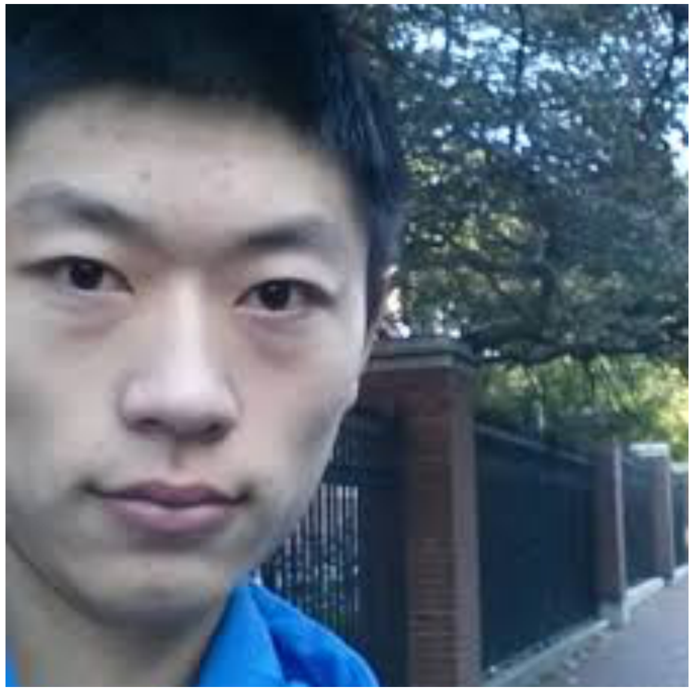
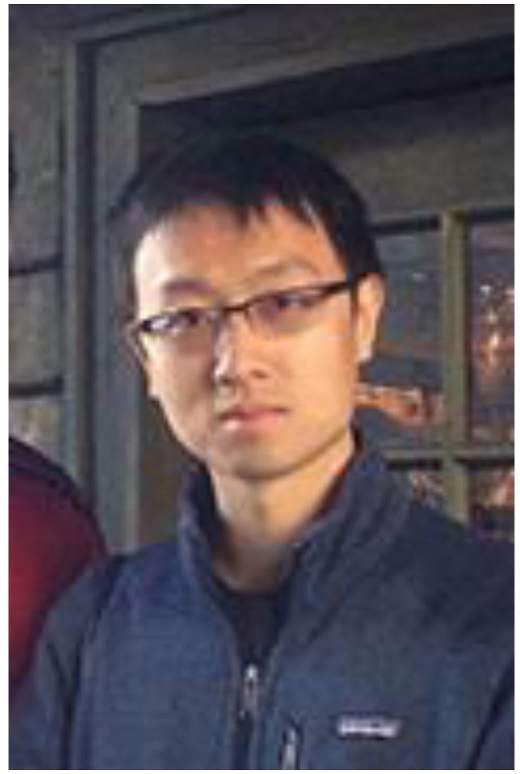
Building strange metals from SYK models

Subir Sachdev
June 25, 2018
Correlated Electron Systems
Gordon Research Conference
Mount Holyoke College

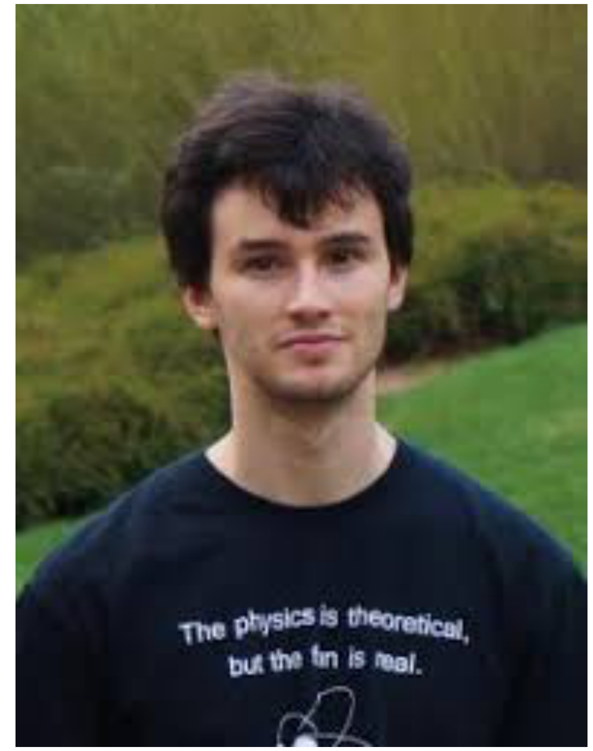
PHYSICS
HARVARD



Wenbo Fu
Harvard



Yingfei Gu
Harvard



Grisha Tarnopolsky
Harvard

arXiv:1804.04130

Daniel Arovas
UCSD

John McGreevy
UCSD

Aavishkar Patel
Harvard

arXiv:1712.05026

and

To appear

Quasiparticles are ubiquitous:

- 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)

What are 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 ε_α

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

In a lattice system of N sites, this parameterizes the energy of $\sim e^{\alpha N}$ states in terms of poly(N) numbers.

What are quasiparticles ?

- 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

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

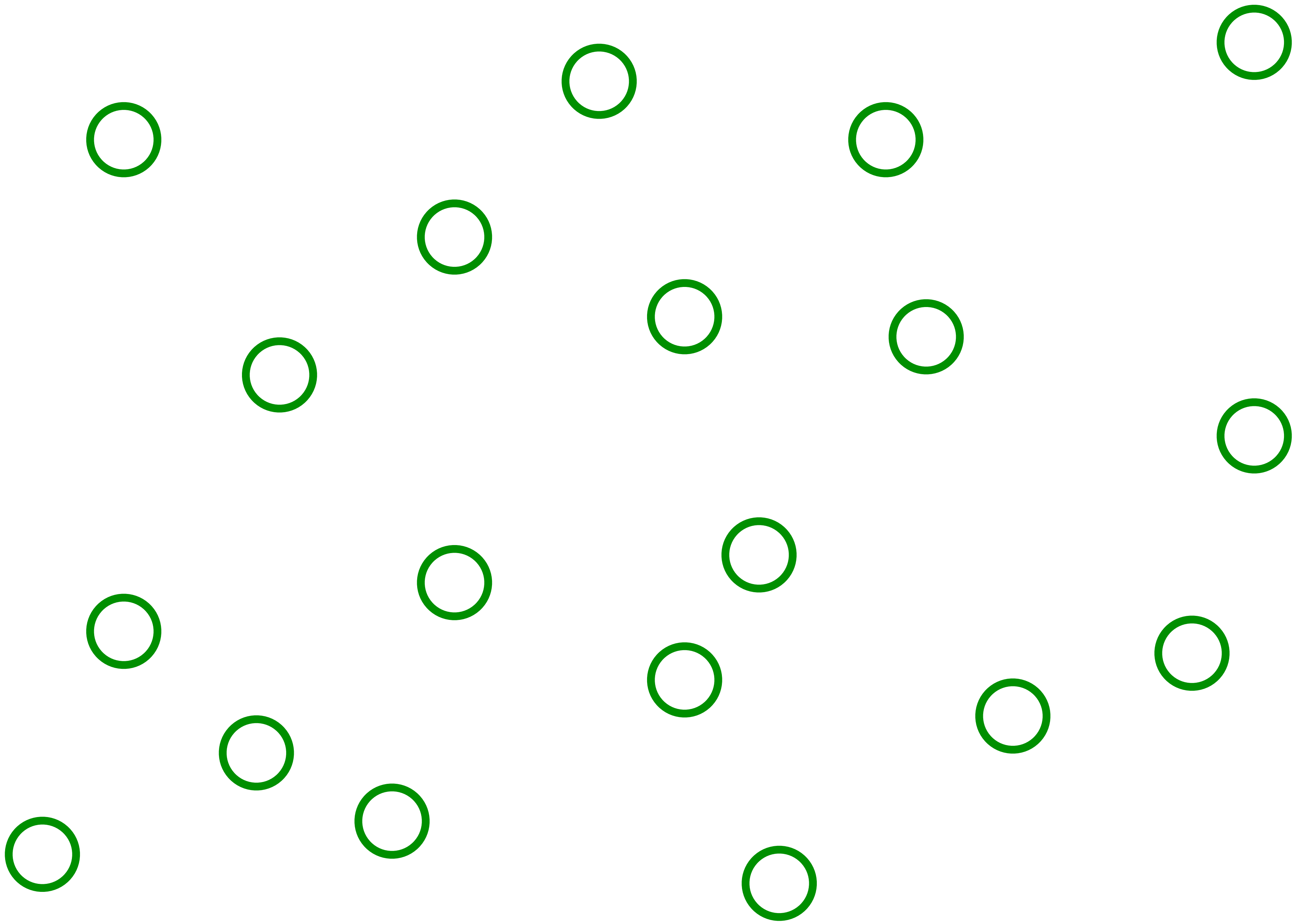
where E_F is the Fermi energy.

1. Solvable model without quasiparticles
   SYK model of a `quantum island'

2. Lattice models of SYK islands
   Theories of strange metals

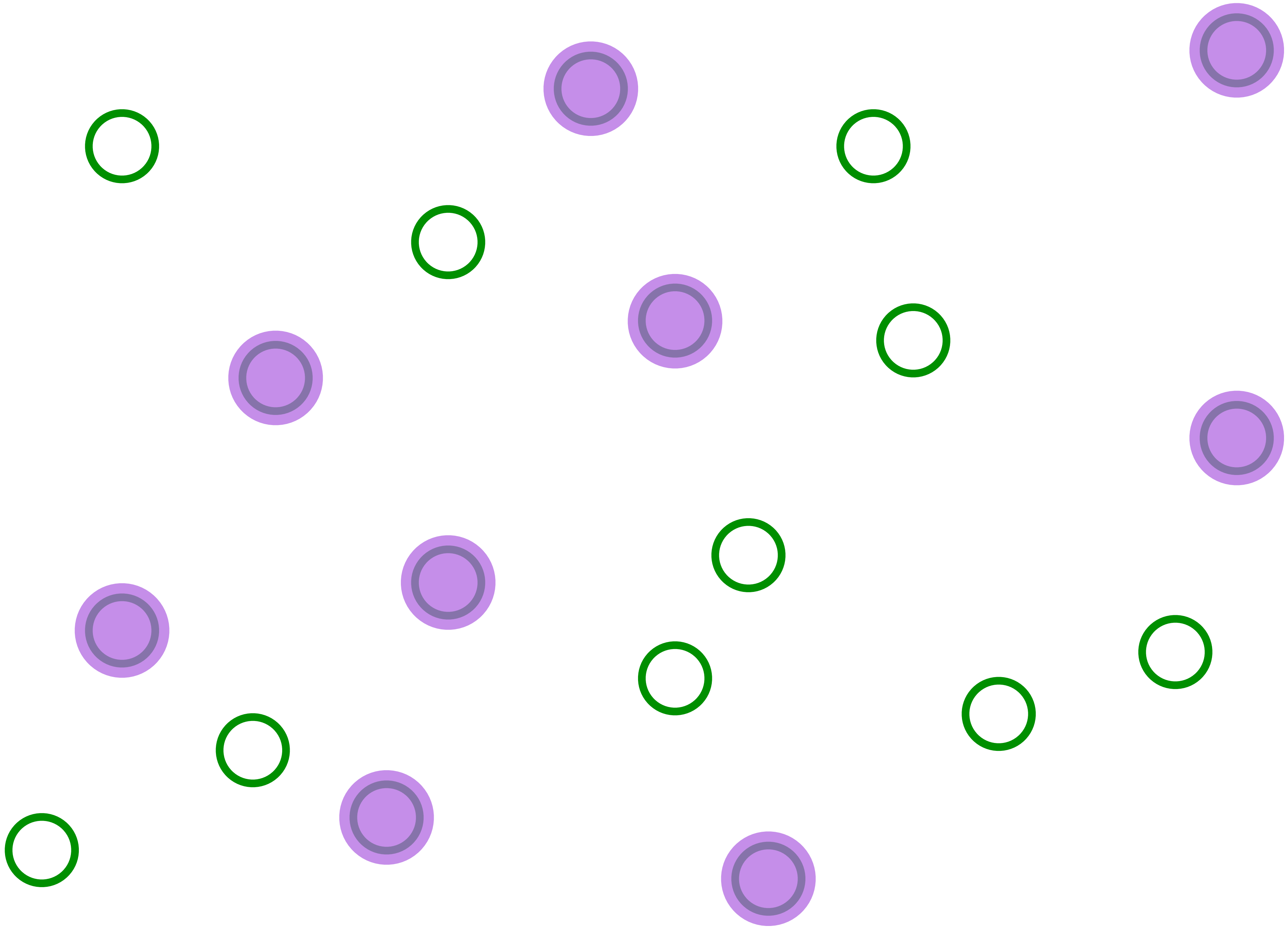
3. SYK U(1) gauge theory
   Solvable model with finite density of fermions, emergent gauge fields, and disorder

The Sachdev-Ye-Kitaev (SYK) model



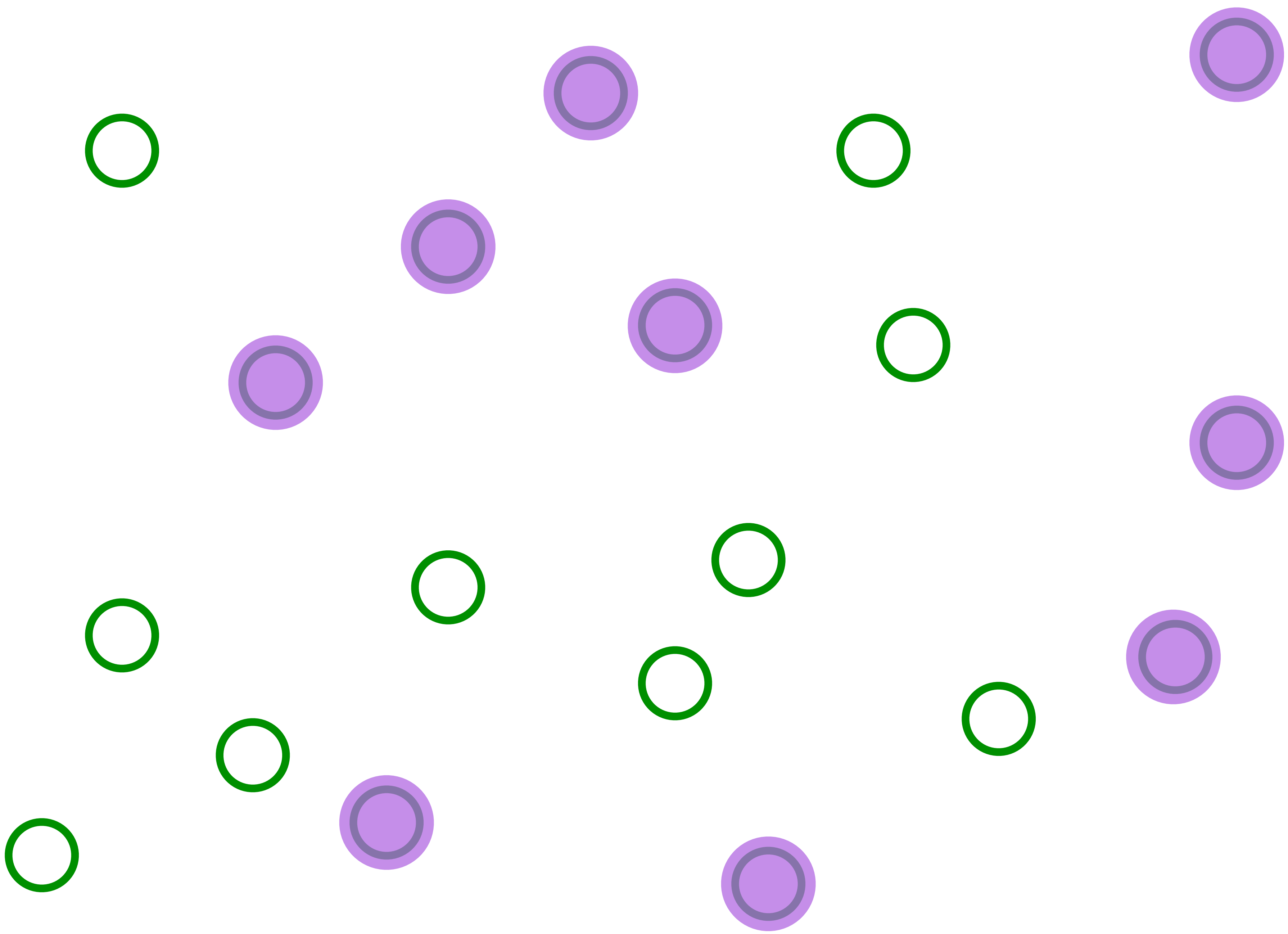
Pick a set of random positions

The SYK model



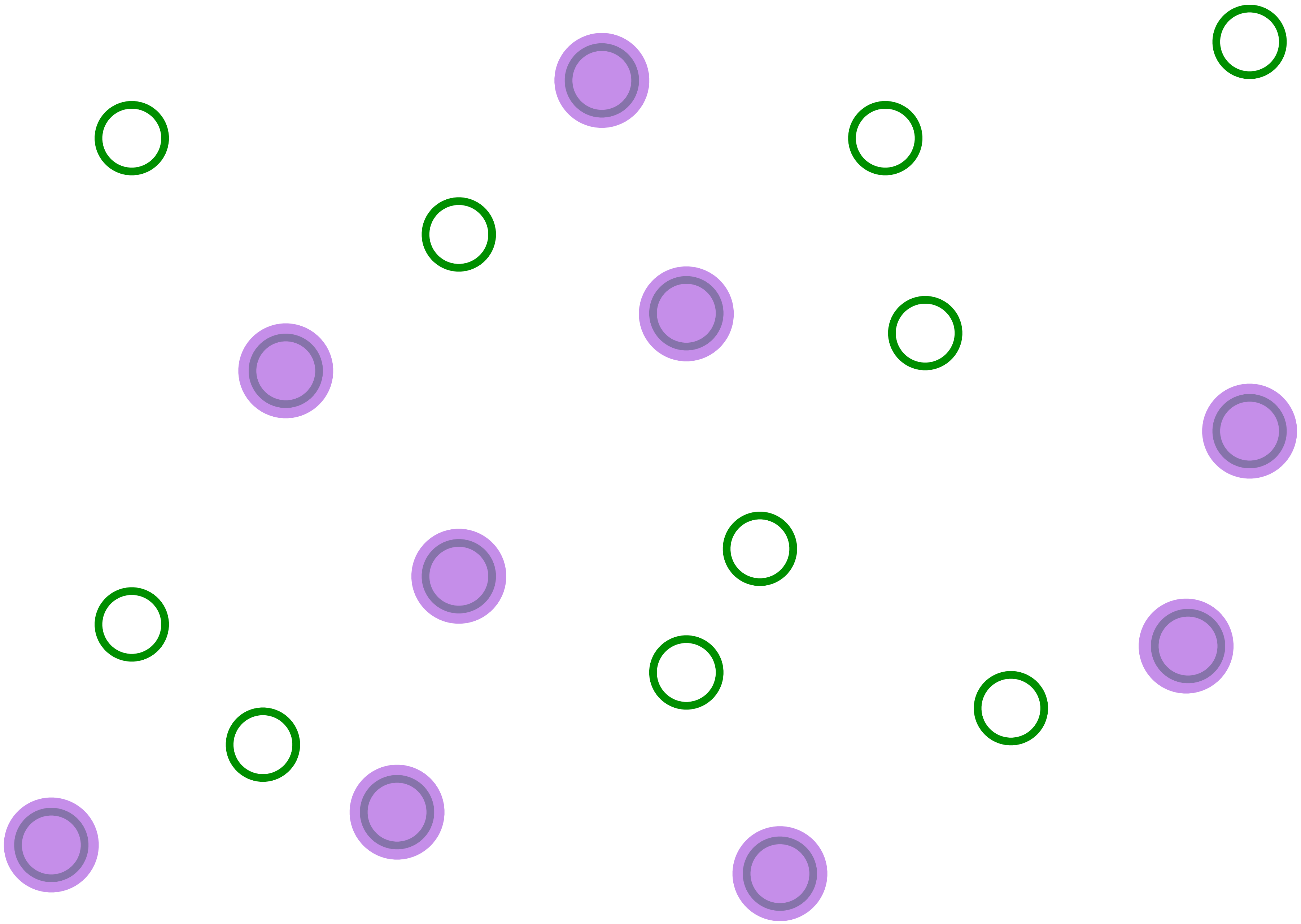
Place electrons randomly on some sites

The SYK model



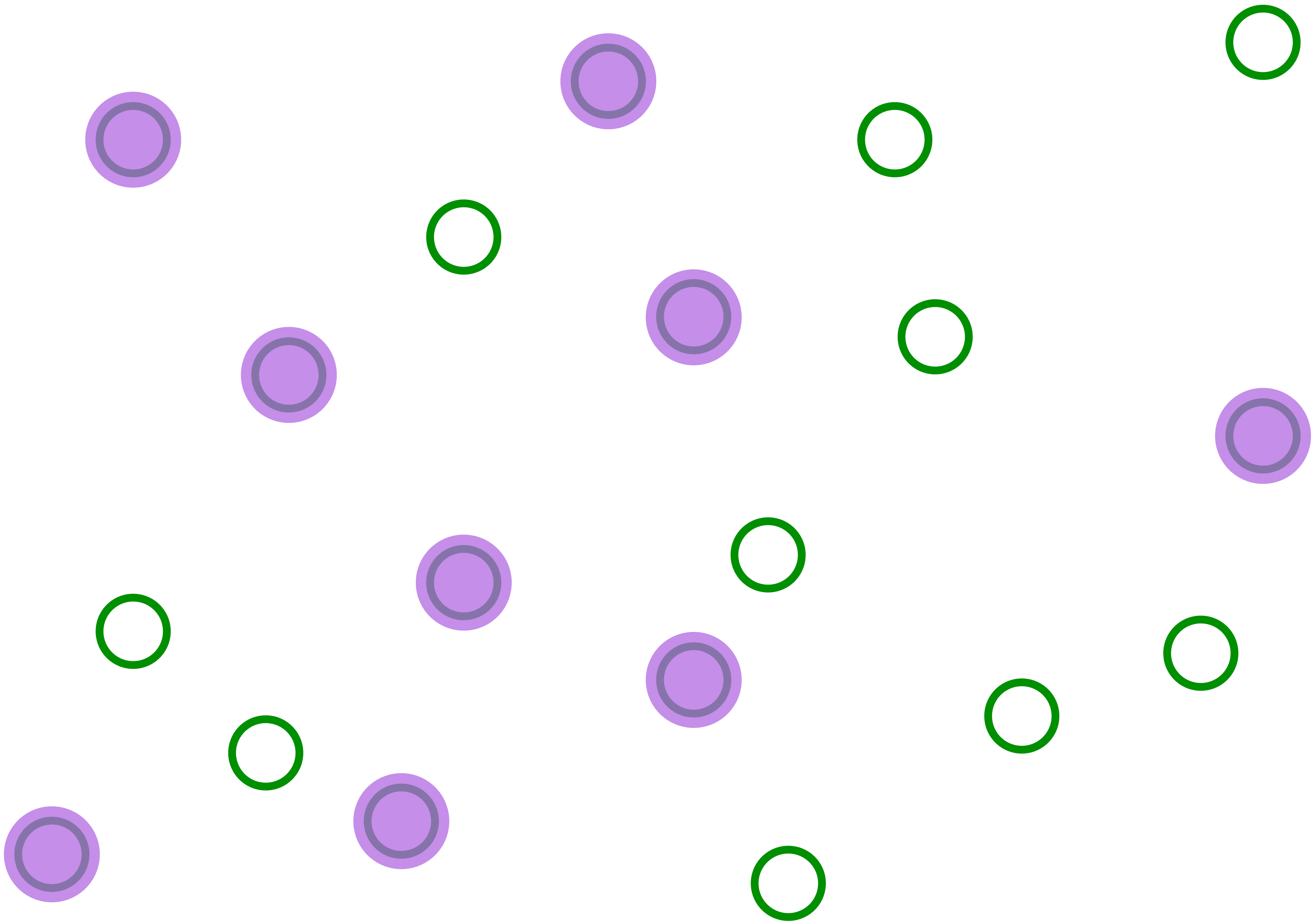
Entangle electrons pairwise randomly

The SYK model



Entangle electrons pairwise randomly

The SYK model



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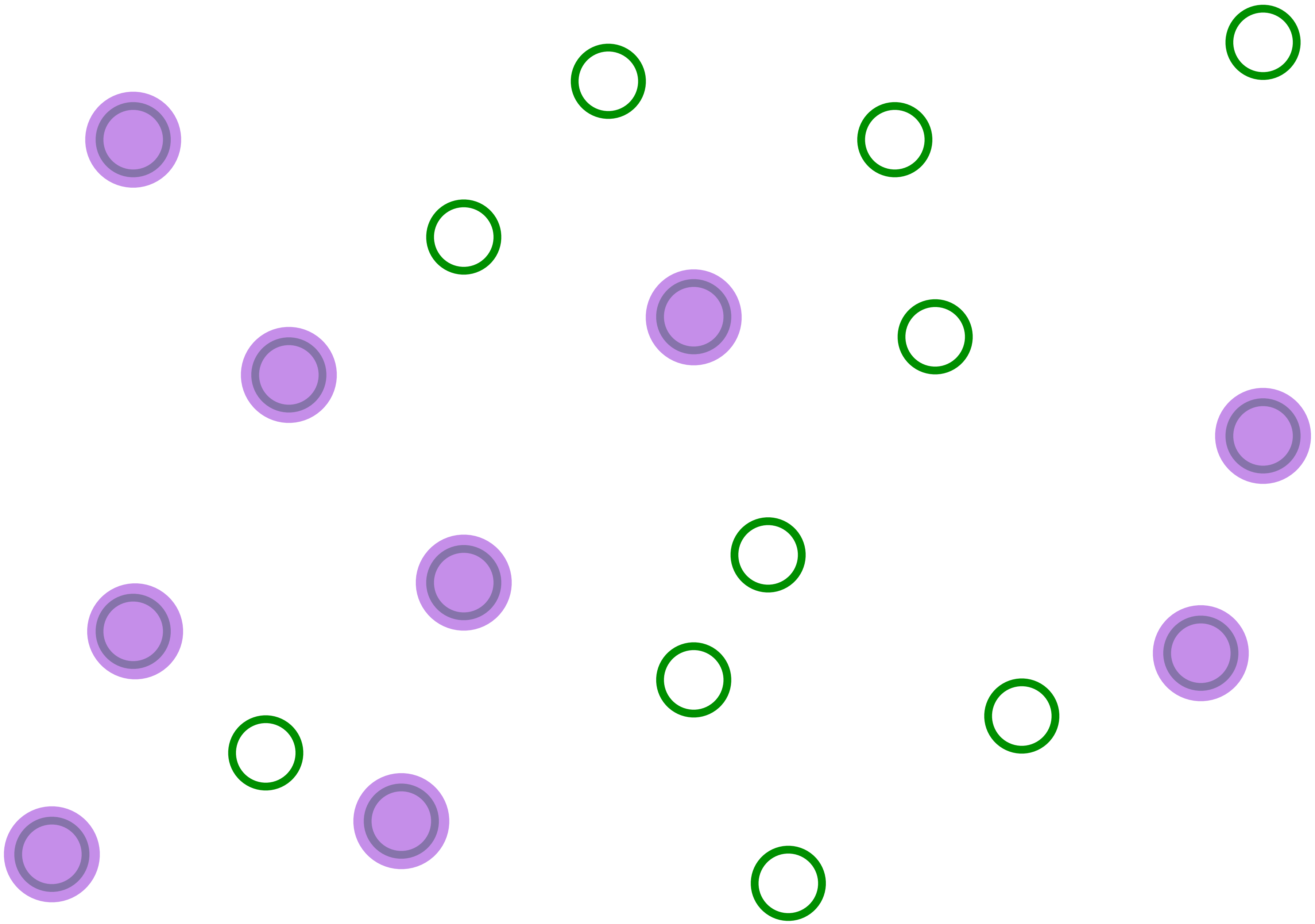
The SYK model



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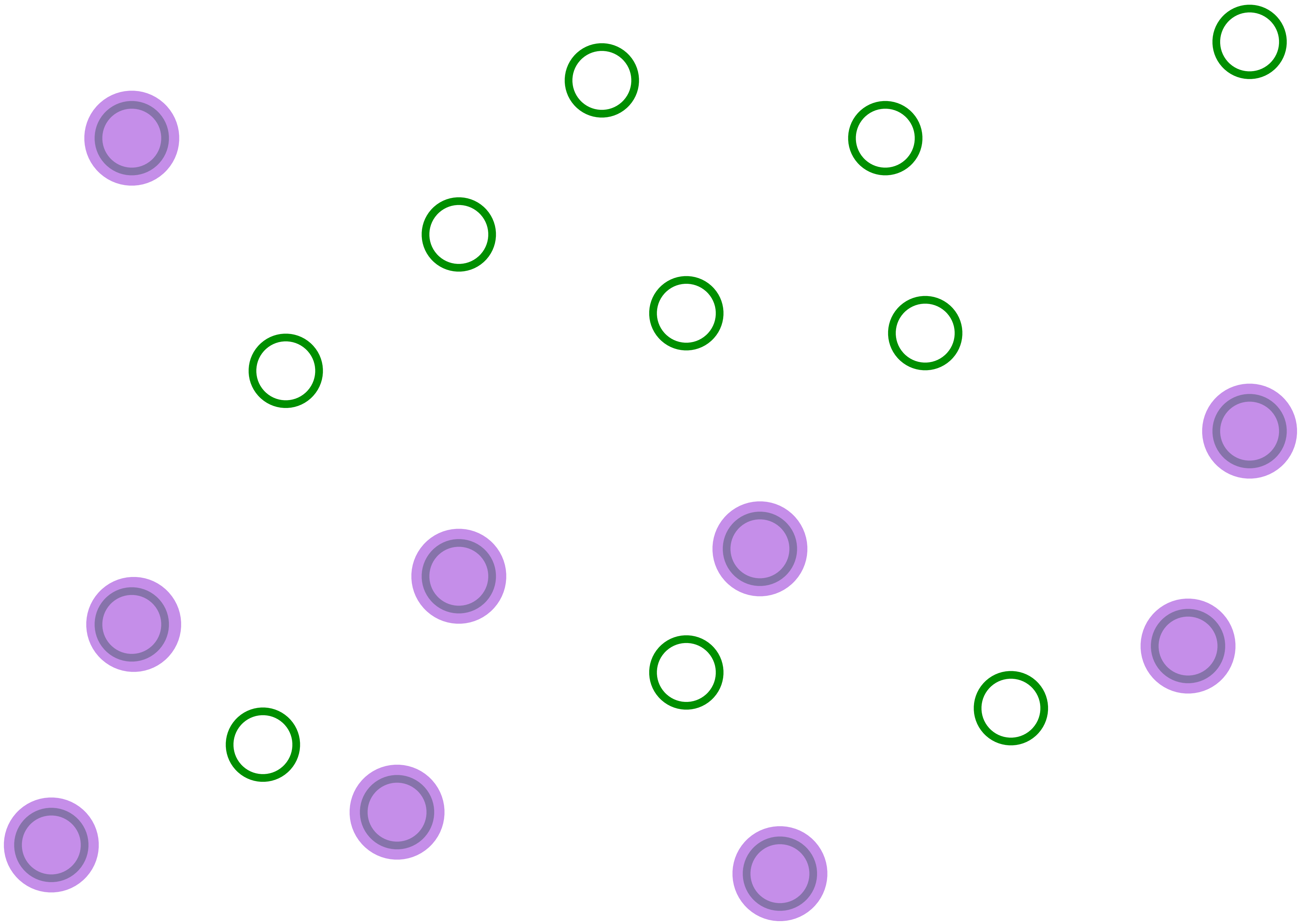

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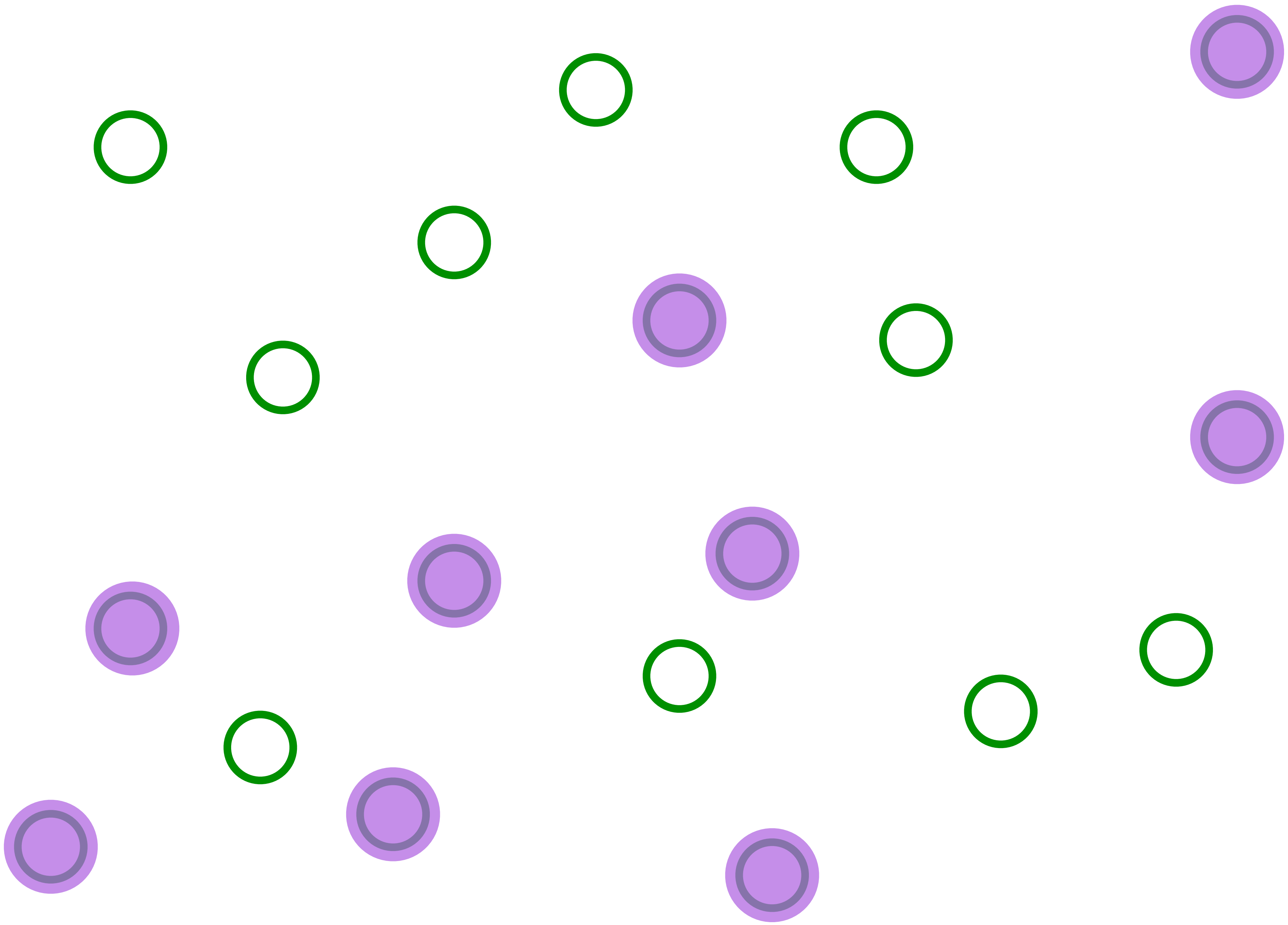

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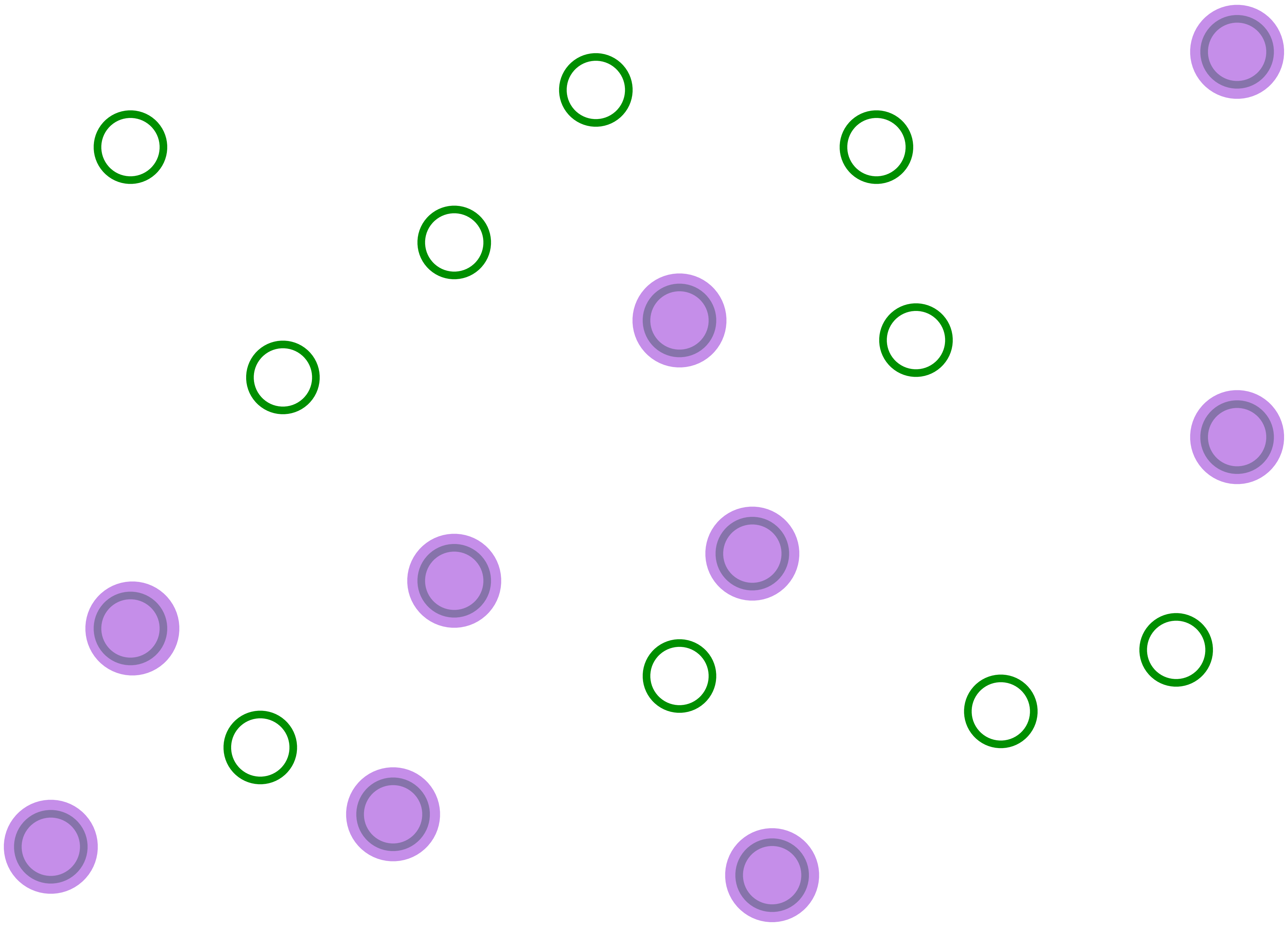


This describes both a strange metal and a black hole!

The SYK model

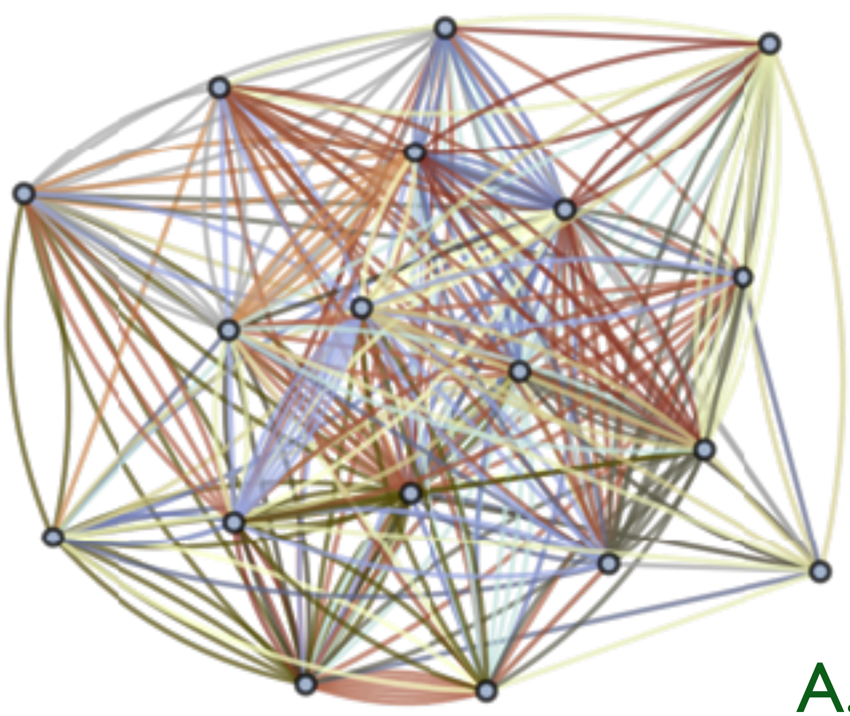
(See also: the "2-Body Random Ensemble" in nuclear physics; did not obtain the large N limit;
T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

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

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

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

$U_{ij;k\ell}$ are independent random variables with $\overline{U_{ij;k\ell}} = 0$ and $\overline{|U_{ij;k\ell}|^2} = U^2$
$N \to \infty$ yields critical strange metal.



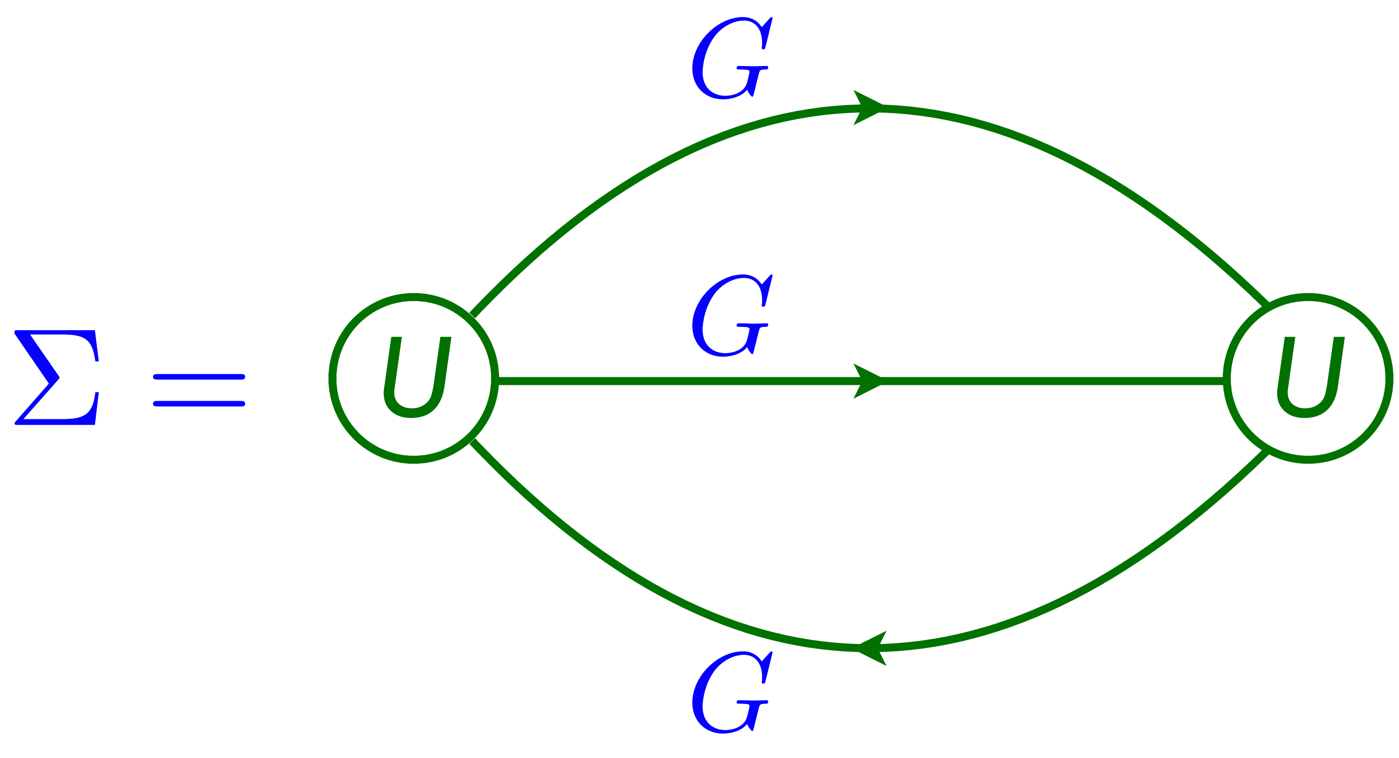
S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

The SYK model

Feynman graph expansion in $U_{ijk\ell}$, and graph-by-graph average, yields exact equations in the large N limit:

$$G(i\omega) = \frac{1}{i\omega + \mu - \Sigma(i\omega)} \quad , \quad \Sigma(\tau) = -U^2 G^2(\tau) G(-\tau)$$
$$G(\tau = 0^-) = \mathcal{Q}.$$



S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)

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$$\boxed{G(i\omega) = \frac{1}{\cancel{i\omega} + \mu - \Sigma(i\omega)} \quad , \quad \Sigma(\tau) = -U^2 G^2(\tau) G(-\tau) \\ G(\tau = 0^-) = \mathcal{Q}.}$$

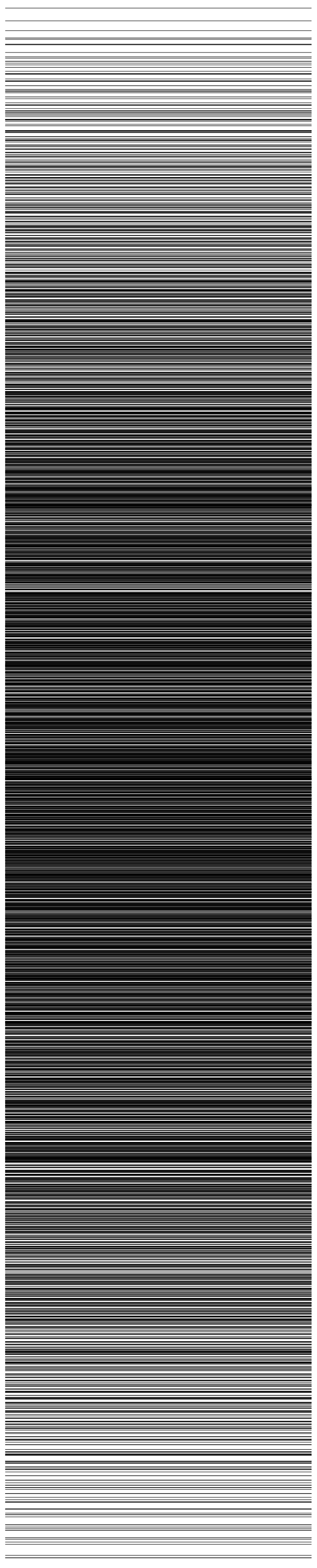
Low frequency analysis shows that the solutions must be gapless and obey

$$\Sigma(z) = \mu - \frac{1}{A}\sqrt{z} + \dots \quad , \quad G(z) = \frac{A}{\sqrt{z}}$$

where $A = e^{-i\pi/4}(\pi/U^2)^{1/4}$ at half-filling. The ground state is a non-Fermi liquid, with a continuously variable density $\mathcal{Q}$.

S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)

The SYK model



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

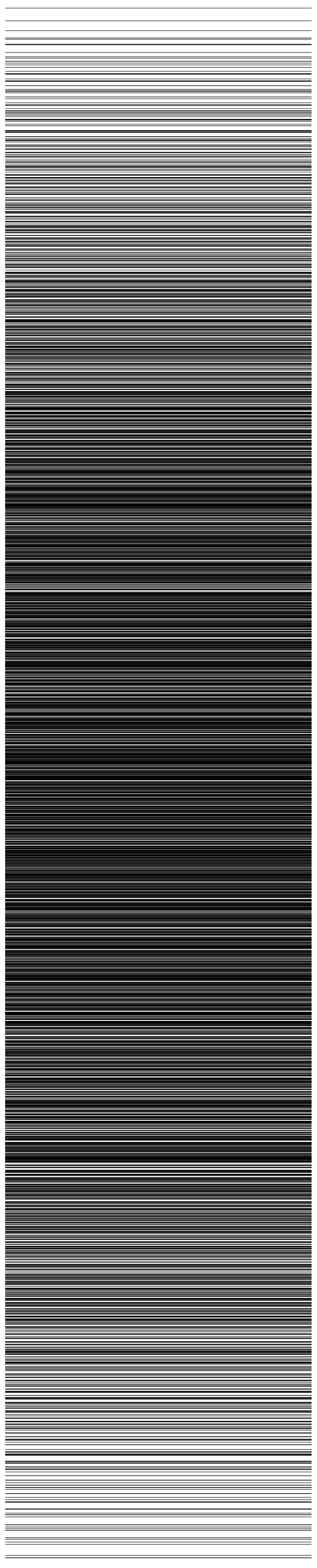
$$
\begin{aligned}
s_0 &= \frac{G}{\pi} + \frac{\ln(2)}{4} = 0.464848\ldots \\
&< \ln 2
\end{aligned}
$$

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)

The SYK model



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

$$< \ln 2$$

No quasiparticles !

$E \neq \sum_\alpha n_\alpha \varepsilon_\alpha$
$+ \sum_{\alpha,\beta} F_{\alpha\beta} n_\alpha n_\beta + \ldots$

PRB **63**, 134406 (2001)

W. Fu and S. Sachdev, PRB **94**, 035135 (2016)

The SYK model

No quasiparticles

- Rapid local thermal equilibration (of fermion correlators) in a 'Planckian' time

$$\tau_{\rm eq} \sim \frac{\hbar}{k_B T} \quad , \quad \text{as } T \to 0.$$

A. Georges and O. Parcollet
PRB **59**, 5341 (1999)
A. Eberlein, V. Kasper, S. Sachdev, and
J. Steinberg, PRB **96**, 205123 (2017)

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A. Georges and O. Parcollet PRB **59**, 5341 (1999)
A. Eberlein, V. Kasper, S. Sachdev, and J. Steinberg, PRB **96**, 205123 (2017)

- Presence of quasiparticles should slow down thermalization, so *all* quantum systems obey

$$\tau_{\rm eq} > C \frac{\hbar}{k_B T} \quad , \quad \text{as } T \to 0.$$

S. Sachdev, *Quantum Phase Transitions*, Cambridge (1999)

Absence of quasiparticles $\Leftrightarrow$ Fastest possible thermalization

SYK models and black holes

- Black holes have an entropy proportional to their surface area, and a temperature, $T_H = \hbar c^3/(8\pi G M k_B)$.
- Black holes relax to thermal equilibrium in a 'Planckian' time $\sim \hbar/(k_B T_H) = 8\pi GM/c^3$.
- Black holes in $d+1$ spatial dimensions are similar to a quantum system without quasiparticles in d spatial dimensions.

Black holes

SYK models and black holes

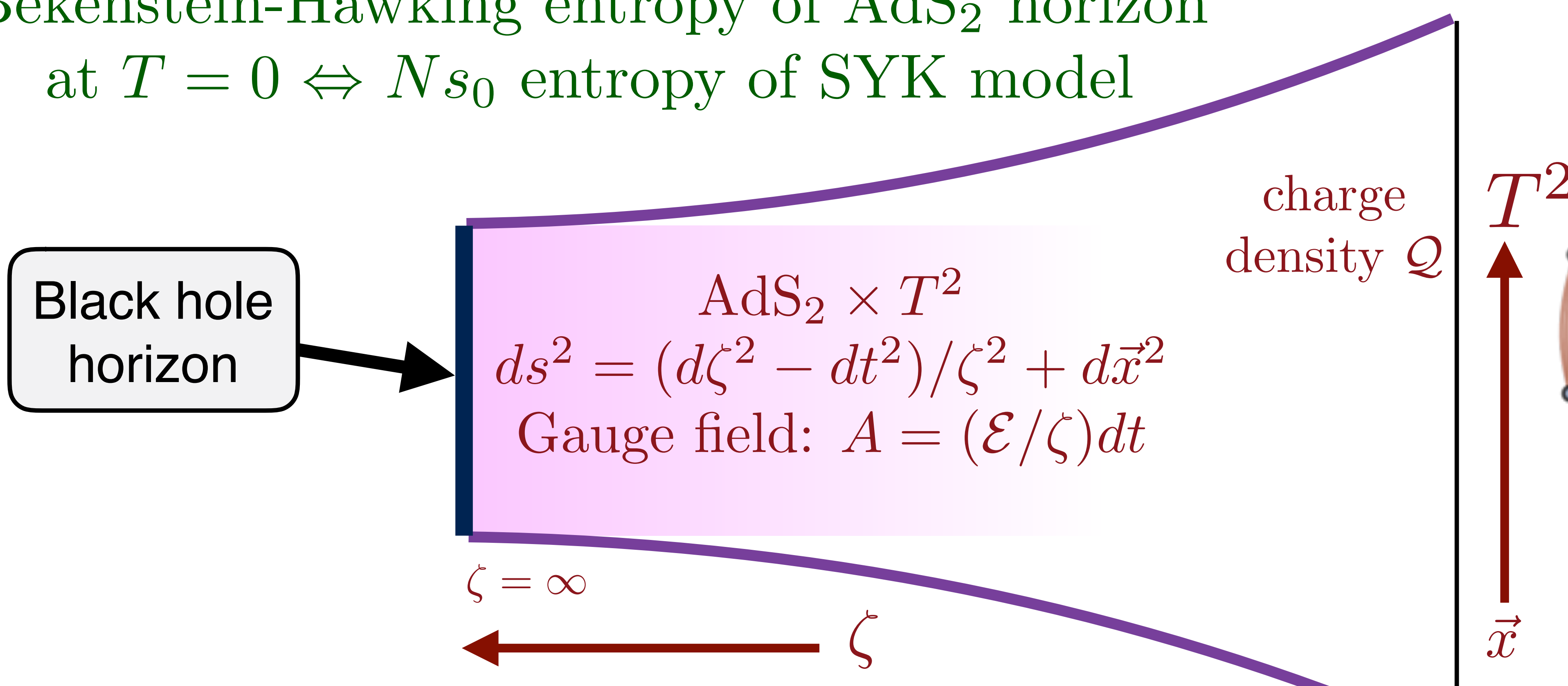
PHYSICAL REVIEW LETTERS **105**, 151602 (2010)

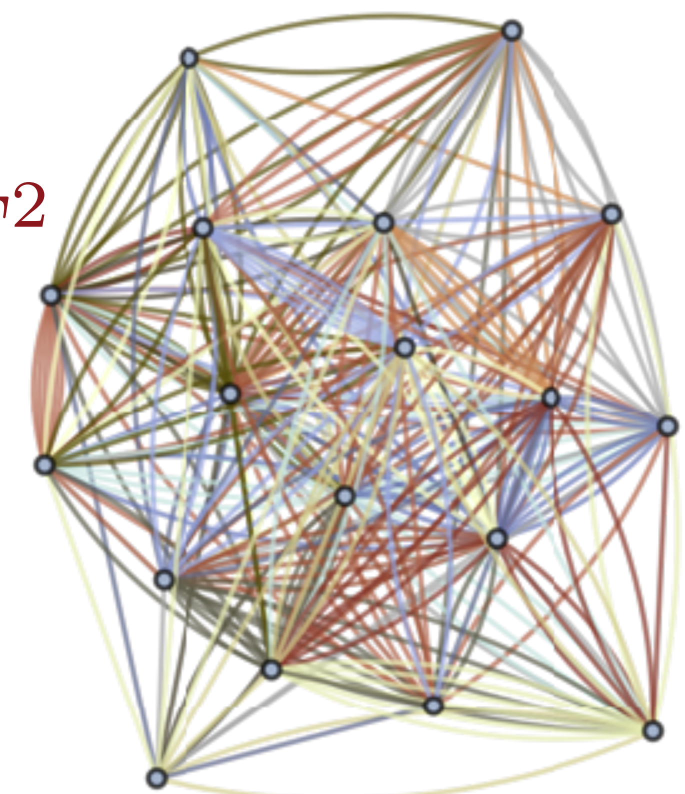
Holographic Metals and the Fractionalized Fermi Liquid

Subir Sachdev
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 23 June 2010; published 4 October 2010)

We show that there is a close correspondence between the physical properties of holographic metals near charged black holes in anti–de Sitter (AdS) space, and the fractionalized Fermi liquid phase of the lattice Anderson model. The latter phase has a "small" Fermi surface of conduction electrons, along with a spin liquid of local moments. This correspondence implies that certain mean-field gapless spin liquids are states of matter at nonzero density realizing the near-horizon, $AdS_2 \times R^2$ physics of Reissner-Nordström black holes.

Bekenstein-Hawking entropy of AdS_2 horizon
at $T = 0 \Leftrightarrow N s_0$ entropy of SYK model





Einstein-Maxwell theory + cosmological constant

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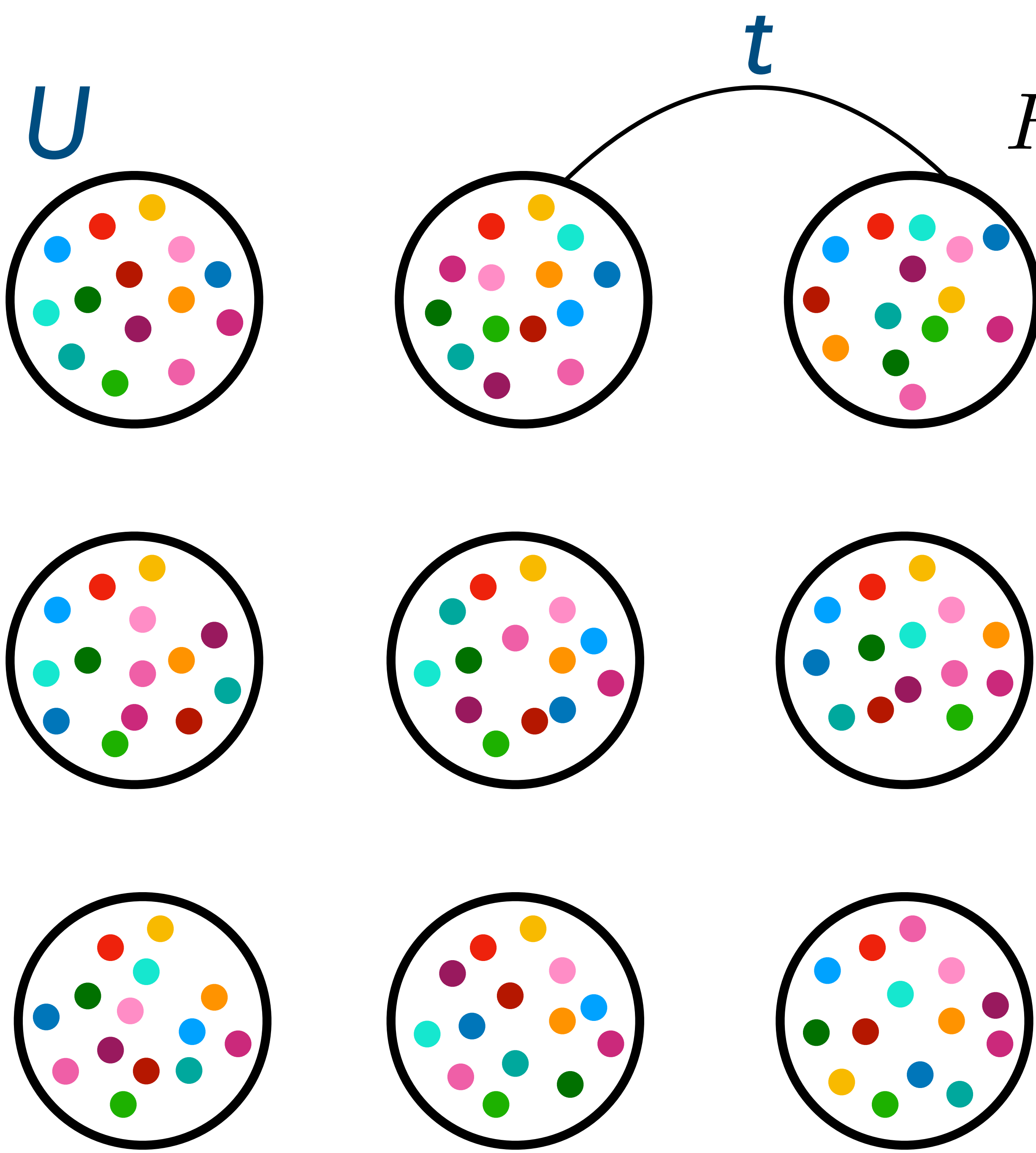
Coupled SYK Islands

SYK quantum islands of electrons with random hopping between them.



$$H = \sum_x \sum_{i<j,k<l} U_{ijkl,x} c^\dagger_{ix} c^\dagger_{jx} c_{kx} c_{lx}$$

$$+ \sum_{\langle xx' \rangle} \sum_{i,j} t_{ij,xx'} c^\dagger_{i,x} c_{j,x'}$$

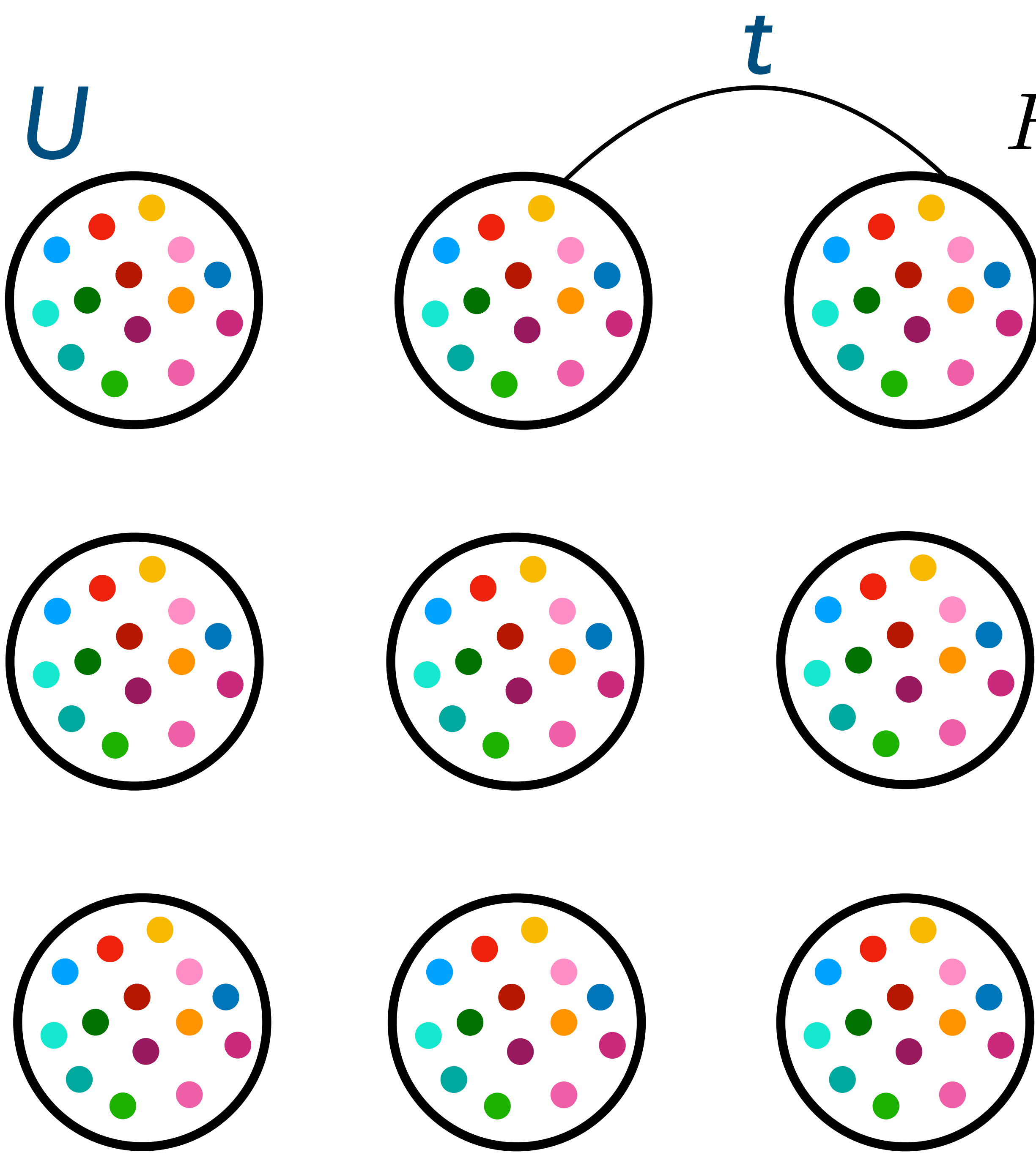
$$\overline{|U_{ijkl}|^2} = \frac{2U^2}{N^3} \qquad \overline{|t_{ij,x,x'}|^2} = t_0^2/N$$

Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017)

See also A. Georges and O. Parcollet PRB **59**, 5341 (1999)

Coupled SYK Islands

Can also use non-random *t*, and the same *U* on all "islands".



$$H = \sum_x \sum_{i<j,k<l} U_{ijkl} \quad c_{ix}^\dagger c_{jx}^\dagger c_{kx} c_{lx}$$

$$+ \sum_{\langle xx' \rangle} \sum_{i,j} t_{ij} \quad c_{i,x}^\dagger c_{j,x'}$$

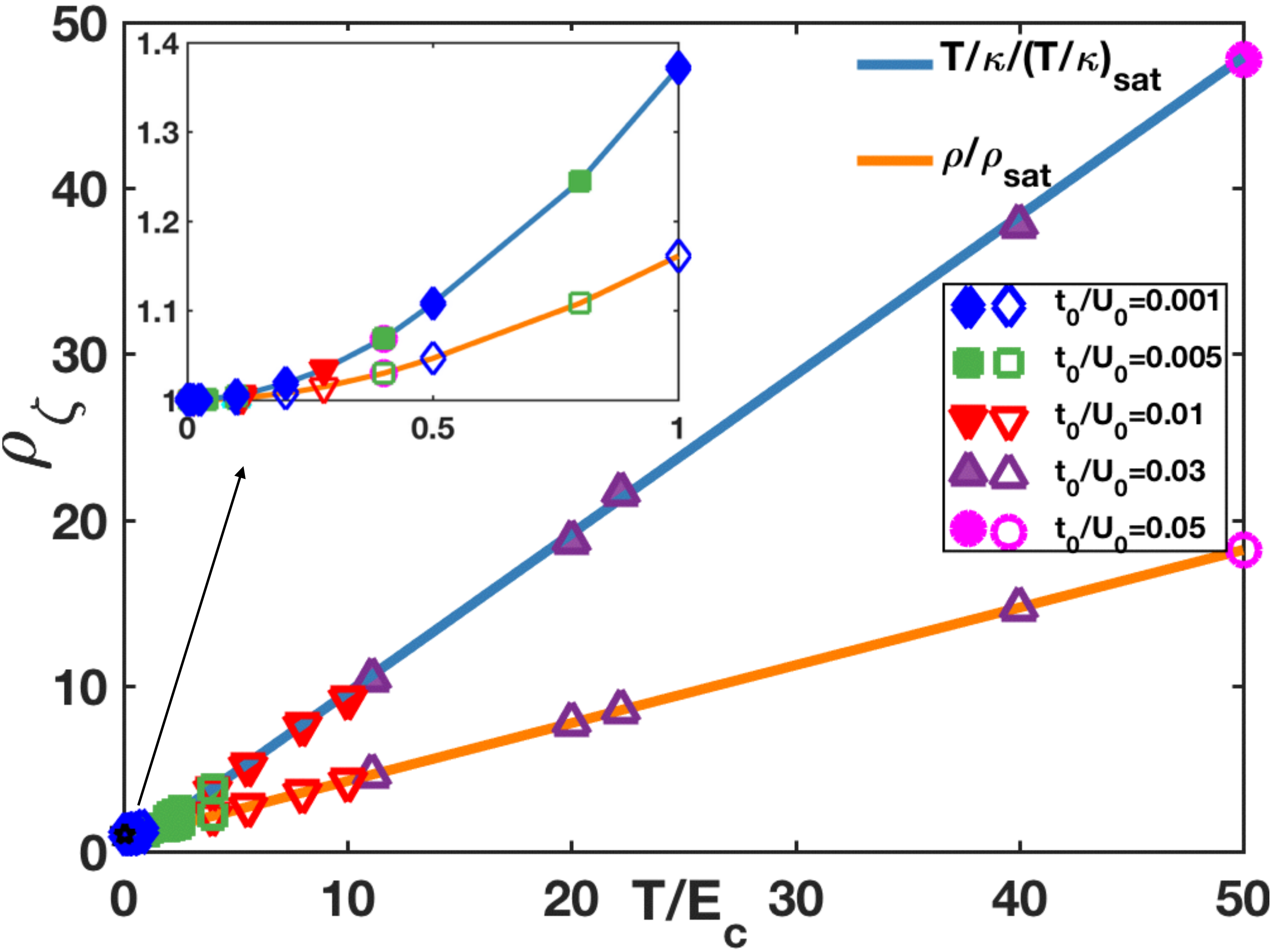
Pengfei Zhang, PRB **96**, 205138 (2017)

Debanjan Chowdhury, Yochai Werman, Erez Berg, T. Senthil, arXiv:1801.06178

See also A. Georges and O. Parcollet PRB **59**, 5341 (1999)

Coupled SYK Islands

Low 'coherence' scale



$$E_c \sim \frac{t_0^2}{U}$$

Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017)

See also A. Georges and O. Parcollet PRB **59**, 5341 (1999)

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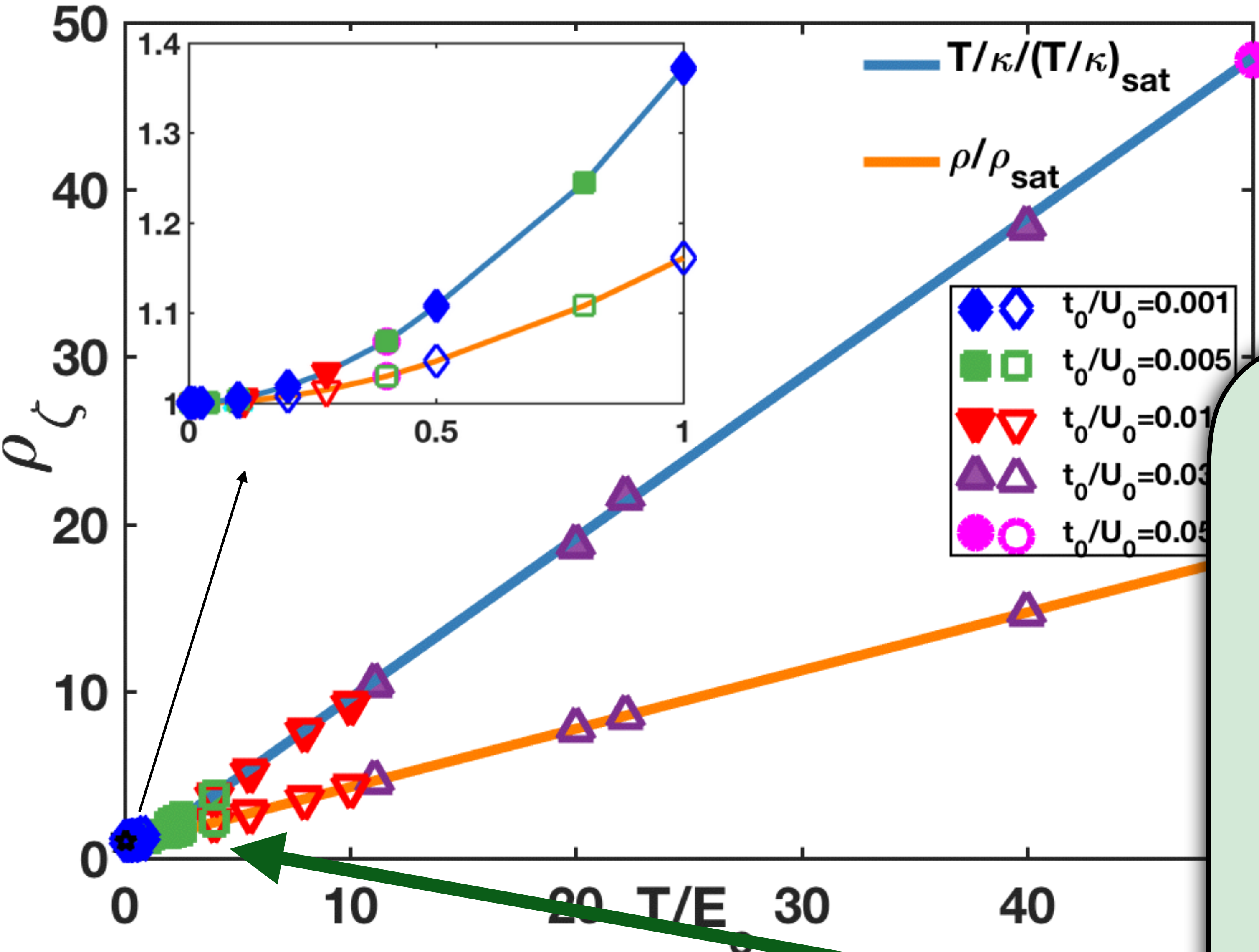

For $T < E_c$, the resistivity, ρ, and entropy density, s, are

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

$$s \sim s_0\left(\frac{T}{E_c}\right)$$

Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017)

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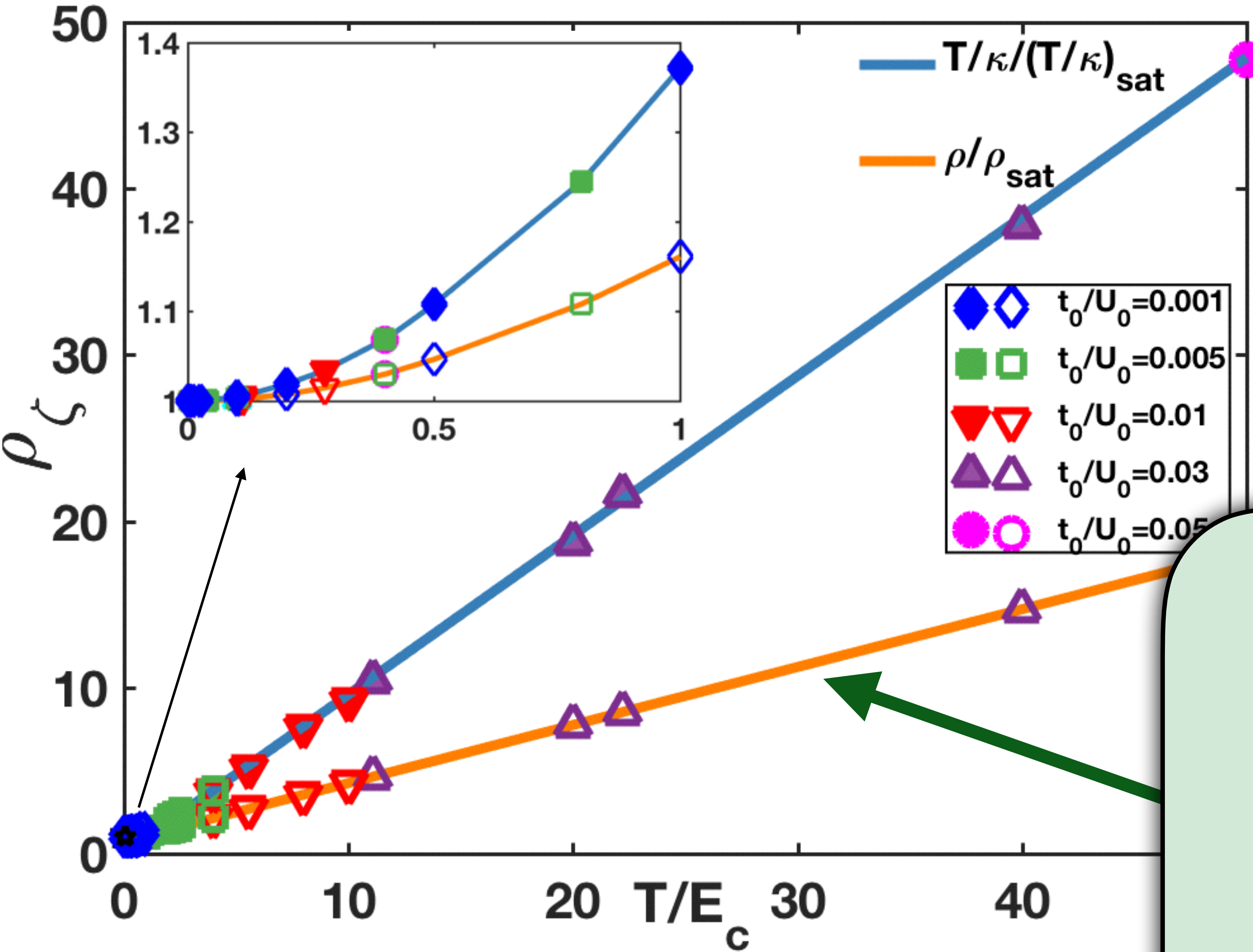


For $E_c < T < U$, the resistivity, ρ, and entropy density, s, are

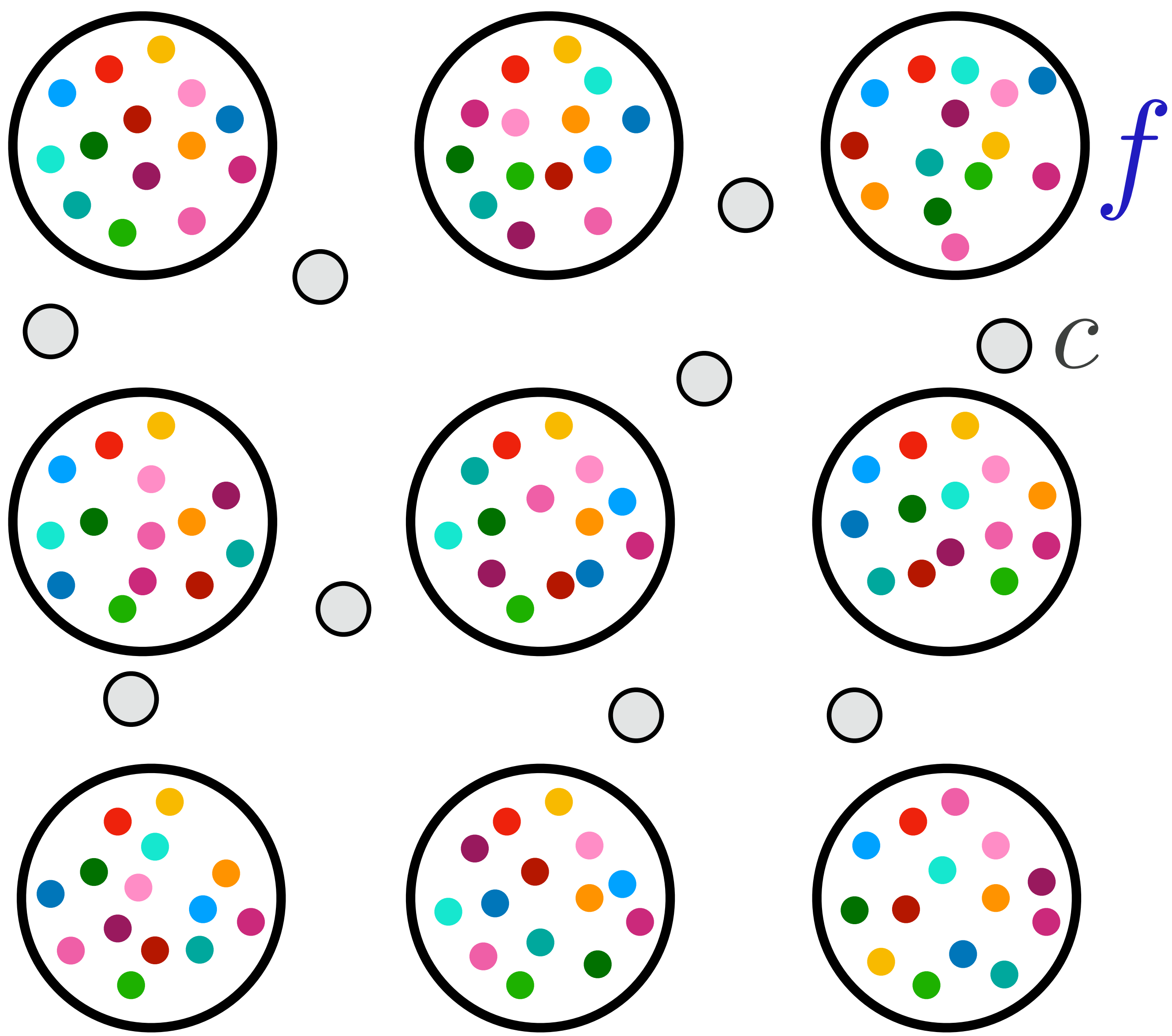
$$\rho \sim \frac{h}{e^2}\left(\frac{T}{E_c}\right) \quad , \qquad s = s_0$$

Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017)

See also A. Georges and O. Parcollet PRB **59**, 5341 (1999)

SYK-Kondo lattice models

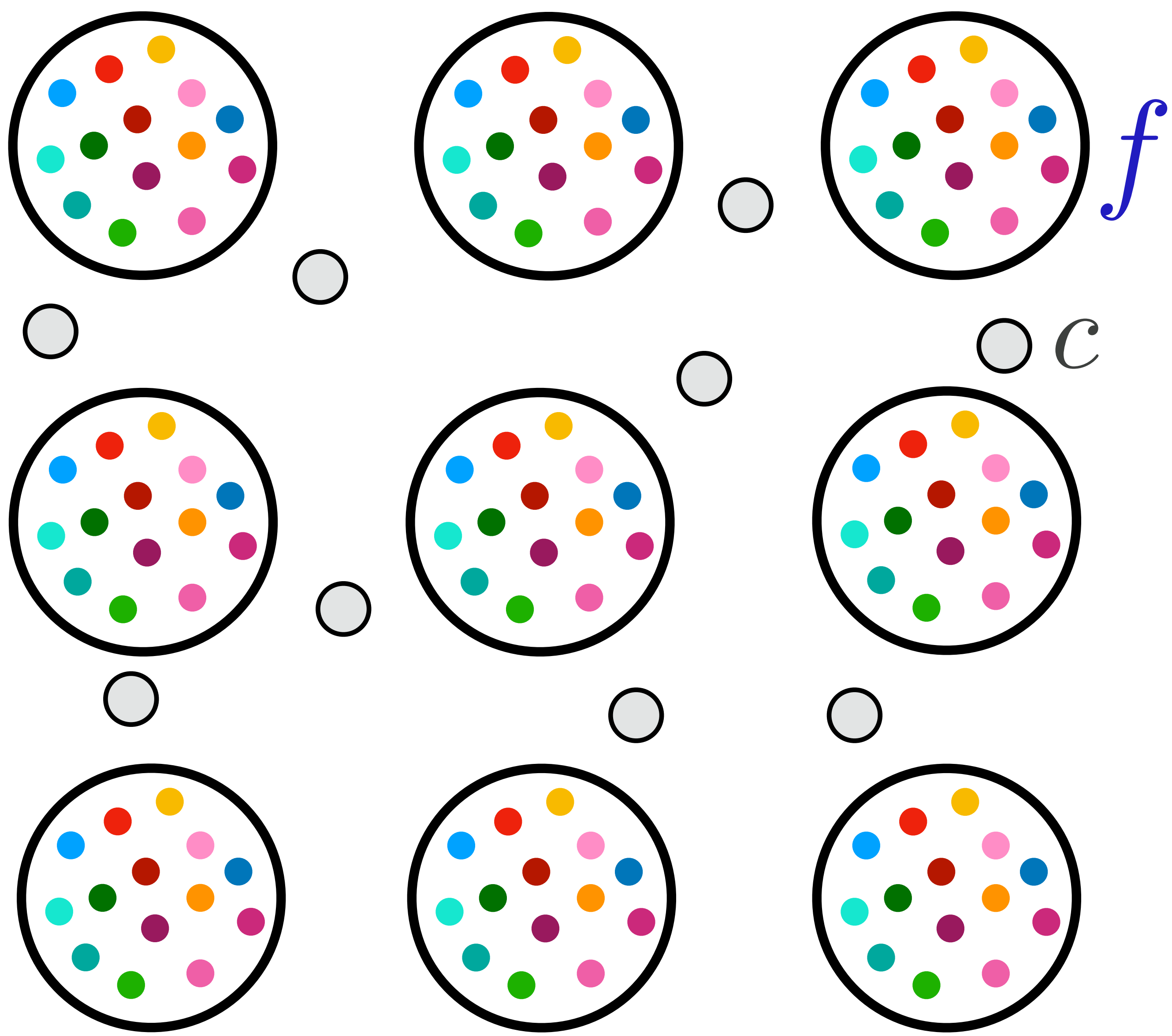
Mobile electrons (c) interacting with SYK quantum islands (f) with random exchange interactions.



Aavishkar A. Patel, John McGreevy, Daniel P. Arovas, Subir Sachdev, PRX **8**, 021049 (2018)

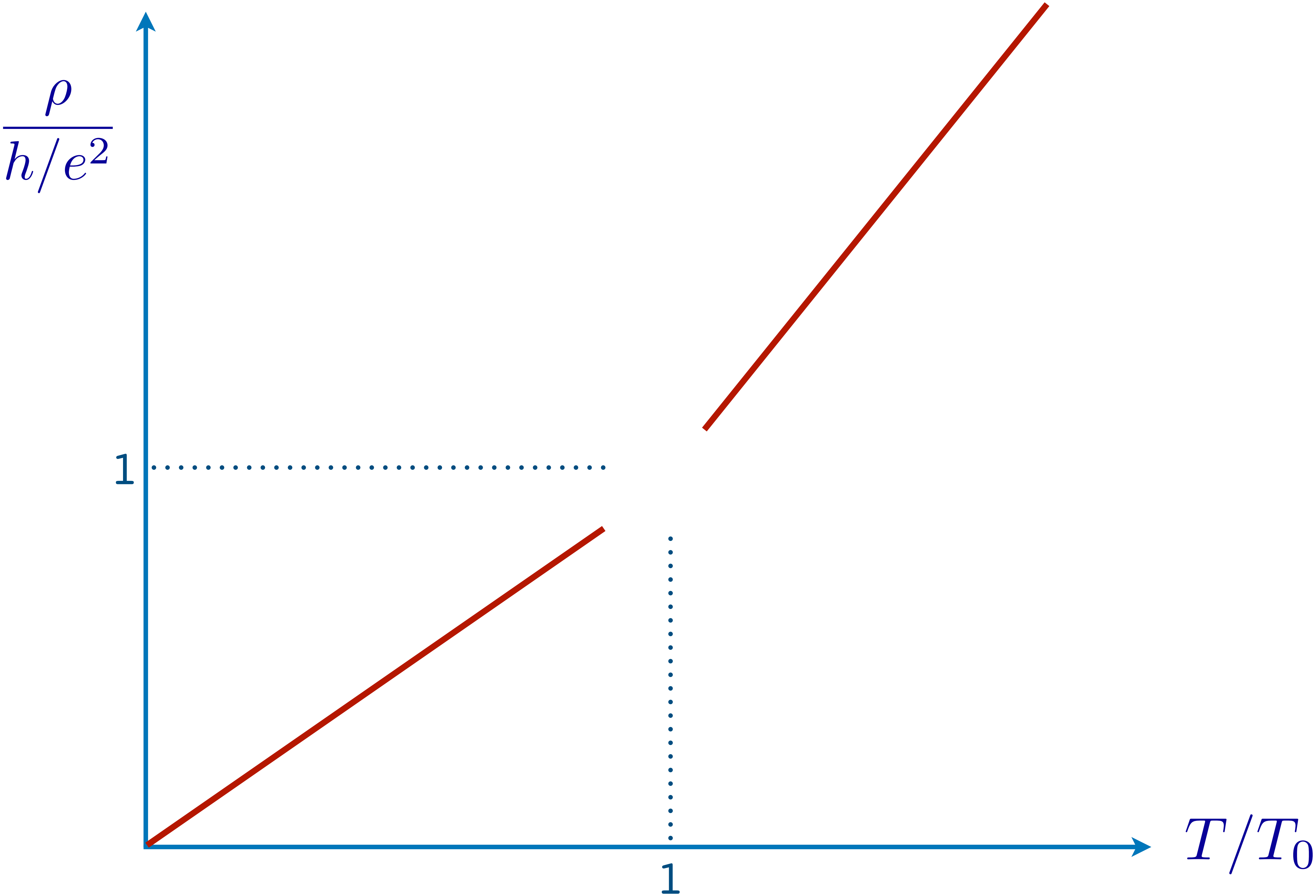
SYK-Kondo lattice models

Mobile electrons (c) interacting with SYK quantum islands (f) with non-random exchange interactions.



Debanjan Chowdhury, Yochai Werman, Erez Berg, T. Senthil, arXiv:1801.06178
(see poster by Debanjan Chowdhury)

SYK-Kondo lattice models



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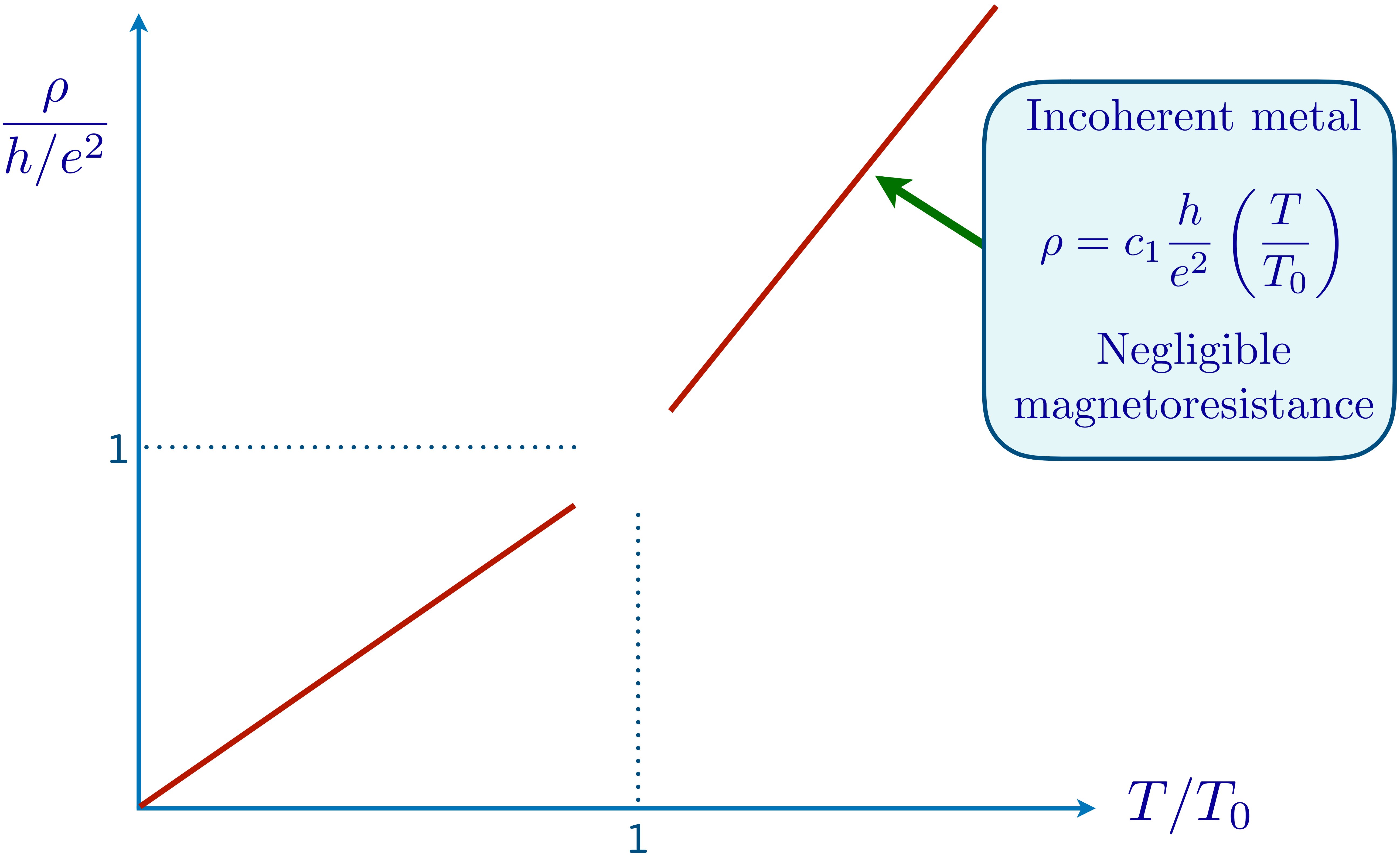

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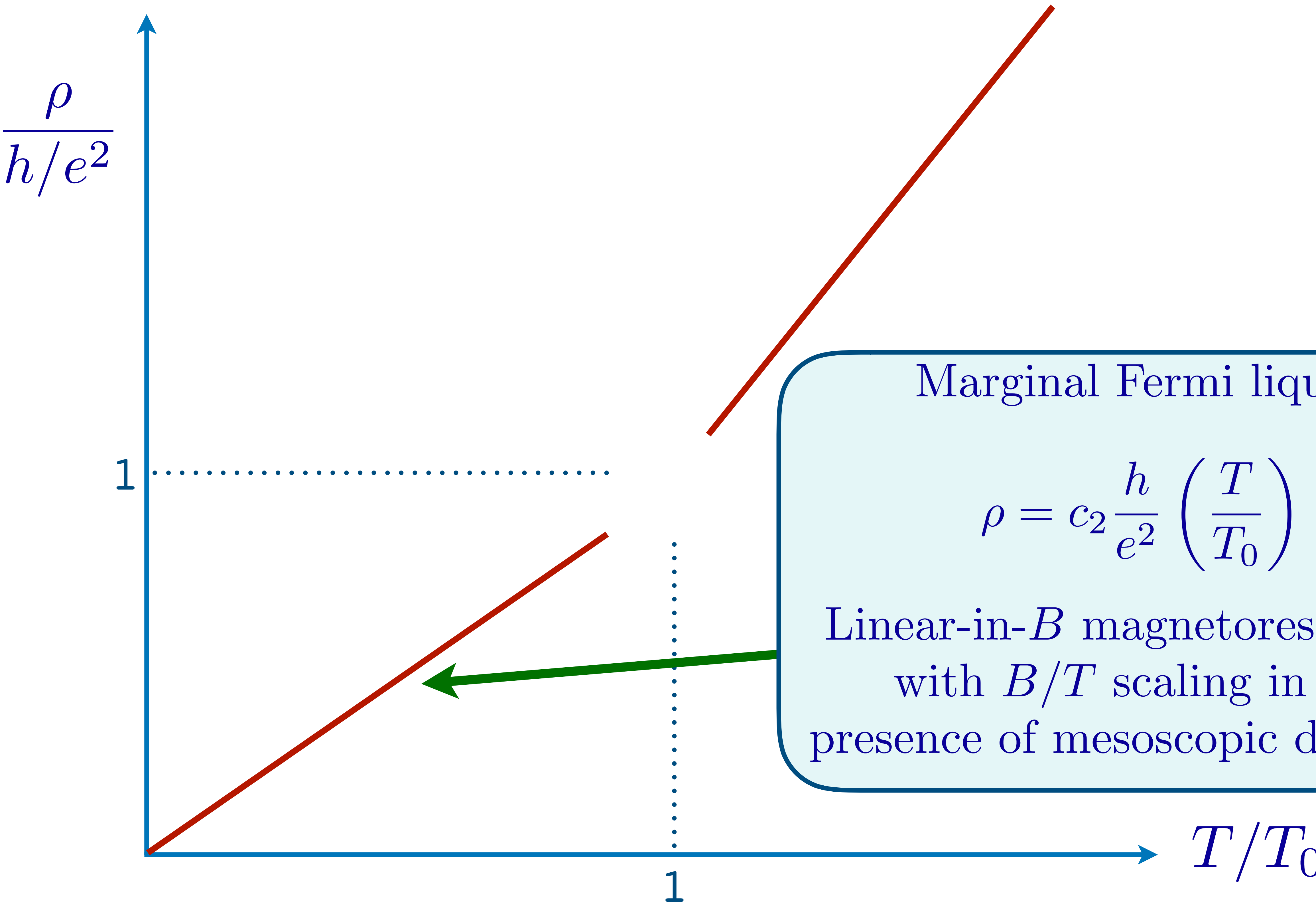


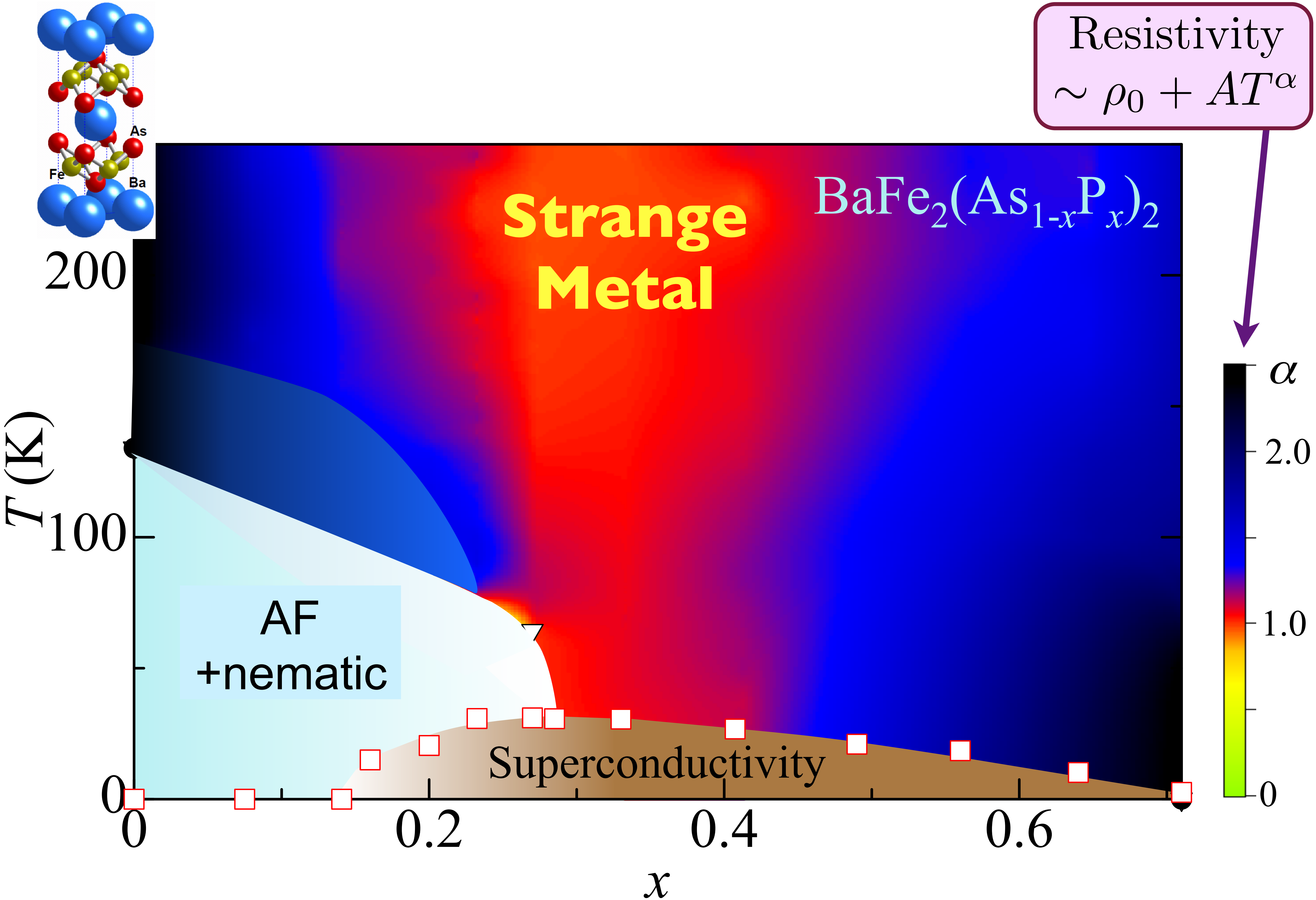
Marginal Fermi liquid

$$\rho = c_2 \frac{h}{e^2}\left(\frac{T}{T_0}\right)$$

Linear-in-B magnetoresistance with B/T scaling in the presence of mesoscopic disorder.

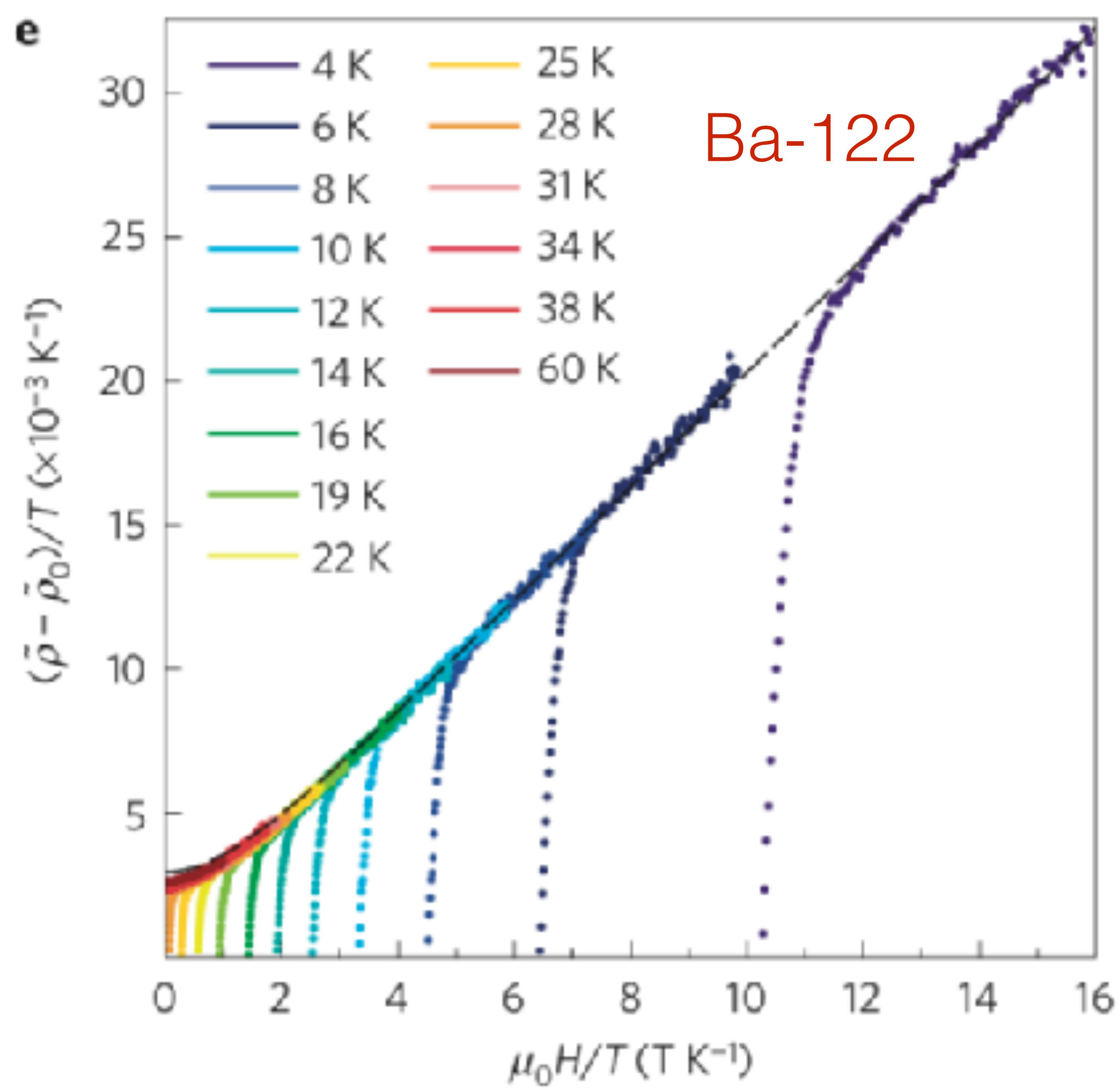
Debanjan Chowdhury, Yochai Werman, Erez Berg, T. Senthil, arXiv:1801.06178

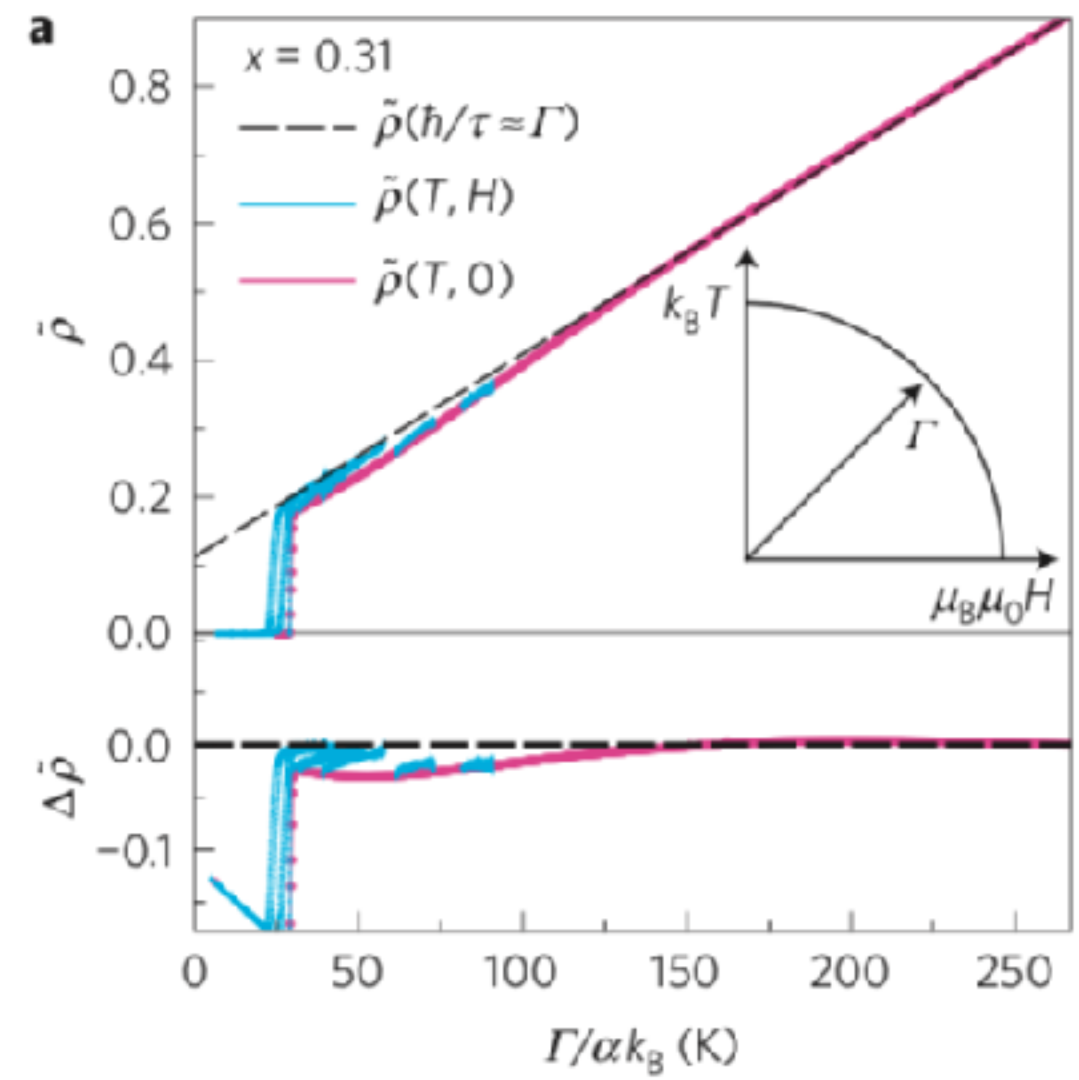
Aavishkar A. Patel, John McGreevy, Daniel P. Arovas, Subir Sachdev, PRX **8**, 021049 (2018)



S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)

Linear-in-B magnetoresistance with B/T scaling



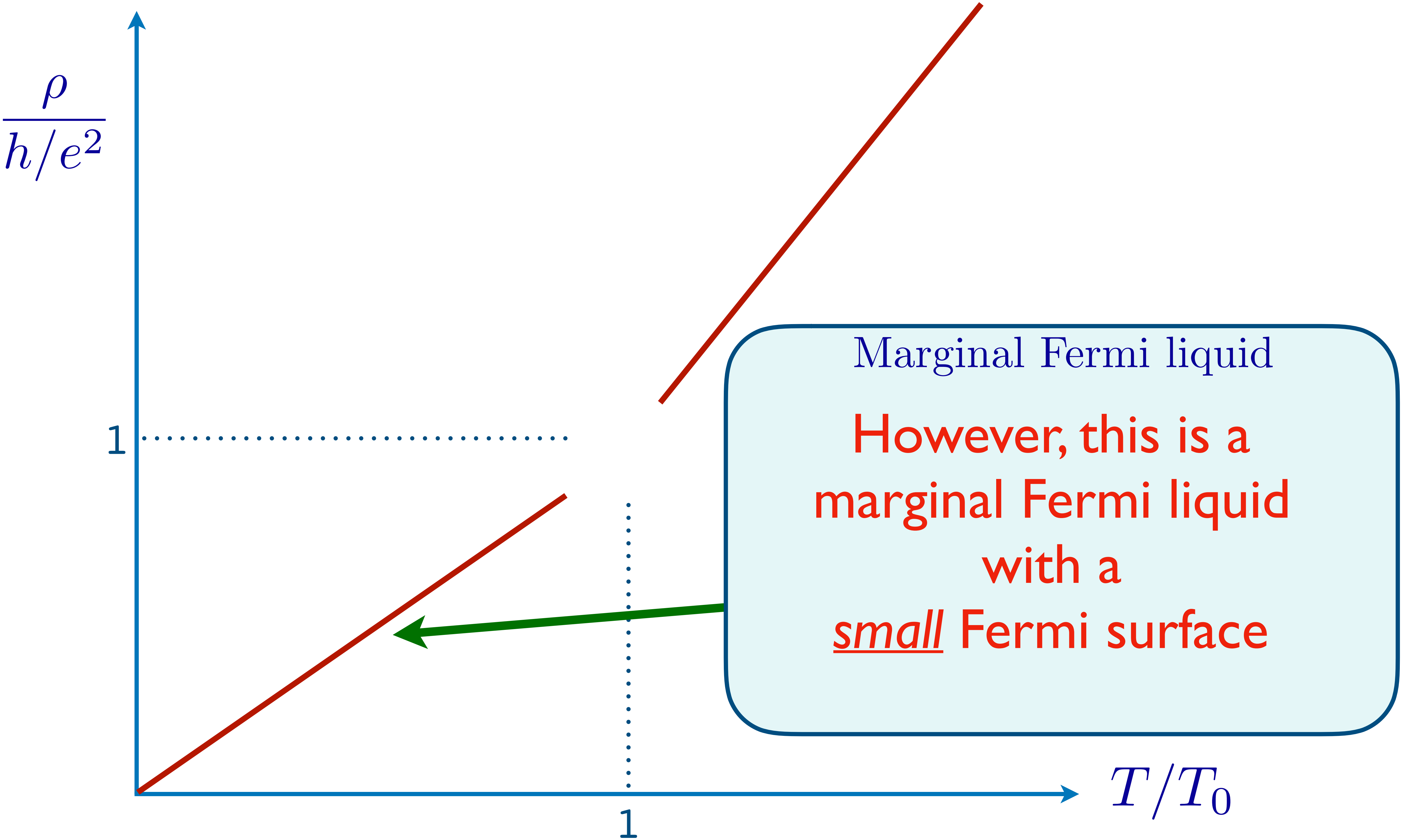


$$\rho(H,T)-\rho(0,0)\propto\sqrt{(\alpha k_B T)^2+\left(\gamma\mu_B\mu_0 H\right)^2}\equiv\Gamma$$

I. M. Hayes, R. D. McDonald, N. P. Breznay, T. Helm, P. J. W. Moll, M. Wartenbe, A. Shekhter, and J. G. Analytis, Nature Physics 12, 916 (2016)

See talk by James Analytis

SYK-Kondo lattice models



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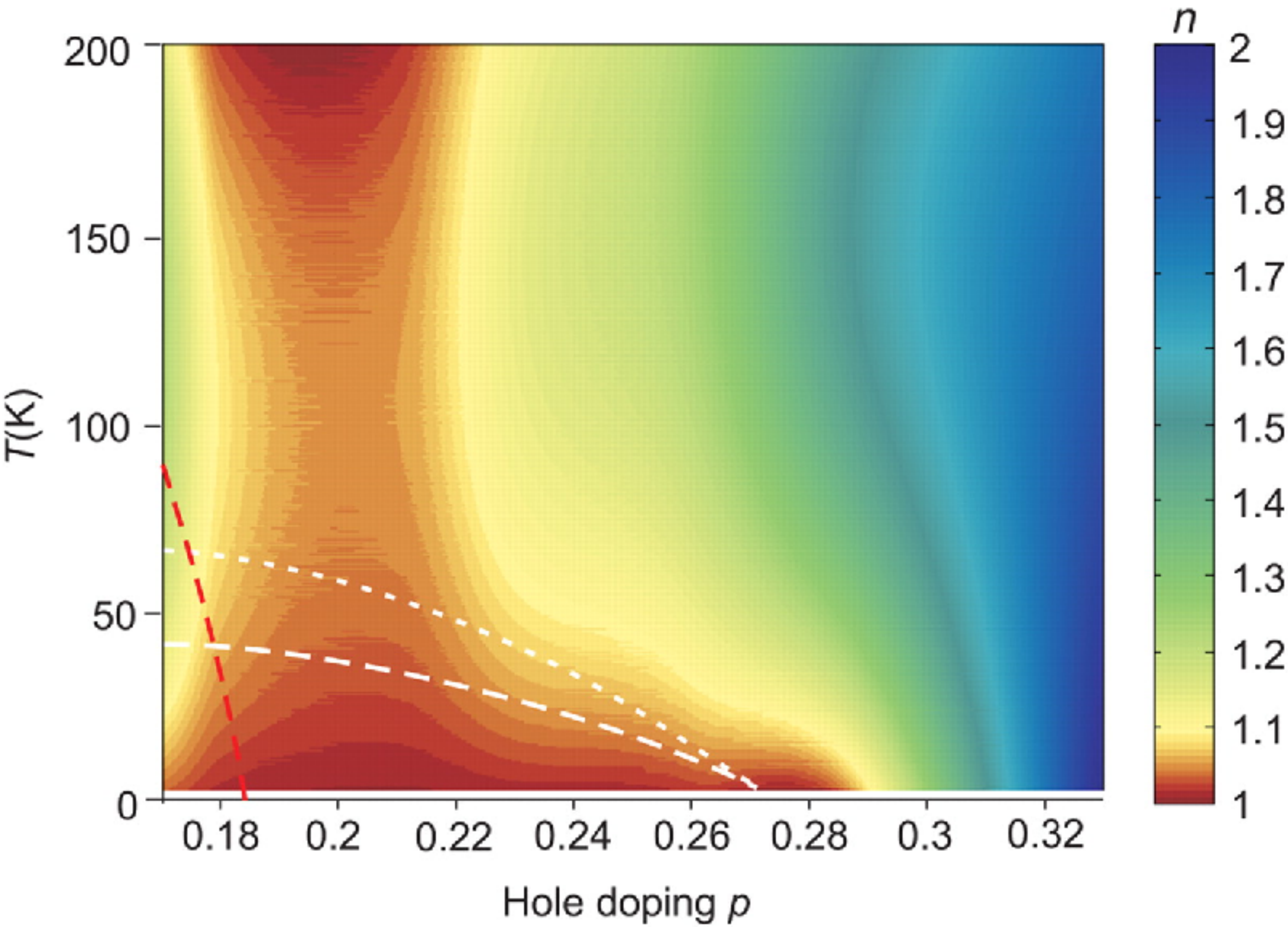
SCIENCE VOL 323 30 JANUARY 2009
603

Anomalous Criticality in the Electrical Resistivity of $La_{2-x}Sr_xCuO_4$

R. A. Cooper,[1] Y. Wang,[1] B. Vignolle,[2] O. J. Lipscombe,[1] S. M. Hayden,[1] Y. Tanabe,[3] T. Adachi,[3] Y. Koike,[3] M. Nohara,[4]* H. Takagi,[4] Cyril Proust,[2] N. E. Hussey[1]†



Universal T-linear resistivity and Planckian limit in overdoped cuprates

arXiv:1805.02512

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]

From the resistivity, they determined the value of the number α defined by

$$\rho(T) = \rho_0 + \alpha \frac{h}{2e^2}\left(\frac{T}{T_F}\right)$$

where $T_F = (\pi\hbar^2/k_B)(n/m^*)$ and m^* is determined from the specific heat. This expression is obtained from the Drude form $\rho = m^*/(ne^2\tau)$ and $\hbar/\tau = \alpha\, k_B T$.

Universal *T*-linear resistivity and Planckian limit in overdoped cuprates

arXiv:1805.02512

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]

Material		n (10^{27} m^{-3})	m^* (m_0)	A_1 / d (Ω / K)	$h / (2e^2 T_F)$ (Ω / K)	α
Bi2212	$p = 0.23$	6.8	8.4 ± 1.6	8.0 ± 0.9	7.4 ± 1.4	1.1 ± 0.3
Bi2201	$p \sim 0.4$	3.5	7 ± 1.5	8 ± 2	8 ± 2	1.0 ± 0.4
LSCO	$p = 0.26$	7.8	9.8 ± 1.7	8.2 ± 1.0	8.9 ± 1.8	0.9 ± 0.3
Nd-LSCO	$p = 0.24$	7.9	12 ± 4	7.4 ± 0.8	10.6 ± 3.7	0.7 ± 0.4
PCCO	$x = 0.17$	8.8	2.4 ± 0.1	1.7 ± 0.3	2.1 ± 0.1	0.8 ± 0.2
LCCO	$x = 0.15$	9.0	3.0 ± 0.3	3.0 ± 0.45	2.6 ± 0.3	1.2 ± 0.3
TMTSF	P = 11 kbar	1.4	1.15 ± 0.2	2.8 ± 0.3	2.8 ± 0.4	1.0 ± 0.3

Slope of *T*-linear resistivity vs Planckian limit in seven materials.

Electronic spectrum in pseudogap metal is well described by the Higgs phase of a SU(2) gauge theory

Wei Wu, M. S. Scheurer, S. Chatterjee, S. Sachdev, A. Georges, and M. Ferrero, PRX **8**, 021048 (2018)

M. S. Scheurer, S. Chatterjee, Wei Wu, M. Ferrero, A. Georges, and S. Sachdev, PNAS **115**, E3665 (2018)

See talk by Antoine Georges and poster by Mathias Scheurer

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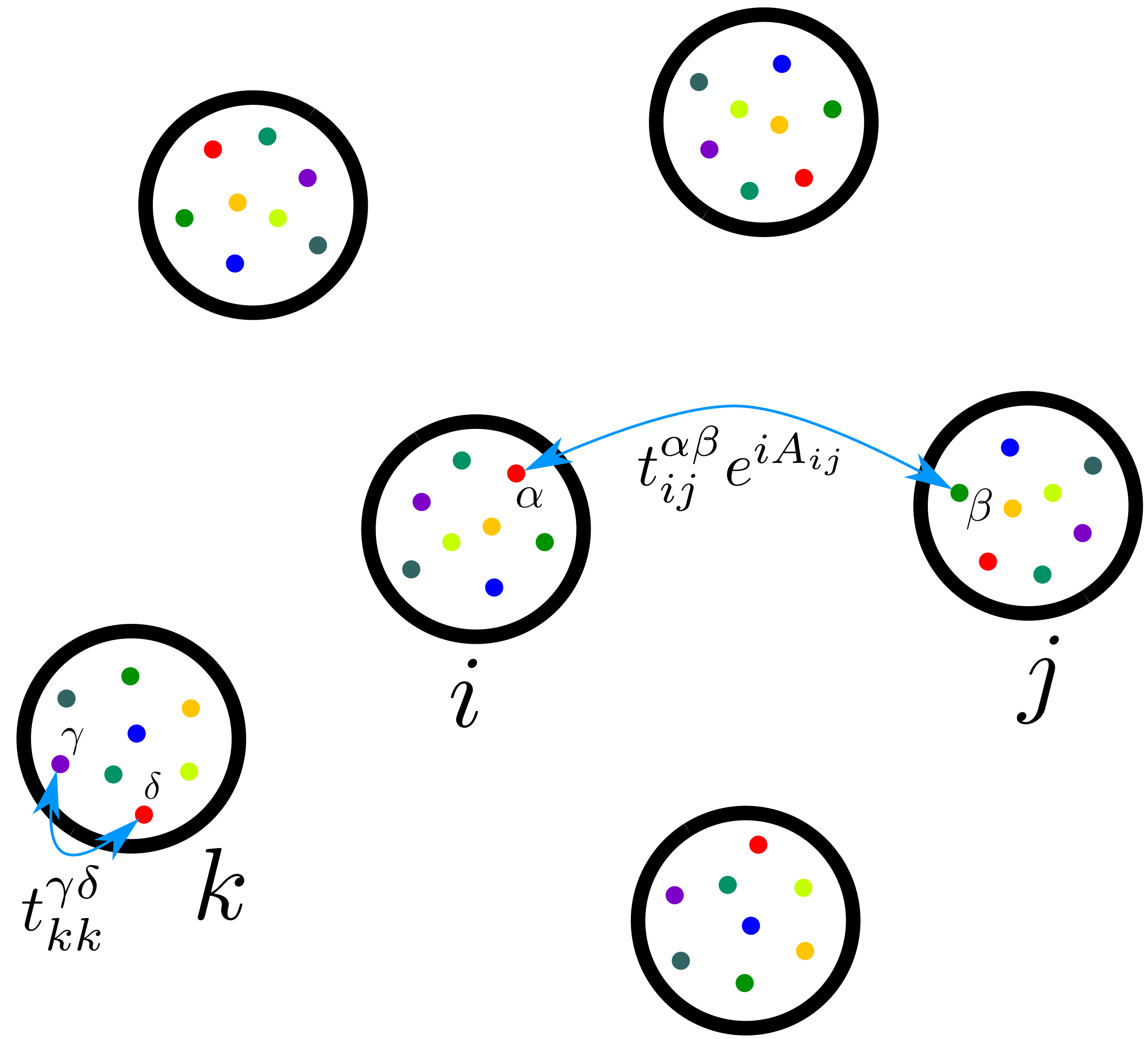
Optimal doping critical point is associated with vanishing of the Higgs condensate. Overdoped regime is described by (a large Fermi surface of) electrically-charged fermions coupled to an emergent SU(2) gauge field in the presence of disorder

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, PRB **80**, 155129 (2009)

D. Chowdhury and S. Sachdev, PRB **91**, 115123 (2015)

Fermions with random hopping coupled to a fluctuating U(1) gauge field

Aavishkar Patel
(see poster)



$$H = -\frac{1}{(MN)^{1/2}} \sum_{ij=1}^{N} \sum_{\alpha\beta=1}^{M} \left[t_{ij}^{\alpha\beta} e^{iA_{ij}} f_{i\alpha}^{\dagger} f_{j\beta} + (MN)^{1/2} \mu \delta_{ij}^{\alpha\beta} f_{i\alpha}^{\dagger} f_{i\alpha} \right]$$

$$\ll t_{ij}^{\alpha\beta} t_{ji}^{\beta\alpha} \gg = \ll |t_{ij}^{\alpha\beta}|^2 \gg = t^2, \quad A_{ji} = -A_{ij}.$$

Fermions with random hopping coupled to a fluctuating U(1) gauge field

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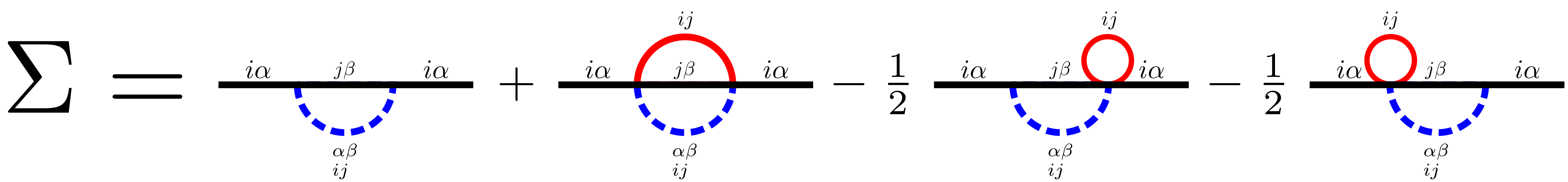
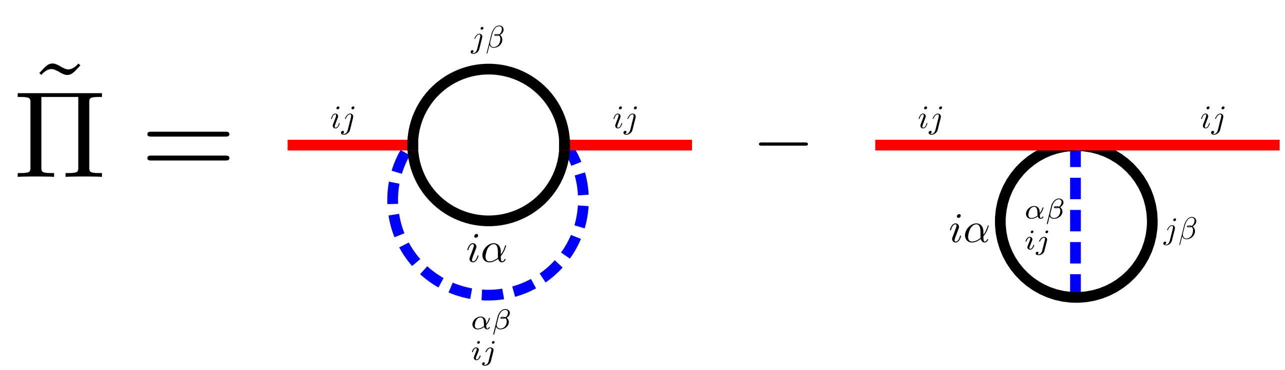
(see poster)

$$\Sigma(i\omega_n) = t^2 G(i\omega_n) + t^2 T \sum_{\Omega_m \neq 0} \frac{G(i\omega_n + i\Omega_m) - G(i\omega_n)}{\Pi(i\Omega_m) - \Pi(i\Omega_m = 0)},$$

$$\Pi(i\Omega_m) = 2t^2 T \frac{M}{N} \sum_{\omega_n} G(i\omega_n) G(i\omega_n + i\Omega_m), \quad G(i\omega_n) = \frac{1}{i\omega_n + \mu - \Sigma(i\omega_n)}.$$





Fermions with random hopping coupled to a fluctuating U(1) gauge field

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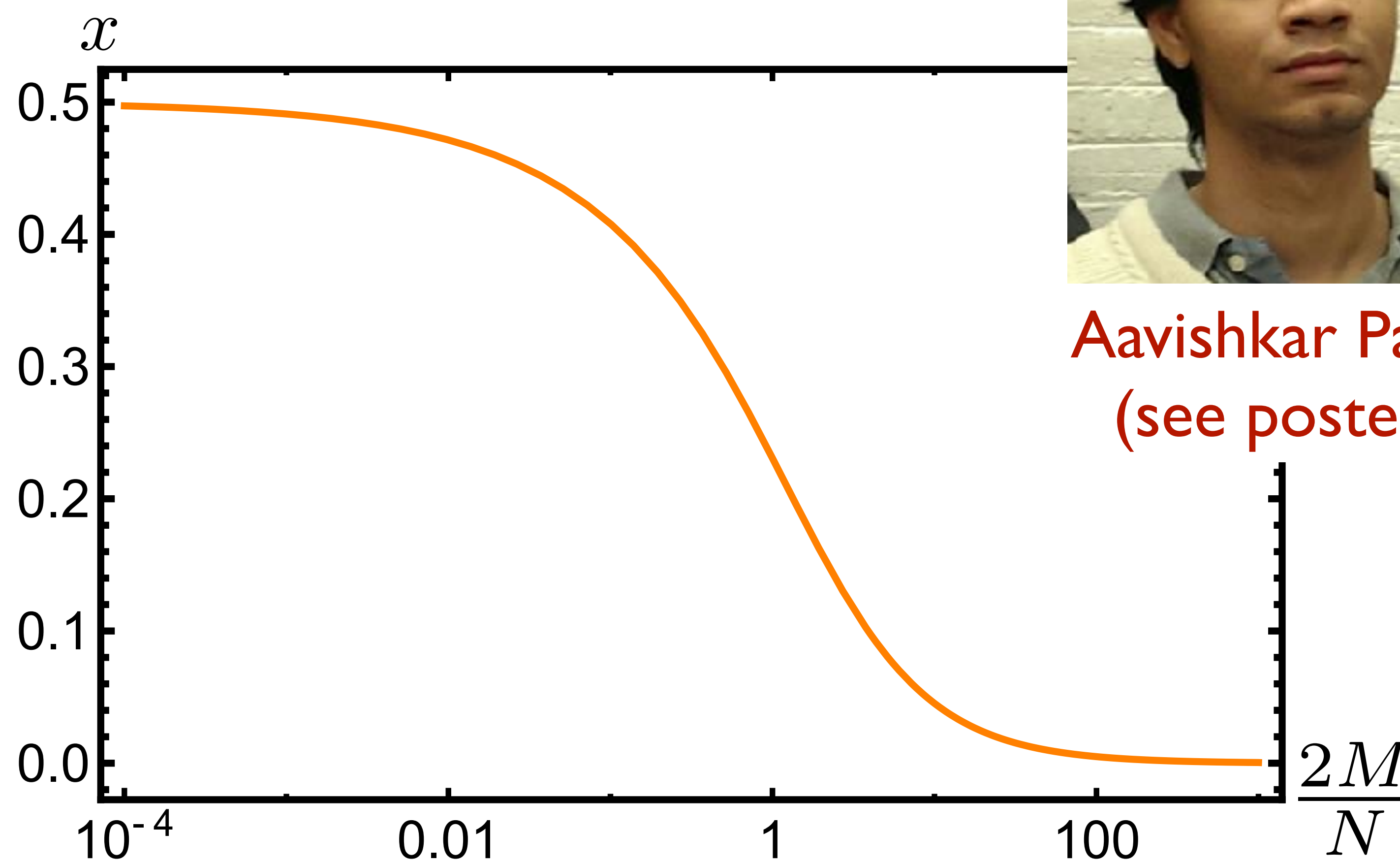


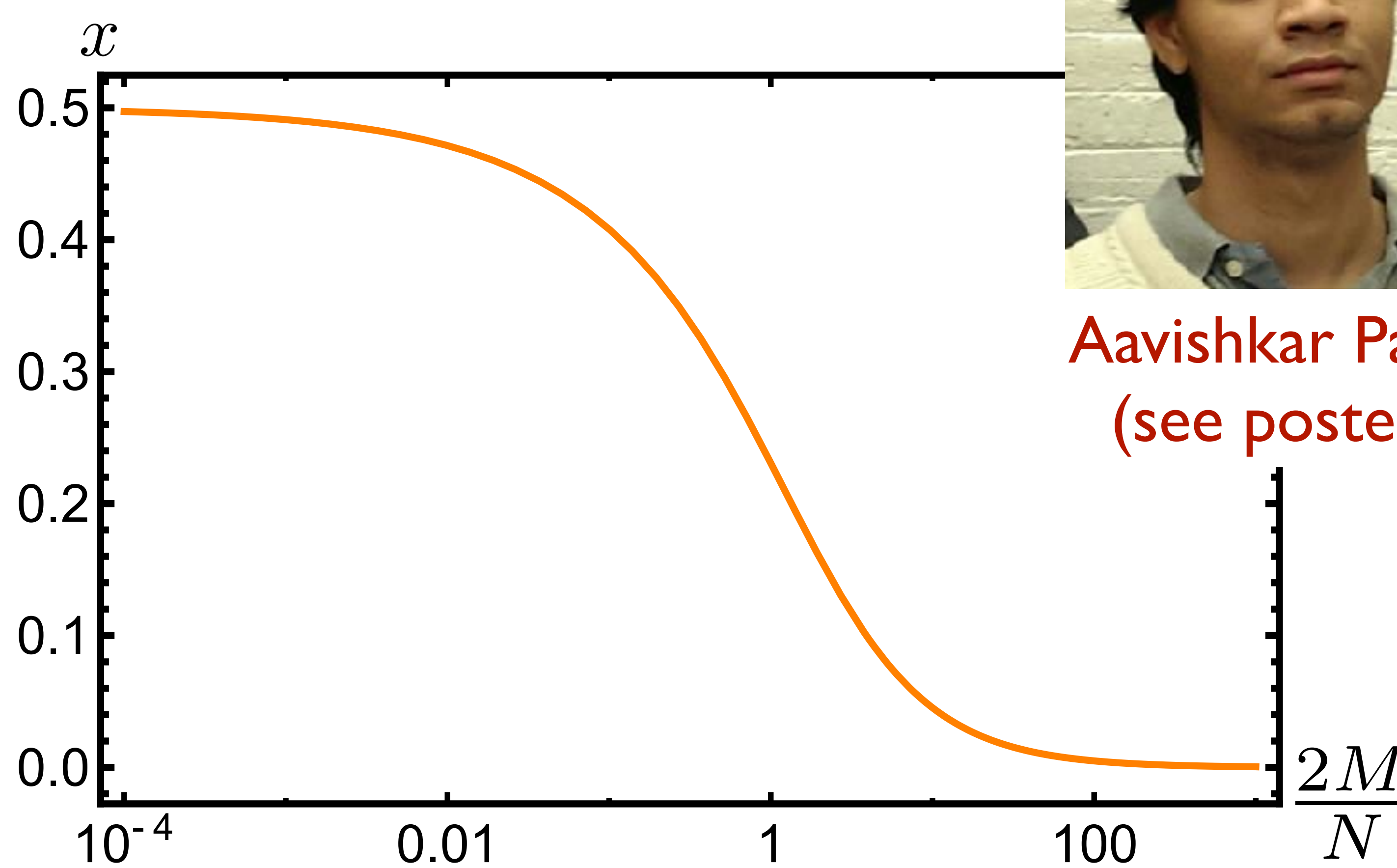
General low energy solution

$$G(\tau > 0) = -\frac{C(\mathcal{E})}{t^{1-x}\tau^{1-x}}, \quad G(\tau < 0) = \frac{C(\mathcal{E})e^{-2\pi\mathcal{E}}}{t^{1-x}|\tau|^{1-x}}.$$

where $\mathcal{E}$ is a parameter universally related to the filling fraction ($\mathcal{E} = 0$ at half-filling). The exponent x is the solution to

$$\frac{(1/x - 2)(\cosh(2\pi\mathcal{E}) - \cos(\pi x))}{\tan(\pi x)\sin(\pi x)} = \frac{2M}{N}.$$

Fermions with random hopping coupled to a fluctuating U(1) gauge field



Aavishkar Patel
(see poster)

$$\text{Resistivity} \quad \rho \sim \frac{h}{e^2} \left(\frac{T}{t} \right)^{2x}$$

Disordered strange metal as $T \to 0$
with <u>*all*</u> electrons contributing to transport.

The SYK model

No quasiparticles

- Rapid local thermal equilibration (of fermion correlators) in a 'Planckian' time

$$\tau_{\rm eq} \sim \frac{\hbar}{k_B T} \quad , \quad \text{as } T \to 0.$$

A. Georges and O. Parcollet PRB **59**, 5341 (1999)
A. Eberlein, V. Kasper, S. Sachdev, and J. Steinberg, PRB **96**, 205123 (2017)

- Presence of quasiparticles should slow down thermalization, so *all* quantum systems obey

$$\tau_{\rm eq} > C \frac{\hbar}{k_B T} \quad , \quad \text{as } T \to 0.$$

S. Sachdev, *Quantum Phase Transitions*, Cambridge (1999)

Absence of quasiparticles $\Leftrightarrow$ Fastest possible thermalization

Conclusions

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- SYK-Kondo lattice models: Bad metal behavior with $\rho \sim (T/T_0)(h/e^2)$ for $T > T_0$, and marginal Fermi liquid (MFL) behavior for $T < T_0$ with $\rho \sim (T/T_0)(h/e^2)$. MFL regime has <u>*small*</u> Fermi surface, and magnetoresistance B/T scaling (with mesoscopic disorder).

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- SYK U(1) gauge theory: solvable model with finite density of fermions, emergent gauge fields, and disorder. Strange metal behavior with $\rho \sim (T/t)^{2x}(h/e^2)$ as $T \to 0$, with <u>*all*</u> electrons mobile.