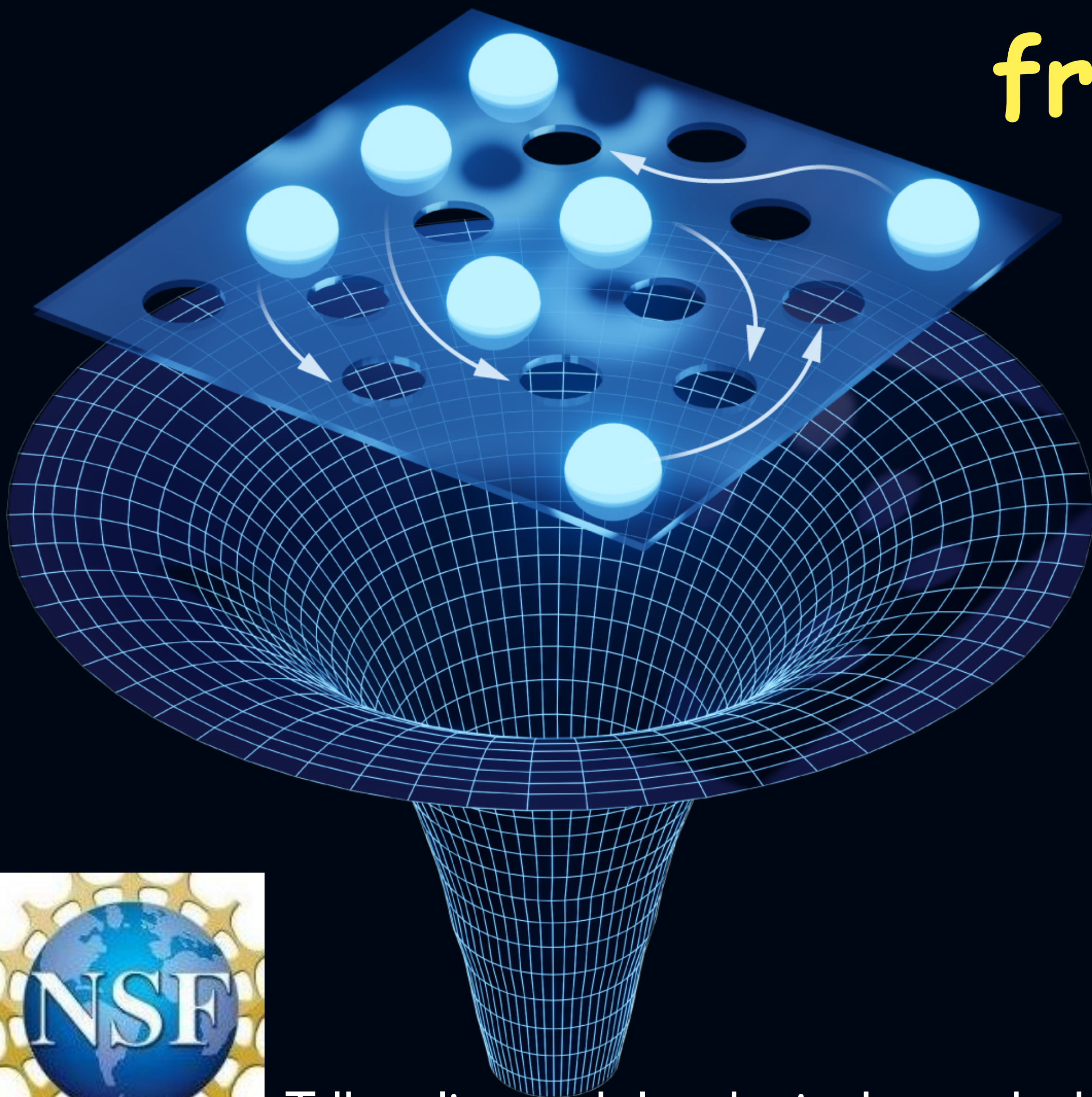


# 100 years of quantum mechanics: from Bose and Einstein to superconductors and black holes



Eminent Speaker Lecture Series  
Indian Institute of Technology, Madras  
January 7, 2025

Subir Sachdev

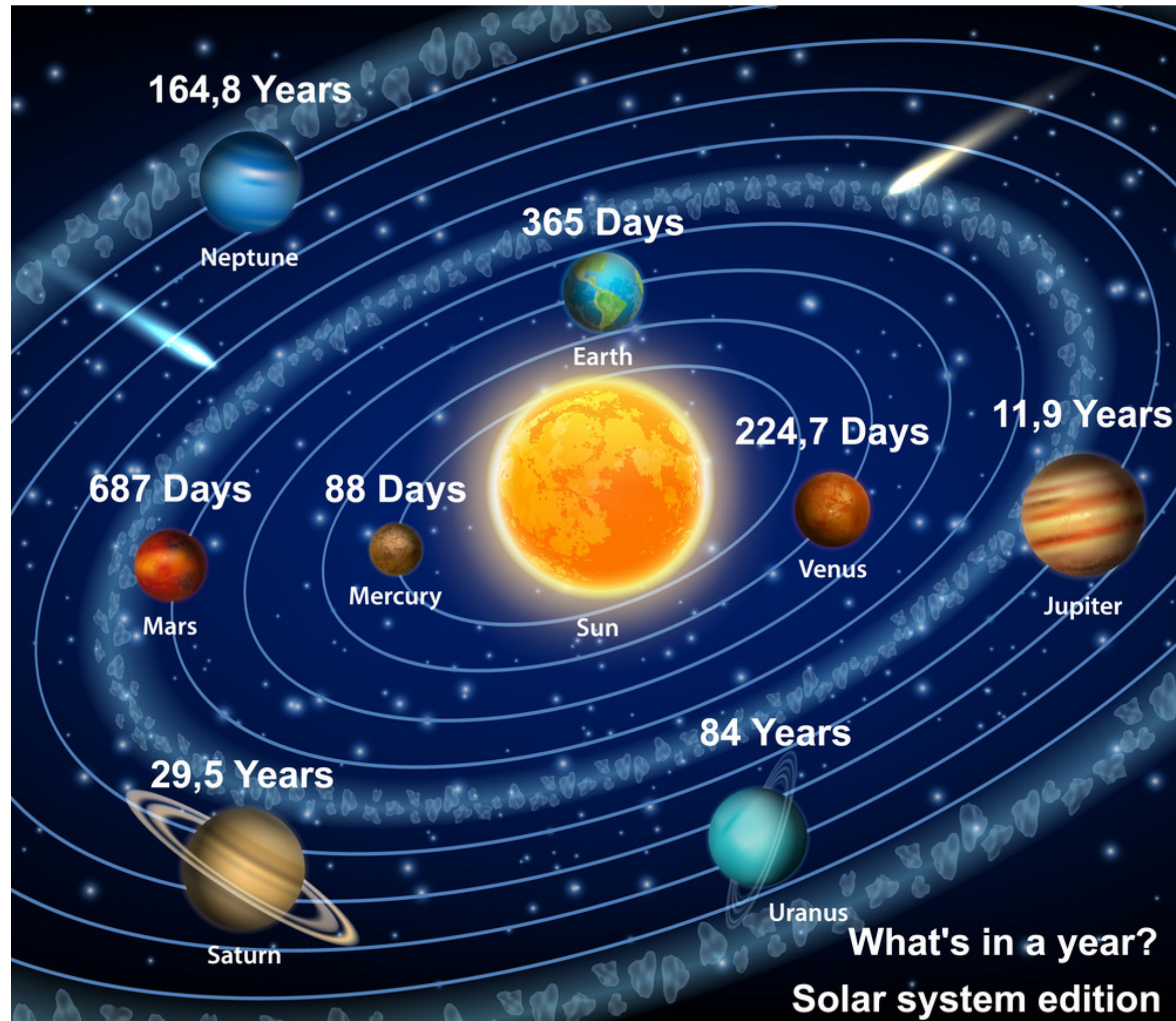


Talk online: [sachdev.physics.harvard.edu](http://sachdev.physics.harvard.edu)



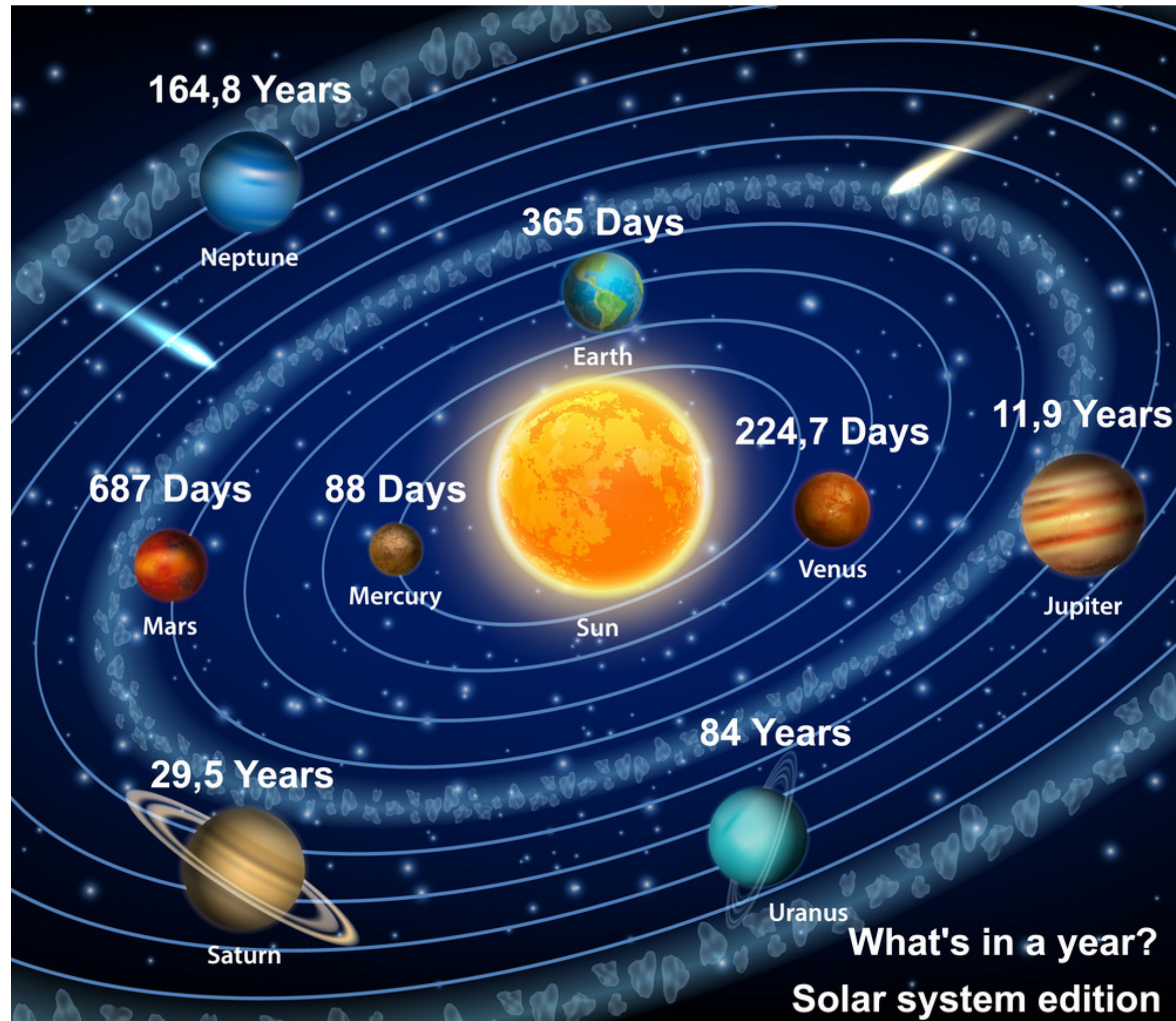
100 years of  
quantum mechanics





Newton showed (1687) that the same laws of motion applied on planetary length scales ( $\sim 1$  trillion meters) and the length scale of an apple tree (1 meter).



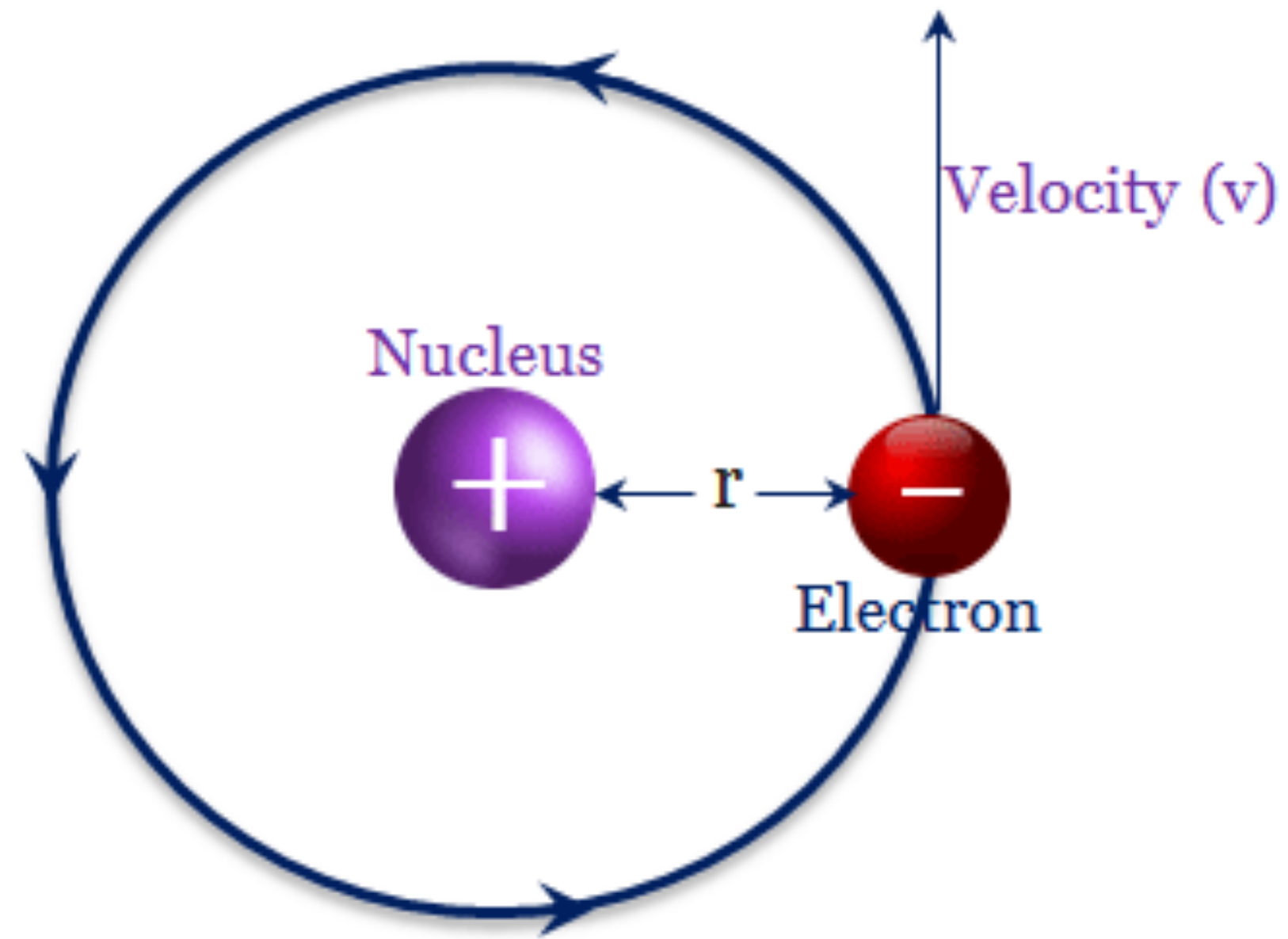


Newton showed (1687) that the same laws of motion applied on planetary length scales ( $\sim 1$  trillion meters) and the length scale of an apple tree (1 meter).

**What happens on smaller distances ?**



# Hydrogen atom

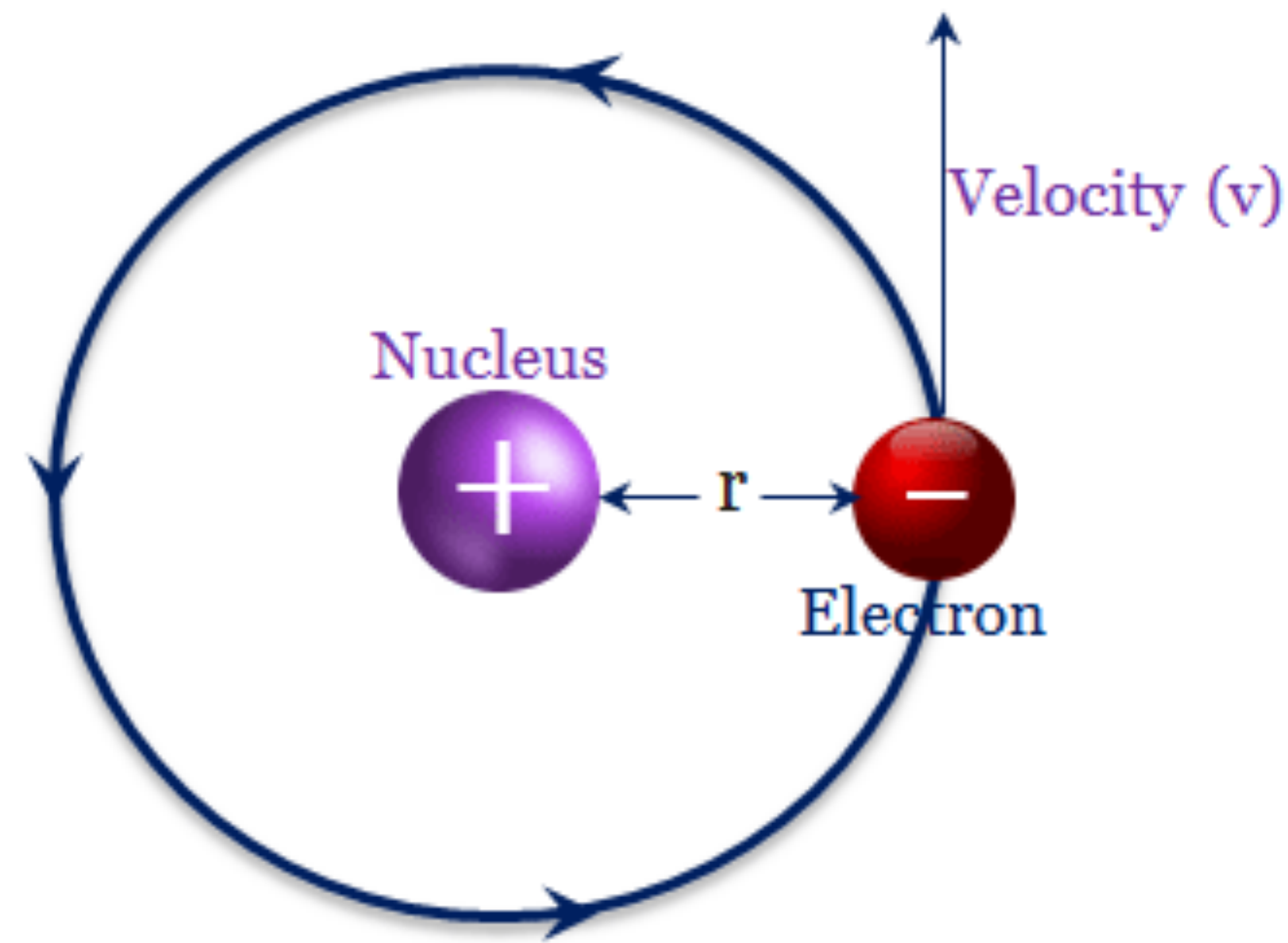


$\Rightarrow 10^{-10}$  meters  $\Leftarrow$

The motion of the electron around the proton is *not* described by the same theory as the motion of the planets around the sun.



# Hydrogen atom



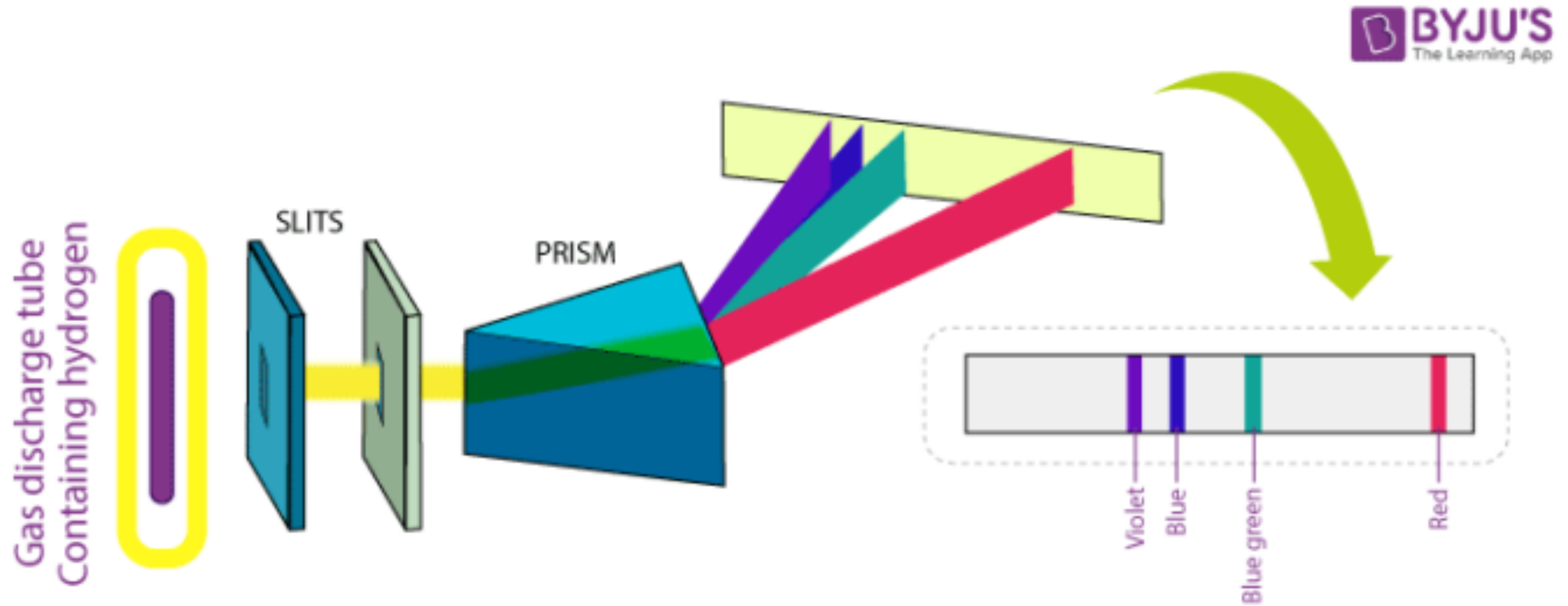
$\Rightarrow 10^{-10}$  meters  $\Leftarrow$

The motion of the electron around the proton is *not* described by the same theory as the motion of the planets around the sun.

It is described by the quantum theory of Schrödinger and Heisenberg (1925).



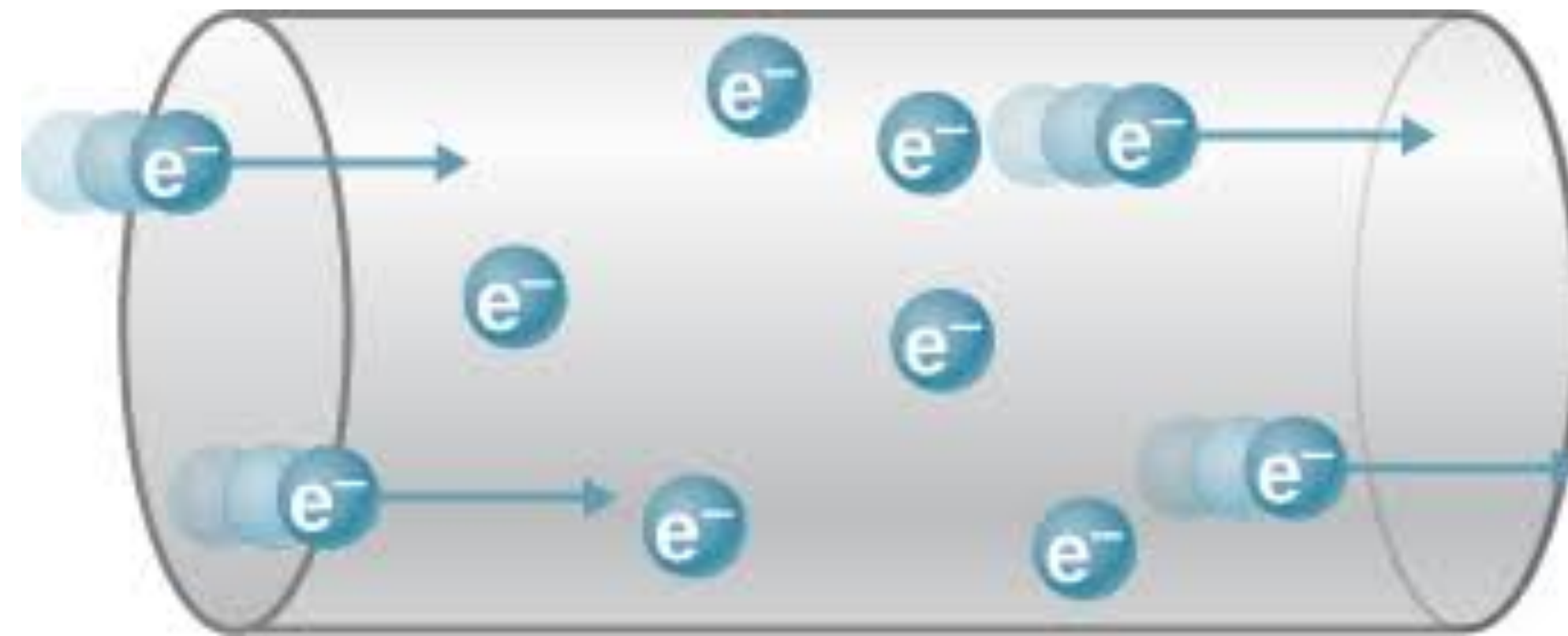
- Schrödinger, Heisenberg (1925): Discovery of the equation obeyed by a single electron, replacing Newton's laws of motion. These equations precisely described the light emission spectrum of a single hydrogen atom.



Hydrogen emission spectrum



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- Bardeen, Cooper, Schrieffer (1957): The same equations can help understand low temperature superconductors.
- Today: The equations of Schrödinger and Heisenberg for many particles exhibit many *emergent phenomena*, related to **quantum entanglement**. These are crucial to understand modern quantum materials, such as the high temperature superconductors, and the quantum properties of black holes.



# Superconductors

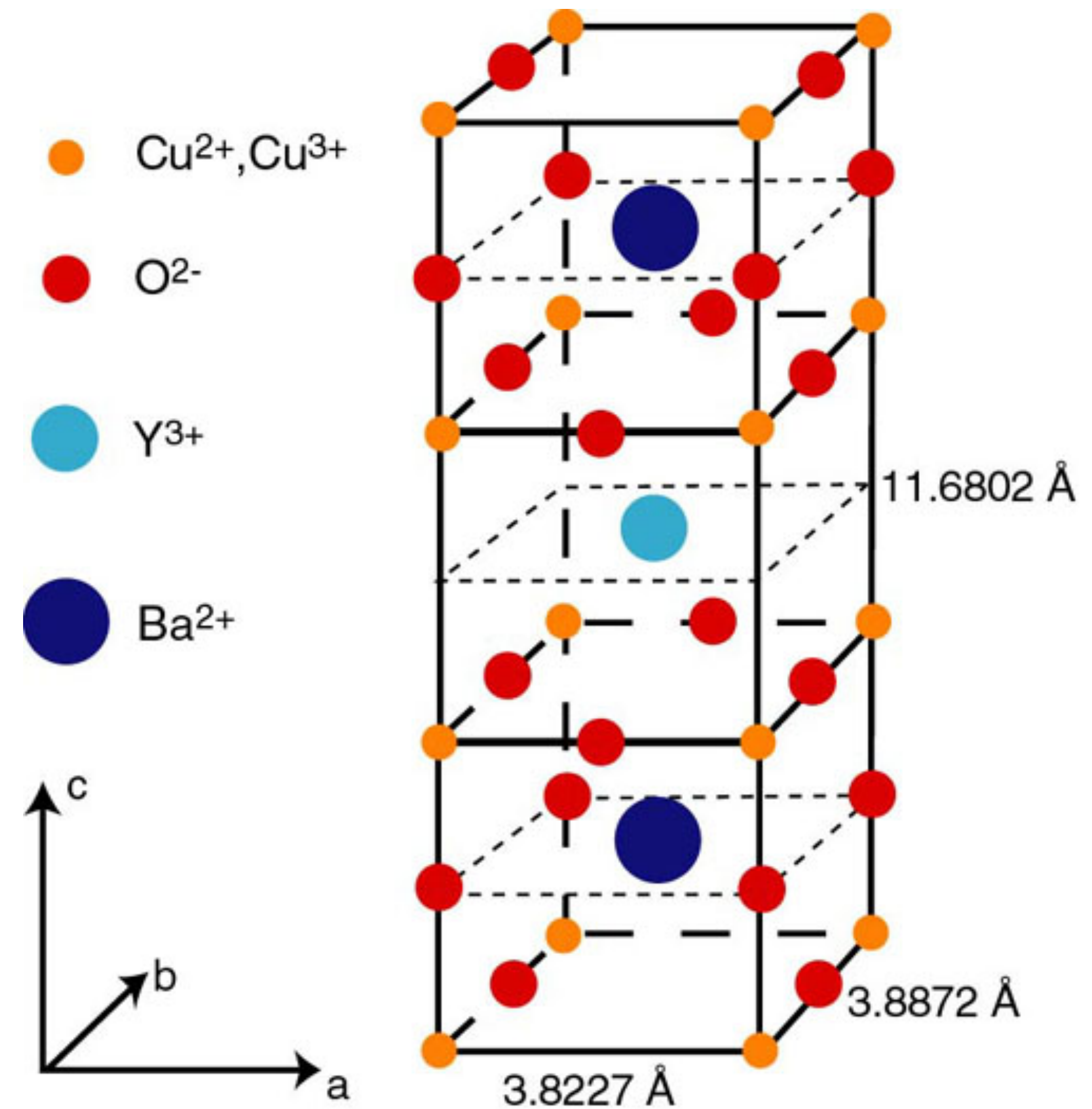




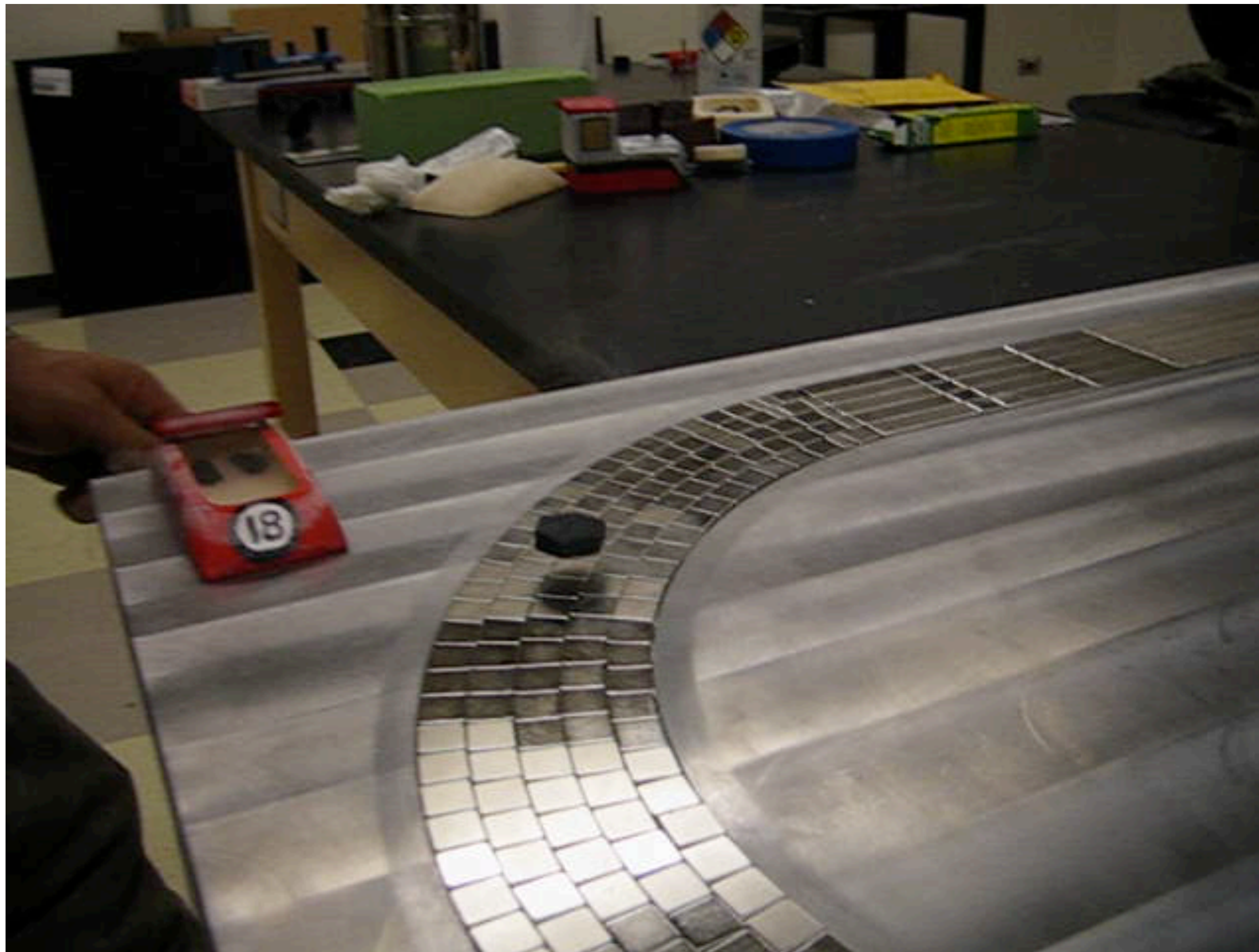
Kamerlingh Onnes 1911:  
Mercury is a superconductor below  $-269\text{ }^{\circ}\text{C}$



# Cuprate high temperature superconductors







Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University



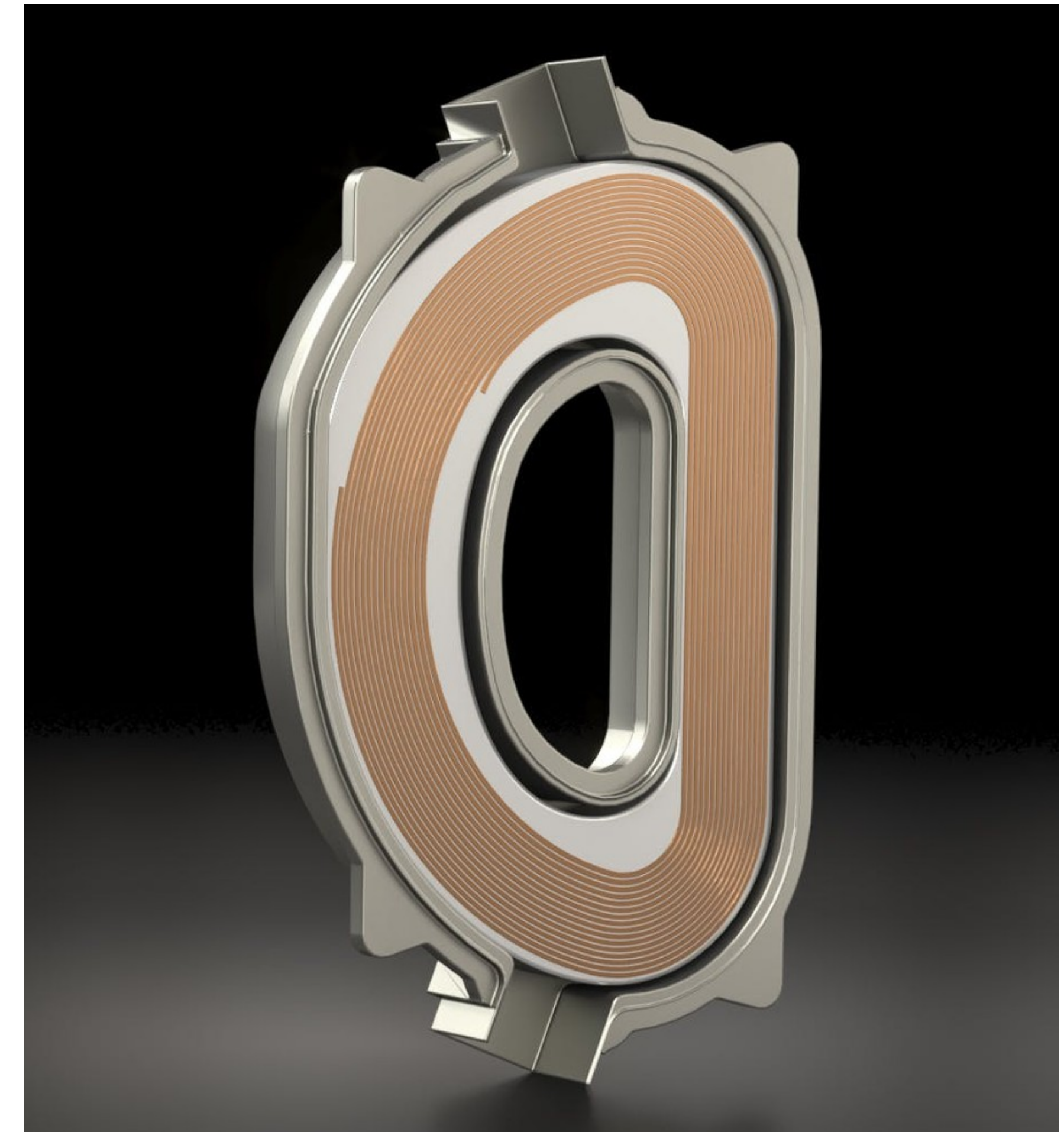
# HTS Magnets: Enabling Technology

The surest path to limitless,  
clean, fusion energy

YBCO magnets allow for smaller,  
faster, and less expensive  
tokamaks for plasma fusion

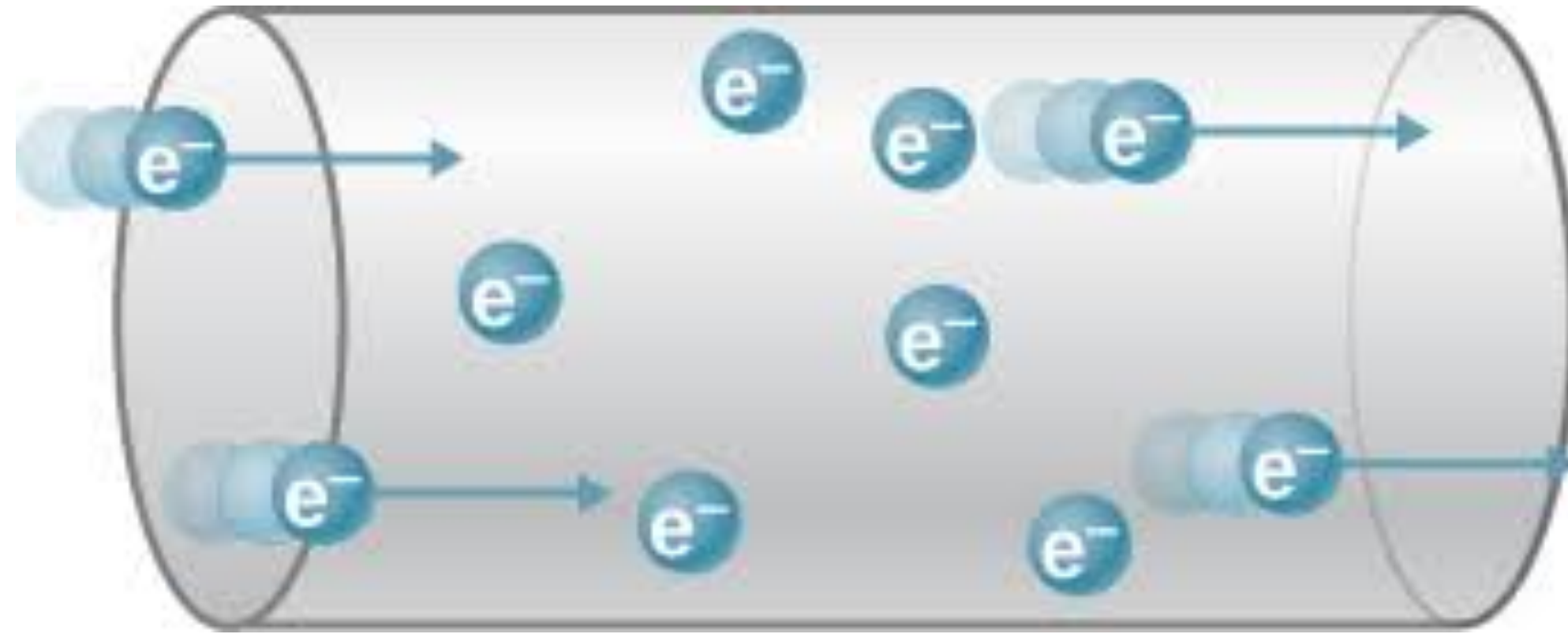


Commonwealth  
Fusion Systems





Ordinary conductors: Cu, Ag



- Sommerfeld (1927): Electrons move freely in conductors as quantum waves with wavelength

$$\lambda = \frac{h}{mv} = \frac{h}{p} \quad \Rightarrow \quad p = \frac{h}{\lambda}$$





*“About your cat, Mr. Schrödinger—I have good news and bad news.”*

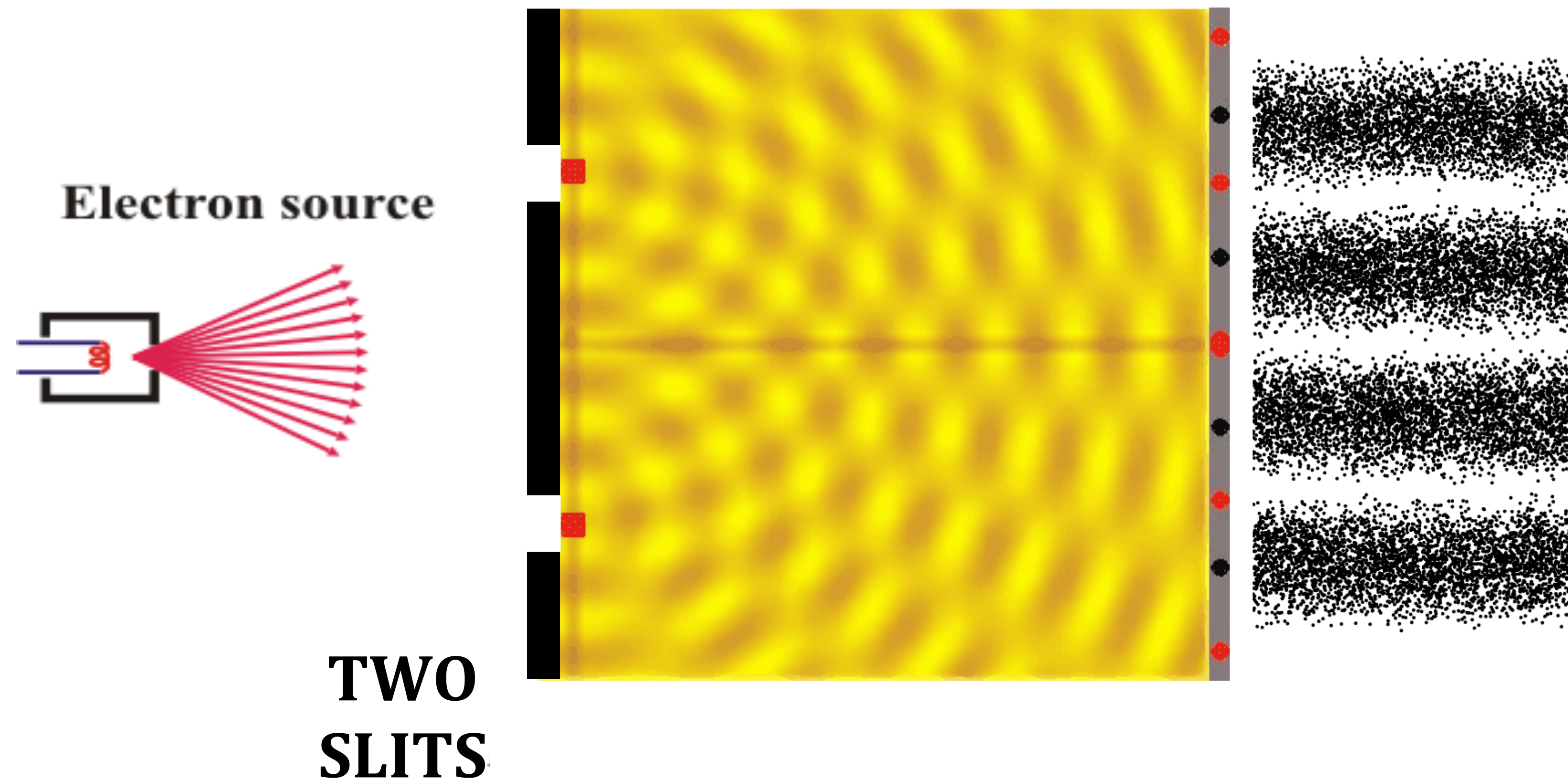


The most remarkable new idea in the quantum theory is the  
*principle of superposition*:  
a physical system can be in a  
superposition of two (or more) distinct states.



# Principles of Quantum Mechanics: I. Quantum Superposition

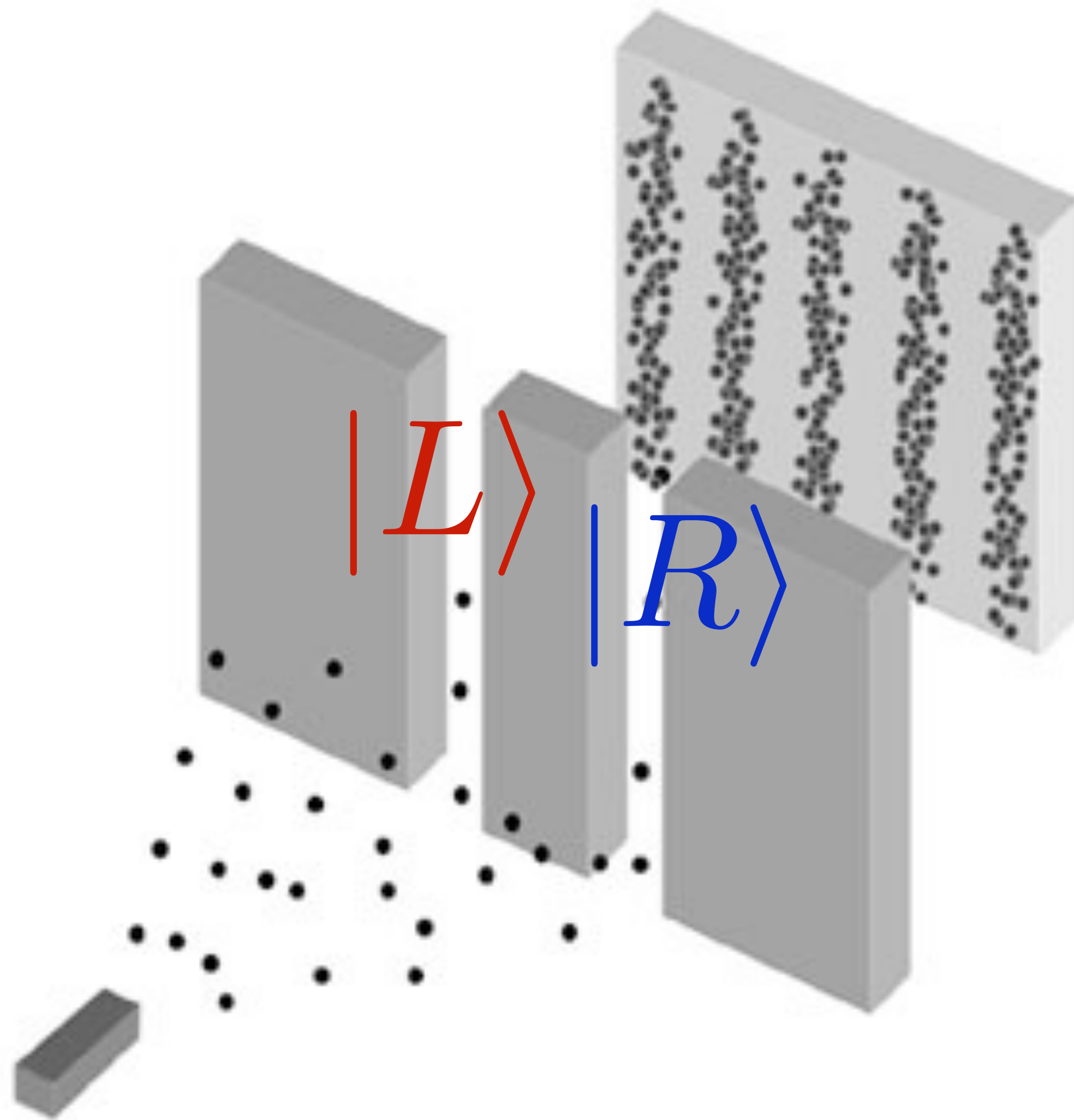
## The double slit experiment



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

Interference of electrons

## The double slit experiment

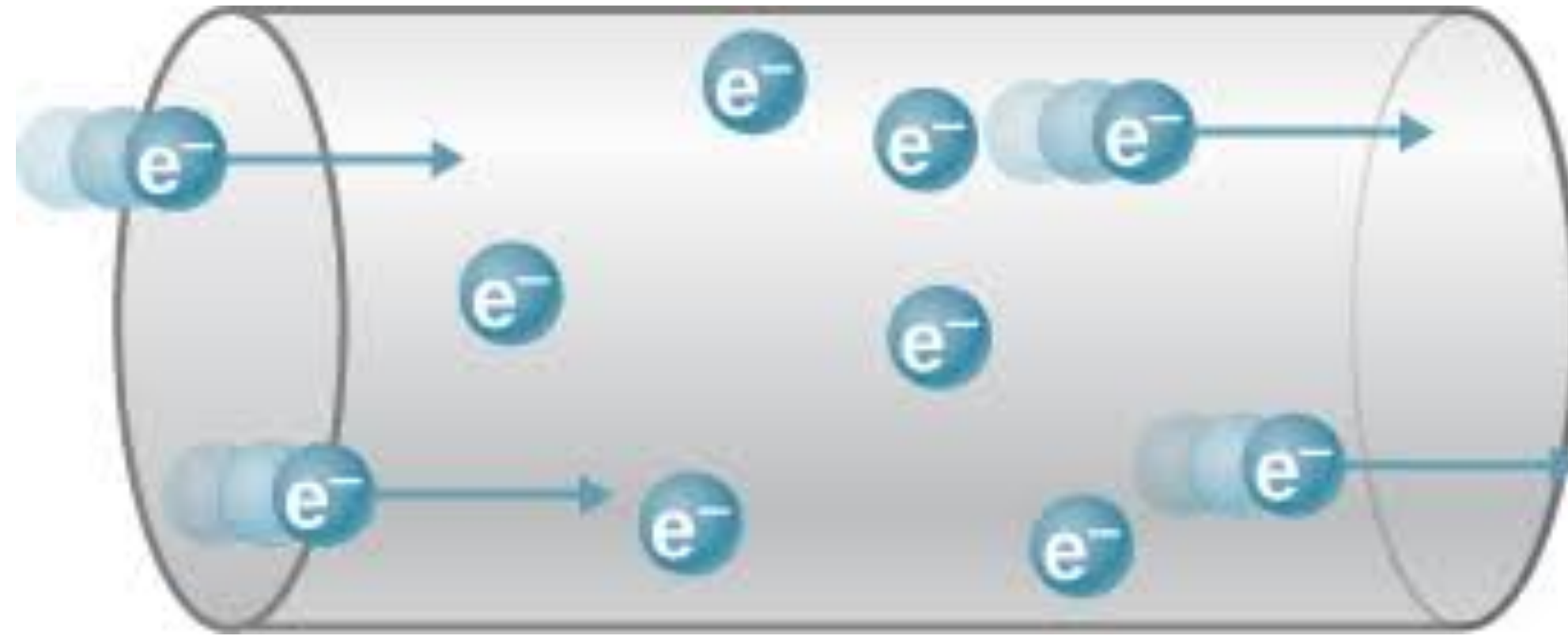


Let  $|L\rangle$  represent the state  
with the electron in the left slit

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

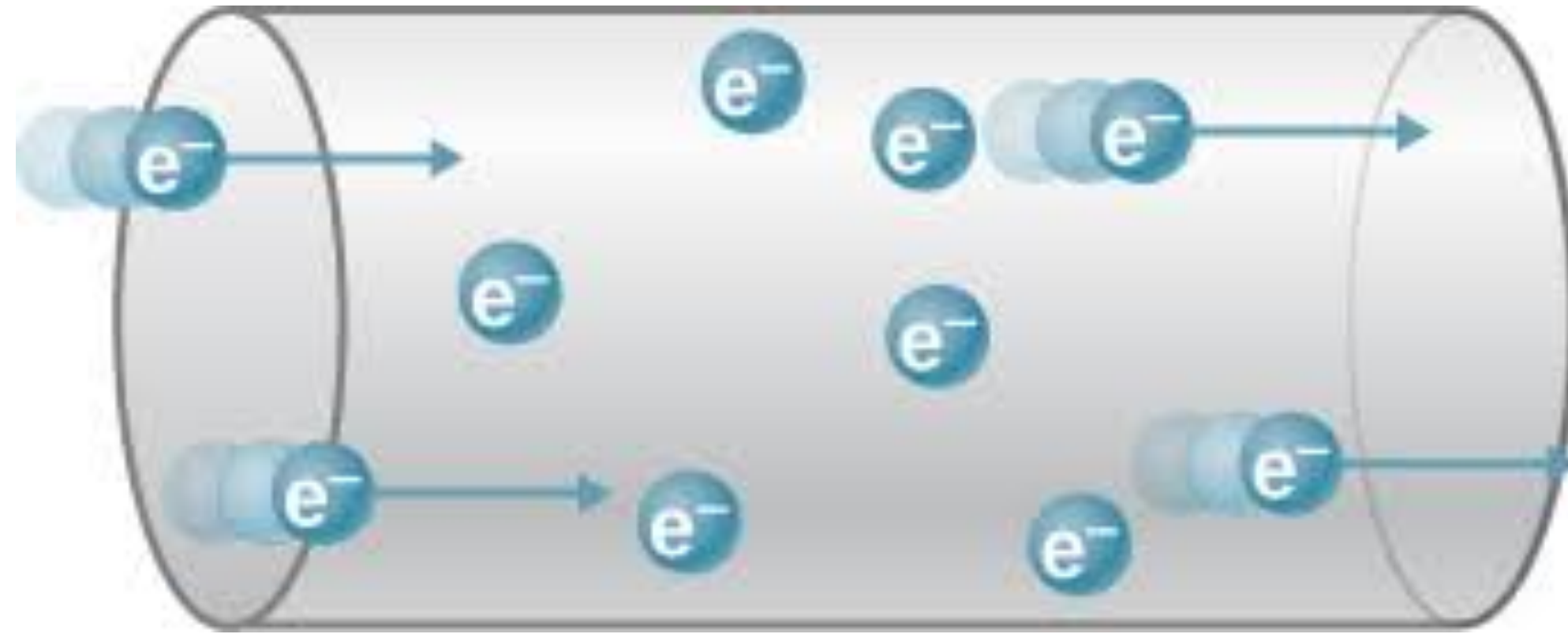
Actual state of *each* electron is  
 $|L\rangle + |R\rangle$





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$$\lambda = \frac{h}{mv} = \frac{h}{p} \quad \Rightarrow \quad p = \frac{h}{\lambda}$$

- Pauli (1925): Electrons are *fermions* and they obey the exclusion principle: no two electrons can have the same wavelength.



# Bose-Einstein condensation and superconductivity

- Planck (1900), Einstein (1905): Light is an electromagnetic wave moving at velocity  $c$ , made of particles (photons) each with momentum

$$p = \frac{h}{\lambda}$$



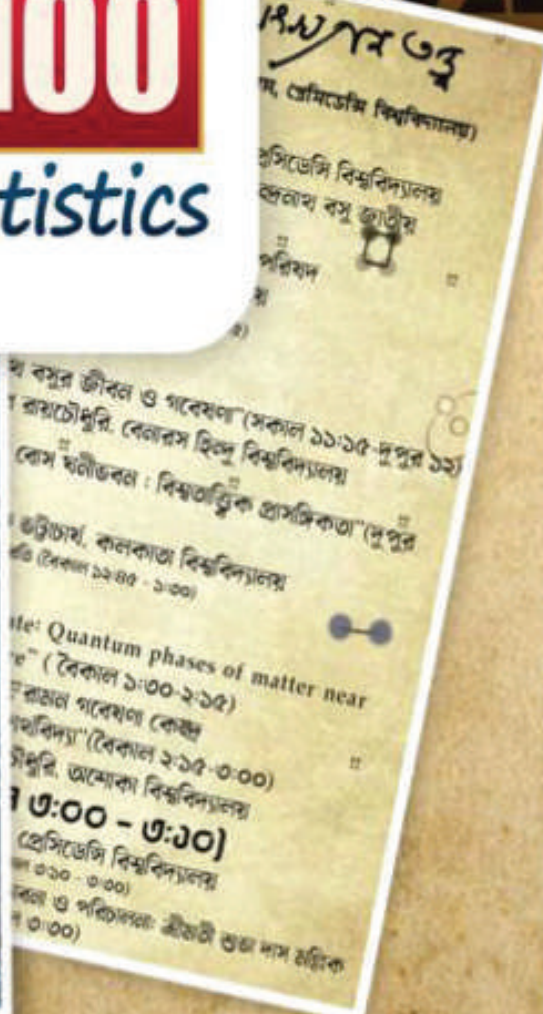
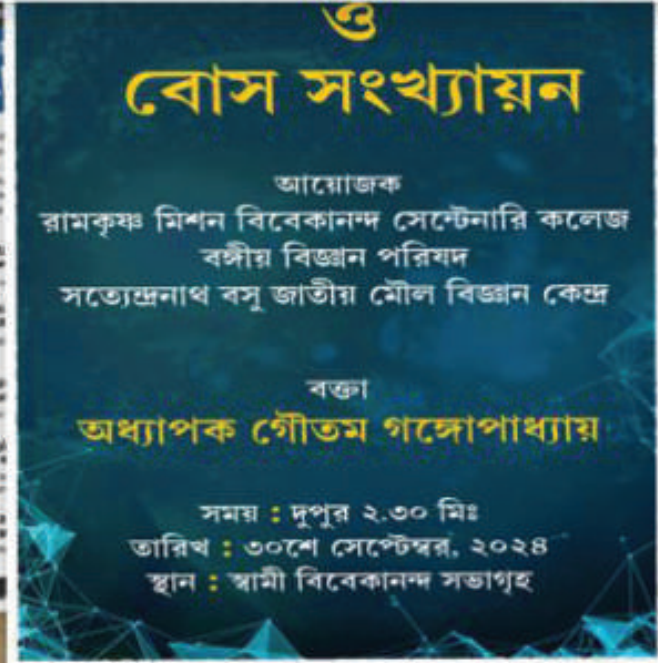
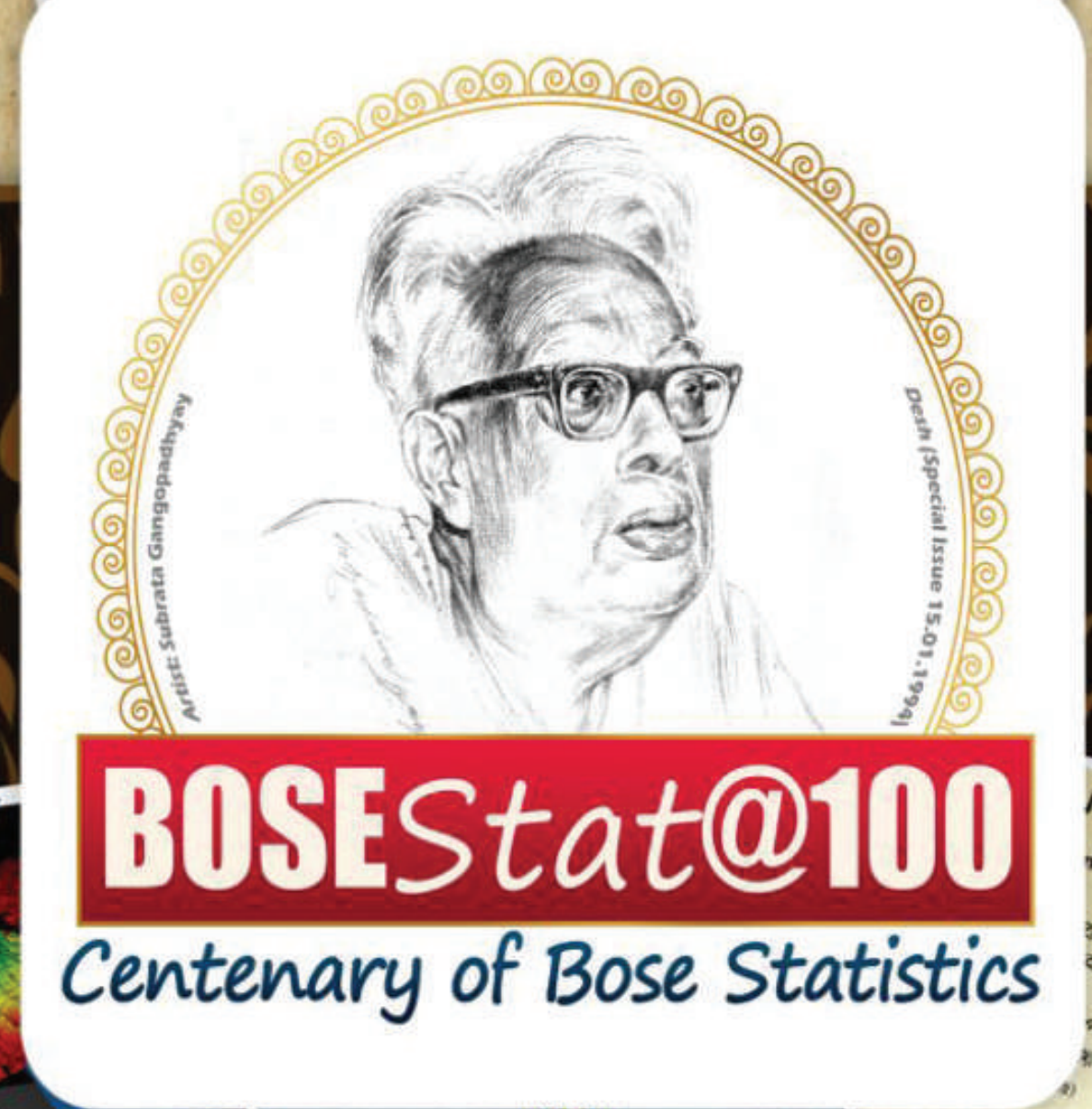
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$$E = \sum_s \frac{8\pi h\nu^s{}^3}{c^3} V \frac{1}{e^{\frac{h\nu^s}{kT}} - 1} d\nu^s$$


*Celebrating a Landmark  
Indian Contribution  
in Quantum Science*

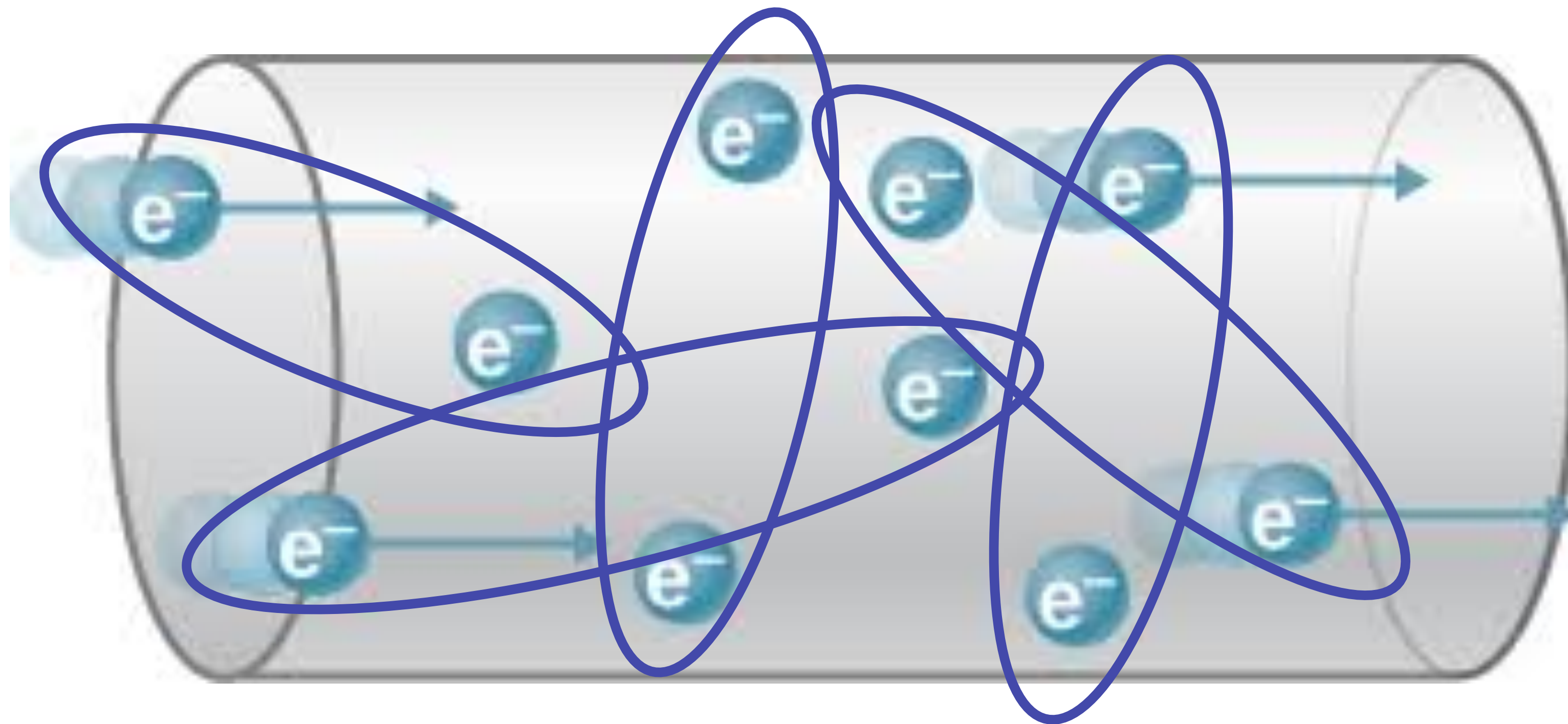


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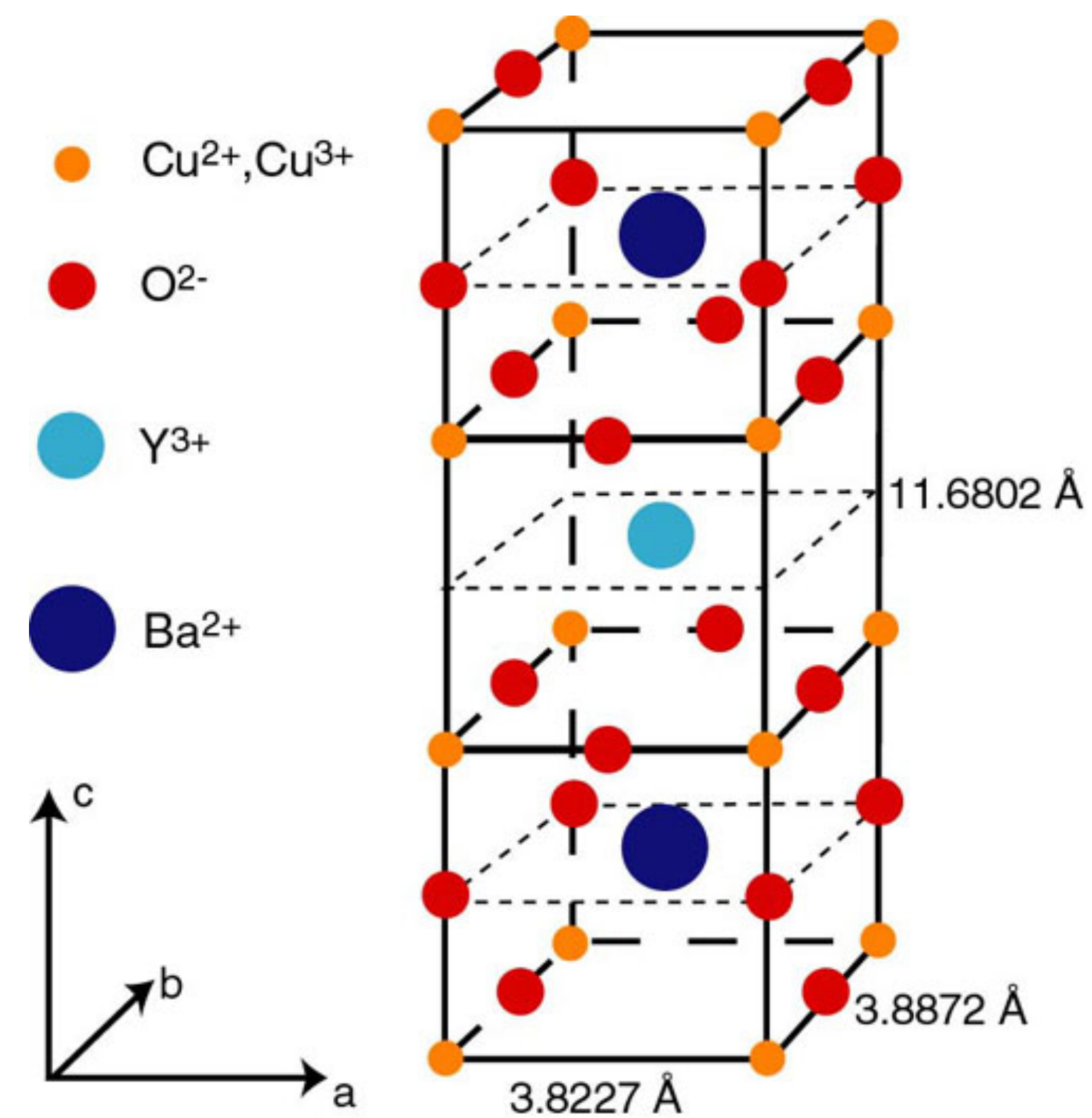
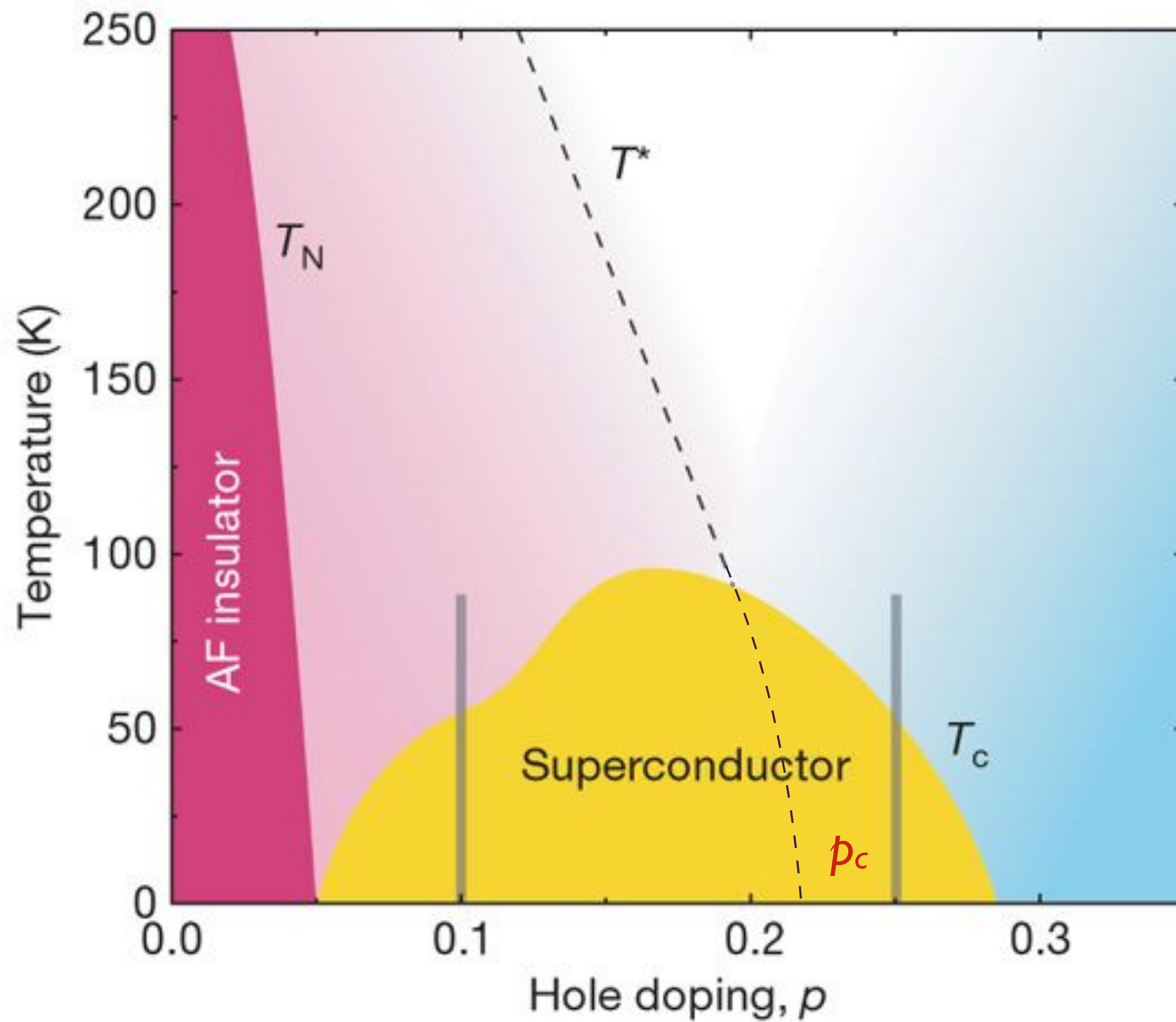
- Bose (1924): Photons are *bosons*: an arbitrary number of indistinguishable photons can be present at each wavelength, and this alone is sufficient to explain Planck's black body spectrum.
- Einstein (1924): If there were bosons which could travel with a velocity  $v < c$ , then they would undergo Bose-Einstein condensation at low temperature *i.e.* a finite fraction of them would have  $v = 0$ .

- Bardeen, Cooper, Schrieffer (1957): *pairs* of fermionic electrons behave like bosons, and the Bose-Einstein condensation of Cooper pairs of electrons is responsible for superconductivity!

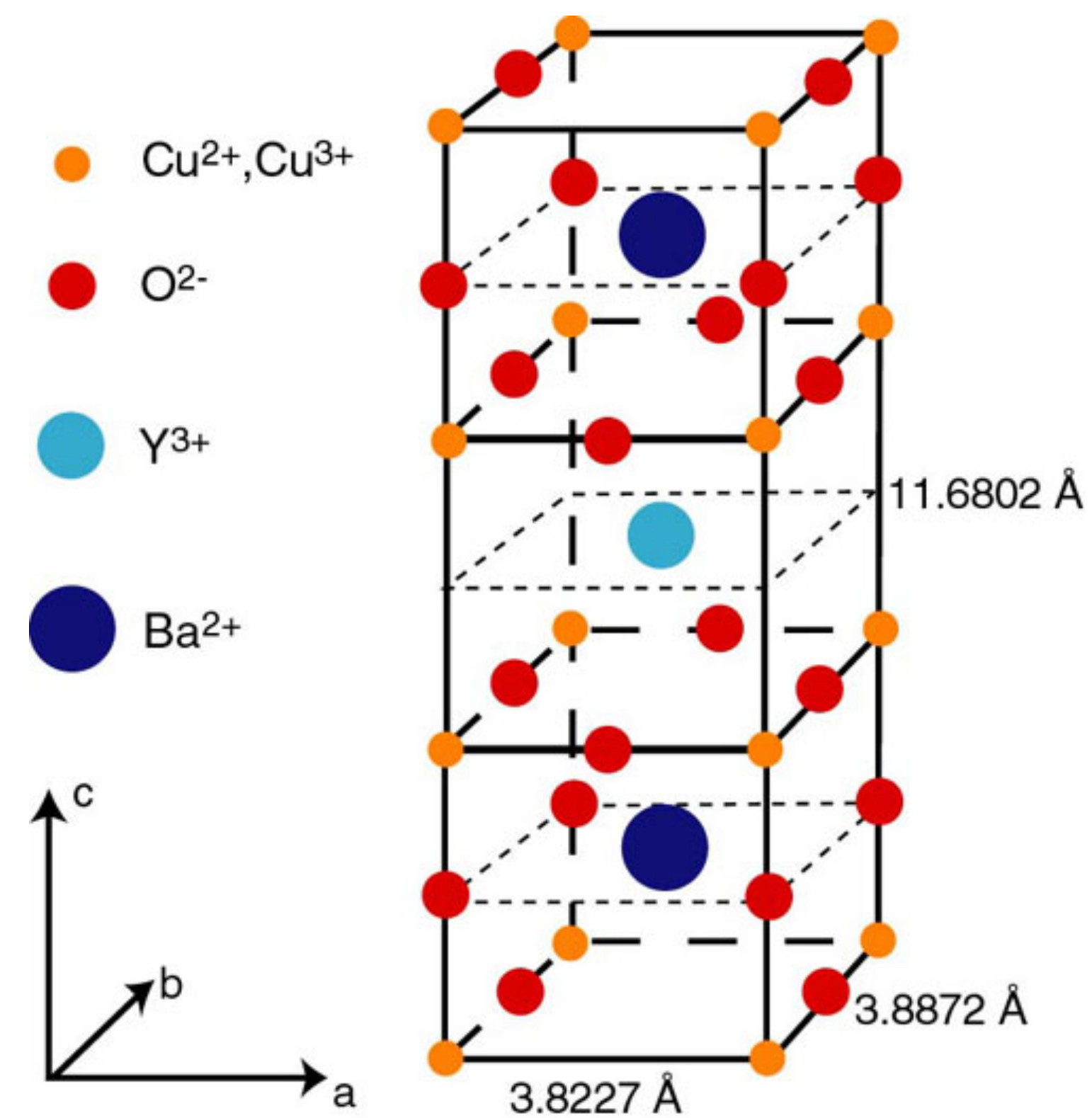
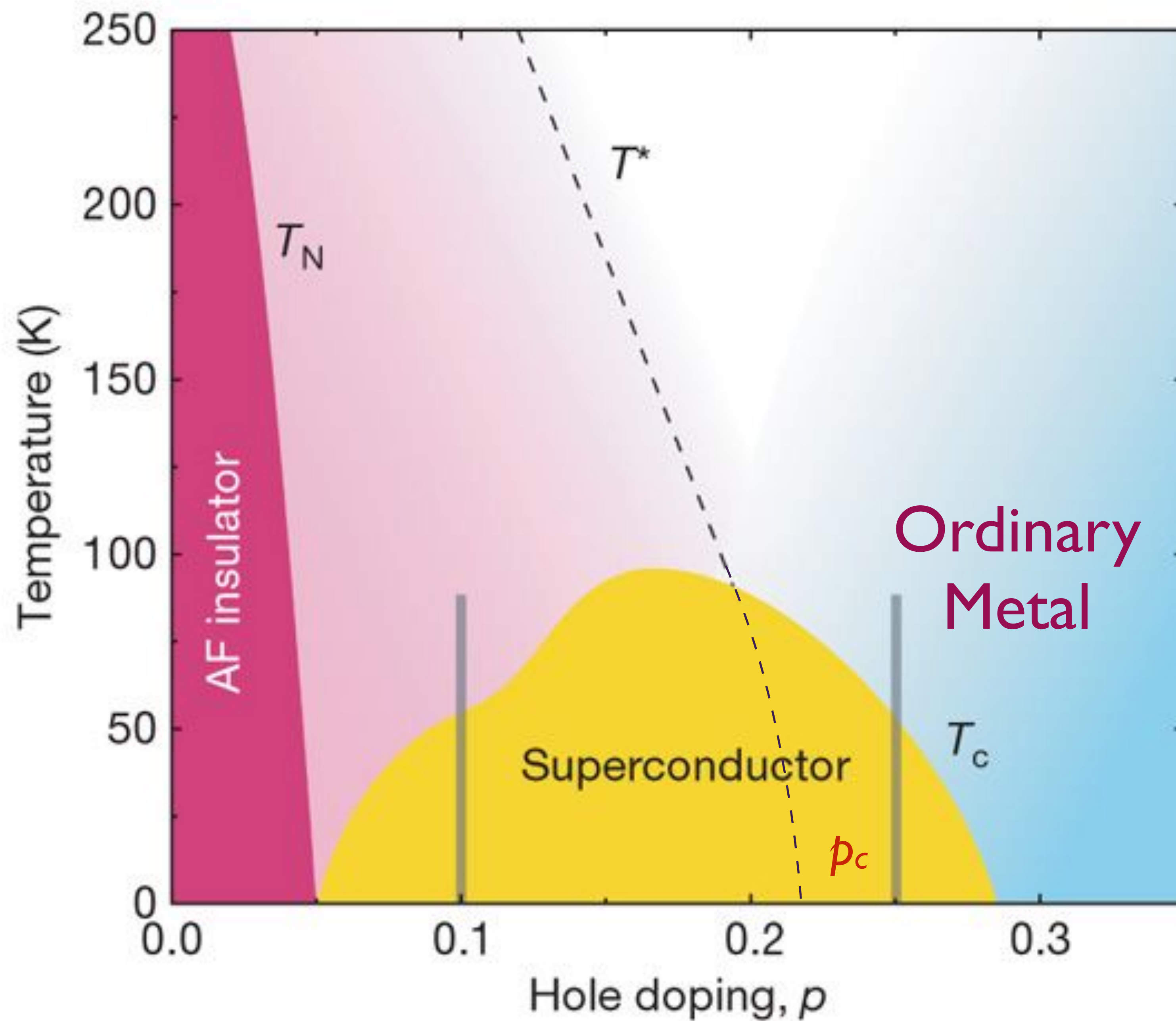


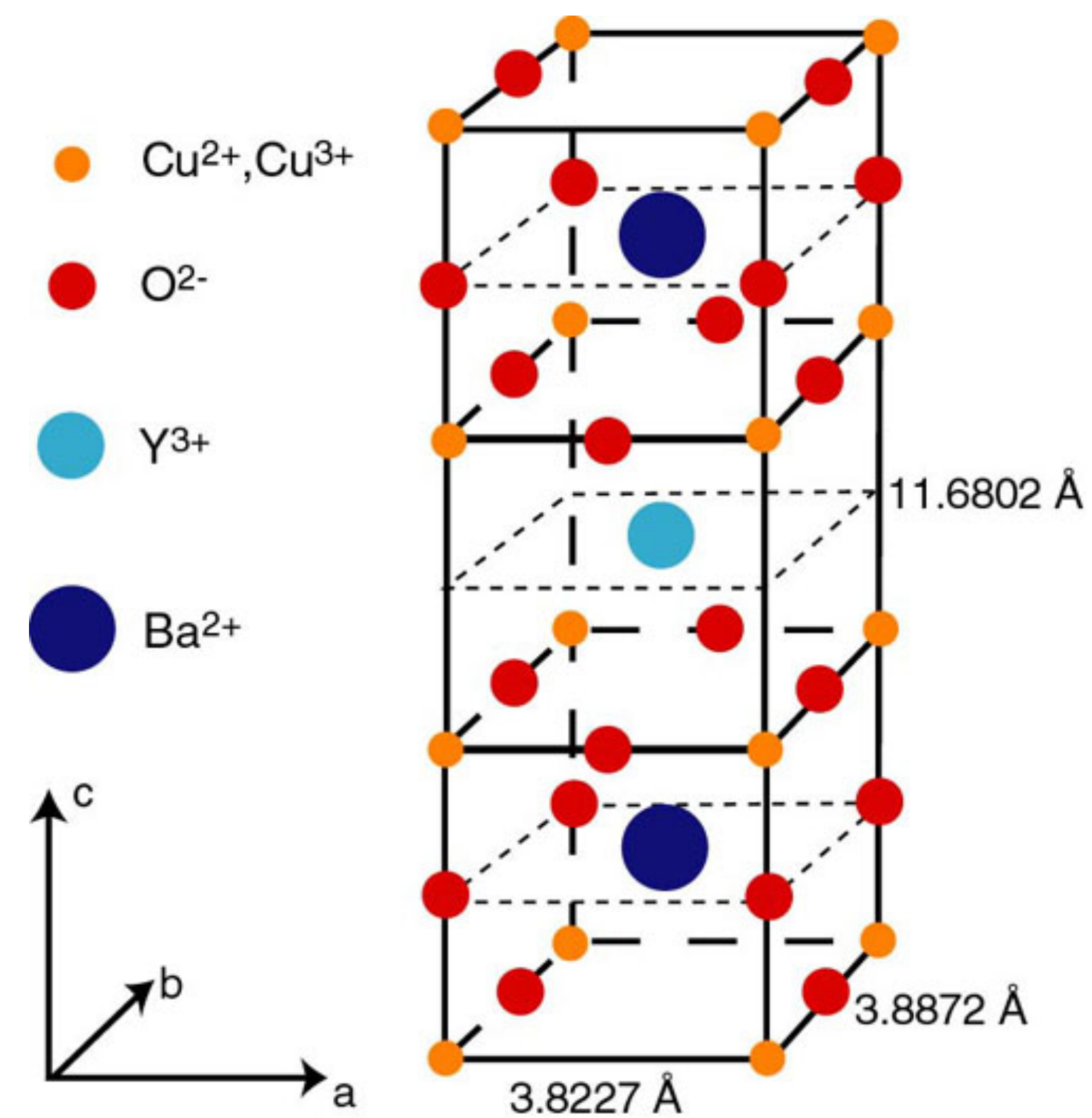
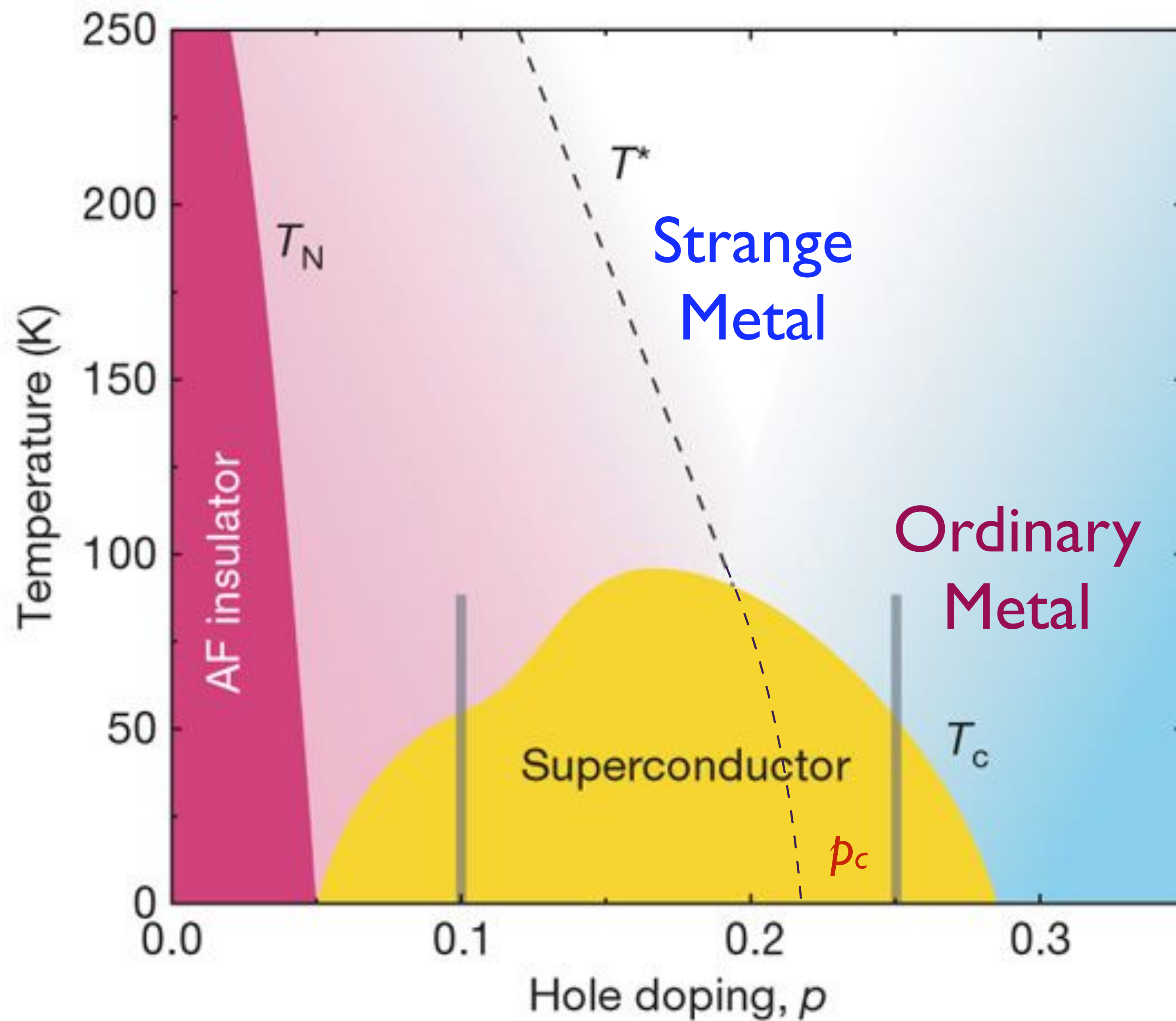


- Bardeen, Cooper, Schrieffer (1957): *pairs* of fermionic electrons behave like bosons, and the Bose-Einstein condensation of Cooper pairs of electrons is responsible for superconductivity!
- This explains low-temperature superconductivity in mercury, but not high temperature superconductivity in YBCO.

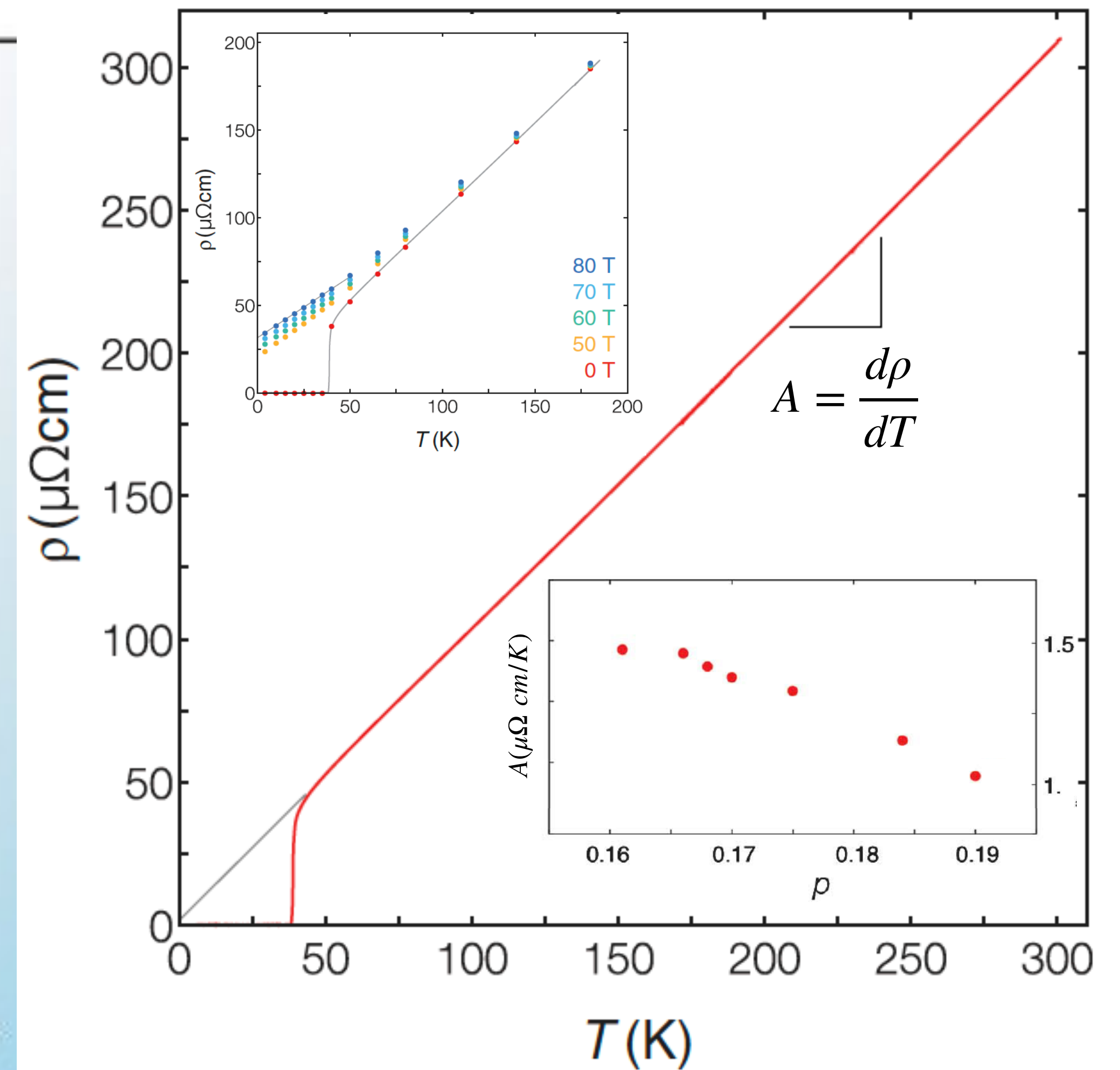
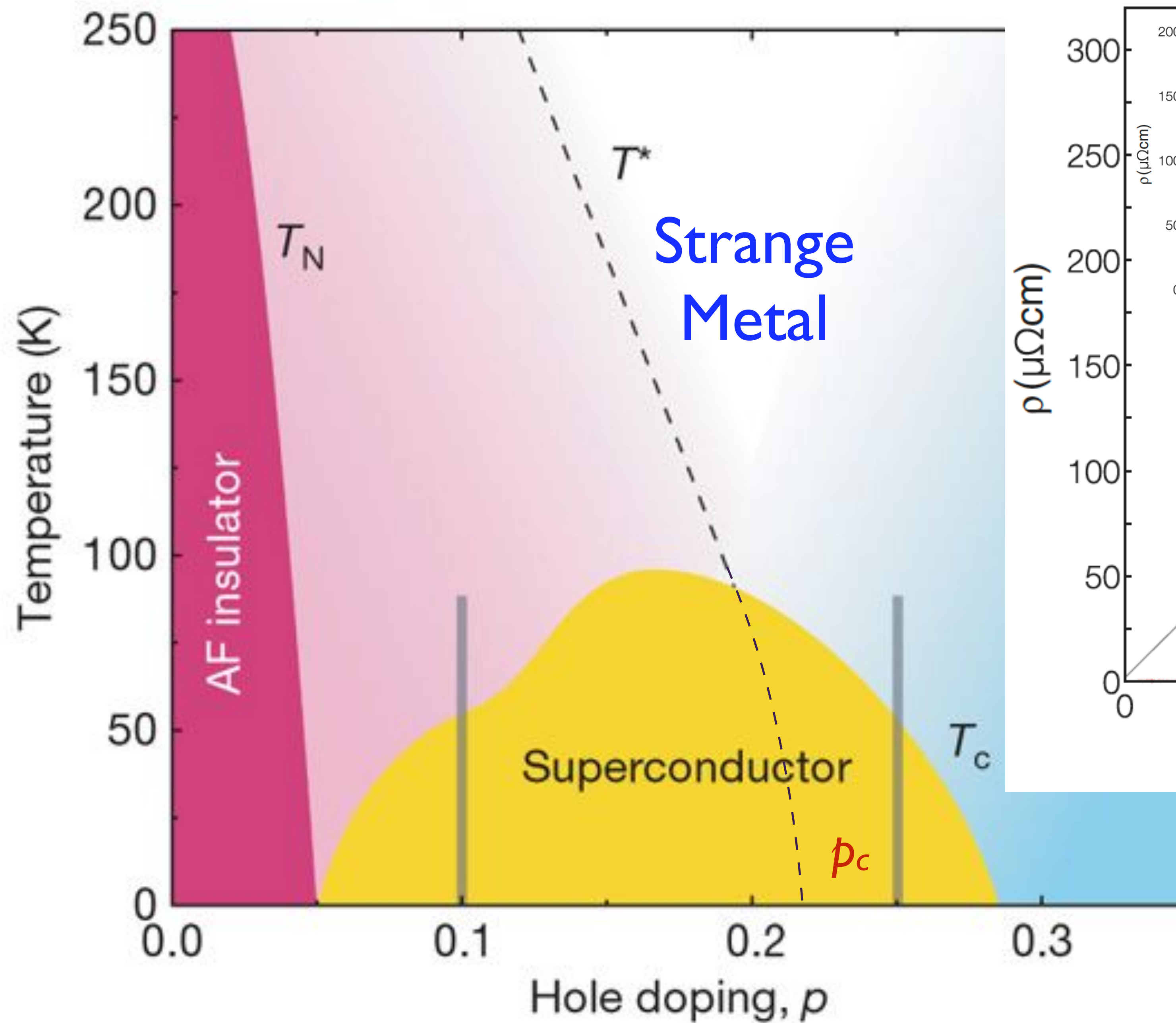












LSCO: Giraldo-Gallo et al. 2018

# Quantum entanglement



MAY 15, 1935

PHYSICAL REVIEW

VOLUME 47

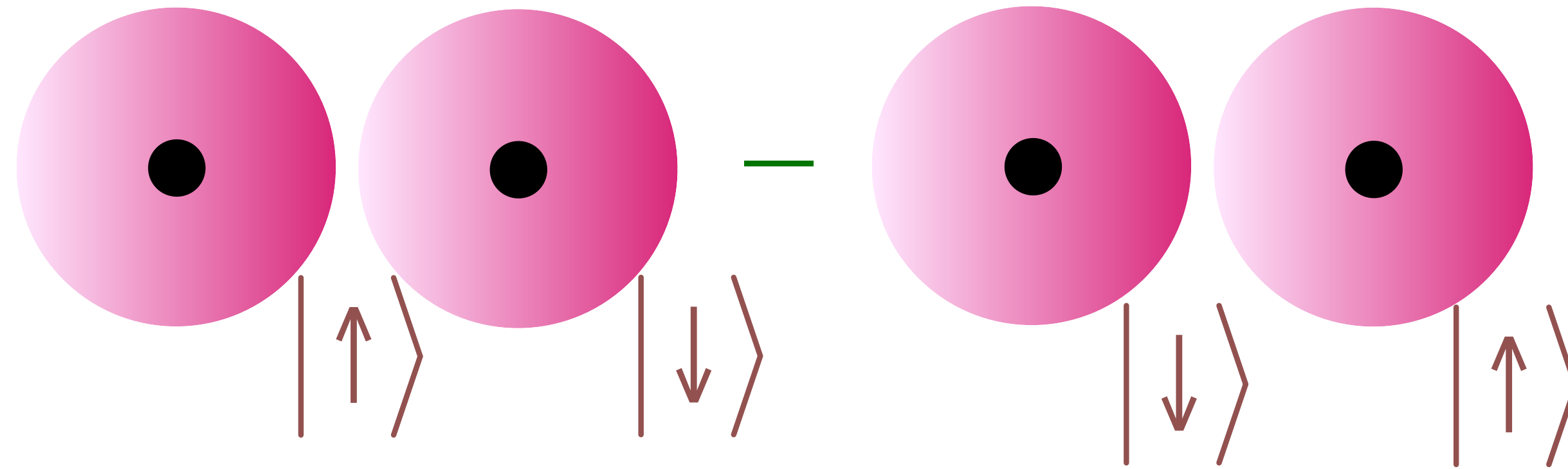
# Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

# Quantum Entanglement

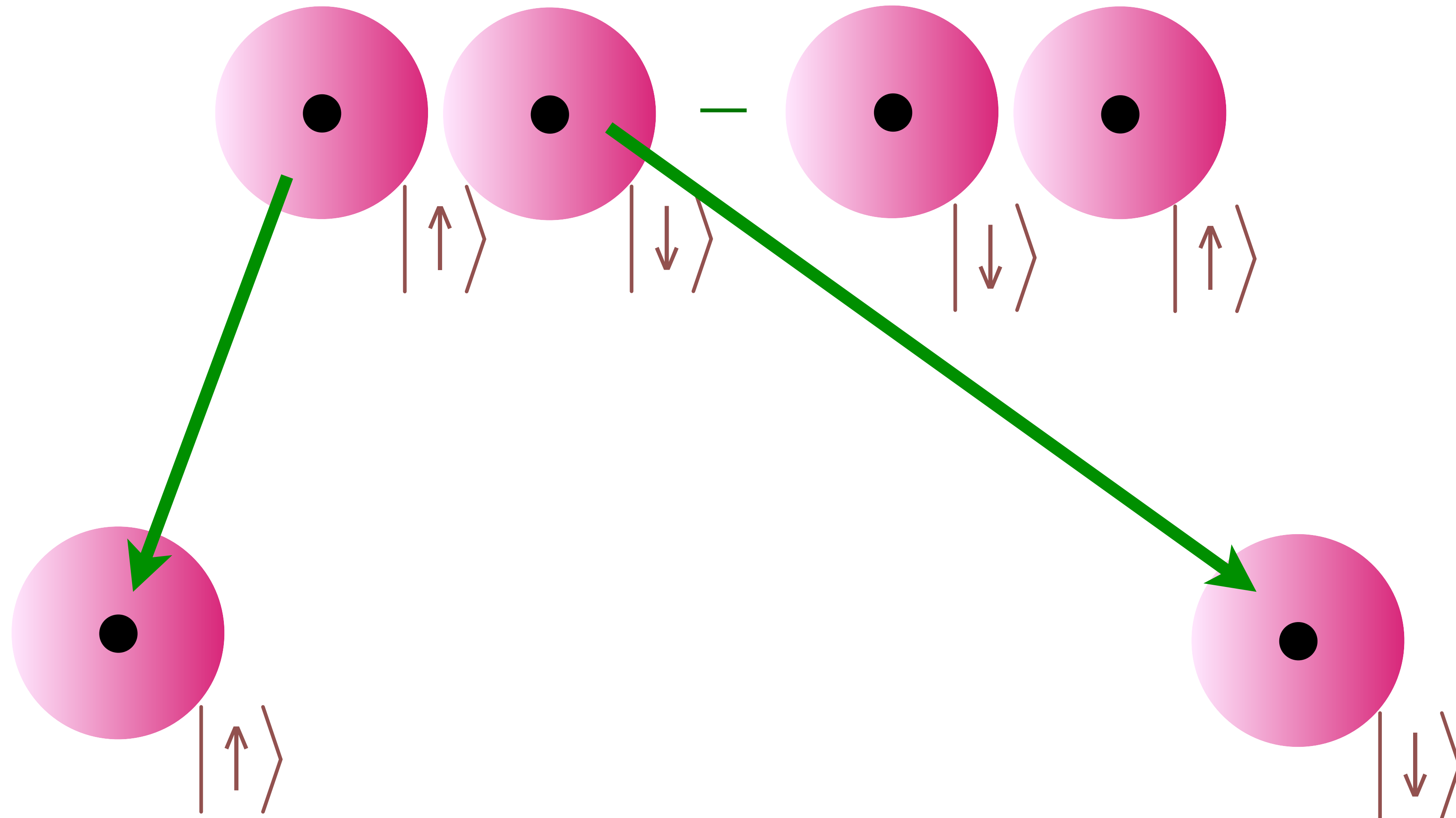
Einstein, Podolsky, Rosen (1935)





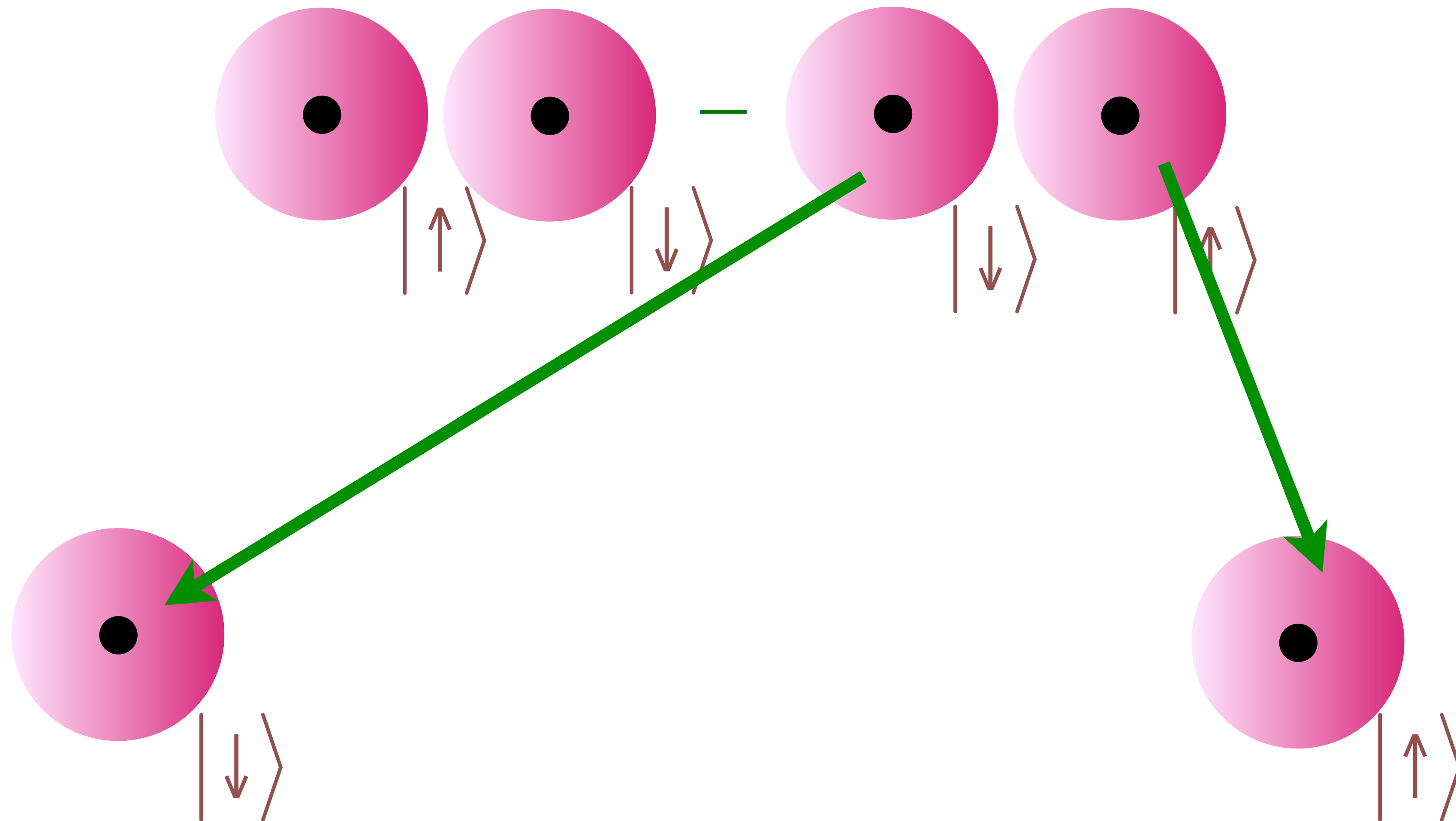
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Einstein, Podolsky, Rosen (1935)



# Quantum Entanglement

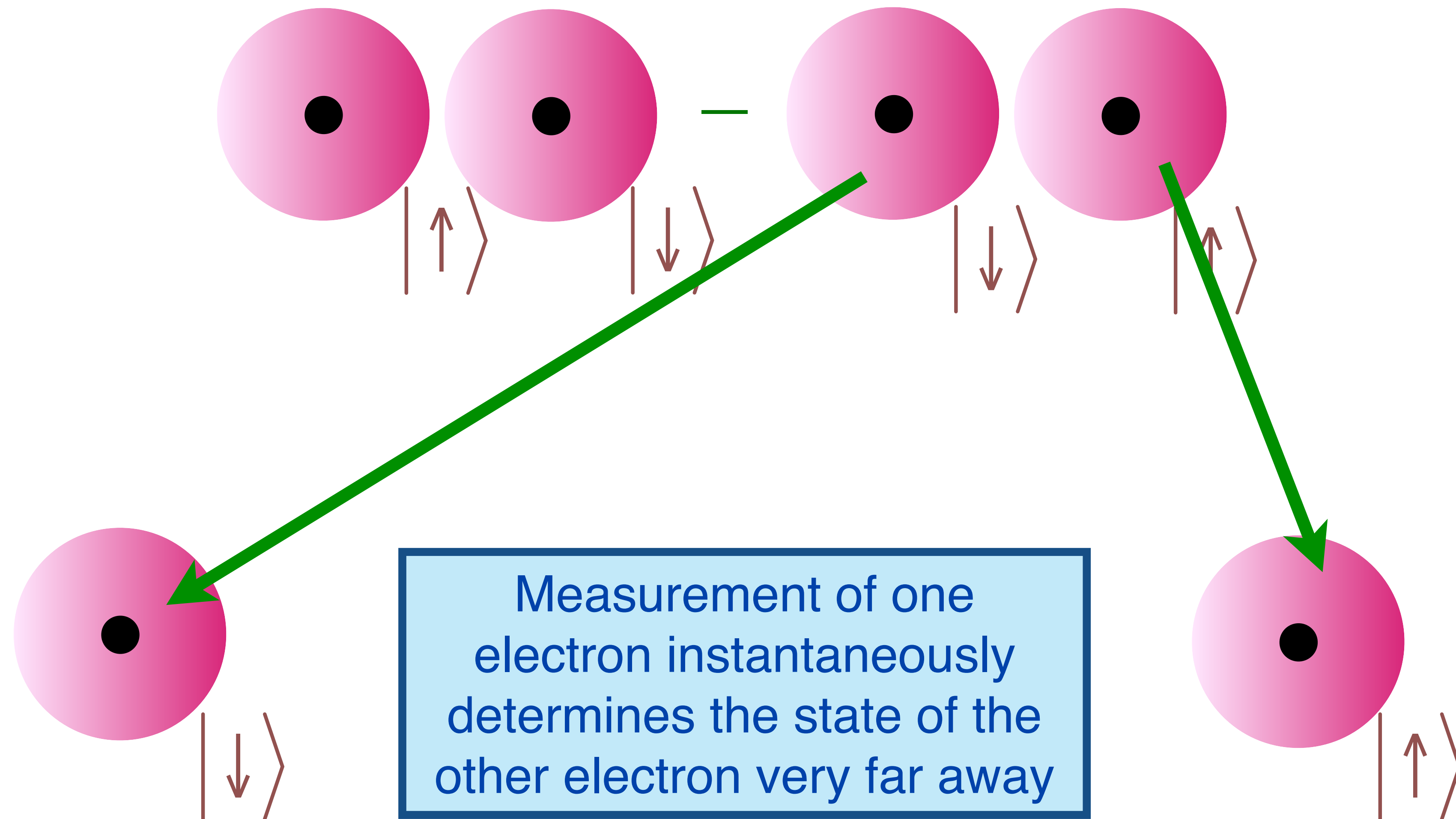
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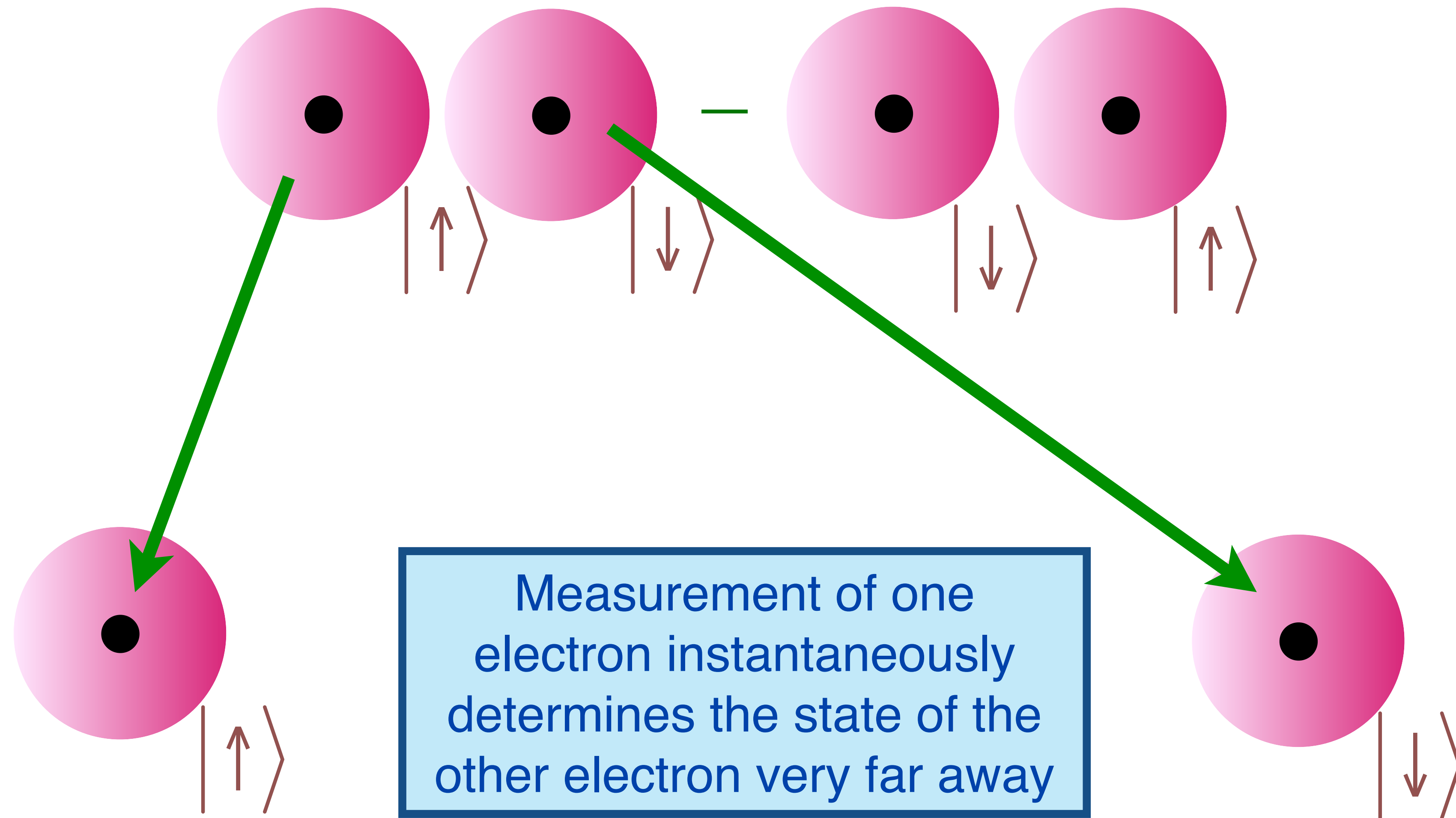
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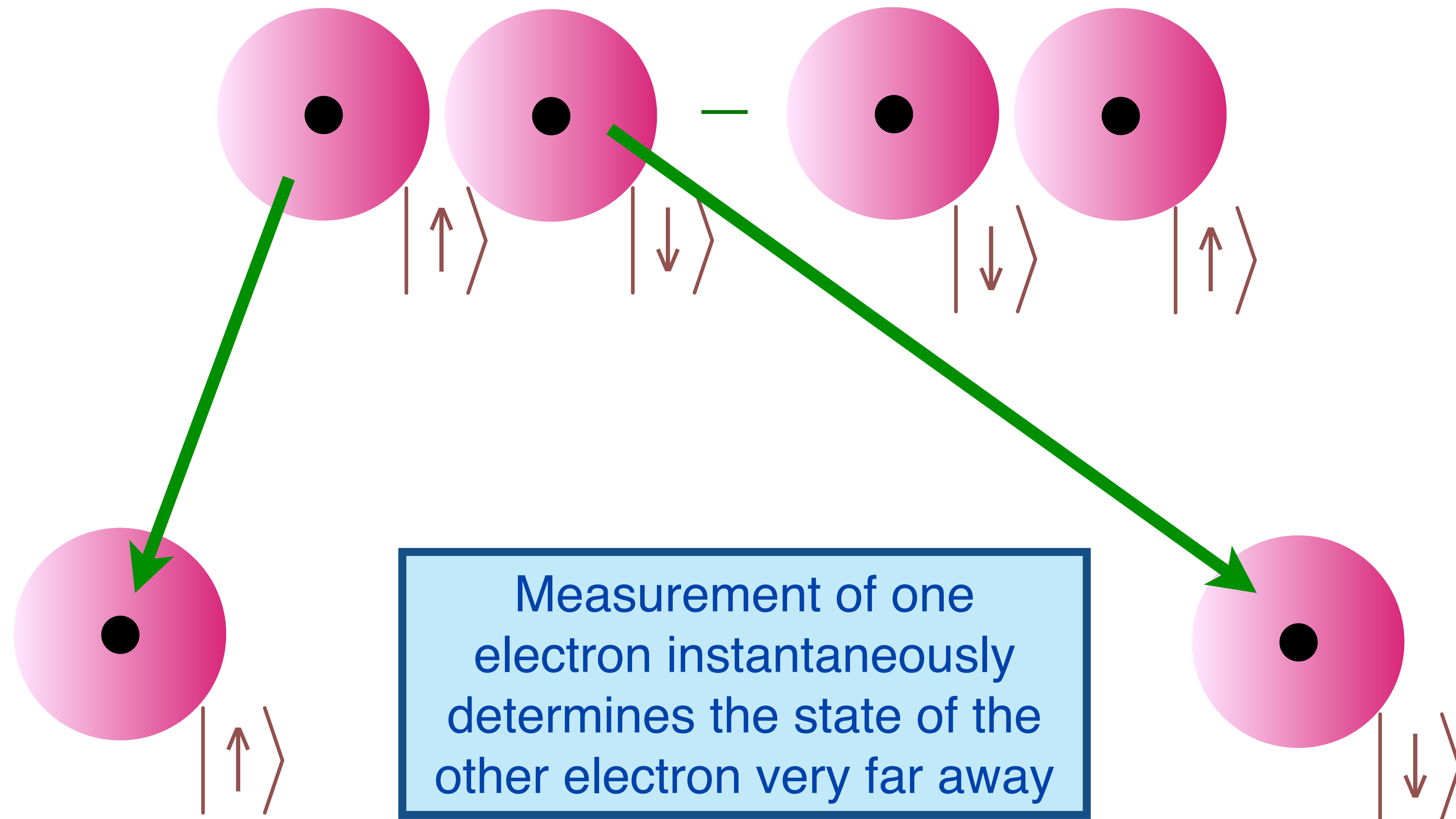
Einstein, Podolsky, Rosen (1935)





# Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



**Spooky action at a distance !**



natürlicher  
deren Notwendigkeit im Raum  
mus ja zuerst von Dir klar erkannt wurde, einen Bedeutung  
Wahrheitsgehalt hat. Ich kann aber deshalb nicht ernsthaft dar-  
an glauben, weil die Theorie mit dem Grundsatz unvereinbar  
ist, daß die Physik eine Wirklichkeit in Zeit und Raum darstel-  
len soll, ohne spukhafte Fernwirkungen. Allerdings bin ich  
überzeugt, daß es wirklich mit der Theorie

I cannot seriously believe in it because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at distance

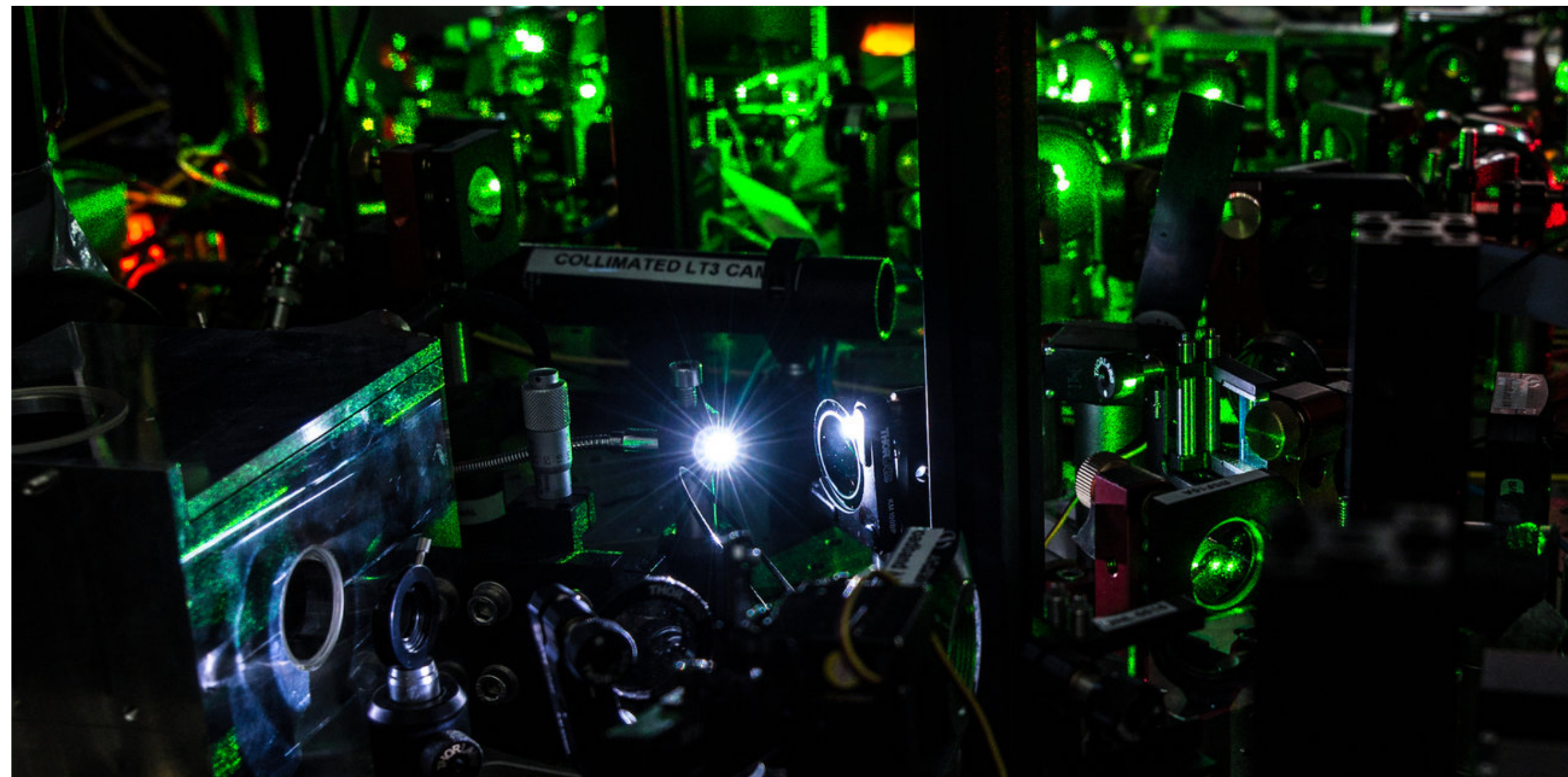
Albert Einstein to Max Born, 3 March 1947



**The New York Times**

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

By **JOHN MARKOFF** OCT. 21, 2015



Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

Needed,  
to solve open problems in the theory of  
superconductivity and black holes:

A solvable model of quantum entanglement  
of  $3, 4, 5, \dots \infty$  particles



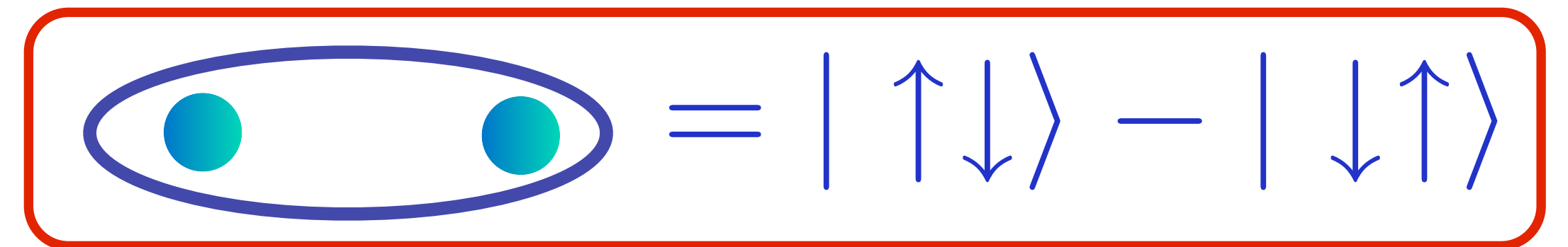
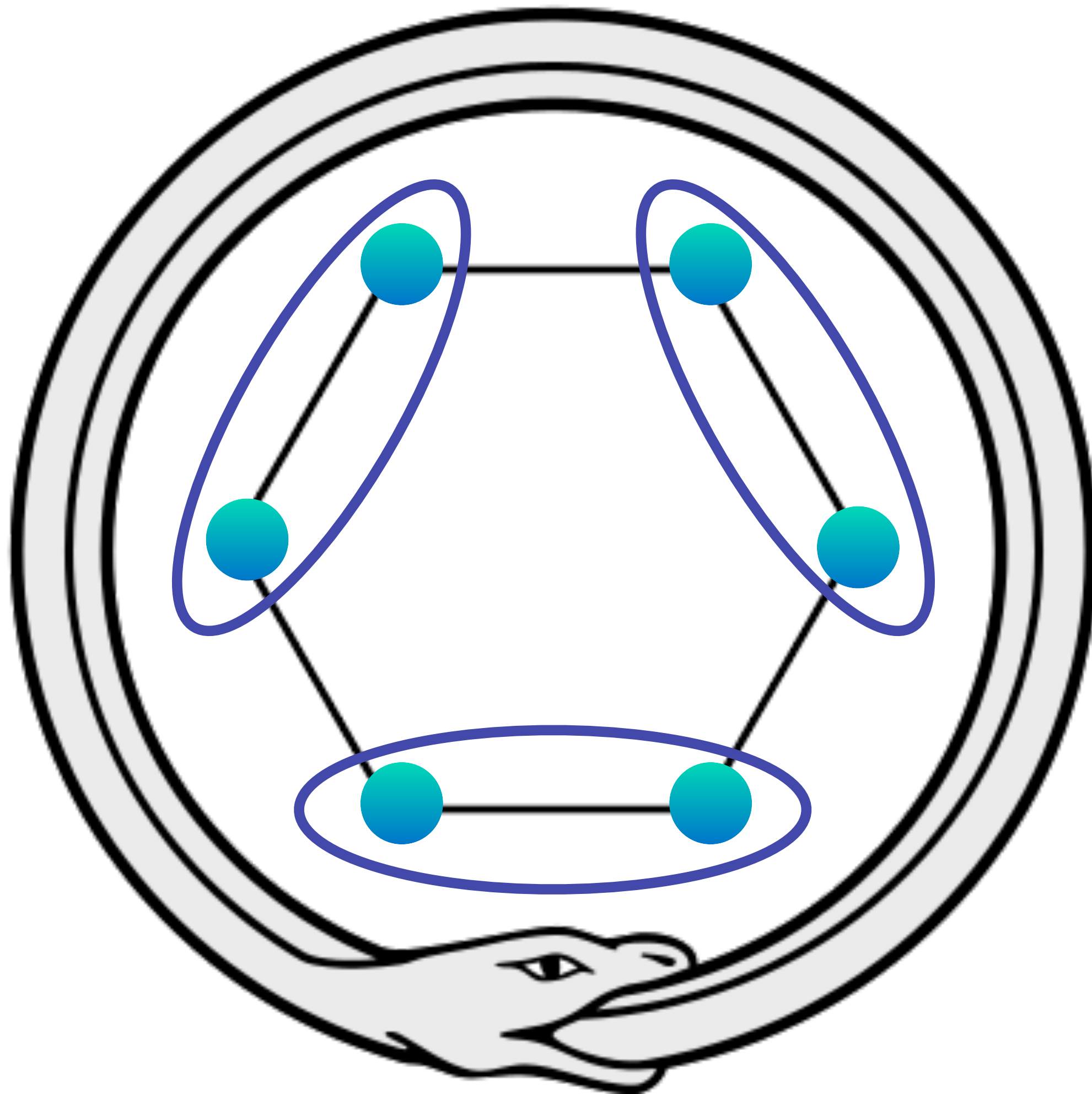
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**The Sachdev-Ye-Kitaev model  
of many-particle entanglement**

# Kekulé's spooky dream (1865)

Kekulé spoke of the creation of the theory. He said that he had discovered the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail<sup>\*</sup>

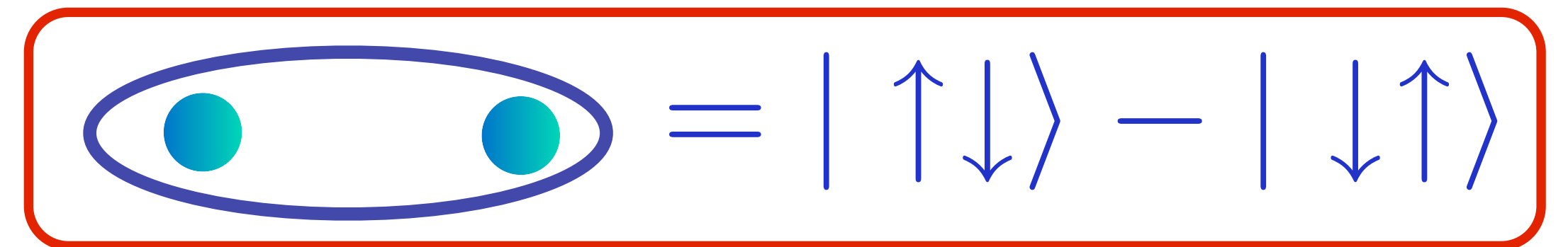
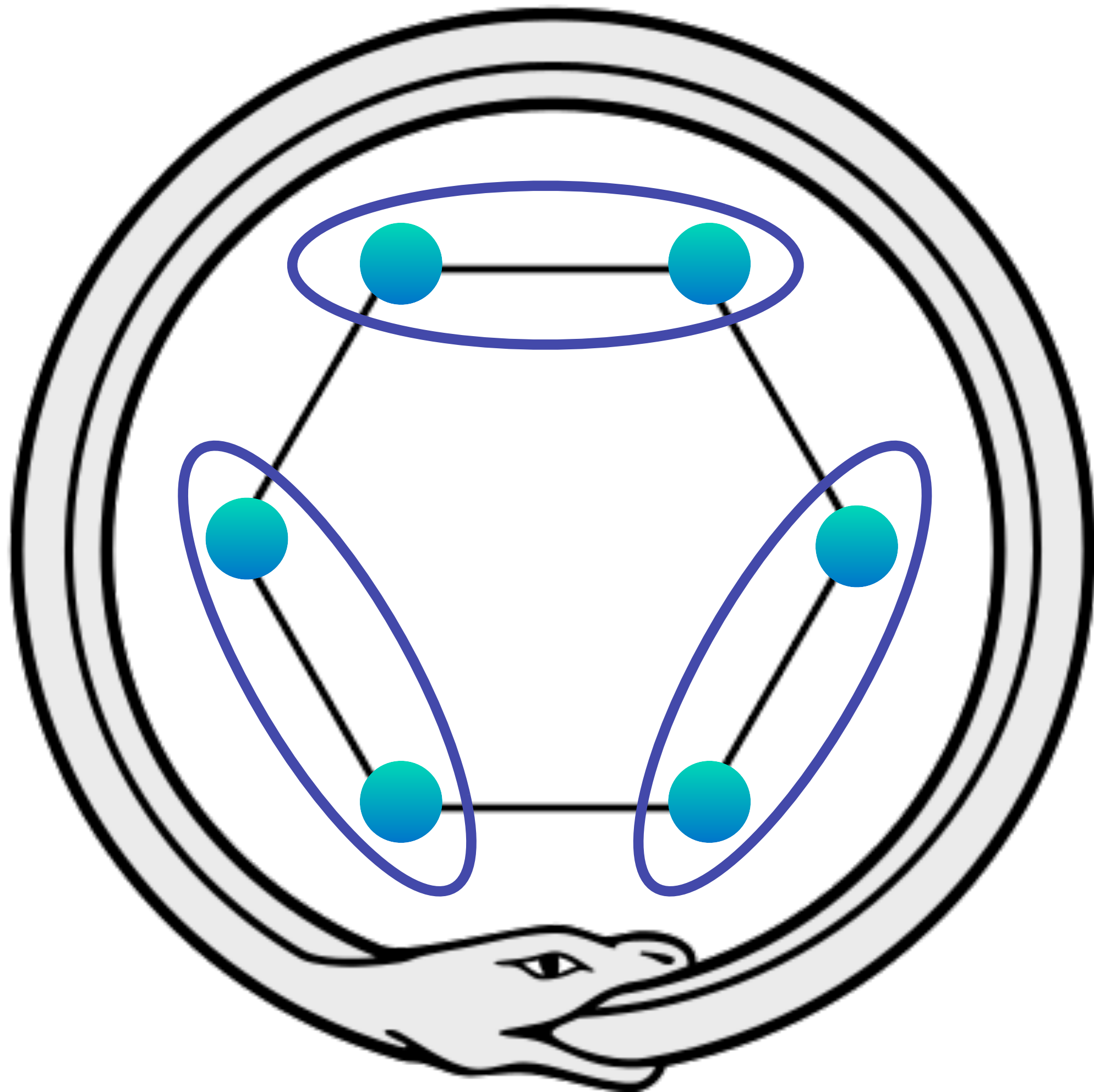


Benzene



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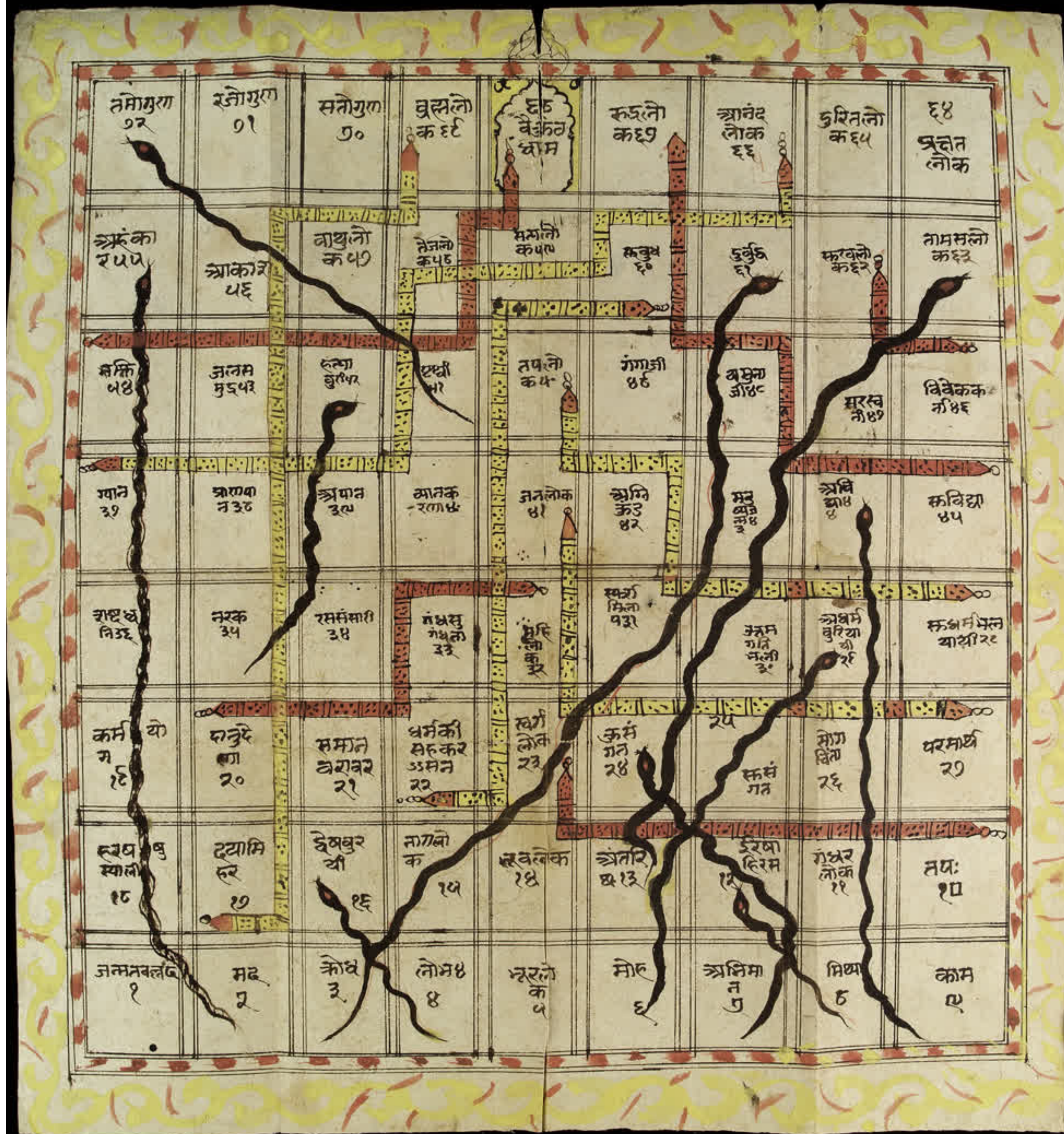
Benzene



My  
spooky  
dream\*

Ancient  
Indian  
game of  
Snakes  
and  
Ladders

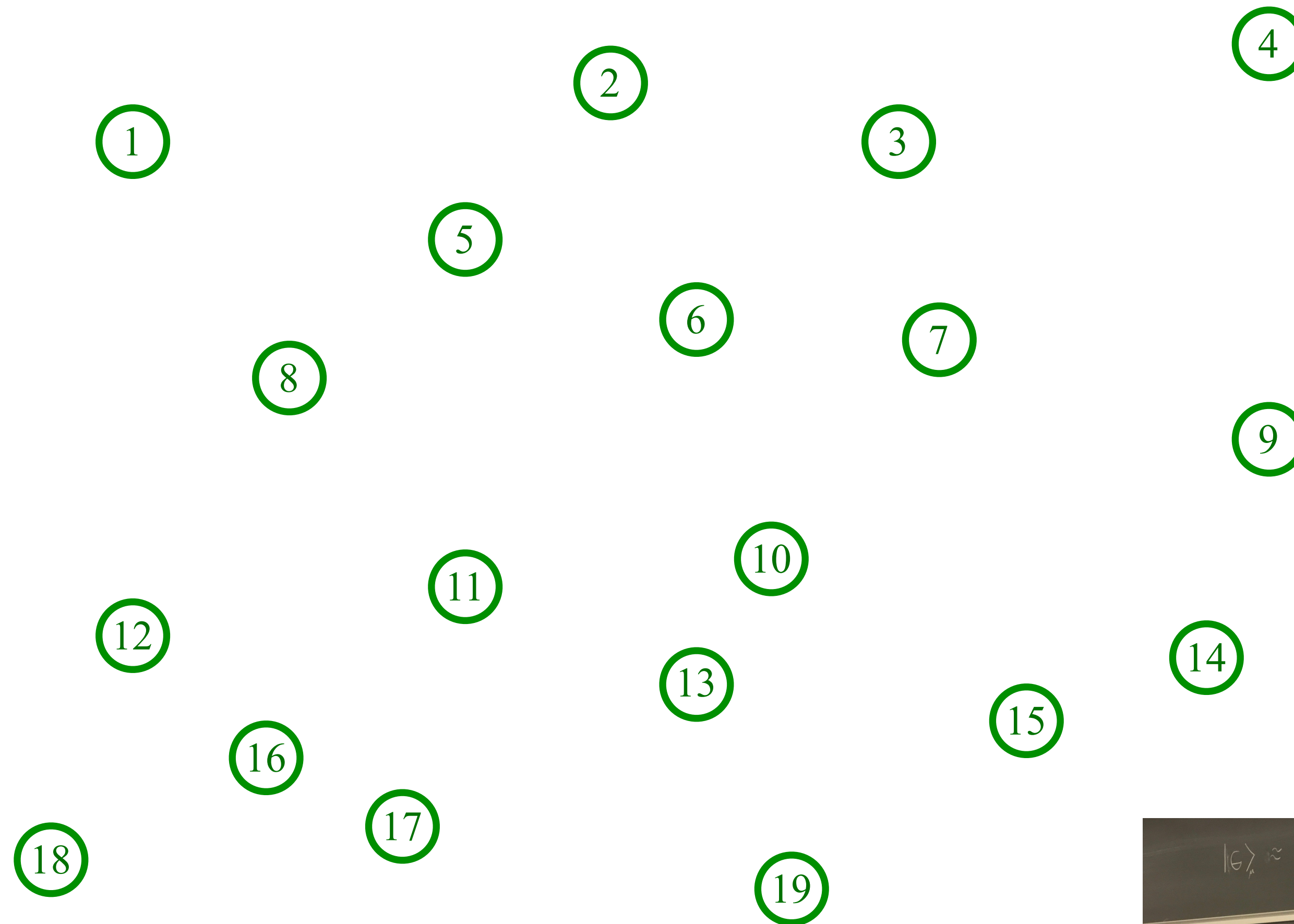
\*Not true



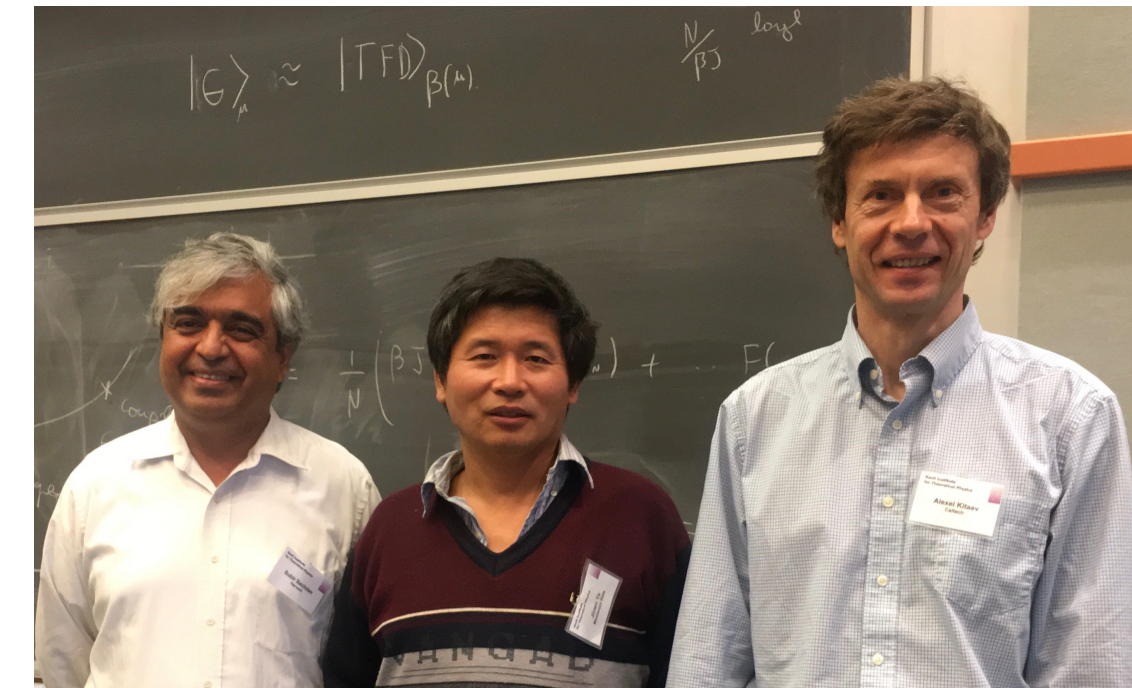


# The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

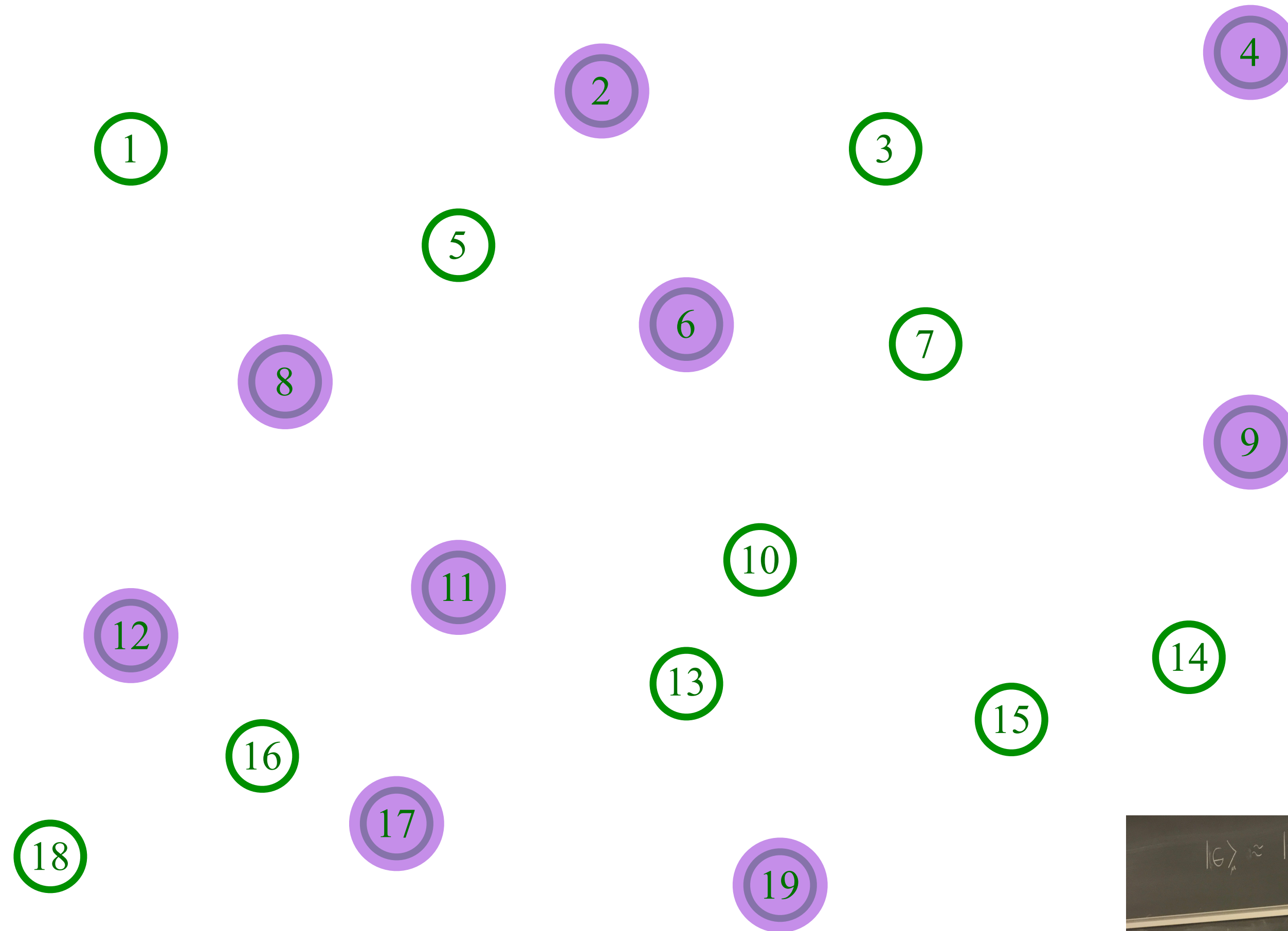


Pick a set of random positions

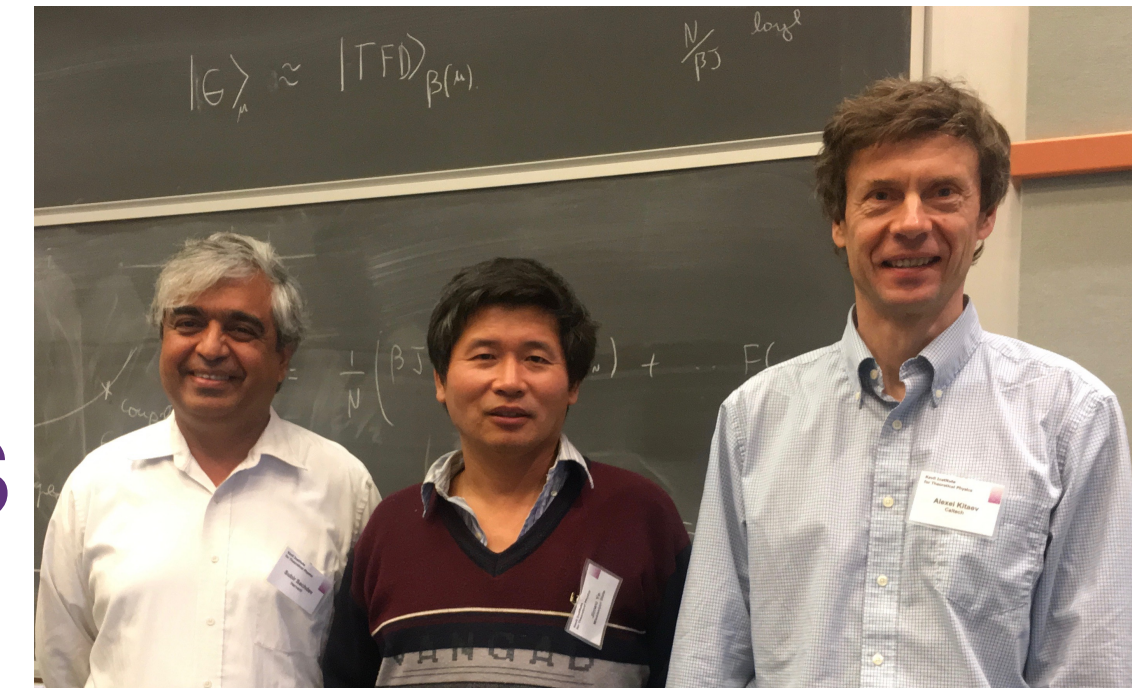


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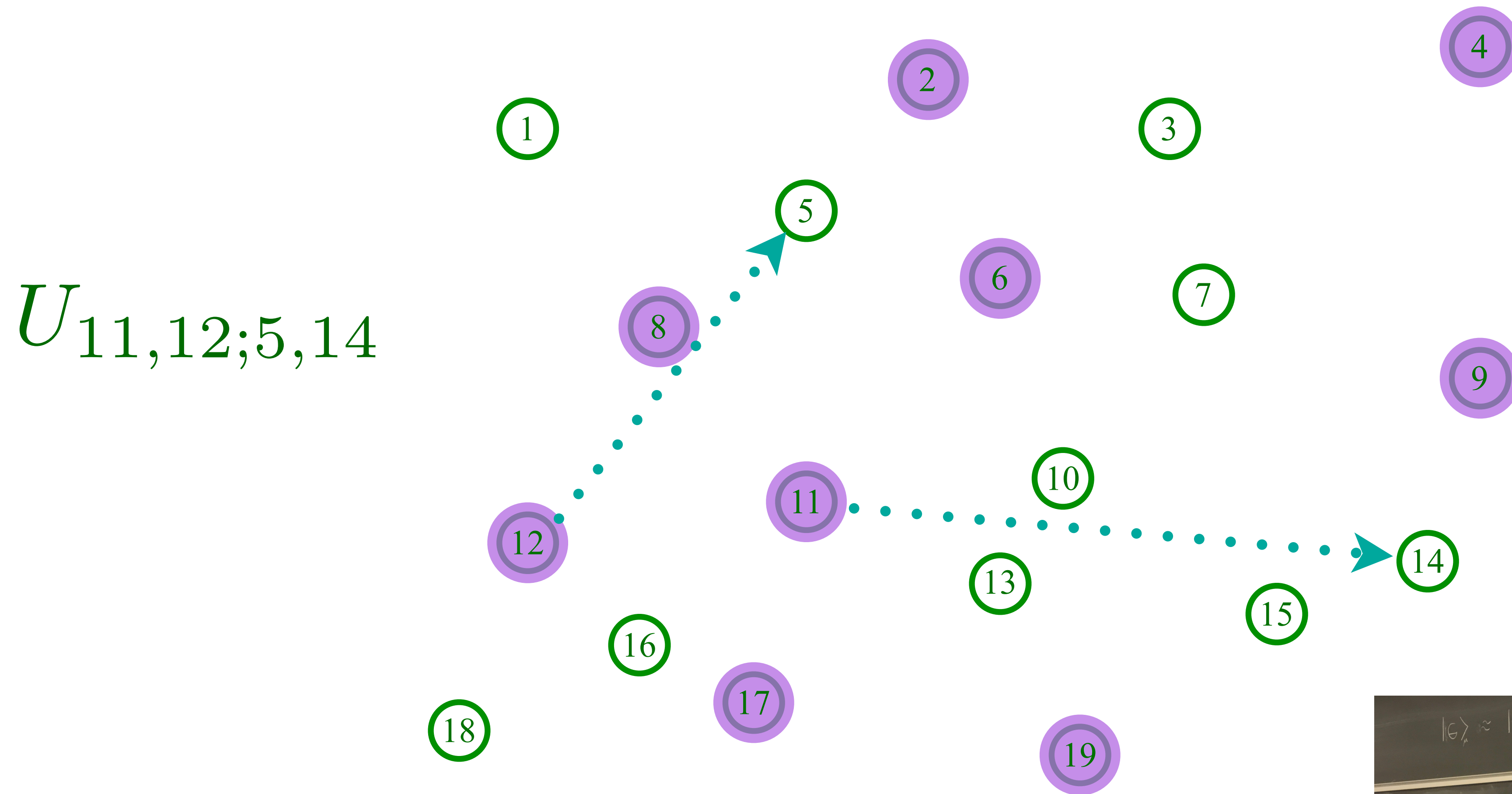
Place electrons randomly on some sites



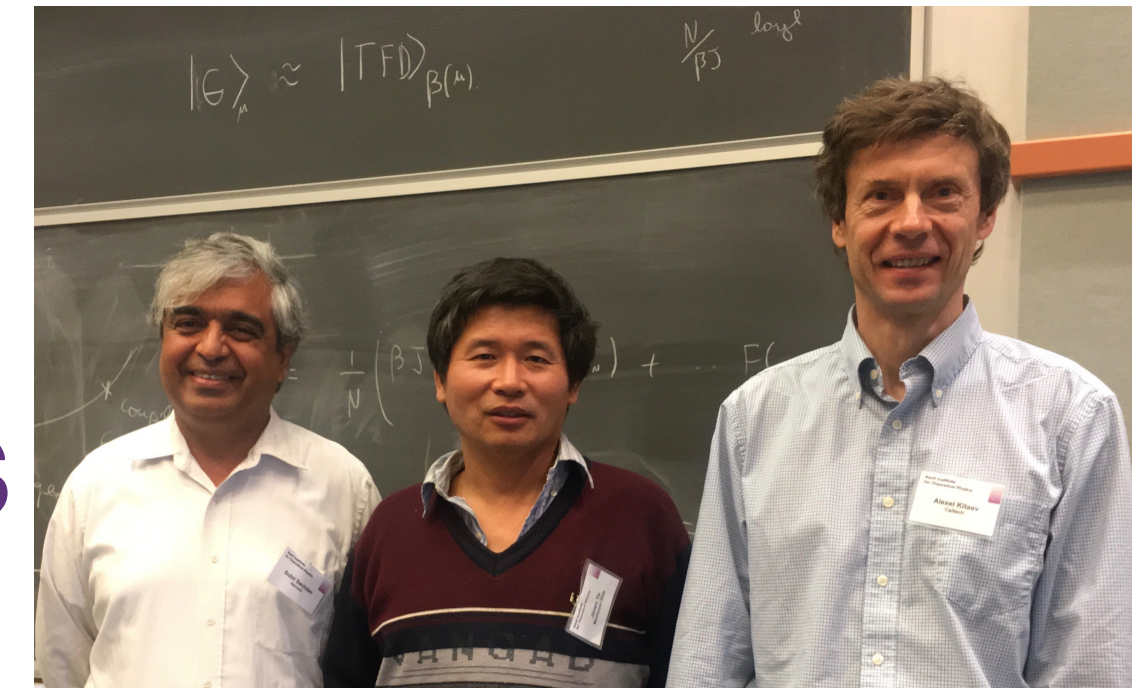


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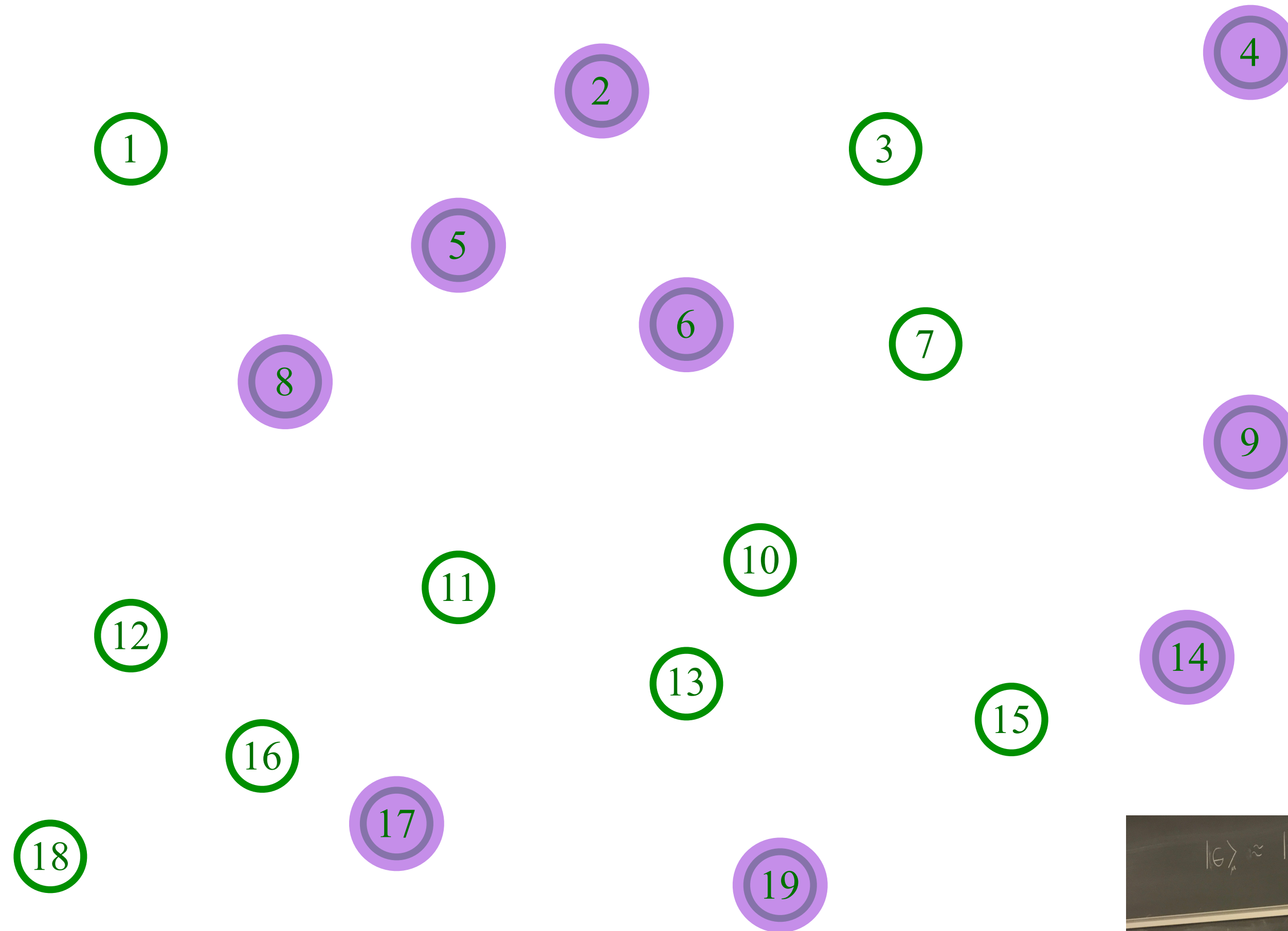
Place electrons randomly on some sites



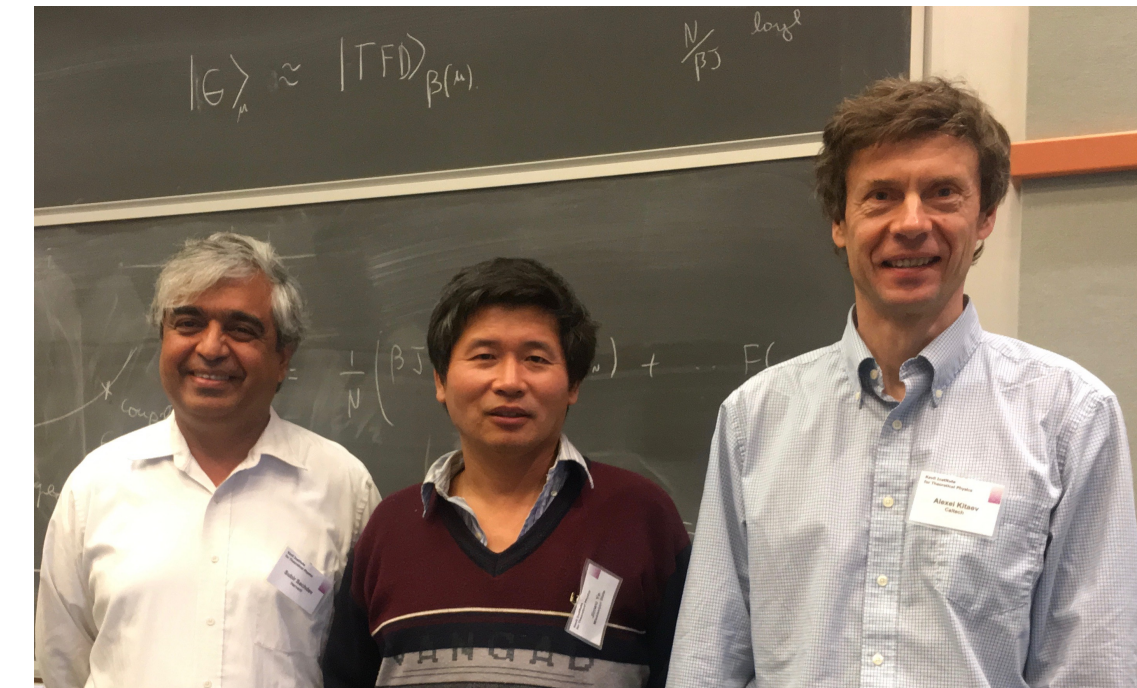
# The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

$$U_{11,12;5,14}$$



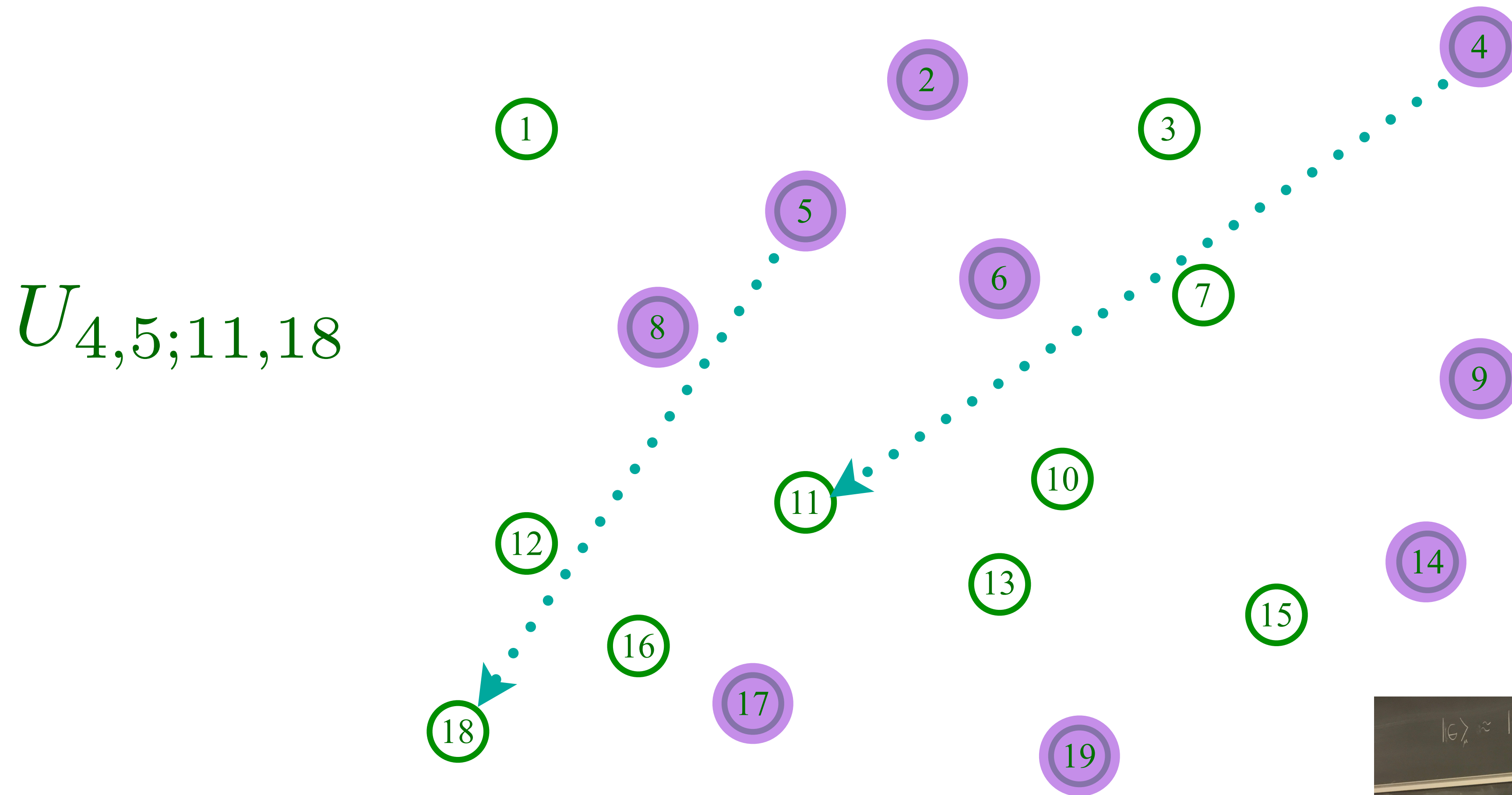
Entangle electrons pairwise randomly



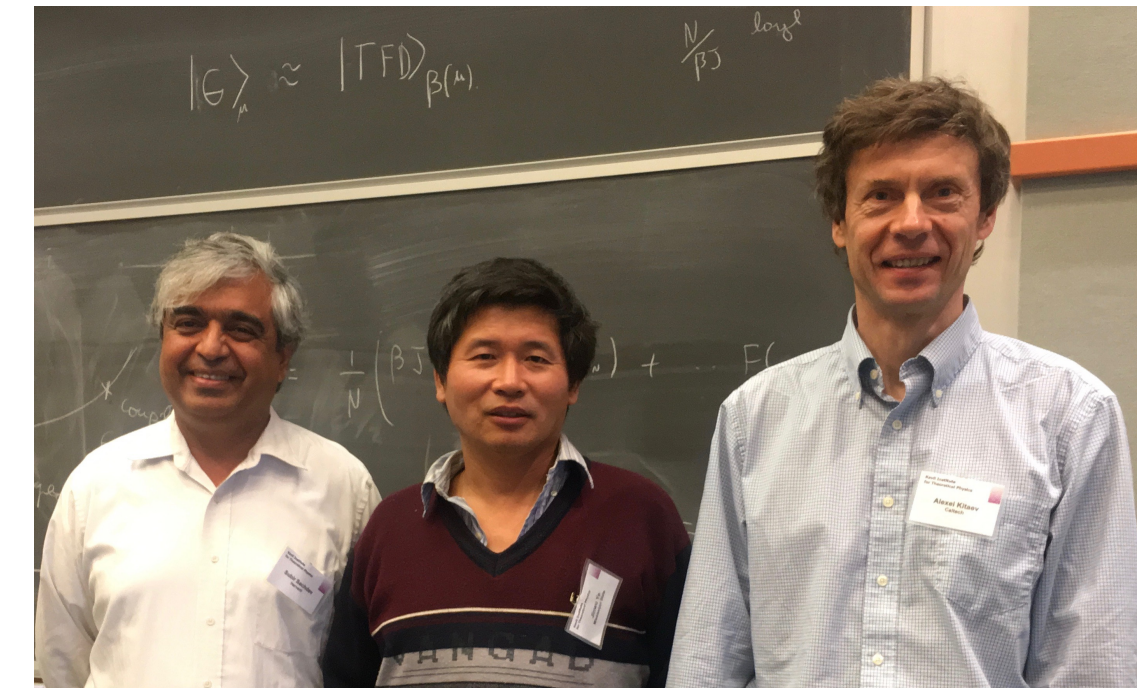


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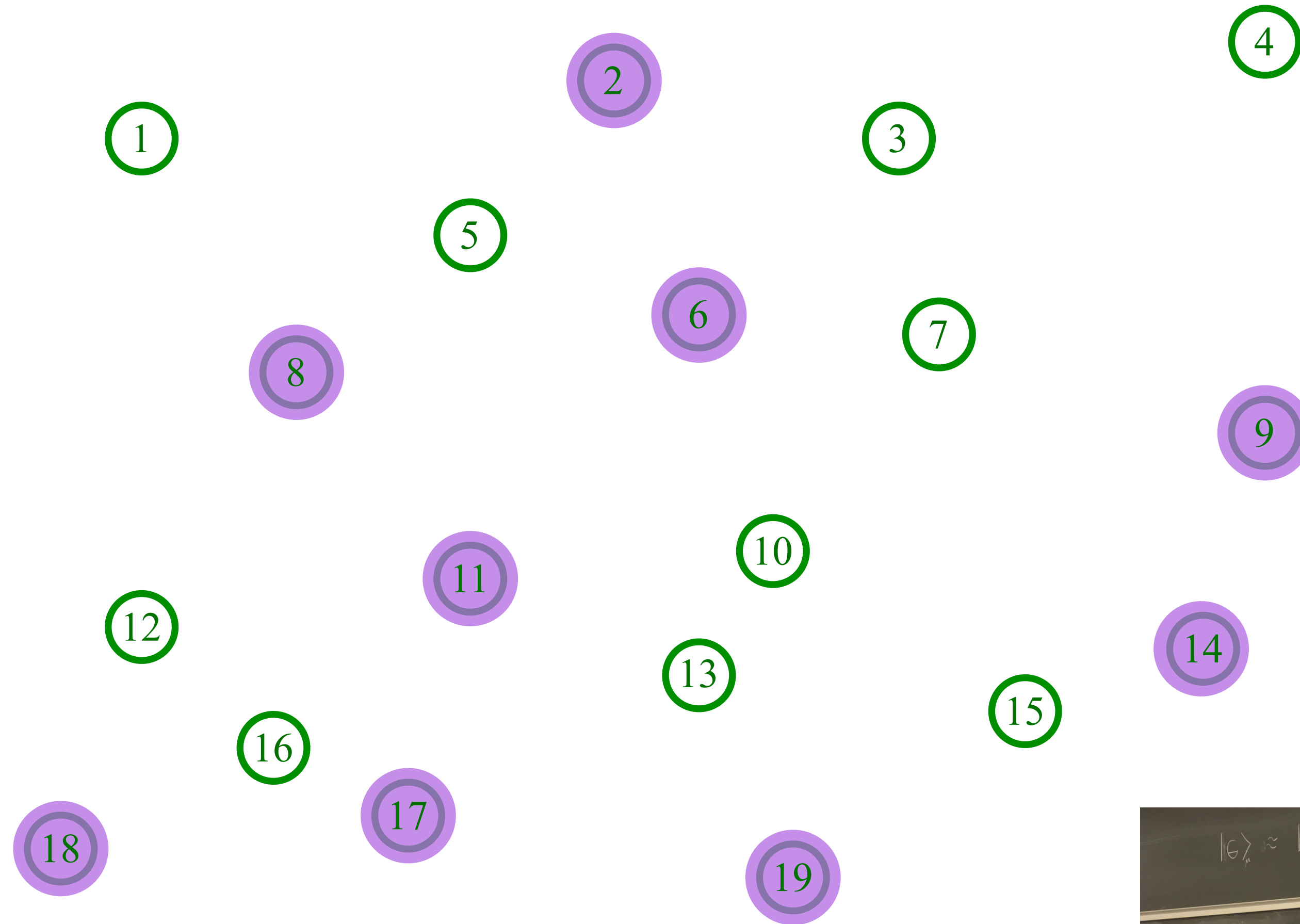
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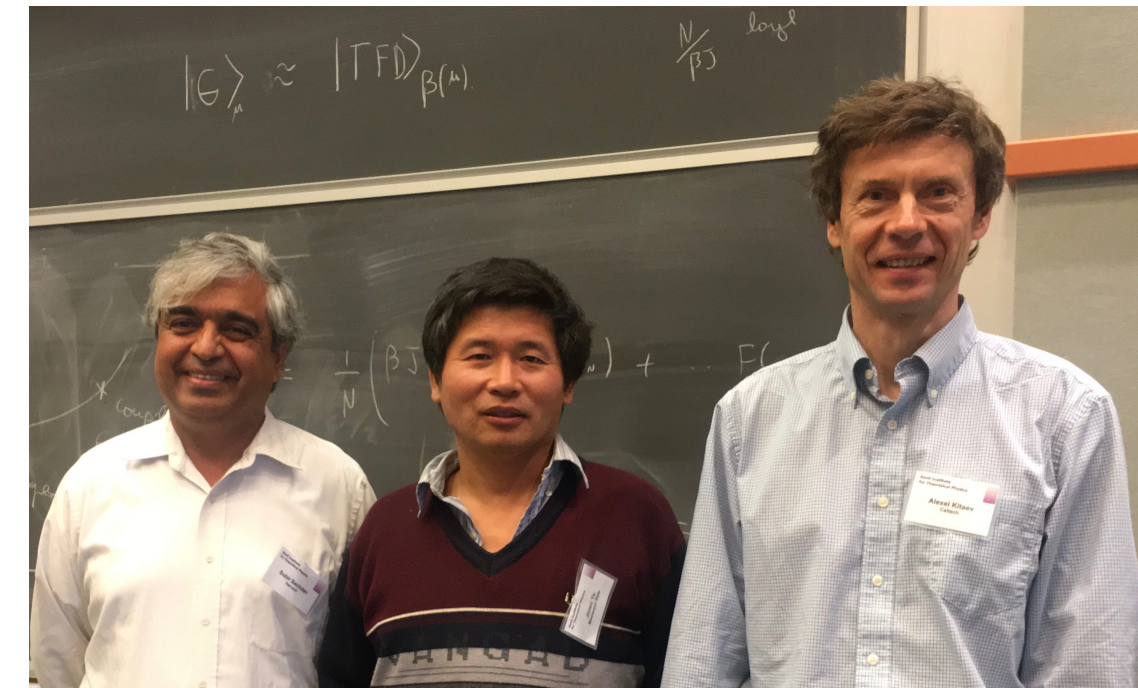
# The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

$$U_{4,5;11,18}$$



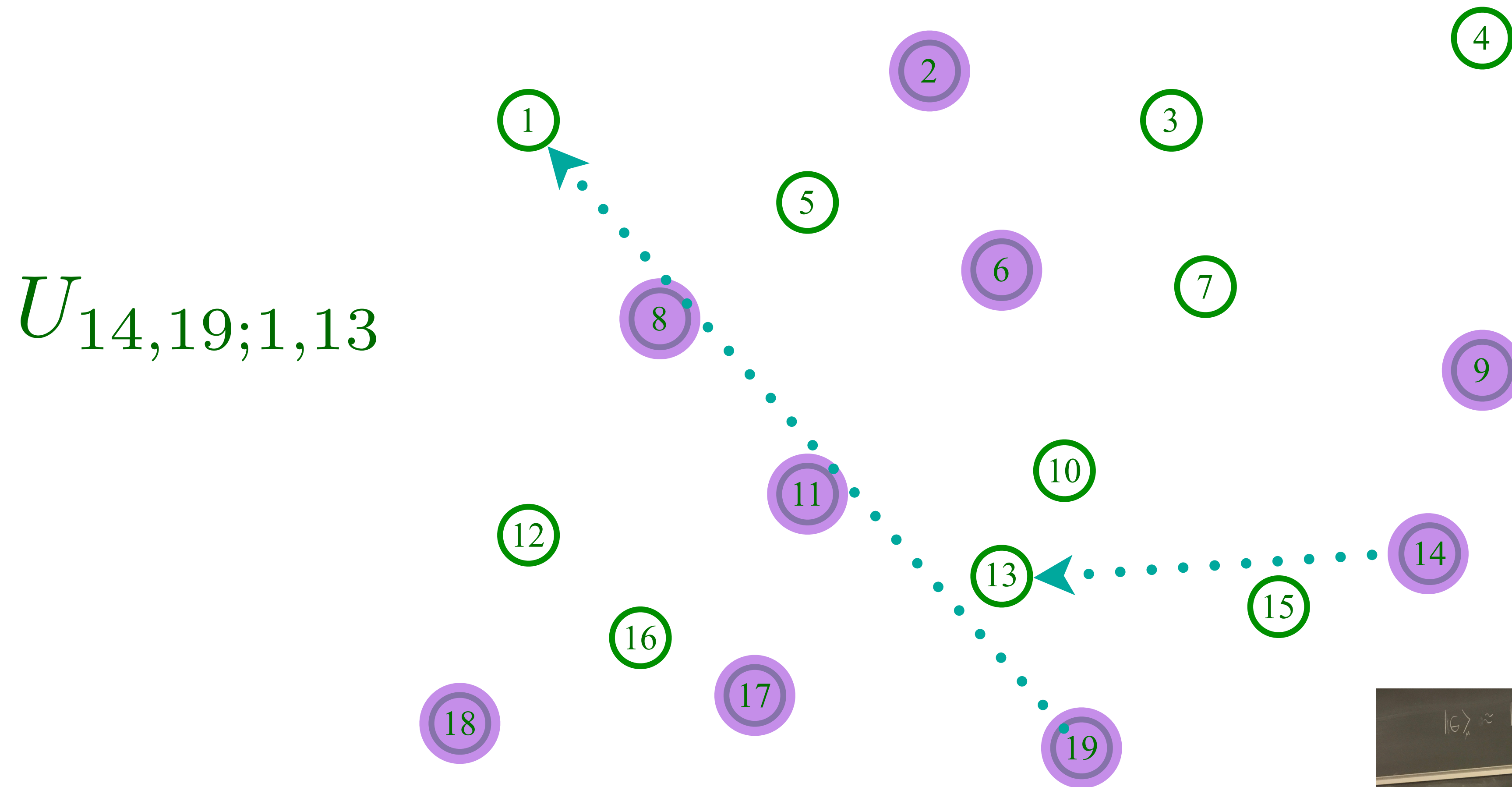
Entangle electrons pairwise randomly



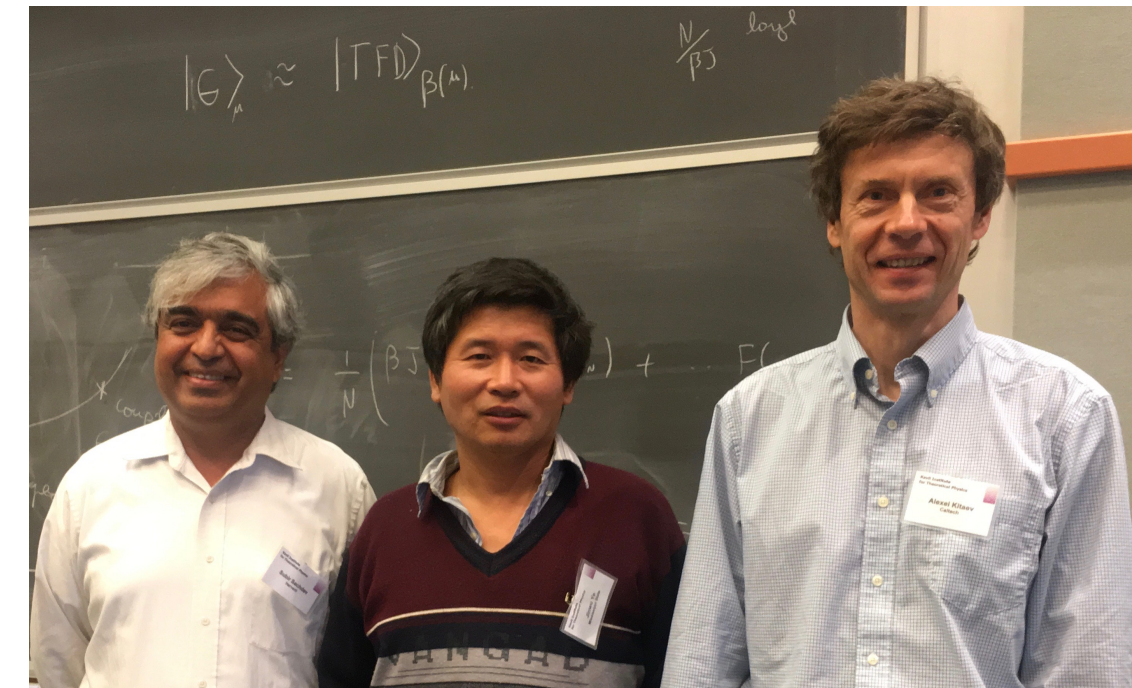


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Sachdev, Ye (1993); Kitaev (2015)



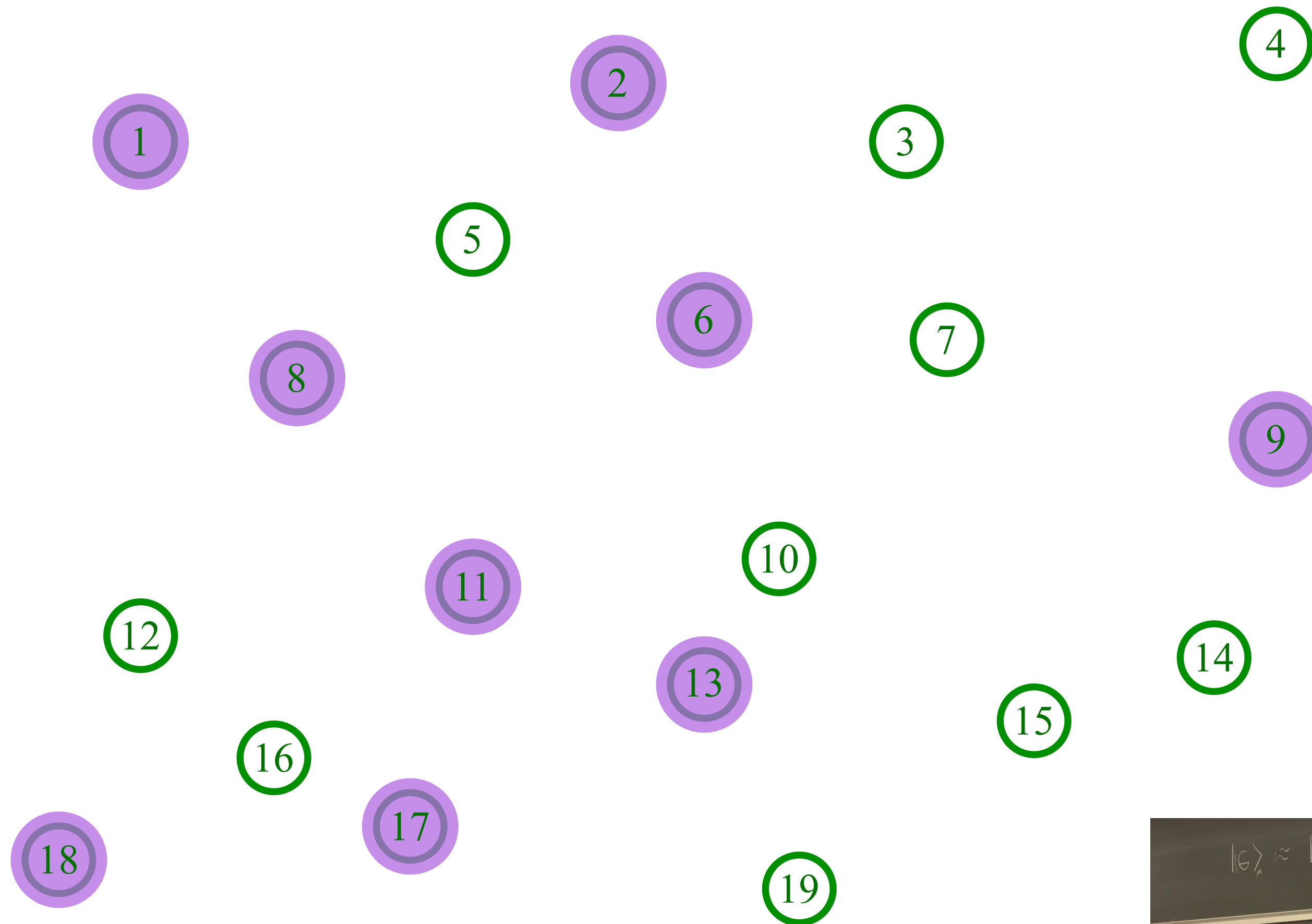
Entangle electrons pairwise randomly



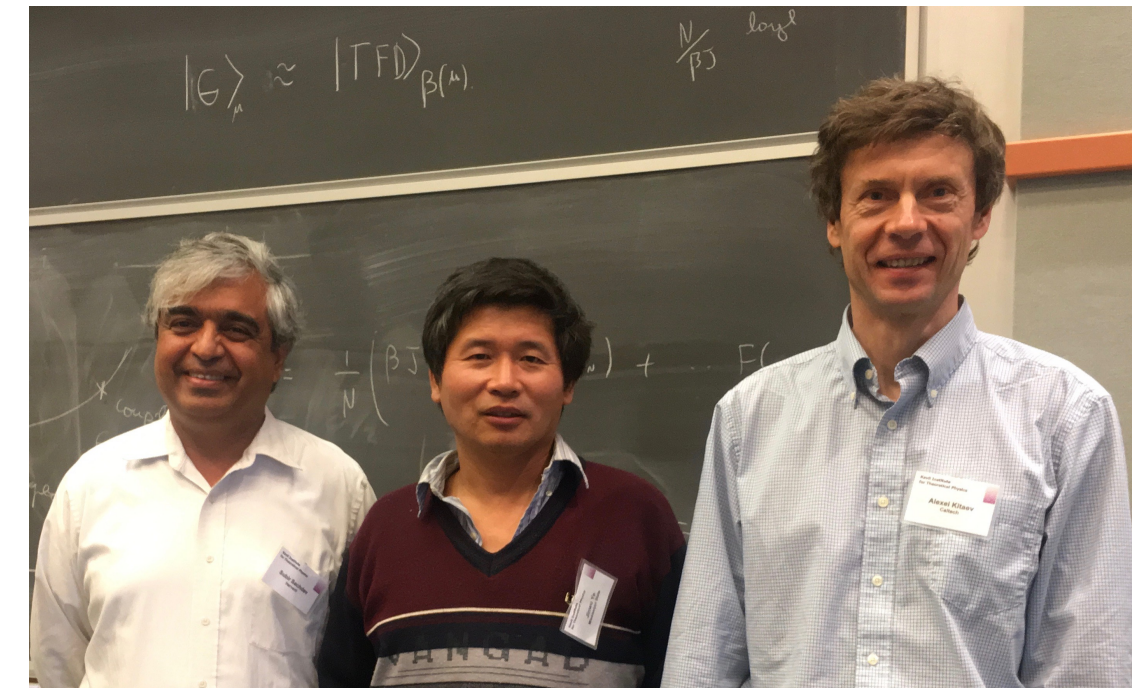
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Sachdev, Ye (1993); Kitaev (2015)

$$U_{14,19;1,13}$$



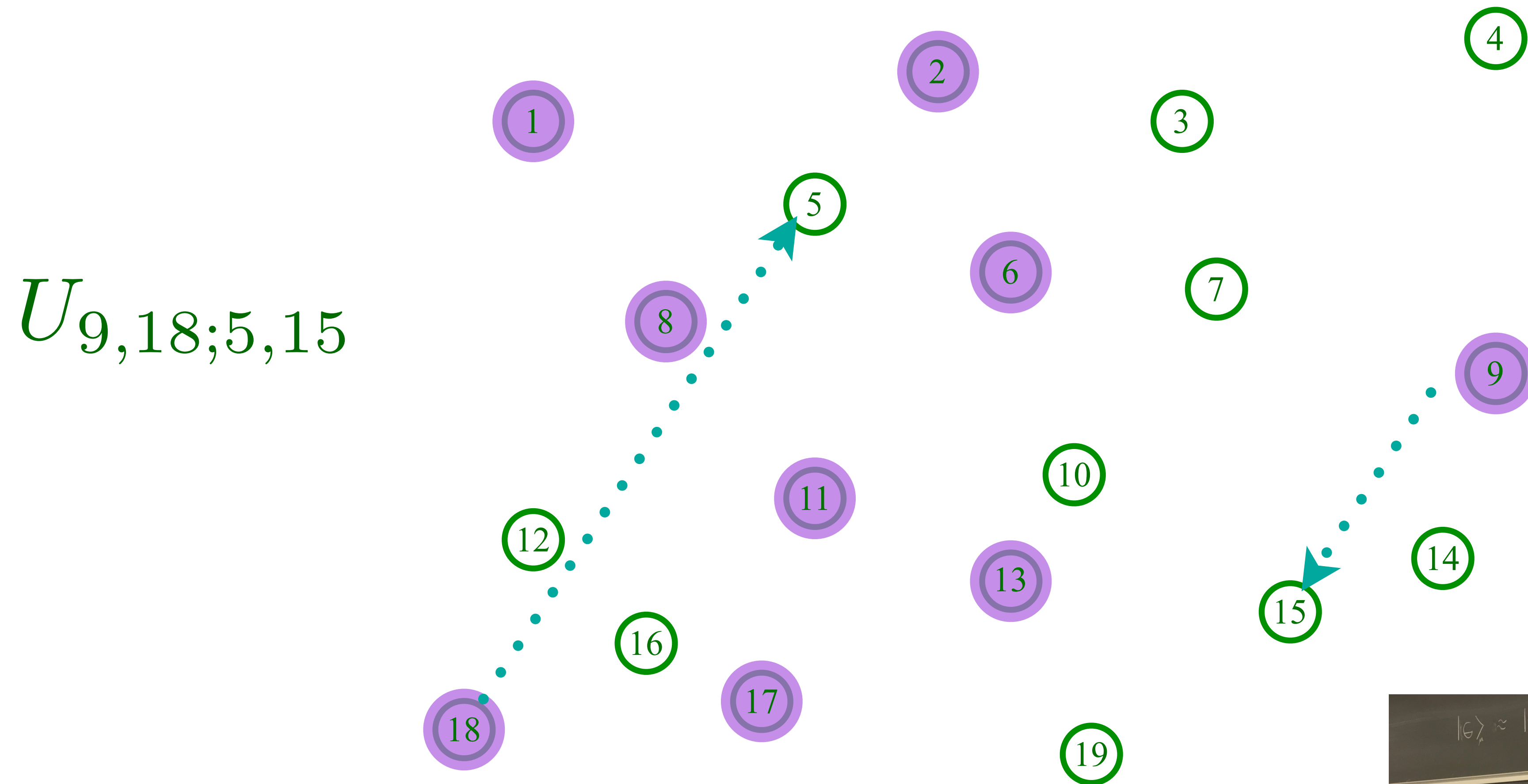
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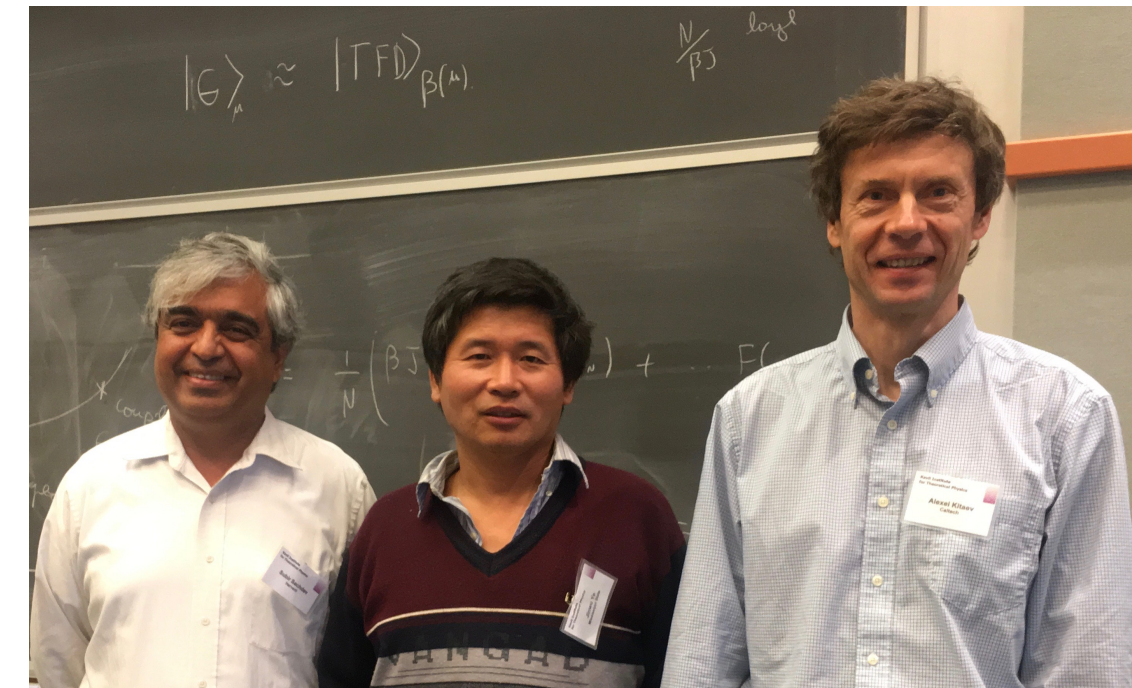


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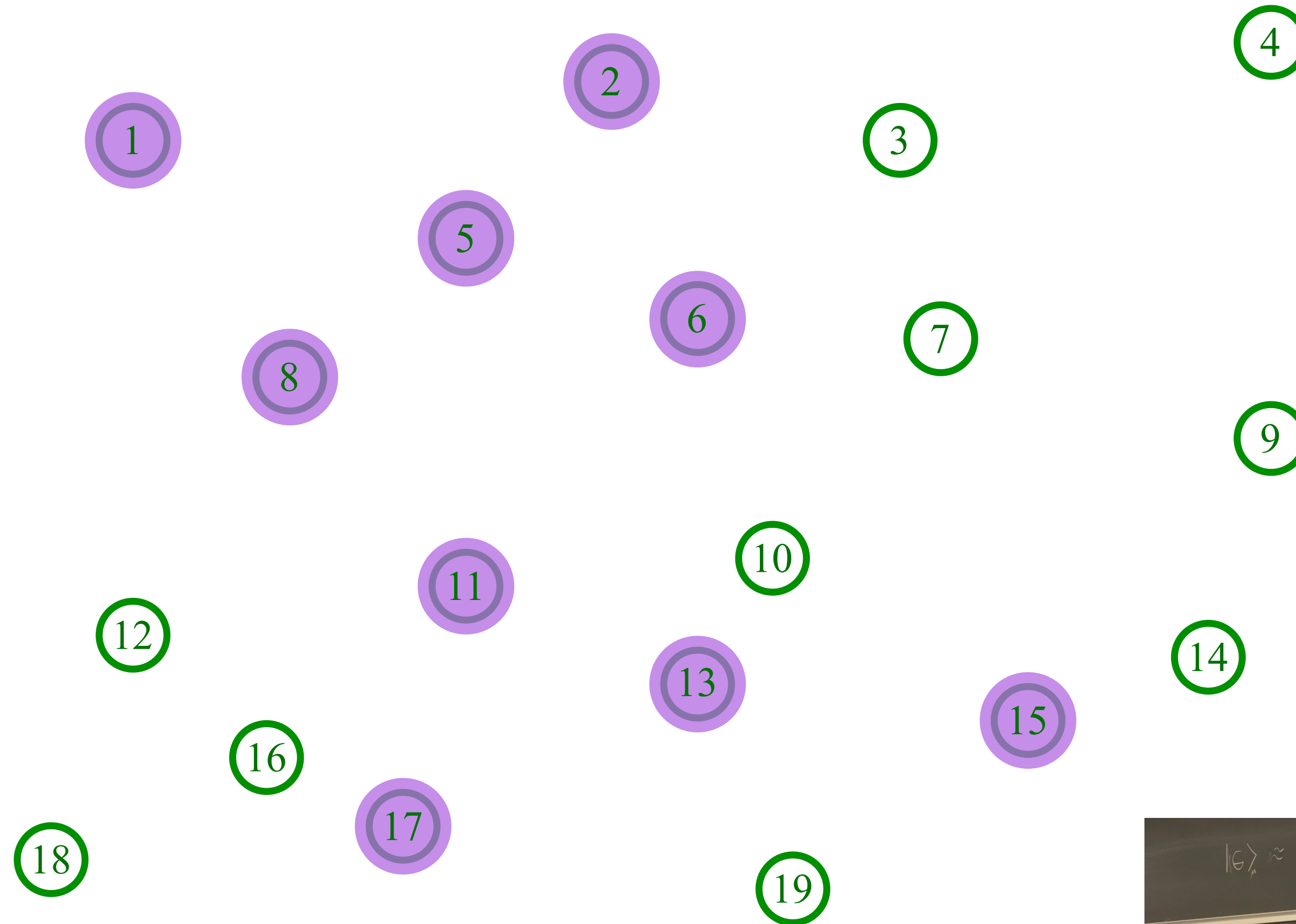
Entangle electrons pairwise randomly



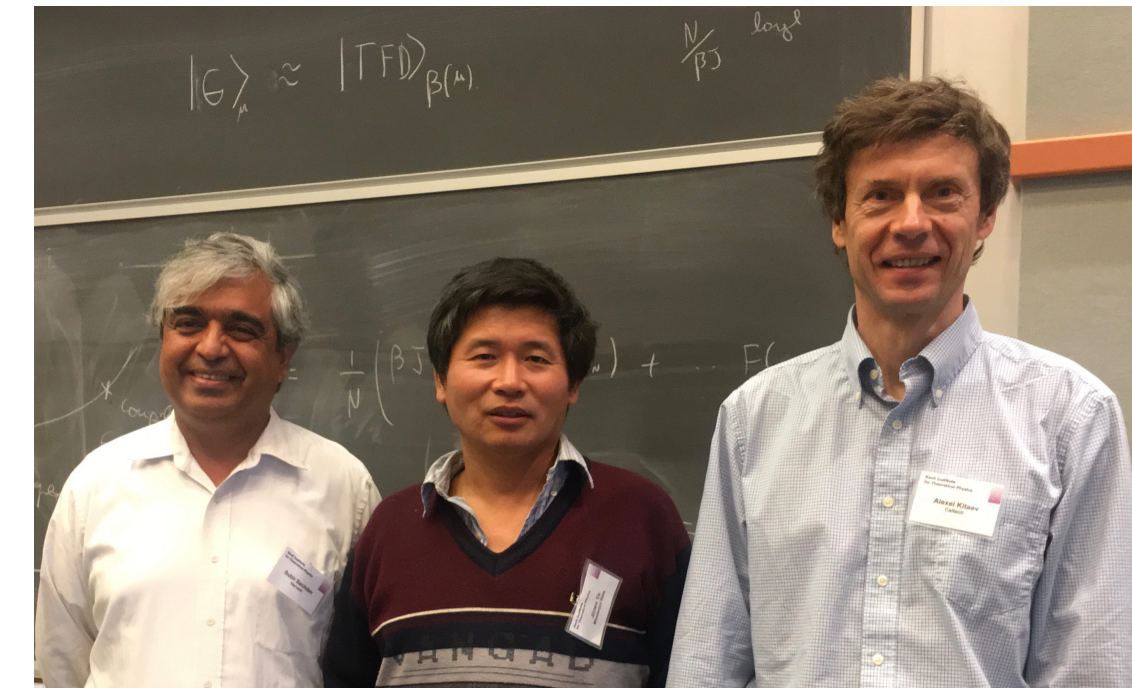
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Sachdev, Ye (1993); Kitaev (2015)

$$U_{9,18;5,15}$$



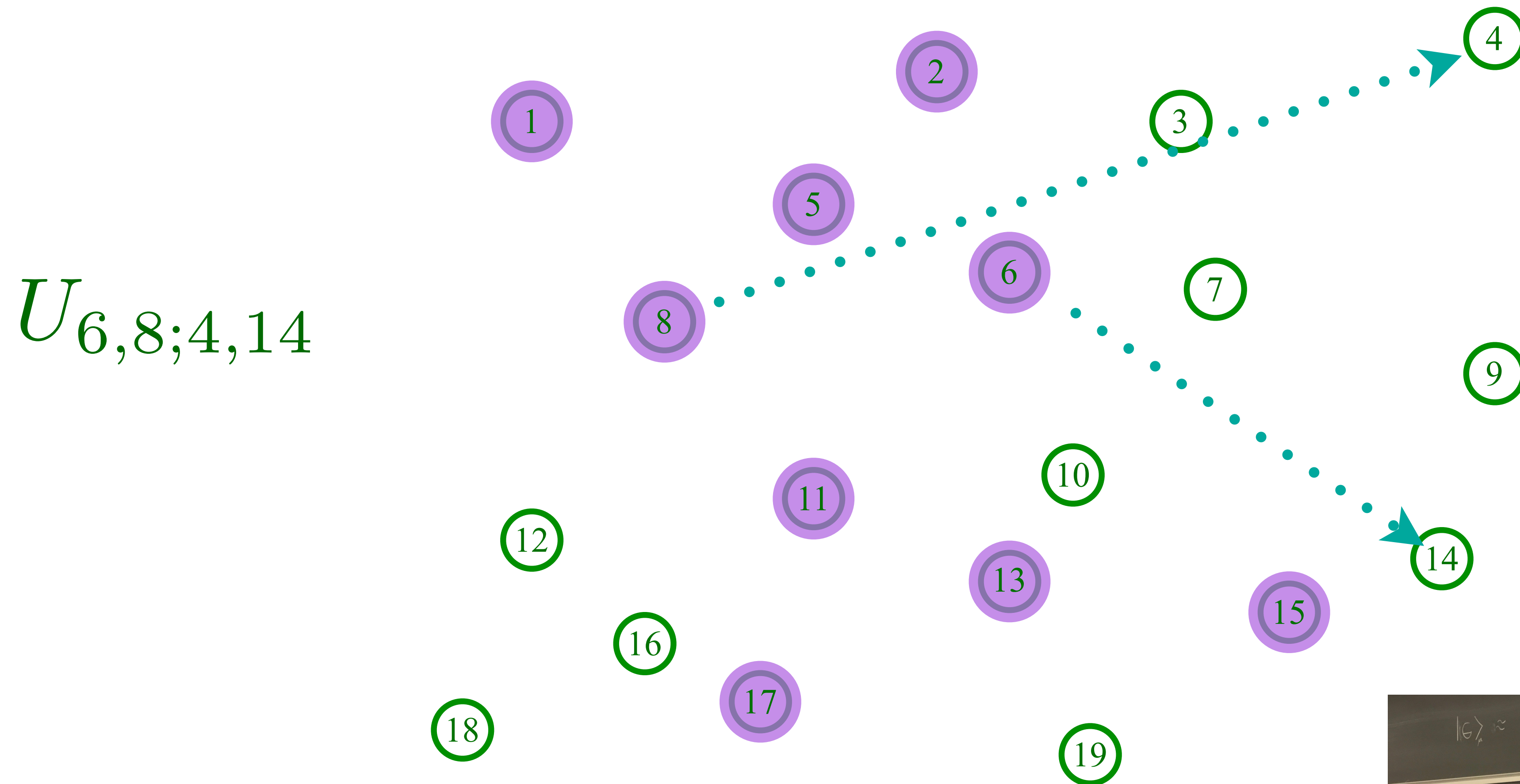
Entangle electrons pairwise randomly



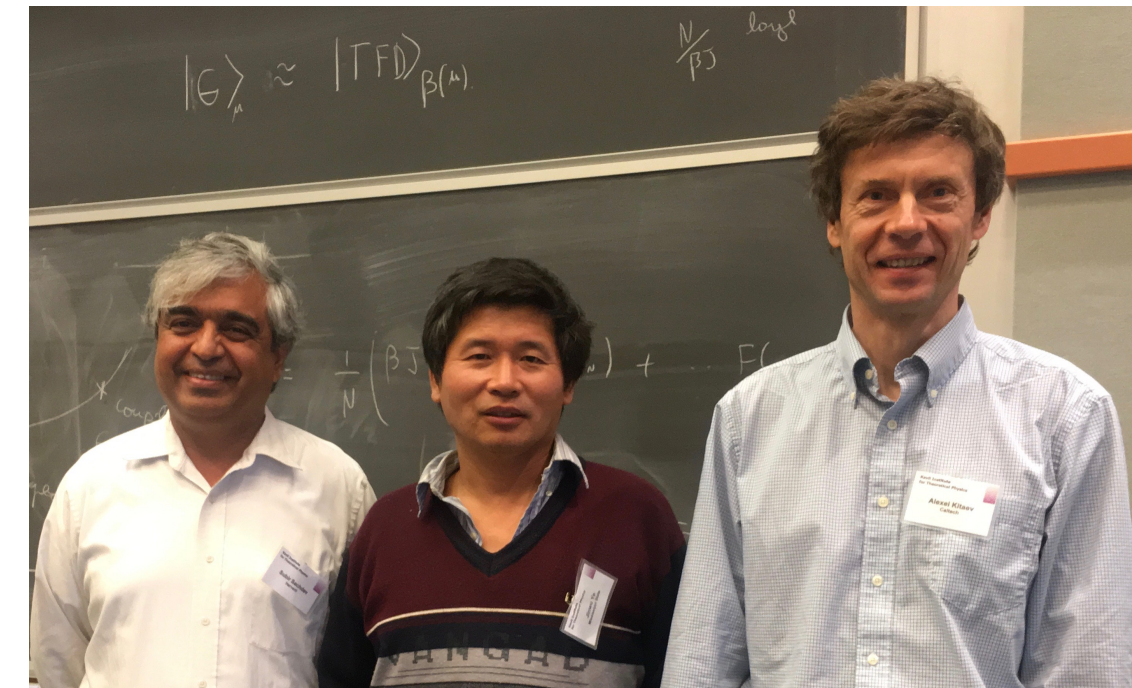


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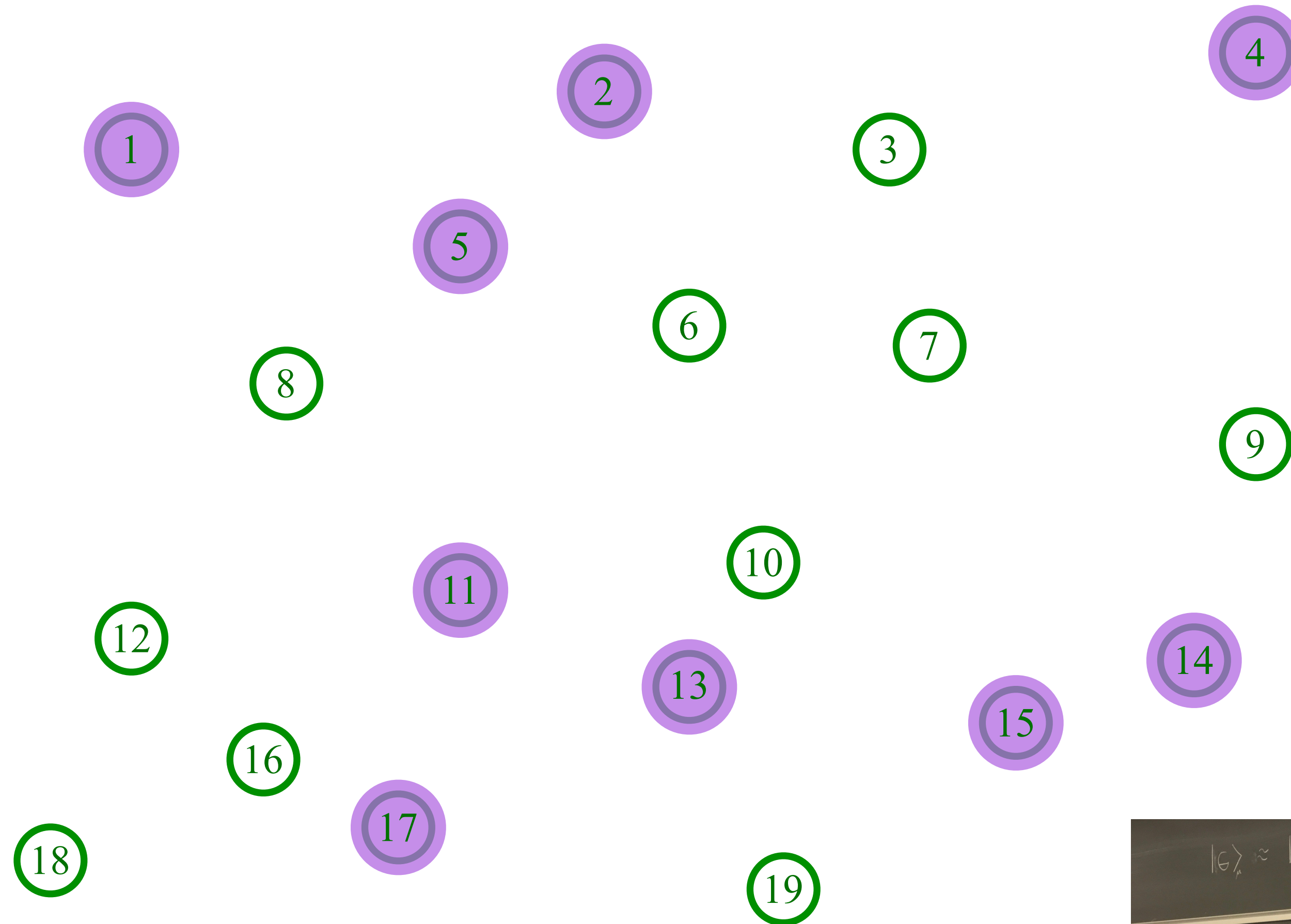
Entangle electrons pairwise randomly



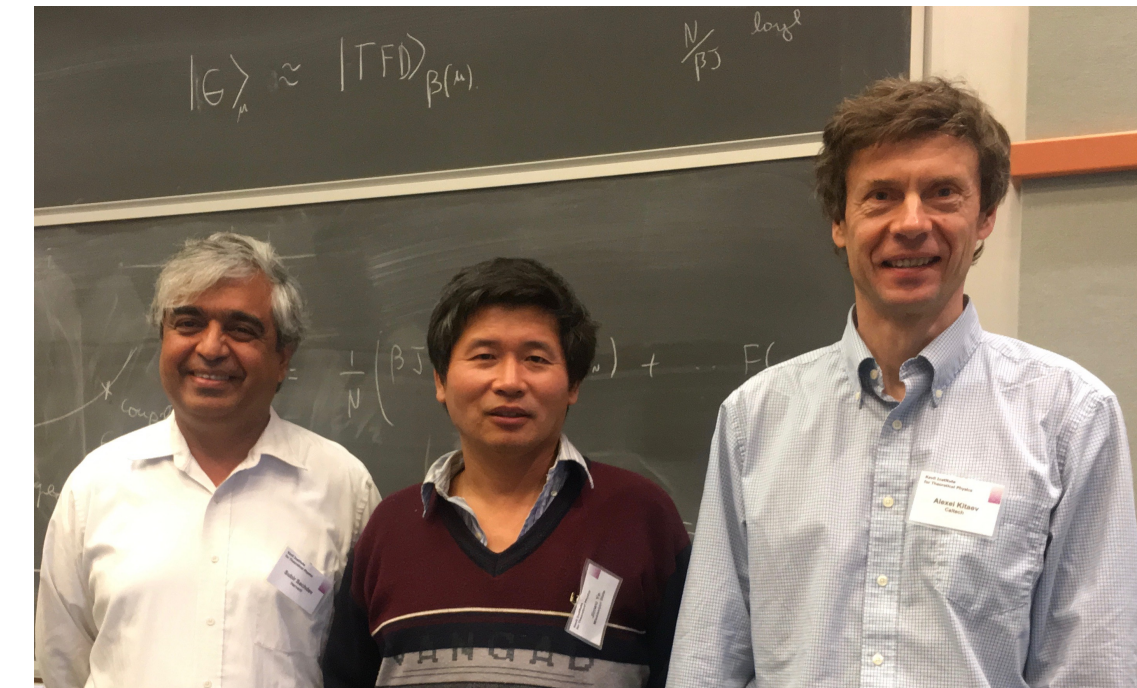
# The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

$$U_{6,8;4,14}$$



Entangle electrons pairwise randomly





# The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

A solvable model of multi-particle  
quantum entanglement.

Yields a metal in which current is carried  
not by individual electrons,  
but by an entangled “quantum soup”

# Quantum entanglement and superconductivity

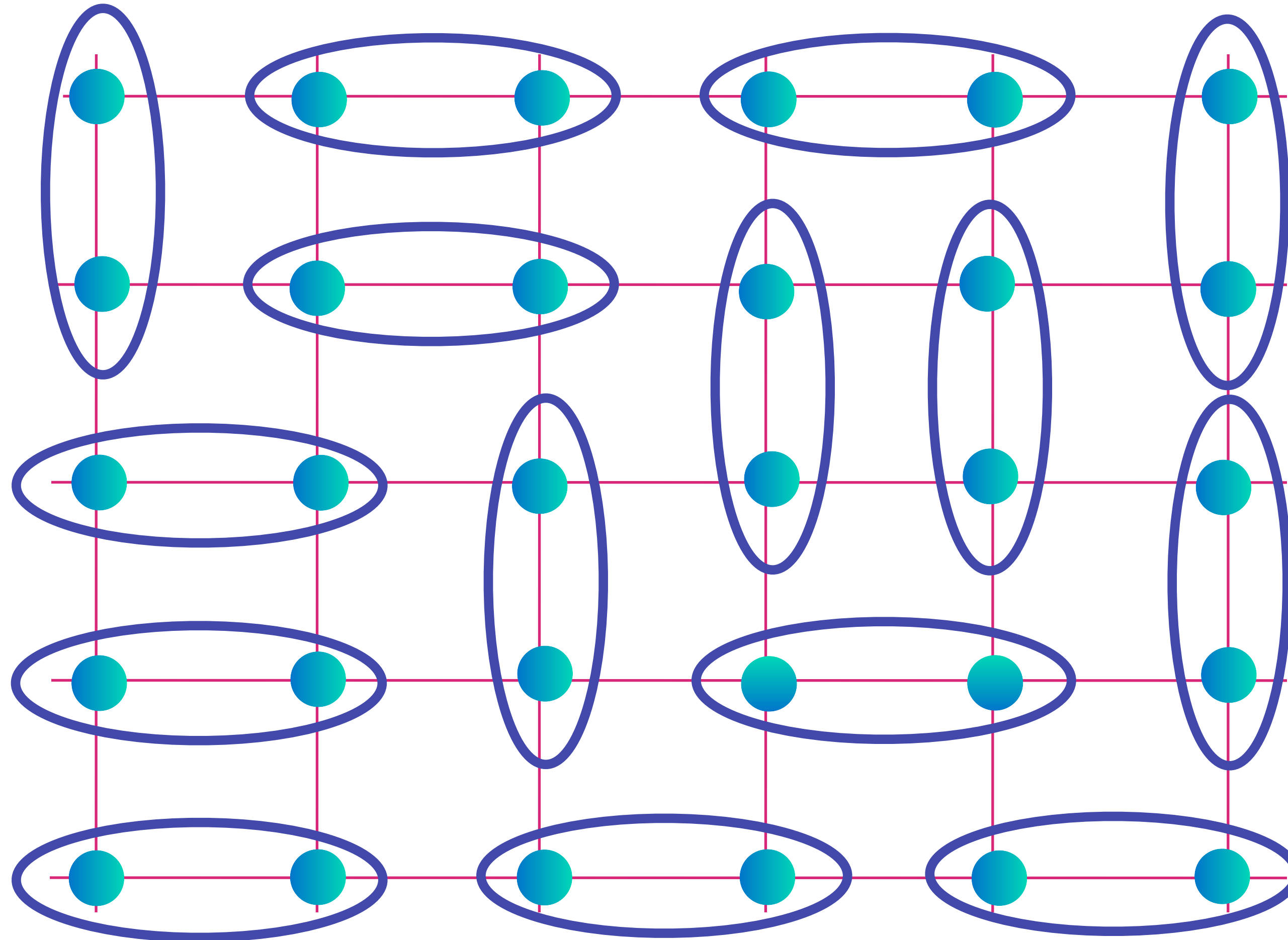


# The dance of electrons on Cu atoms in YBCO

Baskaran+Anderson (1987)

**Spin liquid**

Electrons form entangled pairs, and the pairs entangle across the entire sample



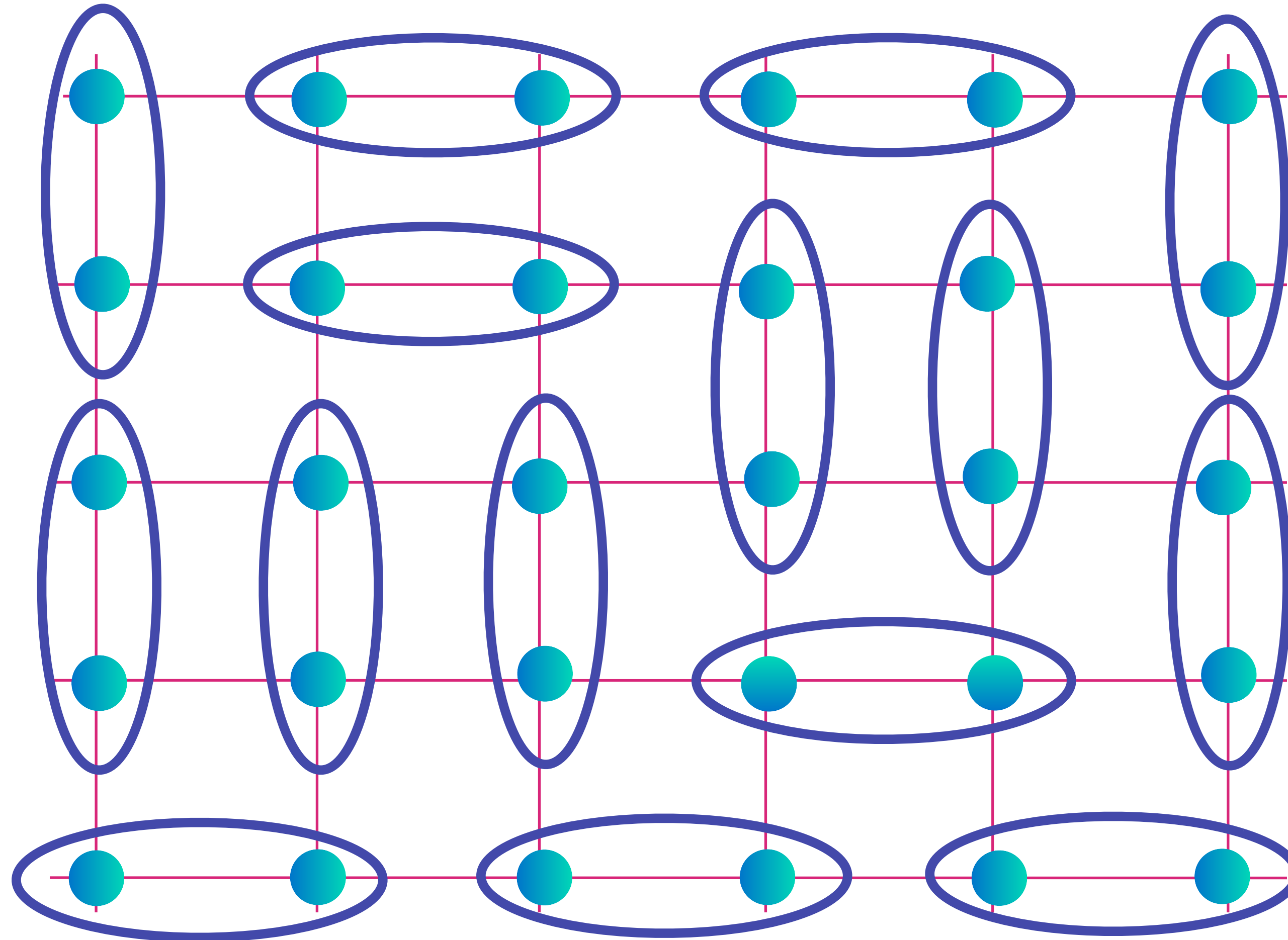
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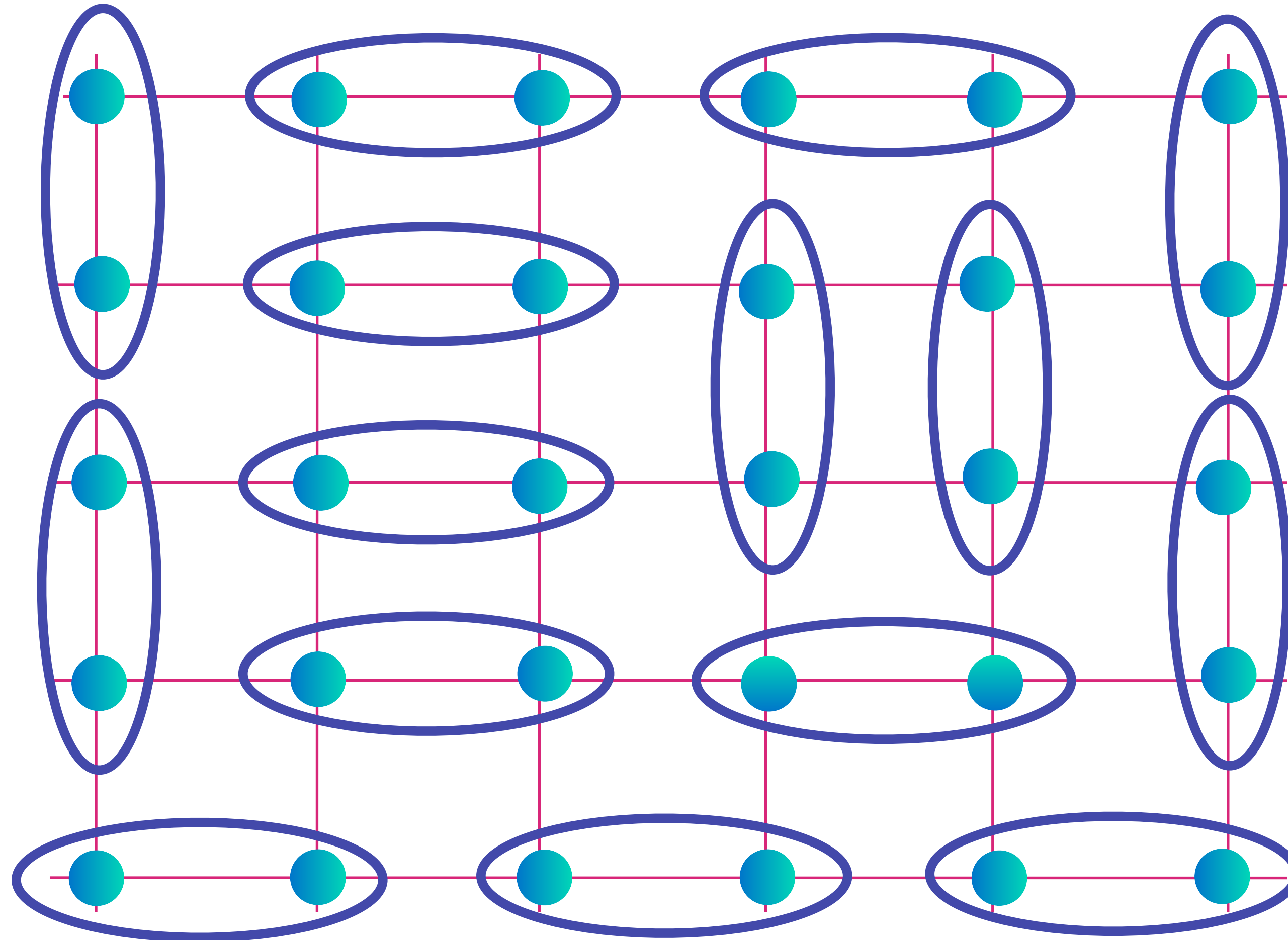


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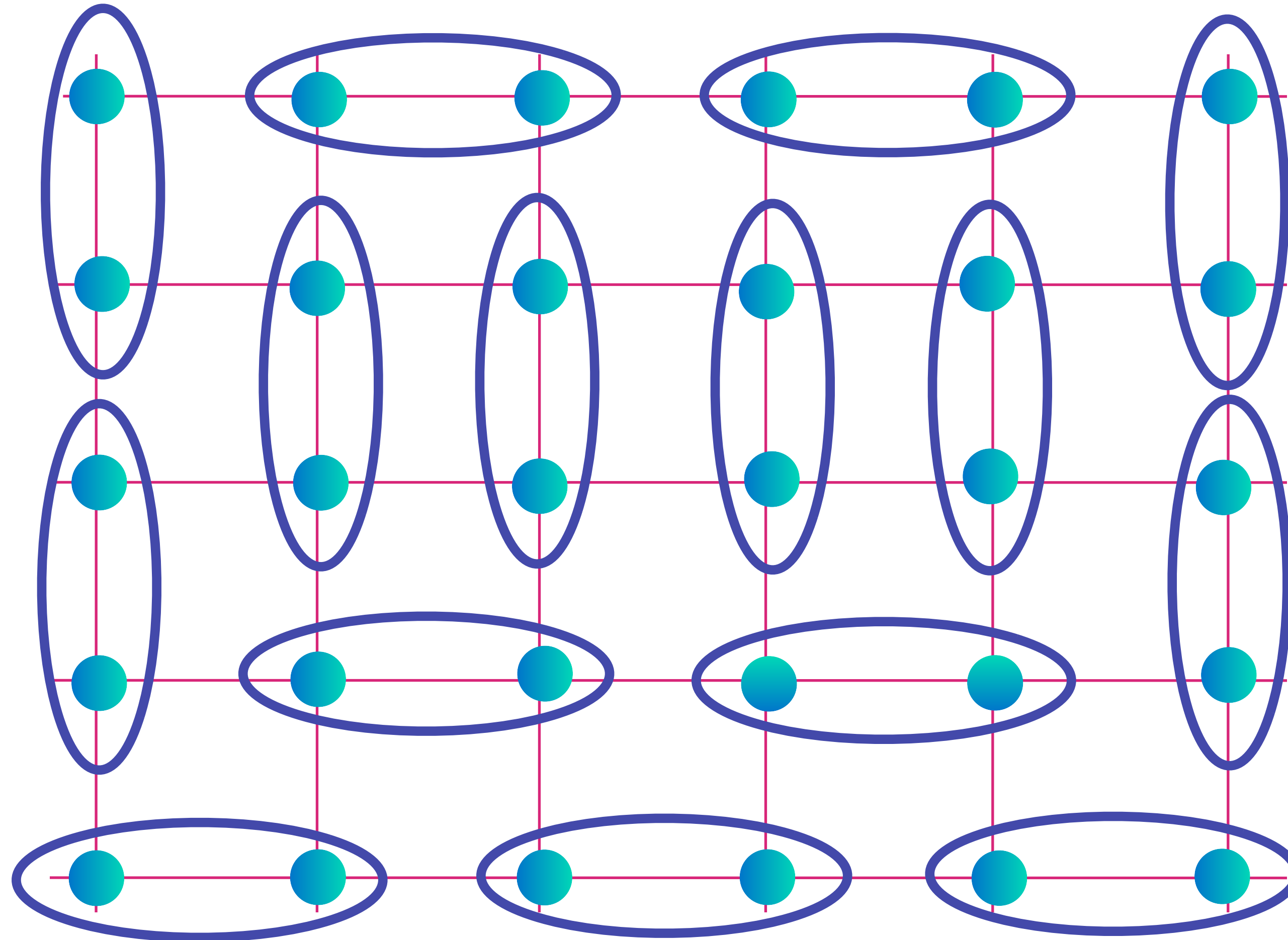
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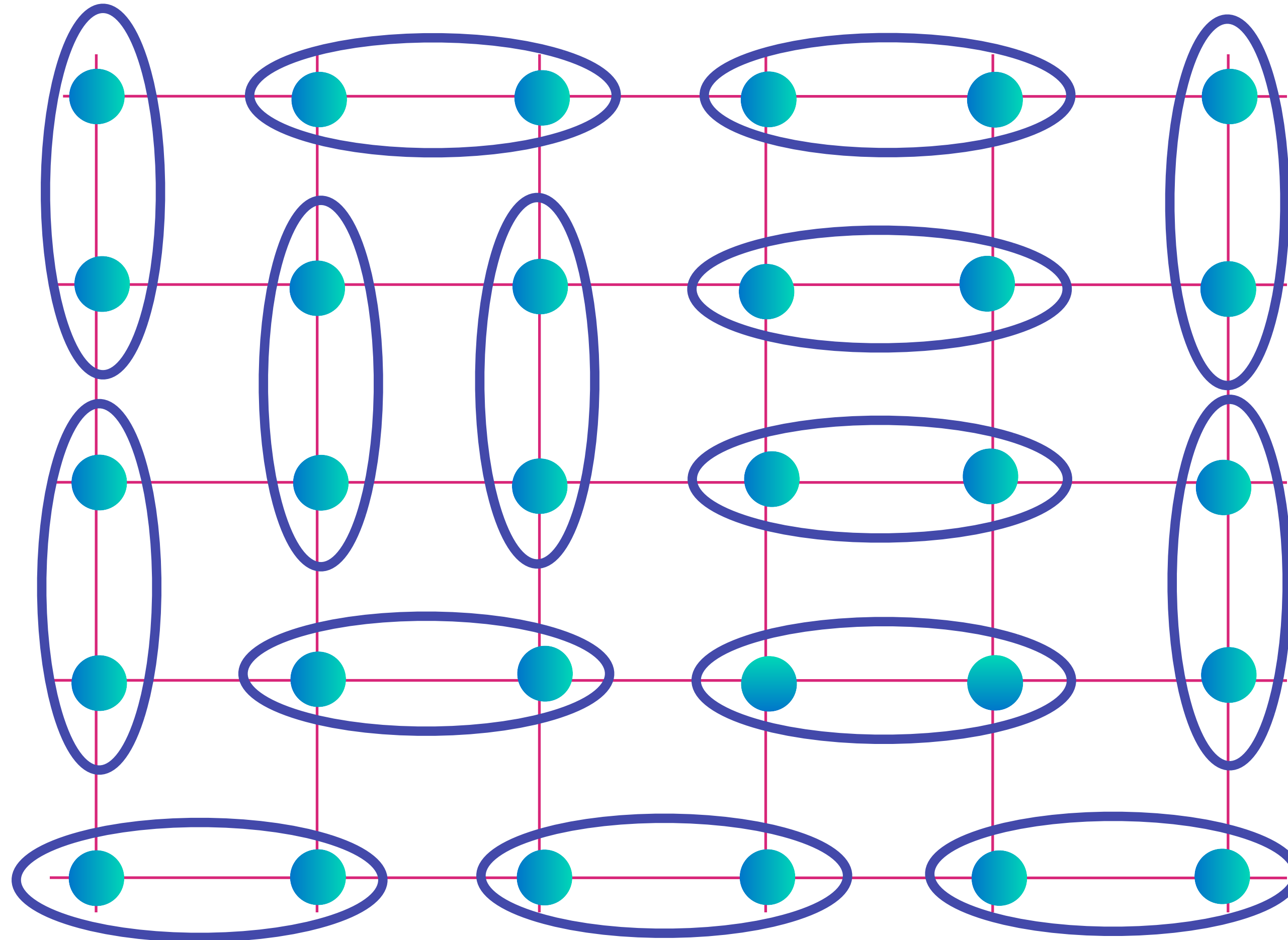


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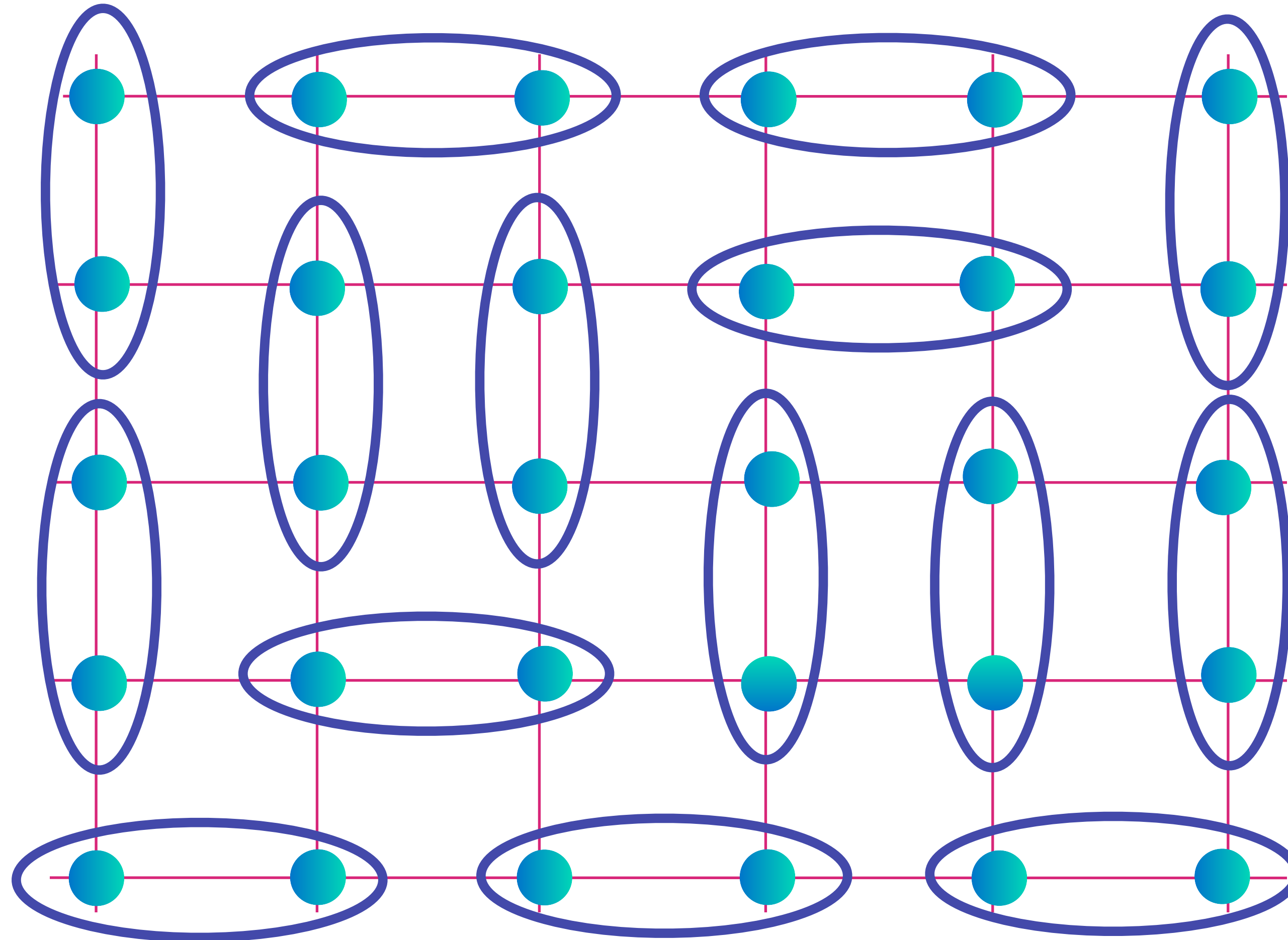
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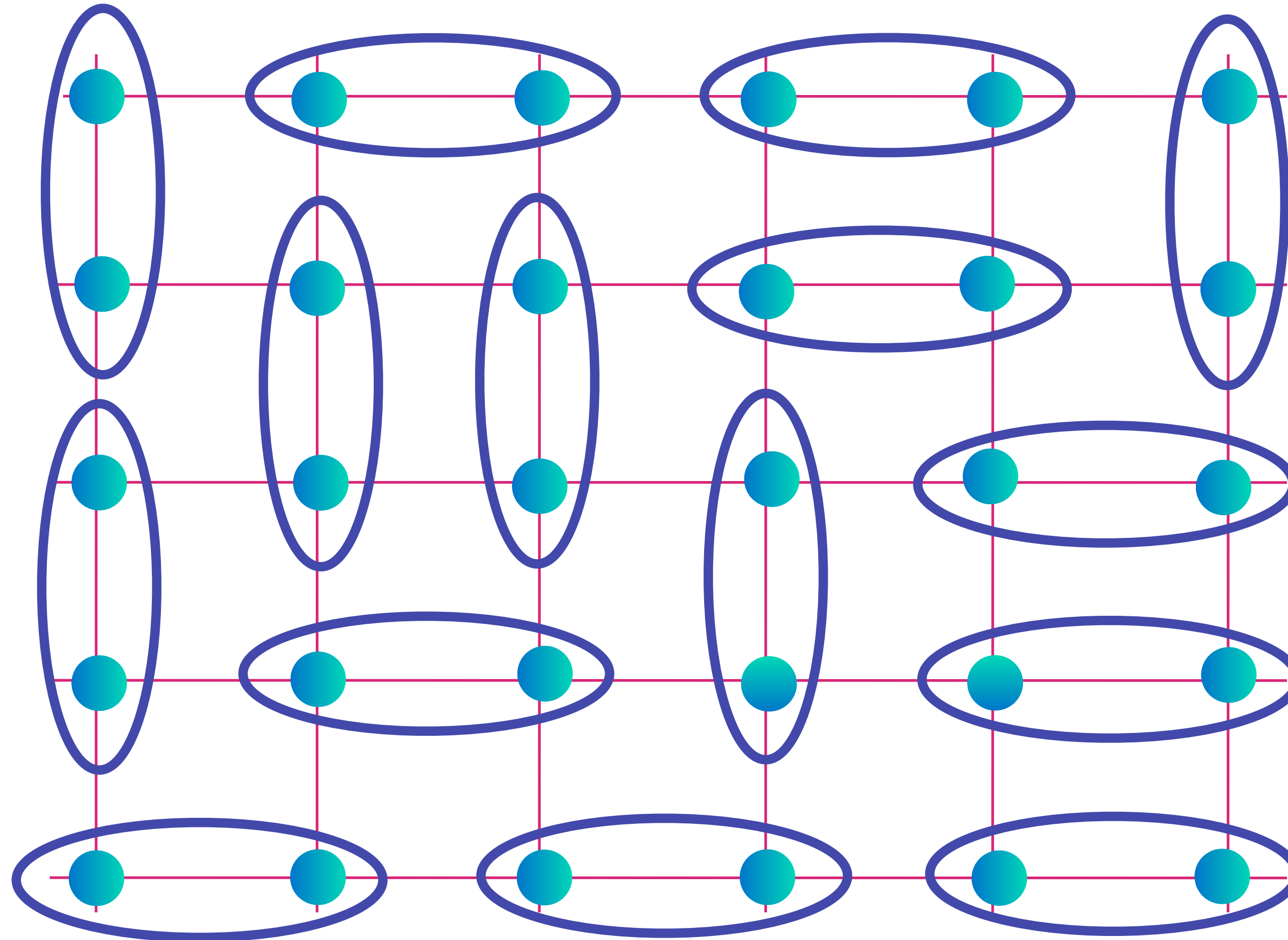


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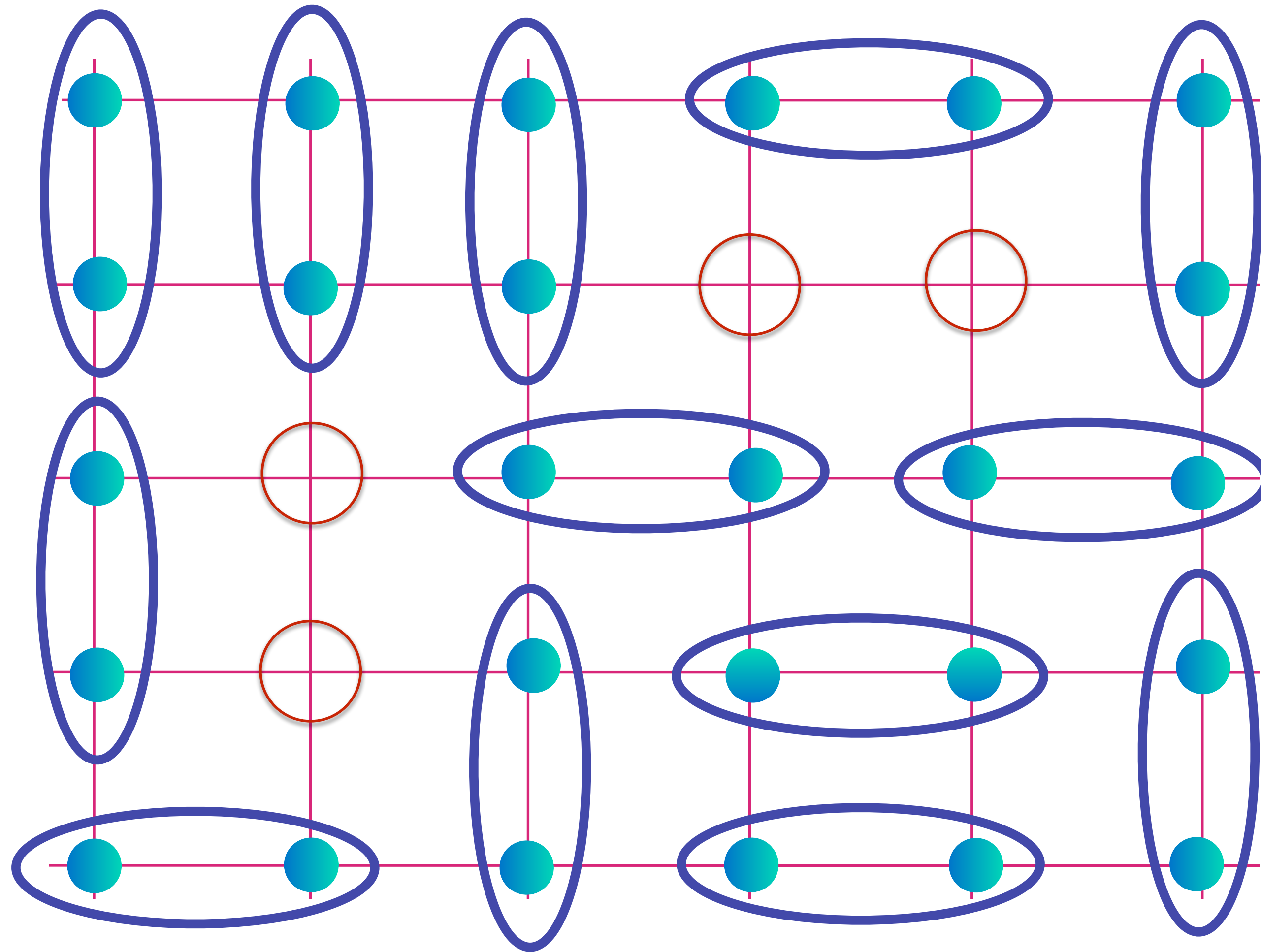
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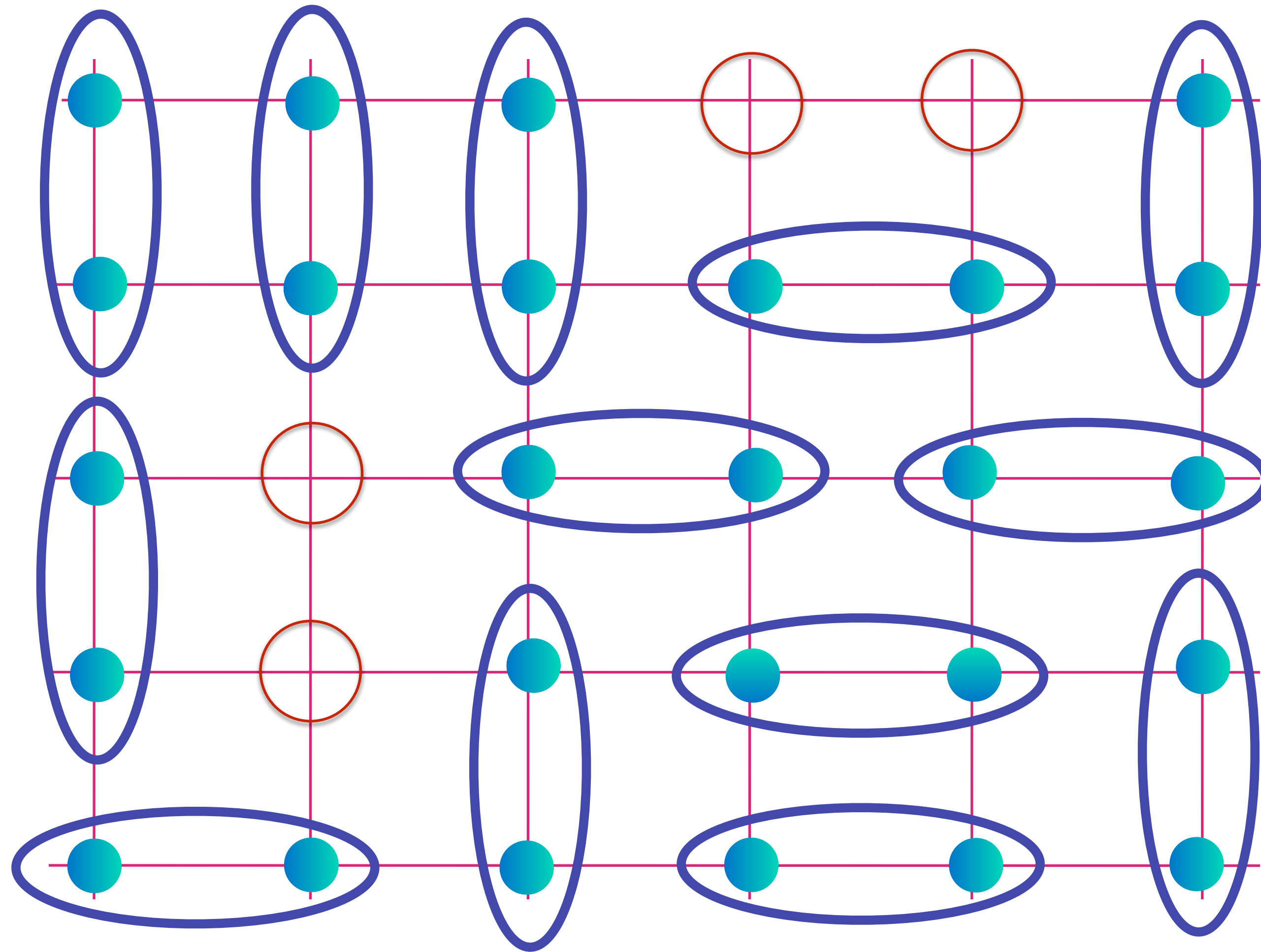
Superconductivity

Bose-Einstein  
condensation of  
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$$\text{Cooper pair} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$



# The dance of electrons on Cu atoms in YBCO

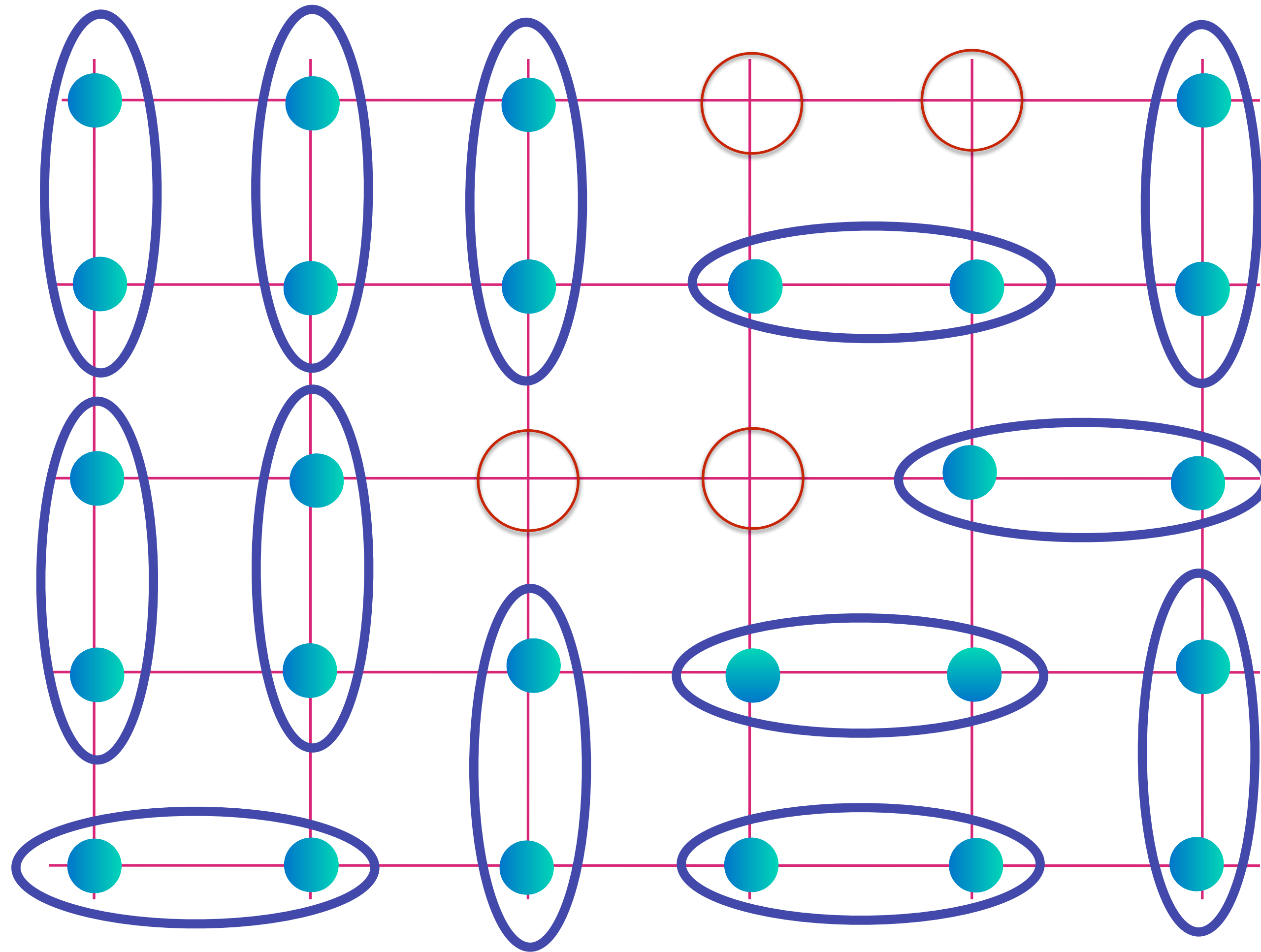


Superconductivity

Bose-Einstein  
condensation of  
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$$\text{Pair} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

# The dance of electrons on Cu atoms in YBCO



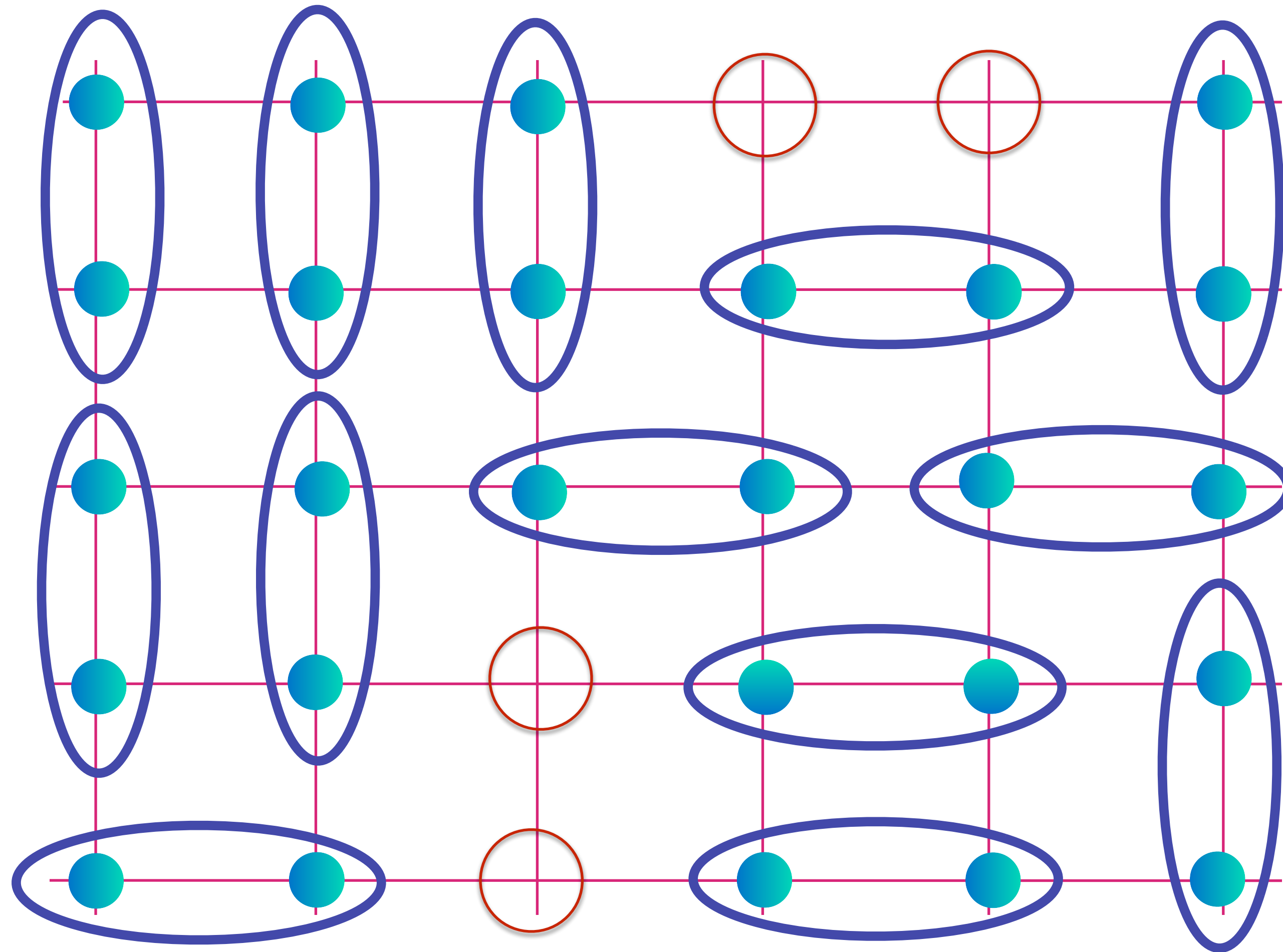
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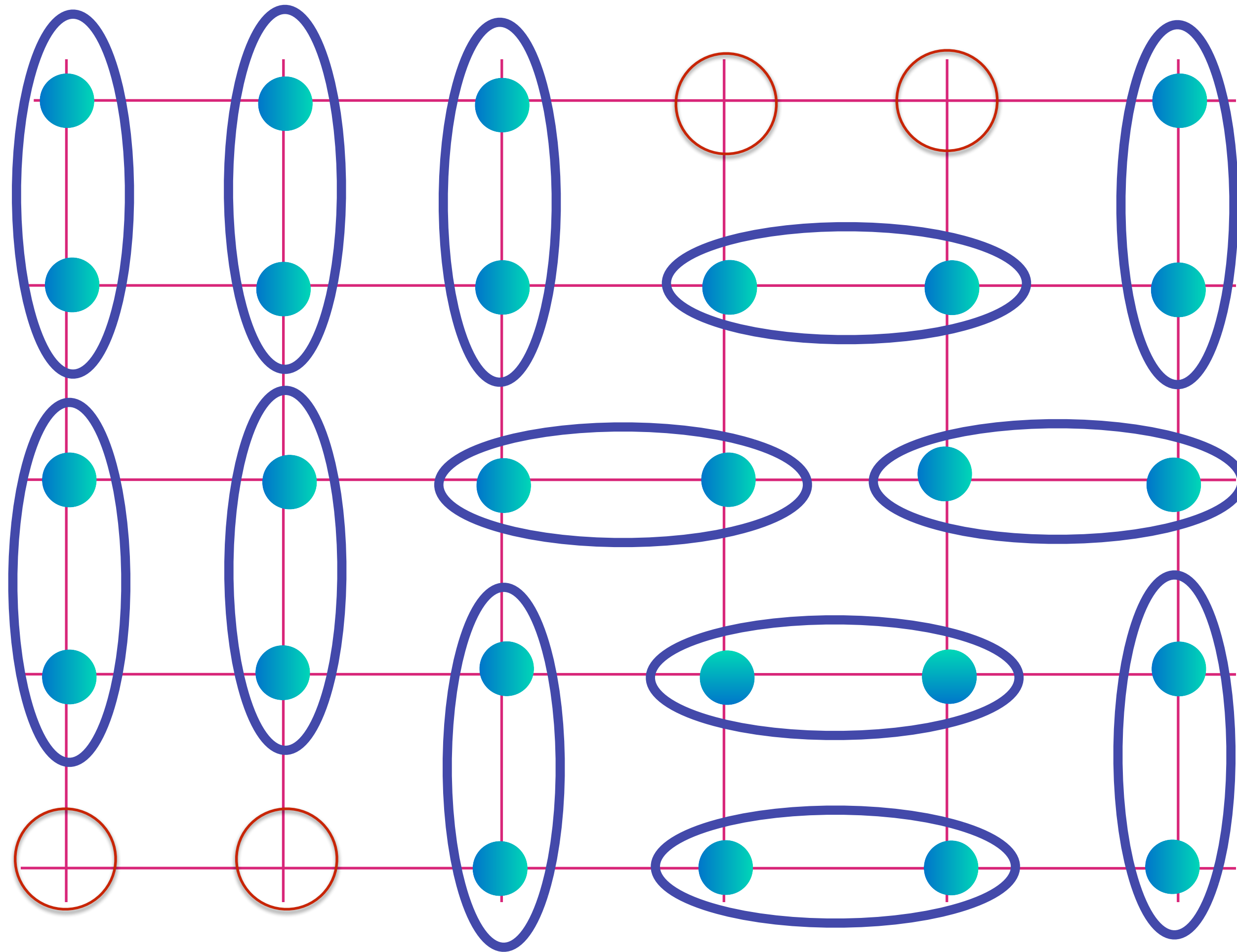


Superconductivity

Bose-Einstein  
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$$\text{[Diagram of a pair of electrons in a blue oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

# The dance of electrons on Cu atoms in YBCO



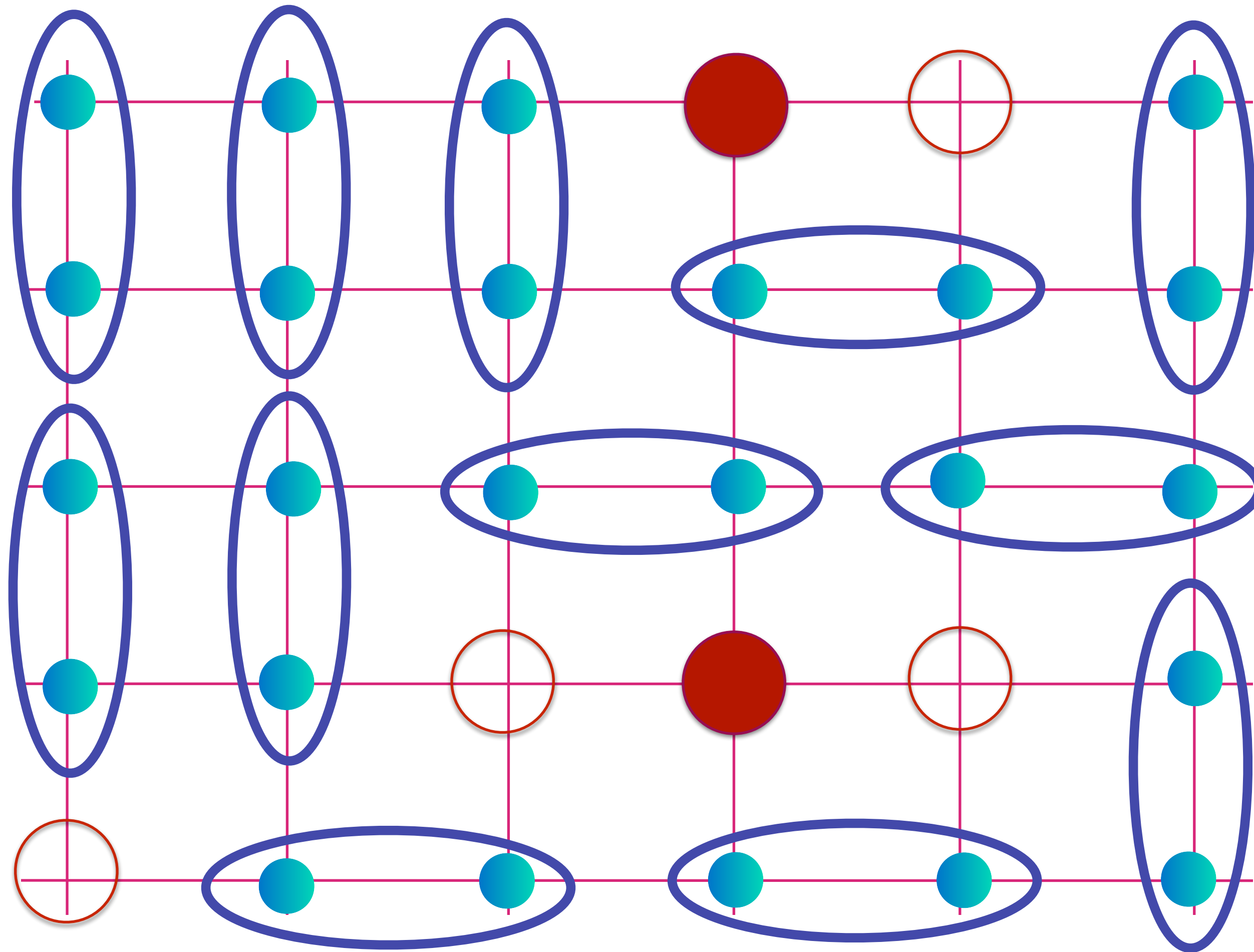
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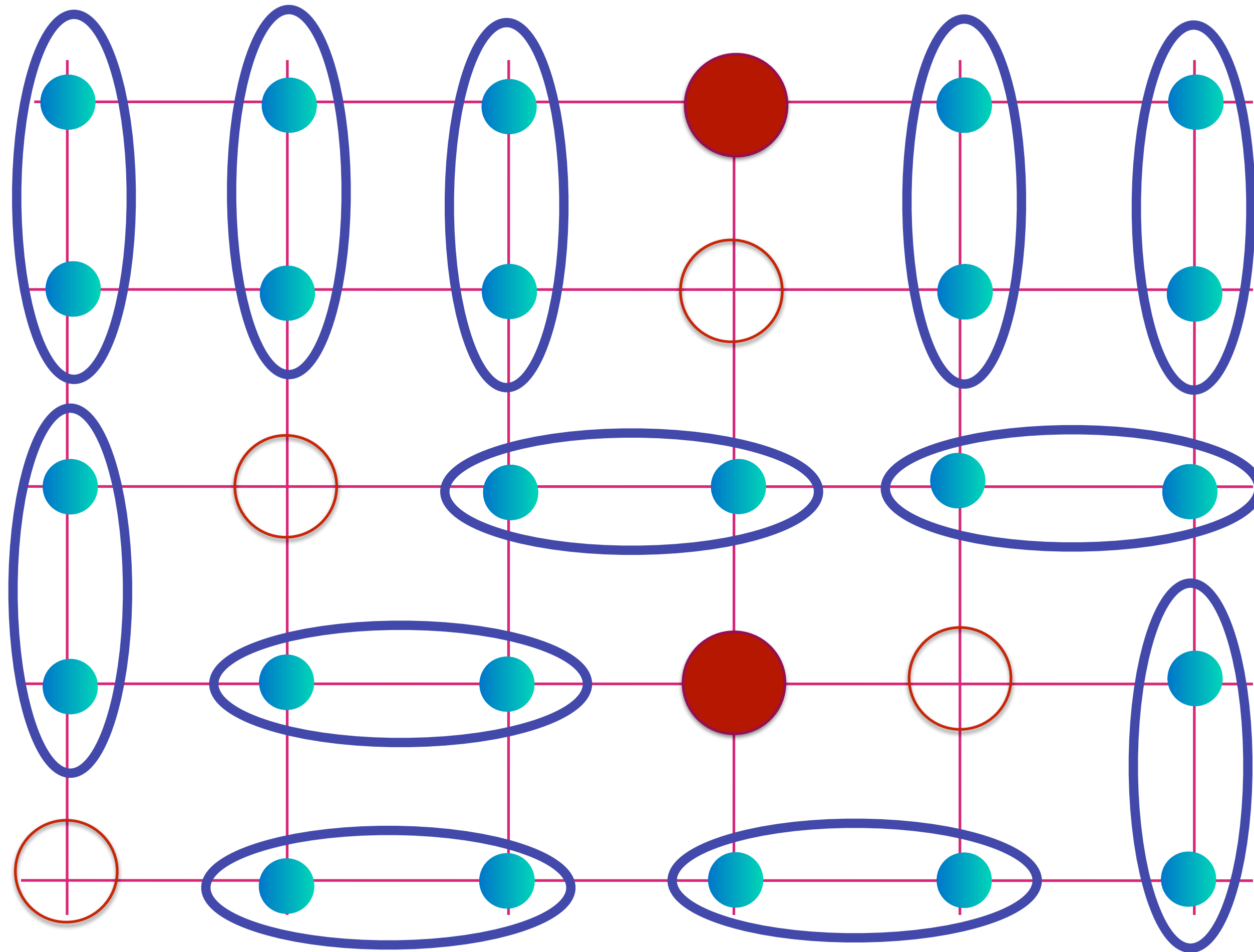


Strange metal

Complex entanglement in the presence of impurities, similar to that in the SYK model

$$\text{[Pair of blue circles in an oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

# The dance of electrons on Cu atoms in YBCO



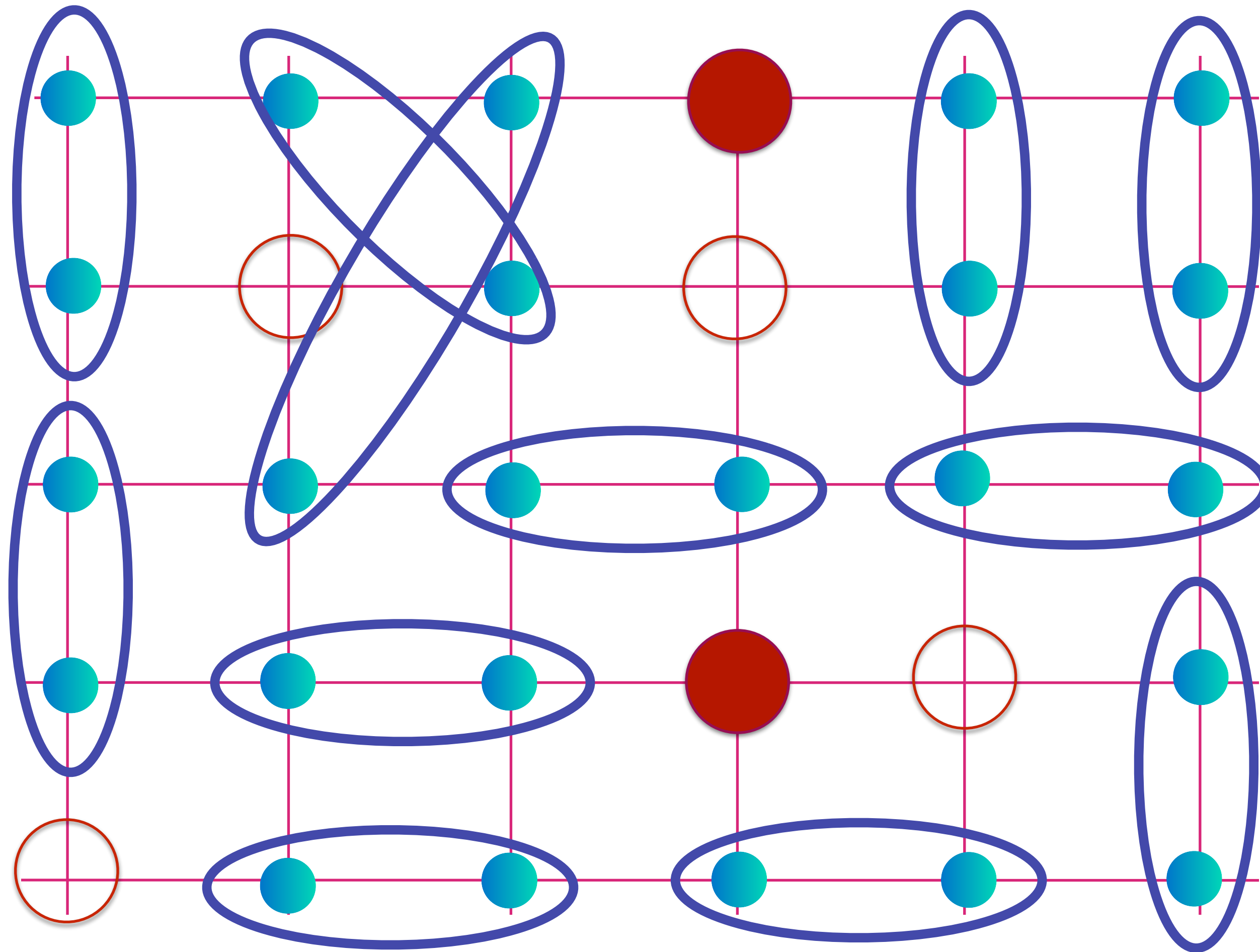
Strange metal

Complex entanglement in the presence of impurities, similar to that in the SYK model

$$\text{[Diagram of two cyan circles in a blue oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$



# The dance of electrons on Cu atoms in YBCO

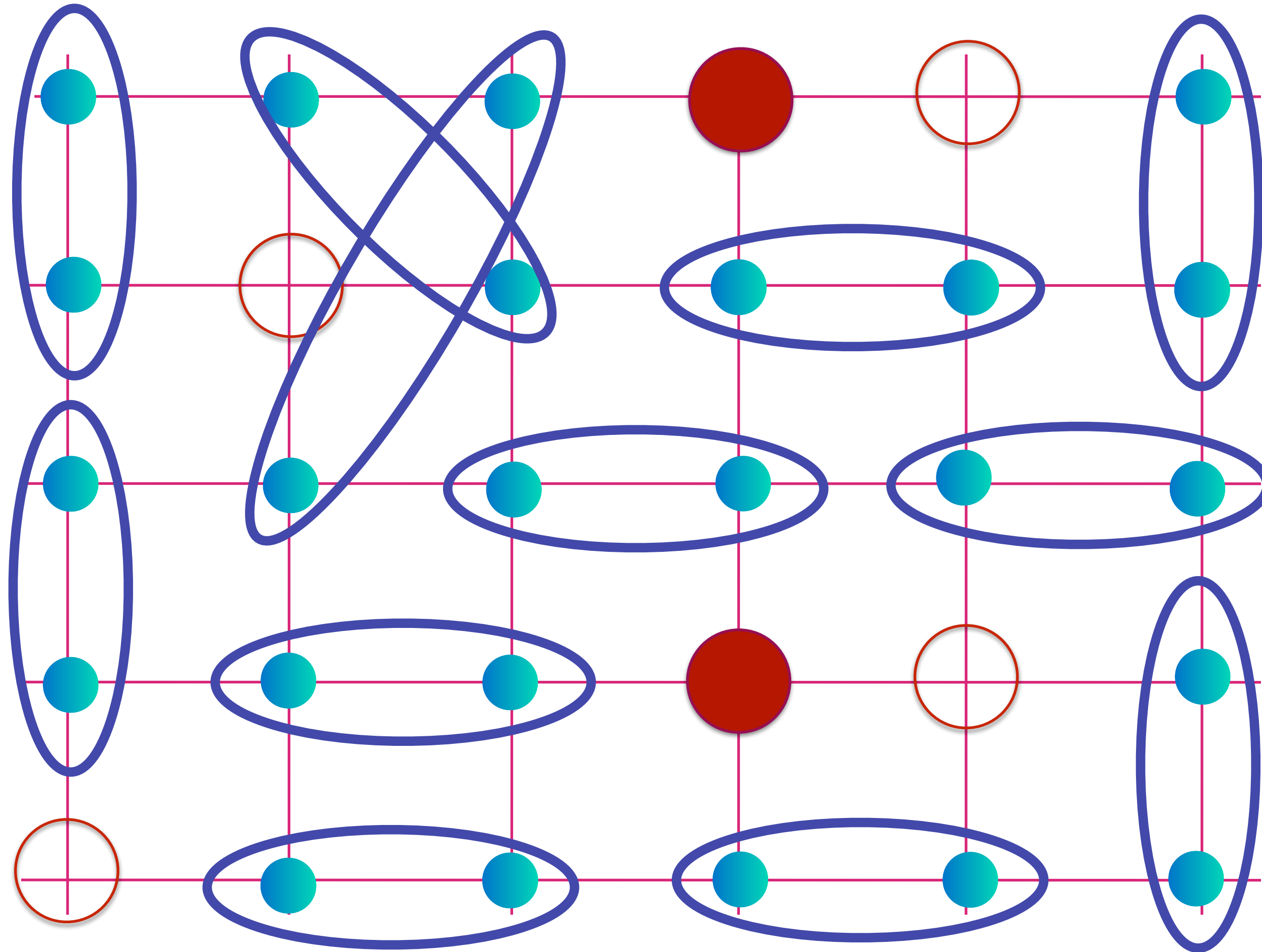


Strange metal

Complex entanglement in the presence of impurities, similar to that in the SYK model

$$\text{Blue oval with two dots} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

# The dance of electrons on Cu atoms in YBCO



Strange metal

Complex entanglement in the presence of impurities, similar to that in the SYK model

$$\text{[Diagram of a blue oval containing two teal dots]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

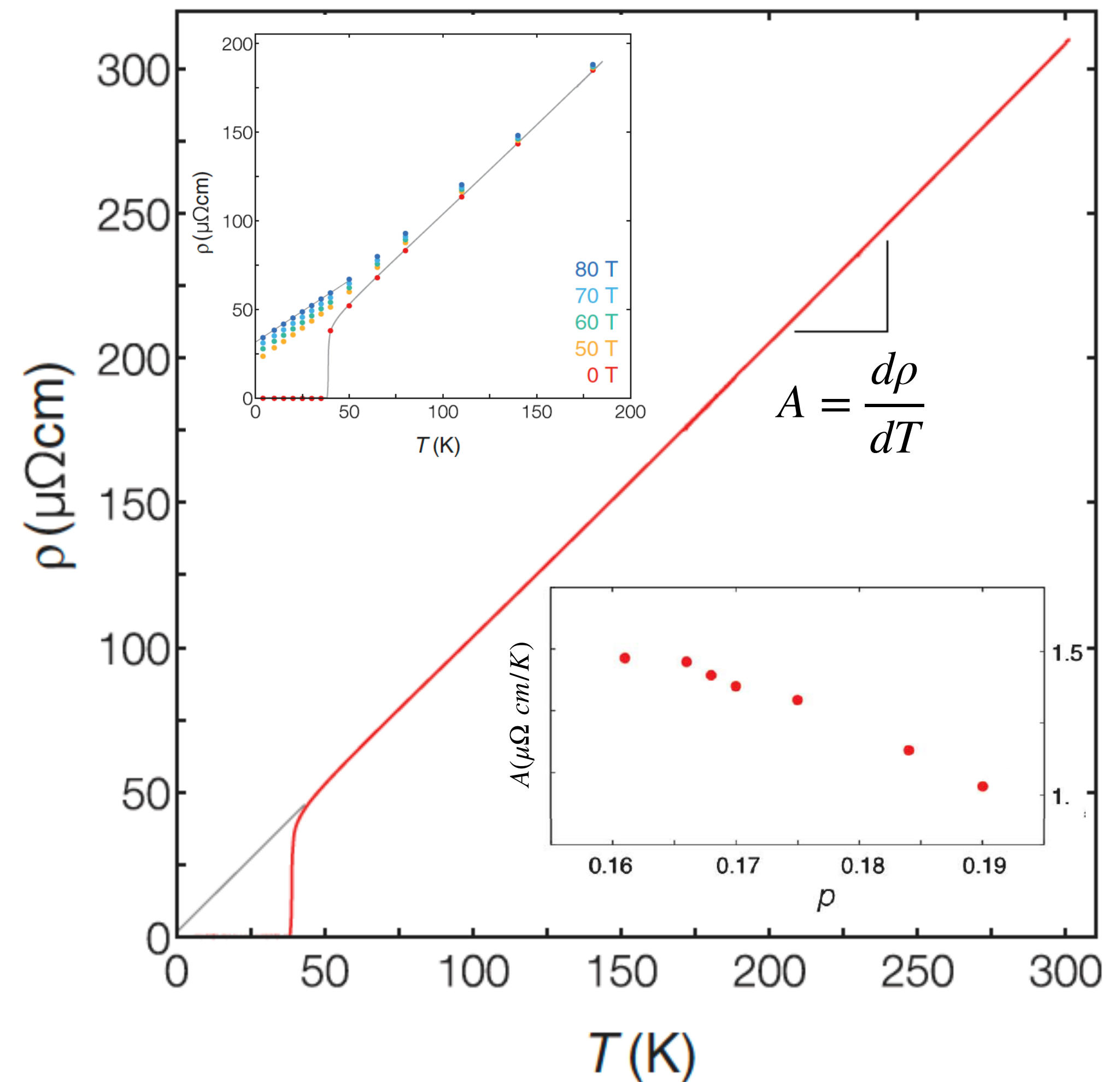
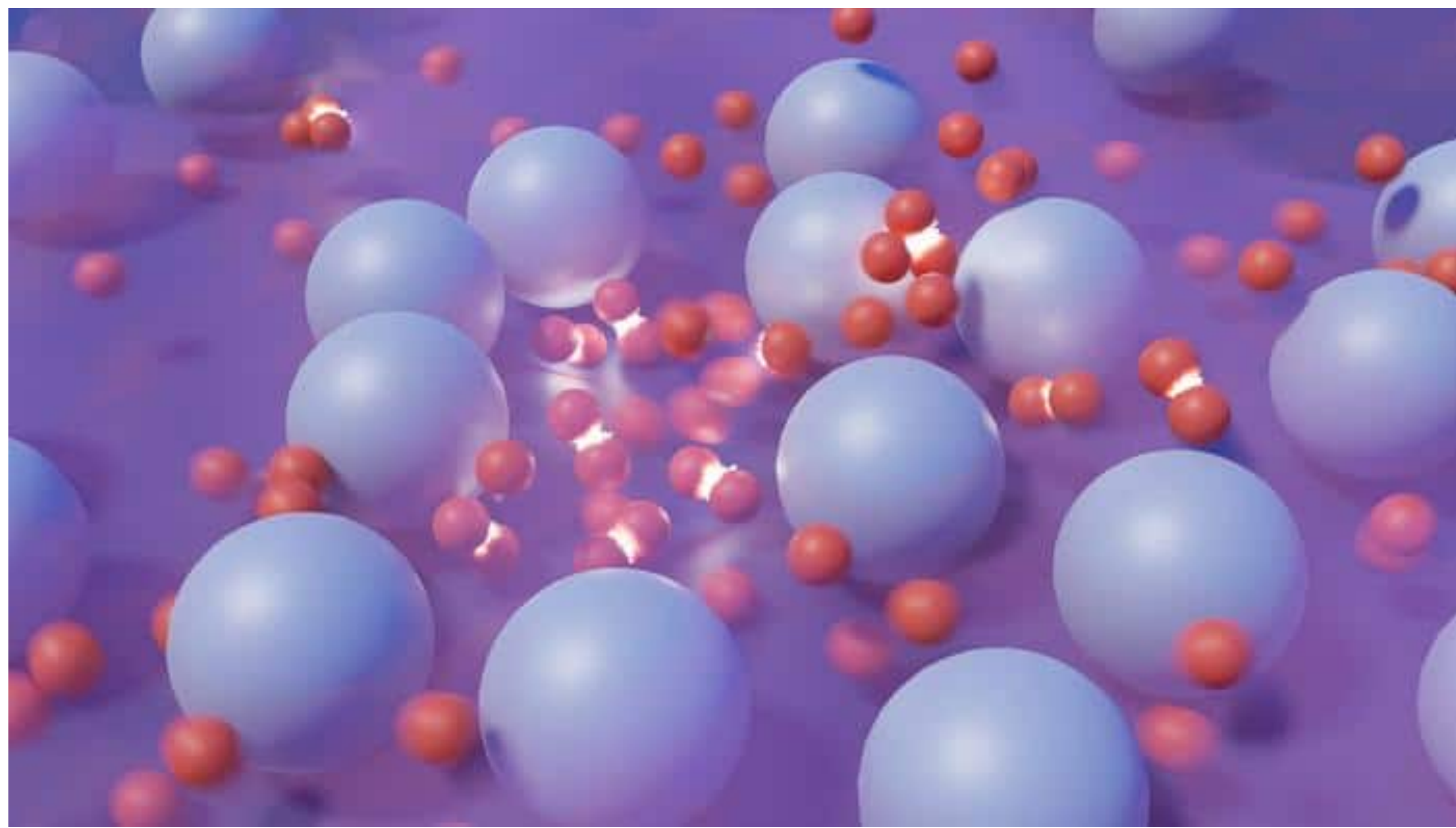




**Aavishkar Patel**  
Flatiron Institute

**Haoyu Guo**  
Cornell

**Ilya Esterlis**  
Wisconsin



**LSCO: Giraldo-Gallo et al. 2018**

Universal theory of strange metals from  
spatially random interactions,  
Aavishkar A. Patel, Haoyu Guo,  
Ilya Esterlis, and S. Sachdev,  
*Science* **381**, 790 (2023)

**Black  
holes**

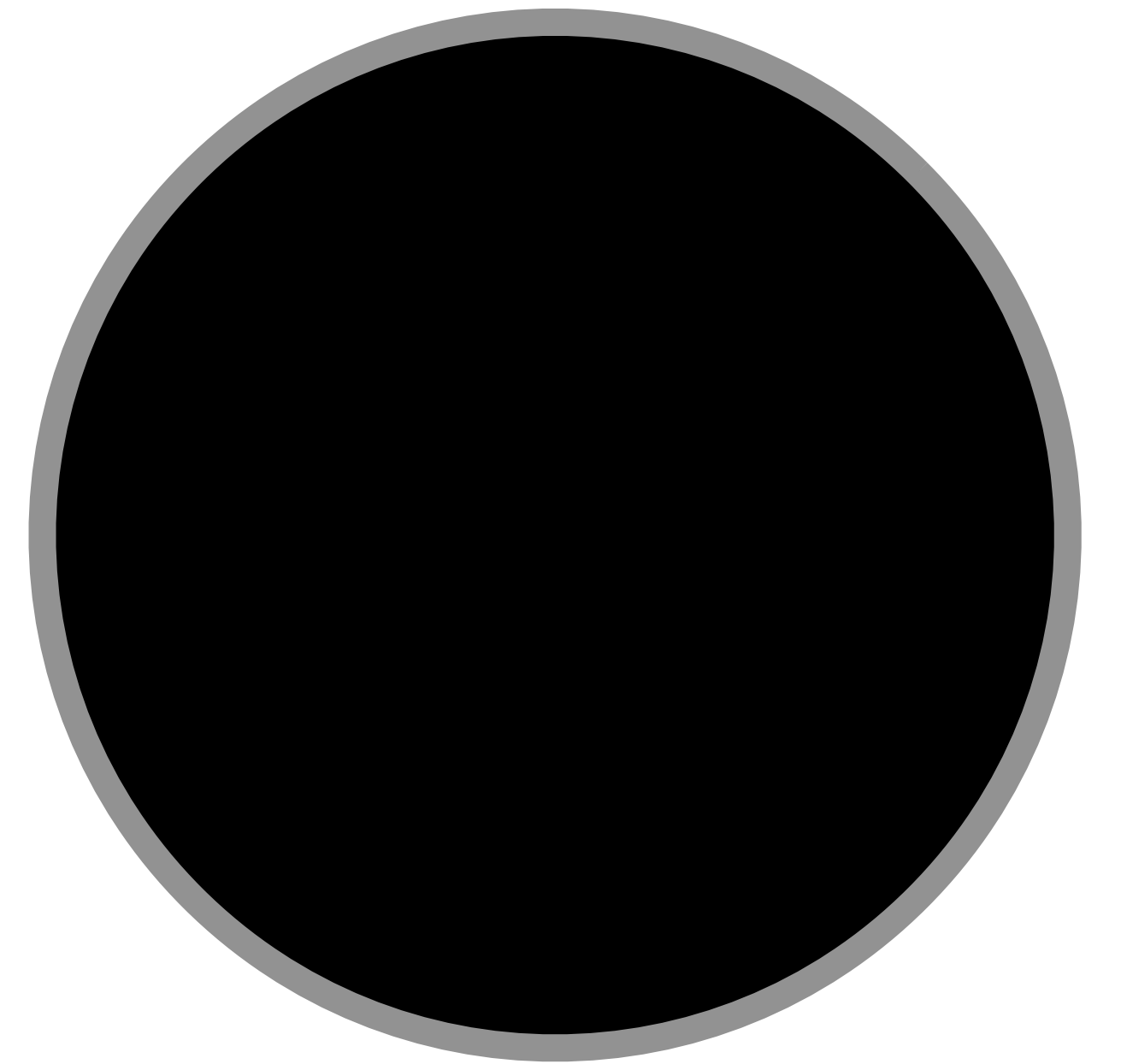


# Black Holes

Objects so dense that light is gravitationally bound to them.



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

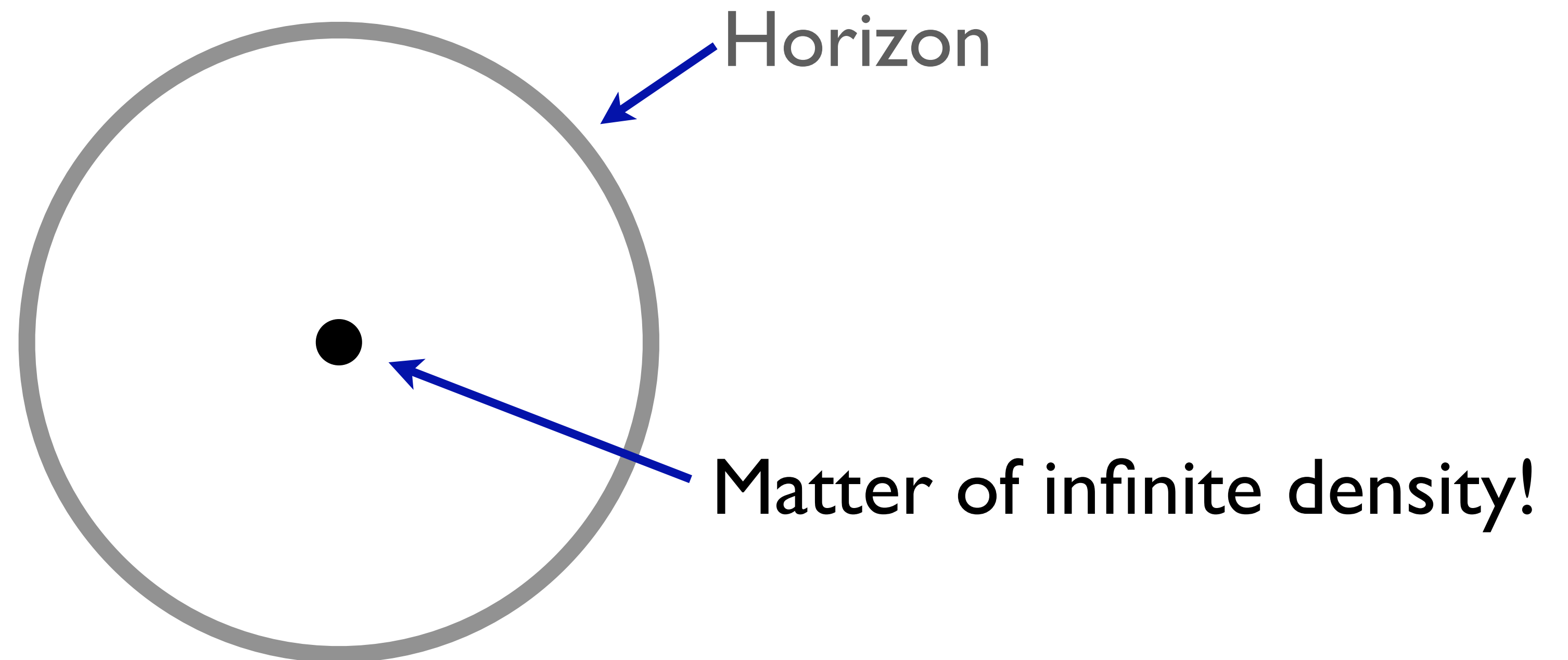


Karl Schwarzschild (1916)

$G$  Newton's constant,  $c$  velocity of light,  $M$  mass of black hole  
For  $M = \text{earth's mass}$ ,  $R \approx 9 \text{ mm}$ !

# What is inside a black hole ???

In Einstein's theory, all the matter in a black hole collapses to a singularity at the center of the black hole.





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In Einstein's theory, all the matter in a black hole collapses to a singularity at the center of the black hole.

This singularity convinced many early on that black holes were unphysical solutions of Einstein's equations, and did not exist in our universe.



The supermassive black hole lurking at the heart of the Milky Way – Sagittarius A\* contains about 4.3 million solar masses

$$R = 1.3 \times 10^{11} \text{ m}$$

$\approx$  earth's orbit

Event Horizon Telescope  
May 12, 2022



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This singularity convinced many early on that black holes were unphysical solutions of Einstein's equations, and did not exist in our universe.

In any case, it was clear that quantum theory should be applied to the collapsed matter, but no one knew how to.



# What is inside a black hole ???

Hawking (1975): when viewed from the outside, black holes have an entropy and a temperature, and slowly evaporate like any thermal object

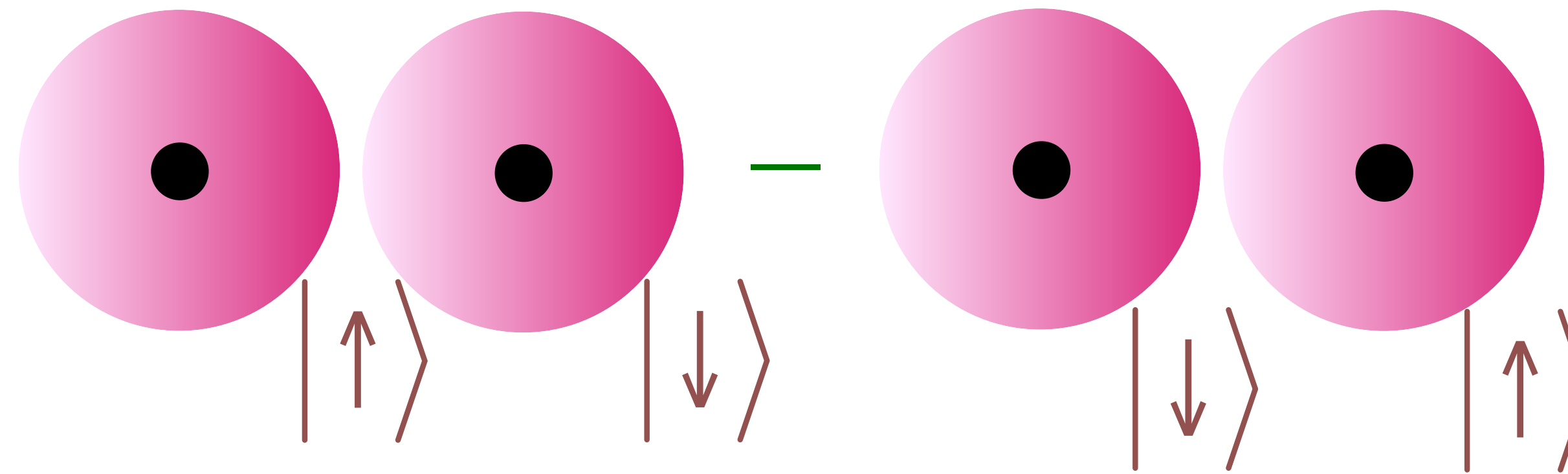


$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

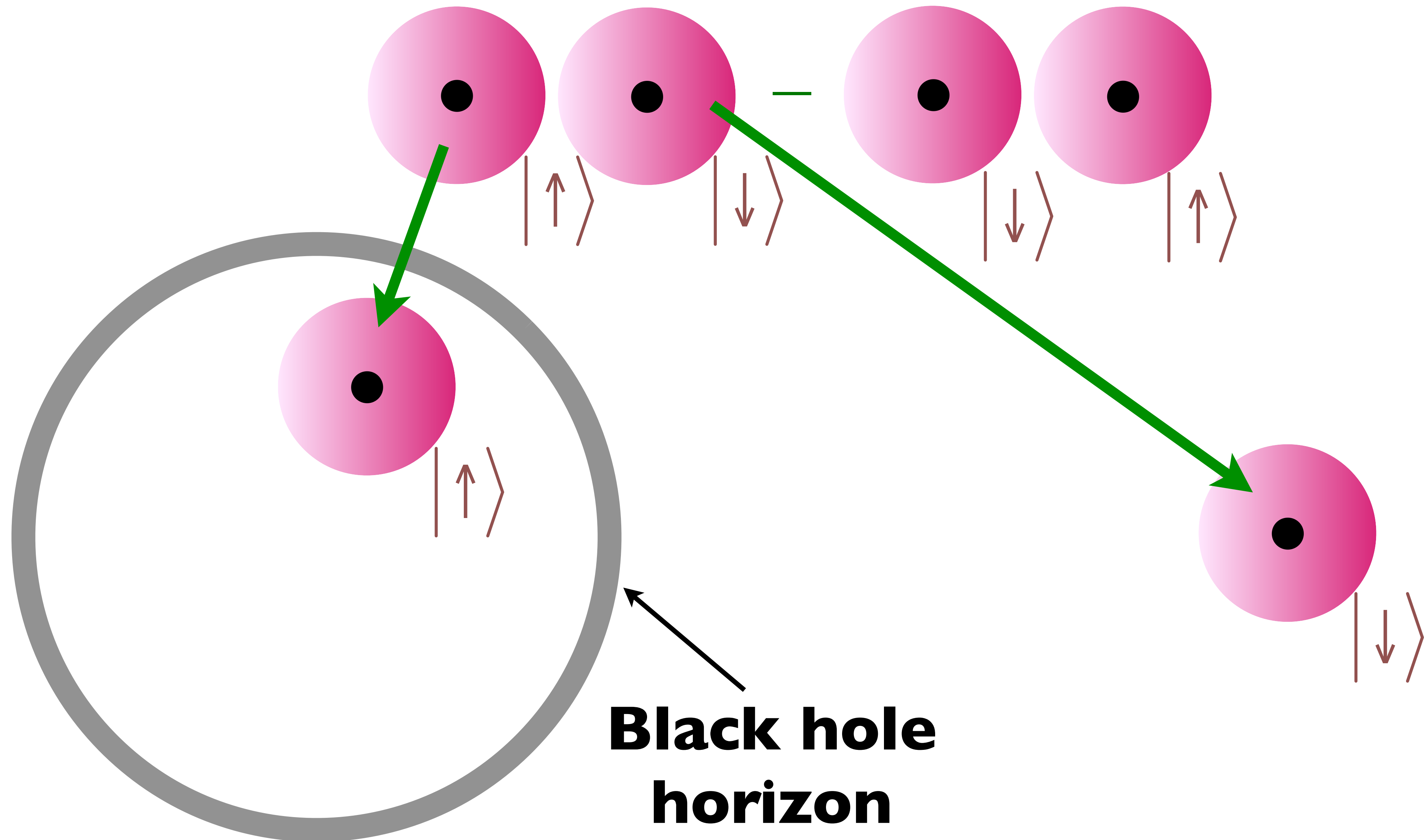
Quantum entanglement,  
the SYK model,  
and black holes  
holes



# Quantum Entanglement across a black hole horizon

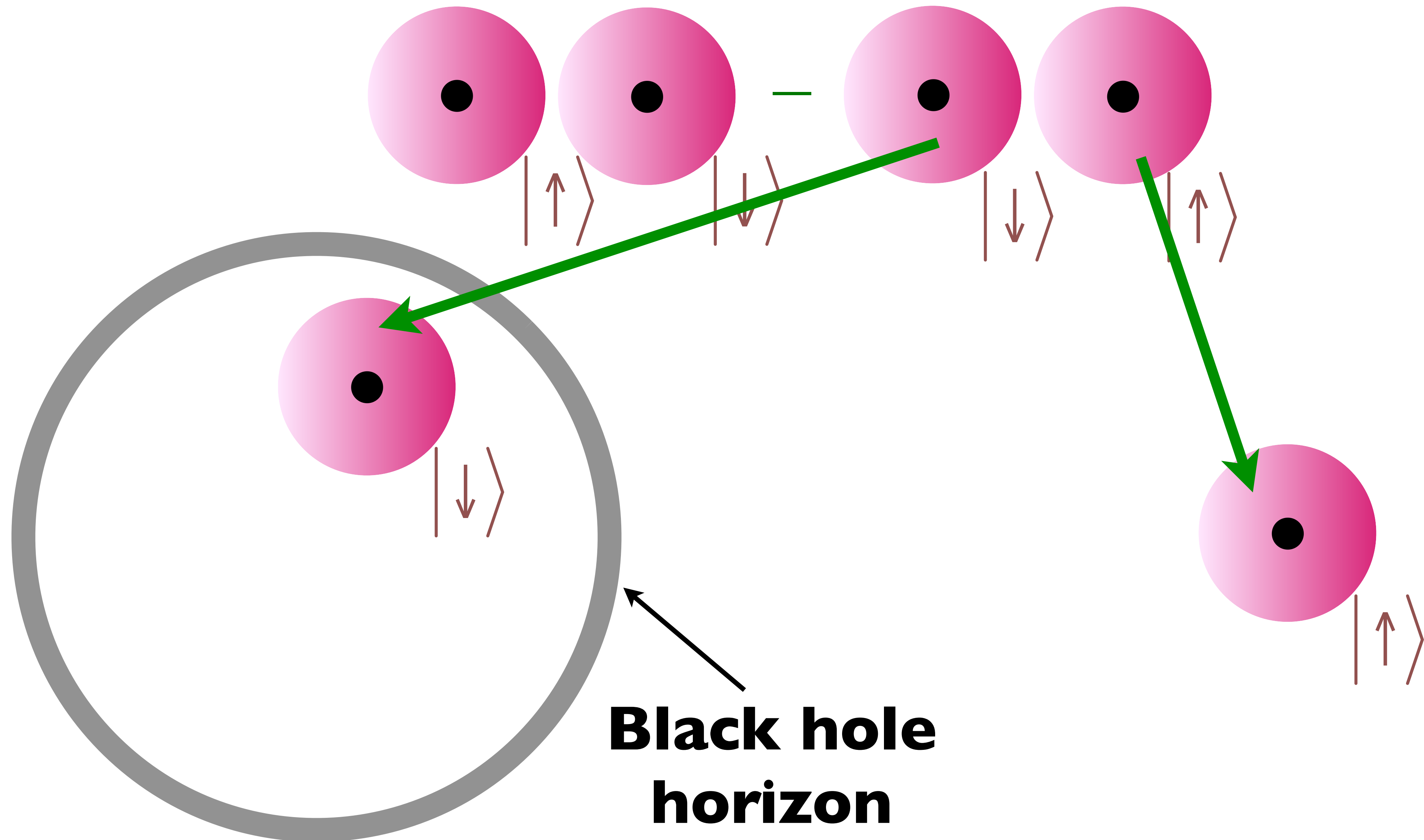


# Quantum Entanglement across a black hole horizon



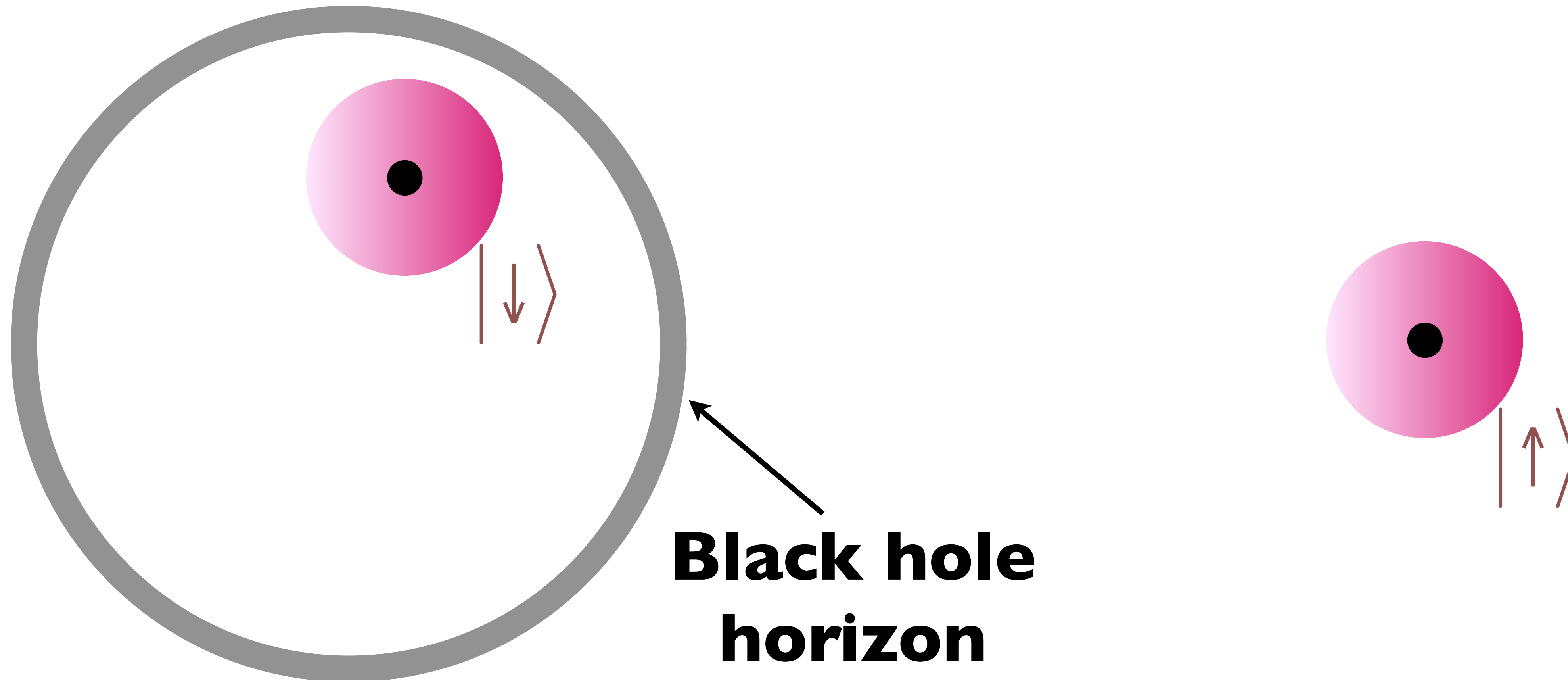


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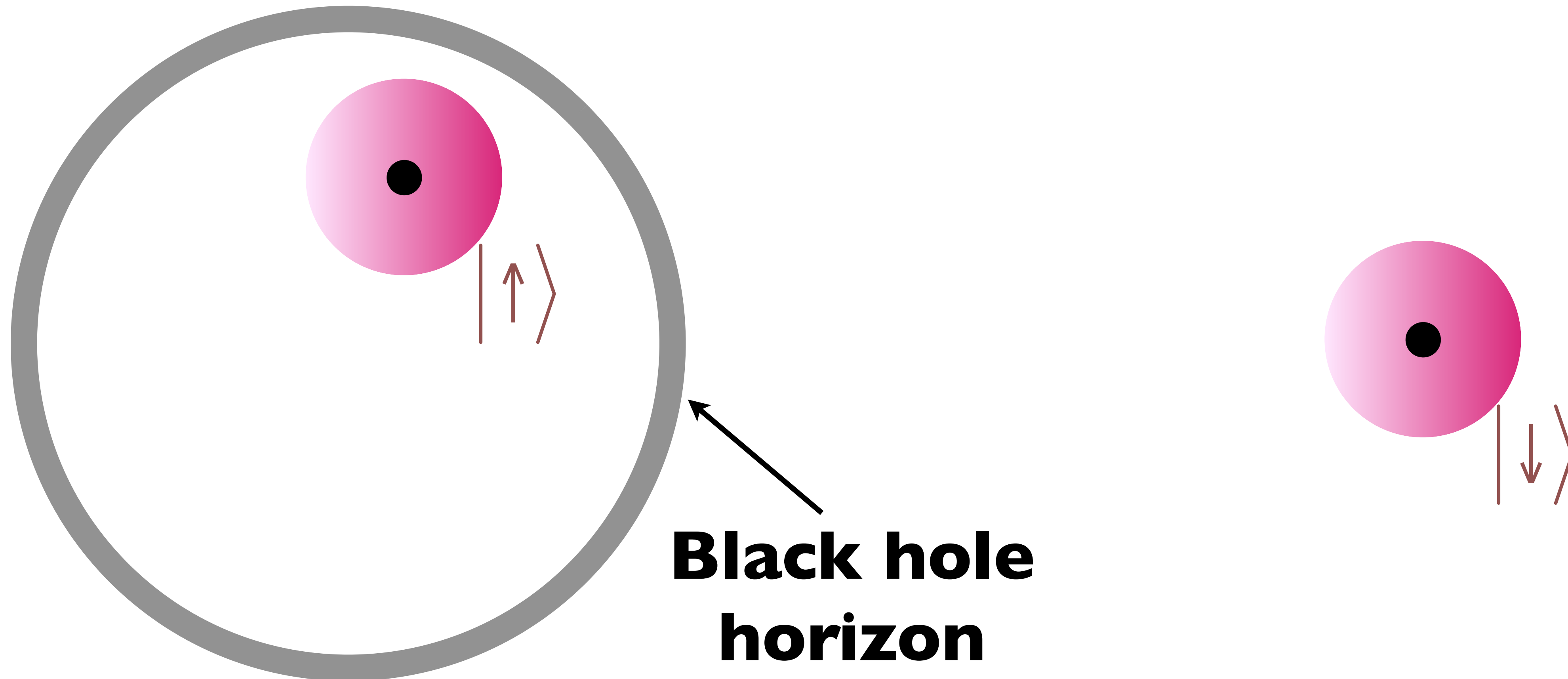
There is quantum entanglement between the inside and outside of a black hole





# Quantum Entanglement across a black hole horizon

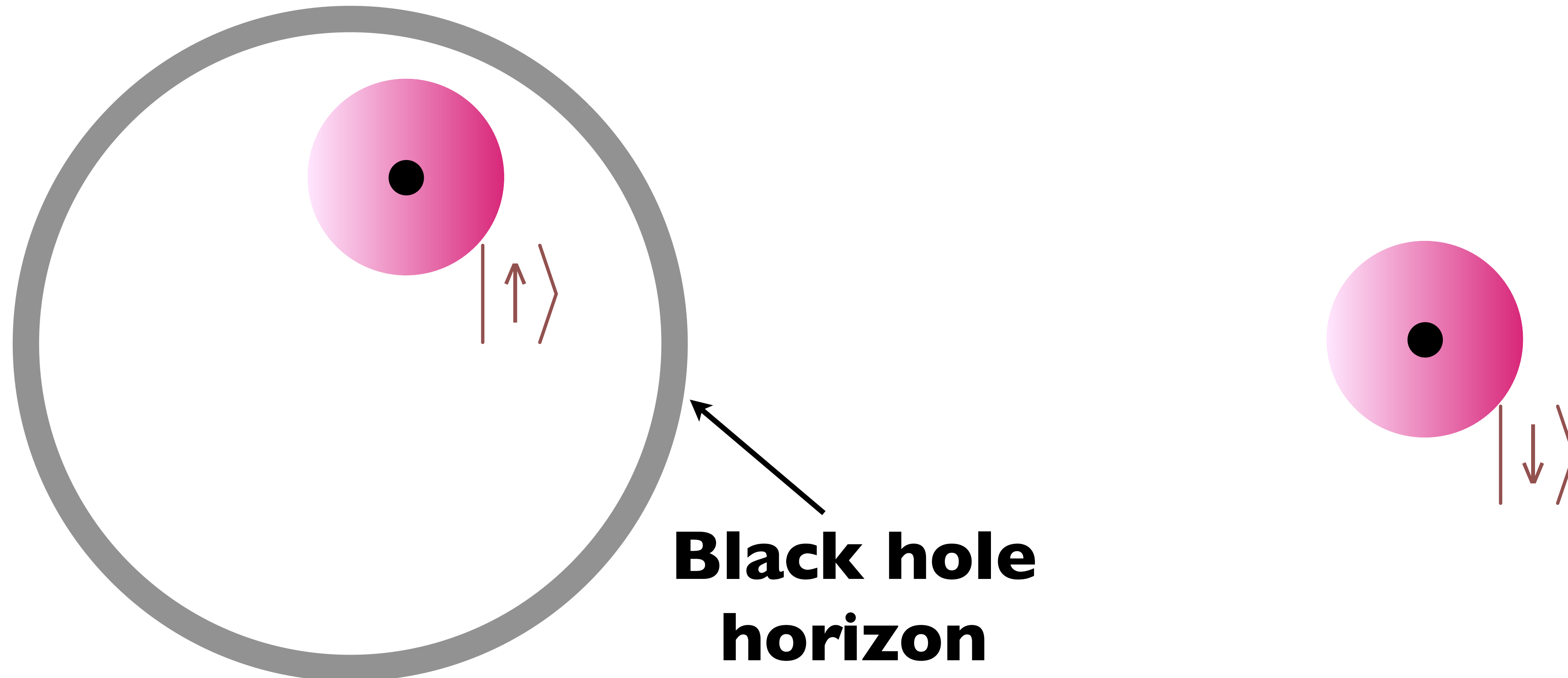
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# Quantum Entanglement across a black hole horizon

*Hawking (1975): Black holes have a temperature and an entropy!*

To an outside observer, the state of the electron inside the black hole cannot be known, and so the outside electron is in a random state.

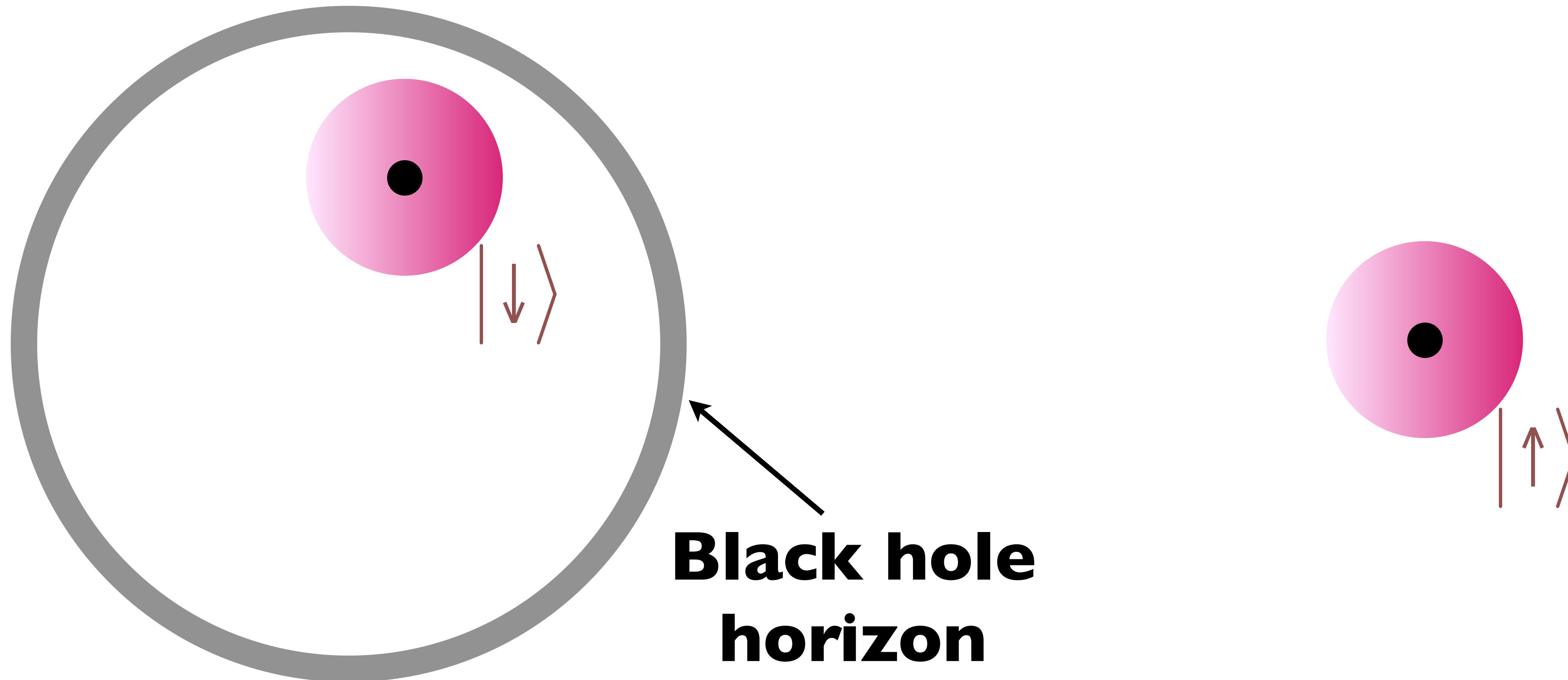




# Quantum Entanglement across a black hole horizon

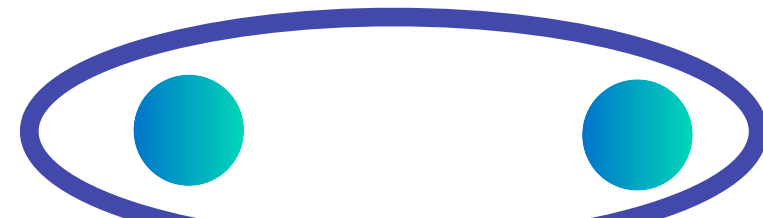
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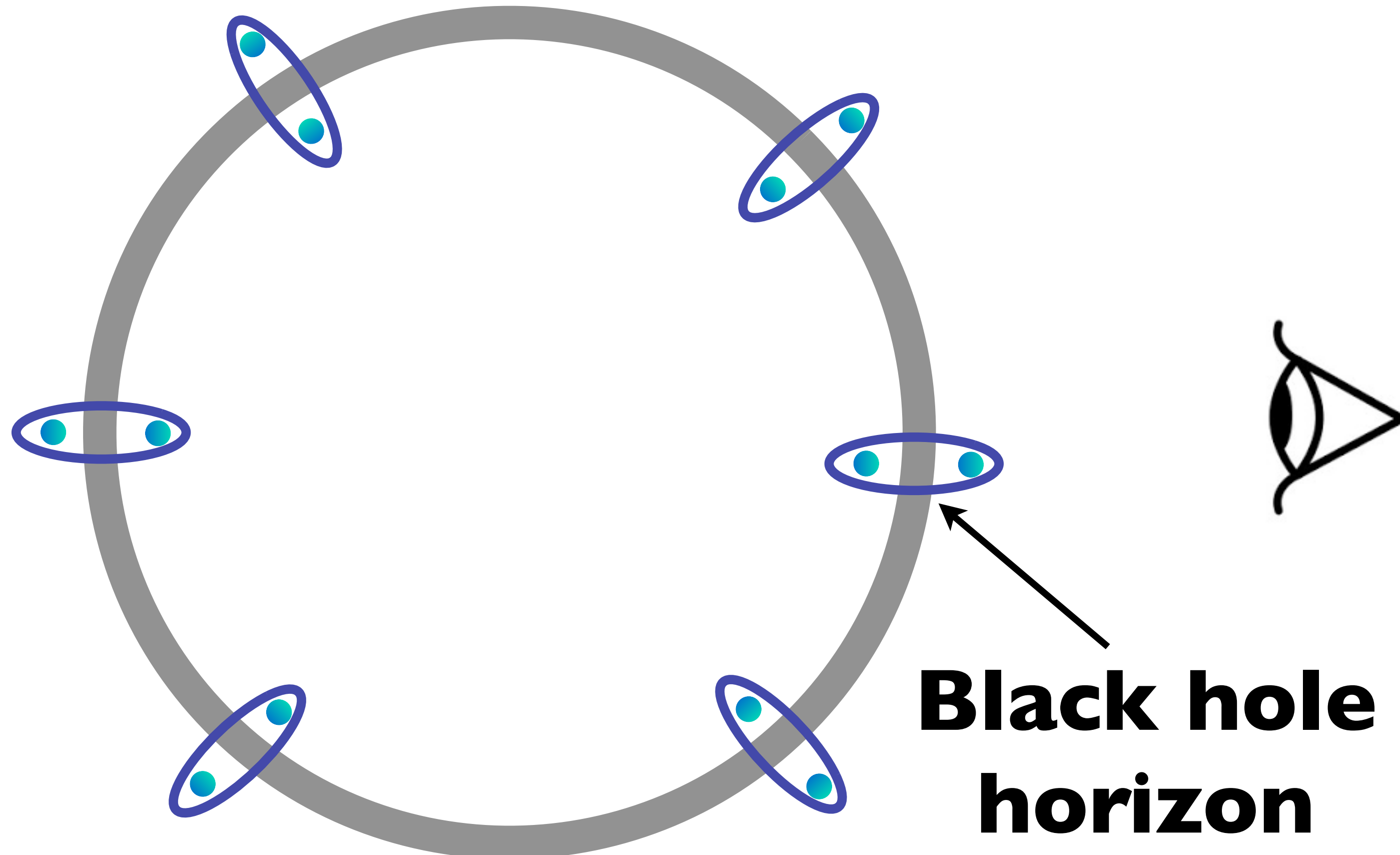
To an outside observer, the state of the electron inside the black hole cannot be known, and so the outside electron is in a random state.



# Quantum Entanglement across a black hole horizon

Quantum entanglement  
on the surface

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



By computations *outside*  
the black hole,  
Hawking obtained

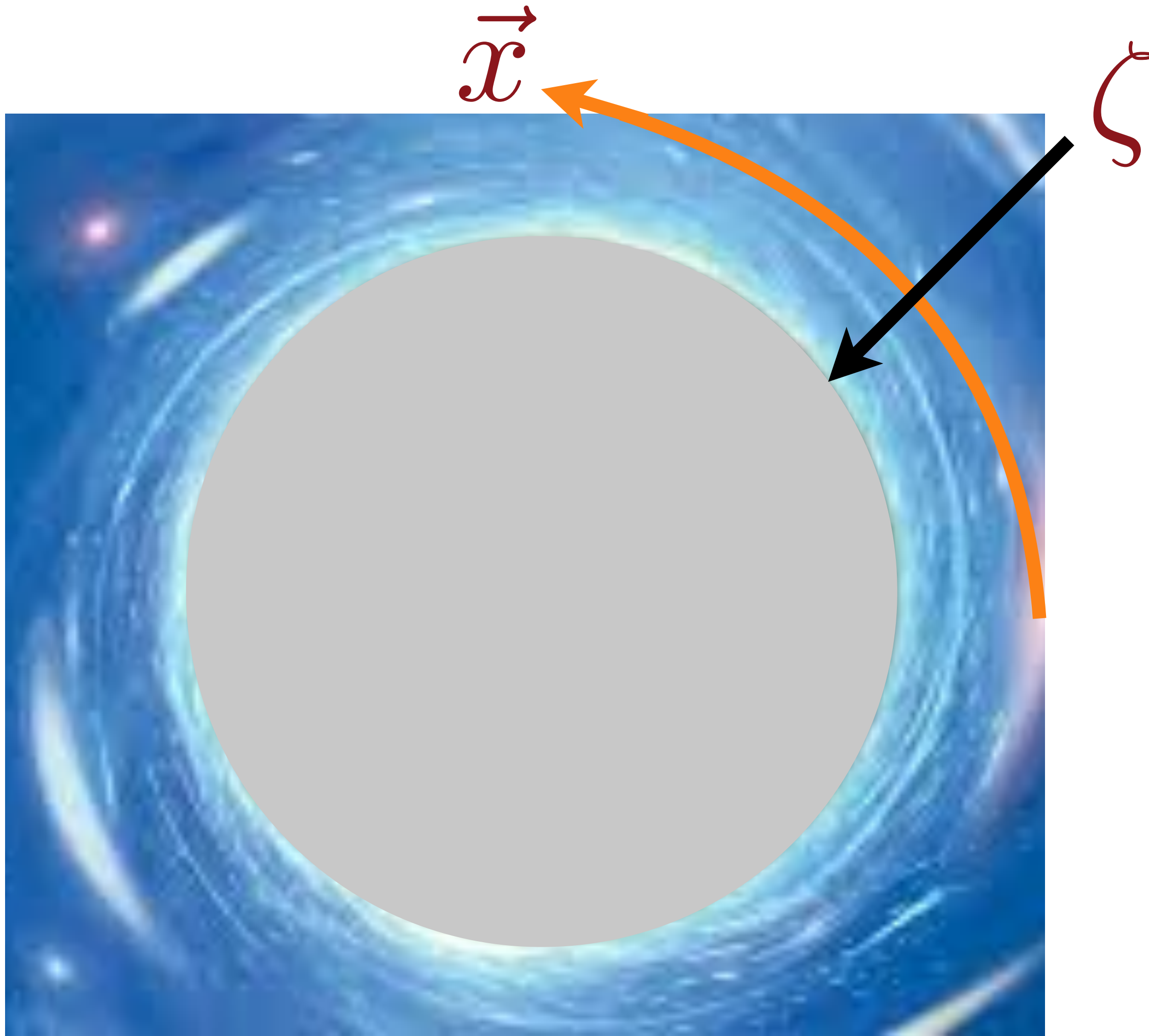
$$S = \frac{Ac^3}{4G\hbar}$$

where  $A$  is area of the  
black hole horizon.

All other systems have  
entropy proportional to  
their volume.



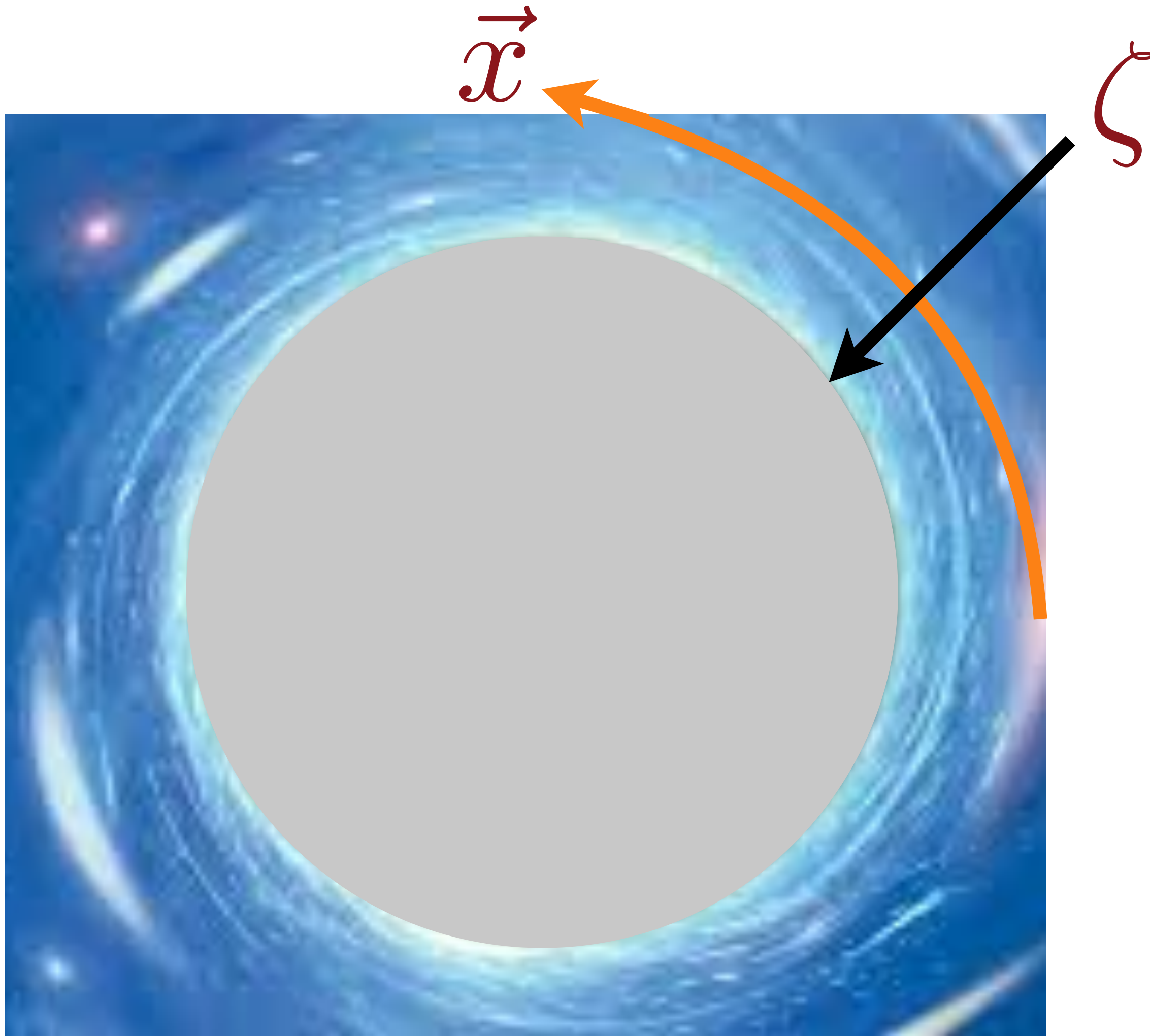
Maxwell's electromagnetism  
and Einstein's general relativity  
allow black hole solutions with a net charge







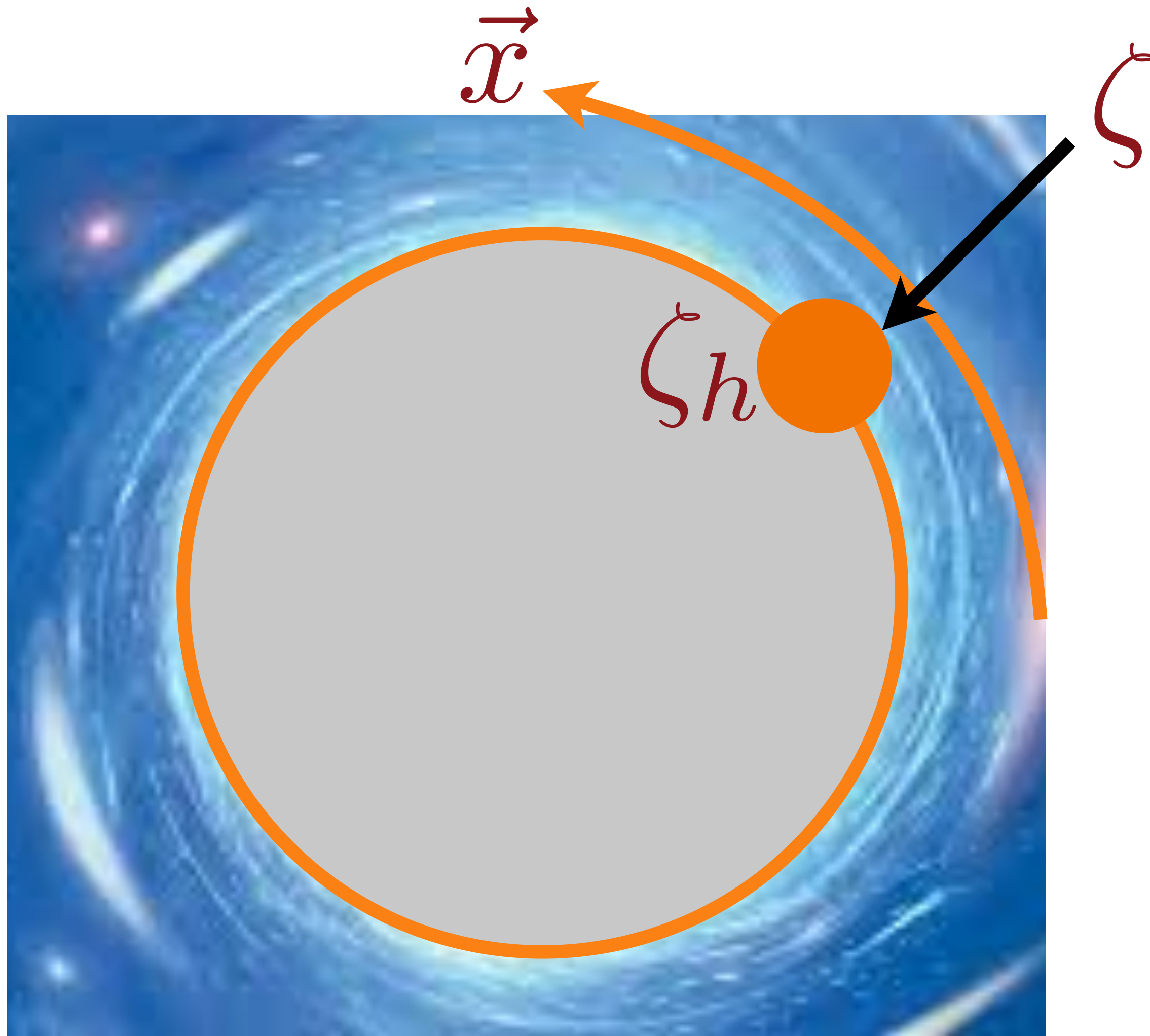
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Zooming into the  
near-horizon region  
of a charged black hole  
at low temperature,  
yields a theory  
in one space ( $\zeta$ ) and  
one time dimension



Maxwell's electromagnetism  
and Einstein's general relativity  
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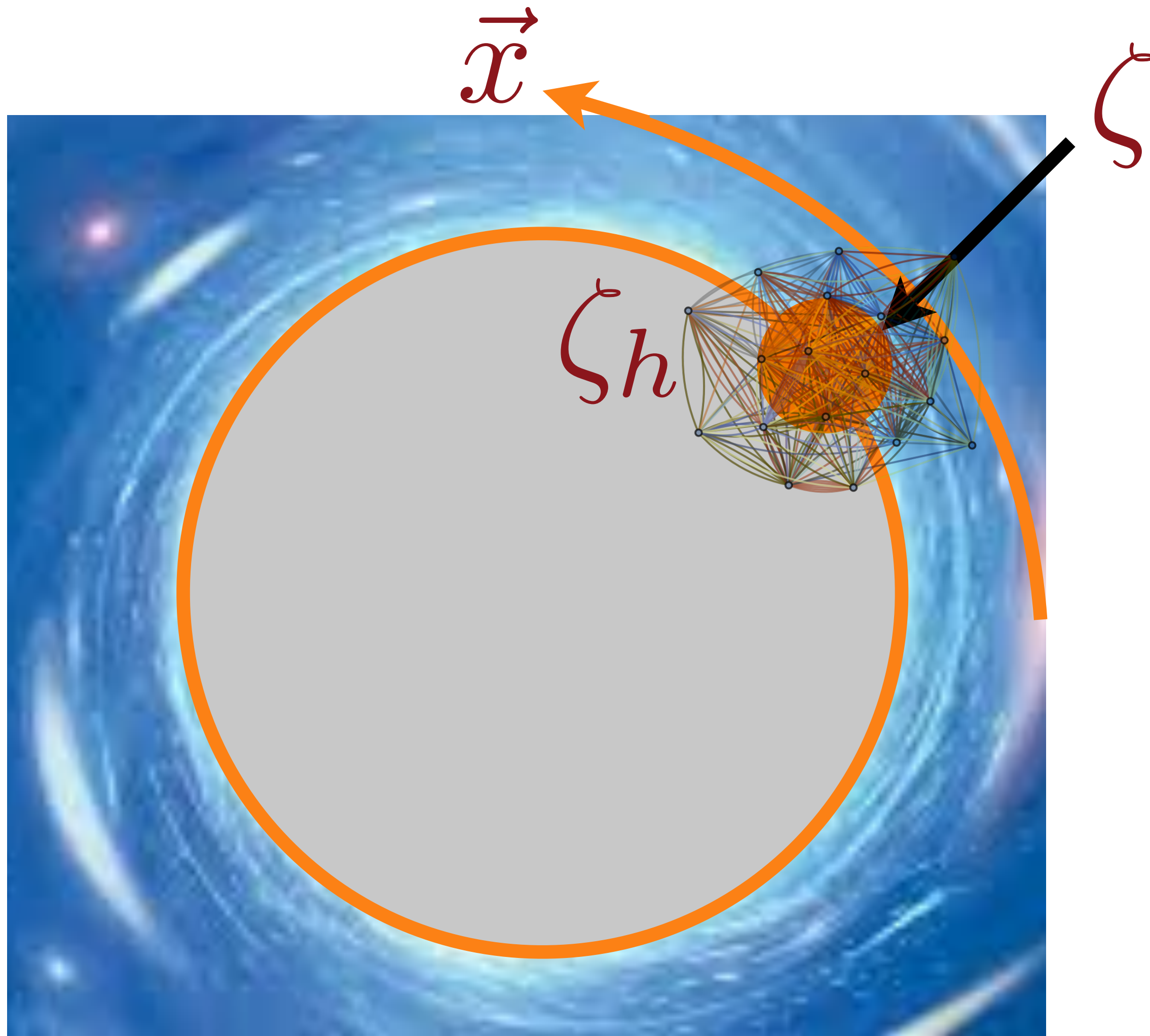


So we need only consider  
complex entanglement at  
one spatial “point”  
on the horizon ( $\zeta = \zeta_h$ ),  
just as is described  
by the SYK model





Maxwell's electromagnetism  
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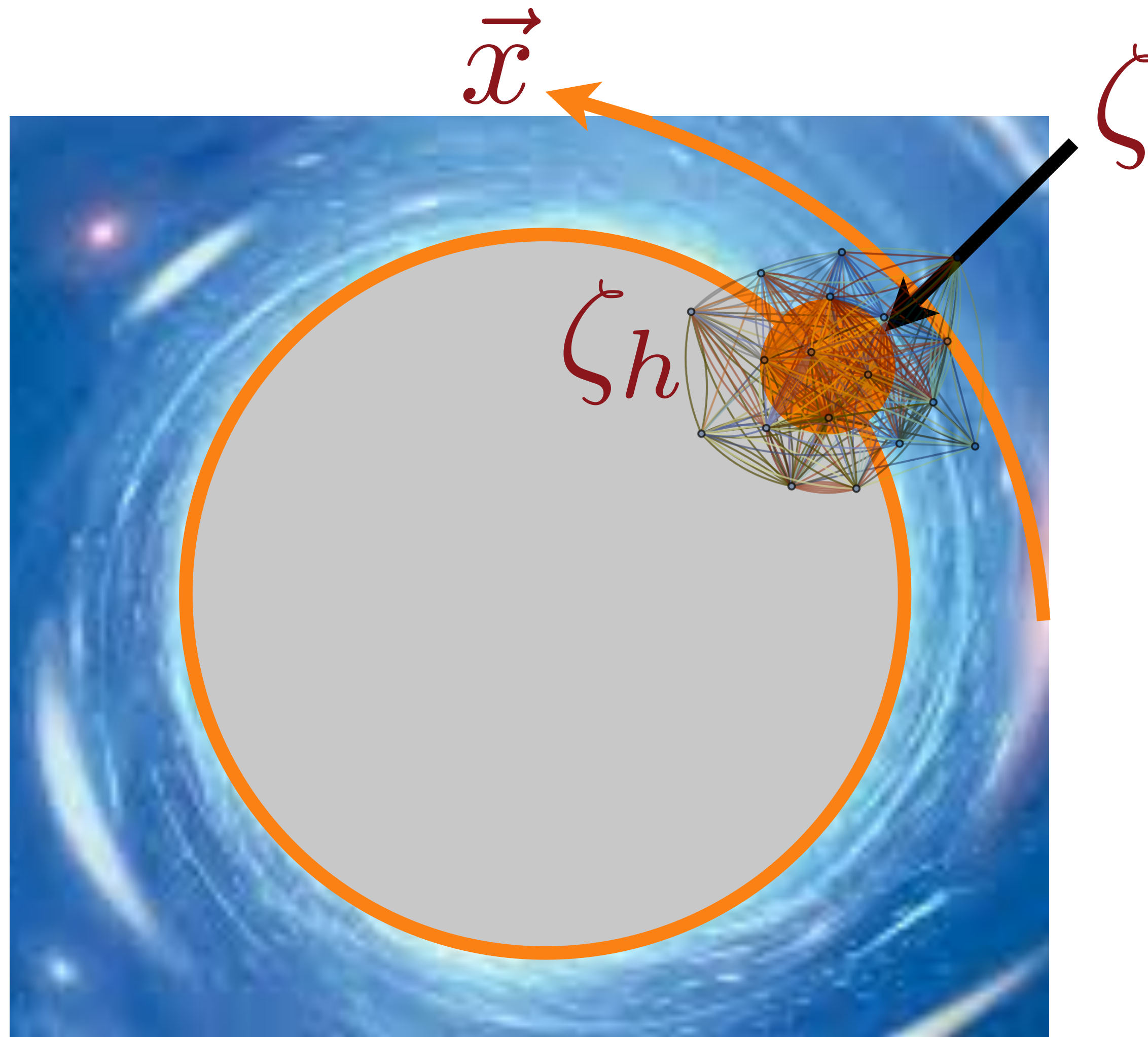


The quantum versions of  
Maxwell's and Einstein's  
equations in this  
two-dimensional spacetime are  
also the equations describing  
electron entanglement in the  
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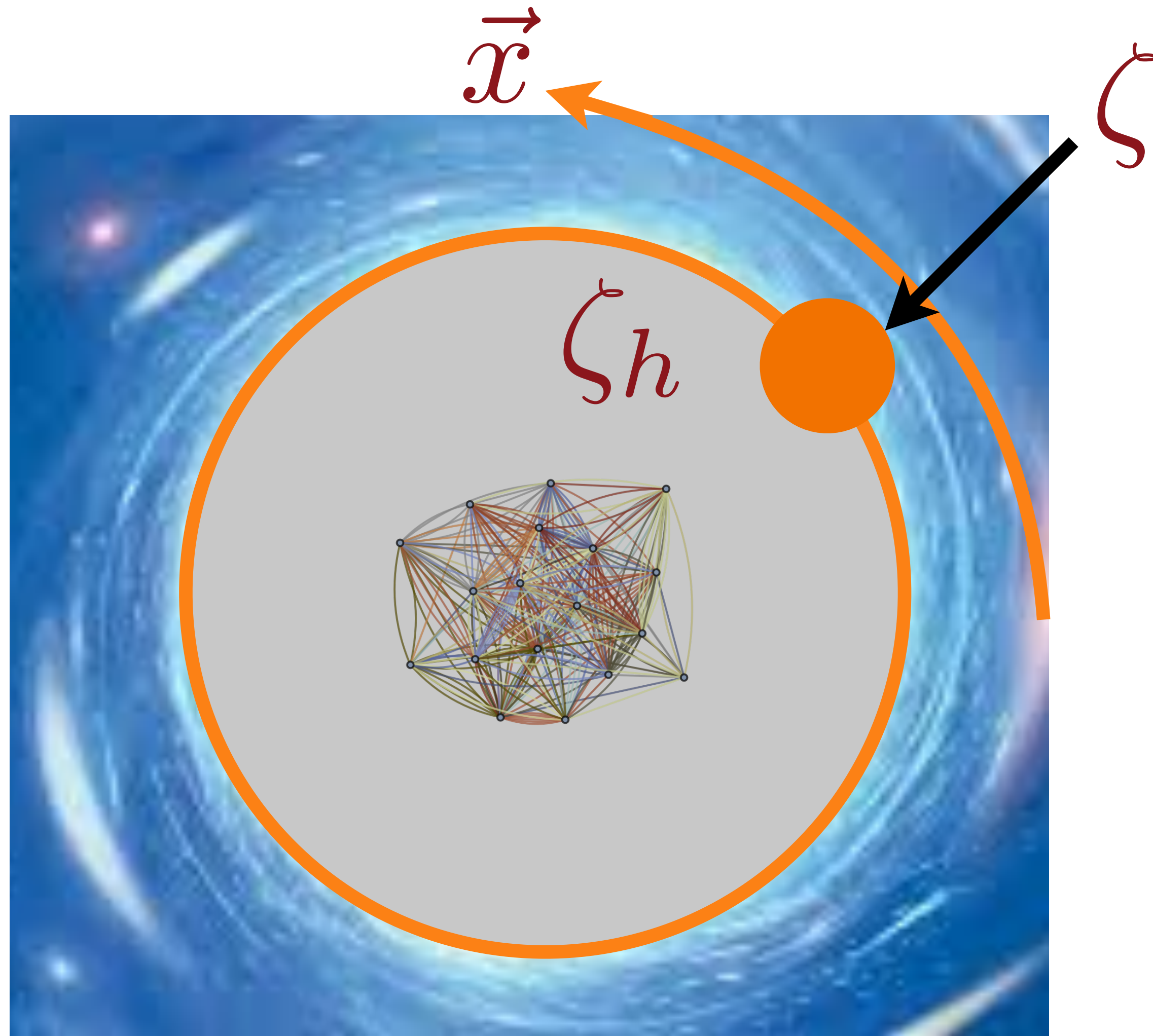


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# D(E) of charged black holes from the SYK model

- For generic charged black holes in 3+1 dimensions with horizon area  $A$  at  $T = 0$  and fixed charge  $Q$  ( $A = 2GQ^2/c^4$ ), the density of quantum states at small energy  $E$  is

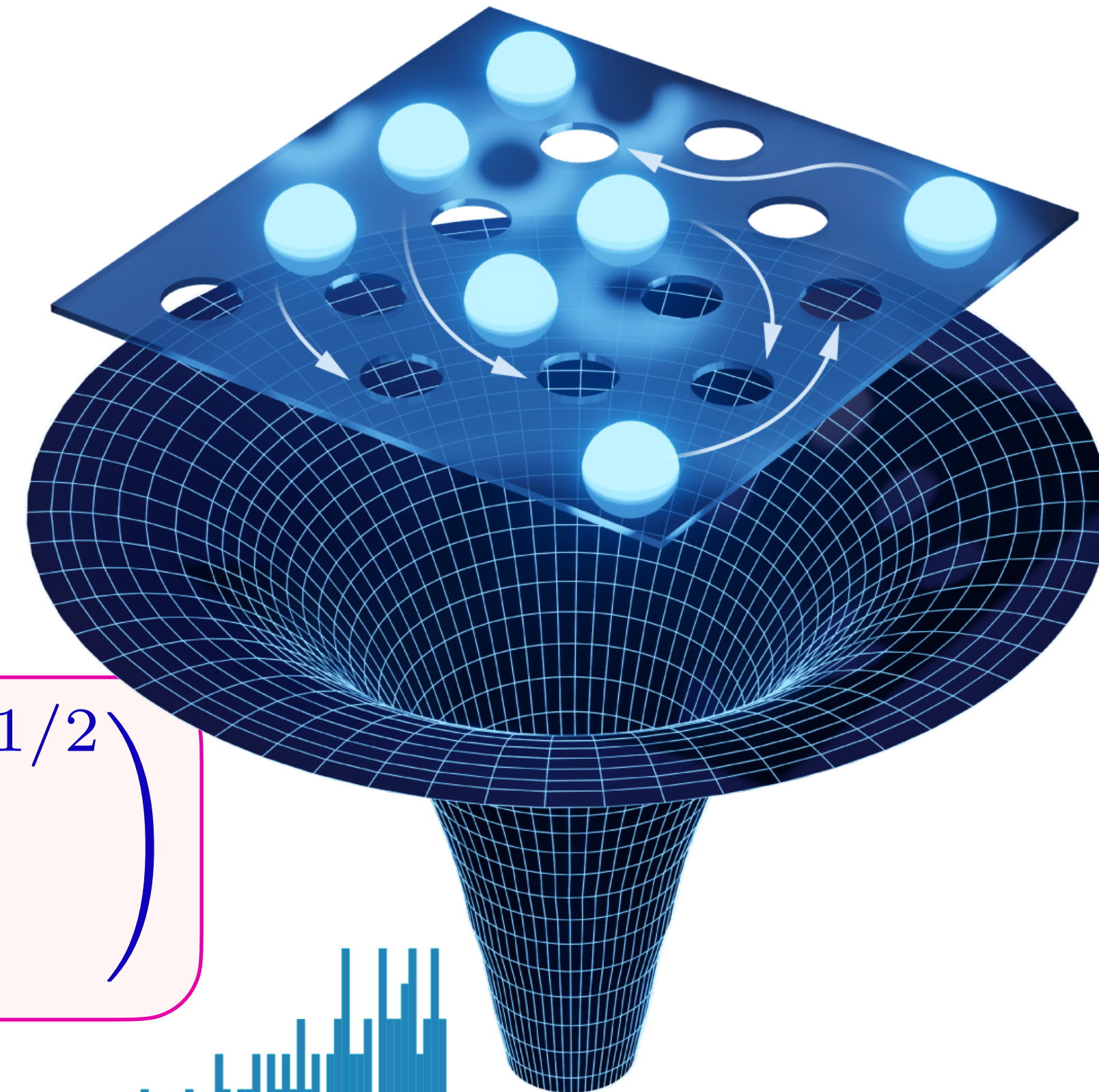
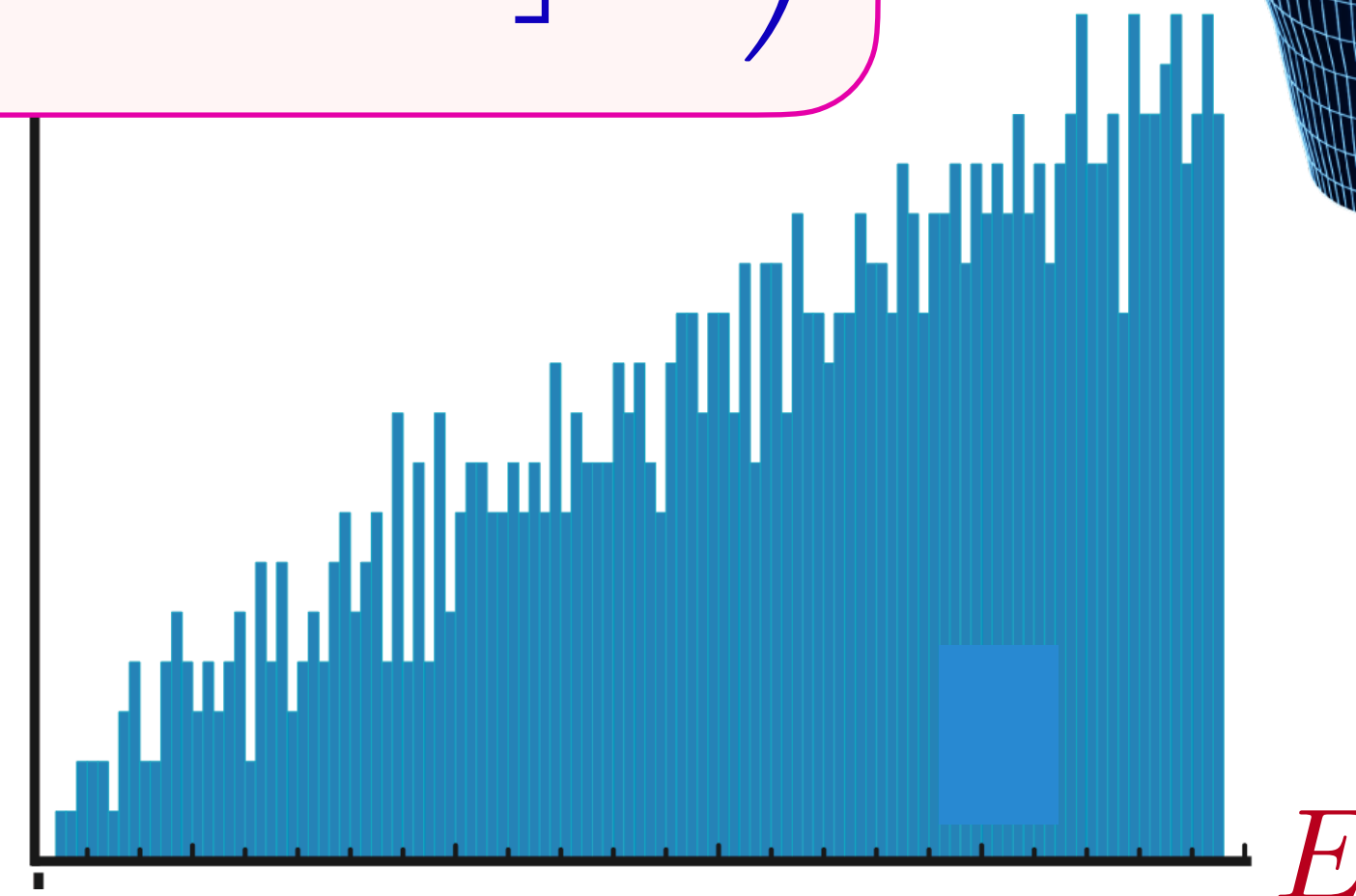
$$D(E) \sim \left( \frac{Ac^3}{\hbar G} \right)^{-347/90} \exp \left( \frac{Ac^3}{4\hbar G} \right) \sinh \left( \left[ \frac{\sqrt{\pi} A^{3/2} c^2}{\hbar^2 G} E \right]^{1/2} \right)$$

Bekenstein-Hawking

Iliesiu, Murthy, Turiaci (2022)

Developments from the SYK model

$D(E)$

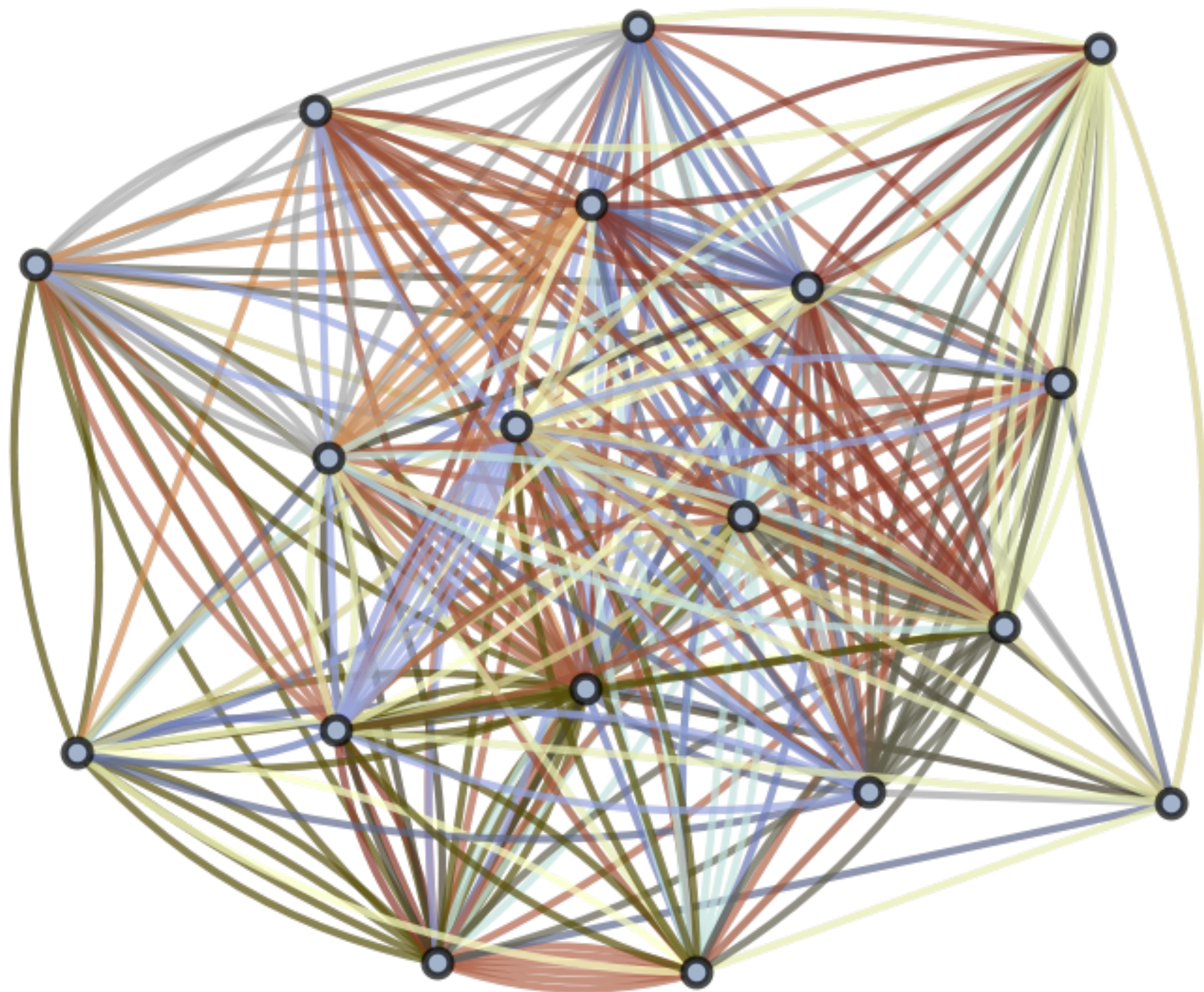




Recap

# The Sachdev-Ye-Kitaev (SYK) model

The SYK model describes multi-particle quantum entanglement resulting in the loss of identity of the particles



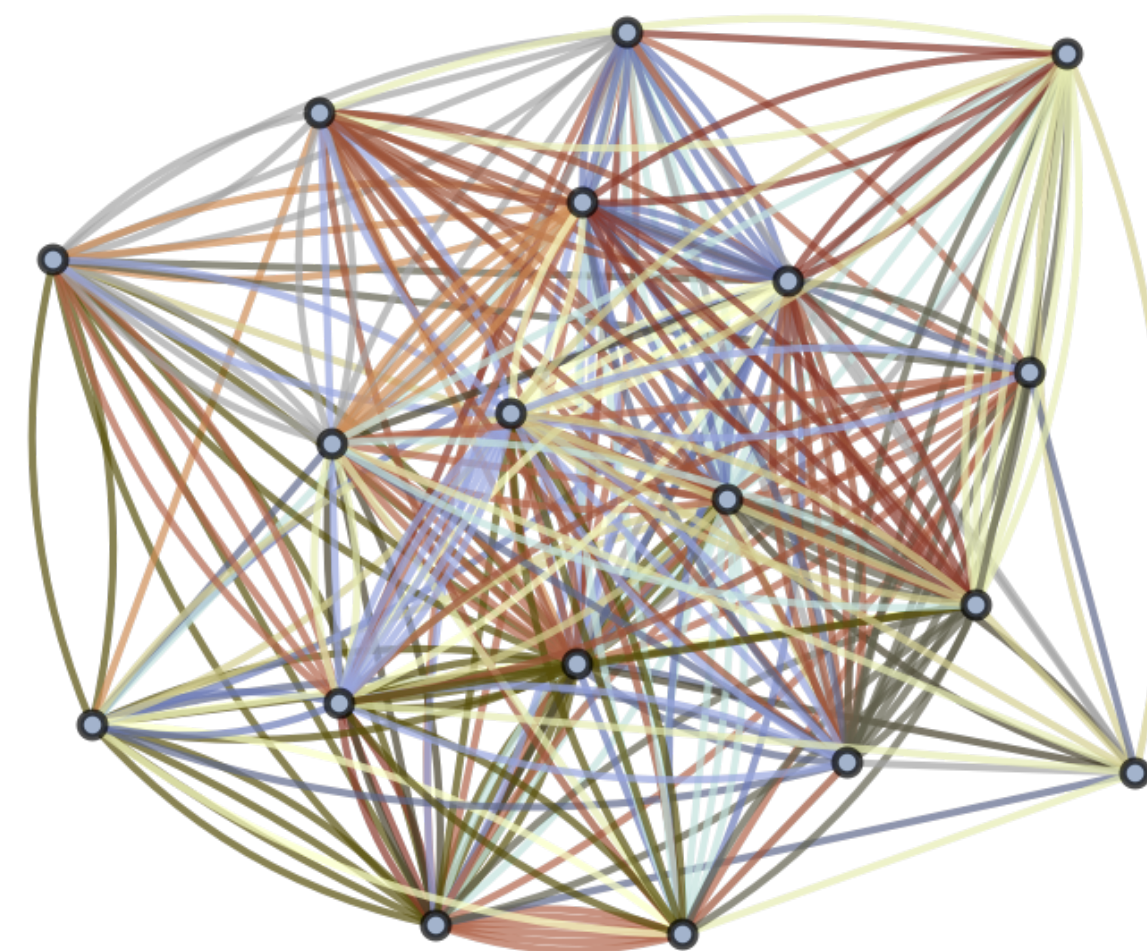
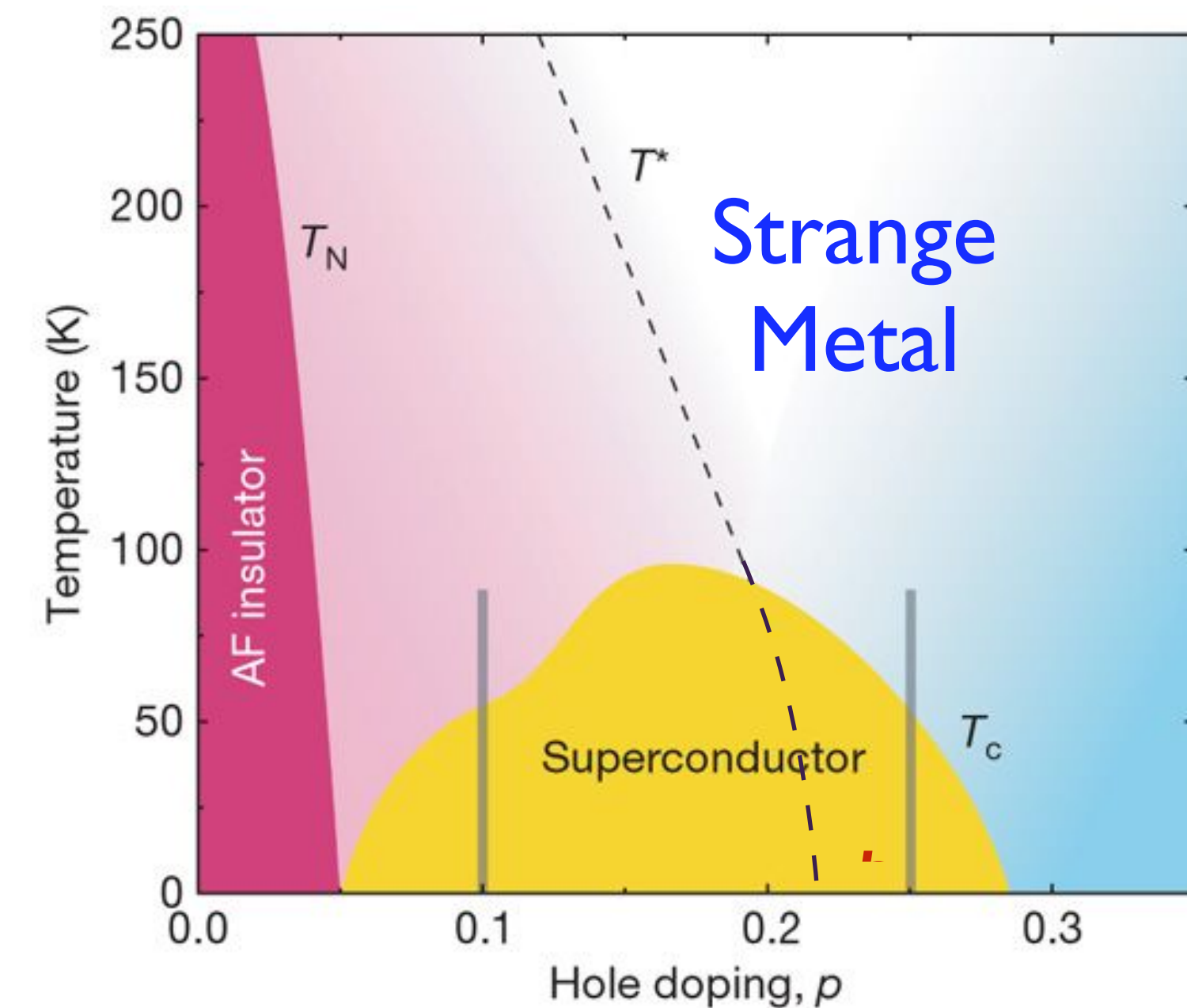


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In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

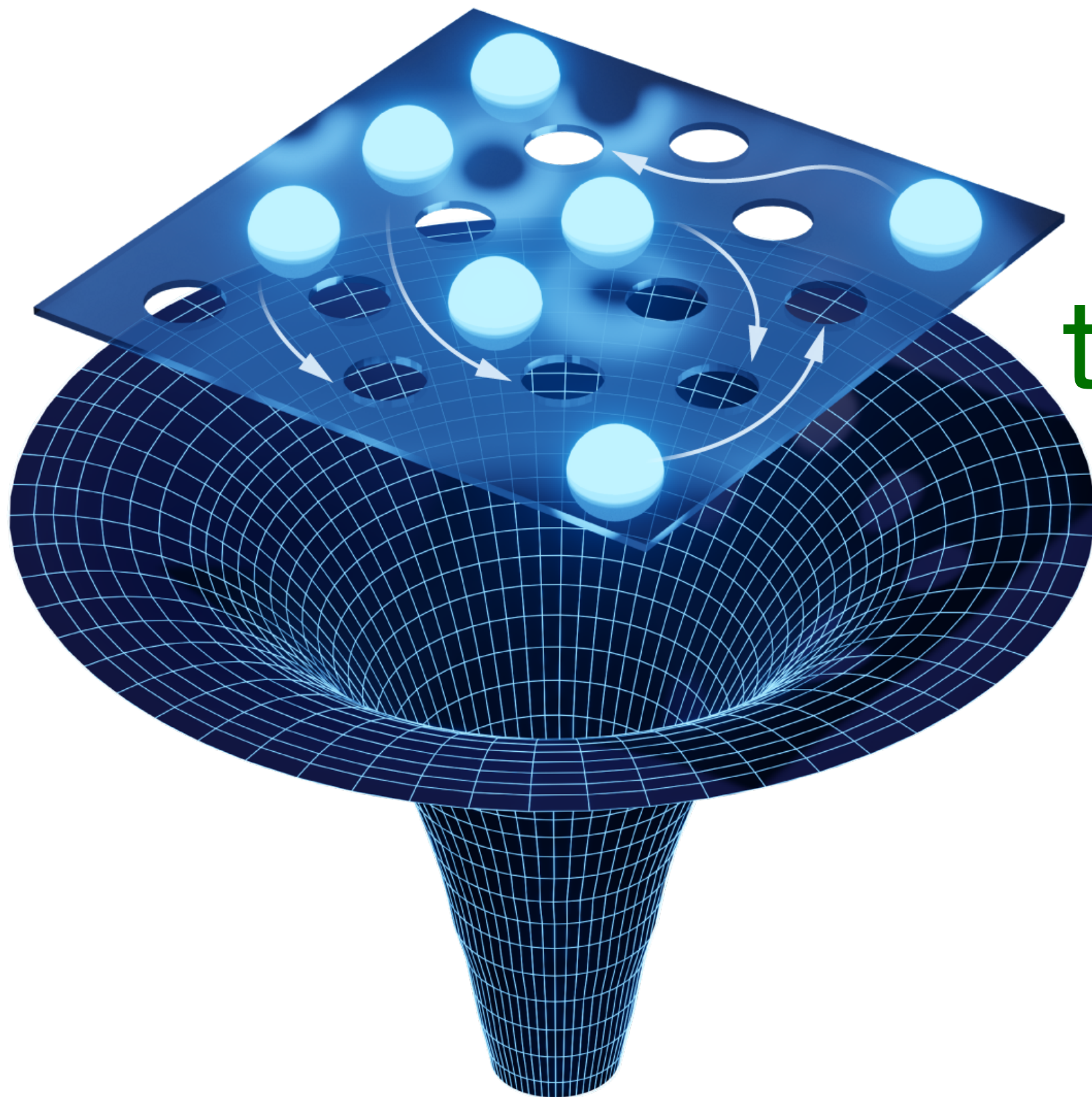
Sachdev, Ye (1993)





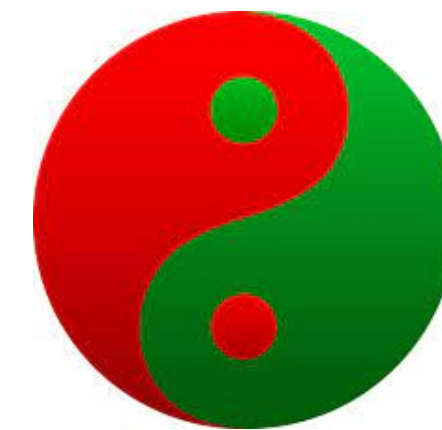
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In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)



In a ***dual*** set of variables it describes the interior of ***charged black holes***

Sachdev (2010), Kitaev (2015), Maldacena Stanford (2015)