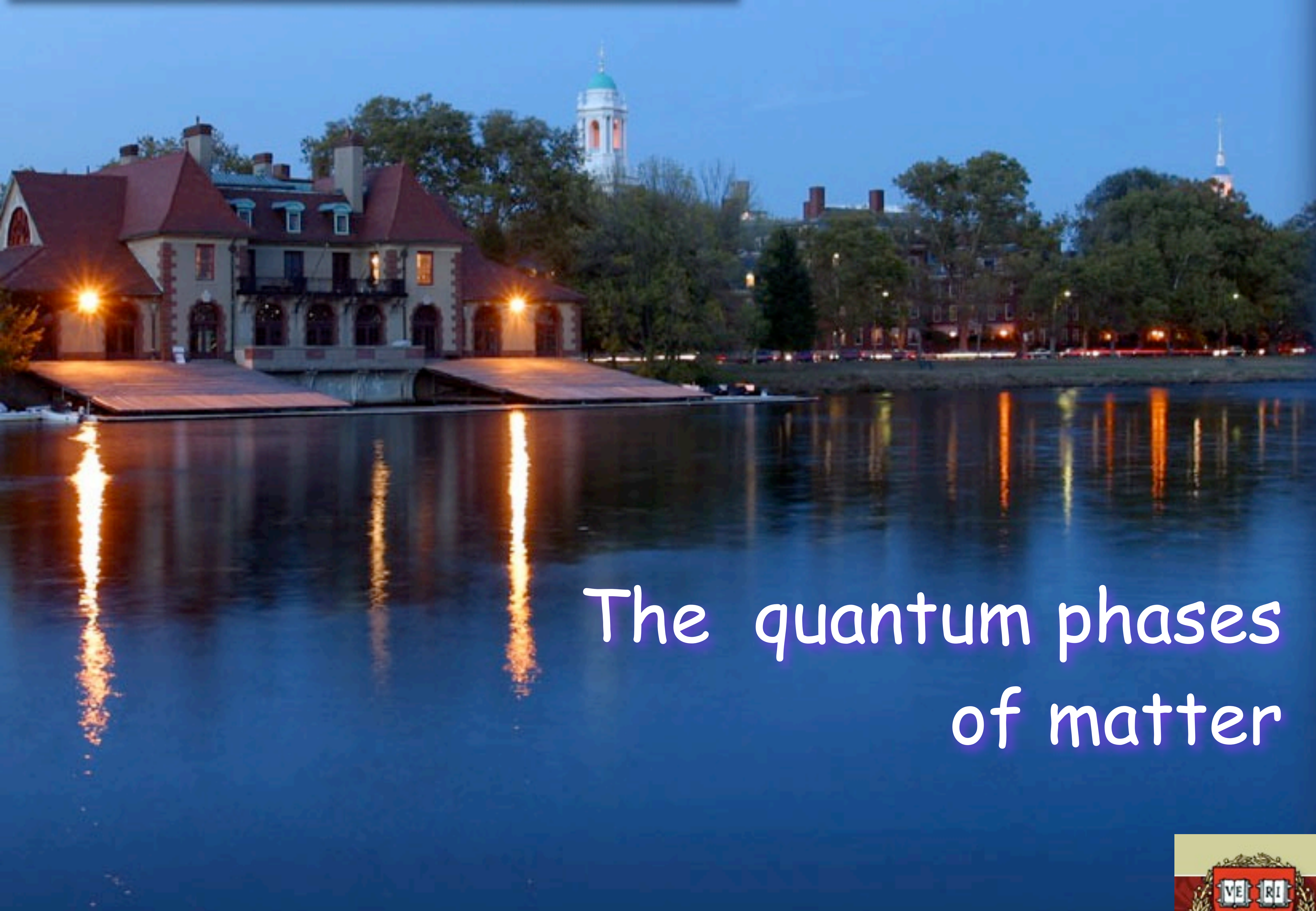


The quantum phases of matter

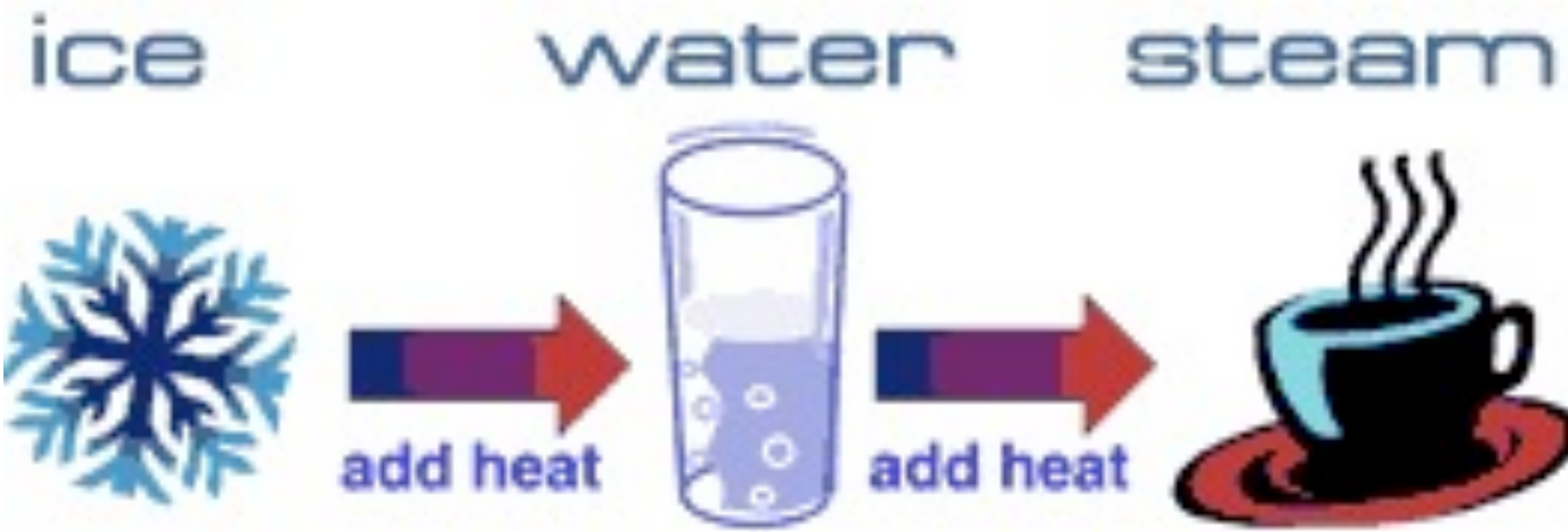
sachdev.physics.harvard.edu

The phases of matter:

The phases of matter:

Solids **Liquids** **Gases**

The phases of matter:

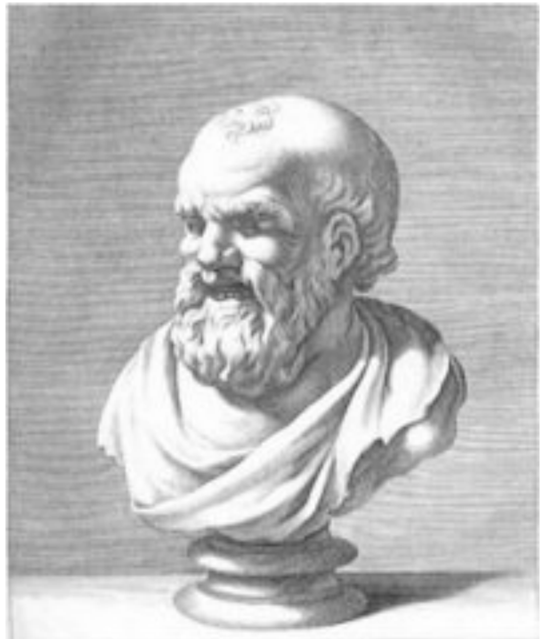


Solids Liquids Gases

Theory of the phases of matter:

Theory of the phases of matter:

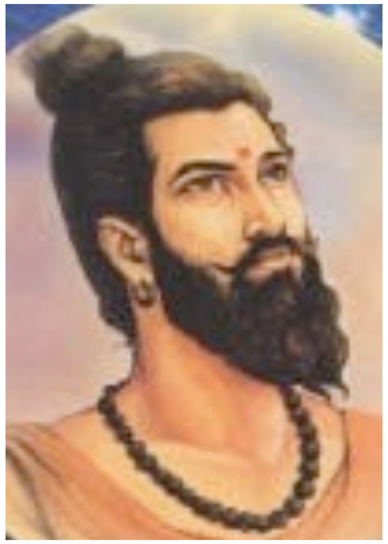
1. Matter is made of atoms



Democritus (4th century B.C.)

Theory of the phases of matter:

1. Matter is made of atoms

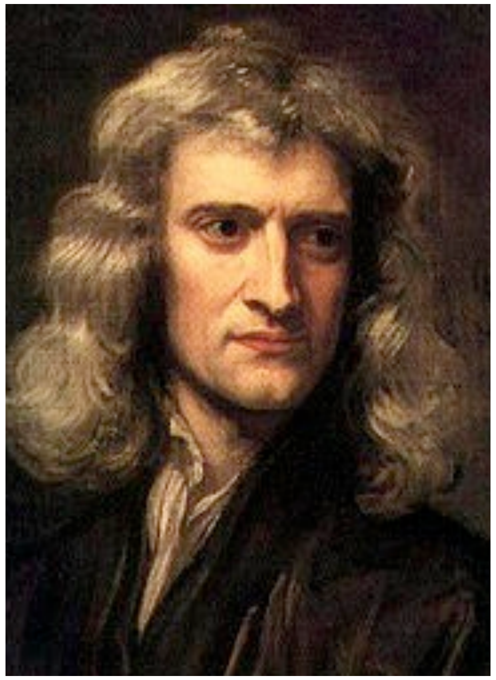


Acharya Kanad (6th century B.C.)

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

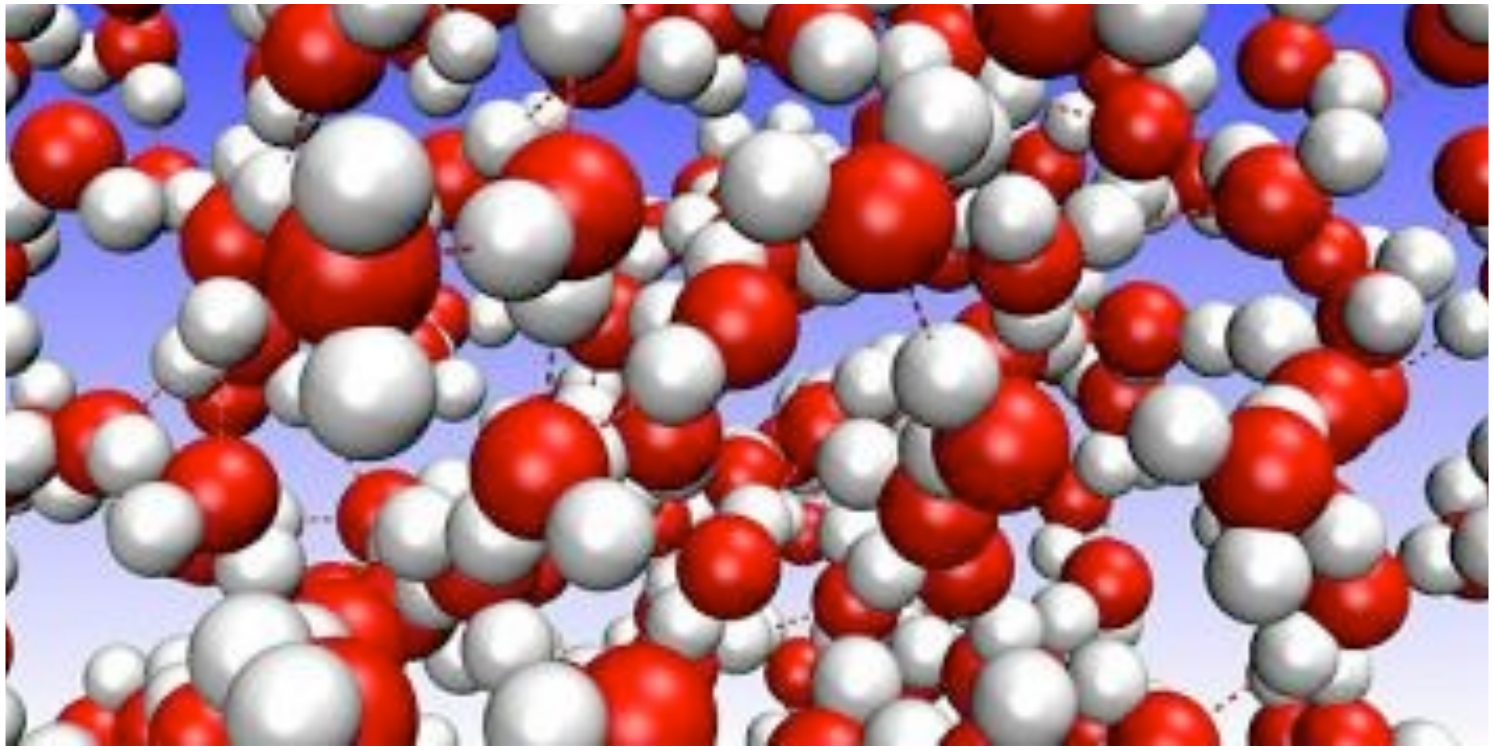
3. The phases of matter are determined by the spatial arrangements of atoms

Boltzmann (1877)

Solids

Ice

Liquids



Water

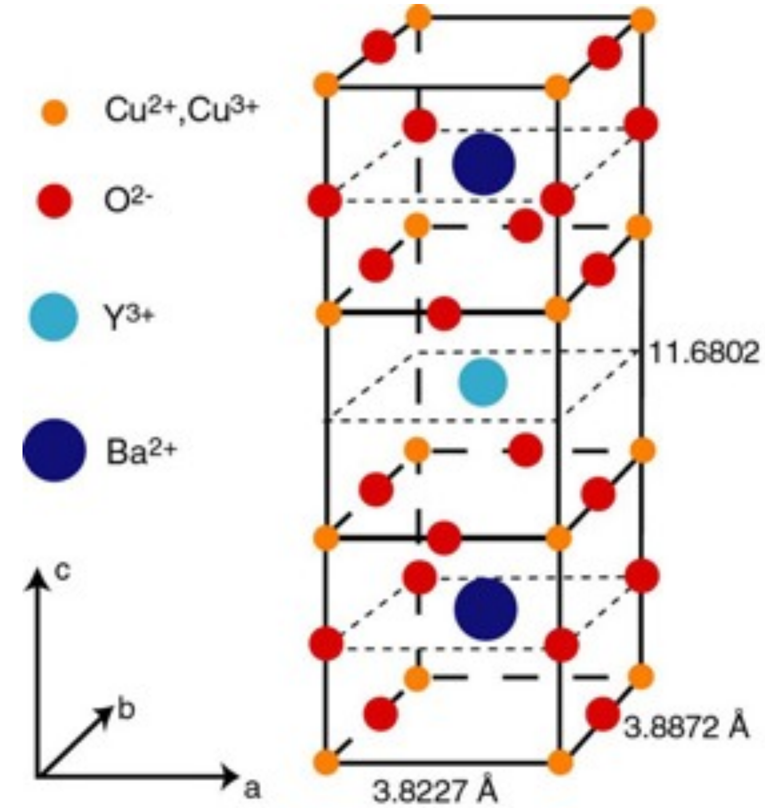
Gases

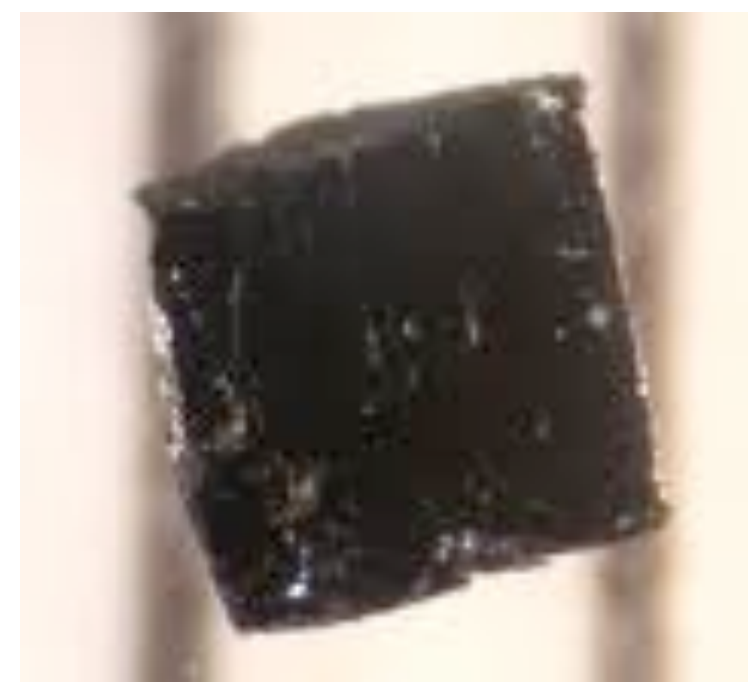
Steam

Solids

Copper

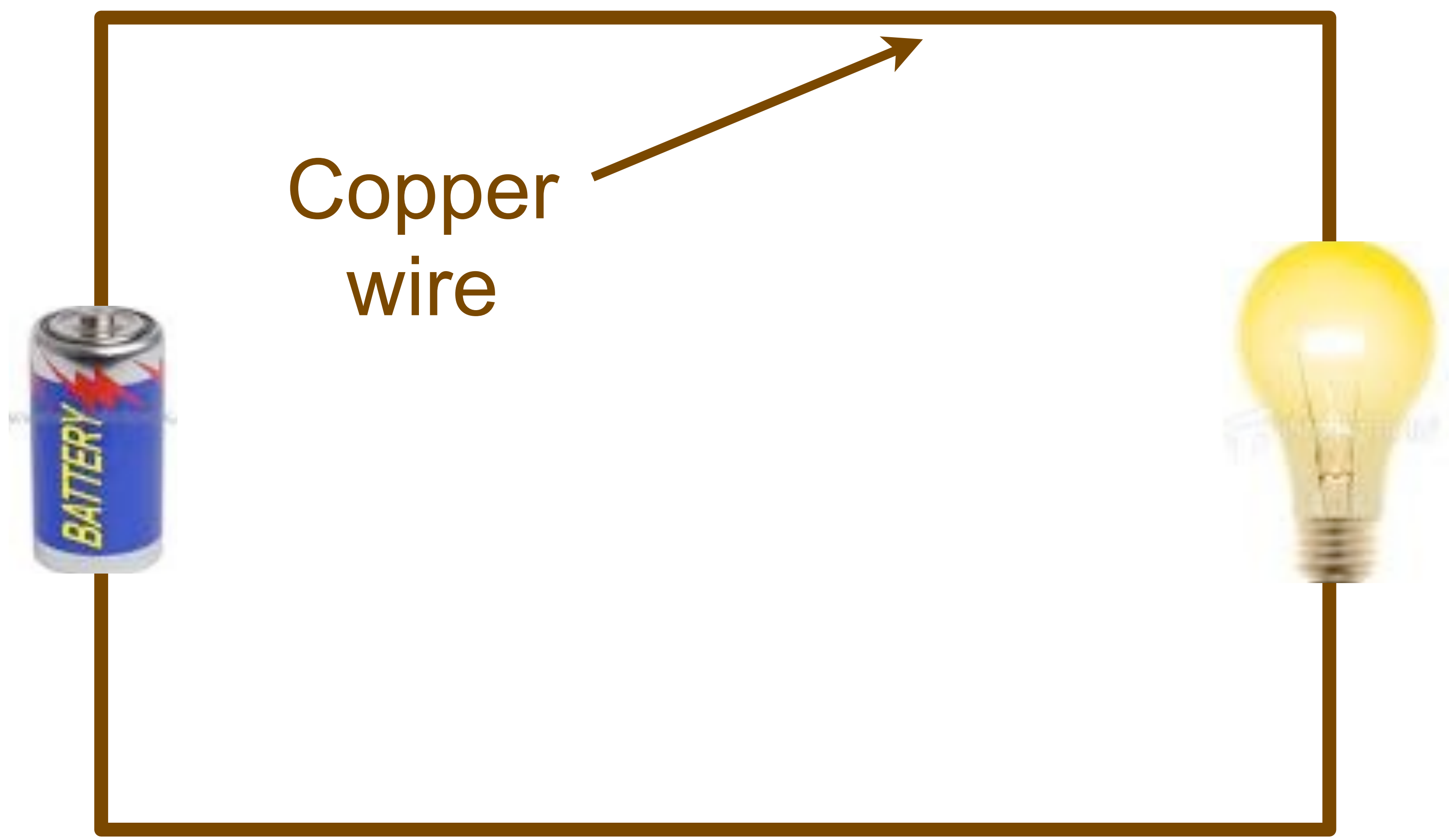
Silicon





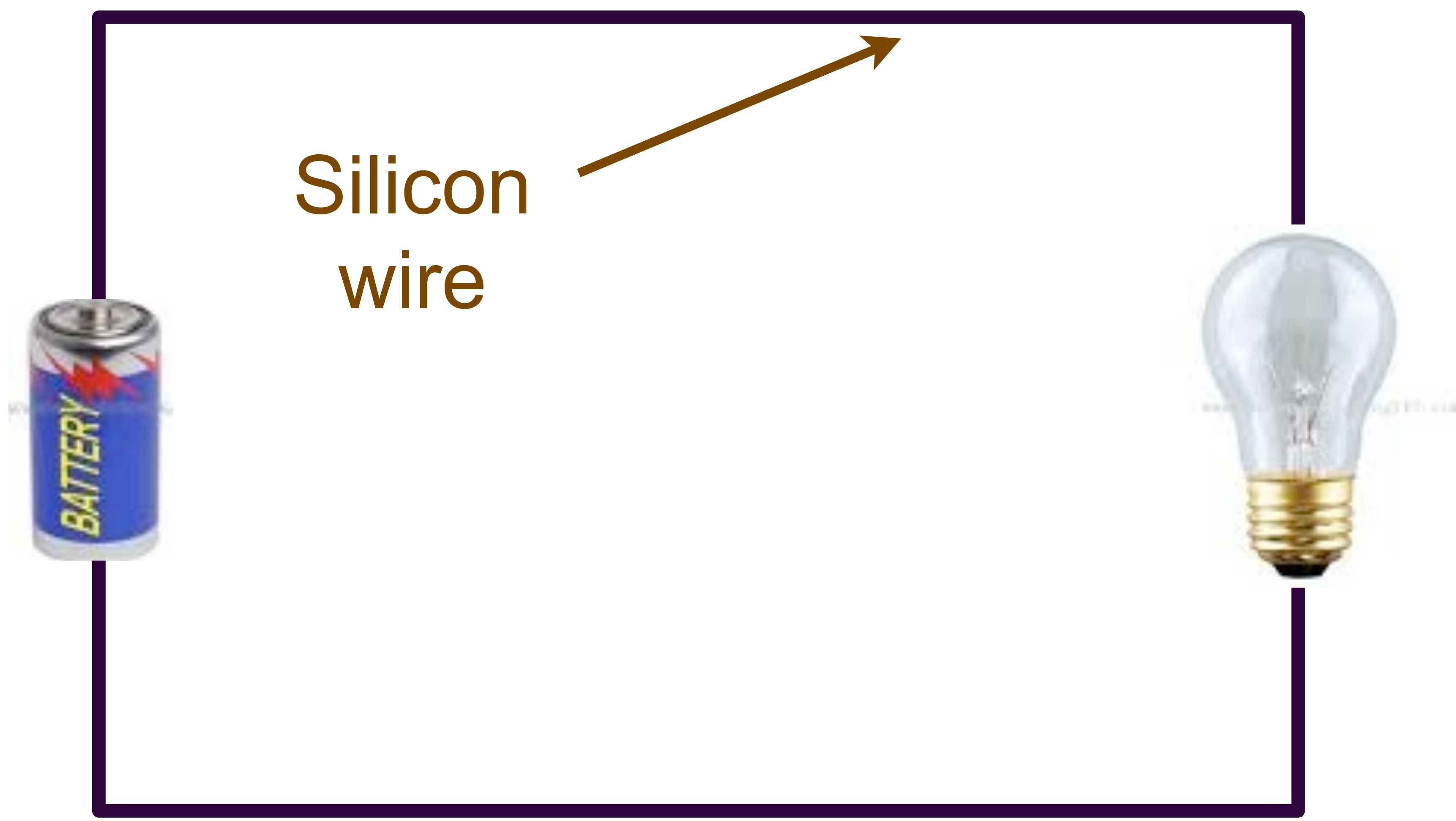
YBCO

These solids have very different electrical and magnetic properties



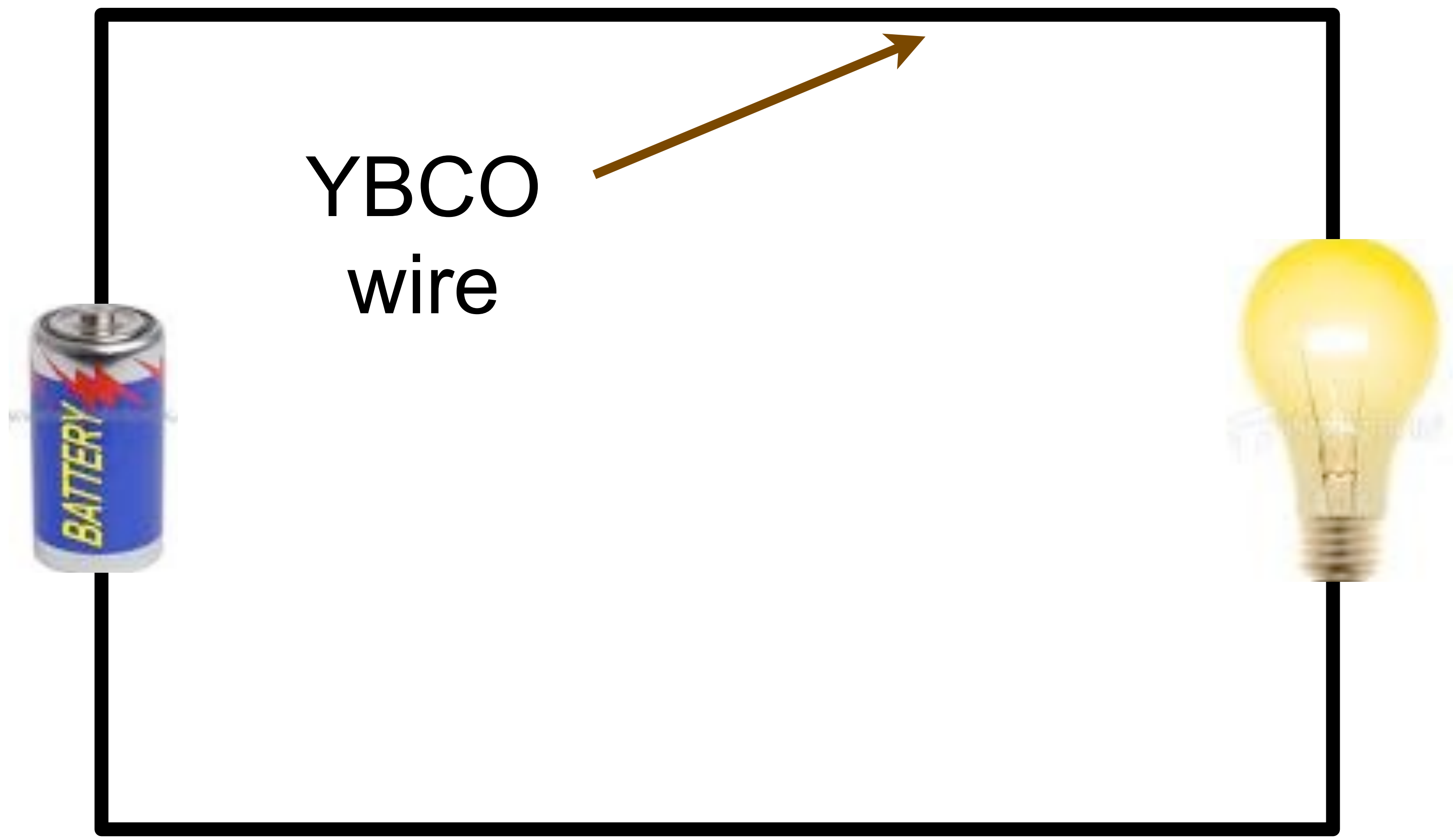
Copper is a conductor of electricity

These solids have very different electrical and magnetic properties



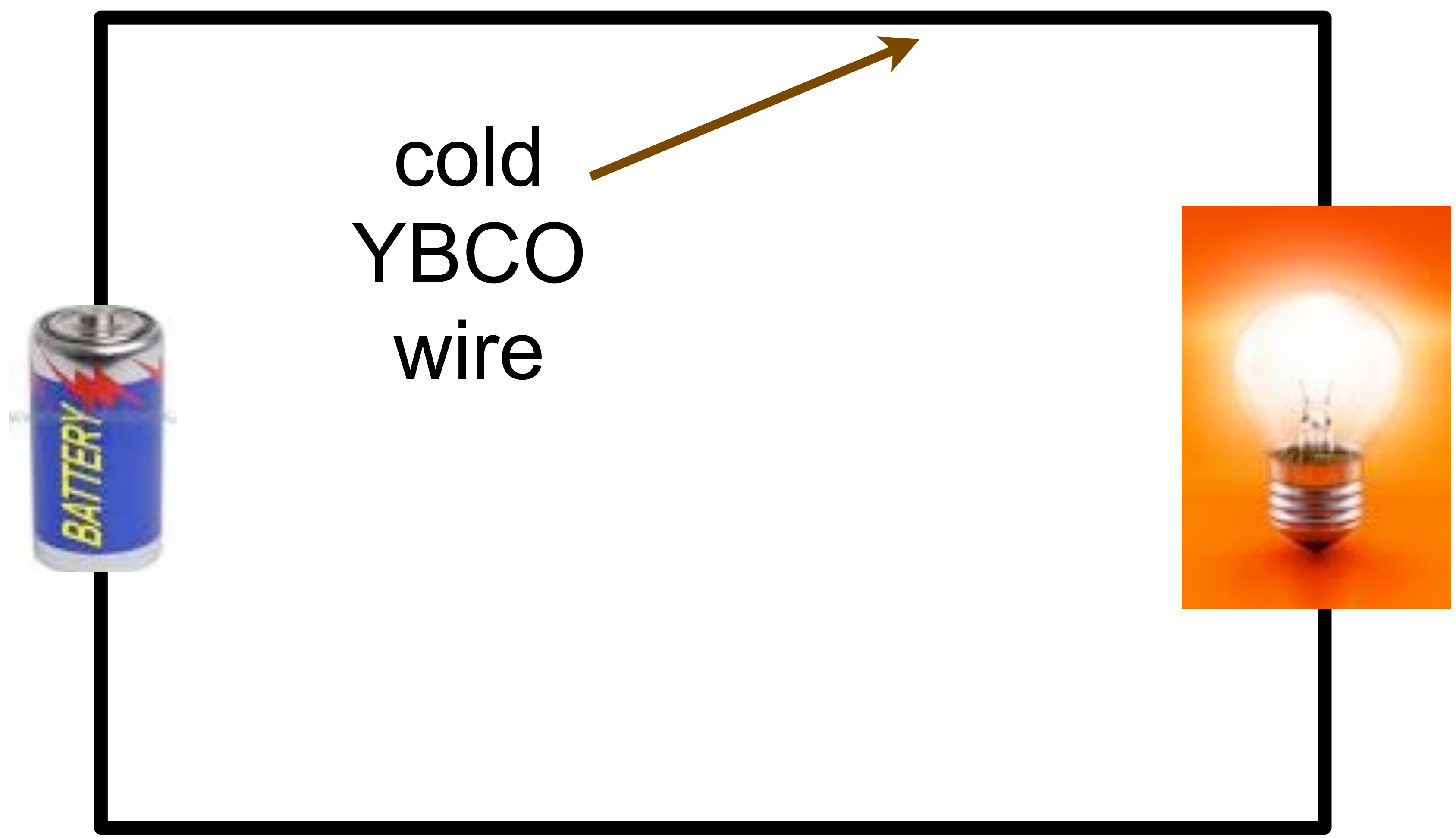
Silicon is an insulator

These solids have very different electrical and magnetic properties



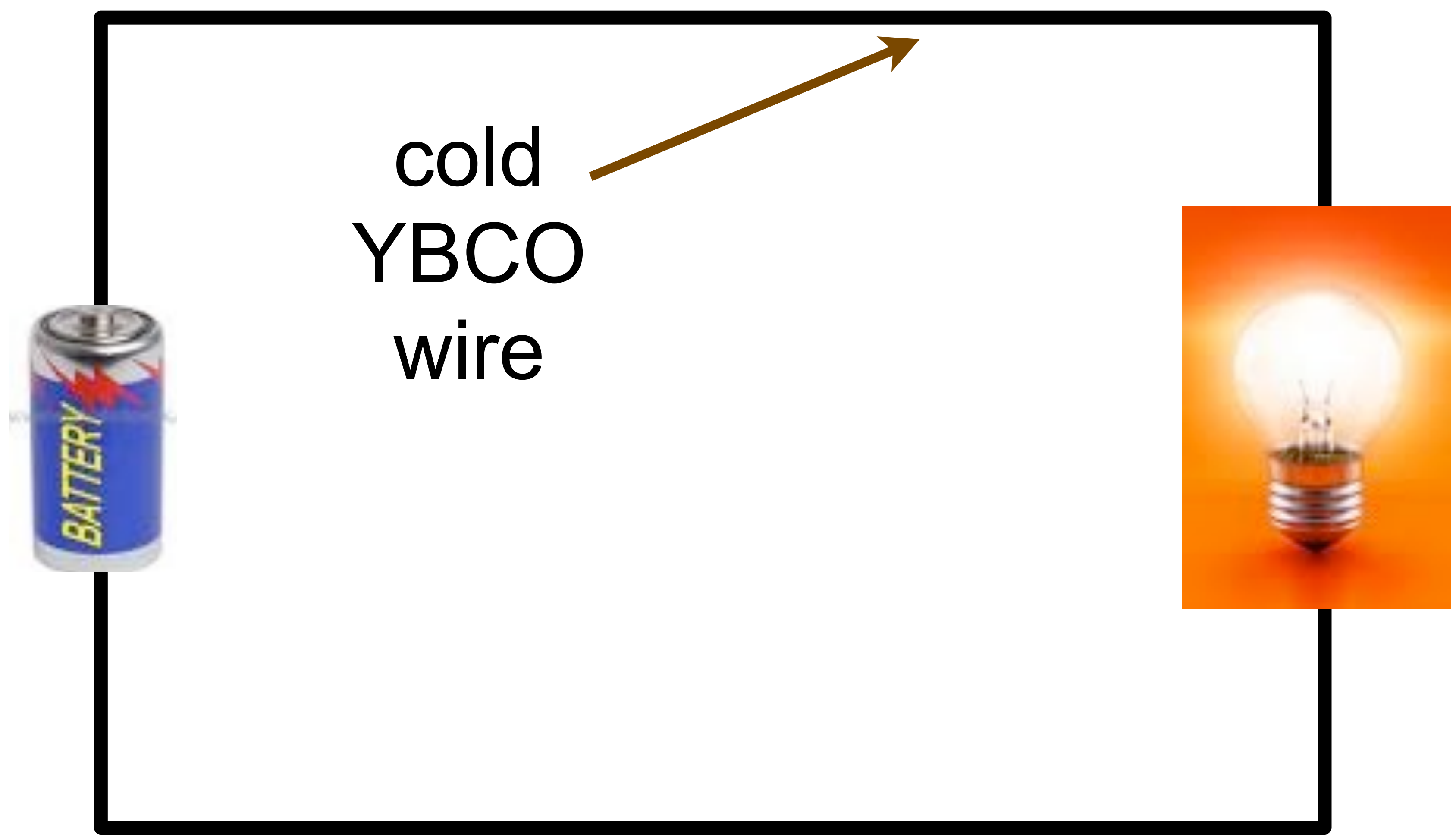
At room temperature, YBCO conducts electricity (but not very well)

These solids have very different electrical and magnetic properties



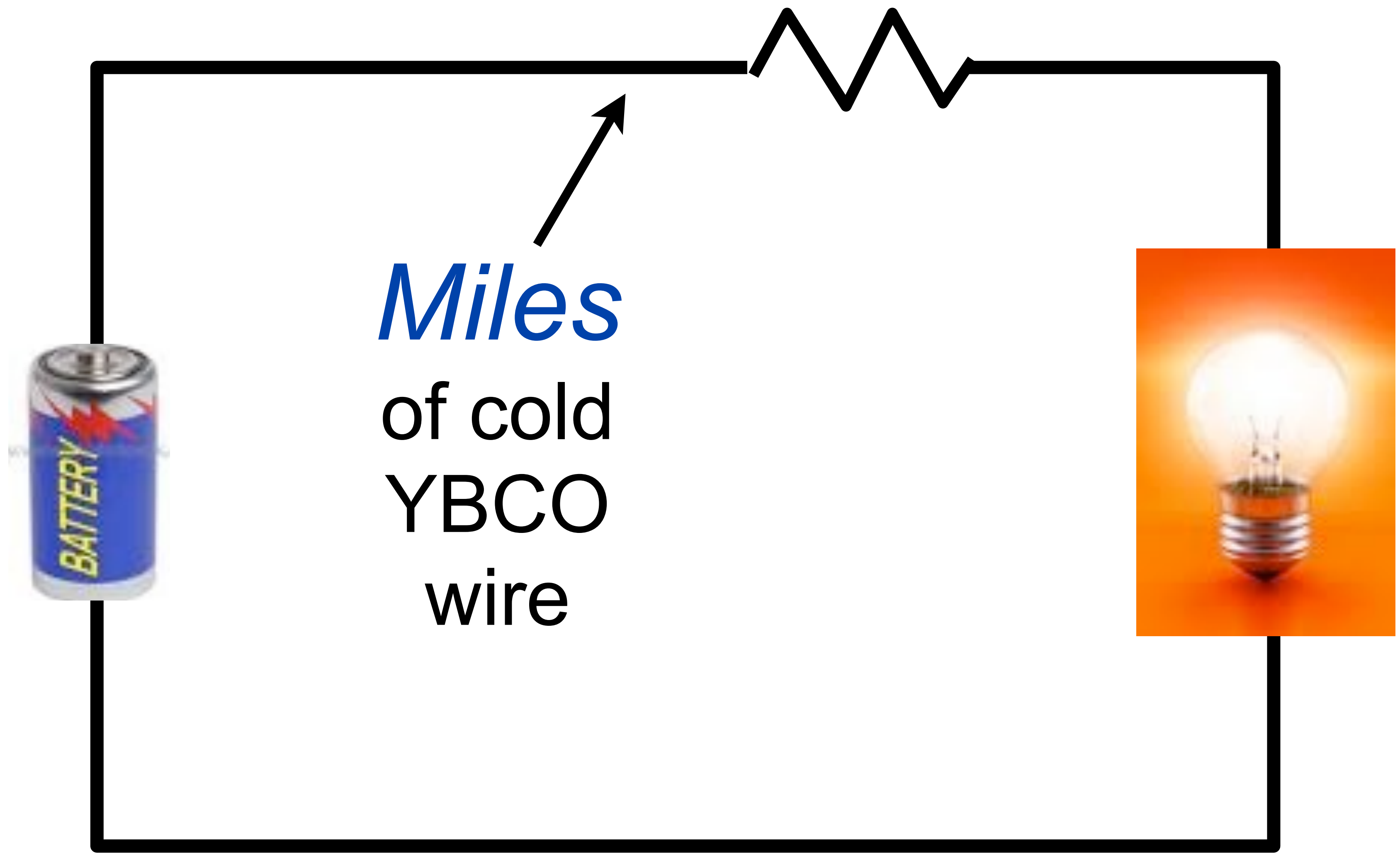
When cooled by liquid nitrogen, YBCO conducts electricity *without* resistance

These solids have very different electrical and magnetic properties



When cooled by liquid nitrogen, YBCO is a SUPERCONDUCTOR !

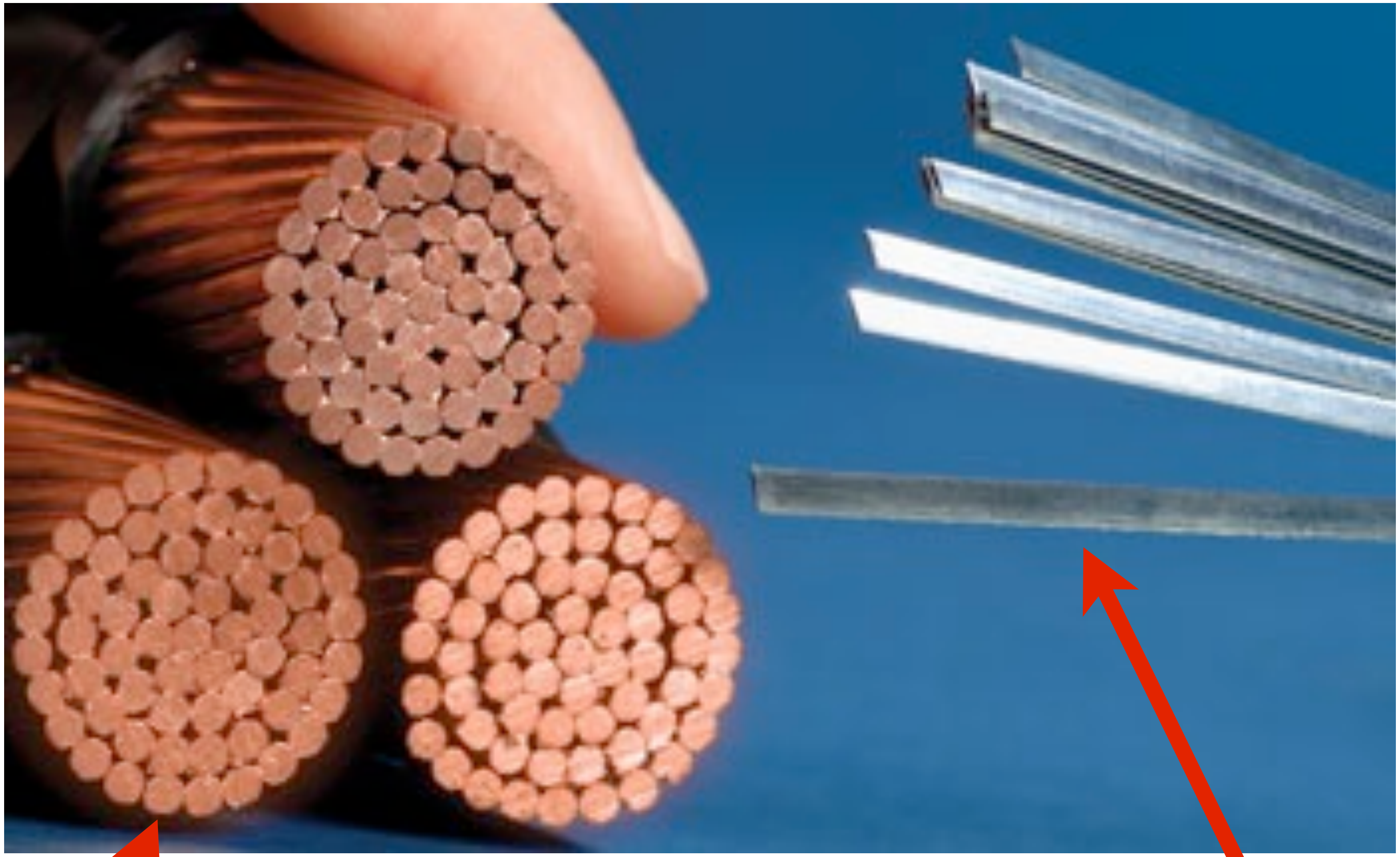
These solids have very different electrical and magnetic properties



When cooled by liquid nitrogen,
YBCO is a SUPERCONDUCTOR !

Transmitting power
with YBCO

American Superconductor Corporation



Cu wires for equivalent power density

YBCO tape

American Superconductor Corporation

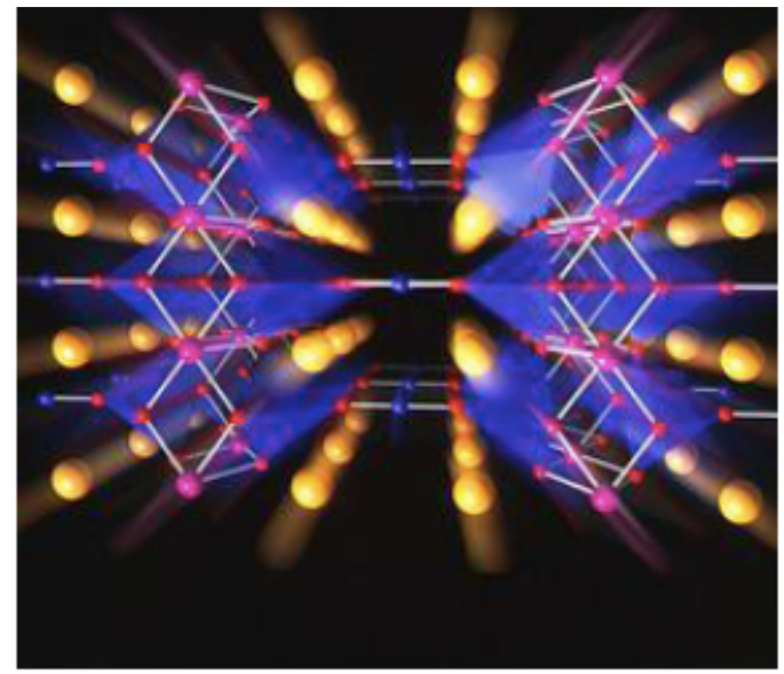
Published online 8 October 2010 | Nature | doi:10.1038/news.2010.527

News

Superconductors come of age

A South Korean company has placed by far the biggest commercial order for superconducting wires.

Superconducting wires could soon help to light up Seoul.



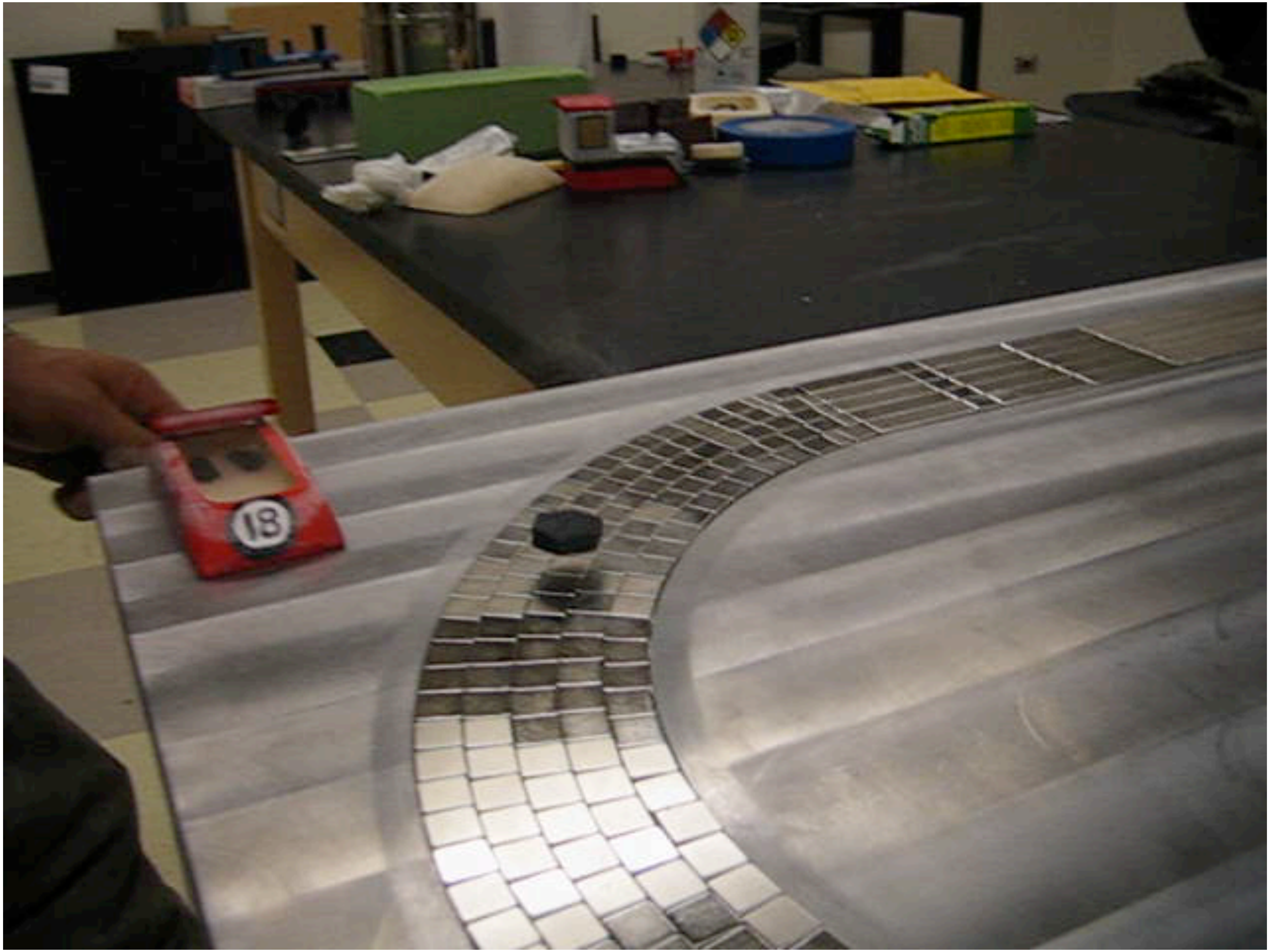
YBCO superconductors are likly to be used in more power grids in future.

LS Cable, a South Korean company based in Anyang-si near Seoul, has ordered three million metres of superconducting wire from US firm American Superconductor in Devens, Massachusetts. Jason Fredette, managing director of corporate communications at the company, says that LS Cable will use the wire to make about 20 circuit kilometres of cable as part of a programme to modernize the South Korean electricity network starting in the capital, Seoul.

The superconducting wire is made using the ceramic compound yttrium barium copper oxide (YBCO), part of a family of 'high-temperature' superconducting ceramics that were first discovered in 1986.

Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University



Nd-Fe-B magnets, YBaCuO superconductor

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Theory of the electrical phases of matter:

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Theory of the electrical phases of matter:

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Theory of the electrical phases of matter:

1. In solids, electrons separate

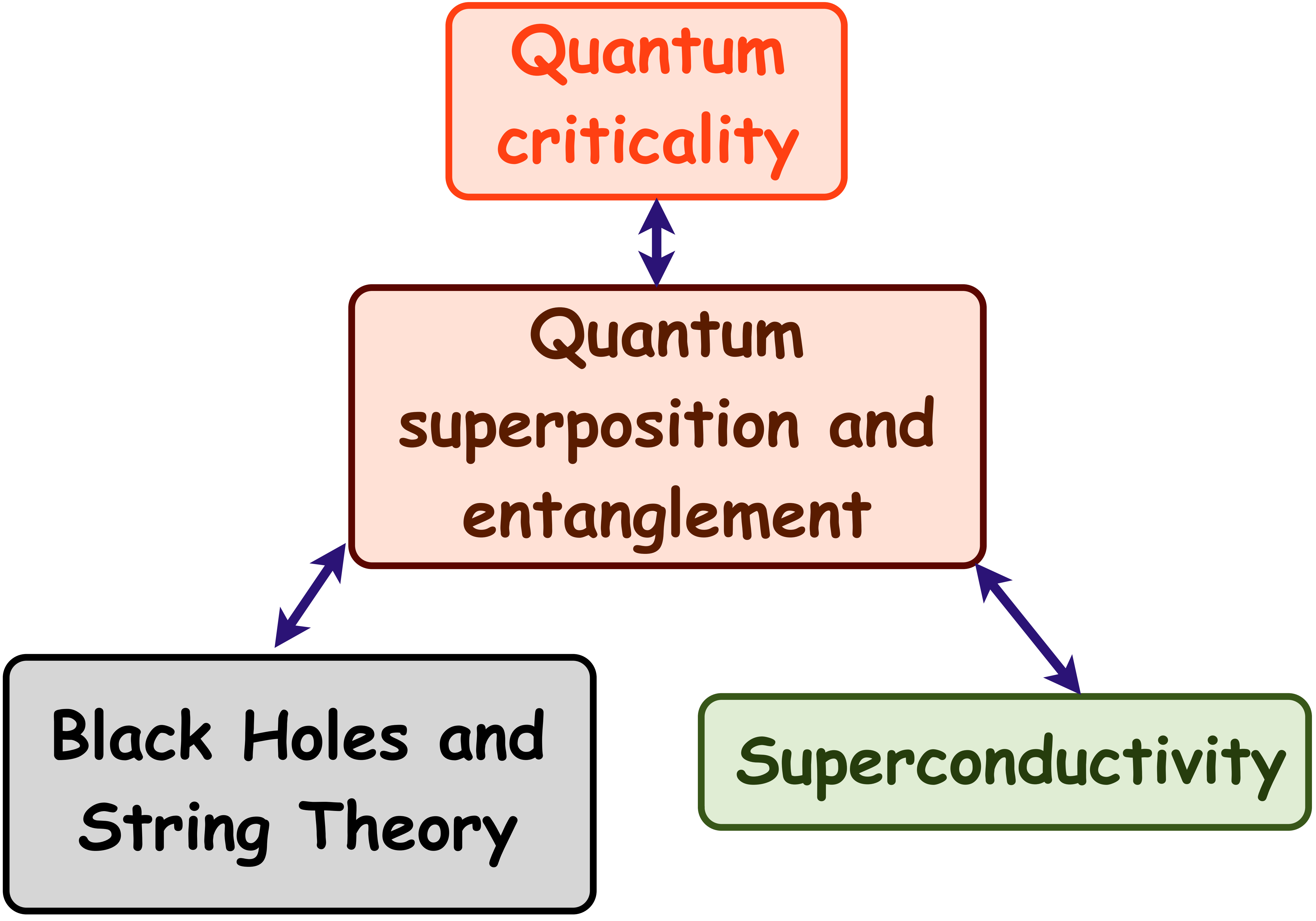
Needed:
A theory for the *quantum* phases of matter

2.

3.

and Schroedinger determines the electrical properties of solids at macroscopic scales

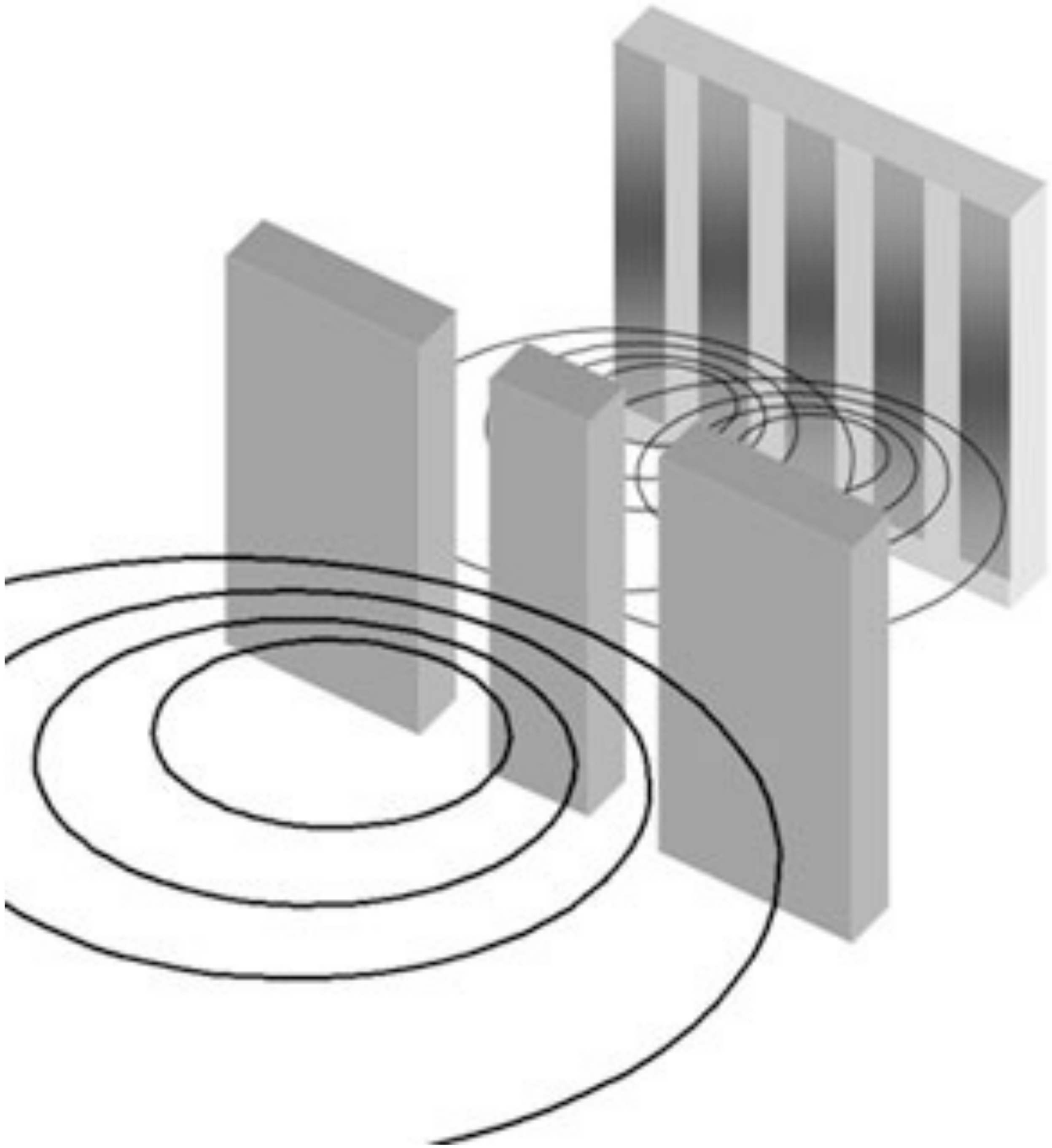
Quantum superposition and entanglement


Quantum criticality
Quantum superposition and entanglement
Black Holes and String Theory
Superconductivity

Quantum superposition and entanglement

Quantum Superposition

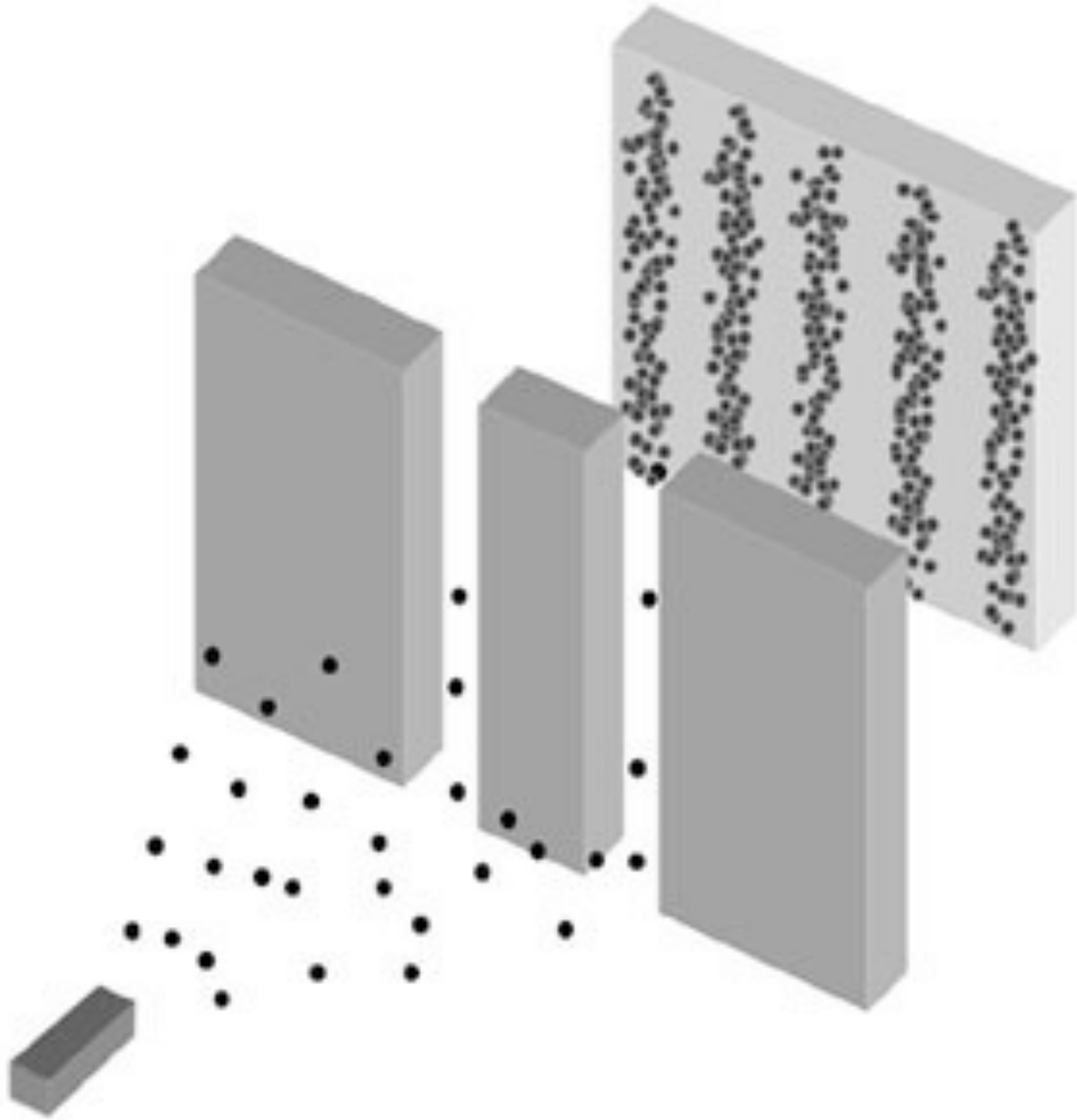
The double slit experiment



Interference of water waves

Quantum Superposition

The double slit experiment

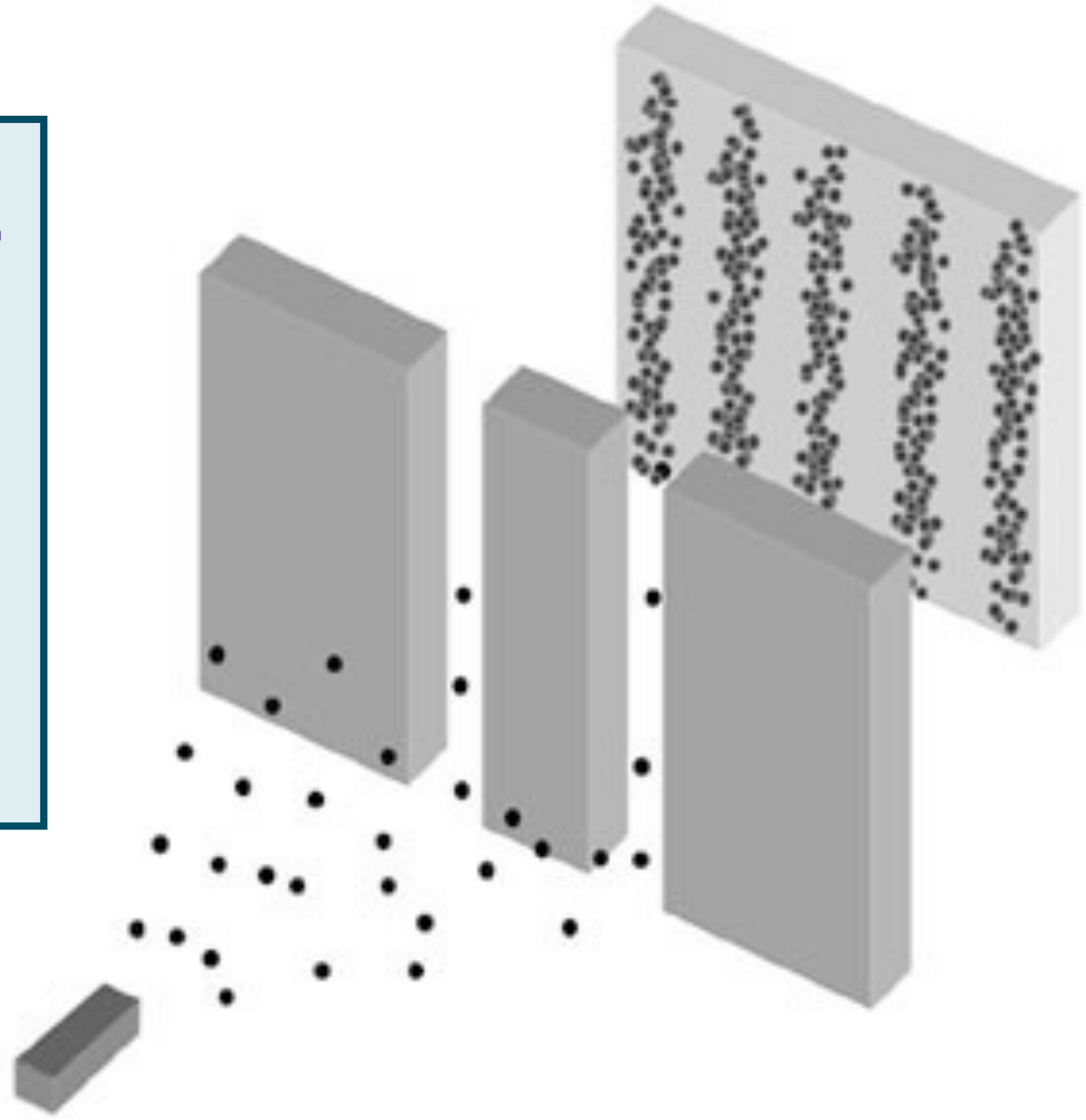


Interference of electrons

Quantum Superposition

The double slit experiment

Which slit does an electron pass through ?

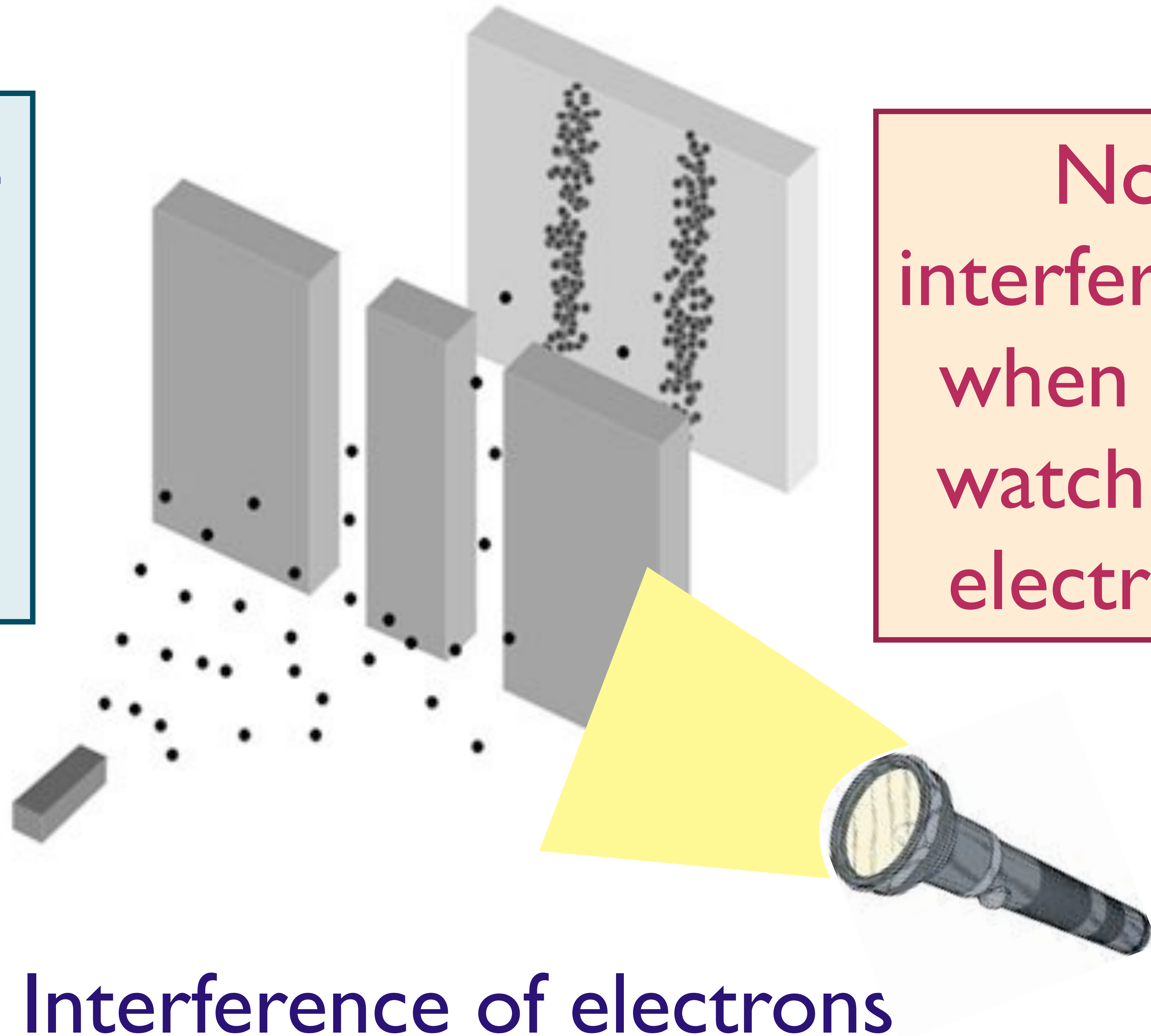


Interference of electrons

Quantum Superposition

The double slit experiment

Which slit does an electron pass through ?



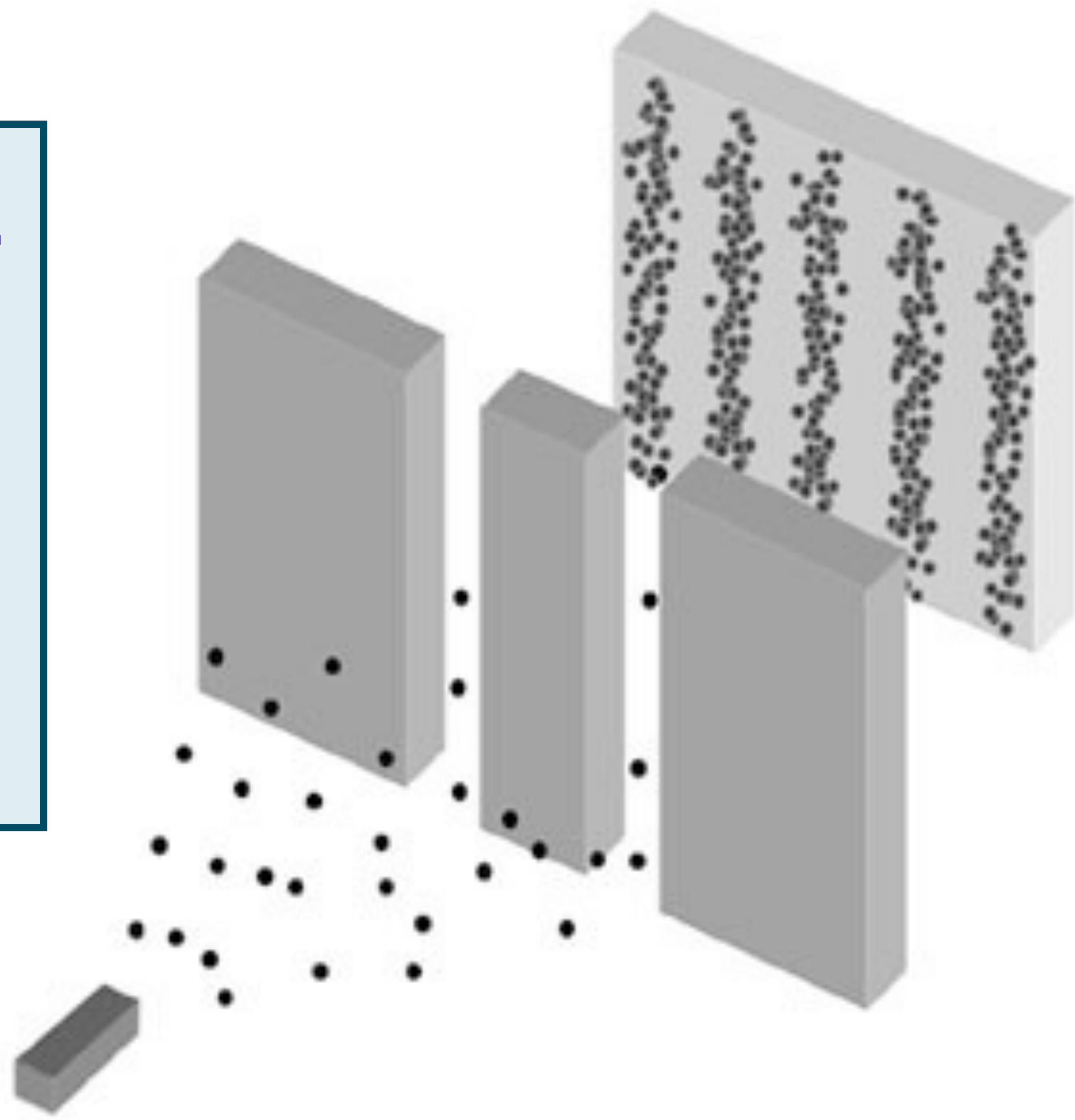
No interference when you watch the electrons

Interference of electrons

Quantum Superposition

The double slit experiment

Which slit does an electron pass through ?

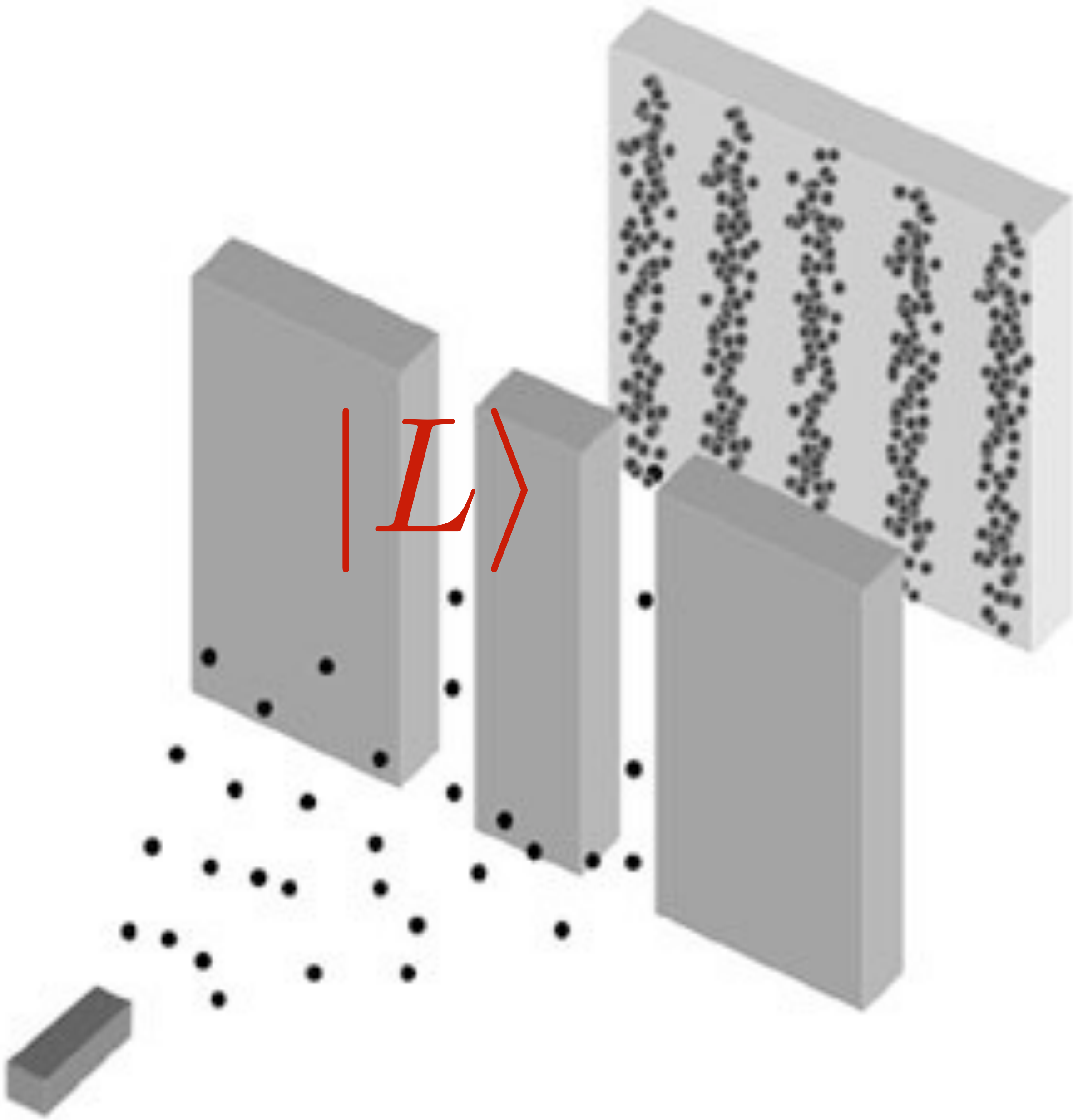


Each electron passes through both slits !

Interference of electrons

Quantum Superposition

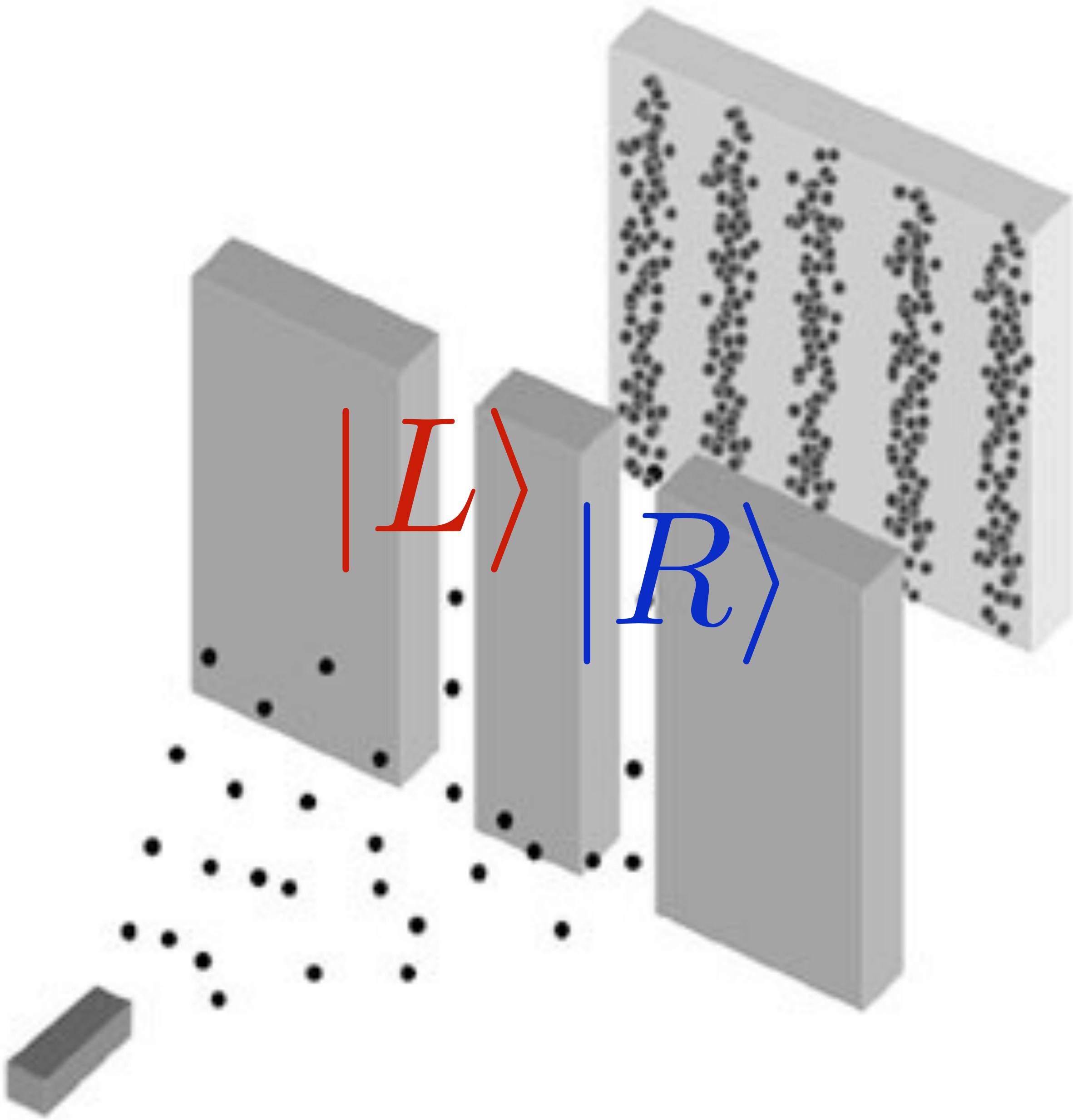
The double slit experiment



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

Quantum Superposition

The double slit experiment

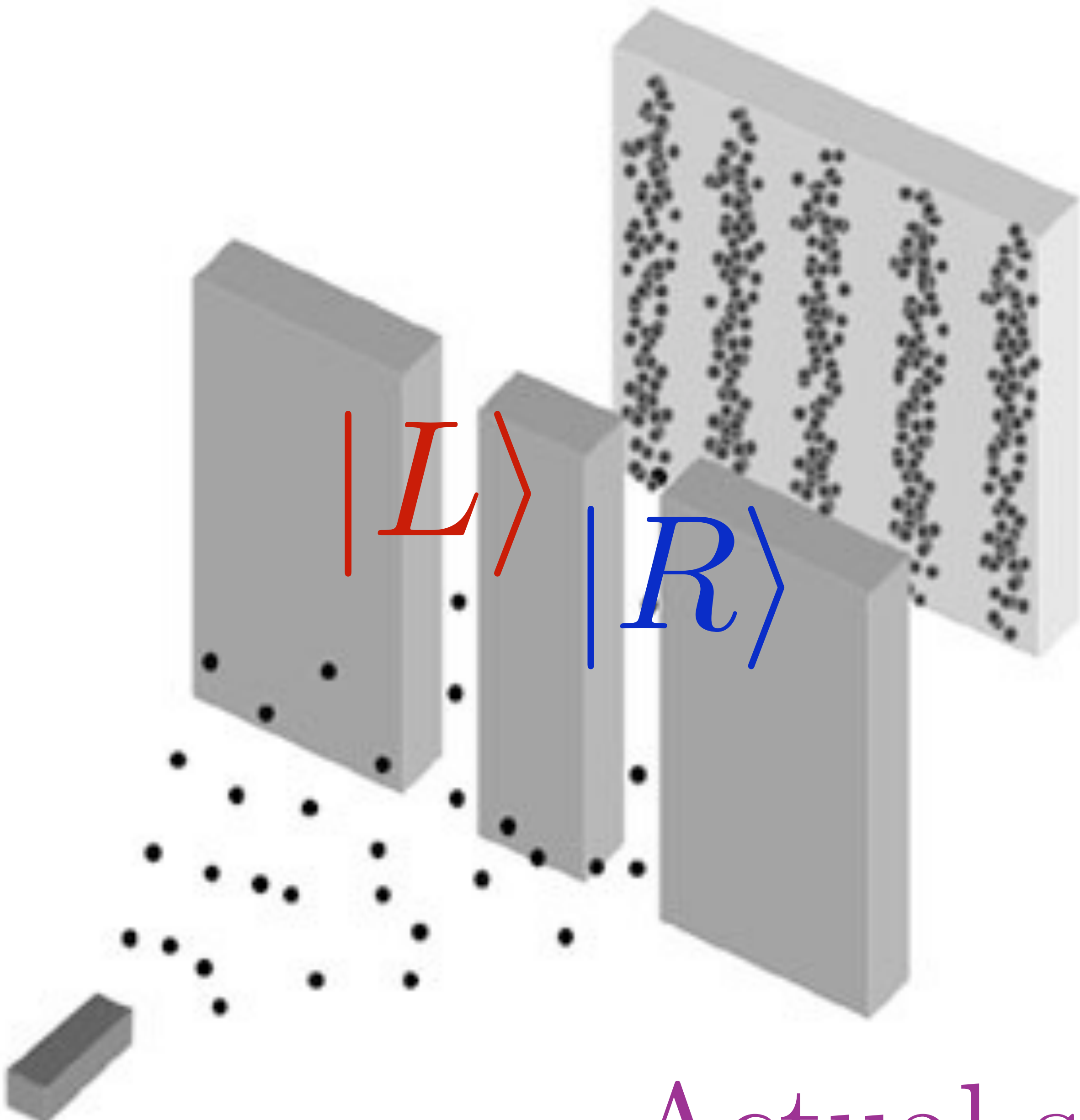


Let $|L\rangle$ represent the state with the electron in the left slit

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

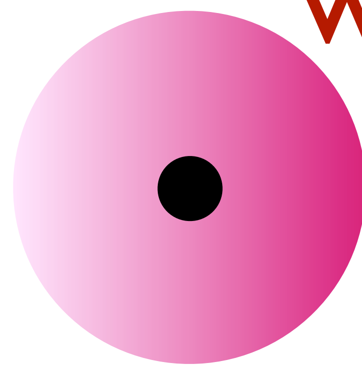
Actual state of the electron is

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

Quantum Entanglement: quantum superposition with more than one particle

Quantum Entanglement: quantum superposition with more than one particle

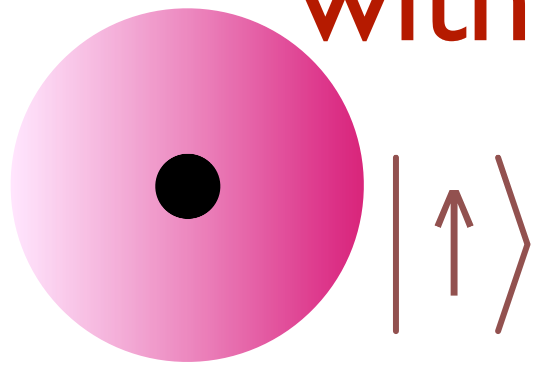
Hydrogen atom:



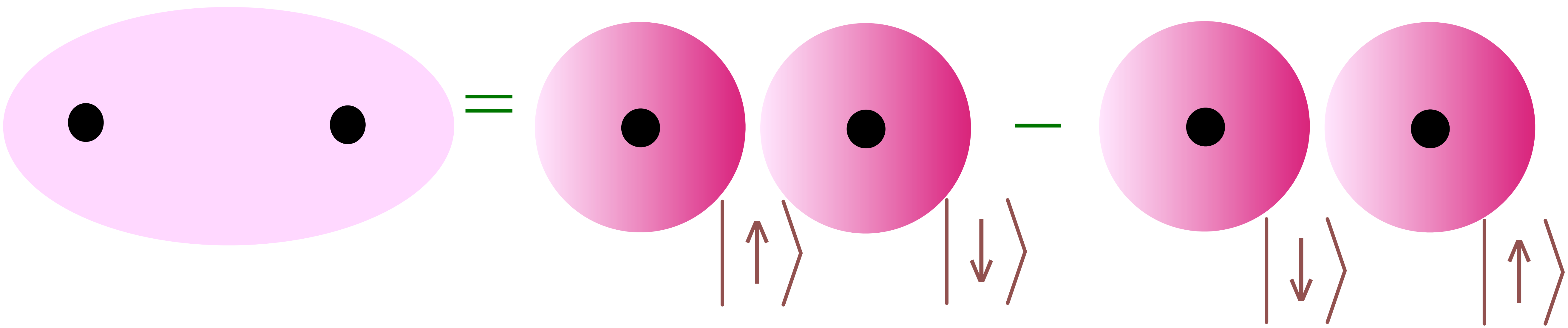
$|\uparrow\rangle$

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:



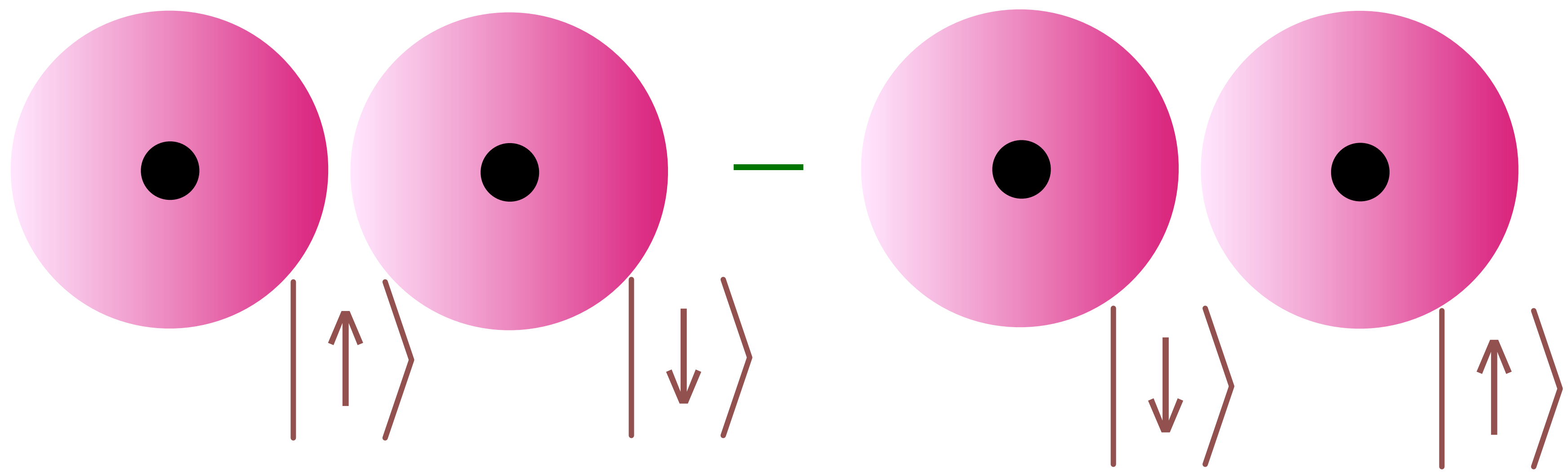
Hydrogen molecule:



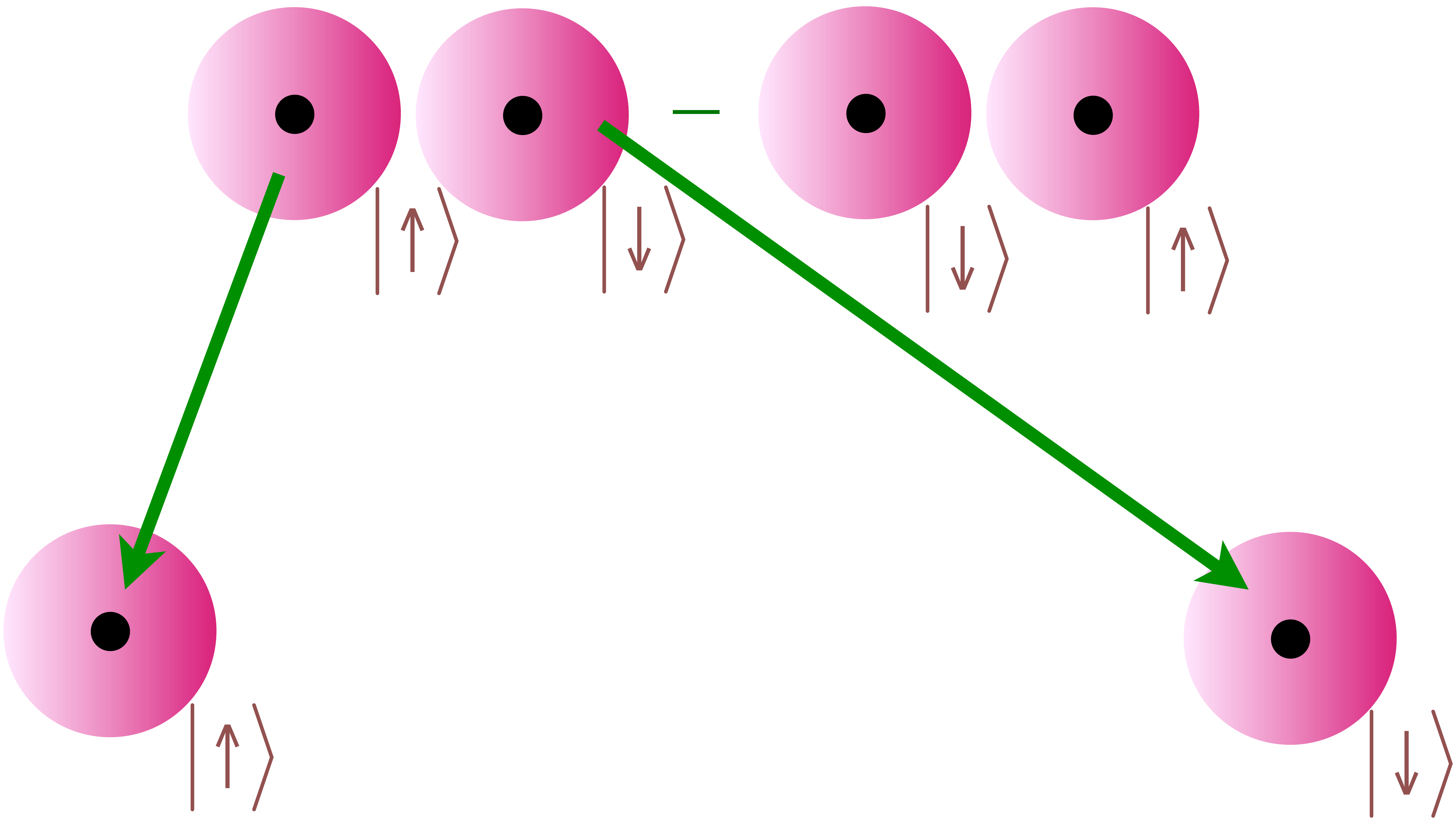
$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

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

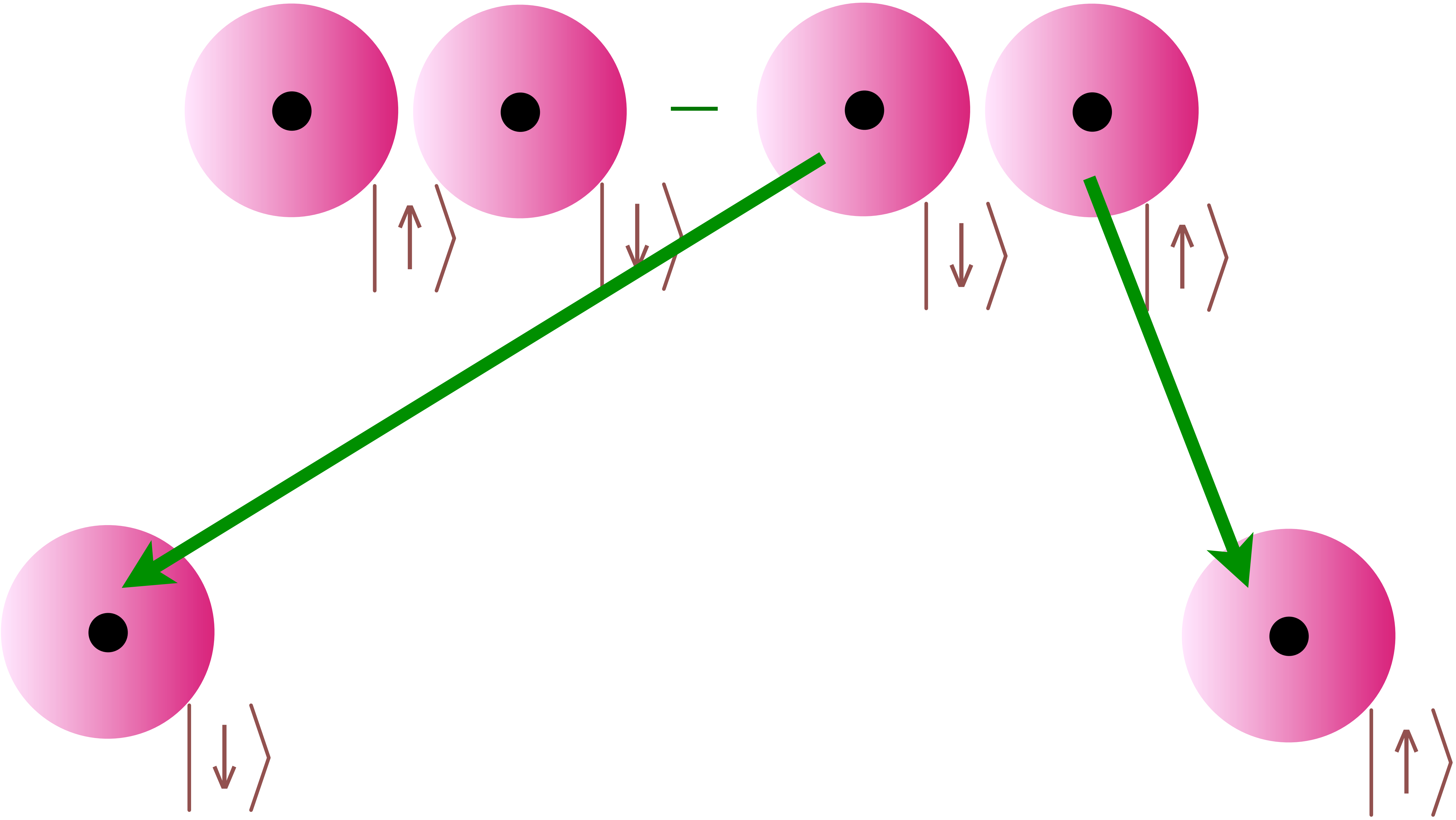
Quantum Entanglement: quantum superposition with more than one particle



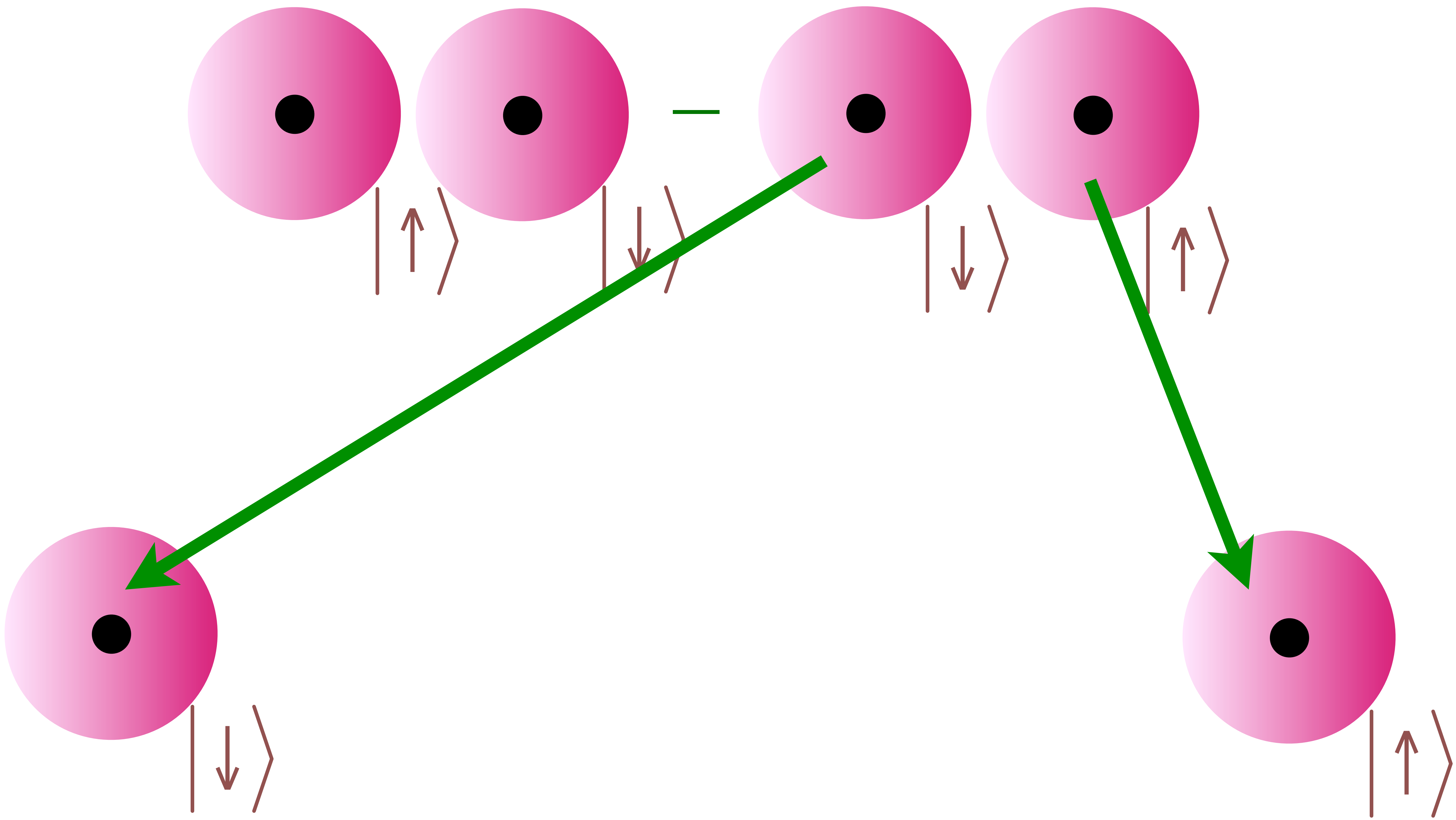
Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle

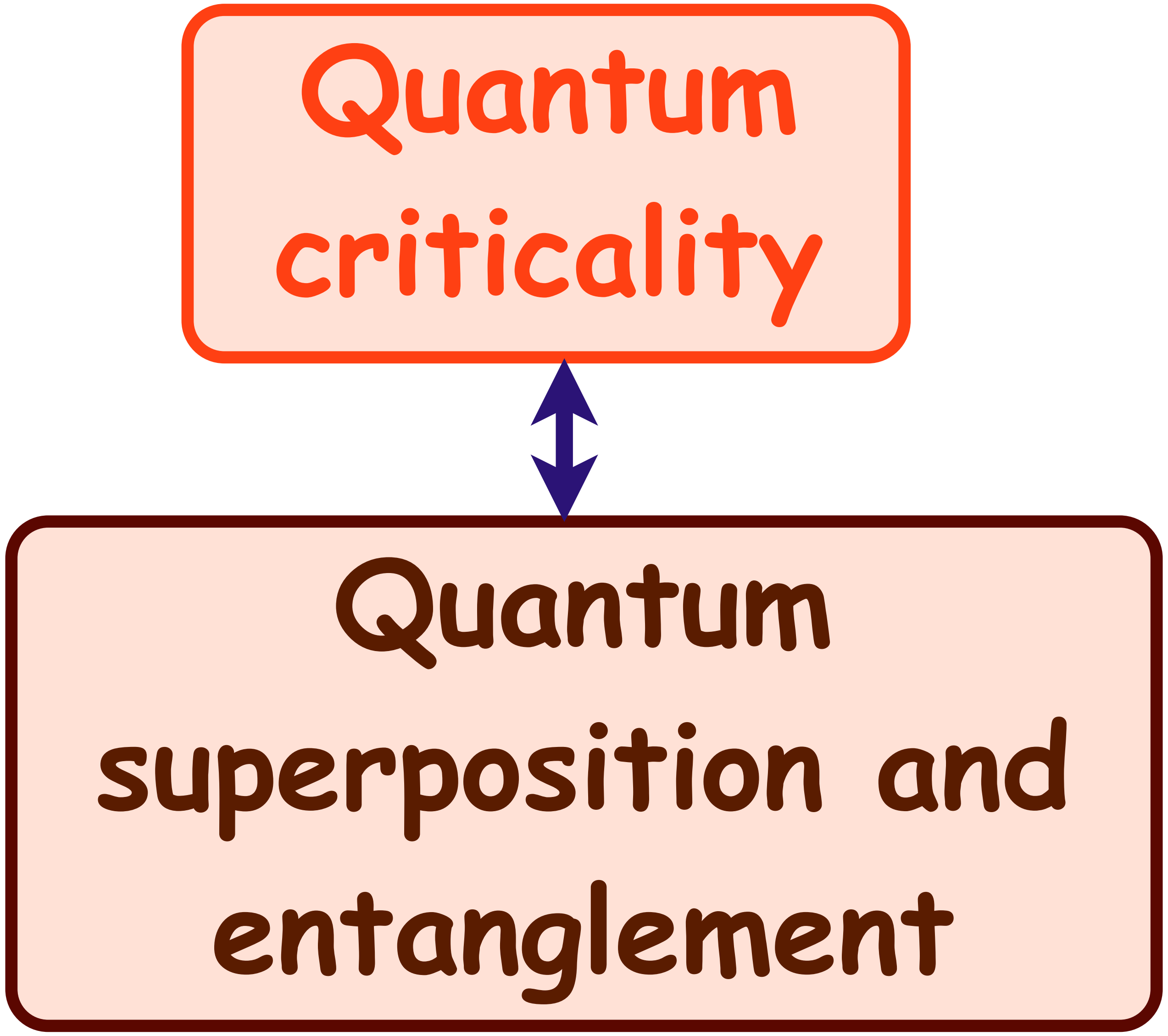


Quantum Entanglement: quantum superposition with more than one particle

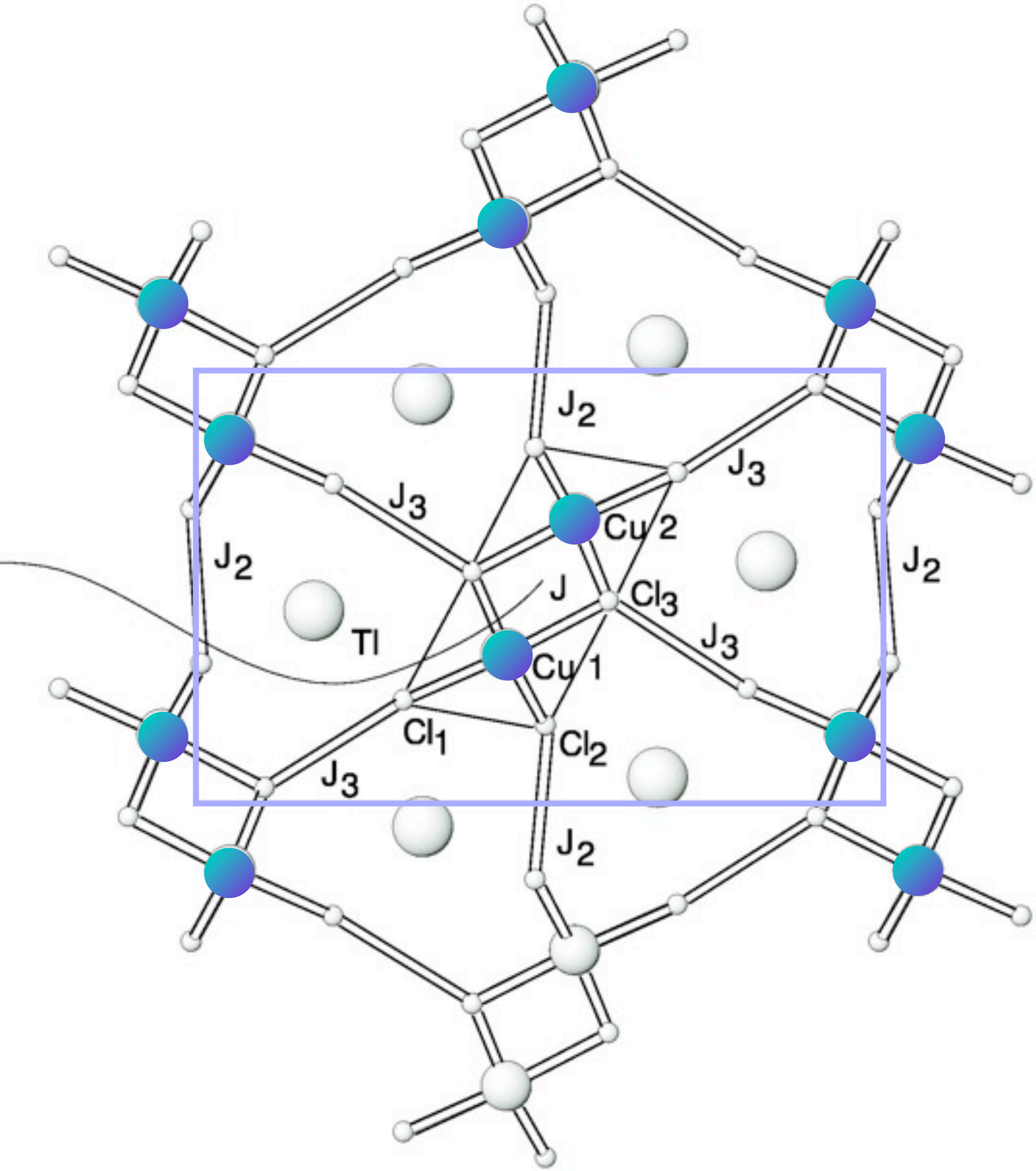


Einstein-Podolsky-Rosen "paradox": Non-local correlations between observations arbitrarily far apart

Quantum superposition and entanglement

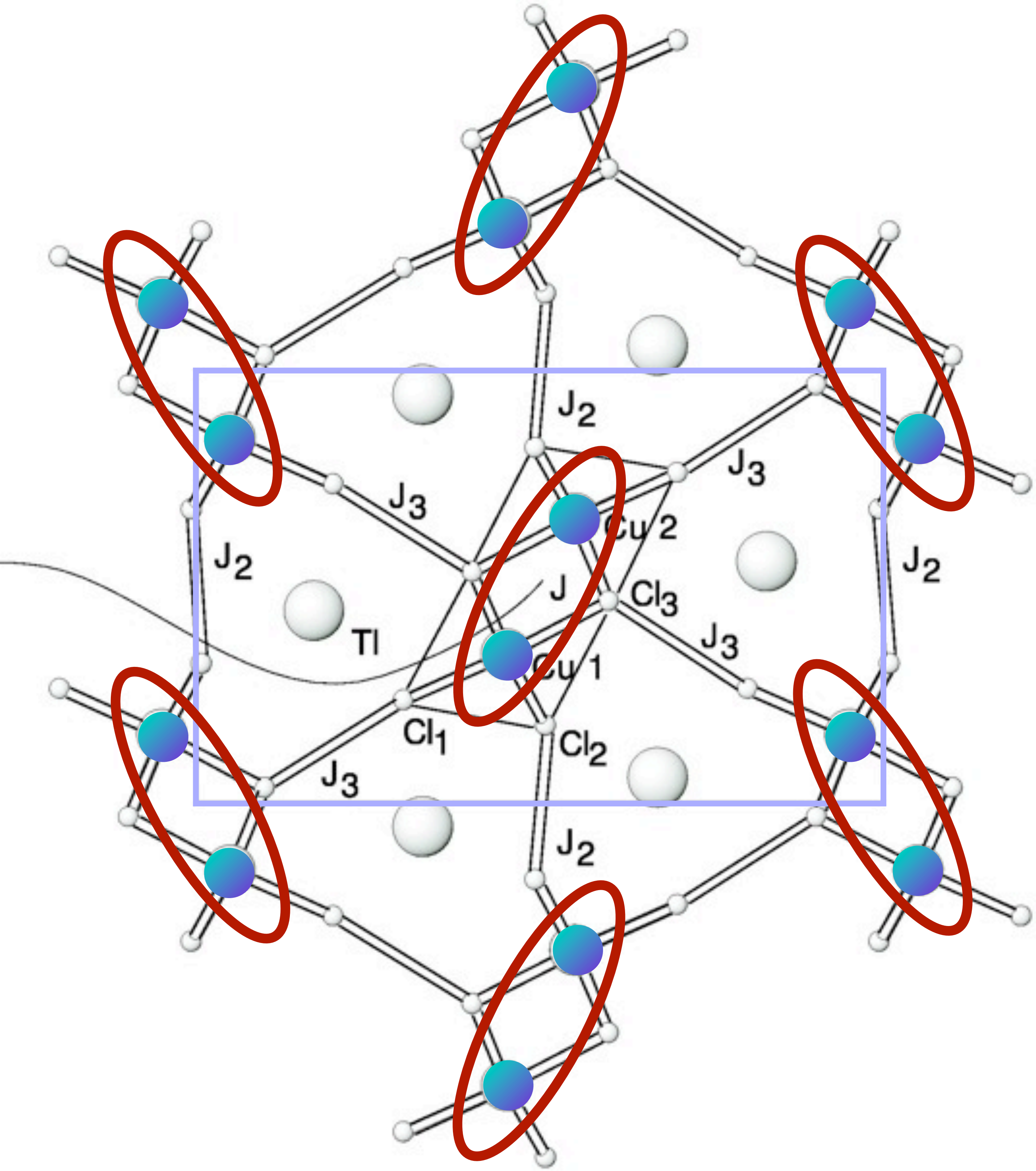

Quantum criticality
Quantum superposition and entanglement

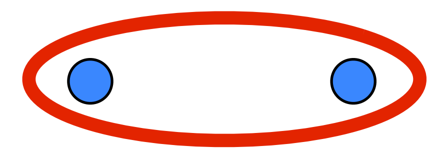
$TlCuCl_3$



An insulator whose magnetic susceptibility vanishes exponentially at low temperatures

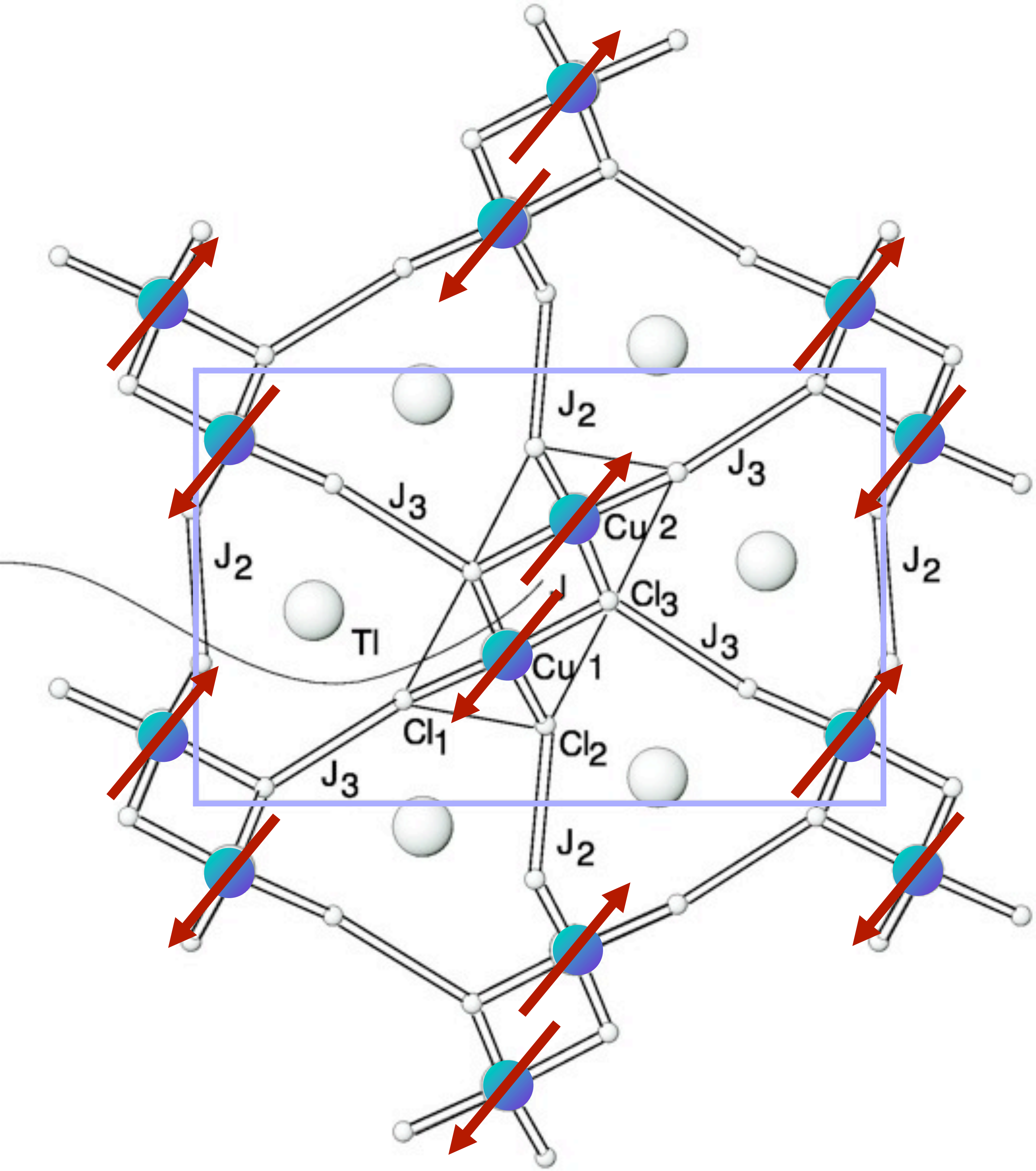
$TlCuCl_3$





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

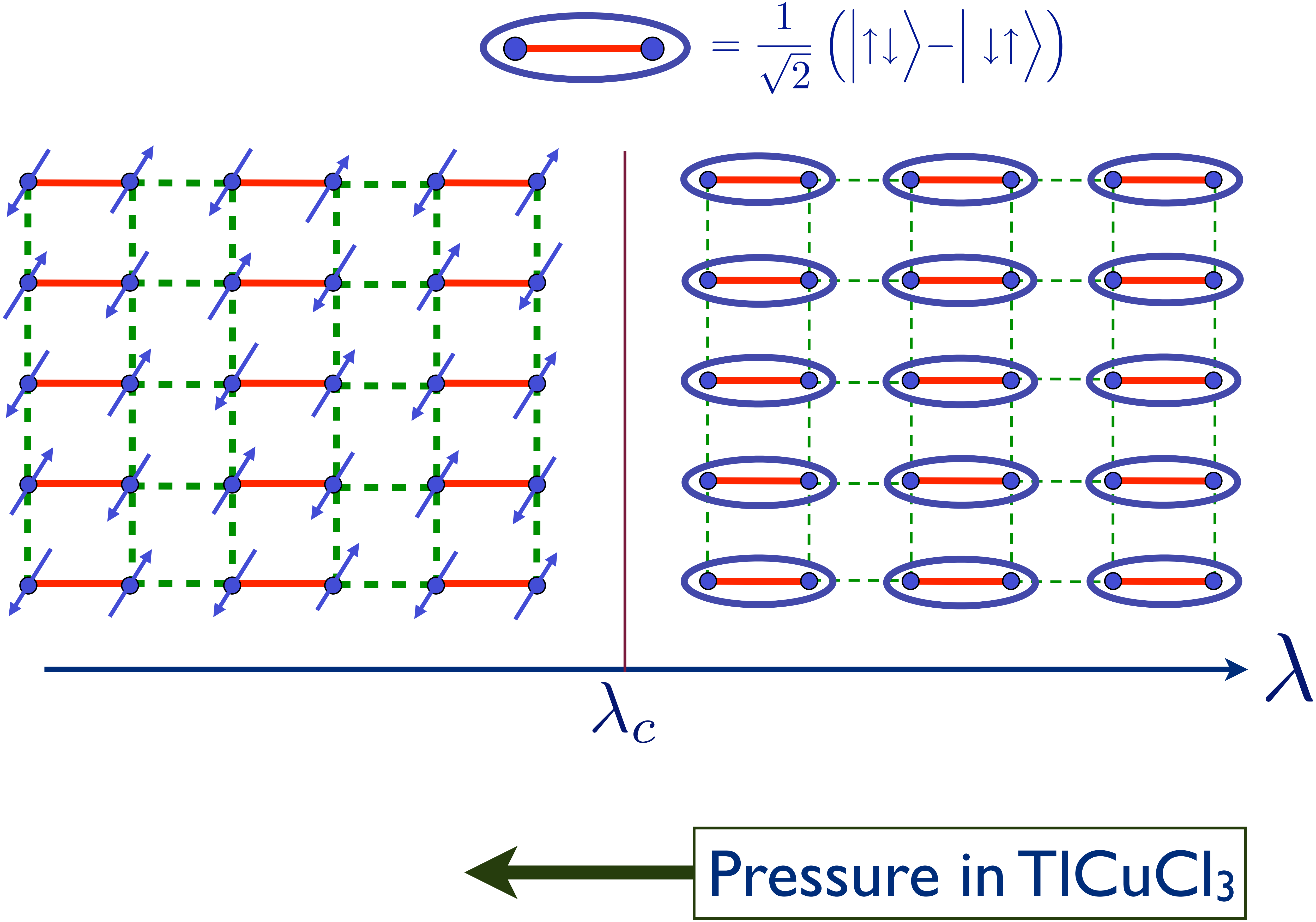
Nearest neighbor electrons are entangled



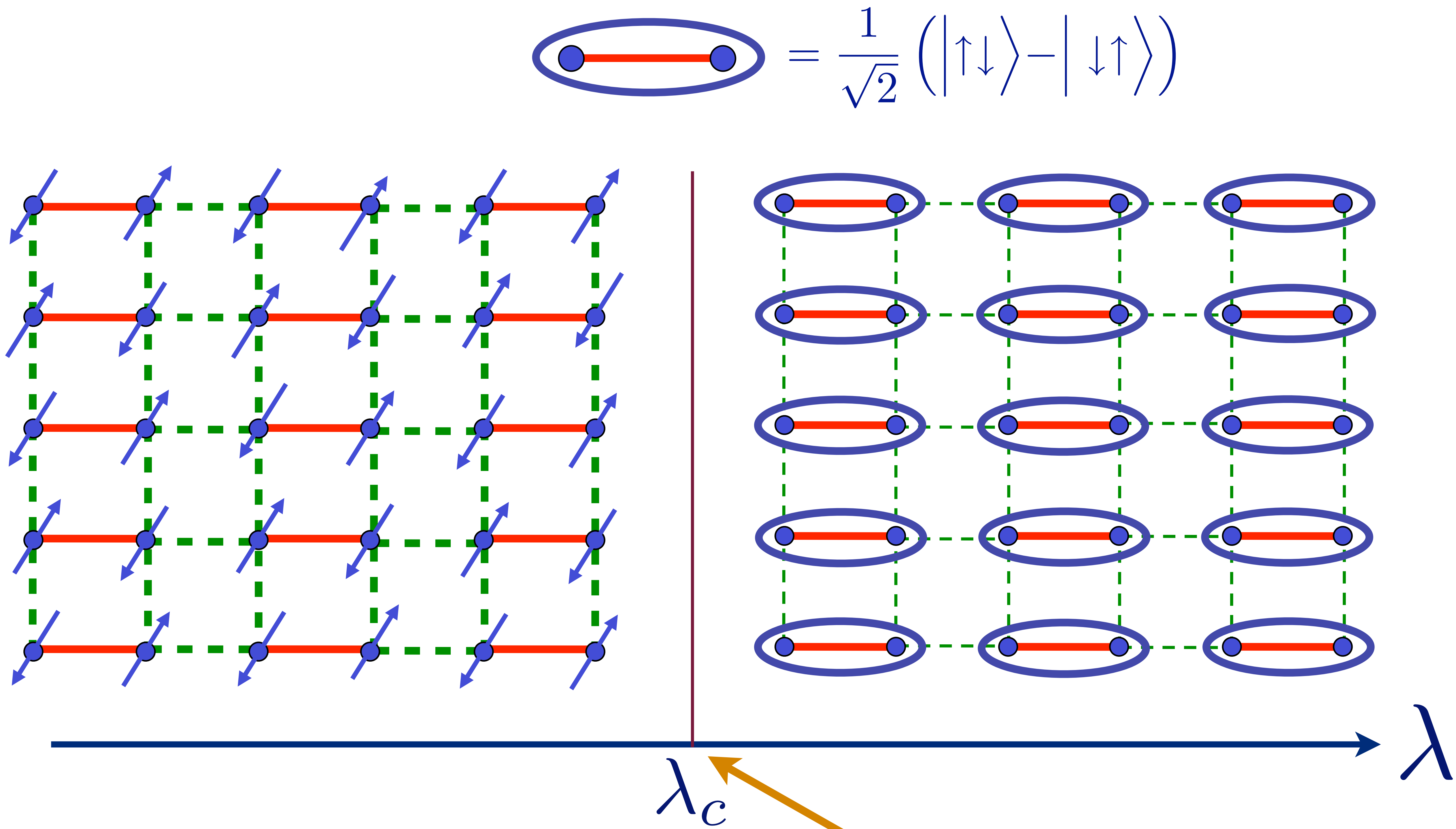
$TlCuCl_3$

Application of pressure reduces entanglement and leads to antiferromagnetism (Neel order)

A. Oosawa, K. Kakurai, T. Osakabe, M. Nakamura, M. Takeda, and H. Tanaka, *Journal of the Physical Society of Japan*, **73**, 1446 (2004).



A. Oosawa, K. Kakurai, T. Osakabe, M. Nakamura, M. Takeda, and H. Tanaka, *Journal of the Physical Society of Japan*, **73**, 1446 (2004).



Quantum critical point with non-local entanglement in spin wavefunction

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

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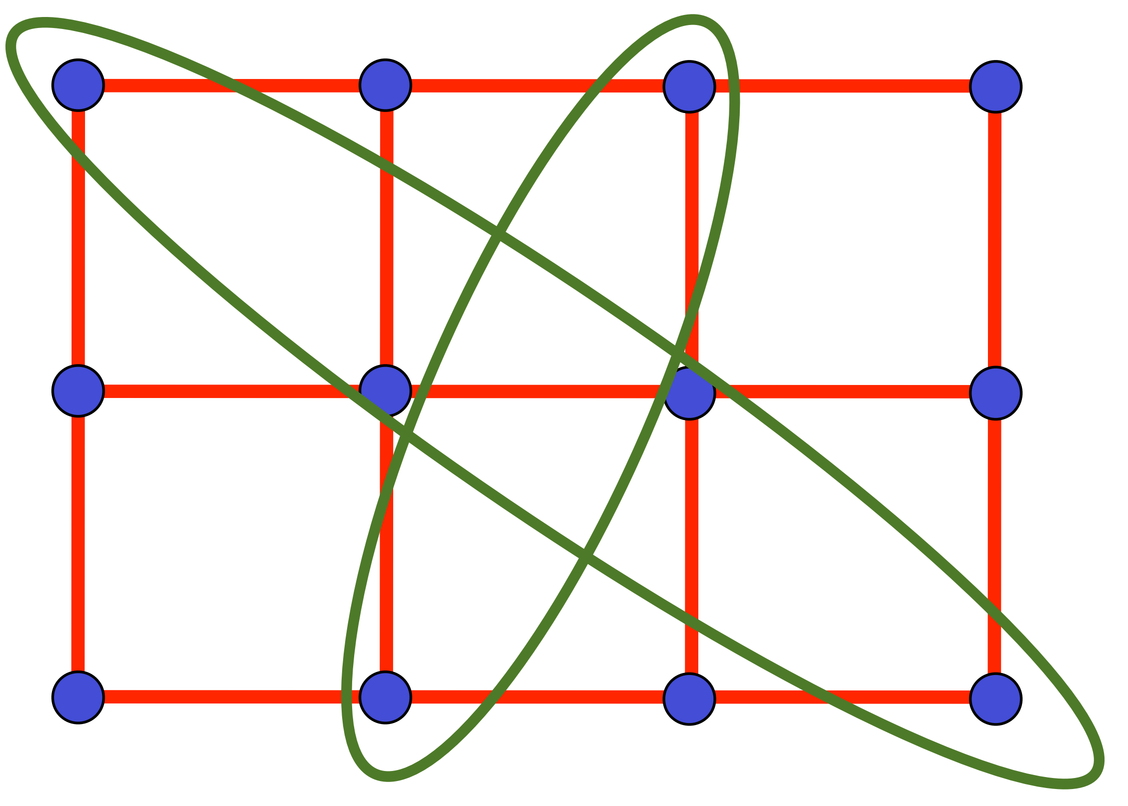
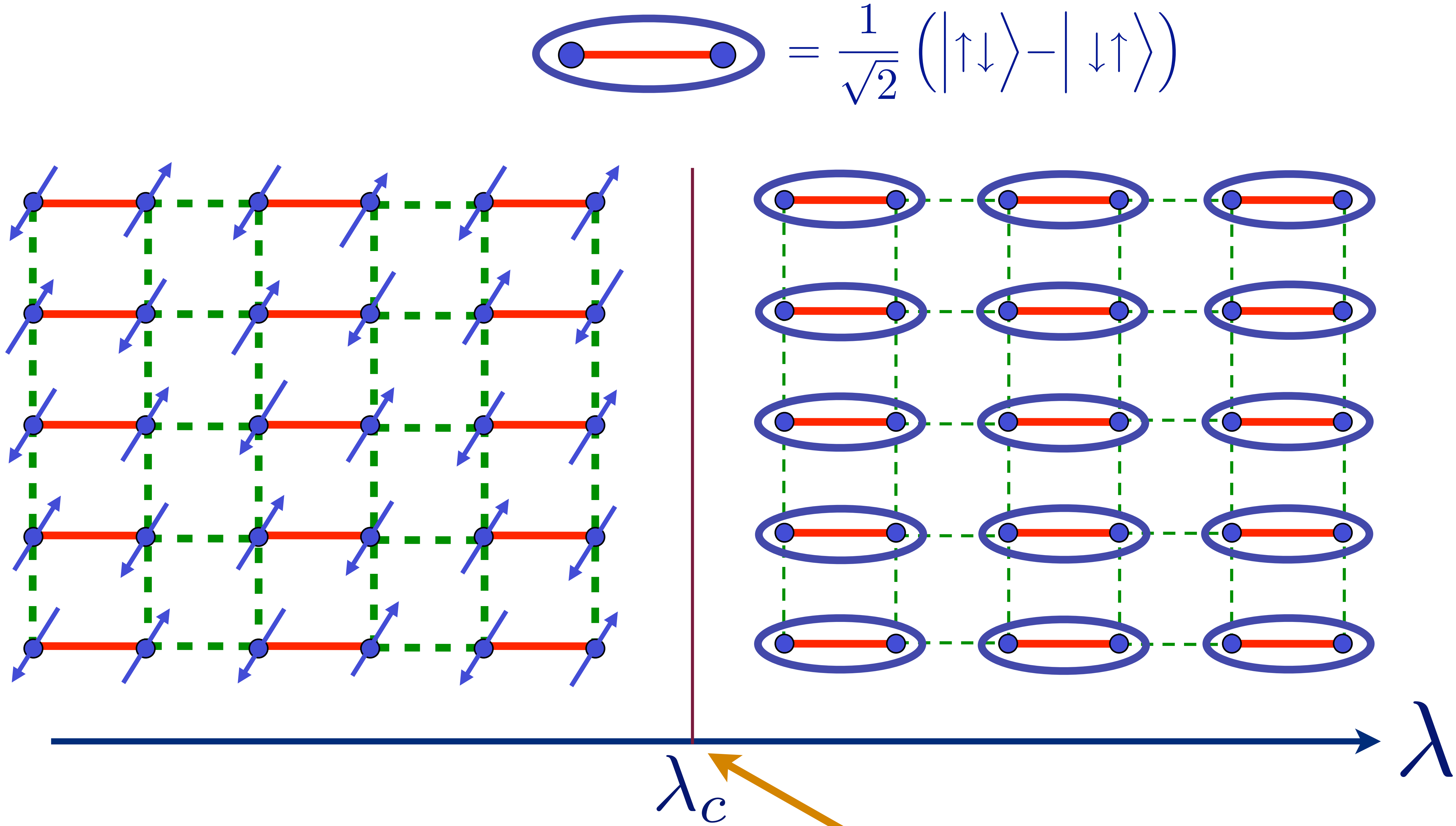
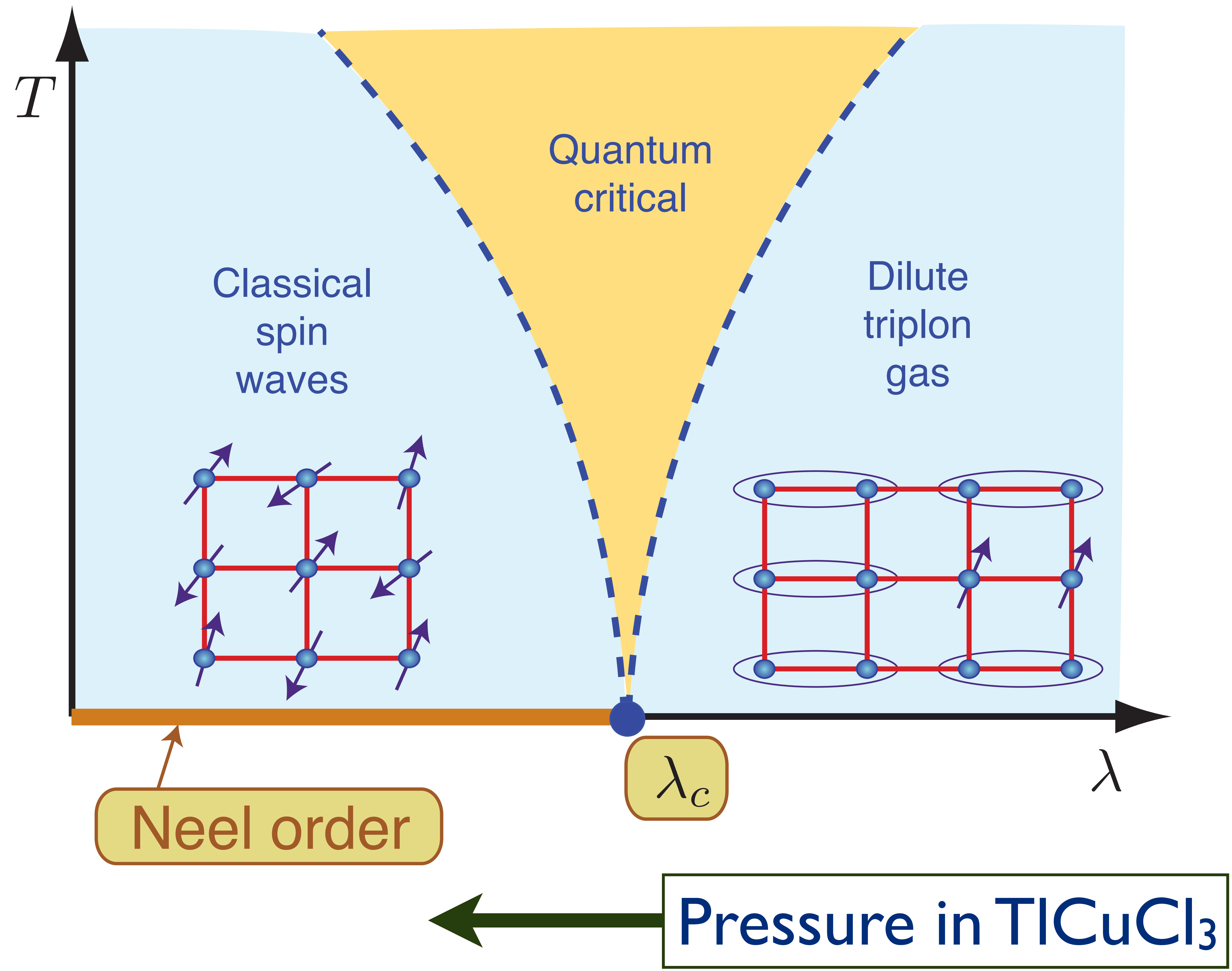
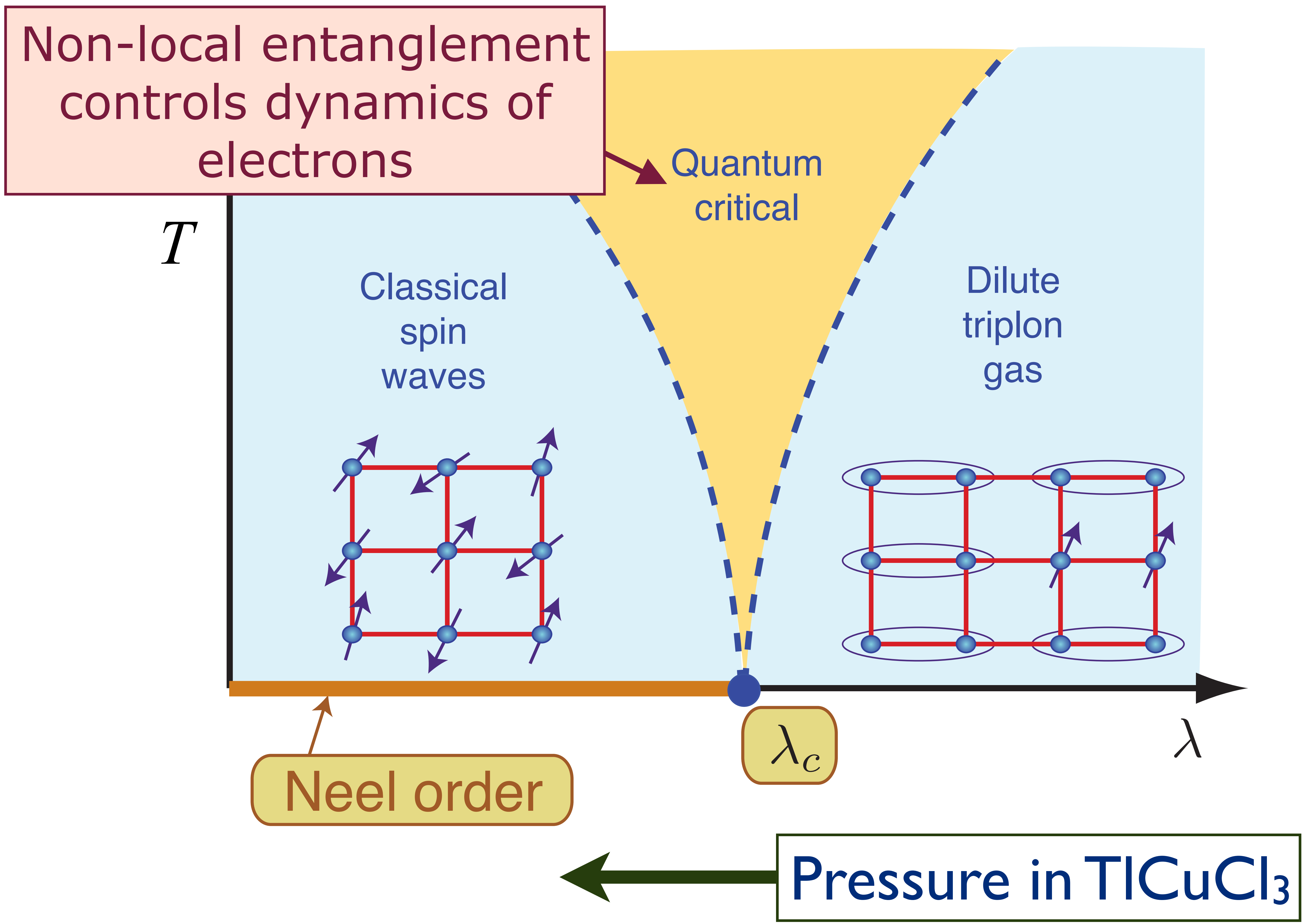




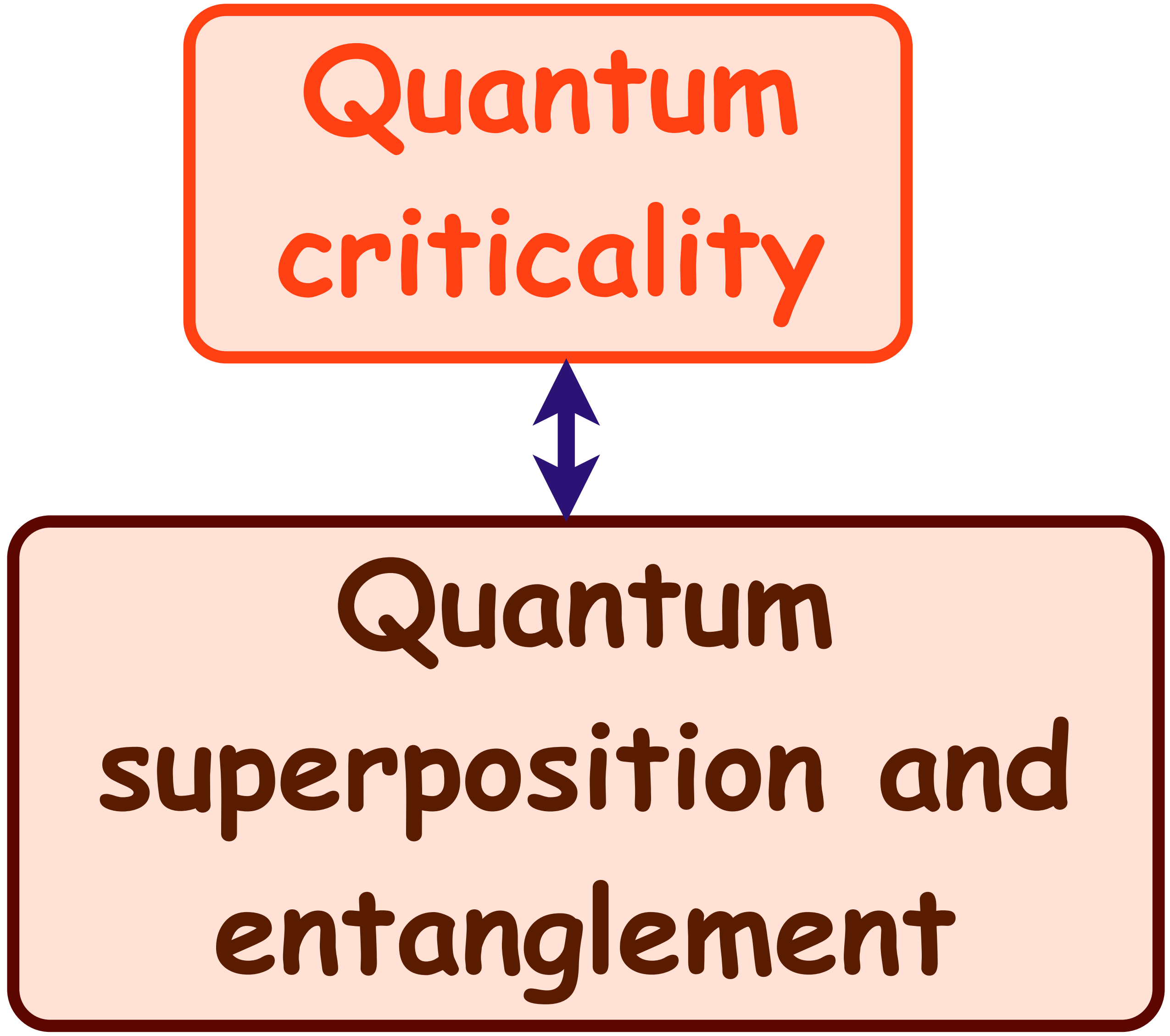
Quantum critical point with non-local entanglement in spin wavefunction

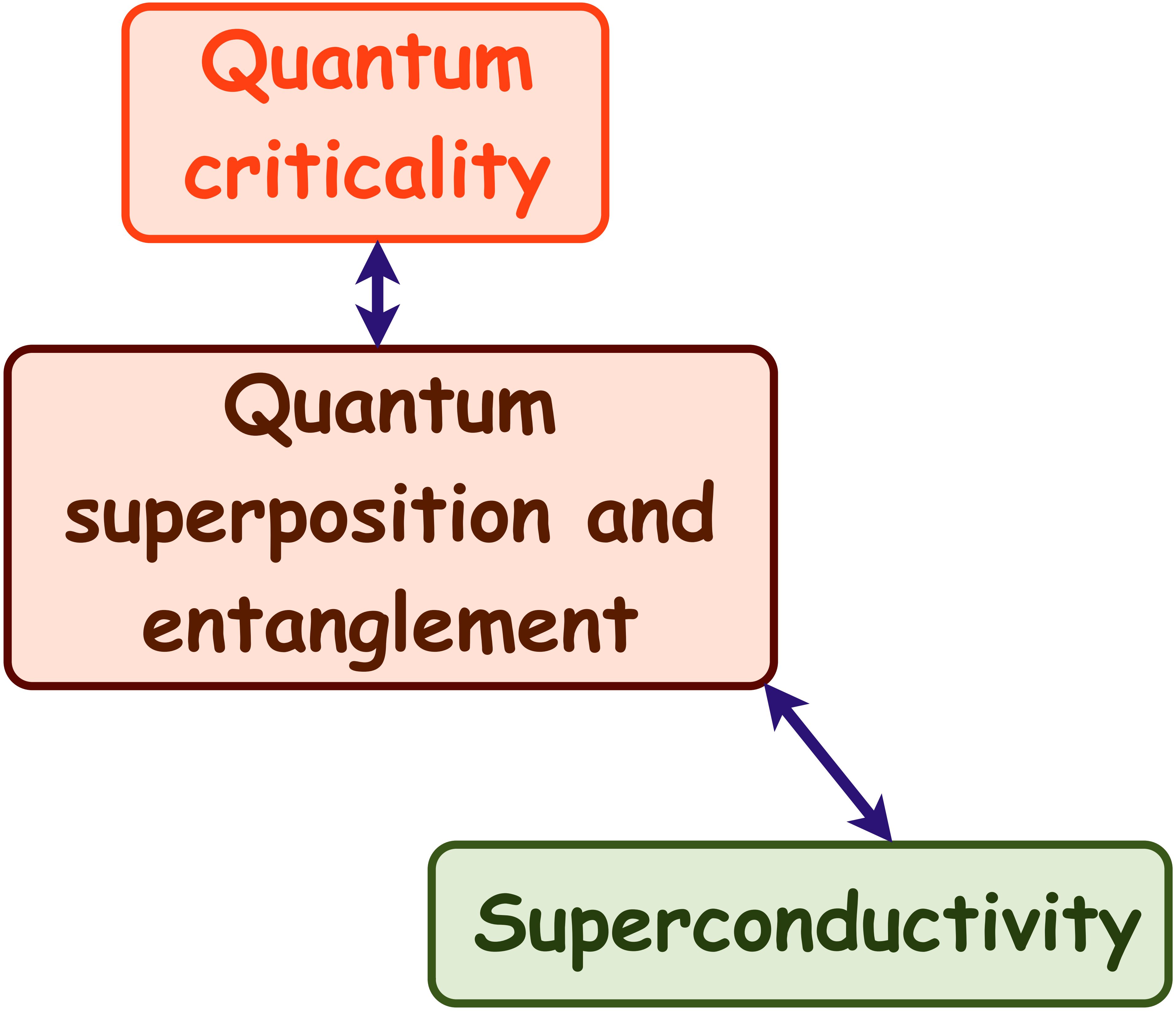


T
Quantum critical
Classical spin waves
Dilute triplon gas
λ_c
λ
Neel order
Pressure in $TlCuCl_3$

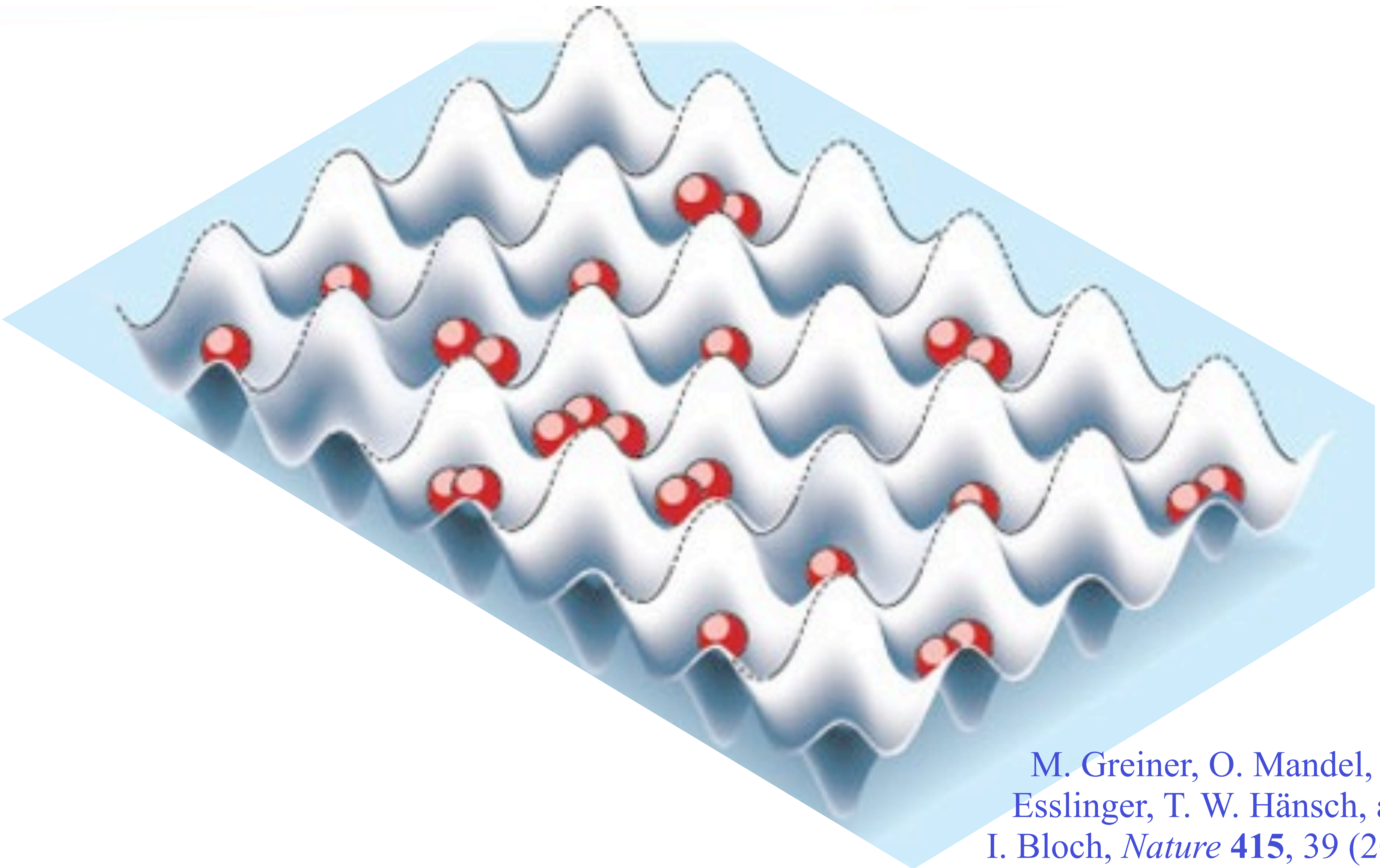


Non-local entanglement controls dynamics of electrons
Quantum critical
T
Classical spin waves
Dilute triplon gas
λ
λc
Neel order
Pressure in TlCuCl3


Quantum criticality
Quantum superposition and entanglement


Quantum criticality
Quantum superposition and entanglement
Superconductivity

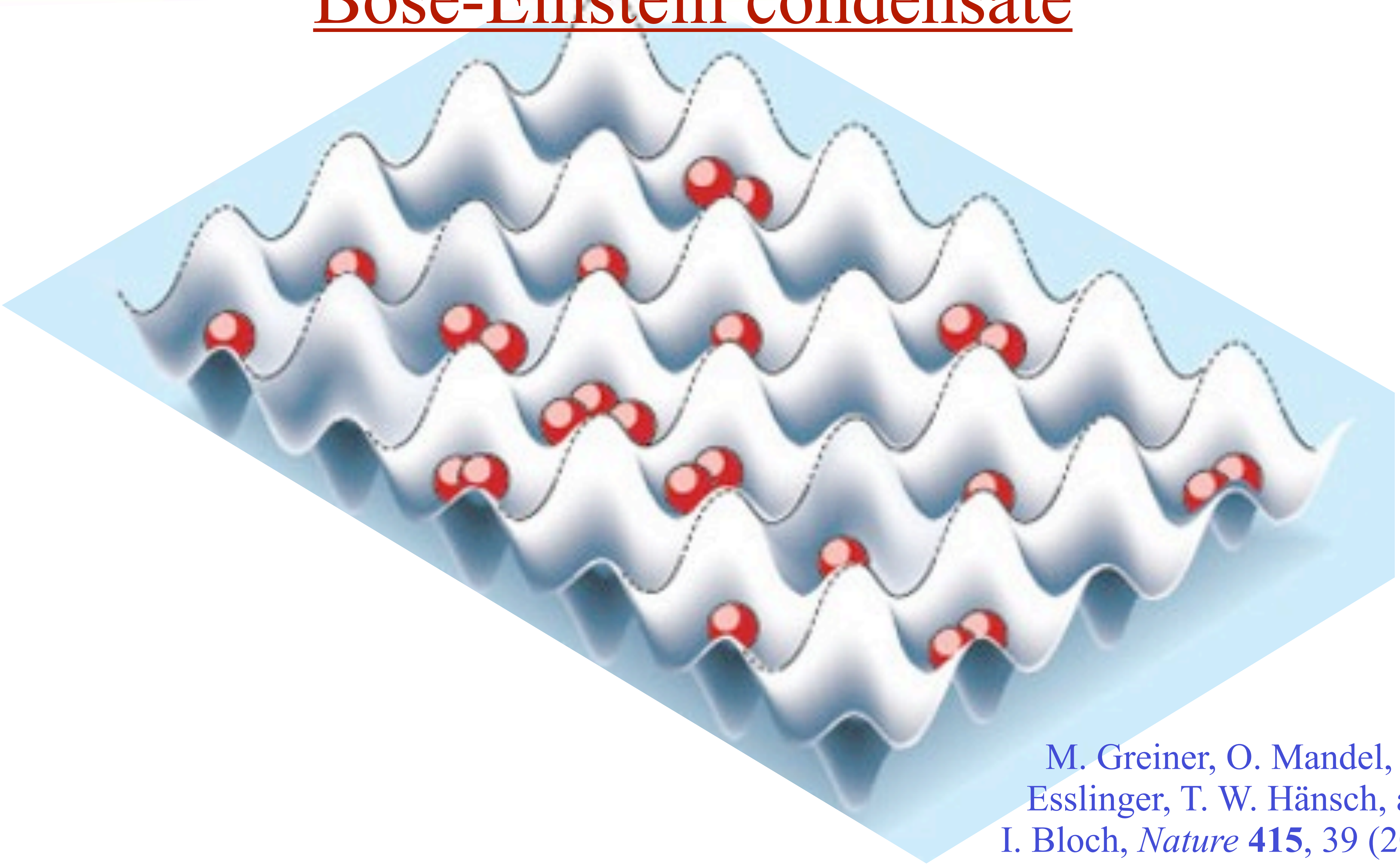
Rubidium atoms in a magnetic trap and standing waves of laser light



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

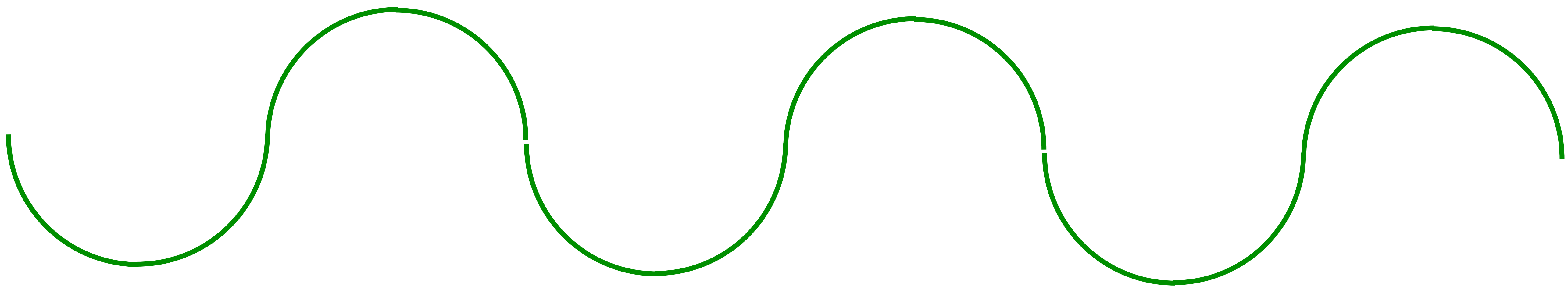
Bose-Einstein condensate

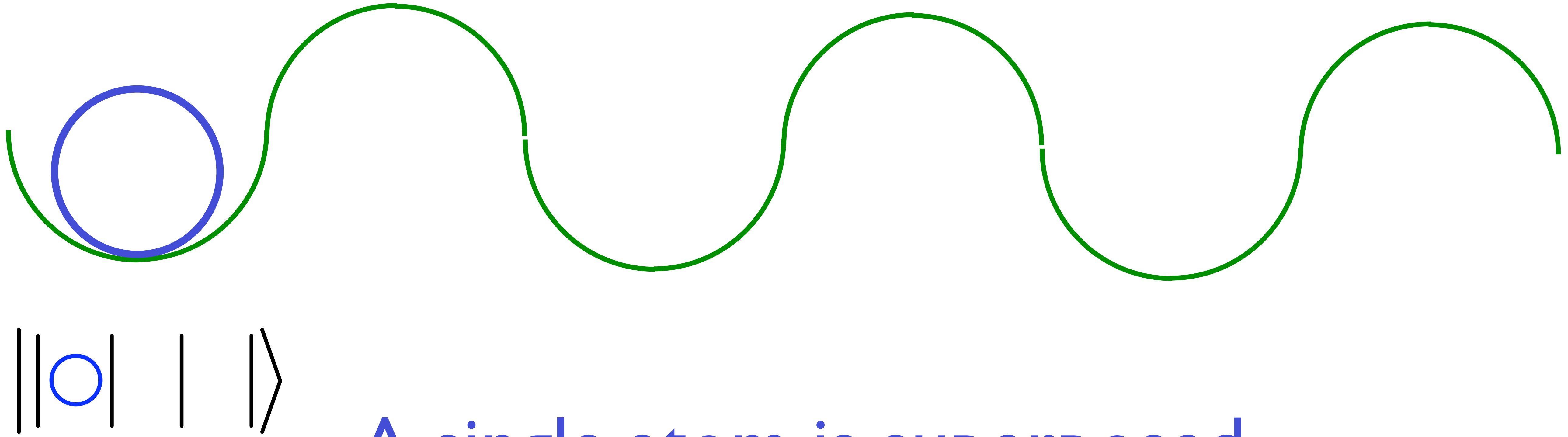


M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

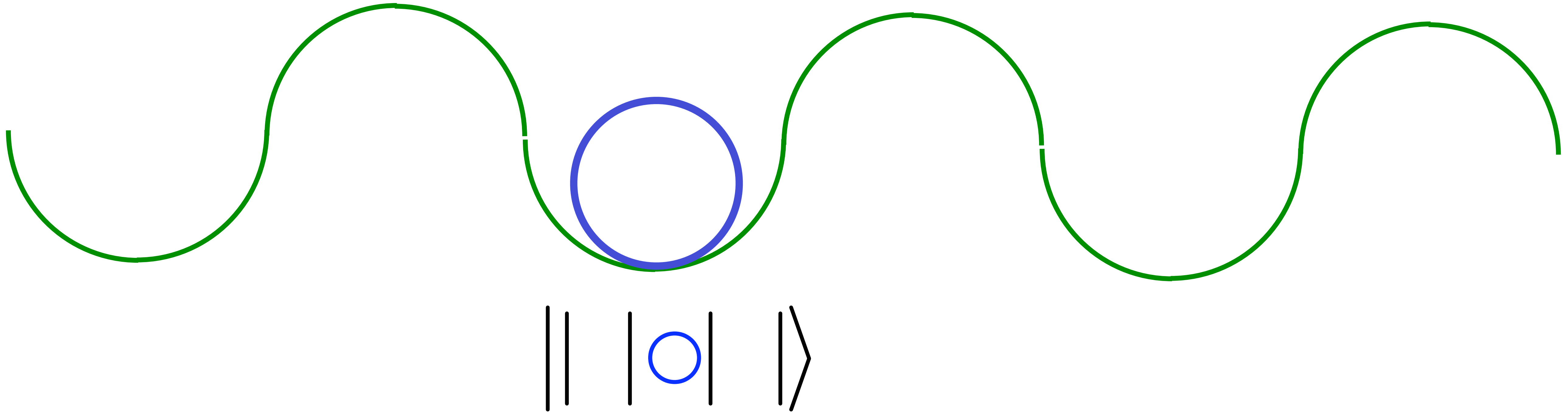
A Bose-Einstein condensate:
An quantum superposition of all the atoms in all positions

A liquid which flows without resistance (a superfluid)





A single atom is superposed between all positions



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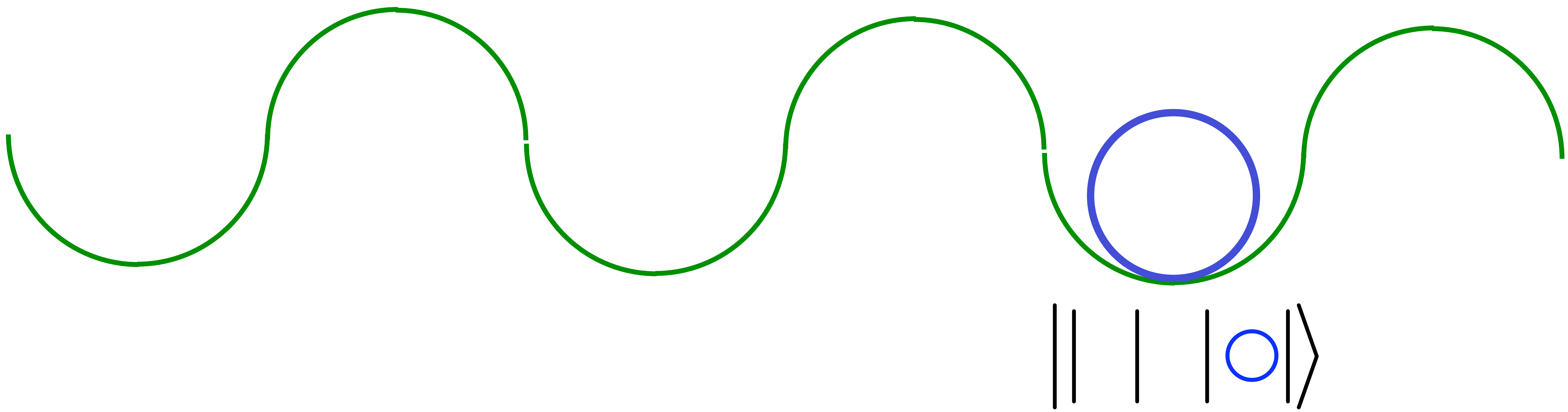

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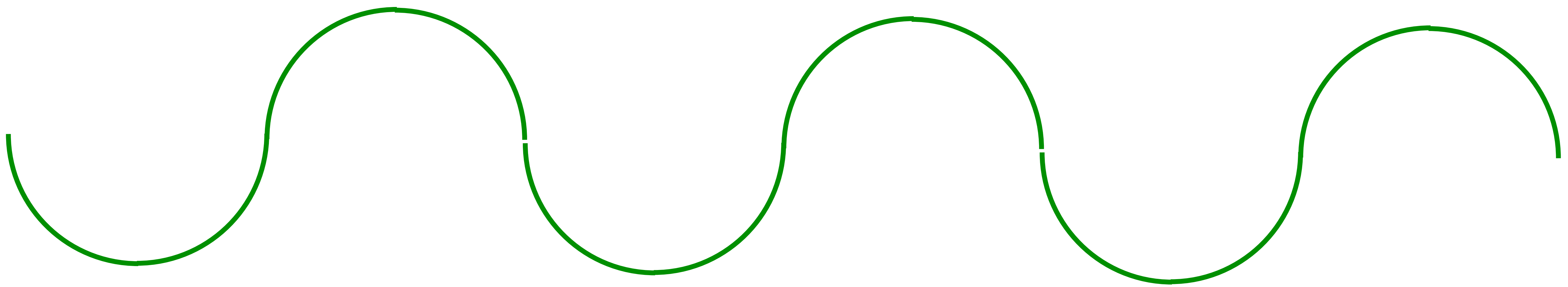


$$|G\rangle = \Big(|\circ|\ \ |\ \ |\rangle + |\ |\ \ |\circ|\ \ |\rangle + |\ |\ \ |\ \ |\circ|\rangle \Big)$$

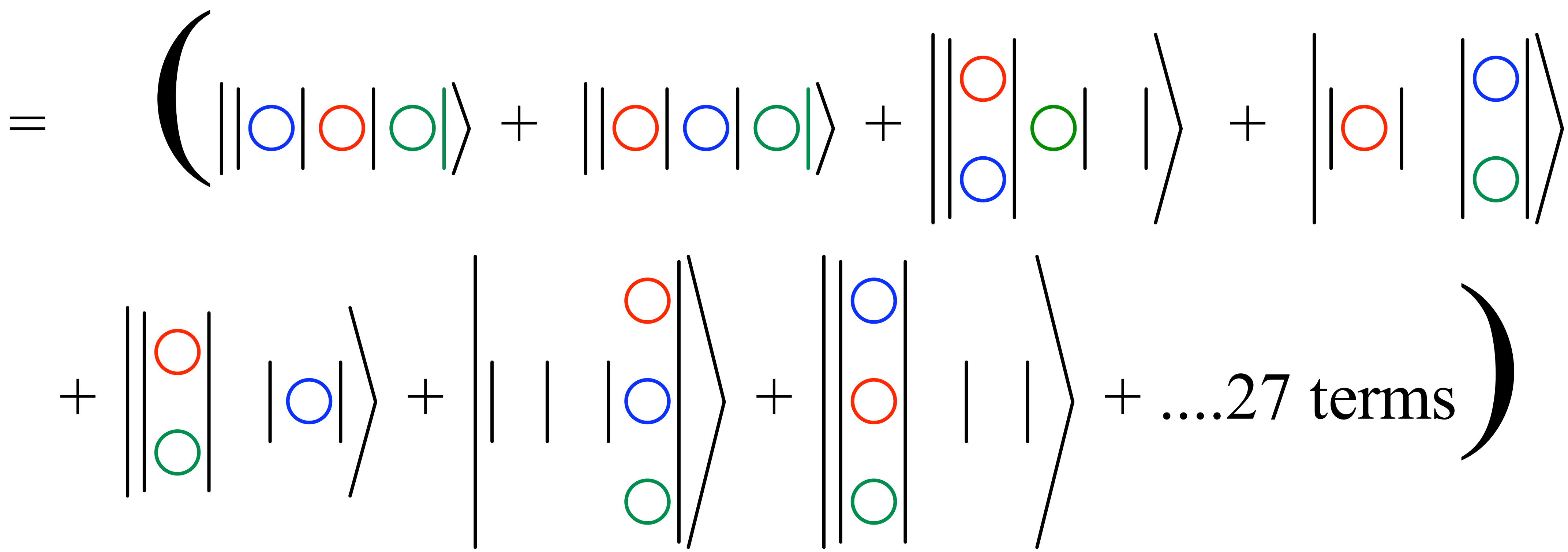
A single atom is superposed
between all positions

Bose-Einstein condensate: superposition between all atoms

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

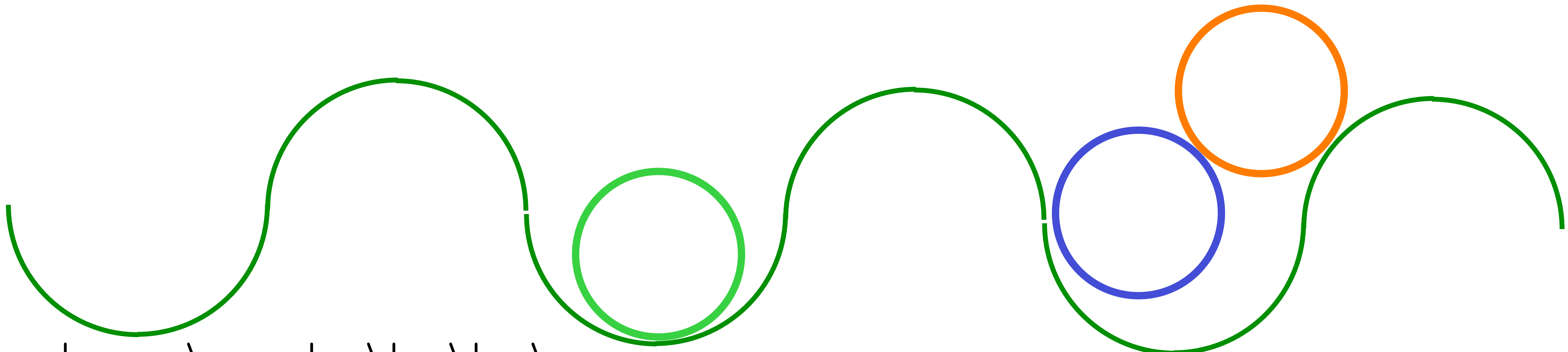
Bose-Einstein condensate: superposition between all atoms

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

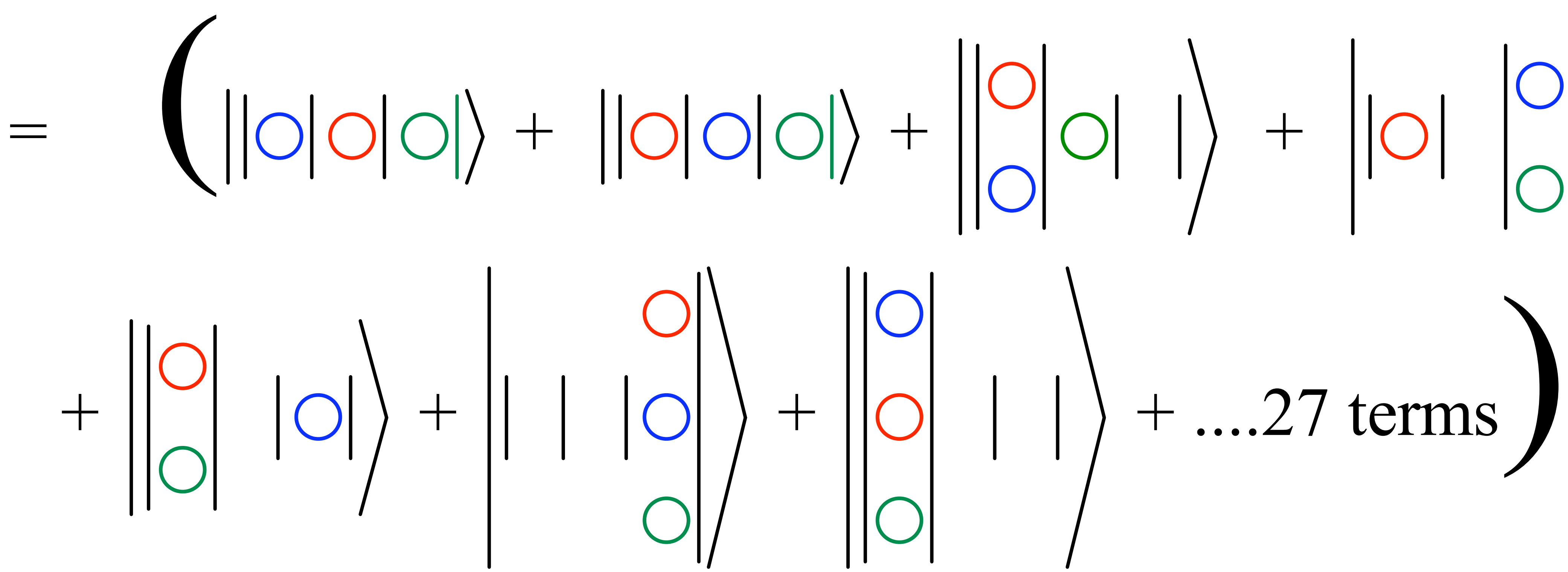


Large fluctuations in number of atoms in each site –
superfluidity (atoms can “flow” without dissipation)

Bose-Einstein condensate: superposition between all atoms

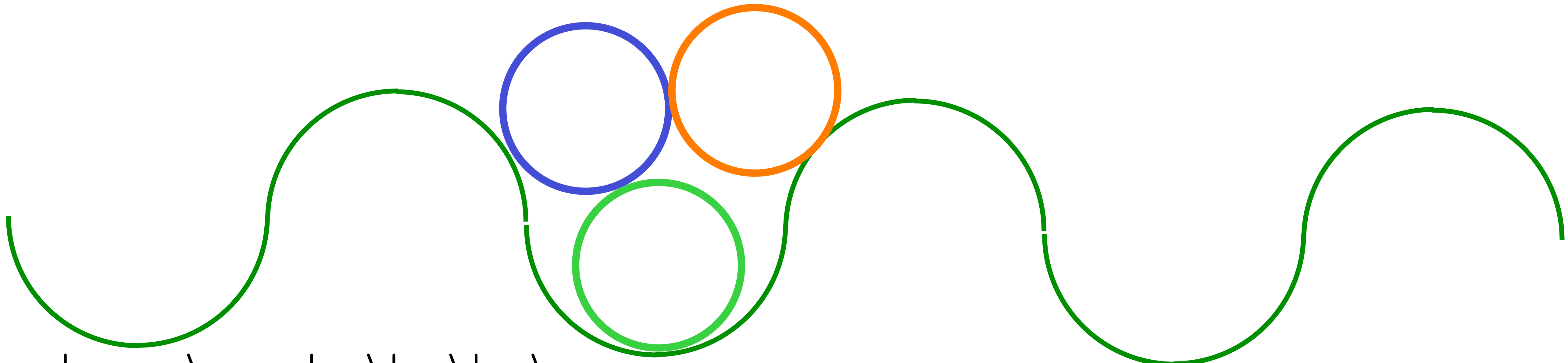


$$|\mathrm{BEC}\rangle = |\mathrm{G}\rangle|\mathrm{G}\rangle|\mathrm{G}\rangle$$



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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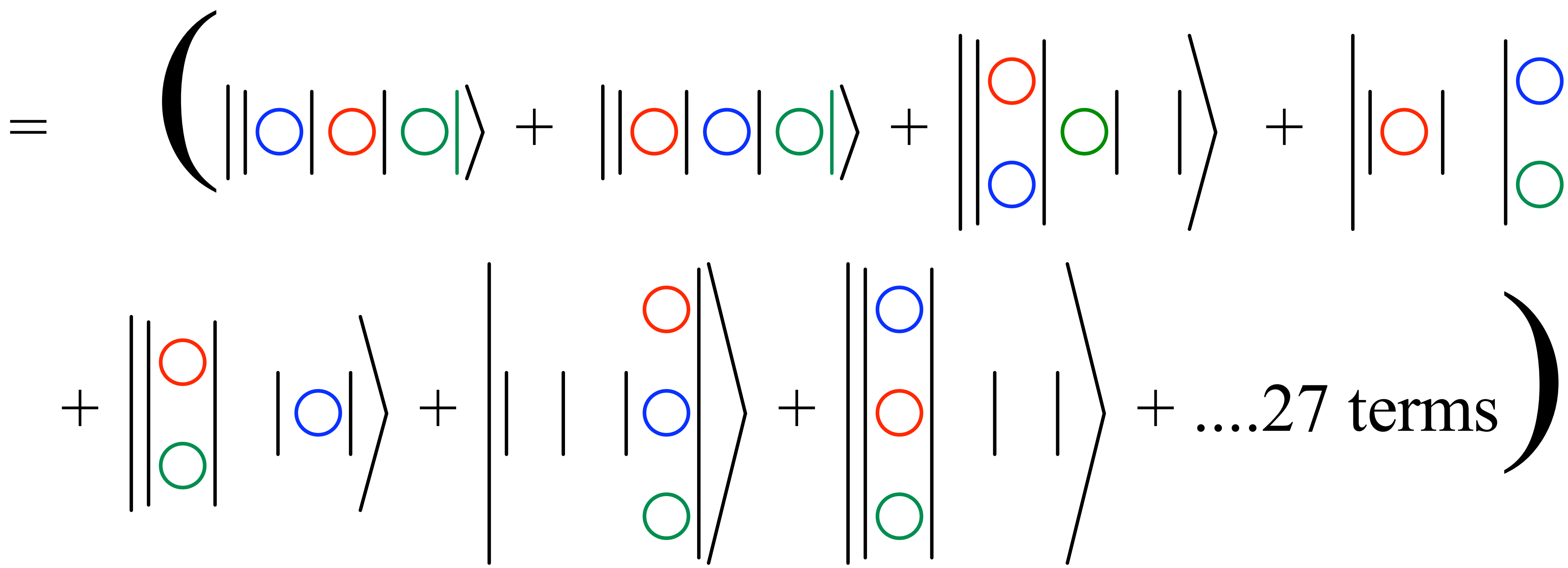

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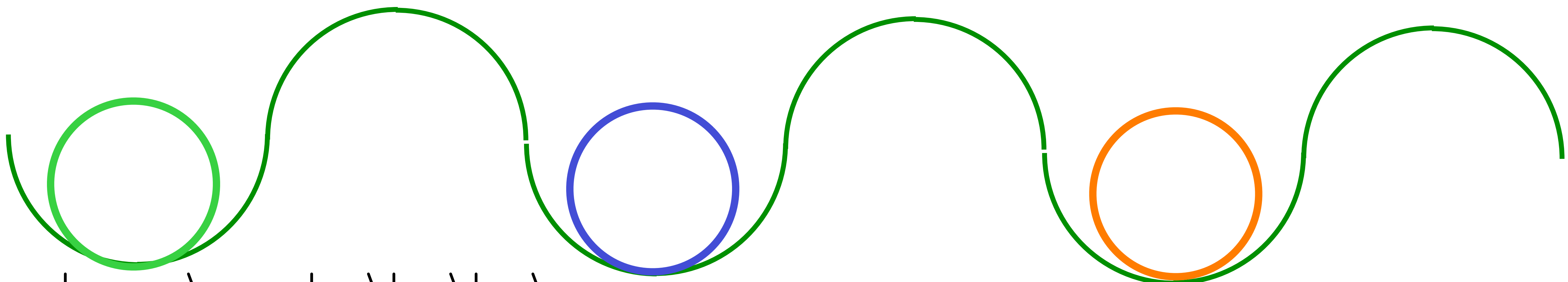

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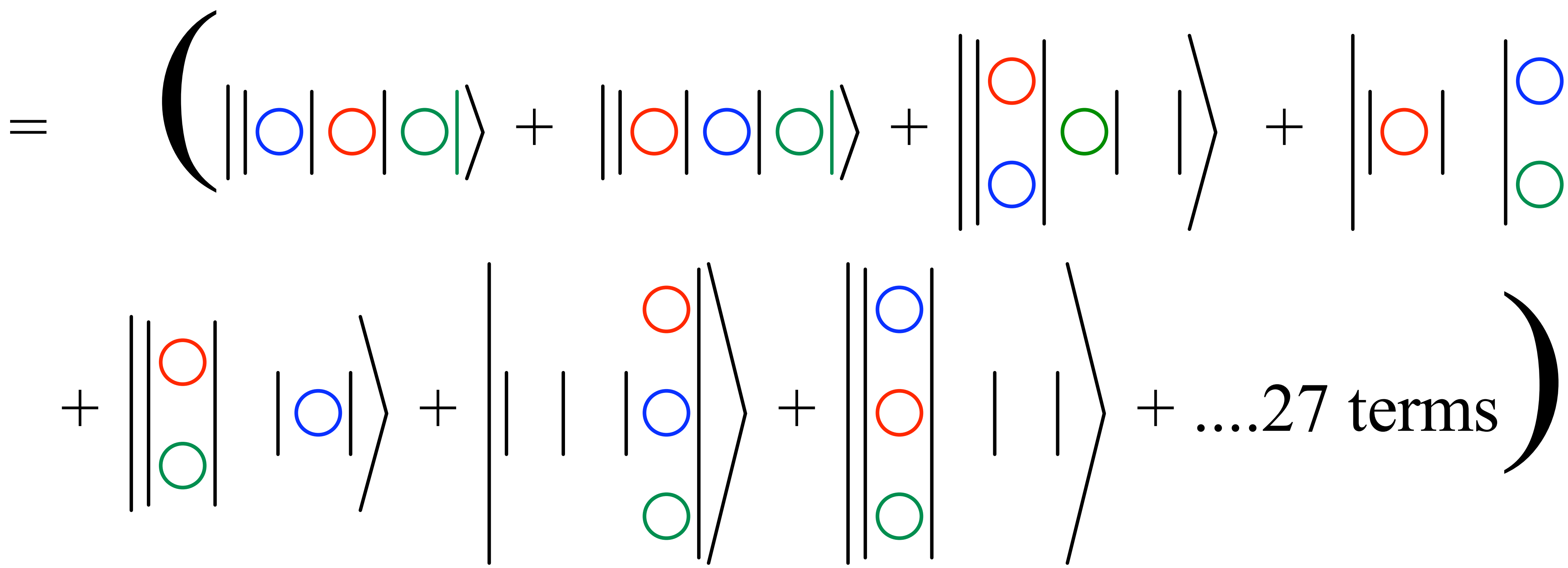

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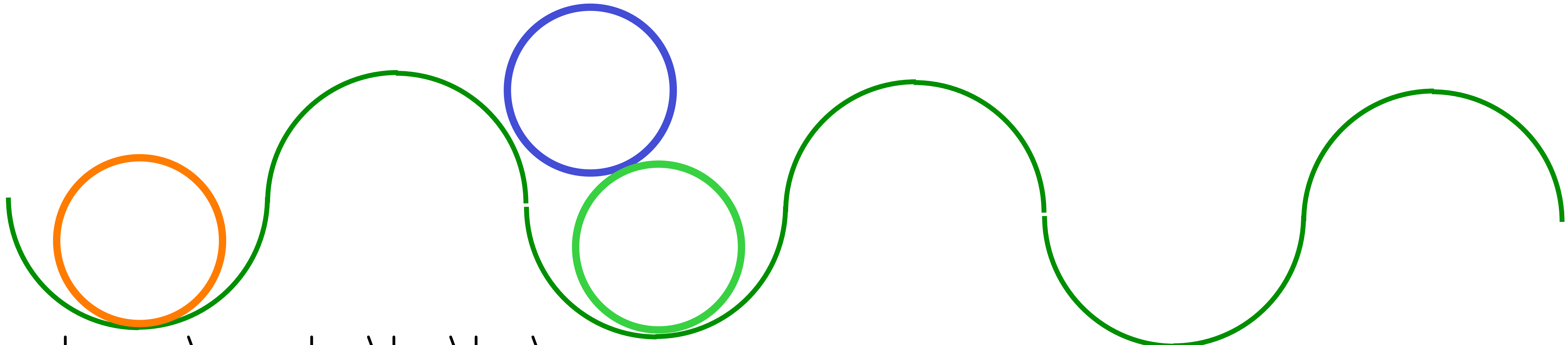

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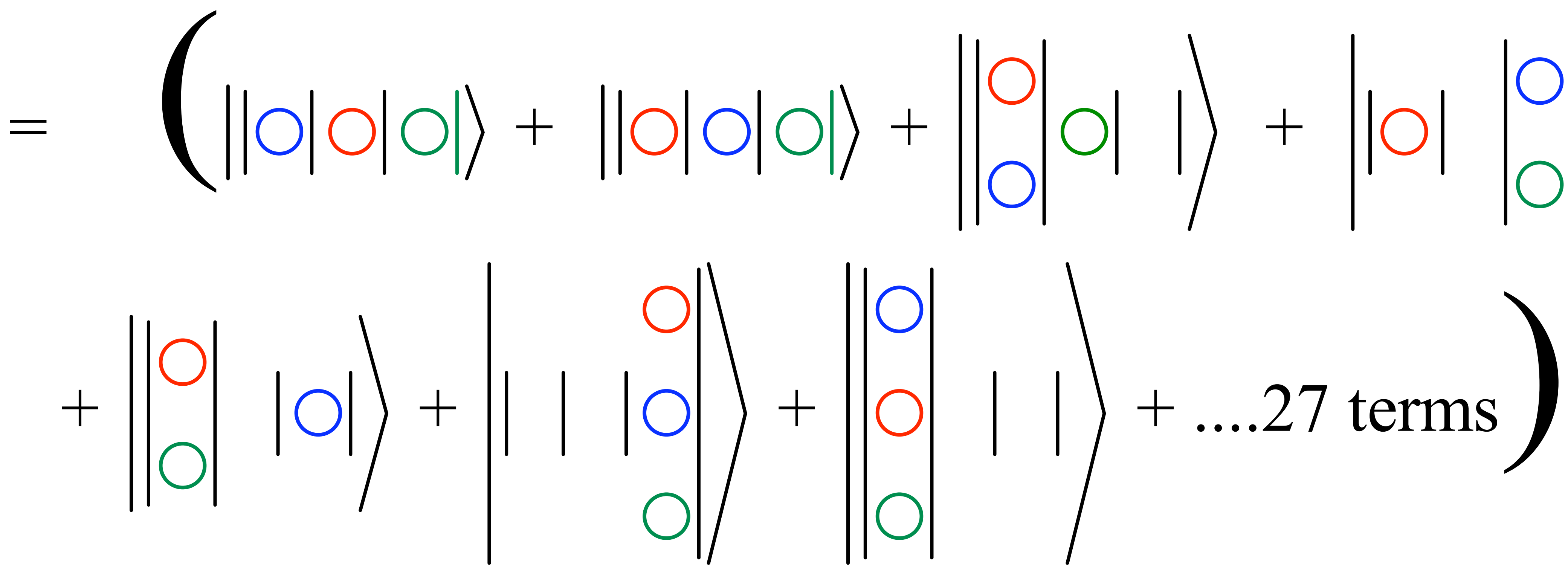

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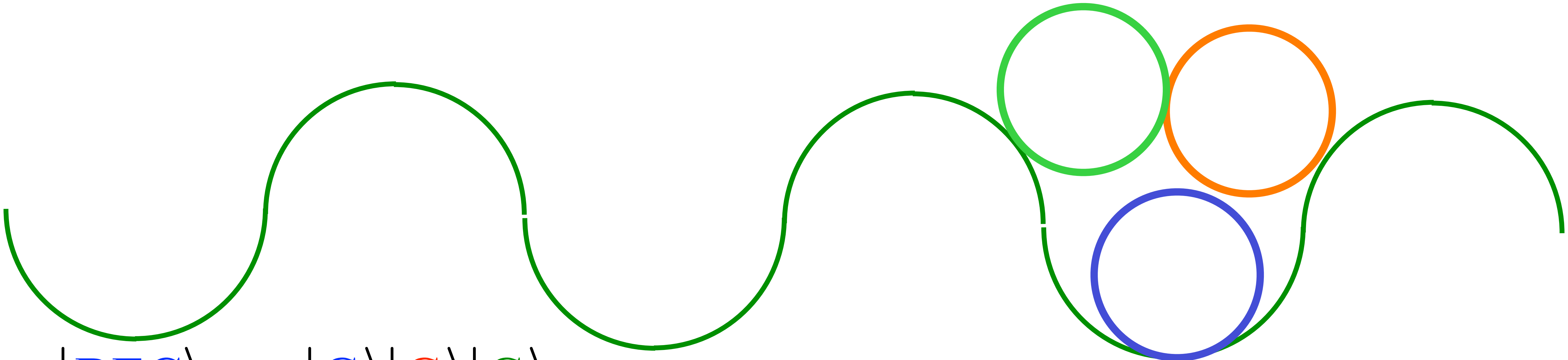

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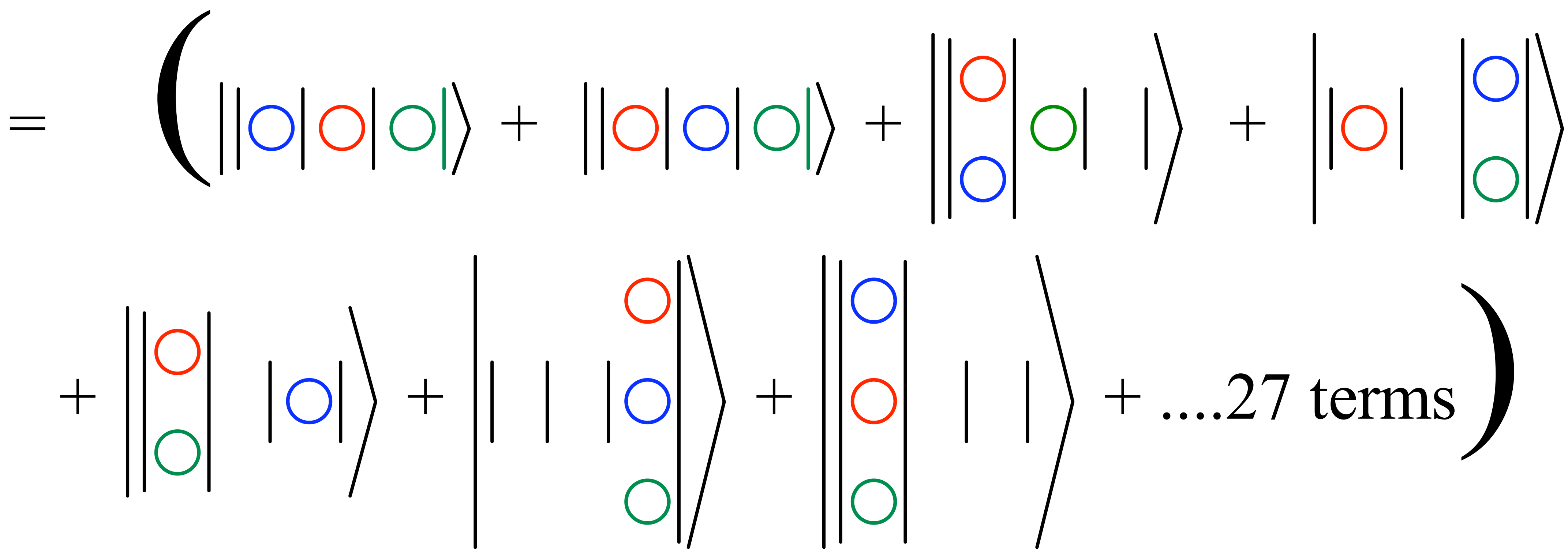

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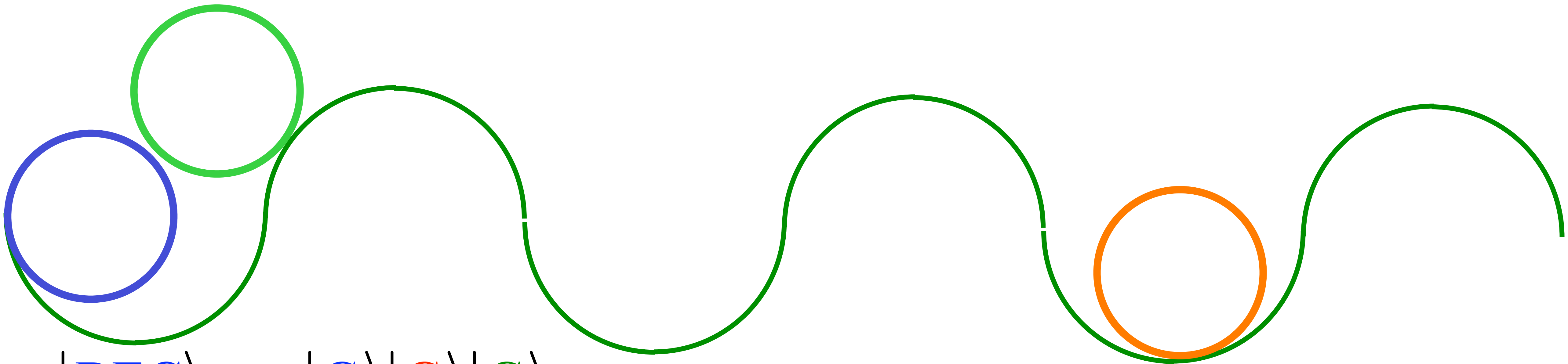

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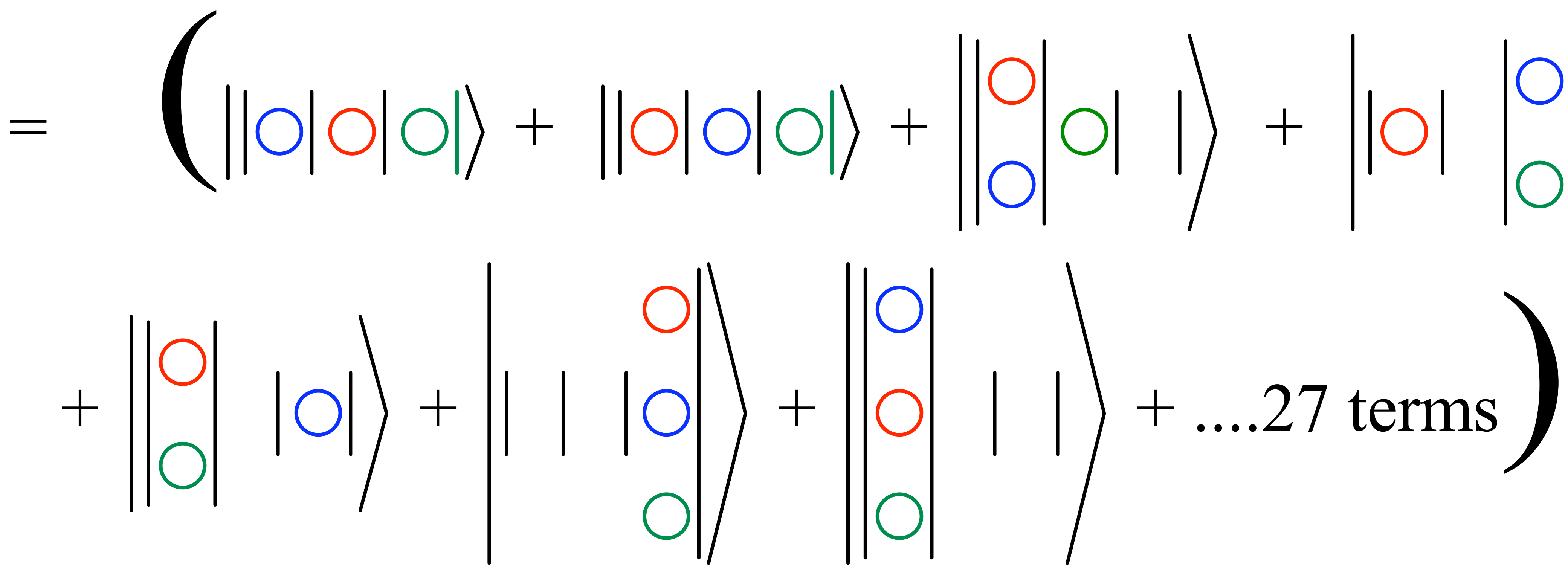
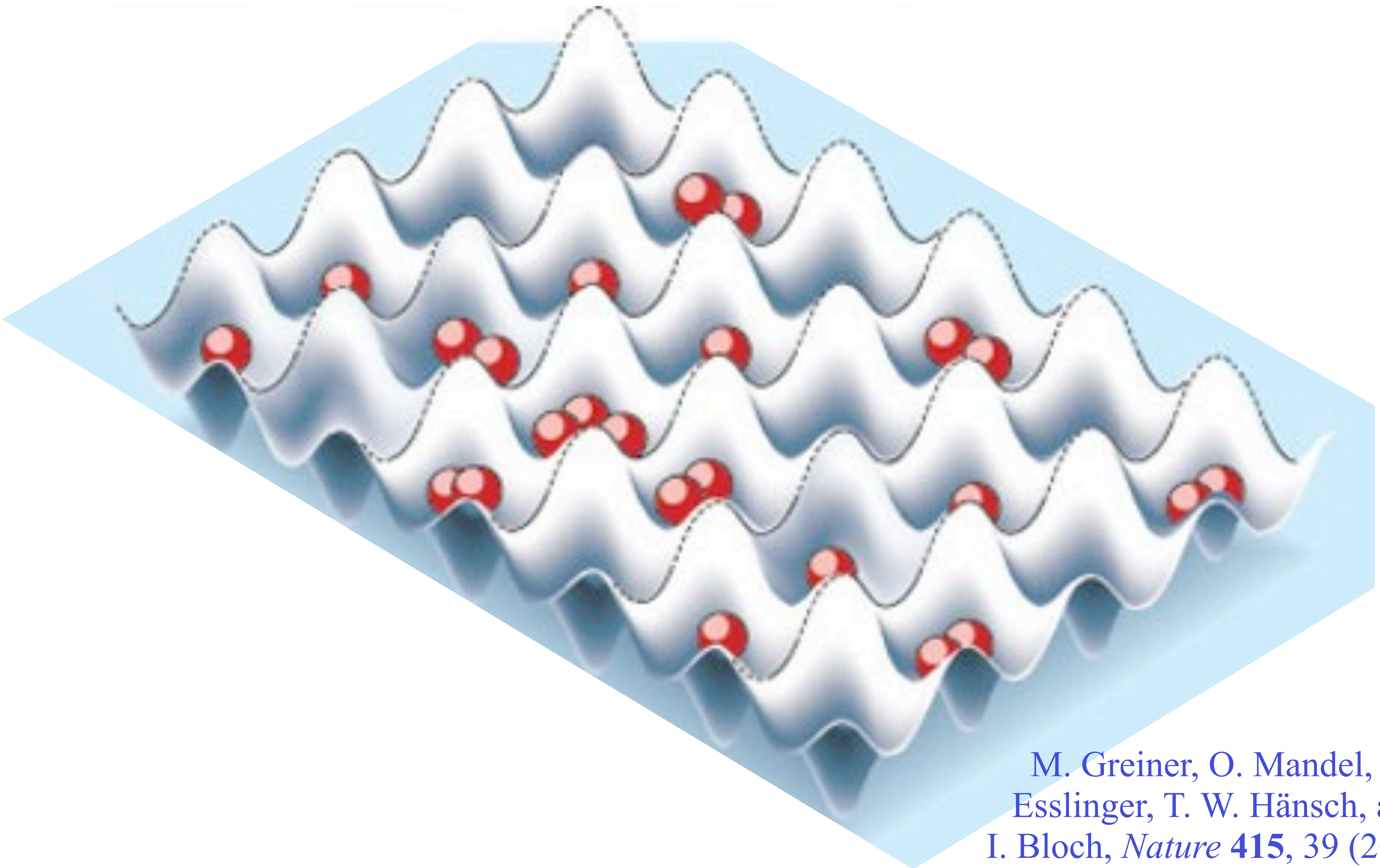


Large fluctuations in number of atoms in each site – *superfluidity* (atoms can “flow” without dissipation)

At very low temperatures and for a weak laser light, the Rubidium atoms form a

<u>Bose-Einstein condensate</u>



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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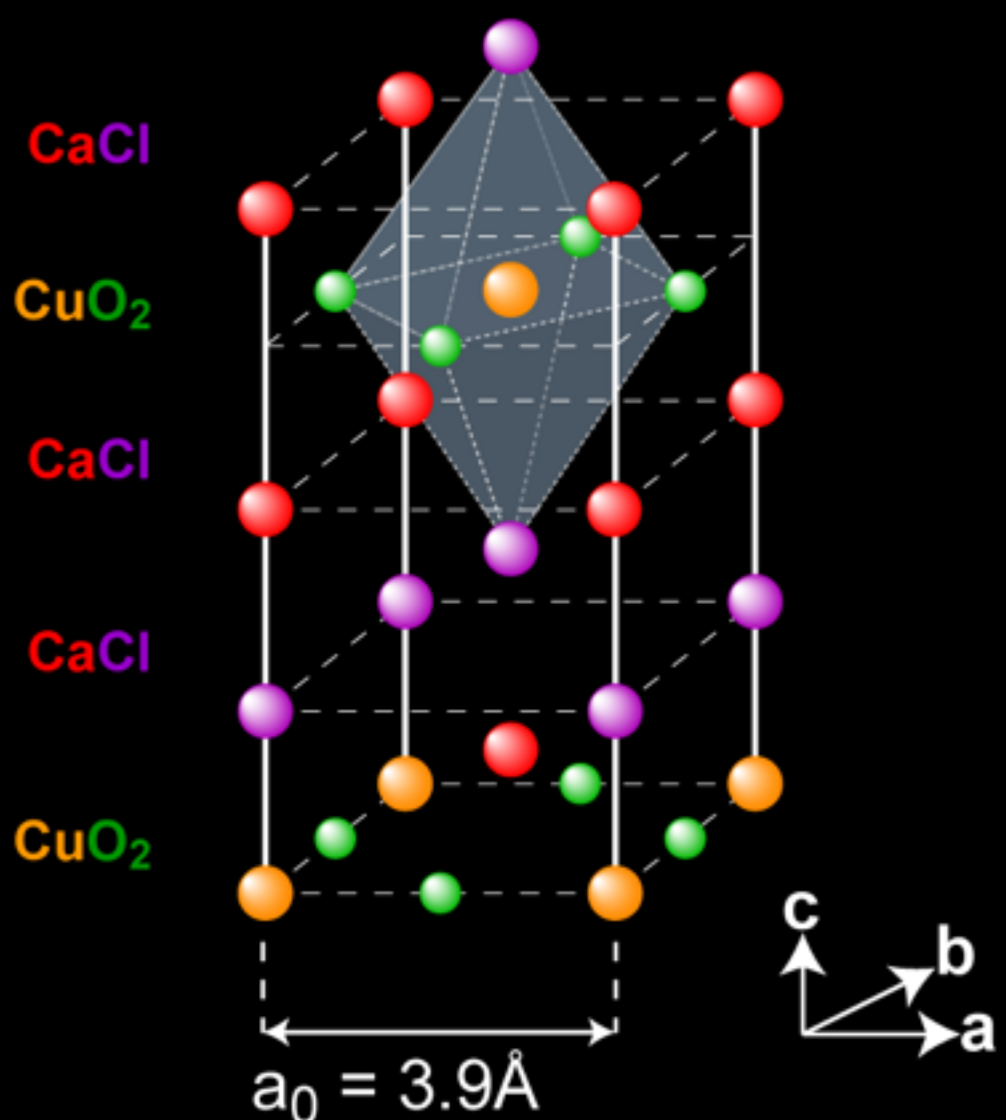
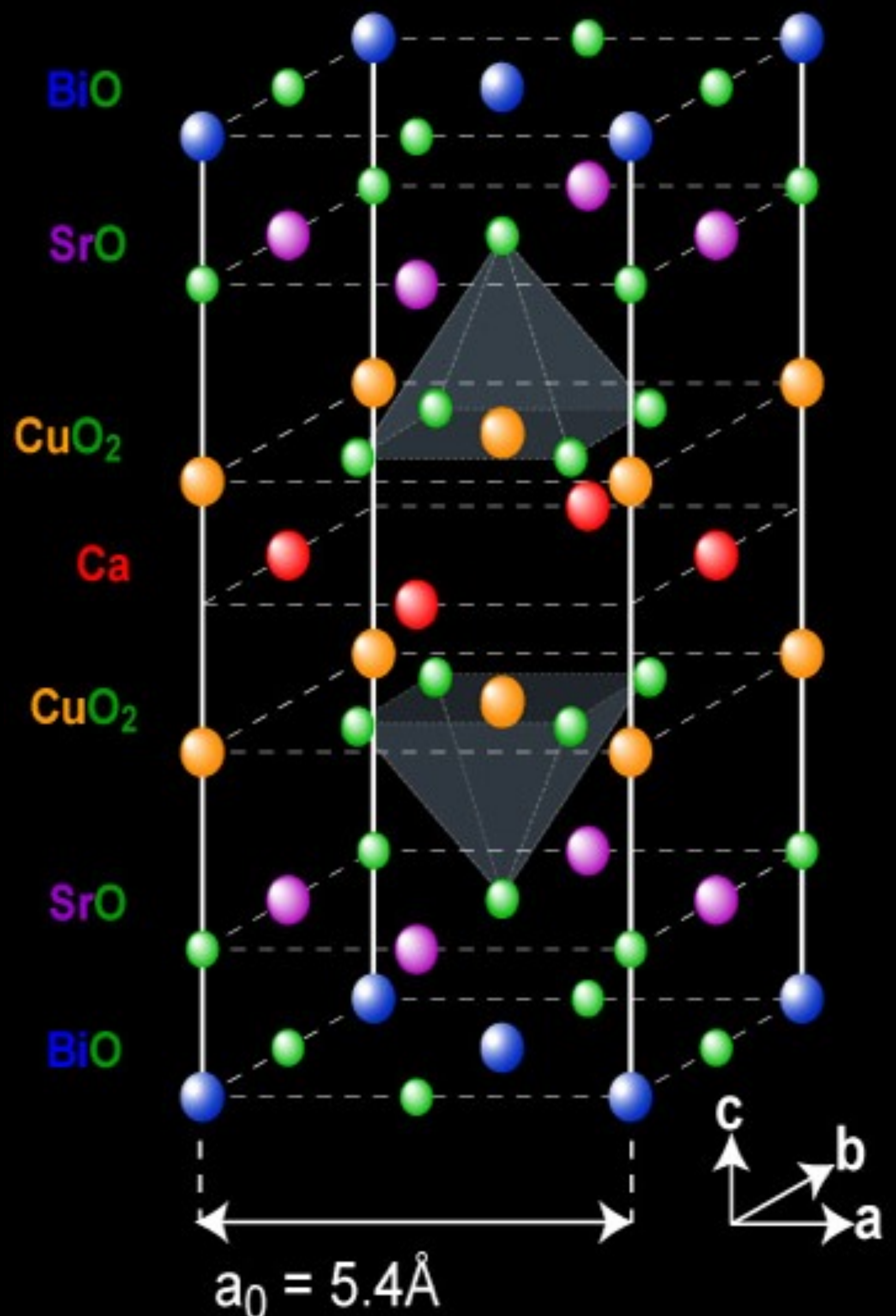
High temperature superconductors

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$

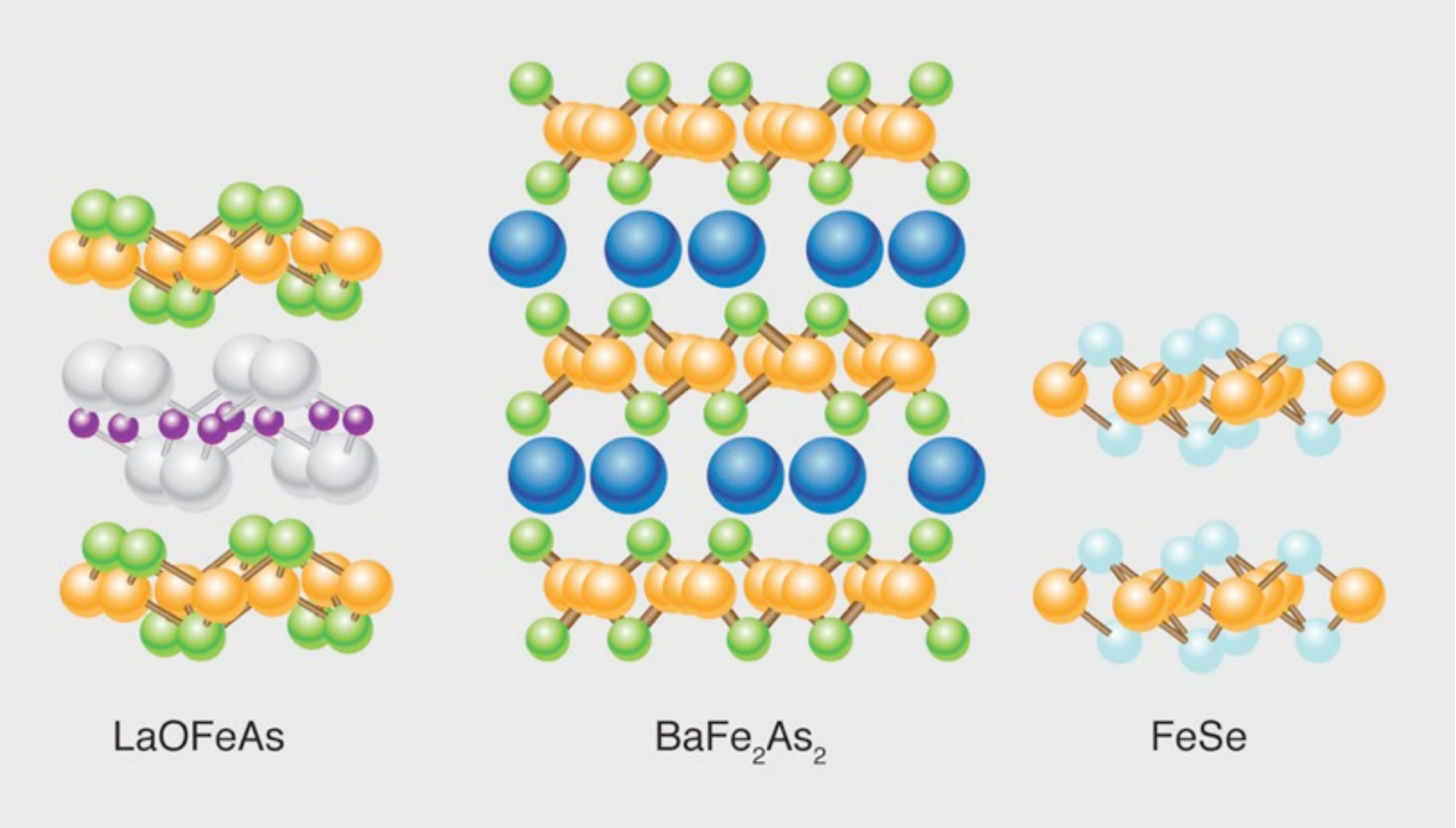


$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$

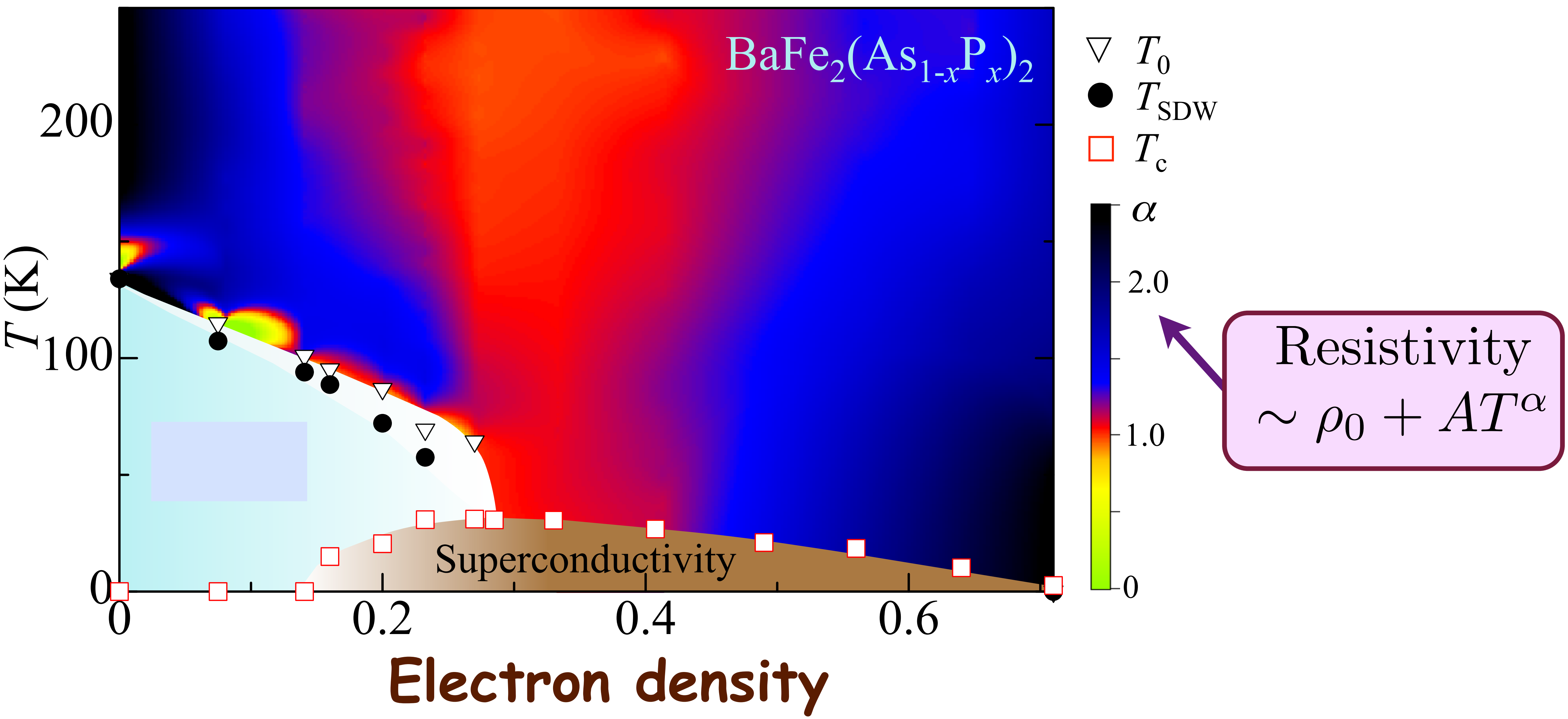


Iron pnictides:

a new class of high temperature superconductors



Temperature-density phase diagram of the iron pnictides:



S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)

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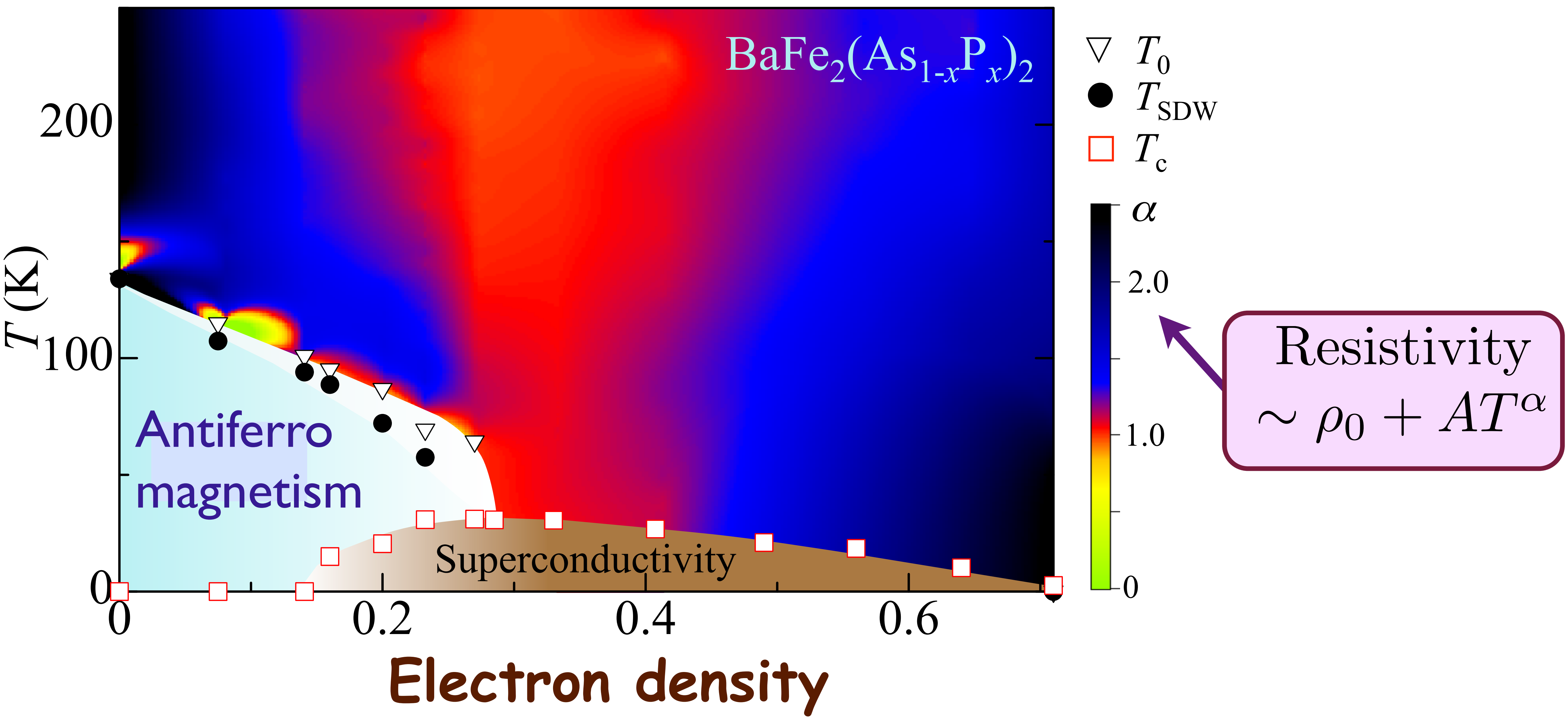

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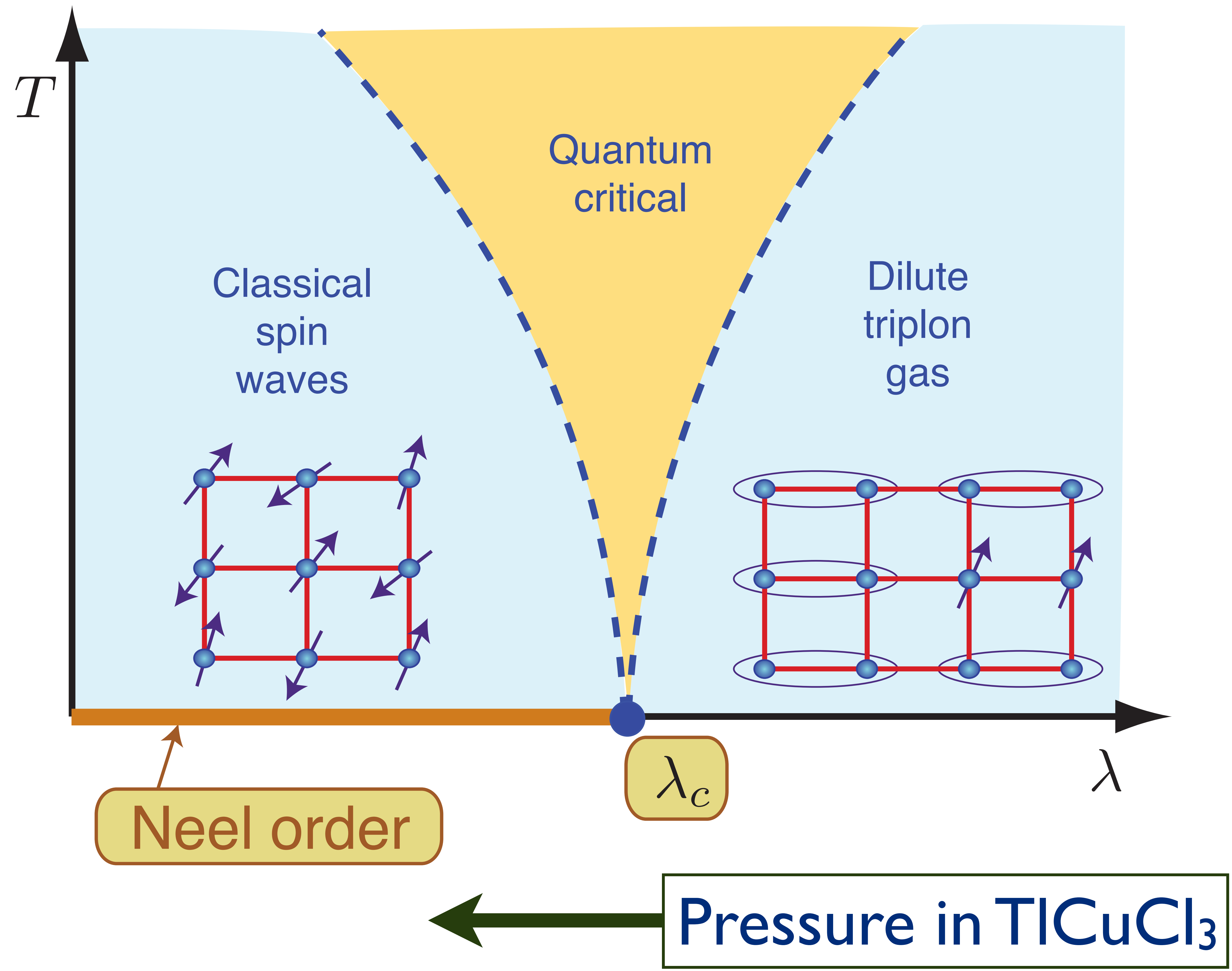
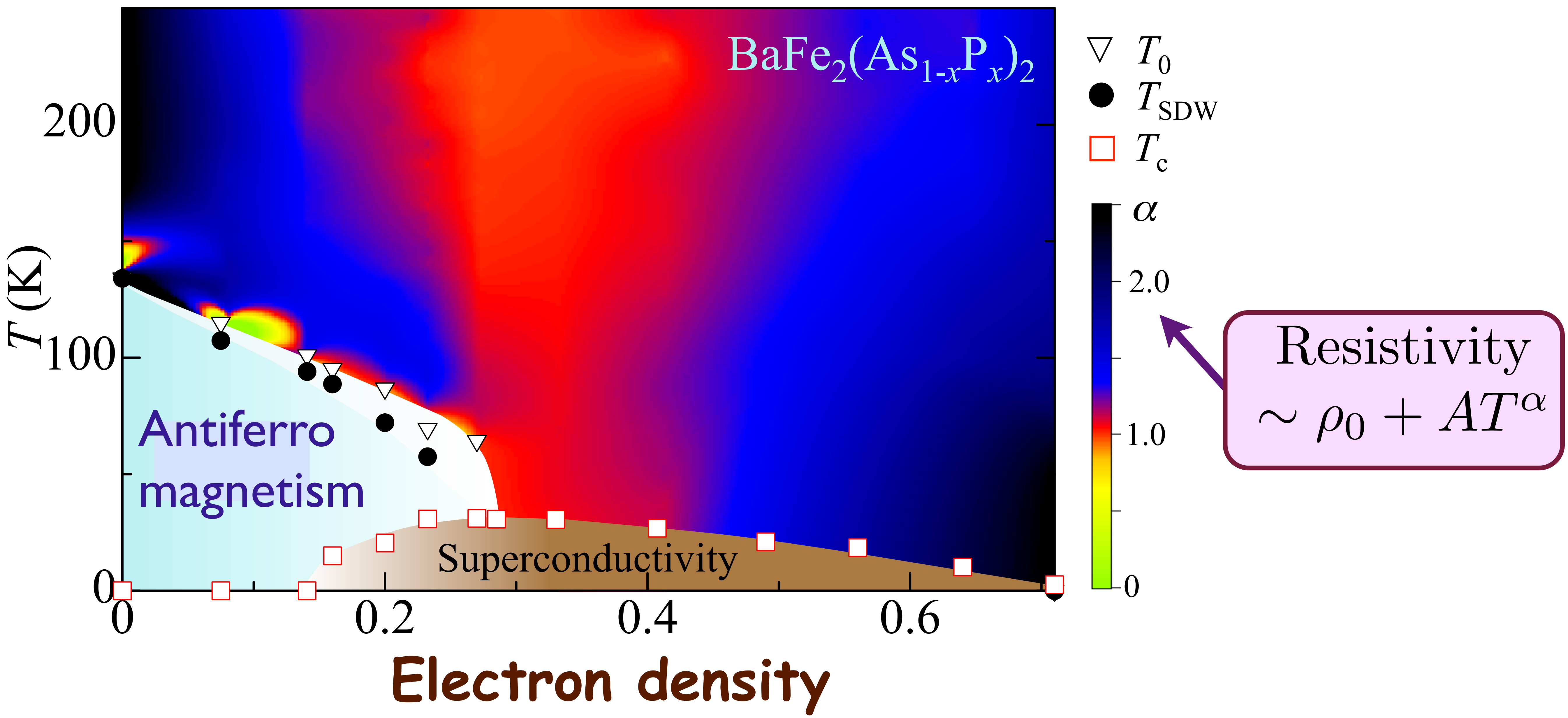


T
Quantum
critical
Classical
spin
waves
Dilute
triplon
gas
λ
λ_c
Neel order
Pressure in TlCuCl3

Temperature-doping phase diagram of the iron pnictides:



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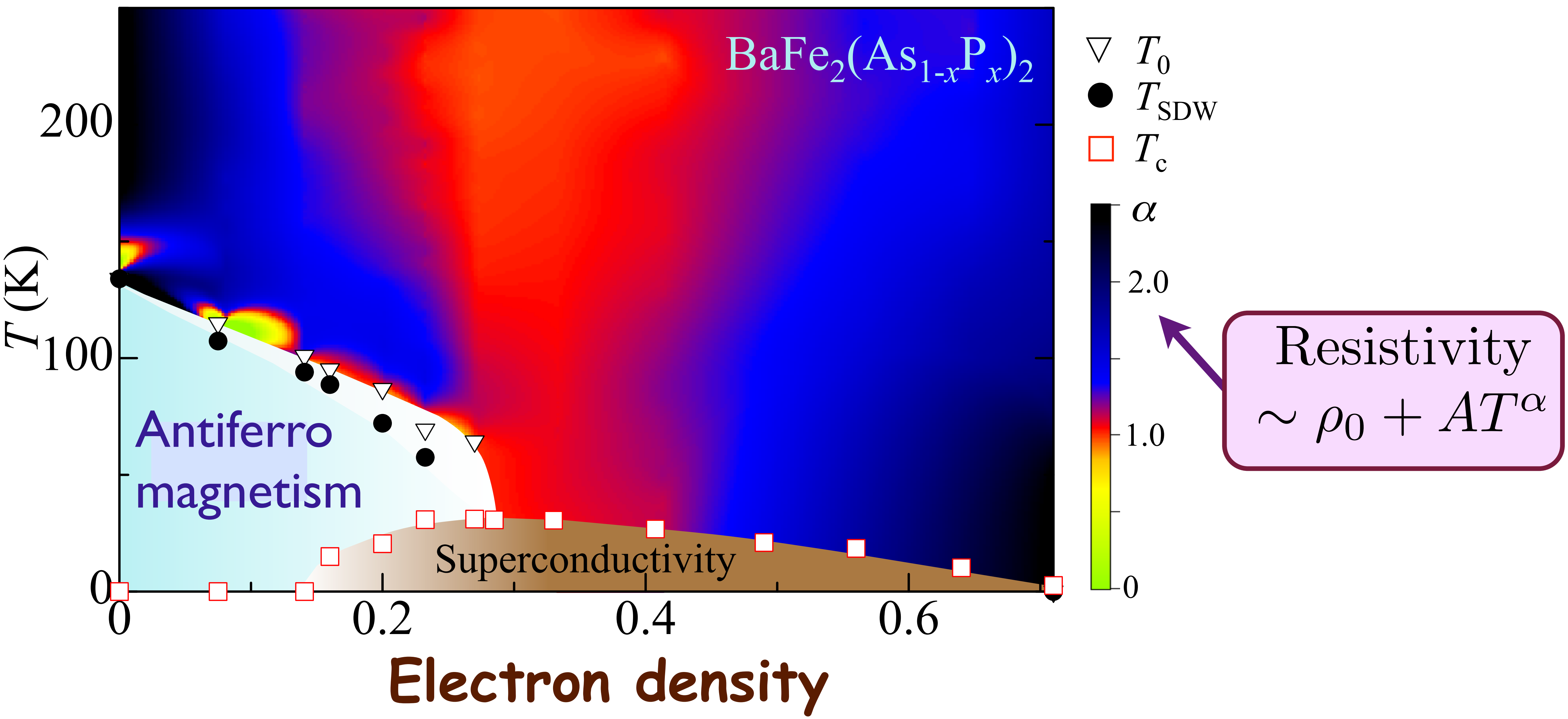

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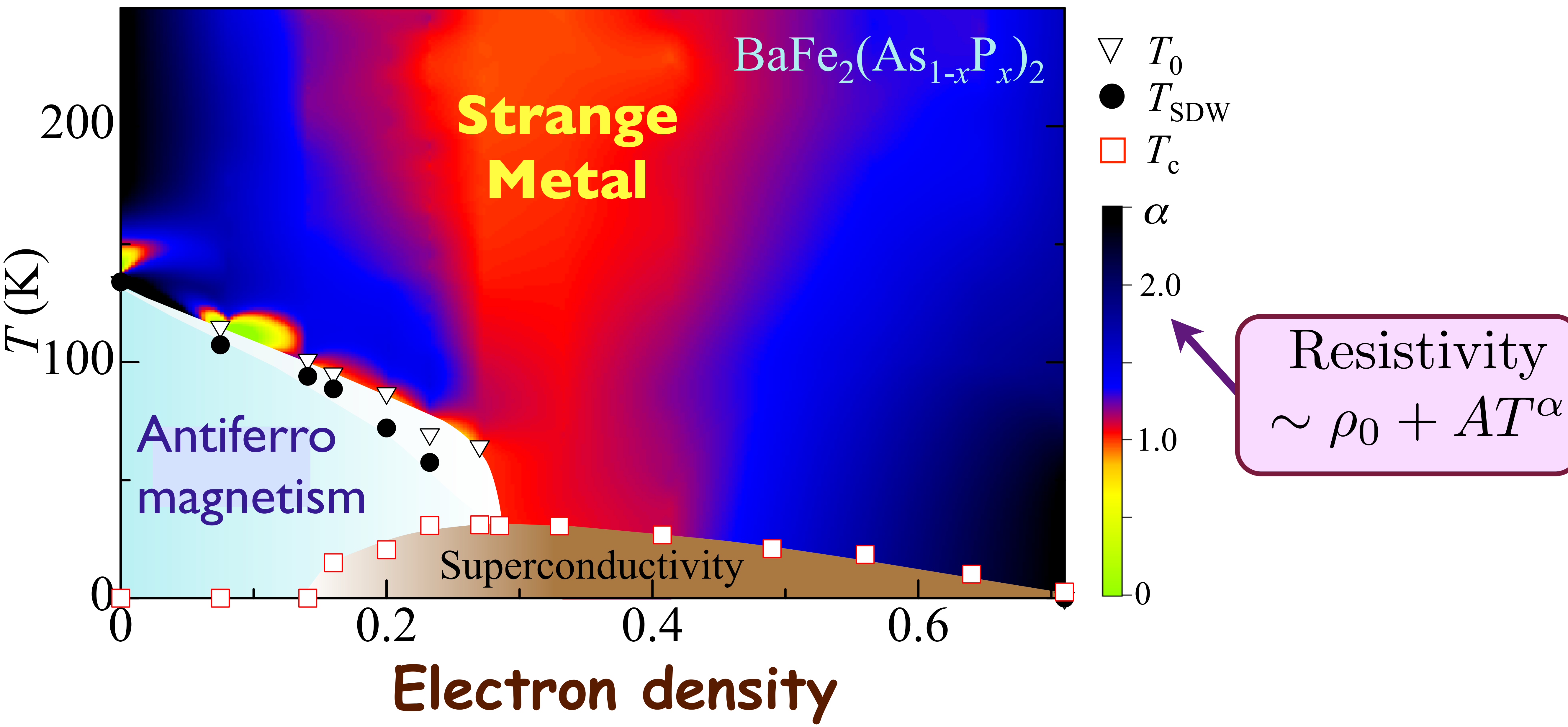

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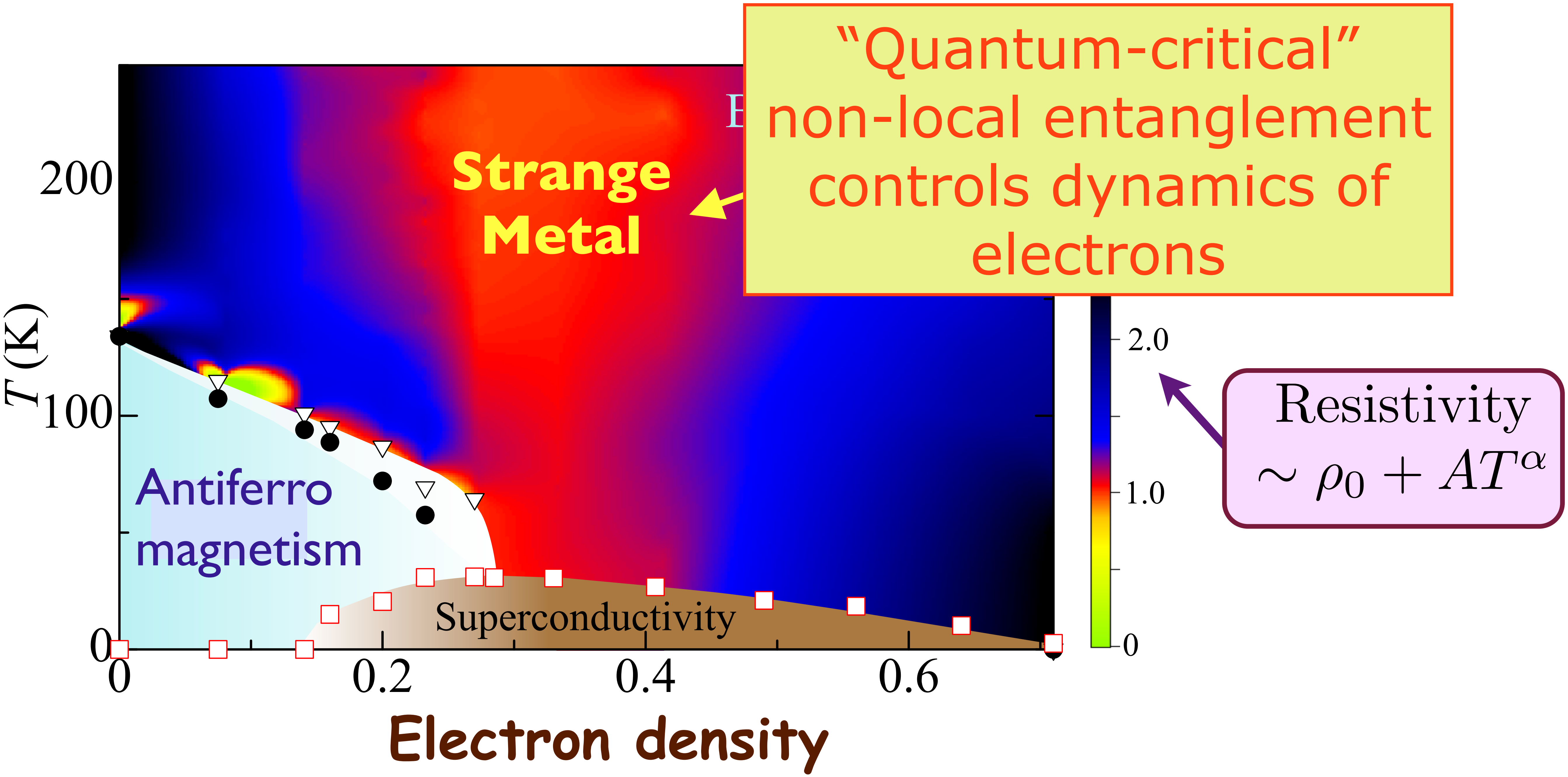

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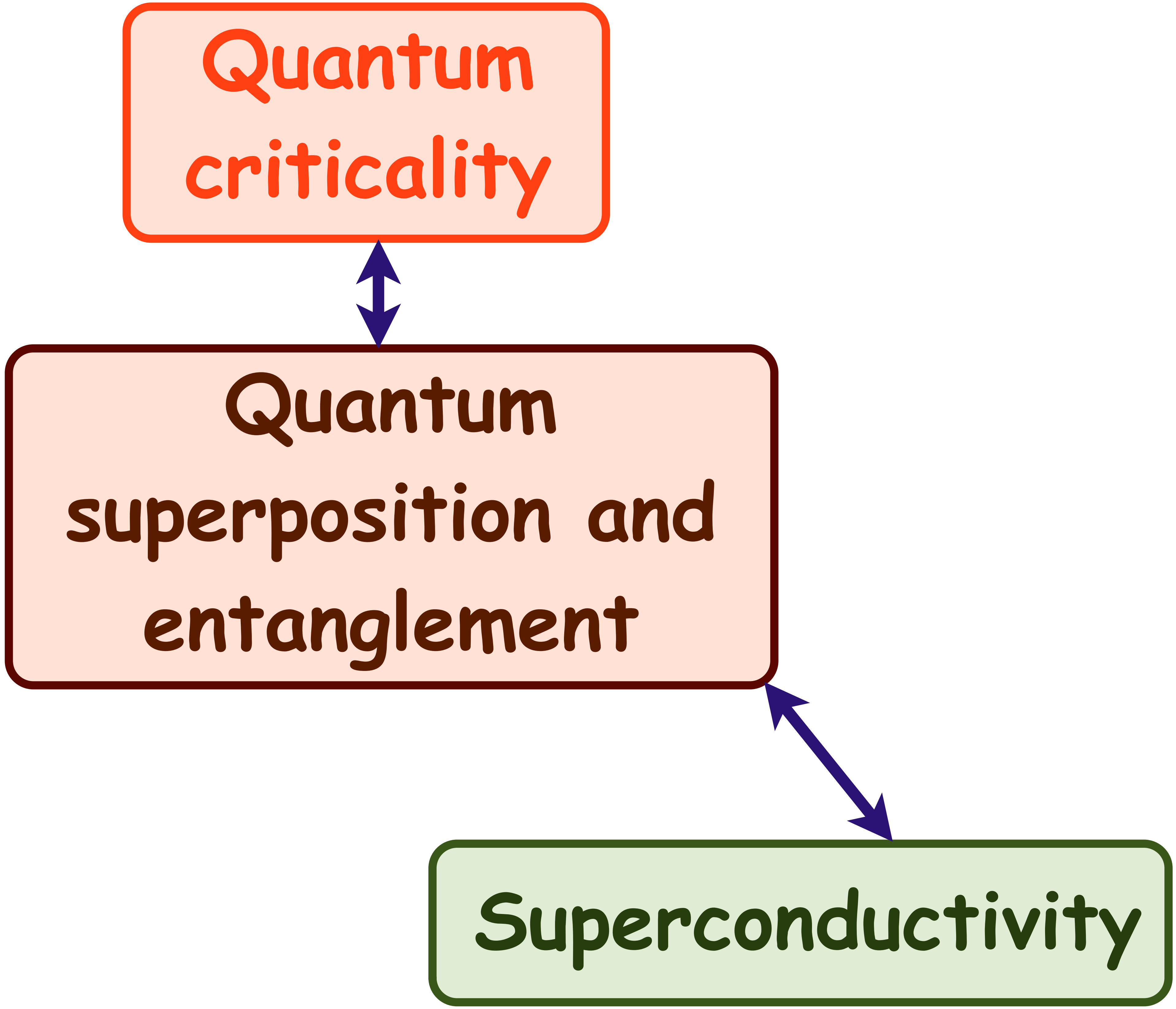
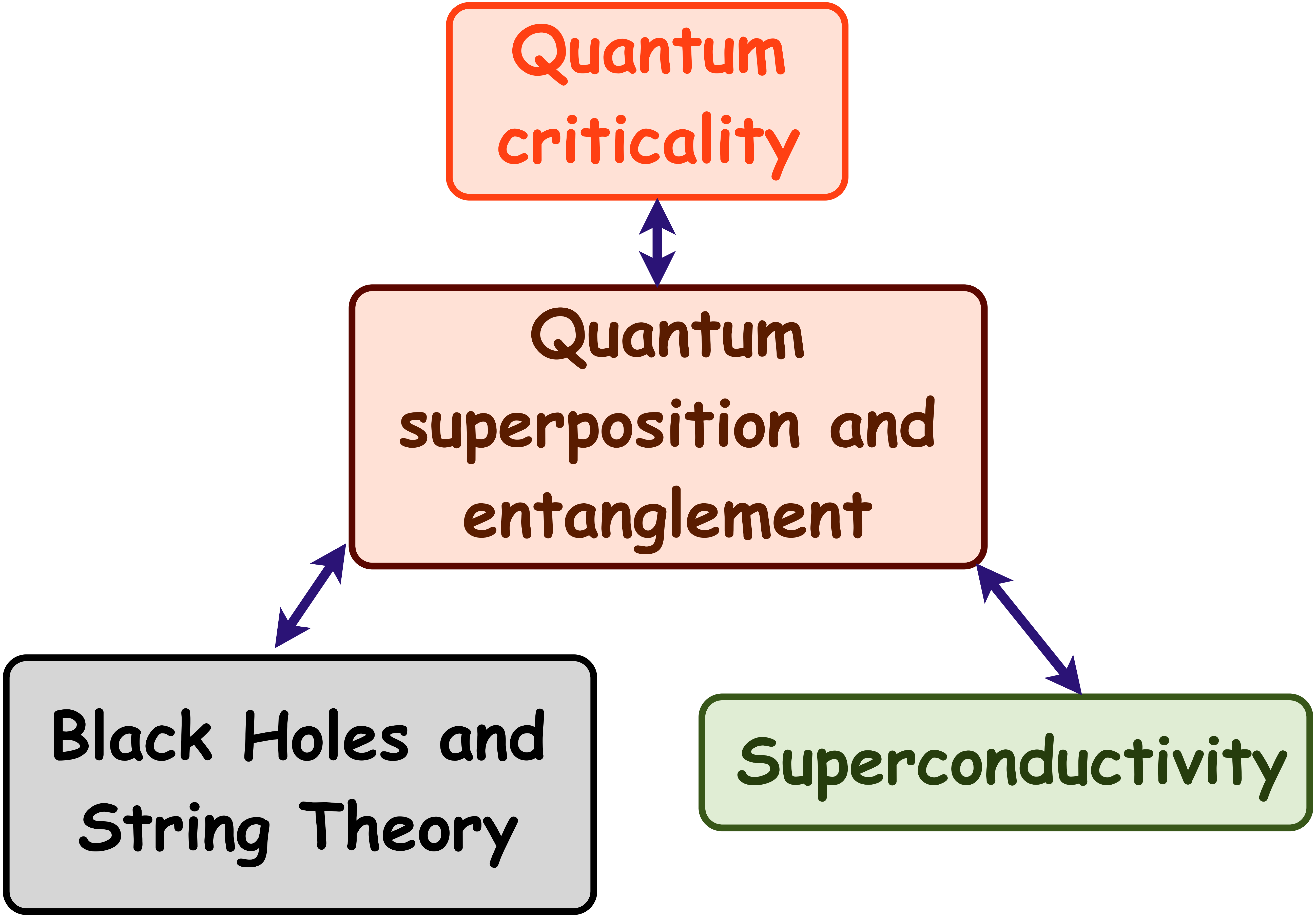
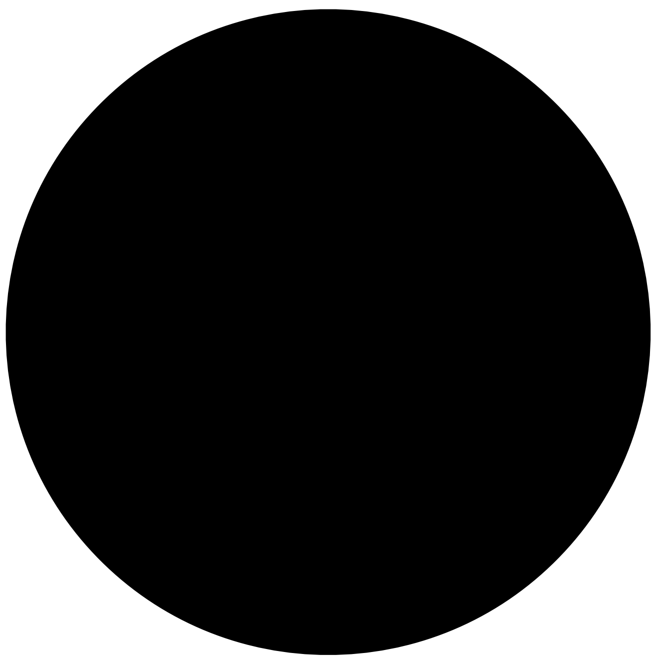

Quantum criticality
Quantum superposition and entanglement
Superconductivity



Quantum criticality
Quantum superposition and entanglement
Black Holes and String Theory
Superconductivity

Black Holes

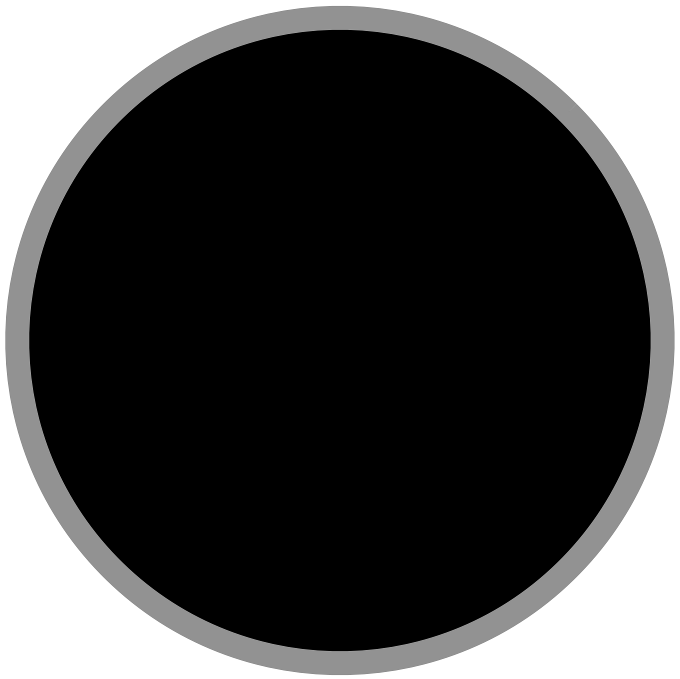
Objects so massive that light is gravitationally bound to them.



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.

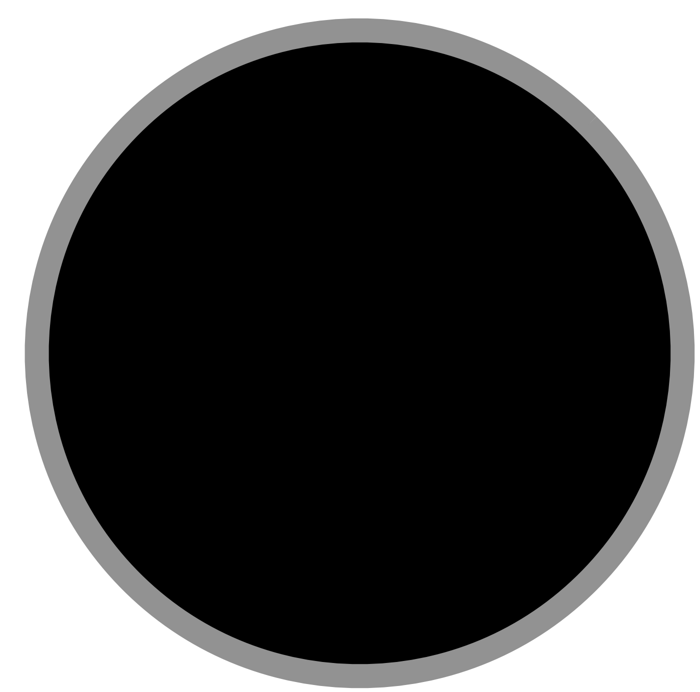


$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

Black Holes

Objects so massive that light is gravitationally bound to them.

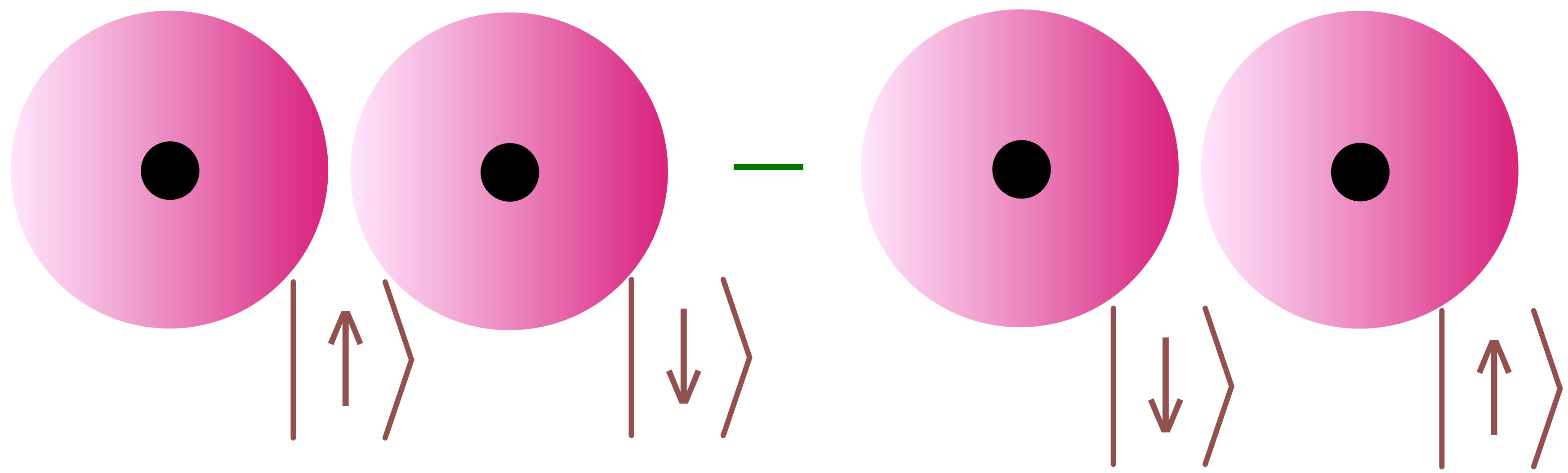
Chandrasekhar showed that certain stars were unstable, and these can collapse to black holes



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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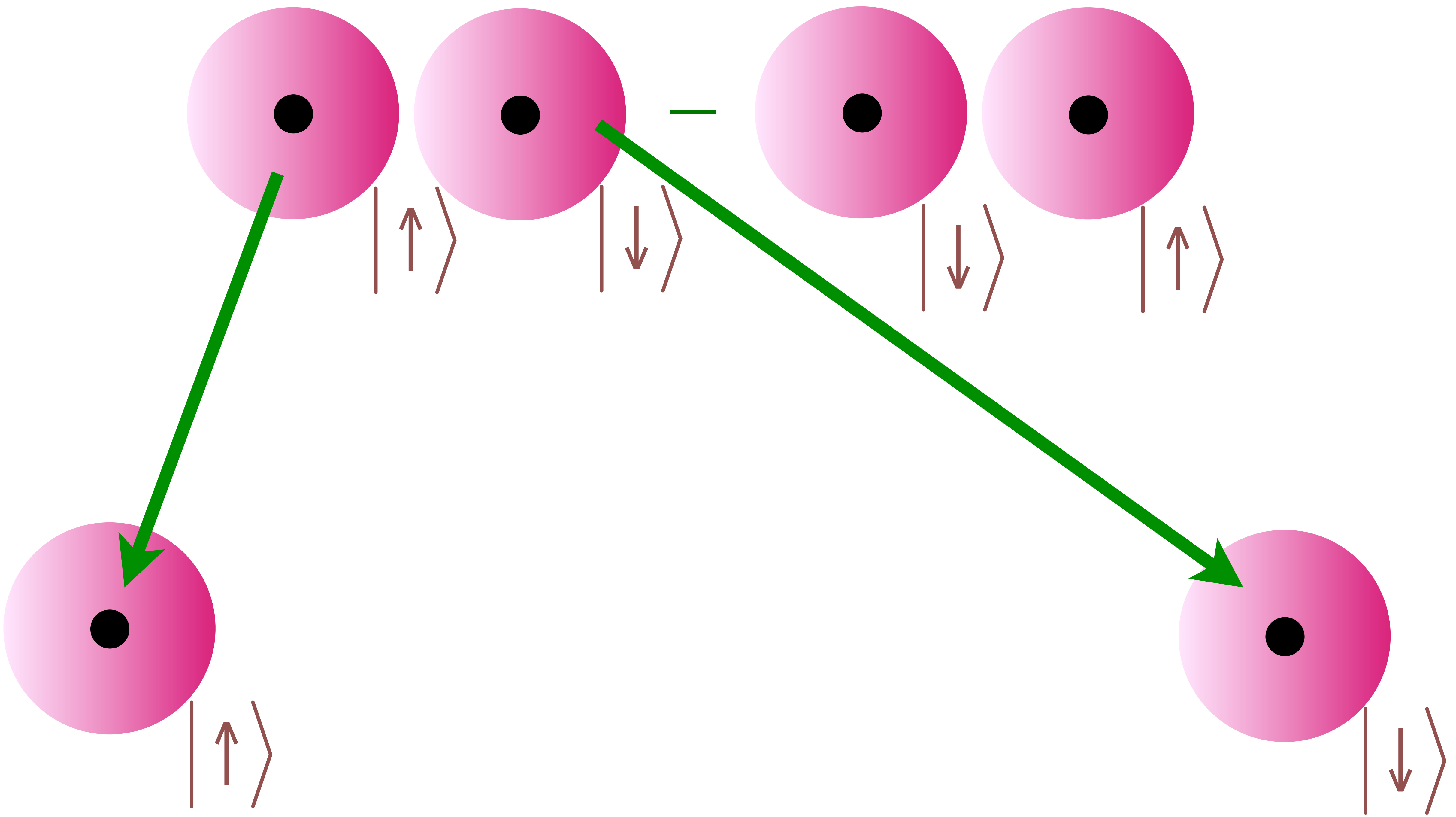

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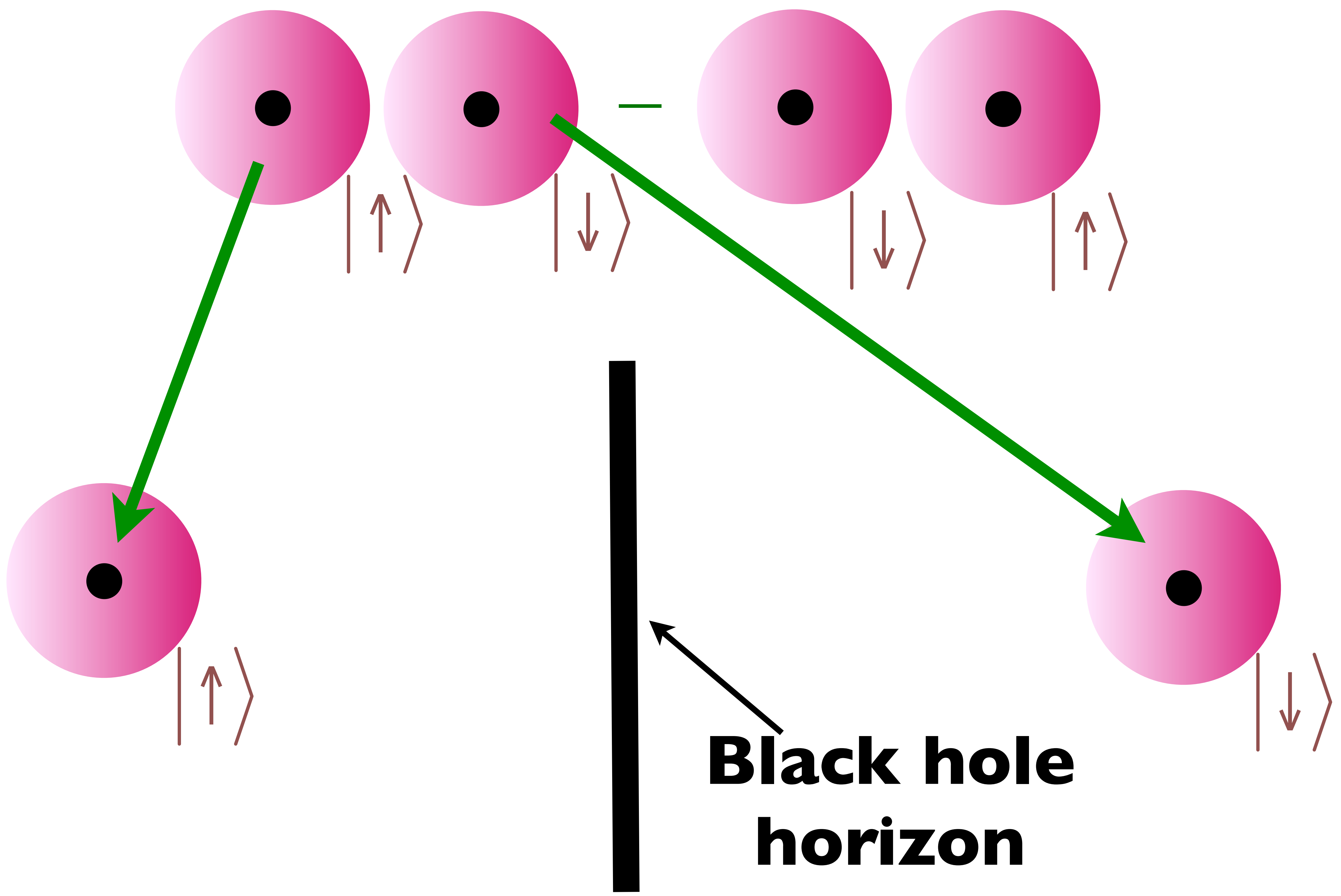

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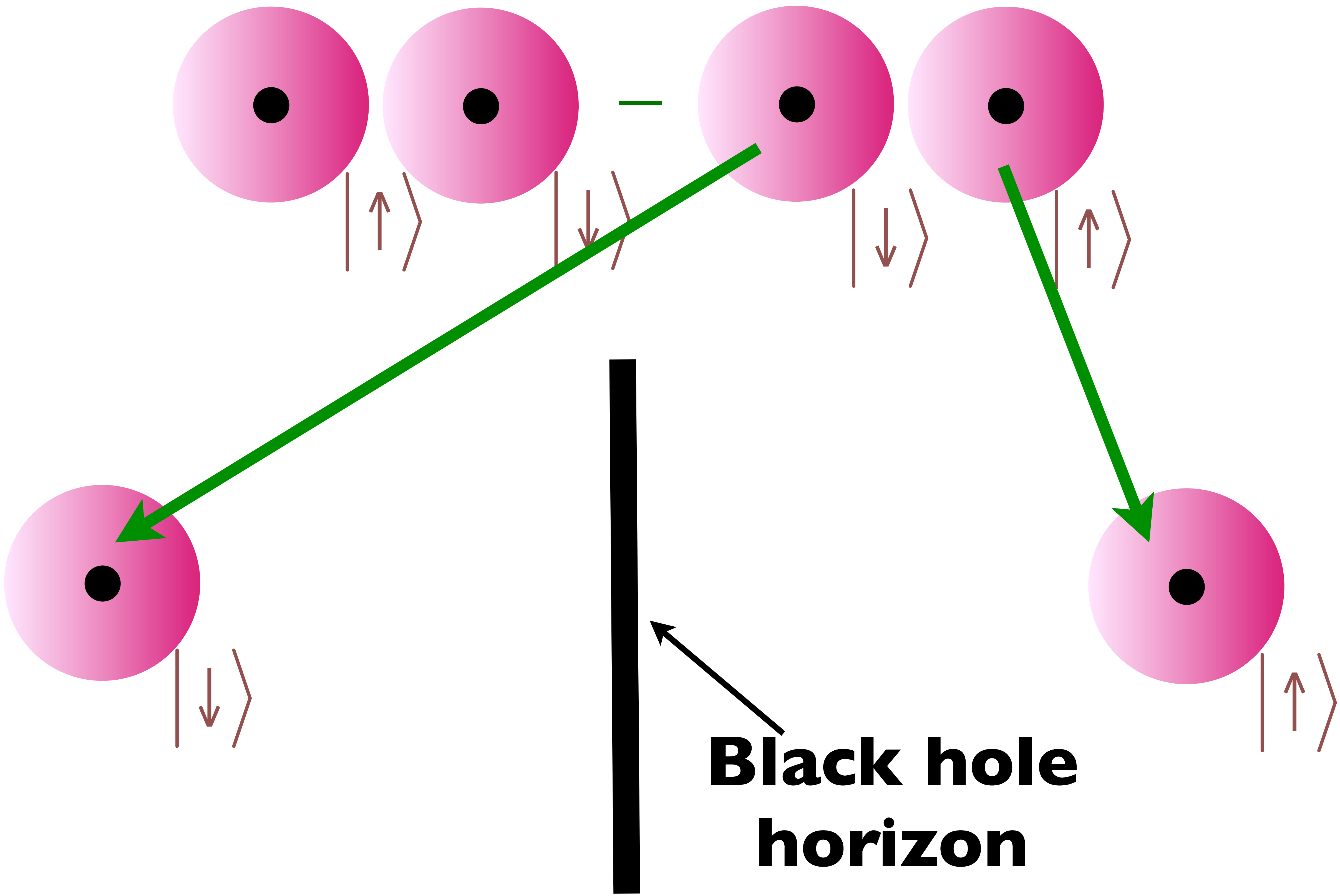
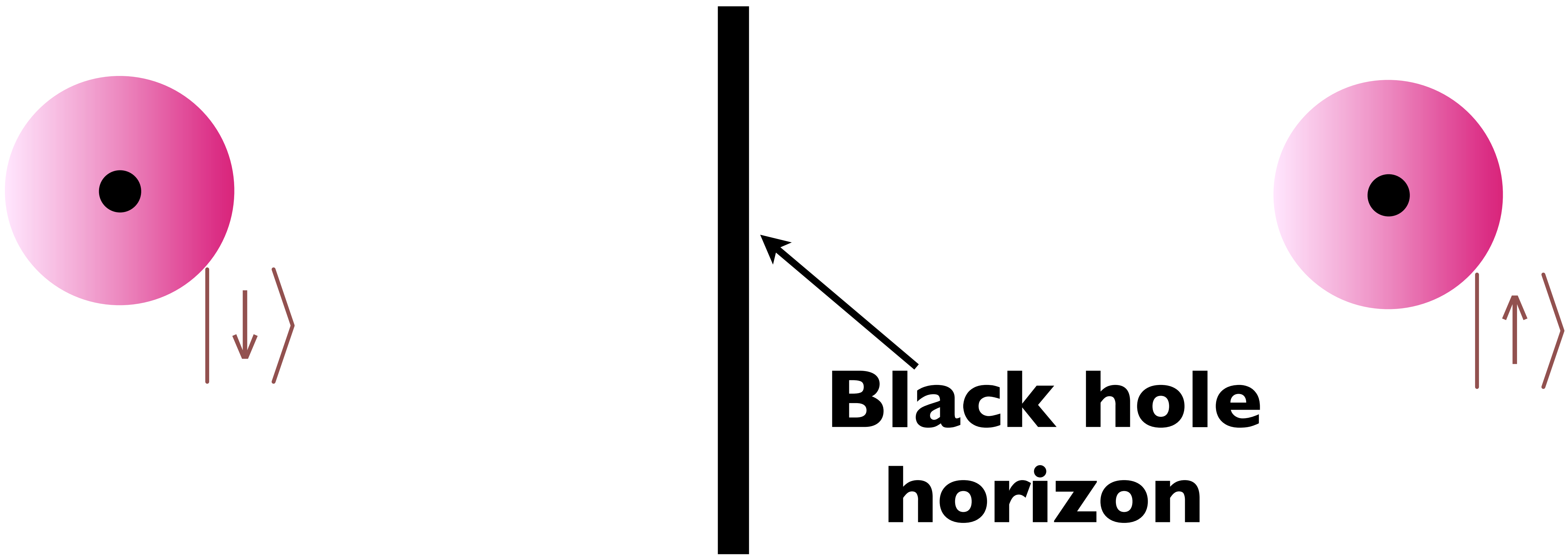


Quantum Entanglement across a black hole horizon

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



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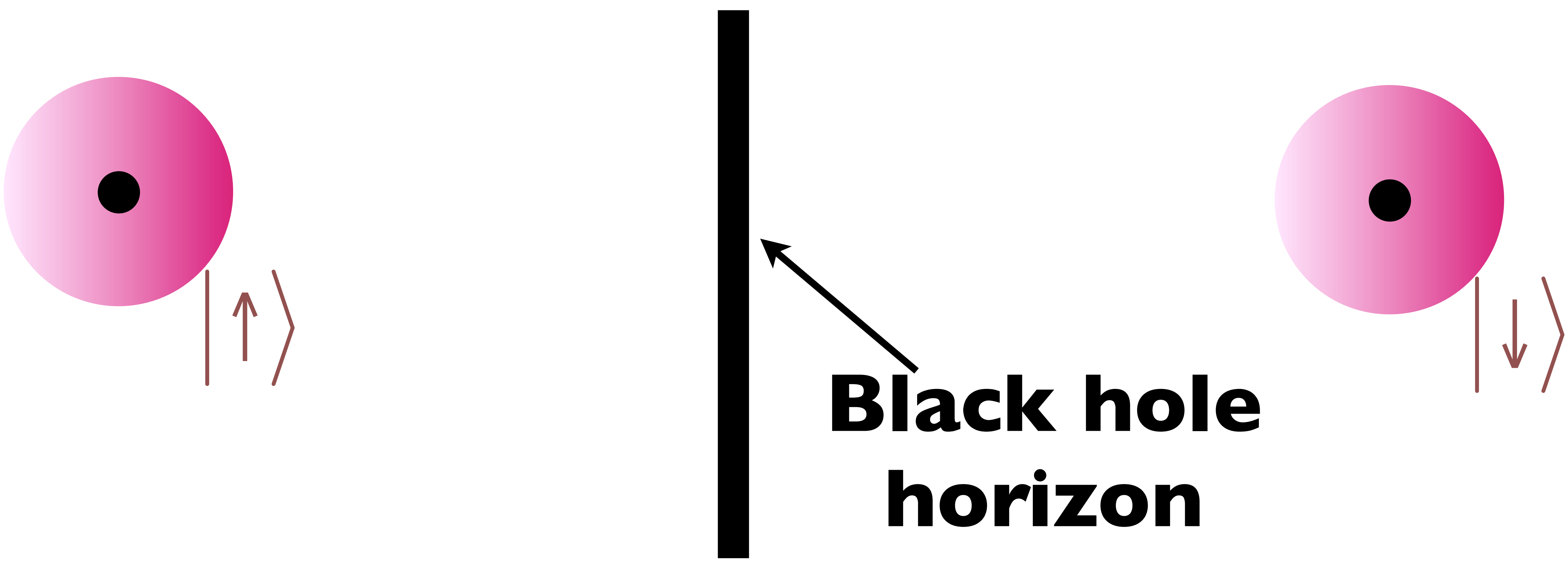


Quantum Entanglement across a black hole horizon

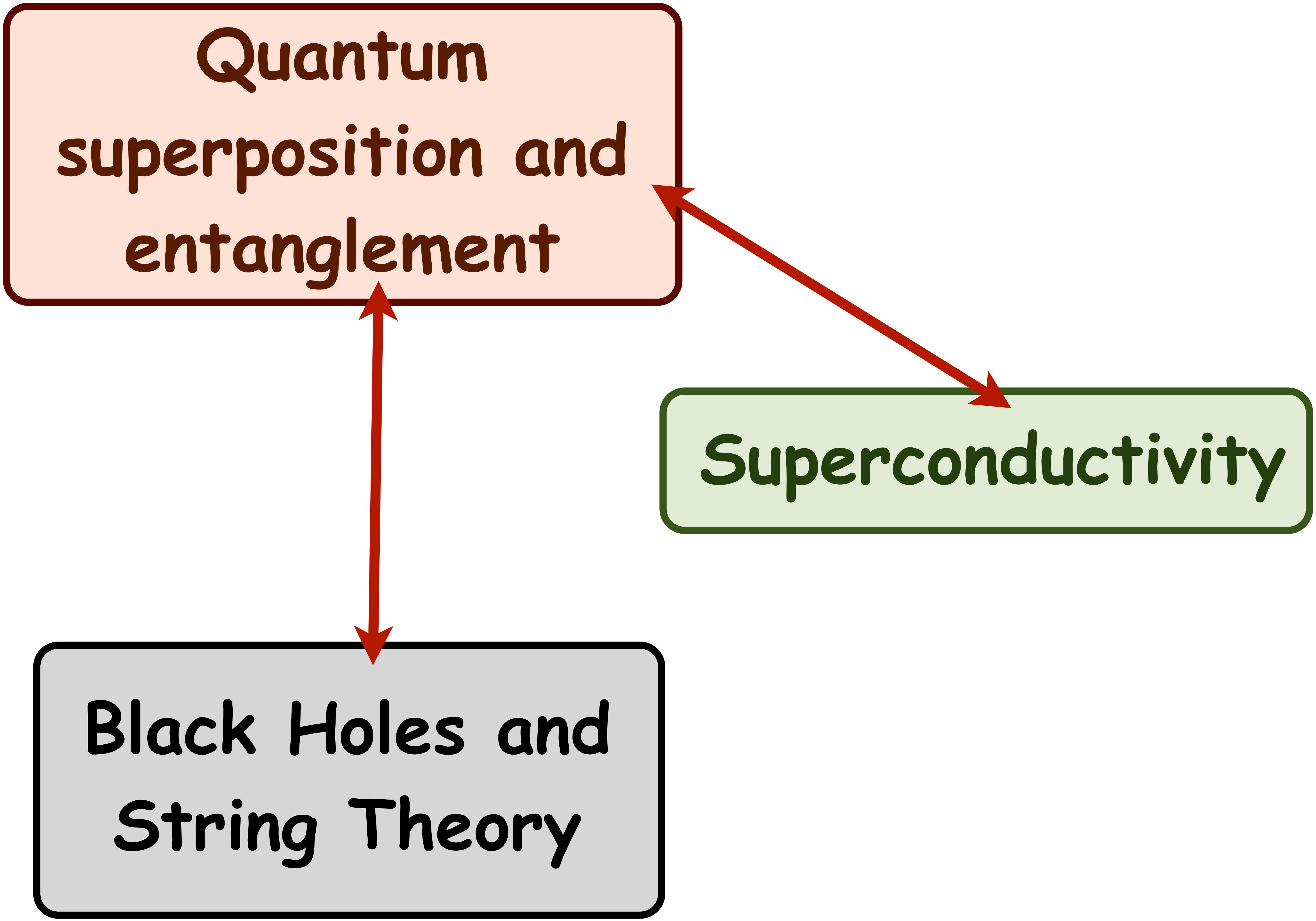
There is a non-local quantum entanglement between the inside and outside of a black hole

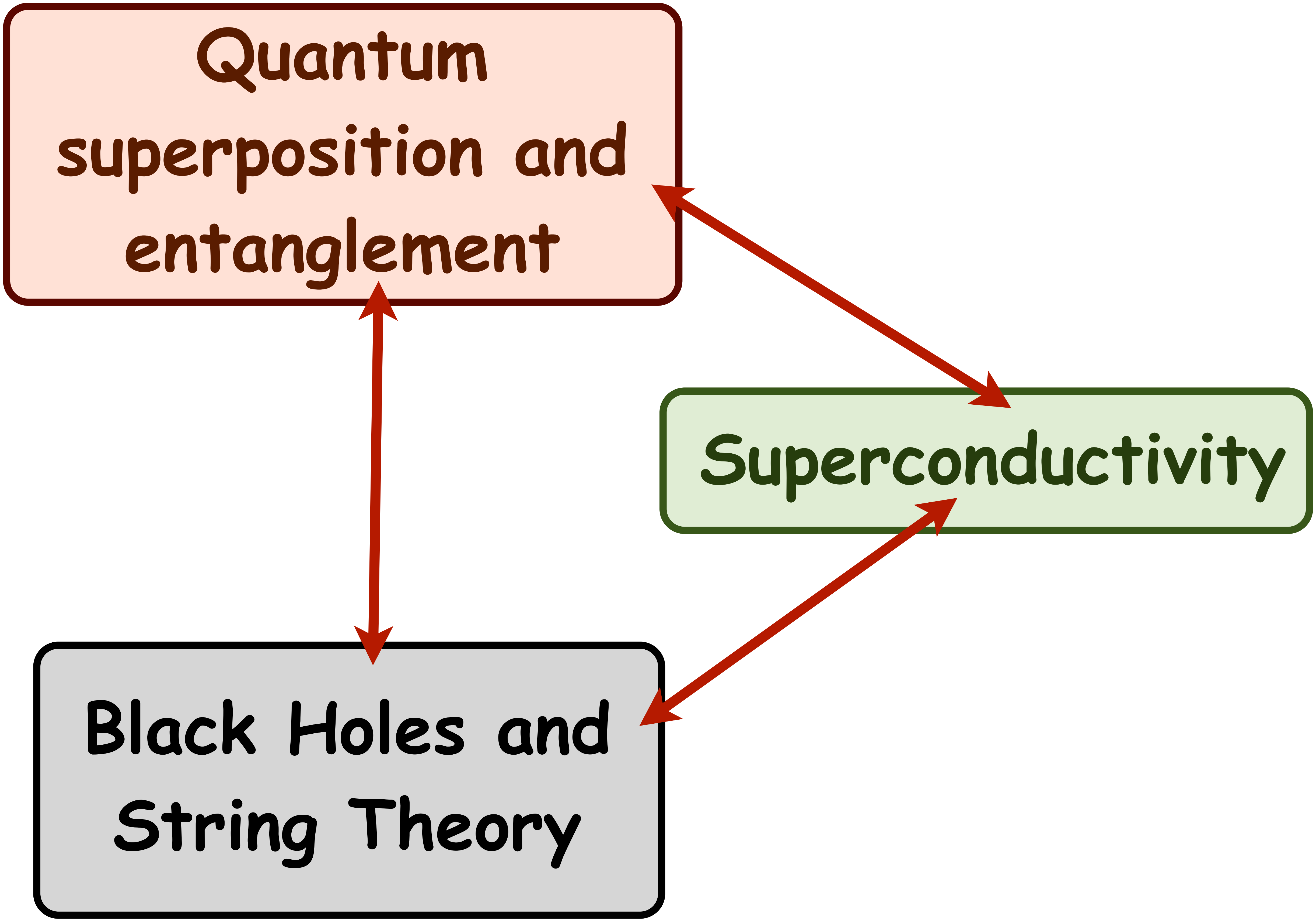
This entanglement leads to a black hole temperature (the Hawking temperature) and a black hole entropy (the Bekenstein entropy)

Quantum superposition and entanglement

Superconductivity

Black Holes and String Theory


Quantum superposition and entanglement
Superconductivity
Black Holes and String Theory


Quantum superposition and entanglement
Superconductivity
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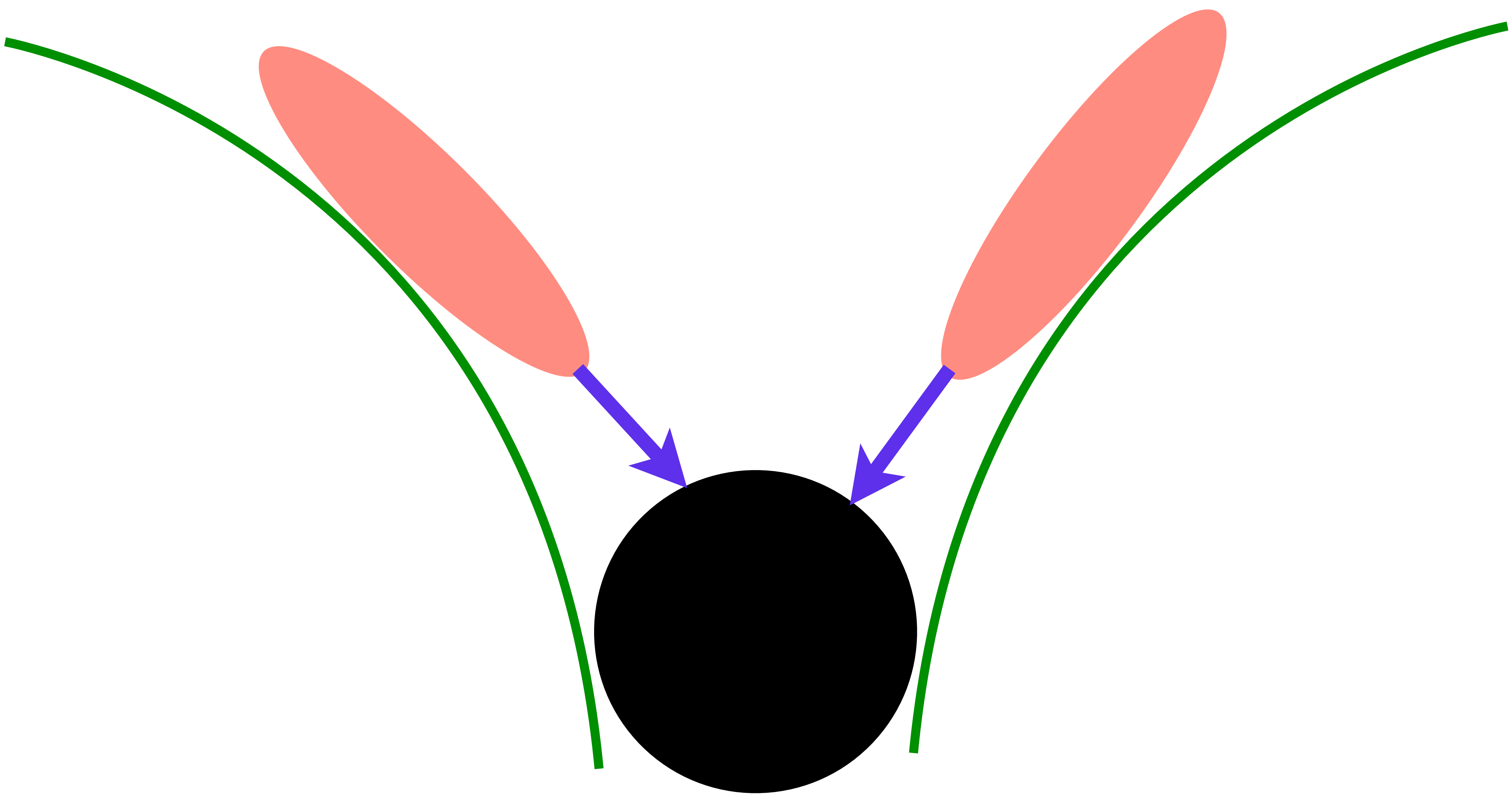
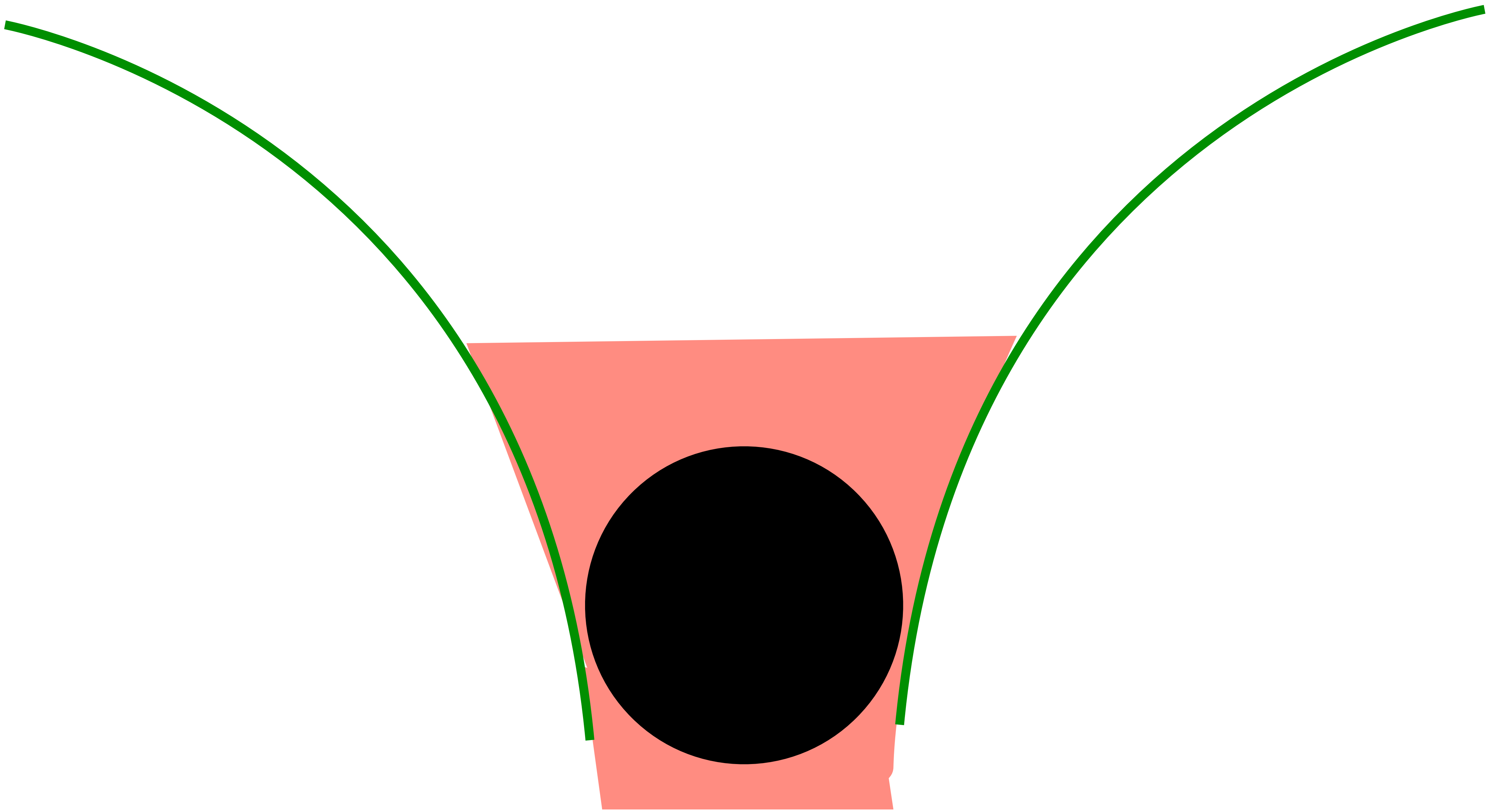
Superconducting Black Holes

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 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

In experiments on antiferromagnets and superconductors, we found long-range entanglement near quantum critical points and in the poorly understood "strange metal"

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

In experiments on antiferromagnets and superconductors, we found long-range entanglement near quantum critical points and in the poorly understood "strange metal"

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