Quantum entanglement: "Spooky action at distance" in the lab, and in black holes

Tilde Cafe, Branford CT

November 9, 2019

Subir Sachdev

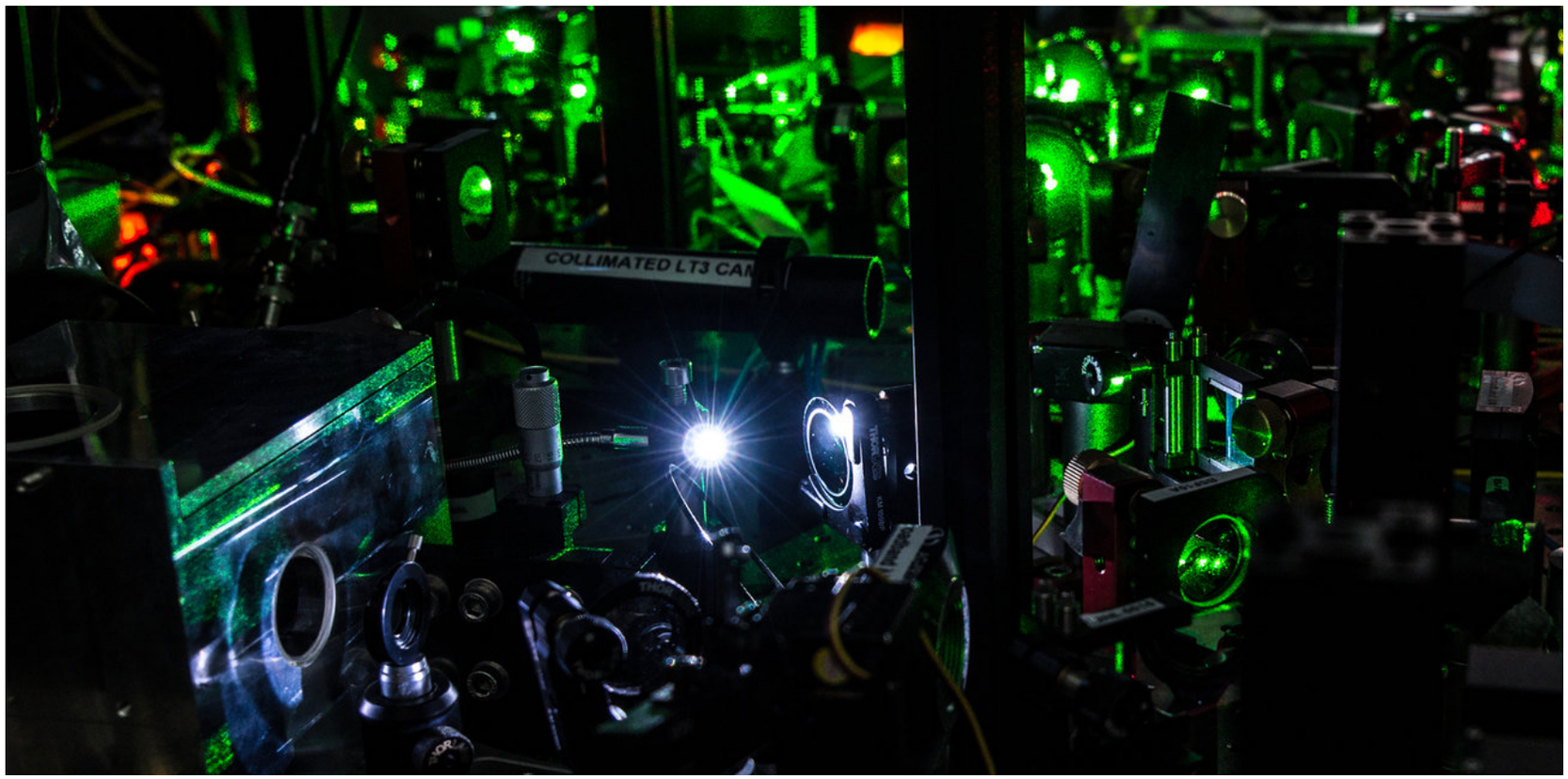
Talk online: sachdev.physics.harvard.edu

The New York Times

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

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

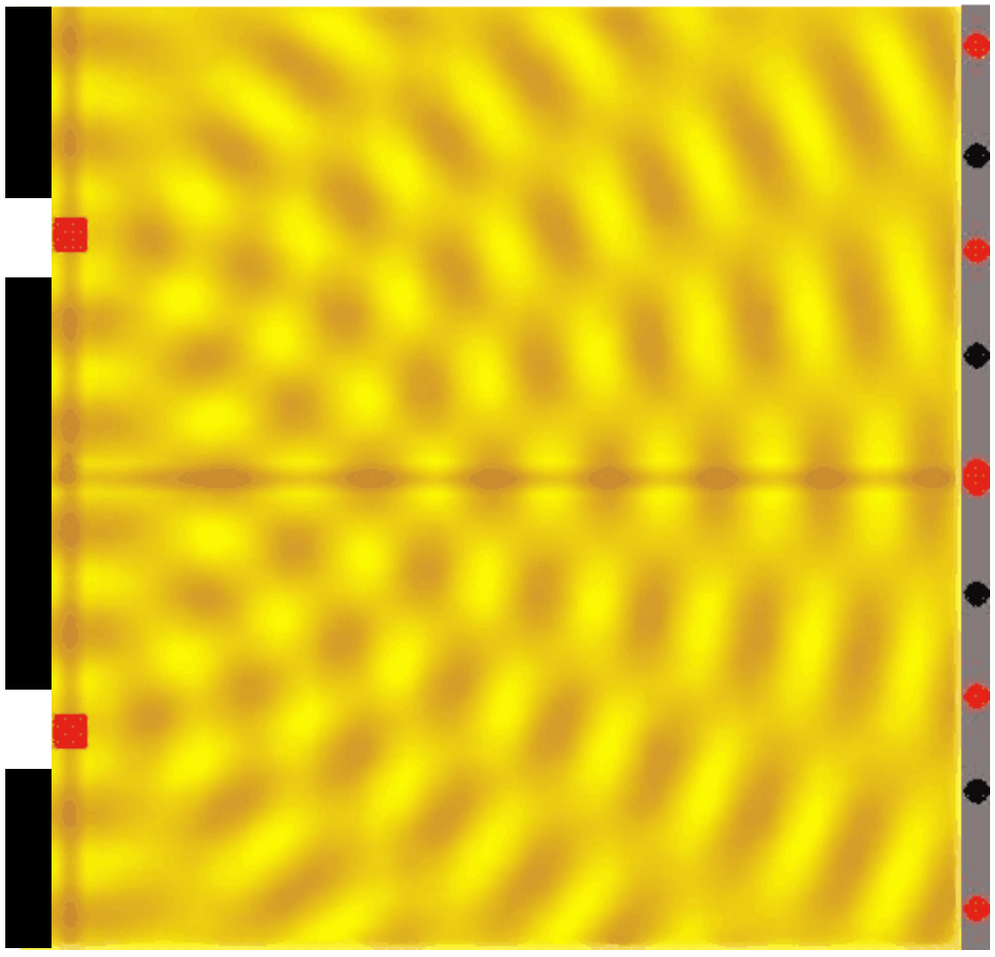
In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other’s behavior.



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

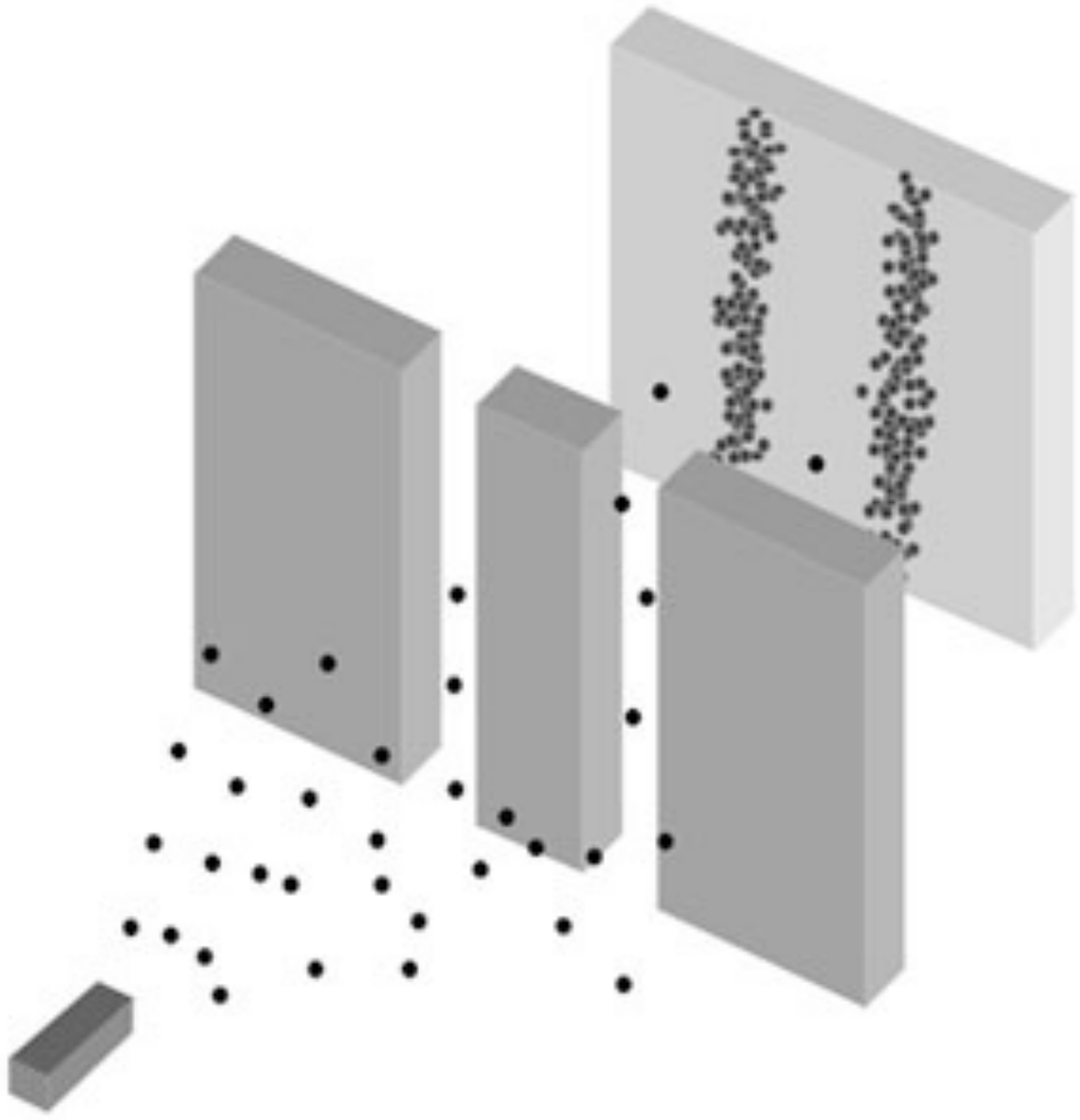
The double slit experiment



TWO SLITS

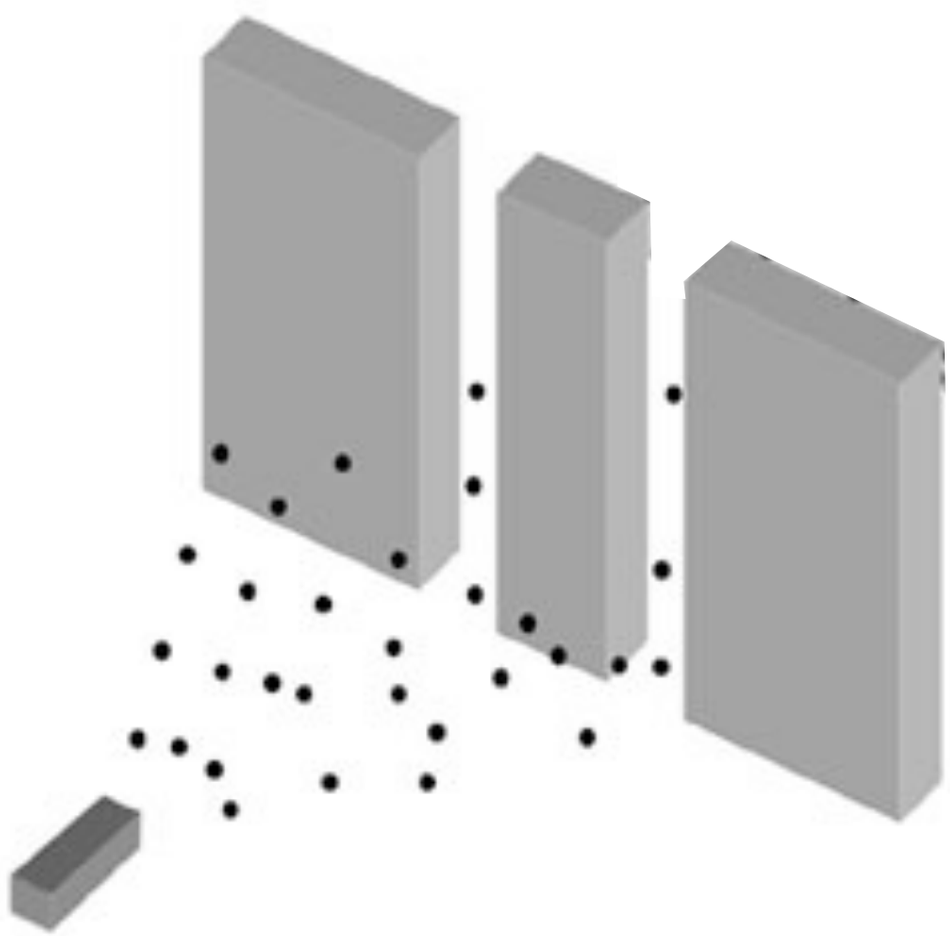
Interference of water waves

The double slit experiment



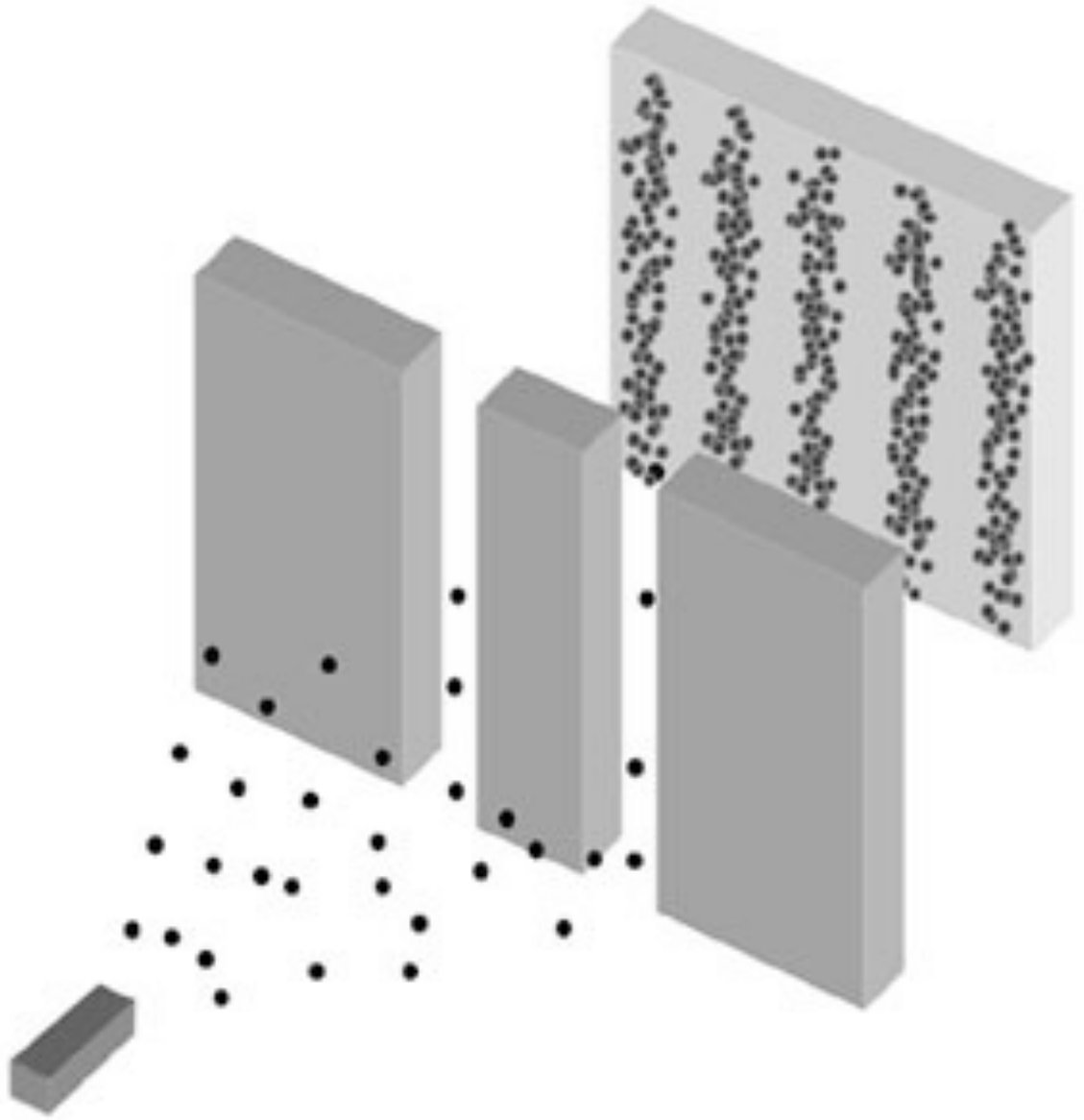
Bullets

The double slit experiment



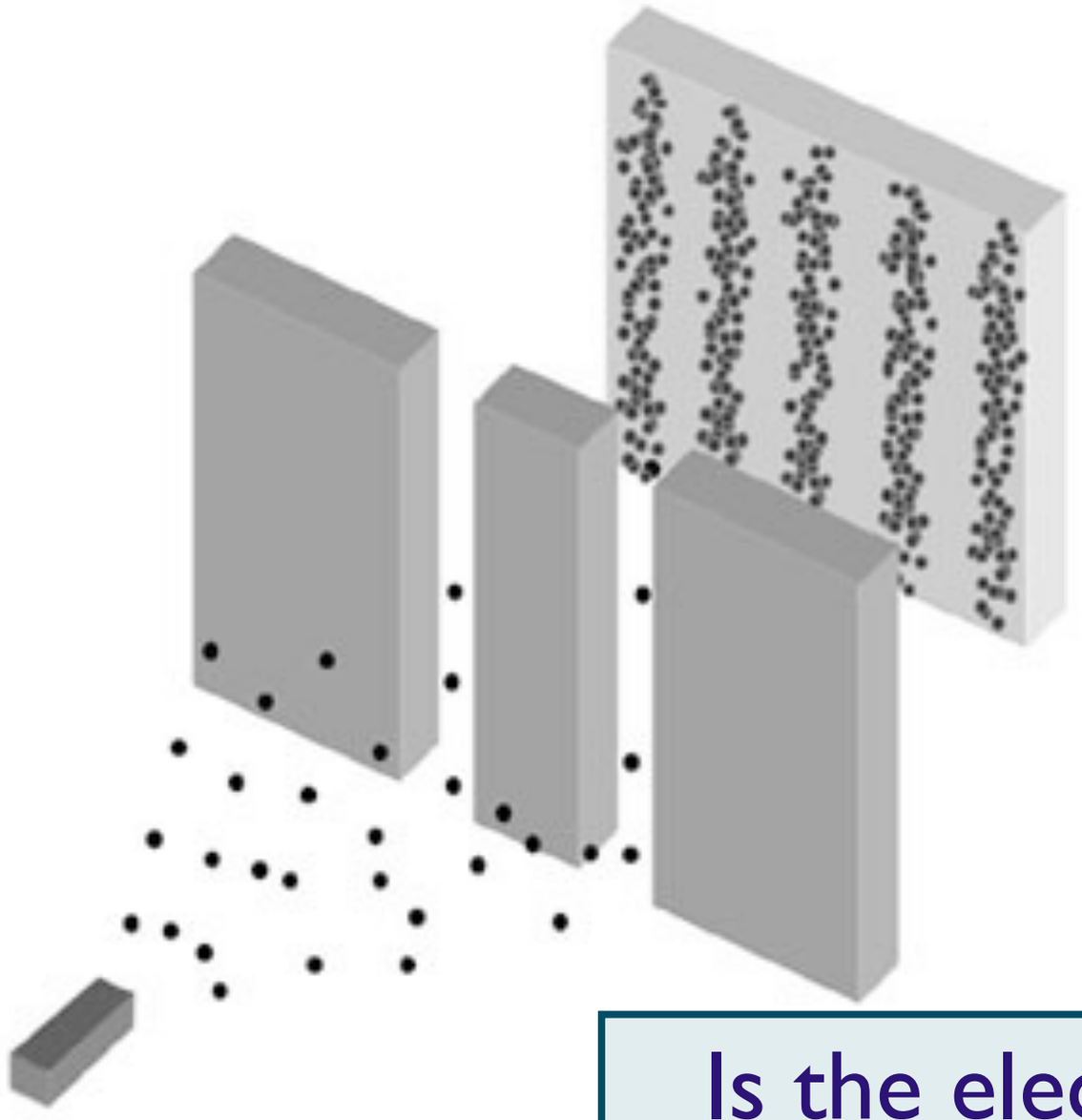
Send electrons through the slits

The double slit experiment



Interference of electrons

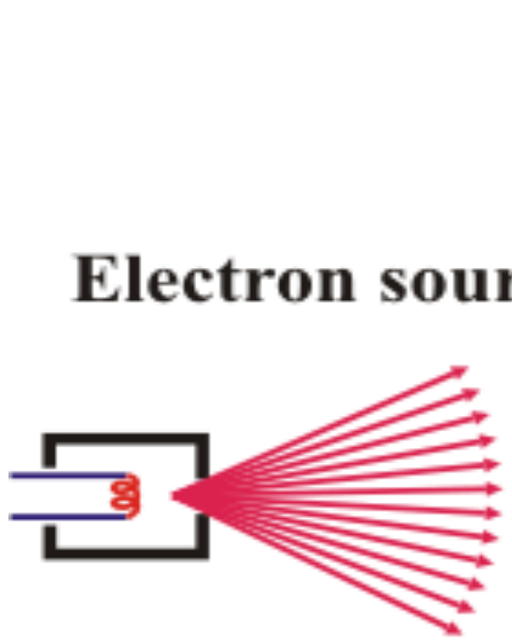
The double slit experiment

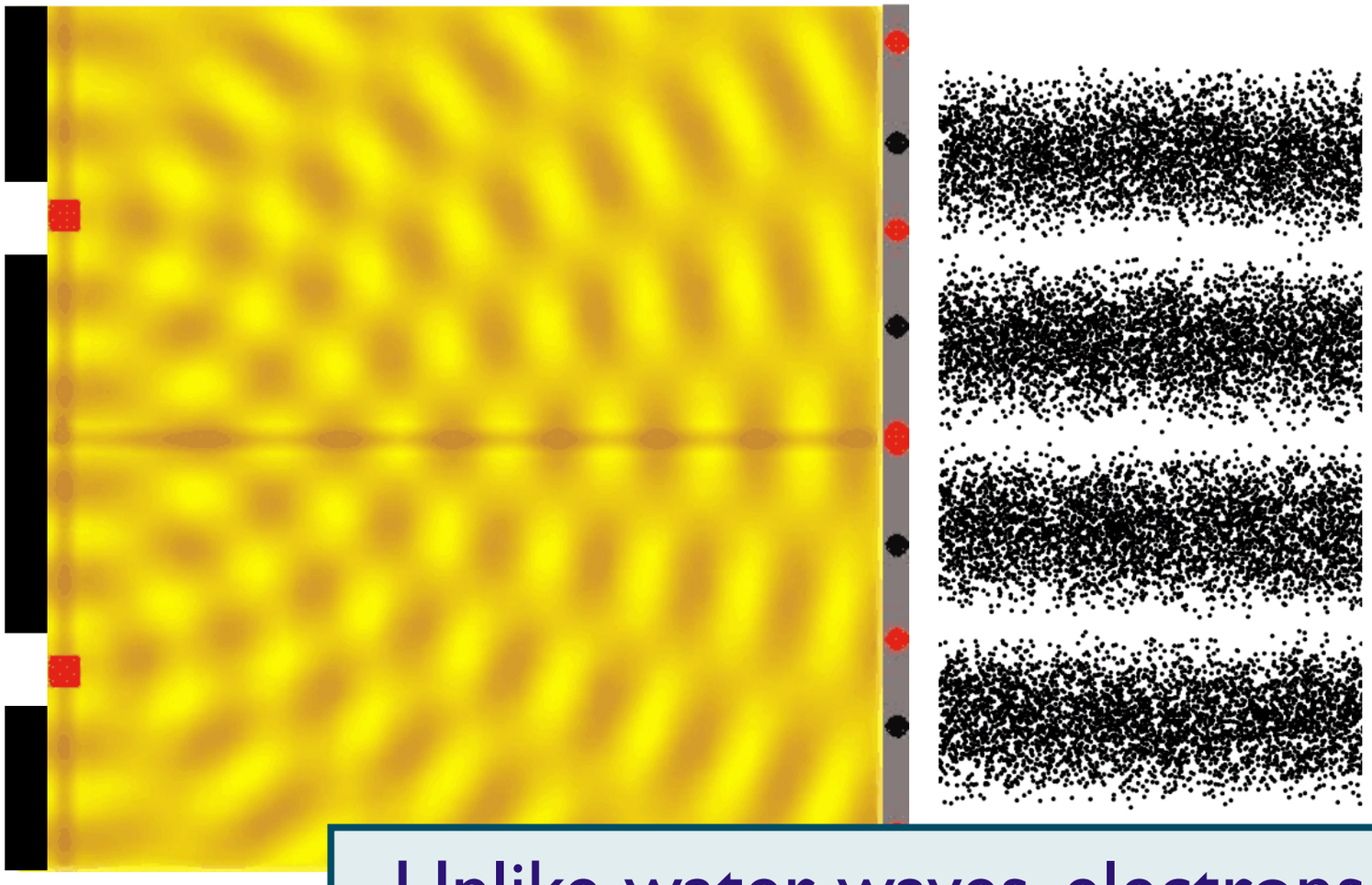


Is the electron a wave ?

Interference of electrons

The double slit experiment





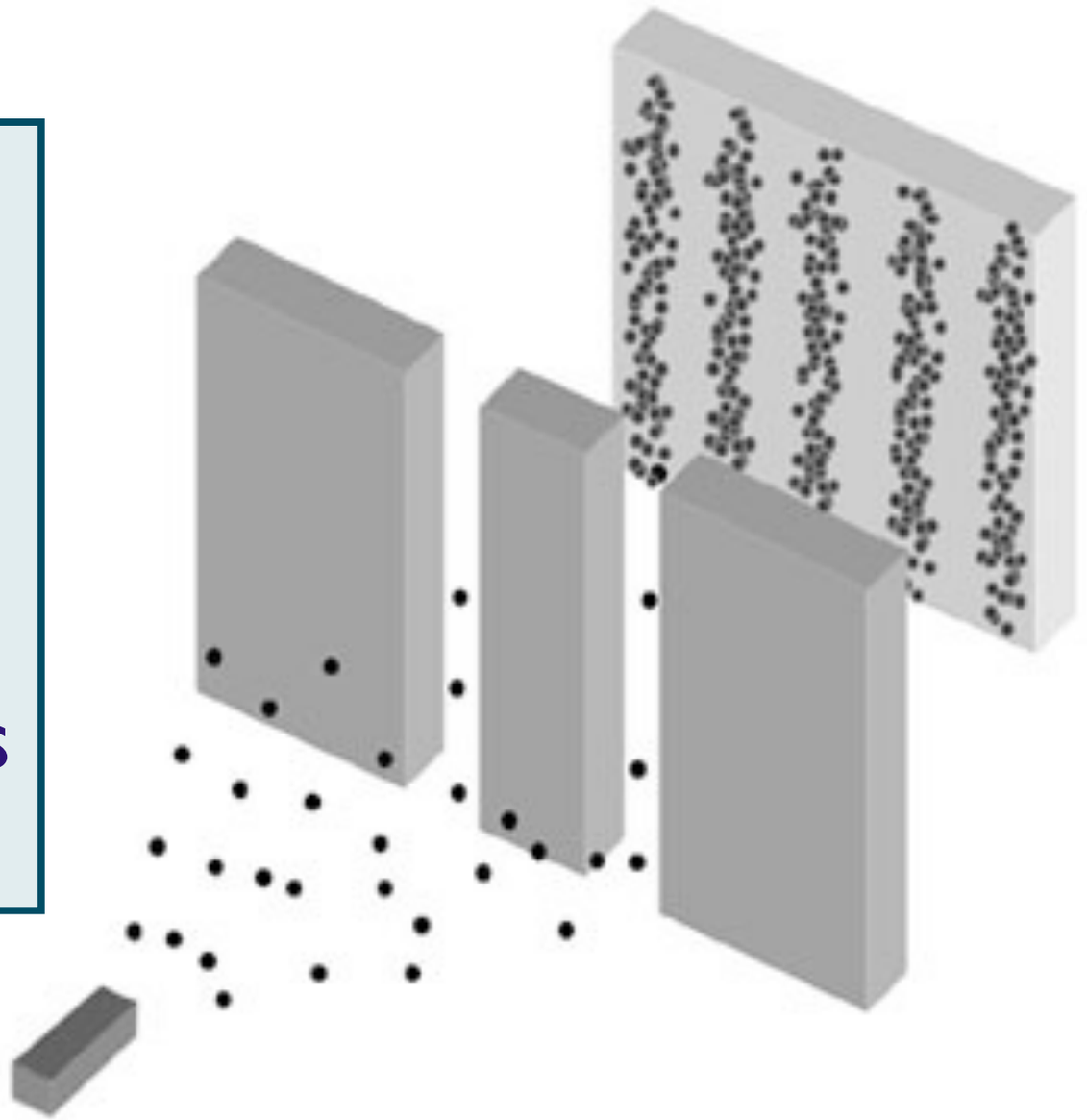
TWO SLITS

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

Interference of electrons

The double slit experiment

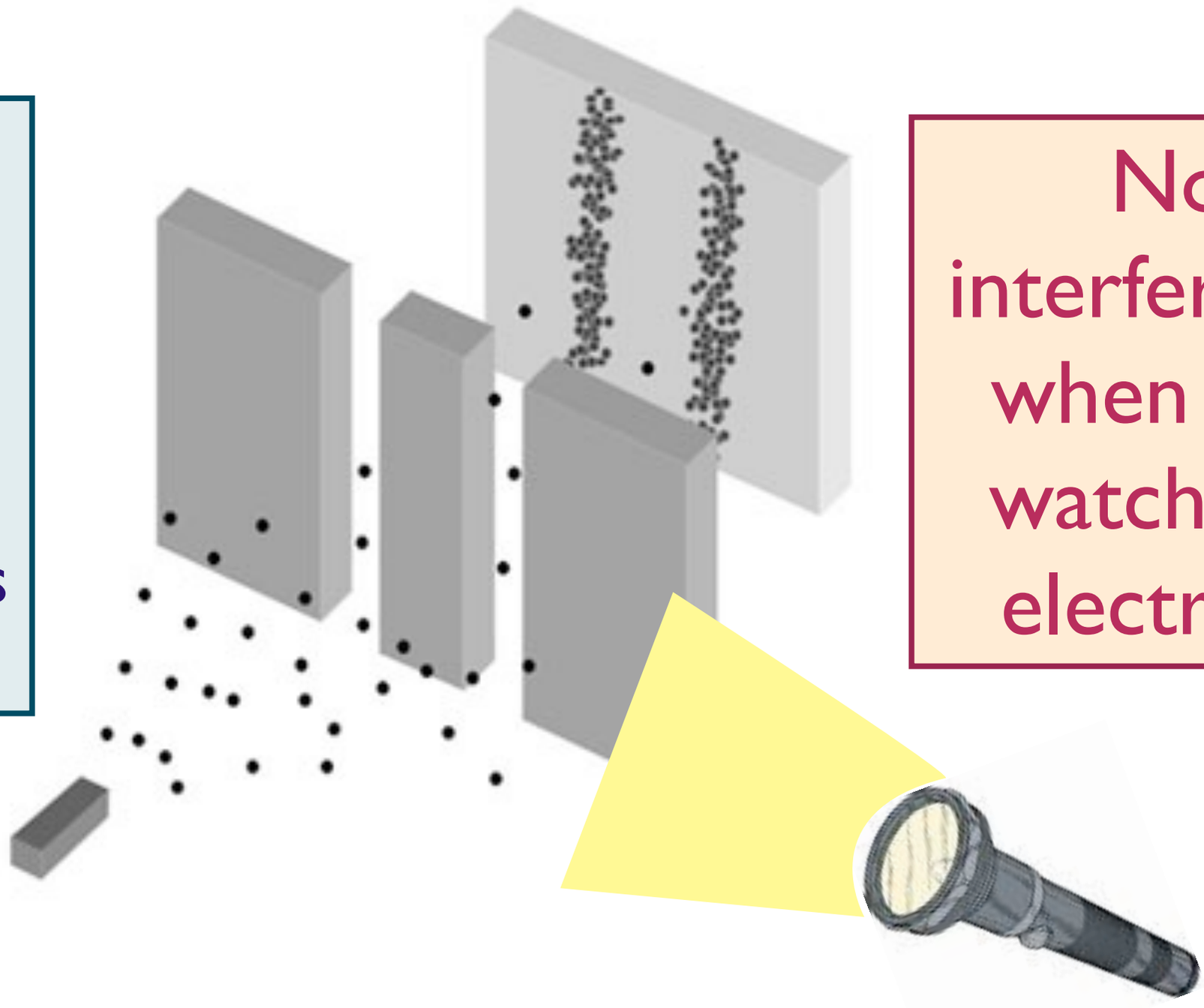
But if it is like a particle, which slit does each electron pass through ?



Interference of electrons

The double slit experiment

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



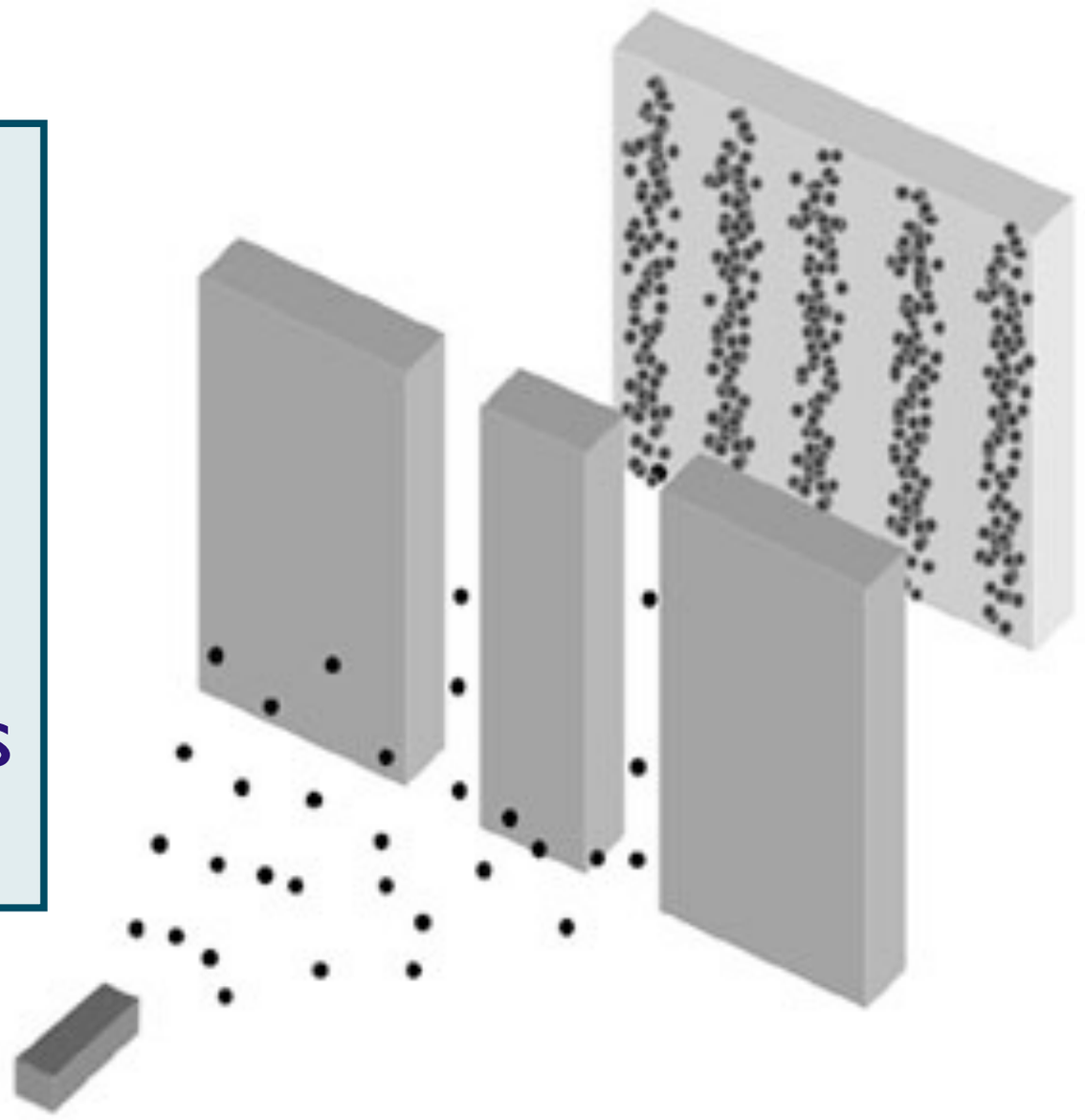
No interference when you watch the electrons

Interference of electrons

Principles of Quantum Mechanics: 1. Quantum Superposition

The double slit experiment

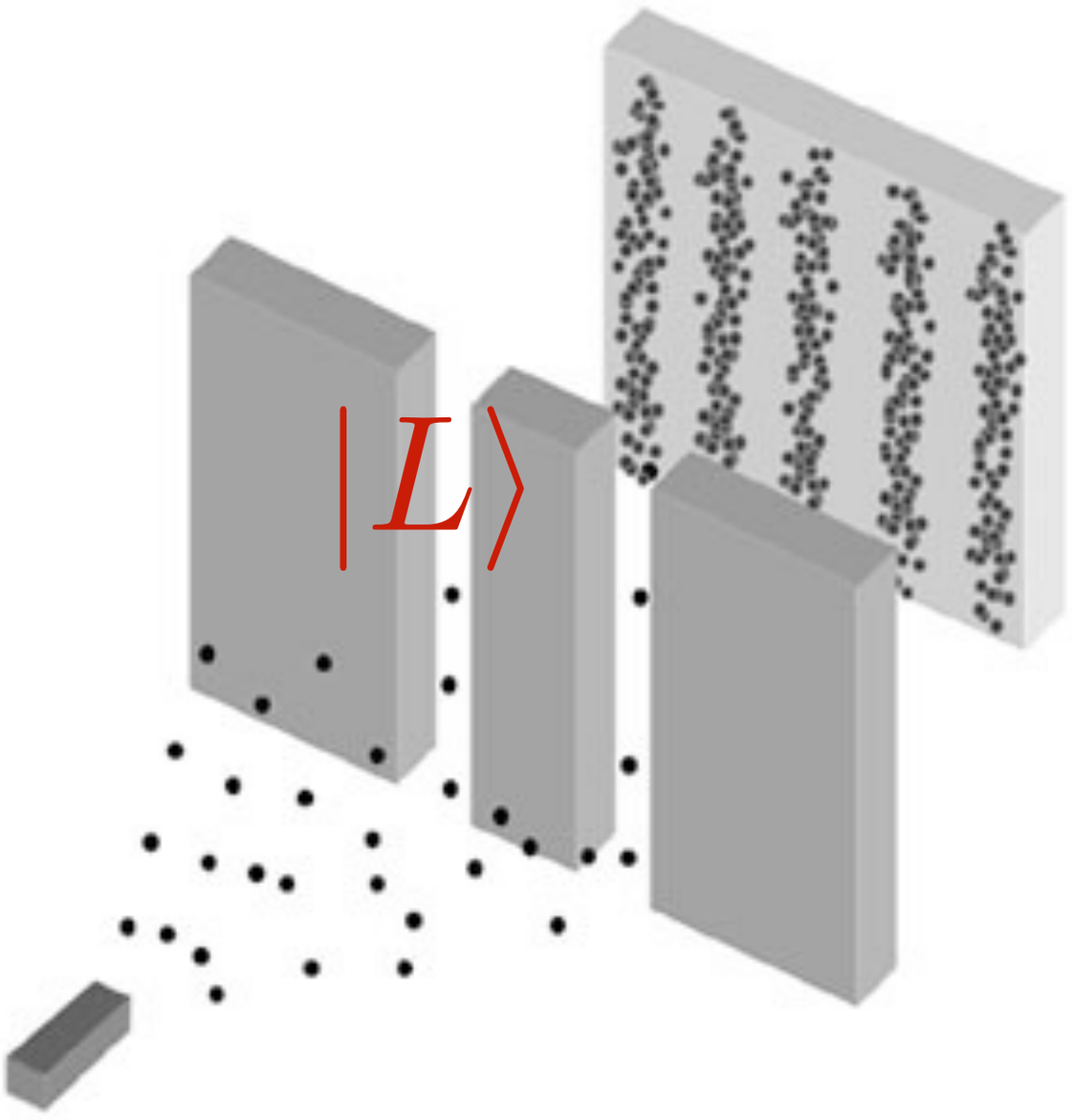
But if it is like a particle, which slit does each electron pass through ?



Each electron passes through both slits !

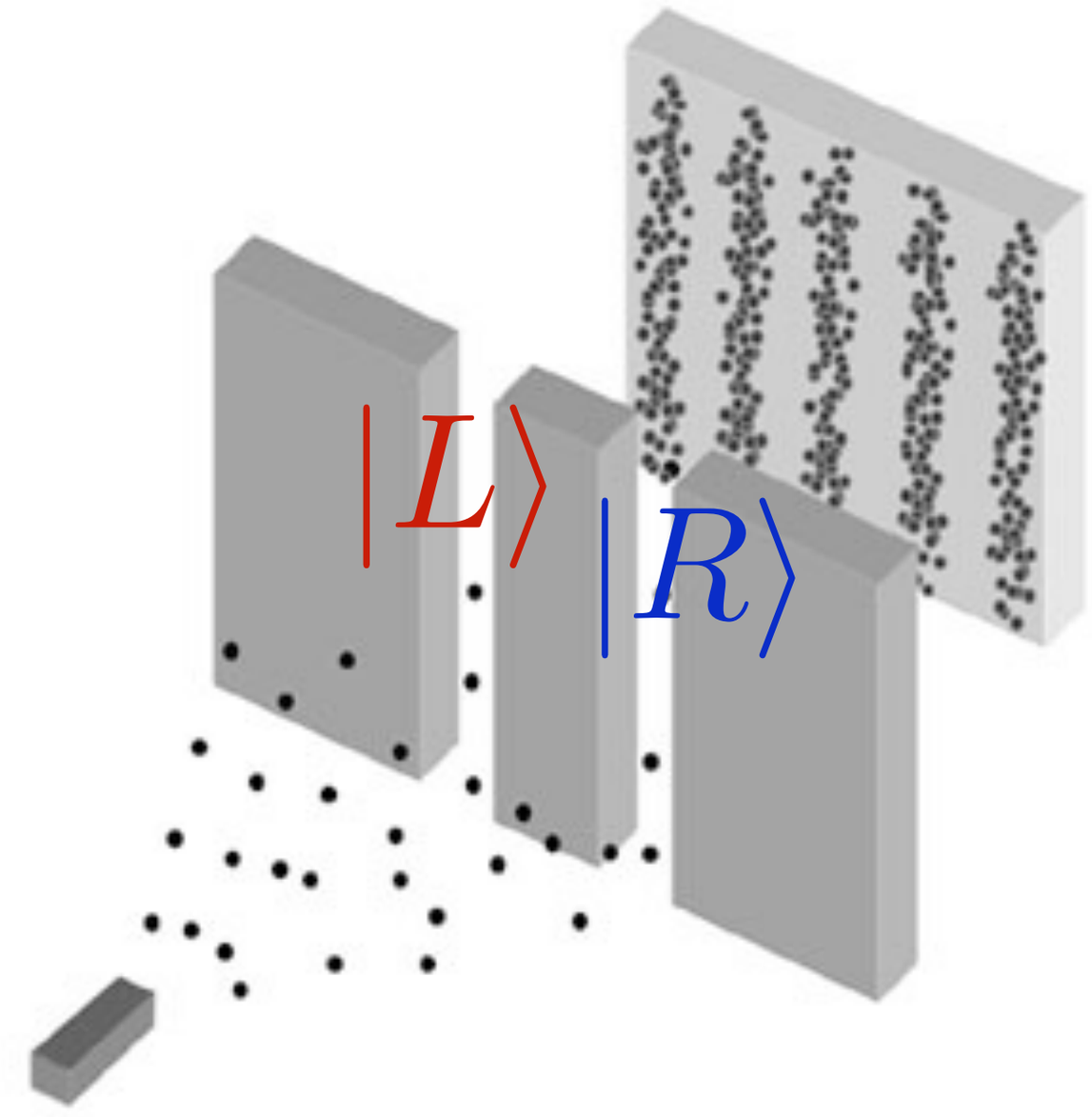
Interference of electrons

The double slit experiment



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

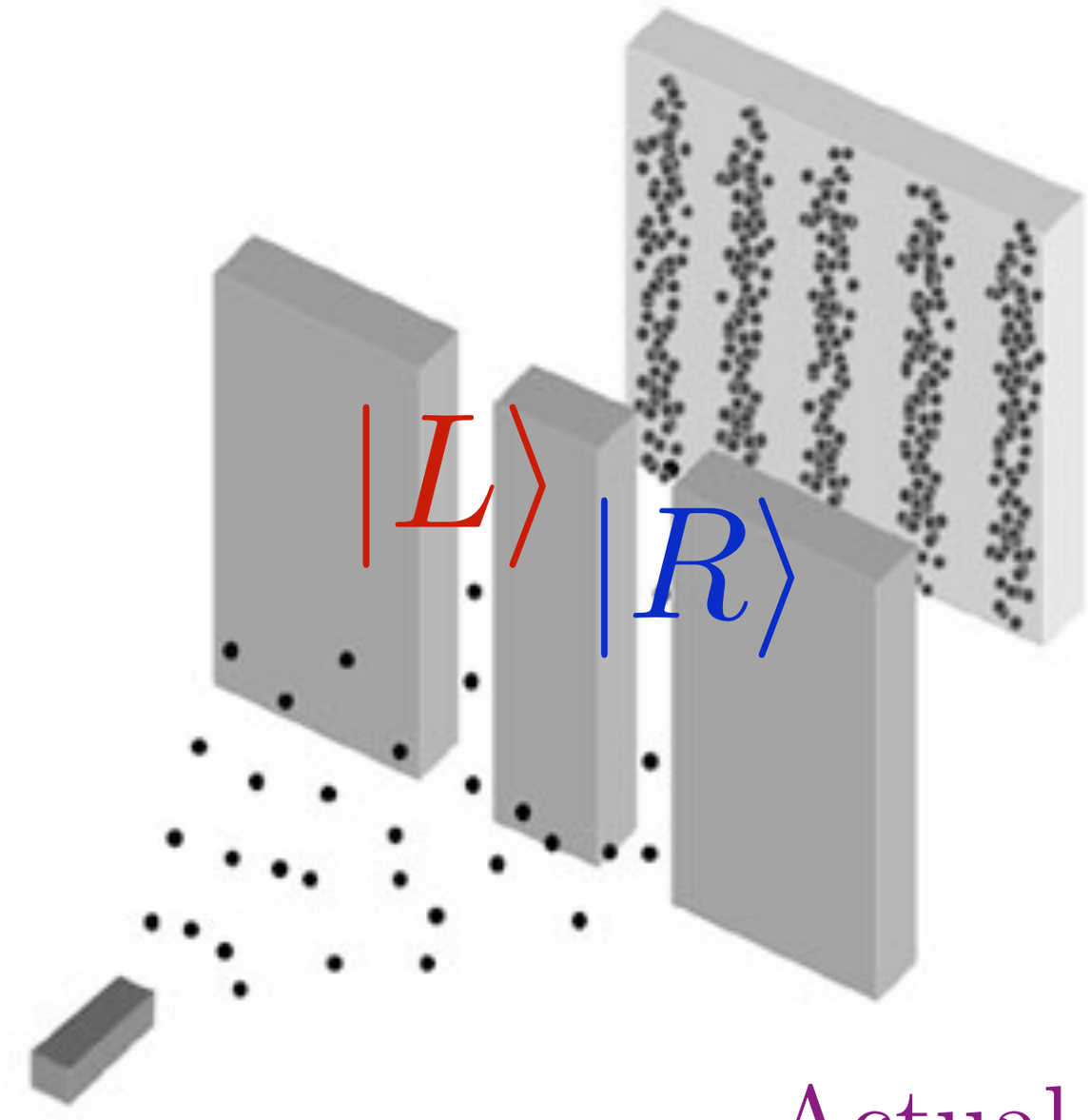
The double slit experiment



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

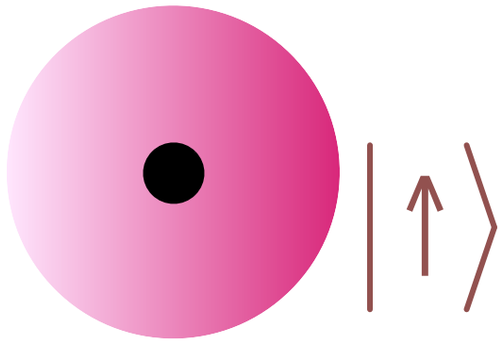
Actual state of *each* electron is

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

Quantum Entanglement: quantum superposition with more than one particle

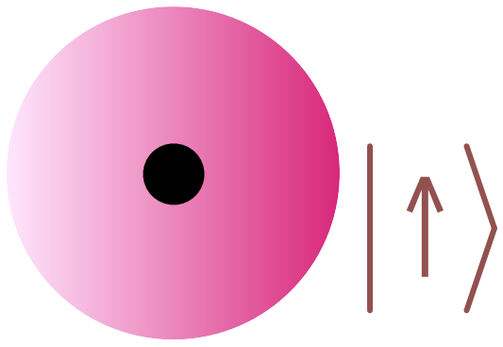
Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

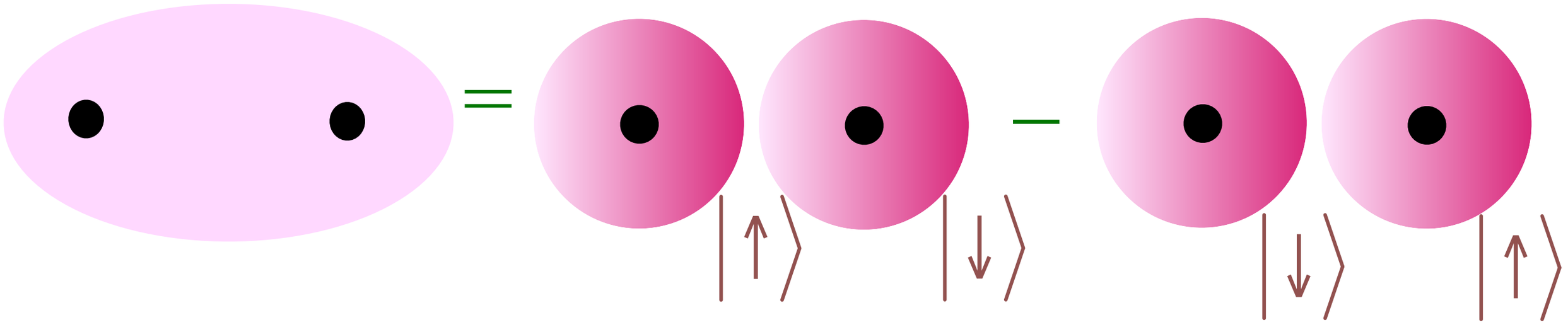


Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

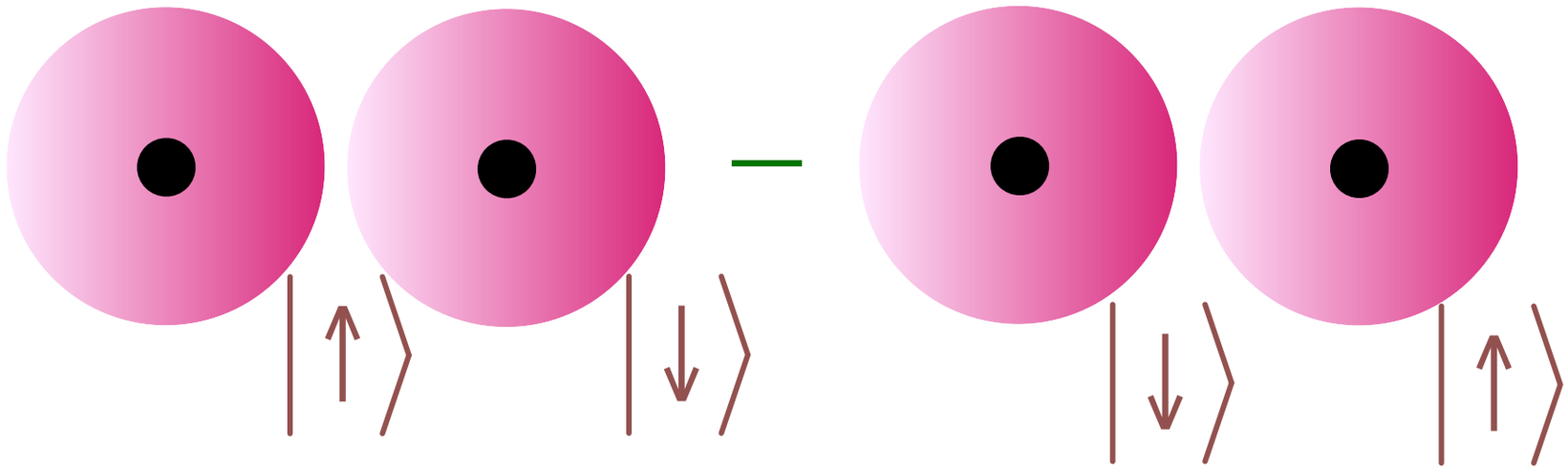


Hydrogen molecule:

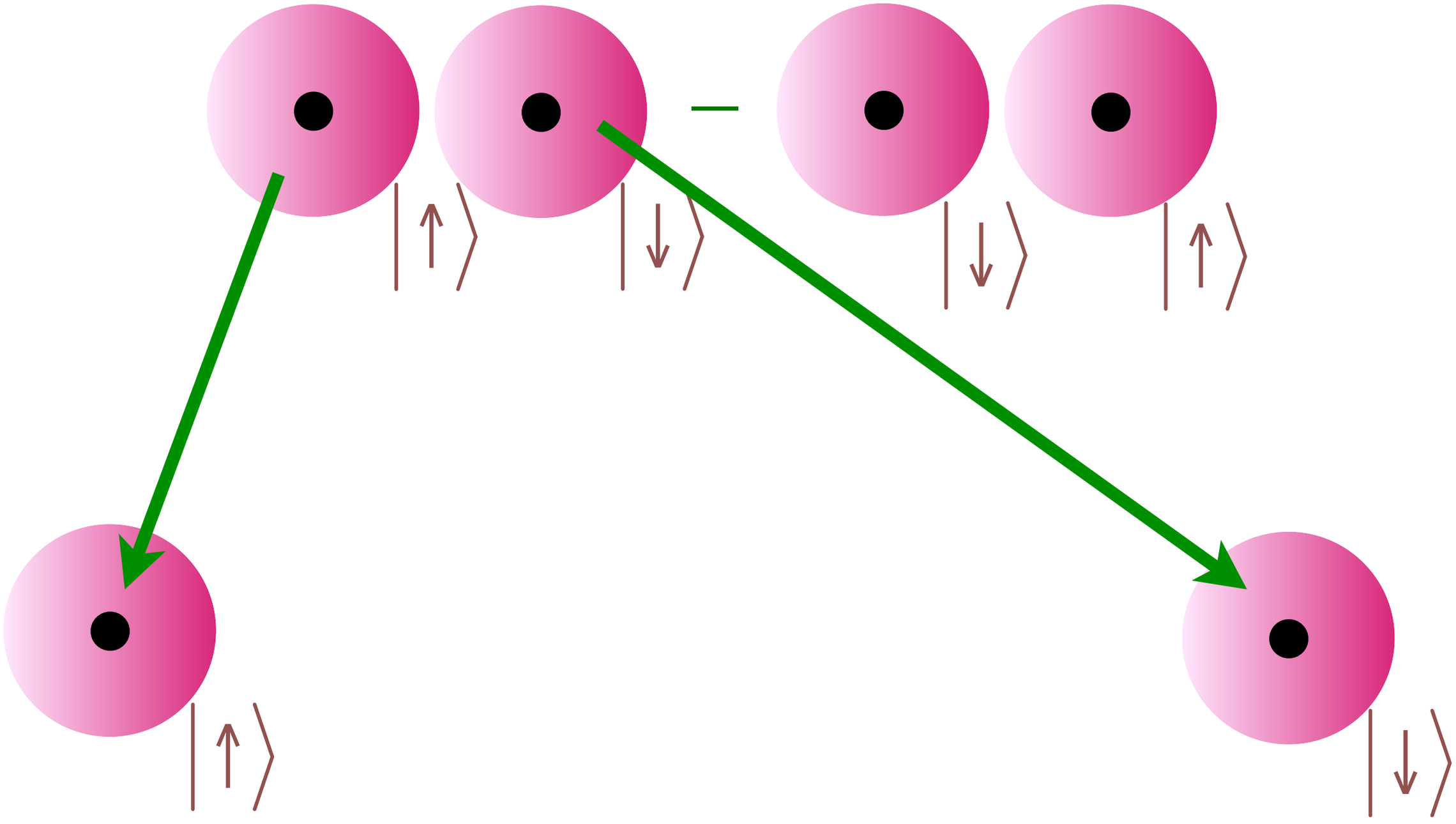


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

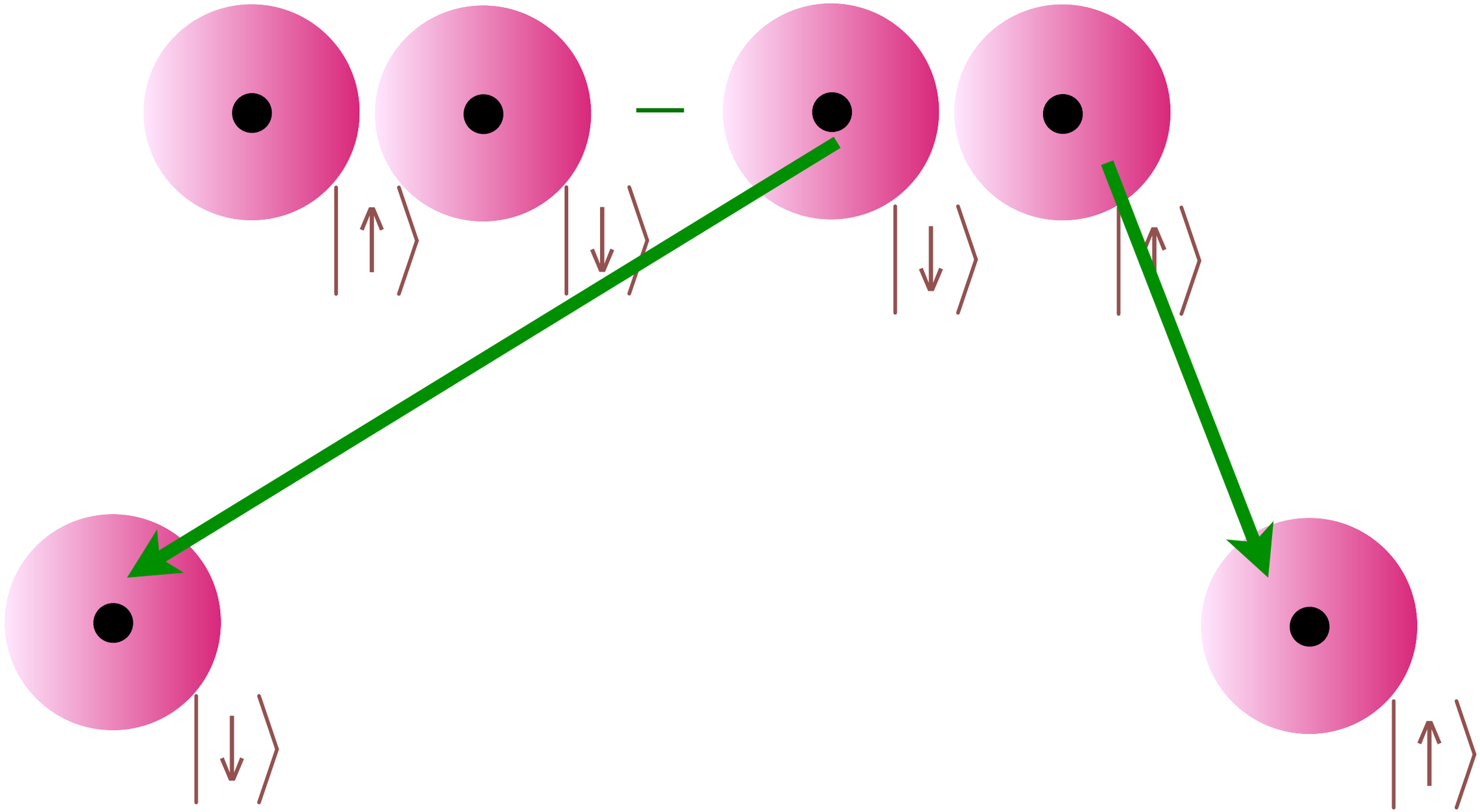
Quantum Entanglement: quantum superposition with more than one particle



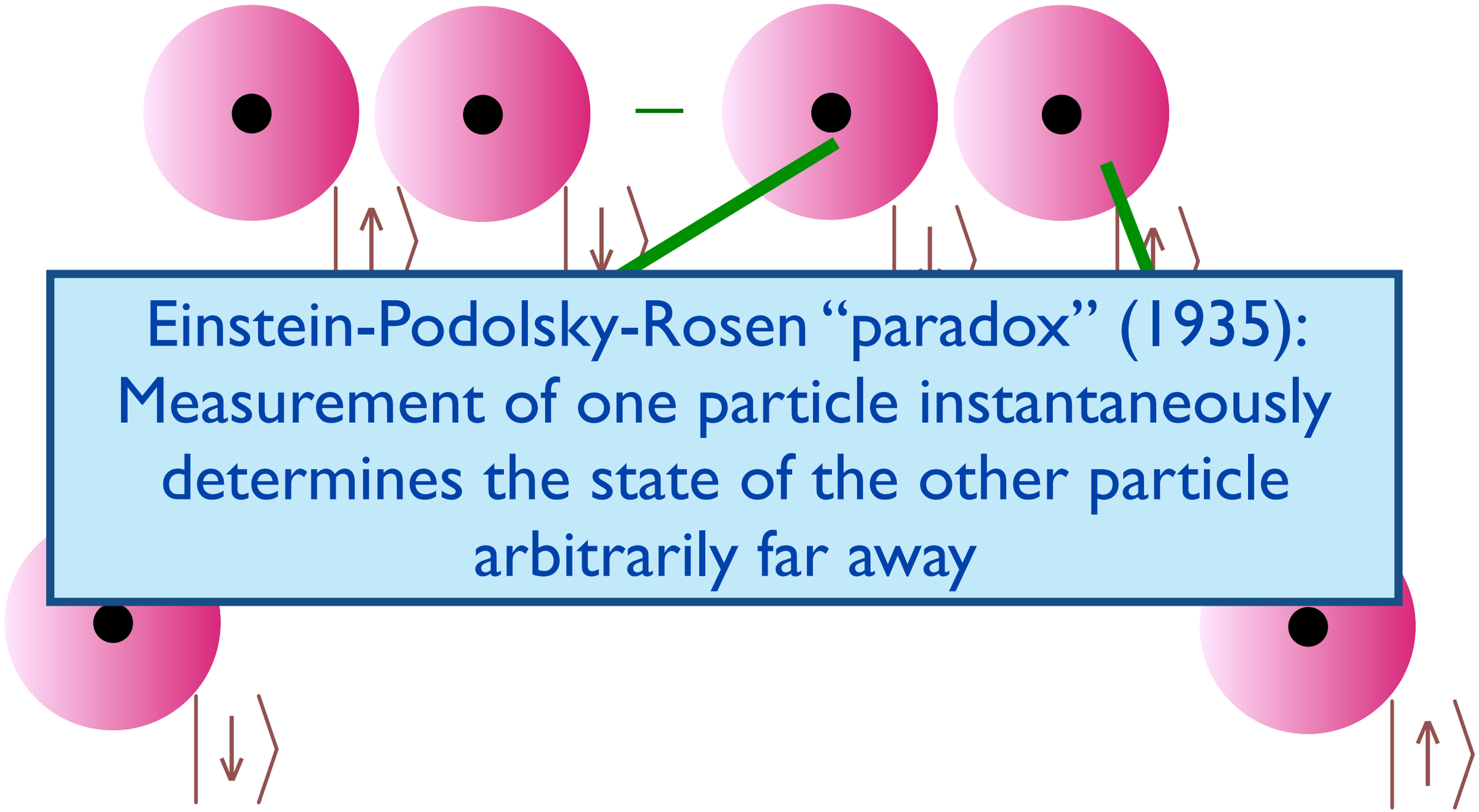
Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



Quantum entanglement

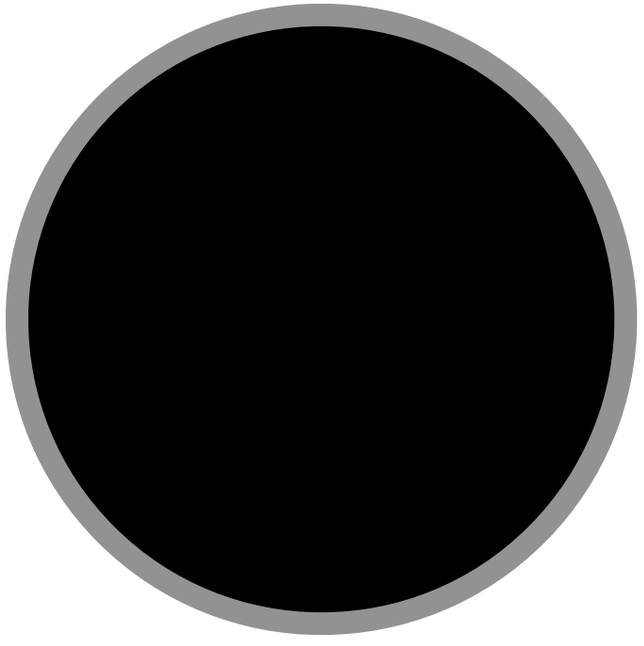
Quantum entanglement

Black holes

Black Holes

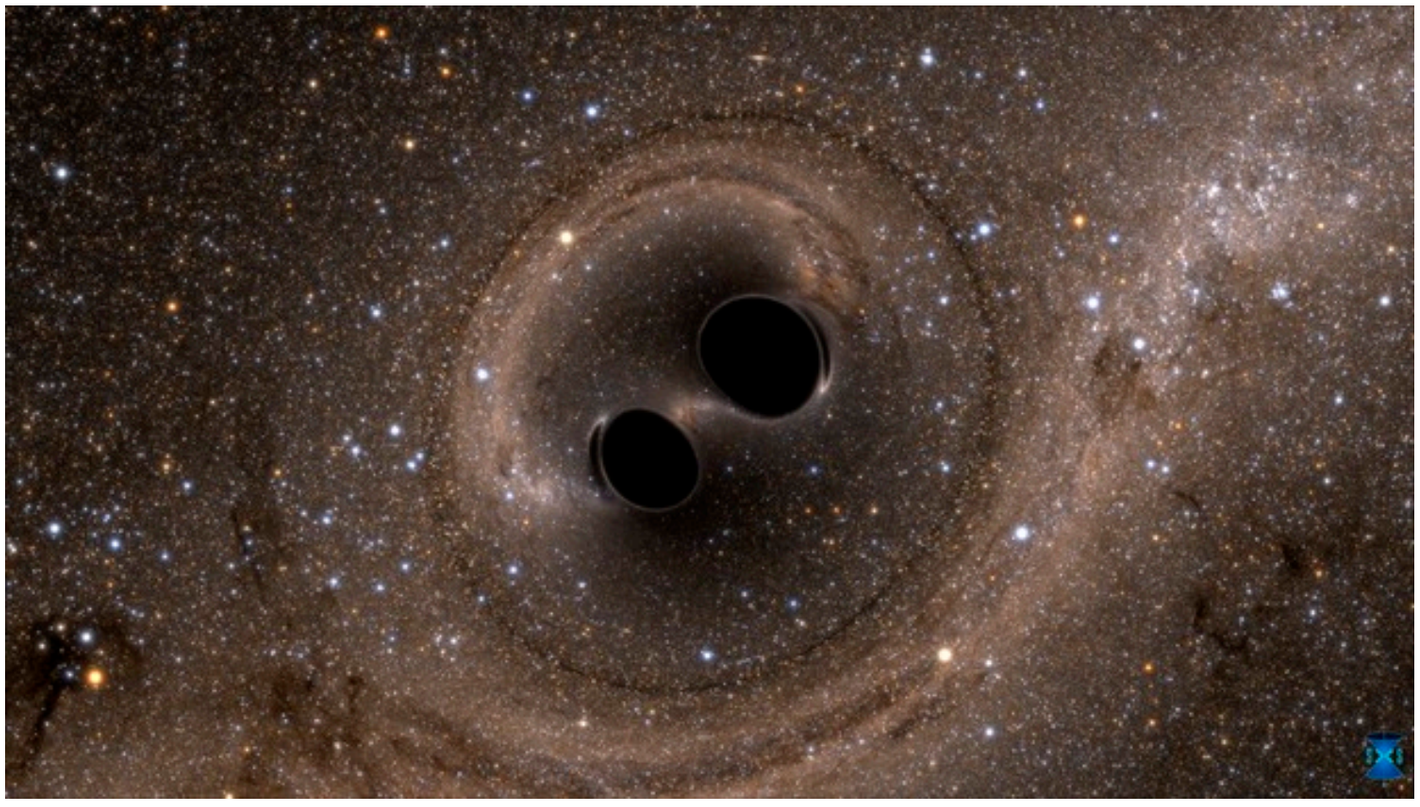
Objects so dense that light is gravitationally bound to them.

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



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

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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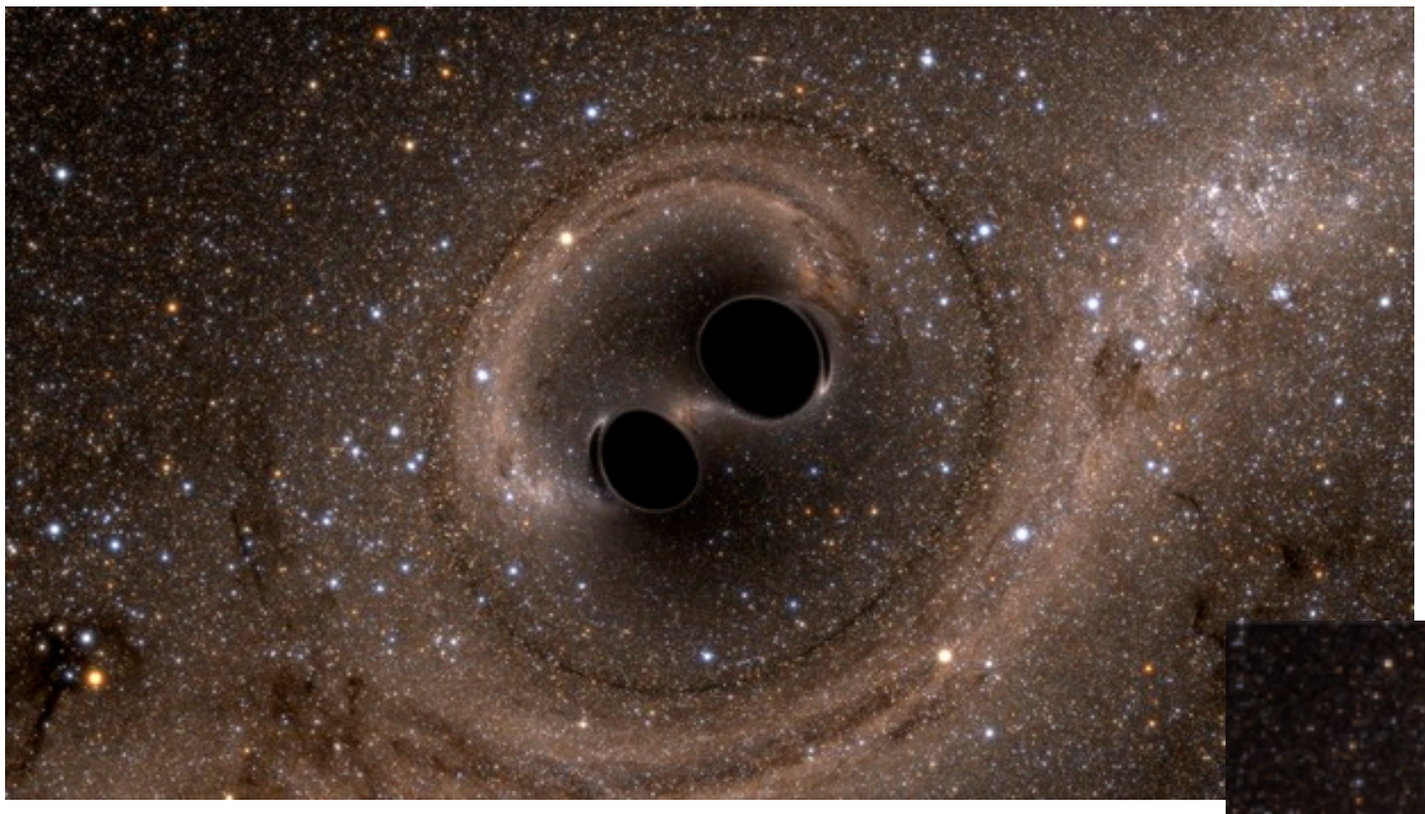
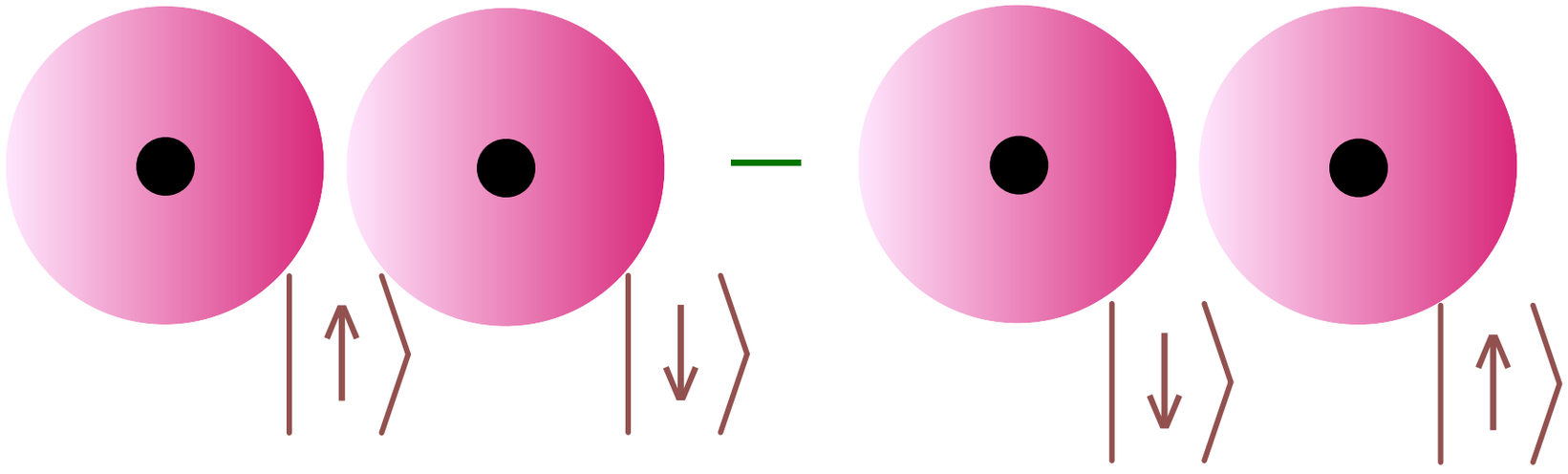


0.1 seconds later !

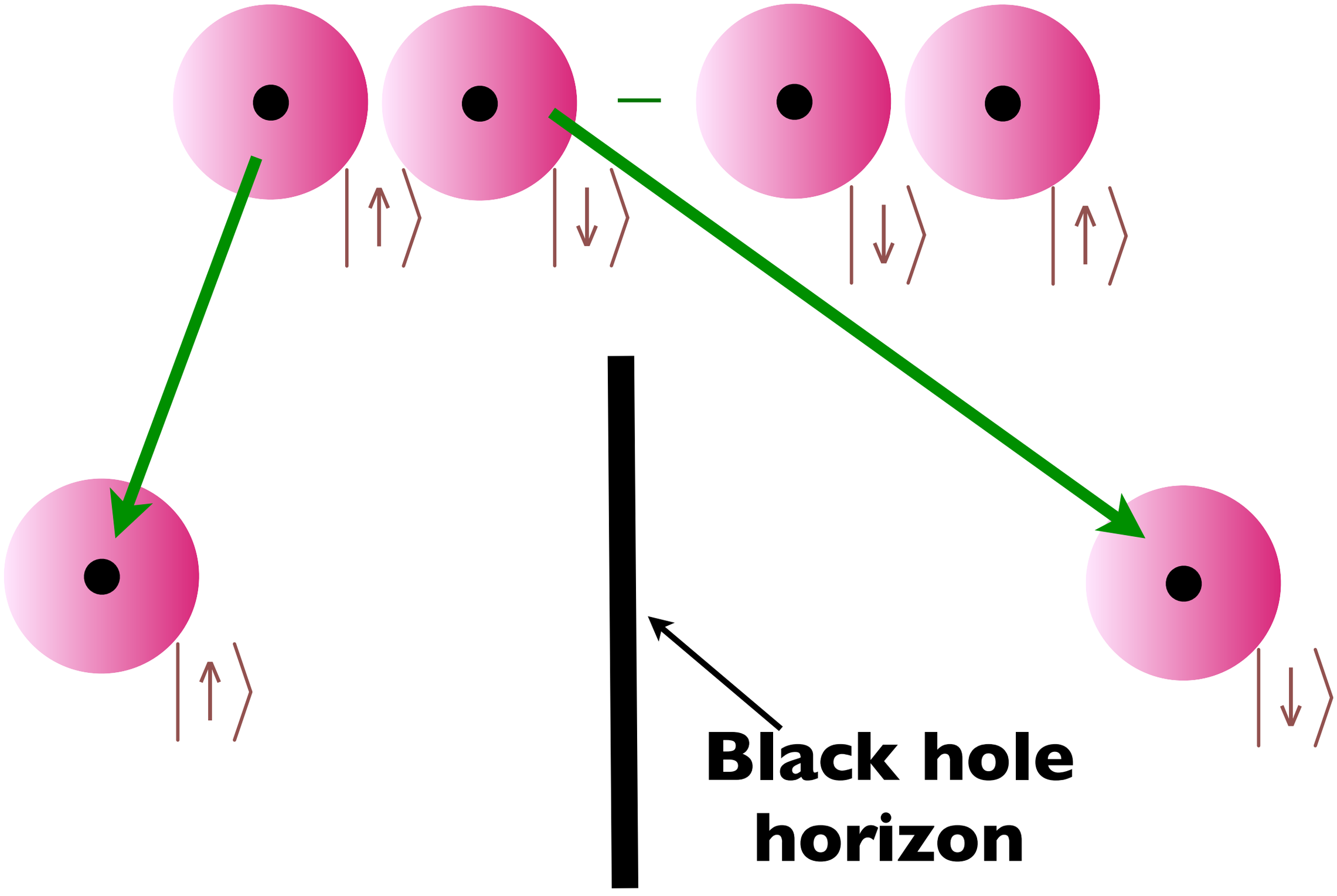
Black Holes + Quantum theory

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

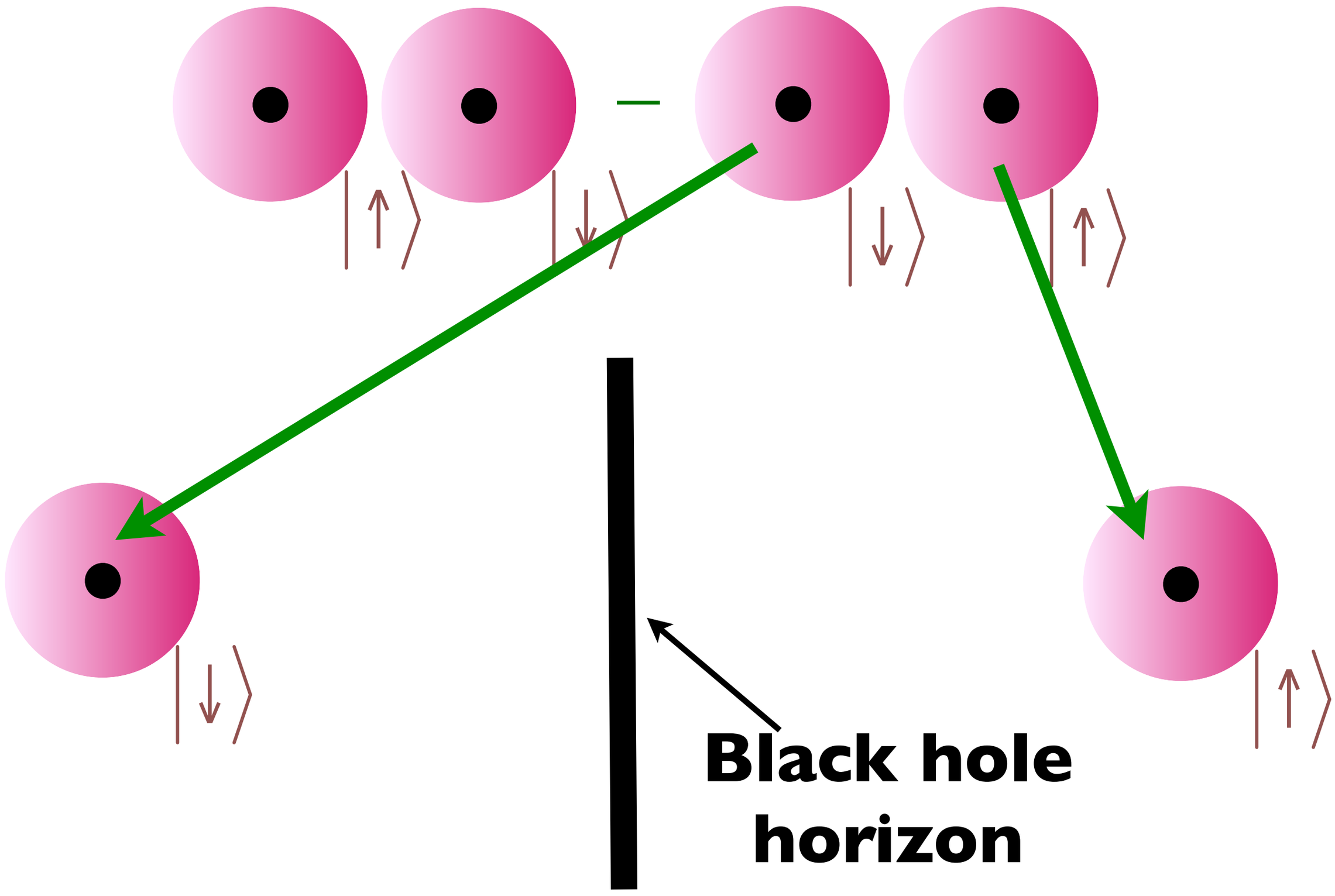
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

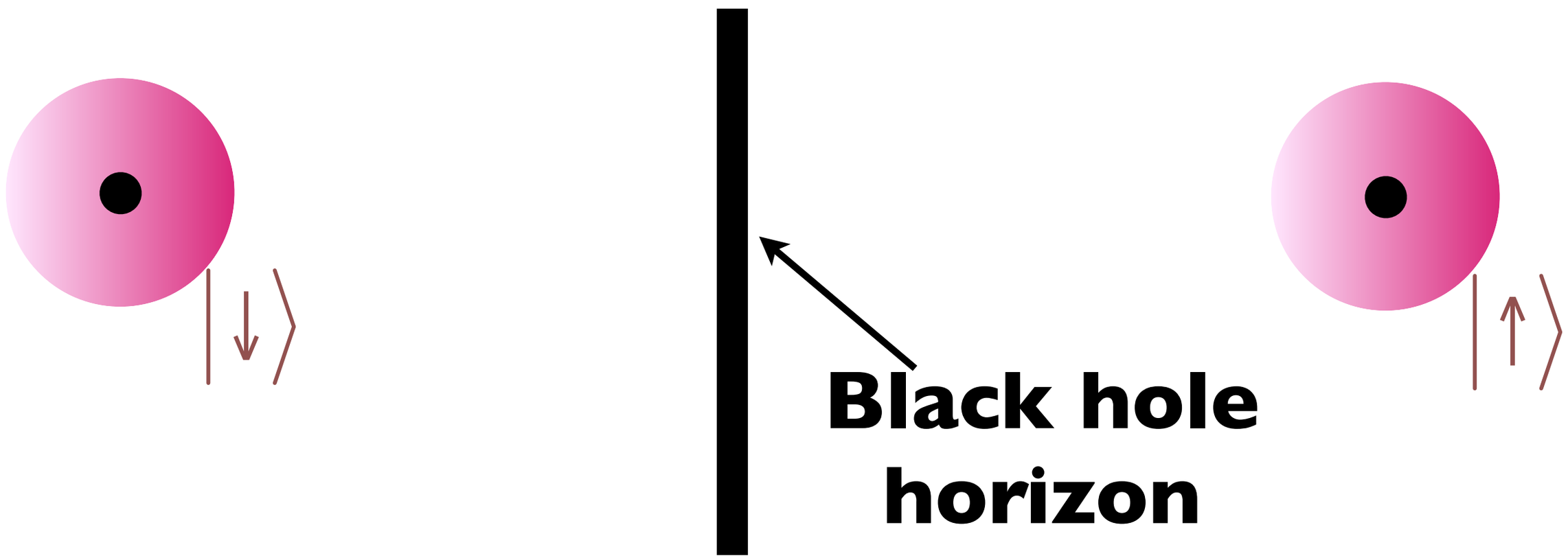


Quantum Entanglement across a black hole horizon



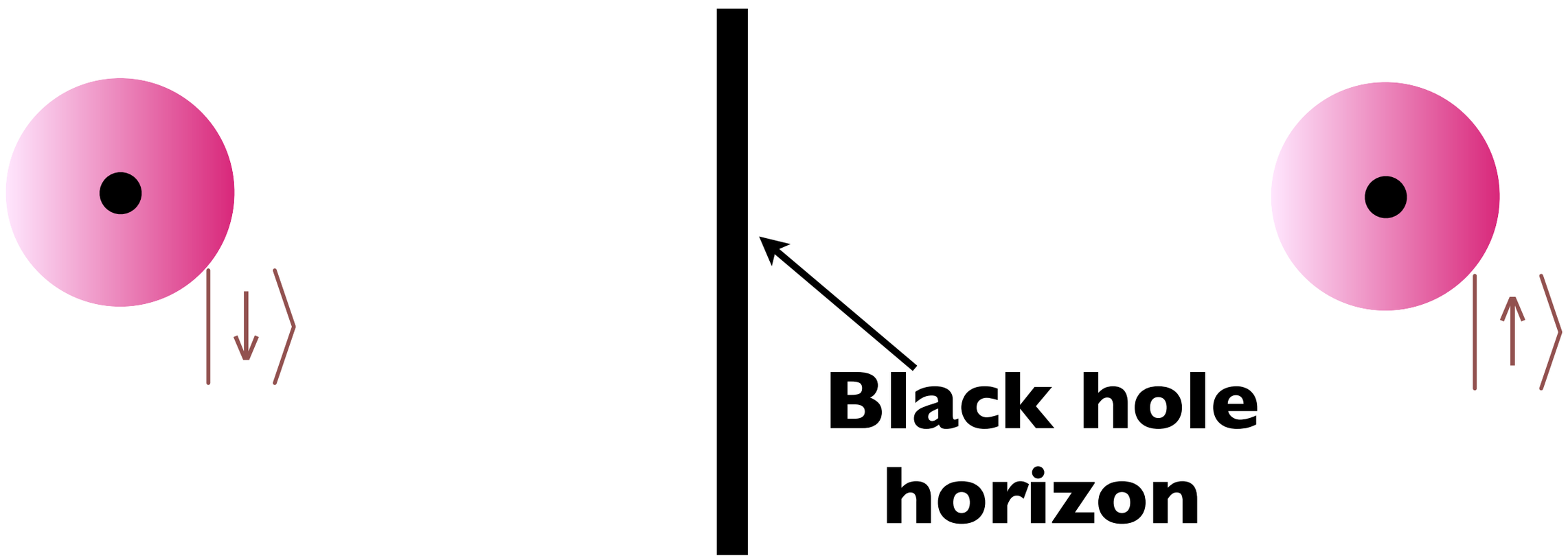
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

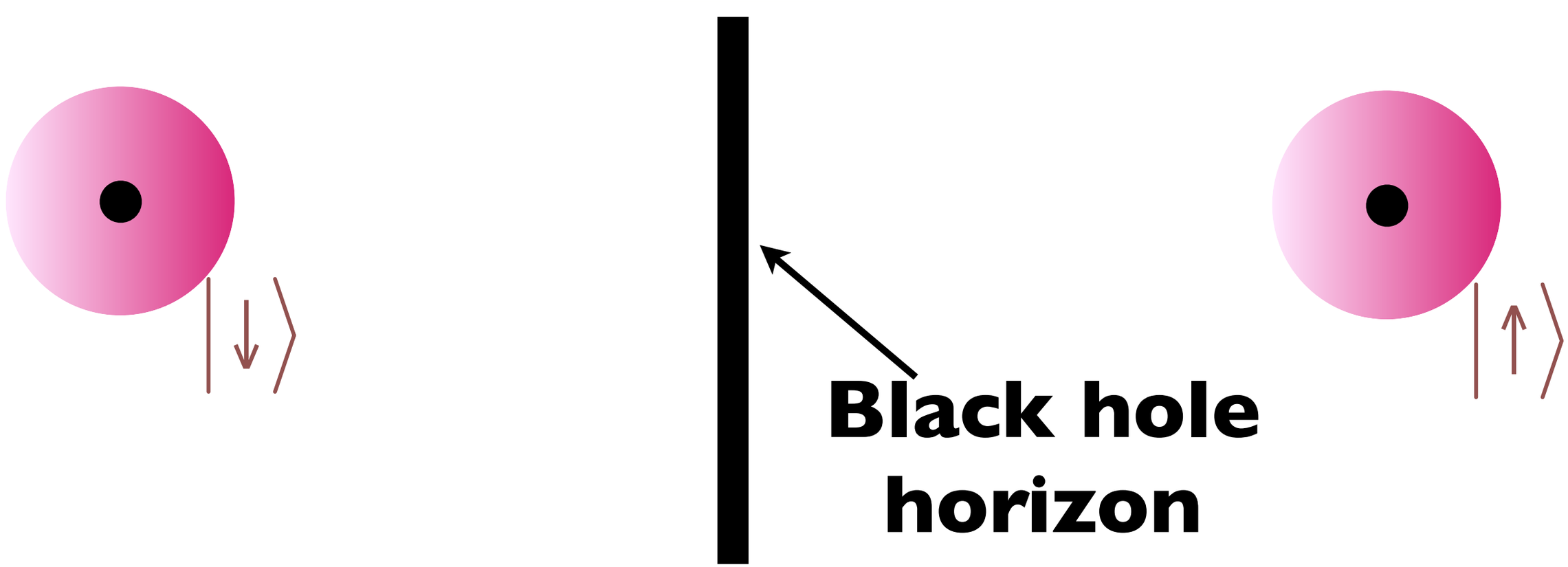
Hawking used this to show that black hole horizons have an entropy and a temperature



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

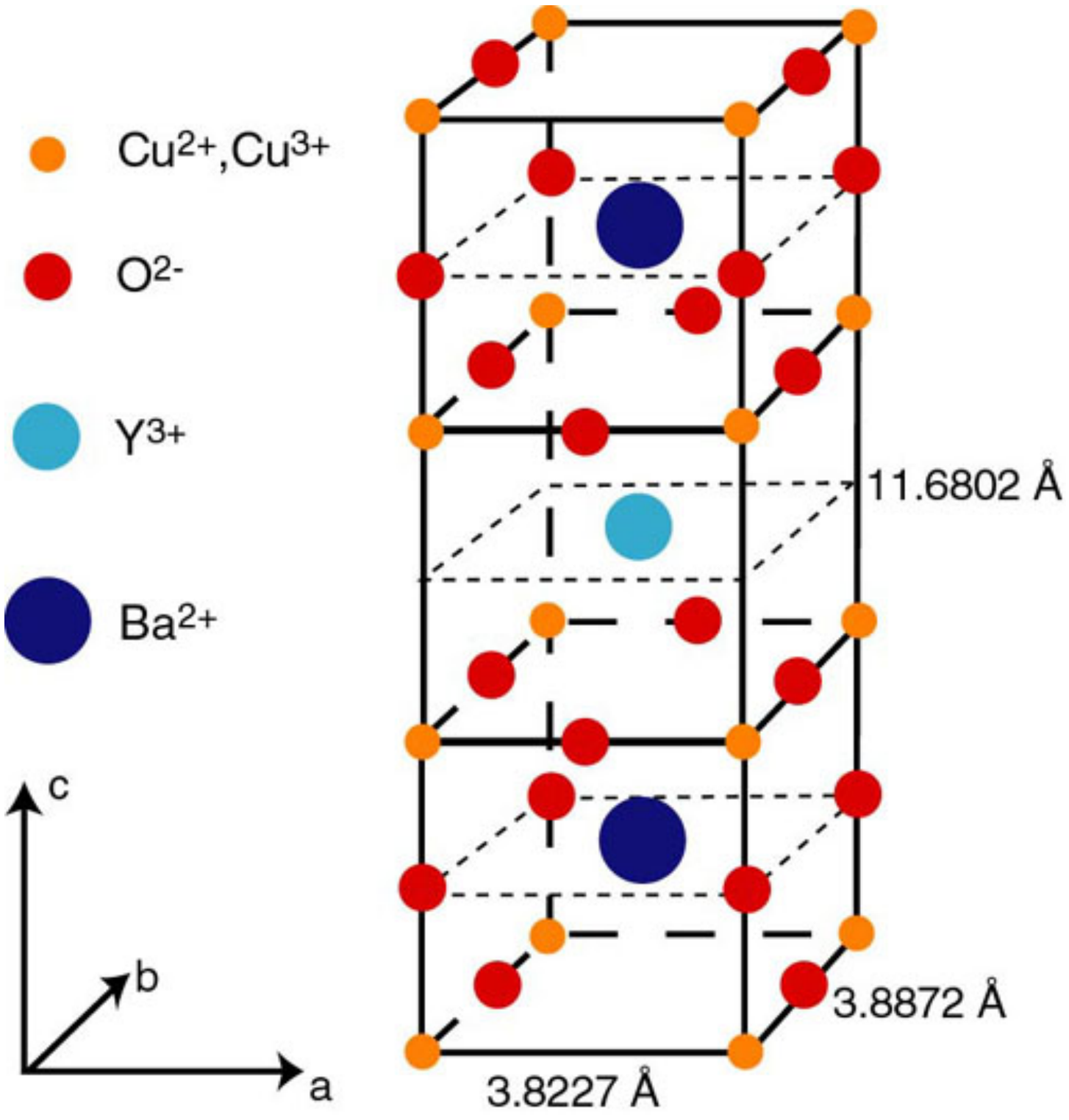
Black holes

Quantum entanglement

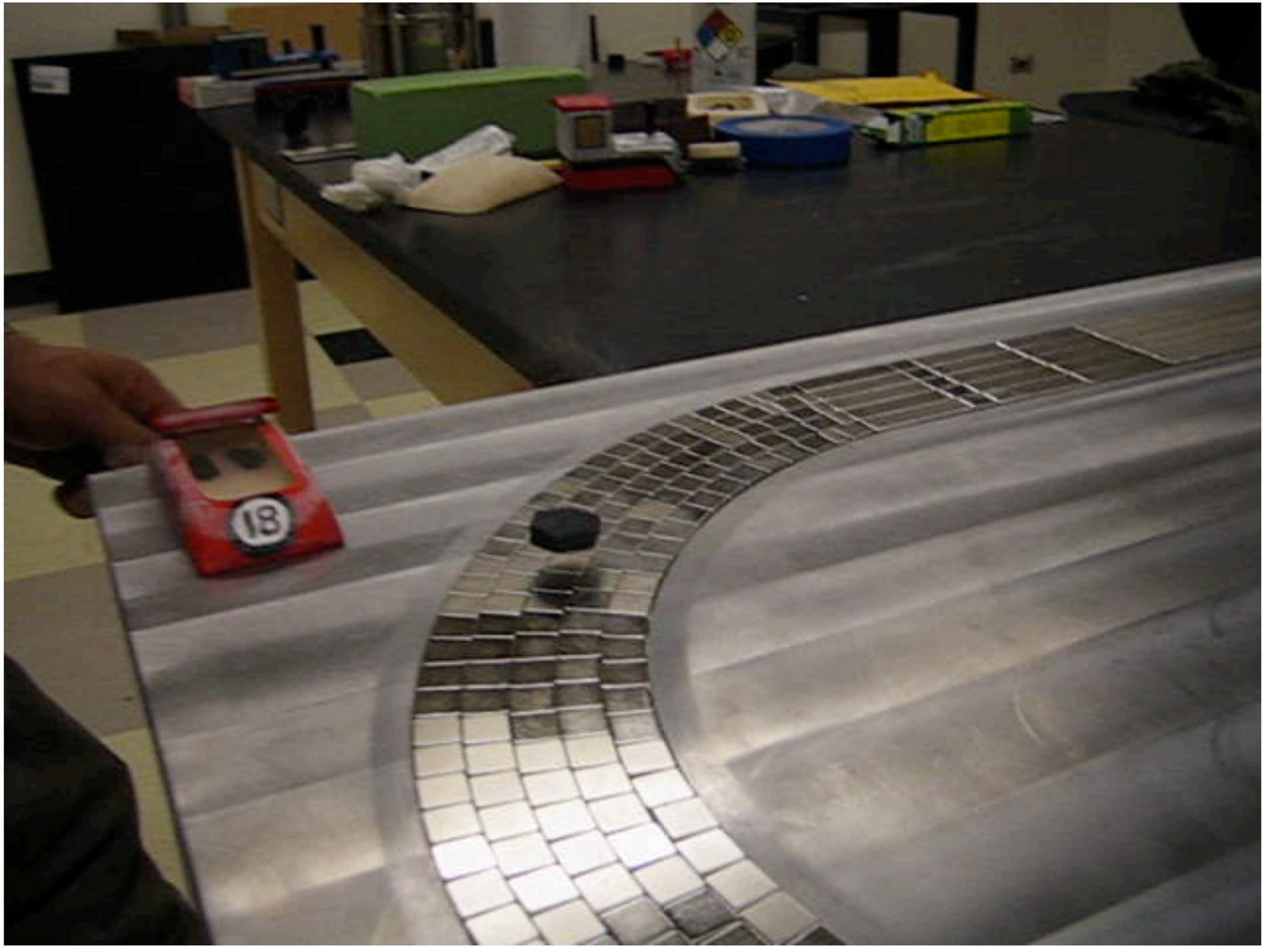
Black holes

Superconductors

High temperature superconductors

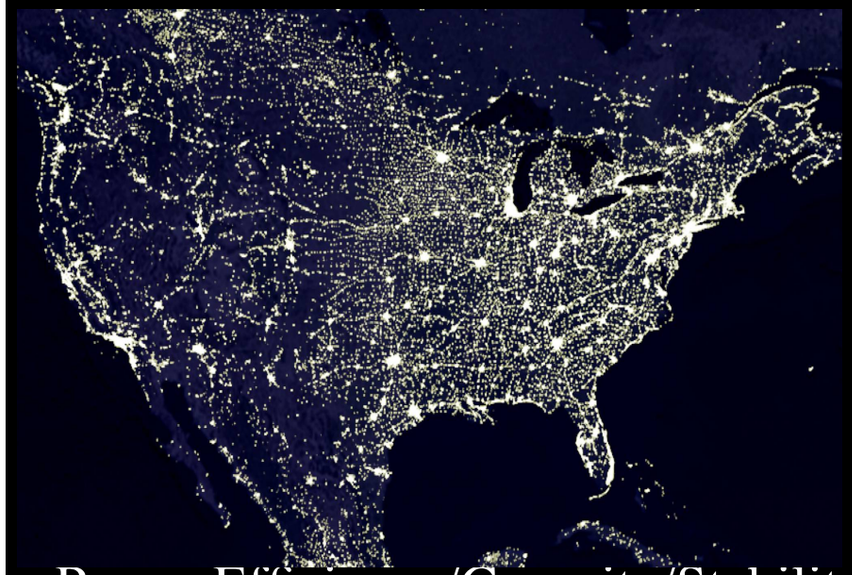


$$YBa_2Cu_3O_{6+x}$$



Nd-Fe-B magnets, YBaCuO superconductor

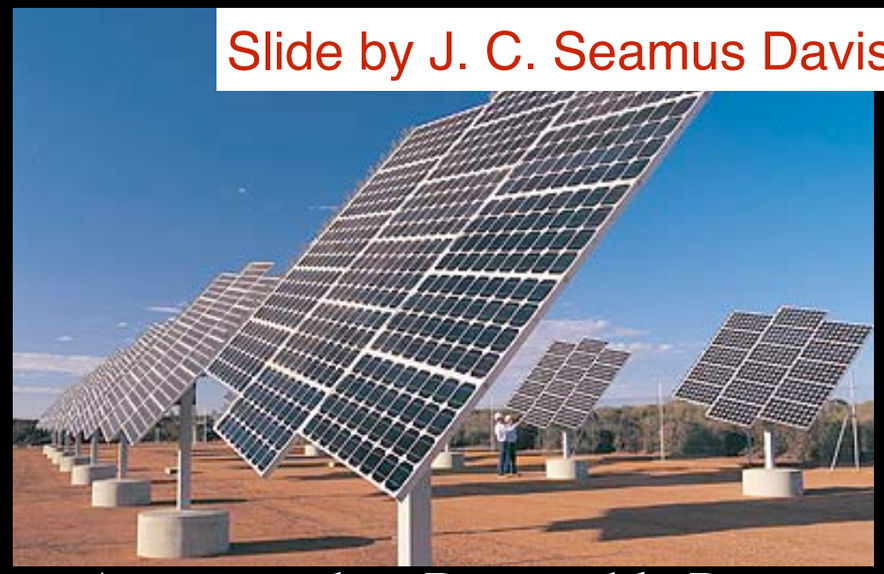
Julian Hetel and Nandini Trivedi, Ohio State University



Power Efficiency/Capacity/Stability

Power Bottlenecks

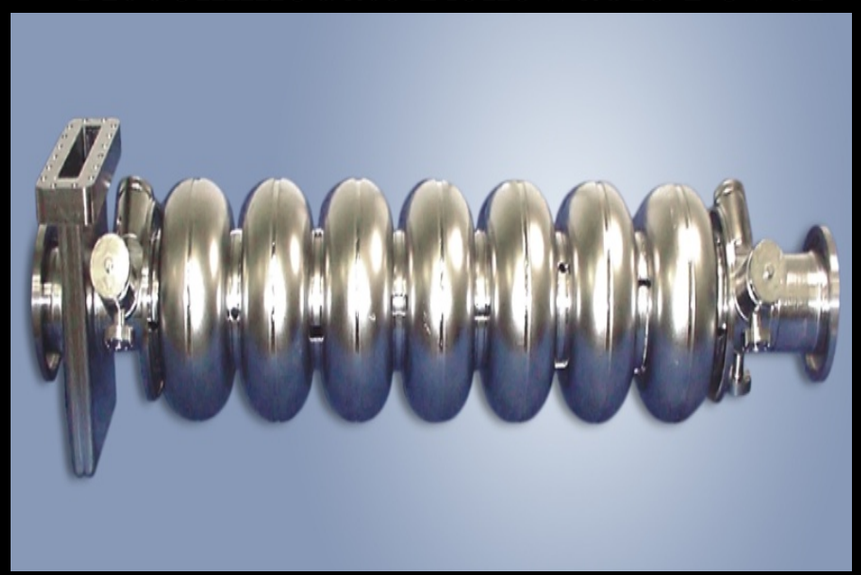
Slide by J. C. Seamus Davis



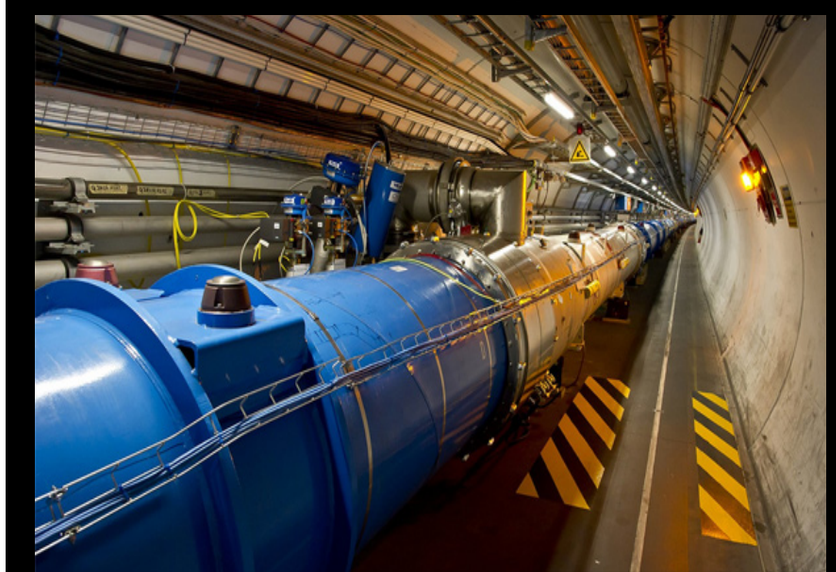
Accommodate Renewable Power

Efficient Rotating Machines

Information Technology



Next Generation HEP

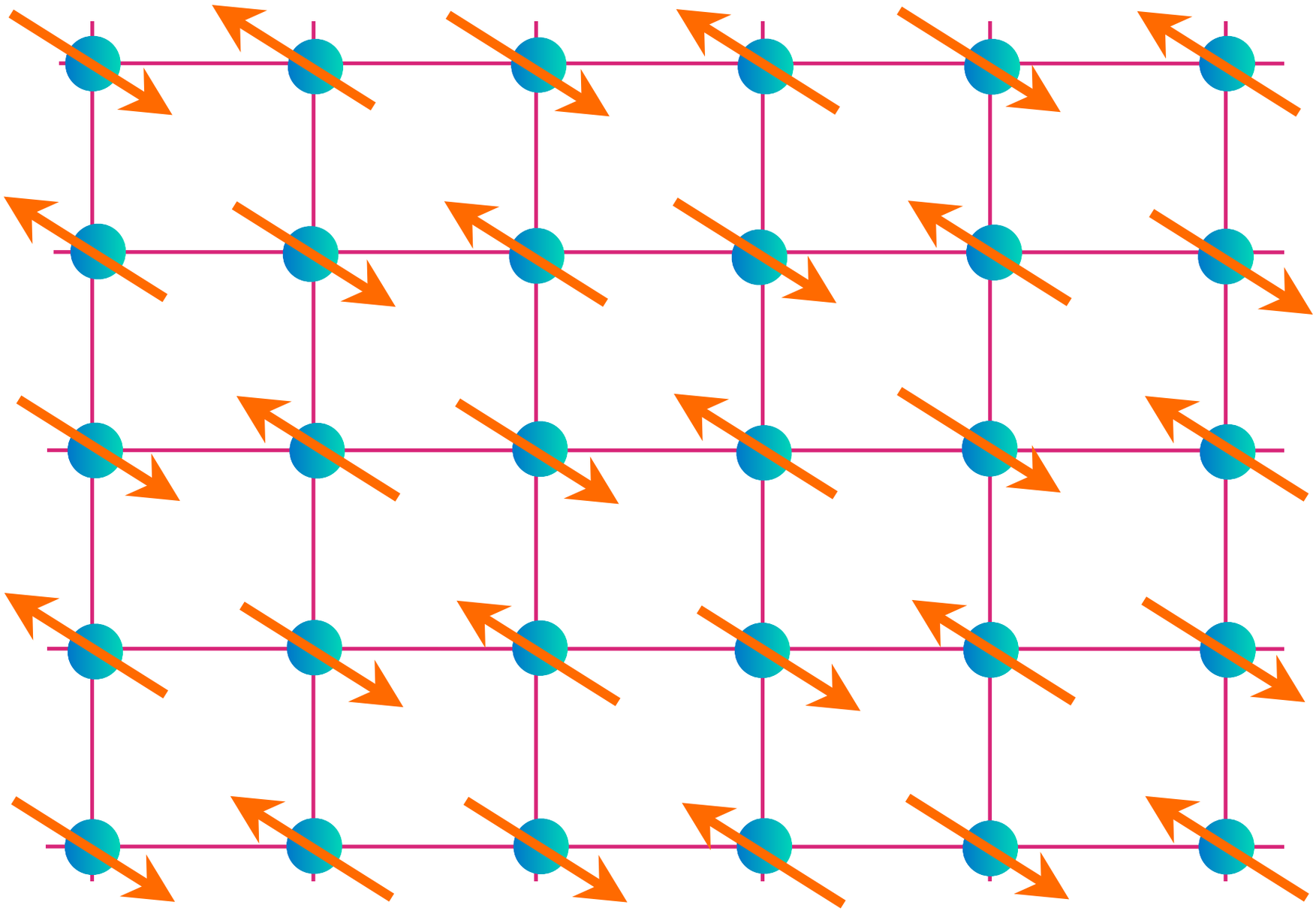


Ultra-High Magnetic Fields

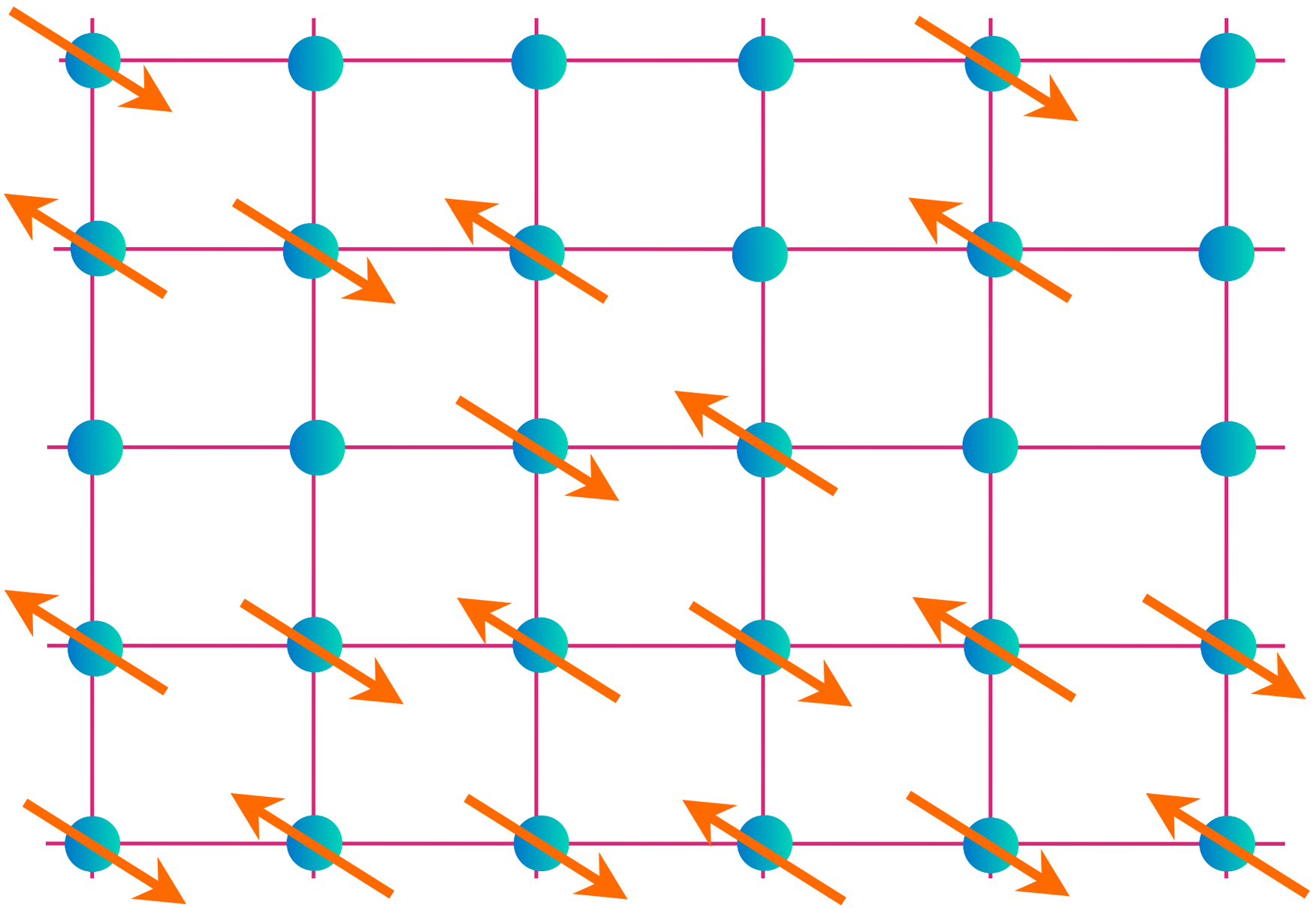
Medical

Transport

Square lattice of Cu sites

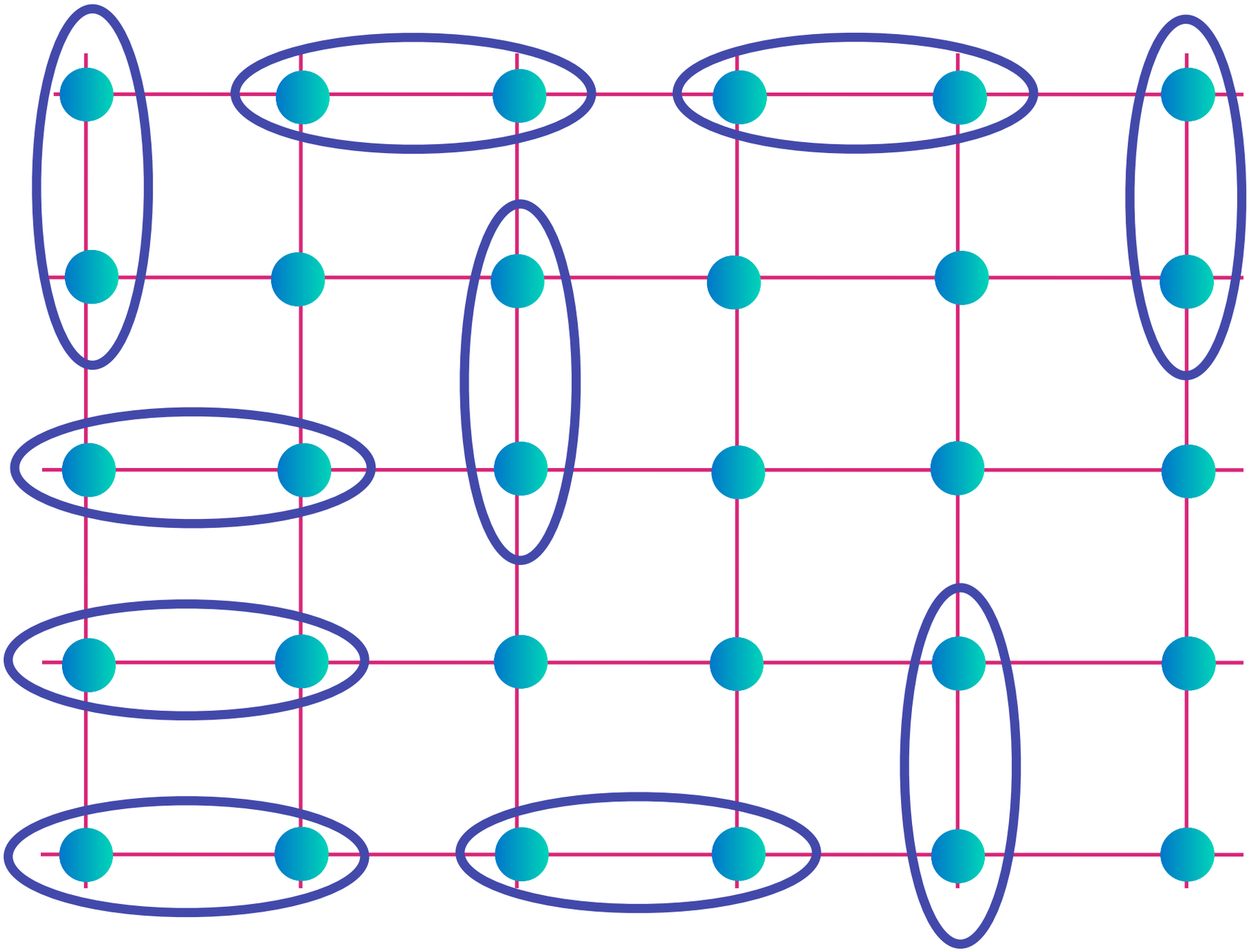


Square lattice of Cu sites

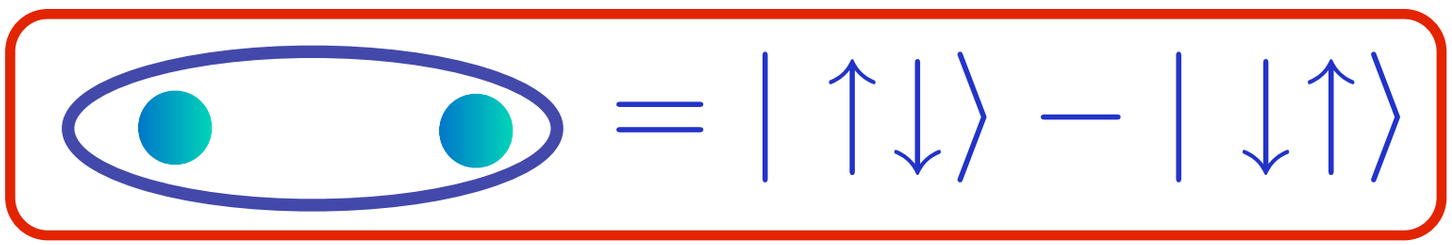


Remove some electrons

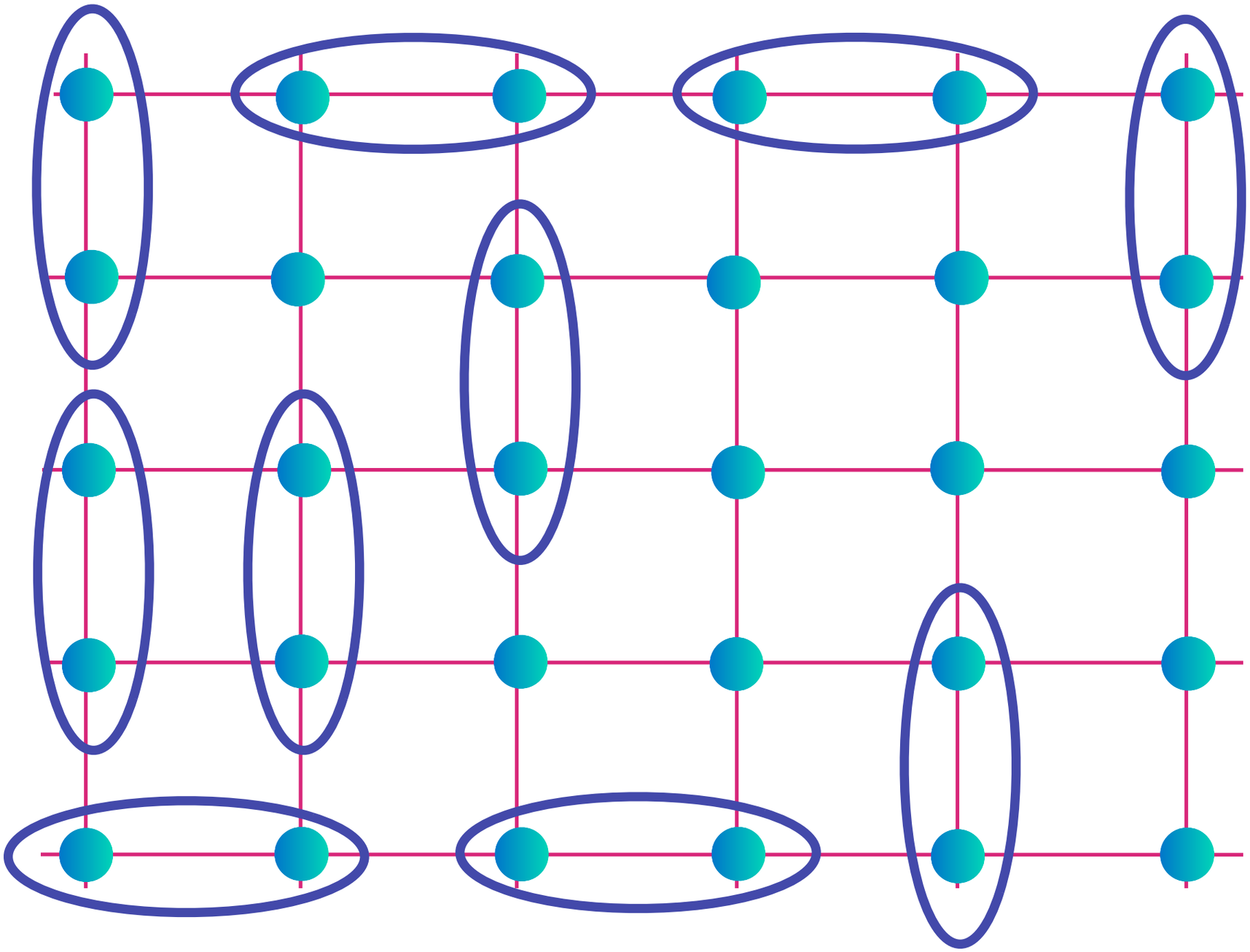
Square lattice of Cu sites



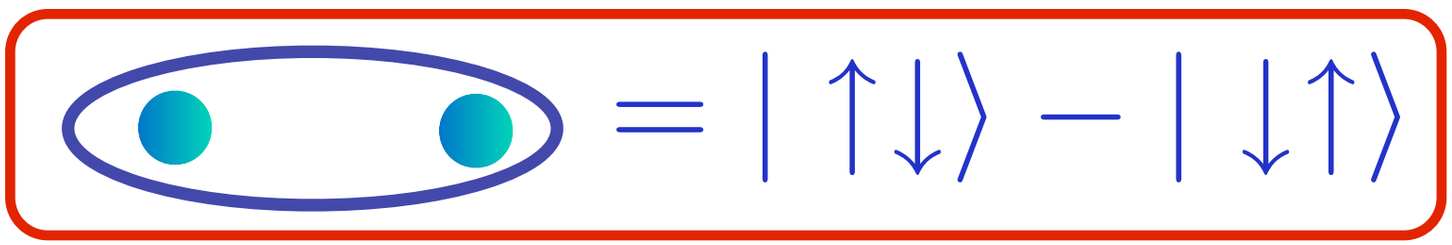
Electrons entangle in ("Cooper") pairs into chemical bonds



Square lattice of Cu sites



Electrons <u>entangle</u> "en masse" by exchanging partners, and there is <u>long-range quantum entanglement</u>



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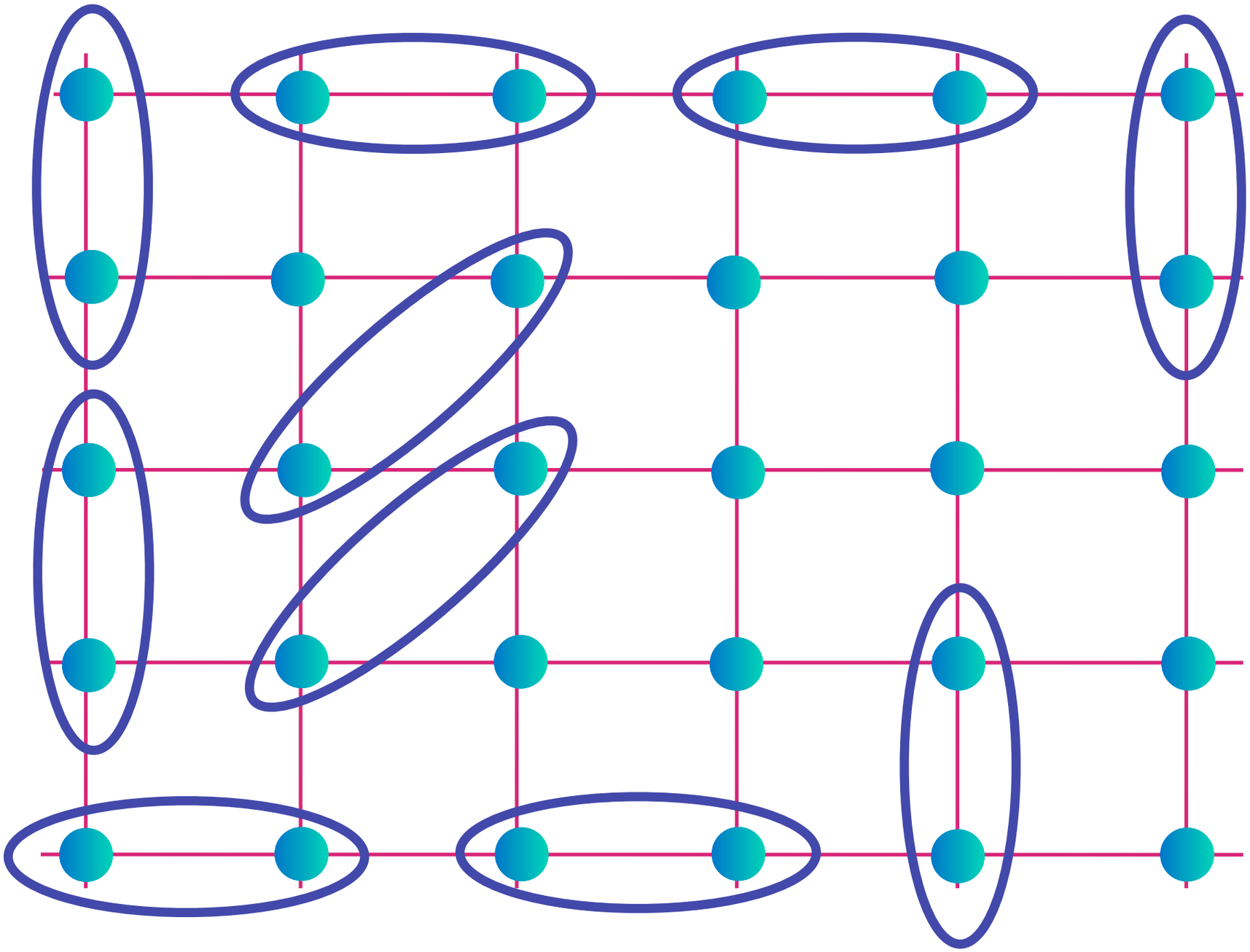

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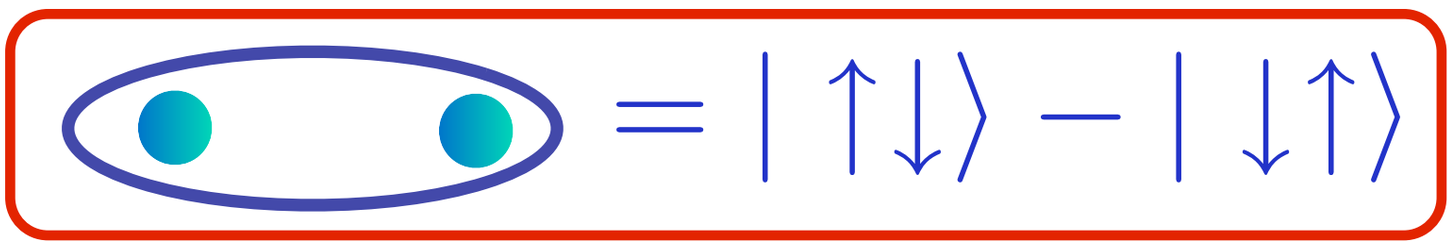
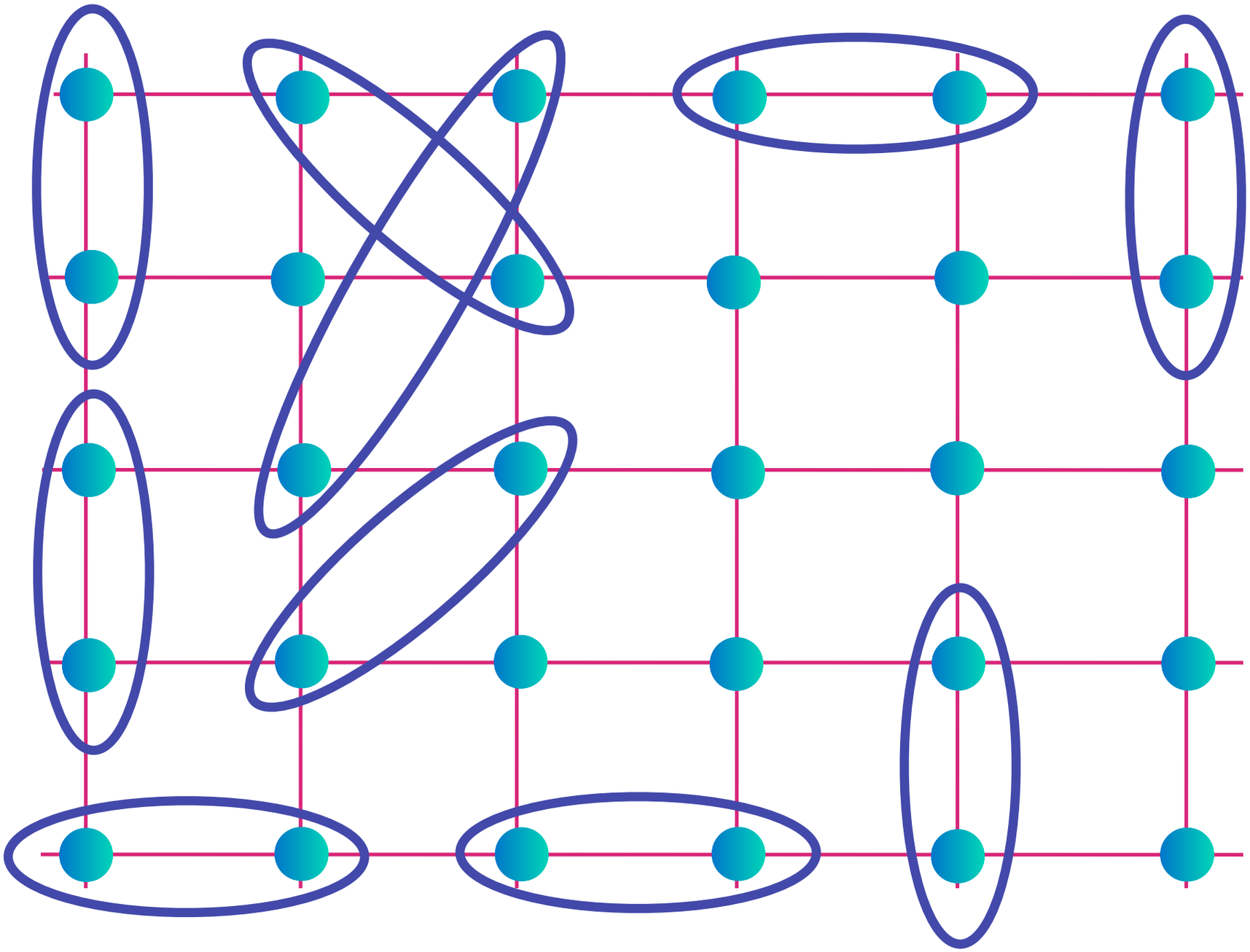


Square lattice of Cu sites



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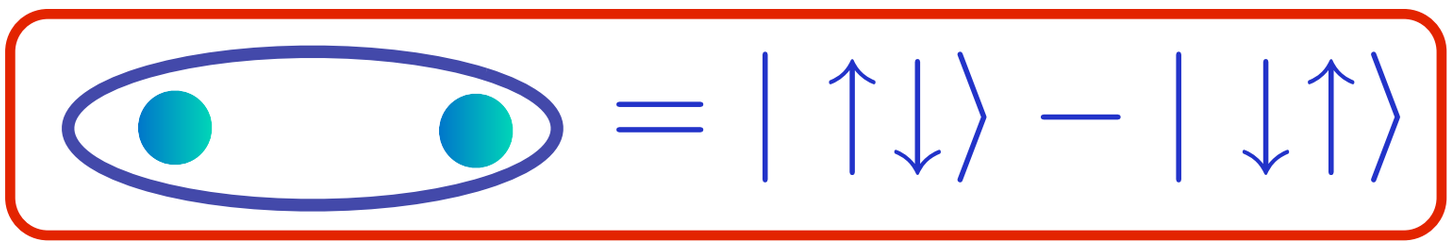

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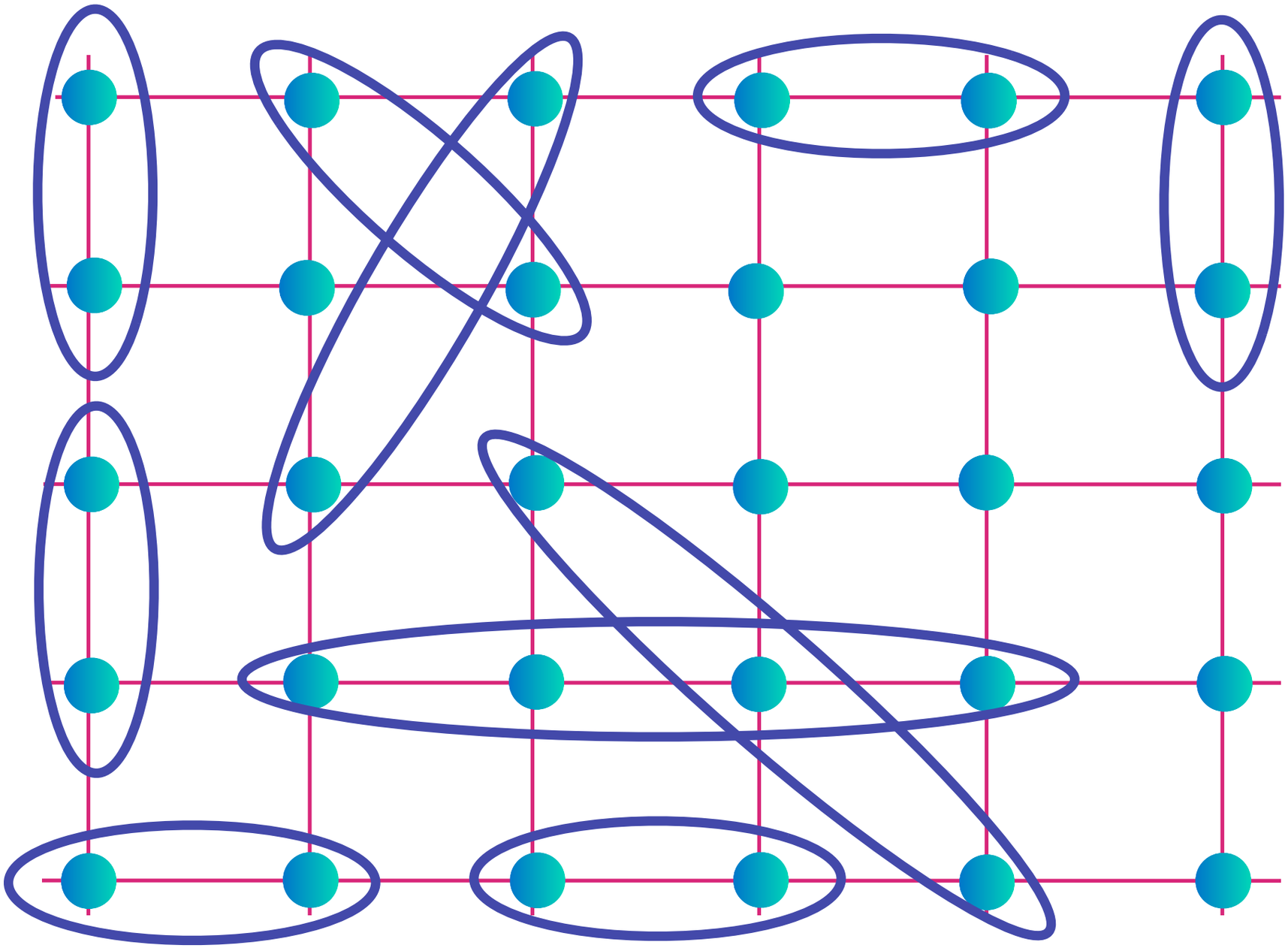
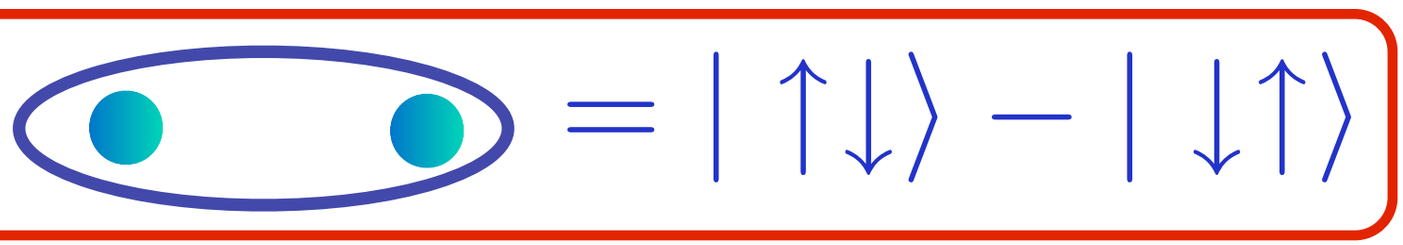


Electrons entangle "en masse" by exchanging partners, and there is long-range quantum entanglement



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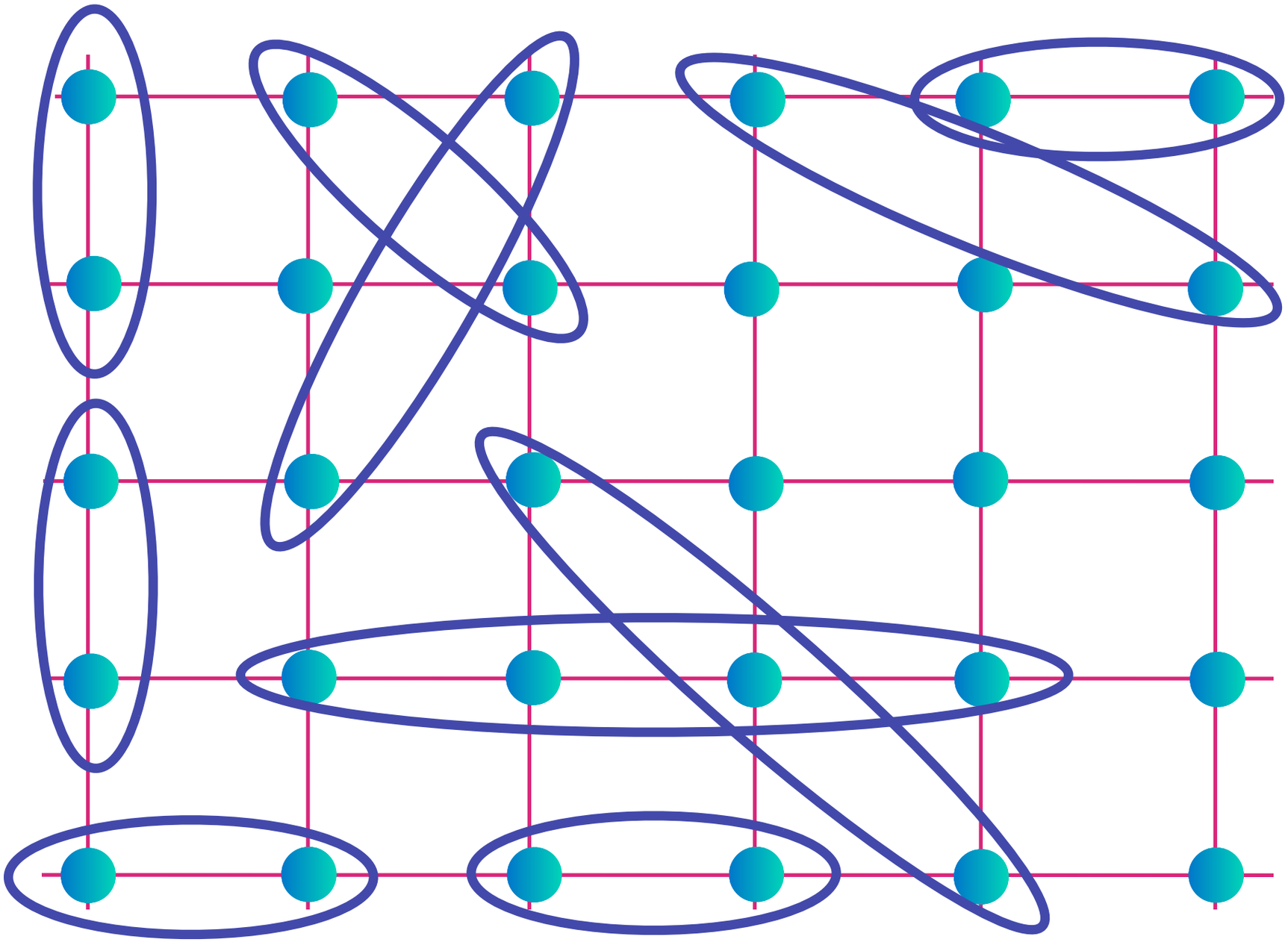

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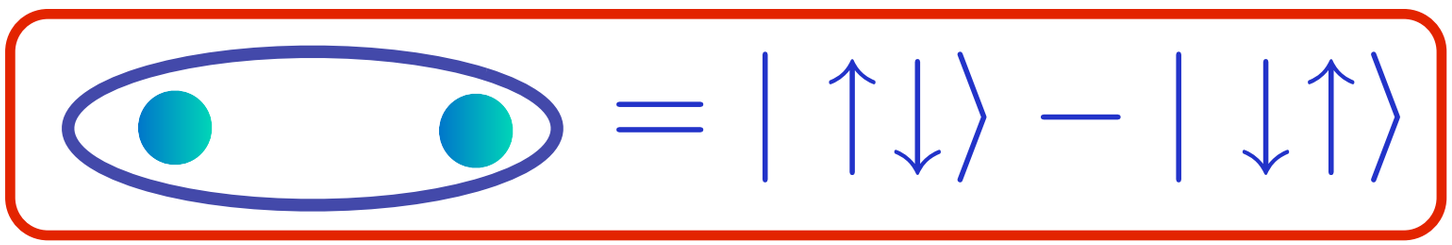


Quantum entanglement

Black holes

Superconductors

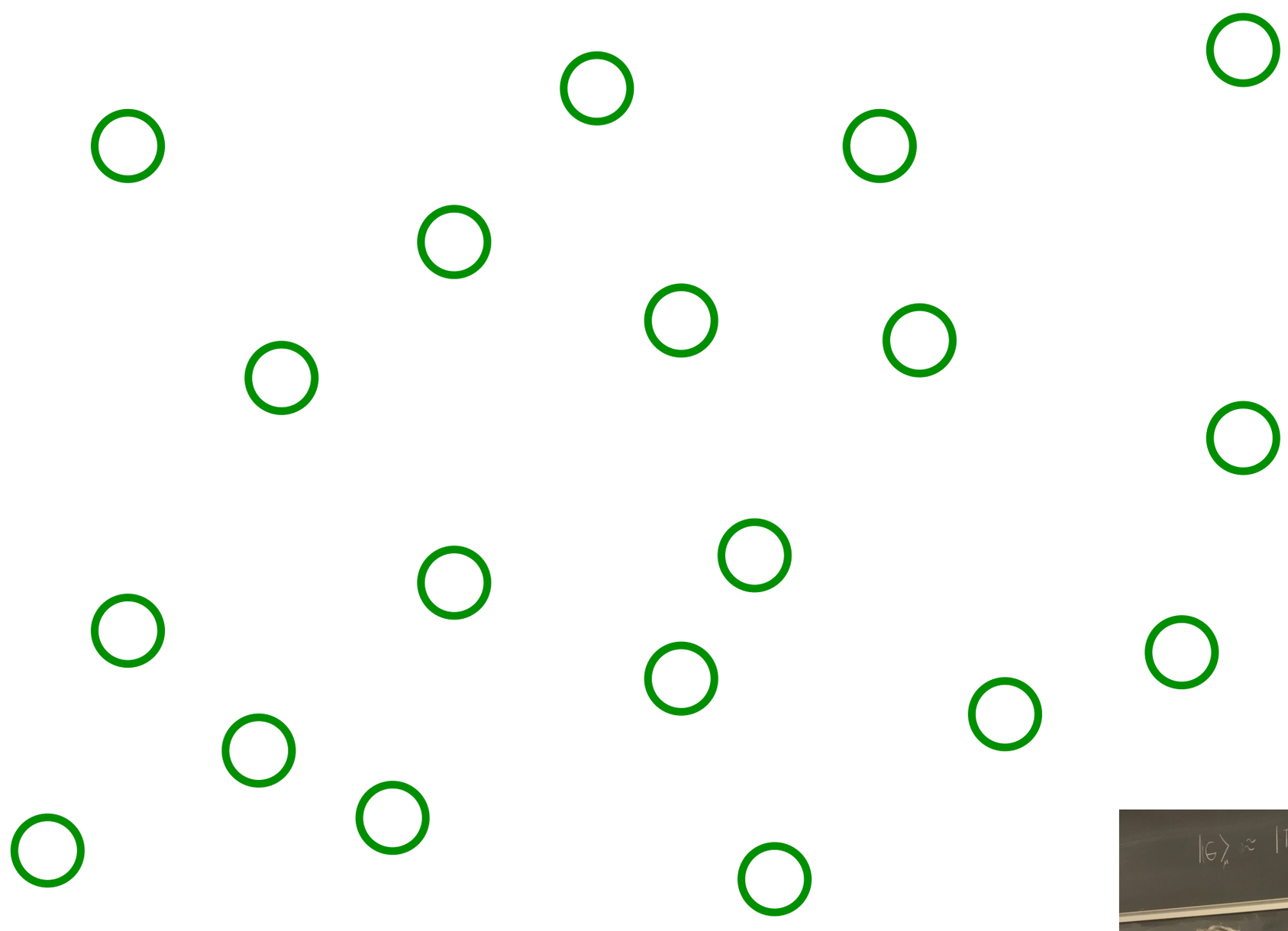
Quantum entanglement

Black holes

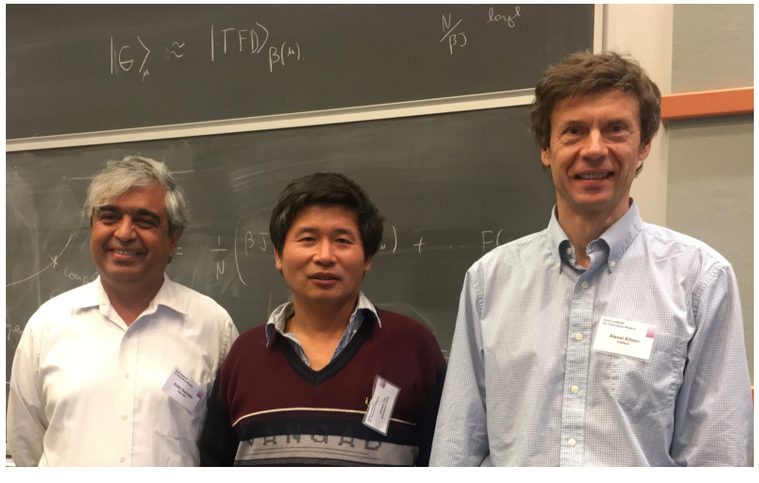
Superconductors

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

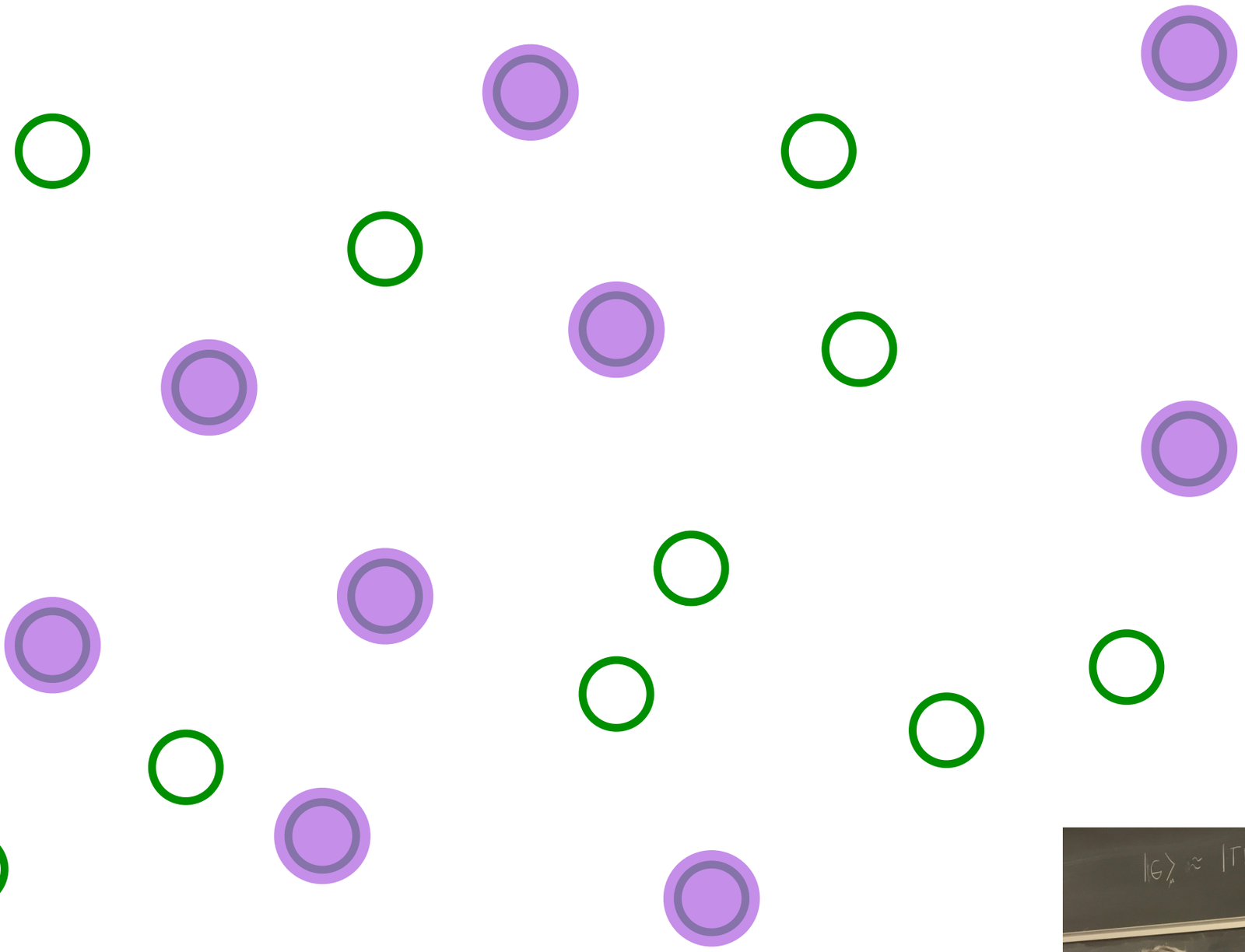
The Sachdev-Ye-Kitaev (SYK) model



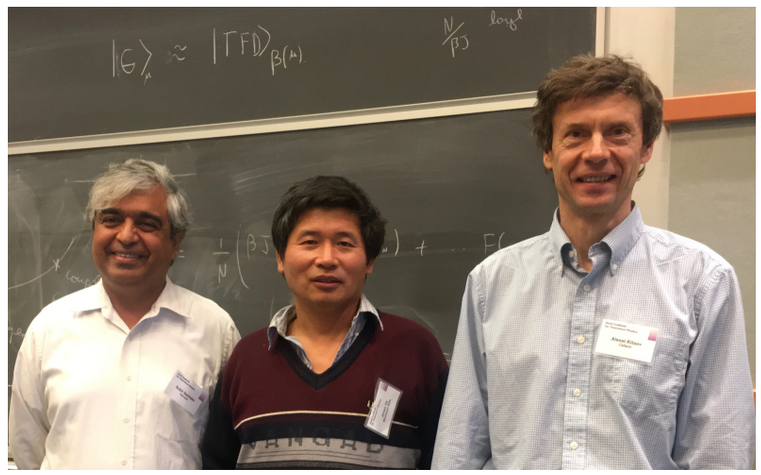
Pick a set of random positions



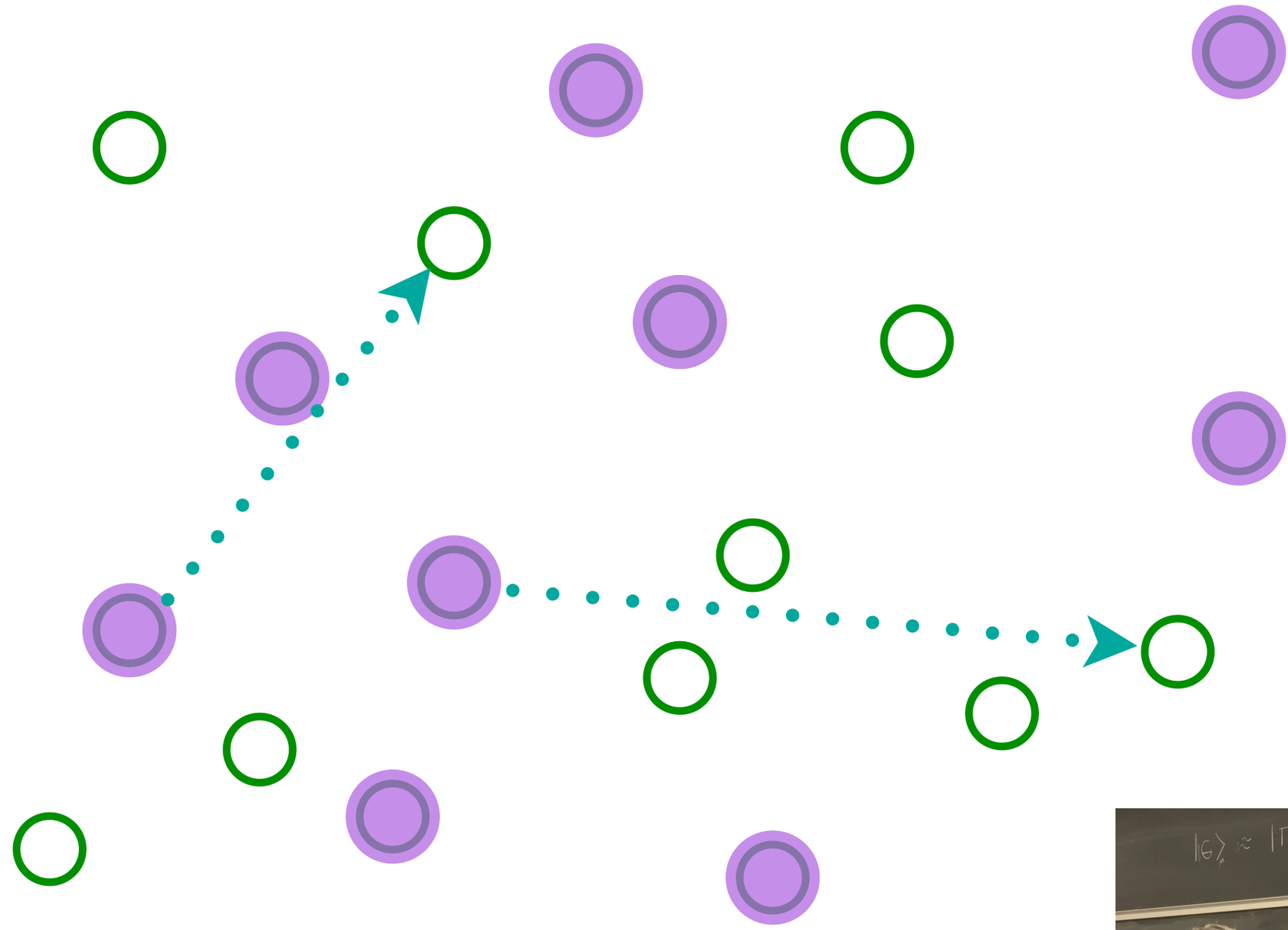
The SYK model



Place electrons randomly on some sites



The SYK model



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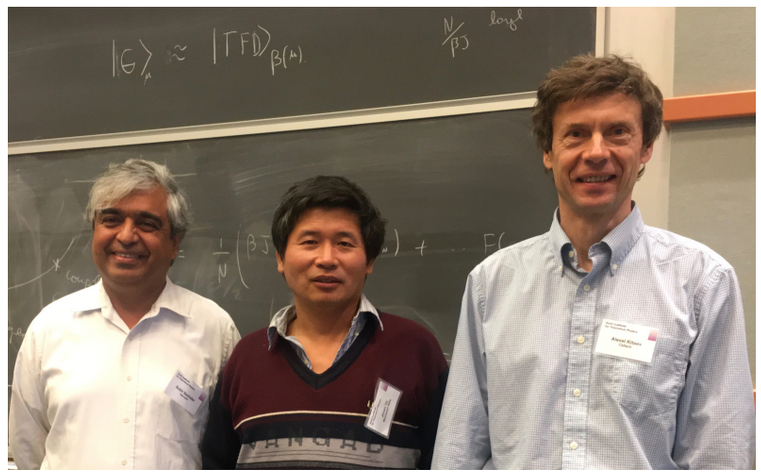
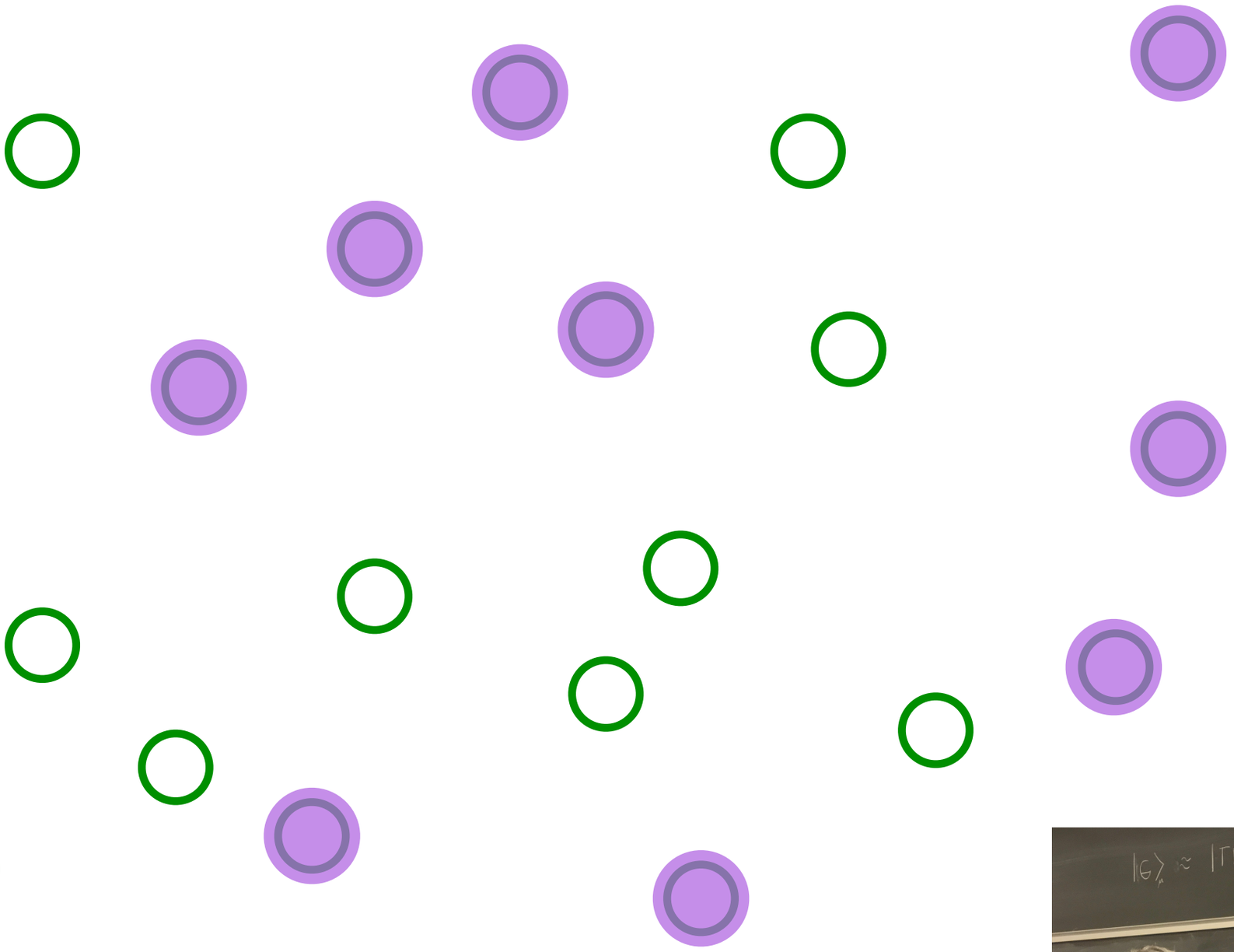
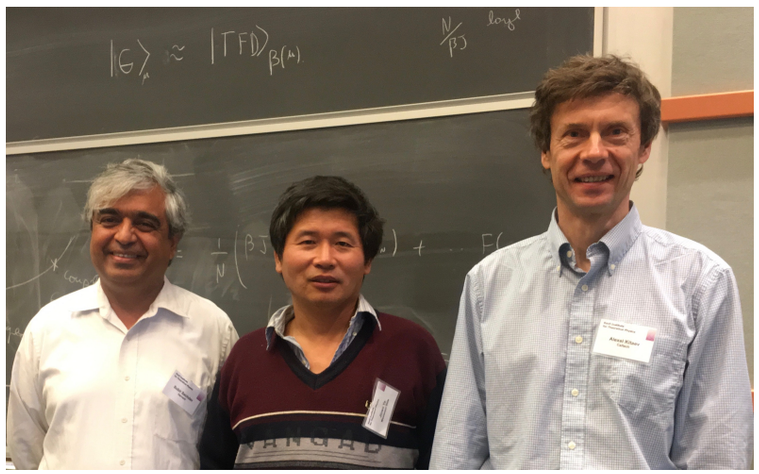


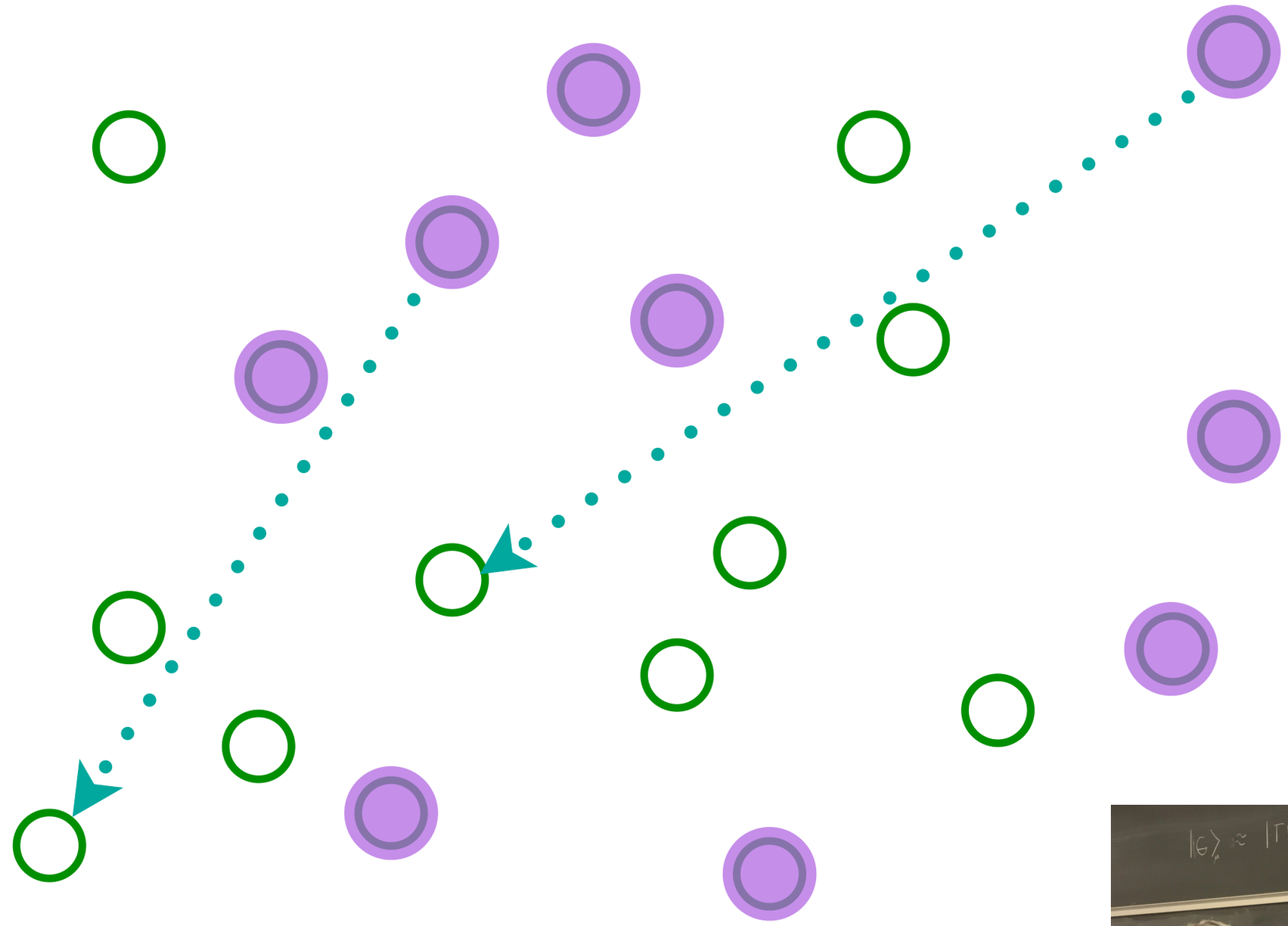
The SYK model



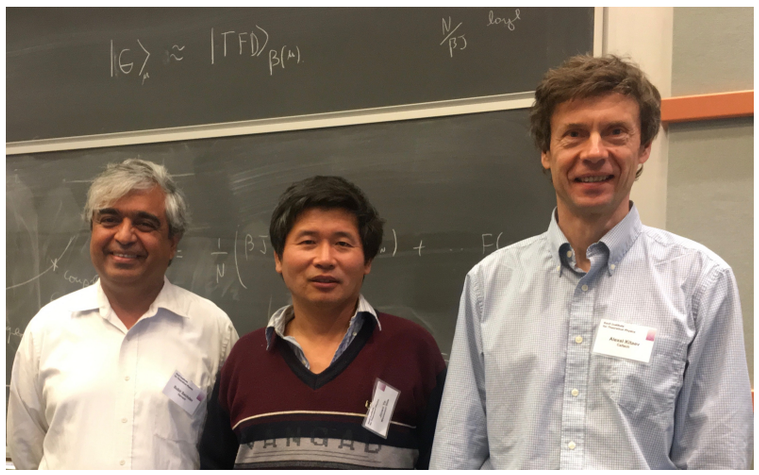
Entangle electrons pairwise randomly



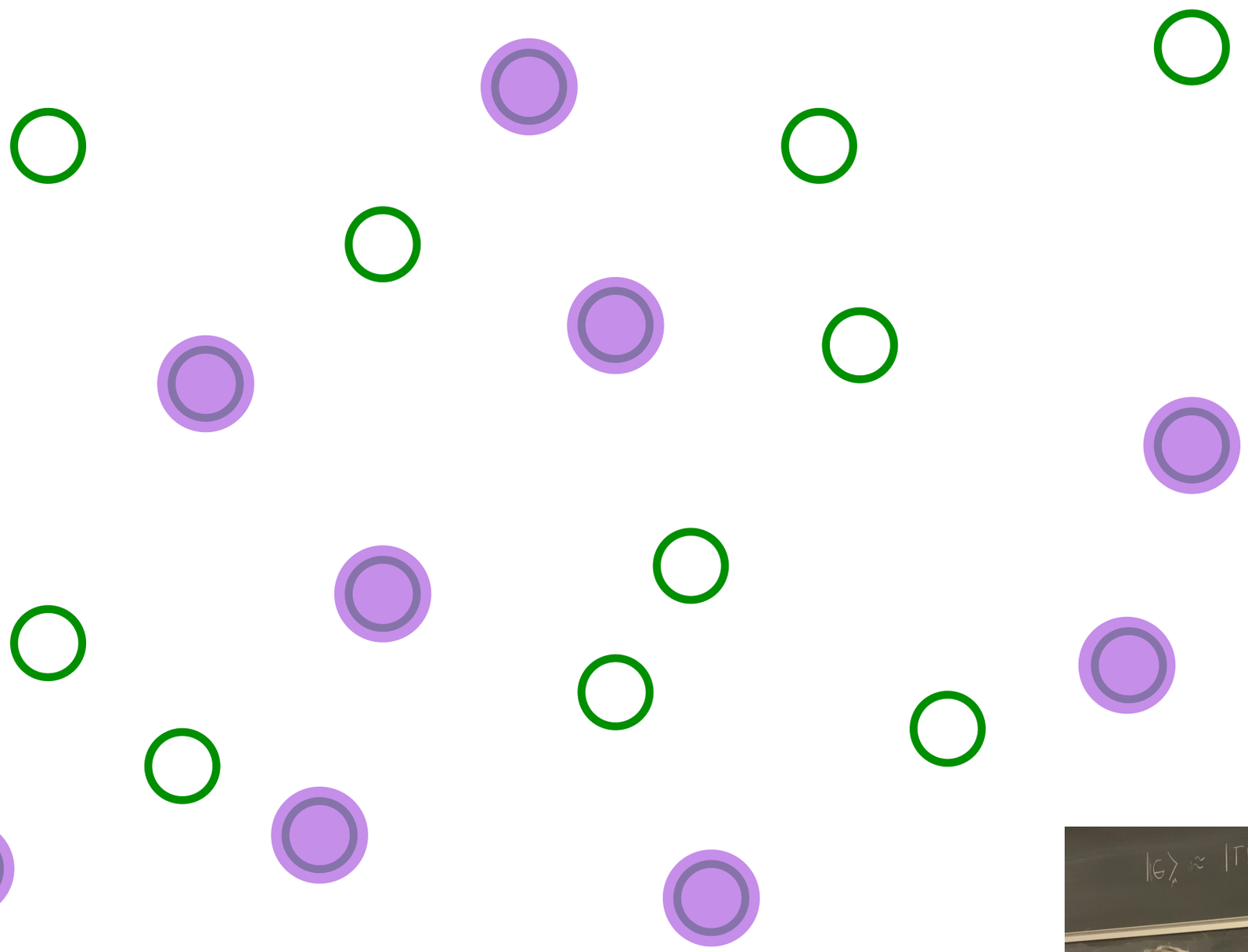
The SYK model



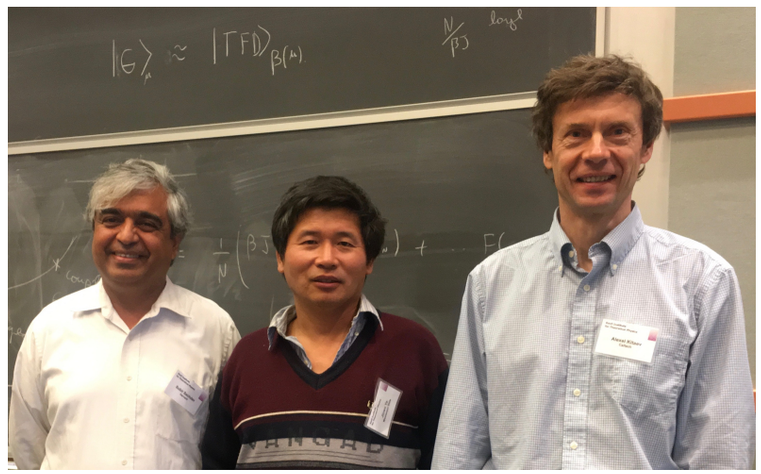
Entangle electrons pairwise randomly



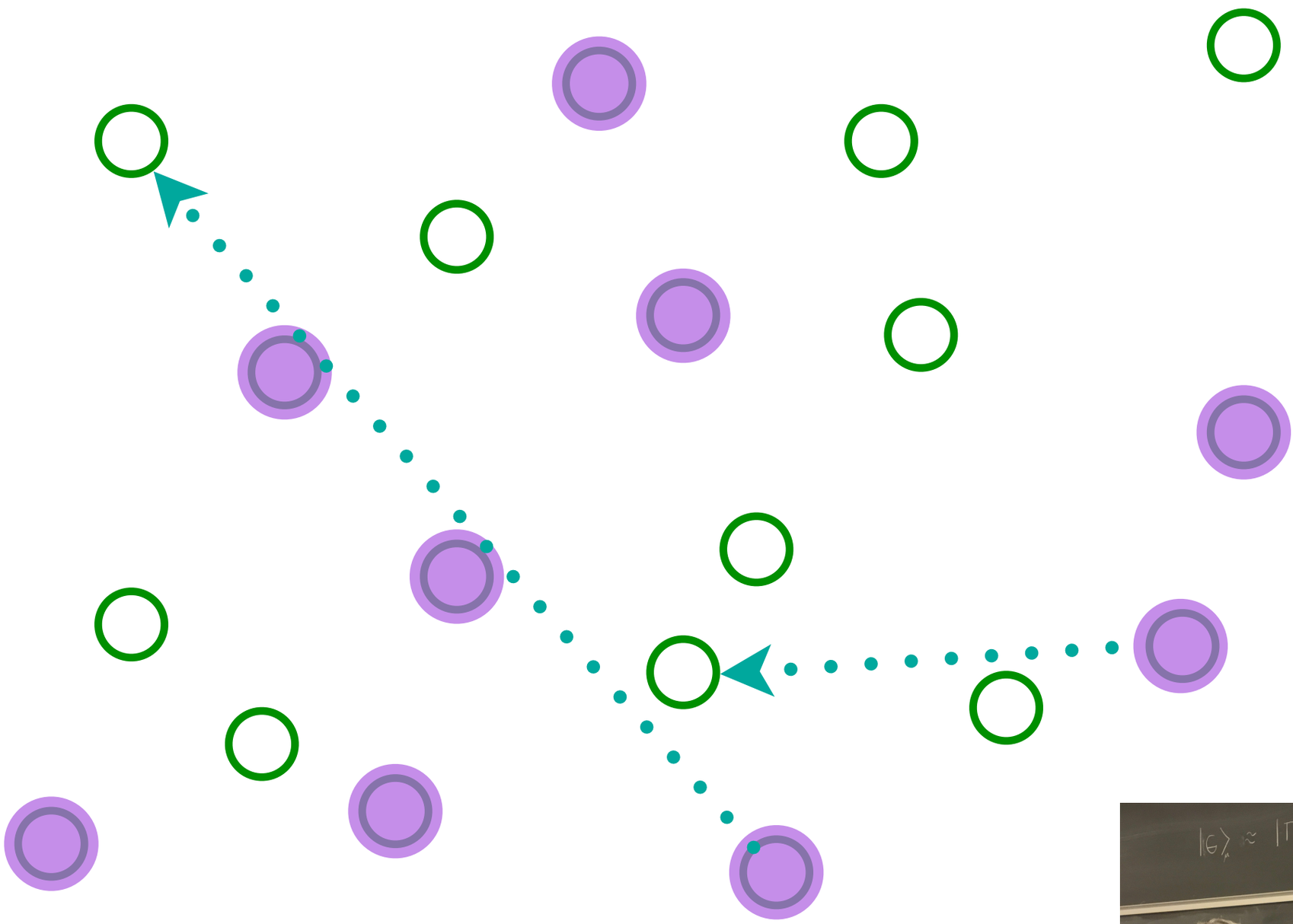
The SYK model



Entangle electrons pairwise randomly



The SYK model



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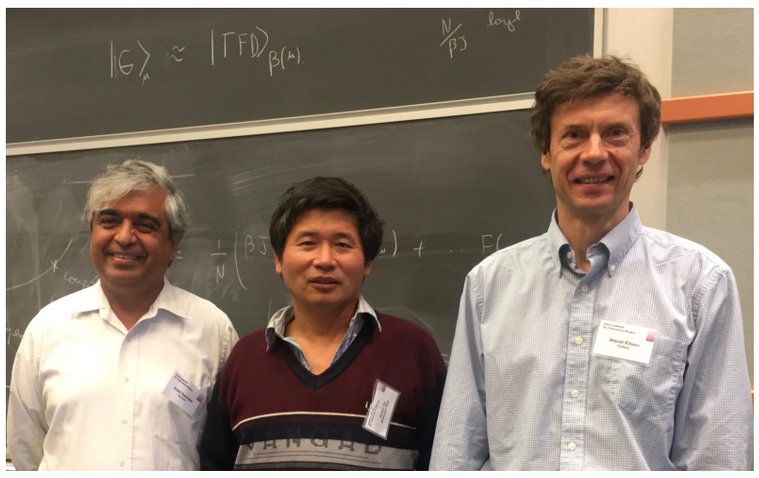
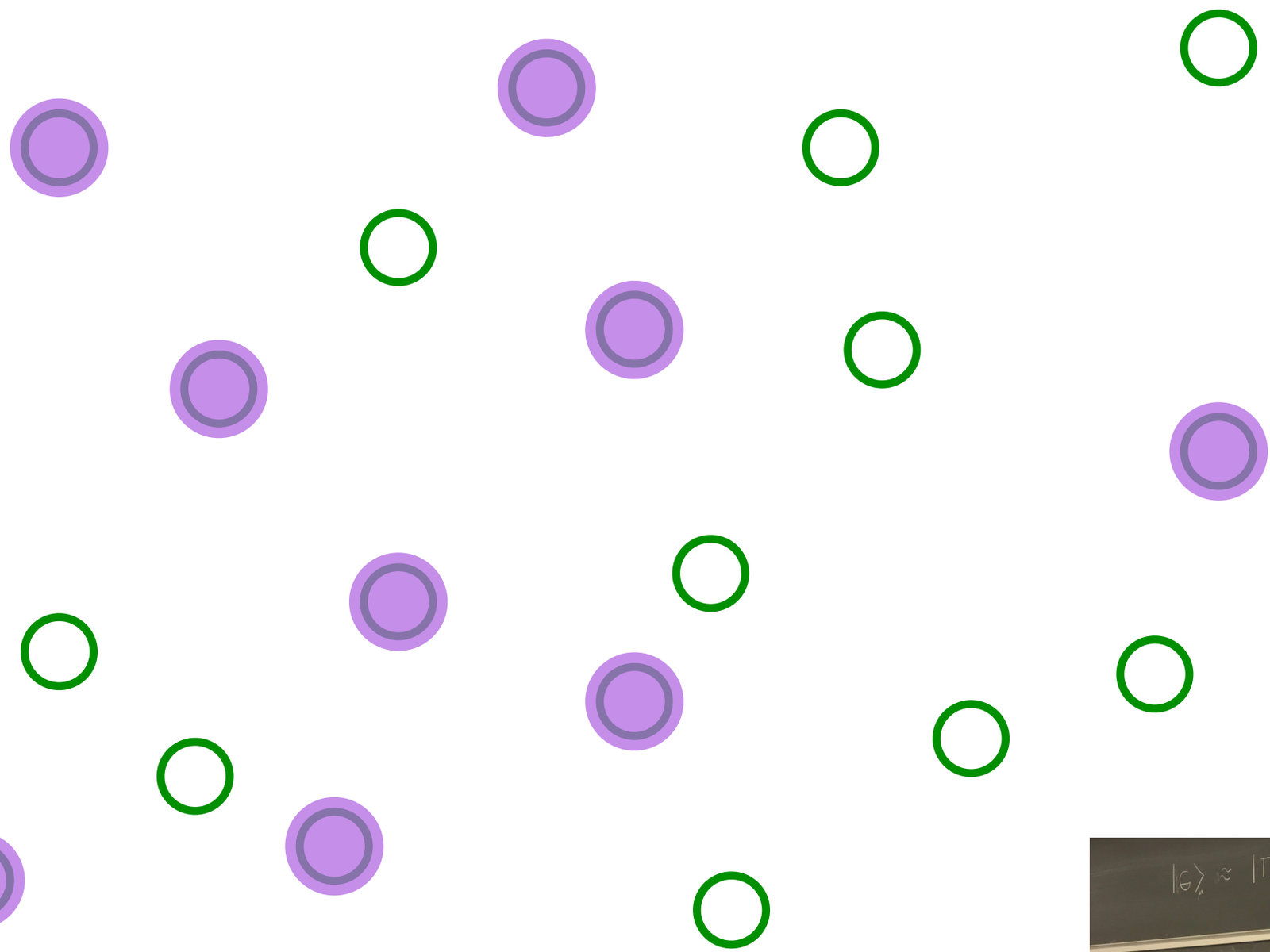


The SYK model



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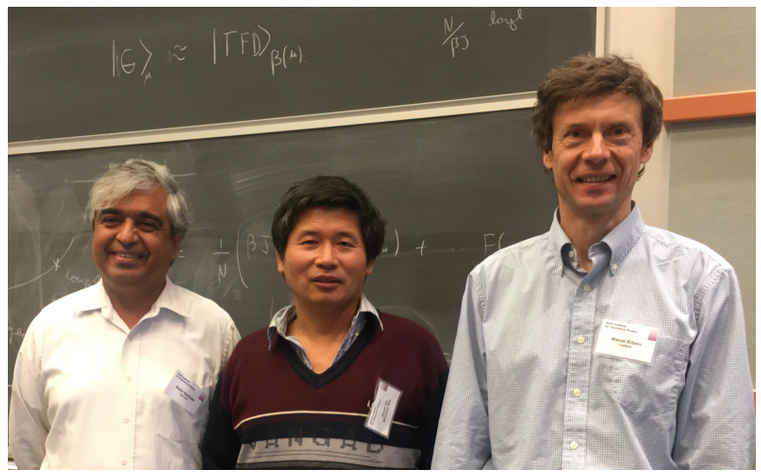
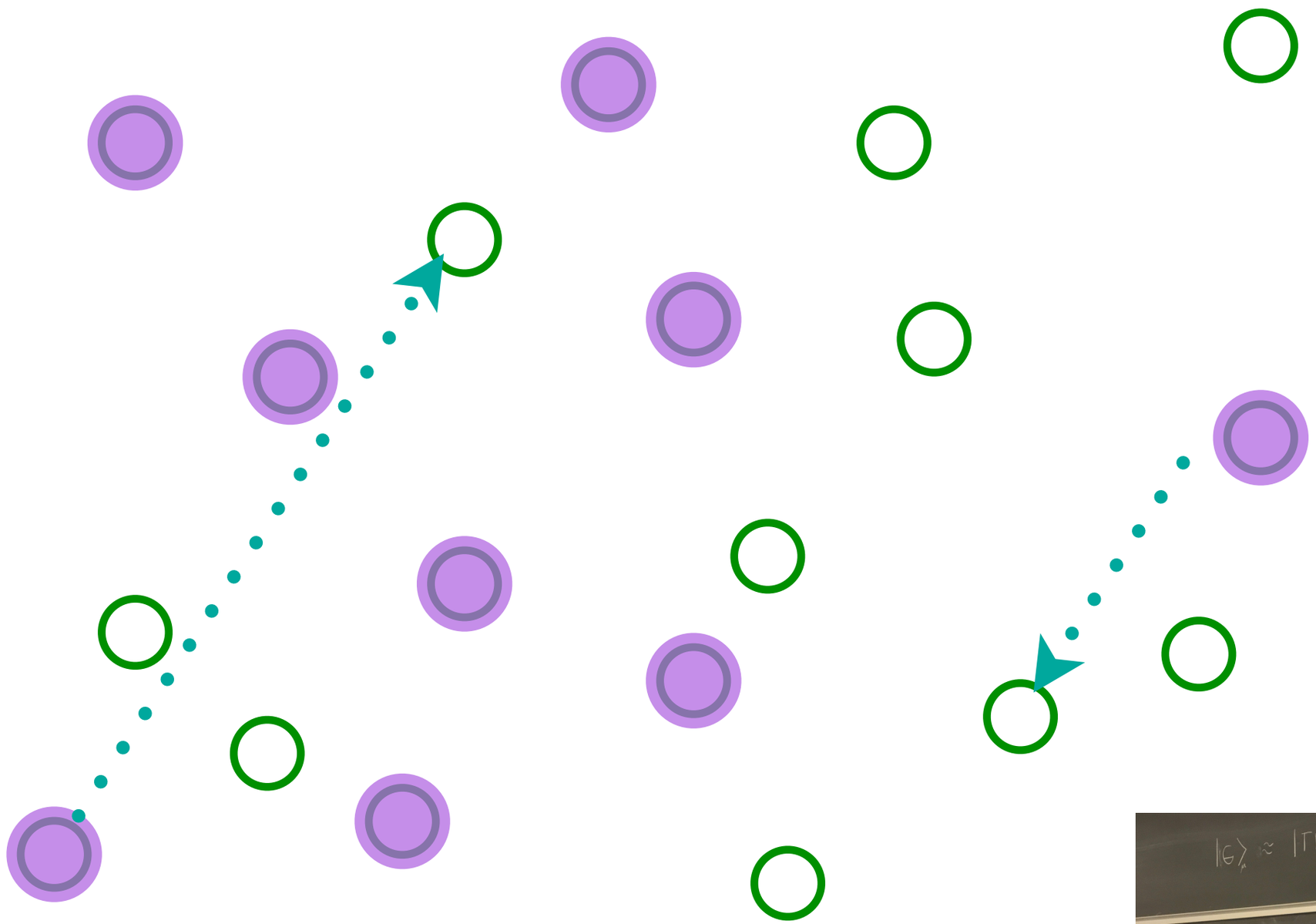
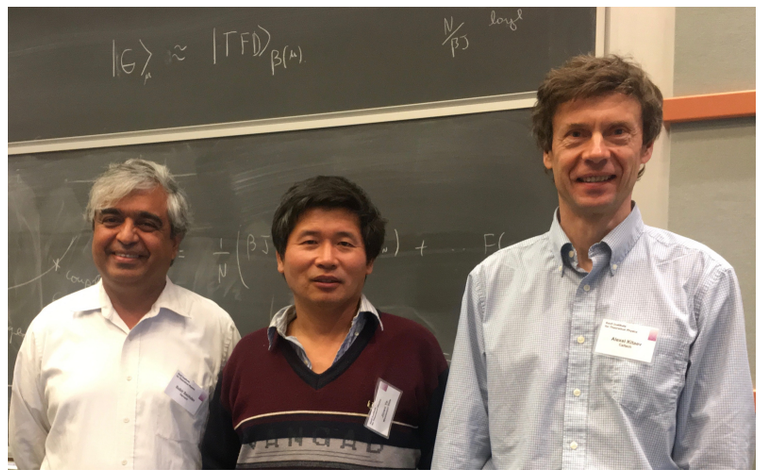


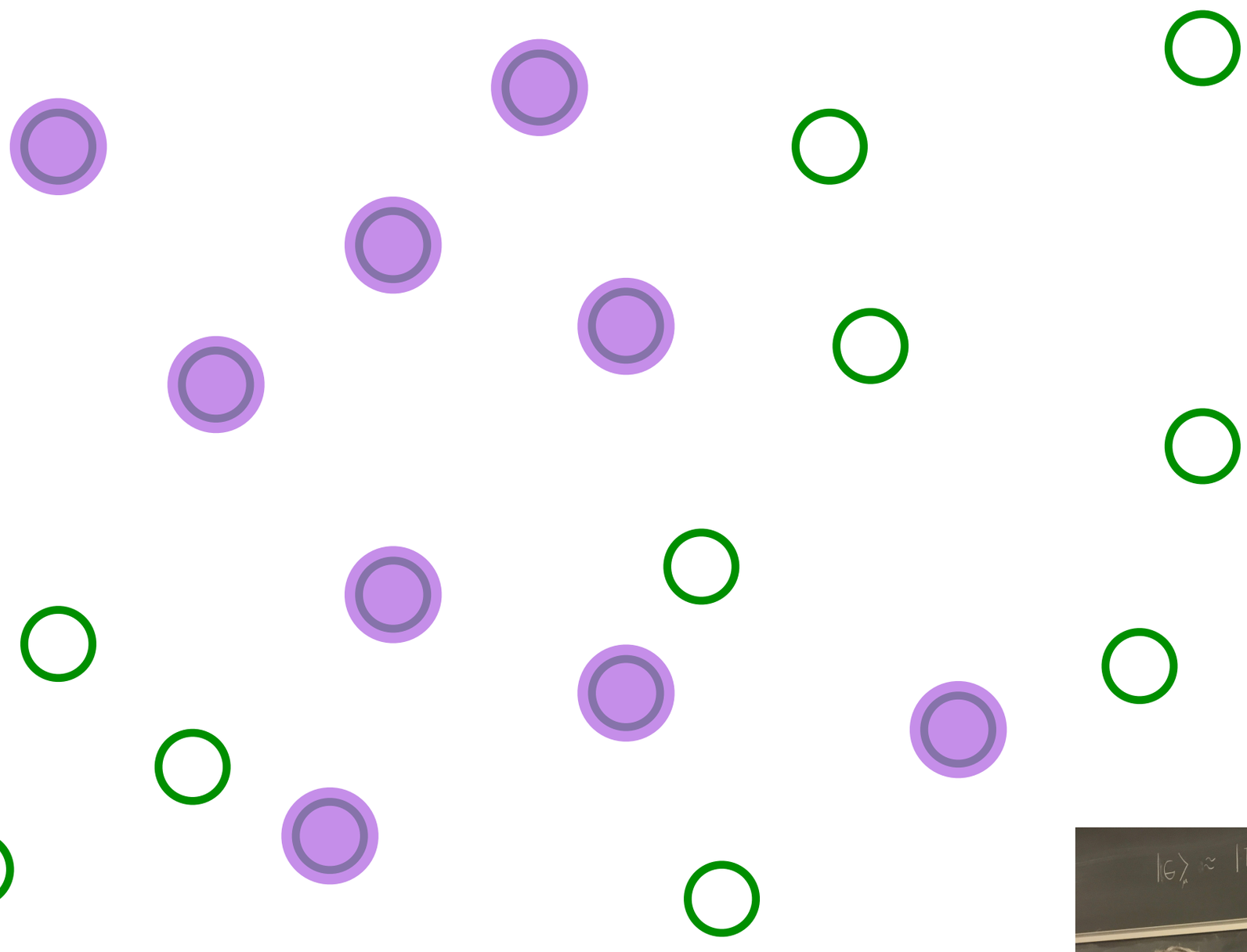
The SYK model



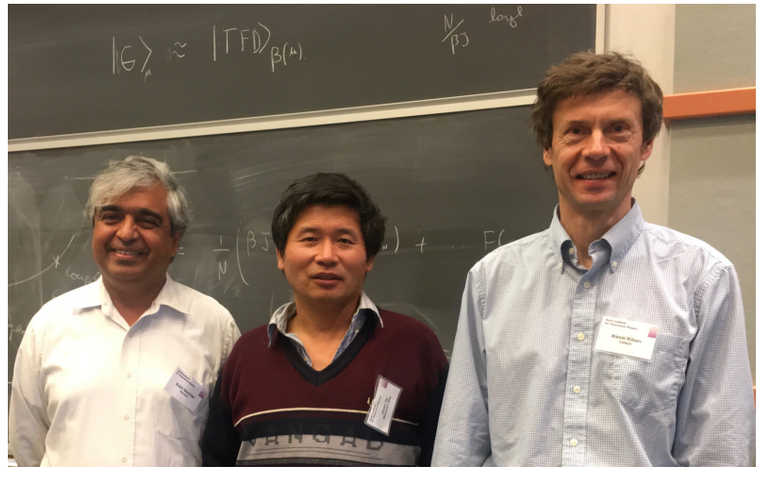
Entangle electrons pairwise randomly



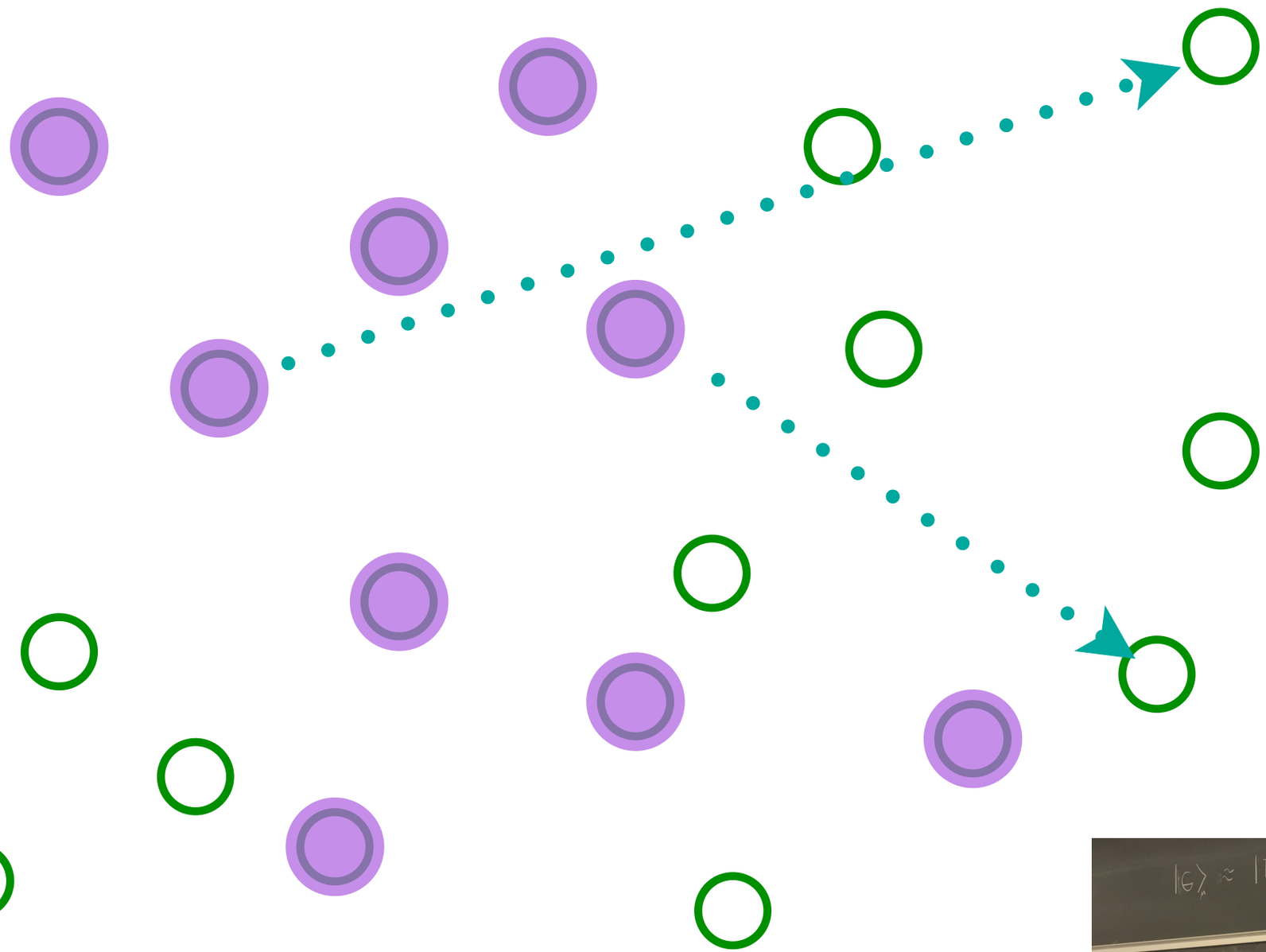
The SYK model



Entangle electrons pairwise randomly



The SYK model



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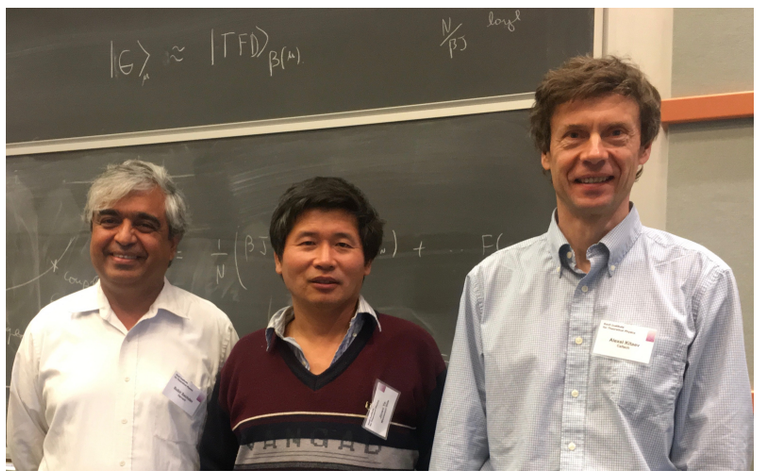
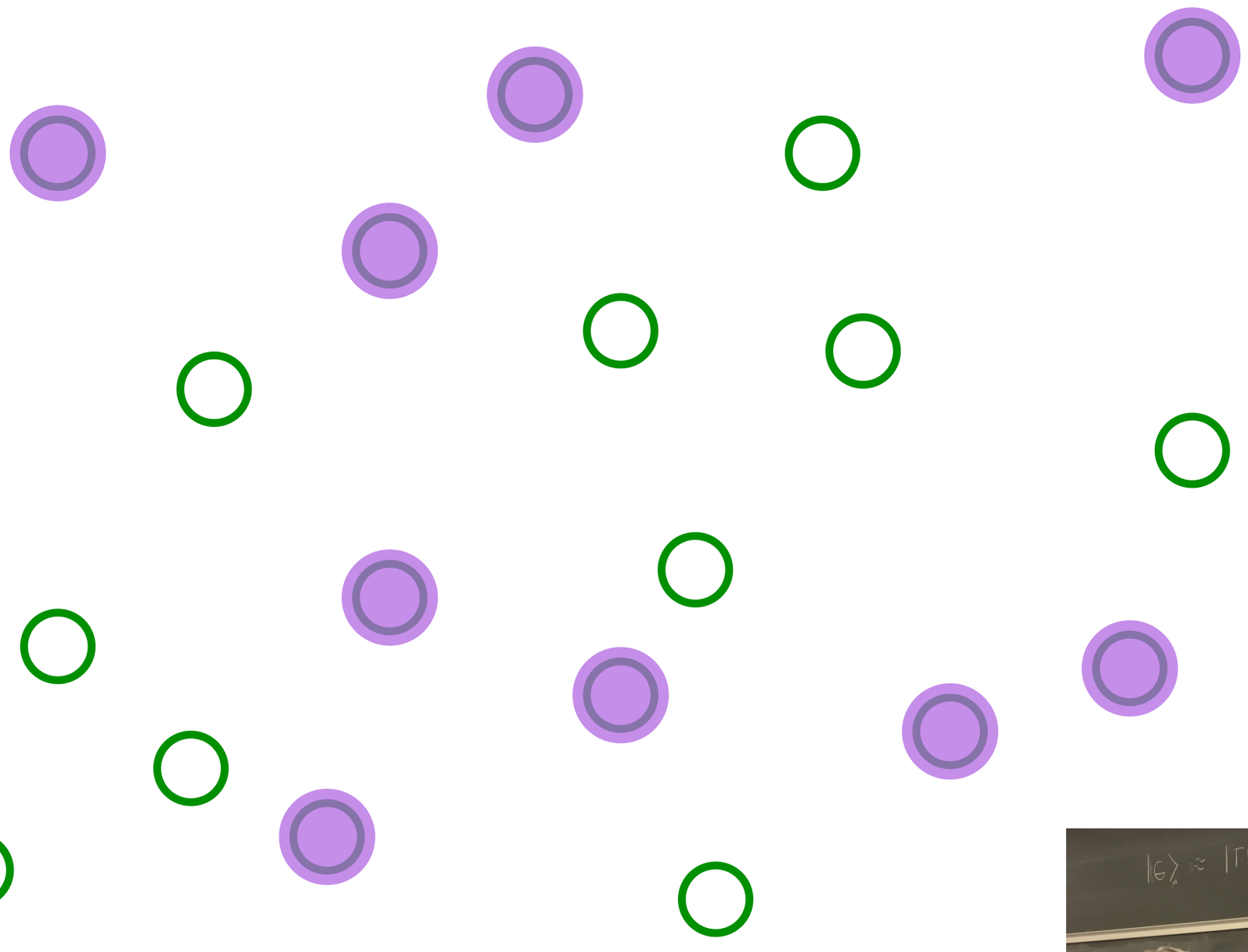
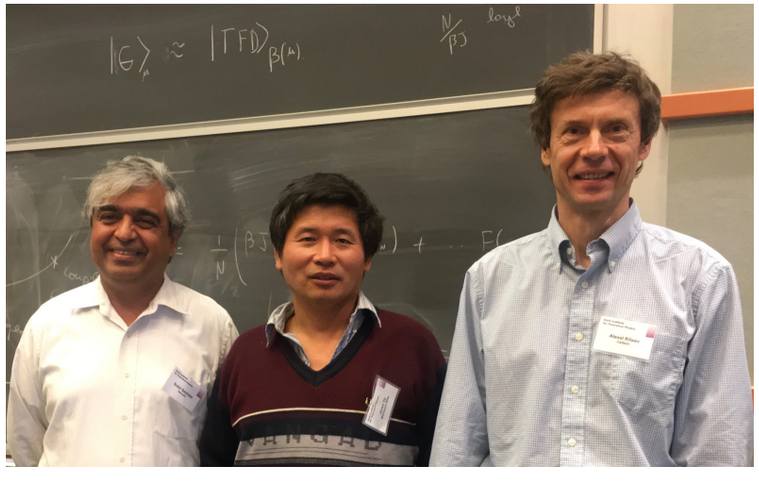


The SYK model

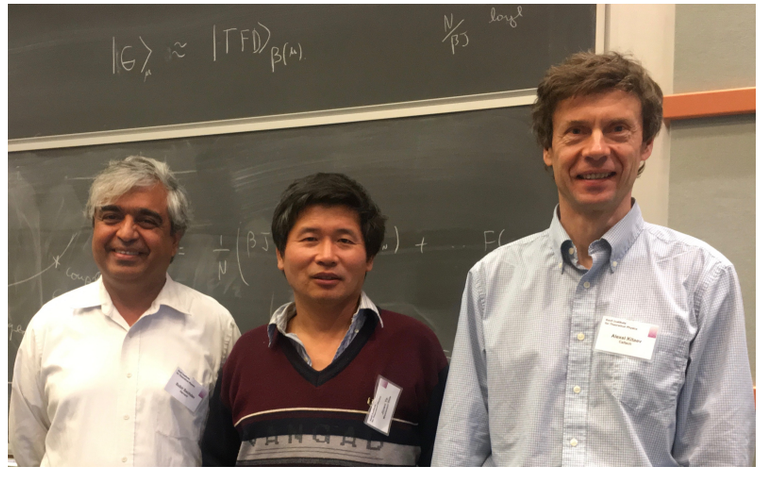


Entangle electrons pairwise randomly

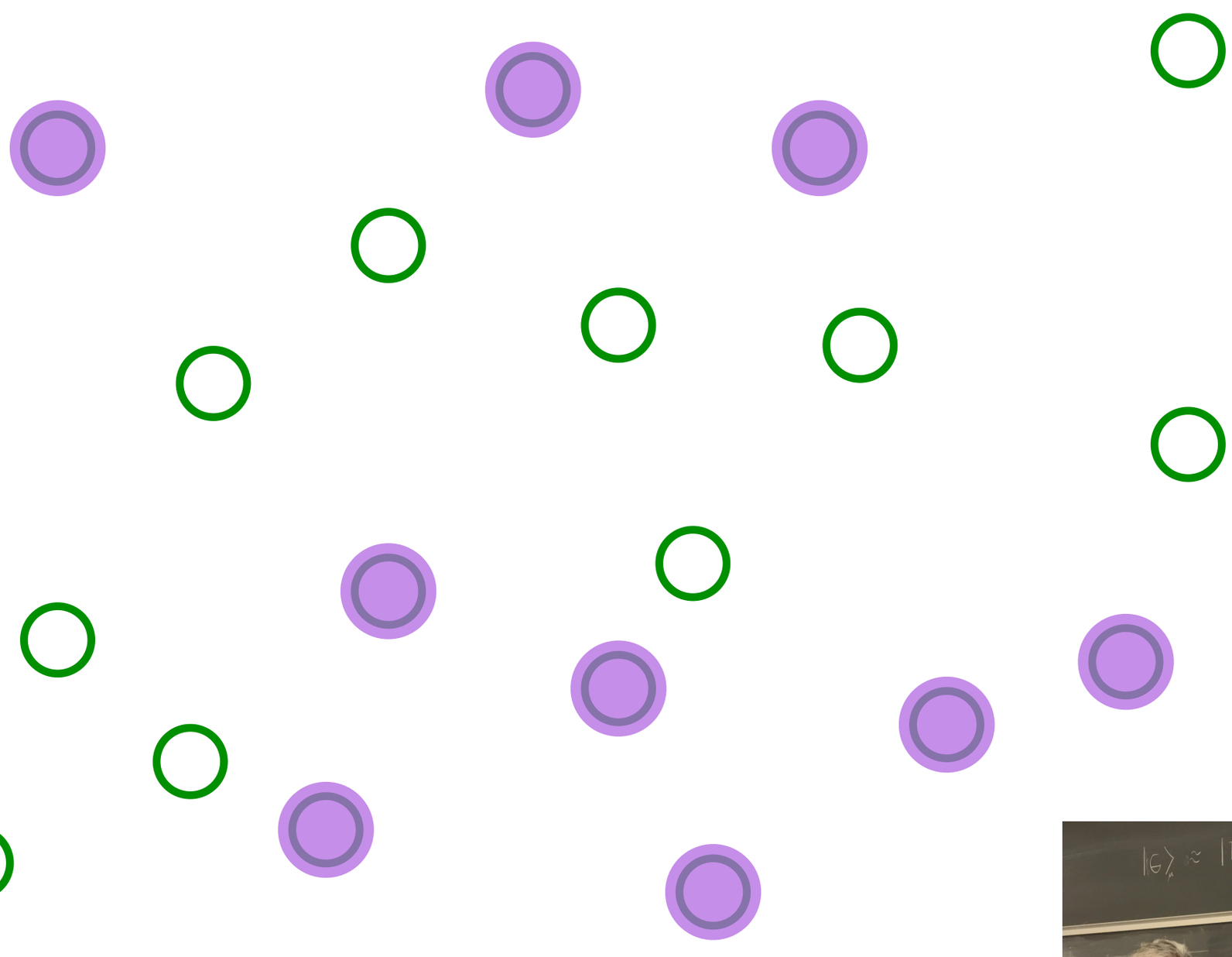


The SYK model

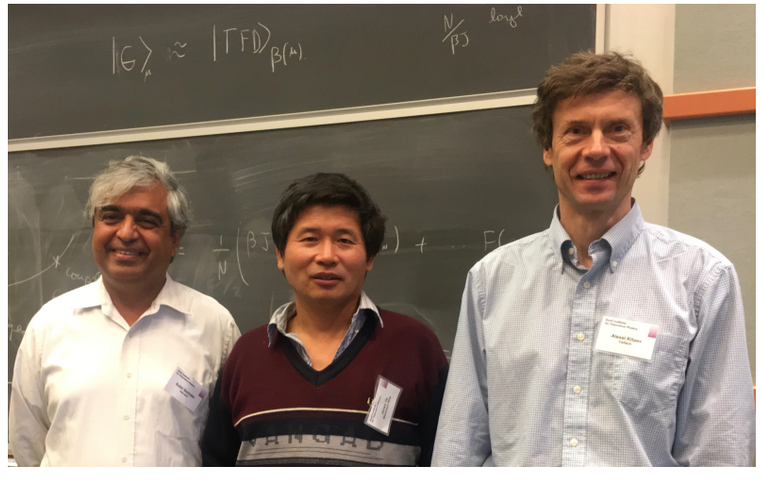
Entangle electrons pairwise randomly



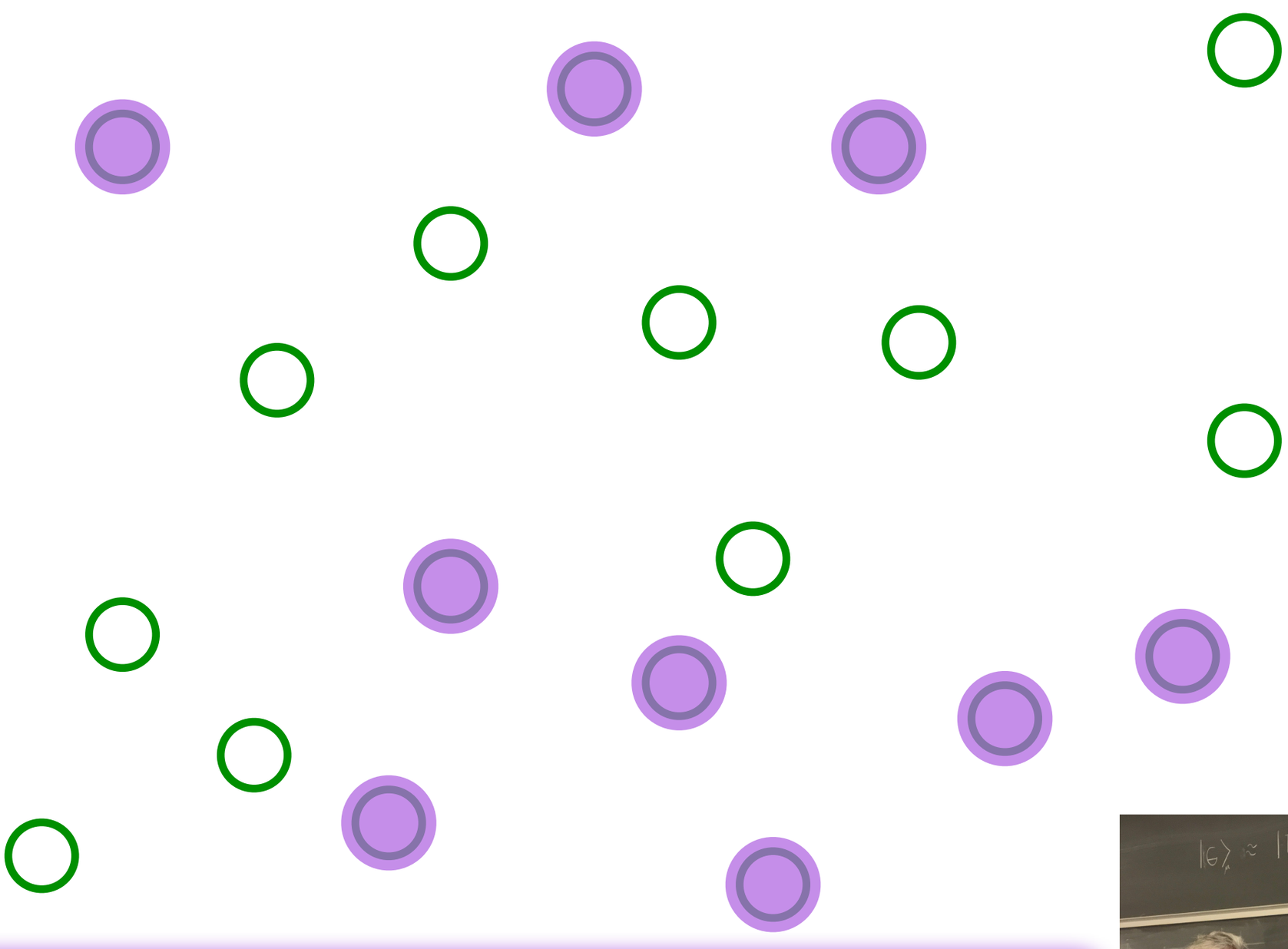
The SYK model



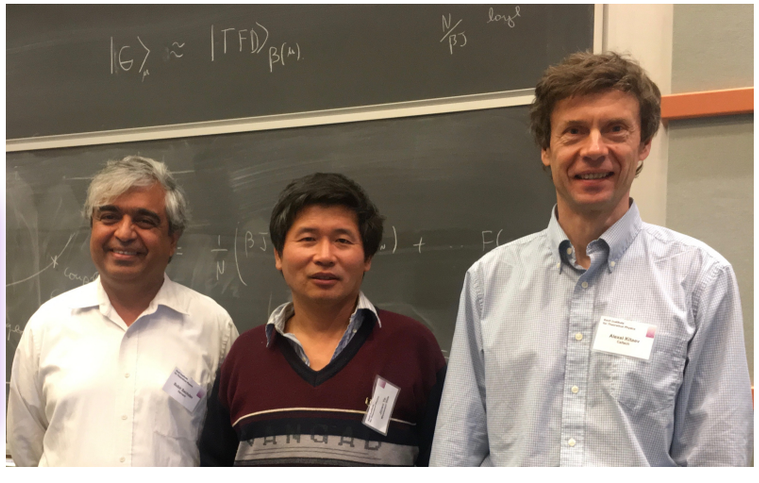
Entangle electrons pairwise randomly



The SYK model

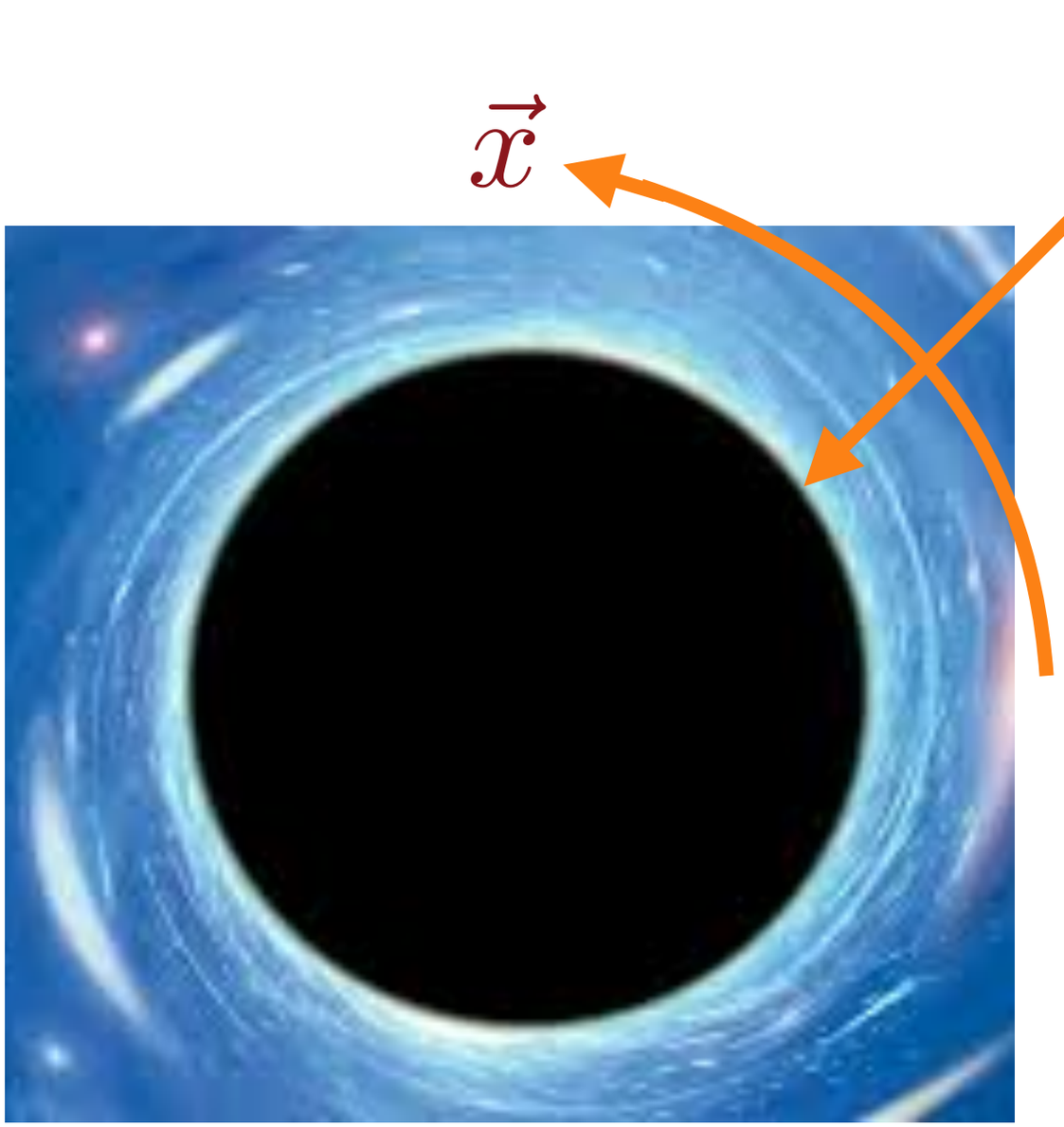


This describes both a superconductor and a black hole!



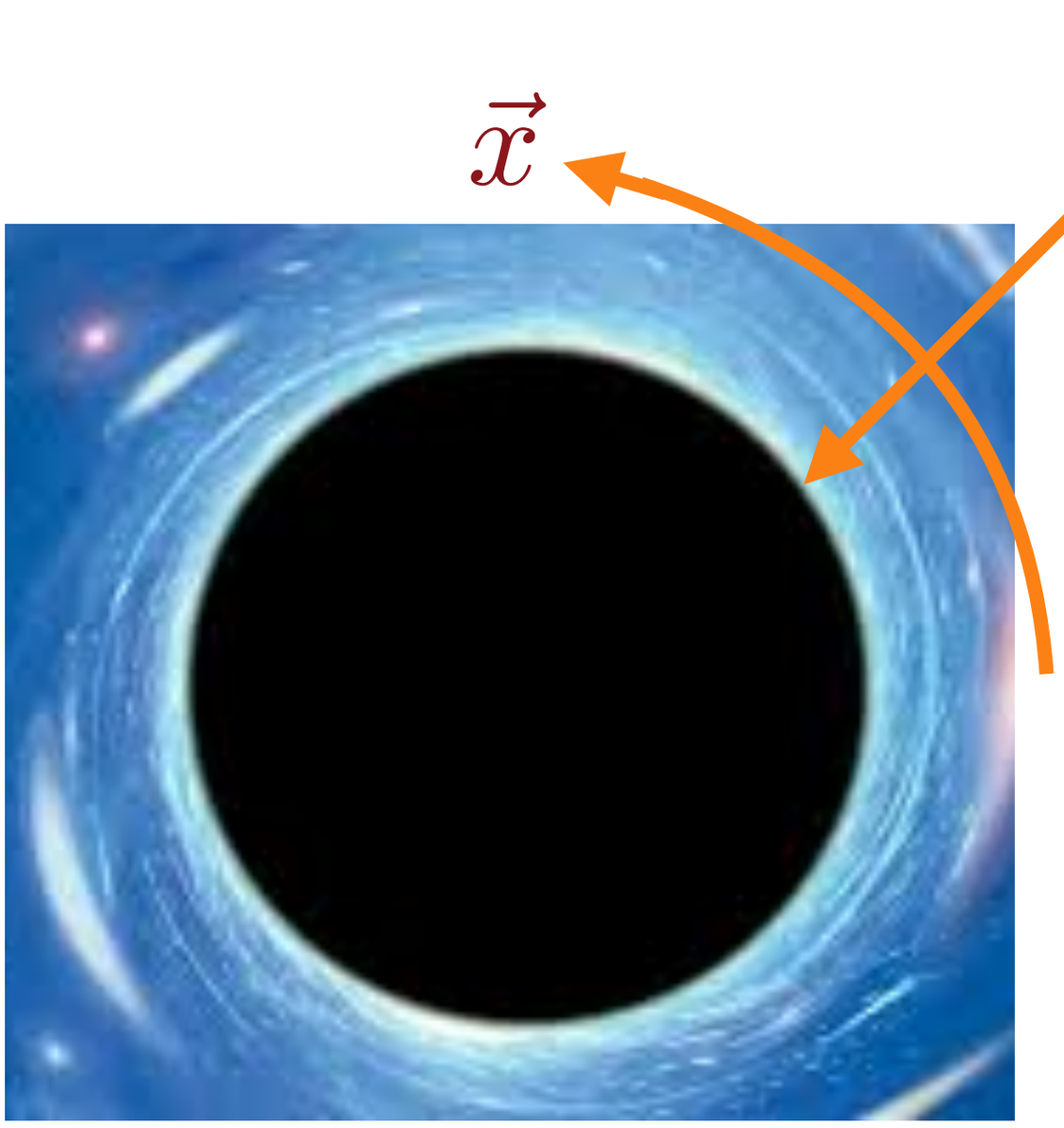
Maxwell's electromagnetism and Einstein's general relativity allow black hole solutions with a net charge

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



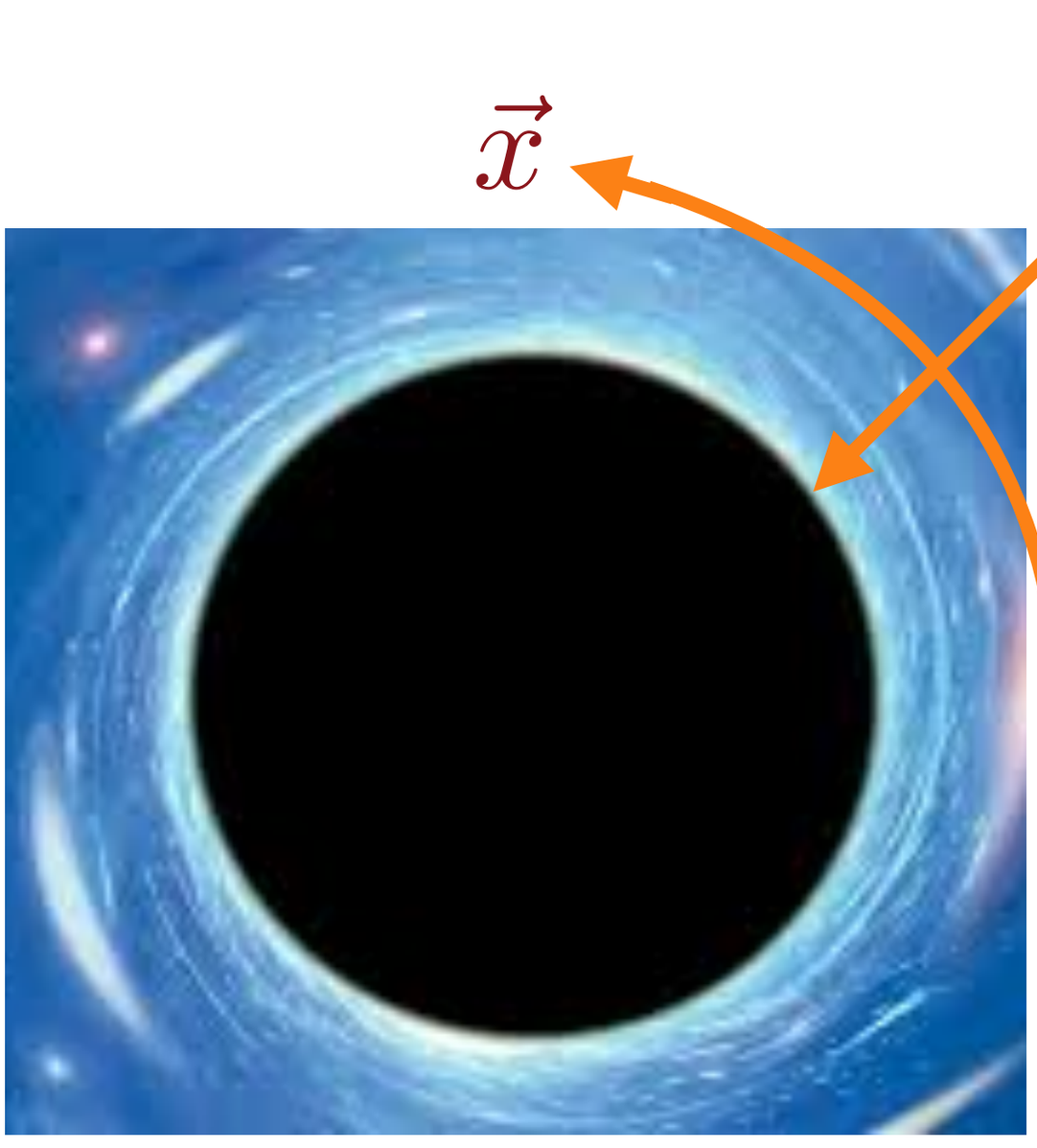
Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space (ζ) and one time dimension

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

Superconductors

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