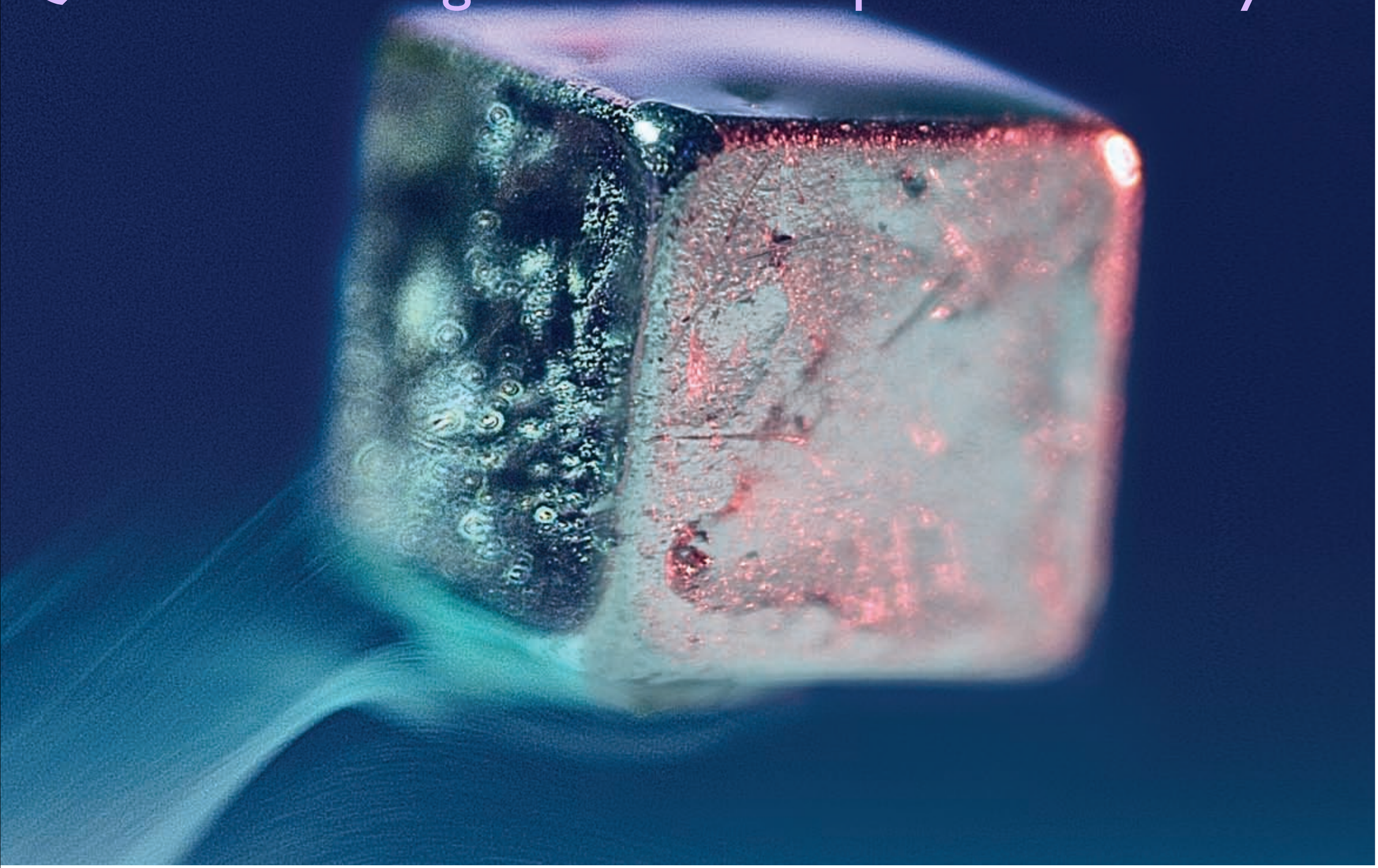
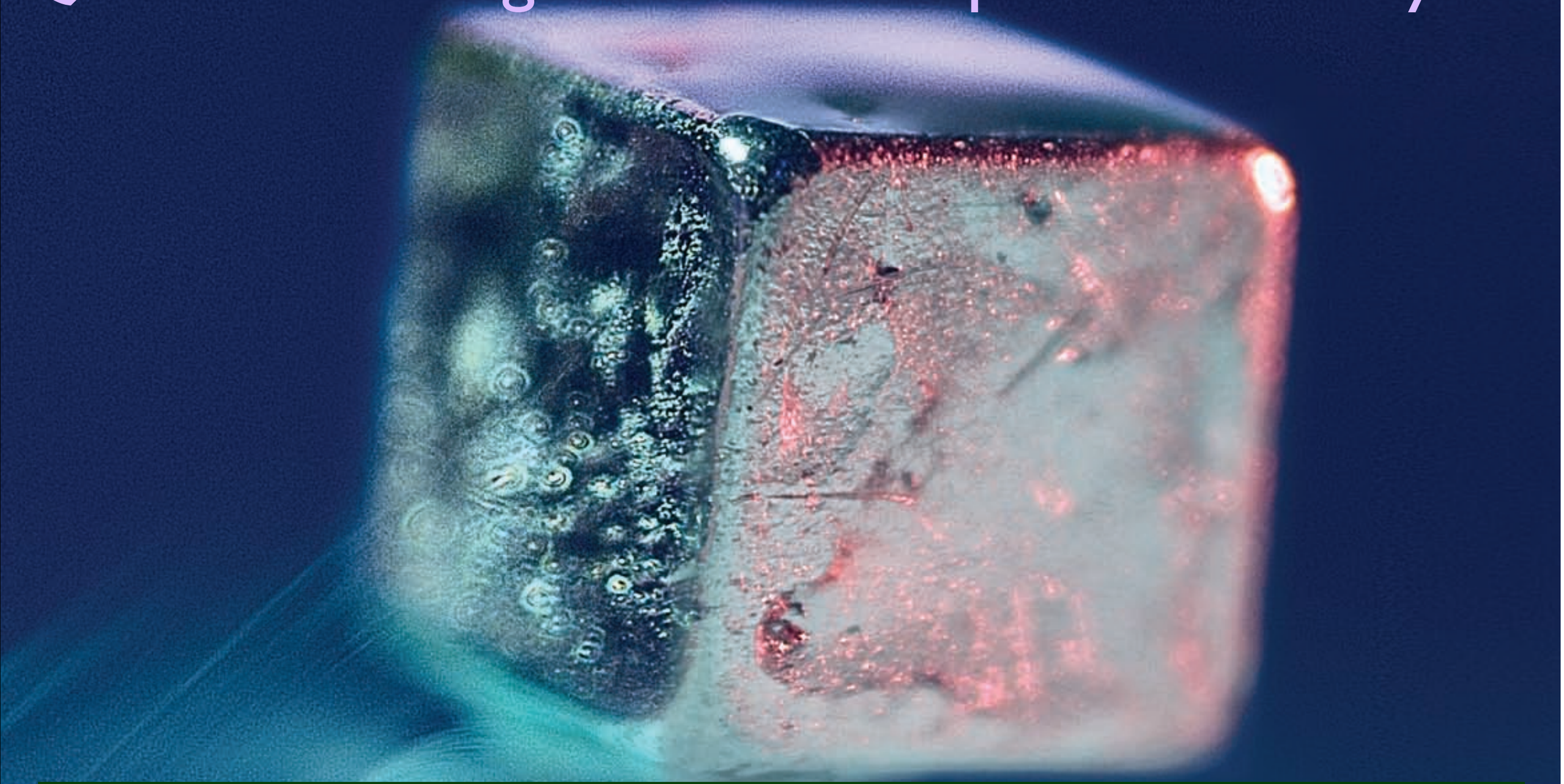
Quantum Entanglement and Superconductivity



Subir Sachdev, Harvard University

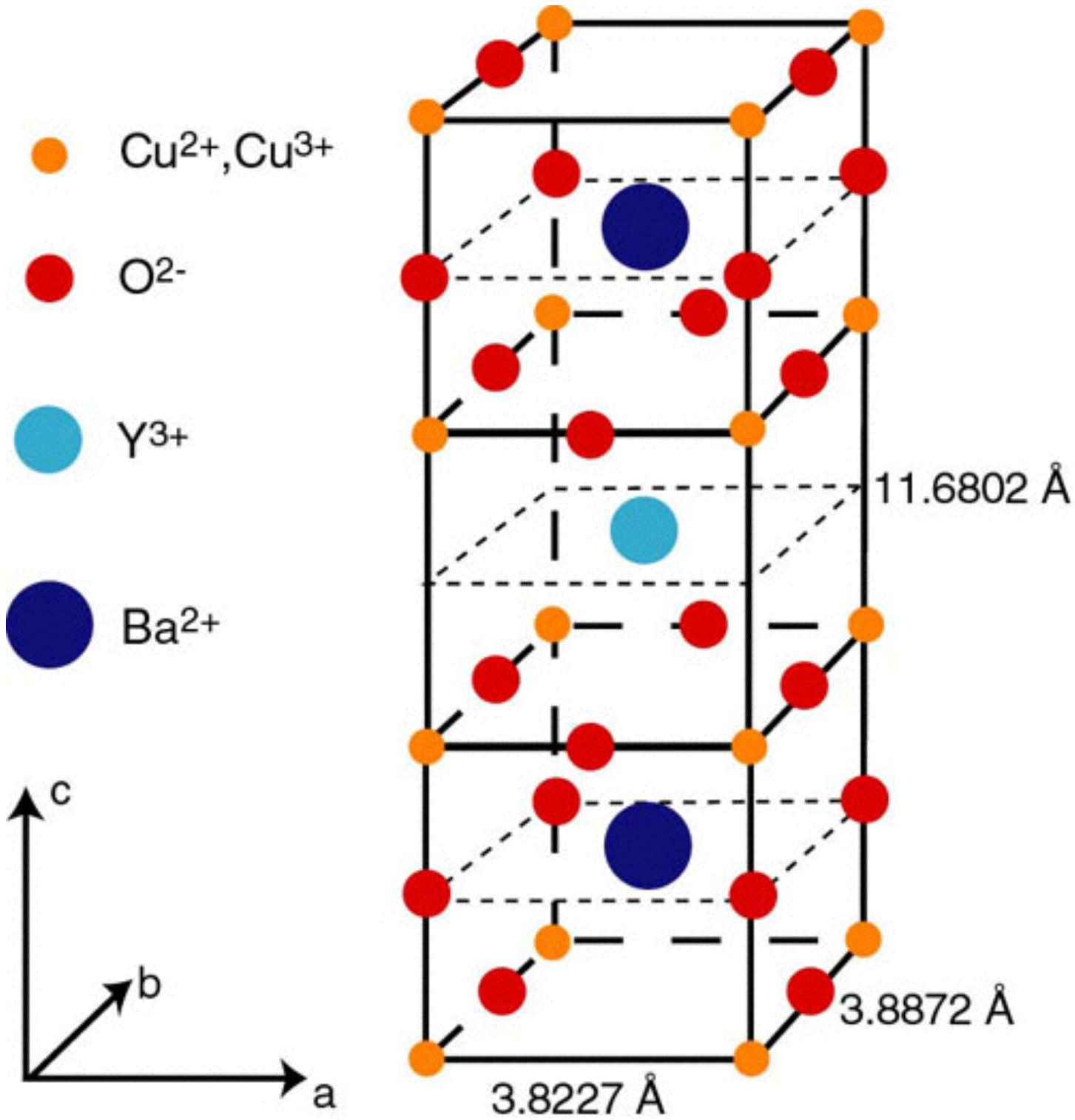
Quantum Entanglement and Superconductivity



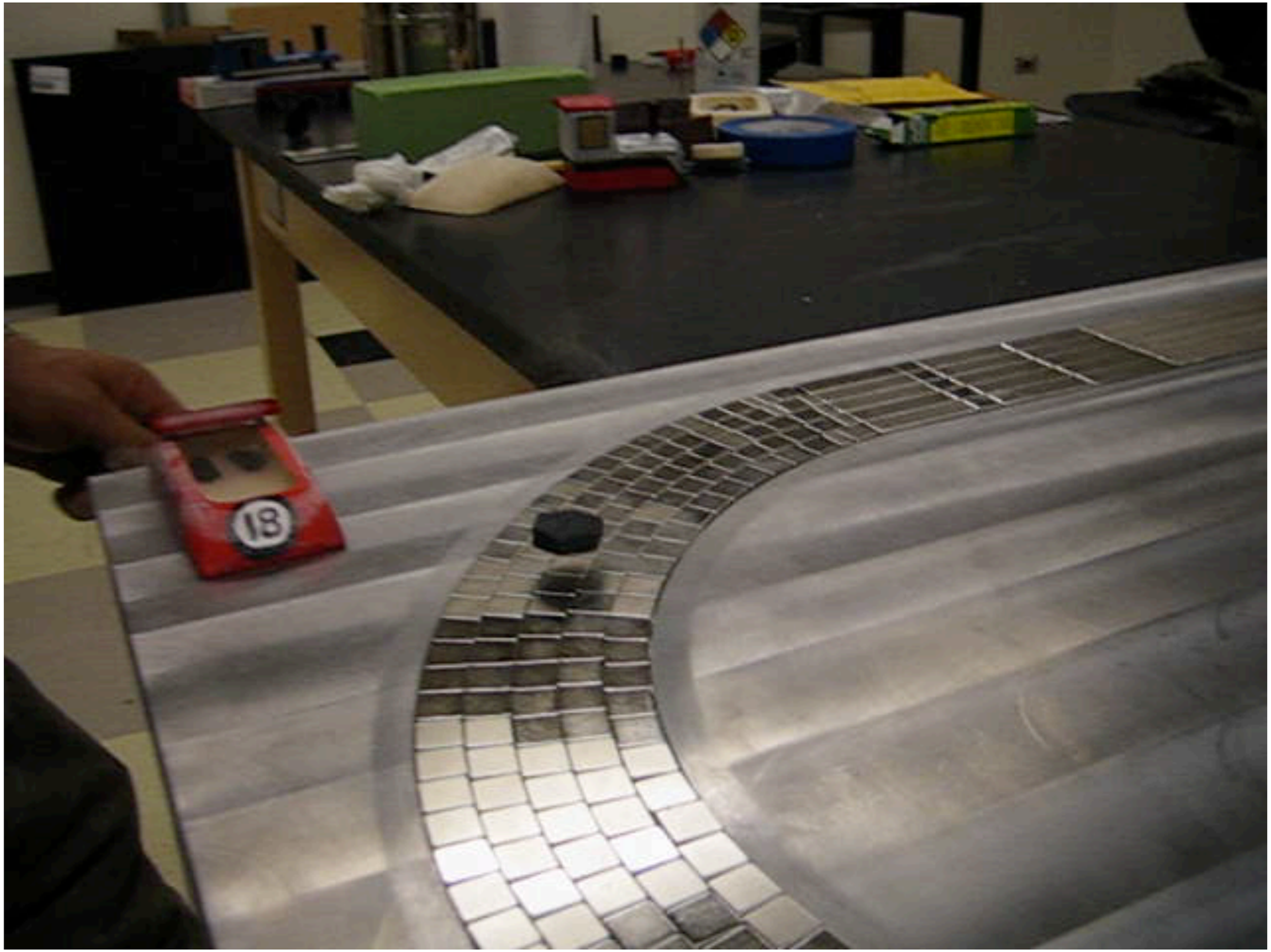
Superconductor, levitated by an unseen magnet, in which countless trillions of electrons form a vast interconnected quantum state.
Scientific American, January 2013

Subir Sachdev, Harvard University

High temperature superconductors

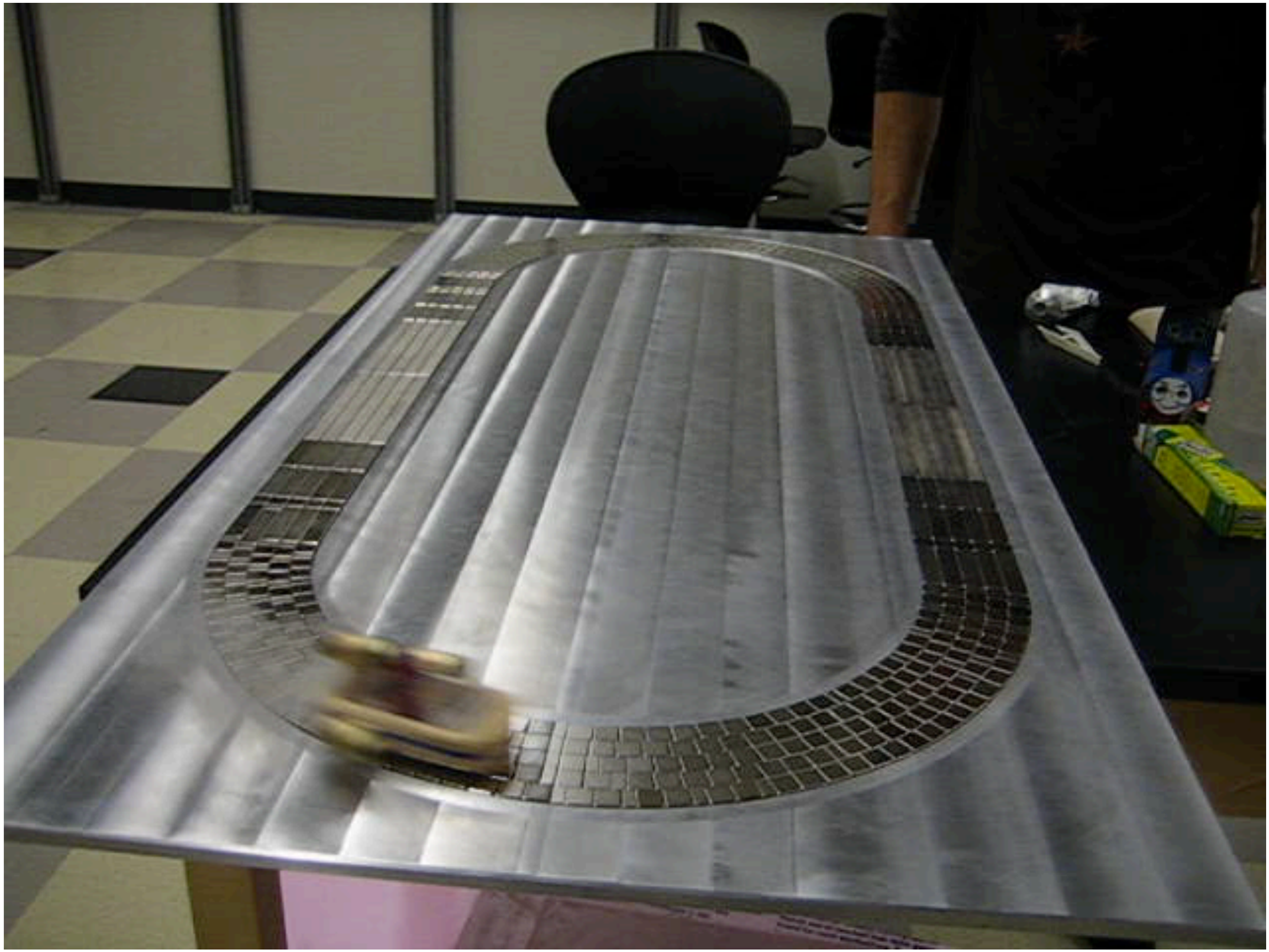


$$YBa_2Cu_3O_{6+x}$$



Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

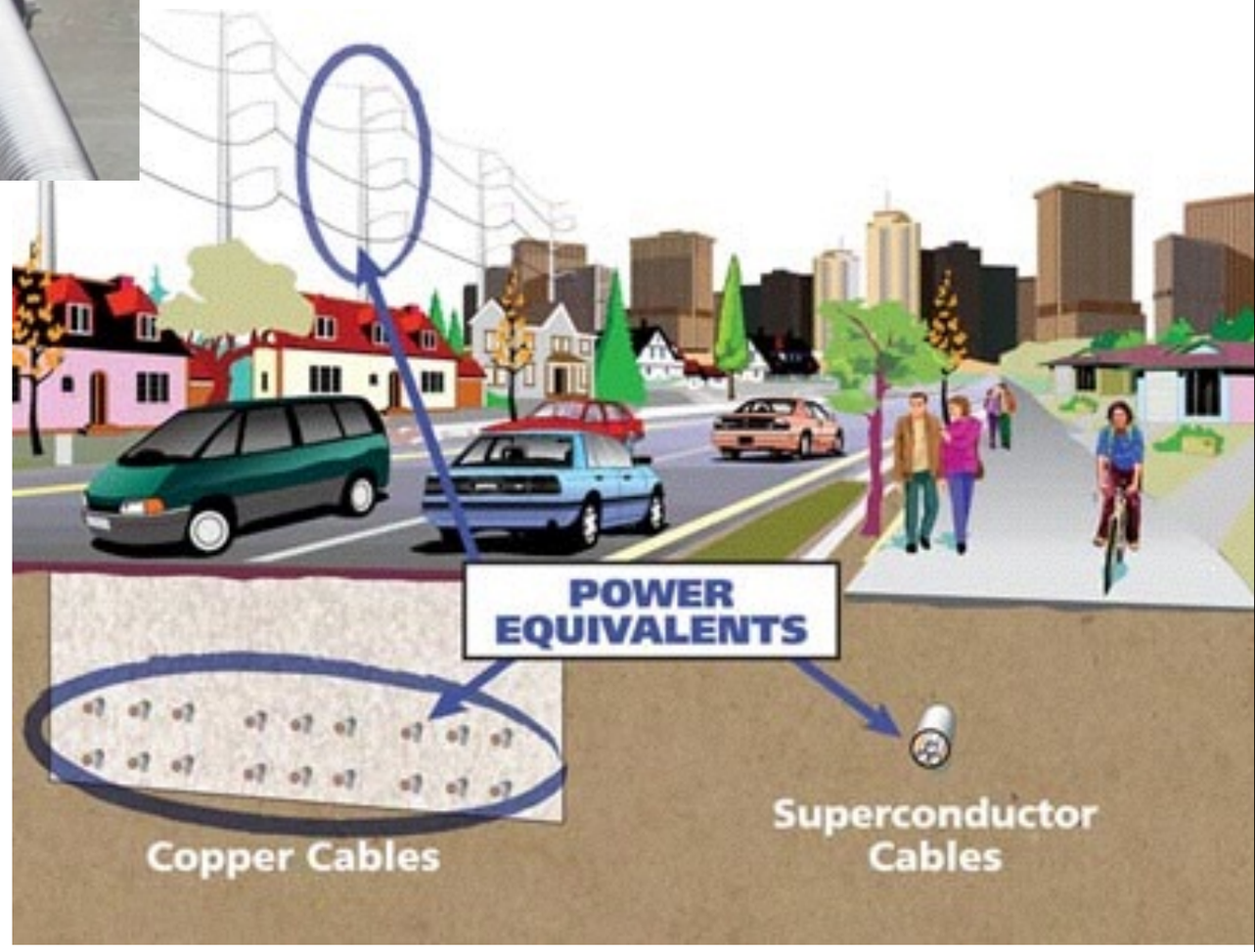


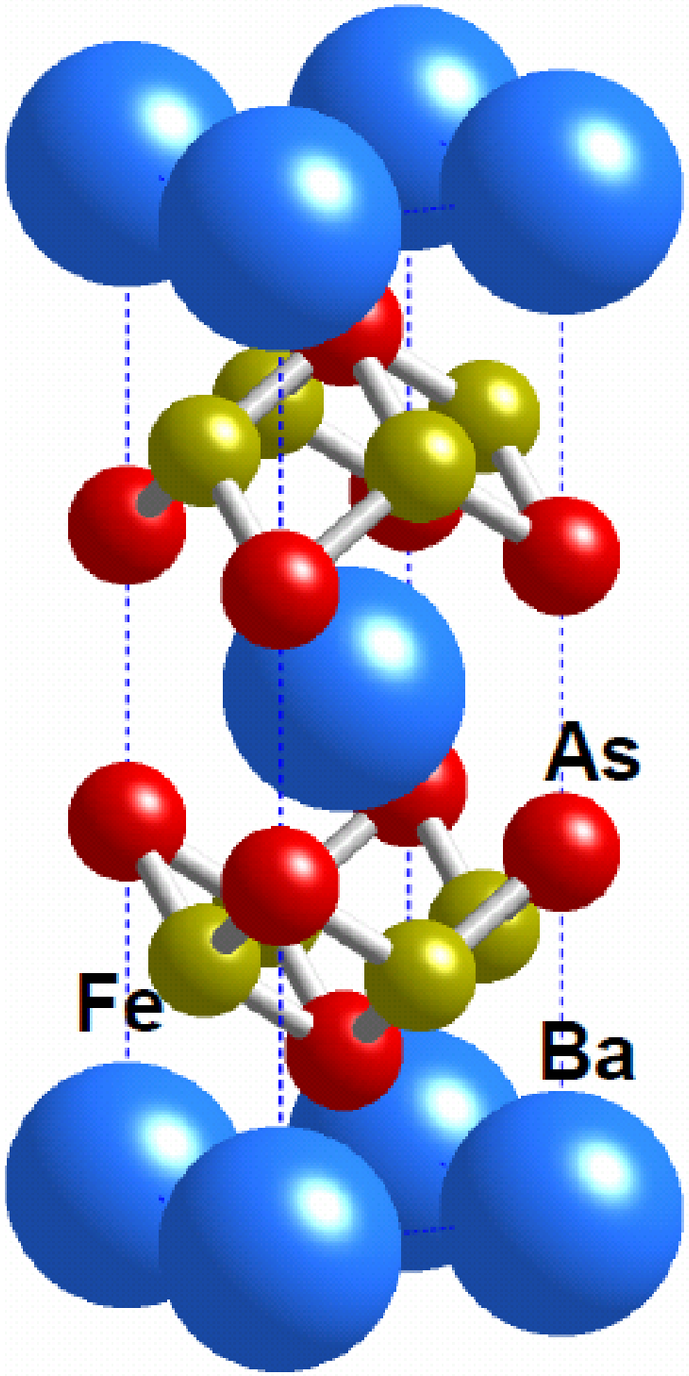
Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

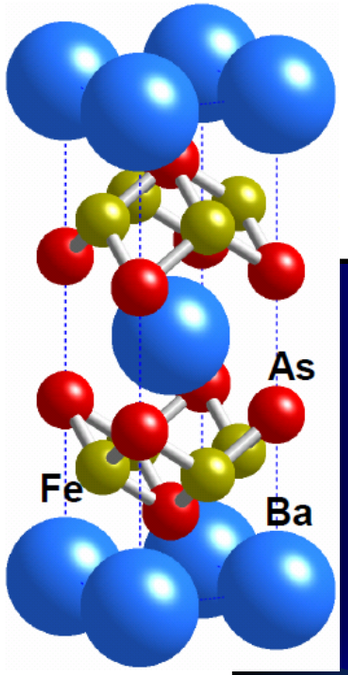
YBCO cables

American Superconductor Corporation





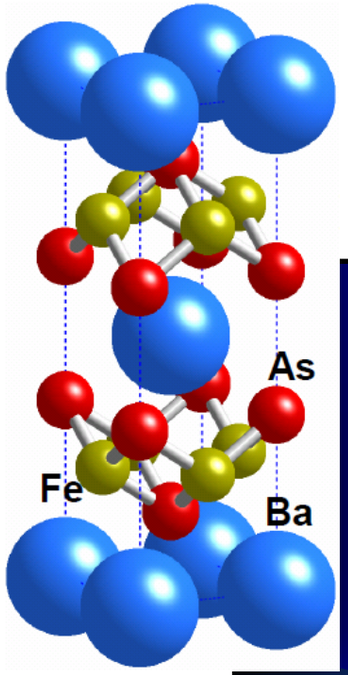
$BaFe_2As_2$



Resistivity
$\sim \rho_0 + AT^{\alpha}$

$BaFe_2(As_{1-x}P_x)_2$

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)



Resistivity
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$BaFe_2(As_{1-x}P_x)_2$

Ordinary metal

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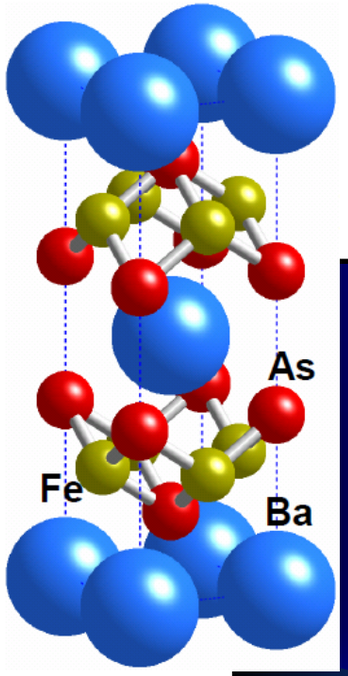

Resistivity
$\sim \rho_0 + AT^{\alpha}$

Strange Metal

$BaFe_2(As_{1-x}P_x)_2$

Superconductivity

Ordinary metal

T (K)

100

0

0

0.2

0.4

0.6

x

α

2.0

1.0

0

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,
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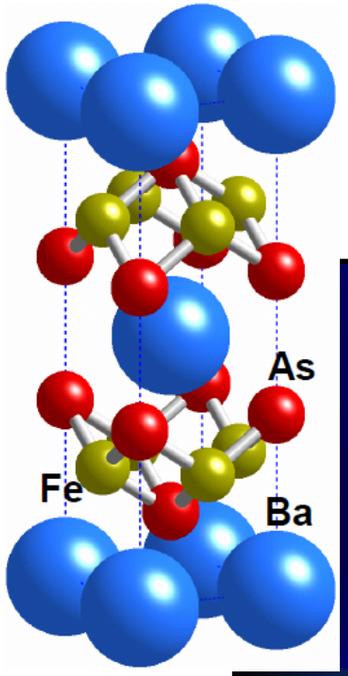

Resistivity
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Strange Metal

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Antiferromagnet

Superconductivity

Ordinary metal

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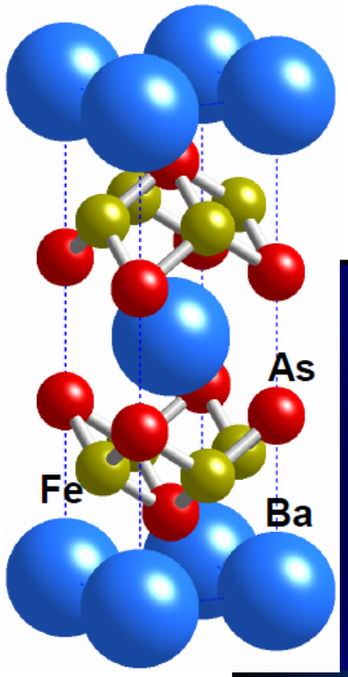
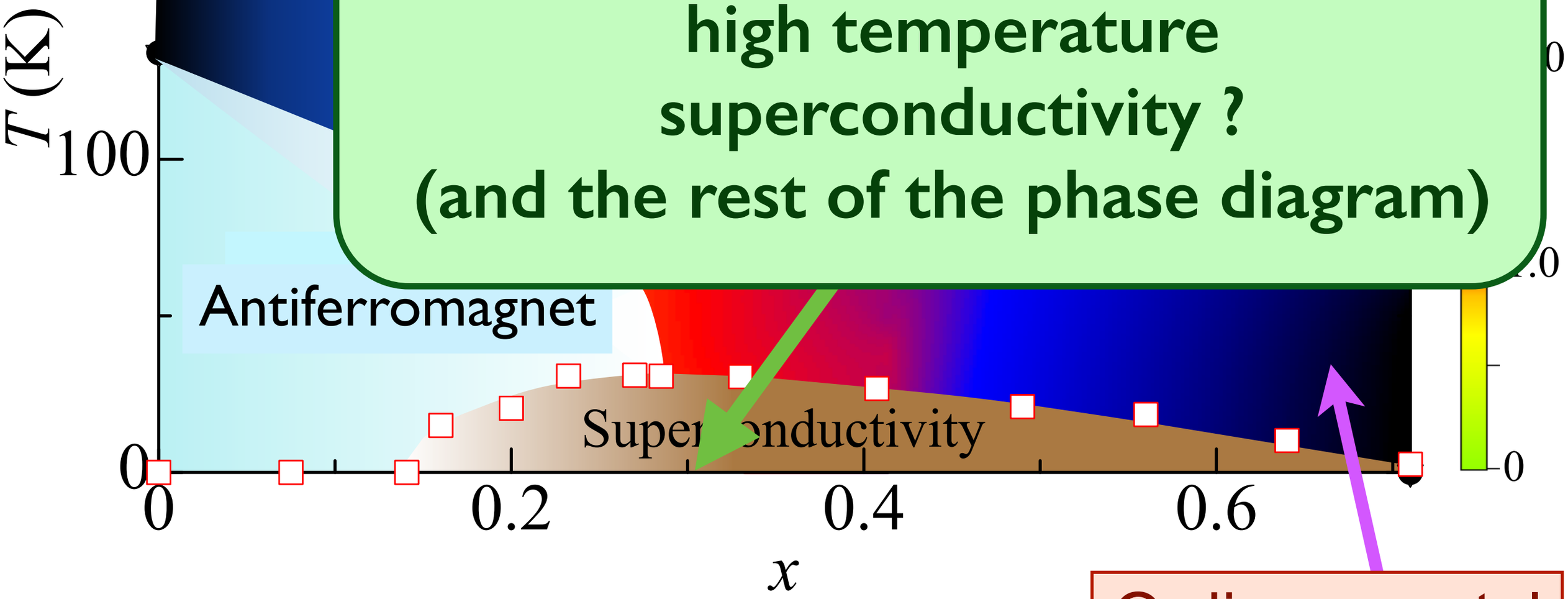
S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)



"Quantum critical point"
with
"long-range quantum entanglement".

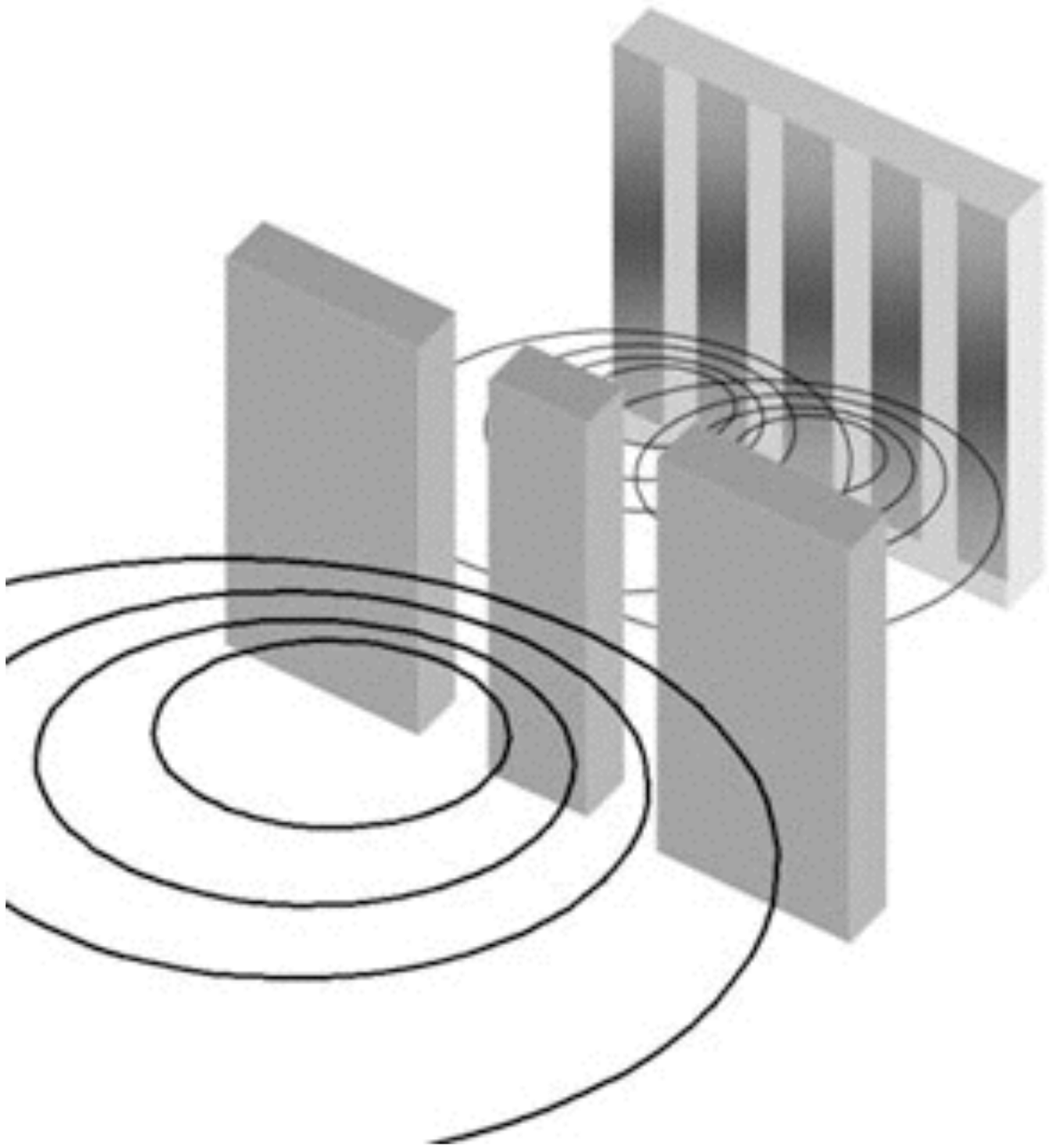
Can this help us understand
high temperature
superconductivity ?
(and the rest of the phase diagram)



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)

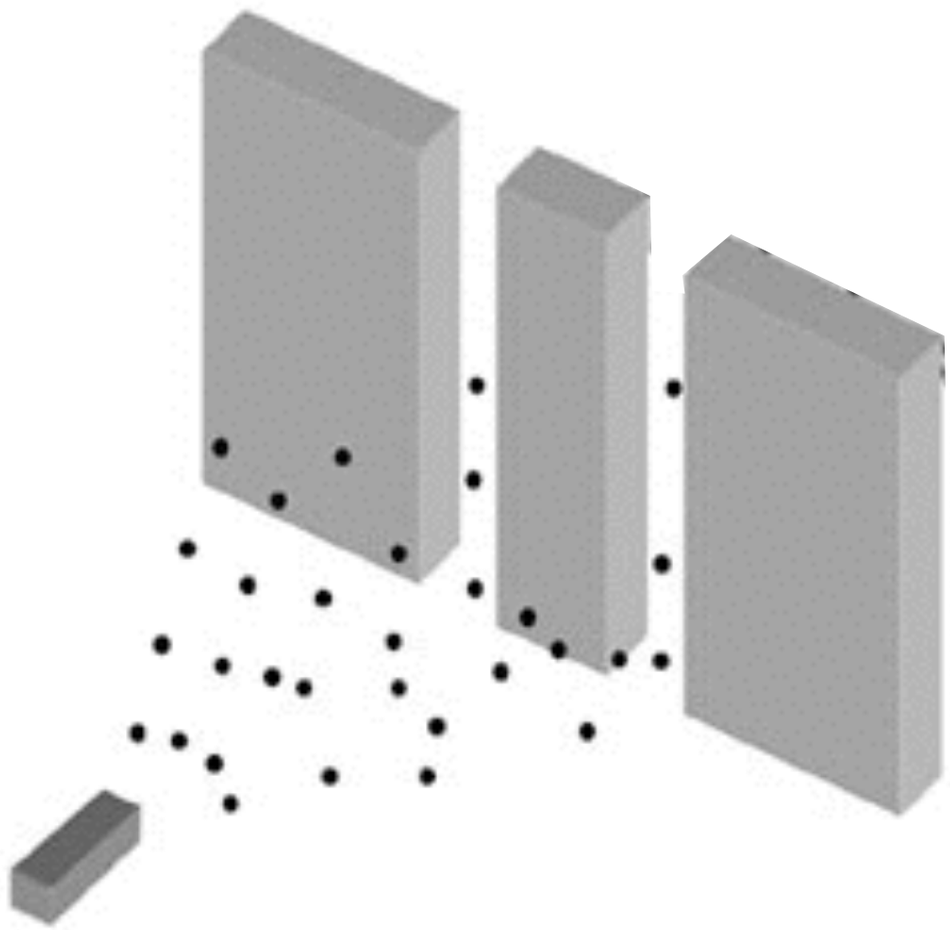
Quantum superposition and entanglement

The double slit experiment



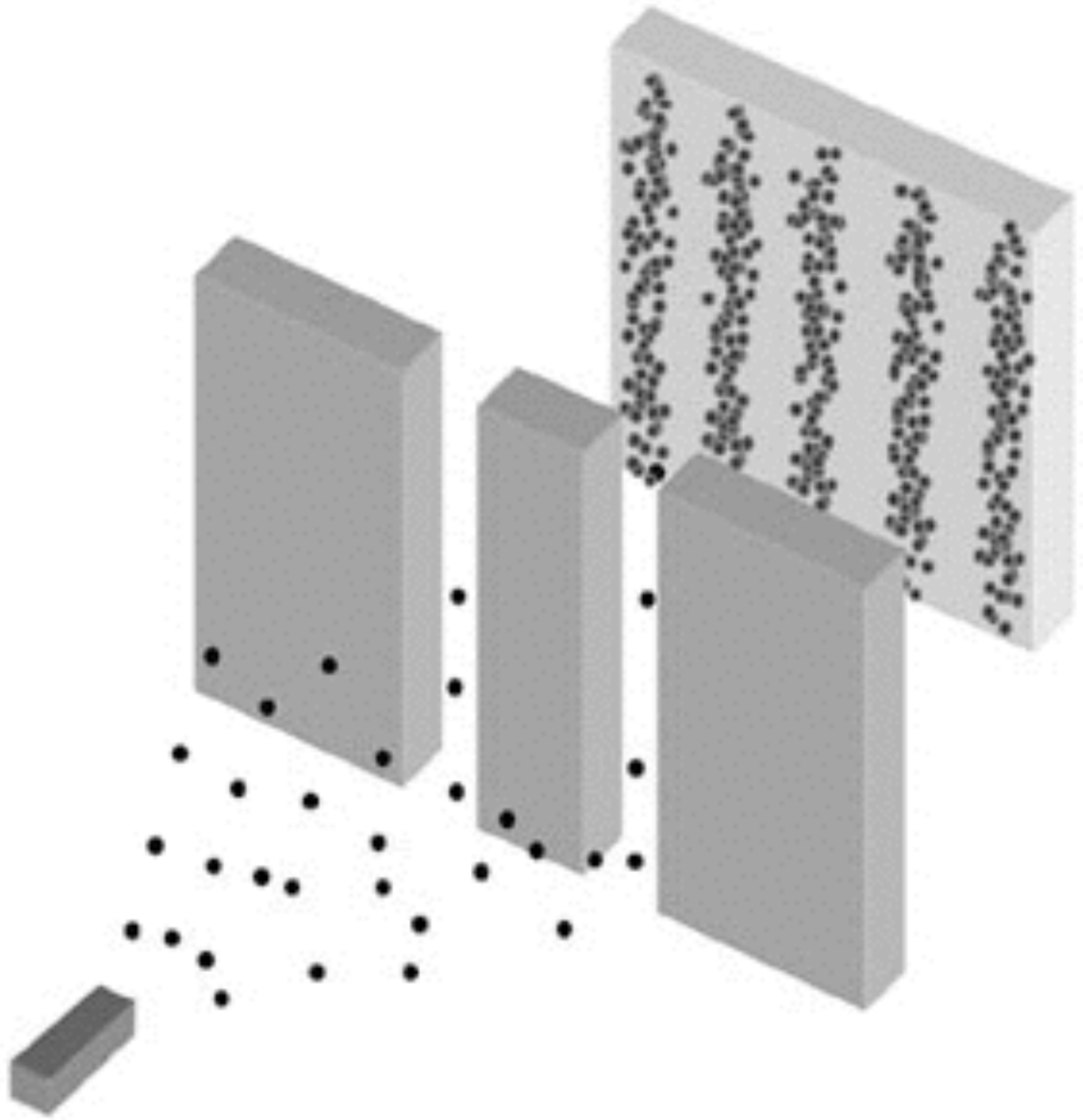
Interference of water waves

The double slit experiment



Send electrons through the slits

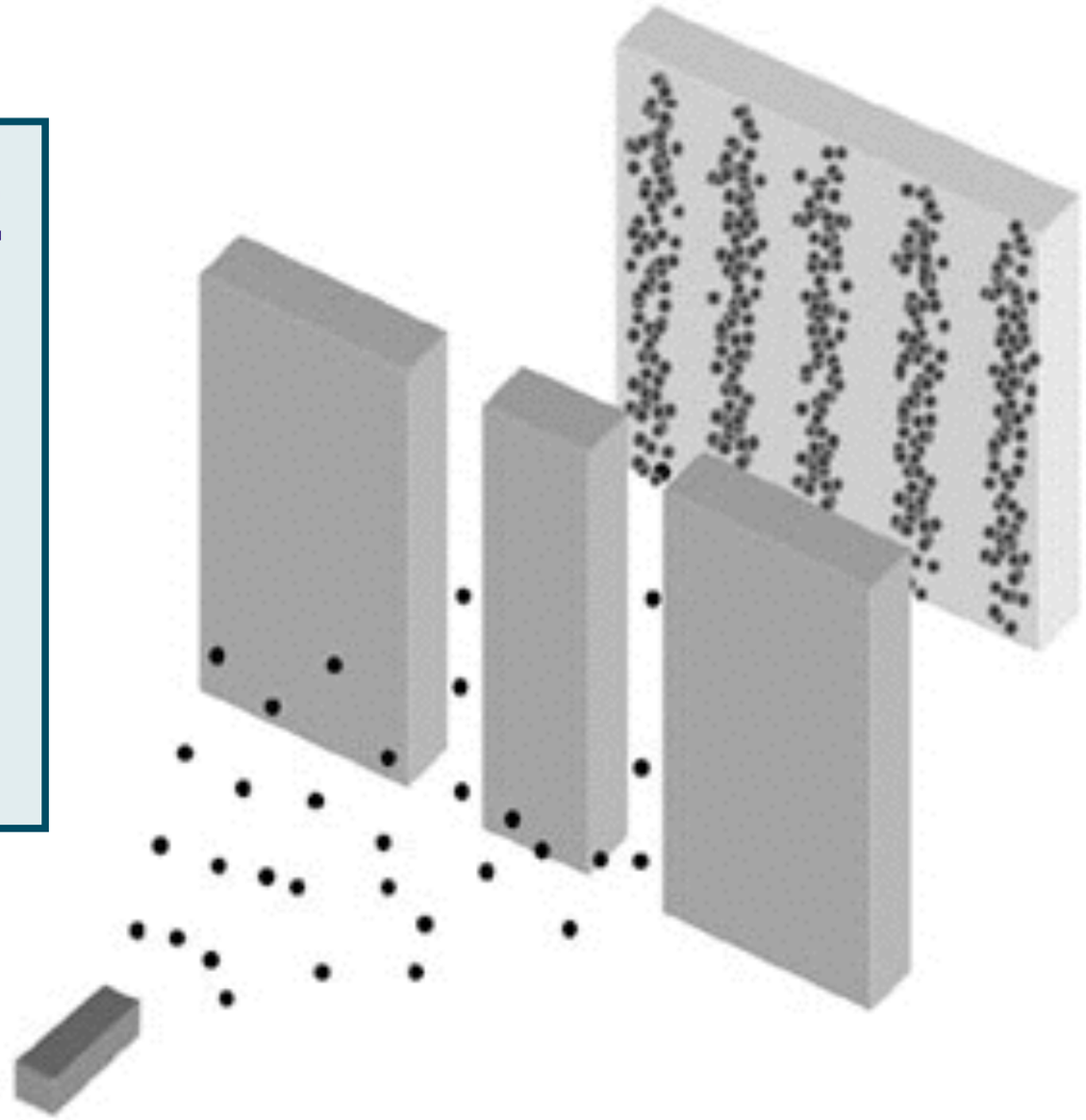
The double slit experiment



Interference of electrons

The double slit experiment

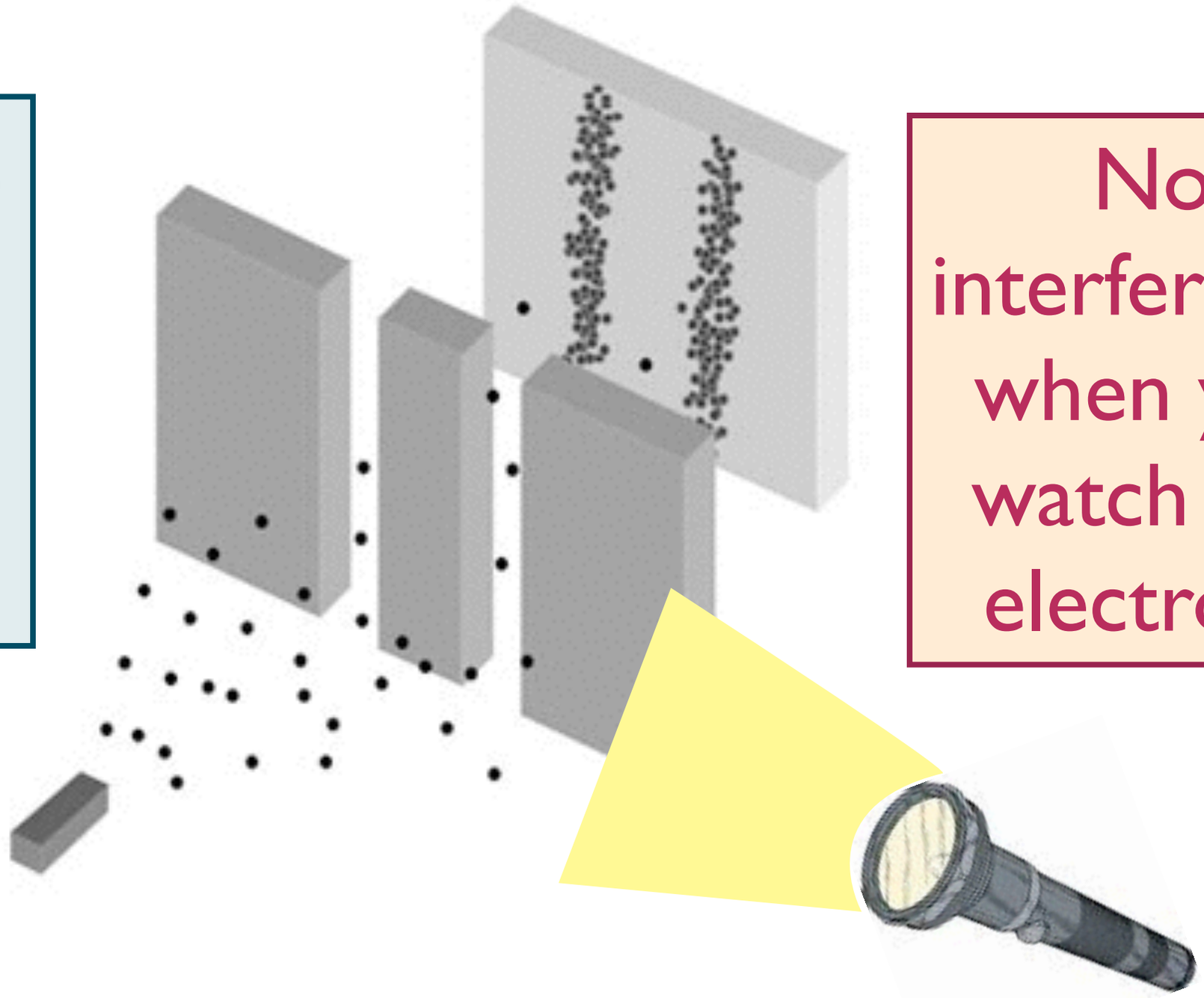
Which slit does an electron pass through ?



Interference of electrons

The double slit experiment

Which slit does an electron pass through ?

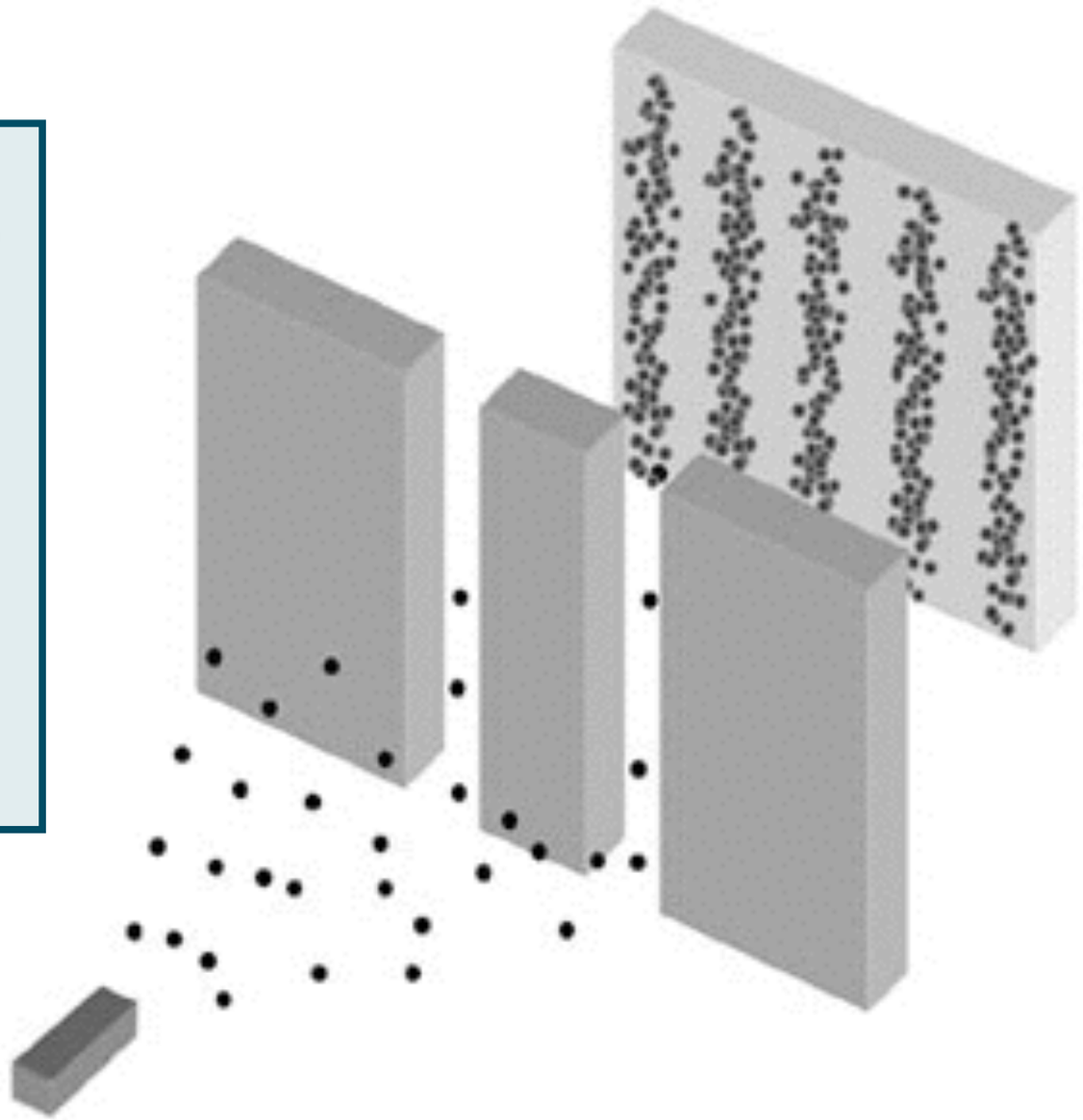


No interference when you watch the electrons

Interference of electrons

The double slit experiment

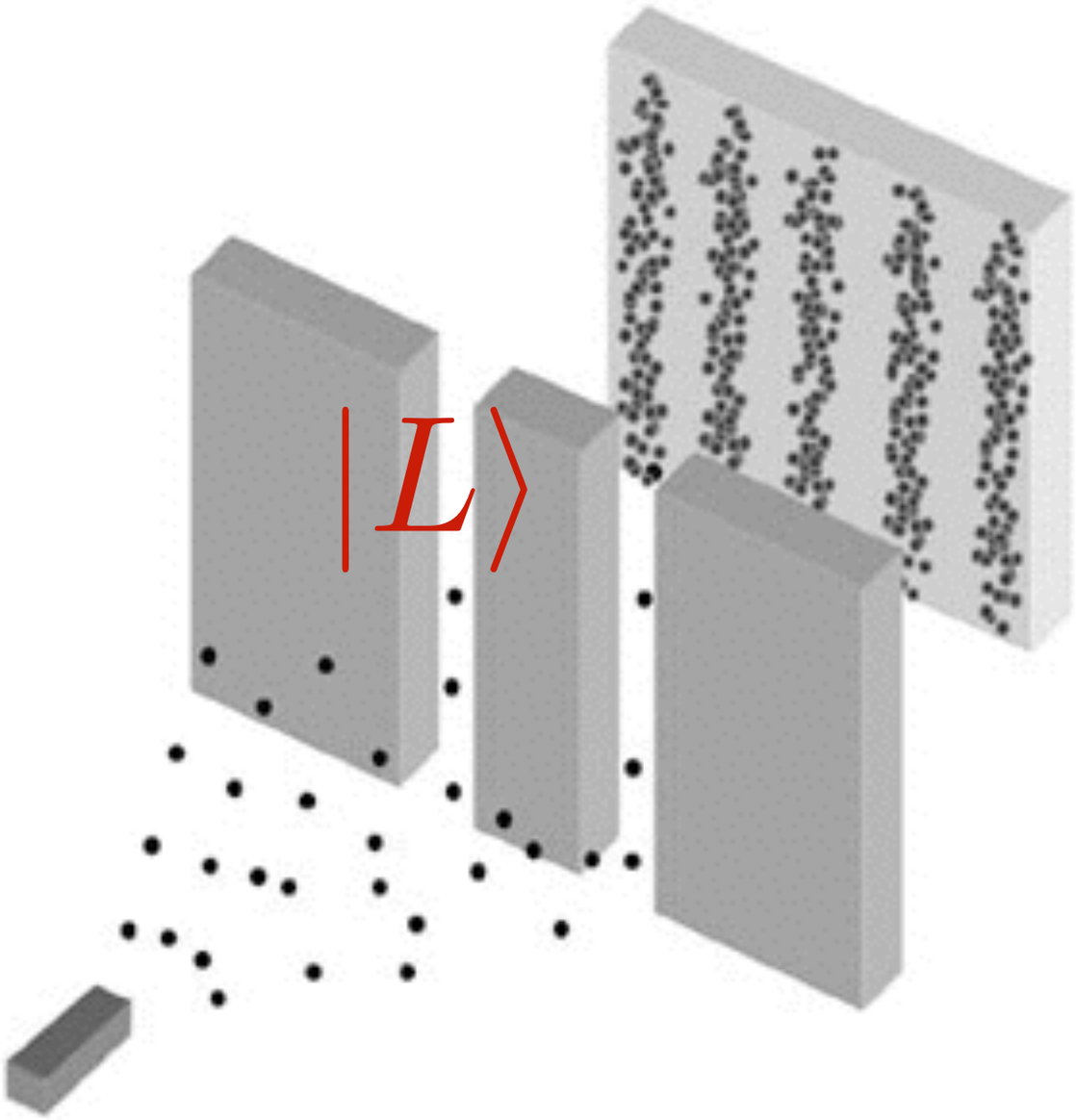
Which slit does an electron pass through ?



Each electron passes through both slits !

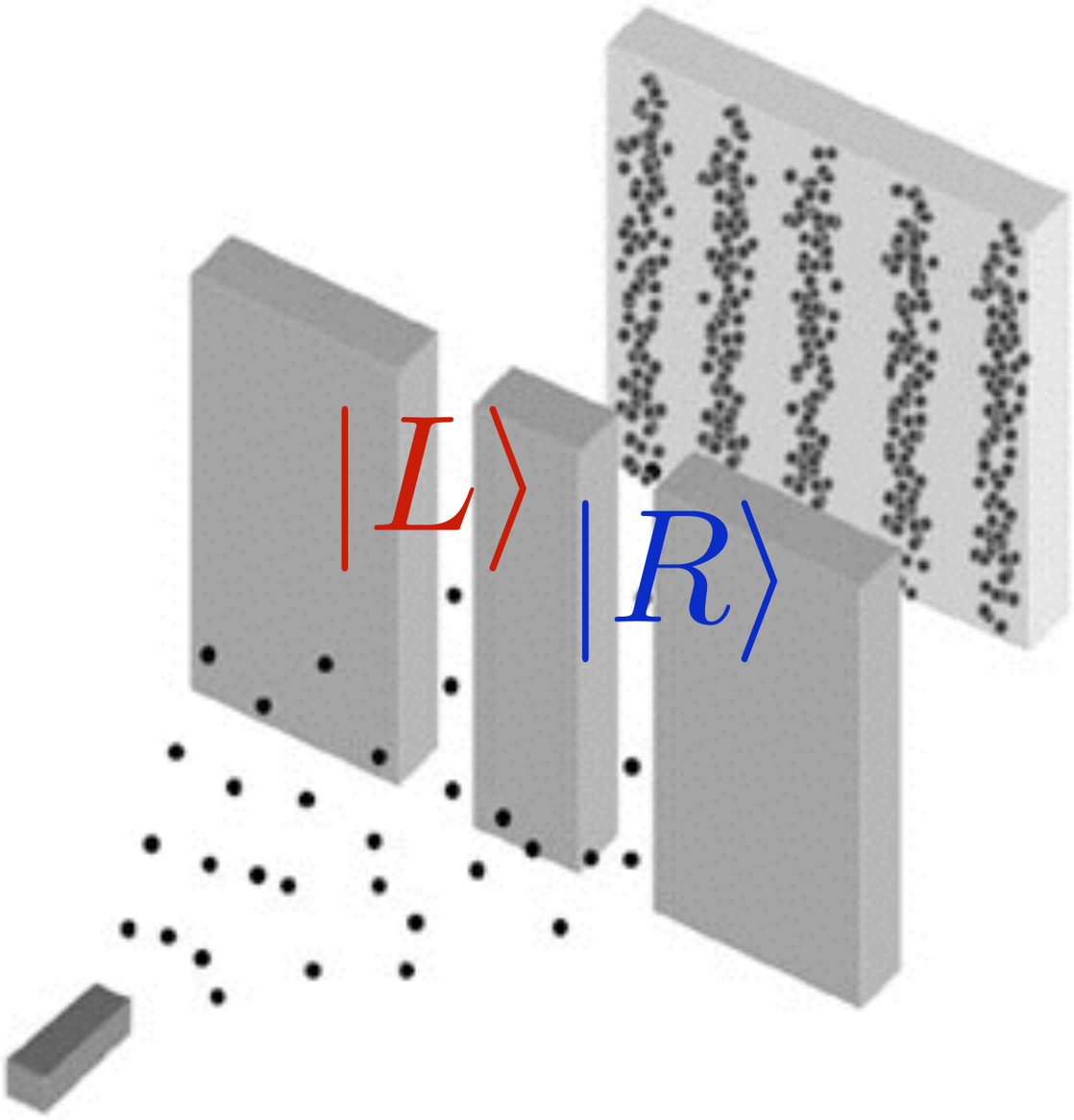
Interference of electrons

The double slit experiment



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

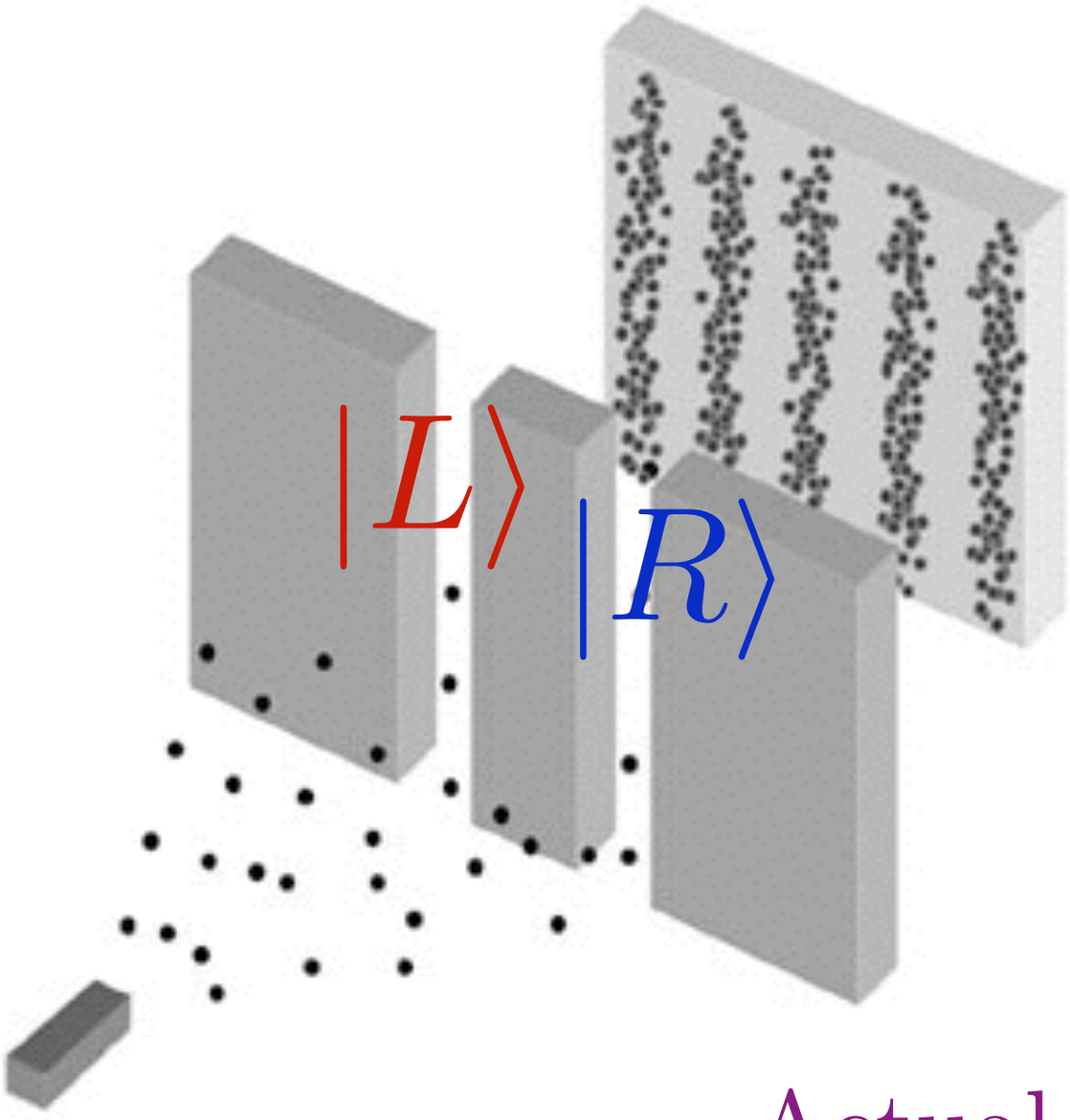
The double slit experiment



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

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

The double slit experiment



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

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

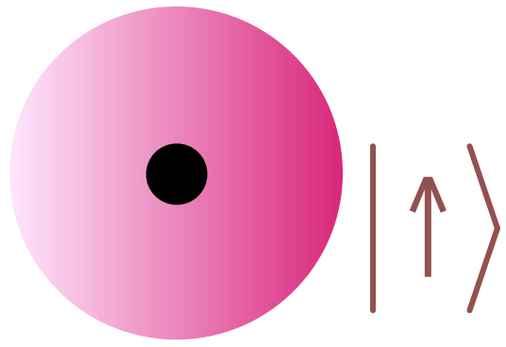
Actual state of *each* electron is

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

Quantum Entanglement: quantum superposition with more than one particle

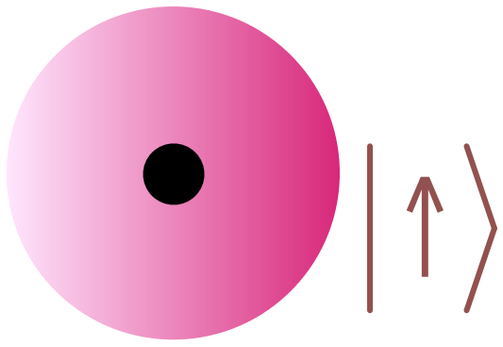
Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

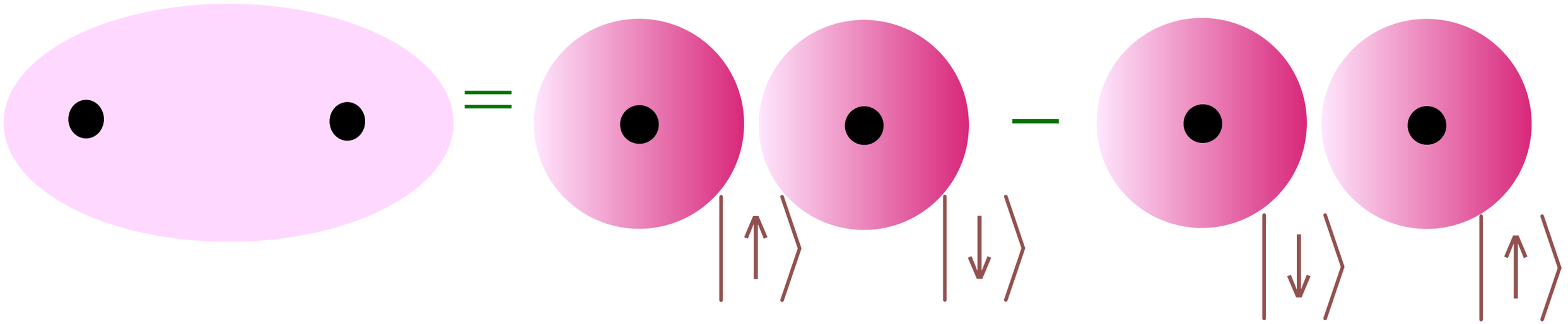


Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

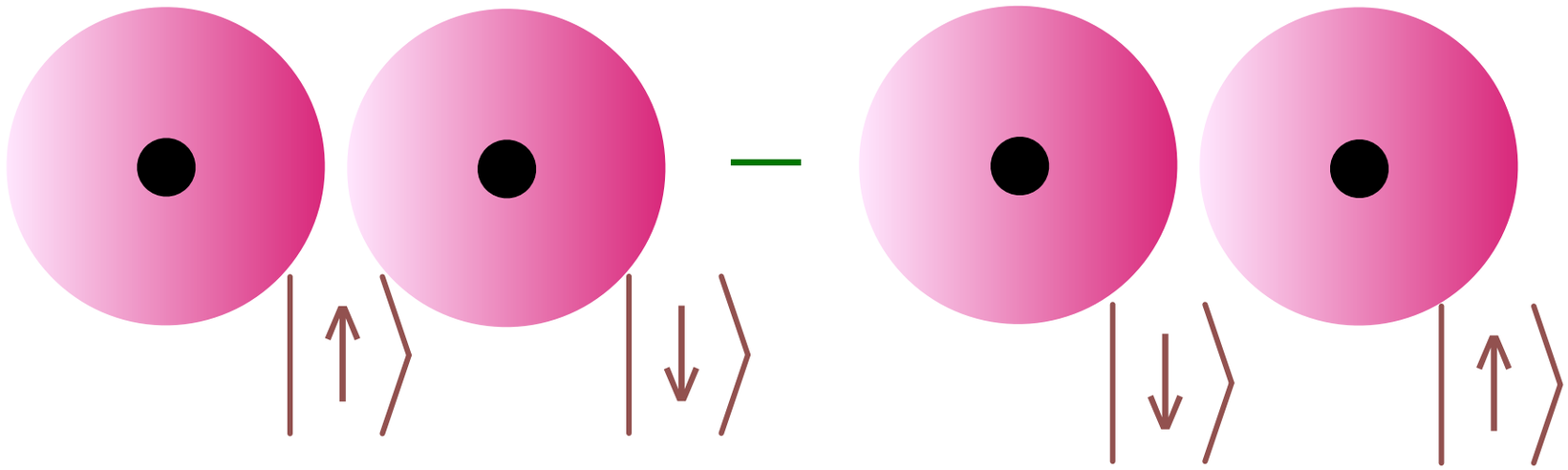


Hydrogen molecule:

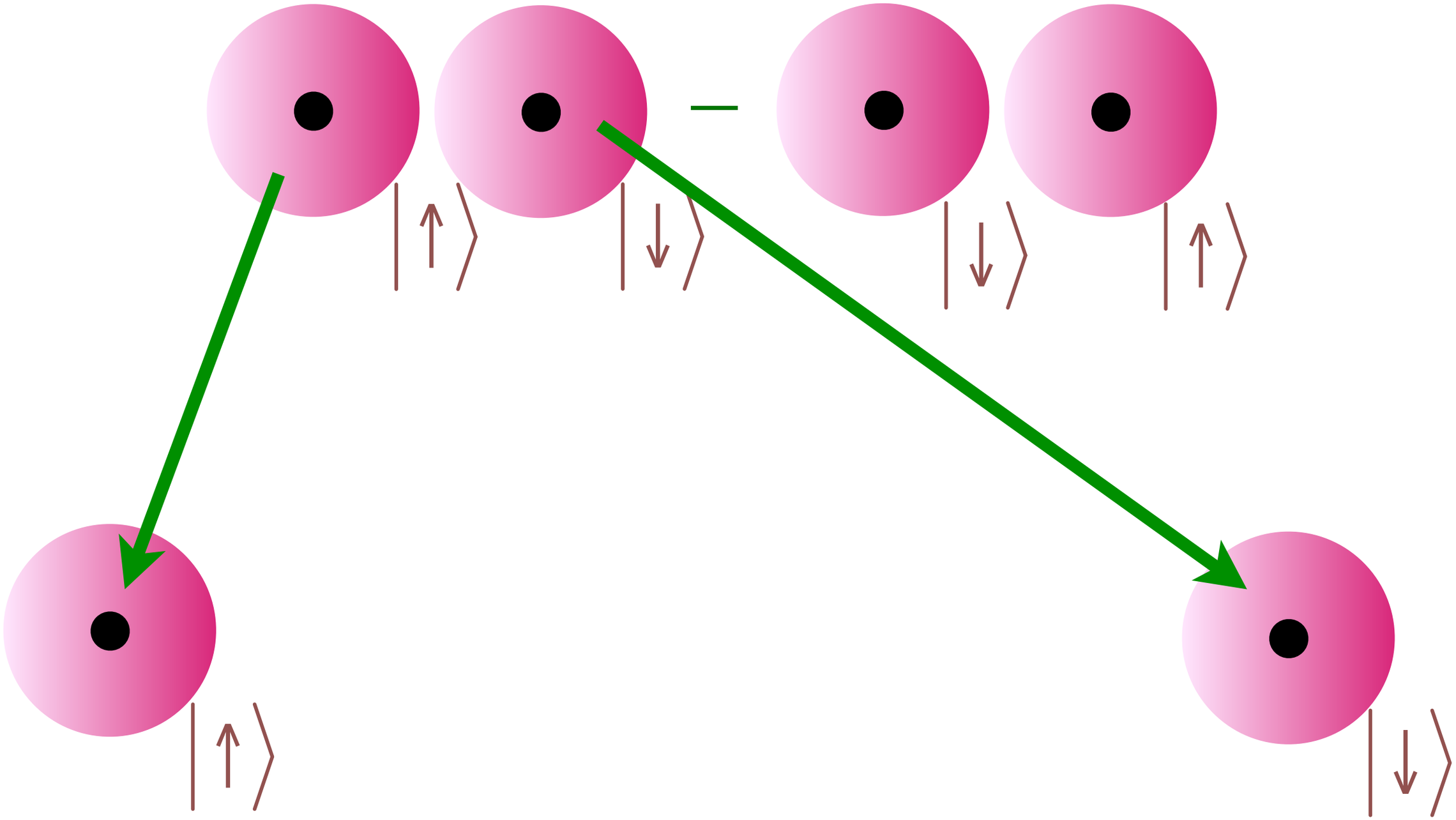


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

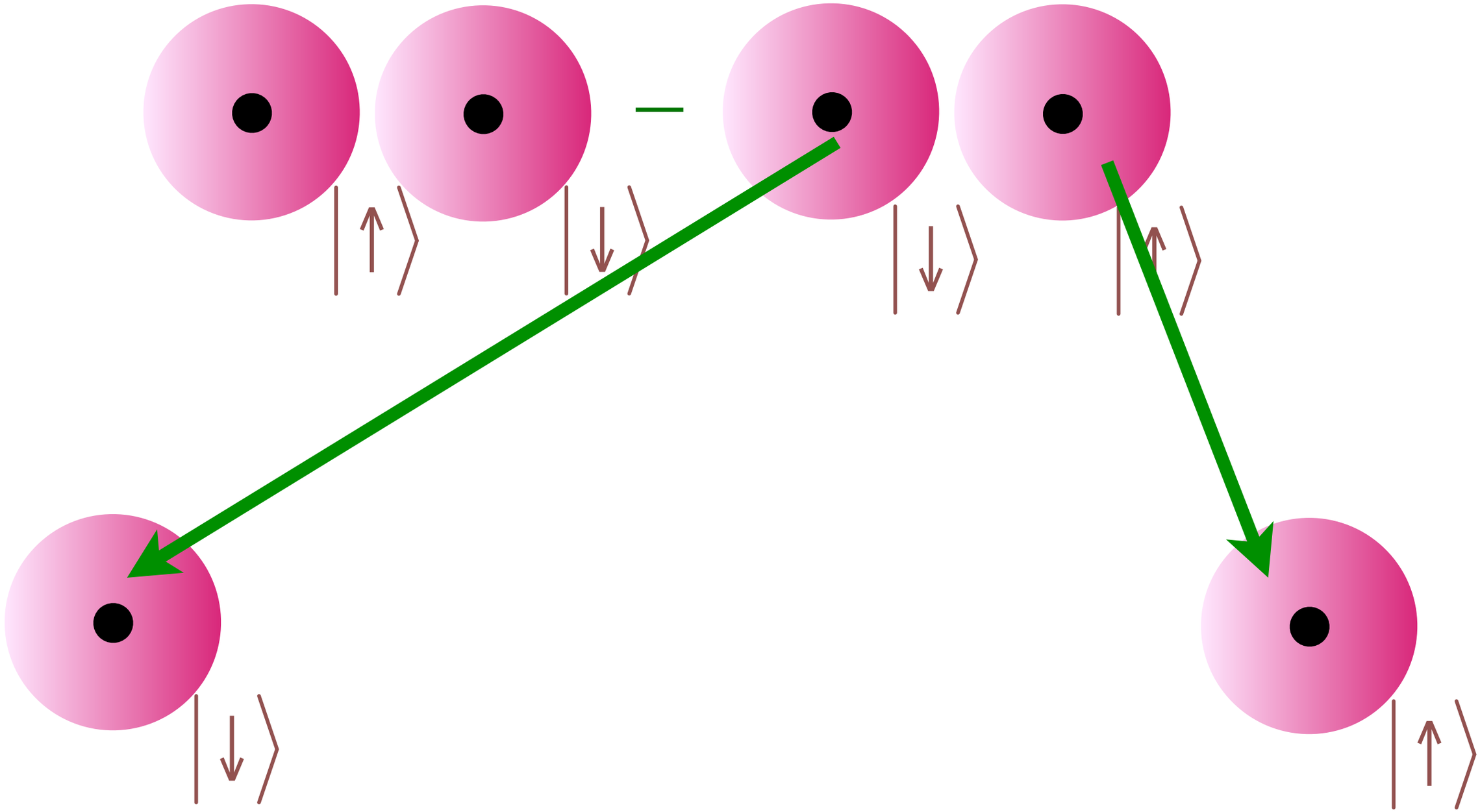
Quantum Entanglement: quantum superposition with more than one particle



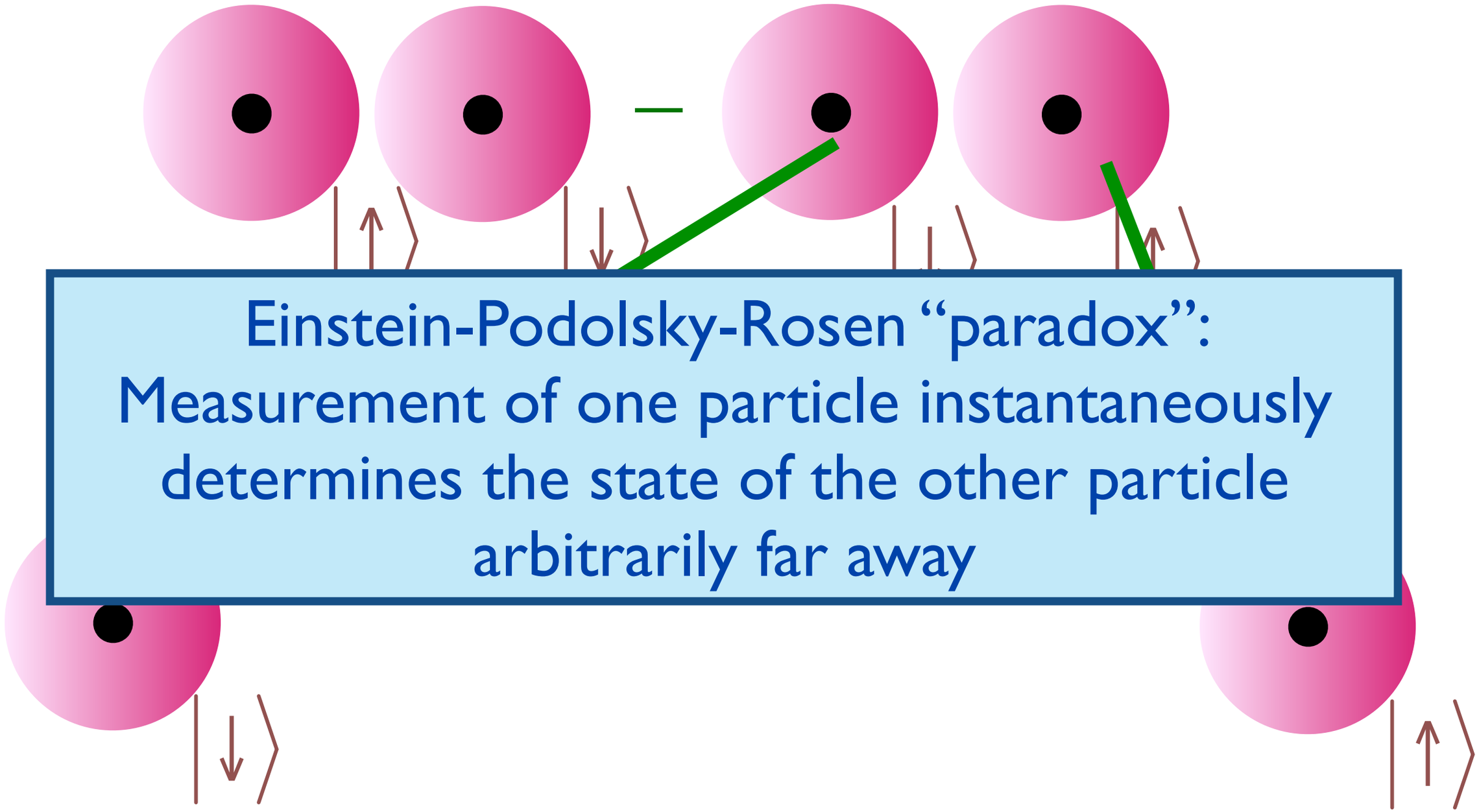
Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



Quantum superposition and entanglement

Quantum superposition and entanglement

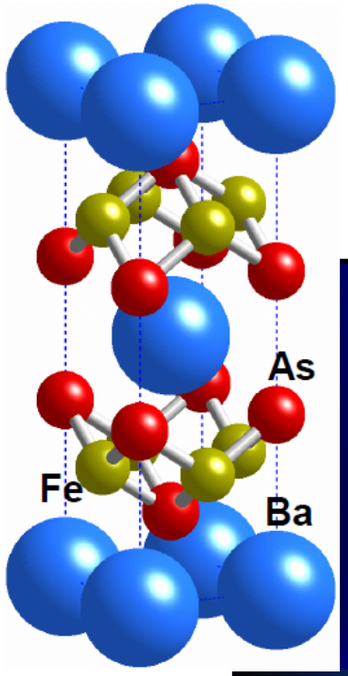
Quantum critical points and long-range entanglement of electrons in crystals

String theory and black holes

Quantum superposition and entanglement

Quantum critical points and long-range entanglement of electrons in crystals

String theory and black holes



Resistivity
$\sim \rho_0 + AT^{\alpha}$

Strange Metal

$BaFe_2(As_{1-x}P_x)_2$

Antiferromagnet

Superconductivity

Ordinary metal

T (K)

100

0

0

0.2

0.4

0.6

x

α

2.0

1.0

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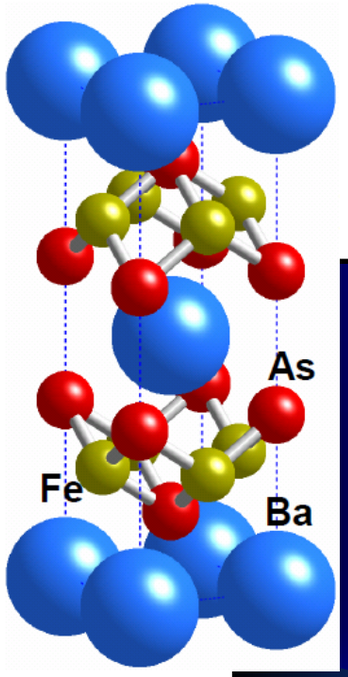
S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)



Electrons pair to form "Cooper pairs" which are *bosons*.

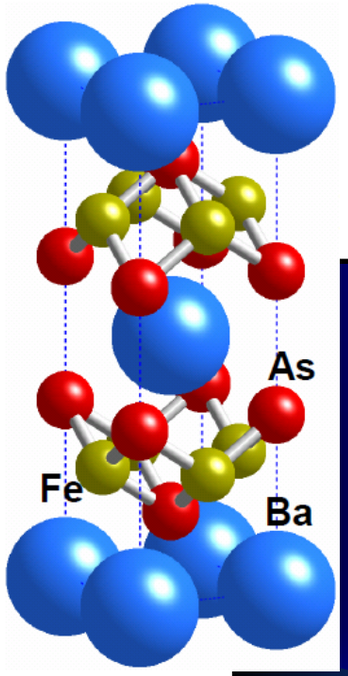
Bosons do not obey the exclusion principle. So all the Cooper pairs occupy the lowest energy state, and we obtain a "Bose-Einstein condensate.

This condensate is responsible for superconductivity.

Resistivity
$\rho = \rho_0 + AT^{\alpha}$

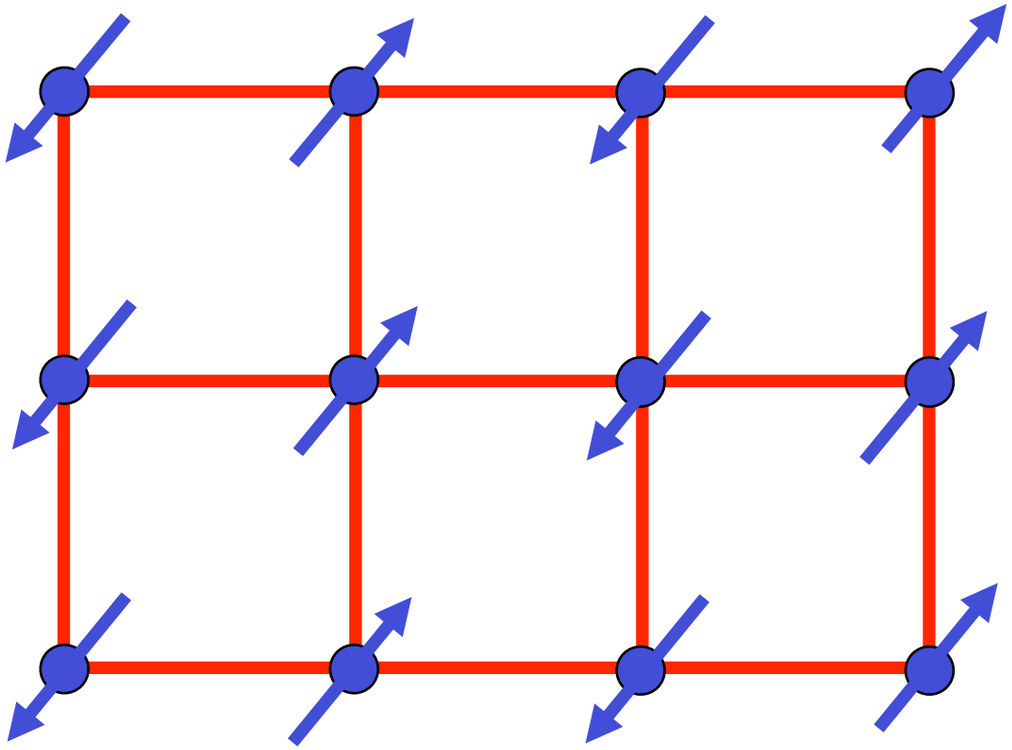
Ordinary metal

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)



Resistivity

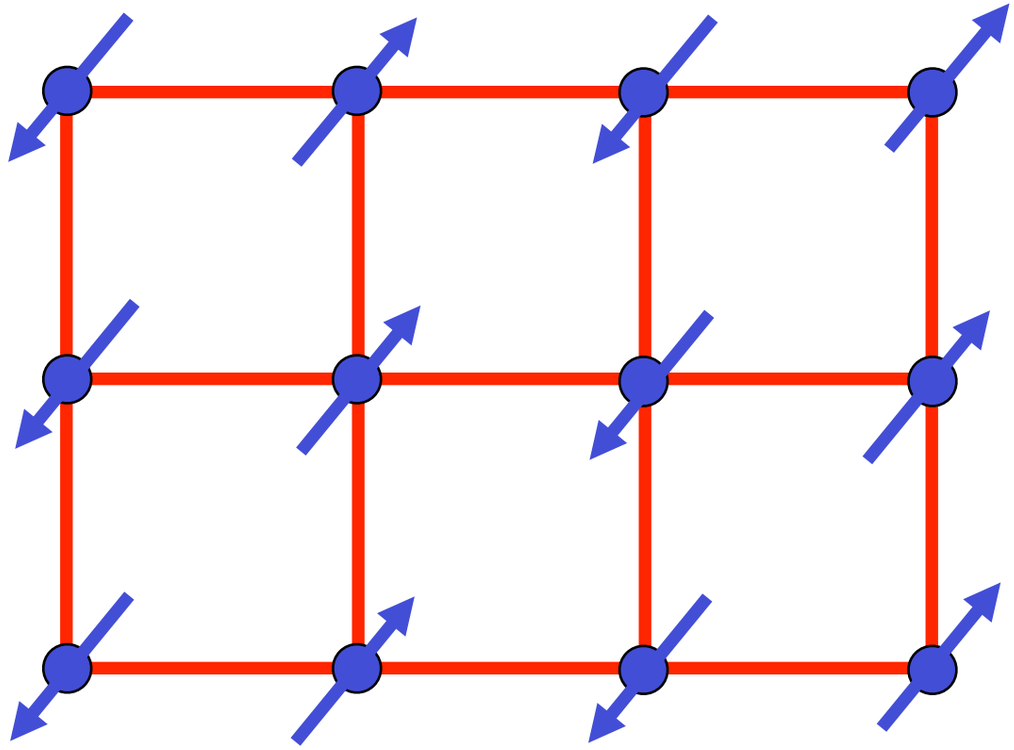
$\rho = \rho_0 + AT^{\alpha}$



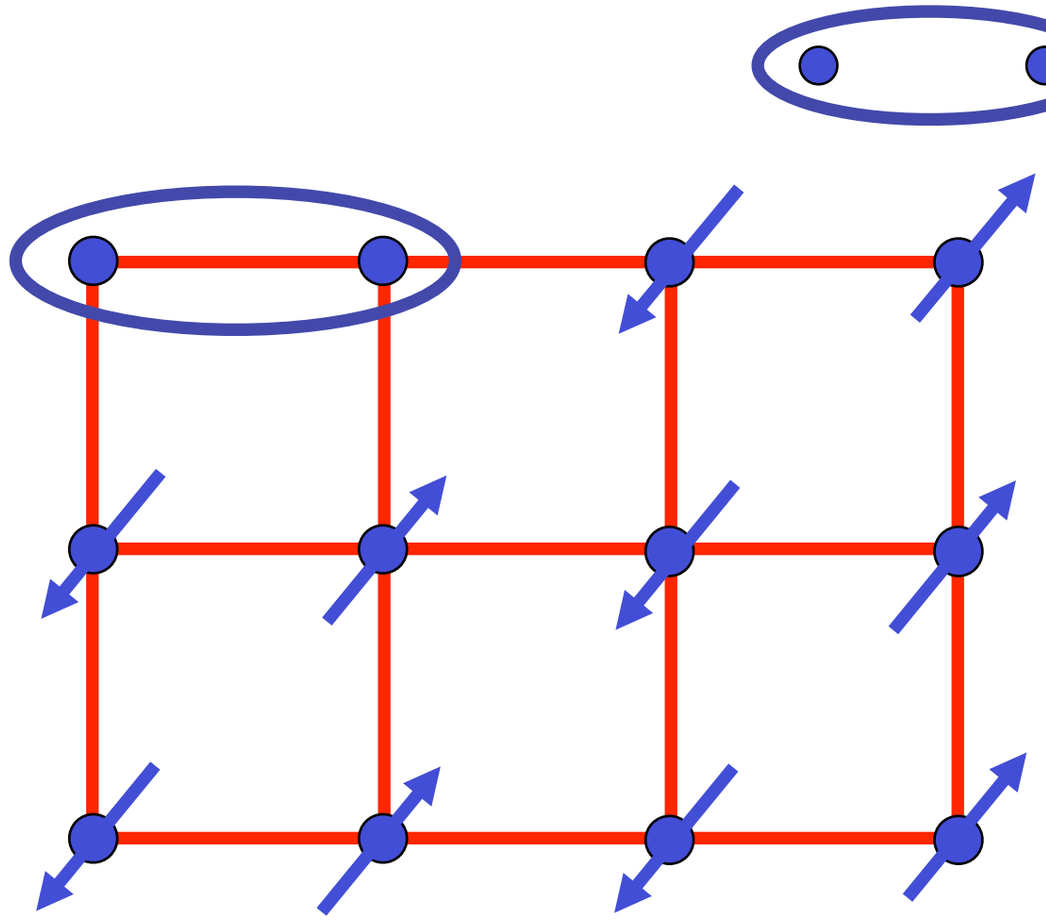
Spins of electrons on Fe sites

Ordinary metal

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)

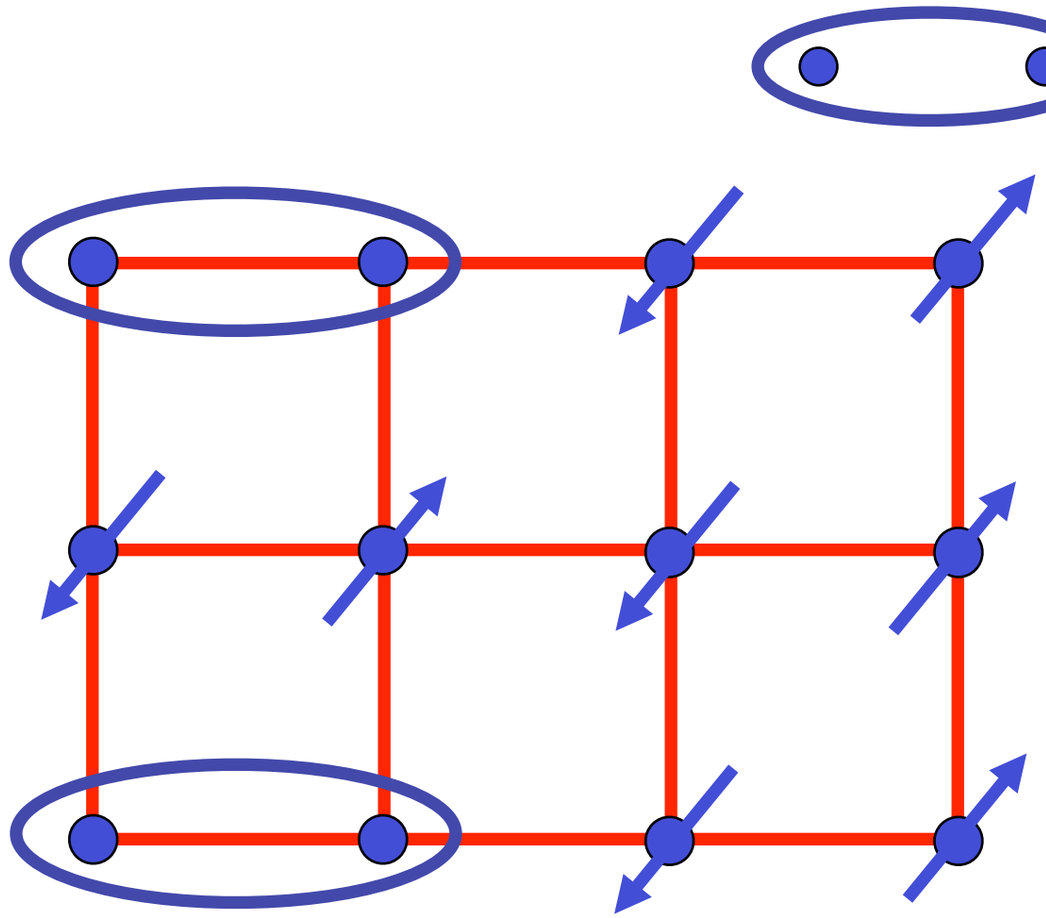


Spins of electrons on Fe sites



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

As we increase *x*, the electron spins entangle in pairs



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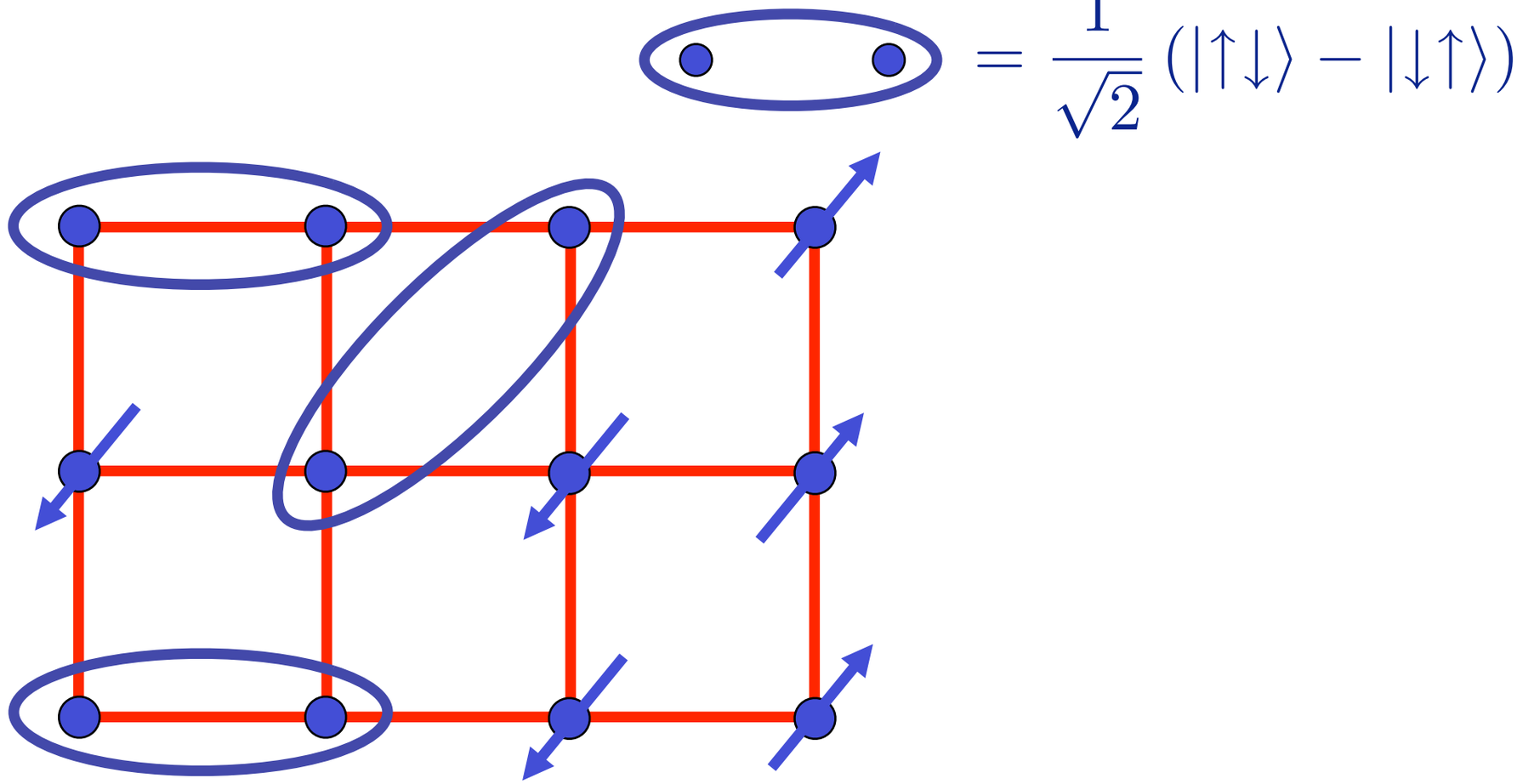
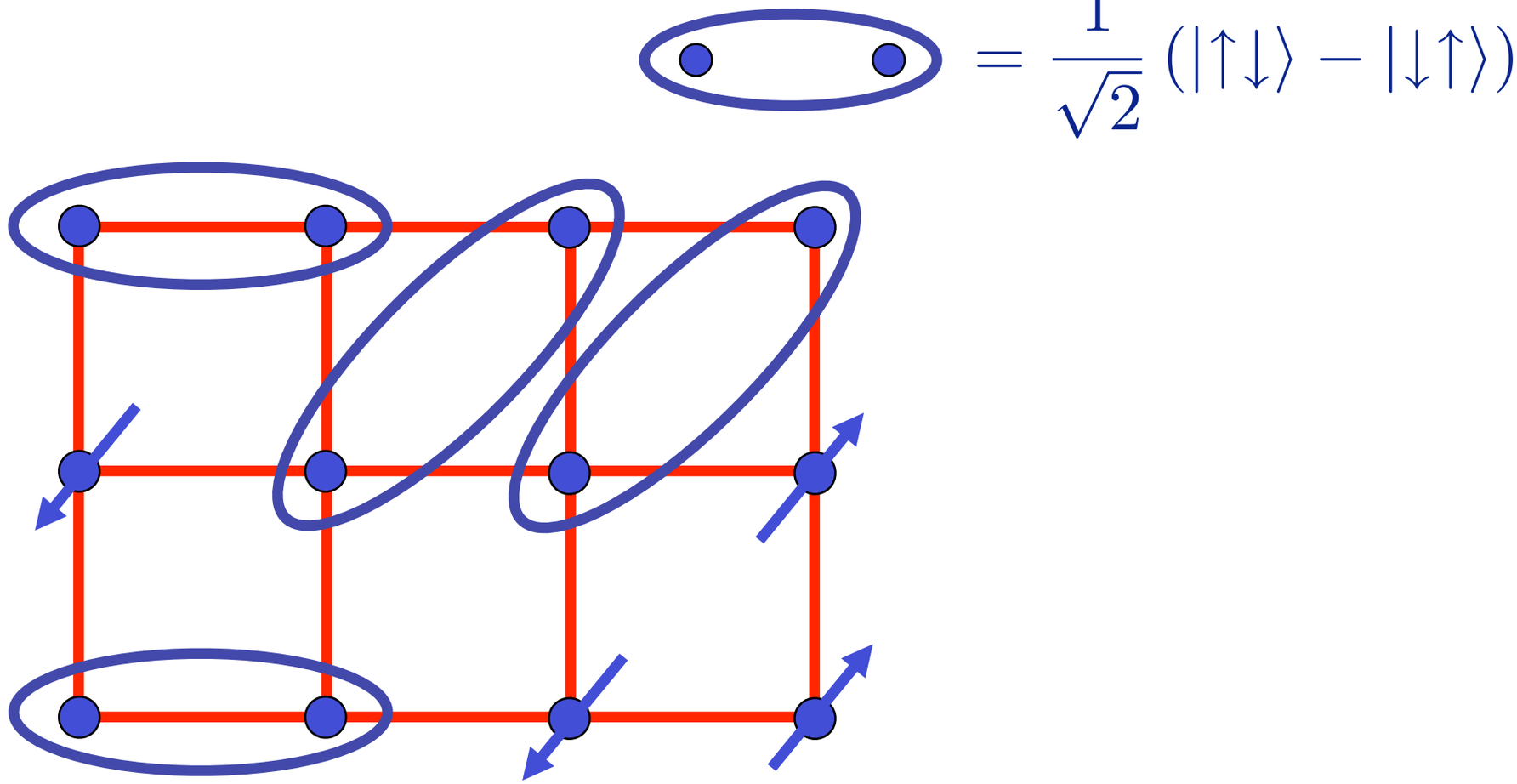


As we increase *x*, the electron spins entangle in pairs



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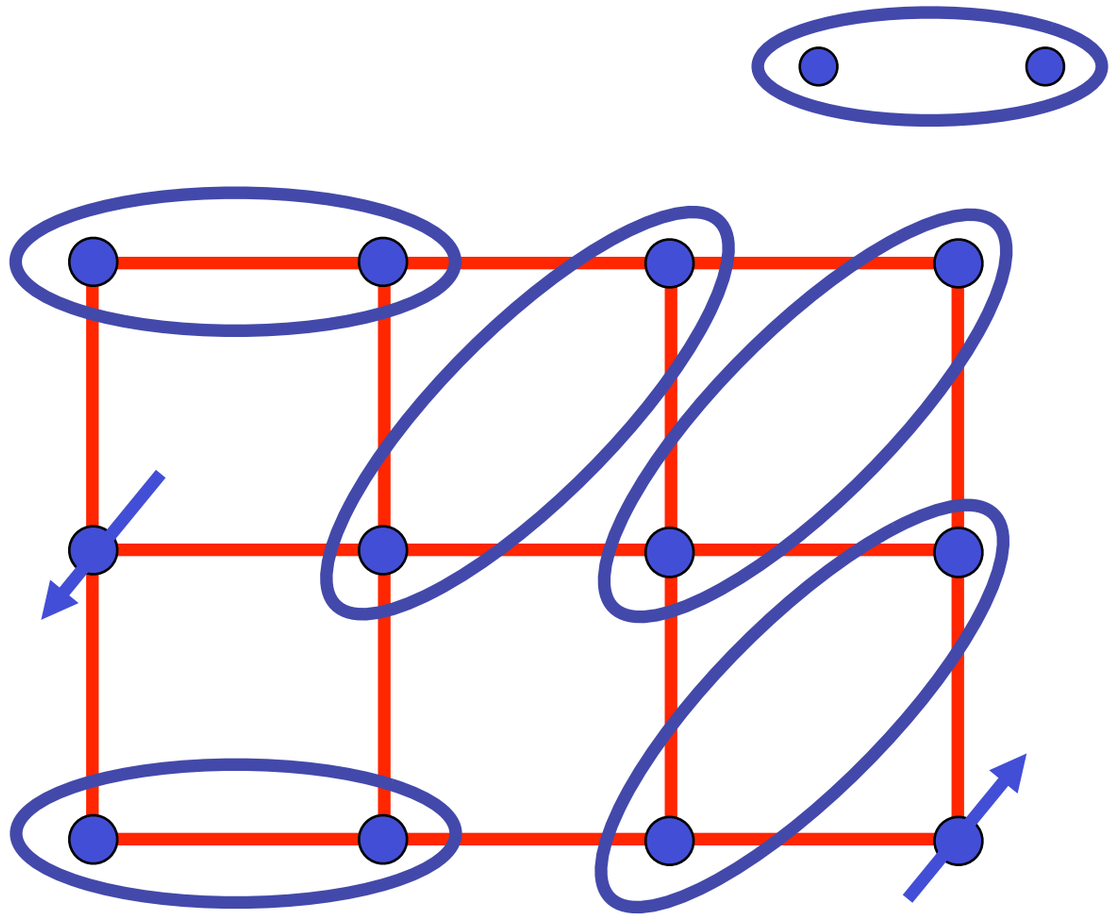

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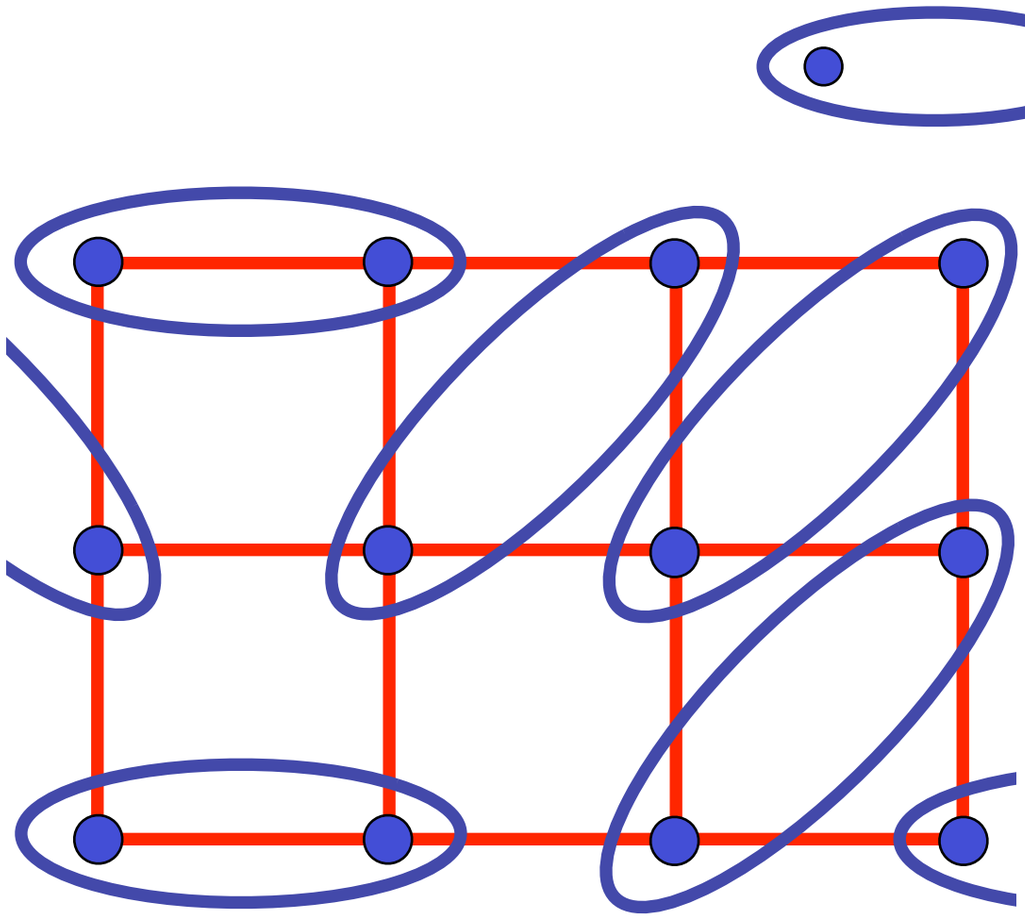

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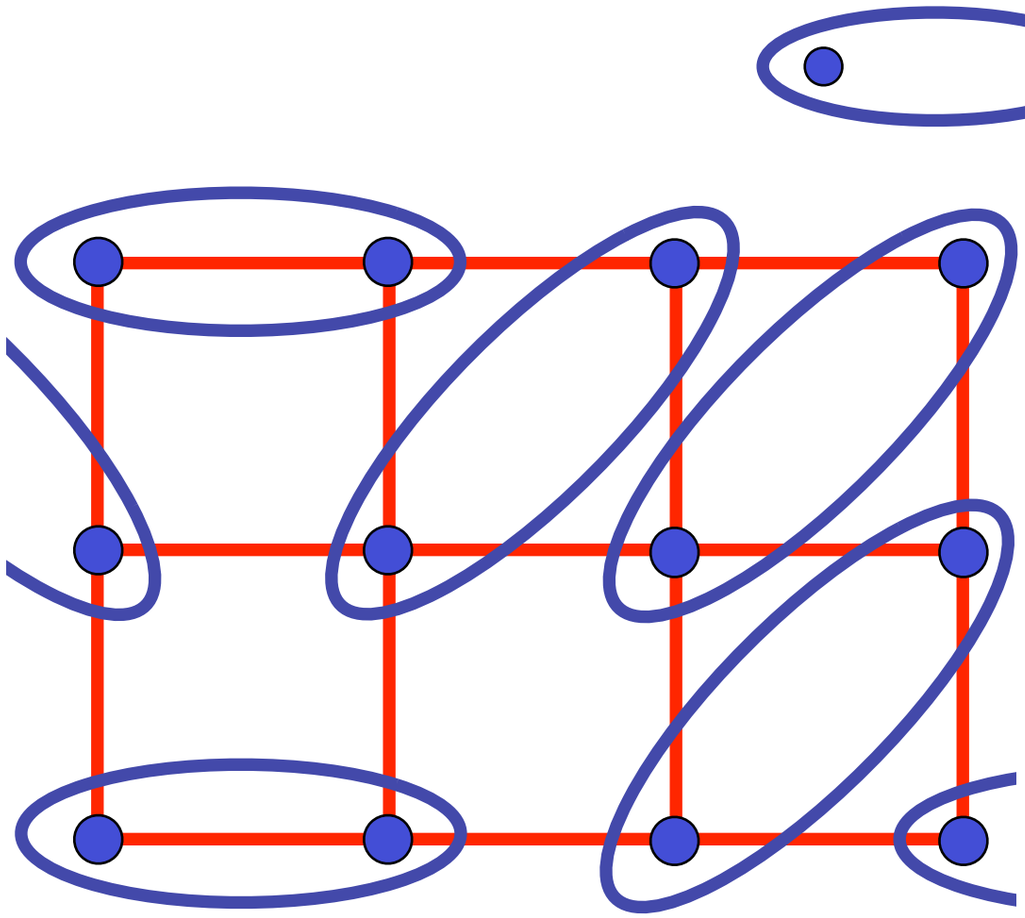
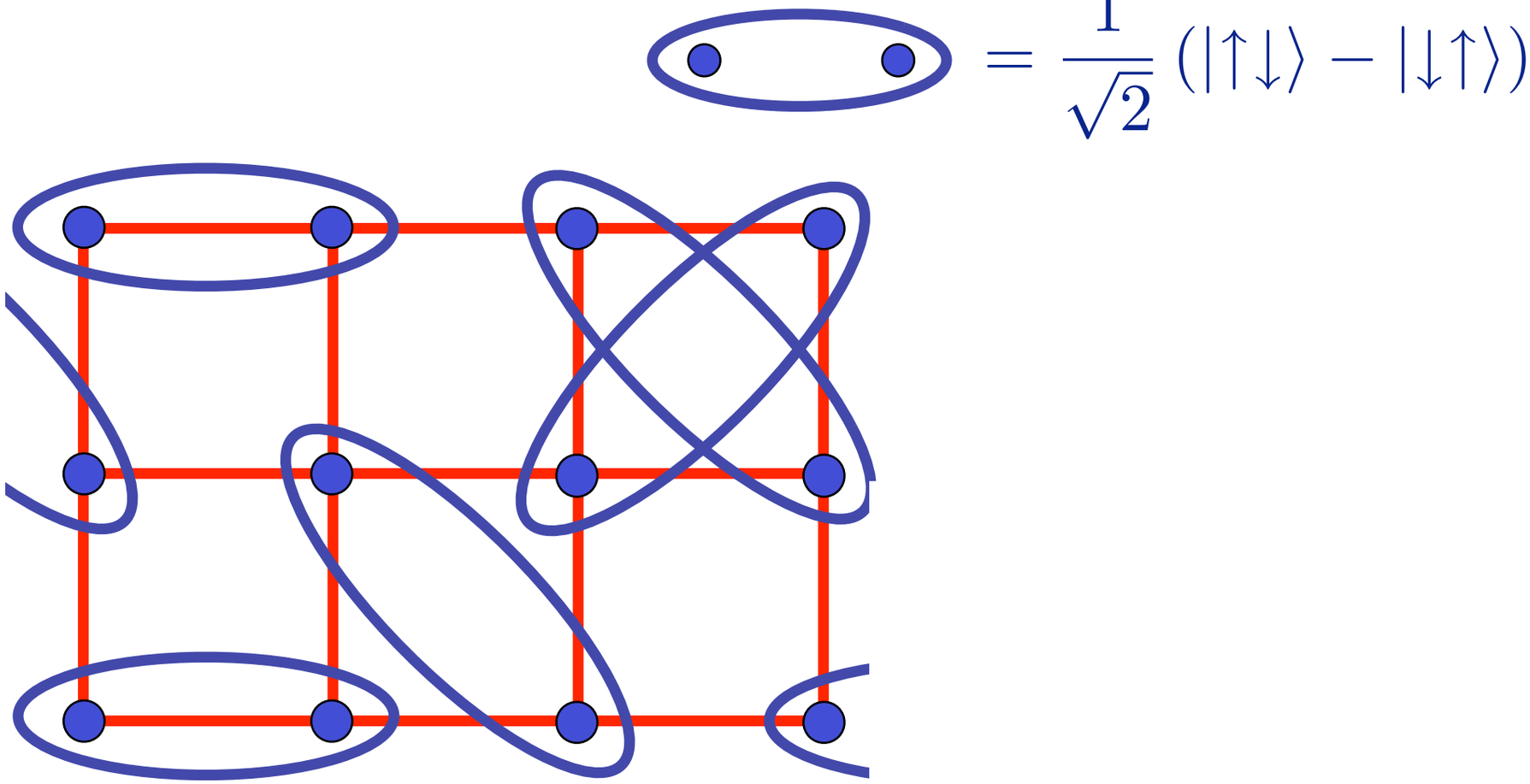


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

As we increase *x*, the electron spins
entangle in pairs.
And then the pairs entangle with each other.



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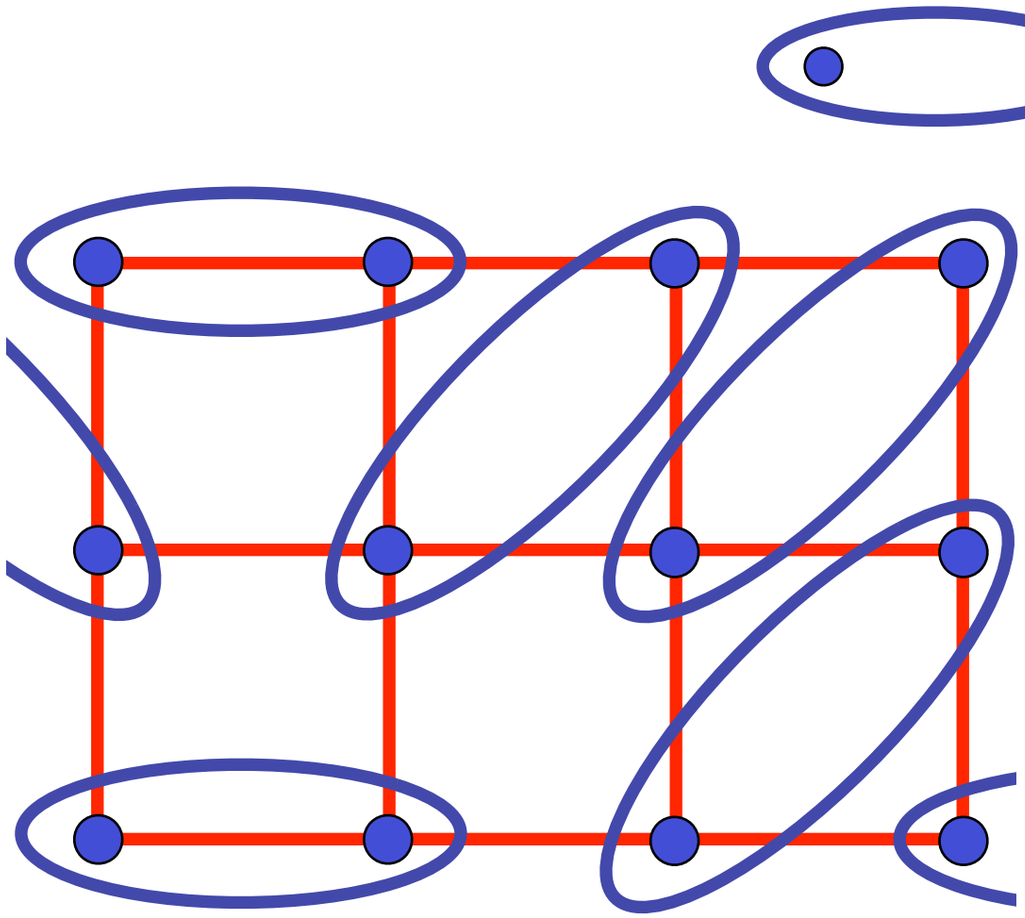

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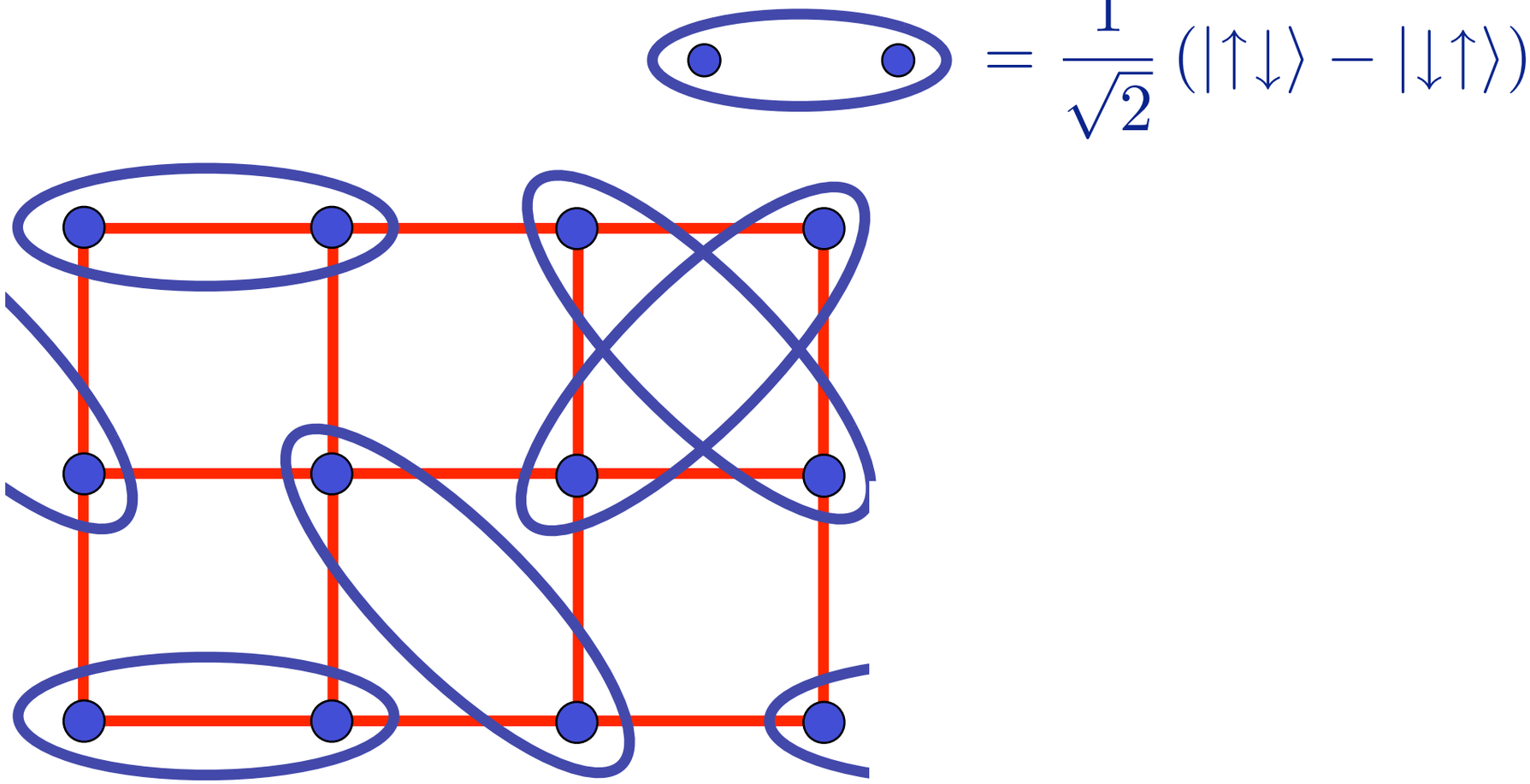

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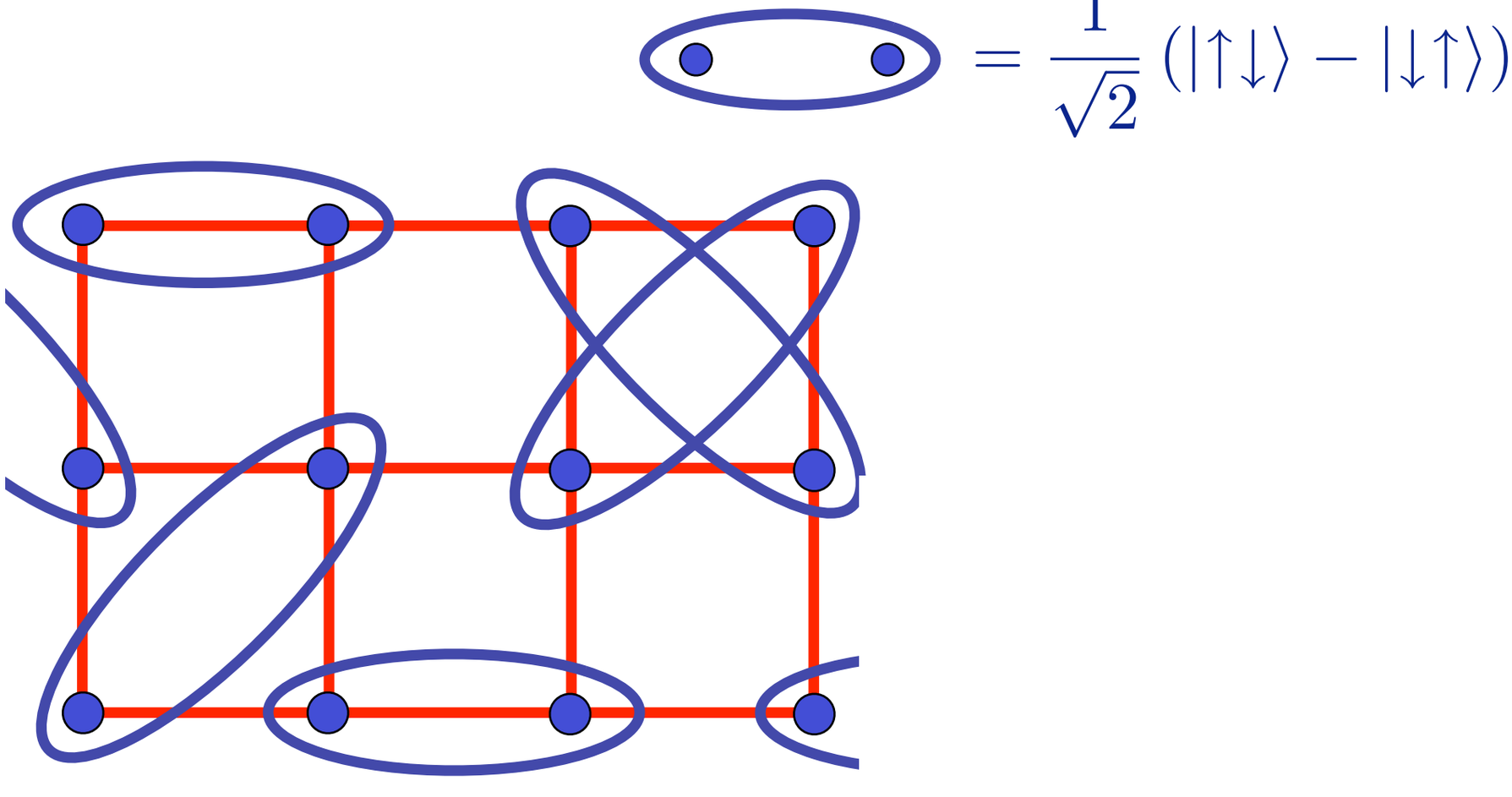

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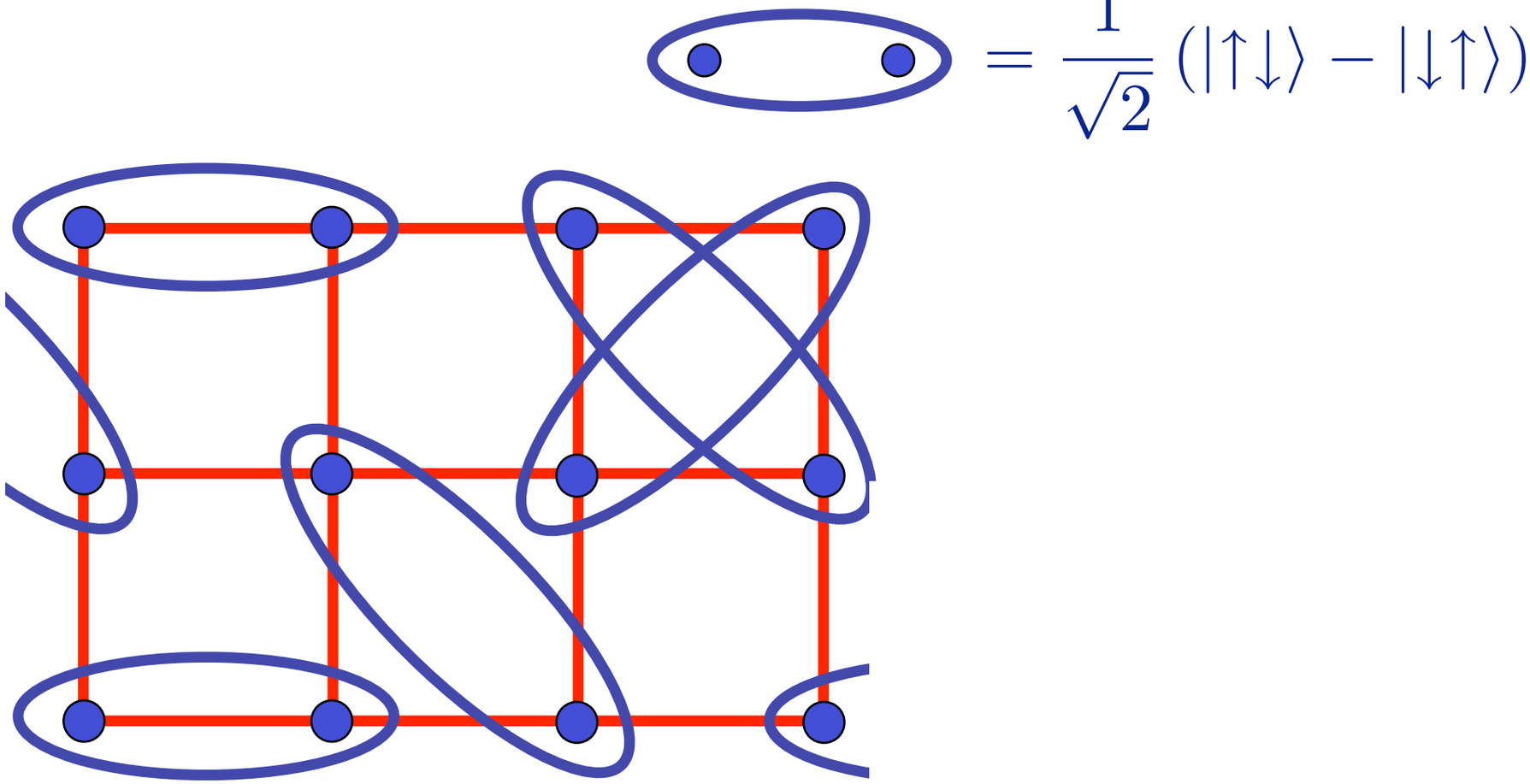

As we increase *x*, the electron spins
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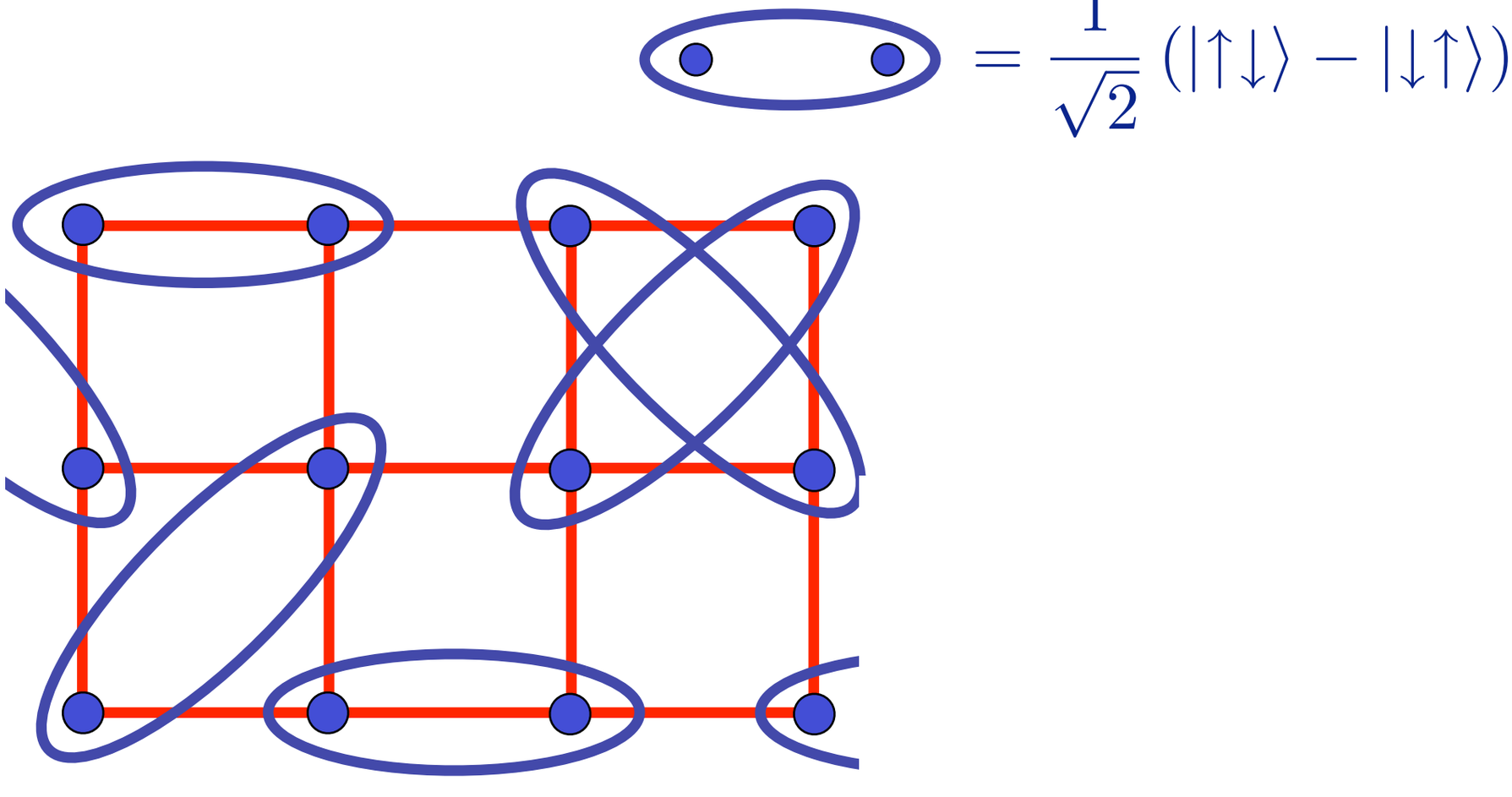

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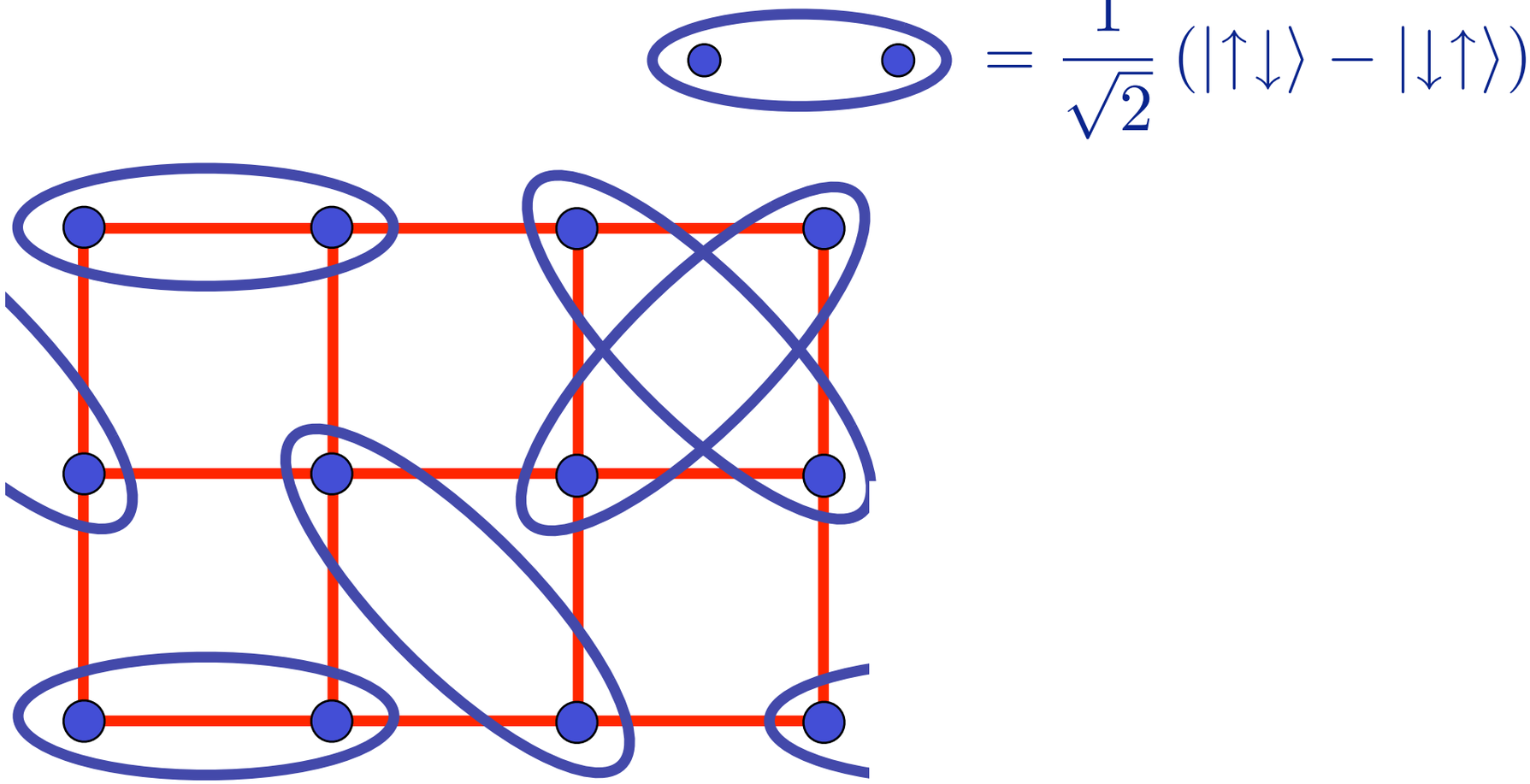

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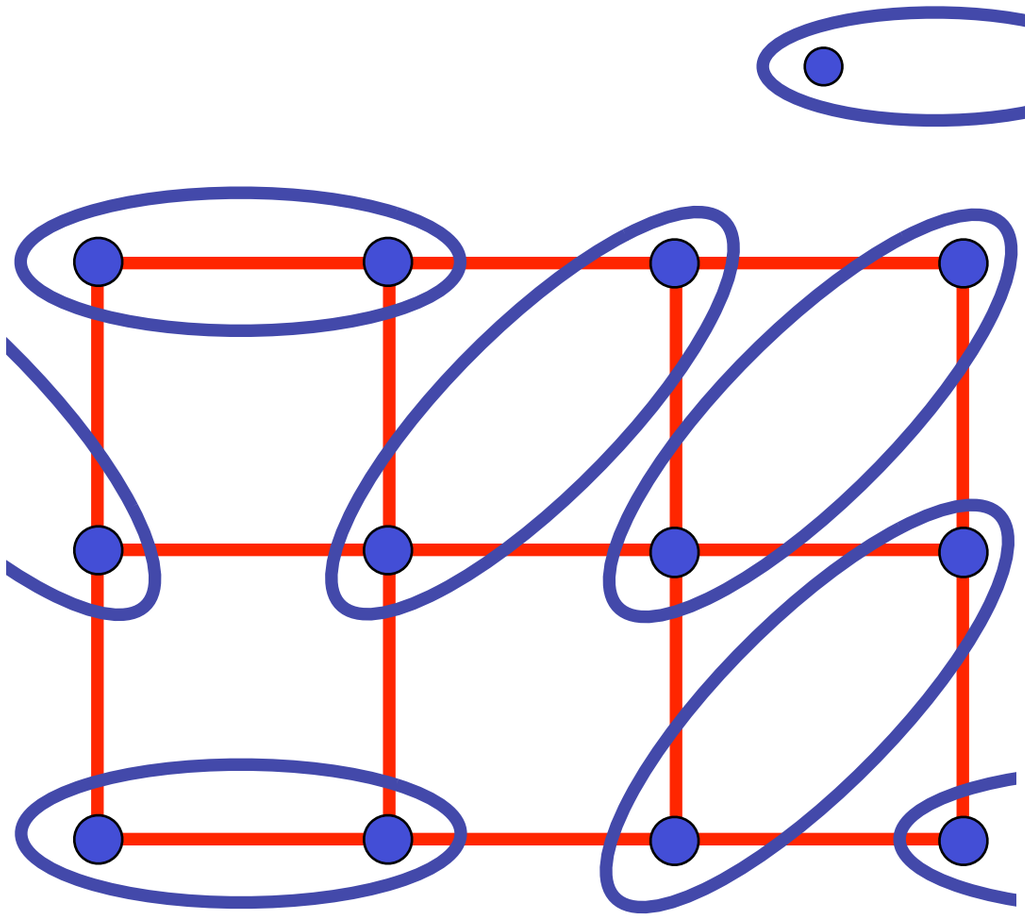

$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

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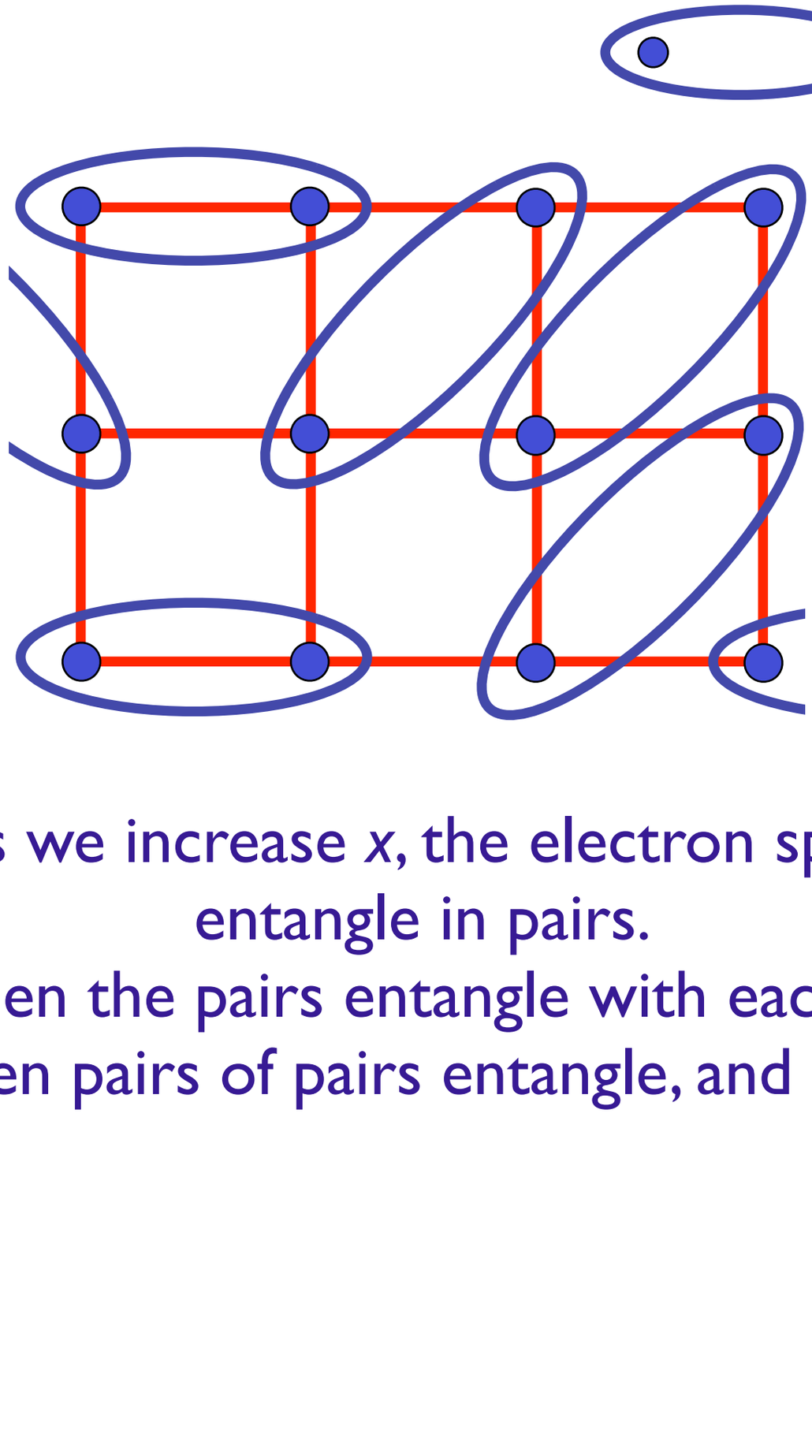

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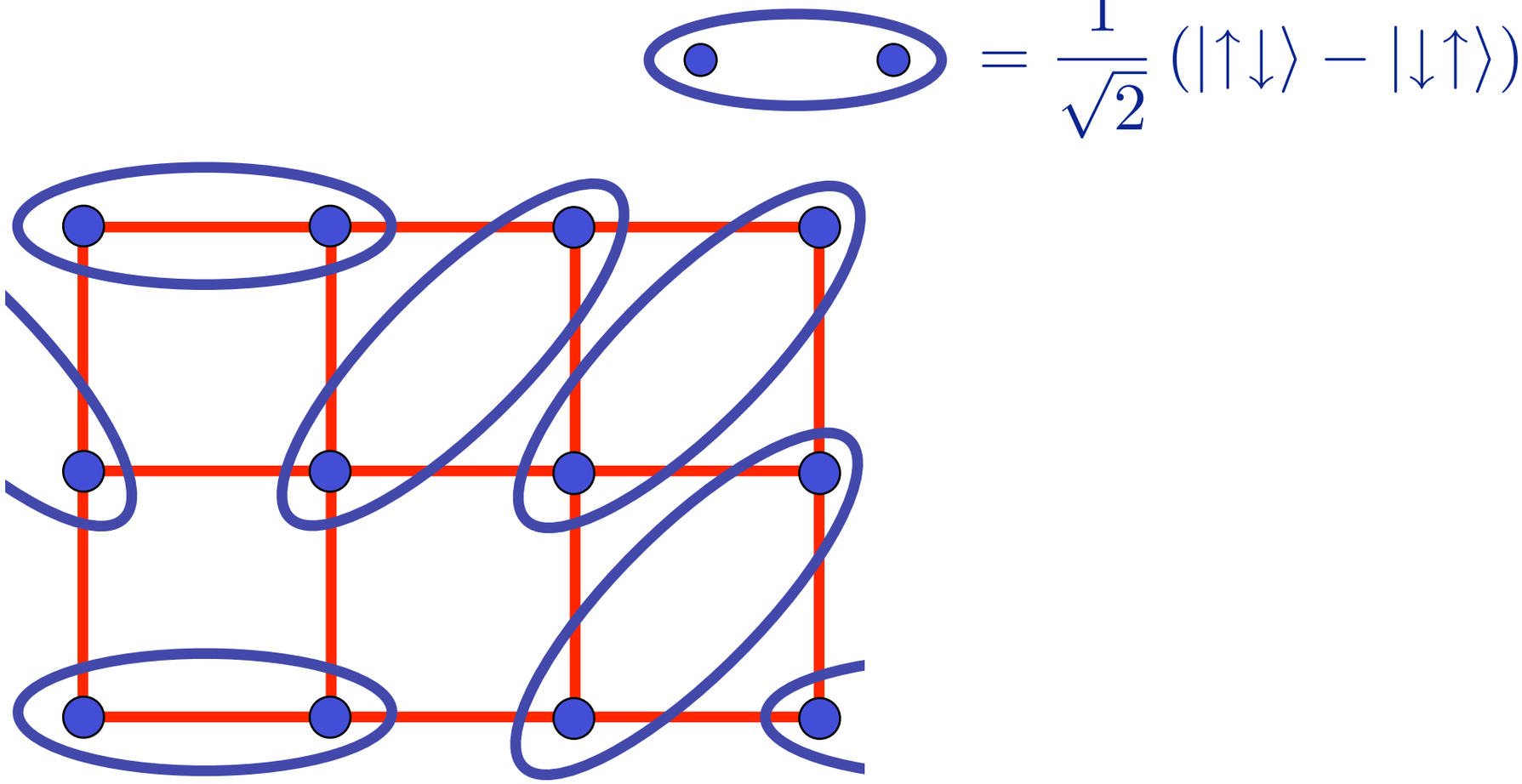
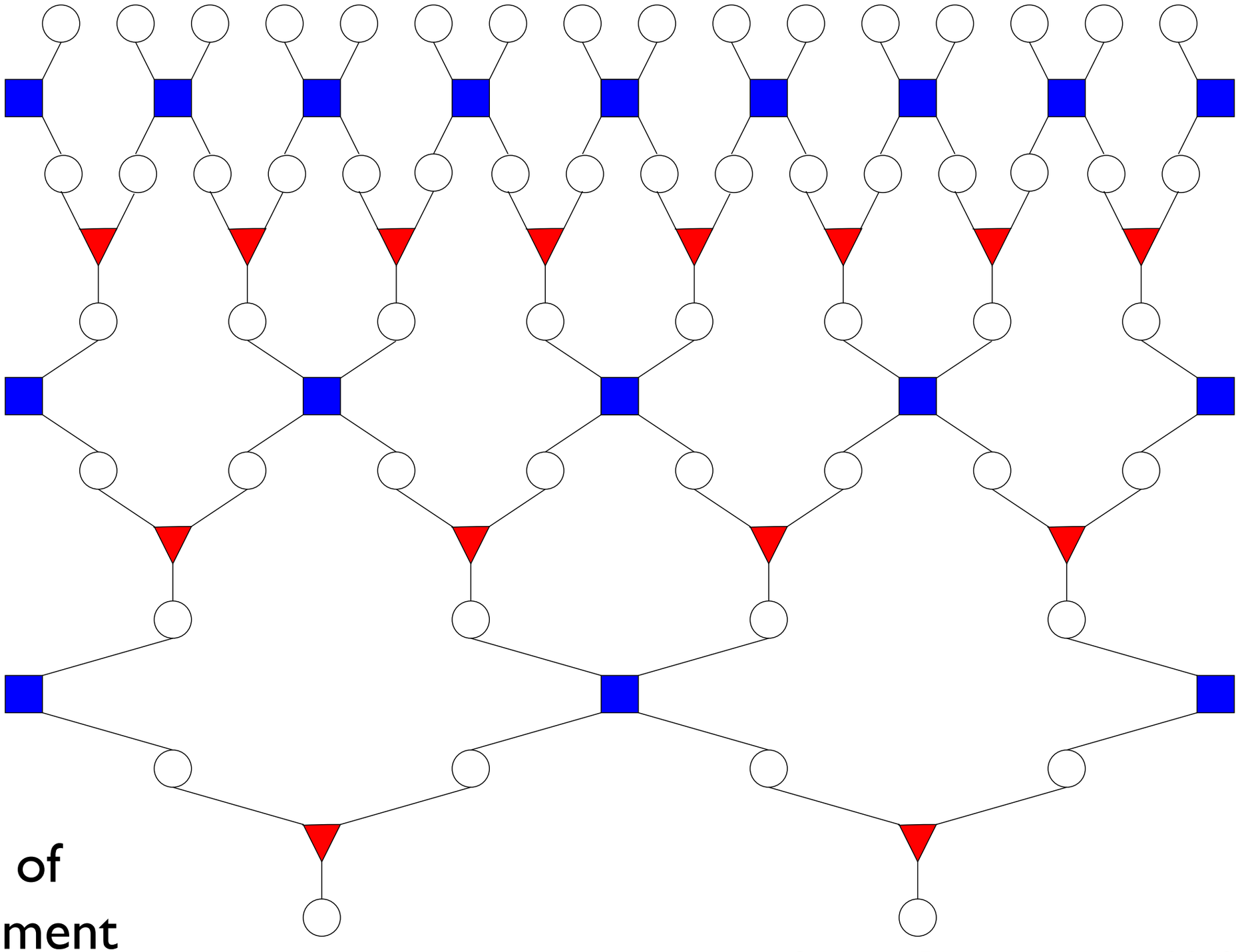


As we increase *x*, the electron spins
entangle in pairs.
And then the pairs entangle with each other.
And then pairs of pairs entangle, and so on….
This goes on ad-infinitum at the
quantum critical point, leading to
long-range quantum entanglement

Tensor network representation of entanglement at quantum critical point

D-dimensional space



depth of entanglement

G. Vidal, Phys. Rev. Lett. 99, 220405 (2007)

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String theory and black holes

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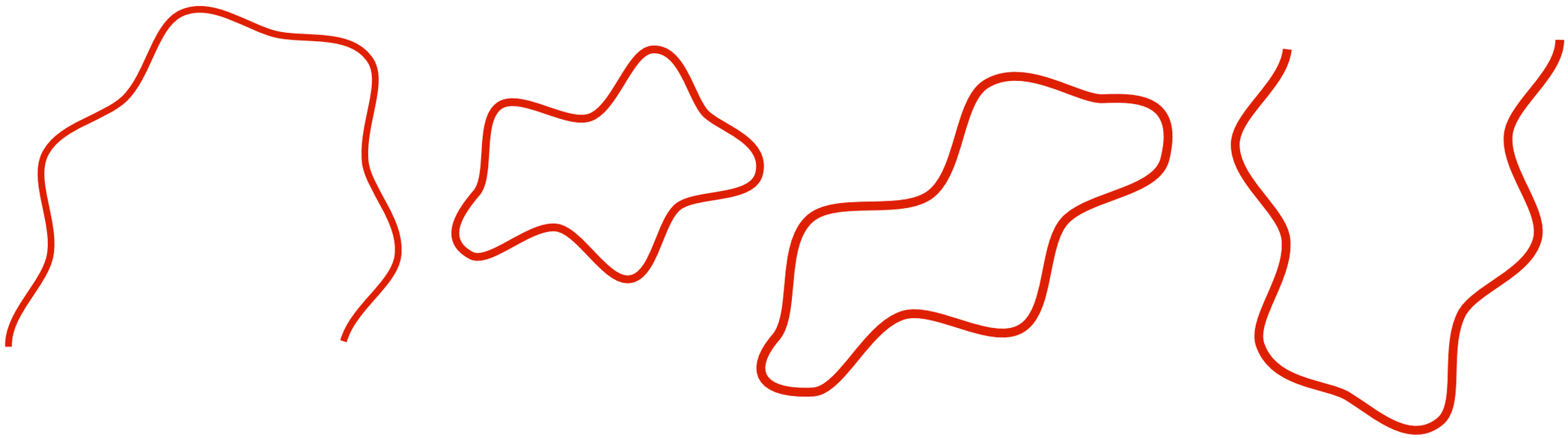
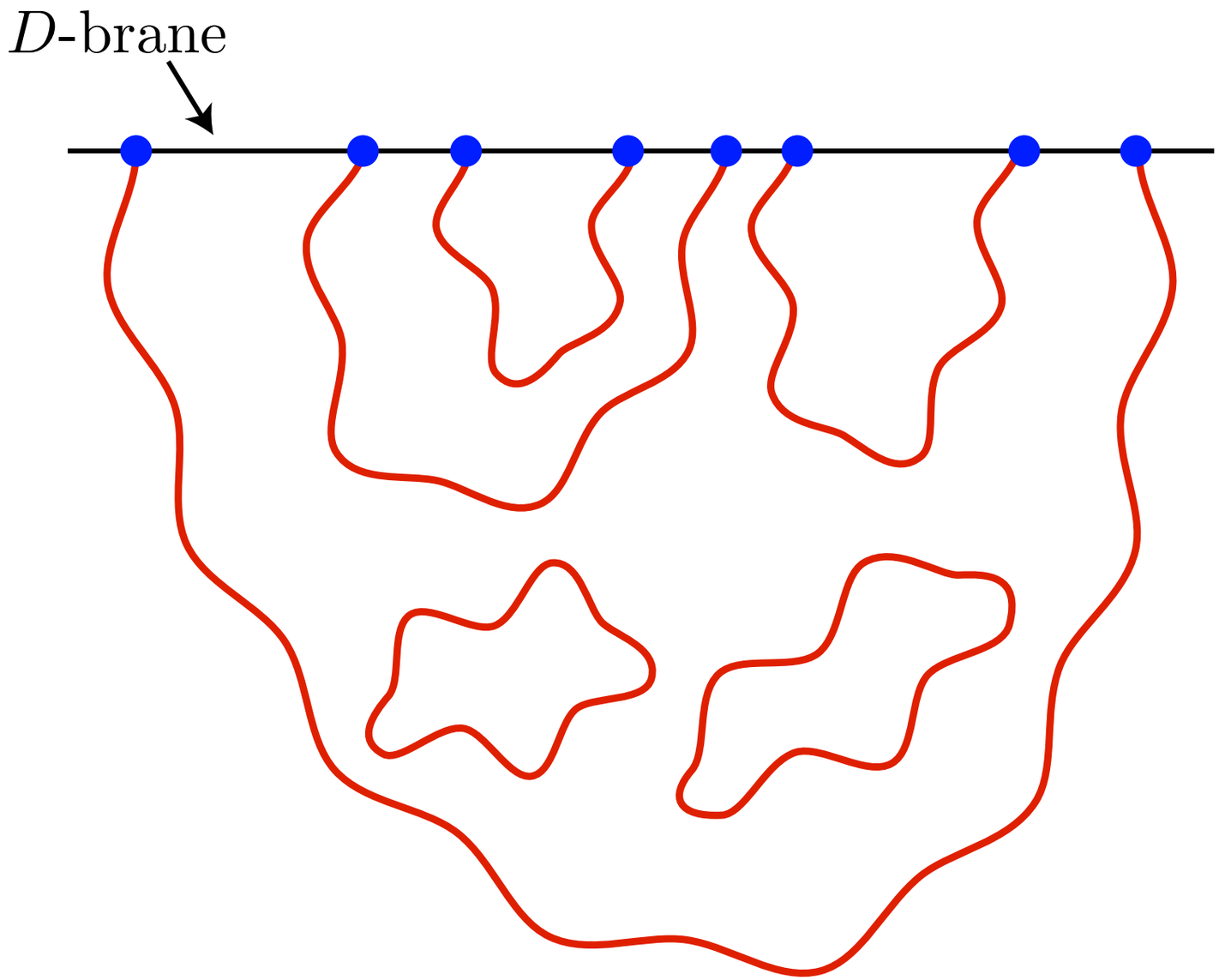
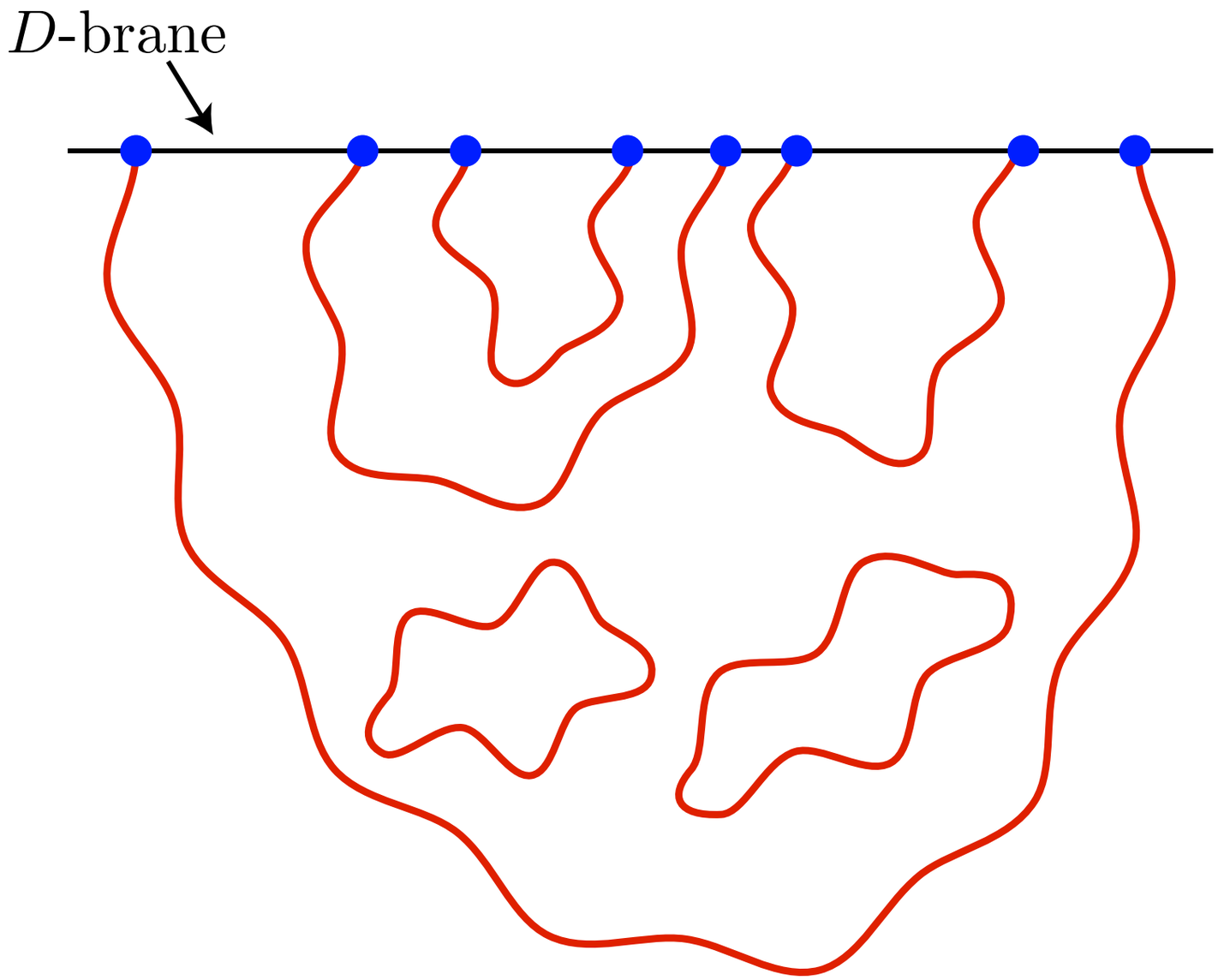
String theory



- Allows unification of the standard model of particle physics with Einstein's theory of gravitation (general relativity).
- Vibrations of a string (its "musical notes") correspond to quarks, gravitons, the Higgs boson, photons, gluons .....



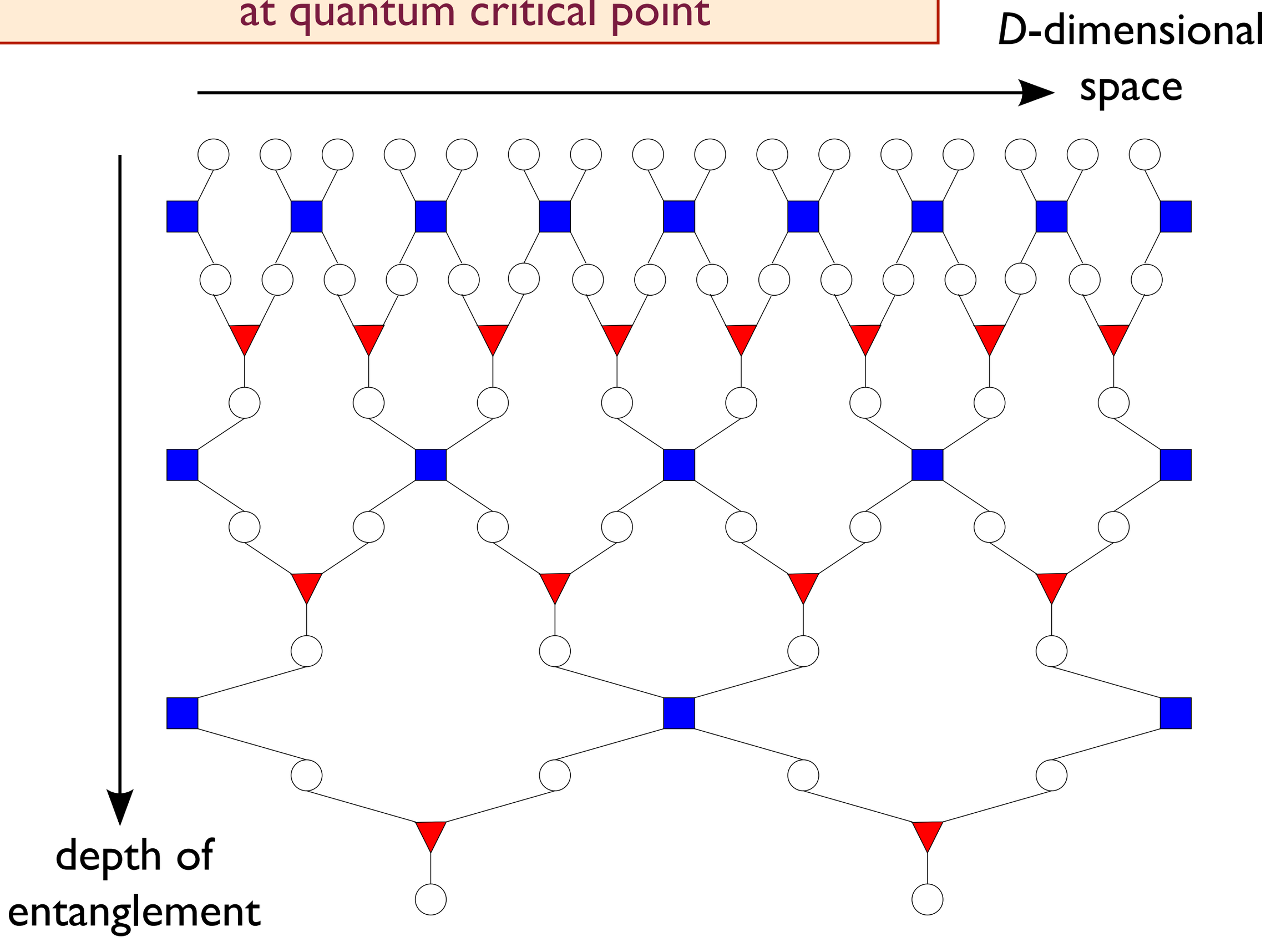
- A D-brane is a D-dimensional surface on which strings can end.



- A D-brane is a D-dimensional surface on which strings can end.

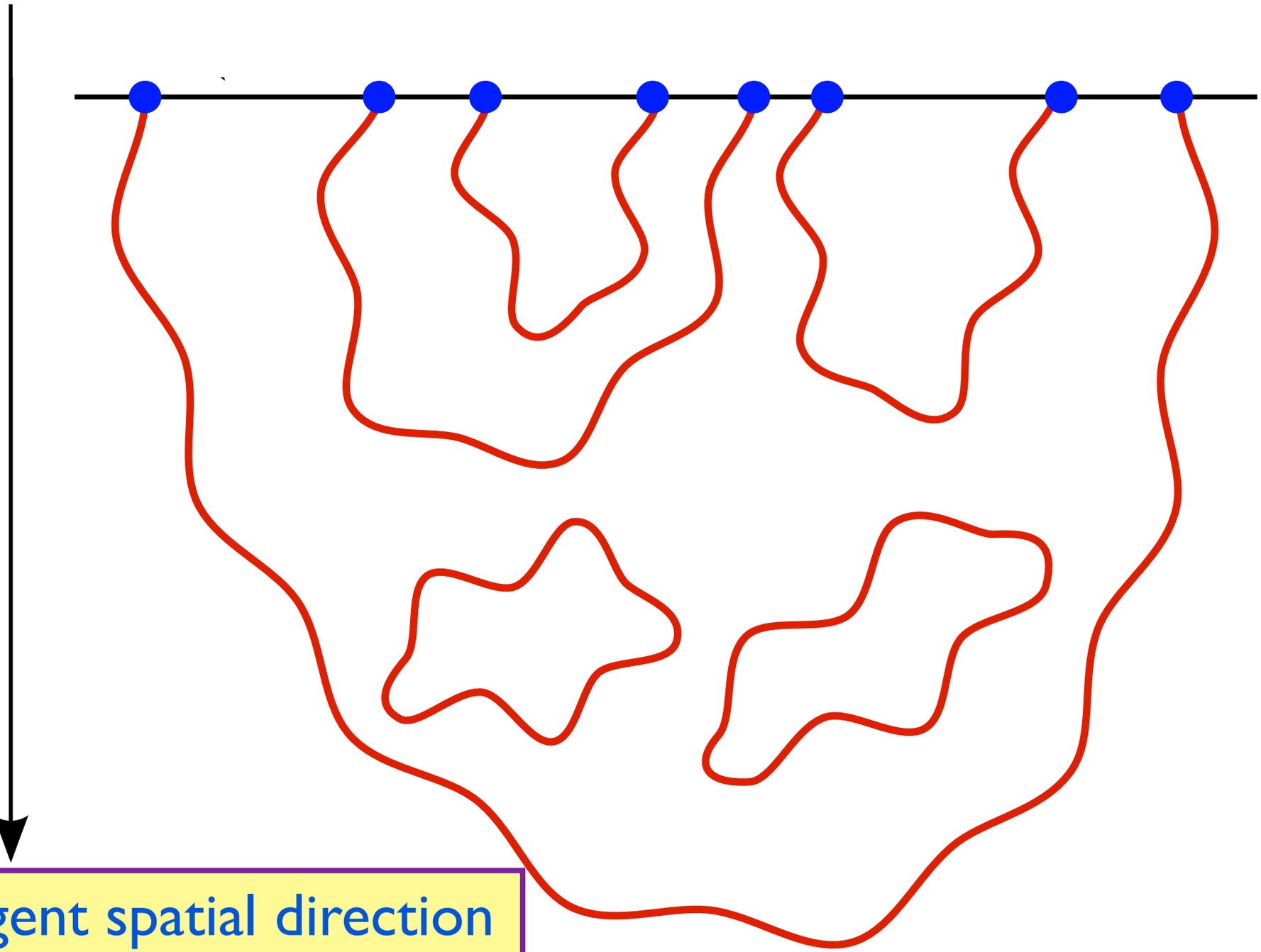
- If we focused only on the blue points on the D-dimensional surface, they would appear to us to have long-range quantum entanglement !

Tensor network representation of entanglement at quantum critical point



String theory near
a D-brane

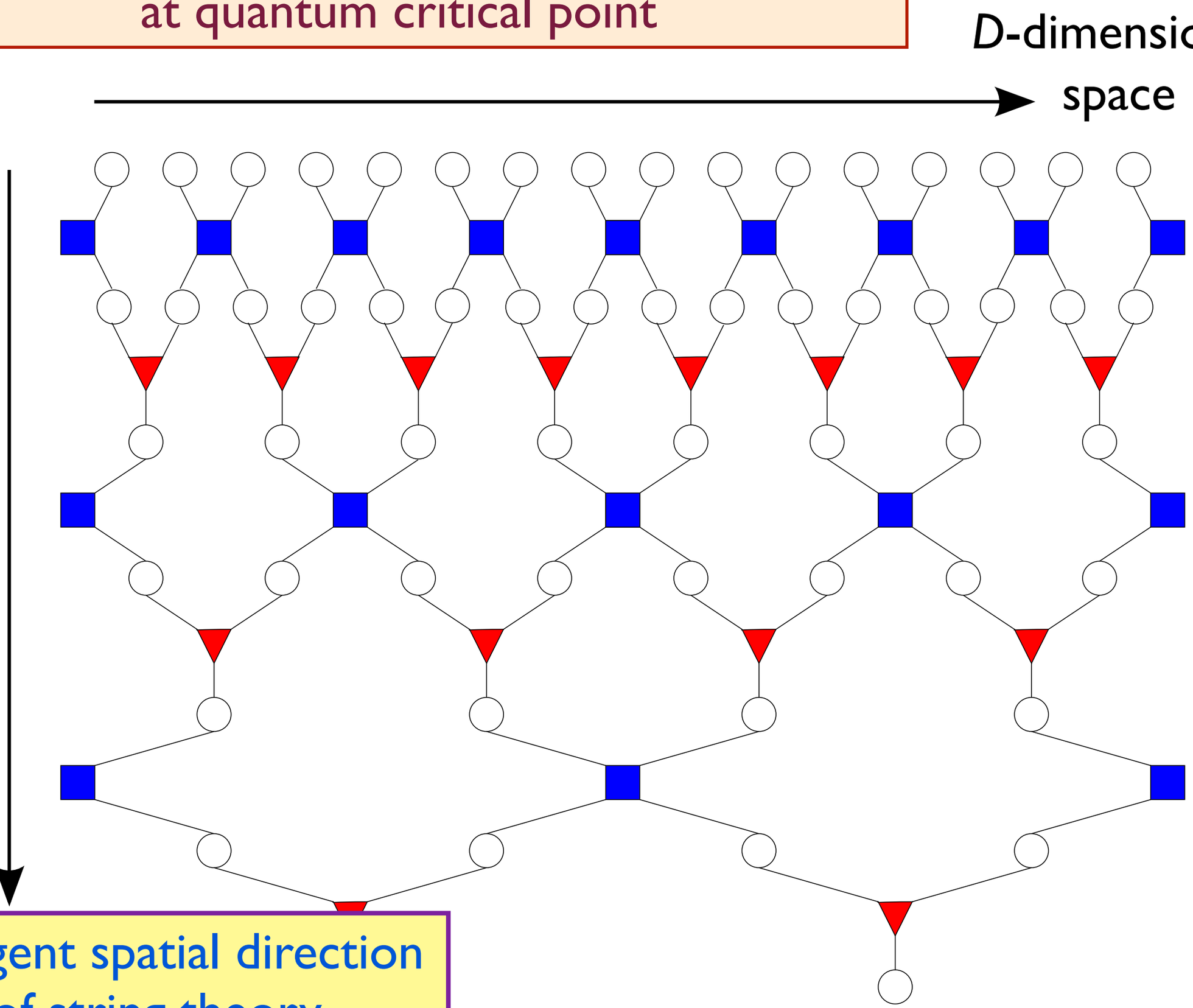
D-dimensional
space



Emergent spatial direction
of string theory

Brian Swingle, arXiv:0905.1317

Tensor network representation of entanglement at quantum critical point



Emergent spatial direction of string theory

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States of matter with
long-range quantum entanglement
in D dimensions

String theory and
Einstein's General Relativity
in D+1 dimensions

States of matter with long-range quantum entanglement in D dimensions

Are there solutions of Einstein's General Relativity in D+1 dimensions which correspond to superconductors and "strange metals" ?

String theory and Einstein's General Relativity in D+1 dimensions

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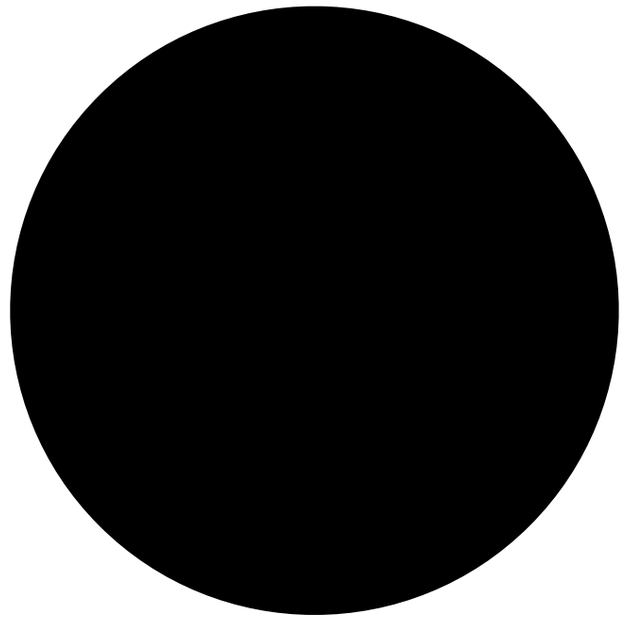
Black Holes

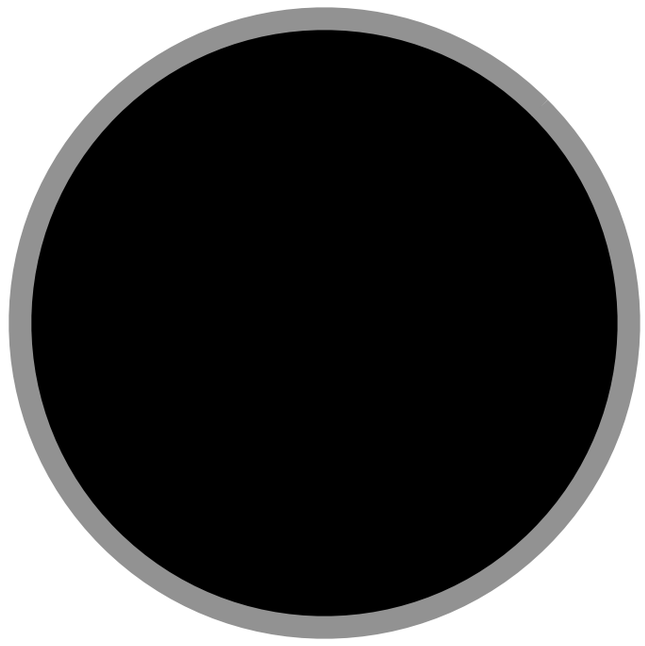
Objects so massive that light is gravitationally bound to them.



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.

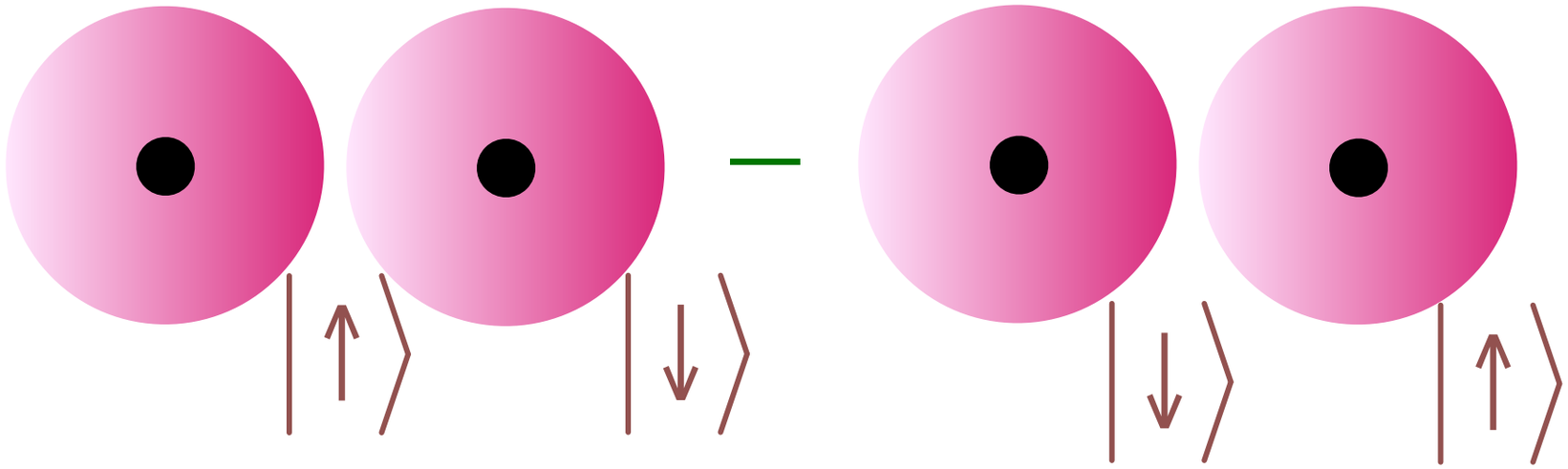


$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

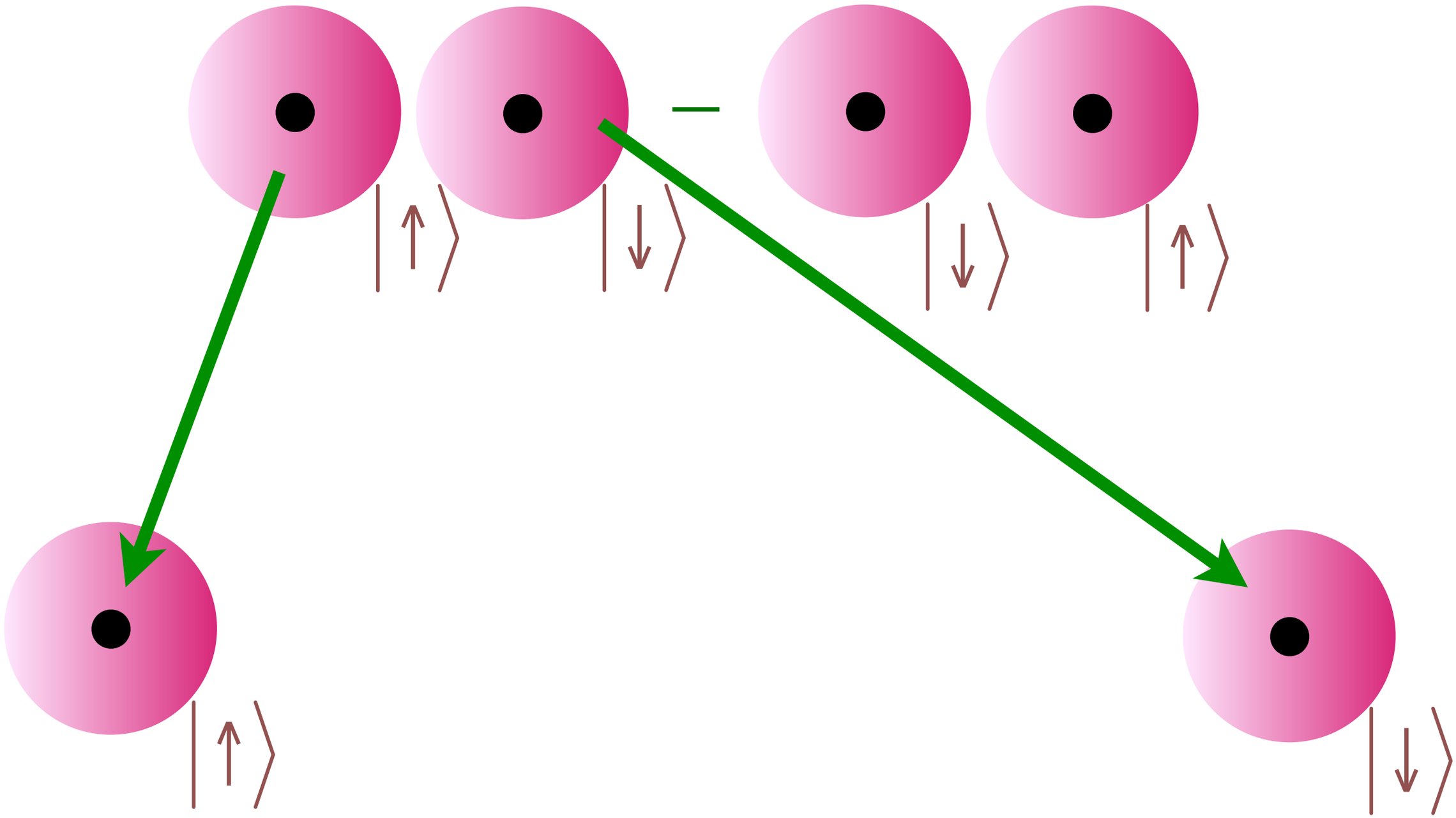
Black Holes + Quantum theory

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

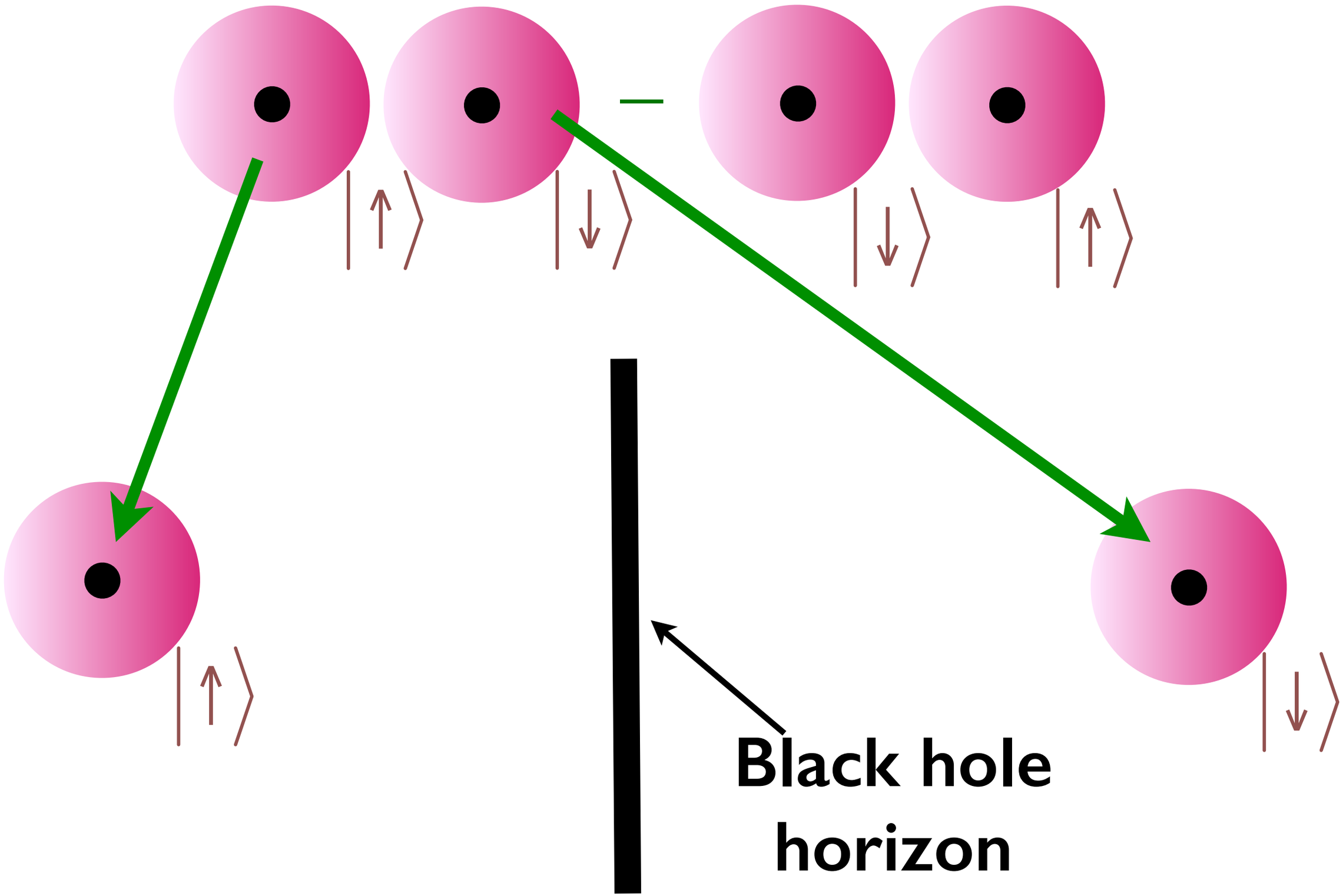
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon



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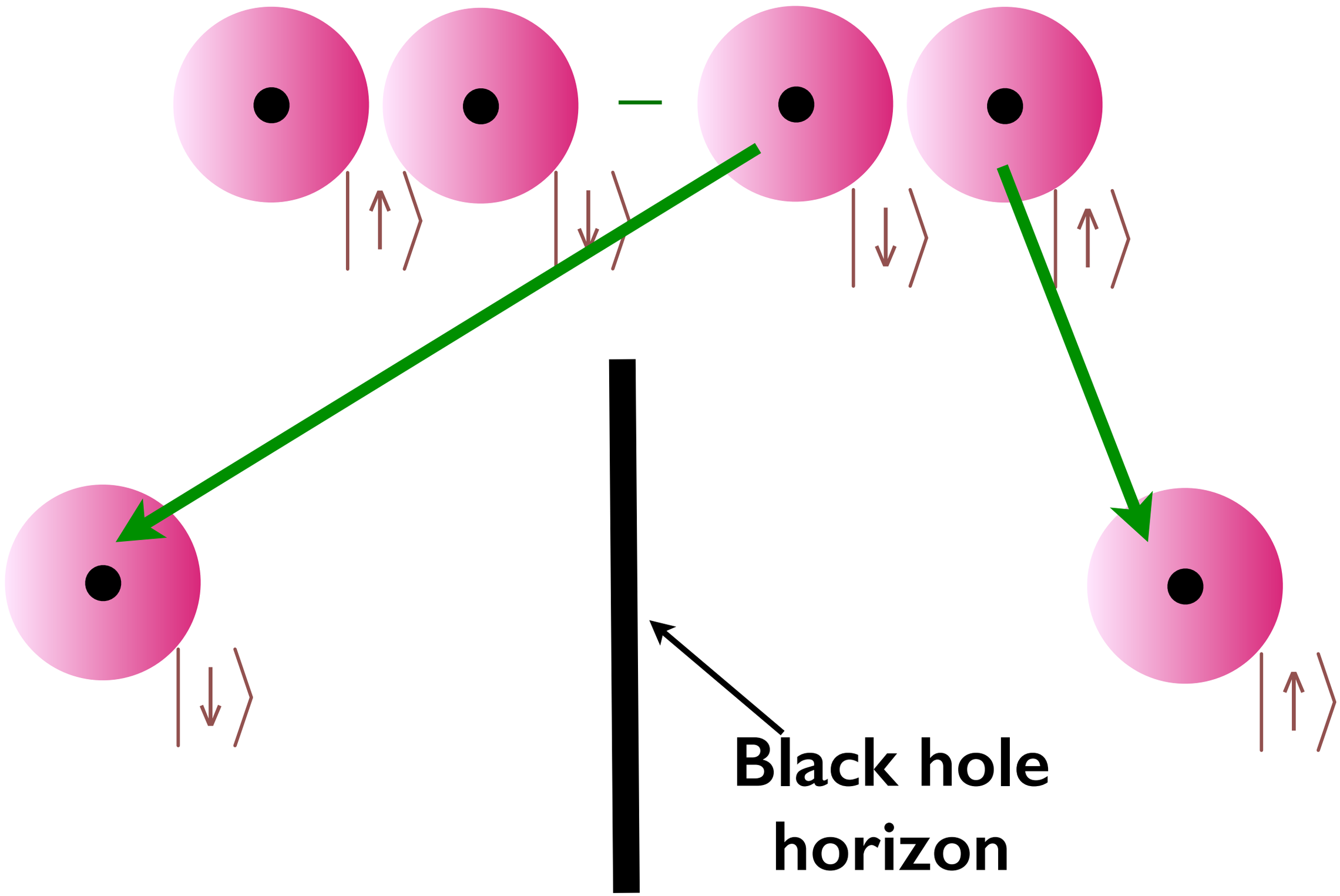
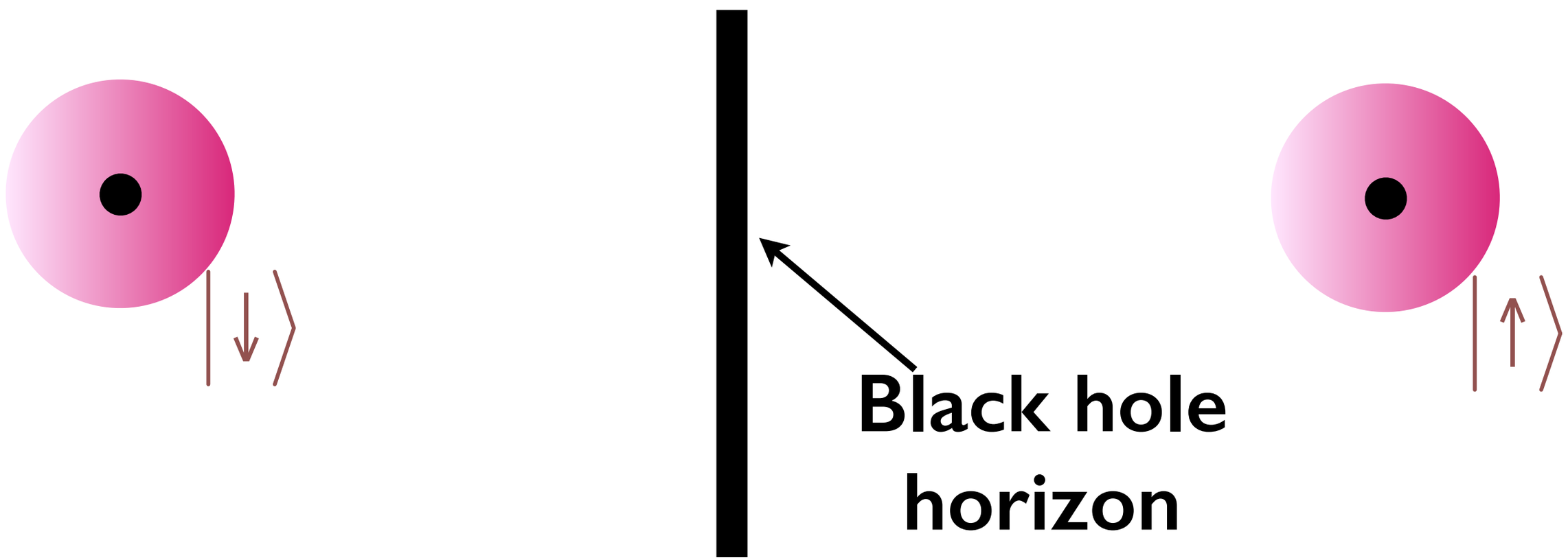


Quantum Entanglement across a black hole horizon

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



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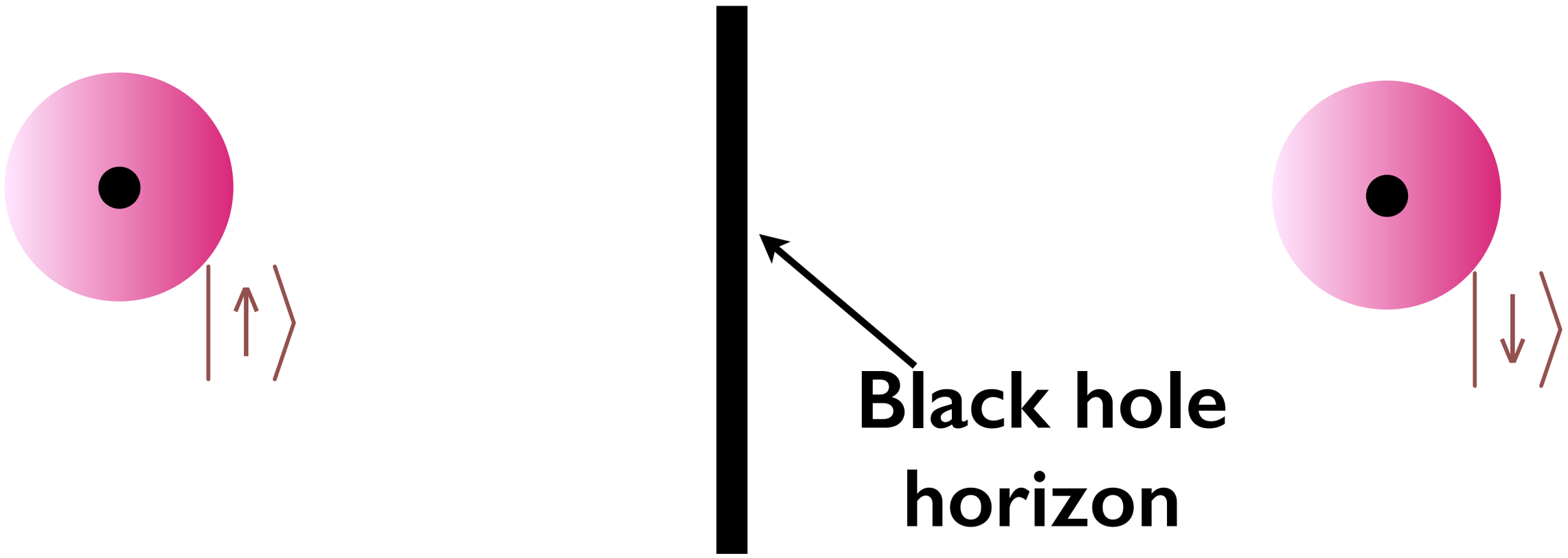


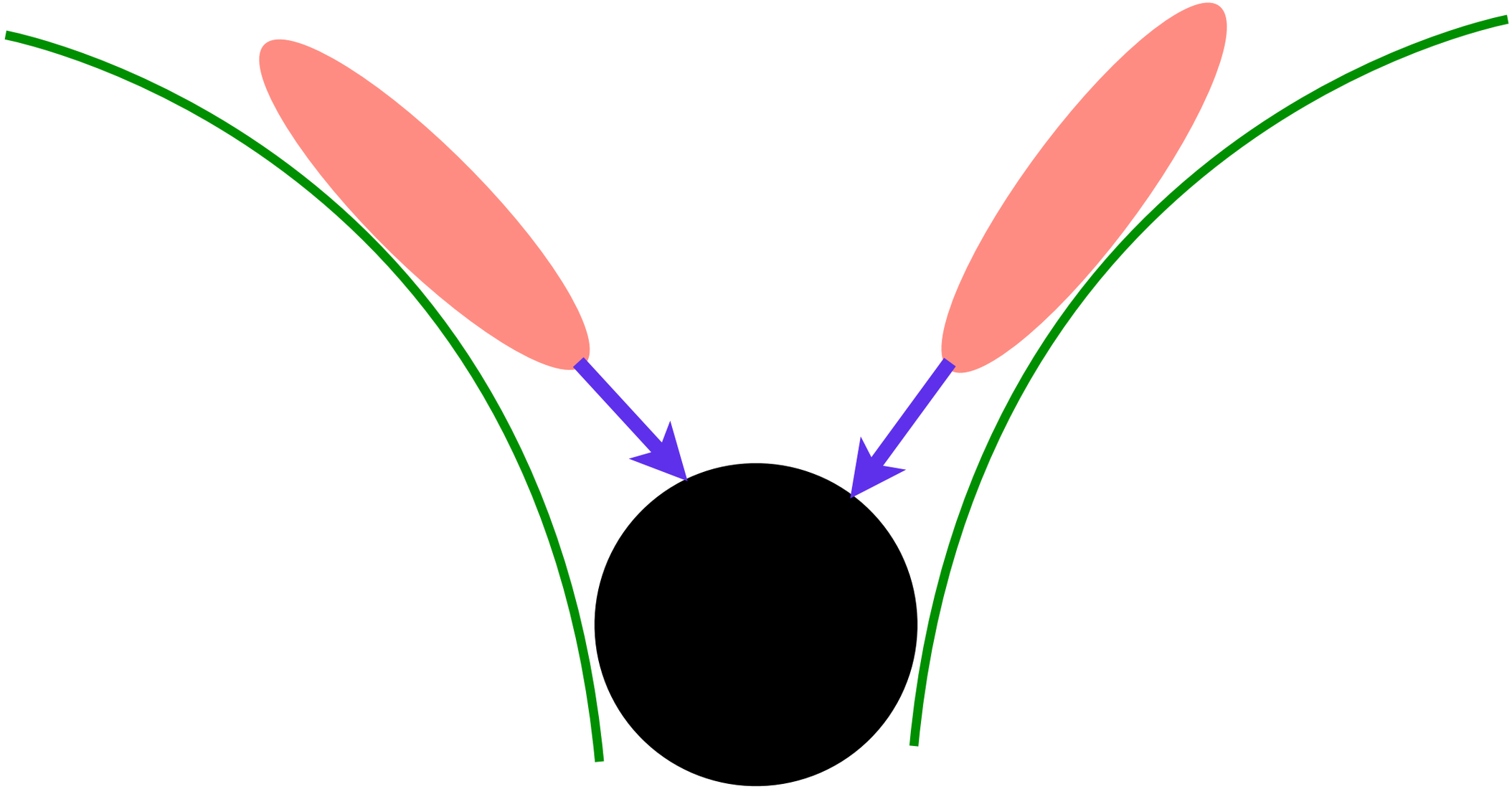
Quantum Entanglement across a black hole horizon

There is long-range 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)

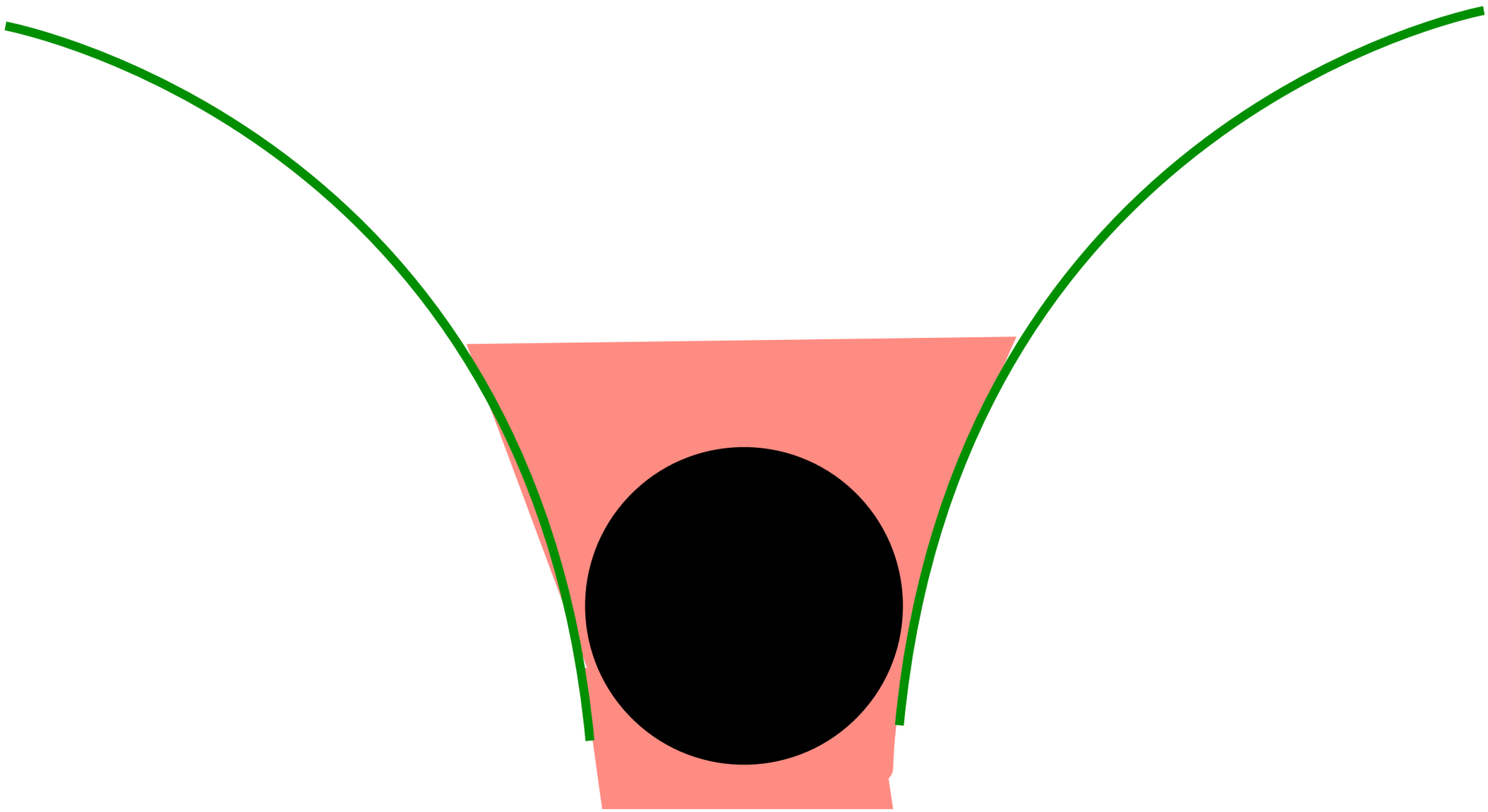
States of quantum matter and black holes

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



States of quantum matter and black holes

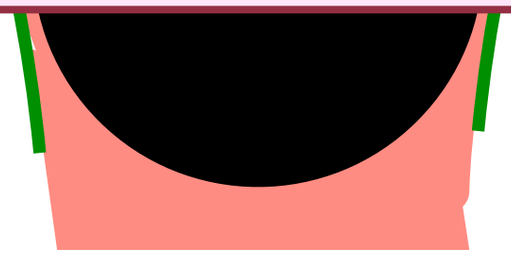
However, eventually there is a balance between the gravitational forces pulling the charges into the black hole, and the repulsive electrical forces which push them out, and a stable state is obtained



States of quantum matter and 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 a stable state is obtained

These black hole states of General Relativity in D+1 dimensions correspond to (and allow us to compute the properties of) superconductors and strange metals in D dimensions



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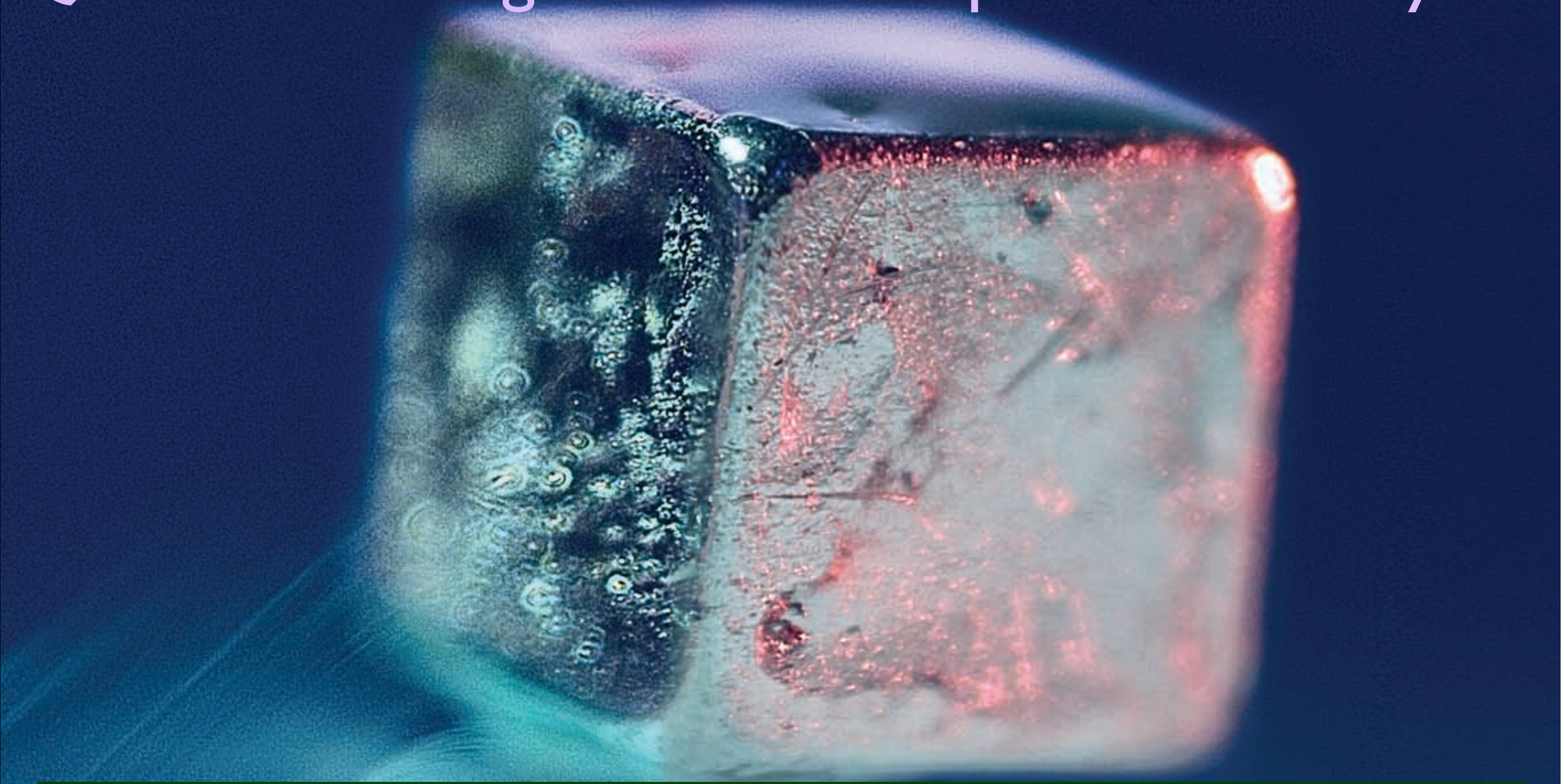
Quantum Entanglement and Superconductivity



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

Subir Sachdev, Harvard University