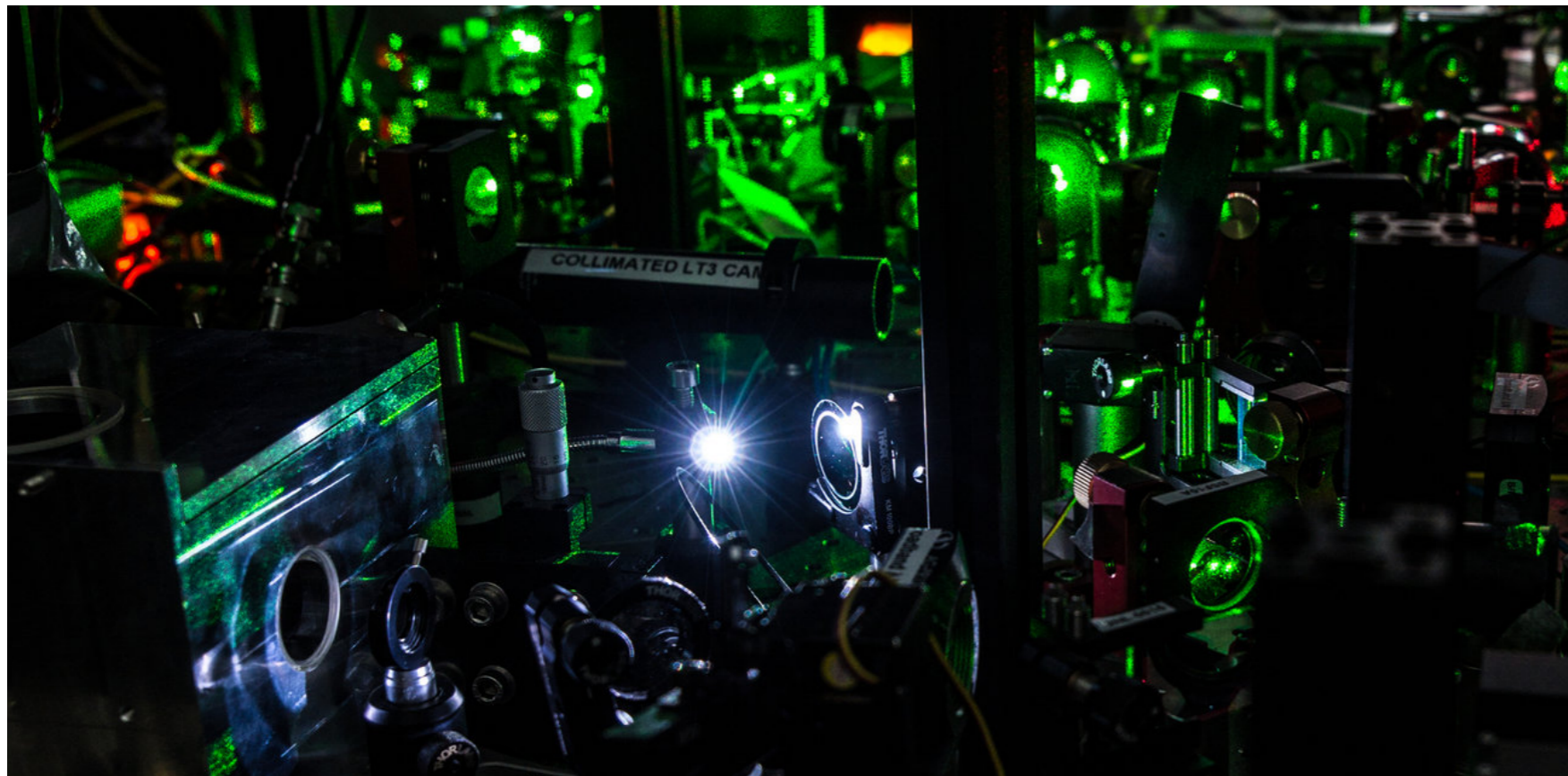


Sorry, Einstein. Quantum Study Suggests ‘Spooky Action’ Is Real.

By **JOHN MARKOFF** OCT. 21, 2015

In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other’s behavior.



Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

Quantum entanglement: spooky action at a distance in the lab and in black holes

Indian Institute of Technology Bombay
January 10, 2020

Subir Sachdev

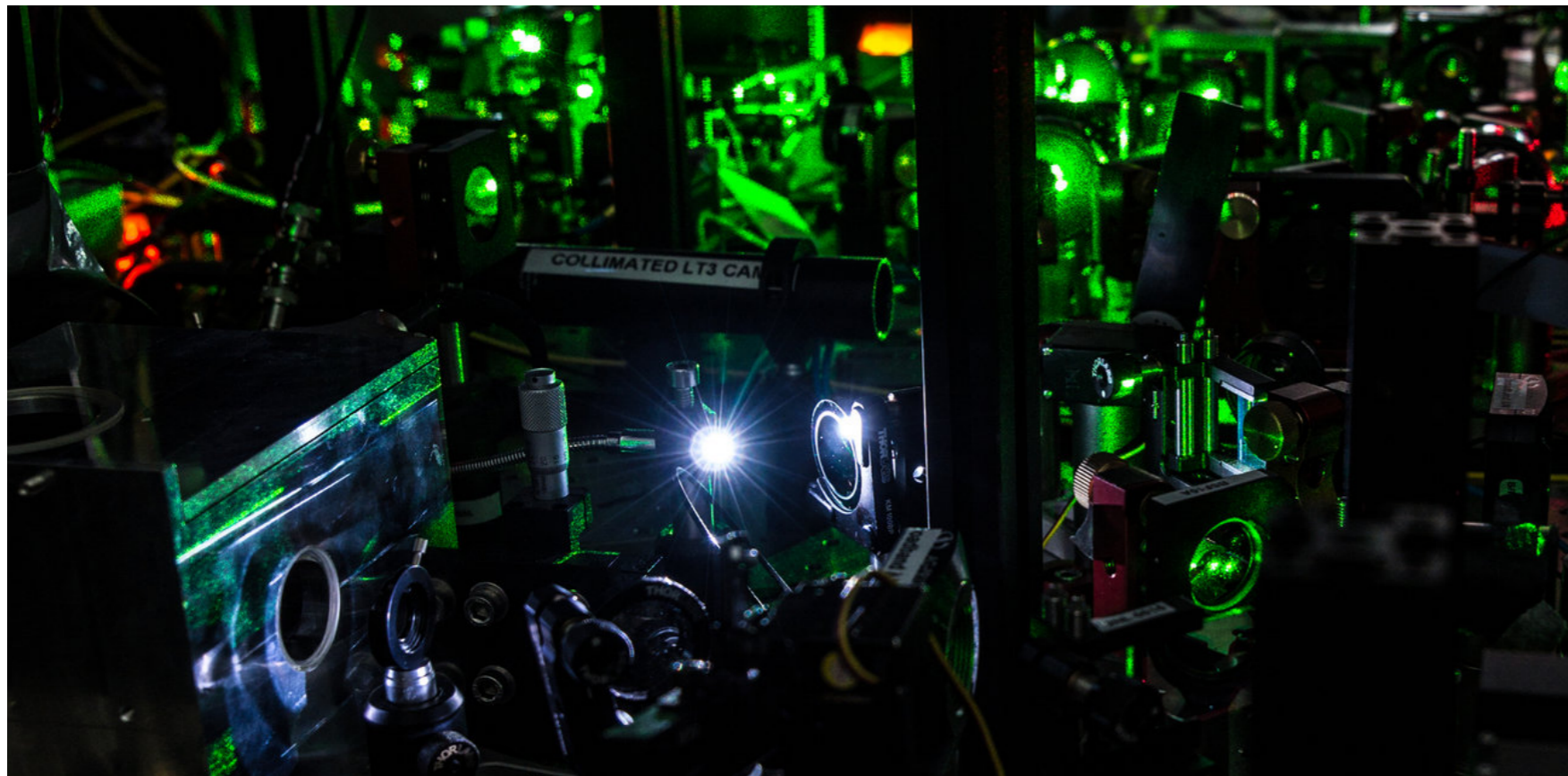
Talk online: sachdev.physics.harvard.edu



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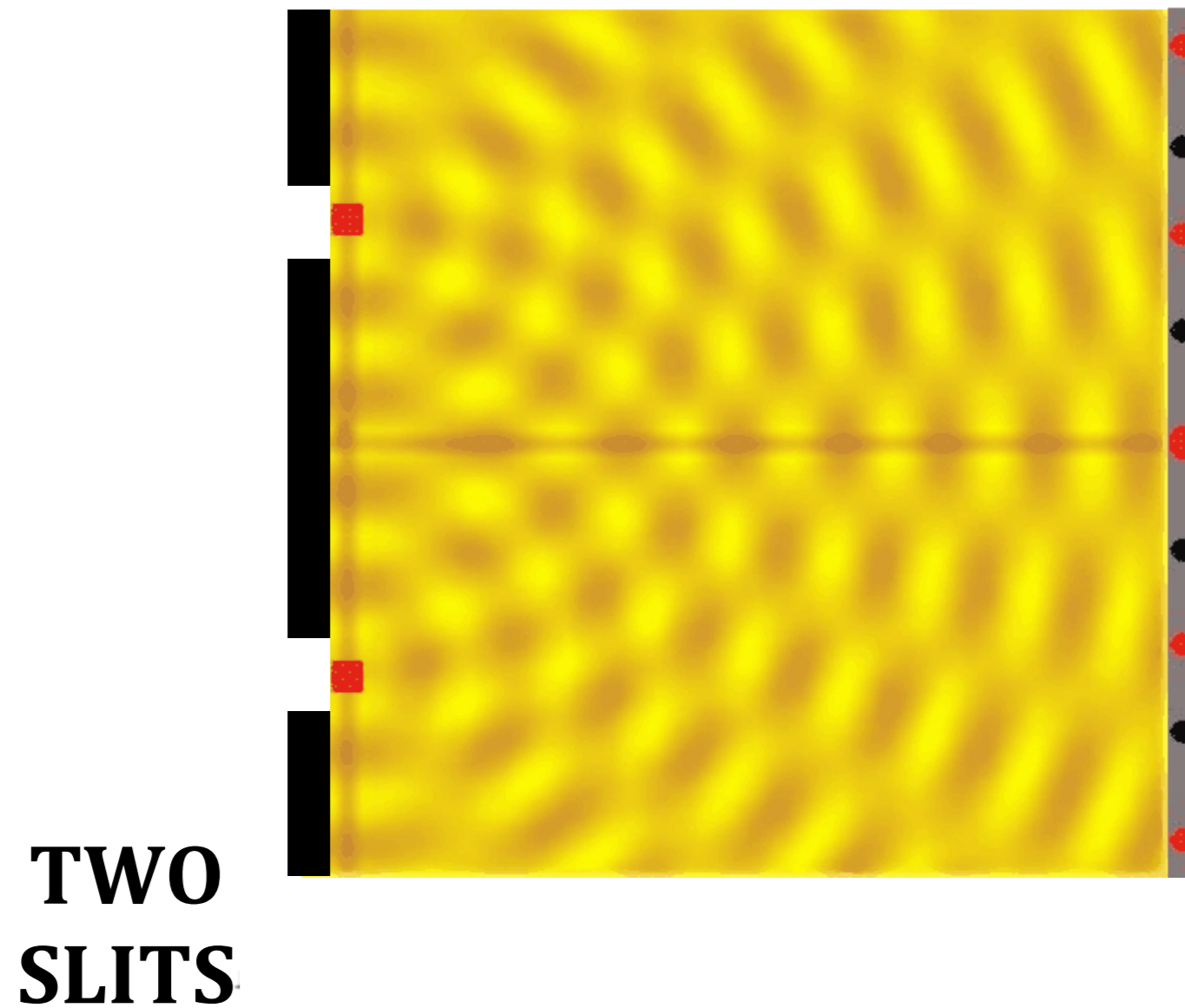
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Quantum entanglement

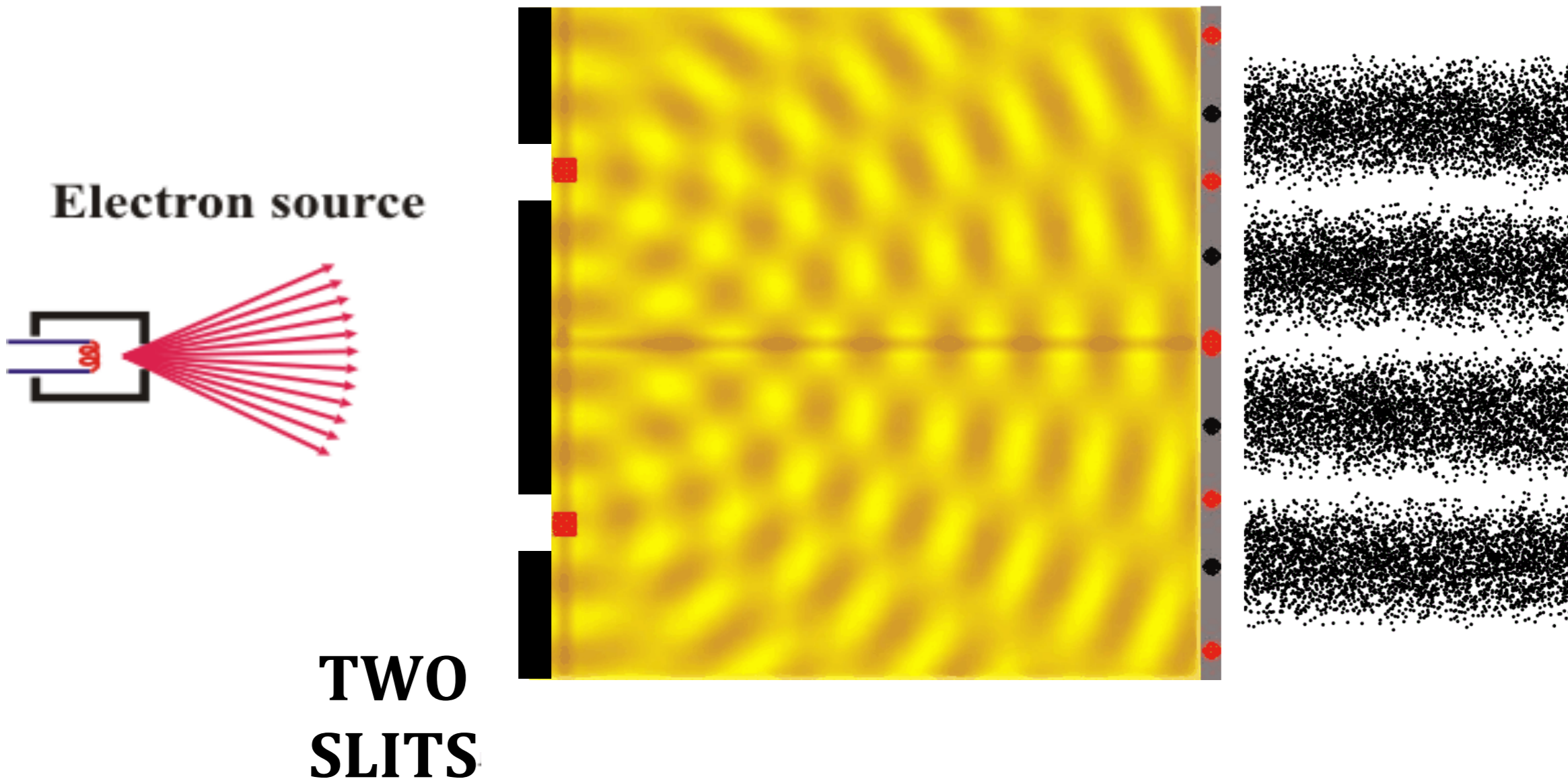
The double slit experiment



Interference of water waves

Principles of Quantum Mechanics: I. Quantum Superposition

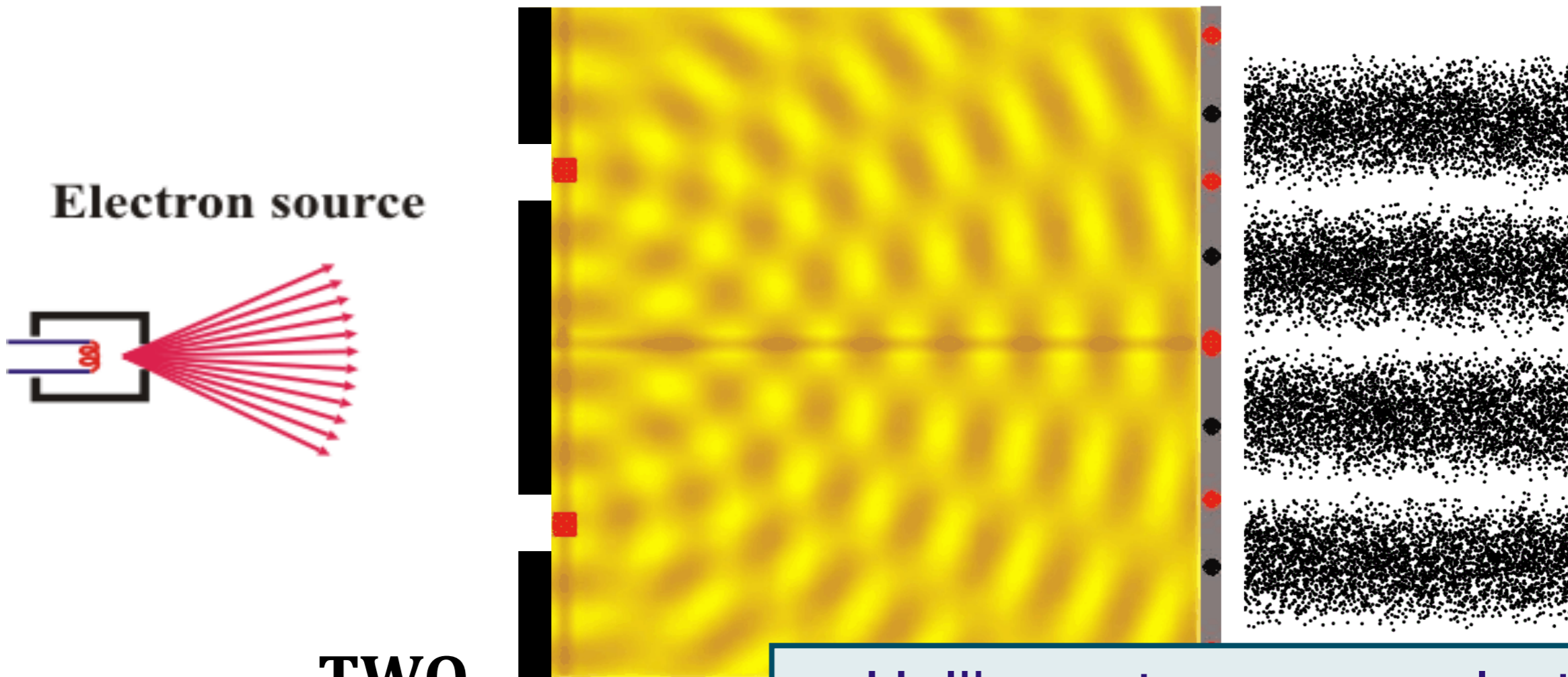
The double slit experiment



Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

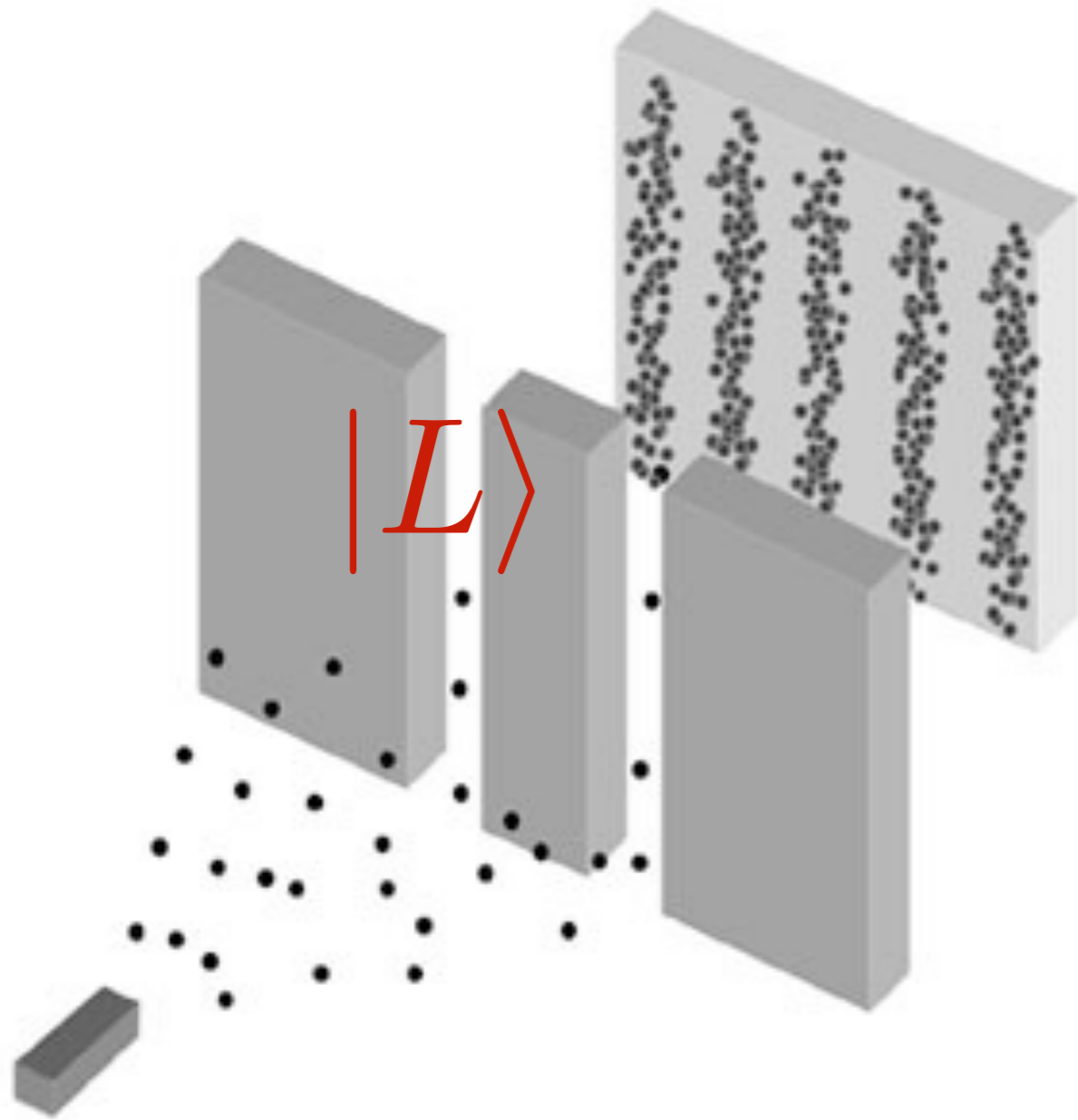


Unlike water waves, electrons arrive one-by-one (so is it like a particle ?)

Interference of electrons

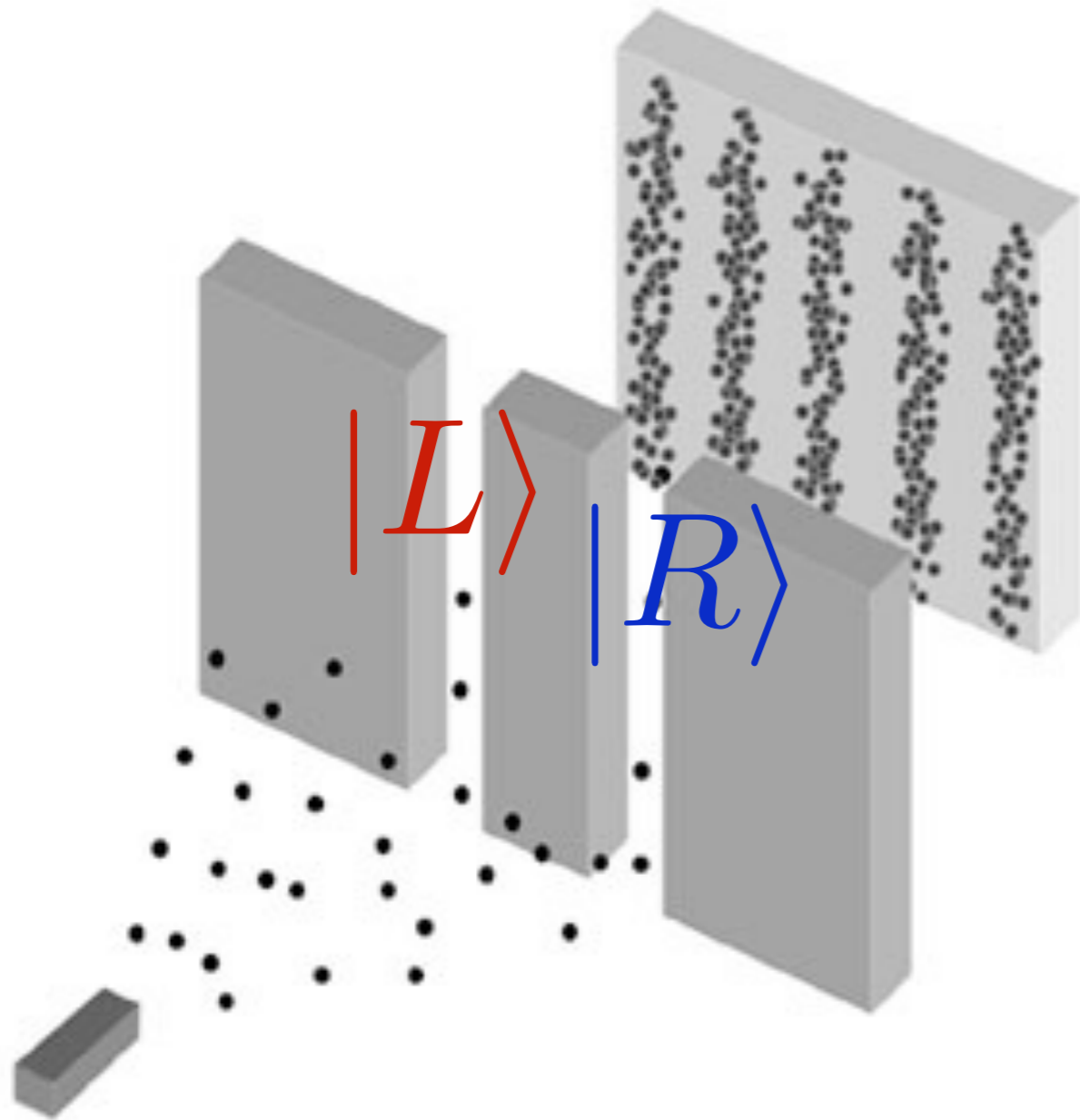
Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment



Let $|L\rangle$ represent the state with the electron in the left slit

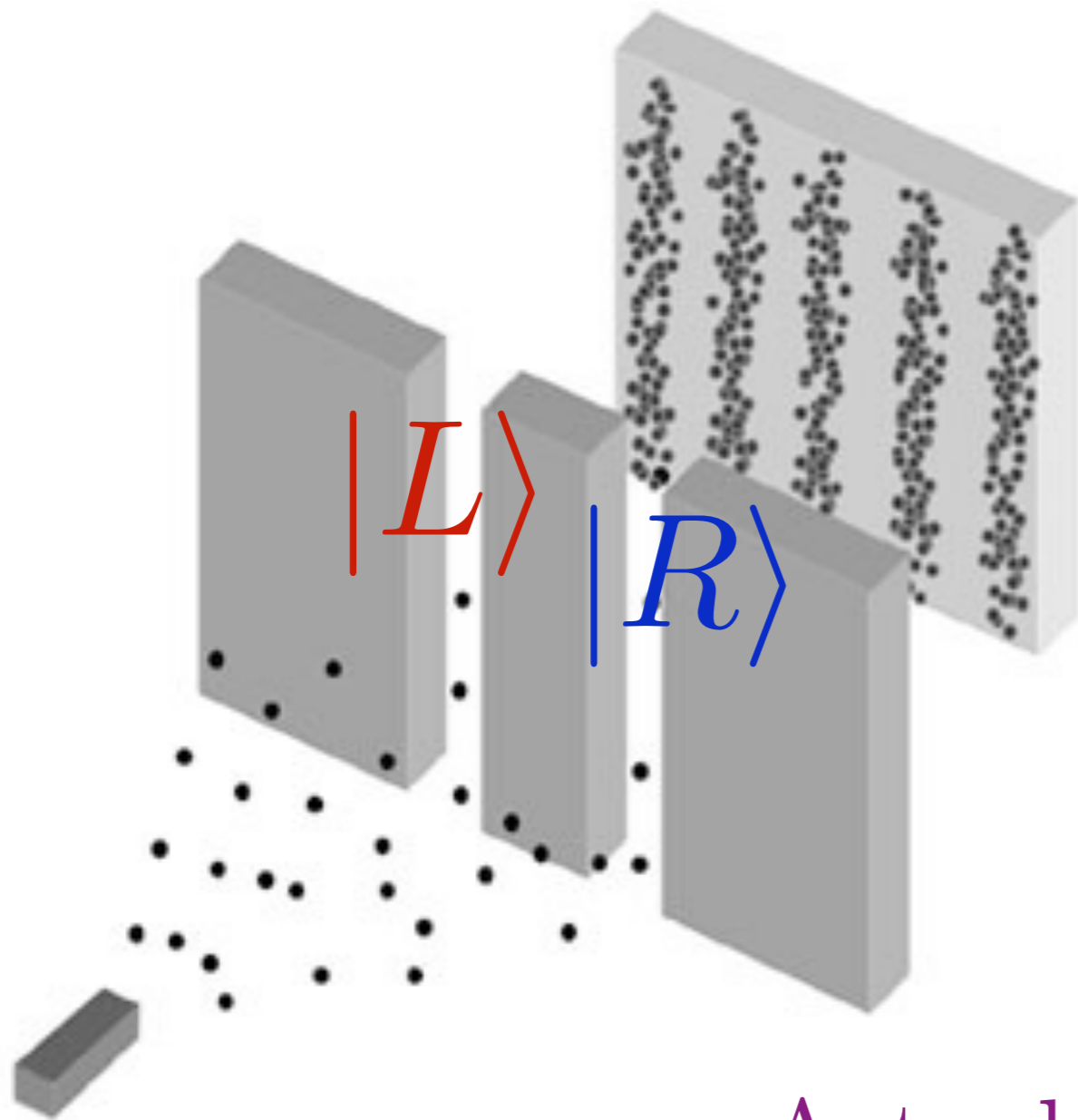
The double slit experiment



Let $|L\rangle$ represent the state with the electron in the left slit

And $|R\rangle$ represents the state with the electron in the right slit

The double slit experiment



Let $|L\rangle$ represent the state with the electron in the left slit

And $|R\rangle$ represents the state with the electron in the right slit

Actual state of *each* electron is

$$|L\rangle + |R\rangle$$

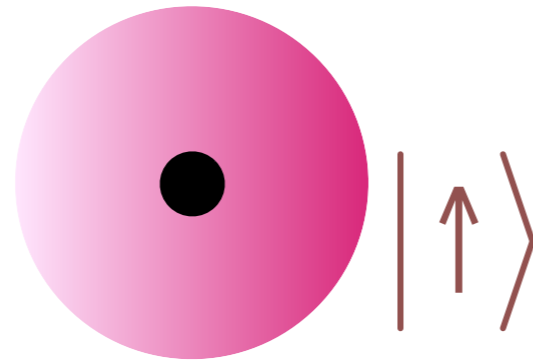
Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition
with more than one particle

Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

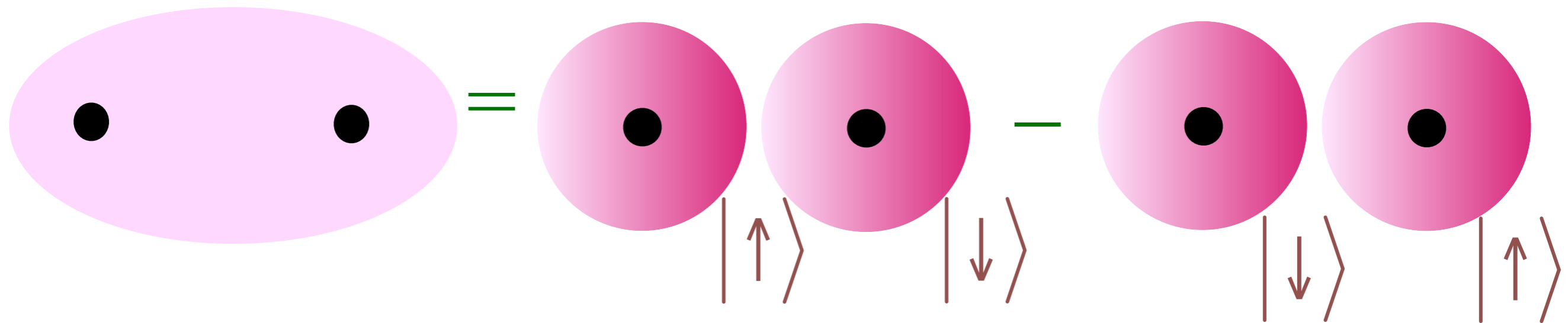


Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom: 

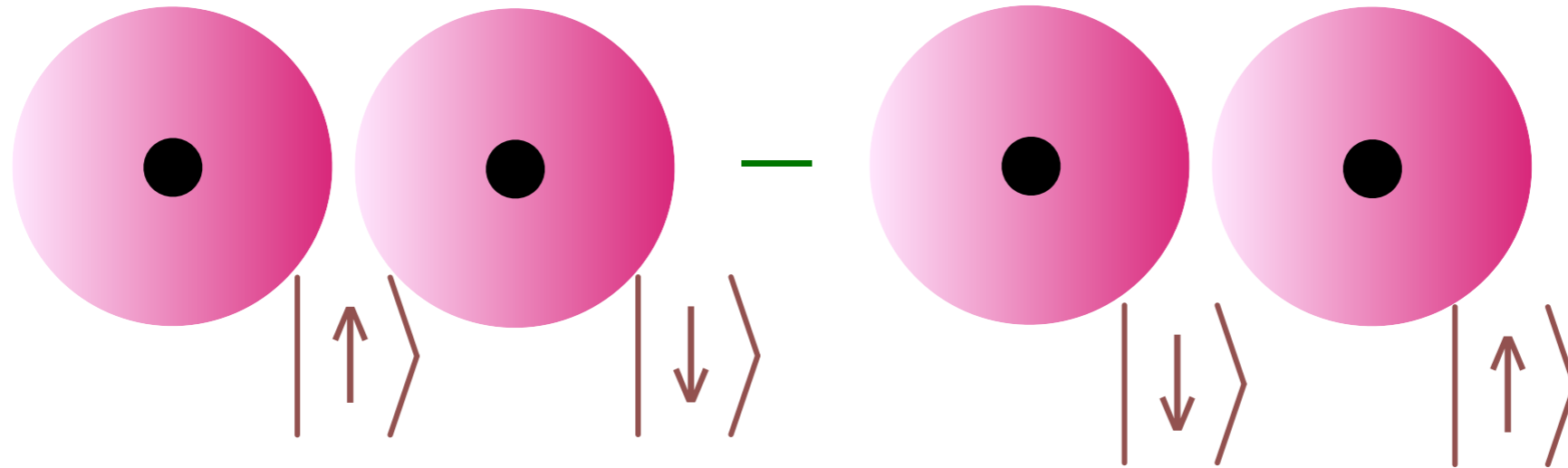
Hydrogen molecule:



$$= \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

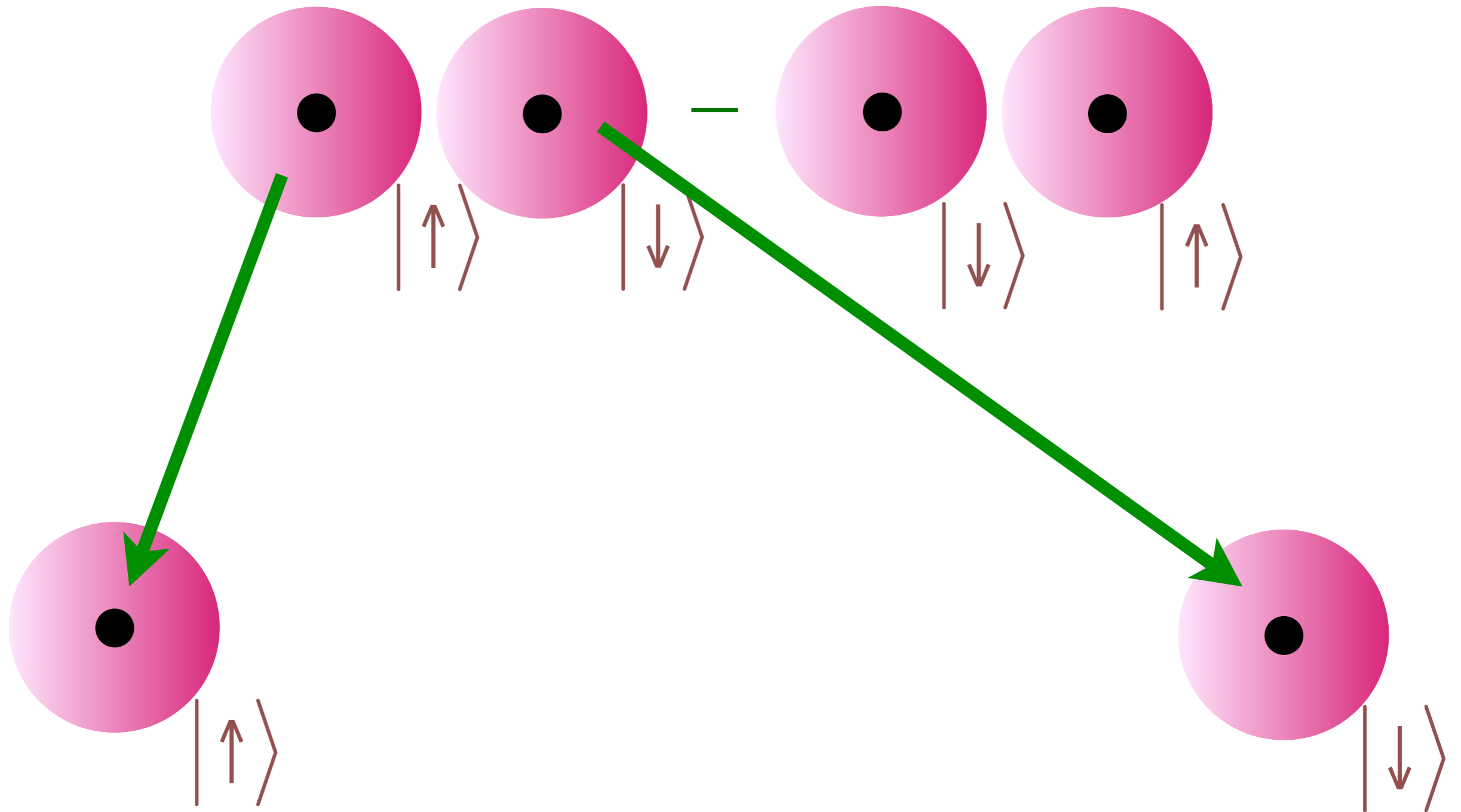
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Quantum Entanglement: quantum superposition with more than one particle



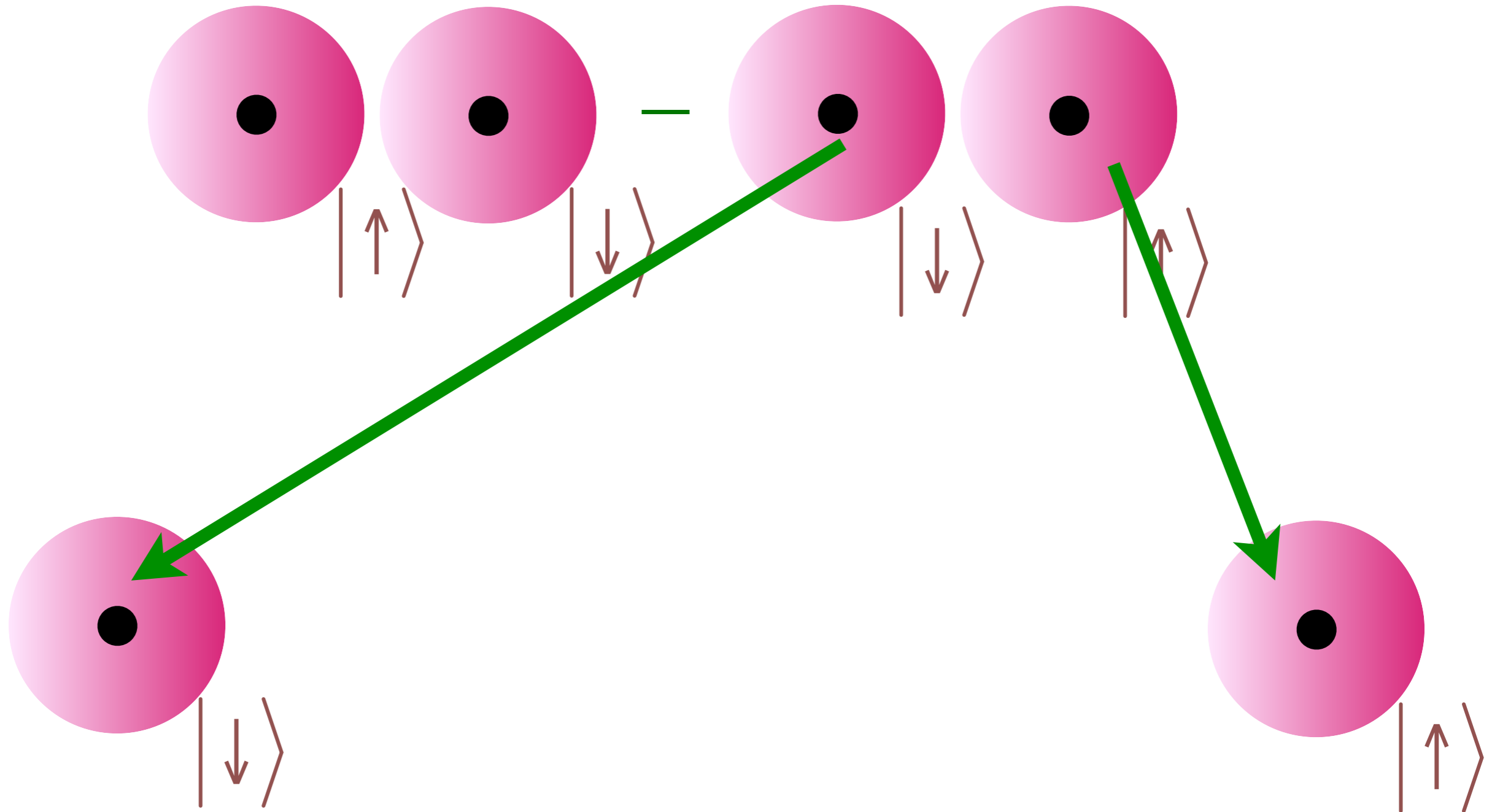
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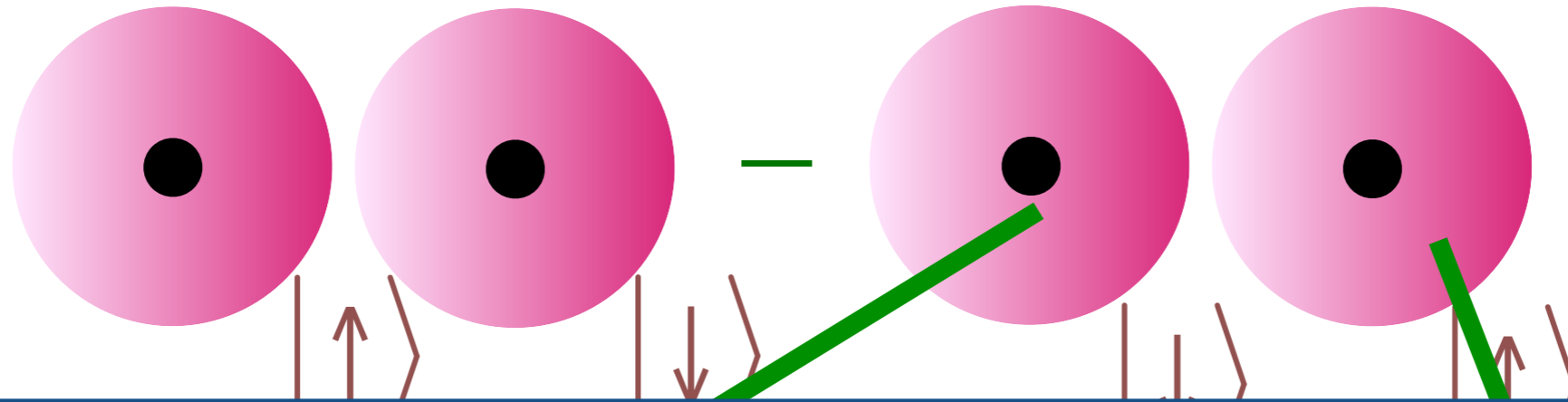
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Quantum Entanglement: quantum superposition with more than one particle

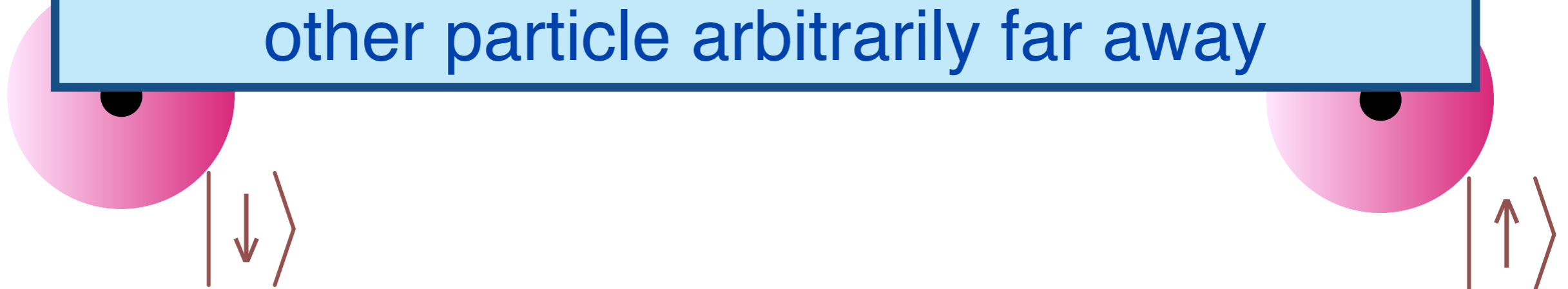


Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle



Einstein-Podolsky-Rosen “paradox” (1935):
Measurement of one particle
instantaneously determines the state of the
other particle arbitrarily far away



Quantum entanglement

**Quantum
entanglement**

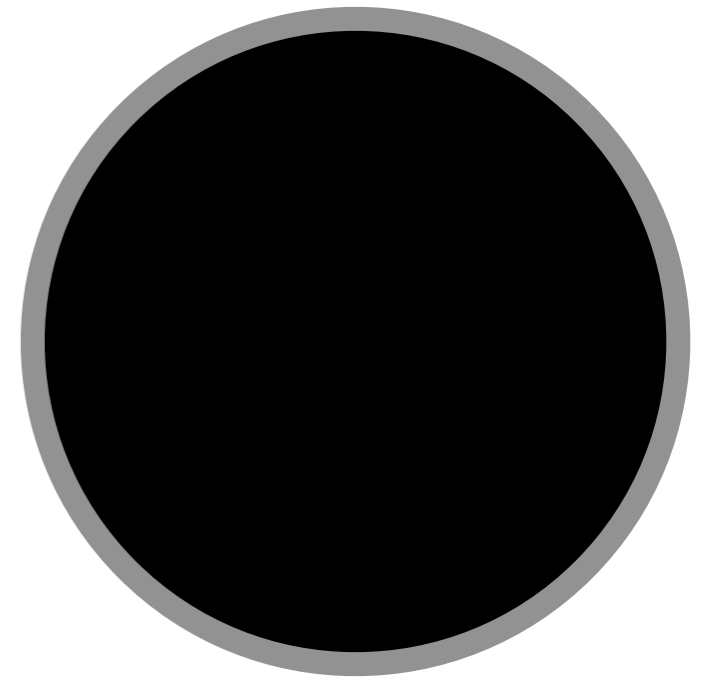
**Black
holes**

Black Holes

Objects so dense that light is gravitationally bound to them.

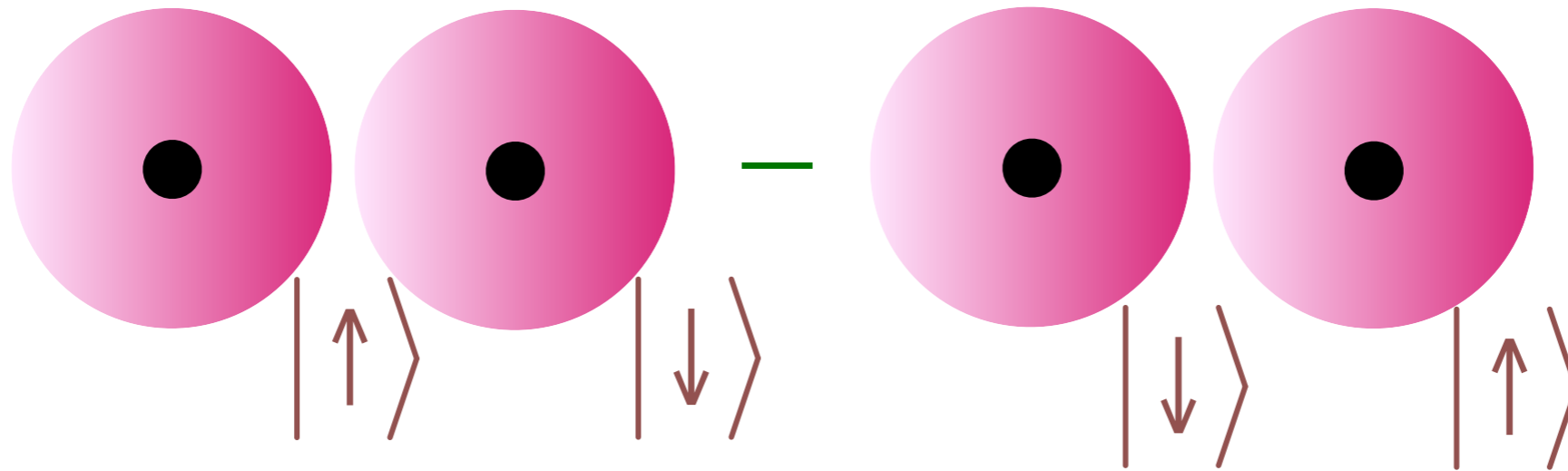
In Einstein's theory, the region inside the black hole **horizon** is disconnected from the rest of the universe.

$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

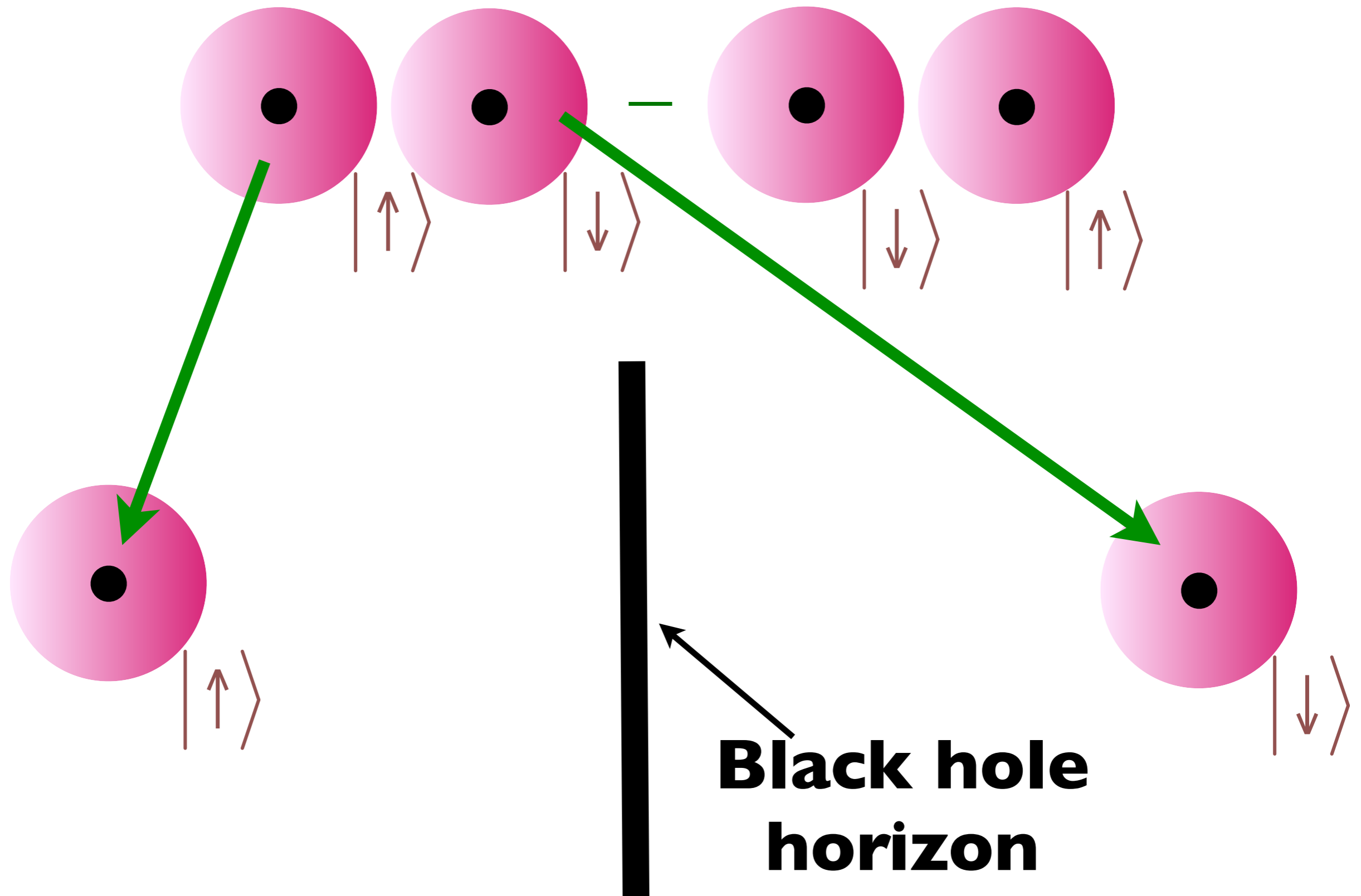


G Newton's constant, c velocity of light, M mass of black hole

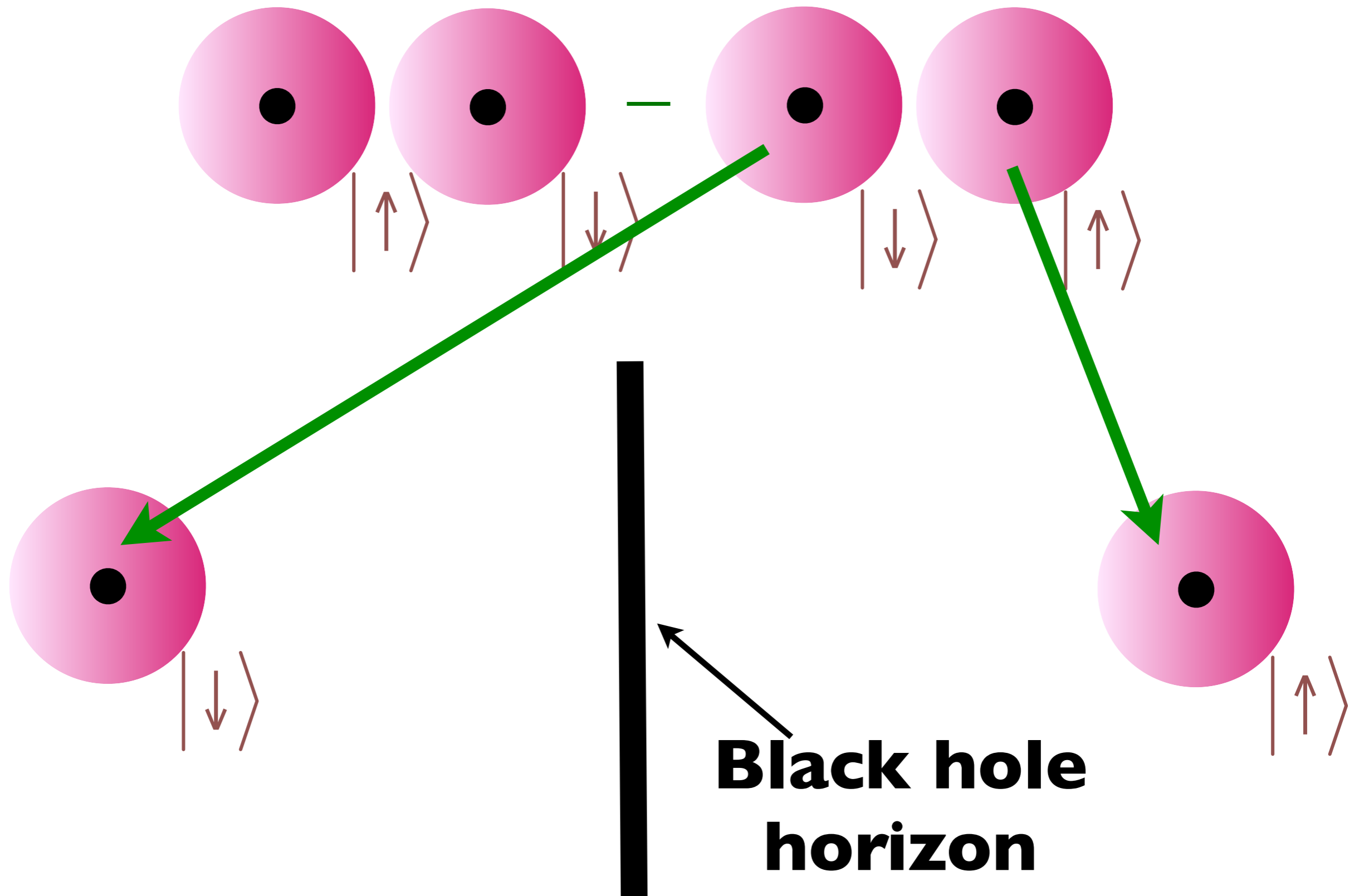
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

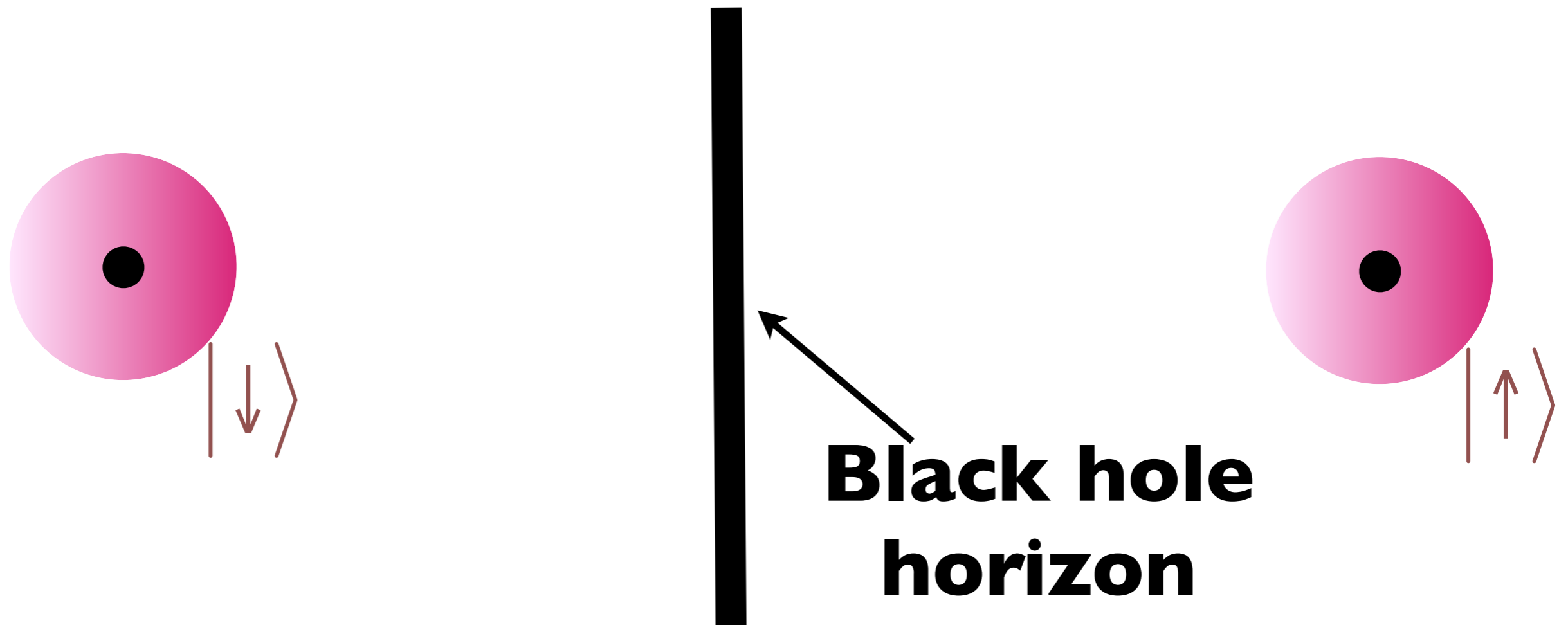


Quantum Entanglement across a black hole horizon



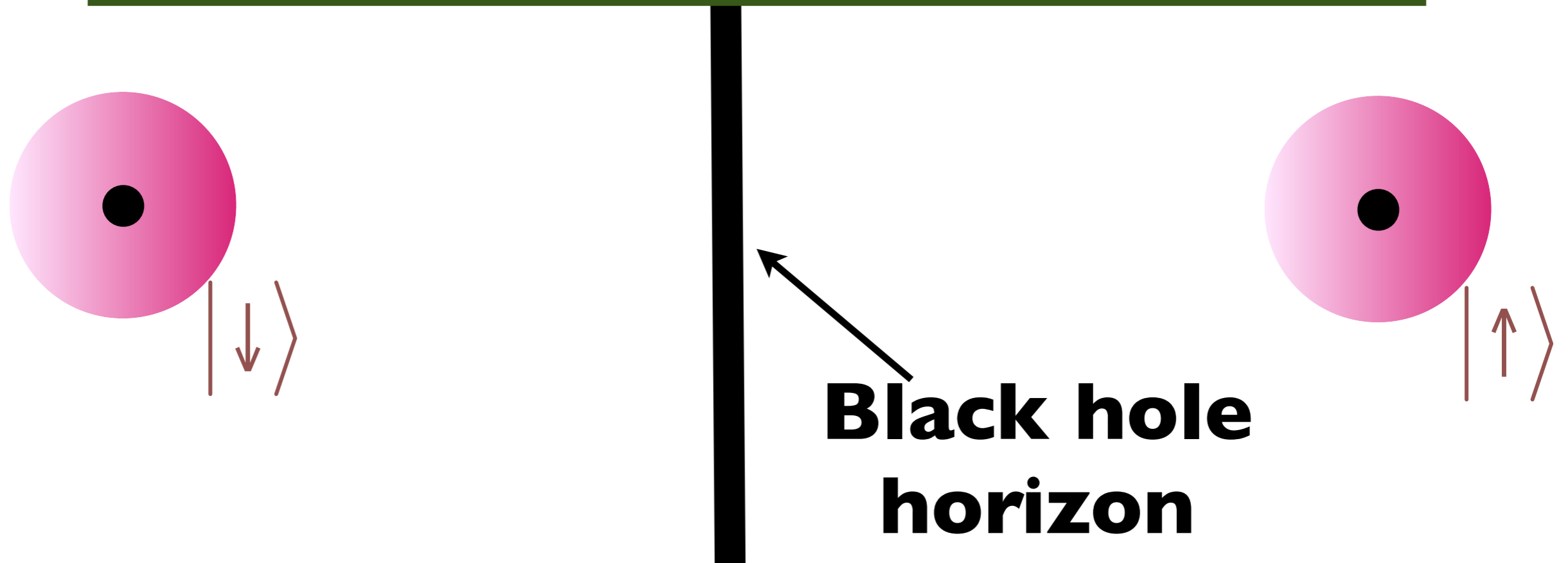
Quantum Entanglement across a black hole horizon

There is quantum entanglement between the inside and outside of a black hole



Quantum Entanglement across a black hole horizon

Hawking used this to show that black hole horizons have an entropy and a temperature (because to an outside observer, the state of the electron inside the black hole is an unknown)



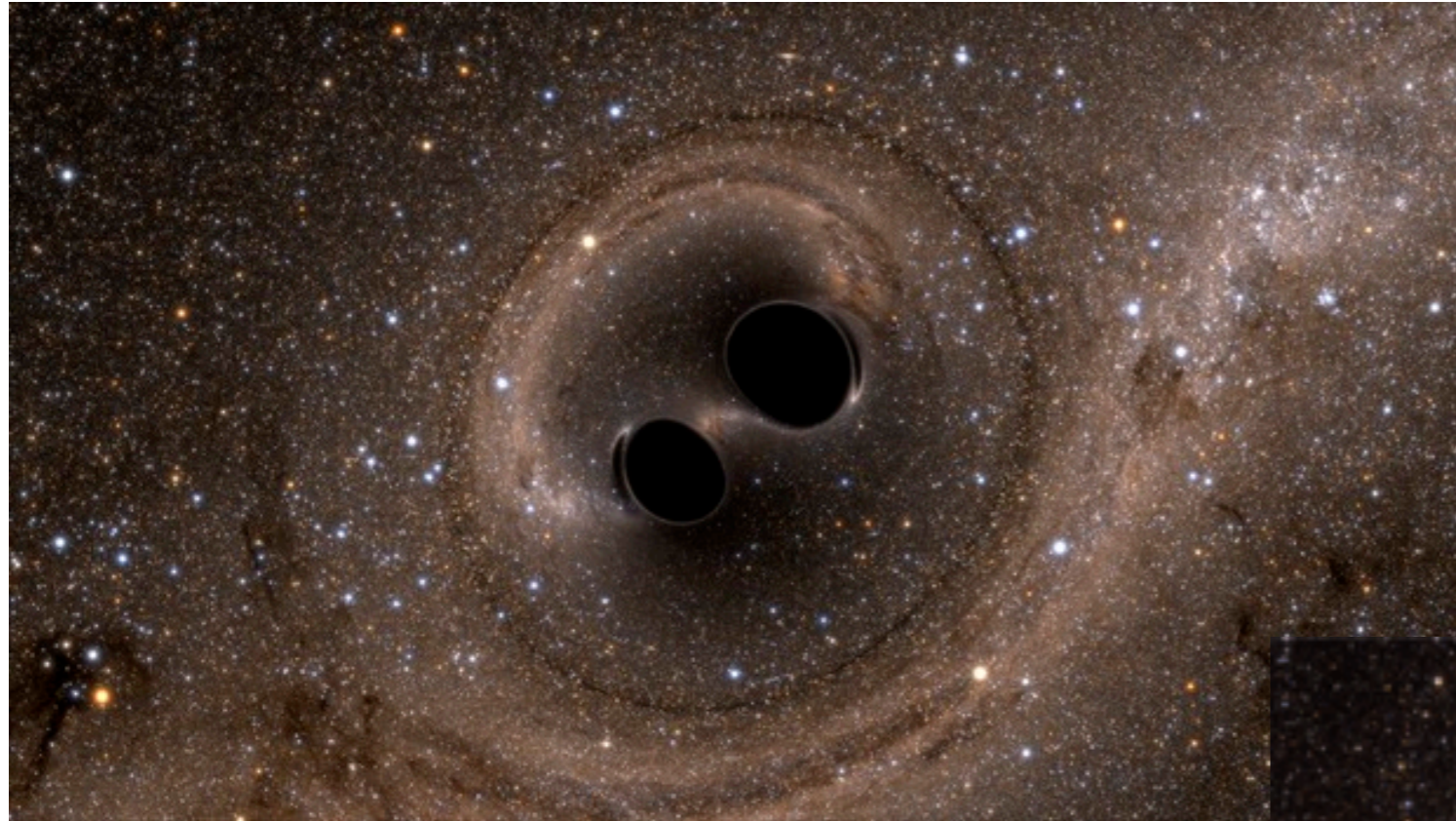
Quantum Black holes

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

J. D. Bekenstein, PRD **7**, 2333 (1973)
S.W. Hawking, Nature **248**, 30 (1974)

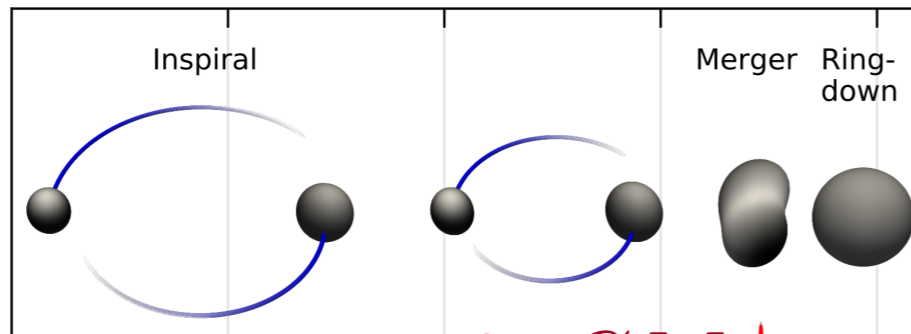
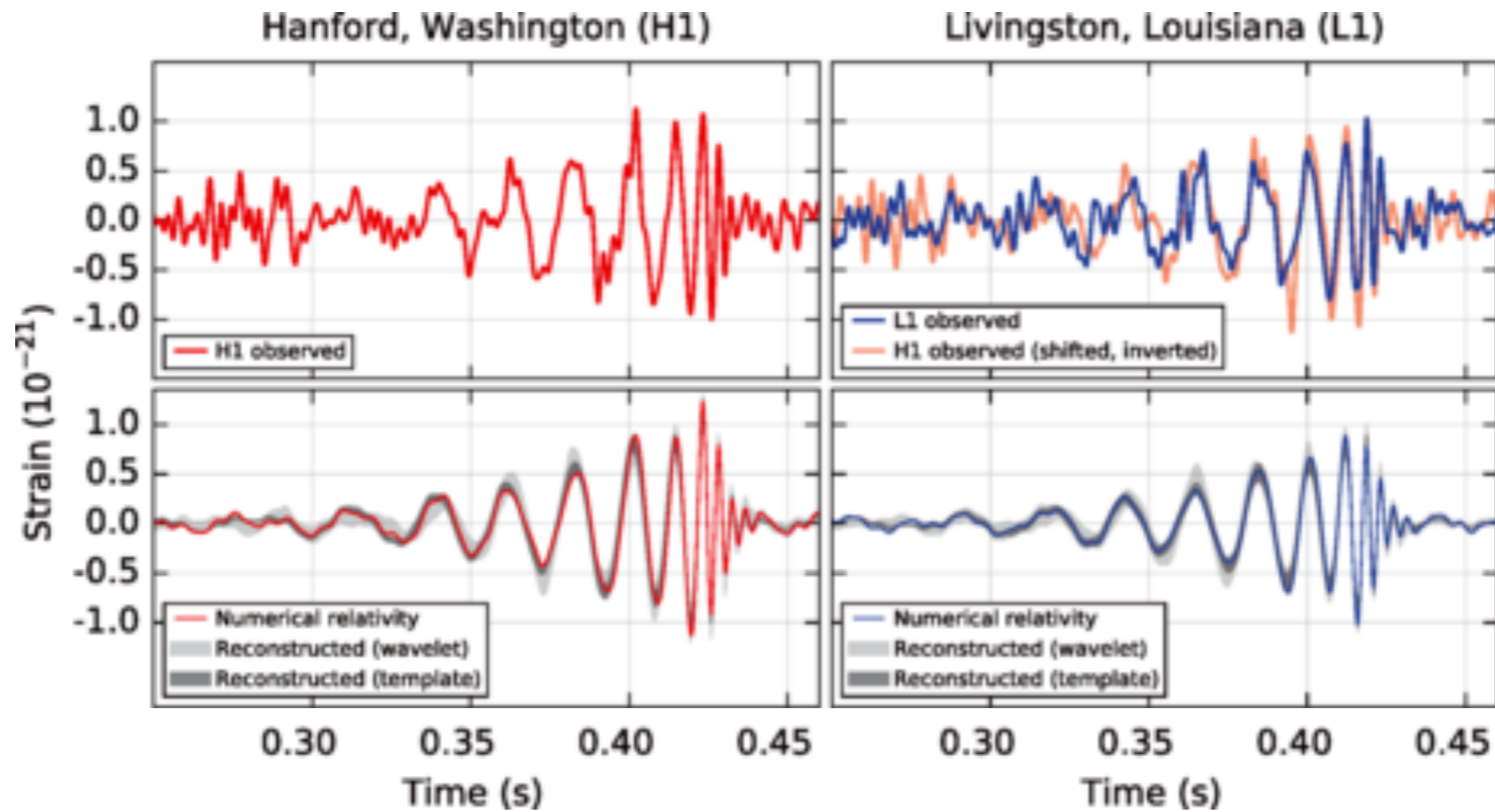


On September 14, 2015, LIGO detected the merger of two black holes, each weighing about 30 solar masses, with radii of about 100 km, 1.3 billion light years away



0.1 seconds later !





LIGO
September 14, 2015

- The ring-down time $\frac{8\pi GM}{c^3} \sim 8$ milliseconds. Curiously, for essentially all types of black holes, the ring-down time equals

$$\frac{\hbar}{k_B T_H}$$

\hbar Planck's constant, k_B Boltzmann's constant

Quantum 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 Planckian time $\sim \hbar/(k_B T_H)$.



**Quantum
entanglement**

**Black
holes**

**Quantum
entanglement**

**Black
holes**

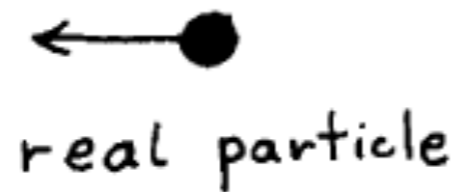
**Metals
(ordinary and strange)
and superconductors**

Ordinary metals

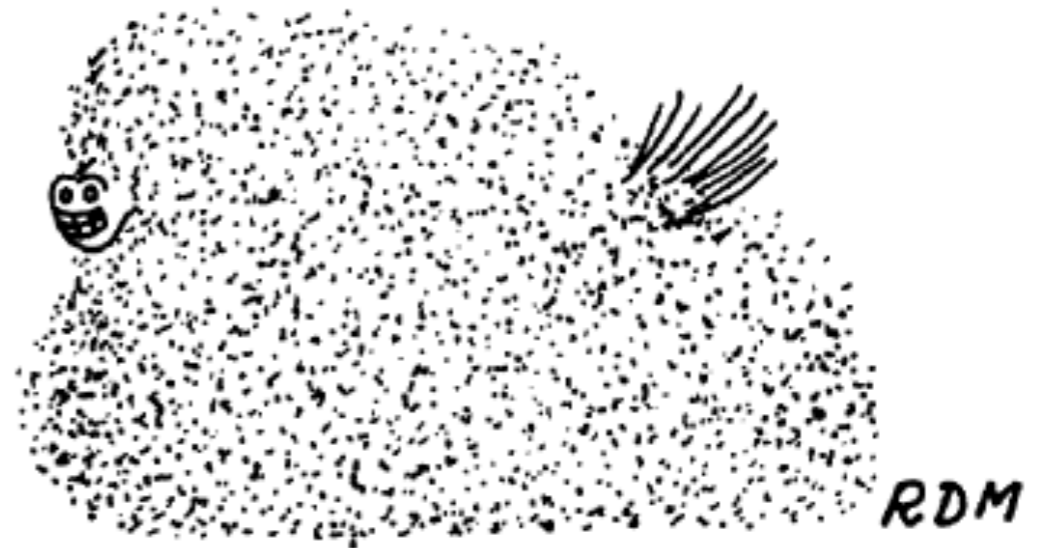


Ordinary metals are shiny, and they conduct heat and electricity efficiently. Each atom donates electrons which are delocalized throughout the entire crystal

Almost all many-electron systems are described by the quasiparticle concept: a quasiparticle is an “excited lump” in the many-electron state which responds just like an ordinary particle.



real horse



quasi horse

Current flow with quasiparticles

- The resistivity, ρ , of a metal from the flow of quasiparticles is

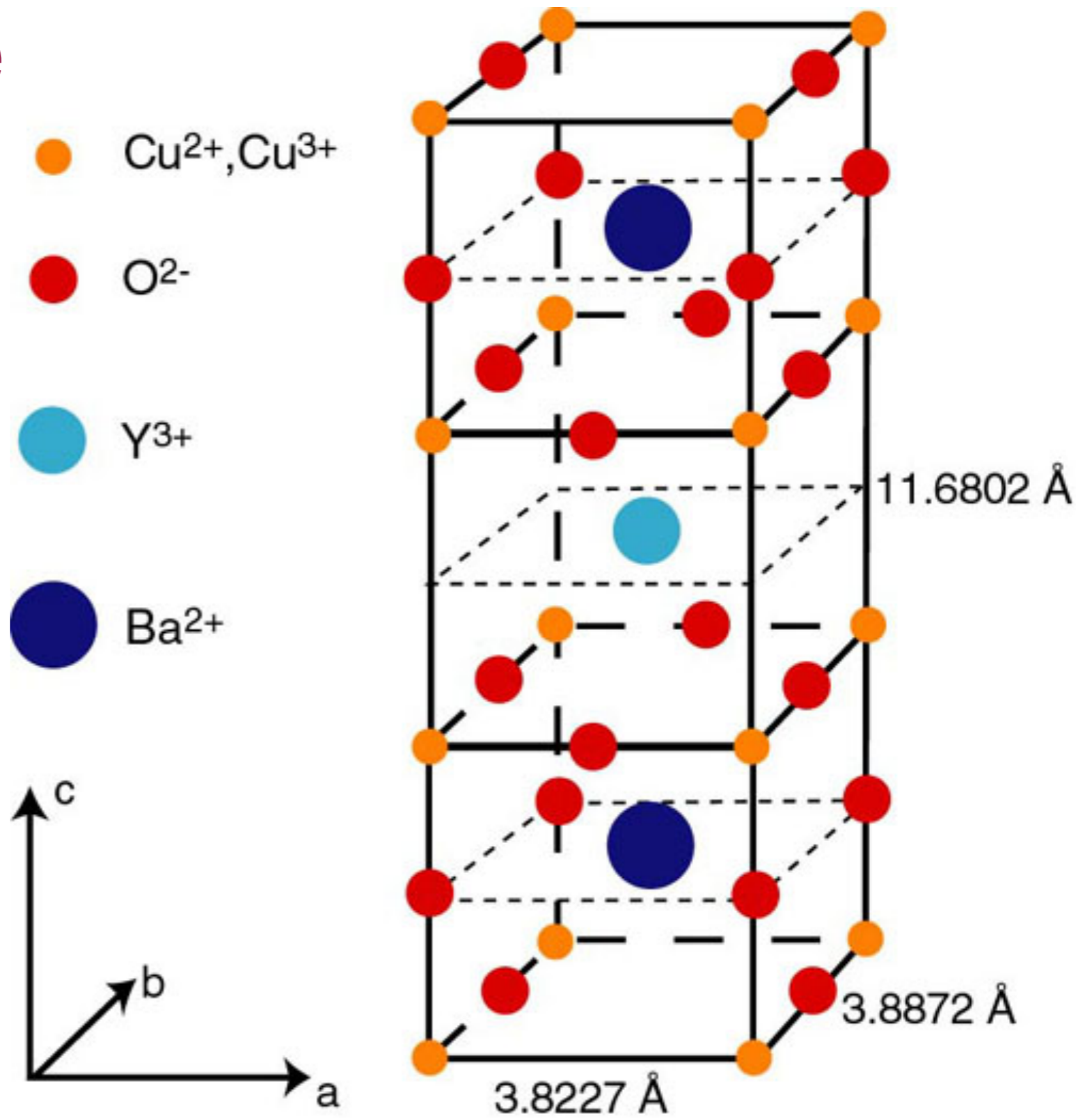
$$\rho = \frac{m^*}{ne^2} \frac{1}{\tau}$$

where m^* is the effective mass of a quasiparticle, n is the density of electrons, e is the charge of an electron, and τ is a quasiparticle scattering time.

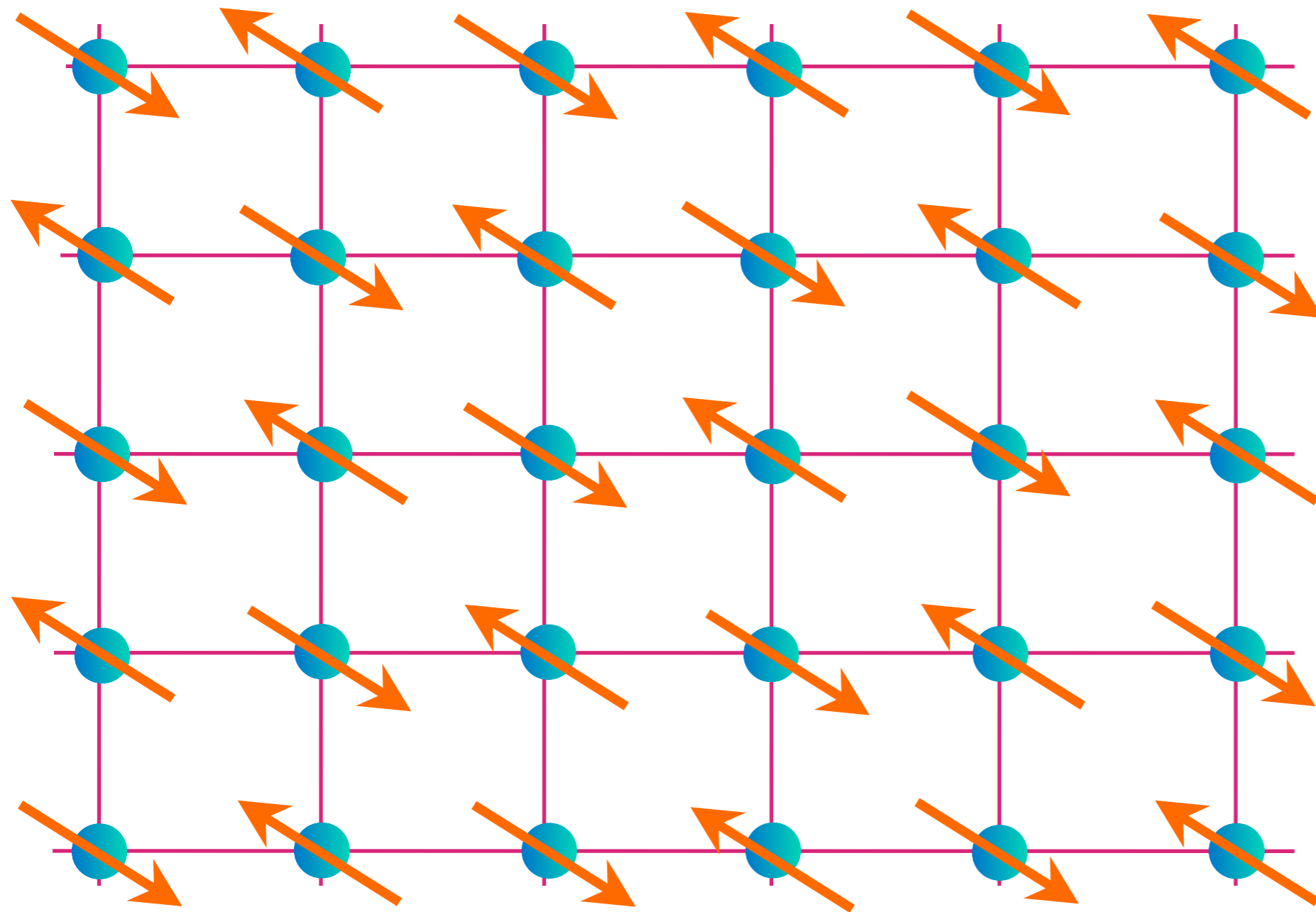
The theory of ordinary metals implies that as the temperature $T \rightarrow 0$

$$\tau \sim \frac{1}{T^2} \gg \frac{\hbar}{k_B T}$$

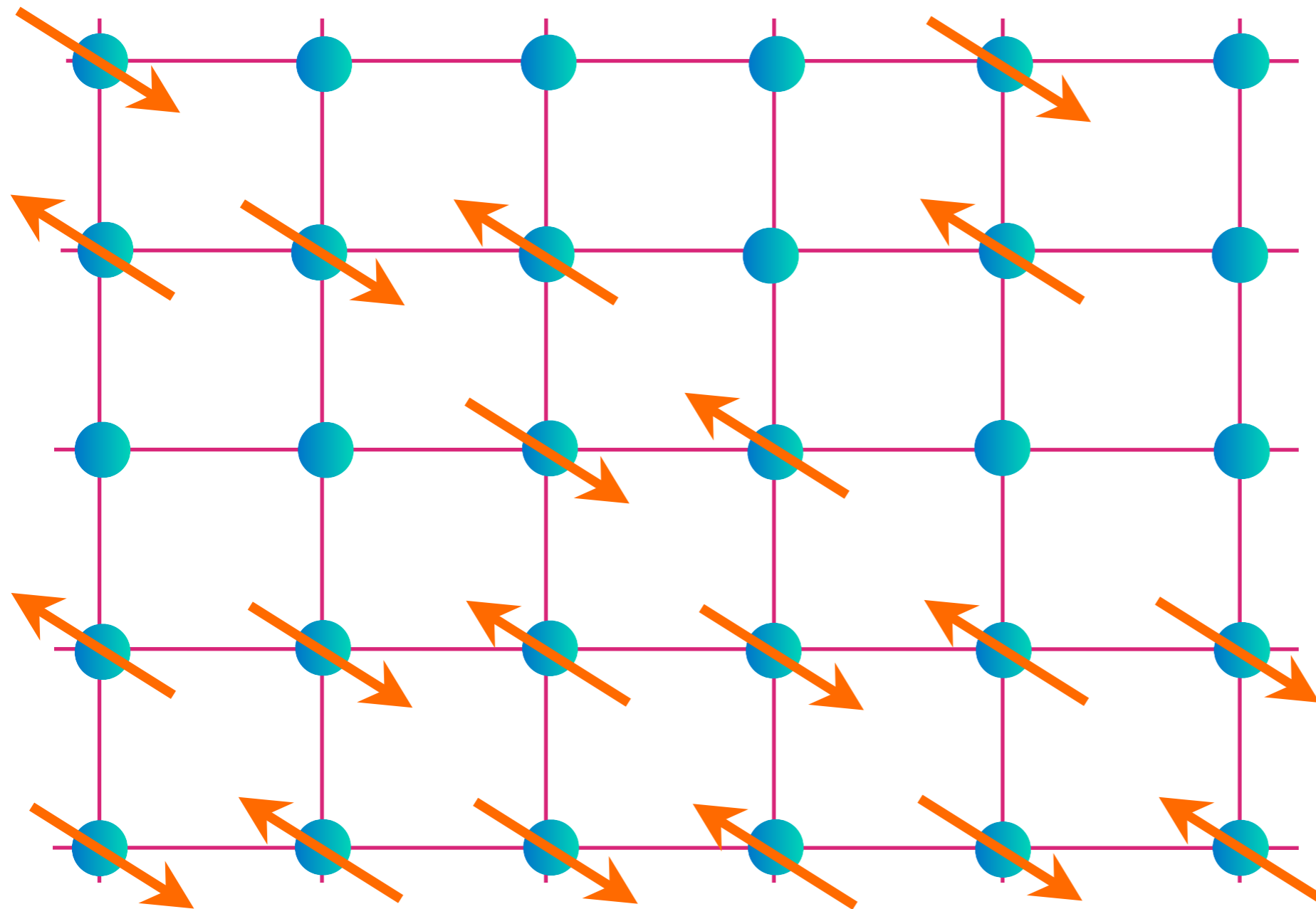
High temperature superconductors



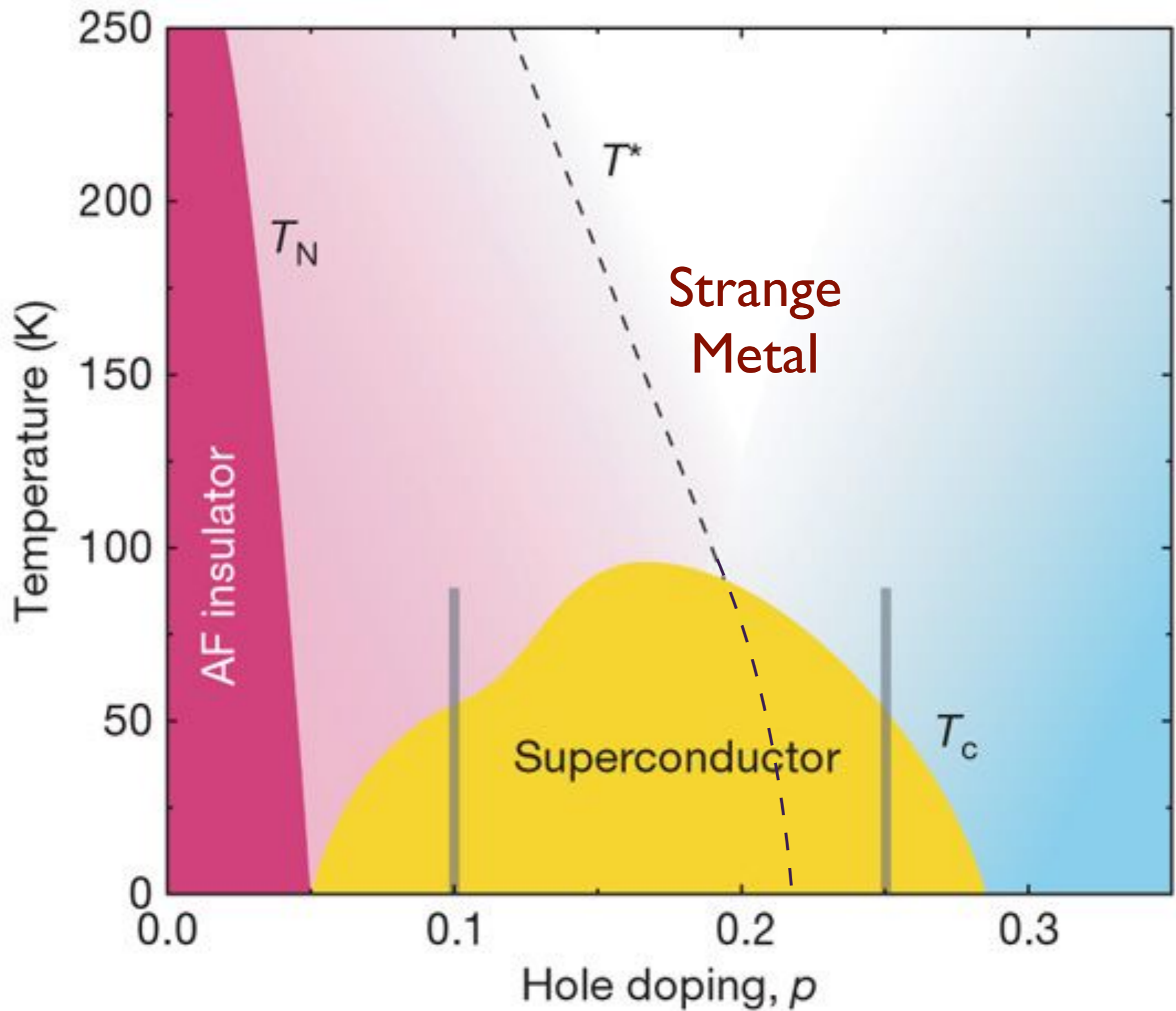
Square lattice of Cu sites

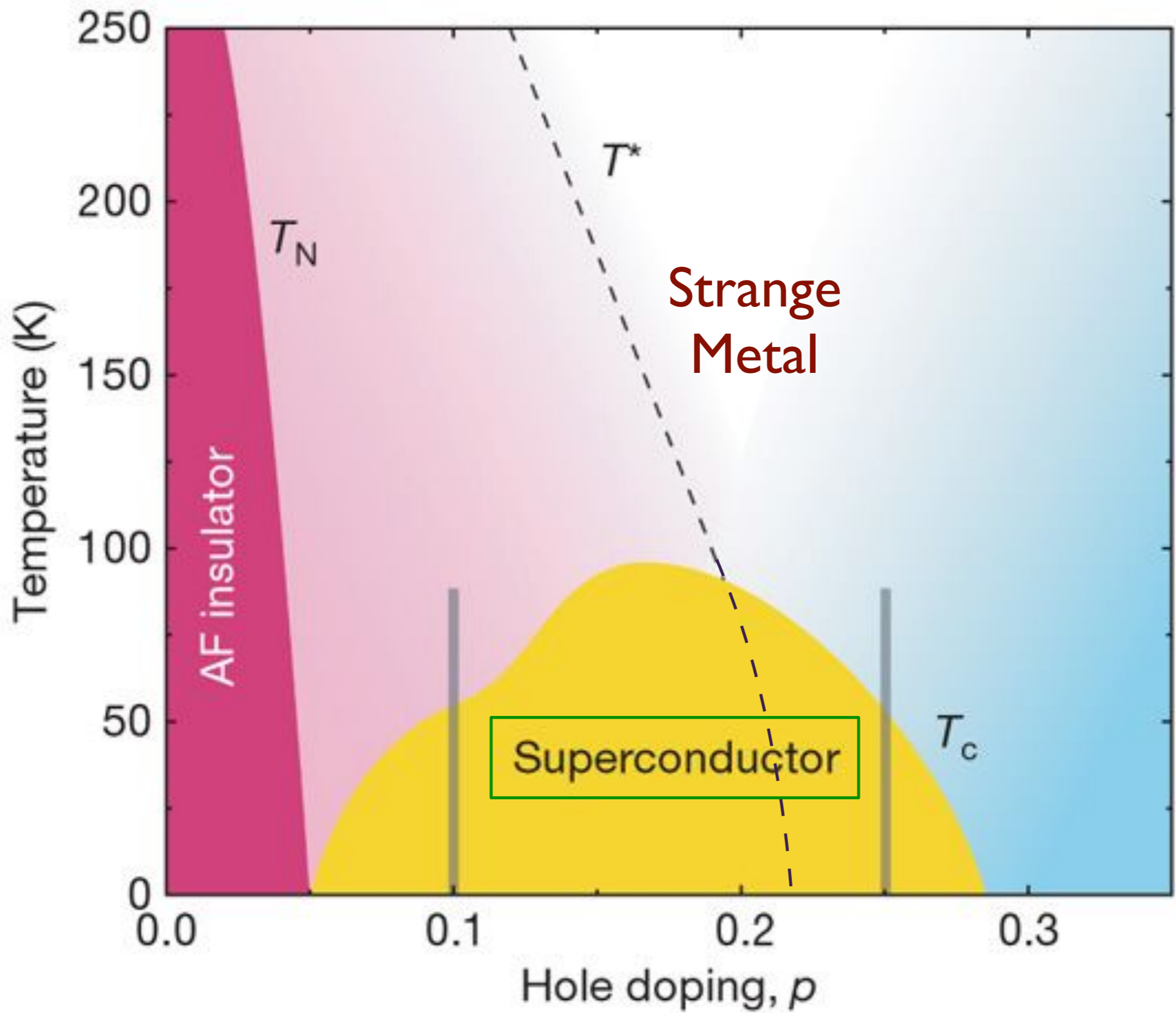


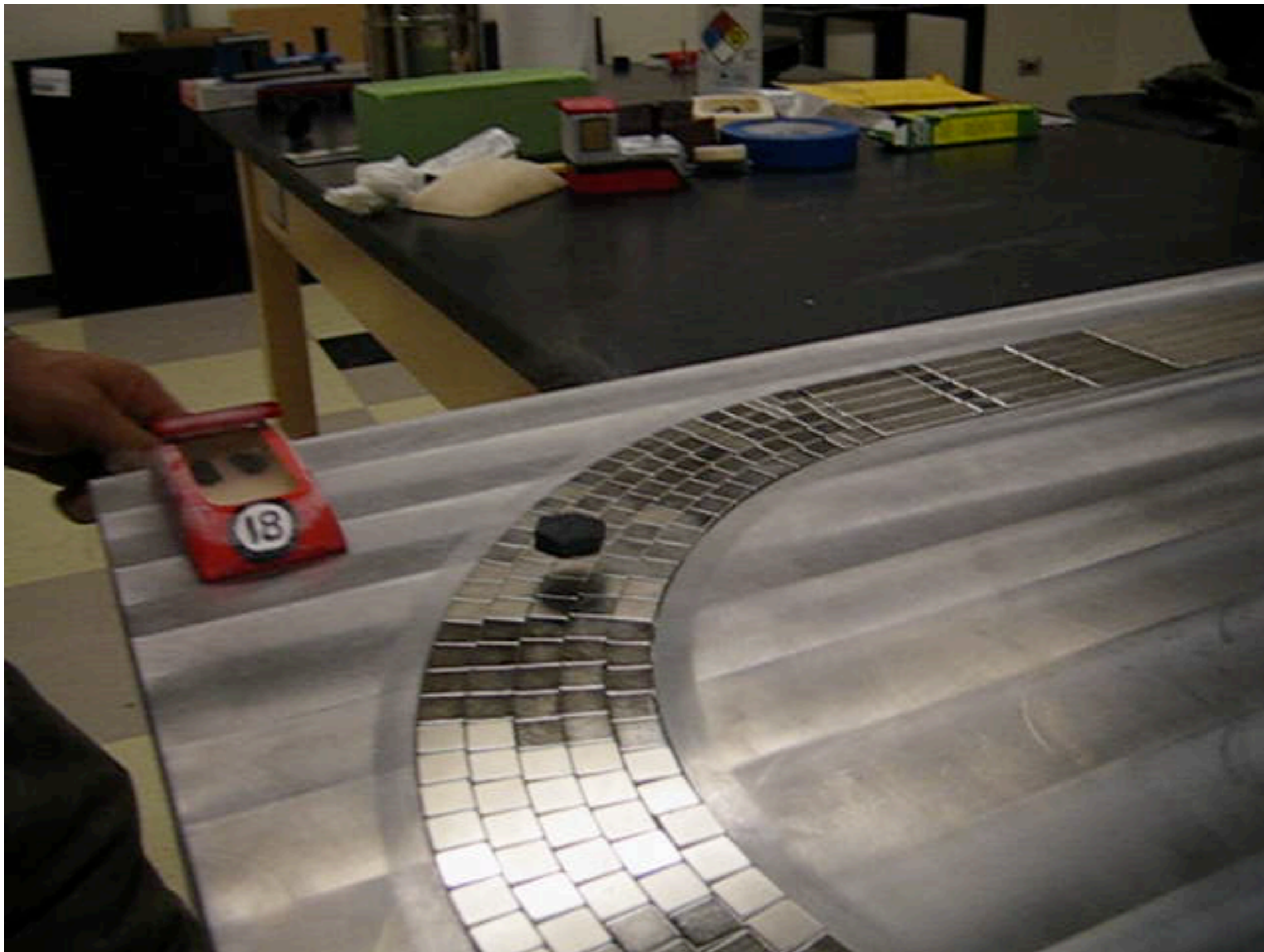
Square lattice of Cu sites



Remove
fraction p
electrons







Nd-Fe-B magnets, YBaCuO superconductor

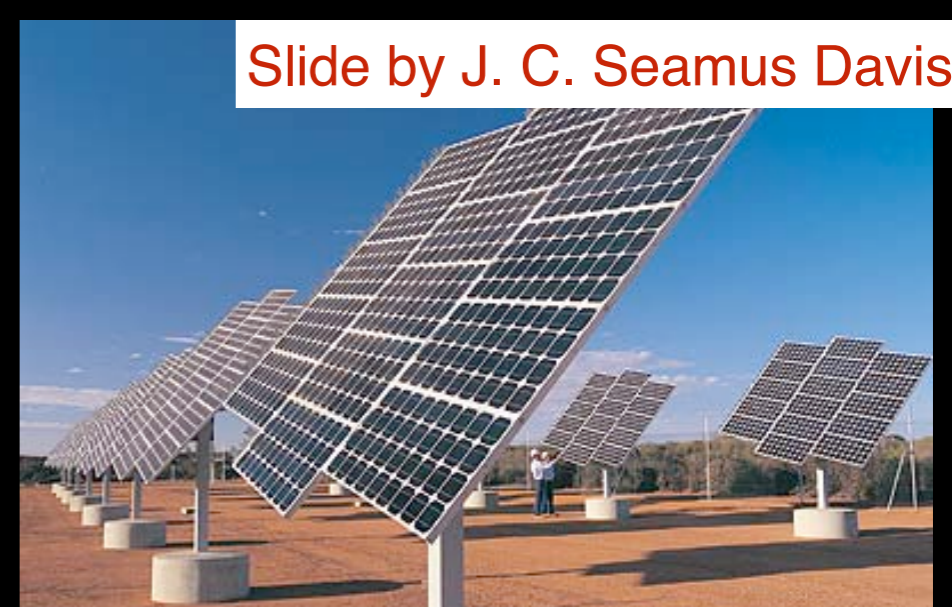
Julian Hetel and Nandini Trivedi, Ohio State University



Power Efficiency/Capacity/Stability



Power Bottlenecks



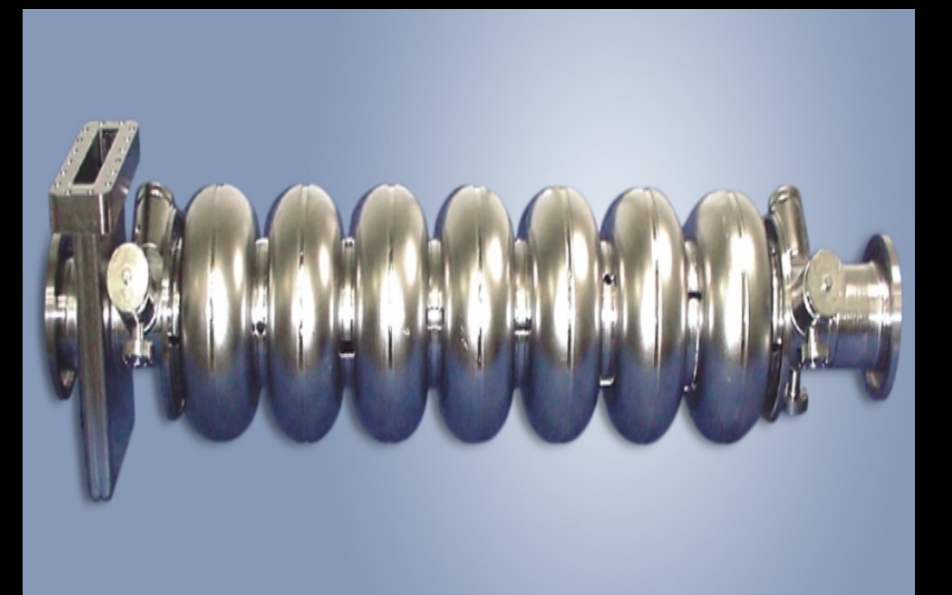
Accommodate Renewable Power



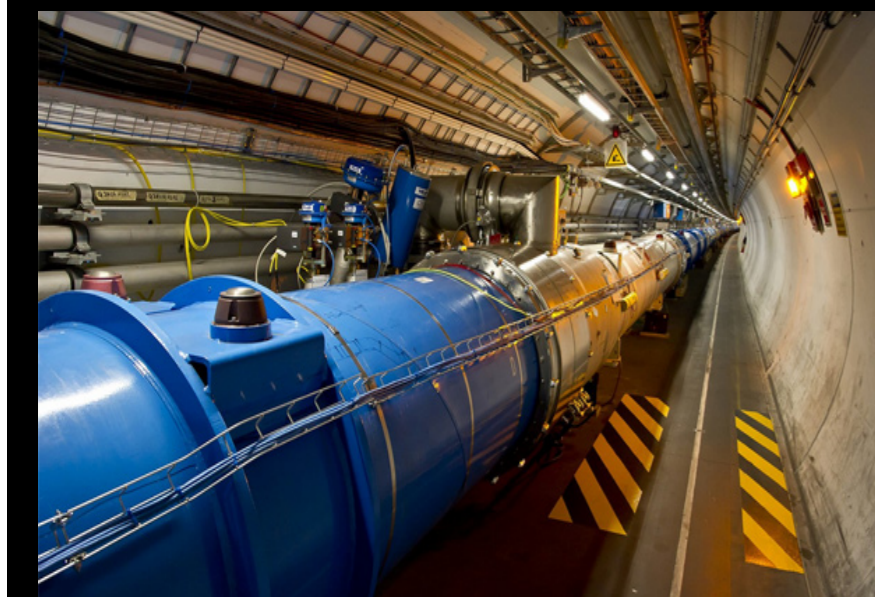
Efficient Rotating Machines



Information Technology



Next Generation HEP



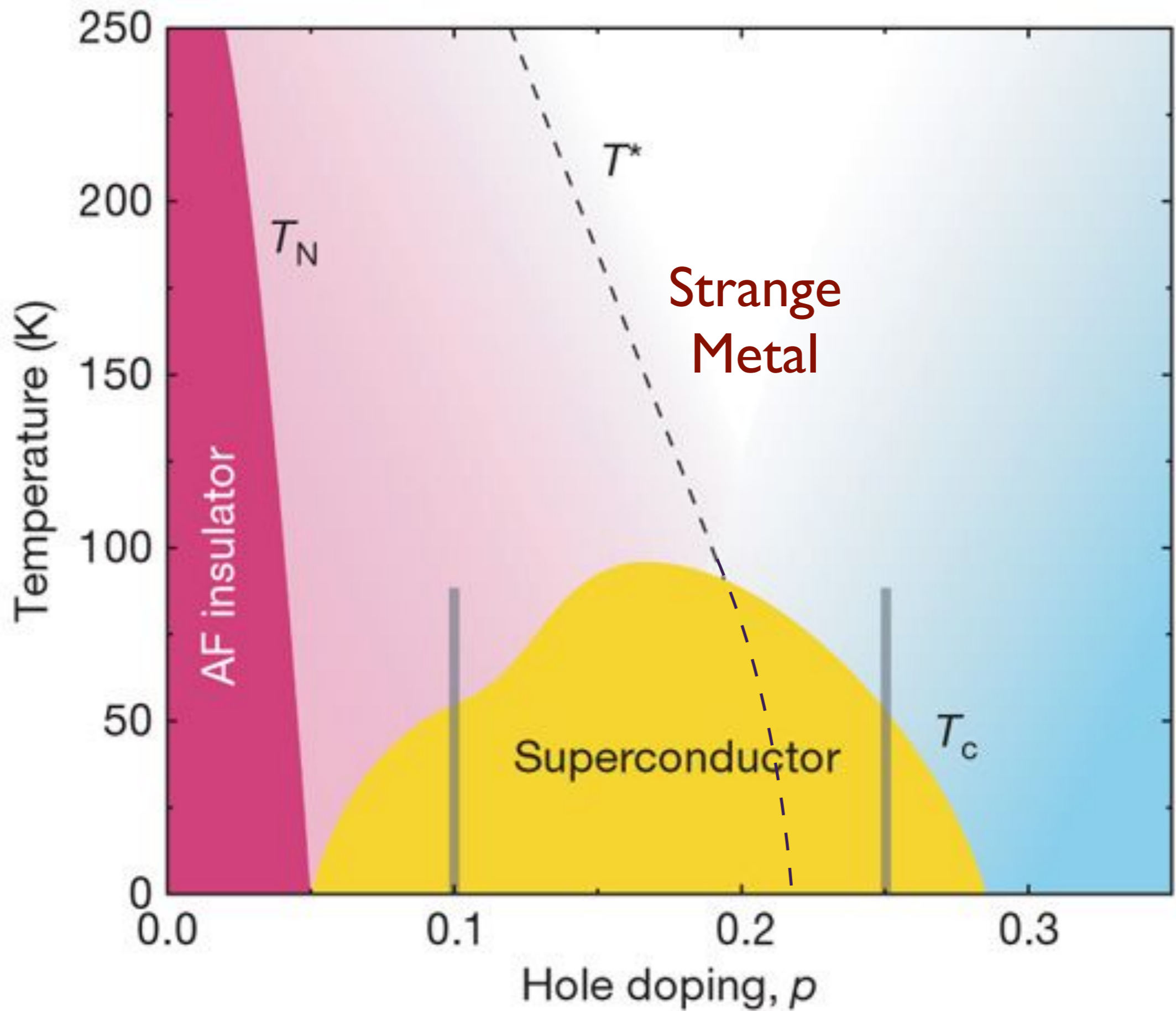
Ultra-High Magnetic Fields

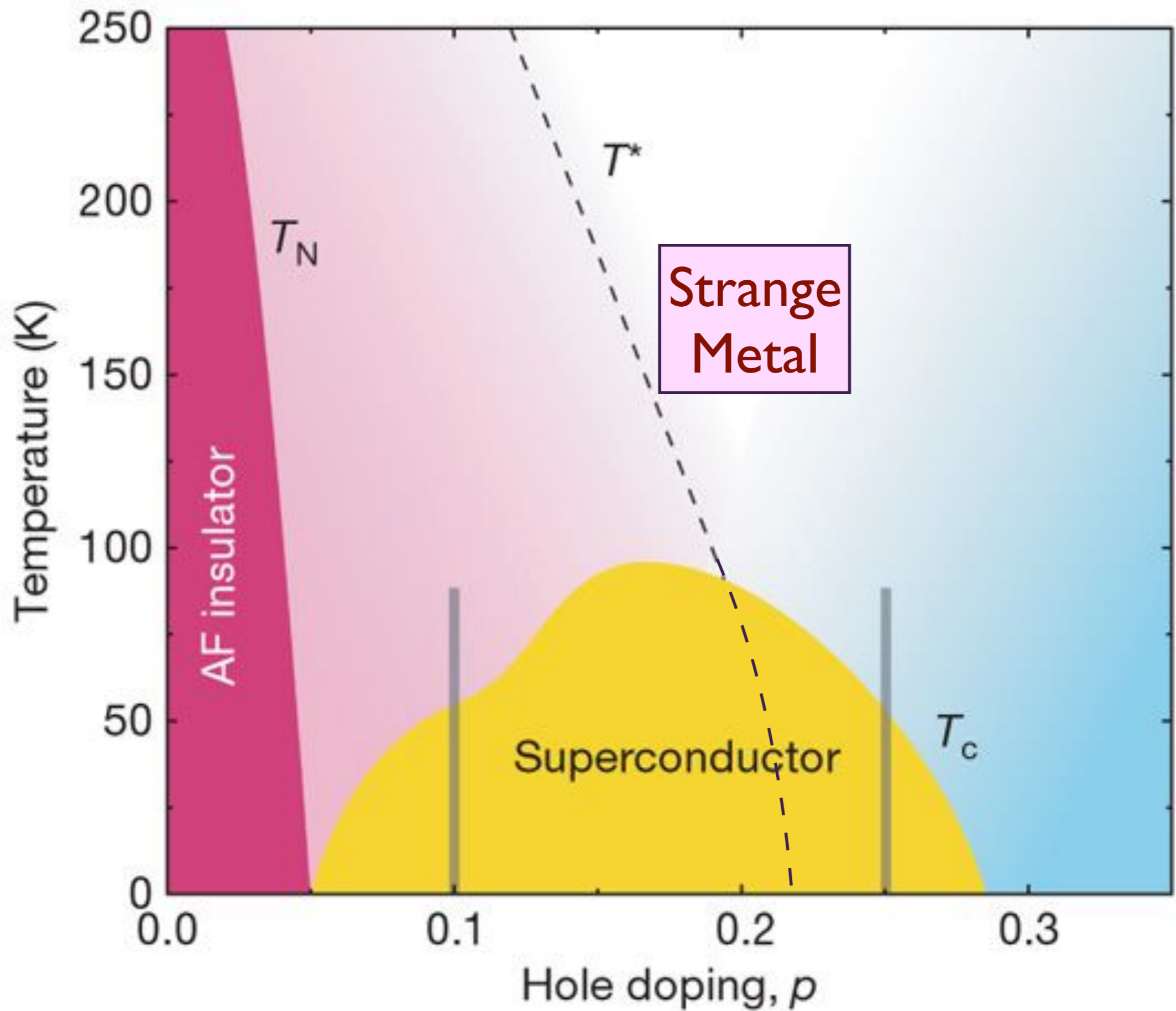


Medical



Transport





Remarkable recent observation of
'Planckian' strange metal transport in cuprates,
pnictides, magic-angle graphene, and
ultracold atoms: the resistivity, ρ , is

$$\rho = \frac{m^*}{ne^2} \frac{1}{\tau}$$

with a universal scattering rate

$$\frac{1}{\tau} \approx \frac{k_B T}{\hbar},$$

independent of the strength of interactions!



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Current flow without quasiparticles

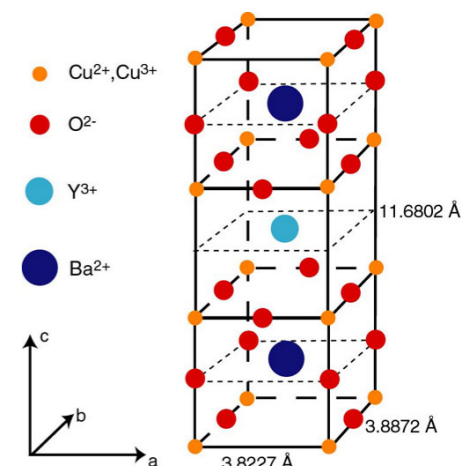


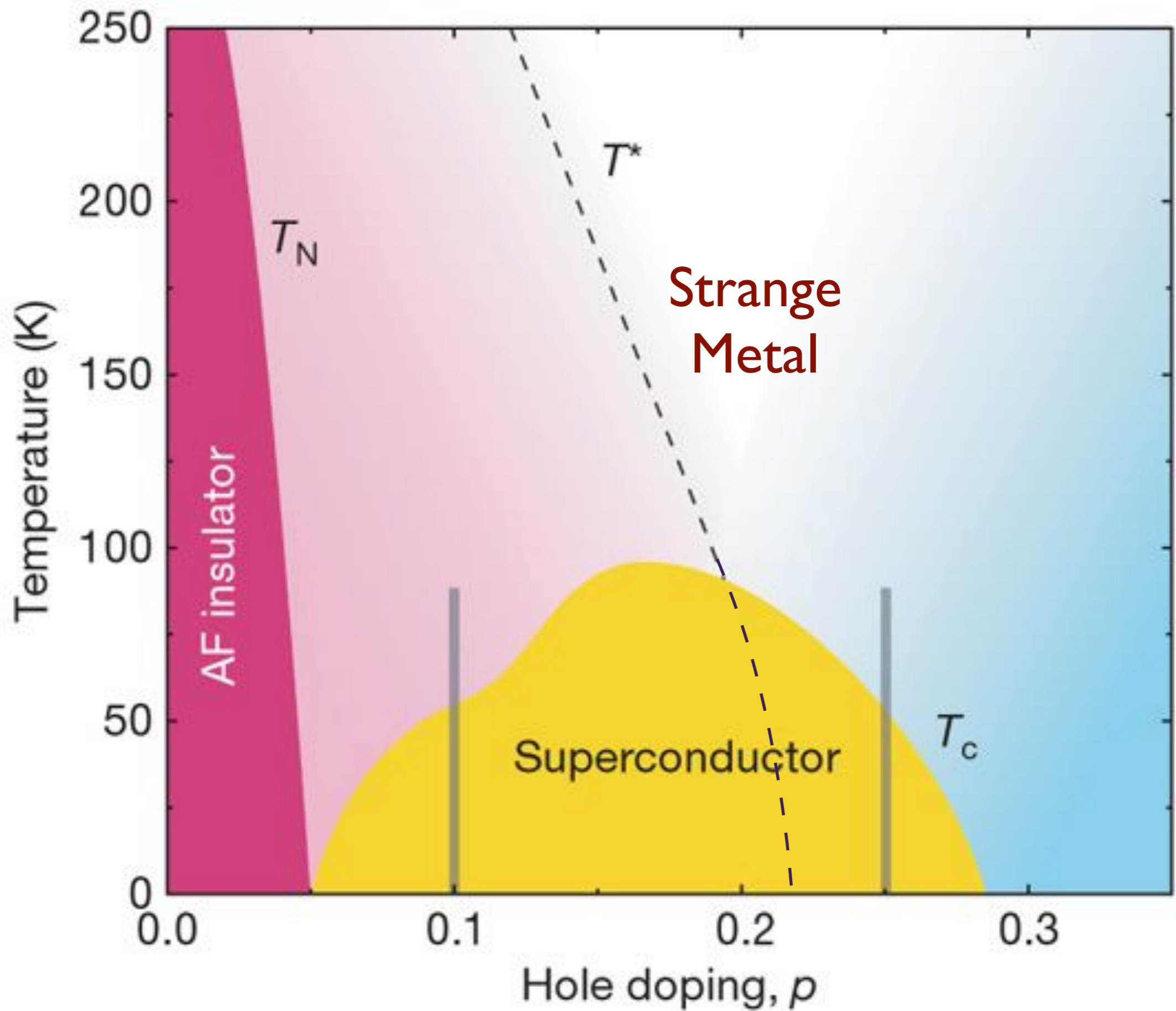
Material		n (10^{27} m^{-3})	m^* (m_0)	A_1 / d (Ω / K)	$h / (2e^2 T_F)$ (Ω / K)	α
Bi2212	$p = 0.23$	6.8	8.4 ± 1.6	8.0 ± 0.9	7.4 ± 1.4	1.1 ± 0.3
Bi2201	$p \sim 0.4$	3.5	7 ± 1.5	8 ± 2	8 ± 2	1.0 ± 0.4
LSCO	$p = 0.26$	7.8	9.8 ± 1.7	8.2 ± 1.0	8.9 ± 1.8	0.9 ± 0.3
Nd-LSCO	$p = 0.24$	7.9	12 ± 4	7.4 ± 0.8	10.6 ± 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	$P = 11 \text{ kbar}$	1.4	1.15 ± 0.2	2.8 ± 0.3	2.8 ± 0.4	1.0 ± 0.3

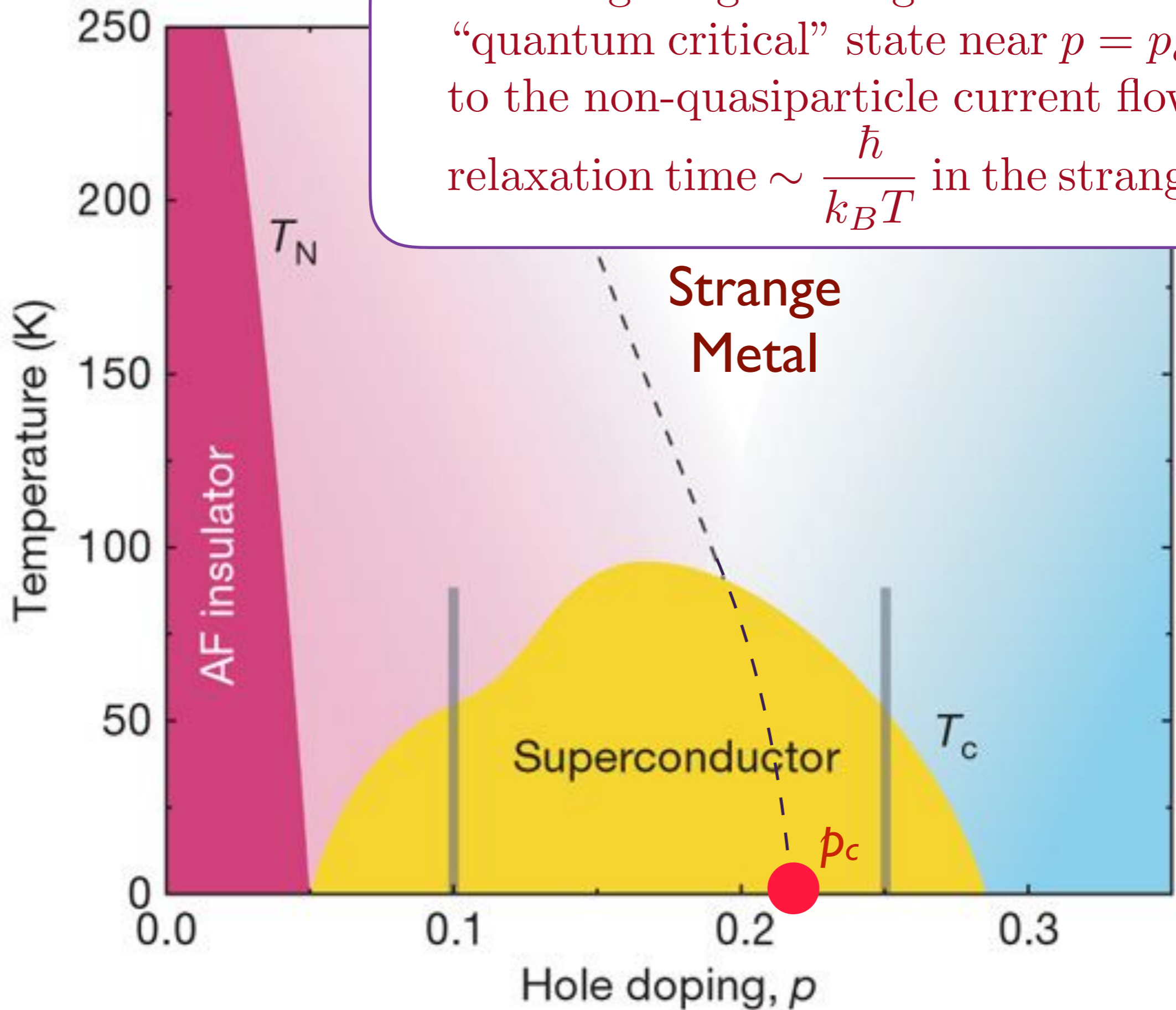
Slope of T -linear resistivity vs Planckian limit in seven materials.

$$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$

Current flow without quasiparticles

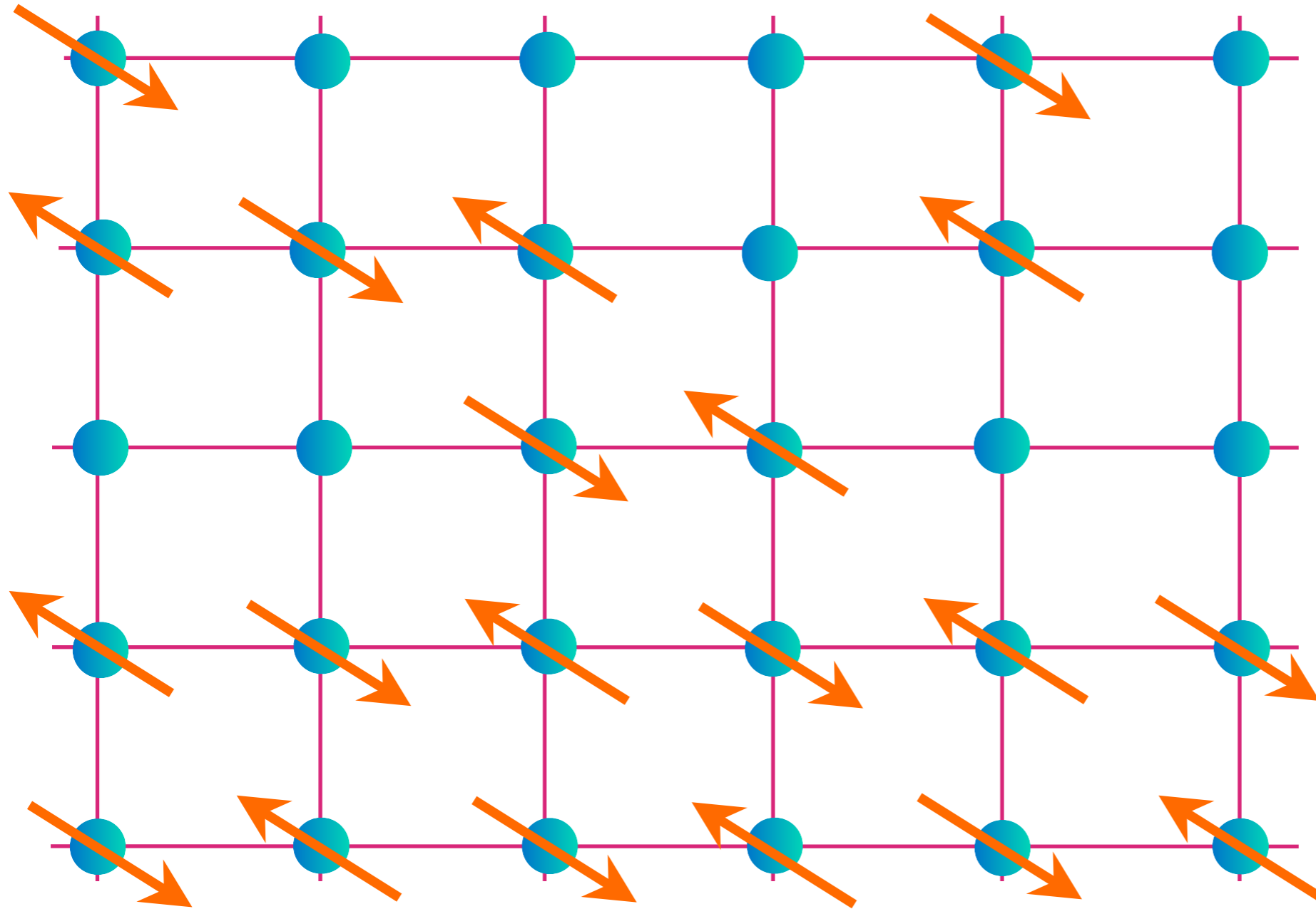






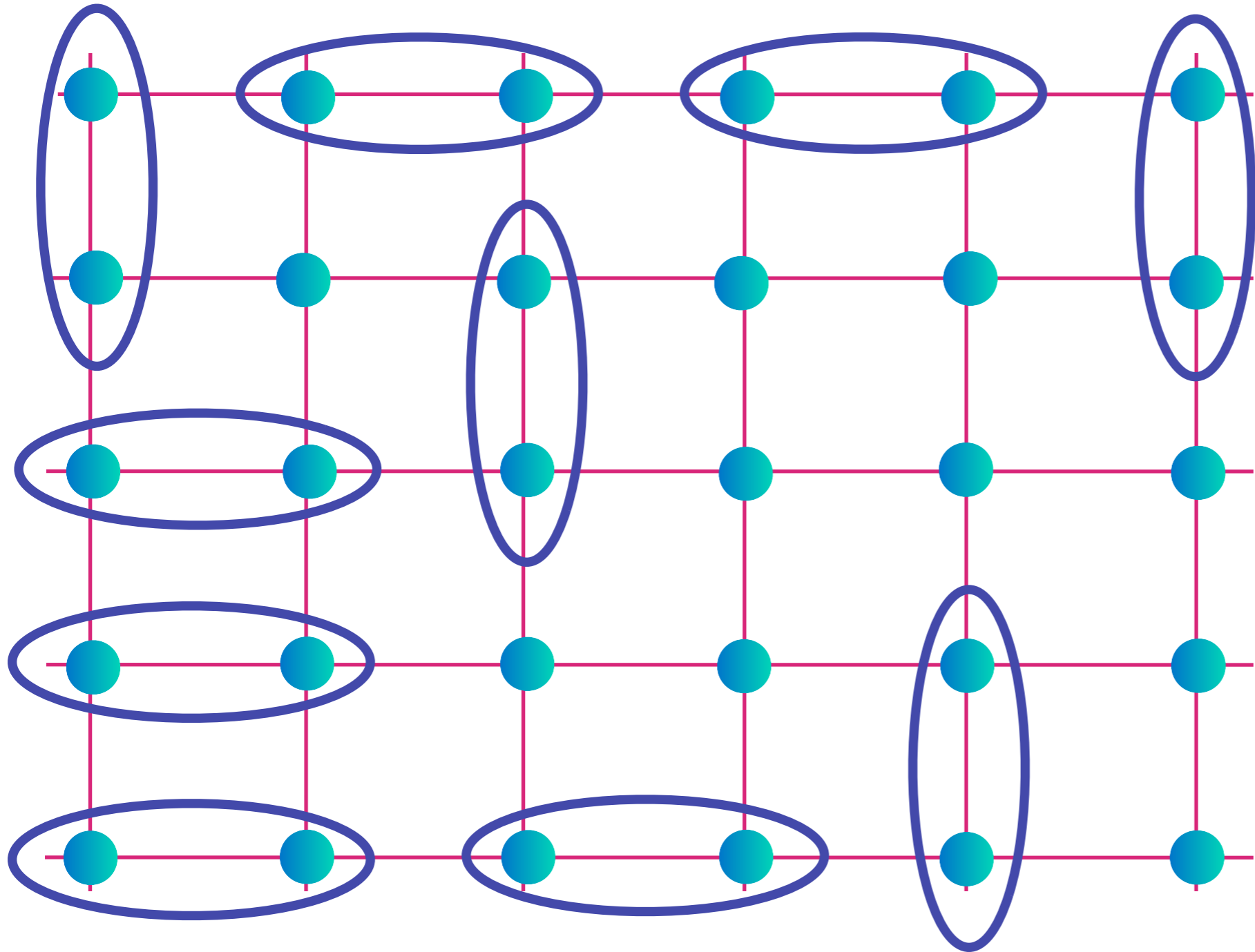
- The long-range entanglement in the “quantum critical” state near $p = p_c$ leads to the non-quasiparticle current flow with relaxation time $\sim \frac{\hbar}{k_B T}$ in the strange metal

Square lattice of Cu sites



Remove
fraction p
electrons

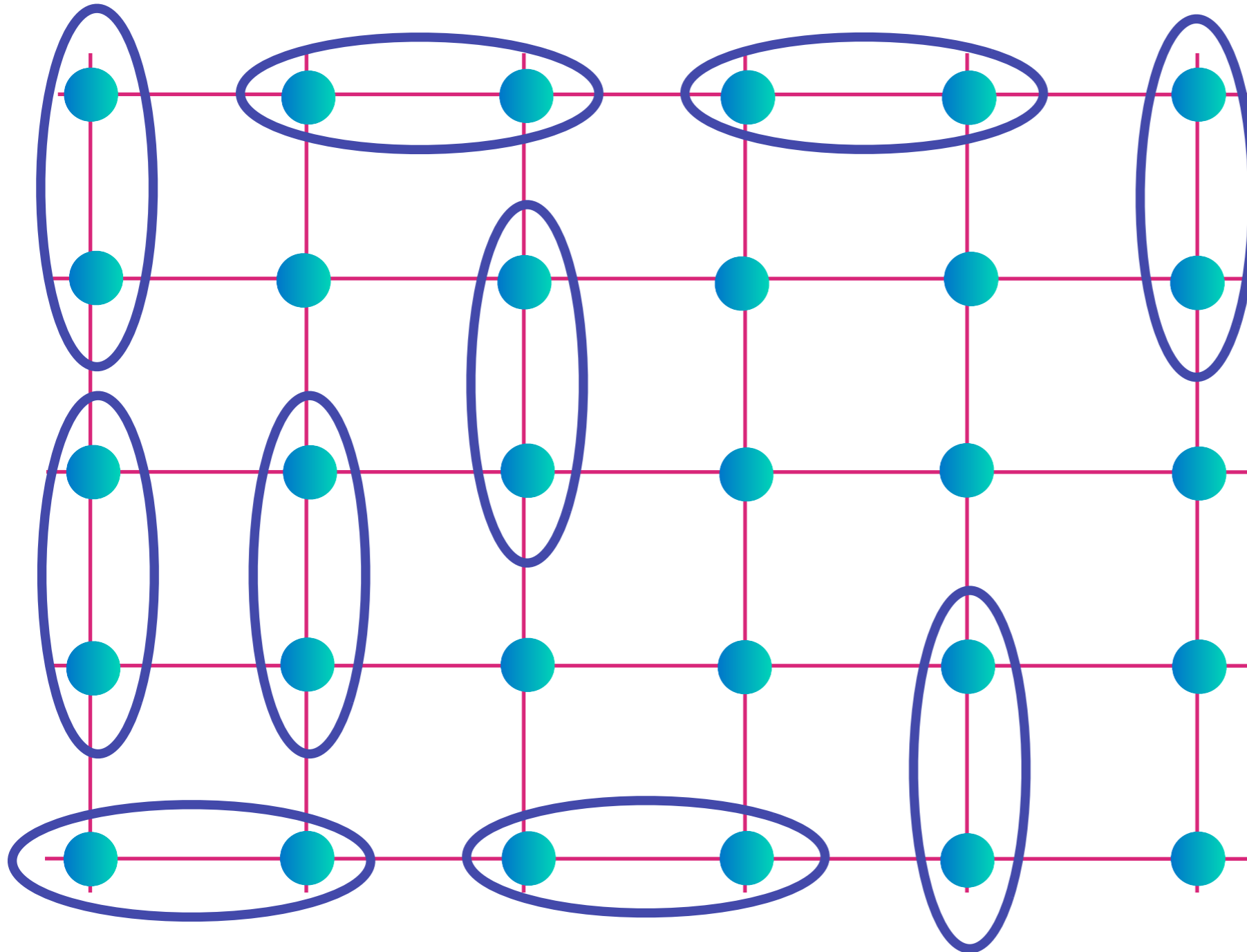
Square lattice of Cu sites at $p=p_c$



Electrons entangle in (“Cooper”) pairs into chemical bonds

$$\text{[Diagram of two sites in an oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

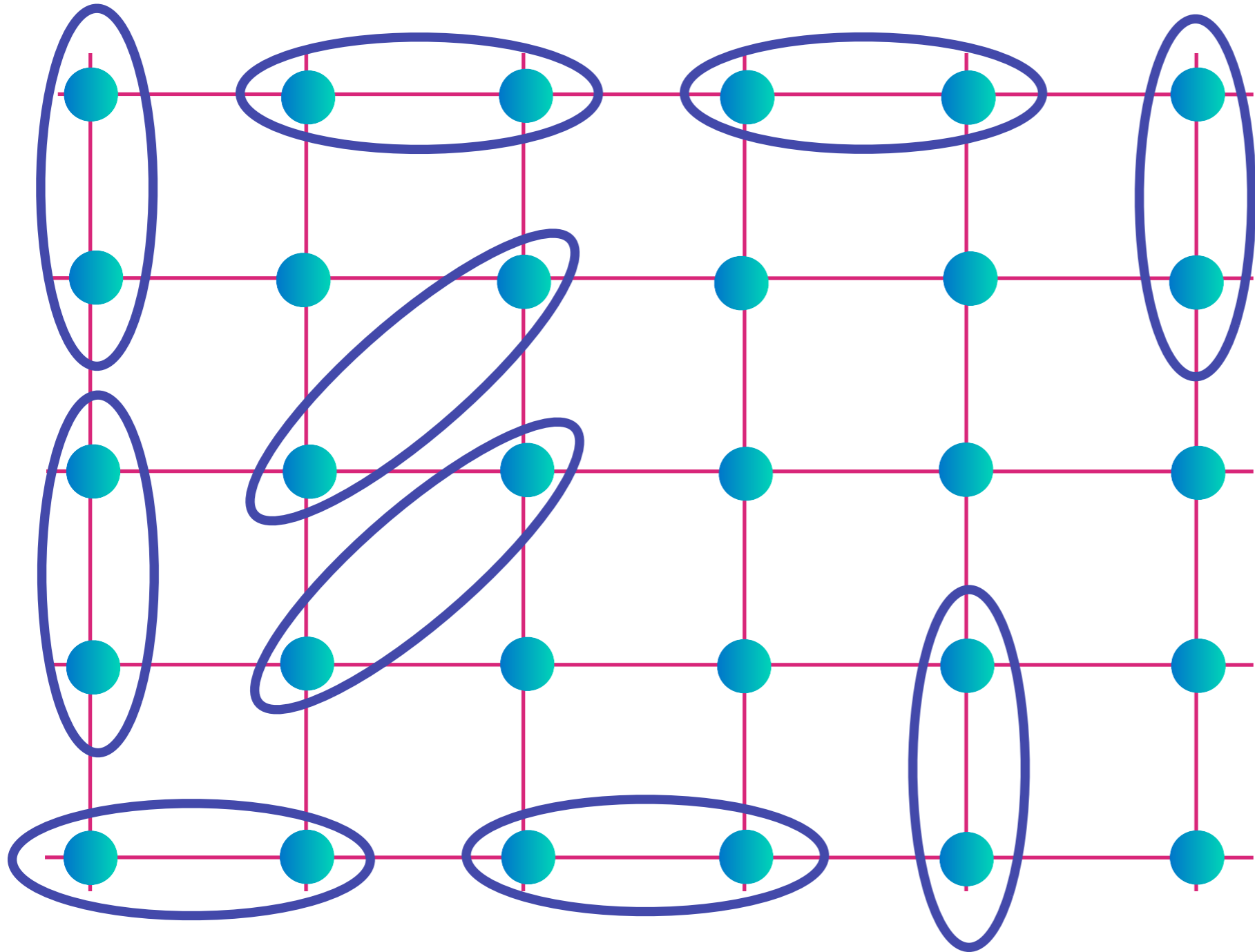
Square lattice of Cu sites at $p=p_c$



Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement

$$\text{[Diagram of two sites in a blue oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

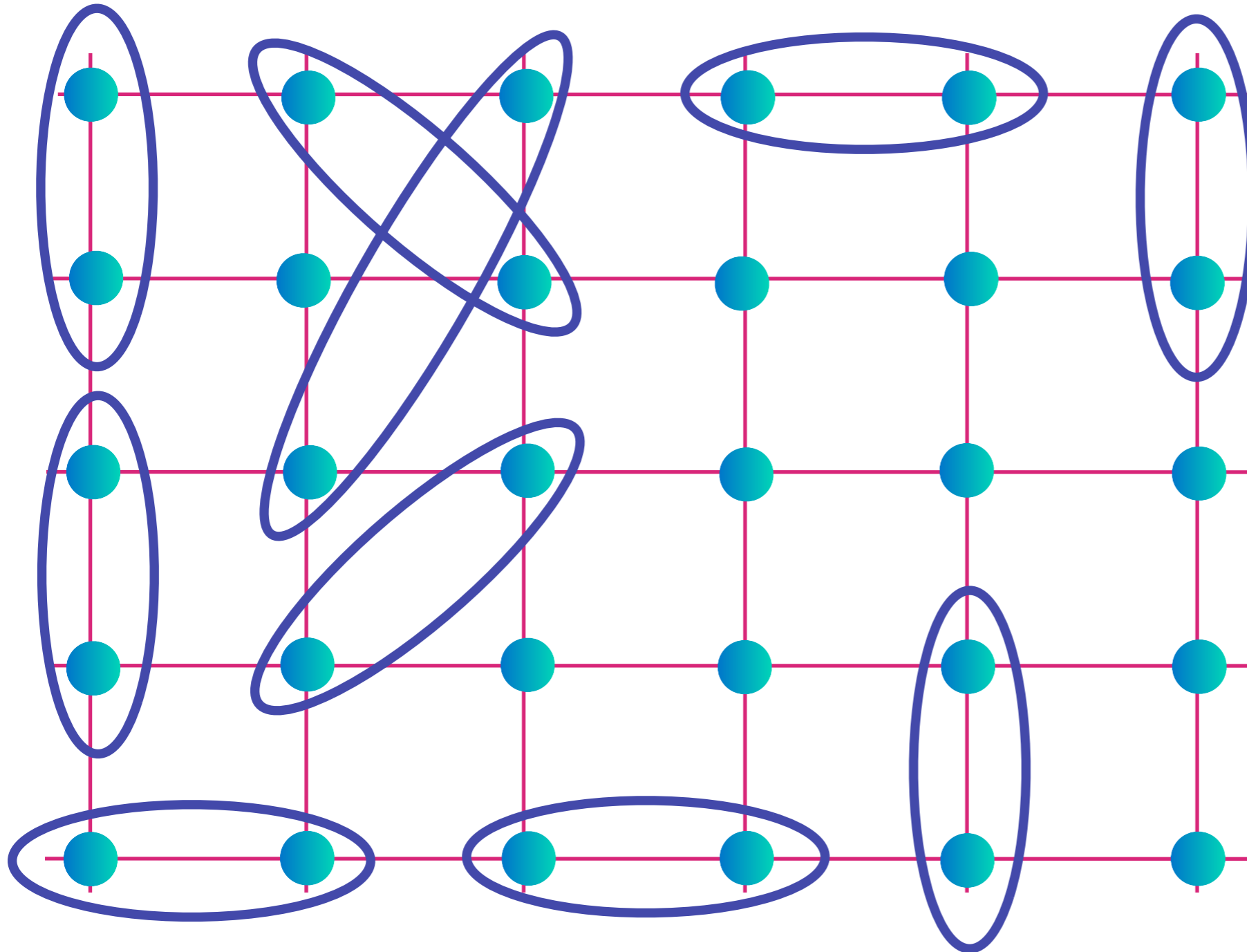
Square lattice of Cu sites at $p=p_c$



Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement

$$\text{[Diagram of two electrons in an oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

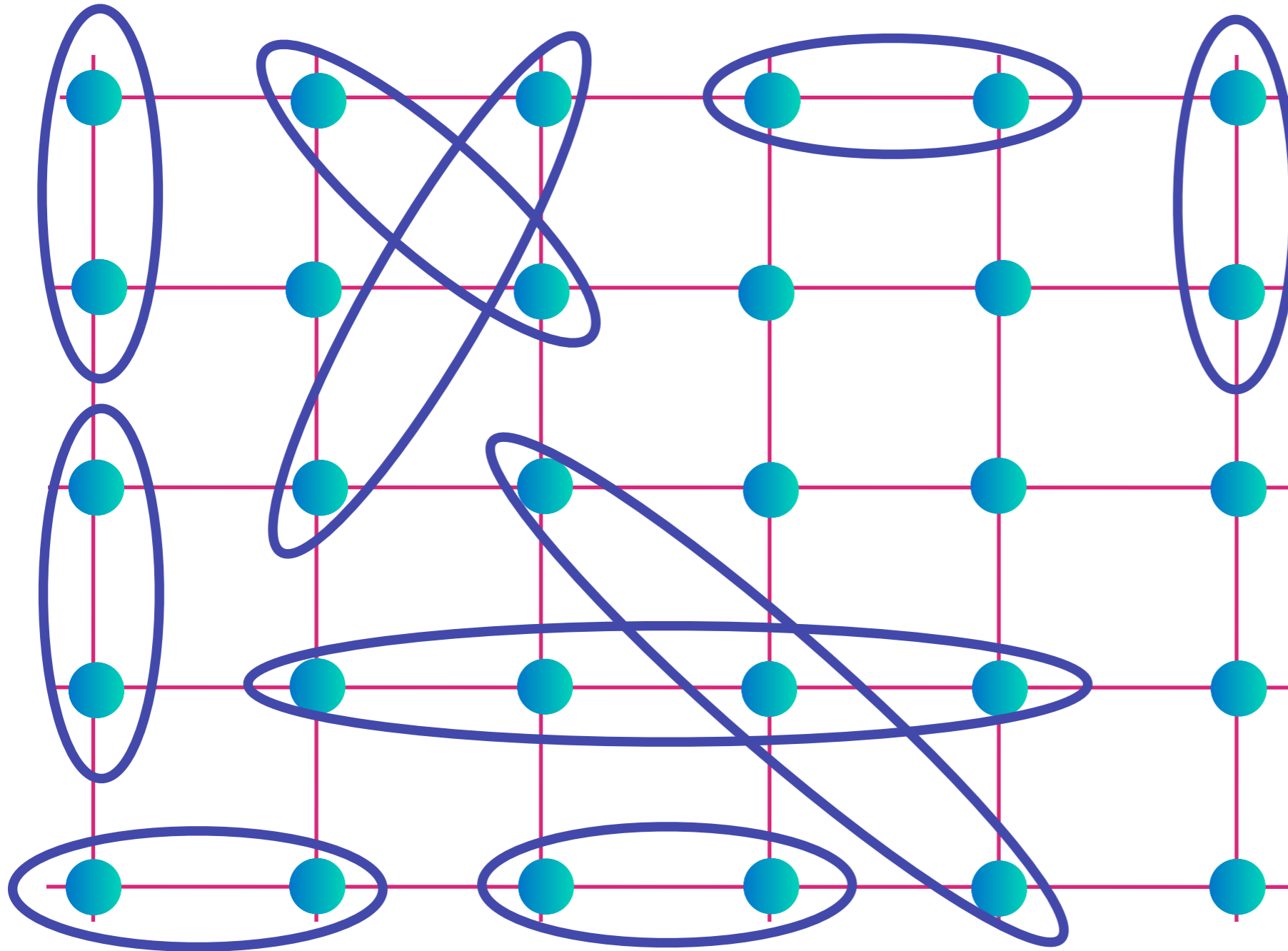
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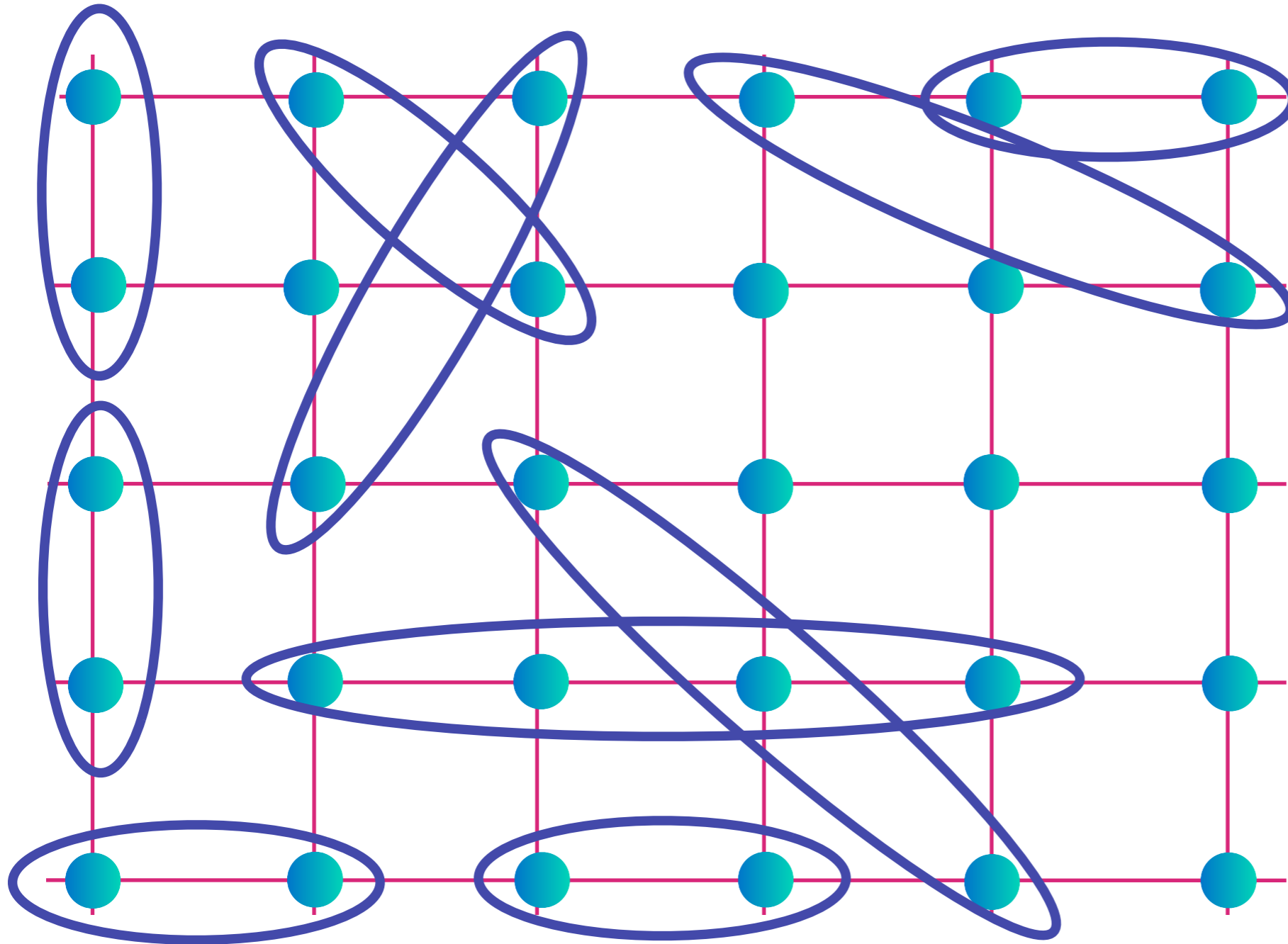
Square lattice of Cu sites at $p=p_c$



Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement

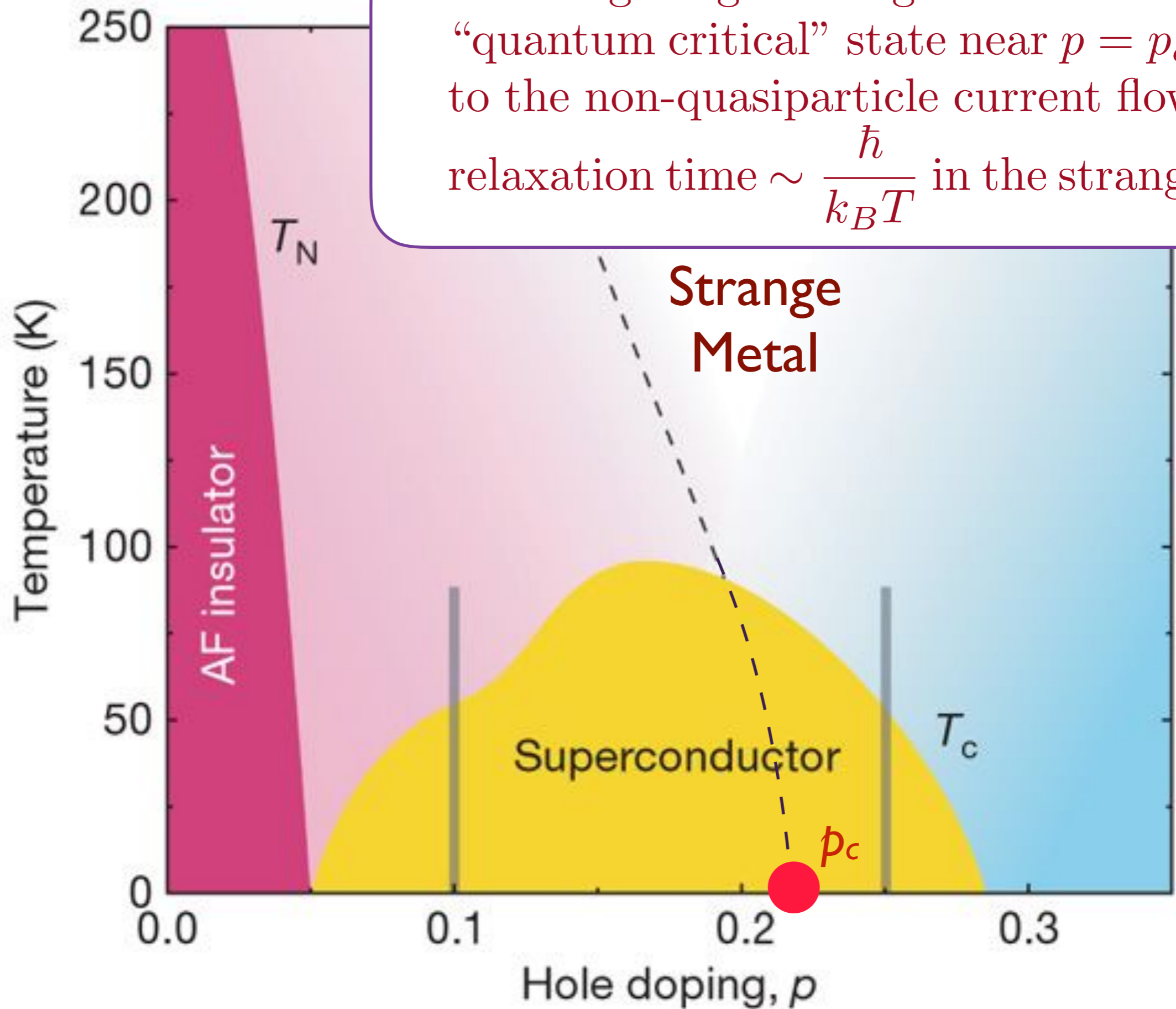
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Square lattice of Cu sites at $p=p_c$



Electrons entangle “en masse” by exchanging partners, and there is long-range quantum entanglement

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**Quantum
entanglement**

**Black
holes**

**Metals
(ordinary and strange)
and superconductors**

Quantum 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 Planckian time $\sim \hbar/(k_B T_H)$.



Quantum Black holes

- Black holes have an entropy and a temperature, T_H
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Holography:

Quantum black holes “look like” quantum-critical many-particle systems without quasiparticle excitations, residing “on” the surface of the black hole

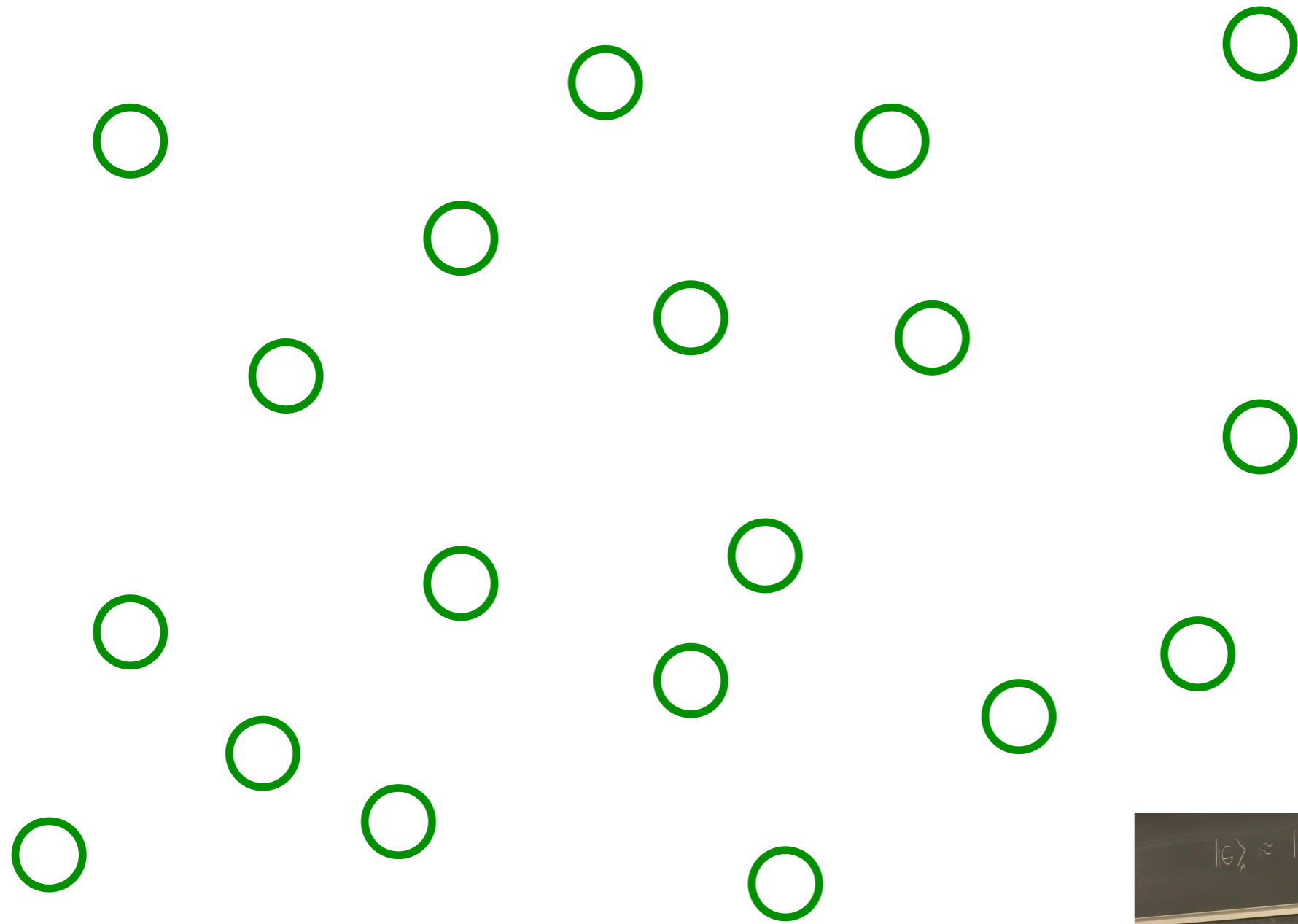
Quantum
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Black
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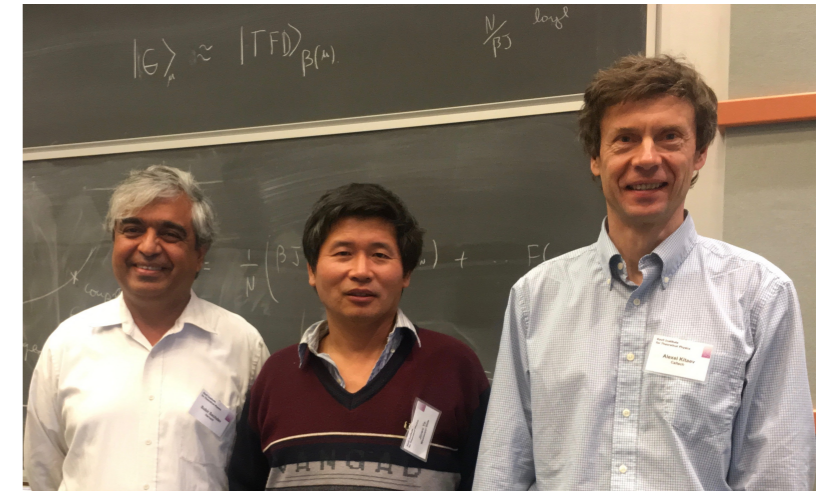
Metals
(ordinary and strange)
and superconductors

A "toy model" which describes both
a strange metal and a black hole!

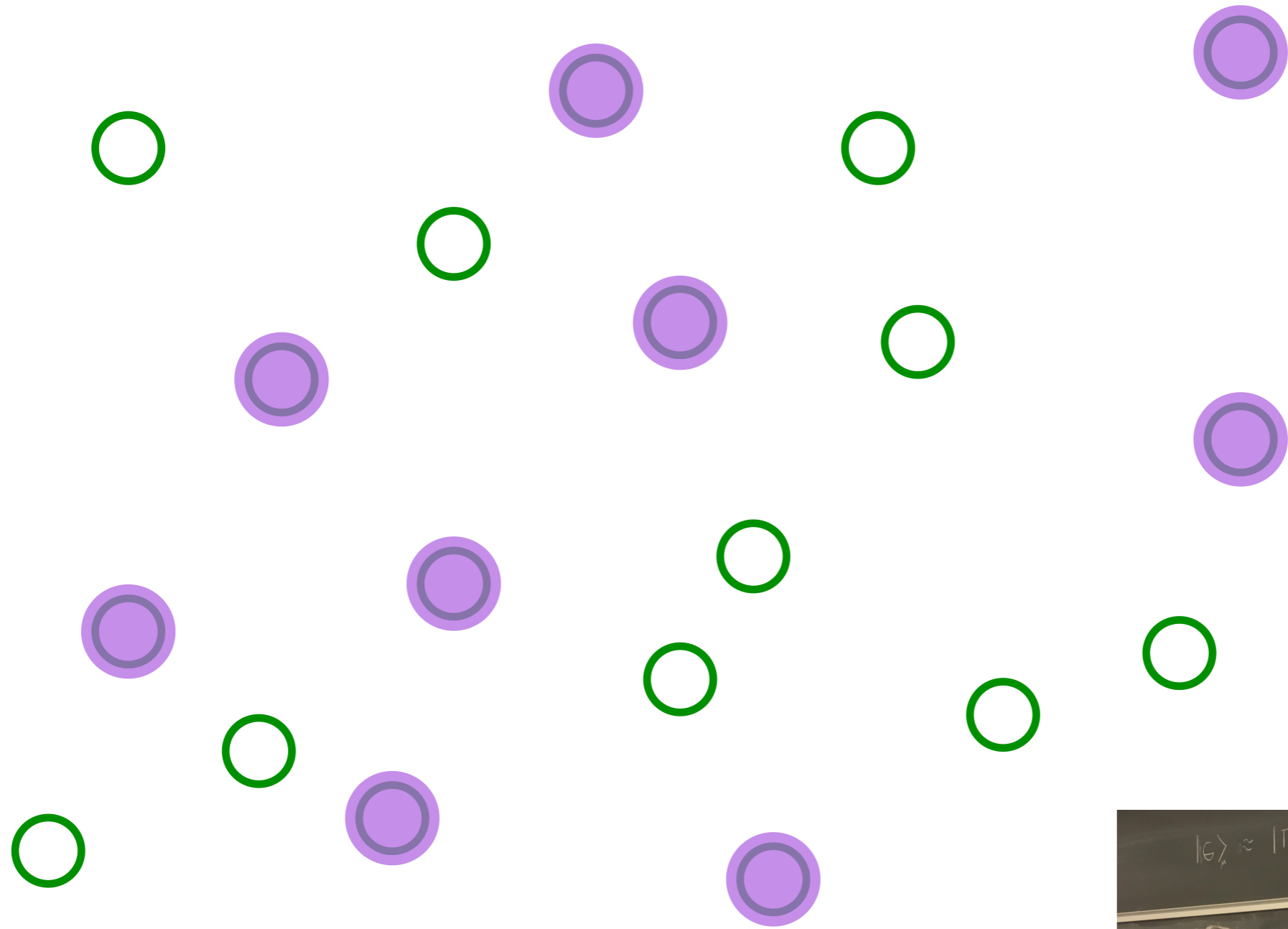
The Sachdev-Ye-Kitaev (SYK) model



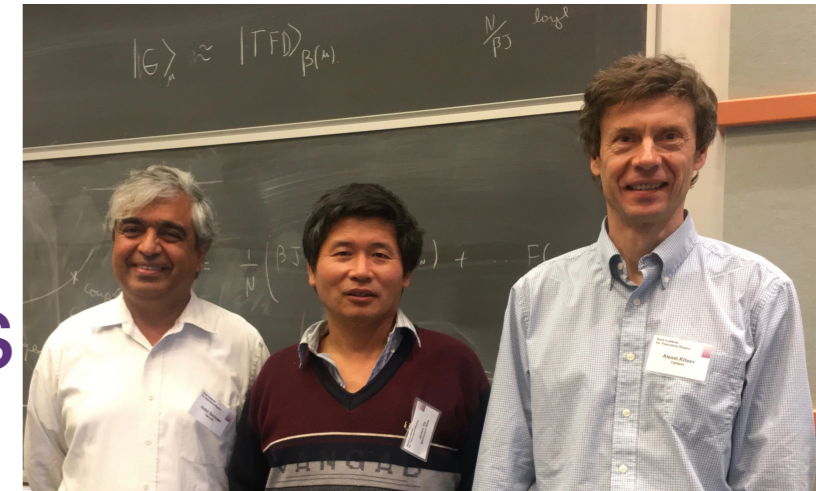
Pick a set of random positions



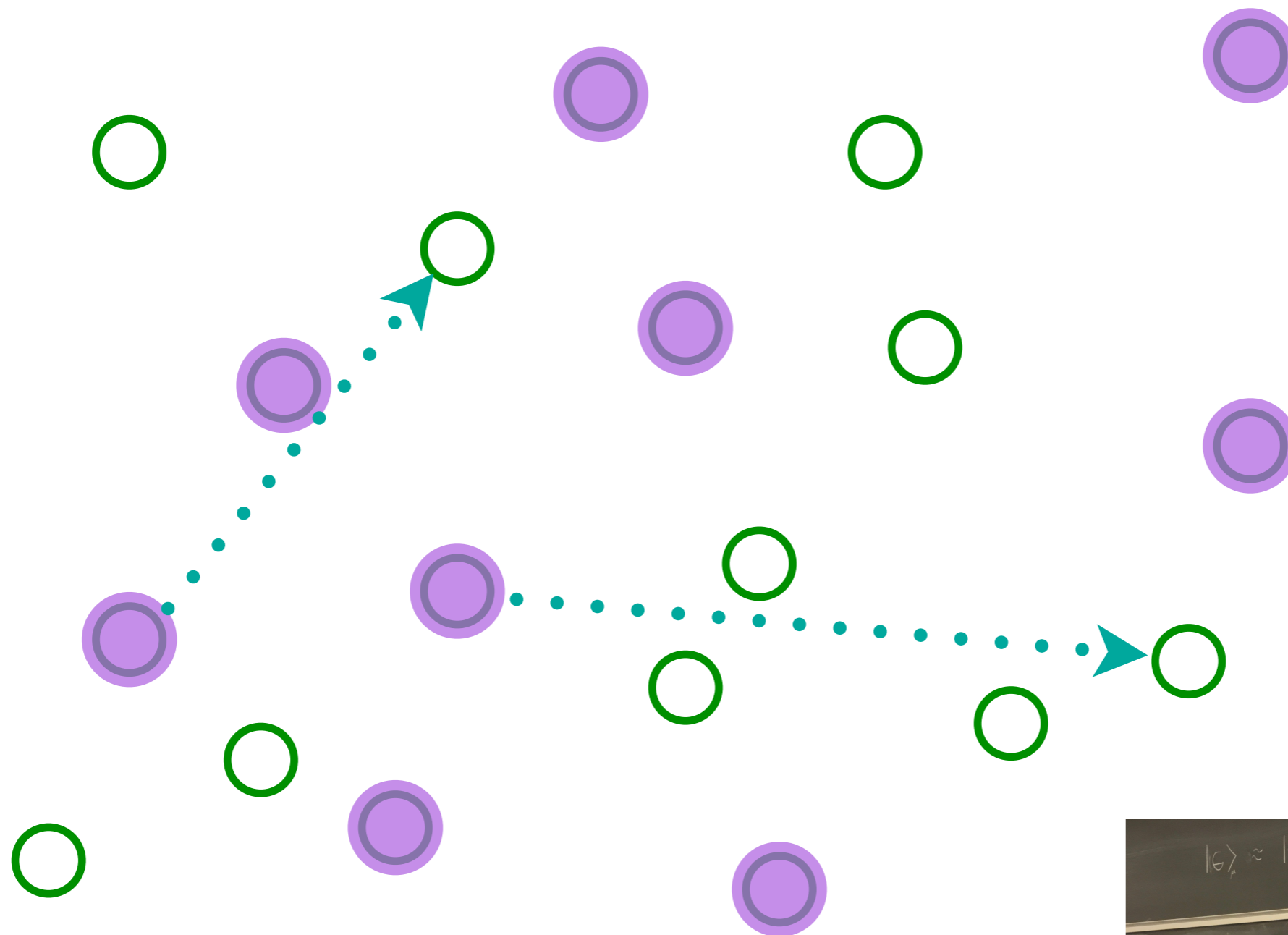
The SYK model



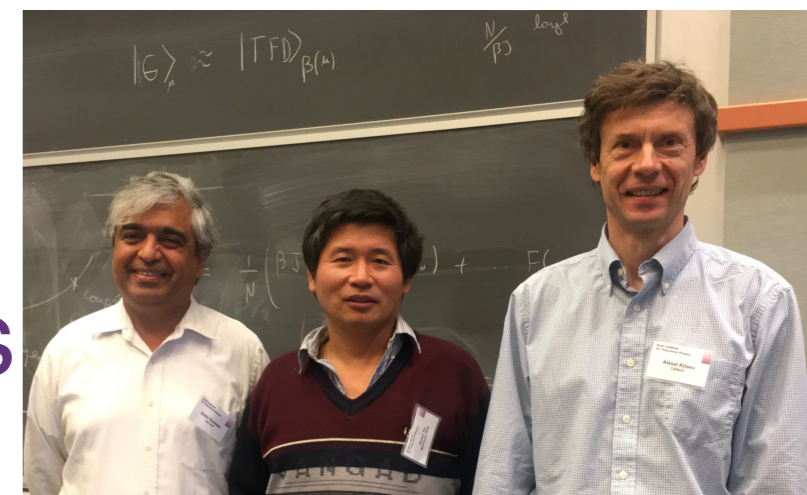
Place electrons randomly on some sites



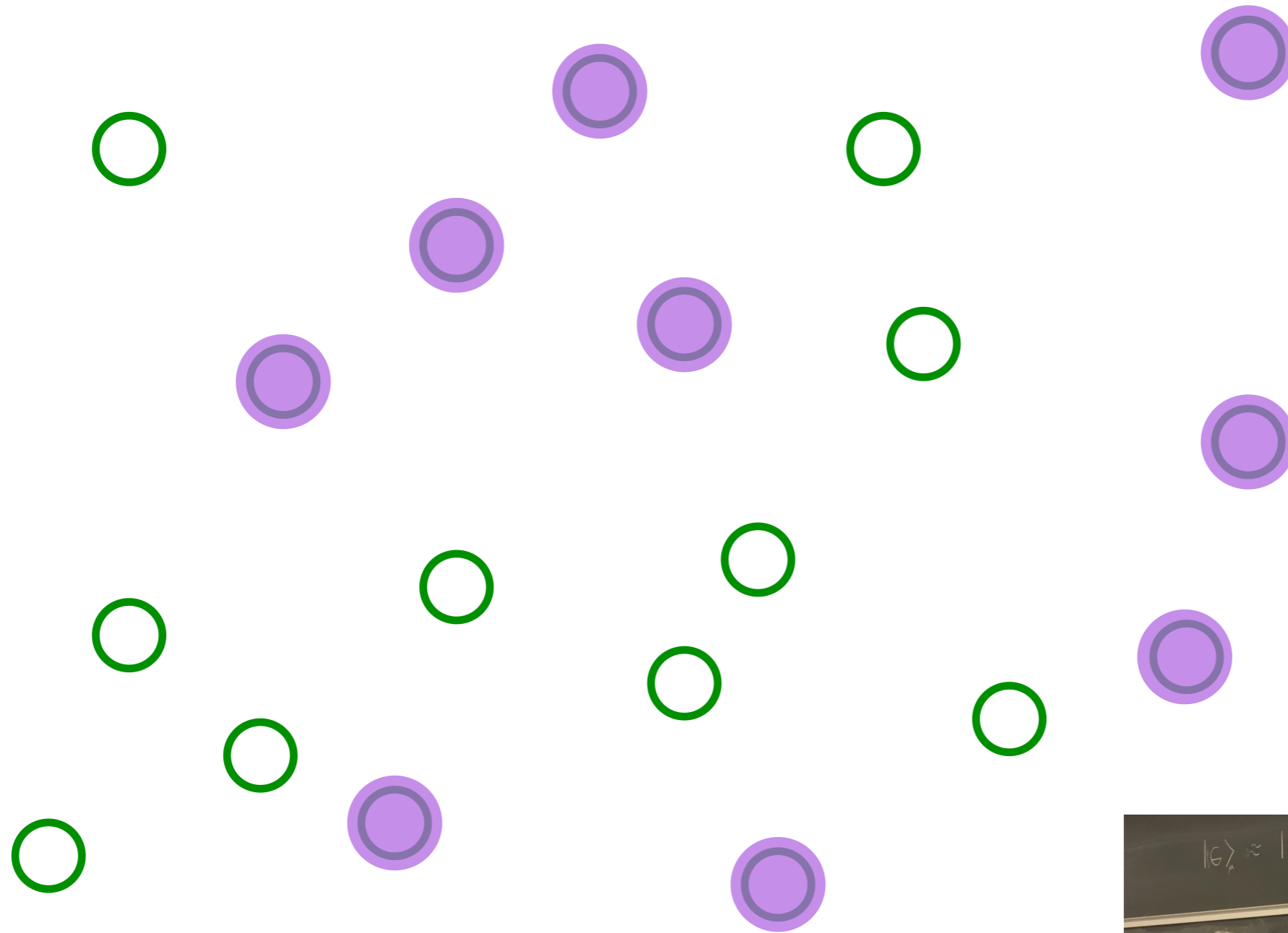
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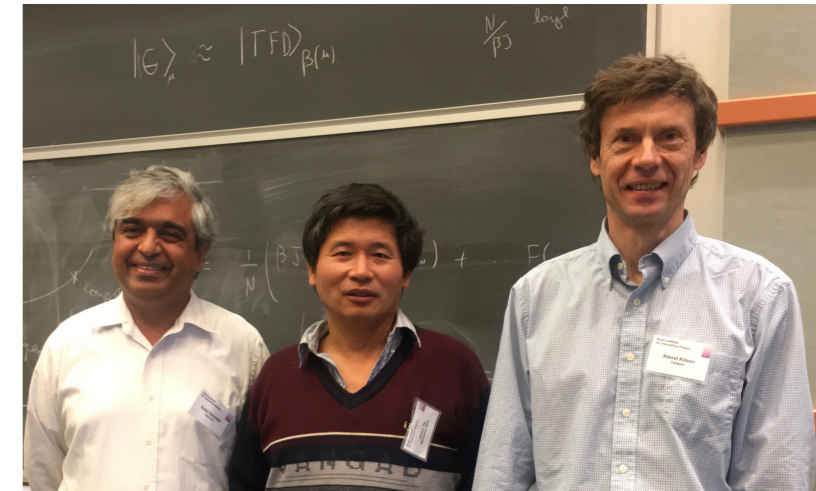
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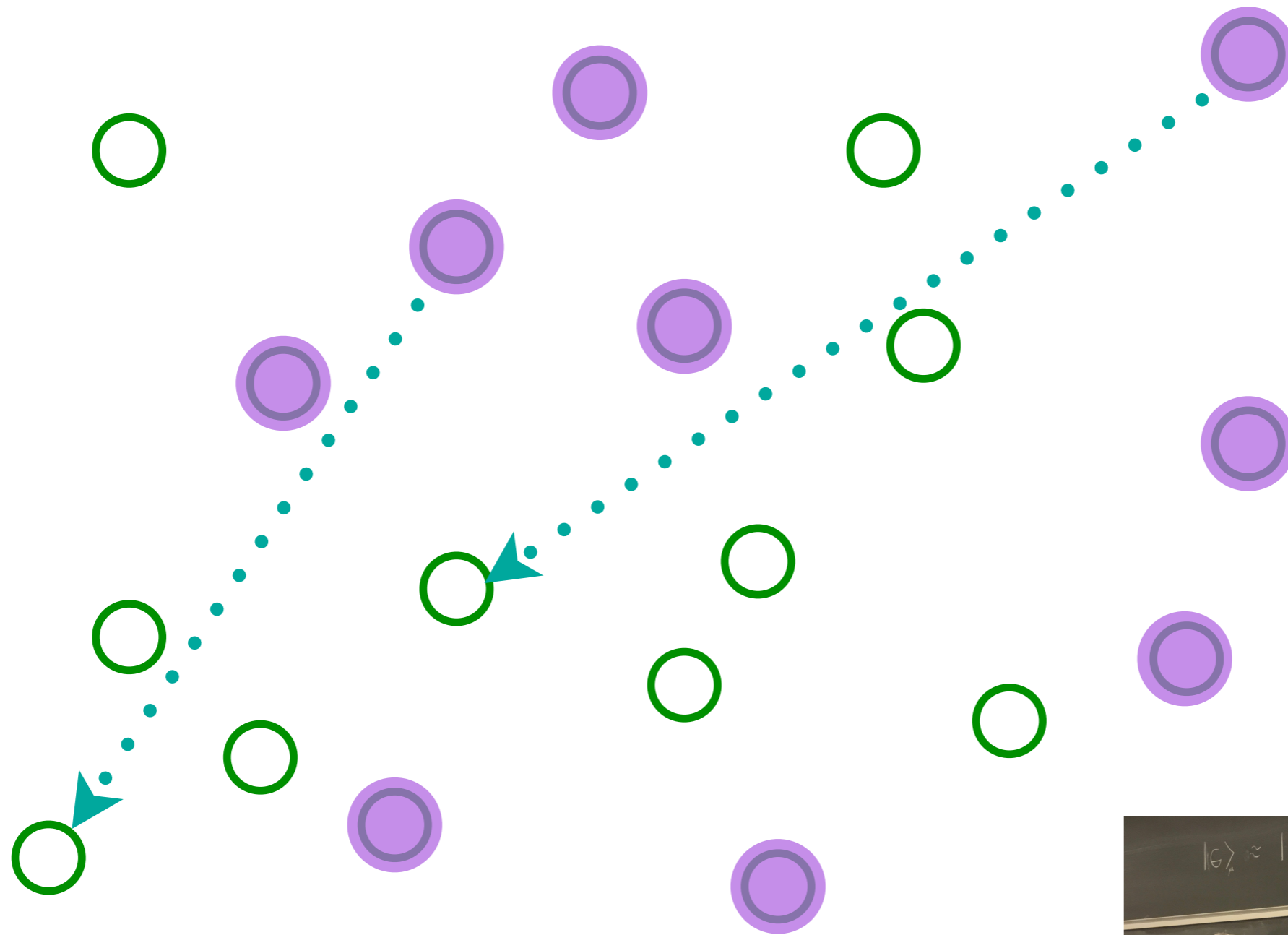
The SYK model



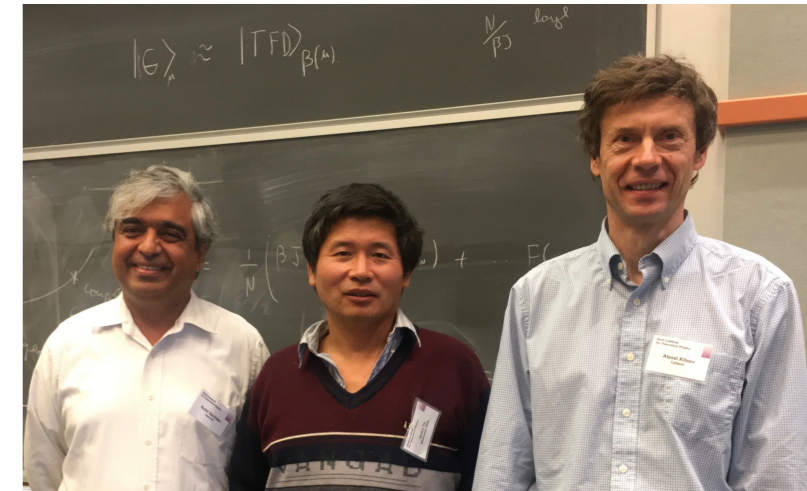
Entangle electrons pairwise randomly



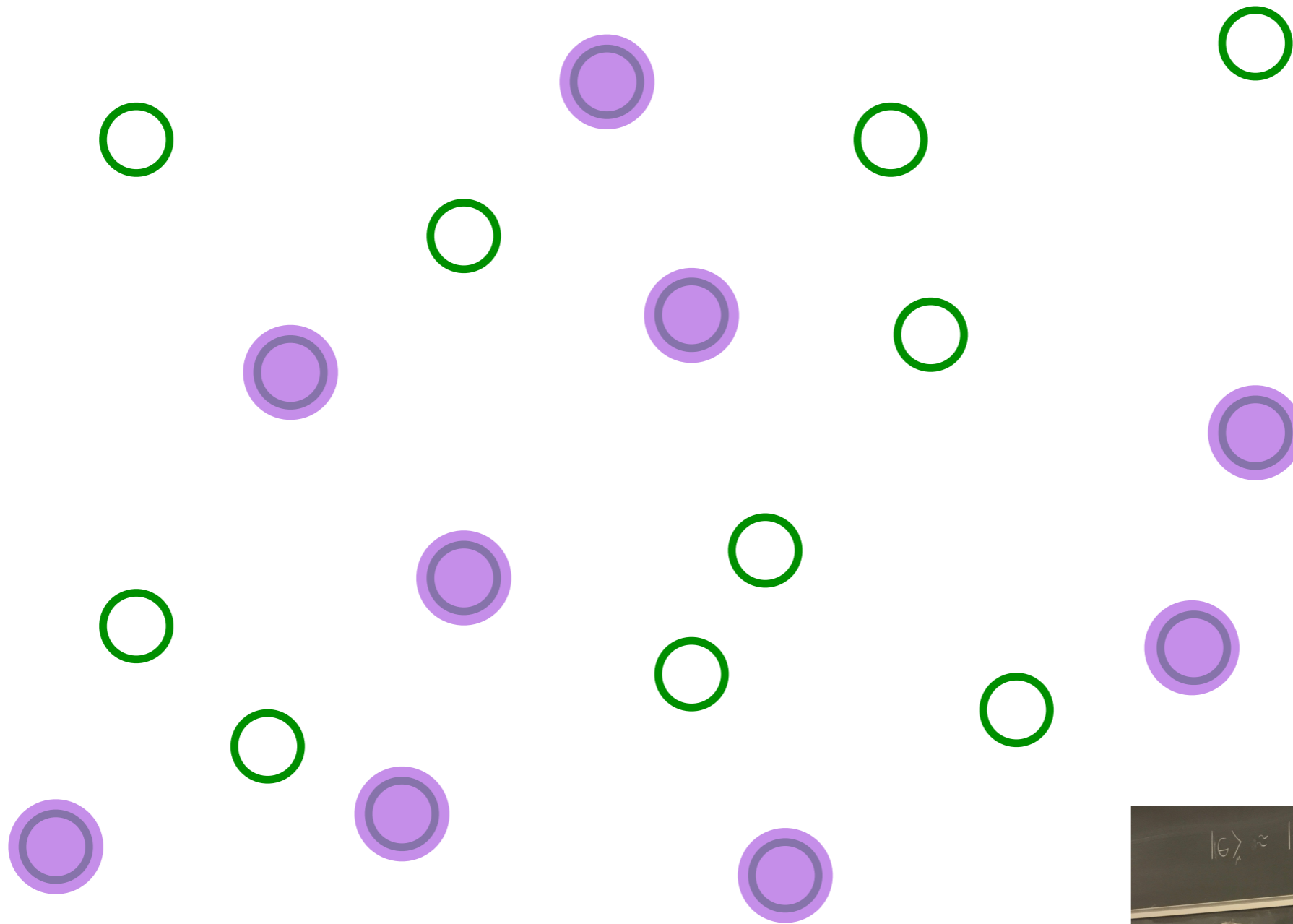
The SYK model



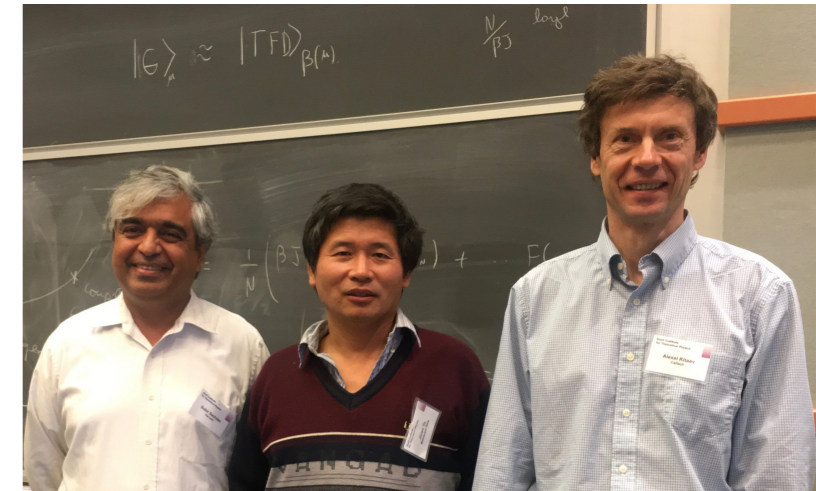
Entangle electrons pairwise randomly



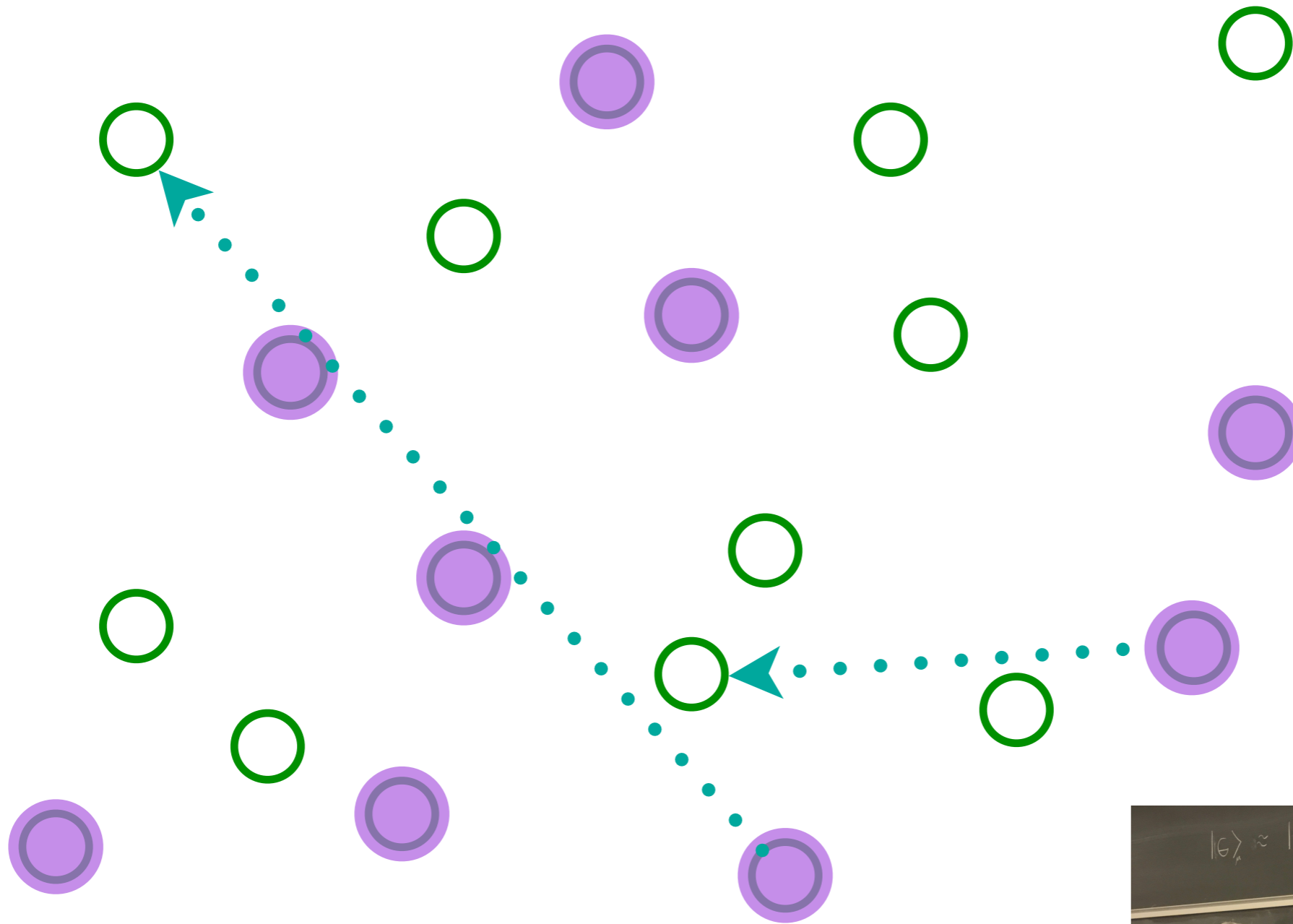
The SYK model



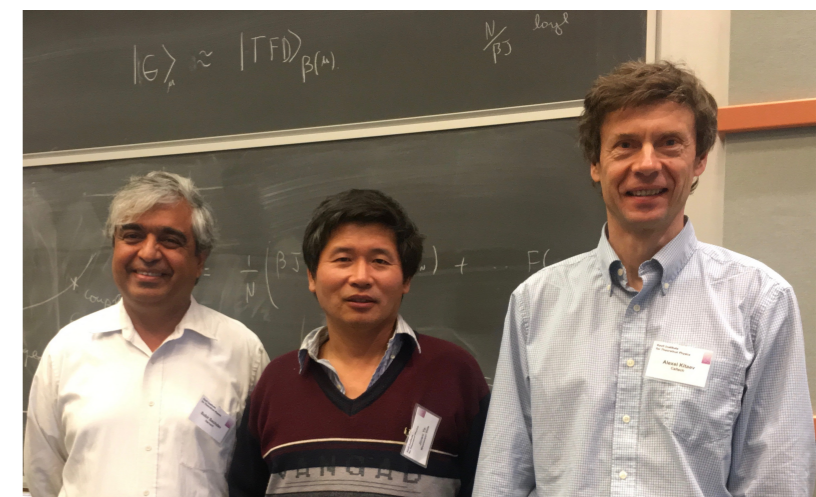
Entangle electrons pairwise randomly



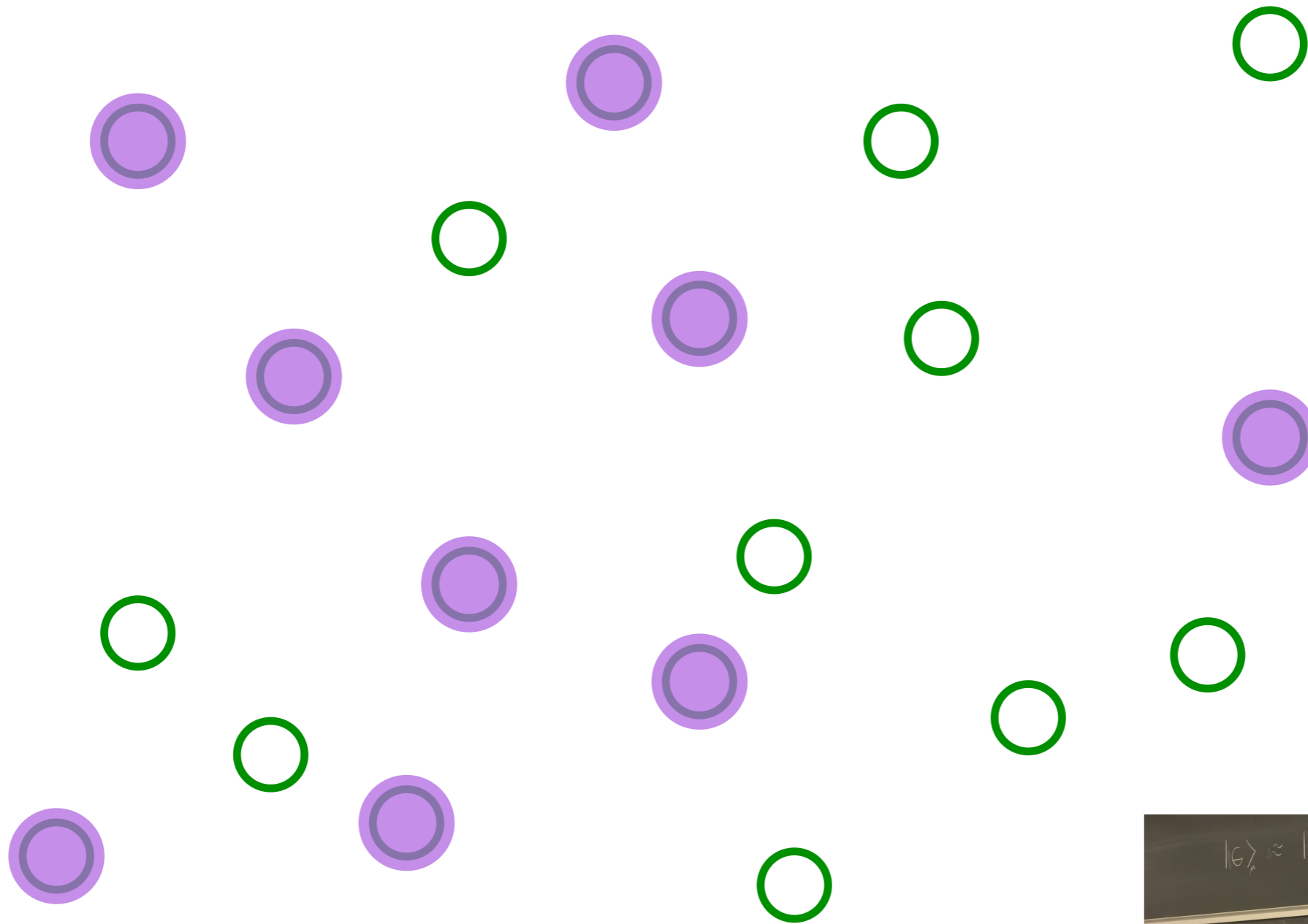
The SYK model



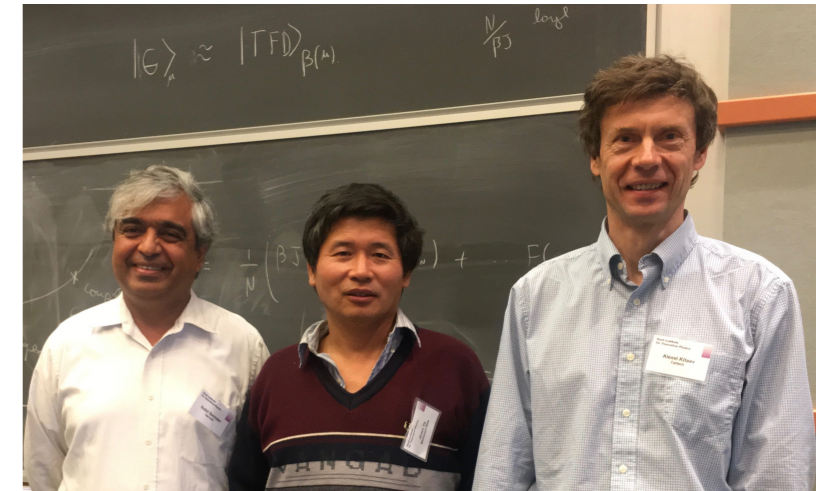
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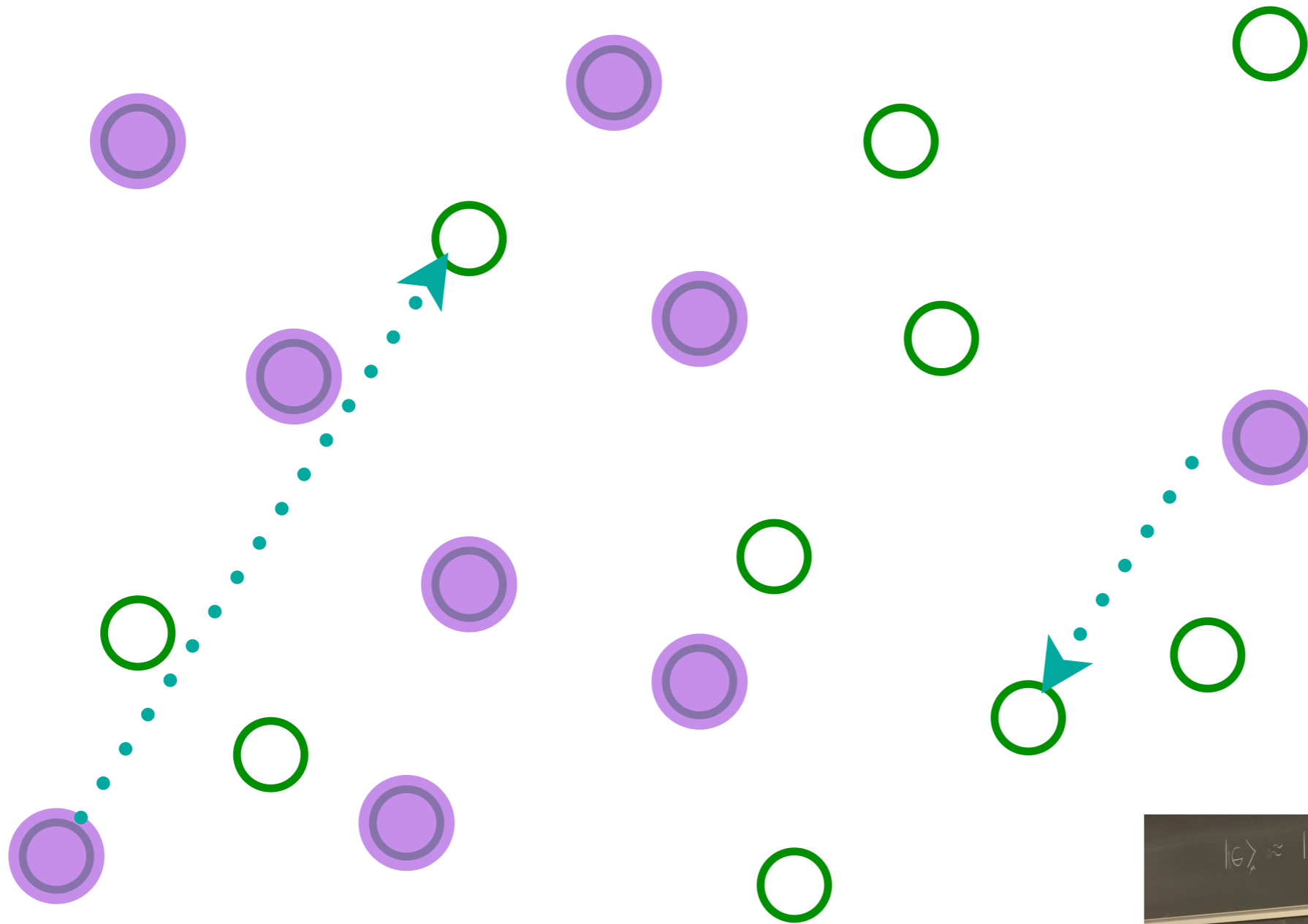
The SYK model



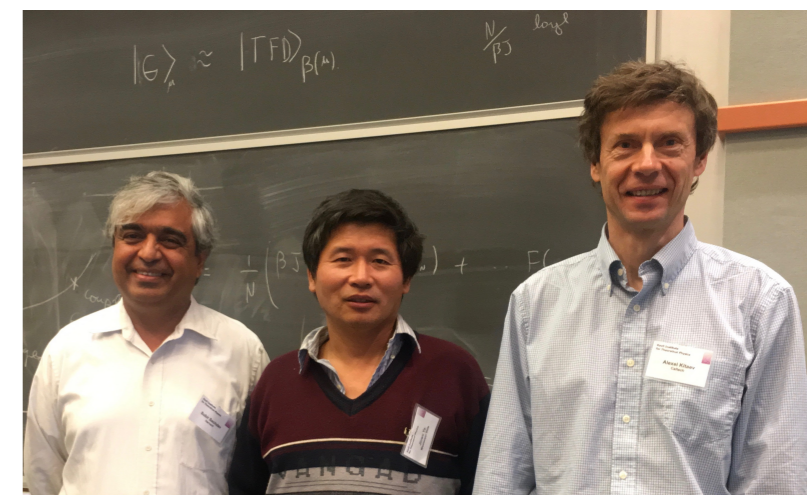
Entangle electrons pairwise randomly



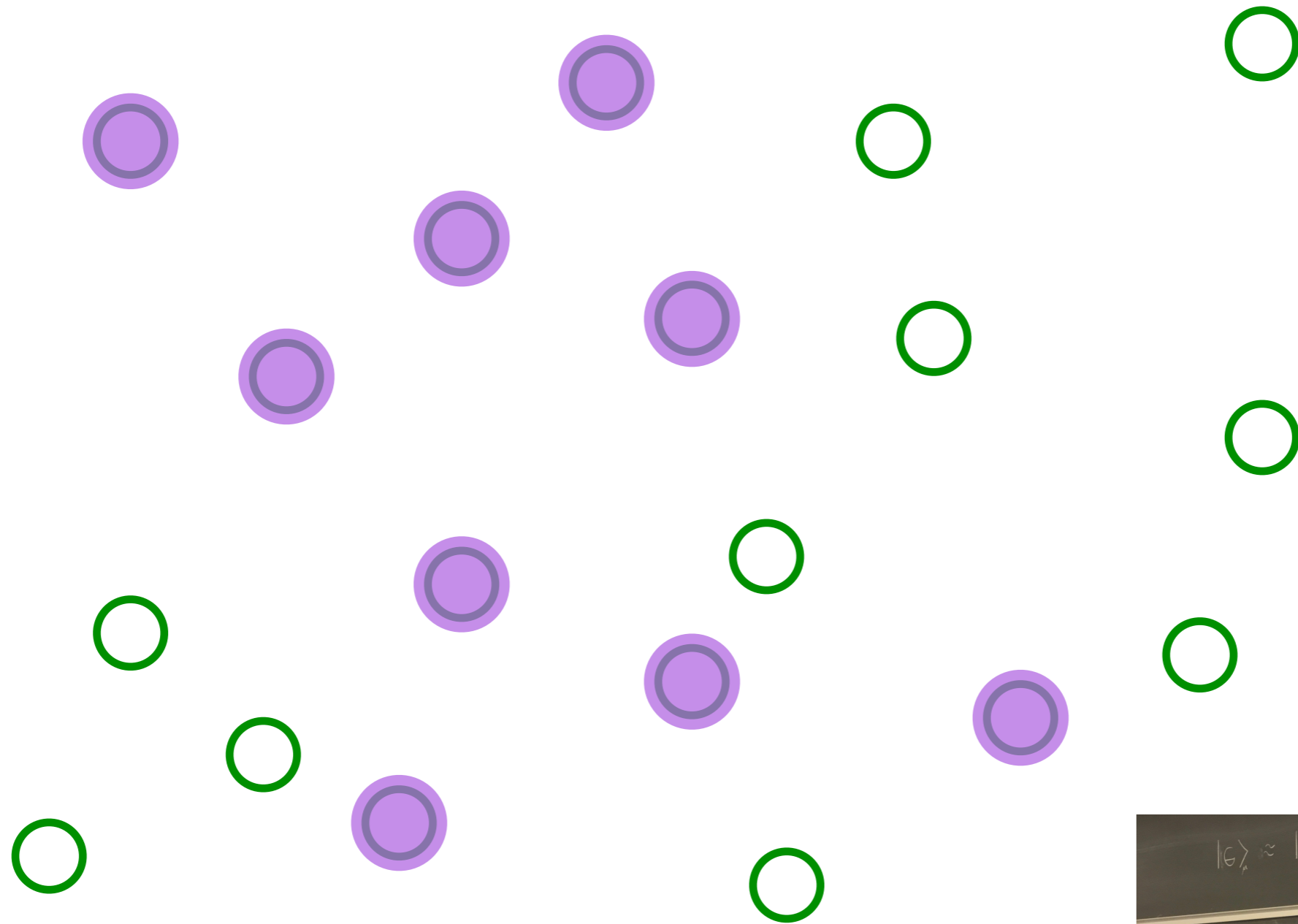
The SYK model



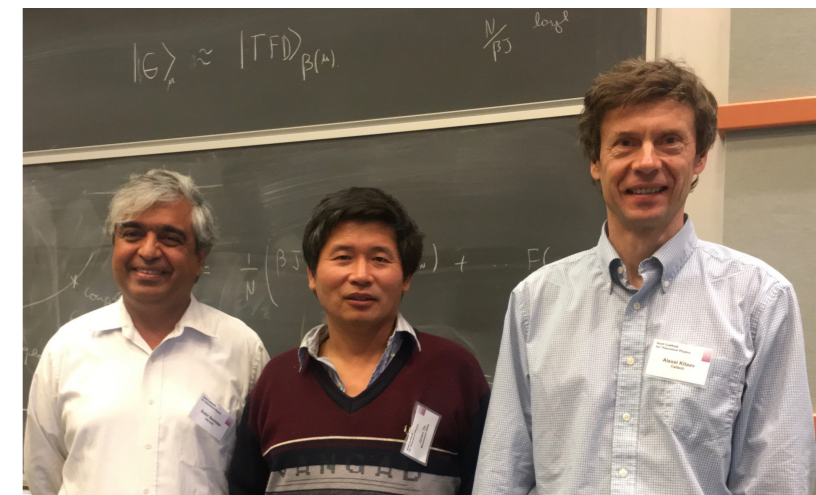
Entangle electrons pairwise randomly



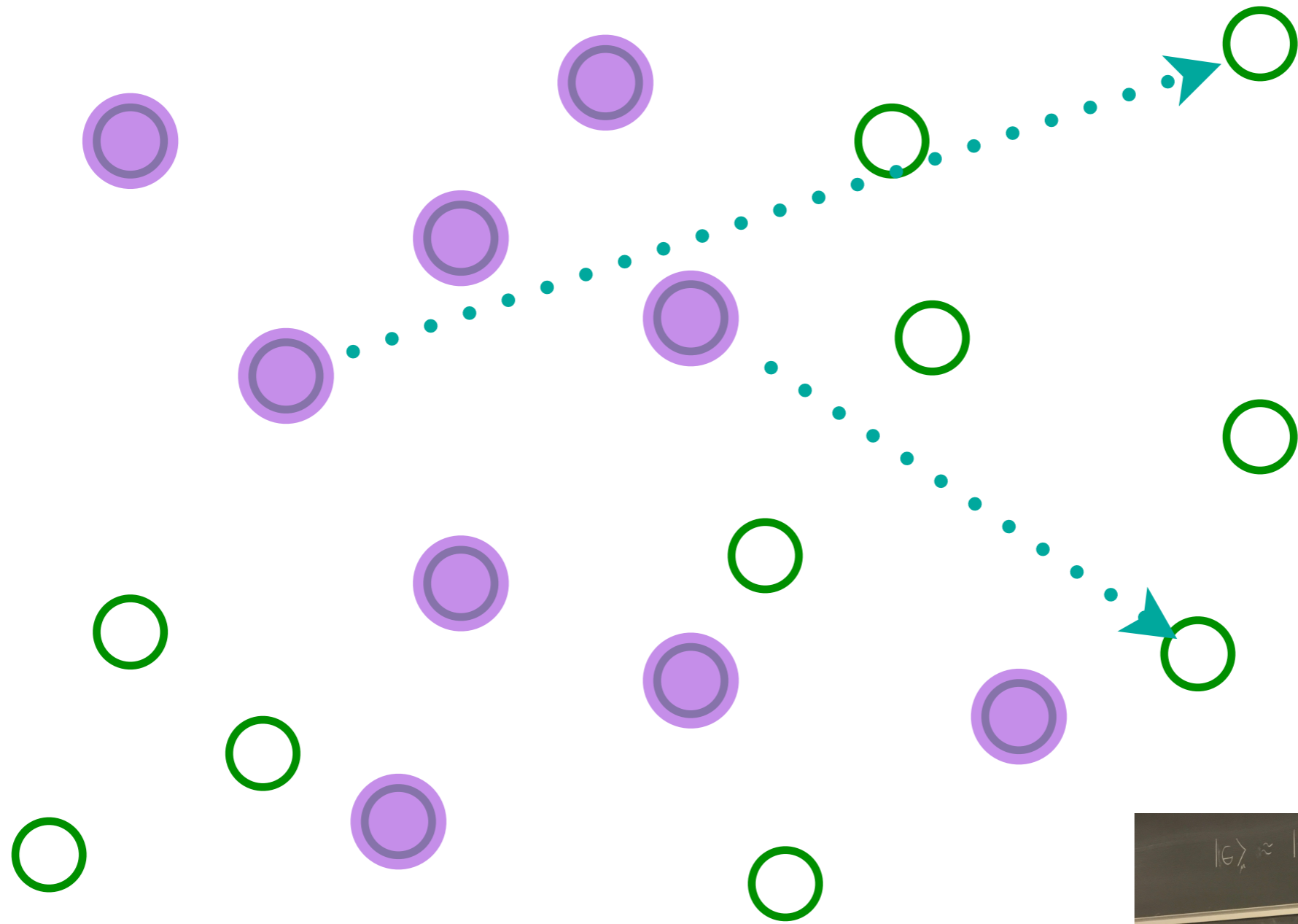
The SYK model



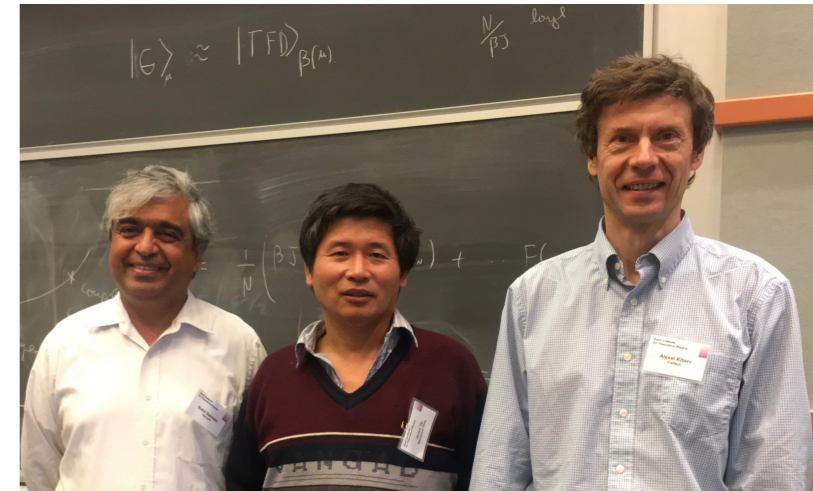
Entangle electrons pairwise randomly



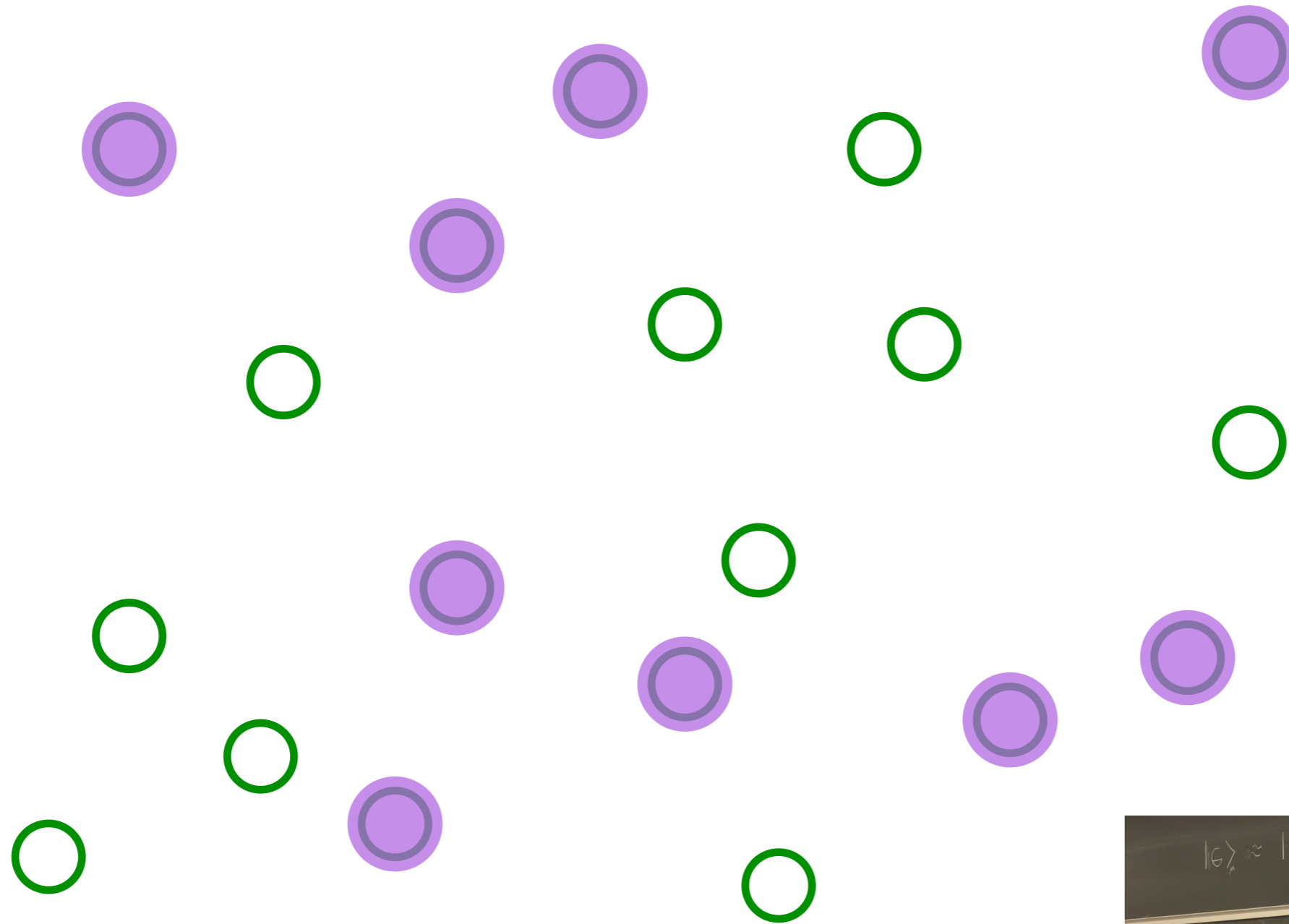
The SYK model



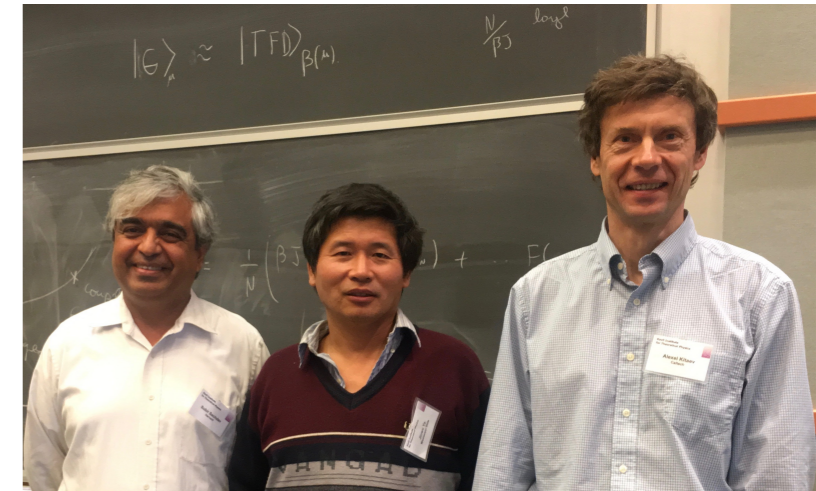
Entangle electrons pairwise randomly



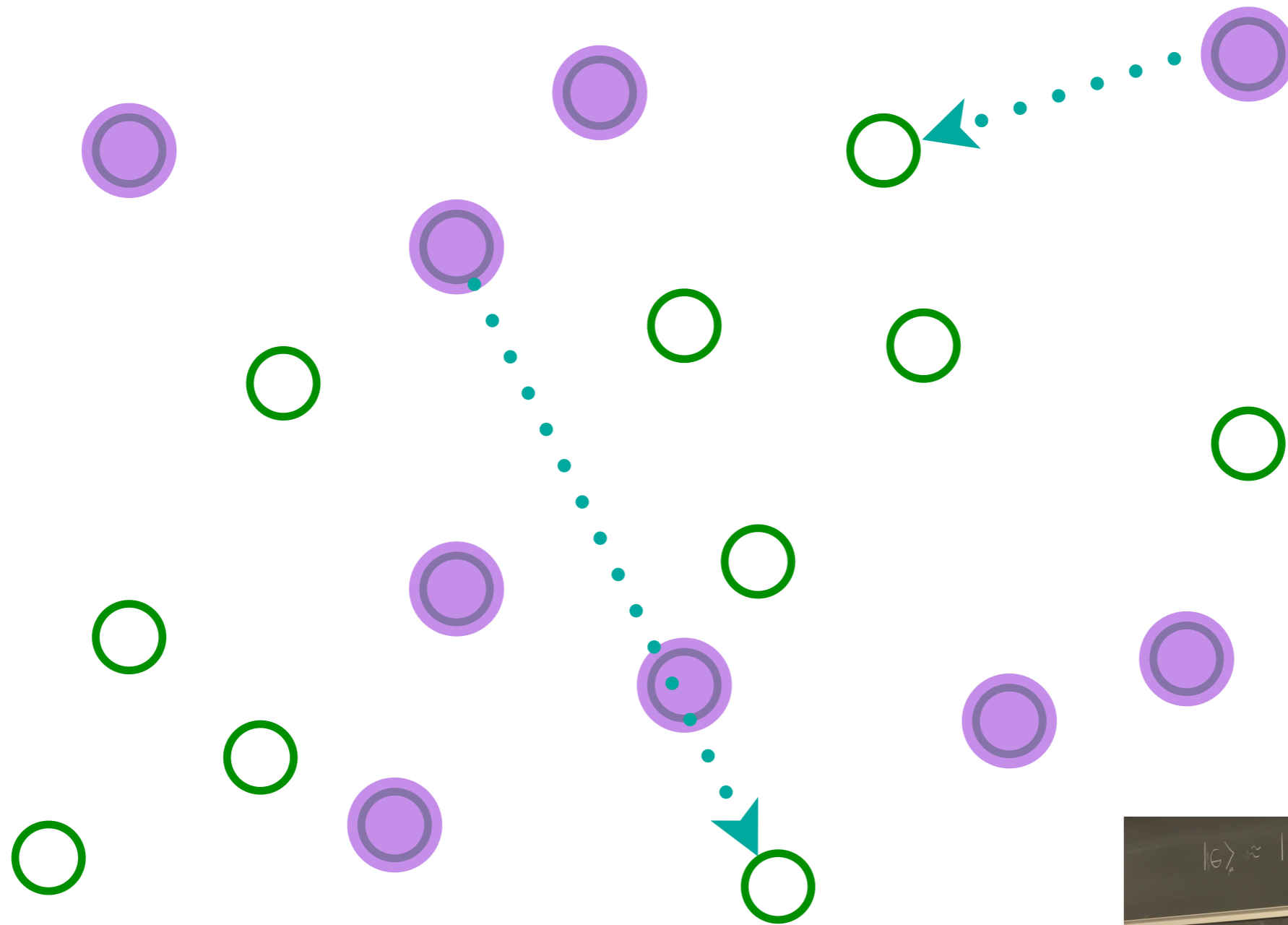
The SYK model



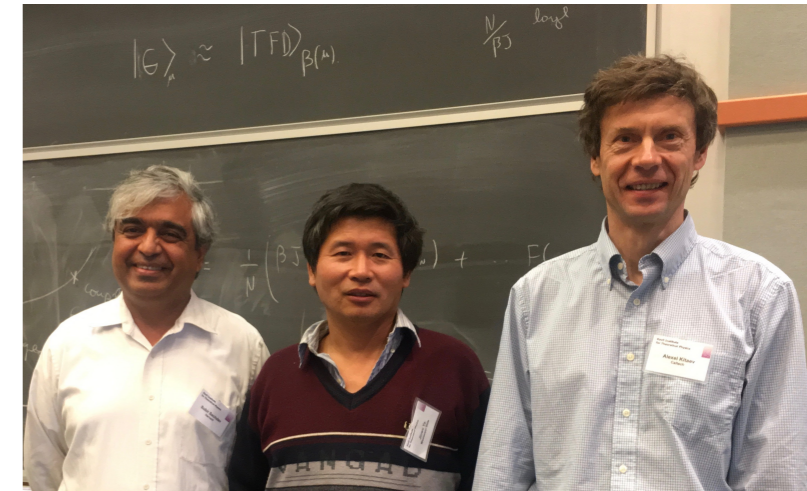
Entangle electrons pairwise randomly



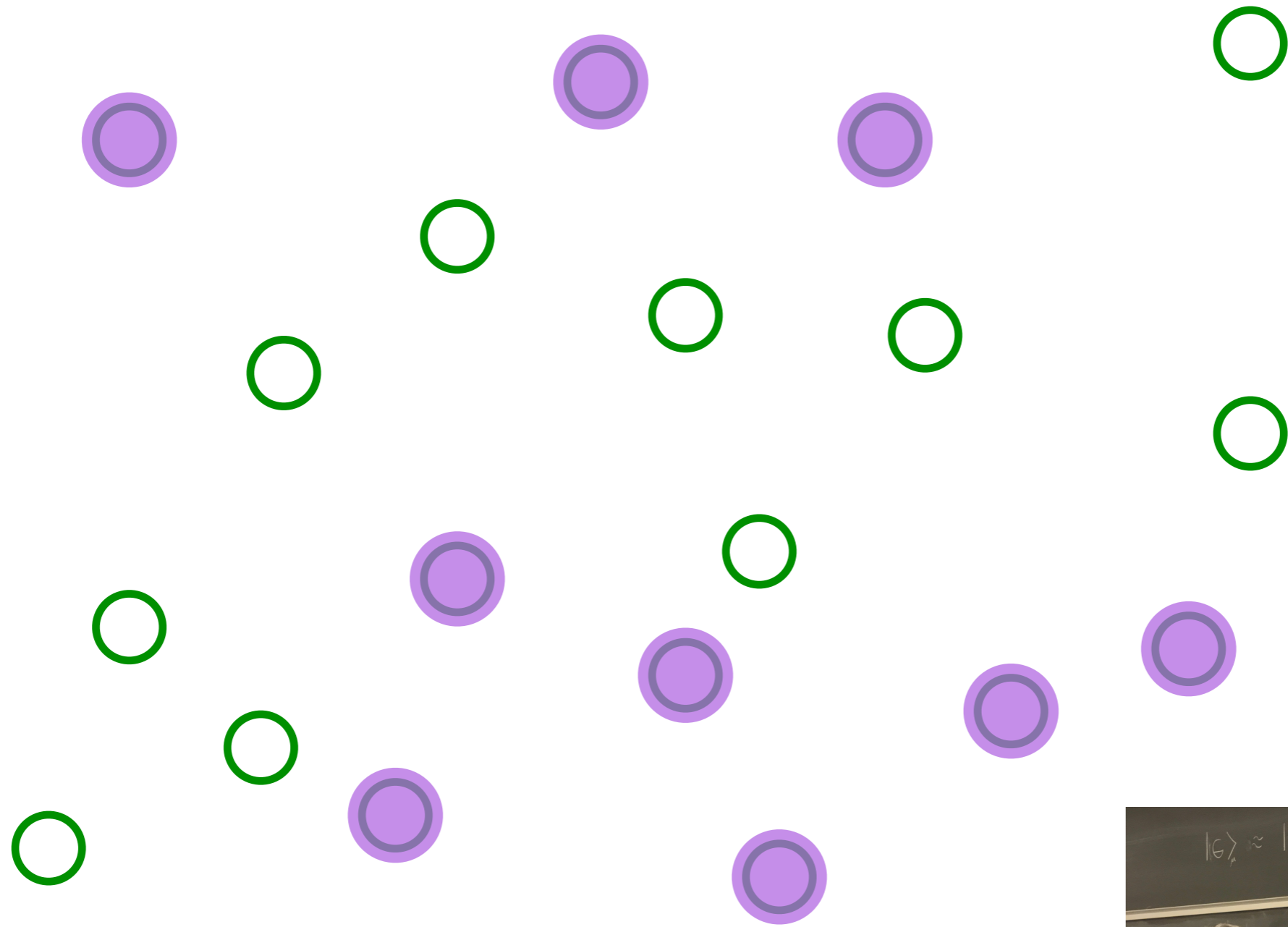
The SYK model



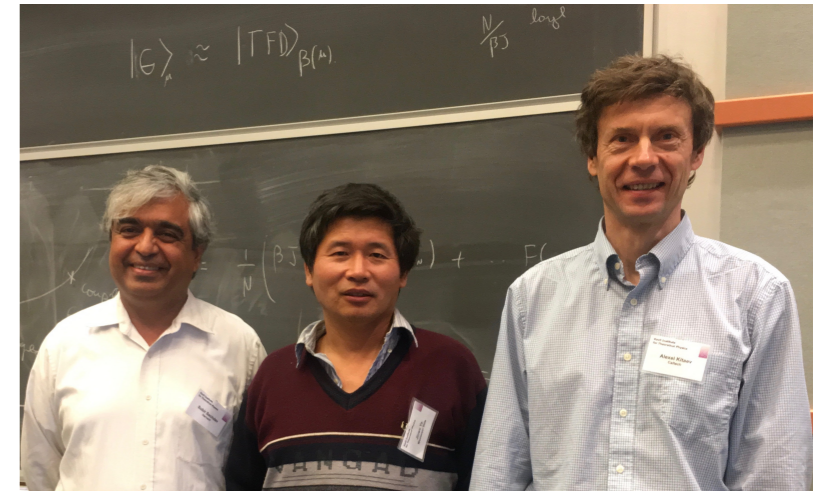
Entangle electrons pairwise randomly



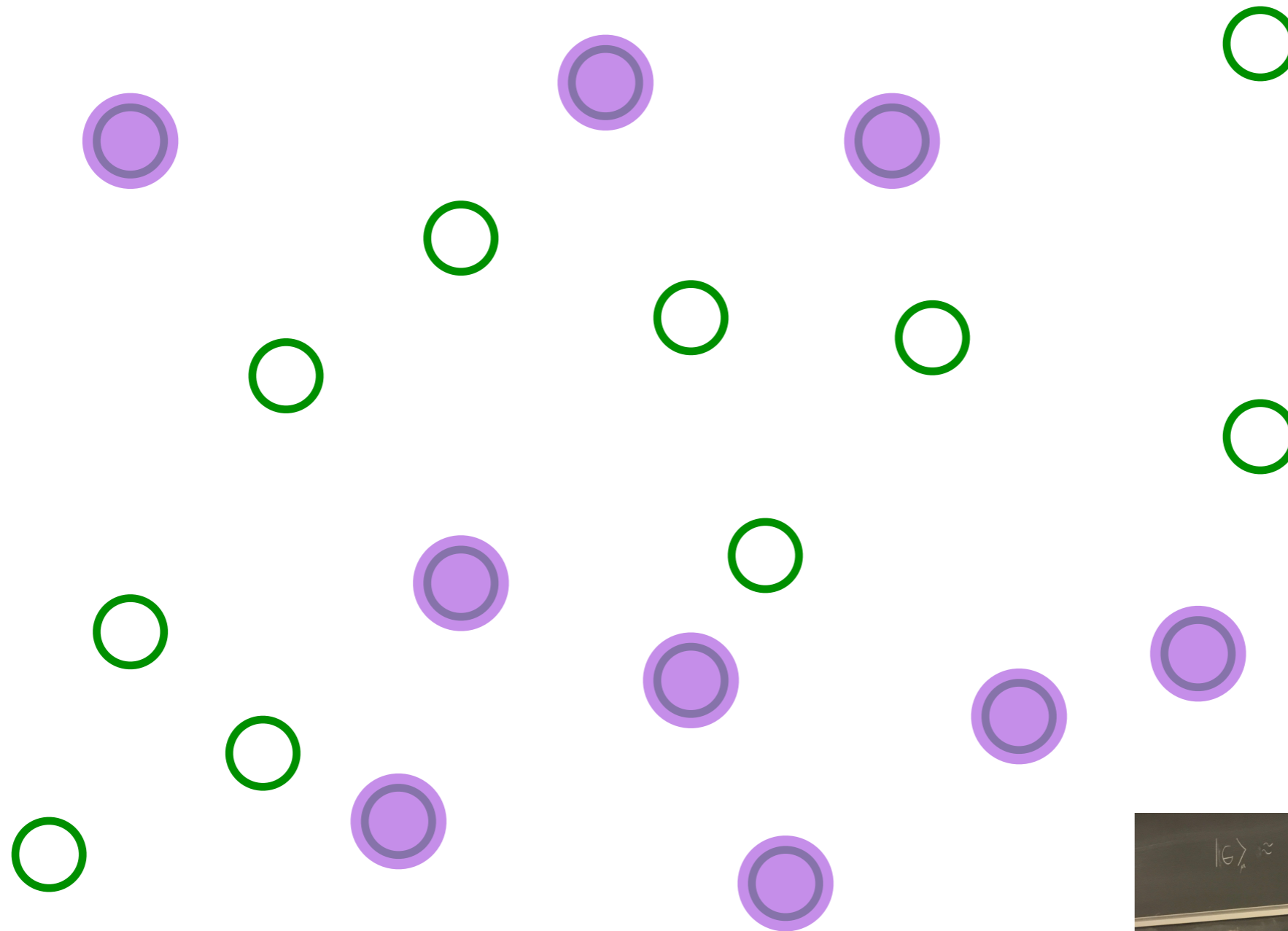
The SYK model



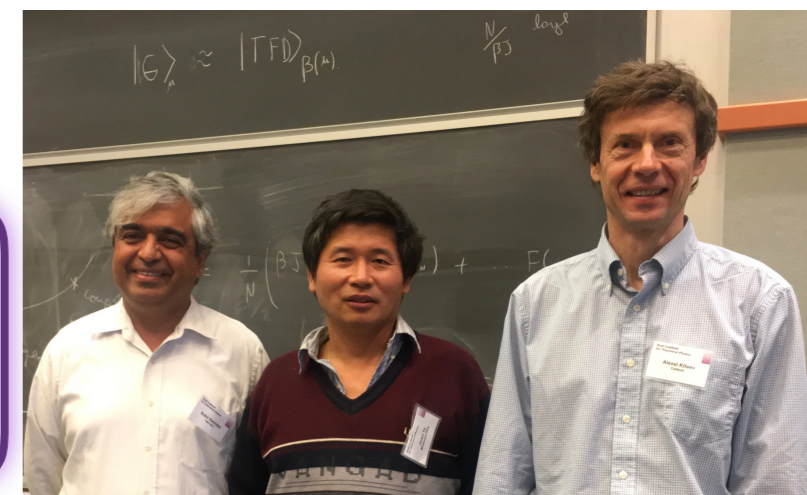
Entangle electrons pairwise randomly



The SYK model



**This describes both a
strange metal and a black hole!**



A strange metal: lattice of SYK islands

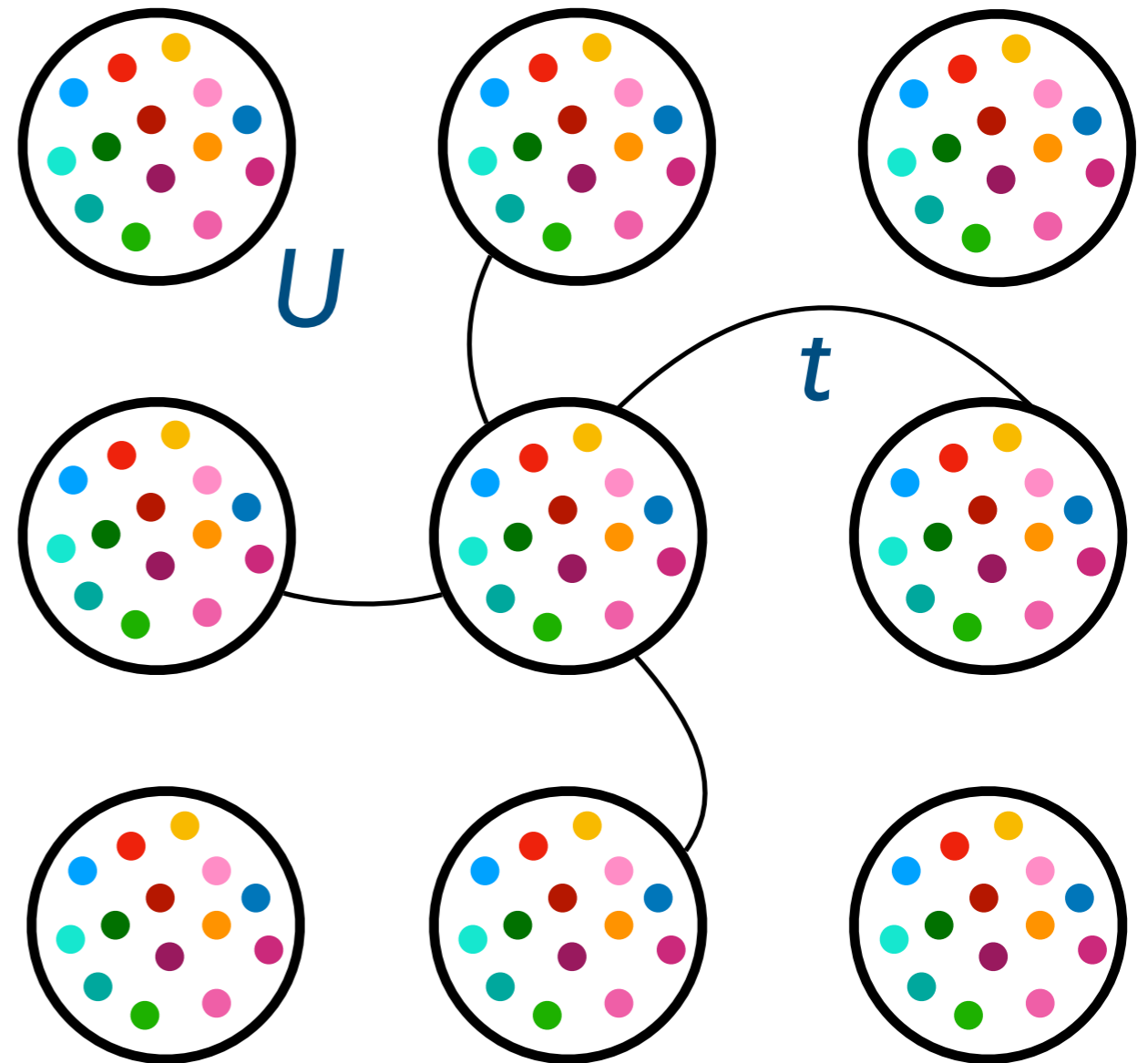
Entanglement amplitude
within each island = U .

Amplitude to hop
between islands = t .

Model yields

$$\rho \sim \frac{1}{\tau} \sim T$$

for $t^2/U \lesssim T \lesssim U$

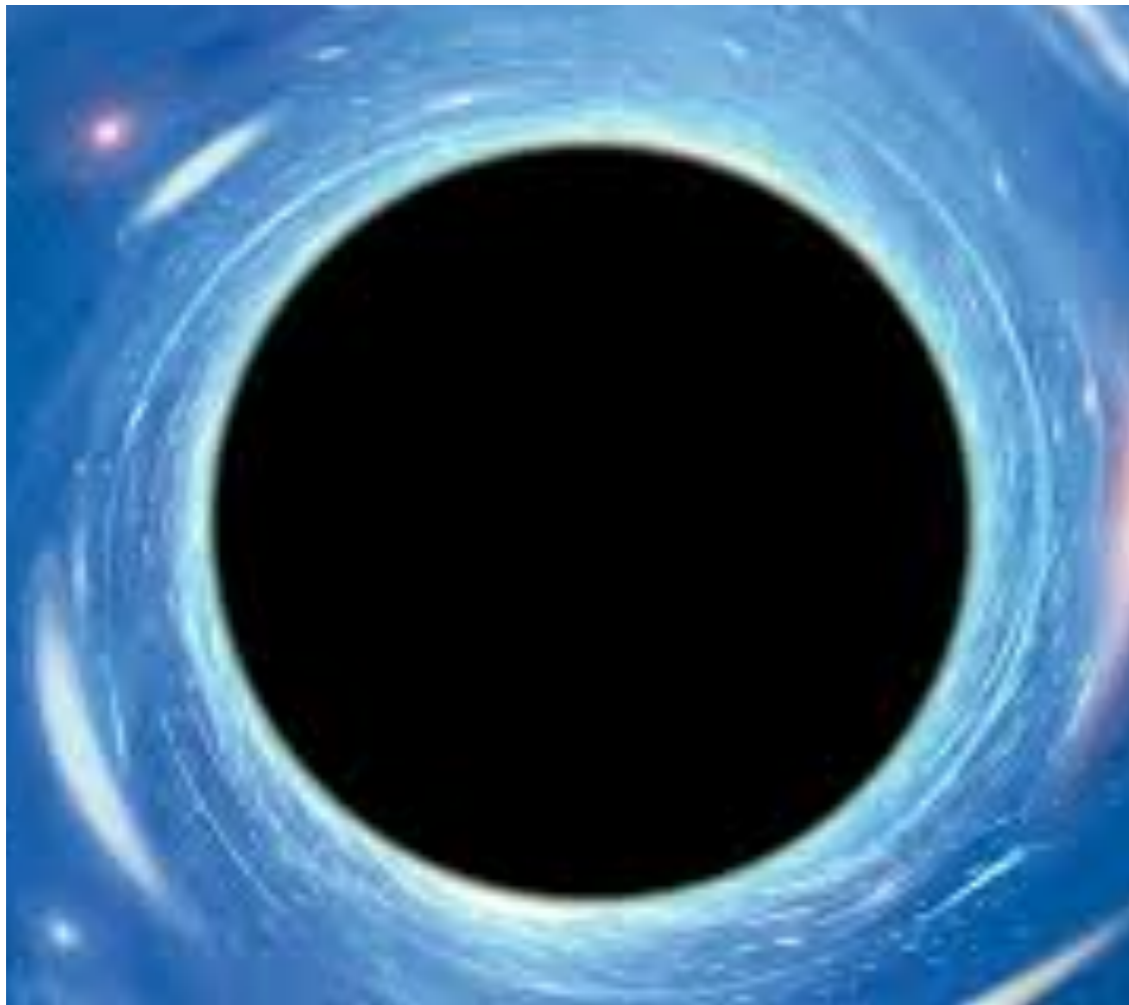


Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017);
Pengfei Zhang, PRB **96**, 205138 (2017); Debanjan Chowdhury, Yochai Werman,
Erez Berg, T. Senthil, PRX **8**, 031024 (2018); Aavishkar A. Patel, John McGreevy,
Daniel P. Arovas, Subir Sachdev, PRX **8**, 021049 (2018)

See also Antoine Georges and Olivier Parcollet PRB **59**, 5341 (1999)

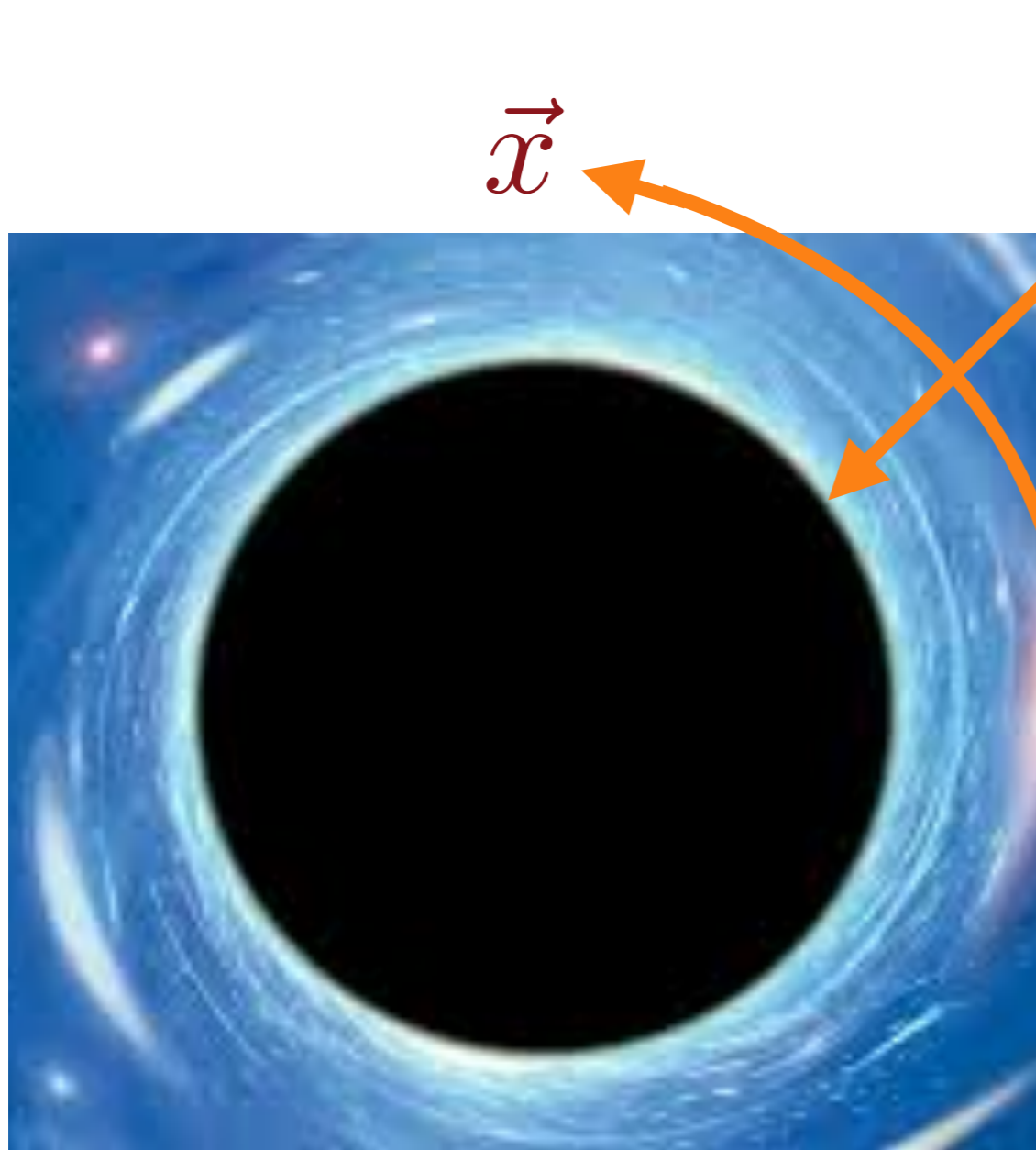


Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge





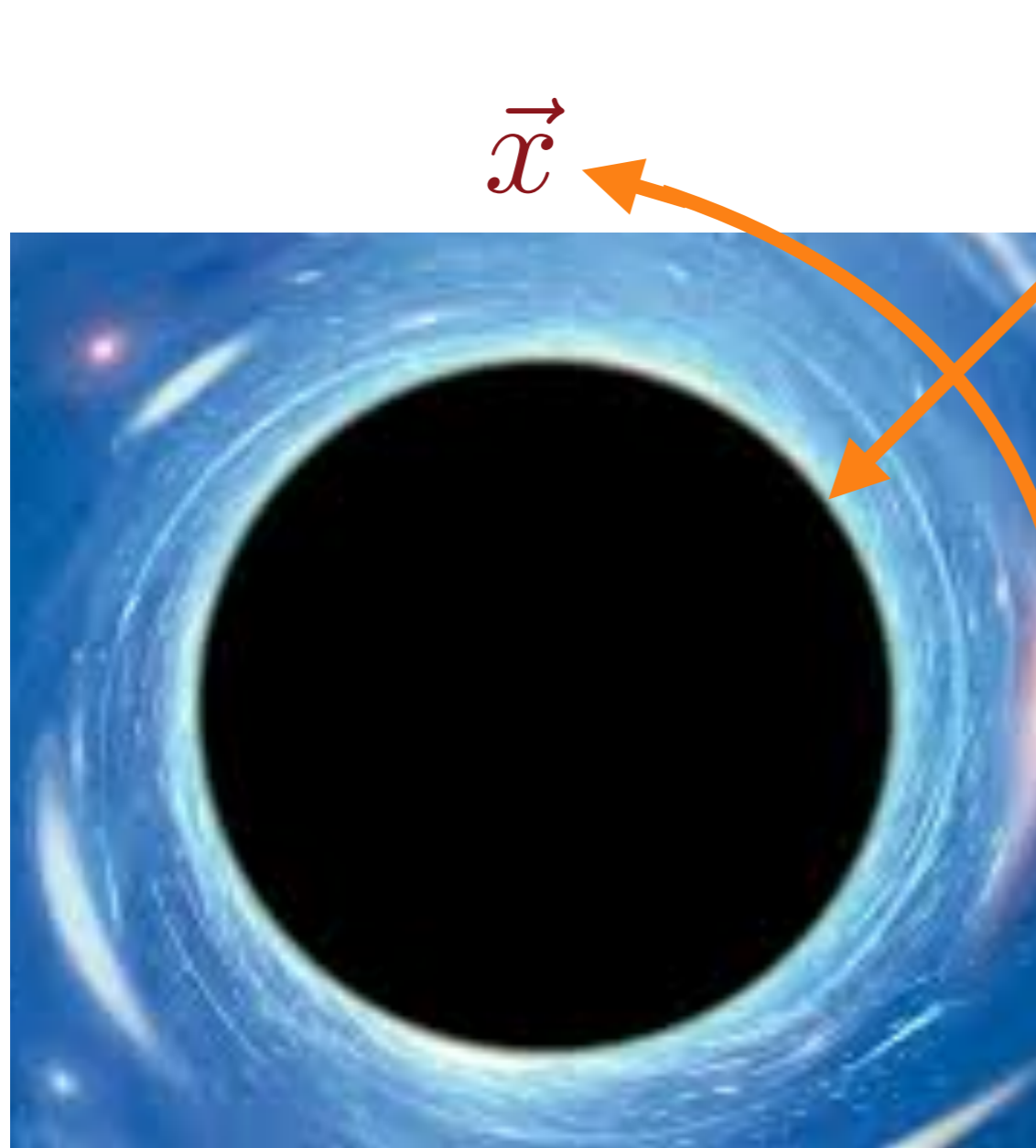
Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space (ζ) and one time dimension



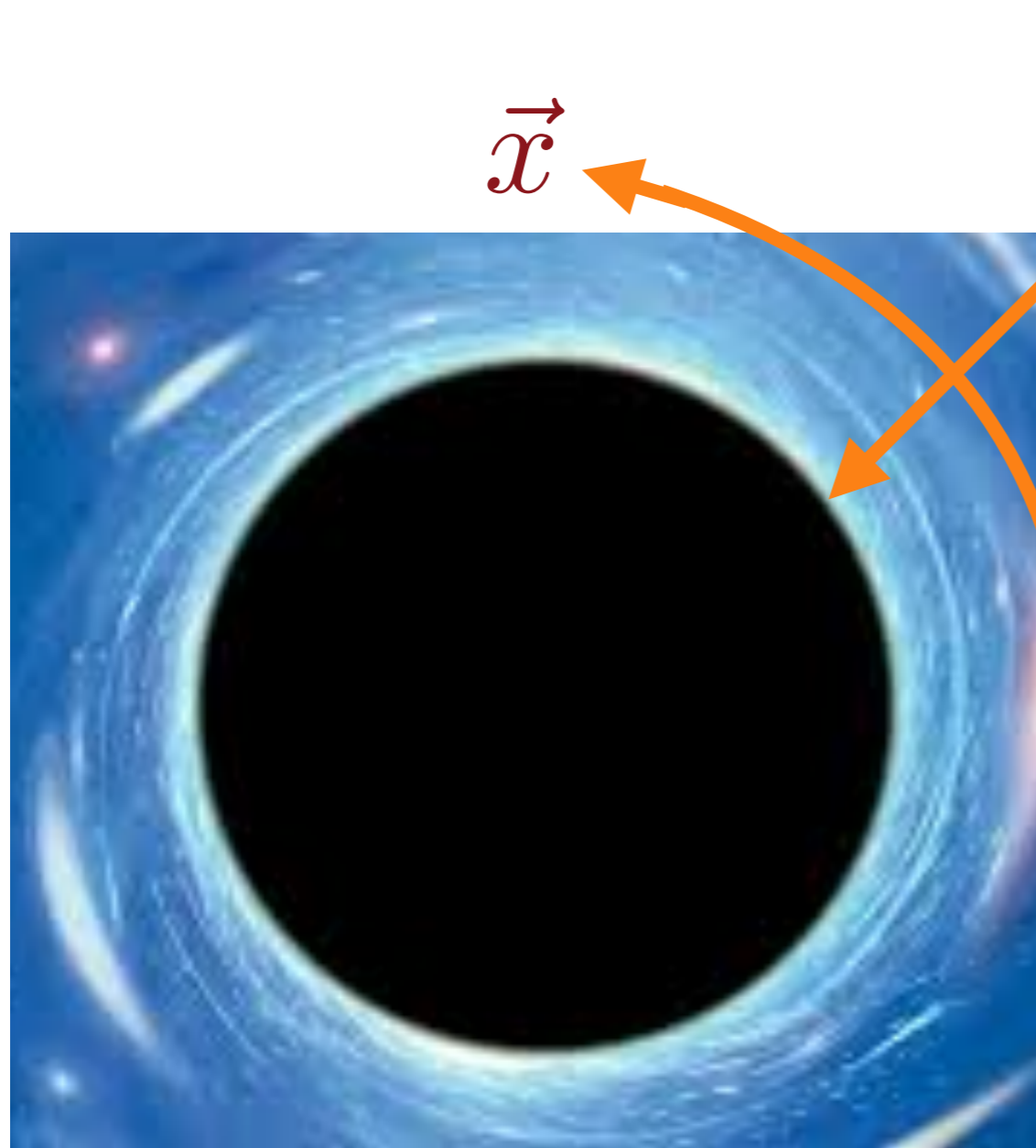
Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



The quantum versions
of Maxwell's and
Einstein's equations in
this two-dimensional
spacetime are also the
equations describing
electron entanglement
in the SYK model



Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



This has led to a deeper understanding of entanglement in superconductors and of Hawking's black hole information "paradox"

Quantum
entanglement

Black
holes

Metals
(ordinary and strange)
and superconductors

A "toy model" which describes both
a strange metal and a black hole!