Holographic transport with random-field disorder

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Lucas, Sachdev, Schalm, *Physical Review* **D89** 066018 (2014)

- **random-field disorder** in a low-energy EFT (d spatial dimensions):

$$H = H_0 + \underbrace{\int \mathrm{d}^d\mathbf{x}\, \mathcal{O}(\mathbf{x}) g(\mathbf{x})}_{\text{linear coupling of disorder}} ,$$

$$\mathbb{E}[g(\mathbf{x})] = 0, \quad \mathbb{E}[g(\mathbf{x})g(\mathbf{y})] = \varepsilon^2 \delta(\mathbf{x}-\mathbf{y}).$$

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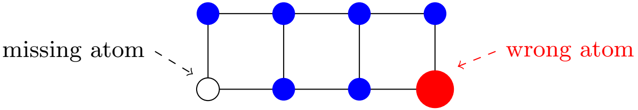
- *defects* act as random-fields in the solid-state lab:



The Harris Criterion at Any z, θ

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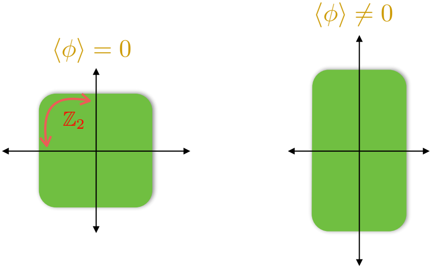
- Harris criterion: $\langle \mathcal{O}(0)\mathcal{O}(x) \rangle \sim x^{-2\Delta}$; disorder relevant if

$$\Delta < \frac{d-\theta}{2} + z$$

- Pomeranchuk instability: Fermi surface distortion ($d = 2$)

$$\phi \sim \sum_{\mathbf{k}} \left(\cos(ak_x) - \cos(ak_y)\right) c^\dagger_{\mathbf{k}} c_{-\mathbf{k}}$$



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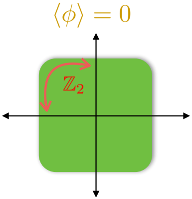

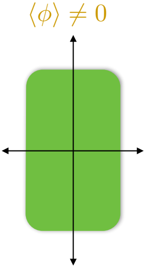

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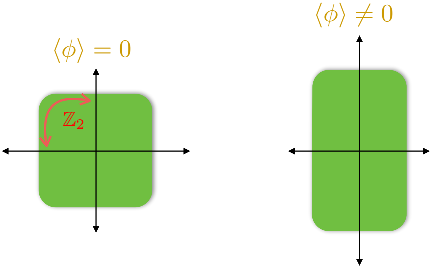

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- Ising-nematic quantum critical point:

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{r_c}{2}\phi^2 - \frac{u}{24}\phi^4 + c^\dagger(\mathrm{i}\partial_t - \epsilon(\mathrm{i}\nabla))c - \lambda c^\dagger c(\partial_x^2 - \partial_y^2)\phi$$

Metlitski, Sachdev, *Physical Review* **B82** 075127 (2010)

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- random-fields *dominate transport* at low T:

$$\rho_{\mathrm{dc}} \sim \mathbb{E}[V^2] + \frac{\mathbb{E}[h^2]}{\sqrt{T\log(T^*/T)}} \longleftarrow$$

calculation breaks down as $T \to 0$!

Hartnoll, Mahajan, Punk, Sachdev, *Physical Review* **B89** 155130 (2014)

- how to understand? strongly-coupled theory relaxes quickly to a "hydrodynamic" regime:

$$\partial_\mu \langle T^{\mu t} \rangle = 0, \quad \partial_\mu \langle T^{\mu i} \rangle = -\frac{1}{\tau} \langle T^{ti} \rangle.$$

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- memory matrix formalism ($\mathcal{L}_{\mathrm{dis}} \sim g\mathcal{O}$, $g \sim \varepsilon$):

$$\rho_{\mathrm{dc}} \sim \varepsilon^2 \int \mathrm{d}^2\mathbf{k}\; k^2 \mathrm{Im}\frac{G^{\mathrm{R}}_{\mathcal{O}\mathcal{O}}(\omega, \mathbf{k})}{\omega}$$

A Massive Gravity Analogy

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- computation of ρ_{dc}:°

$$\rho_{\mathrm{dc}} \sim \tau \sim m^2$$

m^2 perturbatively computable for "holographic lattice" (holographic Higgs mechanism)

* Vegh, arXiv:1301.0537

† Davison, *Physical Review* **D88** 086003 (2013)

° Blake, Tong, Vegh, *Physical Review Letters* **112** 071602 (2014)

- we start with finite charge density EMD geometry (g_{MN}, A_M, Φ) for given z, θ

$$\mathrm{d}s^2 = \frac{L^2}{r^2}\left[\frac{\mathrm{d}r^2}{r^{2\theta/(d-\theta)}f} - \frac{f\mathrm{d}t^2}{r^{2d(z-1)/(d-\theta)}} + \mathrm{d}\mathbf{x}^2\right], \quad f = 1-\left(\frac{r}{r_\mathrm{h}}\right)^{d+dz/(d-\theta)}$$

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- AdS/CFT dictionary: random-field disorder $\Longleftrightarrow$ random (scalar ψ) field in bulk – normalizable mode turned on:

$$\mathcal{L}_\mathrm{dis} = g(\mathbf{k})\mathcal{O}(\mathbf{k}) \Longleftrightarrow \psi(\mathbf{k}, r \to 0) \sim \underbrace{g(\mathbf{k})r^{\nu_+}}_{\text{relevant operator}} + \cdots$$

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- $g(\mathbf{k}) \sim \varepsilon$ “small enough” $\Longrightarrow$ background approx ψ-independent. (“memory matrix” regime)

- for this computation to work, "must" choose

$$S[\psi] = -\frac{1}{2}\int \mathrm{d}^{d+2}x \left(\frac{1}{2}\partial^M\psi\partial_M\psi + \frac{1}{2}B(\Phi)\psi^2\right)$$

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- analogous story with usual AdS/CFT (mass $\Longleftrightarrow$ dimension): $B(\Phi) \approx B_0\mathrm{e}^{-\beta\Phi}$, β fixed by z, θ;

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Aside: Scalar Fields with $\theta \neq 0$

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- if $B(\Phi) = m^2$, "AdS radius" L enters the boundary theory as a length scale in ψ correlation functions!

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- graviton mass a sum of each mode contribution:

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- given ρ_{dc}, coefficients $\bar{\kappa}_{\mathrm{dc}}$, α_{dc} straightforward to obtain*

* Amoretti, Braggio, Maggiore, Magnoli, Musso, arXiv:1407.0306

- mode by mode solution: modes are modified Bessel functions:

$$\psi \sim r^{\#} \quad (r \ll k^{1-\theta/d}), \quad \psi \sim \exp[-kr^{d/(d-\theta)}] \quad (r \gg k^{1-\theta/d})$$

A Hairy Black Hole

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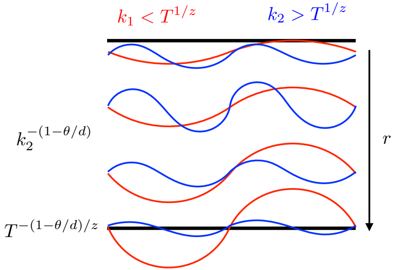
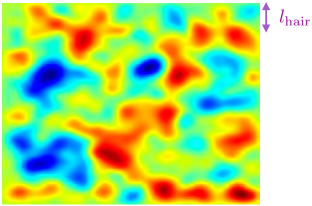


"random Fourier" cartoon



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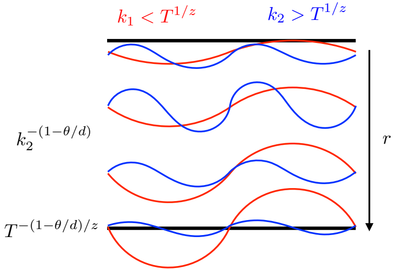

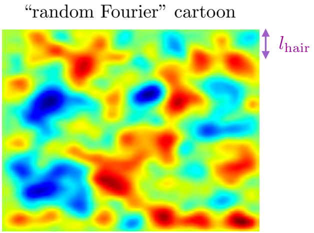

- similar logic valid even when horizon non-perturbative?

The Answer

- "only momenta $k < T^{1/z}$ contribute" to m^2:

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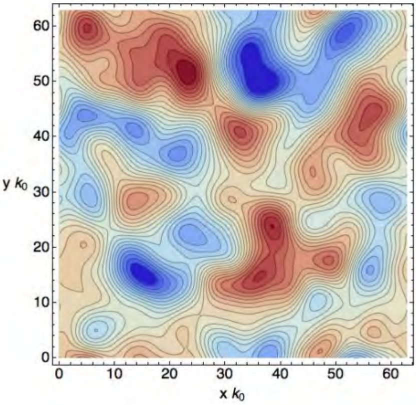
- generically scalar RF disorder has more singular contribution

* Davison, Schalm, Zaanen, *Physical Review* **B89** 245116 (2014)

numerics have recently been performed on $(T = 0)$ disordered horizons with marginal scalars: plot of $\psi(\mathbf{x}, r_\mathrm{h})$:



Hartnoll, Santos, *Physical Review Letters* **112** 231601 (2014)

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- in progress: "easy" interpolating AdS→HV geometry at all T for (almost all) z, θ; holographic check of