2025 Postdoctoral Frontier Symposium in Physics and Astronomy
26 Sep. 2025

Strange Metals from Disorder

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- Y.-L. W., Sang-Jin Sin, arXiv: 2503.19431
- Y.-L. W., Young-Kwon Han, Xian-Hui Ge, Sang-Jin Sin, Phys.Rev.B 112 (2025) 3, 3
- Y.-L. W., Xian-Hui Ge, Sang-Jin Sin, Phys.Rev.B 111 (2025) 11, 115135

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1

Introduction

Introduction

Science
Volume 381, Issue 6659
Aug 2023

ARTICLE

Universal theory of strange metals from spatially random interactions

View article page

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, and Subir Sachdev

Strange Metals

- Normal phase of high-temperature superconductivity.
- Metal phase of strongly interacting systems.
- Violation of various features of Landau Fermi liquids.
- No theoretical framework.

Reference: Aavishkar A. Patel et al., Science381,790-793(2023).

Introduction

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Universal theory of strange metals from spatially random interactions

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SYK-rised Coupling

$$g_{ijl}(r)\psi_i^\dagger(\tau,r)\psi_j(\tau,r)\phi_l(\tau,r)$$

$$\begin{cases} \langle g_{ijl}(\mathbf{r})\rangle = 0 \\ \langle g^*_{ijl}(\mathbf{r})g_{i'j'l'}(\mathbf{r}')\rangle = g^2\delta_{ii'jj'll'}\delta(\mathbf{r}-\mathbf{r}') \end{cases}$$

$$\rho = \rho_0 + AT$$

linear resistivity

Reference: Aavishkar A. Patel et al., Science381,790-793(2023).

2

SYK-rised Vector Model

SYK-rised Vector Model

$$
\begin{aligned}
S = \int d\tau d^2 r \Big[& \sum_{i=1}^{N} \psi_i^\dagger(r,\tau) \left(\partial_\tau - \frac{\nabla^2}{2m} - \mu \right) \psi_i(r,\tau) \\
& + \sum_{i,j=1}^{N} v_{ij}(r) \psi^\dagger(r,\tau) \psi_i(r,\tau) - \frac{1}{2K^2} \sum_{l=1}^{N} g_{ab} a_l^a \left(-\partial_\tau^2 + \mathbf{q}^2 \right) a_l^b \\
& + \sum_{i,j,l=1}^{N} \frac{K_{ijl}(r)}{KN} \frac{\mathrm{i}}{m} \psi_i^\dagger \nabla_a \psi_j \mathbf{a}_l^a + \frac{1}{K^2 N^{3/2}} \sum_{i,j,s,t=1}^{N} \frac{\tilde{K}_{ijst}(r)}{2m} \mathbf{a}_s \cdot \mathbf{a}_t \psi_i^\dagger \psi_j \Big]
\end{aligned}
$$

SYK-rised vector coupling

$$
\begin{aligned}
\langle K_{ijl}(r) \rangle &= 0, \quad \langle K_{ijl}^*(r) K_{i'j'l'}(r') \rangle = K^2 \delta_{ii'jj'll'} \delta(r - r') \\
\langle \tilde{K}_{ijl}(r) \rangle &= 0, \quad \langle \tilde{K}_{ijl}^*(r) \tilde{K}_{i'j'l'}(r') \rangle = \tilde{K}^2 \delta_{ii'jj'll'} \delta(r - r') \\
\langle v_{ij}(r) \rangle &= 0, \quad \langle v_{ij}(r) v_{i'j'}(r') \rangle = \delta_{ii',jj'} \delta(r - r')
\end{aligned}
$$

SYK-rised Vector Model

Dyson's Equations

$$G = G_* = (-\partial_\tau - \varepsilon_k + \mu - \Sigma)^{-1}$$

$$\Sigma = \Sigma_* = v^2 G(\tau, r=0)\delta^3(r) + \frac{(k_1+k_2)^a (k_1+k_2)^b}{4m^2} D_{ab} G\bar{\delta} + \frac{1}{4m^2} D_{ab} D^{ab} G\bar{\delta}$$

$$D_{ab} = D_{*ab} = K^2(-g^{ab}(-\partial_\tau^2 + \mathbf{q}^2) - K^2 \Pi^{ab})^{-1}$$

$$\Pi_{ab} = \Pi_{*ab} = -\frac{(k_1+k_2)_a (k_1+k_2)_b}{4m^2} G\bar{\delta} \cdot G - \frac{1}{4m^2} G D_{ab} G\bar{\delta}$$

Boson self-energy

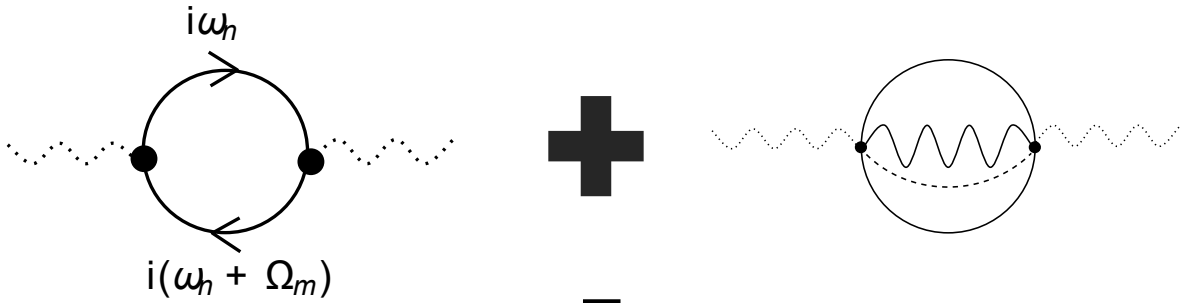
$$\Pi^{ab}(\mathrm{i}\Omega_m) = -c_b \delta^{ab} |\Omega_m|$$

Electron self-energy

$$\Sigma_v(\mathrm{i}\omega_n) \equiv -\mathrm{i}\frac{\Gamma}{2} sgn(\omega_n)$$

$$\Sigma_K(\mathrm{i}\omega_n) \equiv -\mathrm{i}c_K \omega_n \ln\left(\frac{c_0}{\omega_n}\right)$$

SYK-rised Vector Model



Kubo Formula

$$\sigma^{\mu\nu}(\Omega) = -e^2 \frac{\Pi^{\mu\nu}(i\Omega_m \to \Omega + i0)}{i\Omega}$$

Linear resistivity without magnetic field

$$\Re \frac{1}{\sigma(\Omega)} \simeq \frac{m}{n_e e^2}\left(\Gamma + \frac{K^2\Gamma^2\mathcal{N}}{16k_F^2}|\Omega|\right)$$

3

Hall Angle

Hall Angle

Anderson's Criterion

1. Linear Resistivity

$$\rho \sim T$$

2. Quadratic Hall Angle

$$\sigma_{xx}/\sigma_{xy} \sim T^2$$

References:

- P.W. Anderson, Phys. Rev. Lett. 67 (1991) 2092.
- P.W. Anderson, Physics Today 66 (2013) 9.

Hall Angle

Limitation of Anderson's Criterion

Quadratic Hall angle is less universal than linear resistivity.

References

- A. Tyler and A. Mackenzie, Physica C: Superconductivity 282-287 (1997) 1185
- A.P. Mackenzie, S.R. Julian, D.C. Sinclair and C.T. Lin, Phys. Rev. B 53 (1996) 5848.
- Y. Ando and T. Murayama, Phys. Rev. B 60 (1999) R6991.
- A. Legros et al., Nature Phys. 15 (2018) 142
- C. Collignon et al., Phys. Rev. B 95 (2017) 224517.

Hall Angle

Limitation of Anderson's Criterion

Quadratic Hall angle is less universal than linear resistivity.

However Our motivation is to test if this random coupling mechanism could correspond to any realistic materials.

References

- A. Tyler and A. Mackenzie, Physica C: Superconductivity 282-287 (1997) 1185
- A.P. Mackenzie, S.R. Julian, D.C. Sinclair and C.T. Lin, Phys. Rev. B 53 (1996) 5848.
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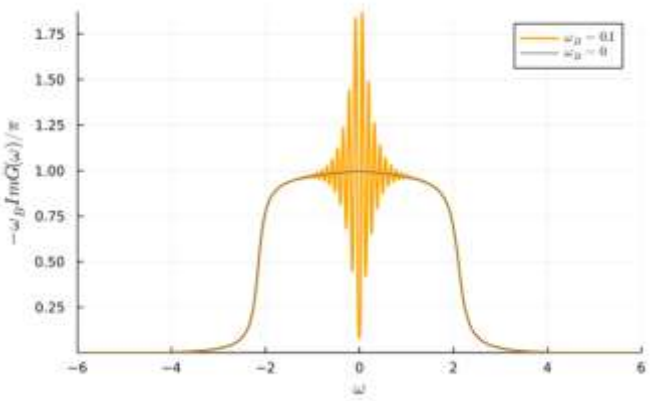
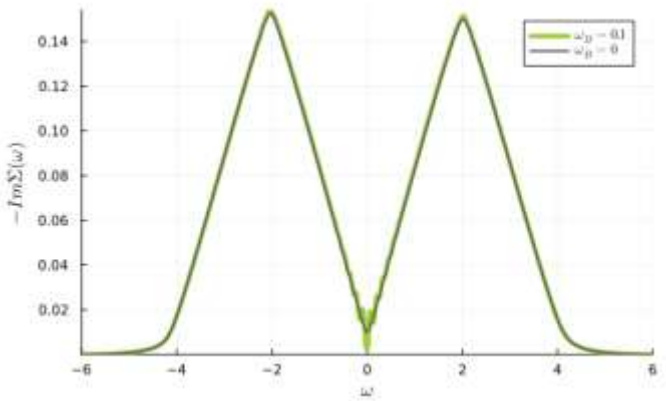
Hall Angle



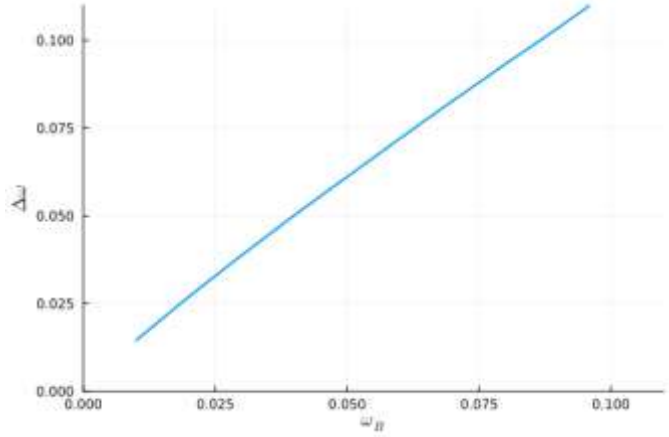


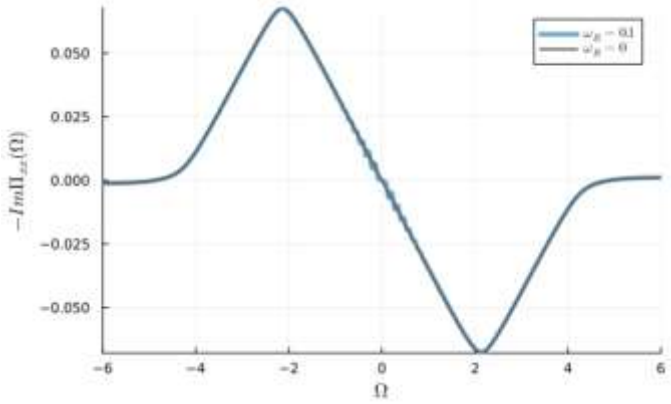
Oscillations

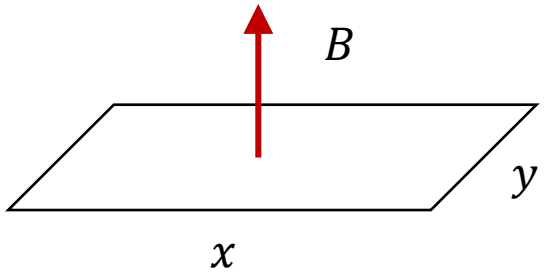
Landau levels

Linearity

Numerical Solutions

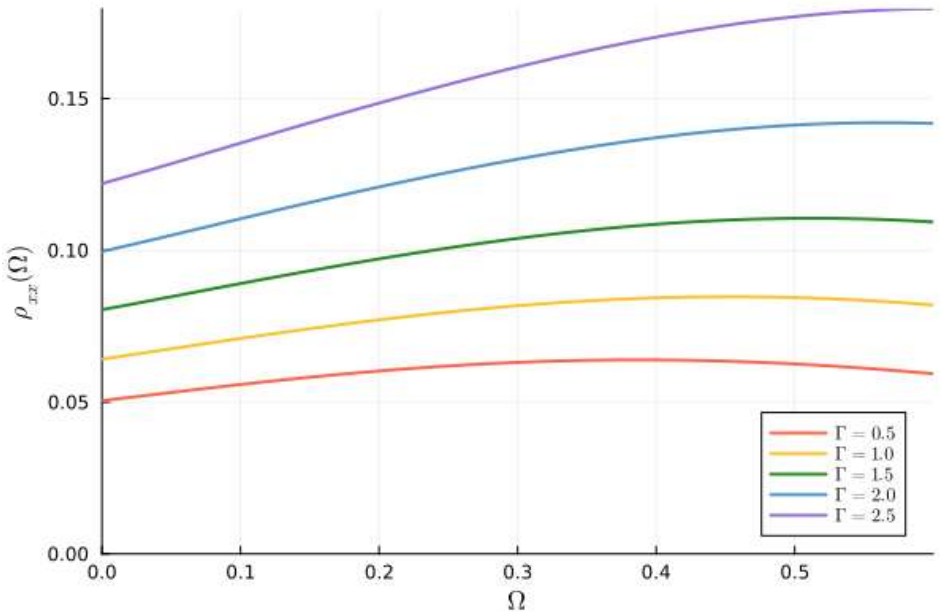




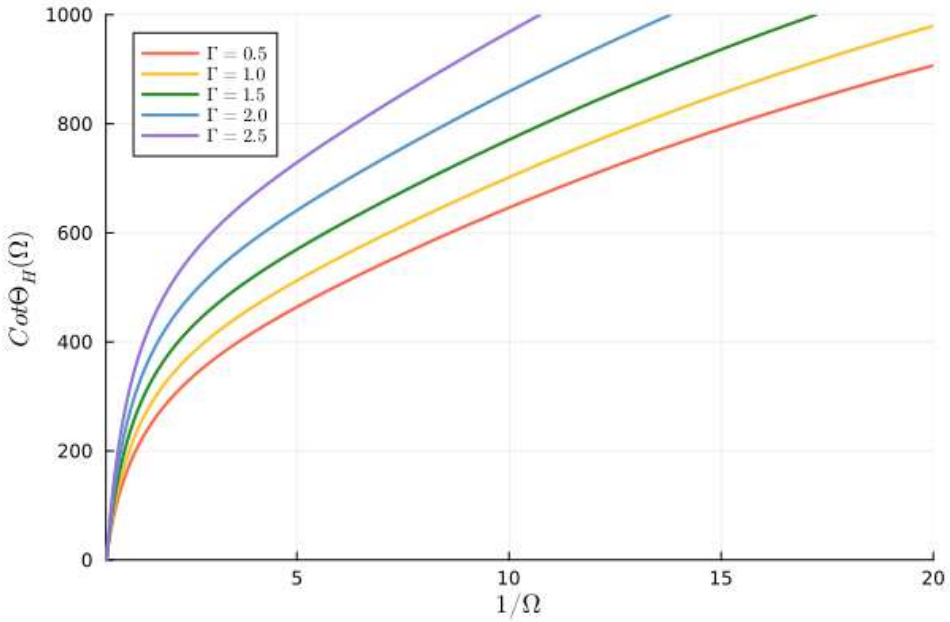


Hall Angle

Resistivity: linear T



Hall Angle: 1/T



Hall angle fails; linear resistivity remains.

Universality of this mechanism of linearity

4

Strange Metals from Quantum Entanglement

Strange Metals from Quantum Entanglement

ER=EPR

The Einstein-Rosen bridge is a manifestation of entanglement.

Disorder

Strange metals may arise from entanglement.

① Interplay between disorder and entanglement?

② Concrete realisation of ER=EPR?

Reference: J. Maldacena and L. Susskind, Fortsch. Phys. 61, 781 (2013)

Scalar Coupling Revisit

$$\frac{1}{N}\sum_{a,b,c=1}^{N} g_{abc}(\mathbf{r})\psi_a^\dagger(\tau,\mathbf{r})\psi_b(\tau,\mathbf{r})\phi_c(\tau,\mathbf{r})$$

quenched

$$\langle \ln(\mathcal{Z}) \rangle_{\text{dis}}$$

$\neq$

annealed

$$\ln \langle \mathcal{Z} \rangle_{\text{dis}}$$

Scalar Coupling Revisit

$$\frac{1}{N}\sum_{a,b,c=1}^{N} g_{abc}(\mathbf{r})\psi_a^\dagger(\tau,\mathbf{r})\psi_b(\tau,\mathbf{r})\phi_c(\tau,\mathbf{r})$$

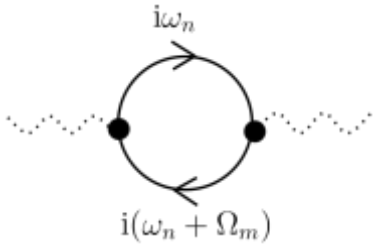
Annealed average

$$S_{\text{eff}} = -\frac{g^2}{2N^2}\int d\tau_1 d\tau_2 d^2r \sum_{a,b,c=1}^{N} [\psi_a^\dagger\psi_b\phi_c](\tau_1,r)[\psi_b^\dagger\psi_a\phi_c](\tau_2,r)$$

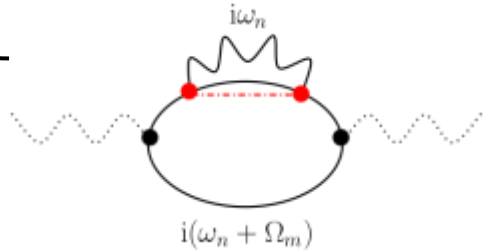
Feynman rule $= -\frac{g^2}{2N^2}\int d\tau_1 d\tau_2 d^2r$

Strange Metals from Quantum Entanglement

Polarisation



$$\tilde{\Pi}_0^{\mu\nu}(i\Omega_m) = -v_F^2 \mathcal{N} \delta^{\mu\nu} \frac{\Omega_m}{\Omega_m + \mathrm{sgn}(\Omega_m)\Gamma}$$



$$\tilde{\Pi}_g^{\mu\nu}(i\Omega_m) = \frac{g^2 v_F^2 \mathcal{N}^2}{16\pi\Gamma^2} \delta^{\mu\nu} \Omega_m^2 \ln\left(\frac{e^3 \Lambda_q^4}{c_g^2 |\Omega_m|^2}\right)$$

Resistivity

$$N\rho = \Re \frac{N}{\sigma} \simeq \frac{\Gamma}{v_F^2 \mathcal{N}} + \frac{1}{v_F^2 \mathcal{N}} \frac{g^2}{8} \Omega + \mathcal{O}(\Omega^2)$$

Linear resistivity

Strange Metals from Quantum Entanglement

quenched

$$\langle \ln(\mathcal{Z}) \rangle_{\mathrm{dis}}$$

$=$

annealed

$$\ln \langle \mathcal{Z} \rangle_{\mathrm{dis}}$$

Strange Metals from Quantum Entanglement

quenched

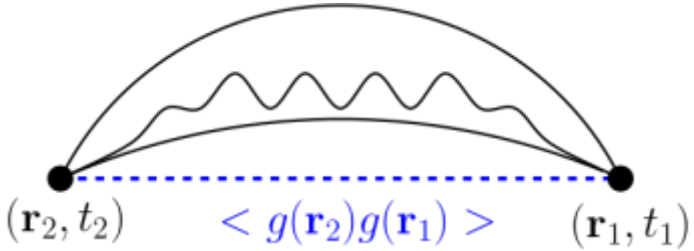
$$\langle \ln(\mathcal{Z}) \rangle_{\text{dis}}$$

$=$

annealed

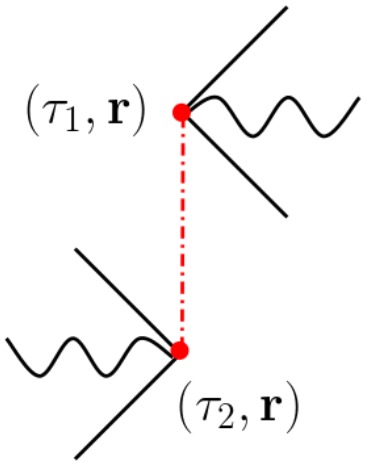
$$\ln \langle \mathcal{Z} \rangle_{\text{dis}}$$

a wormhole connecting two arbitrarily distant spatial points



Strange Metals from Quantum Entanglement

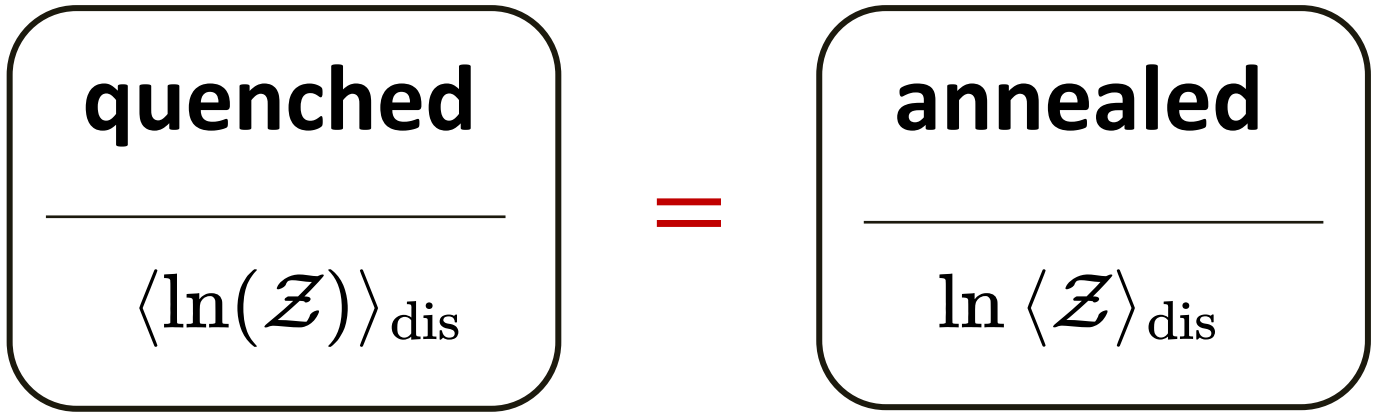
quenched $\langle \ln(\mathcal{Z}) \rangle_{\text{dis}}$ = **annealed** $\ln \langle \mathcal{Z} \rangle_{\text{dis}}$



$$S_{\text{eff}} = -\frac{g^2}{2N^2} \int d\tau_1 d\tau_2 d^2 r \sum_{a,b,c=1}^{N} [\psi_a^\dagger \psi_b \phi_c](\tau_1, r)[\psi_b^\dagger \psi_a \phi_c](\tau_2, r)$$

entanglement between particles at $(\tau_1, \boldsymbol{r})$ and $(\tau_2, \boldsymbol{r})$

Strange Metals from Quantum Entanglement



Wormhole (ER) **EPR (entanglement)**

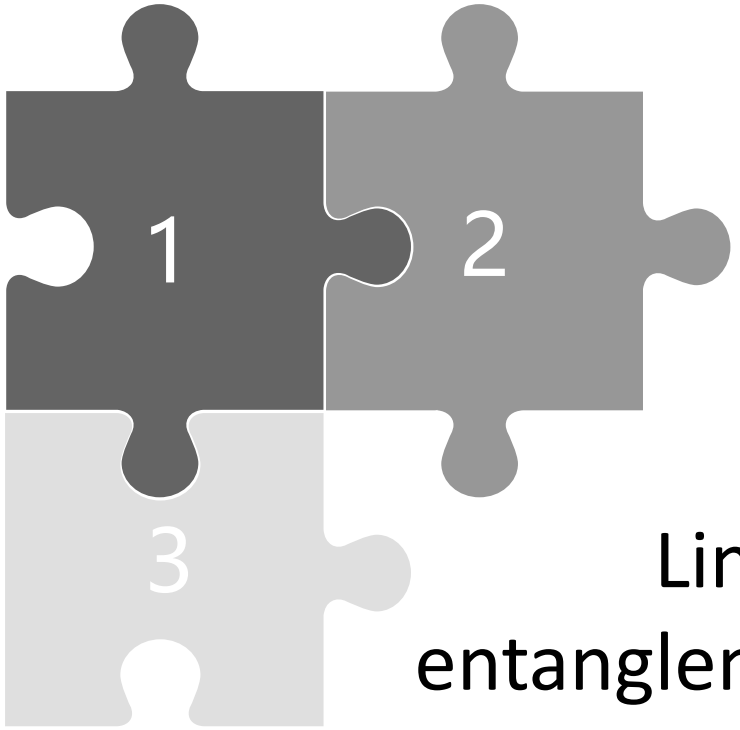
A concrete example of ER=EPR.

5

Discussion

Discussion

SYK-rised vector model



Universality

Link between entanglement and disorder

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Thank You!

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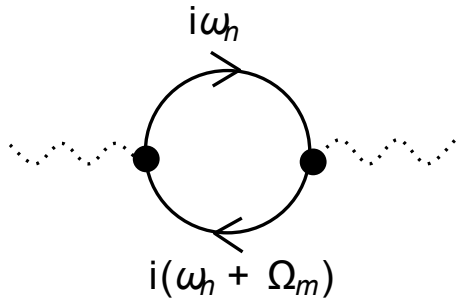
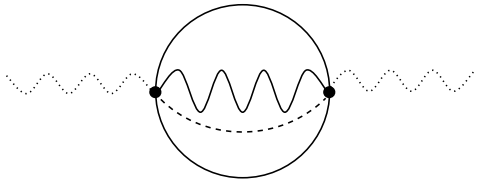
Appendix

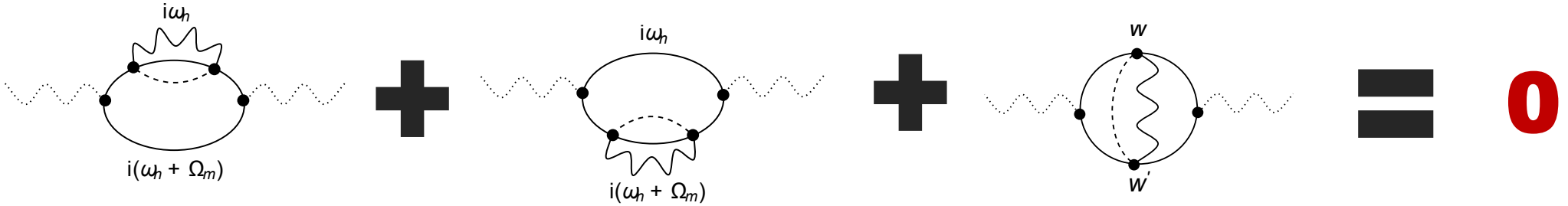
Polarisations



residual resistivity



linearity



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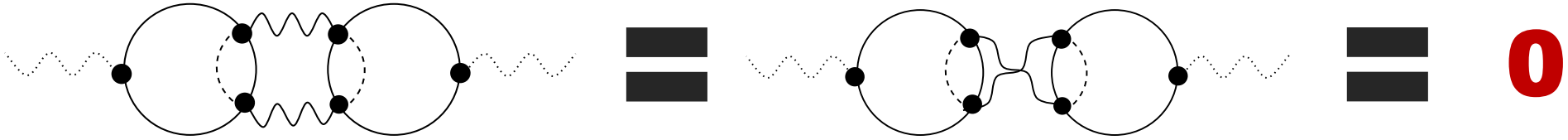

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