

Quantum entanglement: “Spooky action at distance” in modern materials in the lab, and in black holes in the universe

2019 Physics Marker Lectures
Penn State University, State College
December 4, 2019

Subir Sachdev

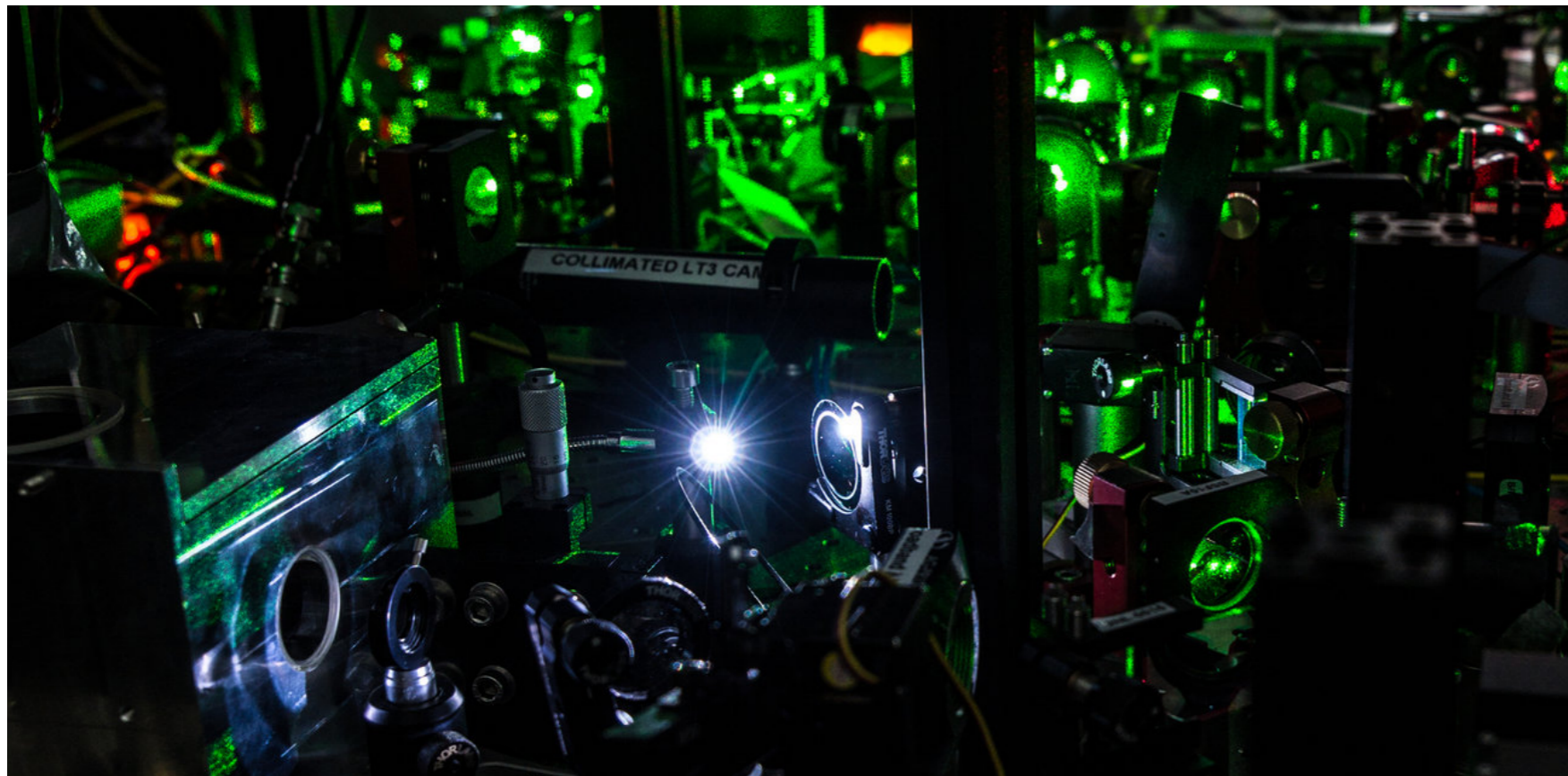
Talk online: sachdev.physics.harvard.edu



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.

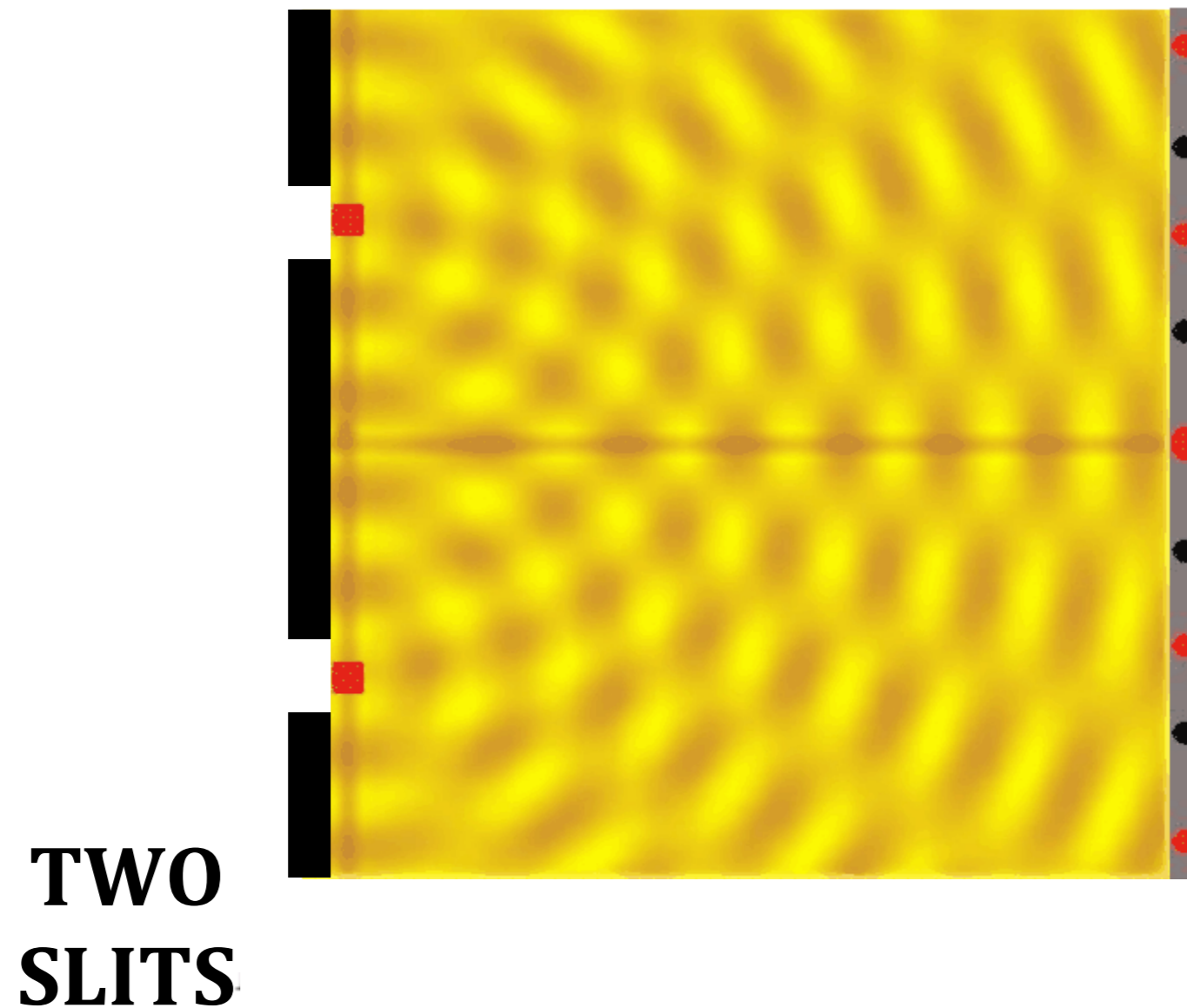


Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

Quantum entanglement

Principles of Quantum Mechanics: I. Quantum Superposition

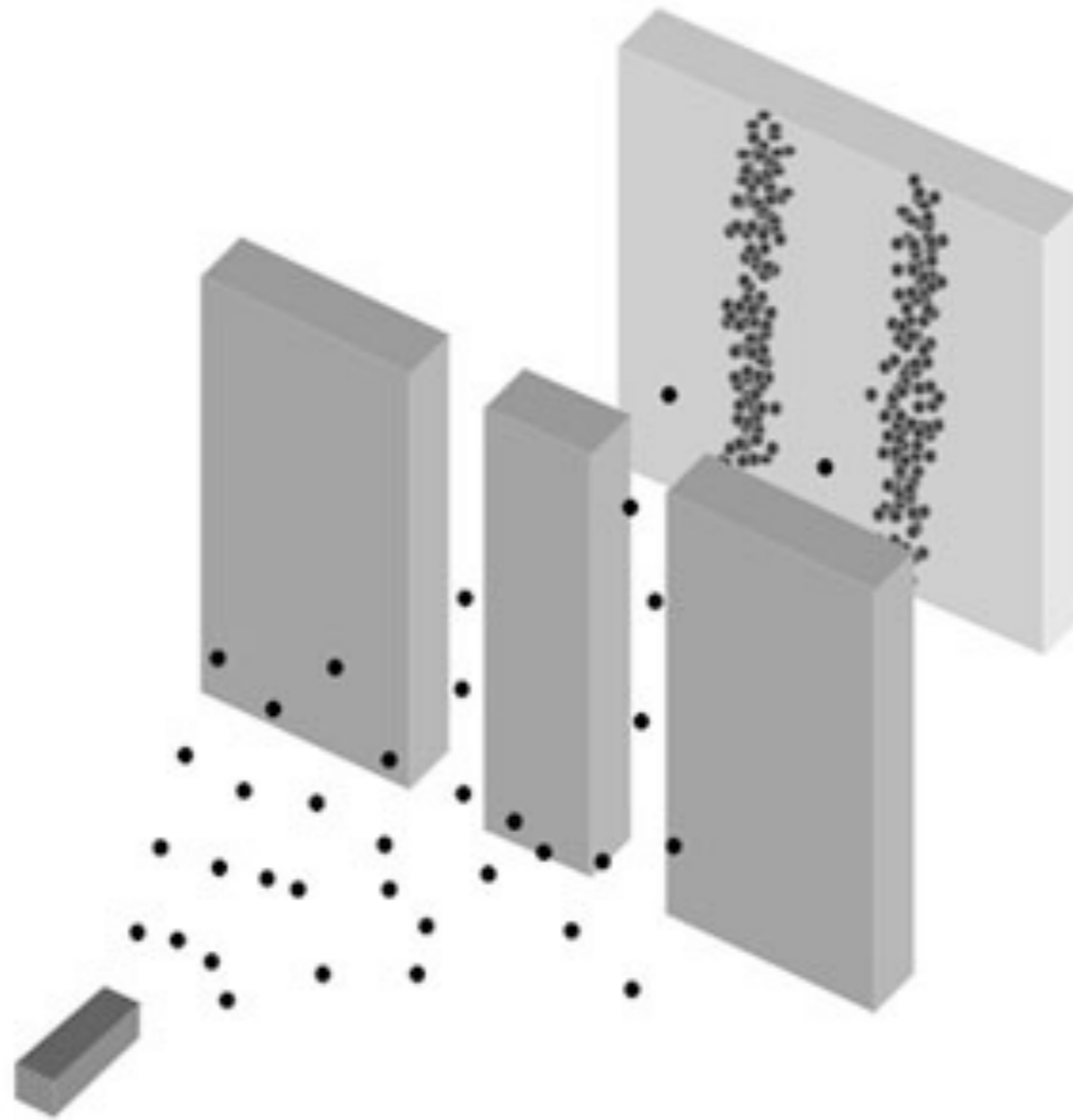
The double slit experiment



Interference of water waves

Principles of Quantum Mechanics: I. Quantum Superposition

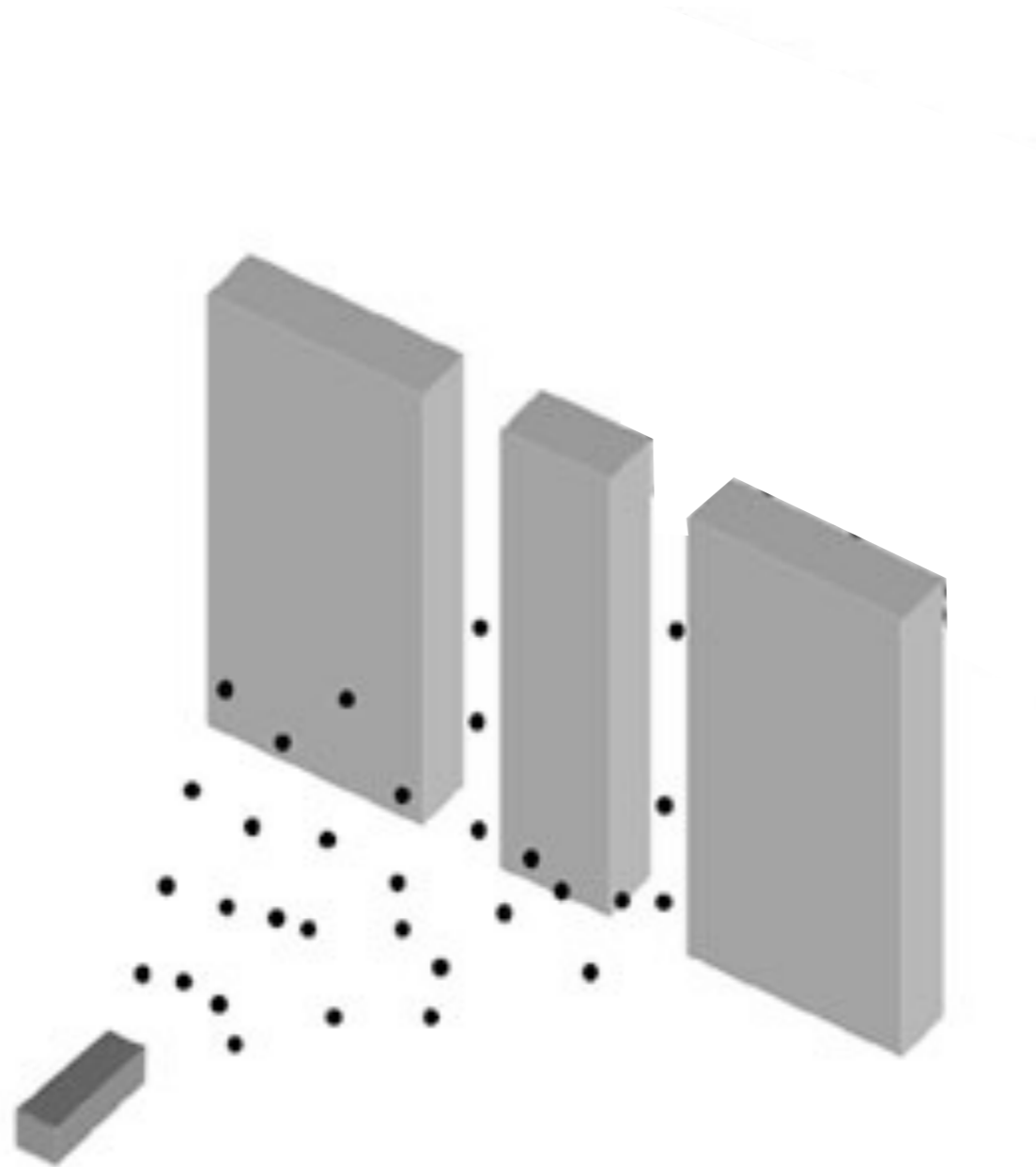
The double slit experiment



Bullets

Principles of Quantum Mechanics: I. Quantum Superposition

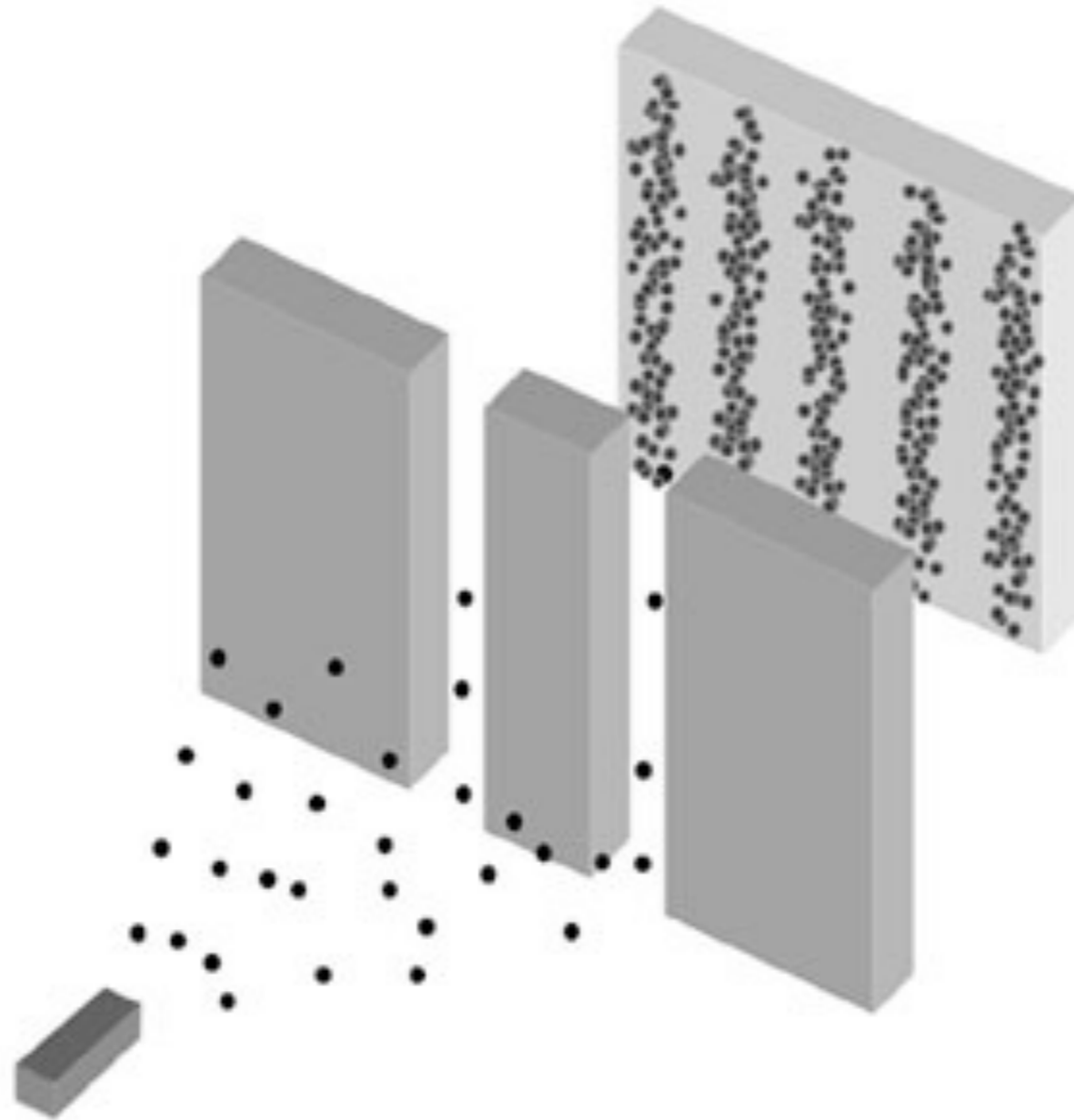
The double slit experiment



Send electrons through the slits

Principles of Quantum Mechanics: I. Quantum Superposition

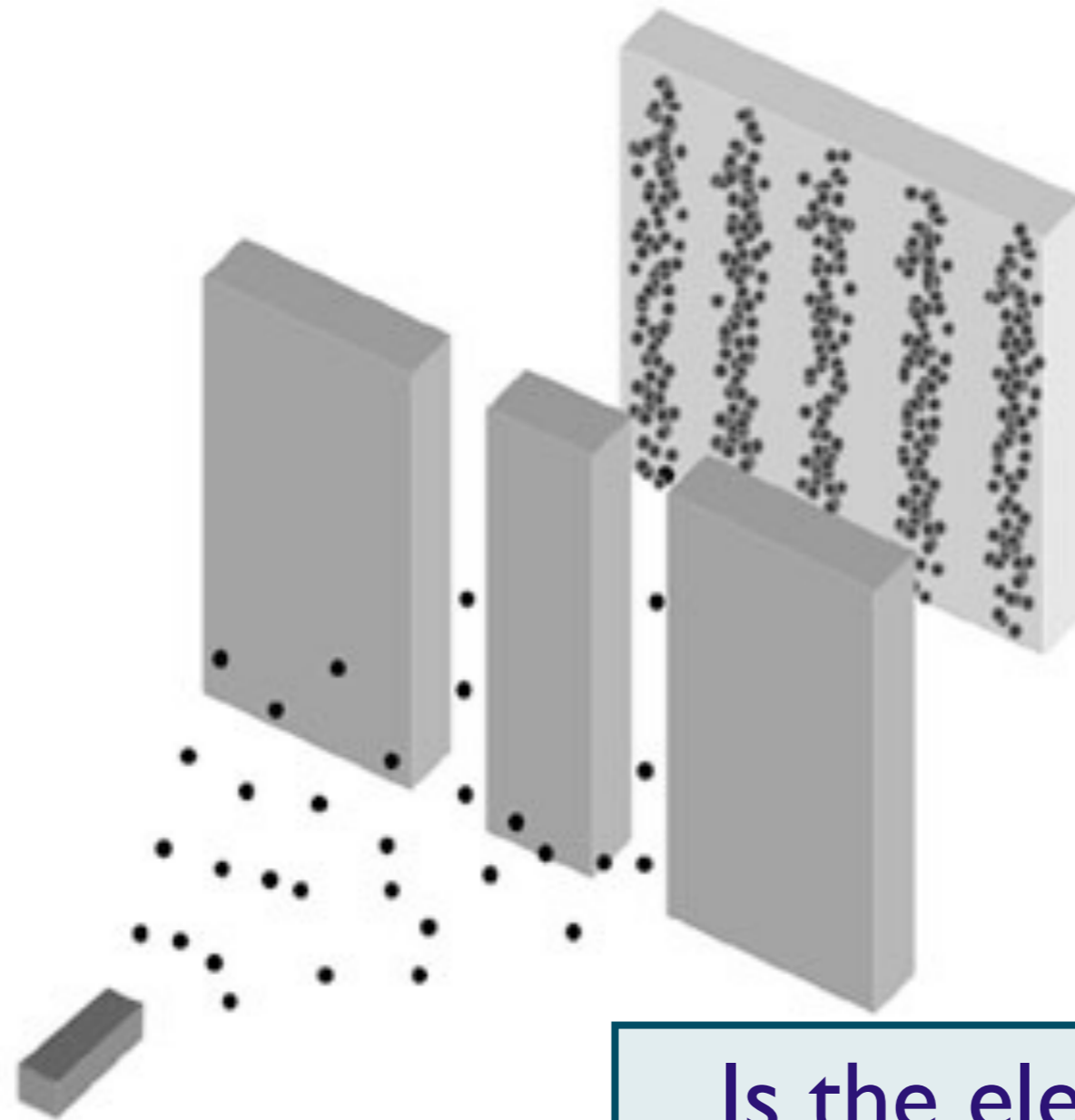
The double slit experiment



Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

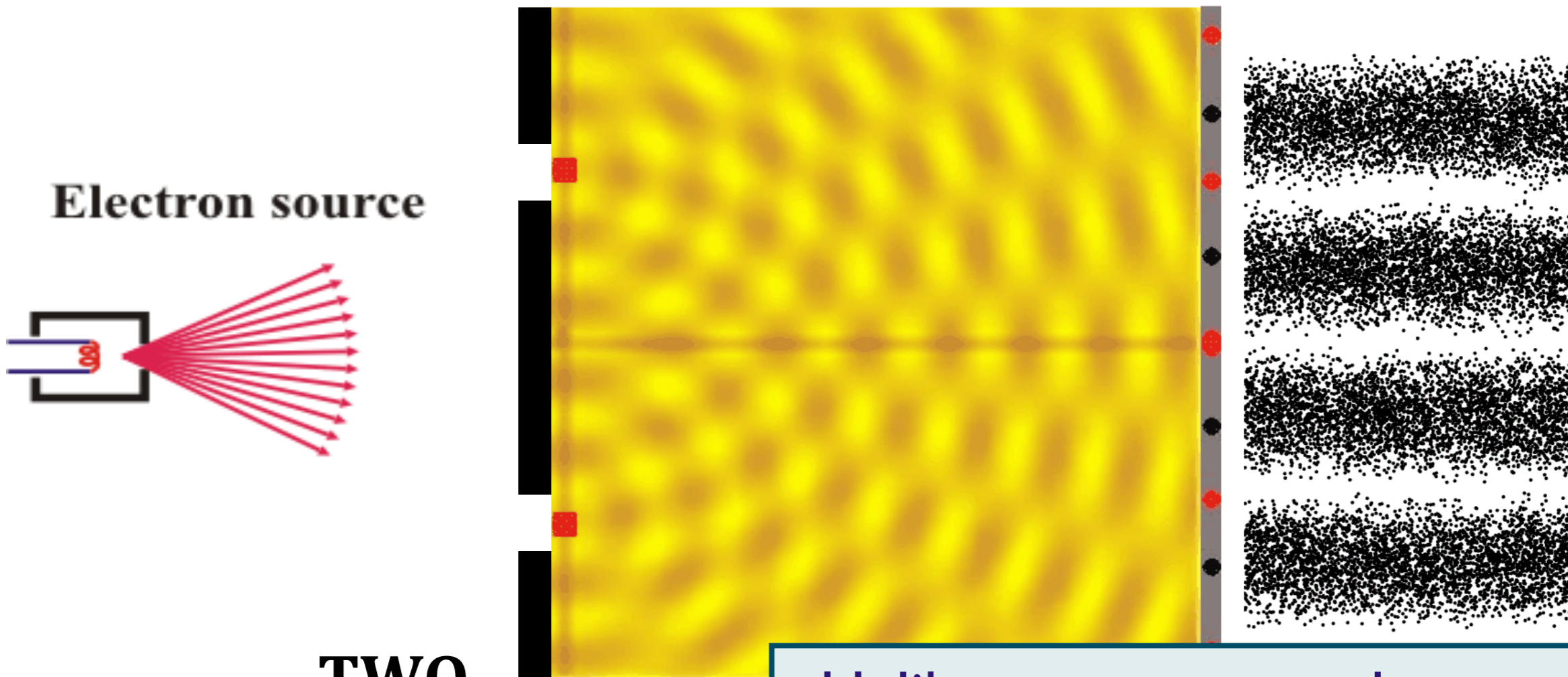


Is the electron a wave ?

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment



**TWO
SLITS**

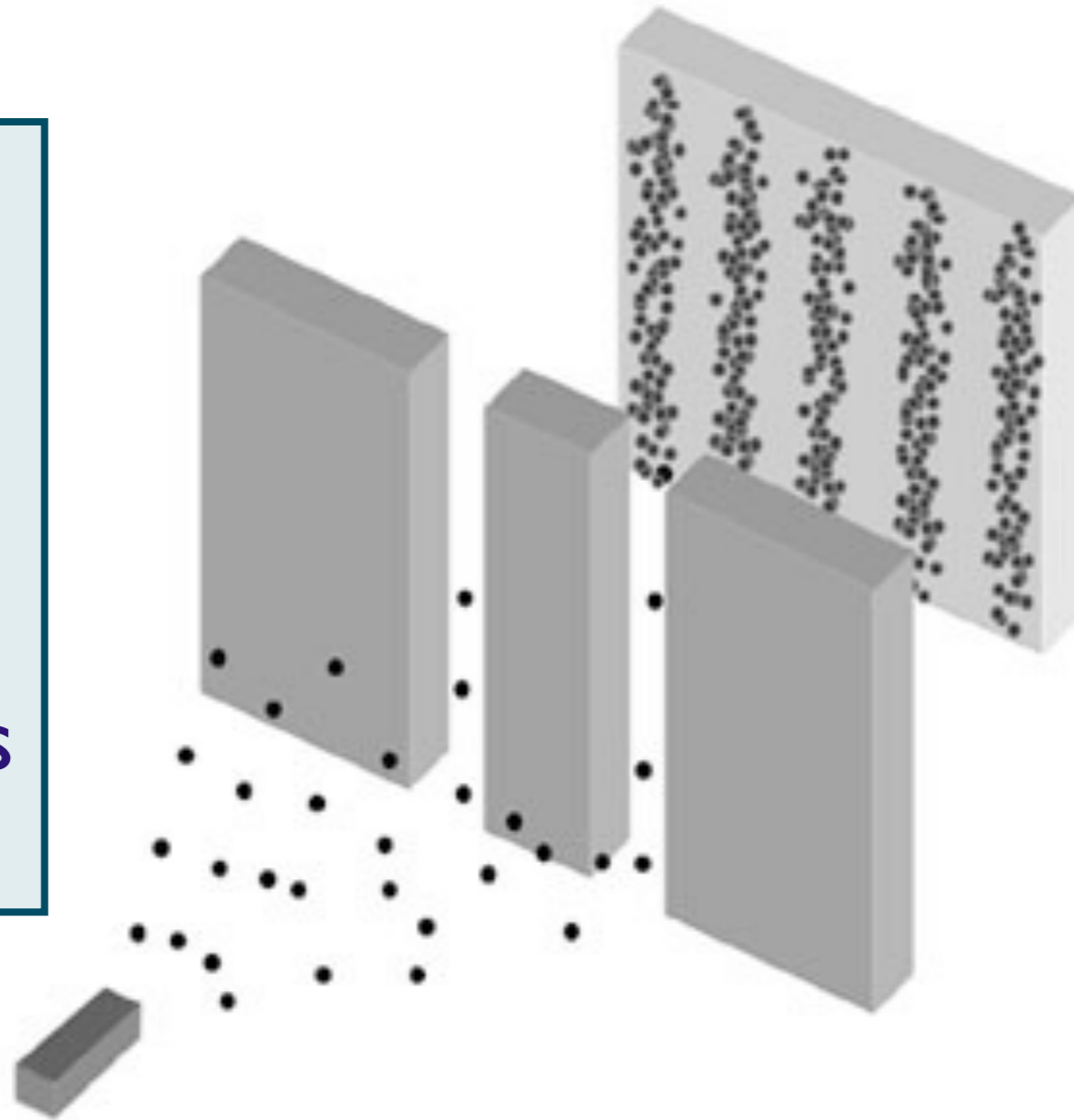
Unlike water waves, electrons arrive
one-by-one
(so is it like a particle ?)

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

But if it is like a particle, which slit does each electron pass through ?

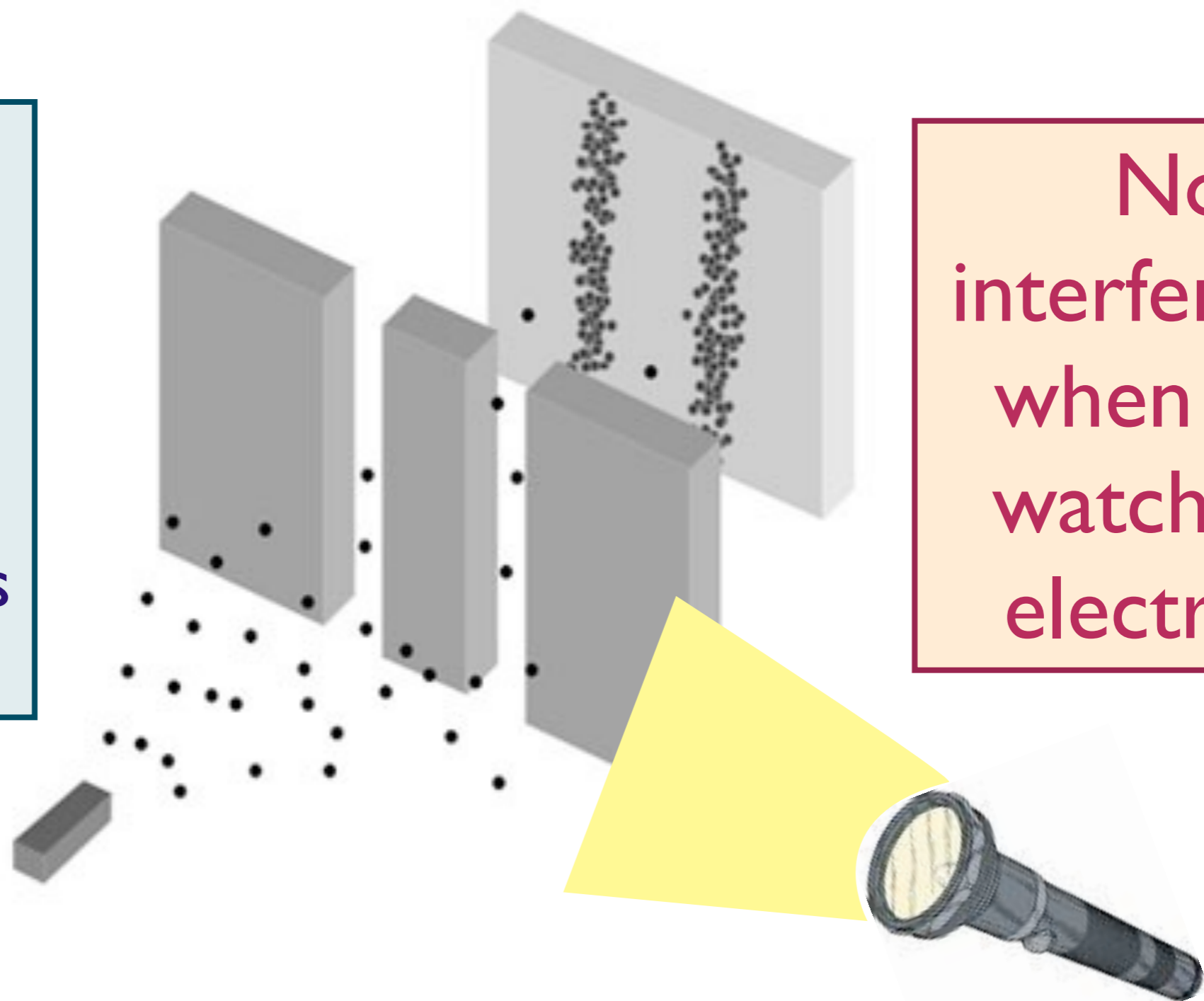


Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

But if it is like a particle, which slit does each electron pass through ?



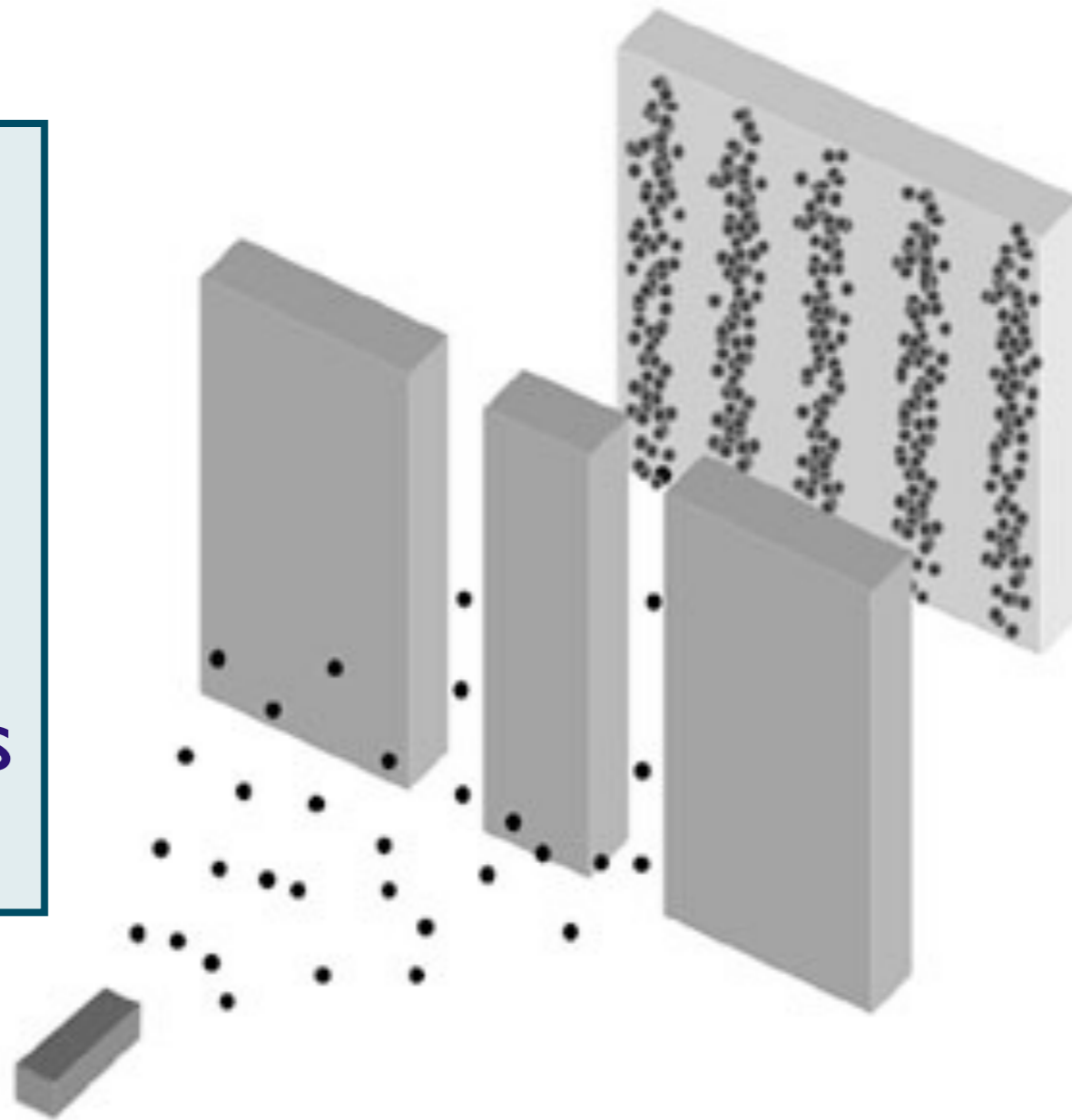
No interference when you watch the electrons

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

But if it is like a particle, which slit does each electron pass through ?

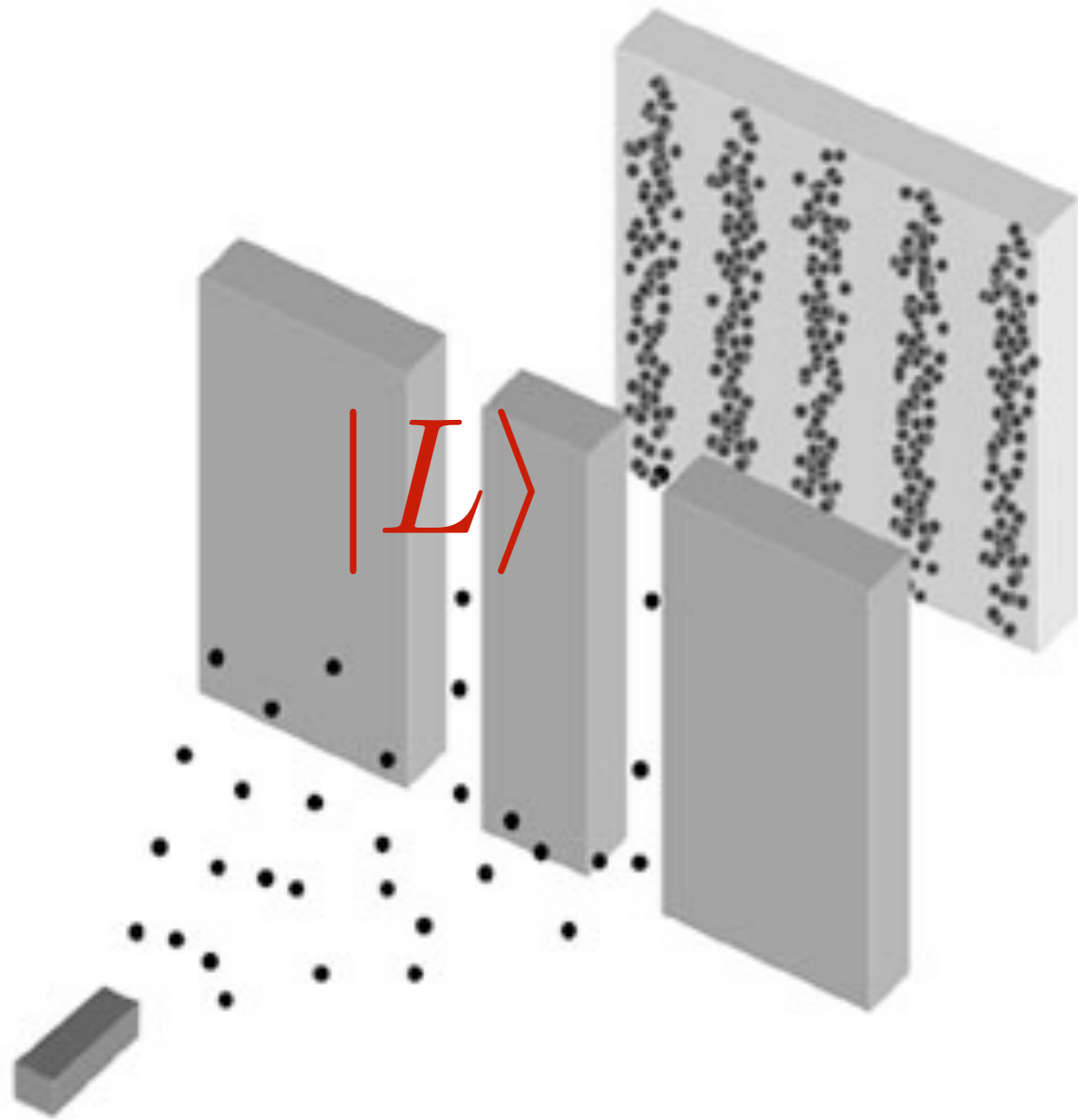


Each electron passes through both slits !

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

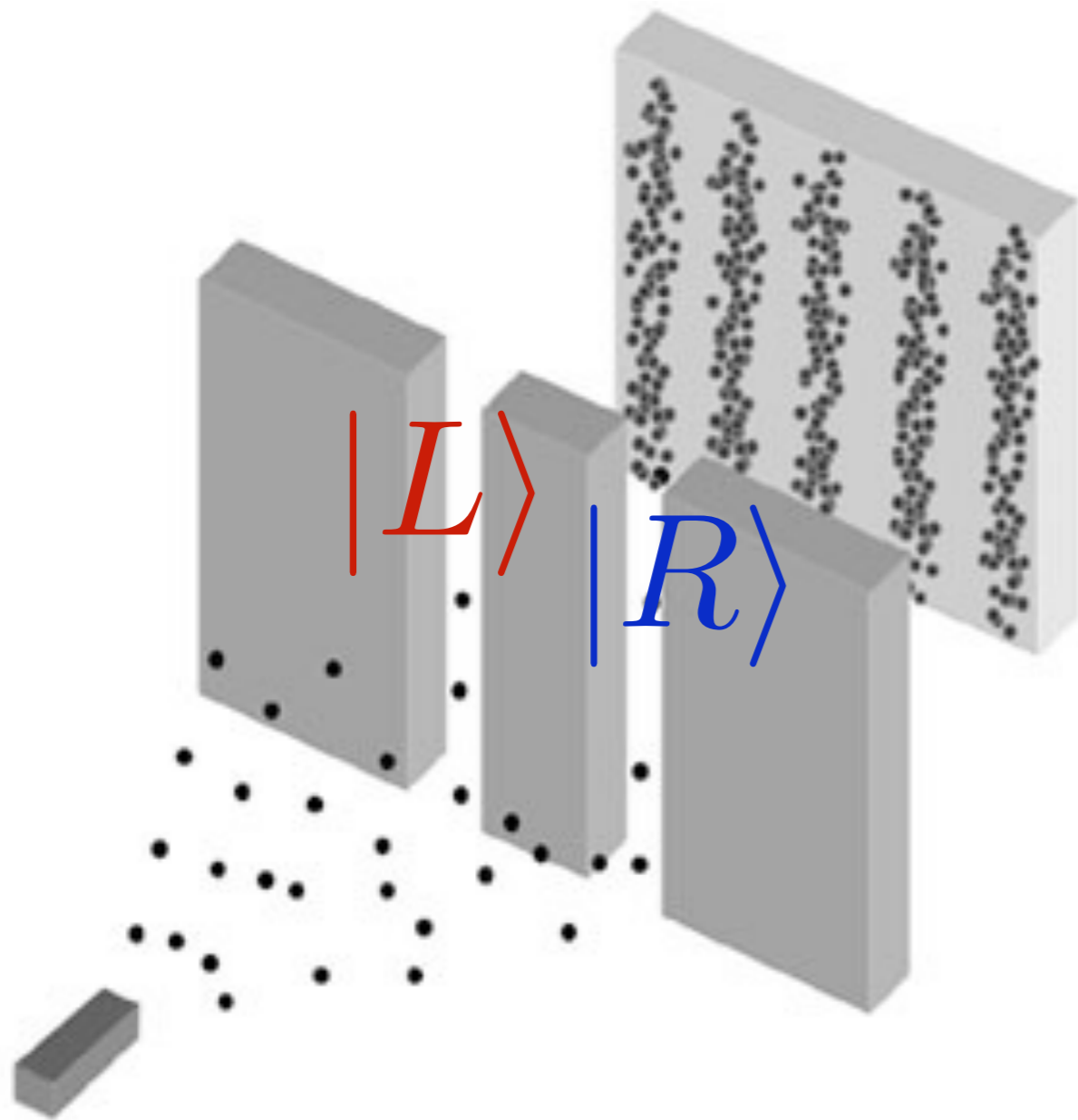
The double slit experiment



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

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

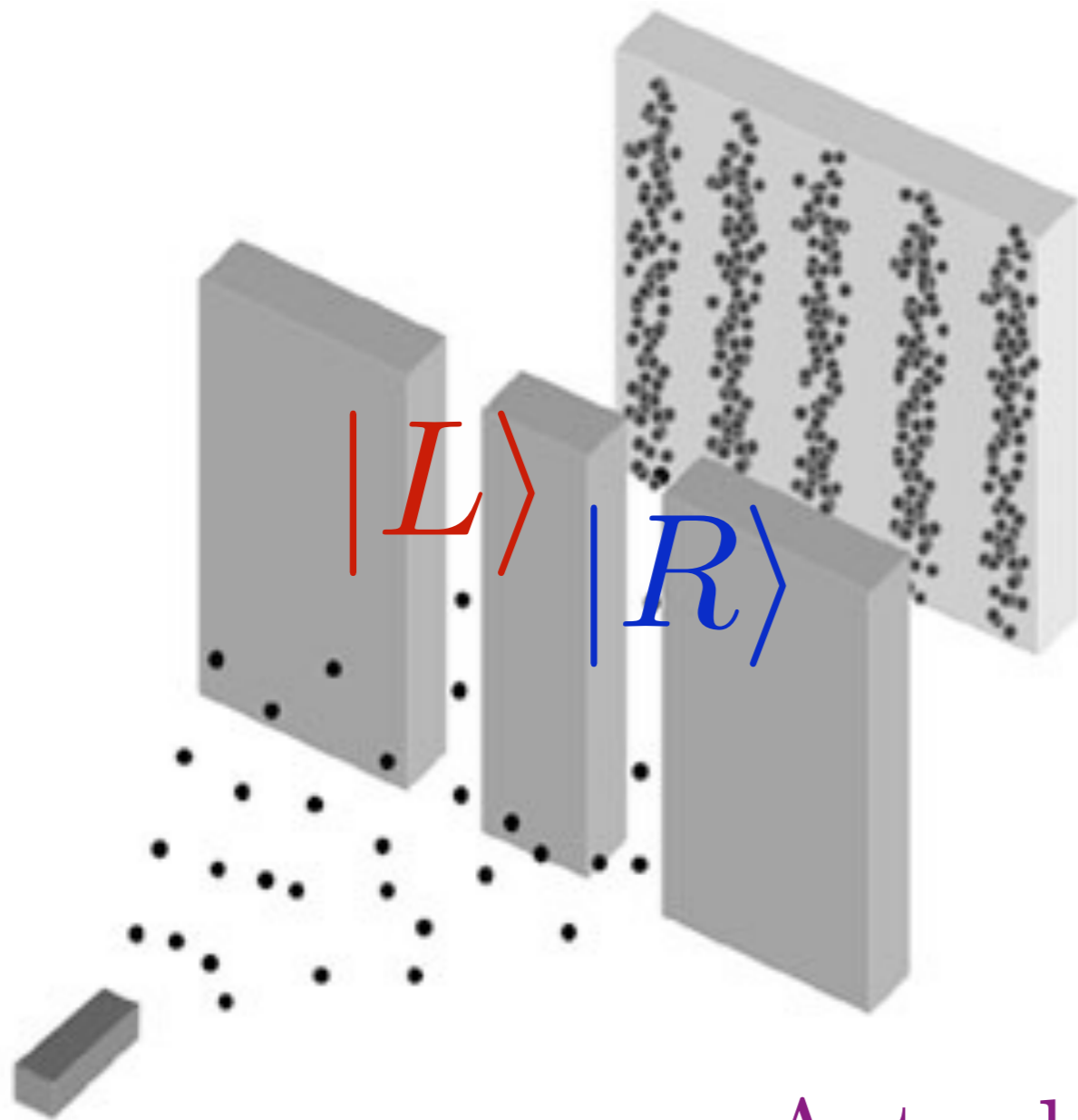


Let $|L\rangle$ represent the state with the electron in the left slit

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

Principles of Quantum Mechanics: I. Quantum Superposition

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

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

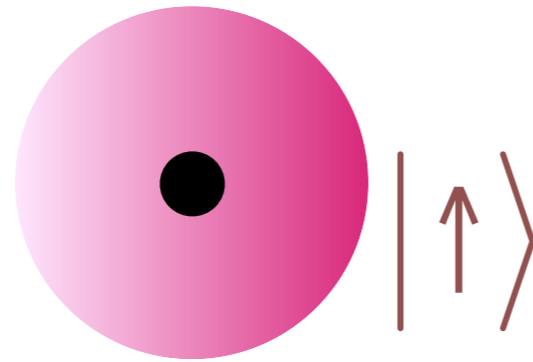
Principles of Quantum Mechanics: II. Quantum Entanglement

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:

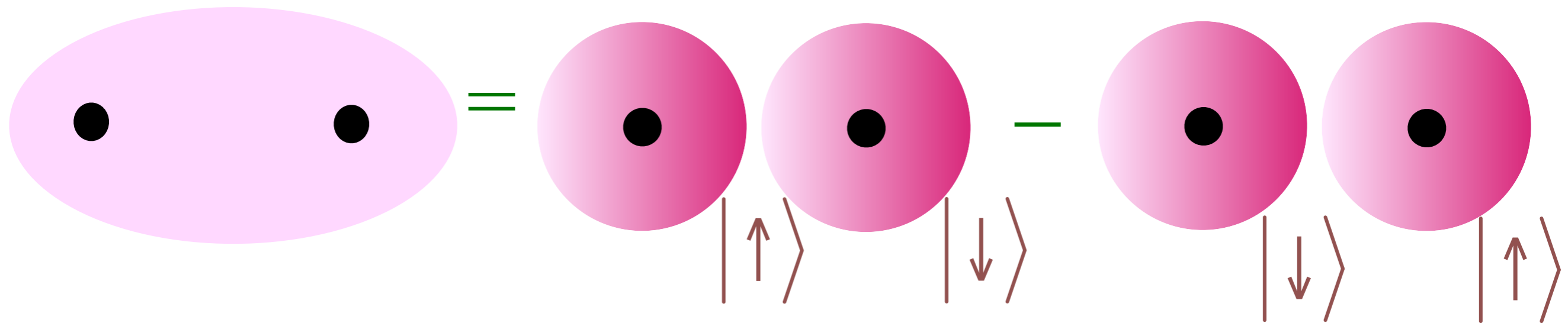


Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom: 

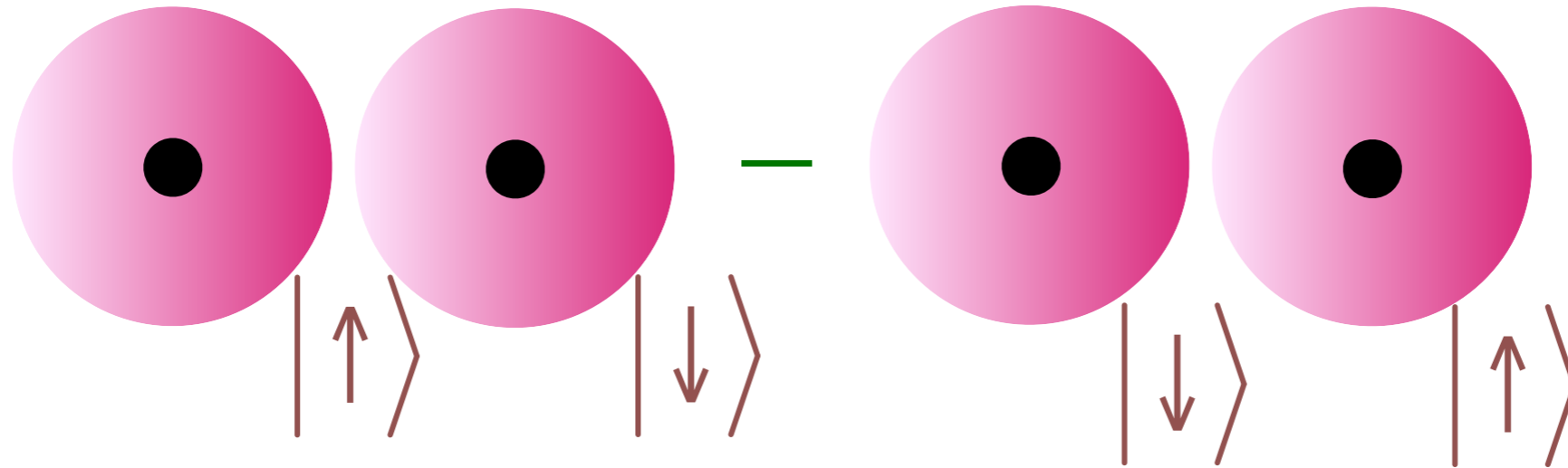
Hydrogen molecule:



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

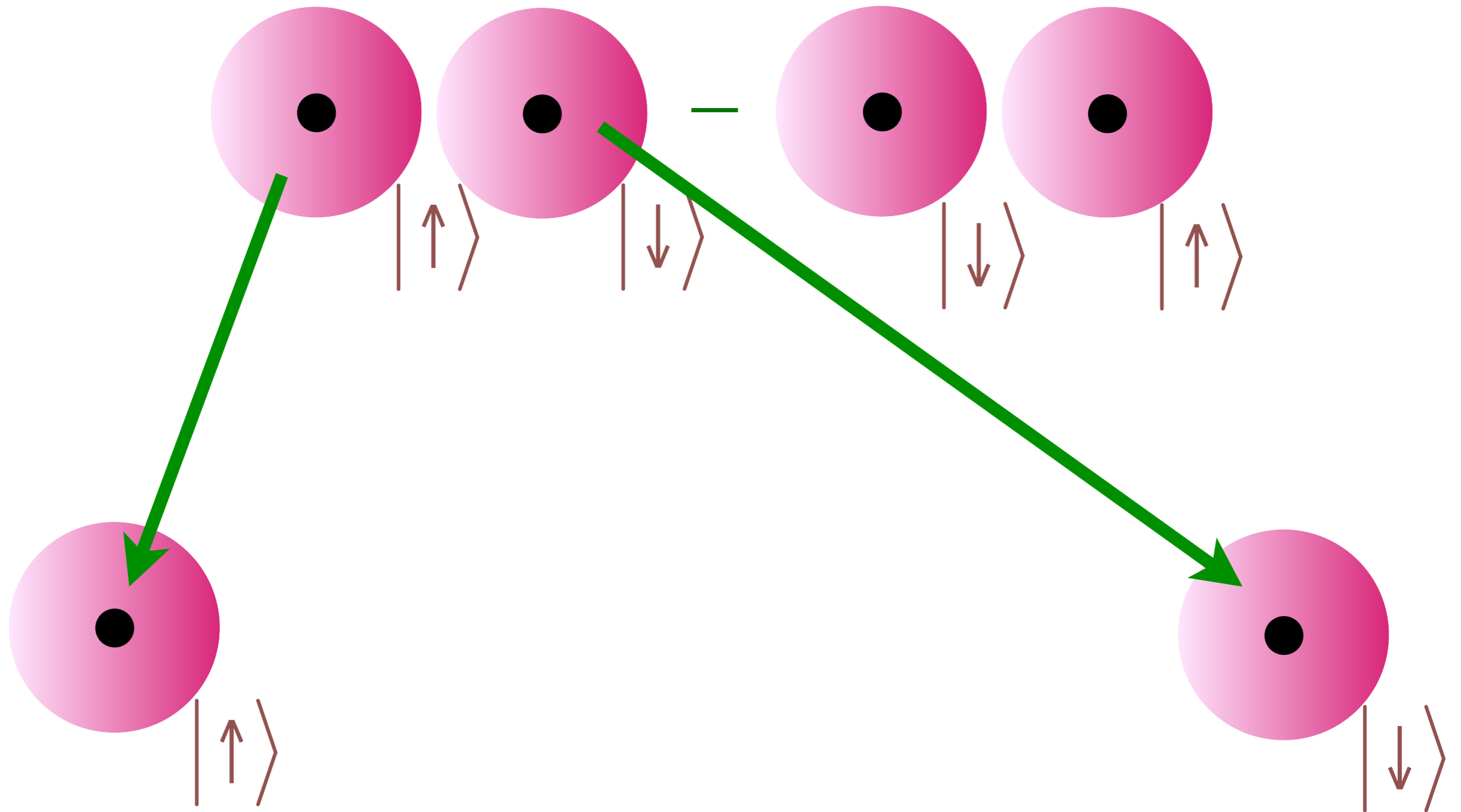
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Quantum Entanglement: quantum superposition with more than one particle



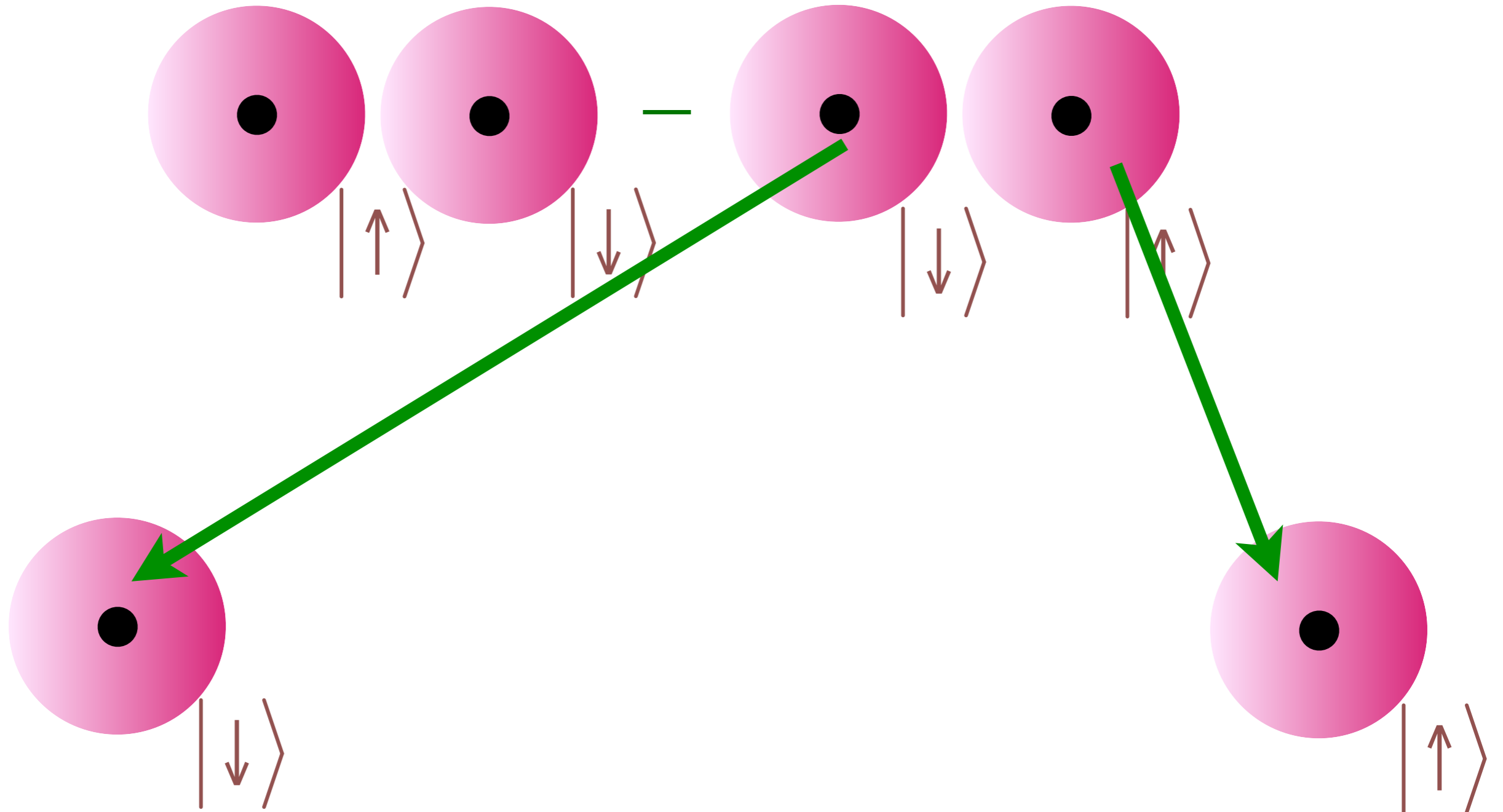
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Quantum Entanglement: quantum superposition with more than one particle



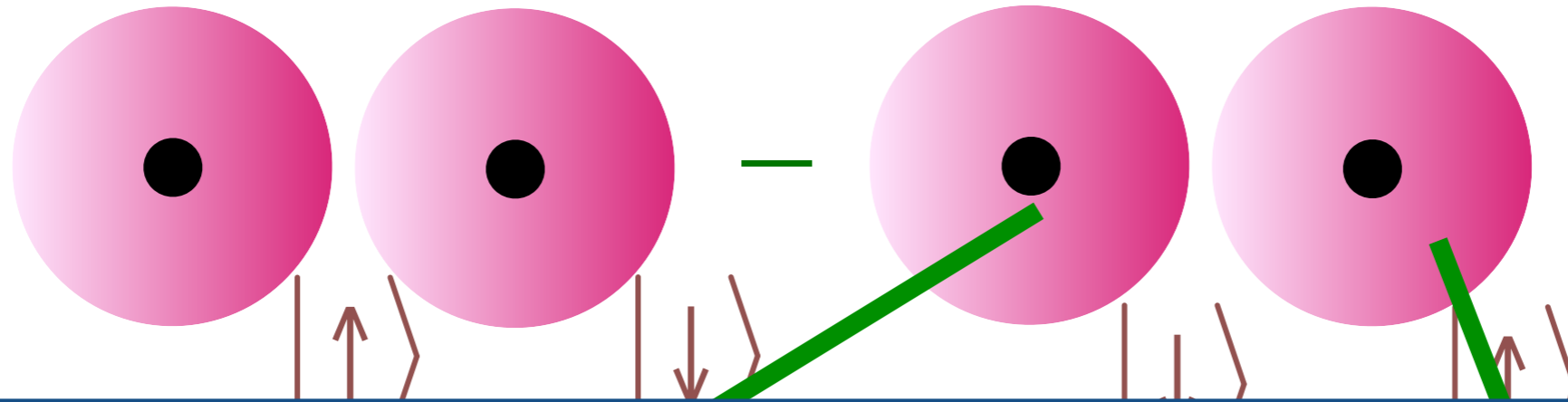
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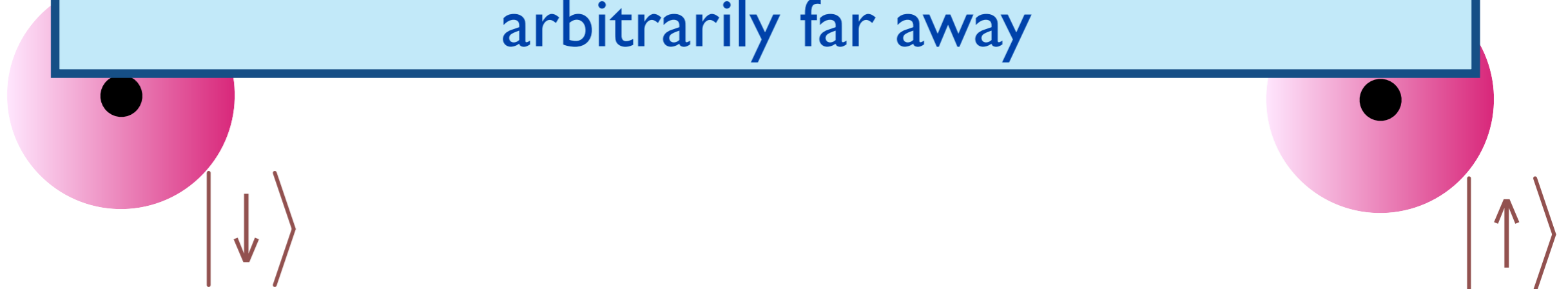


Principles of Quantum Mechanics: II. Quantum Entanglement

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**

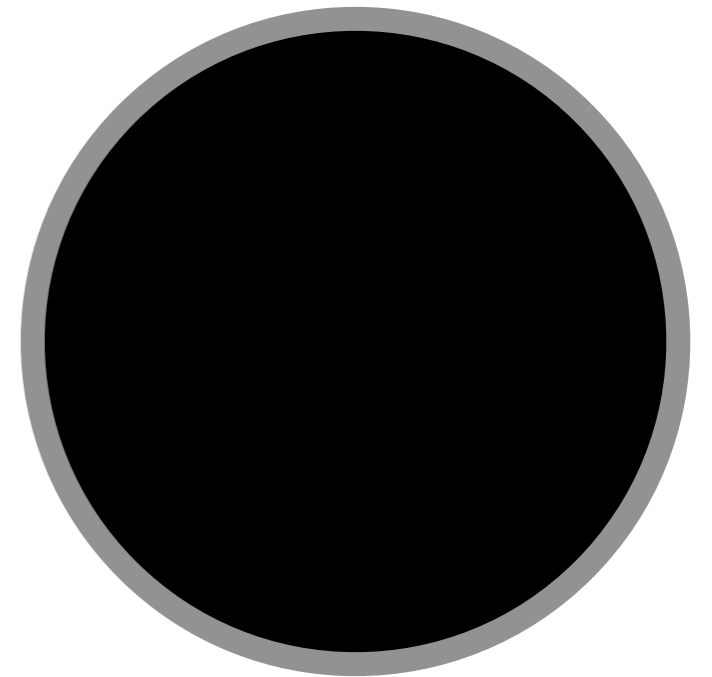
**Black
holes**

Black Holes

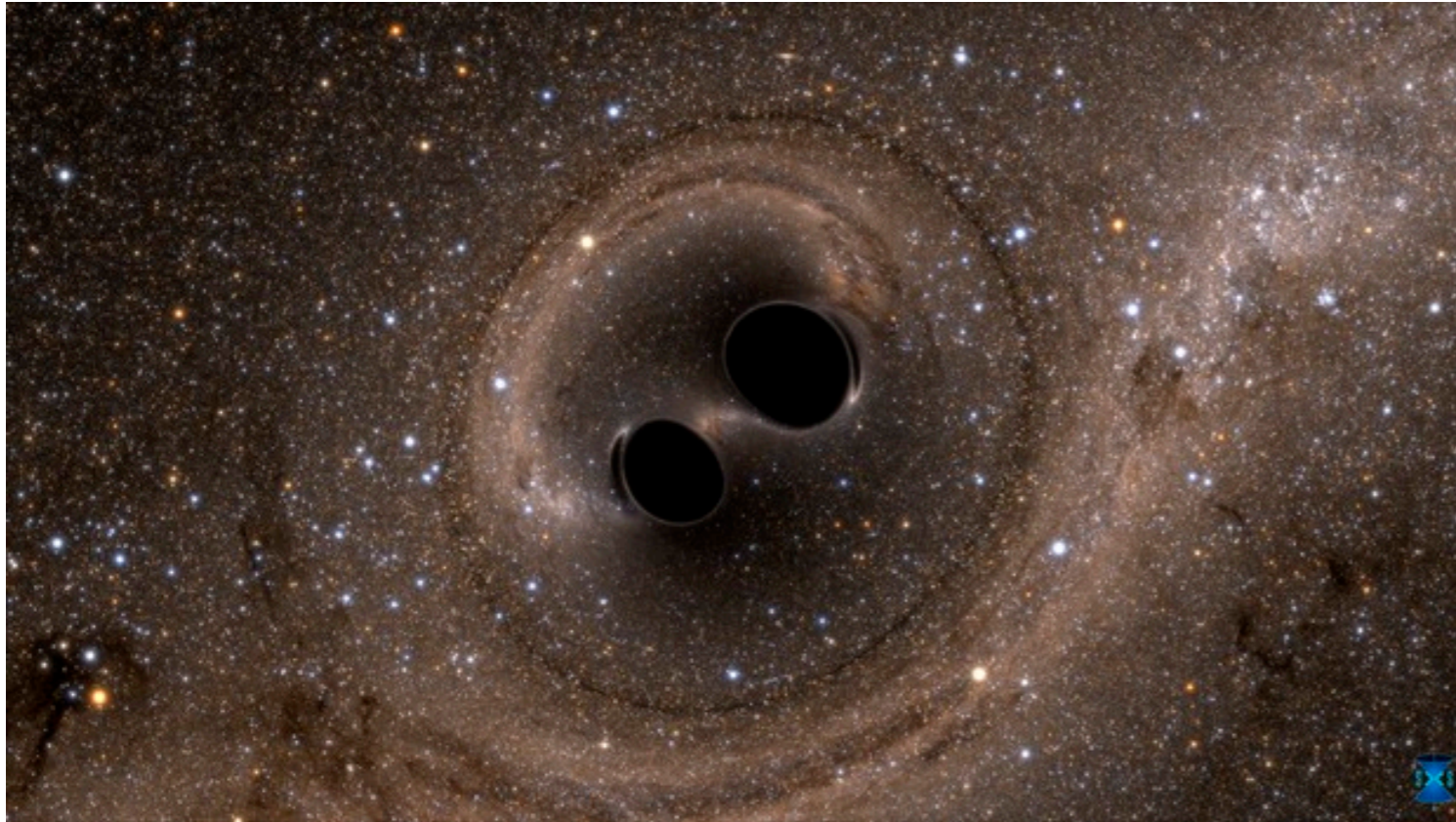
Objects so dense that light is gravitationally bound to them.

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

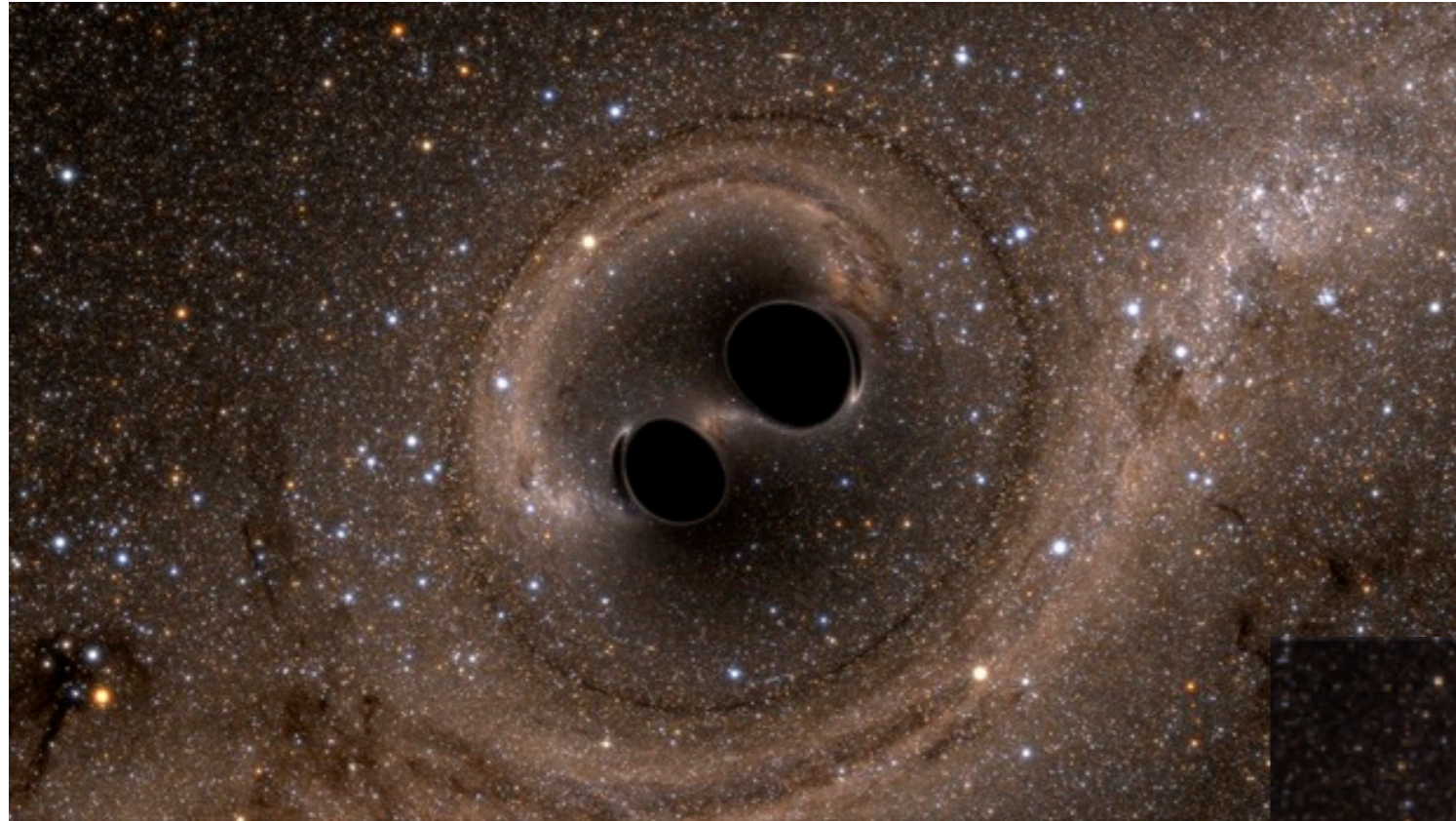
Horizon radius $R = \frac{2GM}{c^2}$



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



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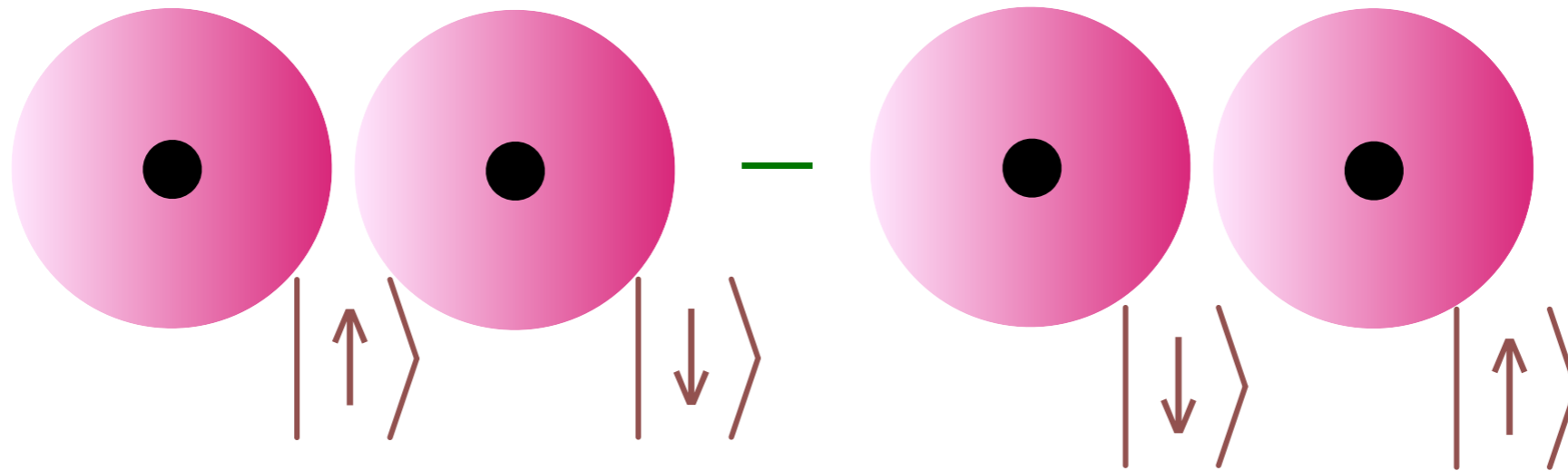
0.1 seconds later !



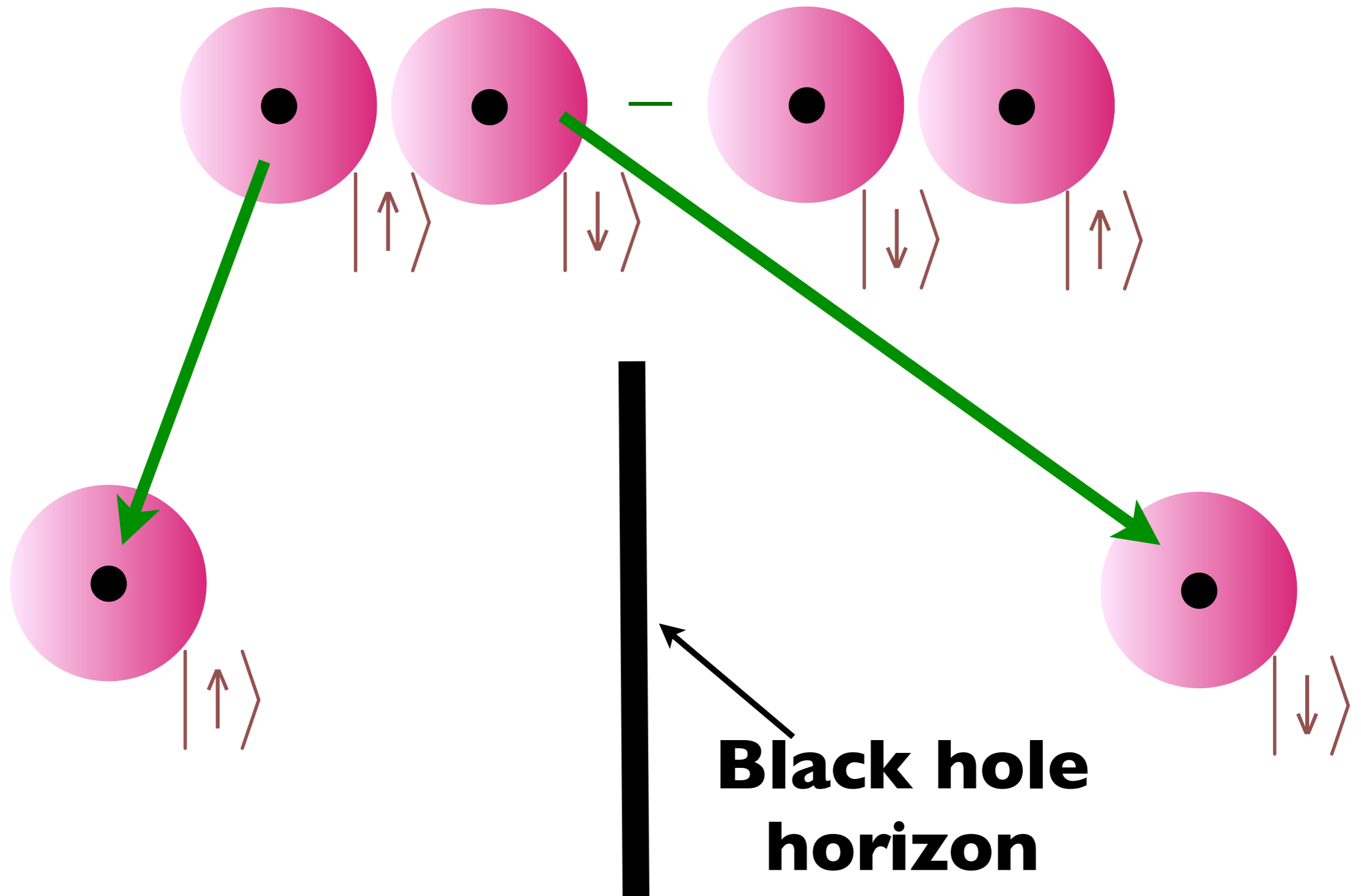
Black Holes + Quantum theory

Around 1974, Bekenstein and Hawking showed that the application of the quantum theory across a black hole horizon led to many astonishing conclusions

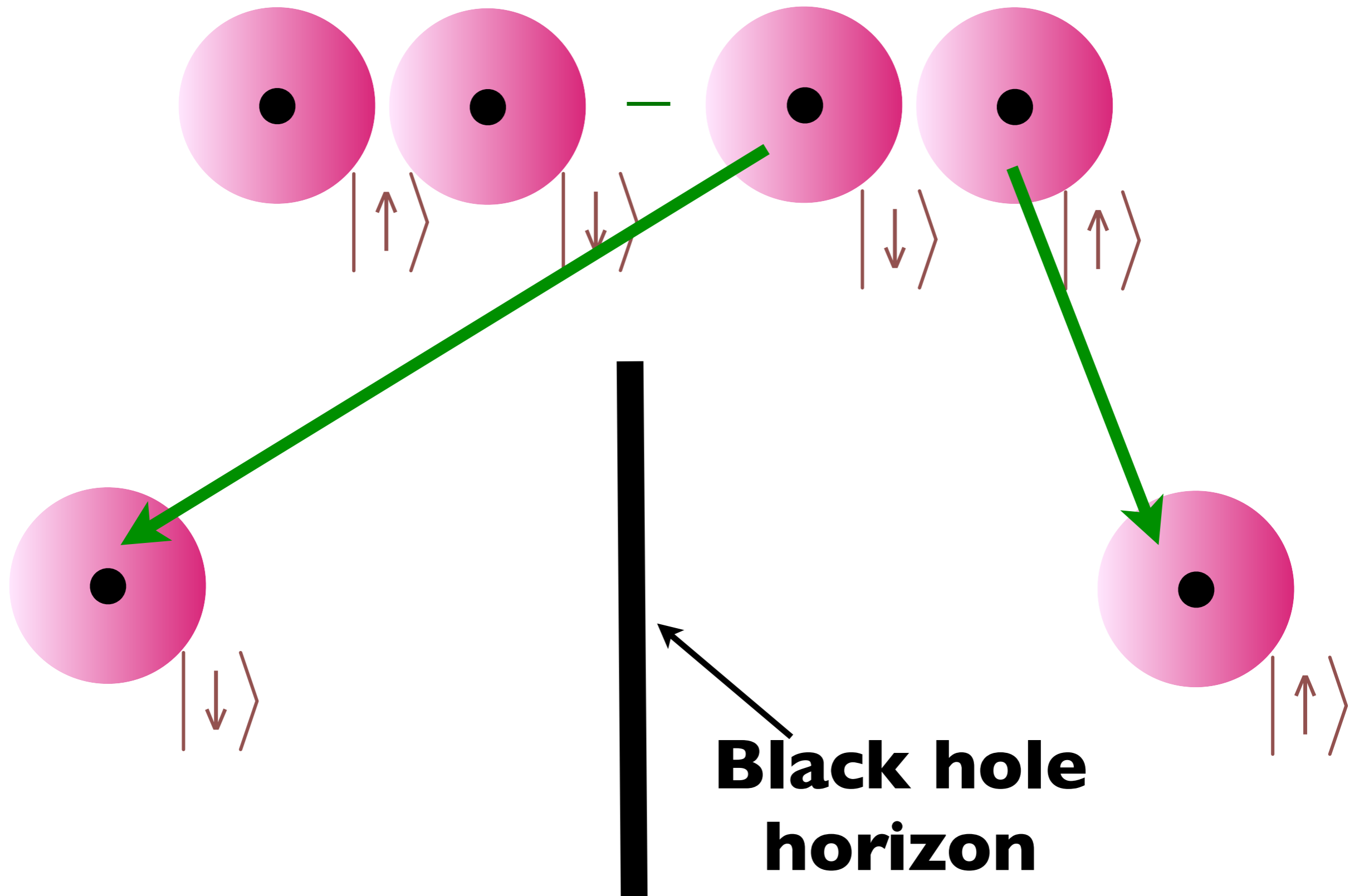
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

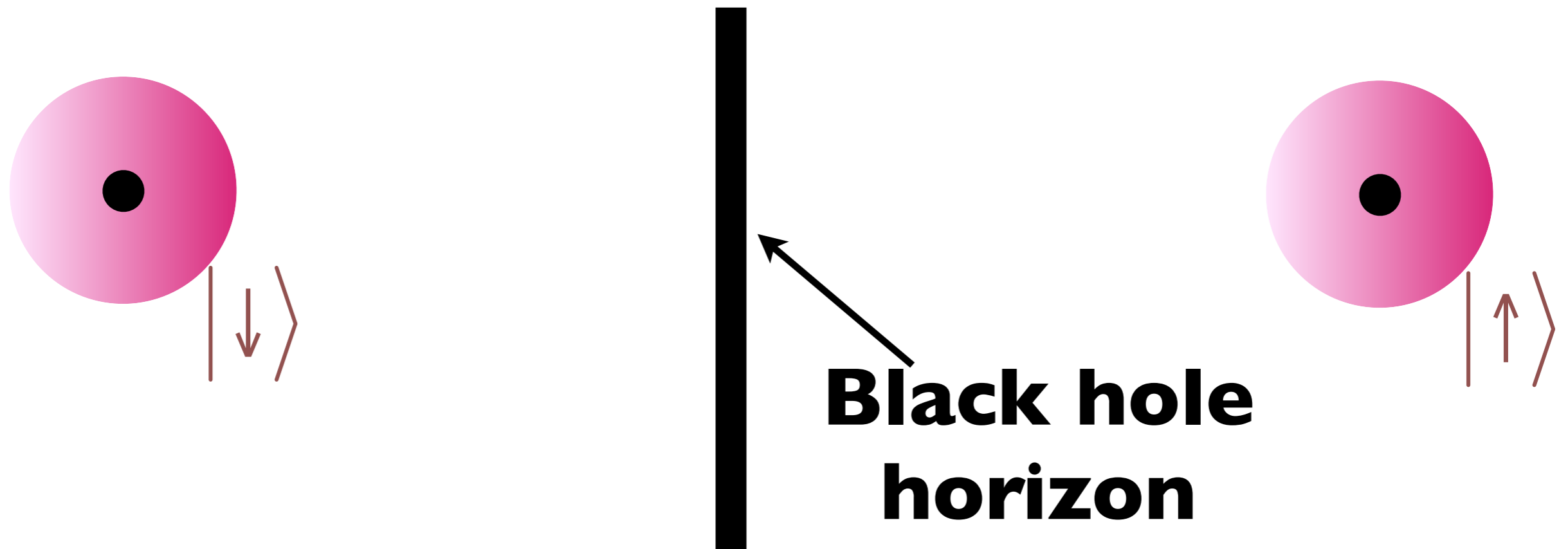


Quantum Entanglement across a black hole horizon



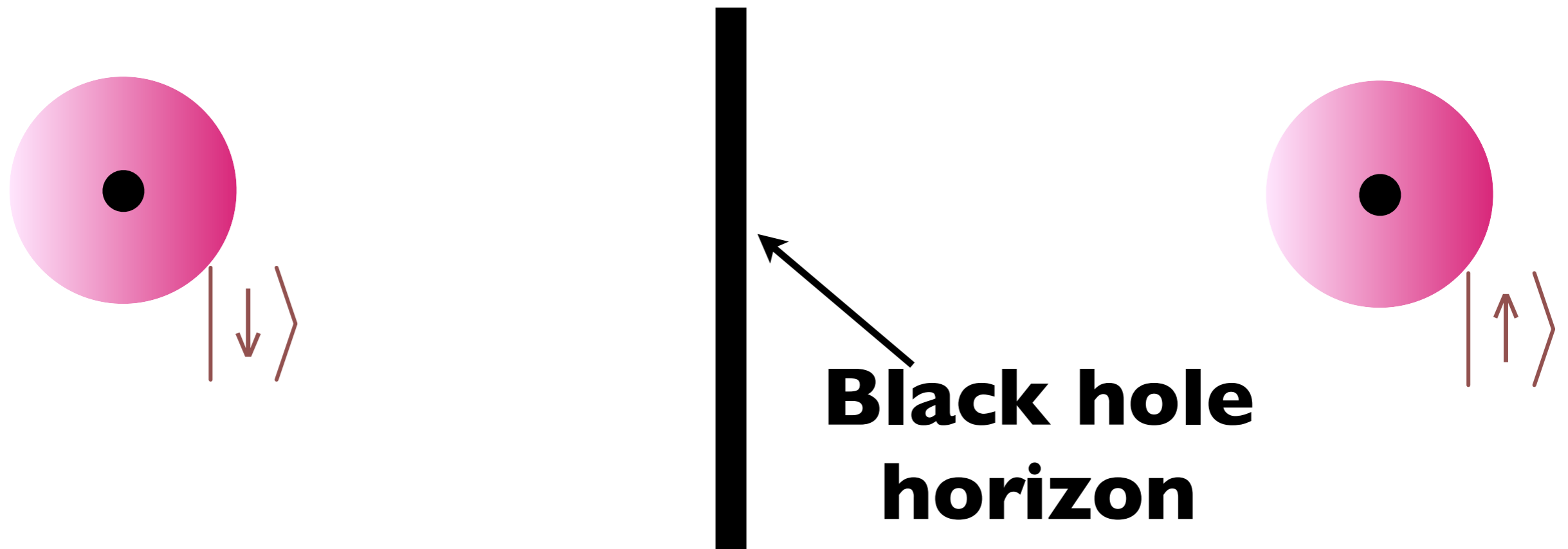
Quantum Entanglement across a black hole horizon

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



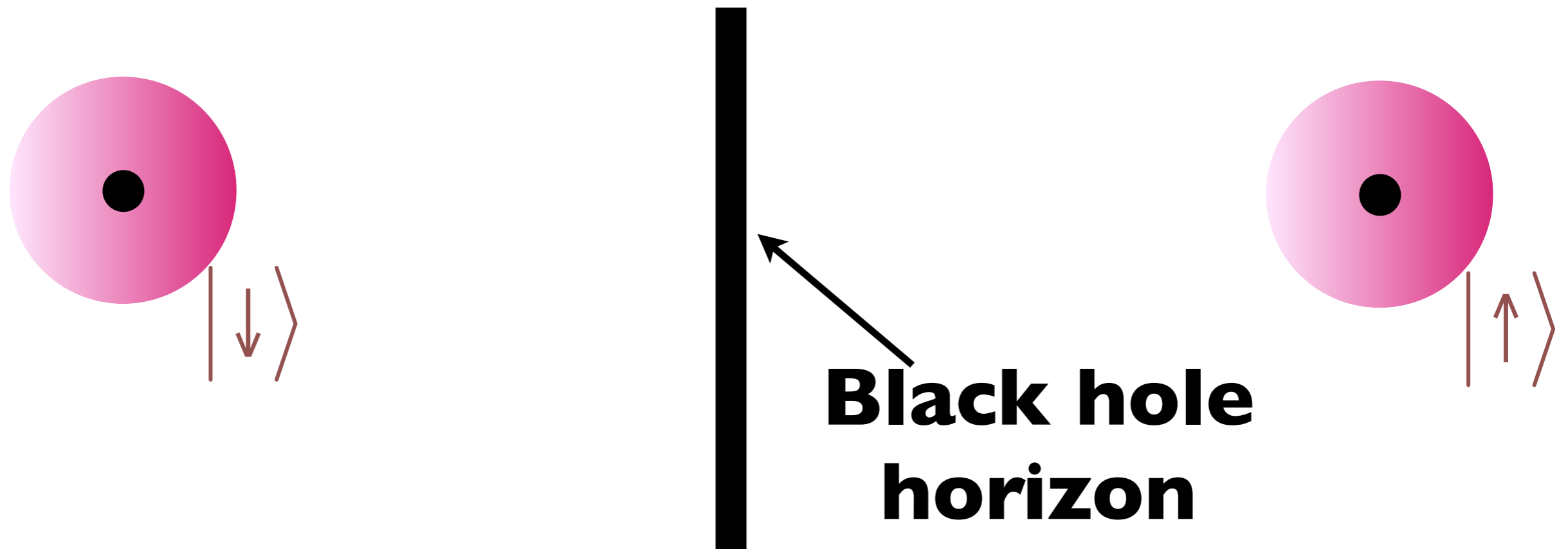
Quantum Entanglement across a black hole horizon

Hawking used this to show that black hole horizons have an entropy and a temperature



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
entanglement**

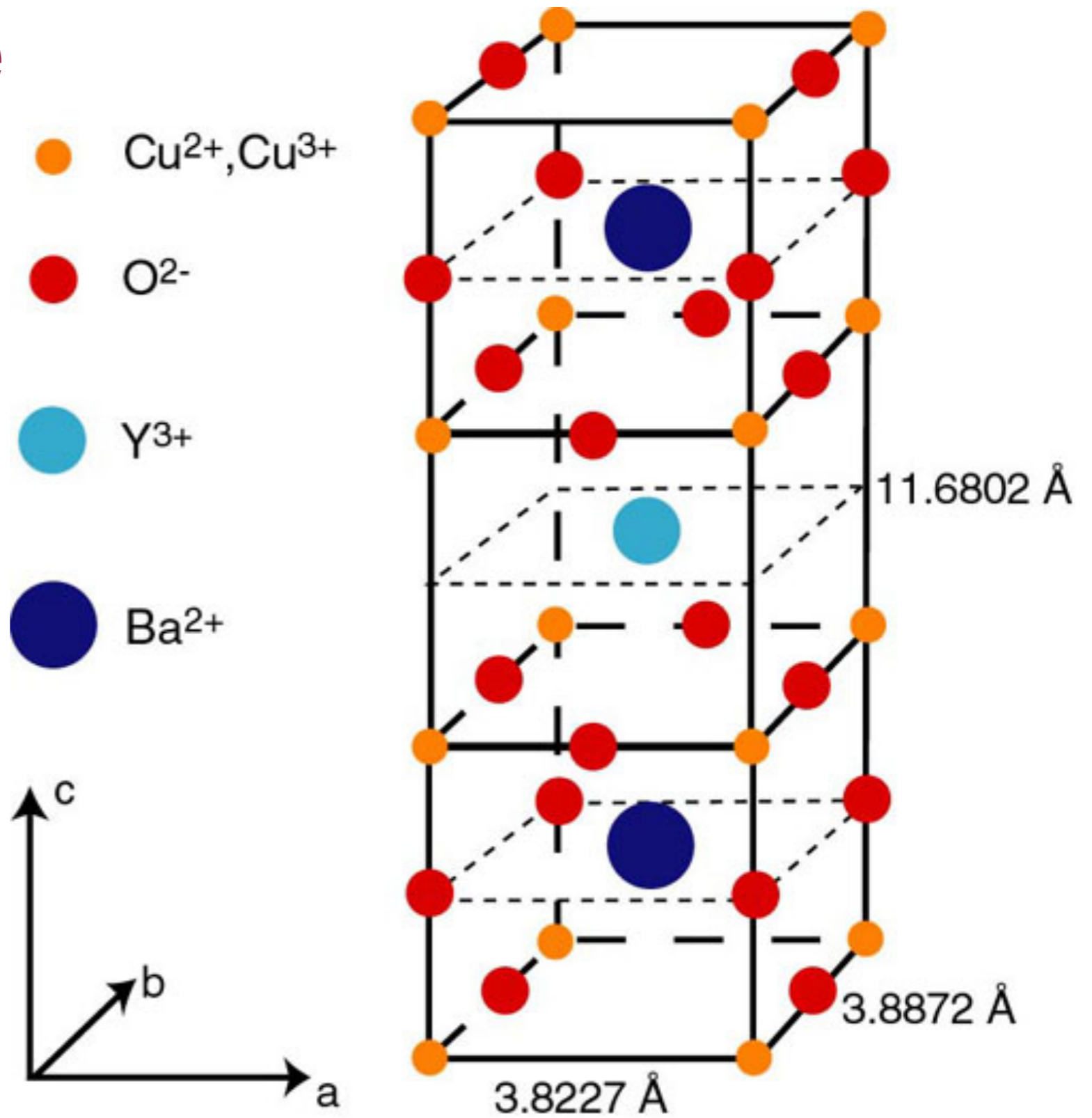
**Black
holes**

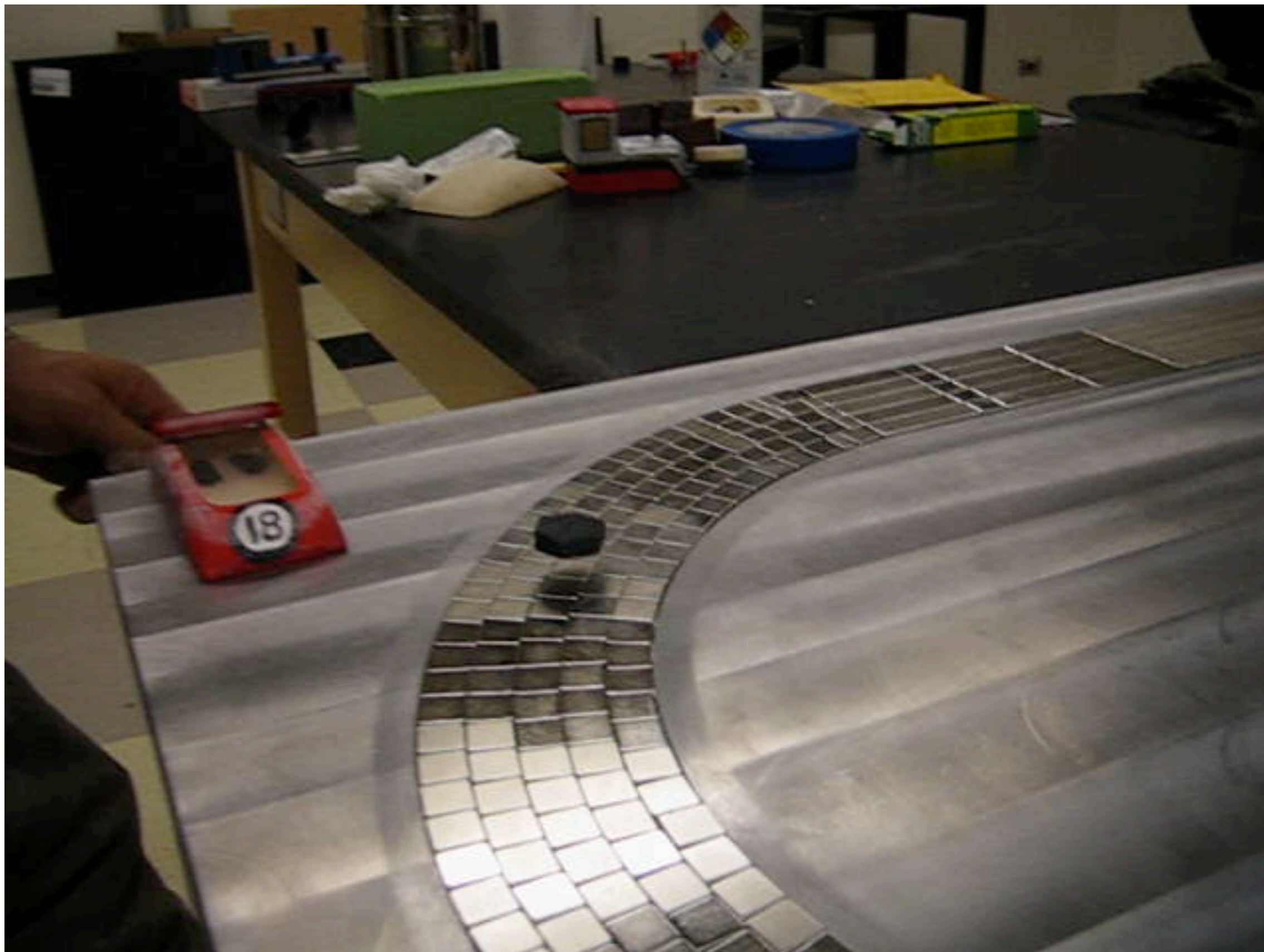
**Quantum
entanglement**

**Black
holes**

Superconductors

High temperature superconductors





Nd-Fe-B magnets, YBaCuO superconductor

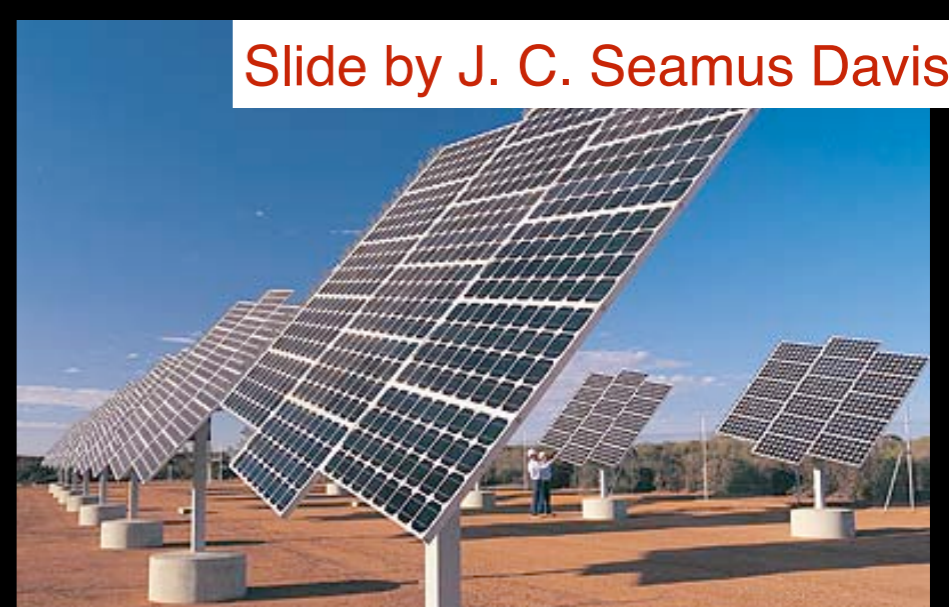
Julian Hetel and Nandini Trivedi, Ohio State University



Power Efficiency/Capacity/Stability



Power Bottlenecks



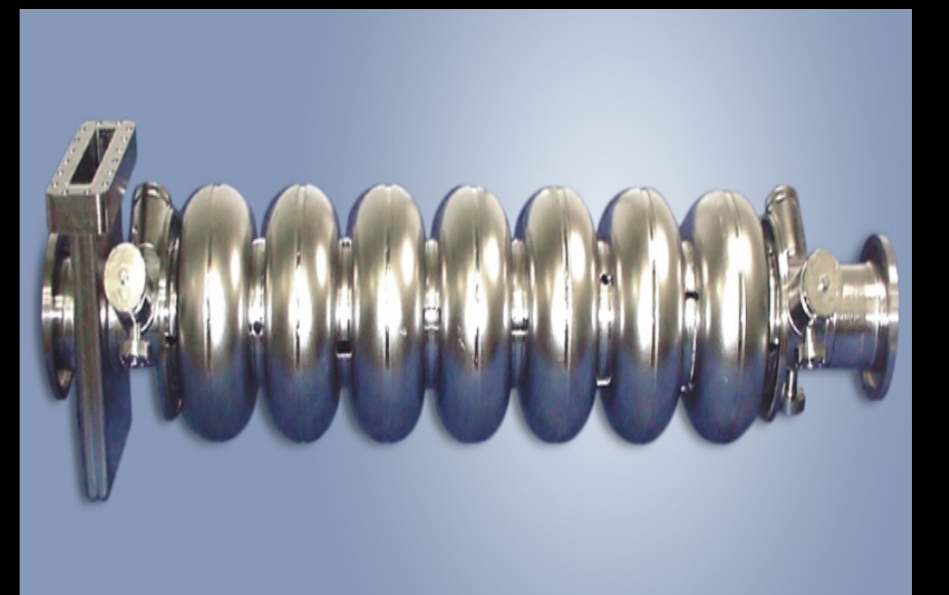
Accommodate Renewable Power



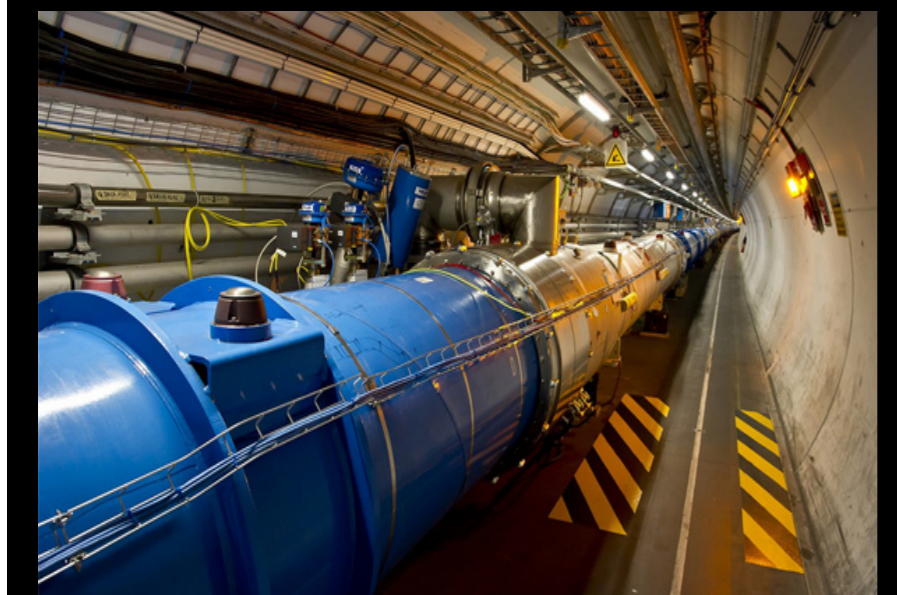
Efficient Rotating Machines



Information Technology



Next Generation HEP



Ultra-High Magnetic Fields

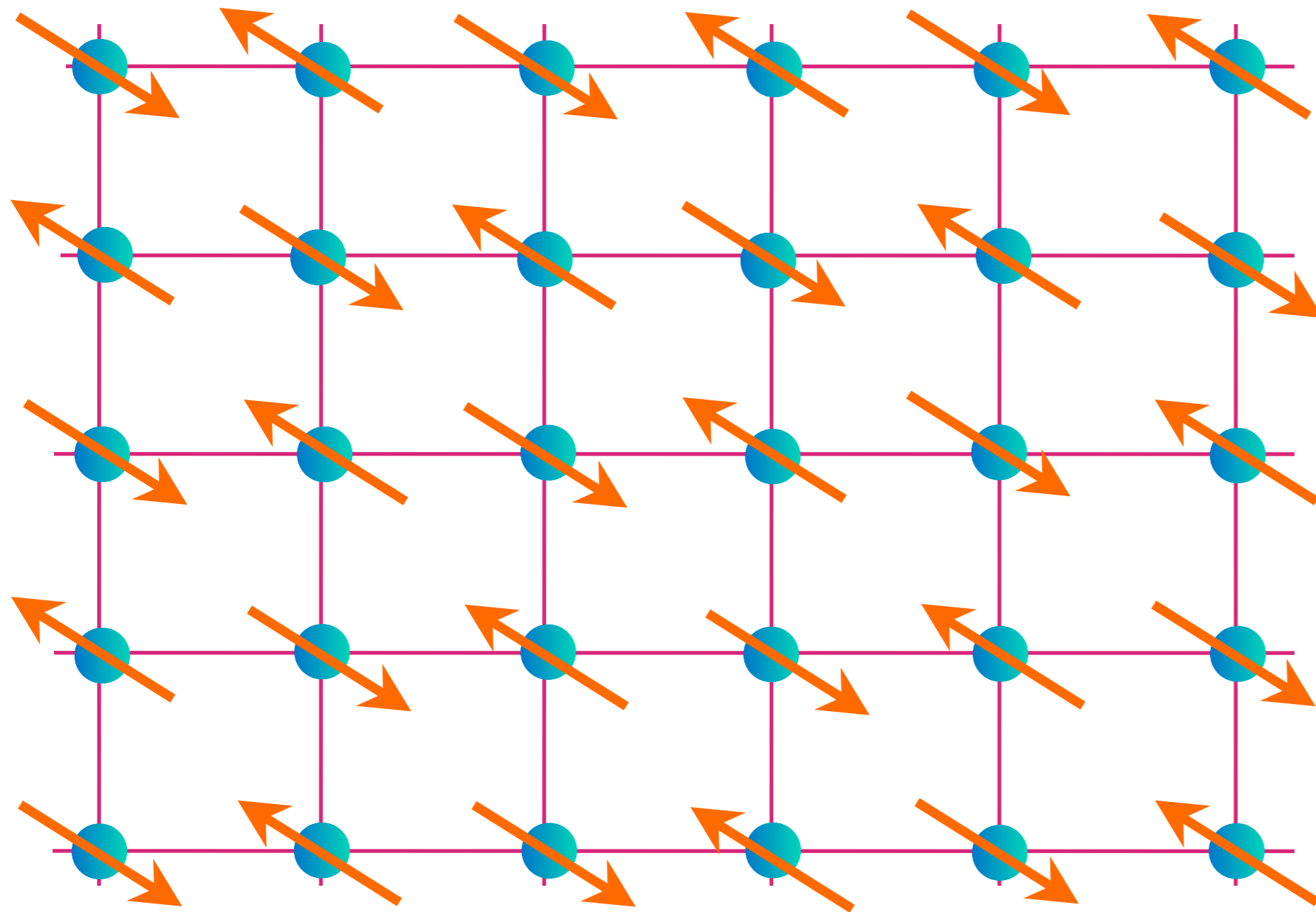


Medical

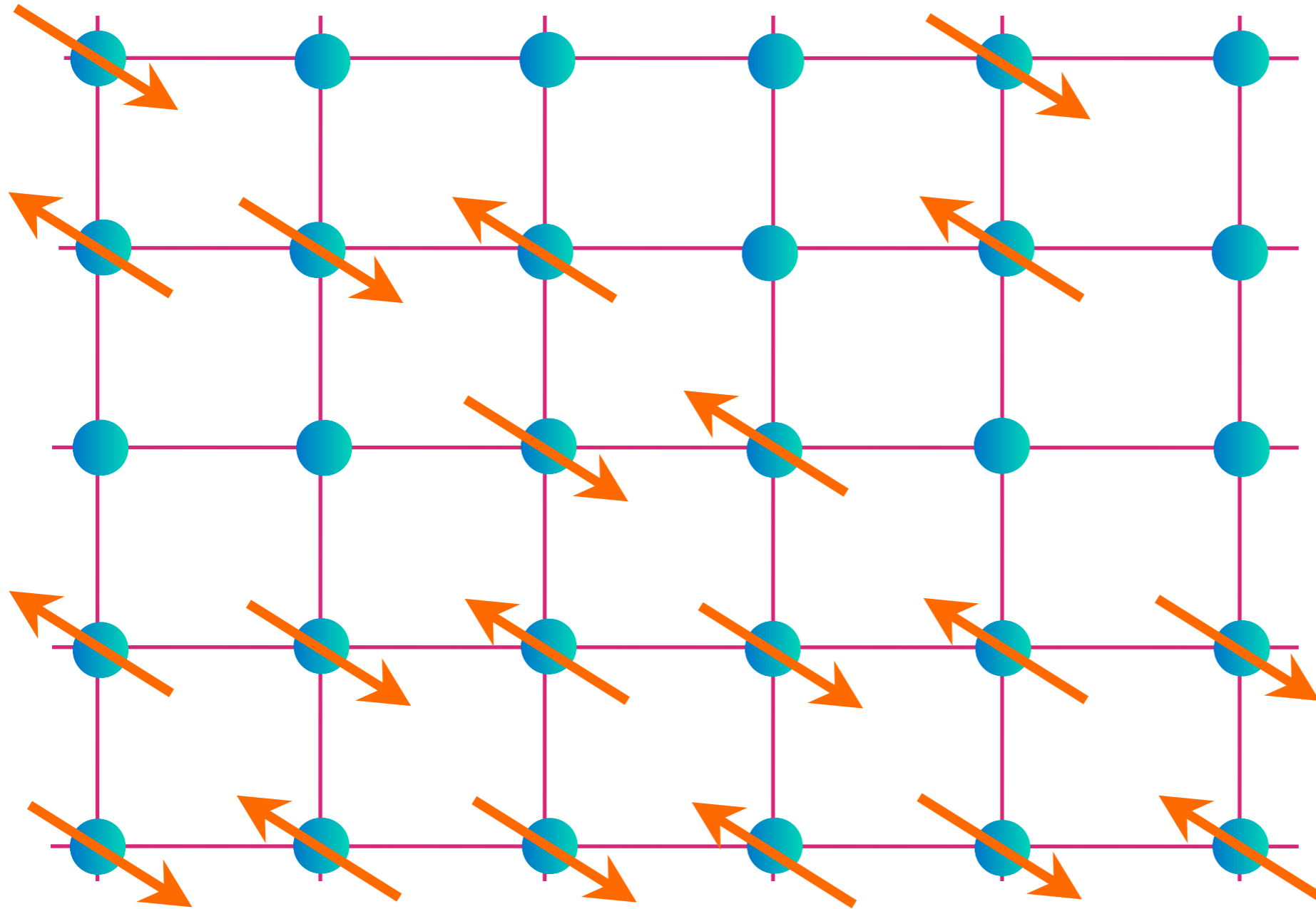


Transport

Square lattice of Cu sites

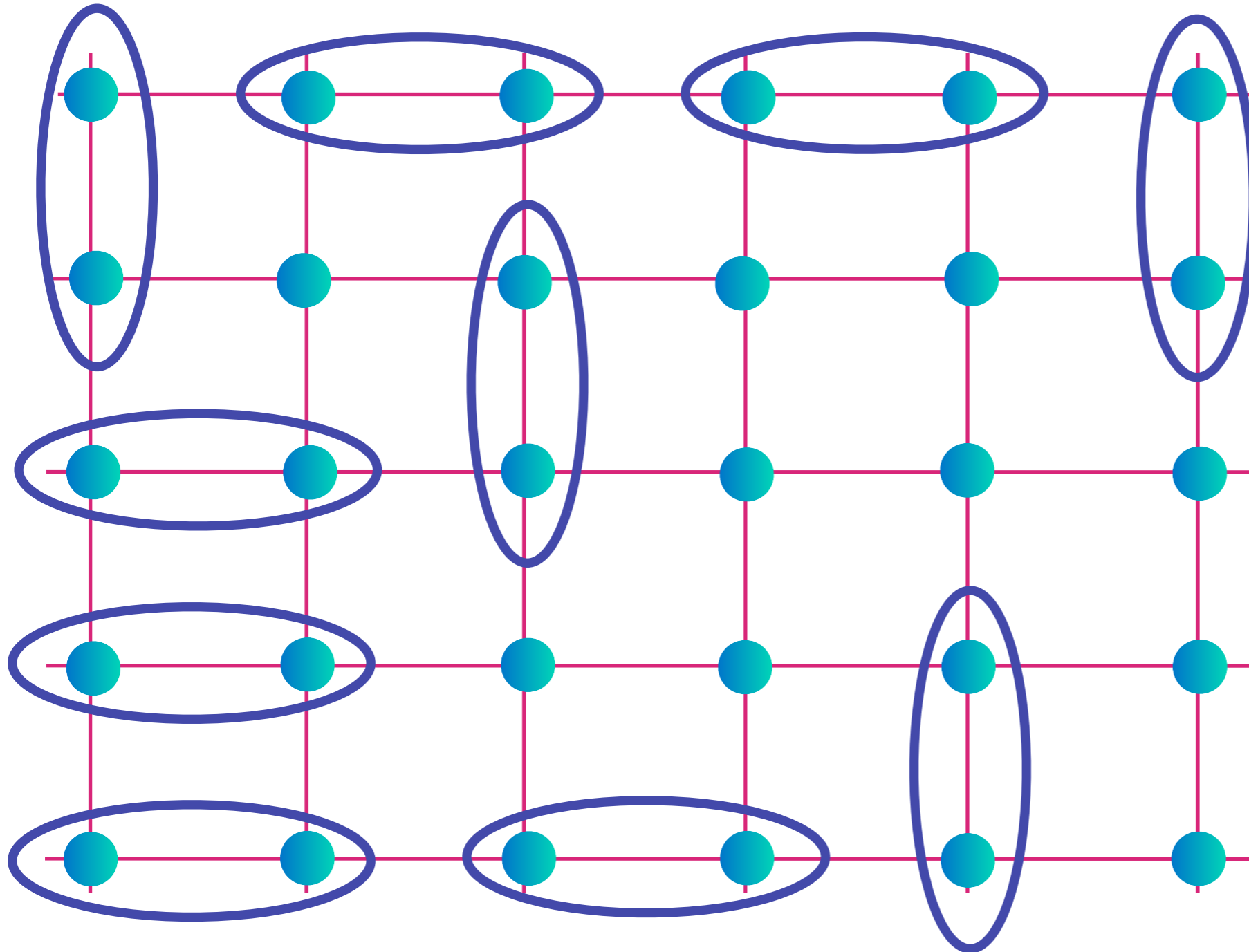


Square lattice of Cu sites



Remove some
electrons

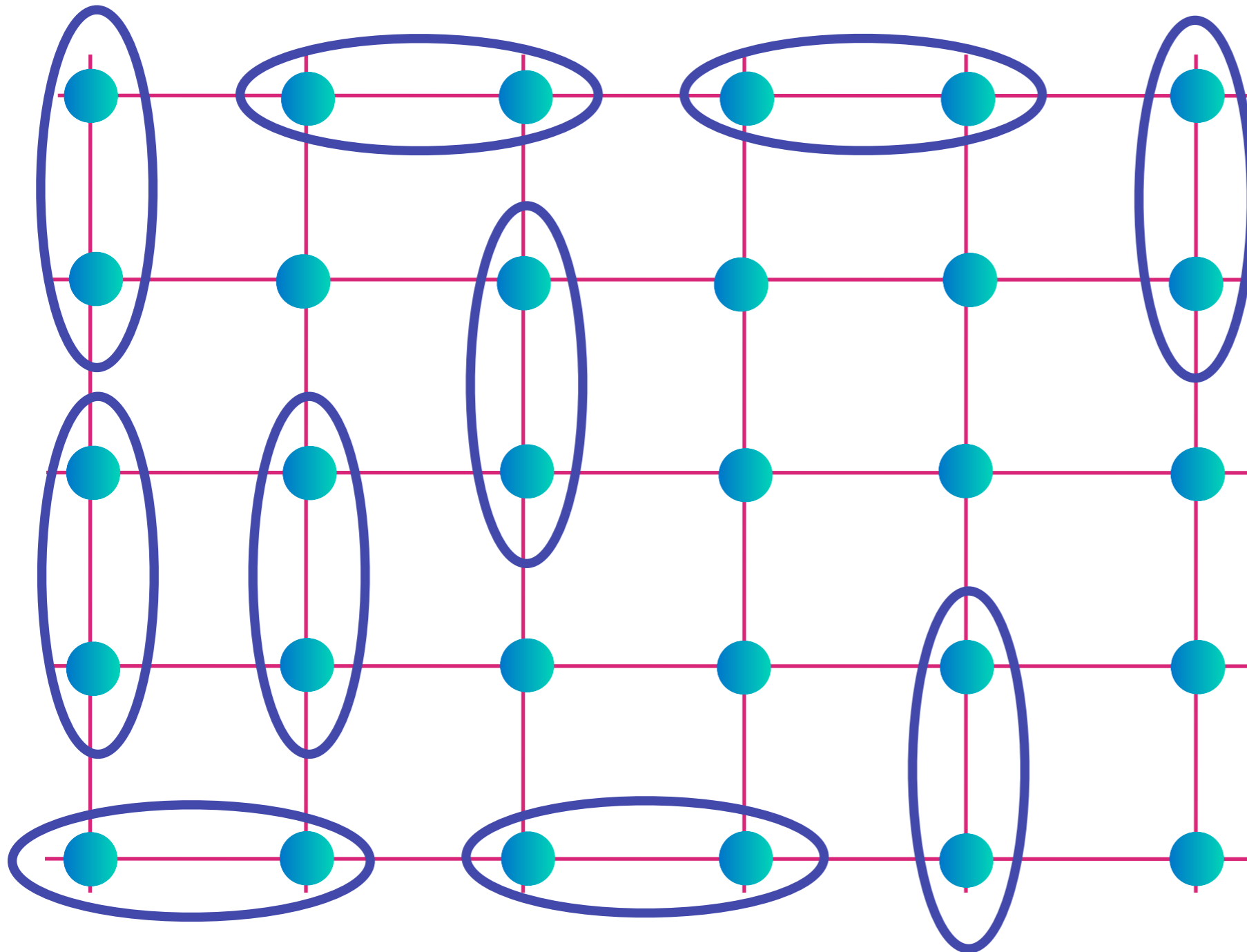
Square lattice of Cu sites



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

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

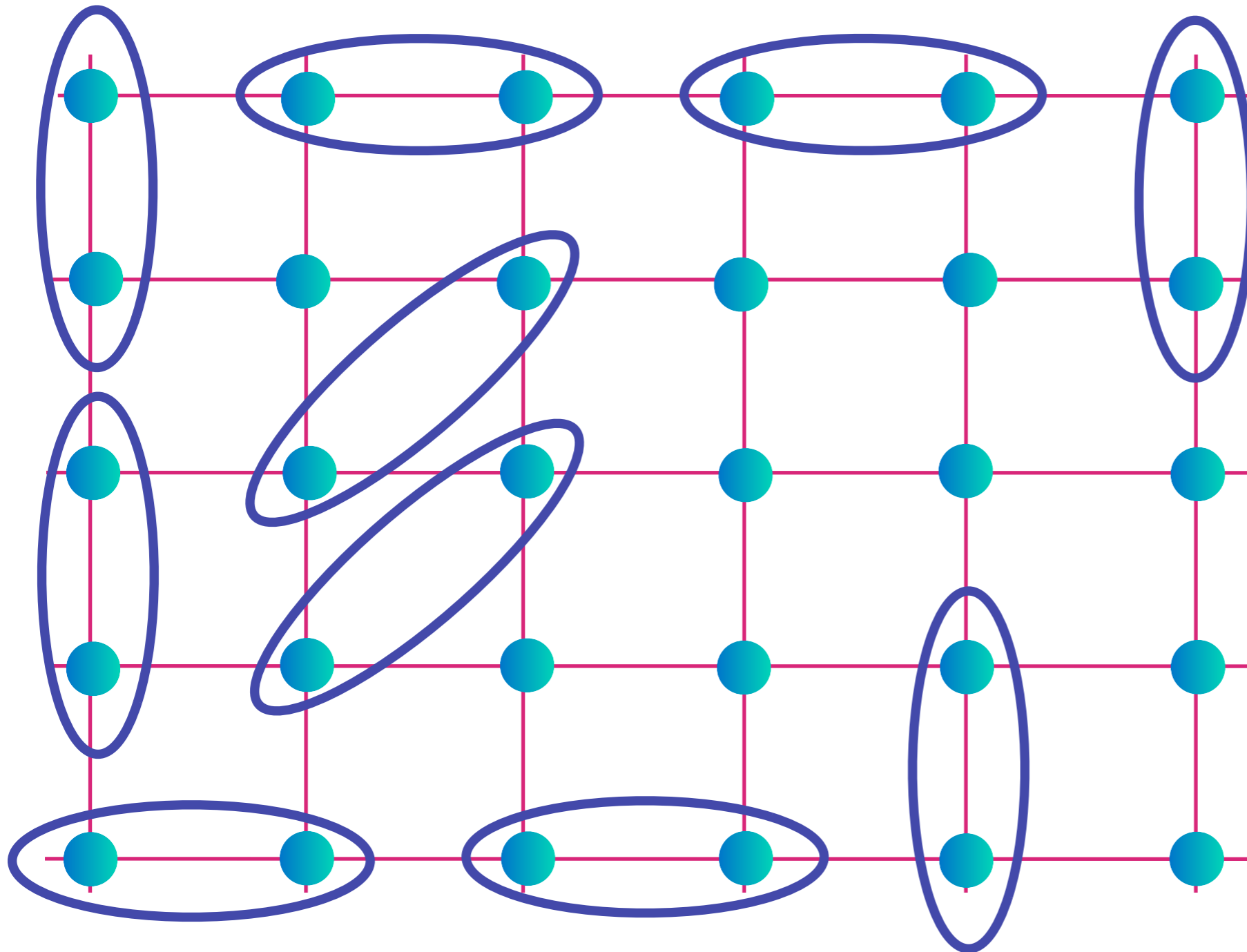
Square lattice of Cu sites



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

$$\text{[Oval with two sites]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

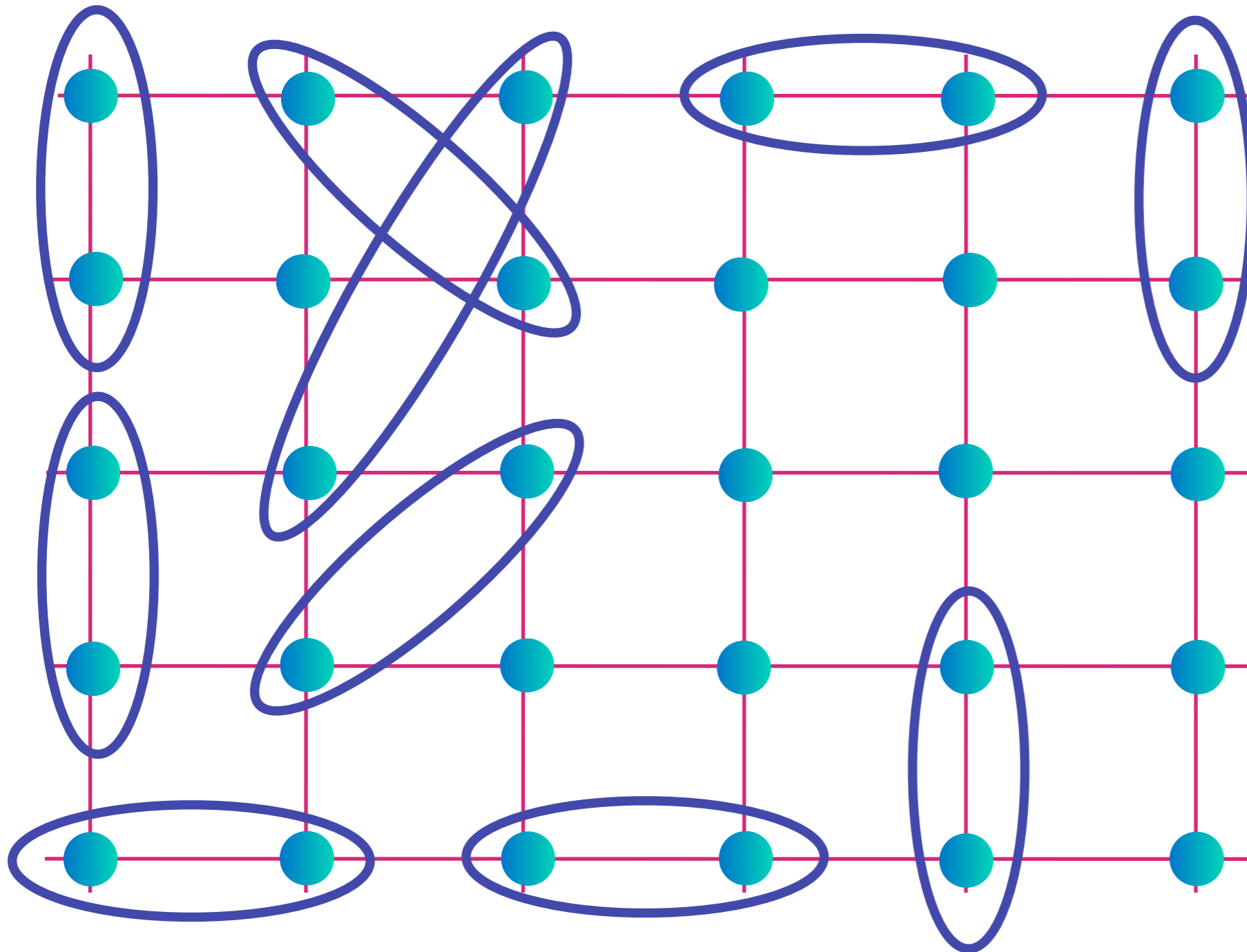
Square lattice of Cu sites



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

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

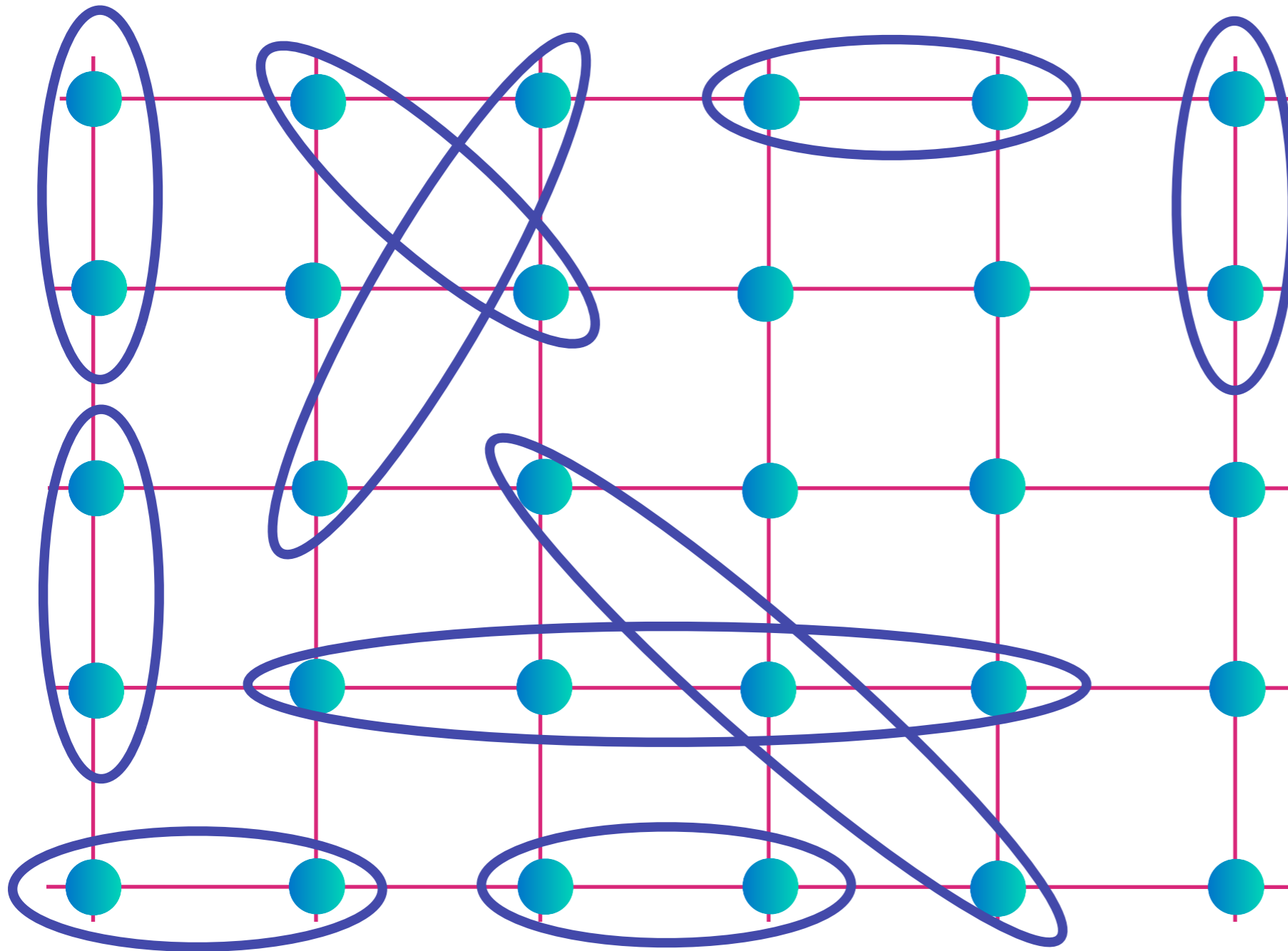
Square lattice of Cu sites



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

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

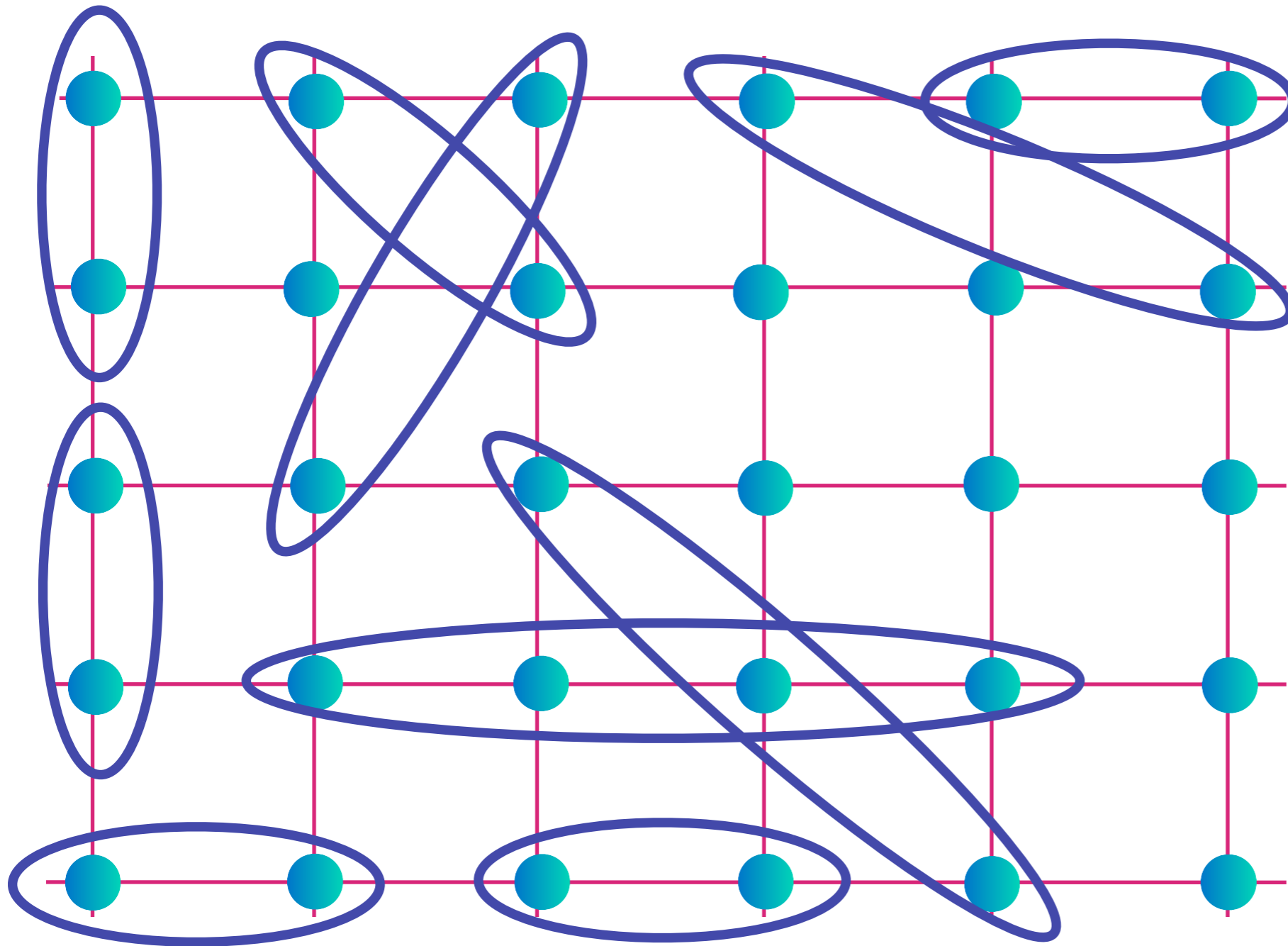
Square lattice of Cu sites



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

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

Square lattice of Cu sites



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

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

**Quantum
entanglement**

**Black
holes**

Superconductors

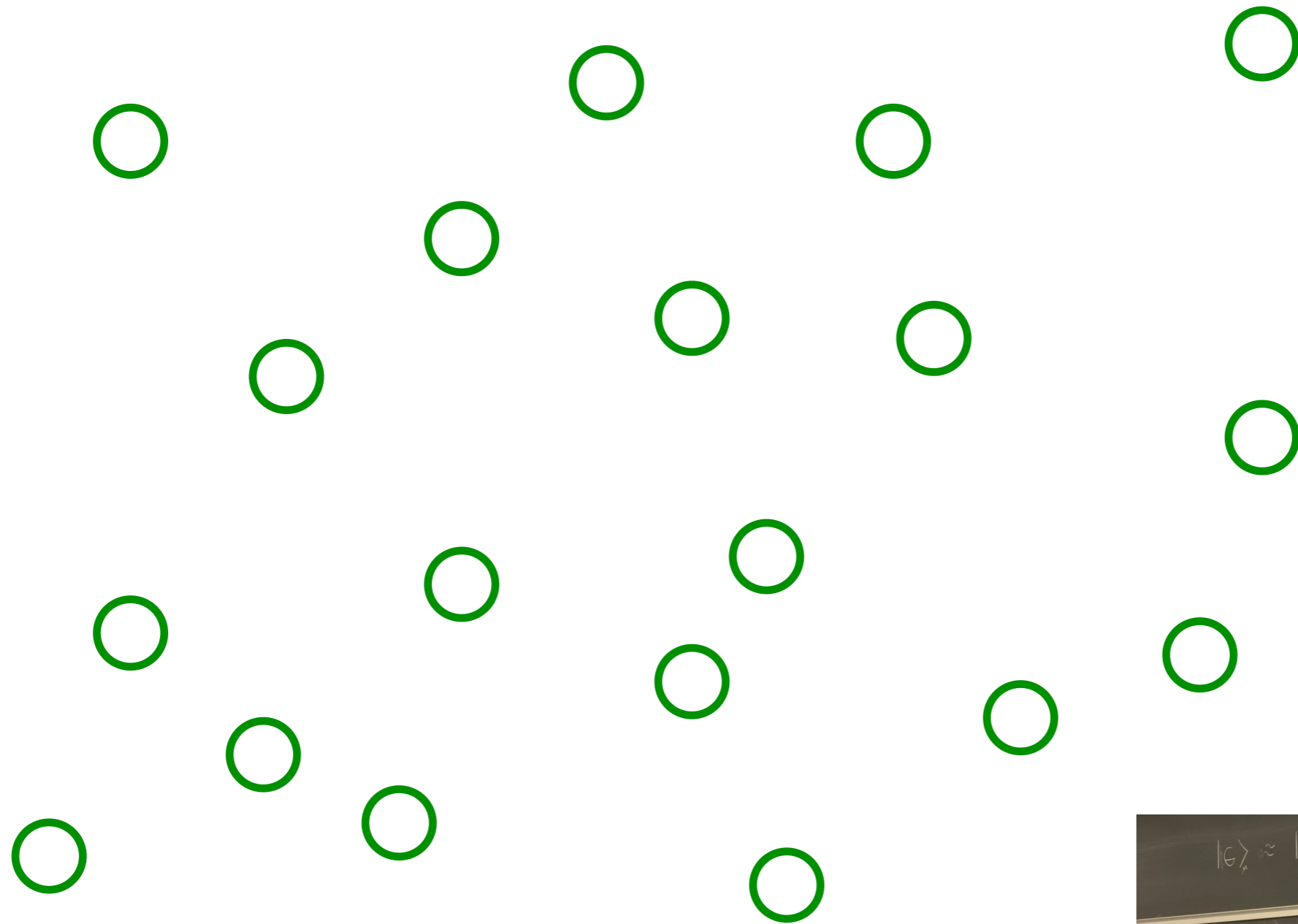
**Quantum
entanglement**

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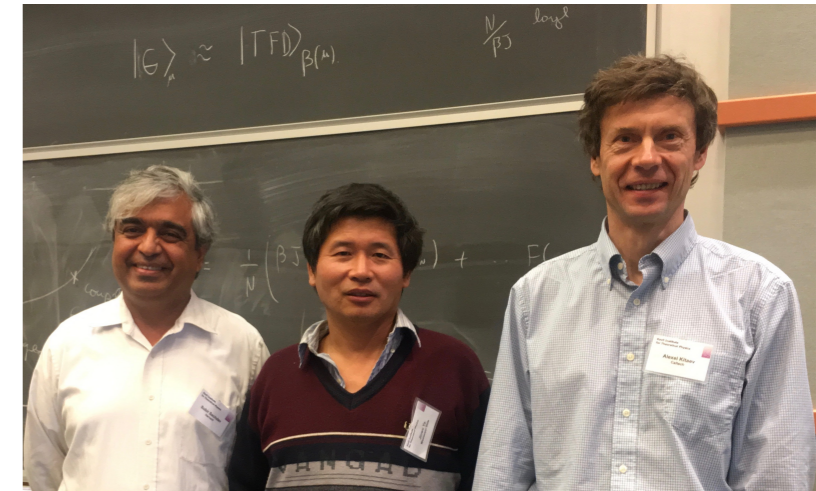
Superconductors

**A “toy model” which describes both
a superconductor and a black hole!**

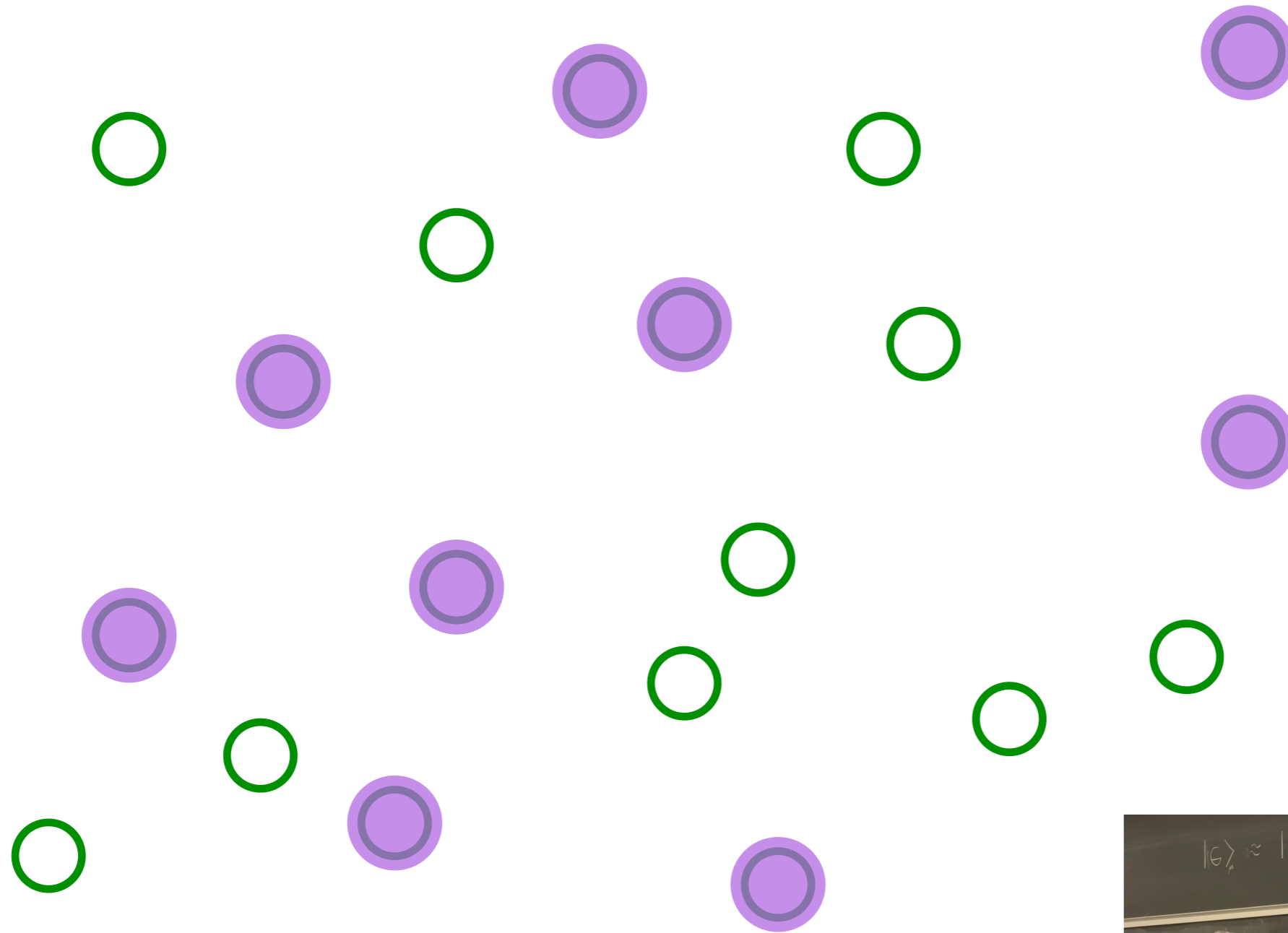
The Sachdev-Ye-Kitaev (SYK) model



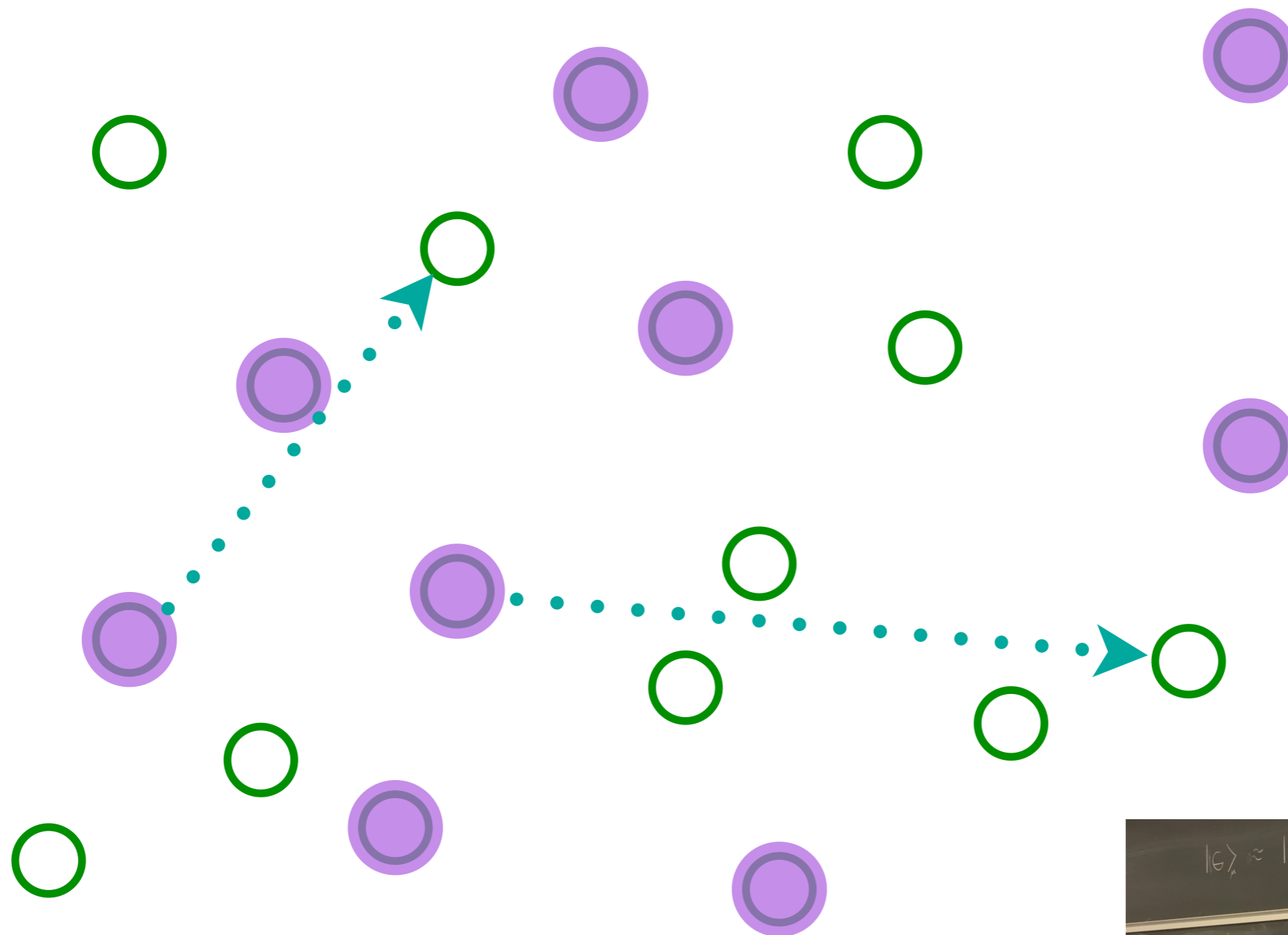
Pick a set of random positions



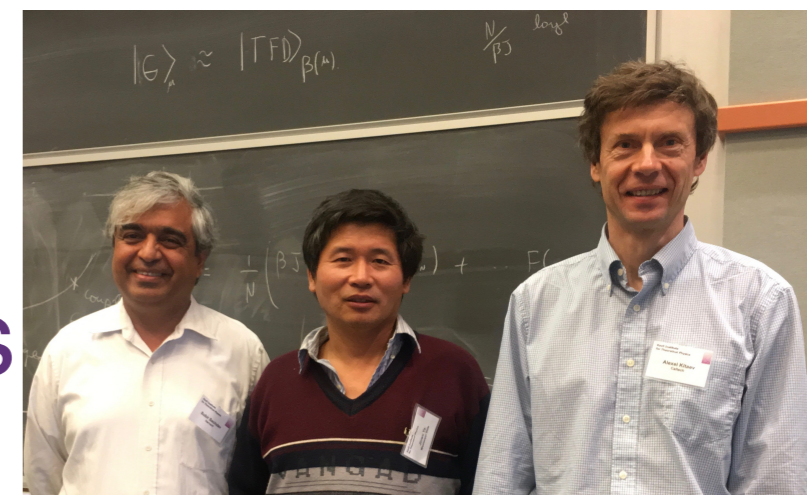
The SYK model



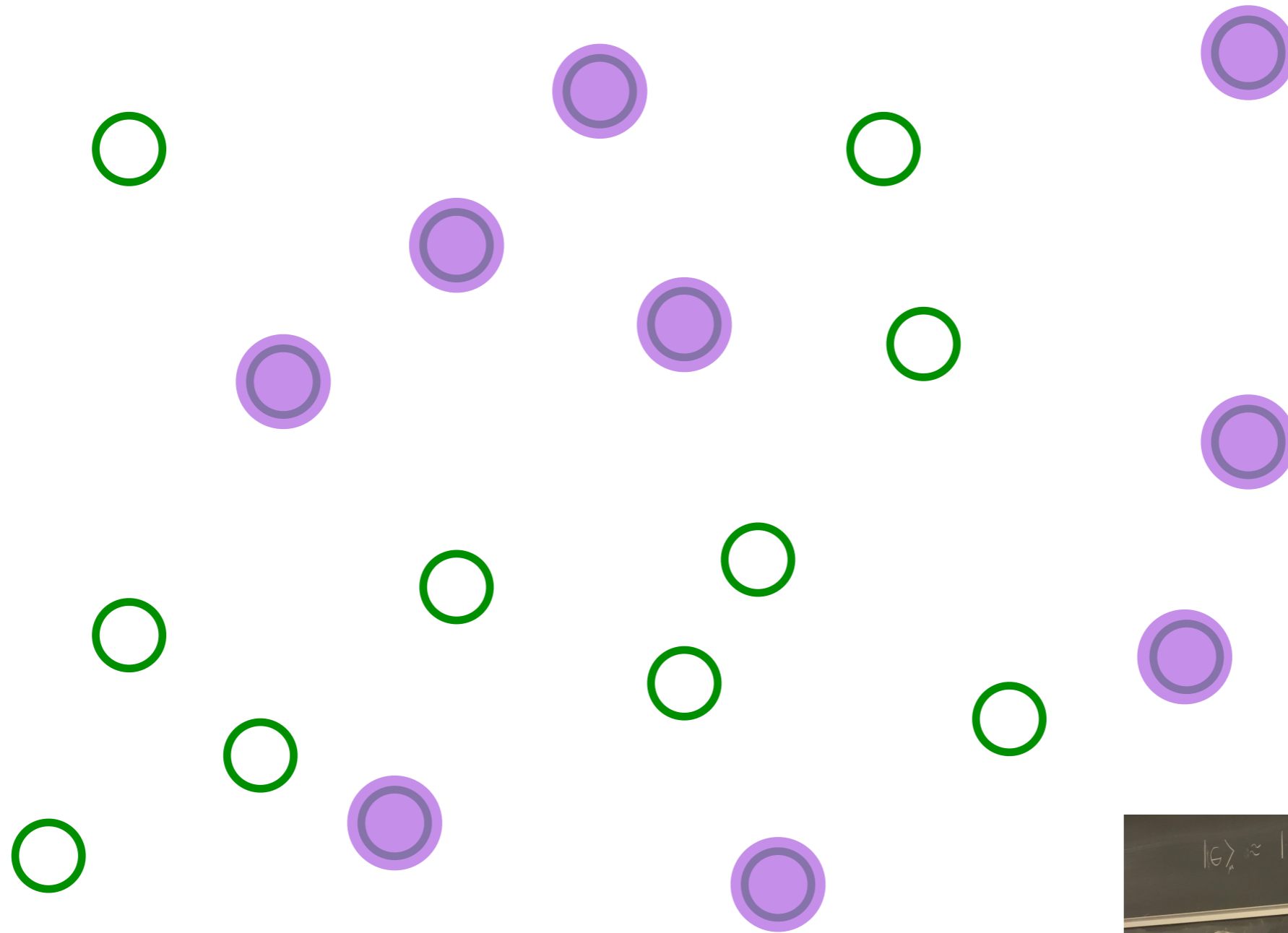
The SYK model



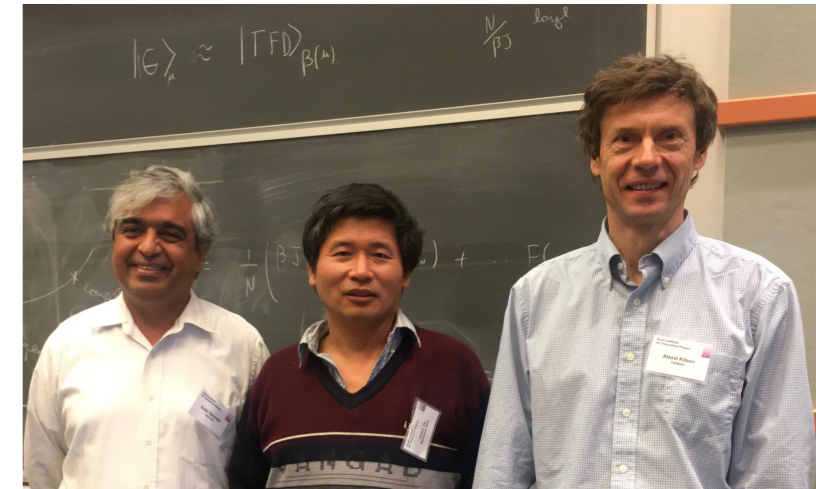
Place electrons randomly on some sites



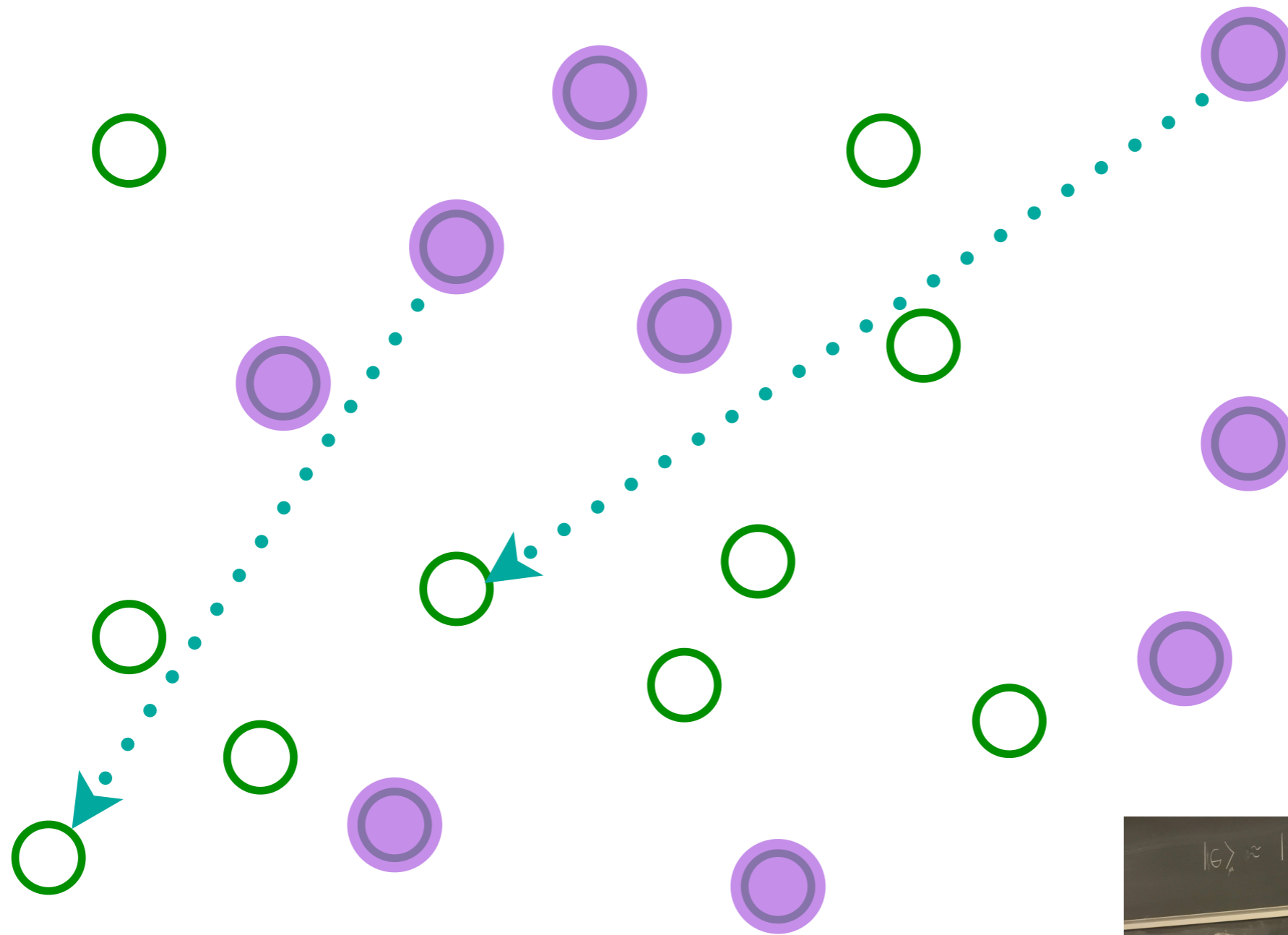
The SYK model



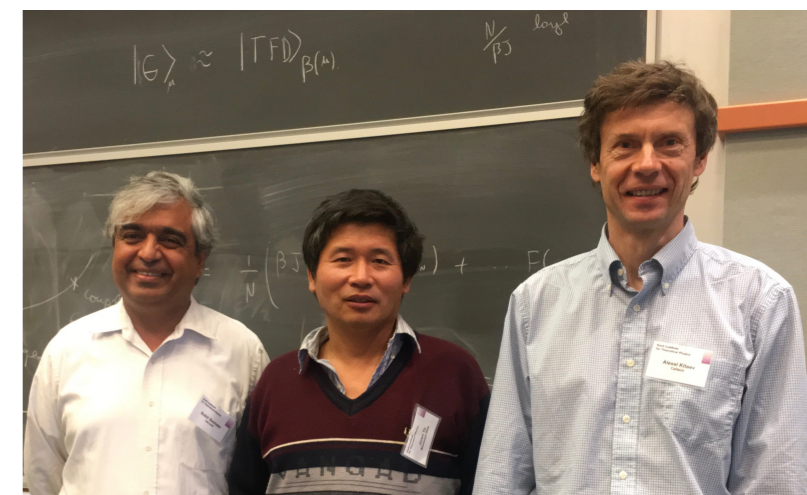
Entangle electrons pairwise randomly



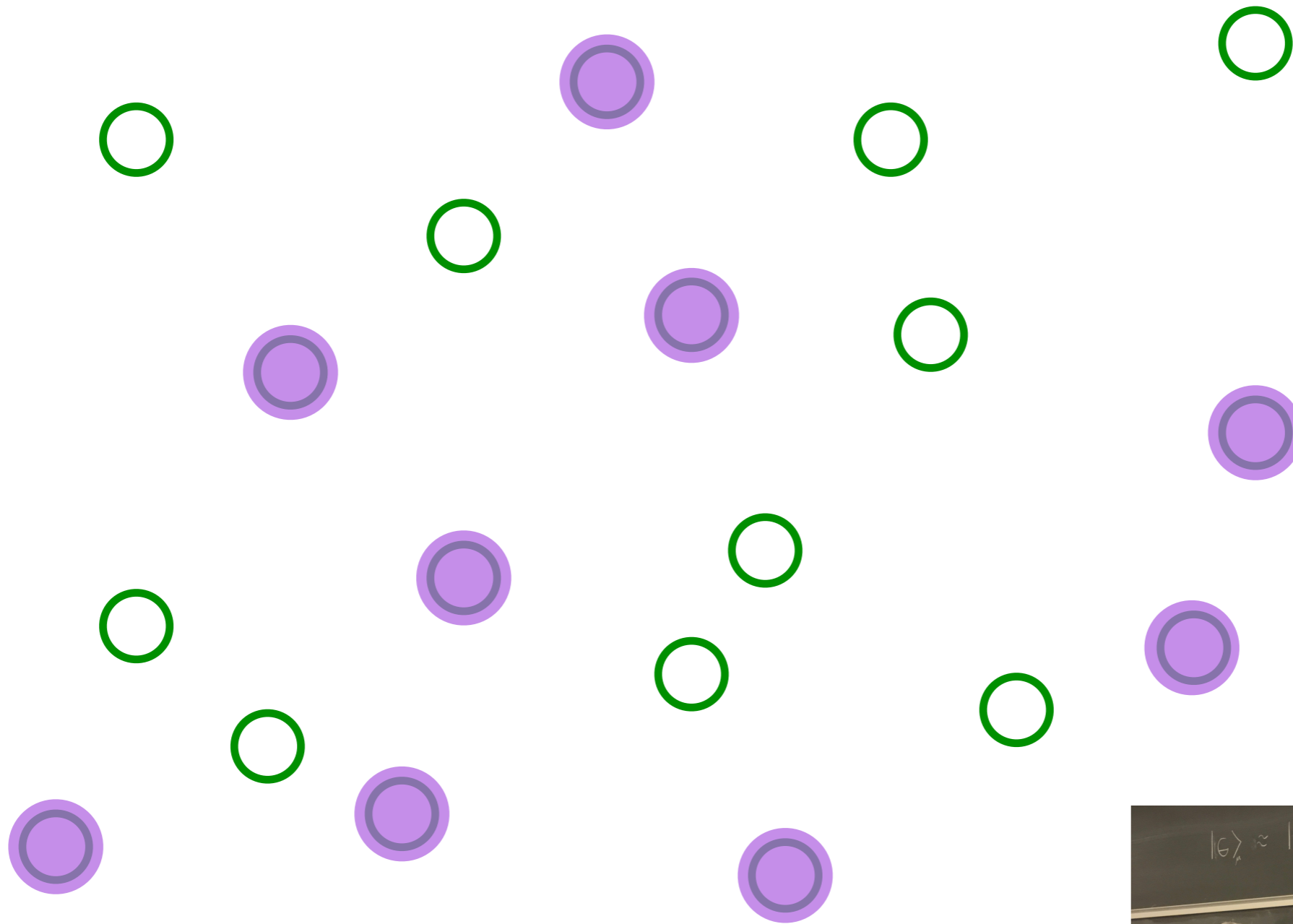
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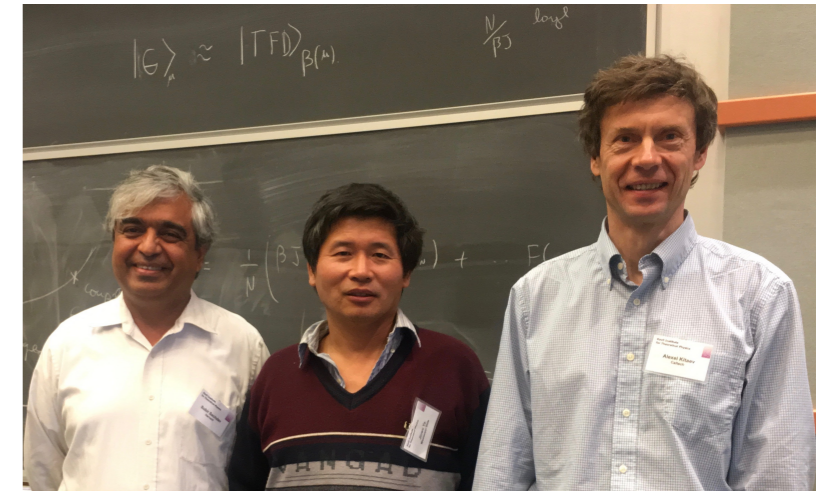
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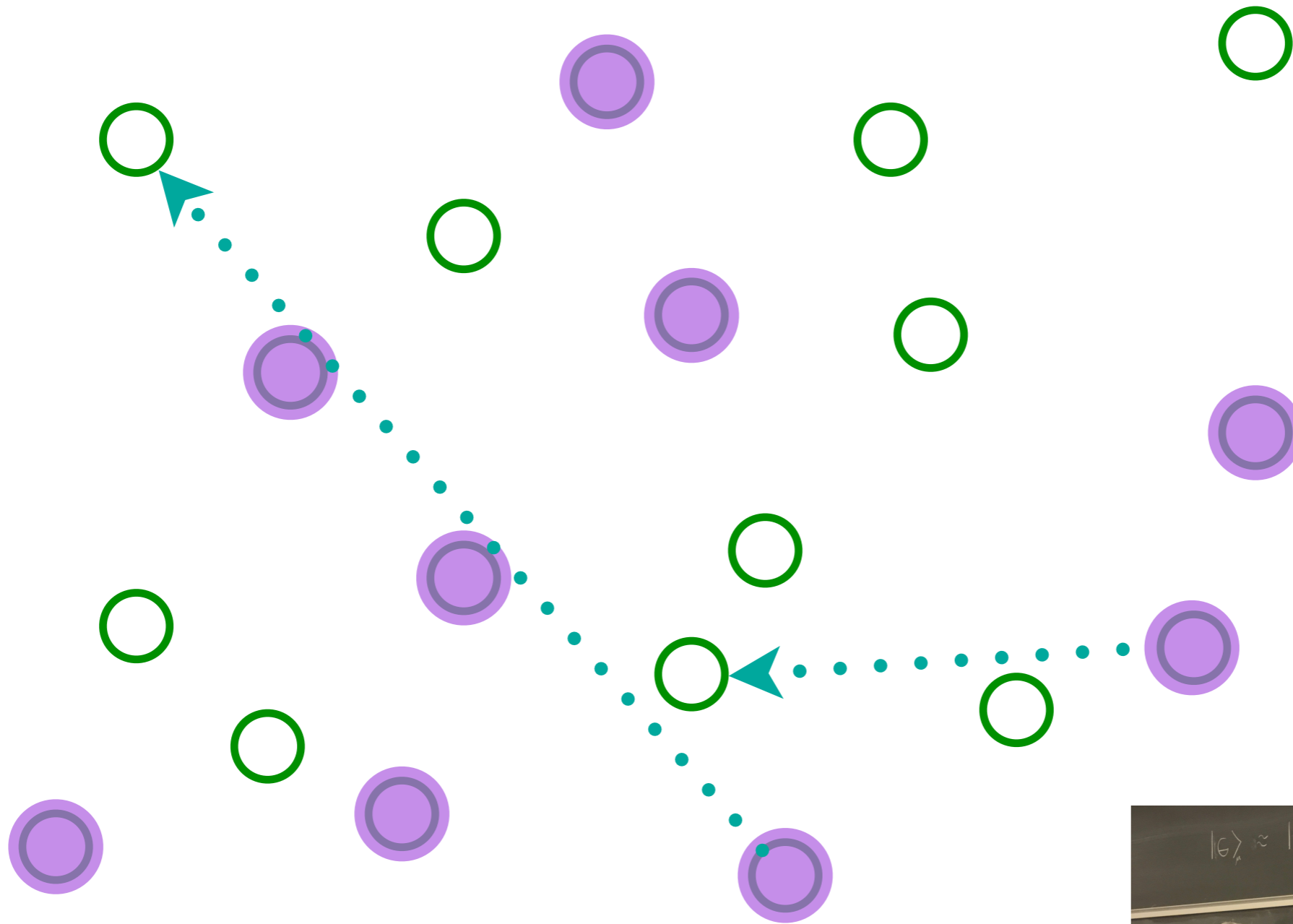
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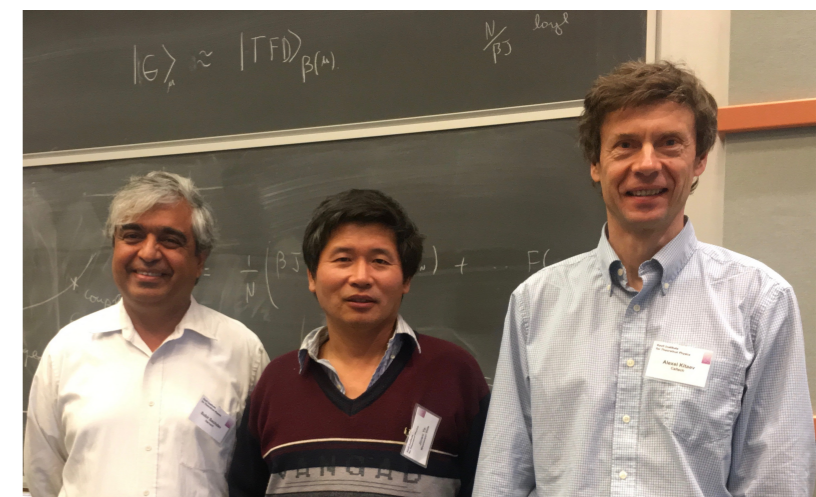
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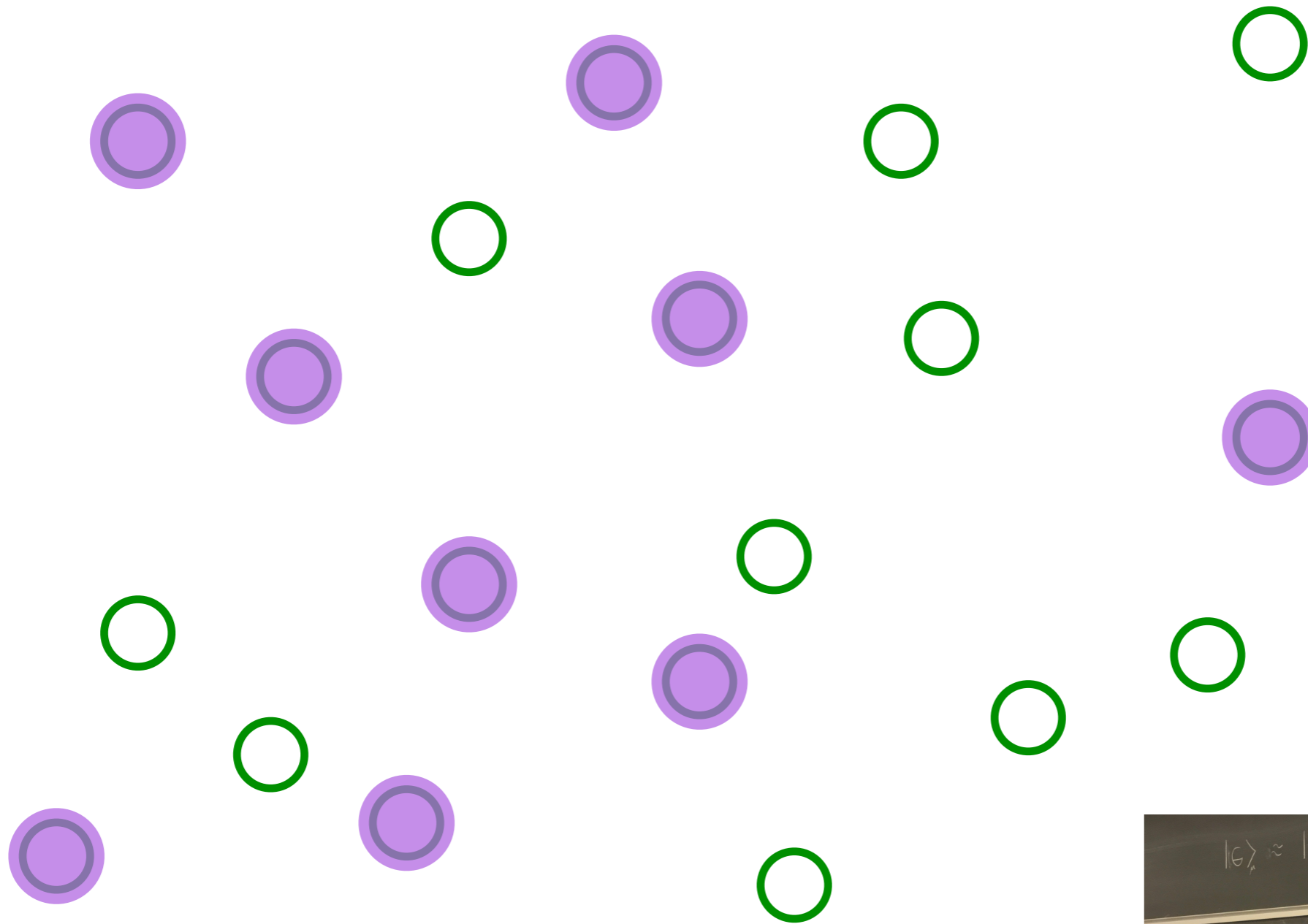
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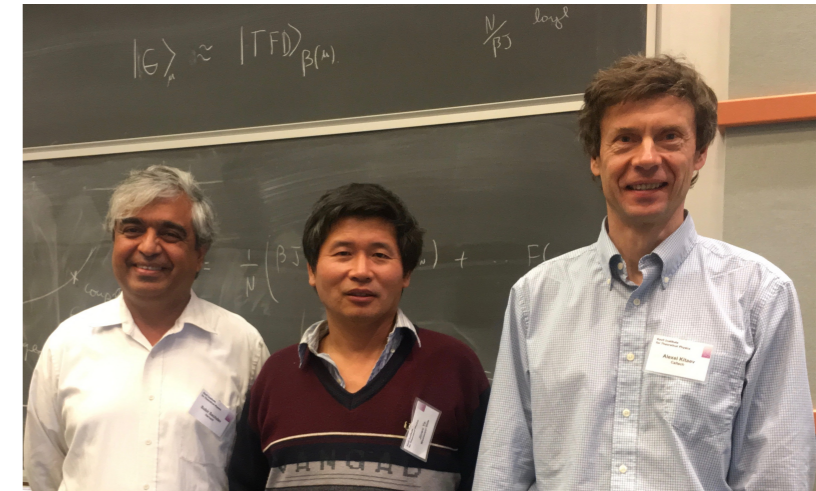
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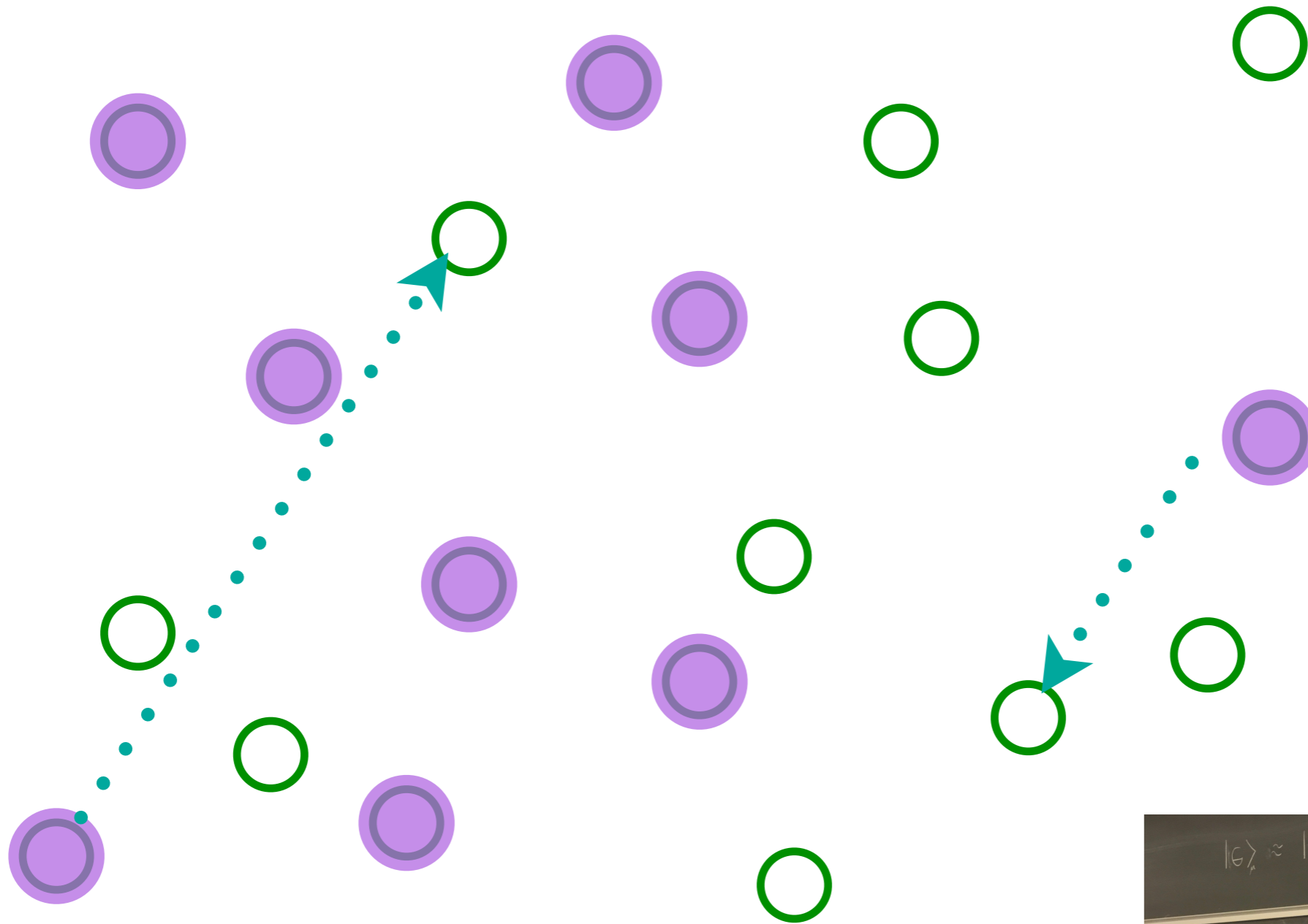
The SYK model



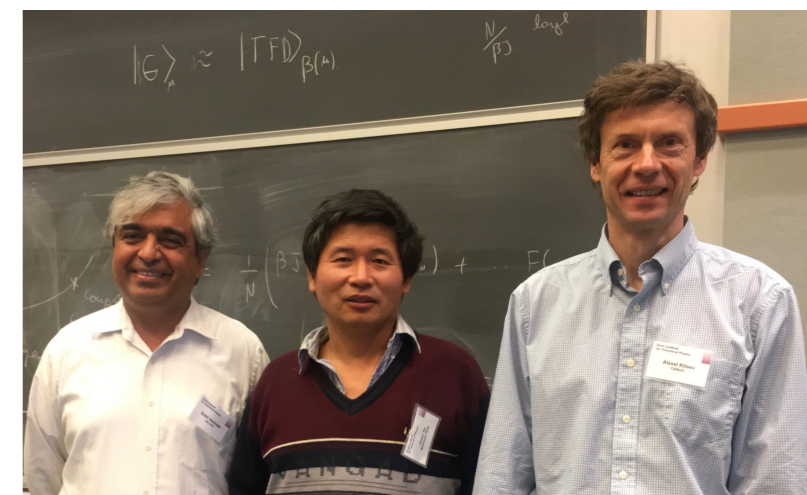
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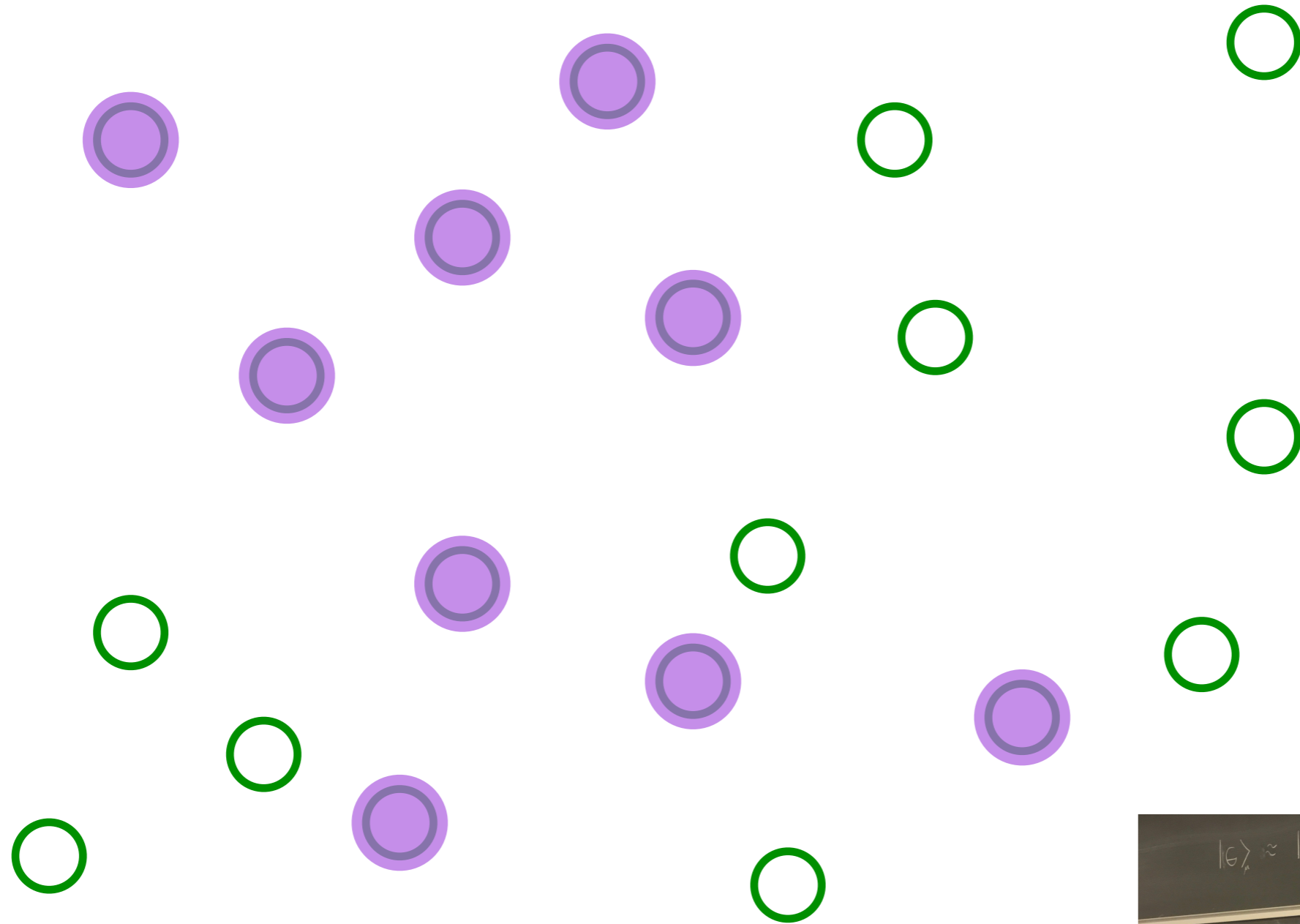
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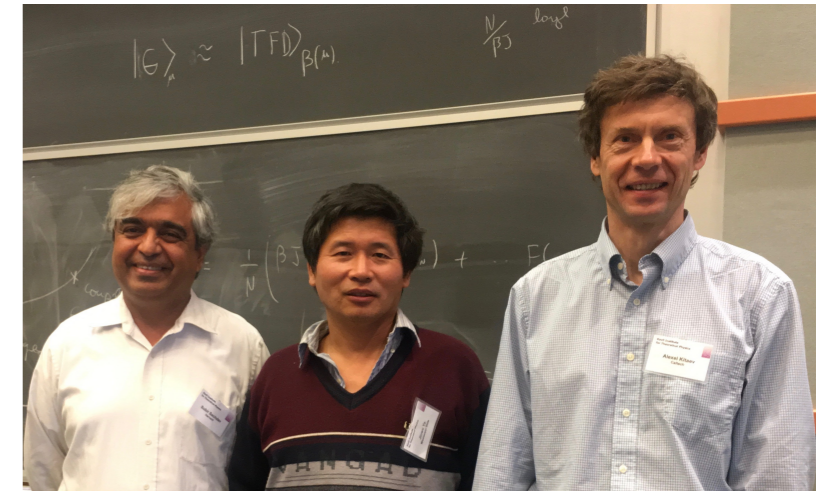
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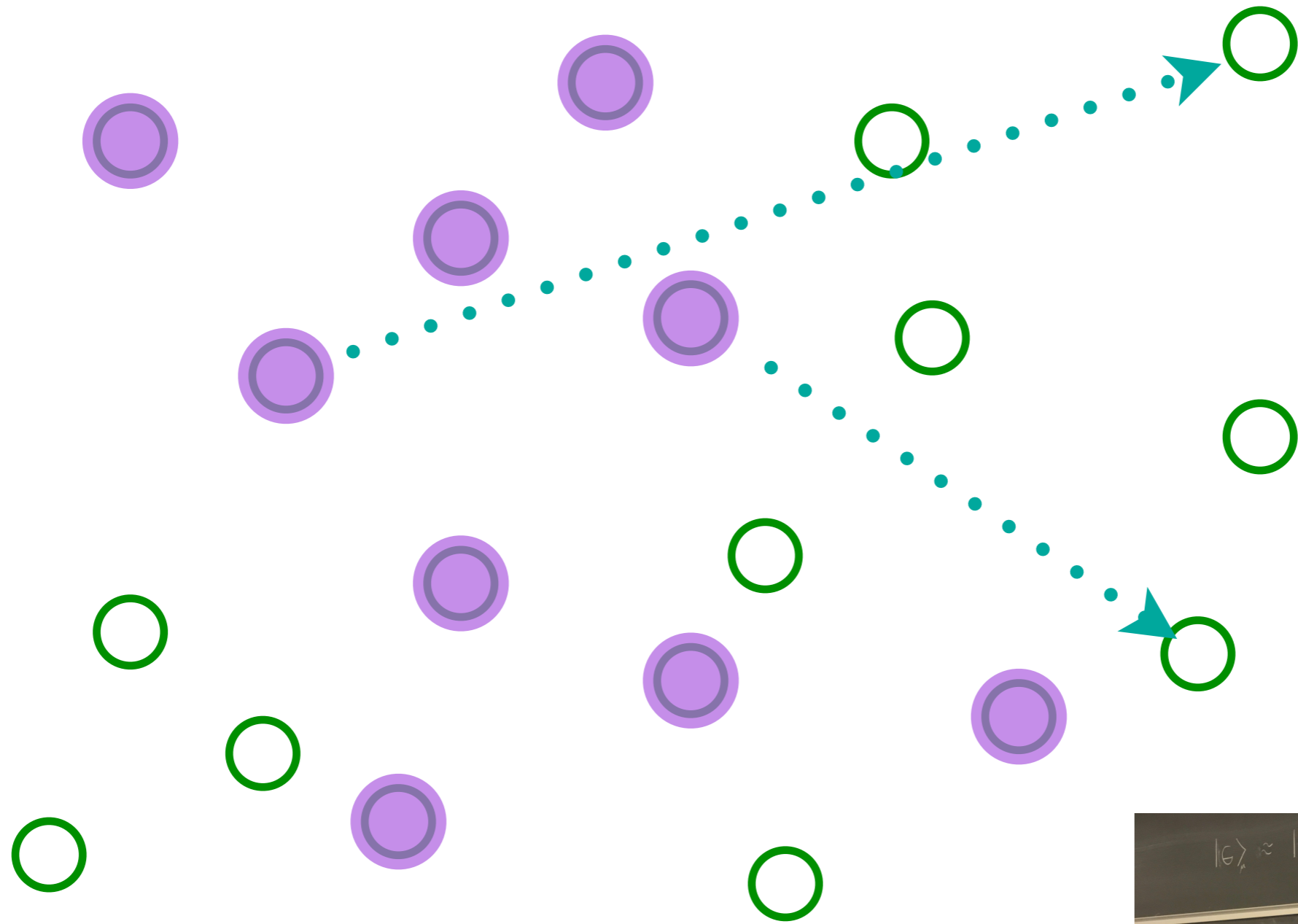
The SYK model



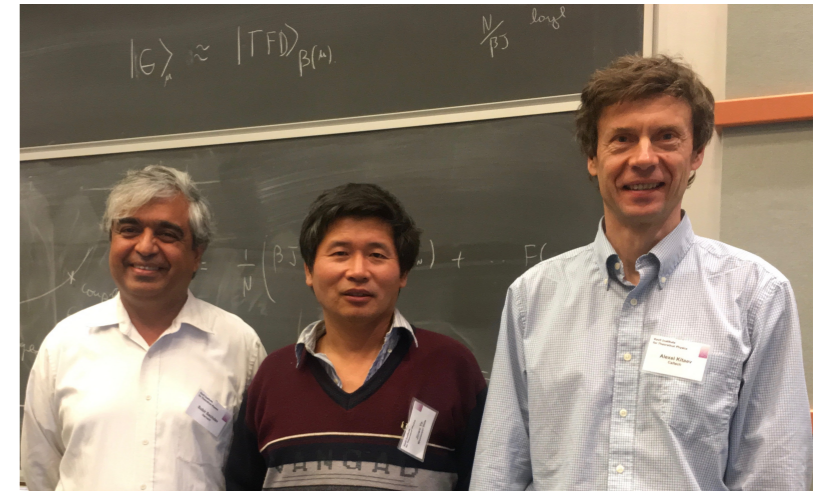
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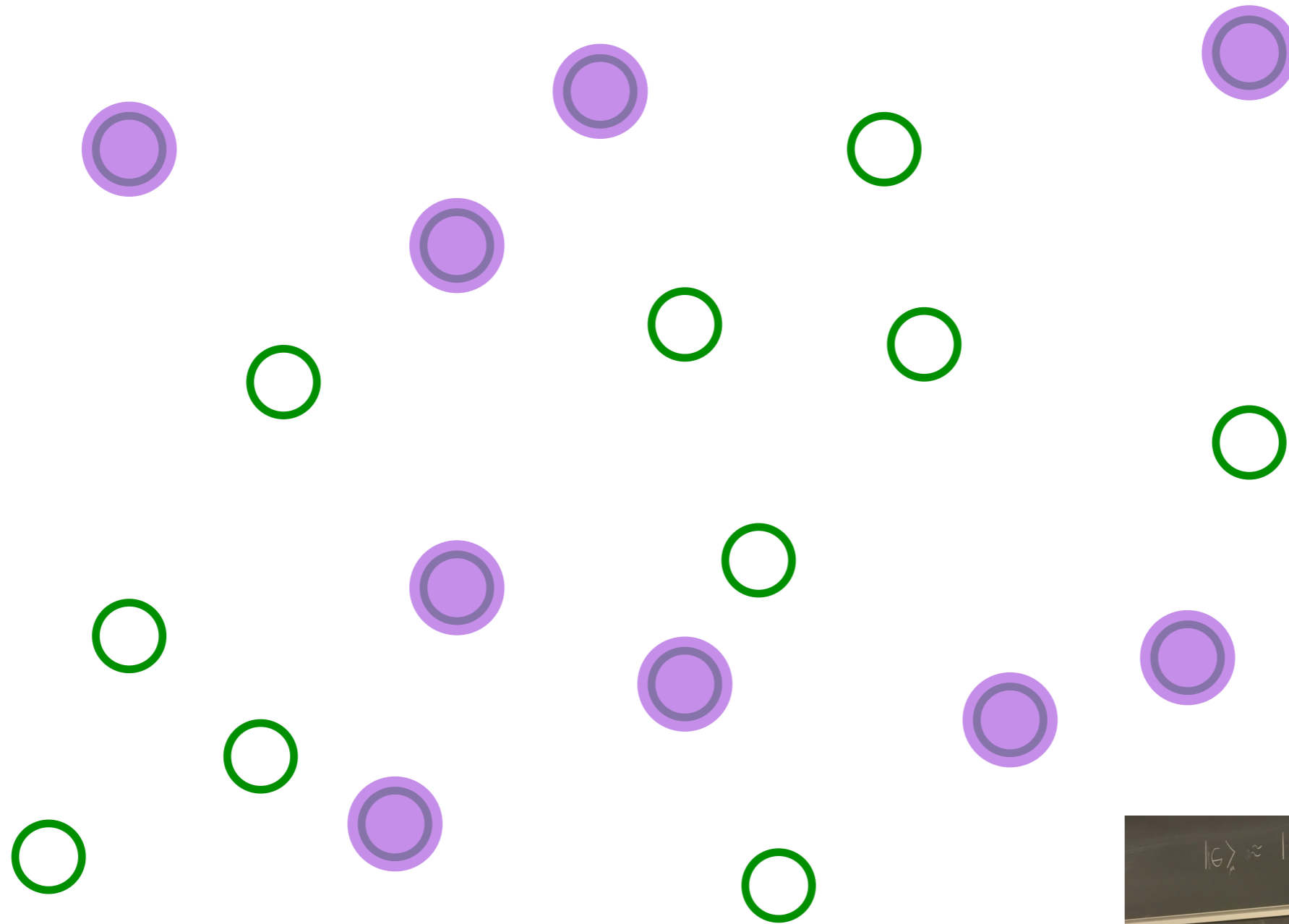
The SYK model



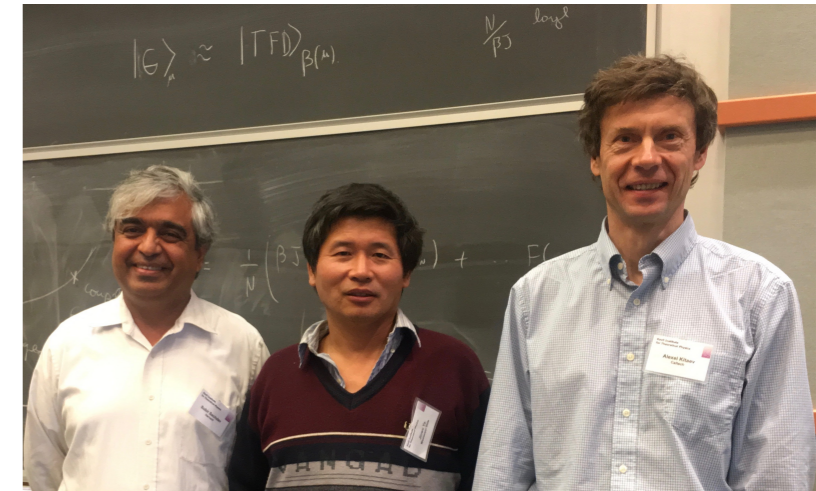
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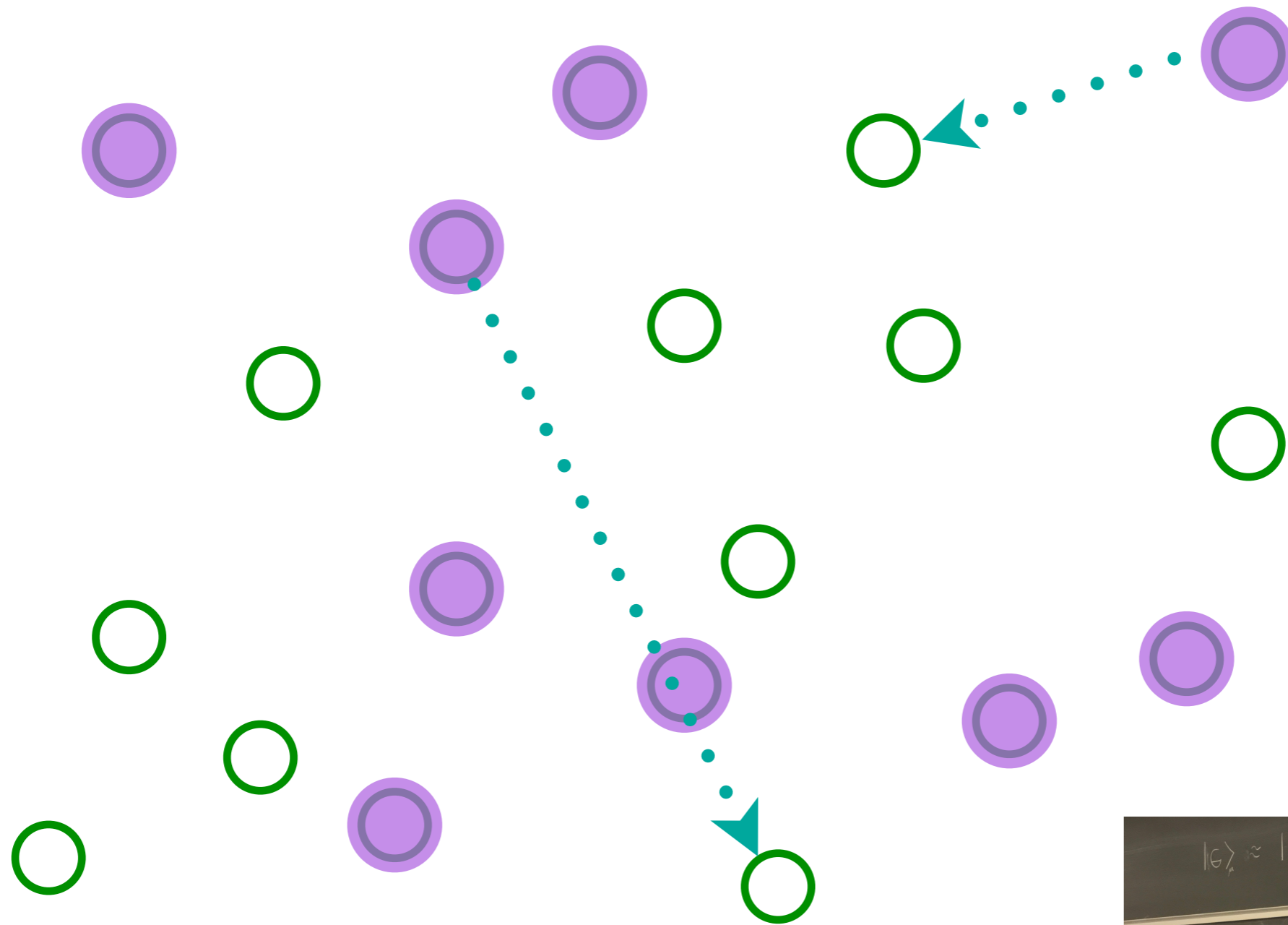
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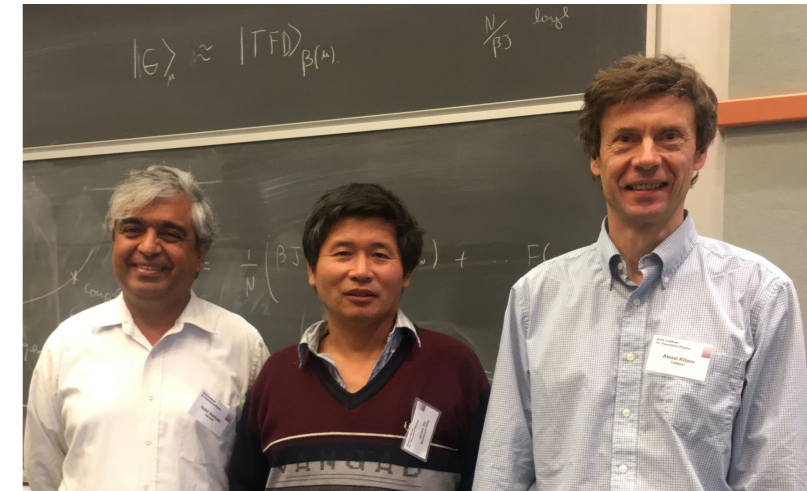
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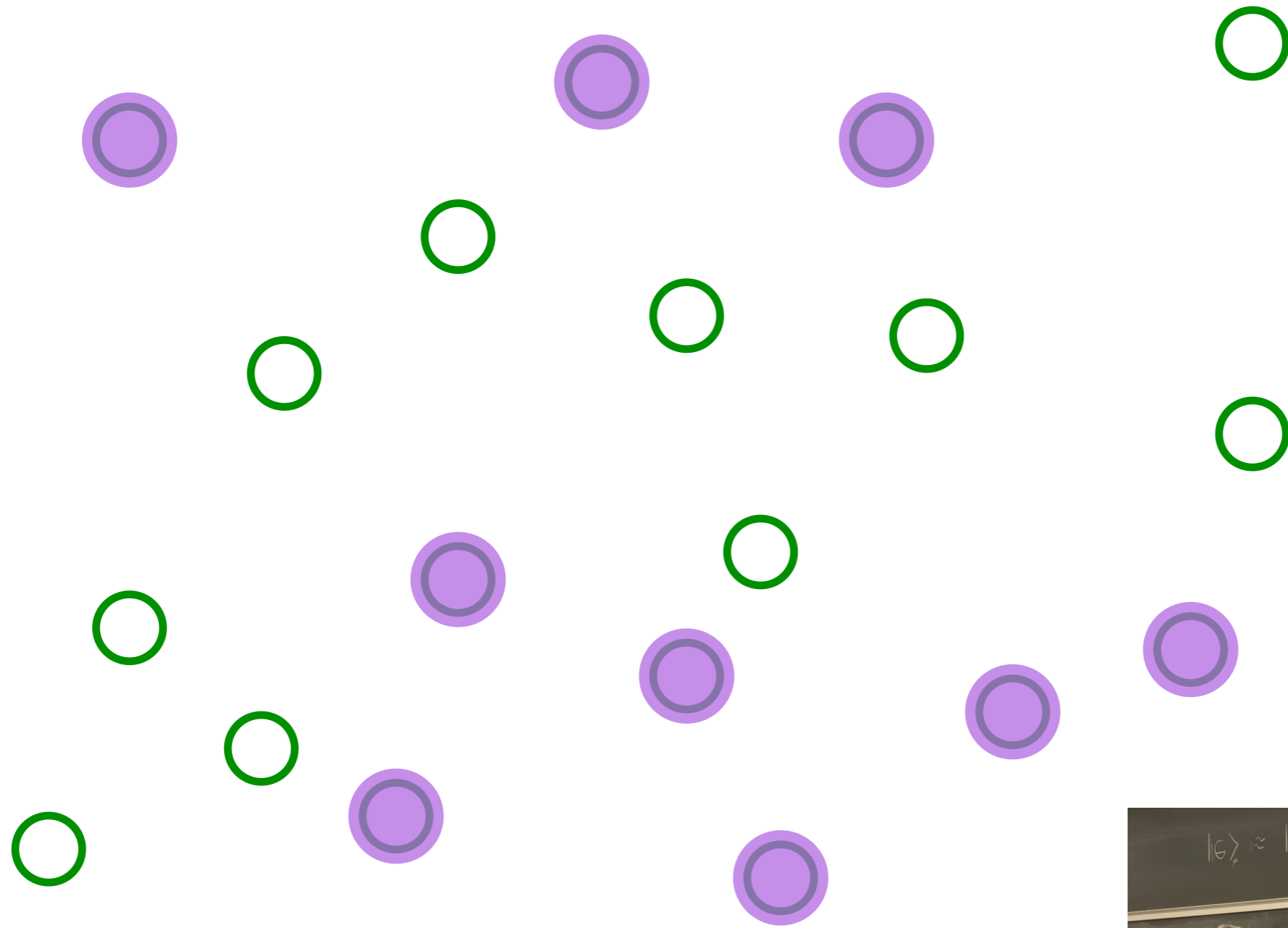
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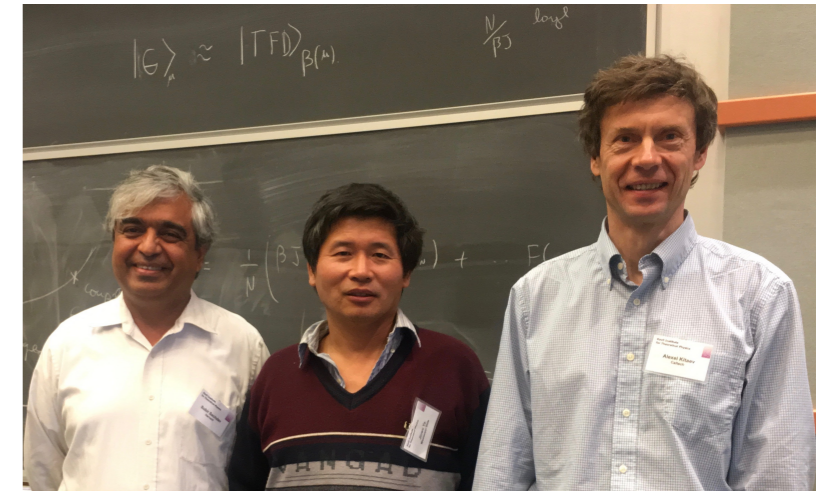
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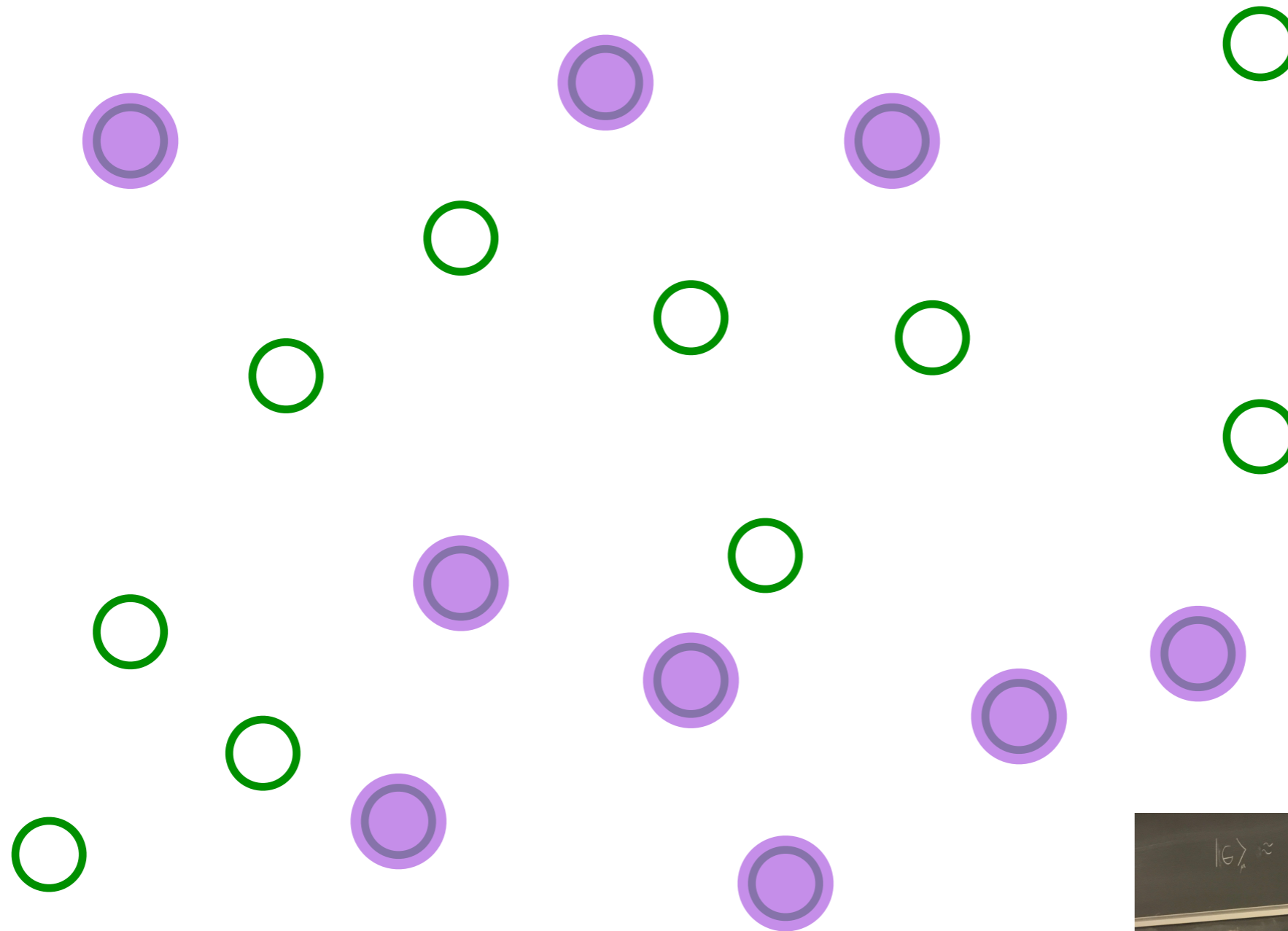
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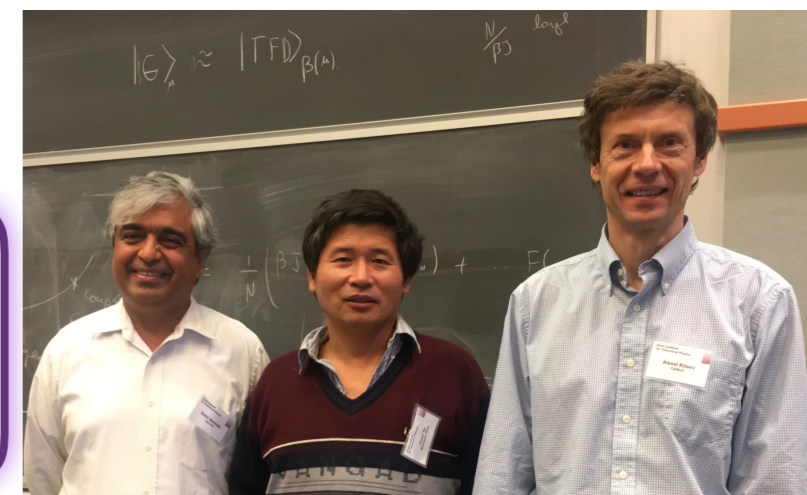
Entangle electrons pairwise randomly



The SYK model

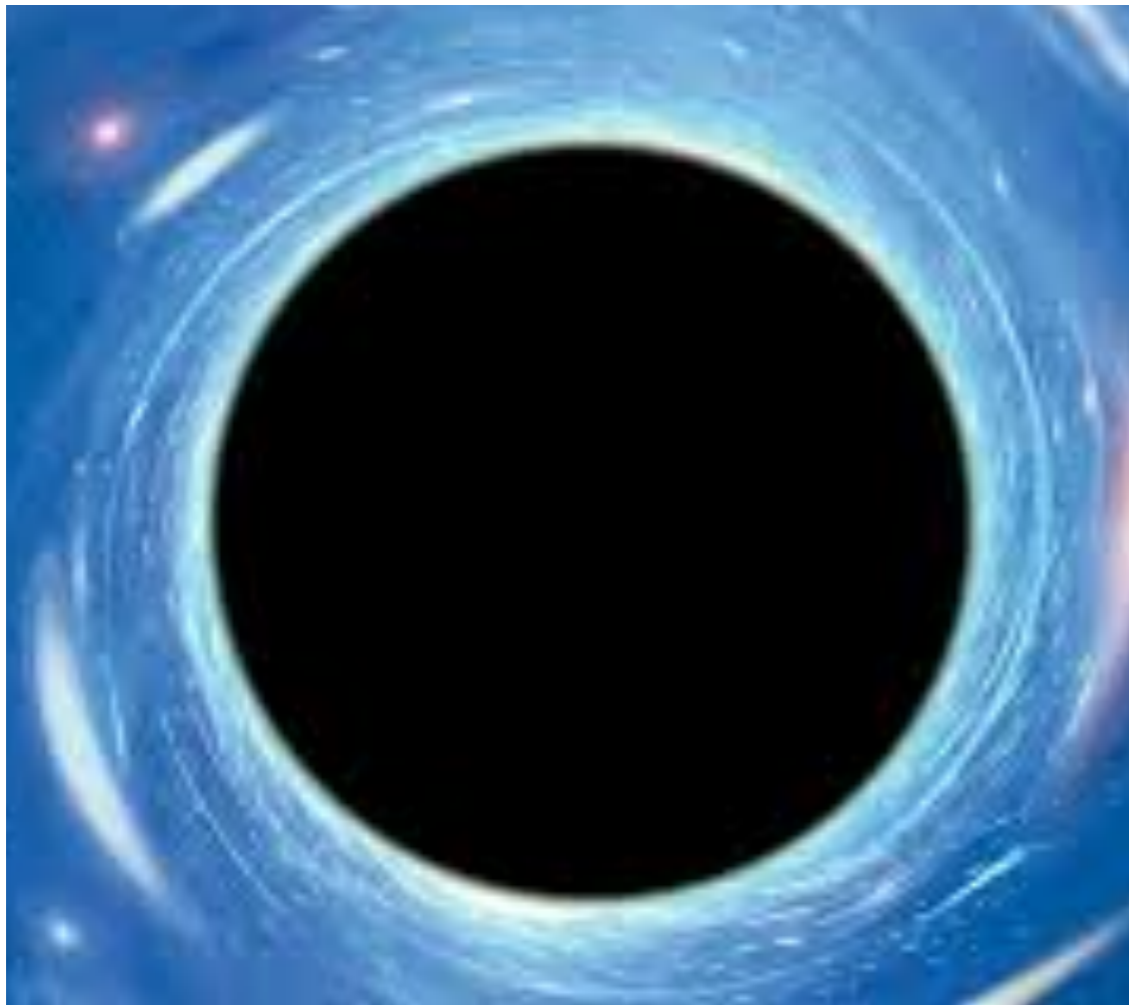


**This describes both a
superconductor and a black hole!**



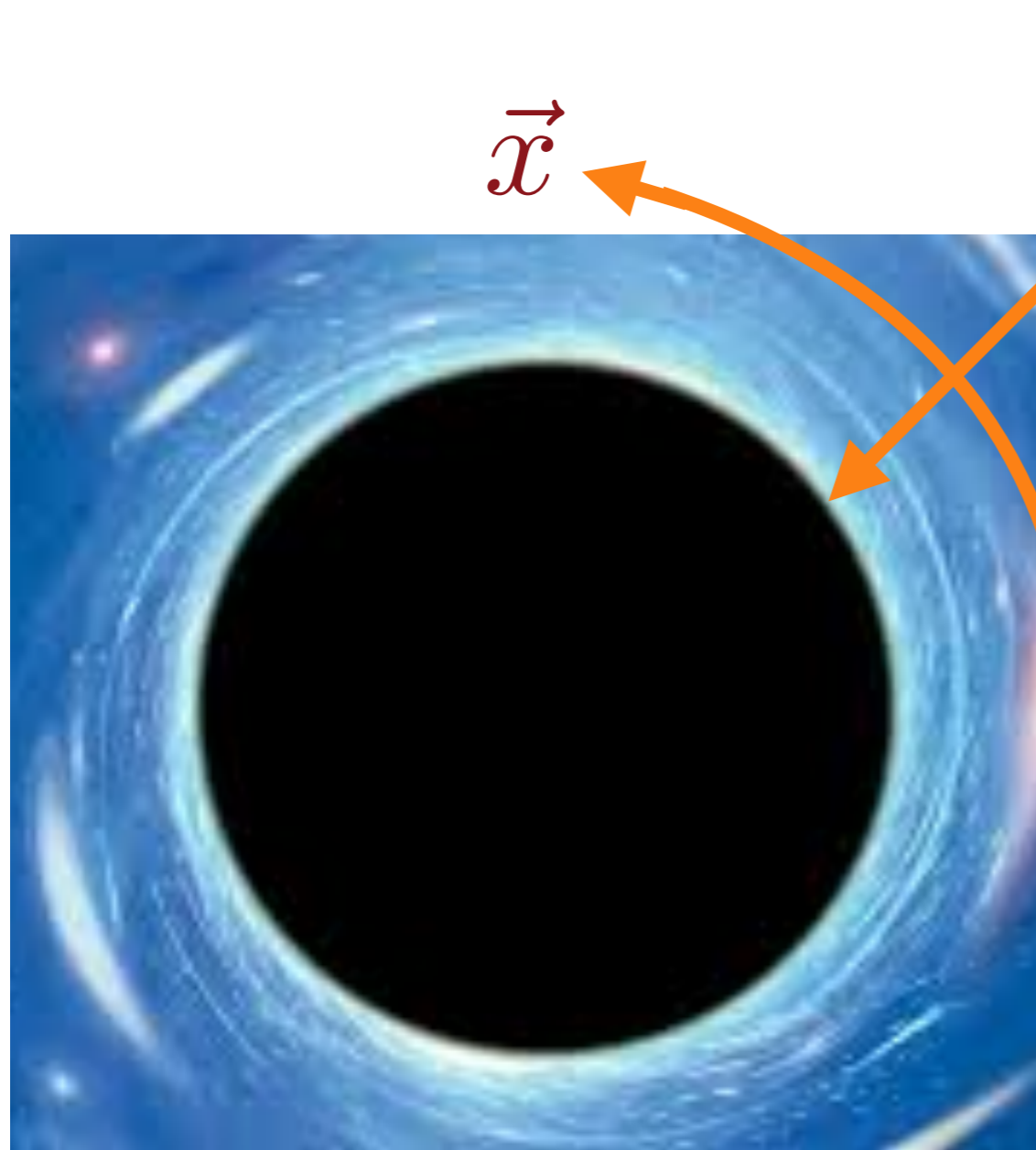


Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge





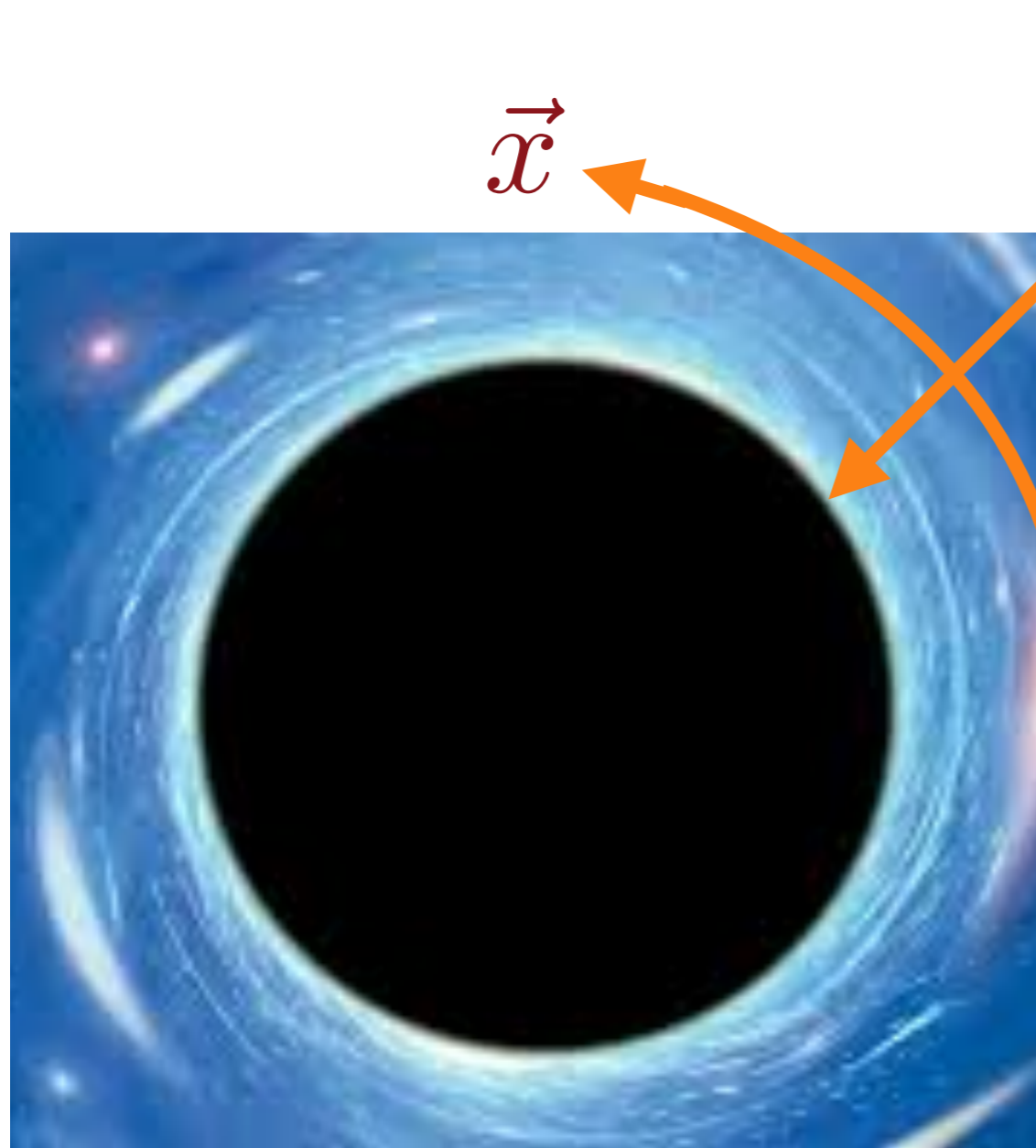
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Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space (ζ) and one time dimension



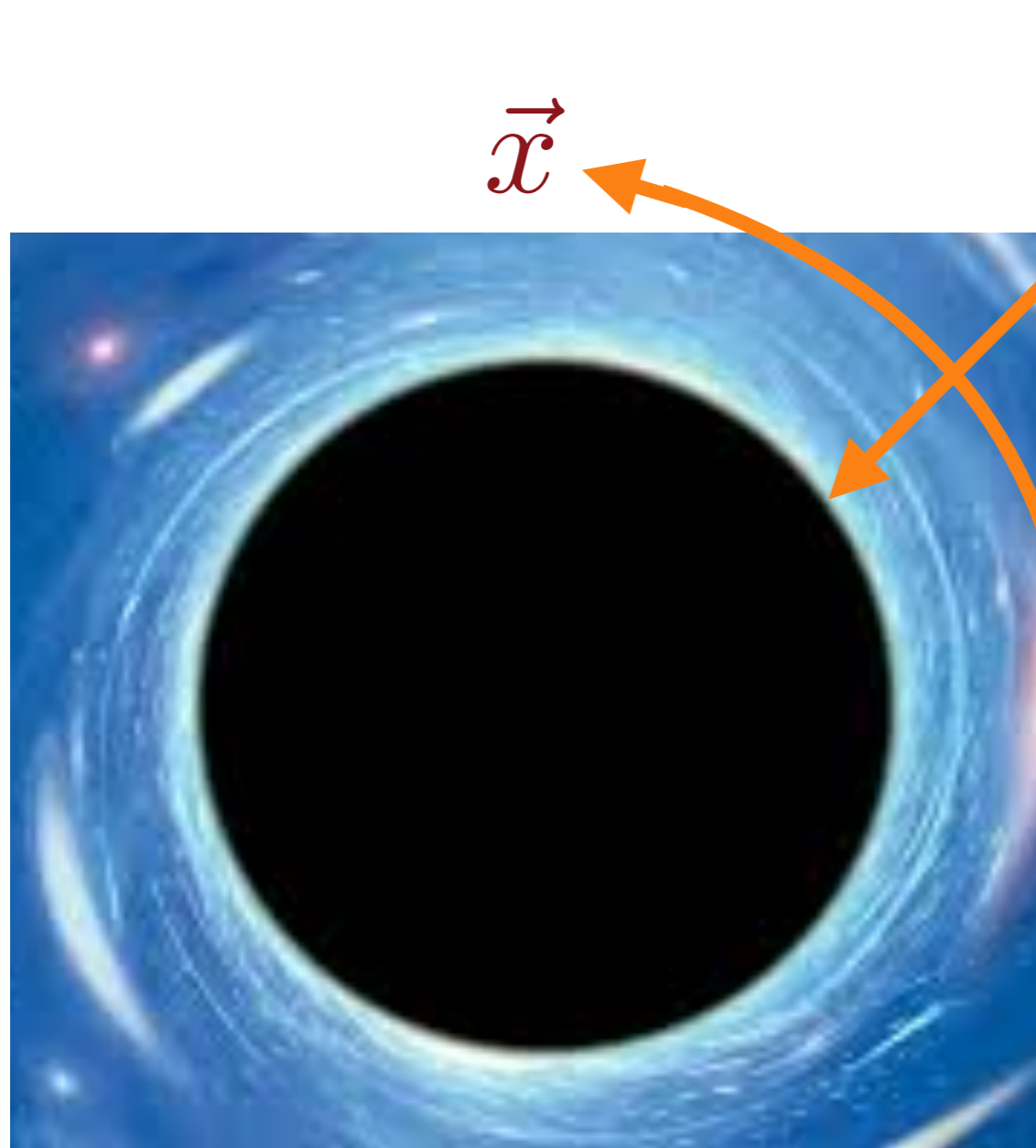
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The quantum versions
of Maxwell's and
Einstein's equations in
this two-dimensional
spacetime are also the
equations describing
electron entanglement
in the SYK model



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**

Superconductors

**A “toy model” which describes both
a superconductor and a black hole!**