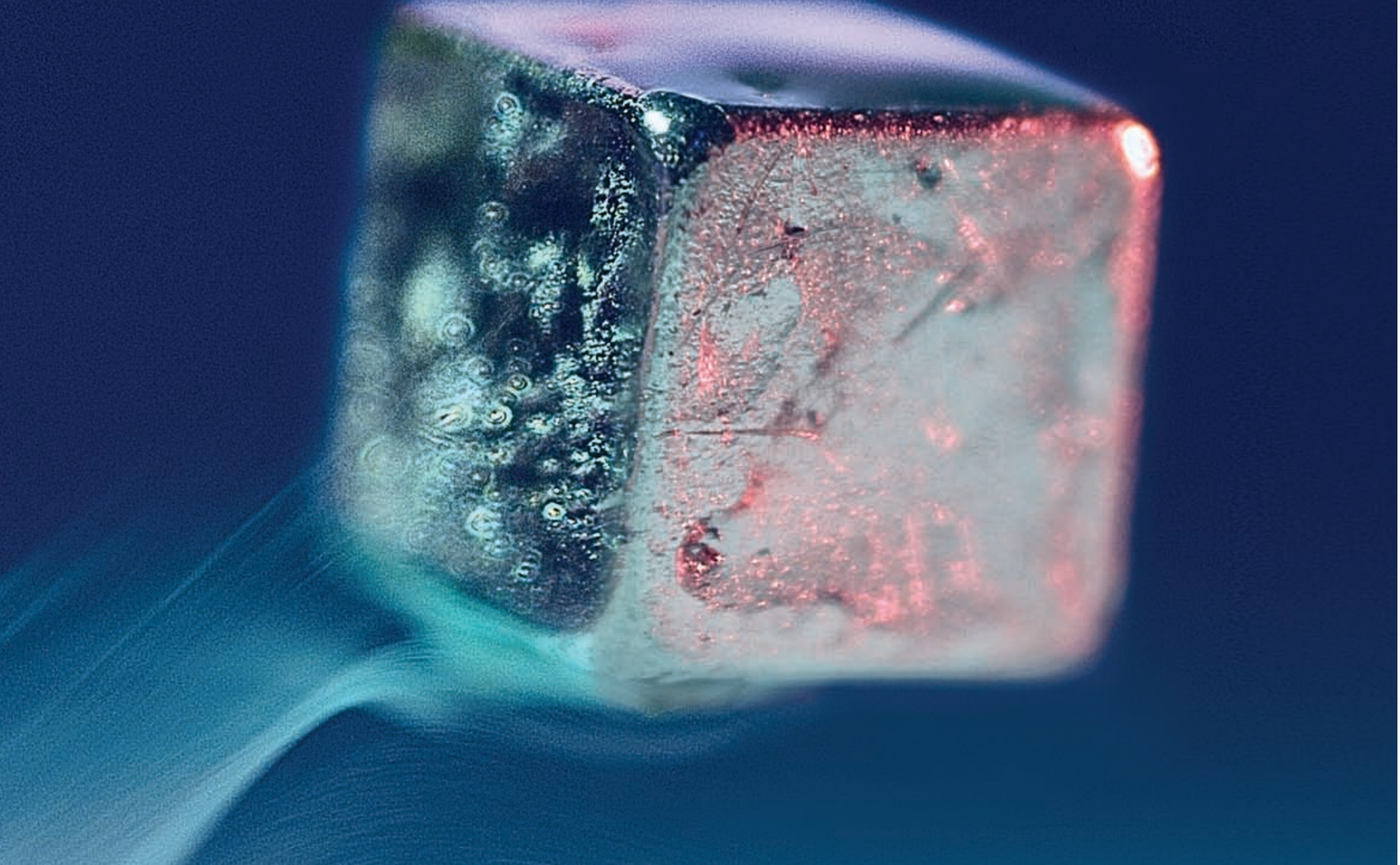


Quantum Entanglement and Superconductivity



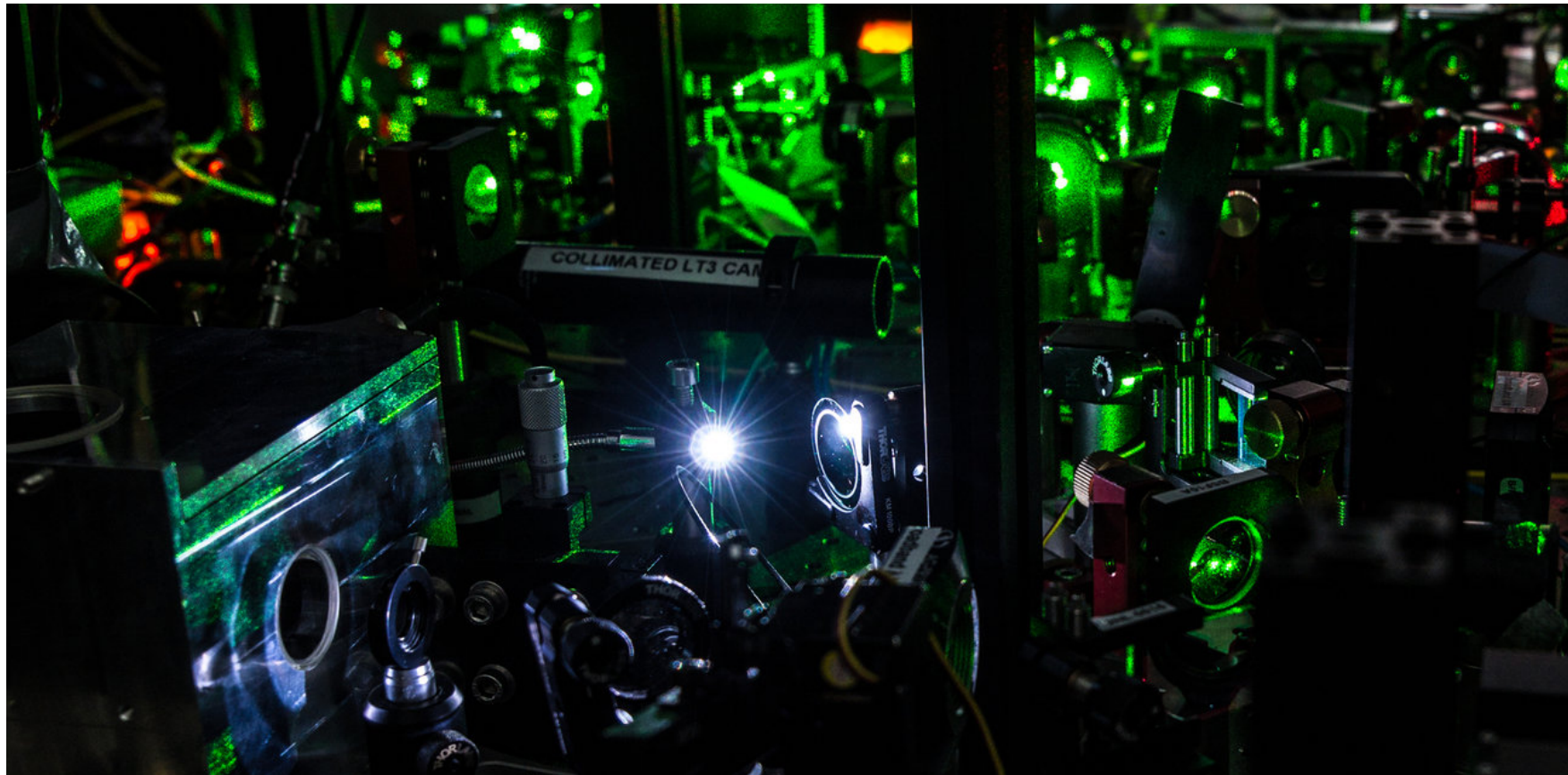
Subir Sachdev, Perimeter Institute and Harvard University

The New York Times

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

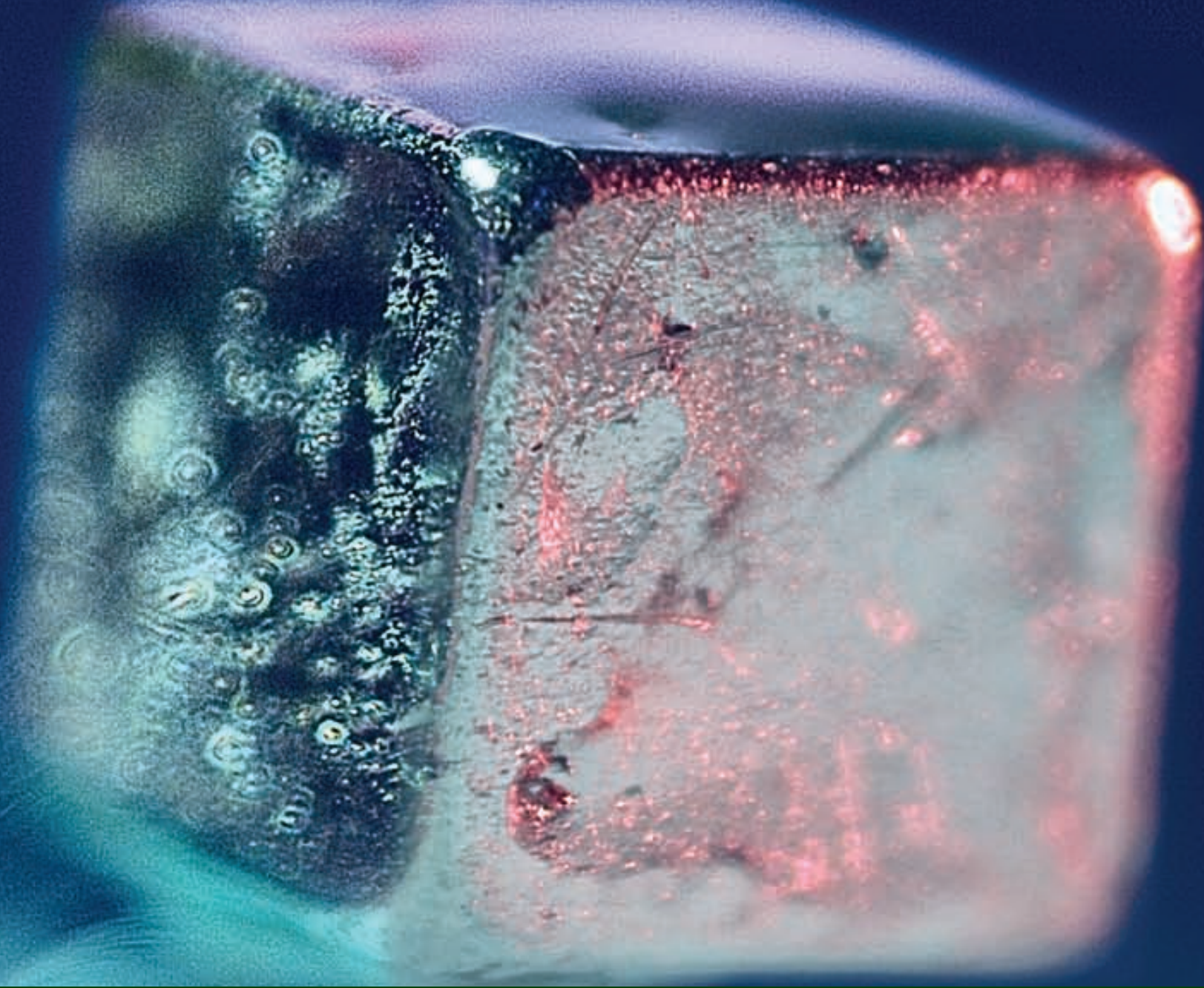
By JOHN MARKOFF OCT. 21, 2015

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.

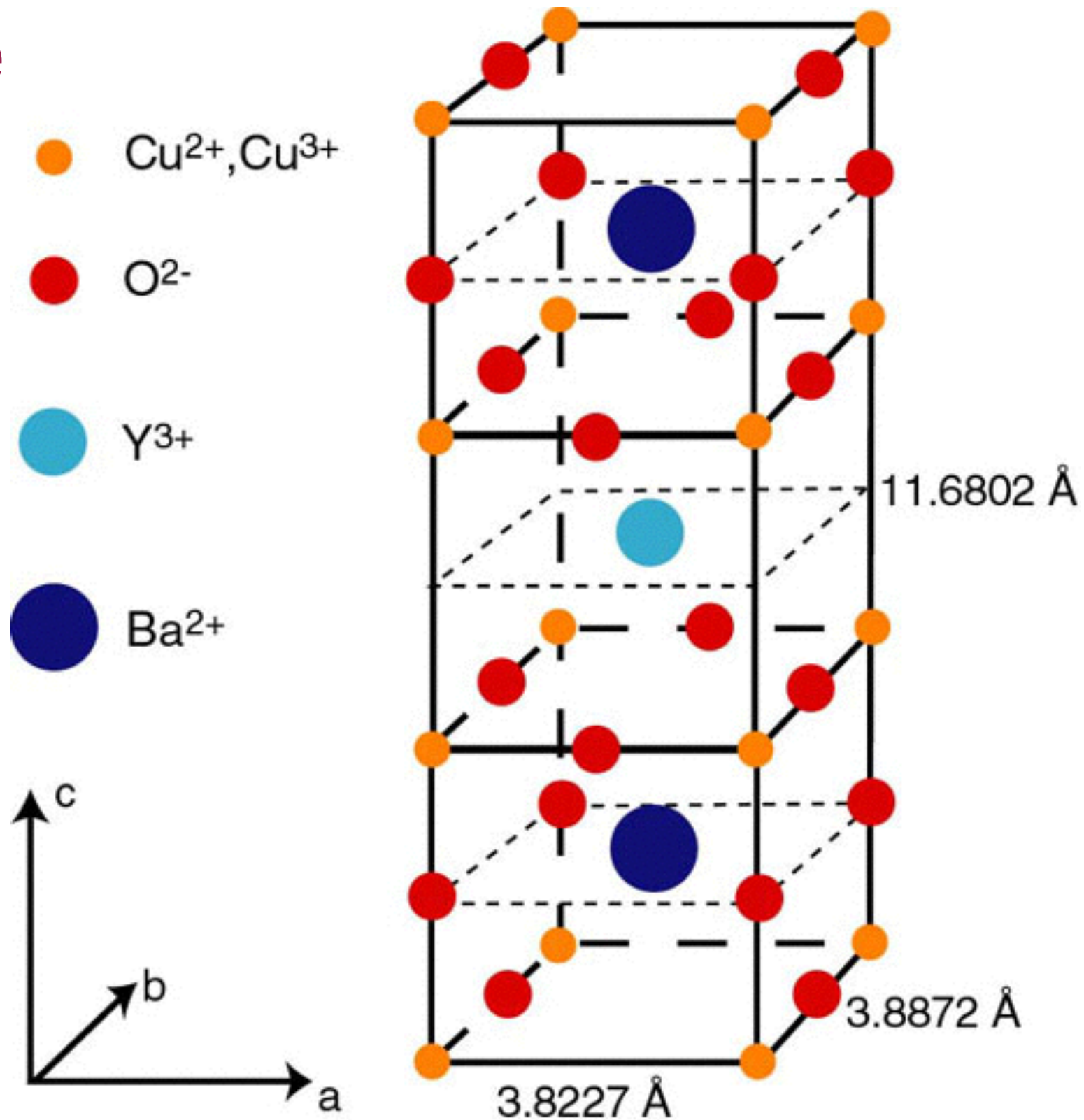
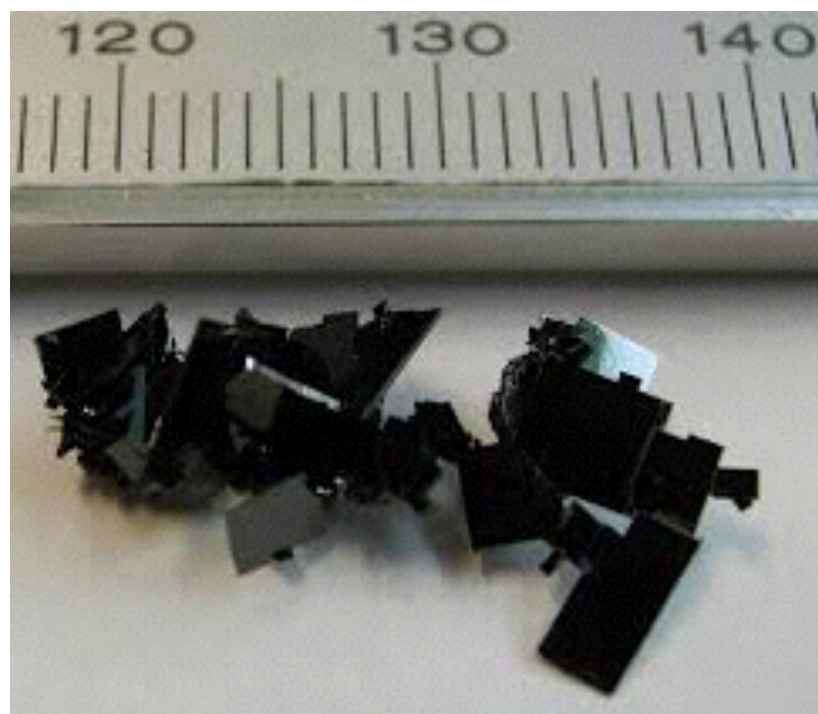
Quantum Entanglement and Superconductivity

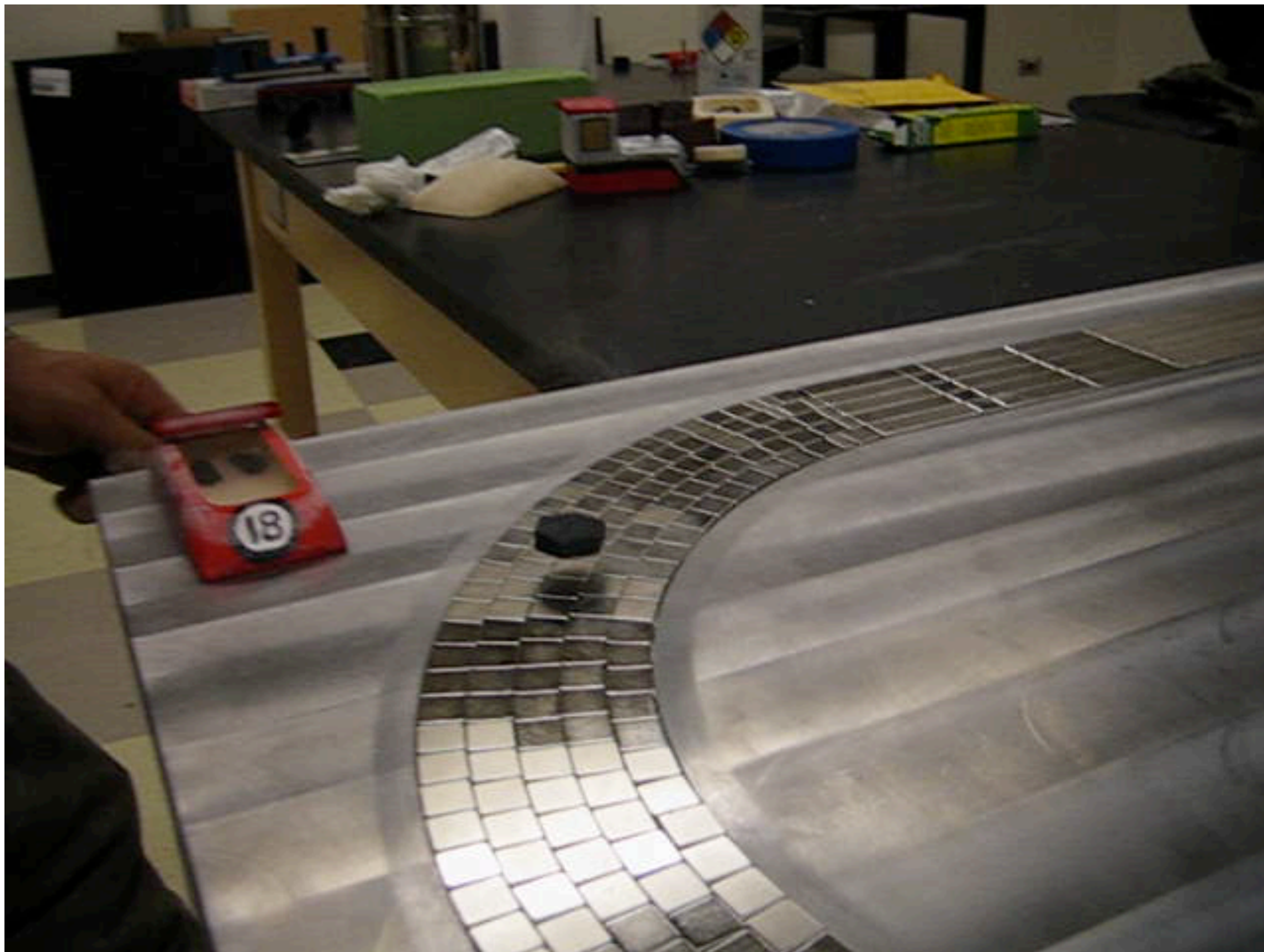


Superconductor, levitated by an unseen magnet, in which countless trillions of electrons form a vast interconnected quantum state.
Scientific American, January 2013

Subir Sachdev, Perimeter Institute and Harvard University

High temperature superconductors





Nd-Fe-B magnets, YBaCuO superconductor

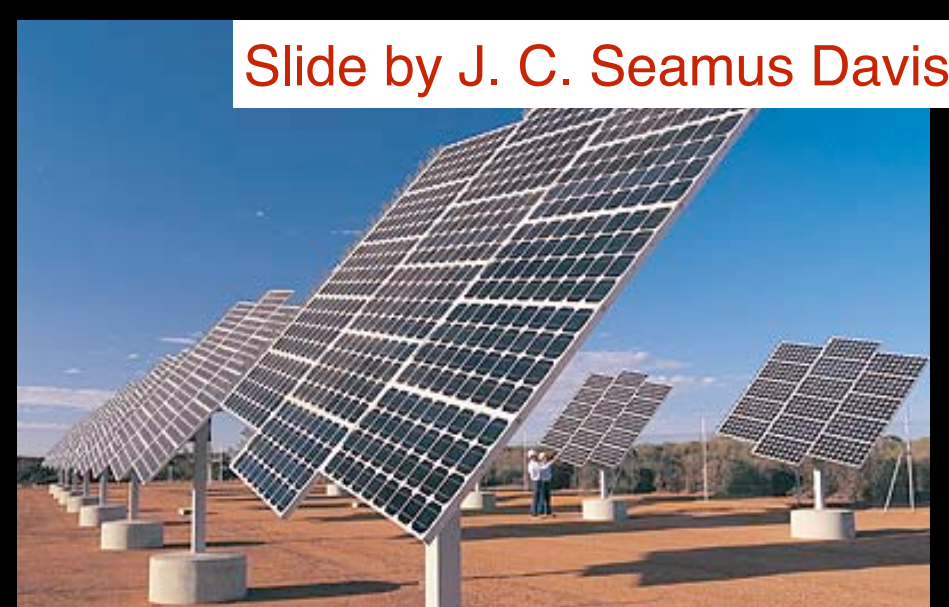
Julian Hetel and Nandini Trivedi, Ohio State University



Power Efficiency/Capacity/Stability



Power Bottlenecks



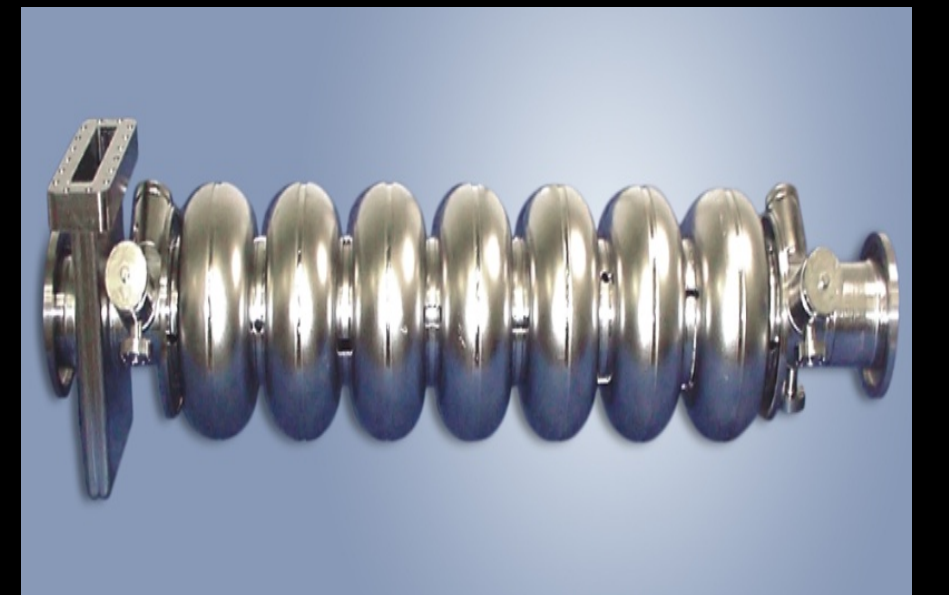
Accommodate Renewable Power



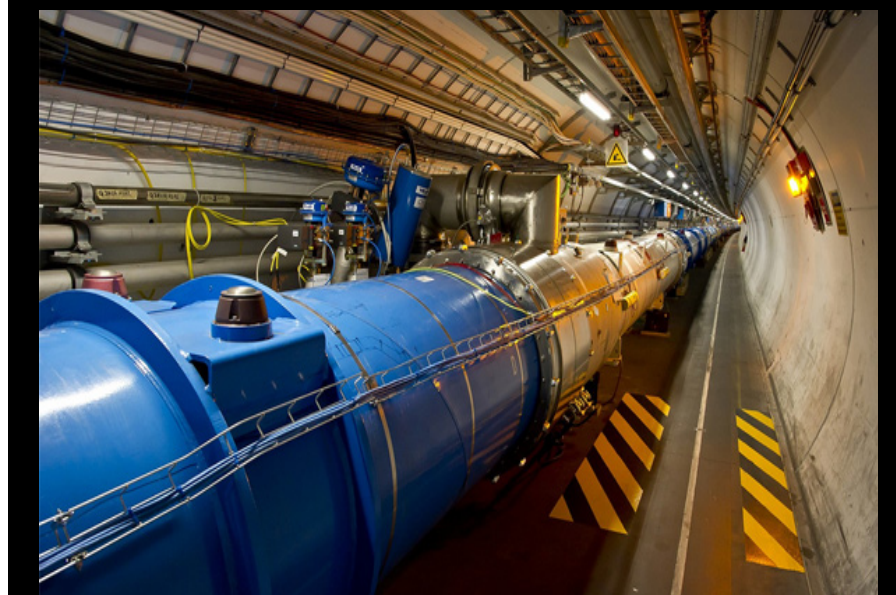
Efficient Rotating Machines



Information Technology



Next Generation HEP



Ultra-High Magnetic Fields



Medical

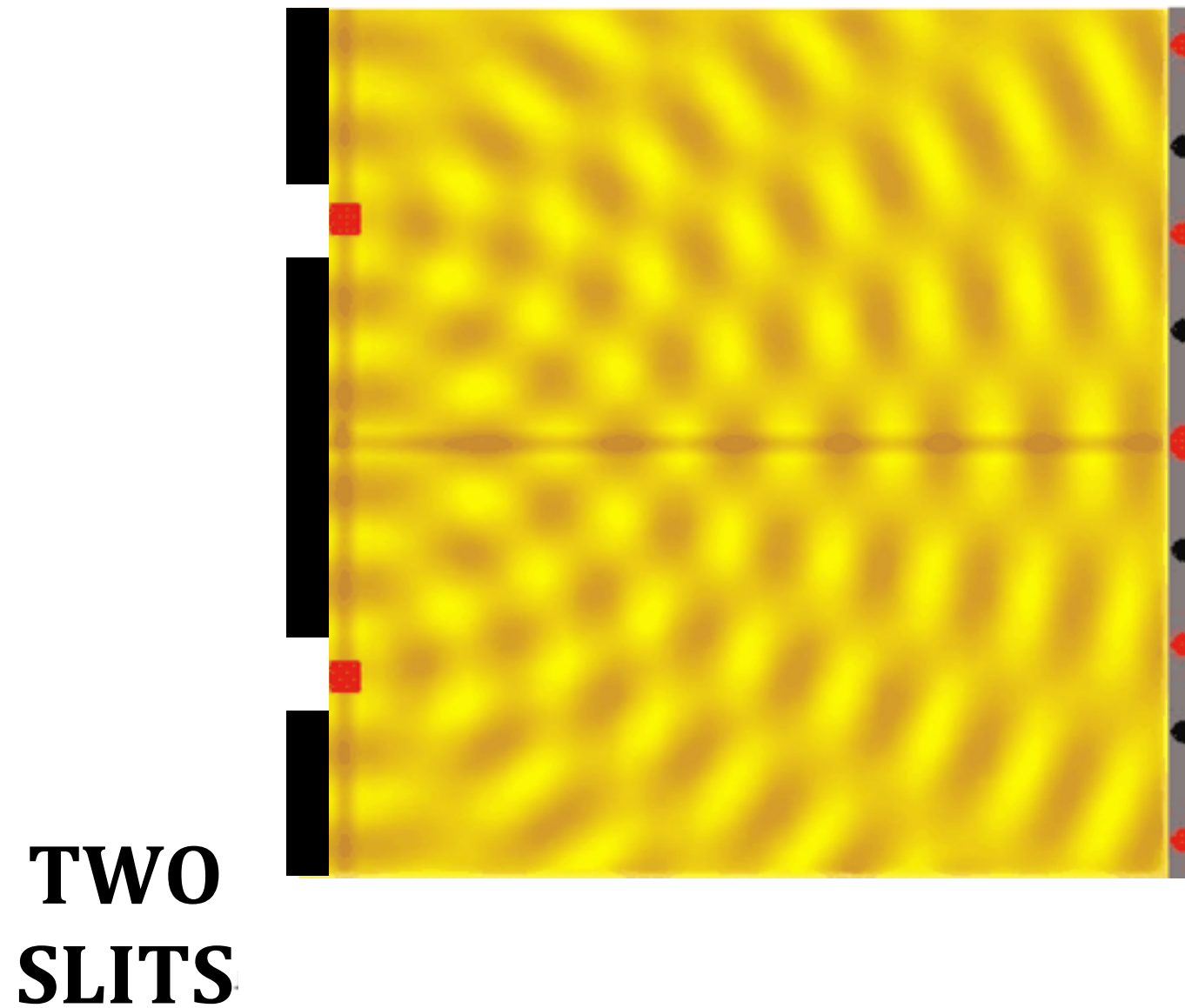


Transport

**Quantum
superposition and
entanglement**

Principles of Quantum Mechanics: I. Quantum Superposition

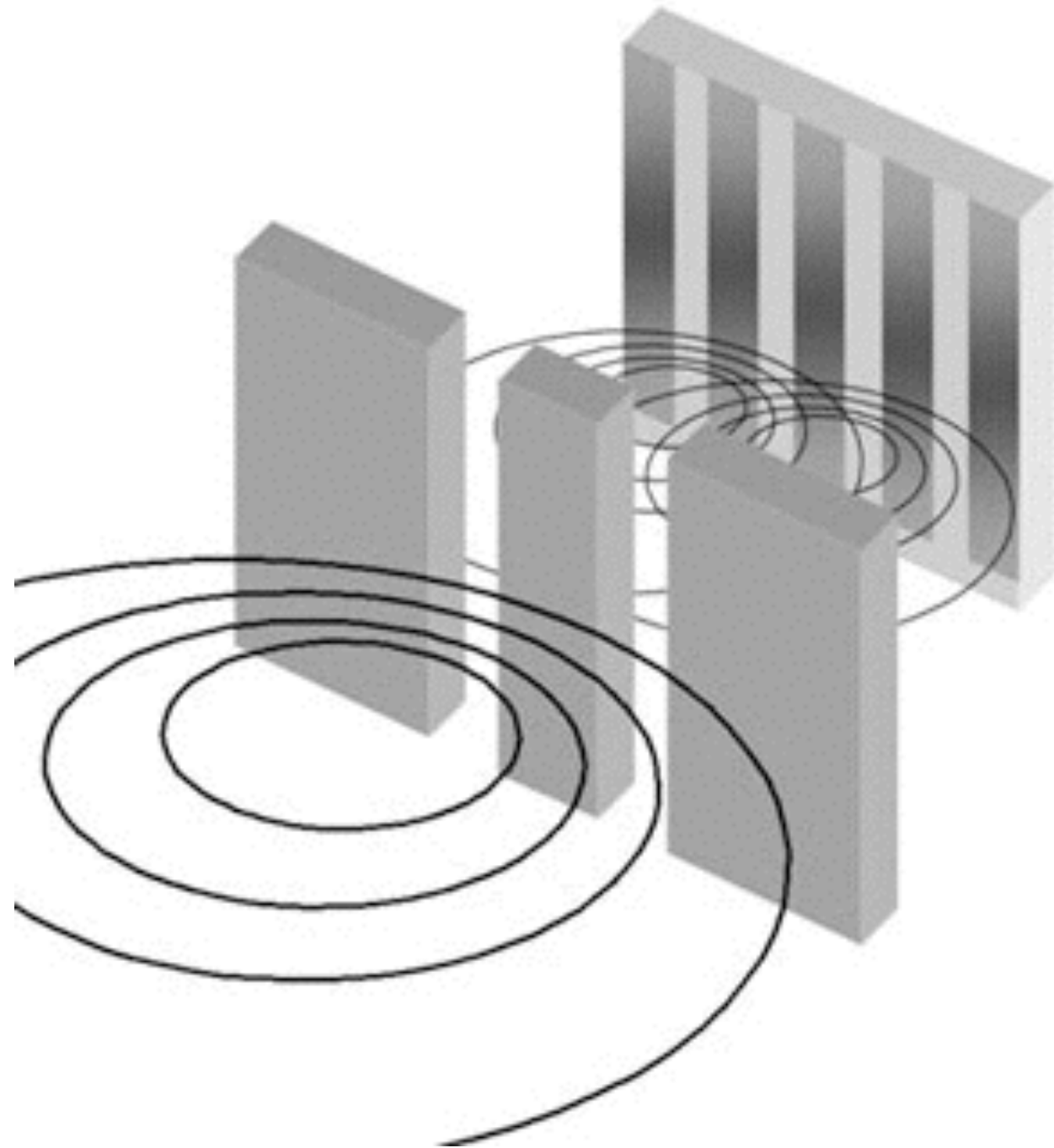
The double slit experiment



Interference of water waves

Principles of Quantum Mechanics: I. Quantum Superposition

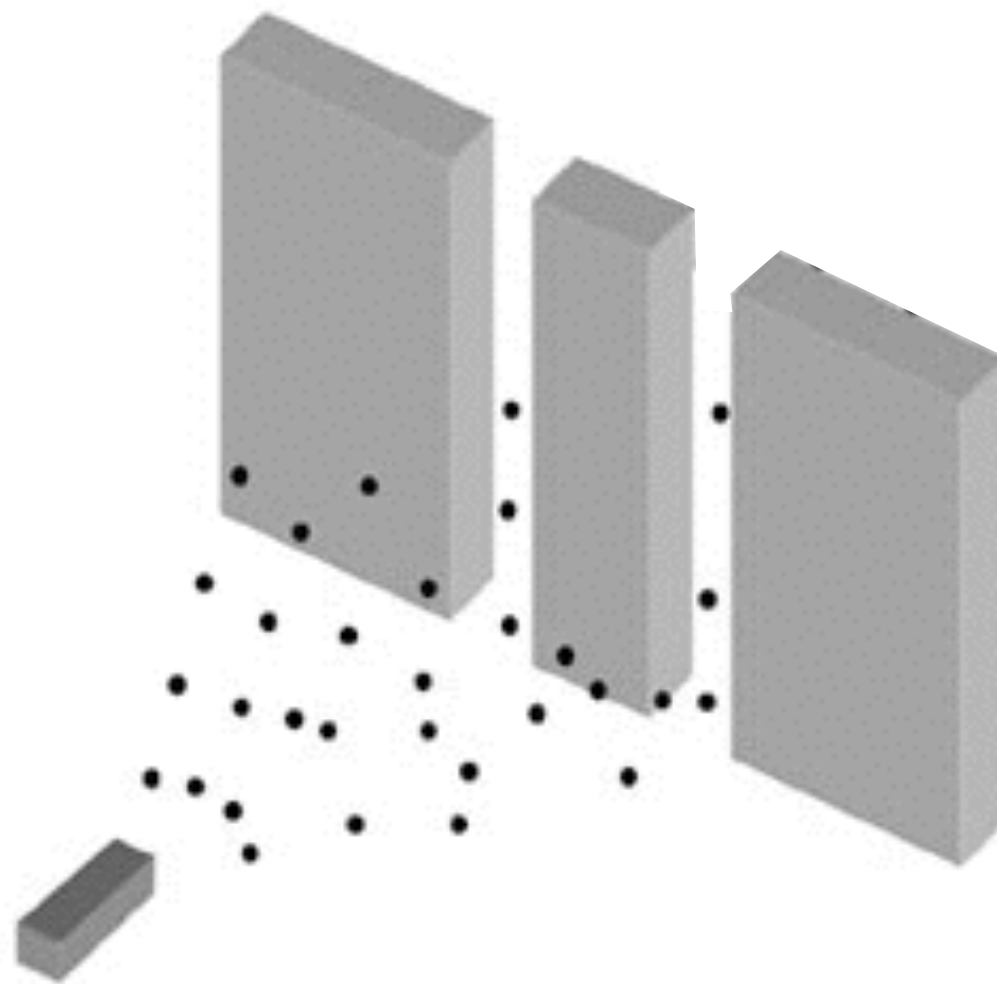
The double slit experiment



Interference of water waves

Principles of Quantum Mechanics: I. Quantum Superposition

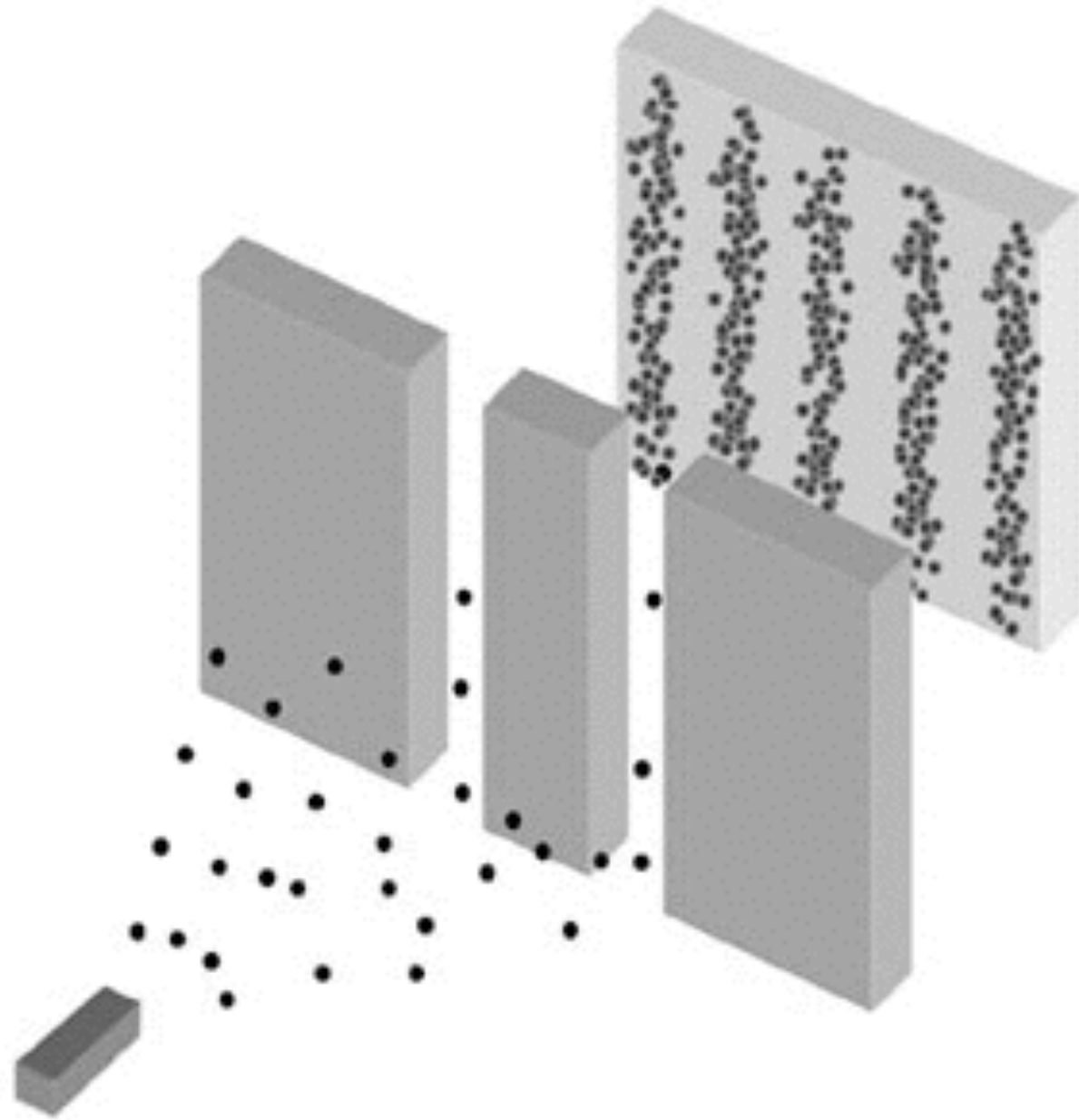
The double slit experiment



Send electrons through the slits

Principles of Quantum Mechanics: I. Quantum Superposition

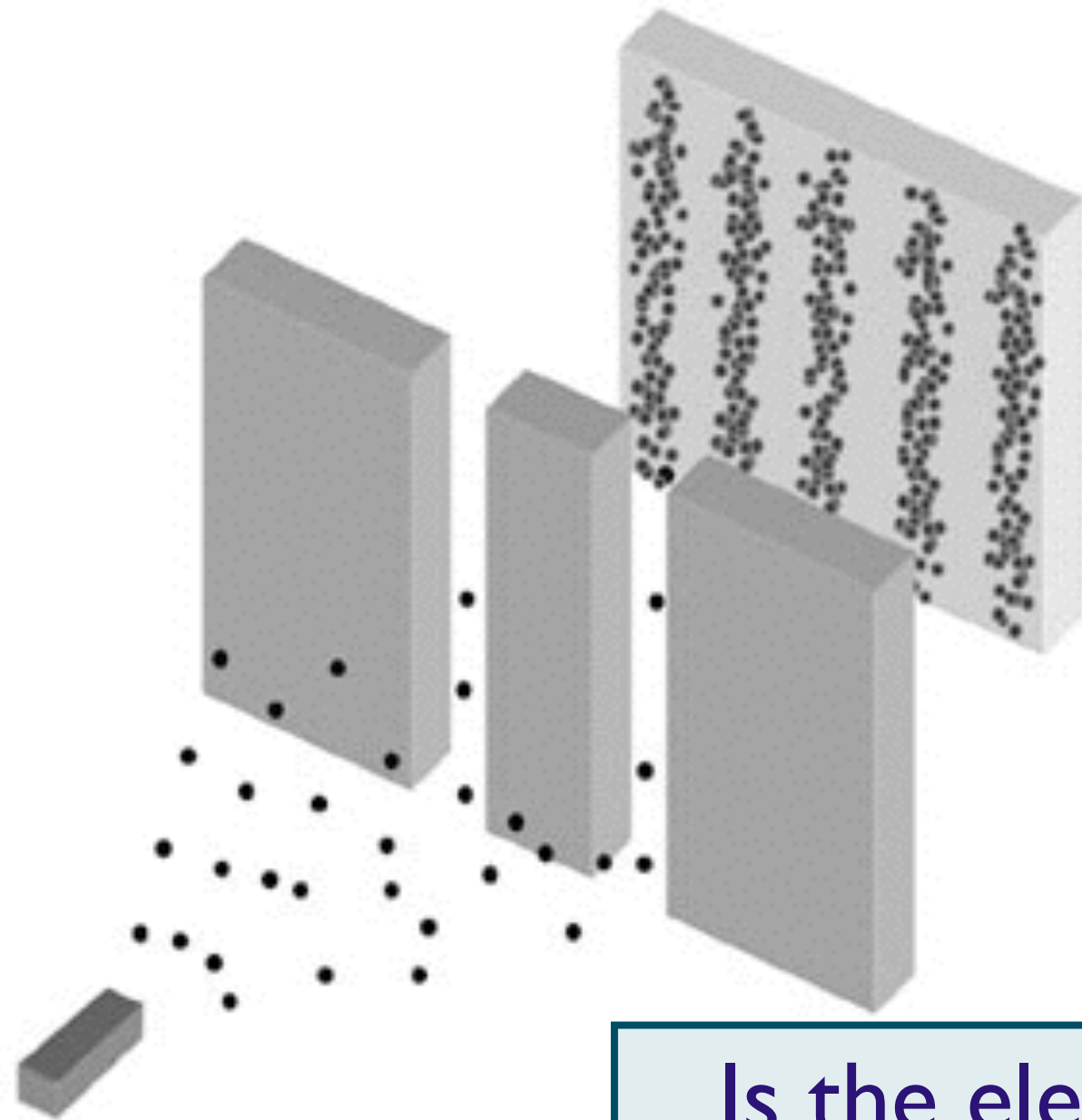
The double slit experiment



Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

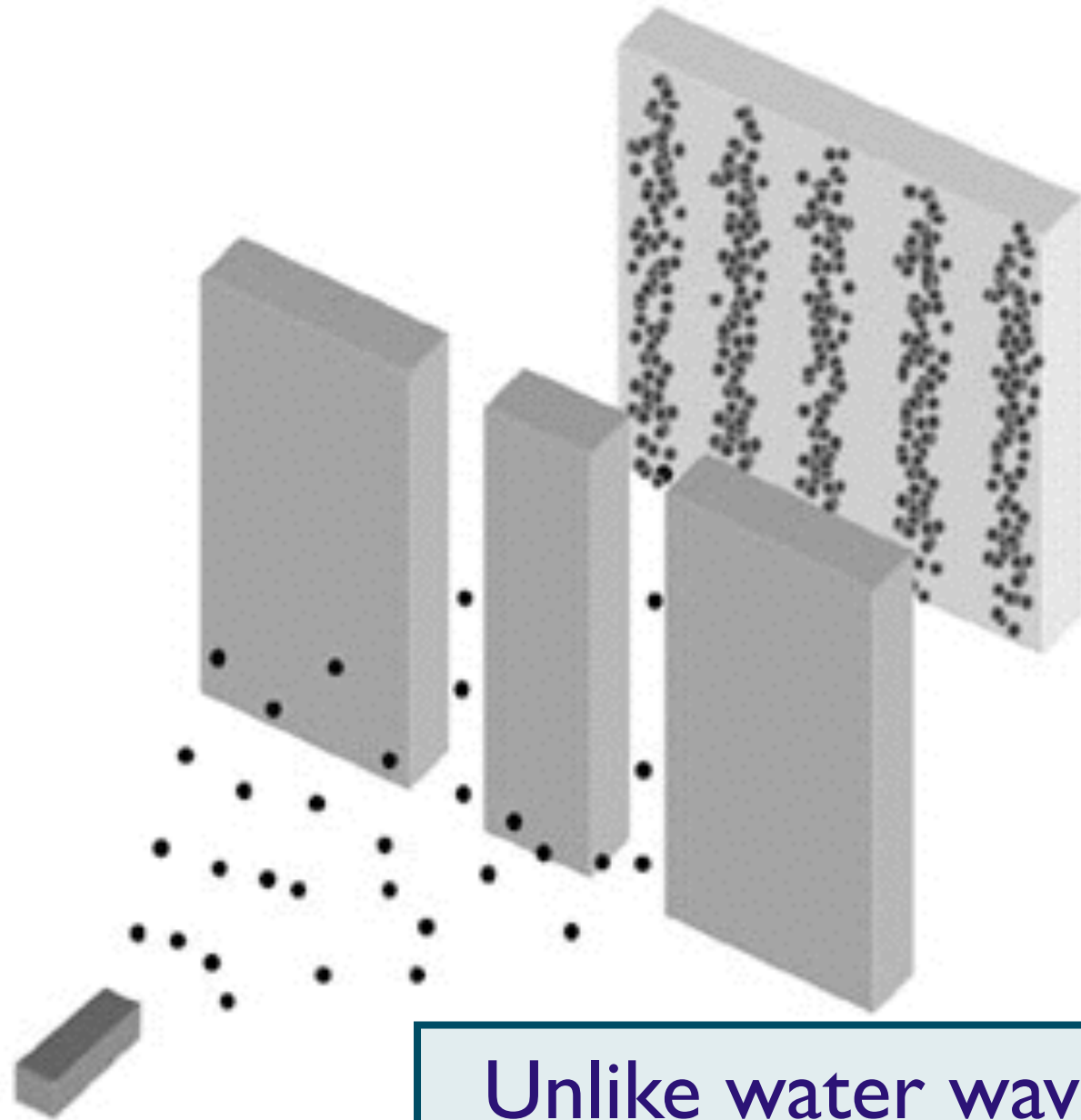


Is the electron a wave ?

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

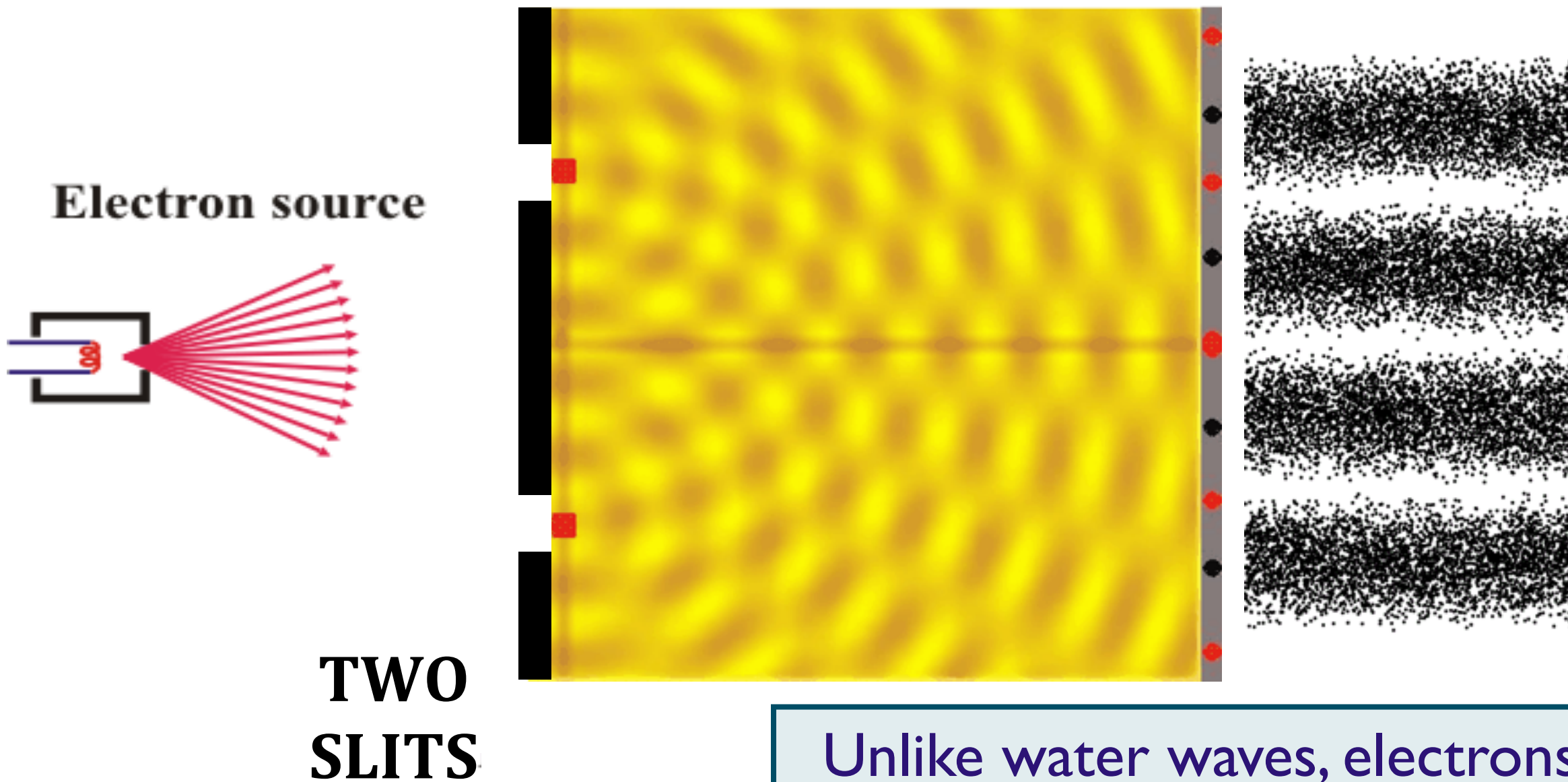


Unlike water waves, electrons arrive one-by-one (so is it like a particle ?)

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment



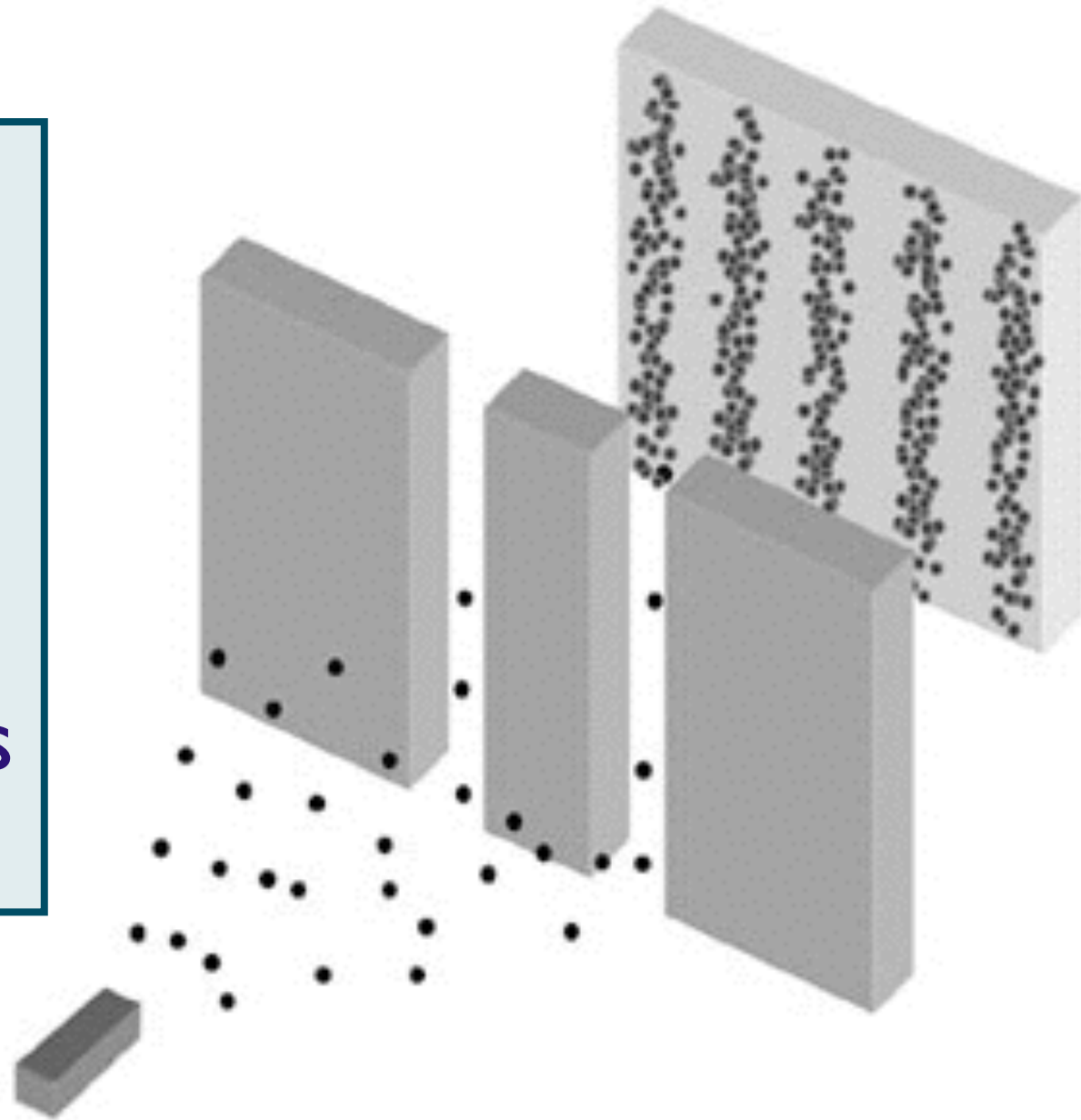
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Interference of electrons

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 ?

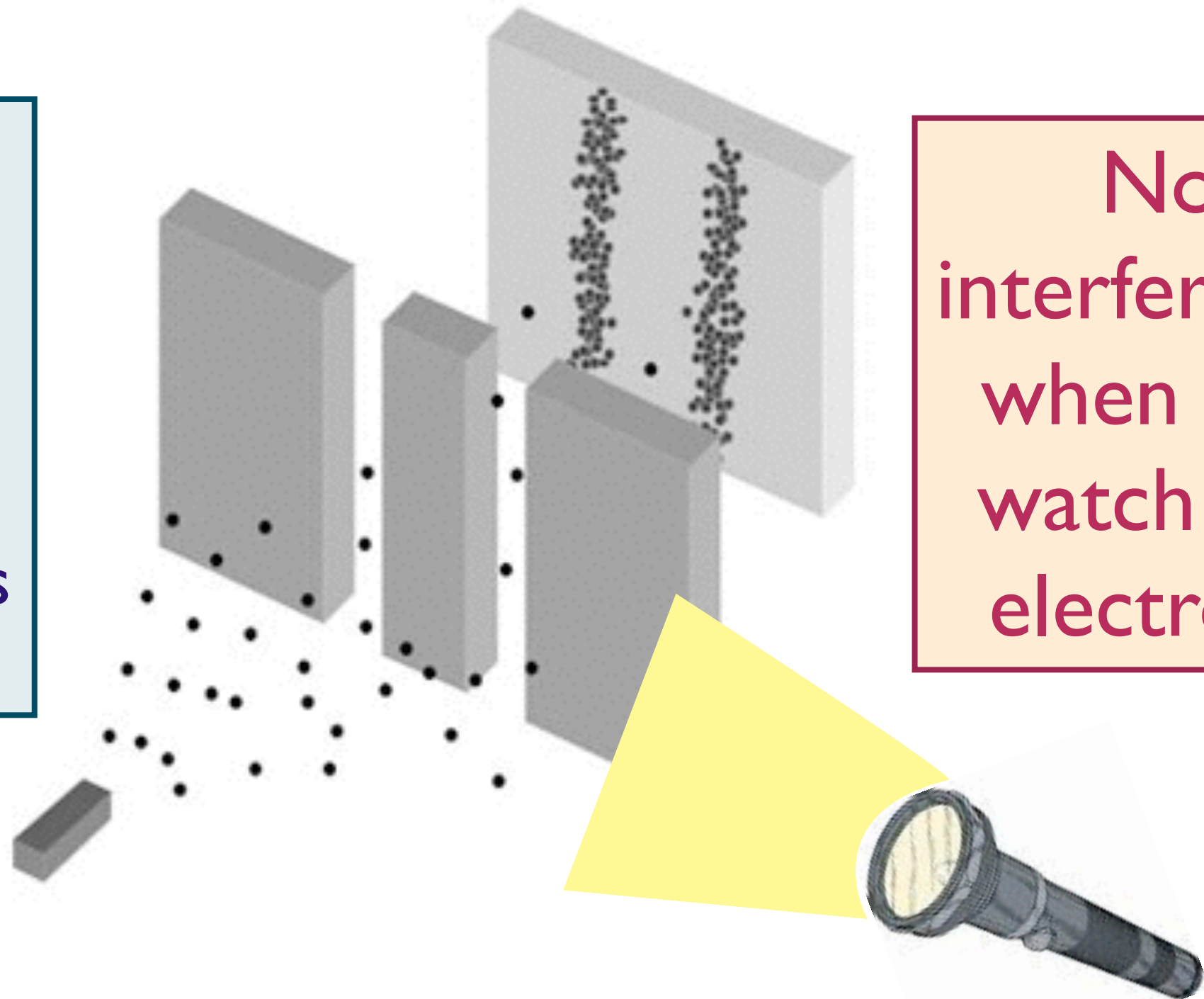


Interference of electrons

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 ?



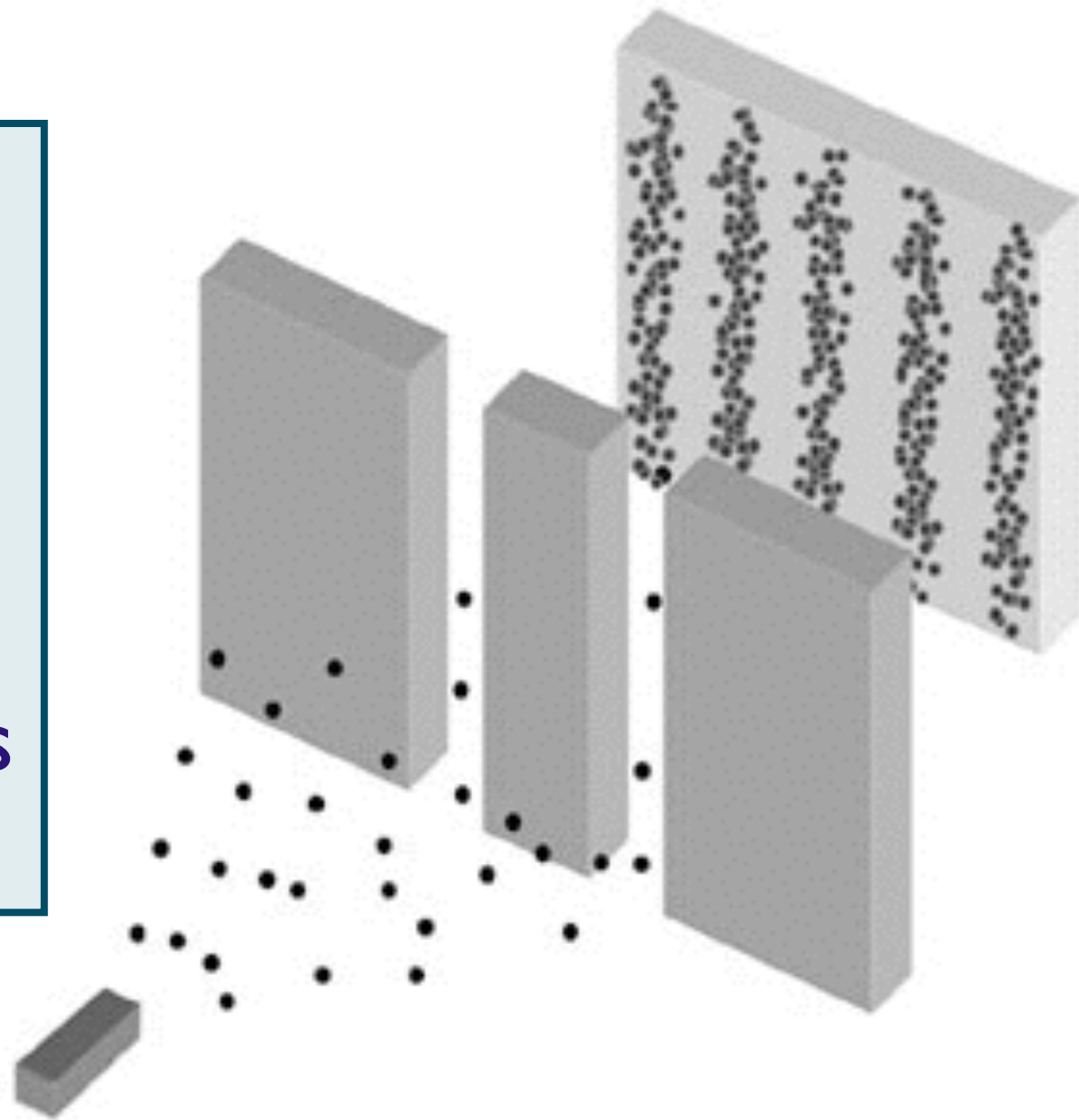
No interference when you watch the electrons

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 ?

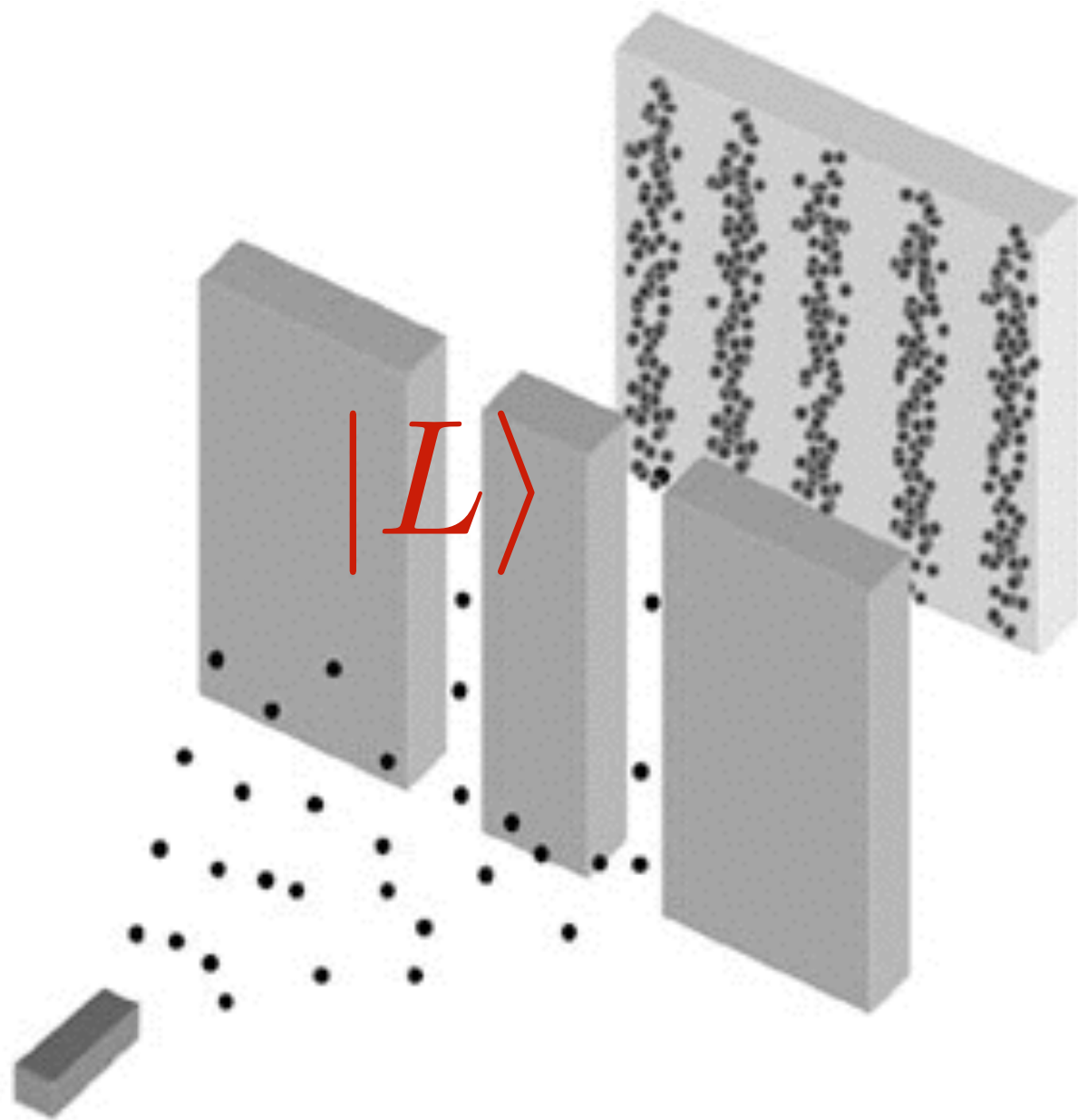


Each electron passes through both slits !

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

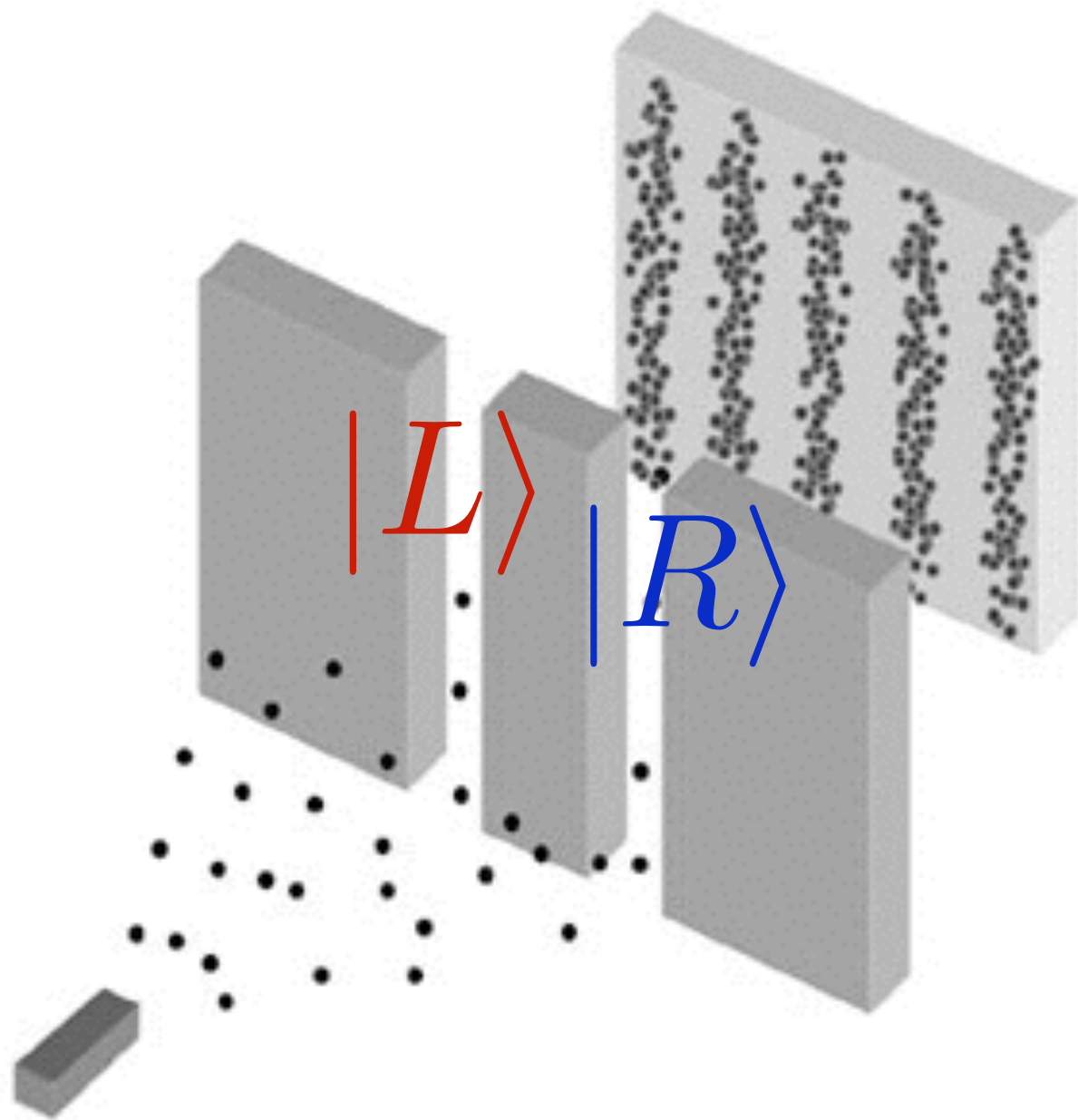
The double slit experiment



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

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

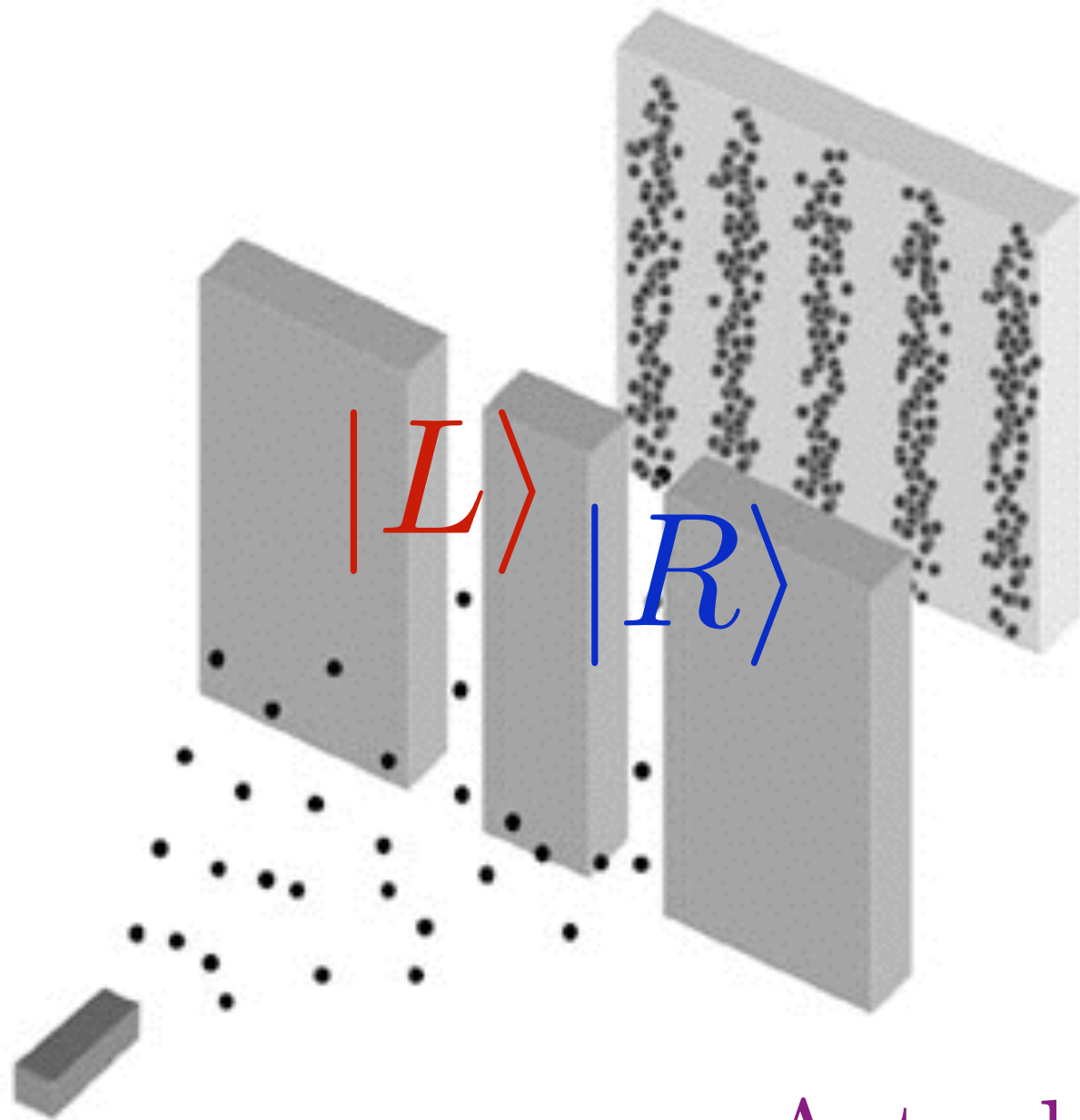


Let $|L\rangle$ represent the state with the electron in the left slit

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

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

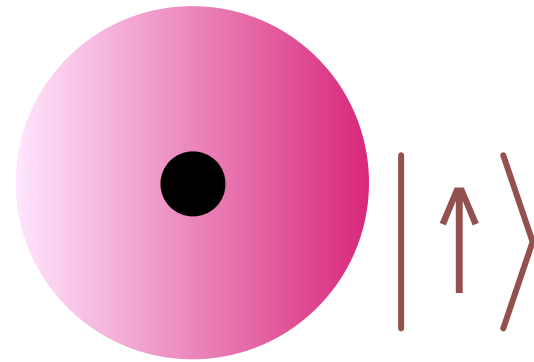
Principles of Quantum Mechanics: II. Quantum Entanglement

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:

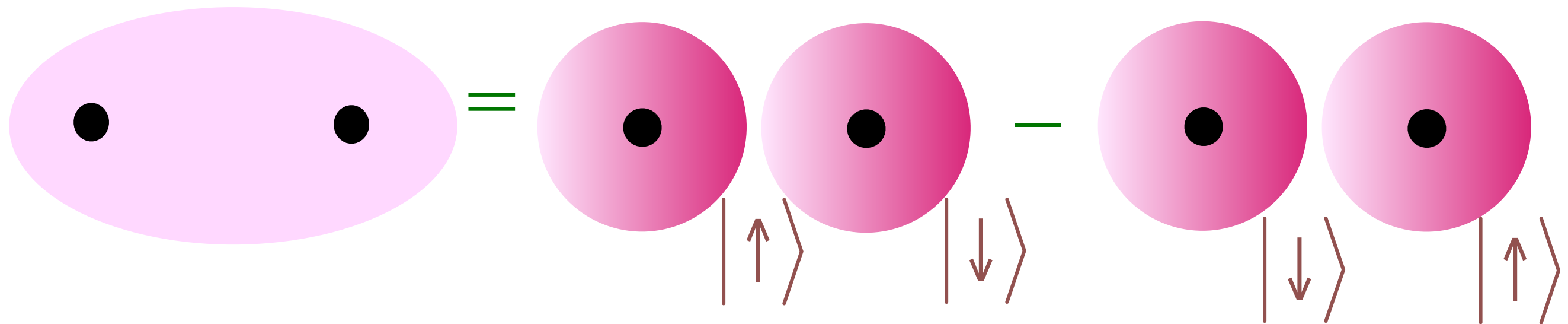


Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom: 

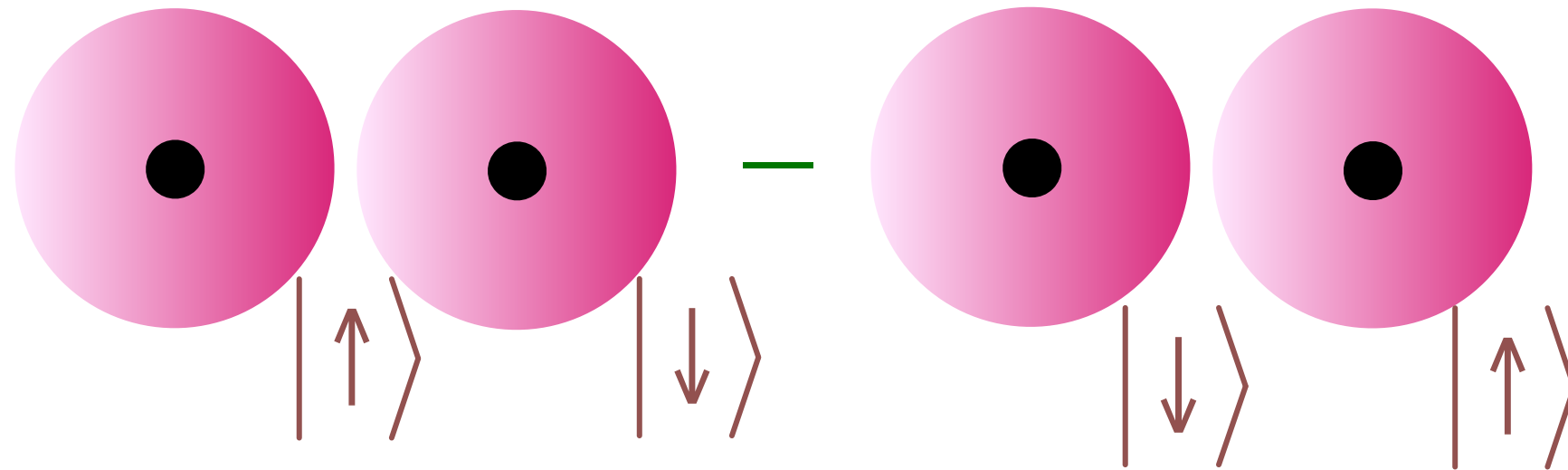
Hydrogen molecule:



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

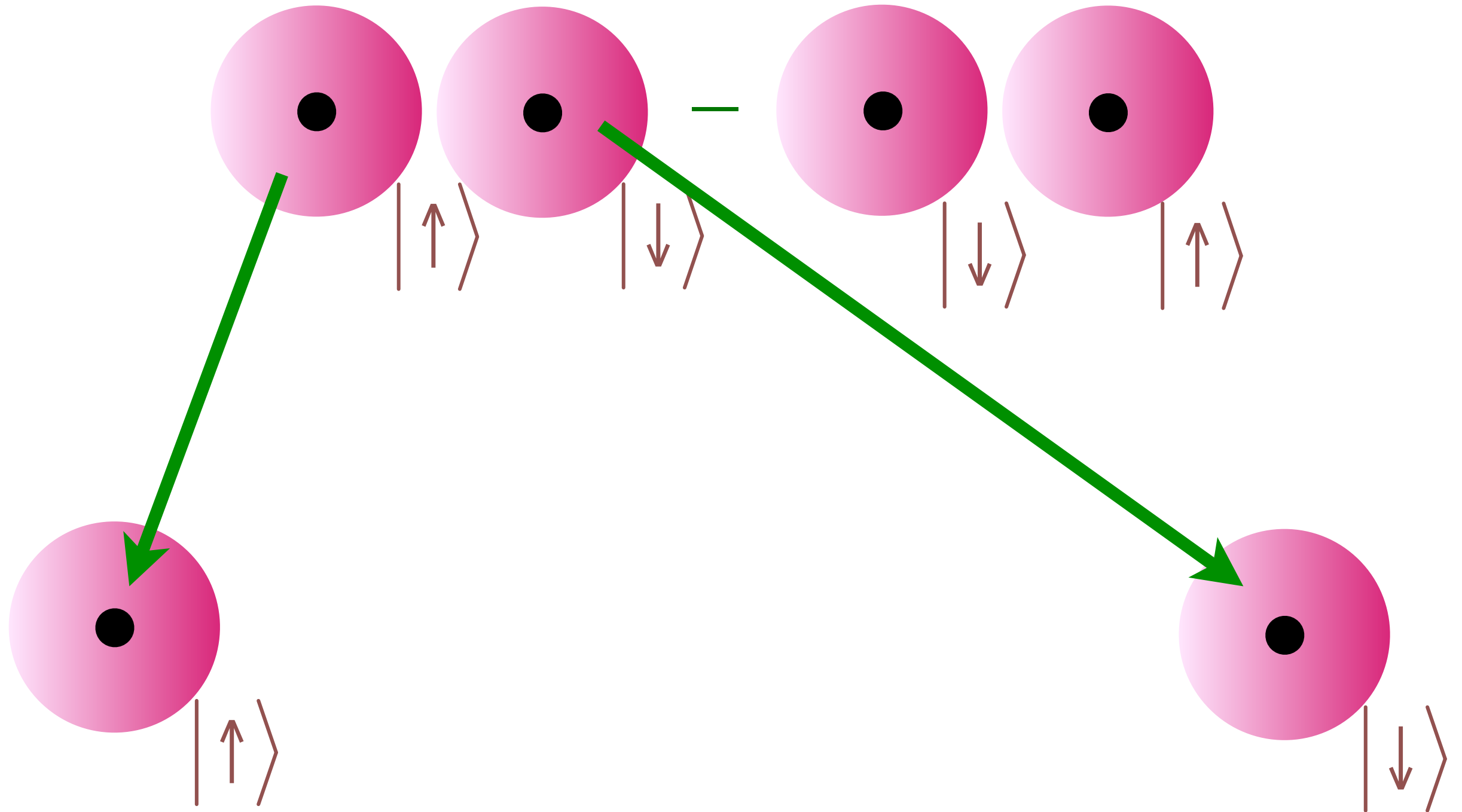
Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle



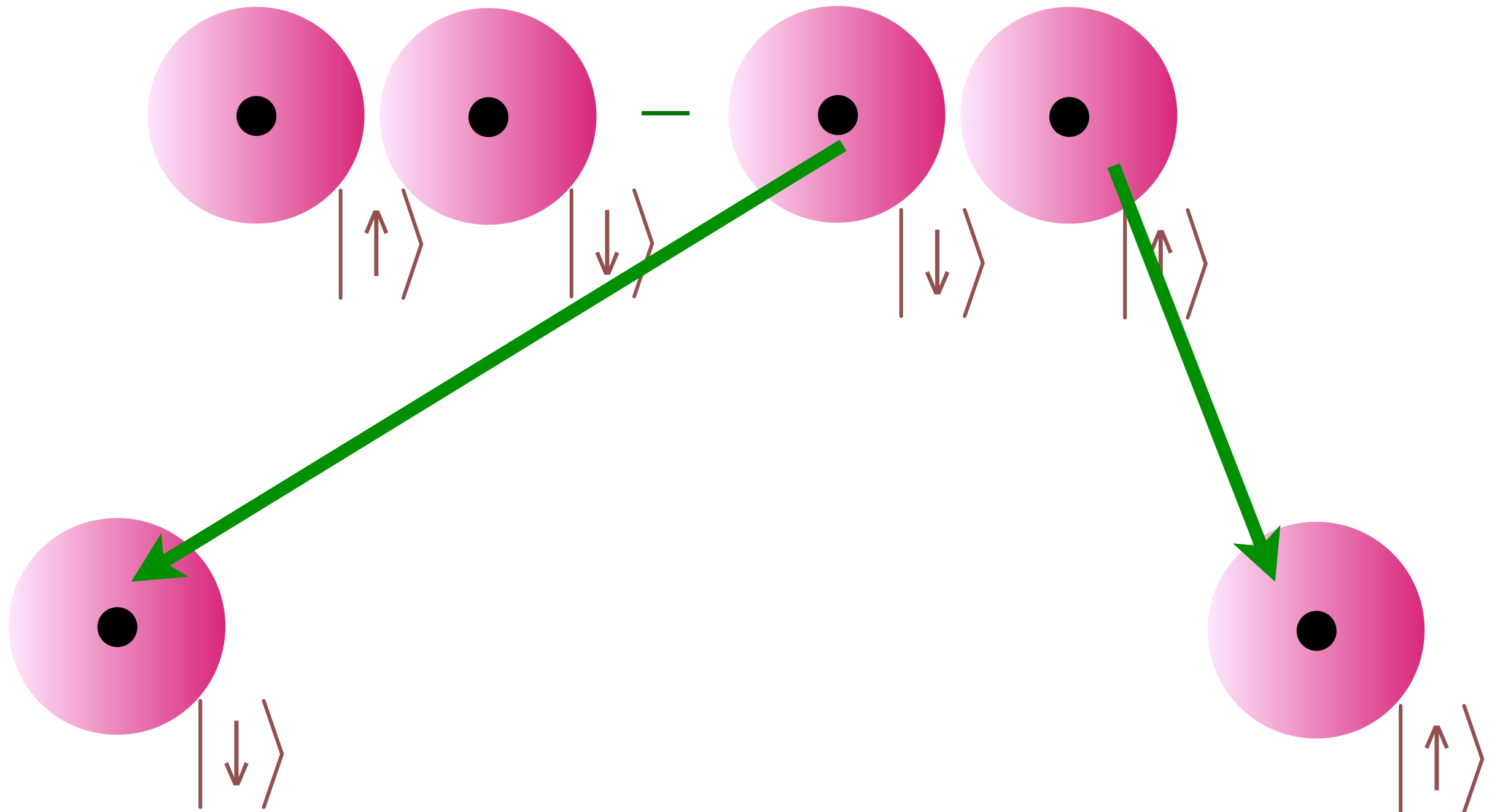
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Quantum Entanglement: quantum superposition with more than one particle



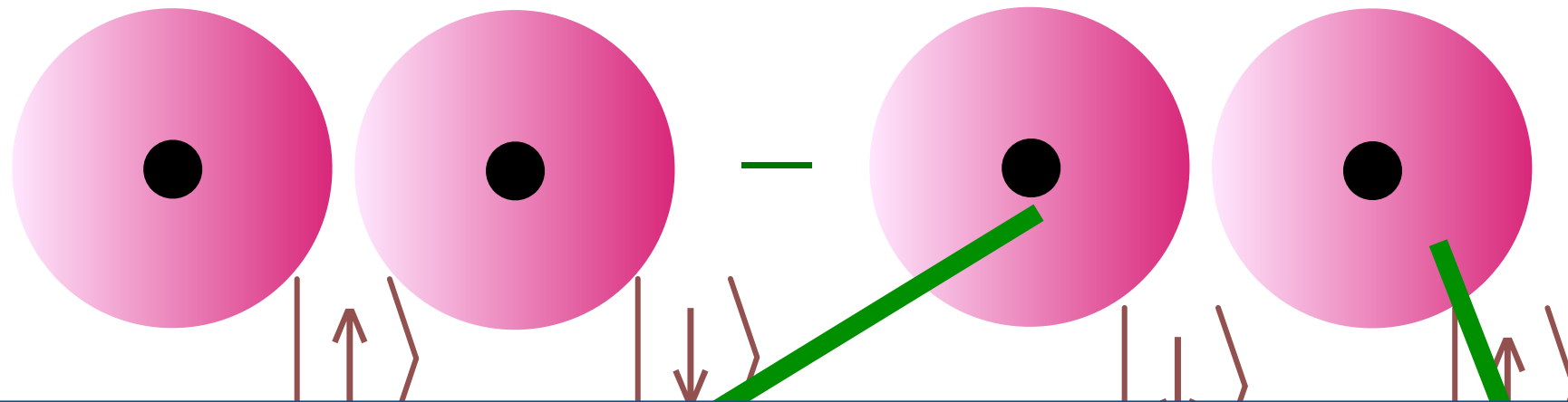
Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

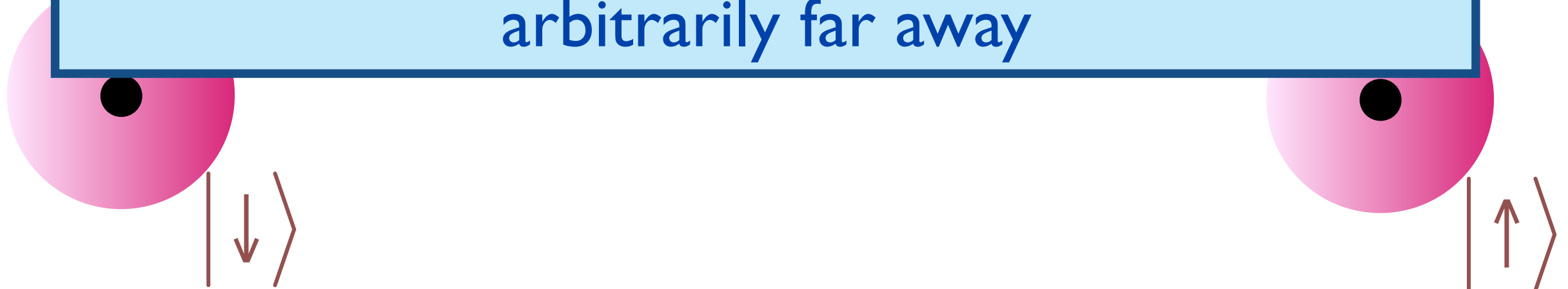


Principles of Quantum Mechanics: II. Quantum Entanglement

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
superposition and
entanglement**

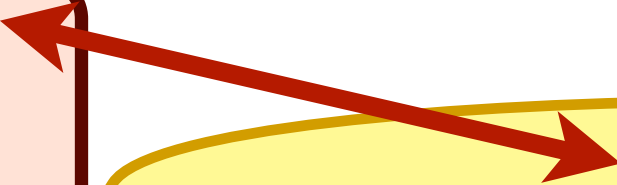
**Quantum
superposition and
entanglement**

**Quantum theory
of black holes**

**Long-range quantum
entanglement of
electrons
in matter:**
(A) **superconductors**
(B) **graphene**

Quantum
superposition and
entanglement

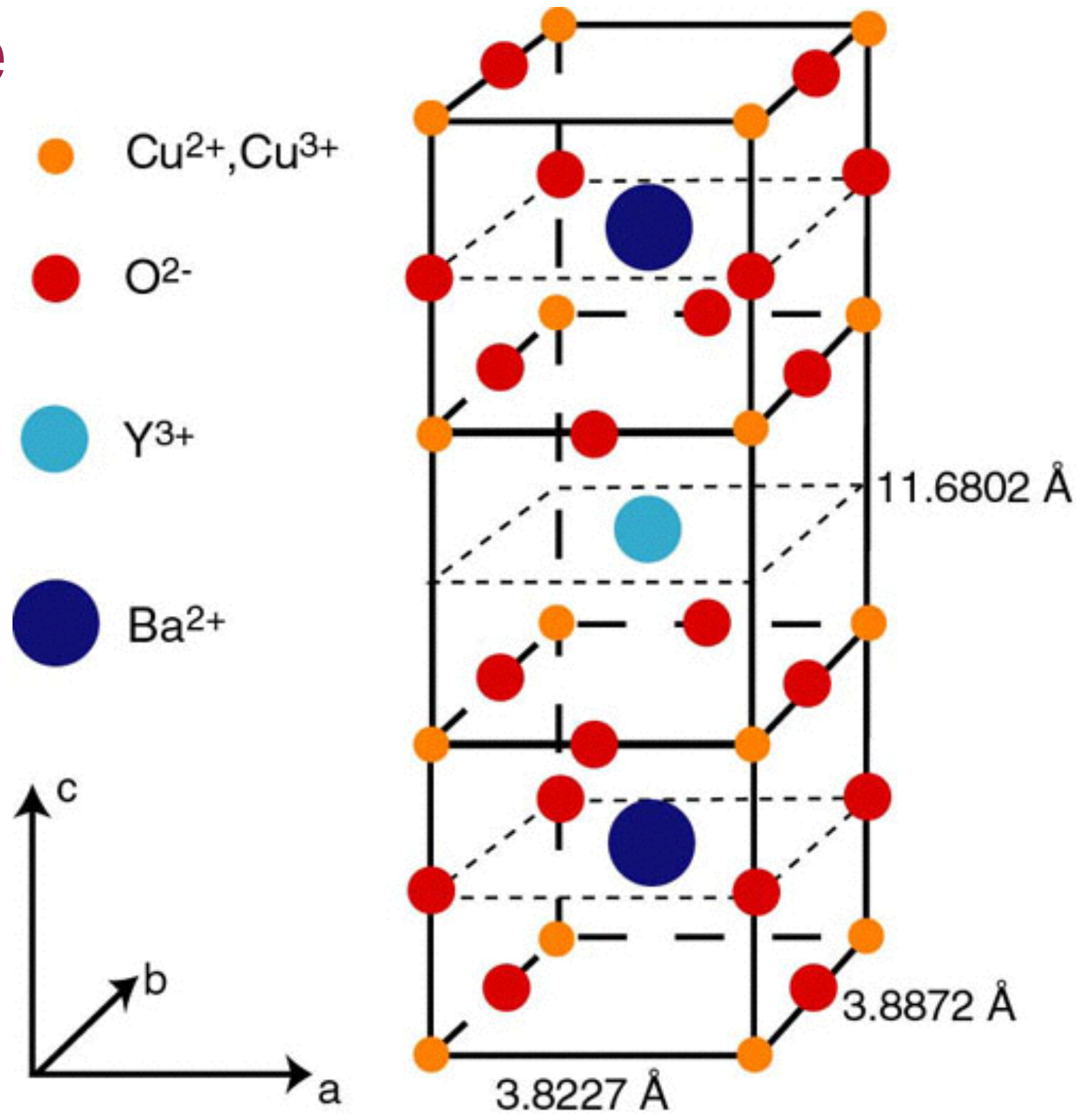
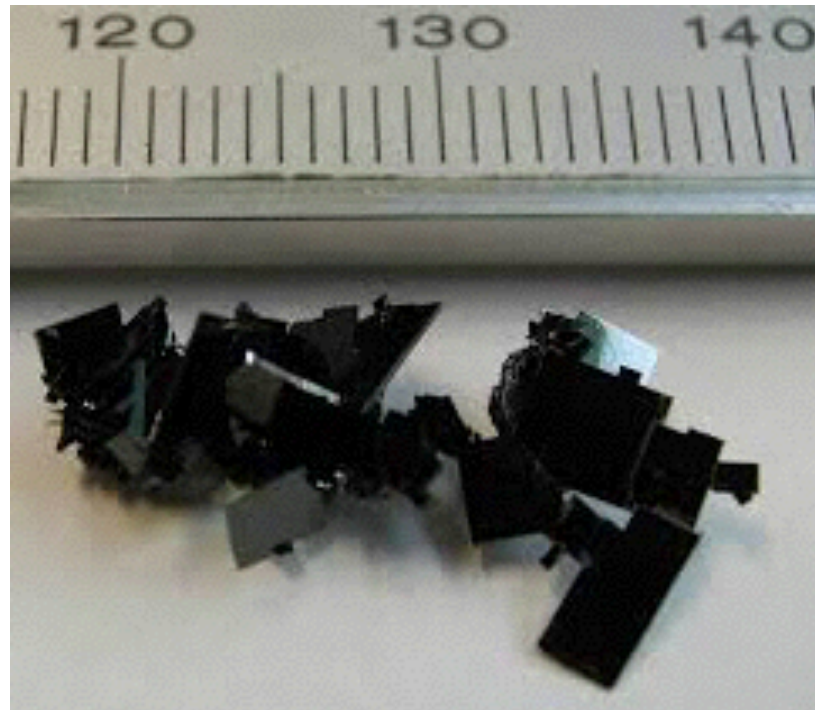
Quantum theory
of black holes



Long-range quantum
entanglement of
electrons
in matter:

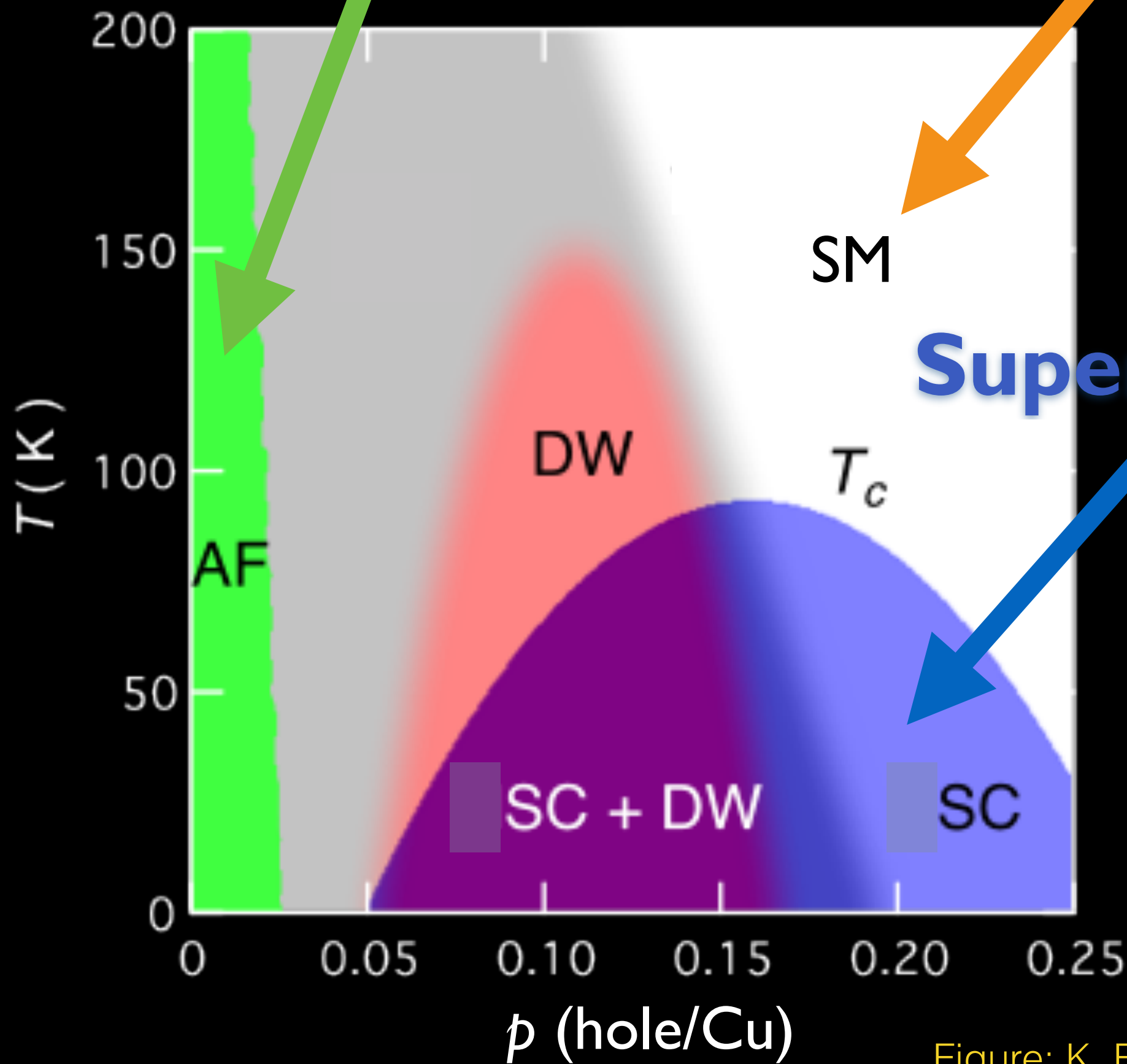
- (A) superconductors
- (B) graphene

High temperature superconductors



Antiferromagnet

Strange metal



Superconductor

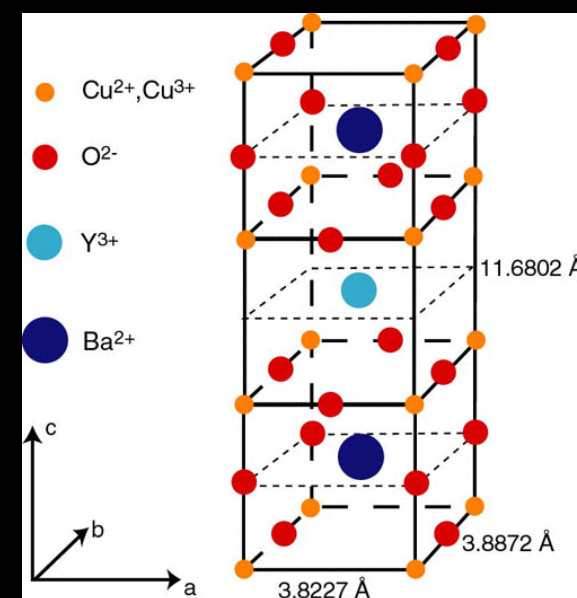


Figure: K. Fujita and J. C. Seamus Davis

Antiferromagnet

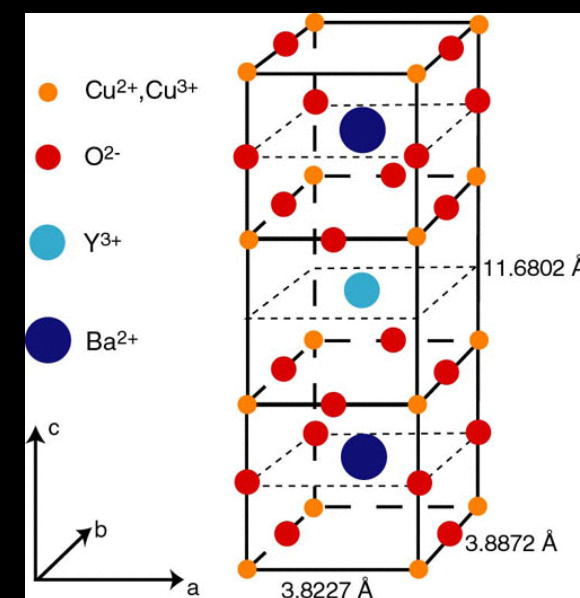
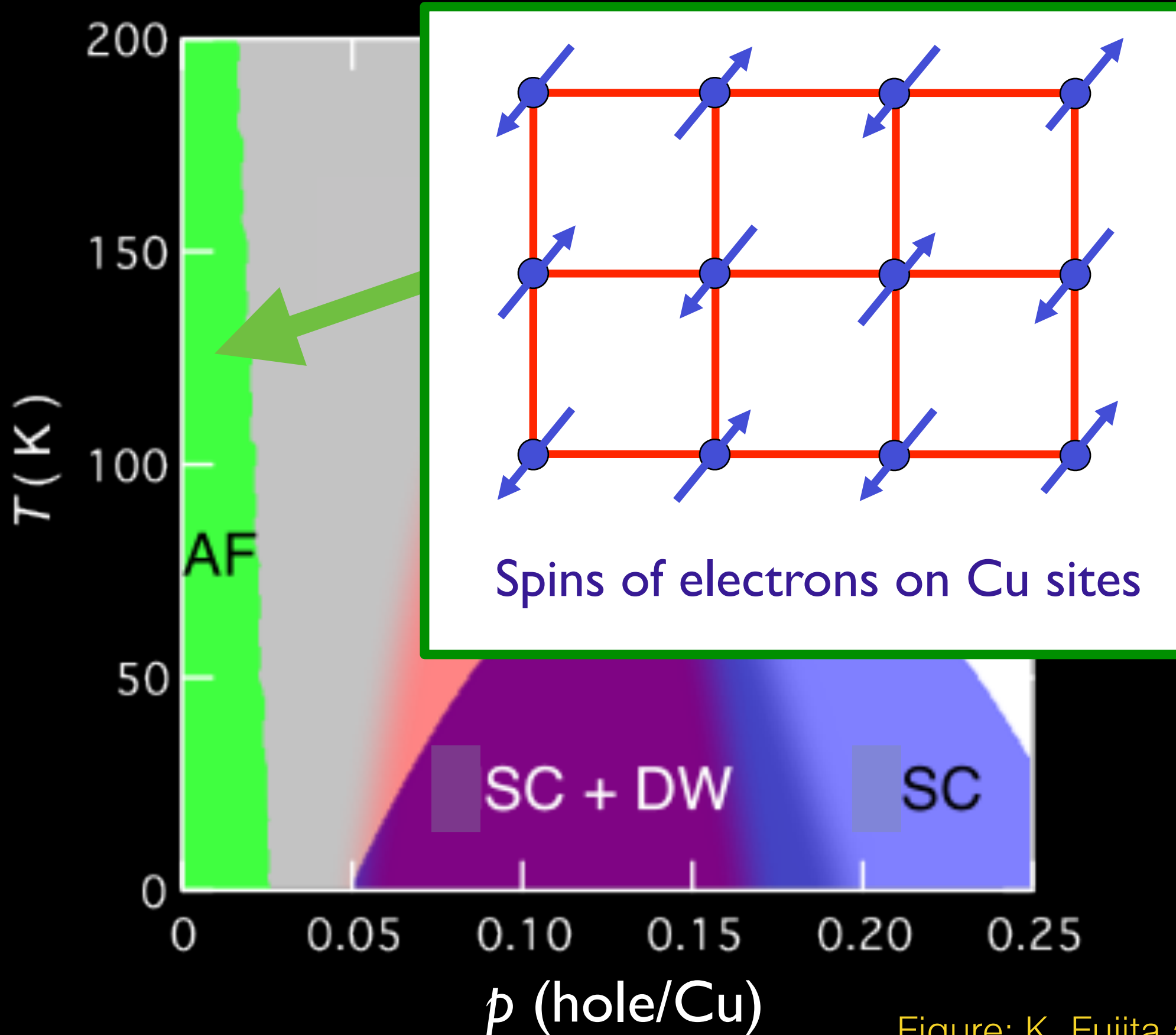
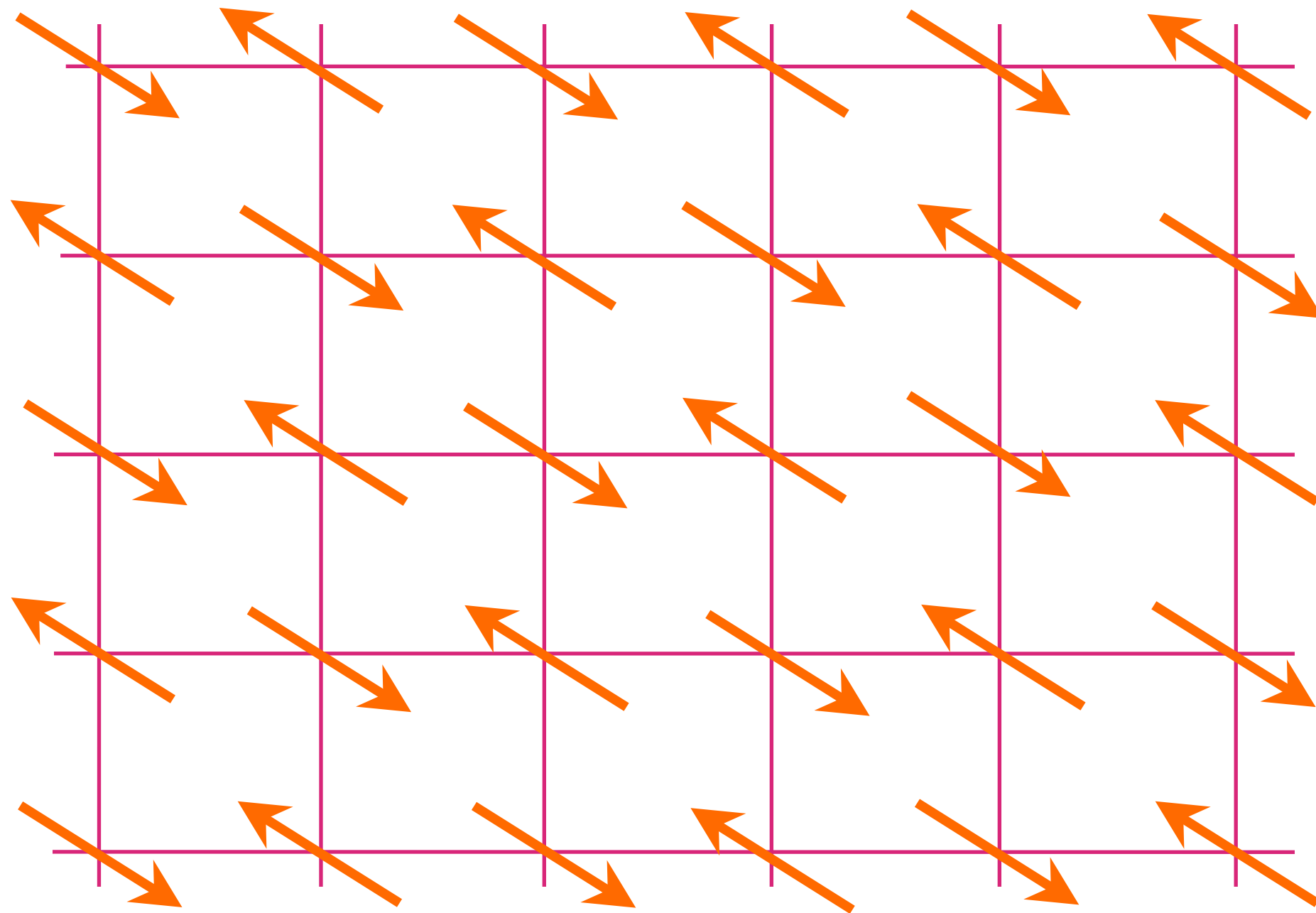
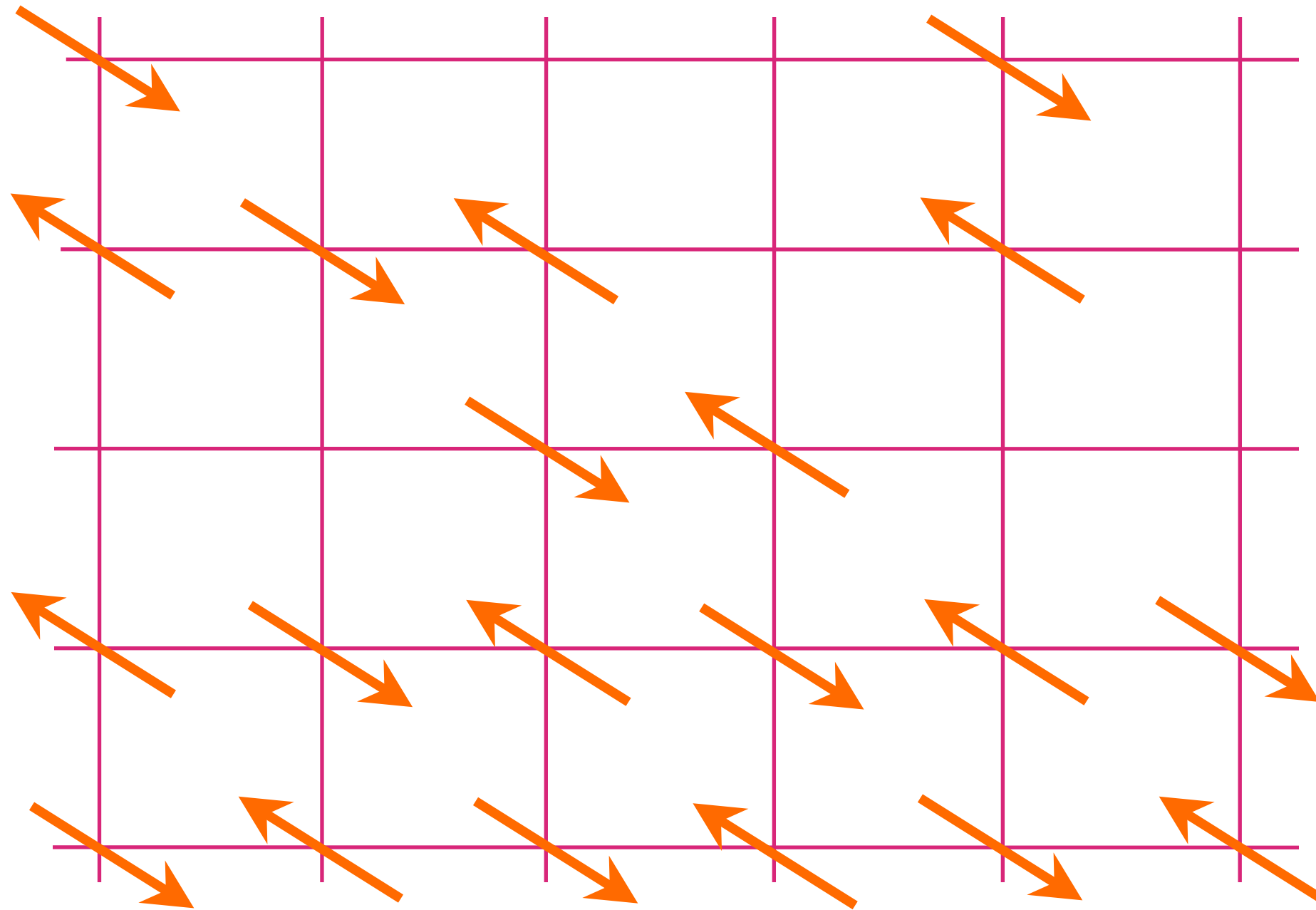


Figure: K. Fujita and J. C. Seamus Davis

Square lattice of Cu sites

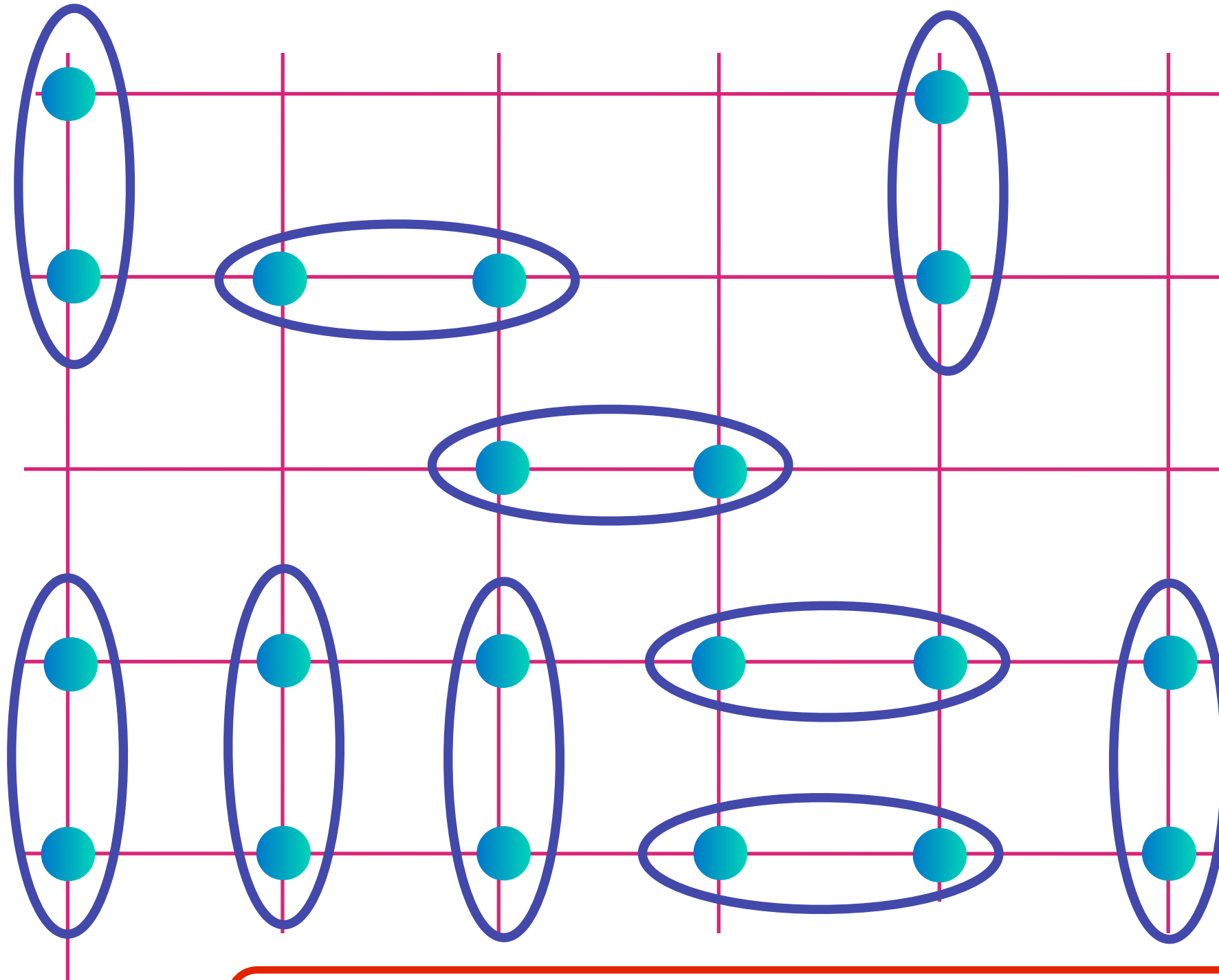


Square lattice of Cu sites



Remove density
 p electrons

Square lattice of Cu sites

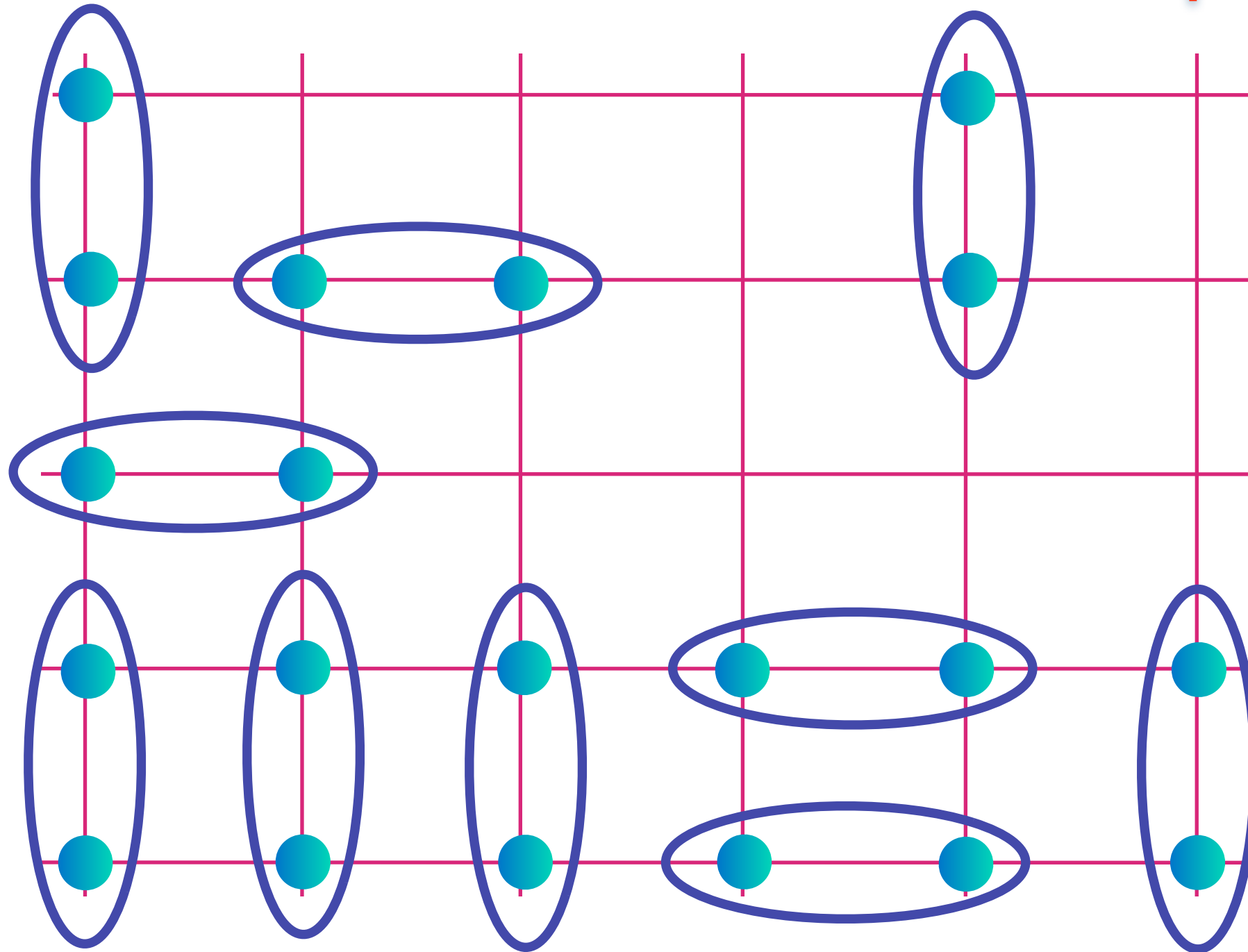


Electrons entangle in (“Cooper”) pairs into chemical bonds

$$\text{[Diagram of a pair of sites]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Square lattice of Cu sites

Superconductivity !

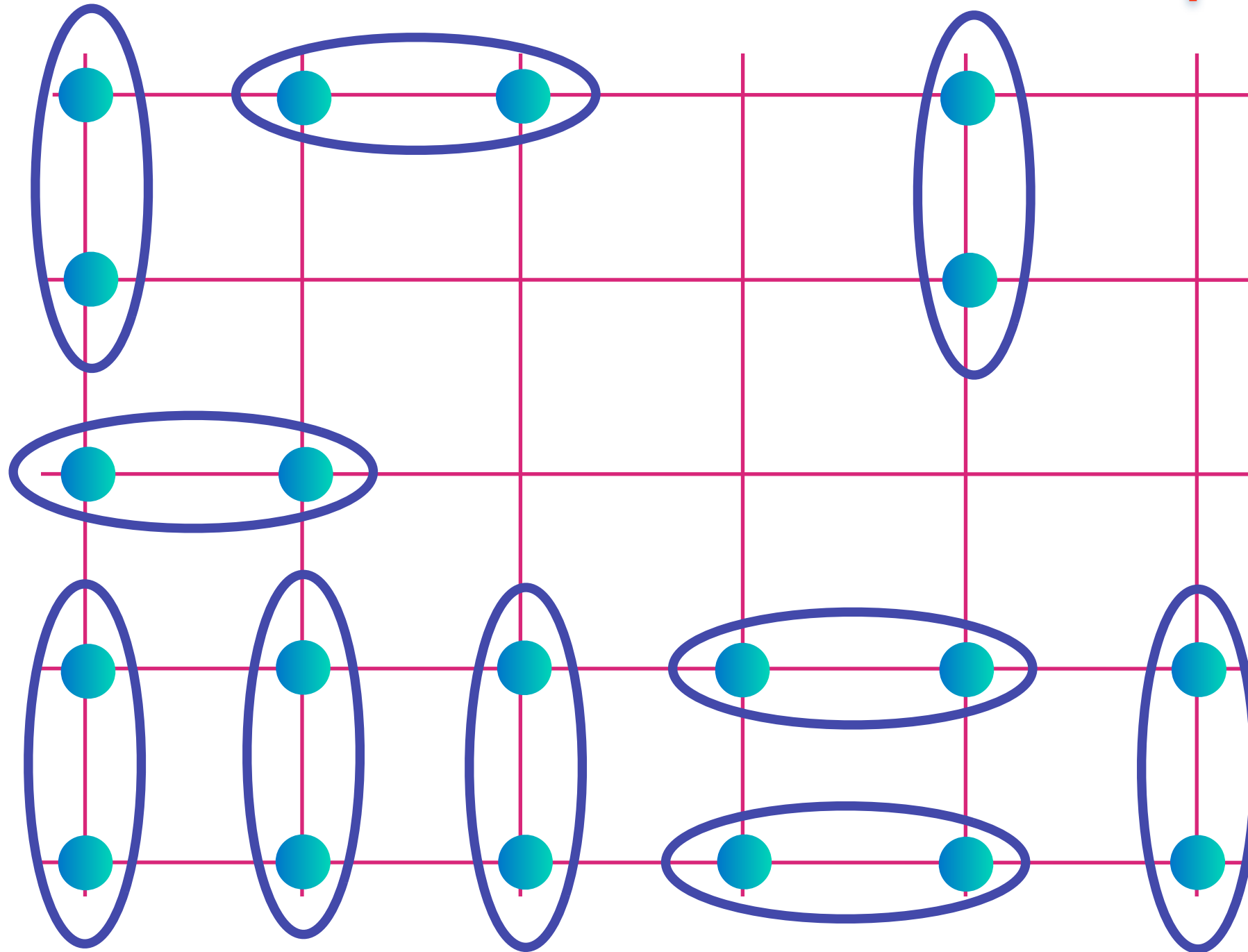


Cooper pairs form quantum superpositions at different locations: “Bose-Einstein condensation” in which all pairs are “everywhere at the same time”

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

Square lattice of Cu sites

Superconductivity !

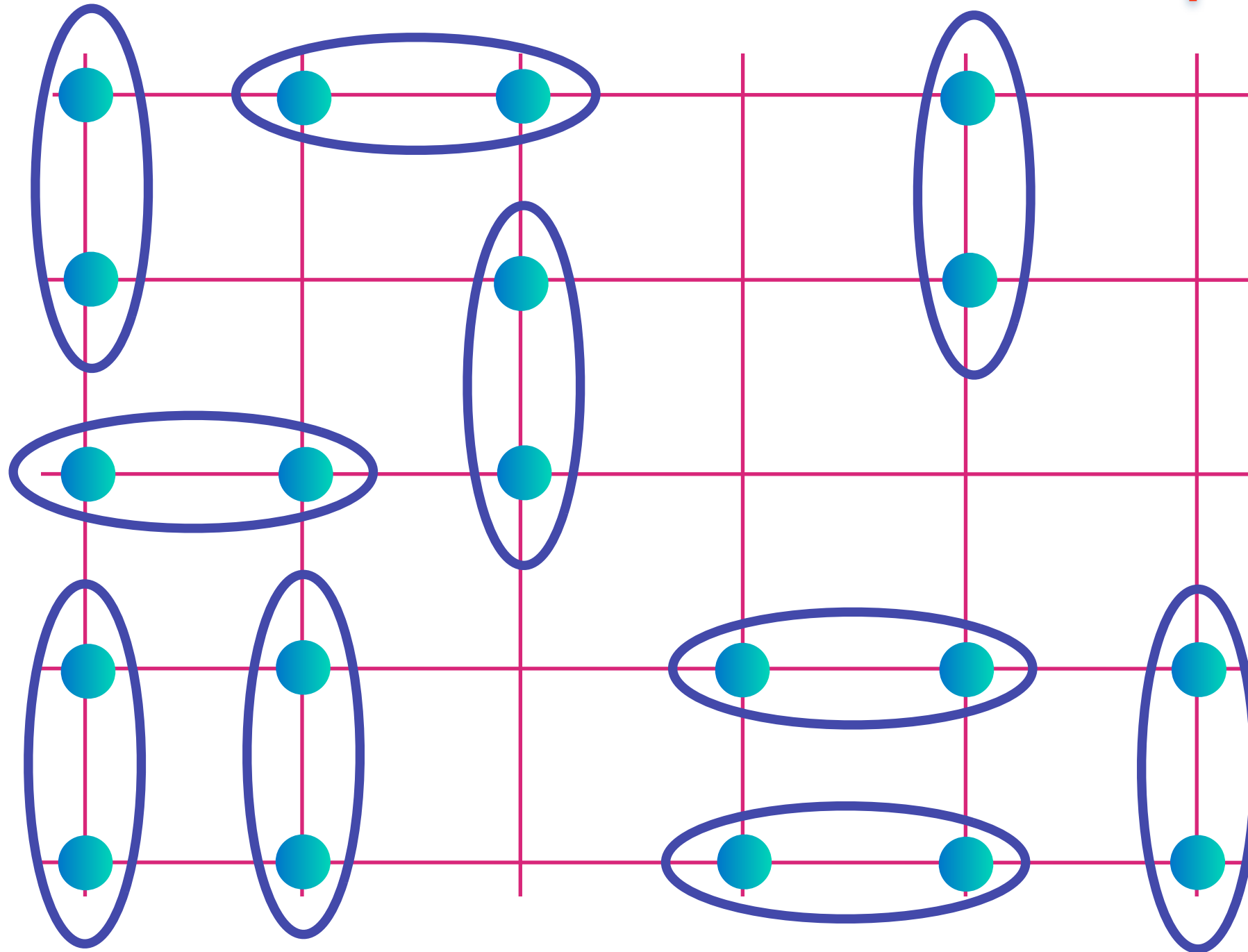


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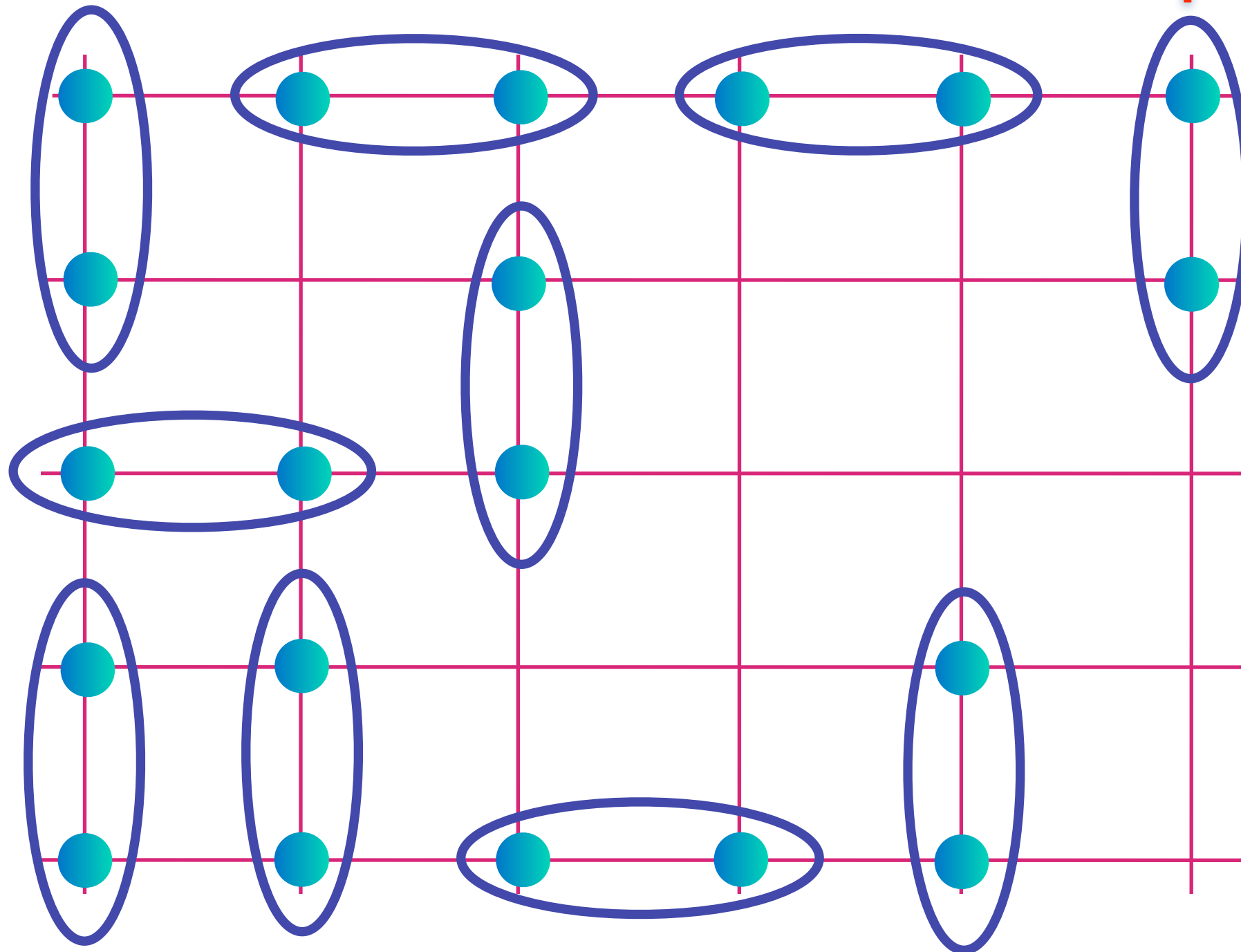


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Square lattice of Cu sites

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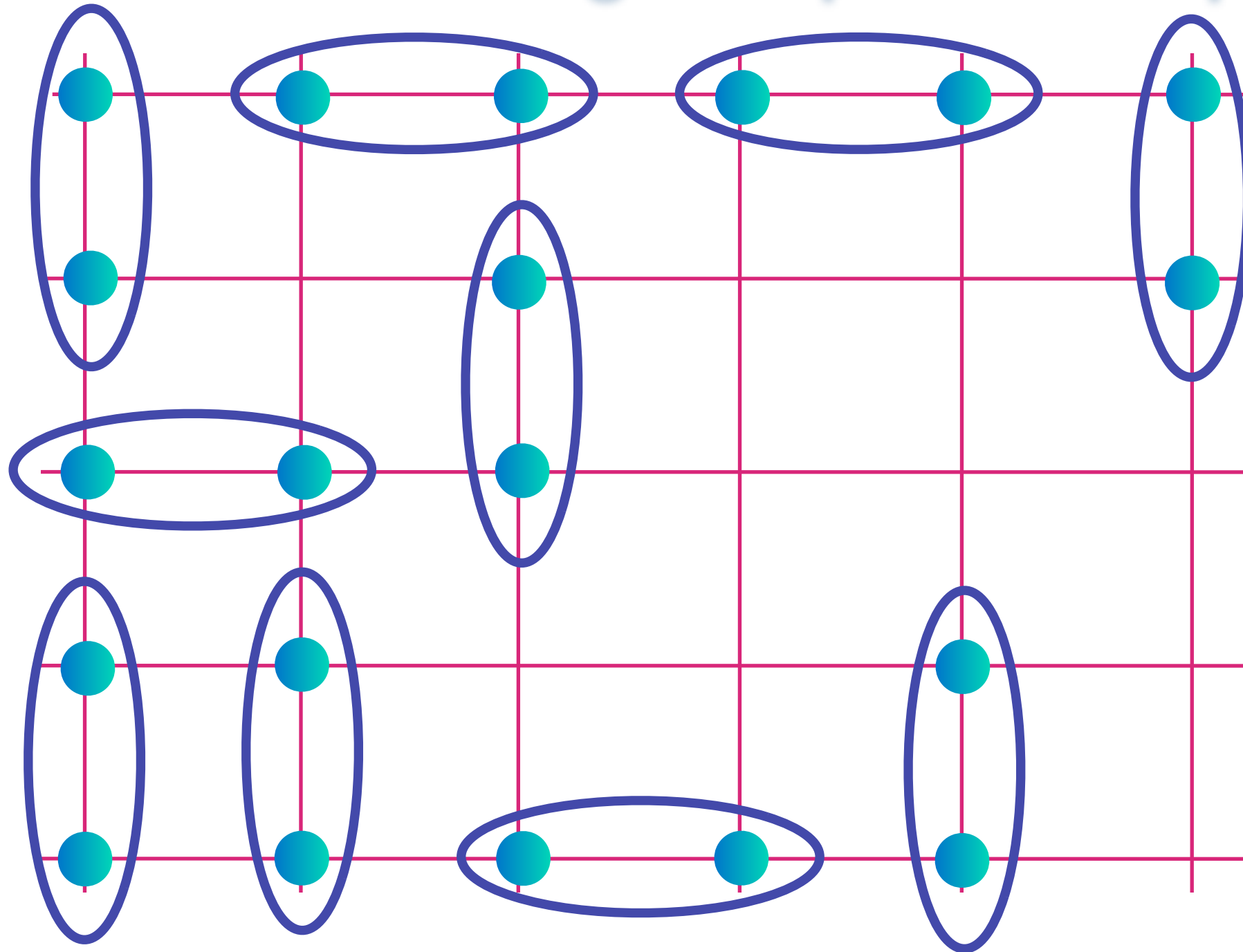


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Square lattice of Cu sites

High temperature superconductivity ?

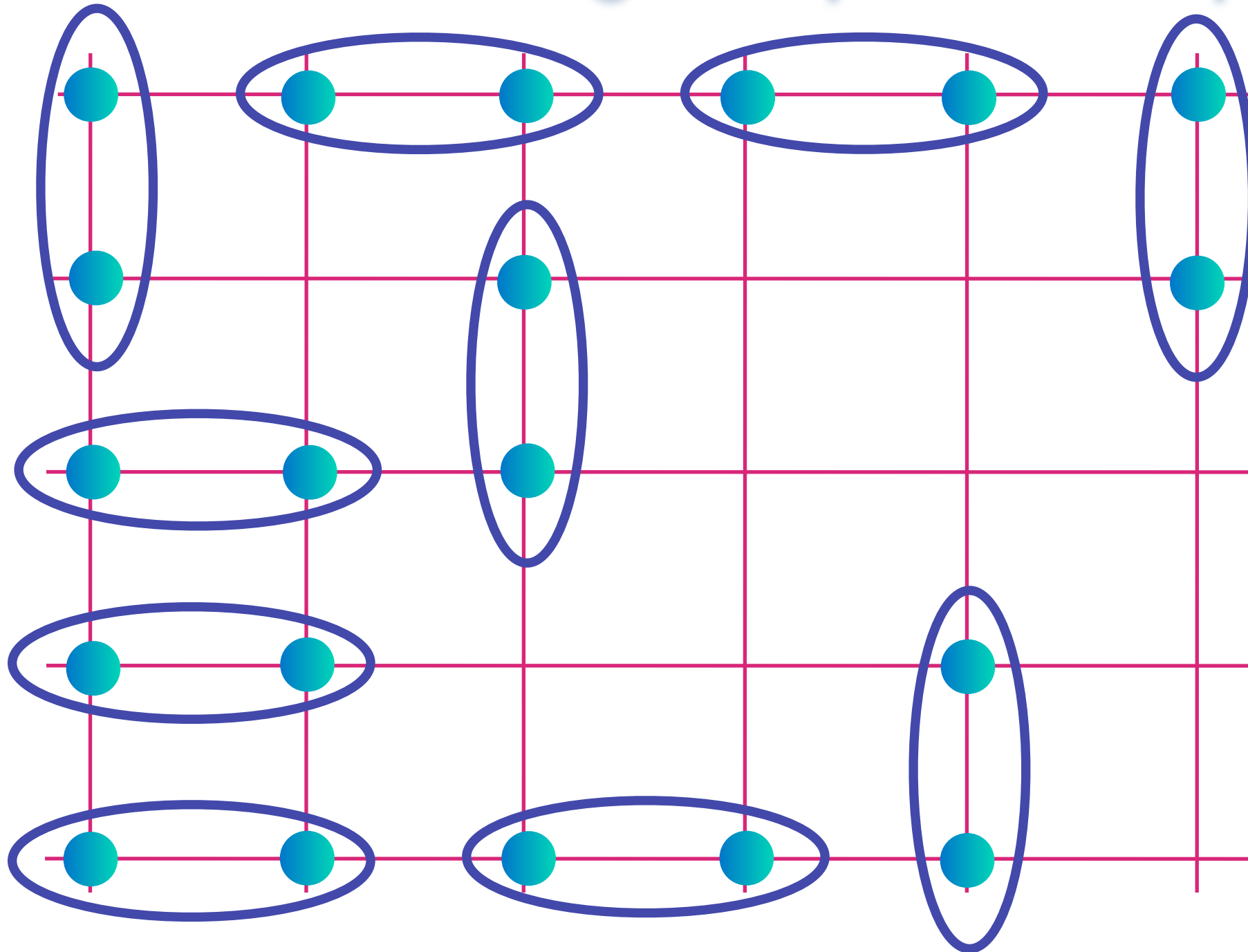


Electrons entangle by exchanging partners, and there is long-range quantum entanglement near the strange metal.

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

Square lattice of Cu sites

High temperature superconductivity ?

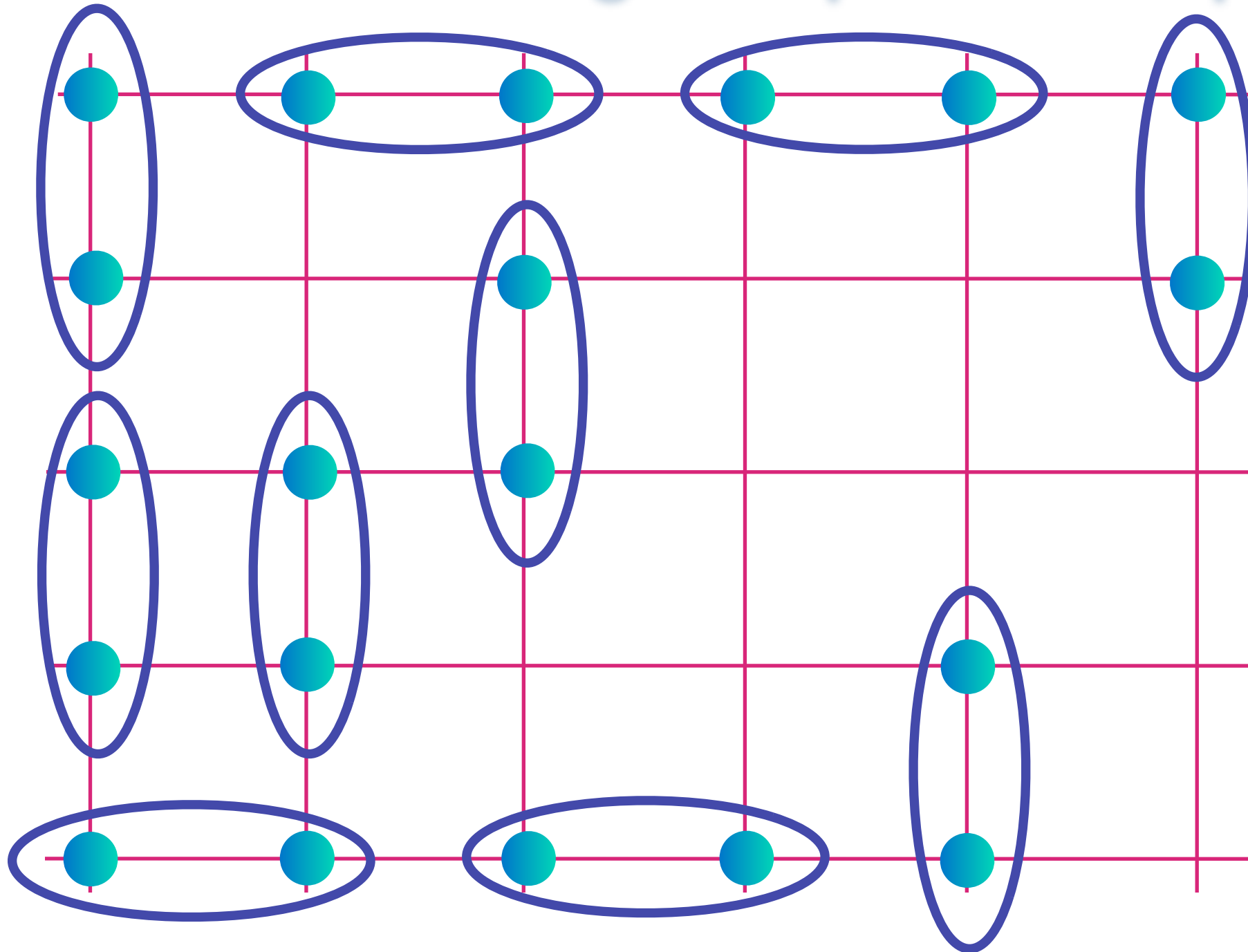


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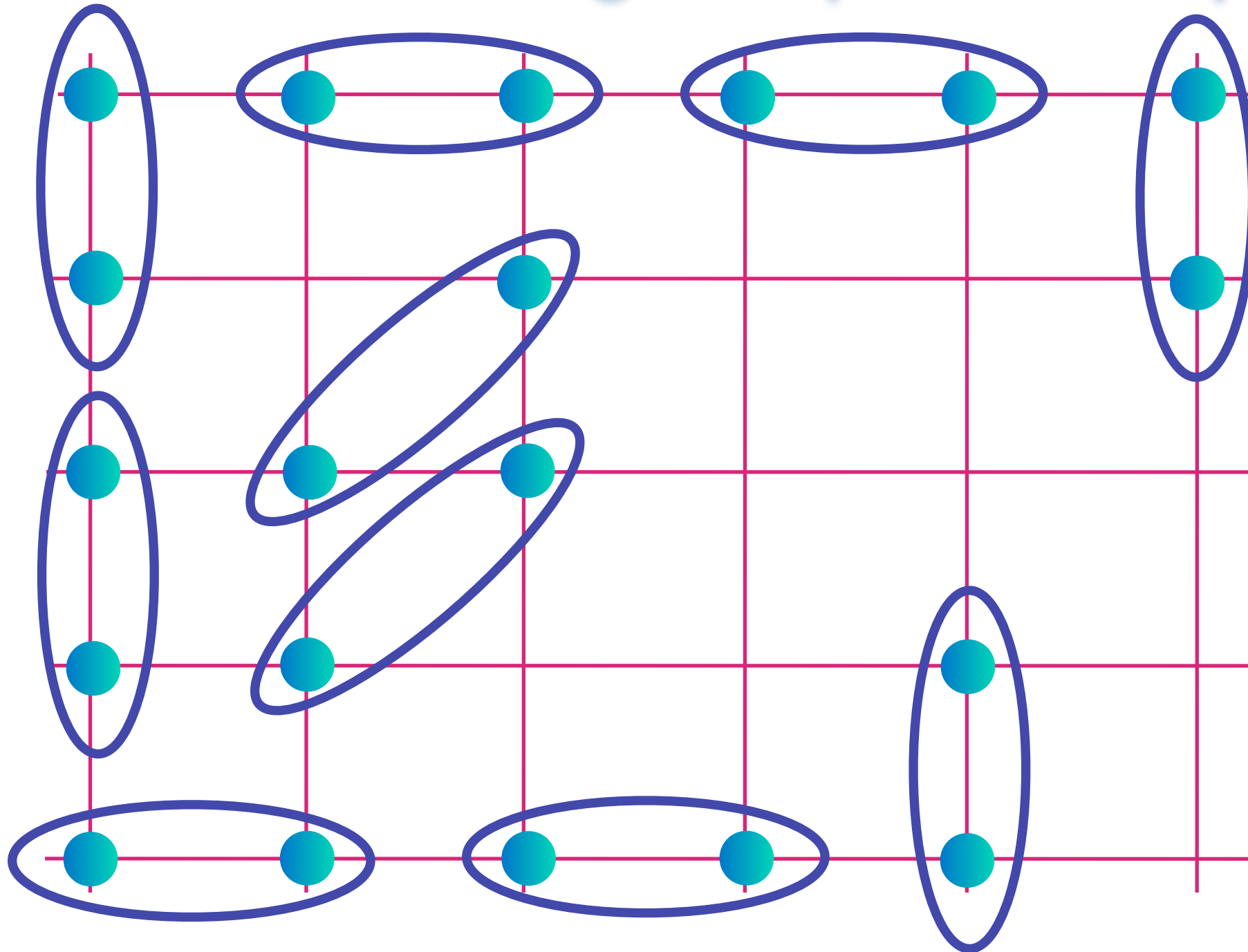


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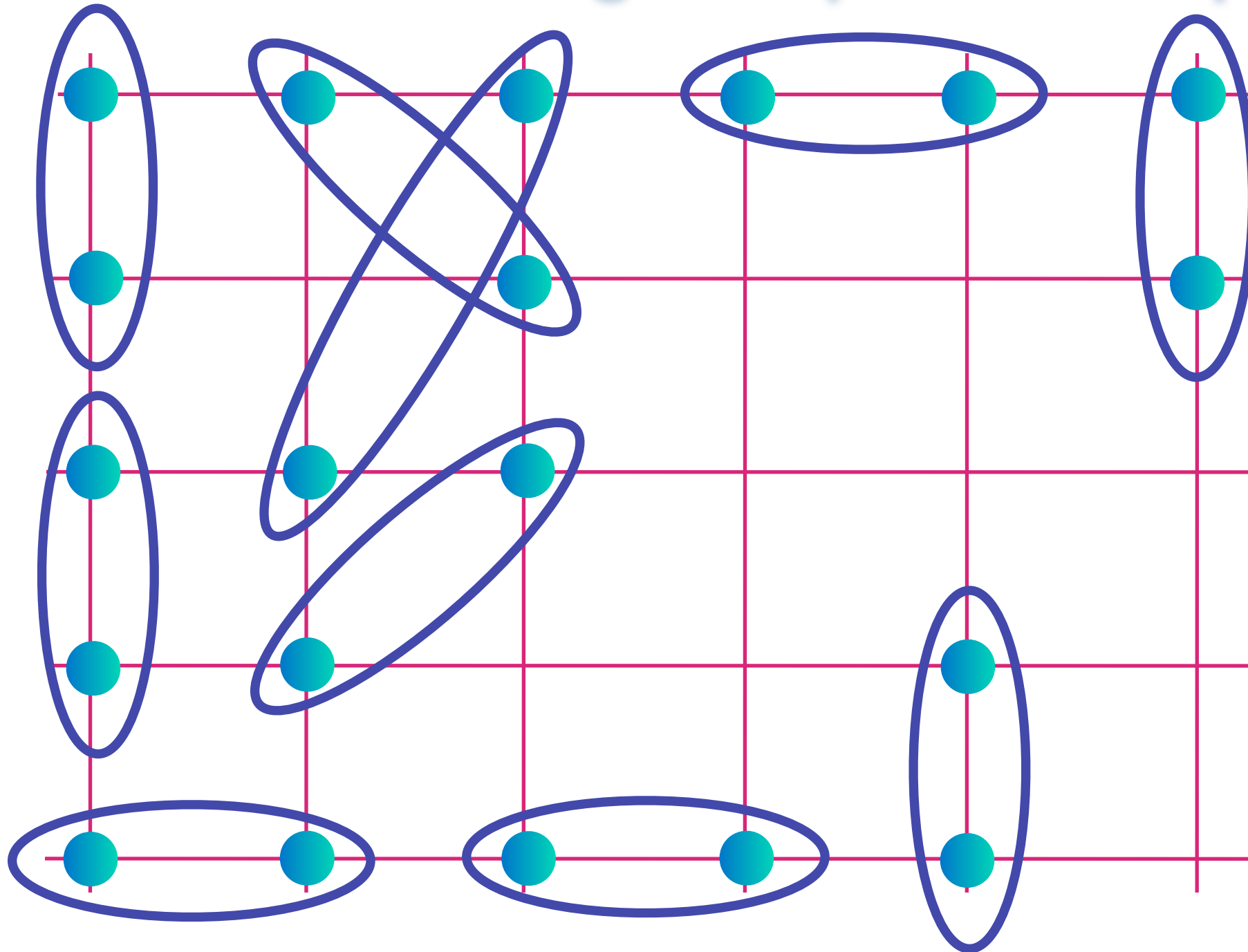


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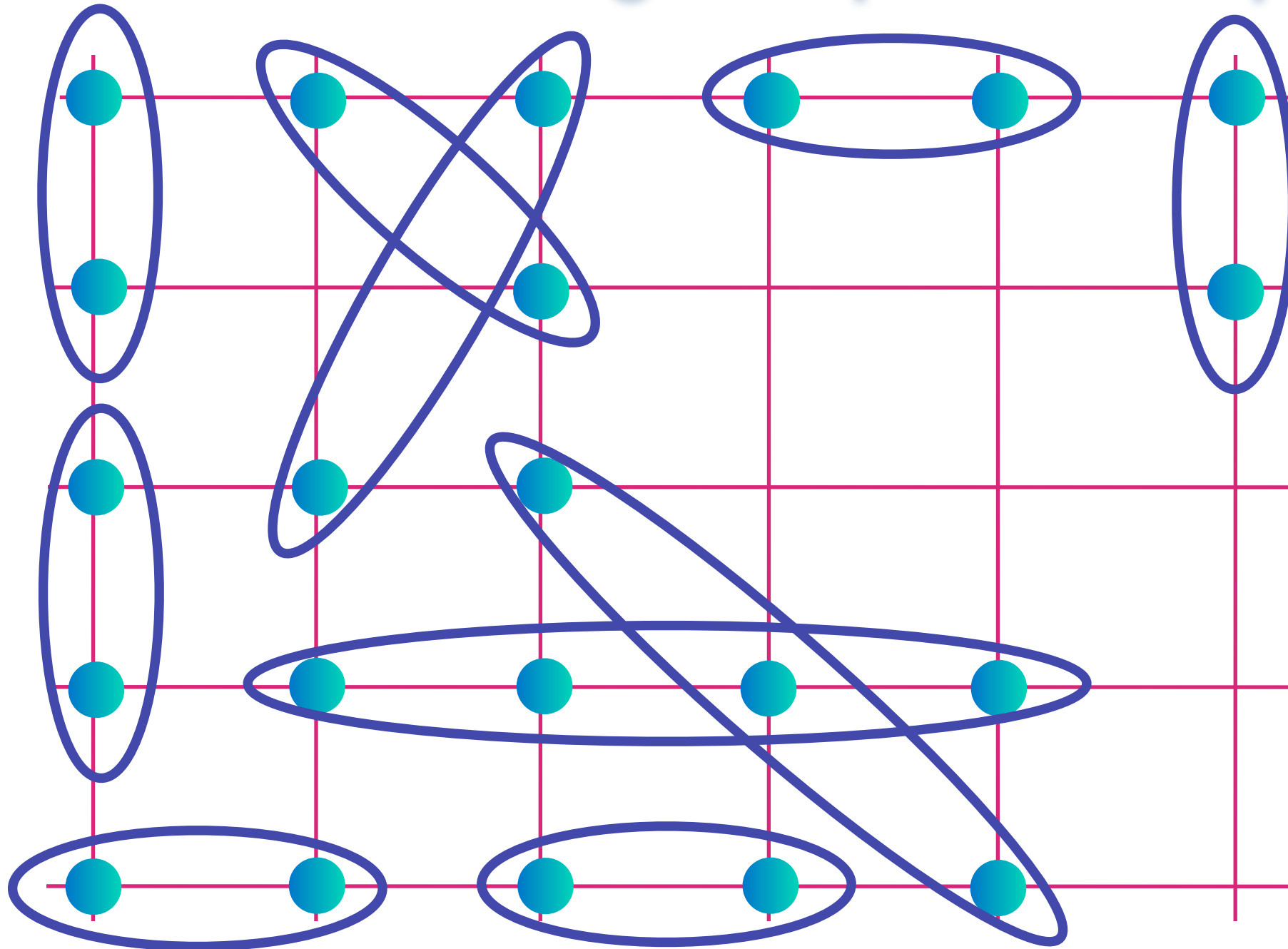


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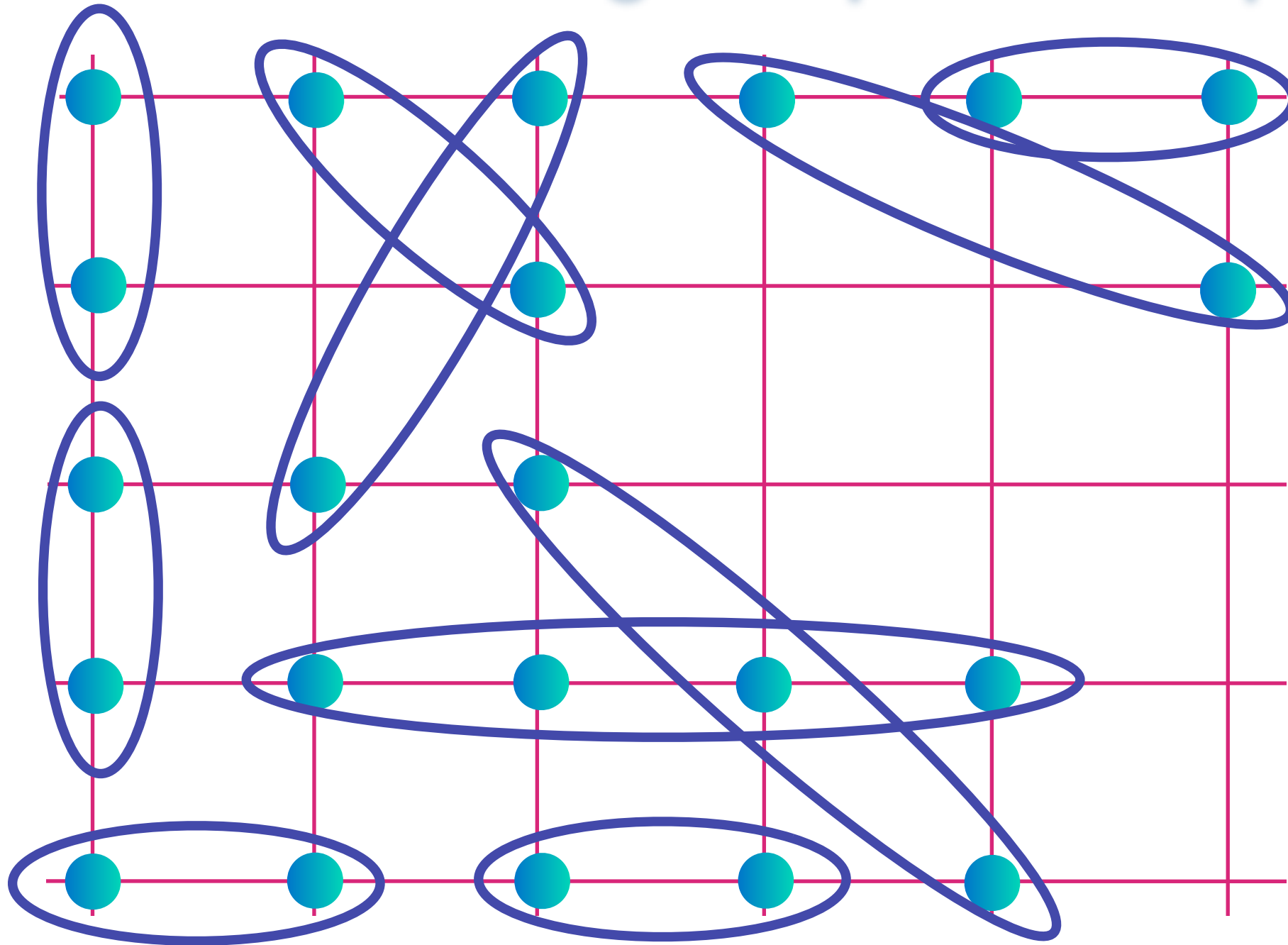


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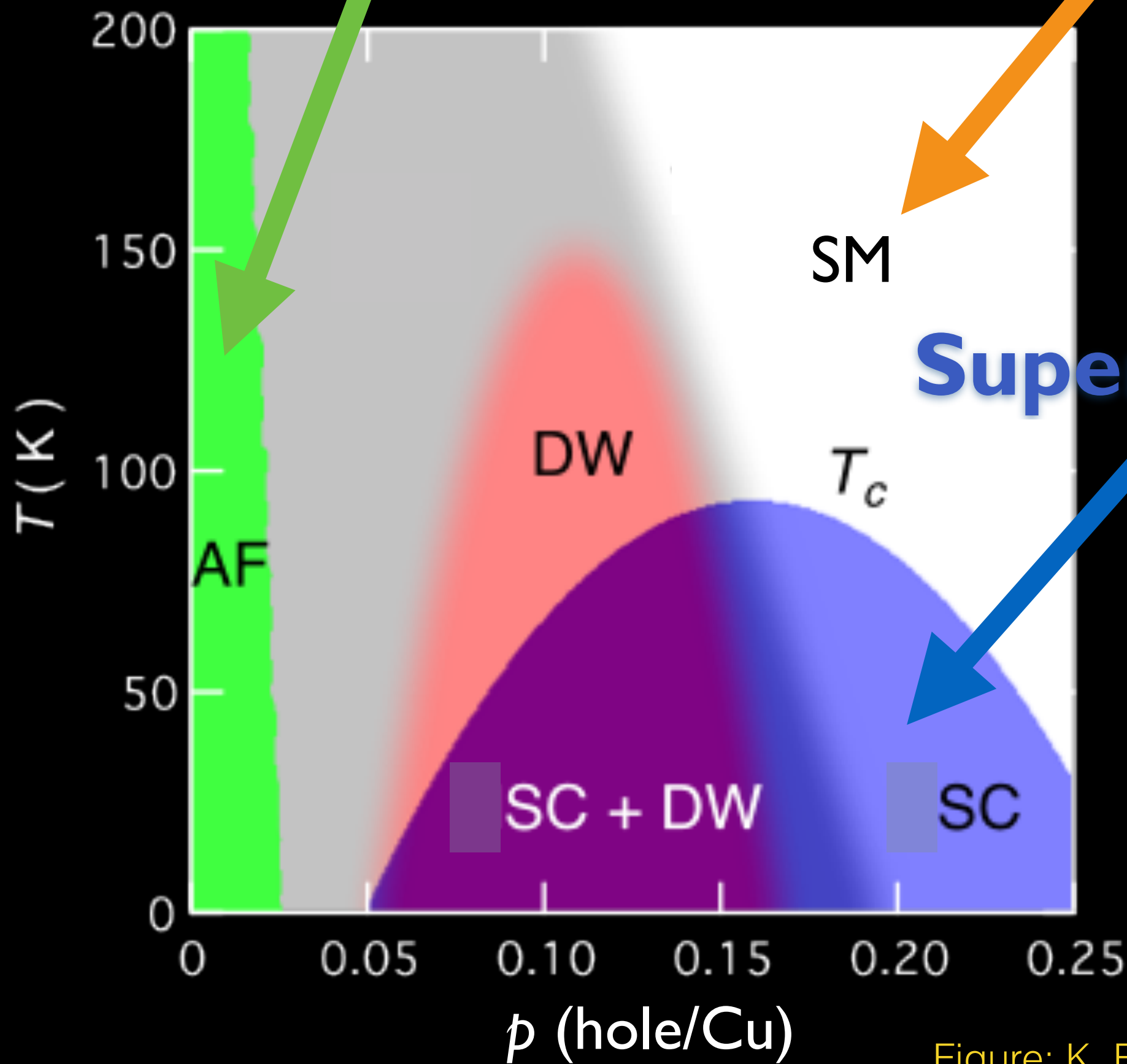


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Antiferromagnet

Strange metal



Superconductor

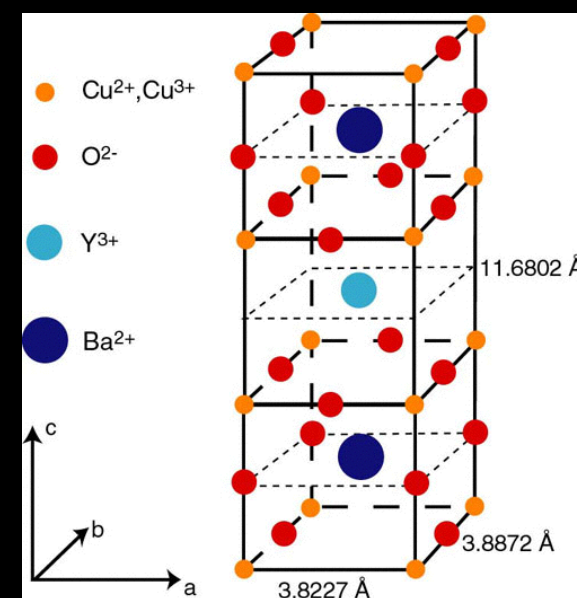
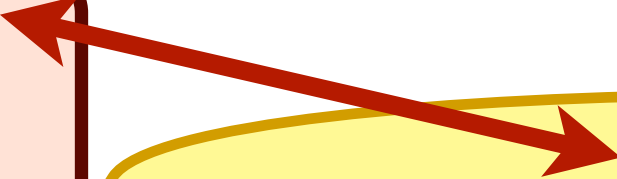


Figure: K. Fujita and J. C. Seamus Davis

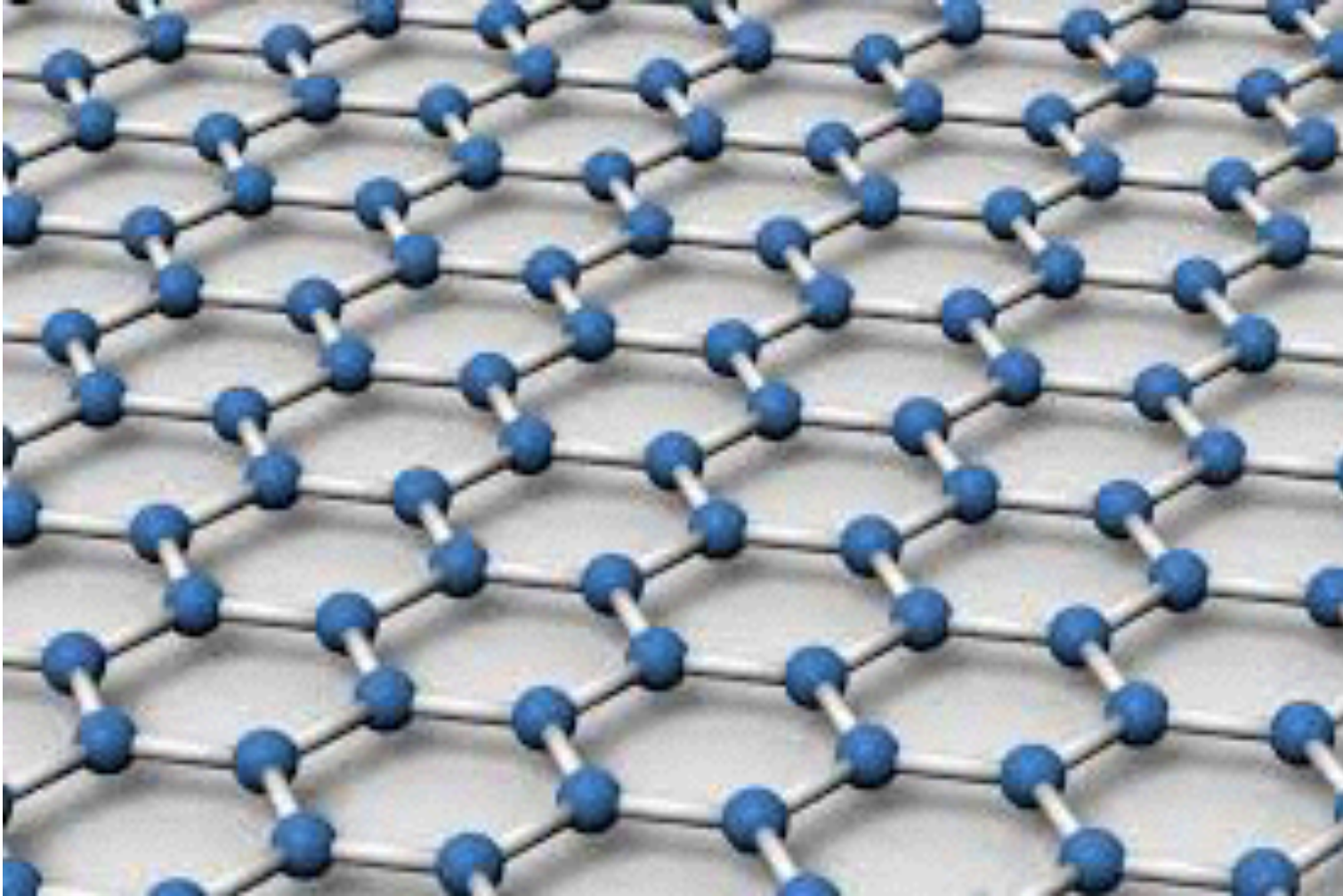
Quantum
superposition and
entanglement

Quantum theory
of black holes



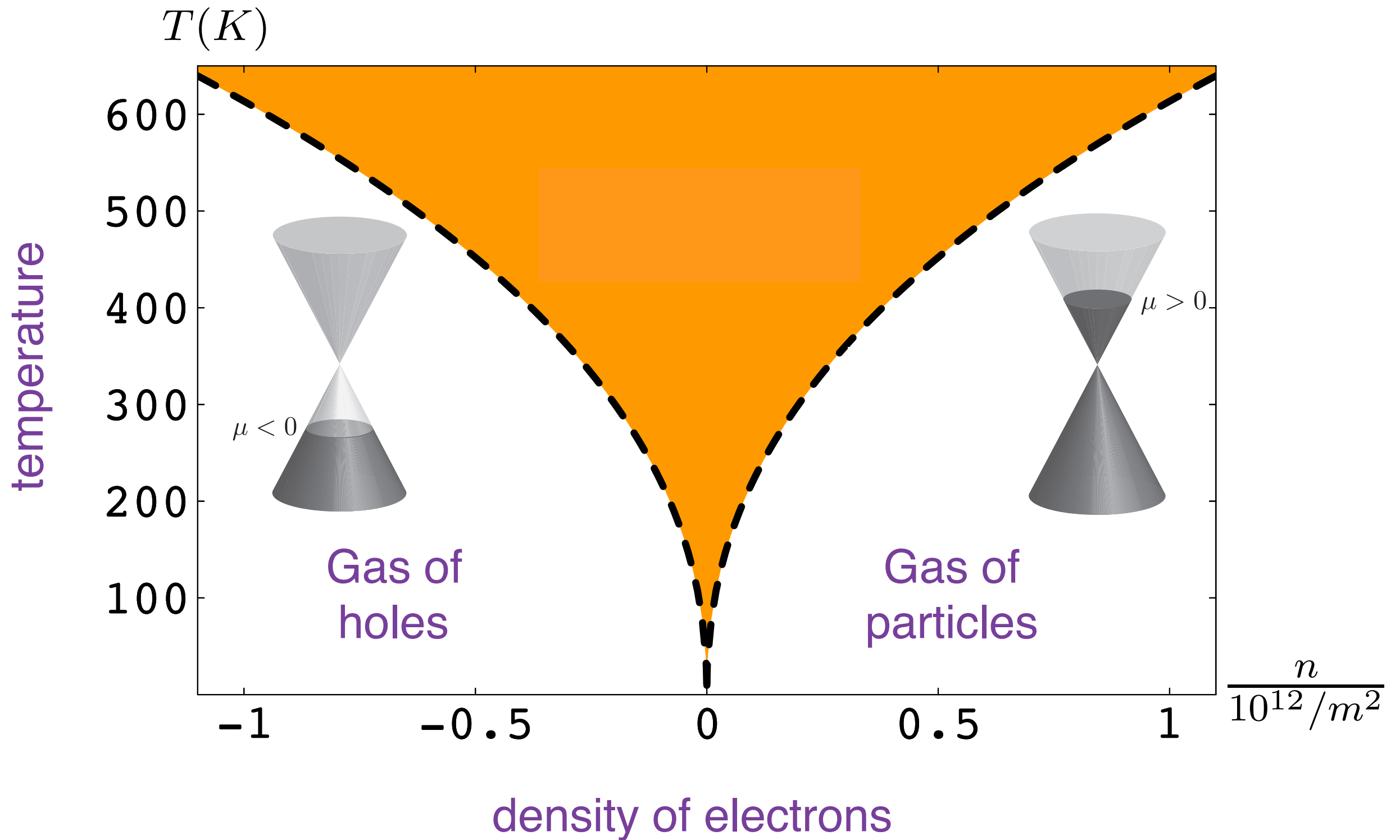
Long-range quantum
entanglement of
electrons
in matter:
(A) superconductors
(B) graphene

Graphene



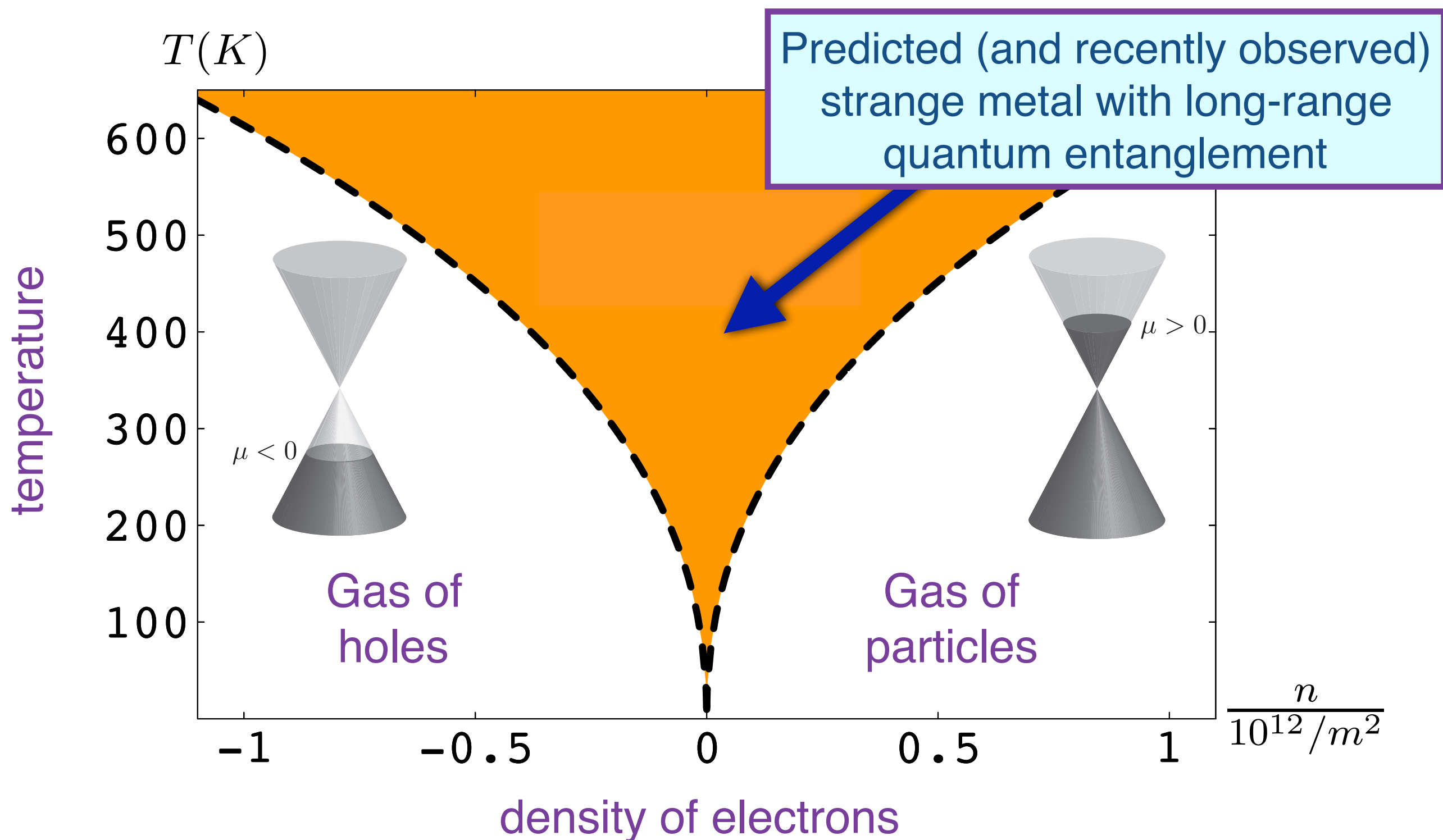
A single layer of carbon atoms
in a honeycomb lattice

Graphene



D. E. Sheehy and J. Schmalian, PRL **99**, 226803 (2007)
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene



The strange metal is a much better conductor of heat than electricity, when compared to ordinary metals

**Quantum
superposition and
entanglement**

**Quantum theory
of black holes**

**Long-range quantum
entanglement of
electrons
in matter:**
(A) **superconductors**
(B) **graphene**

Quantum
superposition and
entanglement

Long-range quantum
entanglement of
electrons
in matter:
(A) superconductors
(B) → graphene

Quantum theory
of black holes

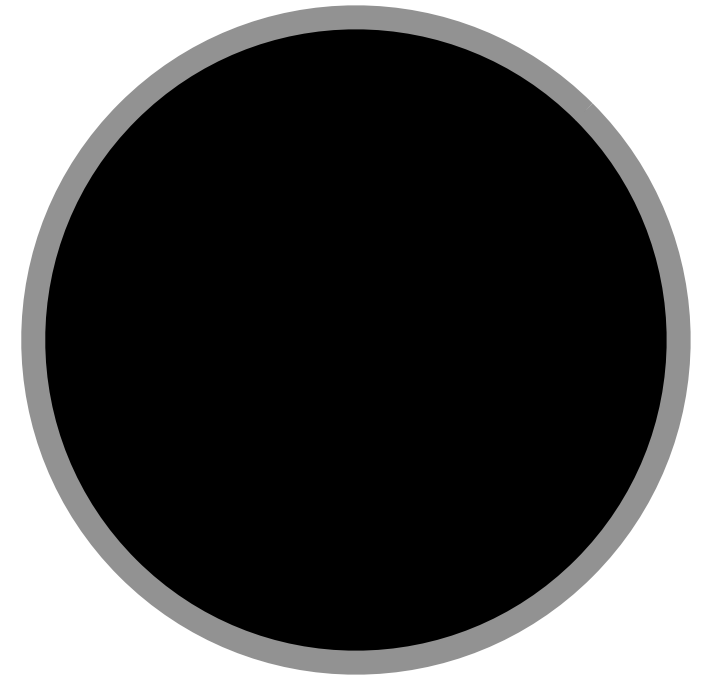


Black Holes

Objects so massive 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.

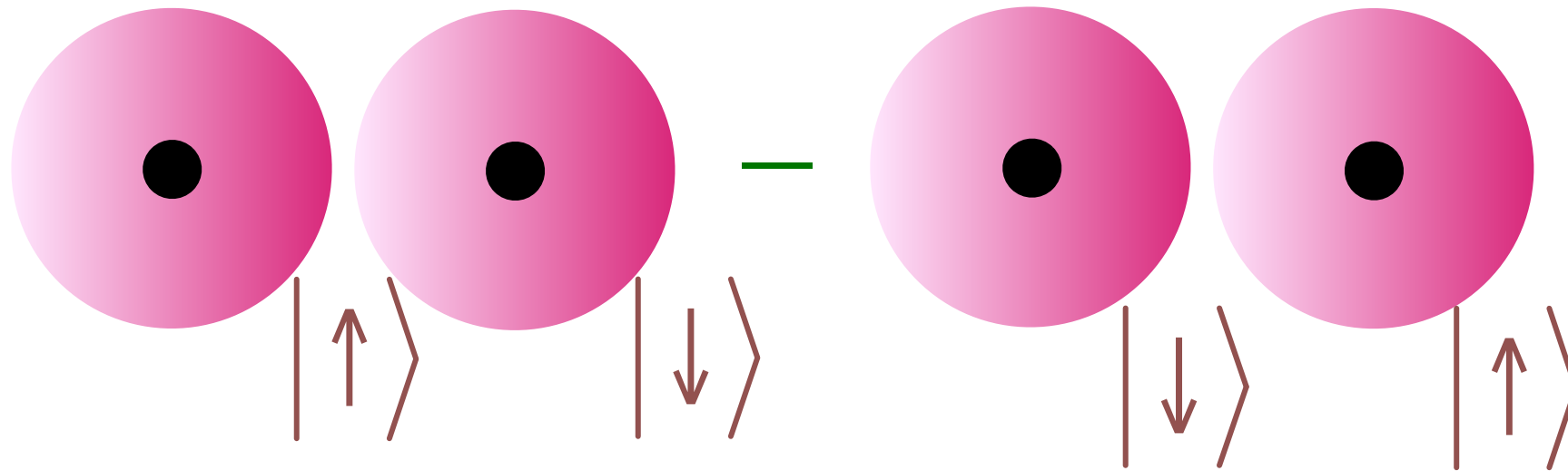
$$\text{Horizon radius } R = \frac{2GM}{c^2}$$



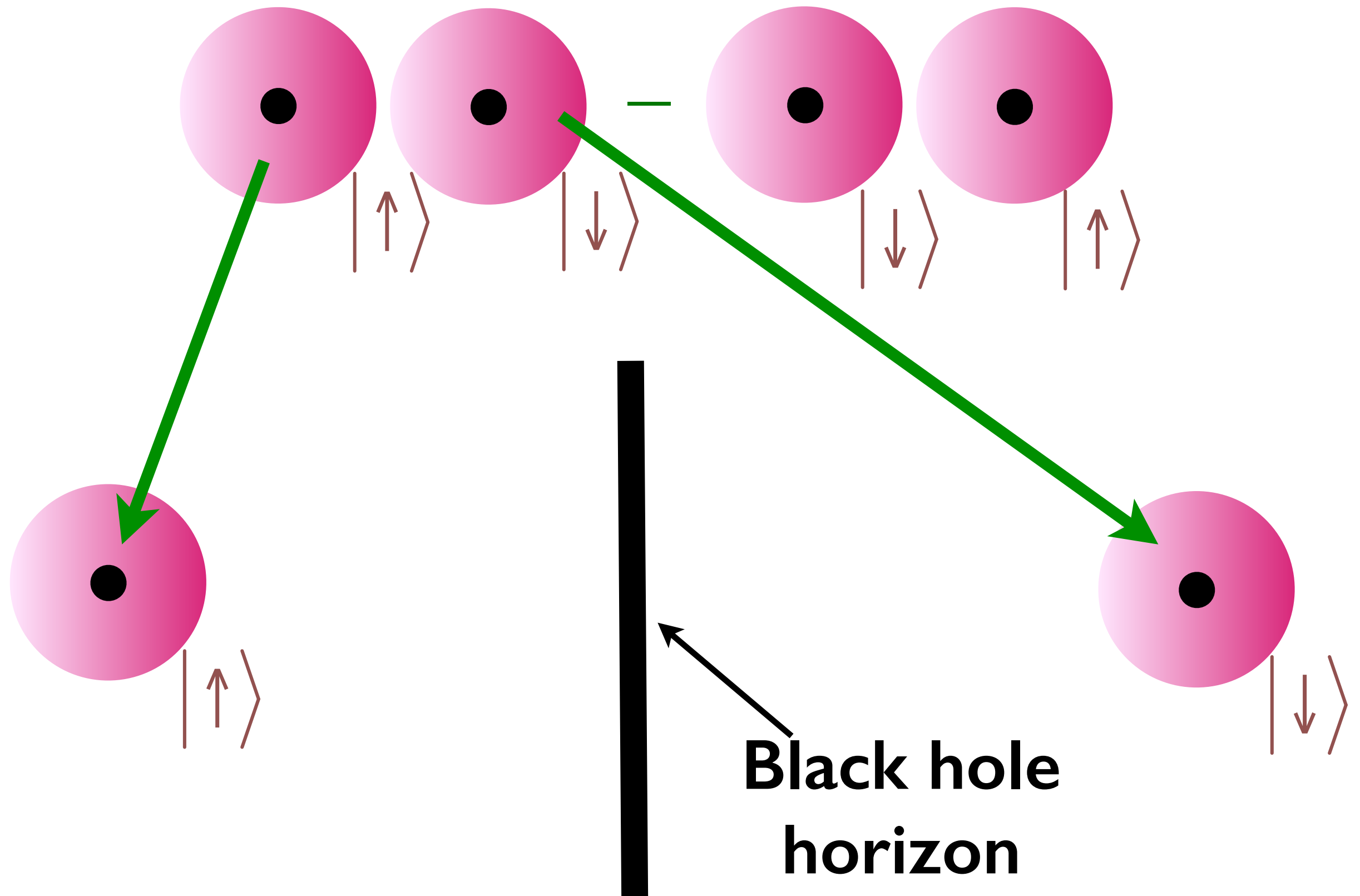
Black Holes + Quantum theory

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

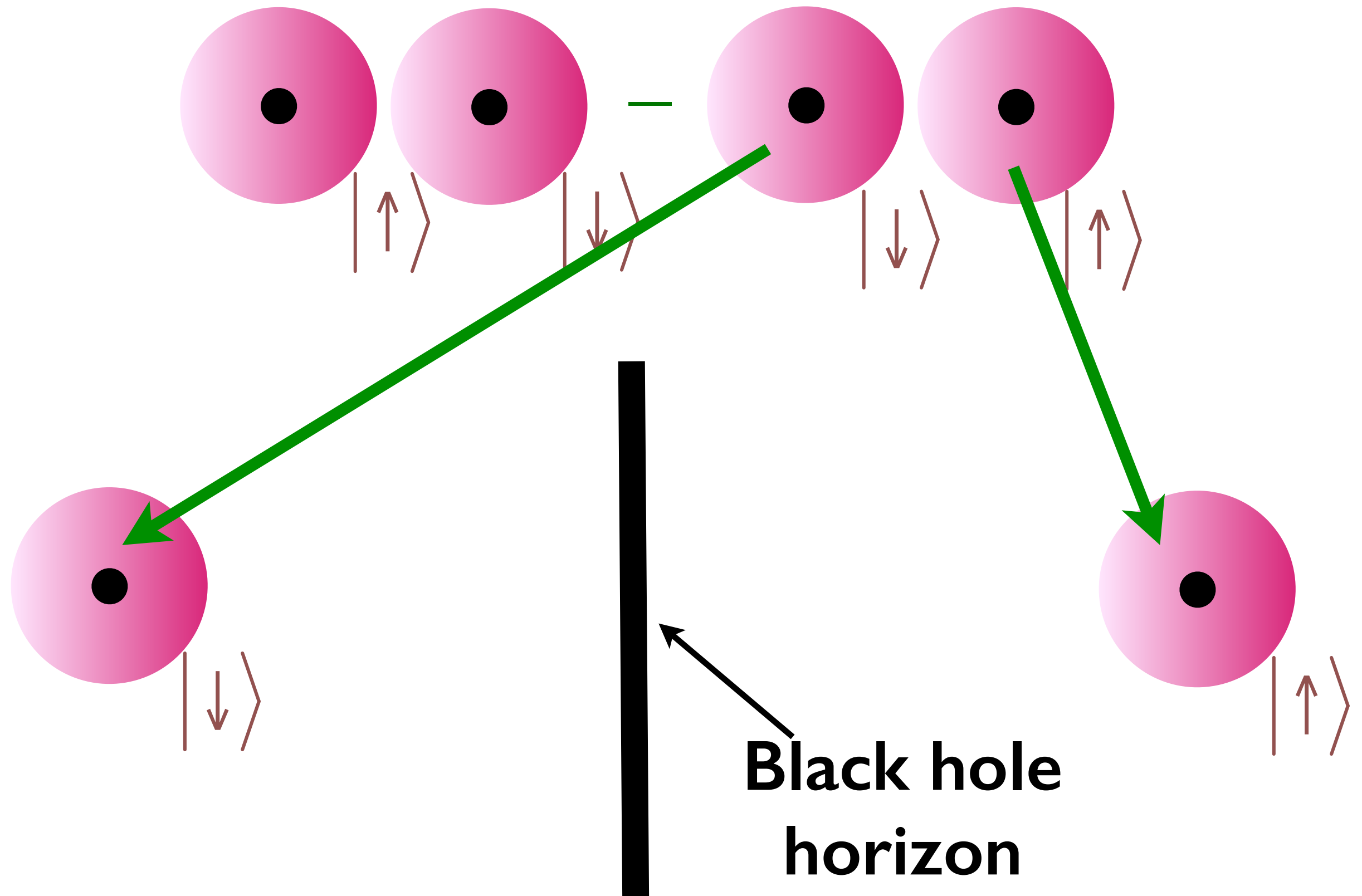
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

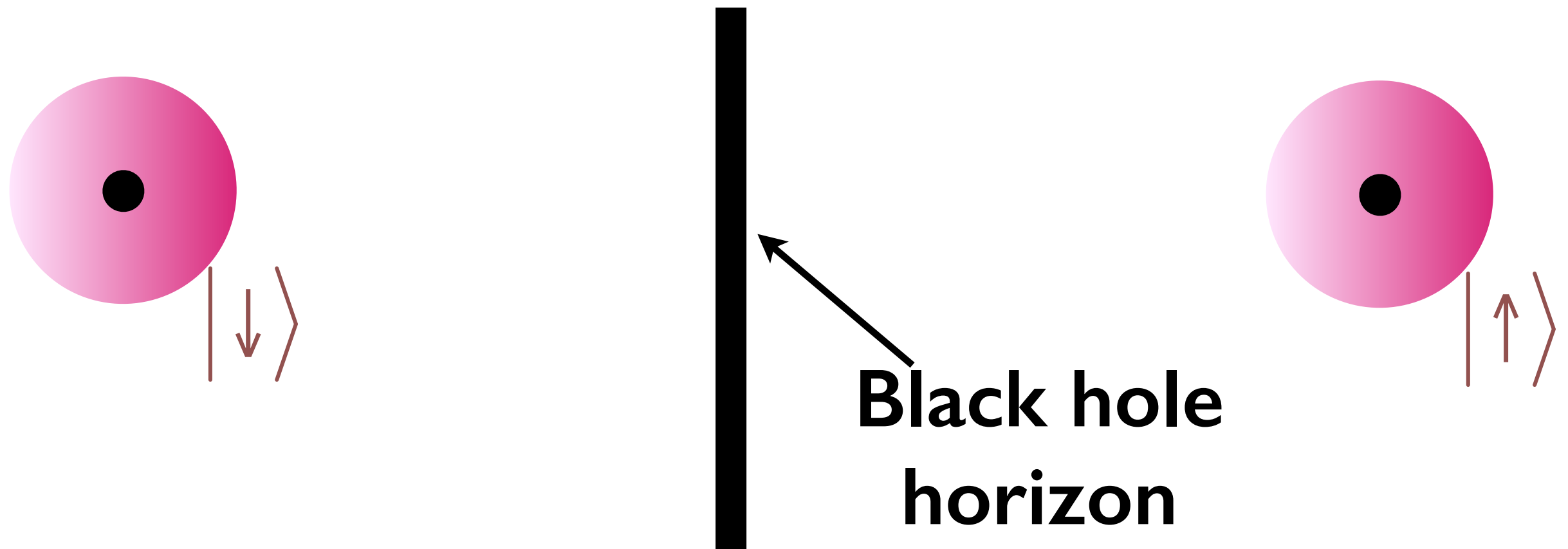


Quantum Entanglement across a black hole horizon



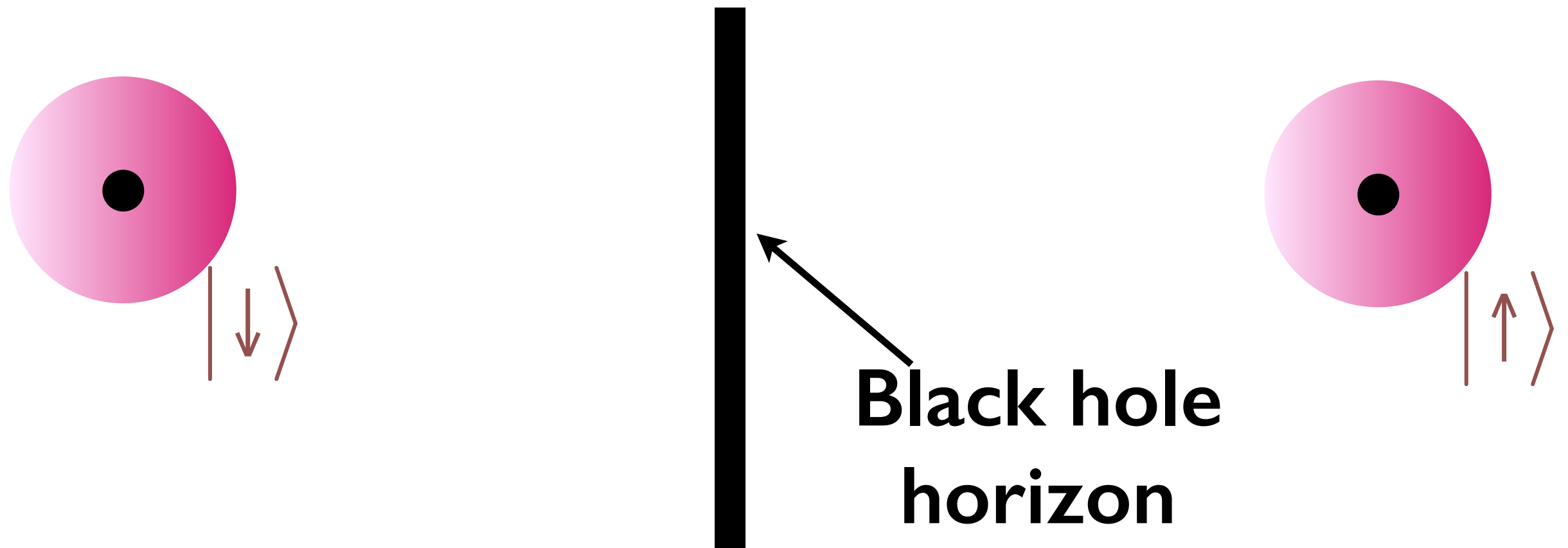
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

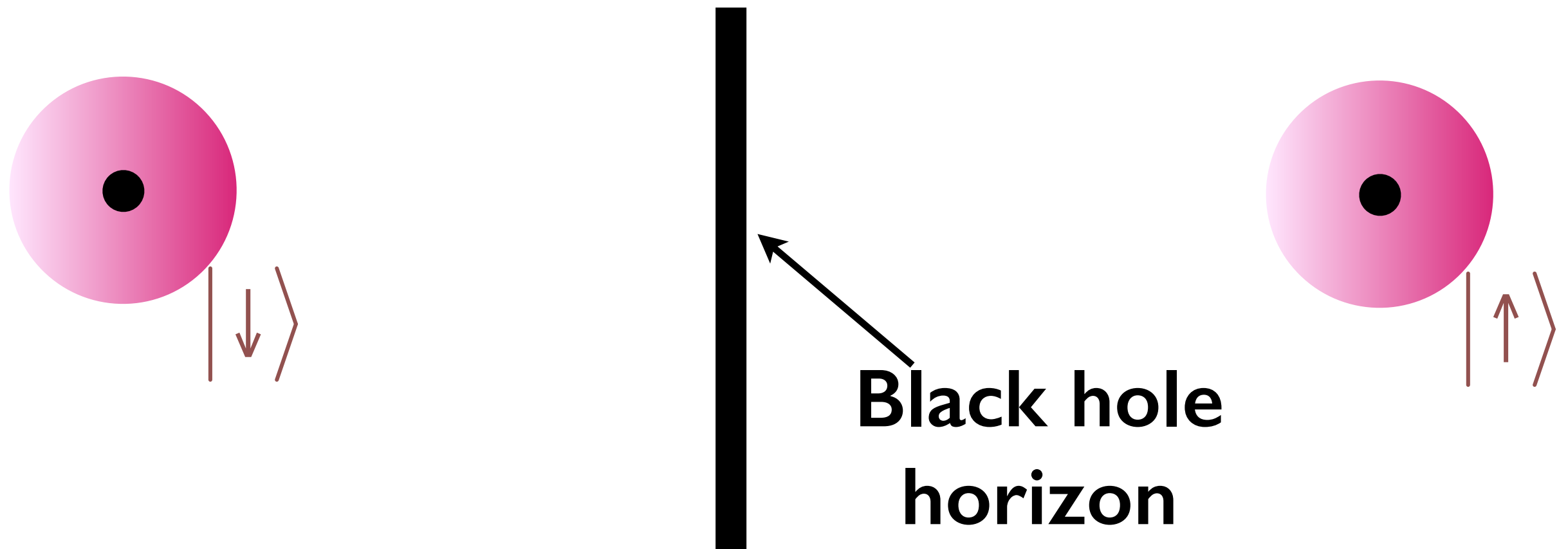
Hawking used this to show that black hole horizons have an entropy and a temperature



Quantum Entanglement across a black hole horizon

The Hawking entropy matches
the entropy of some simple
strange metal states of electrons

(S. Sachdev, 2015)



Quantum Entanglement across a black hole horizon

The Hawking entropy matches
the entropy of some simple
strange metal states of electrons

(S. Sachdev, 2015)

The dynamics of black hole horizons has many similarities to strange metals, and this has led us to a better understanding of the observable properties of strange metals in superconductors and other quantum materials

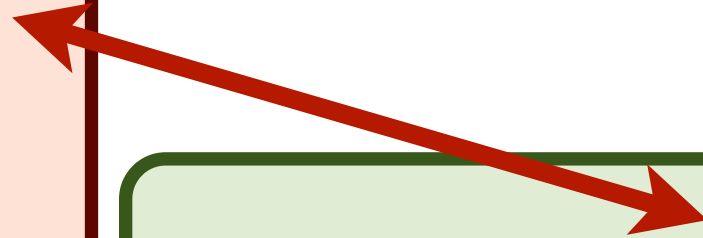
**Black hole
horizon**

**Quantum
superposition and
entanglement**

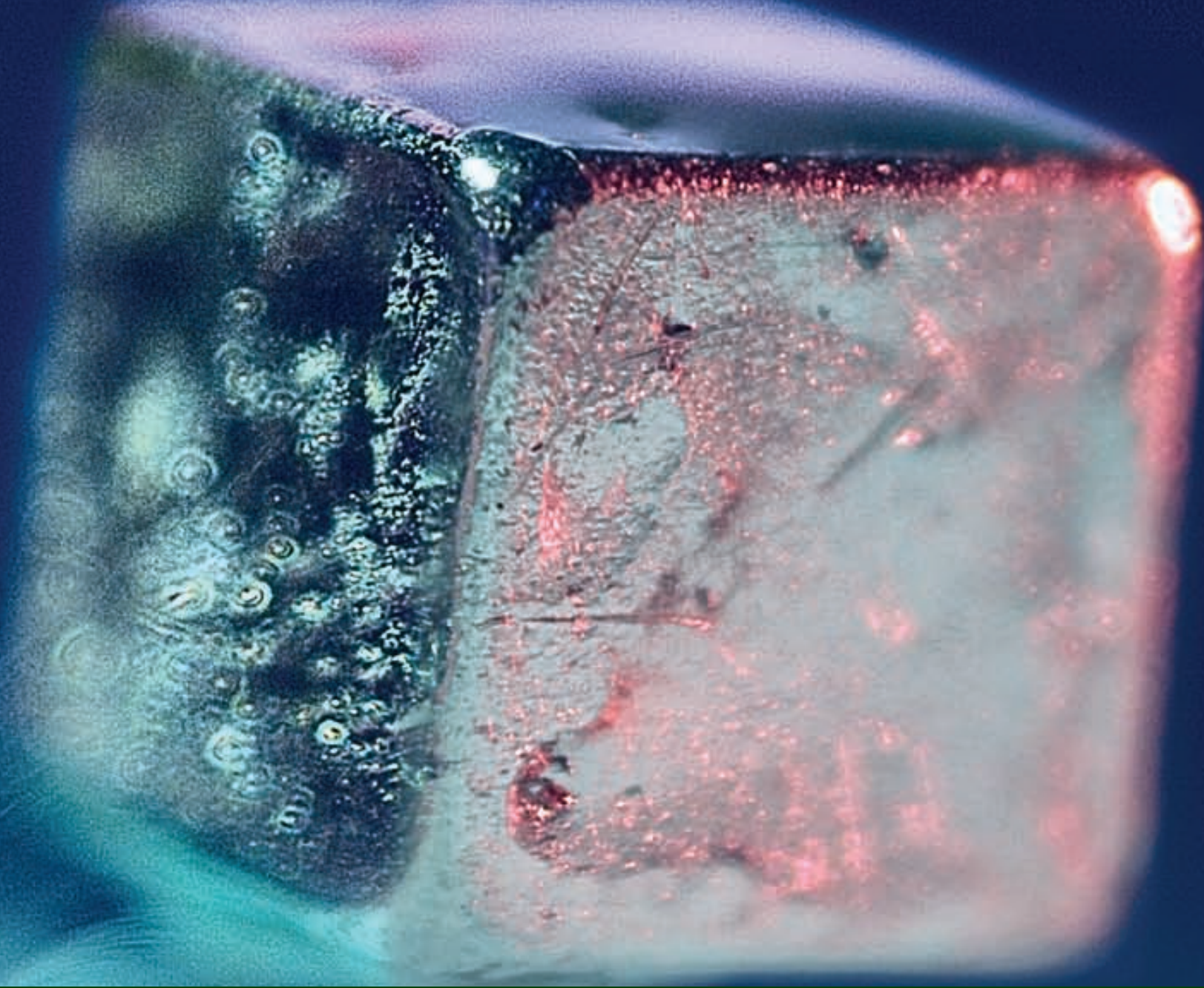
Quantum
superposition and
entanglement

Long-range quantum
entanglement of
electrons
in matter:
(A) superconductors
(B) graphene

Quantum theory
of black holes



Quantum Entanglement and Superconductivity



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

Subir Sachdev, Perimeter Institute and Harvard University