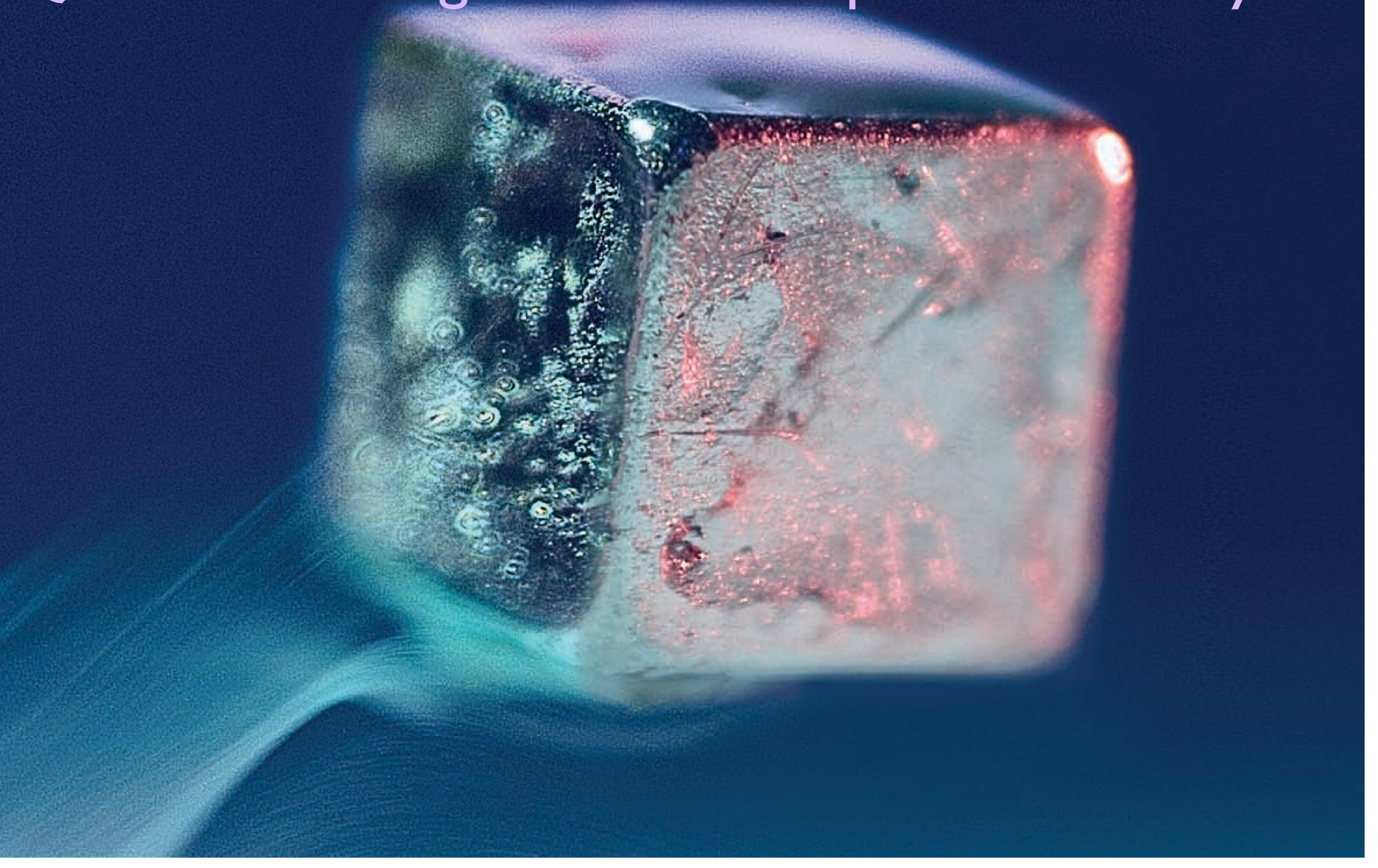
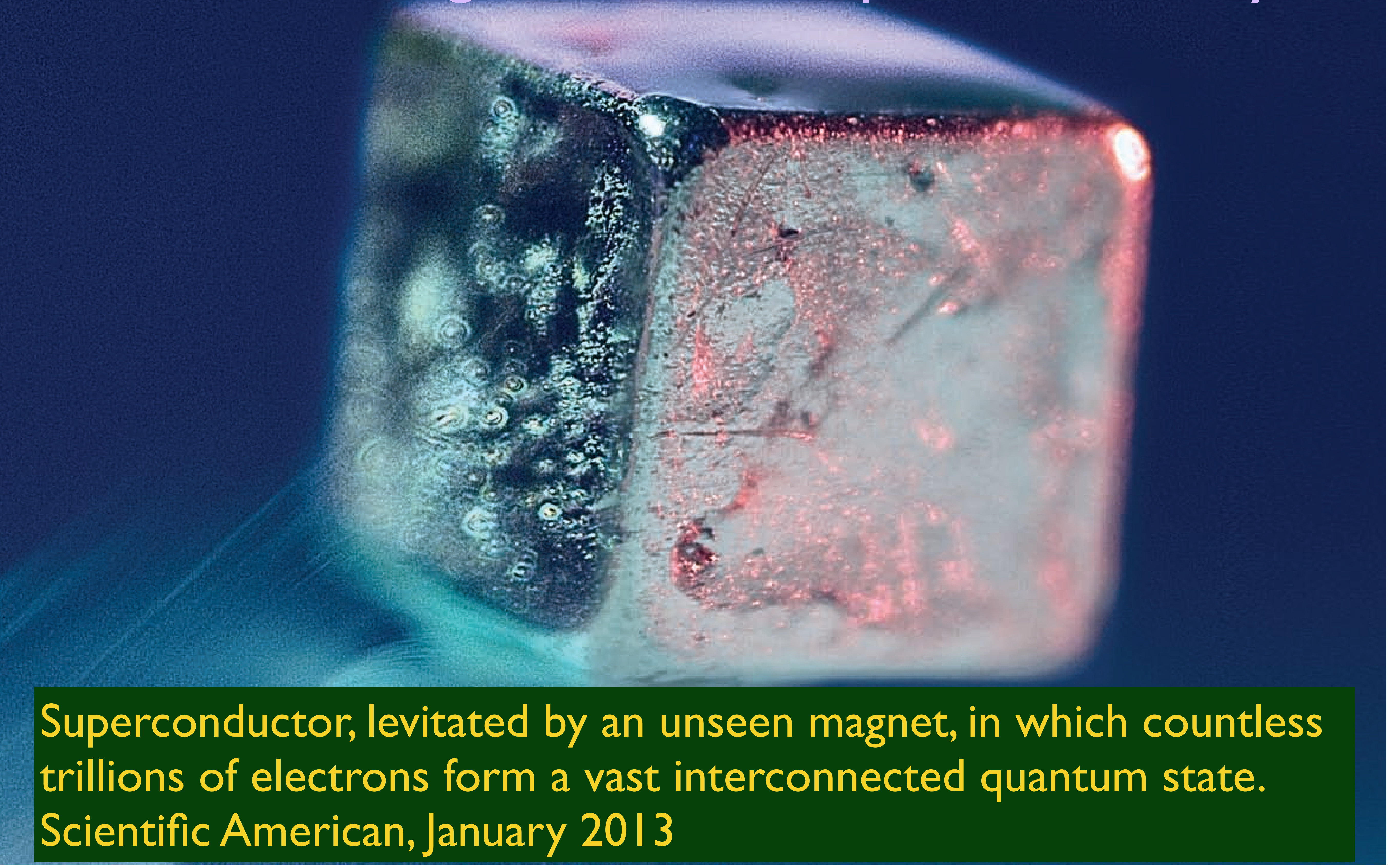
Quantum Entanglement and Superconductivity



Subir Sachdev, Harvard University

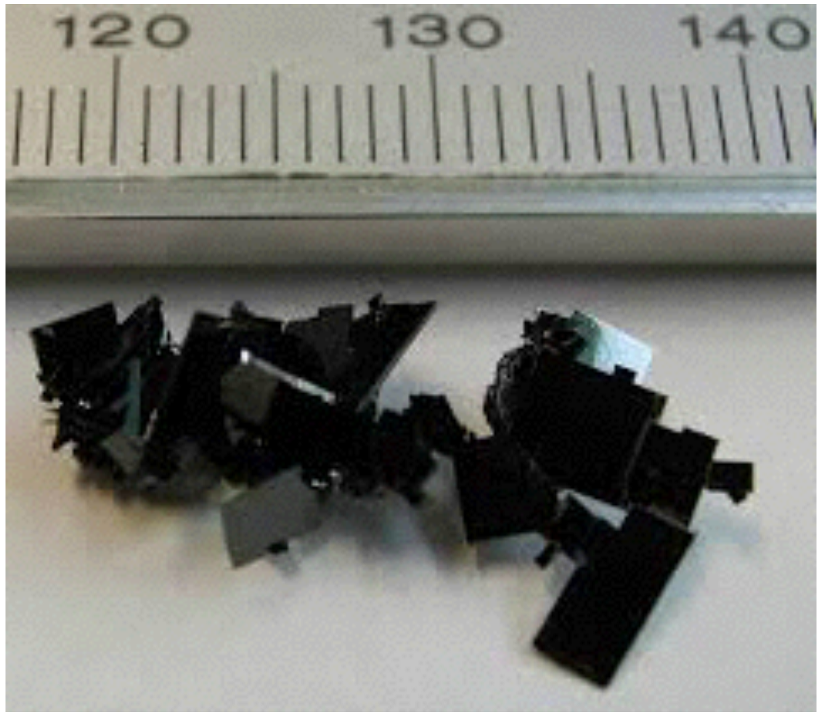
Quantum Entanglement and Superconductivity

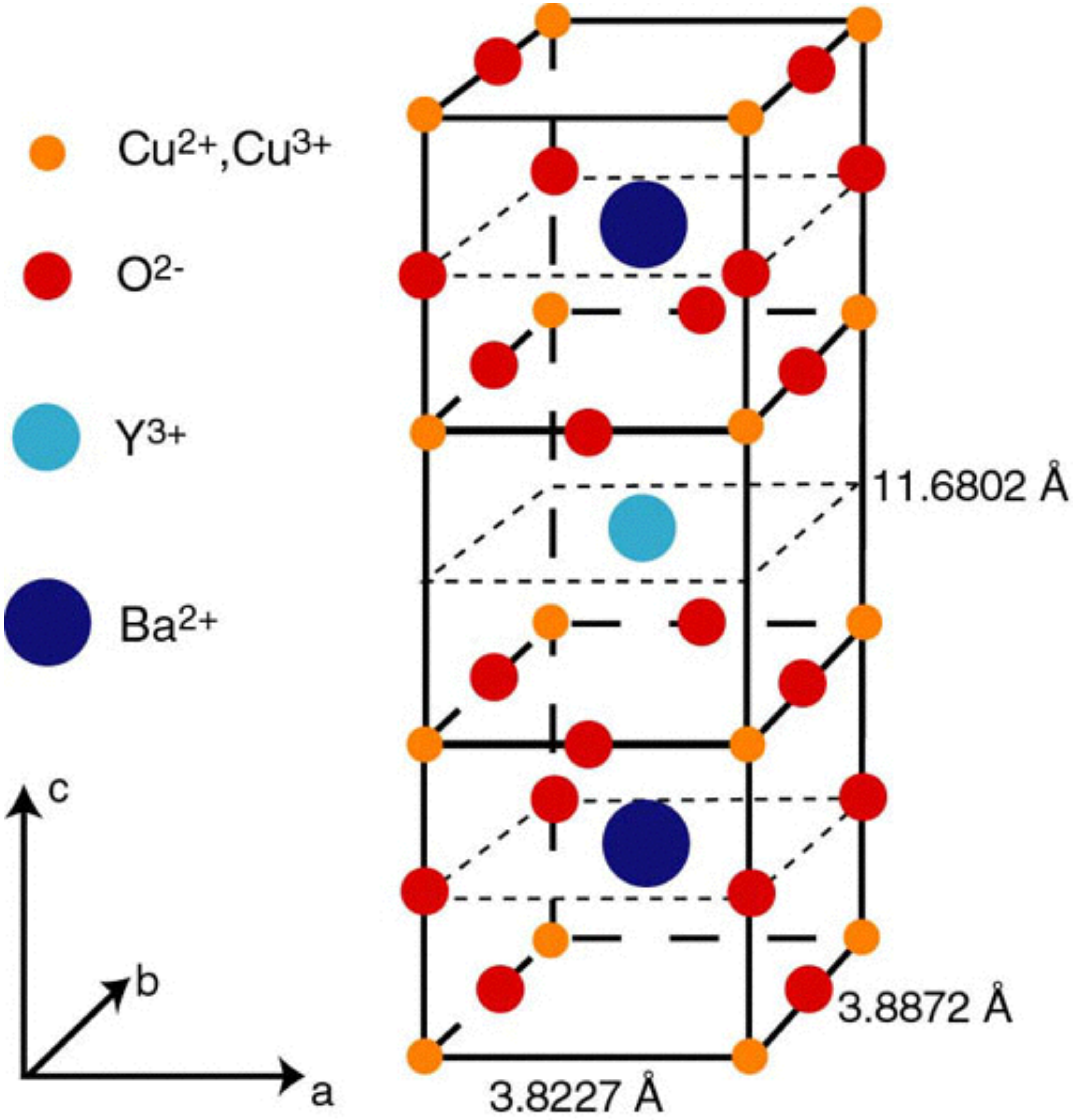


Superconductor, levitated by an unseen magnet, in which countless trillions of electrons form a vast interconnected quantum state.
Scientific American, January 2013

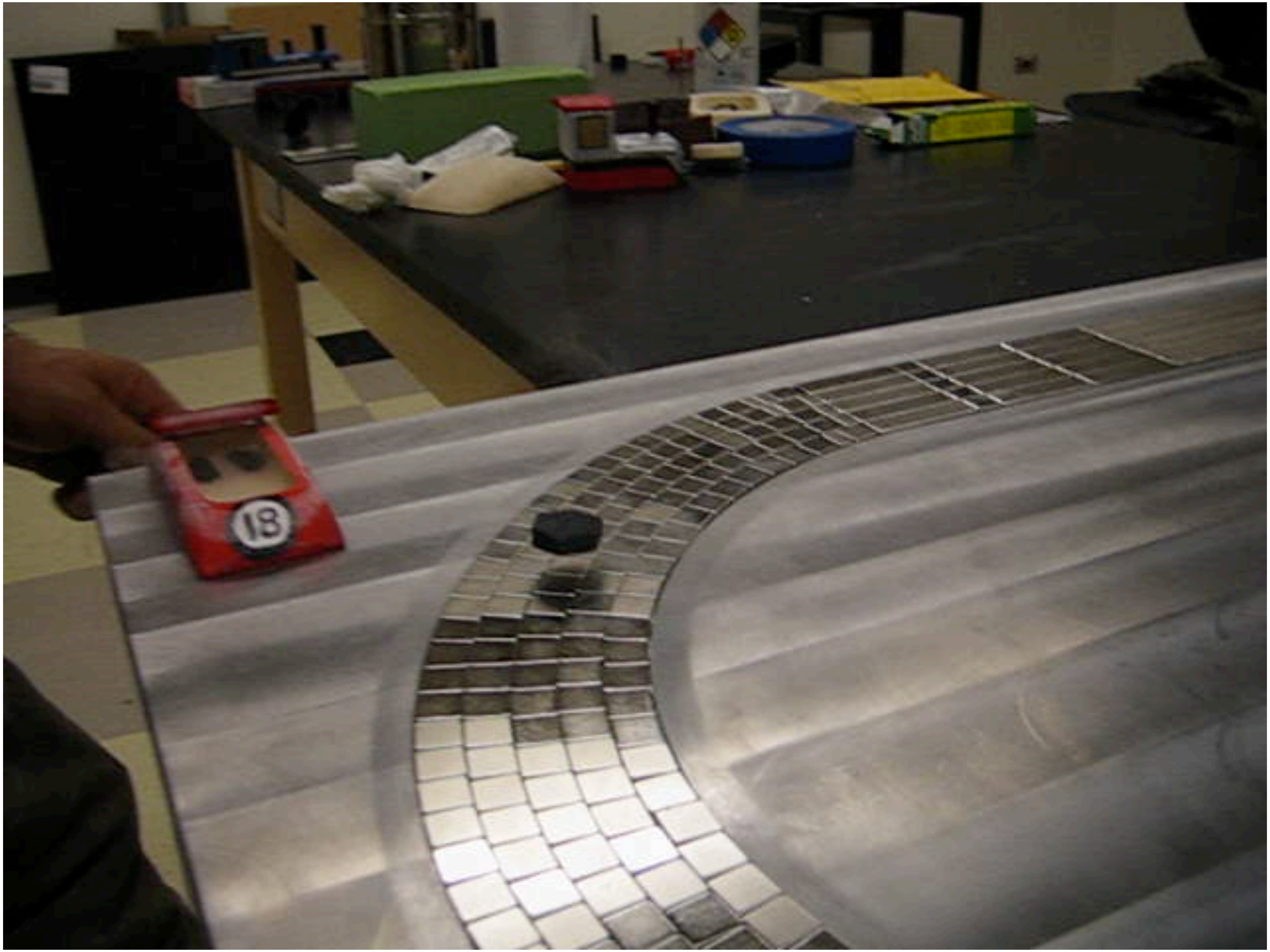
Subir Sachdev, Harvard University

High temperature superconductors



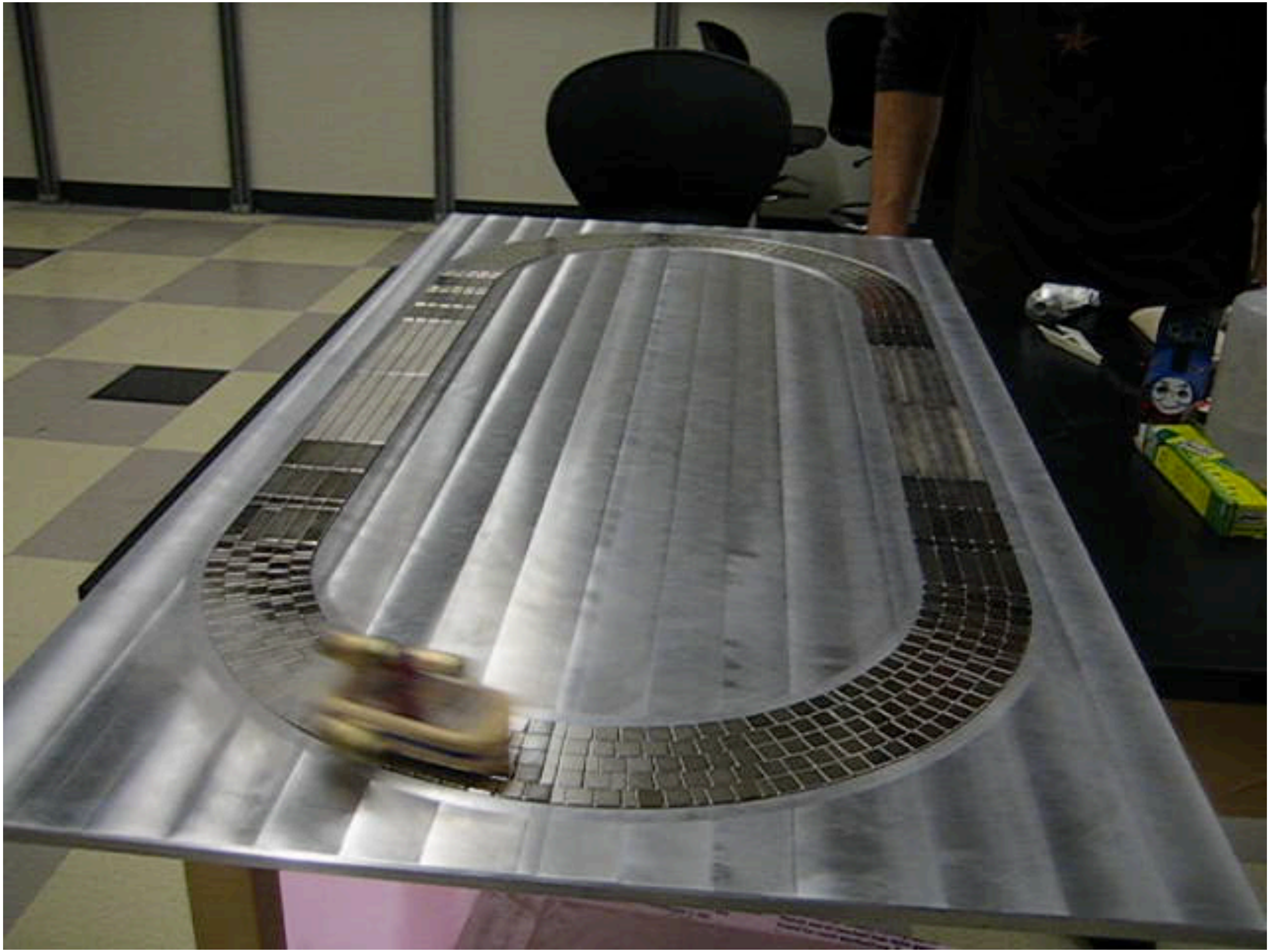


$YBa_2Cu_3O_{6+x}$



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

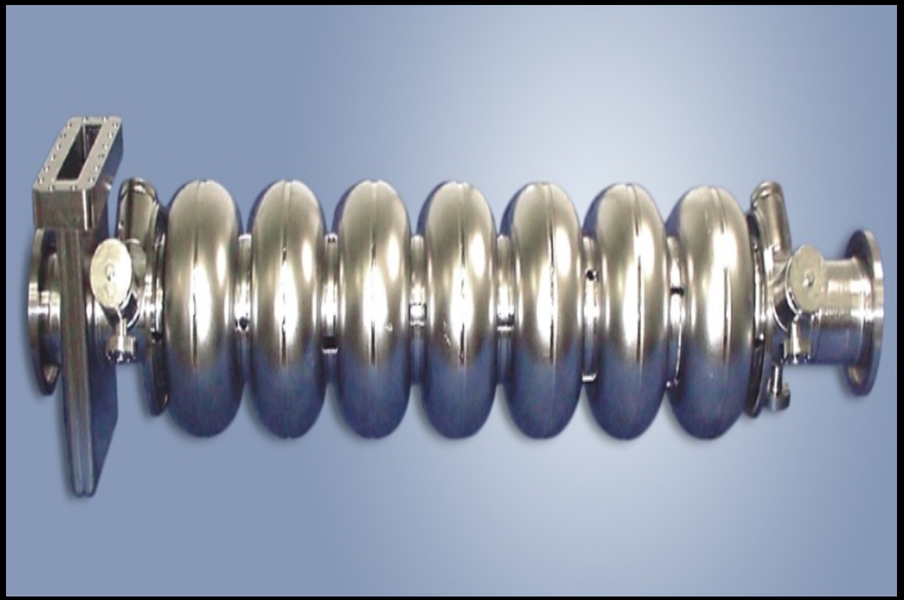

Power Efficiency/Capacity/Stability

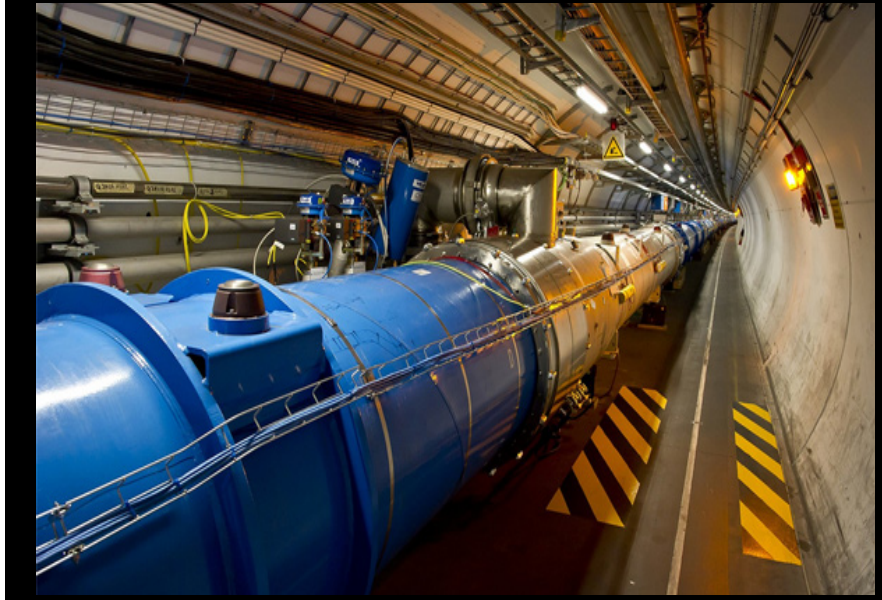

Power Bottlenecks


Accommodate Renewable Power


Efficient Rotating Machines


Information Technology

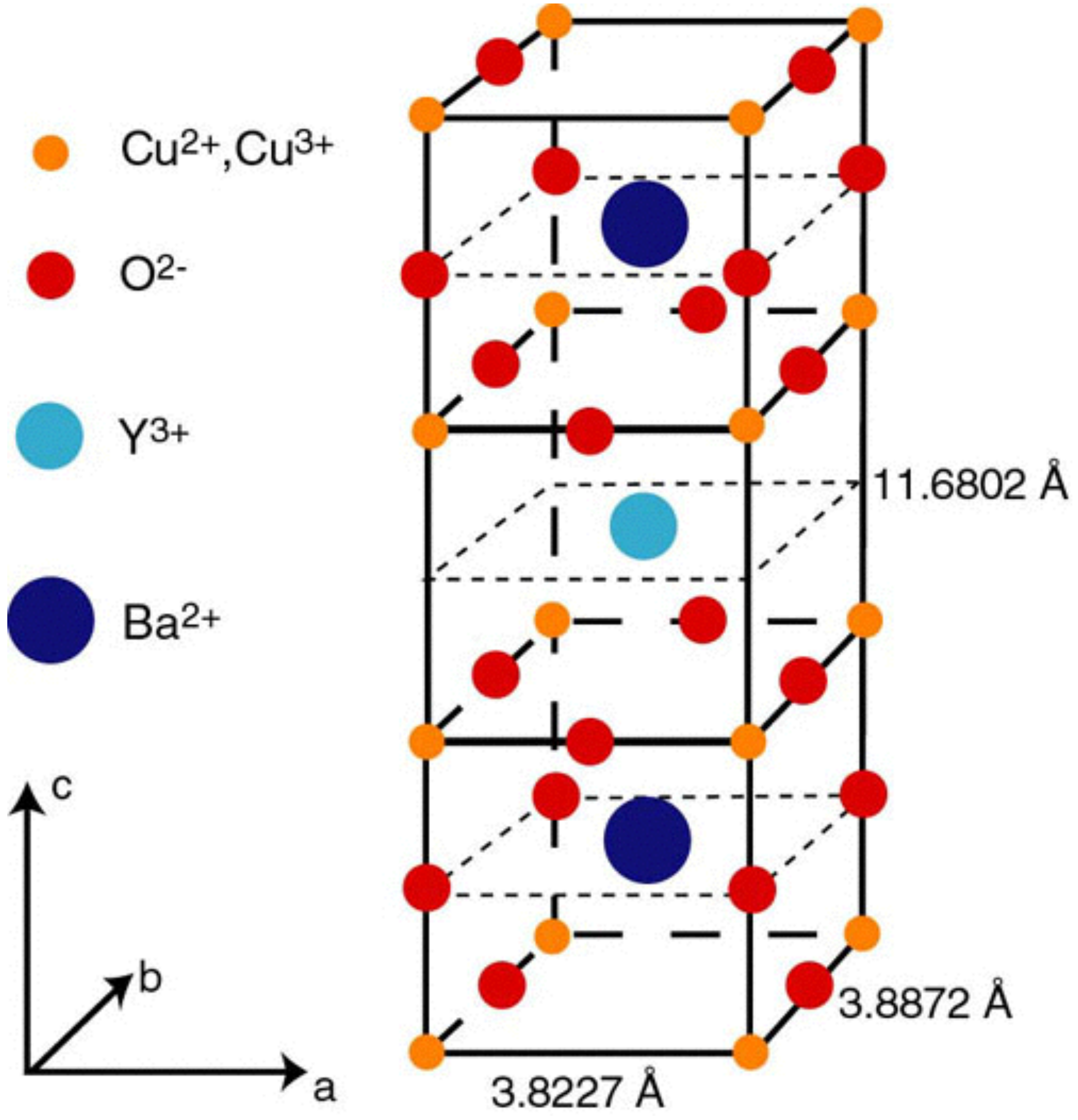

Next Generation HEP


Ultra-High Magnetic Fields


Medical

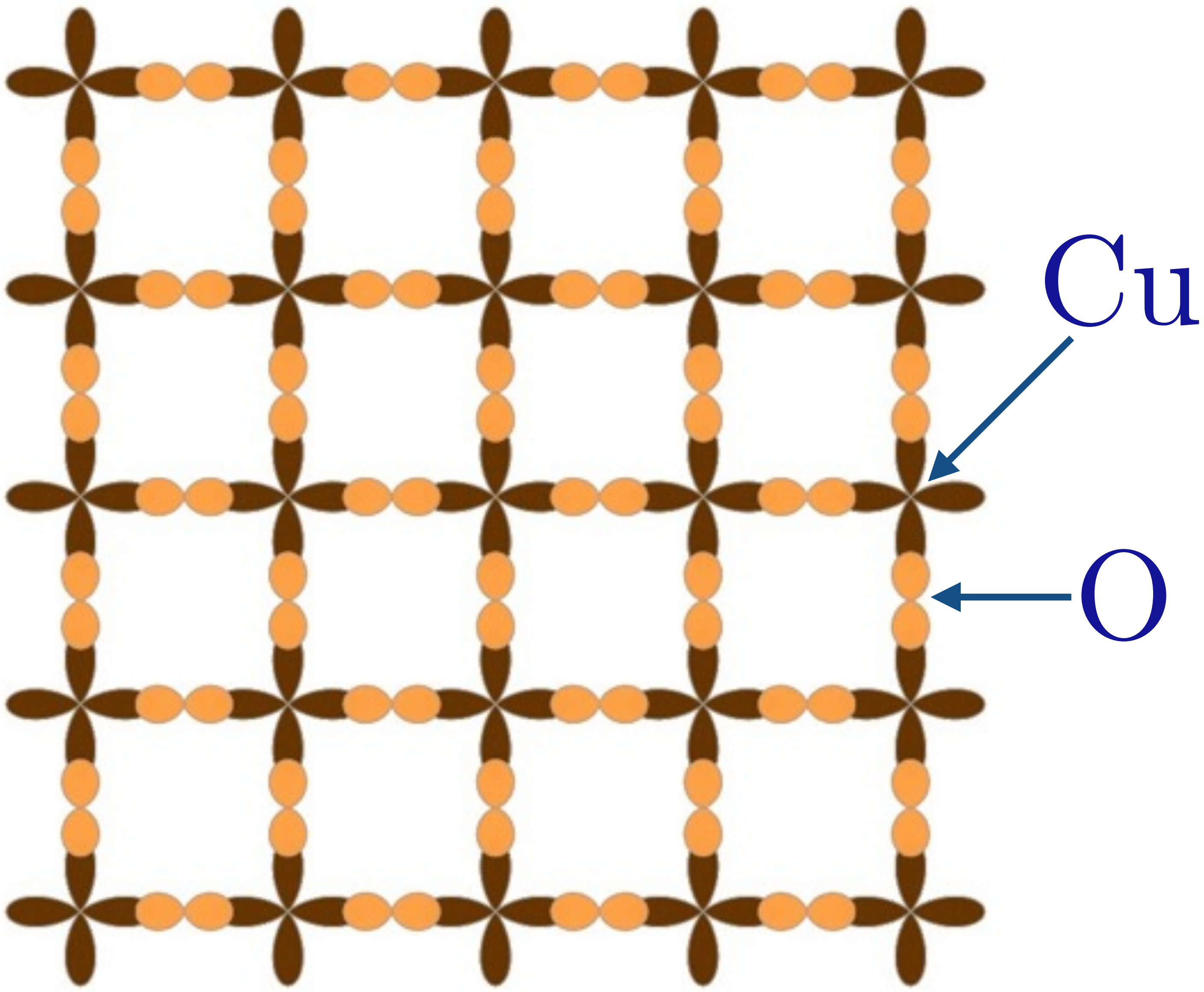

Transport

High temperature superconductors

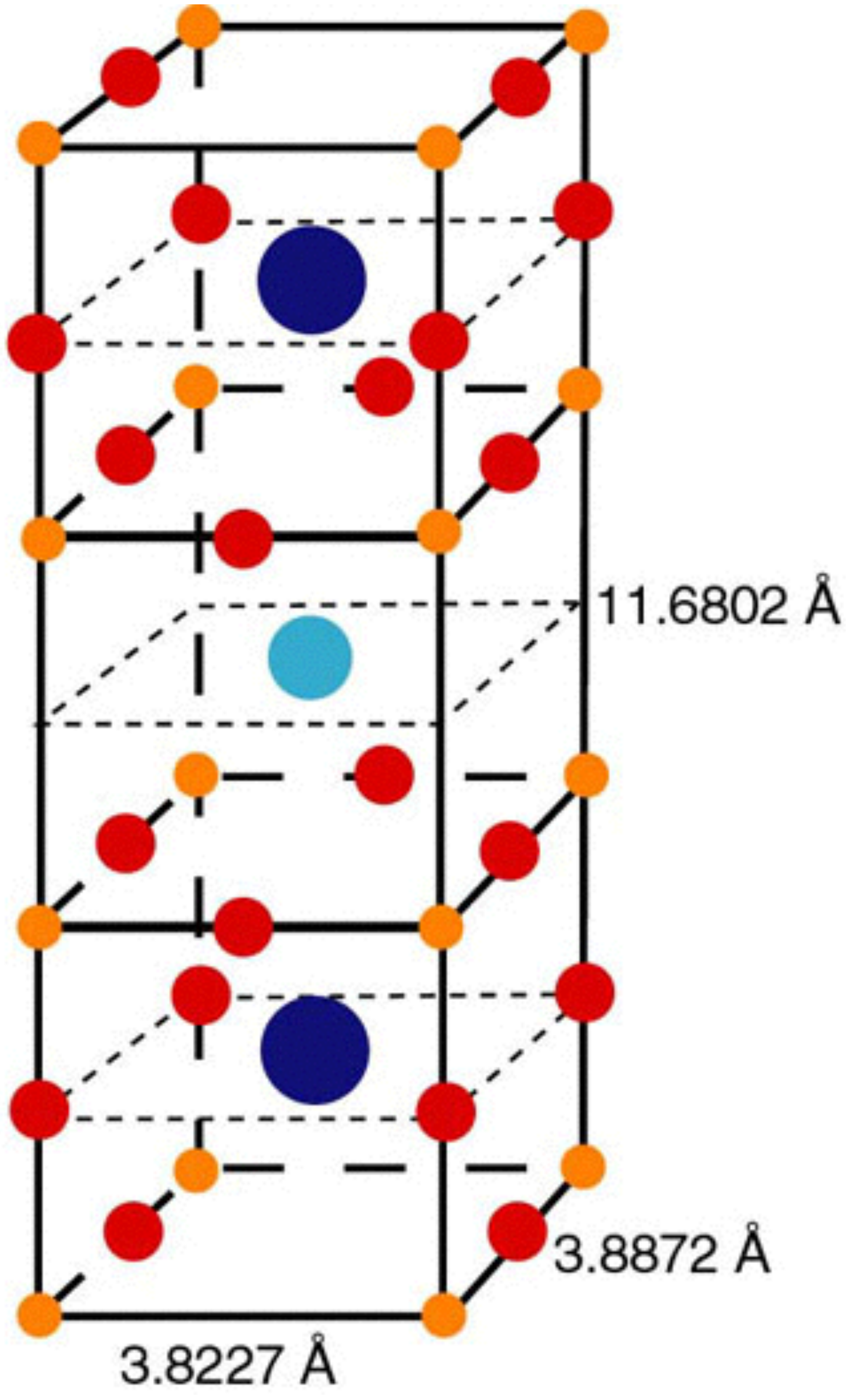


$$\mathrm{YBa_2Cu_3O}_{6+x}$$

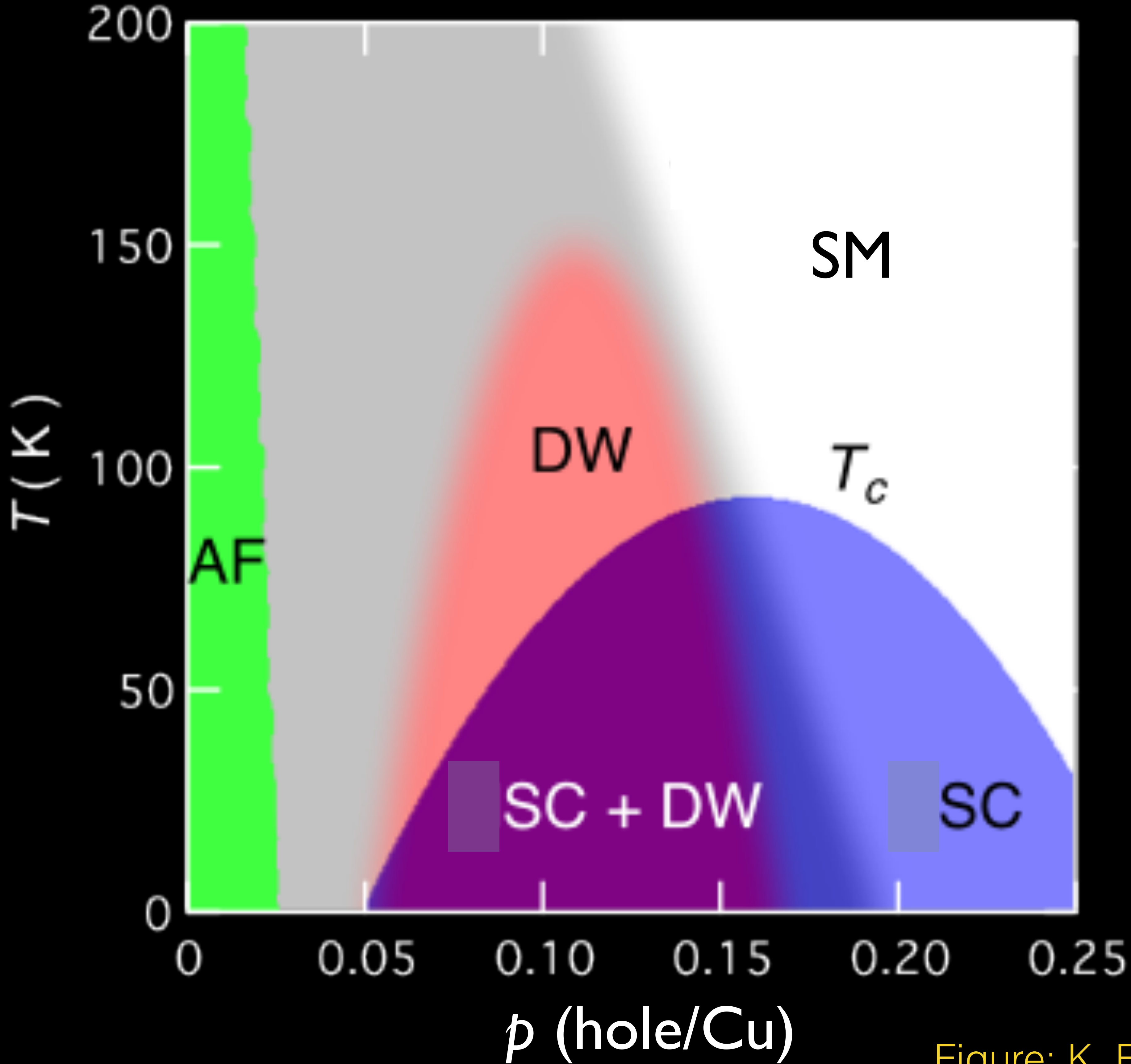
High temperature superconductors



CuO$_2$ plane



$\mathrm{YBa_2Cu_3O}_{6+x}$



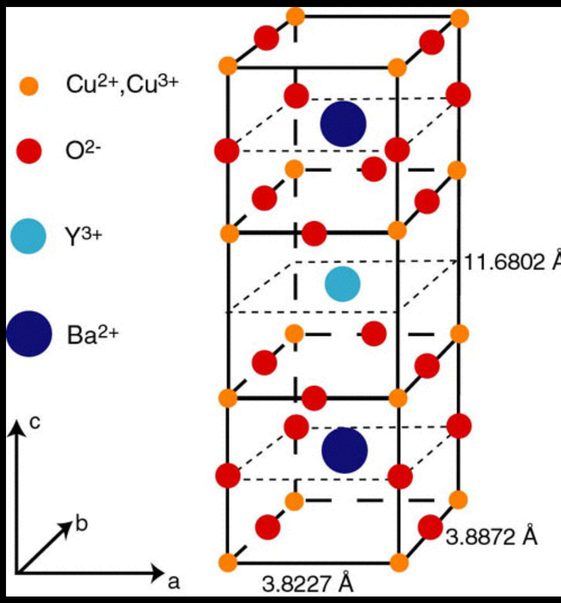
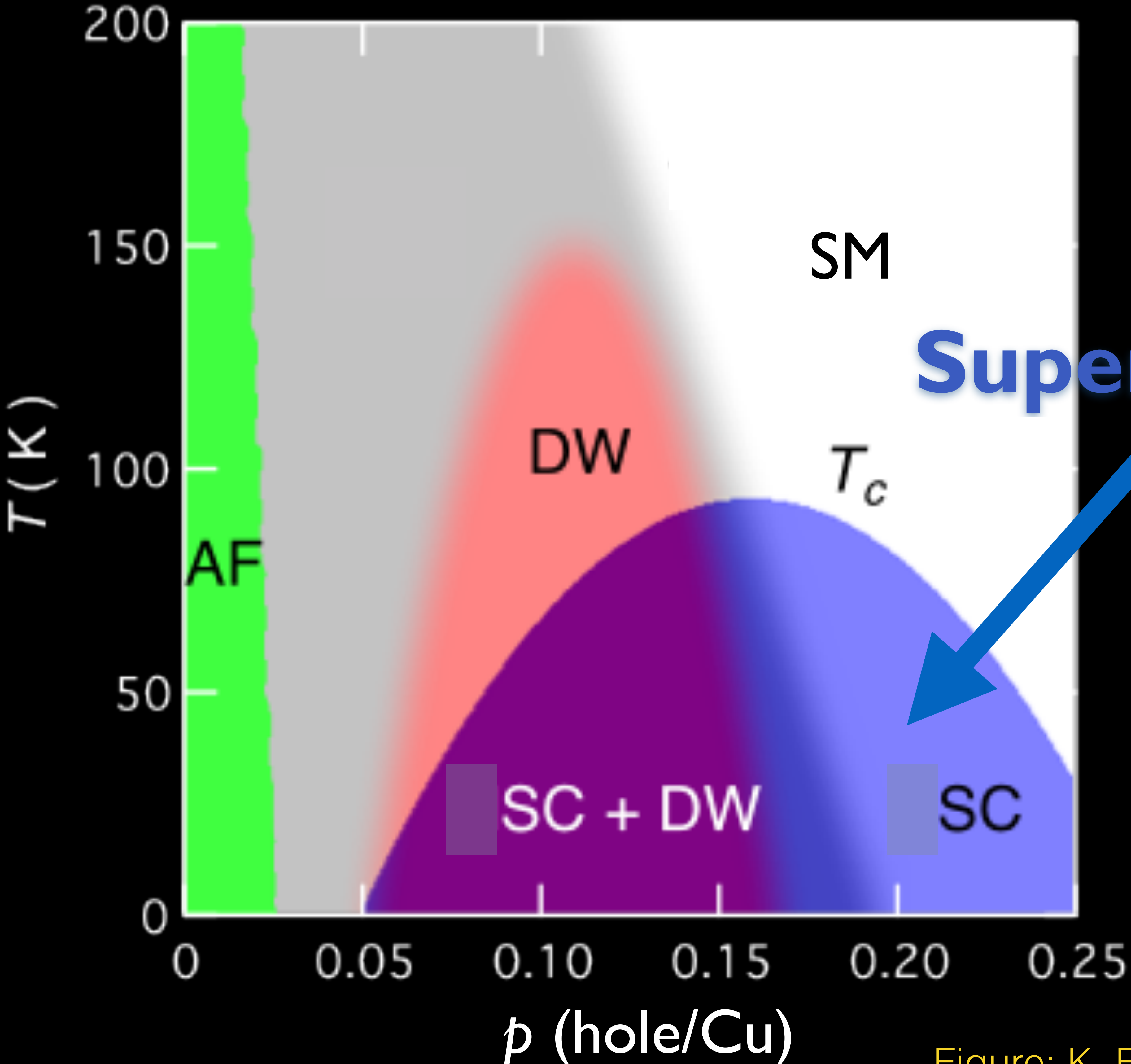


Figure: K. Fujita and J. C. Seamus Davis



Superconductor

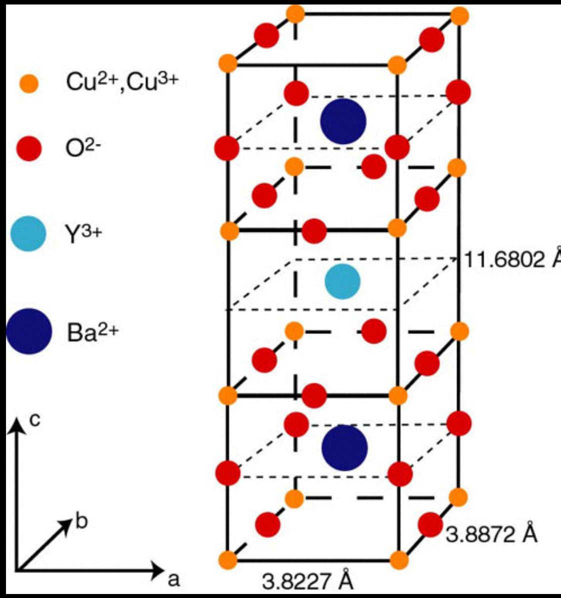
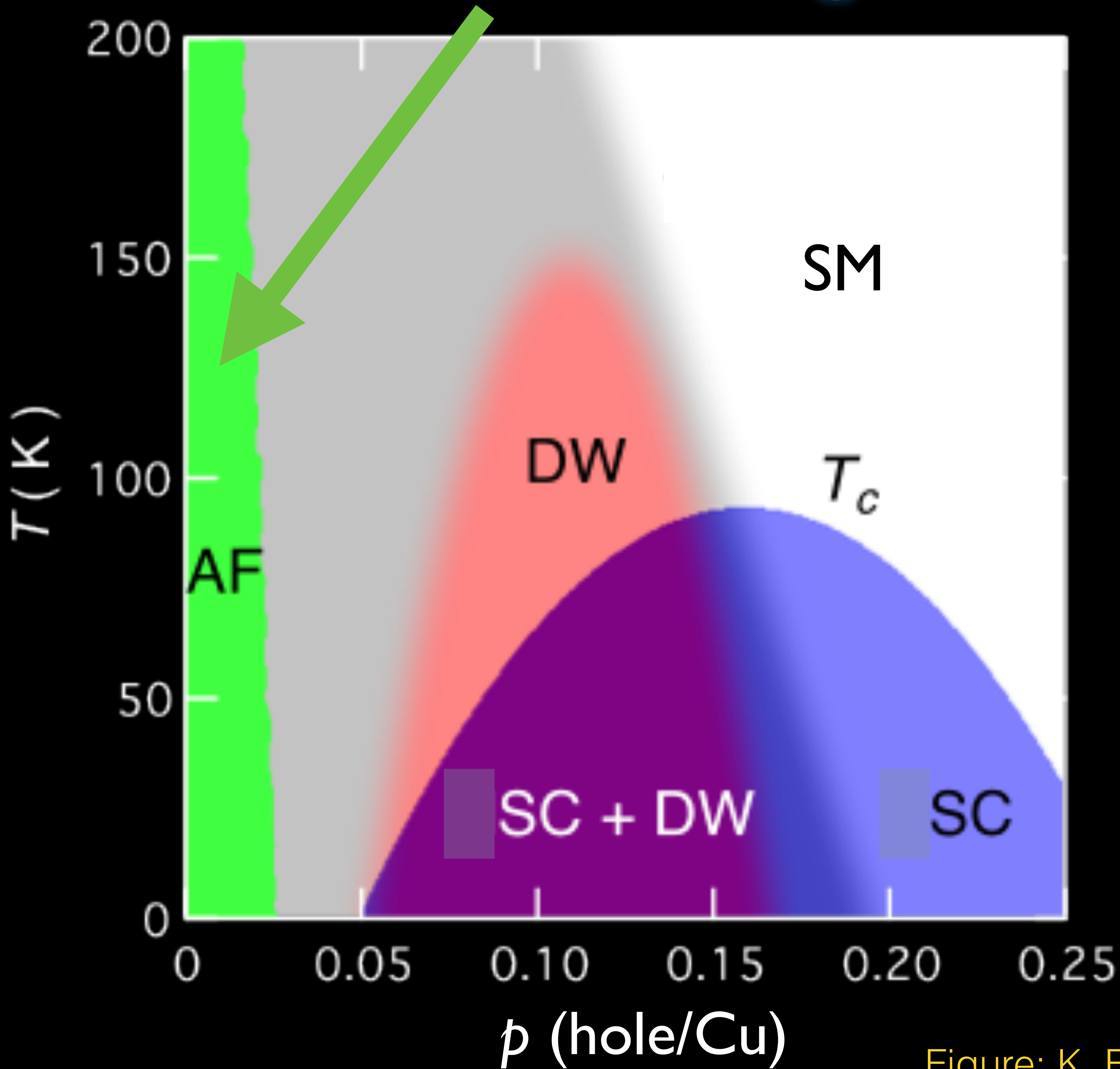


Figure: K. Fujita and J. C. Seamus Davis

Antiferromagnet



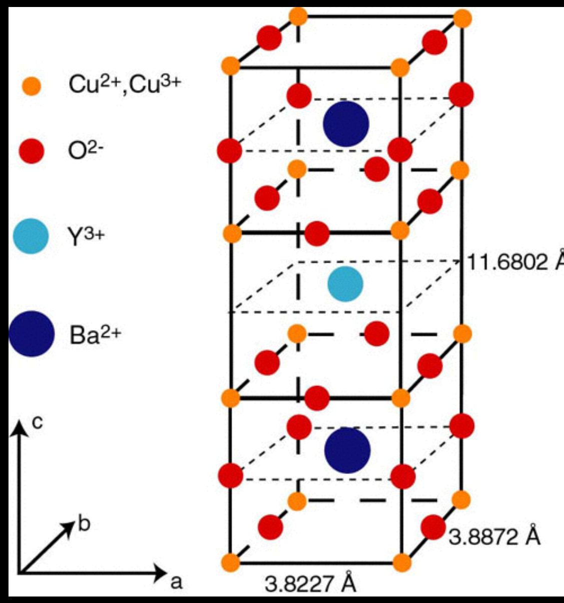
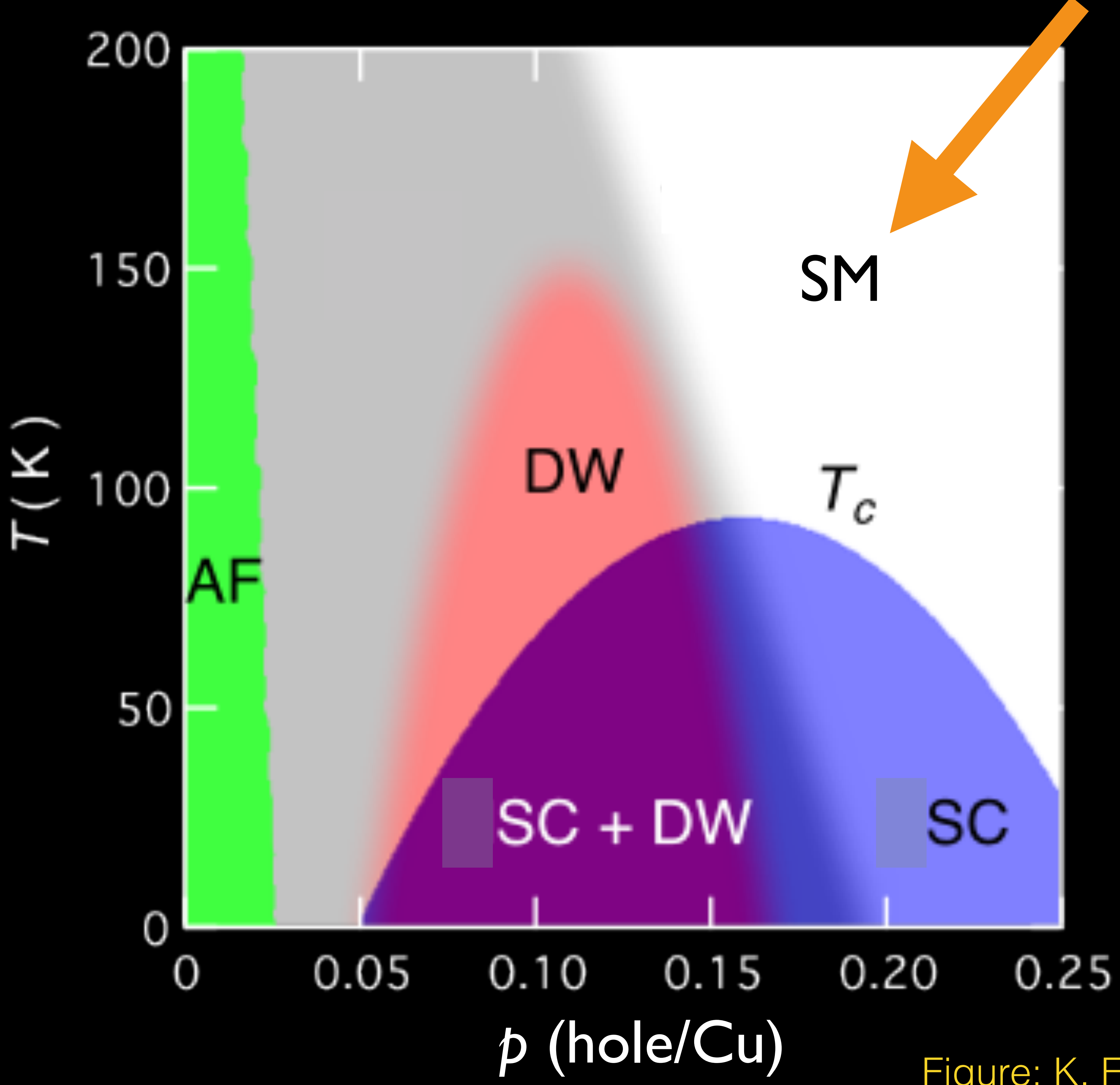


Figure: K. Fujita and J. C. Seamus Davis

Strange metal



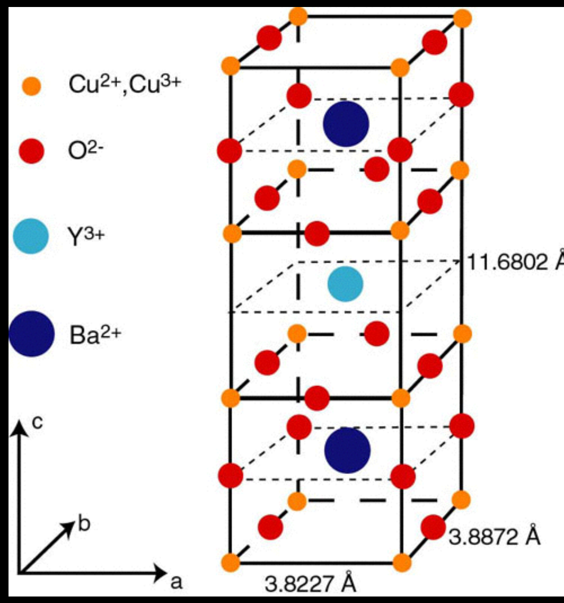


Figure: K. Fujita and J. C. Seamus Davis

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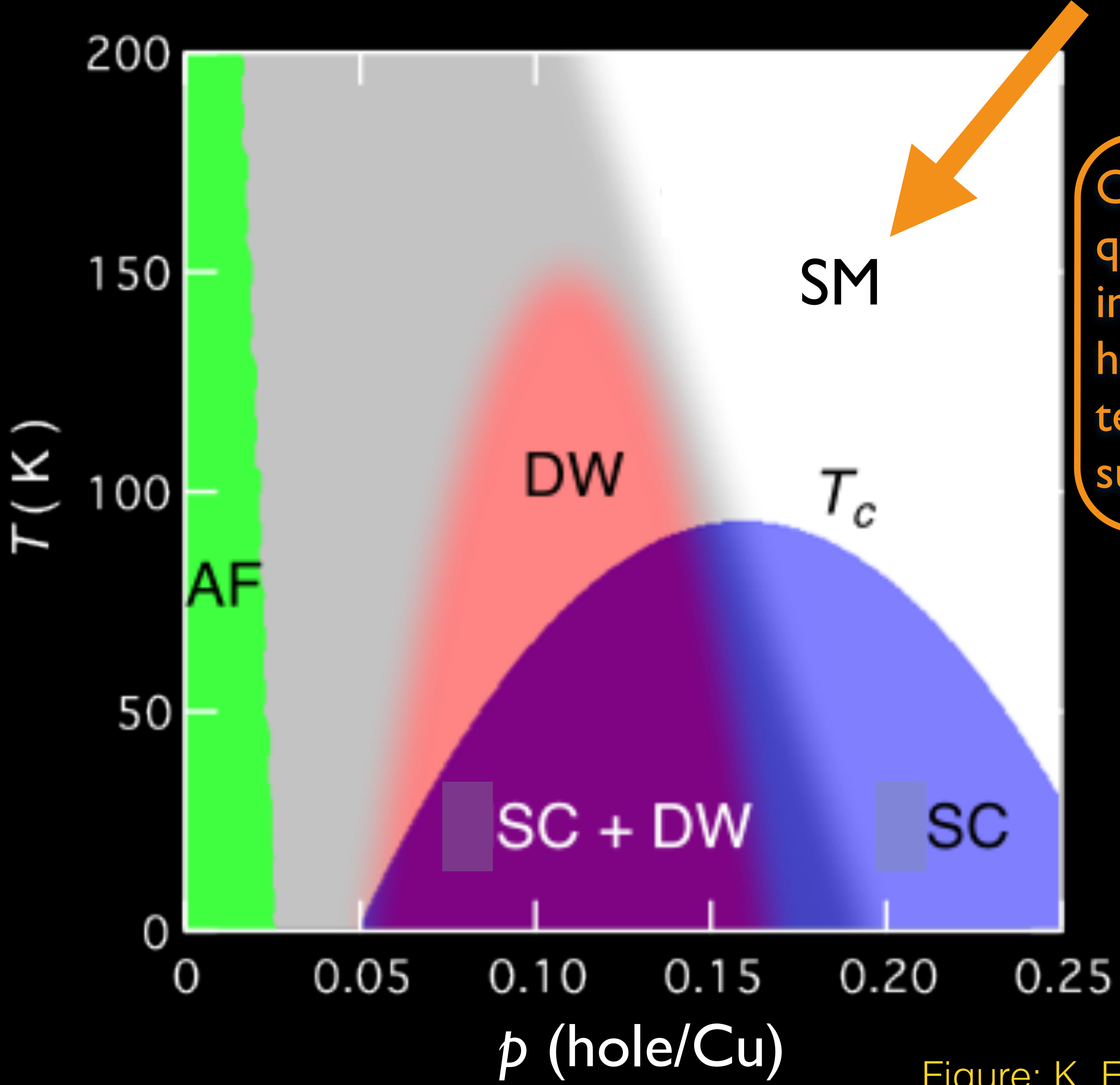


Can the "long-range quantum entanglement" in the strange metal help us understand high temperature superconductivity ?

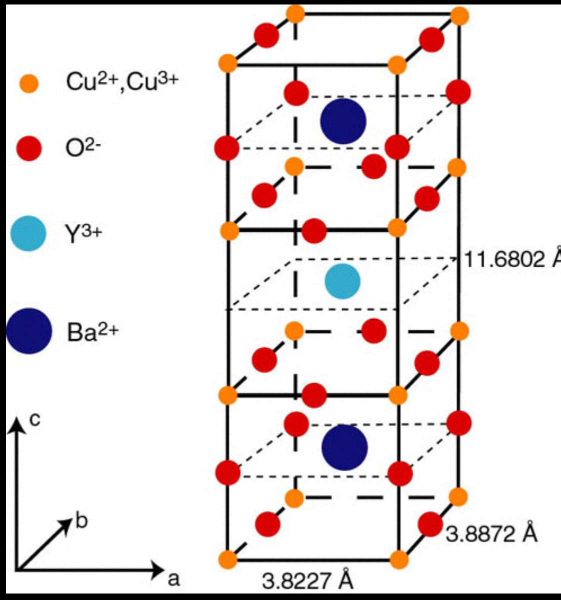
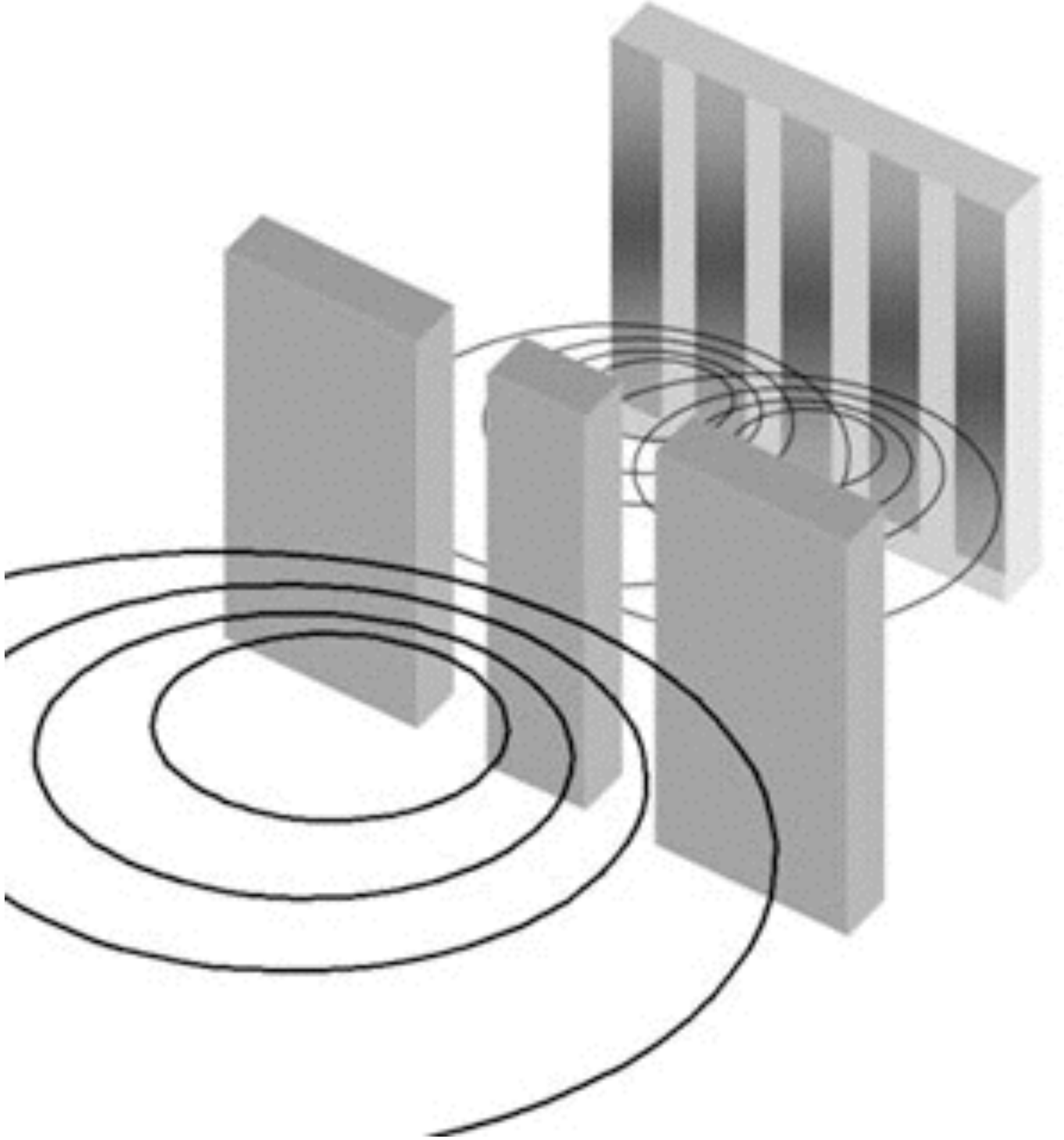


Figure: K. Fujita and J. C. Seamus Davis

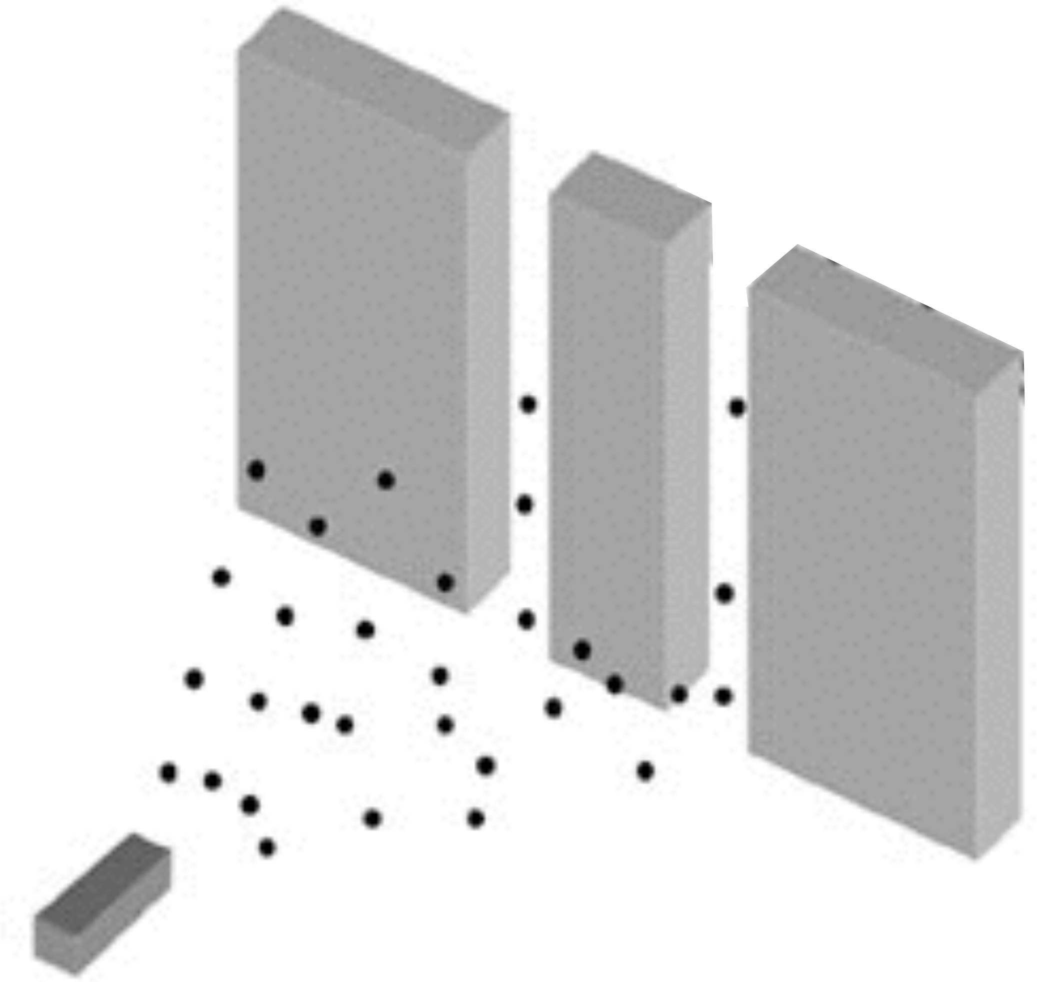
Quantum superposition and entanglement

The double slit experiment



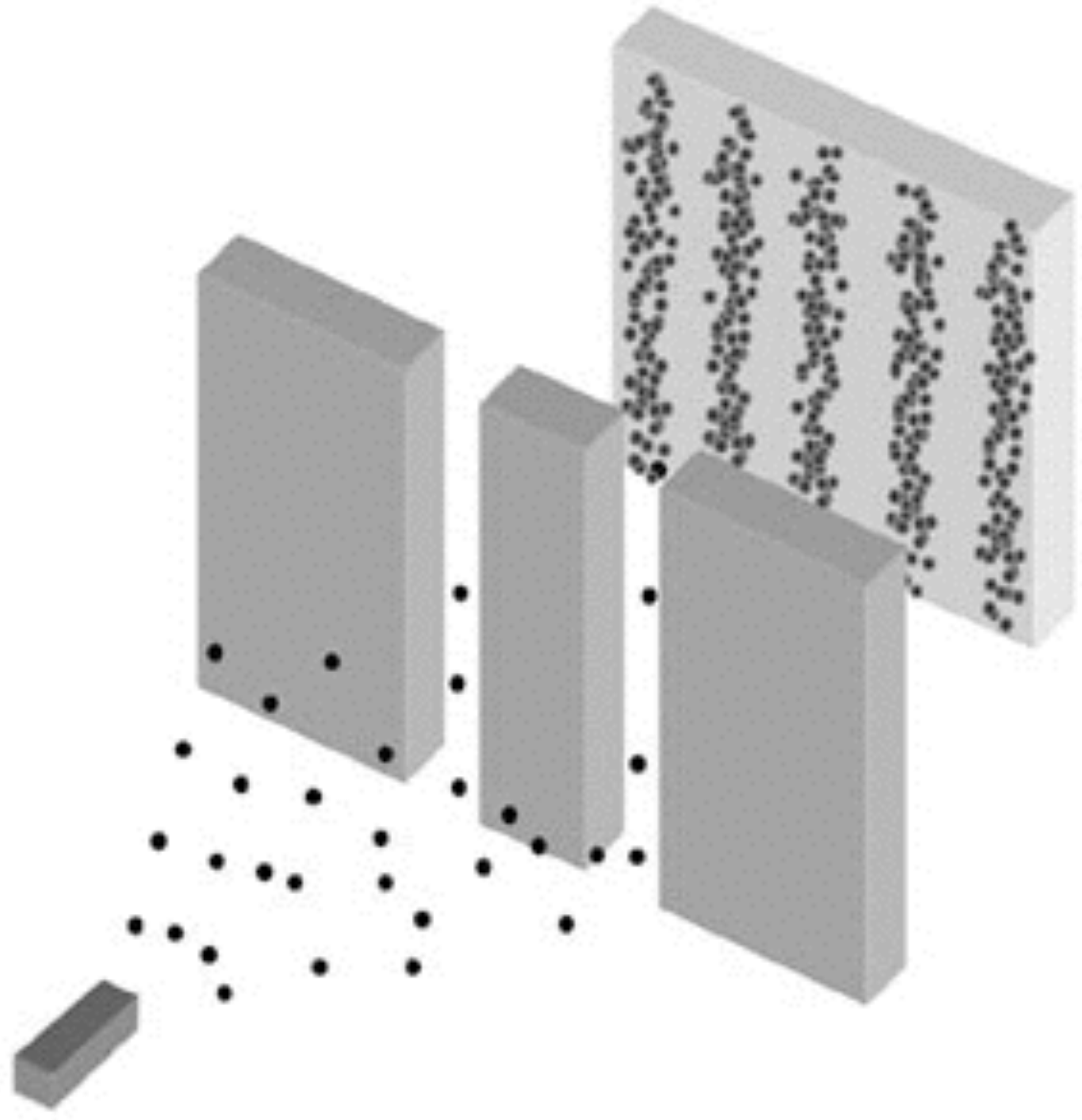
Interference of water waves

The double slit experiment



Send electrons through the slits

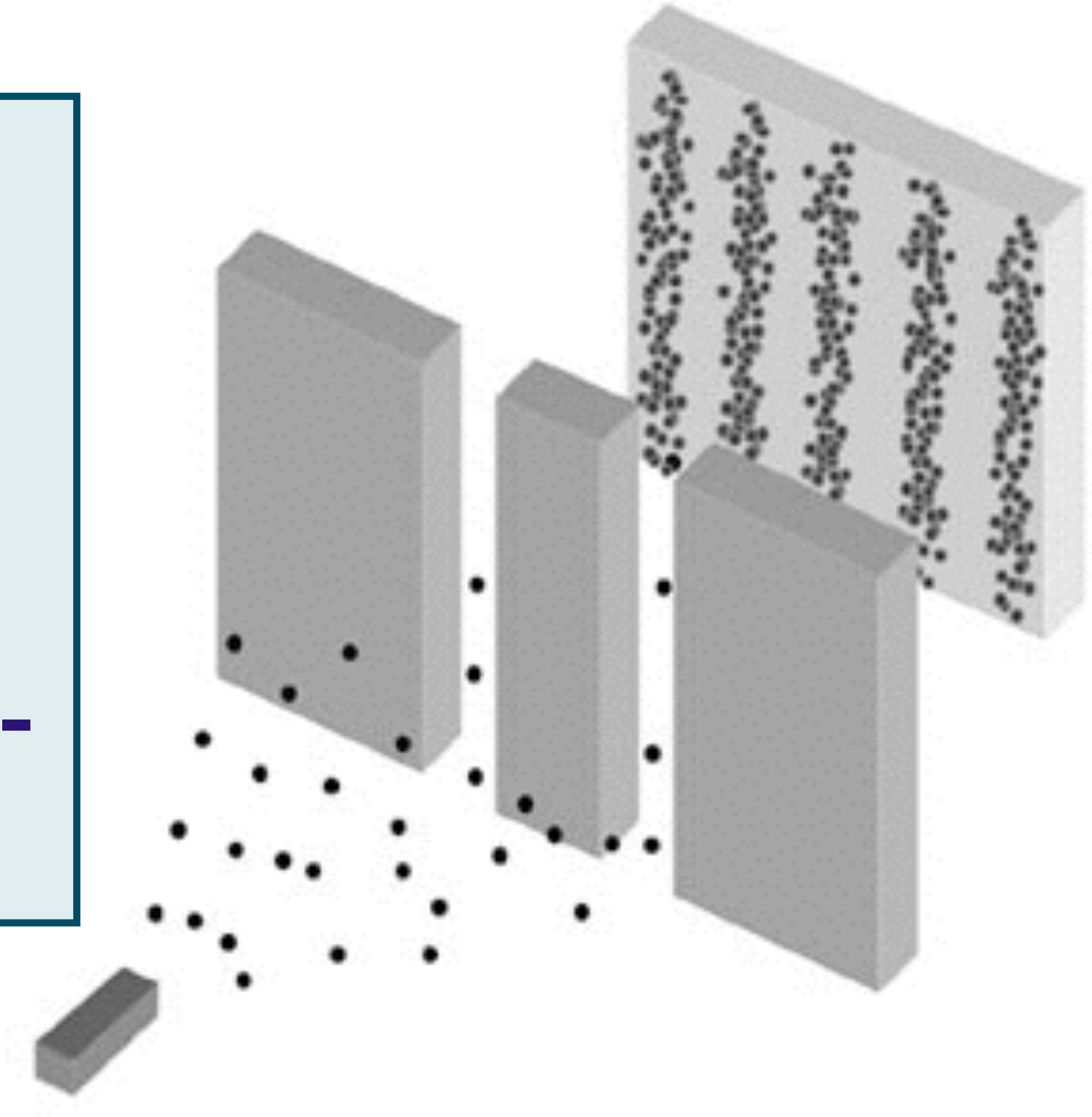
The double slit experiment



Interference of electrons

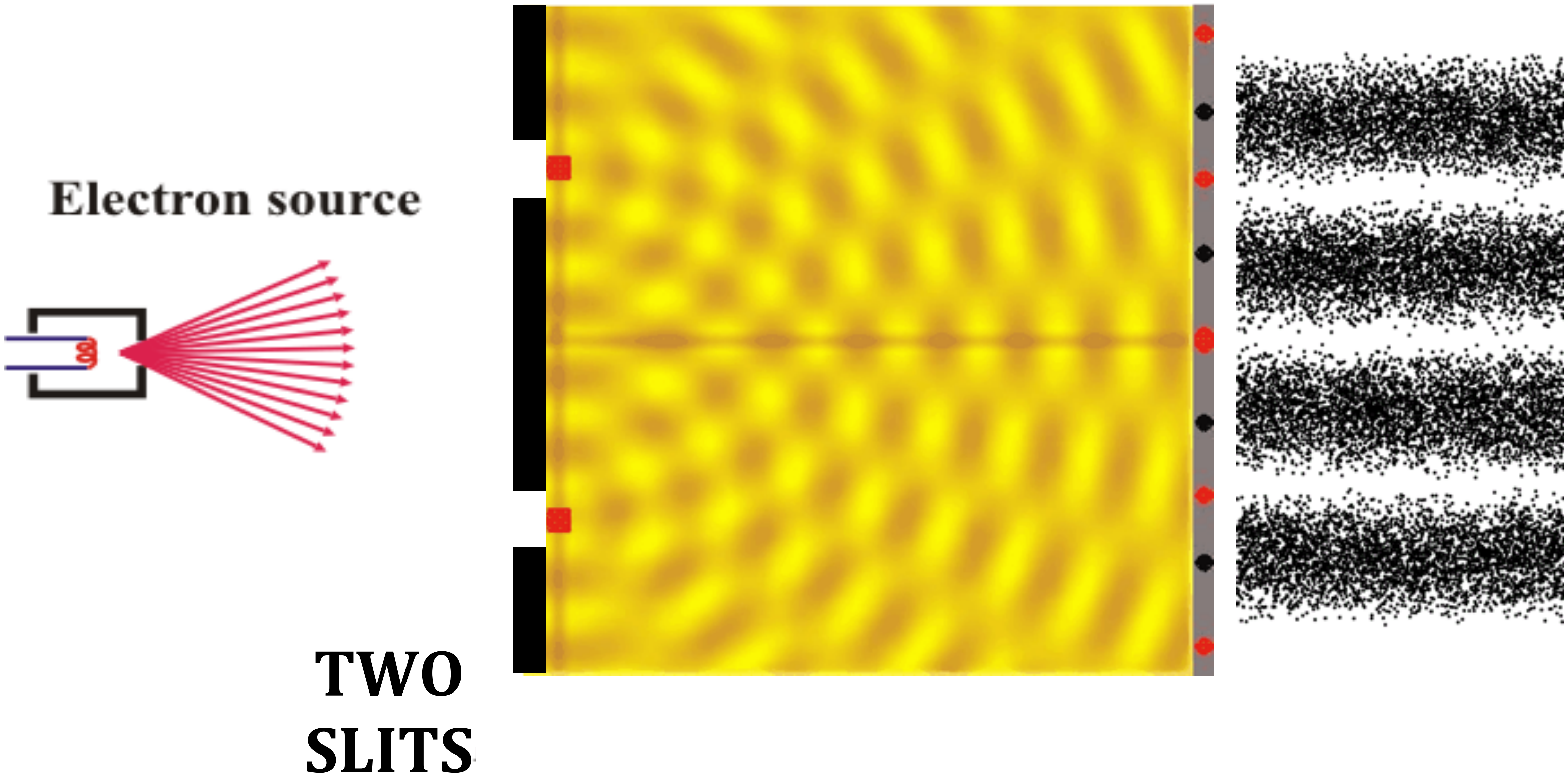
The double slit experiment

Unlike water waves, electrons arrive one-by-one



Interference of electrons

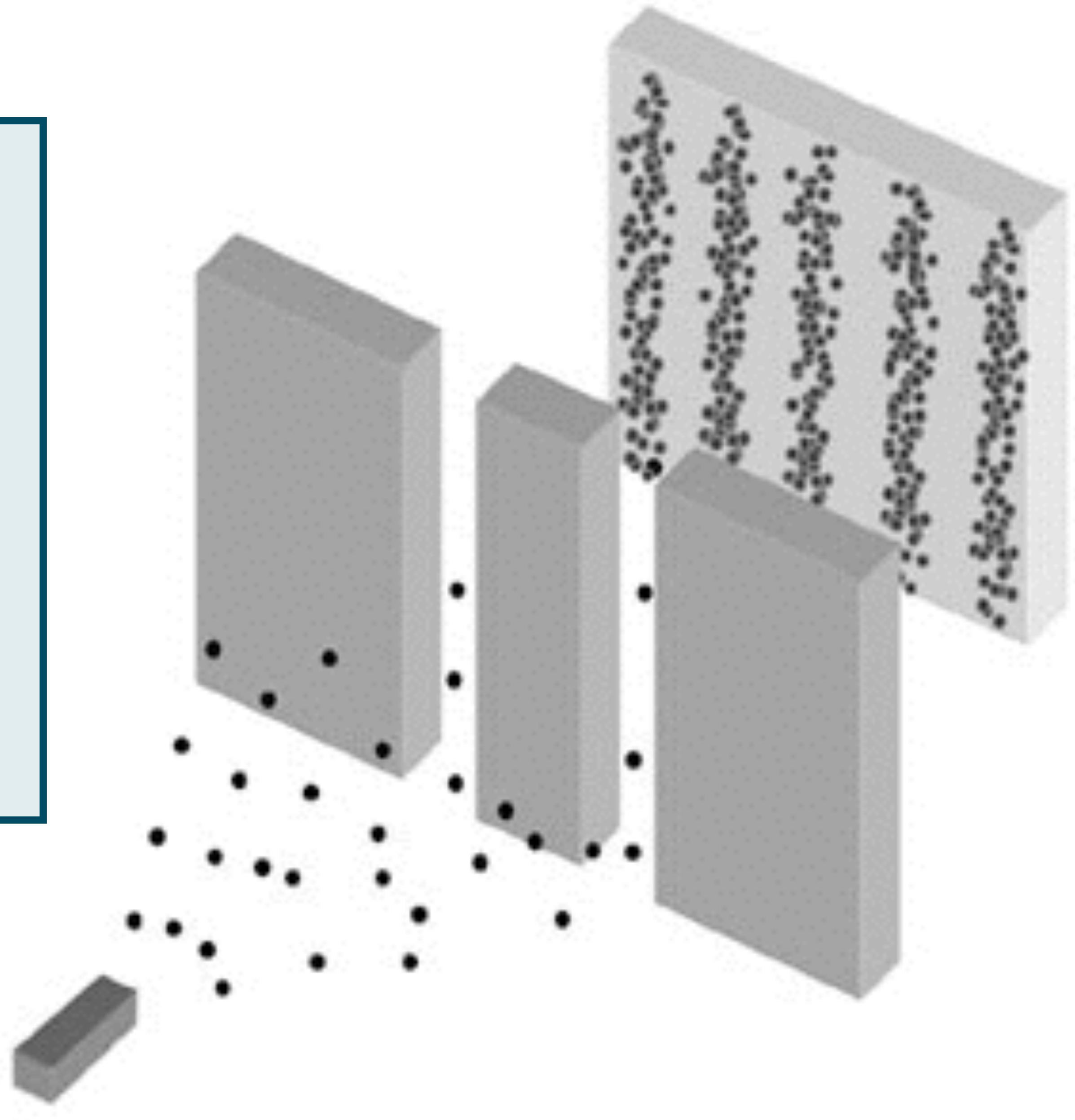
The double slit experiment



Interference of electrons

The double slit experiment

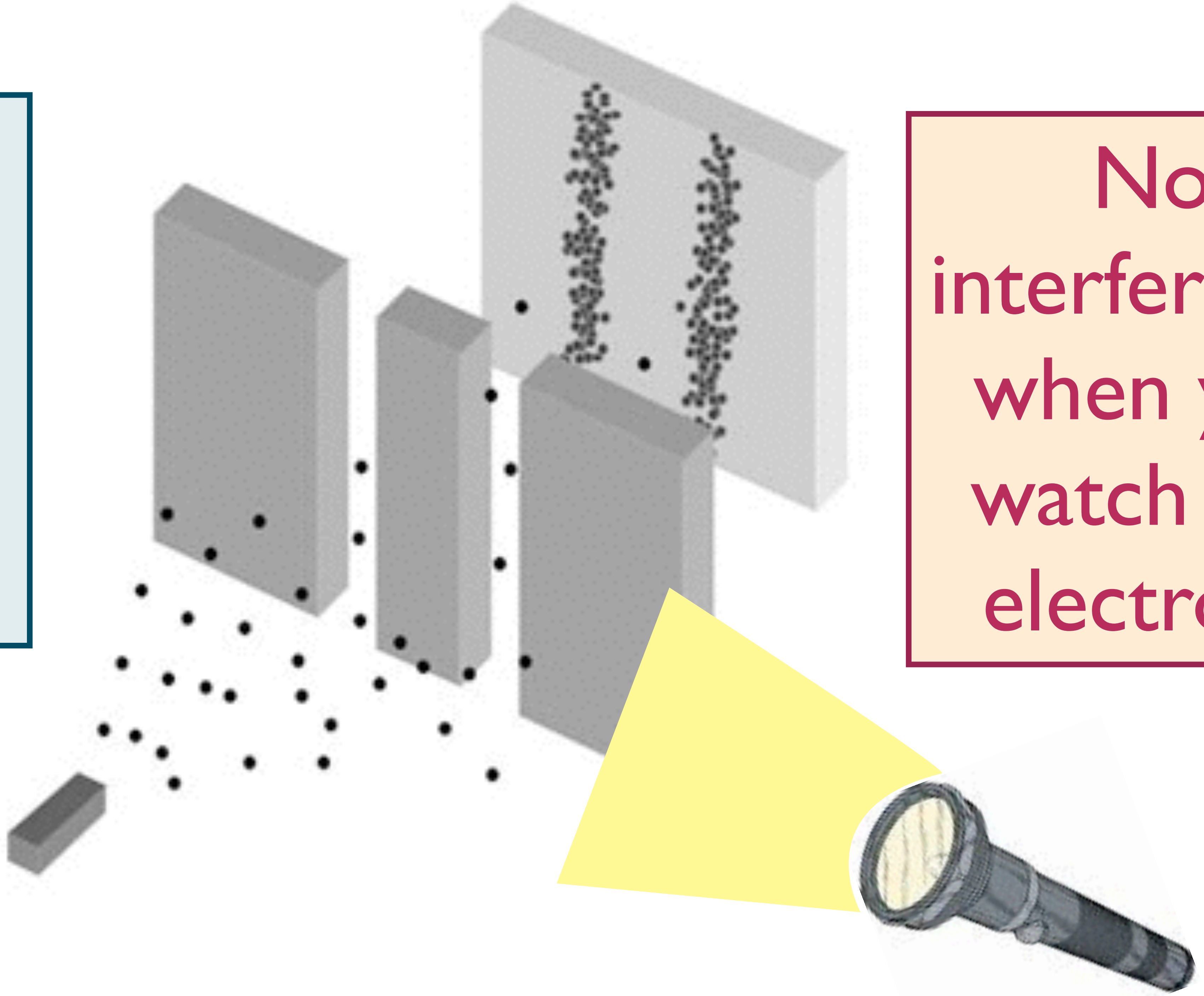
Which slit does an electron pass through ?



Interference of electrons

The double slit experiment

Which slit does an electron pass through ?

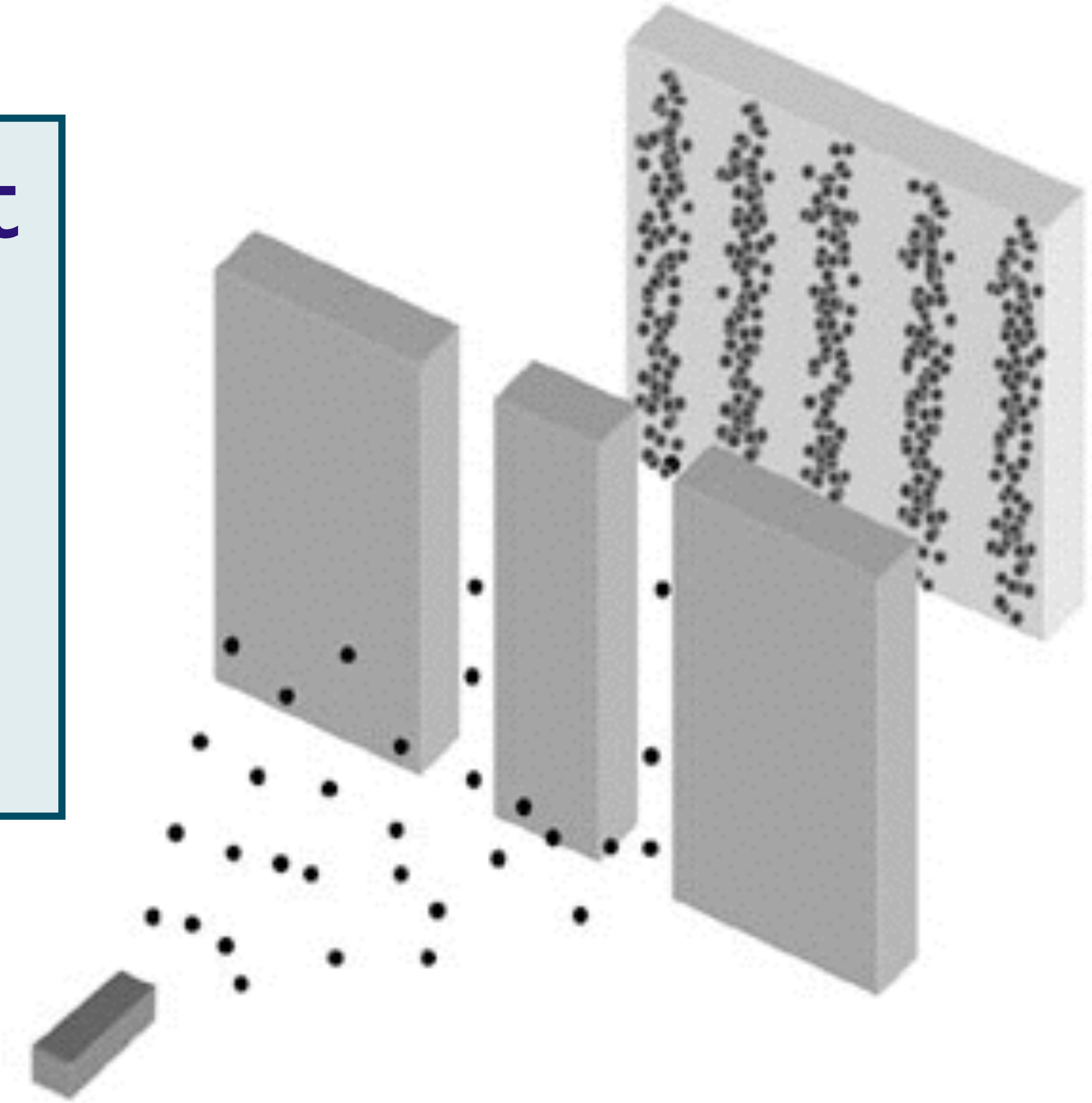


No interference when you watch the electrons

Interference of electrons

The double slit experiment

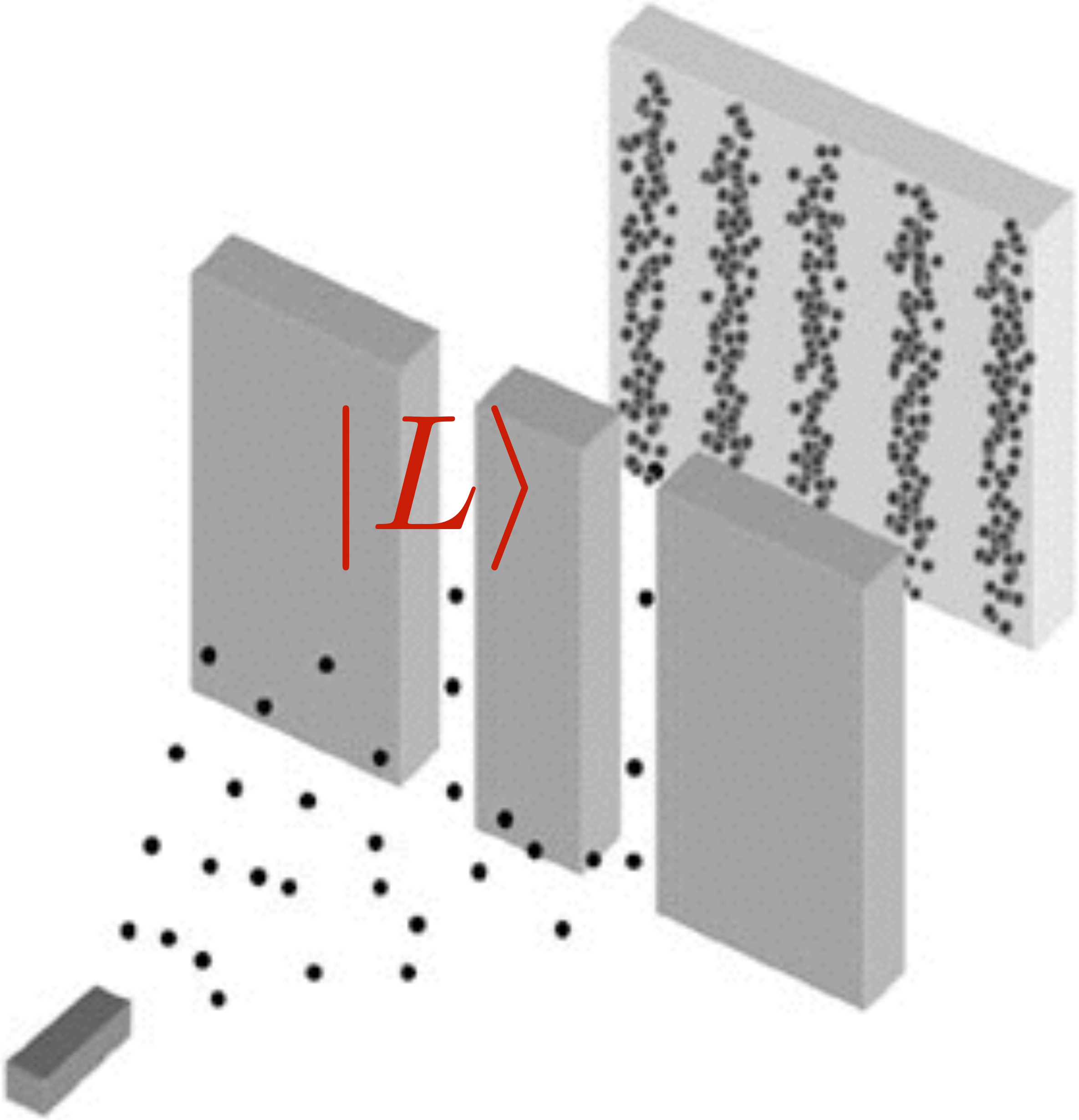
Which slit does an electron pass through ?



Each electron passes through both slits !

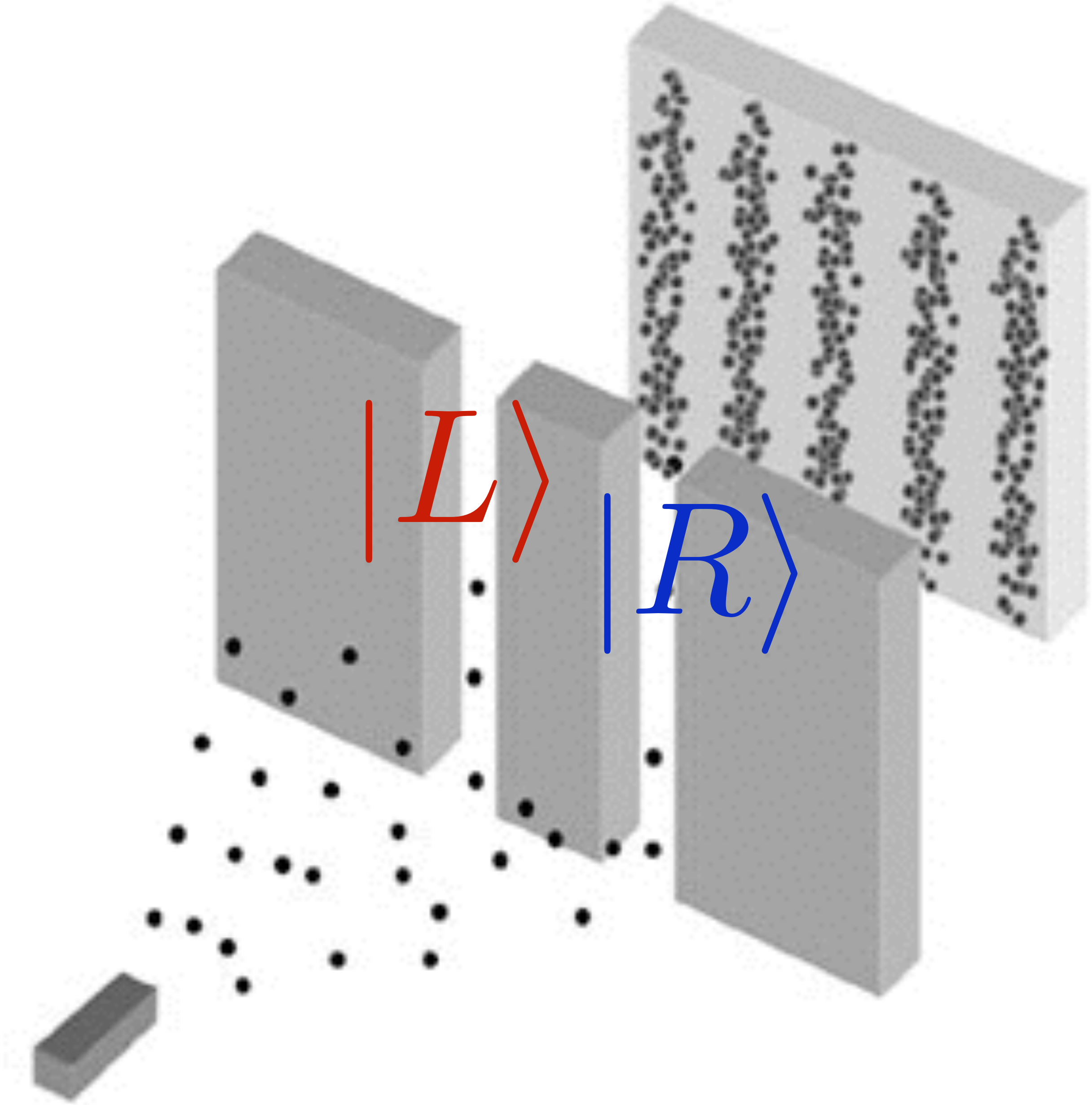
Interference of electrons

The double slit experiment



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

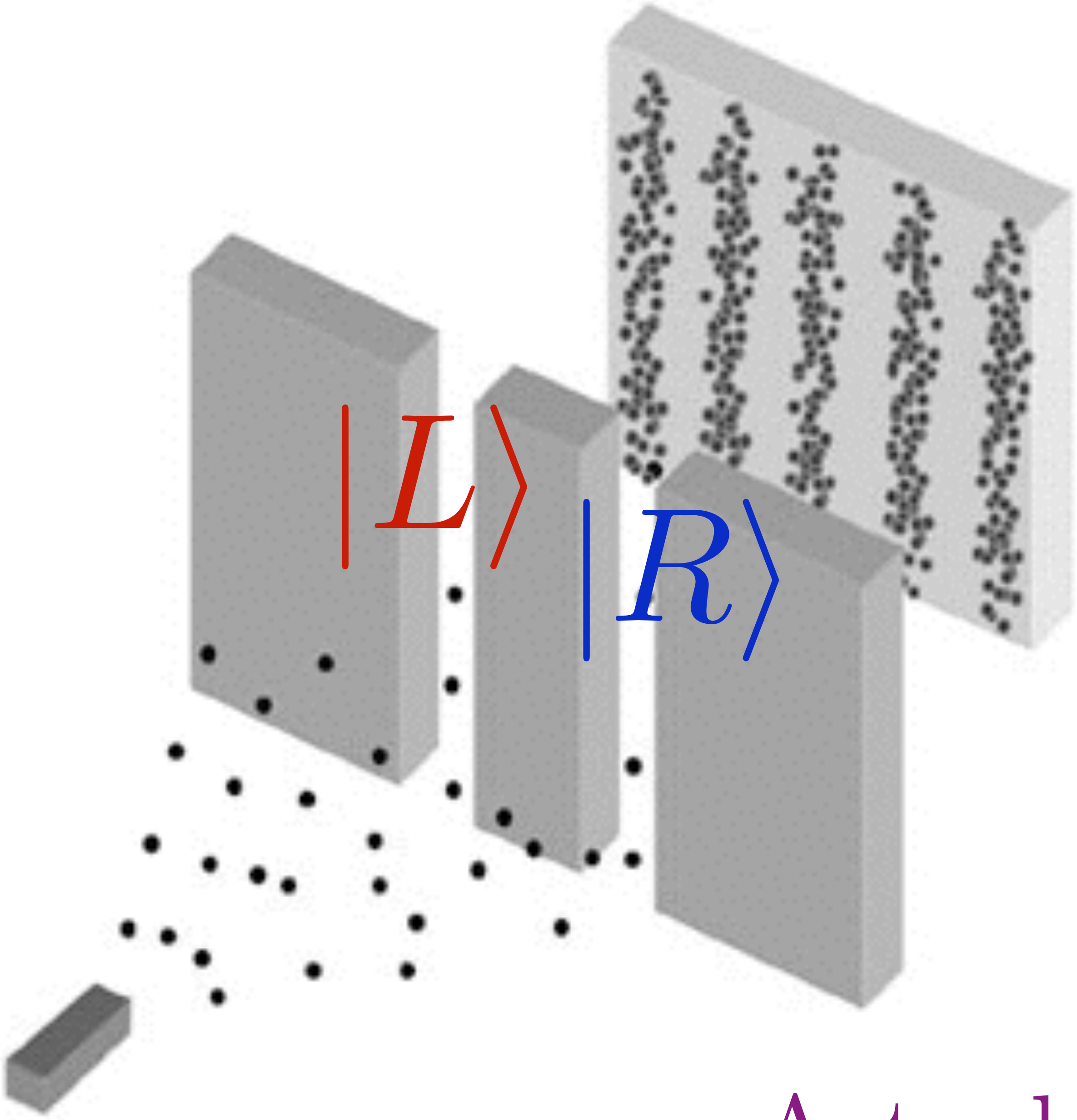
The double slit experiment



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

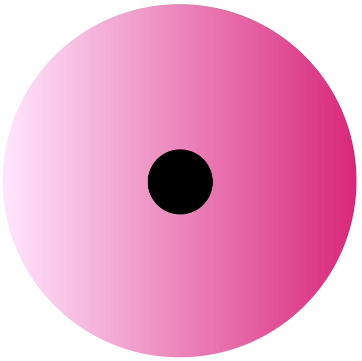
Actual state of *each* electron is

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

Quantum Entanglement: quantum superposition with more than one particle

Quantum Entanglement: quantum superposition with more than one particle

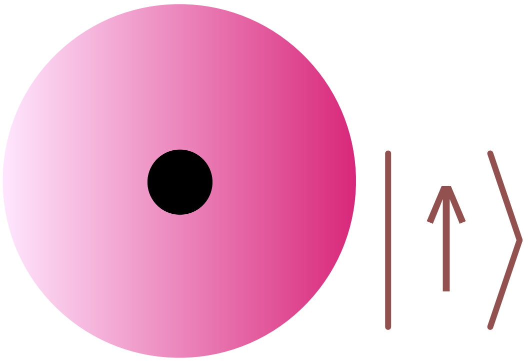
Hydrogen atom:



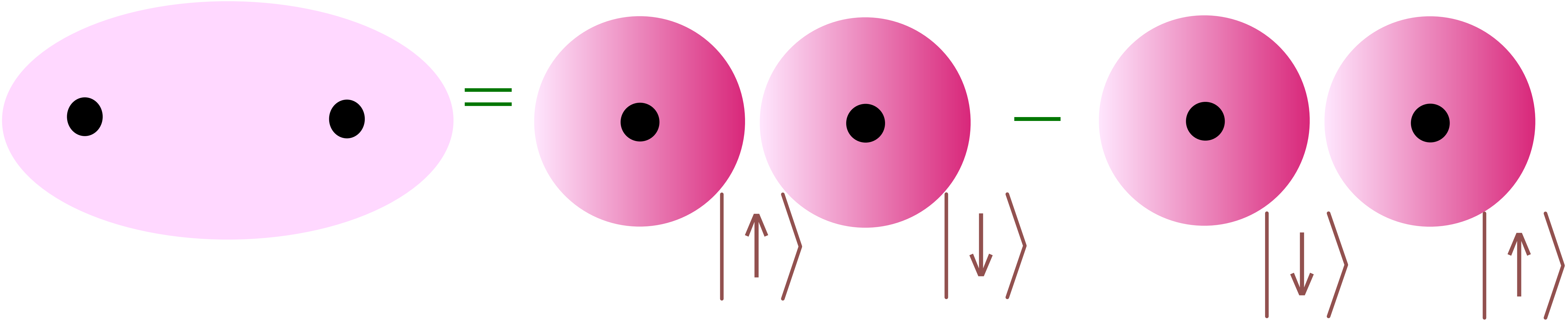
$|\uparrow\rangle$

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

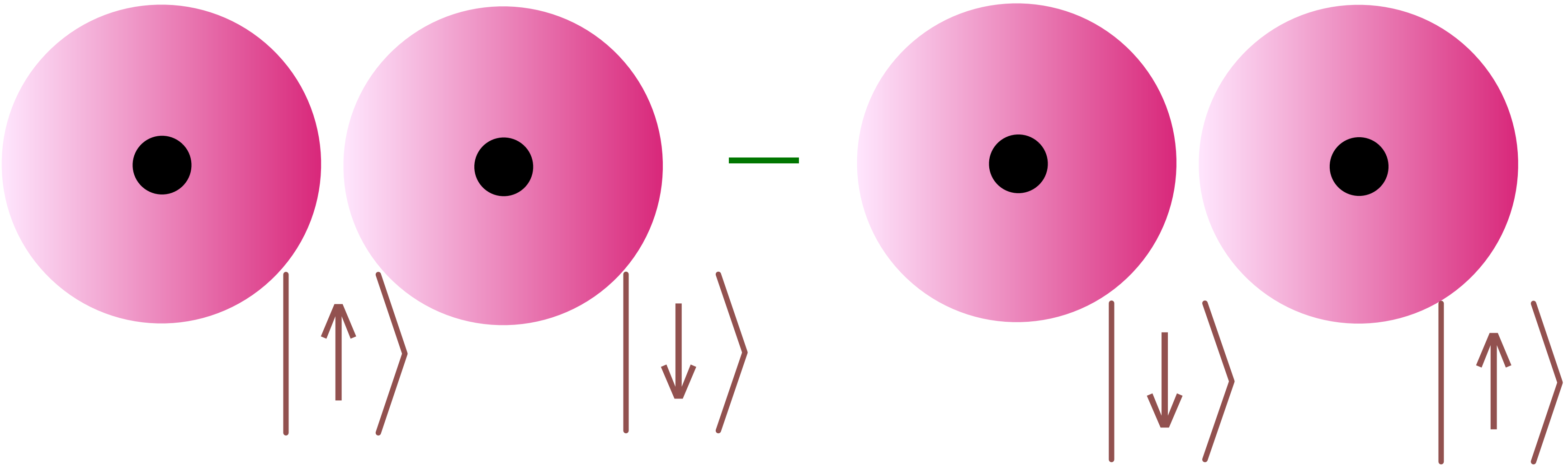


Hydrogen molecule:

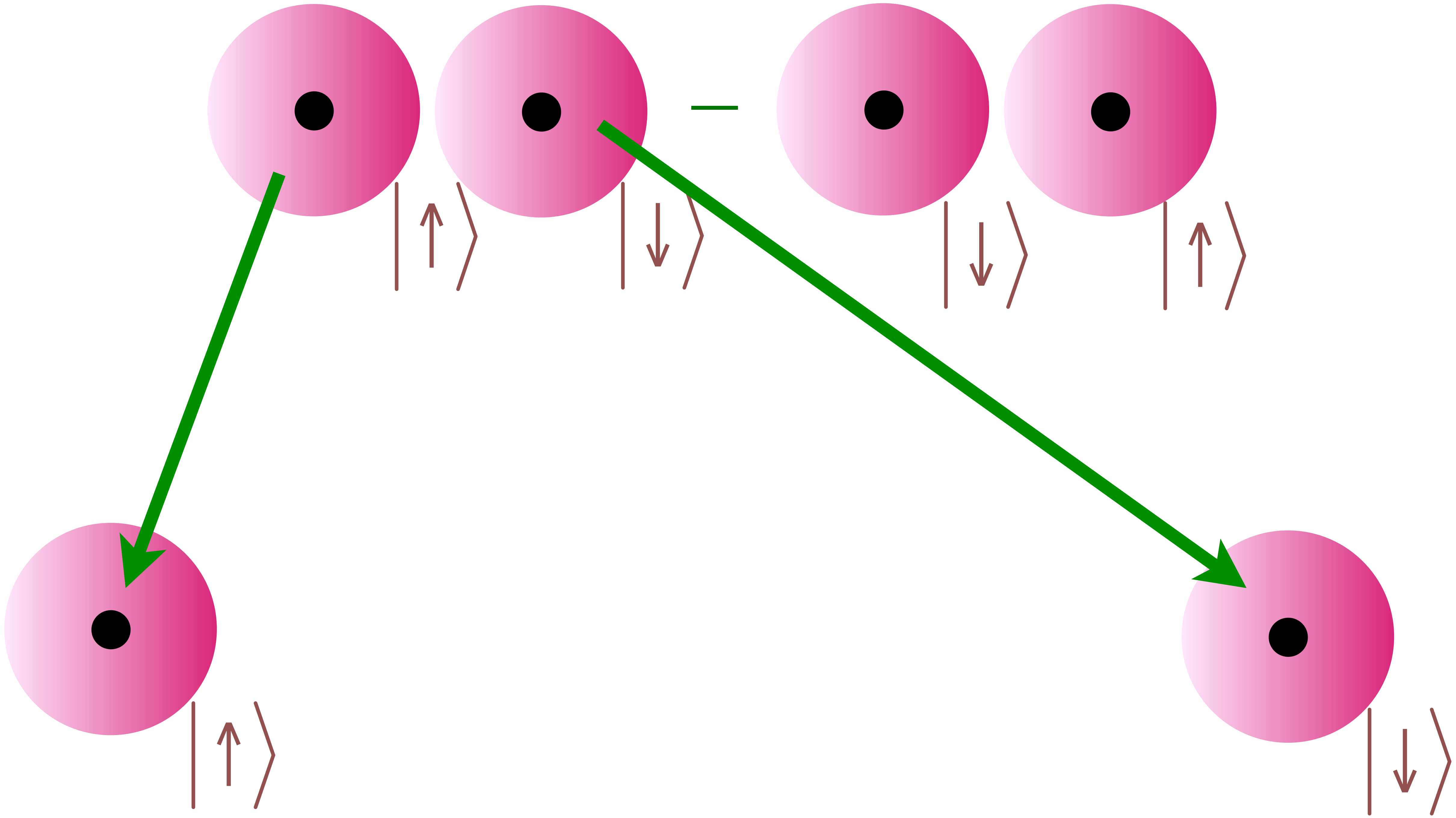


$$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

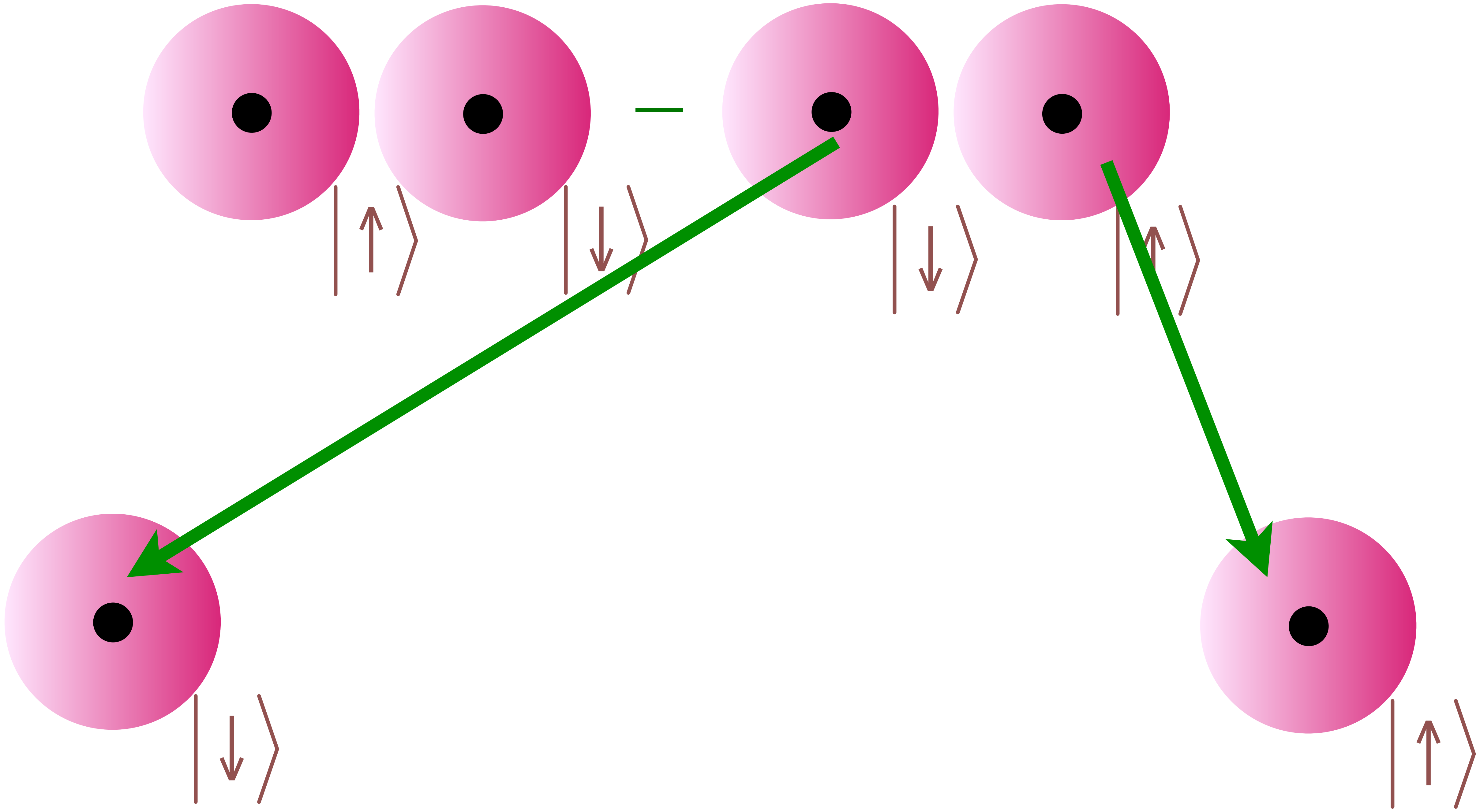
Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle

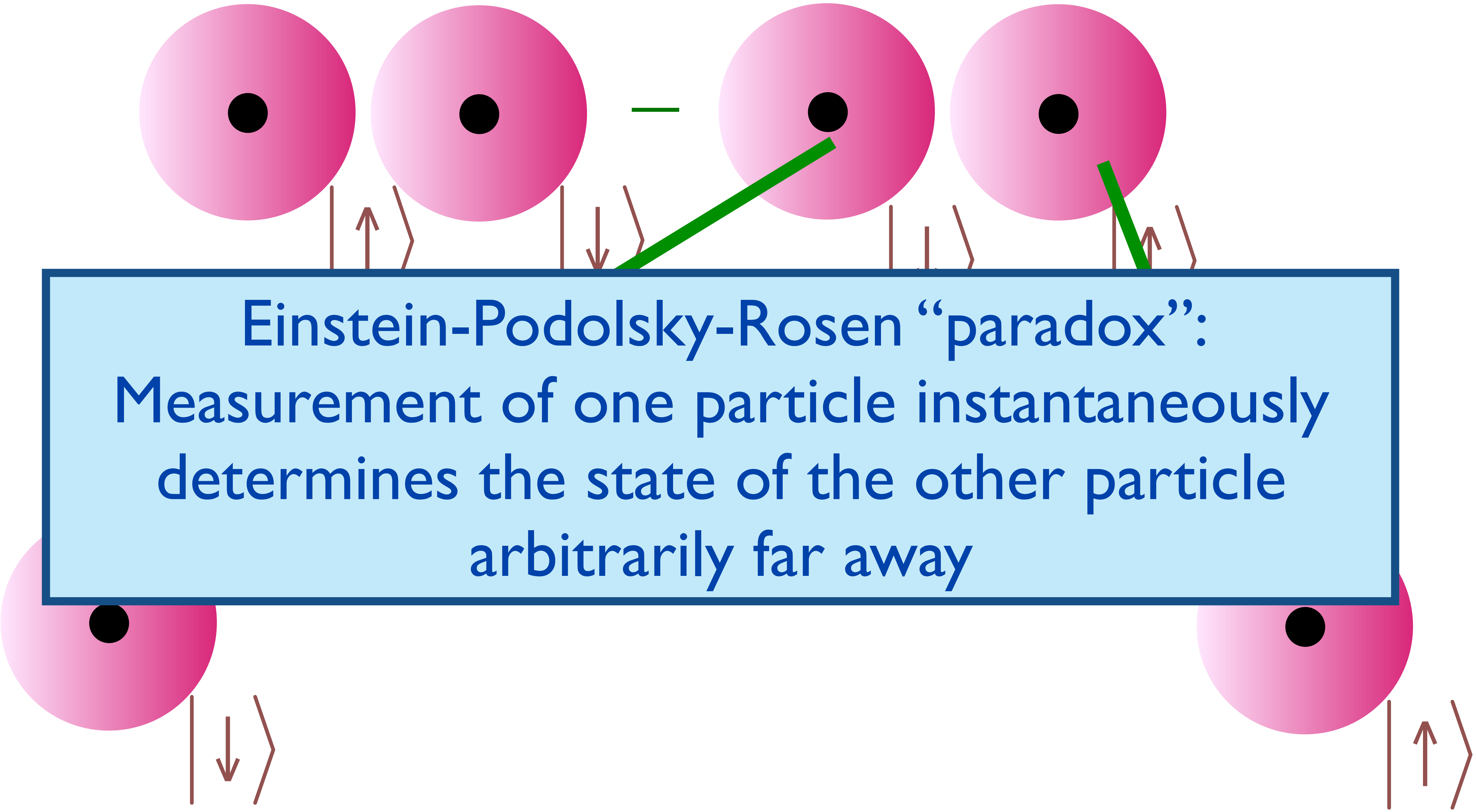


Quantum Entanglement: quantum superposition with more than one particle



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

Quantum Entanglement: quantum superposition with more than one particle



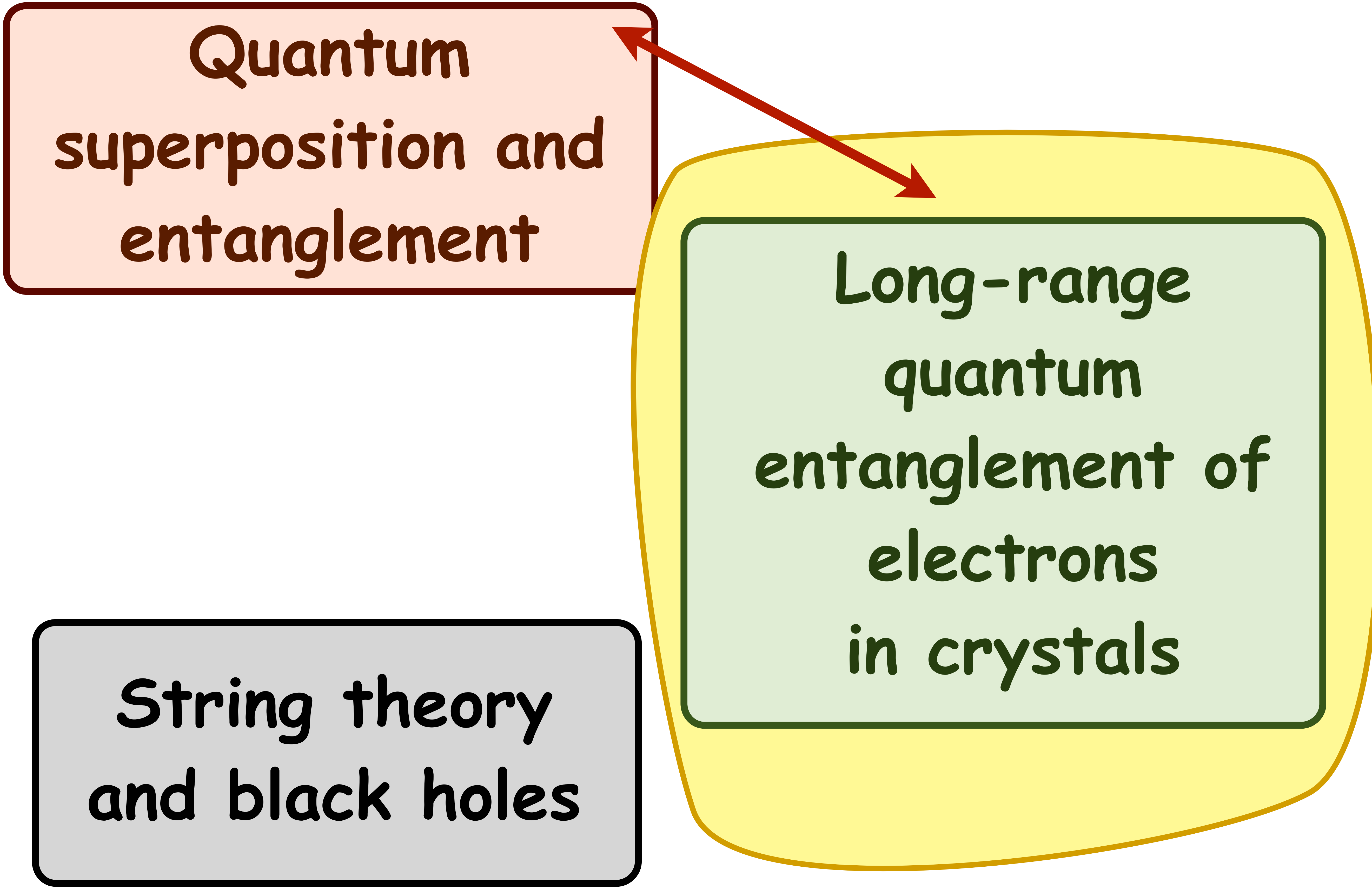
Einstein-Podolsky-Rosen “paradox”:
Measurement of one particle instantaneously determines the state of the other particle arbitrarily far away

Quantum superposition and entanglement

Quantum superposition and entanglement

Long-range quantum entanglement of electrons in crystals

String theory and black holes



Quantum superposition and entanglement

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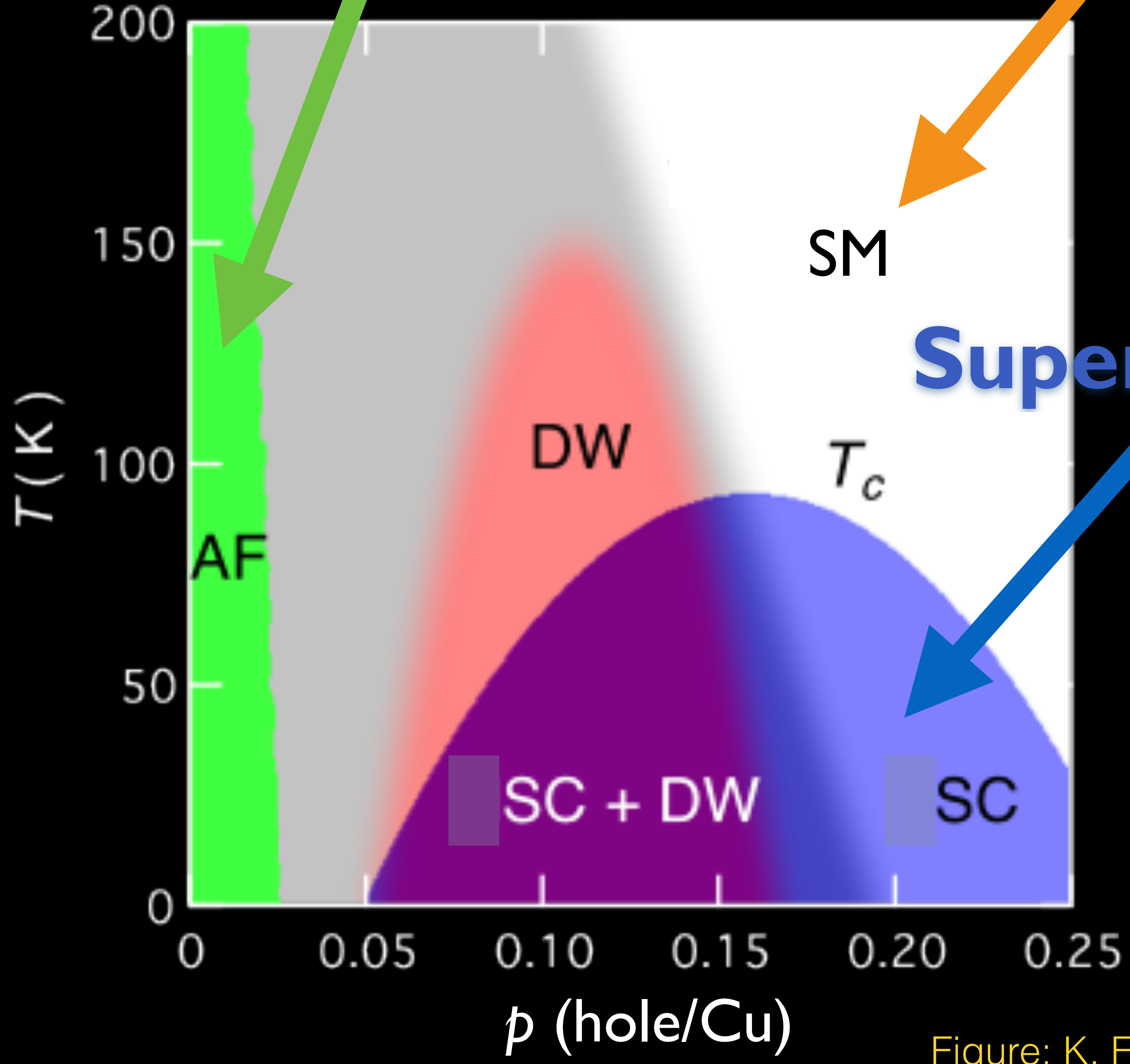
String theory and black holes

Antiferromagnet

Strange metal

Superconductor



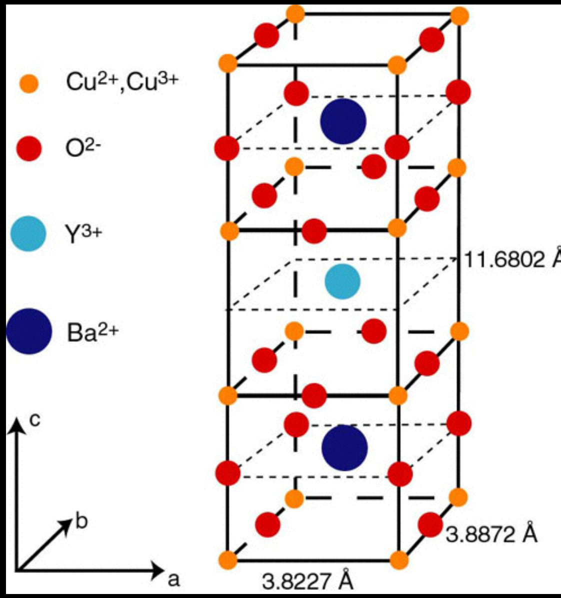
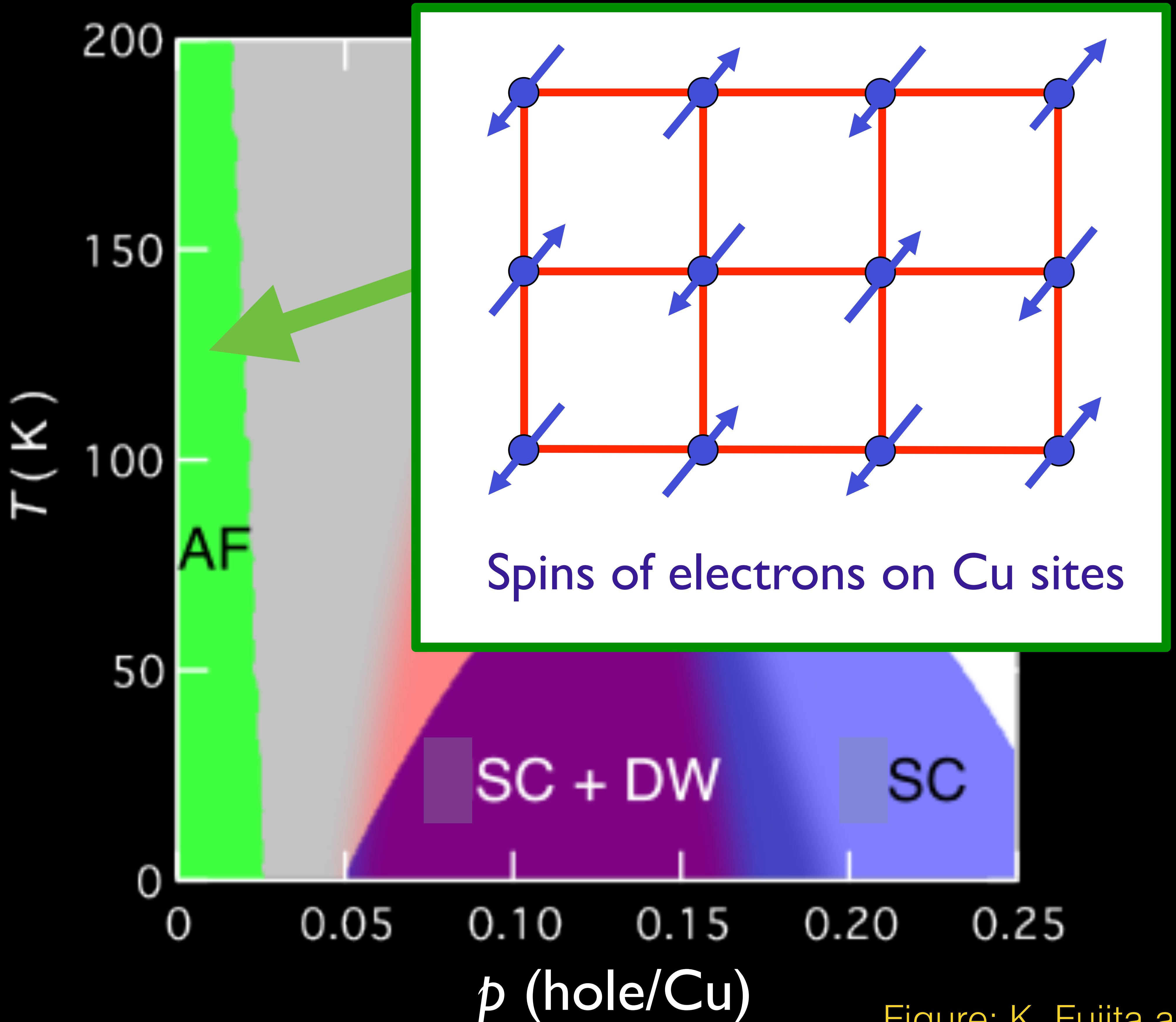


Figure: K. Fujita and J. C. Seamus Davis

Antiferromagnet



Spins of electrons on Cu sites

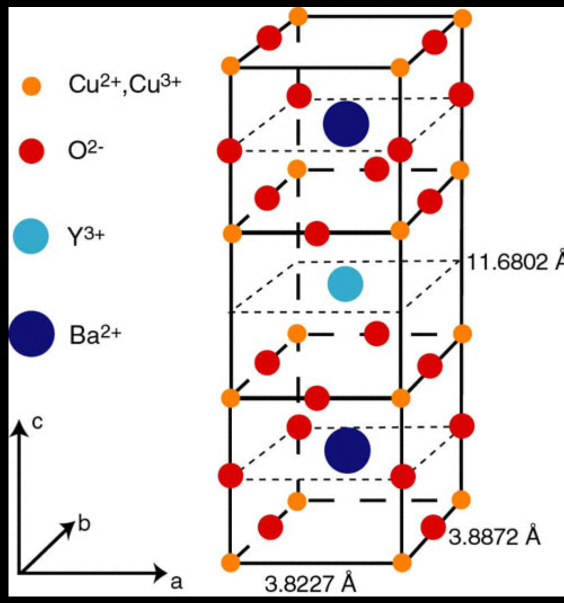
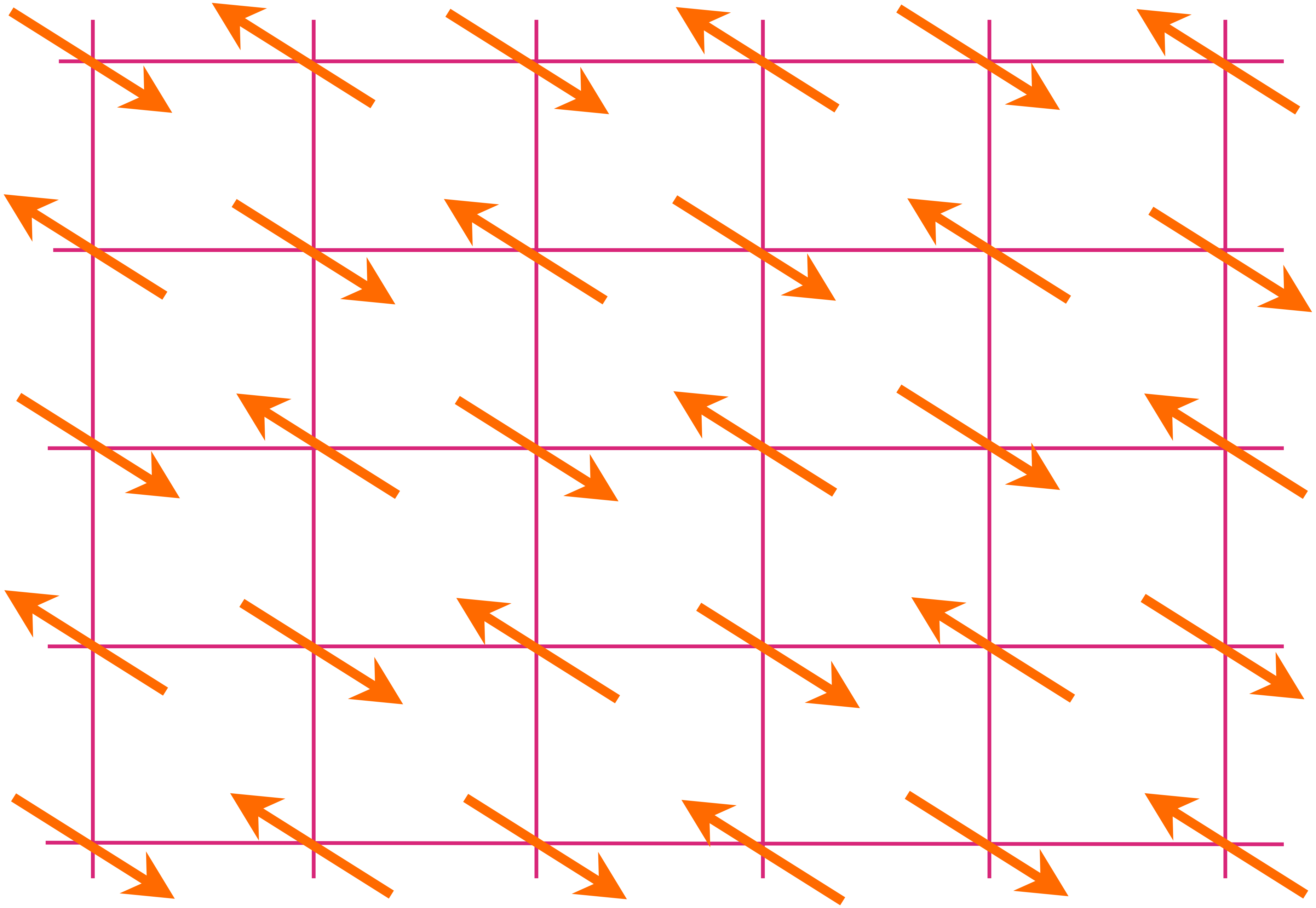
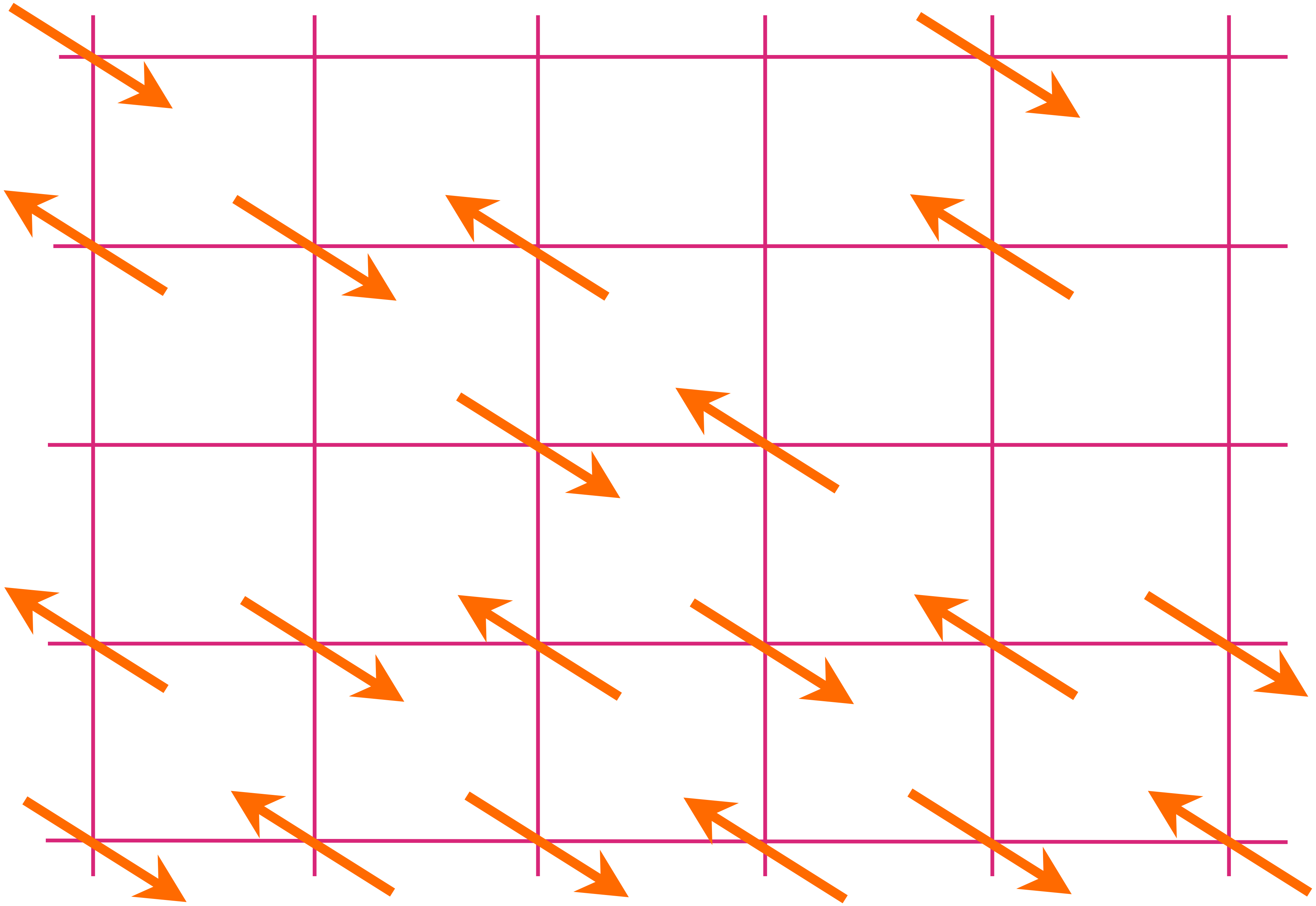


Figure: K. Fujita and J. C. Seamus Davis

Square lattice of Cu sites

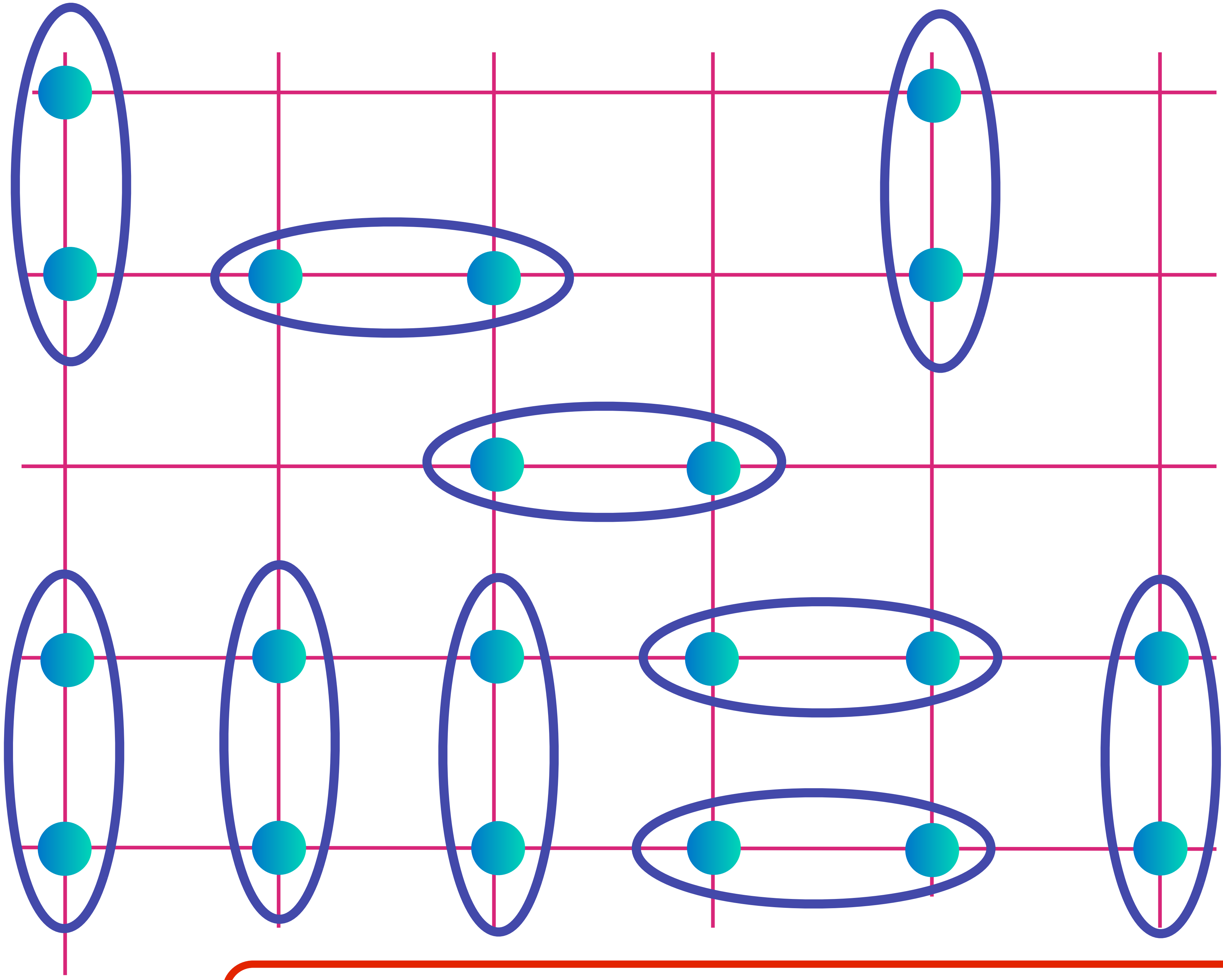


Square lattice of Cu sites

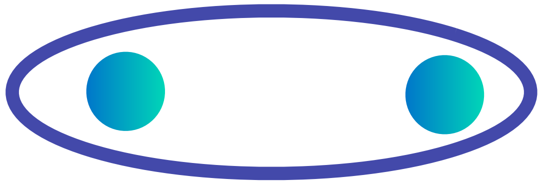


Remove density
p electrons

Square lattice of Cu sites

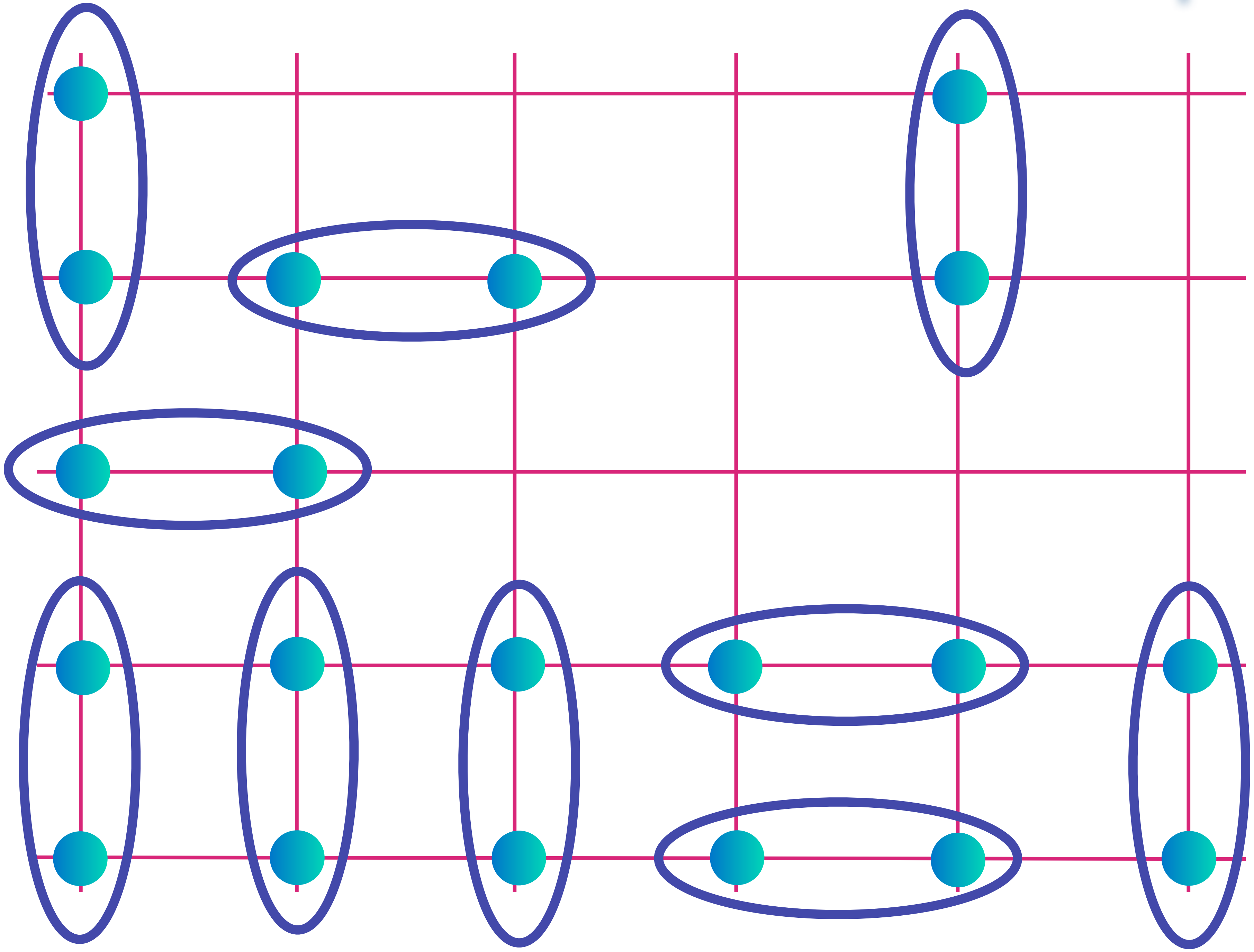


Electrons entangle in ("Cooper") pairs into chemical bonds

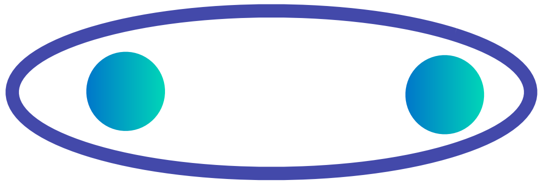
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Square lattice of Cu sites

Superconductivity !



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

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

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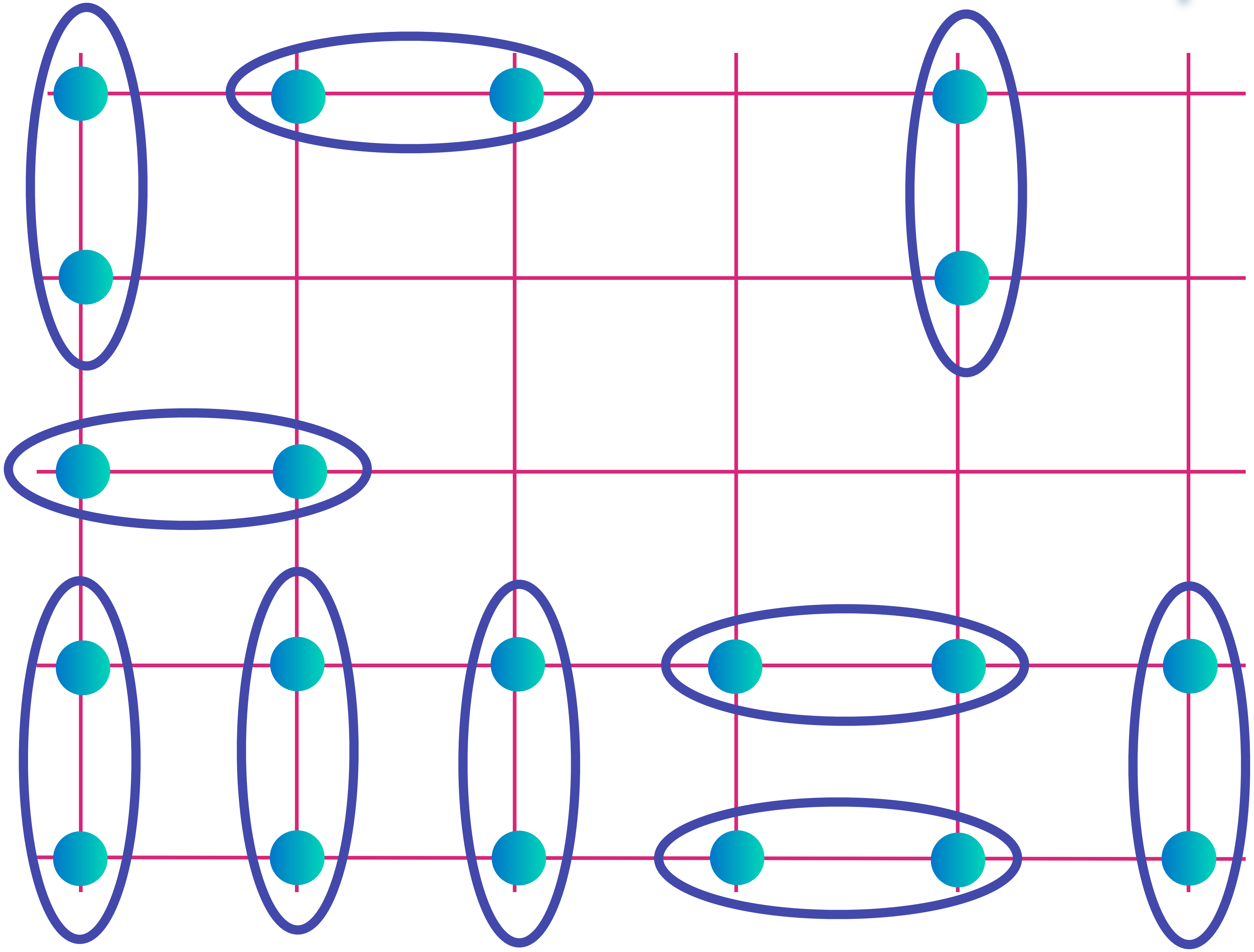

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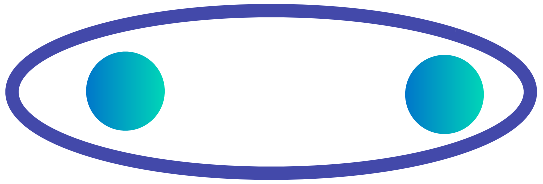
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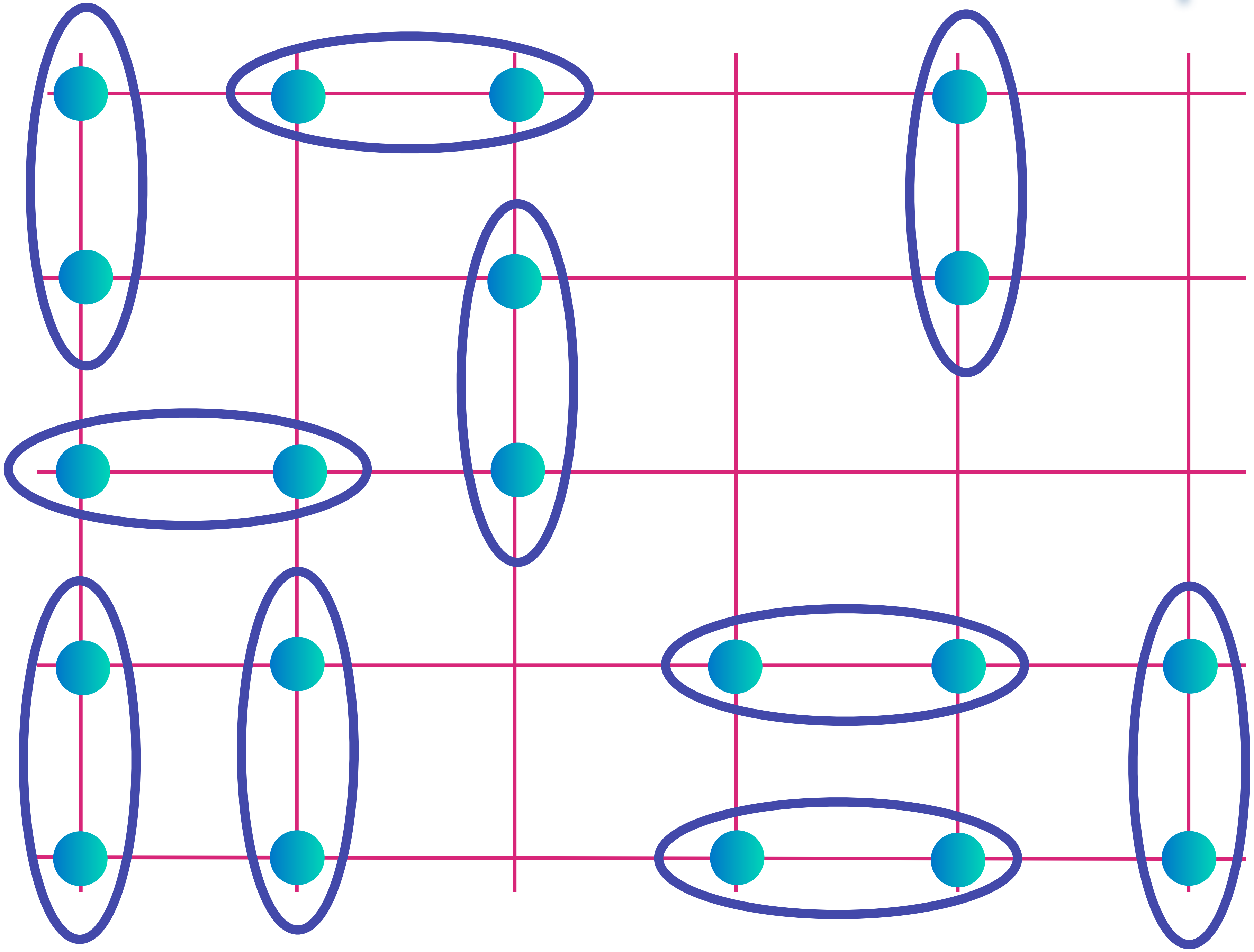

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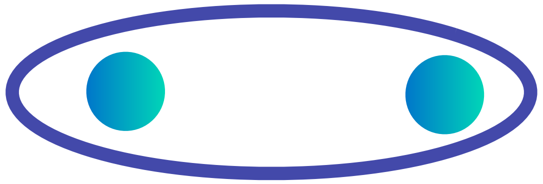

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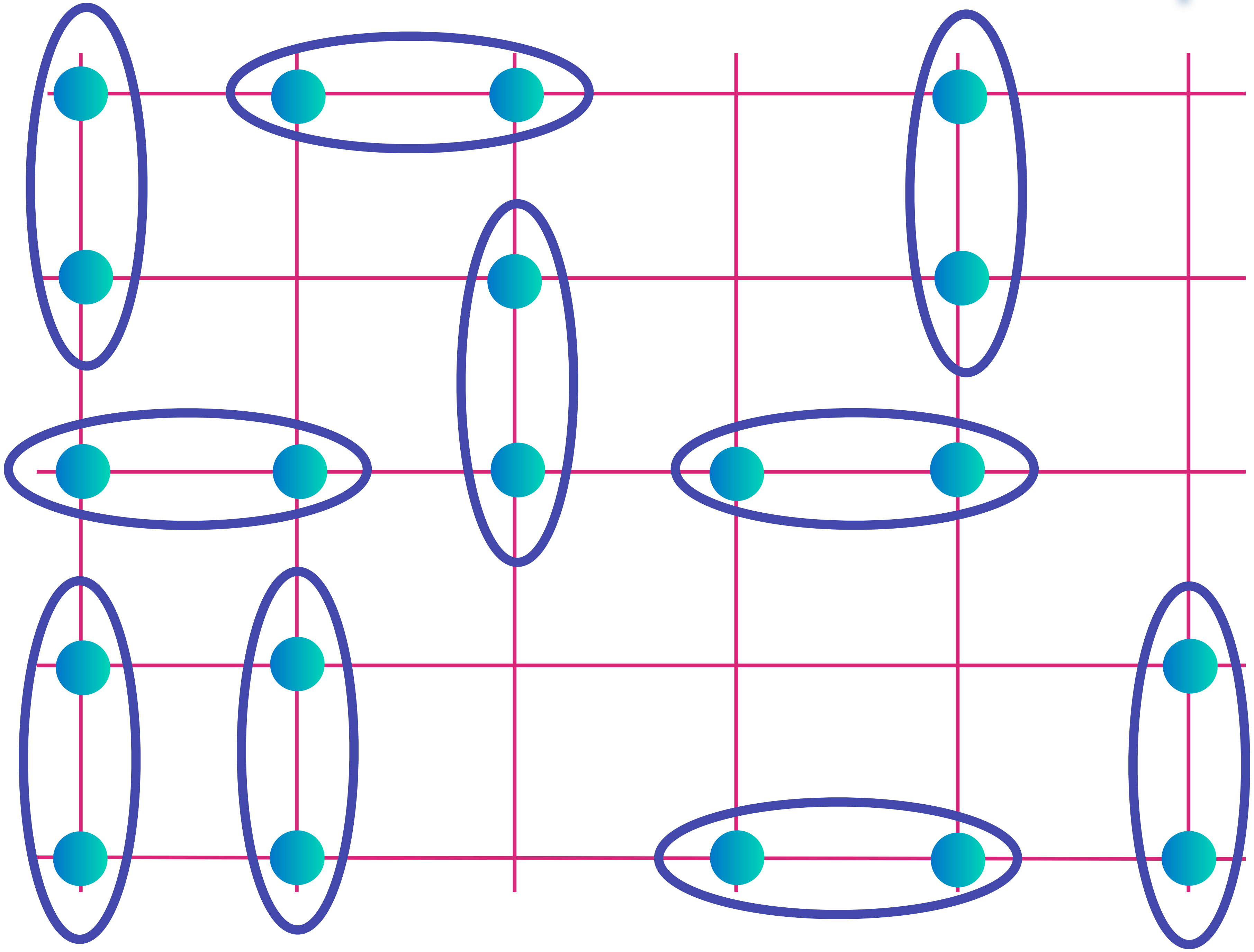

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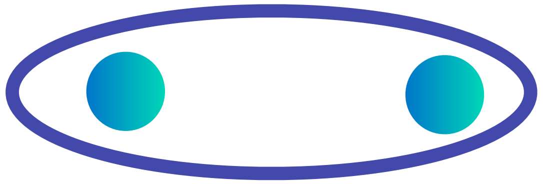

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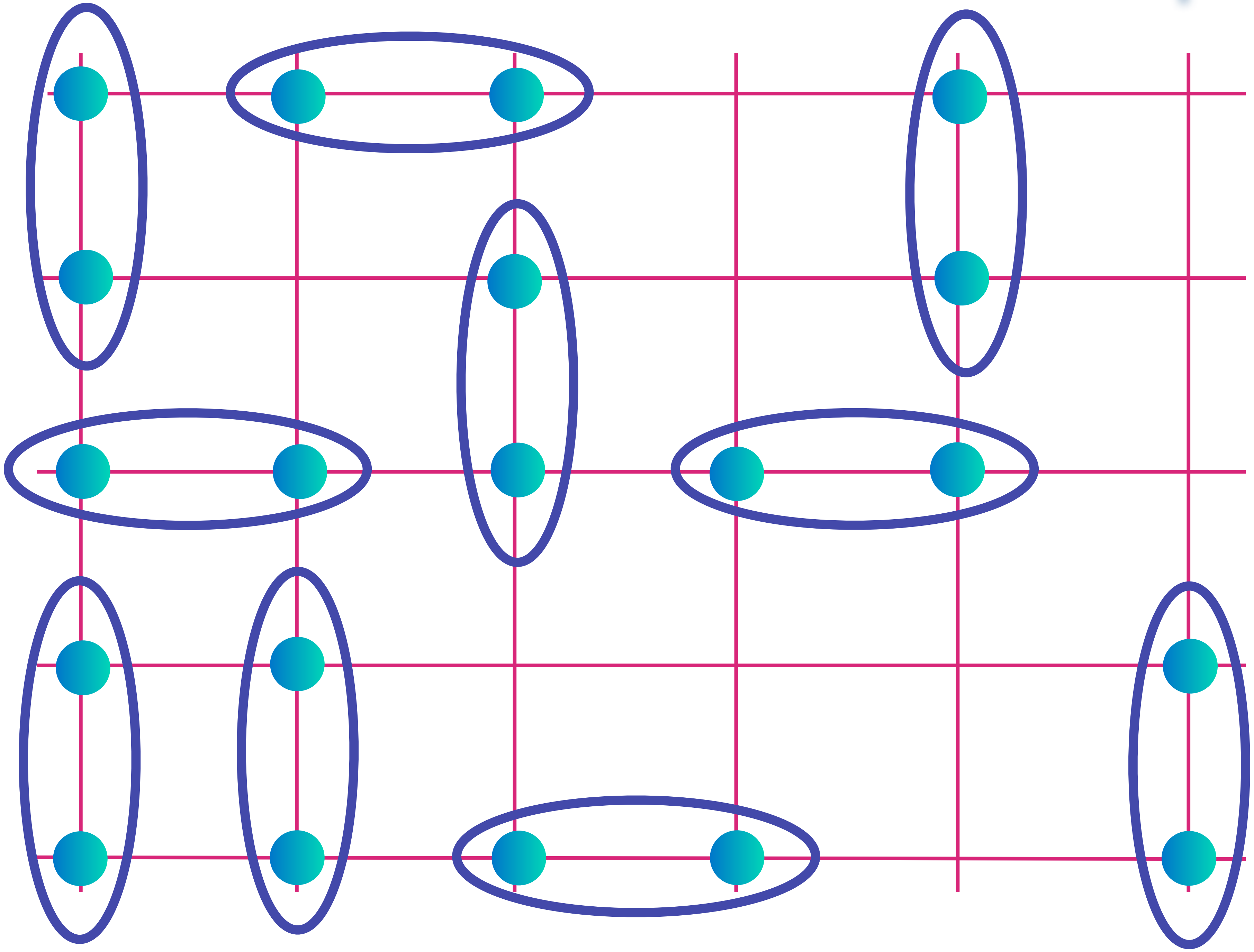

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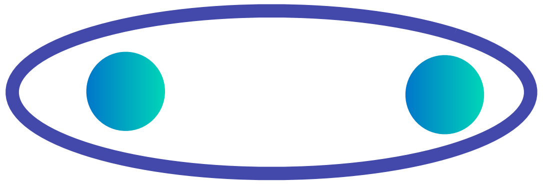

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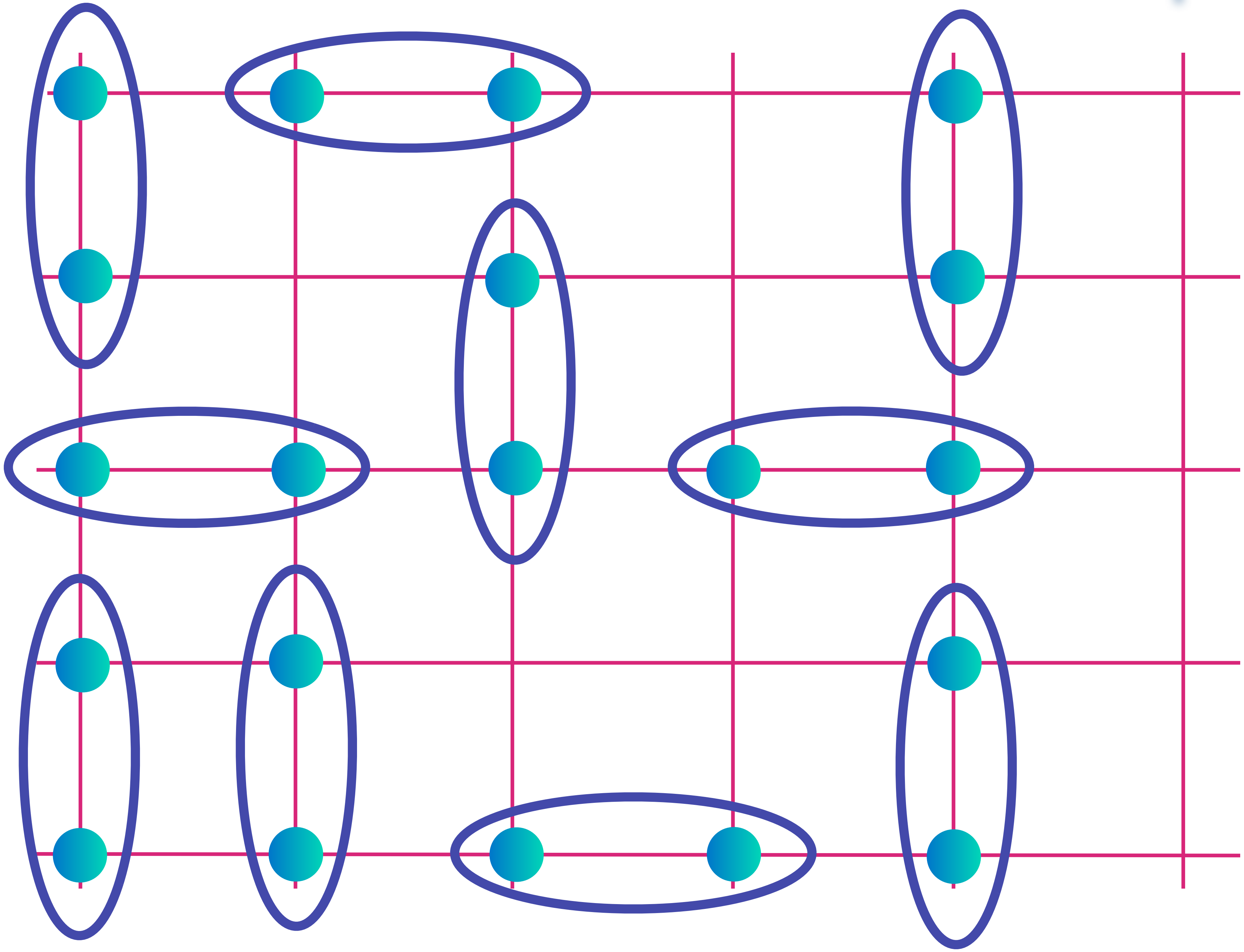

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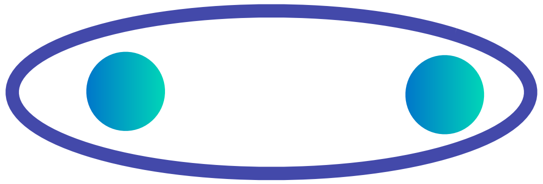

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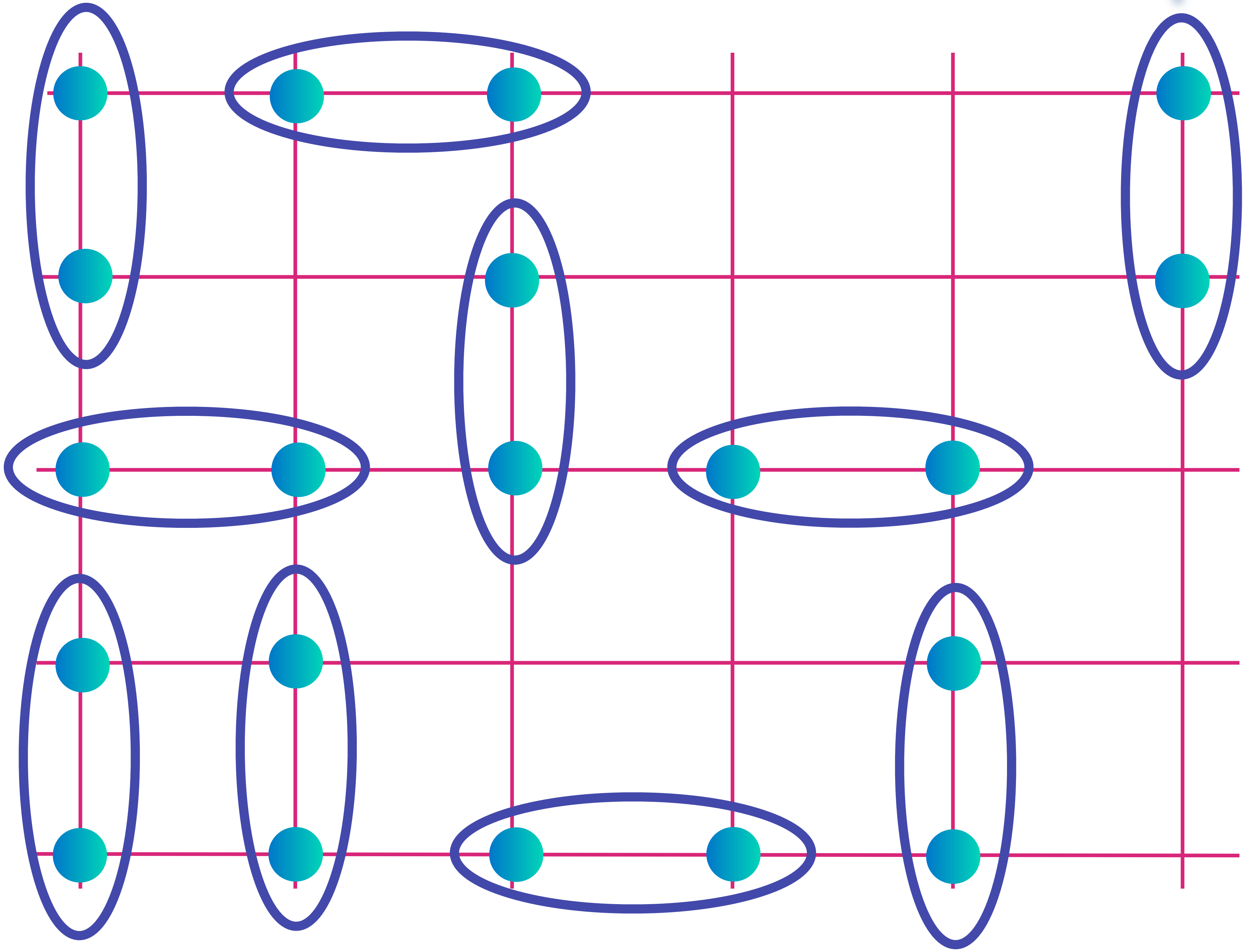

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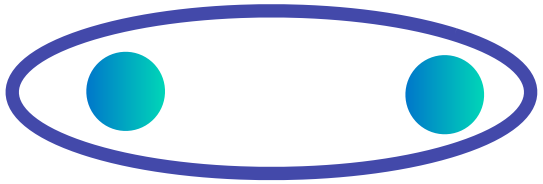

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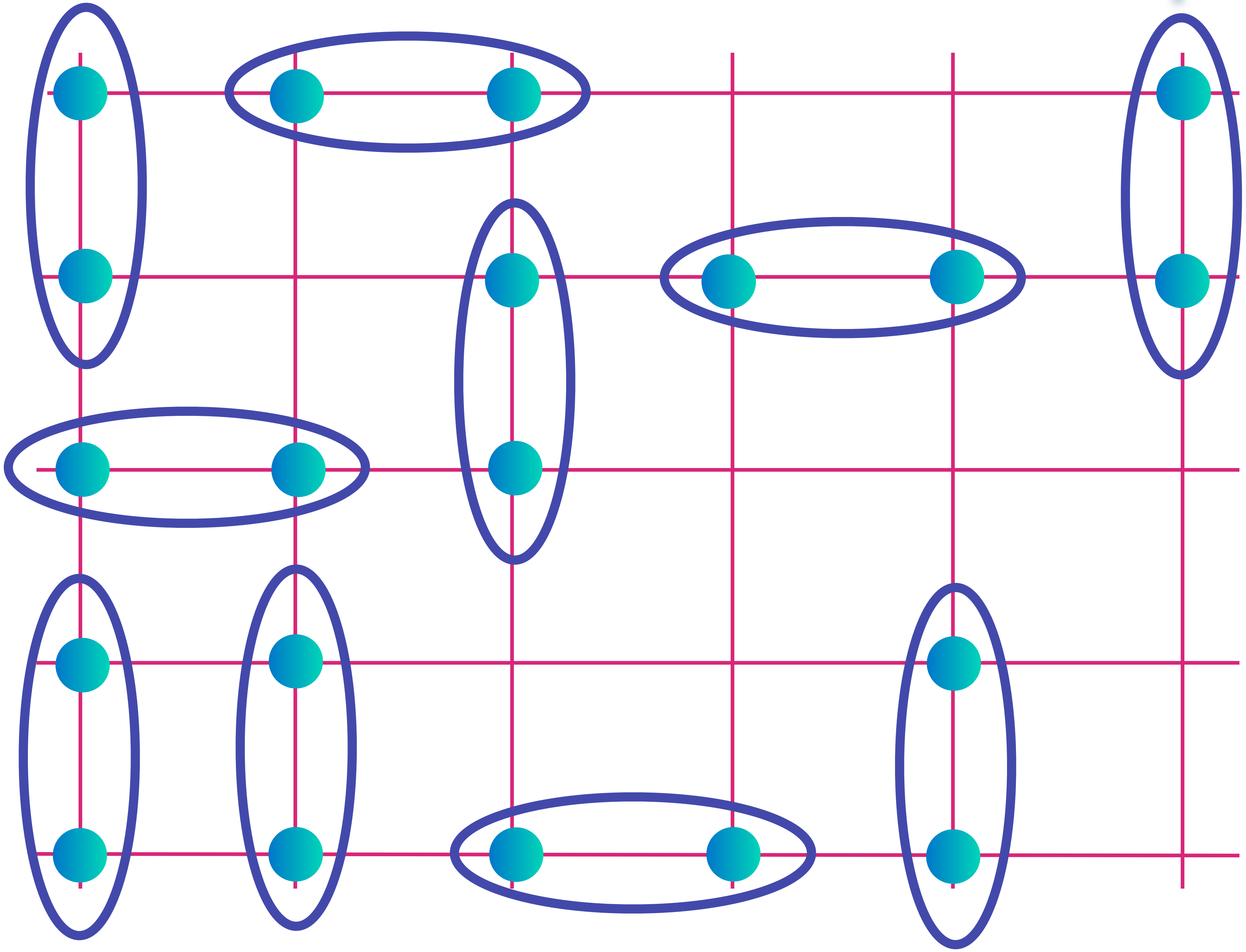
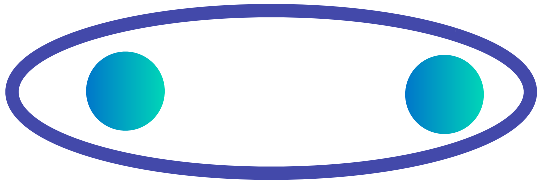
Square lattice of Cu sites

Superconductivity !



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



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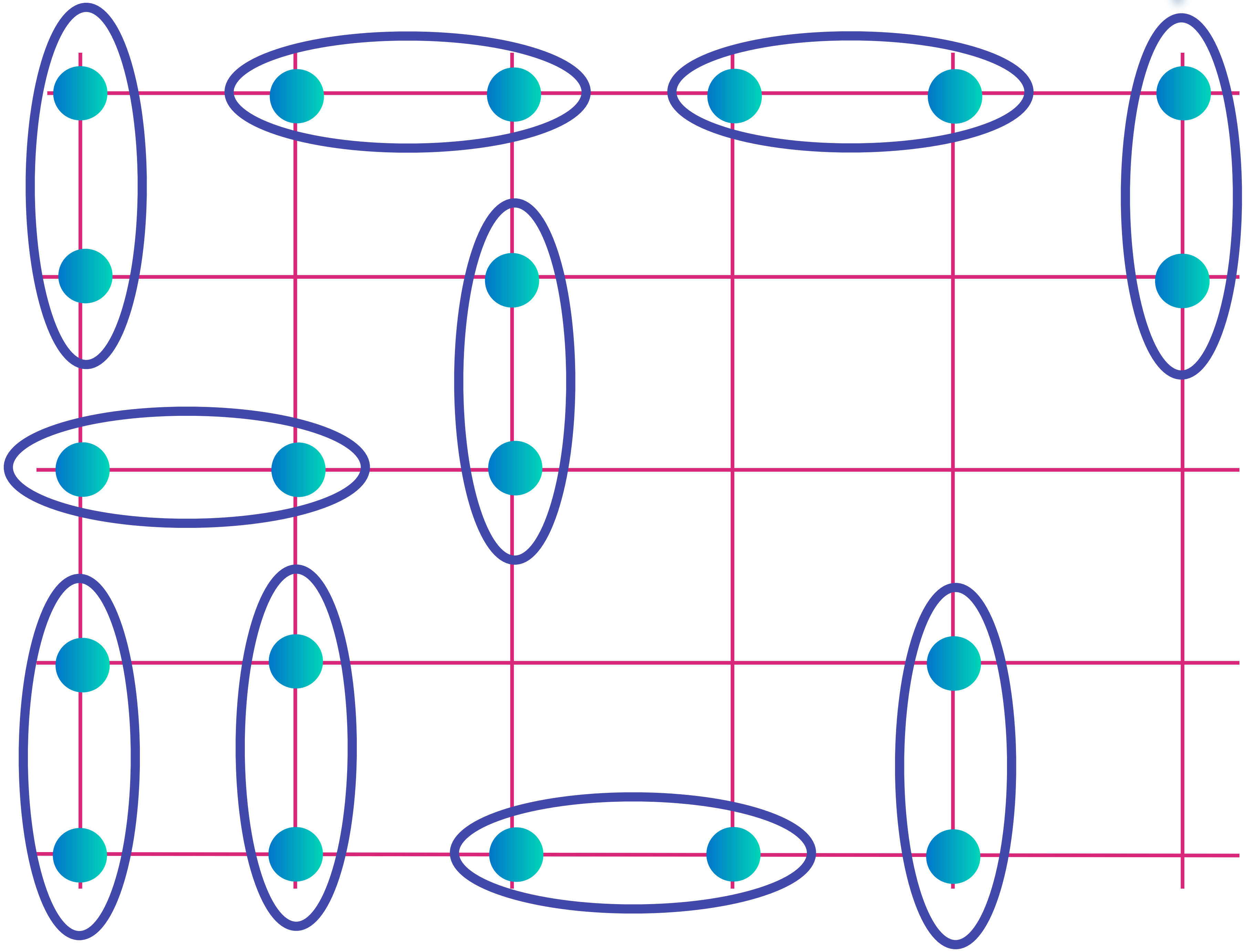

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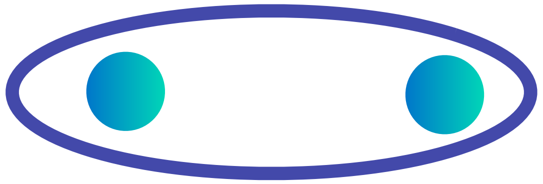

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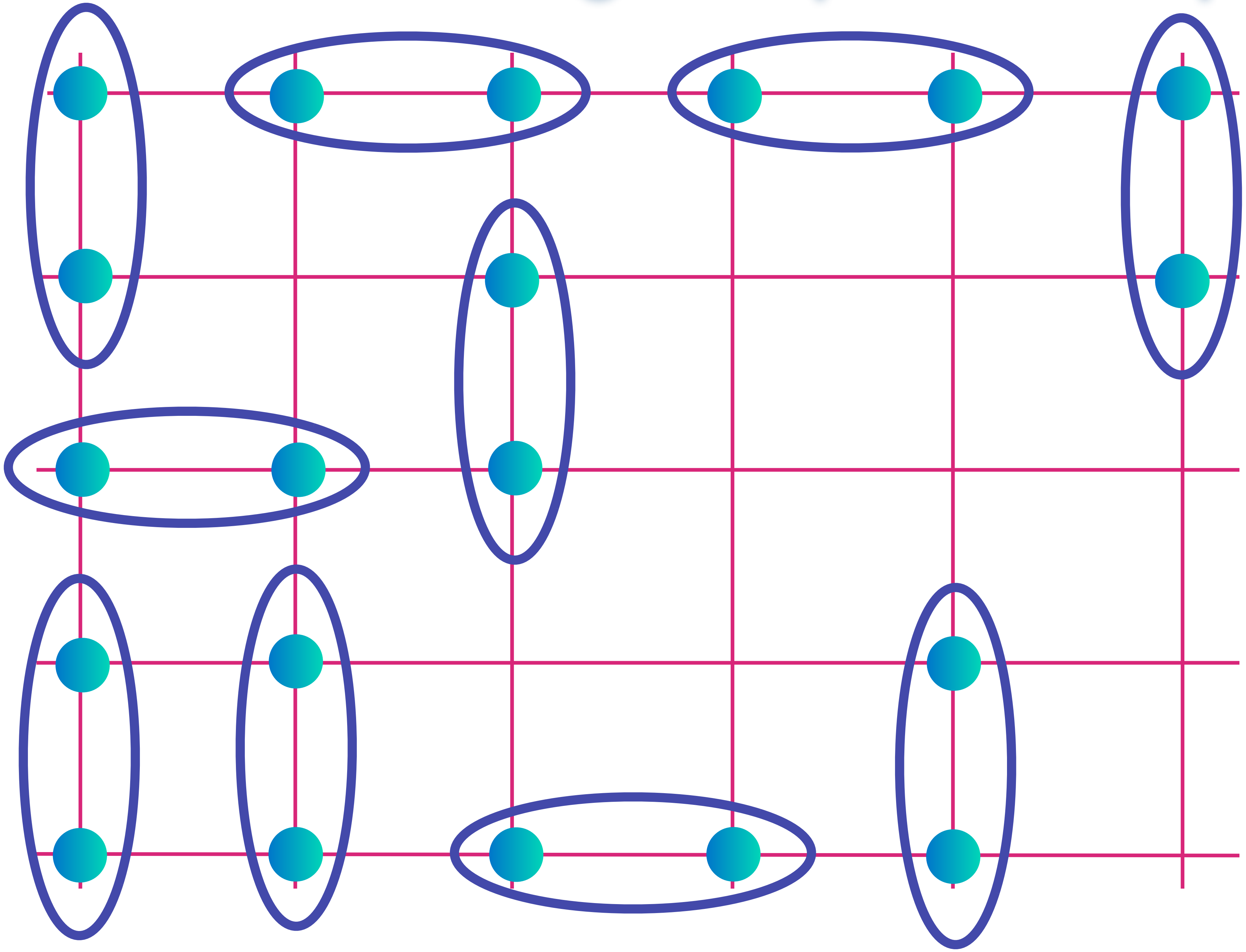
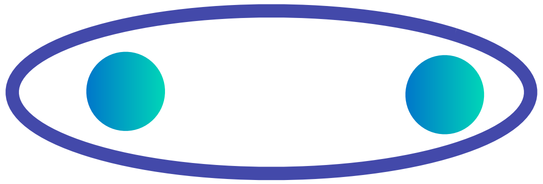
High temperature superconductivity ?



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



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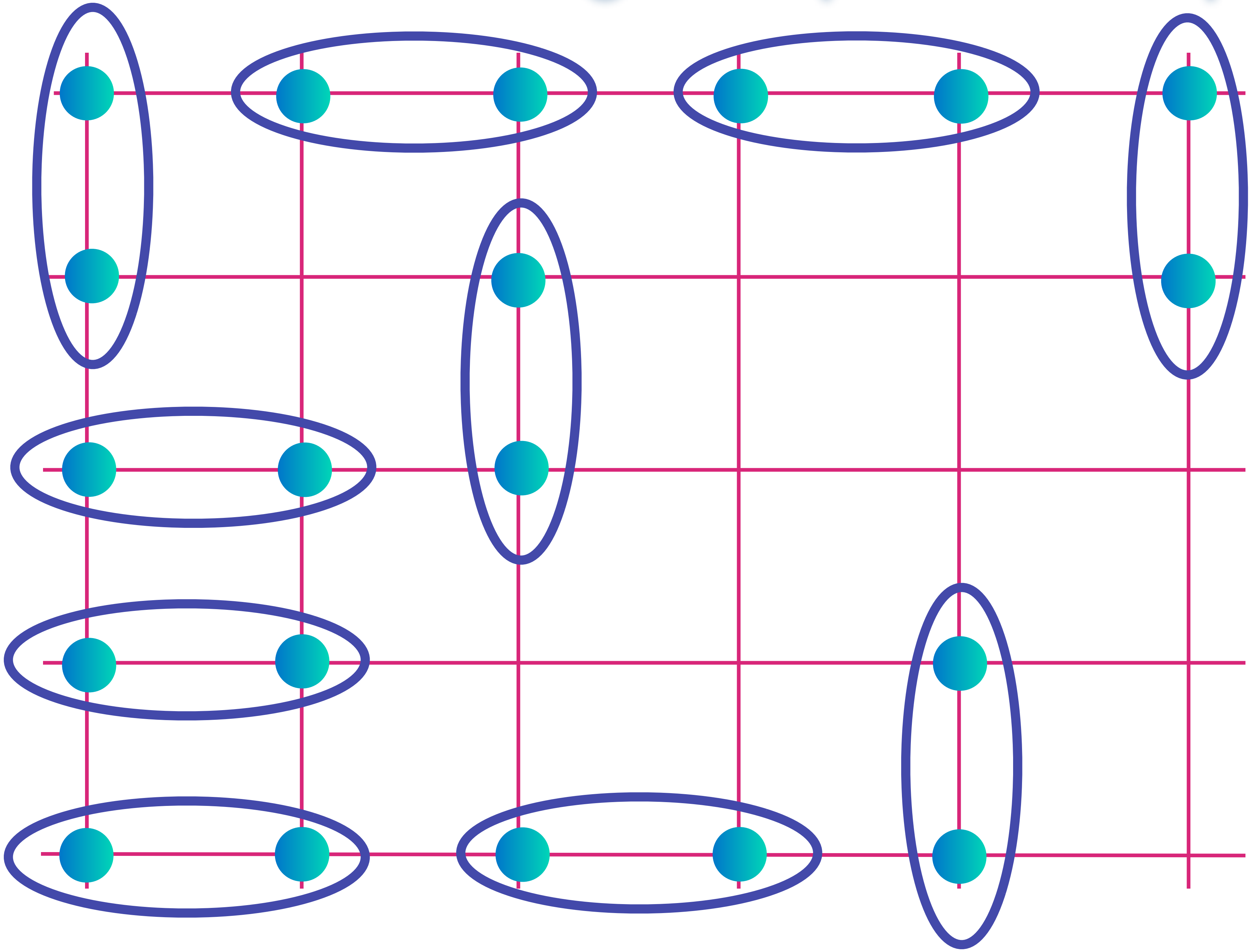

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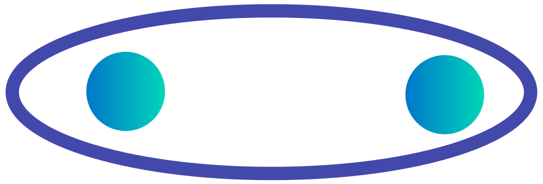

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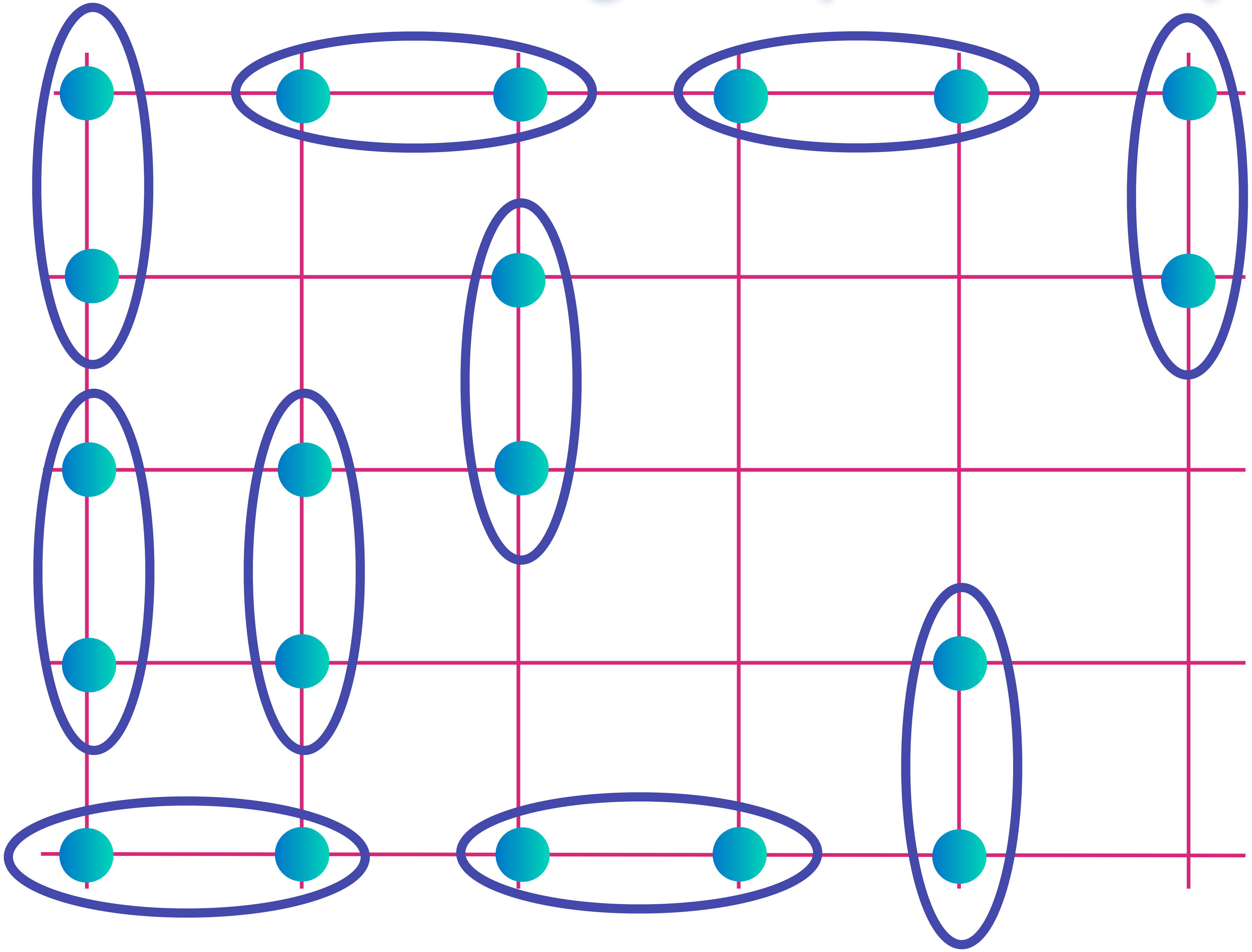

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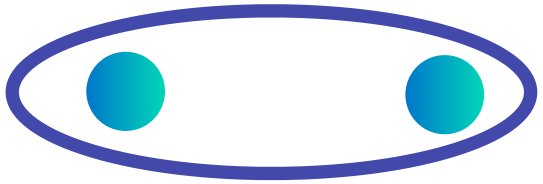

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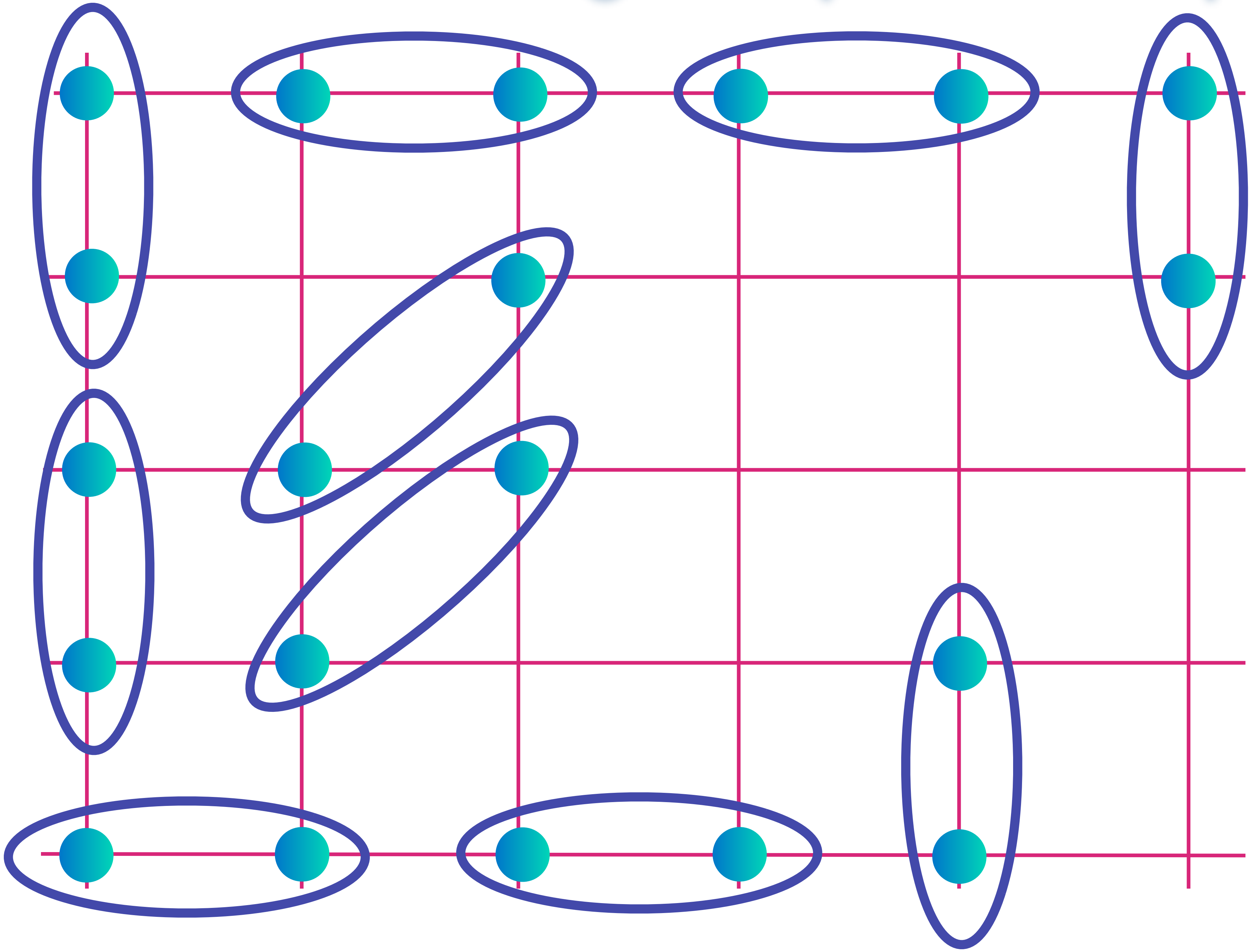

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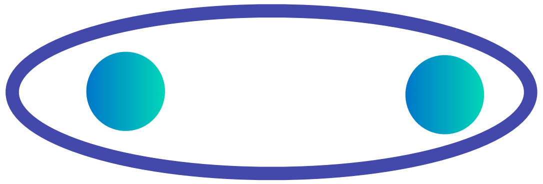

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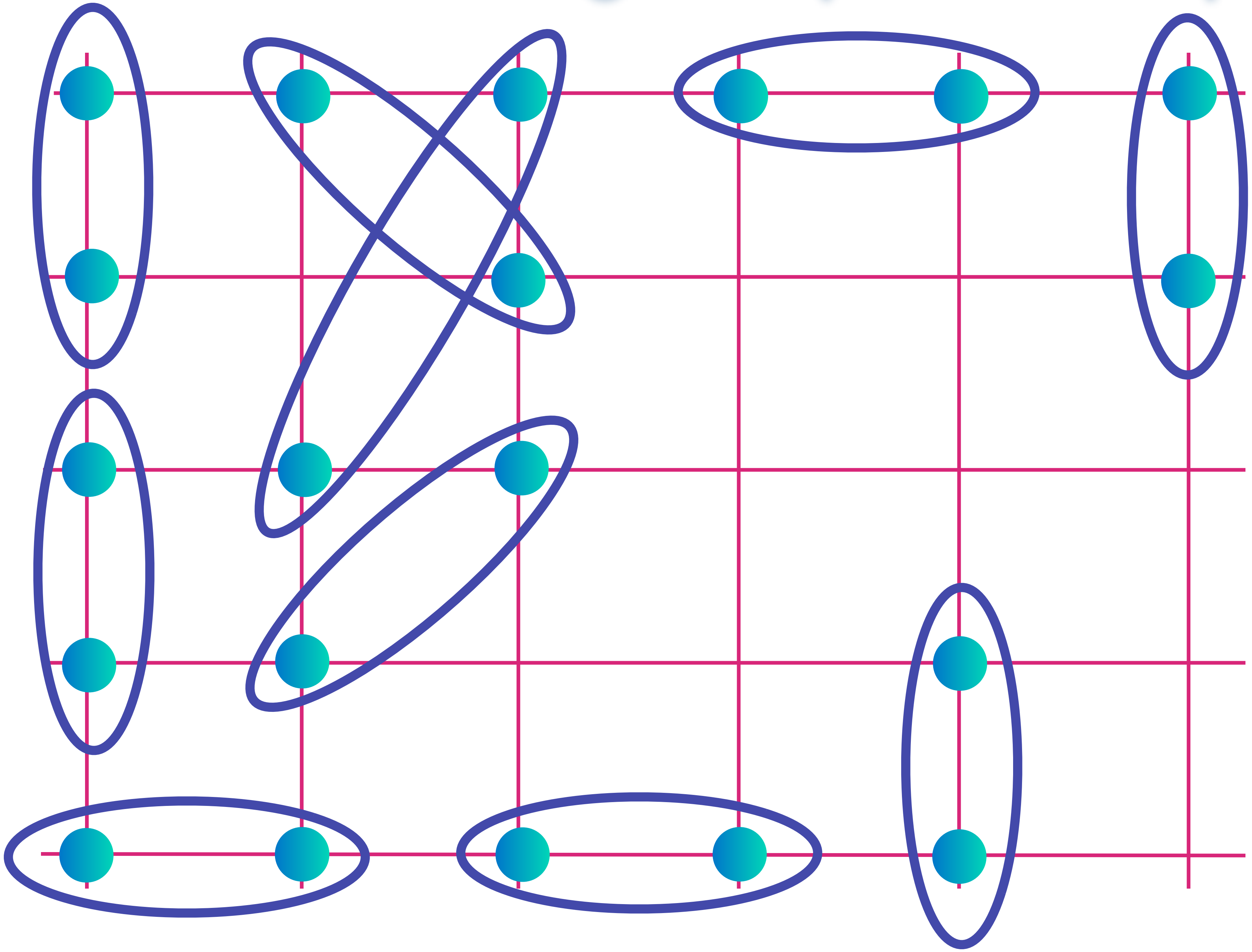

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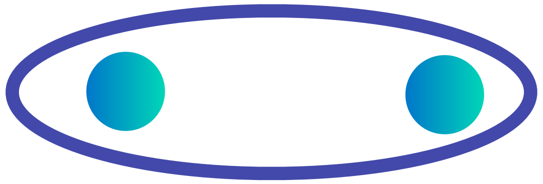

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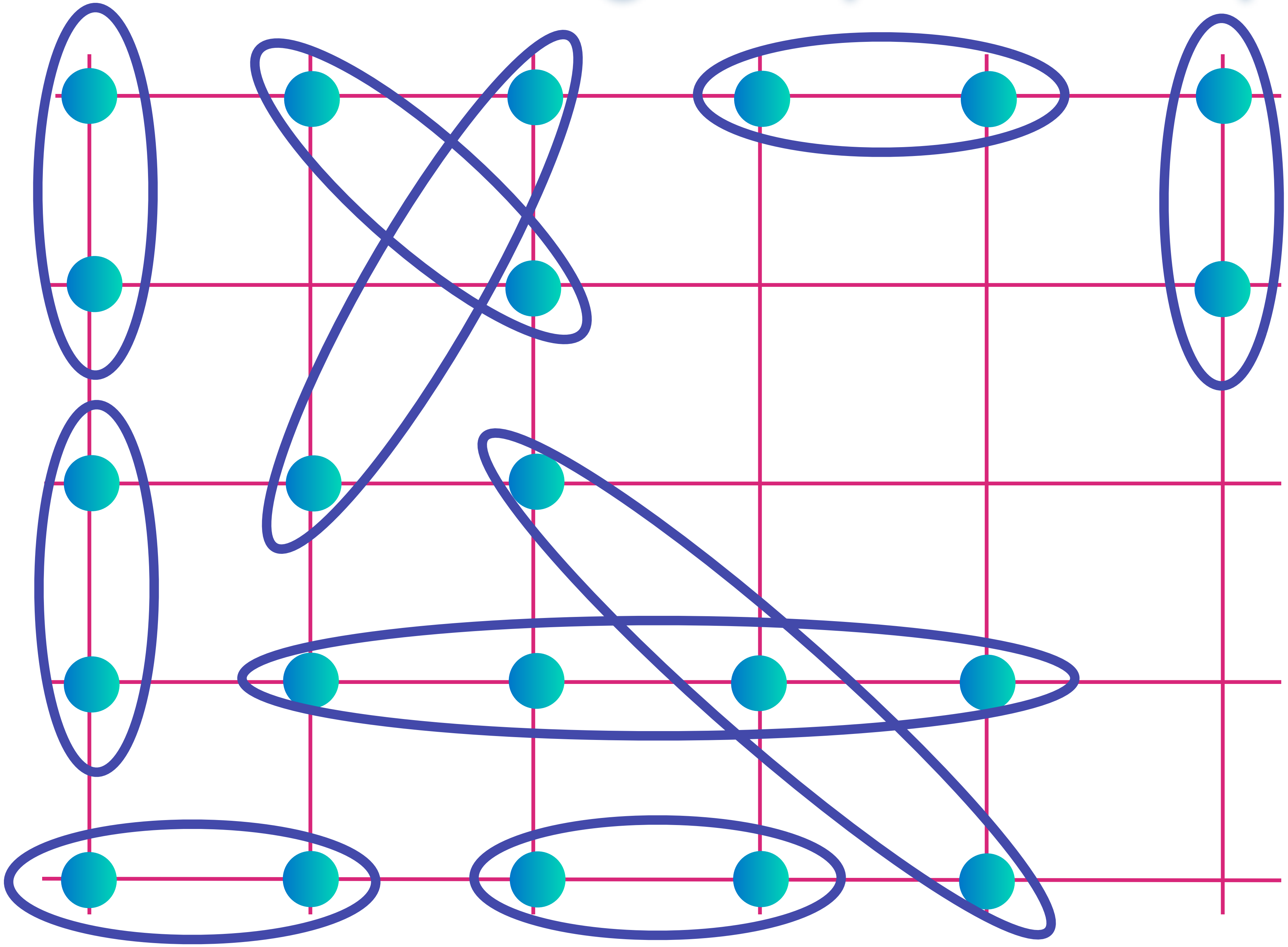

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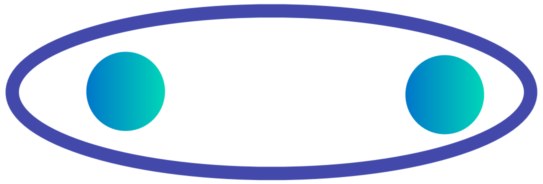 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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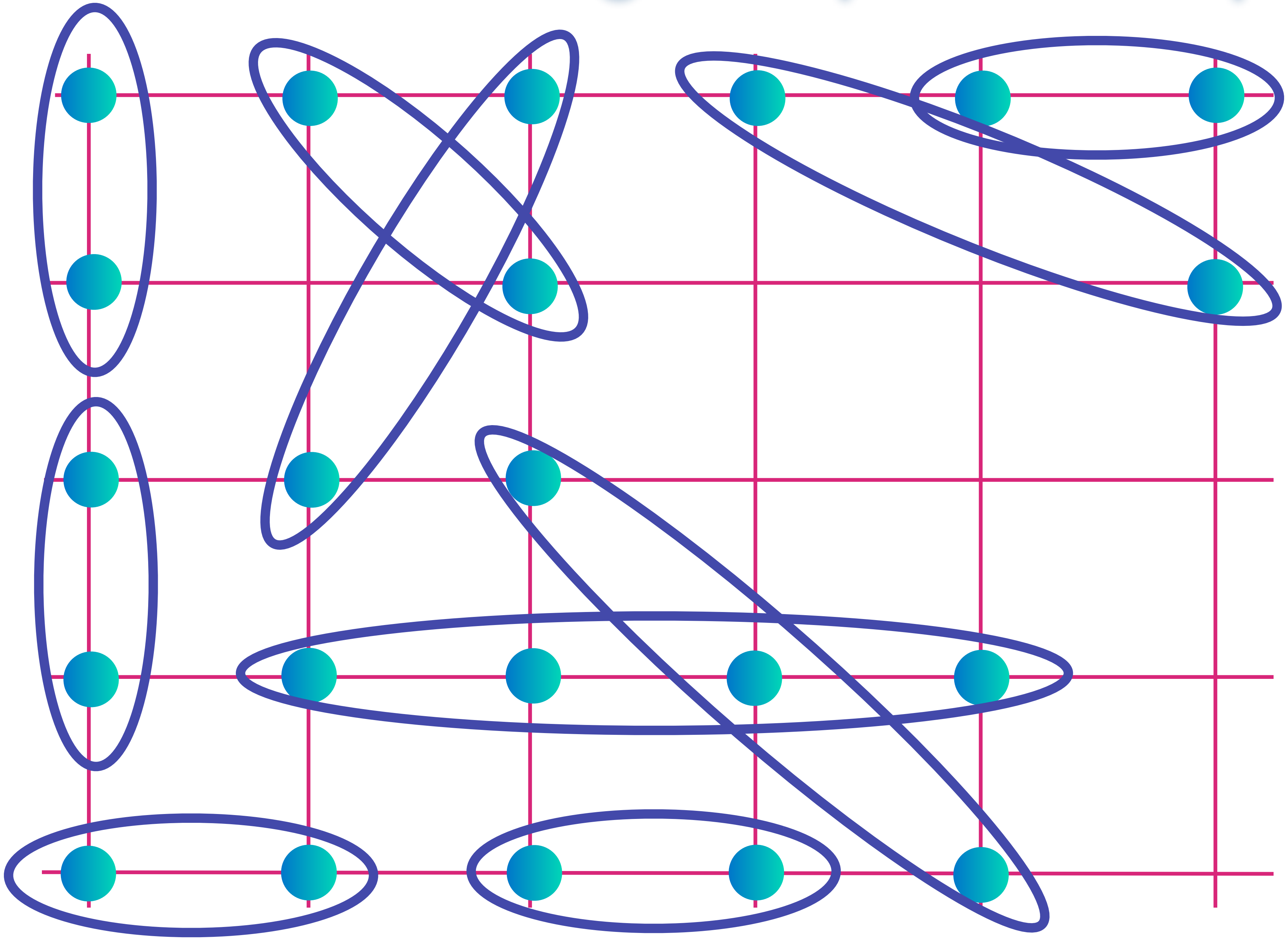

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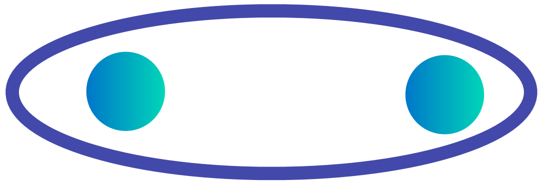

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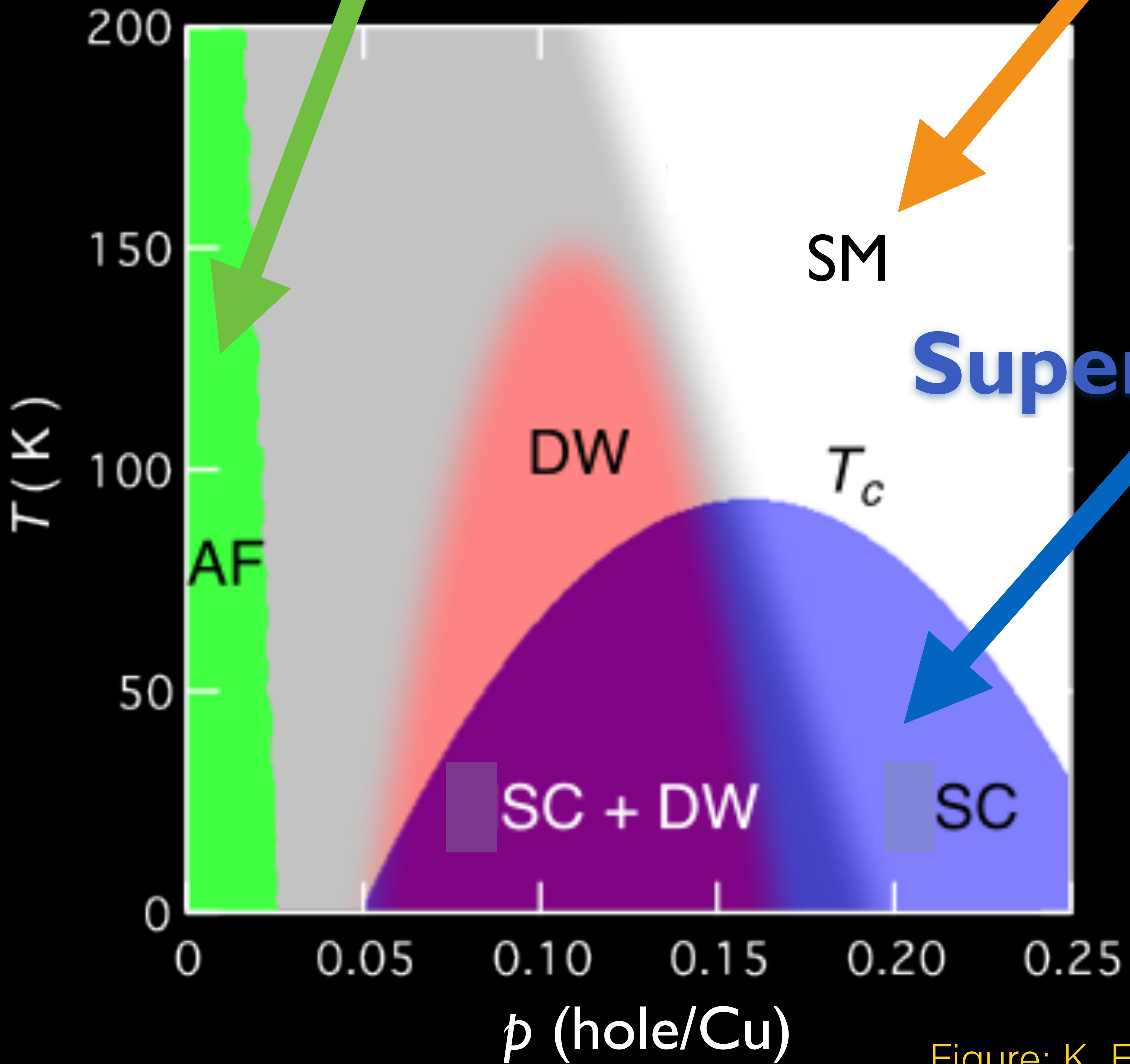
Antiferromagnet

Strange metal

Superconductor



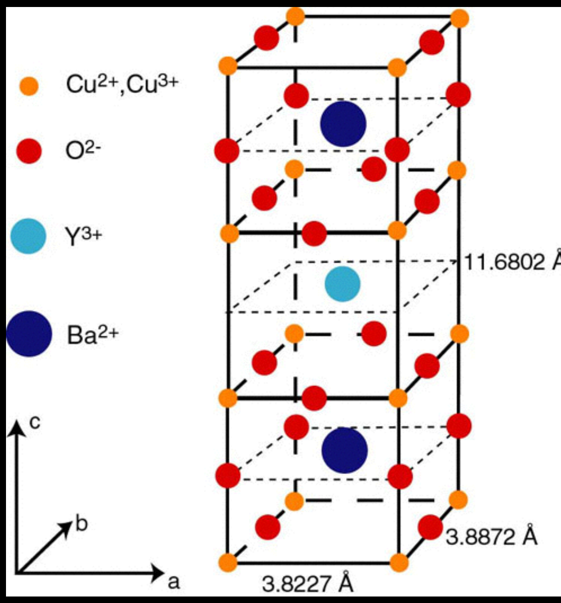
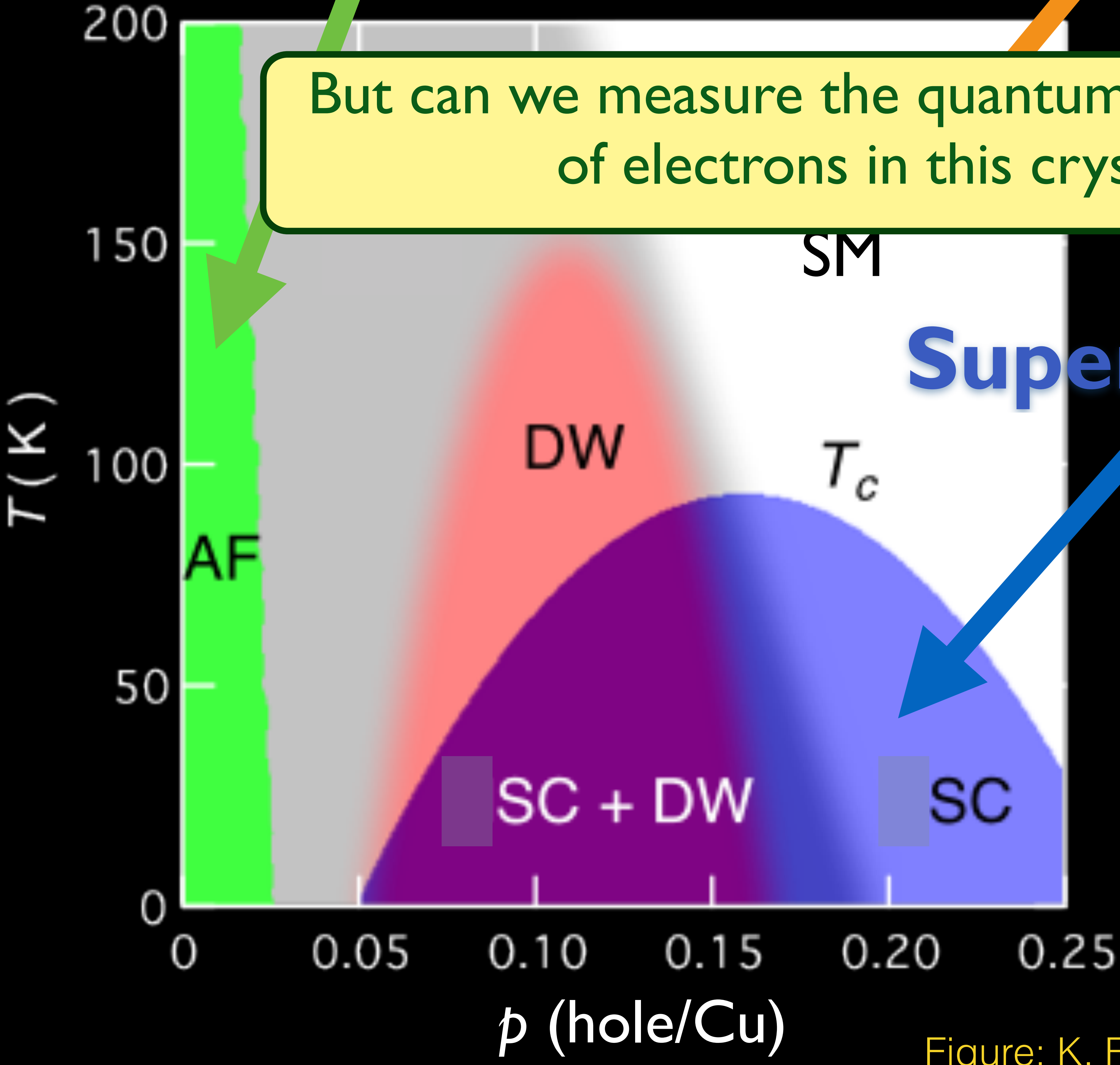


Figure: K. Fujita and J. C. Seamus Davis

Antiferromagnet

Strange metal



But can we measure the quantum entanglement of electrons in this crystal ?

Superconductor

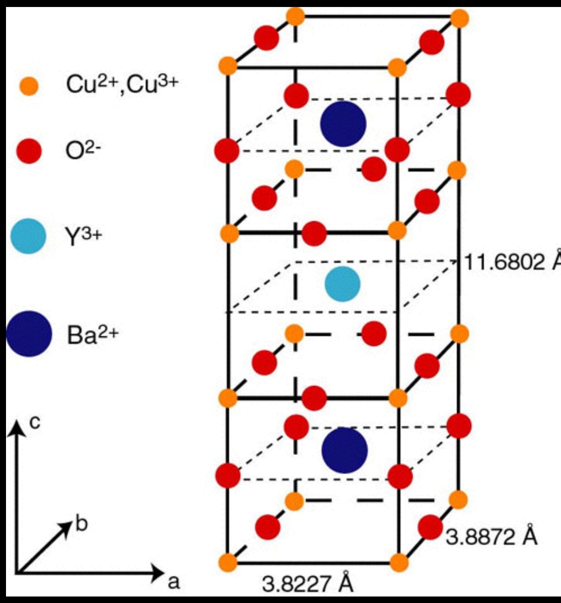


Figure: K. Fujita and J. C. Seamus Davis

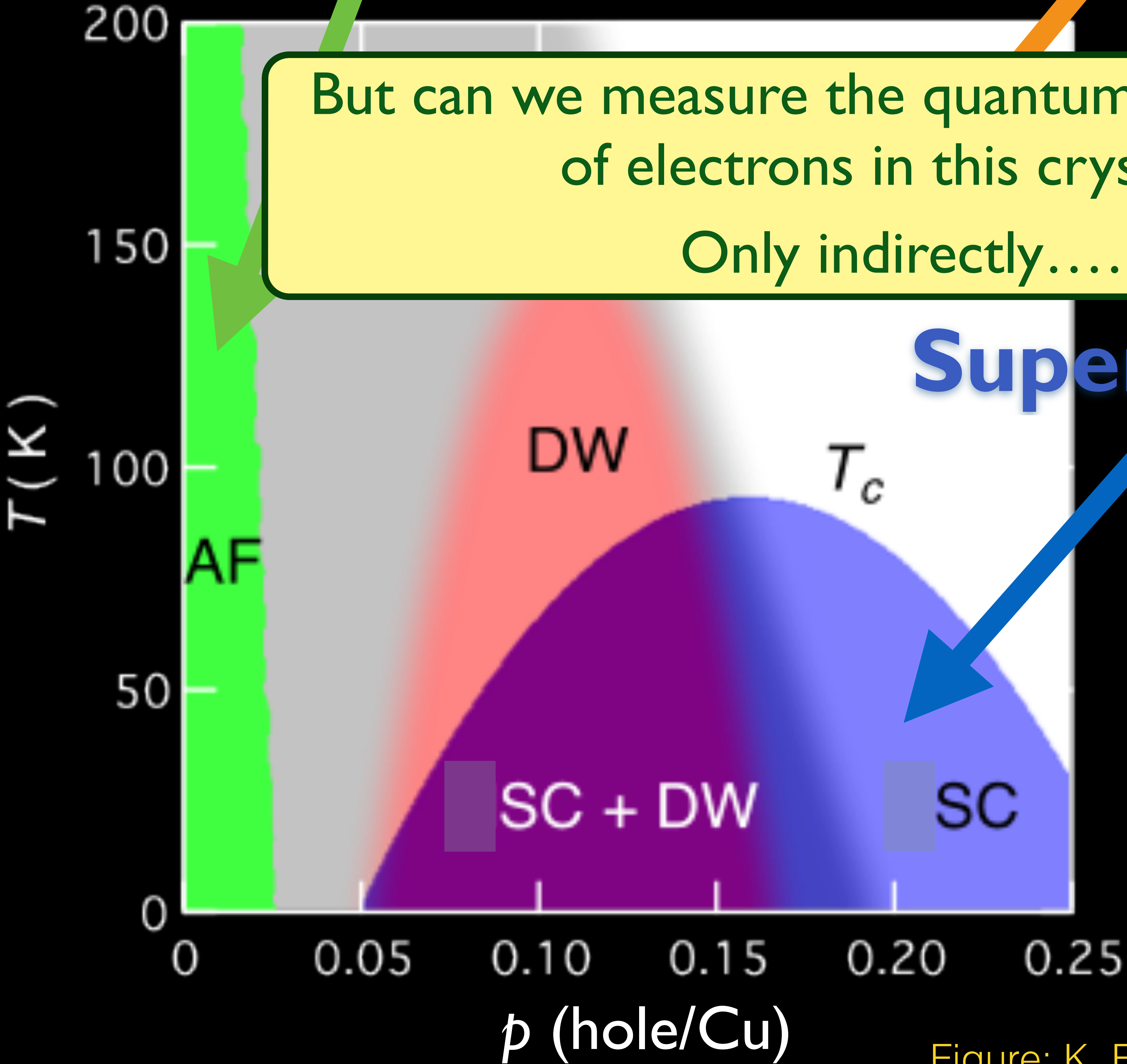
Antiferromagnet

Strange metal

But can we measure the quantum entanglement of electrons in this crystal ?

Only indirectly……

Superconductor



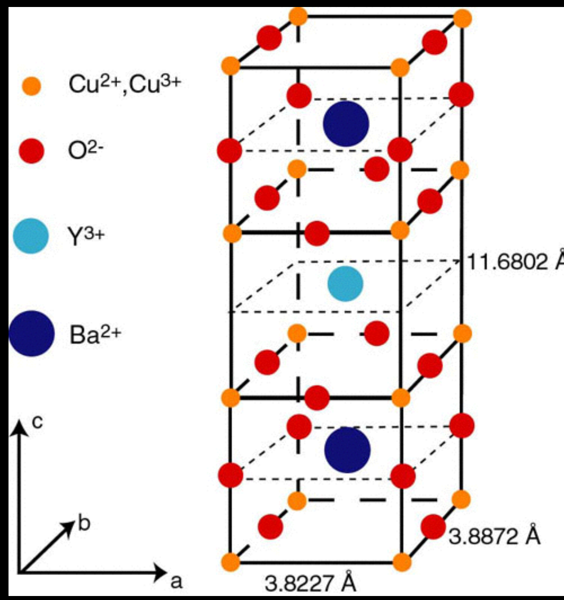
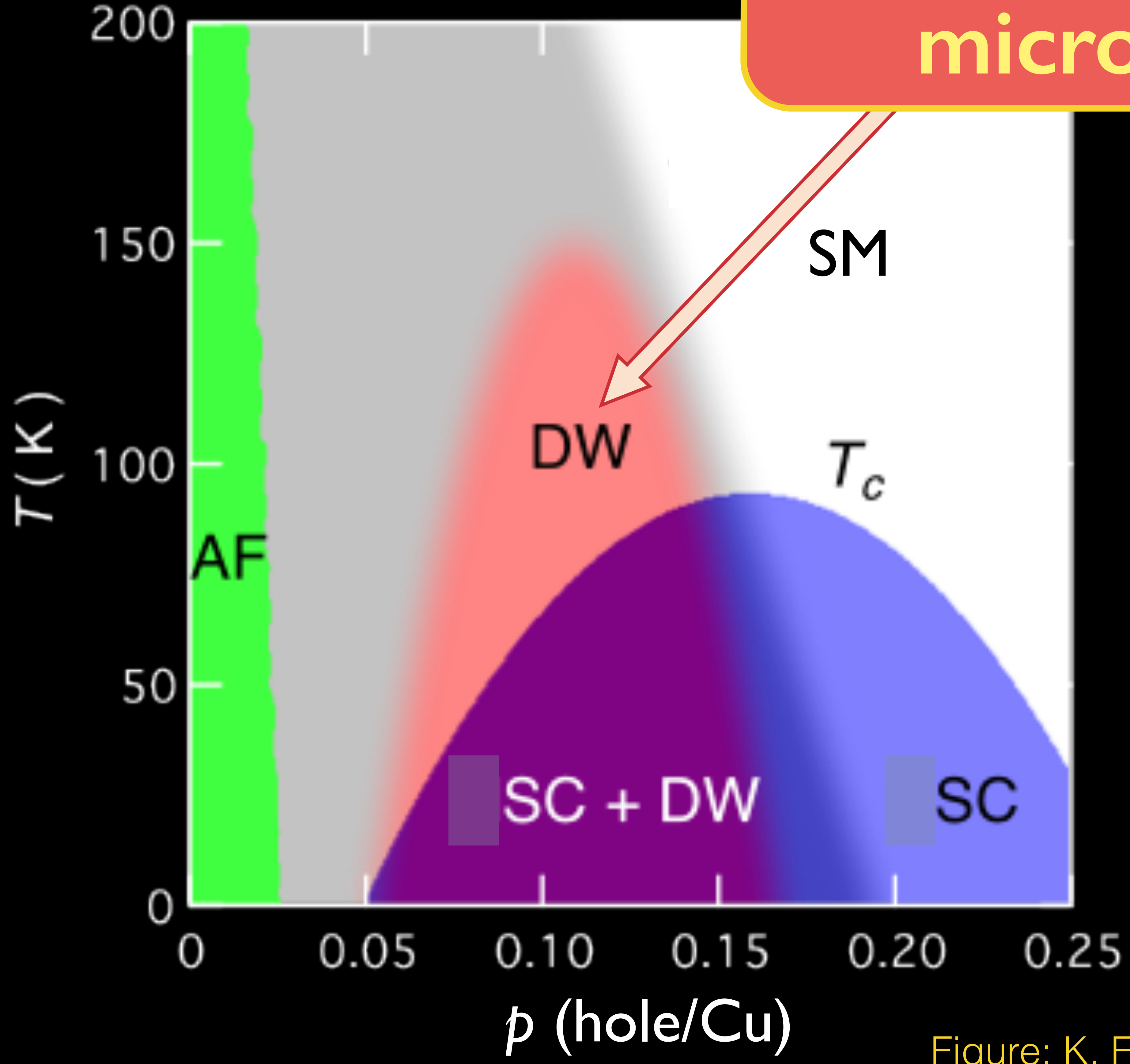


Figure: K. Fujita and J. C. Seamus Davis

Scanning tunneling microscopy



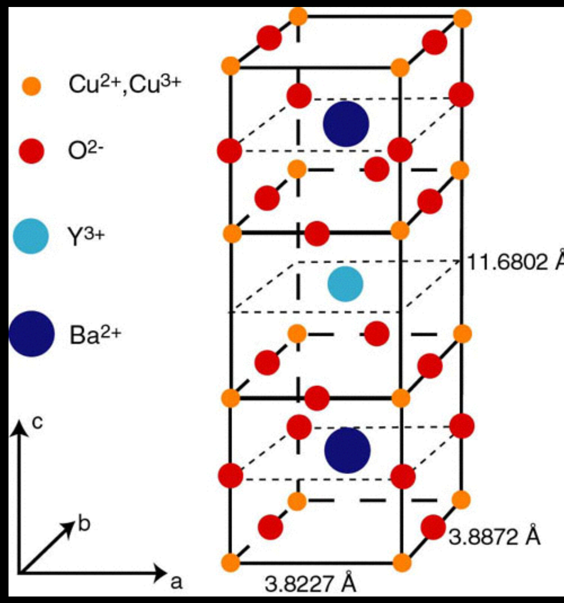
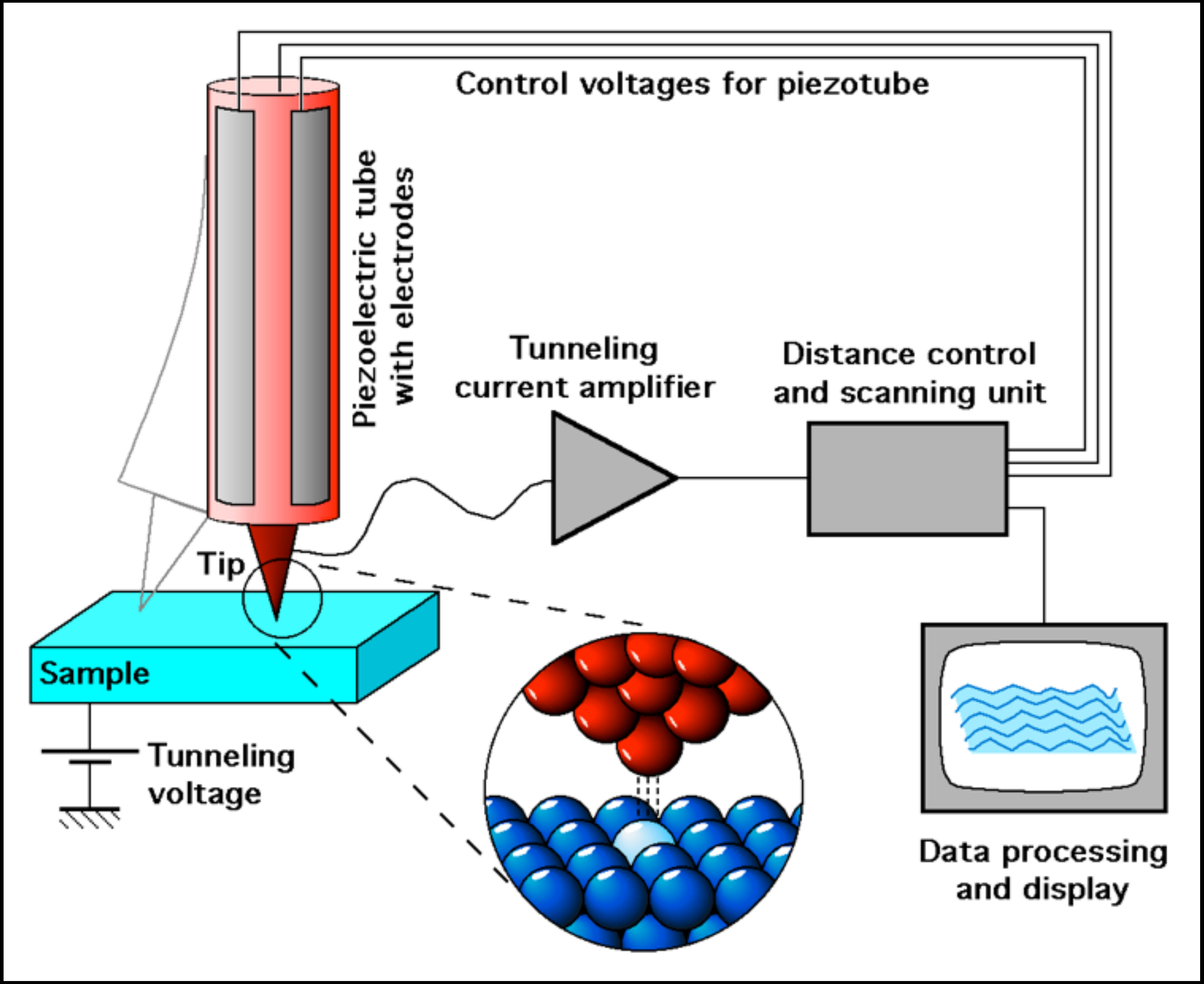


Figure: K. Fujita and J. C. Seamus Davis

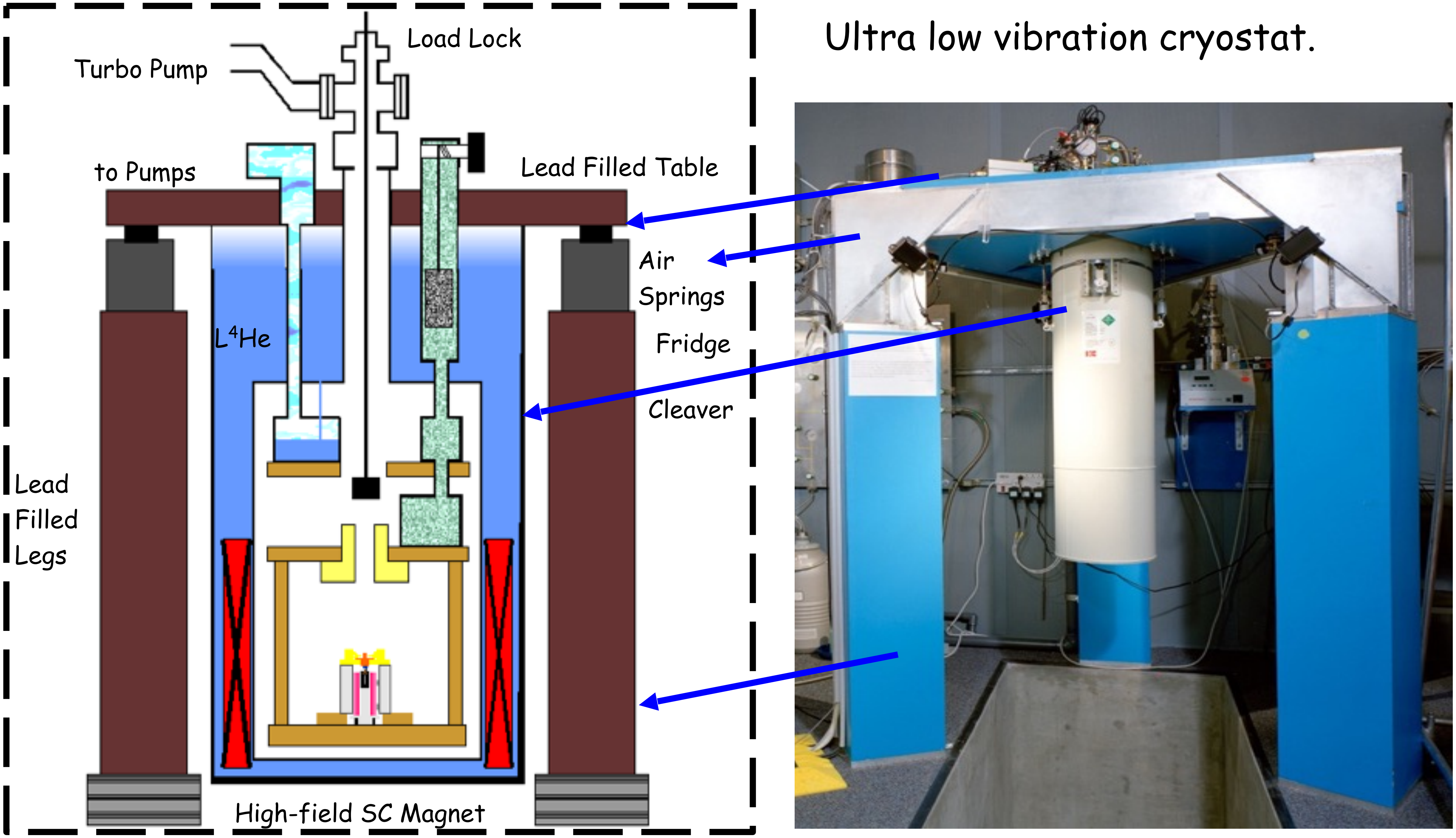
Scanning Tunneling Microscopy



SI-STM System

J. C. Davis group, Rev. Sci. Inst. 70, 1459 (1999).

Ultra low vibration cryostat.



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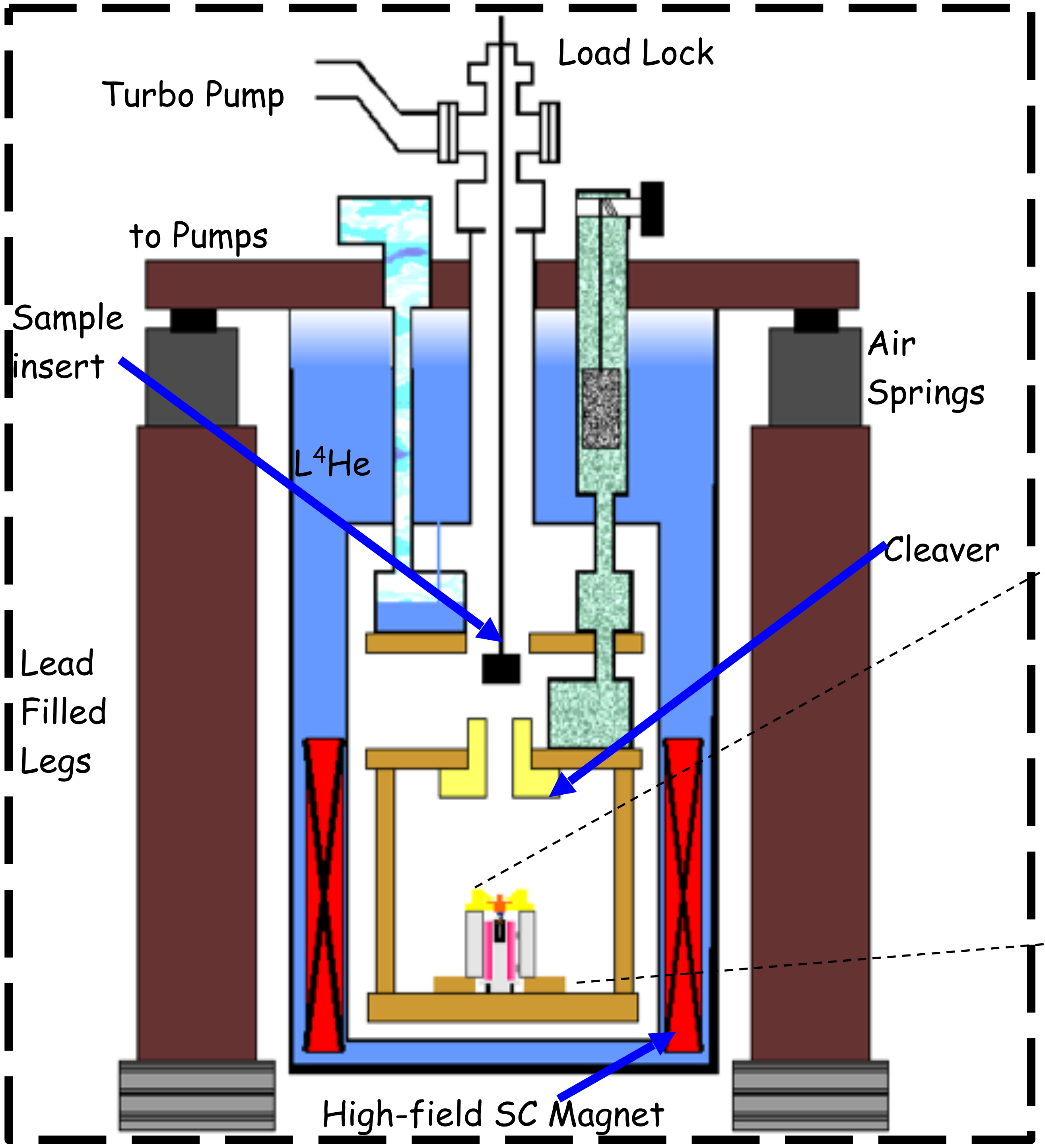
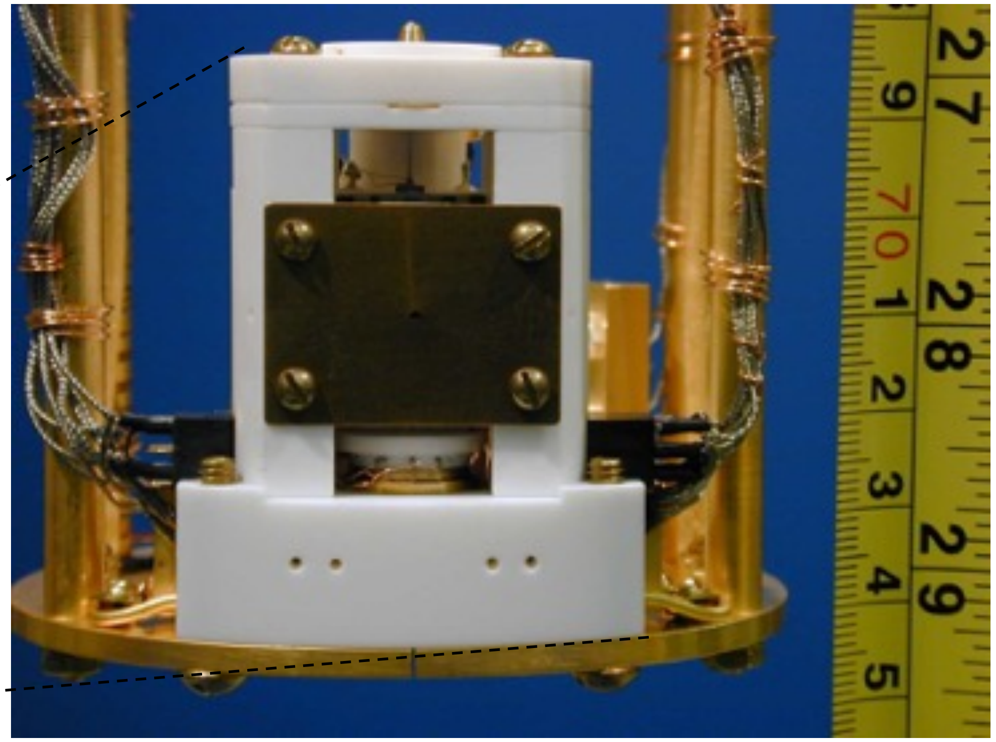
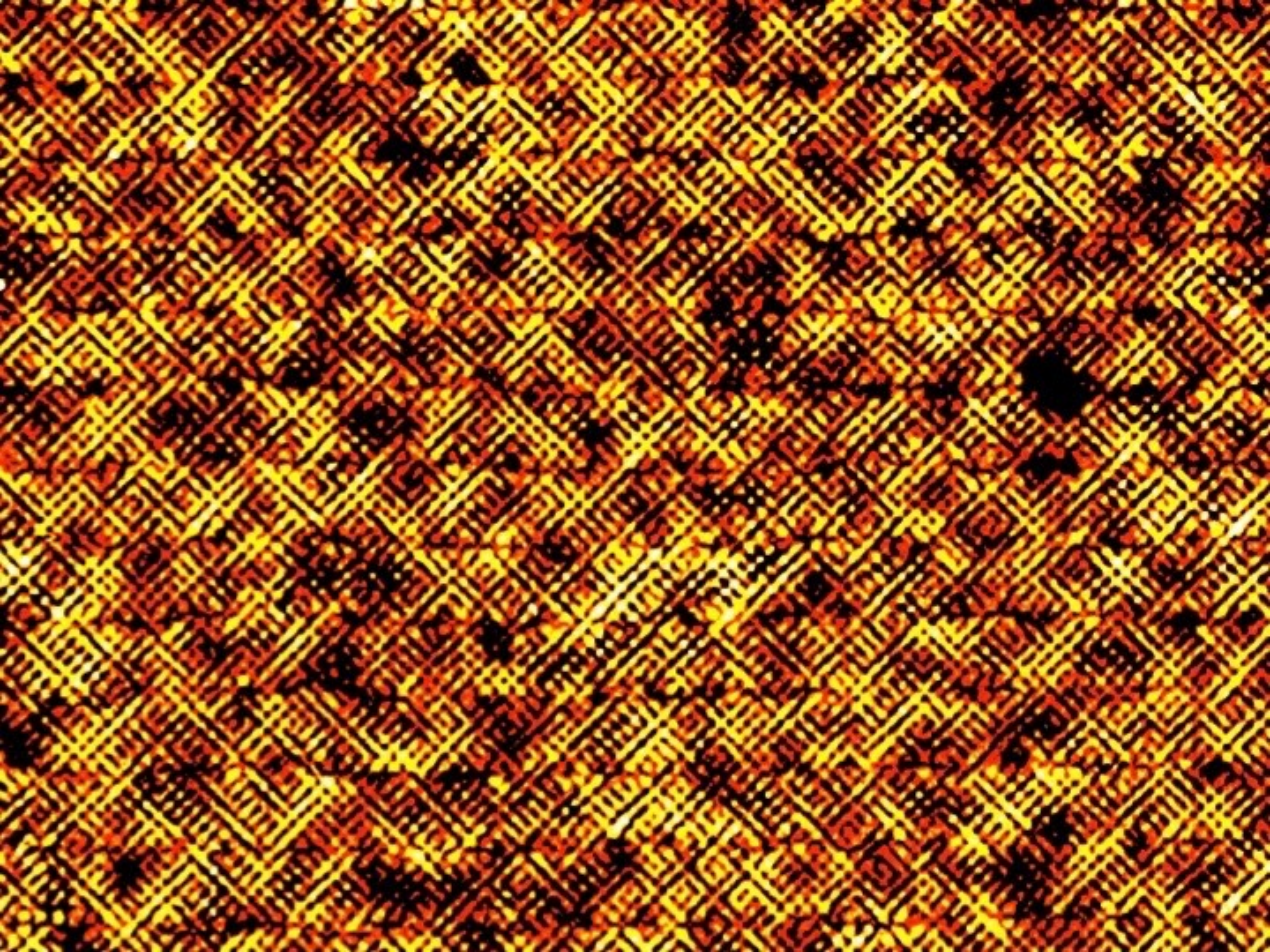
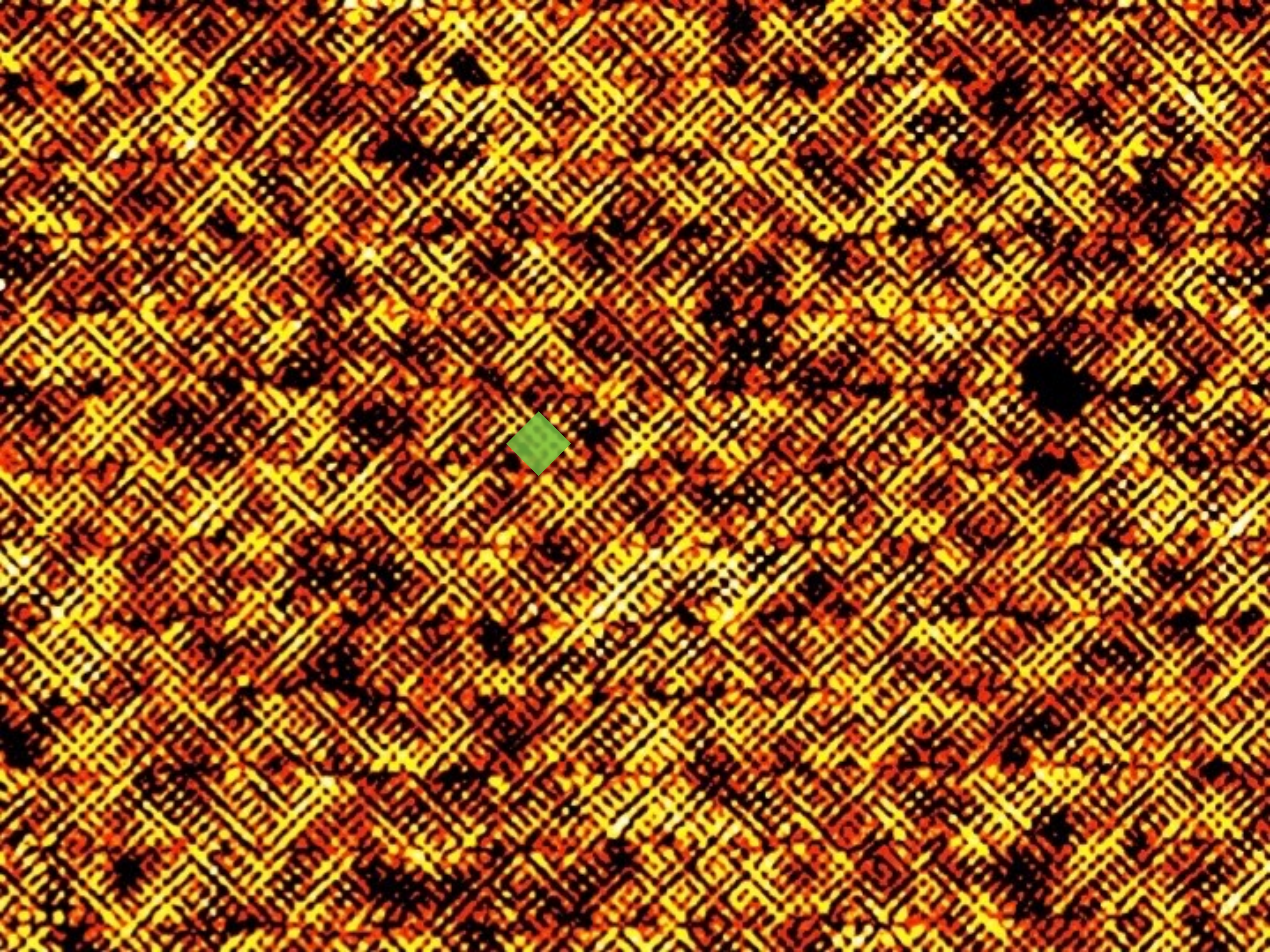


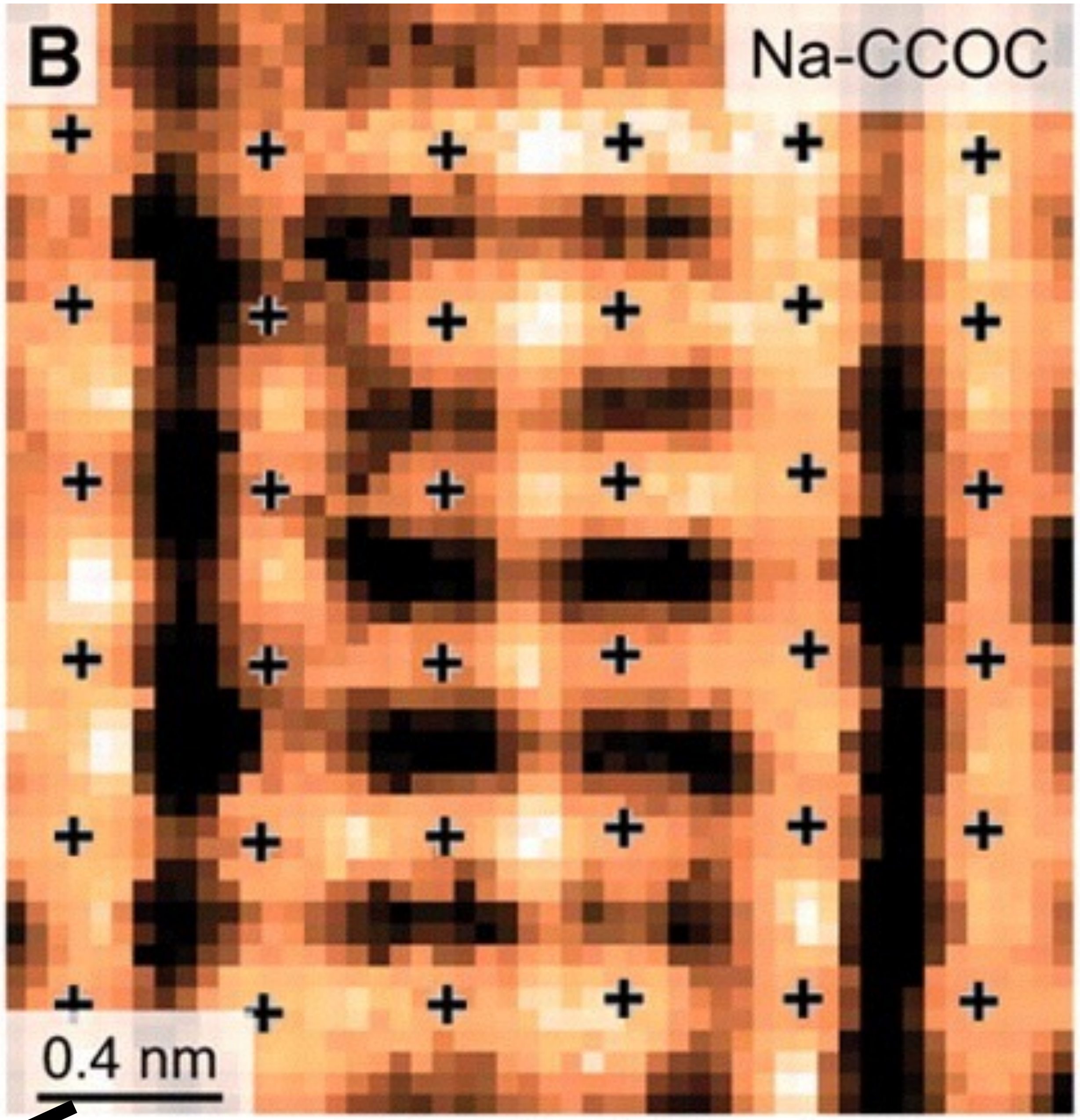
- Massive ULV Cryostat
- Subkelvin Fridge
- STM + High Field Magnet
- Sample Exchange from RT
- Cryogenic UHV Cleave



STM Head

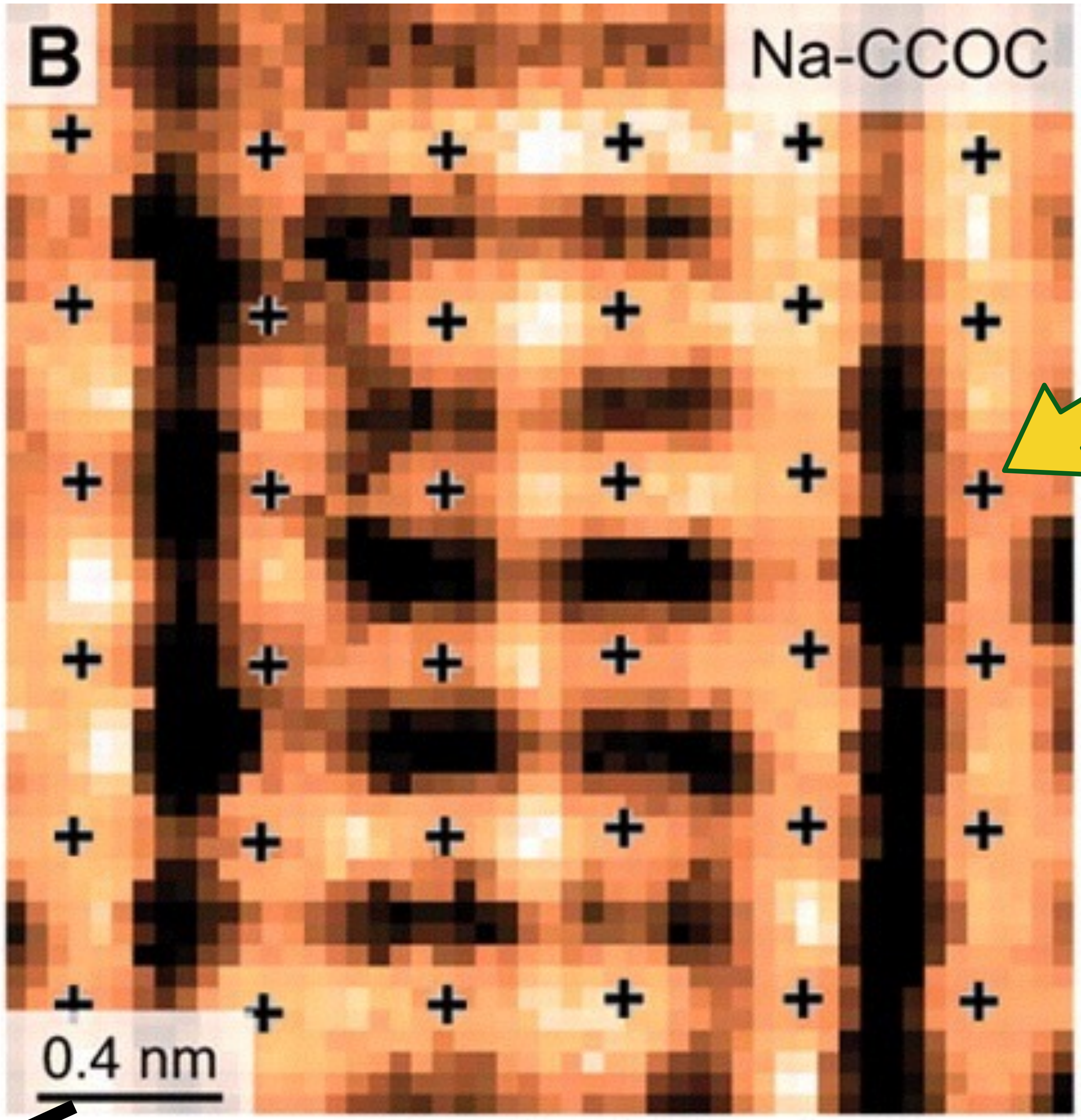






Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

4×10^{-10} meters



Locations of Cu atoms !

Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

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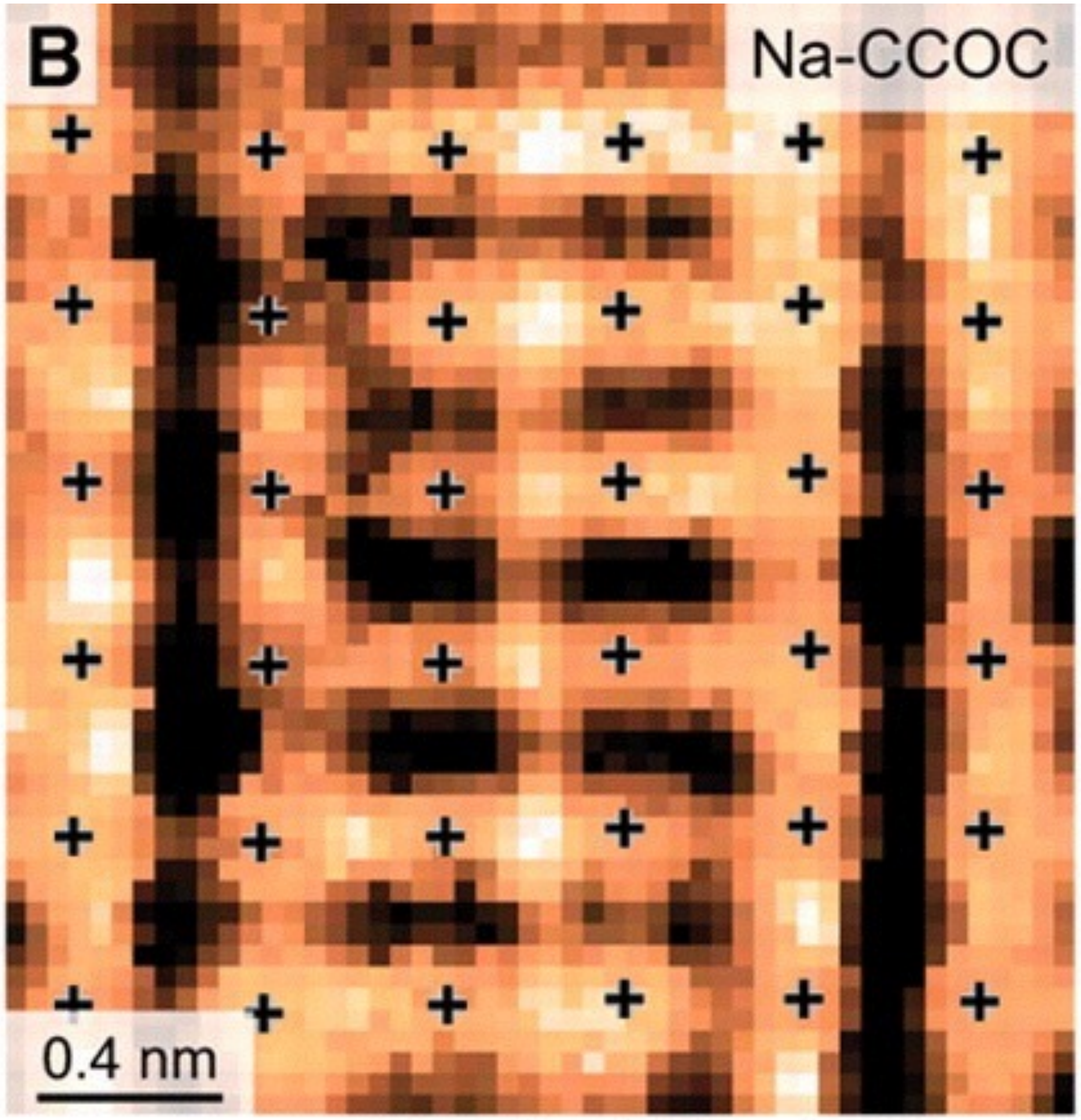

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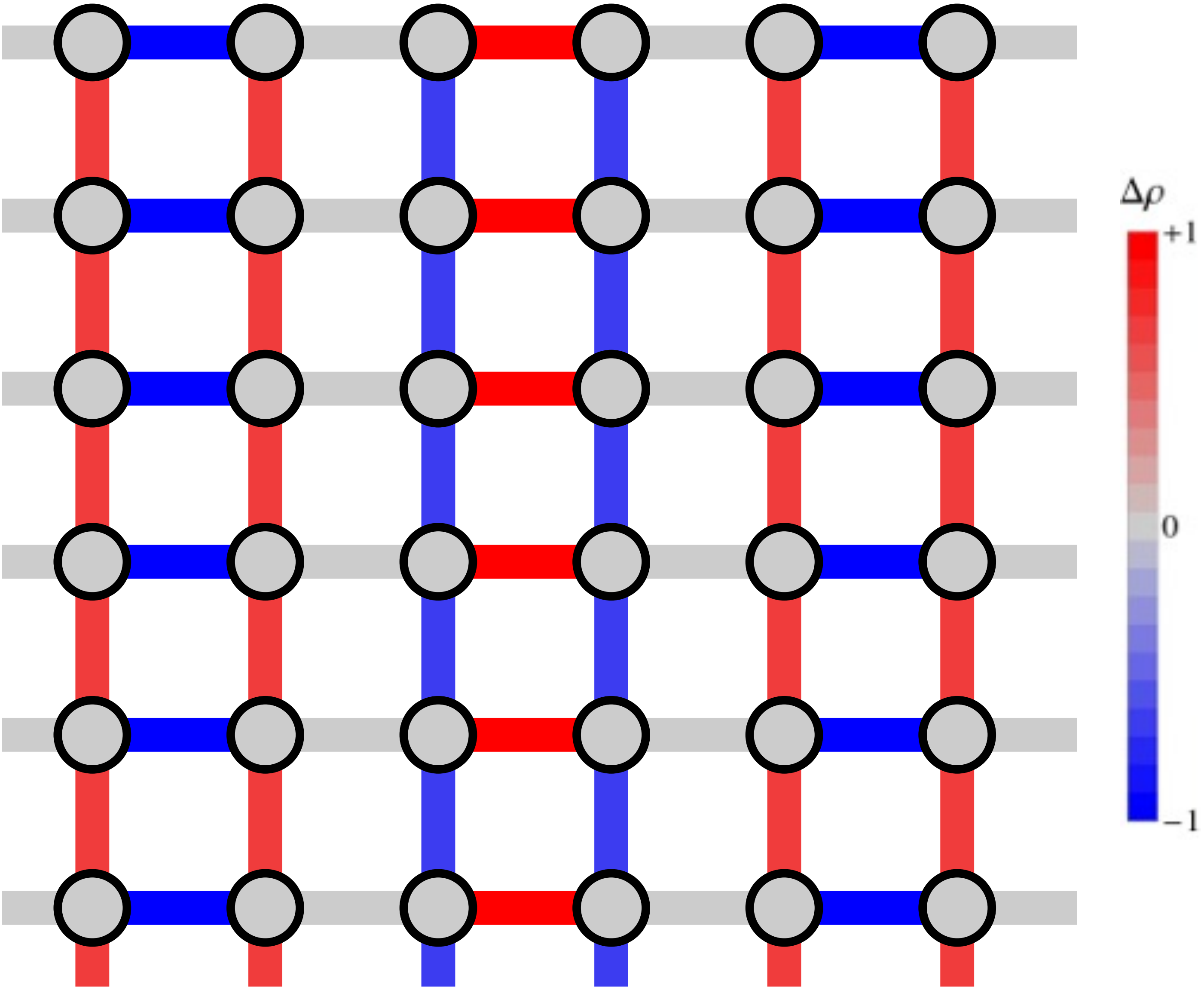
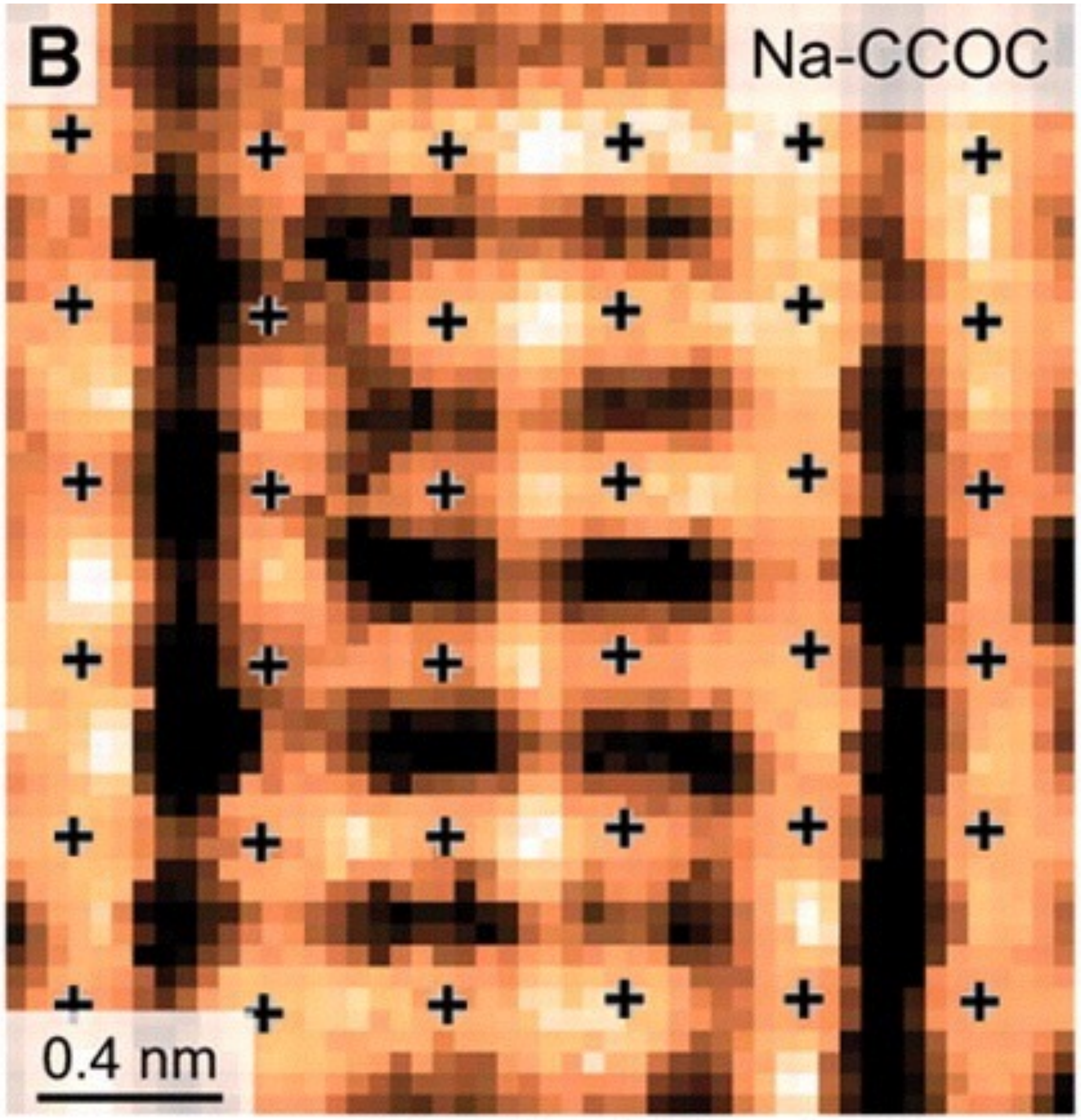


d-form factor density wave order

M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).



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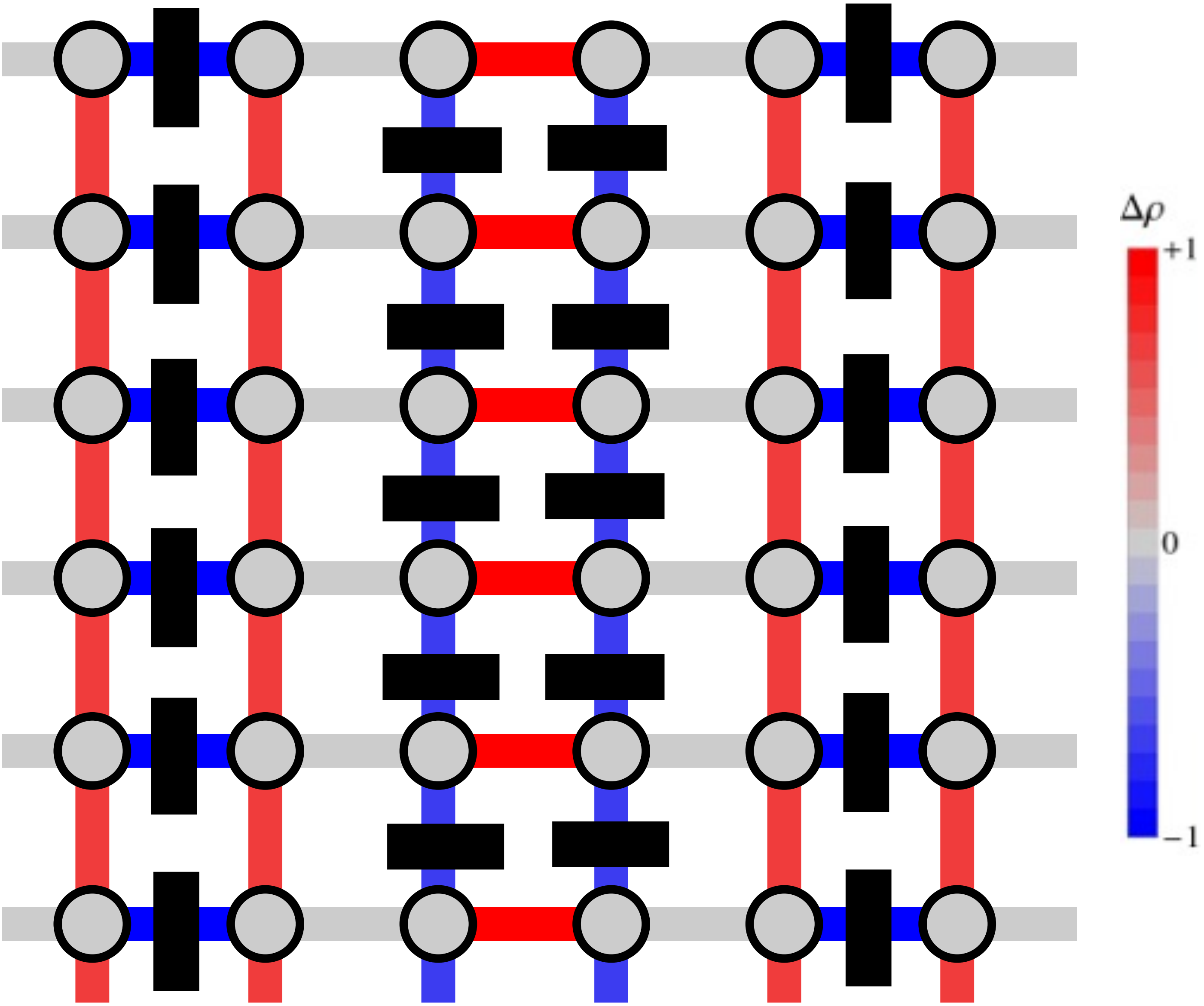

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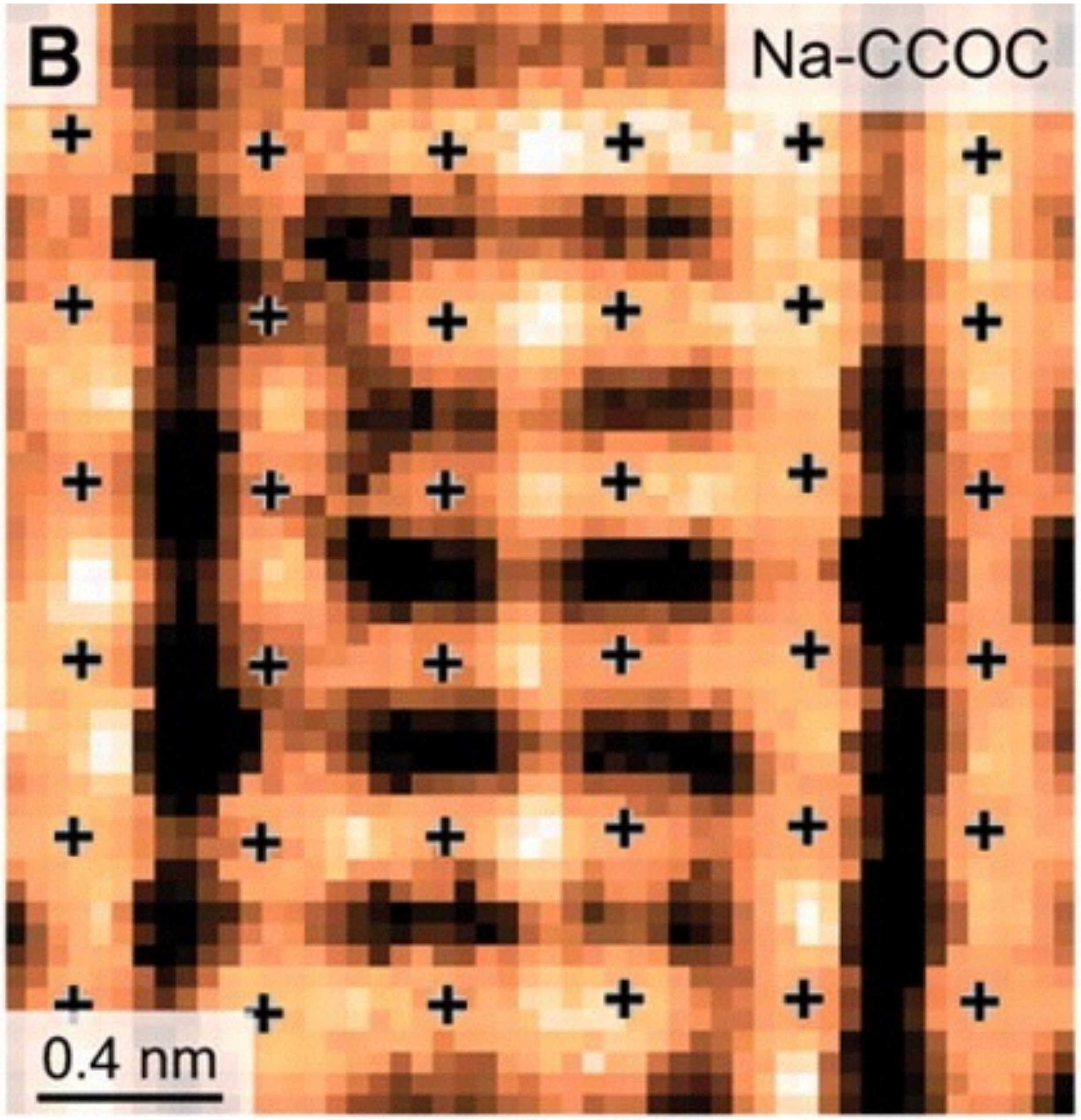

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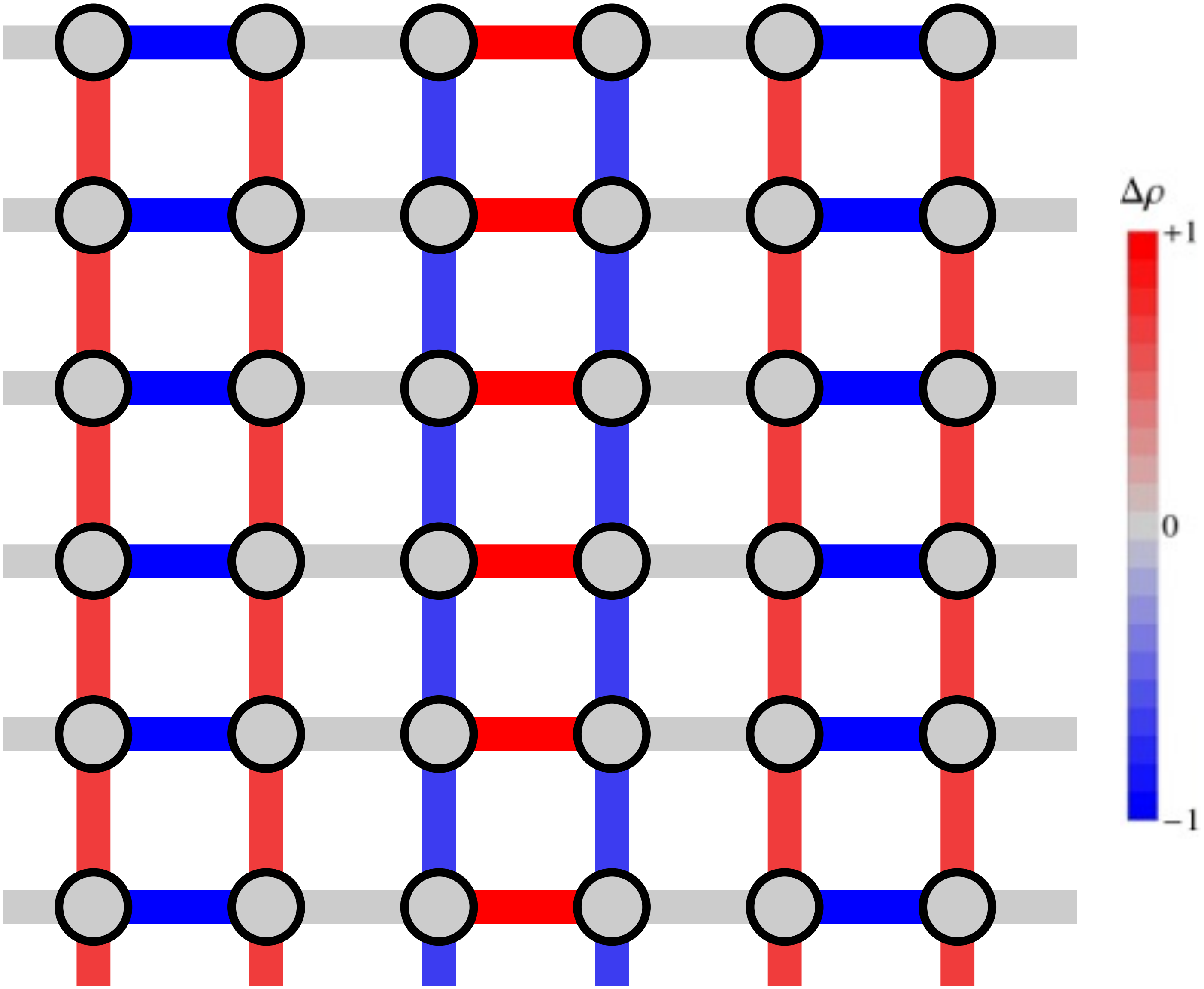
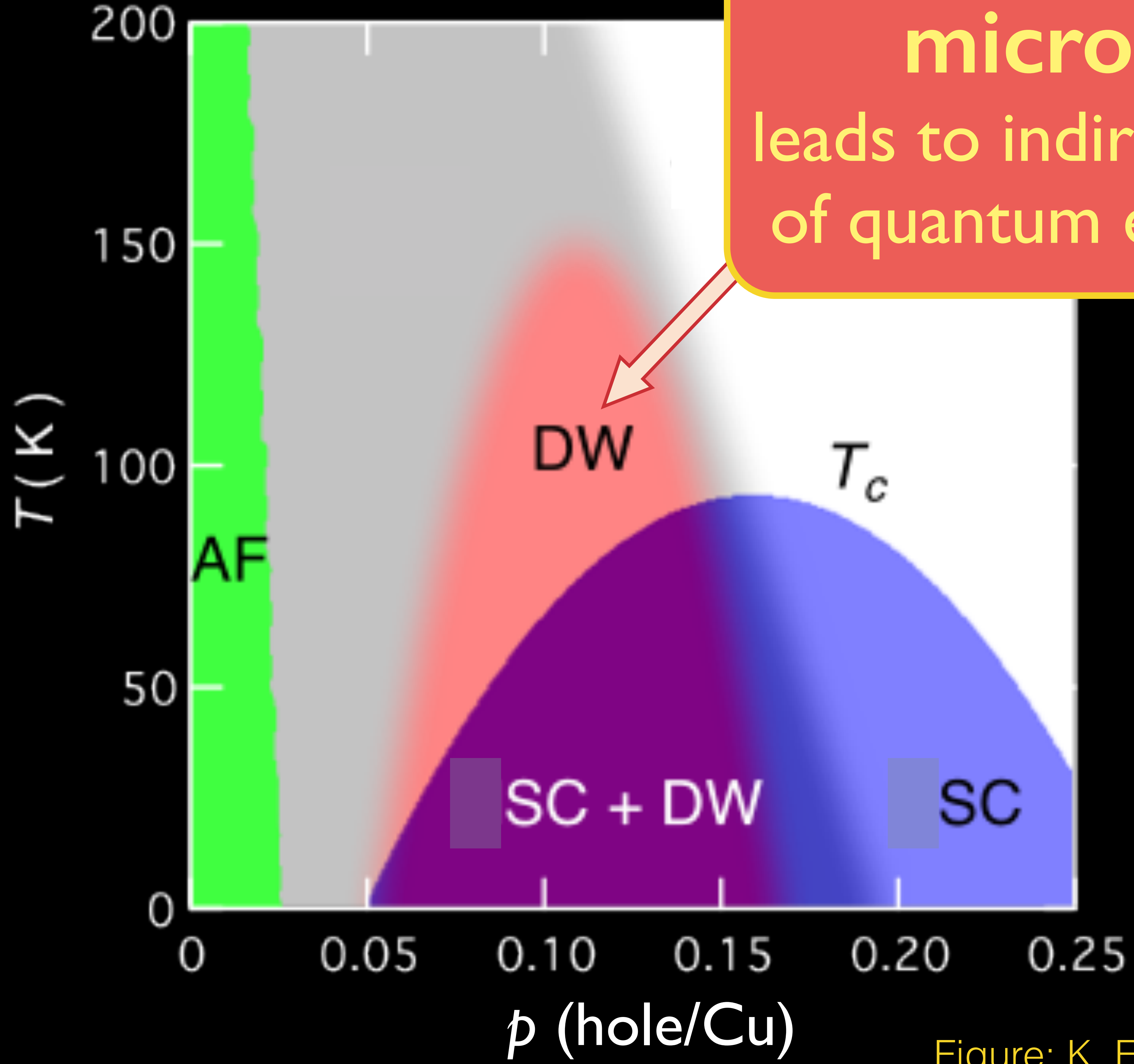


d-form factor density wave order

Intricrate pattern of electron density waves (DW) is giving us important information on the nature of quantum entanglement in neighboring regions

Scanning tunneling microscopy:

leads to indirect signatures of quantum entanglement



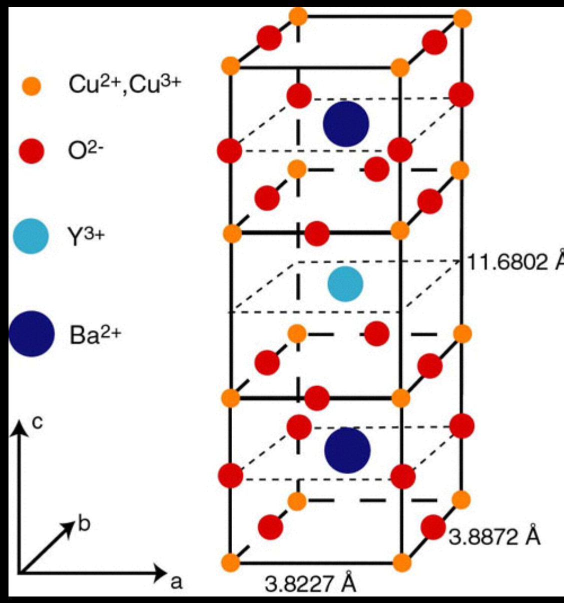
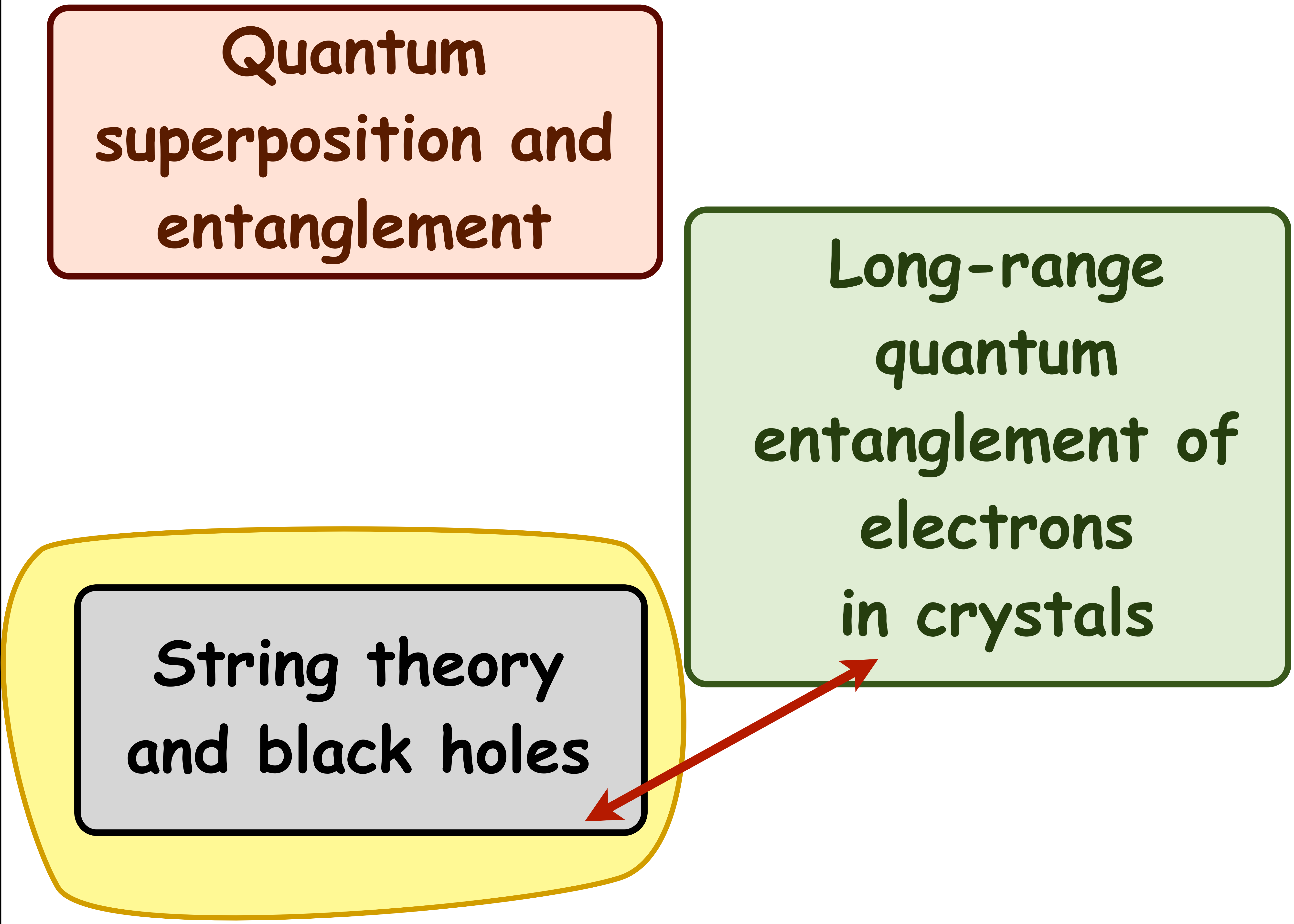


Figure: K. Fujita and J. C. Seamus Davis

Quantum superposition and entanglement

Long-range quantum entanglement of electrons in crystals

String theory and black holes



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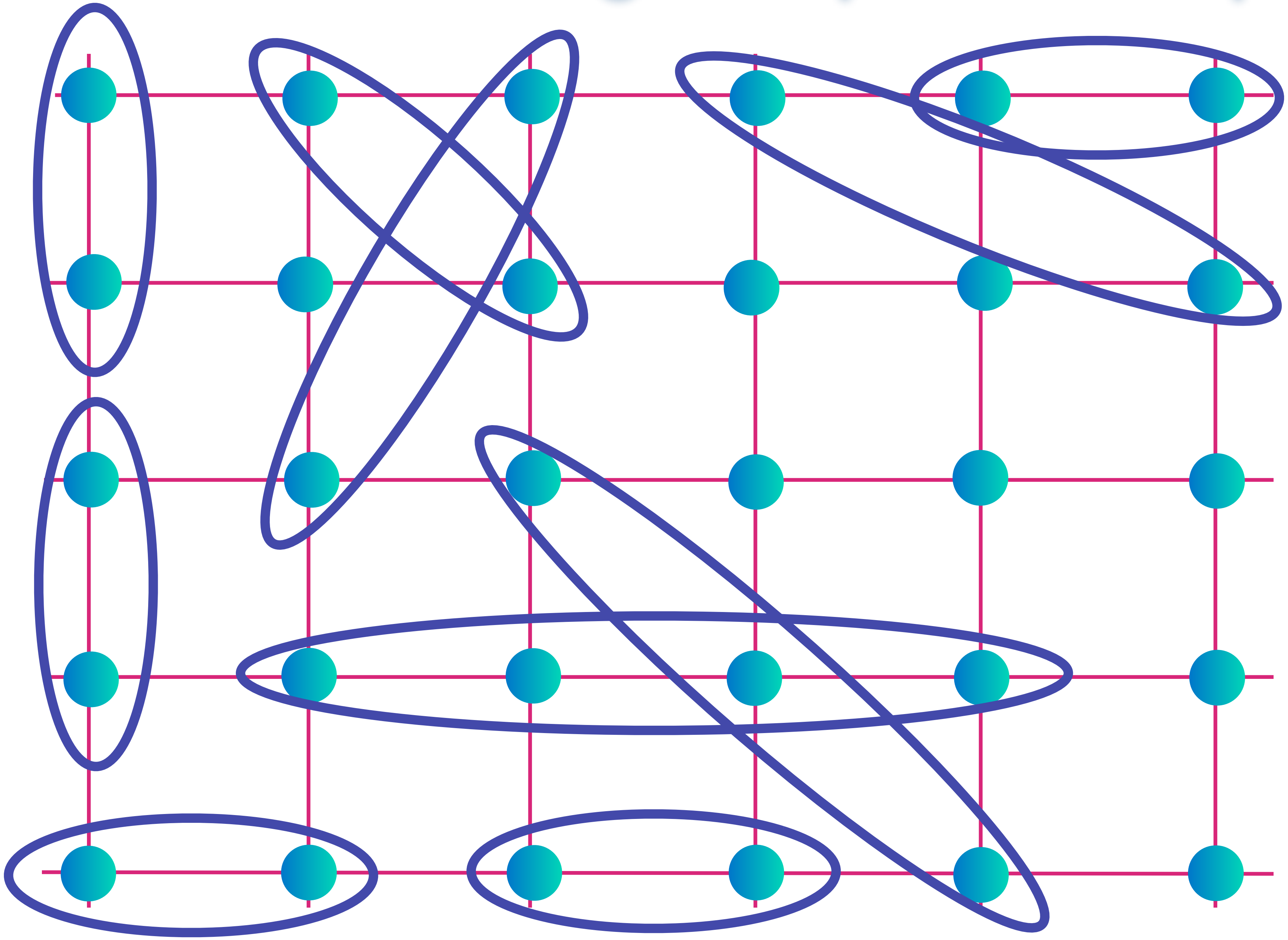
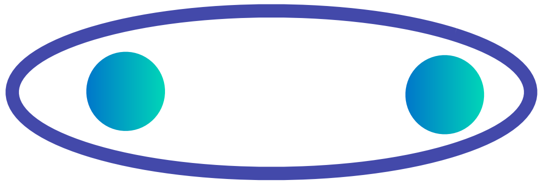
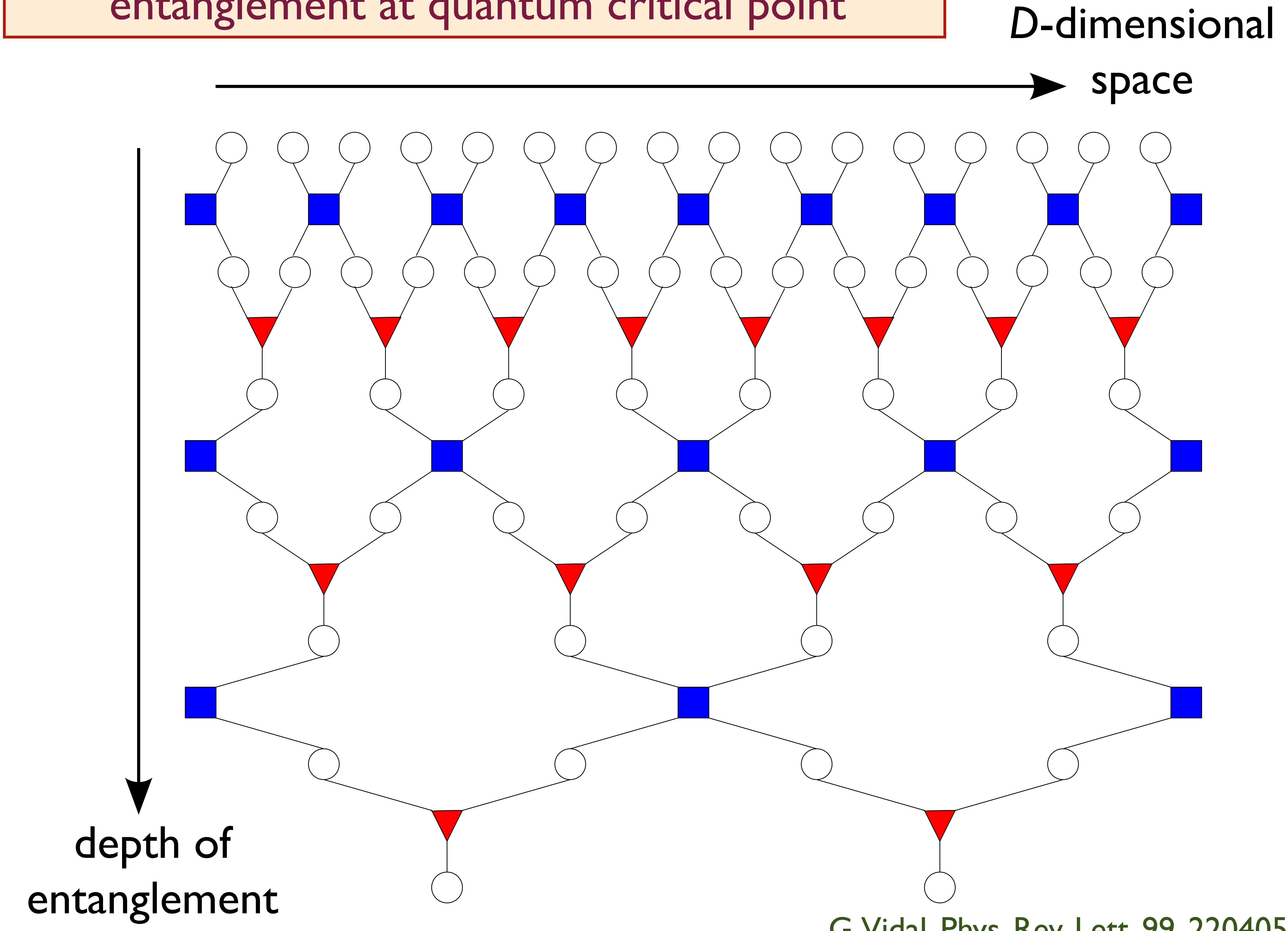


Long-range entanglement has a heiearchical structure: electrons entangle in pairs, pairs entangle with pairs, and so on.....



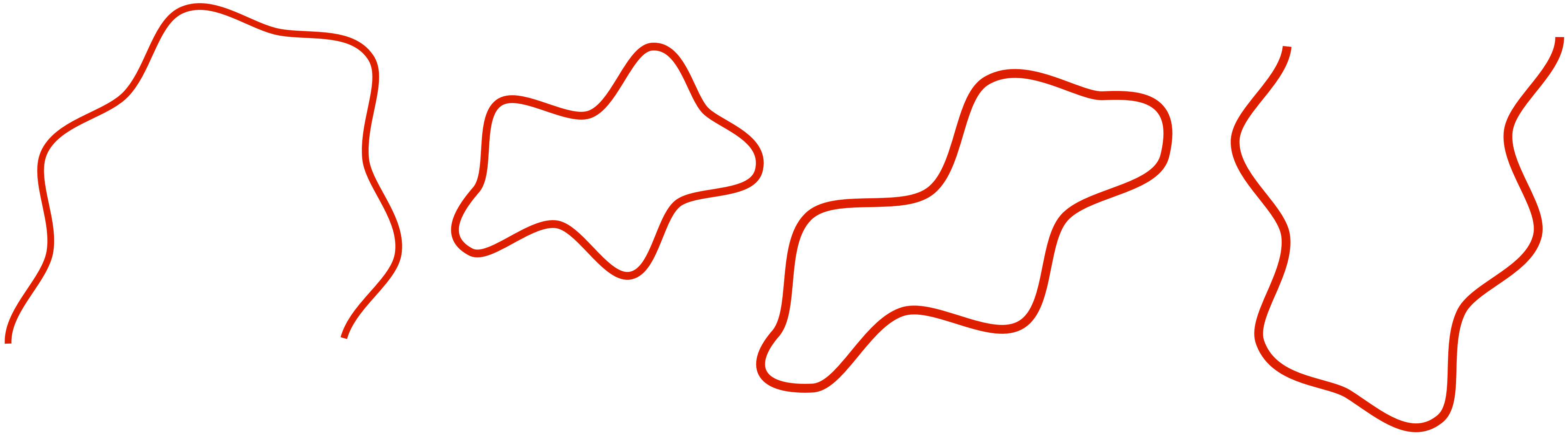
$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Representation of hierarchical entanglement at quantum critical point



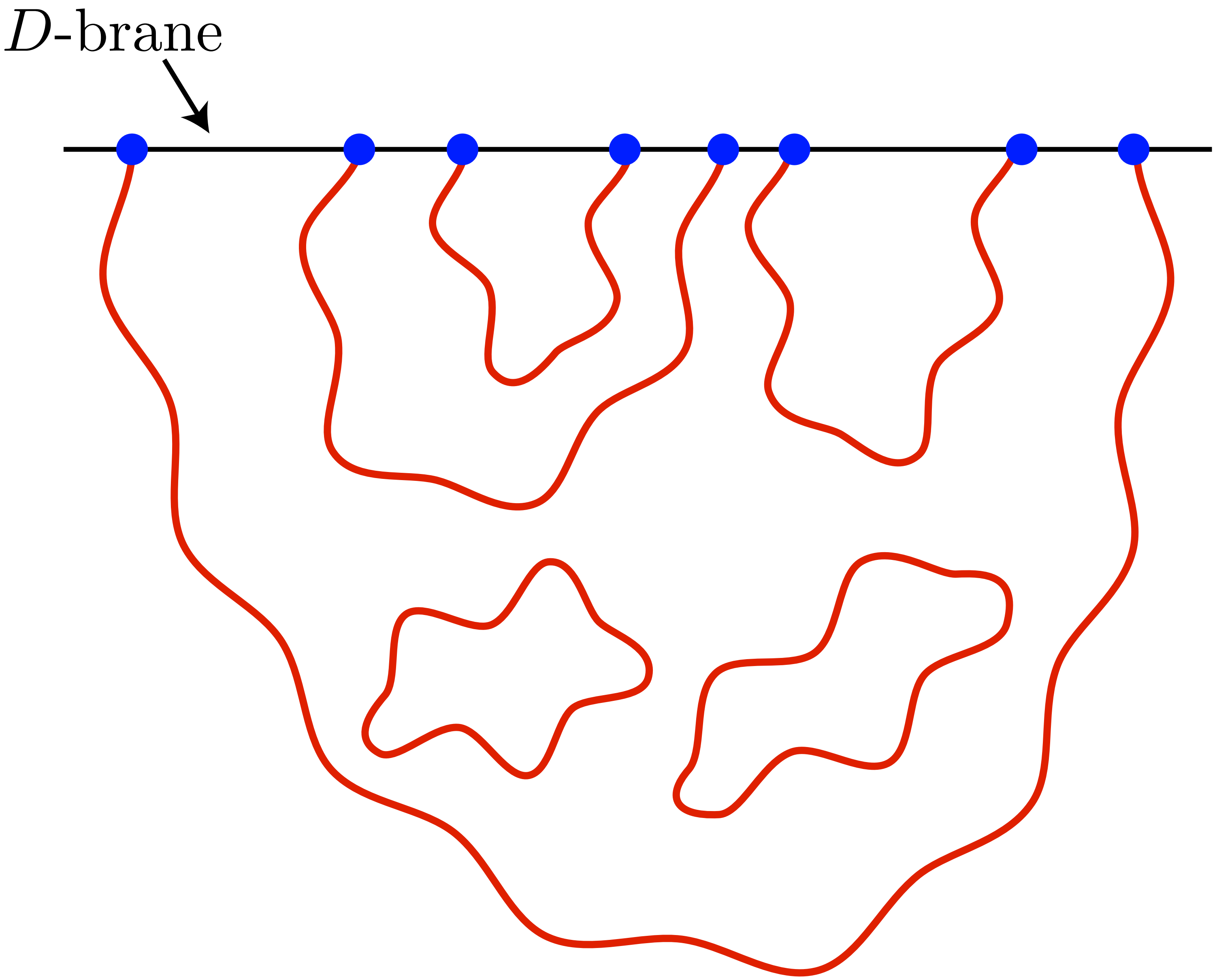
G. Vidal, Phys. Rev. Lett. 99, 220405 (2007)

String theory

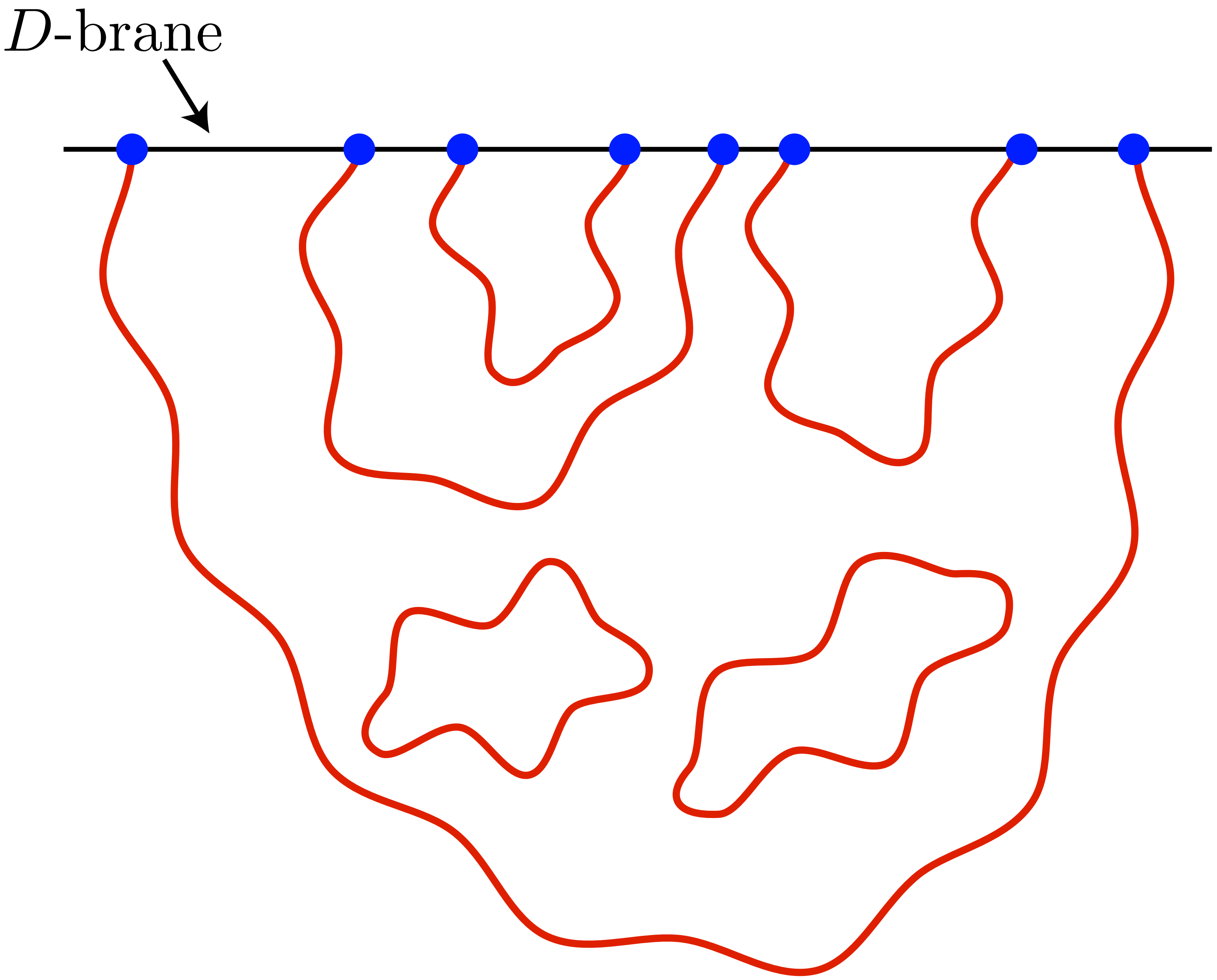


- Allows unification of the standard model of particle physics with Einstein's theory of gravitation (general relativity).

- Vibrations of a string (its "musical notes") correspond to quarks, gravitons, the Higgs boson, photons, gluons . . . . . .



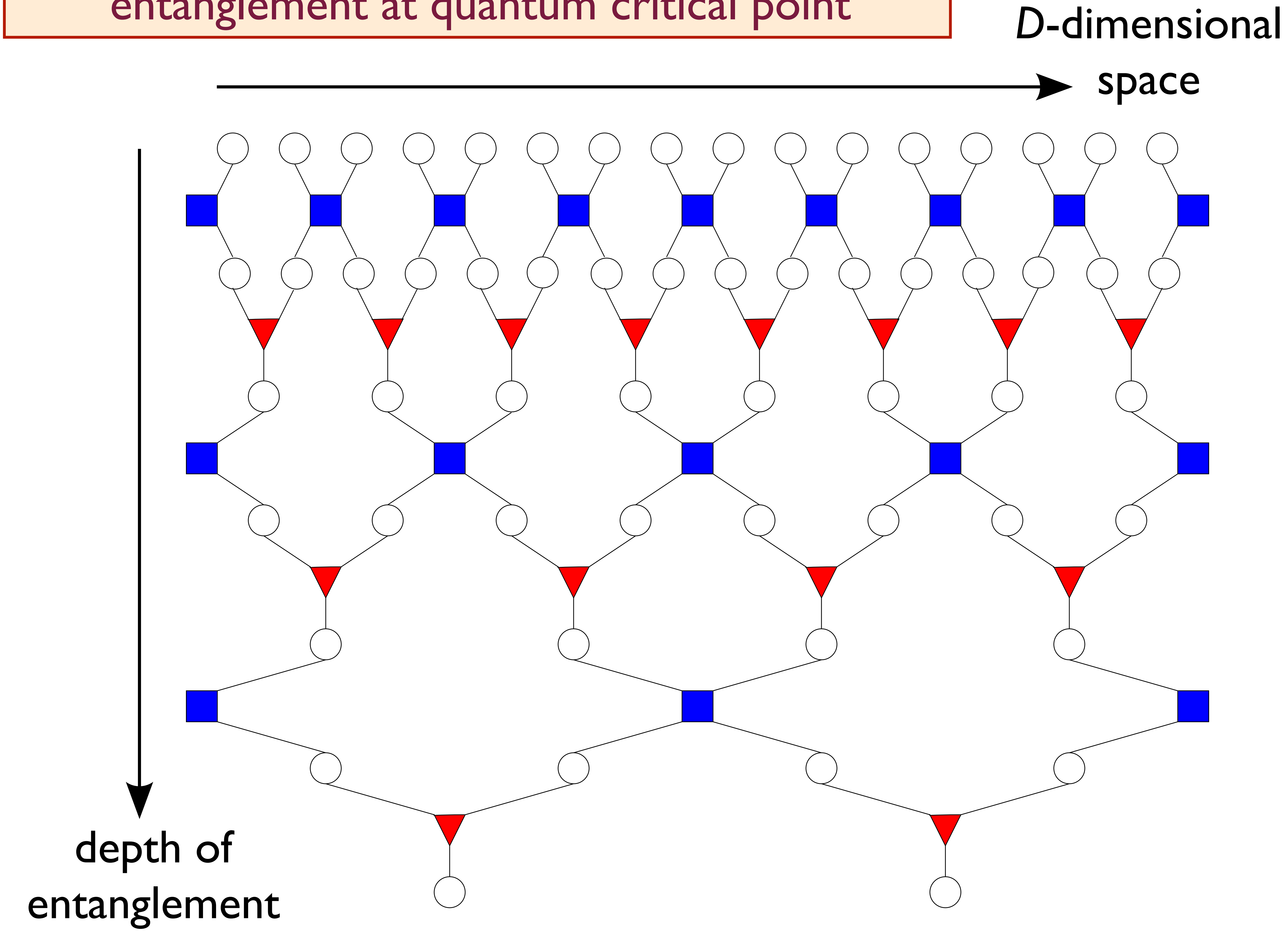
- A D-brane is a D-dimensional surface on which strings can end.



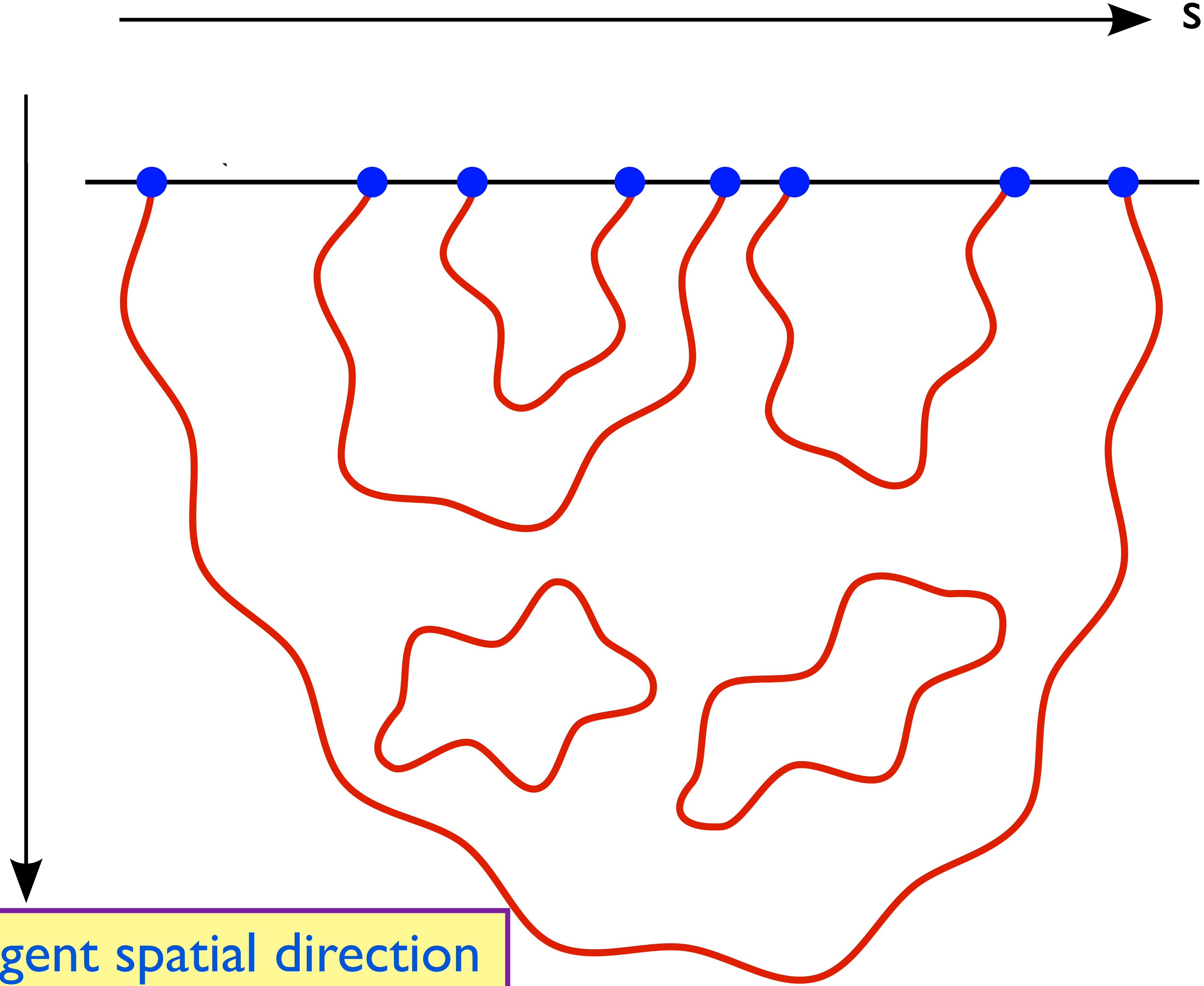
- A D-brane is a D-dimensional surface on which strings can end.

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

Representation of hierarchical entanglement at quantum critical point



String theory near a D-brane

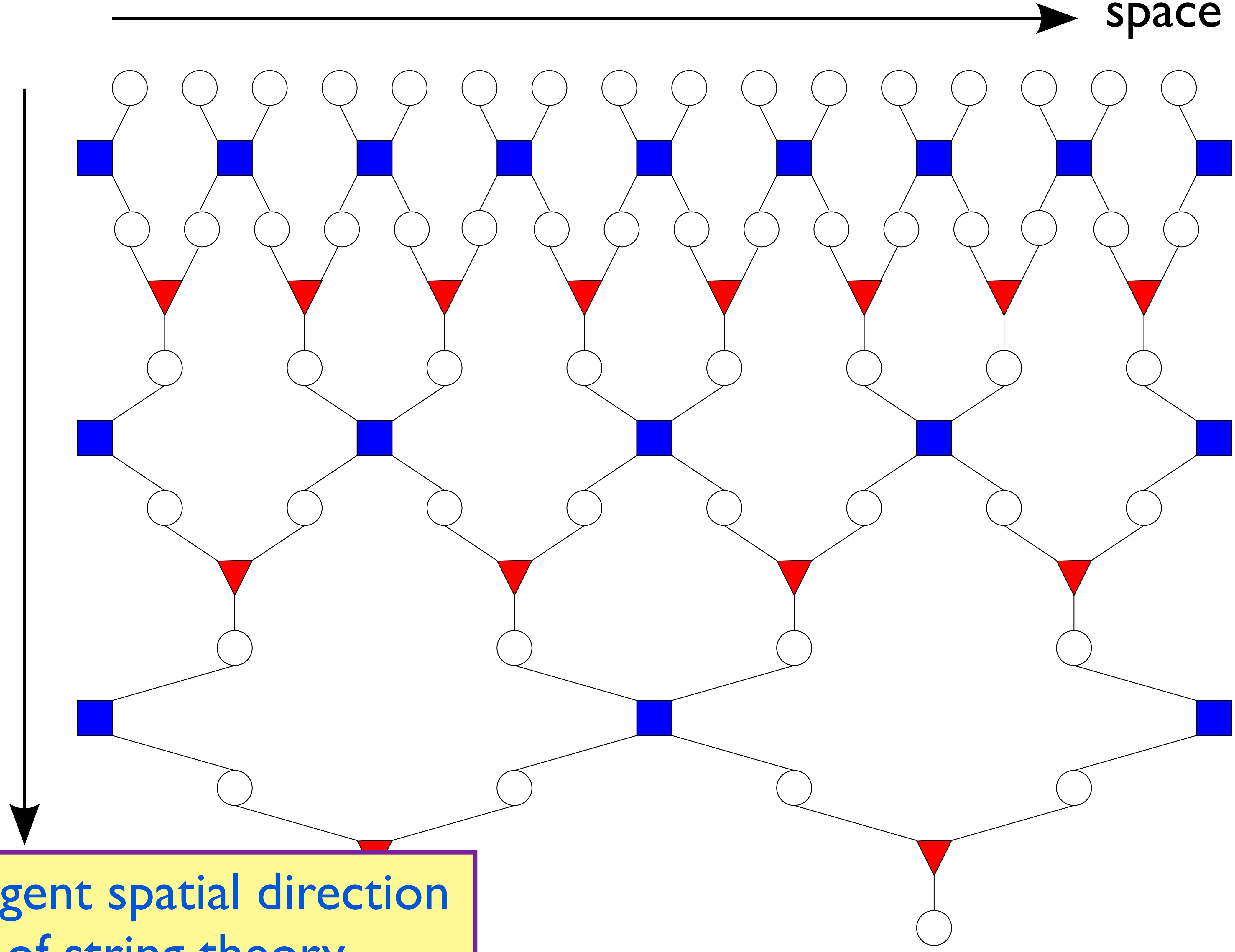


D-dimensional space

Emergent spatial direction of string theory

Brian Swingle, arXiv:0905.1317

Representation of hierarchical entanglement at quantum critical point



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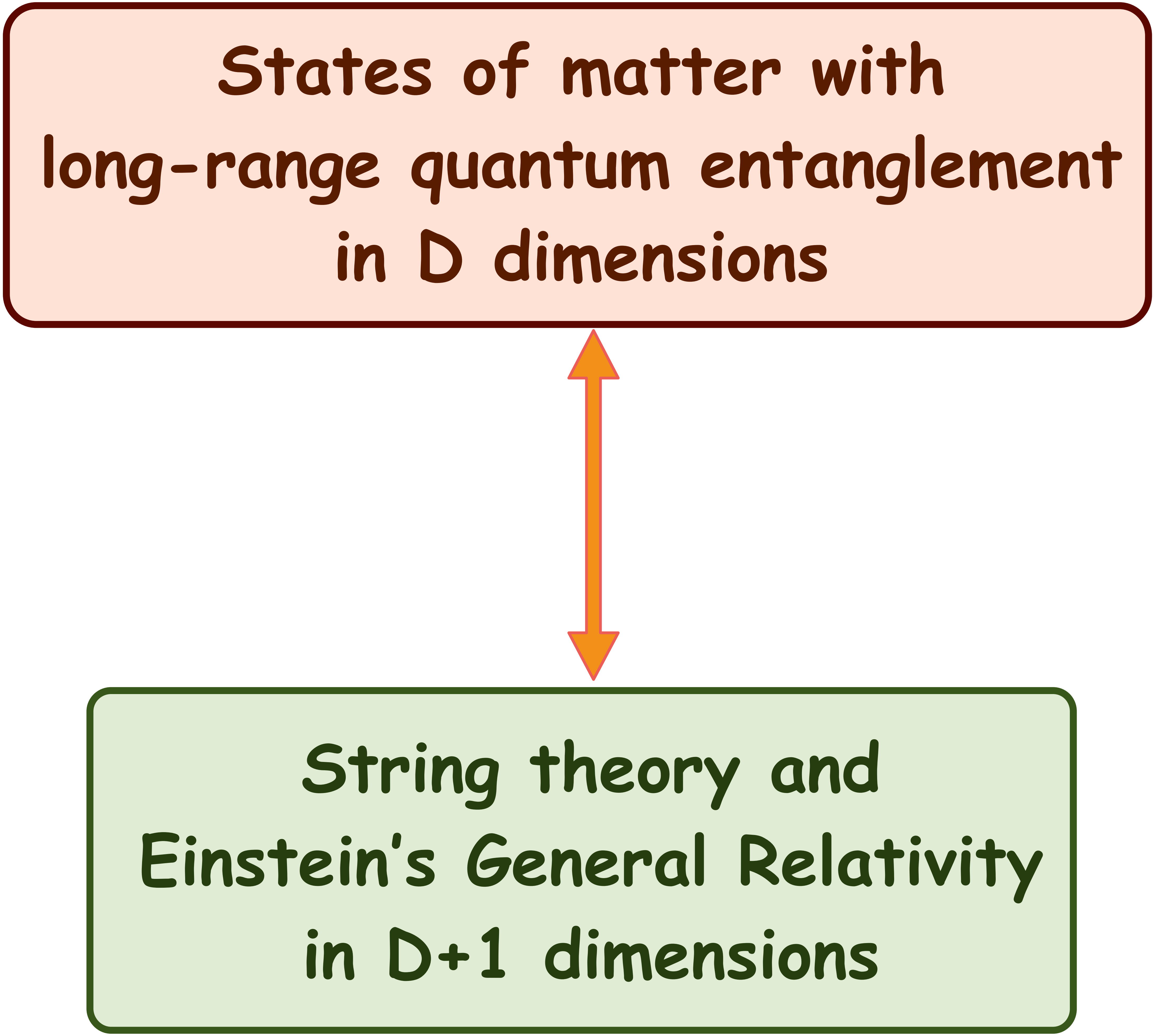


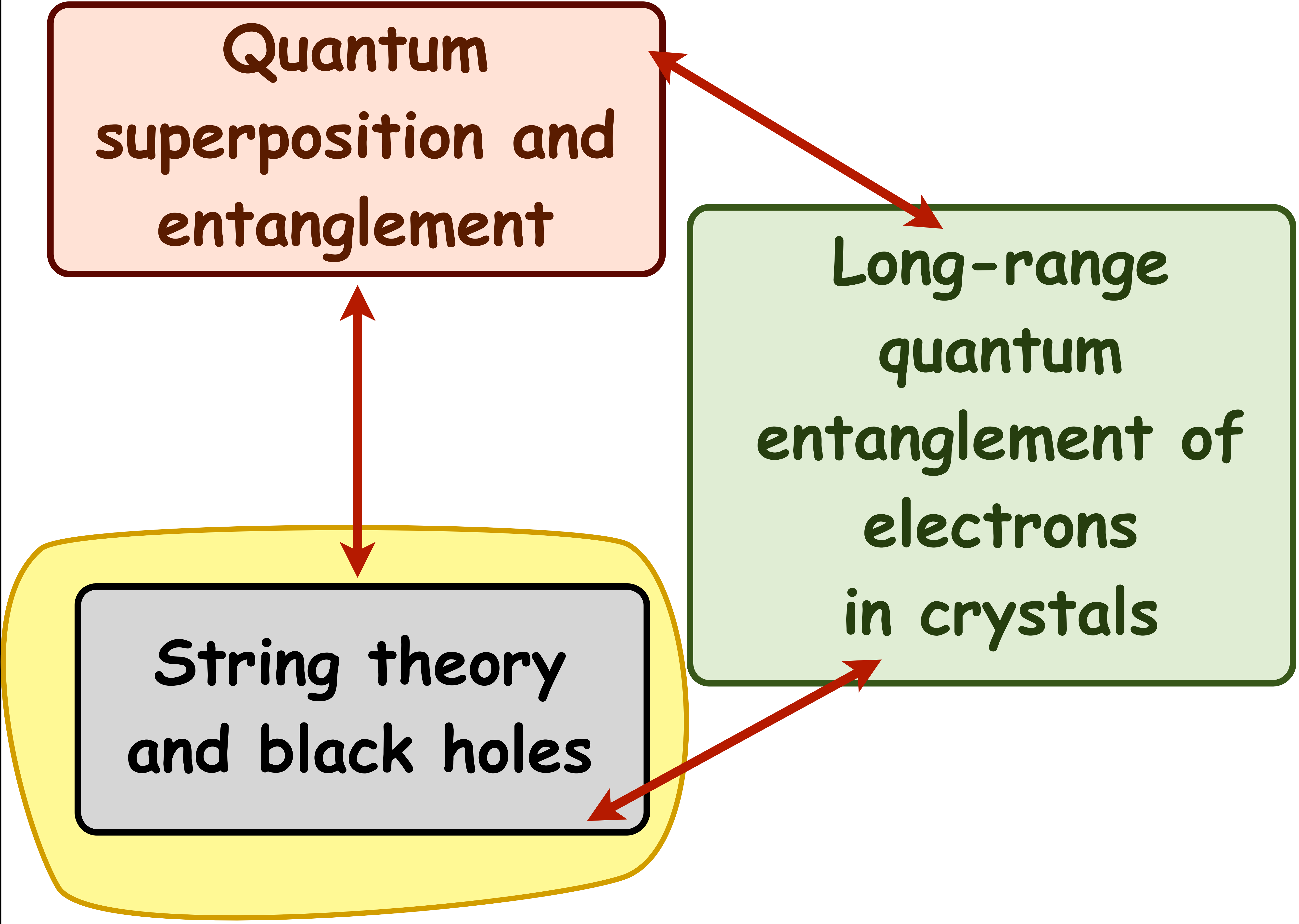
States of matter with
long-range quantum entanglement
in D dimensions

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 have an entanglement structure similar to that of a "strange metal" ?

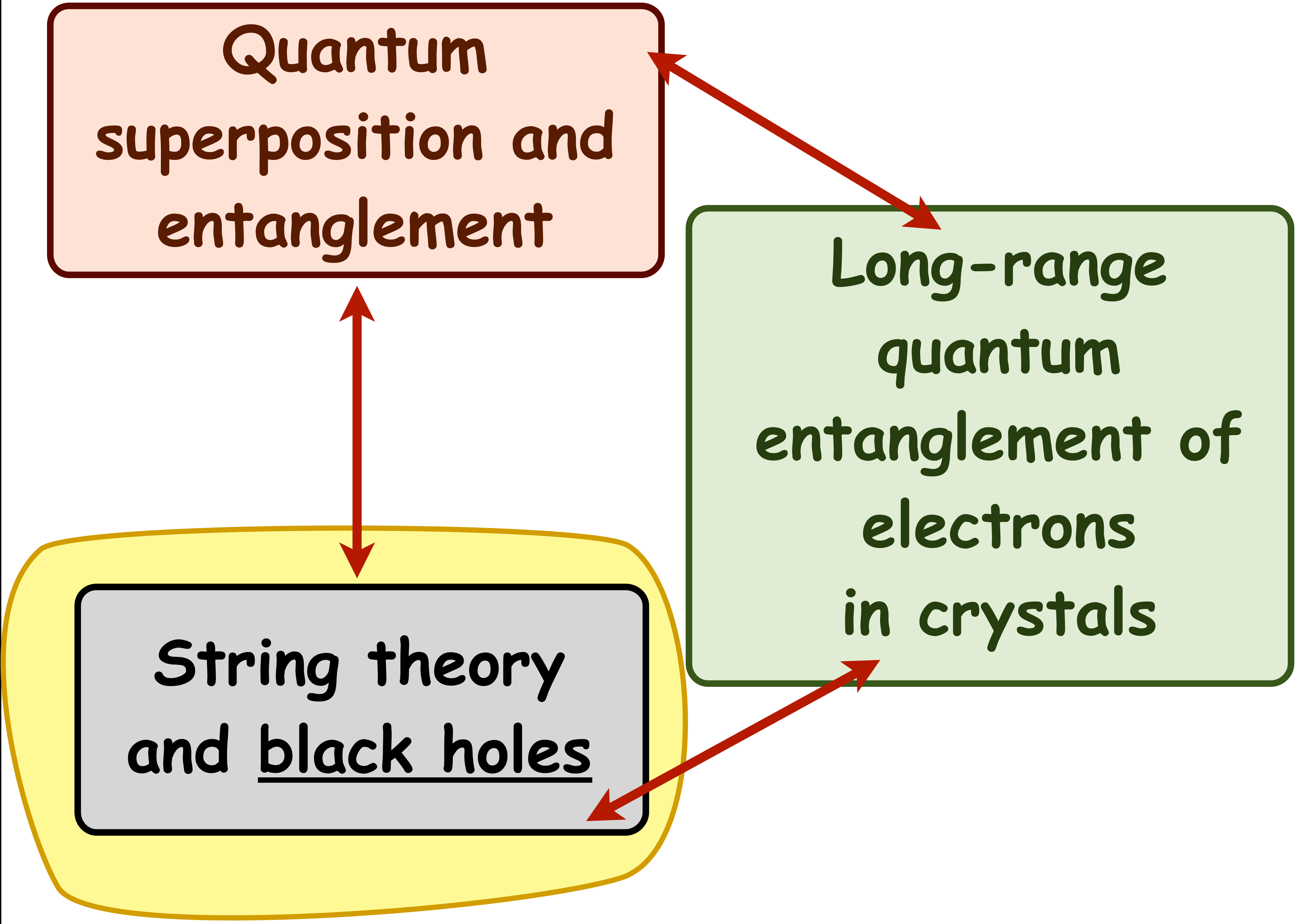
String theory and Einstein's General Relativity in D+1 dimensions



Quantum superposition and entanglement

Long-range quantum entanglement of electrons in crystals

String theory and black holes



Quantum superposition and entanglement

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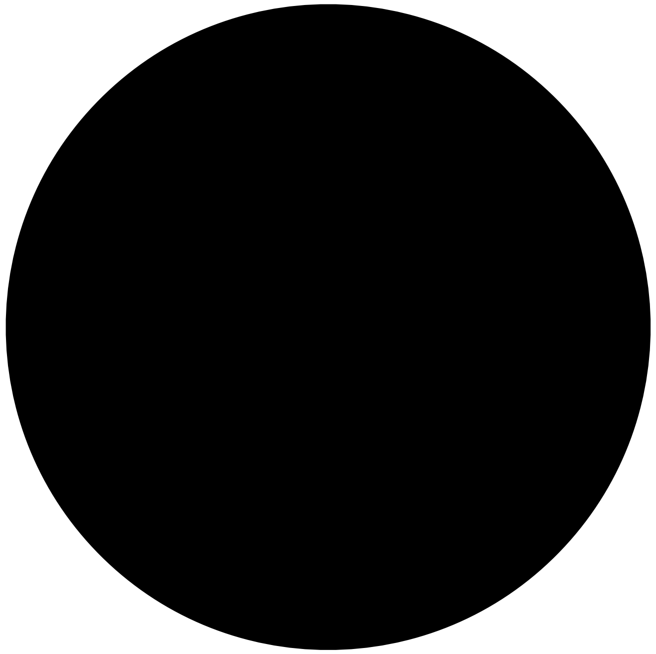
Black Holes

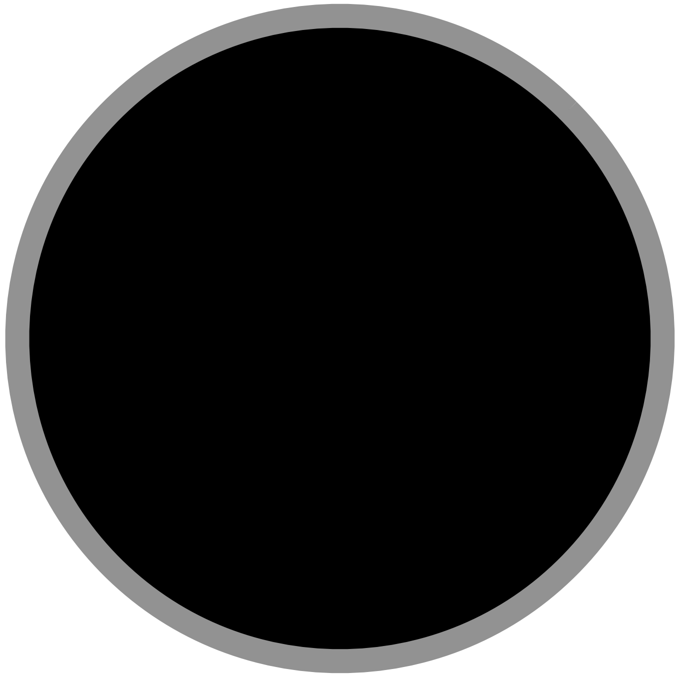
Objects so massive that light is gravitationally bound to them.



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.

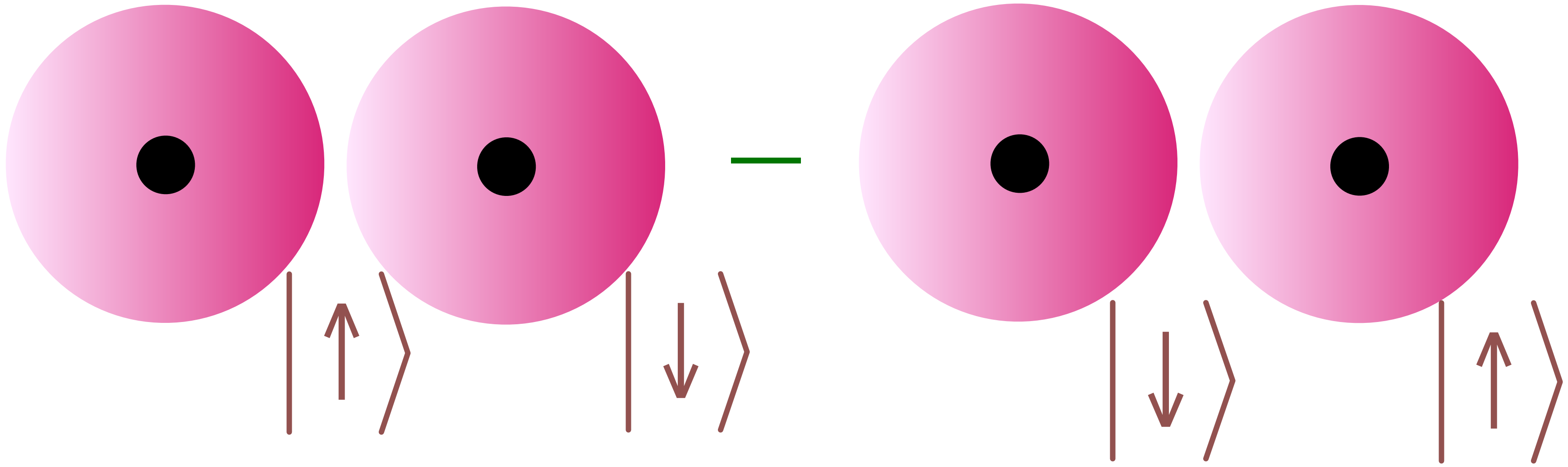


$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

Black Holes + Quantum theory

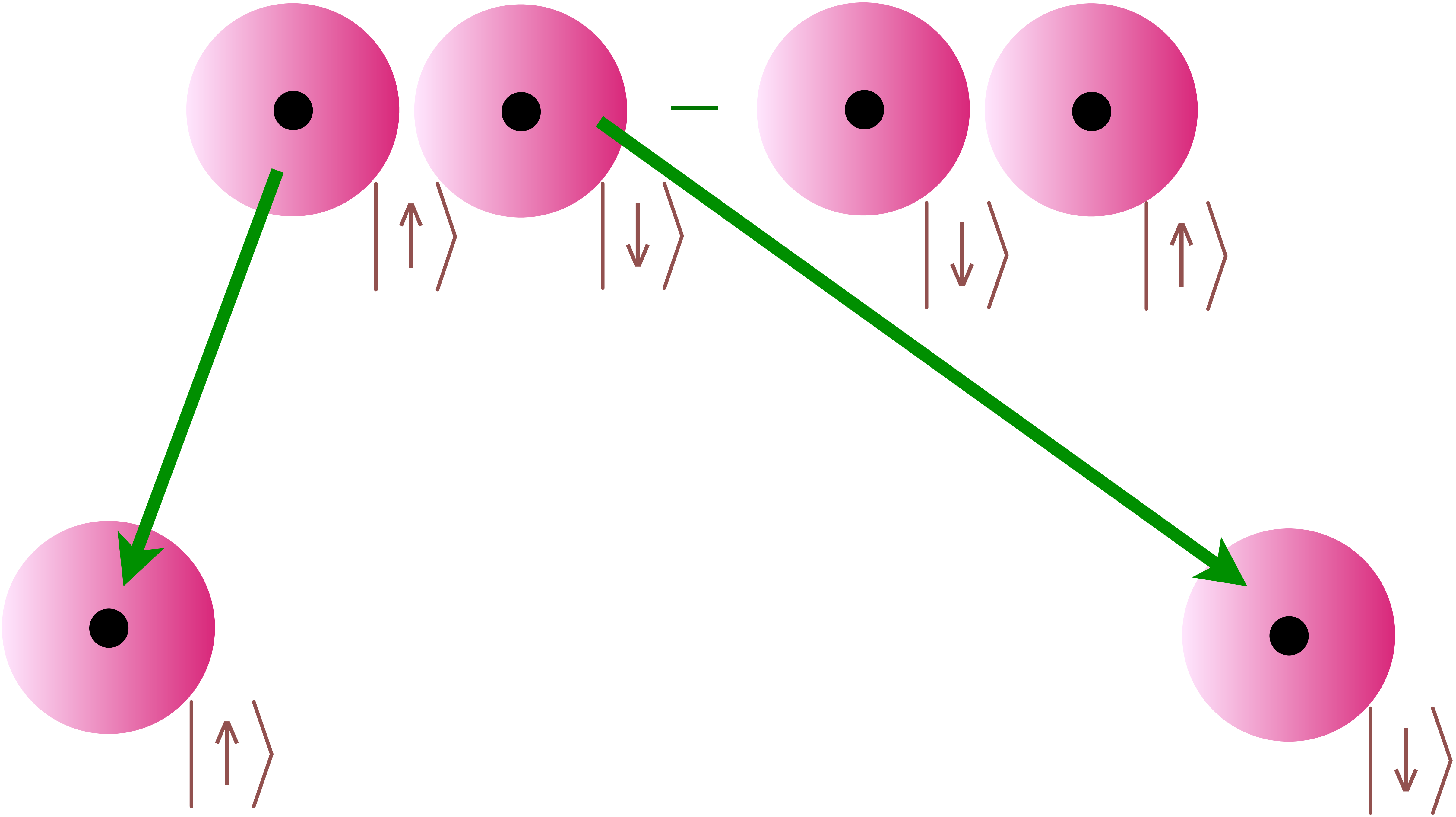
Around 1974, Bekenstein and Hawking showed that the application of the quantum theory across a black hole horizon led to many astonishing conclusions

Quantum Entanglement across a black hole horizon

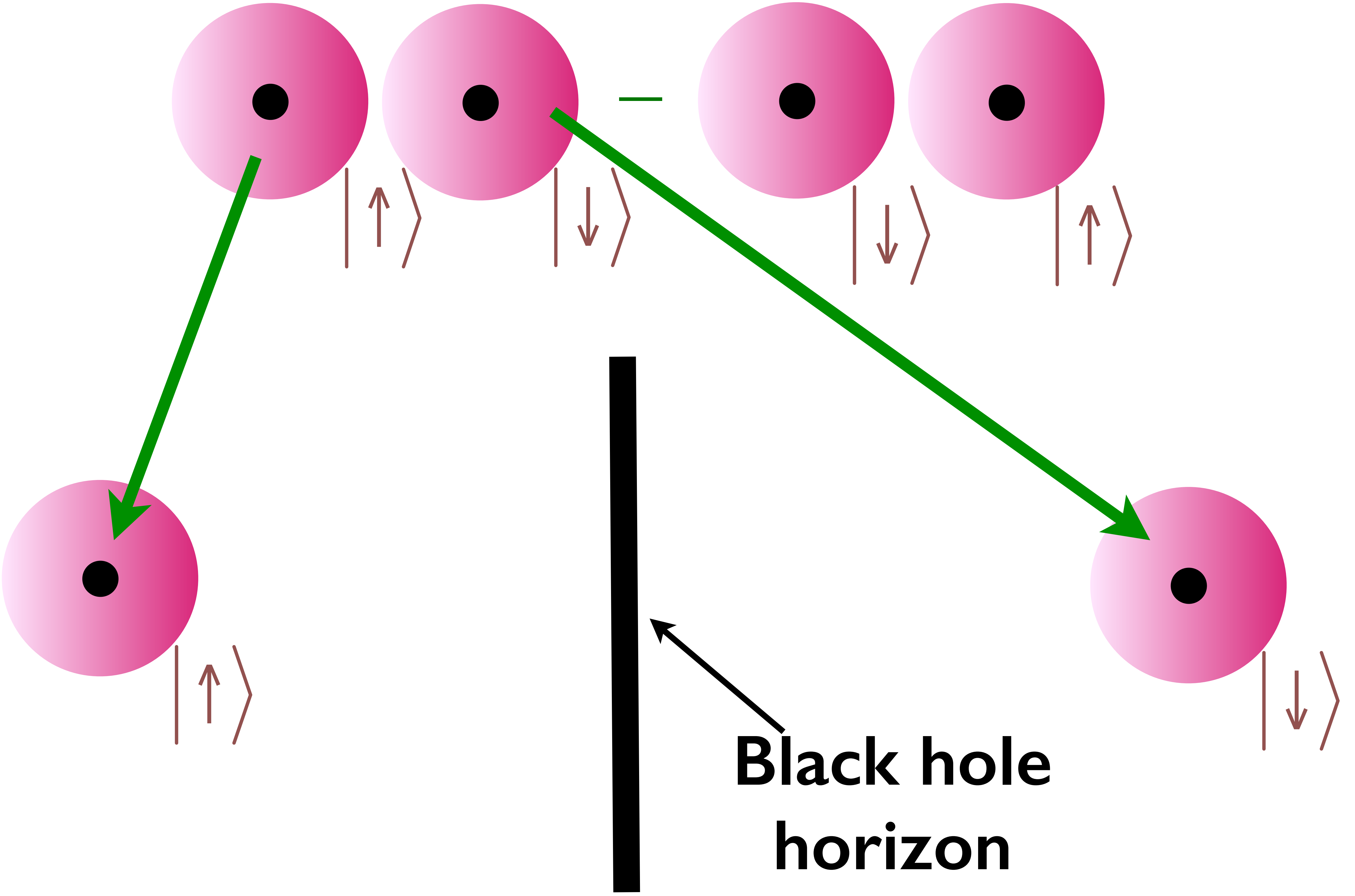


$$|\uparrow\rangle \, |\downarrow\rangle - |\downarrow\rangle \, |\uparrow\rangle$$

Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon



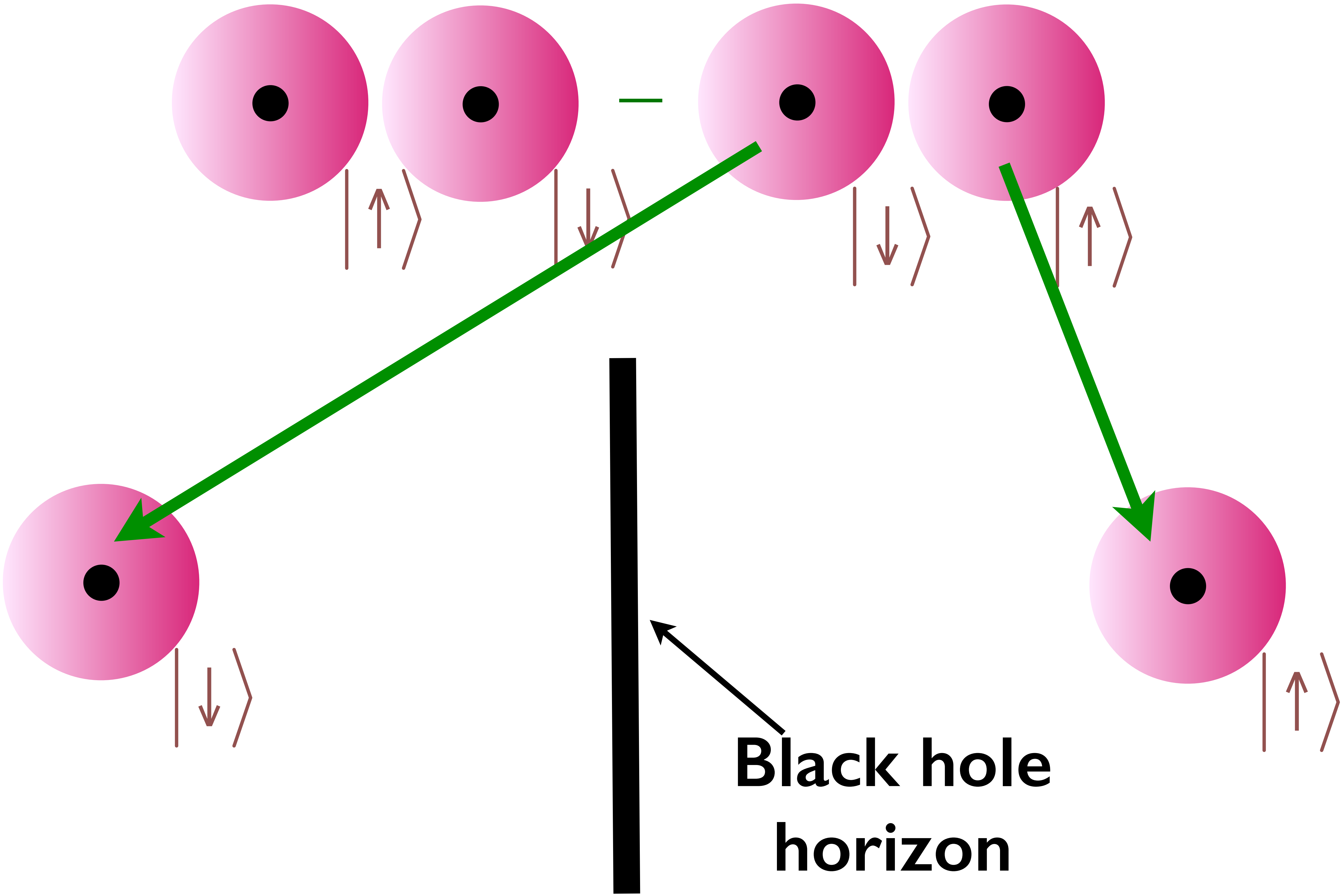
$$|\uparrow\rangle \; |\downarrow\rangle - |\downarrow\rangle \; |\uparrow\rangle$$

$|\uparrow\rangle$

$|\downarrow\rangle$

Black hole horizon

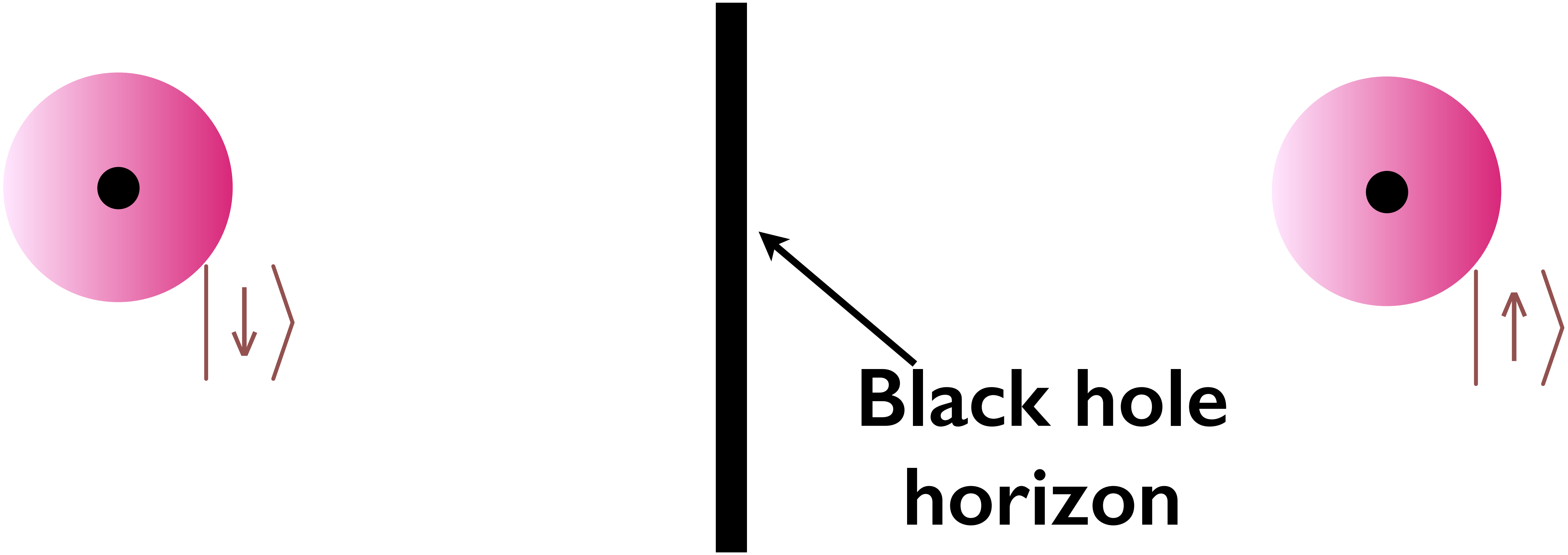
Quantum Entanglement across a black hole horizon



Black hole horizon

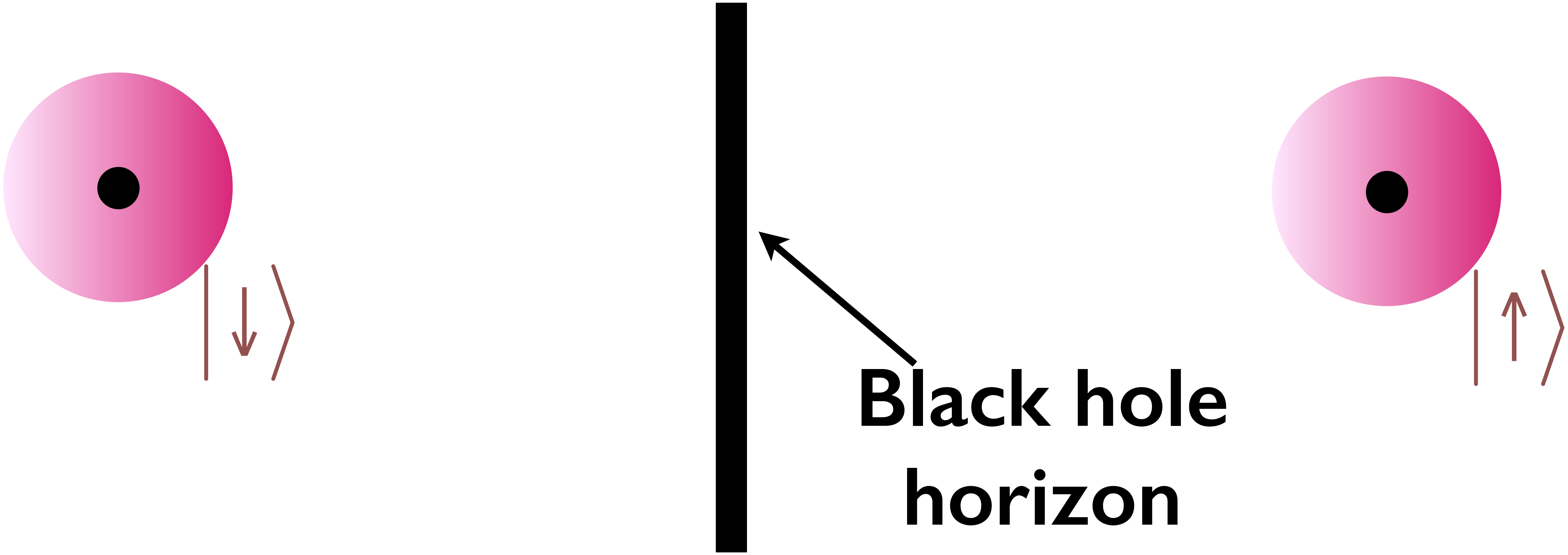
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

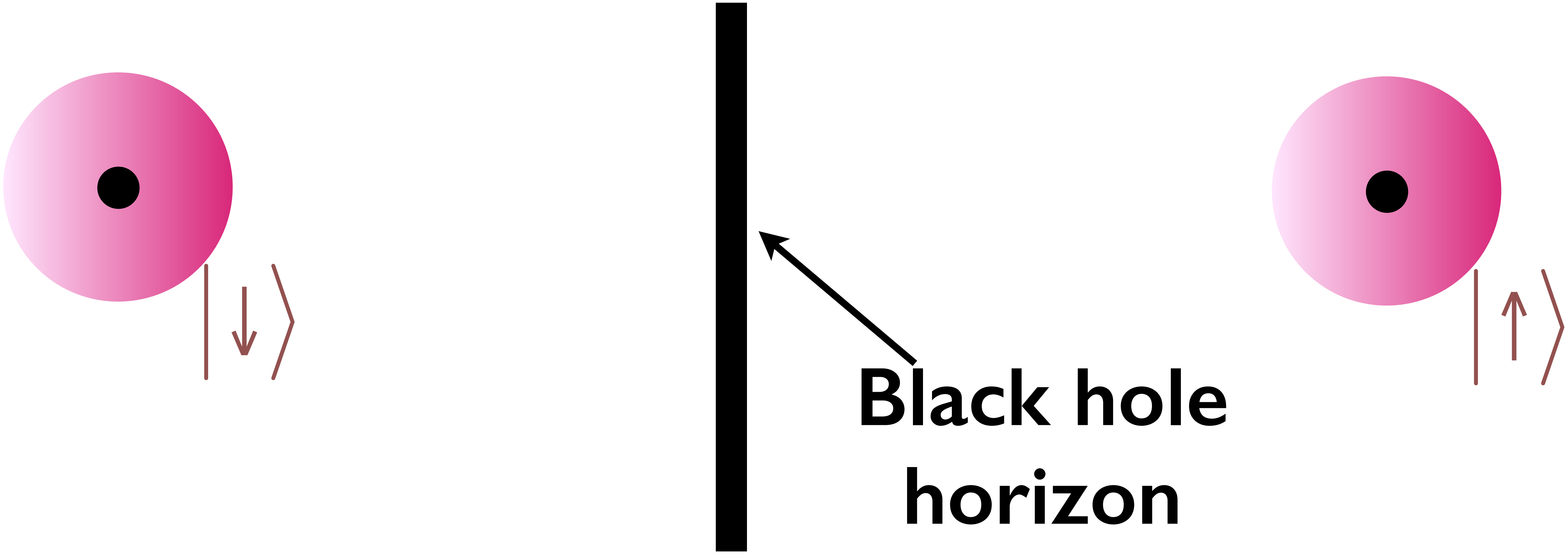
Hawking used this to show that black hole horizons have an entropy and a temperature



Quantum Entanglement across a black hole horizon

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

(S. Sachdev, 2015)



Quantum Entanglement across a black hole horizon

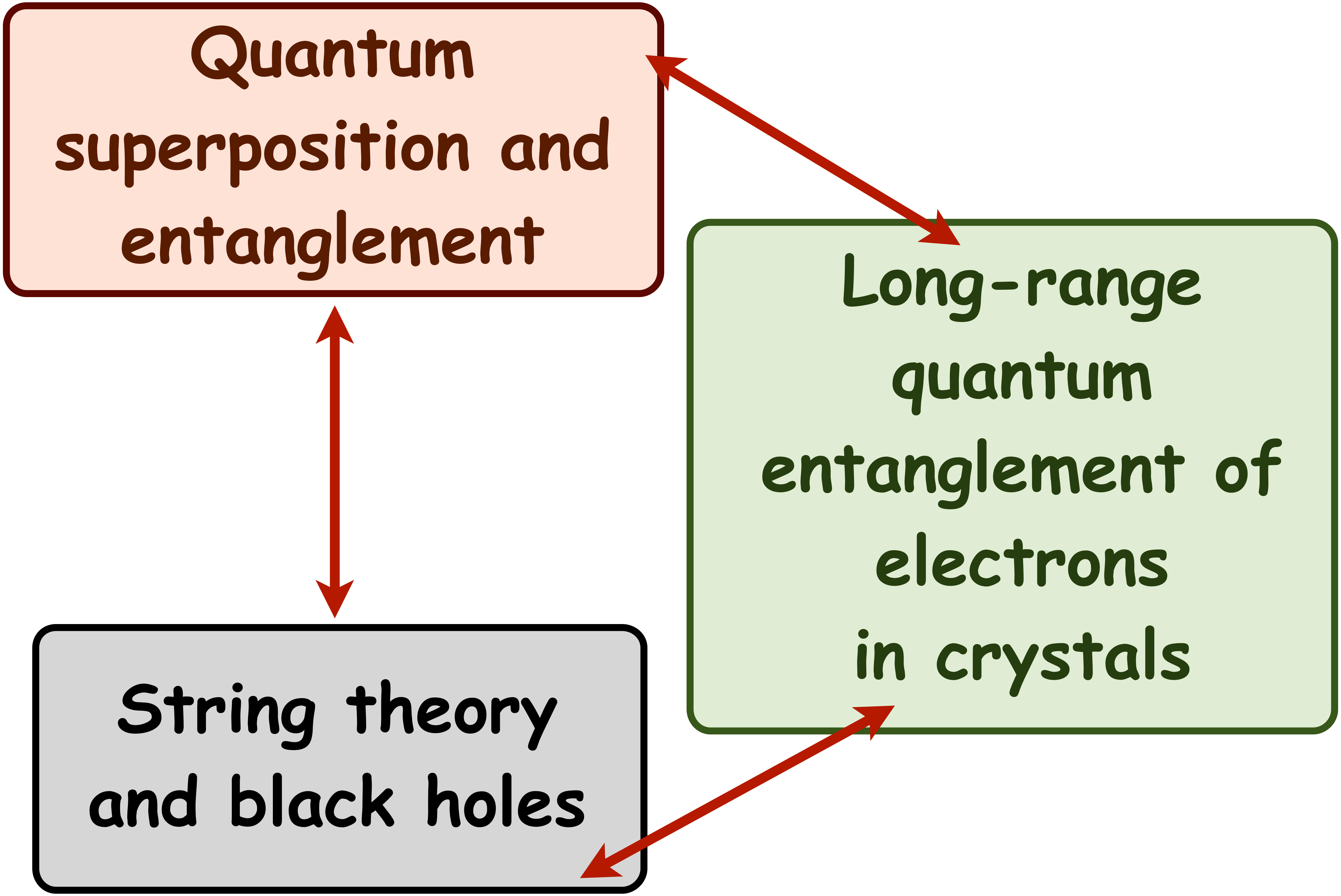
The Hawking entropy matches the entropy of some simple strange metal states of electrons

(S. Sachdev, 2015)

This connection is leading to a better understanding of the observable properties of strange metals in superconductors and other quantumm materials

horizon

Quantum superposition and entanglement

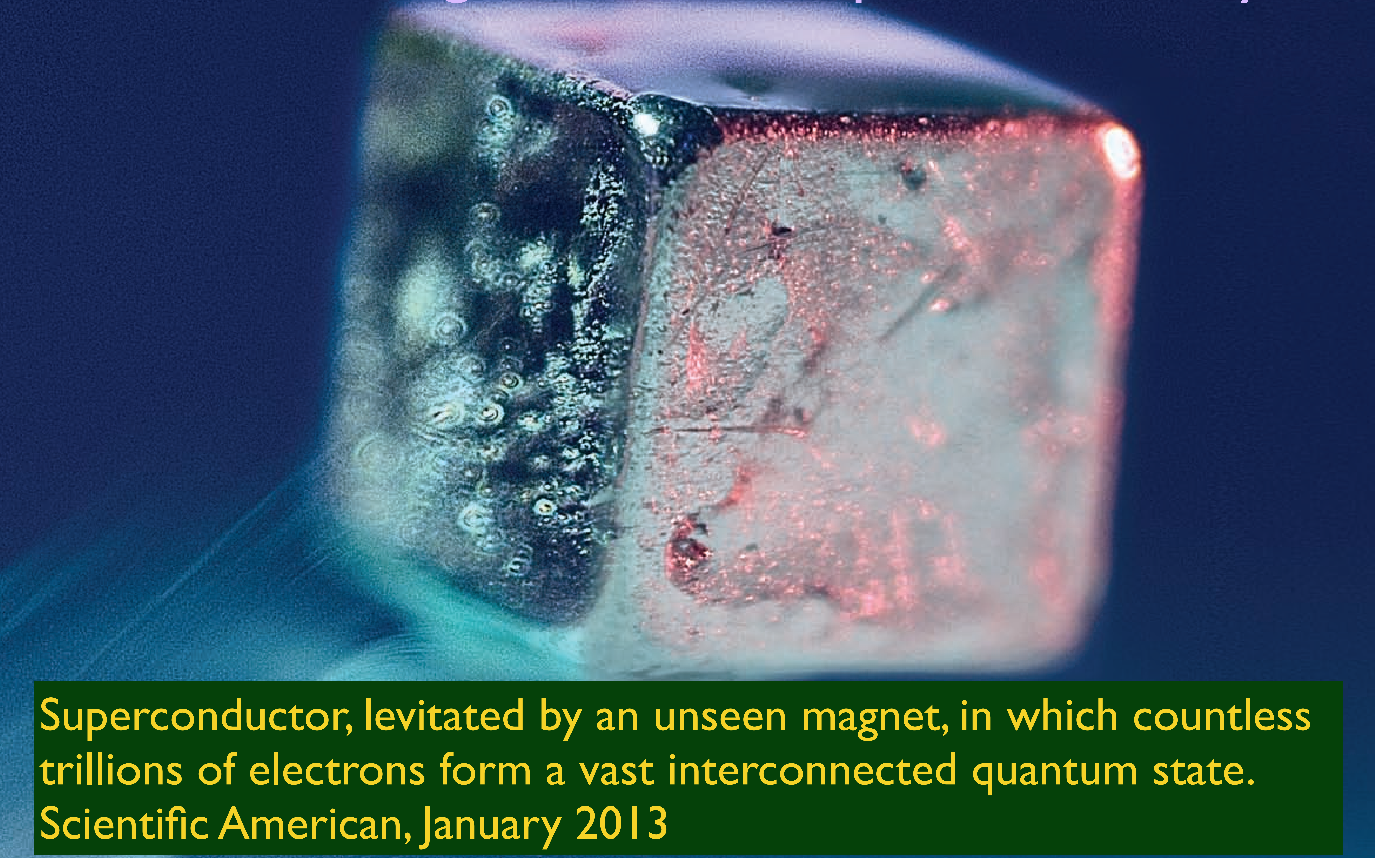


Quantum superposition and entanglement

Long-range quantum entanglement of electrons in crystals

String theory and black holes

Quantum Entanglement and Superconductivity



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

Subir Sachdev, Harvard University