

Quantum matter without quasiparticles: strange metals and black holes

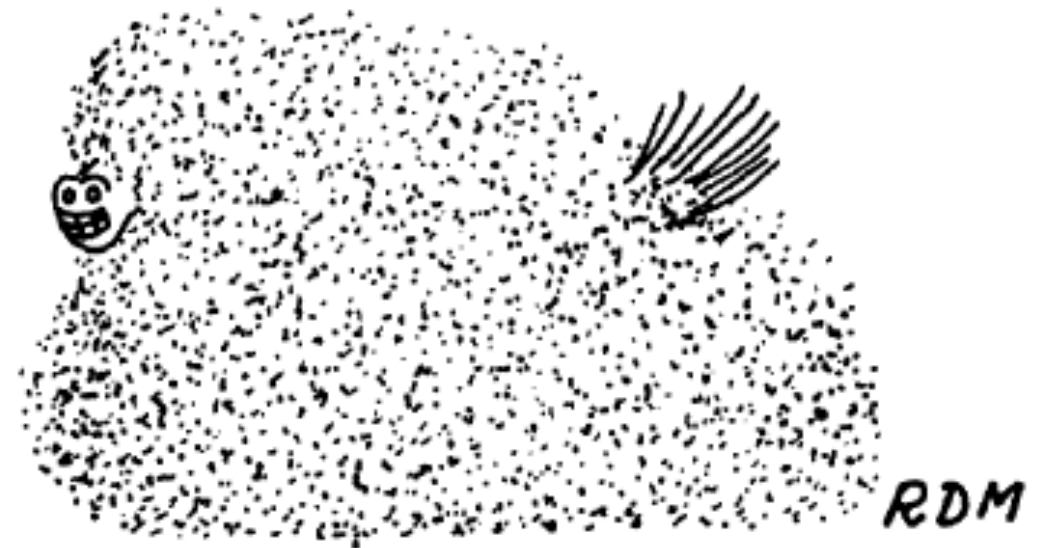
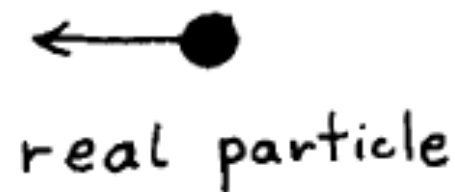
Biard Lecture
California Institute of Technology,
Pasadena, November 2, 2017

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.



real horse

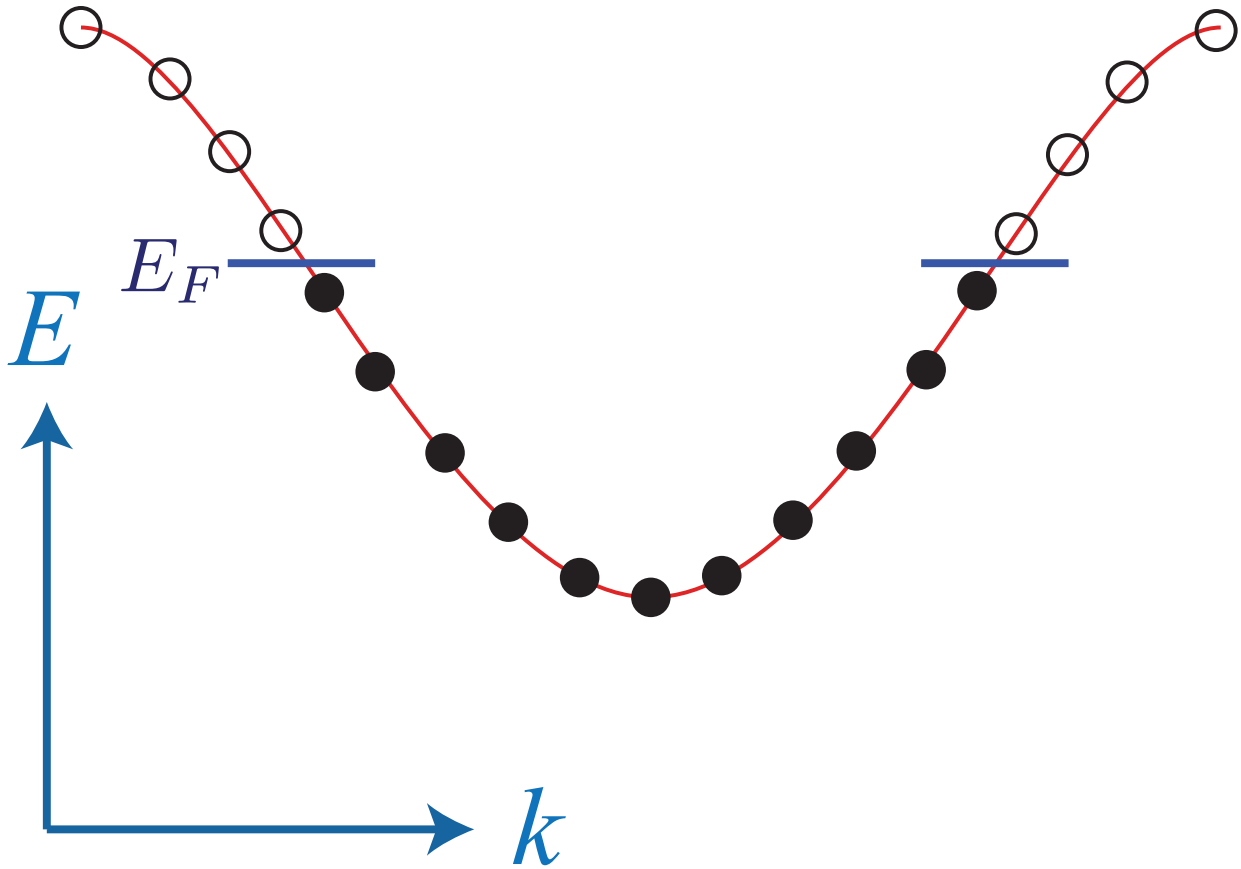
quasi horse

RDM

R.D. Mattuck

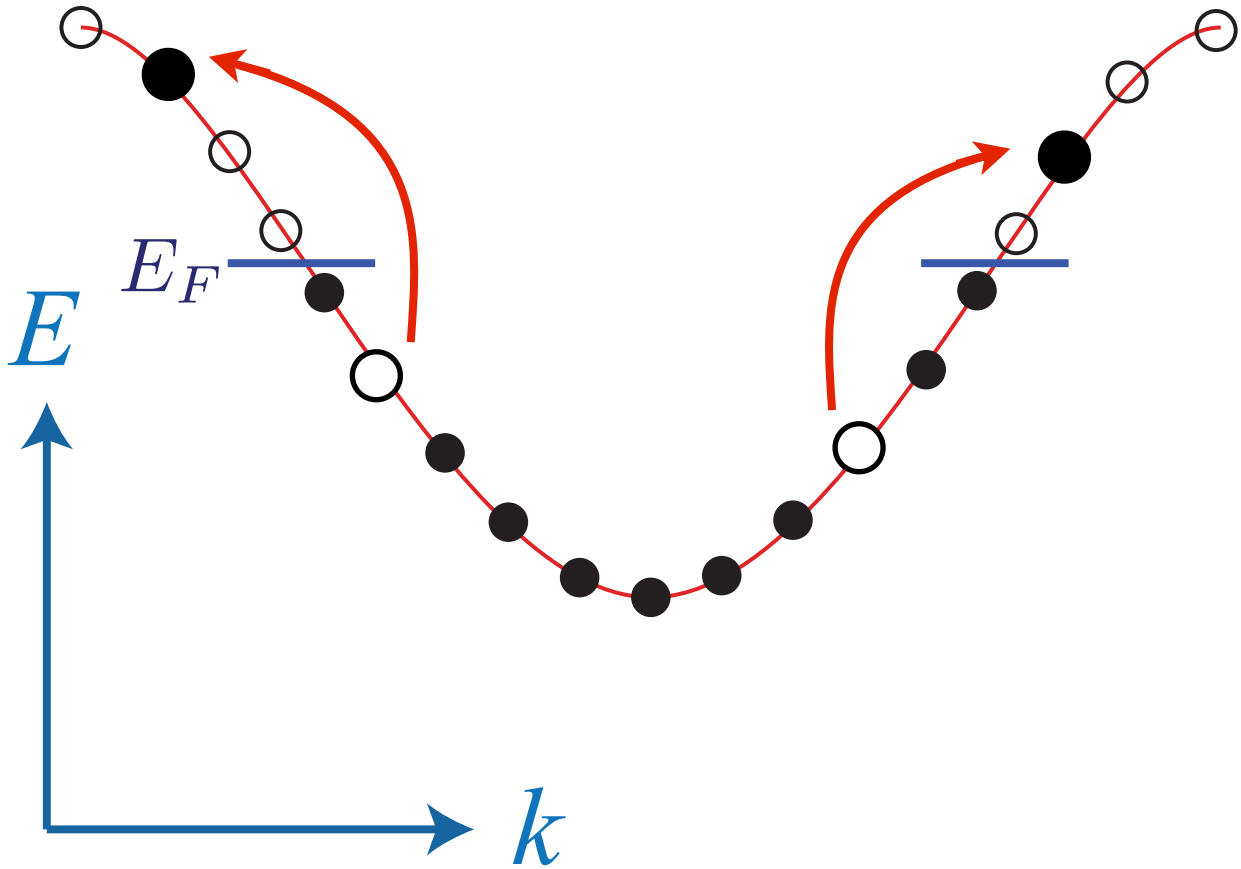
Quantum matter with quasiparticles:

Metals



Quantum matter with quasiparticles:

Metals



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

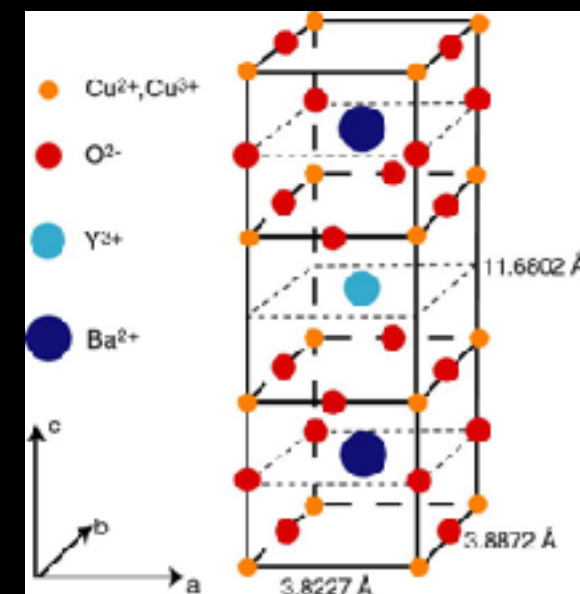
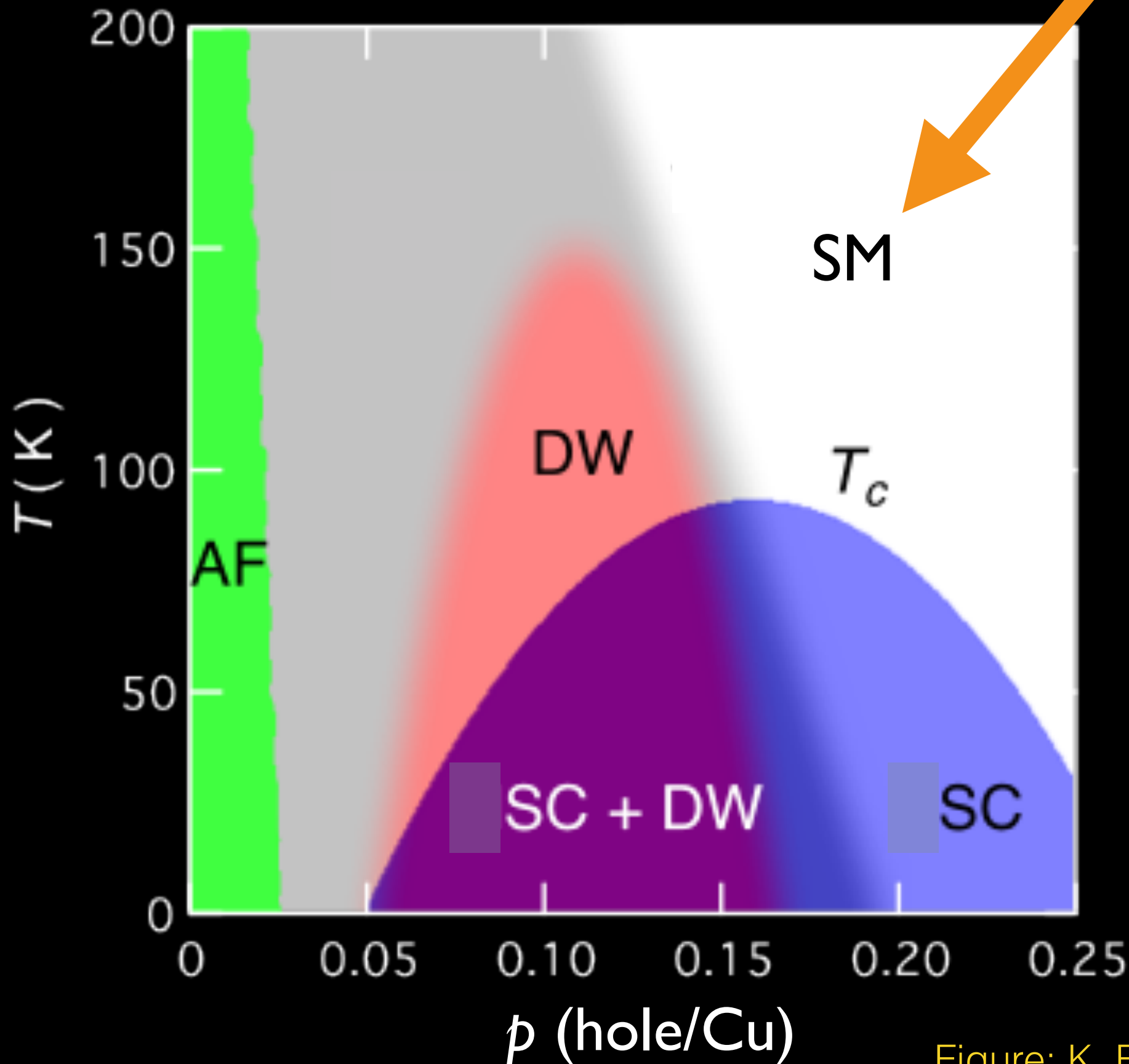


Figure: K. Fujita and J. C. Seamus Davis



“Strange”,

“Bad”,



or “Incoherent”,

metal has a resistivity, ρ , which obeys

$$\rho \sim T,$$

and

$$\rho \gg h/e^2$$

(in two dimensions),
where h/e^2 is the quantum unit of resistance.



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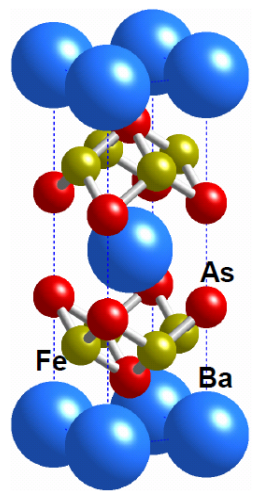
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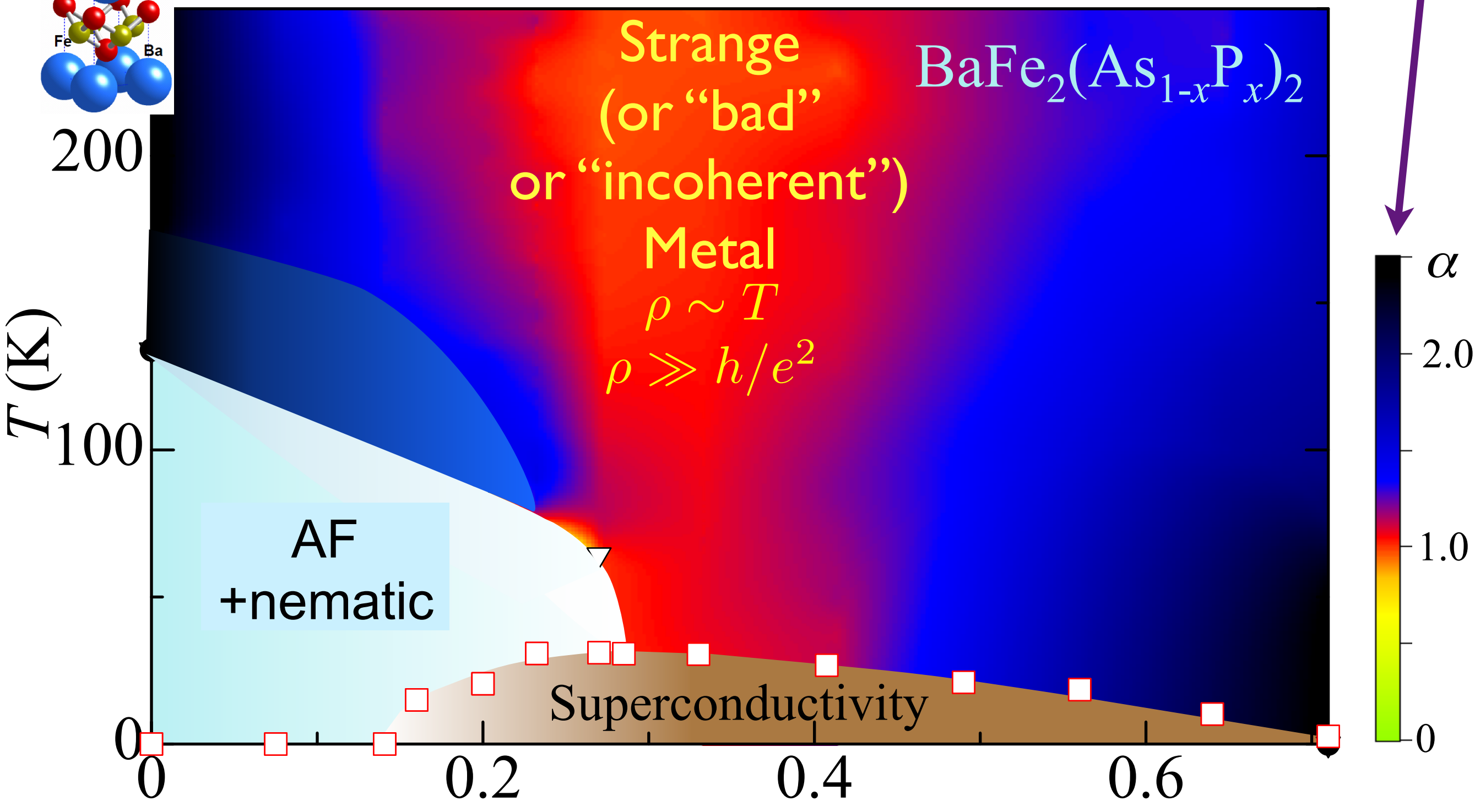


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Quantum matter without quasiparticles

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)

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.



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

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

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

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

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

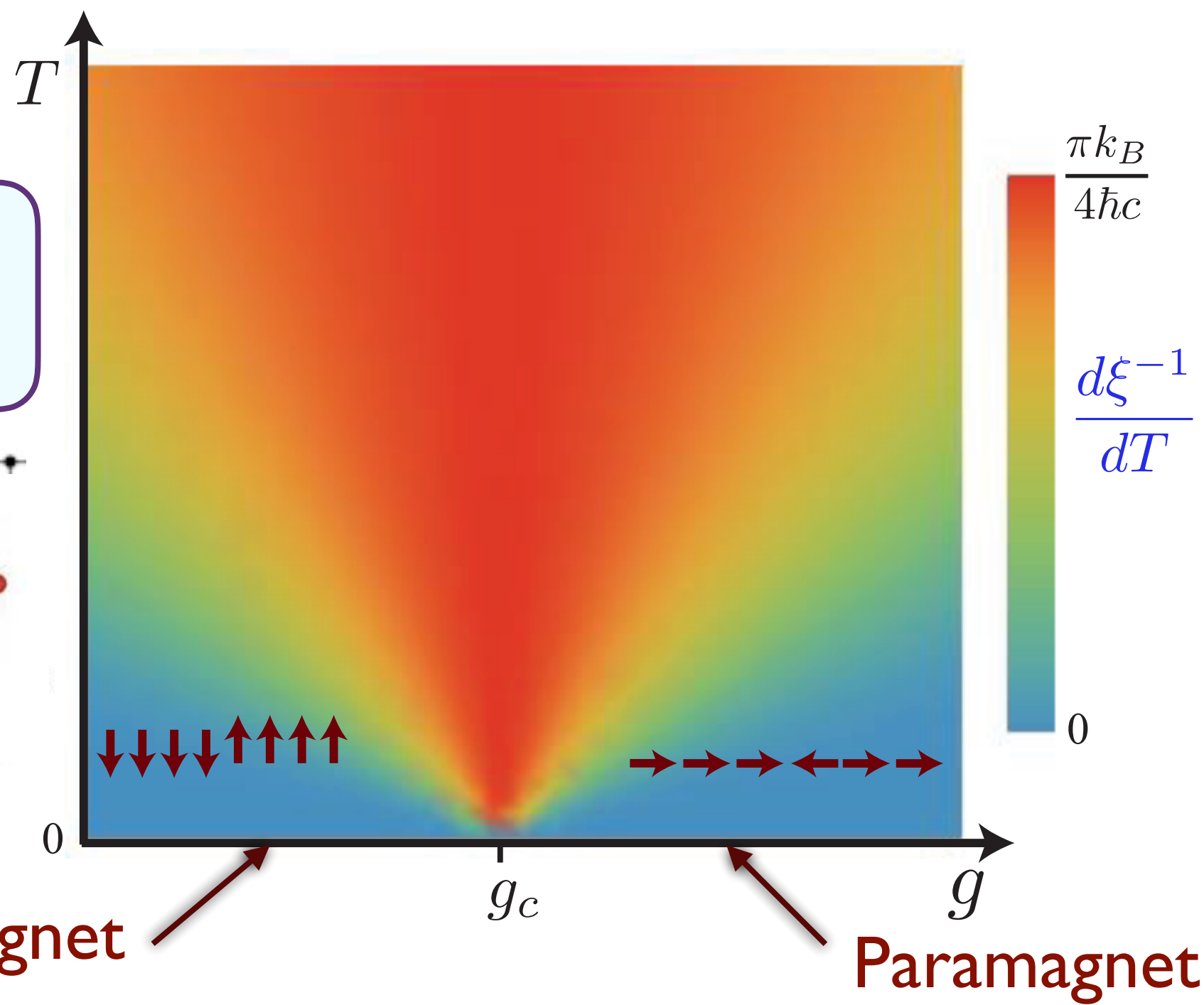
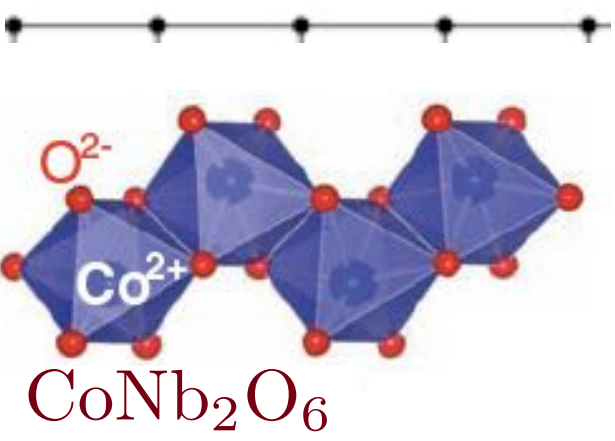
$$|G\rangle = |\cdots \rightarrow\rightarrow\rightarrow\rightarrow \cdots\rangle$$

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

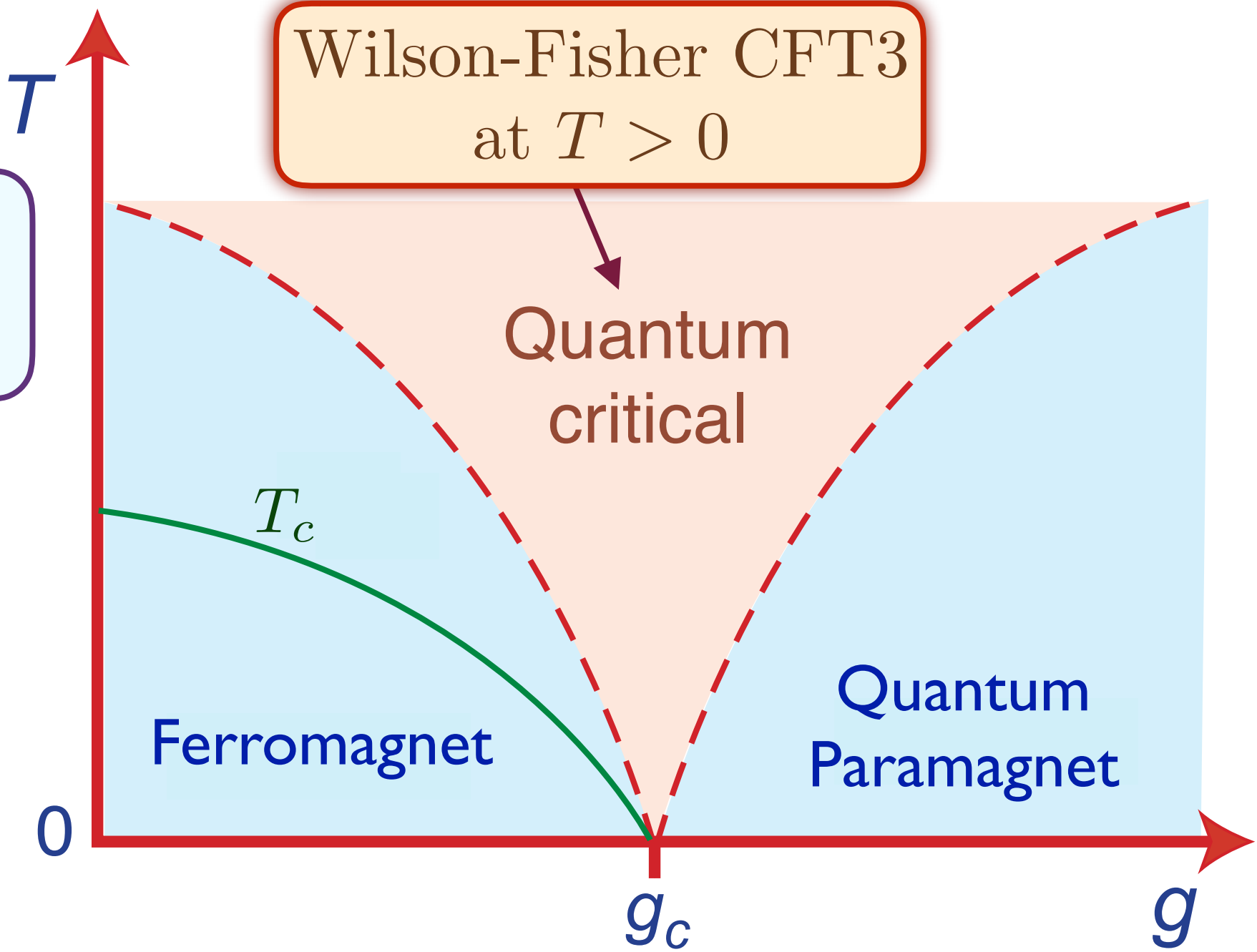
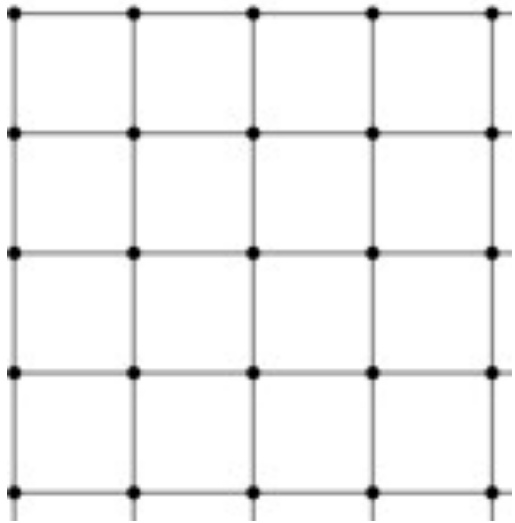
One dimension



- 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

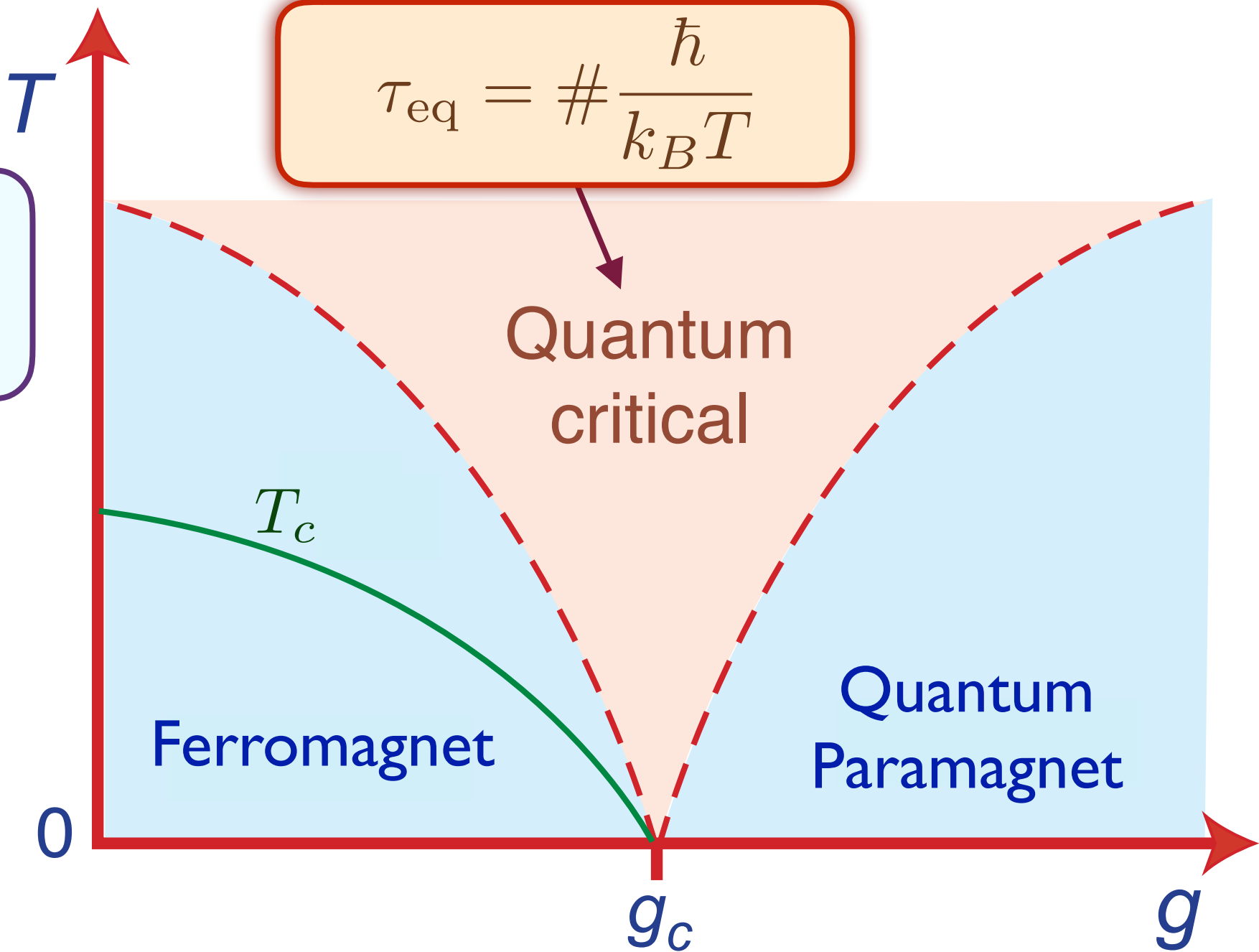
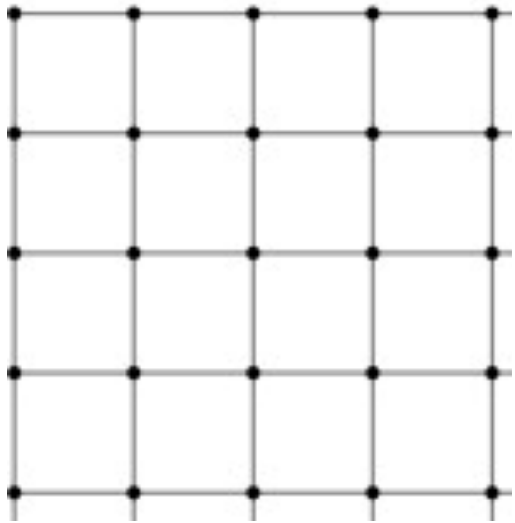
Two dimensions



- 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.

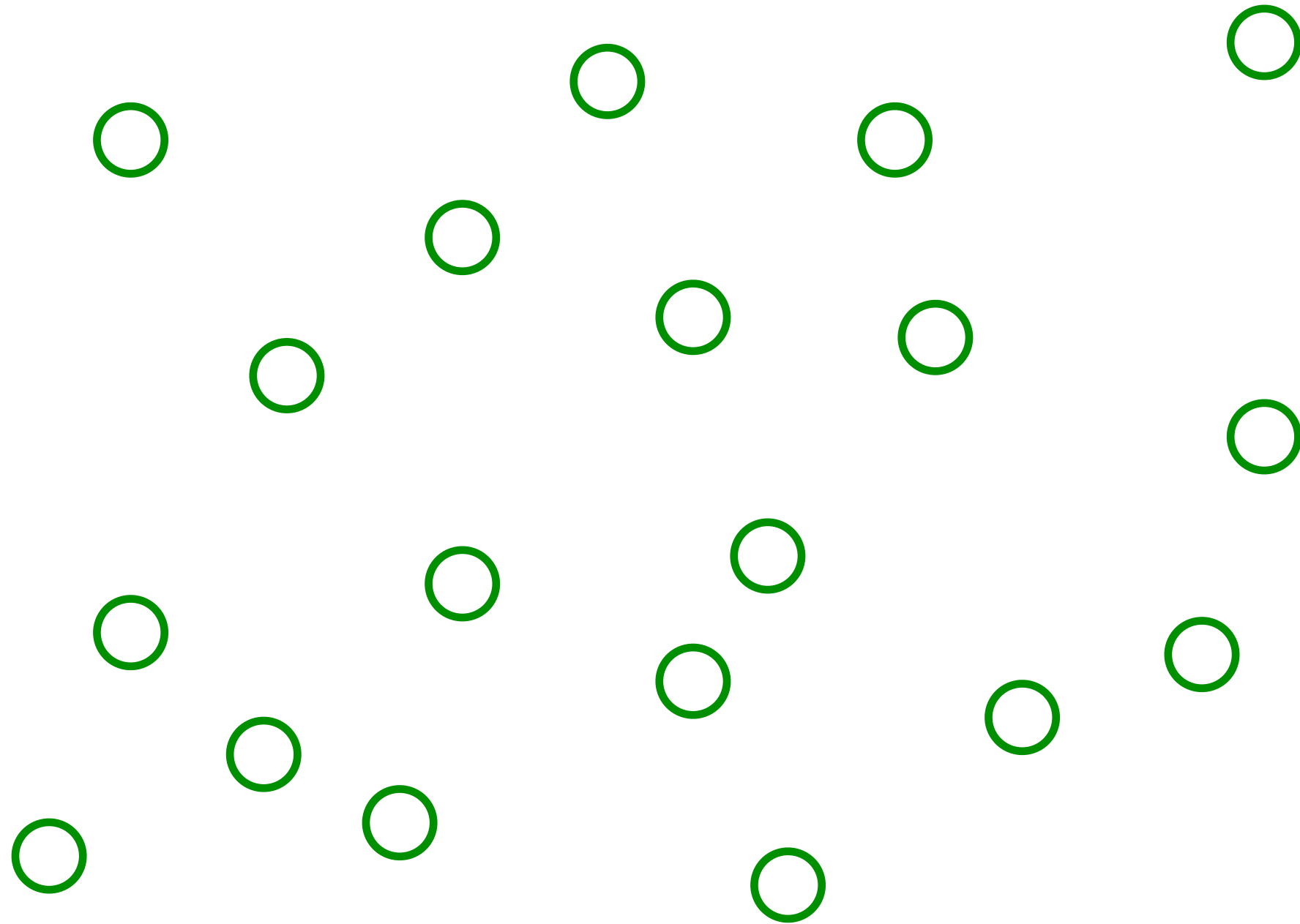
Quantum Ising models

Two dimensions



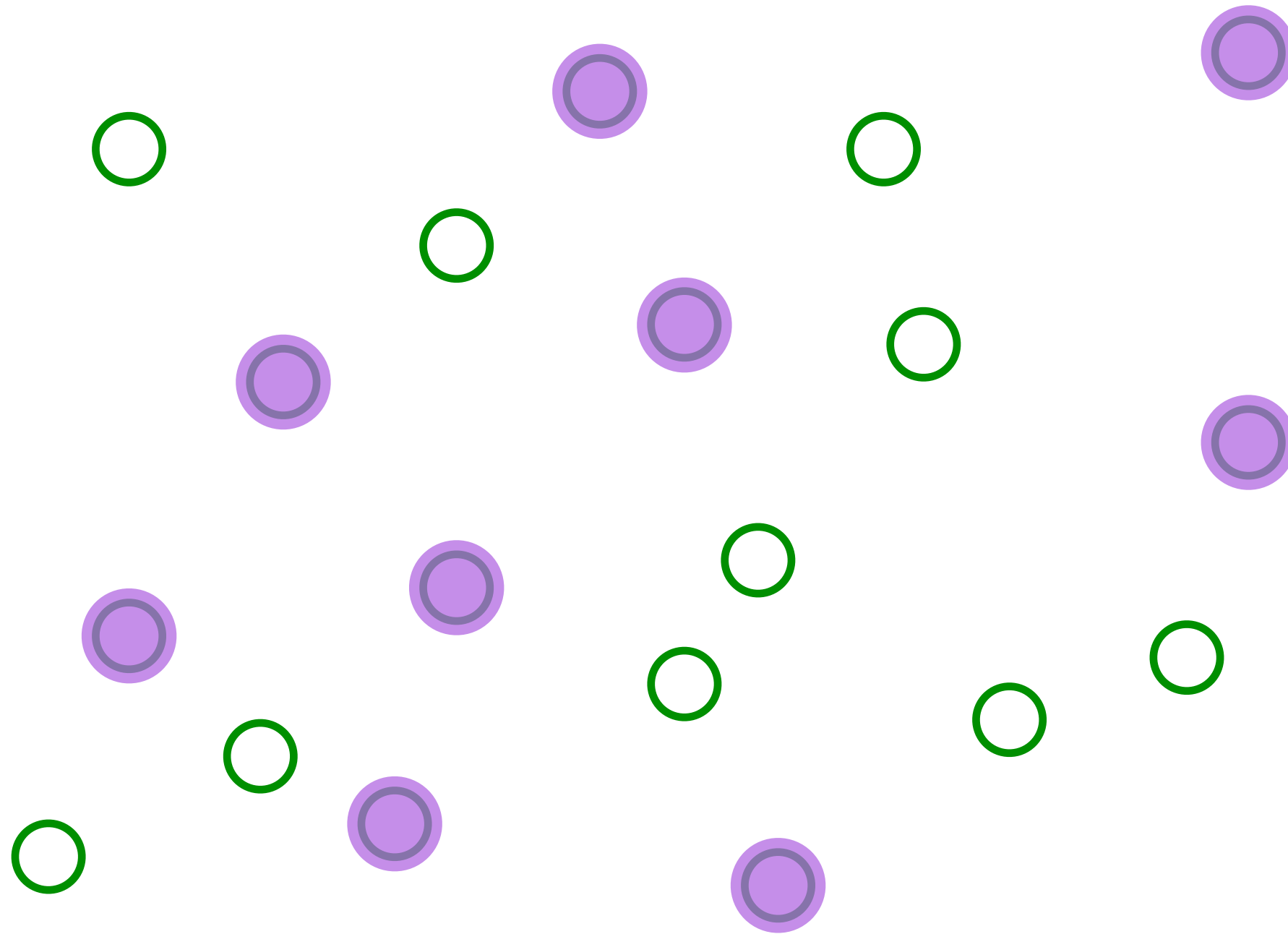
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A simple model of a metal with quasiparticles



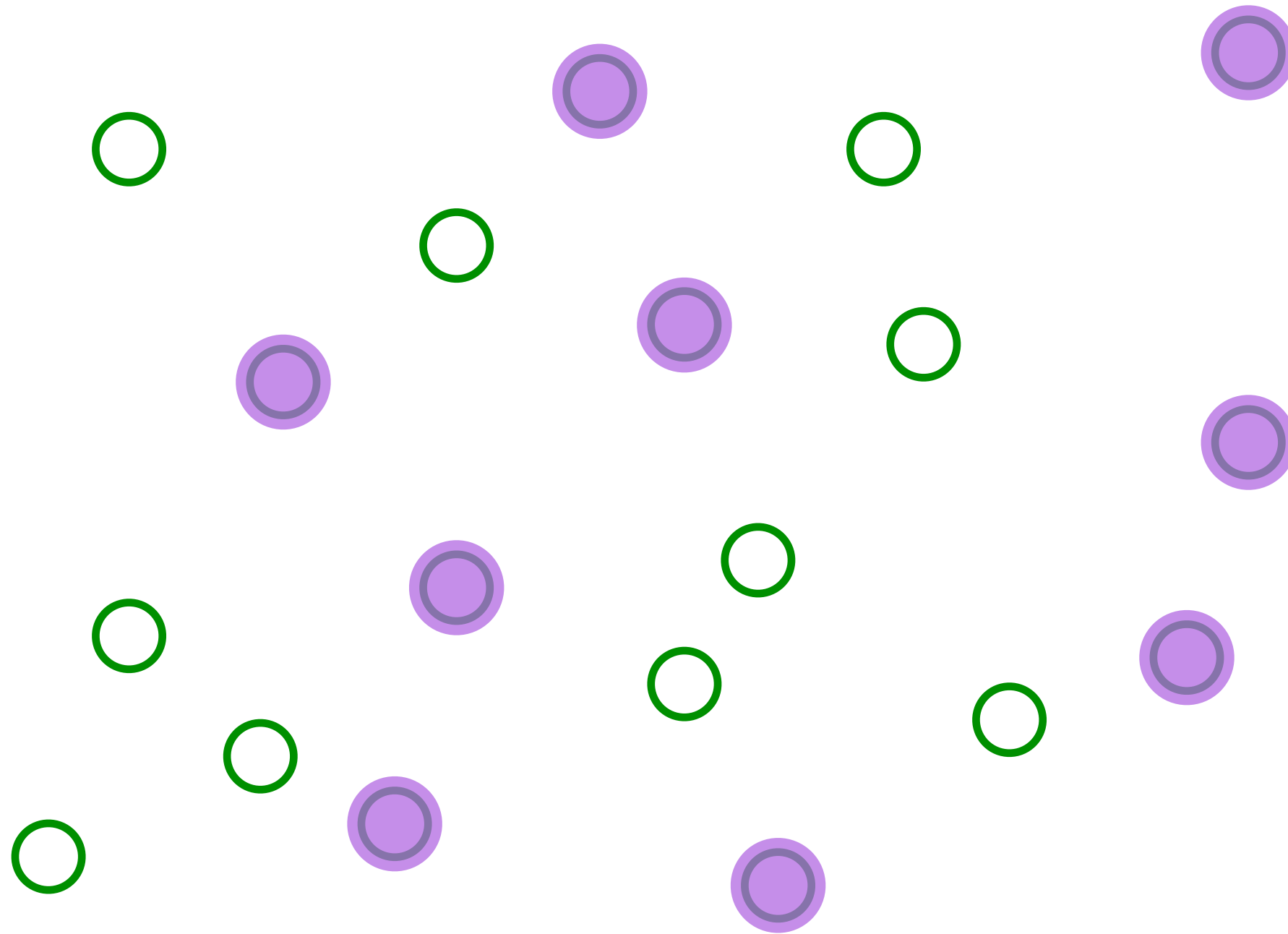
Pick a set of random positions

A simple model of a metal with quasiparticles



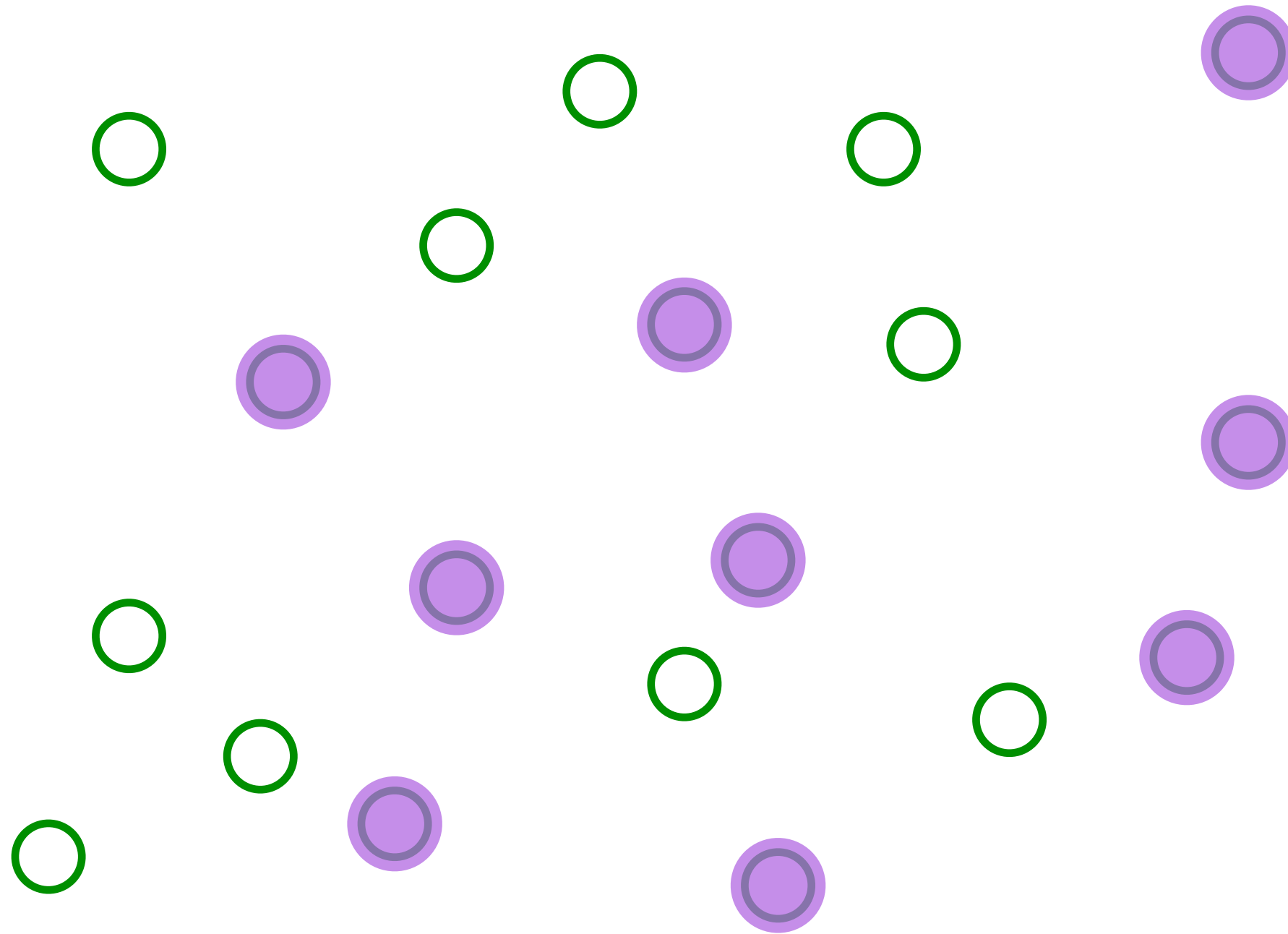
Place electrons randomly on some sites

A simple model of a metal with quasiparticles



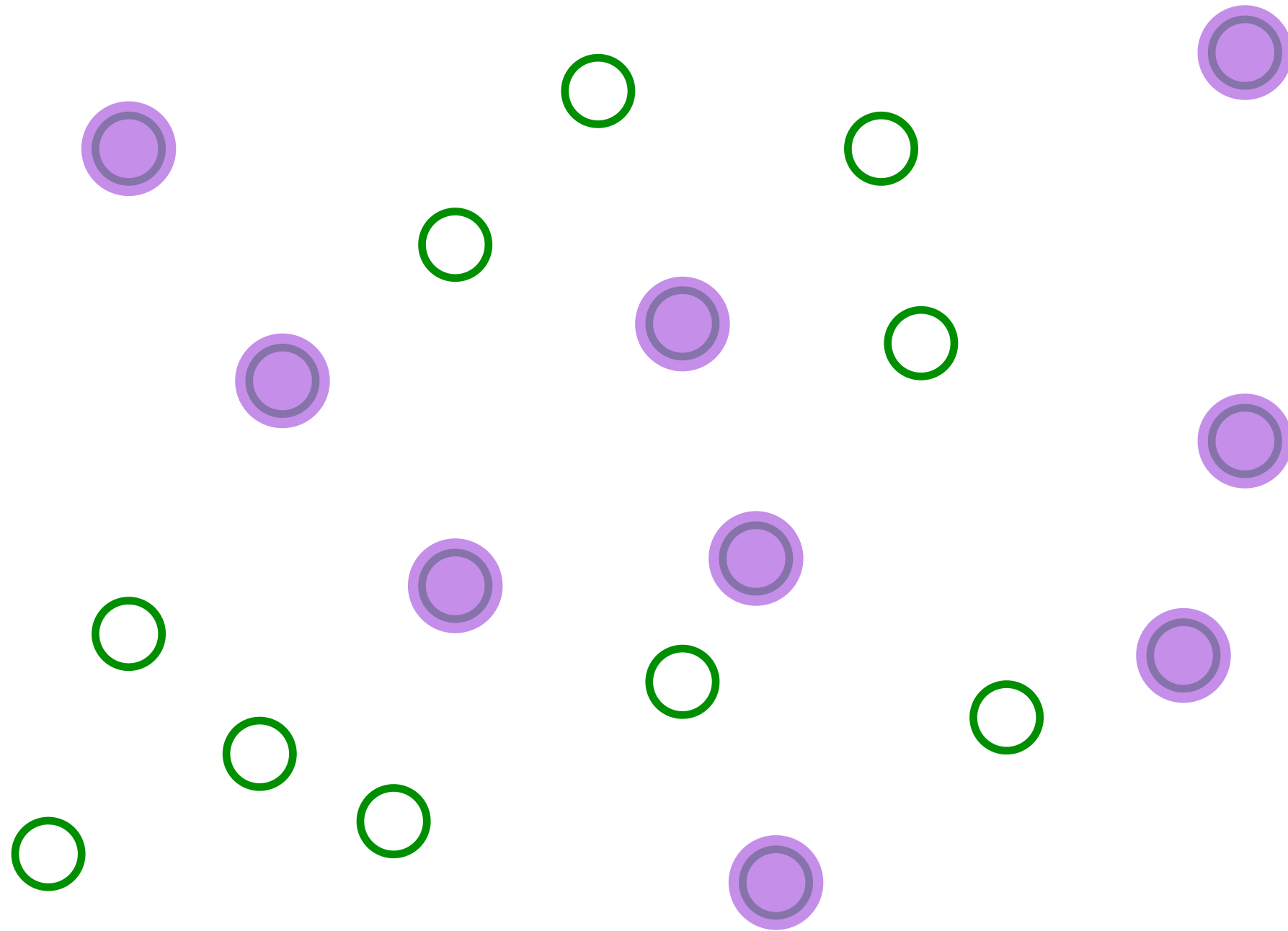
Electrons move one-by-one randomly

A simple model of a metal with quasiparticles



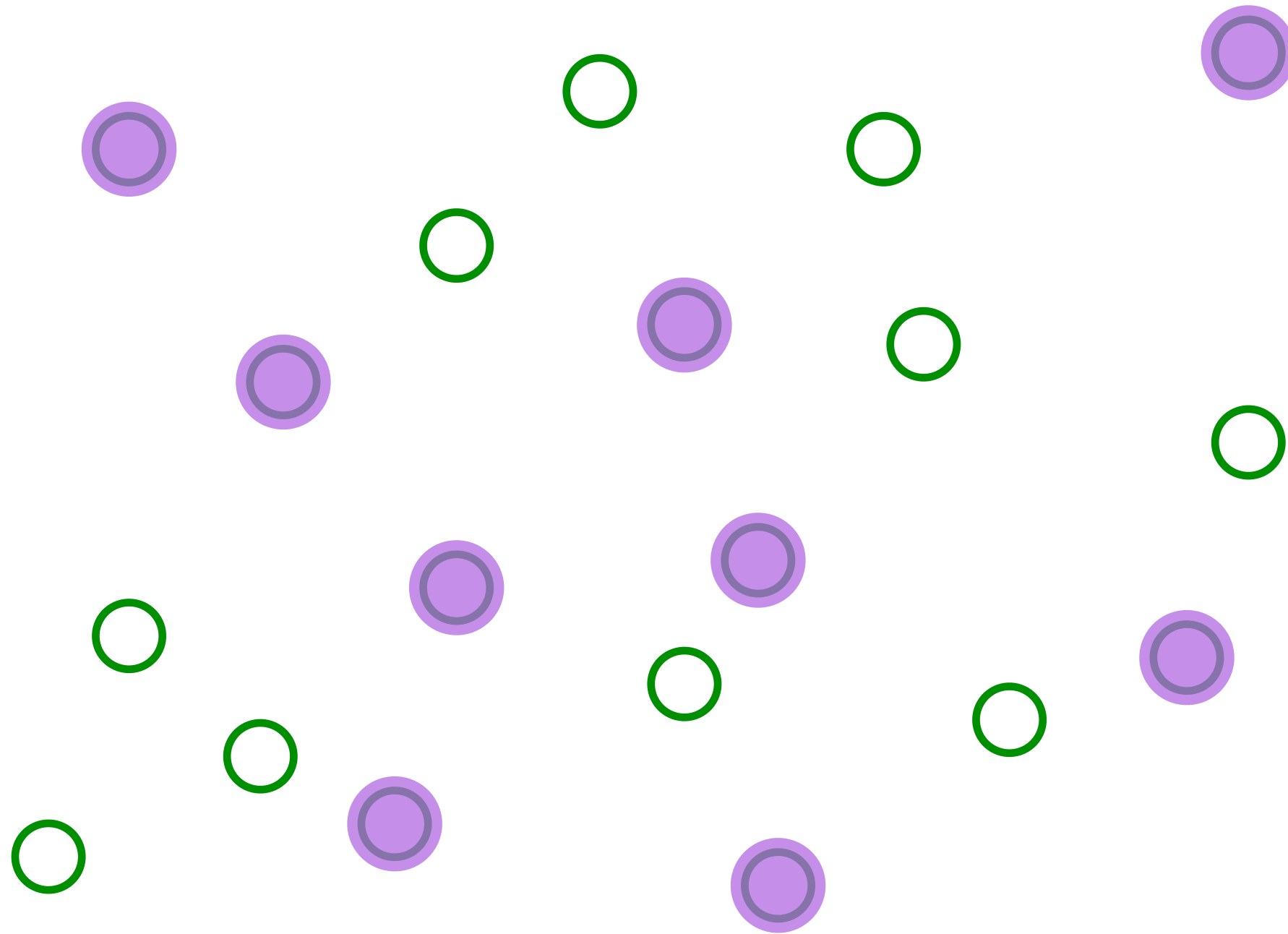
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A simple model of a metal with quasiparticles

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

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

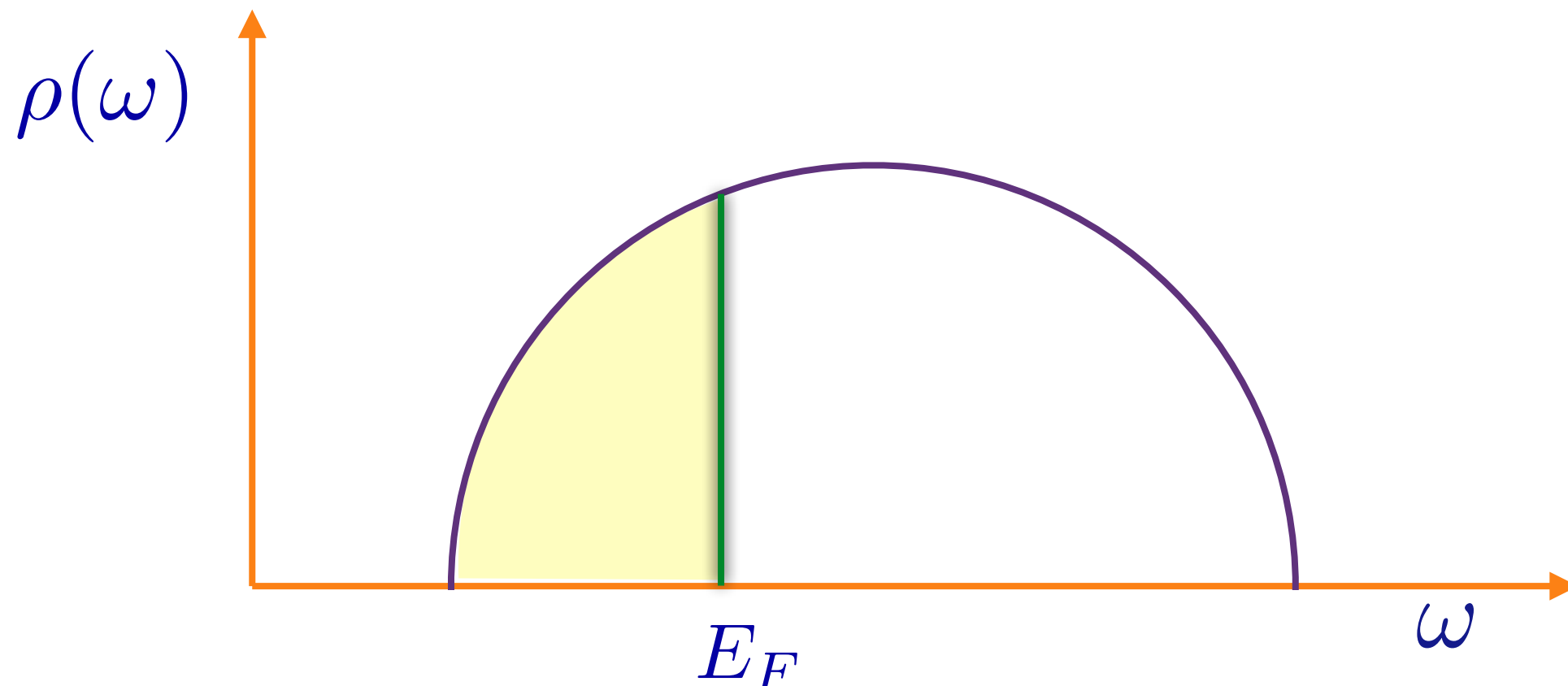
$$\frac{1}{N} \sum_i c_i^\dagger c_i = Q$$

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

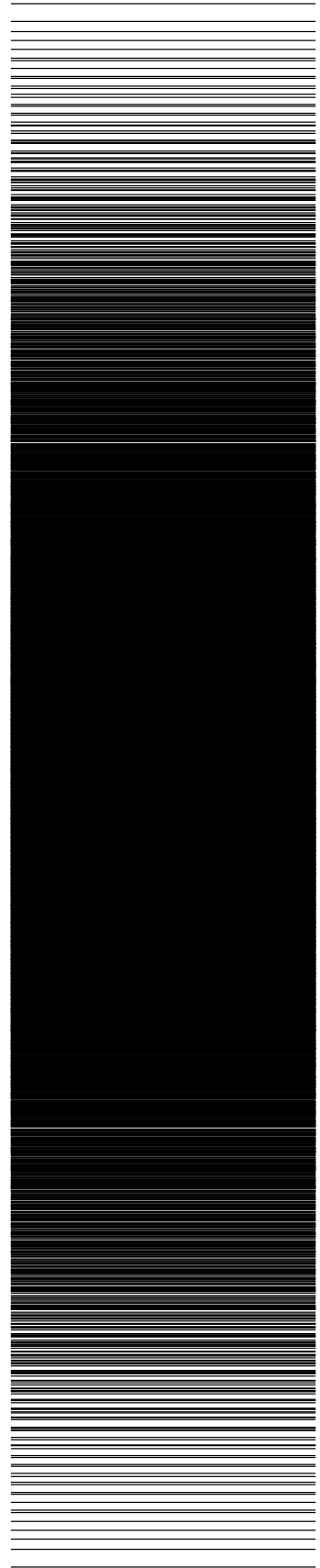
**Fermions occupying the eigenstates of a
 $N \times N$ random matrix**

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 $\sim 1/N$

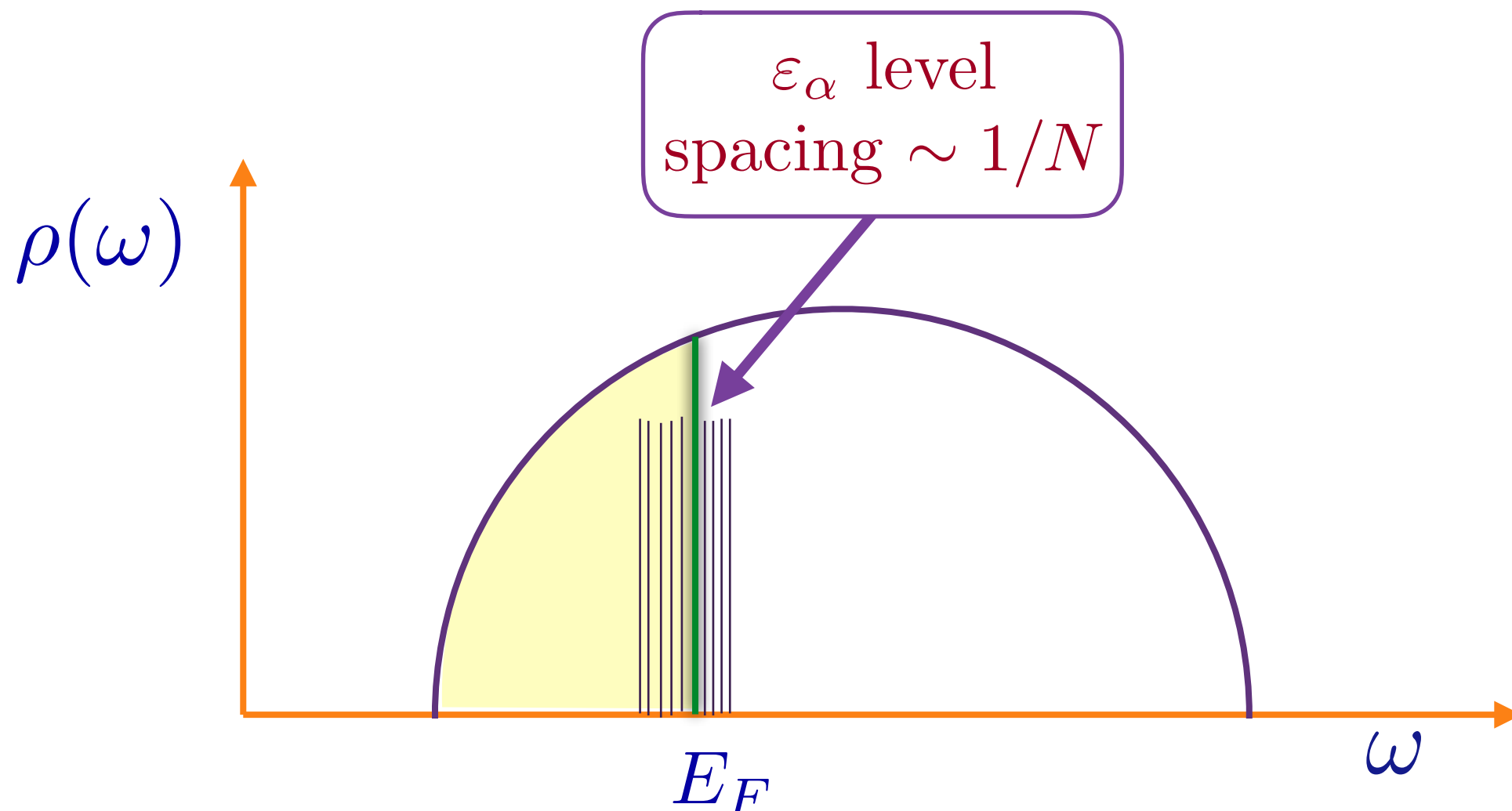
There are 2^N many
body levels with energy

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

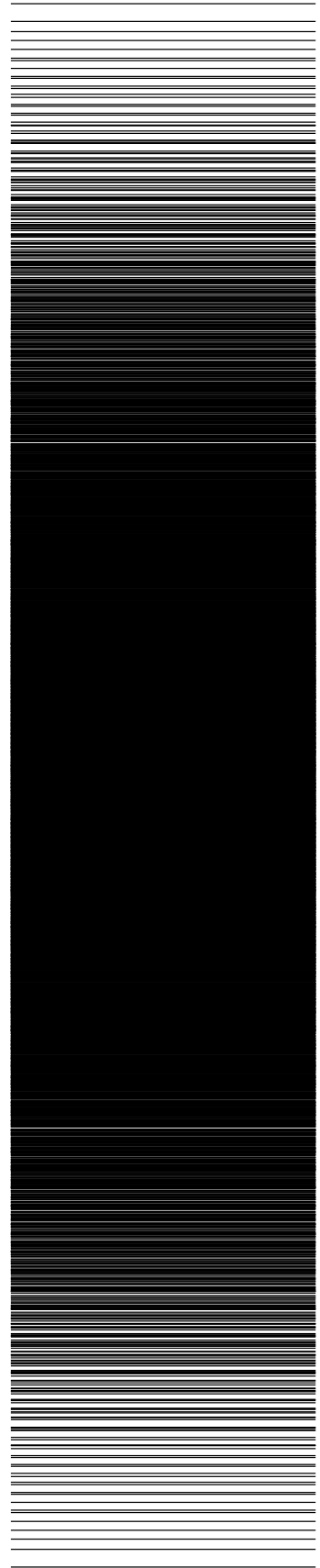
where $n_{\alpha} = 0, 1$. Shown
are all values of E for a
single cluster of size
 $N = 12$. The ε_{α} have a
level spacing $\sim 1/N$.

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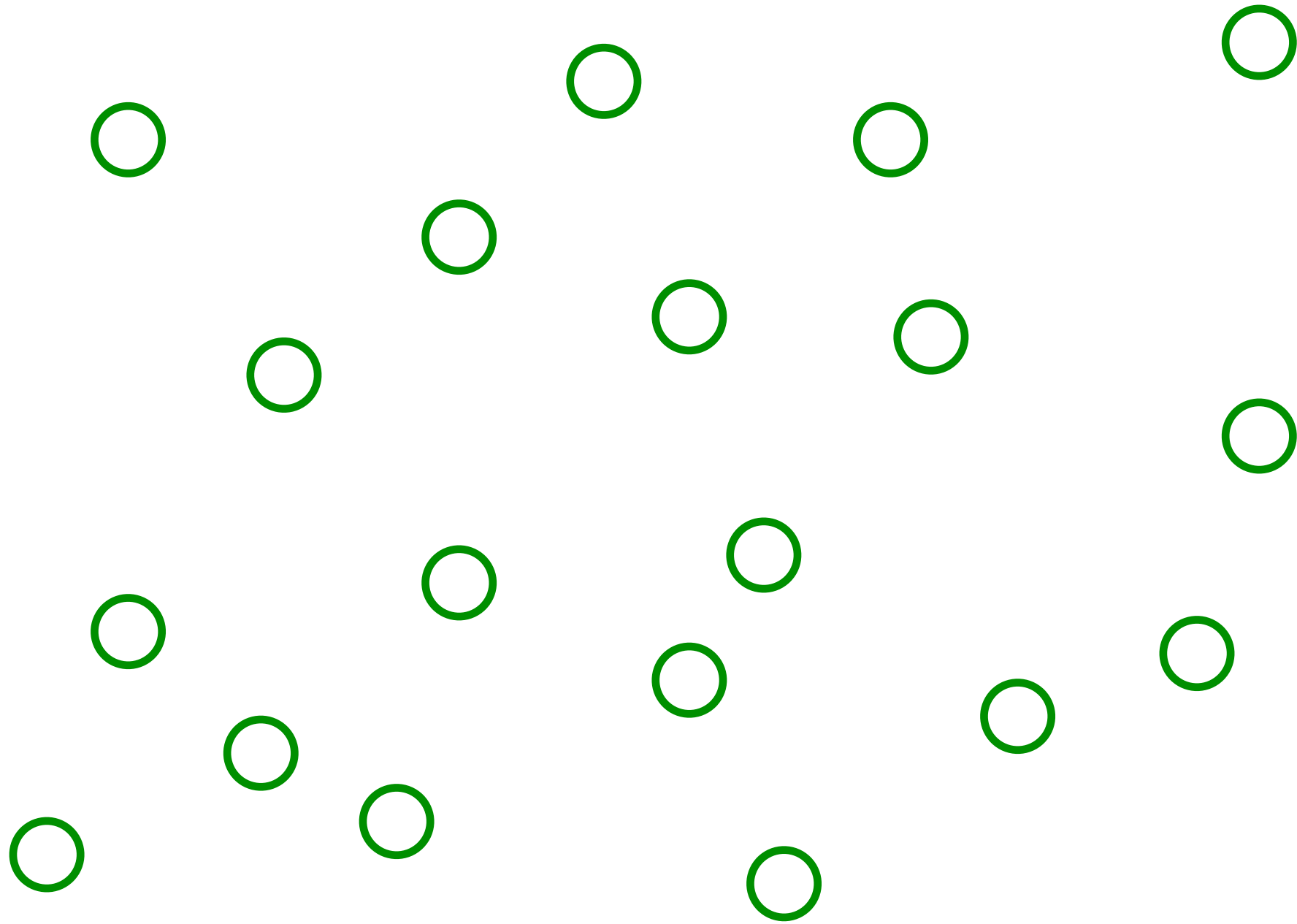
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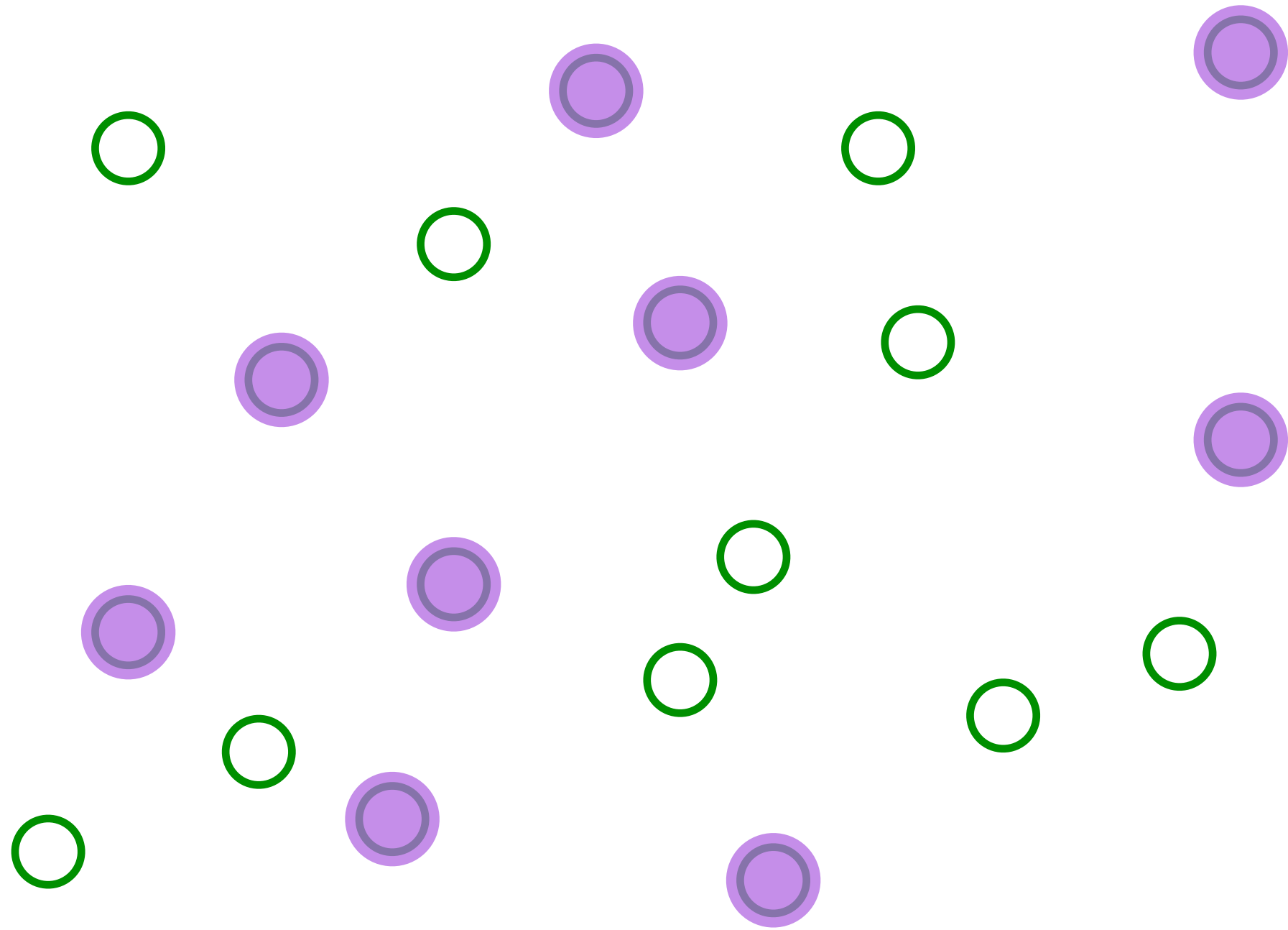
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The Sachdev-Ye-Kitaev (SYK) model



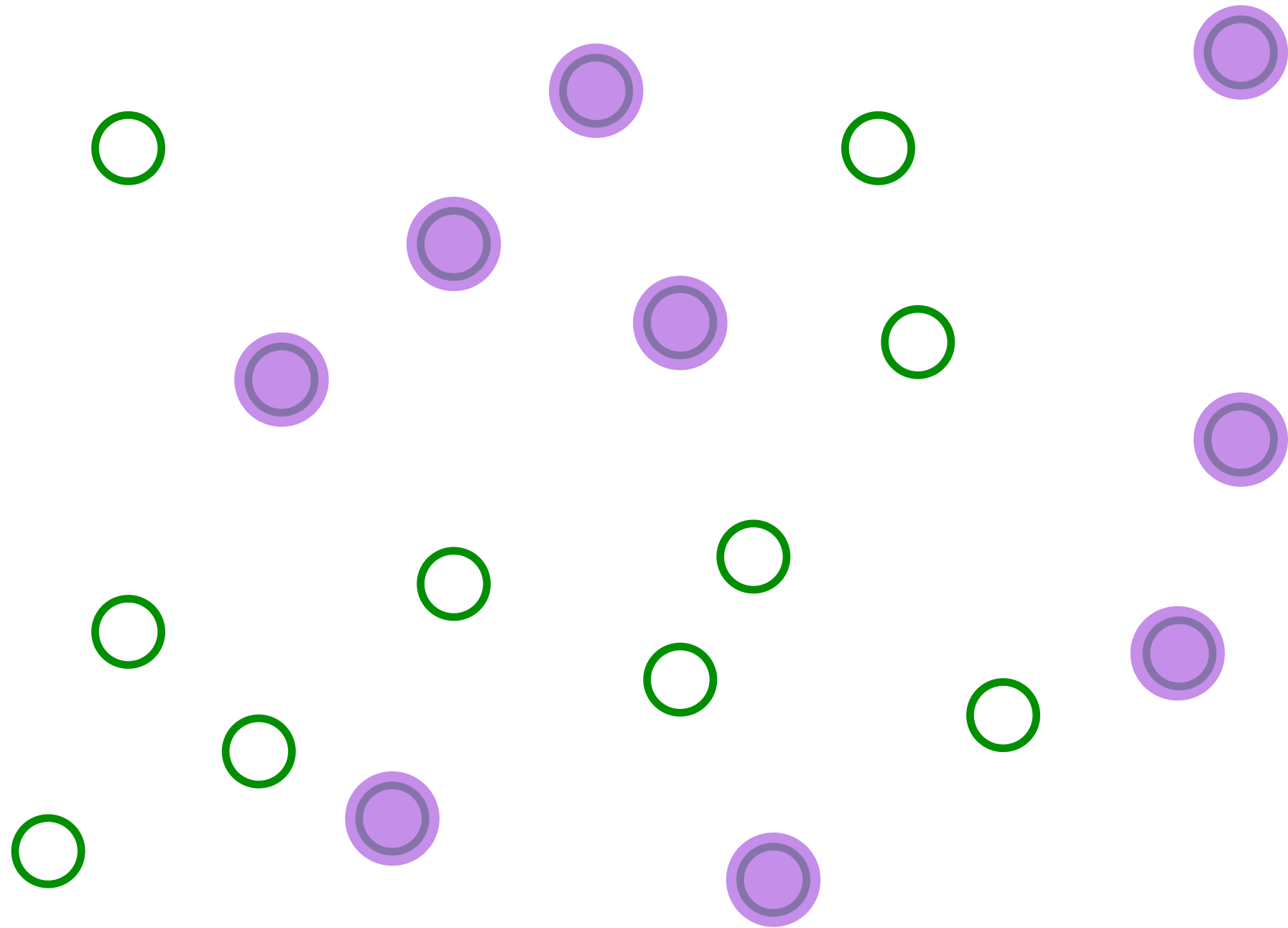
Pick a set of random positions

The SYK model



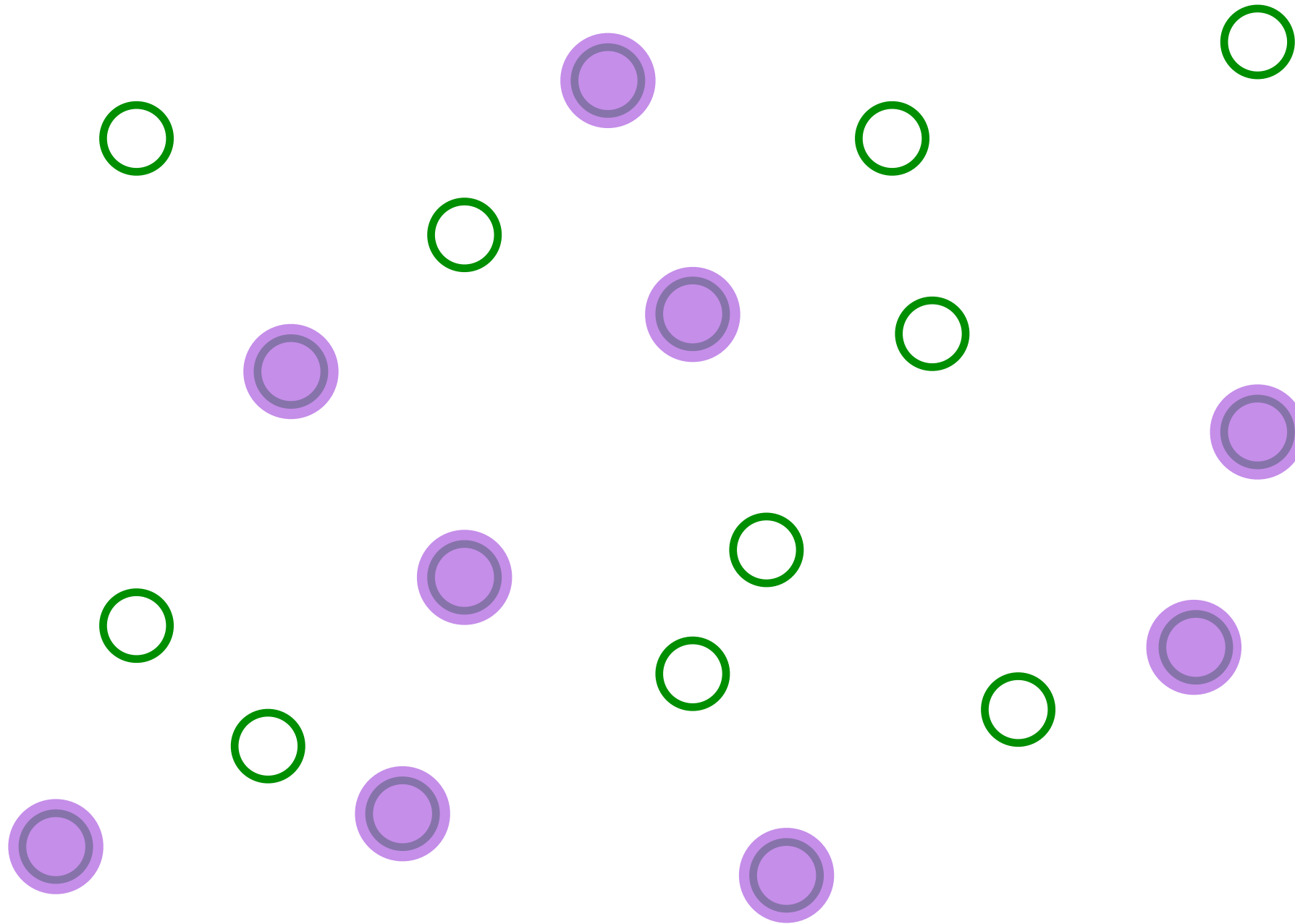
Place electrons randomly on some sites

The SYK model



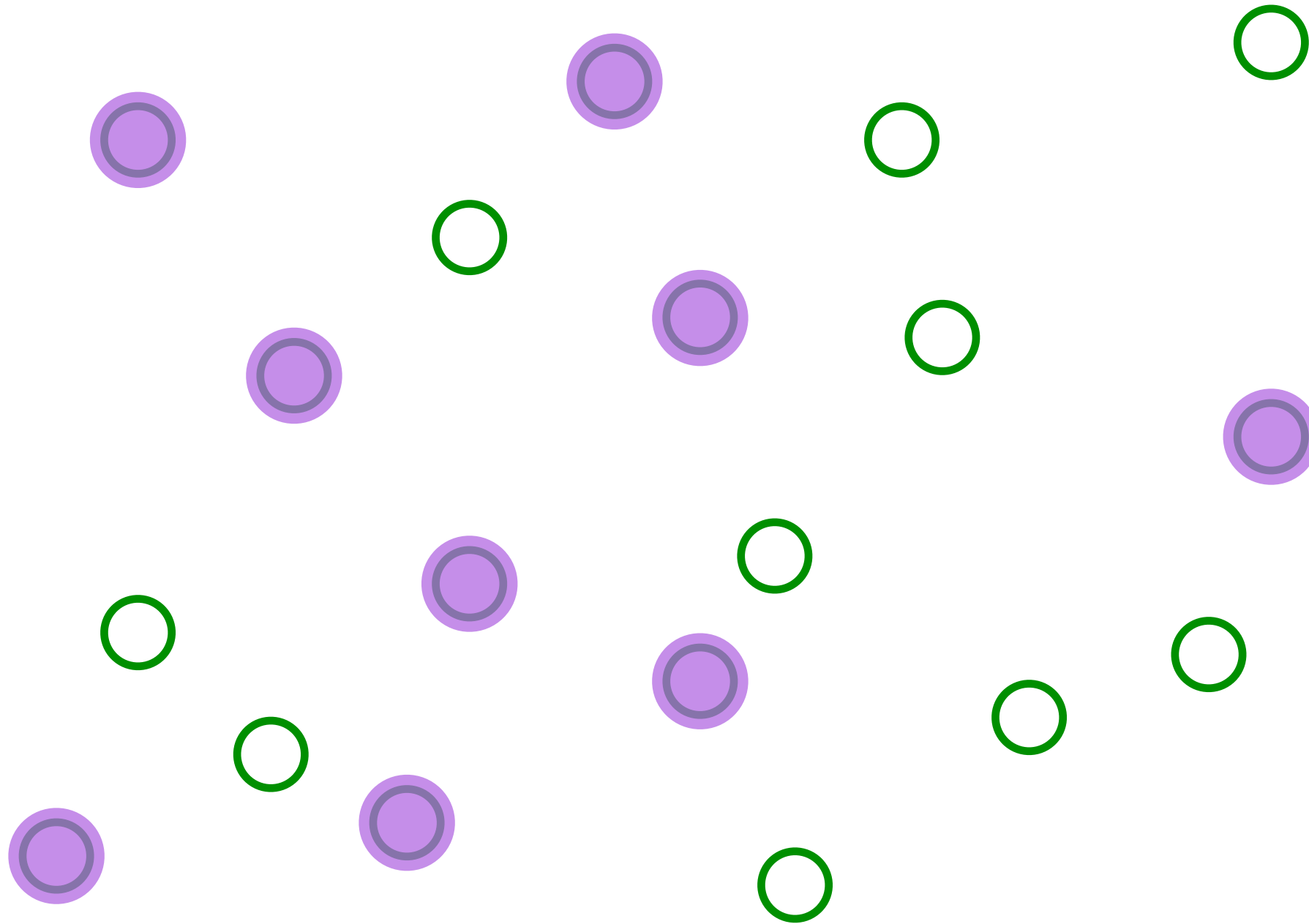
Entangle electrons pairwise randomly

The SYK model



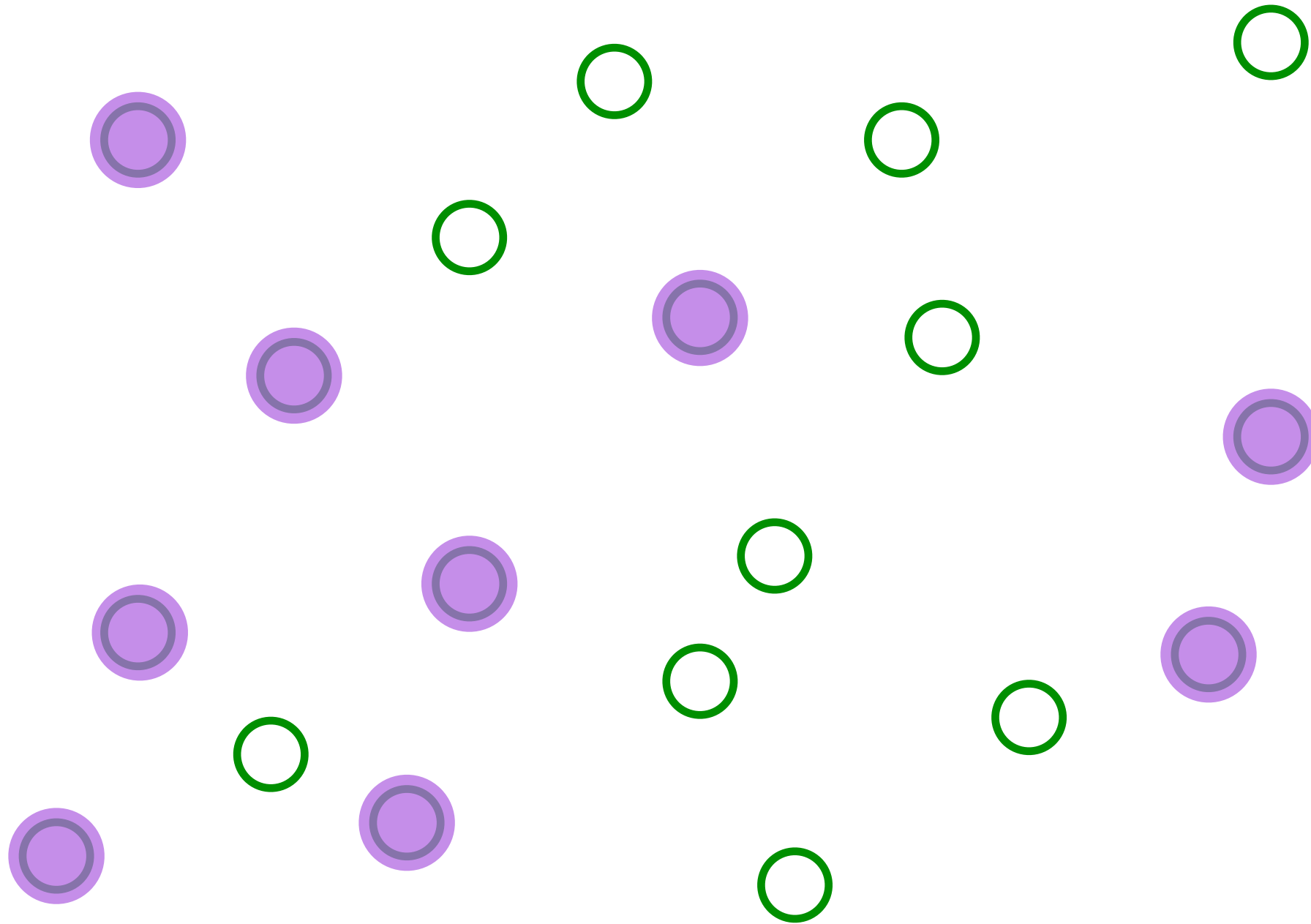
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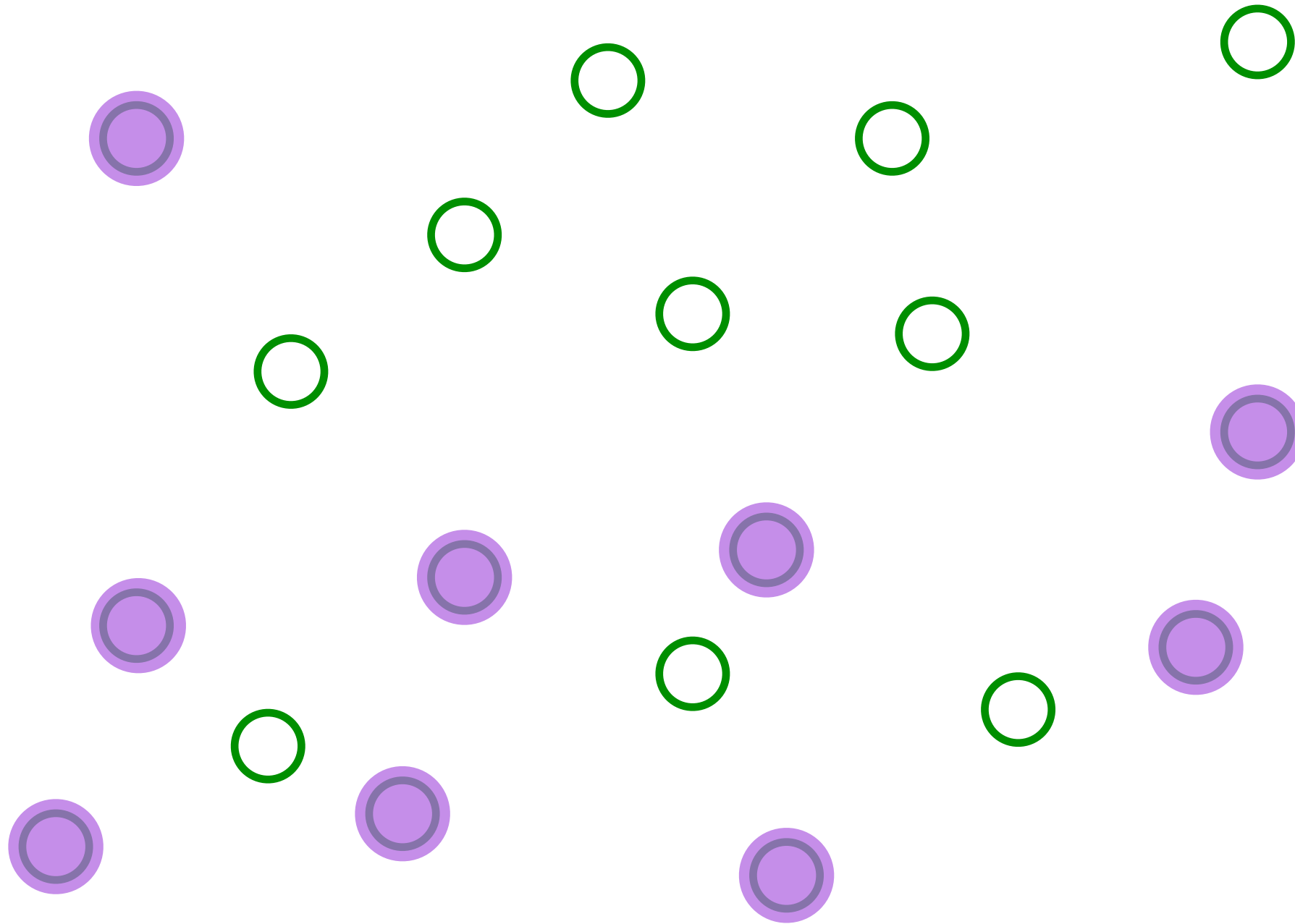
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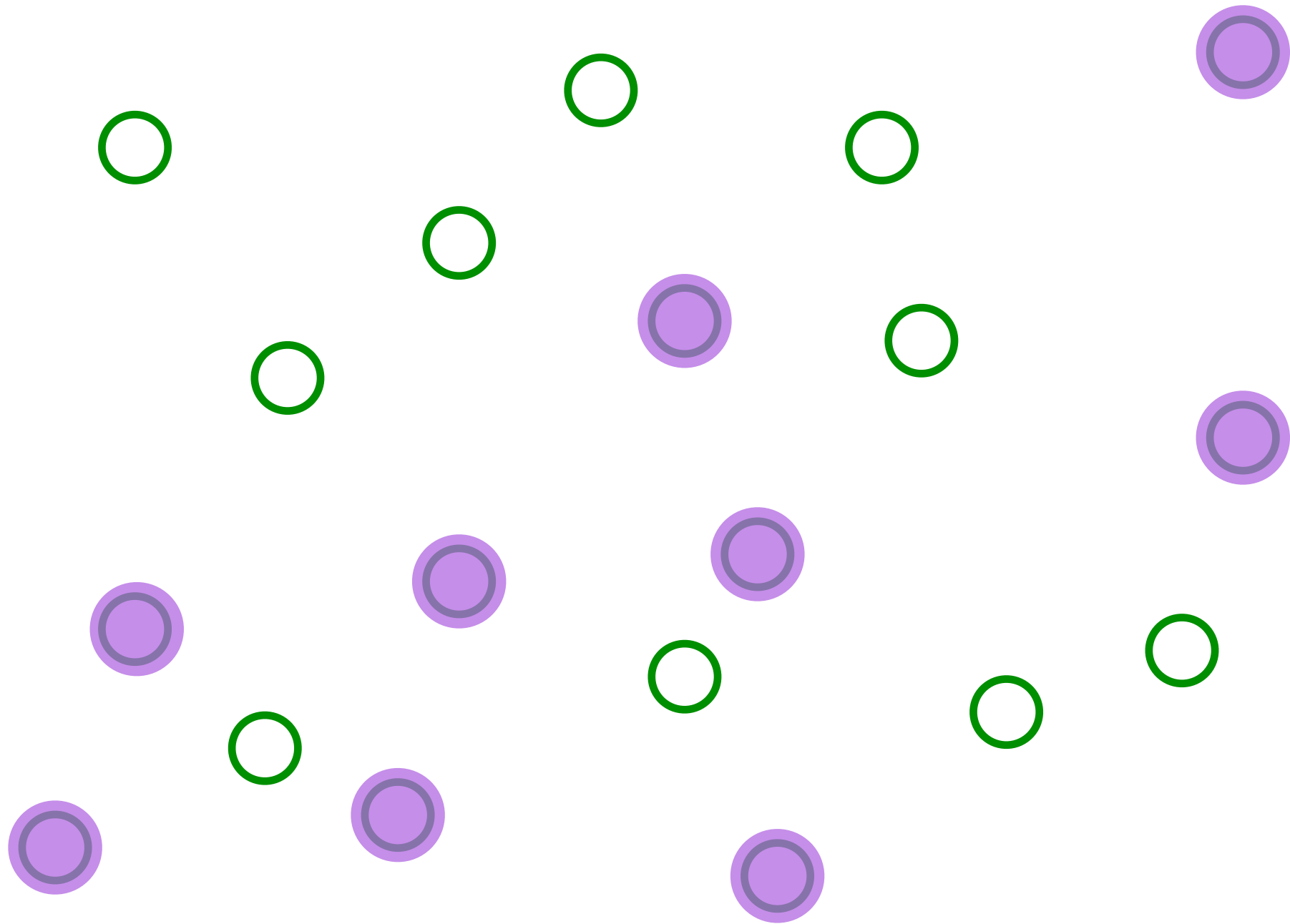
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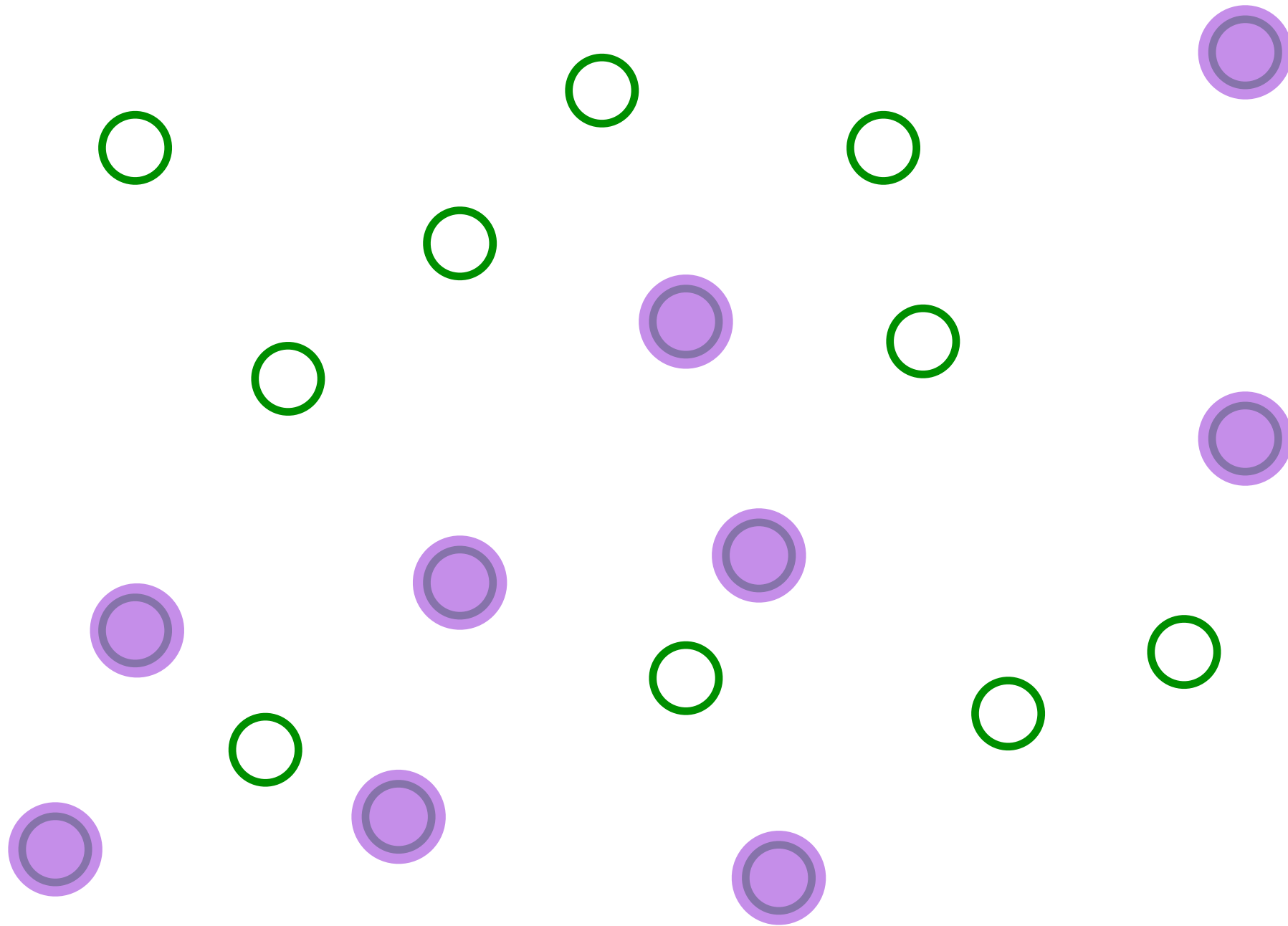
Entangle electrons pairwise randomly

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Entangle electrons pairwise randomly

The SYK model



This describes both a strange metal and a black hole!

The SYK model

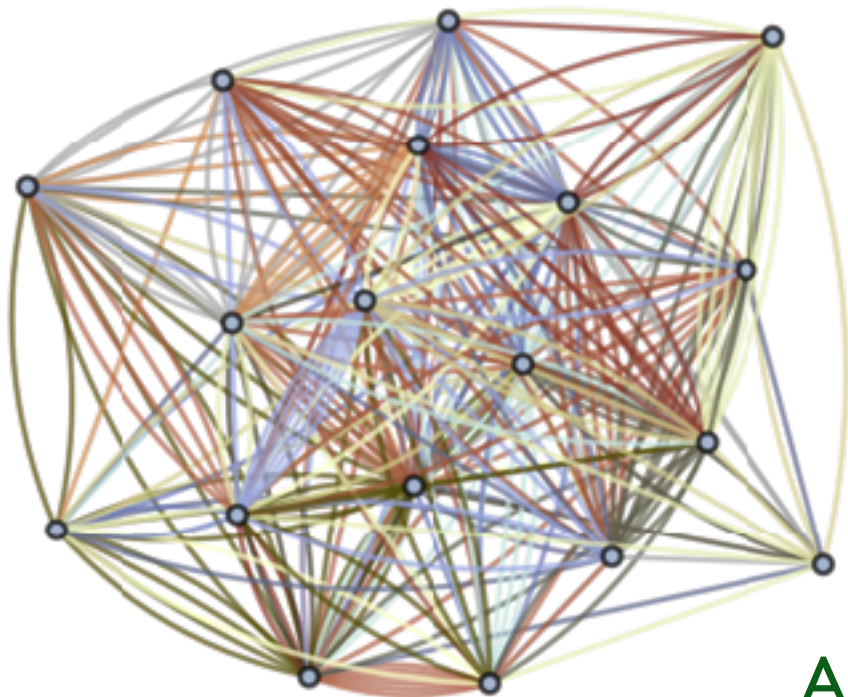
(See also: the “2-Body Random Ensemble” in nuclear physics; did not obtain the large N limit; T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

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

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

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

$U_{ij;k\ell}$ are independent random variables with $\overline{U_{ij;k\ell}} = 0$ and $\overline{|U_{ij;k\ell}|^2} = U^2$
 $N \rightarrow \infty$ 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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No quasiparticles !

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

PRB **63**, 134406 (2001)

The SYK model

- Low energy, many-body density of states

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

(for Majorana model)

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 is incoherent: $G(\tau) \sim \tau^{-1/2}$ at large τ . (Fermi liquids with quasiparticles have the coherent: $G(\tau) \sim 1/\tau$)

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- $T > 0$ Green's function has conformal invariance
 $G \sim (T / \sin(\pi k_B T \tau / \hbar))^{1/2}$

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

The SYK model

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- $T > 0$ 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.

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 $T \rightarrow 0$

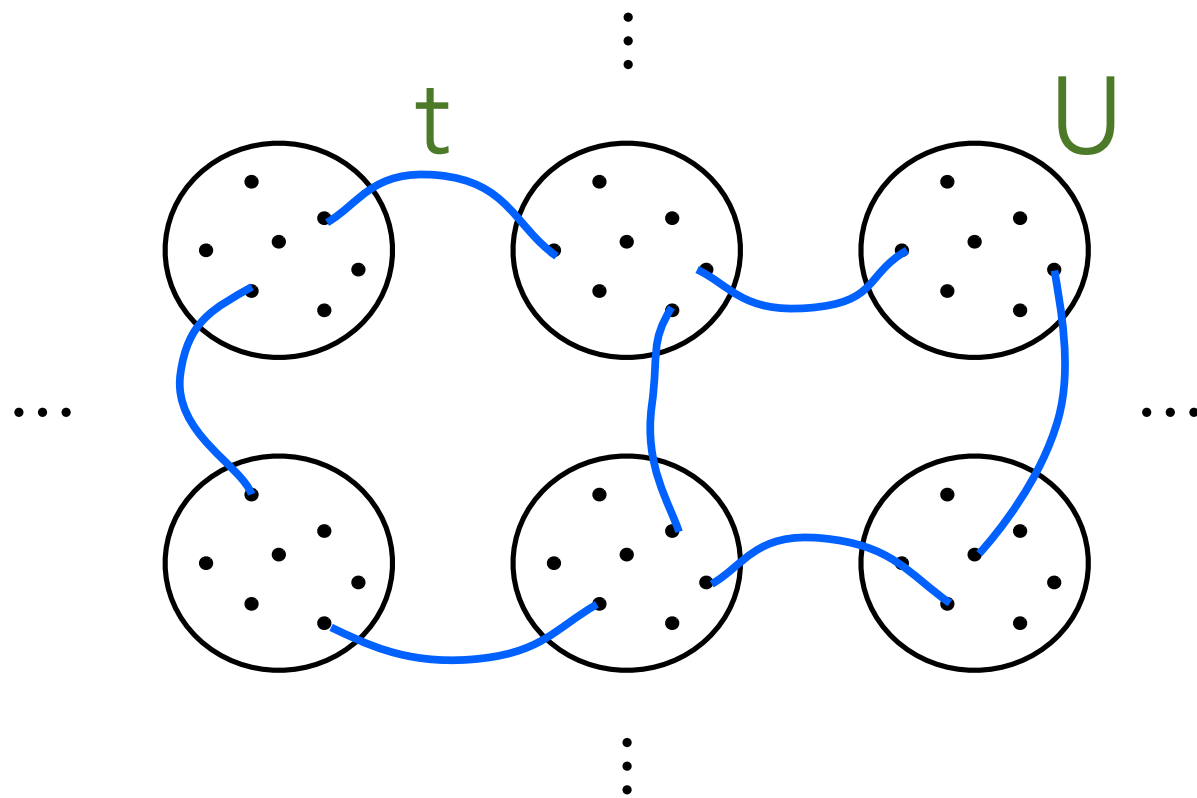
$$\tau_{\text{eq}} > C \frac{\hbar}{k_B T}.$$

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.

[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](#)

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

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

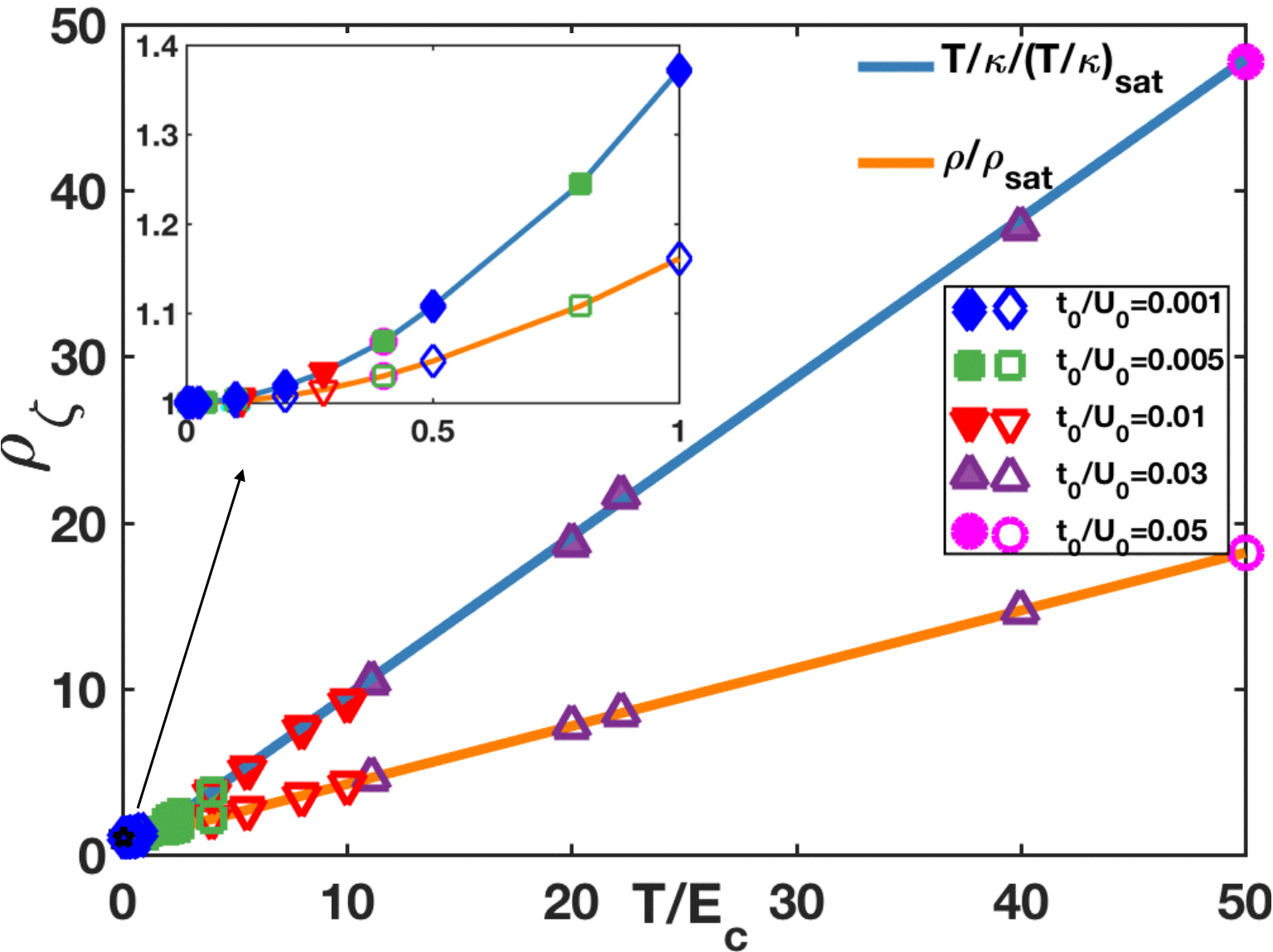
$$\overline{|t_{ij,x,x'}|^2} = t_0^2/N$$

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Low ‘coherence’ scale



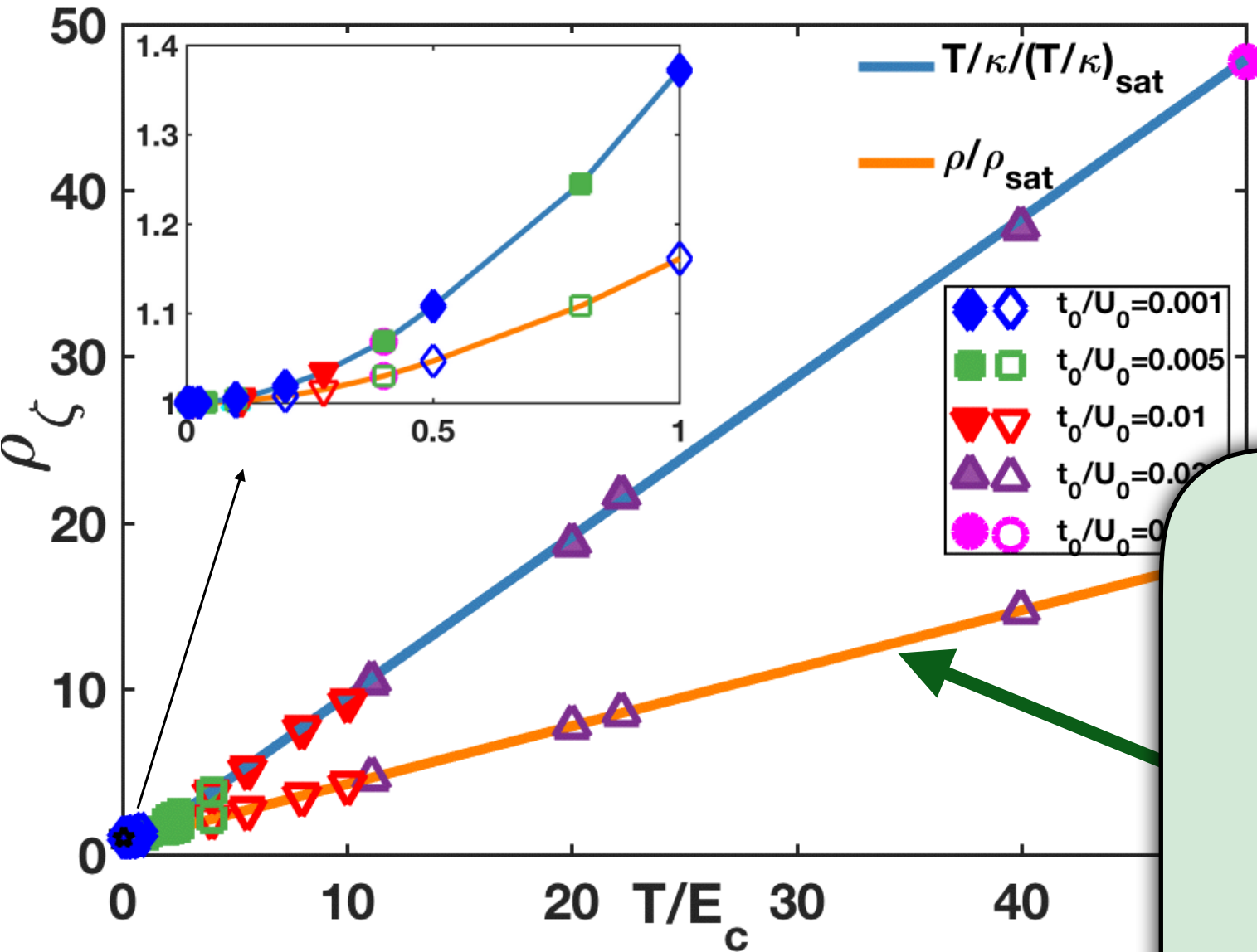
$$E_c \sim \frac{t_0^2}{U}$$

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

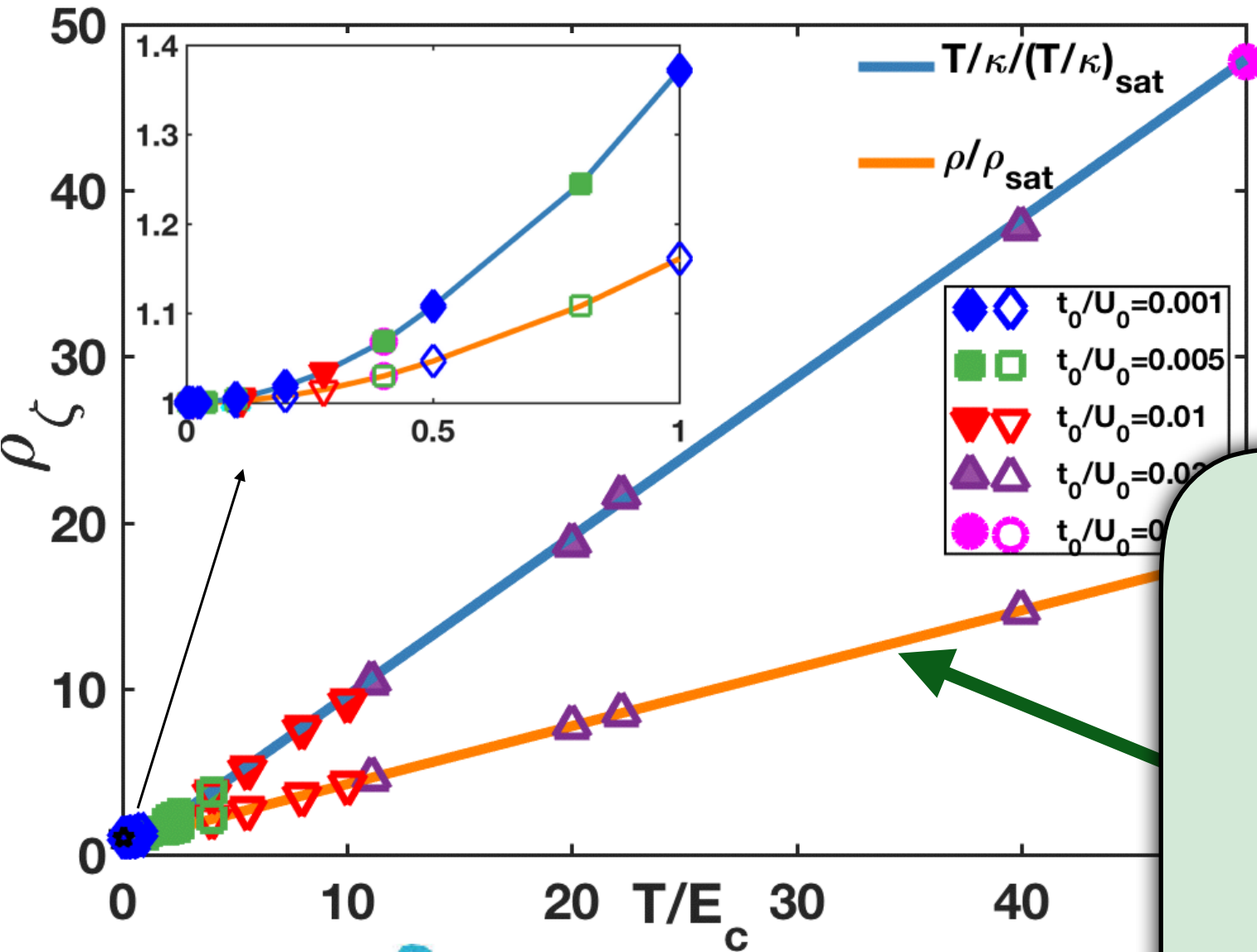
$$\rho \sim \frac{h}{e^2} \left(\frac{T}{E_c} \right), \quad s = s_0$$

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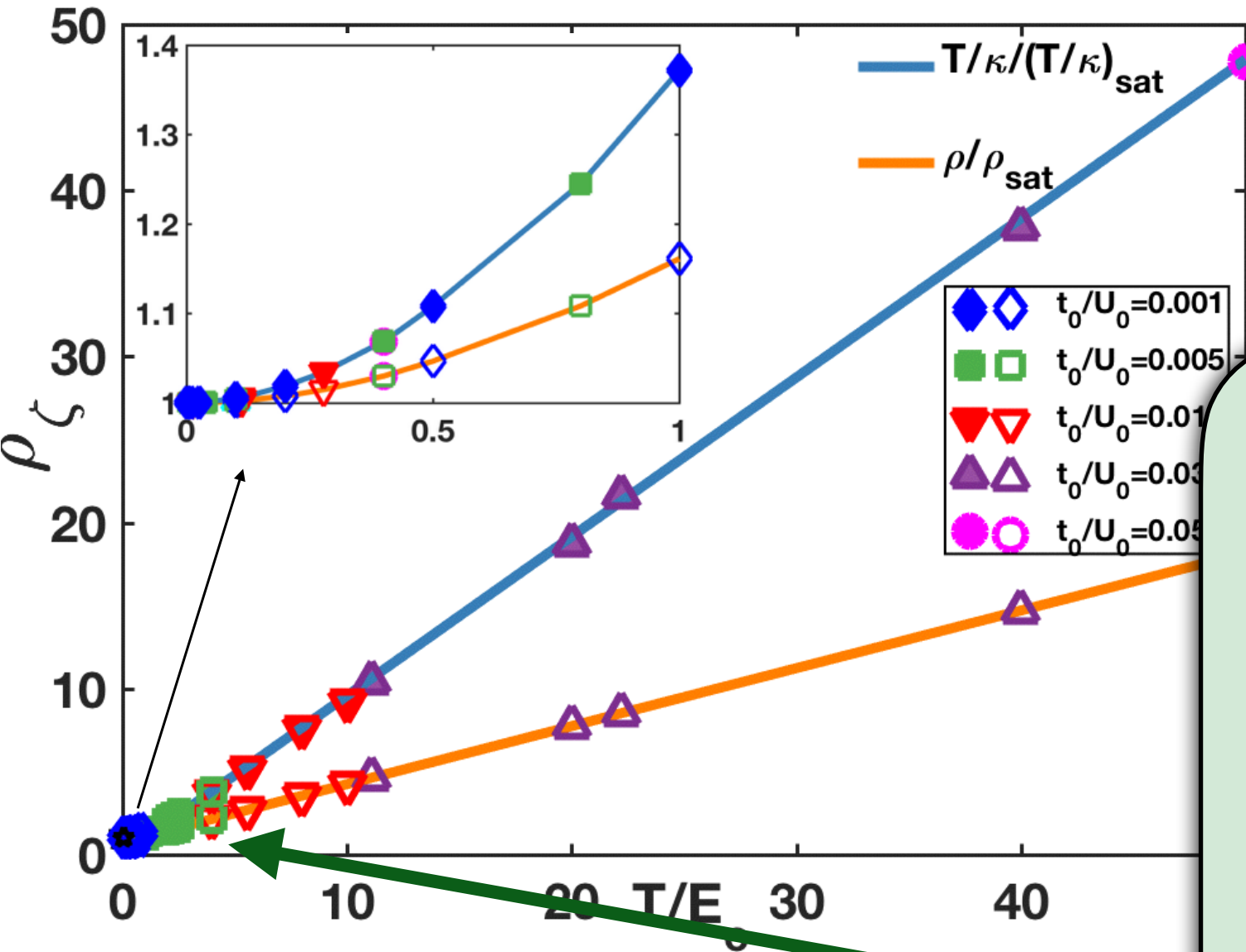


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Low ‘coherence’ scale



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

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

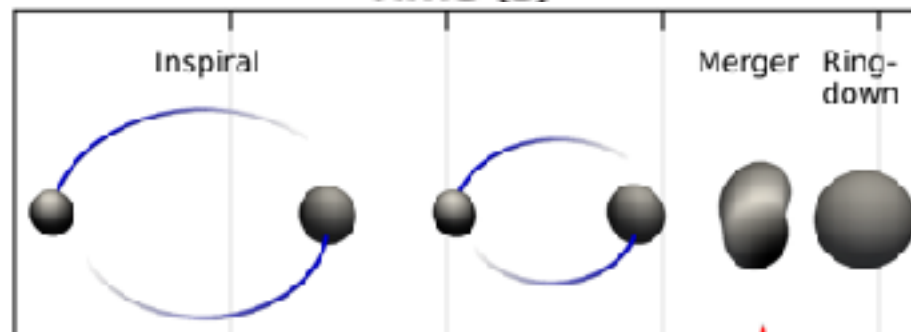
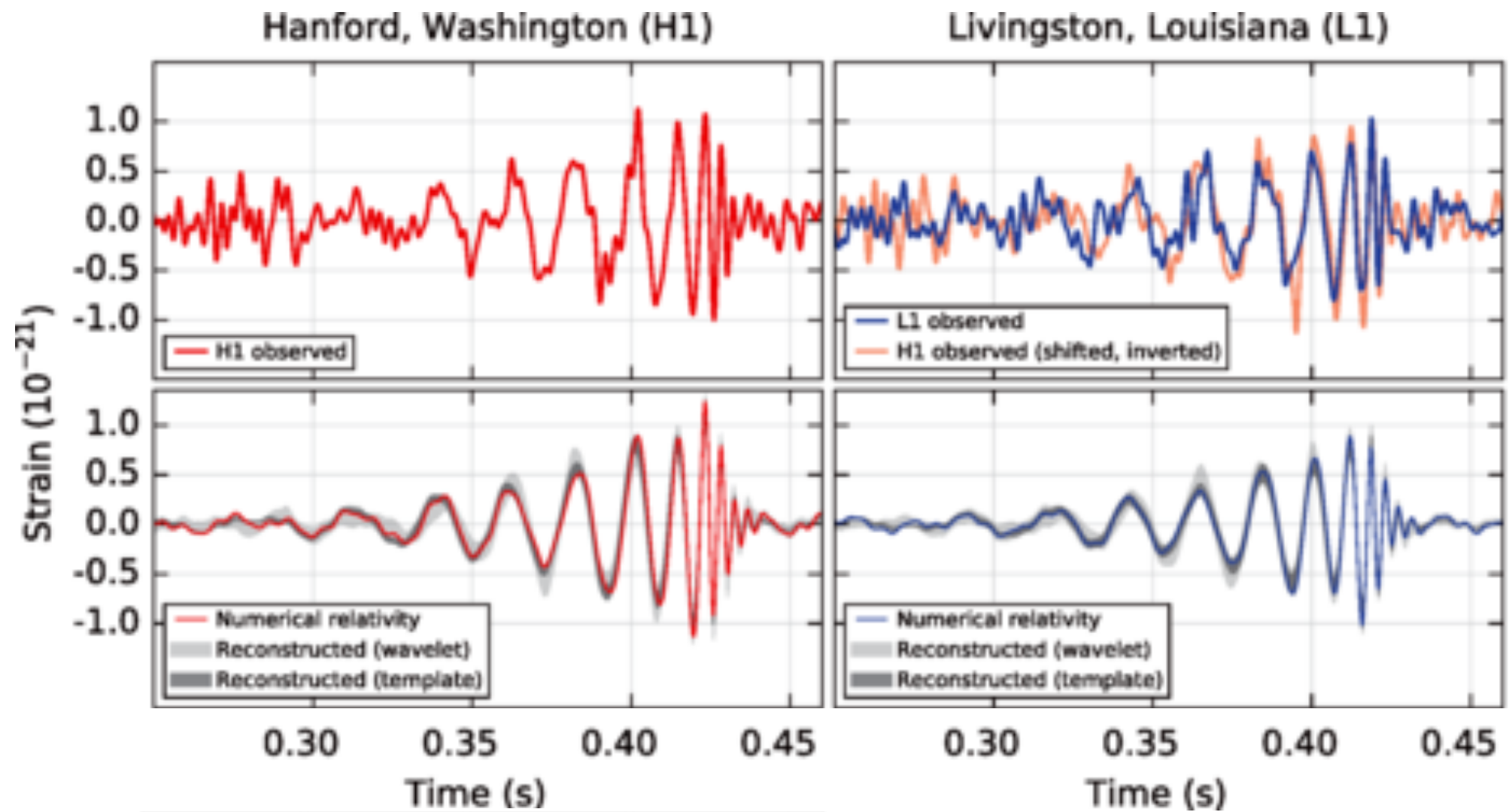
$$\rho = \frac{h}{e^2} \left[c_1 + c_2 \left(\frac{T}{E_c} \right)^2 \right]$$

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

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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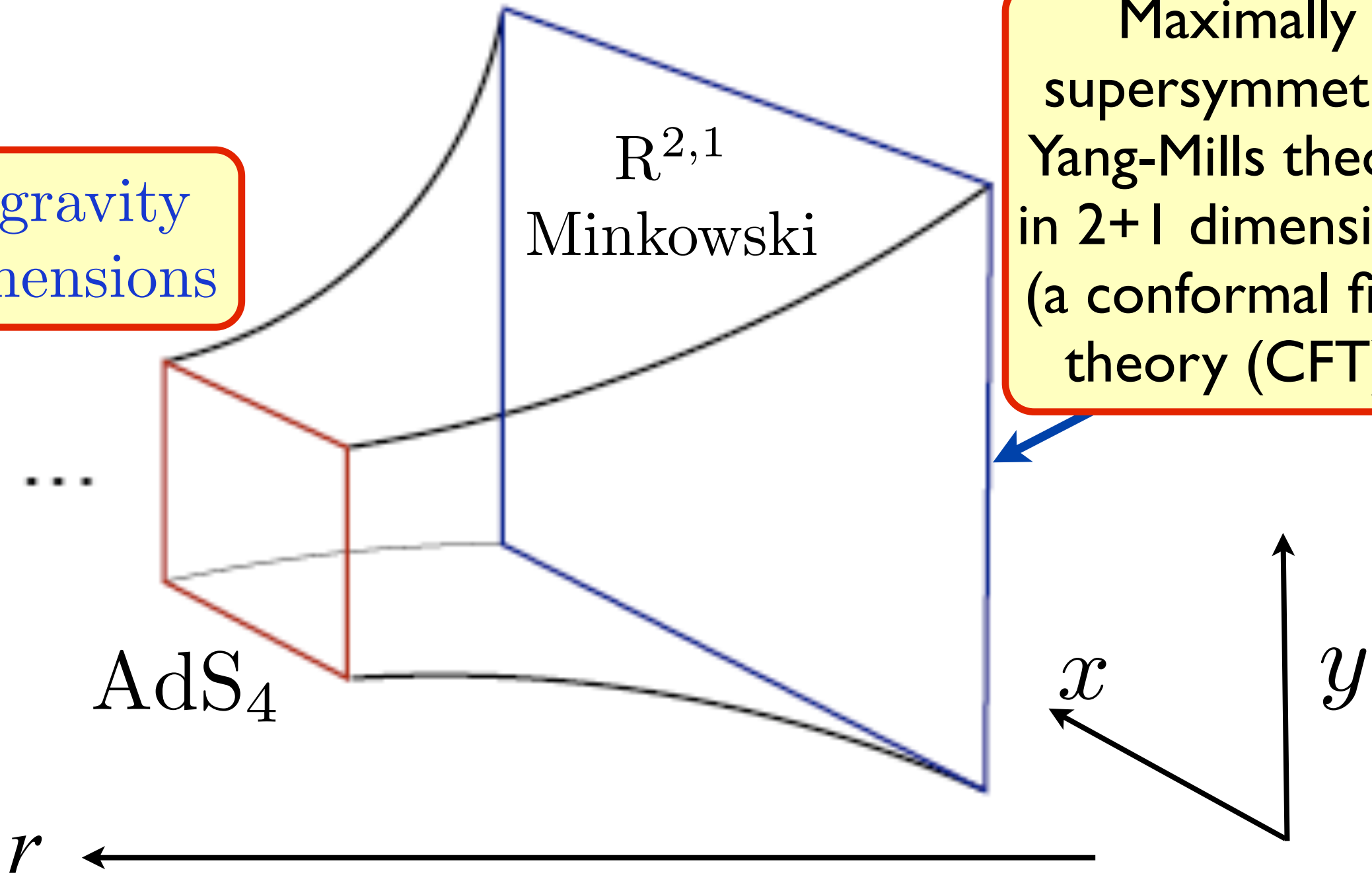
Black holes

- 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



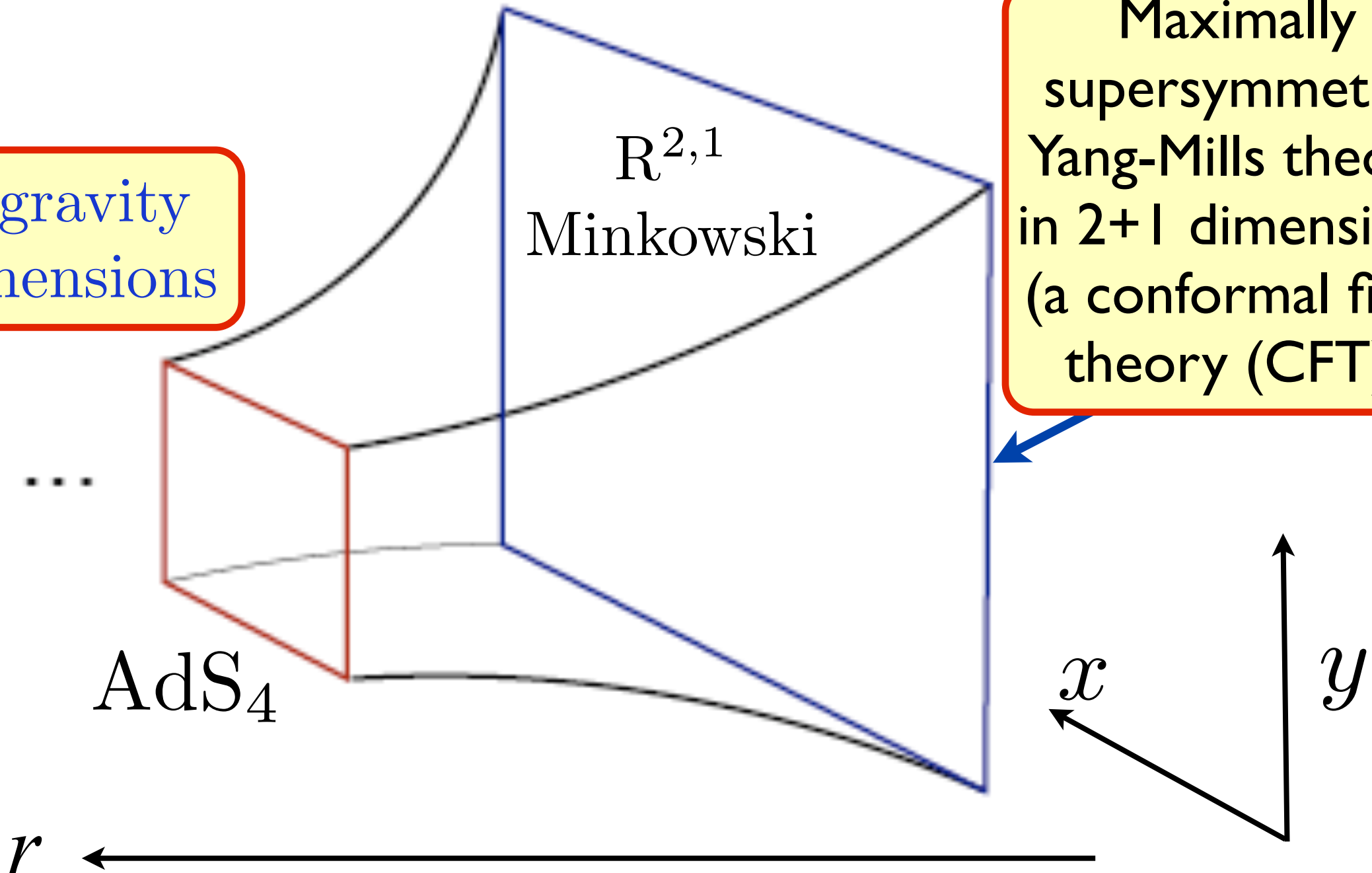
Maximally
supersymmetric
Yang-Mills theory
in 2+1 dimensions
(a conformal field
theory (CFT))

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

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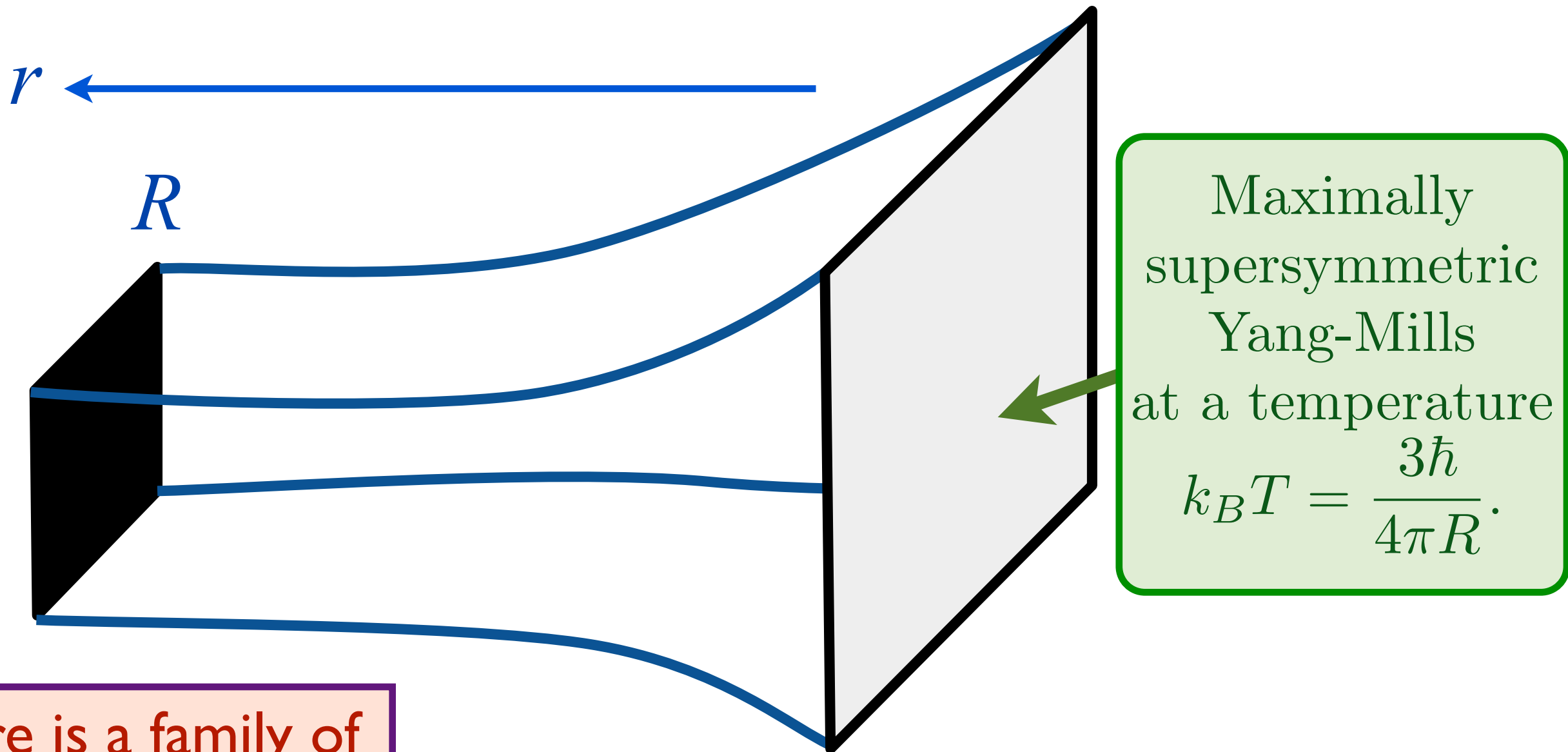


This spacetime is a solution of Einstein gravity with a negative cosmological constant

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

AdS/CFT correspondence at non-zero temperatures

AdS₄-Schwarzschild black-brane



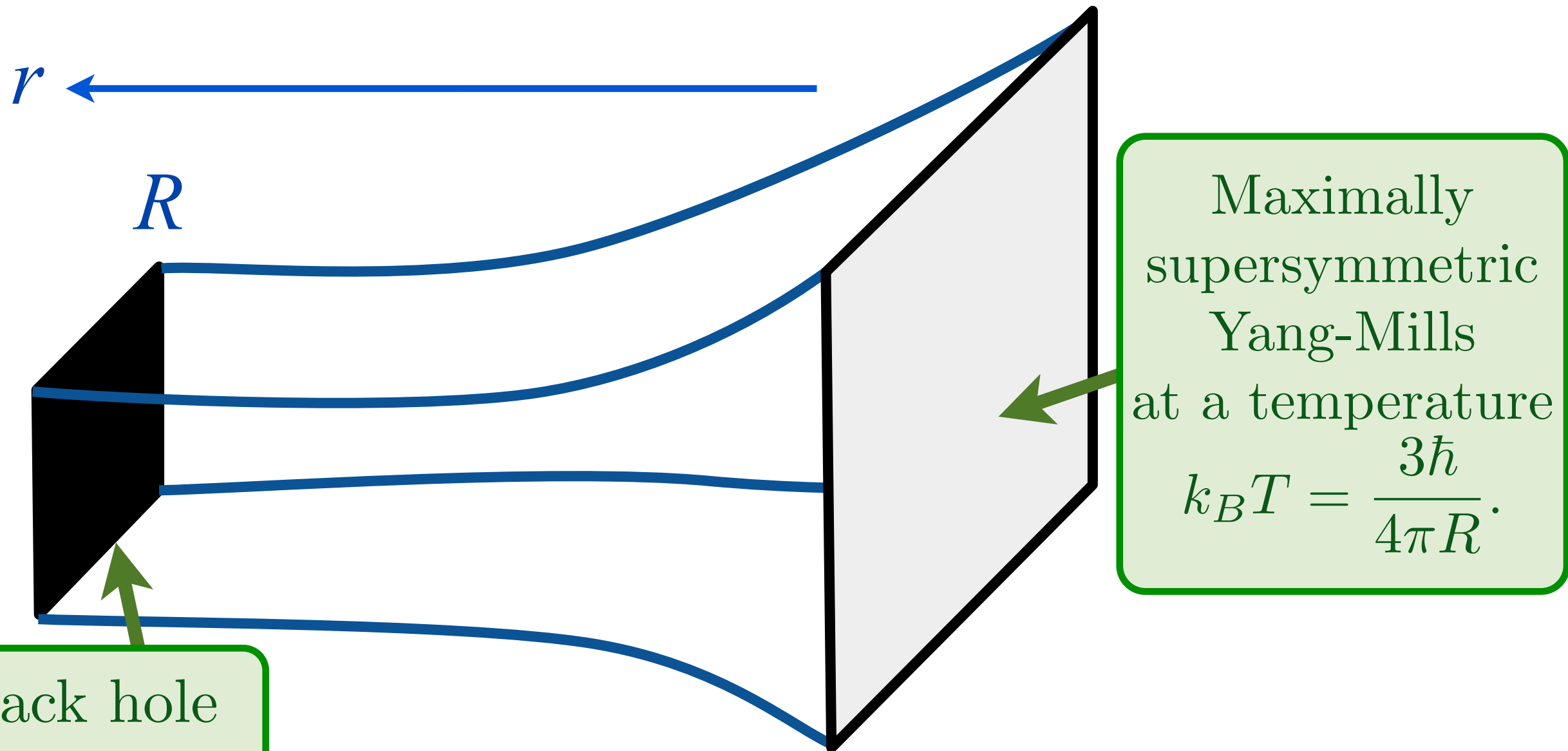
There is a family of solutions of Einstein gravity which describe non-zero temperatures

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

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

AdS/CFT correspondence at non-zero temperatures

AdS₄-Schwarzschild black-brane



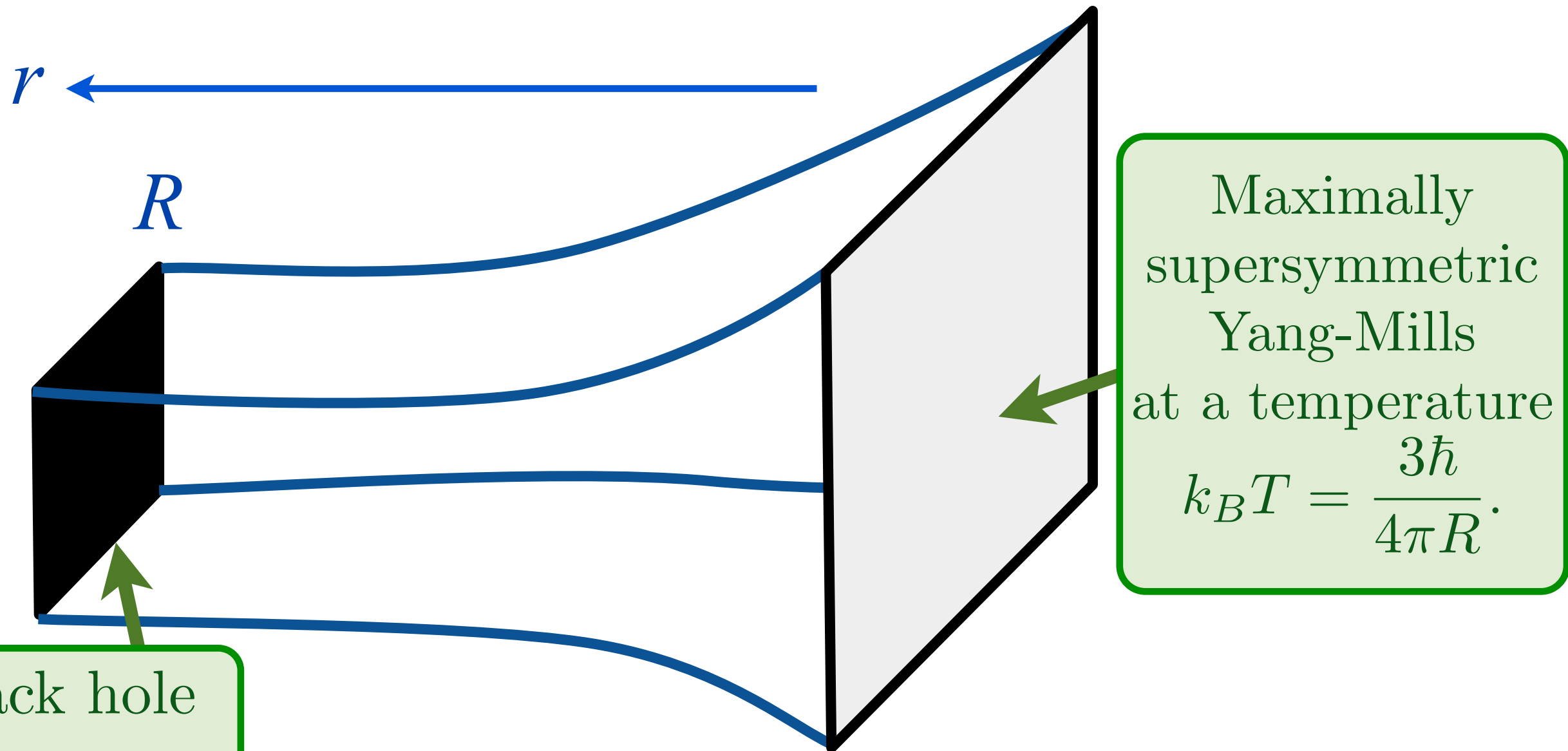
Black hole horizon at a Hawking temperature $T_H = T$

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

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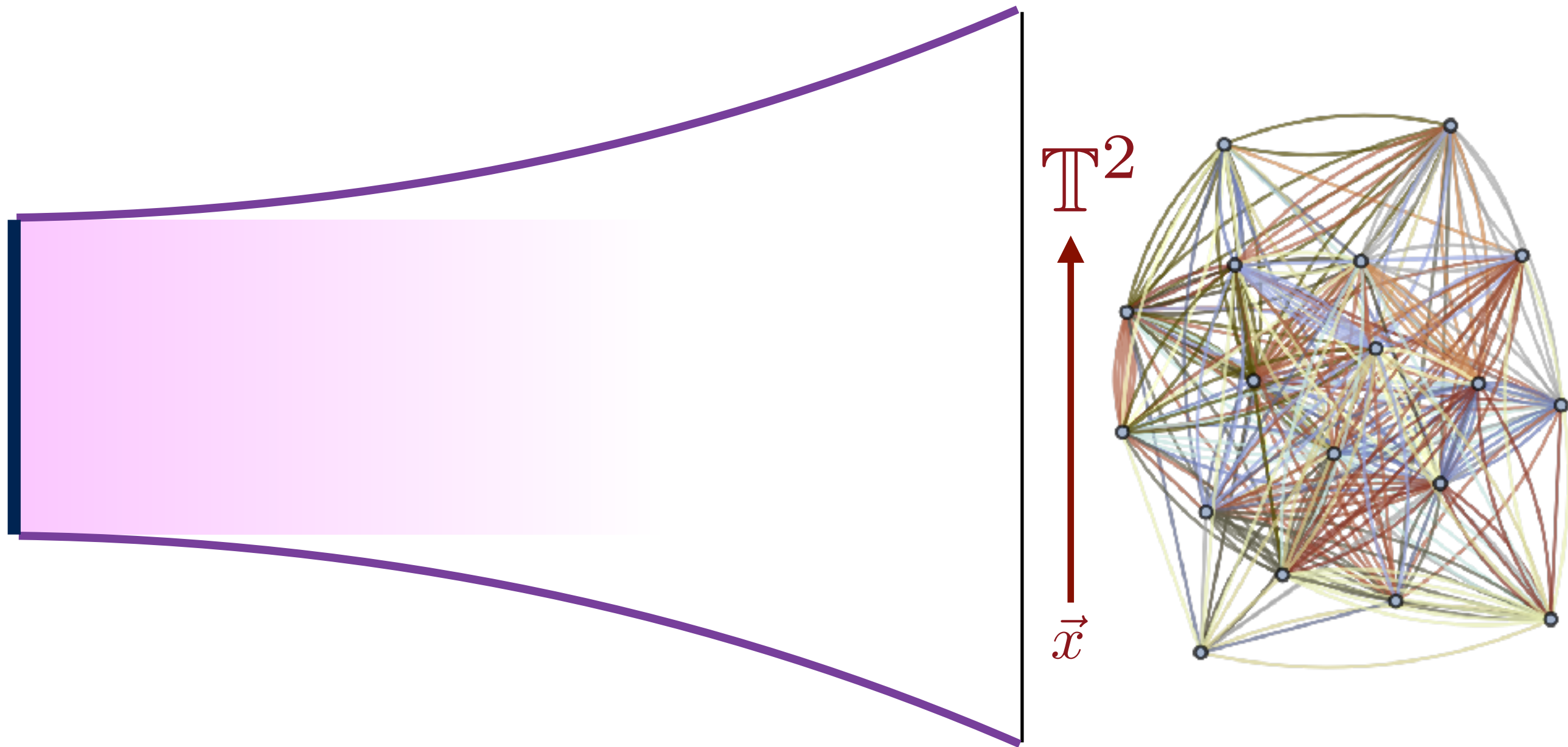
Maximally supersymmetric Yang-Mills at a temperature $k_B T = \frac{3\hbar}{4\pi R}$.

Black hole entropy = Entropy of Yang-Mills theory

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

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SYK and black holes



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

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 . (Fermi liquids with quasiparticles have $G(\tau) \sim 1/\tau$)
- $T > 0$ 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.

The SYK model

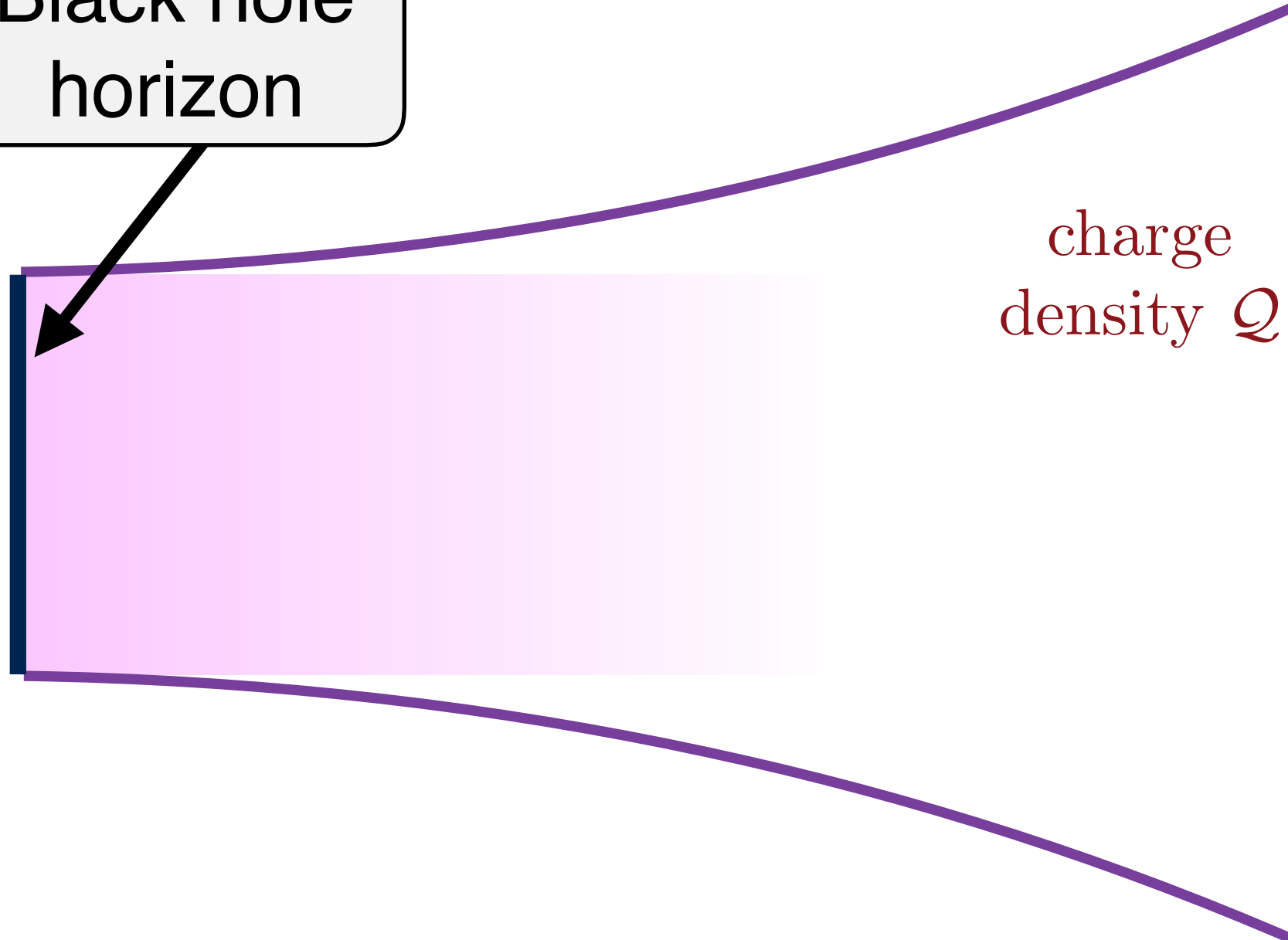
- Low energy, many-body density of states
 $\rho(E) \sim e^{Ns_0}$
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- The **Is there any black hole which holographically matches these properties ?**

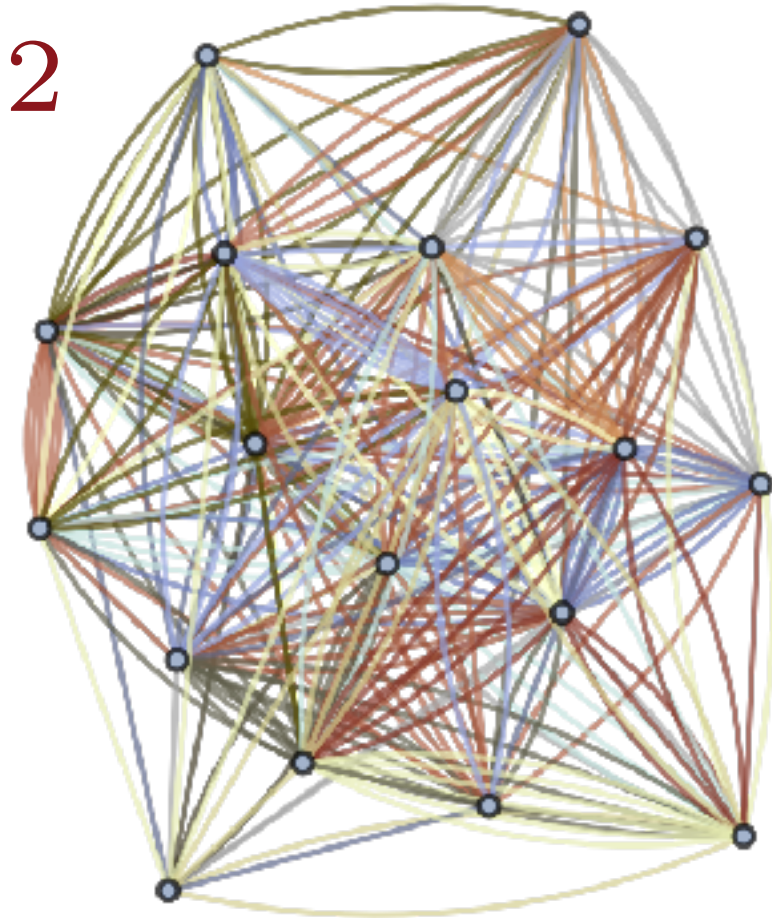
SYK and black holes

Black hole horizon



\mathbb{T}^2

\vec{x}

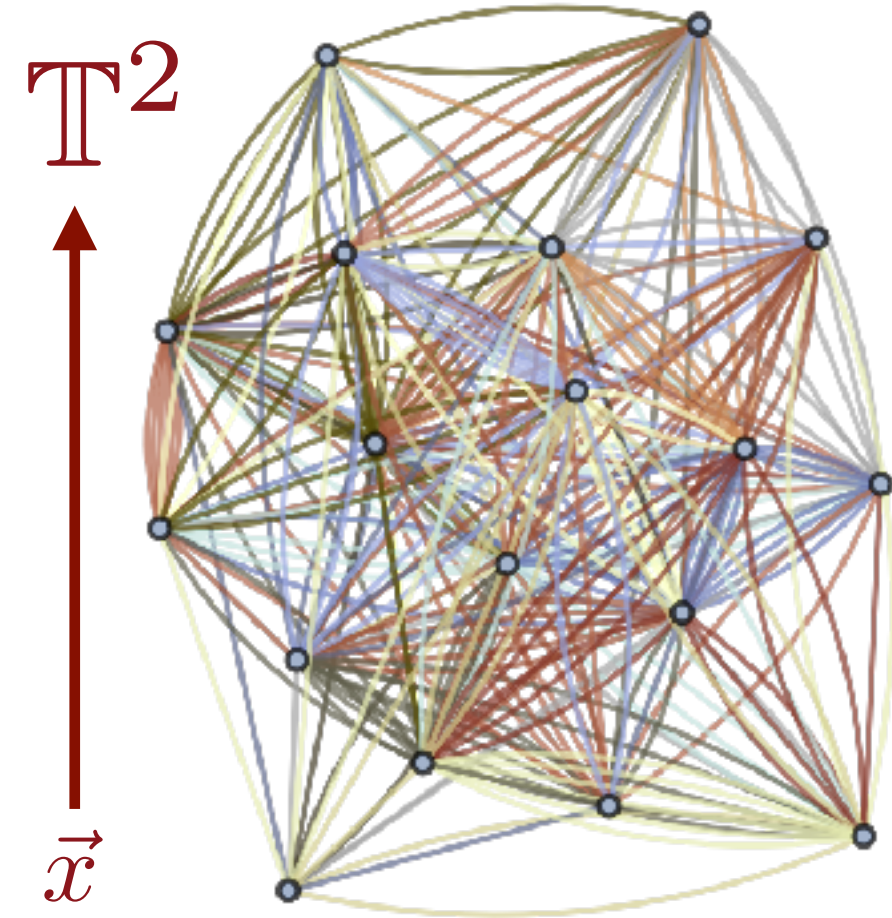
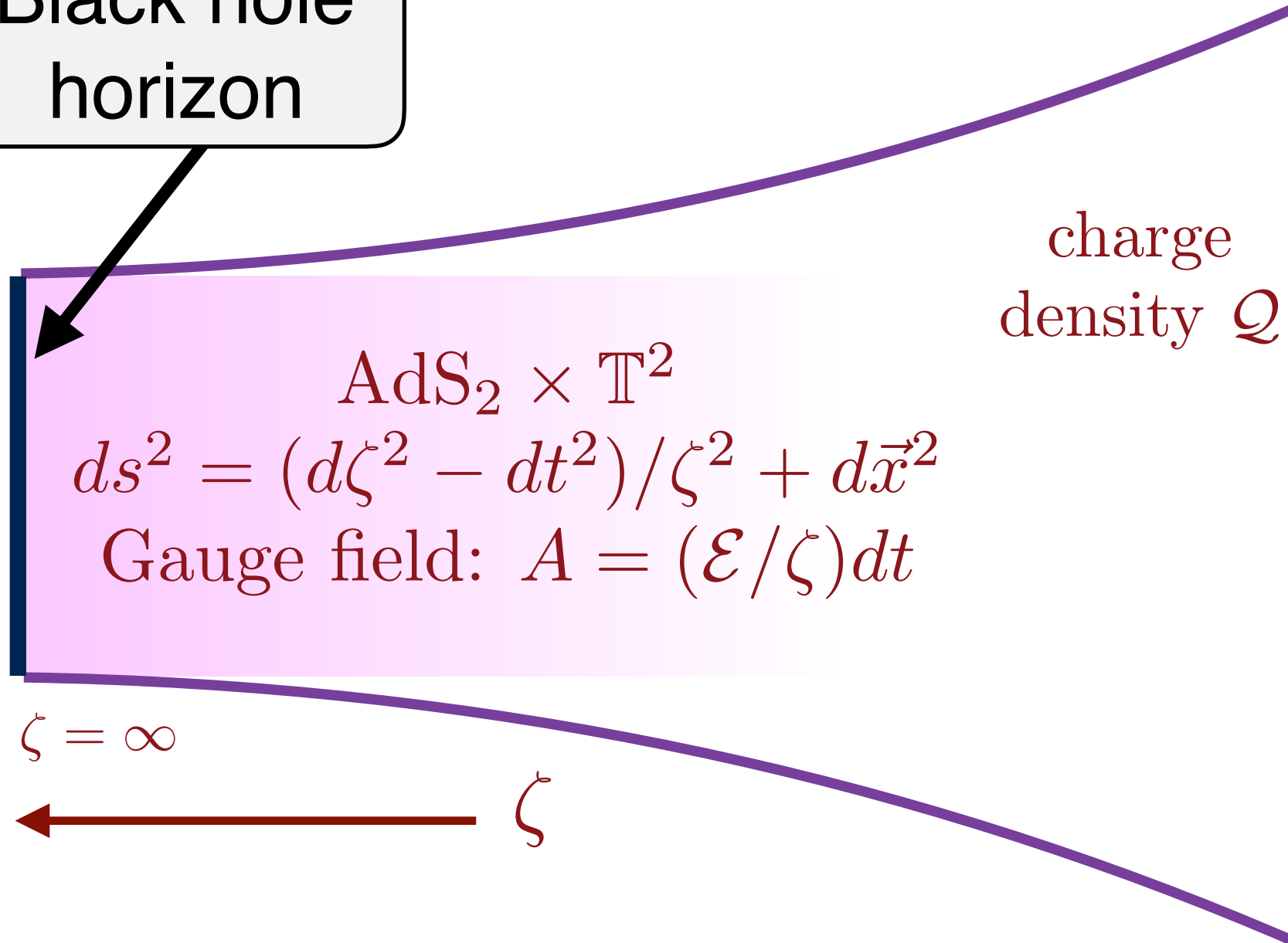


$$S = \int d^4x \sqrt{-\hat{g}} \left(\hat{\mathcal{R}} + 6/L^2 - \frac{1}{4} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \right)$$

Yes, a charged black hole in Einstein-Maxwell theory

SYK and black holes

Black hole horizon

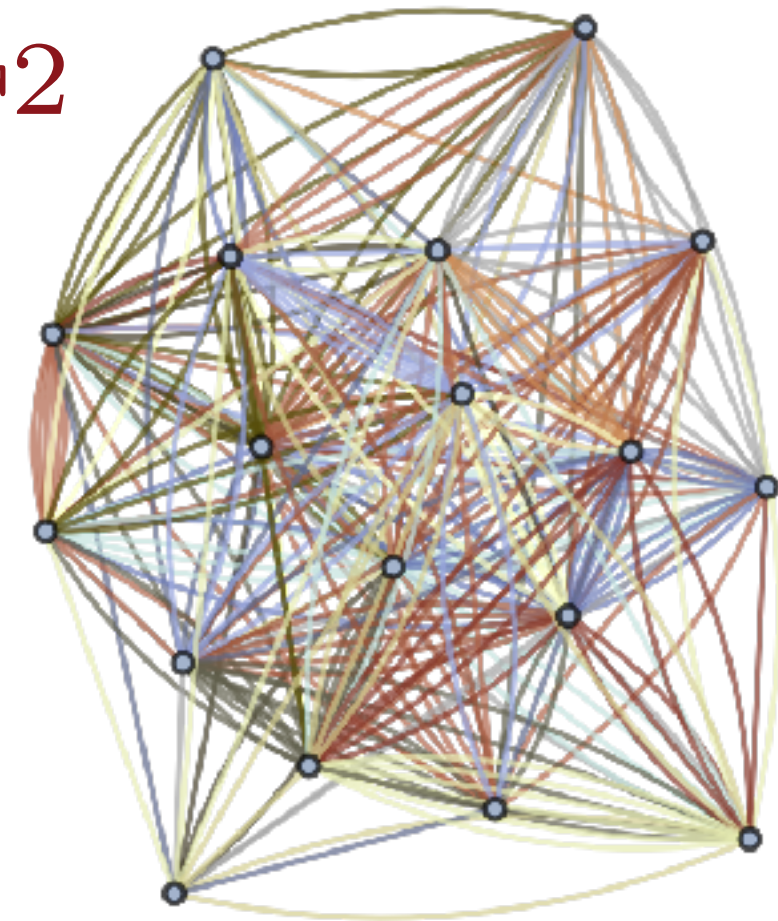
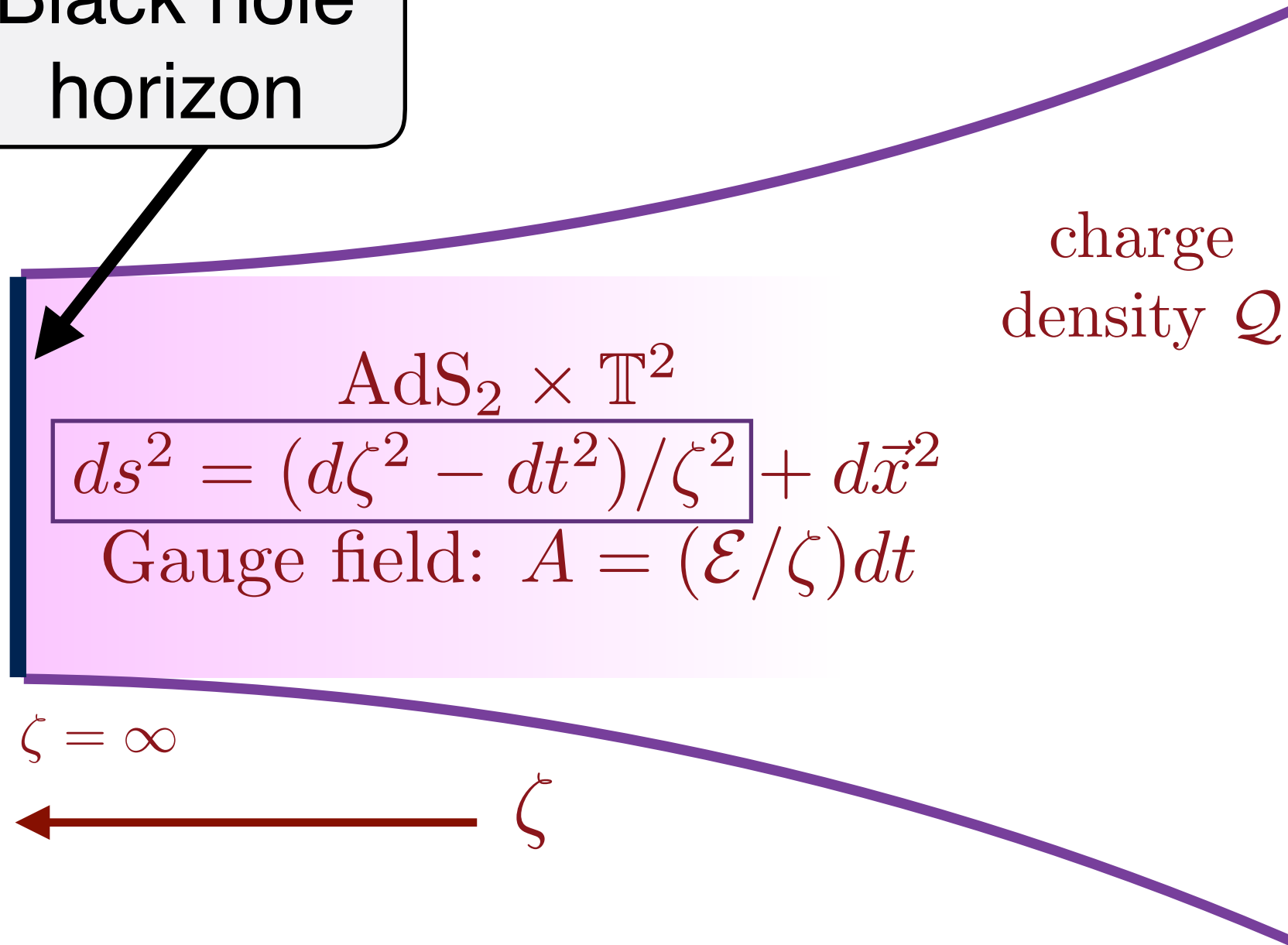


The leading low temperature properties of an AdS-Reissner-Nordstrom black hole (as computed by T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694) match those of the SYK model.

The mapping applies when temperature $\ll 1/(\text{size of } \mathbb{T}^2)$.

SYK and black holes

Black hole horizon



Quantum gravity on the $1+1$ dimensional spacetime AdS_2 (when embedded in AdS_4) is holographically matched to the $0+1$ dimensional SYK model

SYK and black holes

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

SYK and black holes

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- Low temperature entropy $S = Ns_0 + N\gamma T + \dots$
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- $T > 0$ Green's function has conformal invariance

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

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

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

Quantum matter without quasiparticles:

- No quasiparticle

decomposition of low-lying states:

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

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- These are also characteristics of black holes in quantum gravity.