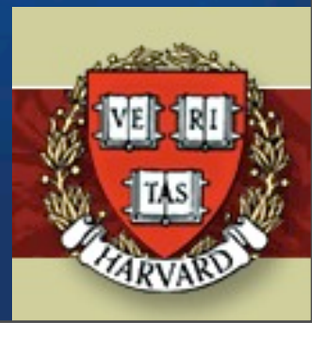
Stringing together the quantum phases of matter

Talk online: sachdev.physics.harvard.edu



The phases of matter:

The phases of matter:

ice

water

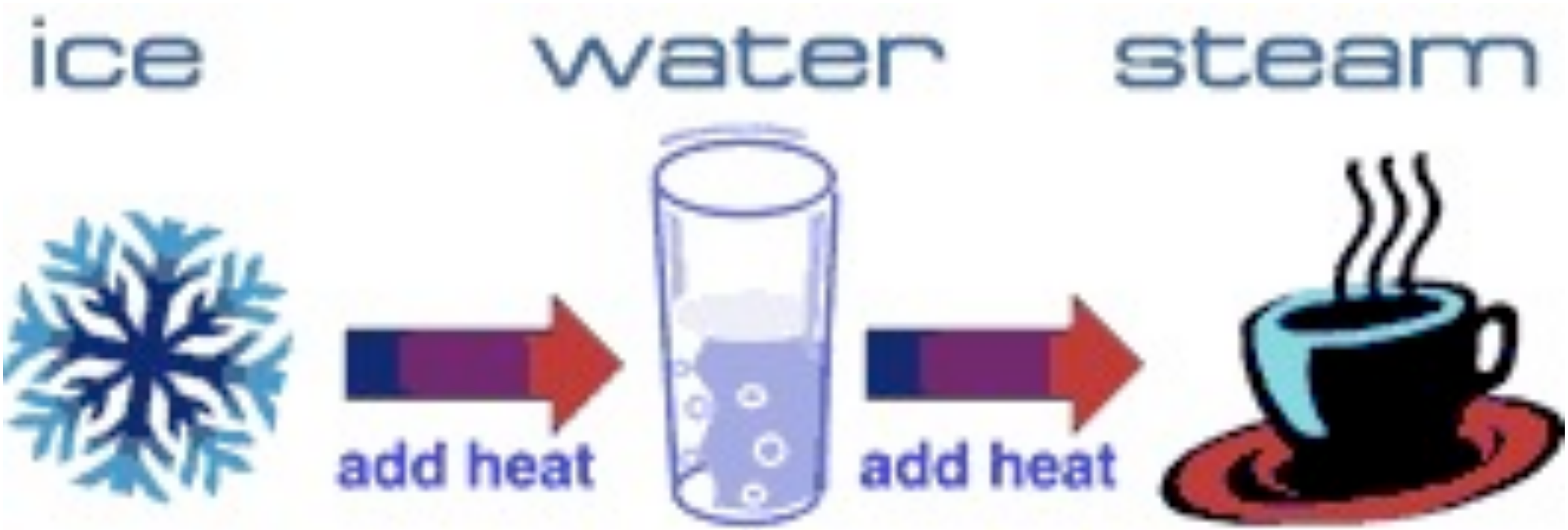
steam

Solids

Liquids

Gases

The phases of matter:



Solids Liquids Gases

Theory of the phases of matter:

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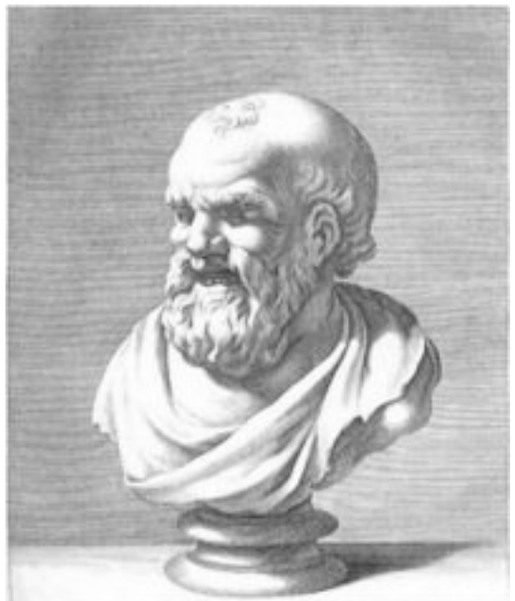
1. Matter is made of atoms



Democritus (4th century B.C.)

Theory of the phases of matter:

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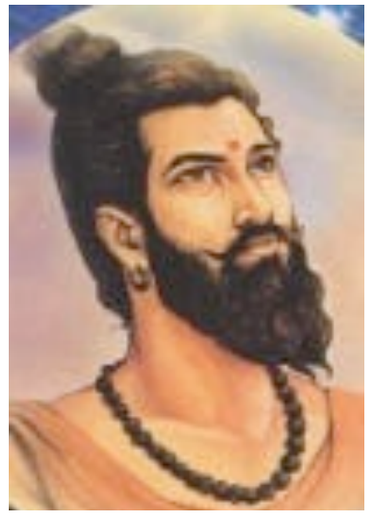
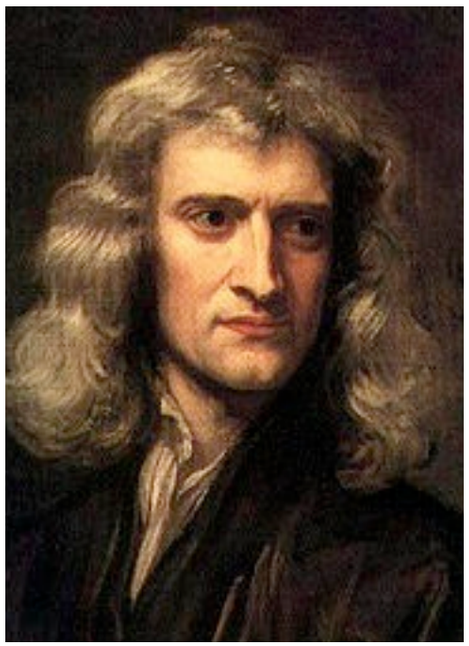


Acharya Kanad (6th century B.C.)

Theory of the phases of matter:

1. Matter is made of atoms

2. The atoms move because of forces acting between them, just like the moon or an apple



Newton (1687)

Theory of the phases of matter:

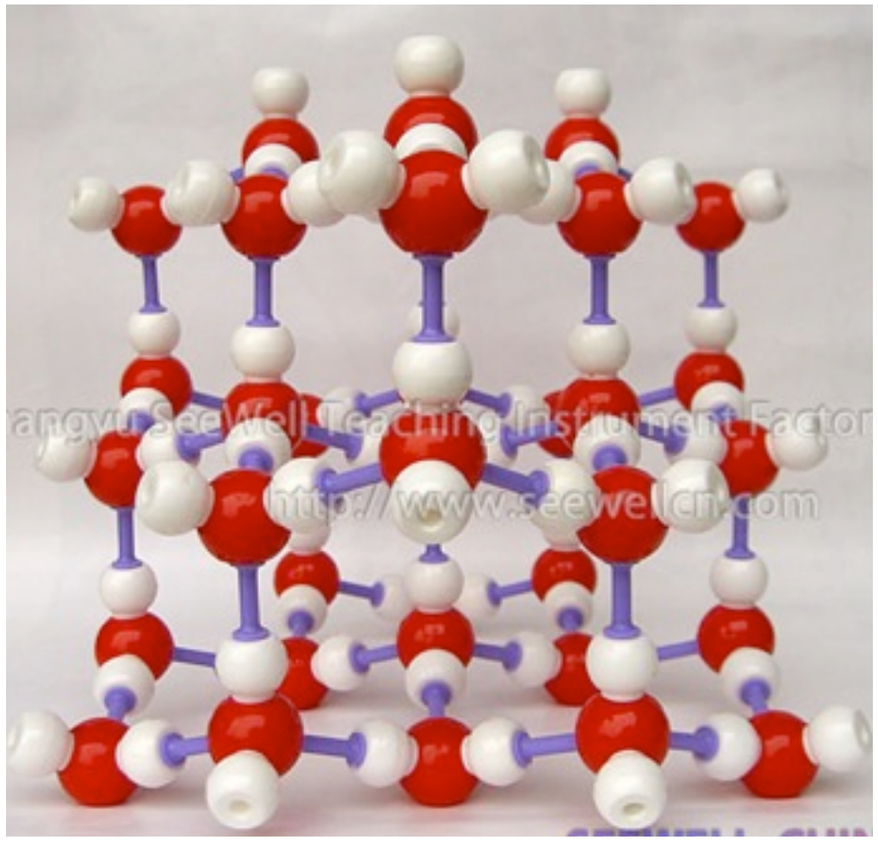
1. Matter is made of atoms

2. The atoms move because of forces acting between them, just like the moon or an apple

3. The phases of matter are determined by the spatial arrangements of atoms

Boltzmann (1877)

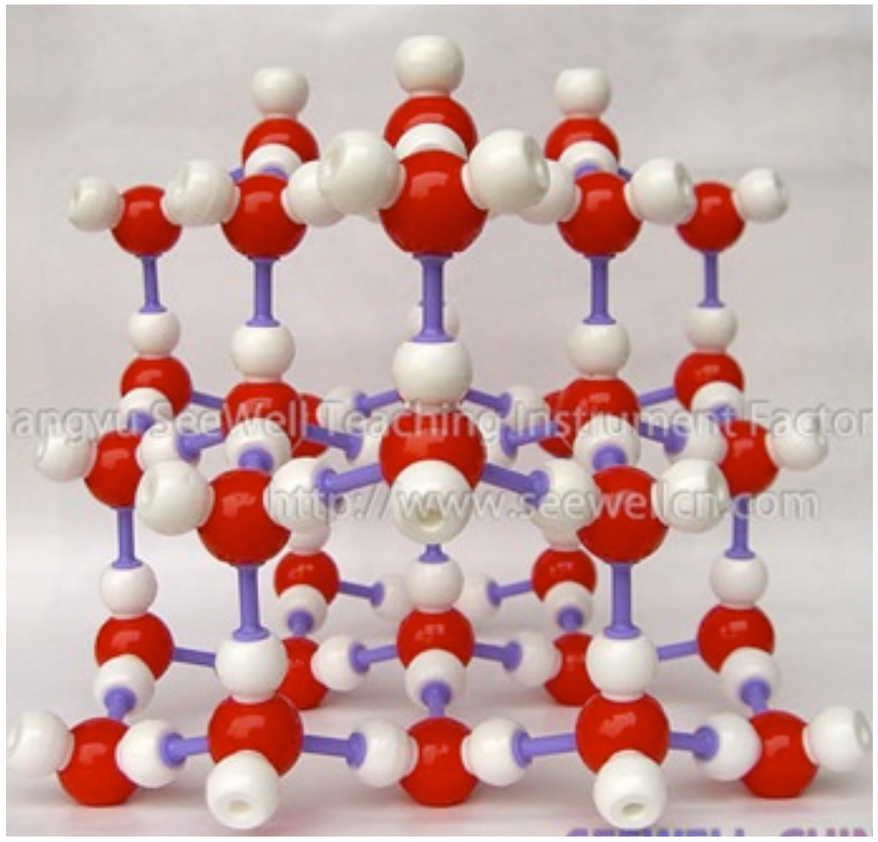
Solids



Ice

Solids

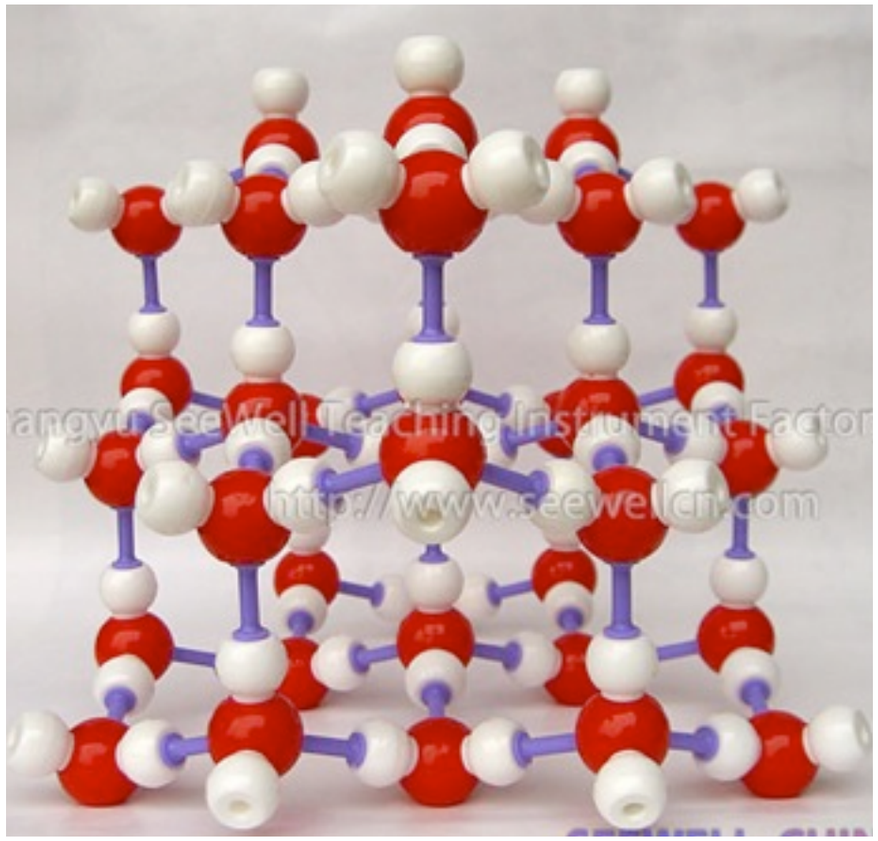
Salt



Ice

Silicon

Solids



Ice

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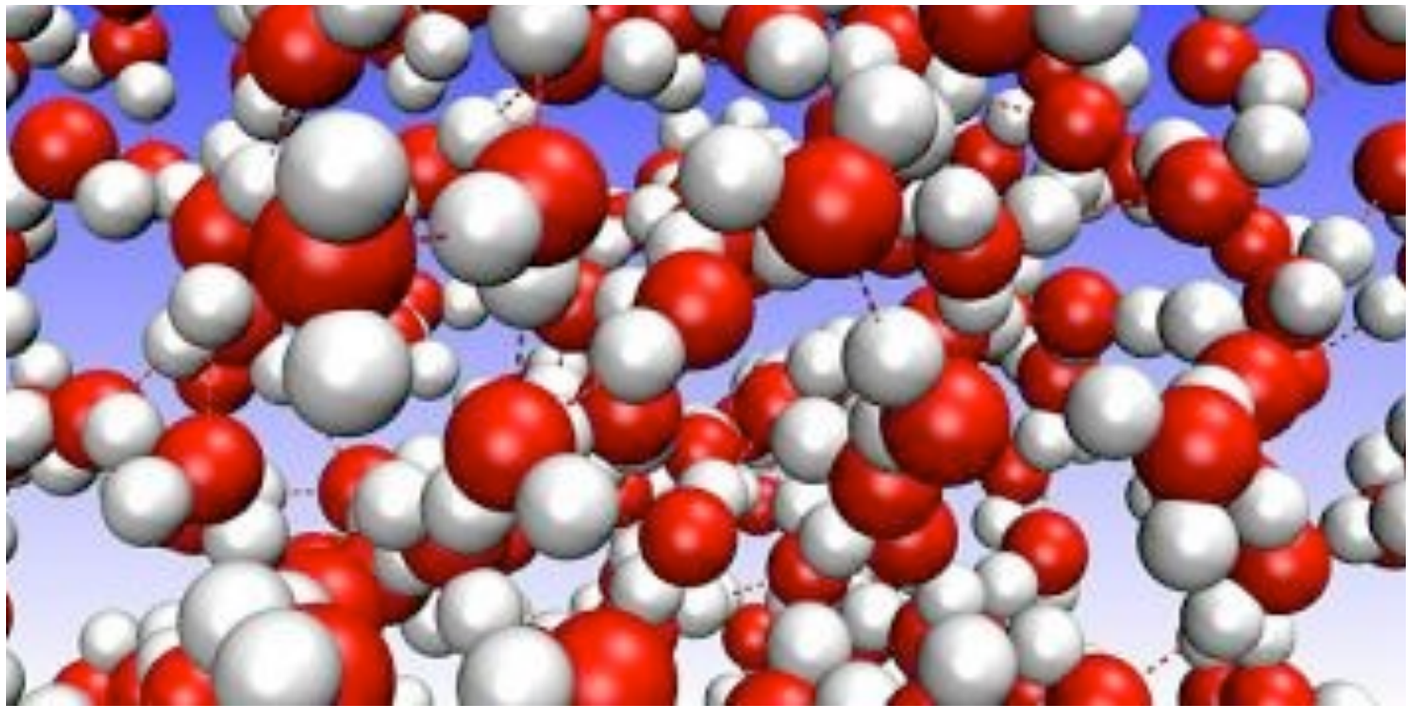
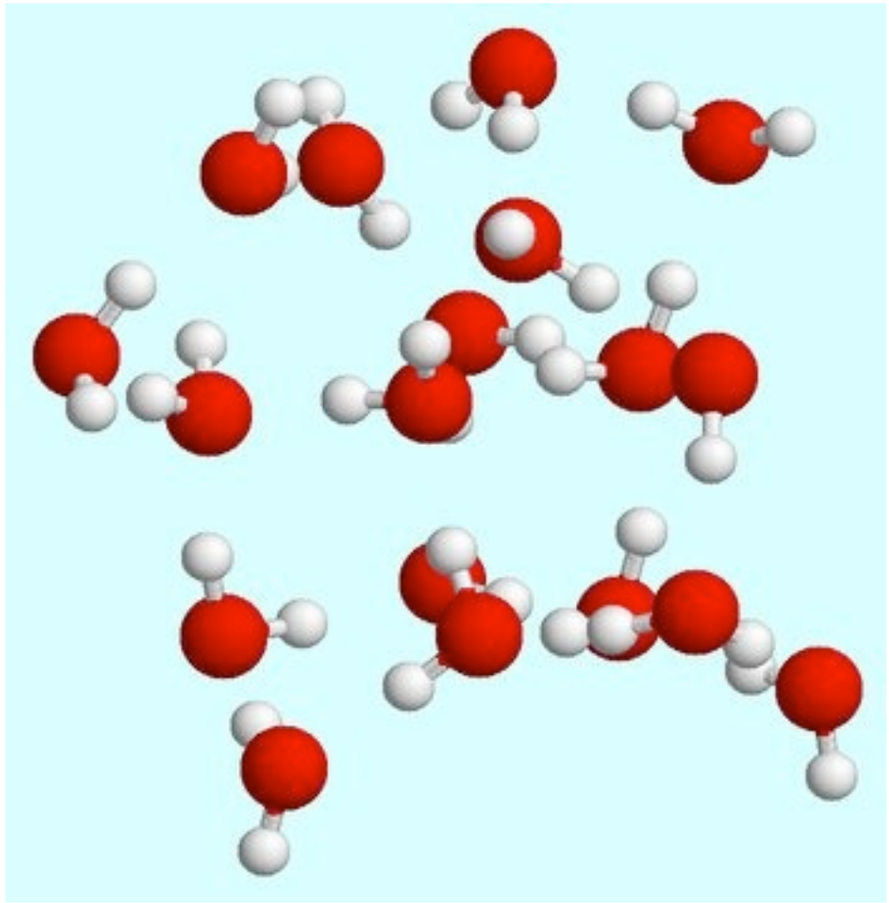


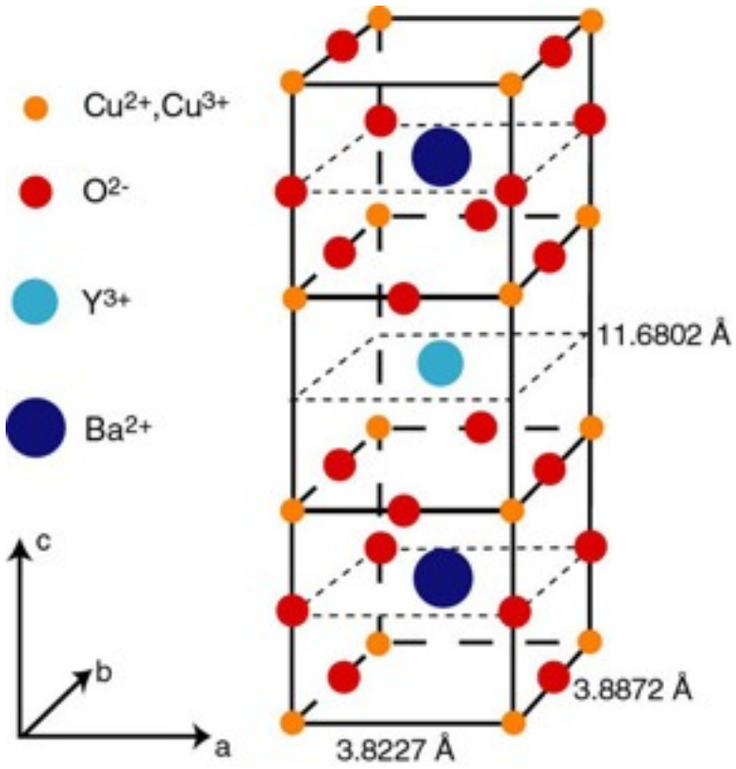
Water

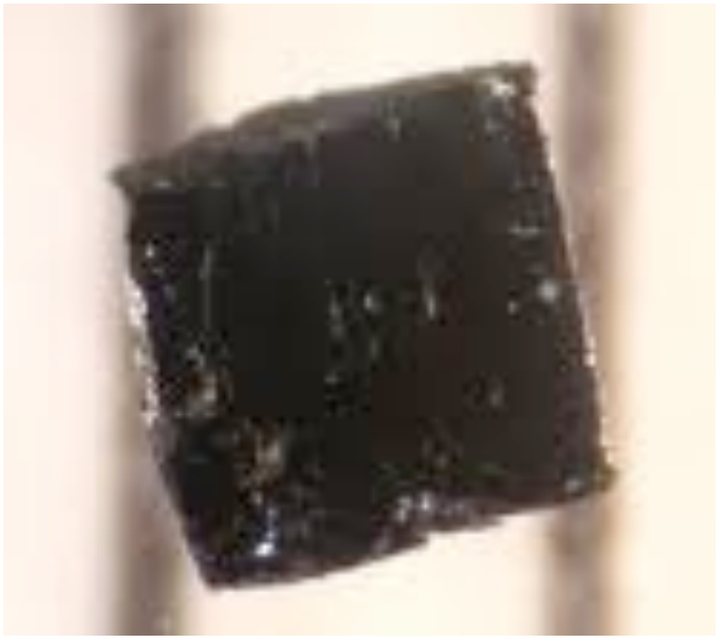
Gases



Steam

Solids



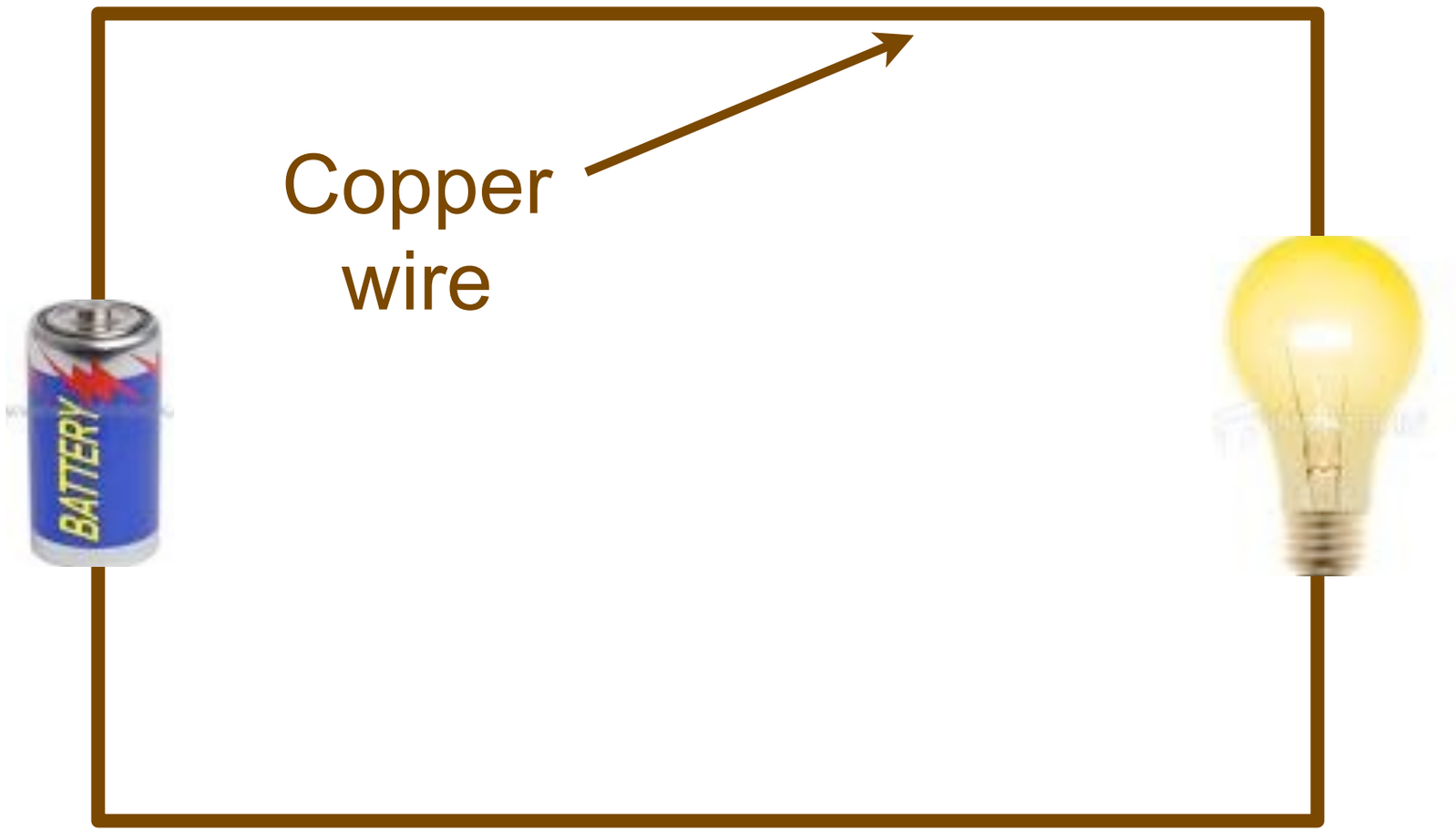


Copper

Silicon

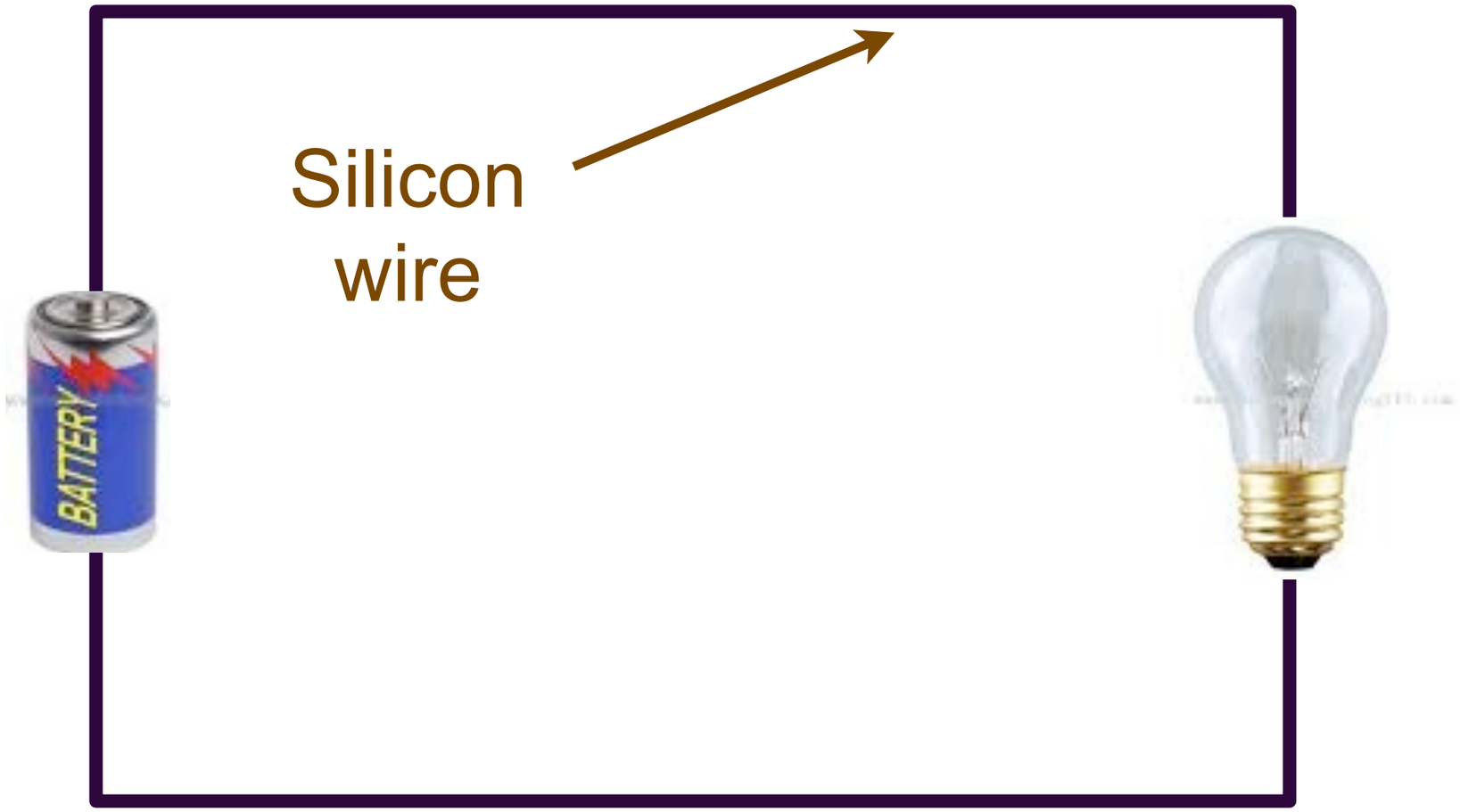
YBCO

These solids have very different electrical and magnetic properties



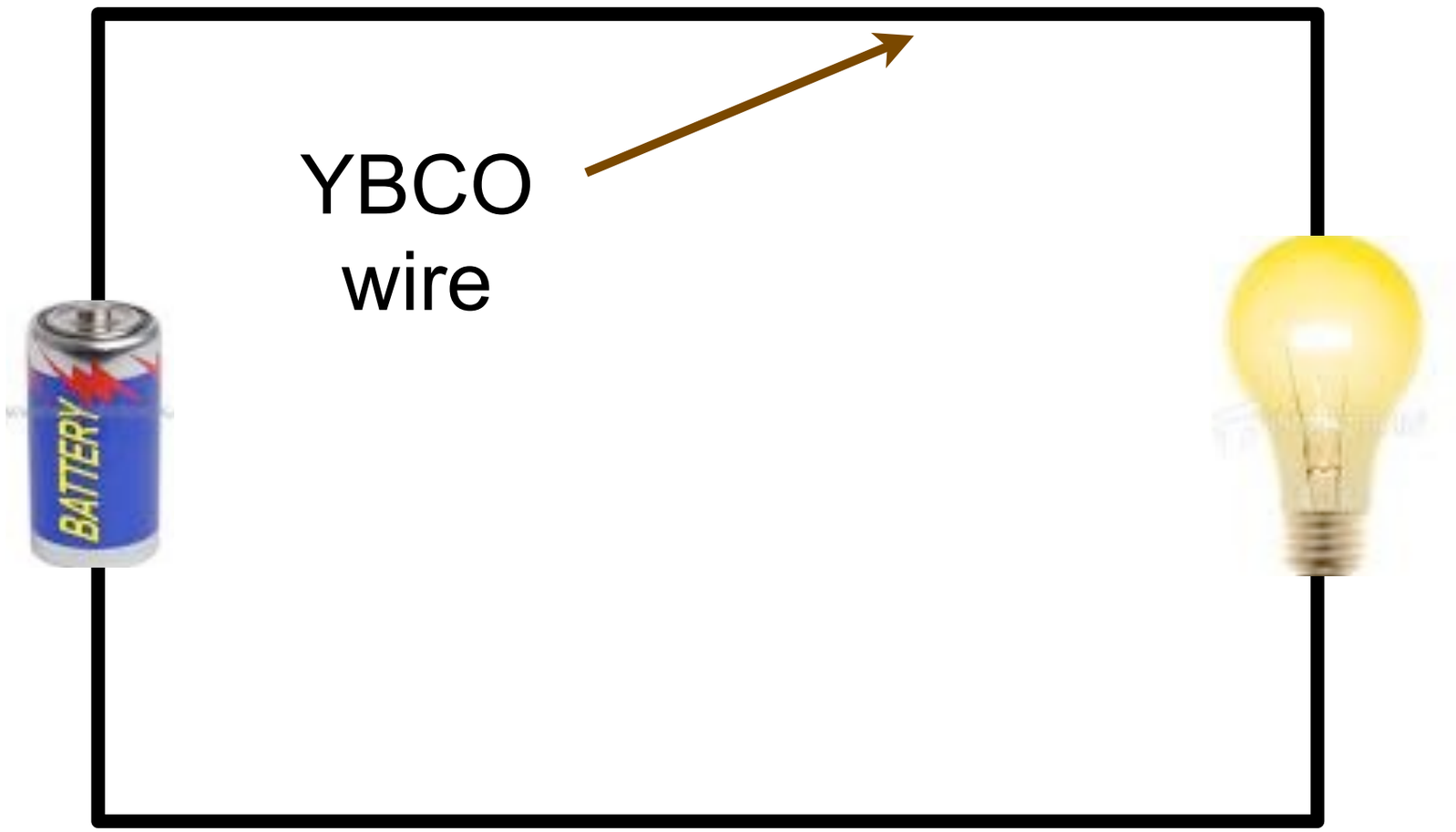
Copper is a conductor of electricity

These solids have very different electrical and magnetic properties



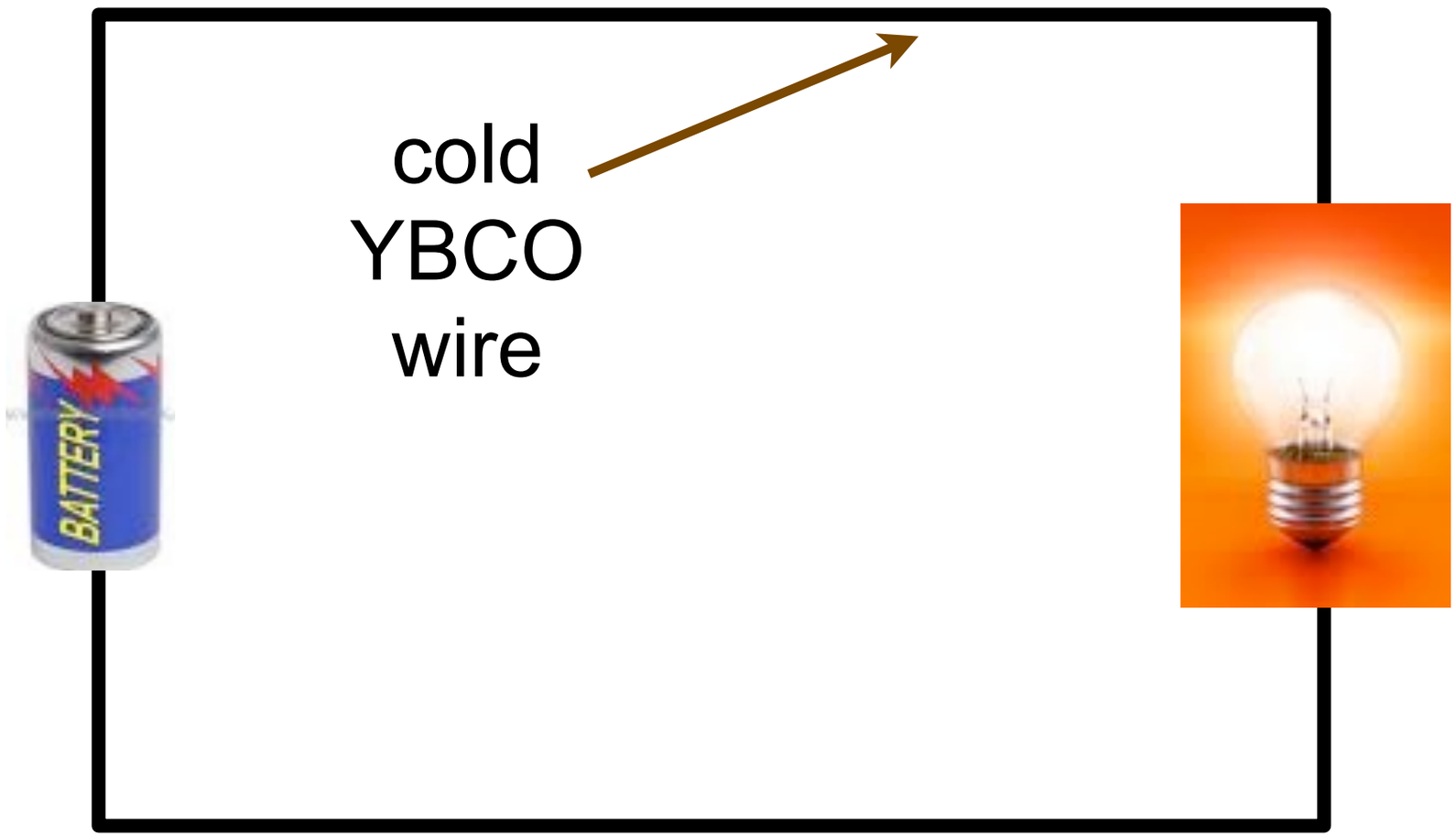
Silicon is an insulator

These solids have very different electrical and magnetic properties



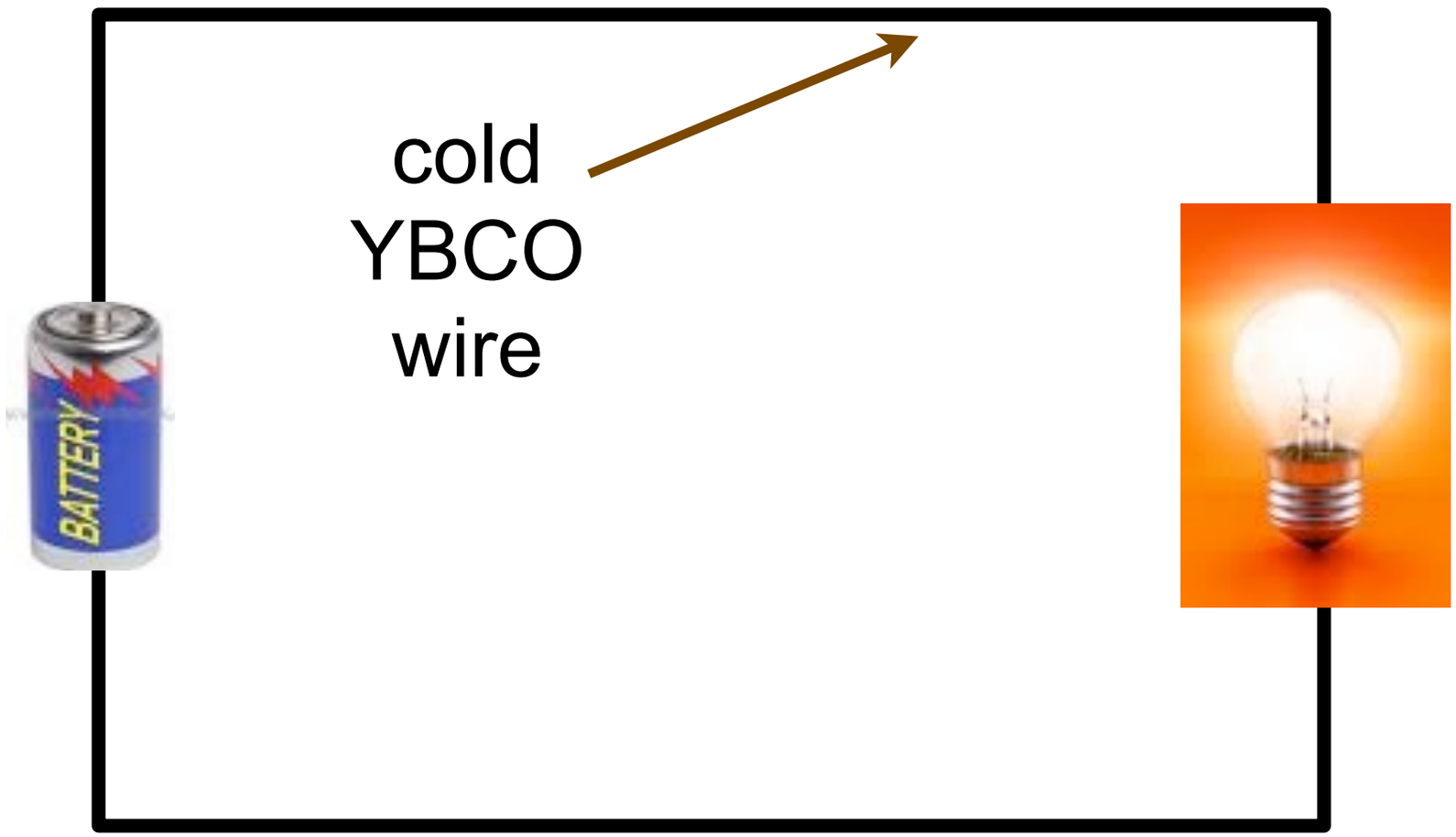
At room temperature, YBCO conducts electricity (but not very well)

These solids have very different electrical and magnetic properties



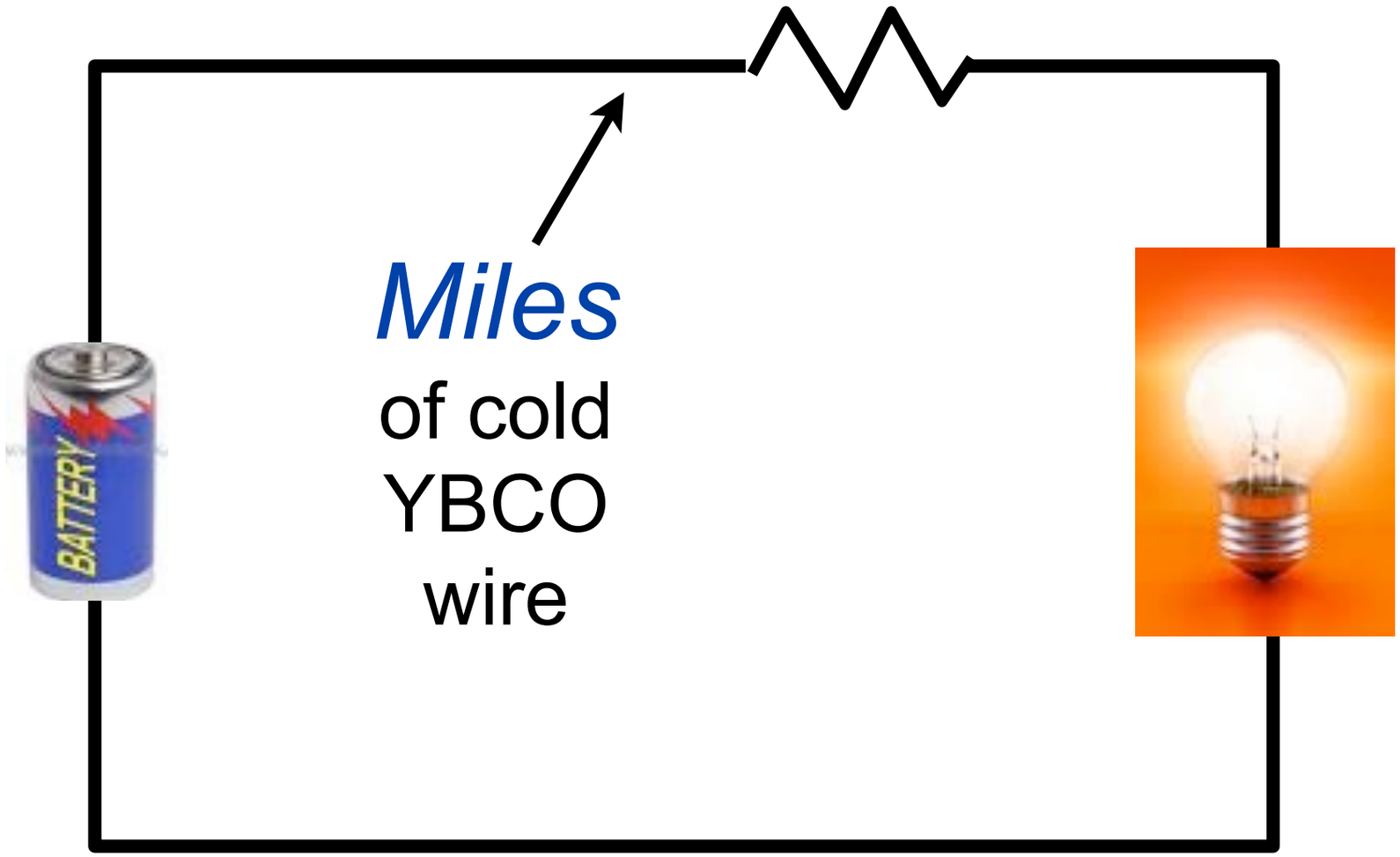
When cooled by liquid nitrogen, YBCO conducts electricity *without* resistance

These solids have very different electrical and magnetic properties



When cooled by liquid nitrogen,
YBCO is a SUPERCONDUCTOR !

These solids have very different electrical and magnetic properties



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YBCO cables

American Superconductor Corporation

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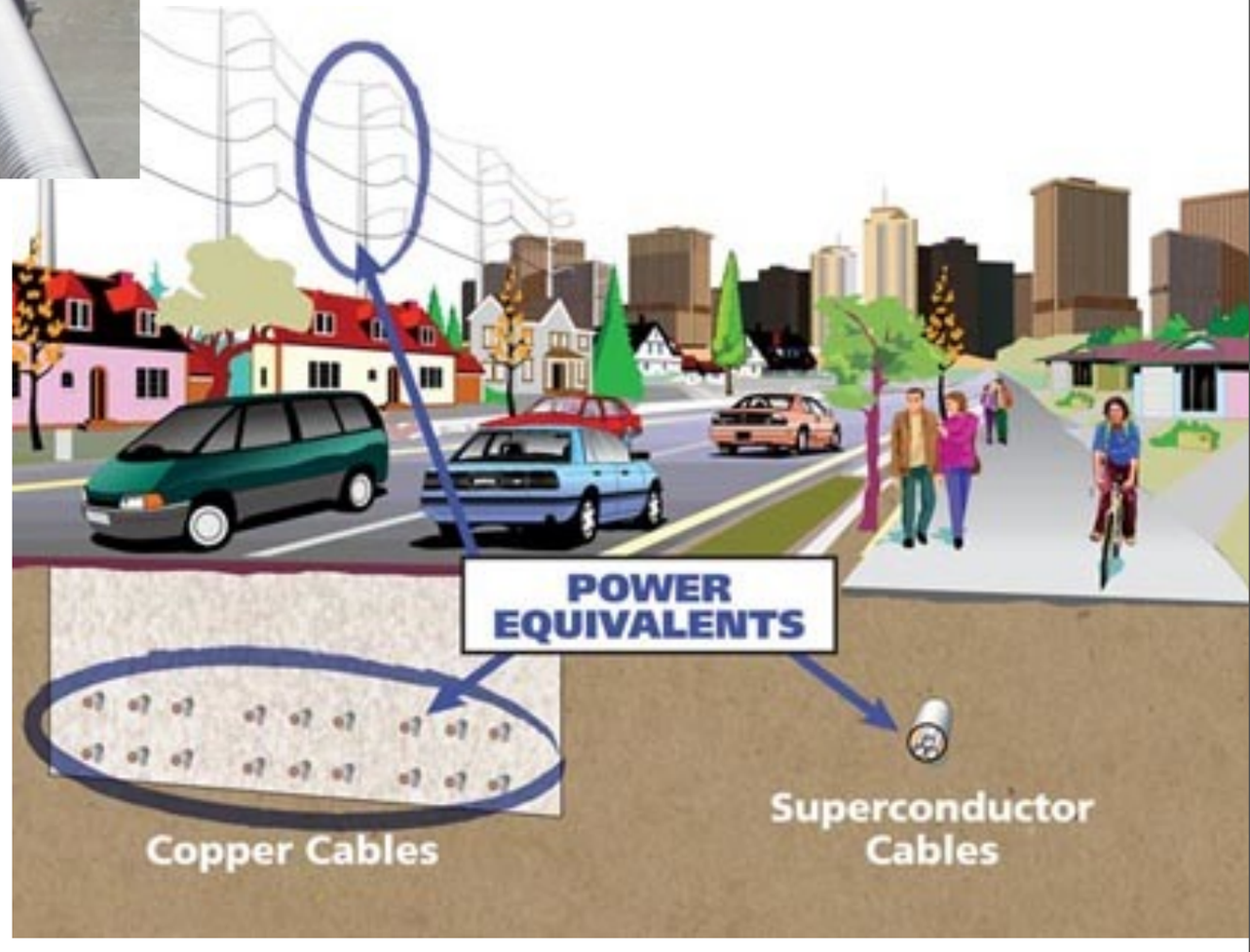
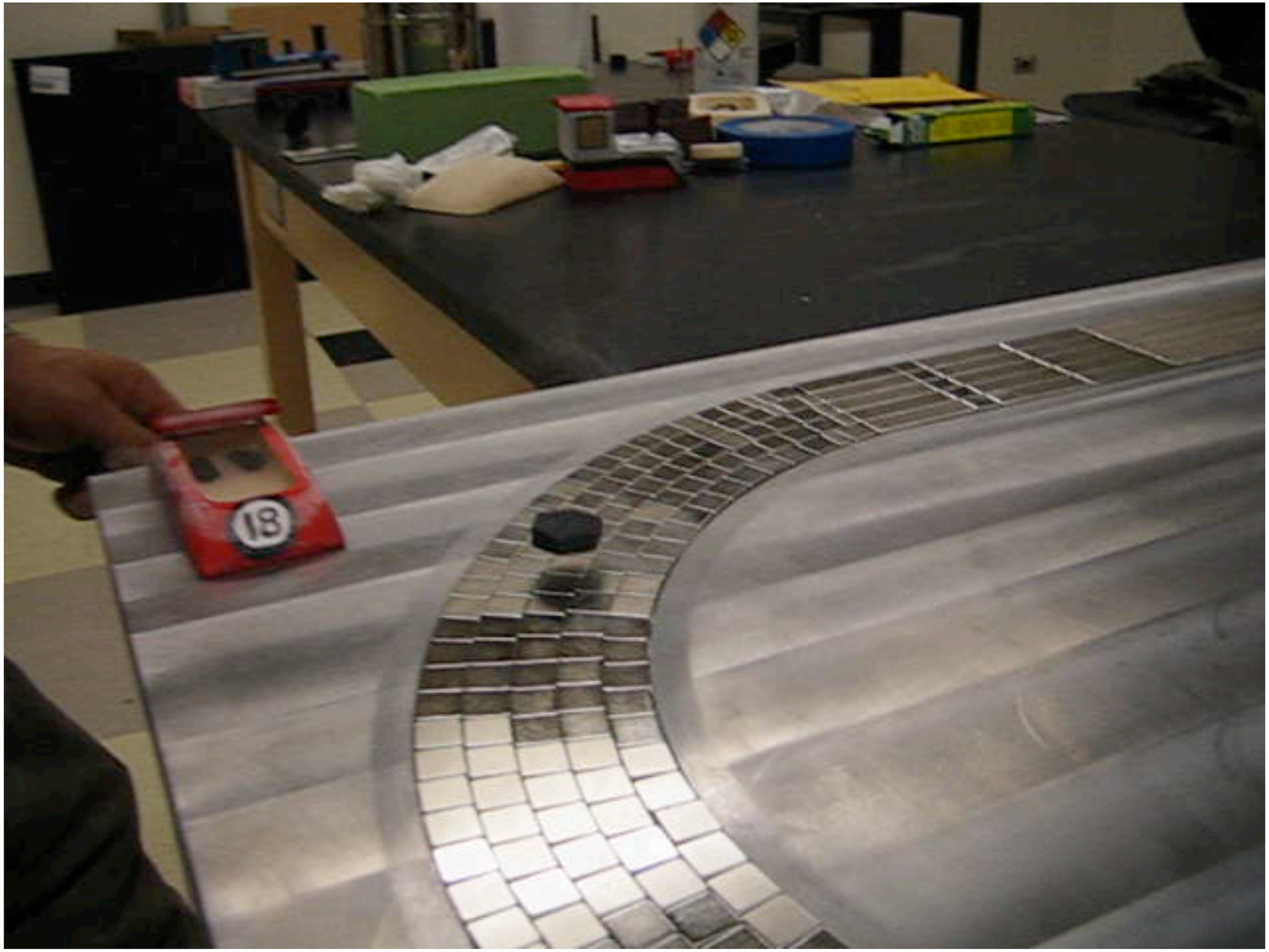


Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University



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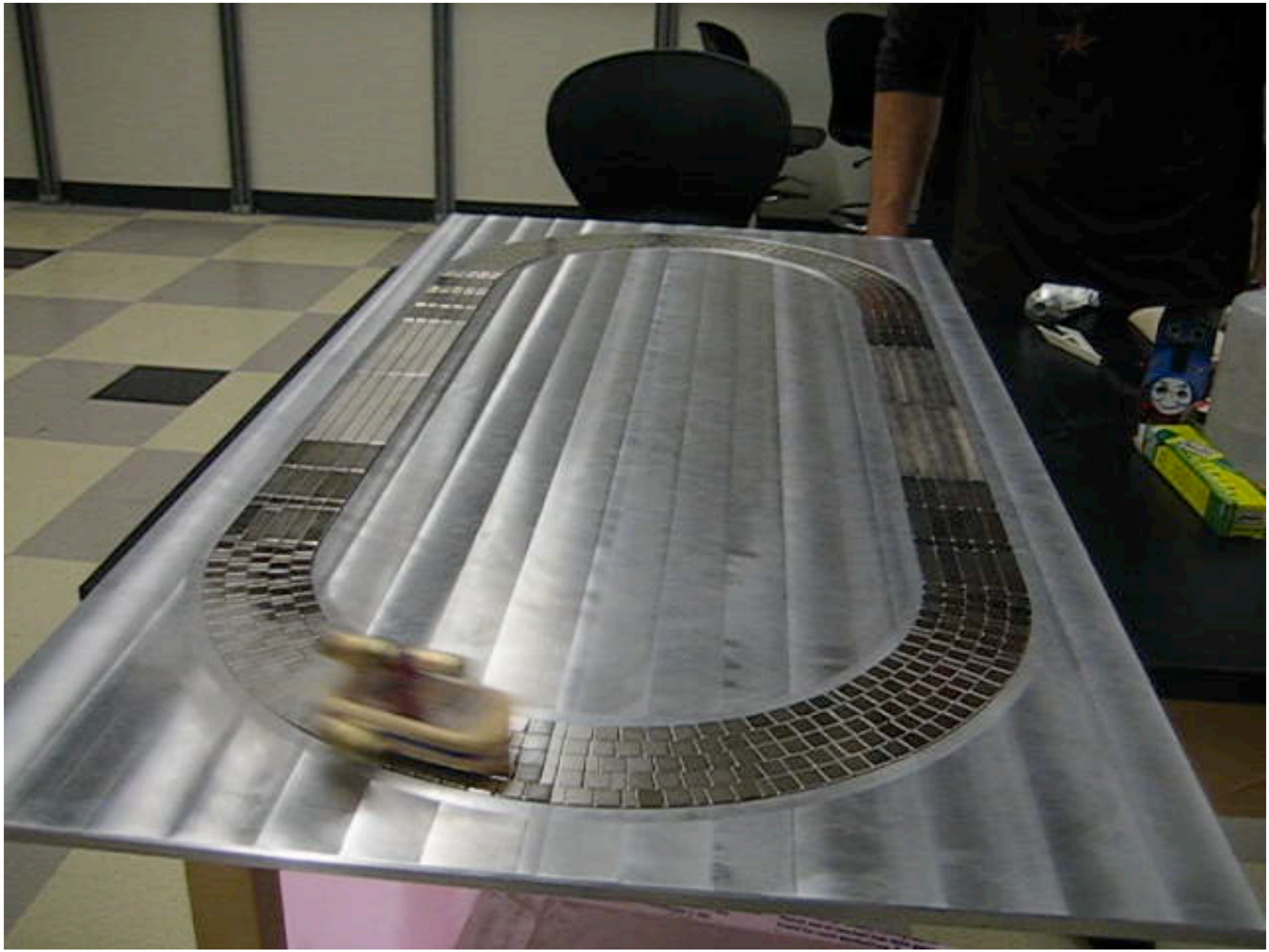

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1. In solids, electrons separate

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Needed:
A theory for the *quantum* phases of matter

Quantum superposition and entanglement

Superconductivity

Black Holes and String Theory

Quantum superposition and entanglement

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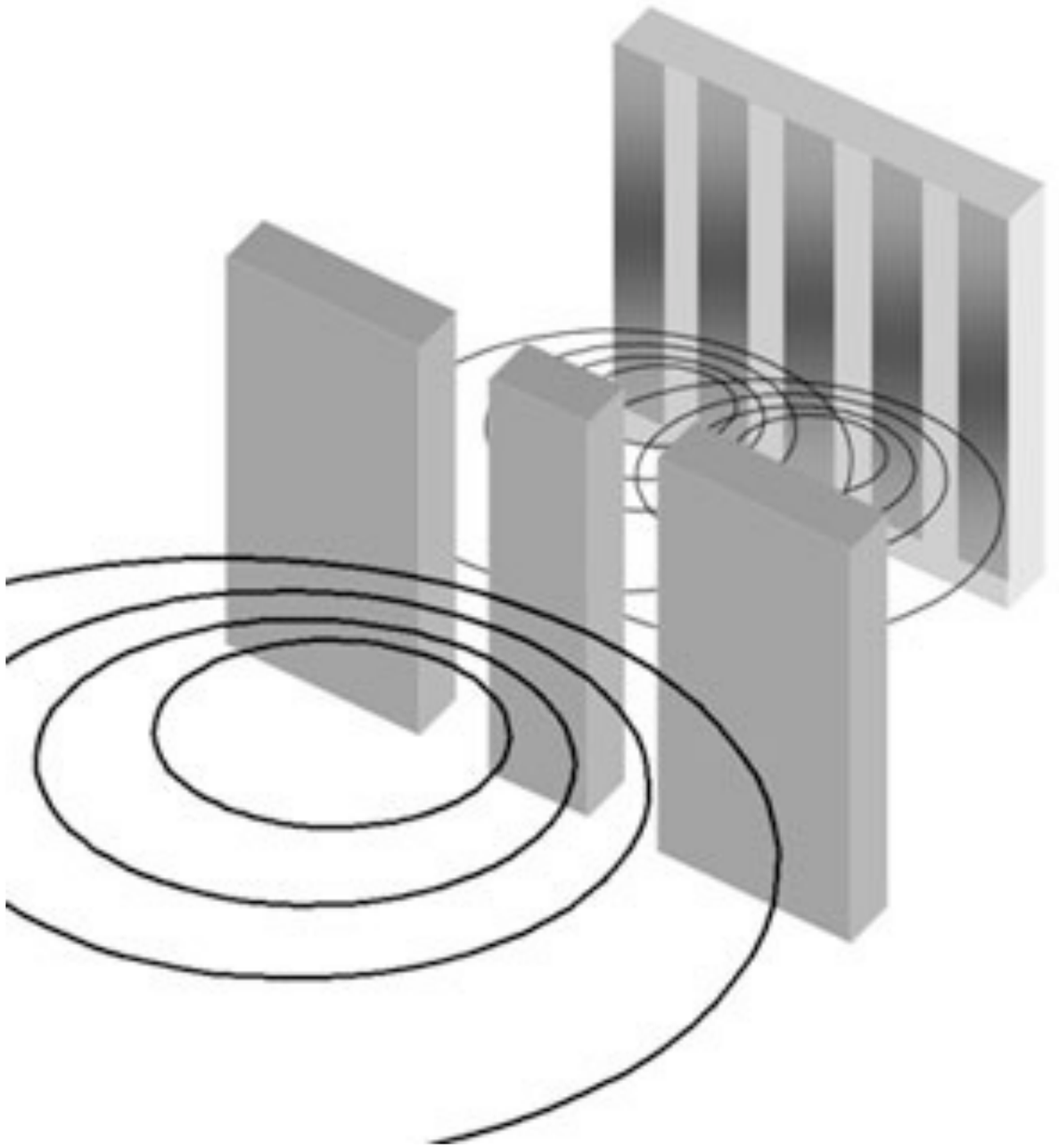
Quantum Superposition

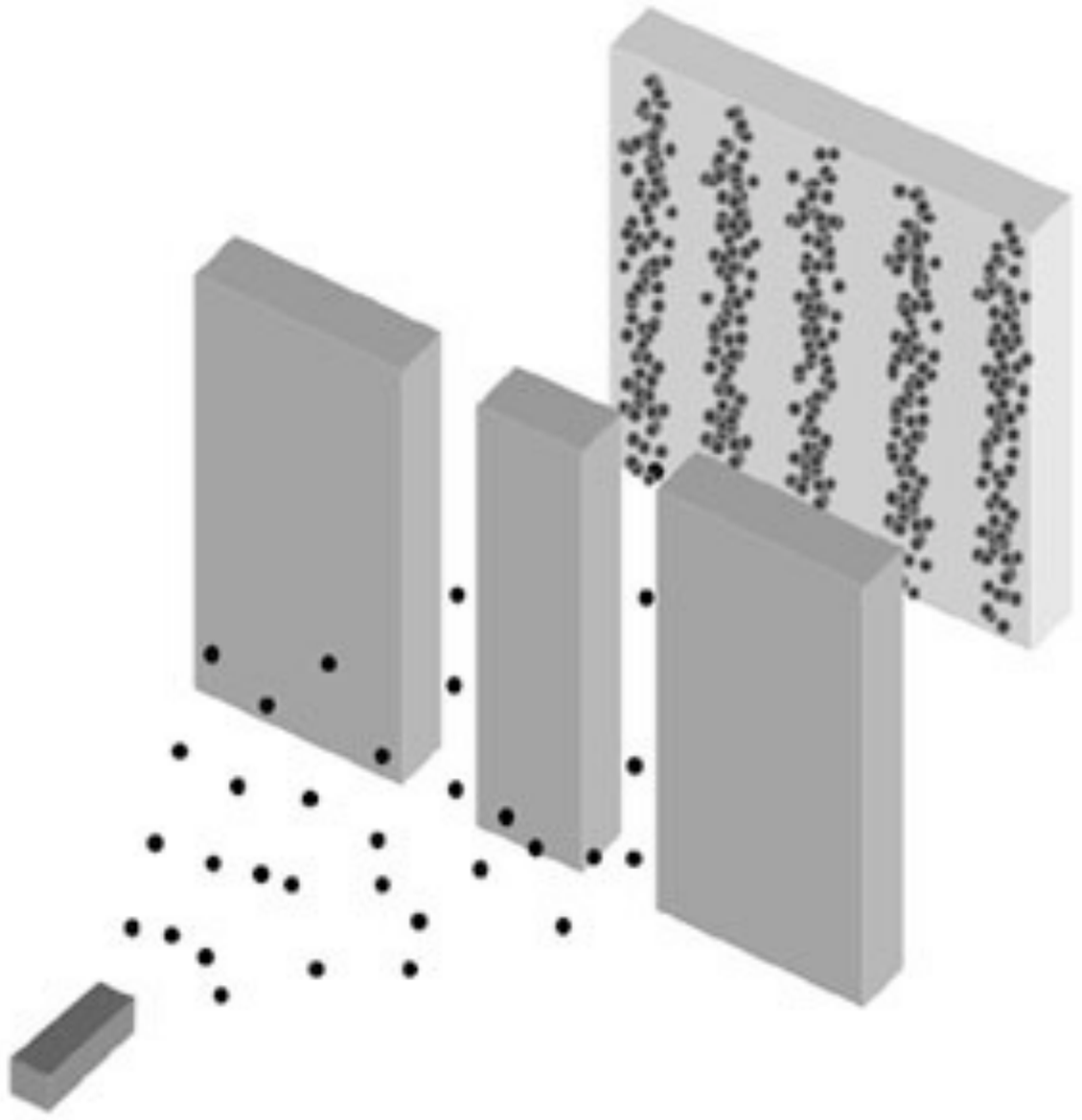
The double slit experiment



Interference of water waves

Quantum Superposition

The double slit experiment

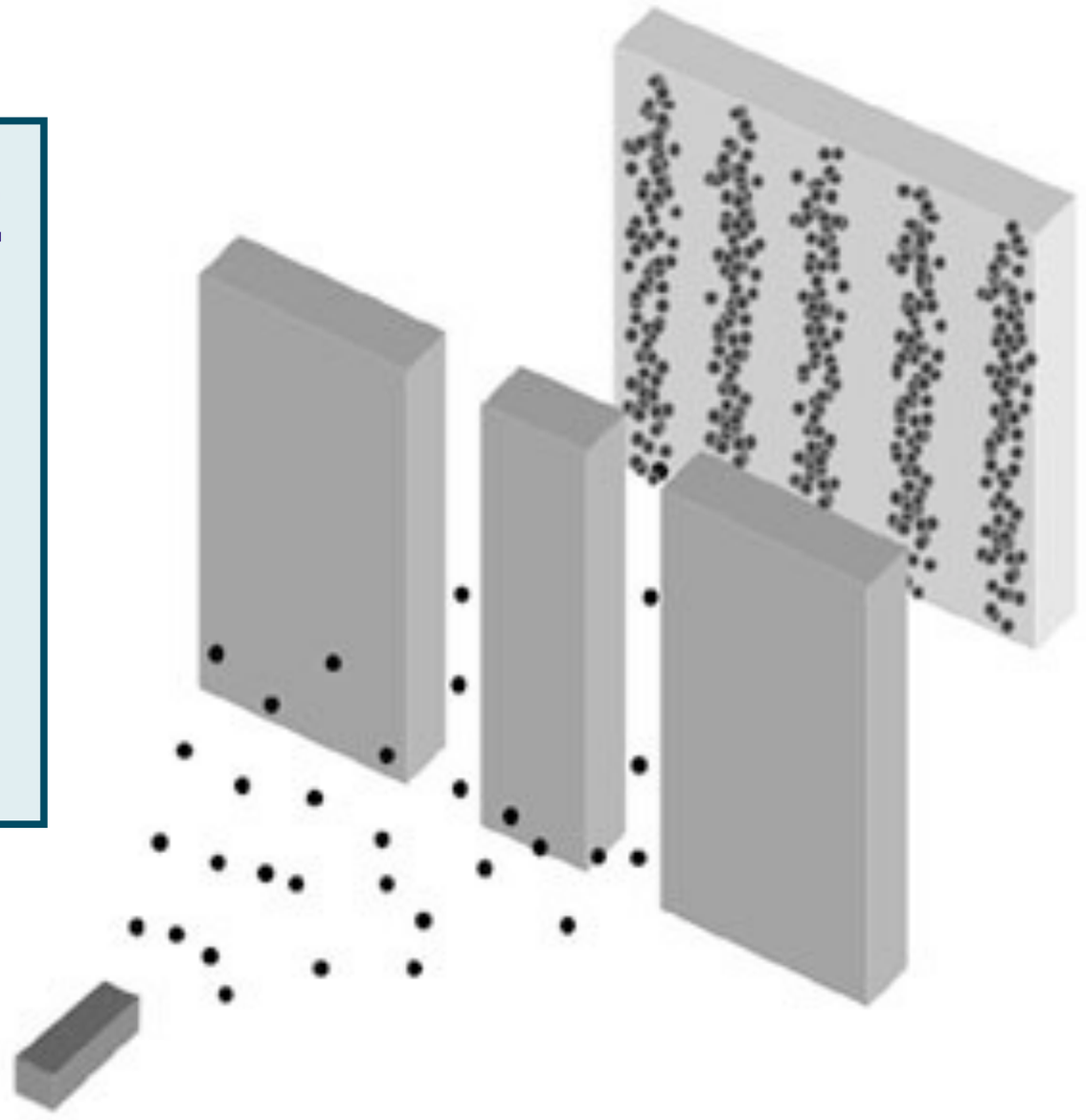


Interference of electrons

Quantum Superposition

The double slit experiment

Which slit does an electron pass through ?



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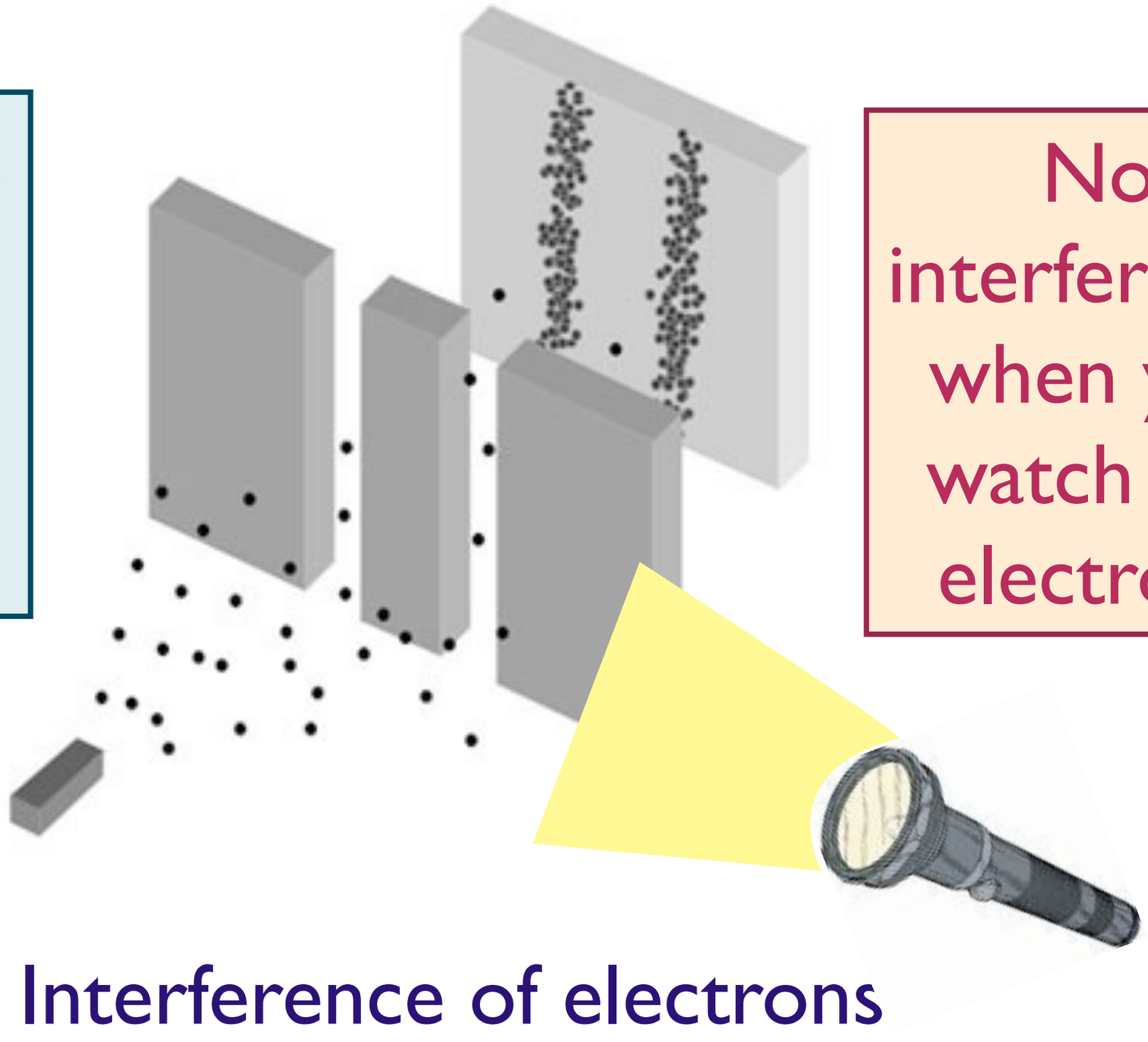


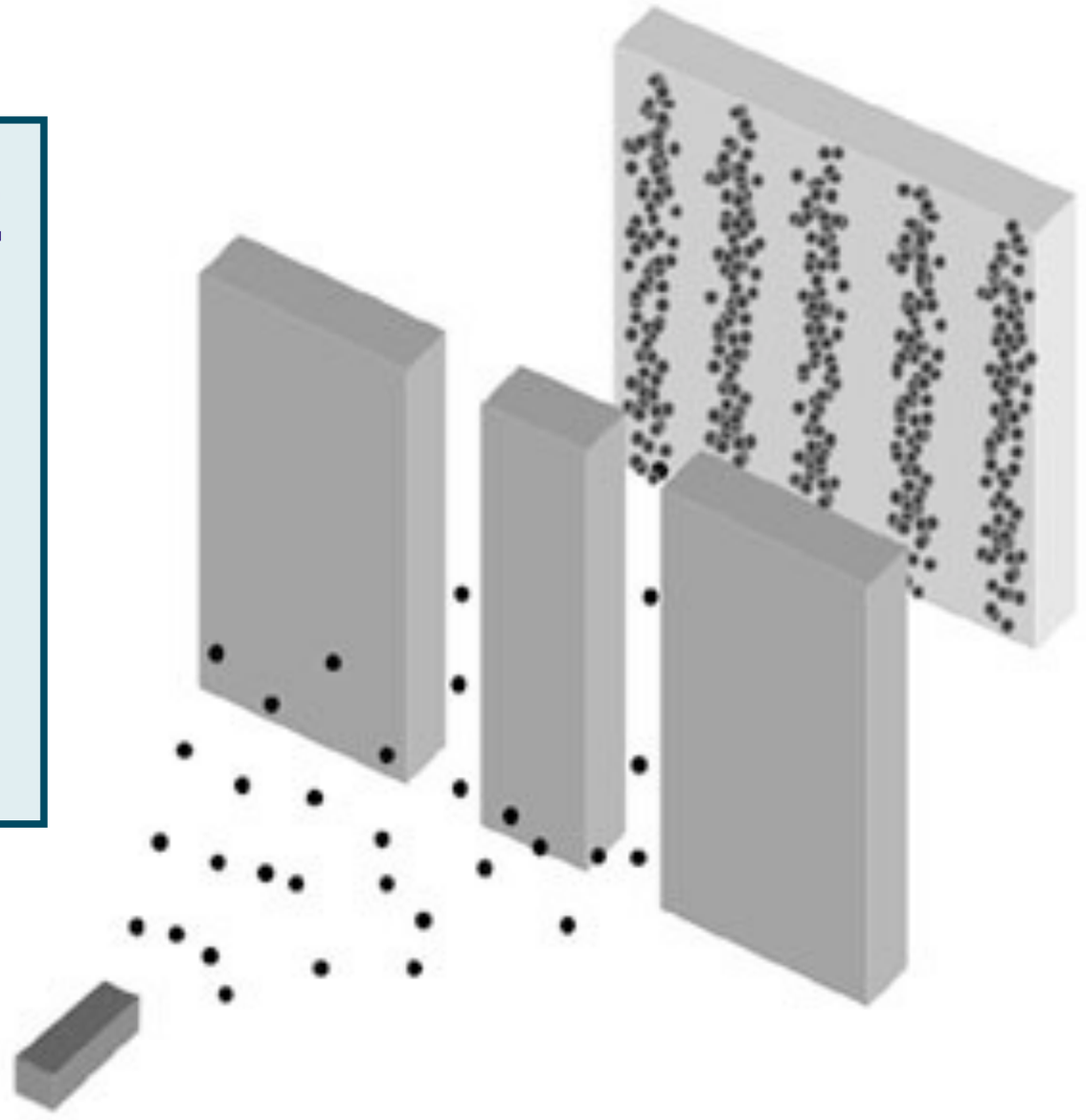
No interference when you watch the electrons

Interference of electrons

Quantum Superposition

The double slit experiment

Which slit does an electron pass through ?

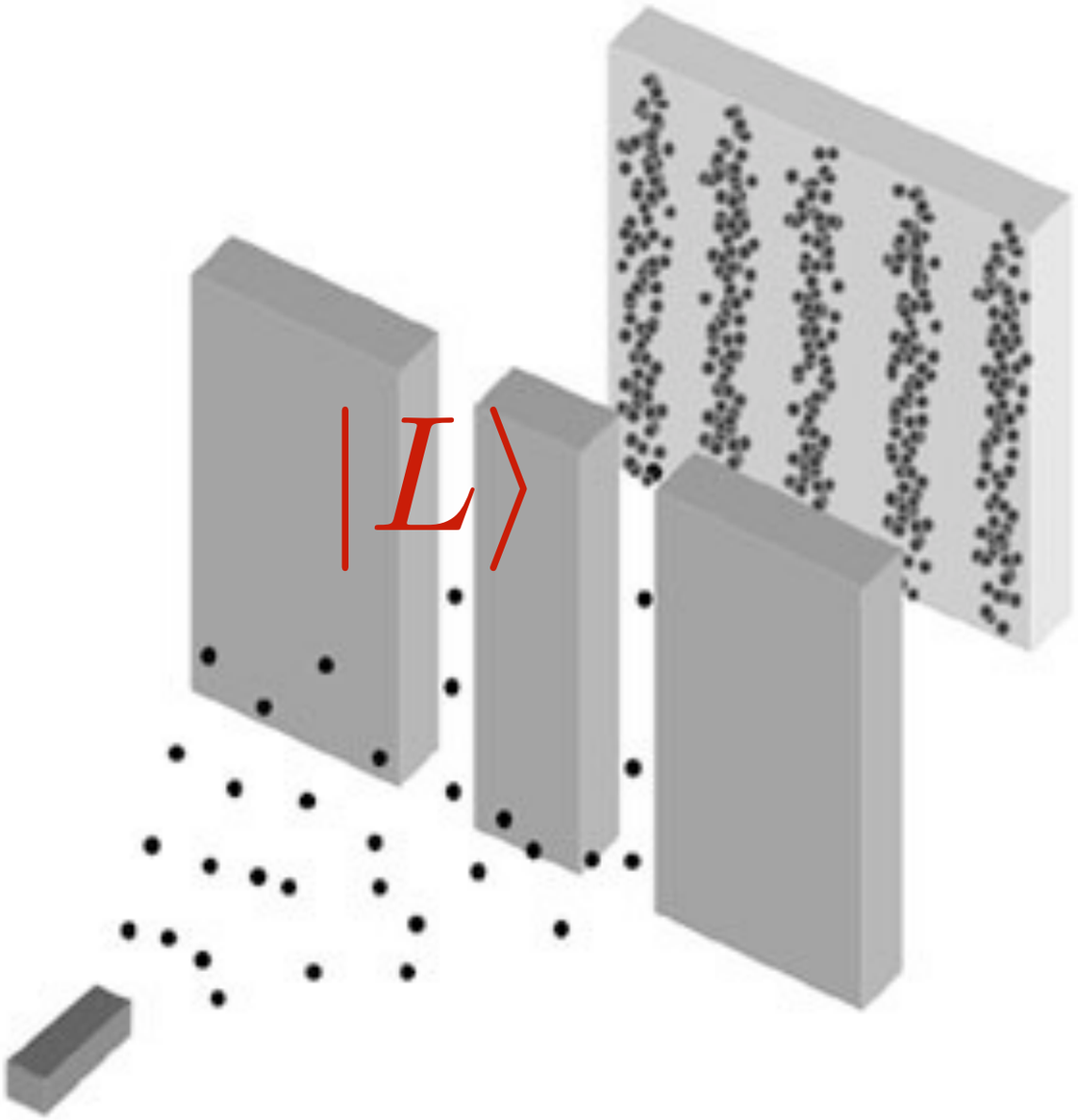


Each electron passes through both slits !

Interference of electrons

Quantum Superposition

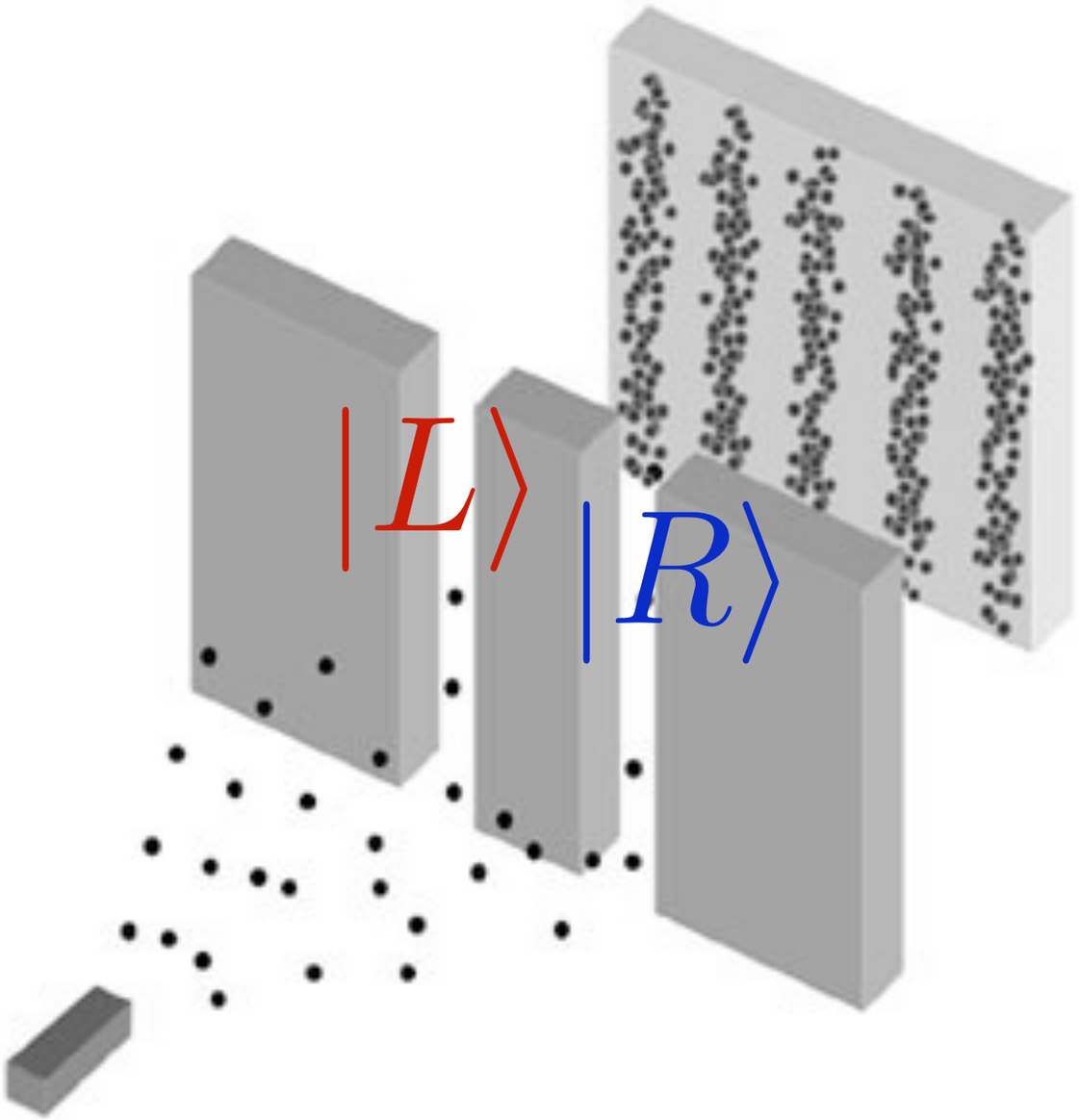
The double slit experiment



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

Quantum Superposition

The double slit experiment

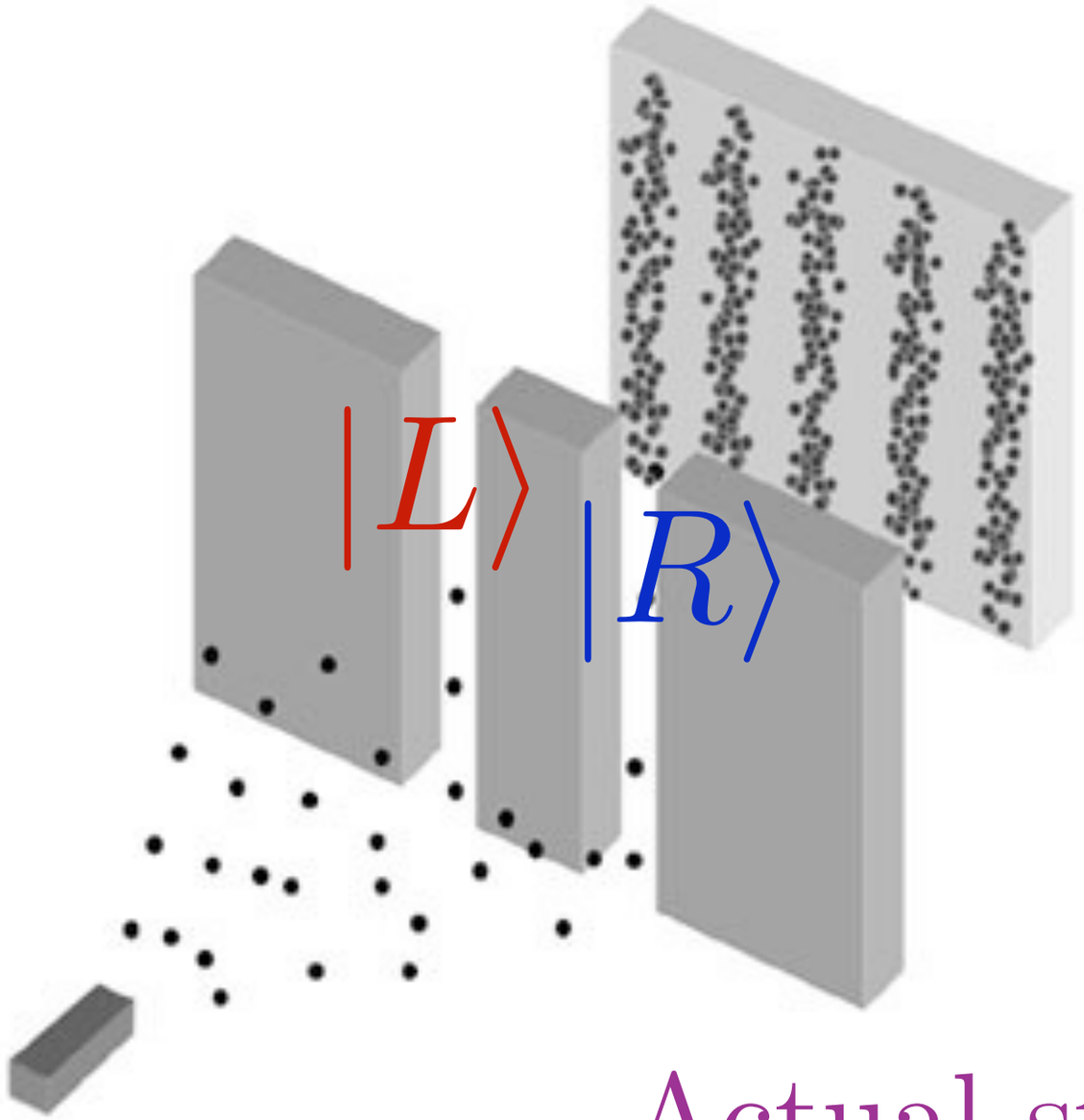


Let $|L\rangle$ represent the state with the electron in the left slit

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

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 the electron is

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

Quantum Entanglement: quantum superposition with more than one particle

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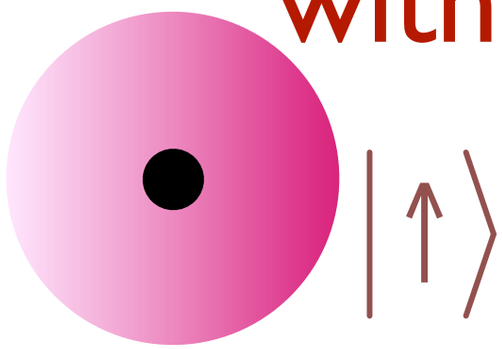
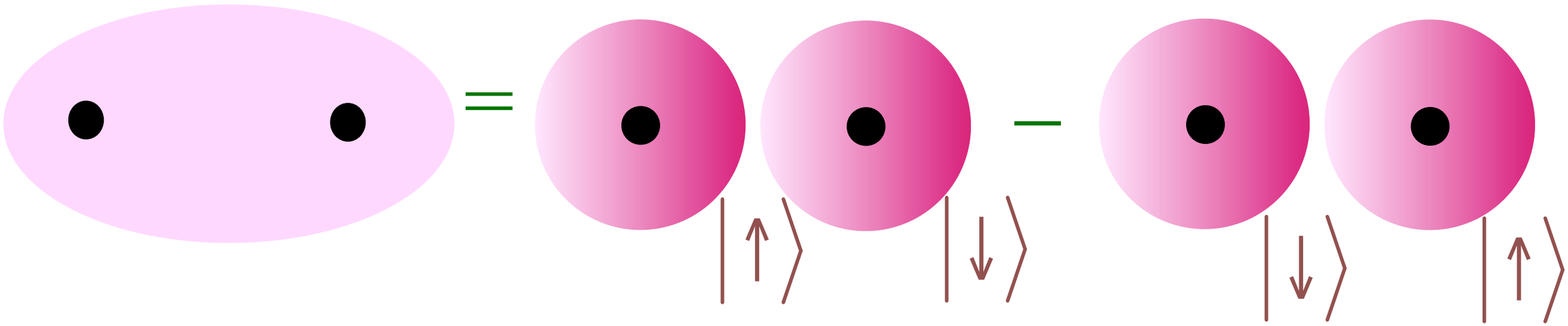
Hydrogen atom:

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:



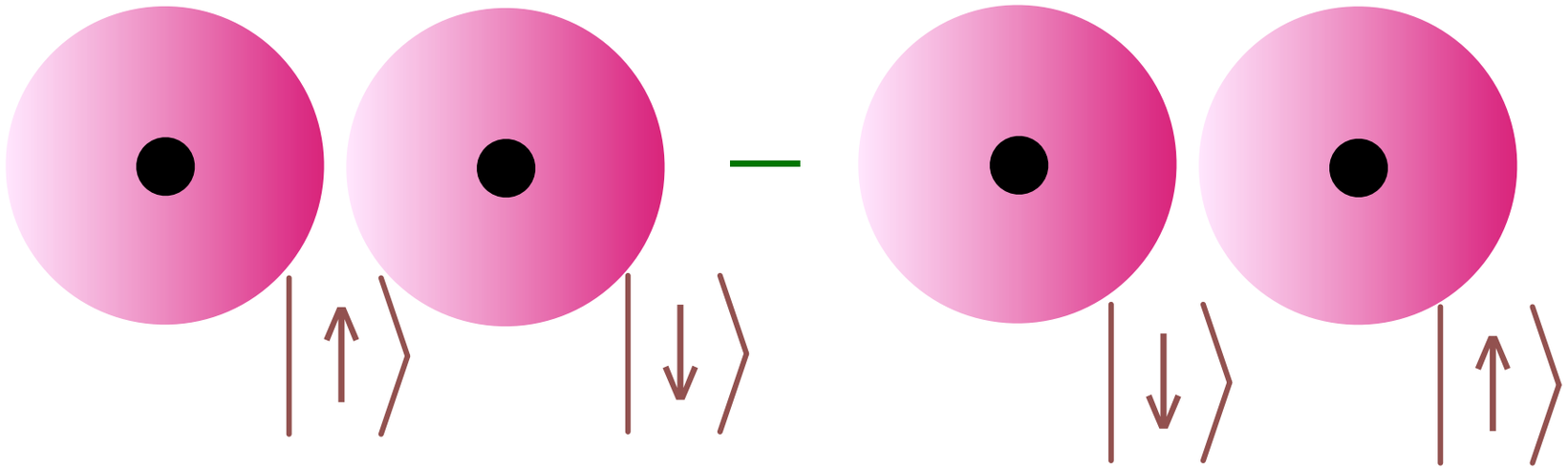
Hydrogen molecule:



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

Superposition of two electron states leads to non-local correlations between spins

Quantum Entanglement: quantum superposition with more than one particle



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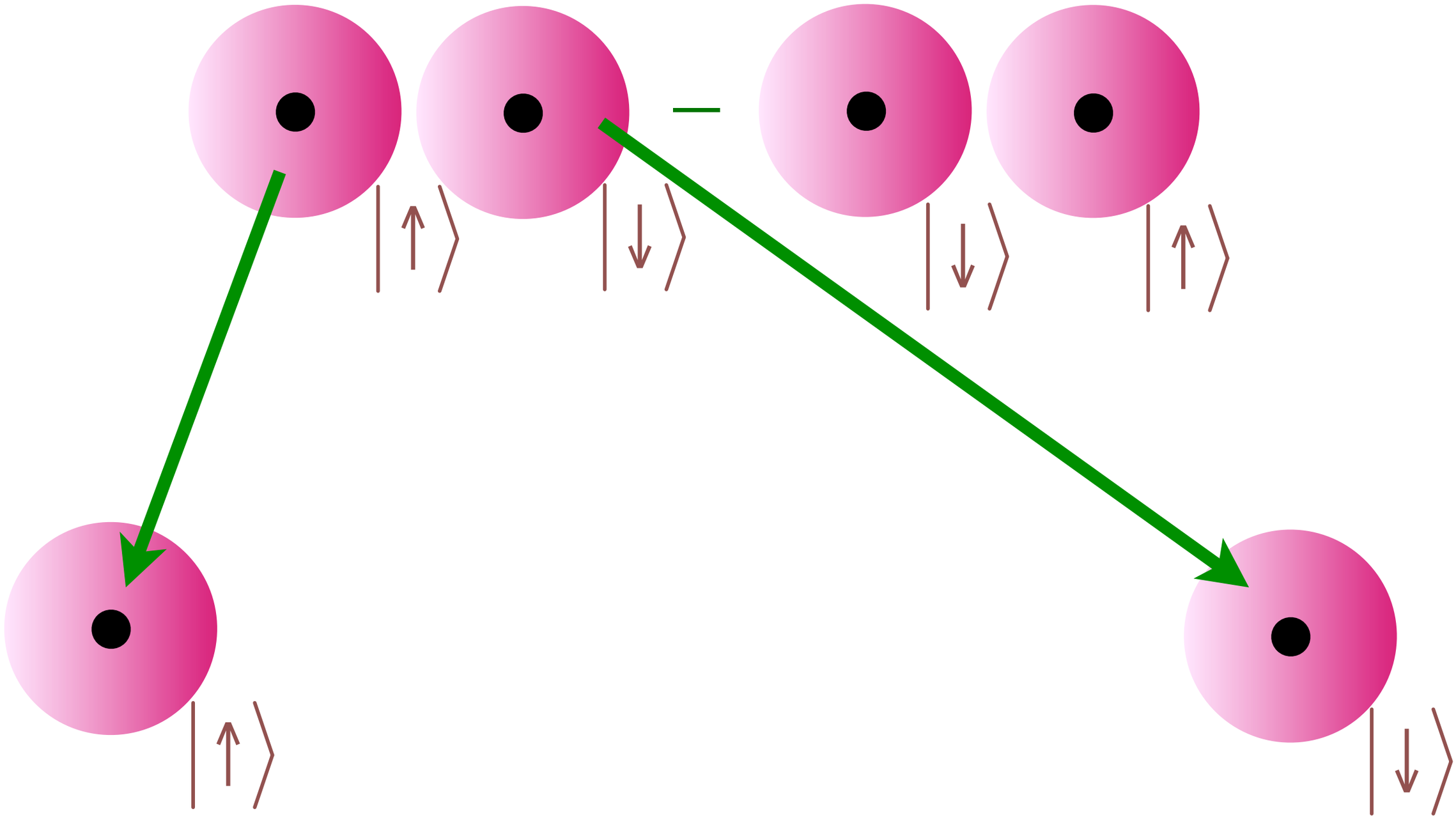

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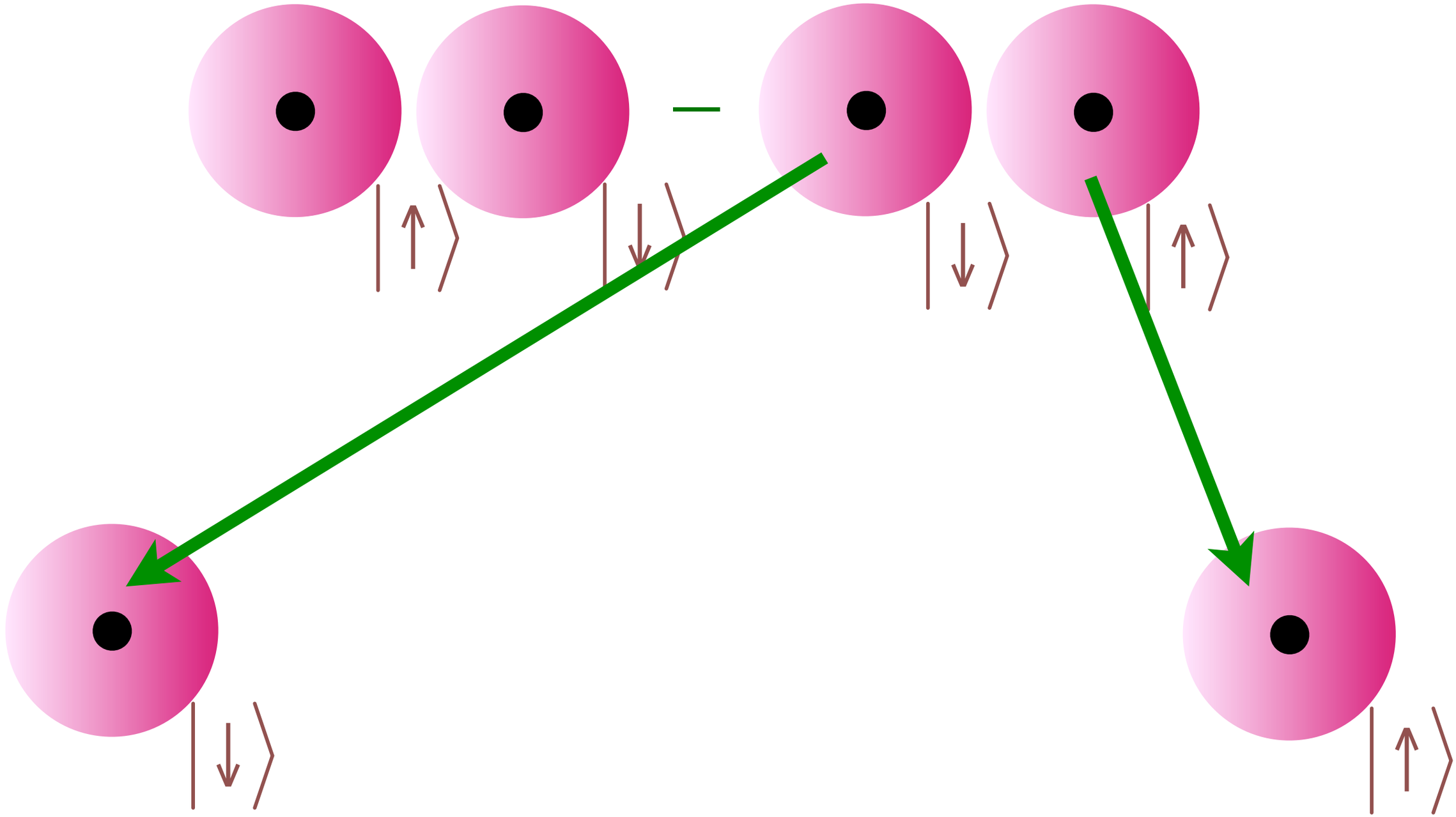

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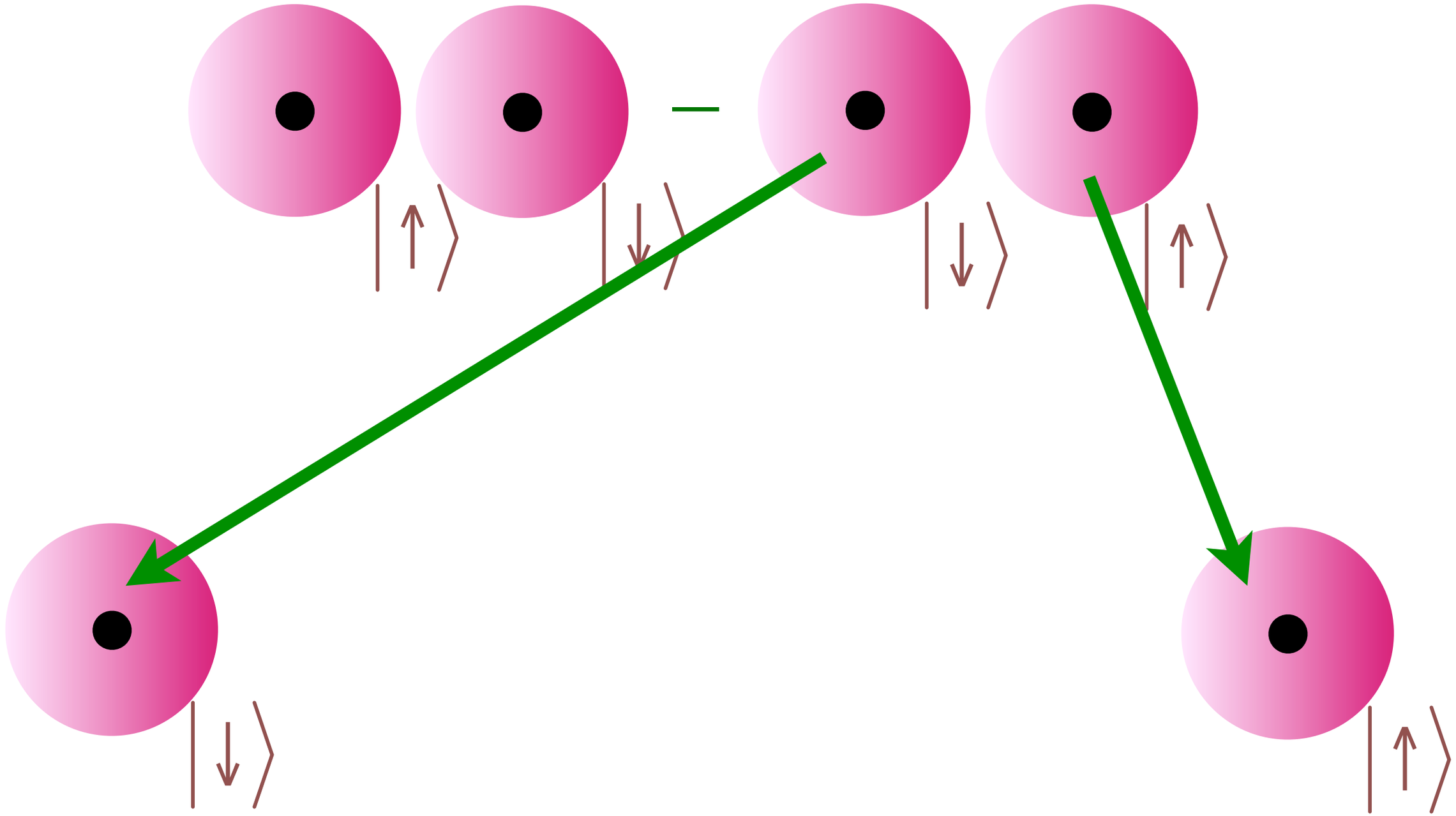
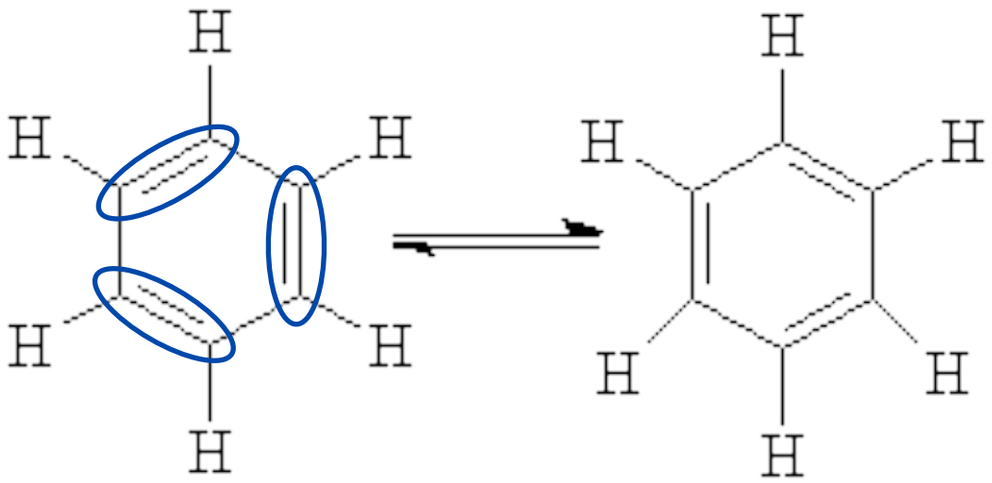


Einstein-Podolsky-Rosen "paradox": Non-local correlations between observations arbitrarily far apart

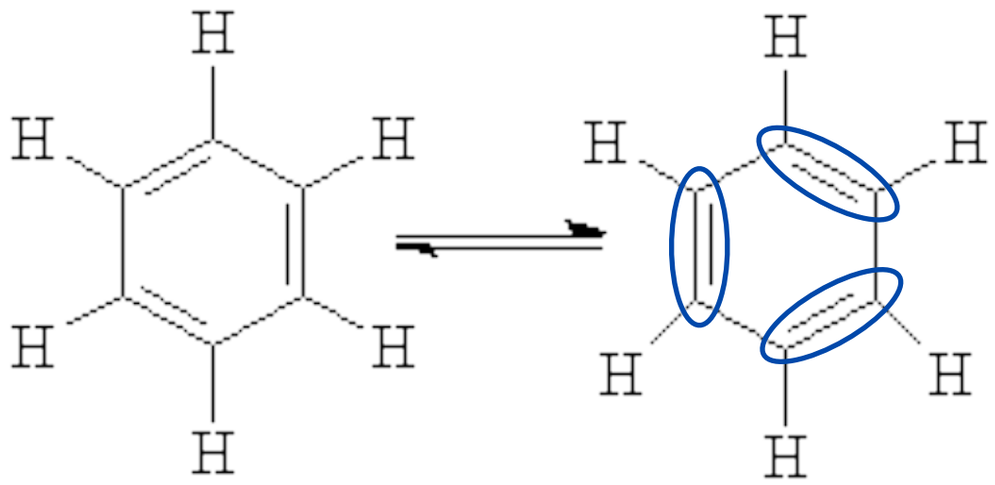
Entanglement of chemical bonds



Resonance in benzene leads to a symmetric configuration of chemical bonds

(*F. Kekulé, L. Pauling*)

Entanglement of chemical bonds



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Quantum superposition and entanglement

Superconductivity

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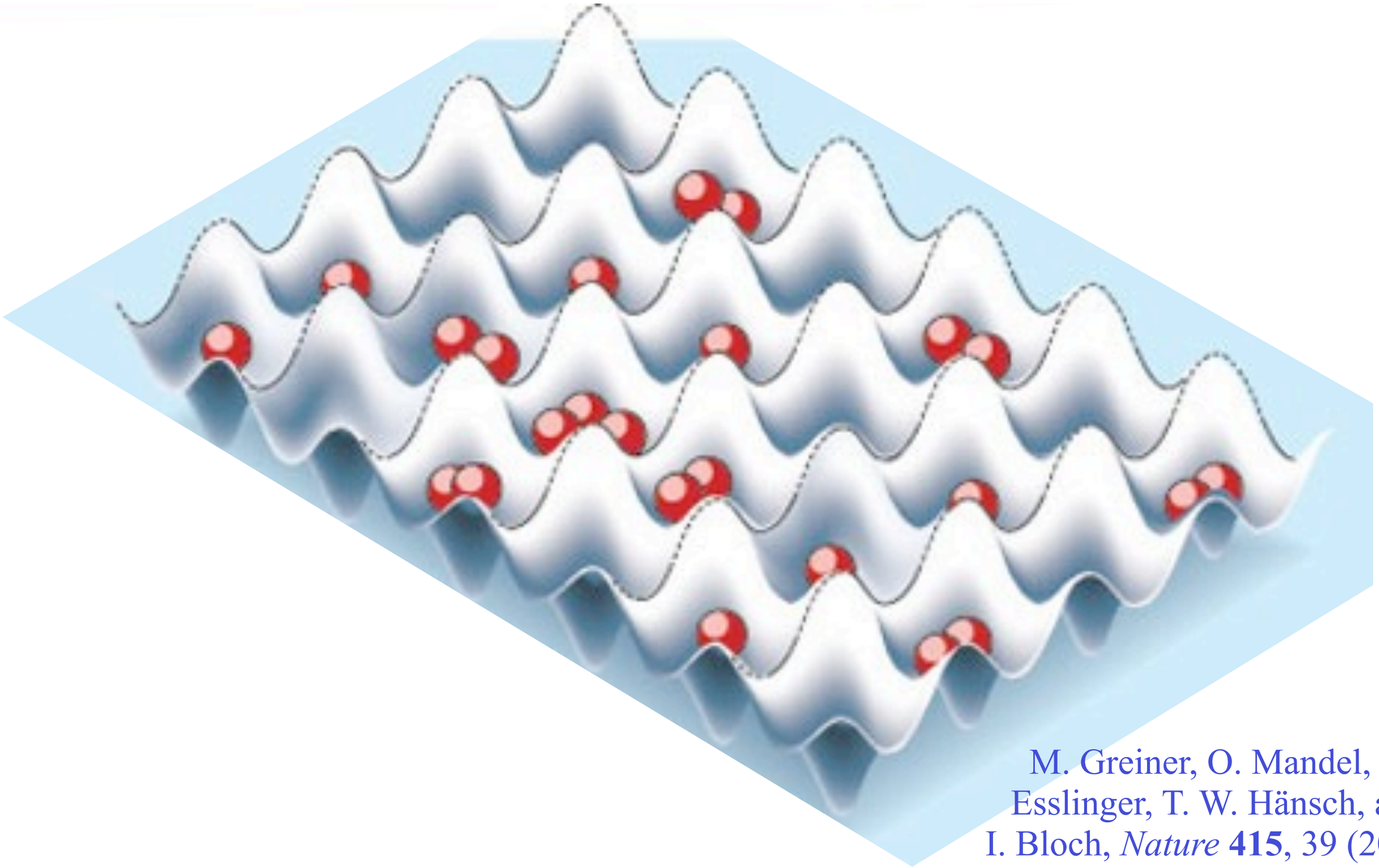
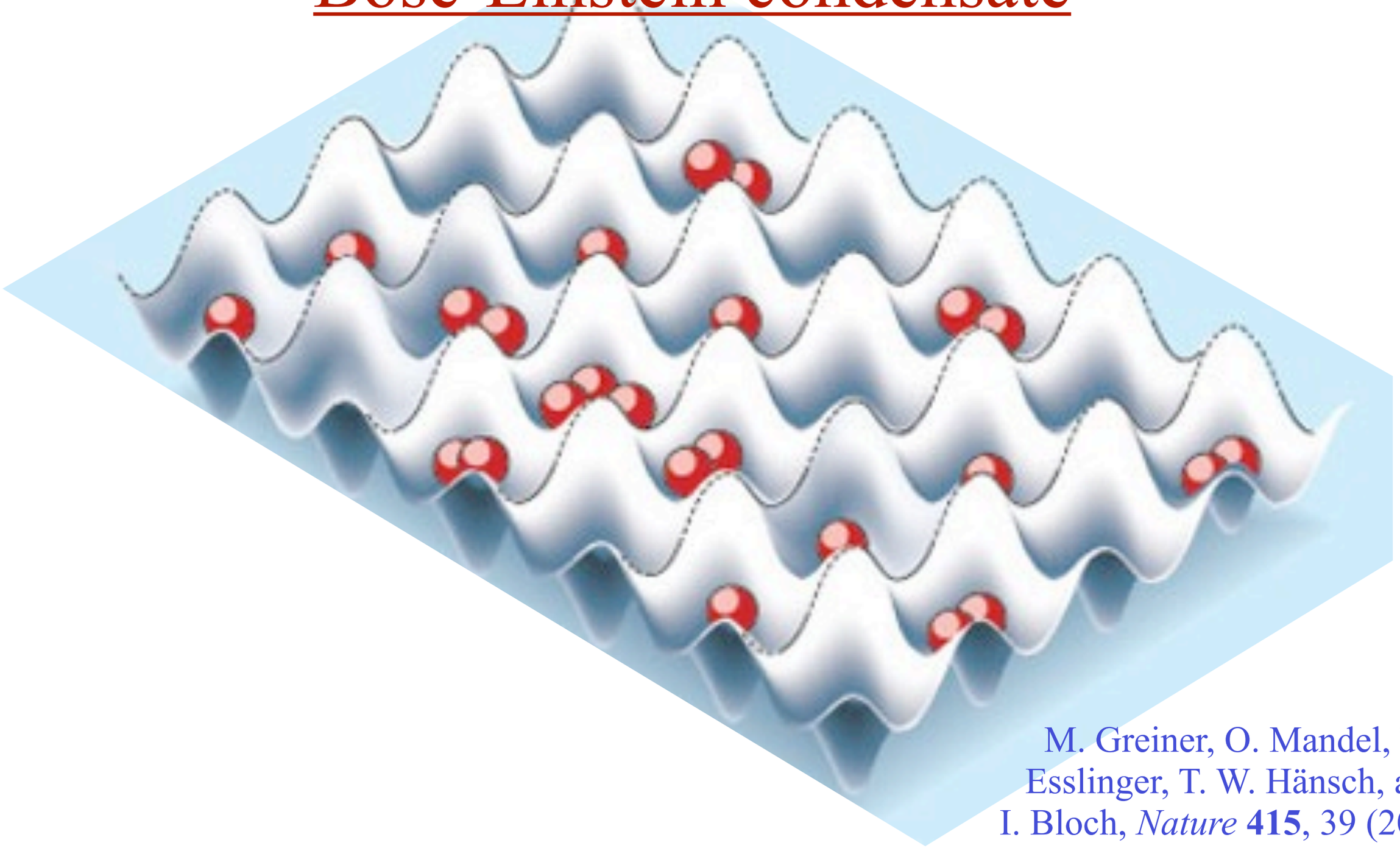
Rubidium atoms in a magnetic trap and standing waves of laser light



M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

At very low temperatures and for a weak laser light, the Rubidium atoms obey quantum mechanics and form a Bose-Einstein condensate



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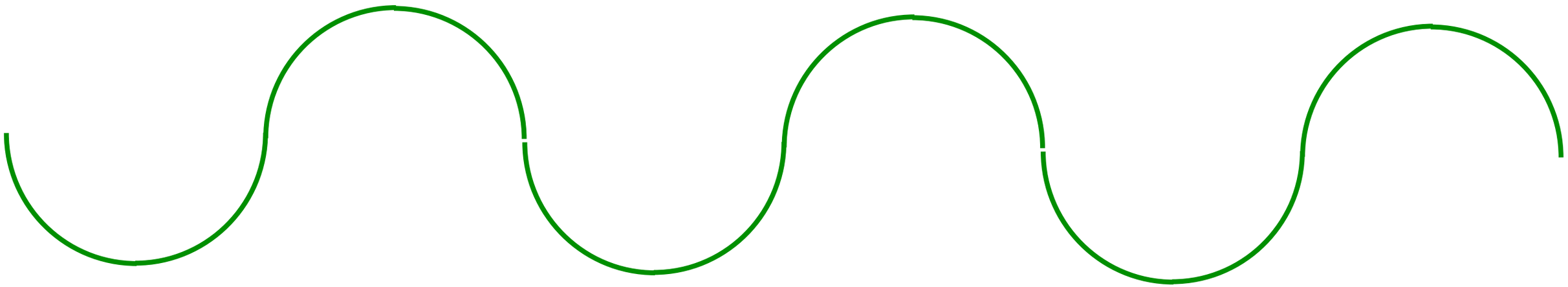
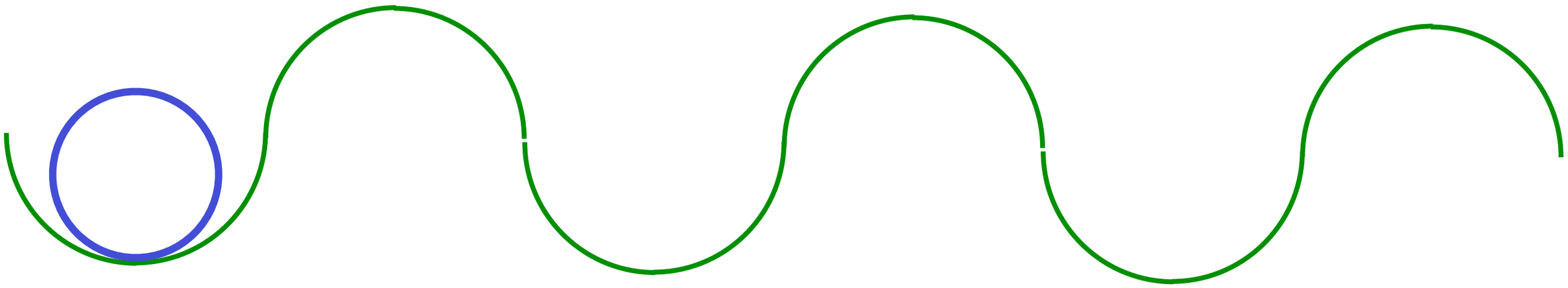
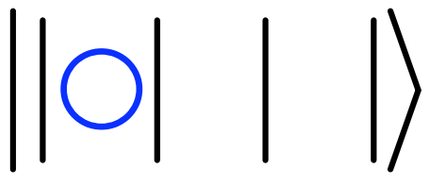
A Bose-Einstein condensate: An quantum superposition of all the atoms in all positions

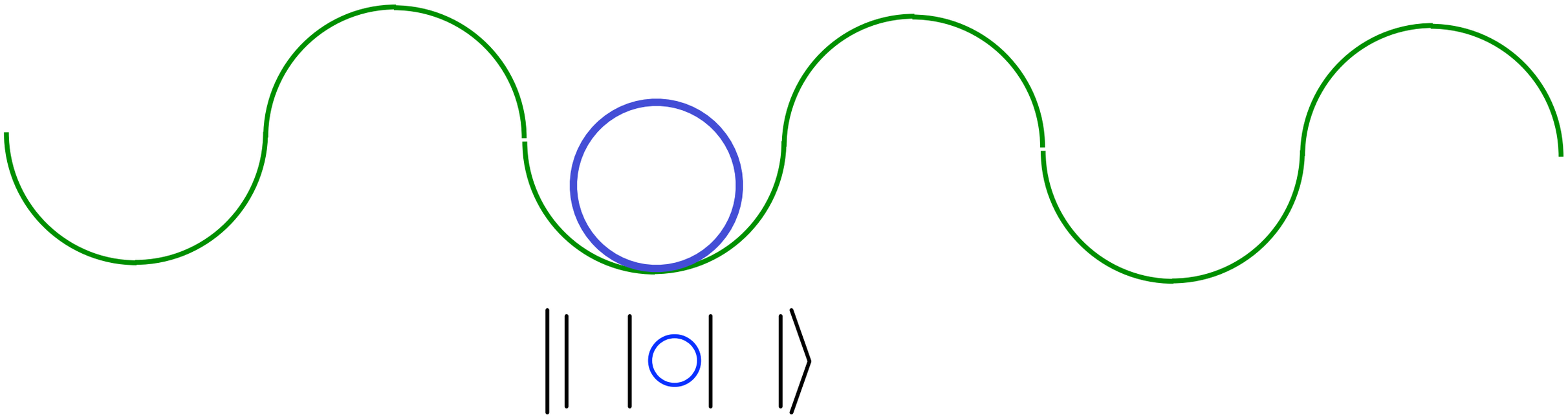
A liquid which flows without resistance (a superfluid)







A single atom is superposed between all positions



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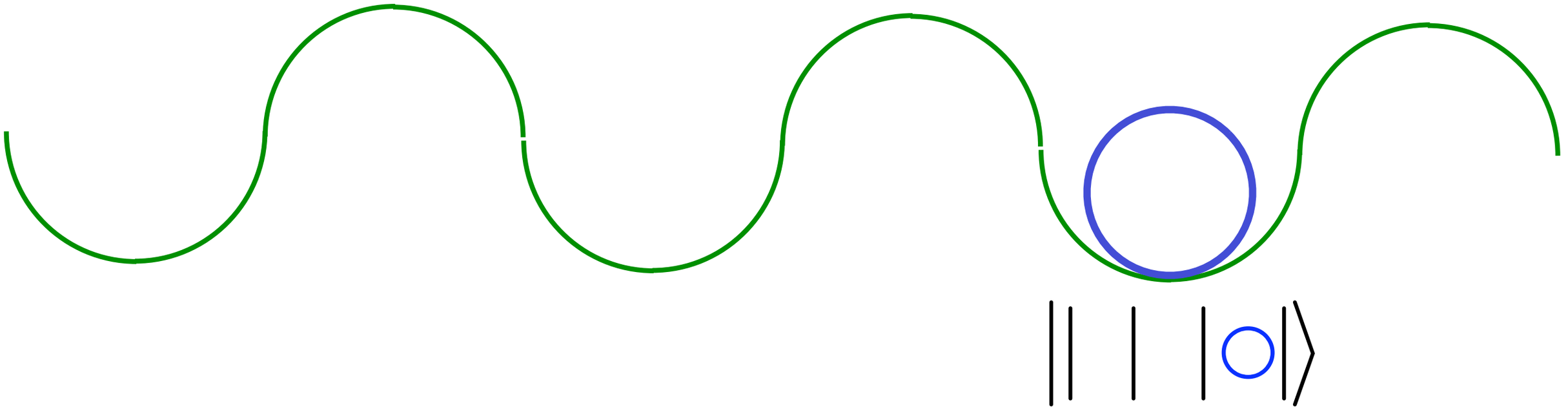

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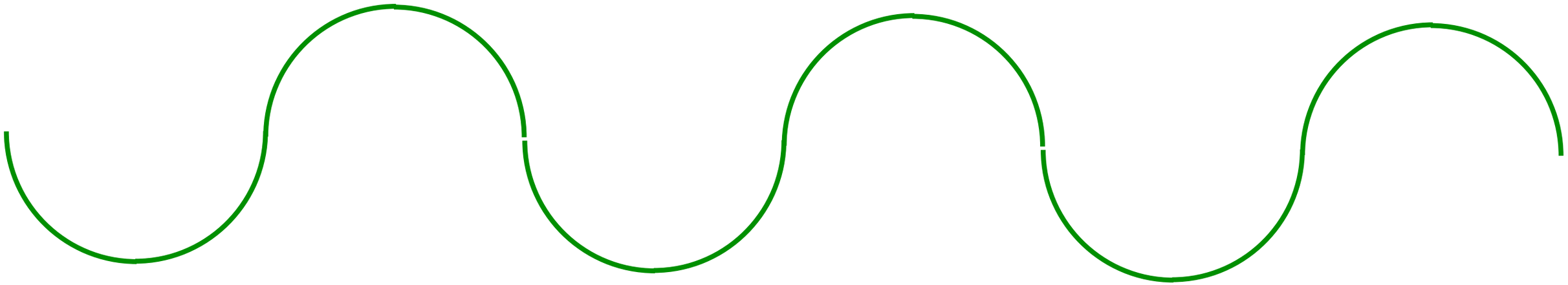

$$|\mathrm{G}\rangle = \left(|\bigcirc| \; | \; |\rangle + || \; |\bigcirc| \; |\rangle + || \; | \; |\bigcirc|\rangle \right)$$

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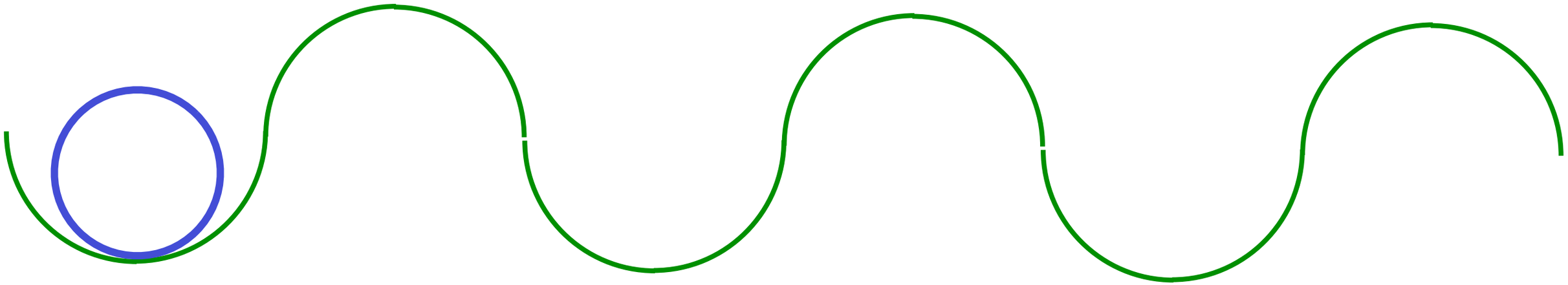

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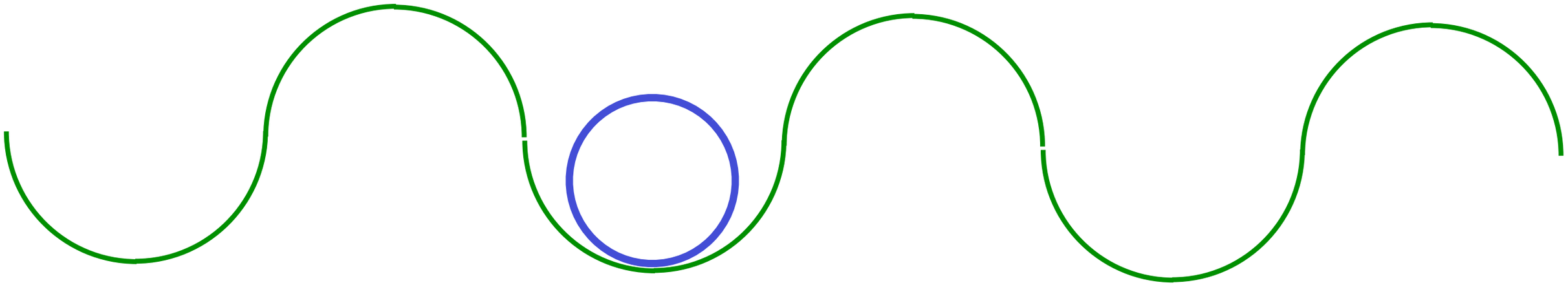

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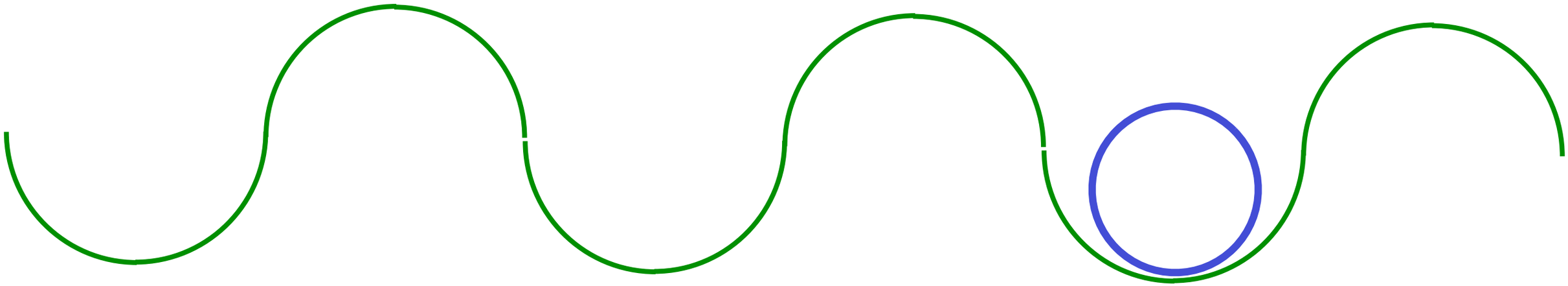

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A single atom is superposed between all positions

Bose-Einstein condensate: superposition between all atoms

$$|\mathrm{BEC}\rangle = |\mathrm{G}\rangle|\mathrm{G}\rangle|\mathrm{G}\rangle$$

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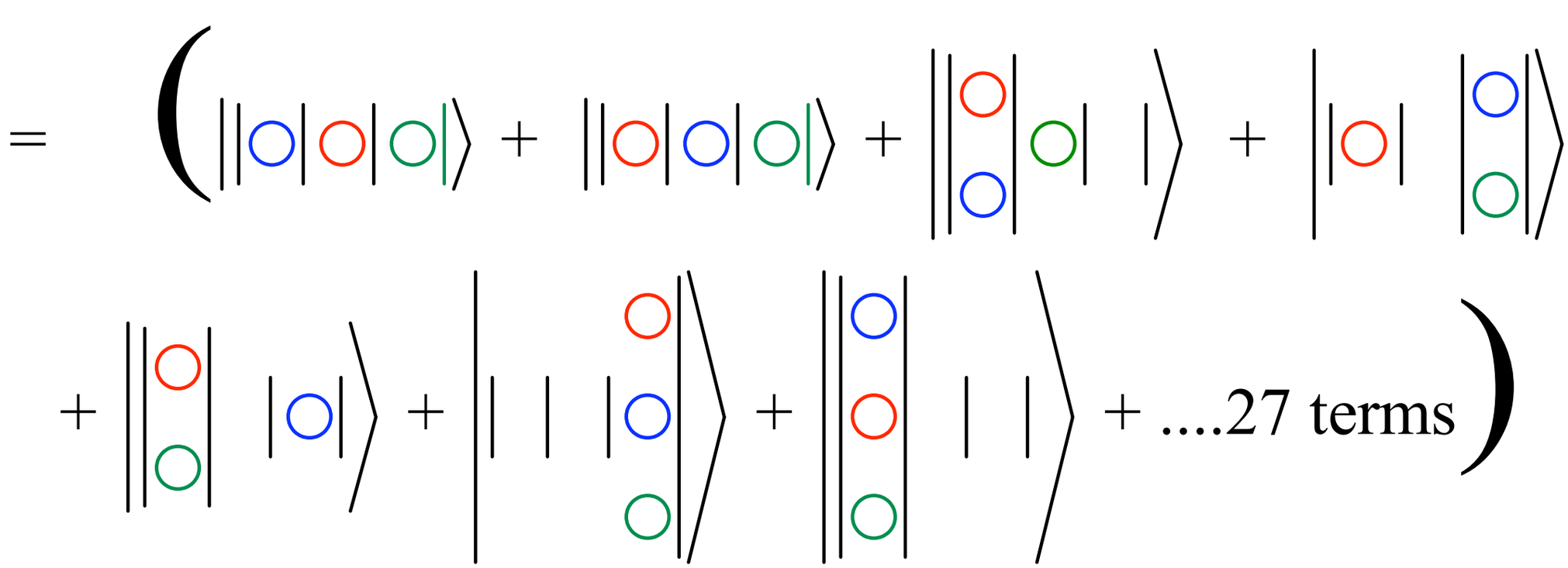
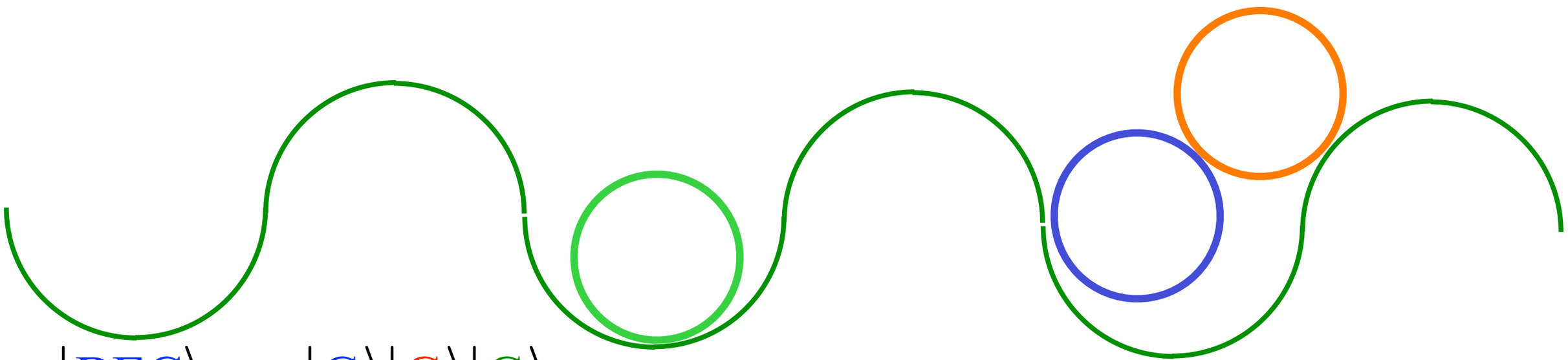


Large fluctuations in number of atoms in each site – *superfluidity* (atoms can "flow" without dissipation)

Bose-Einstein condensate: superposition between all atoms



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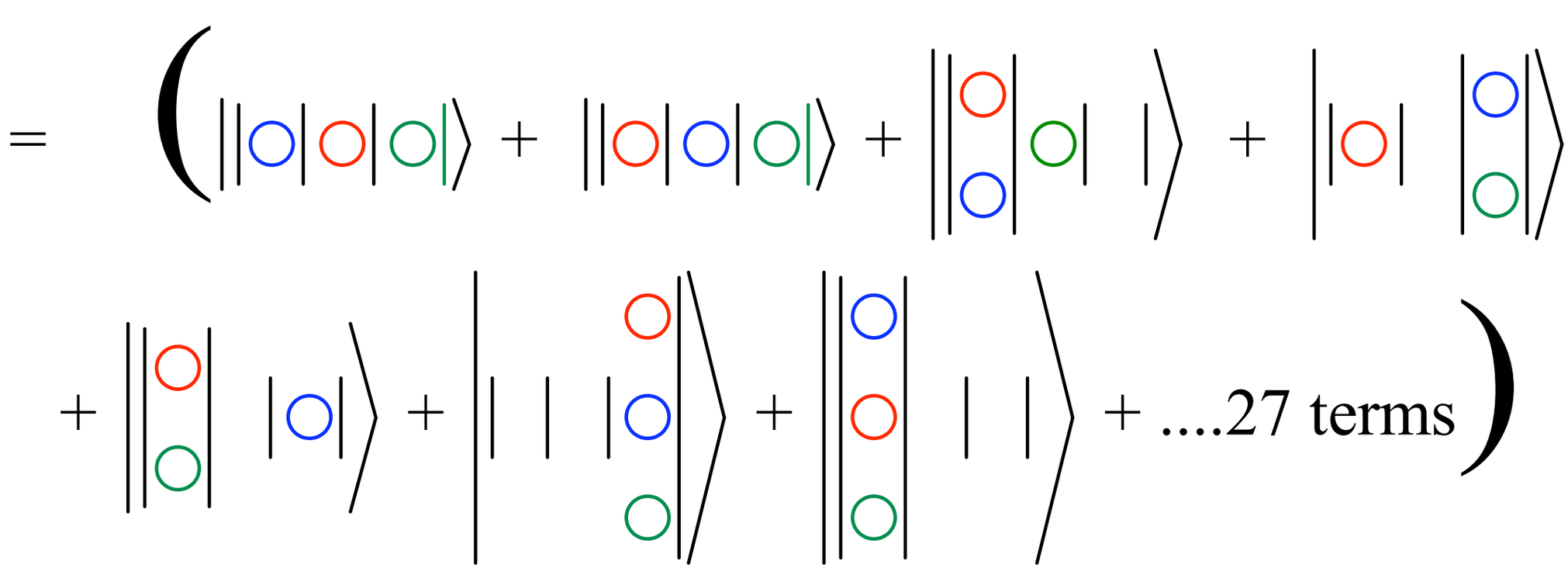

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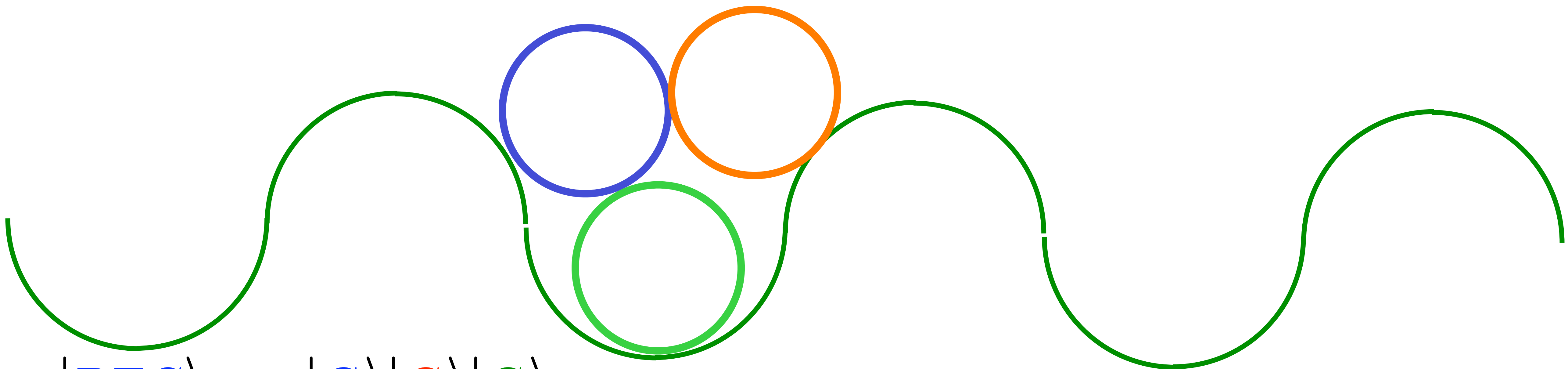

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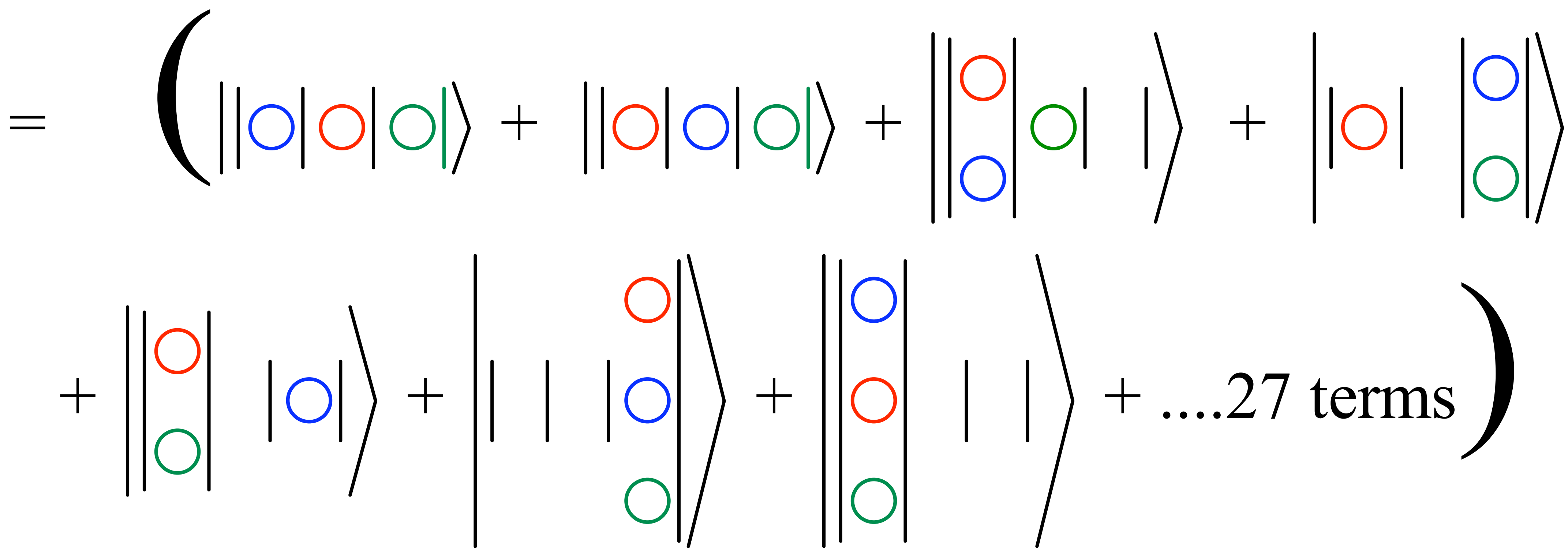

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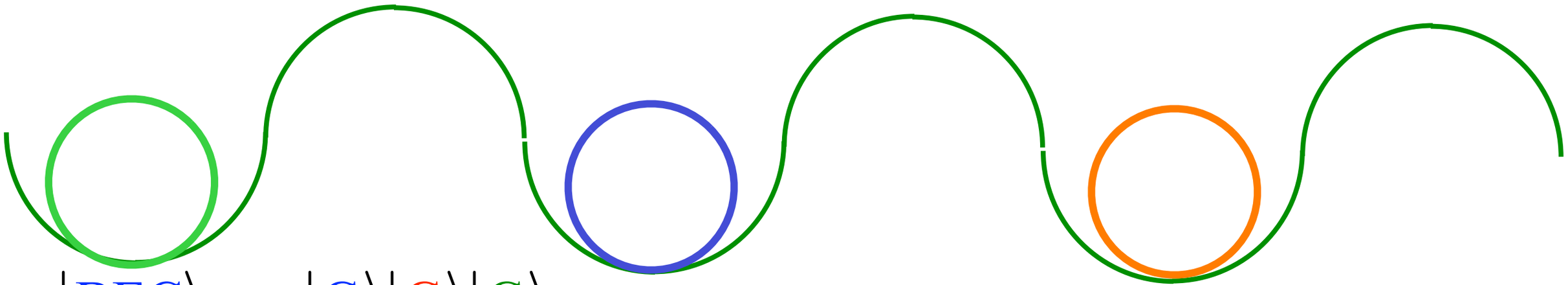

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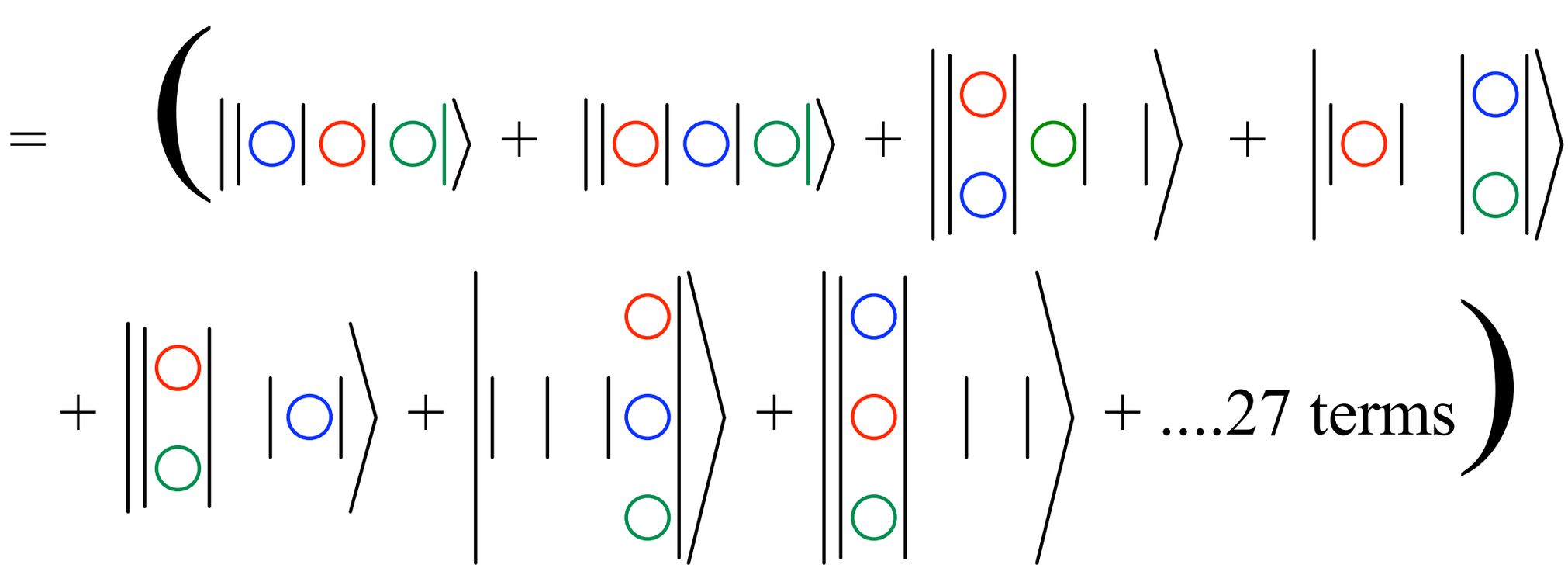

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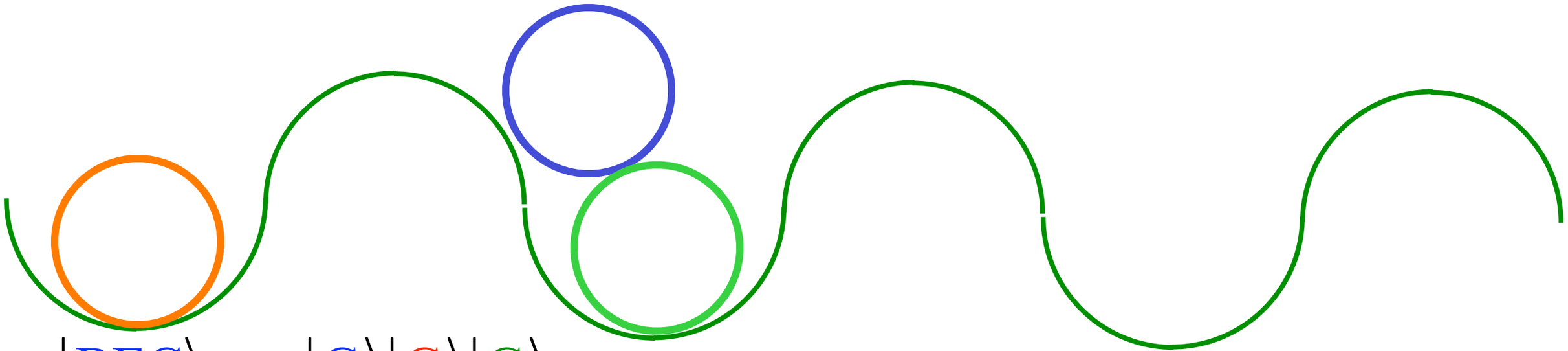

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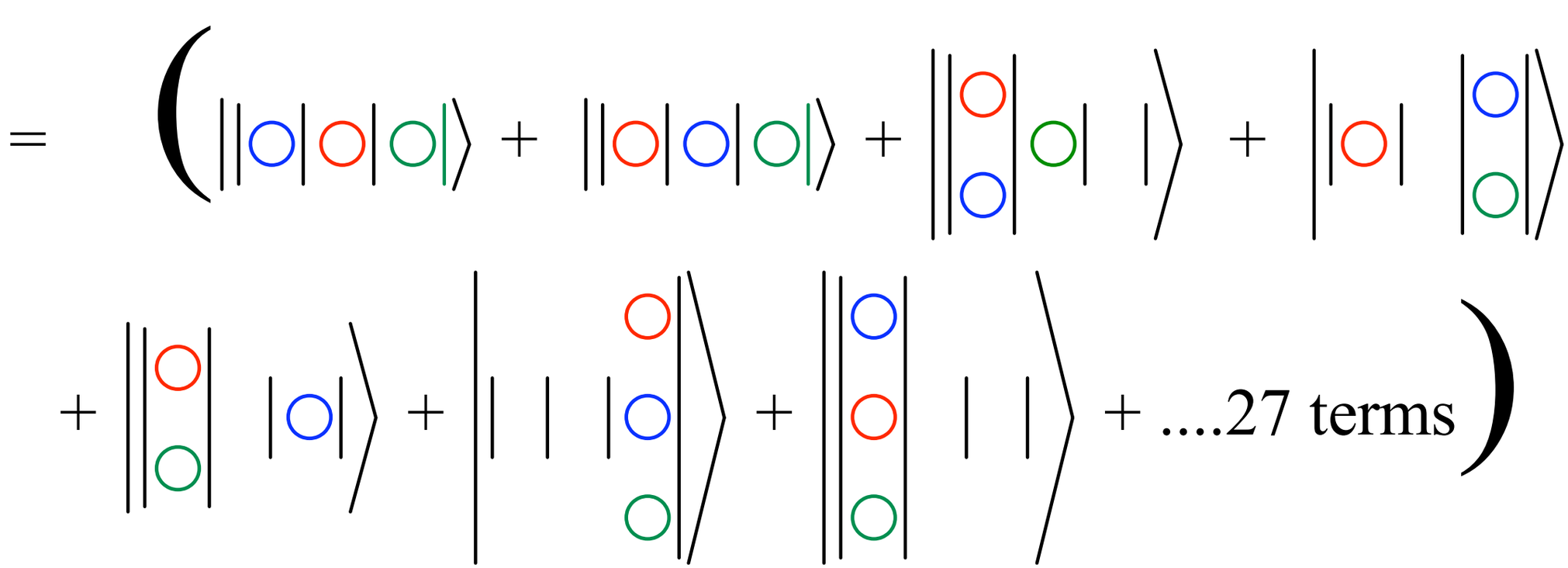

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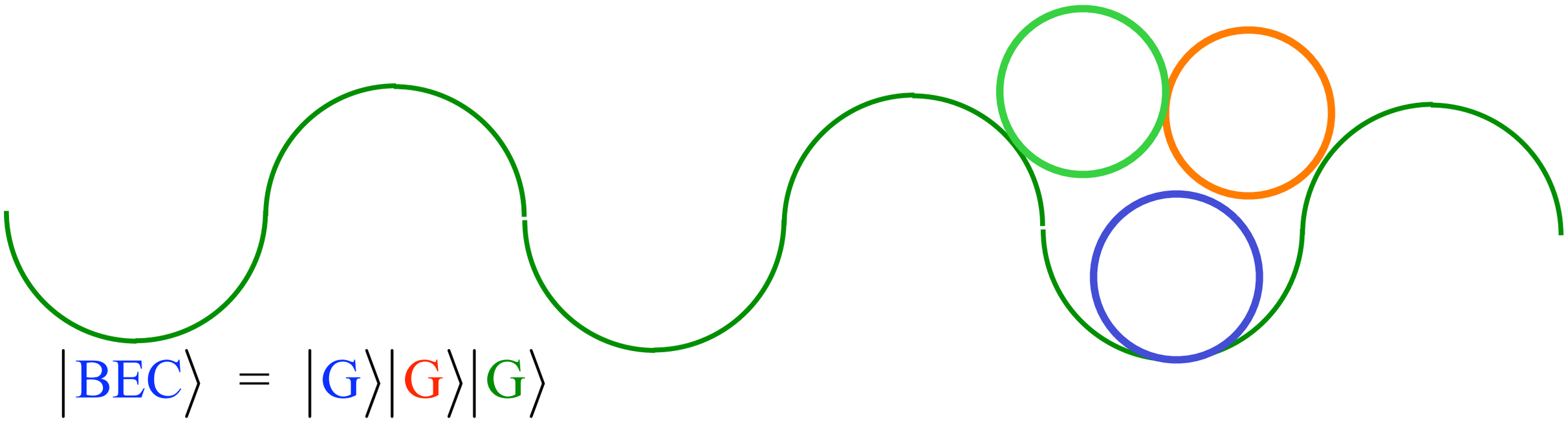

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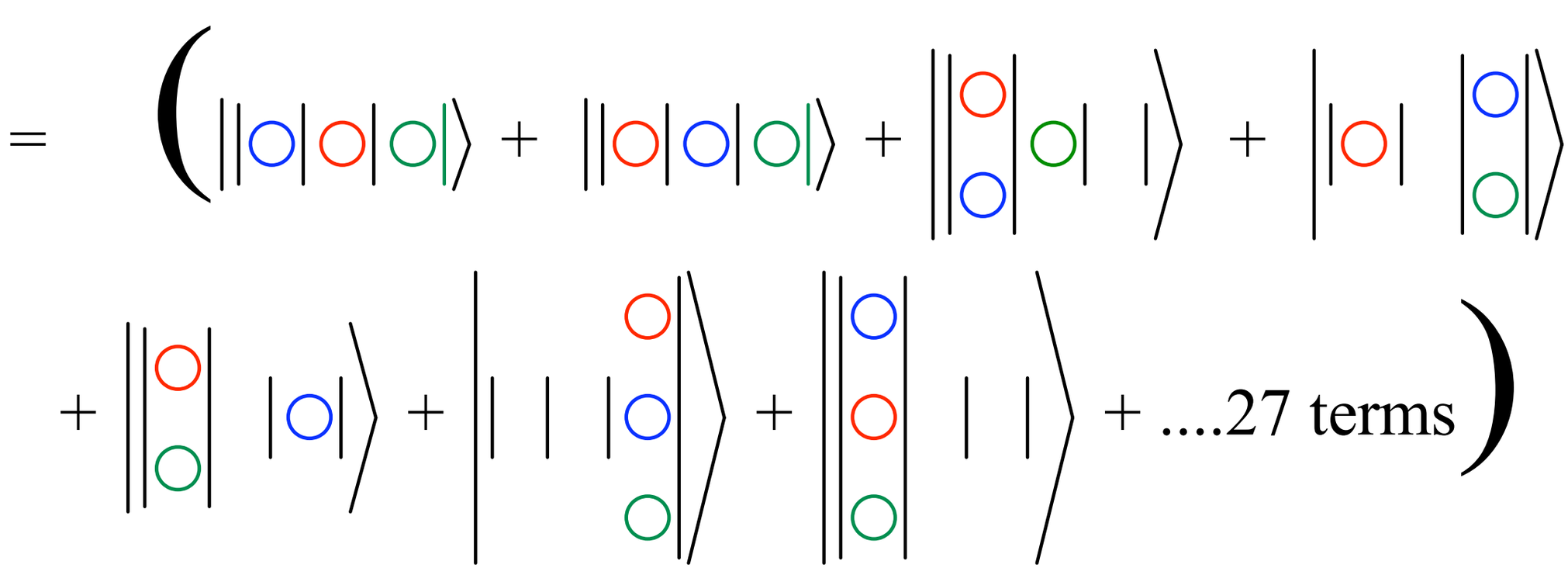

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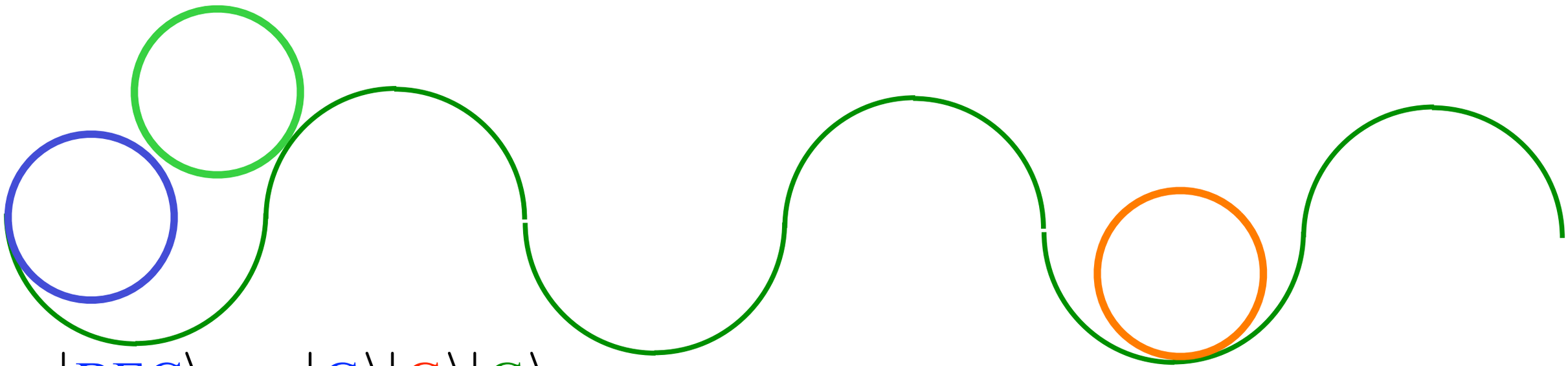

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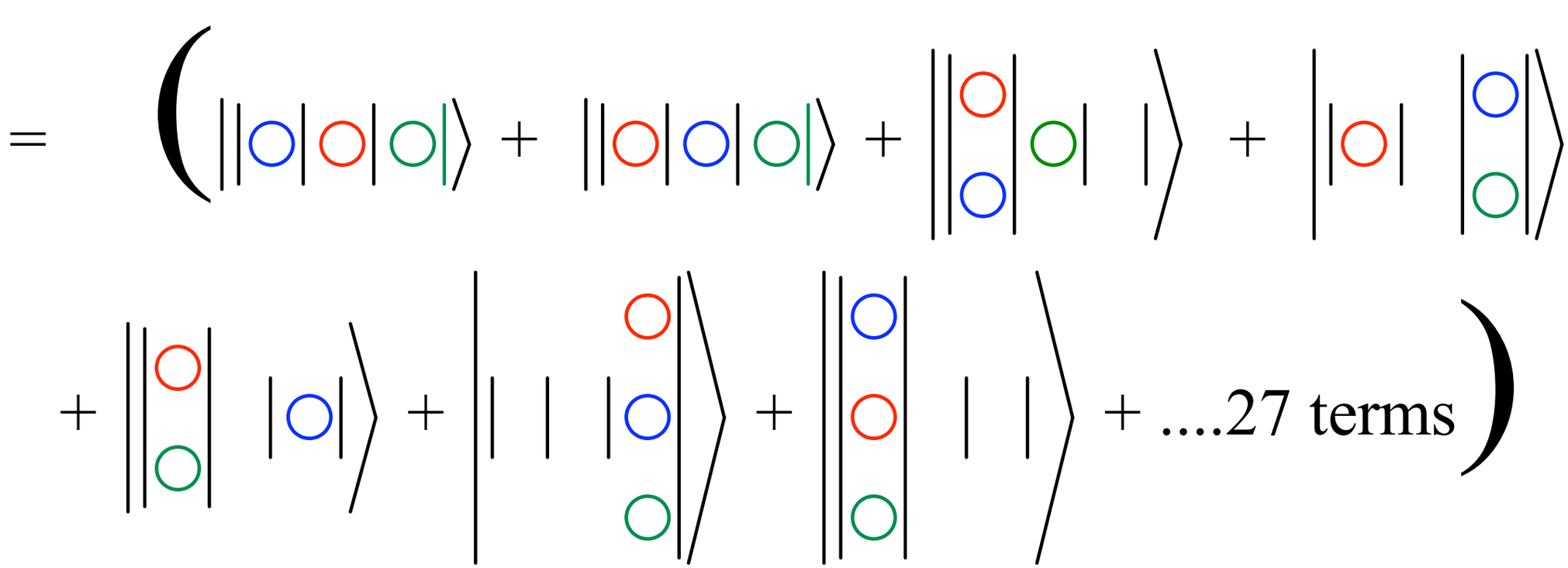
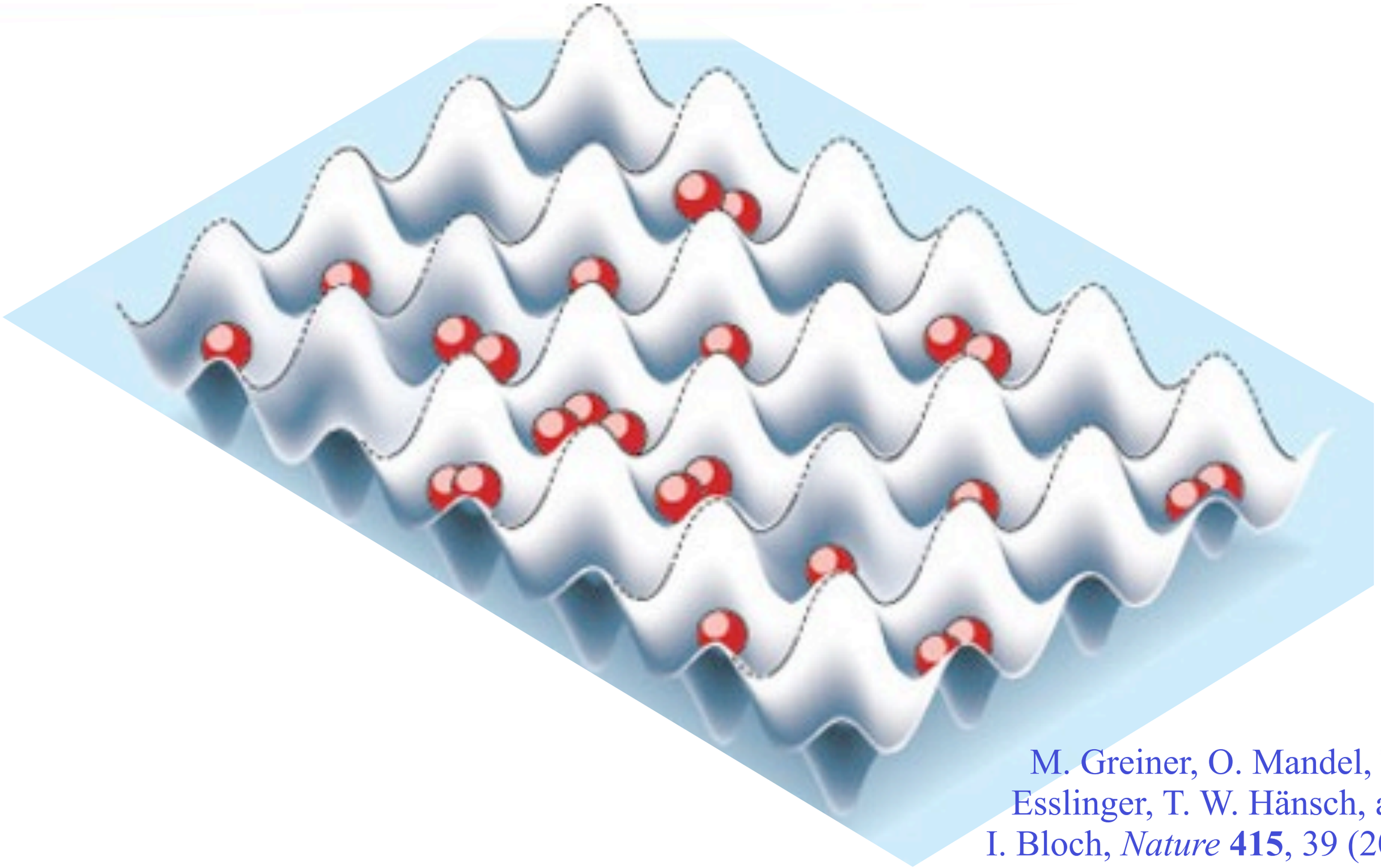


Large fluctuations in number of atoms in each site – *superfluidity* (atoms can "flow" without dissipation)

At very low temperatures and for a weak laser light, the Rubidium atoms form a Bose-Einstein condensate



M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

Bose-Einstein condensate: superposition between all atoms

$$|\mathrm{BEC}\rangle = |\mathrm{G}\rangle|\mathrm{G}\rangle|\mathrm{G}\rangle$$

(Strictly speaking: this is not entanglement between the atoms because the BEC is a product of simple "wave" states of the atoms)

A superconductor: a Bose condensate of pairs of electrons in a "chemical bond" in a metal

$$|\mathrm{BEC}\rangle = |\mathrm{G}\rangle|\mathrm{G}\rangle|\mathrm{G}\rangle$$

$$|G\rangle \equiv |\uparrow\downarrow - \downarrow\uparrow\rangle$$

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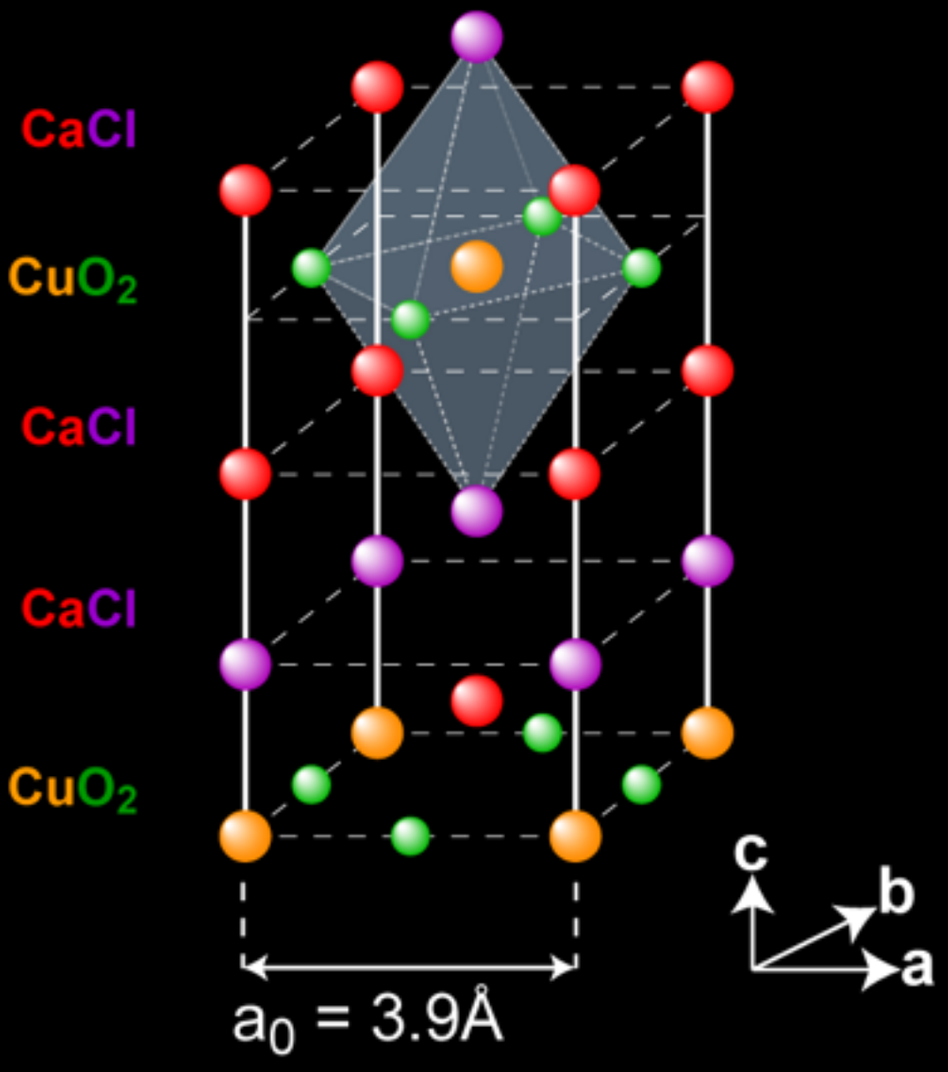
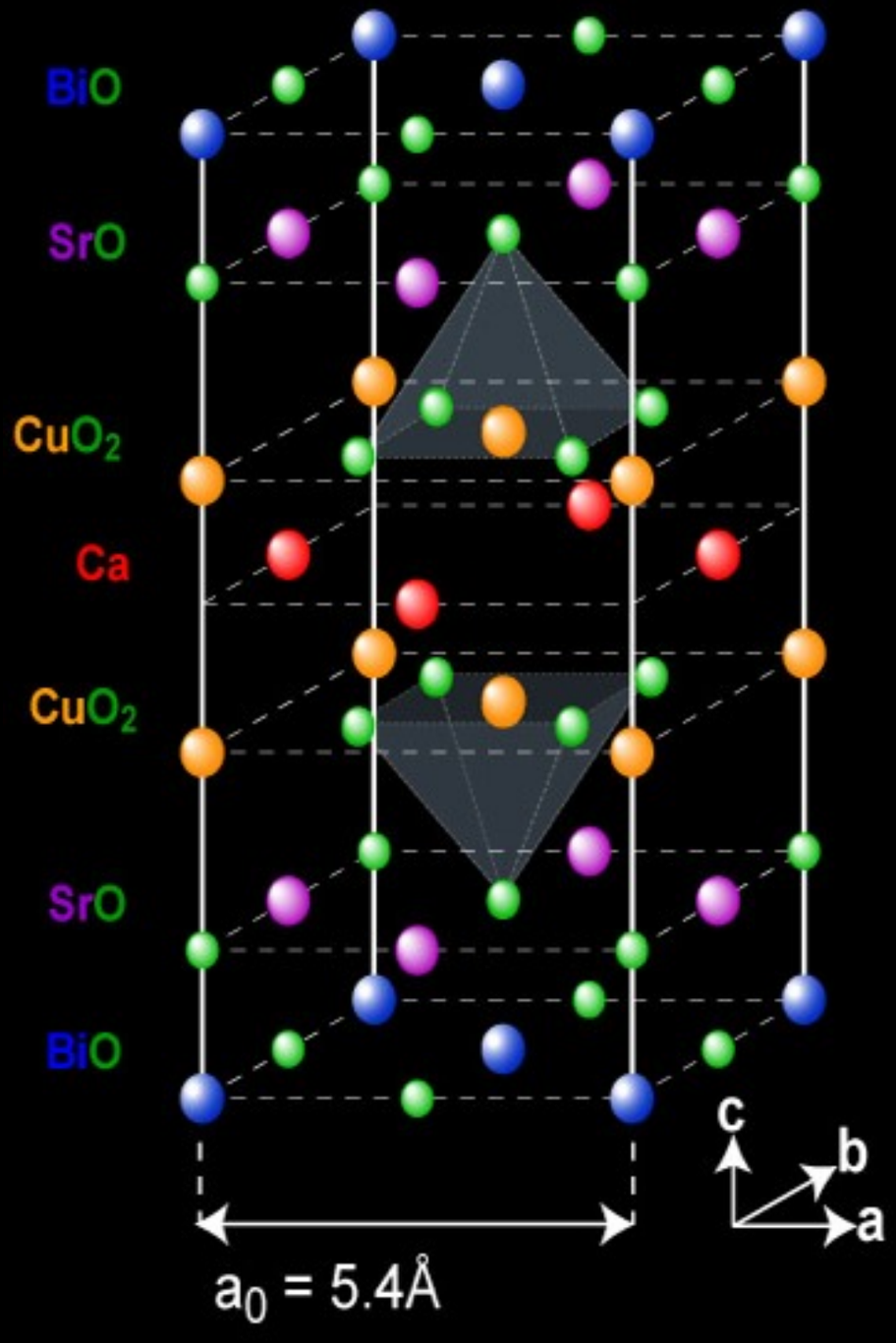
High temperature superconductors

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



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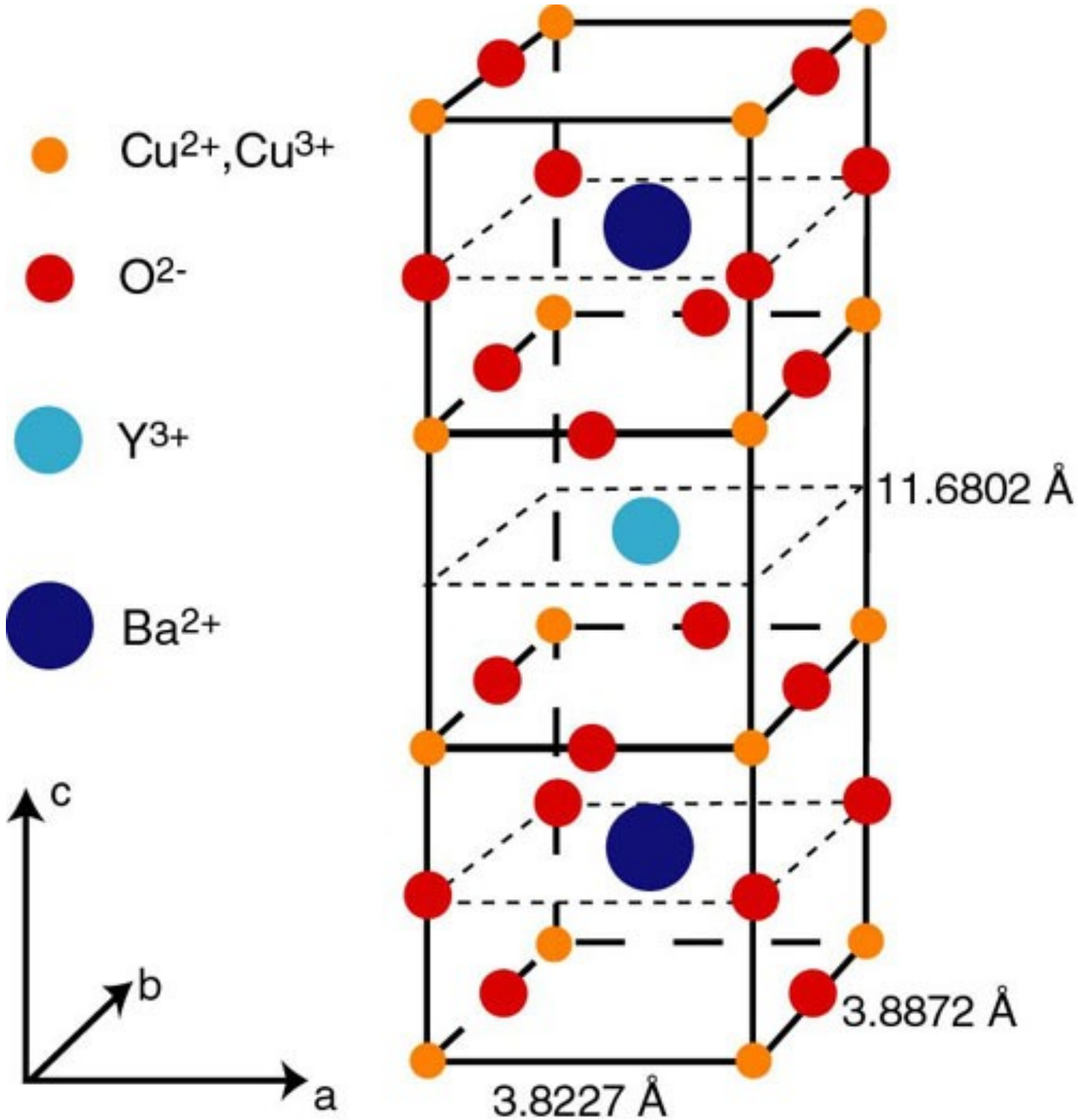
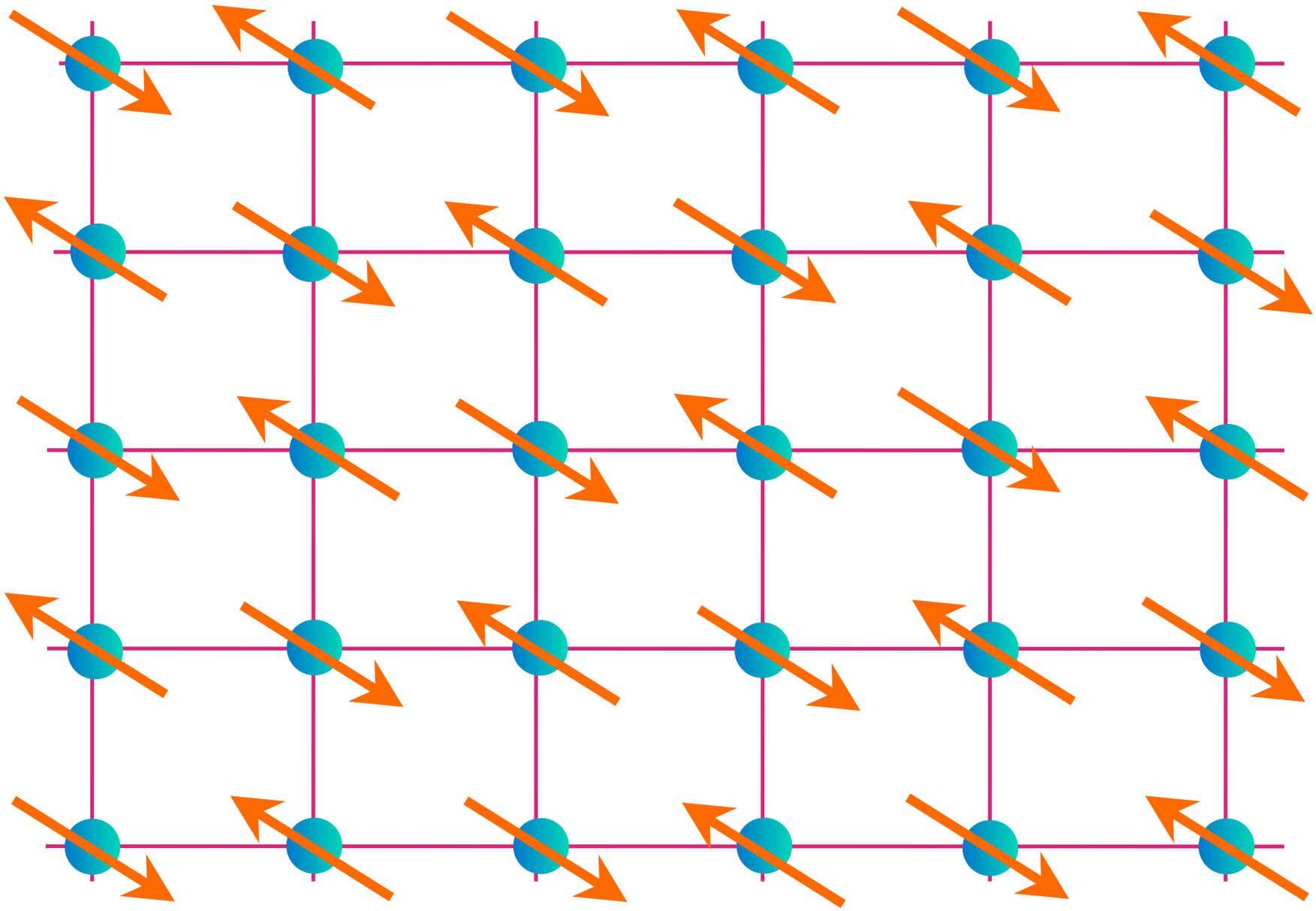


$$YBa_2Cu_3O_{6+x}$$

Square lattice of Cu sites



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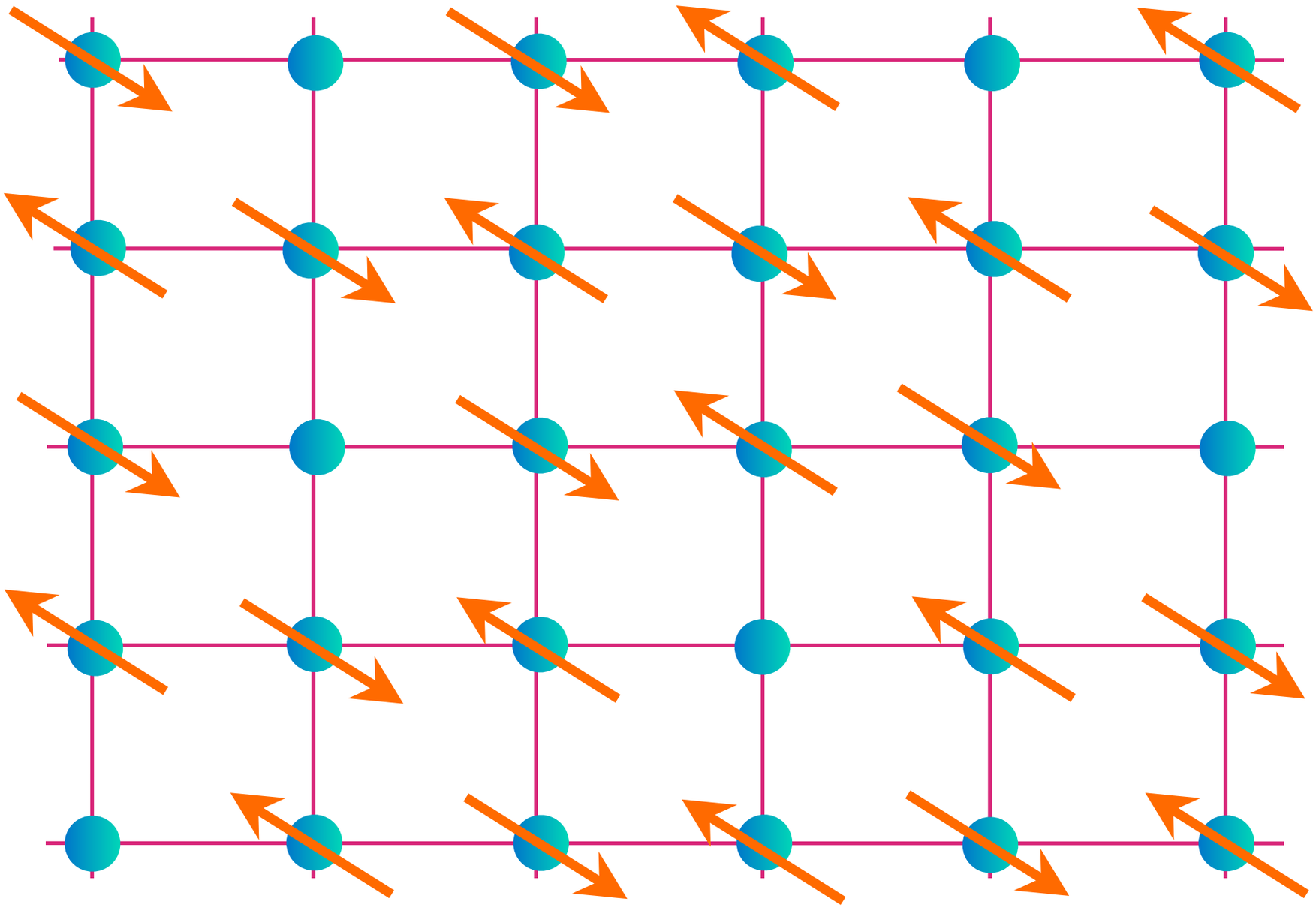
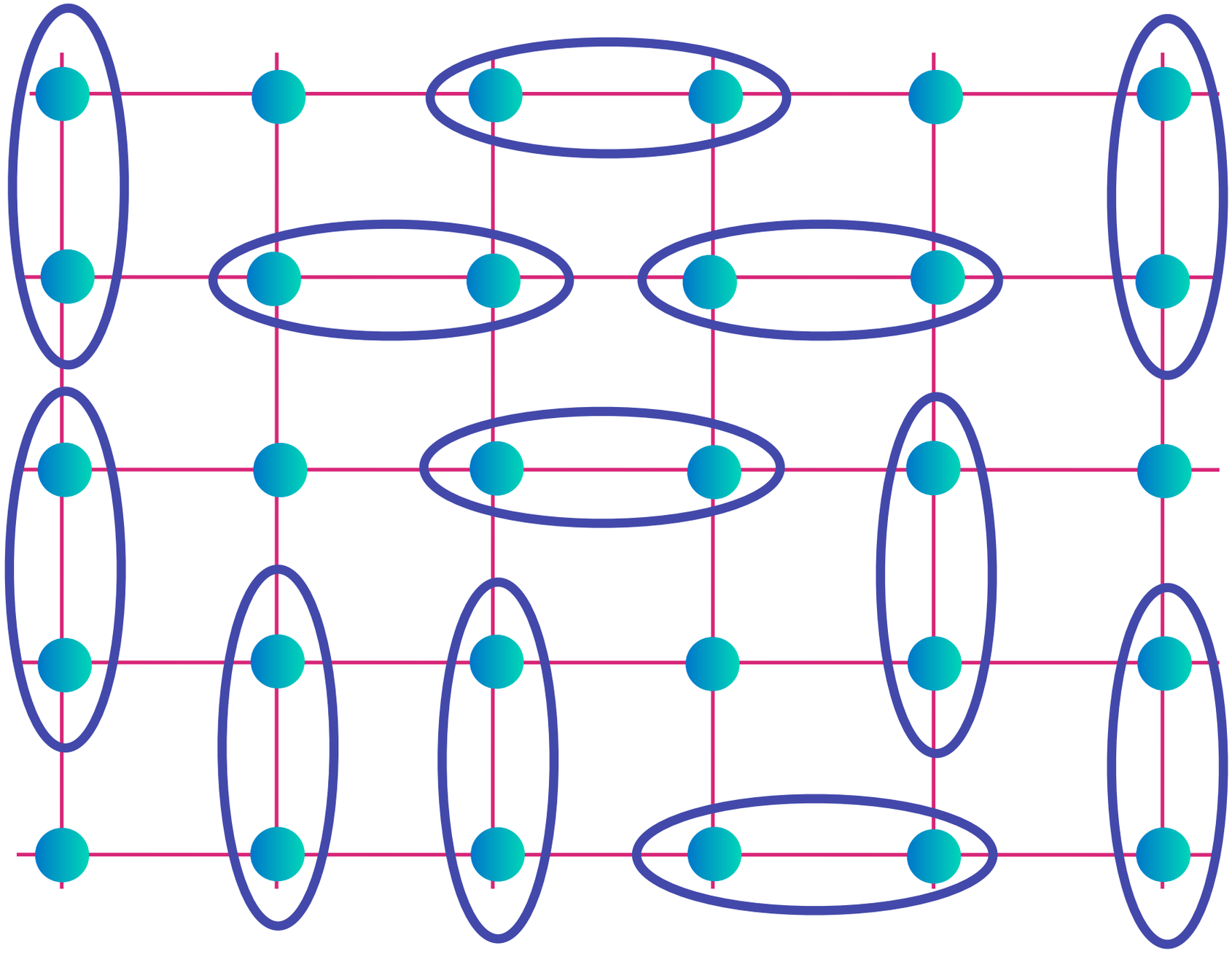


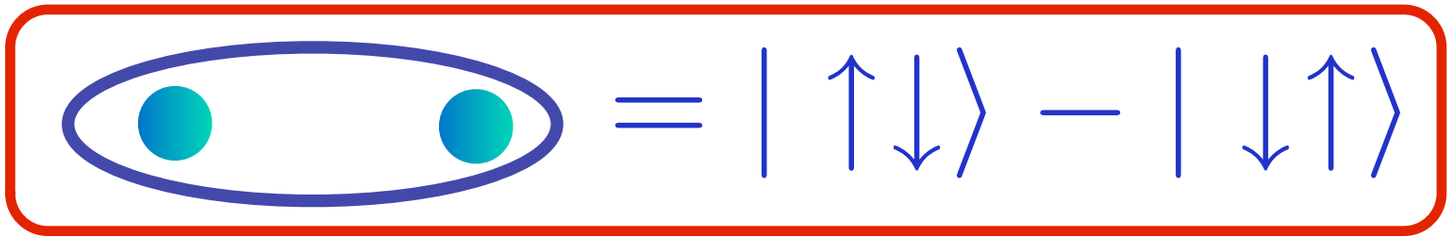
1. Remove some electrons

Square lattice of Cu sites



1. Remove some electrons

2. Electrons entangle into chemical bonds



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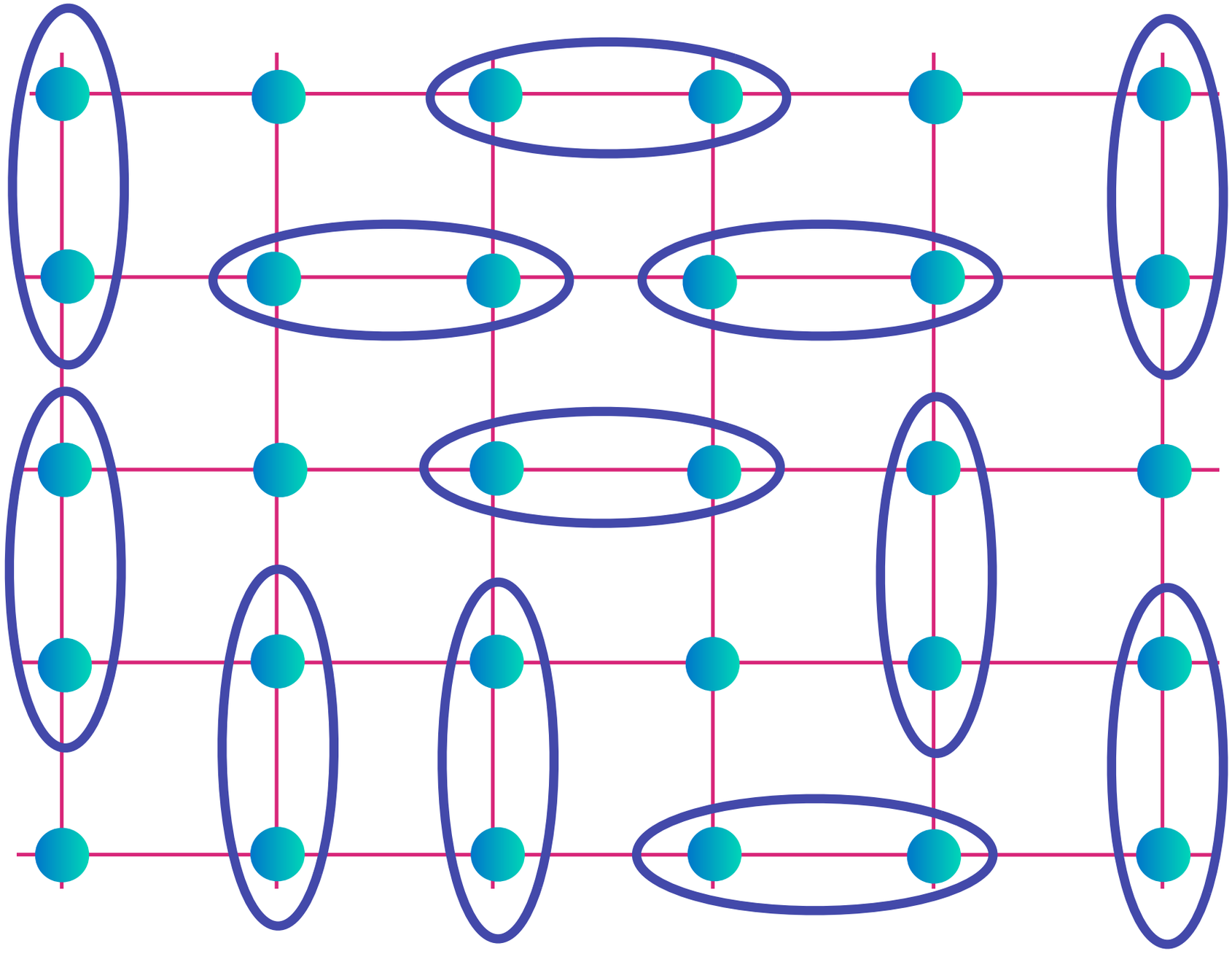

$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

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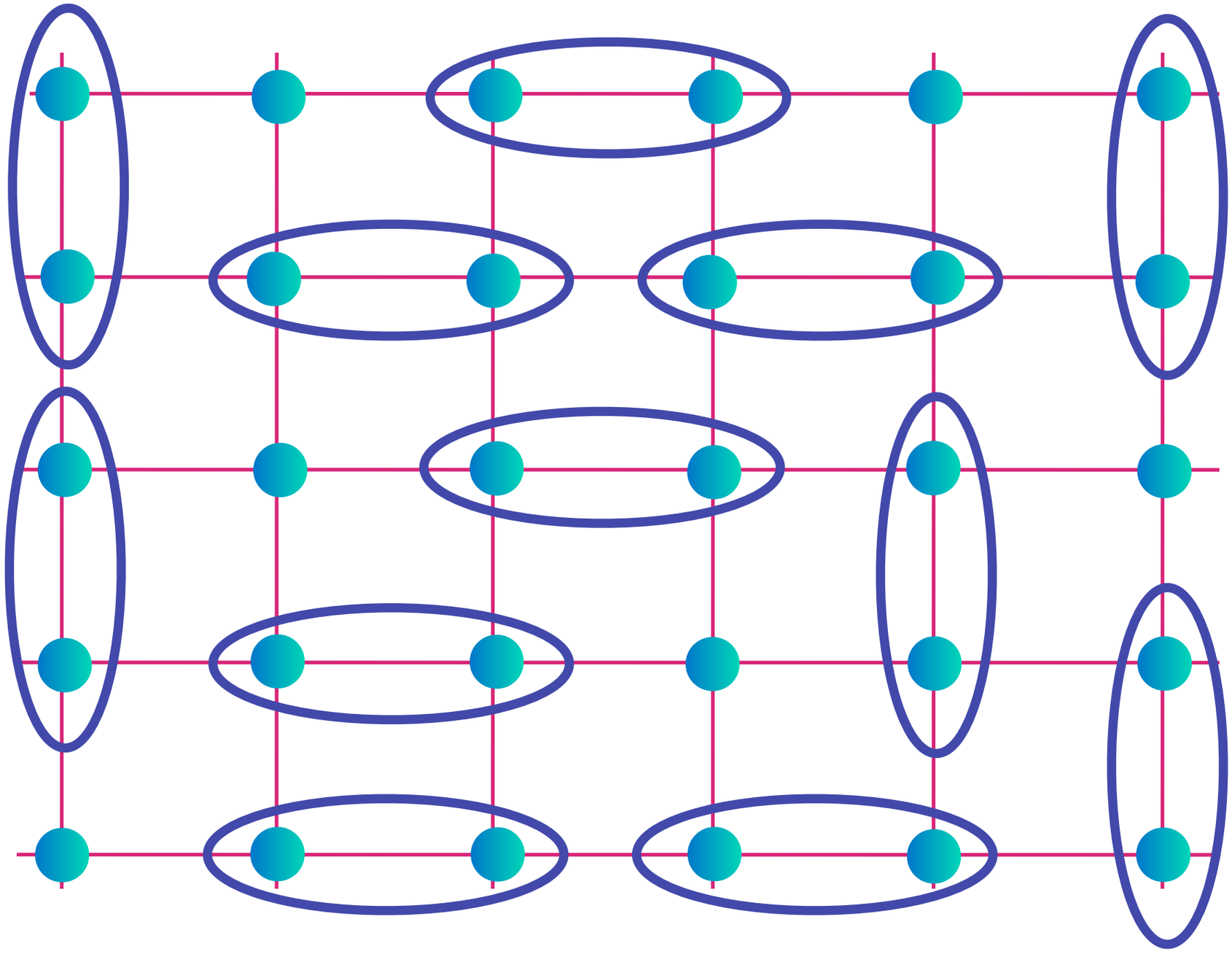

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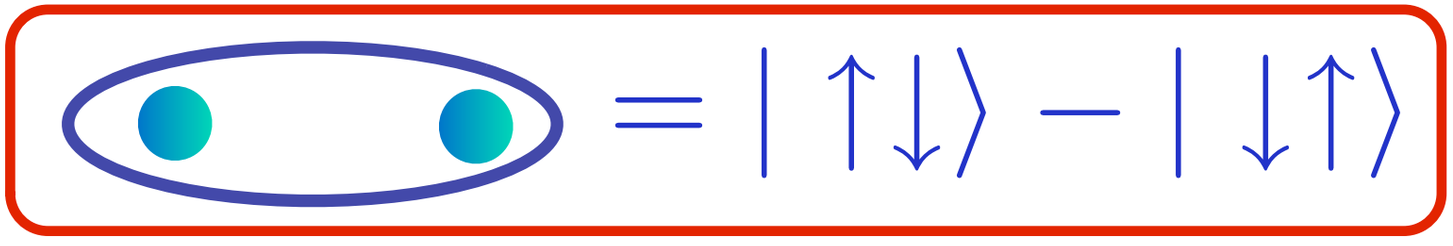

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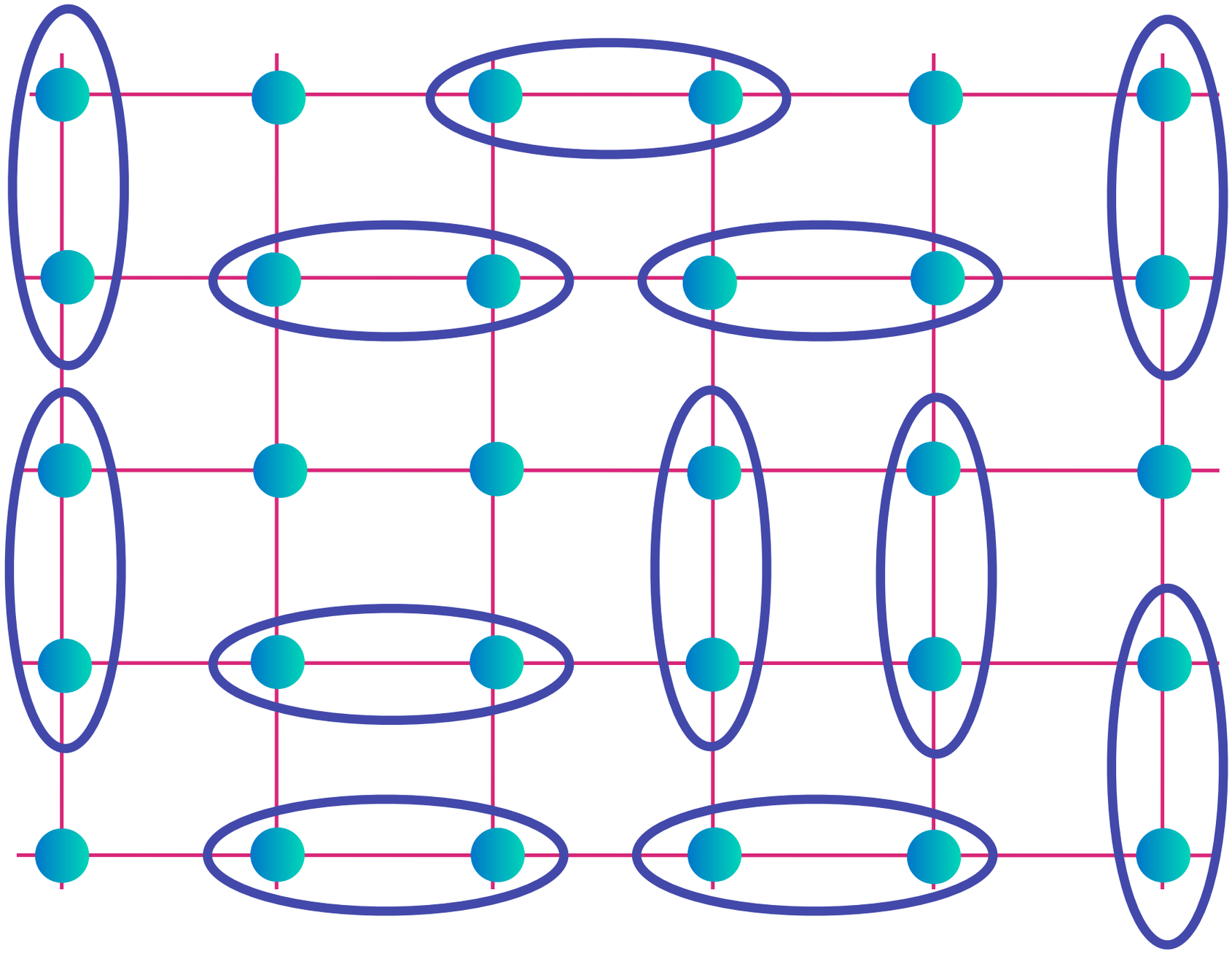

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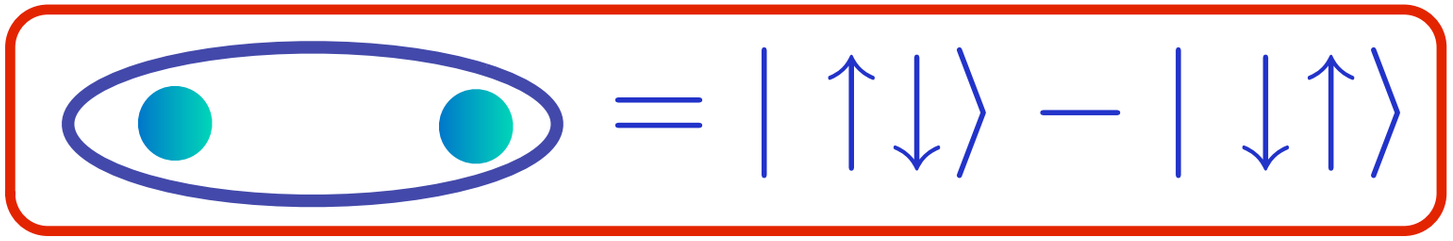

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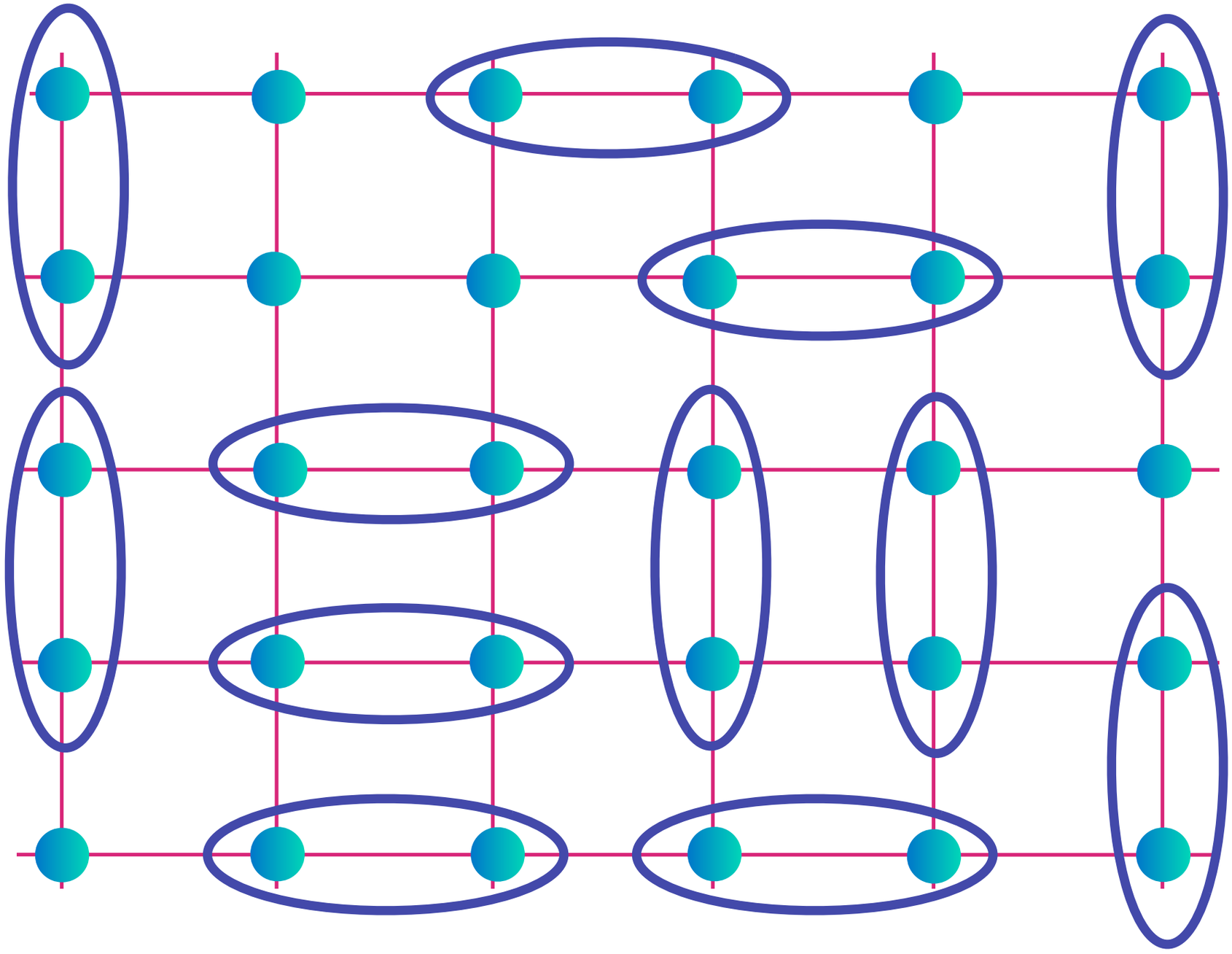

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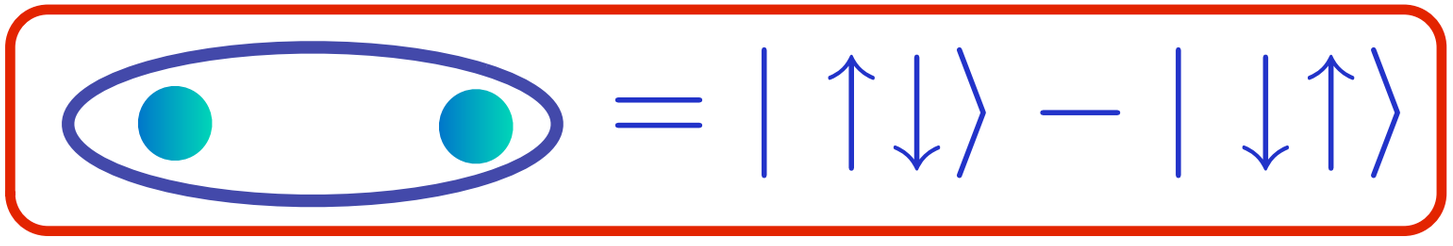
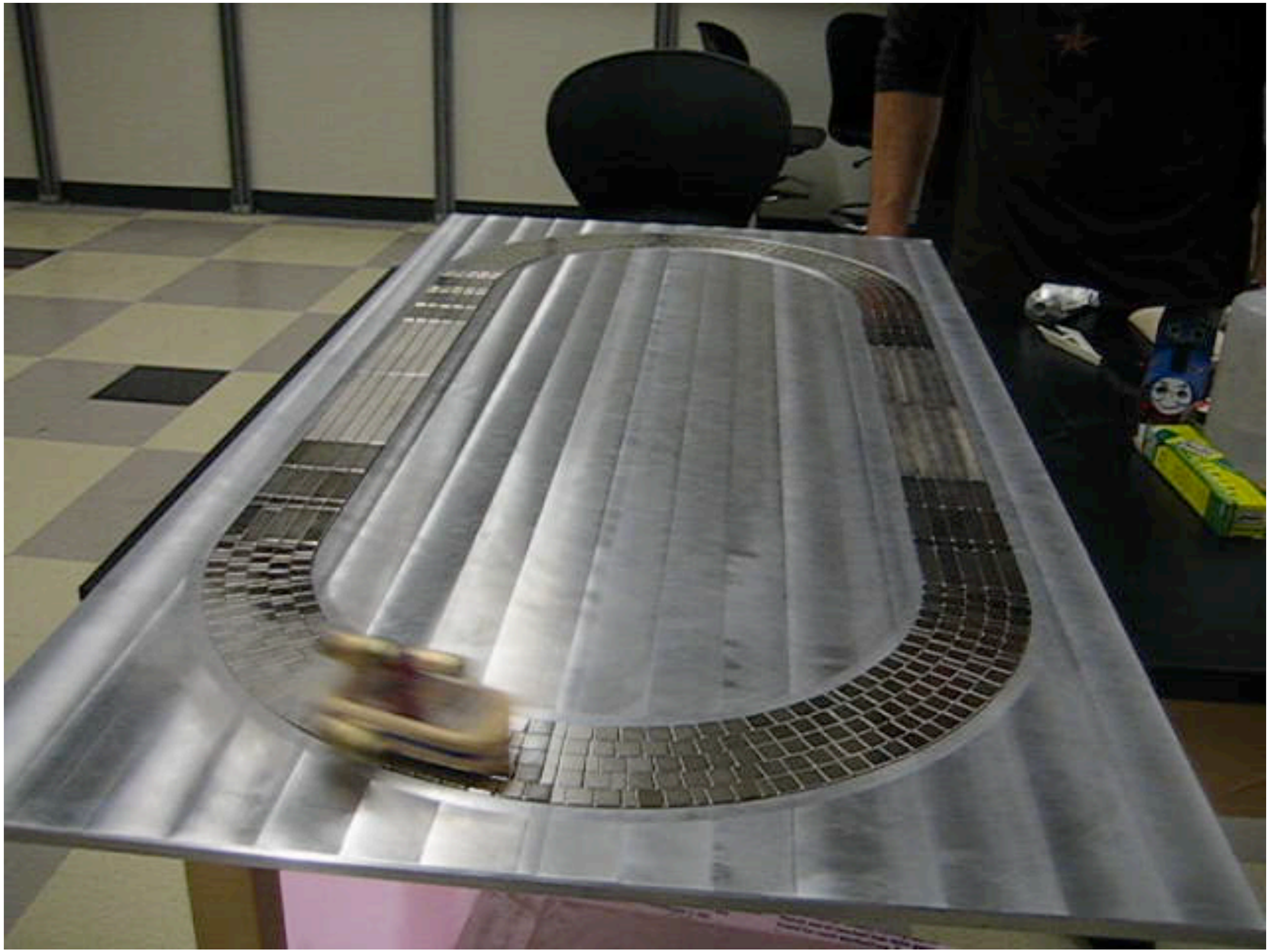


Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University



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Quantum superposition and entanglement

Superconductivity

Black Holes and String Theory

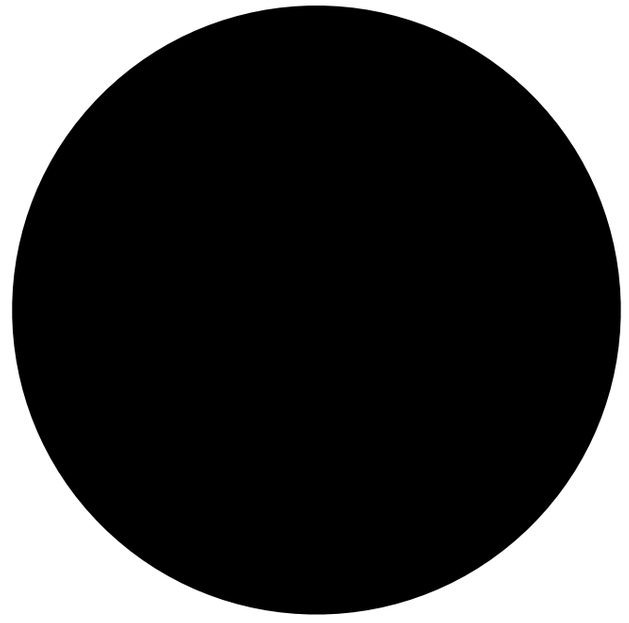
Quantum superposition and entanglement

Superconductivity

Black Holes and String Theory

Black Holes

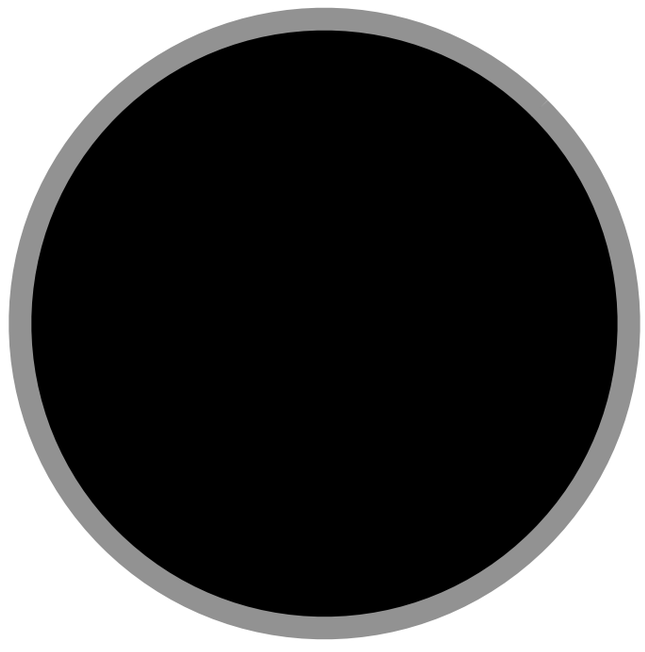
Objects so massive that light is gravitationally bound to them.



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.

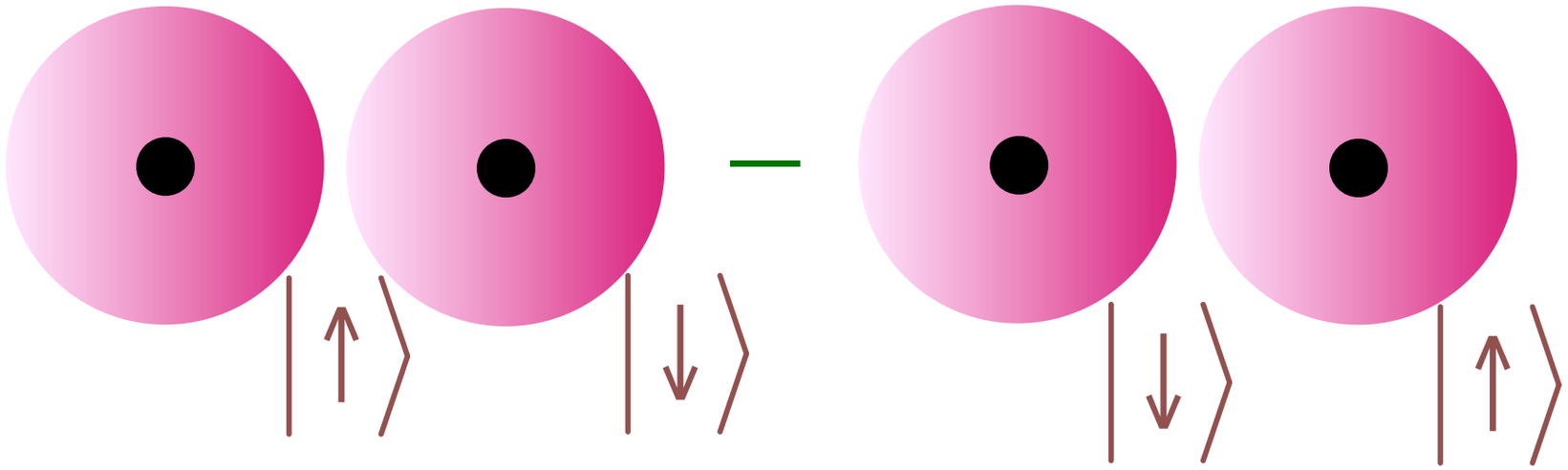


$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

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



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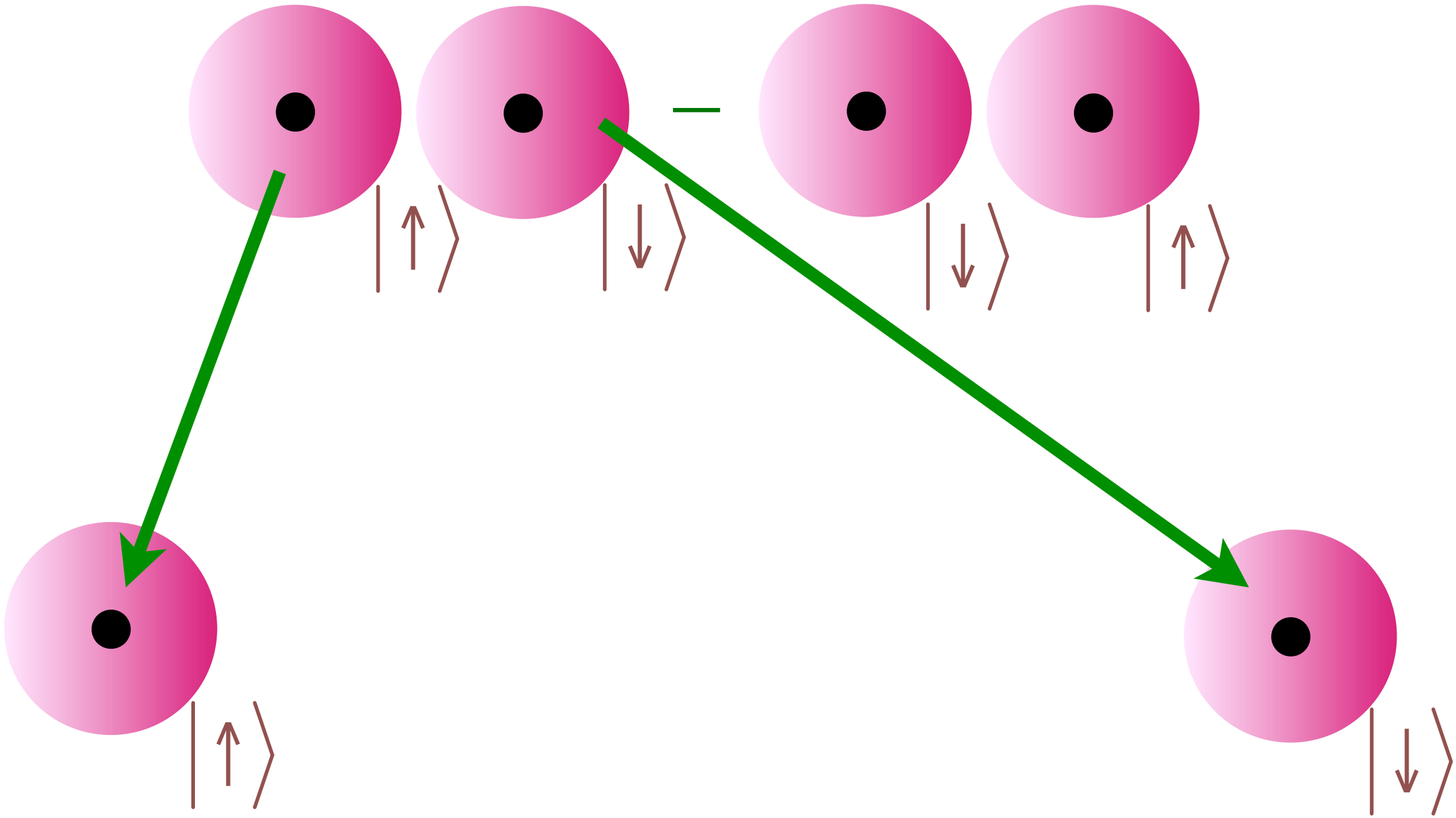

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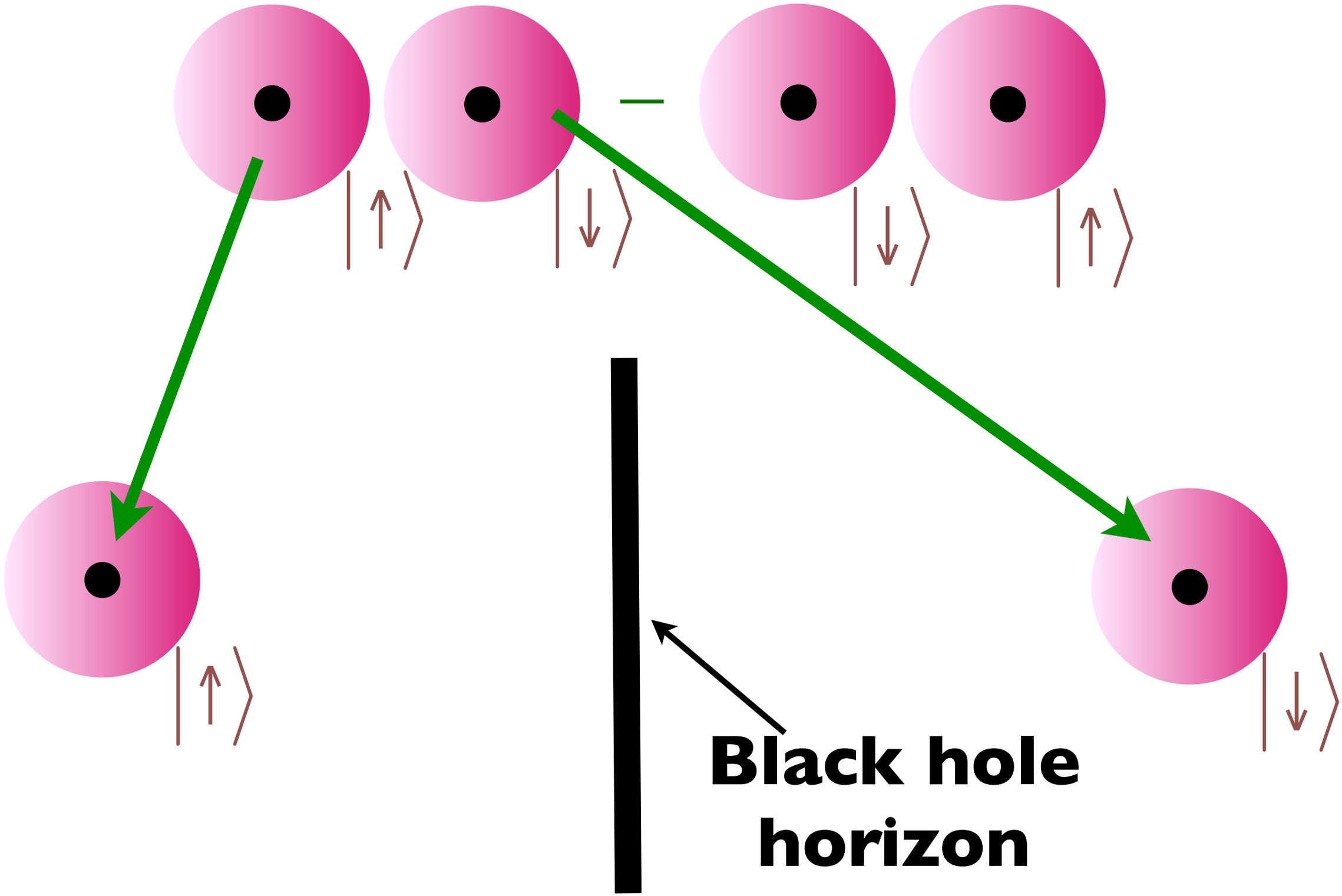

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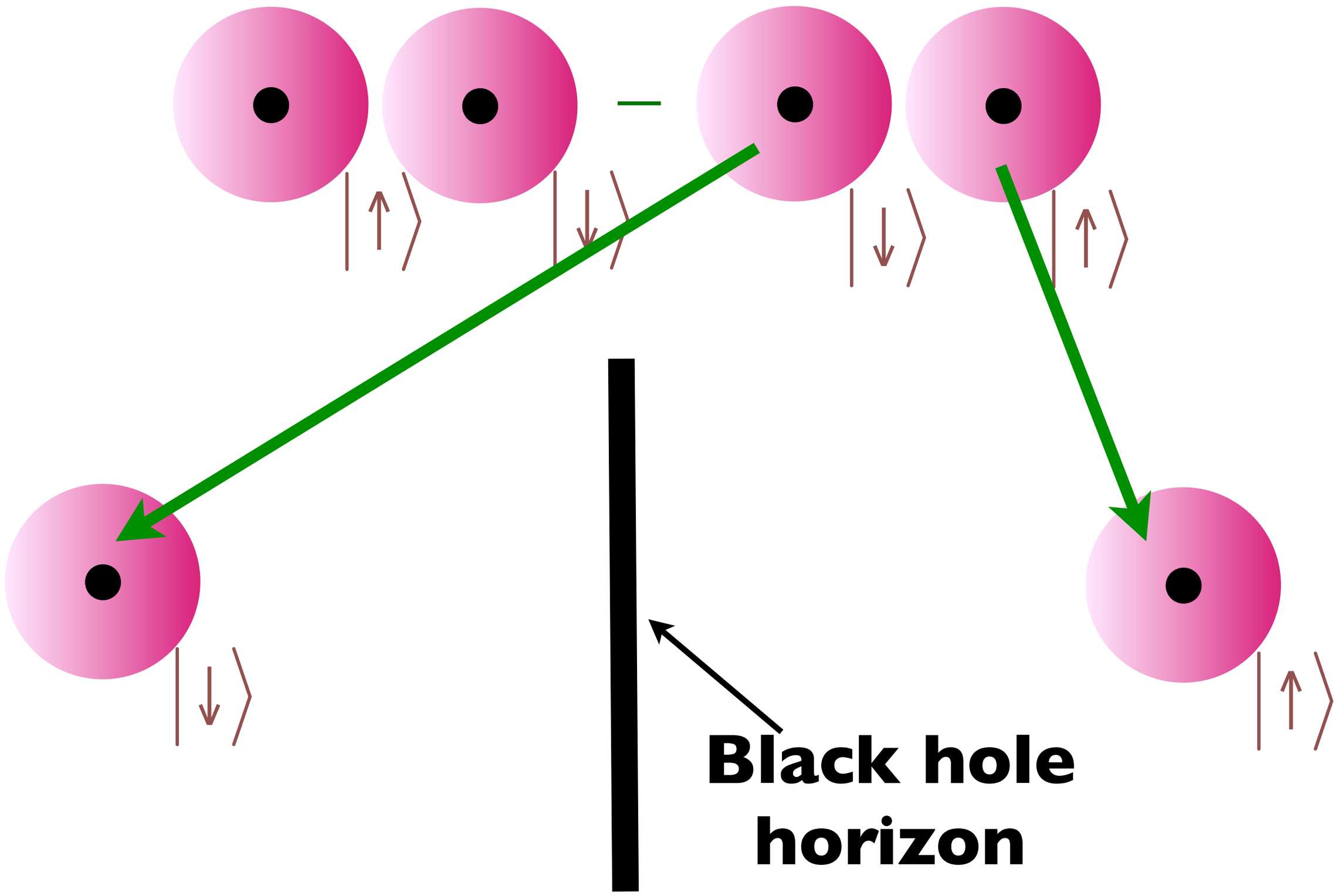
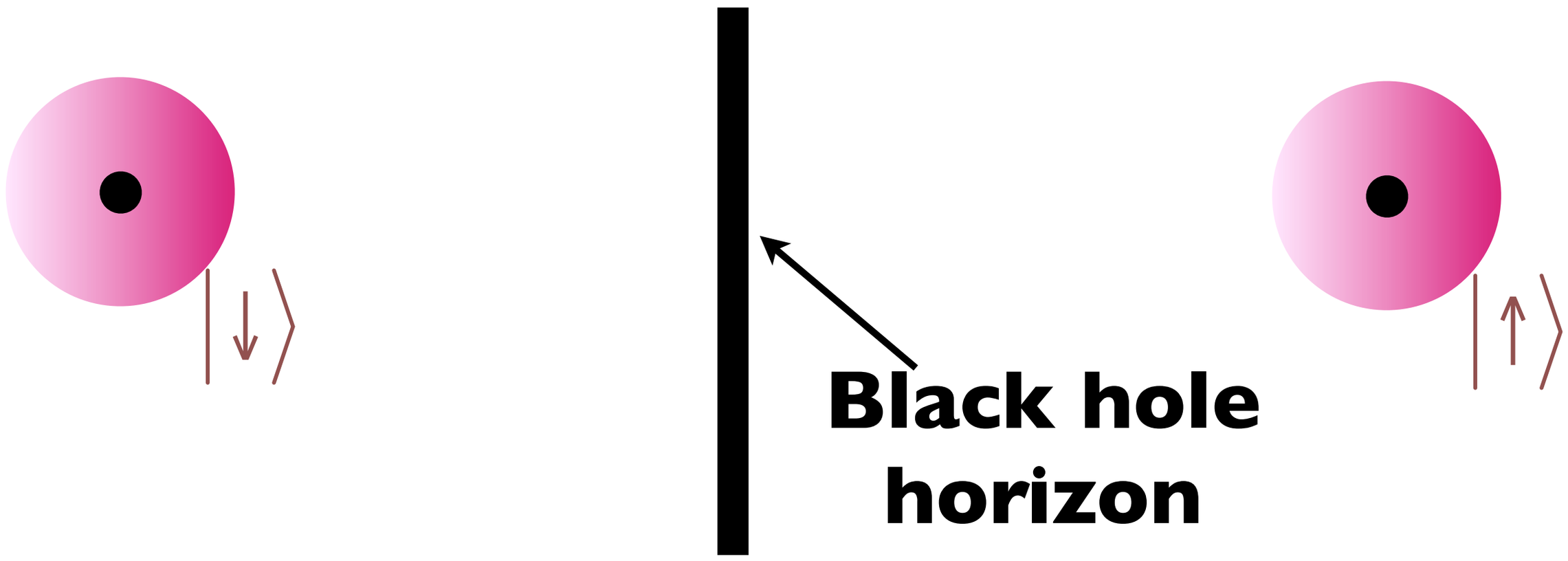


Quantum Entanglement across a black hole horizon

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



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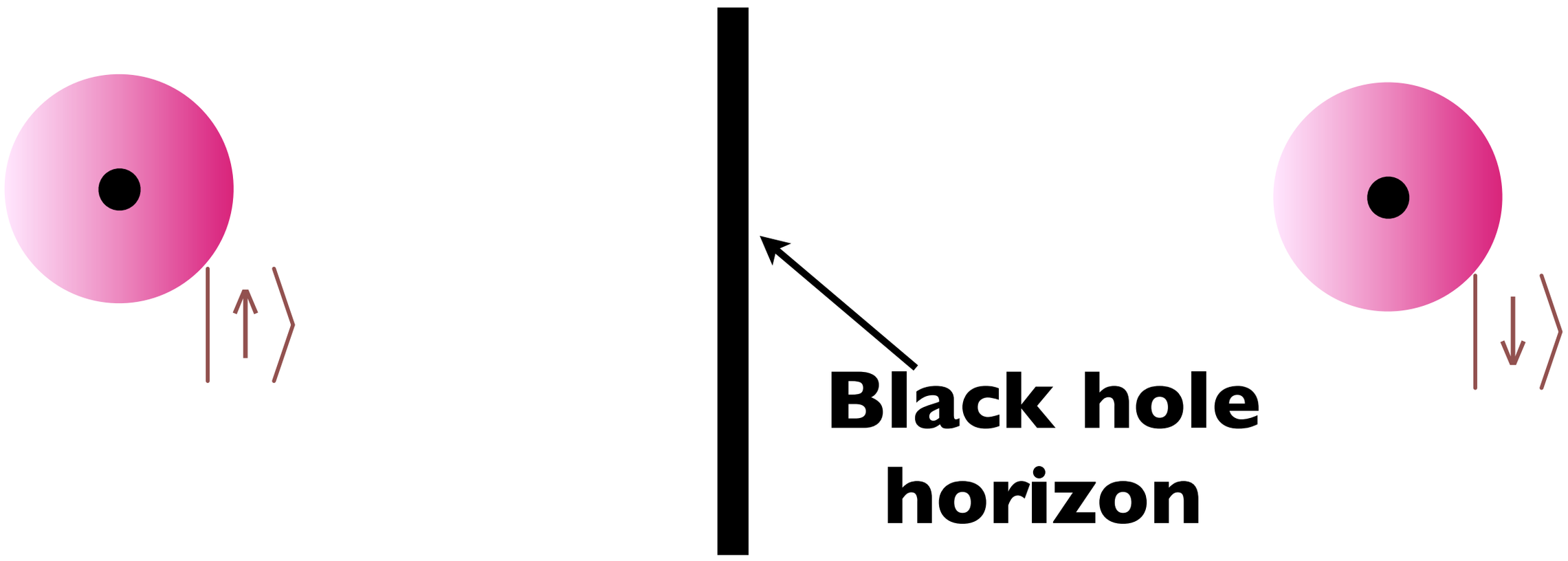

Quantum Entanglement across a black hole horizon

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

This entanglement leads to a black hole temperature (the Hawking temperature) and a black hole entropy (the Bekenstein entropy)

Quantum superposition and entanglement

Superconductivity

Black Holes and String Theory

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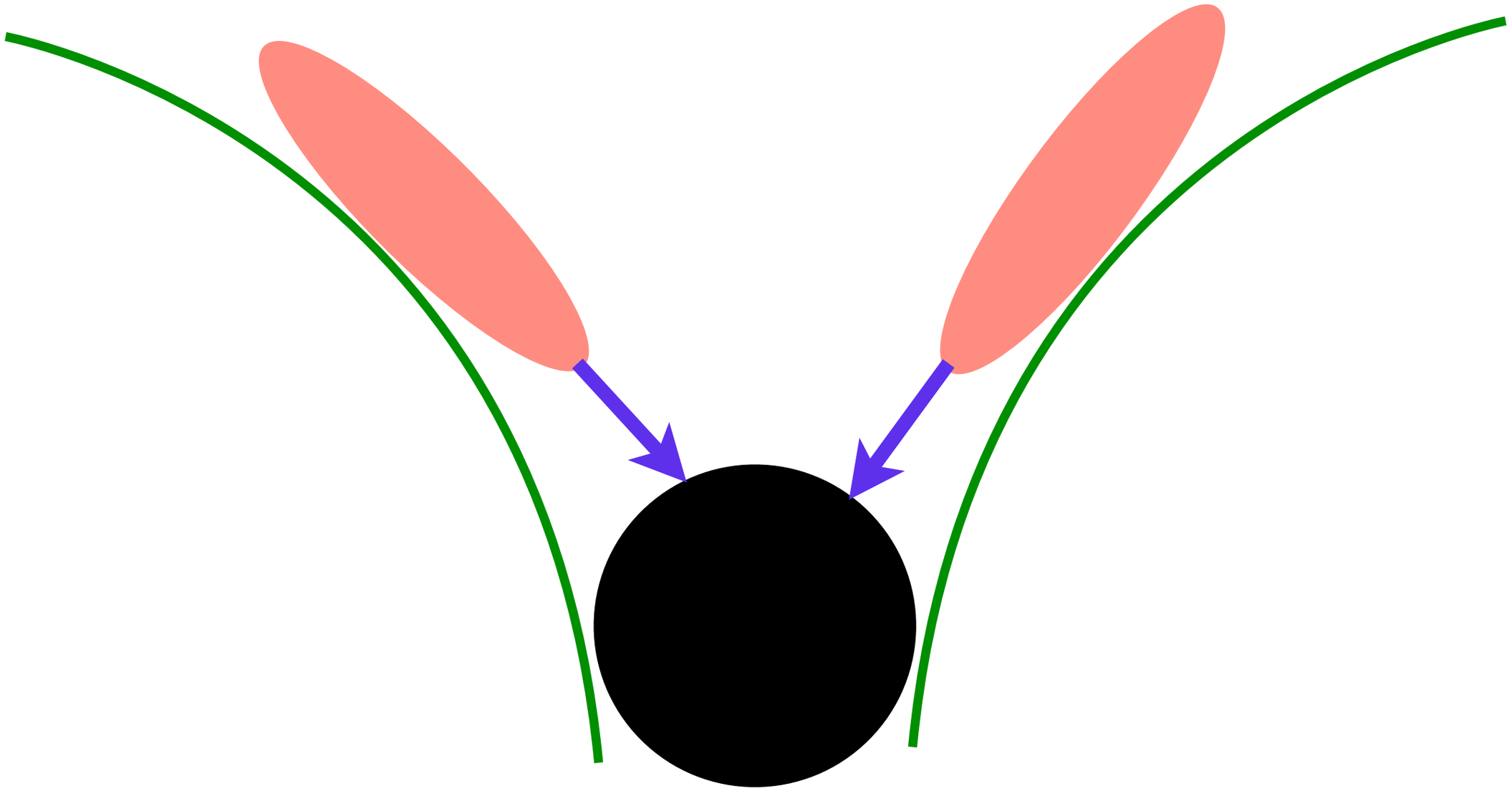
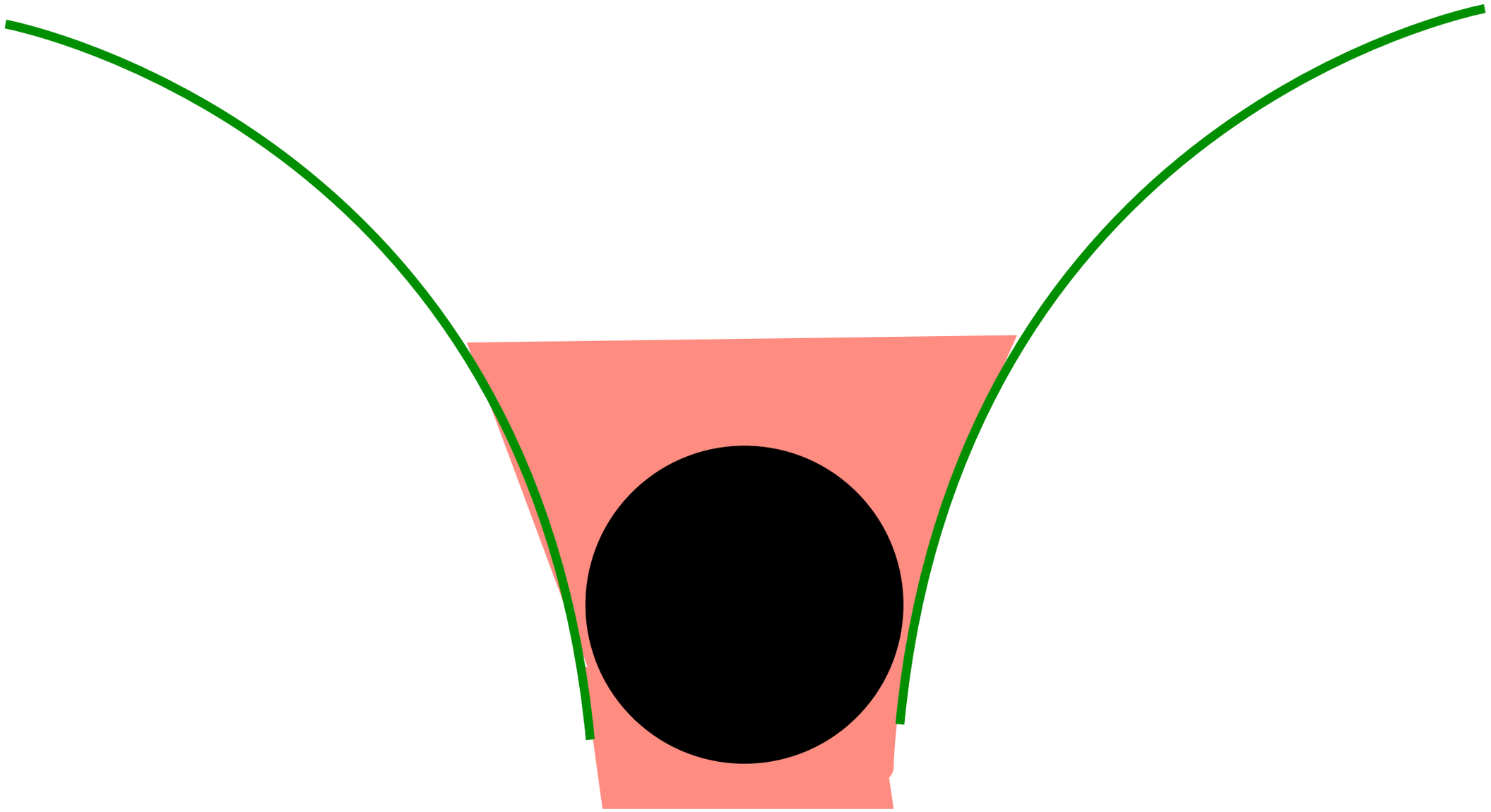
Superconducting Black Holes

Add electrical charge to a black hole in a curved spacetime: initially the charges fall past the horizon into the black hole



Superconducting Black Holes

However, eventually there is a balance between the gravitational forces pulling the charges into the black hole, and the repulsive electrical forces which push them out, and the resulting state is a superconductor !



More generally, string theory shows that there is a deep correspondence between the states of a black hole, and the quantum phases of matter (AdS/CFT correspondence)

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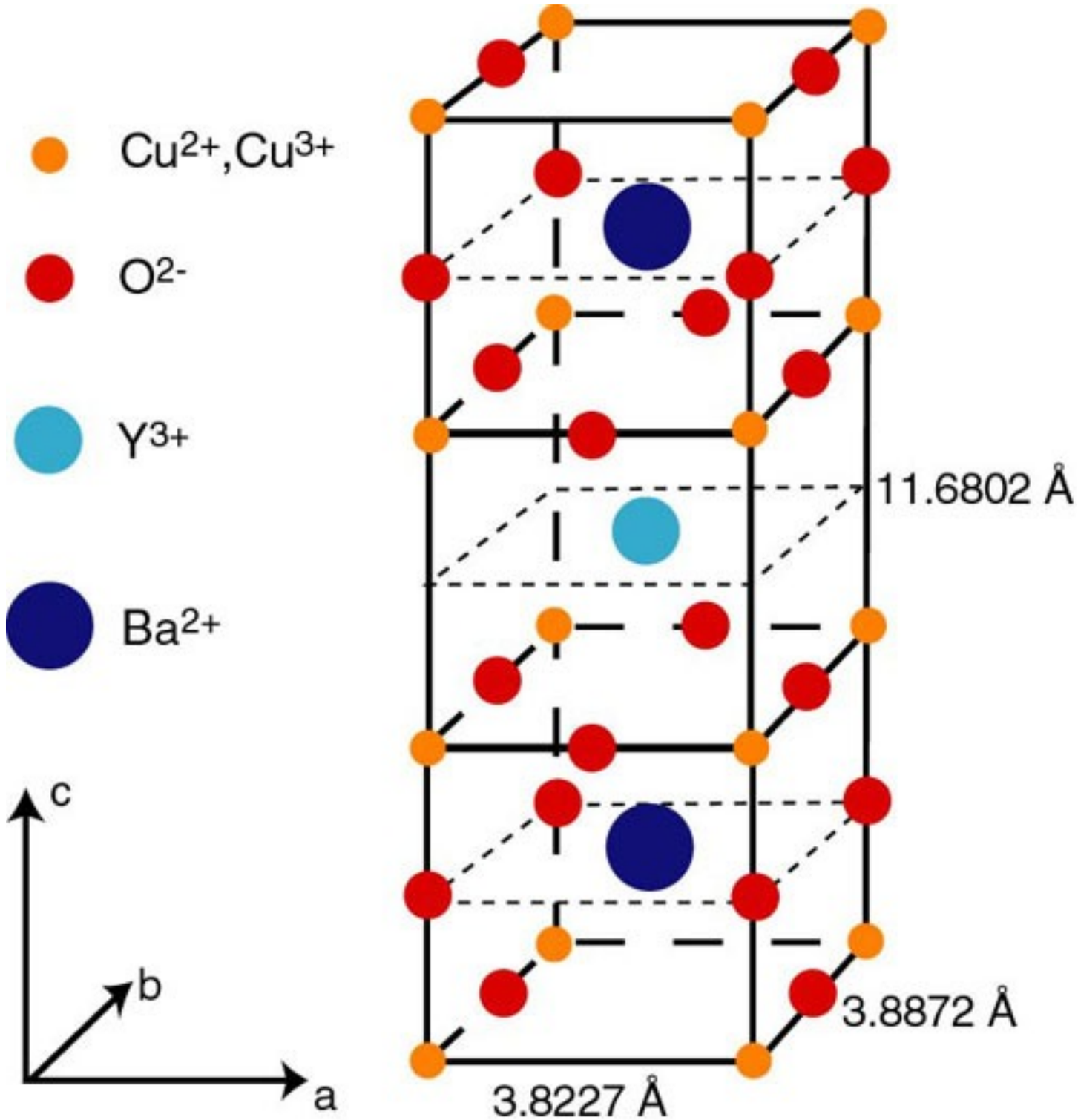
This has helped enrich our understanding of the physics of black holes, and also of the possible quantum phases of electrons in crystals

Quantum phases we do not understand yet:

Quantum phases we do not understand yet:

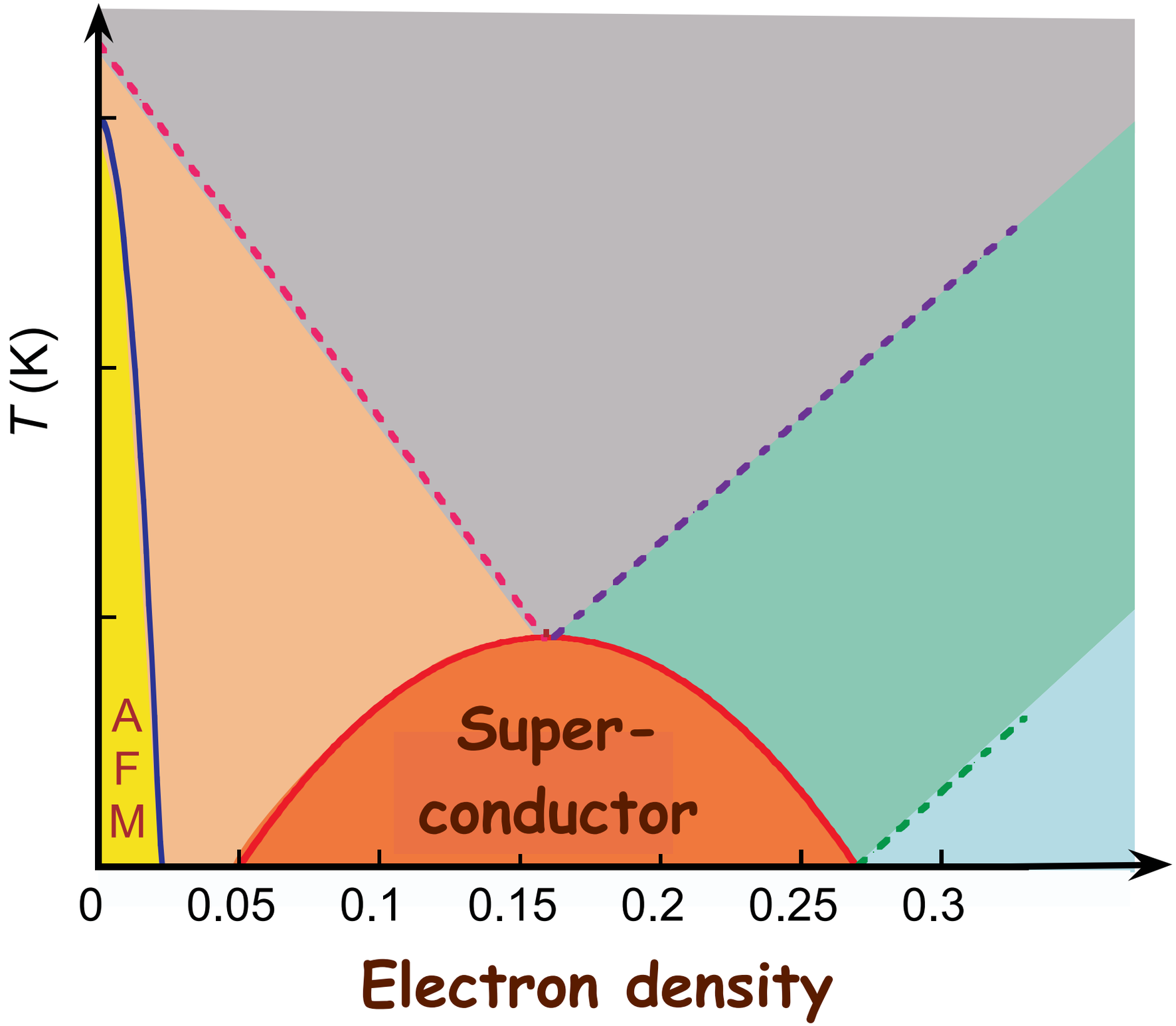
The phases around the high temperature superconductor YBCO as we vary the density of electrons

High temperature superconductors



$$YBa_2Cu_3O_{6+x}$$

Phase diagram of YBCO



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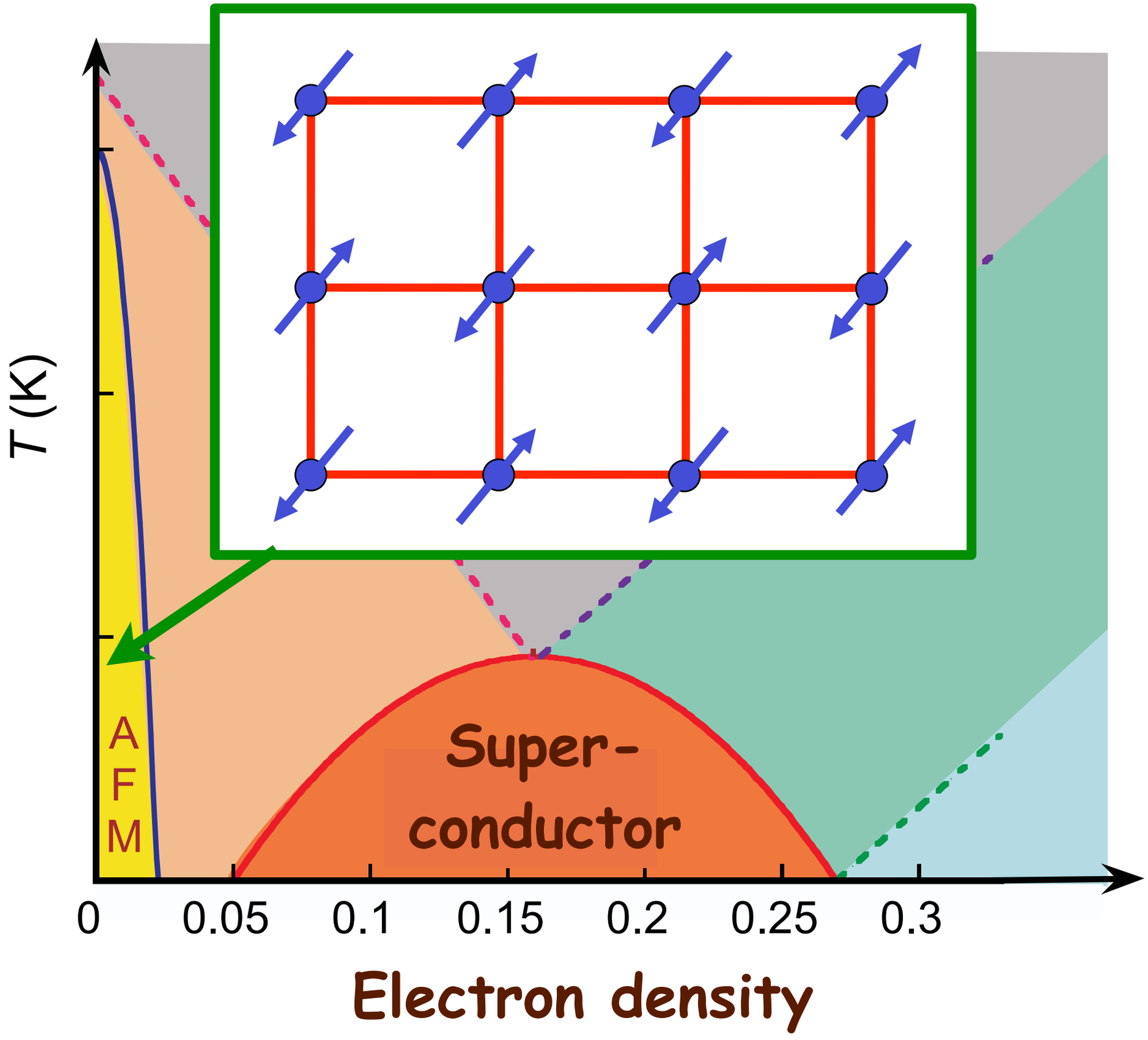

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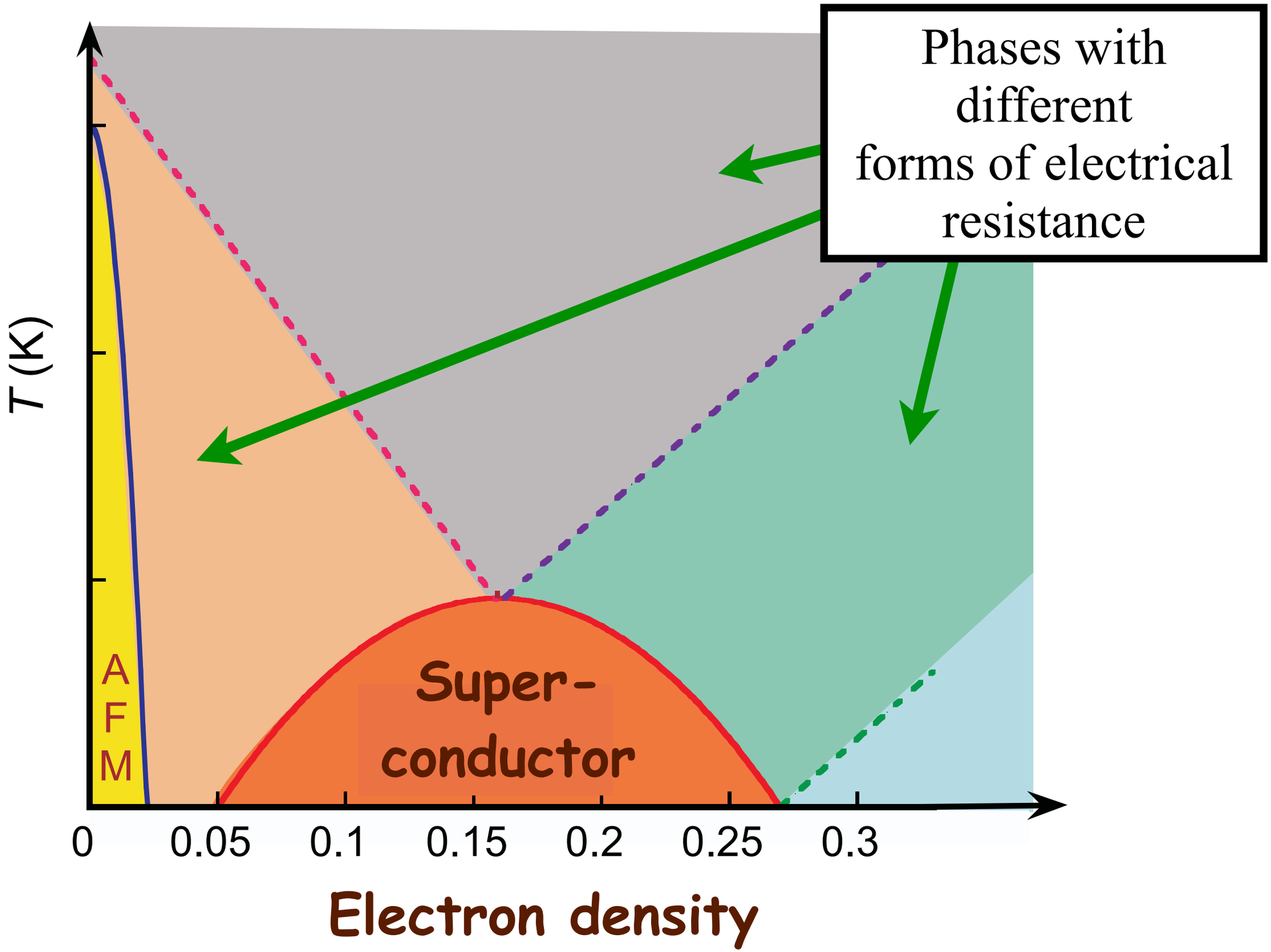

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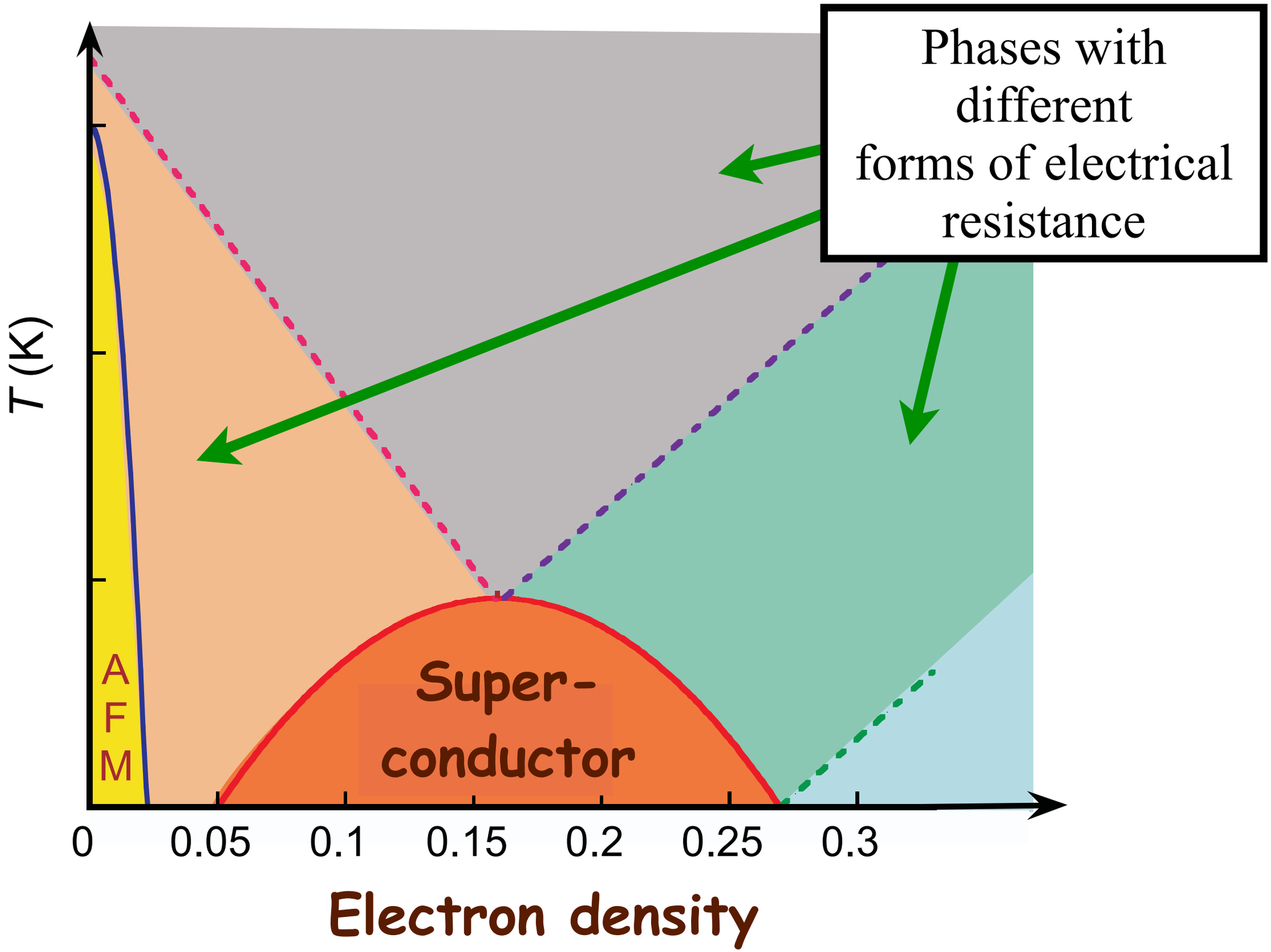

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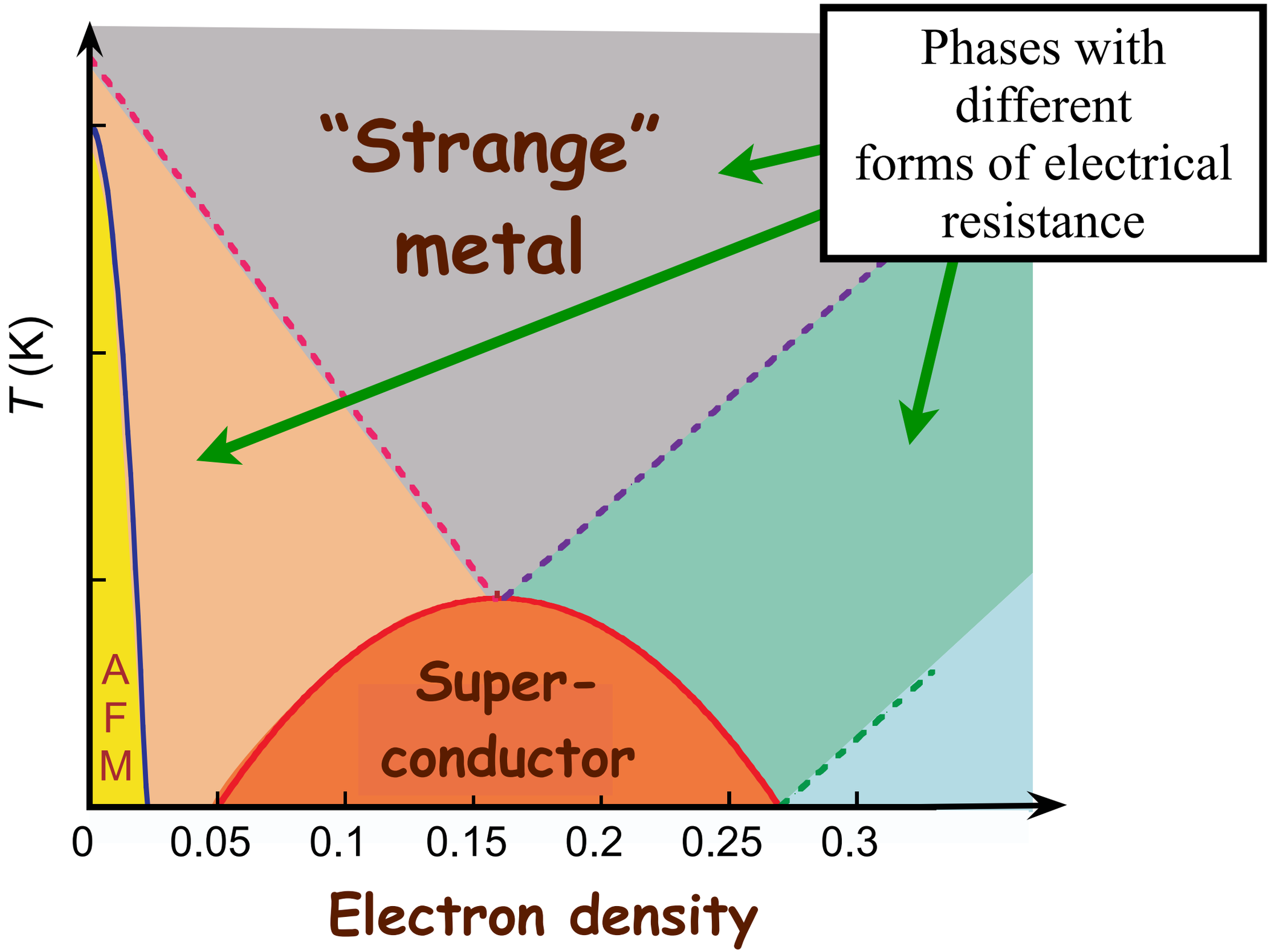

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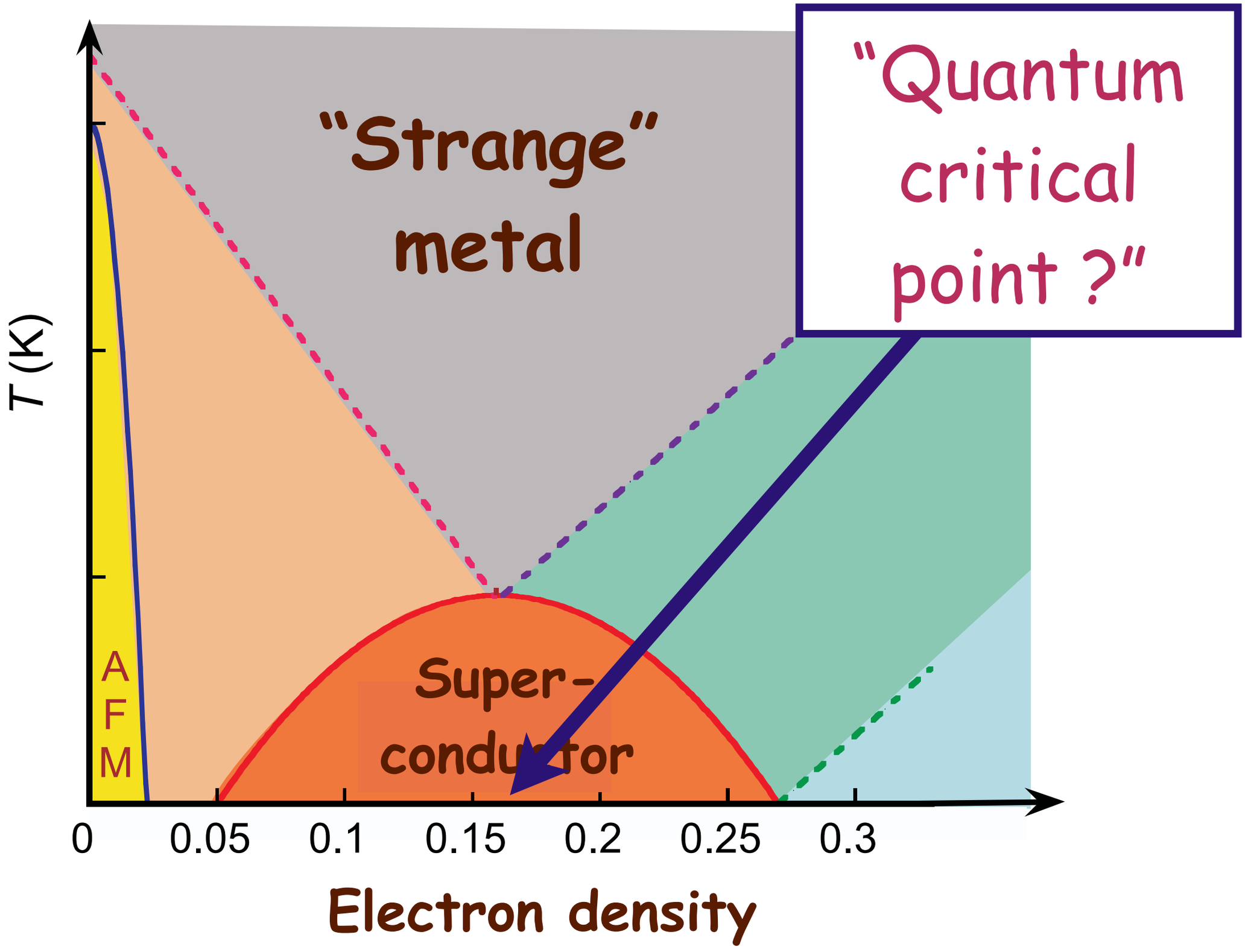

A "quantum critical point" is a special point between quantum phases where quantum entanglement is truly long-range

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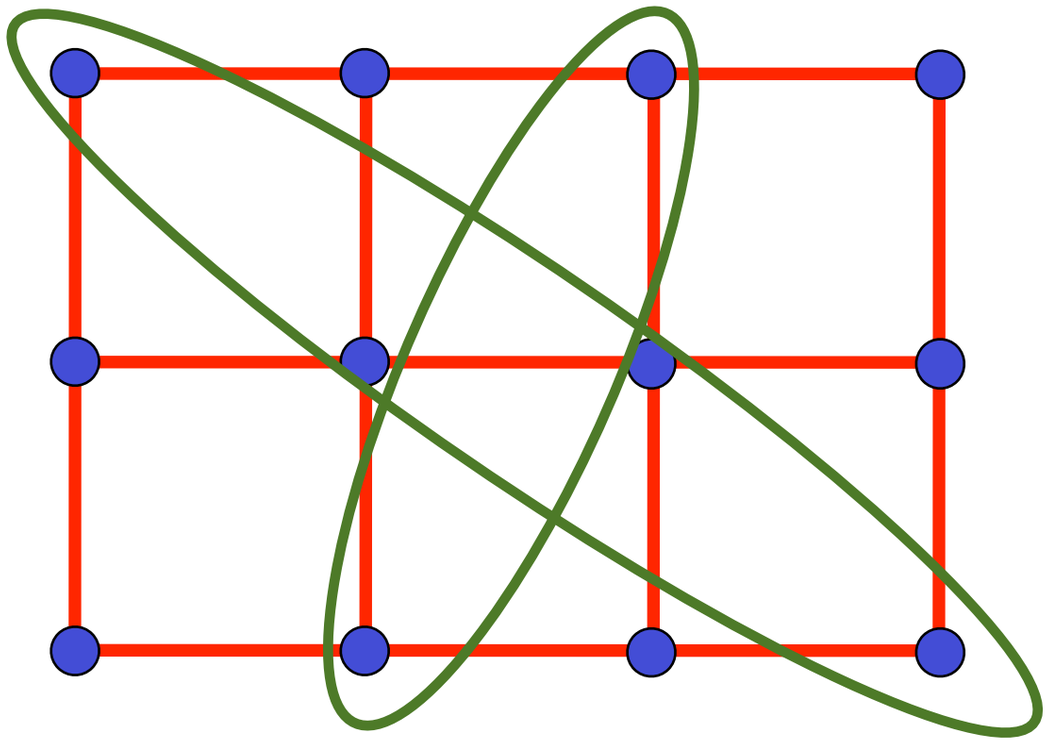

A "quantum critical point" is a special point between quantum phases where quantum entanglement is truly long-range

Long-range quantum entanglement is also found in string theories of black holes

A "quantum critical point" is a special point between quantum phases where quantum entanglement is truly long-range

Can string theory improve our understanding of quantum critical points, and of high temperature superconductors like YBCO ?