

Quantum matter without quasiparticles: strange metals and black holes

University of California, Santa Cruz
October 9, 2017

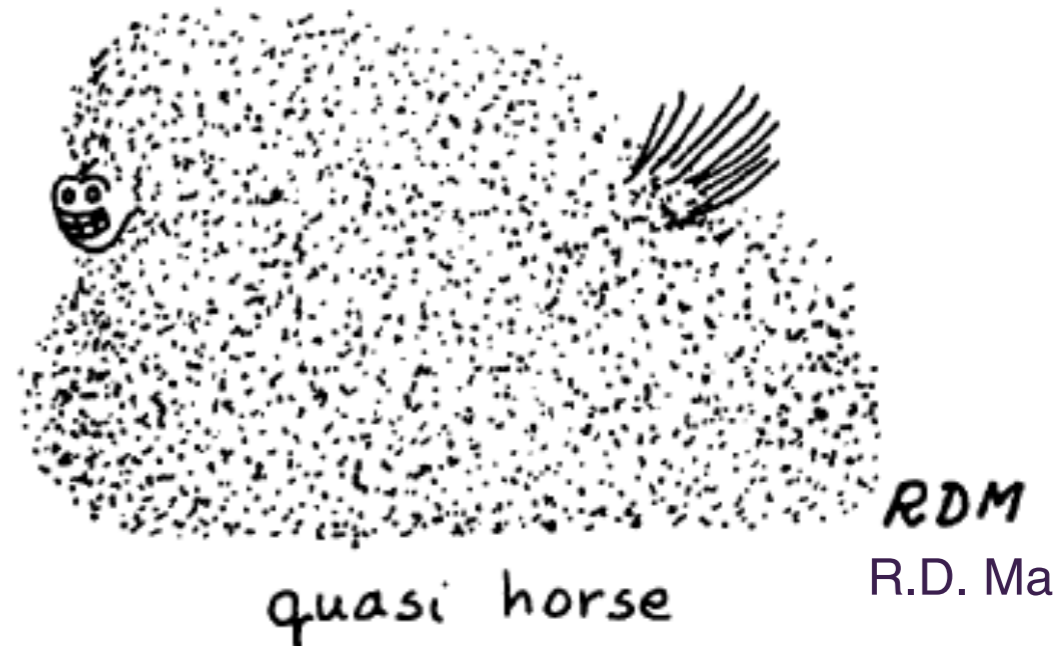
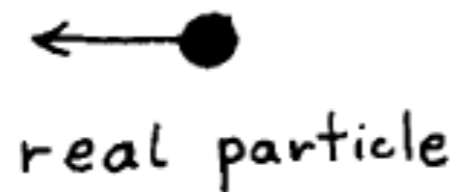
Subir Sachdev

Talk online: sachdev.physics.harvard.edu



Quantum matter with quasiparticles:

A quasiparticle is an “excited lump” in the many-electron state which responds just like an ordinary particle.



Quantum matter with quasiparticles:

The quasiparticle idea is the key reason for the many successes of quantum condensed matter physics:

- 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)

Quantum matter without quasiparticles

Strange metal

Entangled electrons lead to “strange” temperature dependence of resistivity and other properties

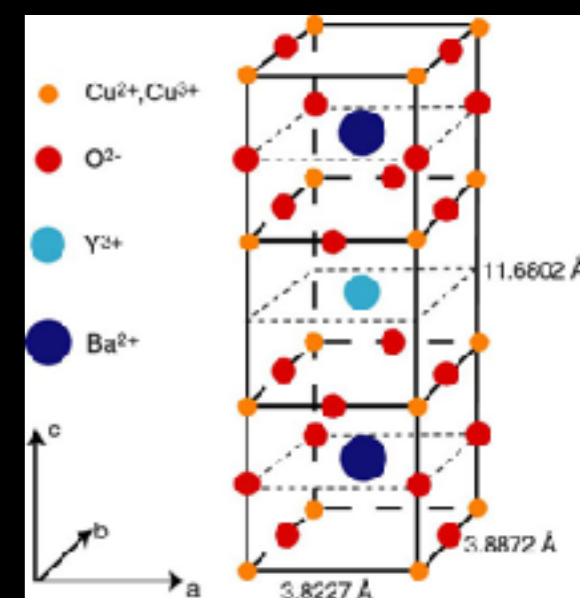
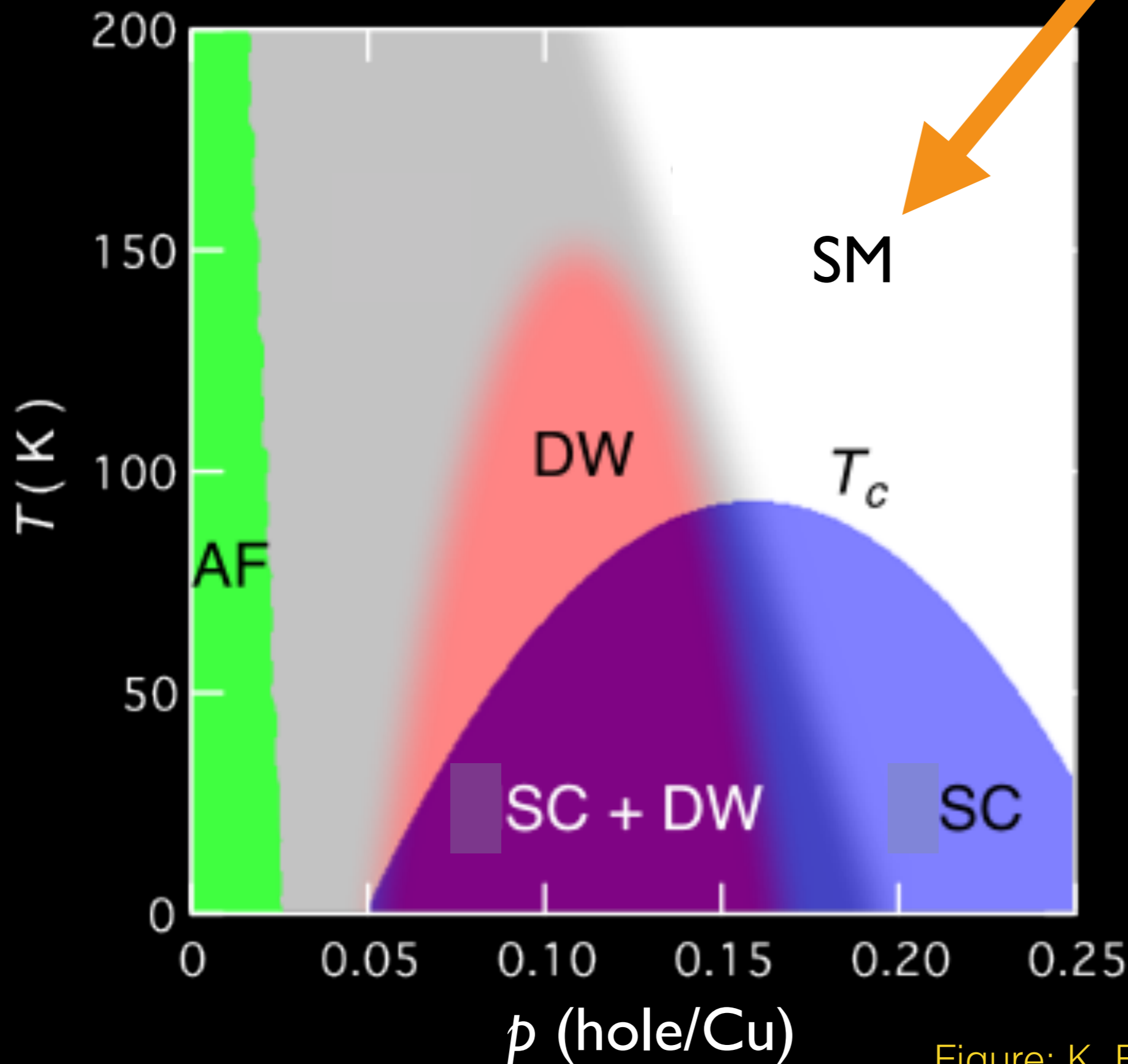
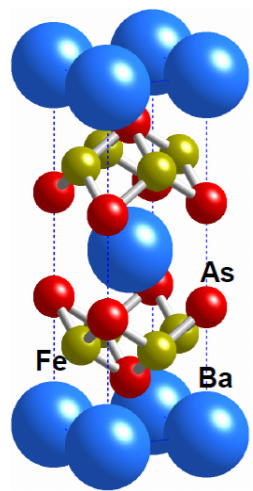
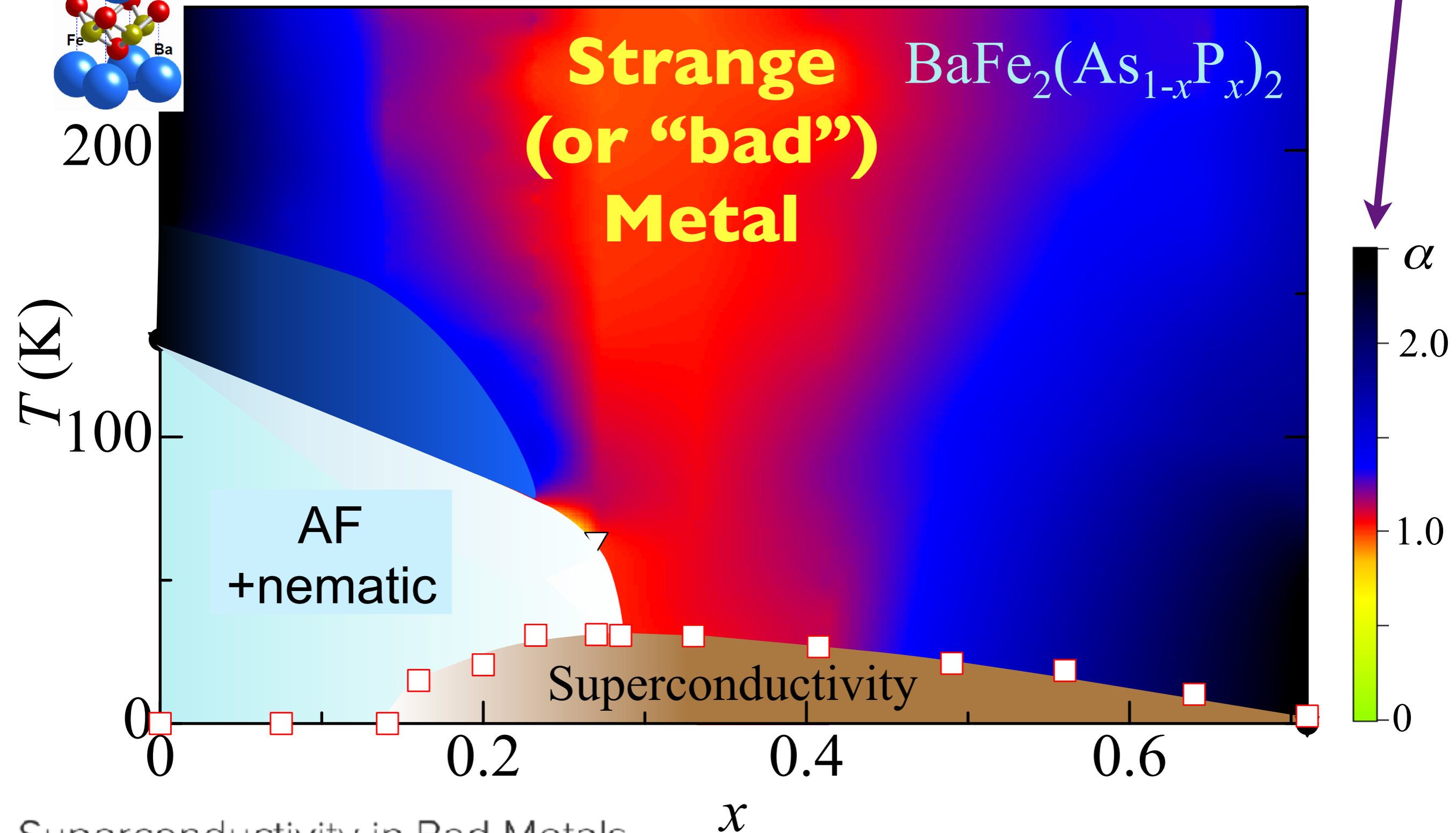


Figure: K. Fujita and J. C. Seamus Davis



Quantum matter without quasiparticles

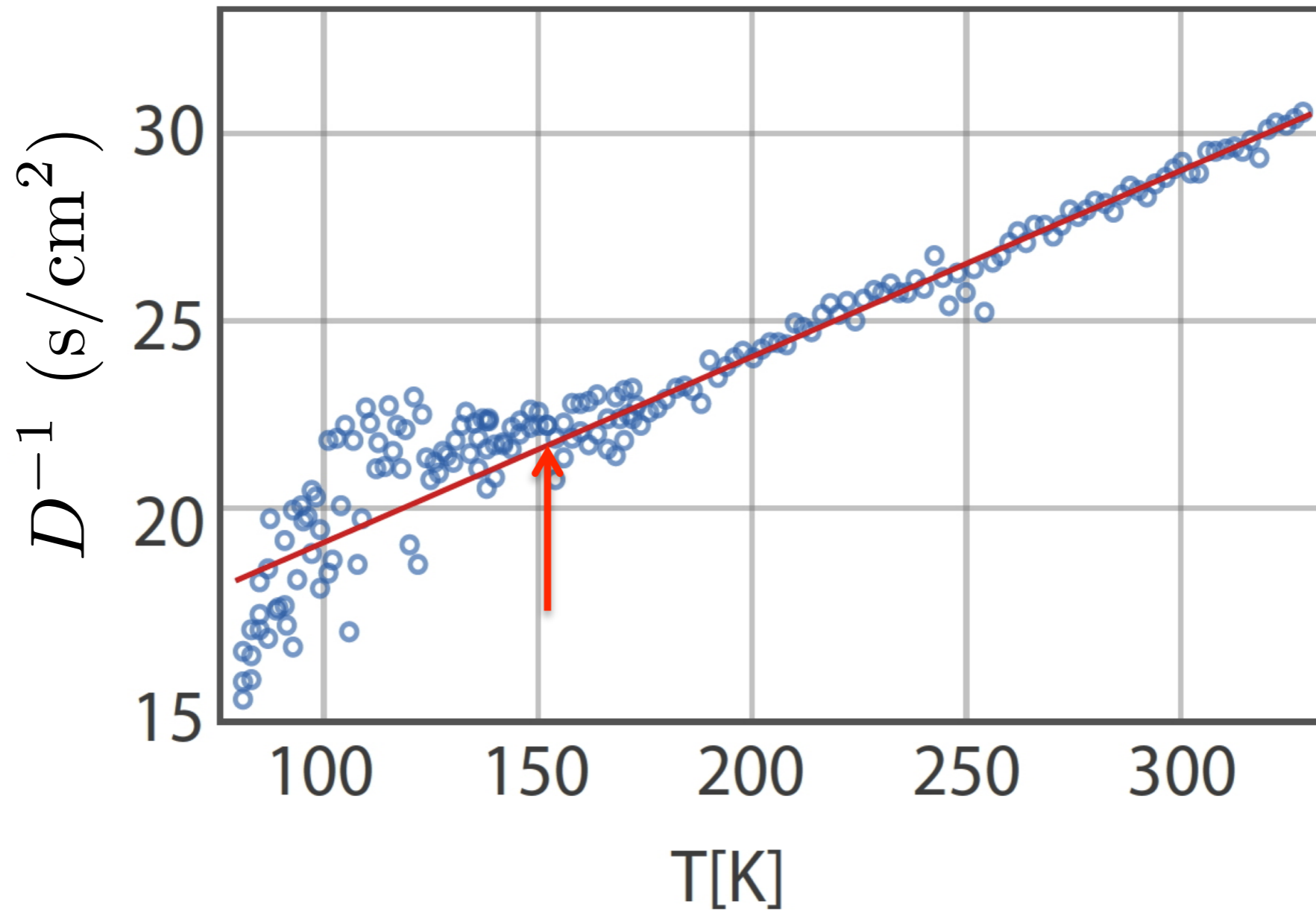
Resistivity
 $\sim \rho_0 + AT^\alpha$



Superconductivity in Bad Metals

V. J. Emery and S. A. Kivelson
 Phys. Rev. Lett. **74**, 3253 – Published 17 April 1995

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, *PRB* **81**, 184519 (2010)



Thermal diffusivity measurements by the group of A. Kapitulnik in $(\text{Sm}_{1.839}\text{Ce}_{0.161})_2\text{CuO}_4$

Quantum matter with 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

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

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

Quantum matter with 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

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

where E_F is the Fermi energy.

Quantum Ising models

Qubits with states $|\uparrow\rangle_i, |\downarrow\rangle_i$, on the sites, i , of a regular lattice.

$$\begin{aligned}\sigma^z |\uparrow\rangle &= |\uparrow\rangle & , & & \sigma^z |\downarrow\rangle &= -|\downarrow\rangle \\ \sigma^x |\uparrow\rangle &= |\downarrow\rangle & , & & \sigma^x |\downarrow\rangle &= |\uparrow\rangle\end{aligned}$$

$$H = -J \left(\sum_{\langle ij \rangle} \sigma_i^z \sigma_j^z + g \sum_i \sigma_i^x \right)$$

For $g = 0$, ground state is a ferromagnet:

$$|G\rangle = |\cdots \uparrow\uparrow\uparrow\uparrow\uparrow \cdots\rangle \quad \text{or} \quad |\cdots \downarrow\downarrow\downarrow\downarrow\downarrow \cdots\rangle$$

For $g \gg 1$, unique ‘paramagnetic’ ground state:

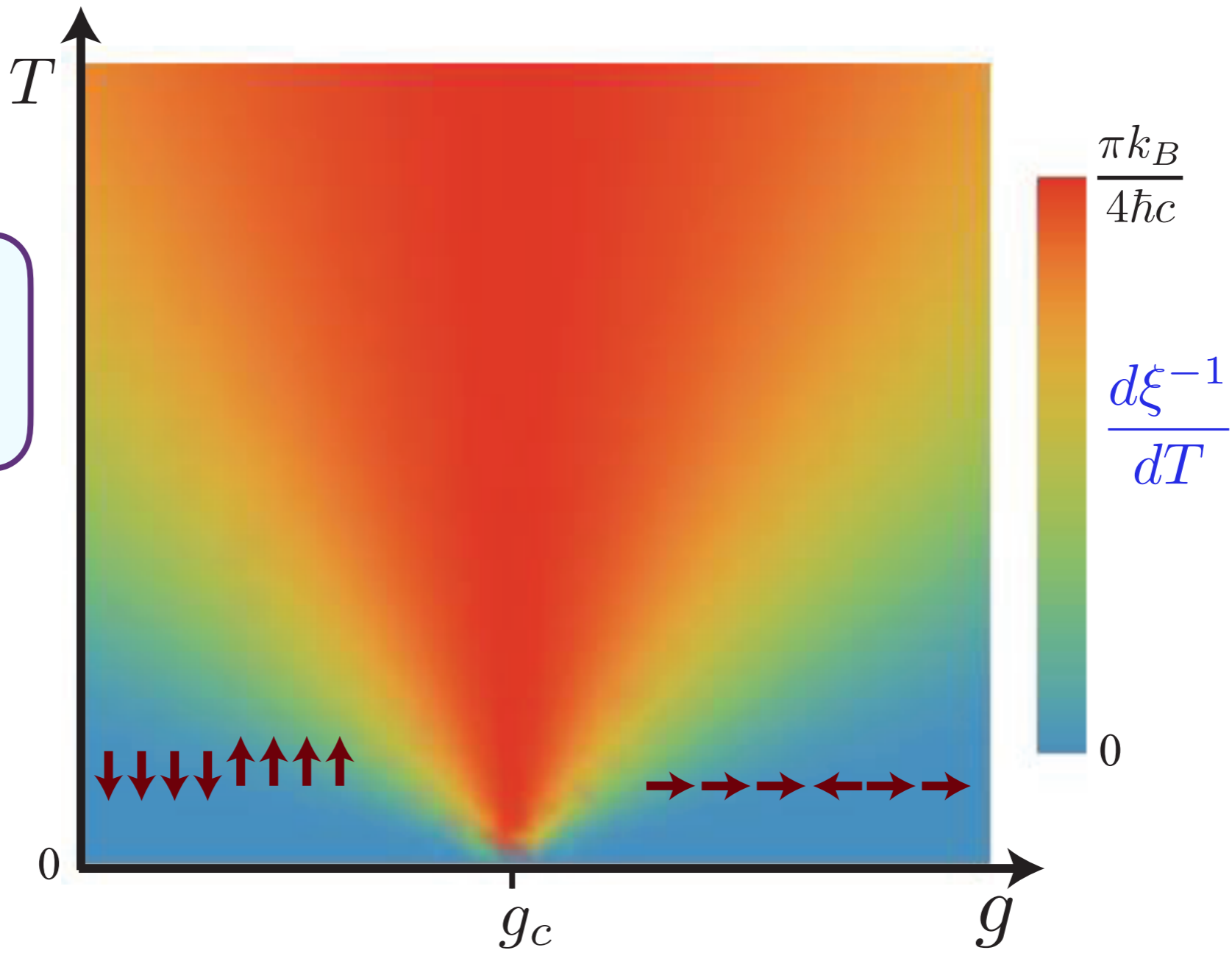
$$|G\rangle = |\cdots \rightarrow\rightarrow\rightarrow\rightarrow\rightarrow \cdots\rangle$$

where

$$|\rightarrow\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle) \quad , \quad |\leftarrow\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle - |\downarrow\rangle)$$

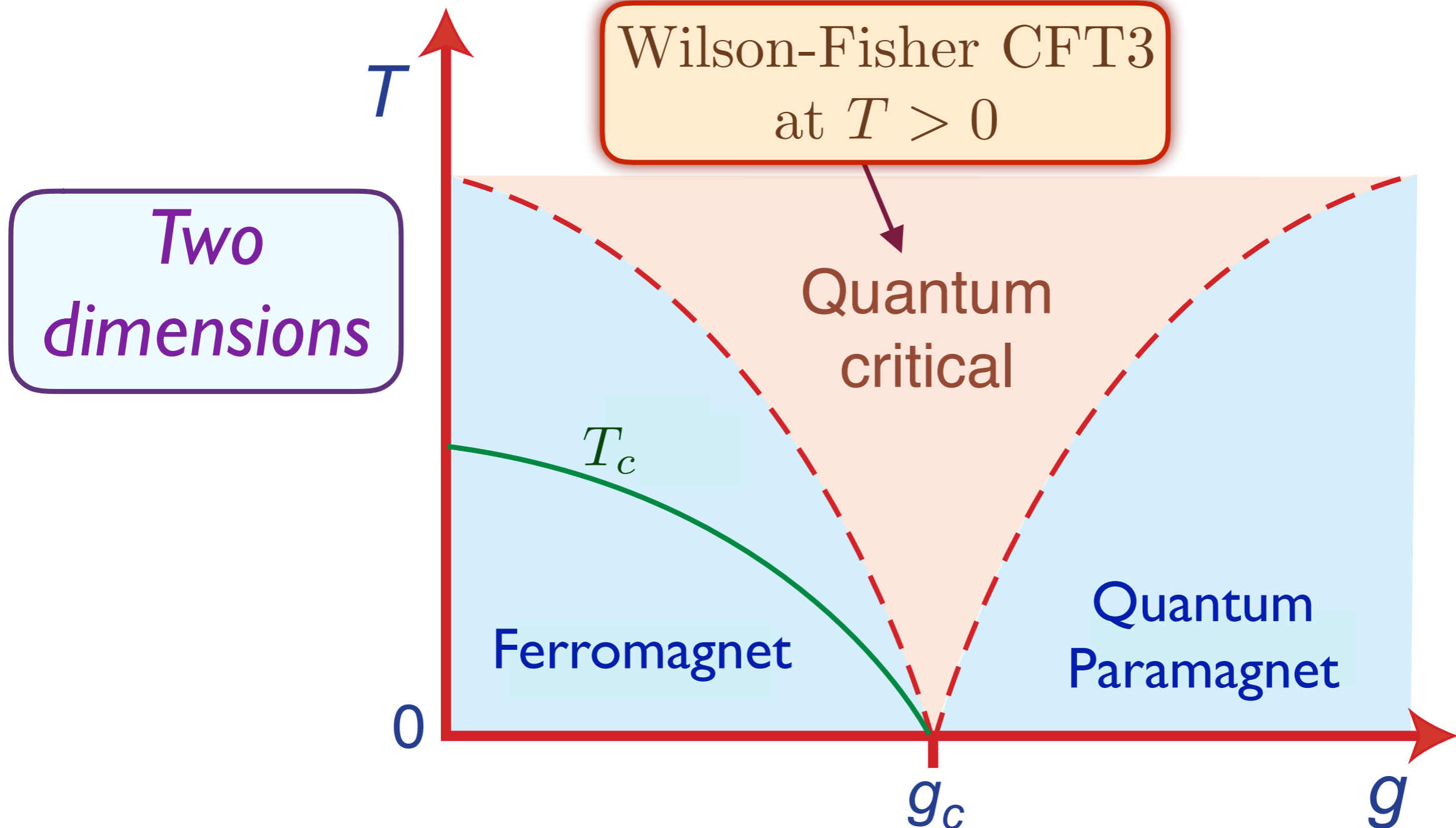
Quantum Ising models

One dimension



- In one dimension, quasiparticles exist even at the quantum critical point: there is a non-local transformations from the qubits to a system of free fermions.

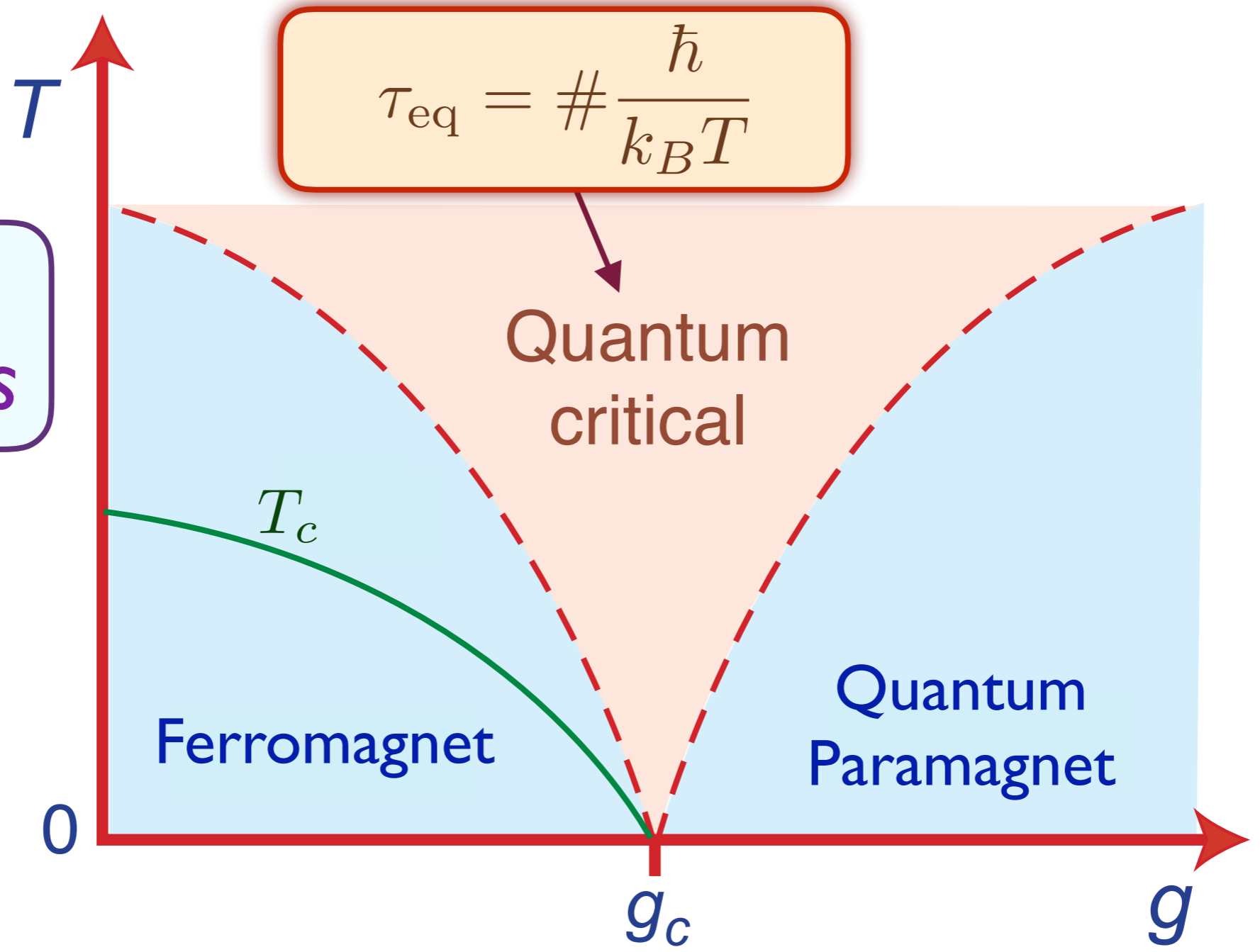
Quantum Ising models



- In two dimensions, the “quantum critical” region provides us the first example of a system without a quasiparticle description. This is described by a strongly-coupled conformal field theory (CFT) in 2+1 dimensions, and dynamic properties cannot be computed accurately.

Quantum Ising models

Two dimensions



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Quantum matter without quasiparticles:

- If there are no quasiparticles, then

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

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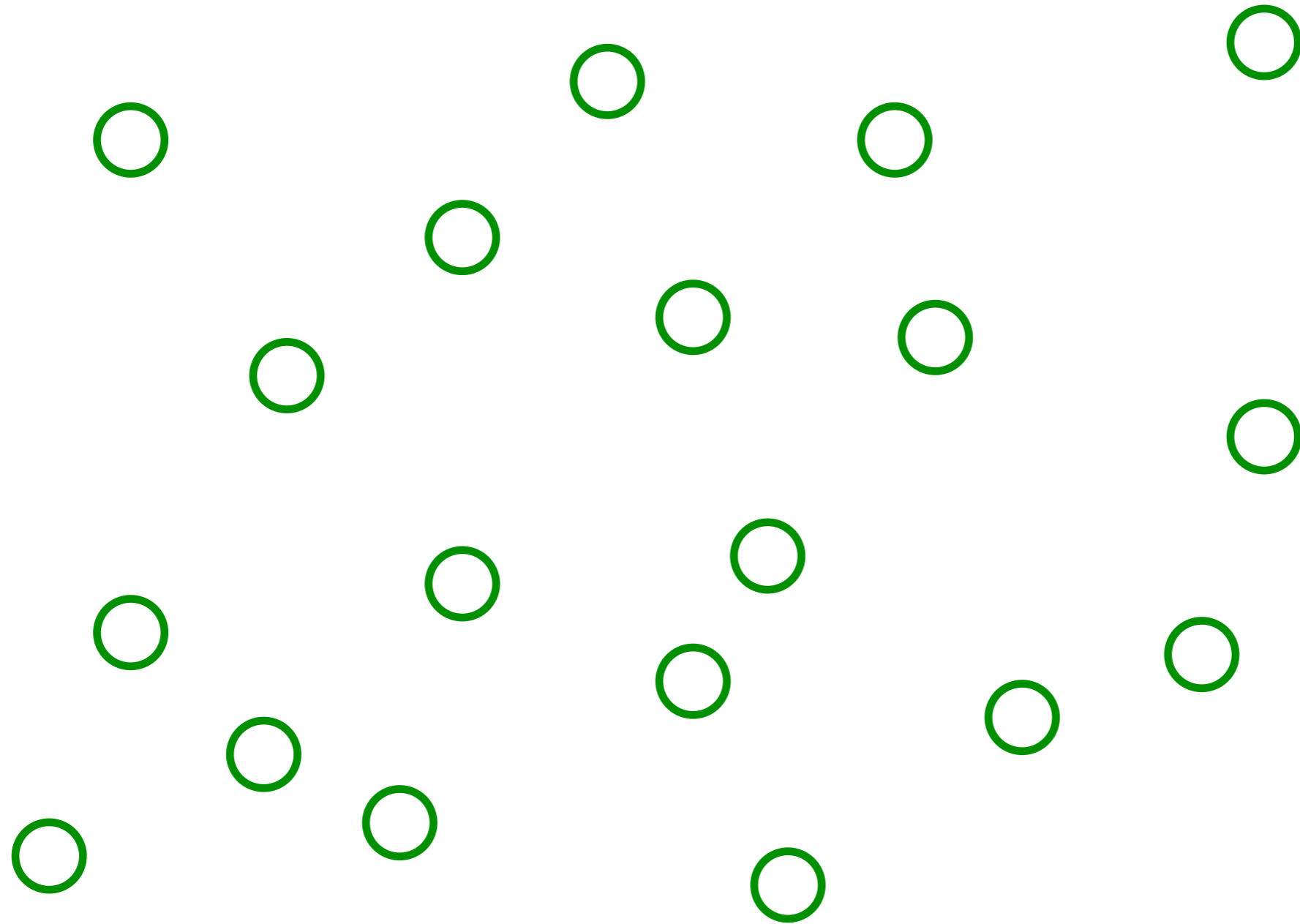
- Systems without quasiparticles are the fastest possible in reaching local equilibrium, and all many-body quantum systems obey, as $T \rightarrow 0$

$$\tau_{\text{eq}} > C \frac{\hbar}{k_B T}.$$

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

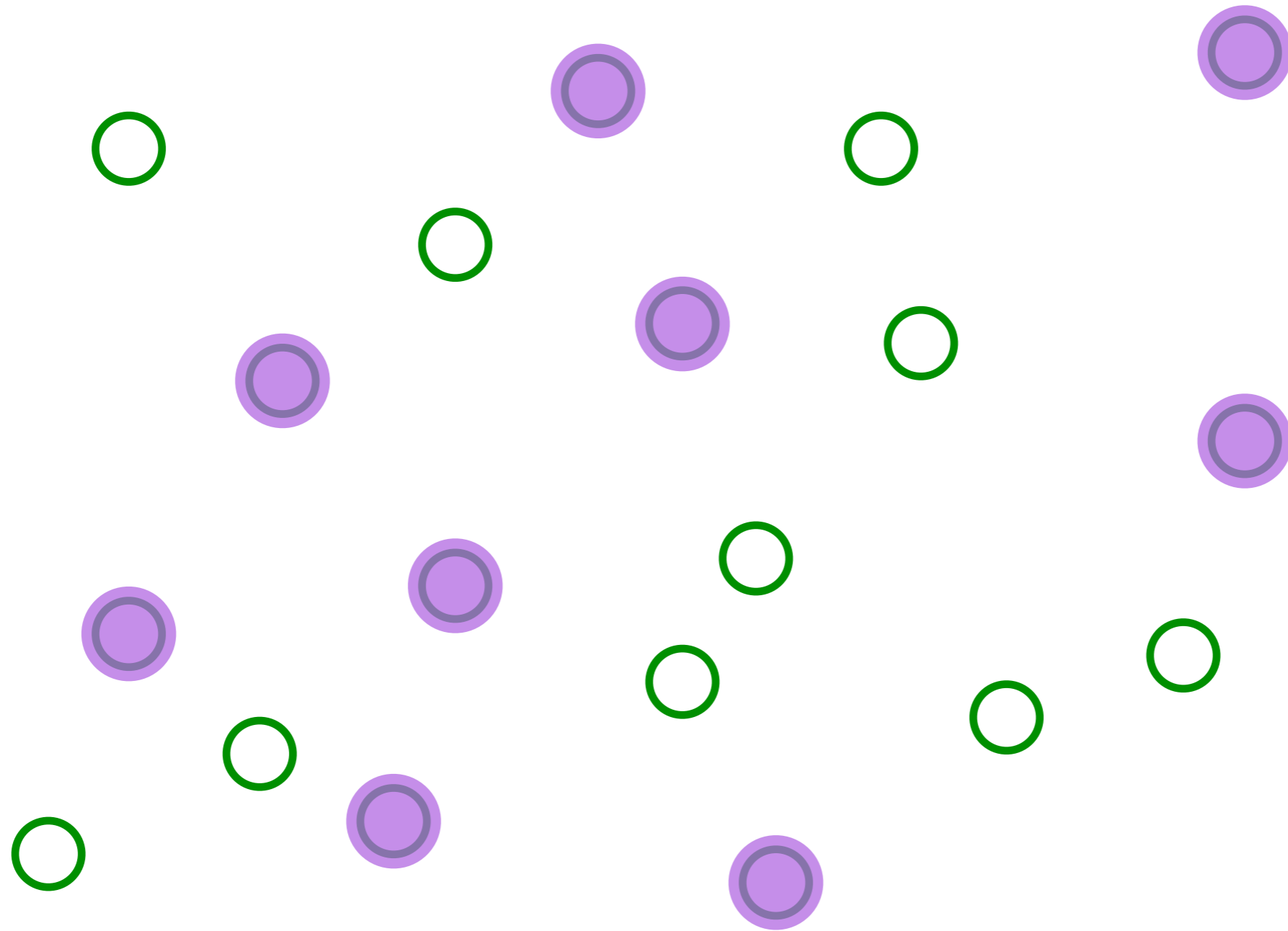
- In Fermi liquids $\tau_{\text{eq}} \sim 1/T^2$, and so the bound is obeyed as $T \rightarrow 0$.
- This bound rules out quantum systems with *e.g.* $\tau_{\text{eq}} \sim \hbar/(Jk_B T)^{1/2}$.
- There is no bound in classical mechanics ($\hbar \rightarrow 0$). By cranking up frequencies, we can attain equilibrium as quickly as we desire.

A simple model of a metal with quasiparticles



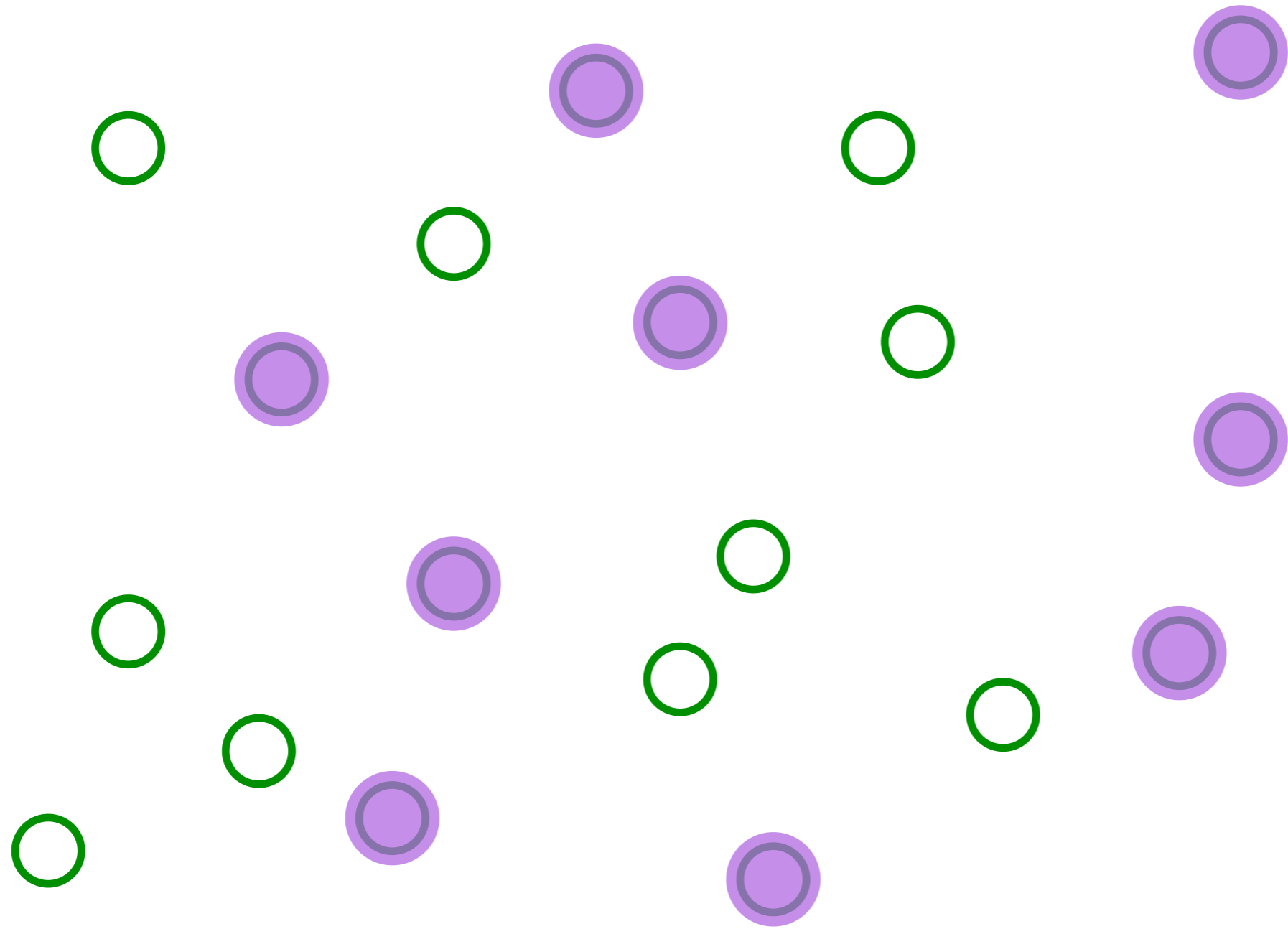
Pick a set of random positions

A simple model of a metal with quasiparticles



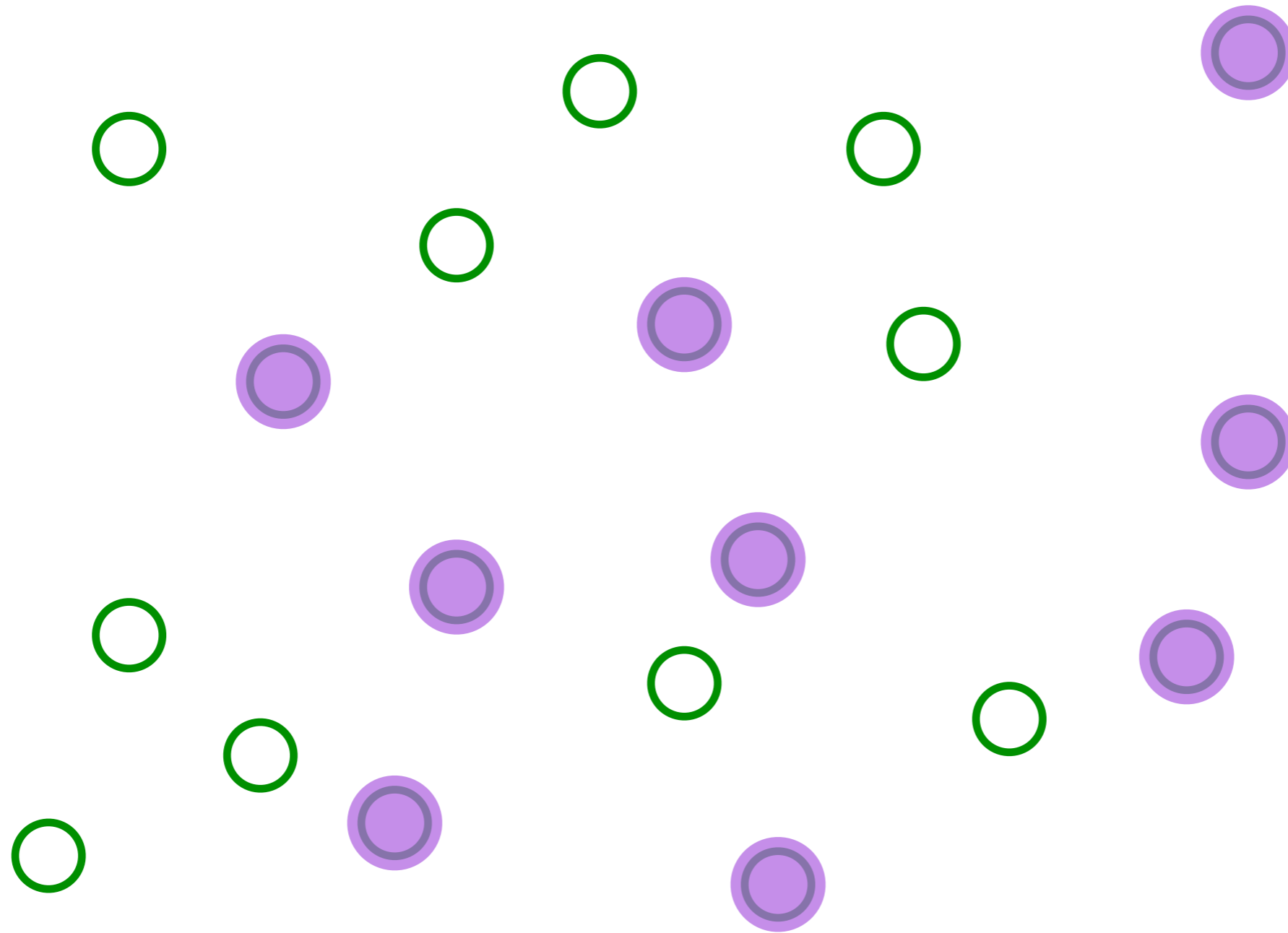
Place electrons randomly on some sites

A simple model of a metal with quasiparticles



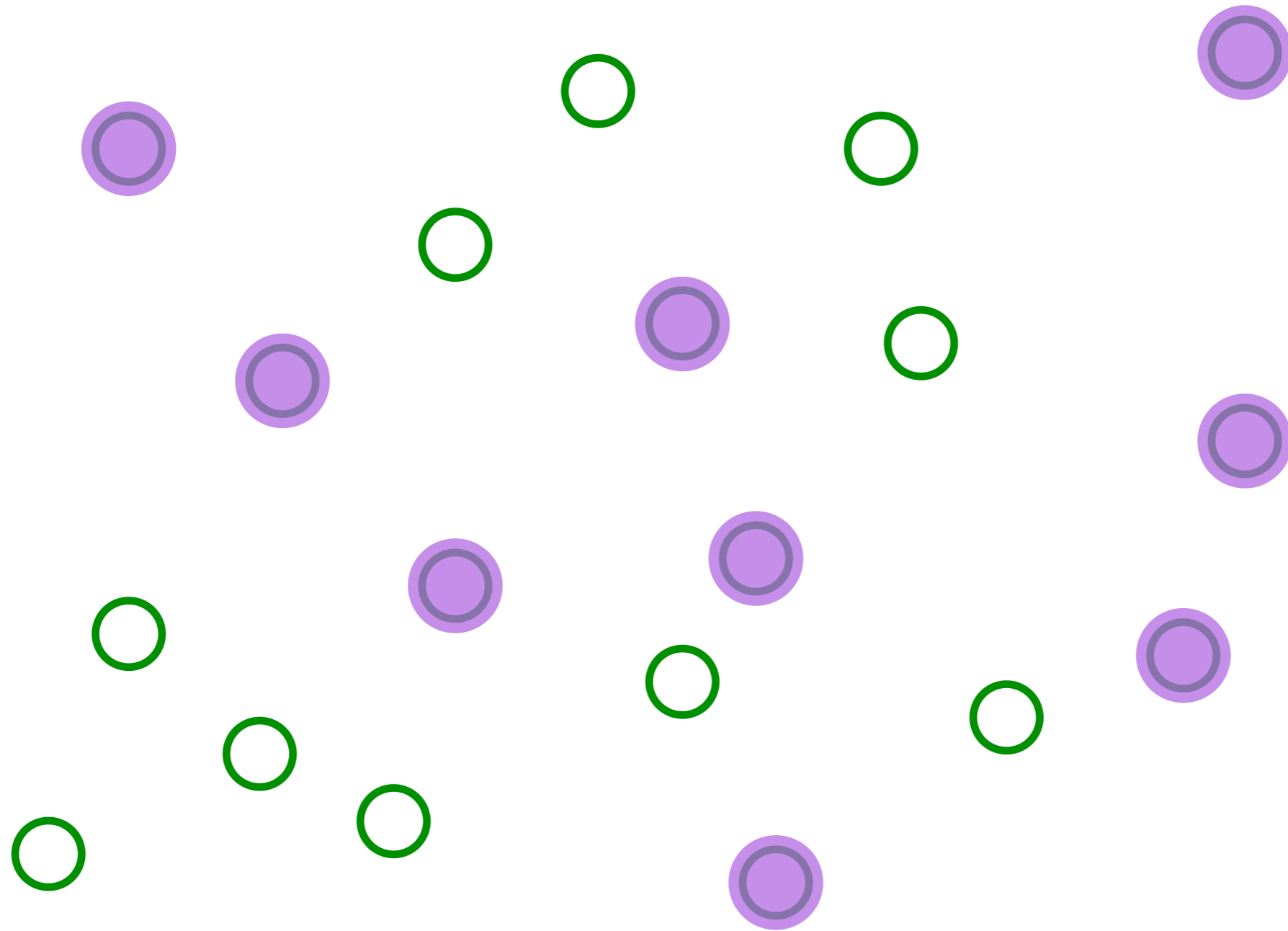
Electrons move one-by-one randomly

A simple model of a metal with quasiparticles



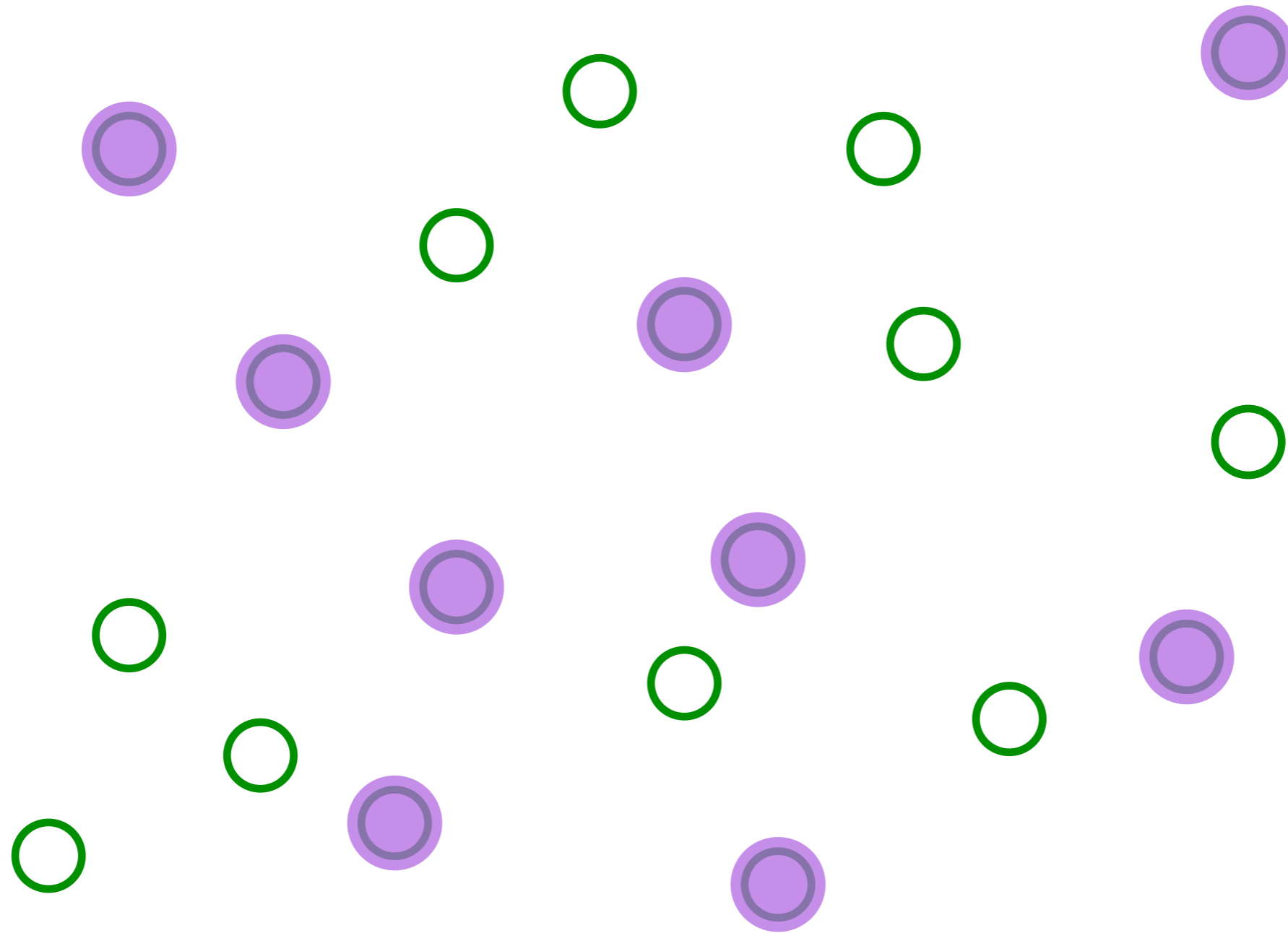
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A simple model of a metal with quasiparticles

$$H = \frac{1}{(N)^{1/2}} \sum_{i,j=1}^N t_{ij} c_i^\dagger c_j + \dots$$

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

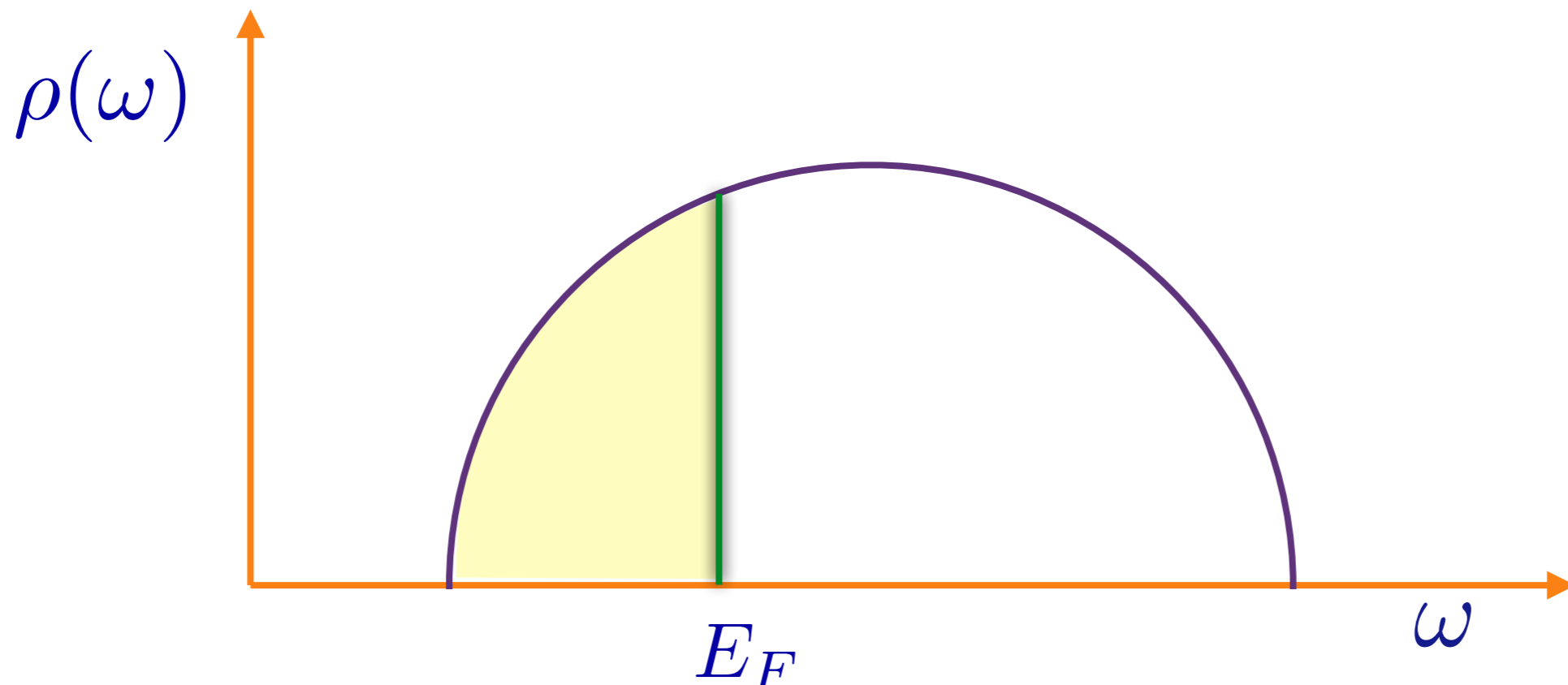
$$\frac{1}{N} \sum_i c_i^\dagger c_i = Q$$

t_{ij} are independent random variables with $\overline{t_{ij}} = 0$ and $\overline{|t_{ij}|^2} = t^2$

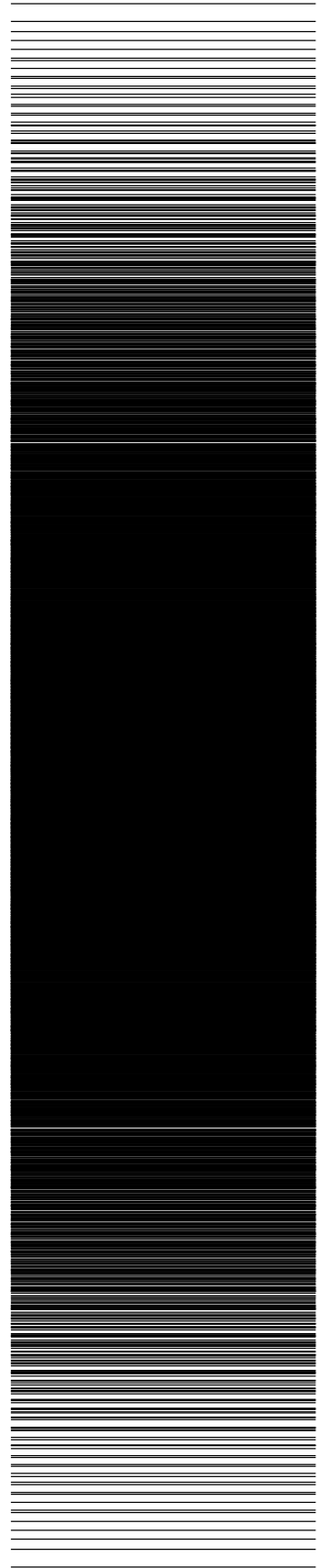
**Fermions occupying the eigenstates of a
 $N \times N$ random matrix**

A simple model of a metal with quasiparticles

Let ε_α be the eigenvalues of the matrix t_{ij}/\sqrt{N} . The fermions will occupy the lowest NQ eigenvalues, upto the Fermi energy E_F . The density of states is $\rho(\omega) = (1/N) \sum_\alpha \delta(\omega - \varepsilon_\alpha)$.



A simple model of a metal with quasiparticles



Many-body
level spacing
 $\sim 2^{-N}$

Quasiparticle
excitations with
spacing $\sim 1/N$

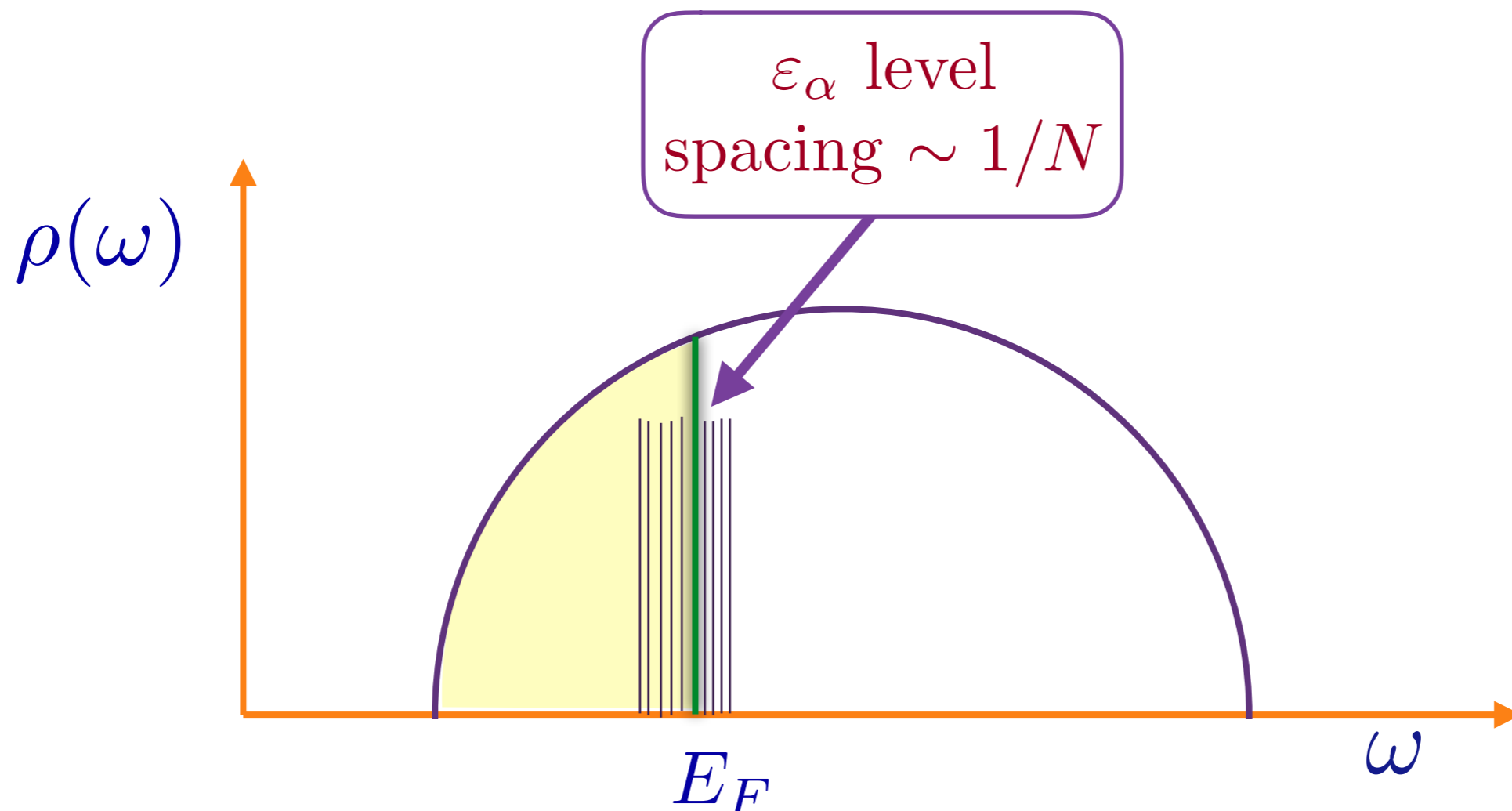
There are 2^N many
body levels with energy

$$E = \sum_{\alpha=1}^N n_{\alpha} \varepsilon_{\alpha},$$

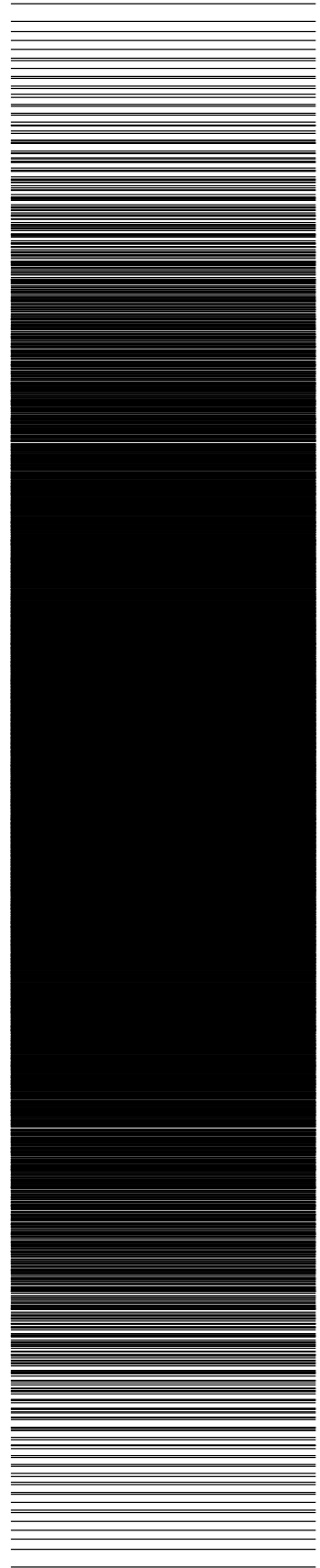
where $n_{\alpha} = 0, 1$. Shown
are all values of E for a
single cluster of size
 $N = 12$. The ε_{α} have a
level spacing $\sim 1/N$.

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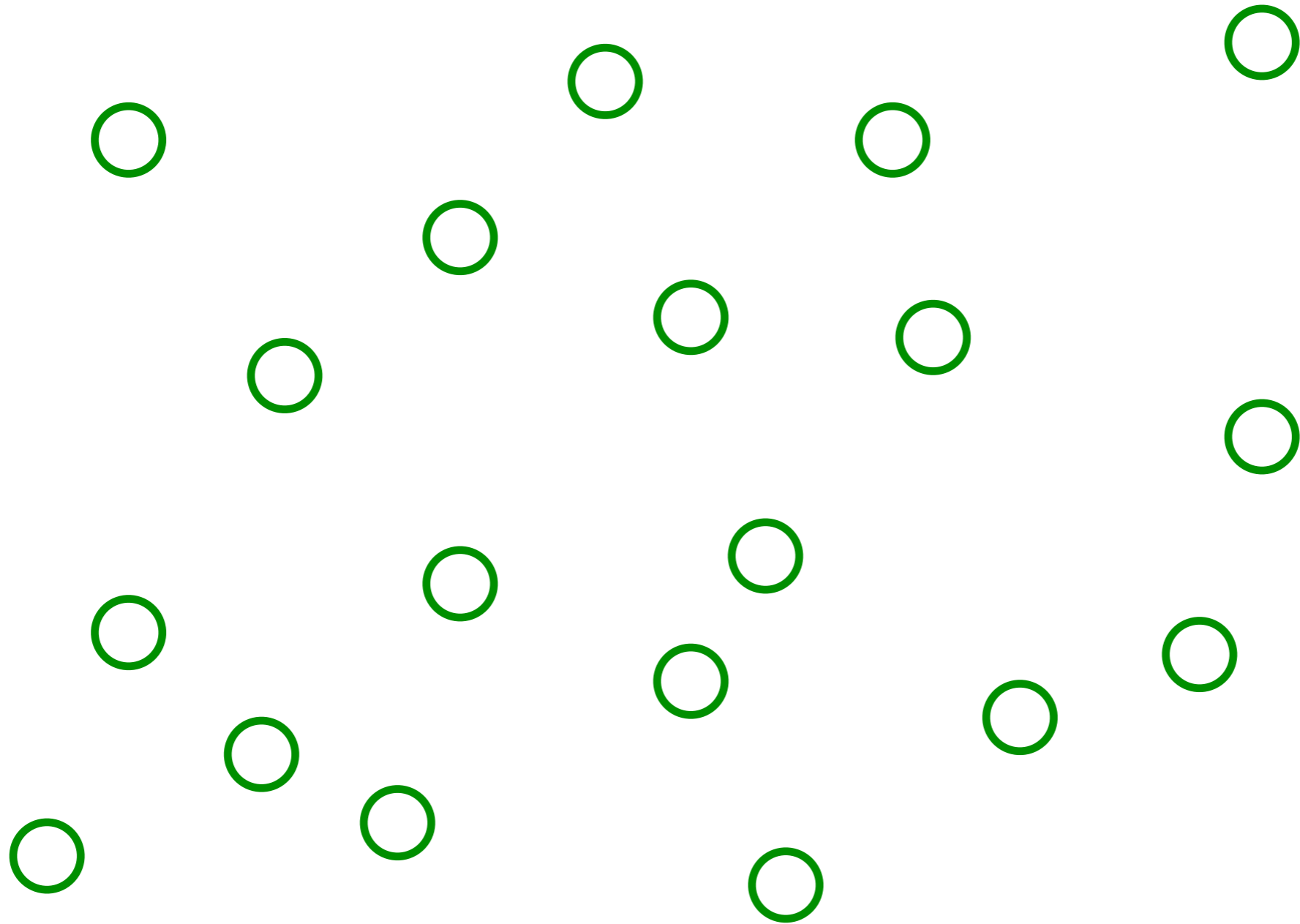
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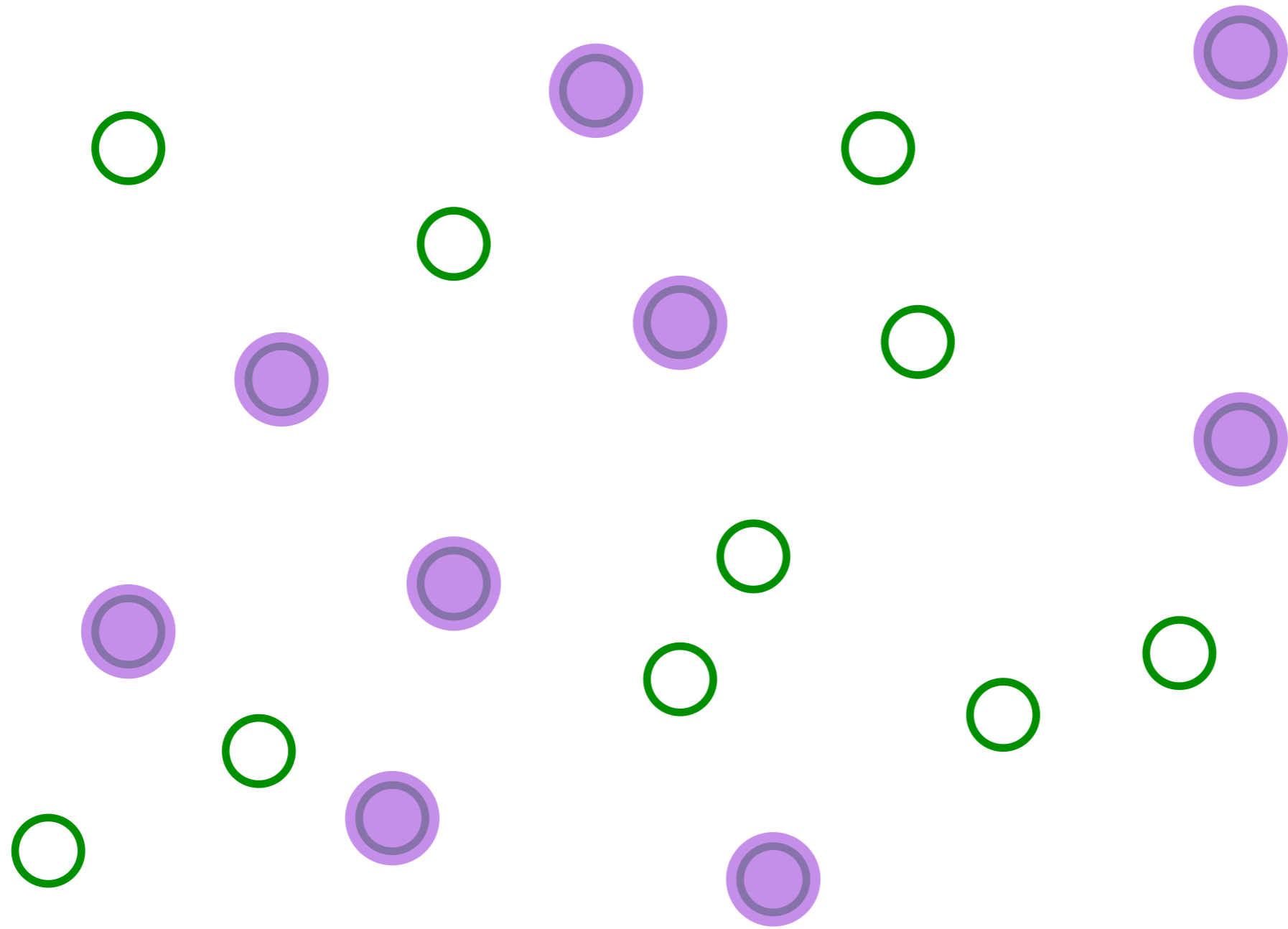
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The Sachdev-Ye-Kitaev (SYK) model



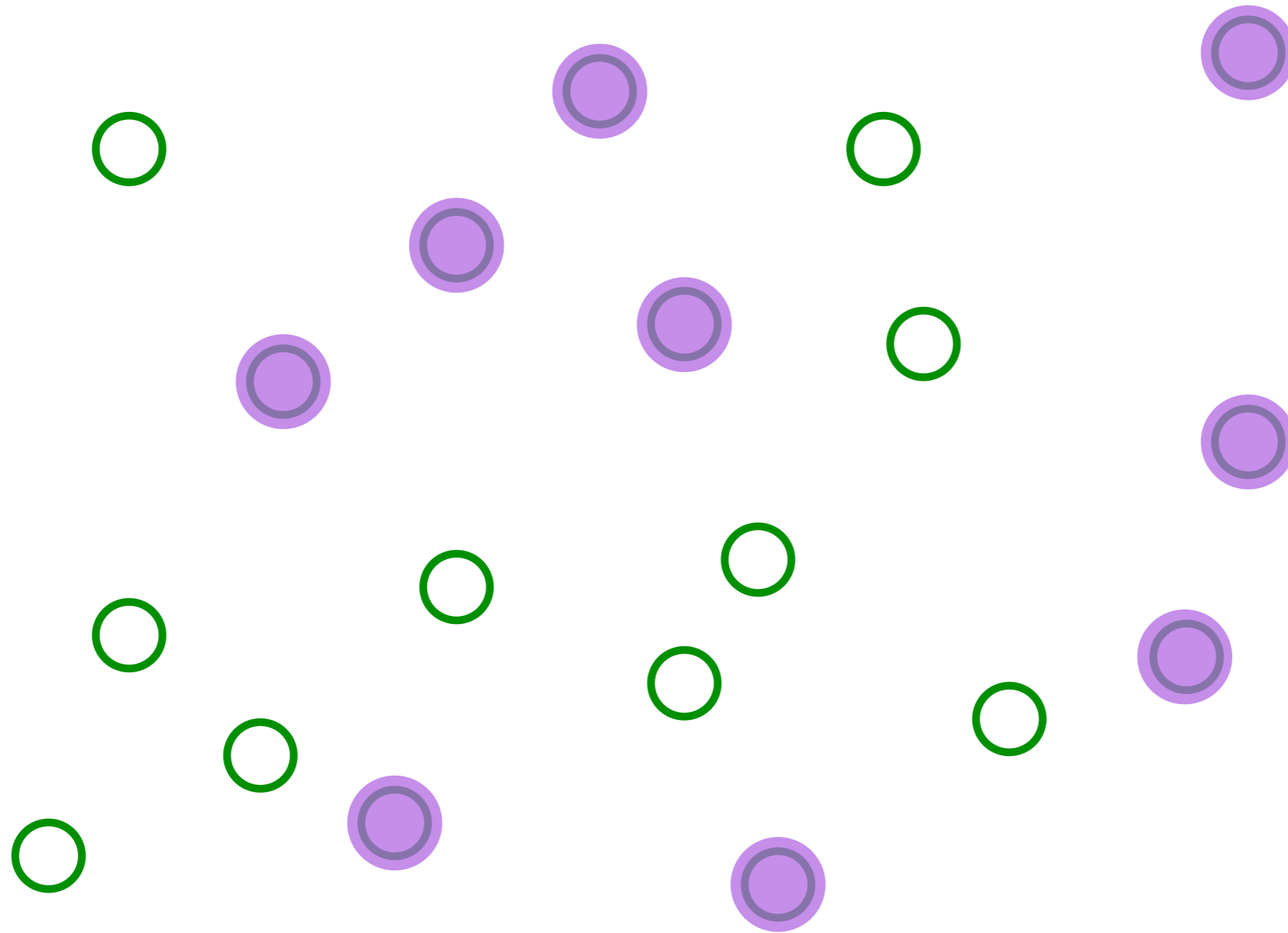
Pick a set of random positions

The SYK model



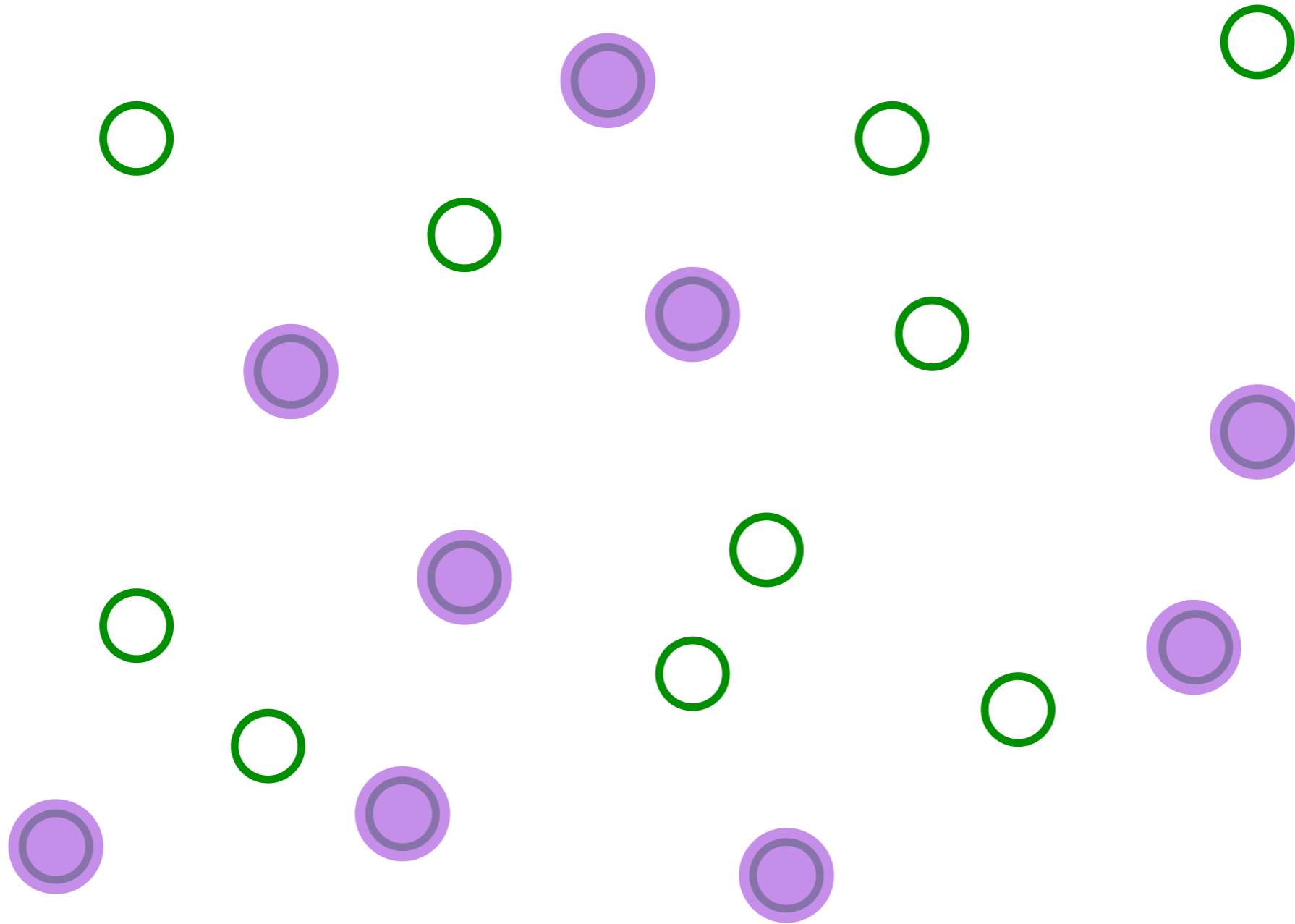
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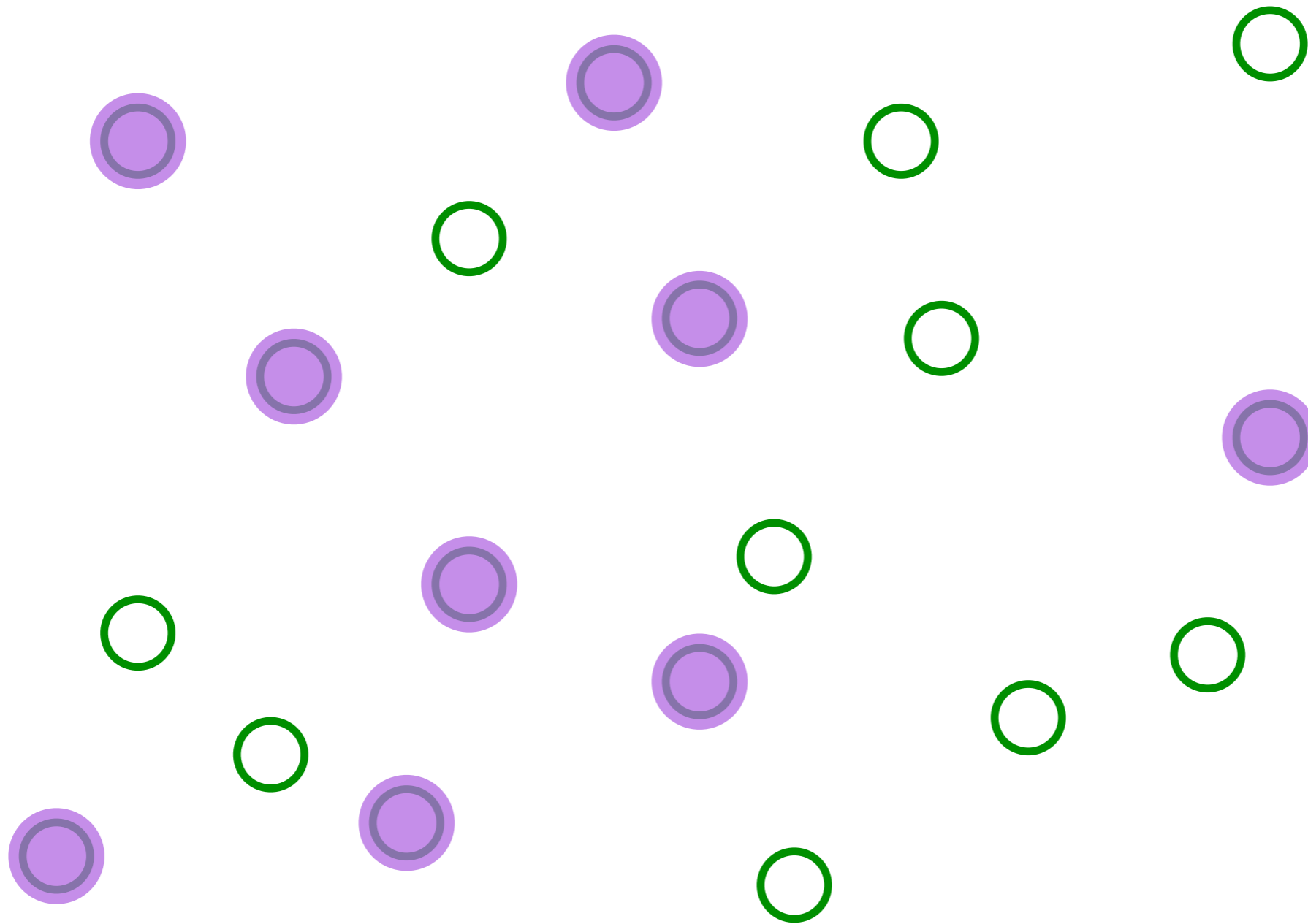
Entangle electrons pairwise randomly

The SYK model



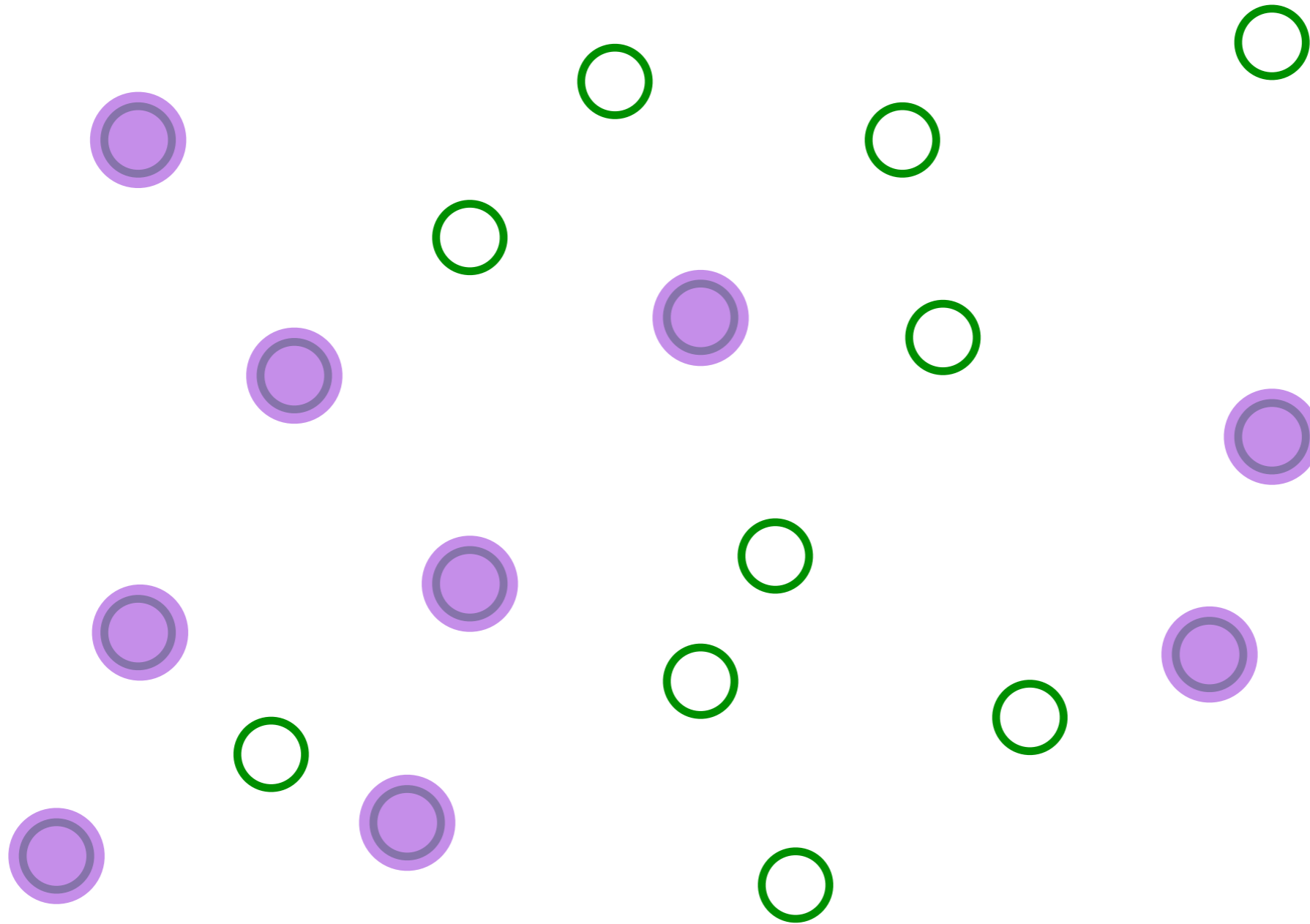
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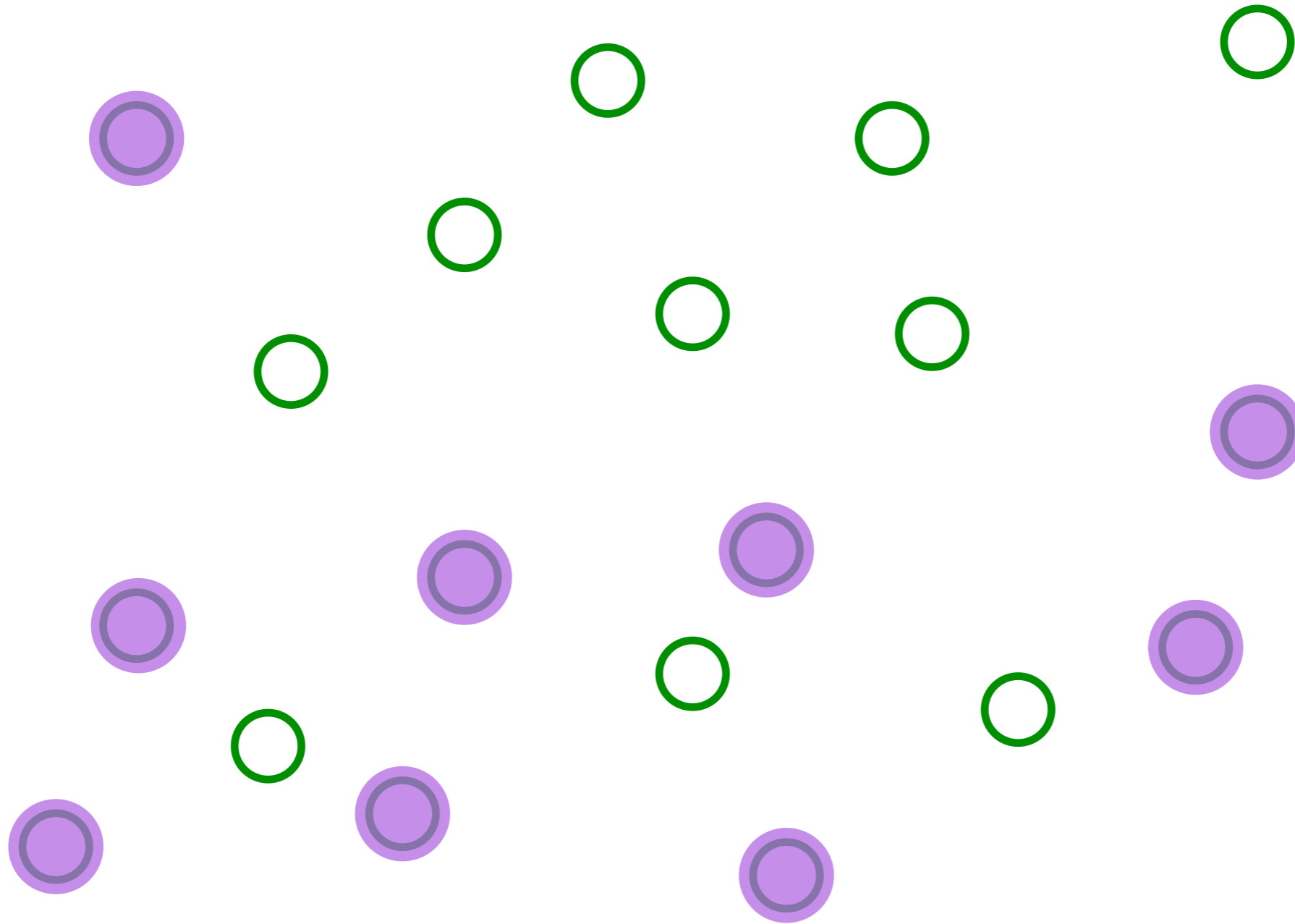
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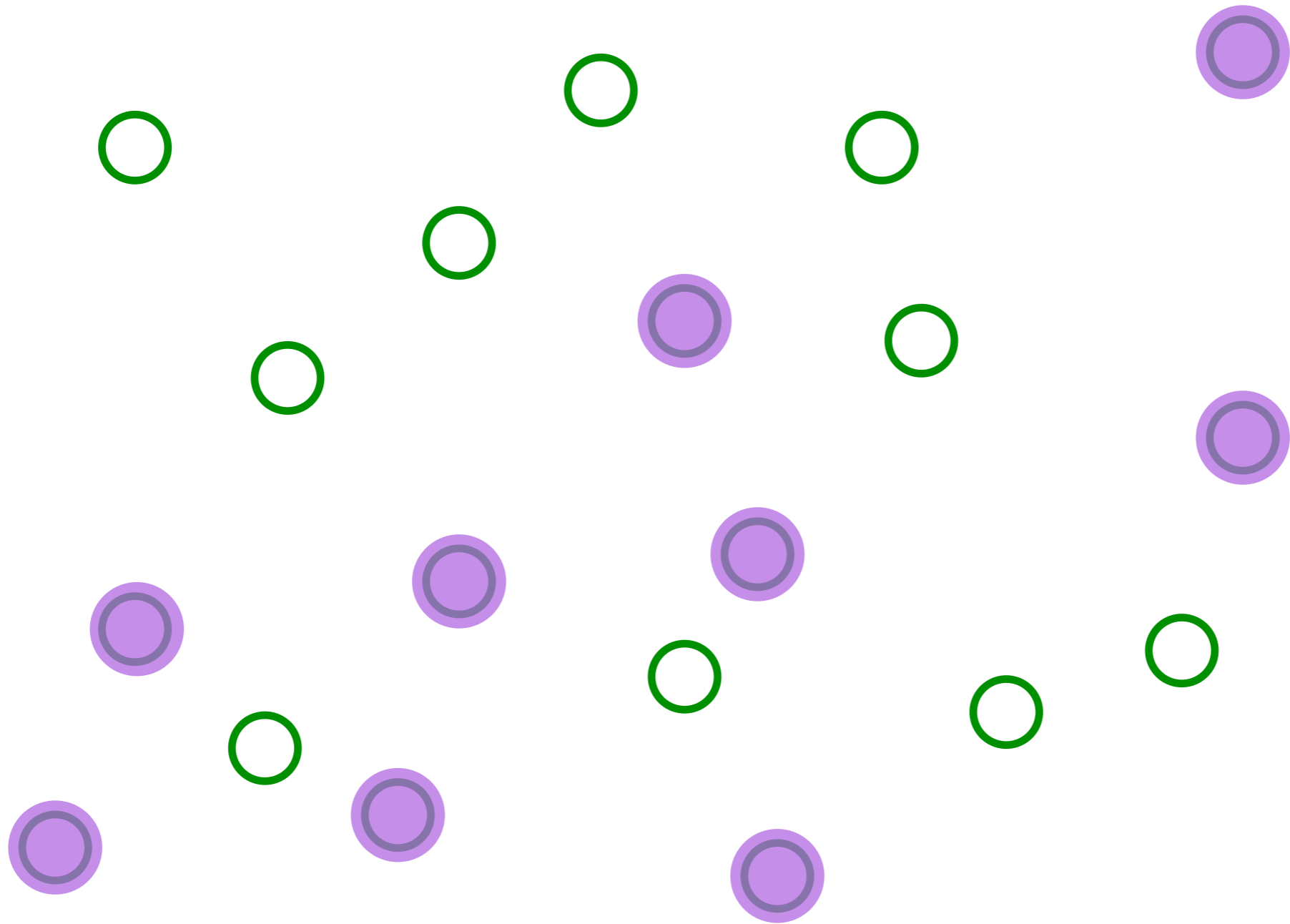
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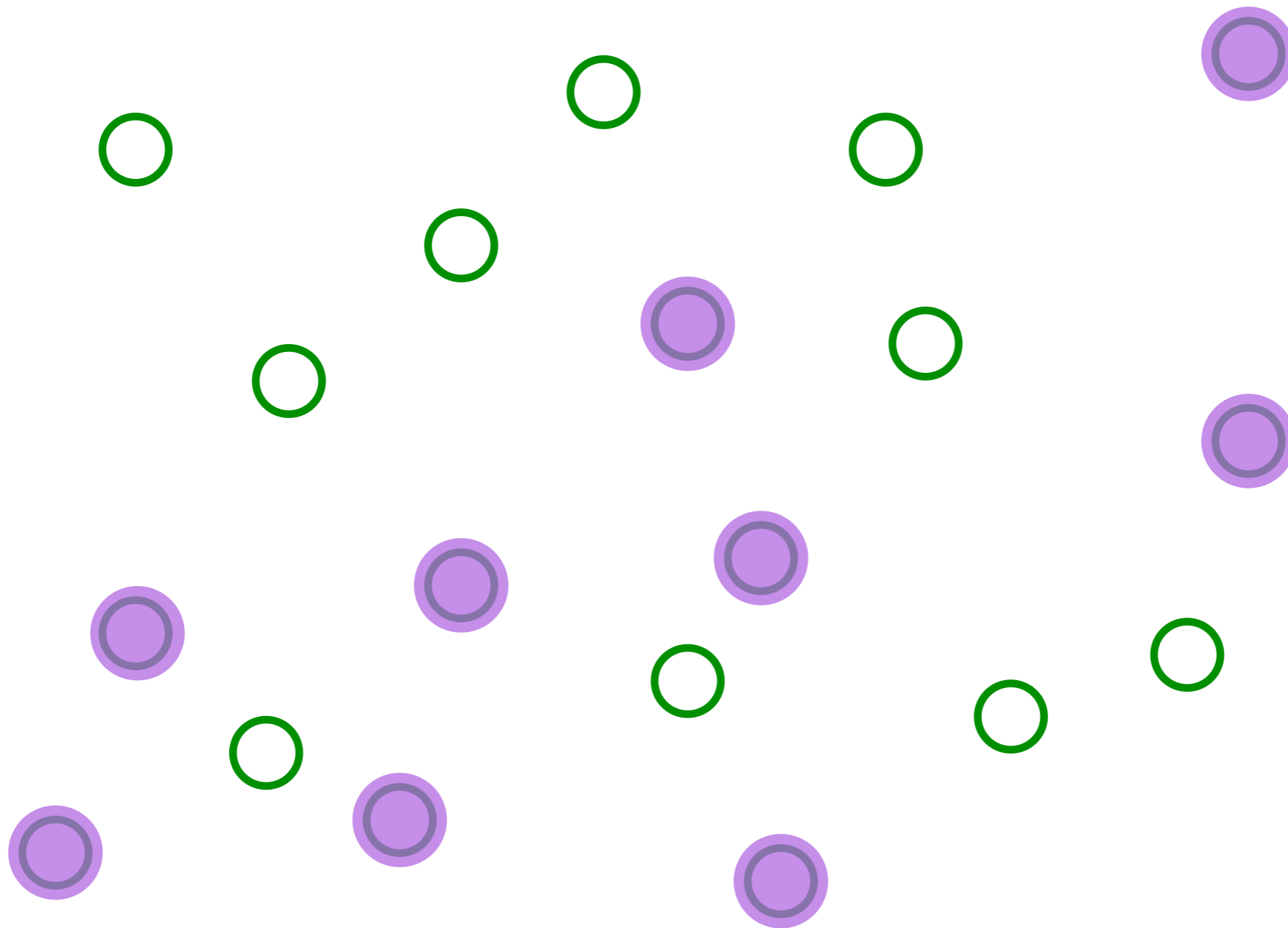
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Entangle electrons pairwise randomly

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This describes both a strange metal and a black hole!

The SYK model

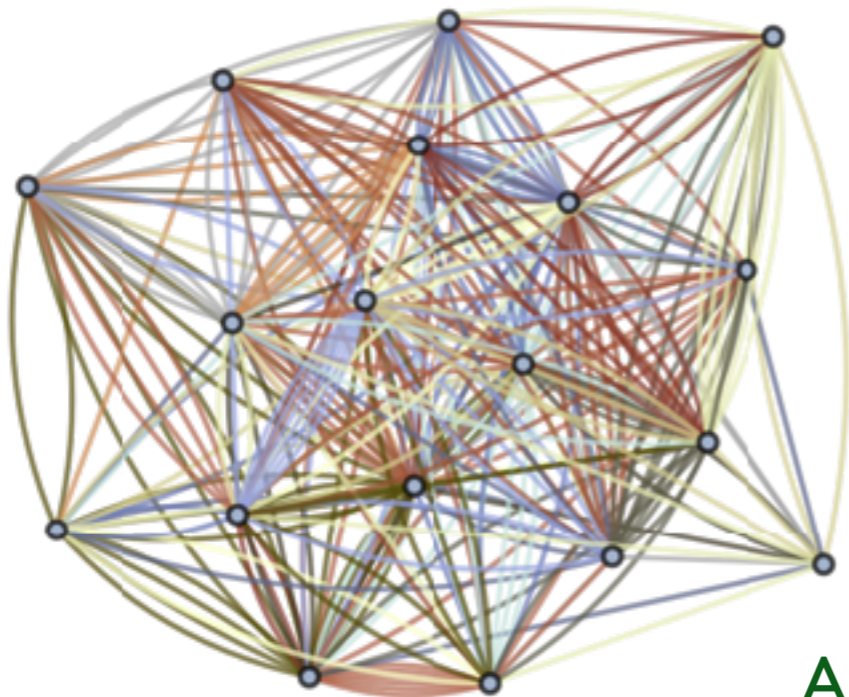
(See also: the “2-Body Random Ensemble” in nuclear physics; did not obtain the large N limit; T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

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

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

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

$J_{ij;kl}$ are independent random variables with $\overline{J_{ij;kl}} = 0$ and $\overline{|J_{ij;kl}|^2} = J^2$
 $N \rightarrow \infty$ 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

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 $T \rightarrow 0$ state has an entropy $S_{GPS} = N s_0$ with

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

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)

Many-body level spacing $\sim 2^{-N} = e^{-N \ln 2}$

Non-quasiparticle excitations with spacing $\sim e^{-N s_0}$

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PRB **63**, 134406 (2001)

The SYK model

- Low energy, many-body density of states

$$\rho(E) \sim e^{N s_0} \sinh(\sqrt{2(E - E_0)N\gamma})$$

A. Georges, O. Parcollet, and S. Sachdev, PRB **63**, 134406 (2001)

D. Stanford and E. Witten, 1703.04612

A. M. Garcia-Garcia, J.J.M. Verbaarschot, 1701.06593

D. Bagrets, A. Altland, and A. Kamenev, 1607.00694

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- Low temperature entropy $S = Ns_0 + N\gamma T + \dots$

A. Kitaev, unpublished
J. Maldacena and D. Stanford, 1604.07818

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- $T = 0$ fermion Green's function $G(\tau) \sim \tau^{-1/2}$ at large τ .

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 $G \sim (T / \sin(\pi k_B T \tau / \hbar))^{1/2}$

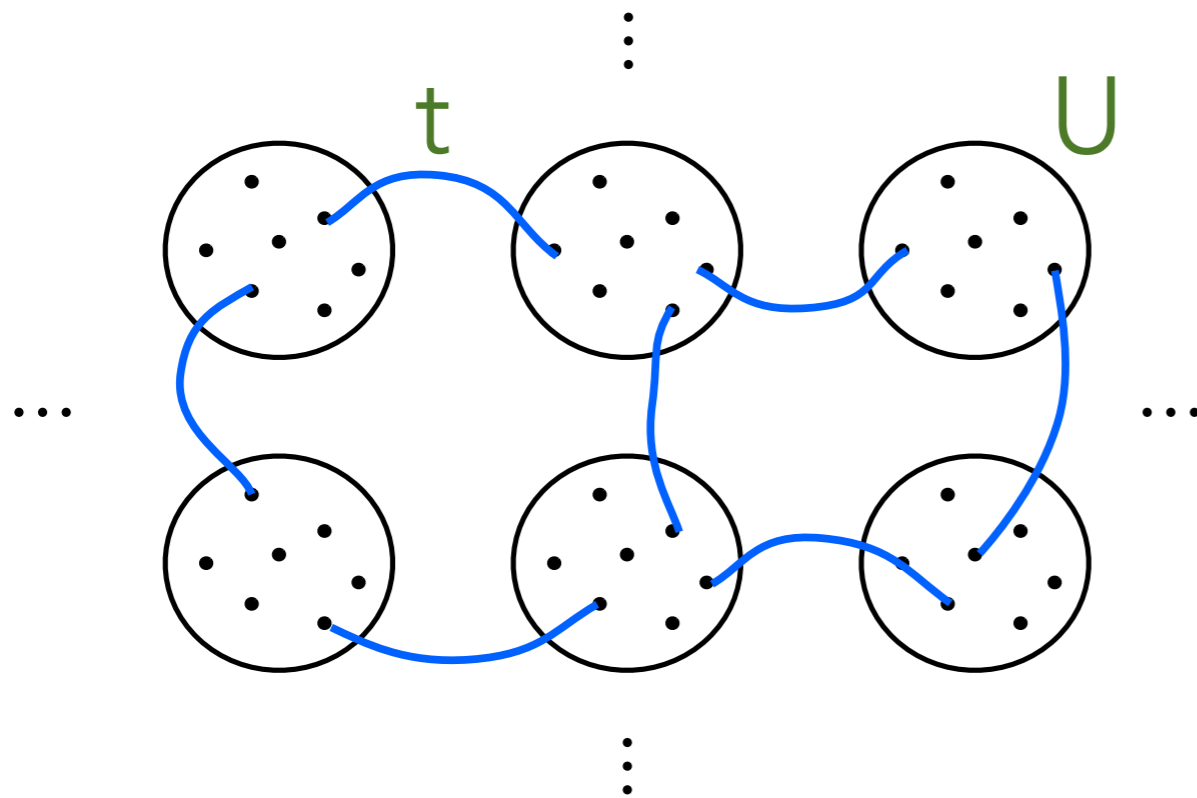
A. Georges and O. Parcollet PRB **59**, 5341 (1999)

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- The last property indicates $\tau_{\text{eq}} \sim \hbar / (k_B T)$, and this has been found in a recent numerical study.

[arXiv:1705.00117](https://arxiv.org/abs/1705.00117)

Title: A strongly correlated metal built from Sachdev-Ye-Kitaev models

Authors: [Xue-Yang Song](#), [Chao-Ming Jian](#), [Leon Balents](#)

$$H = \sum_x \sum_{i < j, k < l} U_{ijkl,x} c_{ix}^\dagger c_{jx}^\dagger c_{kx} c_{lx} + \sum_{\langle xx' \rangle} \sum_{i,j} t_{ij,xx'} c_{i,x}^\dagger c_{j,x'}$$

$$\overline{|U_{ijkl}|^2} = \frac{2U^2}{N^3}$$

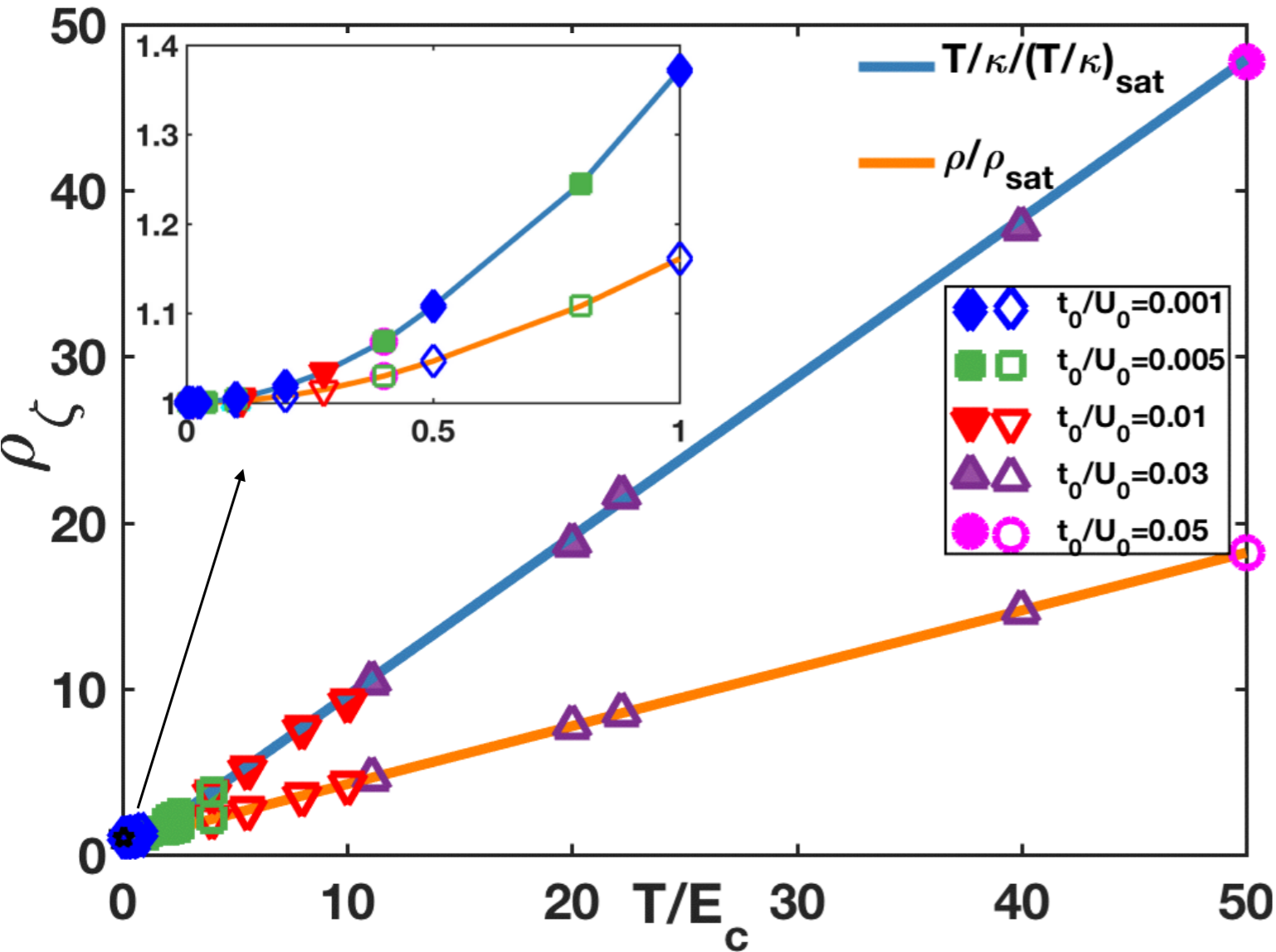
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Low ‘coherence’ scale



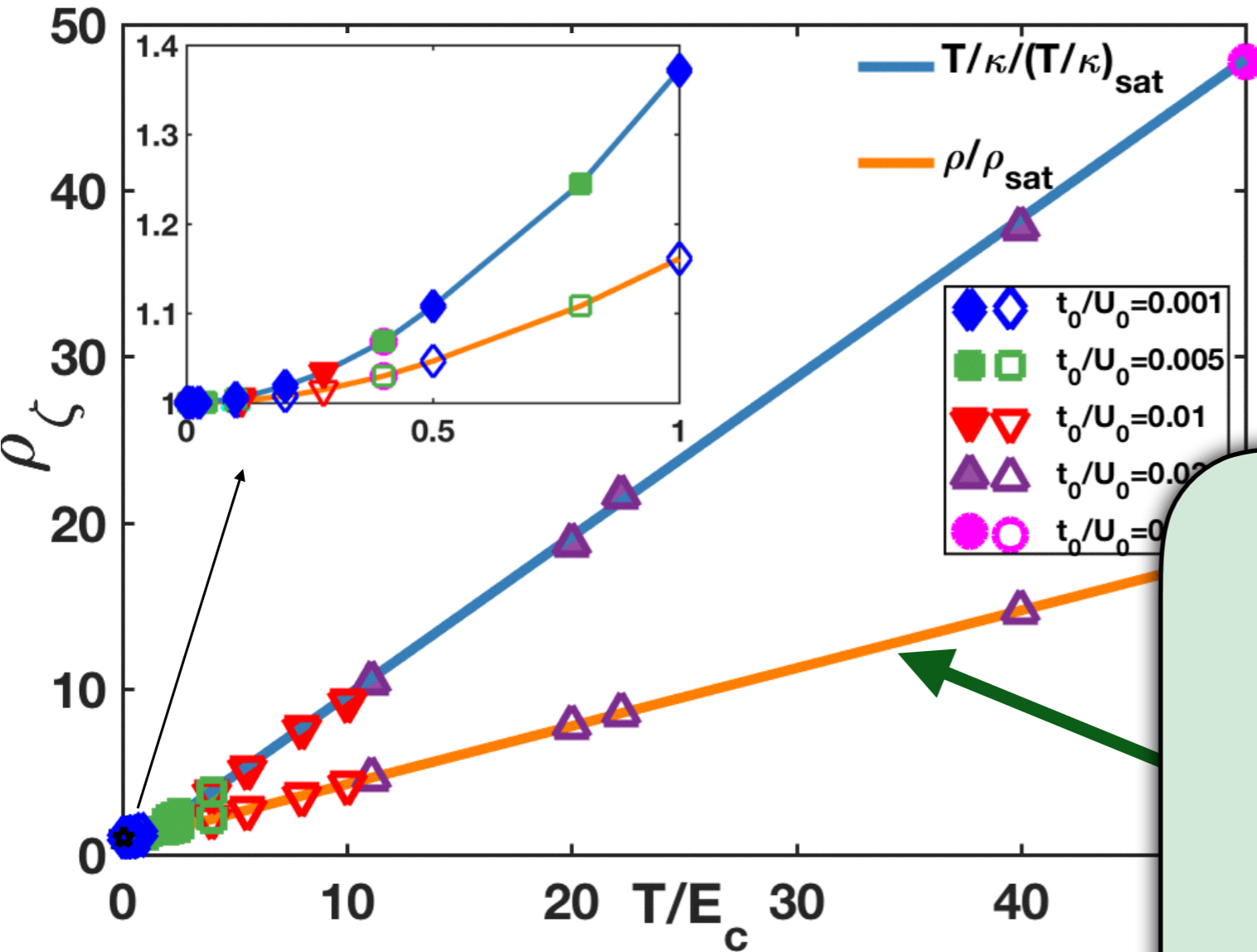
$$E_c \sim \frac{t_0^2}{U}$$

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

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

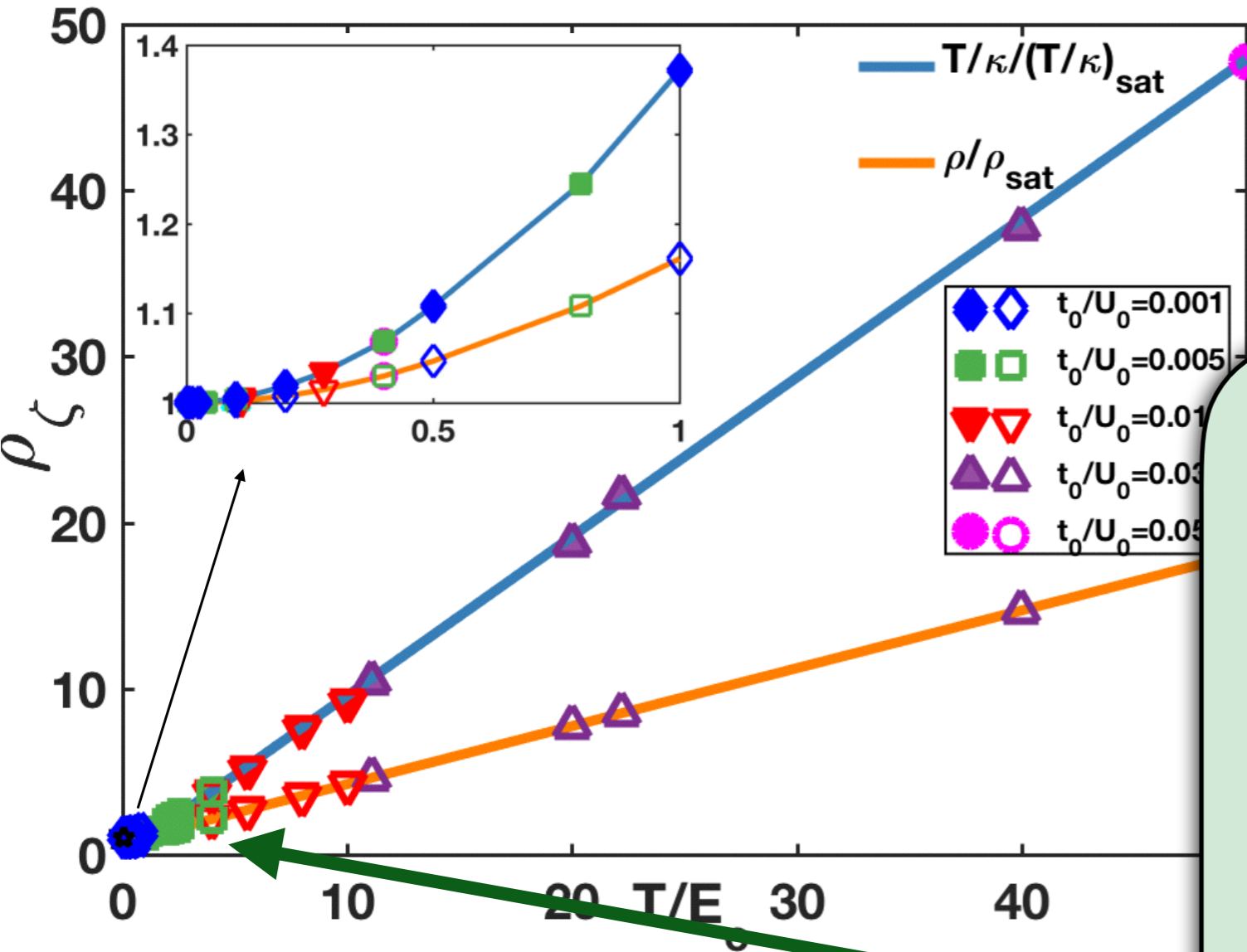
$$\rho \sim \frac{h}{e^2} \left(\frac{T}{E_c} \right), \quad s = s_0$$

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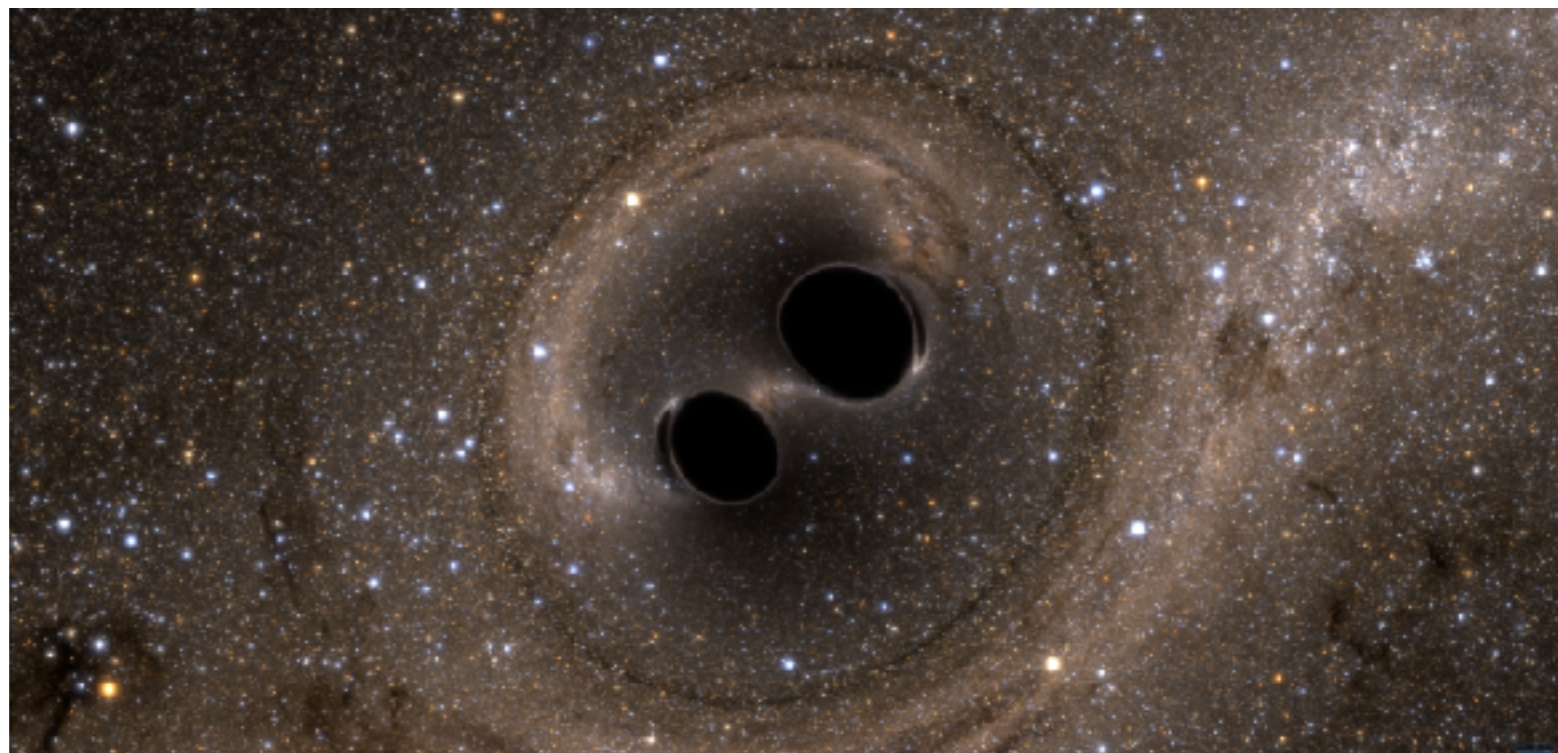
For $T < E_c$, the resistivity, ρ , and entropy density, s , are

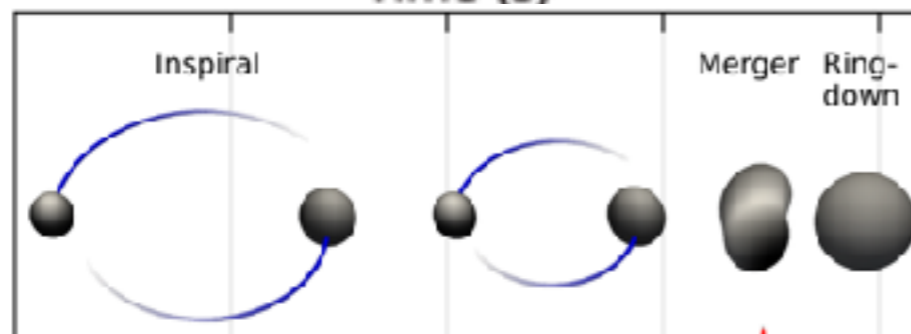
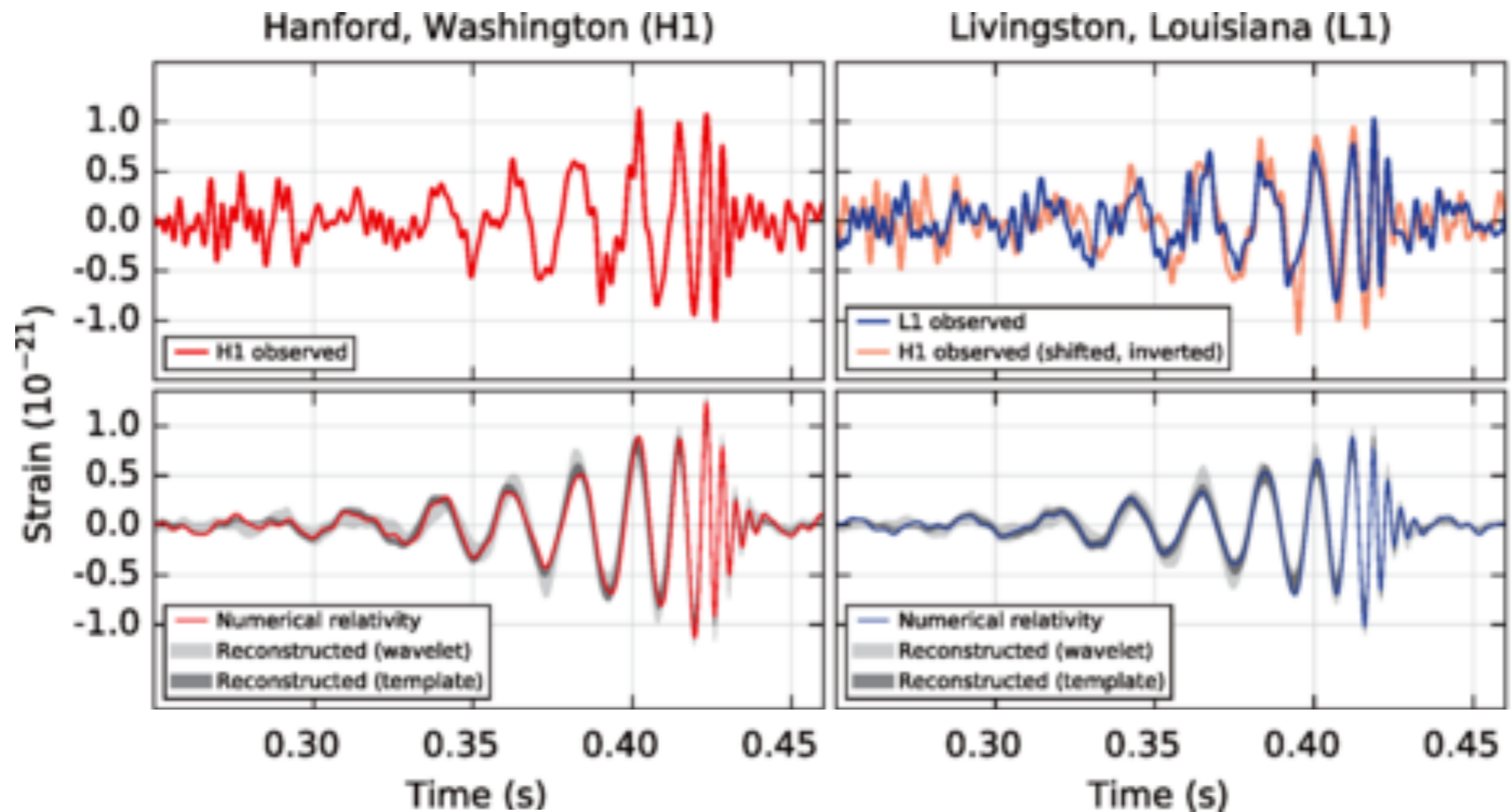
$$\rho = \frac{h}{e^2} \left[c_1 + c_2 \left(\frac{T}{E_c} \right)^2 \right]$$

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

Black holes

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





LIGO
September 14, 2015

- The Hawking temperature, T_H influences the radiation from the black hole at the very last stages of the ring-down (not observed so far). The ring-down (approach to thermal equilibrium) happens very rapidly in a time $\sim \frac{\hbar}{k_B T_H} = \frac{8\pi GM}{c^3} \sim 8$ milliseconds.

Black holes

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- The entropy is proportional to their surface area.



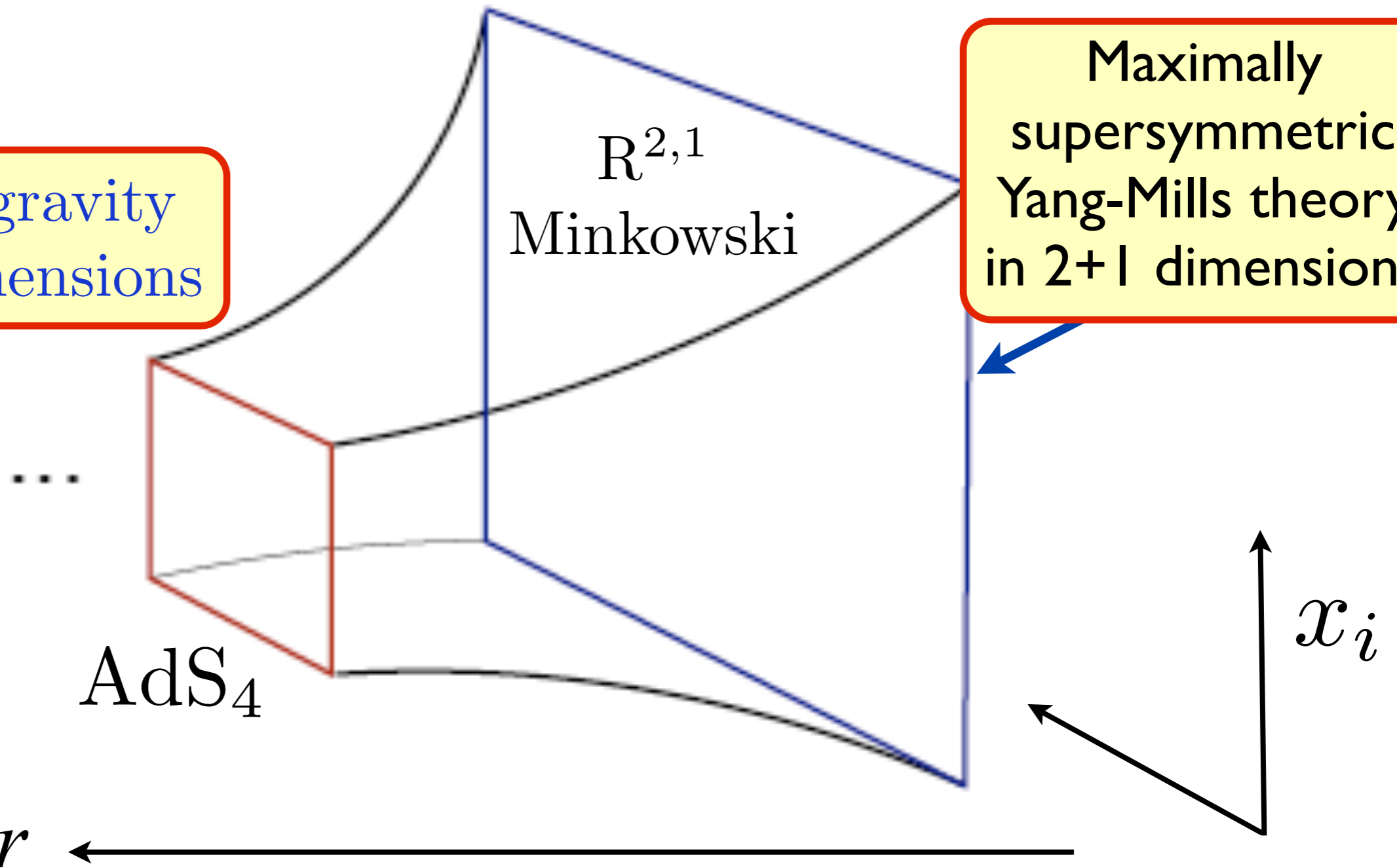
Black holes

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



AdS/CFT correspondence at zero temperature

Quantum gravity
in 3+1 dimensions



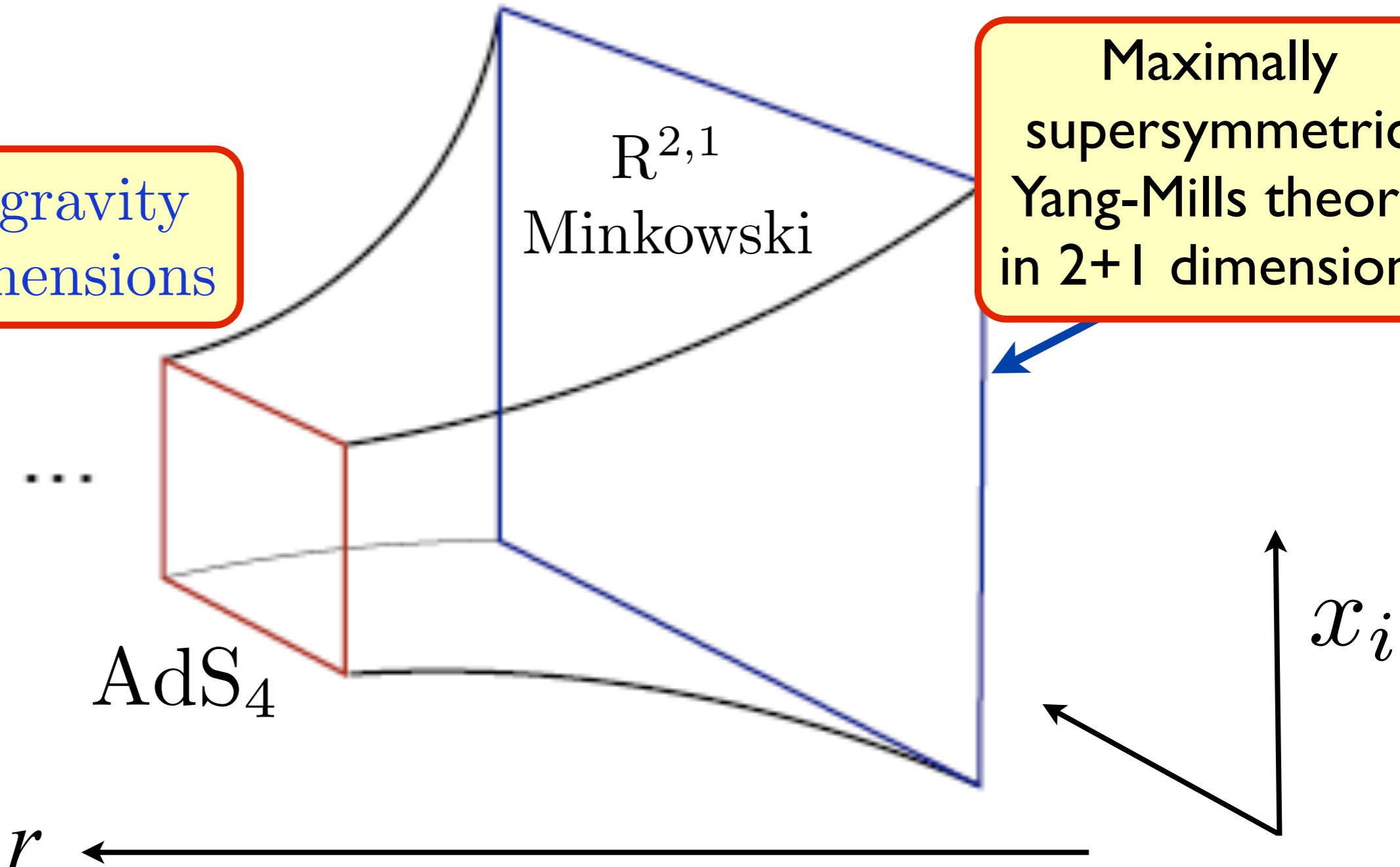
Maximally
supersymmetric
Yang-Mills theory
in 2+1 dimensions

$$ds^2 = \left(\frac{L}{r}\right)^2 [dr^2 - dt^2 + dx^2 + dy^2]$$

AdS/CFT correspondence at zero temperature

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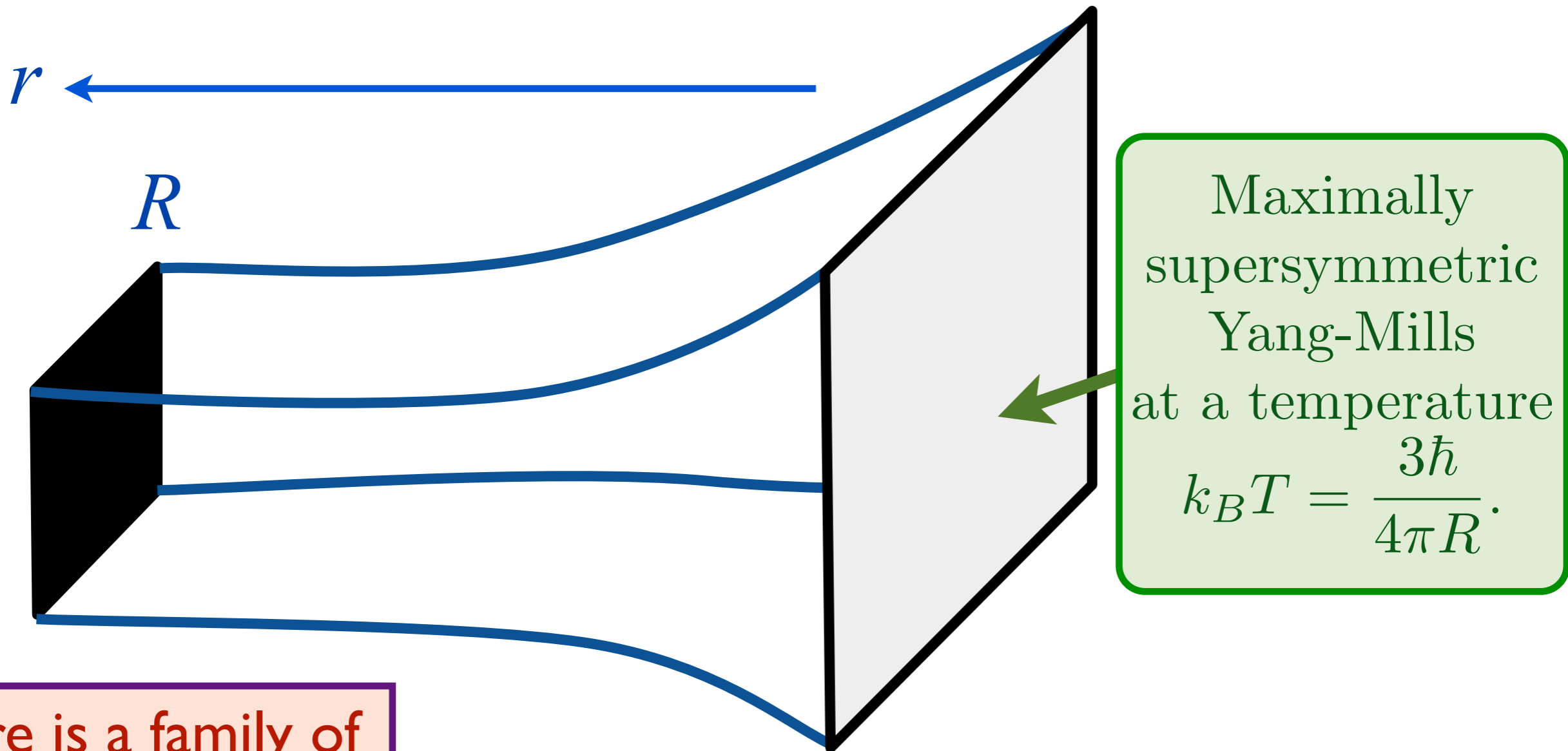


This spacetime is a solution of Einstein gravity with a negative cosmological constant

$$S_E = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} \left(R + \frac{6}{L^2} \right) \right]$$

AdS/CFT correspondence at non-zero temperatures

AdS₄-Schwarzschild black-brane



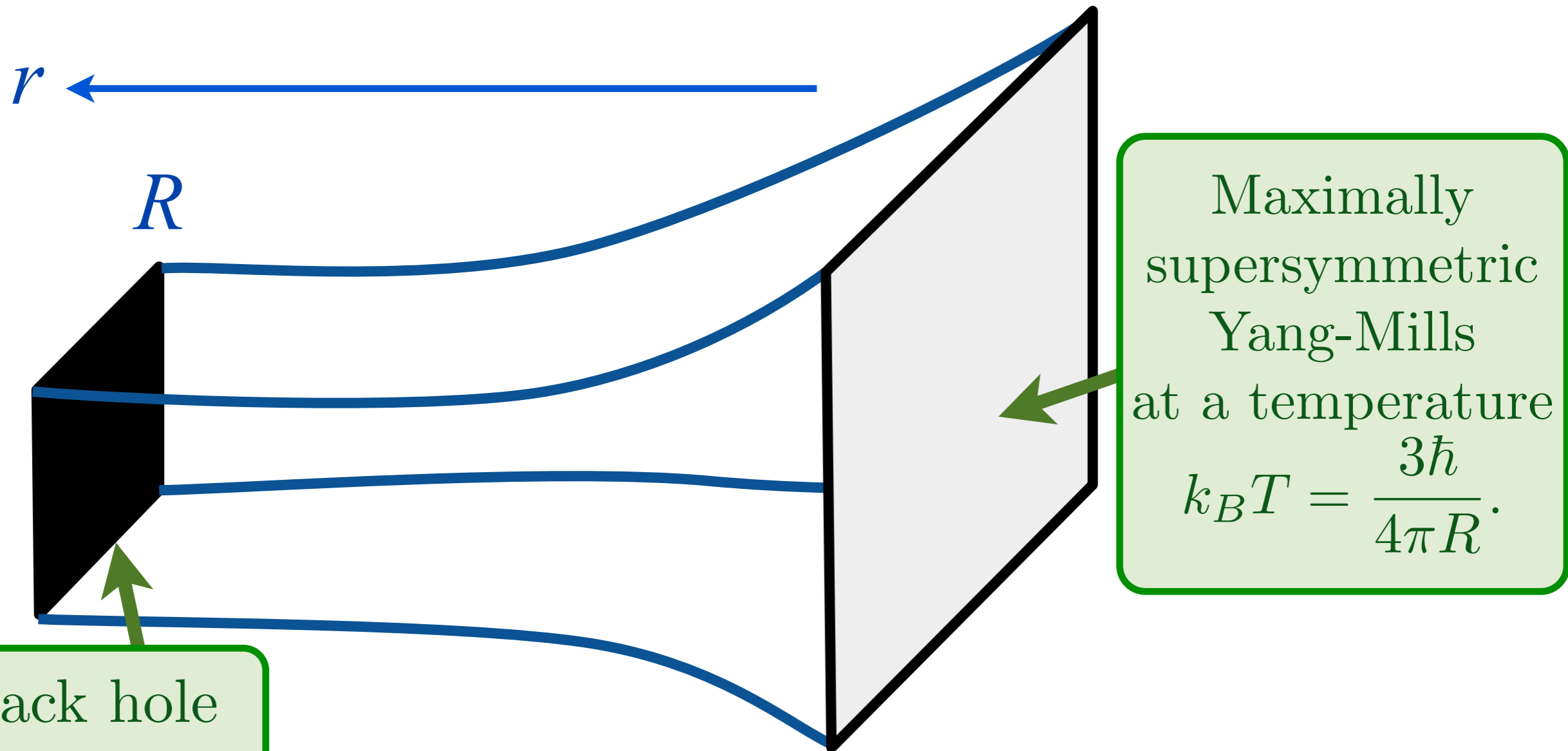
There is a family of solutions of Einstein gravity which describe non-zero temperatures

$$ds^2 = \left(\frac{L}{r}\right)^2 \left[\frac{dr^2}{f(r)} - f(r)dt^2 + dx^2 + dy^2 \right]$$

with $f(r) = 1 - (r/R)^3$

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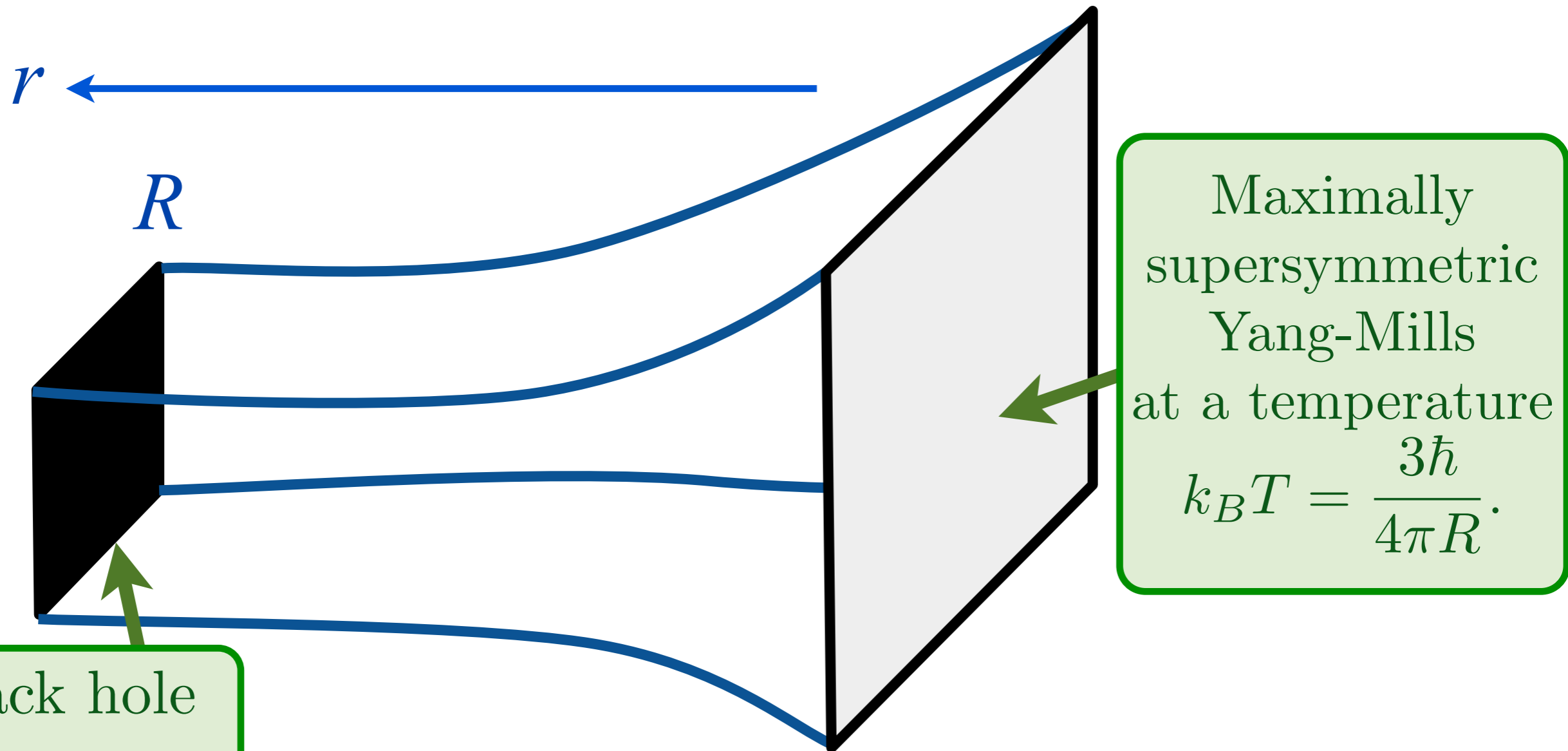
Black hole horizon at a Hawking temperature $T_H = T$

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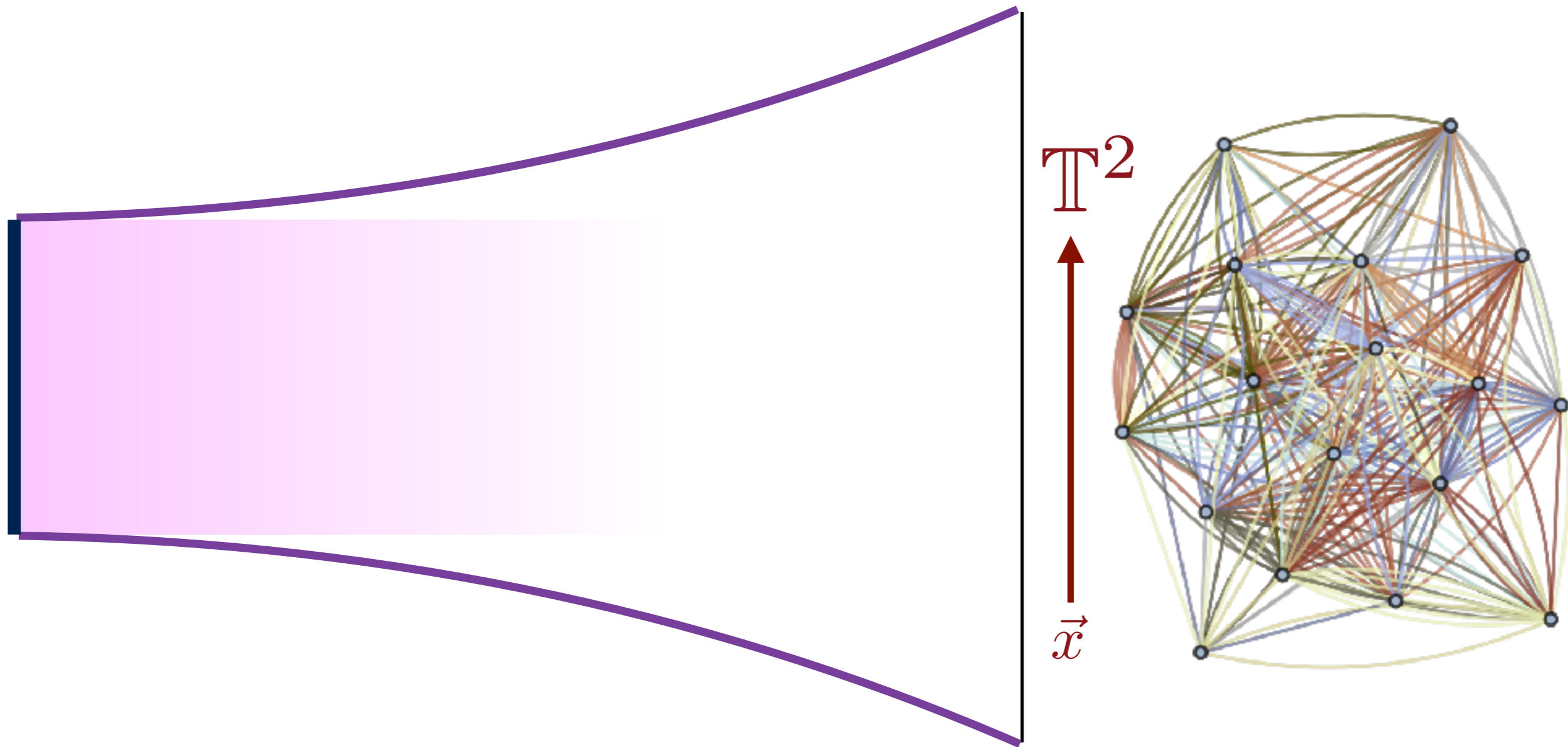
Maximally supersymmetric Yang-Mills at a temperature $k_B T = \frac{3\hbar}{4\pi R}$.

Black hole entropy = Entropy of Yang-Mills theory

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SYK and black holes

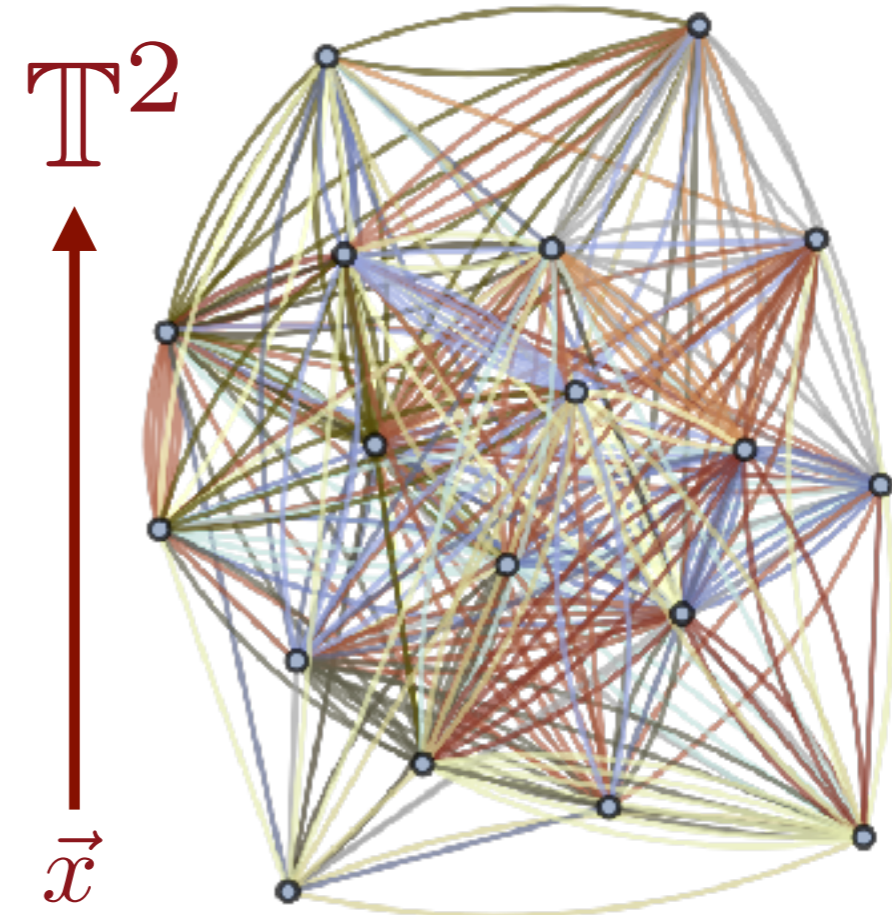
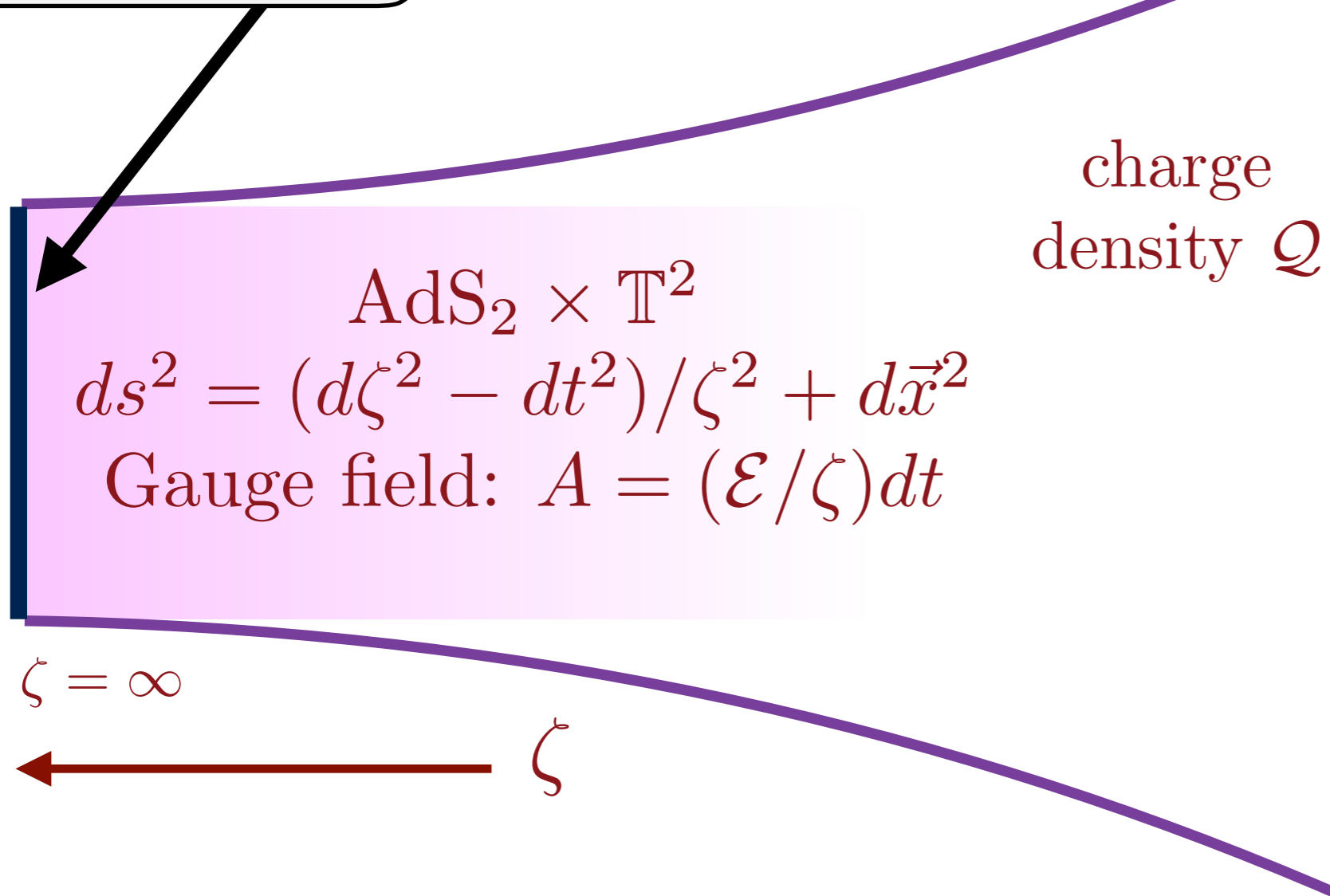


Is there a holographic quantum gravity dual of the SYK model ?

SYK and black holes

$$S = \int d^4x \sqrt{-\hat{g}} \left(\hat{\mathcal{R}} + 6/L^2 - \frac{1}{4} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \right)$$

Black hole horizon



The leading low temperature properties of the Einstein-Maxwell theory holographically match those of the SYK model.
The mapping applies when temperature $\ll 1/(\text{size of } \mathbb{T}^2)$.

The SYK model

- Low energy, many-body density of states
 $\rho(E) \sim e^{Ns_0}$
- Low temperature entropy $S = Ns_0$
- $T = 0$ fermion Green's function $G(\tau) \sim \tau^{-1/2}$ at large τ .
- $T > 0$ Green's function has conformal invariance
 $G \sim (T / \sin(\pi k_B T \tau / \hbar))^{1/2}$
- The last property indicates $\tau_{\text{eq}} \sim \hbar / (k_B T)$, and this has been found in a recent numerical study.

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• All these properties of the SYK model match those of the AdS₂ horizon on Einstein-Maxwell theory

The SYK model

- Low energy, many-body density of states
 $\rho(E) \sim e^{Ns_0} \sinh(\sqrt{2(E - E_0)N\gamma})$
- Low temperature entropy $S = Ns_0 + N\gamma T + \dots$
- $T = 0$ fermion Green's function $G(\tau) \sim \tau^{-1/2}$ at large τ .
- $T > 0$ Green's function has conformal invariance
 $G \sim (T / \sin(\pi k_B T \tau / \hbar))^{1/2}$

**Schwarzian theory of quantum gravity
fluctuations also matches these corrections**

A Kitaev, unpublished, J. Maldacena, D. Stanford, and Zhenbin Yang, arXiv:1606.01857;
D. Stanford and E. Witten, arXiv:1703.04612

Many-body quantum chaos

- Using holographic analogies, Shenker and Stanford introduced the “Lyapunov time”, τ_L , the time over which a generic many-body quantum system loses memory of its initial state.

S. Shenker and D. Stanford, arXiv:1306.0622

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- A shortest-possible time to reach quantum chaos was established

$$\tau_L \geq \frac{\hbar}{2\pi k_B T}$$

J. Maldacena, S. H. Shenker and D. Stanford, arXiv:1503.01409

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- The SYK model, and black holes in Einstein gravity, saturate the bound on the Lyapunov time

$$\tau_L = \frac{\hbar}{2\pi k_B T}$$

A. Kitaev, unpublished
J. Maldacena and D. Stanford,
arXiv:1604.07818

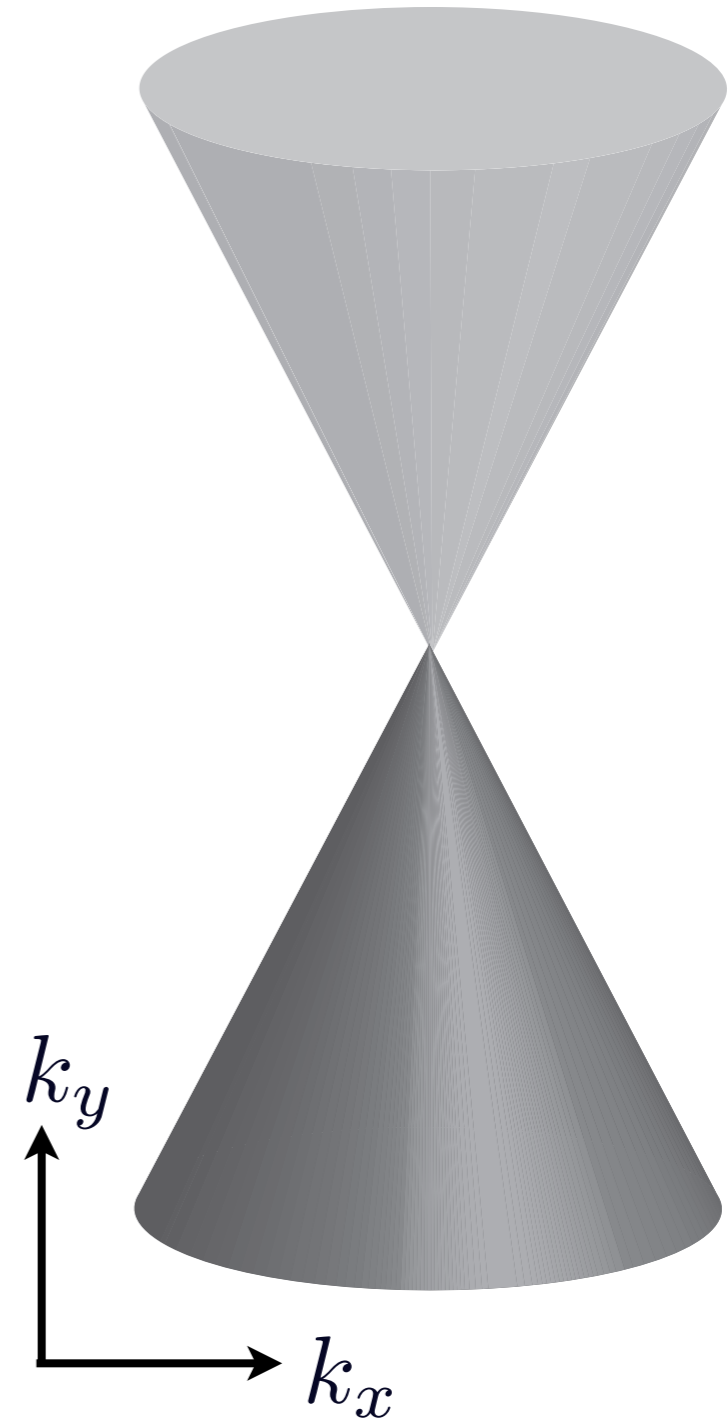
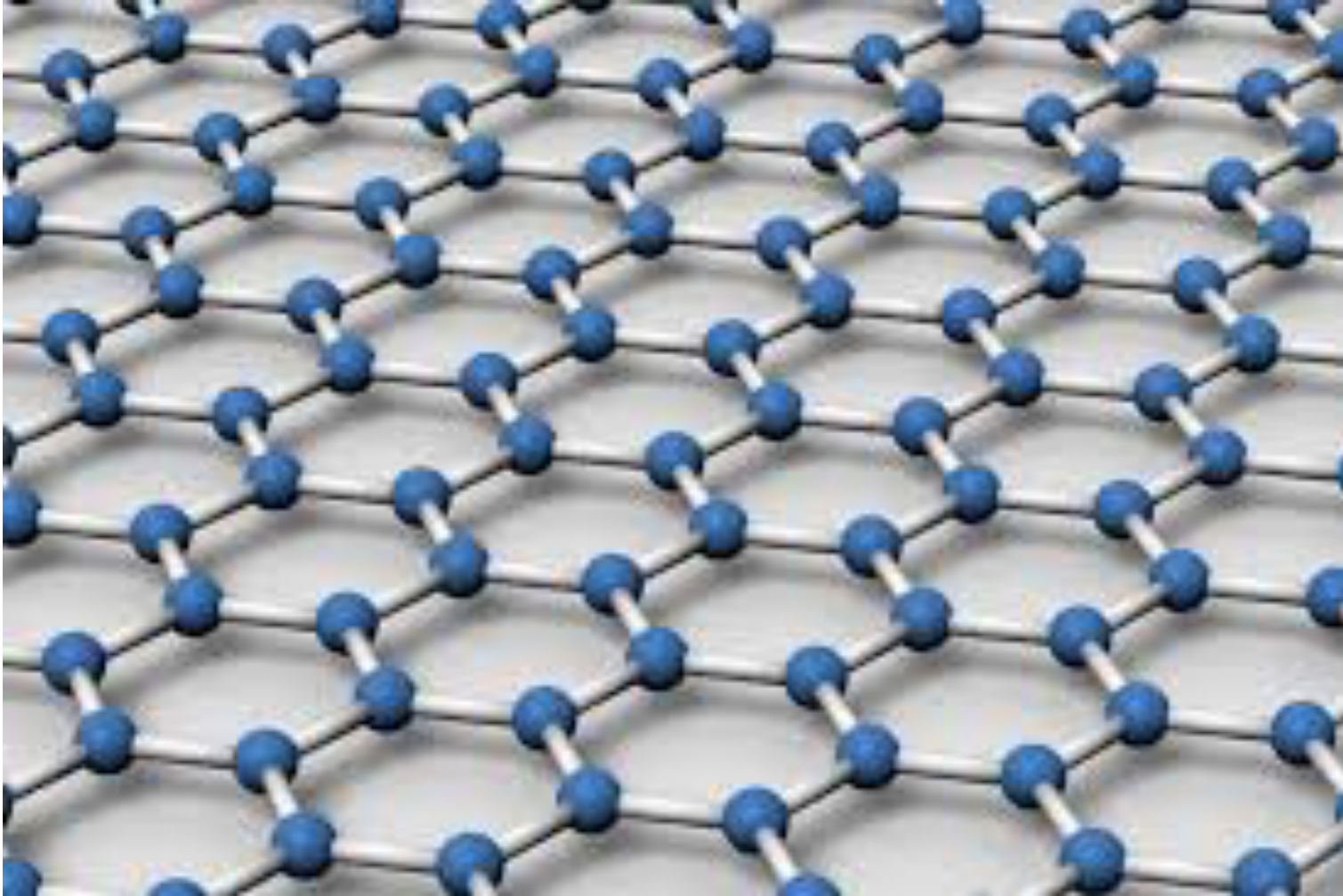
Quantum matter without quasiparticles:

- No quasiparticle decomposition of low-lying states:
$$E \neq \sum_{\alpha} n_{\alpha} \varepsilon_{\alpha} + \sum_{\alpha, \beta} F_{\alpha\beta} n_{\alpha} n_{\beta} + \dots$$
- Thermalization and many-body chaos in the shortest possible time of order $\hbar/(k_B T)$.

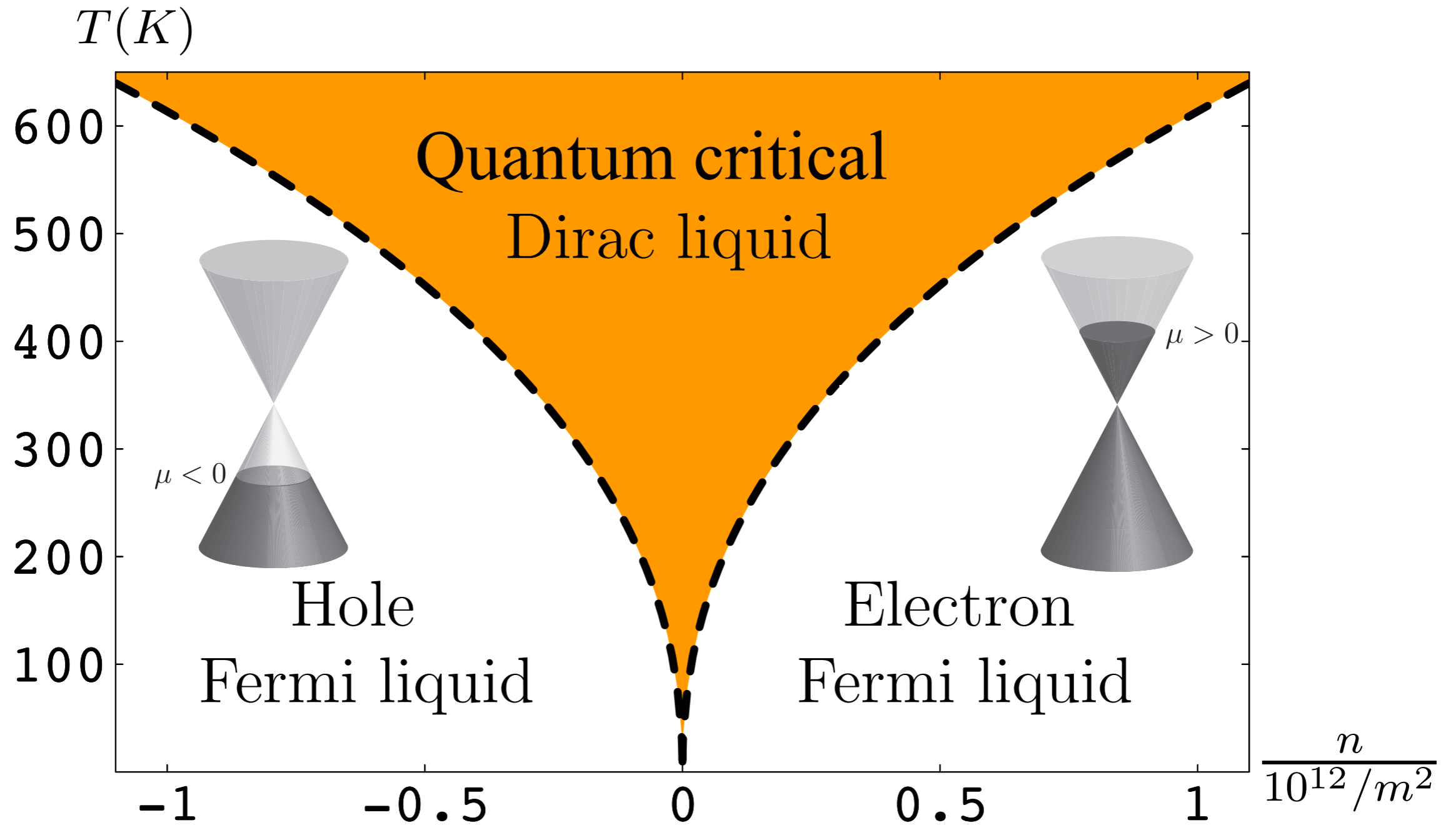
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- Thermalization and many-body chaos in the shortest possible time of order $\hbar/(k_B T)$.
- These are also characteristics of black holes in quantum gravity.

Graphene



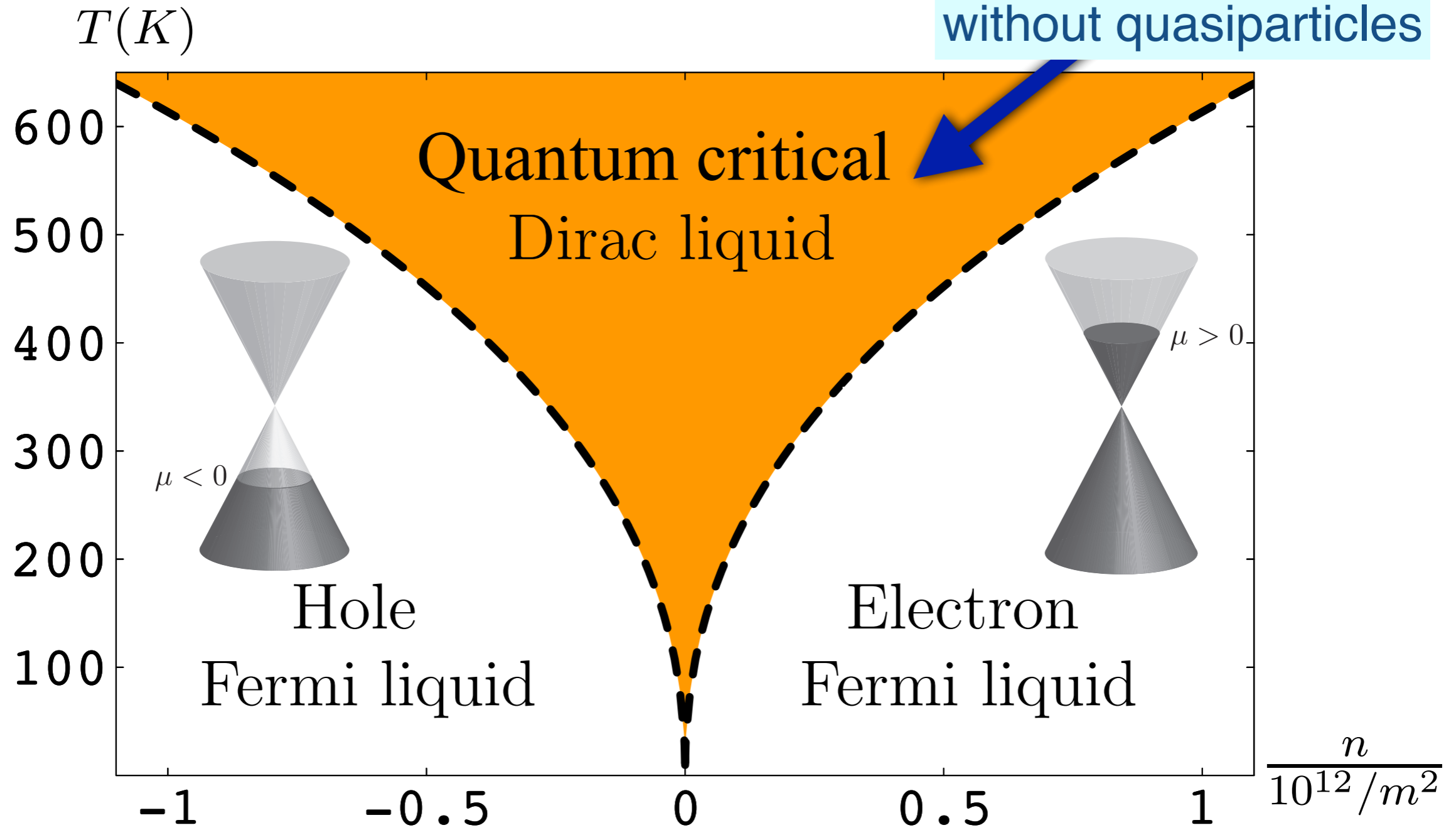
Graphene



D. E. Sheehy and J. Schmalian, PRL **99**, 226803 (2007)
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene

Predicted
“strange metal”
without quasiparticles

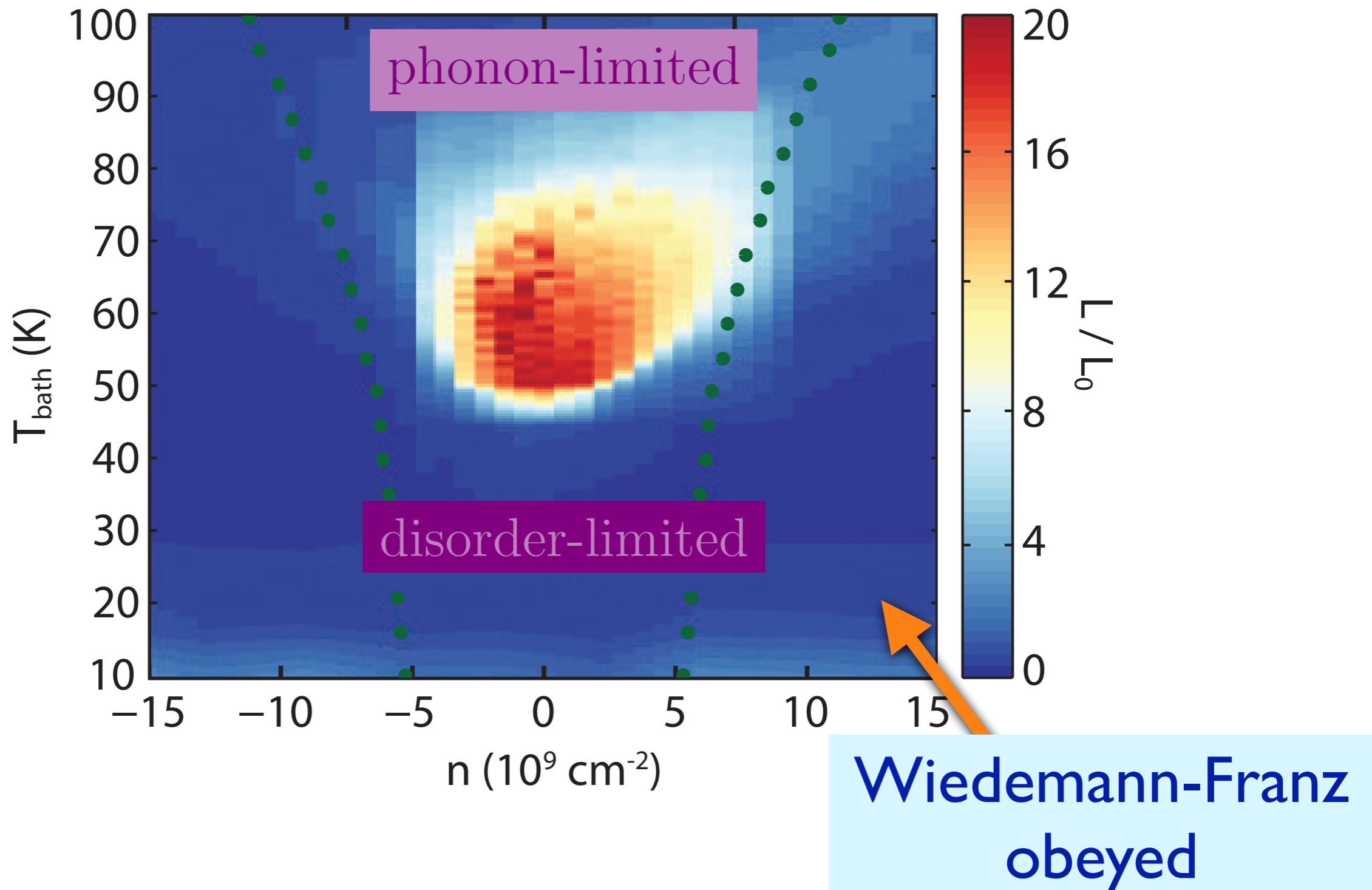


M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)

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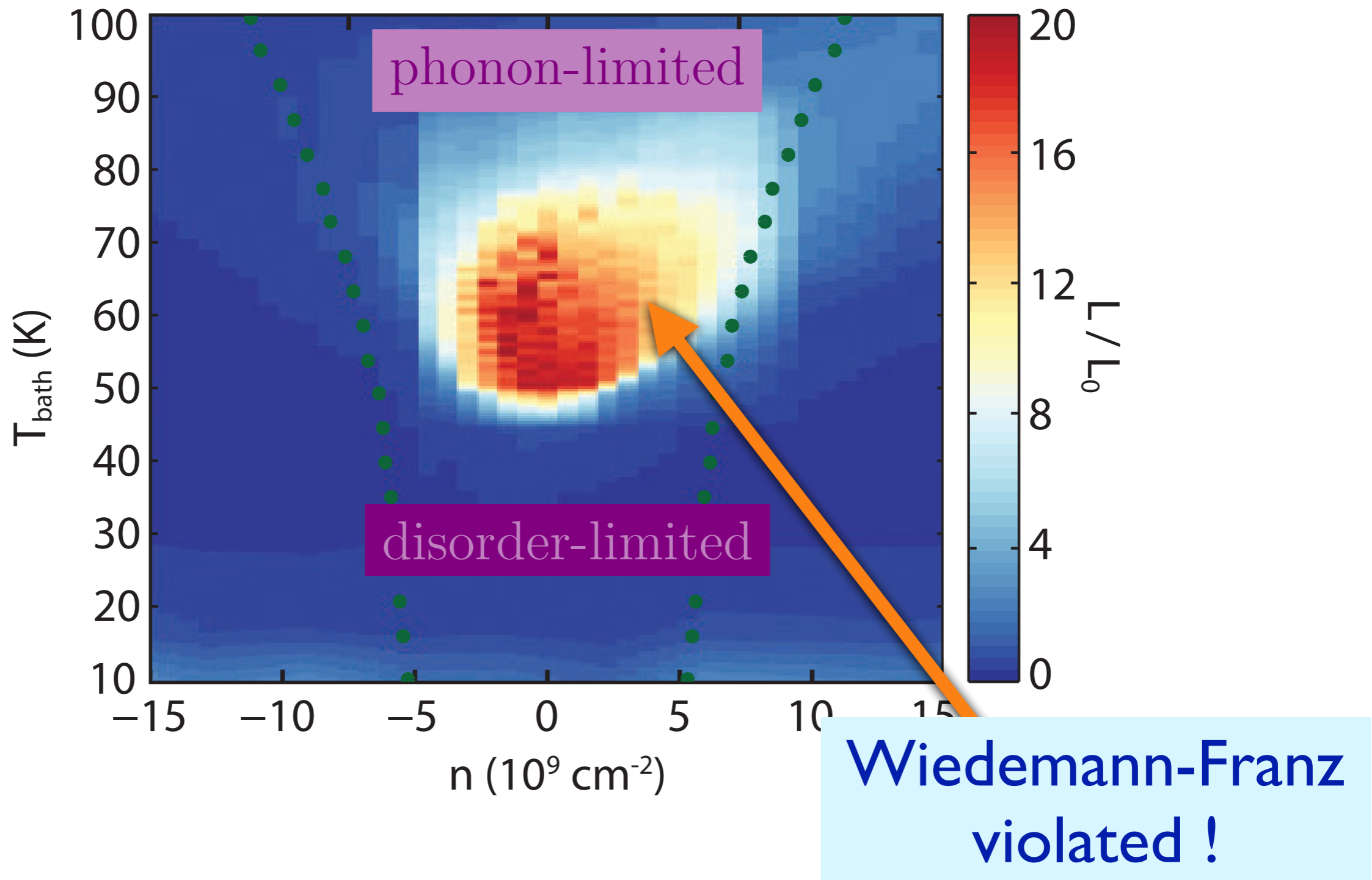
Strange metal in graphene

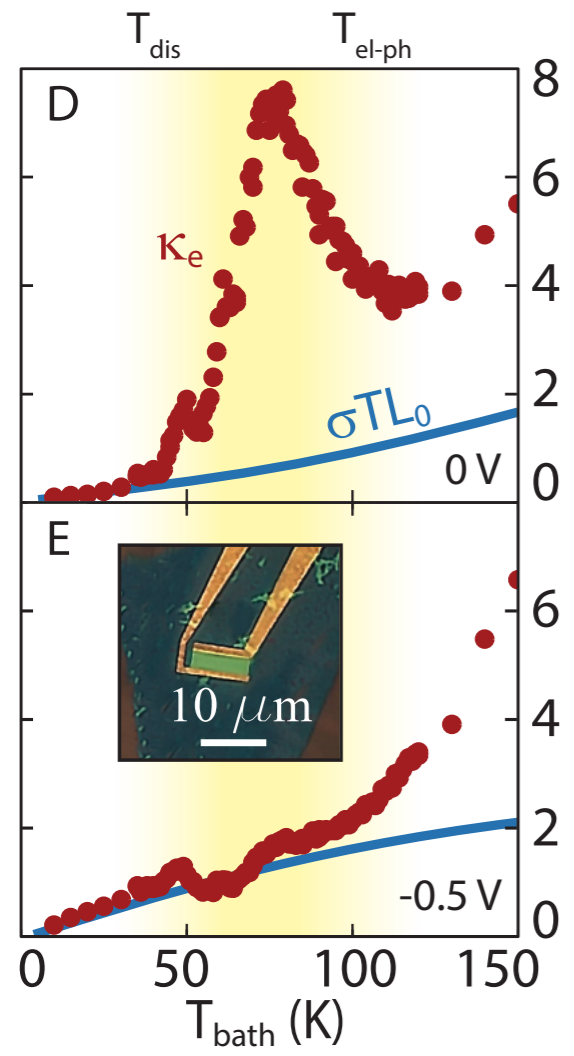
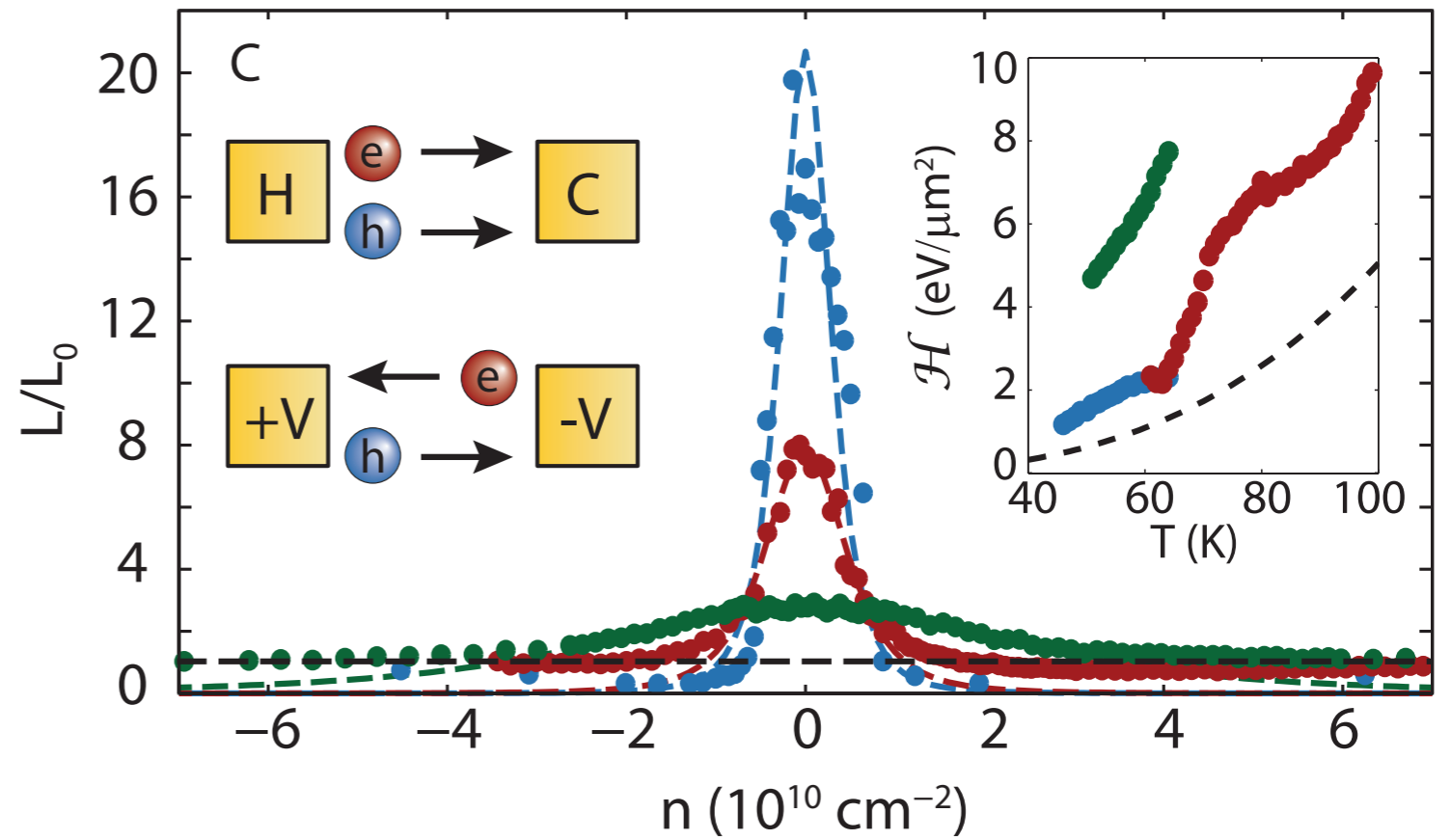
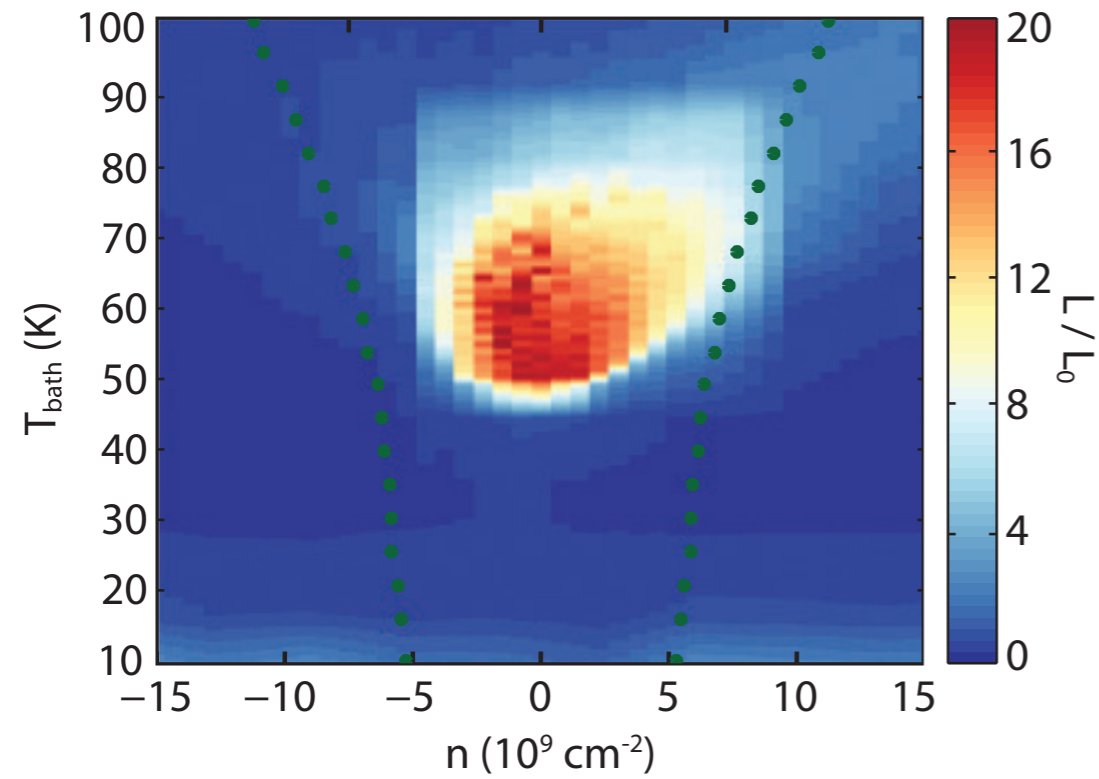
Measurements of the Lorenz ratio L , between the thermal and electrical conductivities



Strange metal in graphene

Measurements of the Lorenz ratio L , between the thermal and electrical conductivities





Lorentz ratio $L = \kappa / (T\sigma)$

$$= \frac{v_F^2 \mathcal{H} \tau_{\text{imp}}}{T^2 \sigma_Q} \frac{1}{(1 + e^2 v_F^2 Q^2 \tau_{\text{imp}} / (\mathcal{H} \sigma_Q))^2}$$

$Q \rightarrow$ electron density; $\mathcal{H} \rightarrow$ enthalpy density

$\sigma_Q \rightarrow$ quantum critical conductivity

$\tau_{\text{imp}} \rightarrow$ momentum relaxation time from impurities

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

J. Crossno et al., Science **351**, 1058 (2016)