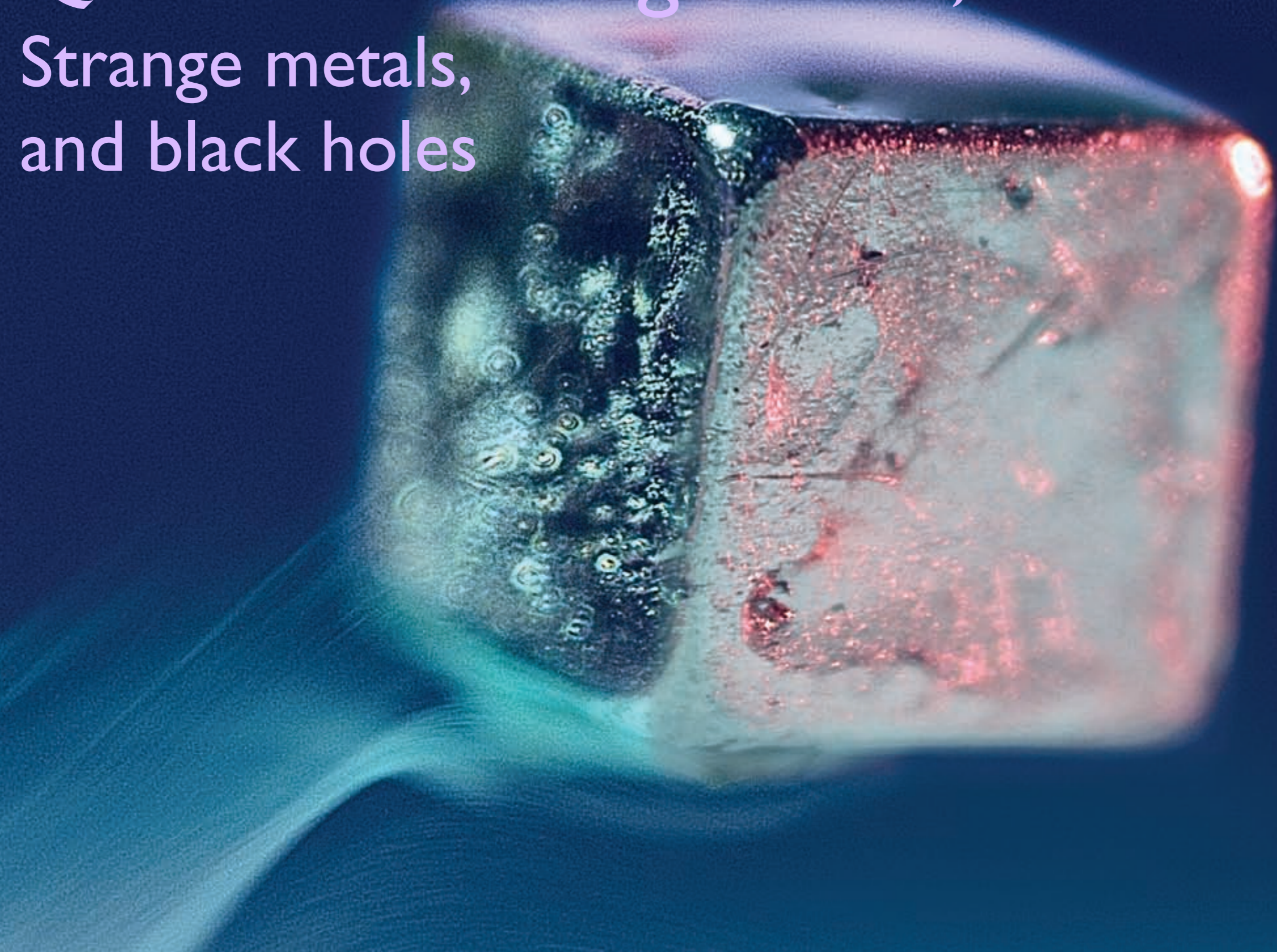
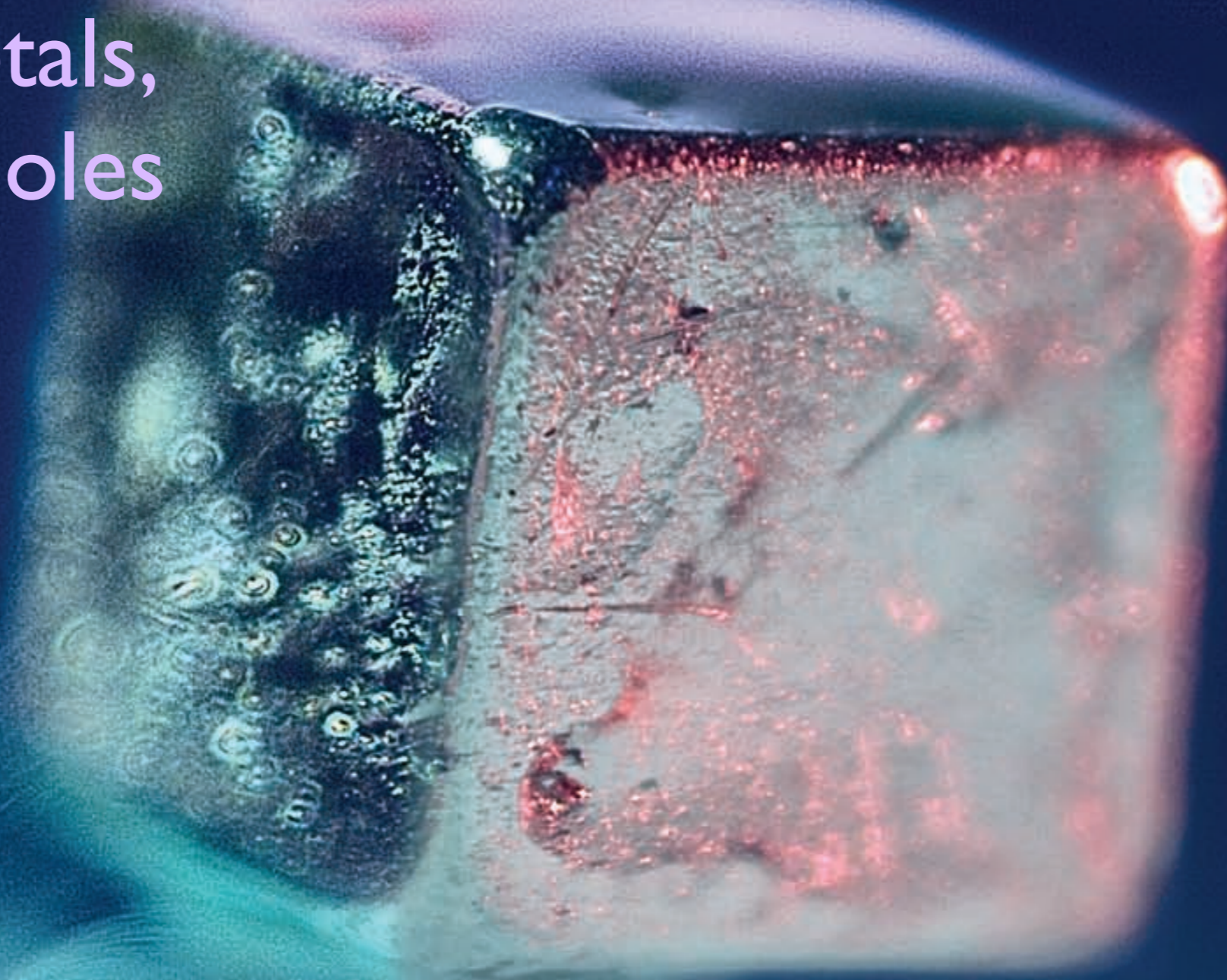


Quantum Entanglement, Strange metals, and black holes



Subir Sachdev, Harvard University and TIFR

Quantum Entanglement, Strange metals, and black holes



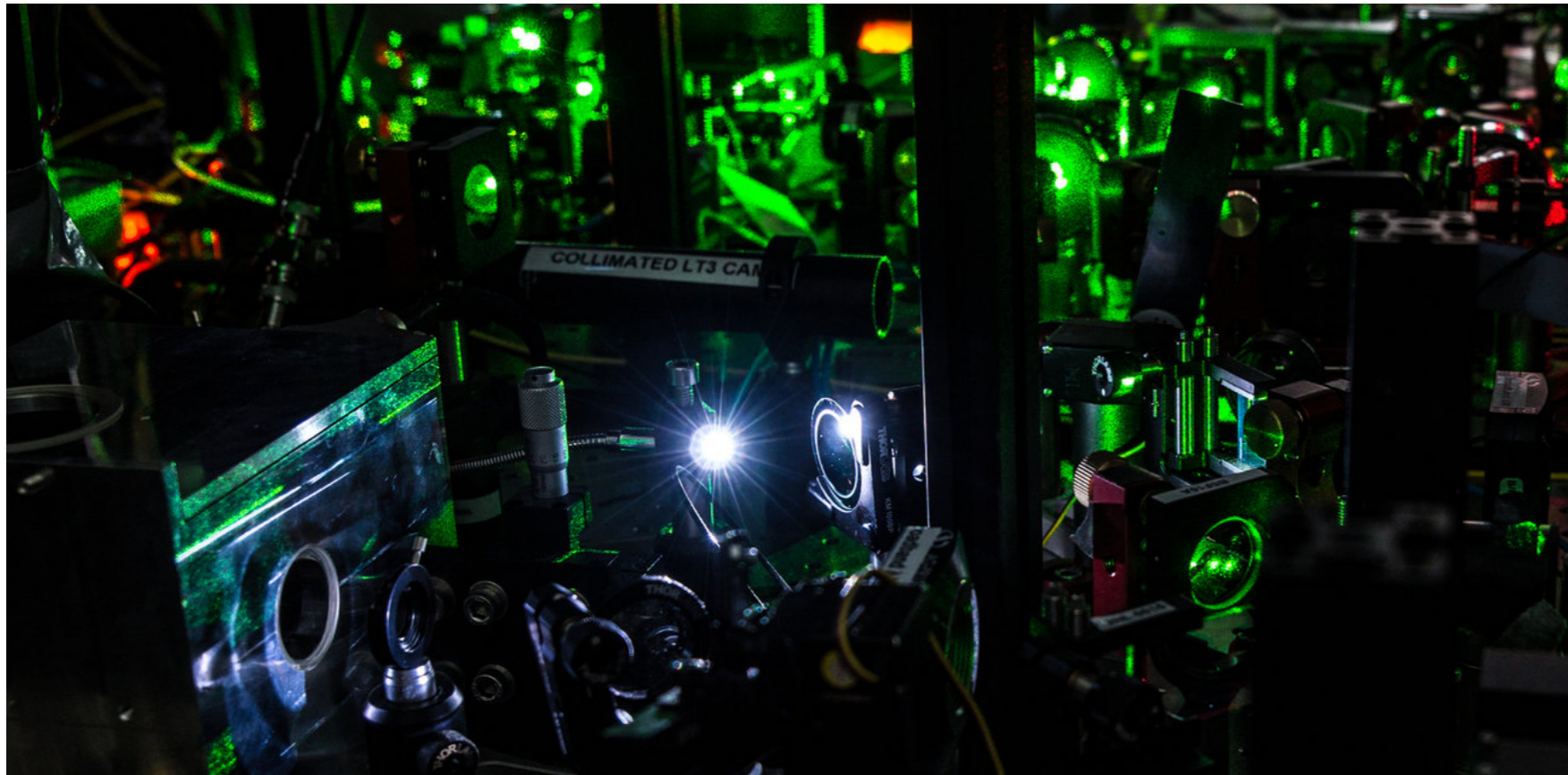
Superconductor, levitated by an unseen magnet, in which countless trillions of electrons form a vast interconnected quantum state.
Scientific American, January 2013

Subir Sachdev, Harvard University and TIFR

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

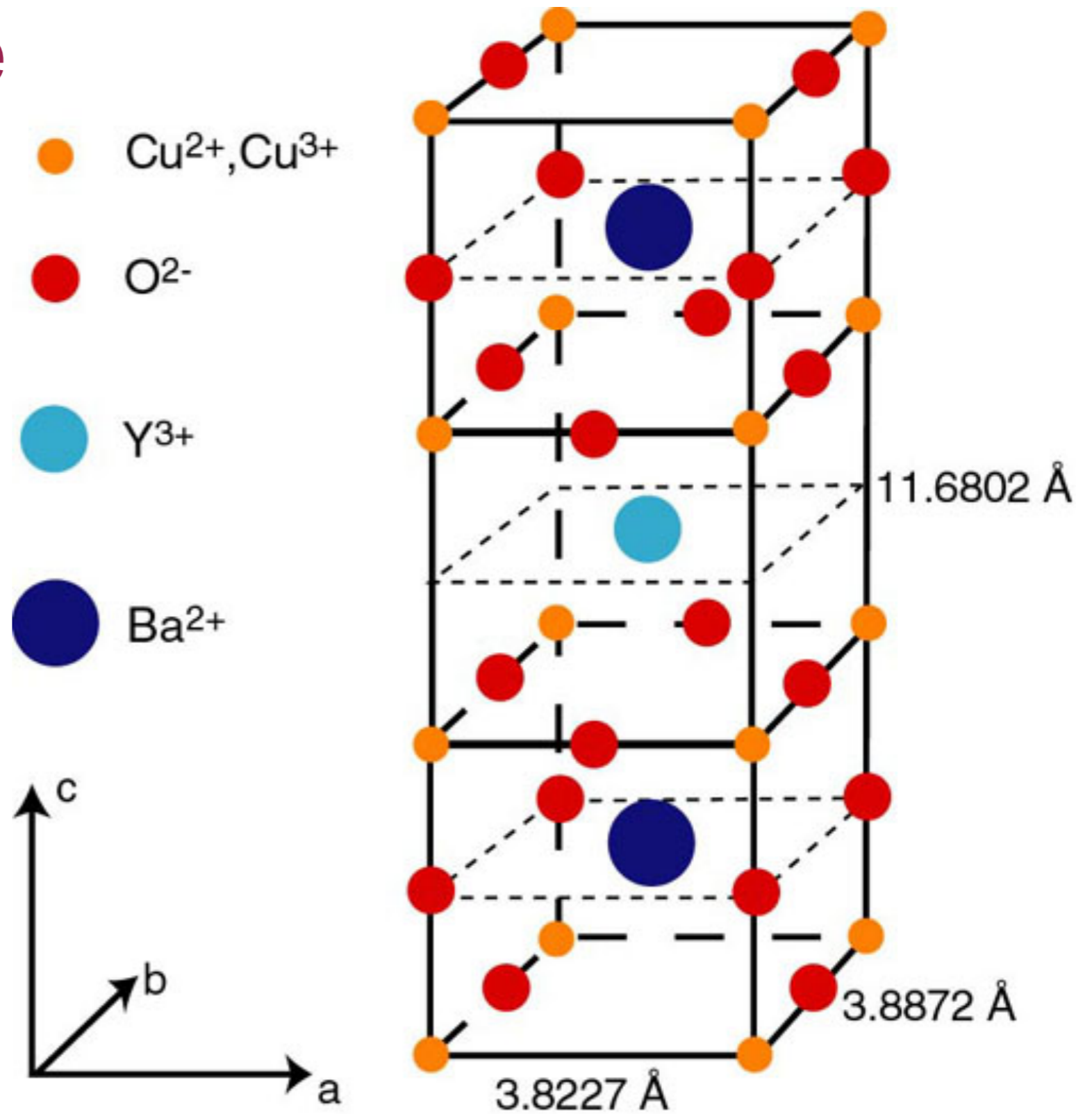
By **JOHN MARKOFF** OCT. 21, 2015

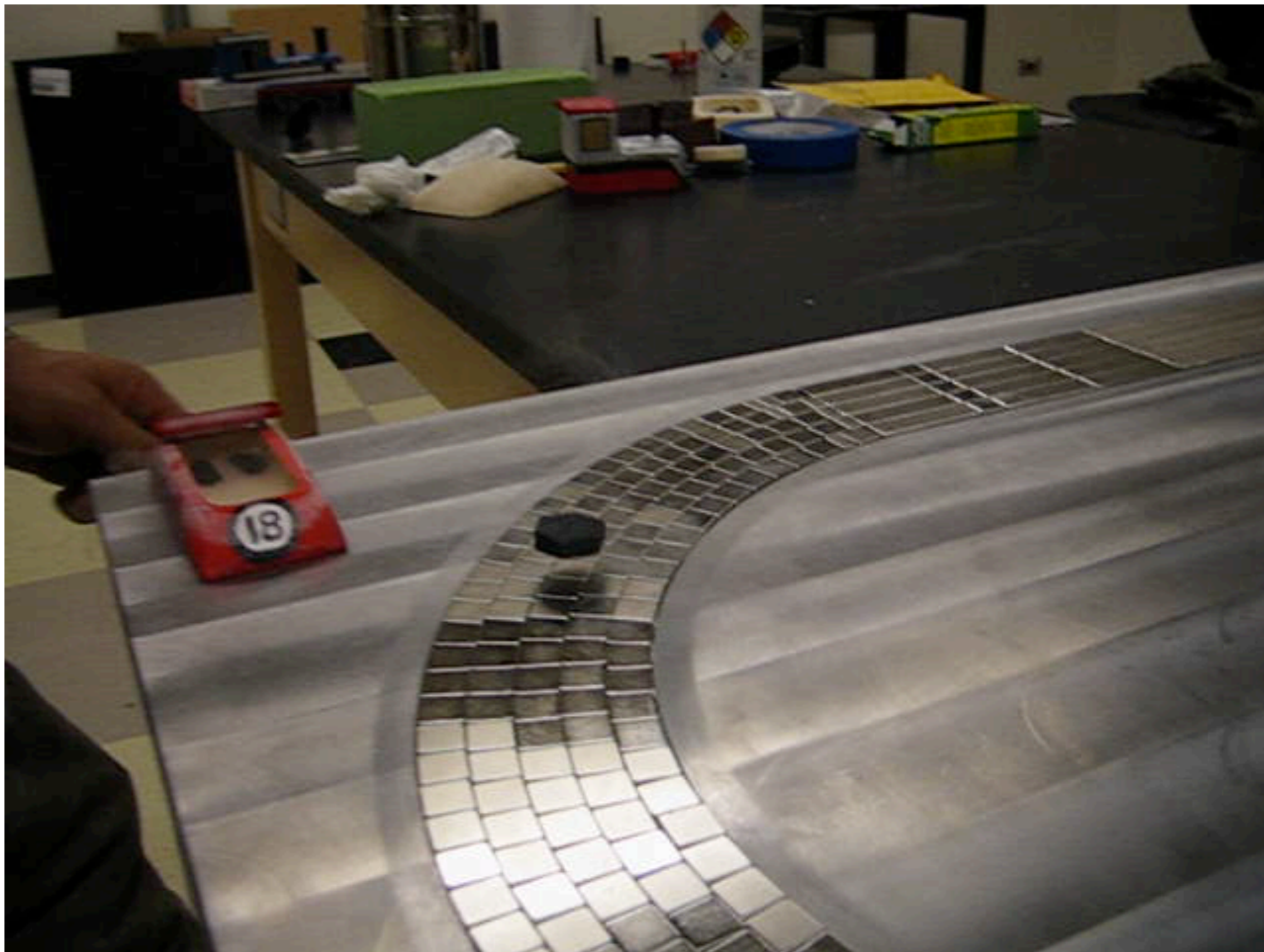
In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other’s behavior.



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.

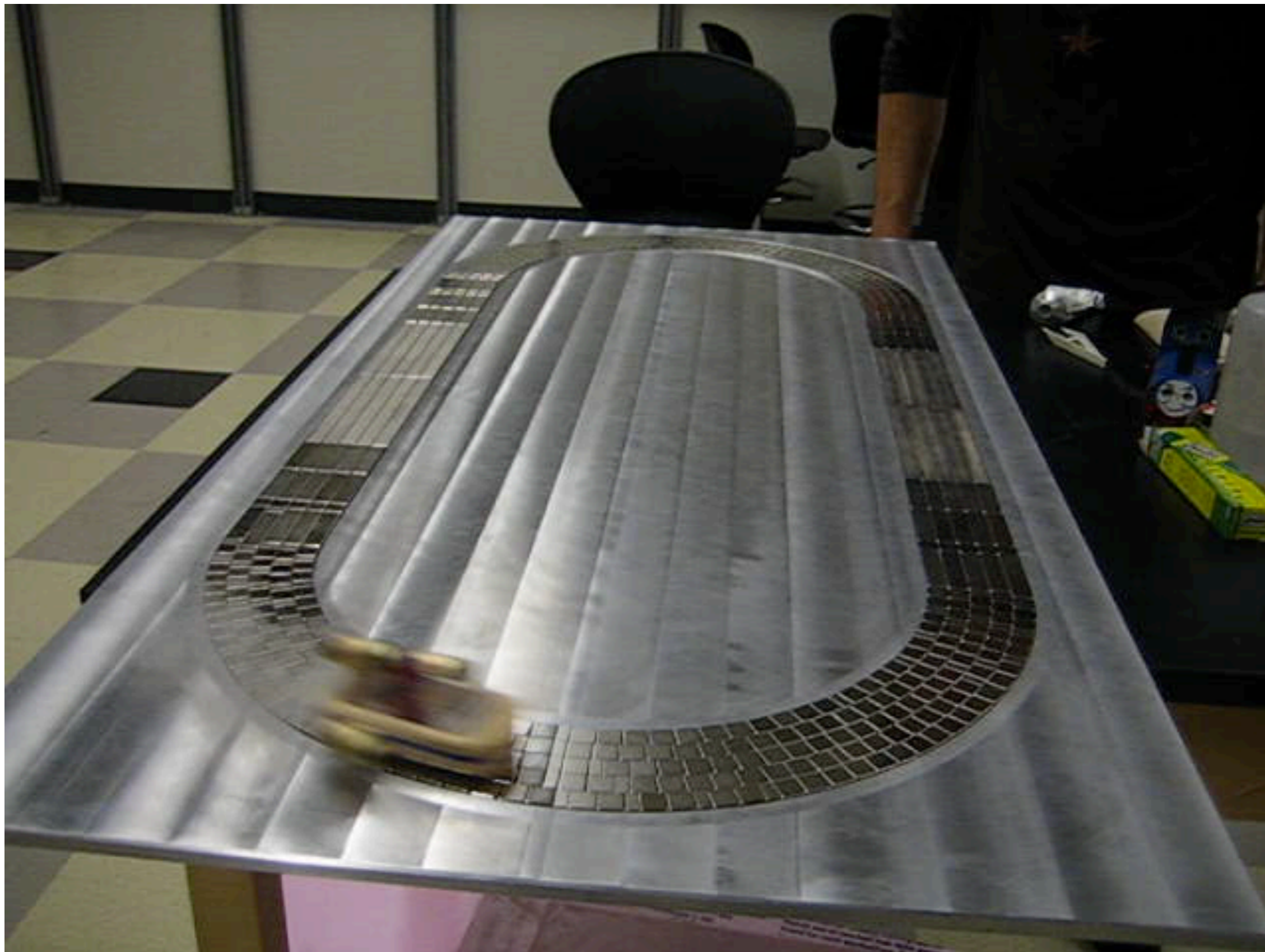
High temperature superconductors





Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University



Nd-Fe-B magnets, YBaCuO superconductor

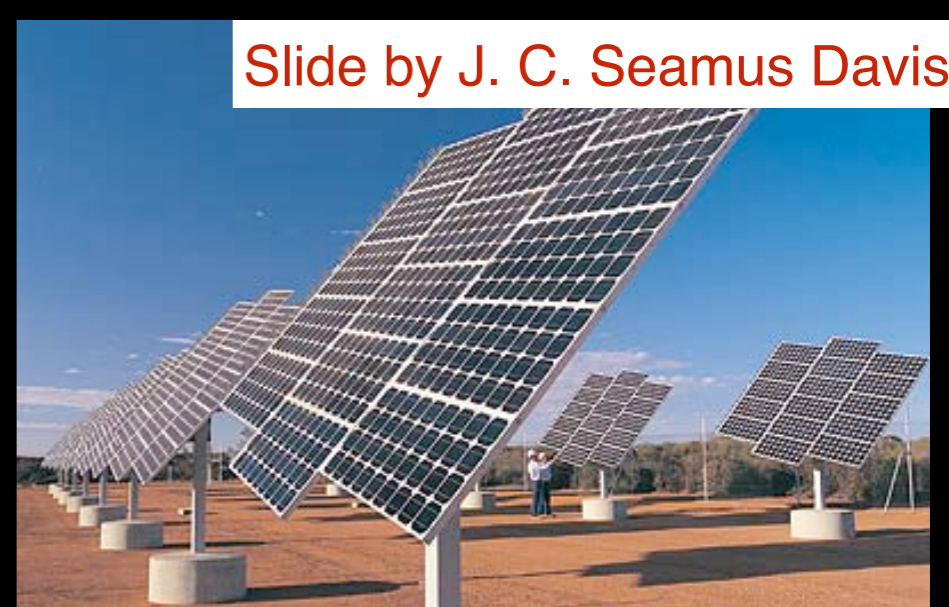
Julian Hetel and Nandini Trivedi, Ohio State University



Power Efficiency/Capacity/Stability



Power Bottlenecks



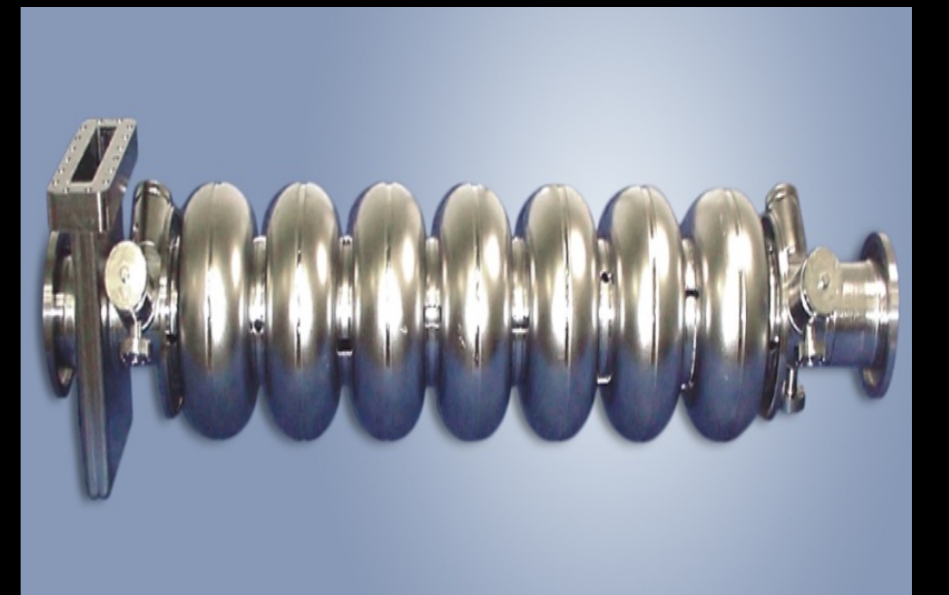
Accommodate Renewable Power



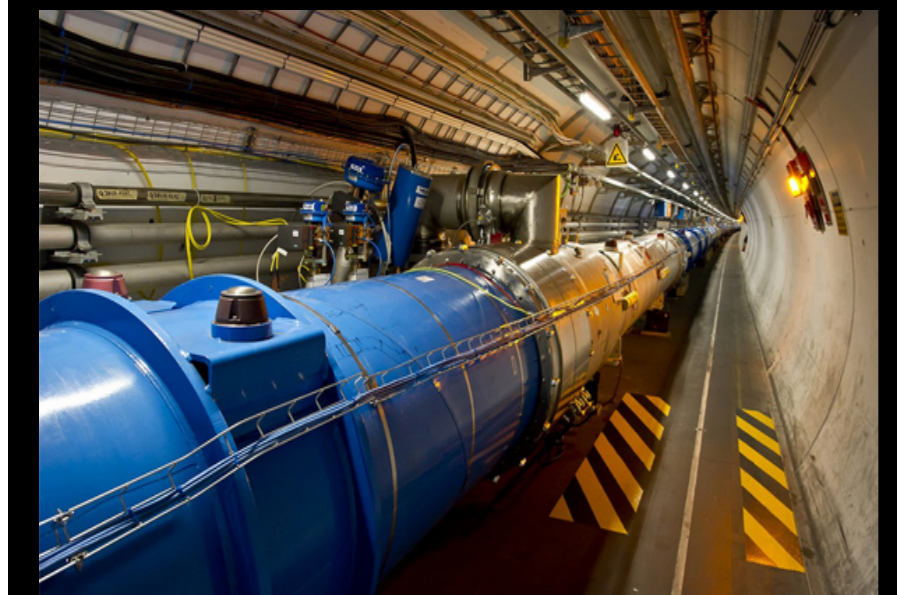
Efficient Rotating Machines



Information Technology



Next Generation HEP



Ultra-High Magnetic Fields



Medical

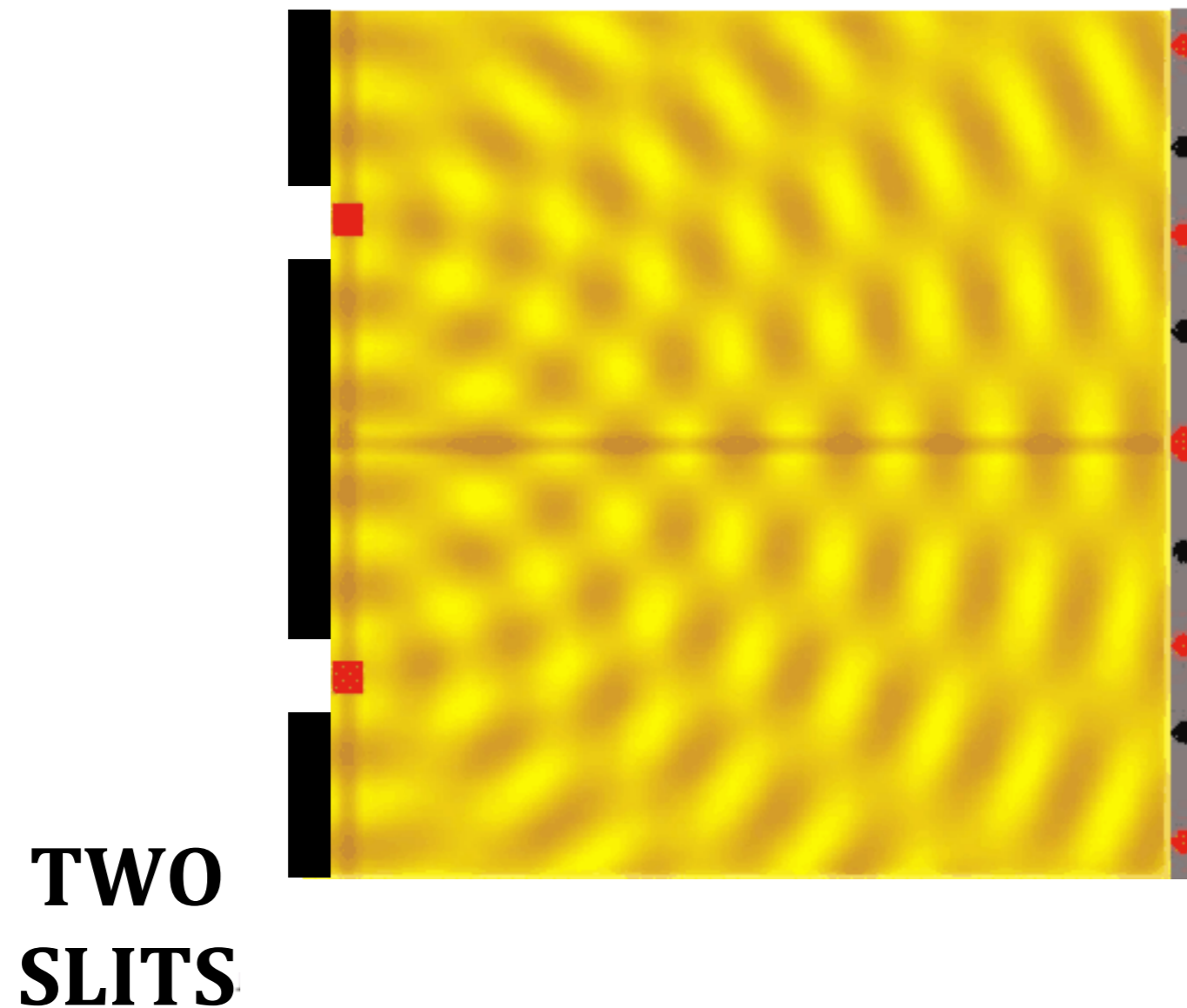


Transport

Quantum entanglement

Principles of Quantum Mechanics: I. Quantum Superposition

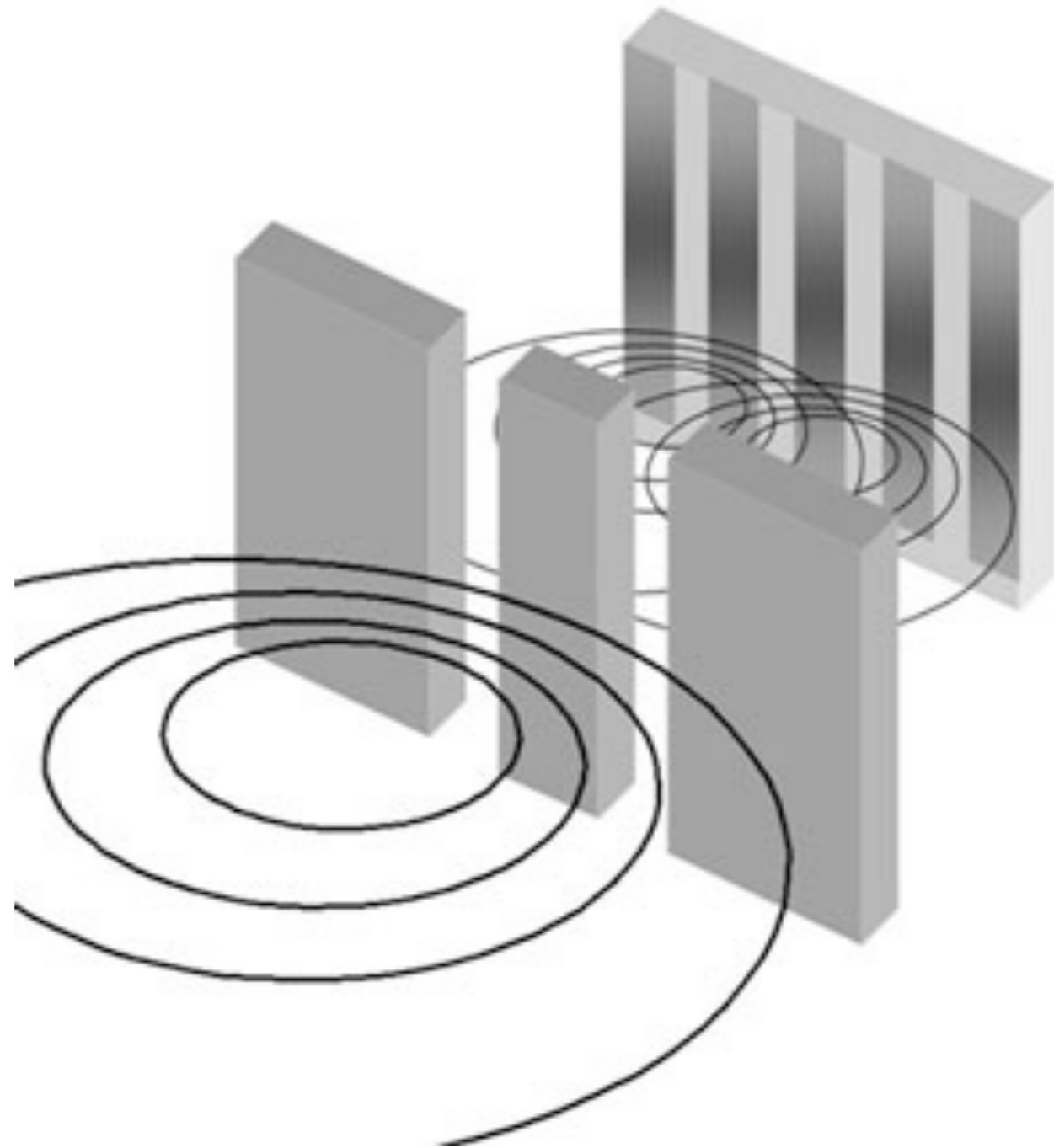
The double slit experiment



Interference of water waves

Principles of Quantum Mechanics: I. Quantum Superposition

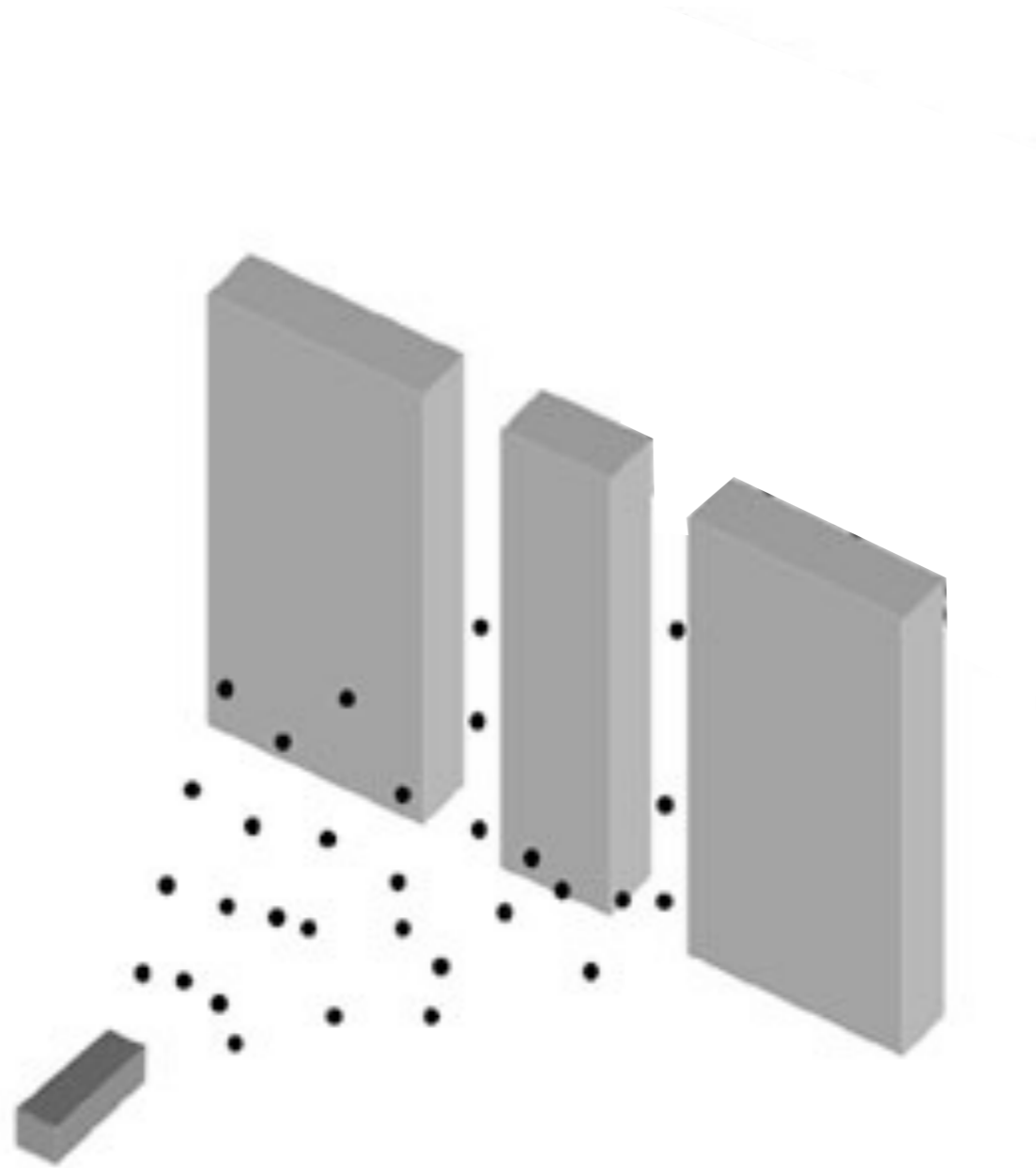
The double slit experiment



Interference of water waves

Principles of Quantum Mechanics: I. Quantum Superposition

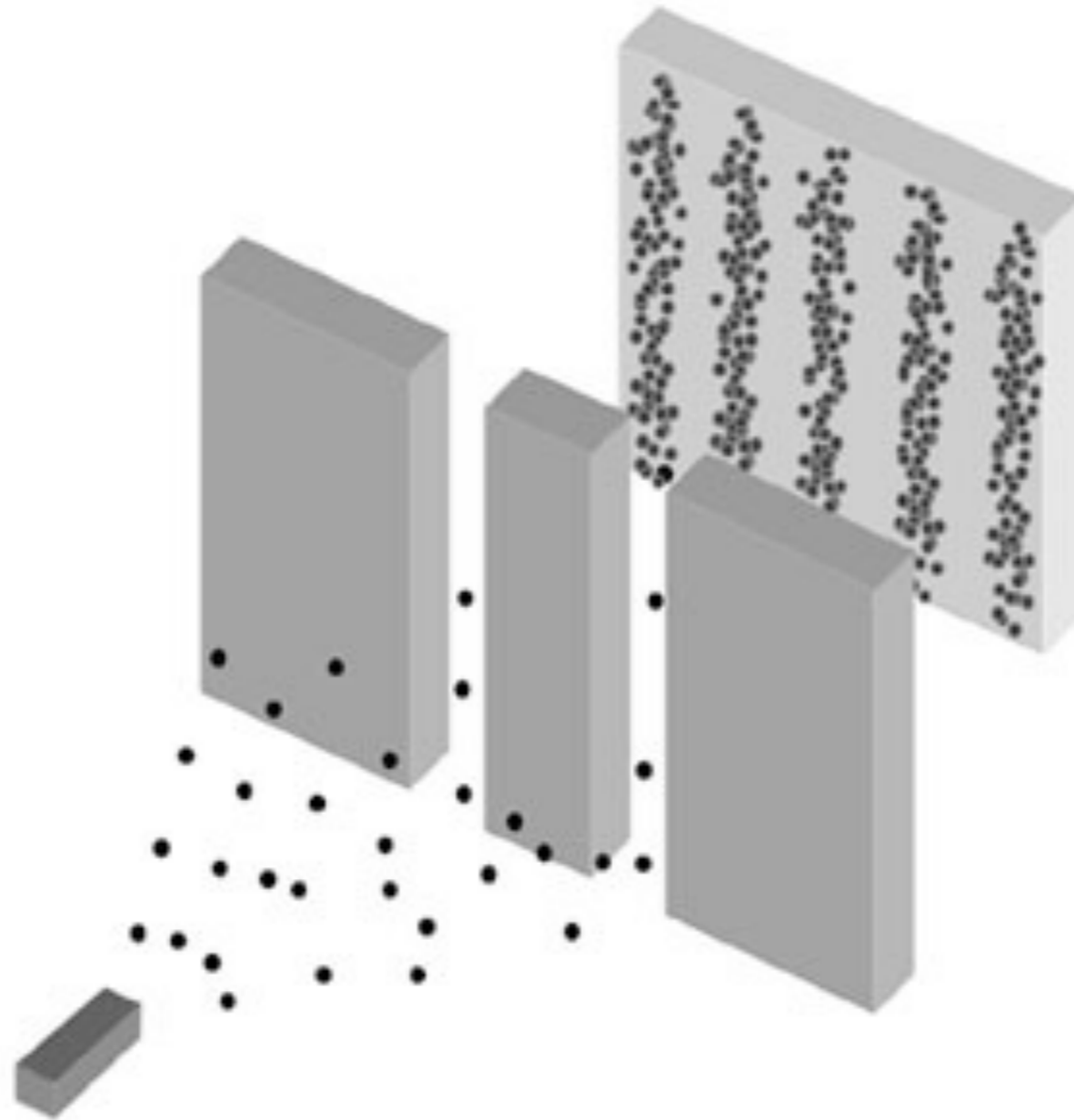
The double slit experiment



Send electrons through the slits

Principles of Quantum Mechanics: I. Quantum Superposition

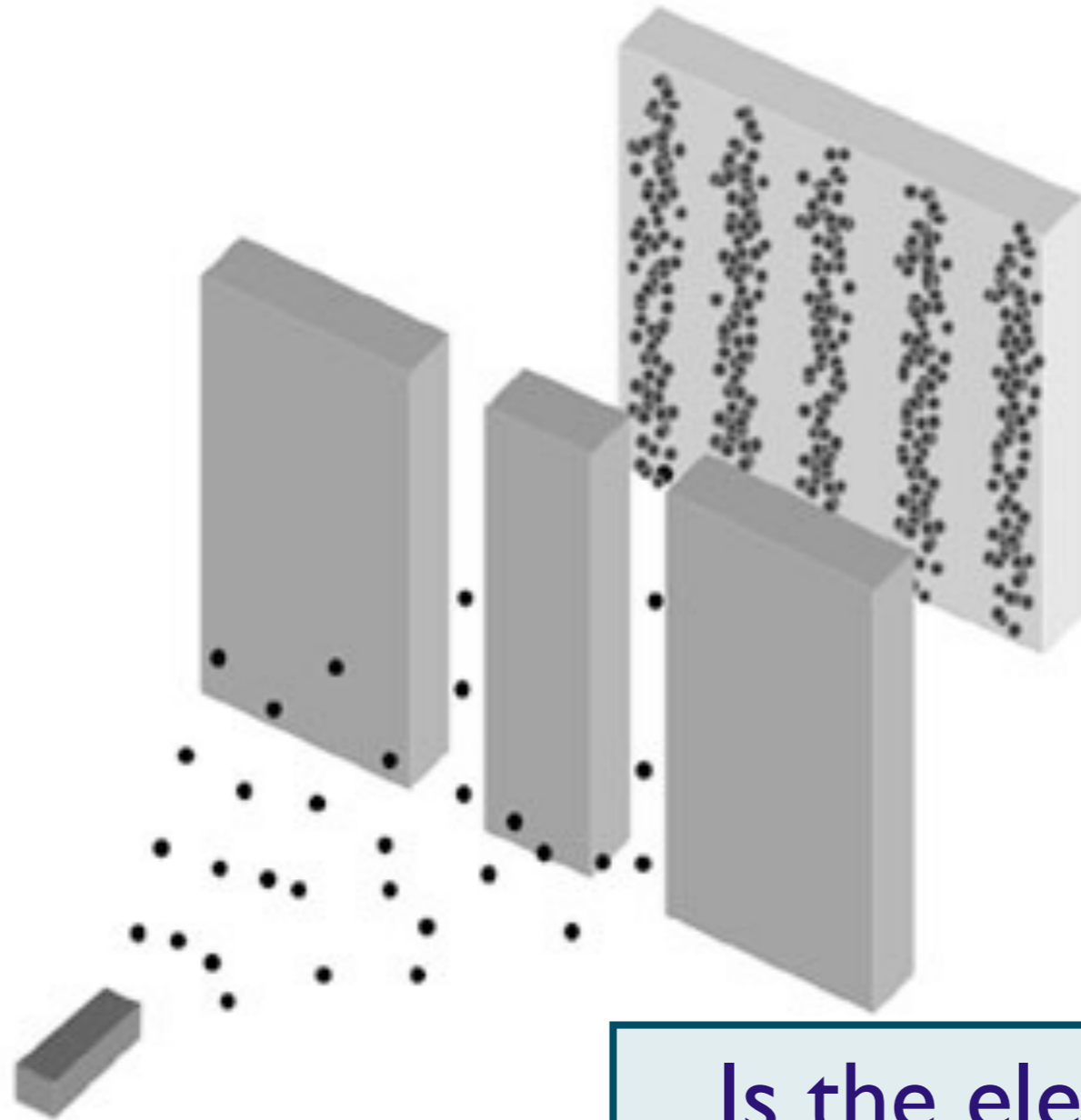
The double slit experiment



Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

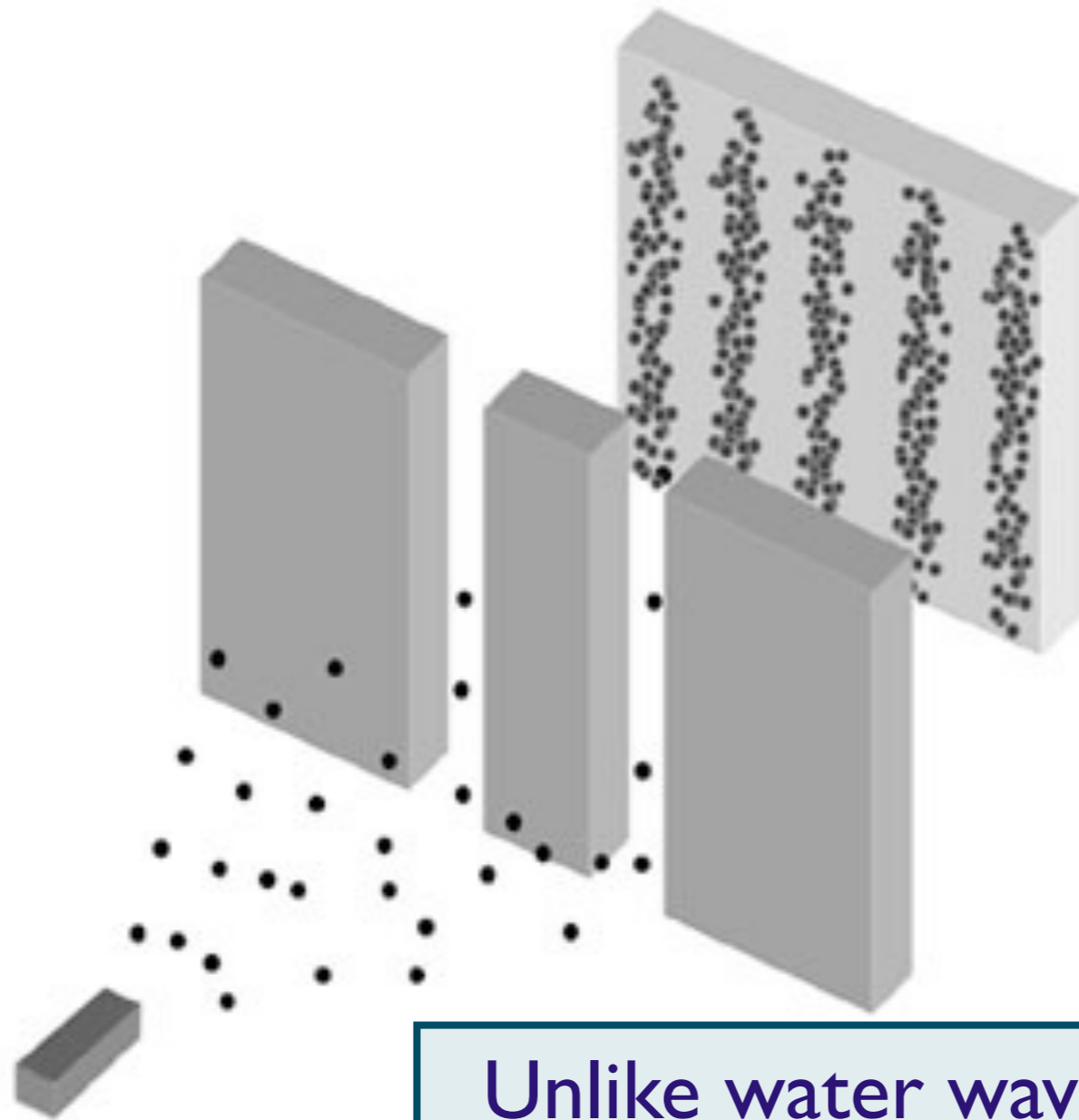


Is the electron a wave ?

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

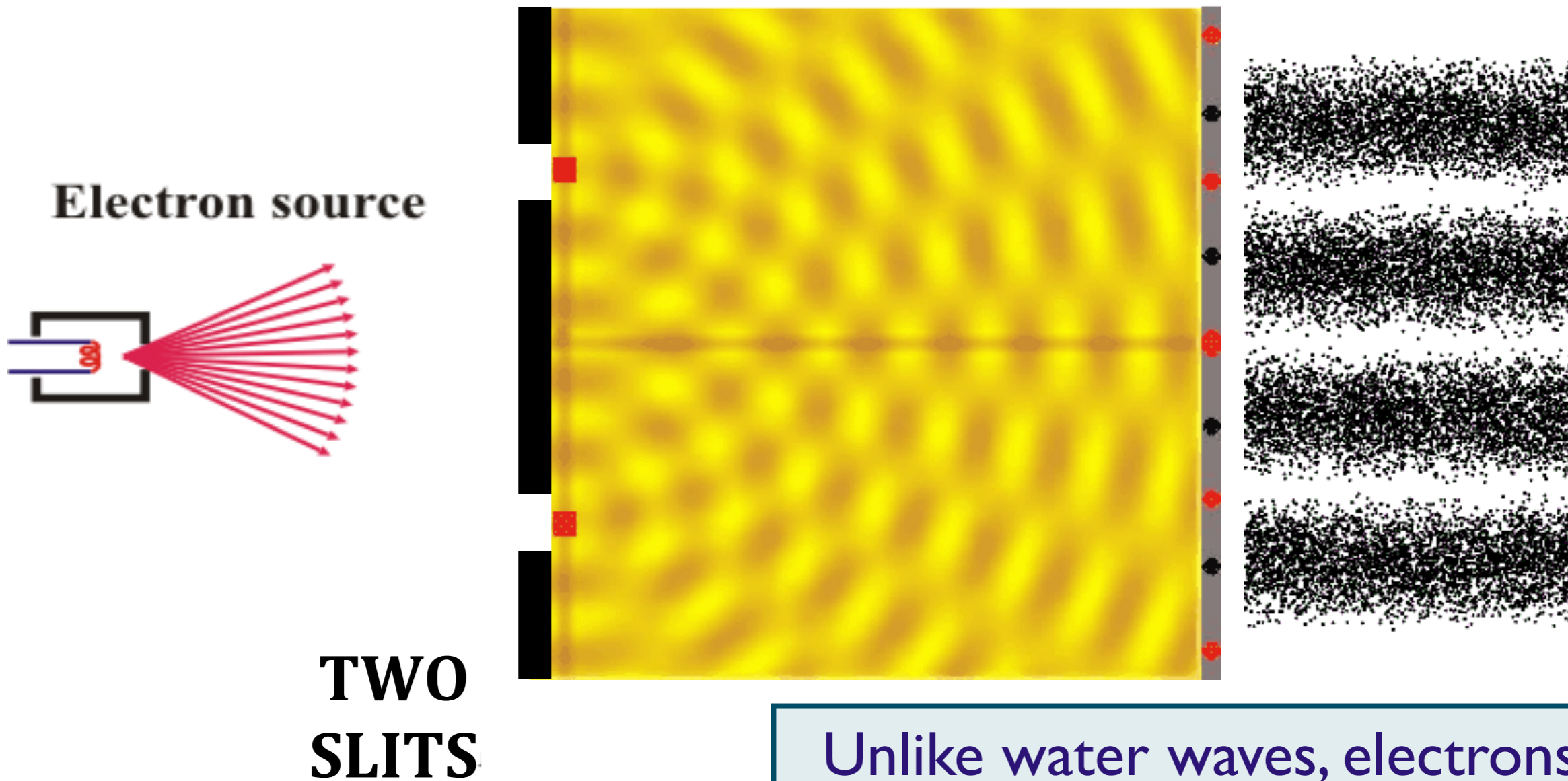


Unlike water waves, electrons arrive one-by-one (so is it like a particle ?)

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment



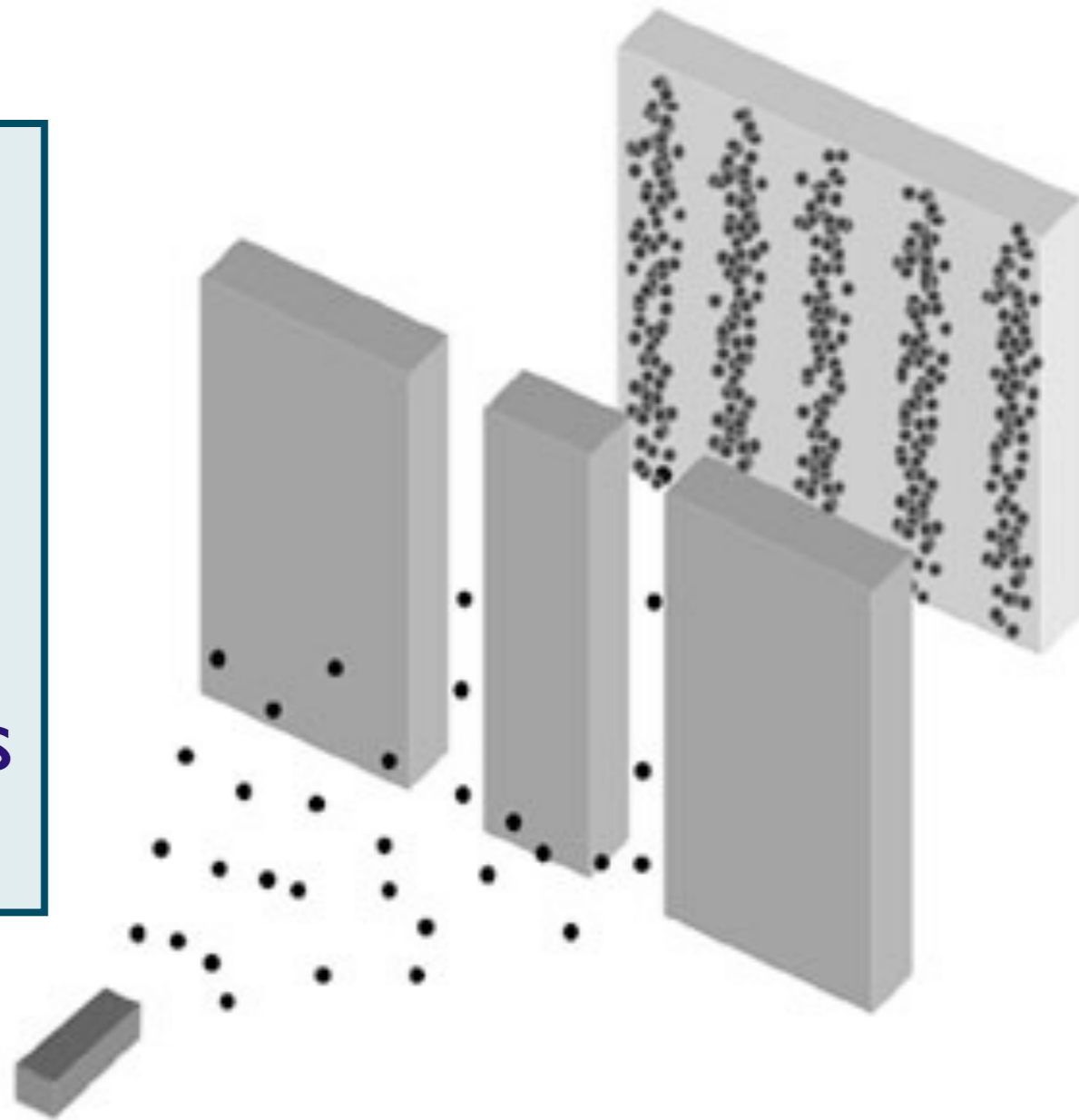
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Interference of electrons

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 ?

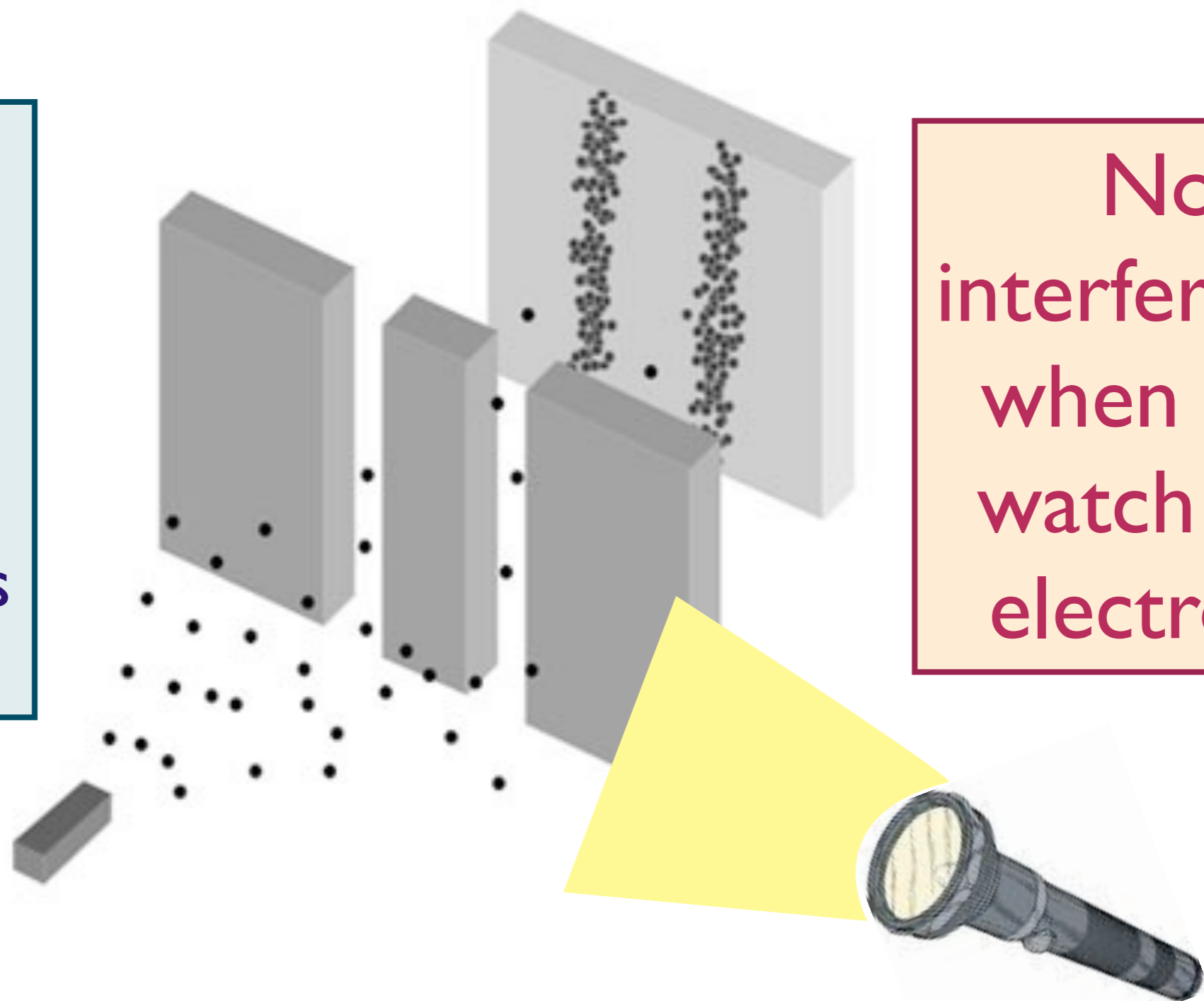


Interference of electrons

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 ?



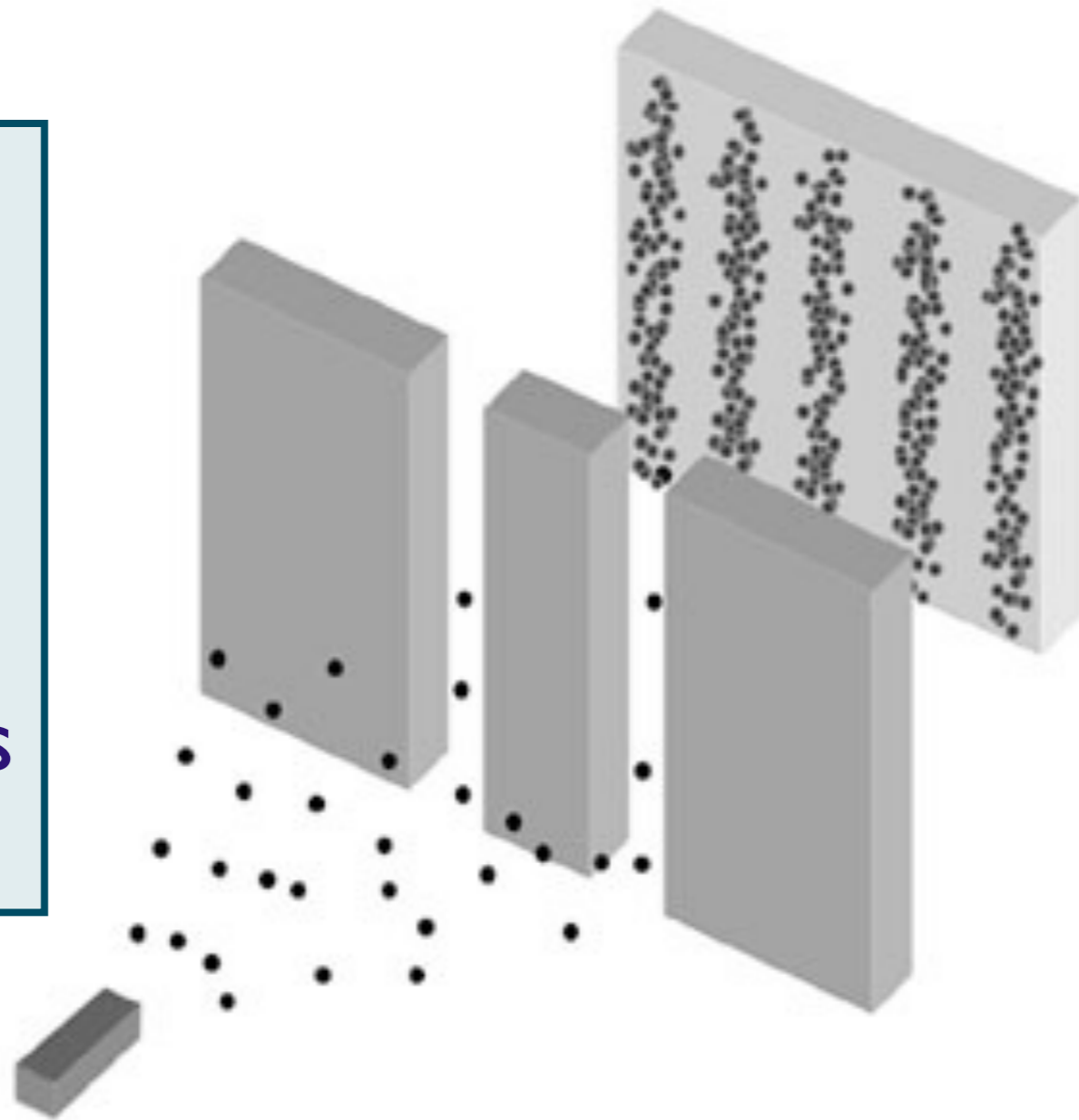
No interference when you watch the electrons

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 ?

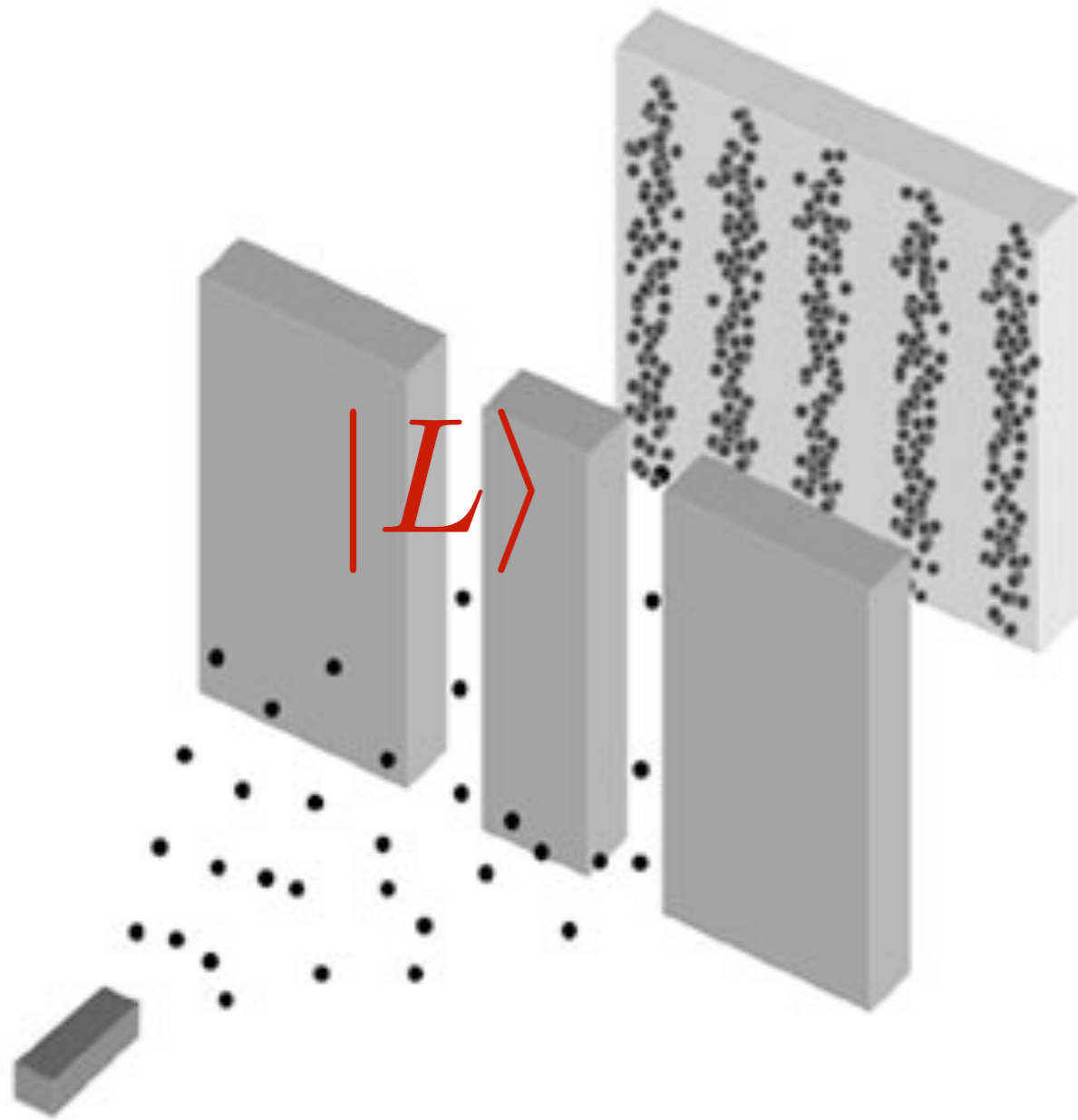


Each electron passes through both slits !

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

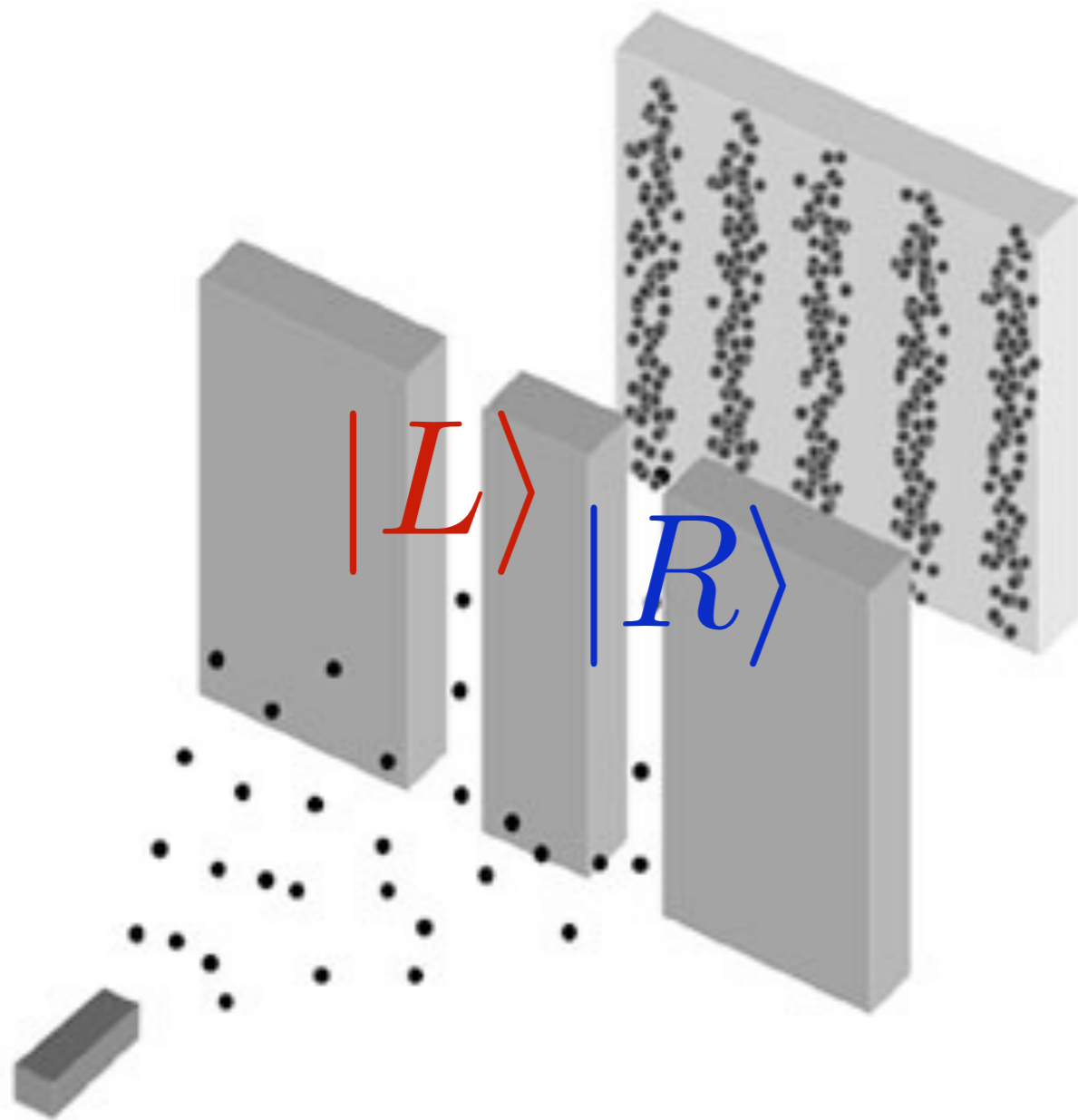
The double slit experiment



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

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

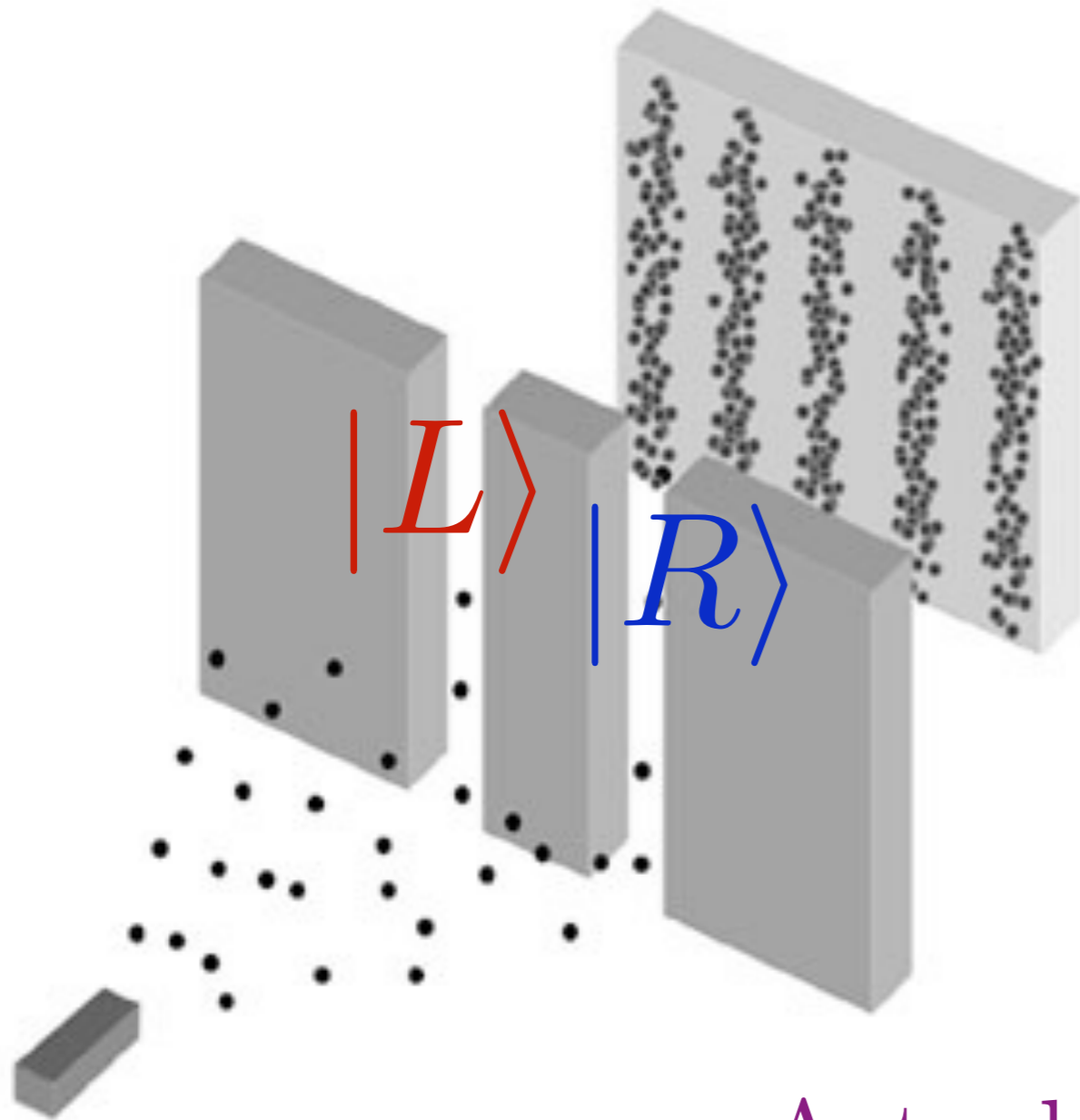


Let $|L\rangle$ represent the state with the electron in the left slit

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

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

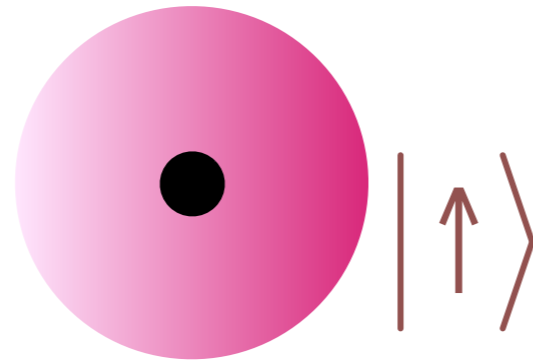
Principles of Quantum Mechanics: II. Quantum Entanglement

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:

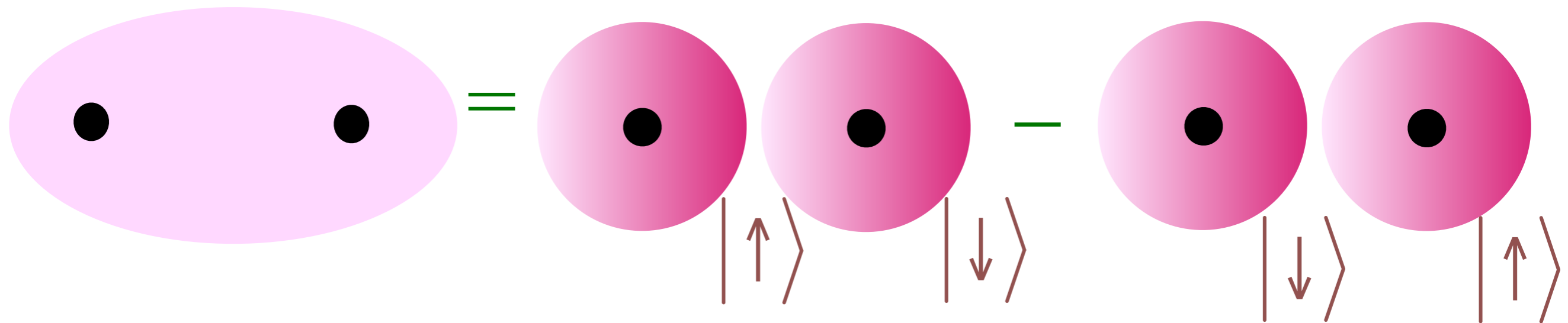


Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom: 

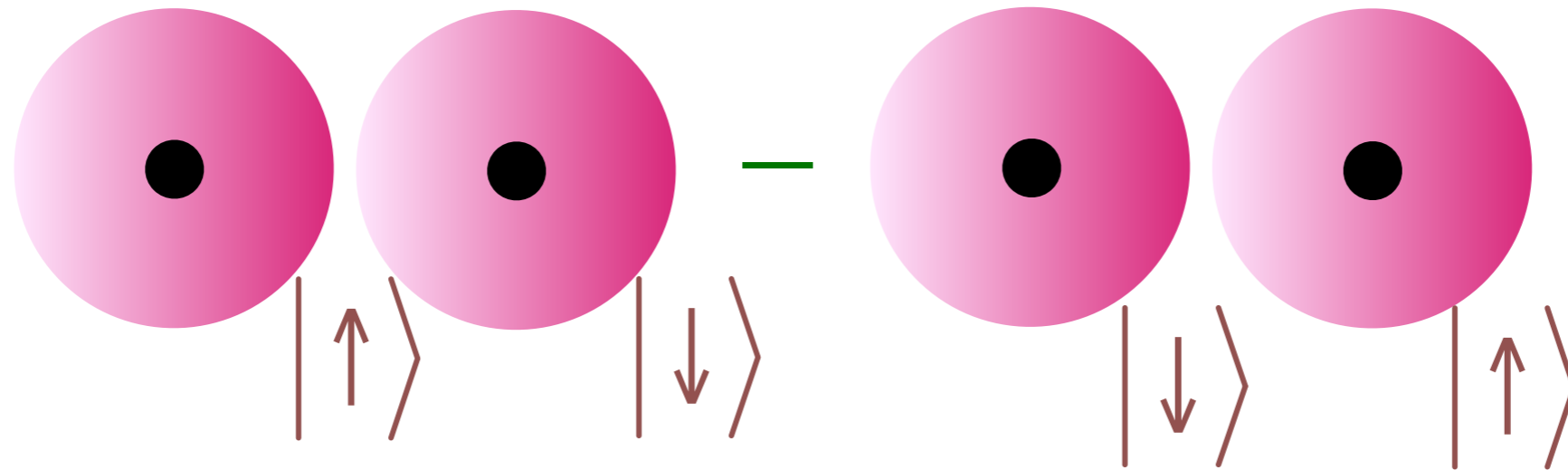
Hydrogen molecule:



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

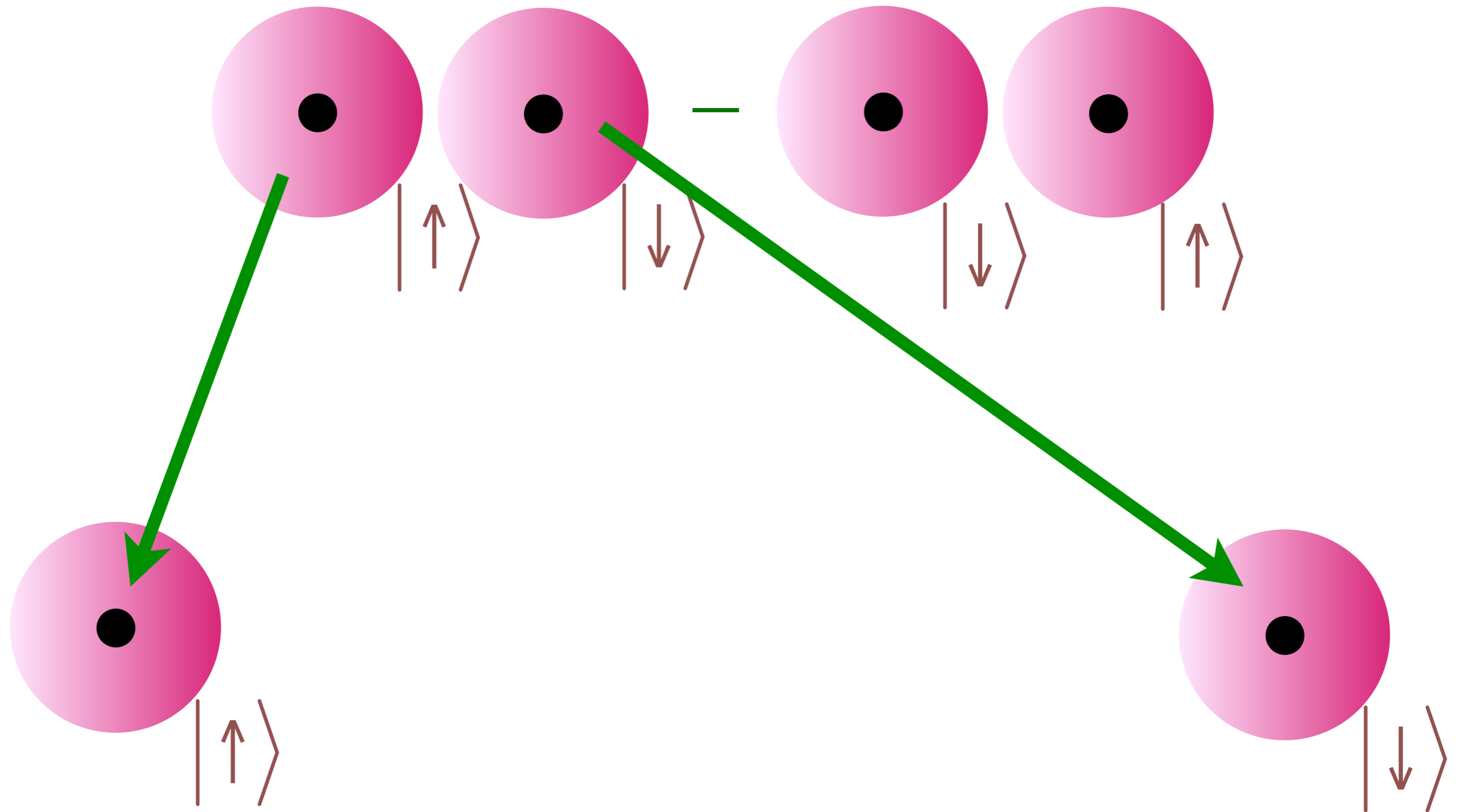
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Quantum Entanglement: quantum superposition with more than one particle



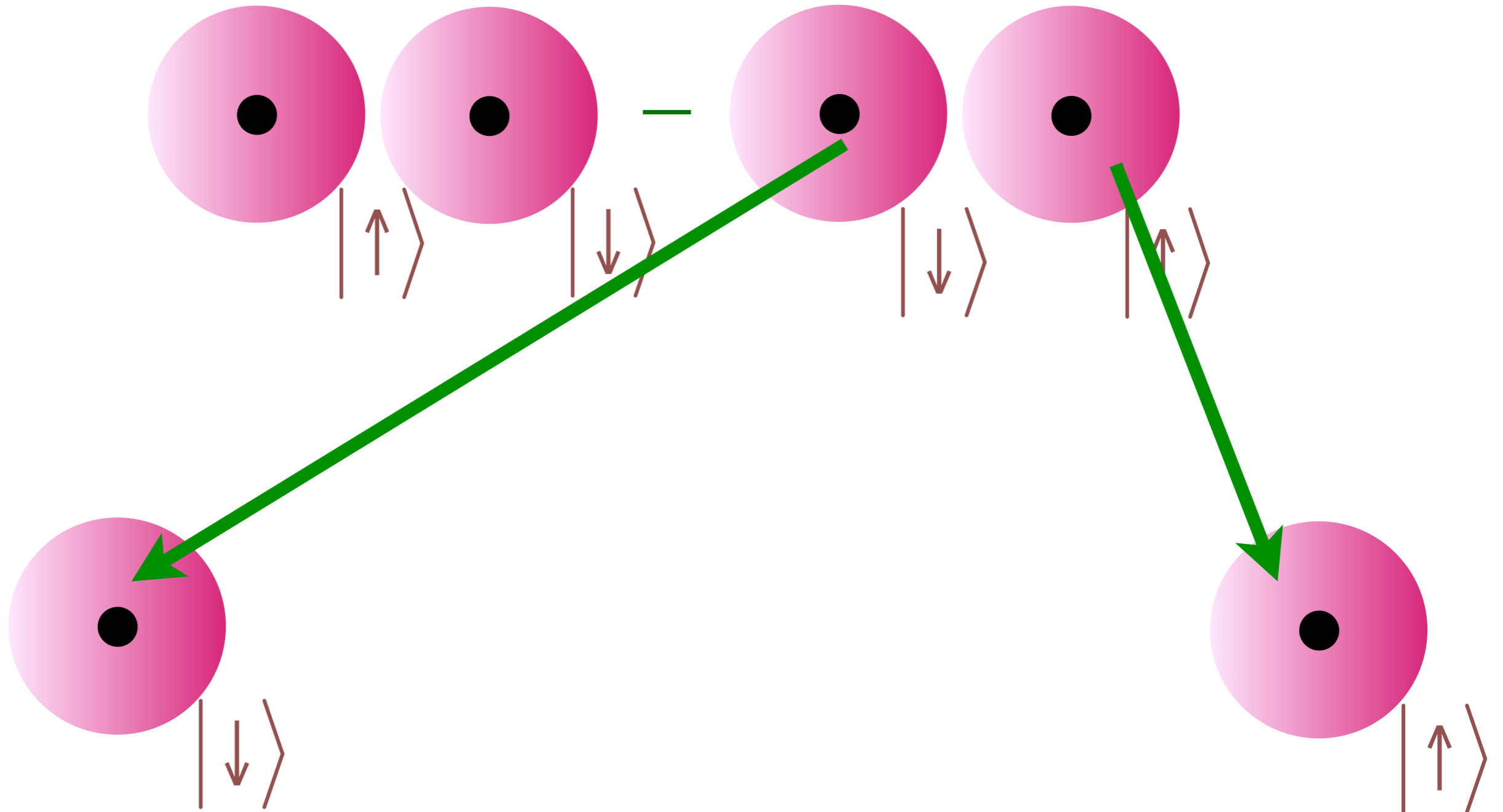
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Quantum Entanglement: quantum superposition with more than one particle



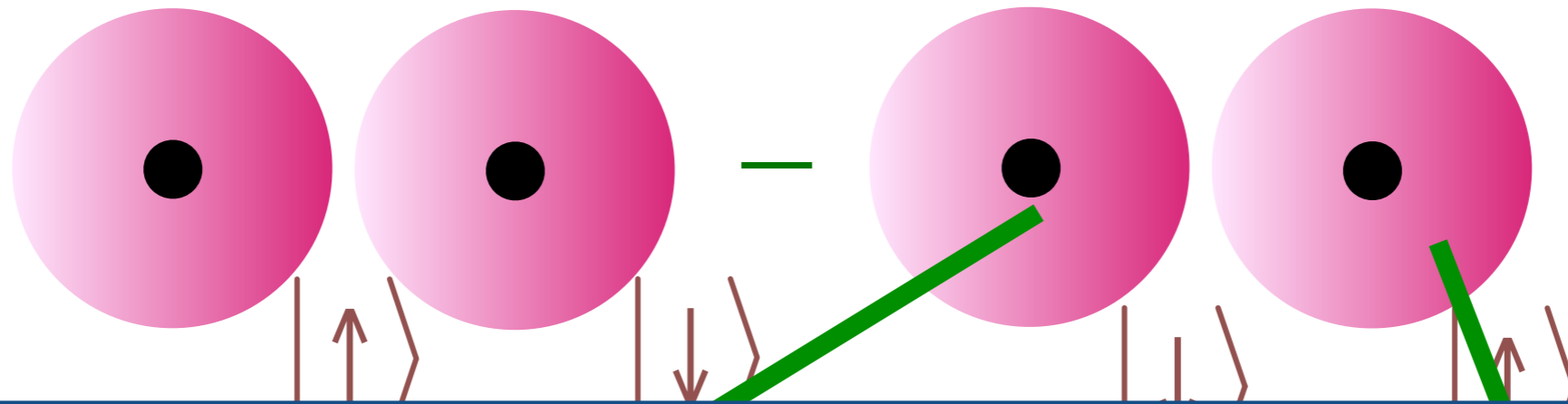
Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

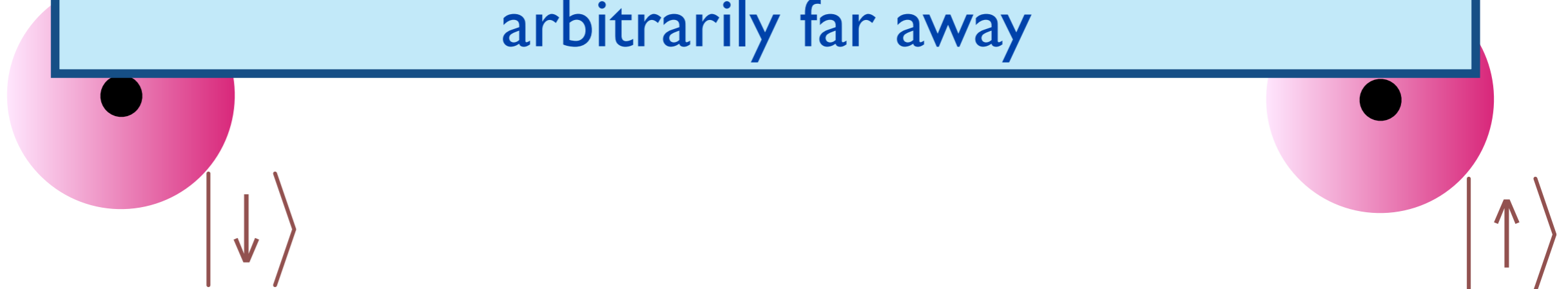


Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle



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



Quantum entanglement

**Quantum
entanglement**

**Black
holes**

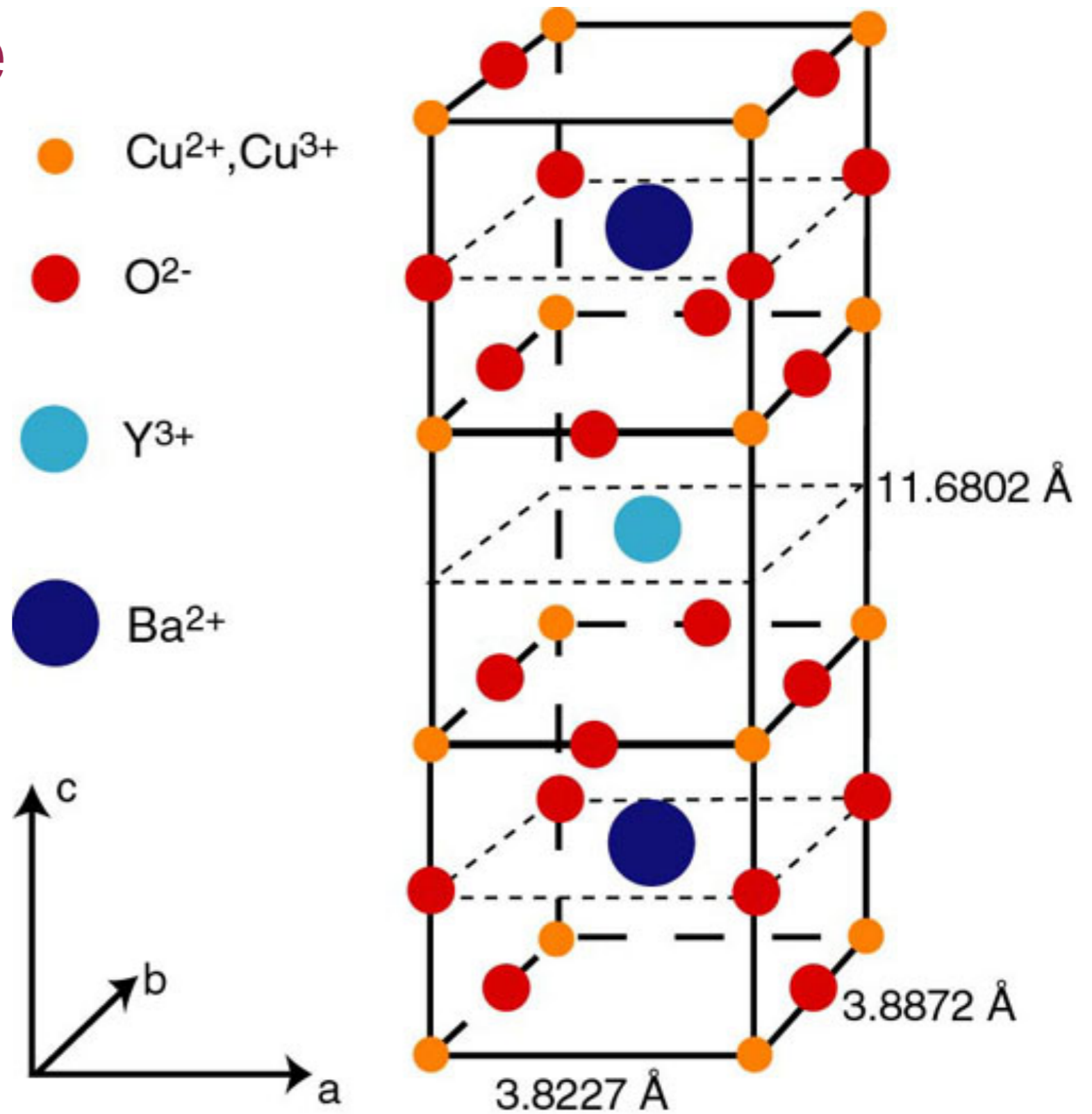
**Strange
metals**

**Quantum
entanglement**

**Black
holes**

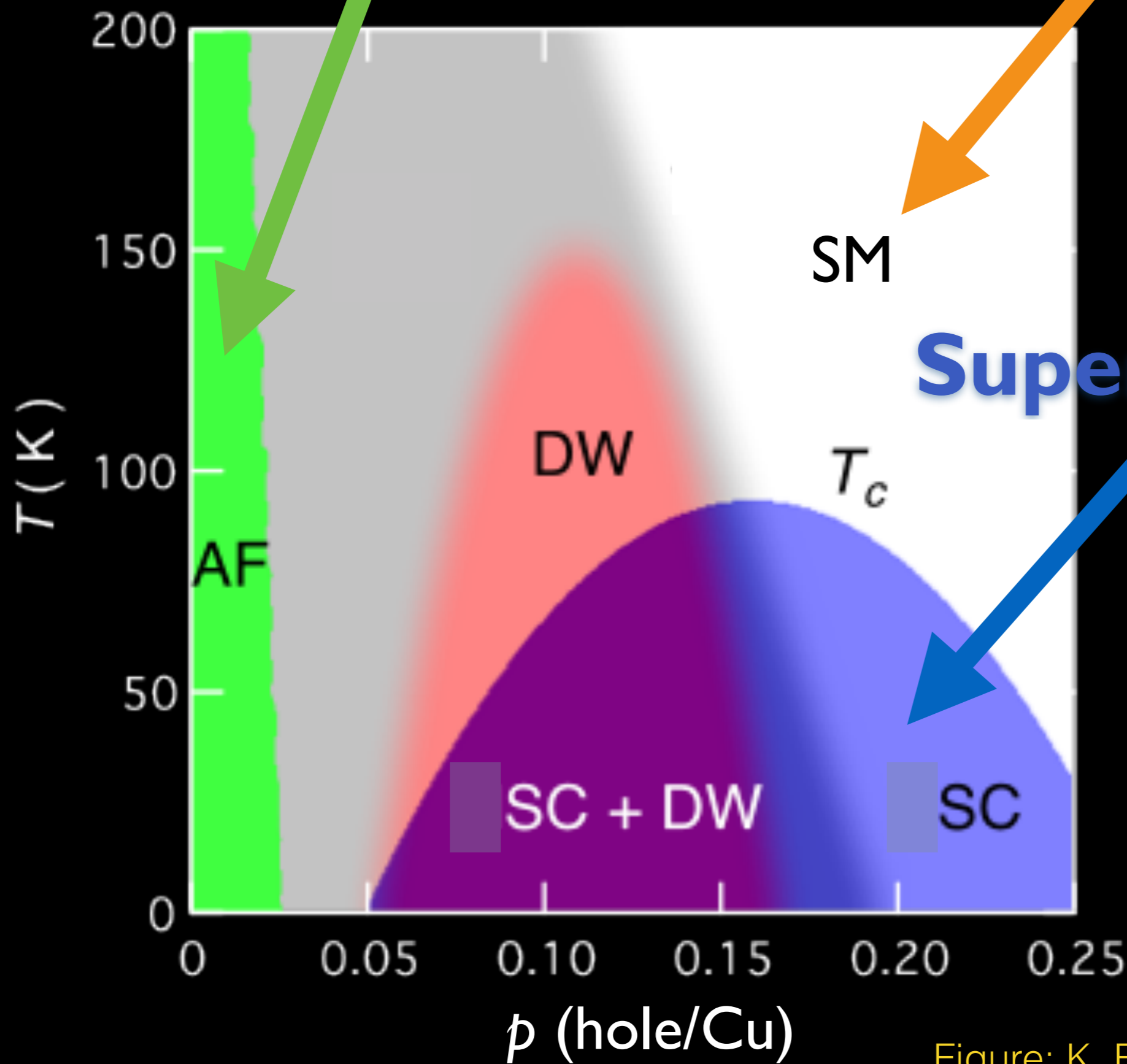
**Strange
metals**

High temperature superconductors



Antiferromagnet

Strange metal



Superconductor

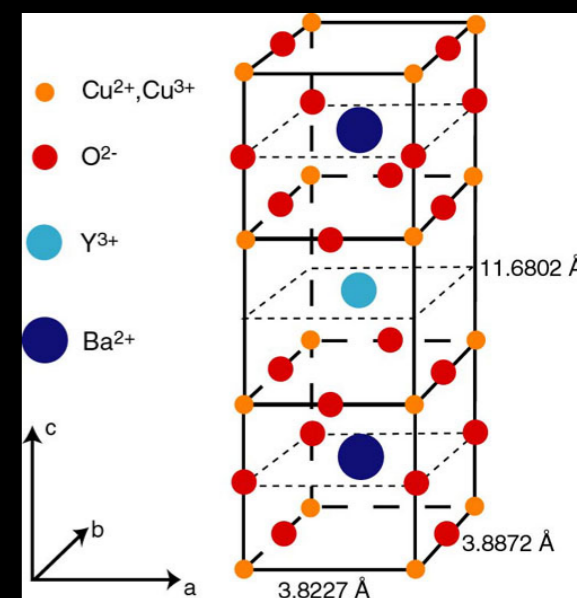


Figure: K. Fujita and J. C. Seamus Davis

Antiferromagnet

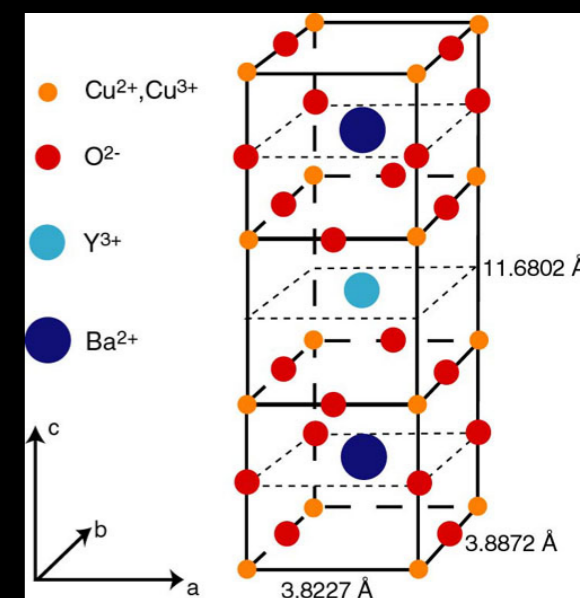
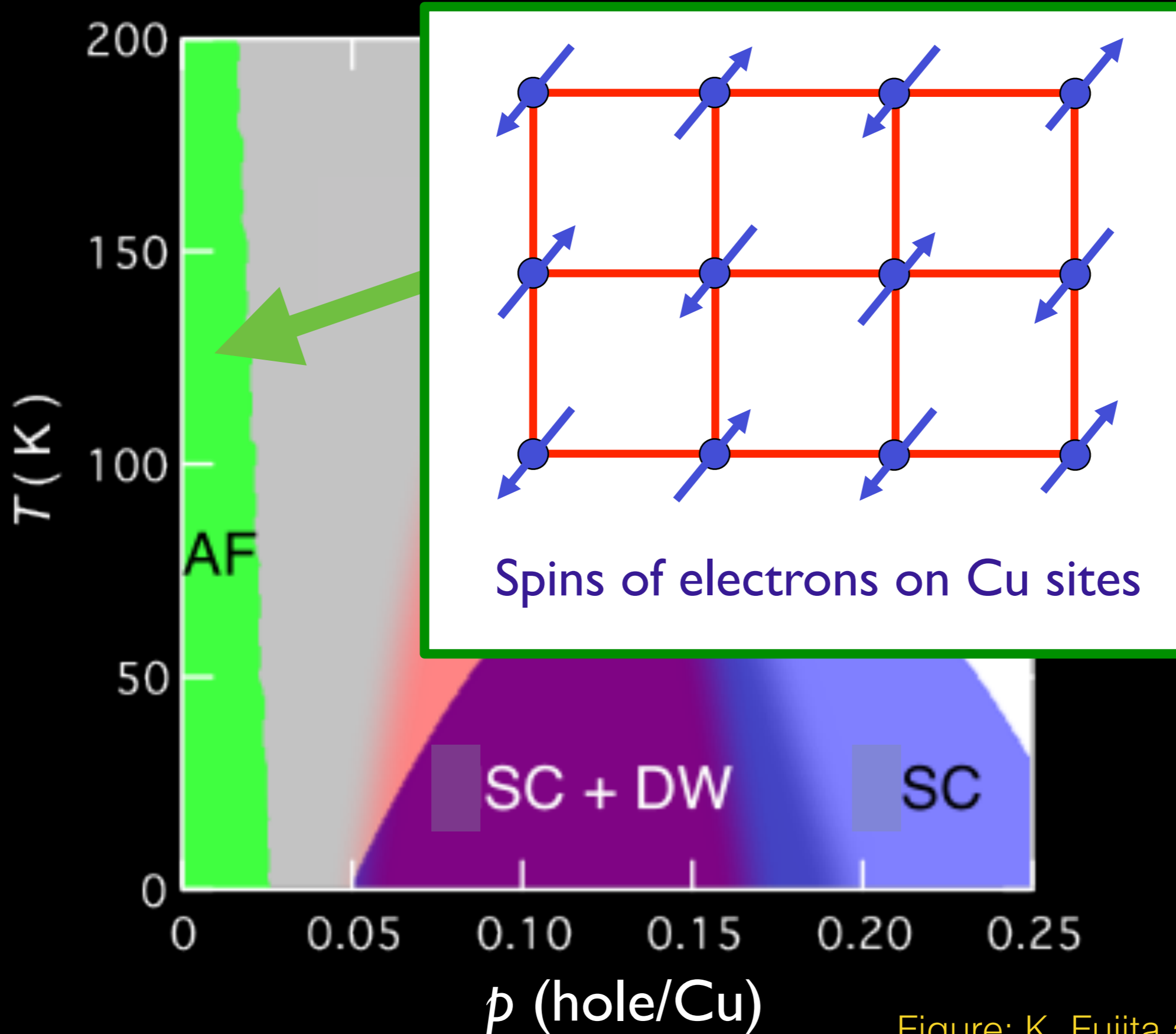
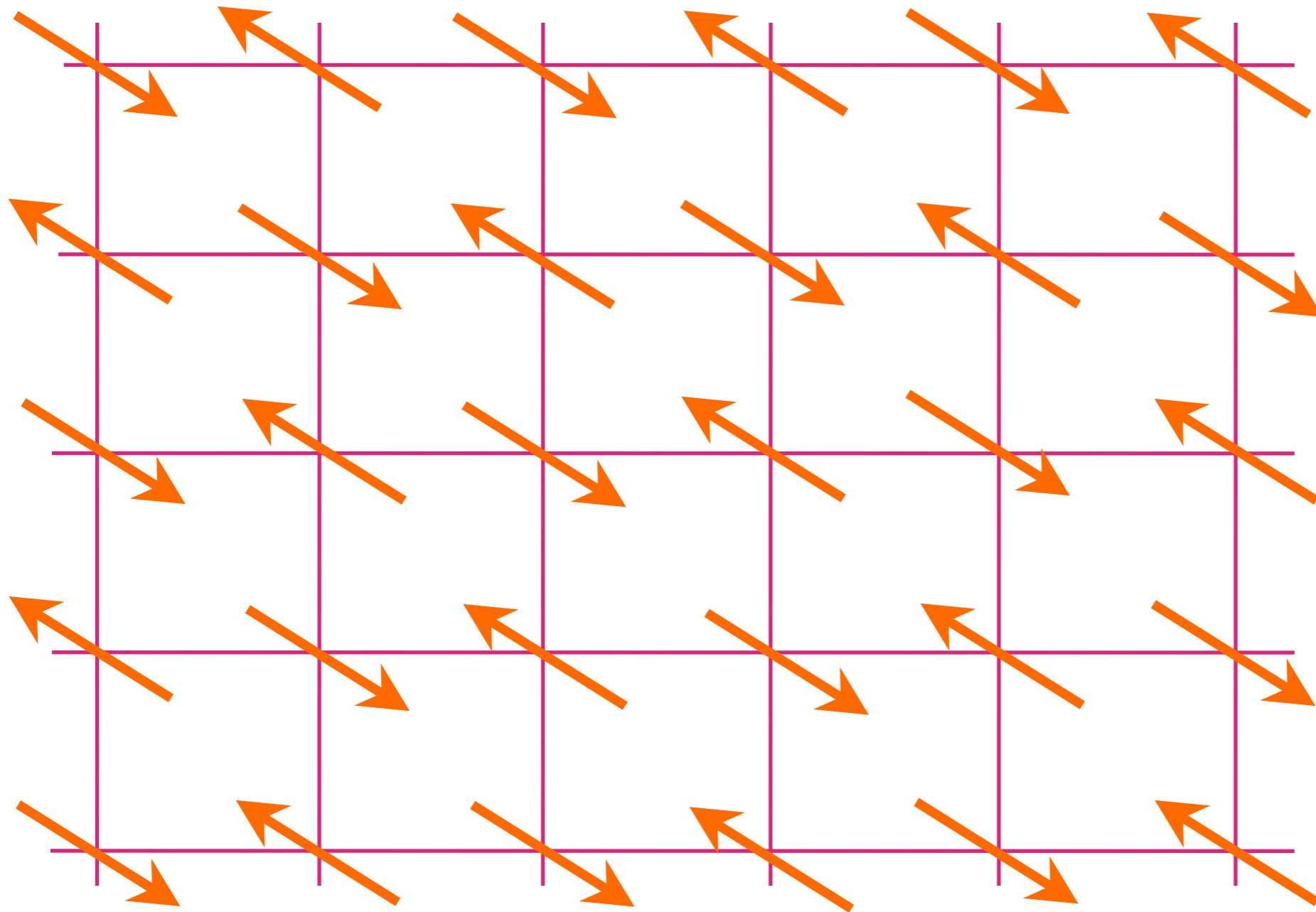
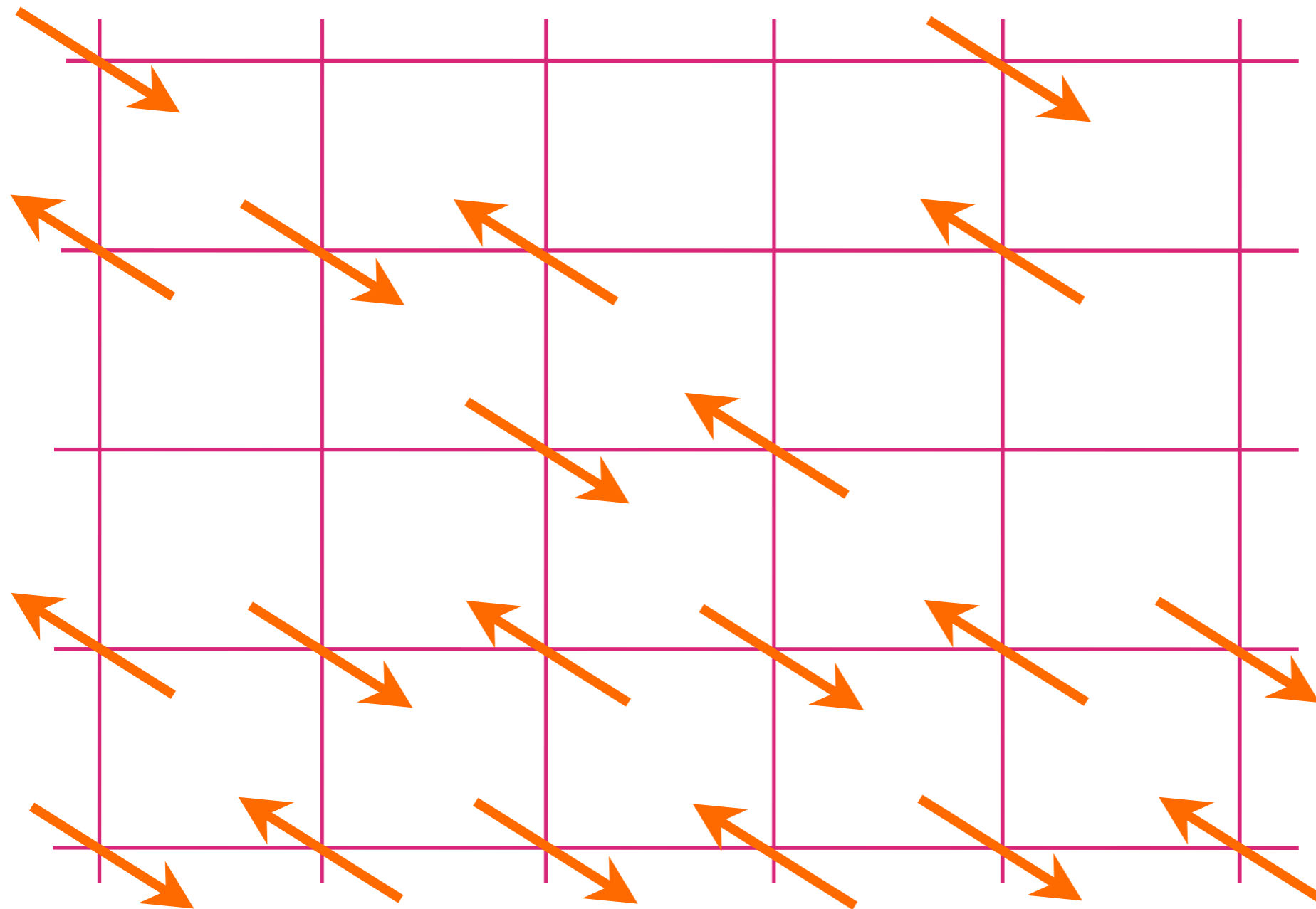


Figure: K. Fujita and J. C. Seamus Davis

Square lattice of Cu sites

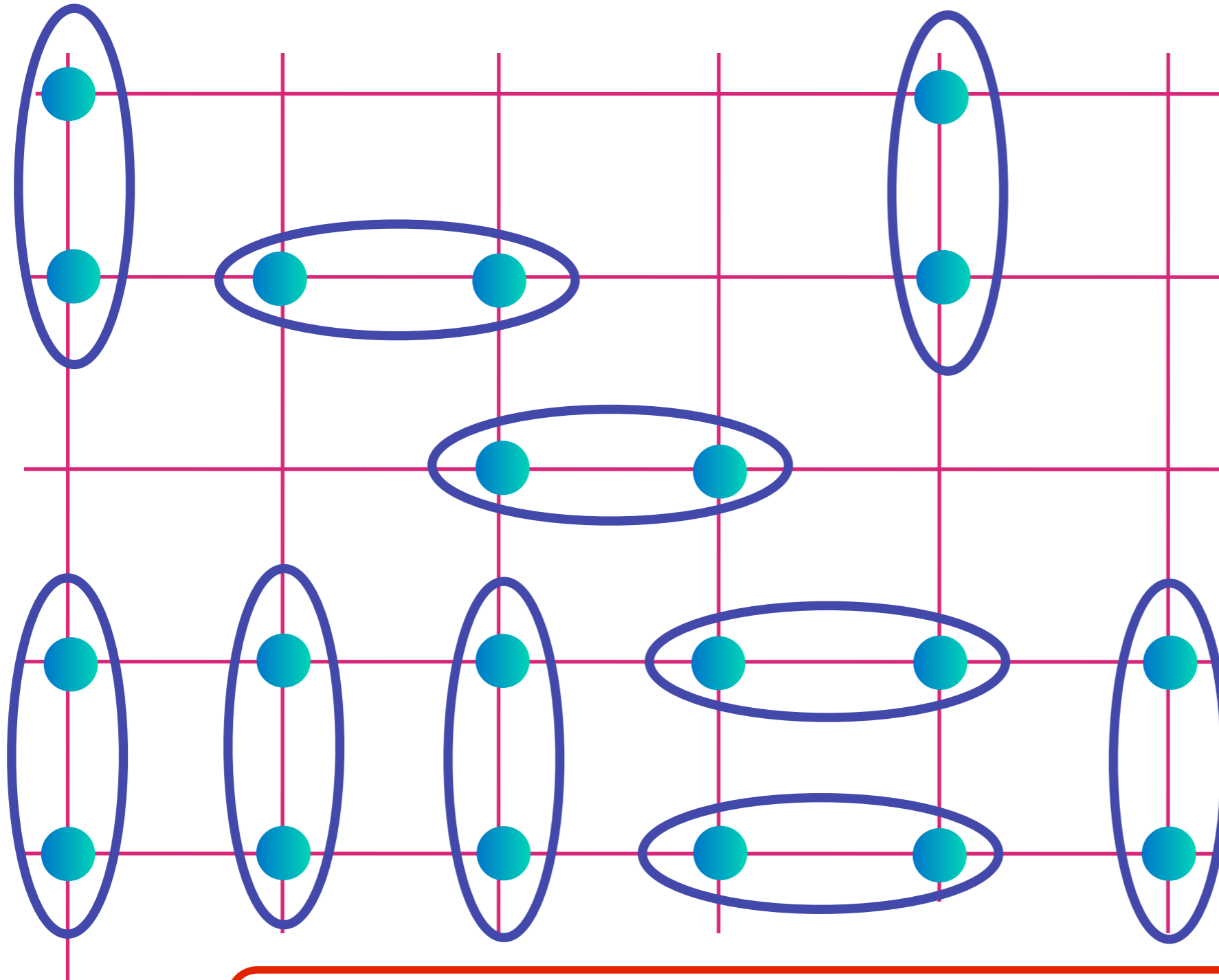


Square lattice of Cu sites



Remove density
 p electrons

Square lattice of Cu sites

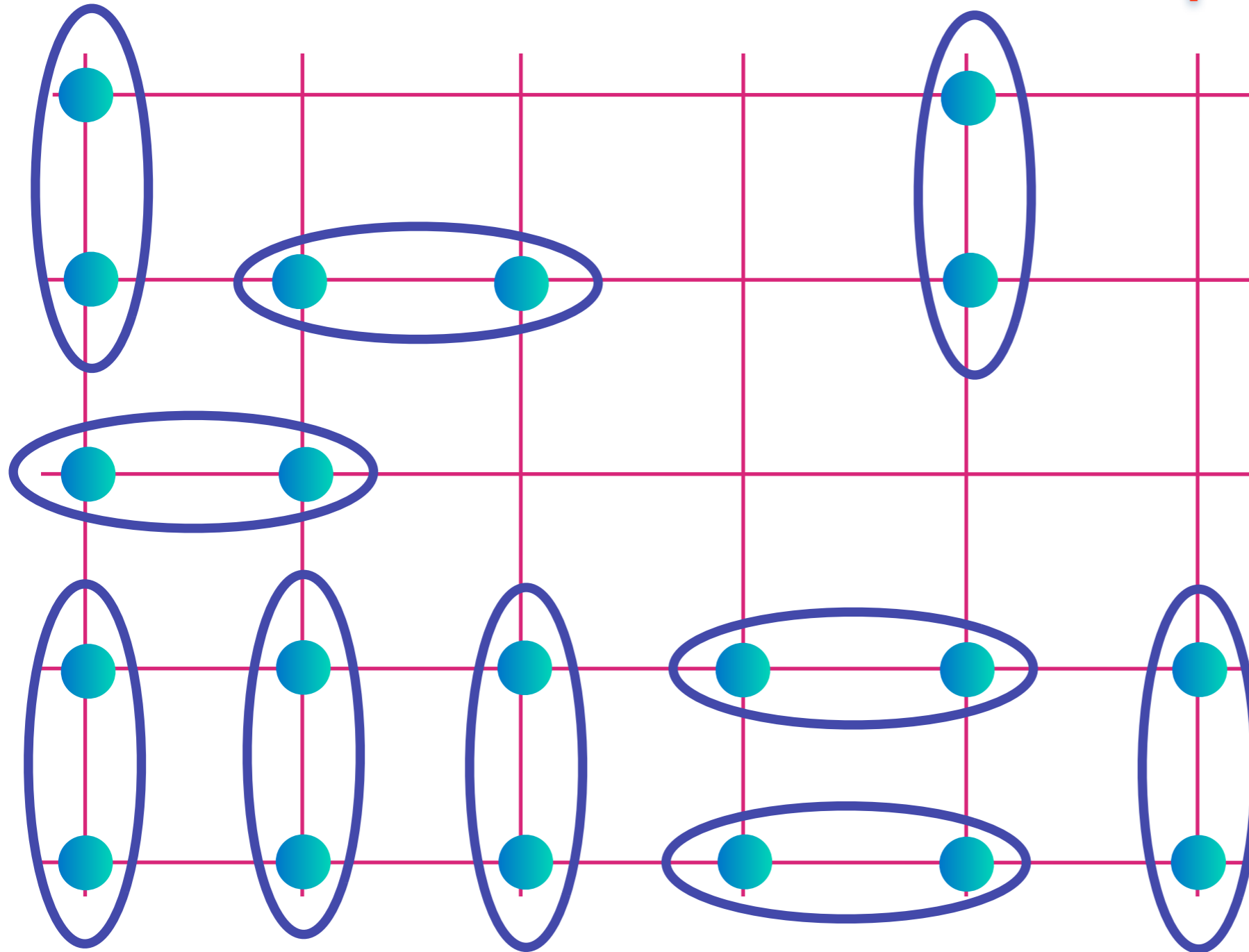


Electrons entangle in ("Cooper") pairs into chemical bonds

$$\text{Cooper pair} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Square lattice of Cu sites

Superconductivity

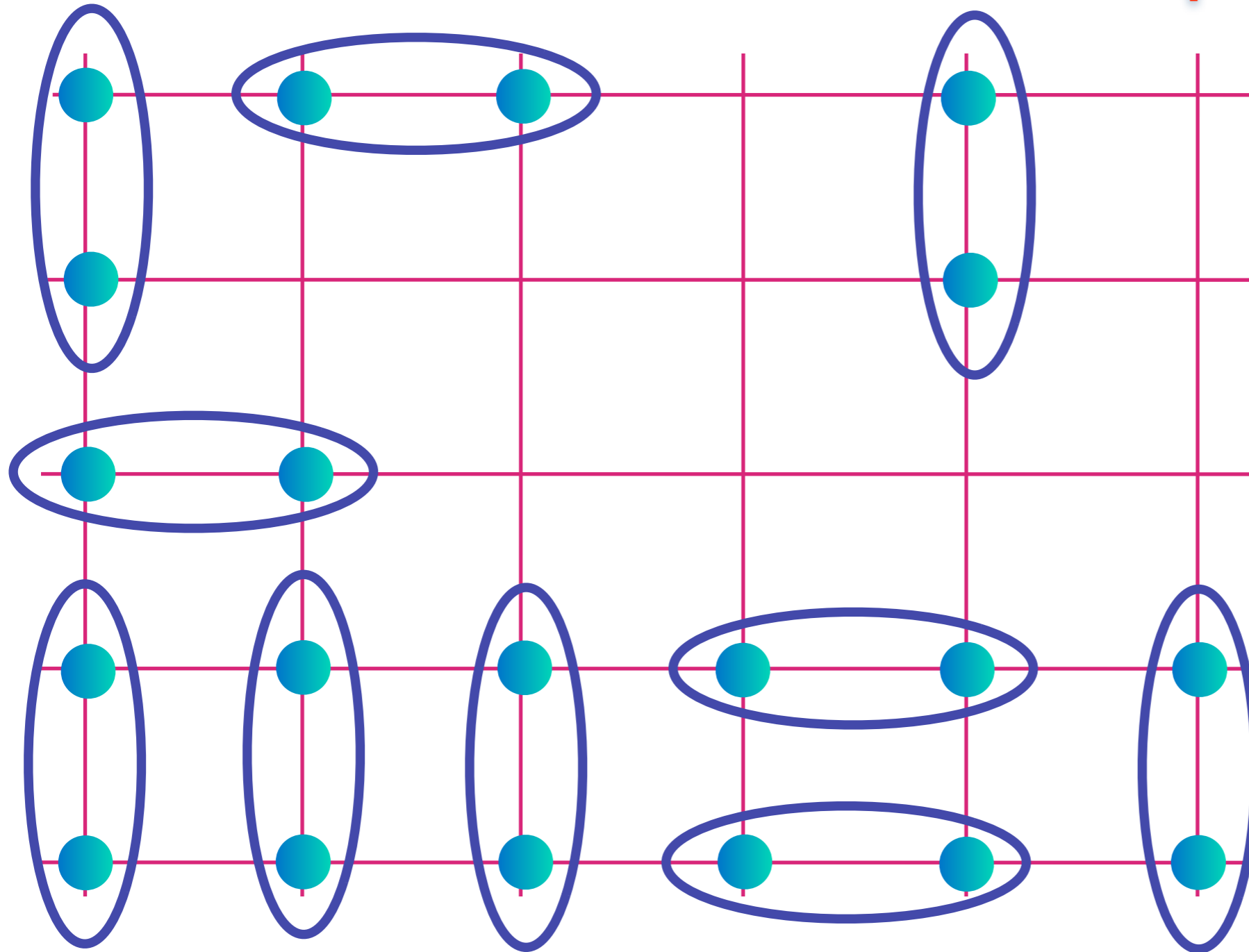


Cooper pairs form quantum superpositions at different locations: “Bose-Einstein condensation” in which all pairs are “everywhere at the same time”

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Square lattice of Cu sites

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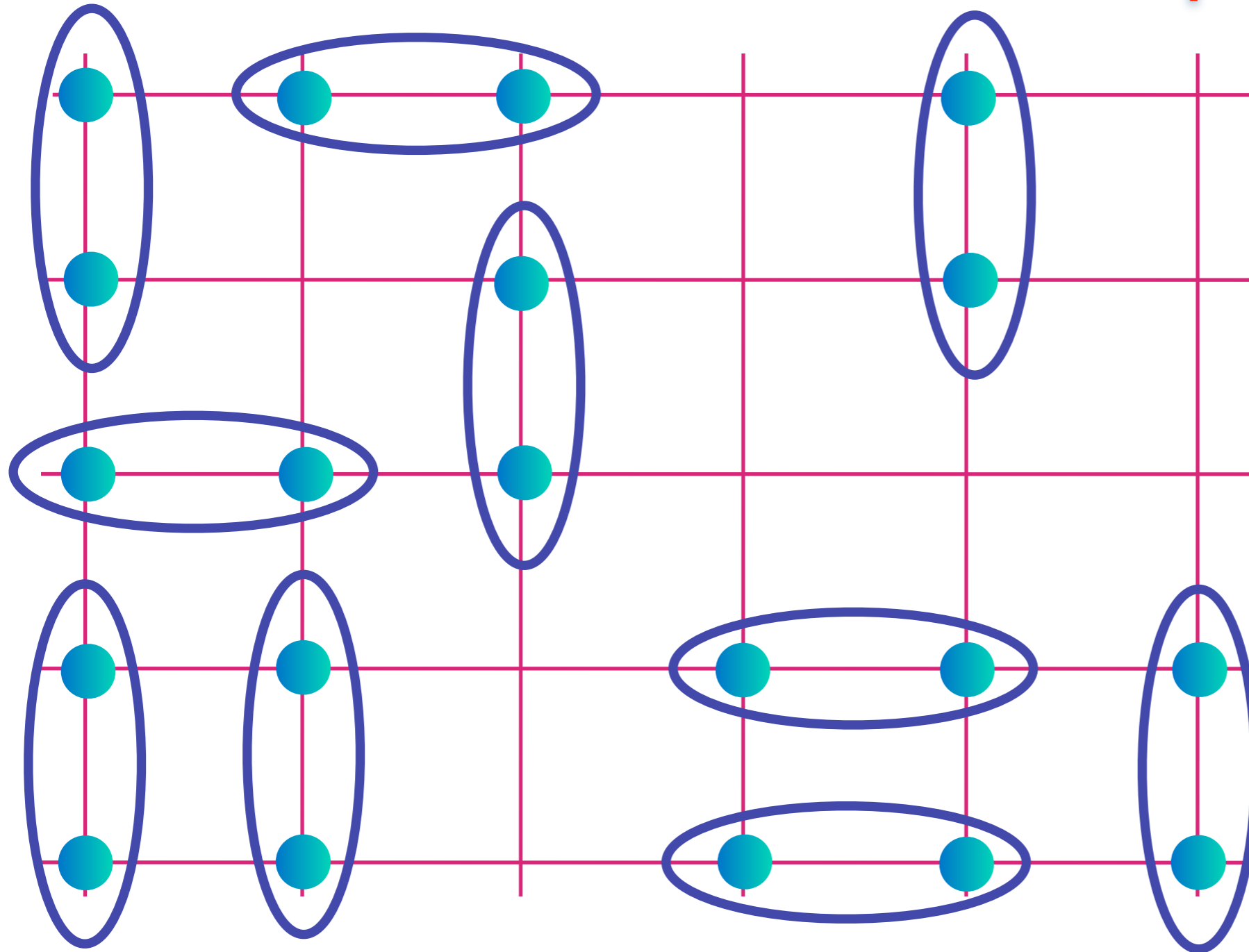


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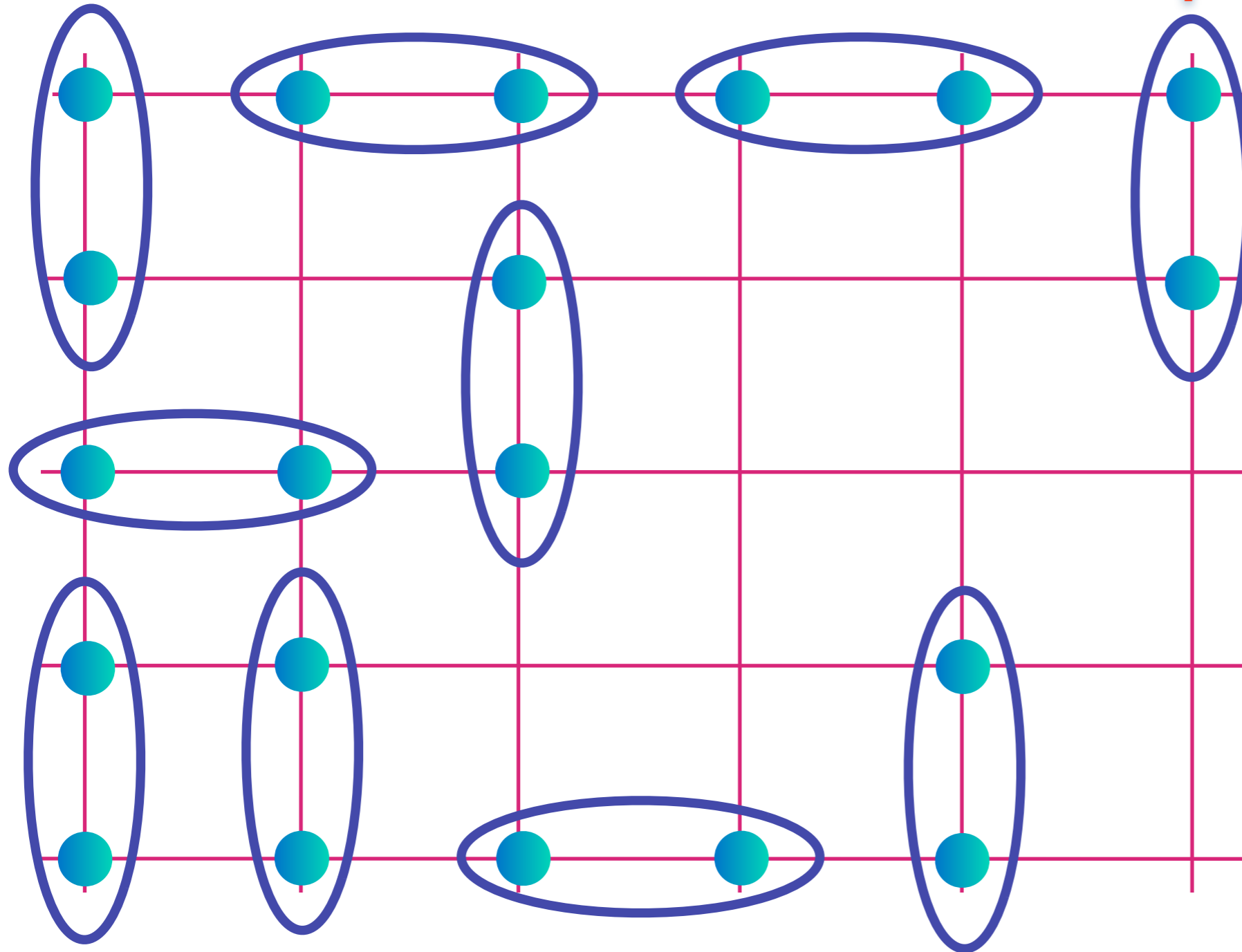


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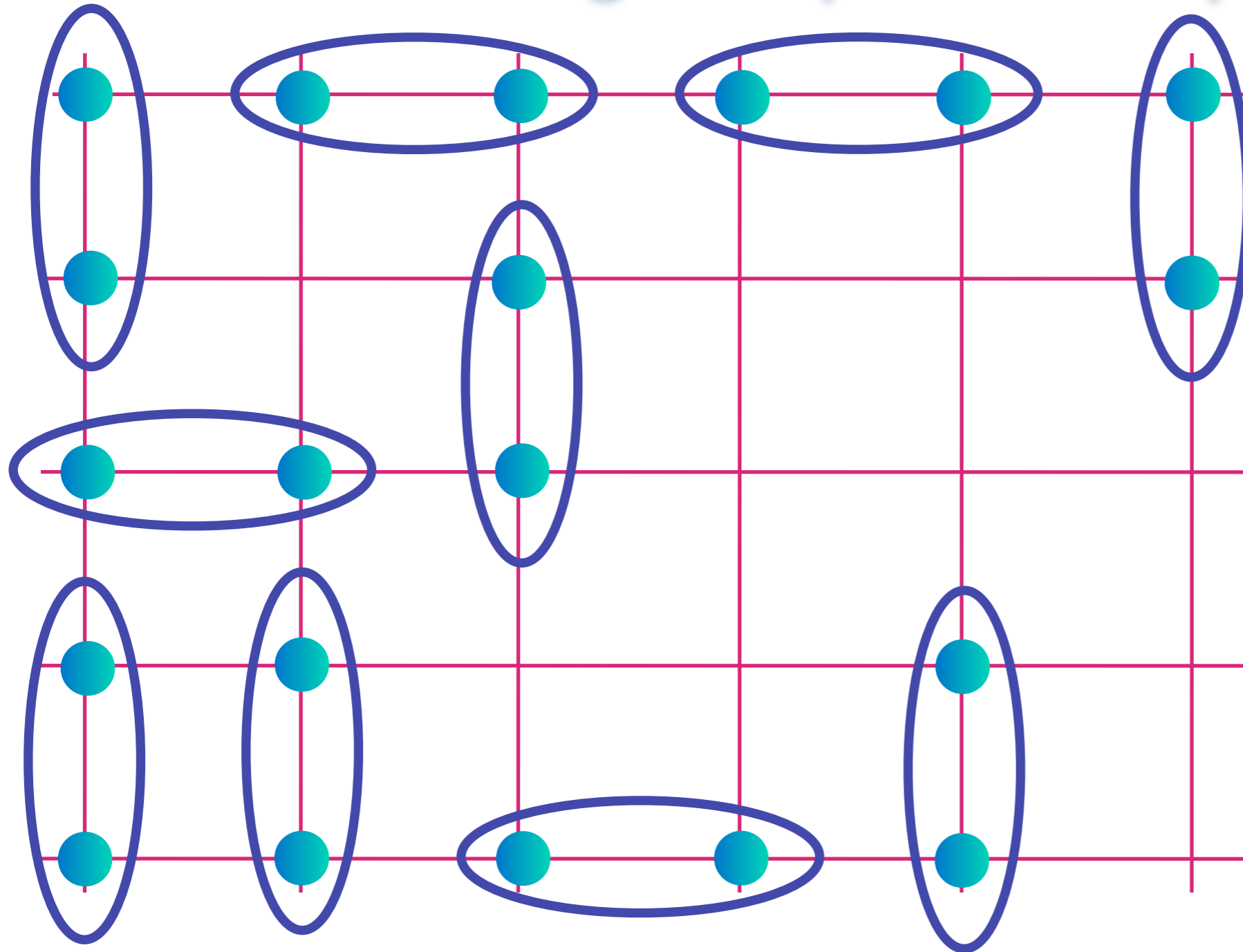


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Square lattice of Cu sites

High temperature superconductivity !

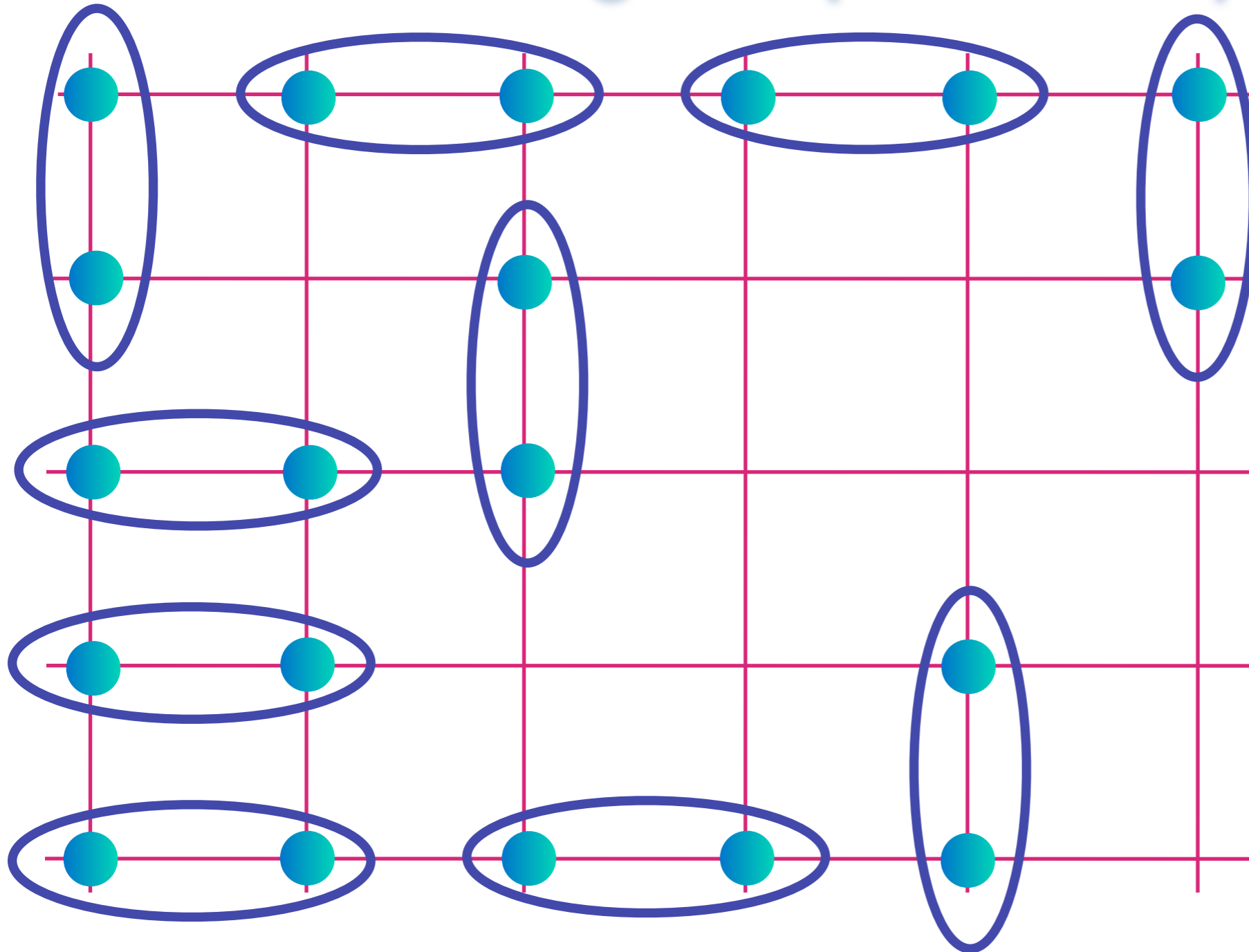


Electrons entangle by exchanging partners, and there is long-range quantum entanglement in the strange metal.

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

Square lattice of Cu sites

High temperature superconductivity !

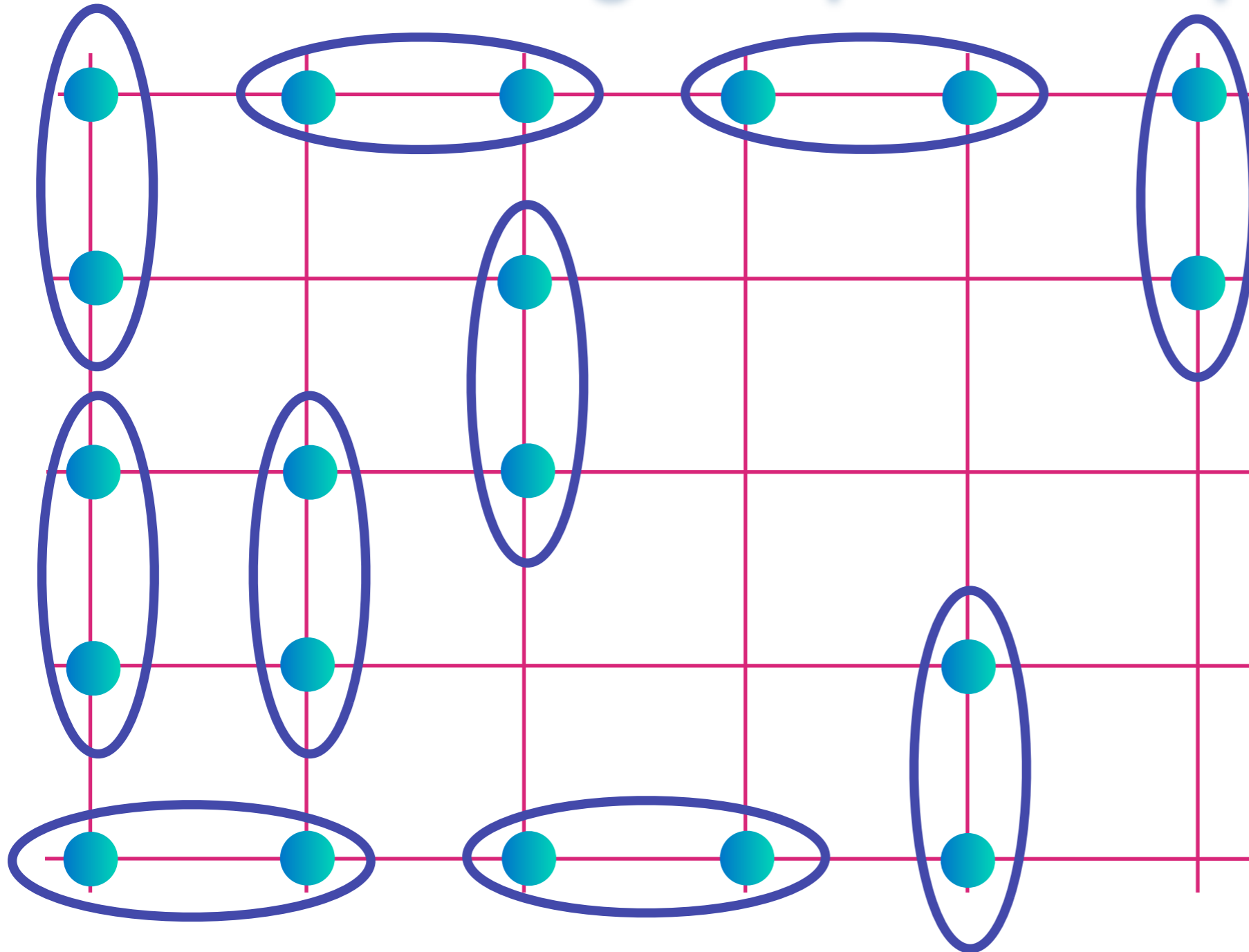


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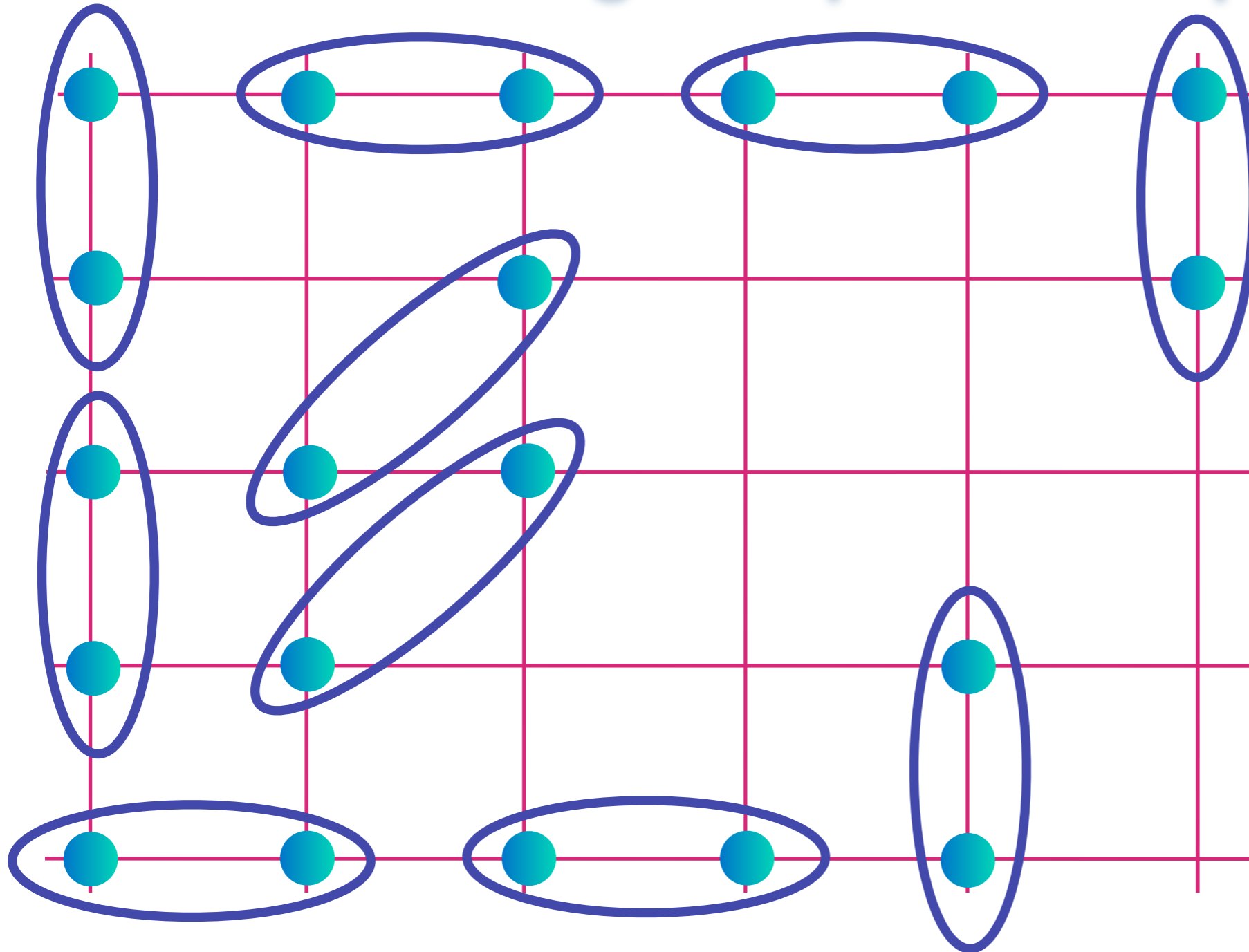


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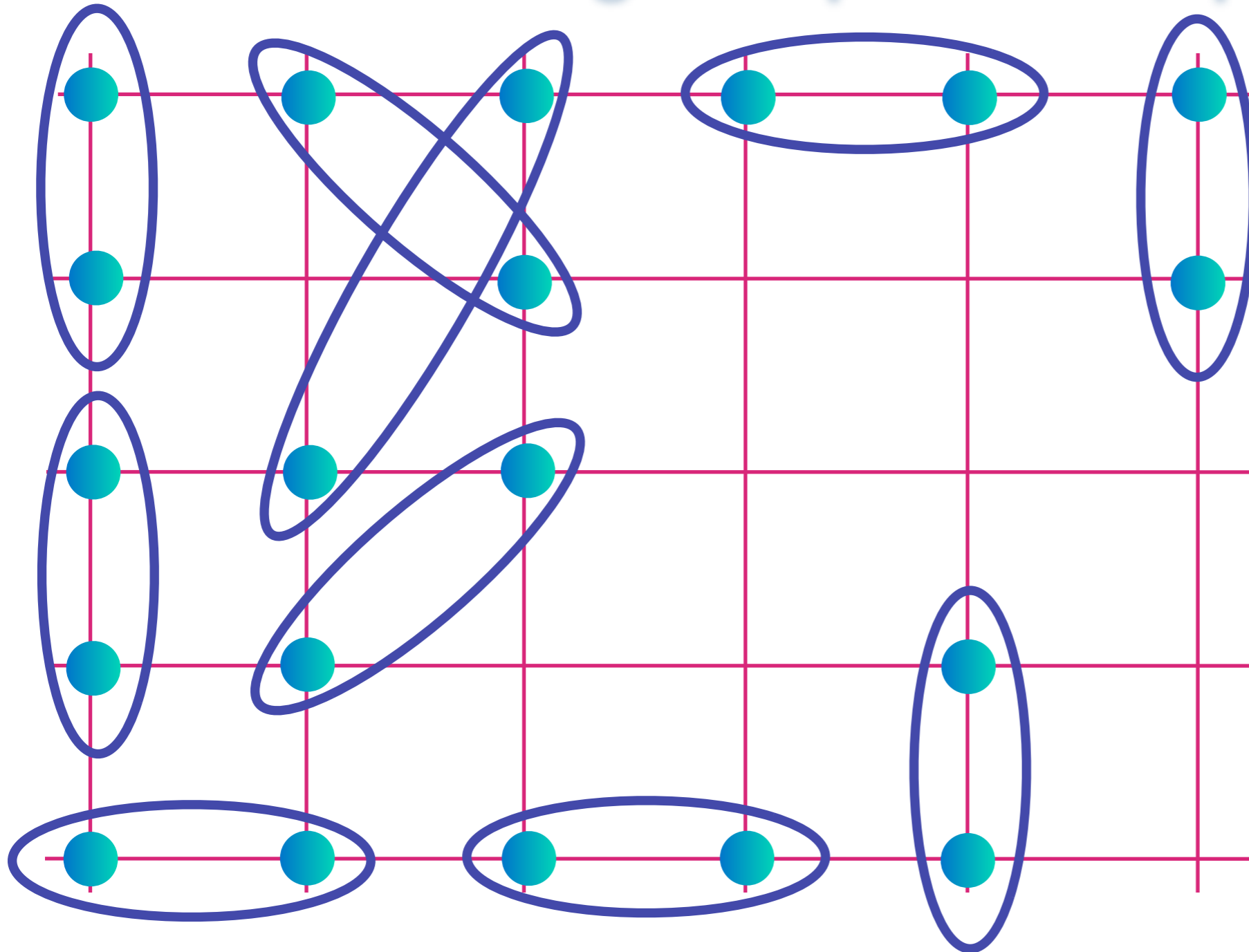


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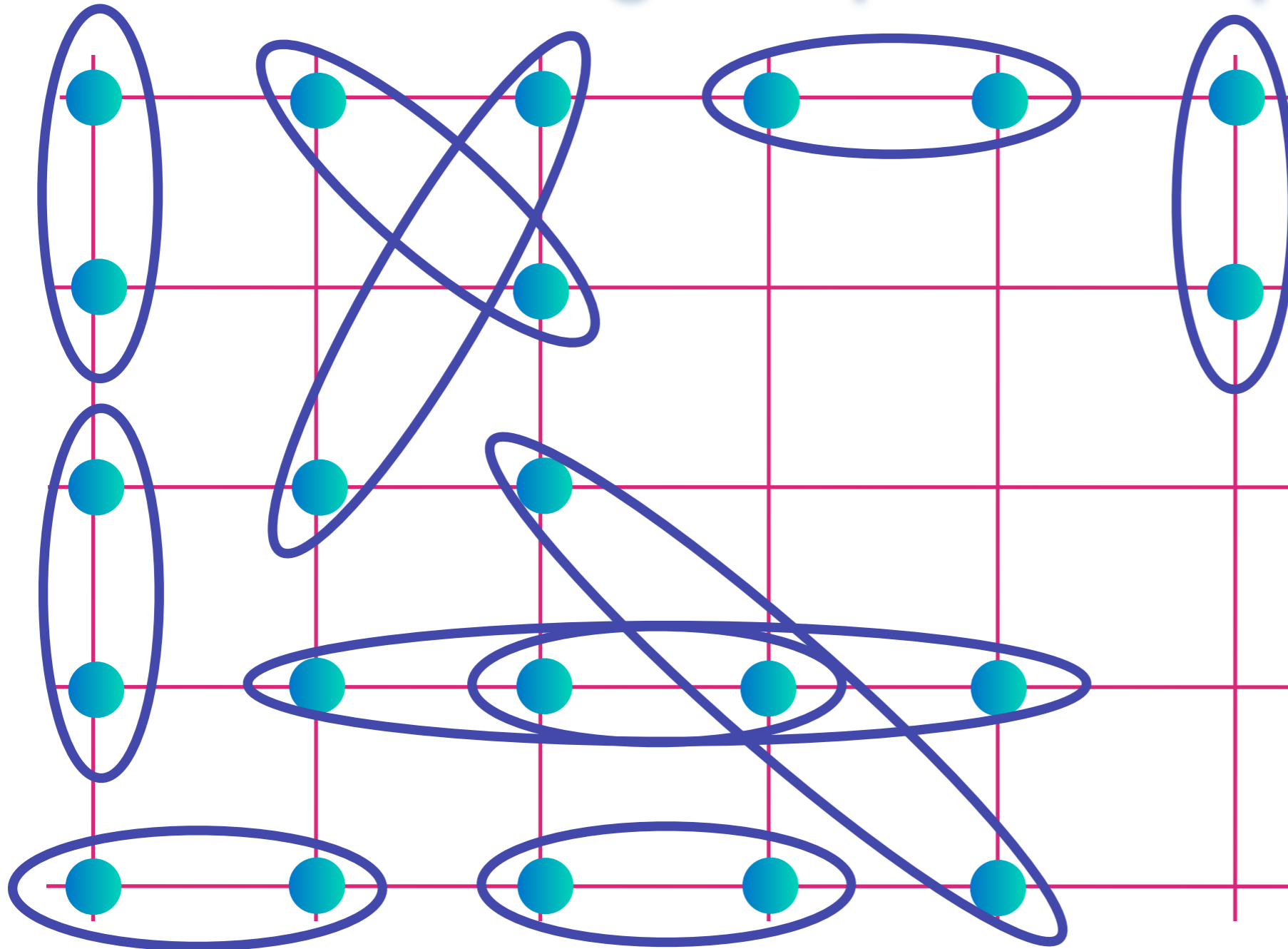


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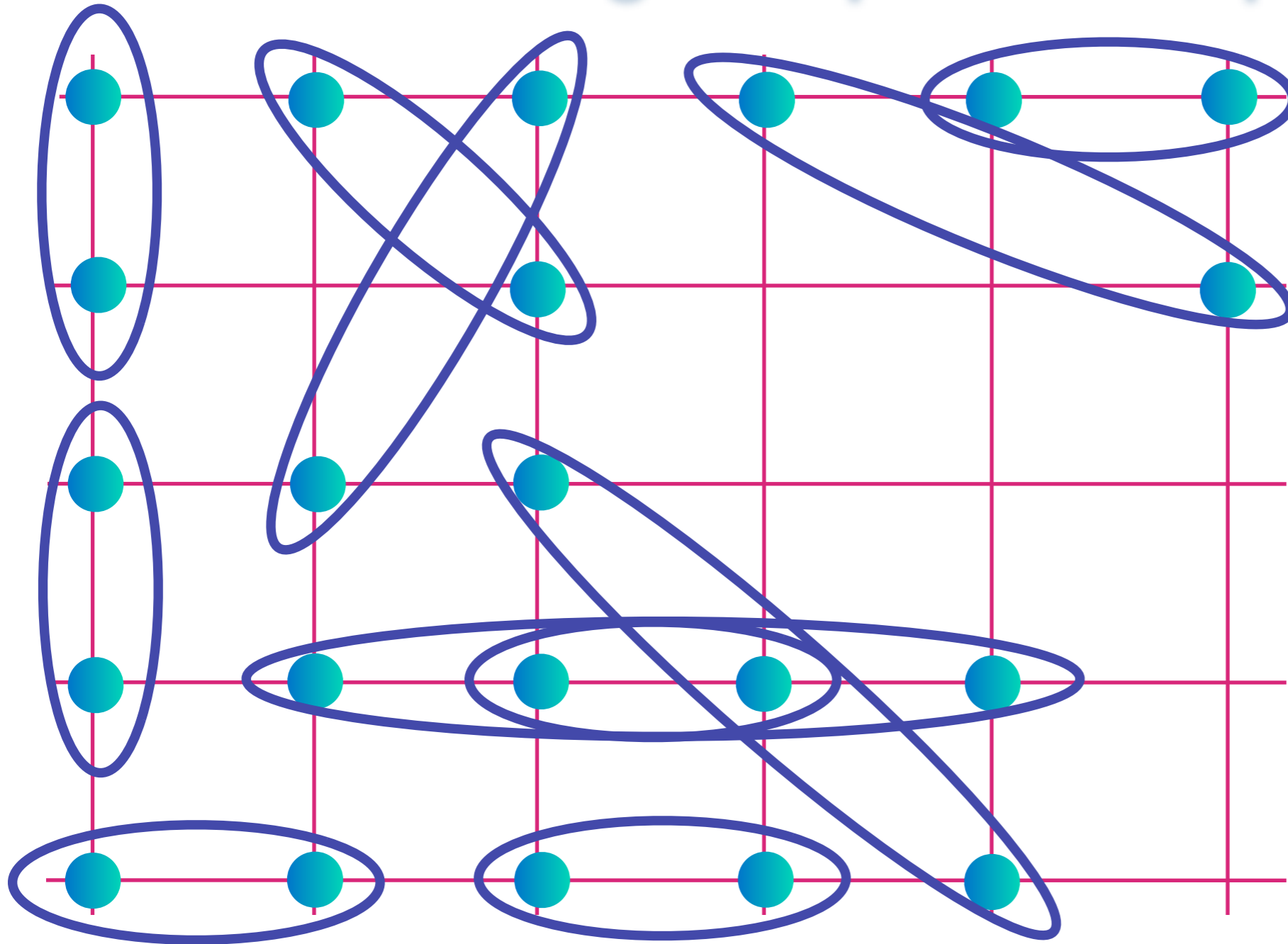


Electrons entangle by exchanging partners, and there is long-range quantum entanglement in the strange metal.

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Square lattice of Cu sites

High temperature superconductivity !



Electrons entangle by exchanging partners, and there is long-range quantum entanglement in the strange metal.

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

Strange metal

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

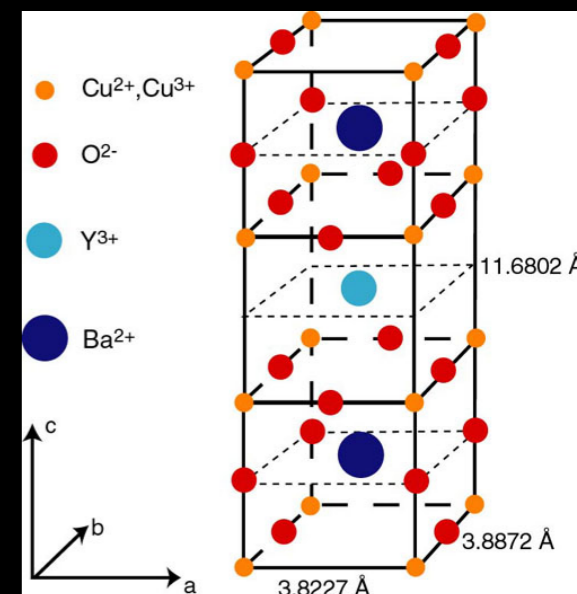
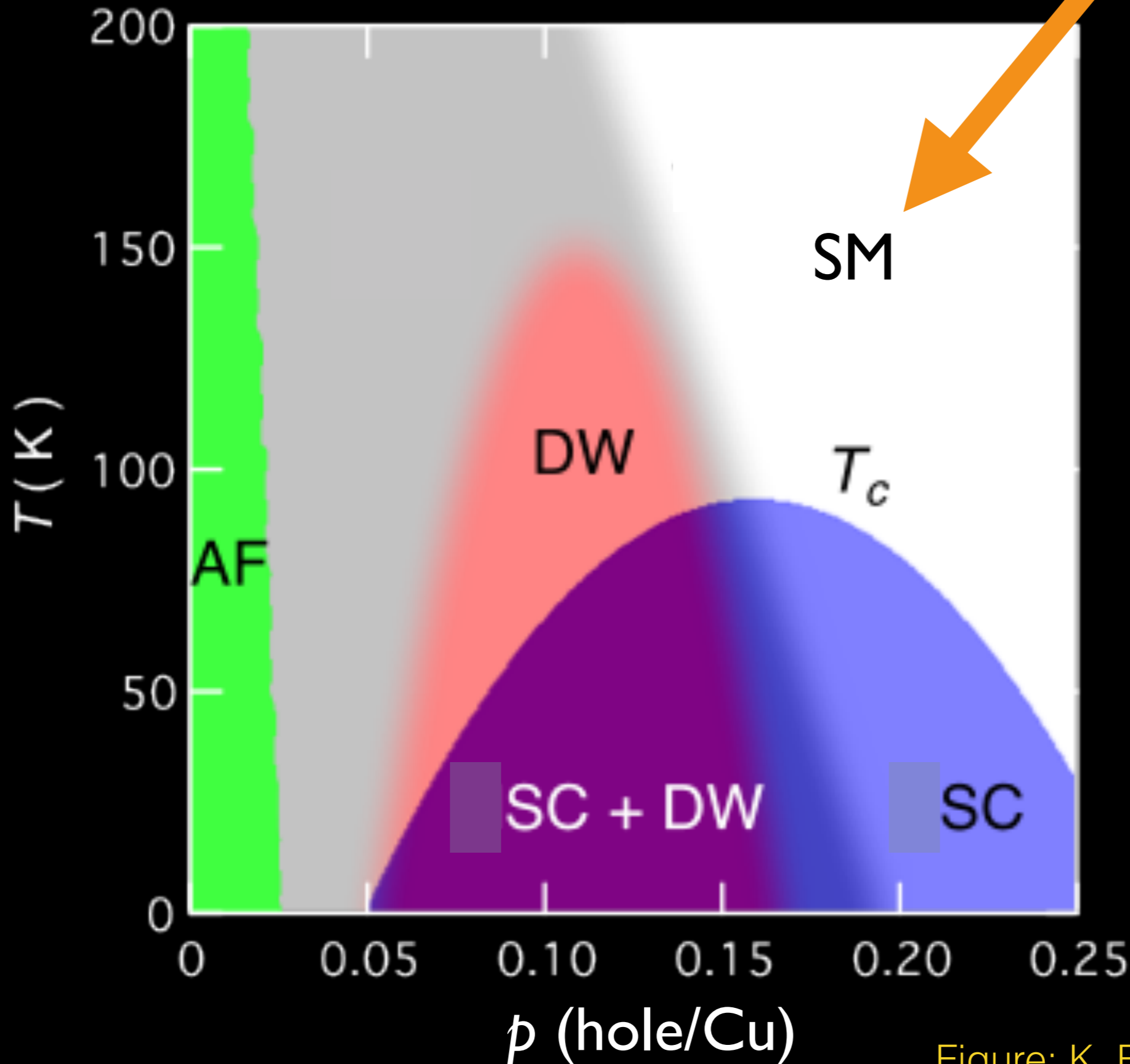


Figure: K. Fujita and J. C. Seamus Davis

**Quantum
entanglement**

**Black
holes**

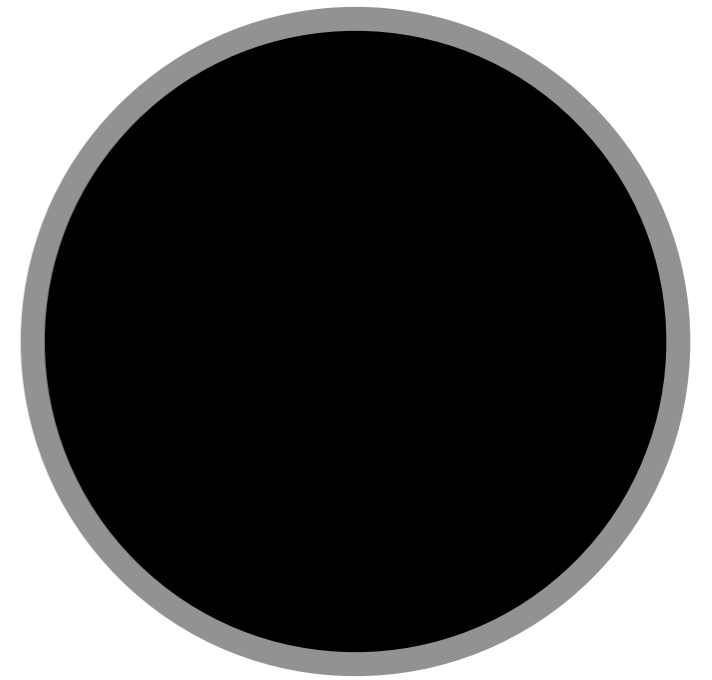
**Strange
metals**

Black Holes

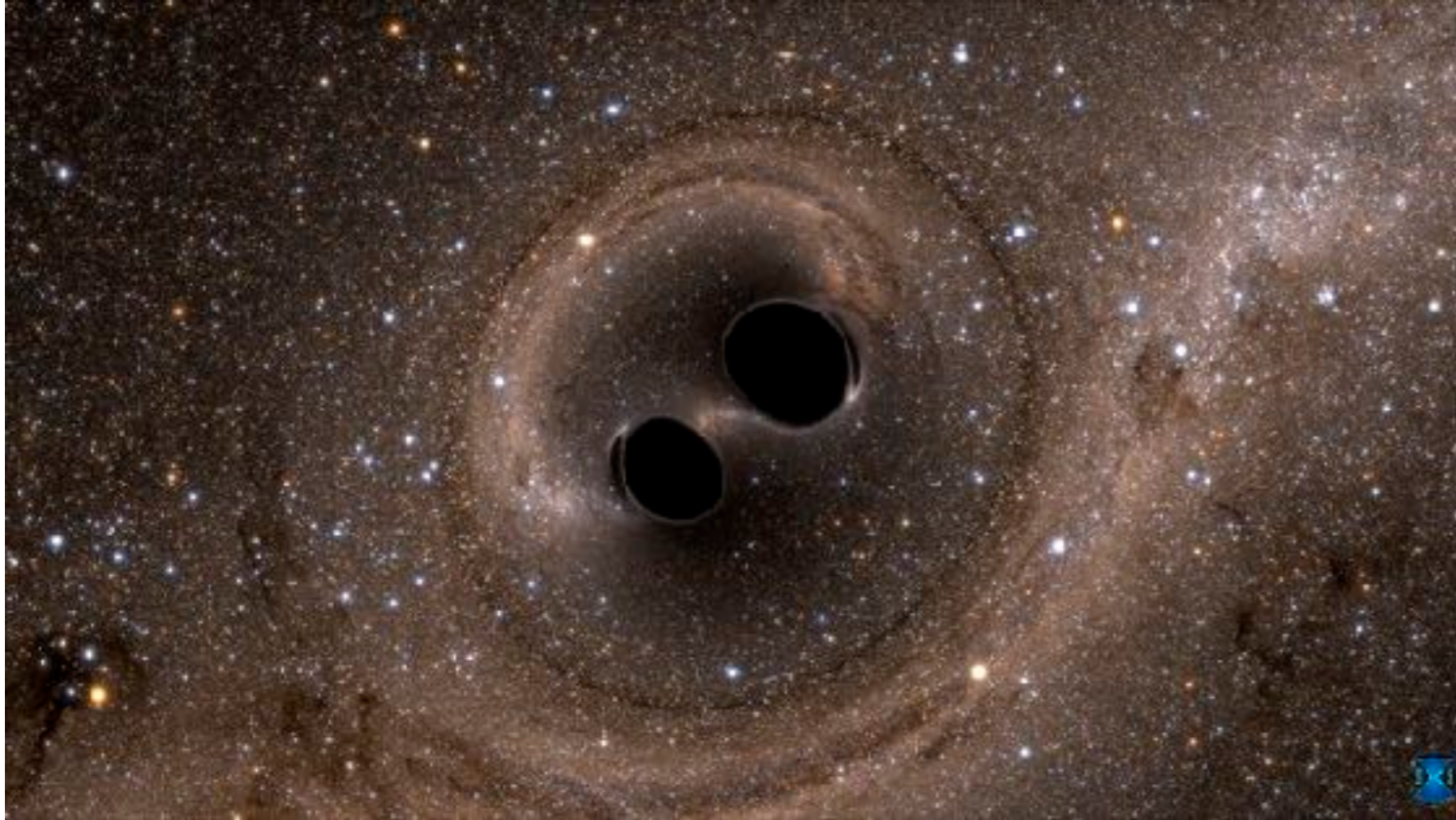
Objects so dense that light is gravitationally bound to them.

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

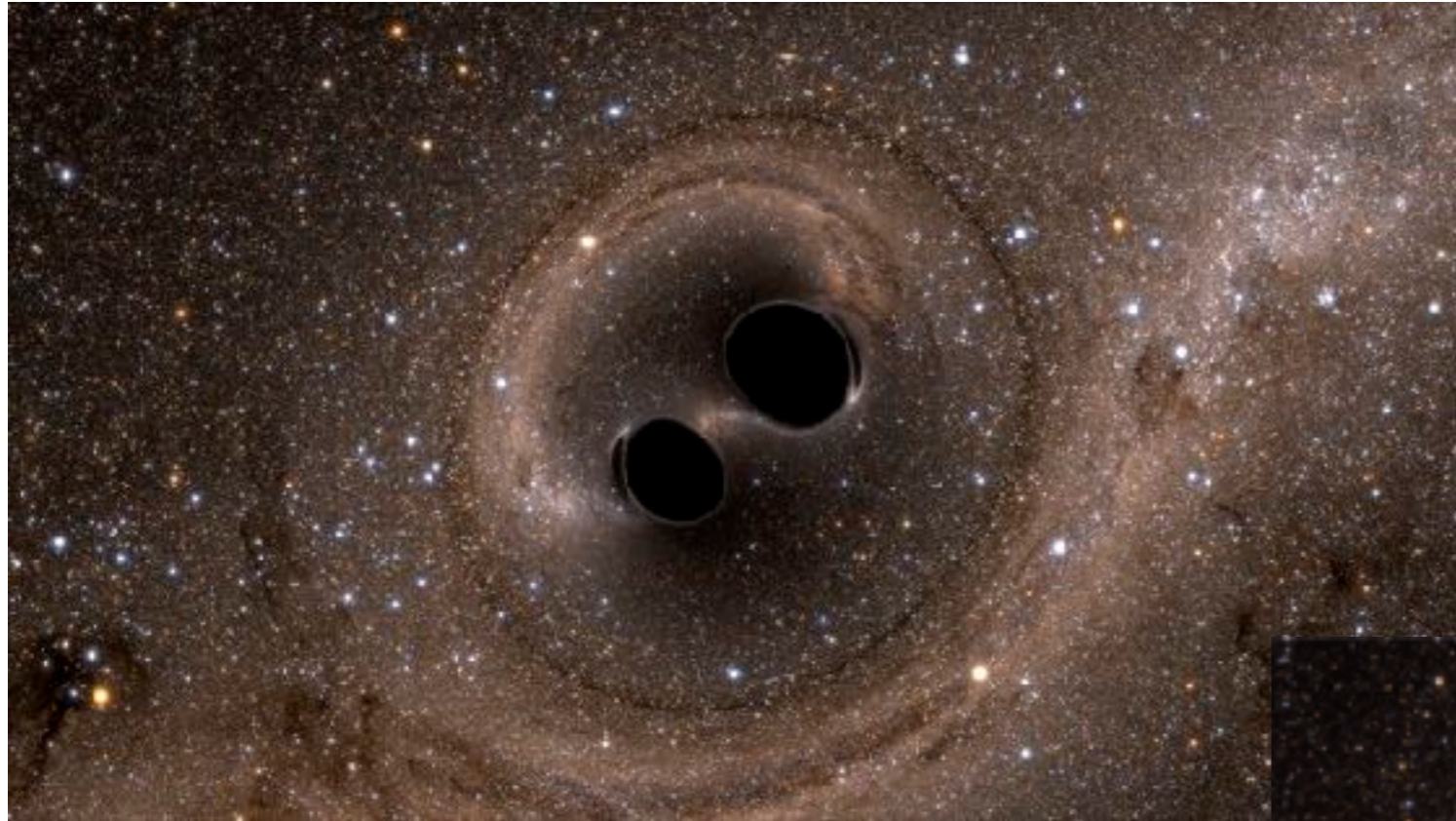
Horizon radius $R = \frac{2GM}{c^2}$



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

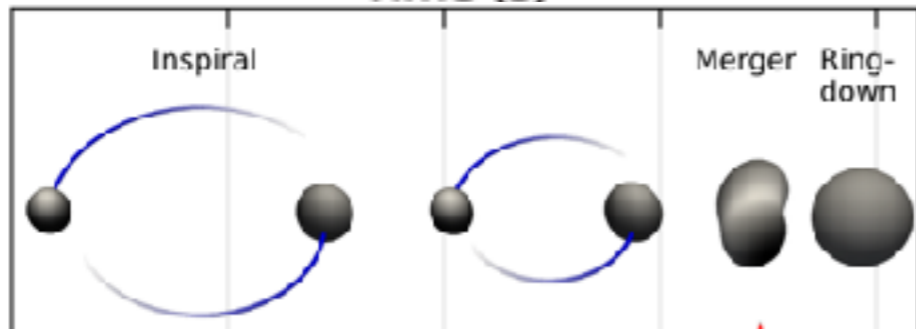
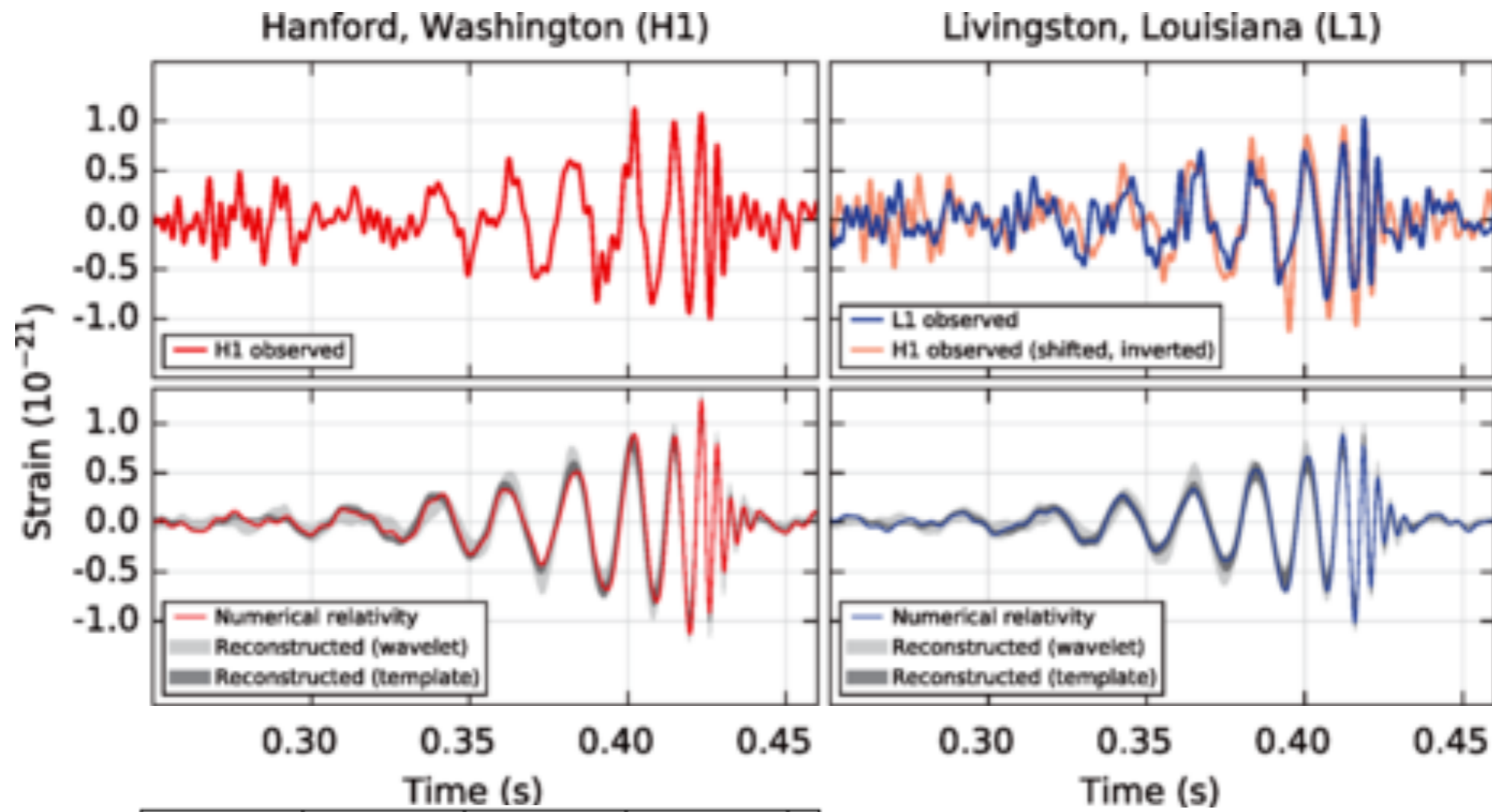


On September 14, 2015, LIGO detected the merger of two black holes, each weighing about 30 solar masses, with radii of about 100 km, 1.3 billion light years away



0.1 seconds later !



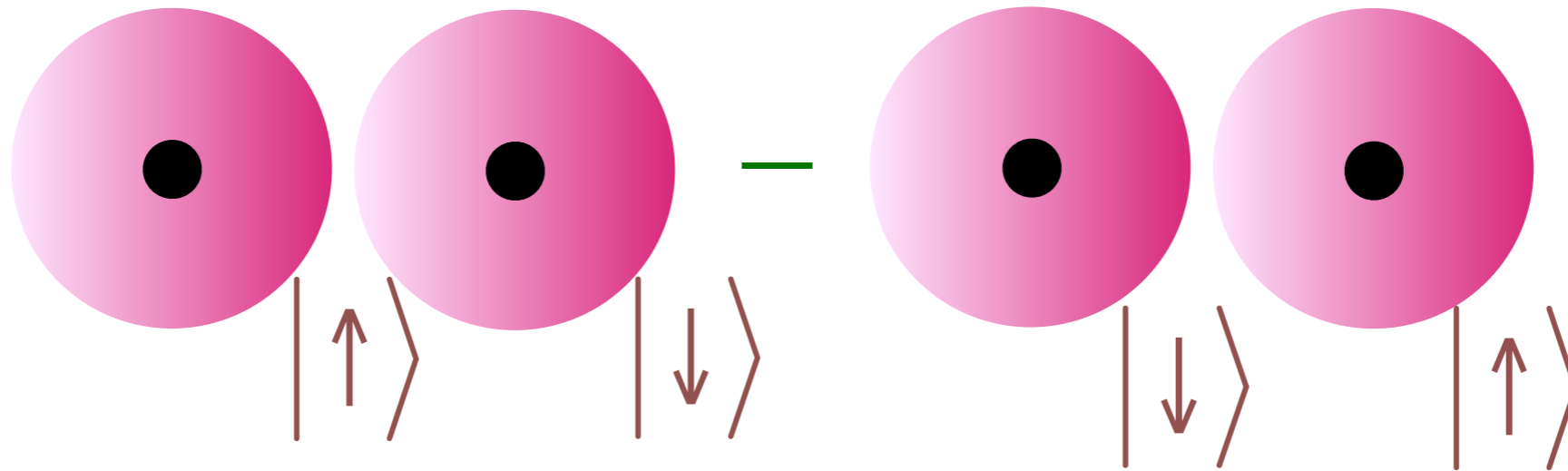


LIGO
September 14, 2015

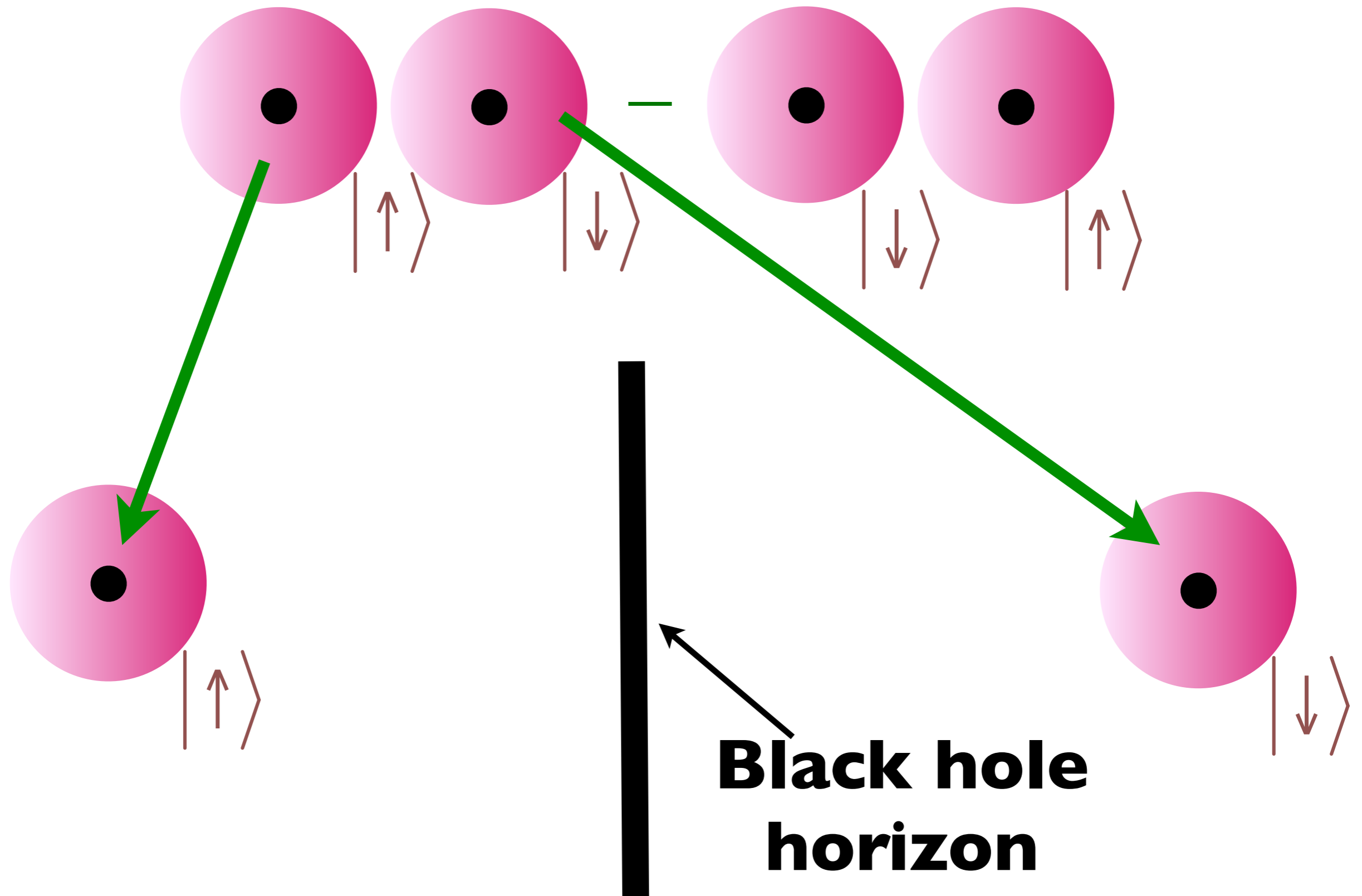
Black Holes + Quantum theory

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

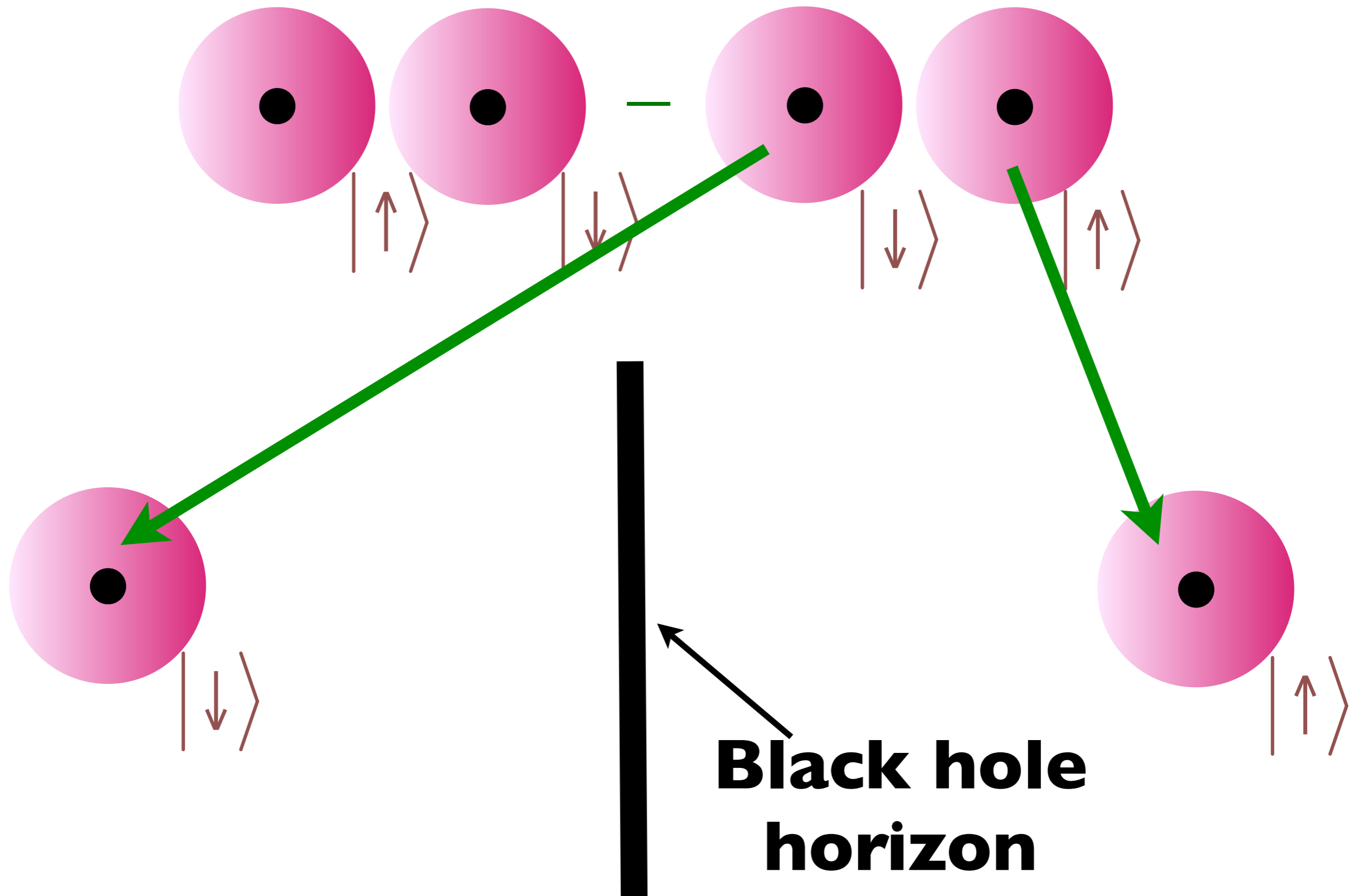
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

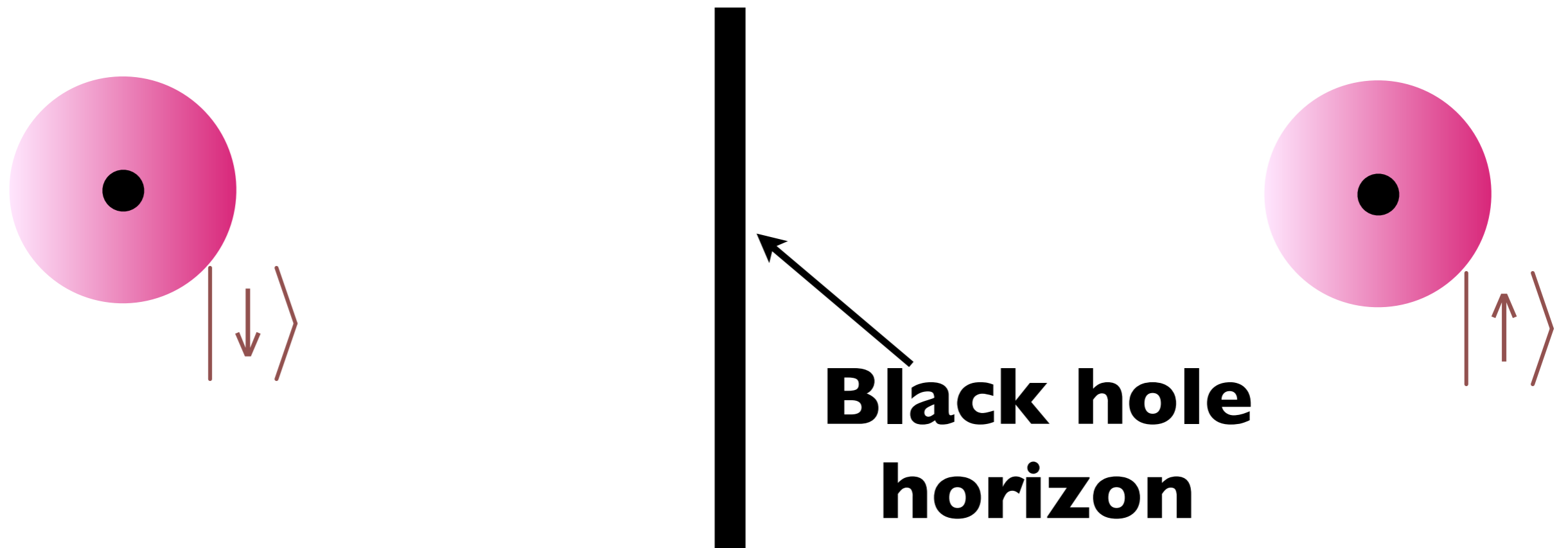


Quantum Entanglement across a black hole horizon



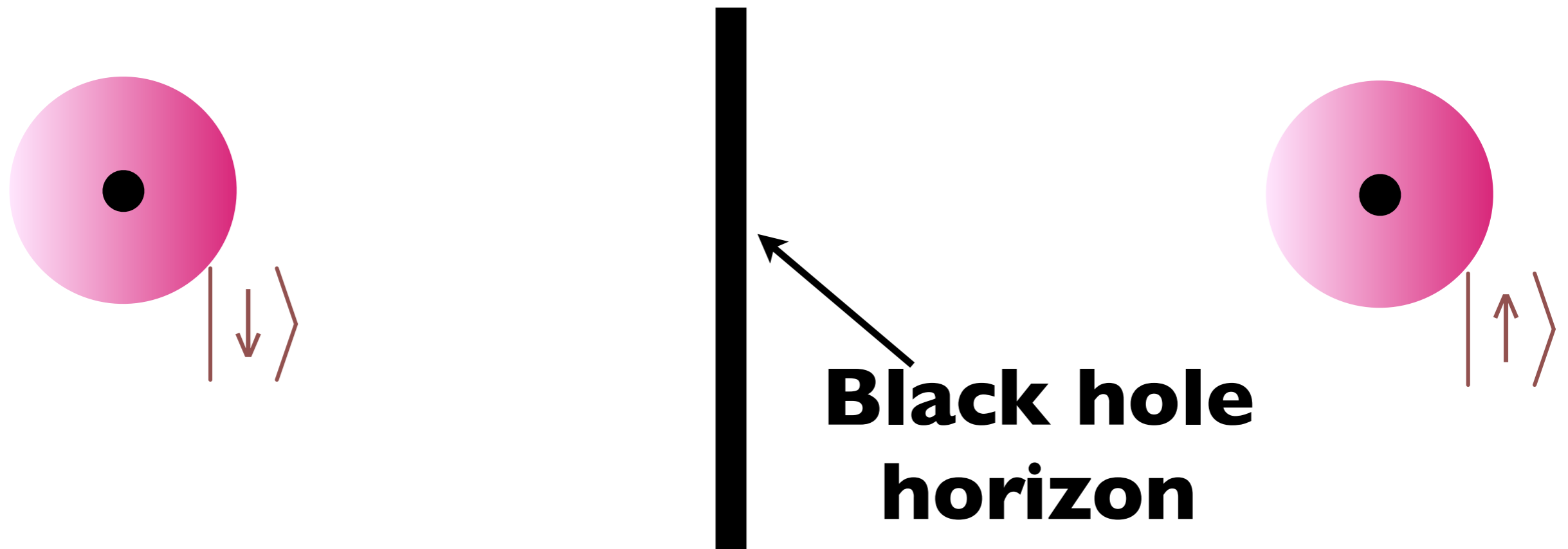
Quantum Entanglement across a black hole horizon

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



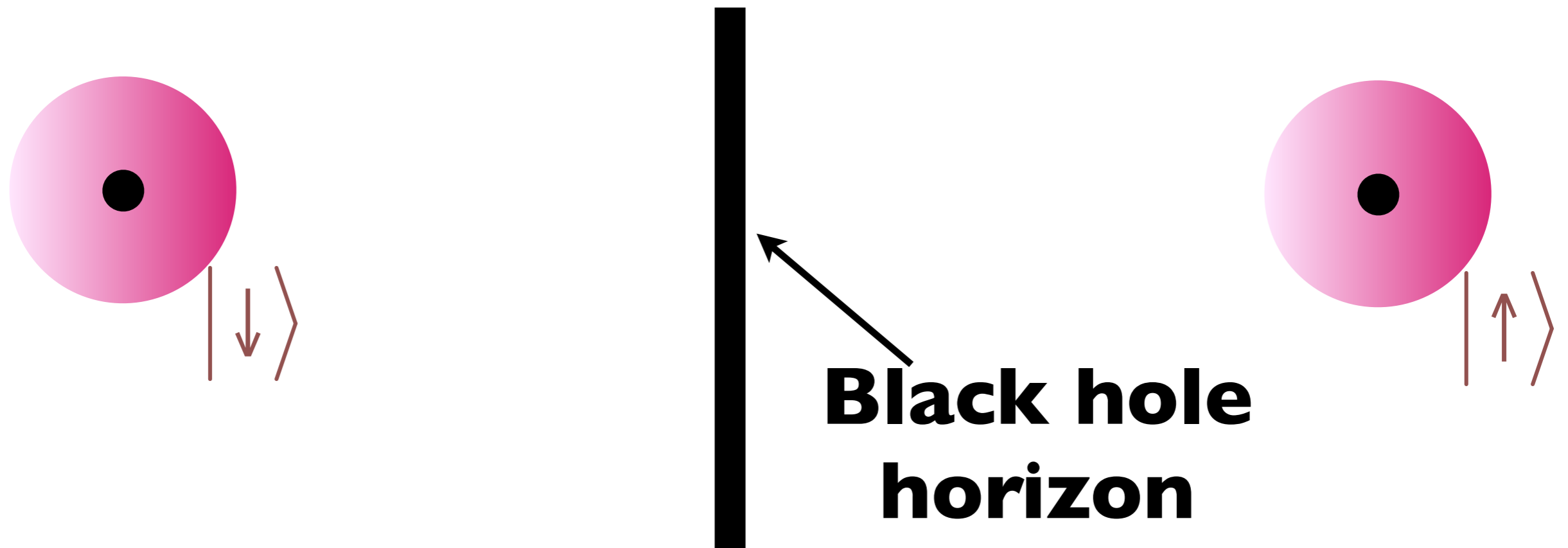
Quantum Entanglement across a black hole horizon

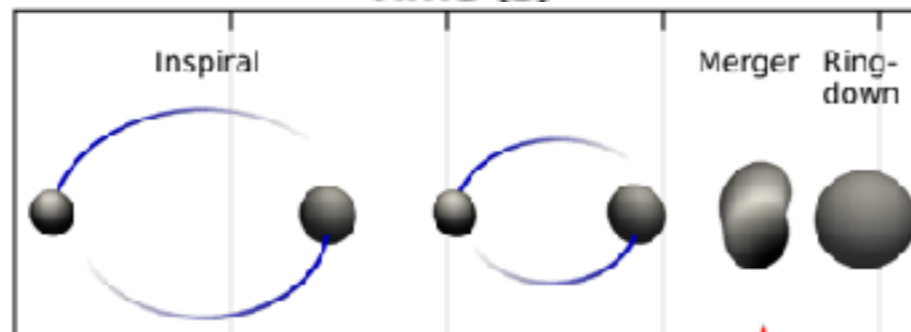
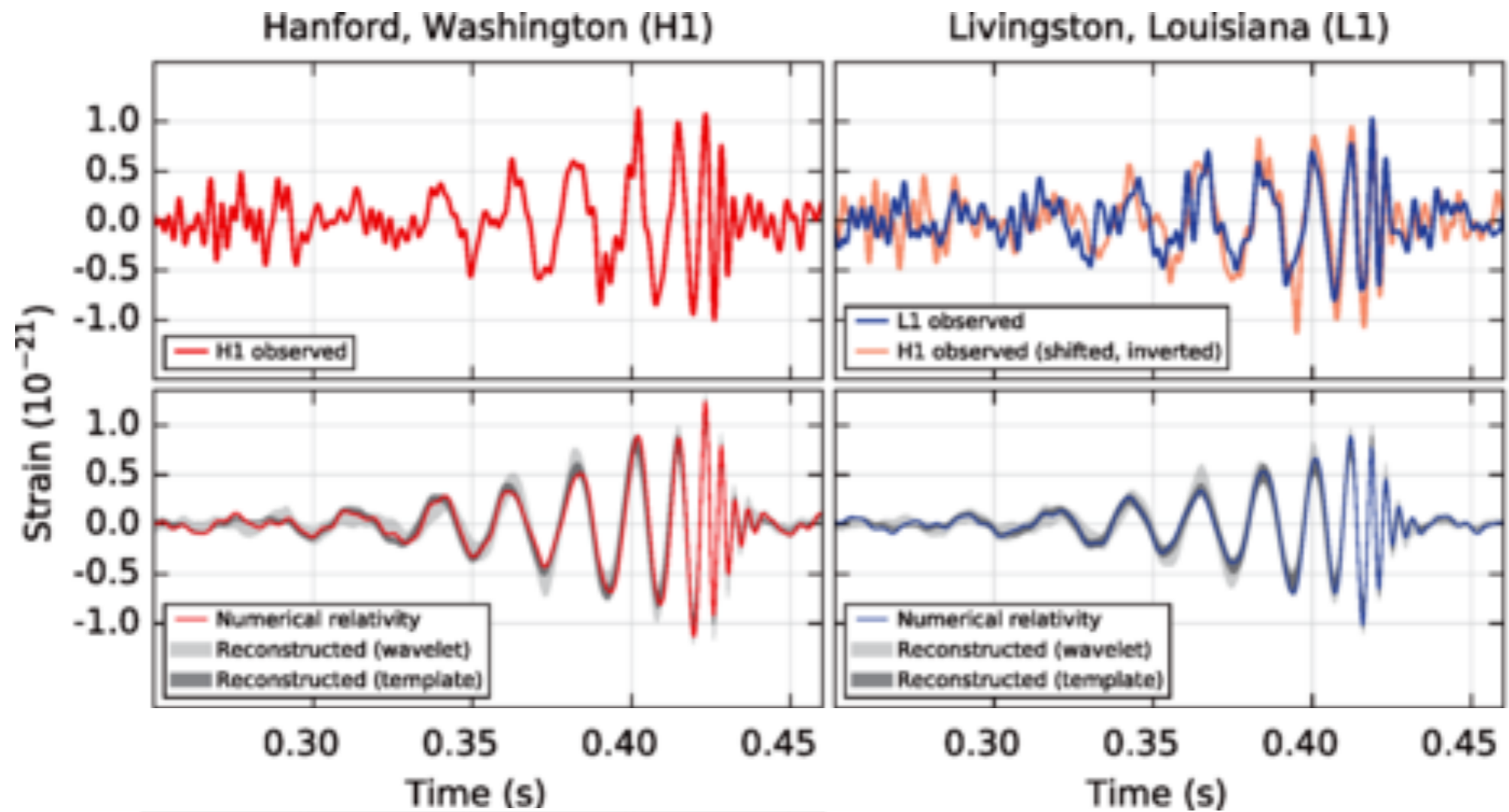
Hawking used this to show that black hole horizons have an entropy and a temperature



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)





LIGO
September 14, 2015

- The Hawking temperature influences the radiation from the black hole at the very last stages of the ring-down (not observed so far).

**Quantum
entanglement**

**Black
holes**

**Strange
metals**

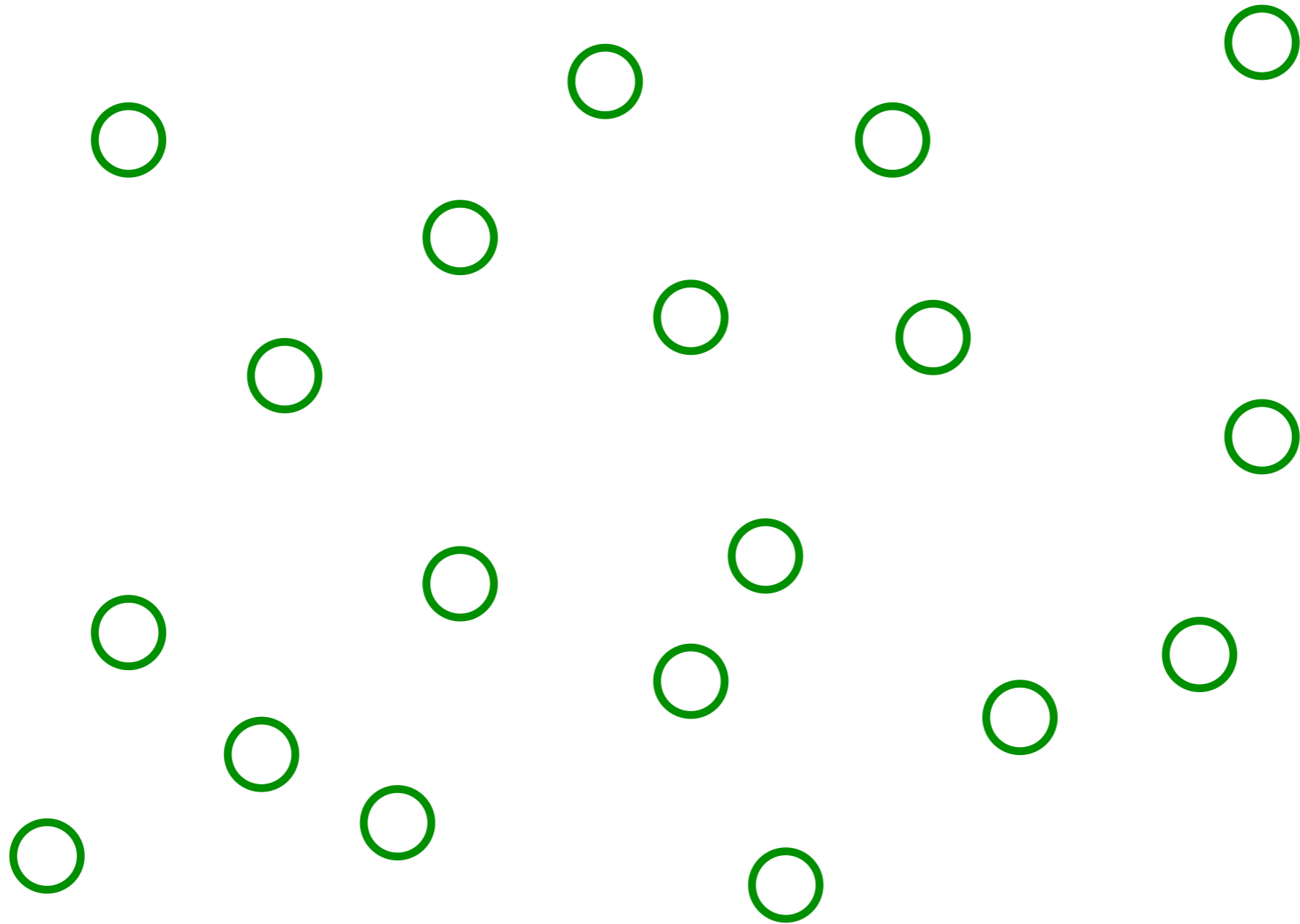
**Quantum
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**Strange
metals**

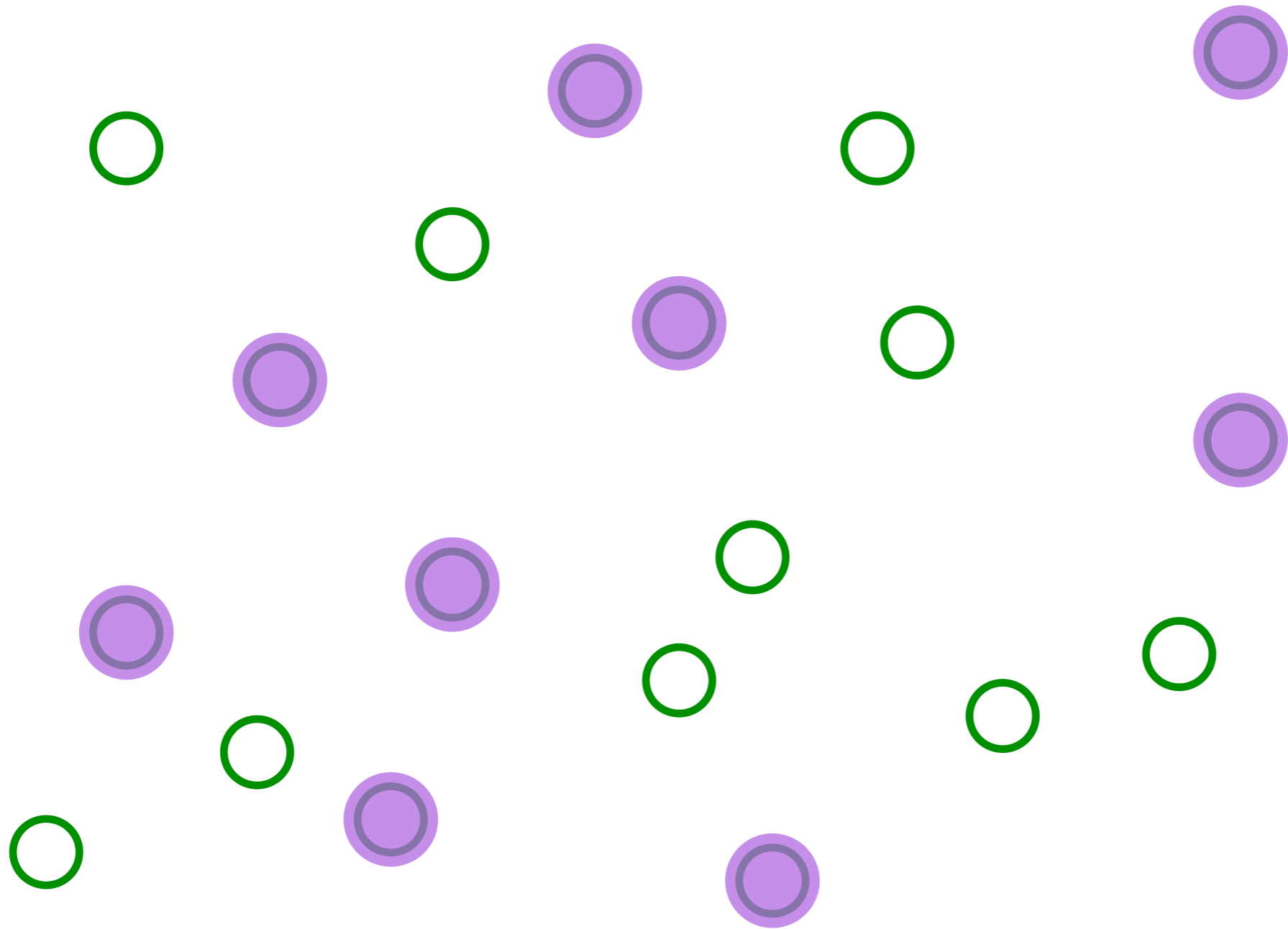
**A "toy model" which is both a
strange metal and a black hole!**

The Sachdev-Ye-Kitaev (SYK) model



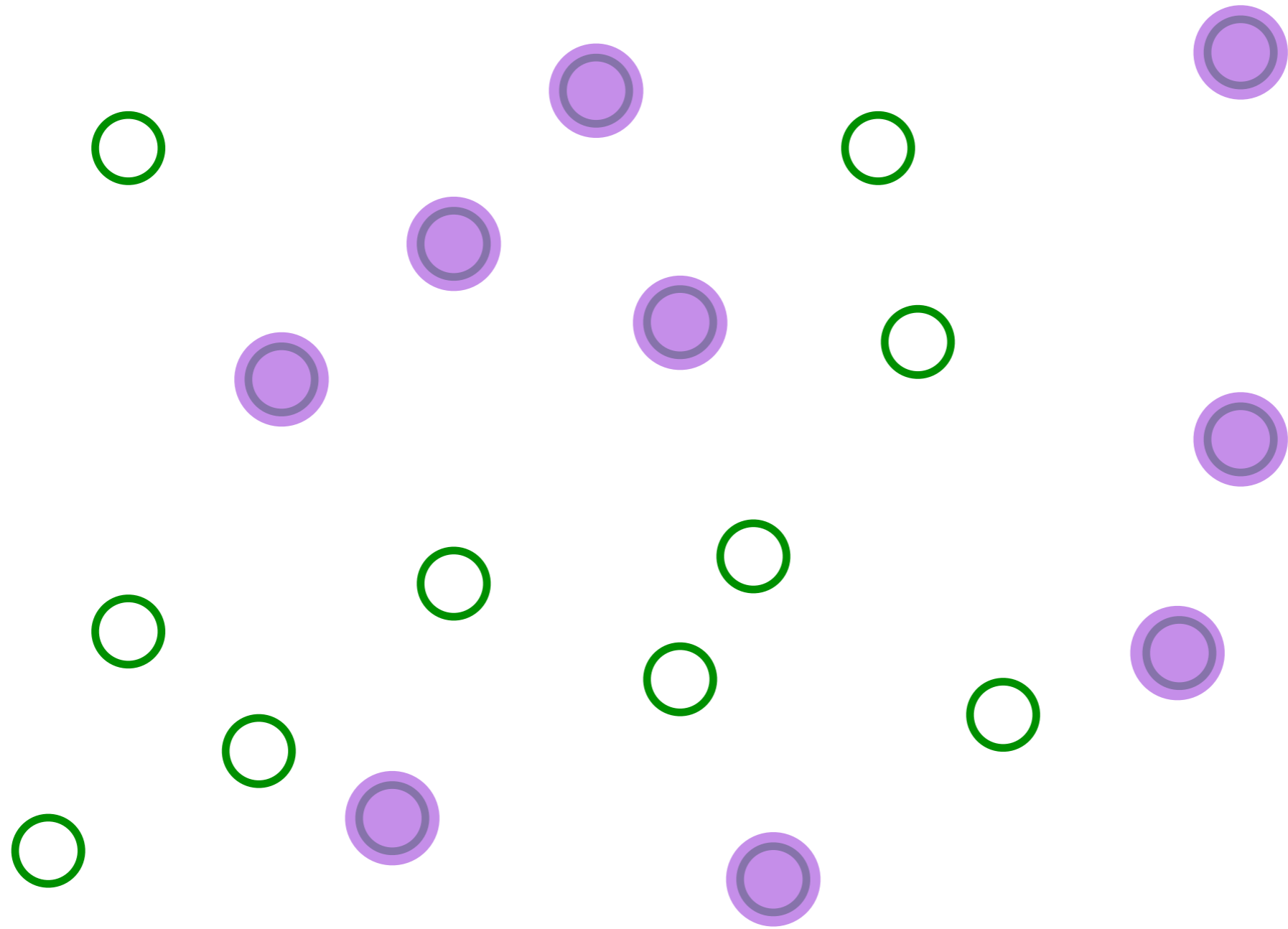
Pick a set of random positions

The Sachdev-Ye-Kitaev (SYK) model



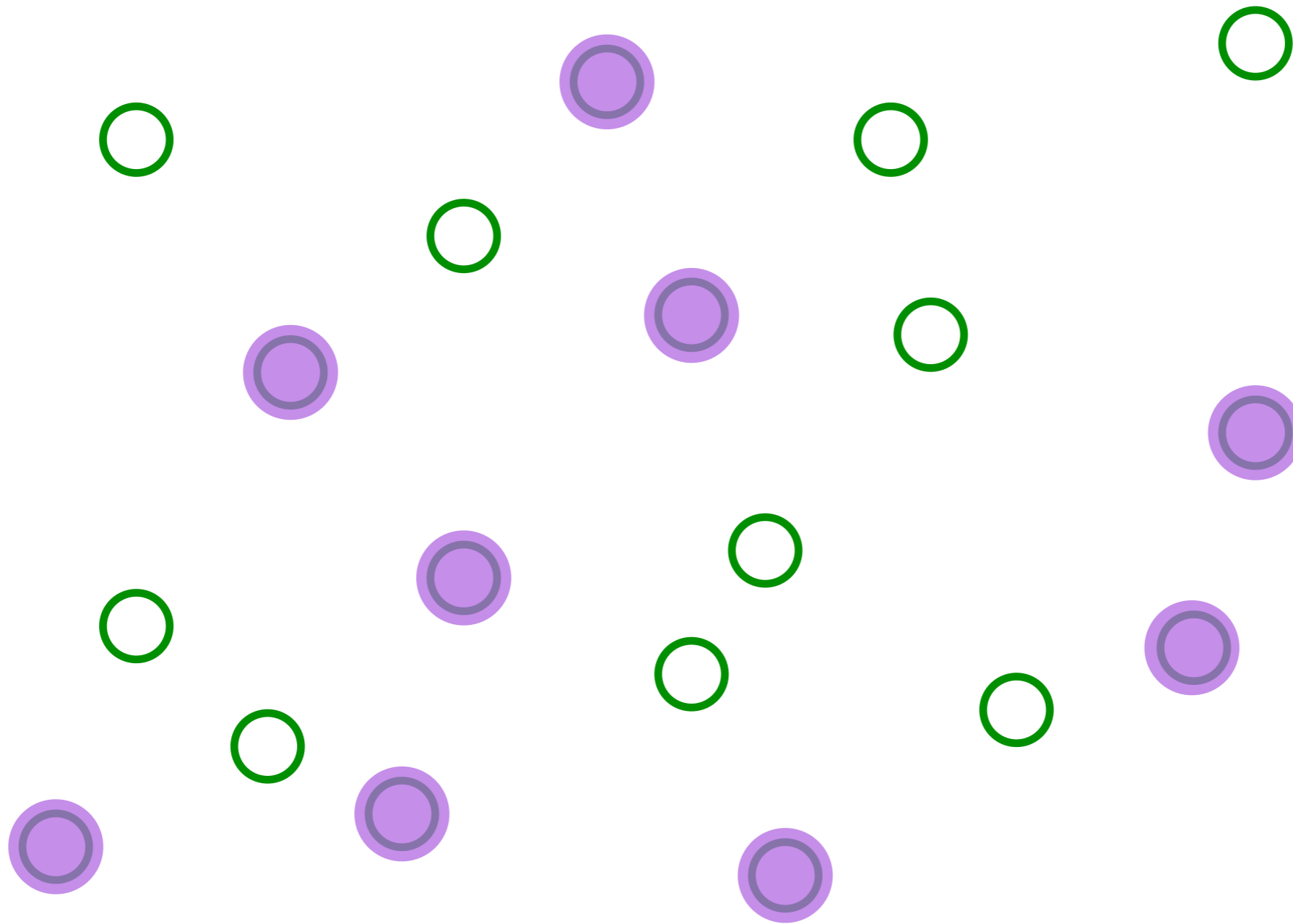
Place electrons randomly on some sites

The Sachdev-Ye-Kitaev (SYK) model



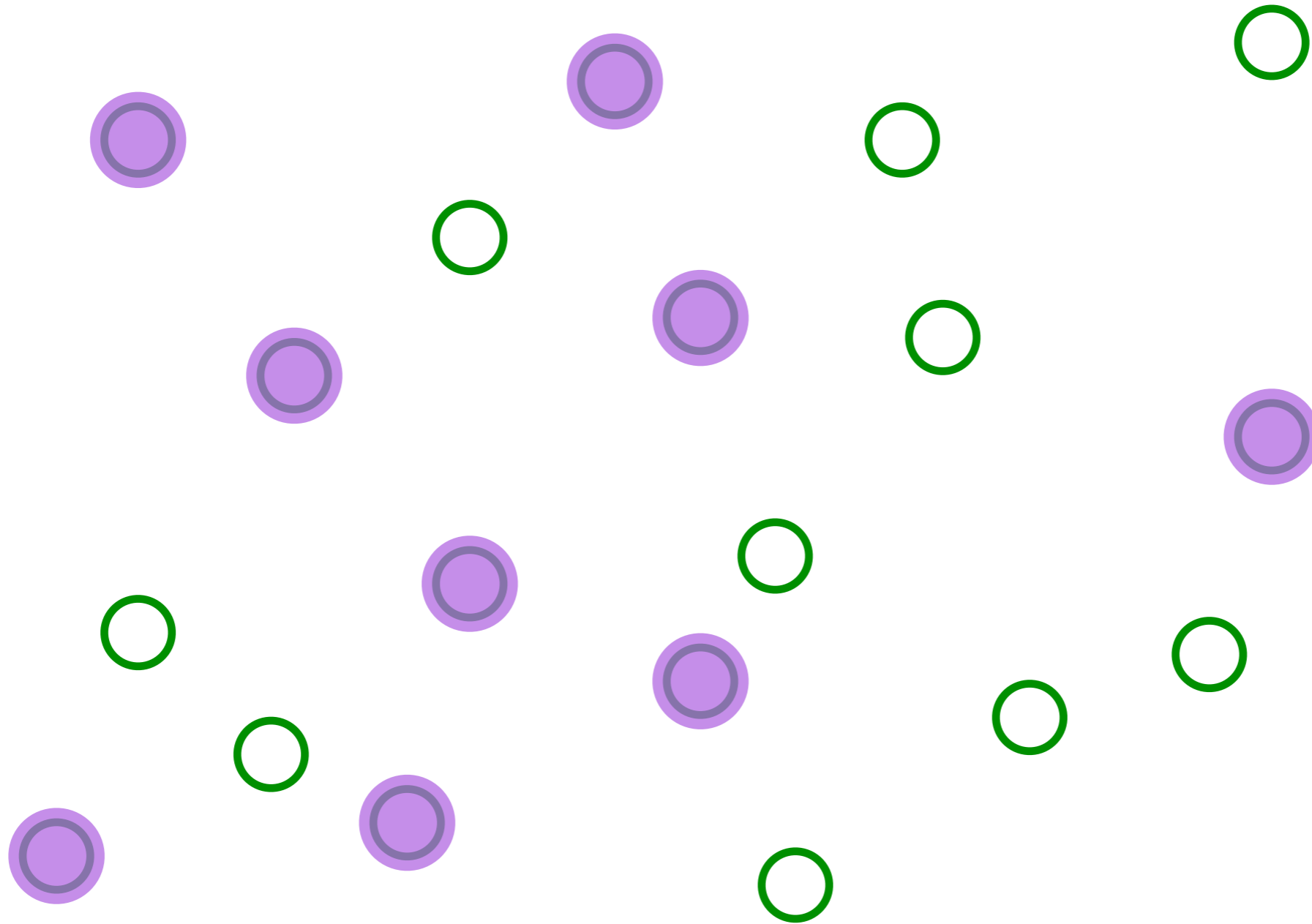
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



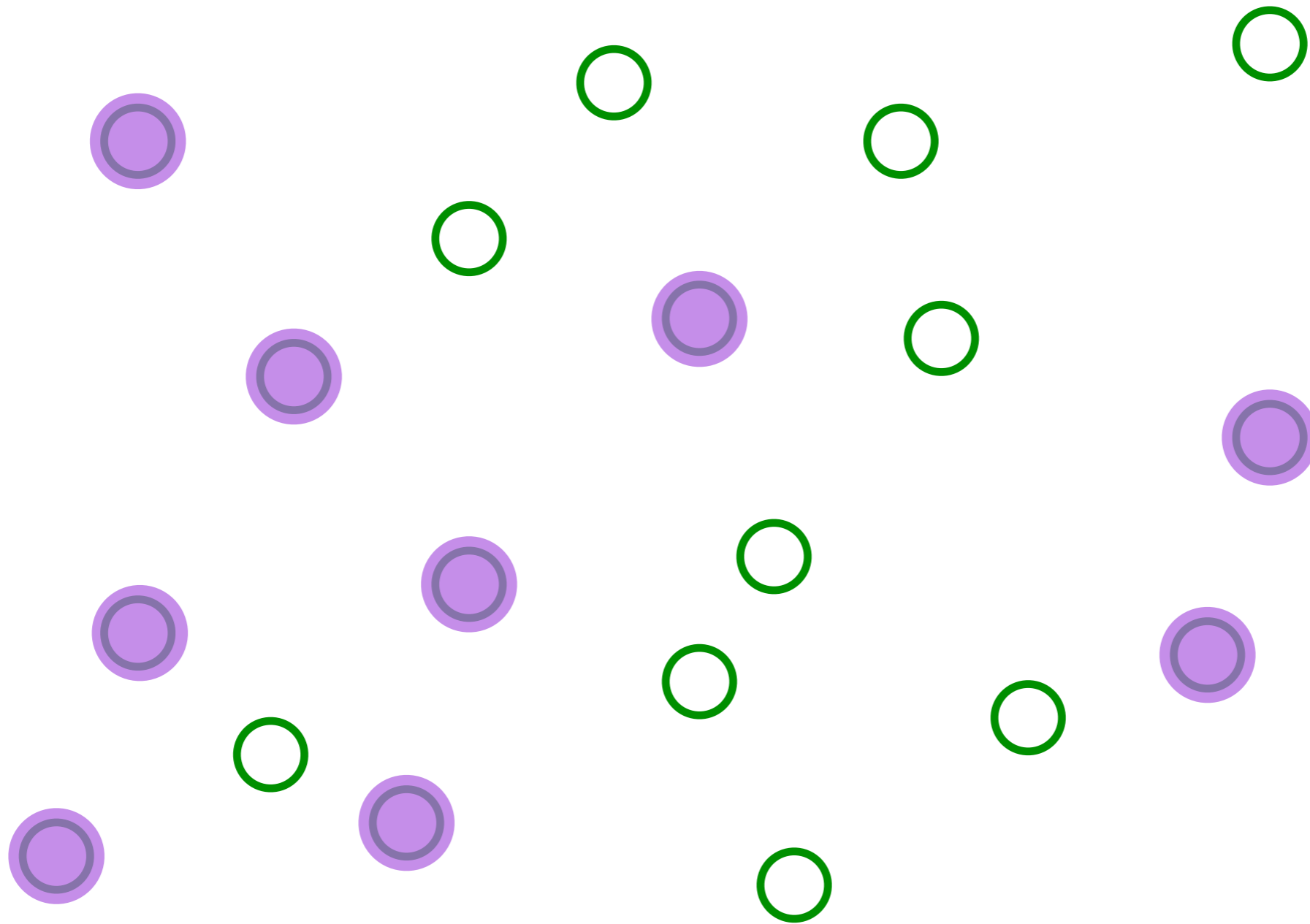
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



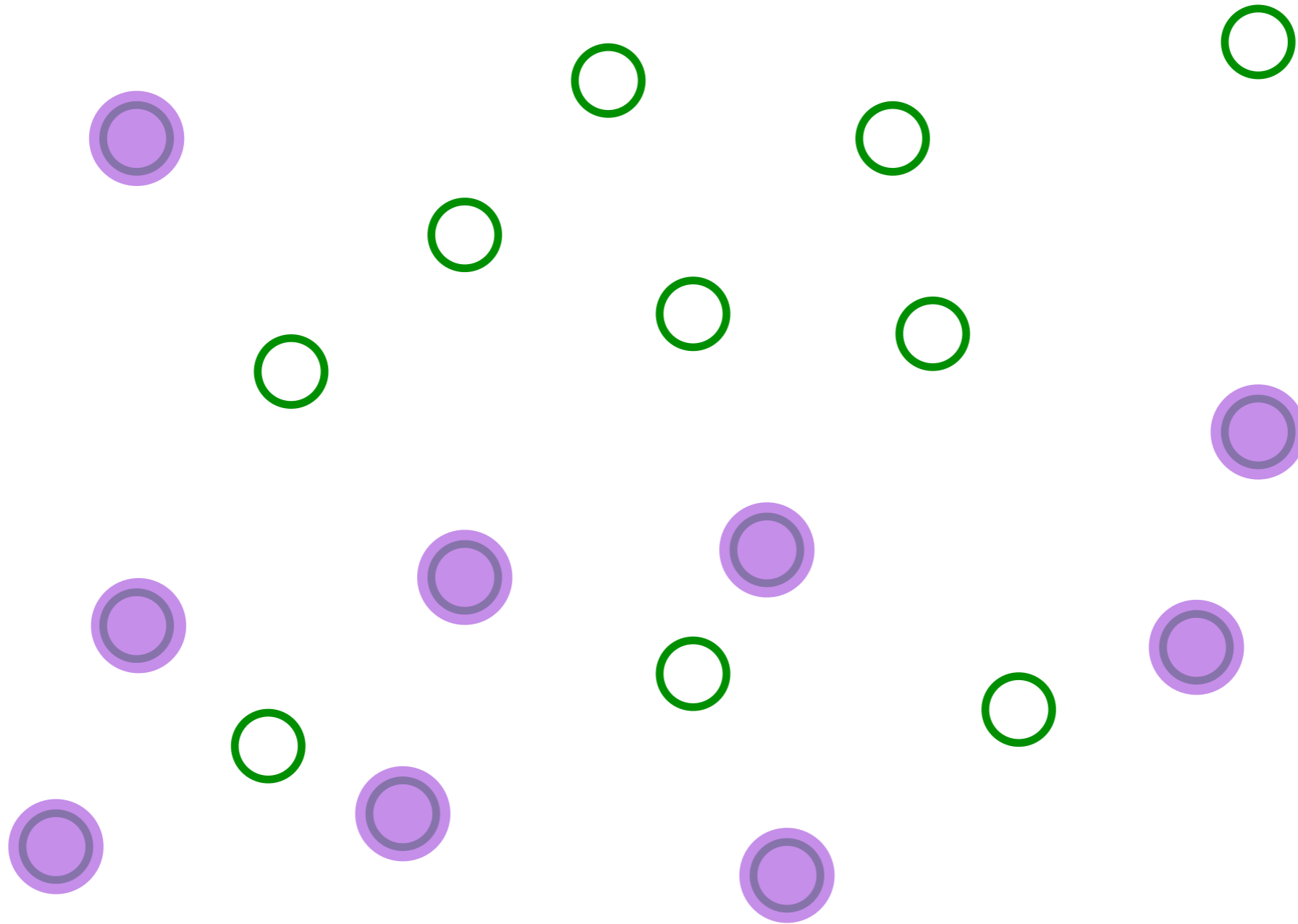
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



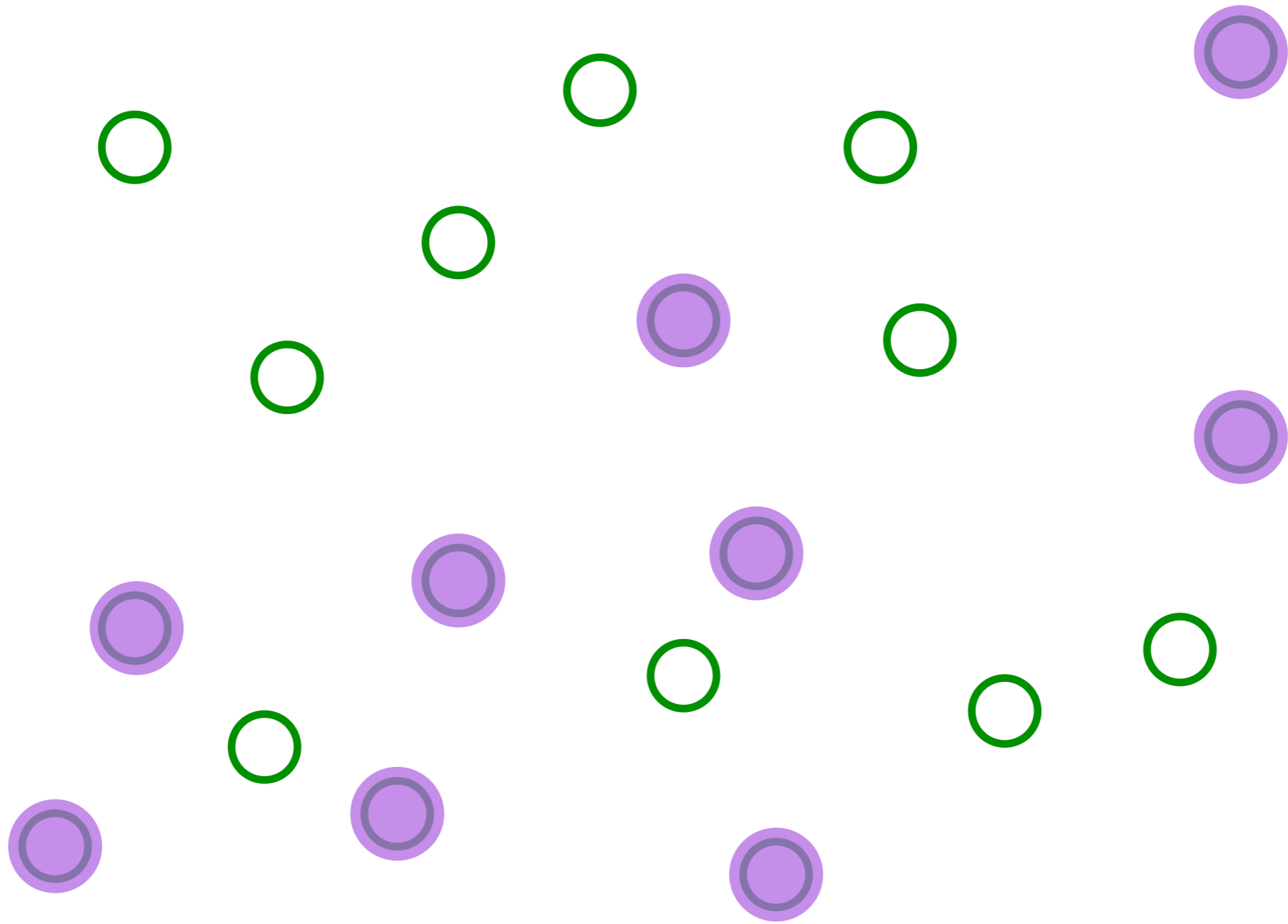
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



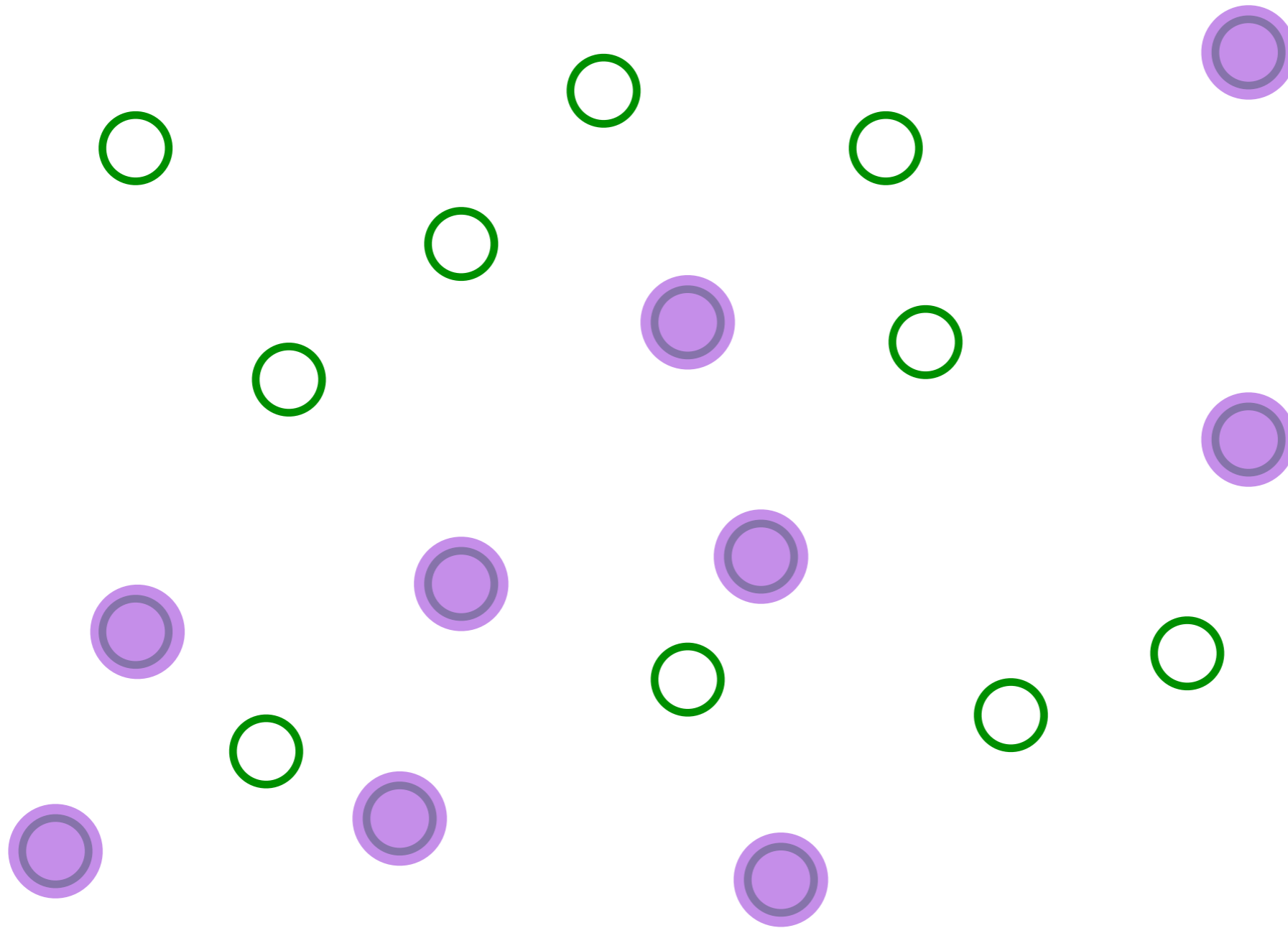
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



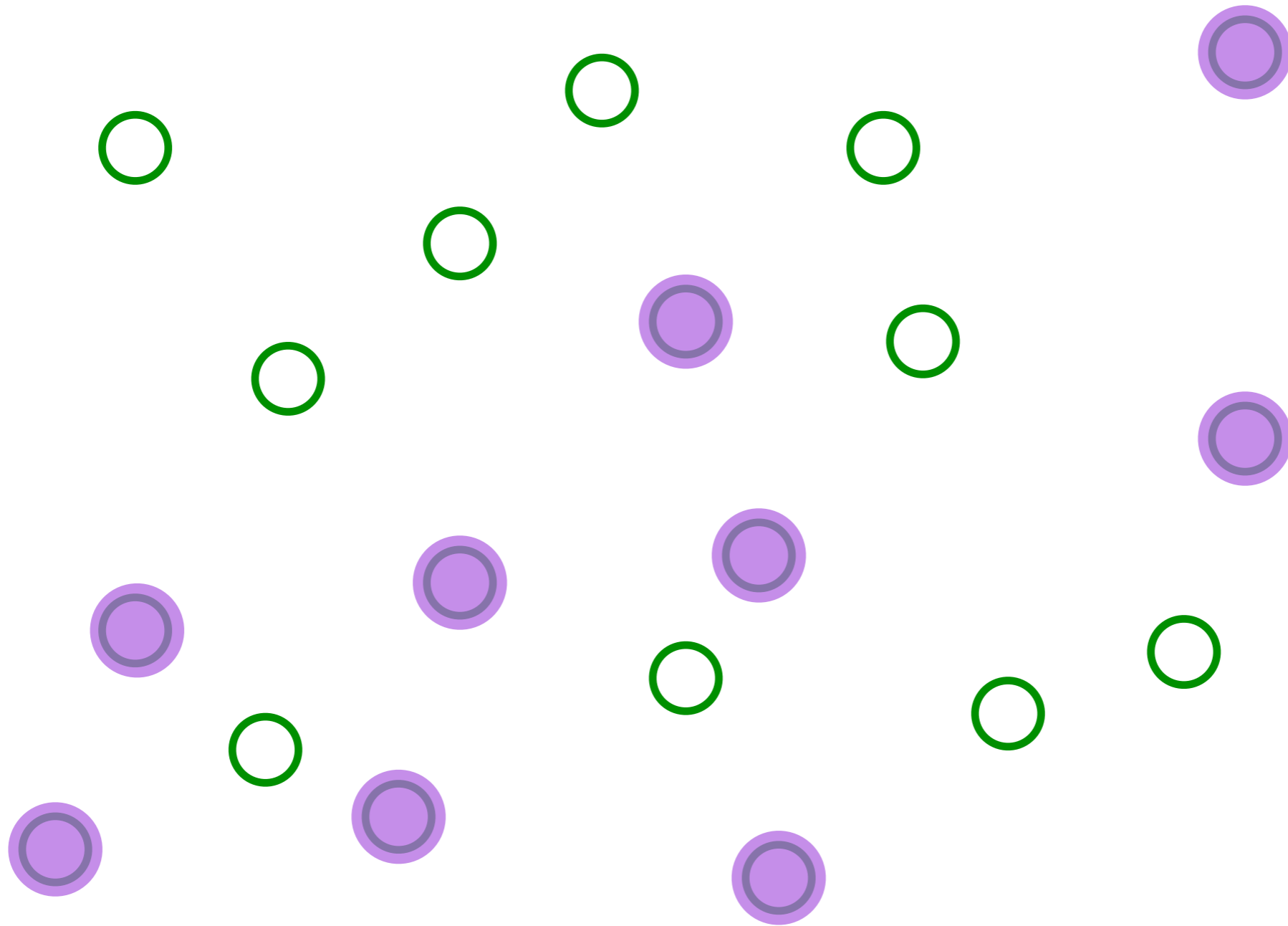
Entangle electrons pairwise randomly

The Sachdev-Ye-Kitaev (SYK) model



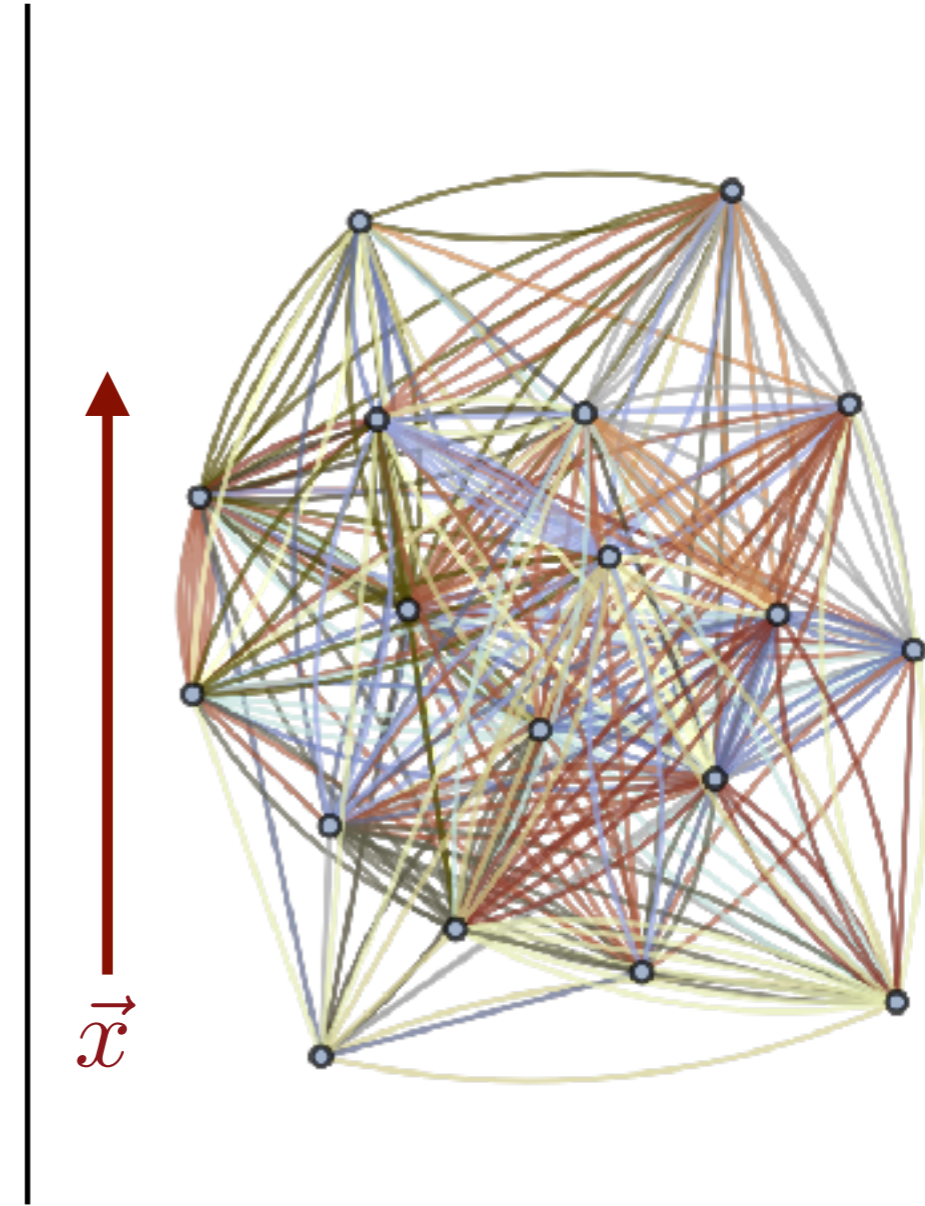
The SYK model has “nothing but entanglement”

The Sachdev-Ye-Kitaev (SYK) model

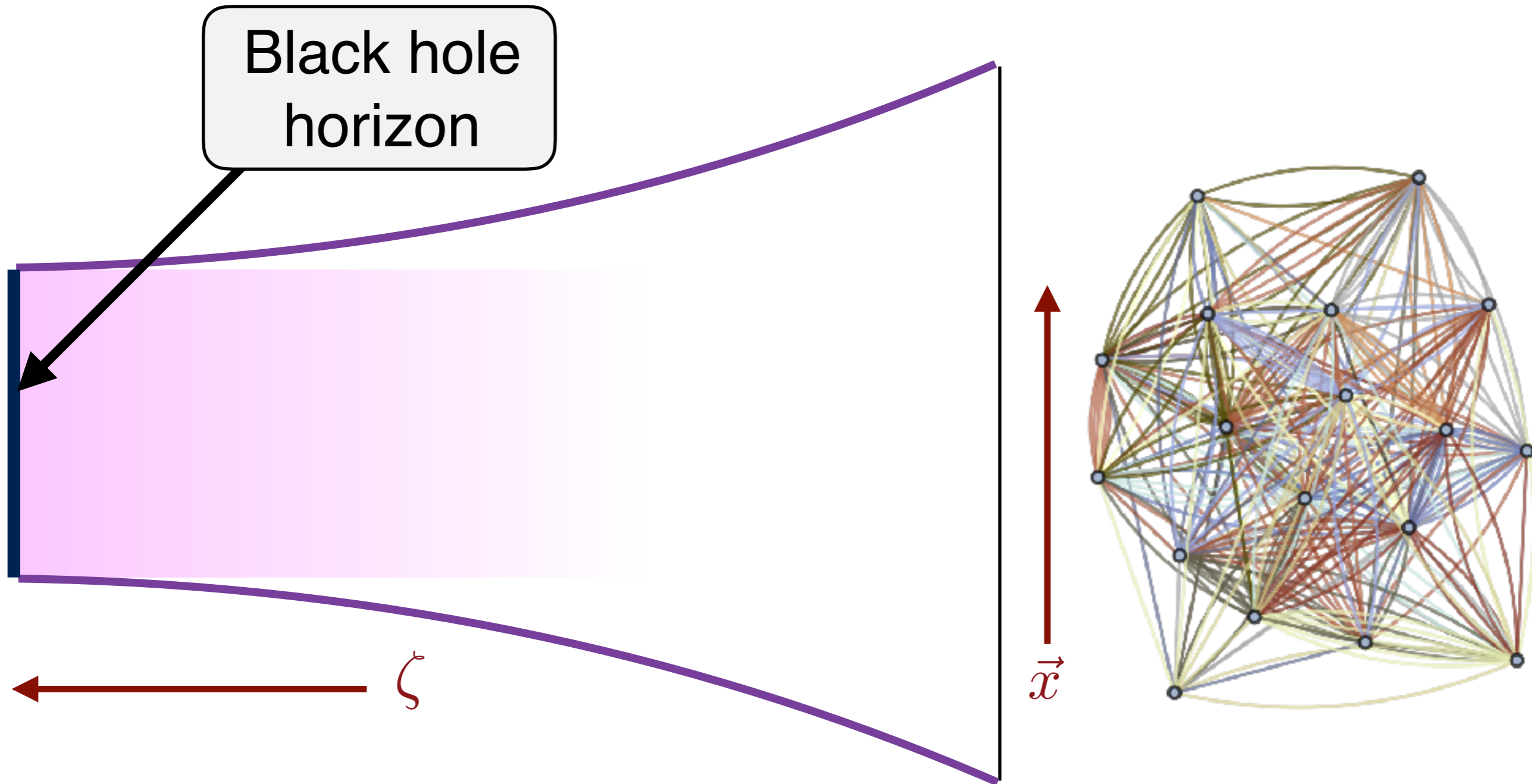


This describes both a strange metal and a black hole!

SYK and black holes

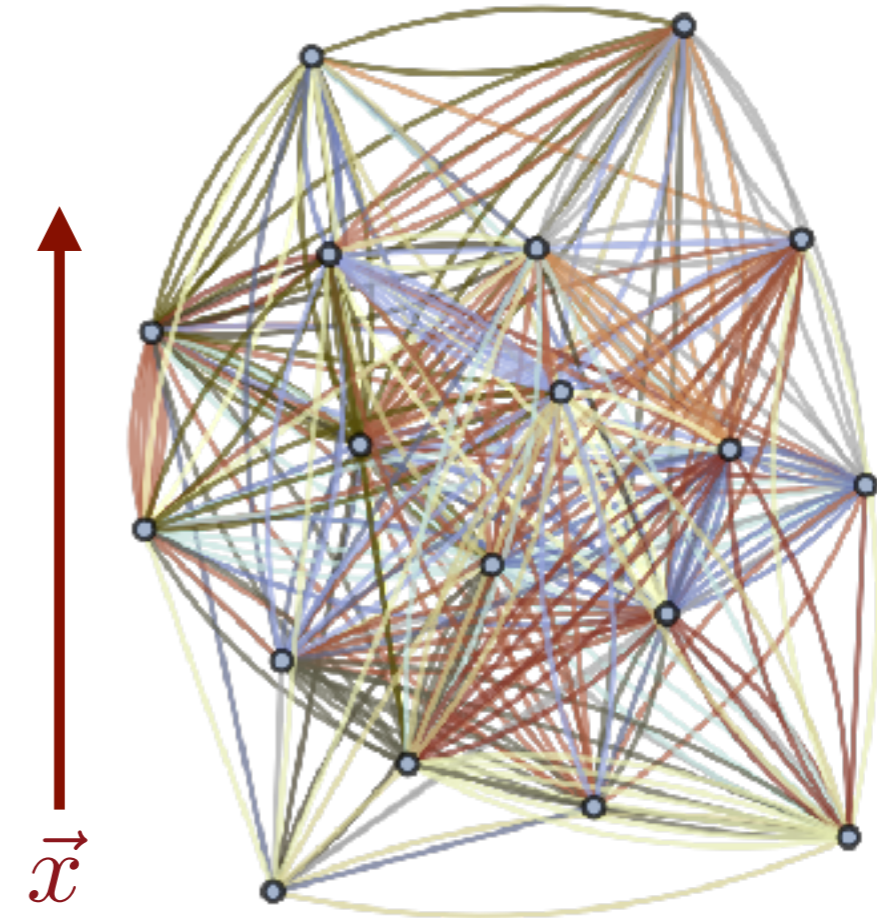
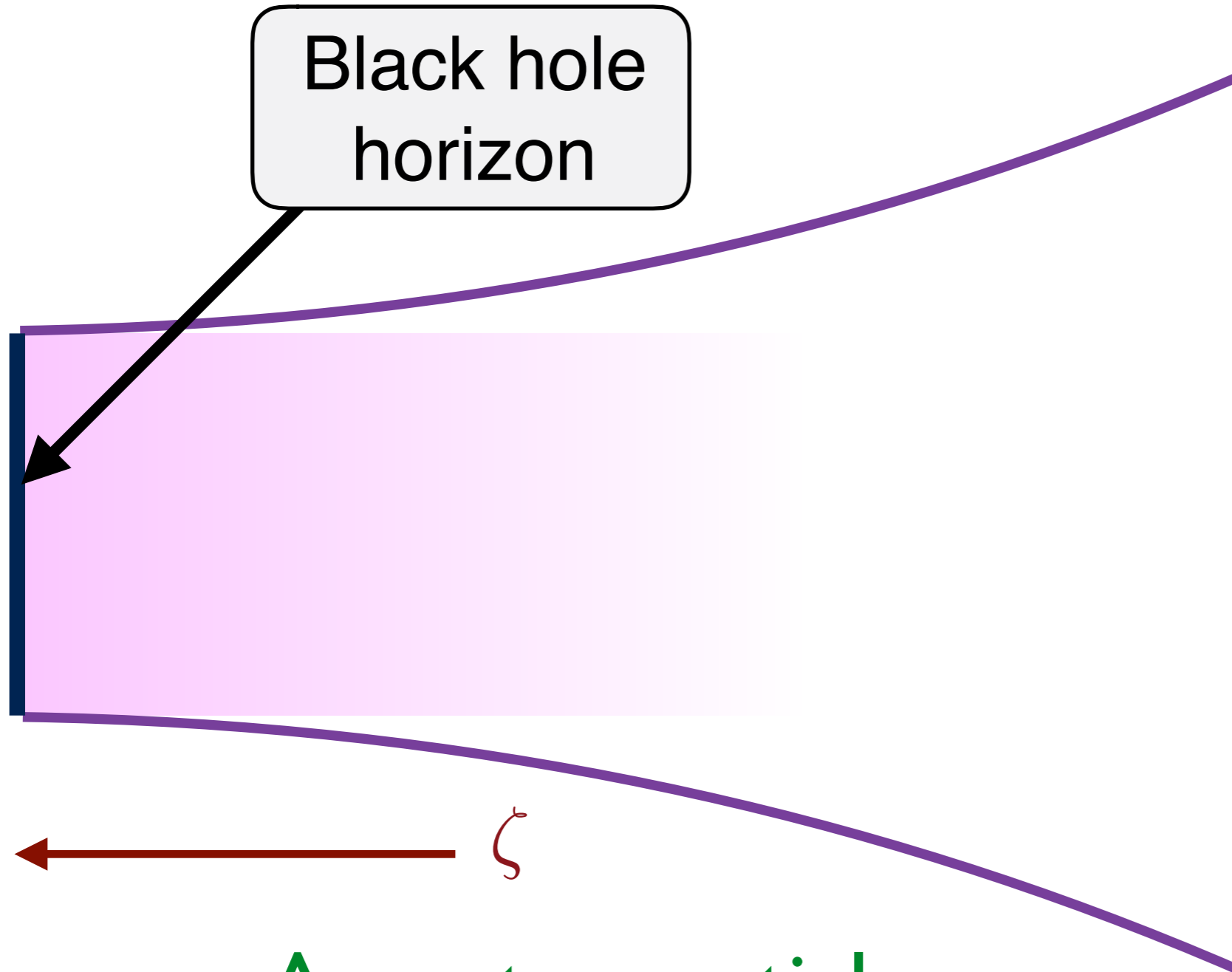


SYK and black holes



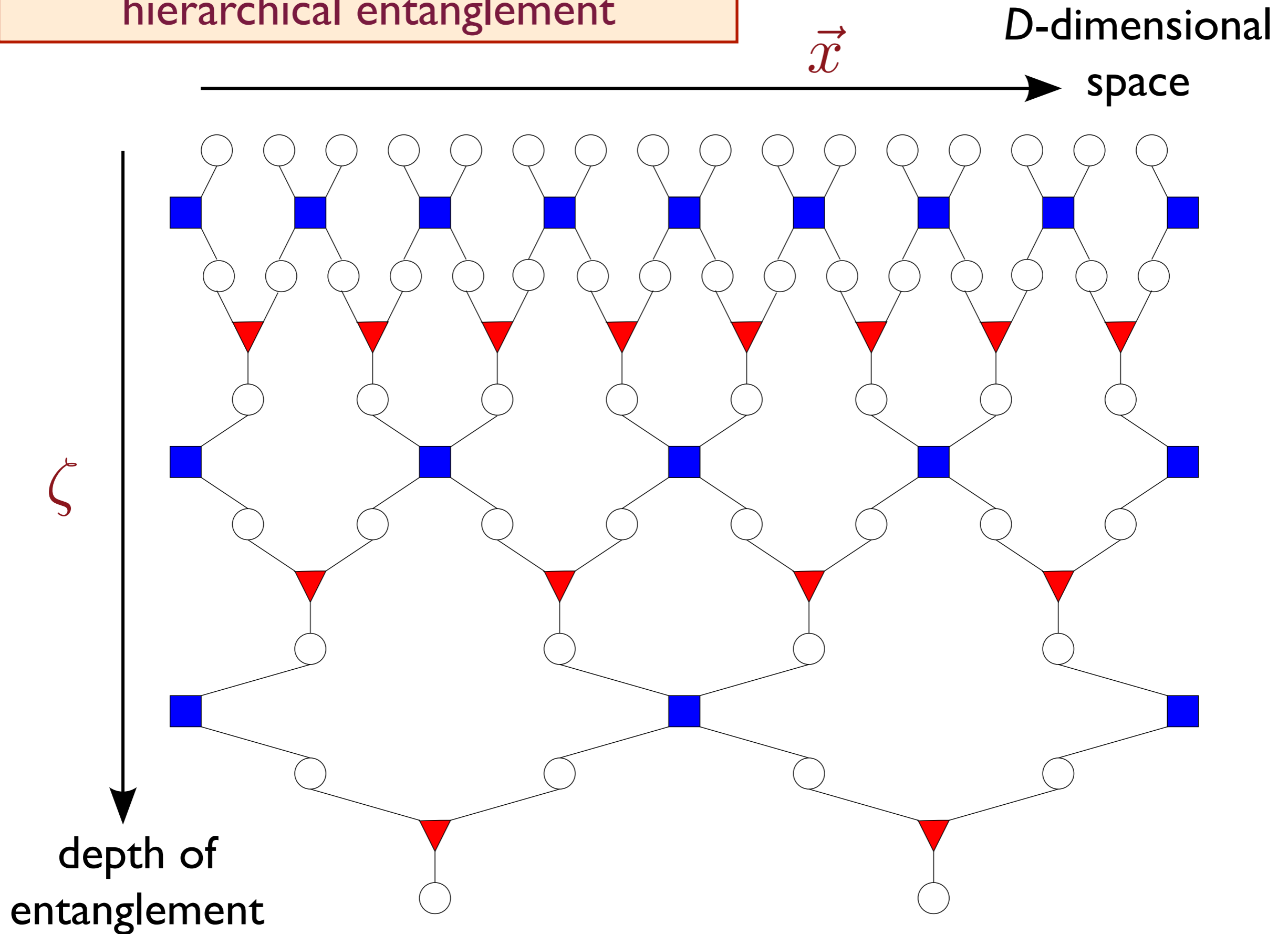
The SYK model has “dual” description in which an extra spatial dimension, ζ , emerges. The curvature of this “emergent” spacetime is described by Einstein’s theory of general relativity

SYK and black holes



An extra spatial dimension emerges from quantum entanglement!

Tensor network of hierarchical entanglement



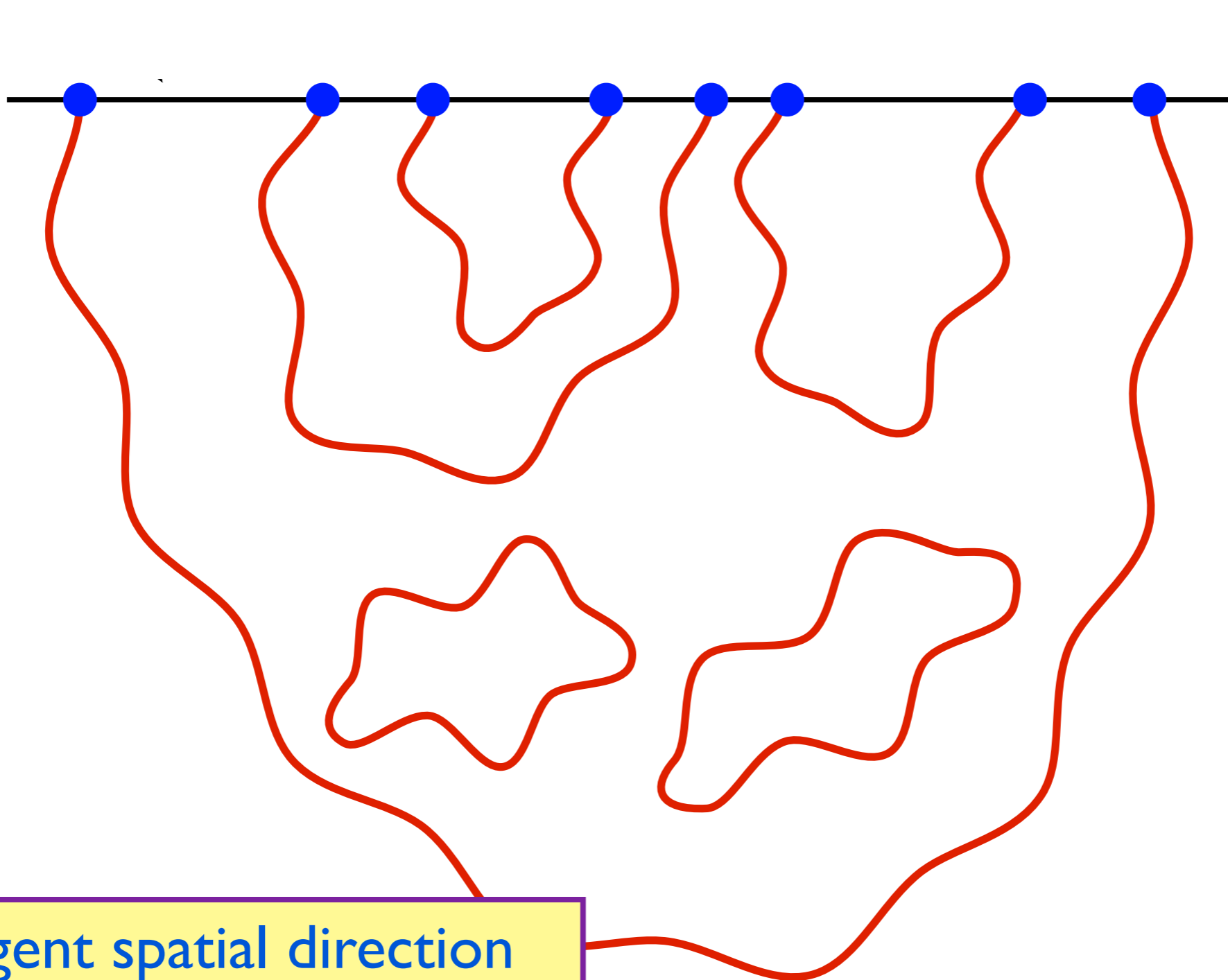
String theory near
a "D-brane"

\vec{x}

D-dimensional
space

ζ

Emergent spatial direction
of SYK model or string theory



String theory near
a “D-brane”

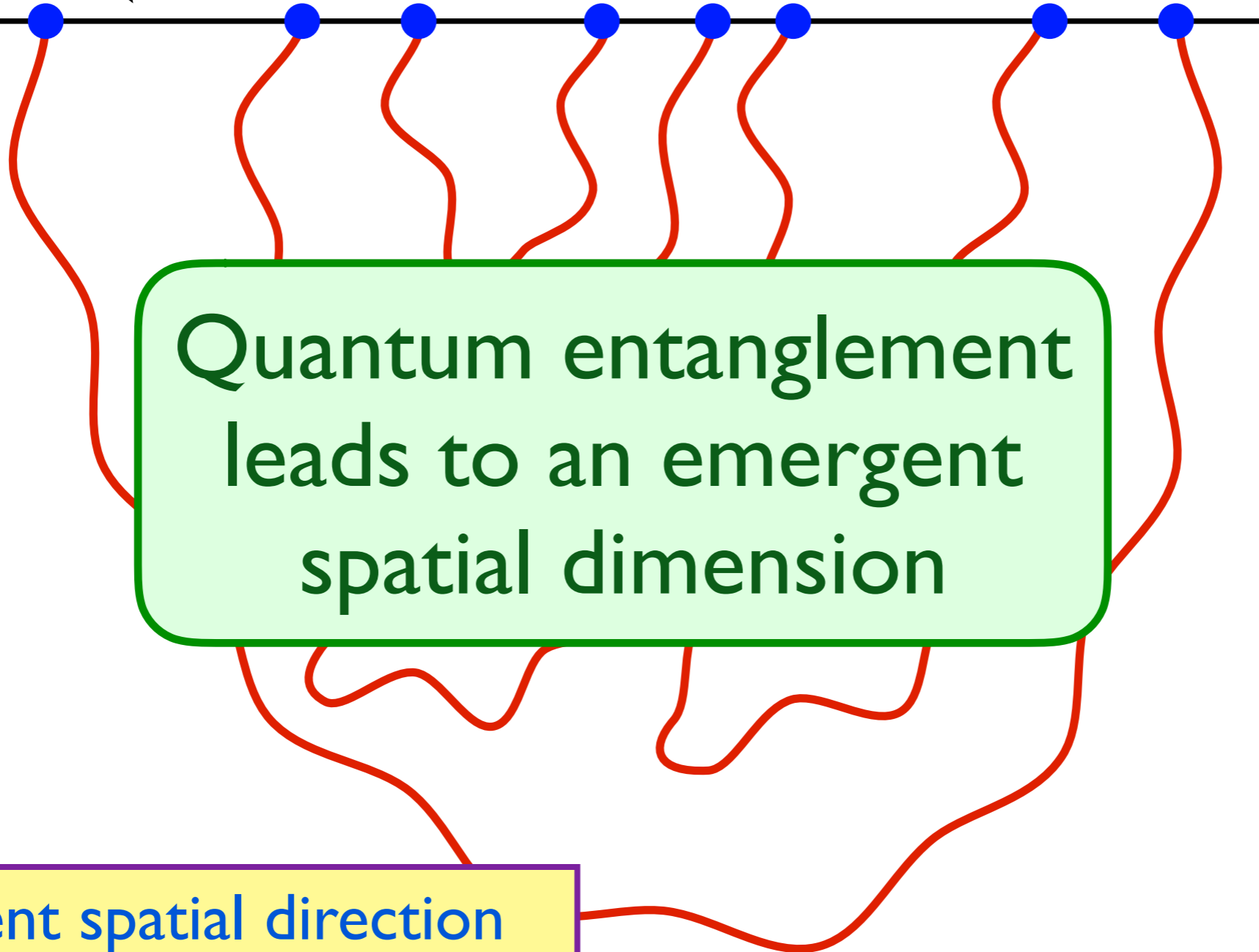
\vec{x}

D-dimensional
space



Quantum entanglement
leads to an emergent
spatial dimension

Emergent spatial direction
of SYK model or string theory



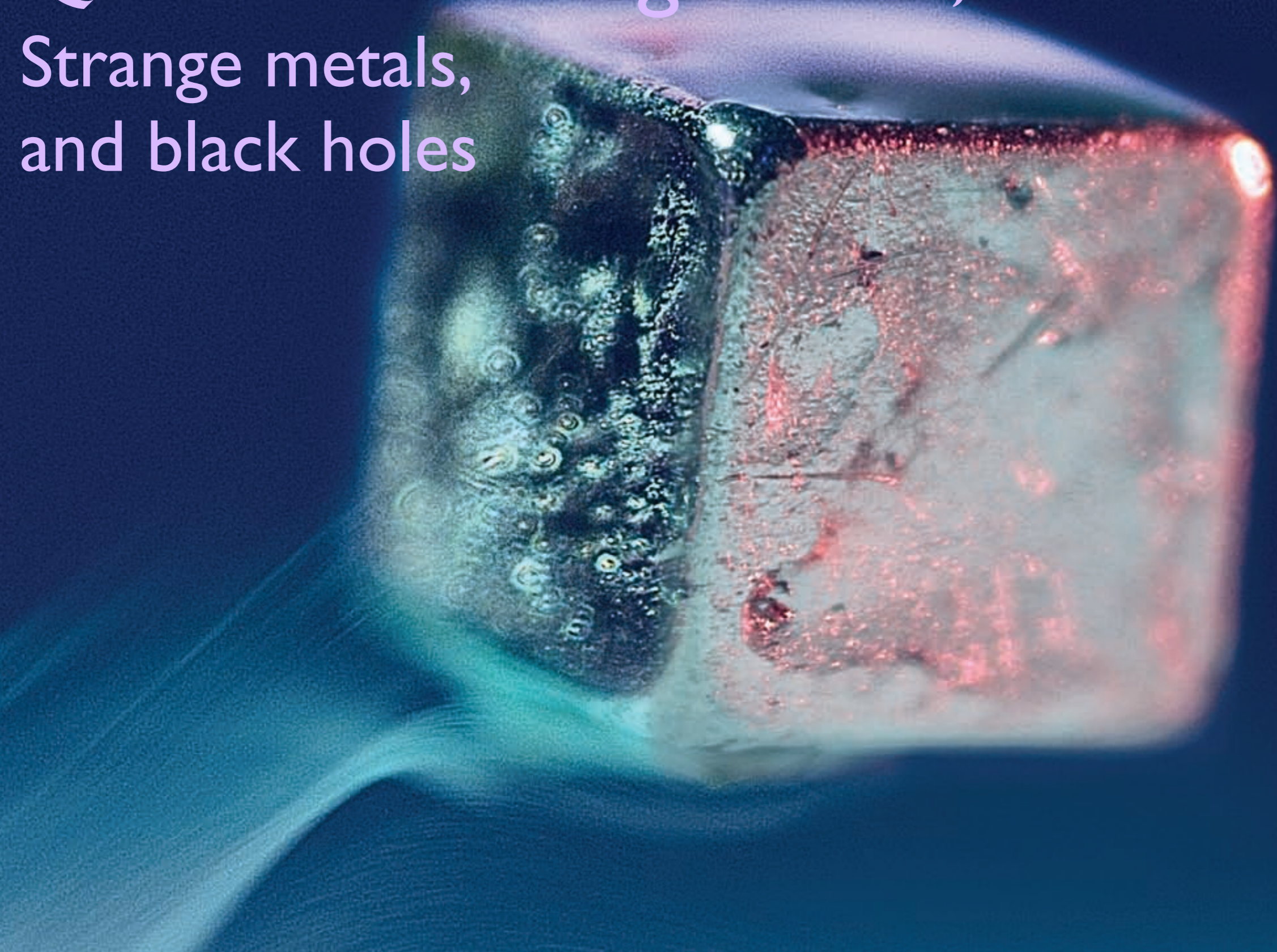
**Quantum
entanglement**

**Black
holes**

**Strange
metals**

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

Quantum Entanglement, Strange metals, and black holes



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