen, Sachdev; *Nature Phys.* **10** 361 (2014)]

- critical Fermi surface (N fermions coupled to U(1) gauge field)

[Patel, Sachdev; *PNAS* **114** 1844 (2017)]

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  [Patel, Sachdev; *PNAS* **114** 1844 (2017)]
- SYK models [Maldacena, Stanford; *Phys. Rev.* **D94** 106002 (2016)]

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Given bulk scalar equation

$$\nabla_a \nabla^a \phi = m^2 \phi = \frac{1}{\sqrt{-g}} \partial_r \left(\sqrt{-g} g^{rr} \partial_r \phi \right) + \omega^2 |g^{tt}| \phi - k^2 g^{xx} \phi,$$

for what (ω, k) is there an *infalling* solution

$$\phi \sim \mathrm{e}^{\mathrm{i}(kx - \omega t)} \left[0 \cdot r^{d+1-\Delta} + r^{\Delta} + \cdots \right]$$

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Study numerically in black hole (AdS-Schwarzchild) background:

$$\mathrm{d}s^2 = \frac{1}{r^2} \left[\frac{\mathrm{d}r^2}{f(r)} - f(r) \mathrm{d}t^2 + \mathrm{d}\mathbf{x}_d^2 \right].$$

In holography, one finds a discrete quasinormal mode spectrum:

[Horowitz, Hubeny; *Phys. Rev.* **D62** 024027 (2000)]

$$\omega_n \sim (\pm 1 - \mathrm{i})(n + c)\,T \quad (n = 0, 1, 2, \ldots).$$

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In field theory, we then expect:

$$G^{\mathrm{R}}_{\mathcal{O}\mathcal{O}} \sim \sum_n \frac{c_n}{\omega - \omega_n},$$

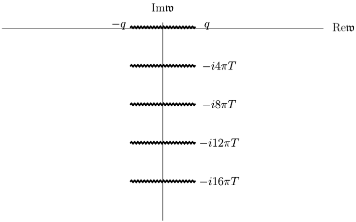
implying that in real time,

$$\langle \mathcal{O}(t)\mathcal{O}(0)\rangle \sim \mathrm{e}^{-cTt}\cos(cTt).$$

This decays on the Planckian time scale!

It is also useful to study how the spectrum of quasinormal modes changes in a field theory from weak to strong coupling:

[Grozdanov, Kaplis, Starinets; *JHEP* **07** 151 (**2016**)]



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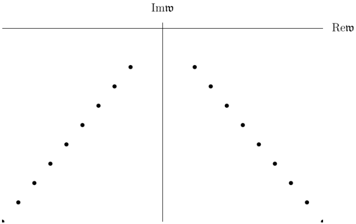

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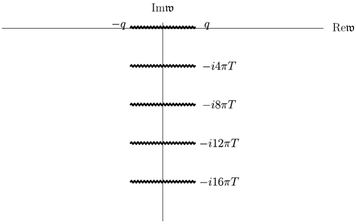

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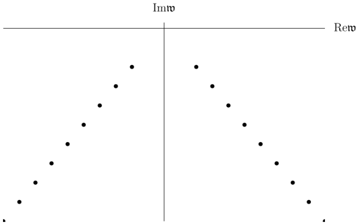
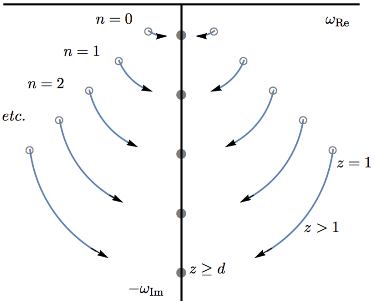


strong coupling

Adding "weak coupling" corrections to holography, inspired by string theory, poles begin to cluster together and move towards $\mathrm{Im}(\omega_n) \to 0$.

Similar phenomena hold for Lifshitz ($z > 1$) geometries!

[Sybesma, Vandoren; *JHEP* **05** 021 (**2015**)]



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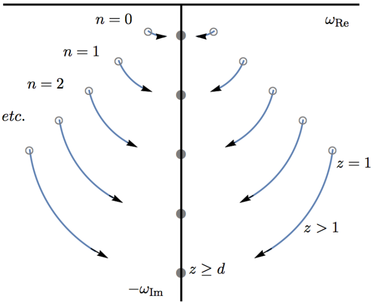

We saw before that "universal emblackening factor" captures $T \to 0$ black holes in AdS/CMT. Quasinormal modes very generically have Planckian decay! 👍

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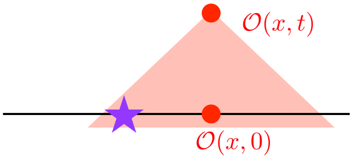

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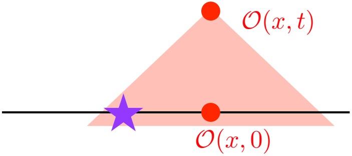


After time t, it's detected by local operators far away:

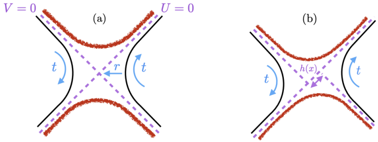
$$[\mathcal{O}(x,t), A] \neq 0.$$

Out-of-time-ordered correlators quantify this. Intuitively,

$$\mathrm{tr}\left([\mathcal{O}(x,t), A]^2\right) \to \langle \mathcal{O}(x,t) A \mathcal{O}(x,t) A \rangle_\beta$$

In holography, OTOCs of heavy operators are calculated by studying gravitational shockwaves near two-sided black hole horizons.

[Roberts, Shenker, Stanford; *JHEP* **03** 051 (**2015**)]



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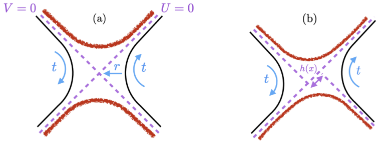

The physical outcome is that

$$\langle \mathcal{O}_0(t)\mathcal{O}_x\mathcal{O}_0(t)\mathcal{O}_x\rangle_\beta \sim 1 - \frac{1}{N^2}\mathrm{e}^{\lambda_\mathrm{L}(t-|x|/v_\mathrm{B})}$$

where Lyapunov exponent λ_L and butterfly velocity v_B are

$$\lambda_\mathrm{L} = 2\pi T, \quad , v_\mathrm{B} \sim T^{1-1/z}.$$

The Lyapunov exponent

[Maldacena, Shenker, Stanford; *JHEP* **08** 106 (**2016**)]

$$\lambda_{\mathrm{L}} \leq 2\pi T$$

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[Roberts, Swingle; *Phys. Rev. Lett.* **117** 091602 (2016)]

$$v_{\mathrm{B}} \sim T^{1-1/z}$$

is also determined by physics at the horizon.

So far, the Planckian rate T (or time T^{-1}) shows up in:

- black hole quasinormal modes, i.e.

$$G^{\mathrm{R}}_{\mathcal{O}\mathcal{O}}(t) \gtrsim \mathrm{e}^{-cTt}.$$

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Not *generically.* We've already seen that σ_{dc} can have complicated T-dependence in holography. ☹

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[Hartnoll; *Nature Phys.* **11** 54 (2015)]

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σ is calculated near the horizon in holographic models, as is v_B, suggesting that

$$D \sim \frac{v_\mathrm{B}^2}{T}$$

is a generic holographic result.

[Blake; *Phys. Rev. Lett.* **117** 091601 (2016)]

In many models one does find

$$D \sim \frac{v_{\mathrm{B}}^2}{T}.$$

Usually in **thermal diffusivity**: [Blake; *Phys. Rev.* **D94** 086014 (2016)]

- AdS_2 horizons (breakdown of naive scaling)
  [Blake, Davison, Sachdev; *Phys. Rev.* **D96** 106008 (2017)]
- SYK chains [Gu, Qi, Stanford; *JHEP* **05** 125 (**2017**)]
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But there are also some exceptions:

- holographic charge diffusion with certain exponents [Davison, Gentle, Goutéraux; *Phys. Rev.* **D100** 086020 (2019)]
- spatial inhomogeneity [Lucas, Steinberg; *JHEP* **10** 143 (**2016**)]

Planckian bounds in general?

Hard to find universal Planckian bounds:

- transport bounds will have exceptions:

$$\rho \to \infty \quad \text{near metal-insulator transition}$$

- correlation function decay

$$\langle \mathcal{O}(t)\mathcal{O}(0)\rangle \sim \mathrm{e}^{-t/\tau_{\mathrm{imp}}}$$

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Is there a Planckian bound on operator growth in effective low-energy subspace? [Lucas; *Phys. Rev. Lett.* **122** 216601 (2019)]

Similar bounds exist in low density (of conserved charge) subspaces.

[Chen, Gu, Lucas; *SciPost Phys.* **9** 071 (2020)]

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Consider a **quantum quench** protocol, in which

$$H(t) = H_0\Theta(-t) + H_1\Theta(+t).$$

Suppose that for $t < 0$,

$$|\psi(t < 0)\rangle = |\text{g.s. of } H_0\rangle.$$

What happens for $t > 0$?

We propose that $|\psi(t<0)\rangle$ is a highly excited state of H_1, so it will look **thermal** for a local observable $\mathcal{O}$:

$$\langle\psi(t)|\mathcal{O}|\psi(t)\rangle \sim \frac{\mathrm{tr}\left(\mathrm{e}^{-\beta H}\mathcal{O}\right)}{\mathrm{tr}\left(\mathrm{e}^{-\beta H}\right)}.$$

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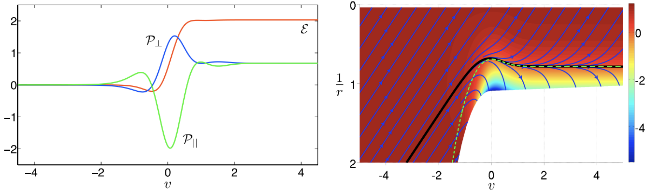
This can be studied using numerical general relativity!

[Chesler, Yaffe; *Phys. Rev. Lett.* **102** 211601 (2009)]



The **AdS-Vaidya** metric provides an analytically solvable model of black hole formation:

[Bhattacharyya, Minwalla; *JHEP* **09** 034 (**2009**)]

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Our naive quench protocol suggests instant thermalization?

$$F(v) = r_0^{-d-1}\Theta(v)$$

Local correlators will abruptly relax at Planckian times.

When is holography useful?

Holographic models naturally give us:

- access to real time dynamics and transport
- in models without quasiparticles (i.e. strongly coupled)

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Interplay between holographic and non-holographic thinking led to the most important impact of AdS/CMT in condensed matter.

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AdS/CMT is a mature field. 👴 What's left?

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A biased list...: 👶

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Or, just as importantly, holography will be a good set of models for checking future conjectures/ideas about strongly correlated matter!