

Superconductors, Black Holes, and Quantum Matter

GCU

Lahore

April 8, 2026

Subir Sachdev



PHYSICS



HARVARD





Study in the
home
of
Prof. Abdus Salam
in London

Ahmad
Salam



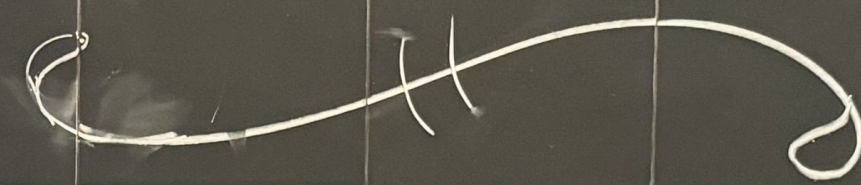
Study in the
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Weinberg-Salam theory of weak interactions in the nucleus

$$\mathcal{L} = \sqrt{-g} \left[R - F^2 + \bar{\psi} \not{D} \psi \right.$$

$$\left. - |D\Phi|^2 + \gamma \bar{\psi} \Phi \psi + \text{h.c.} - V(\Phi) \right]$$

The Lagrangian density of the universe

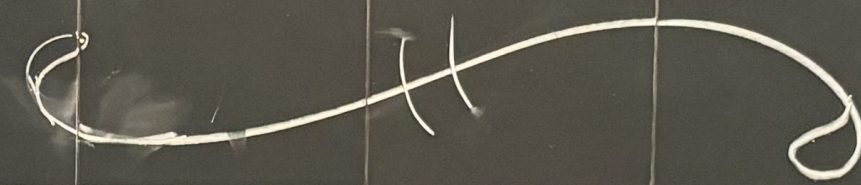


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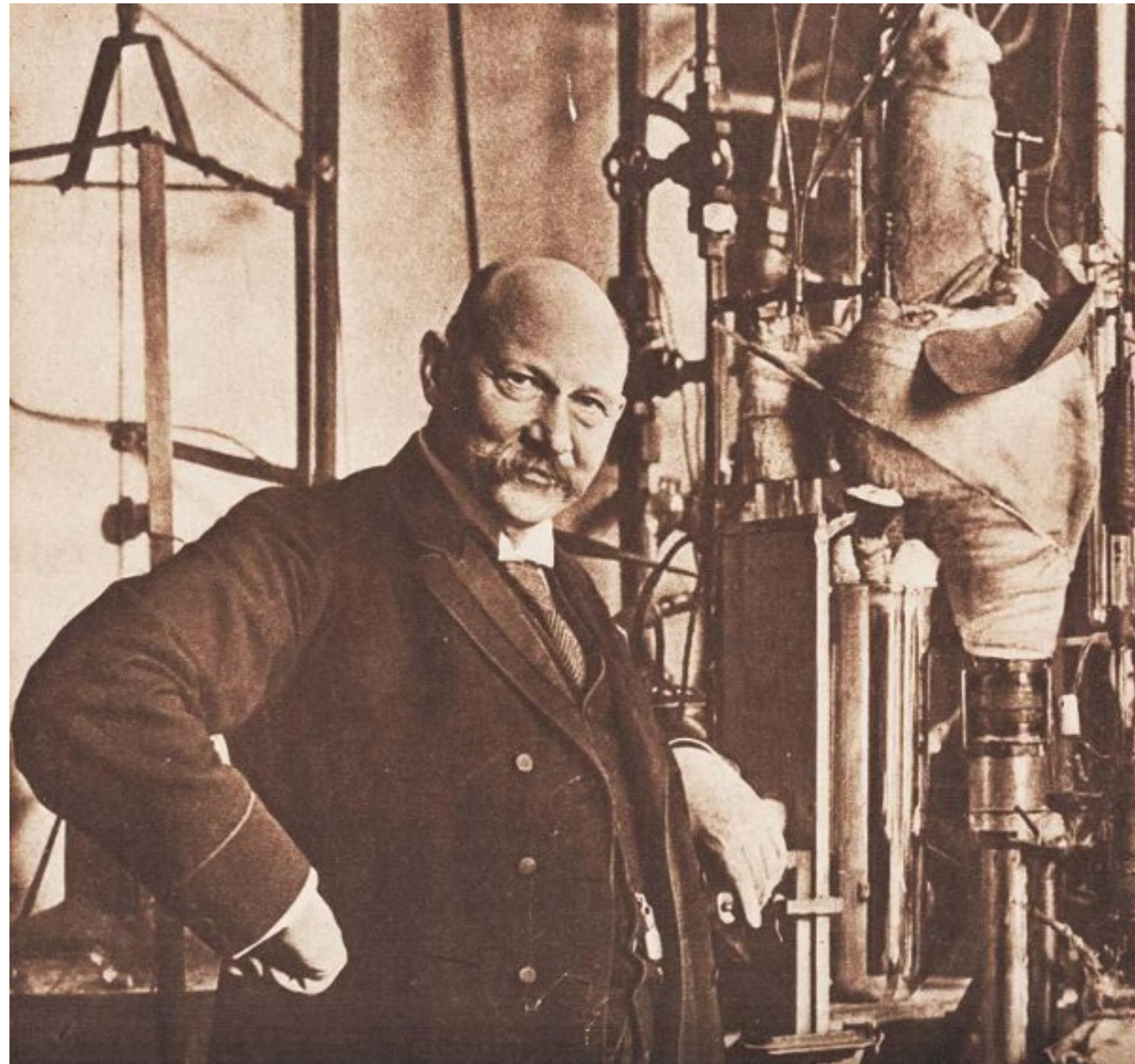
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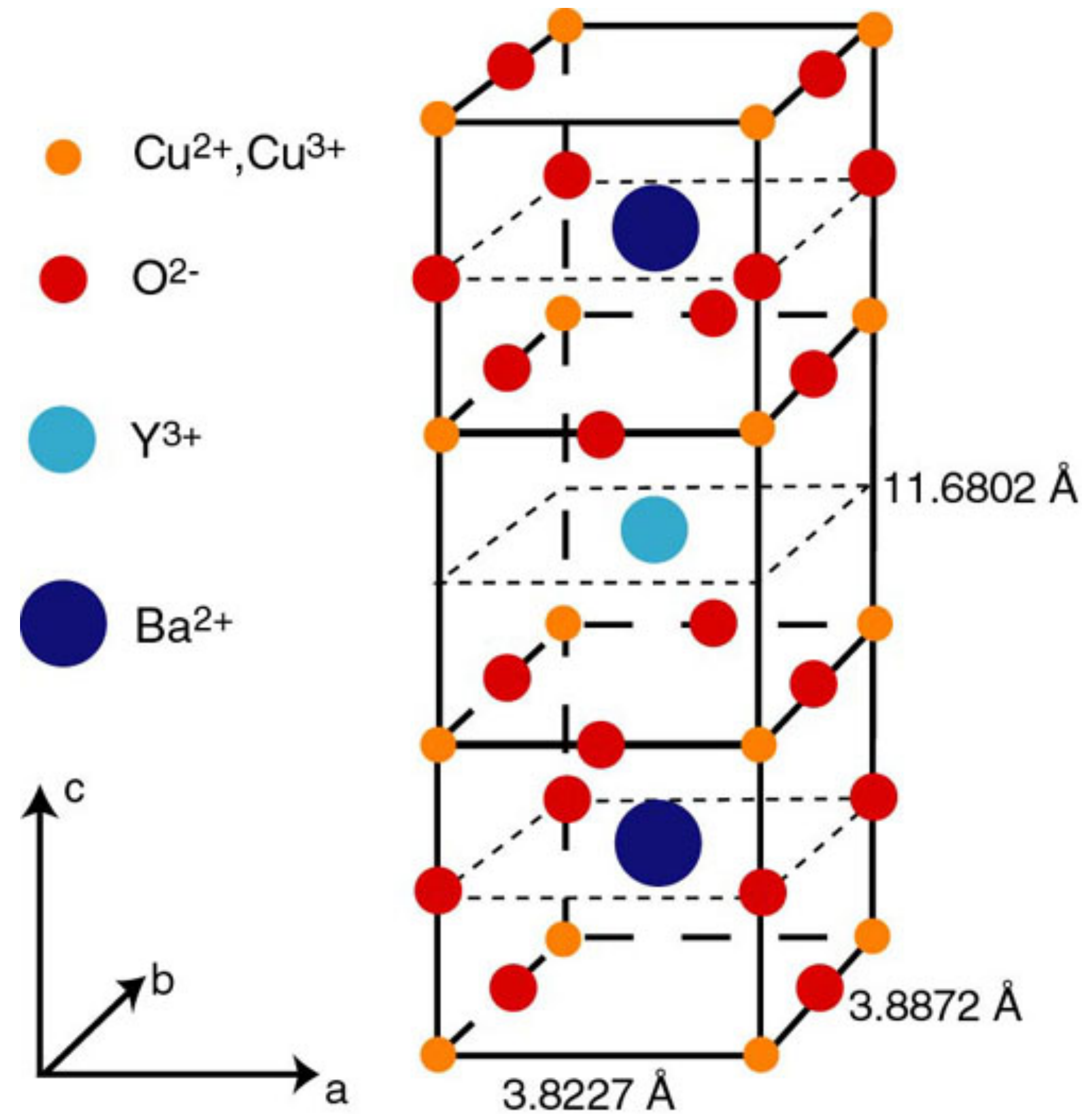
Similar theory describes a new type of superconductivity...

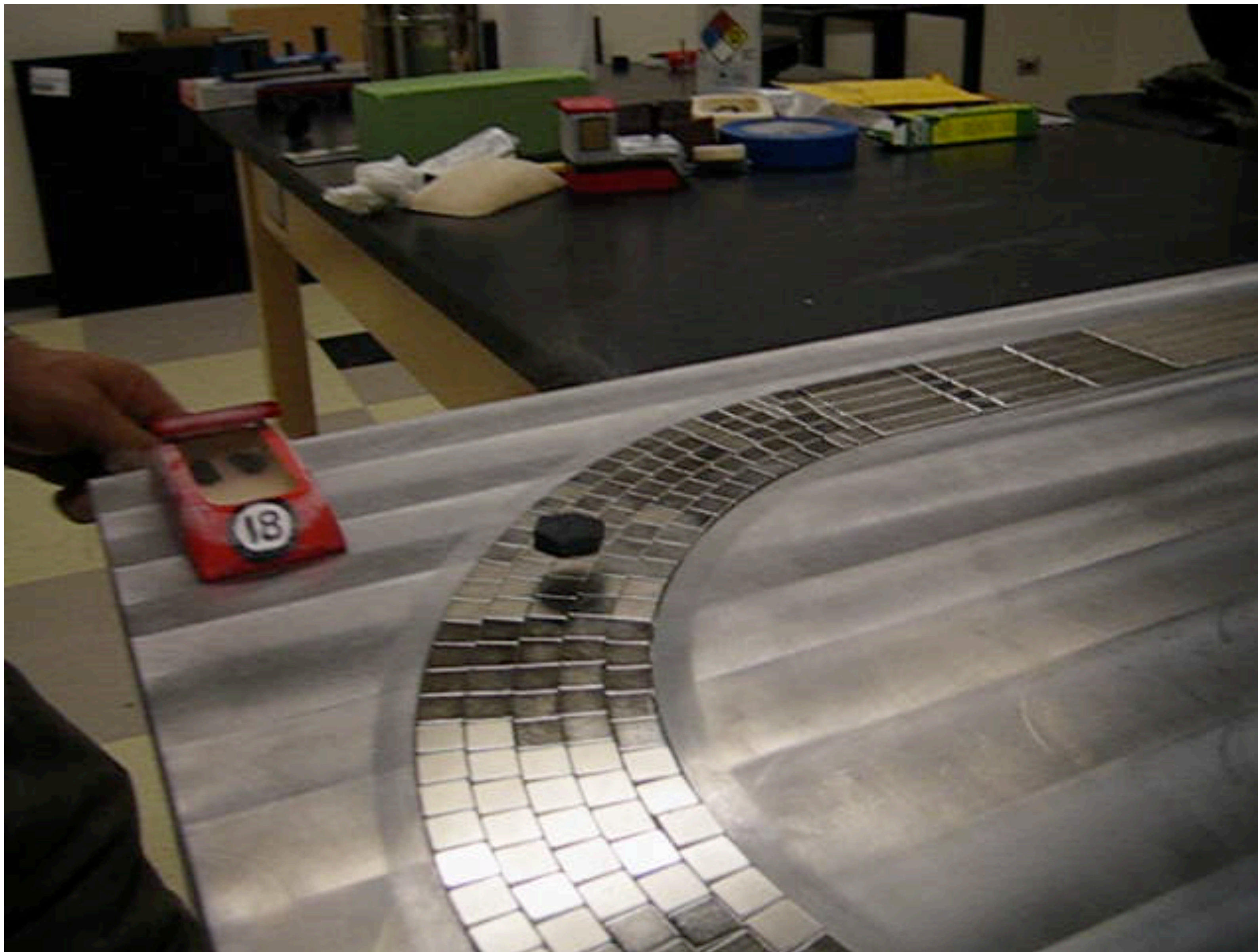
Superconductors



Kamerlingh Onnes 1911:
Mercury is a superconductor below $-269\text{ }^{\circ}\text{C}$
Electric current can flow with zero resistance.

Cuprate high temperature superconductors (1986)





Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

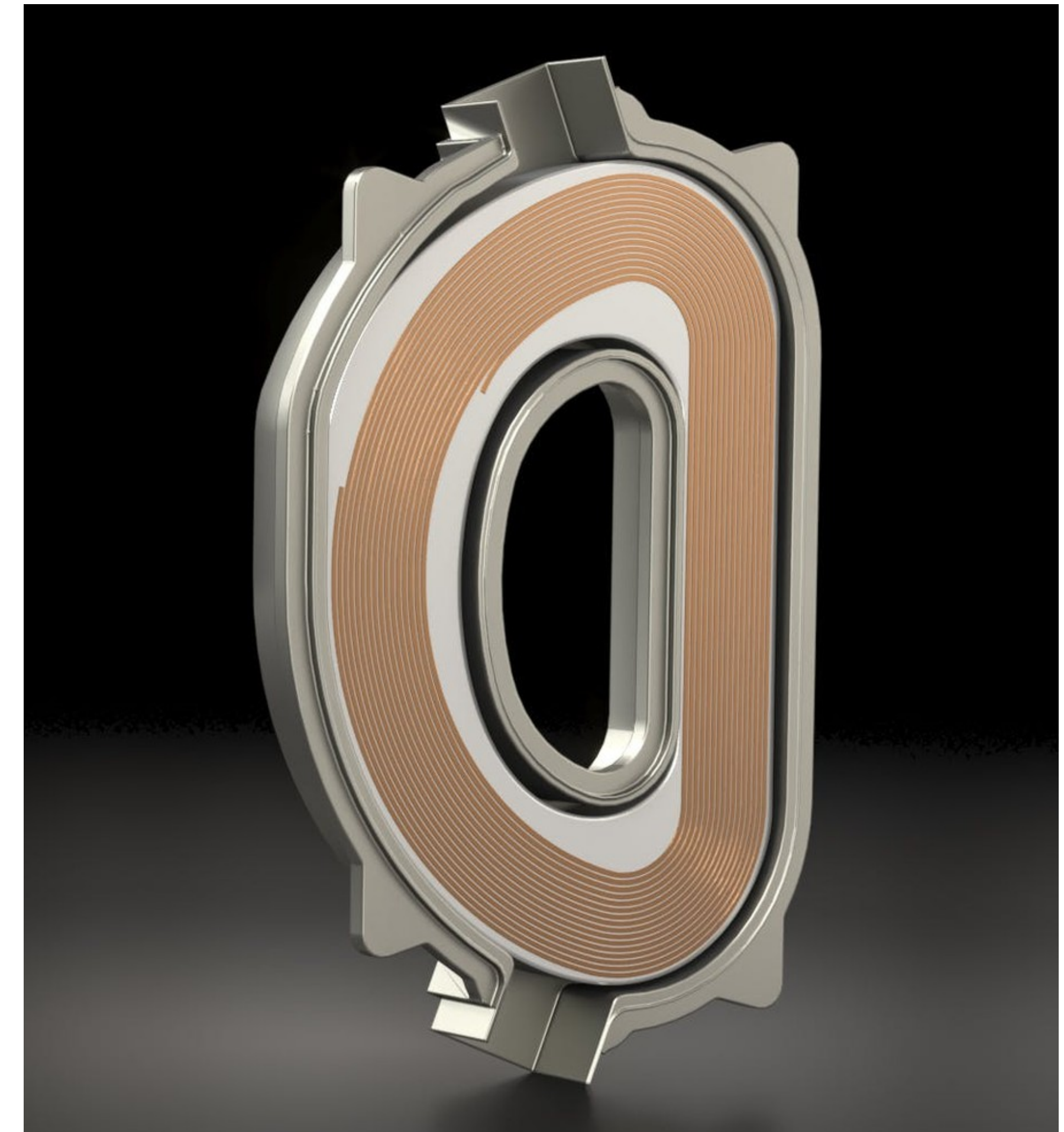
HTS Magnets: Enabling Technology

The surest path to limitless,
clean, fusion energy

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



Commonwealth
Fusion Systems



Central questions:

Why do the cuprates become superconducting at temperatures higher than the boiling point of liquid nitrogen?

Are there other materials which superconduct at even higher temperatures, perhaps even at room temperature?

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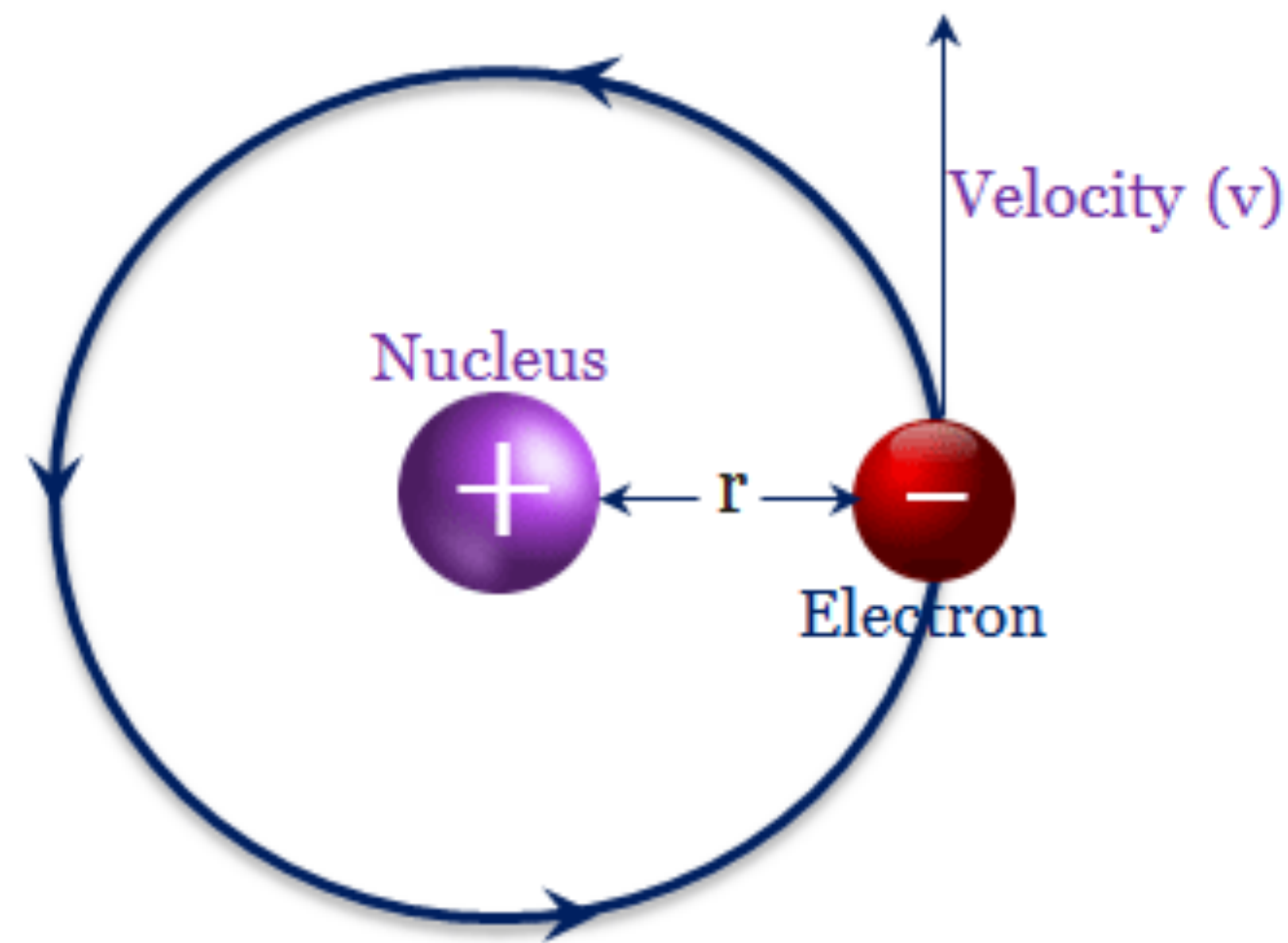
Are there other materials which superconduct at even higher temperatures, perhaps even at room temperature?

Much progress has been made in addressing the first question in last 3 decades.

But an unexpected bi-product has been a much deeper understanding of the quantum theory of many particles, which has impacted numerous other fields of physics, including the quantum theory of black holes, and quantum computing

Quantum mechanics
to
quantum materials

Hydrogen atom

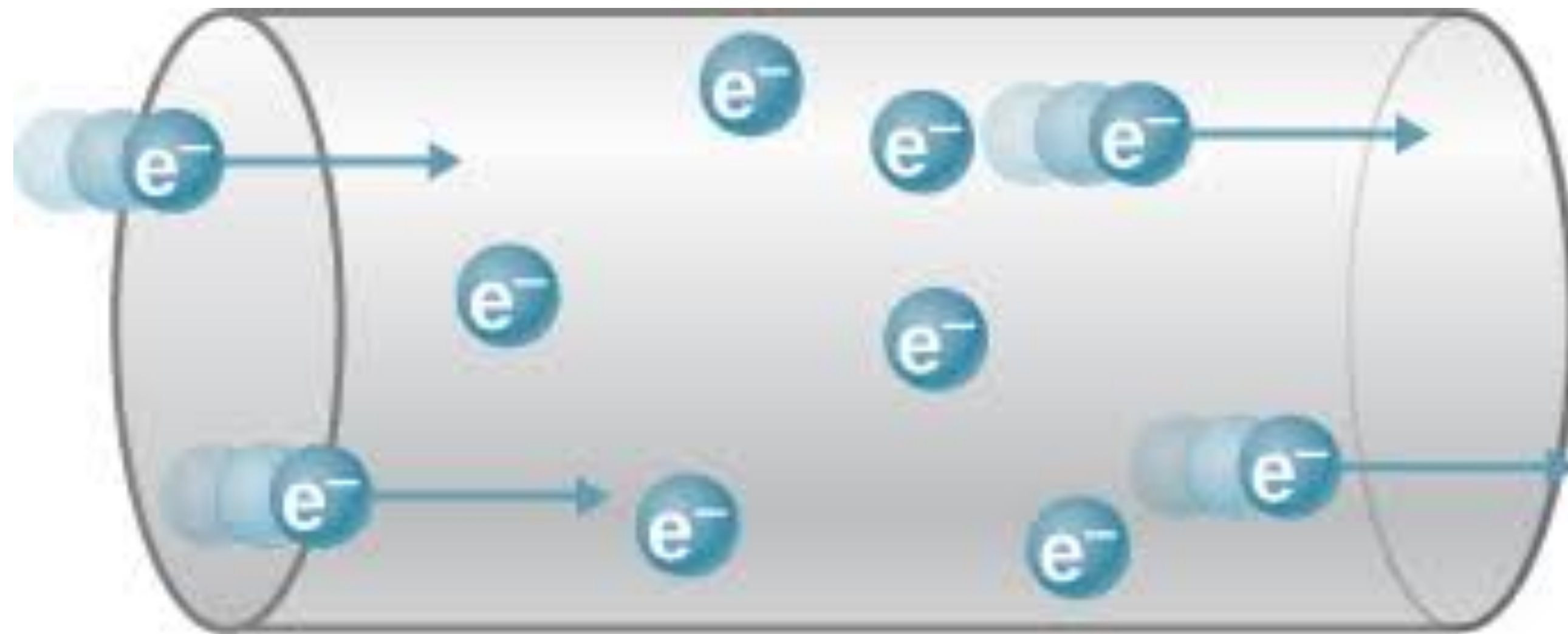


$\Rightarrow 10^{-10}$ meters \Leftarrow

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).
Electrons are in quantized orbital “states”.

- Sommerfeld (1927): The same equations also describe the motion of $\sim 10^{23}$ electrons in a metal. Each electron is a **fermion**, named after Fermi (1926), which obey exclusion—at most one fermion can occupy each quantum orbital.



- Bose, Einstein (1924): Particles now known as **bosons**, which do not obey exclusion. Many bosons can condense into a single macroscopic quantum state, which is today understood to be the key to superfluidity and superconductivity.

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- Bardeen, Cooper, Schrieffer (1957): Pairs of electrons behave like **bosons**, and this is the explanation for superconductivity.

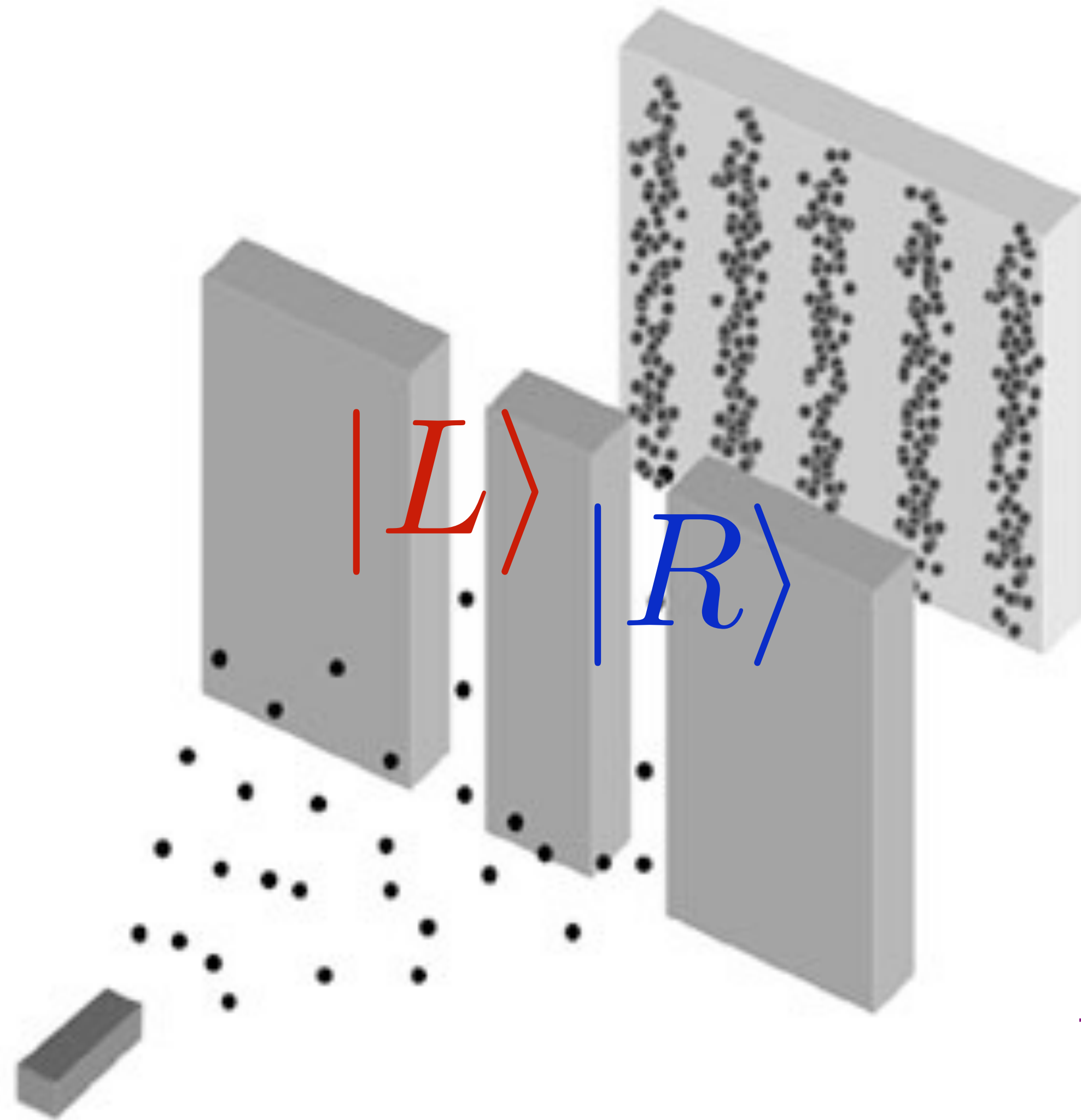
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- Ideas on multi-particle entanglement in quantum materials have strongly influenced the theory of black holes (and vice versa).

Quantum entanglement

Principles of Quantum Mechanics I01: Quantum Superposition

The double slit experiment



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

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

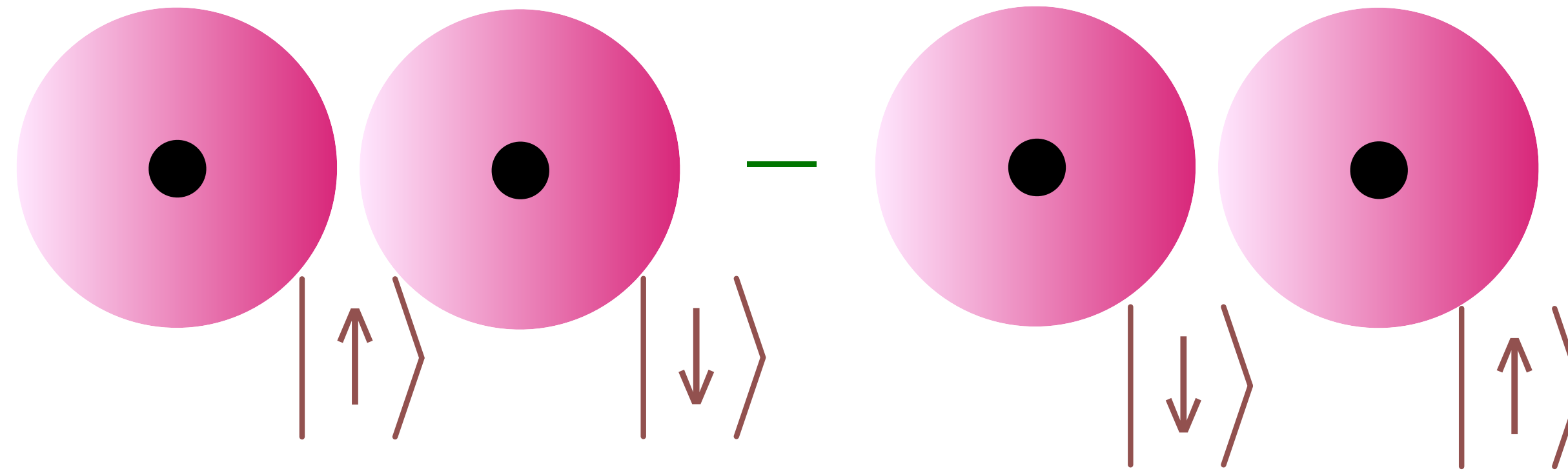
Actual state of *each* electron is

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

Quantum Entanglement:

quantum superposition of more than one particle

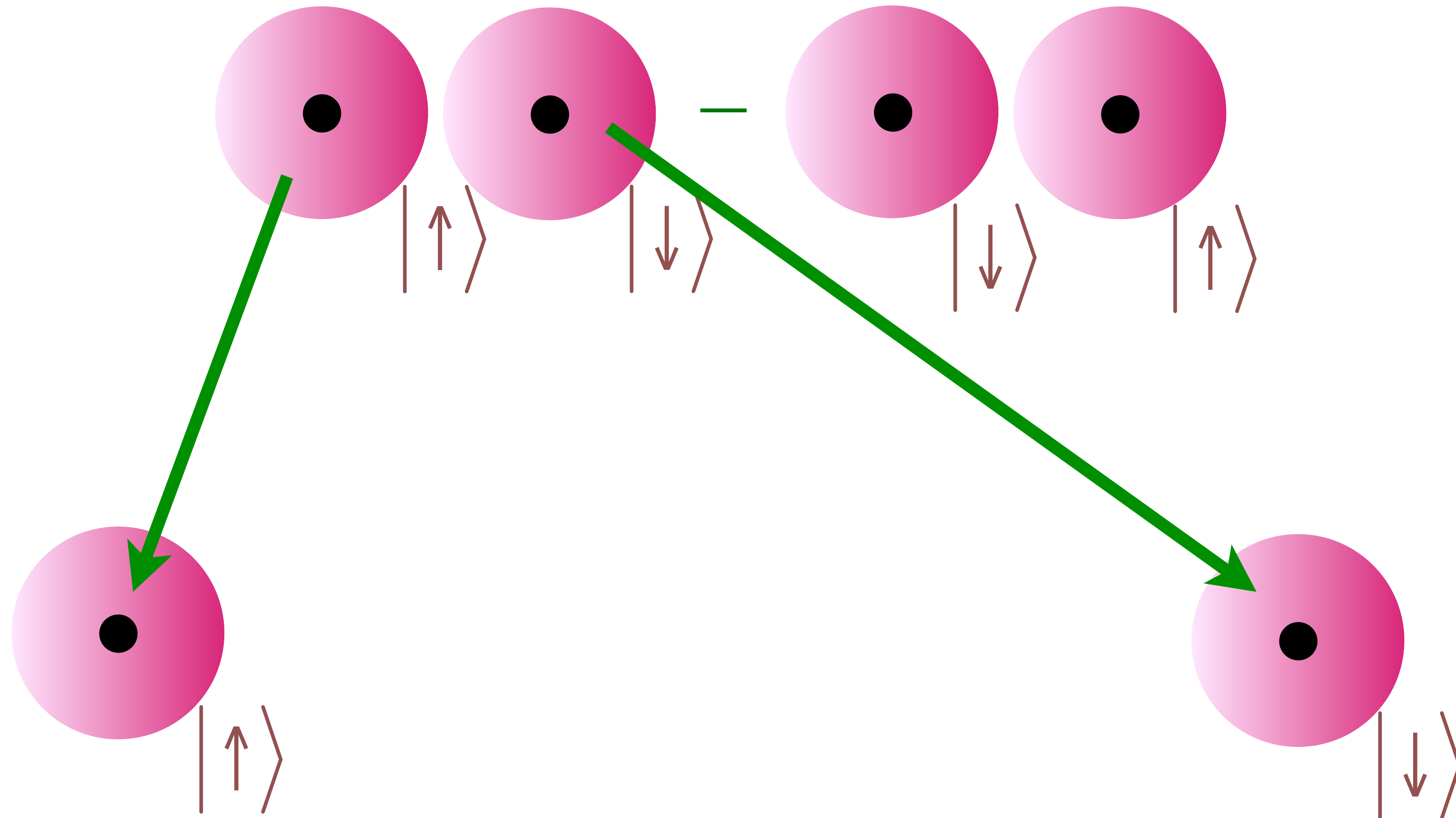
Einstein, Podolsky, Rosen (1935)



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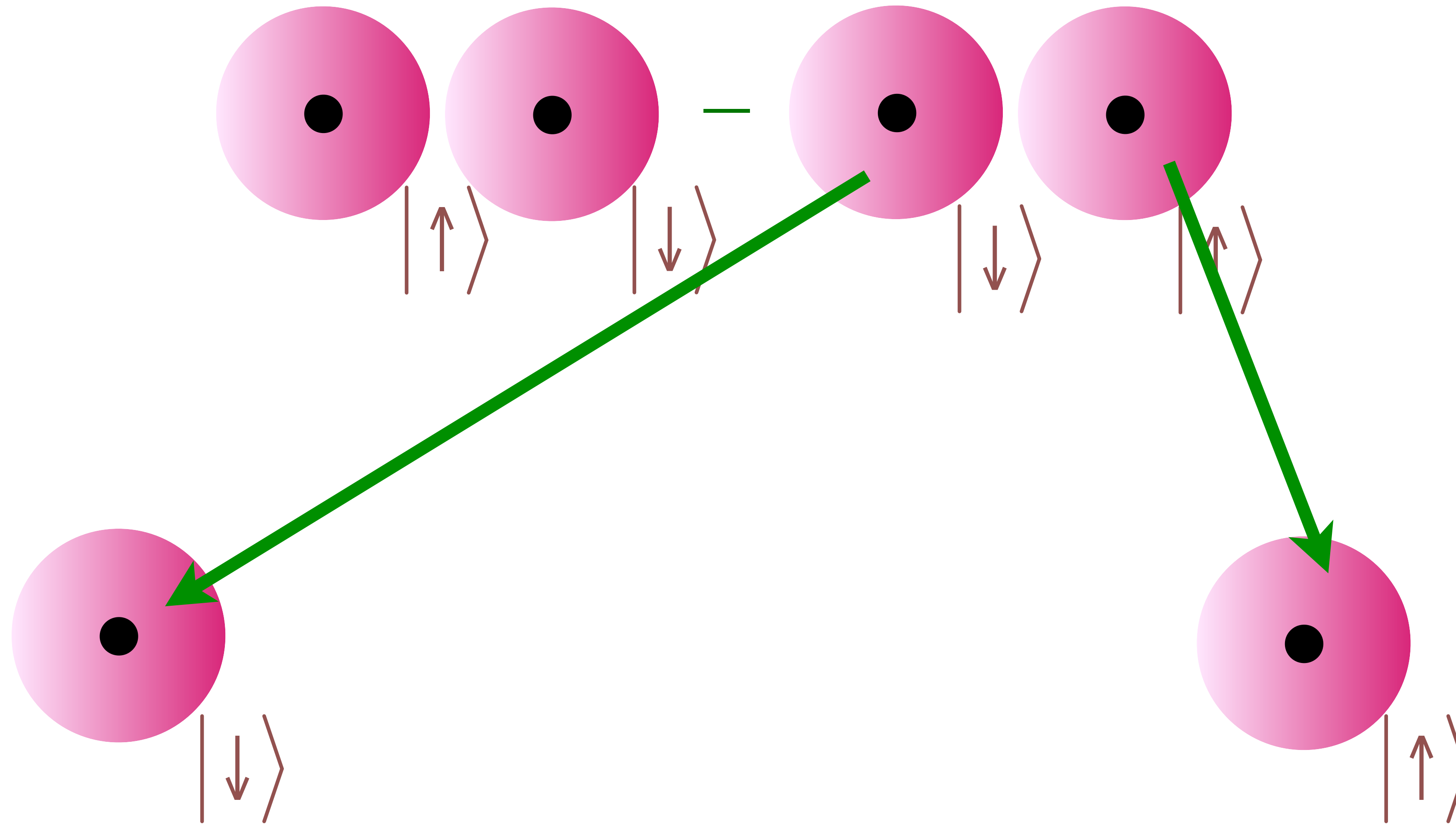
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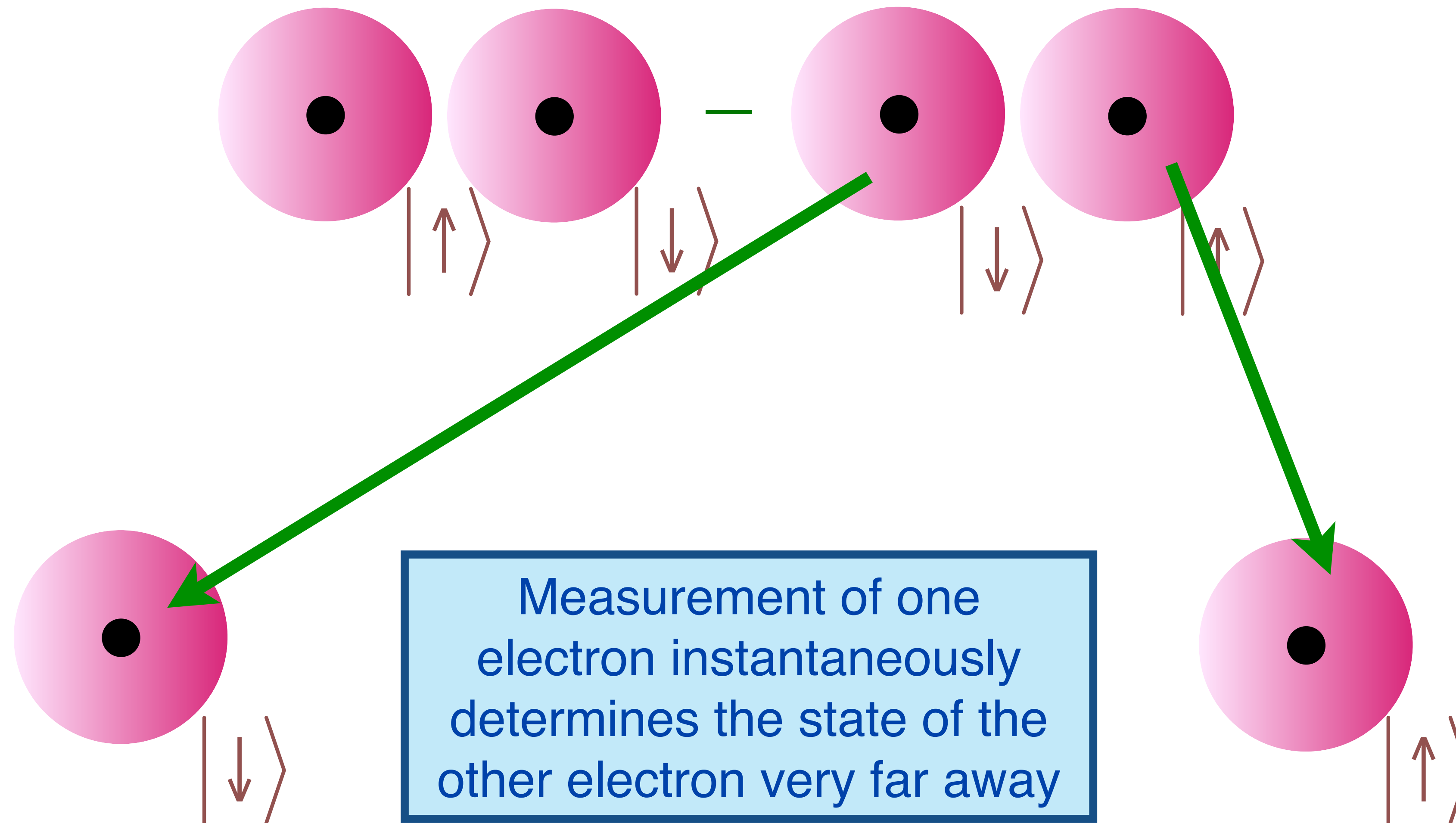
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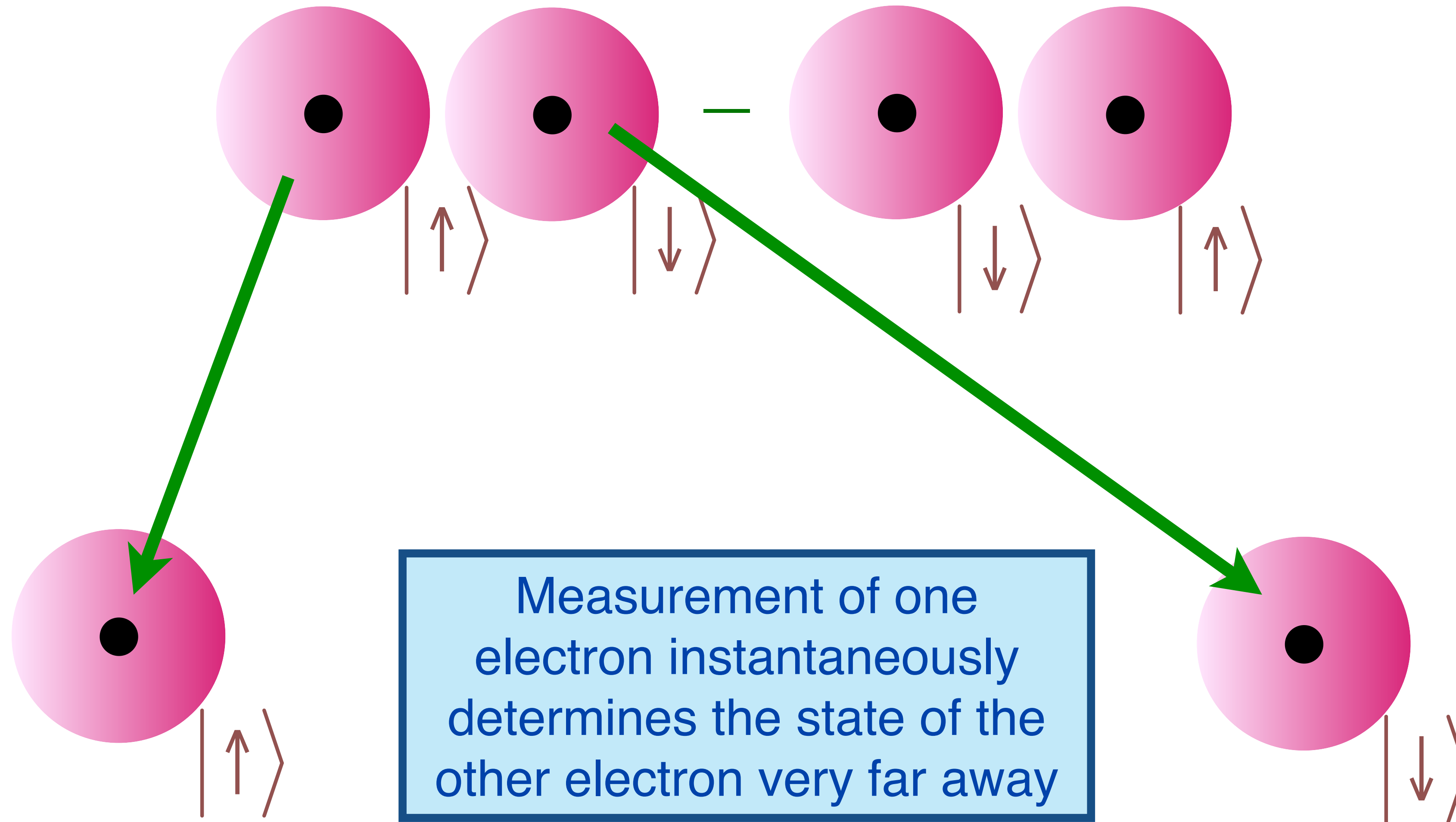
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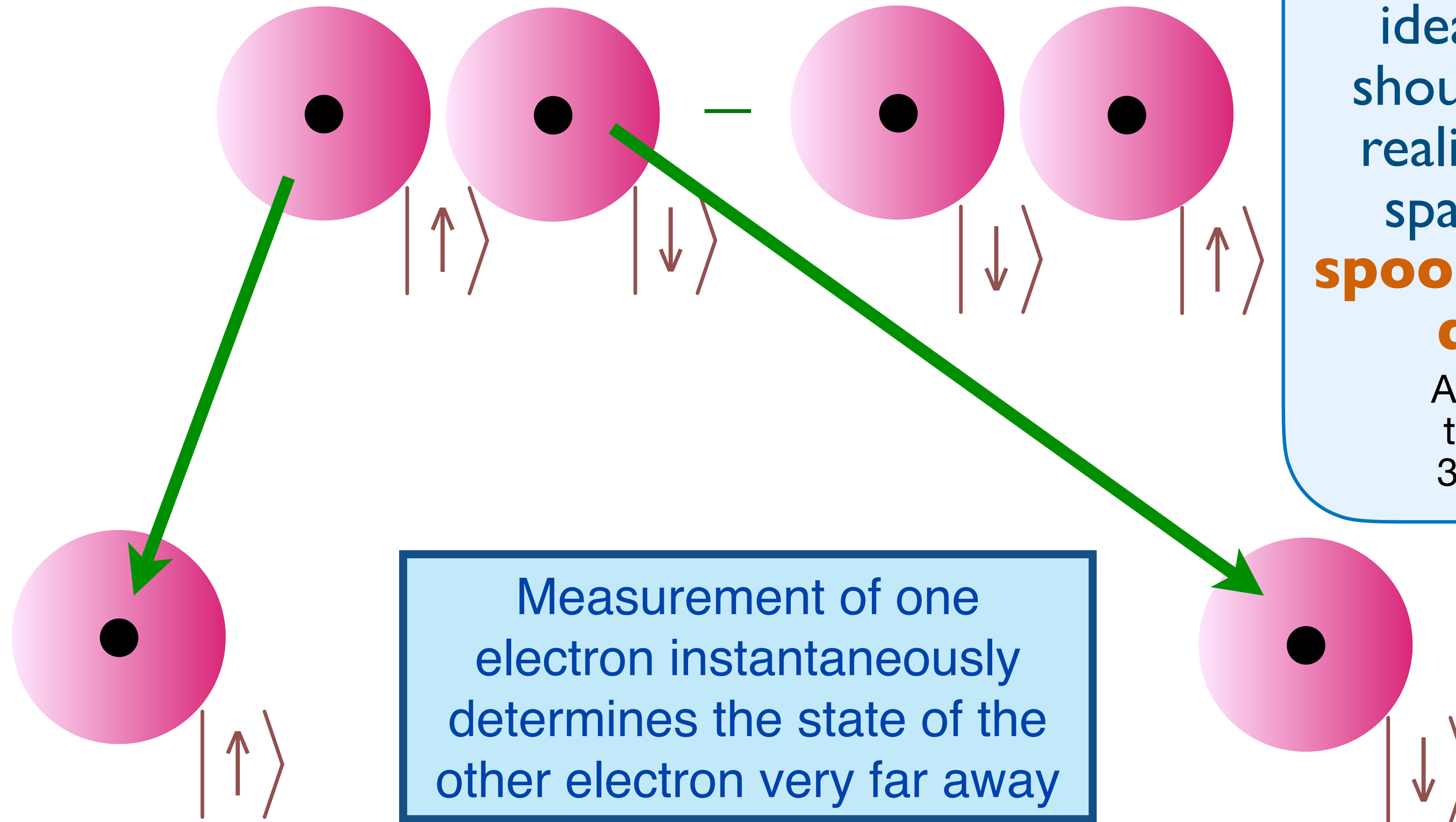
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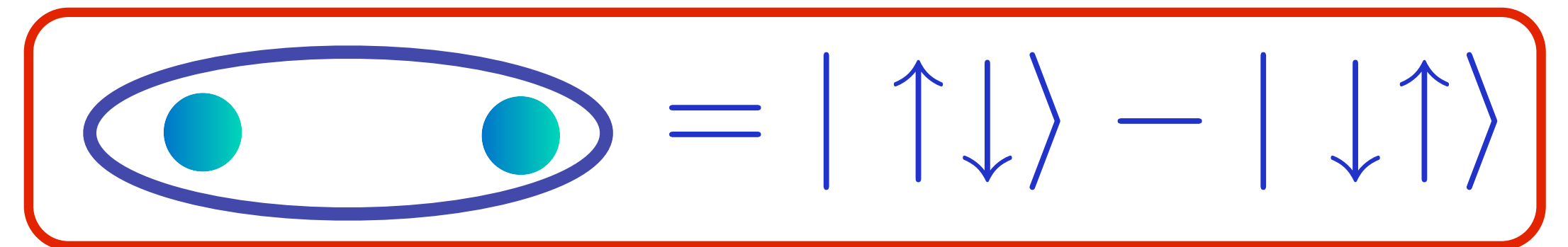
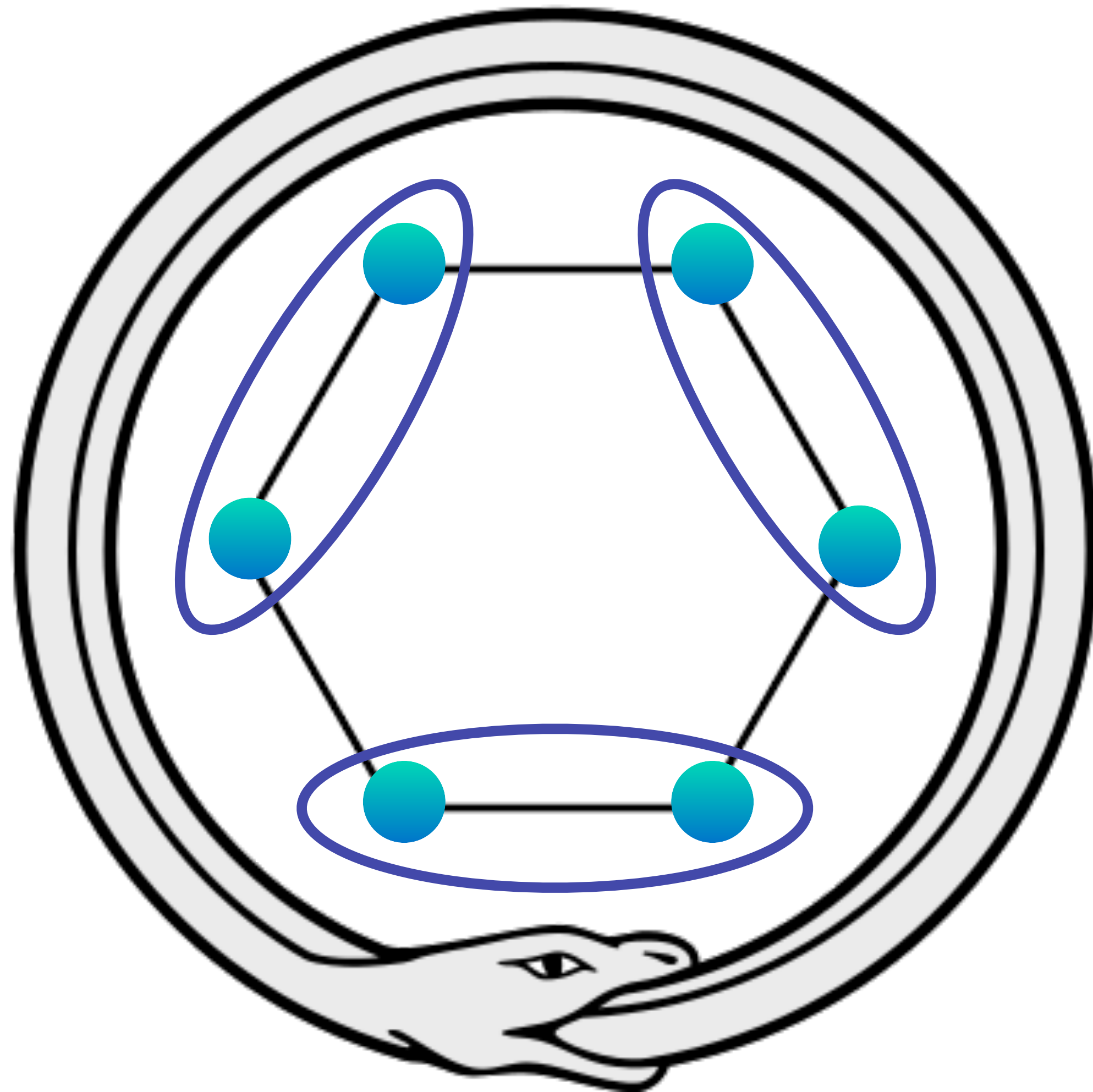


Measurement of one electron instantaneously determines the state of the other electron very far away

“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

Kekulé's spooky dream (1865)

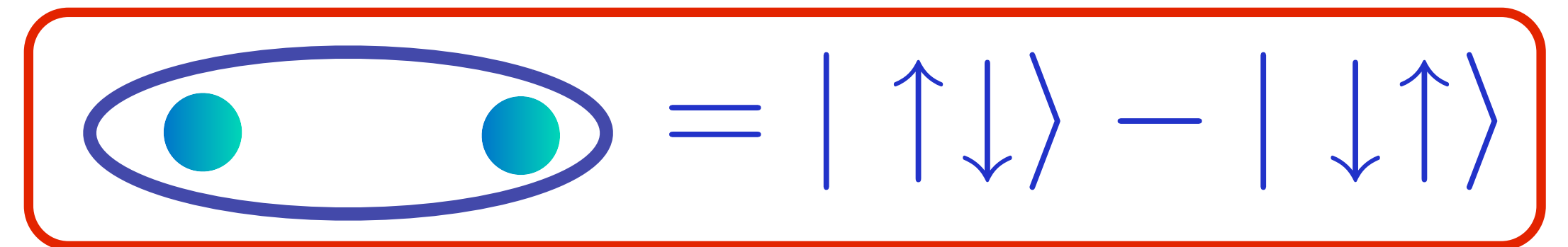
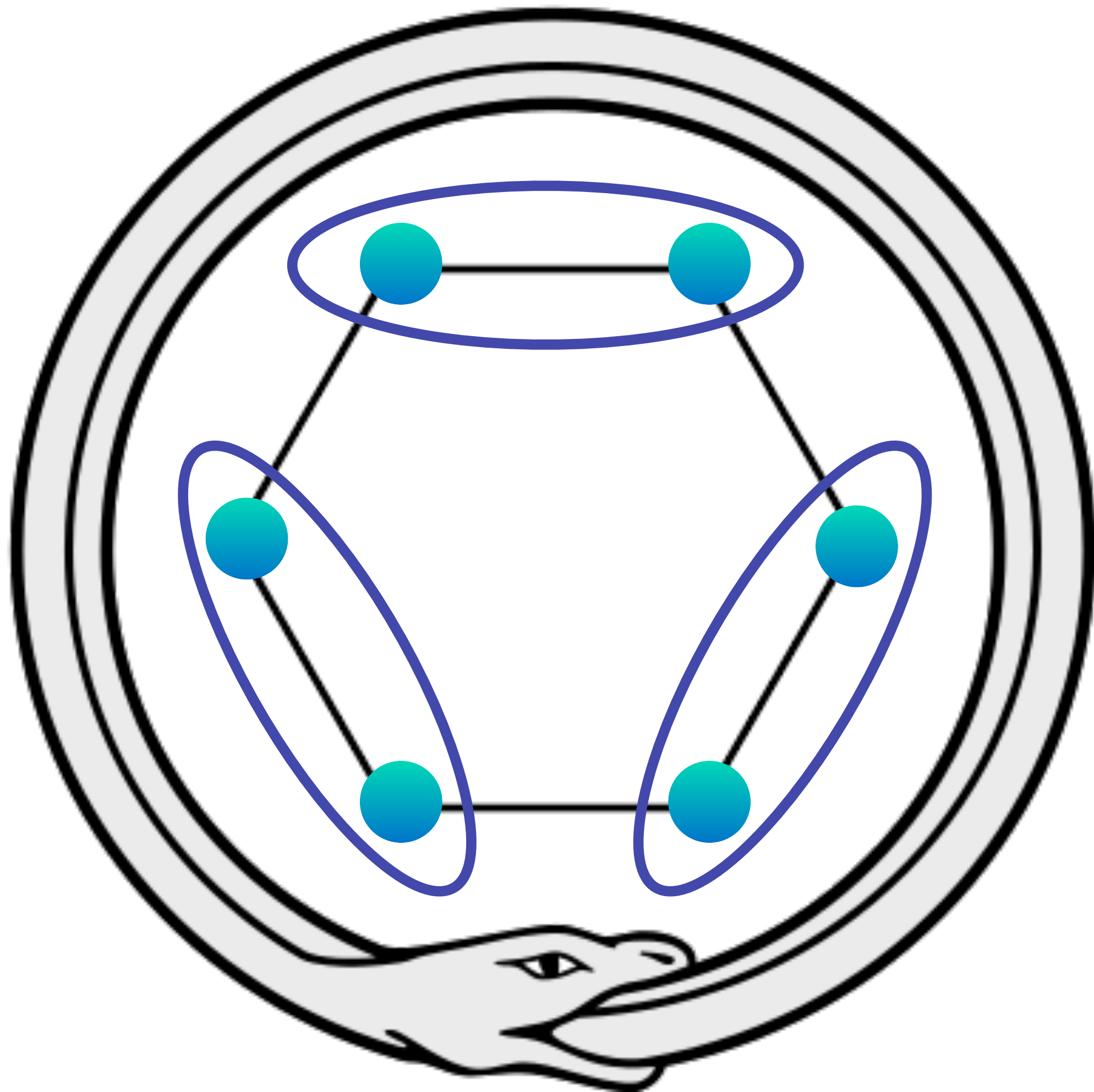
Kekulé spoke of the creation of the theory. He said that he had discovered the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail*



Benzene

Kekule's spooky dream (1865)

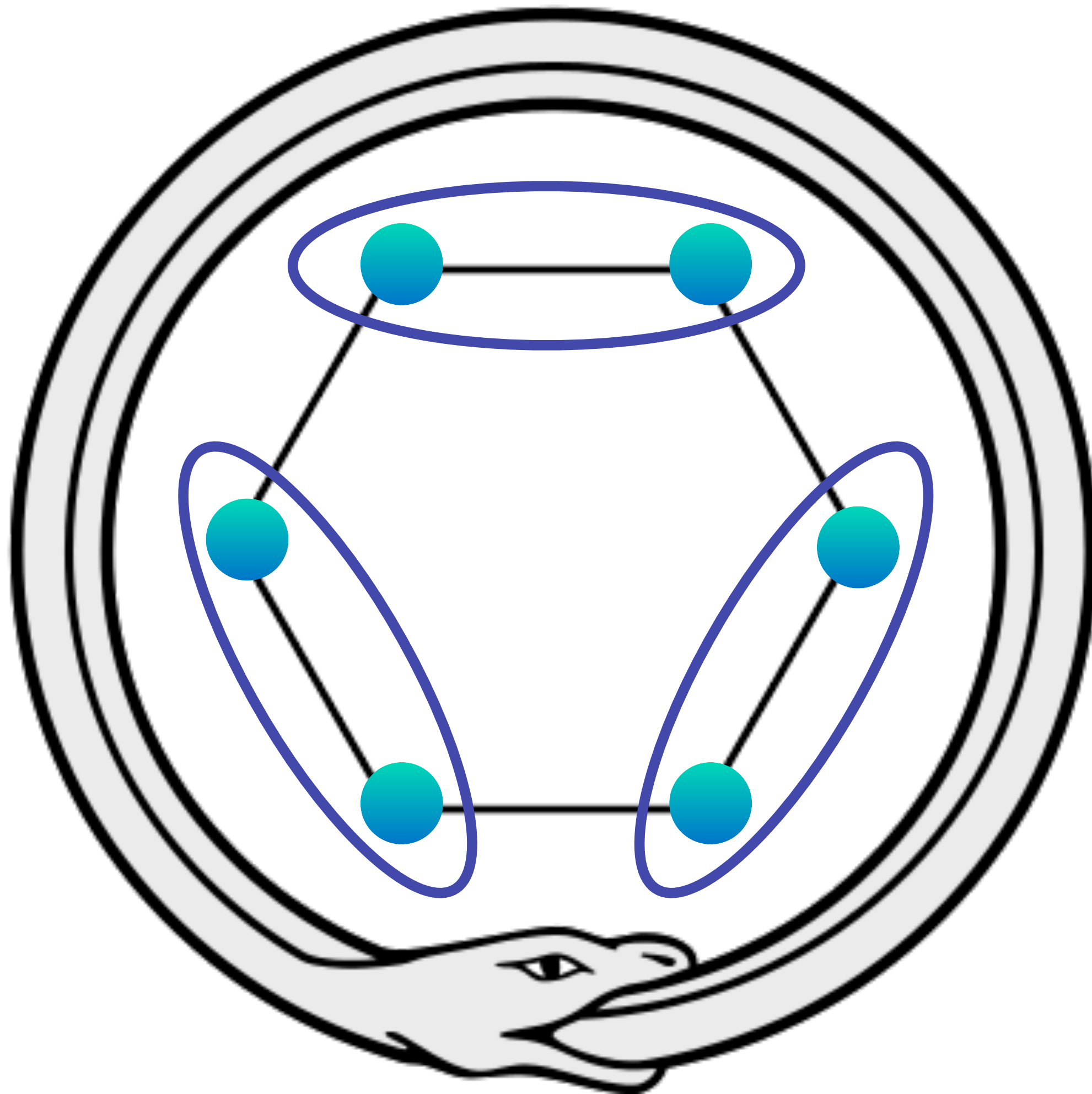
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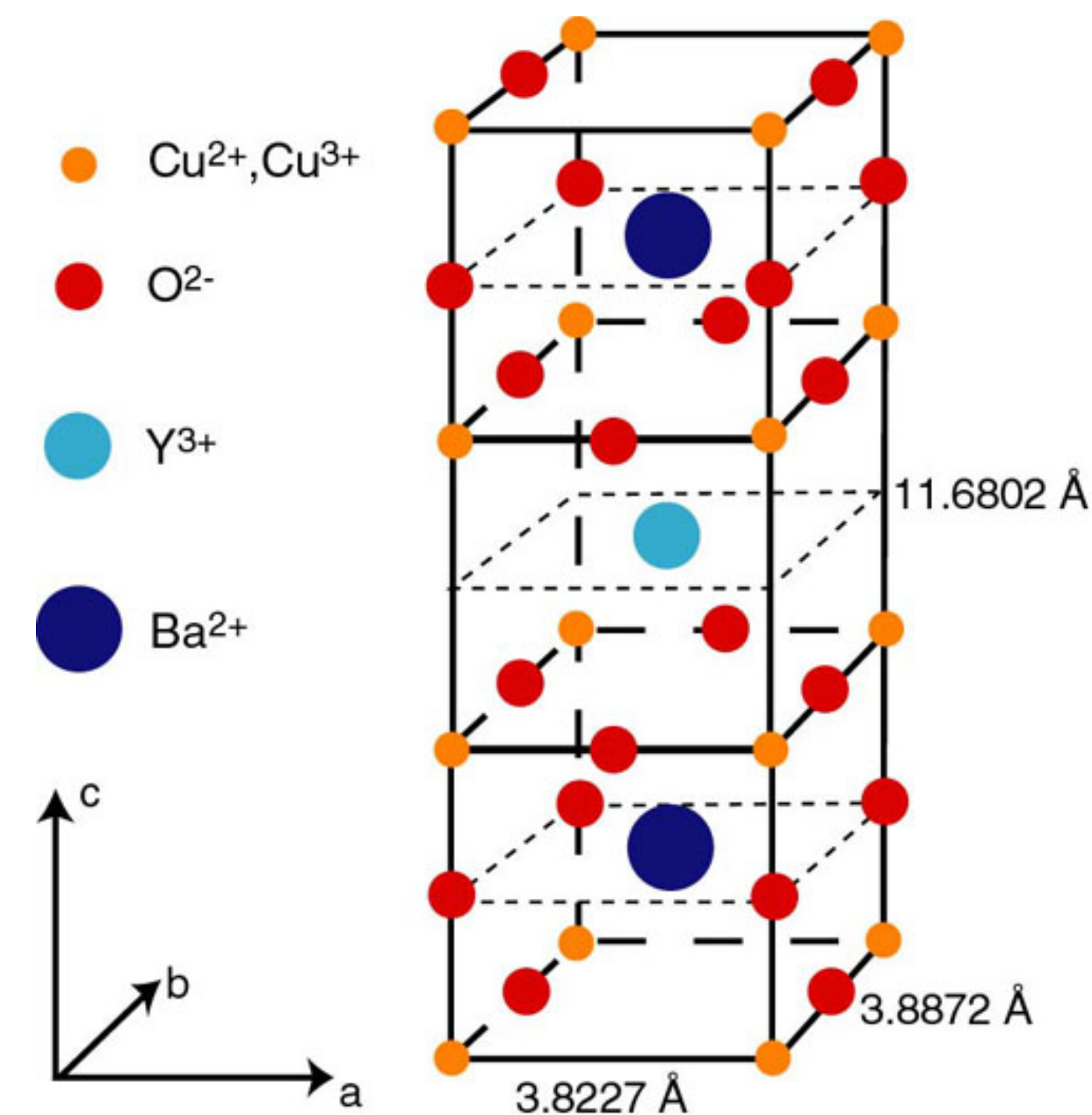
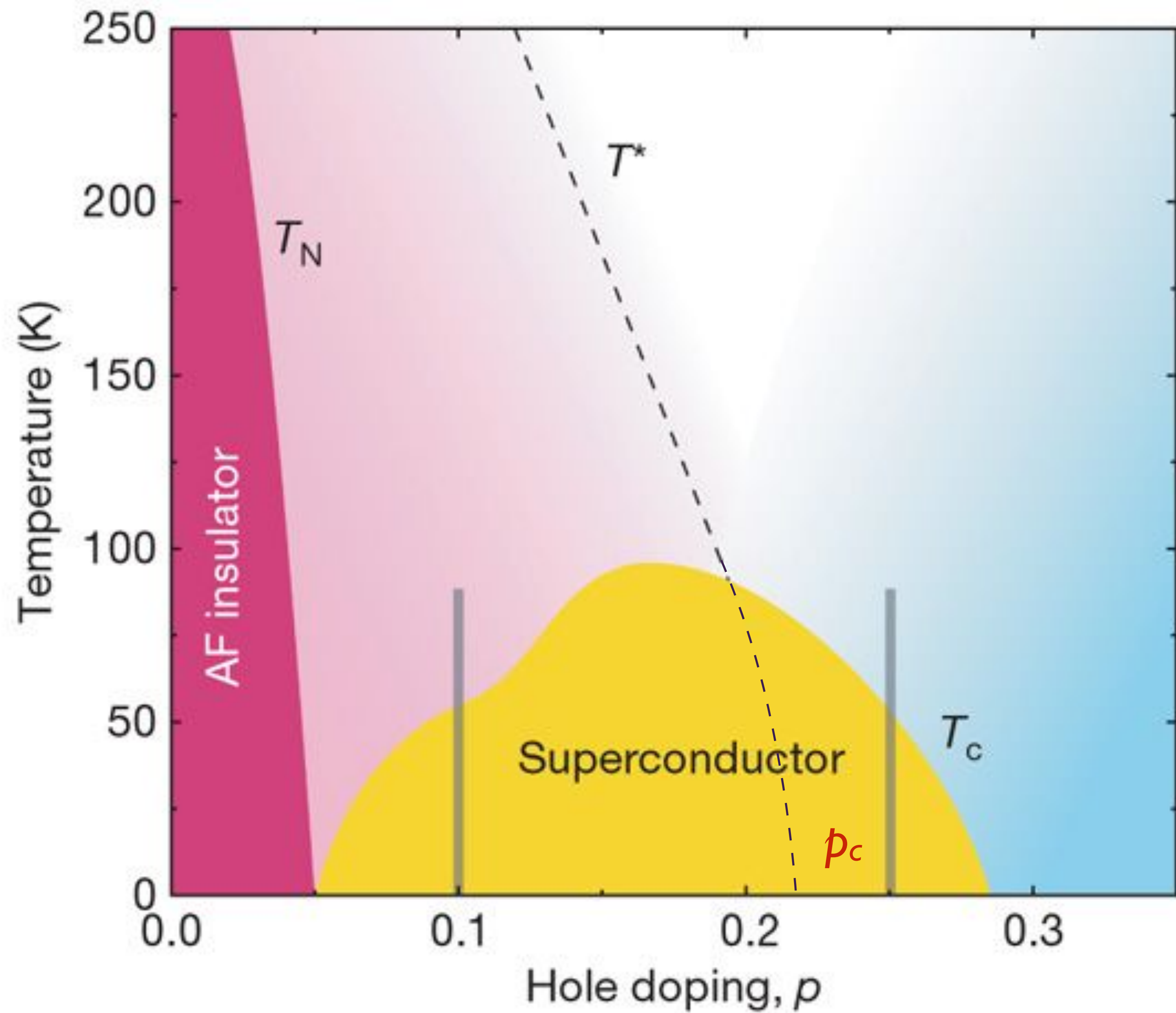
Quantum Entanglement
of 6 electron spins!

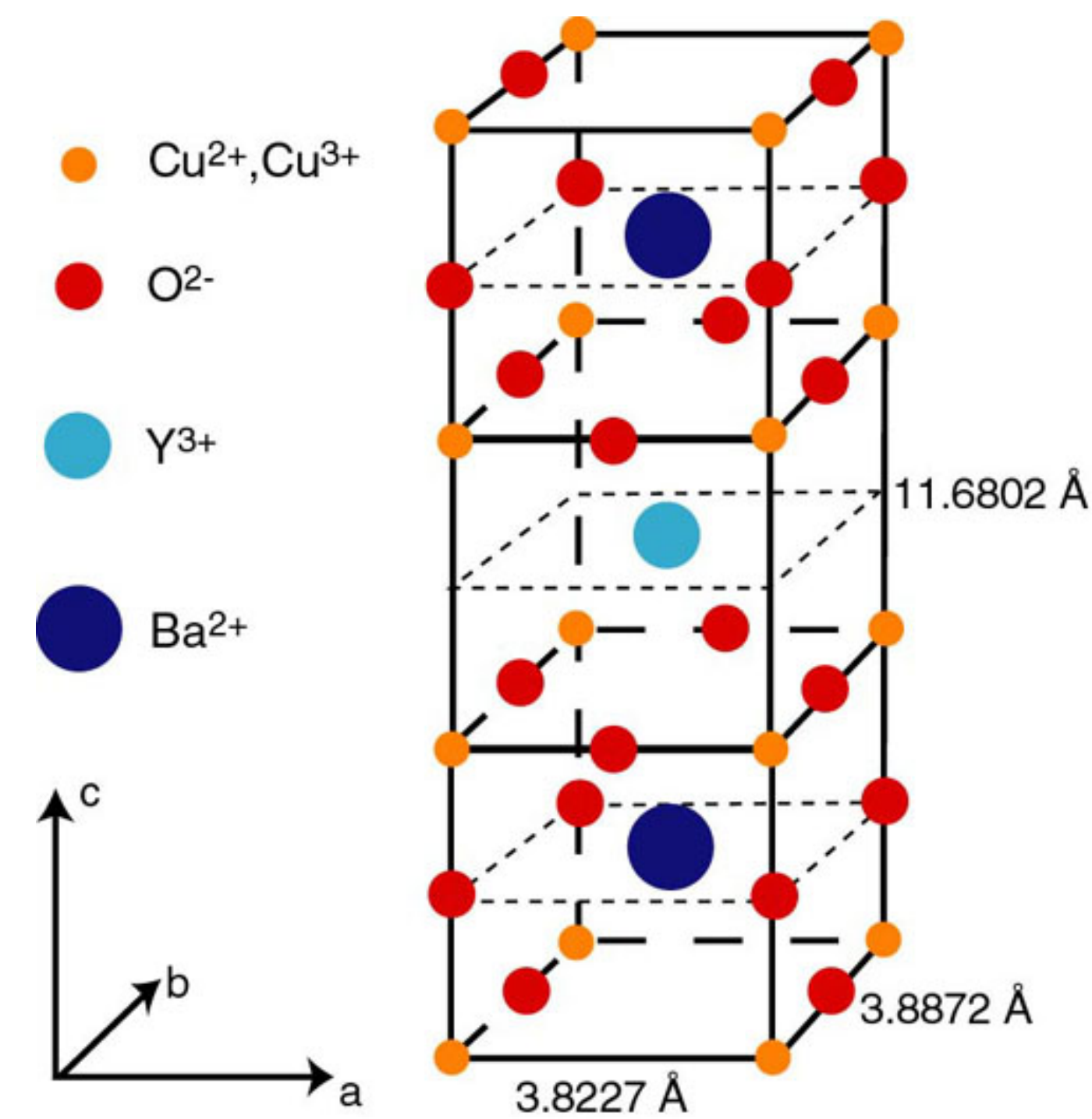
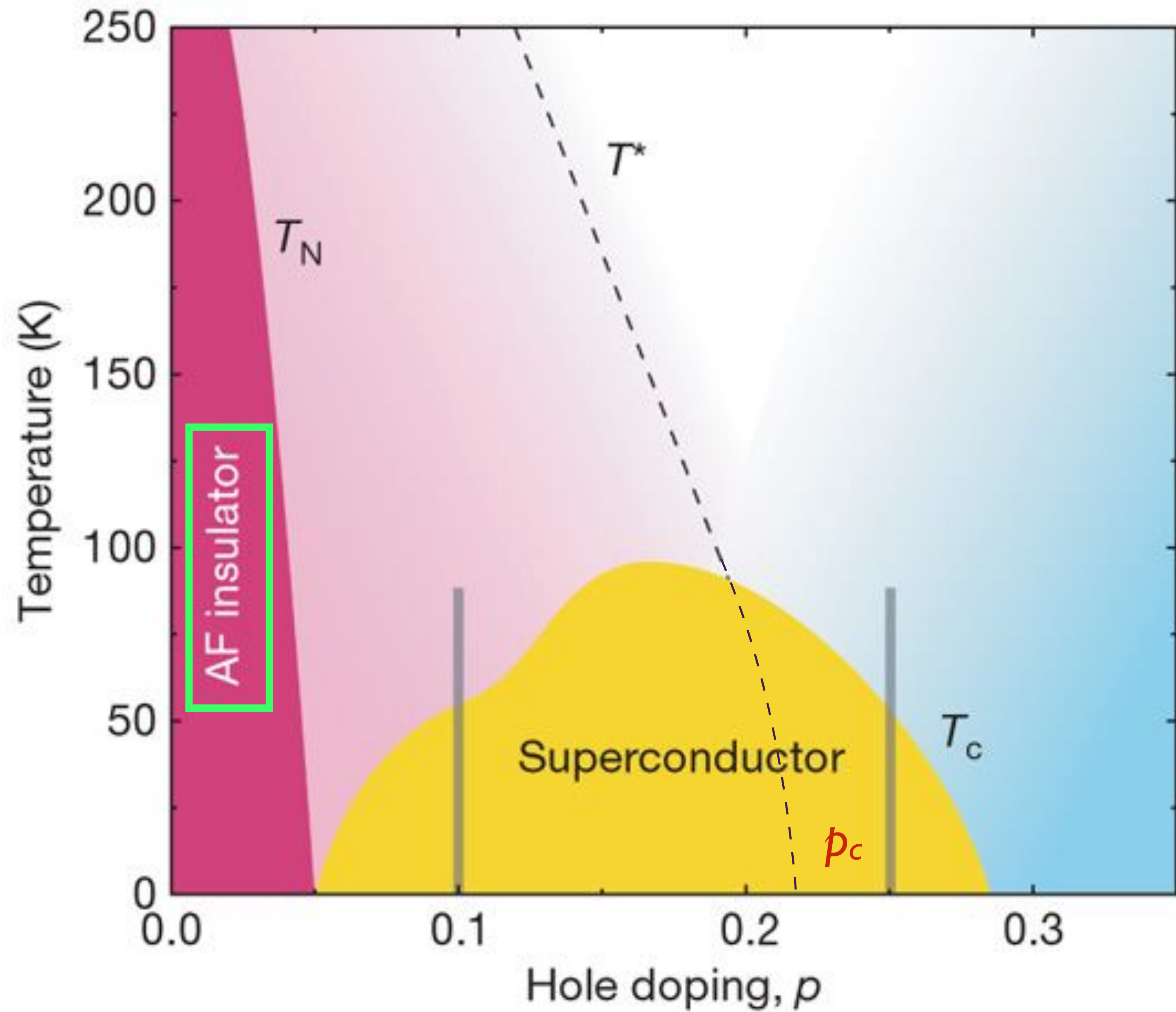


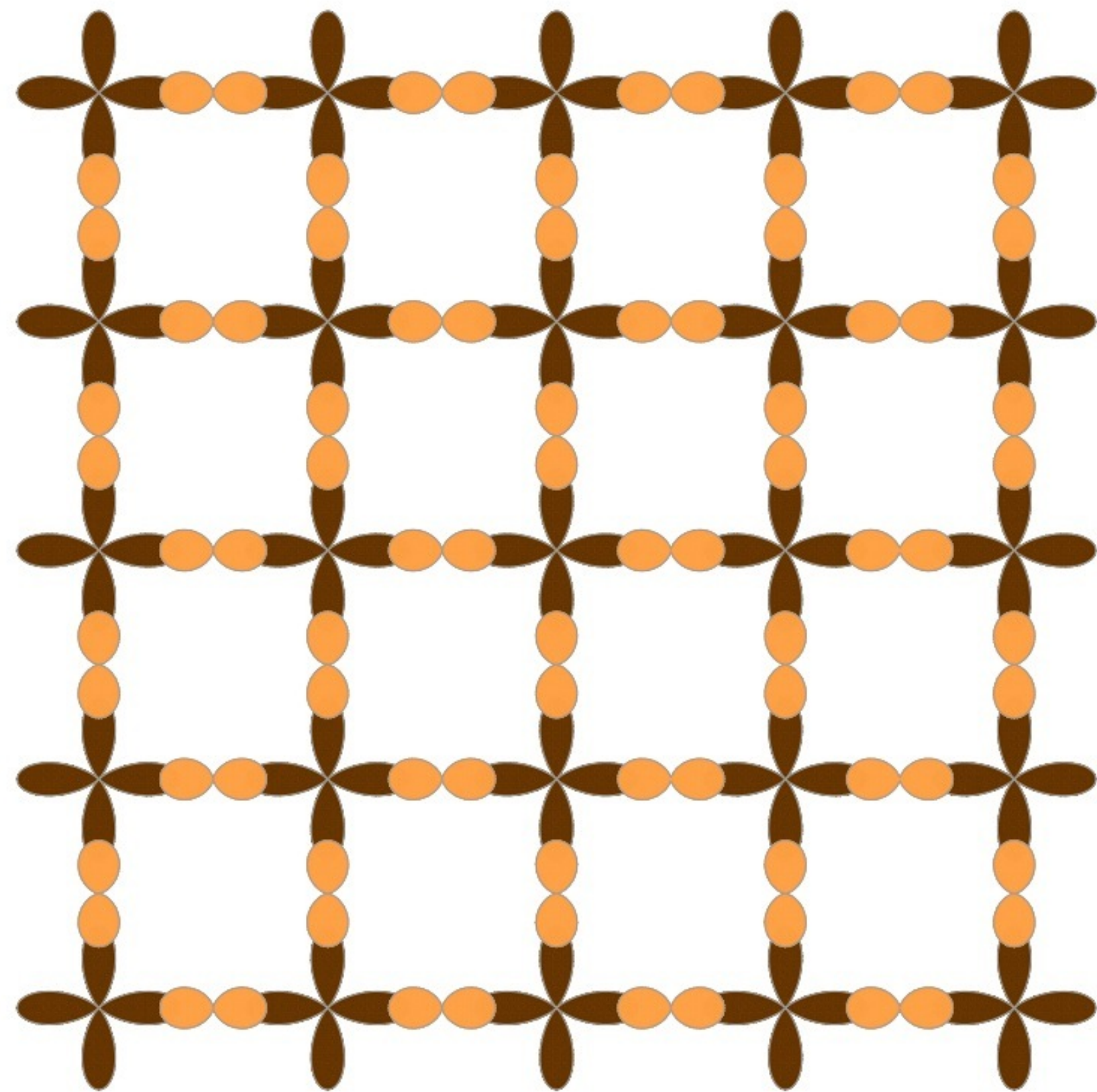
The diagram shows two electron spins (represented by blue dots) enclosed in a blue oval. To the right of the oval is an equals sign followed by the quantum state $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$.

Benzene

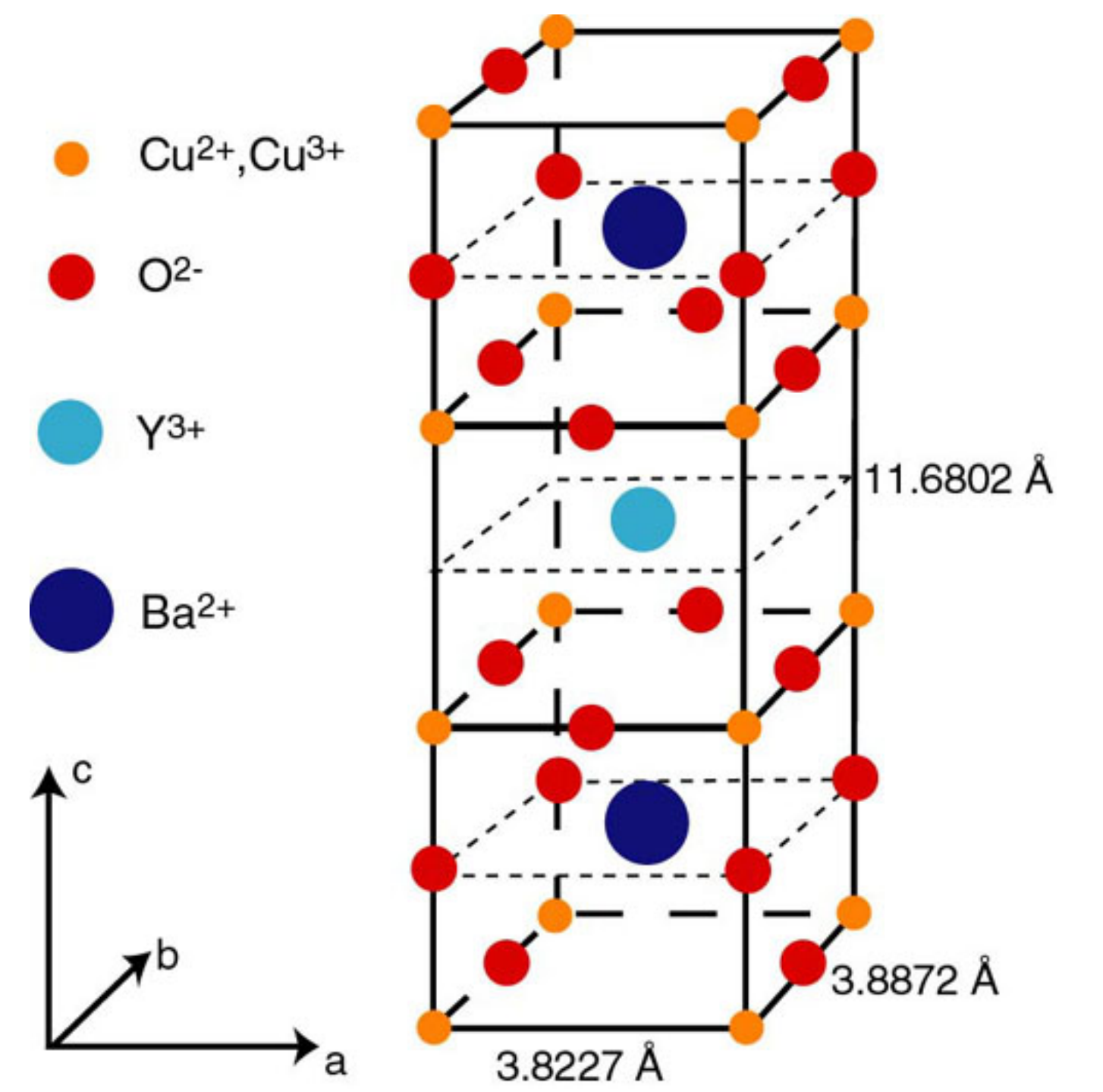
Spin entanglement and the cuprates

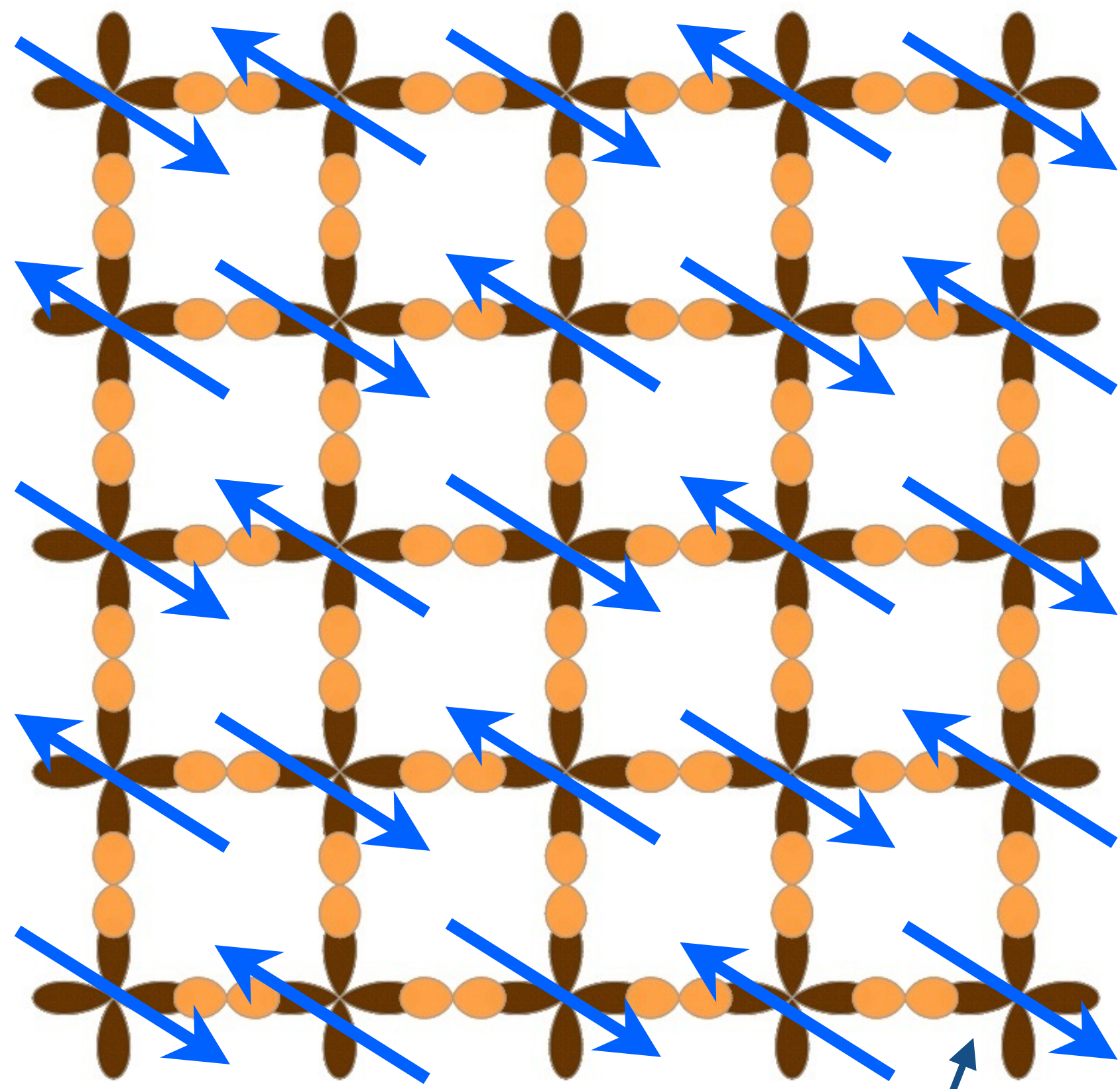




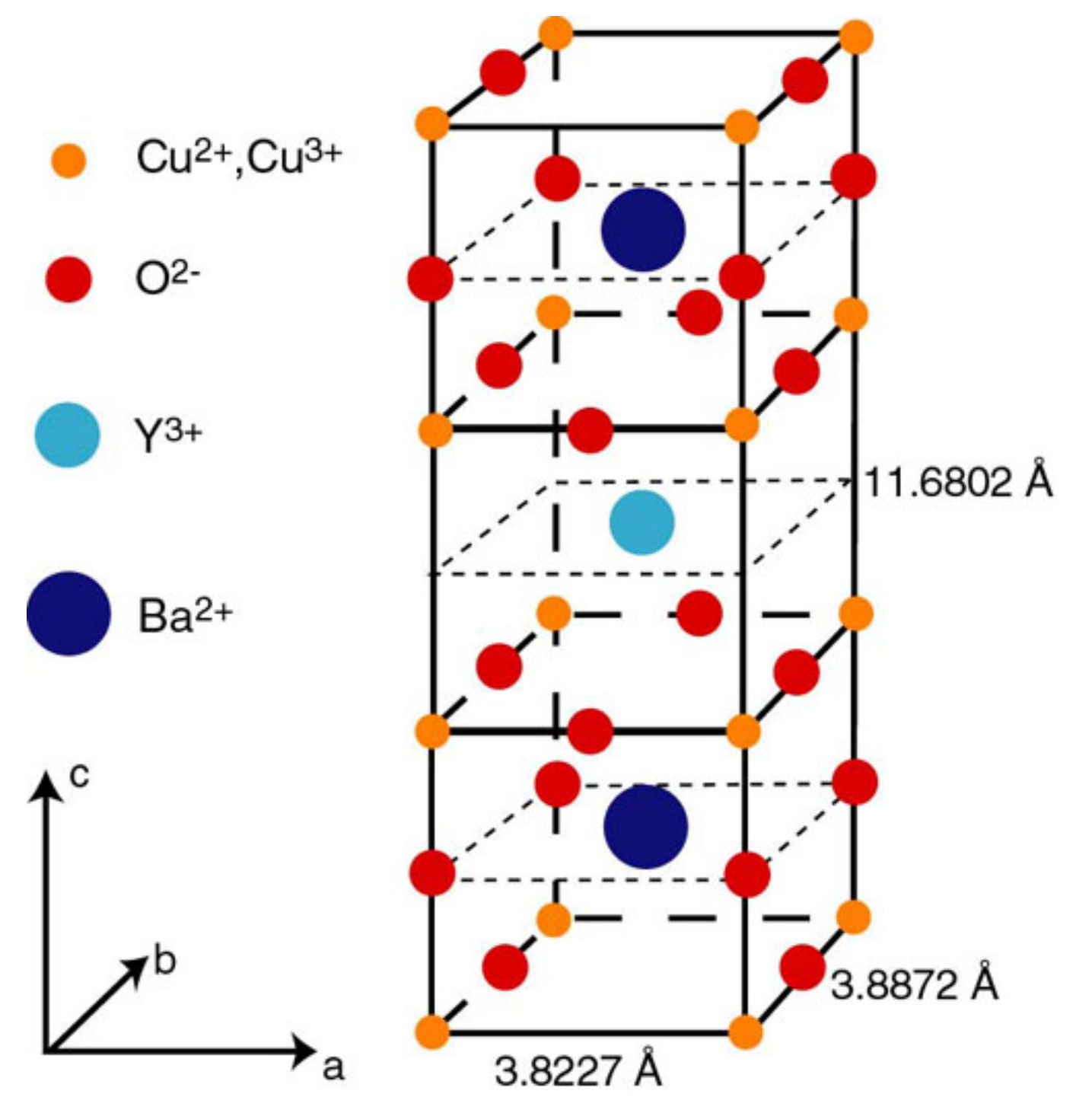


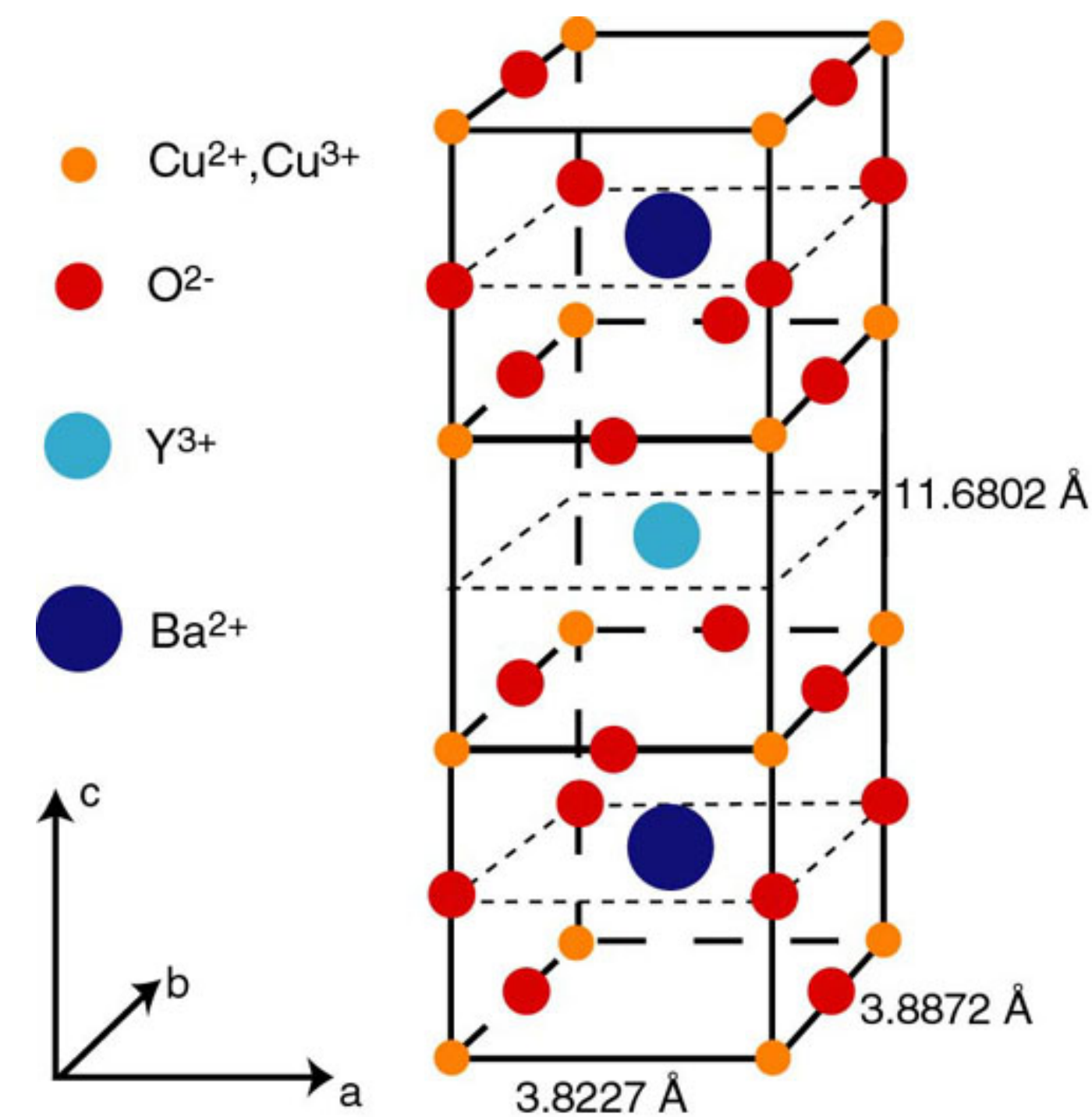
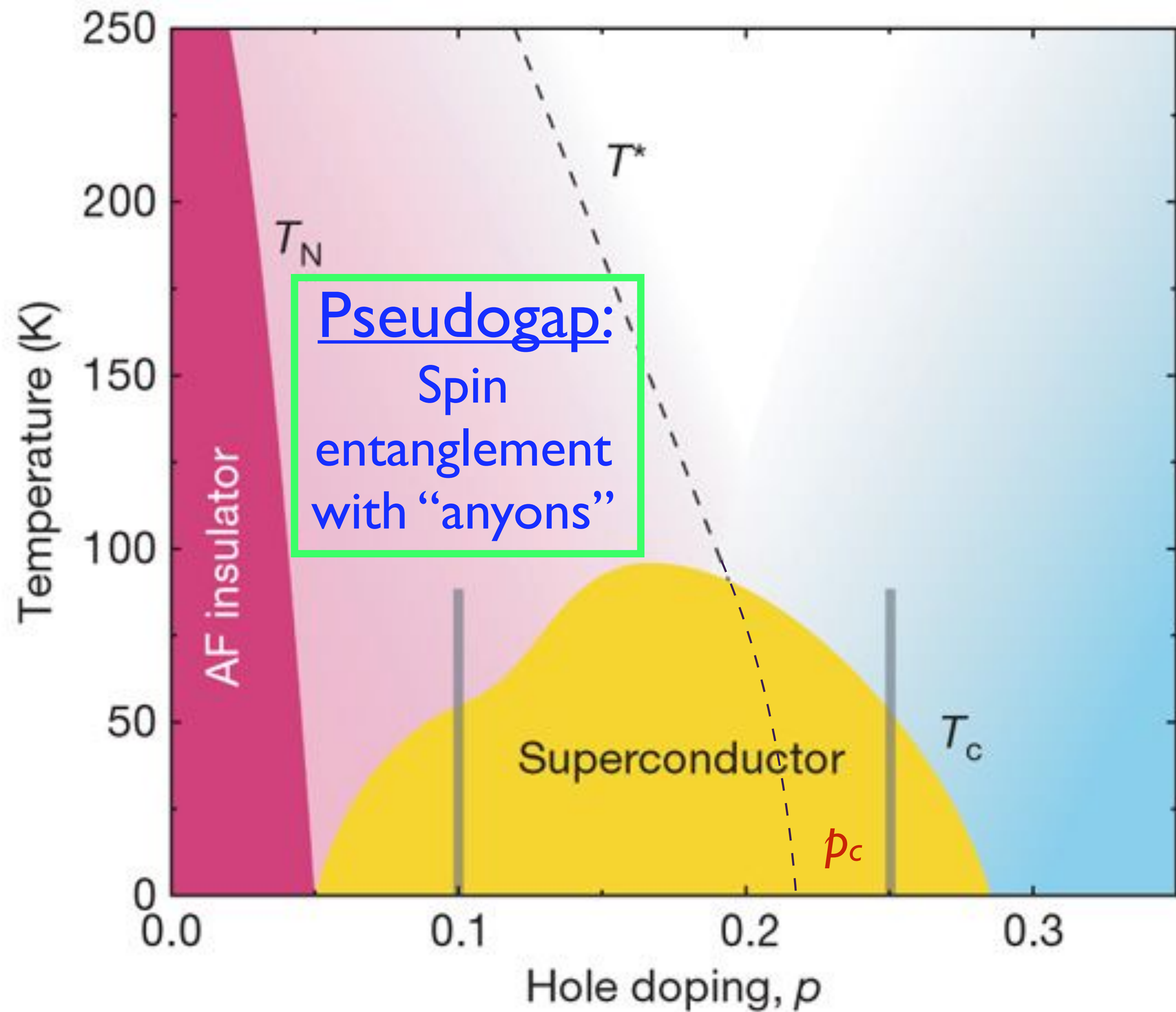
Cu



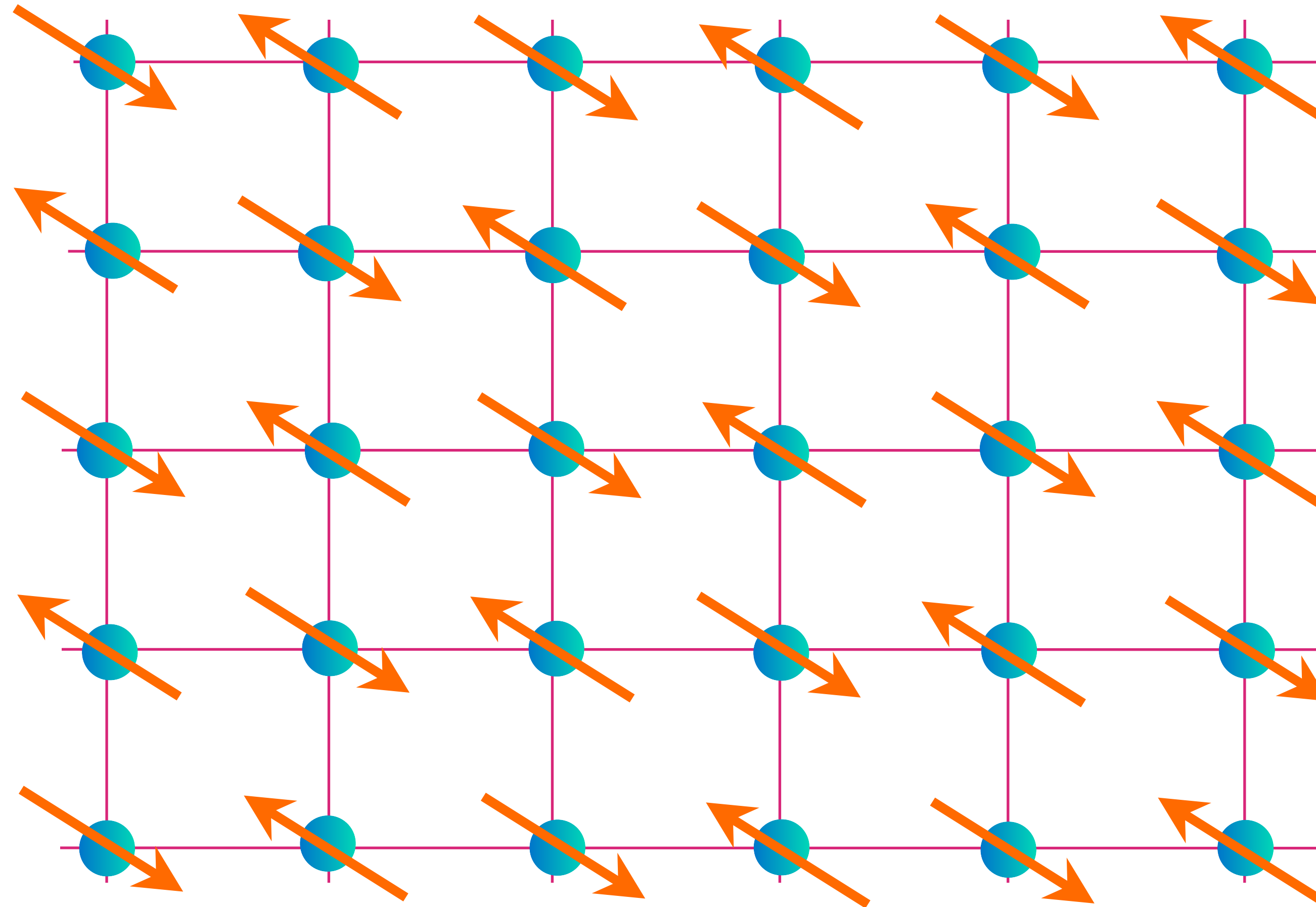


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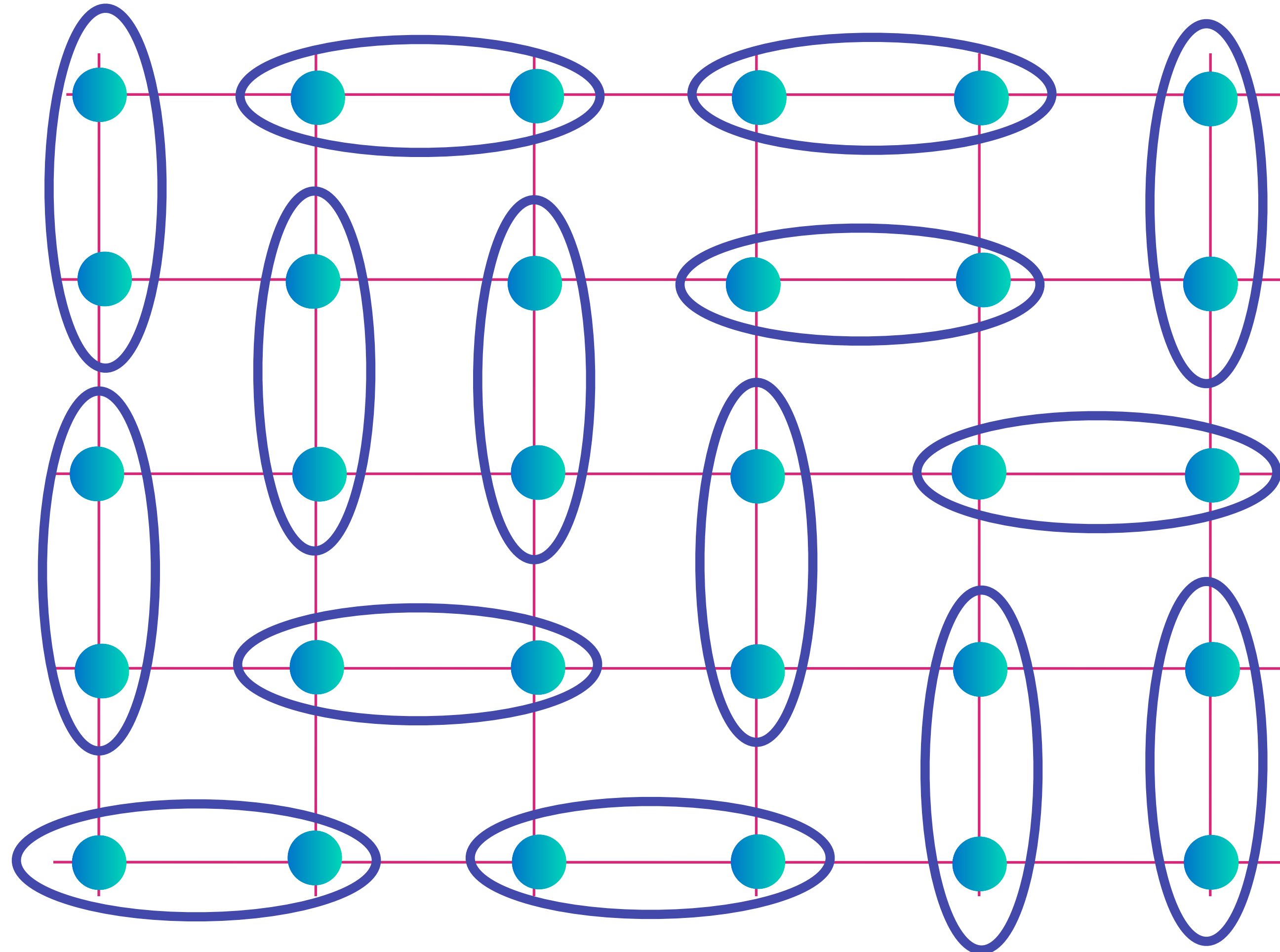




Antiferromagnet



Anderson's Resonating Valence Bond (1972, 1987)

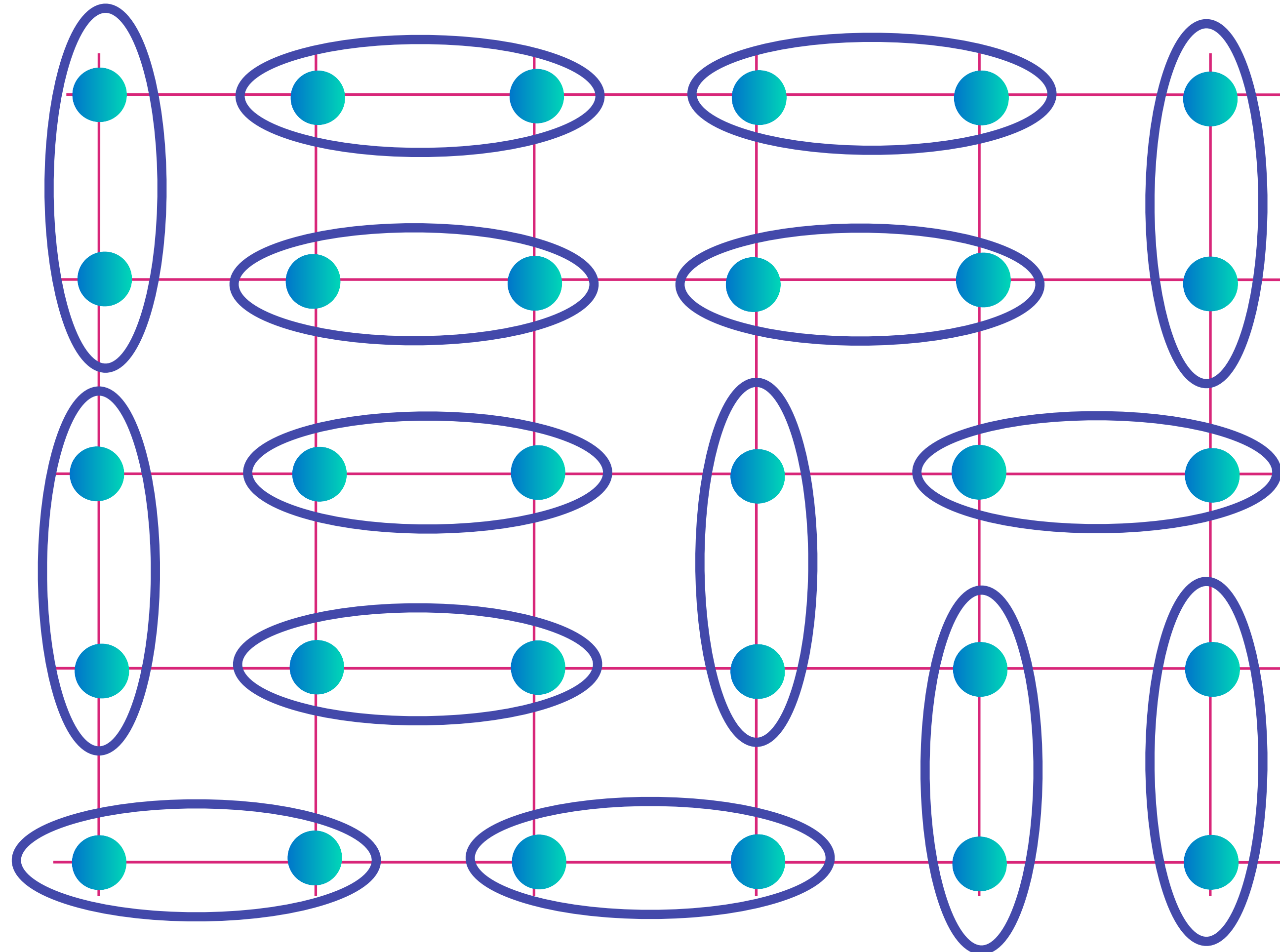


$$\text{oval} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

$\mathcal{D} \rightarrow$ dimer covering
of lattice

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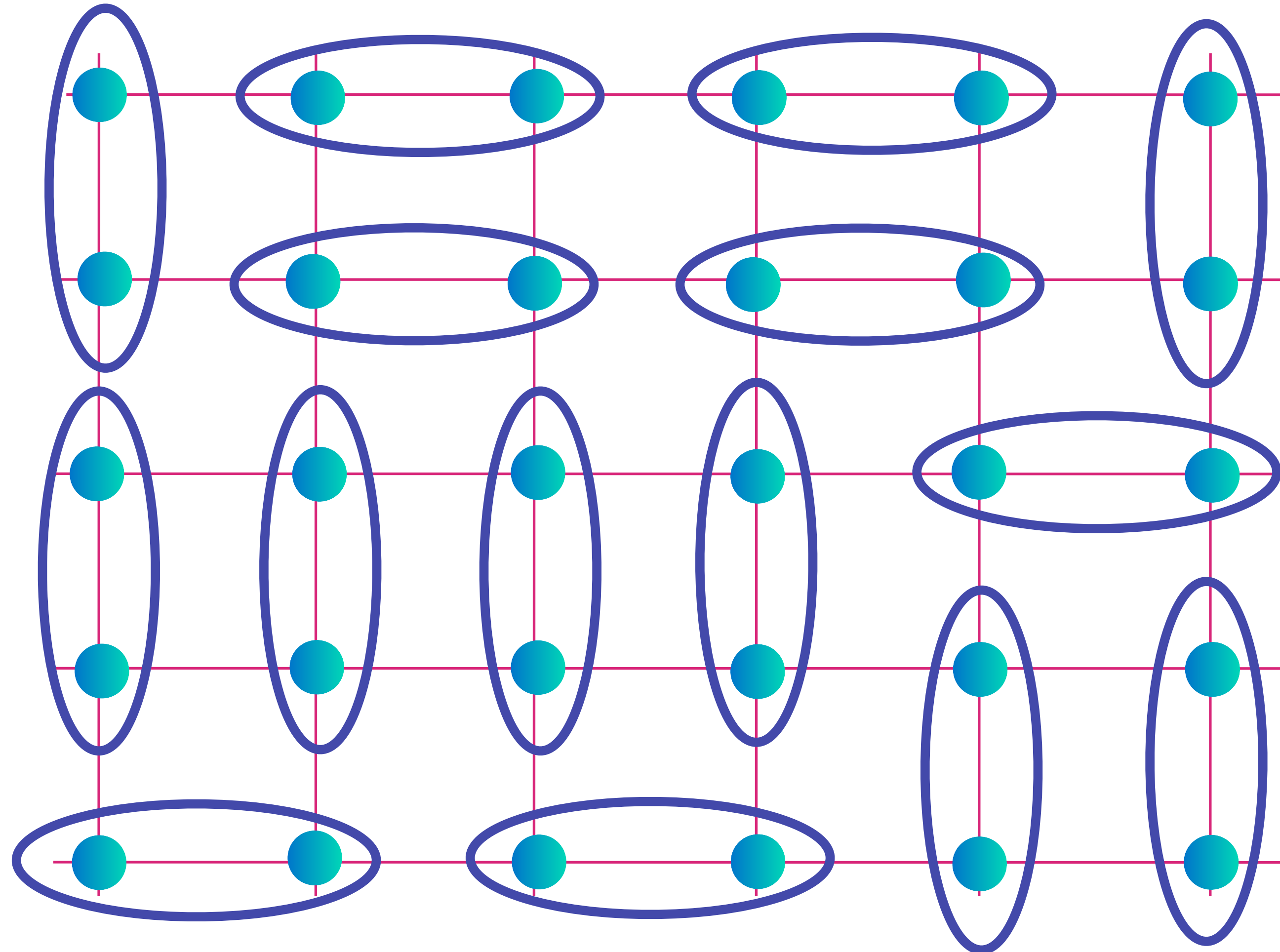


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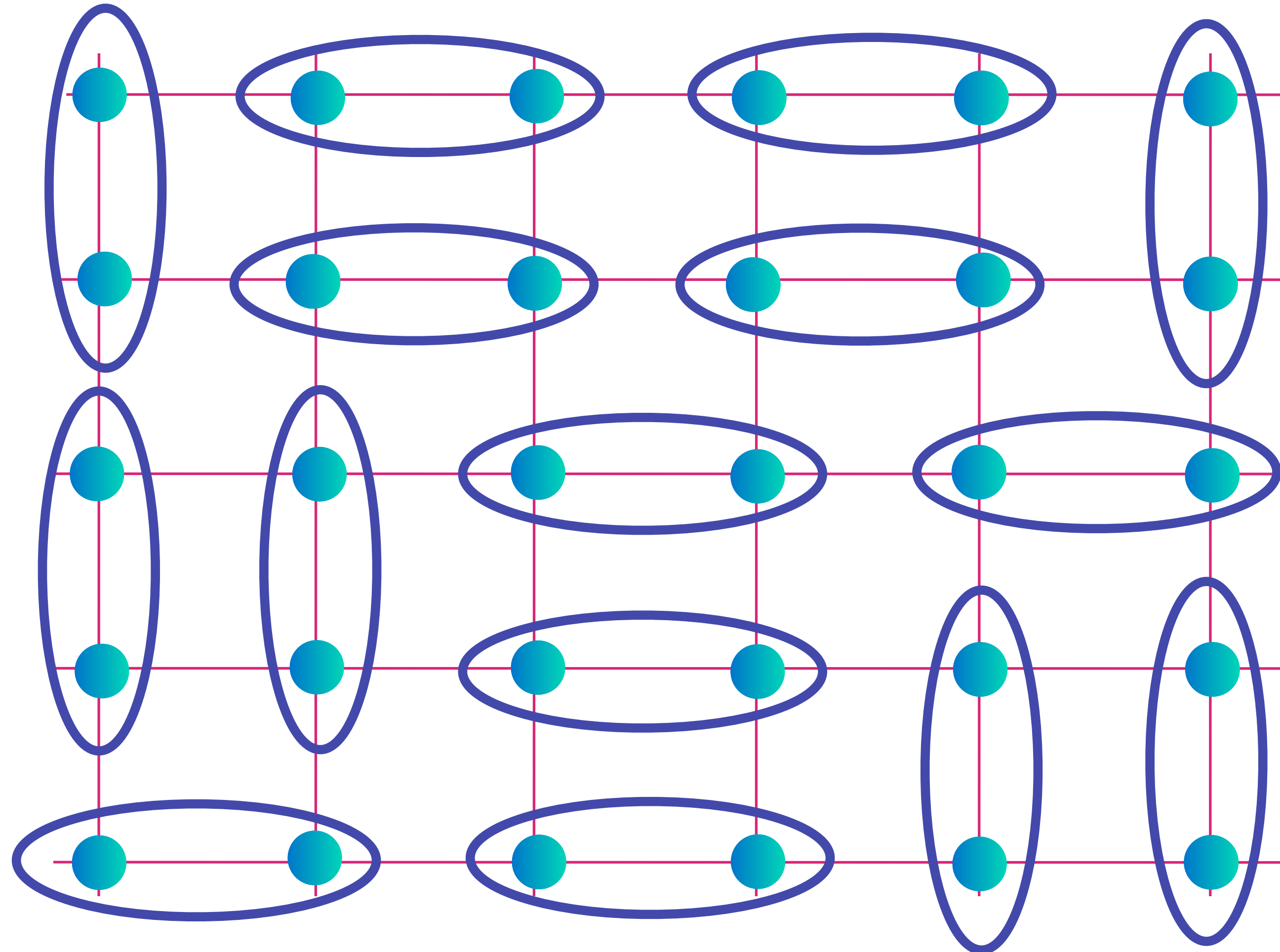


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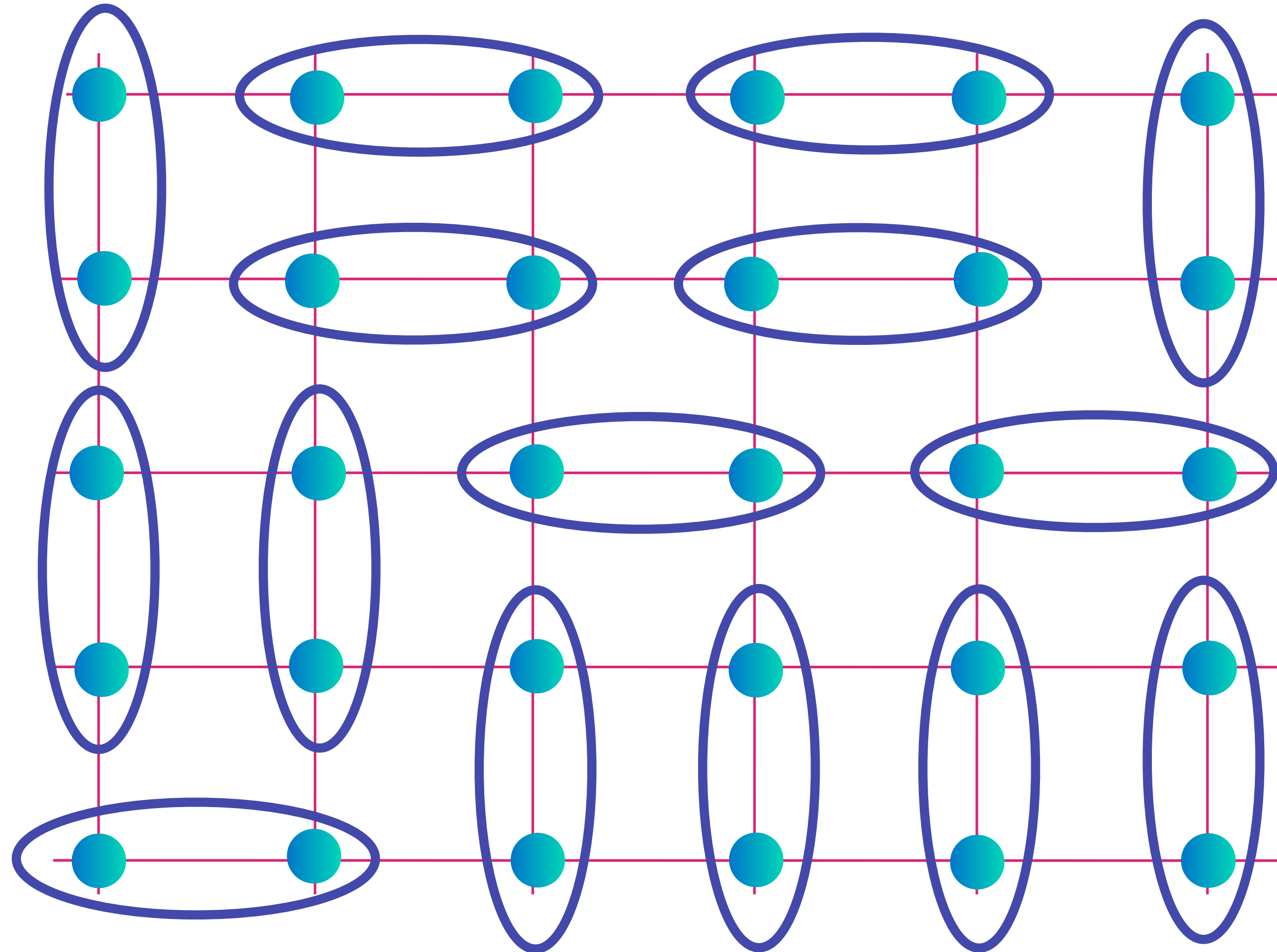


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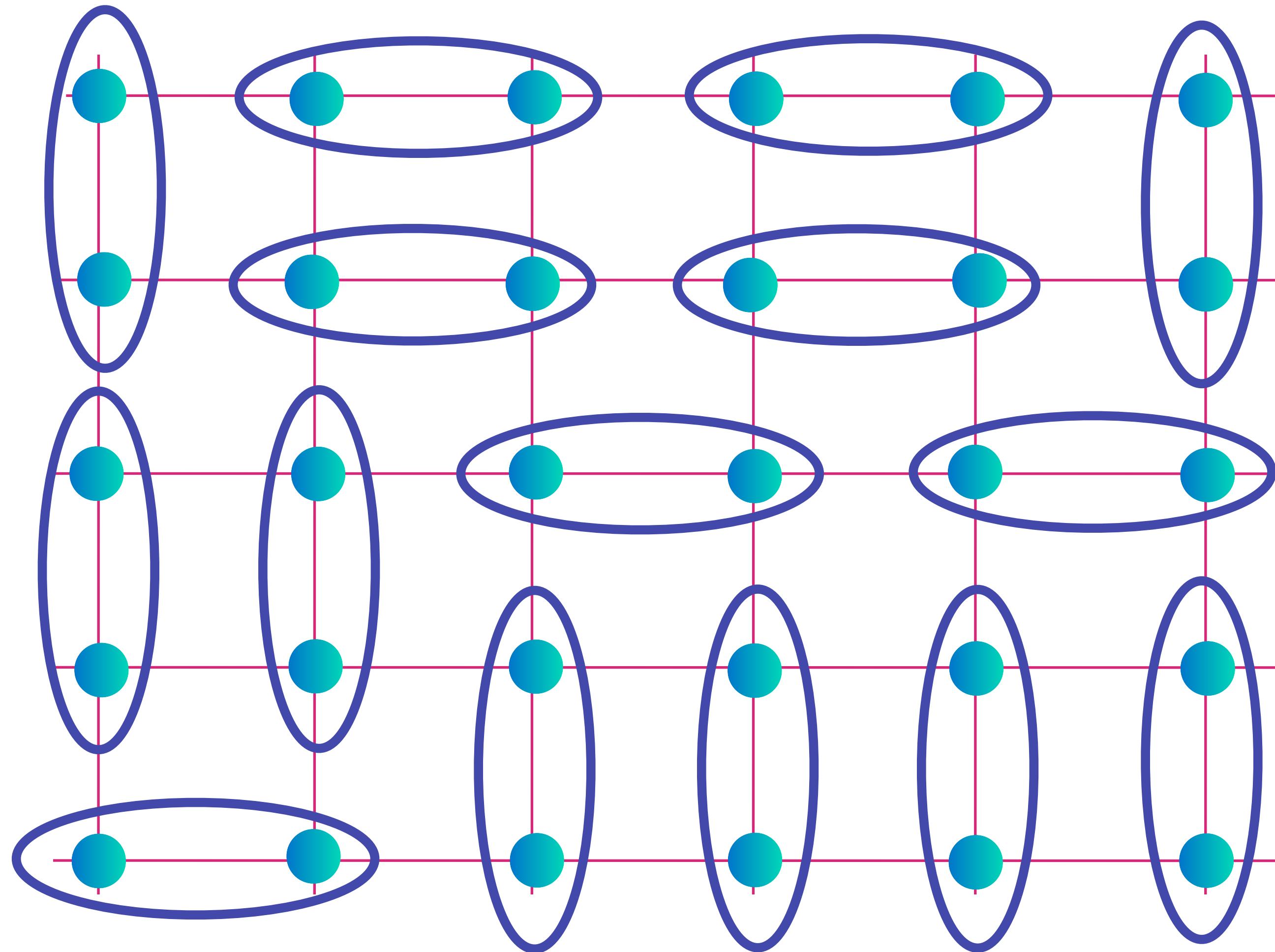


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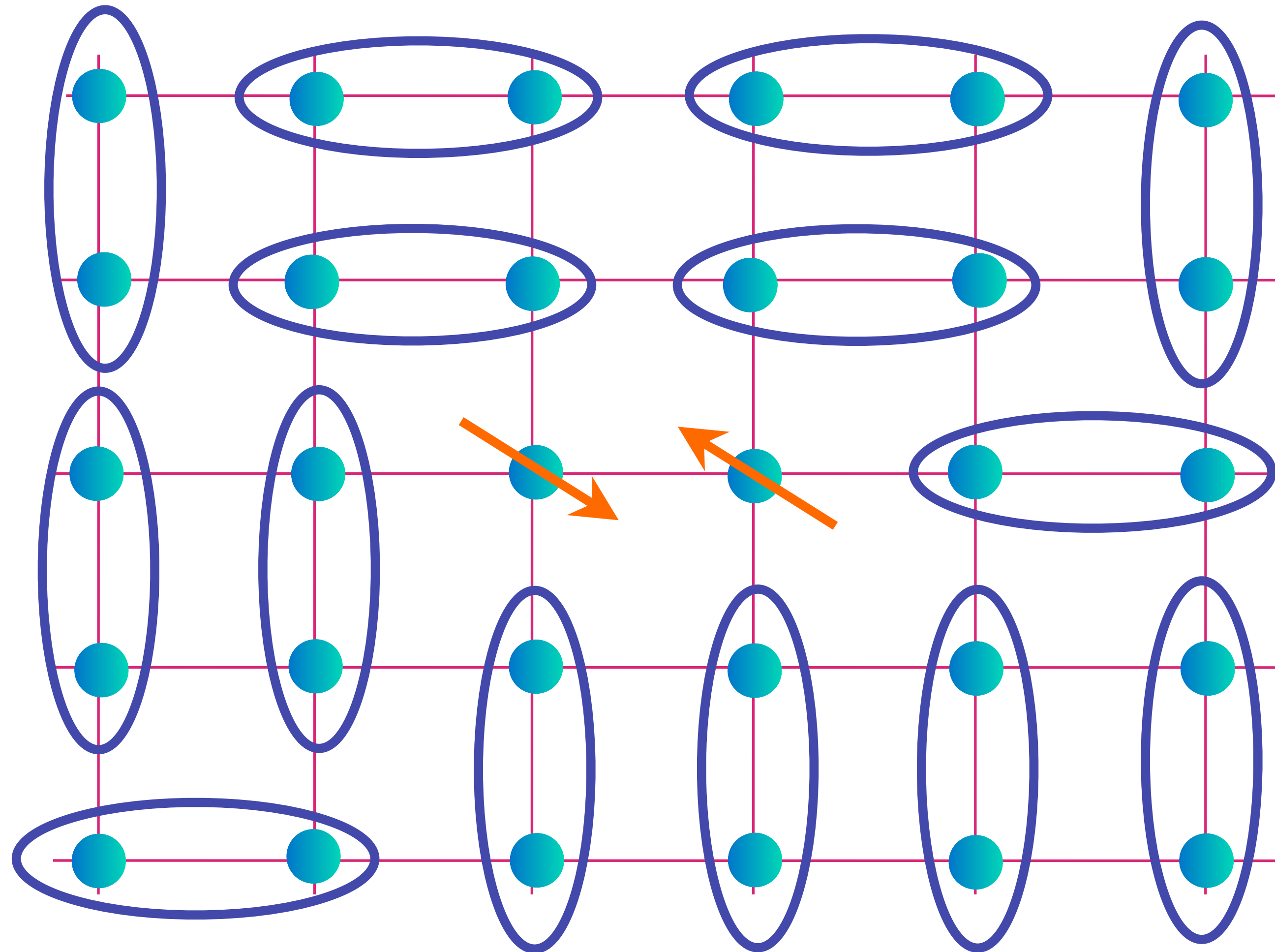
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Quantum
Entanglement
of an infinite
number of spins!

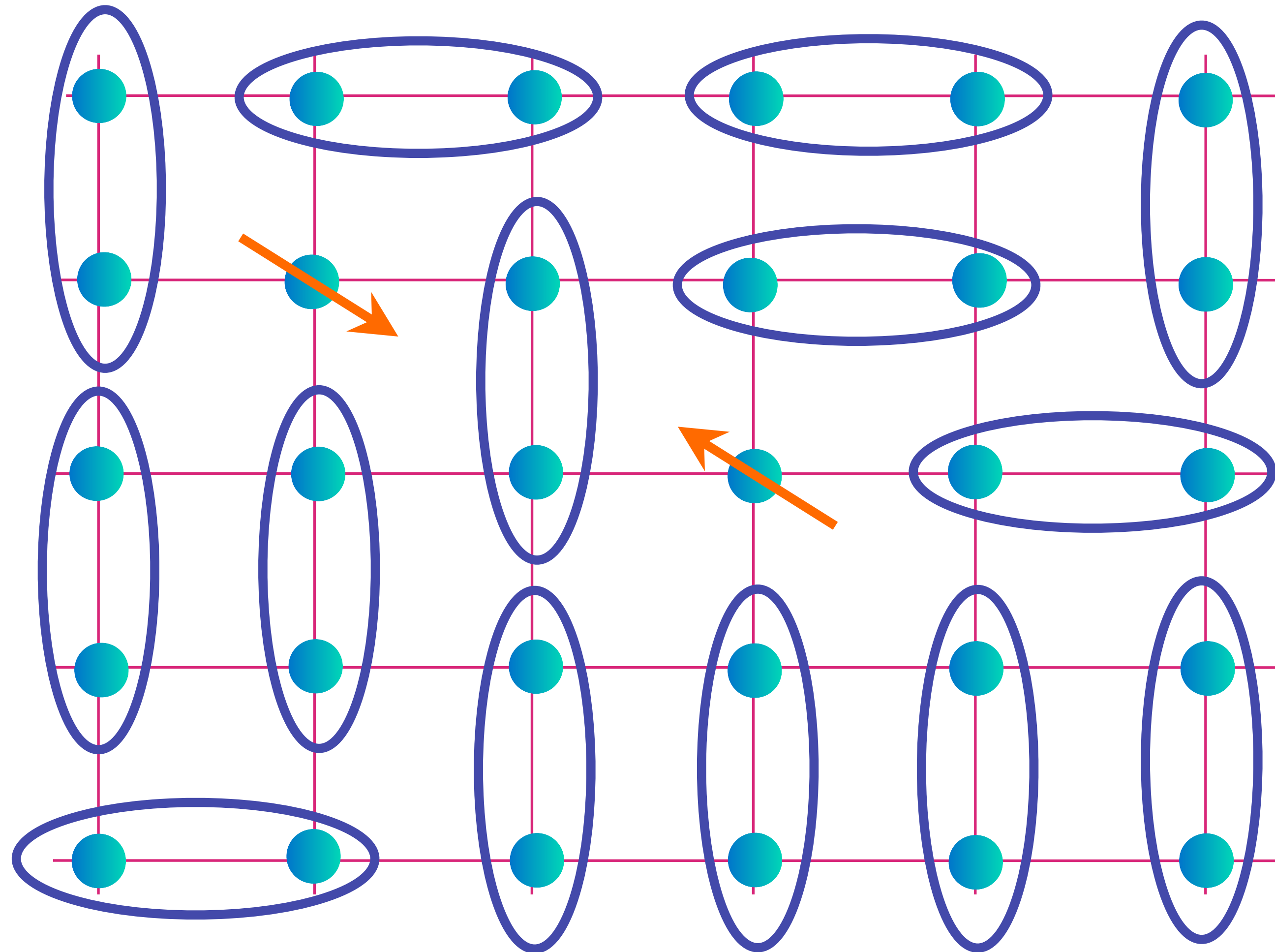
Anderson's Resonating Valence Bond (1972, 1987)



Spinon:
an “anyon”
which cannot be
created by a
local operation

$$\text{[Diagram of a pair of cyan dots in a blue oval]} = \frac{(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)}{\sqrt{2}}$$

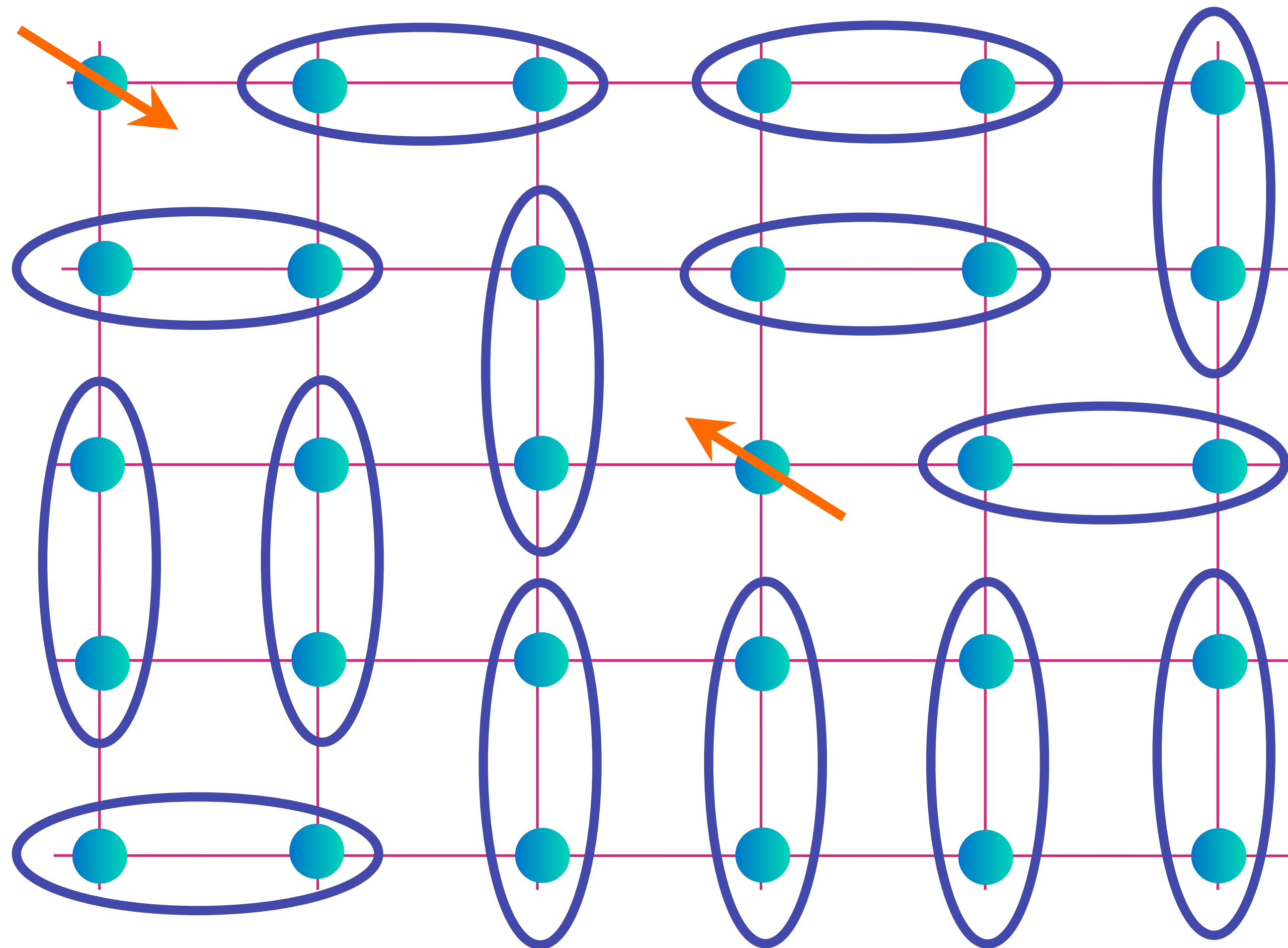
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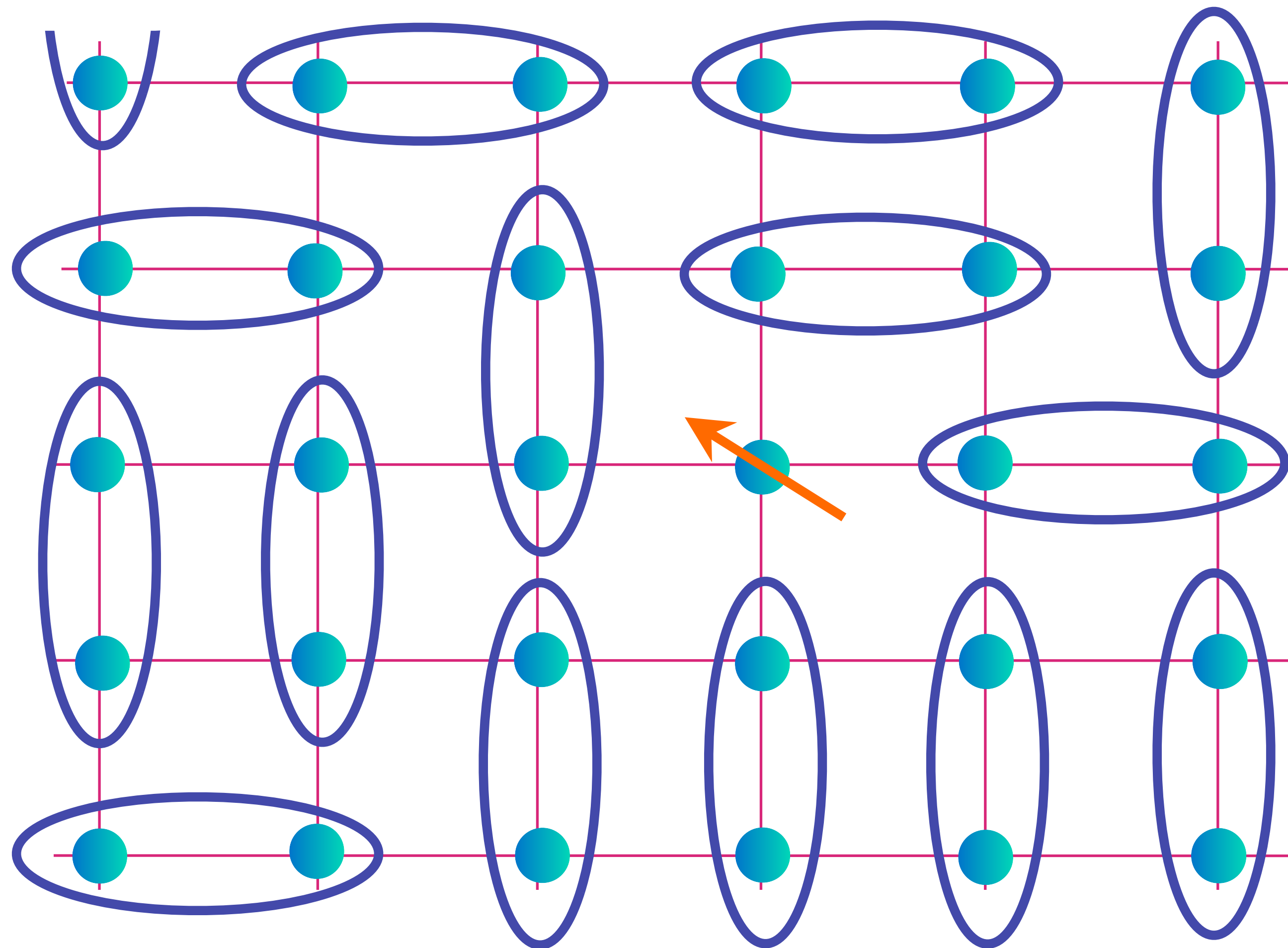
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$$\text{[oval with two dots]} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

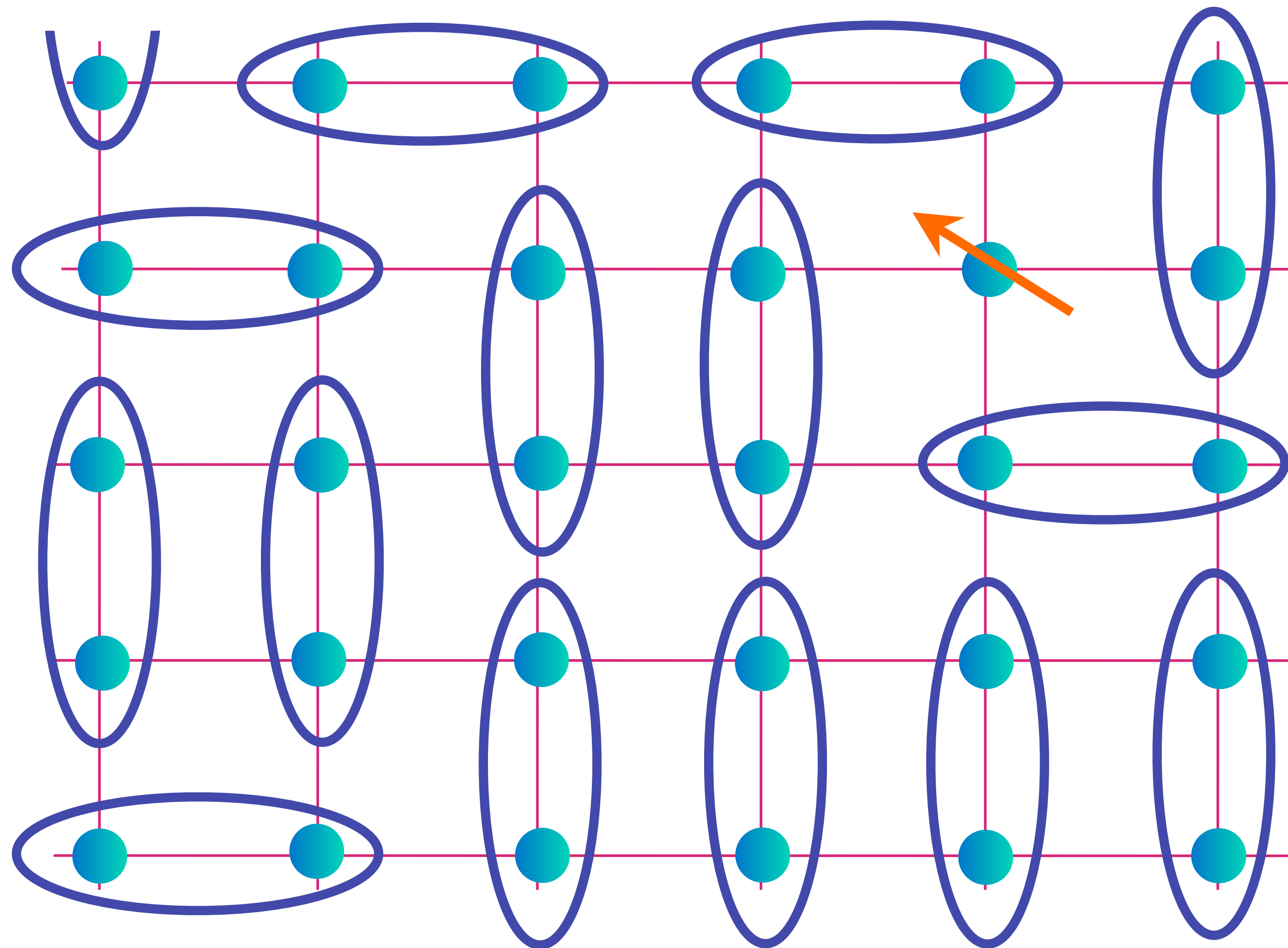
Anderson's Resonating Valence Bond (1972, 1987)



Spinon:
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$$\text{[Diagram of a blue oval containing two teal dots]} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

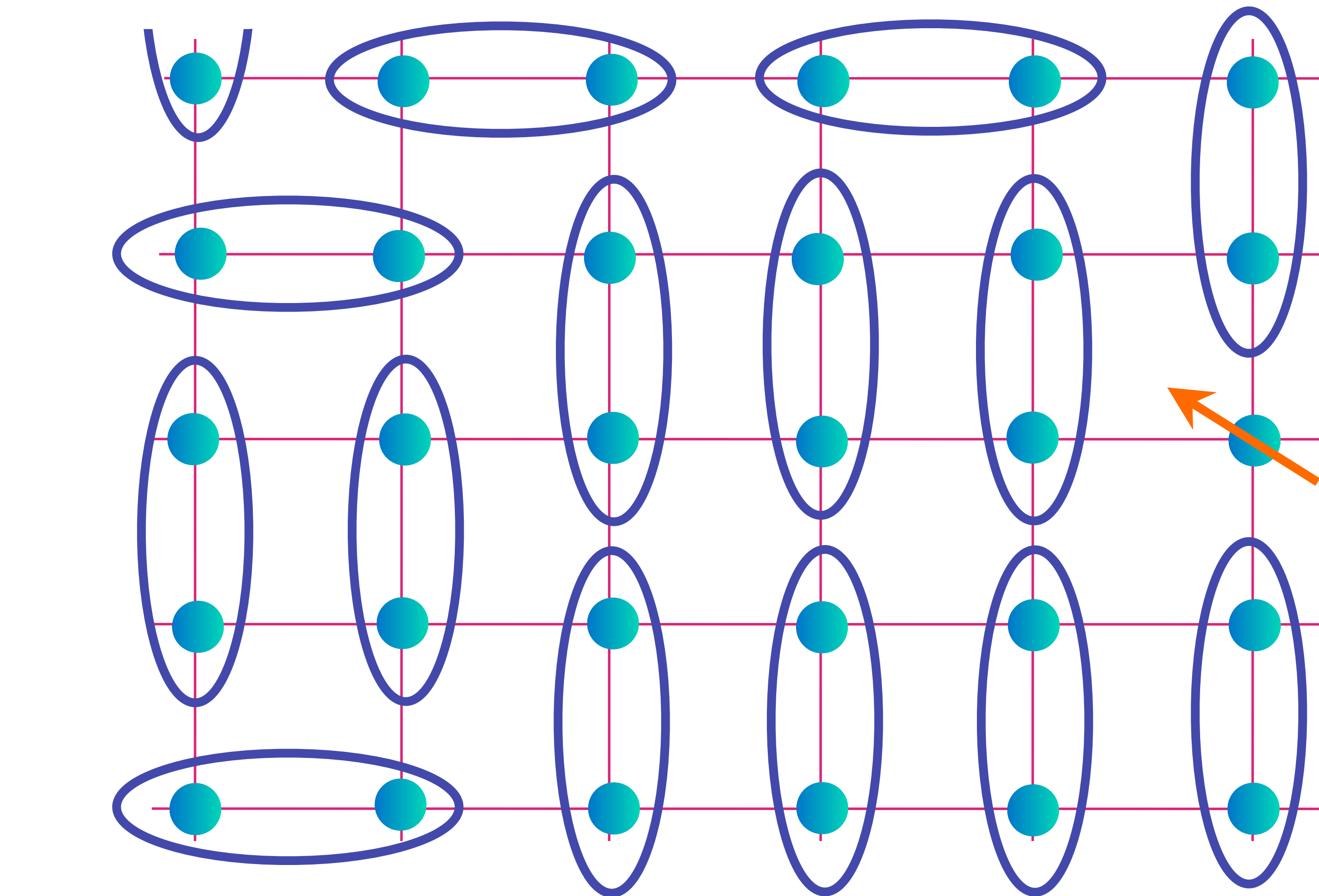
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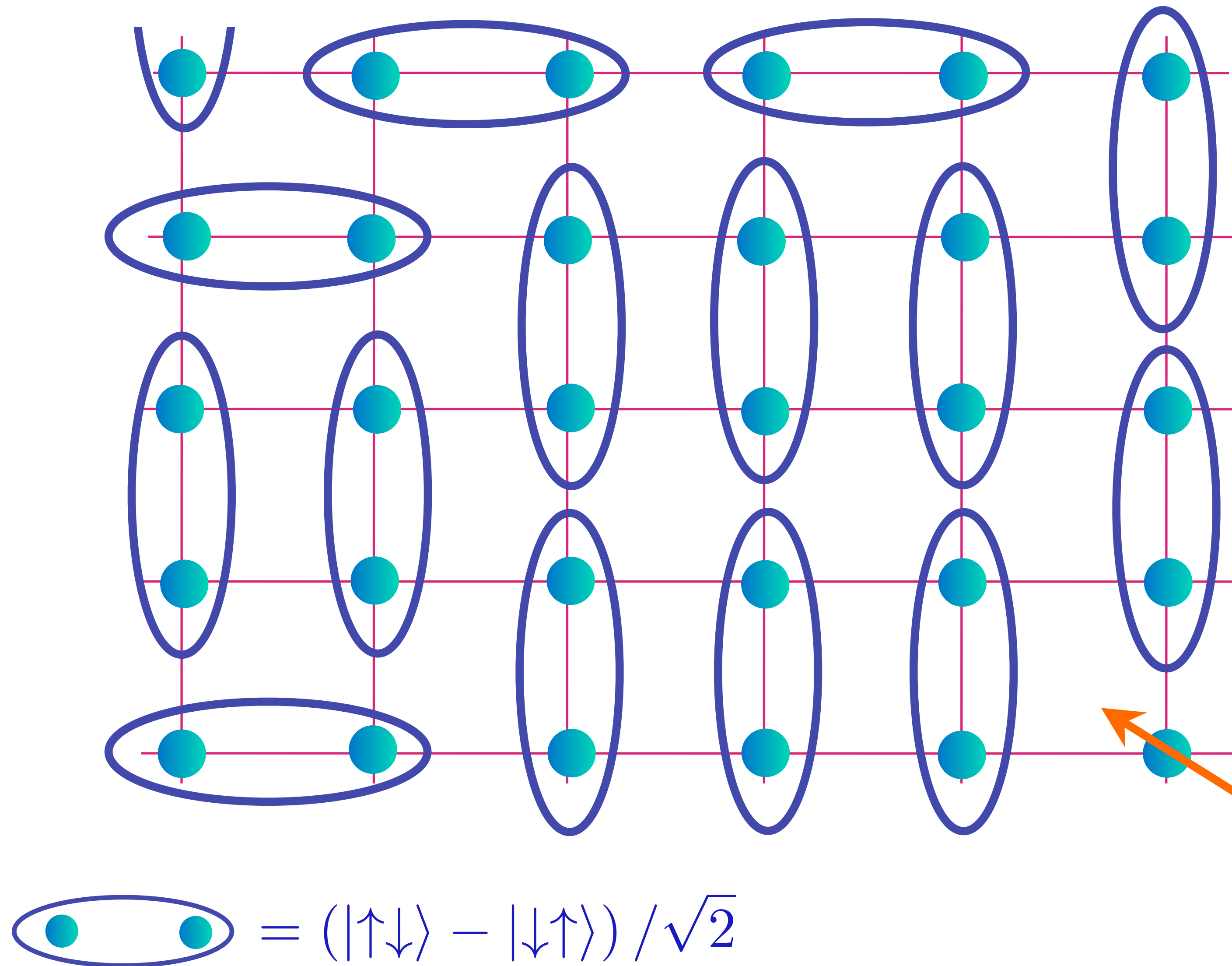
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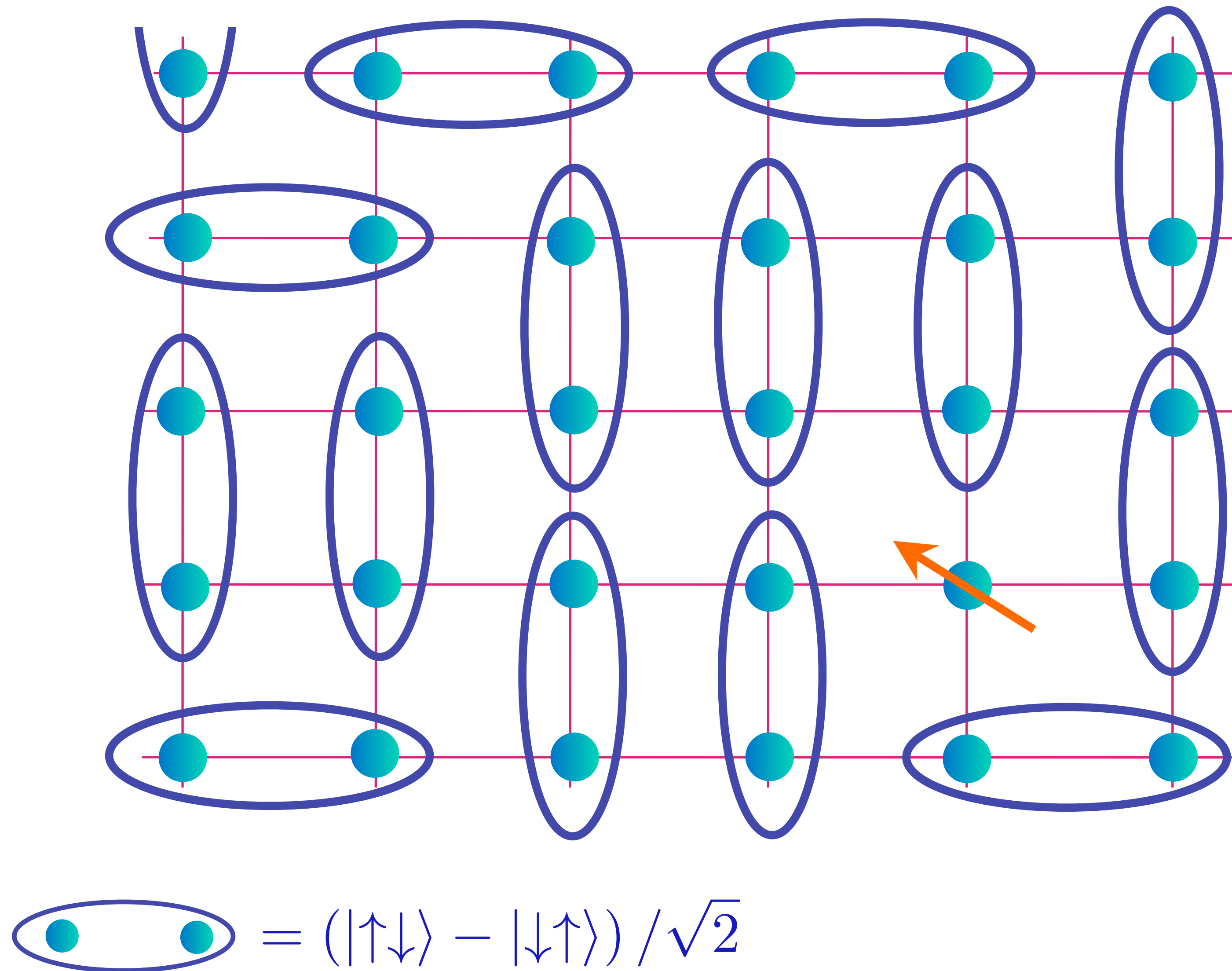
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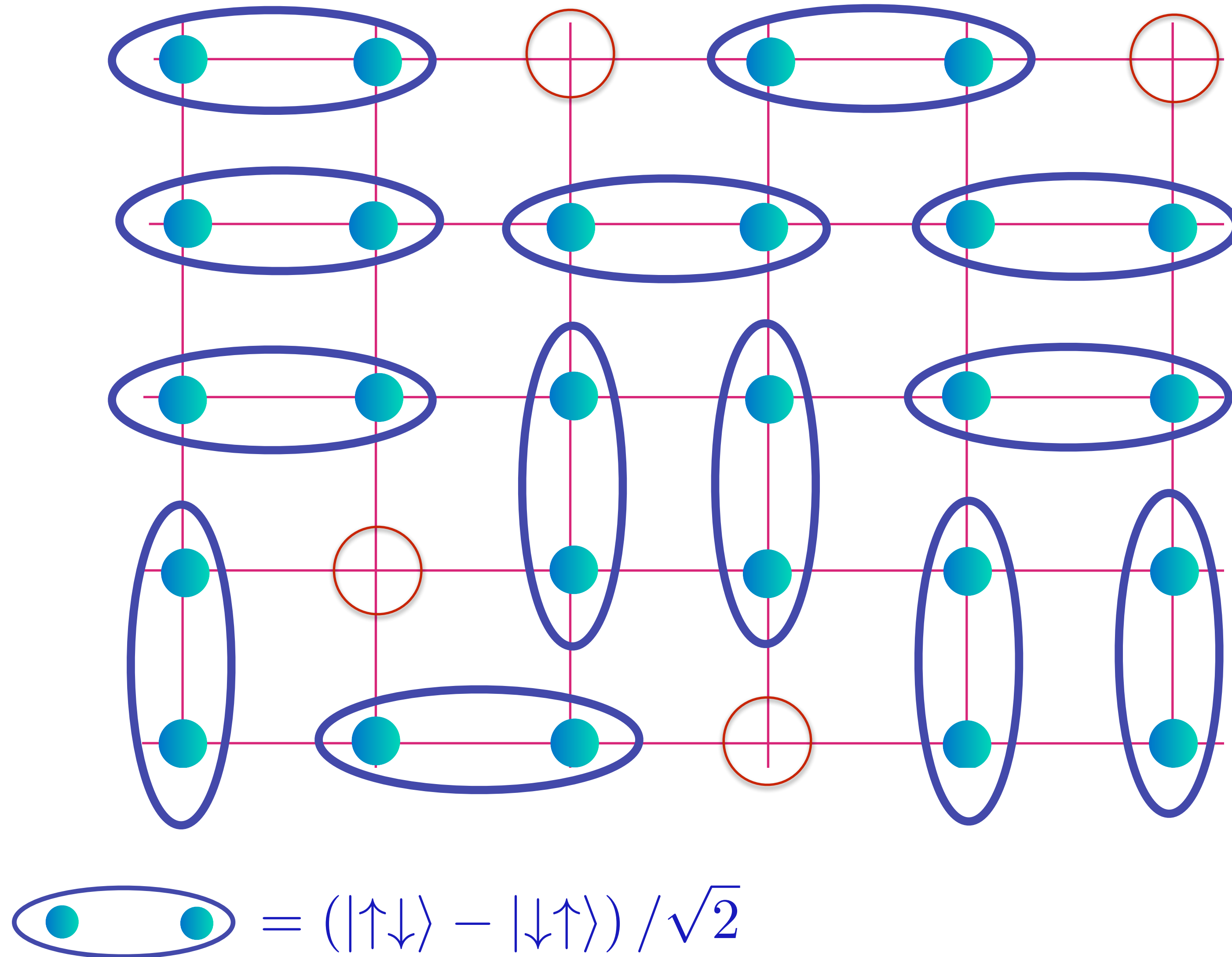
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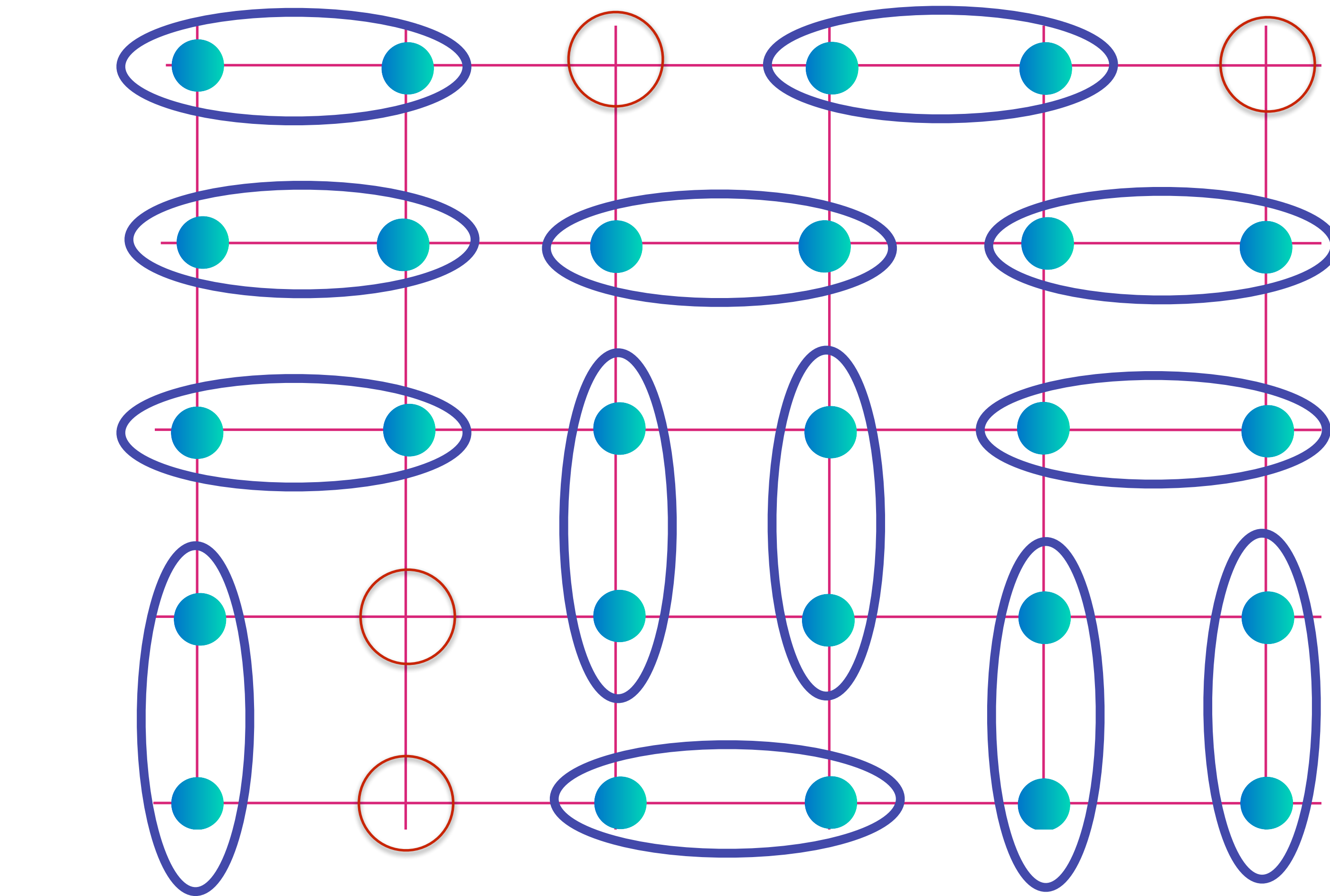
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To obtain a (super)conductor we have to
remove a density ρ of electrons




“Holons”:
anyons of
charge $+e$

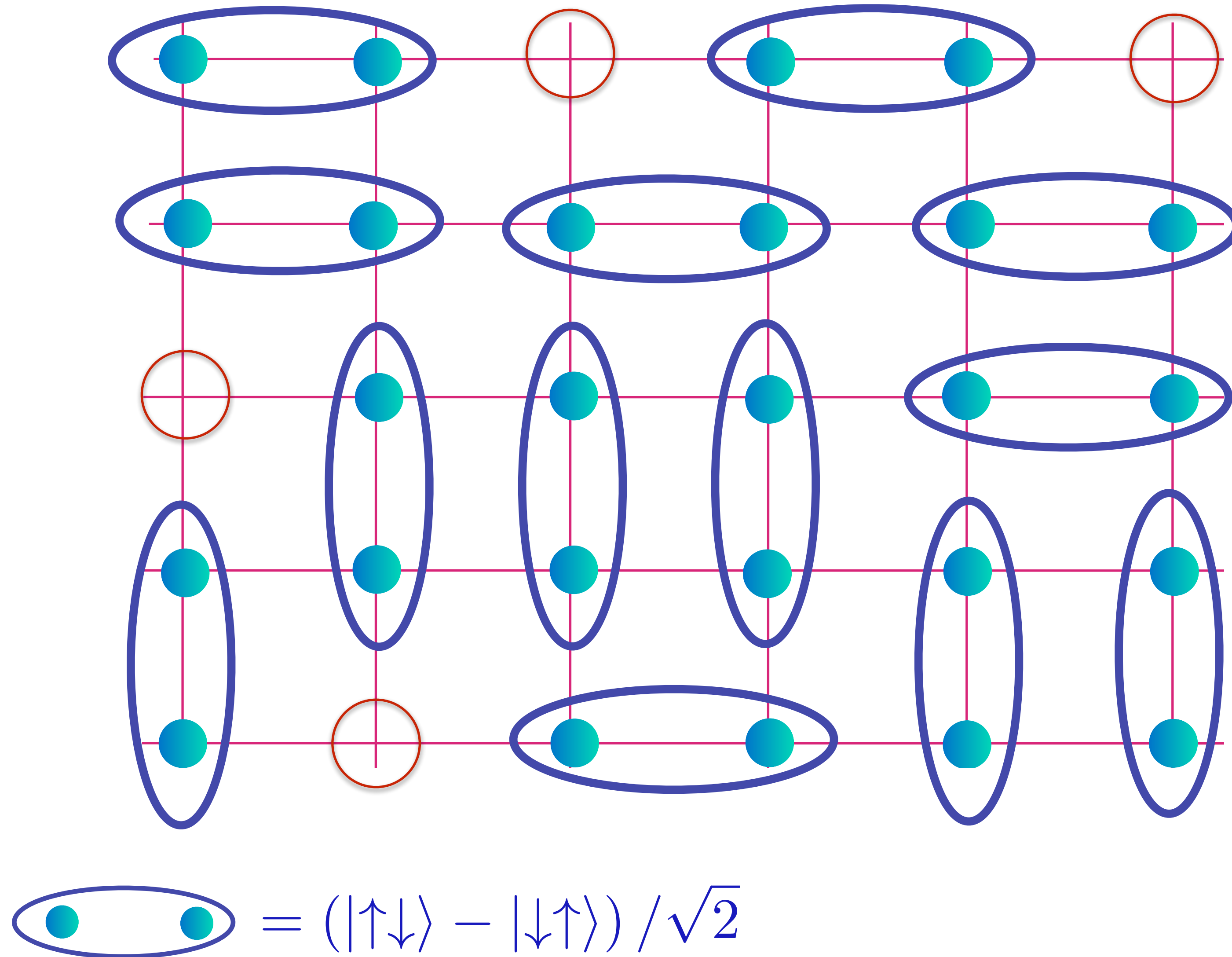
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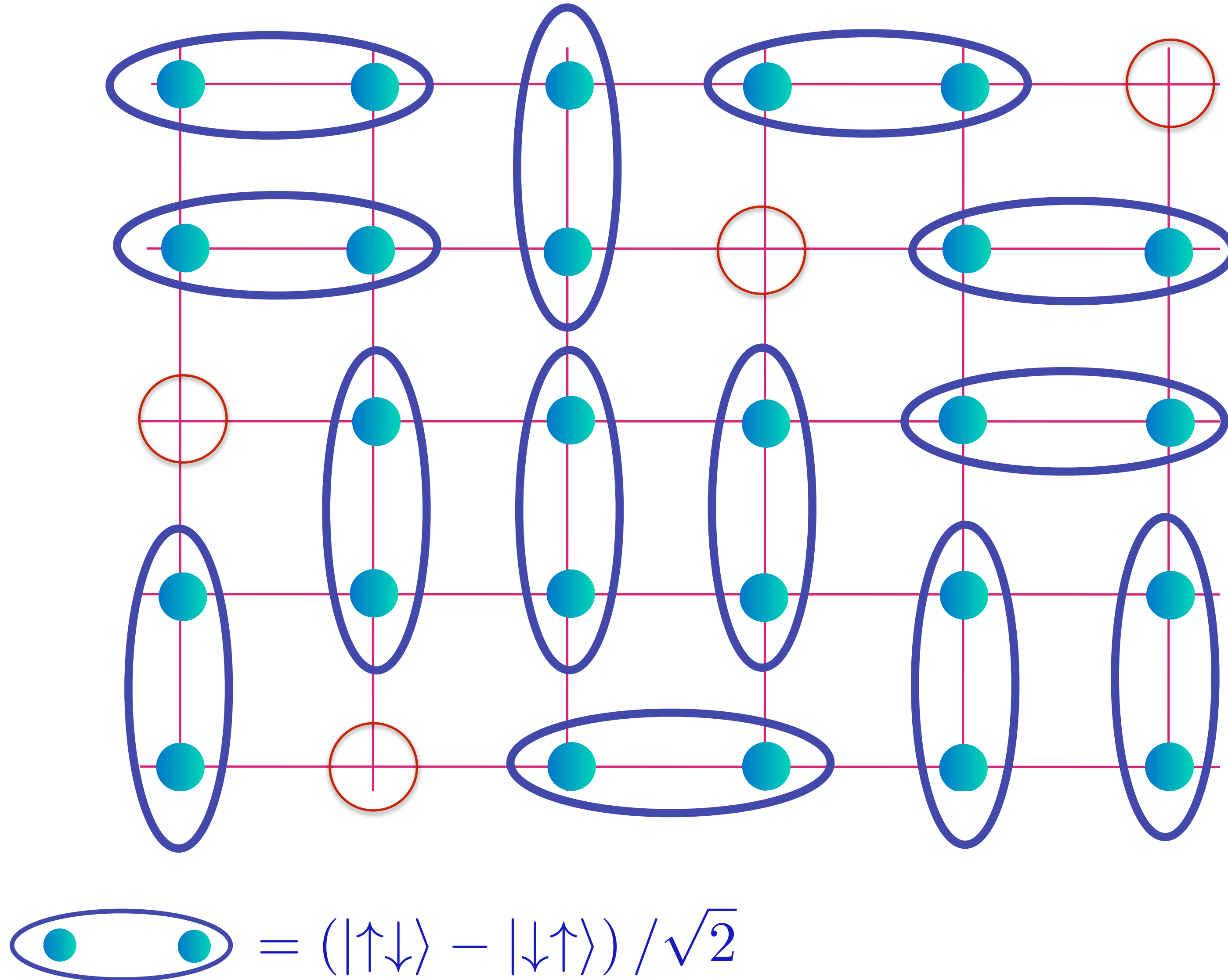
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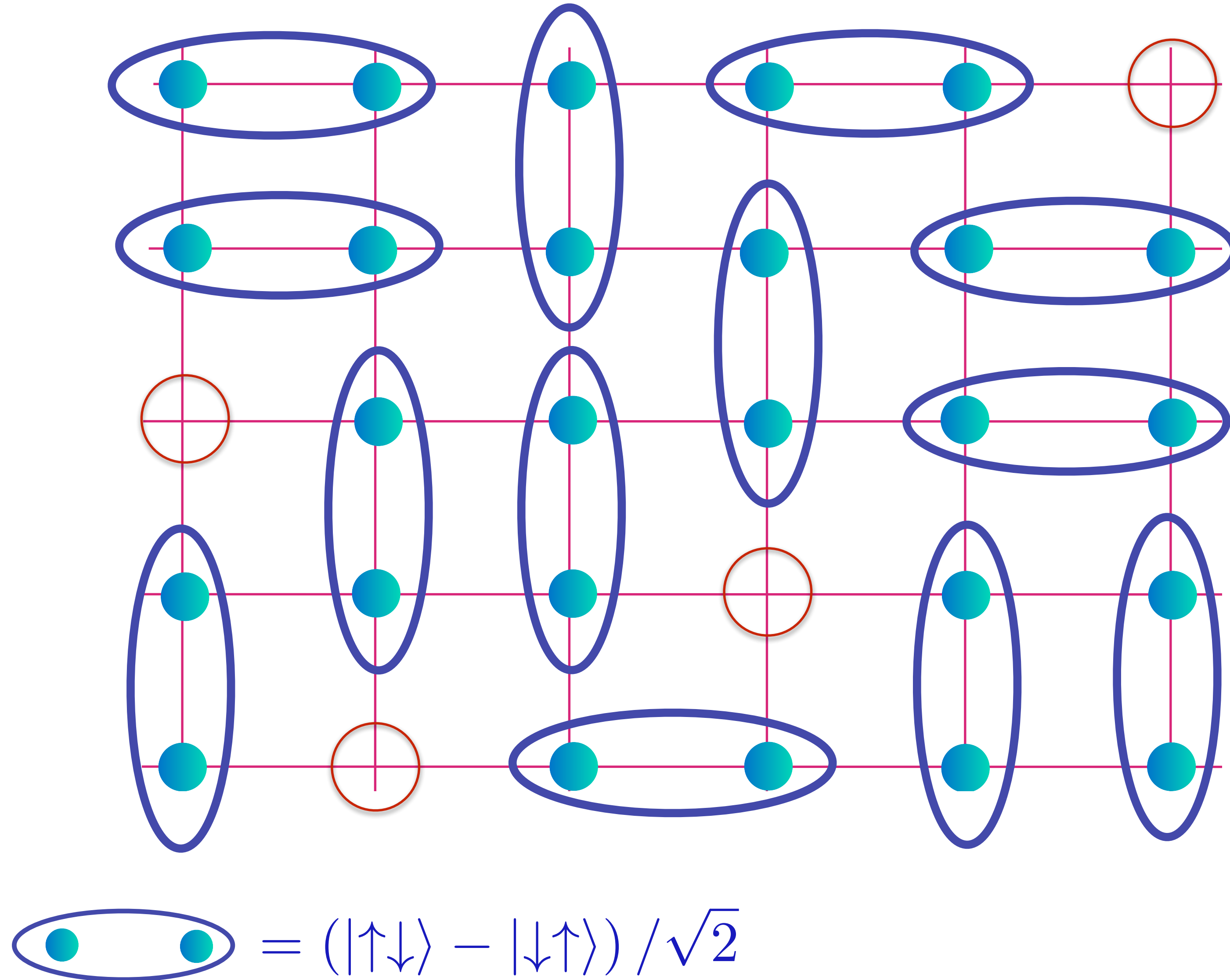
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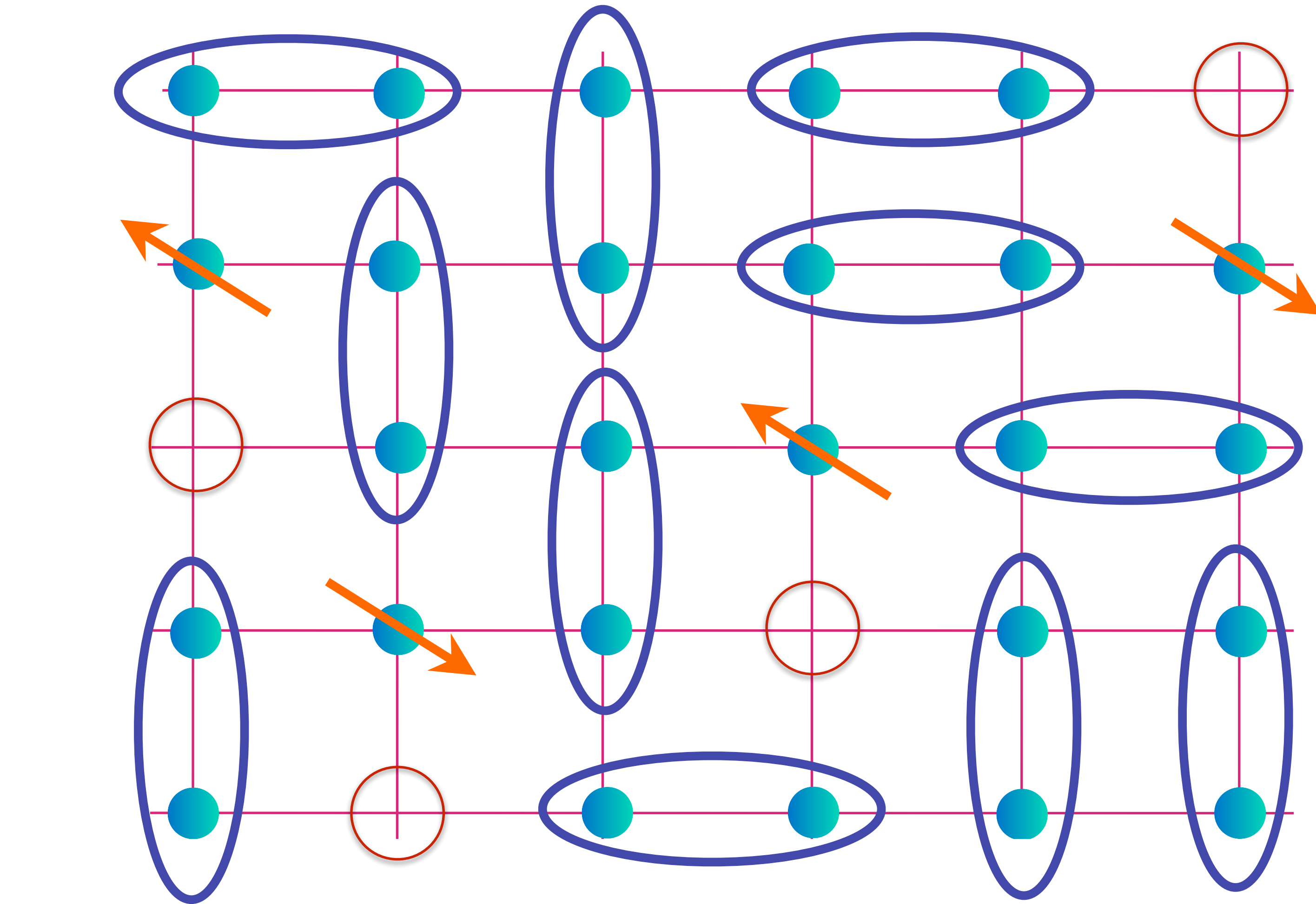
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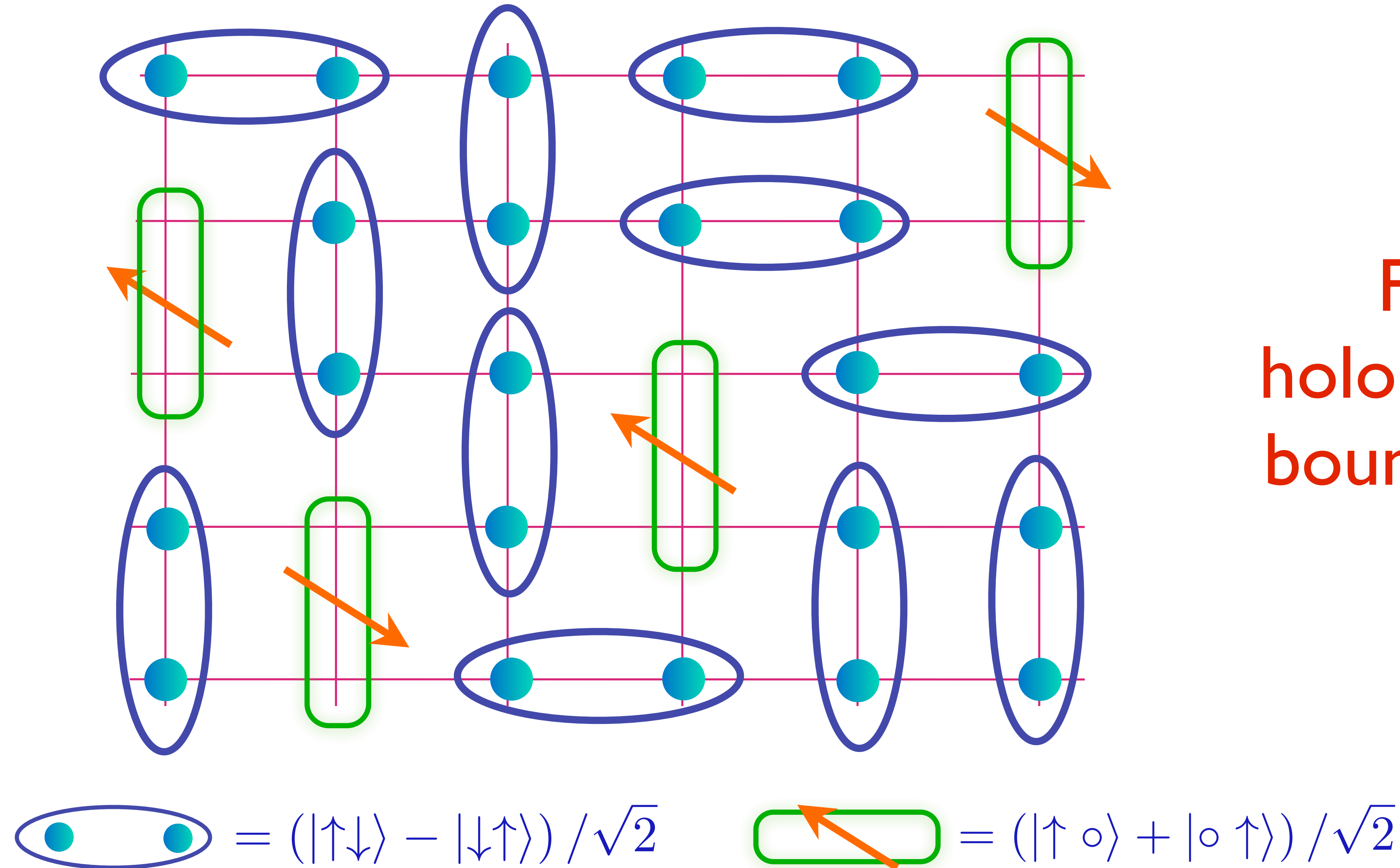
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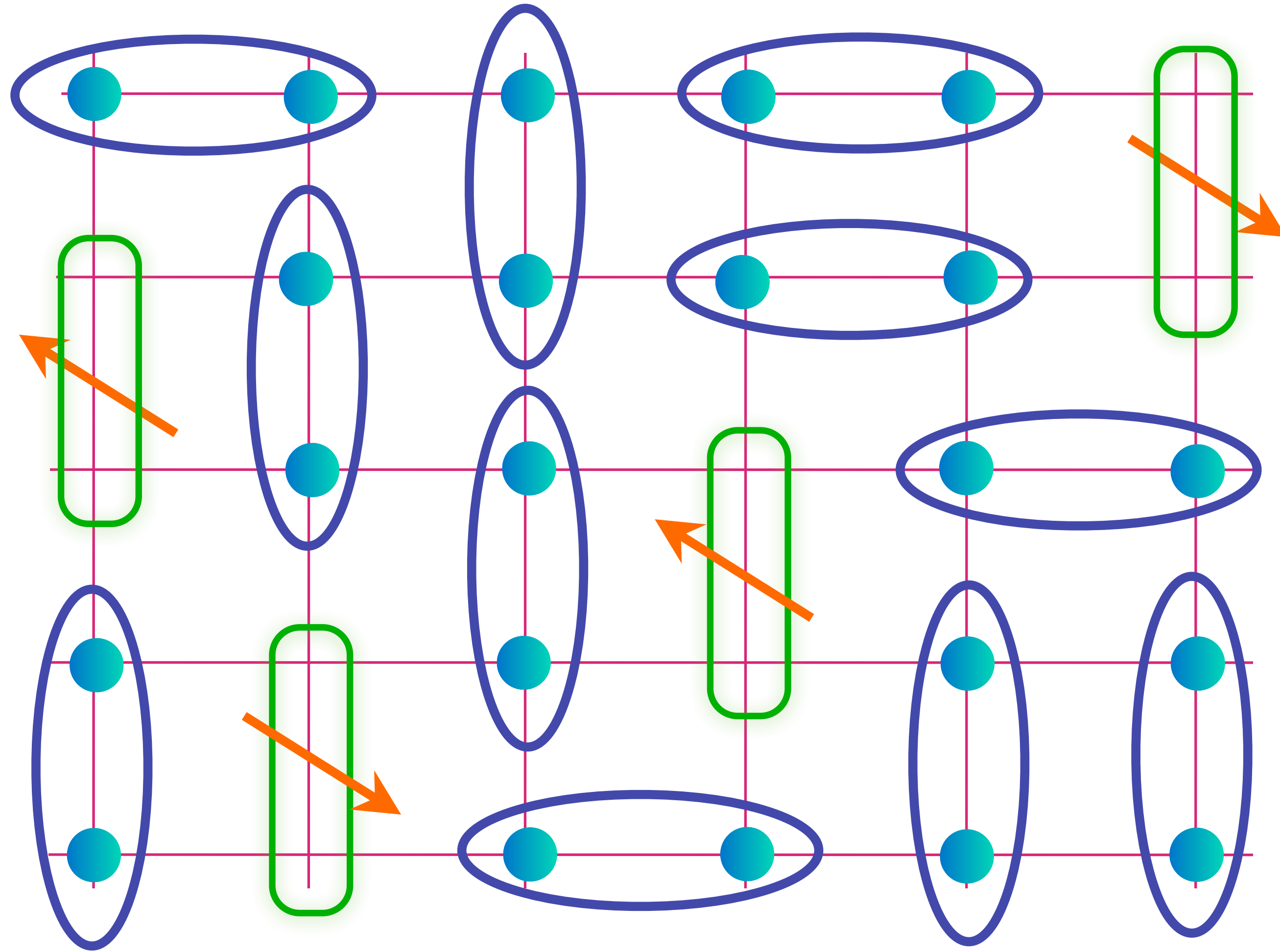
Form
holon-spinon
bound states

$$\text{[Blue oval with two teal dots]} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

To obtain a (super)conductor we have to
remove a density ρ of electrons



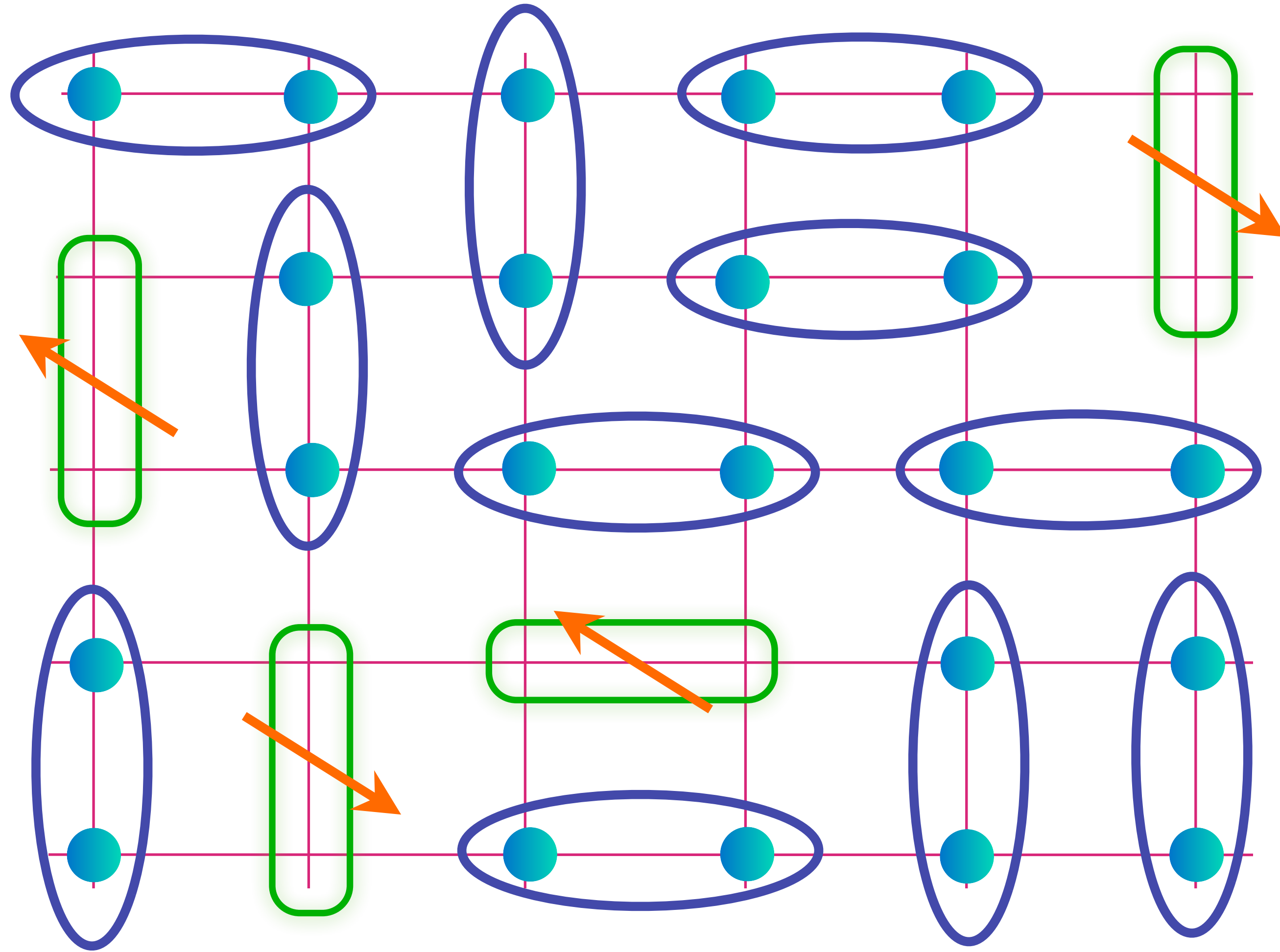
To obtain a (super)conductor we have to remove a density ρ of electrons



$$\text{Horizontal pair} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$\text{Vertical pair} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

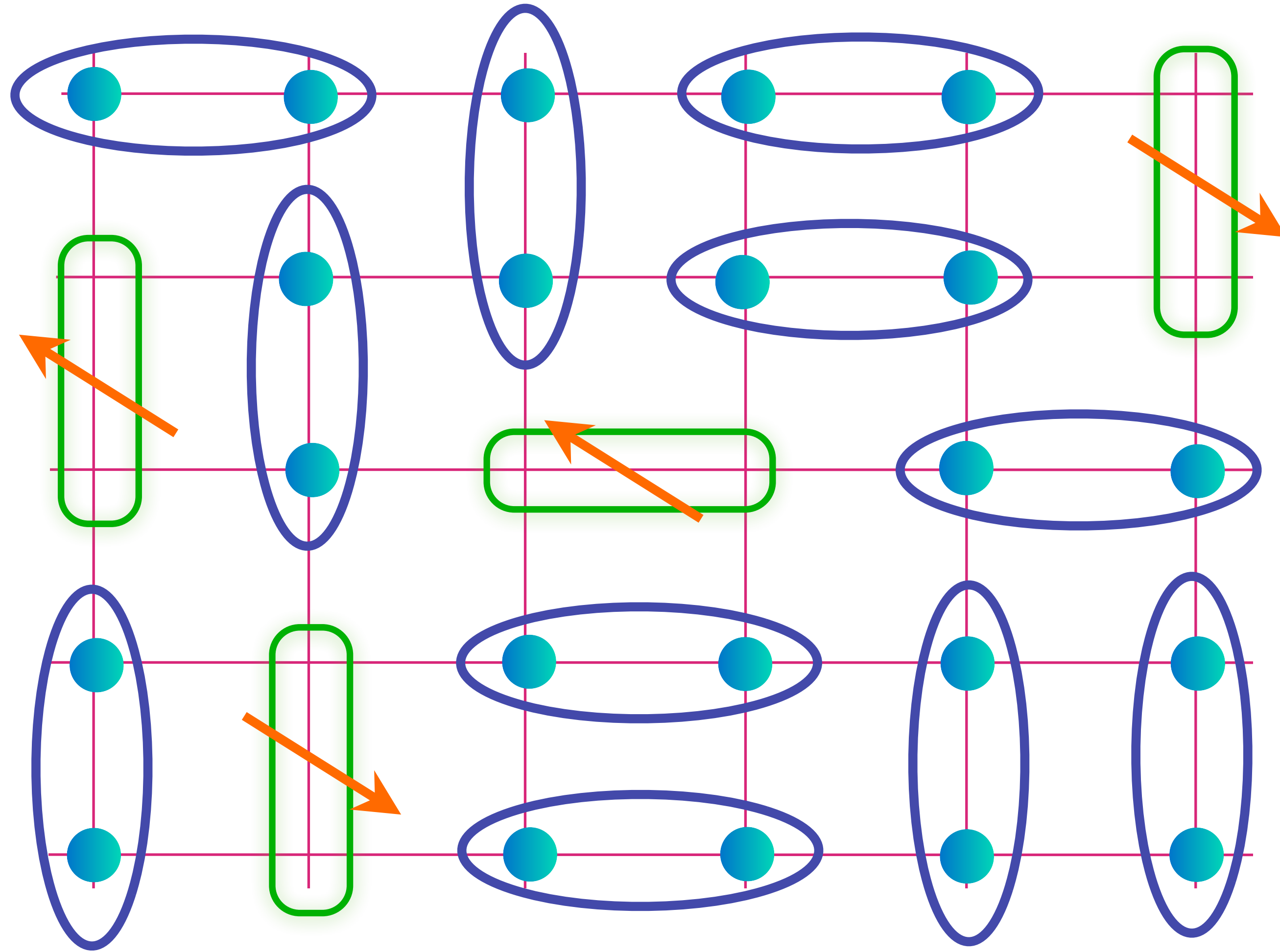
To obtain a (super)conductor we have to remove a density ρ of electrons



$$\text{blue oval} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$\text{green rectangle} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

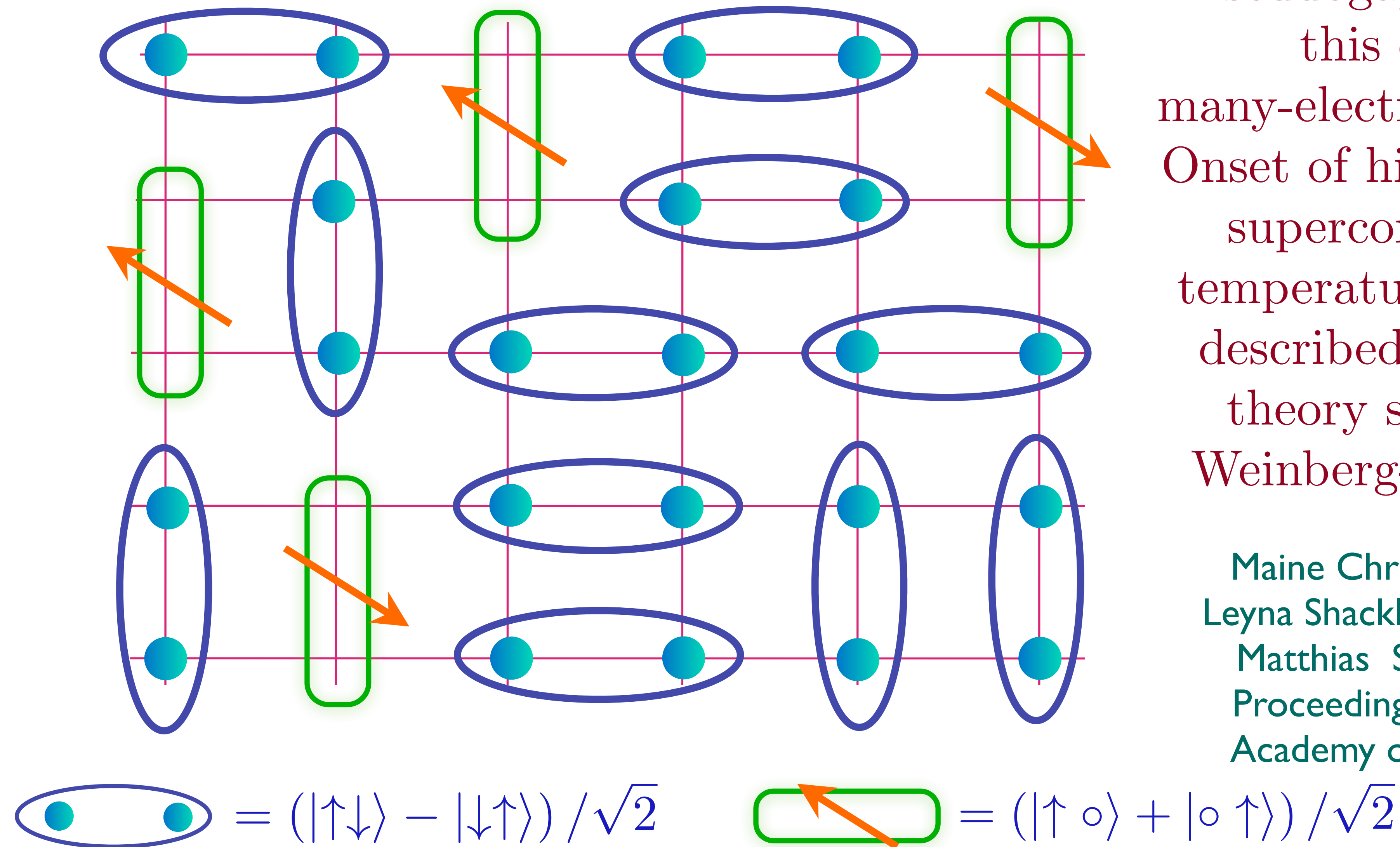
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$$\text{Blue oval} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

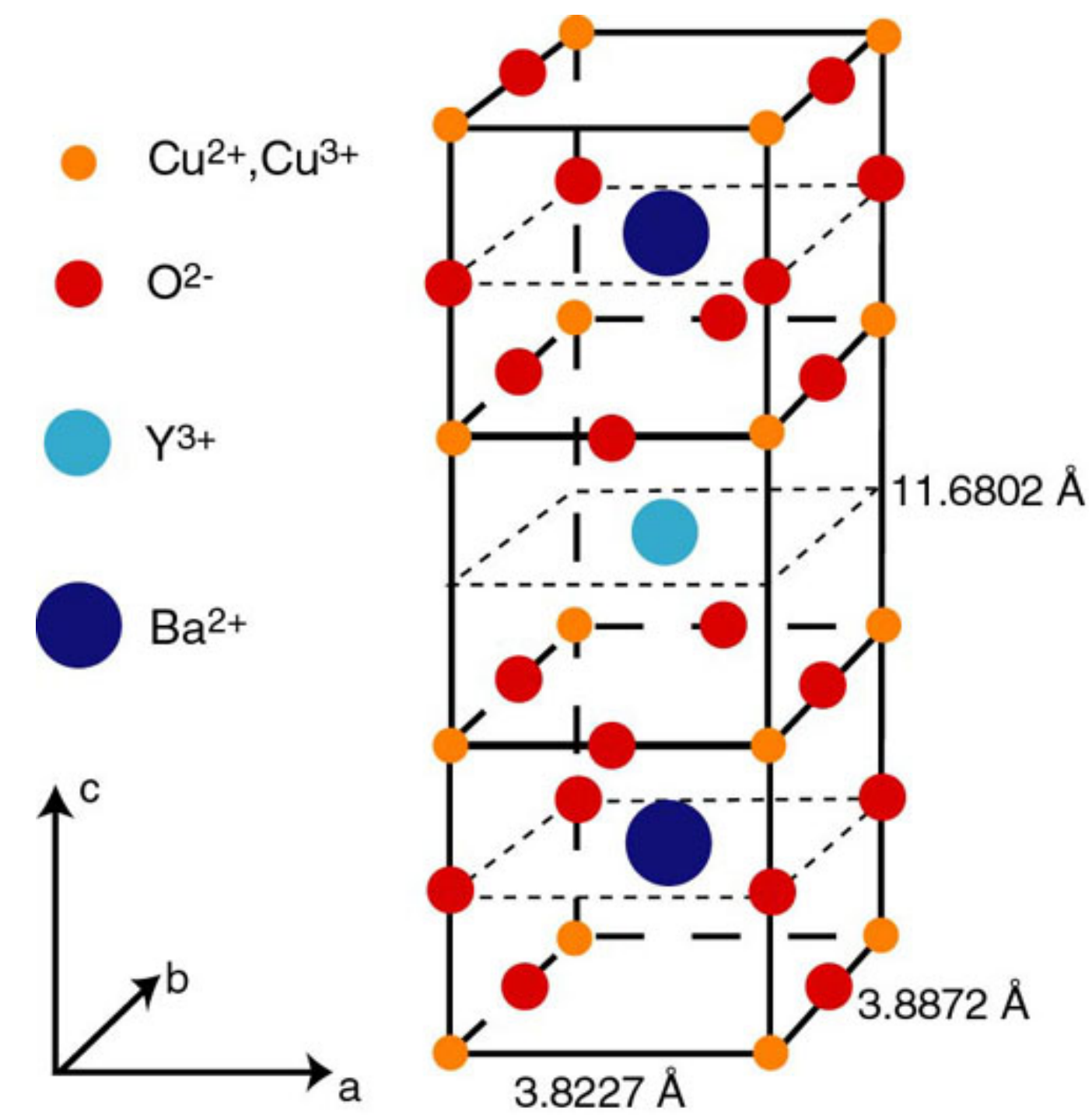
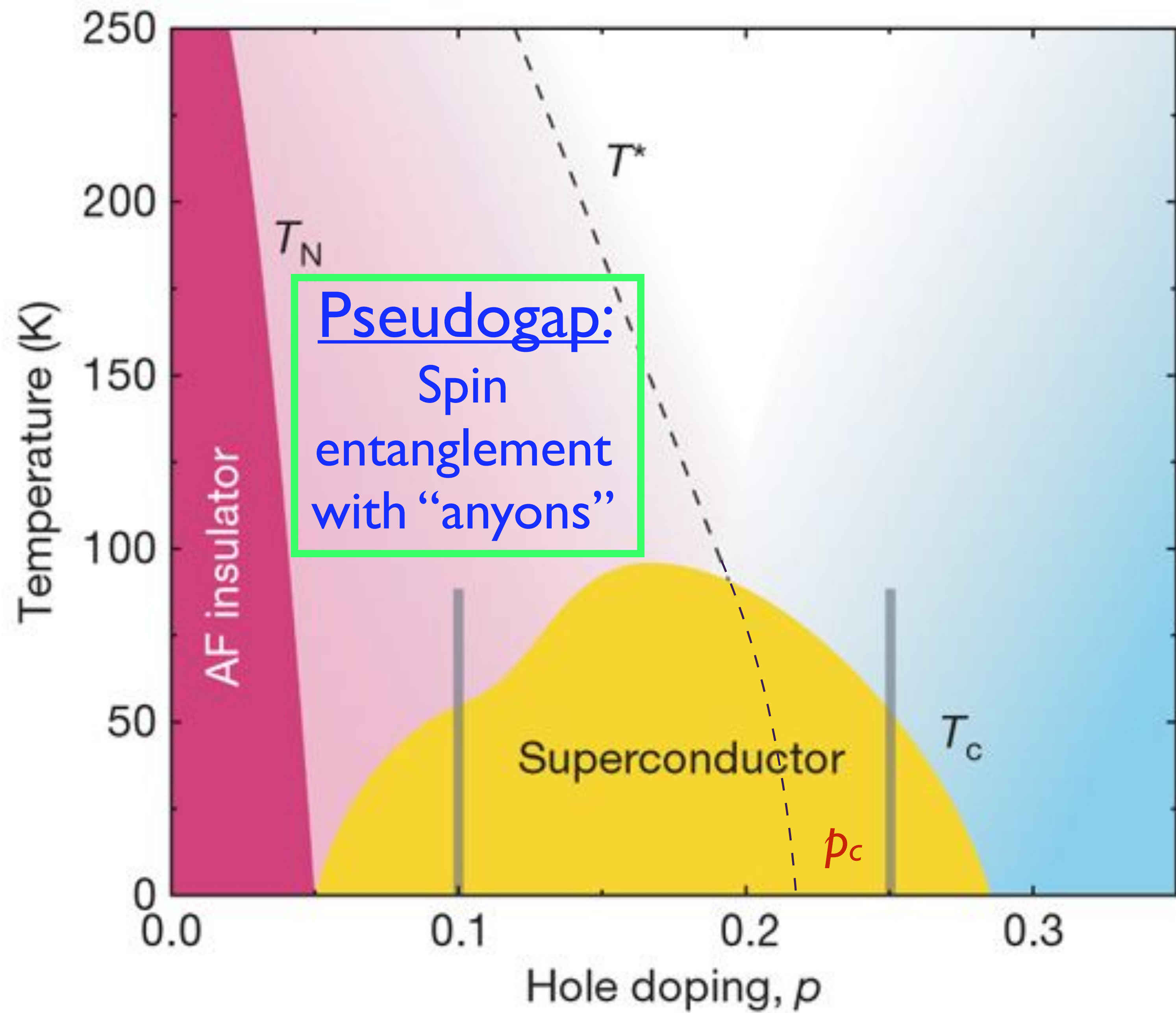
$$\text{Green oval} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

To obtain a (super)conductor we have to
remove a density ρ of electrons



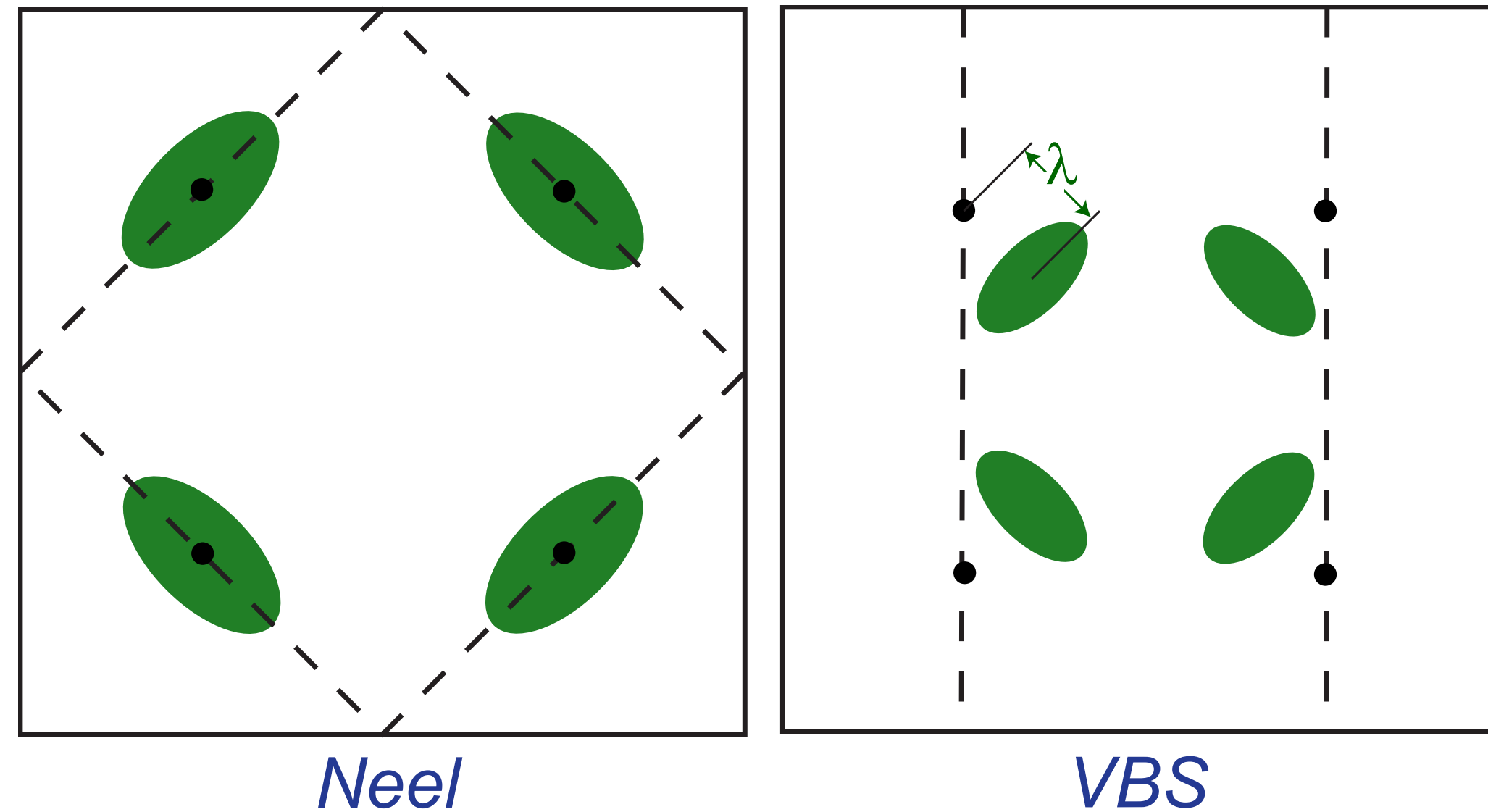
Pseudogap described by
this entangled
many-electron state (FL*).
Onset of high temperature
superconductivity as
temperature is lowered is
described by a “gauge”
theory similar to the
Weinberg-Salam theory.

Maine Christos, Zhu-Xi Luo,
Leyna Shackleton, Ya-Hui Zhang,
Matthias Scheurer, and S.S.,
Proceedings of the National
Academy of Sciences (2023)



Hole dynamics in an antiferromagnet across a deconfined quantum critical point

Ribhu K. Kaul,¹ Alexei Kolezhuk,^{1,2} Michael Levin,¹ Subir Sachdev,¹ and T. Senthil^{3,4}



The dashed line in the Néel phase indicates the boundary of the magnetic Brillouin zone. Only the Fermi surfaces within this zone contribute to the Luttinger counting, and so the area of each ellipse is $\mathcal{A}_F = (2\pi)^2 \delta/4$. In the VBS phase, all four pockets are inequivalent, and so the area of each ellipse is $\mathcal{A}_F = (2\pi)^2 \delta/8$.

$$\delta = p$$

Thermal disordered and “quantum disordered” antiferromagnets are distinct!

Factor of 2 difference in Fermi surface size.

Observation of the Yamaji effect in a cuprate superconductor

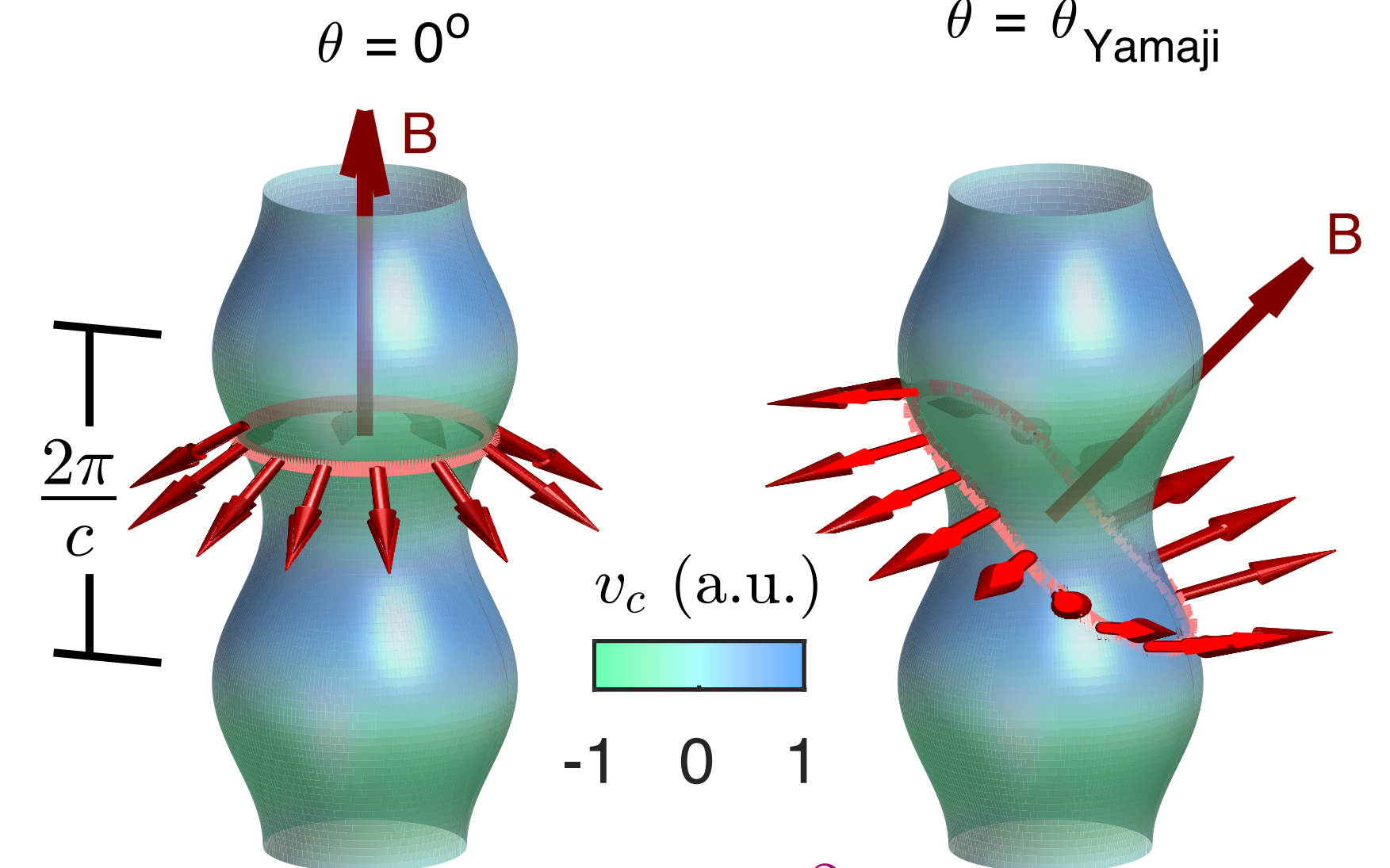
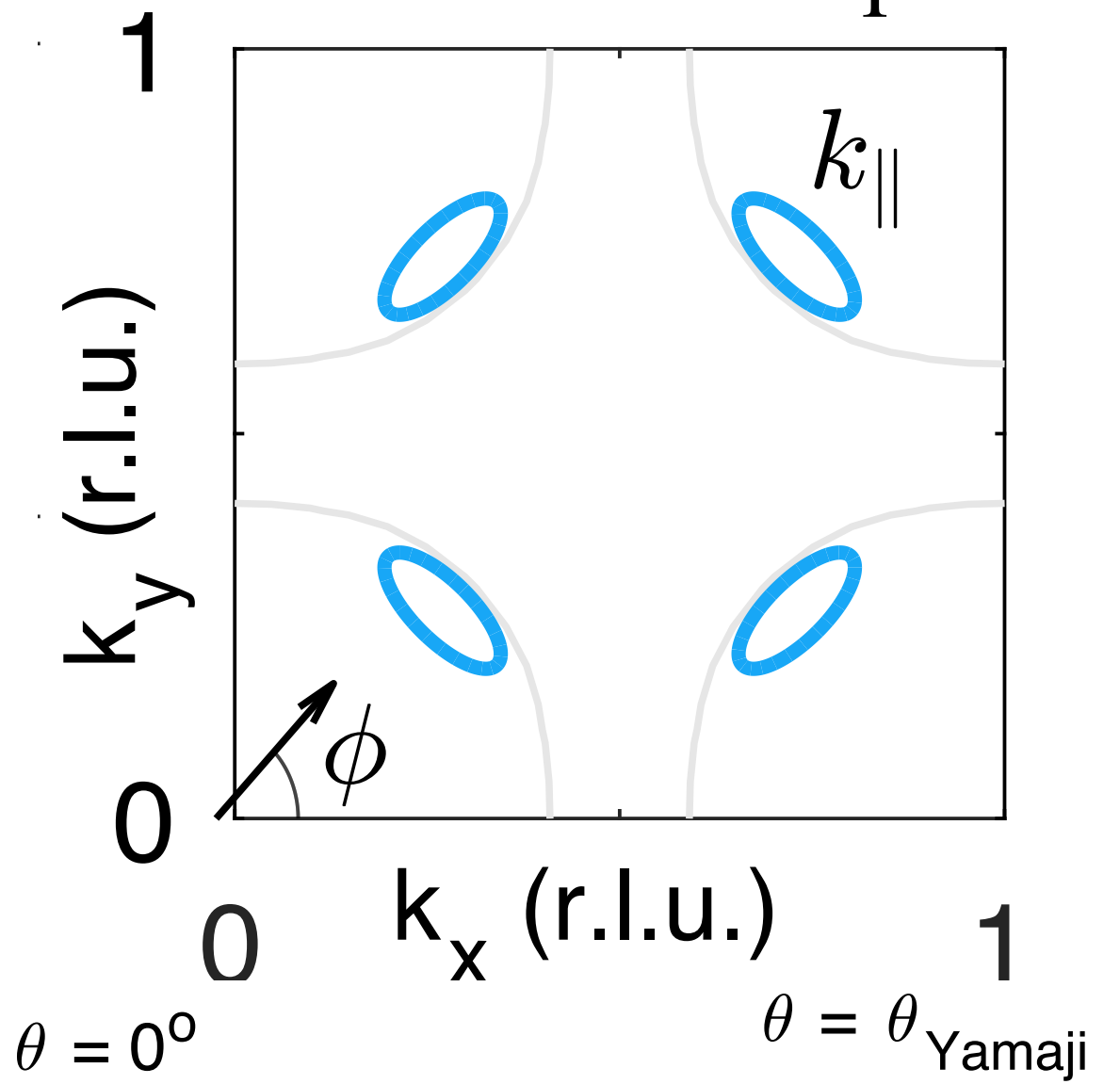
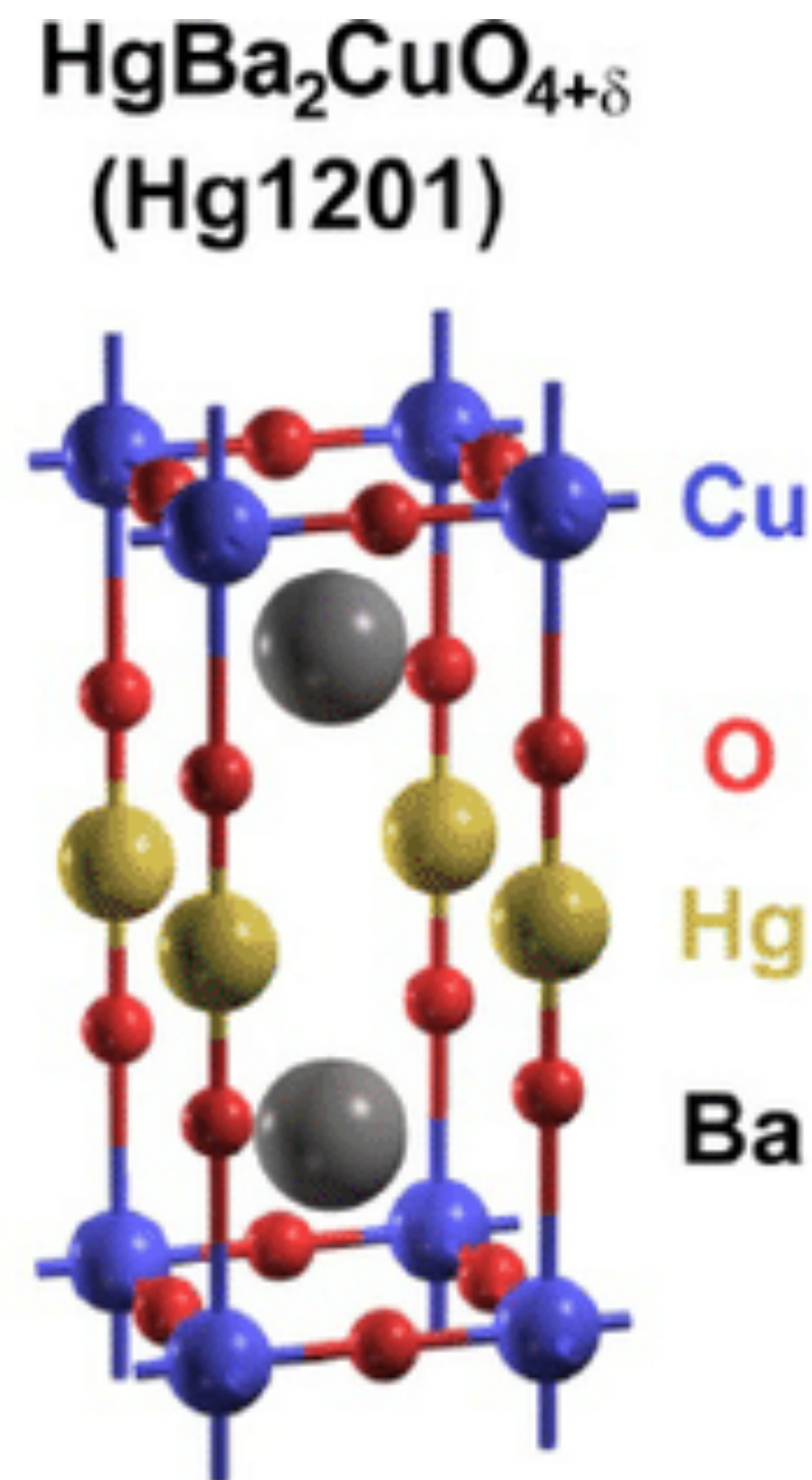
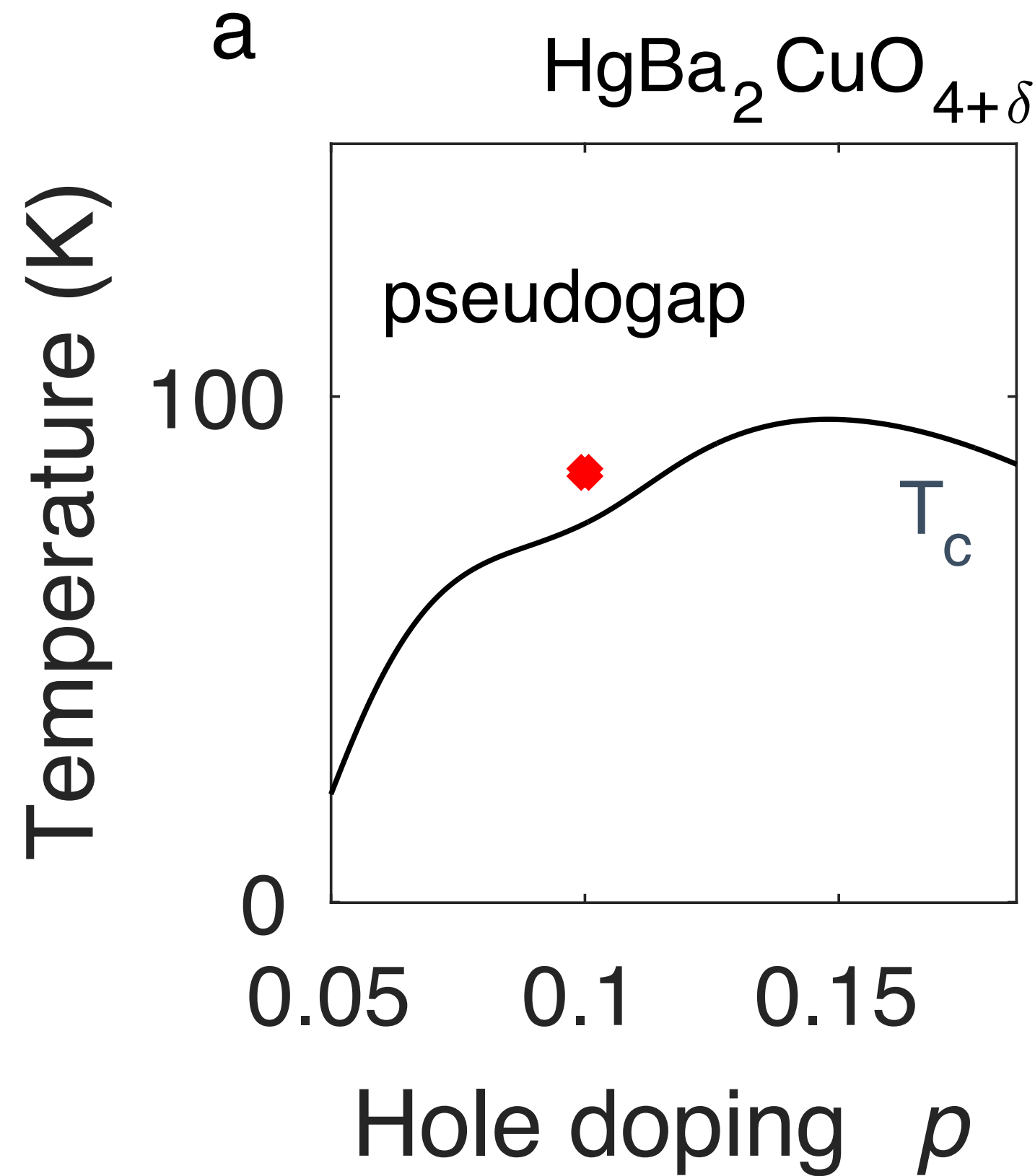
superconductor

Mun K. Chan¹✉, Katherine A. Schreiber¹, Oscar E. Ayala-Valenzuela¹,
Eric D. Bauer², Arkady Shekhter¹ & Neil Harrison¹

nature physics

21, 1753 (2025)

Published online: 16 September 2025



$$\epsilon(\mathbf{k}) = \frac{k_x^2}{2m_1} + \frac{k_y^2}{2m_2} - 2t_\perp \cos(k_z c)$$

At the Yamaji angle, the orbits in the plane orthogonal to \mathbf{B} have an area which is independent of momentum in the c direction, to first order in the hopping along the c direction.

K. Yamaji JPSJ **58**, 1520 (1989)

Observation of the Yamaji effect in a cuprate superconductor

nature physics

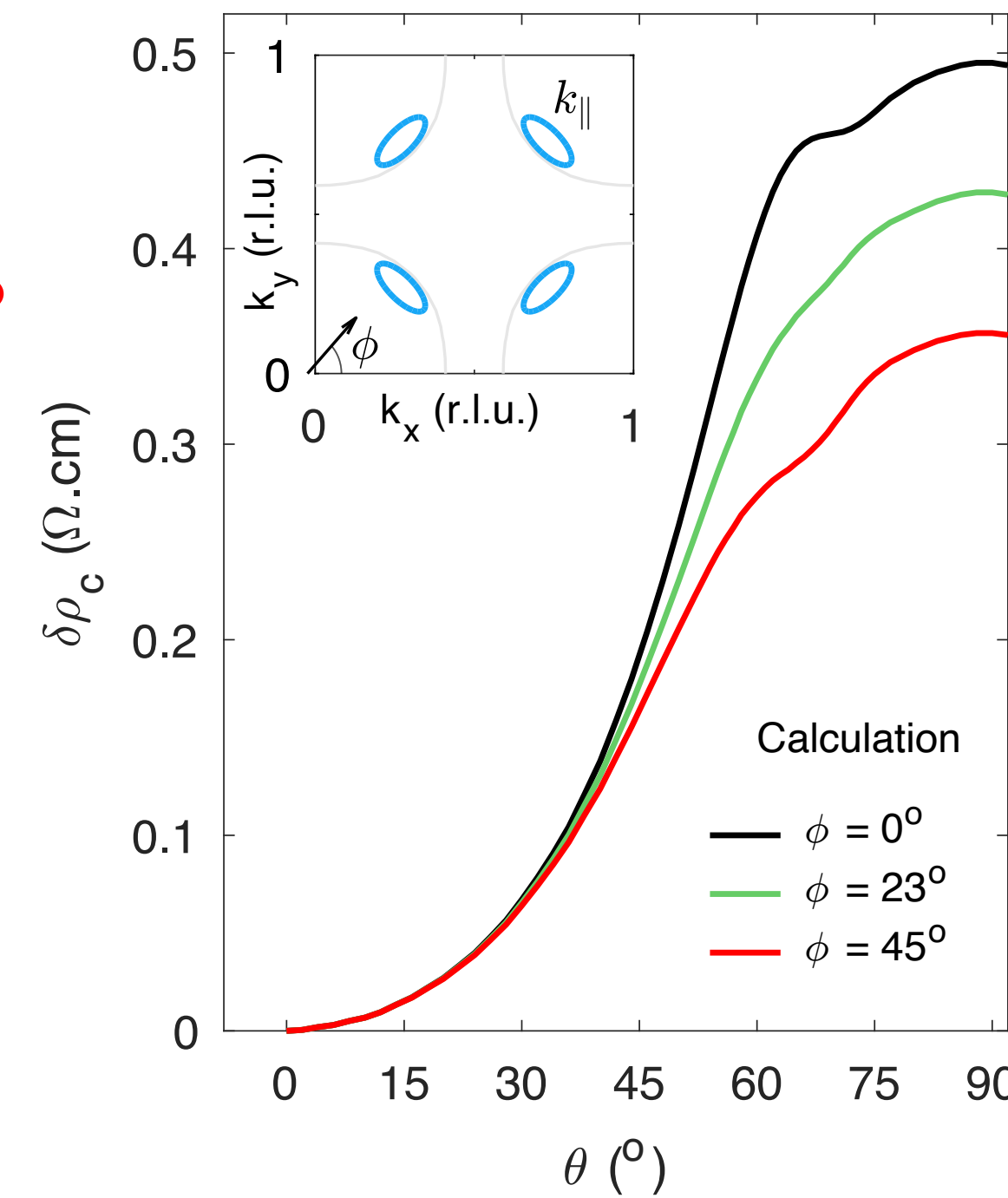
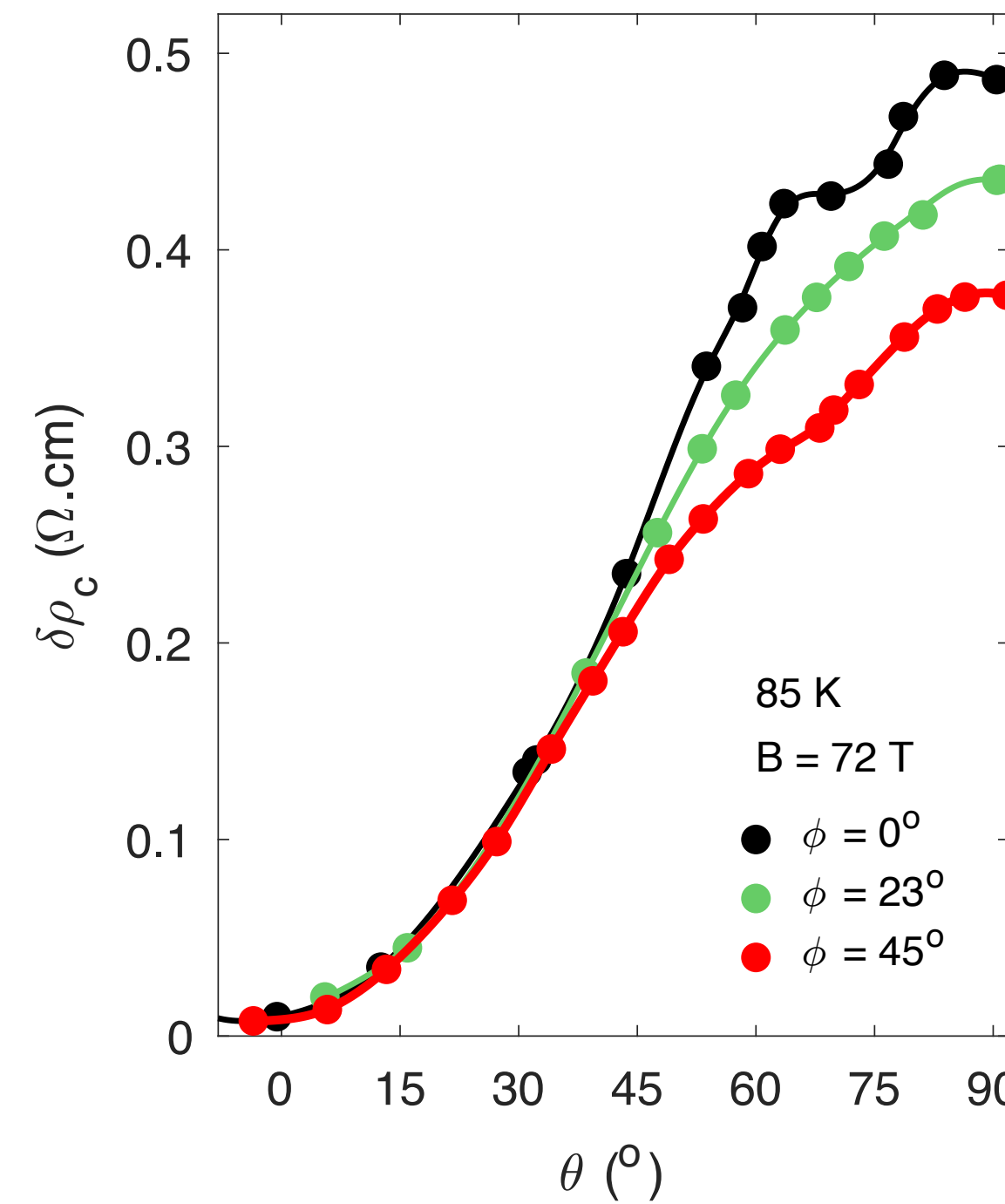
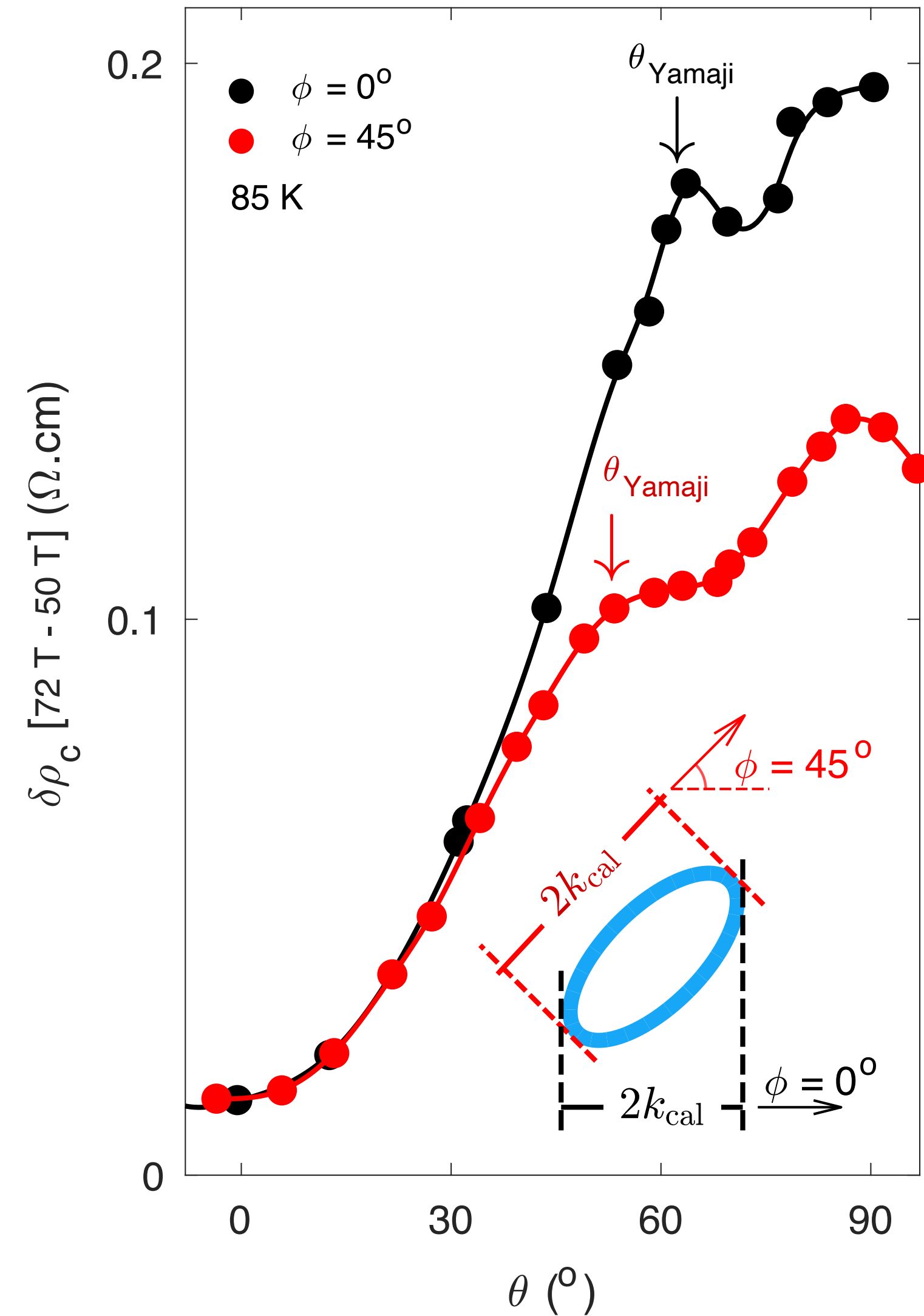
21, 1753 (2025)

superconductor

Mun K. Chan ¹✉, Katherine A. Schreiber¹, Oscar E. Ayala-Valenzuela ¹,

Eric D. Bauer ², Arkady Shekhter ¹ & Neil Harrison ¹

Published online: 16 September 2025



Doping
 $p = 0.1$

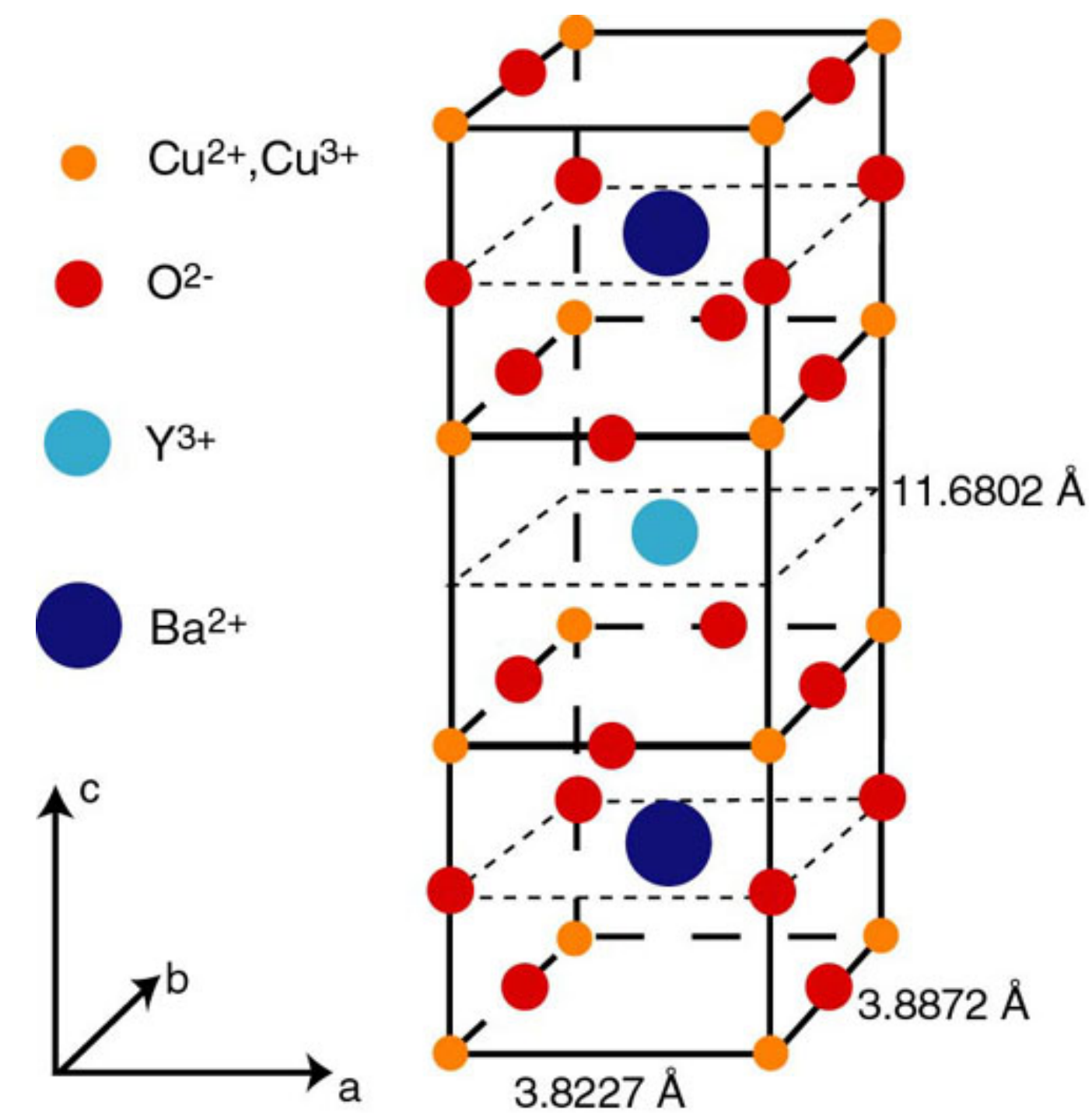
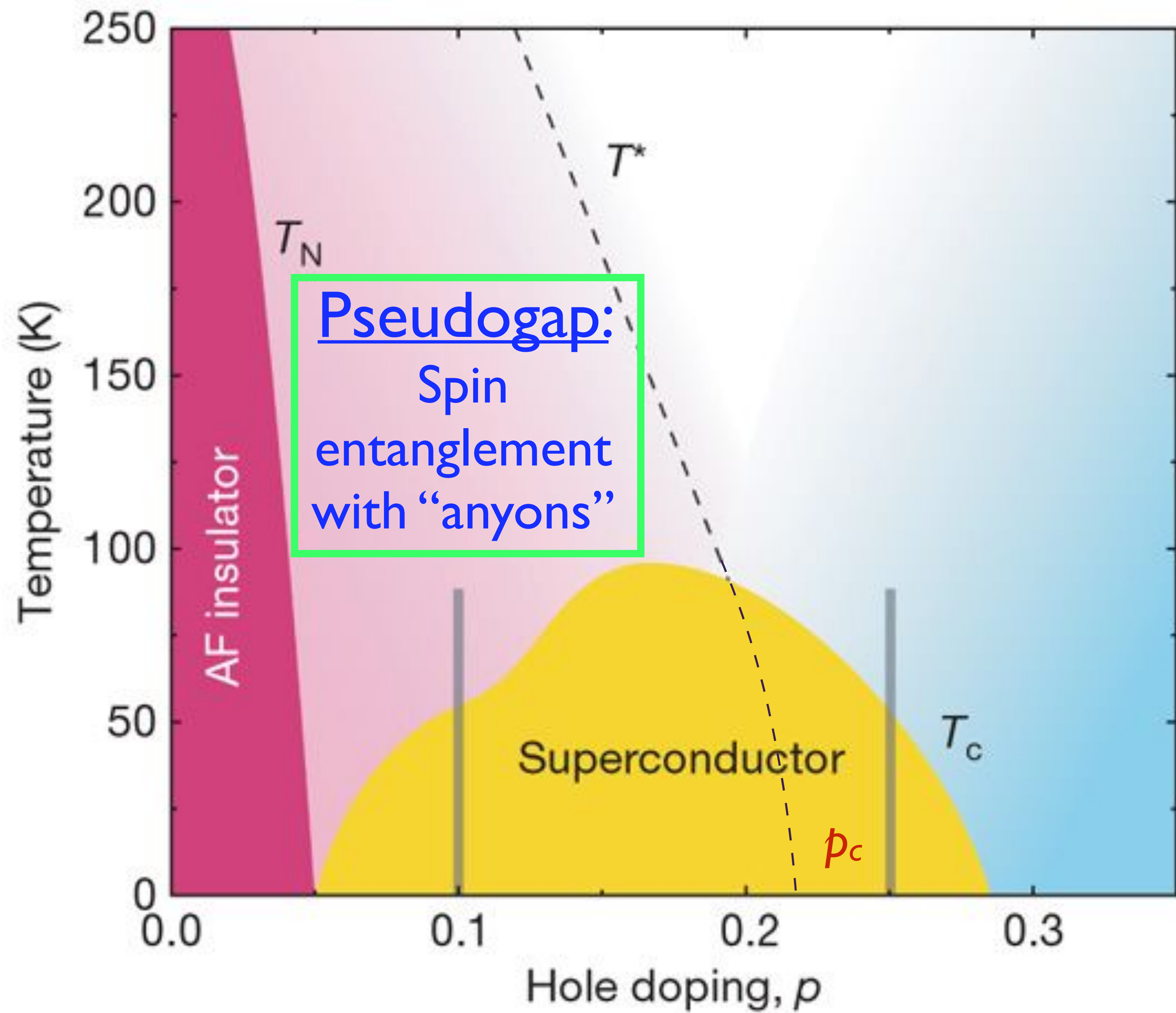
The observation of the Yamaji peak is evidence for small Fermi-surface pockets in the normal state of the pseudogap phase. The small size of the pockets, each estimated to occupy only 1.3% of the Brillouin zone area, is not expected given the absence of long-range broken translational symmetry.

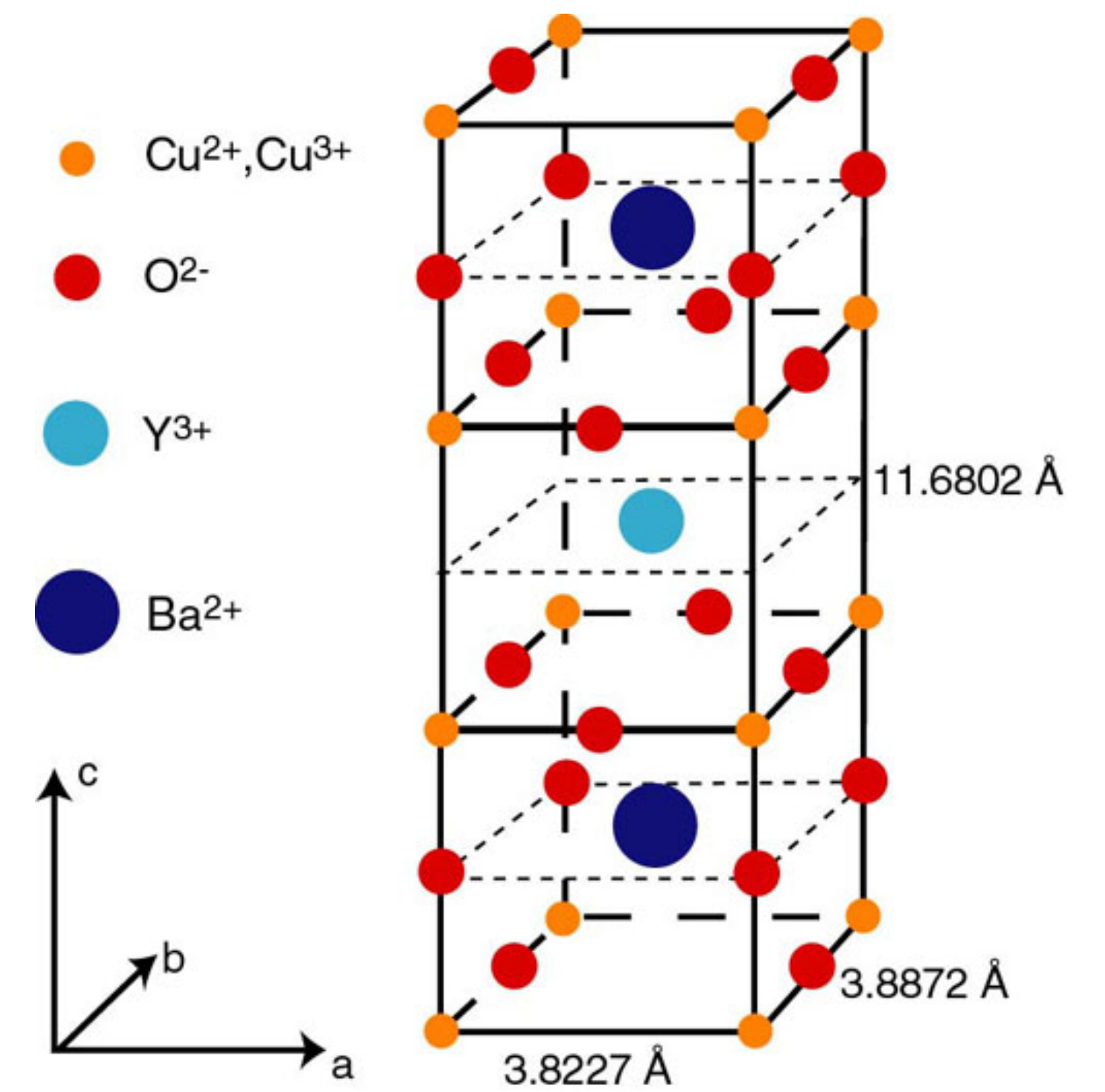
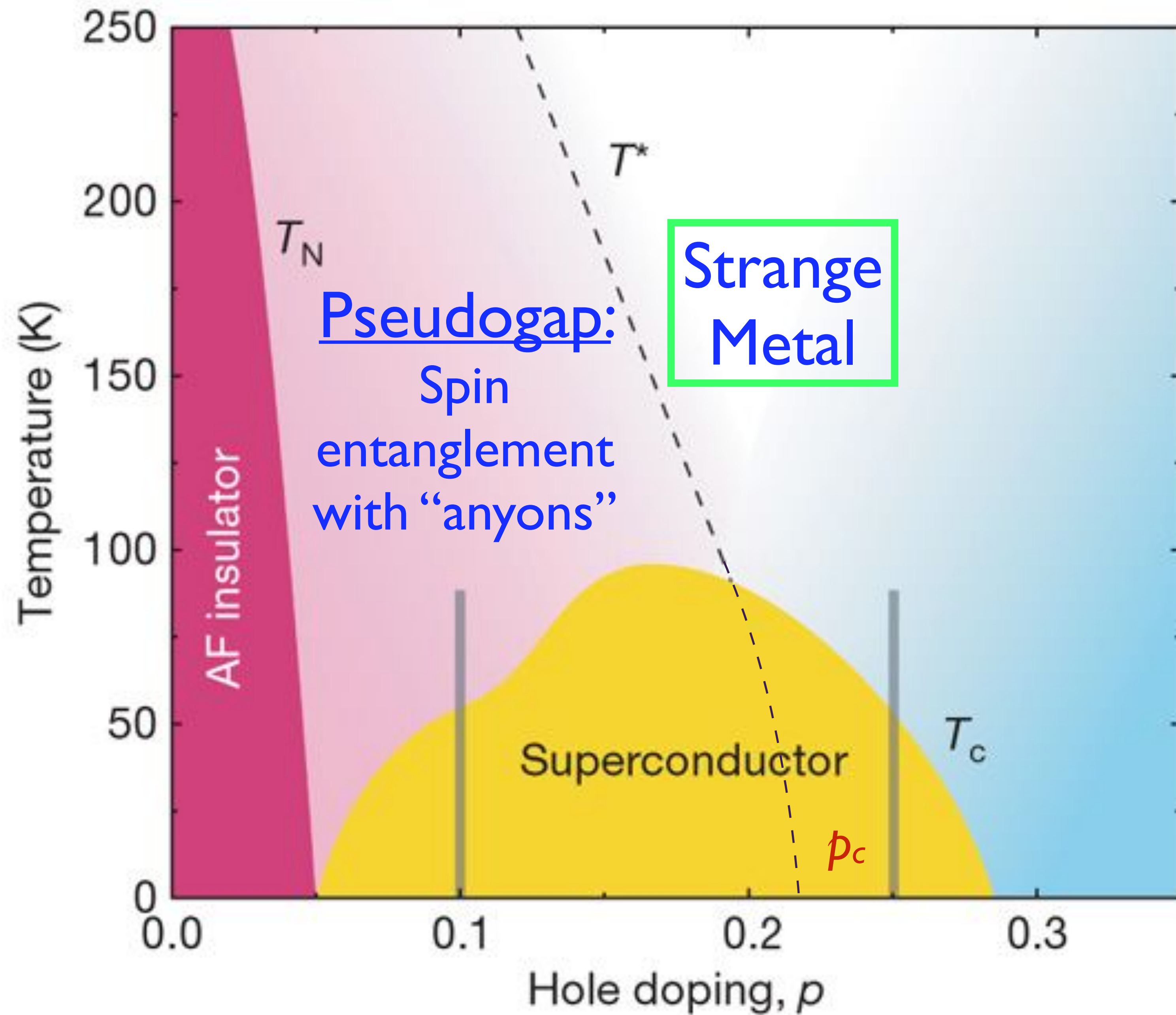
Predicted FL* pocket fraction = $p/8 = 1.25\%$!

Fluctuating AF metal fraction = $p/4 = 2.5\%$.

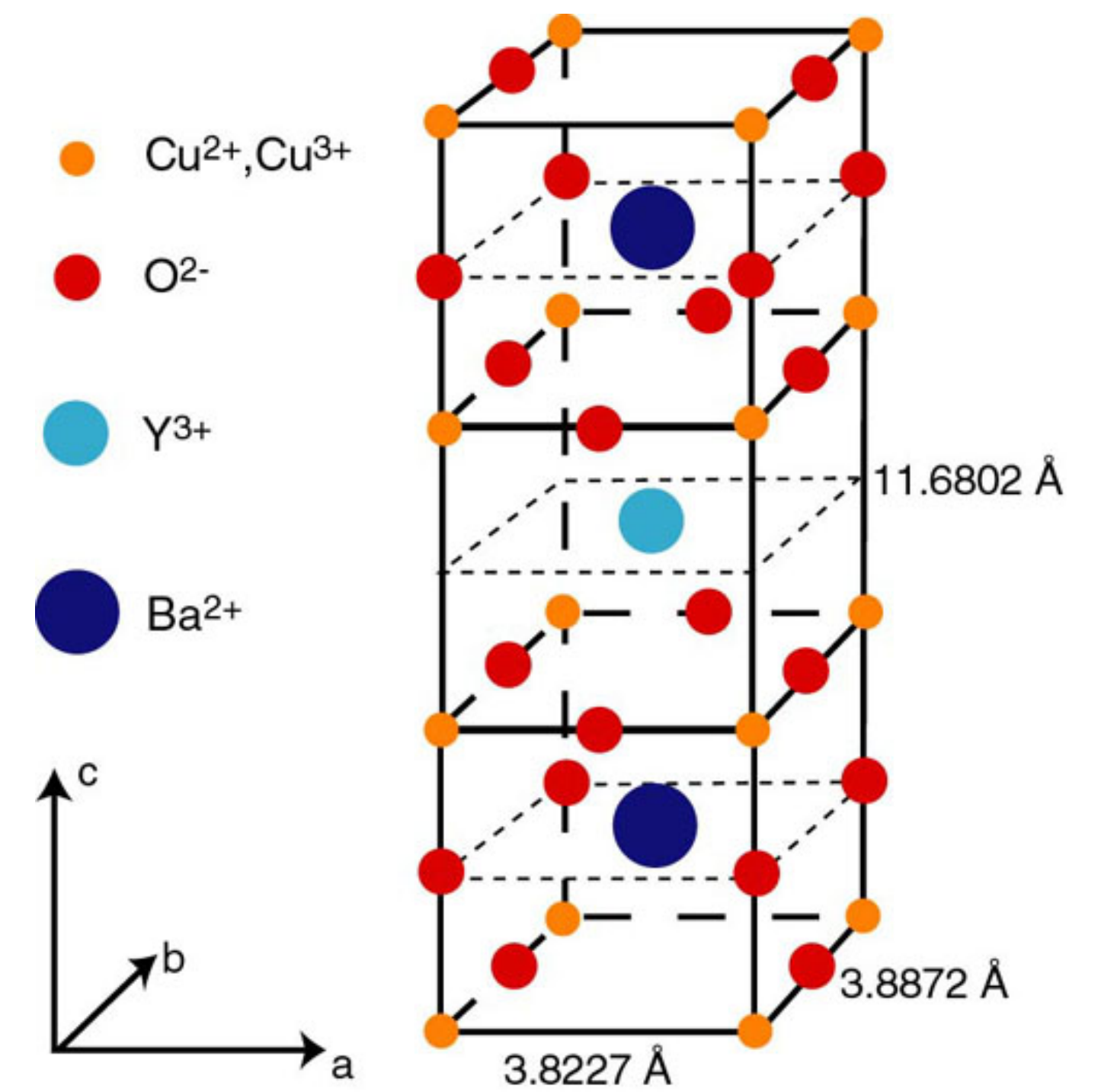
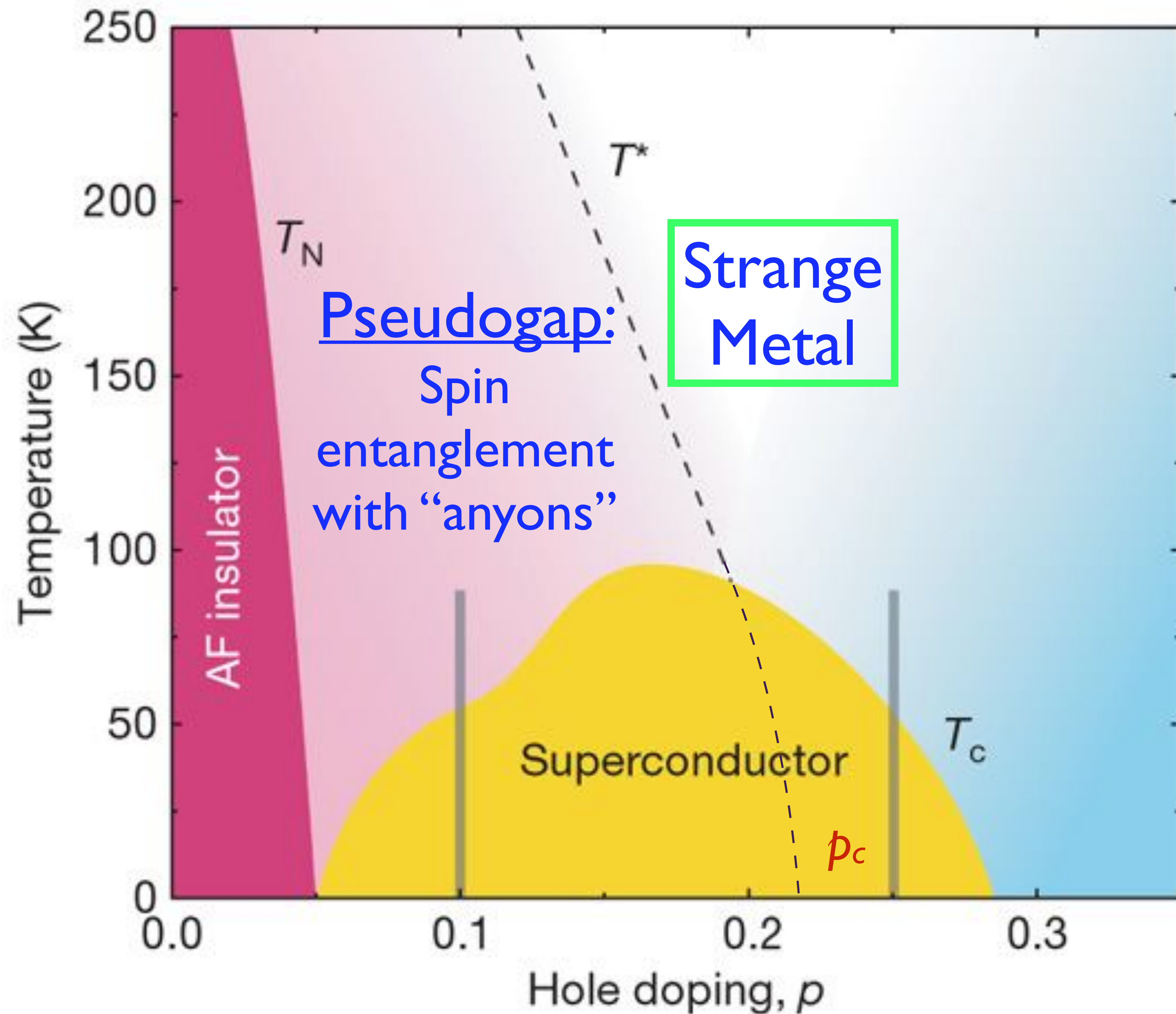
($p/8$ also in Yang-Rice-Zhang ansatz, Peter Johnson photoemission, and Jenny Hoffman and Seamus Davis STMs; Stanescu-Kotliar)

Jing-Yu Zhao, S. Chatterjee, S. S., Ya-Hui Zhang, arXiv:2510.13943





Above the highest critical temperatures for superconductivity, we have the Strange Metal



The Strange Metal has no particle-like/anyon excitations.

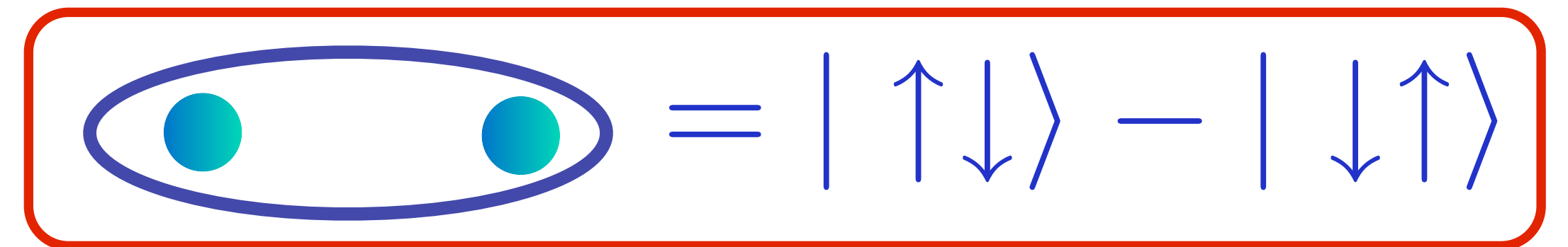
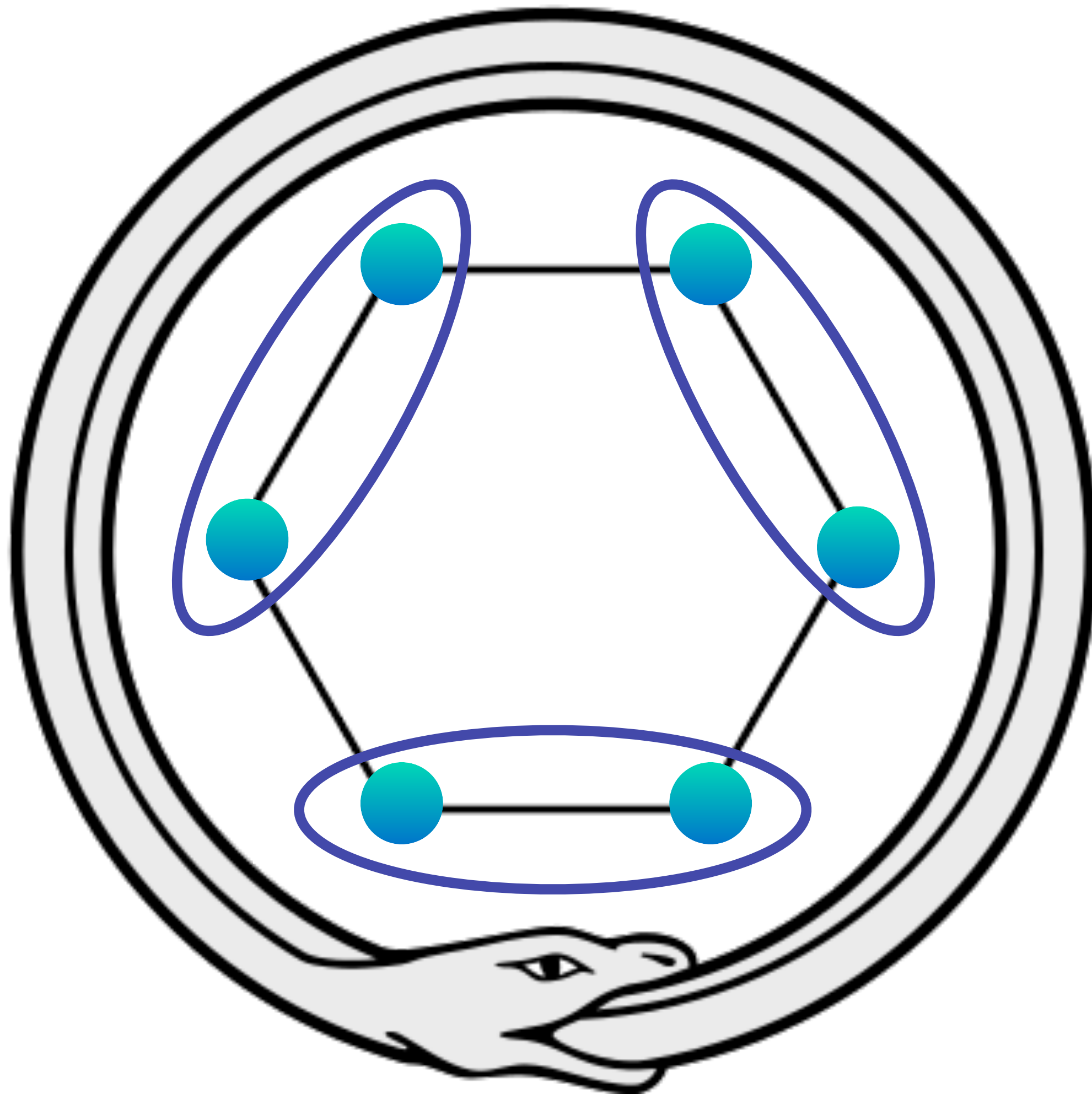
Its theory requires many-fermion entanglement (not just of spins)

The Sachdev-Ye-Kitaev model of entanglement of mobile fermions and the cuprates



Kekule's spooky dream (1865)

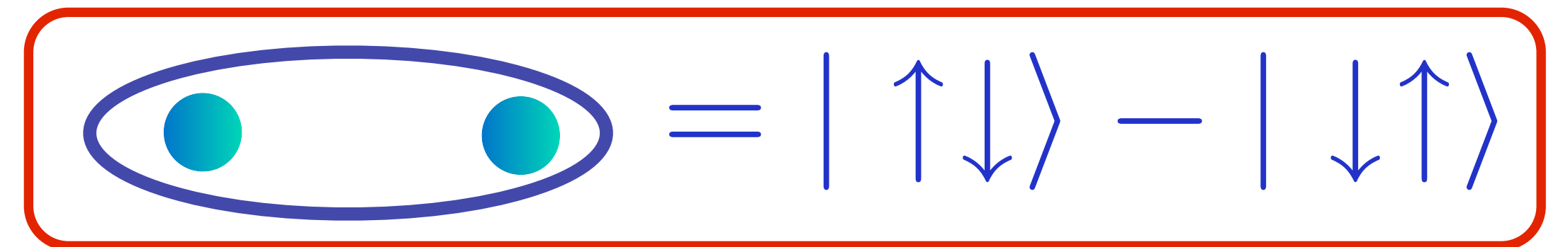
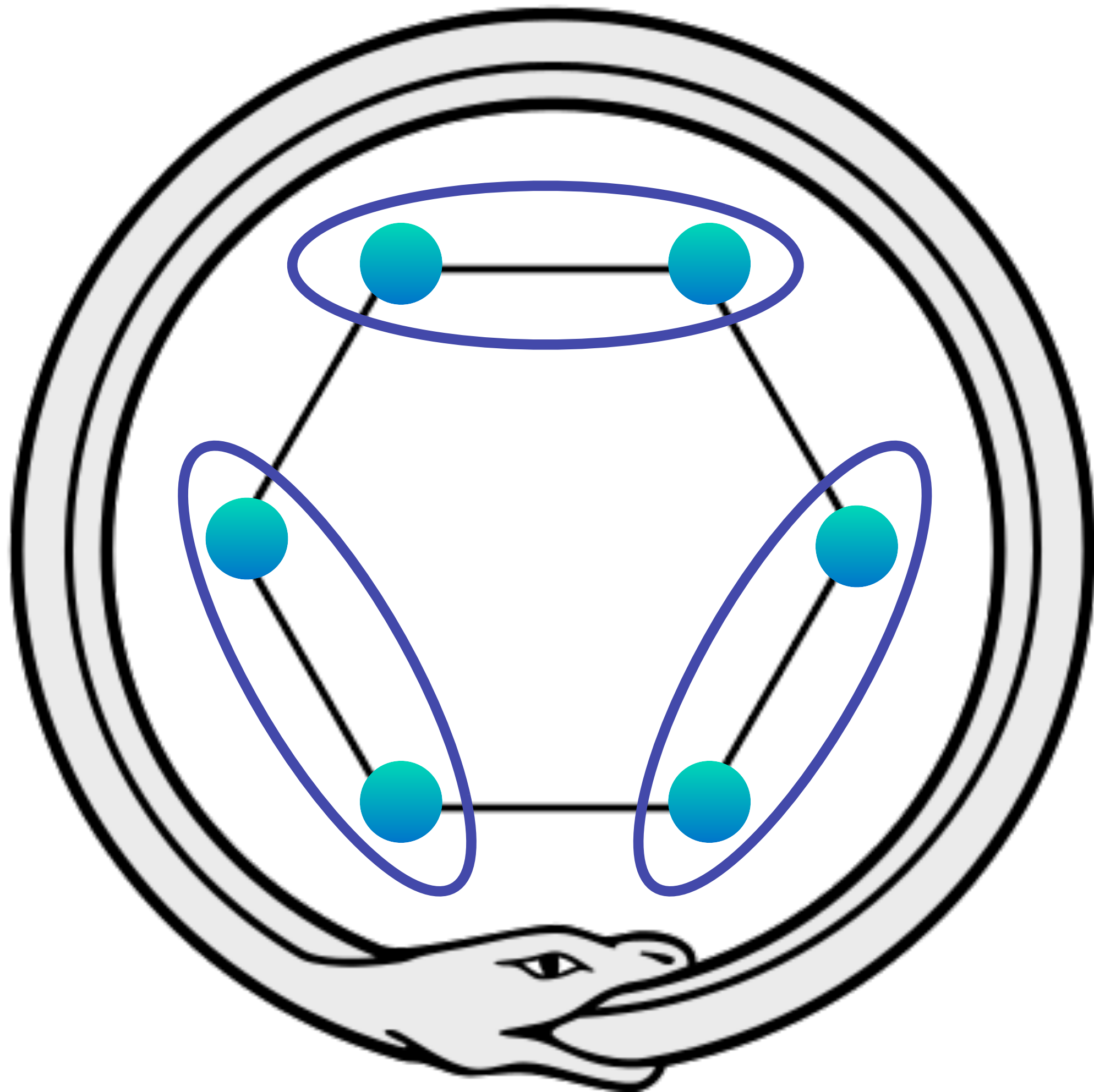
Kekulé spoke of the creation of the theory. He said that he had discovered the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail*



Benzene

Kekule's spooky dream (1865)

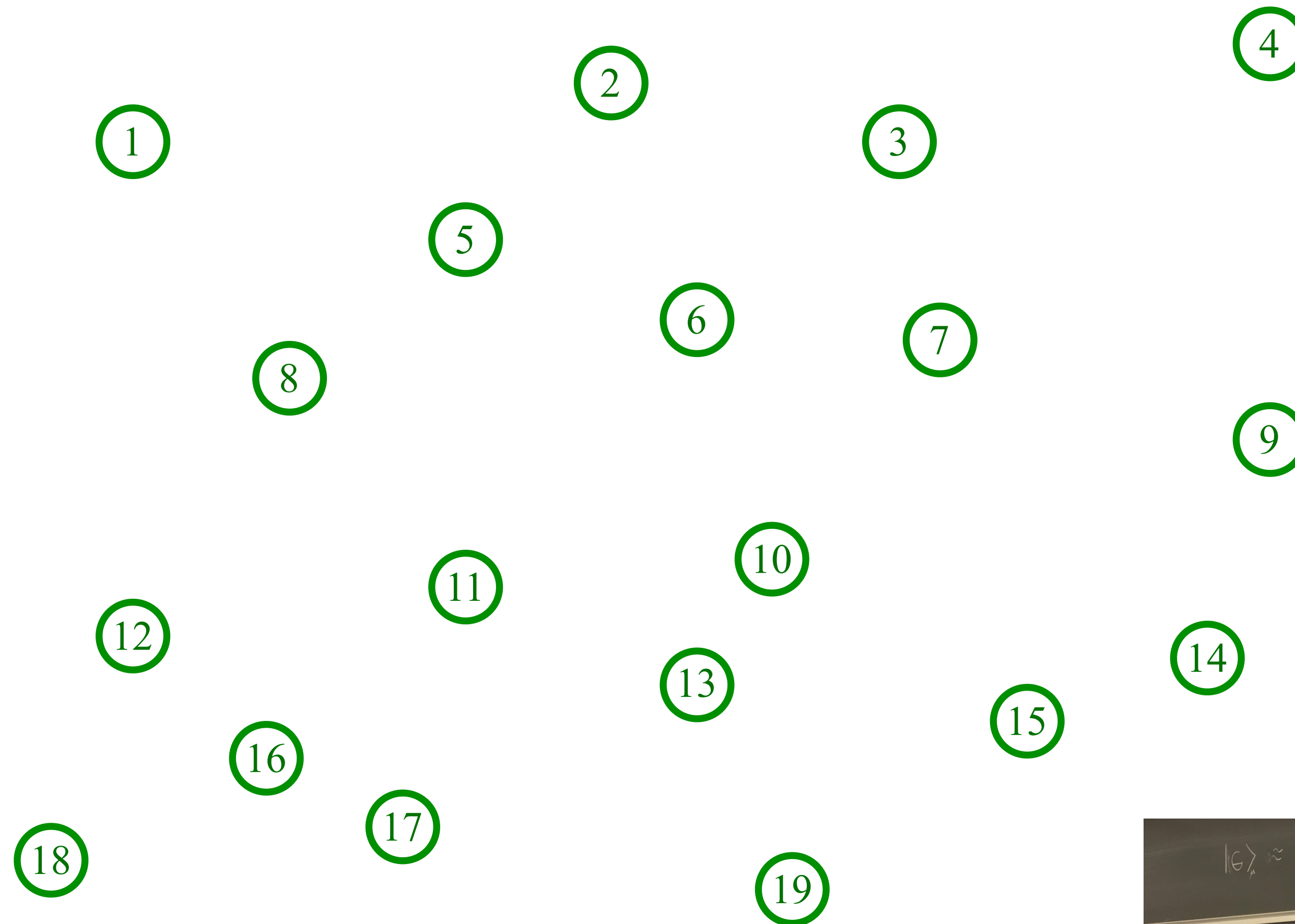
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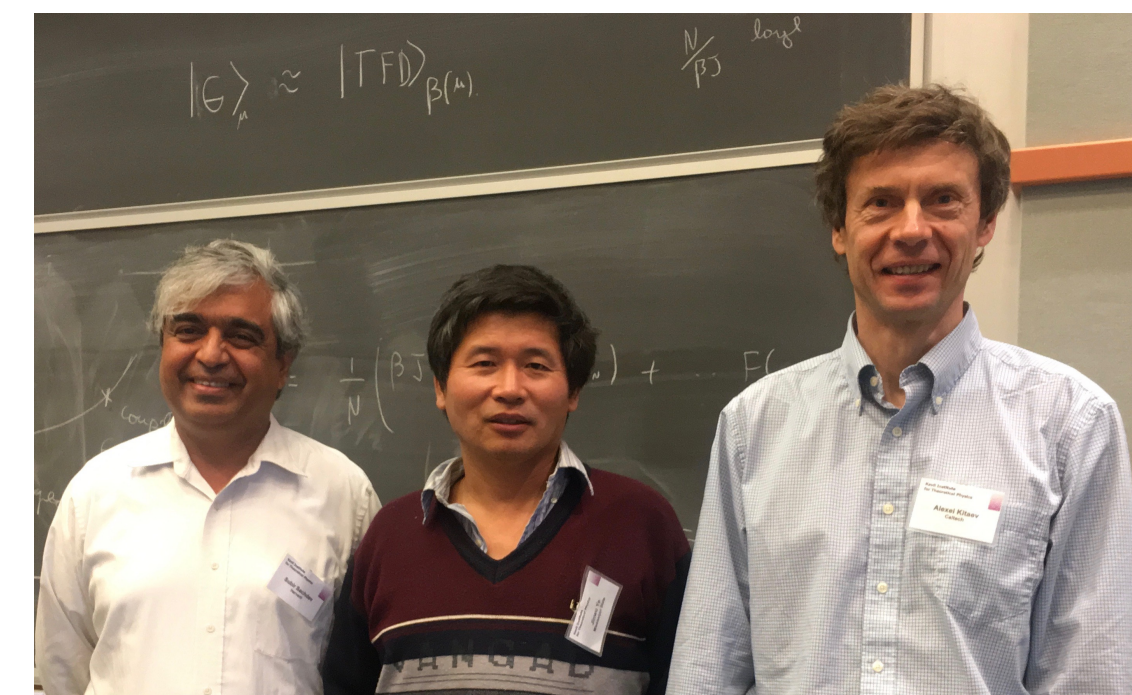
Benzene

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

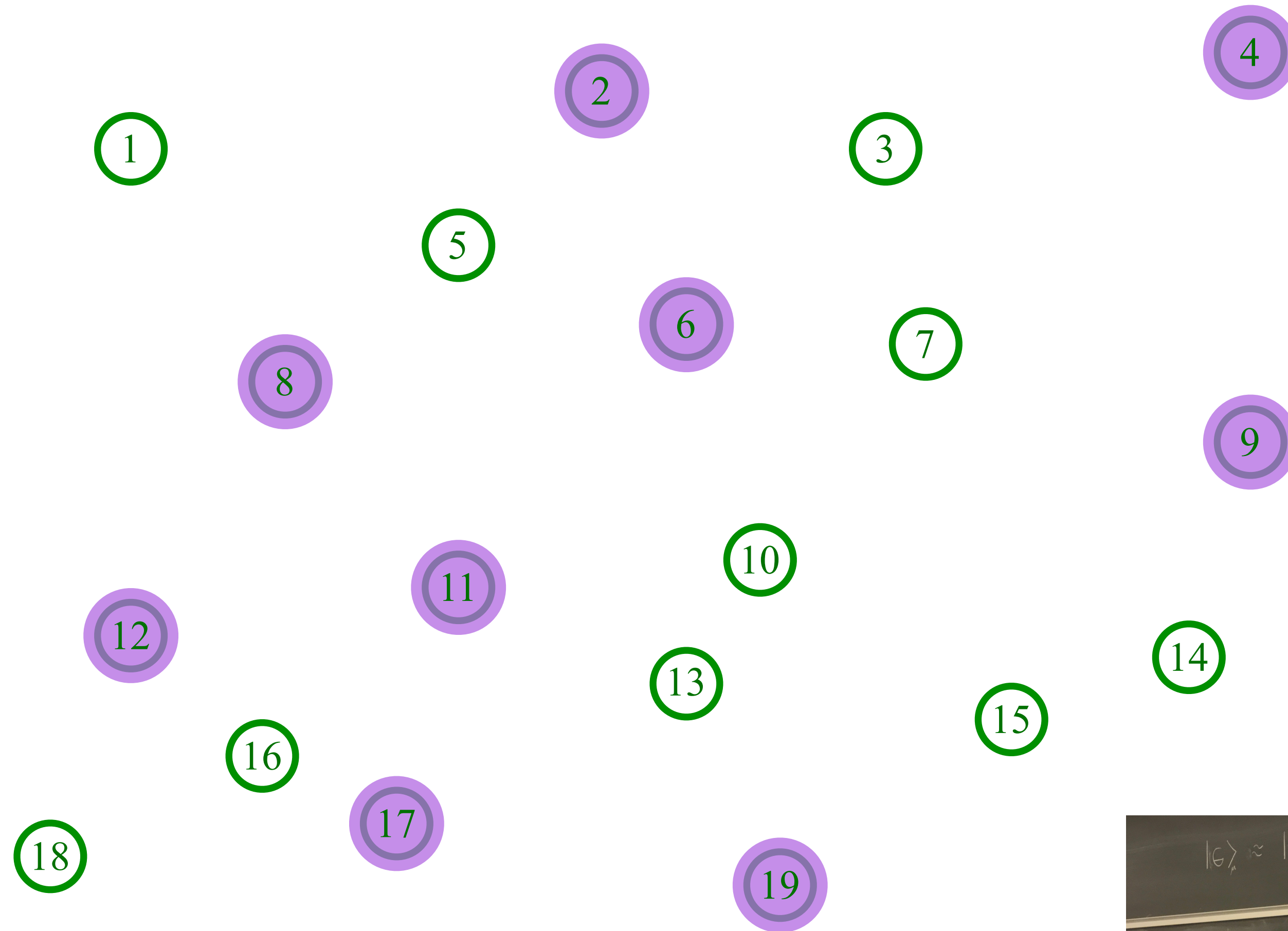


Pick a set of random positions

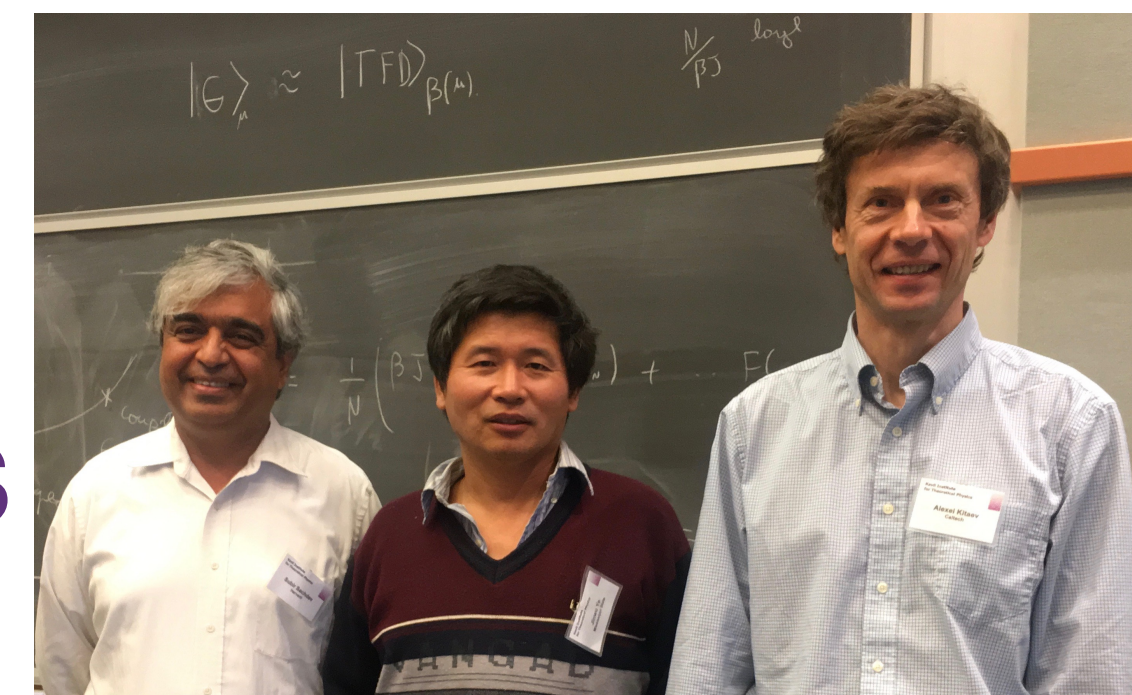


The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)



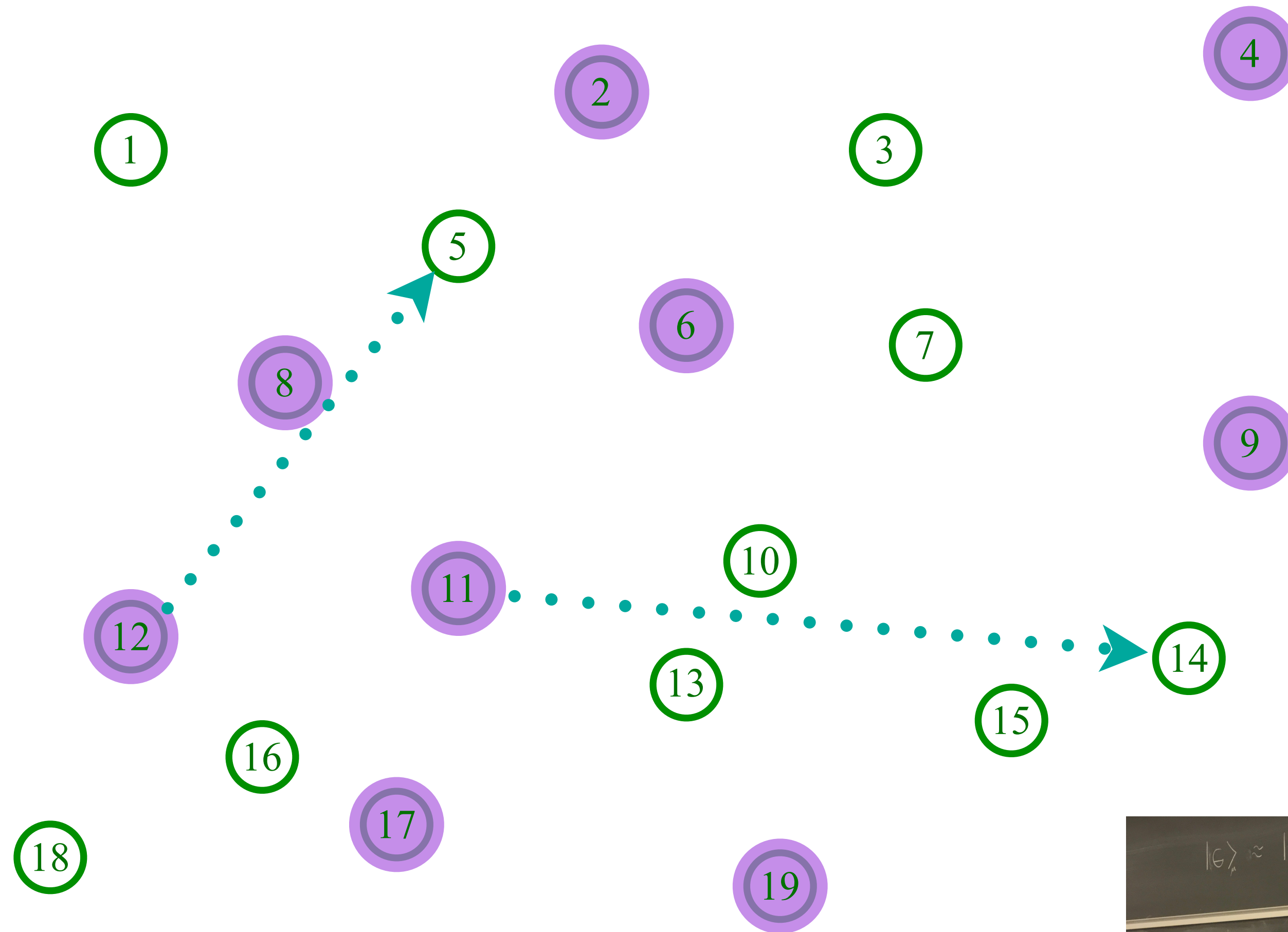
Place electrons randomly on some sites



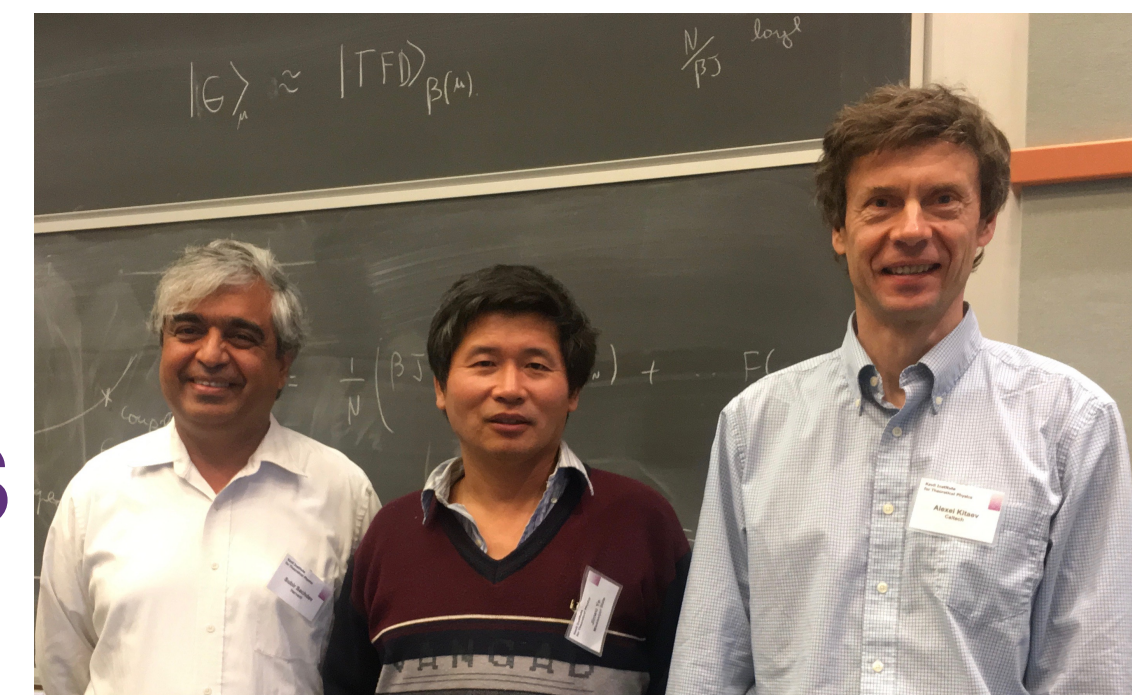
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



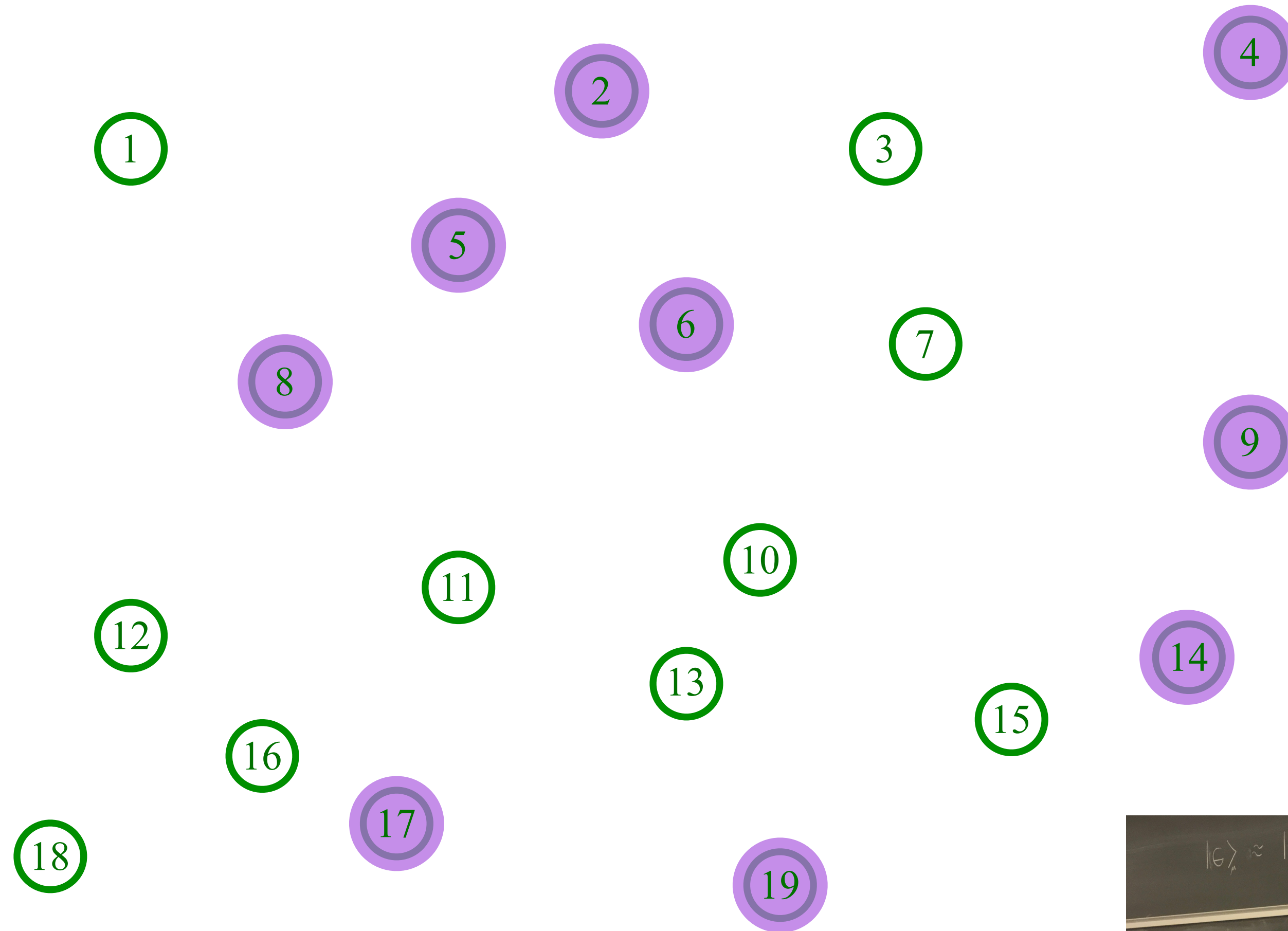
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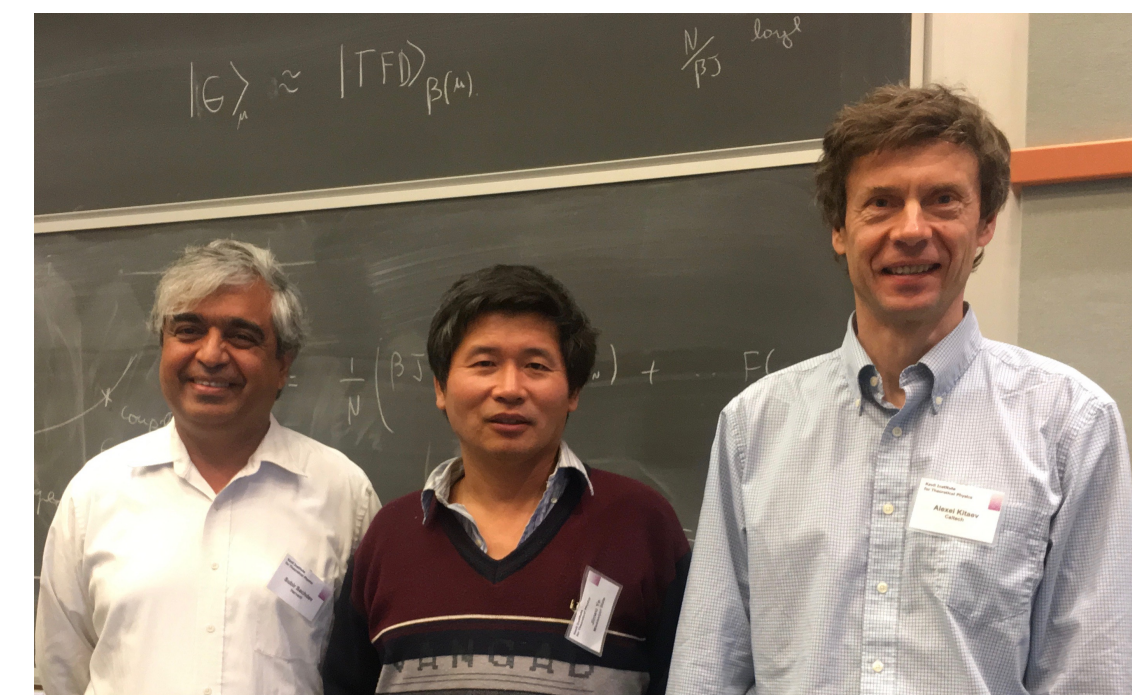
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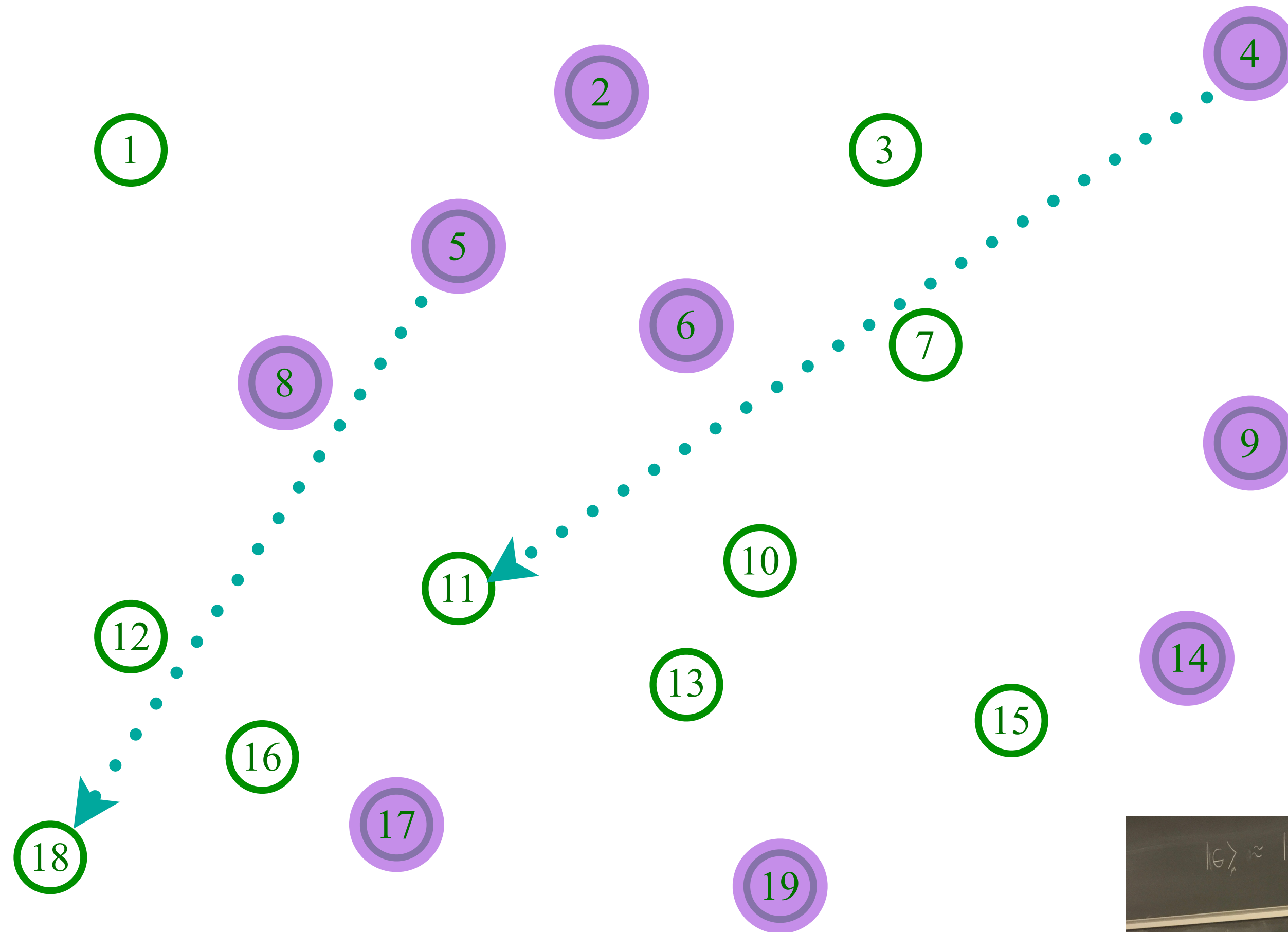
Entangle electrons pairwise randomly



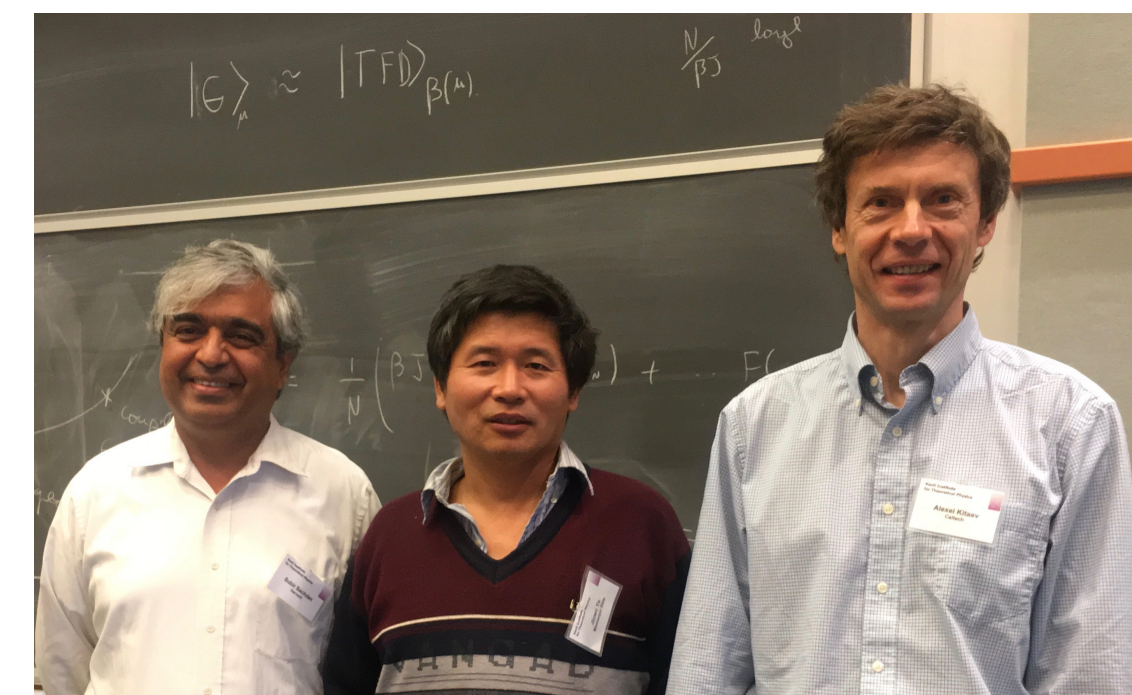
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



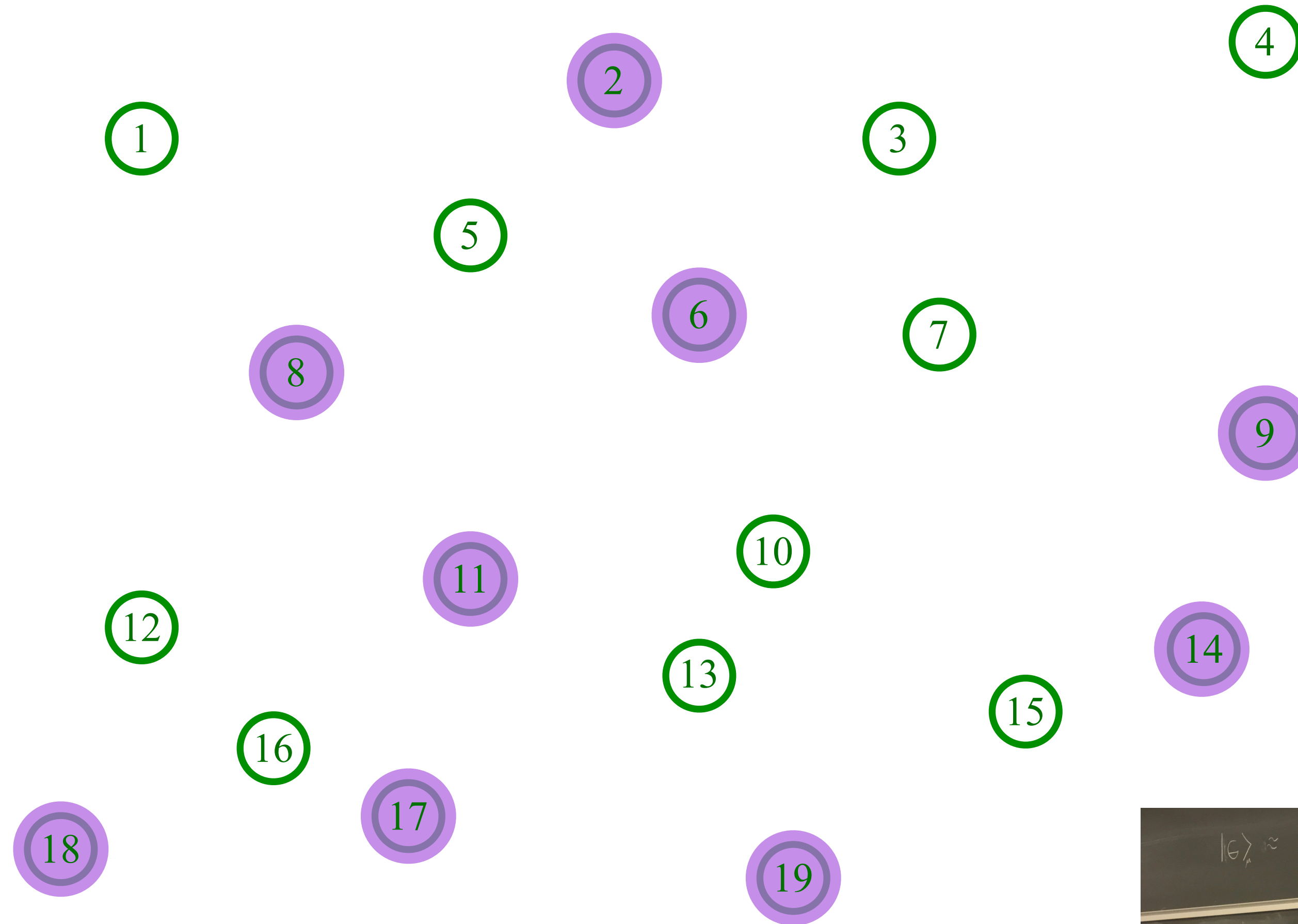
Entangle electrons pairwise randomly



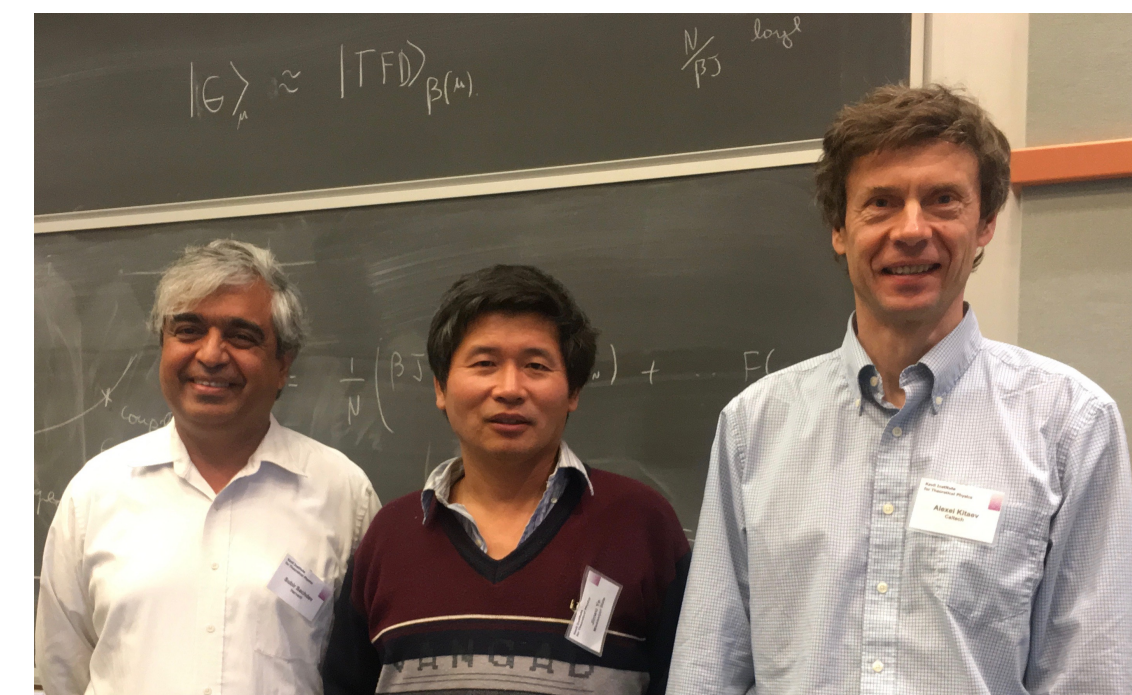
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Sachdev, Ye (1993); Kitaev (2015)

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



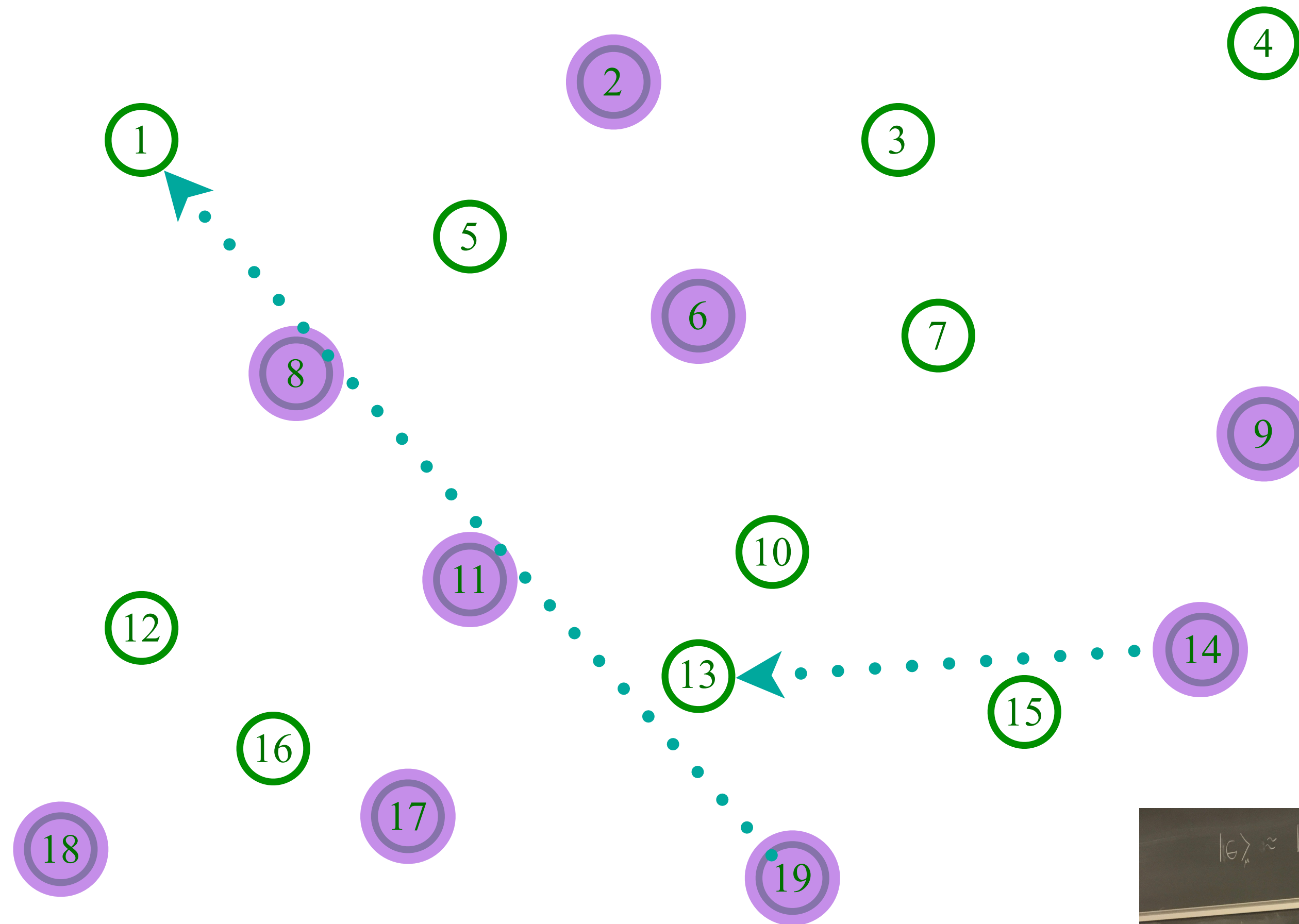
Entangle electrons pairwise randomly



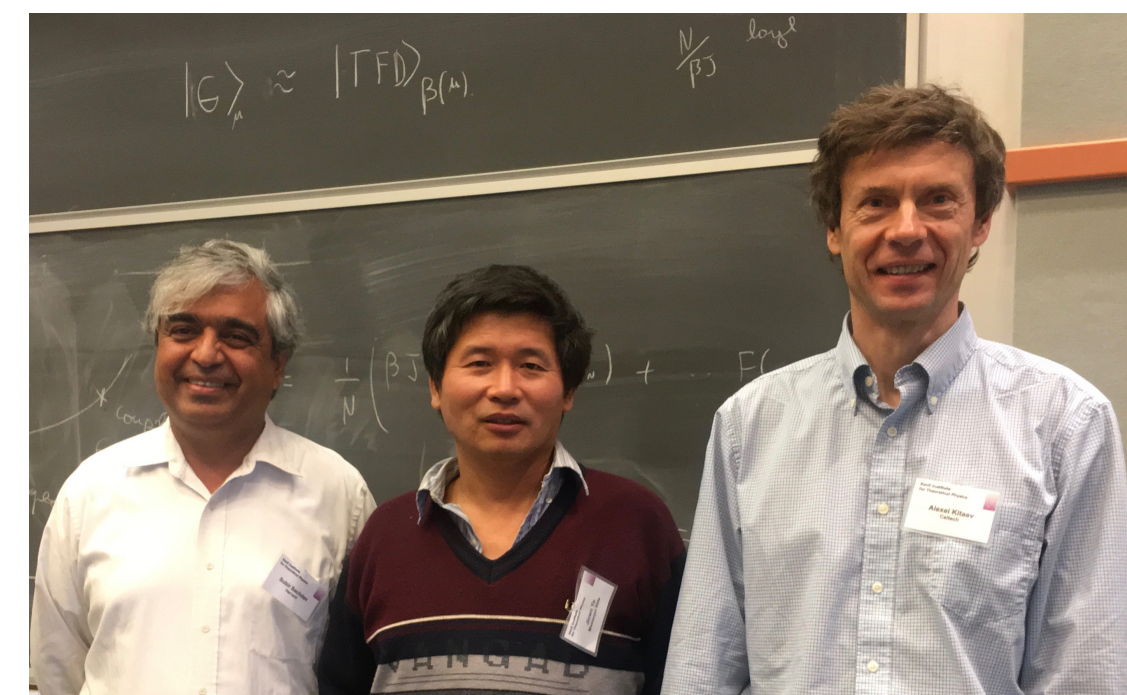
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



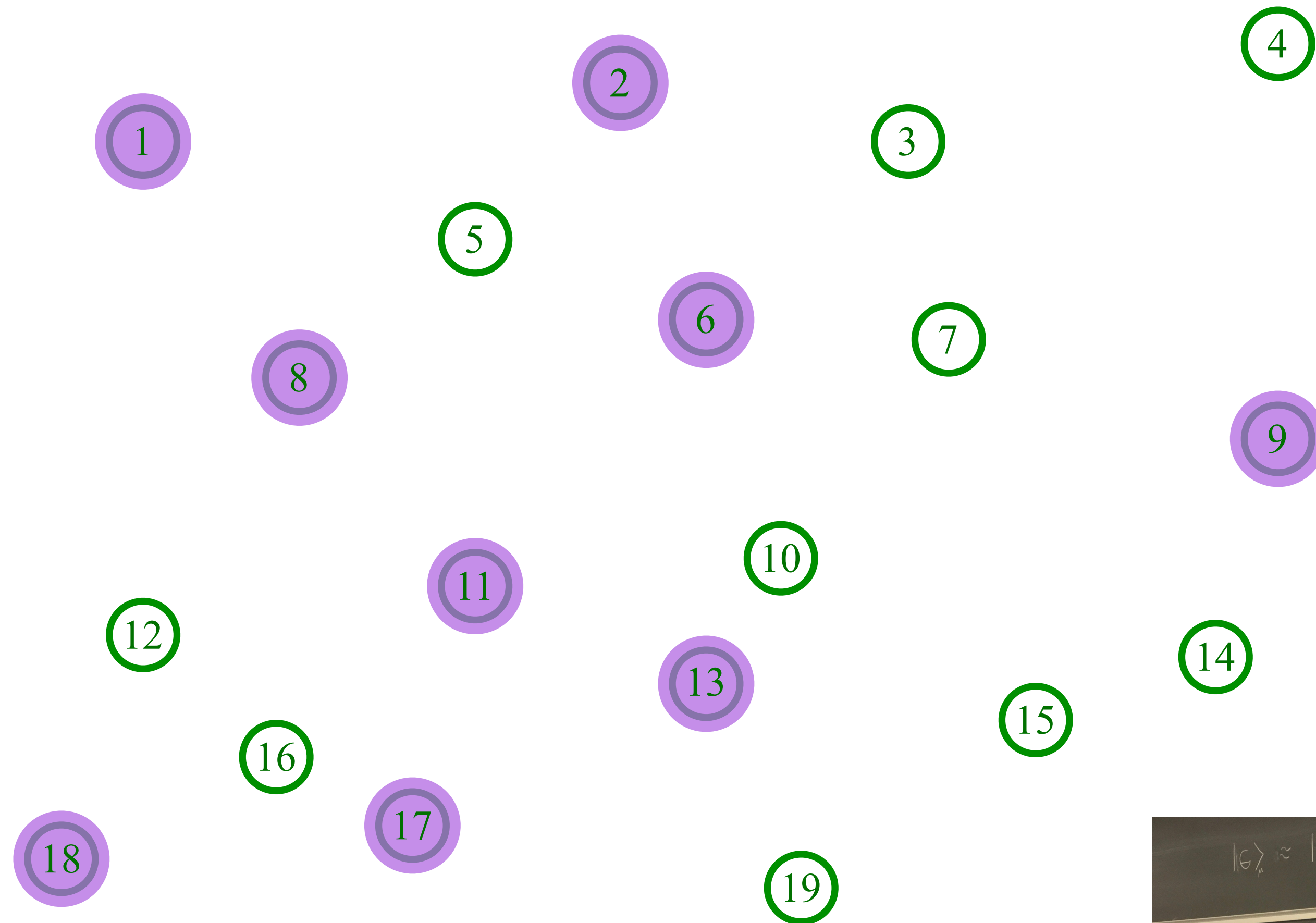
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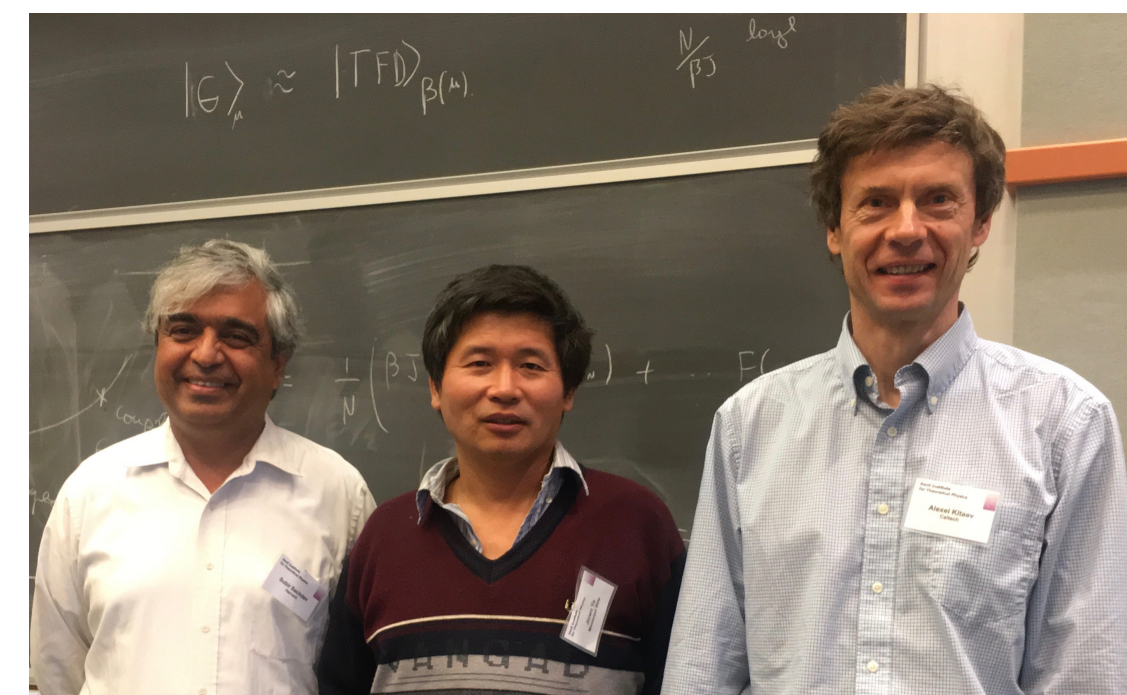
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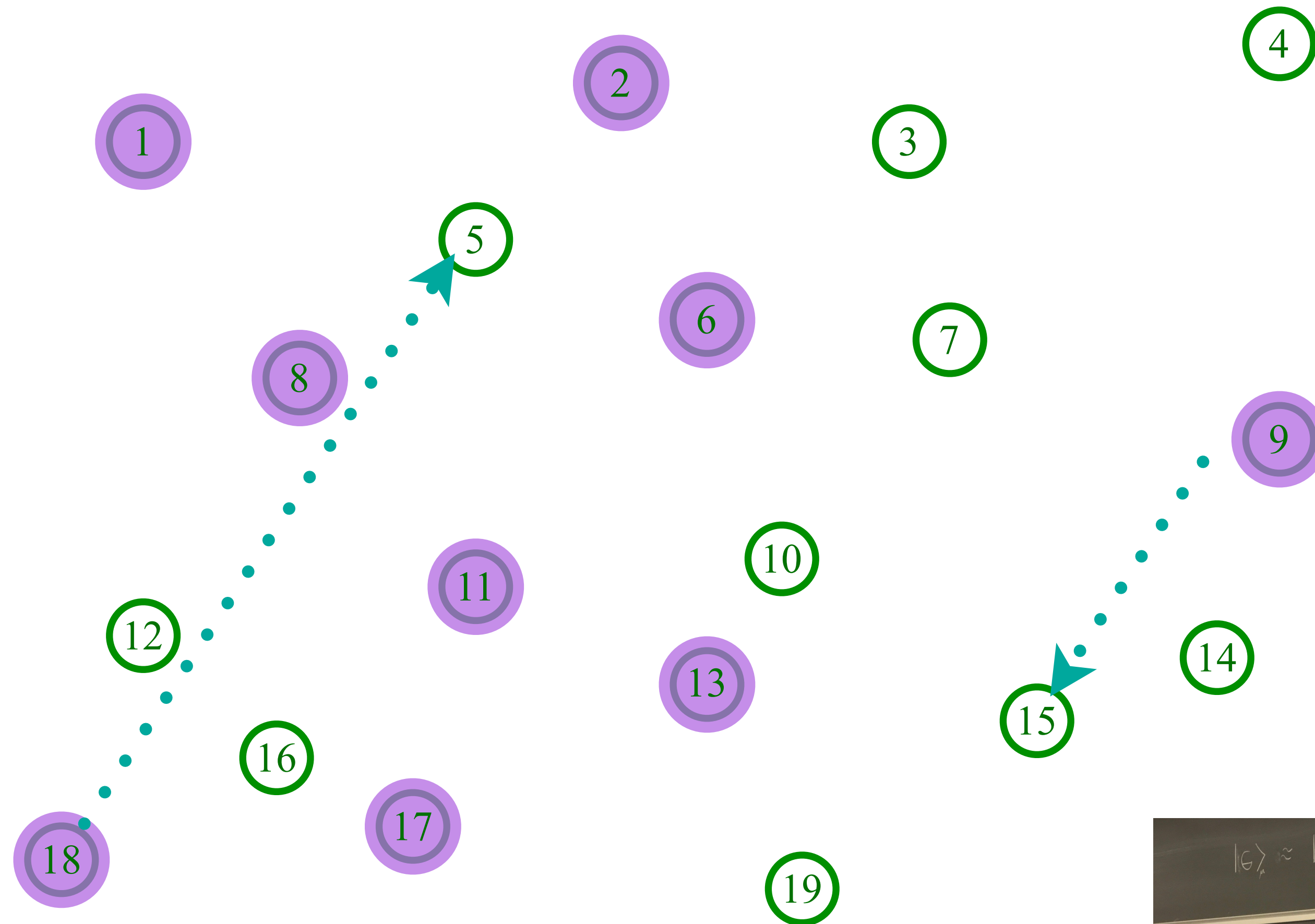
Entangle electrons pairwise randomly



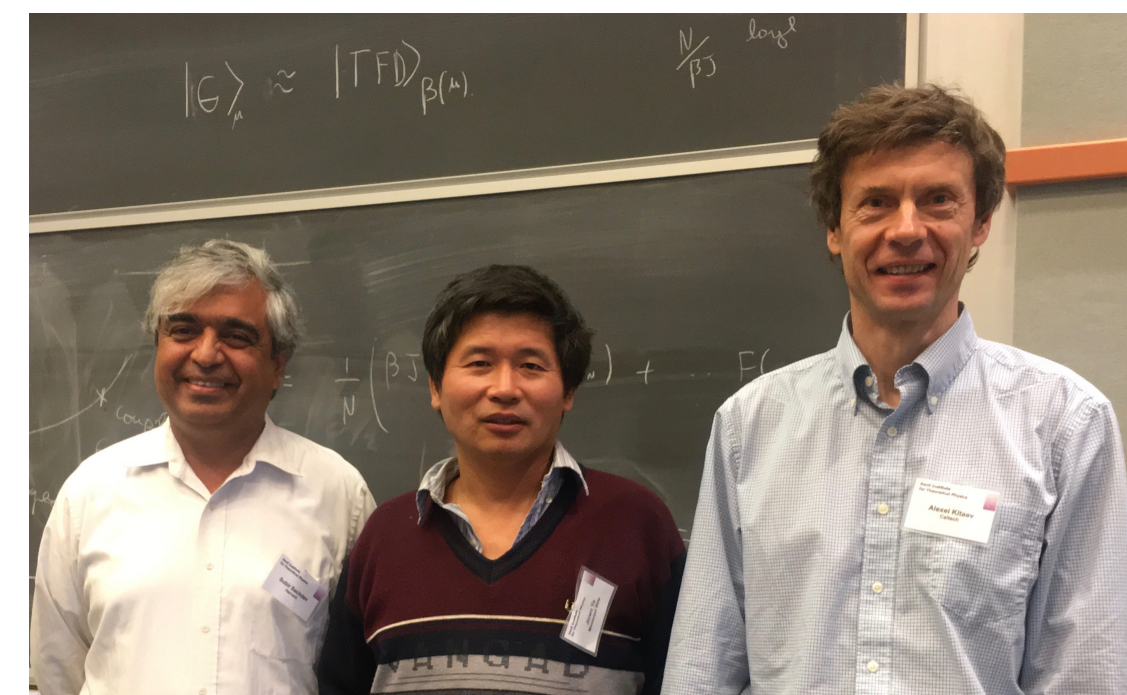
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



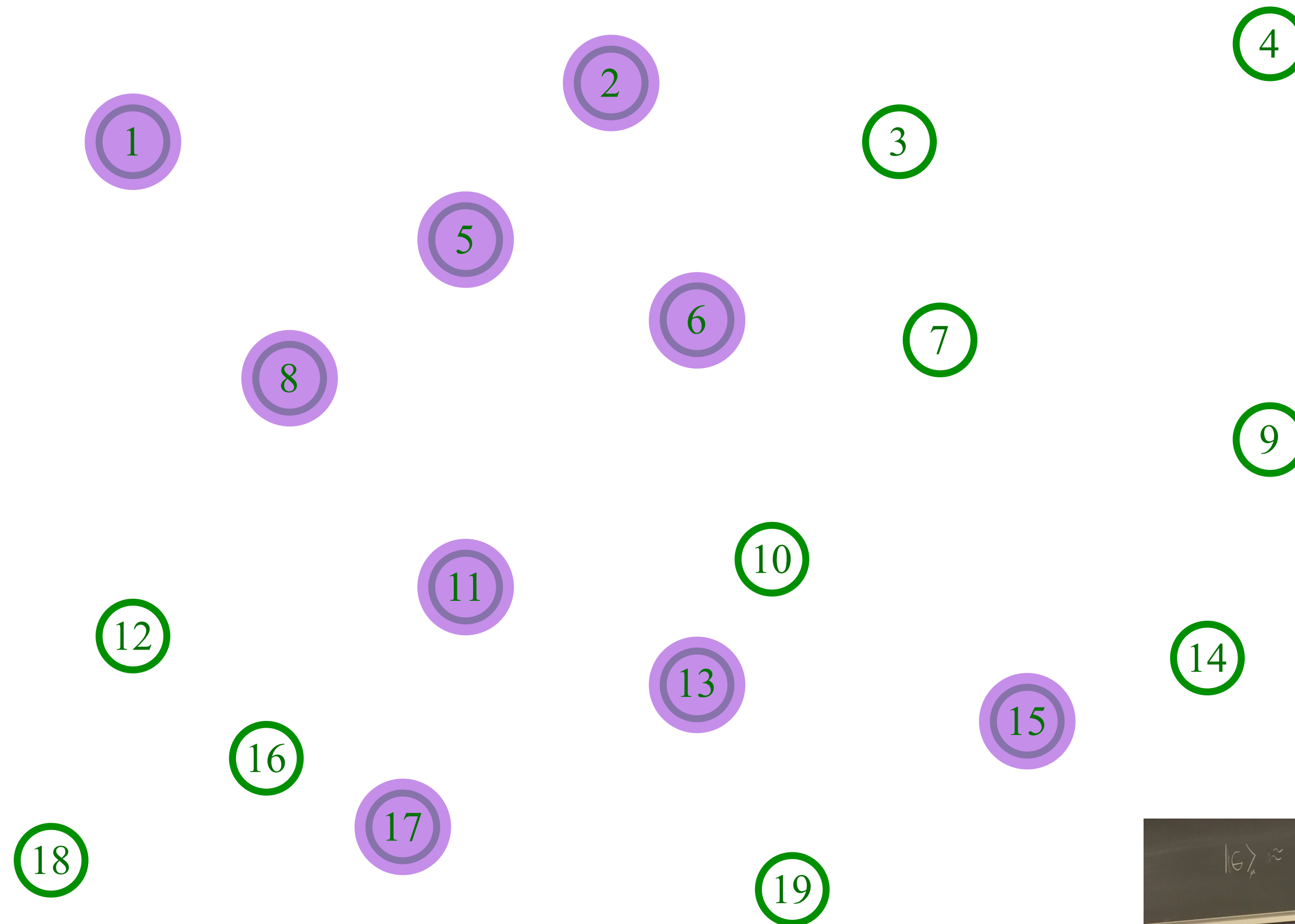
Entangle electrons pairwise randomly



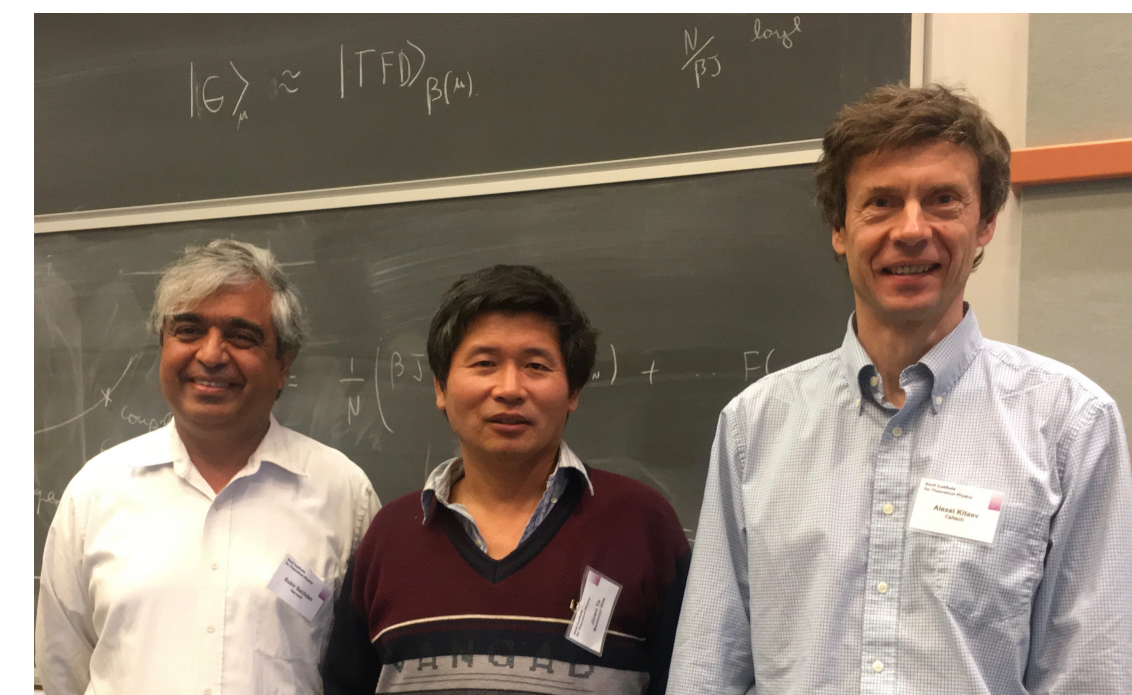
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Sachdev, Ye (1993); Kitaev (2015)

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



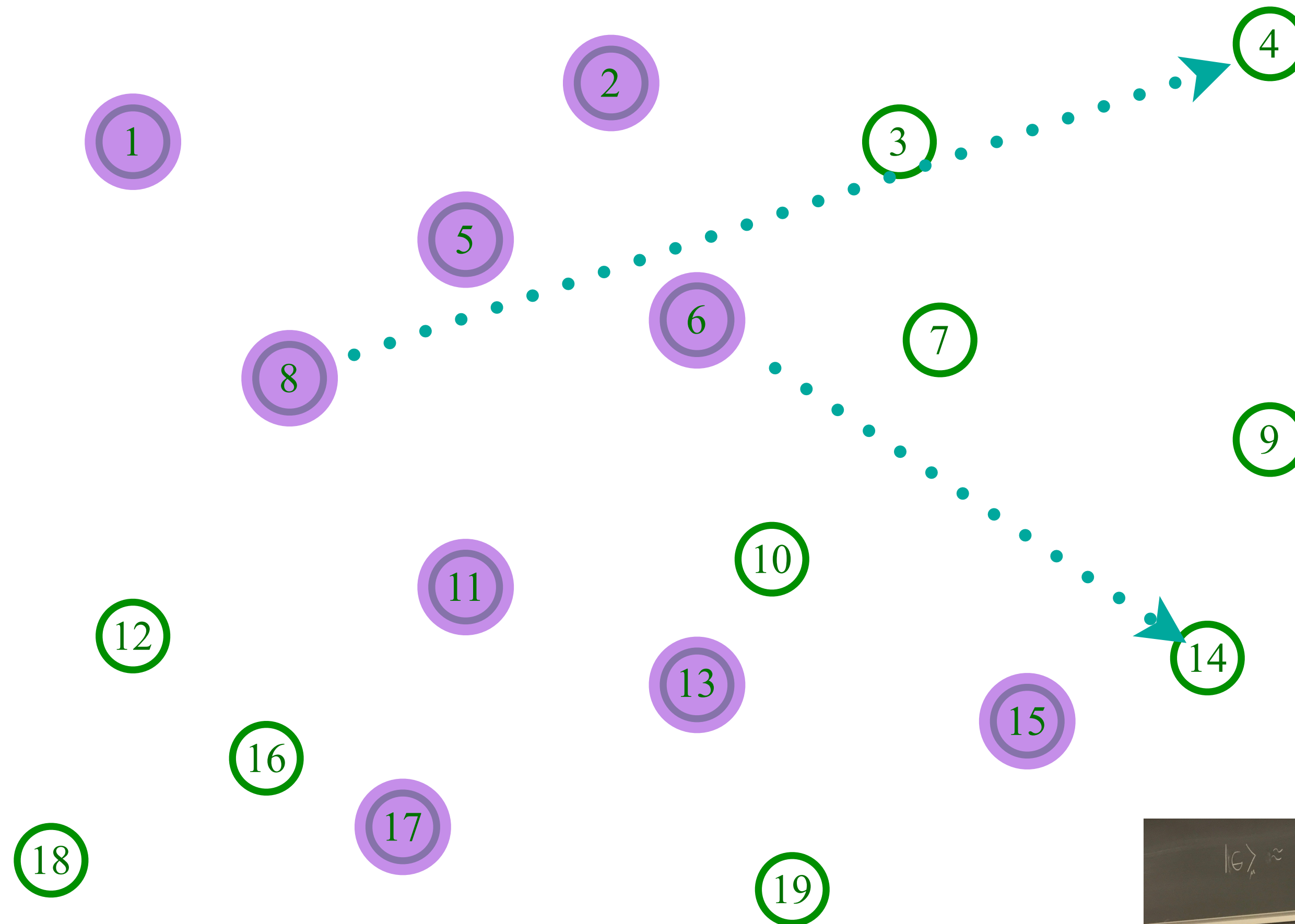
Entangle electrons pairwise randomly



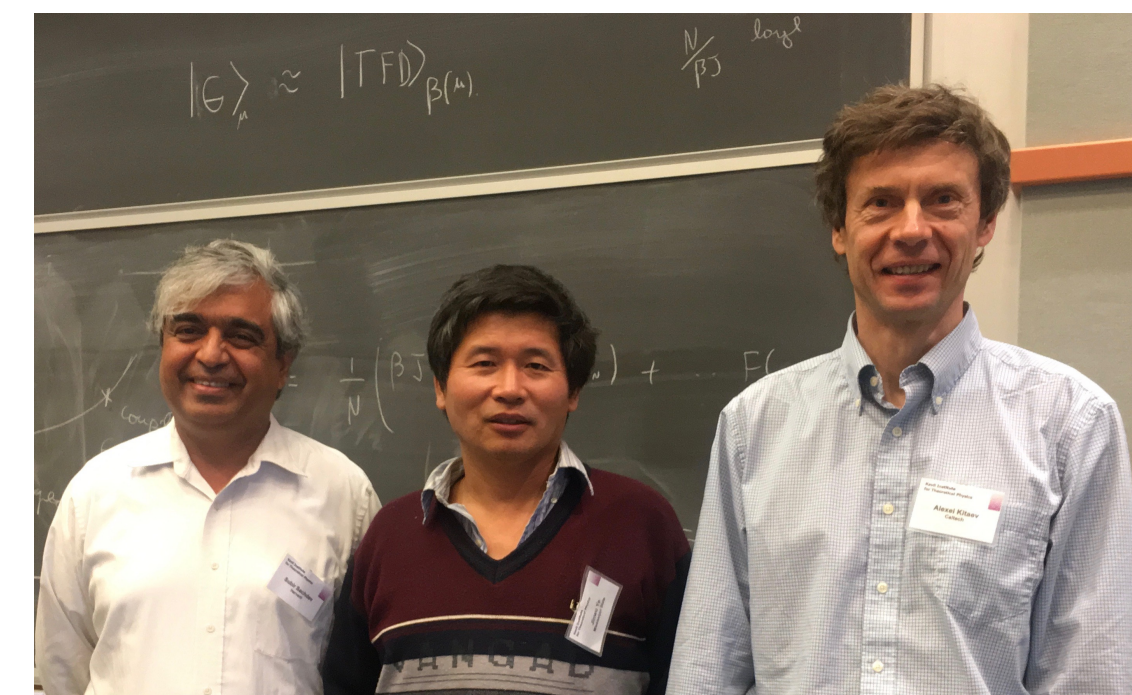
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



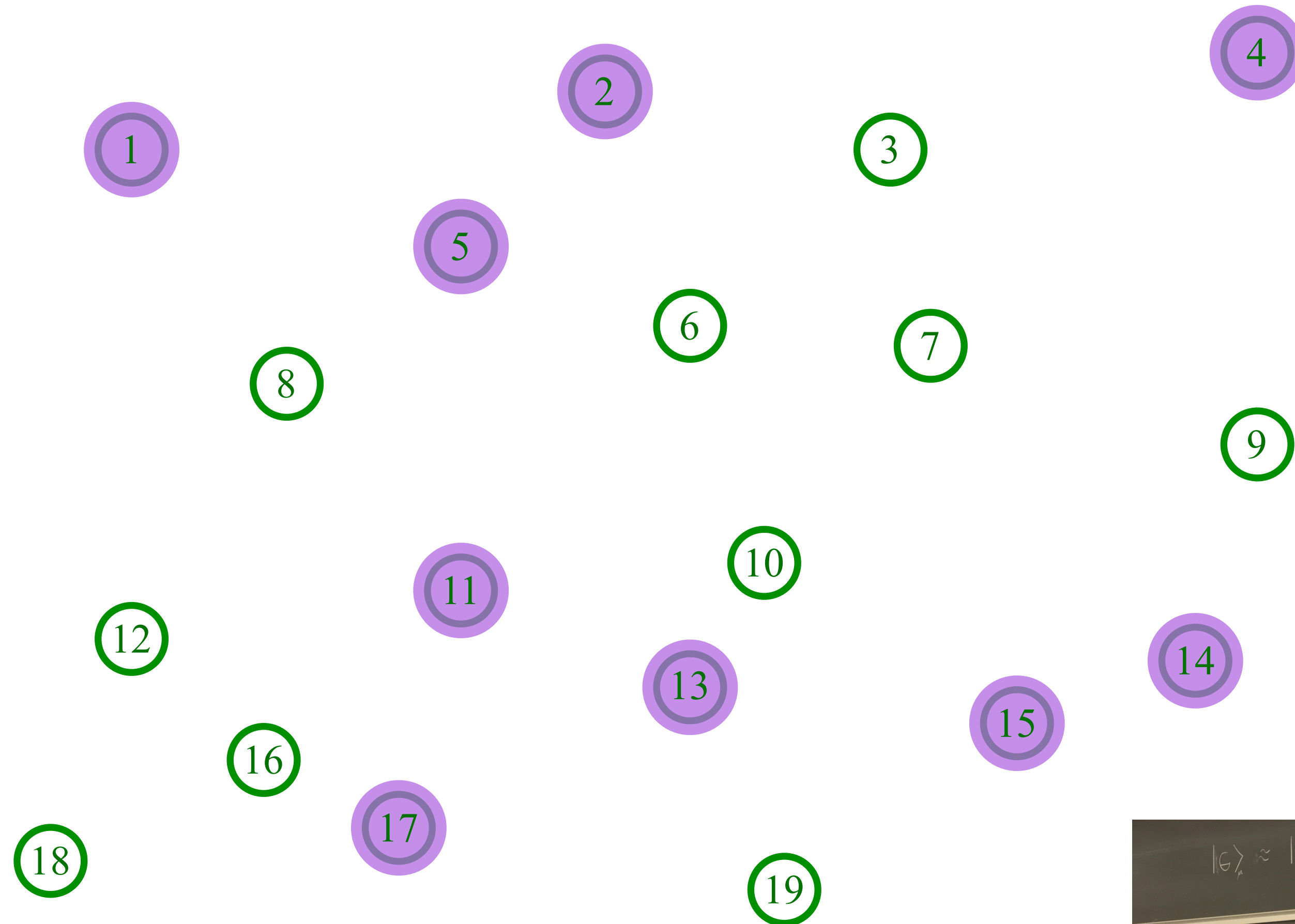
Entangle electrons pairwise randomly



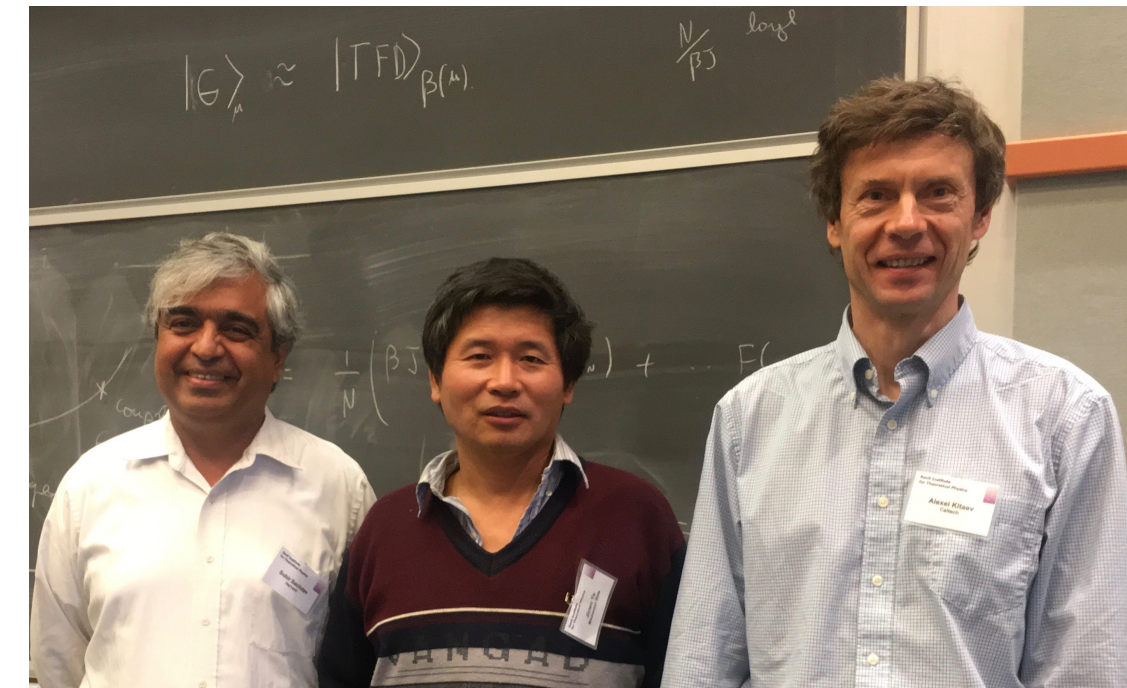
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



Entangle electrons pairwise randomly



The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

A solvable model of multi-particle
quantum entanglement.

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

Yields a quantum state whose excitations are not particle-like i.e. no bosons, fermions, anyons....

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

Yields a quantum state whose excitations are not particle-like i.e. no bosons, fermions, anyons....

Current is carried by an “entangled quantum soup”

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

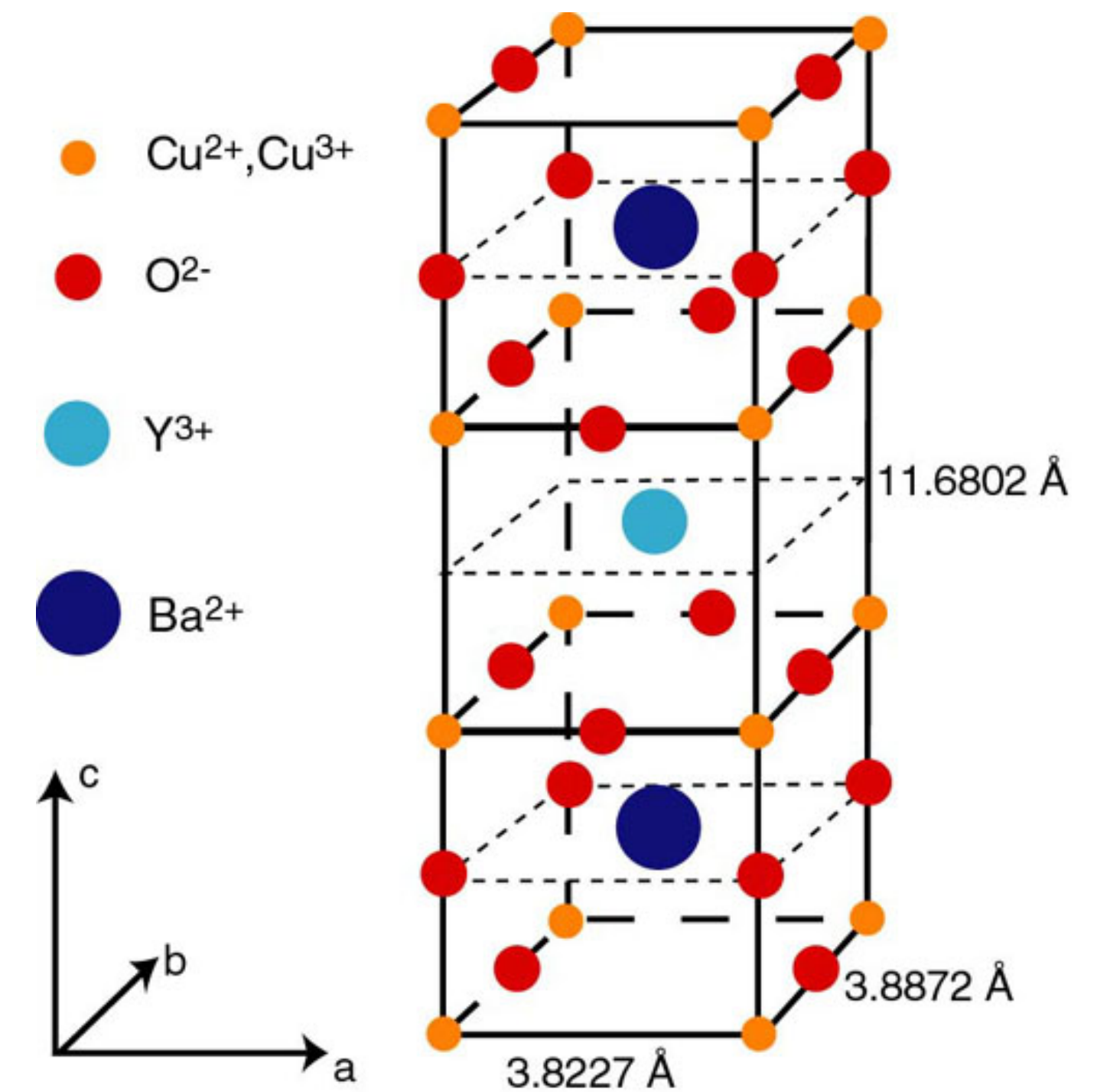
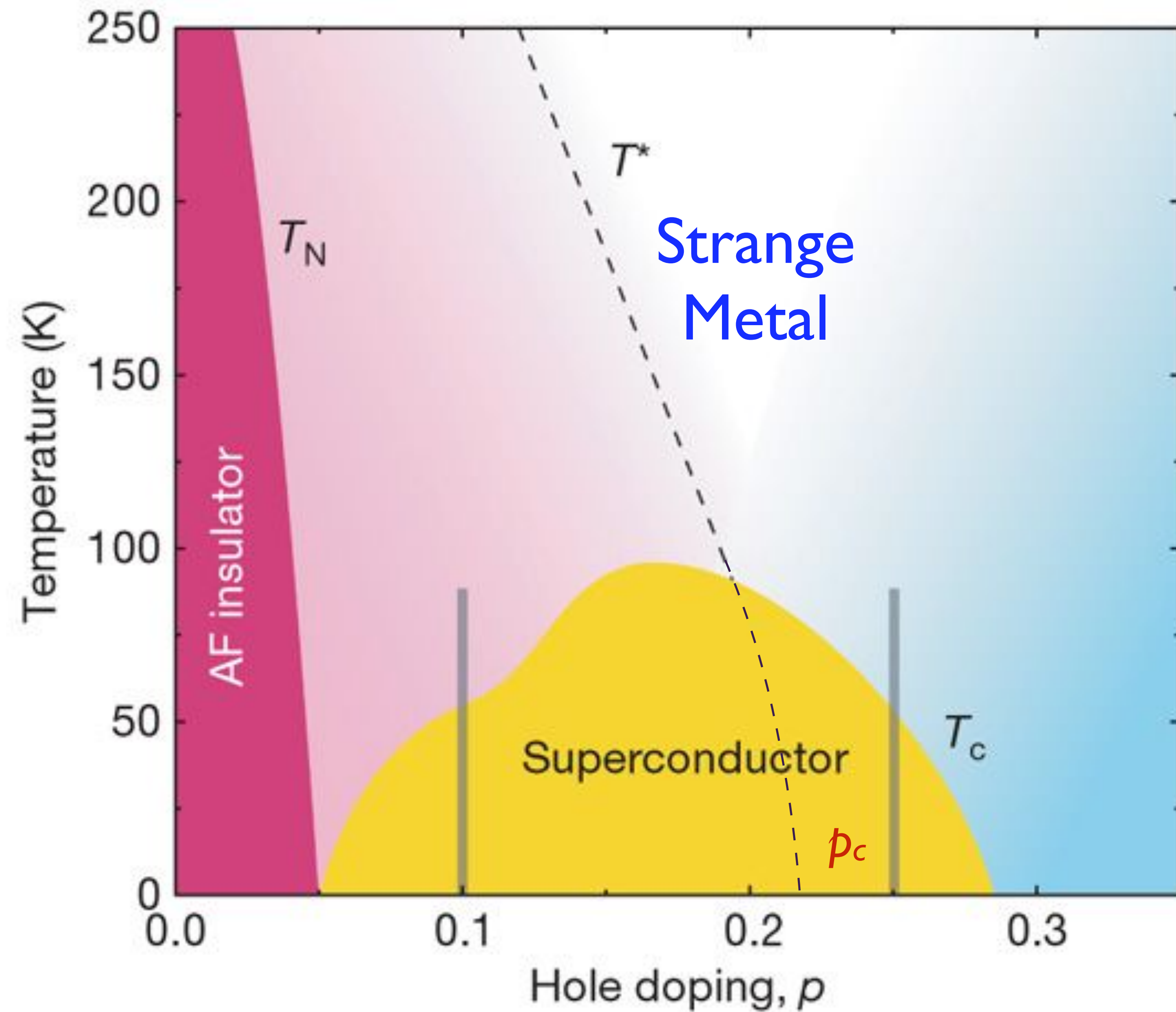
Yields a quantum state whose excitations are not particle-like i.e. no bosons, fermions, anyons....

A key consequence of the absence of the particle-like excitations is Universal Planckian Dissipation.

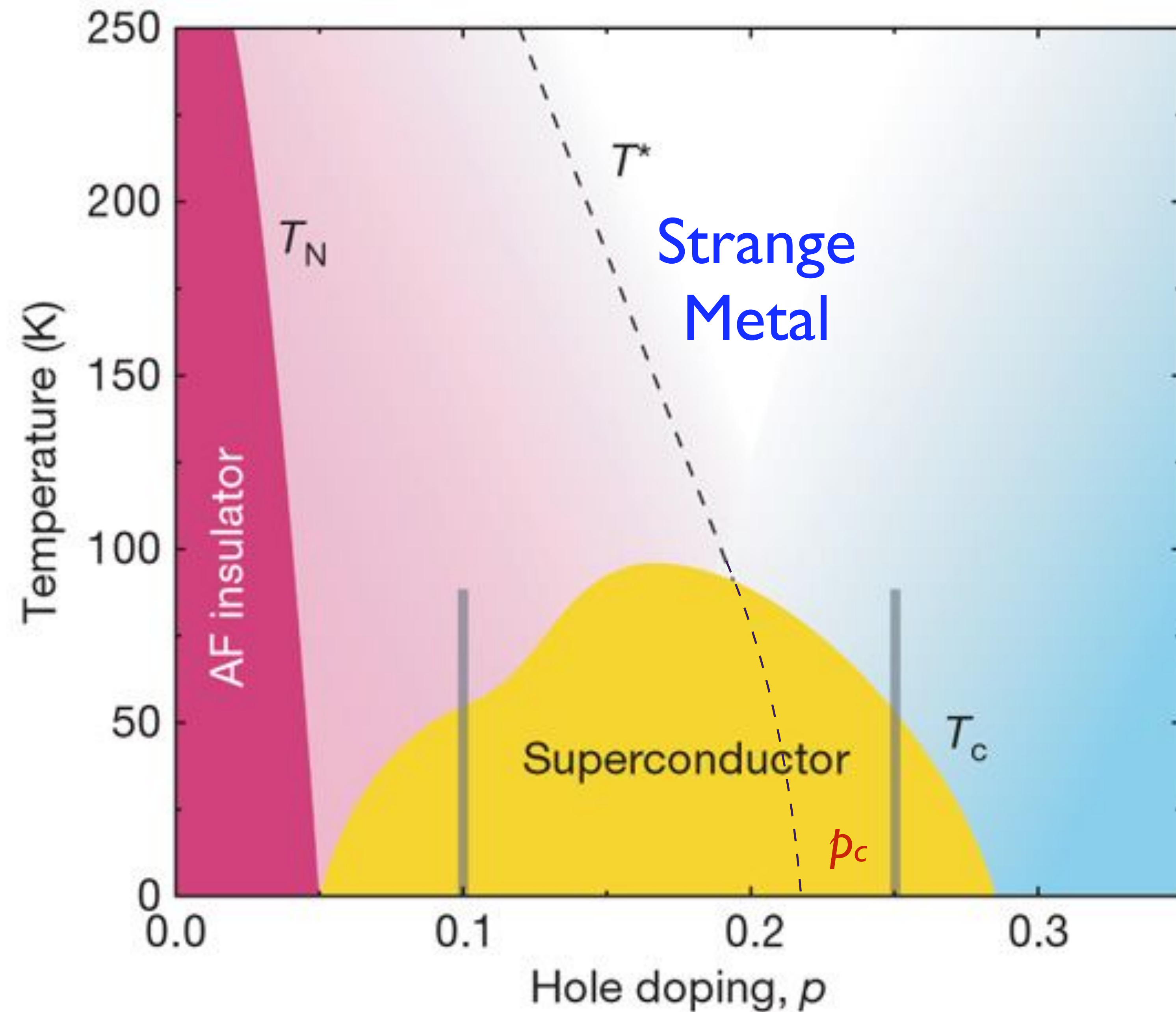
The relaxation time, τ , when perturbed at a frequency ω is given by

$$\tau = \frac{\hbar}{k_B T} F \left(\frac{\hbar \omega}{k_B T} \right)$$

where \hbar is Planck's constant, T is temperature, and the function F is independent of the strength of interaction between the particles.



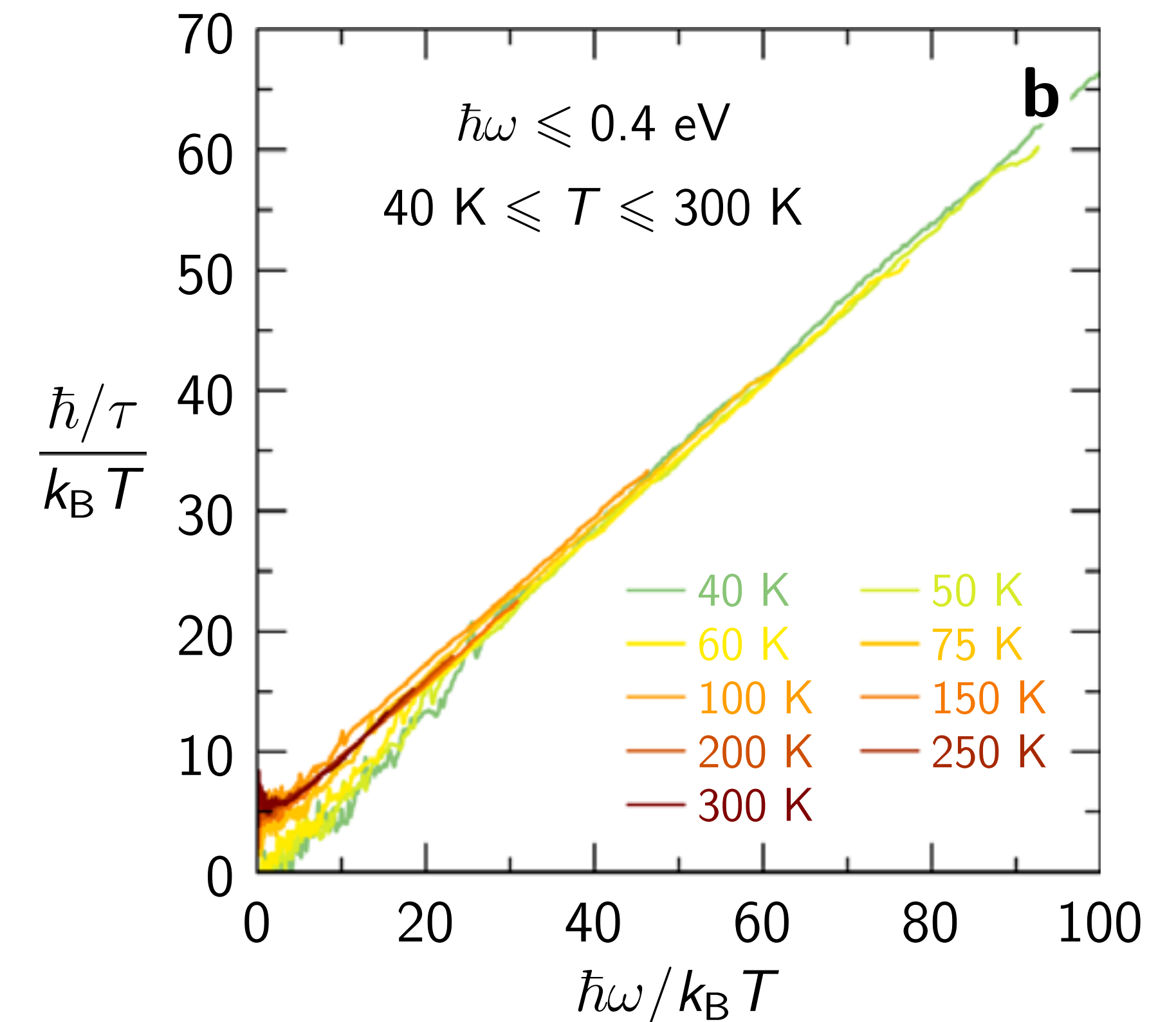
The Strange Metal has no particle-like/anyon excitations



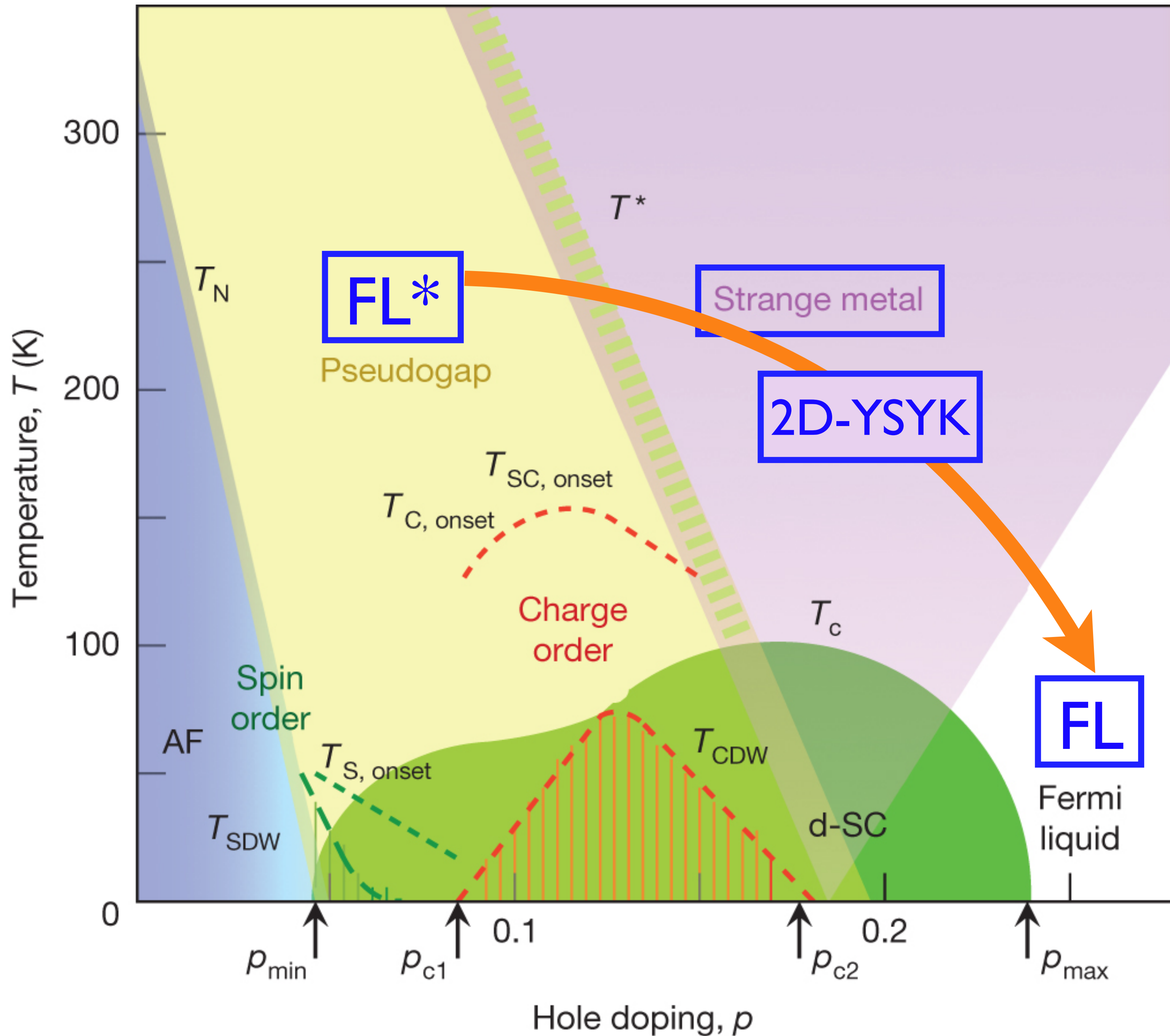
Planckian dynamics !

Electron scattering time τ
from optical conductivity

$$\tau(\omega) = \frac{\hbar}{k_B T} F\left(\frac{\hbar\omega}{k_B T}\right)$$



B. Michon, C. Berthod, C.W. Rischau, A. Ataei, L. Chen, S. Komiyama, S. Ono, L. Taillefer, D. van der Marel, A. Georges, Nature Comm. **14**, 3033 (2023)



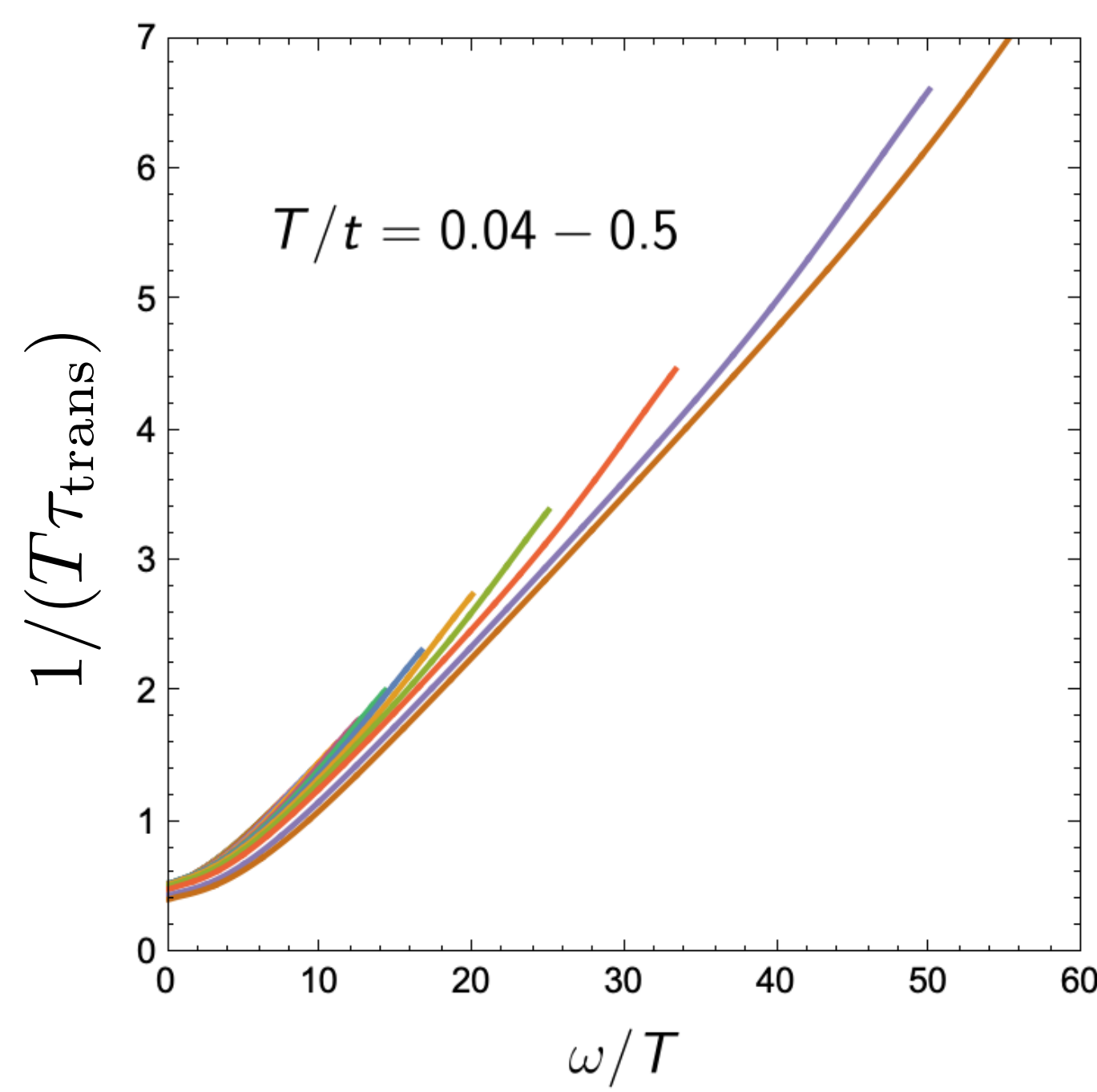
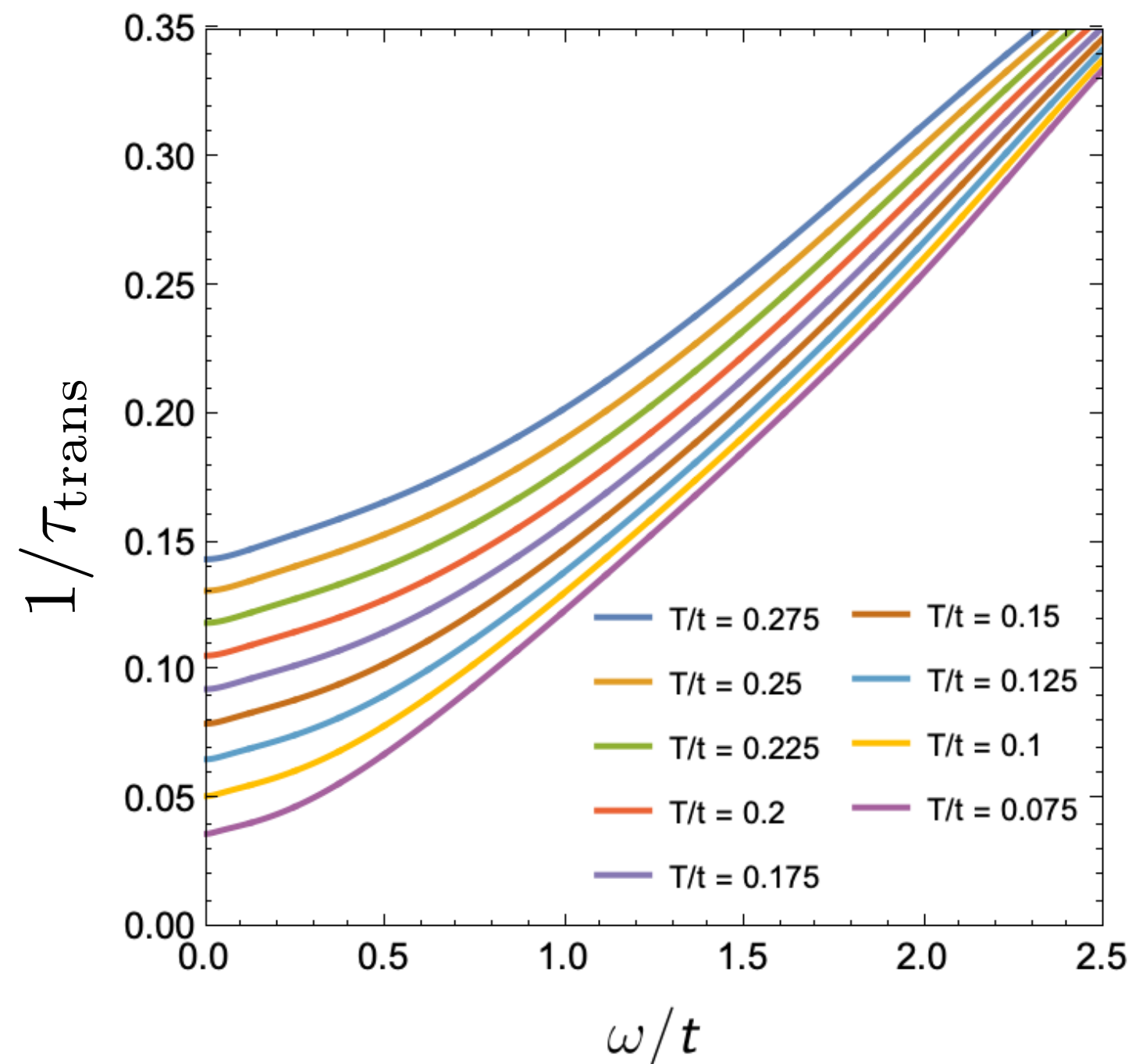
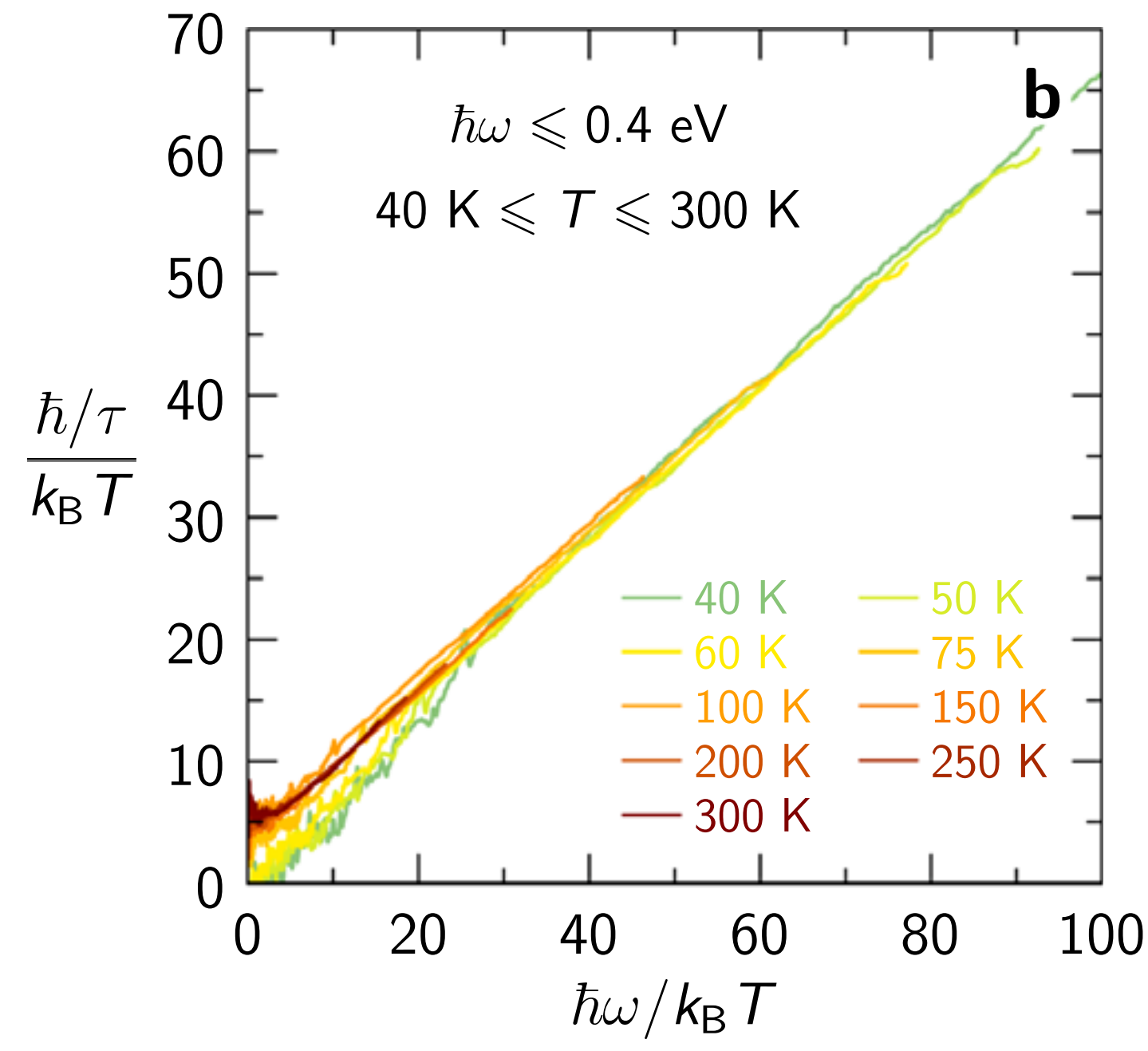
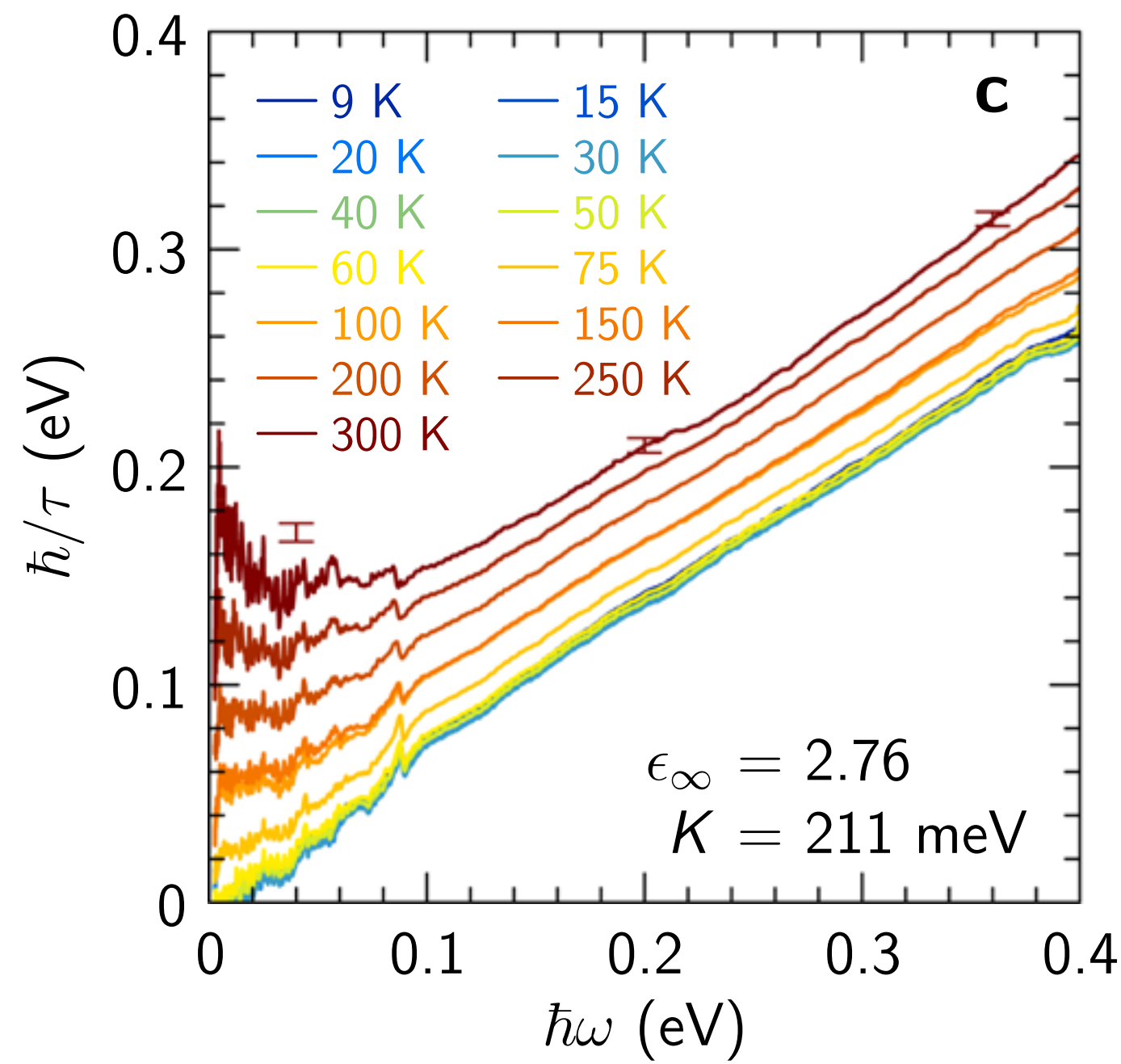
Quantum entanglement of mobile fermions without an energy gap

Sachdev-Ye-Kitaev (SYK) liquid

- 2D-YSYK: universal theory of strange metals: FL*-FL transition in cuprates.

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. S., *Science* **381**, 790 (2023)

Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentini, Jorg Schmalian, S.S., Ilya Esterlis, *PRL* **133**, 186502 (2024)



$$\sigma(\omega) = i \frac{e^2 K / (\hbar d_c)}{\hbar\omega \frac{m^*(\omega)}{m} + i \frac{\hbar}{\tau(\omega)}}$$

From
optical conductivity
data of
Michon et al. (2023)

$$\frac{\hbar}{\tau(\omega)} = k_B T \Phi_\tau \left(\frac{\hbar\omega}{k_B T} \right)$$

2d-YSYK theory

Aavishkar A. Patel, Haoyu Guo, Ilya Esterlis, S. S., *Science* **381**, 790 (2023)

Chenyuan Li, Aavishkar A. Patel, Haoyu Guo, Davide Valentini, Jorg Schmalian, S.S., Ilya Esterlis, *PRL* **133**, 186502 (2024)

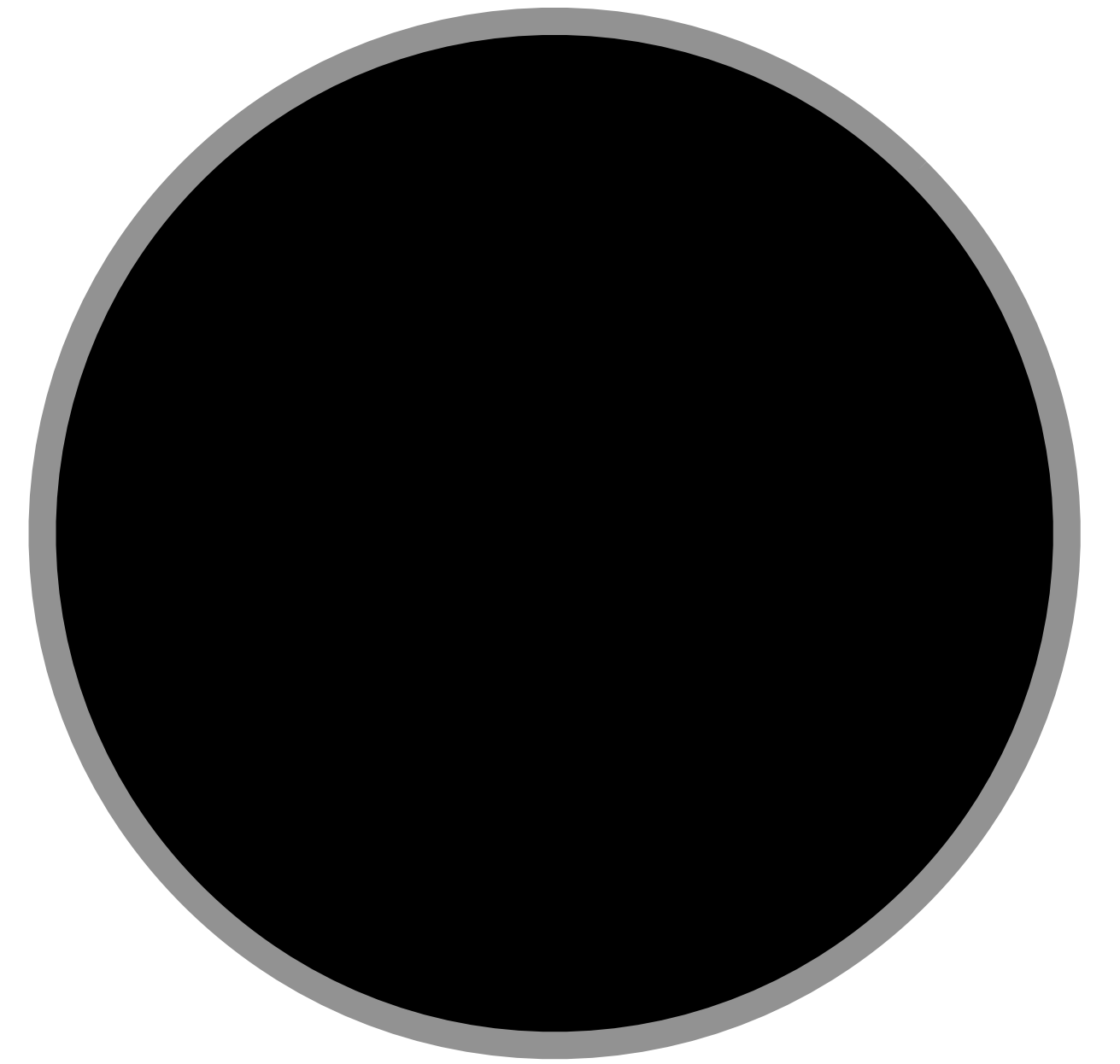
Quantum entanglement,
the SYK model,
and black holes

Black Holes

Objects so dense that light is gravitationally bound to them.



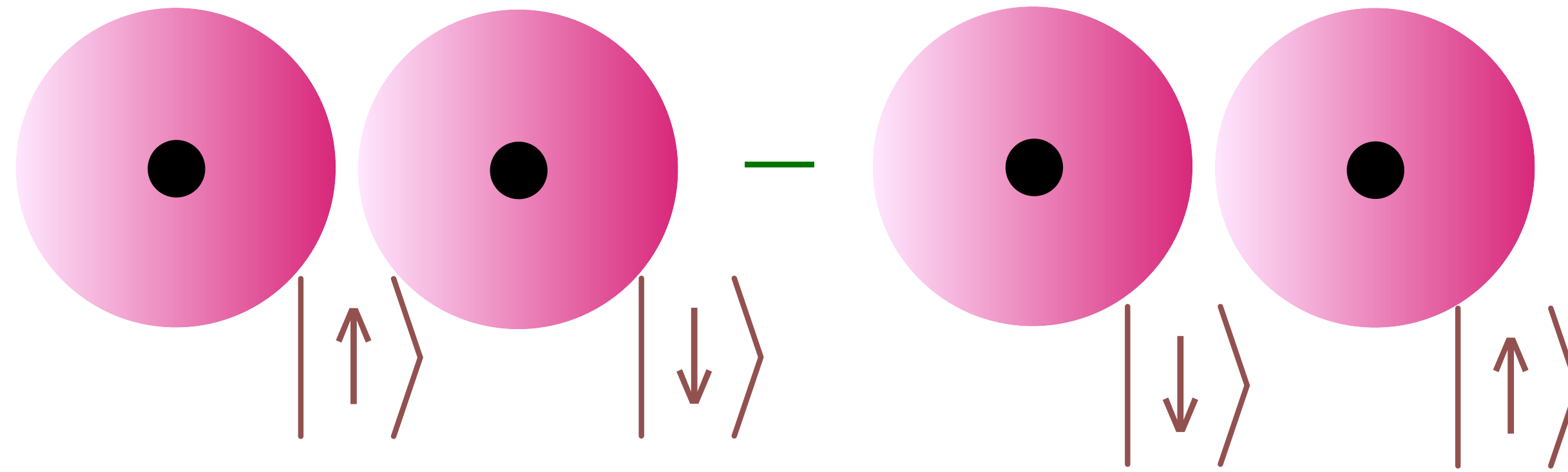
Horizon radius $R = \frac{2GM}{c^2}$



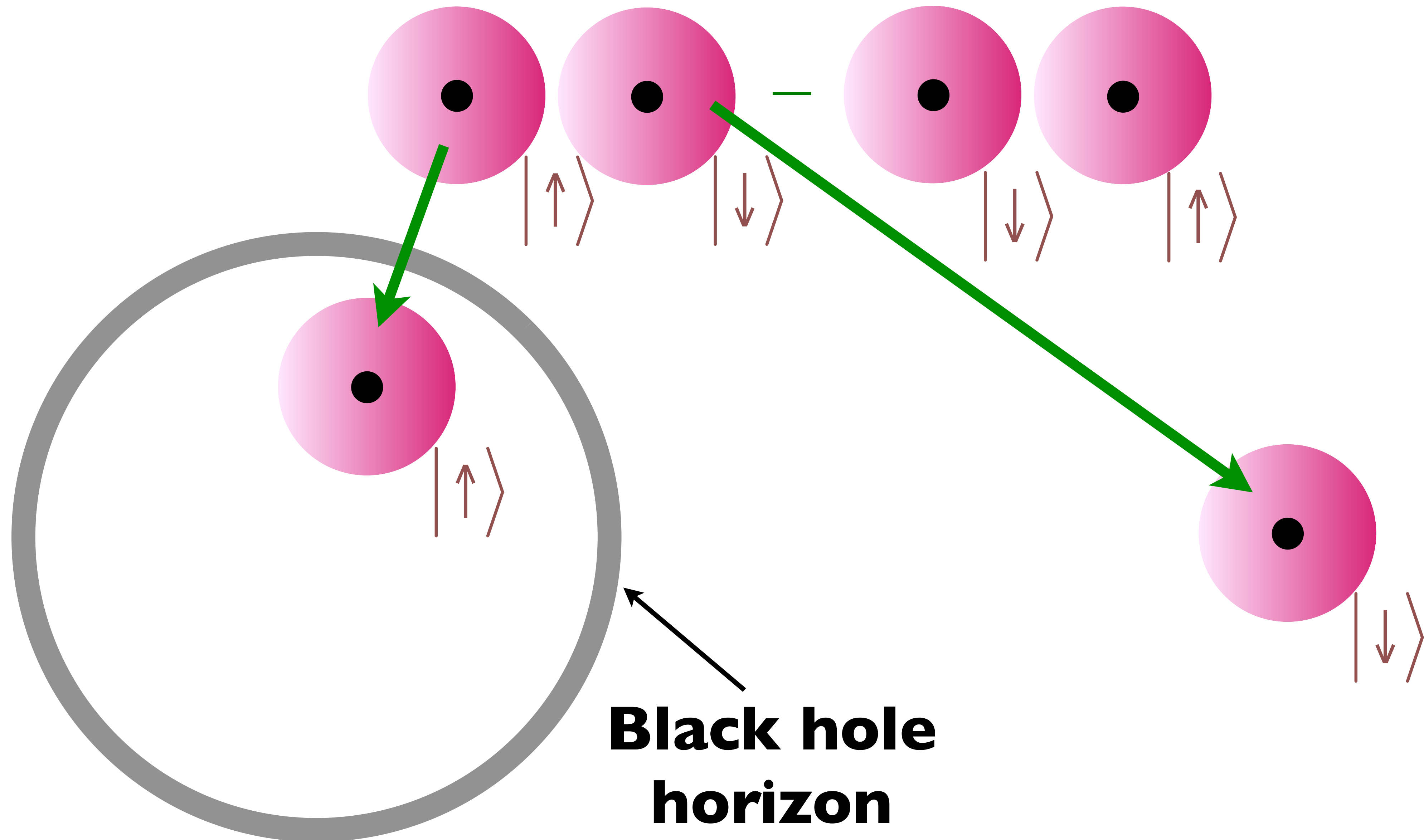
Karl Schwarzschild (1916)

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

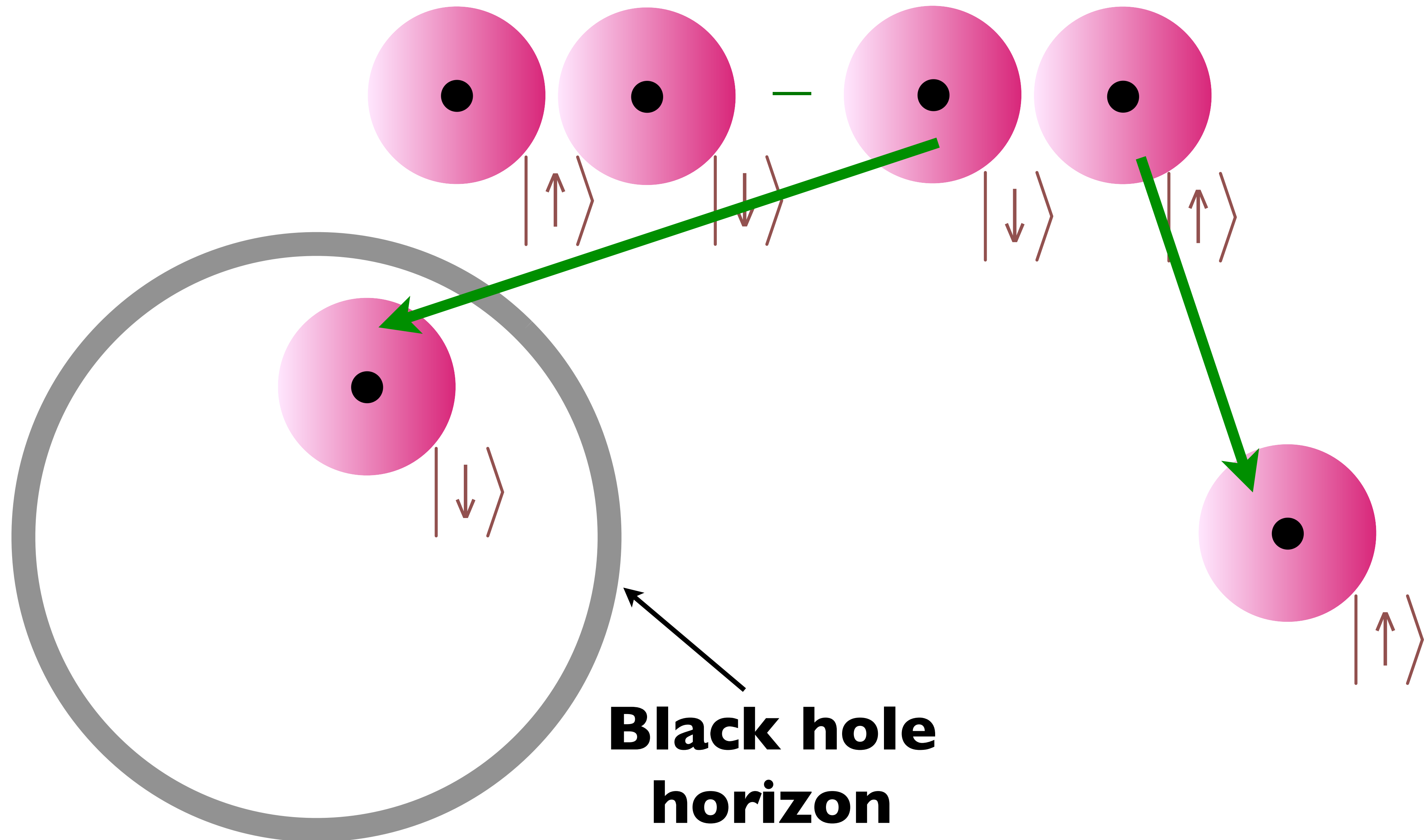
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

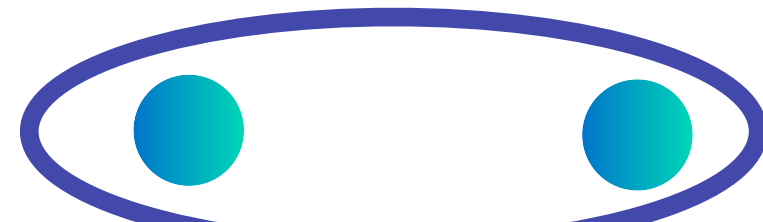


Quantum Entanglement across a black hole horizon



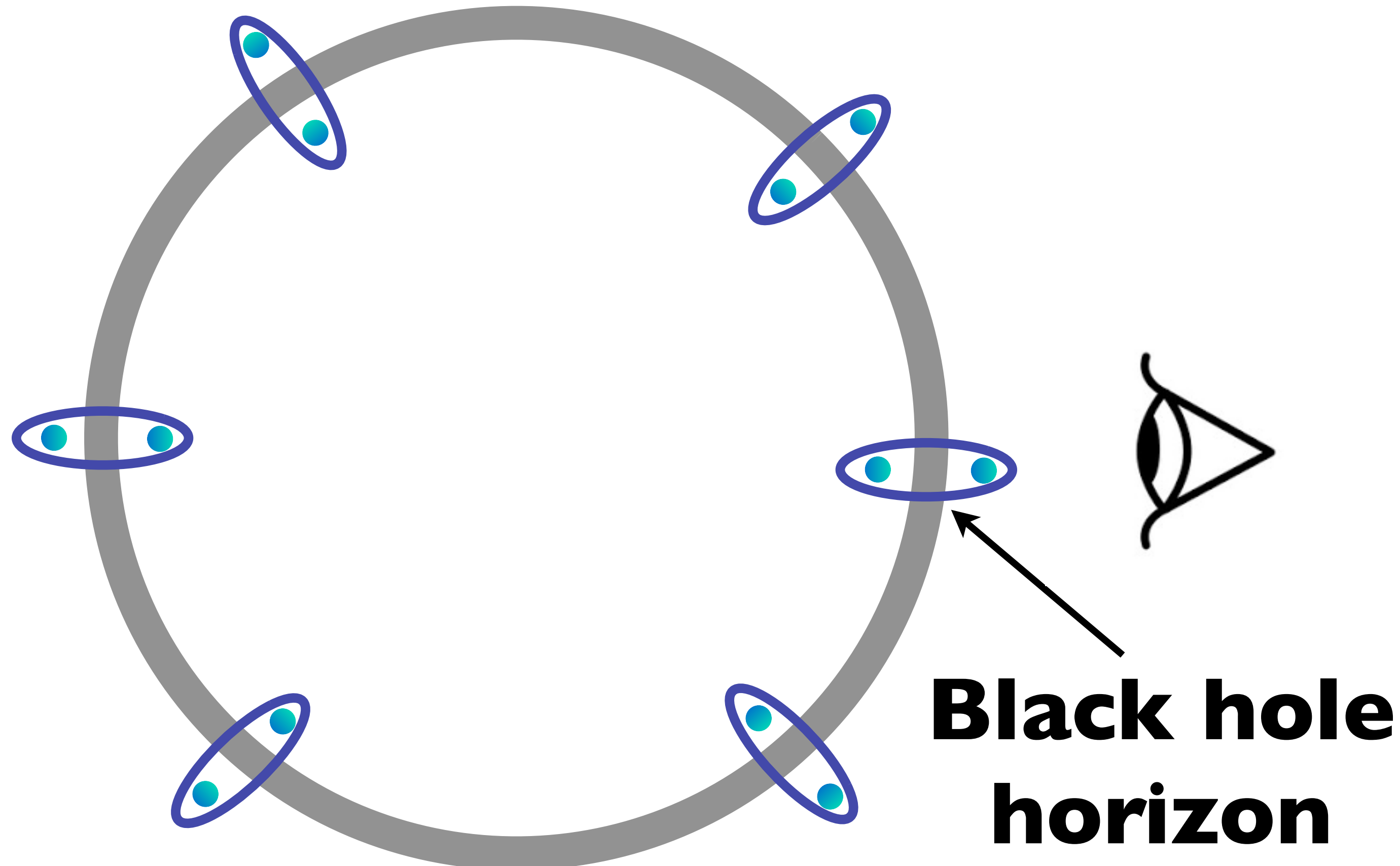
Quantum Entanglement across a black hole horizon

Quantum entanglement
on the surface



A diagram showing two blue dots representing particles inside a blue oval, representing an entangled state.

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



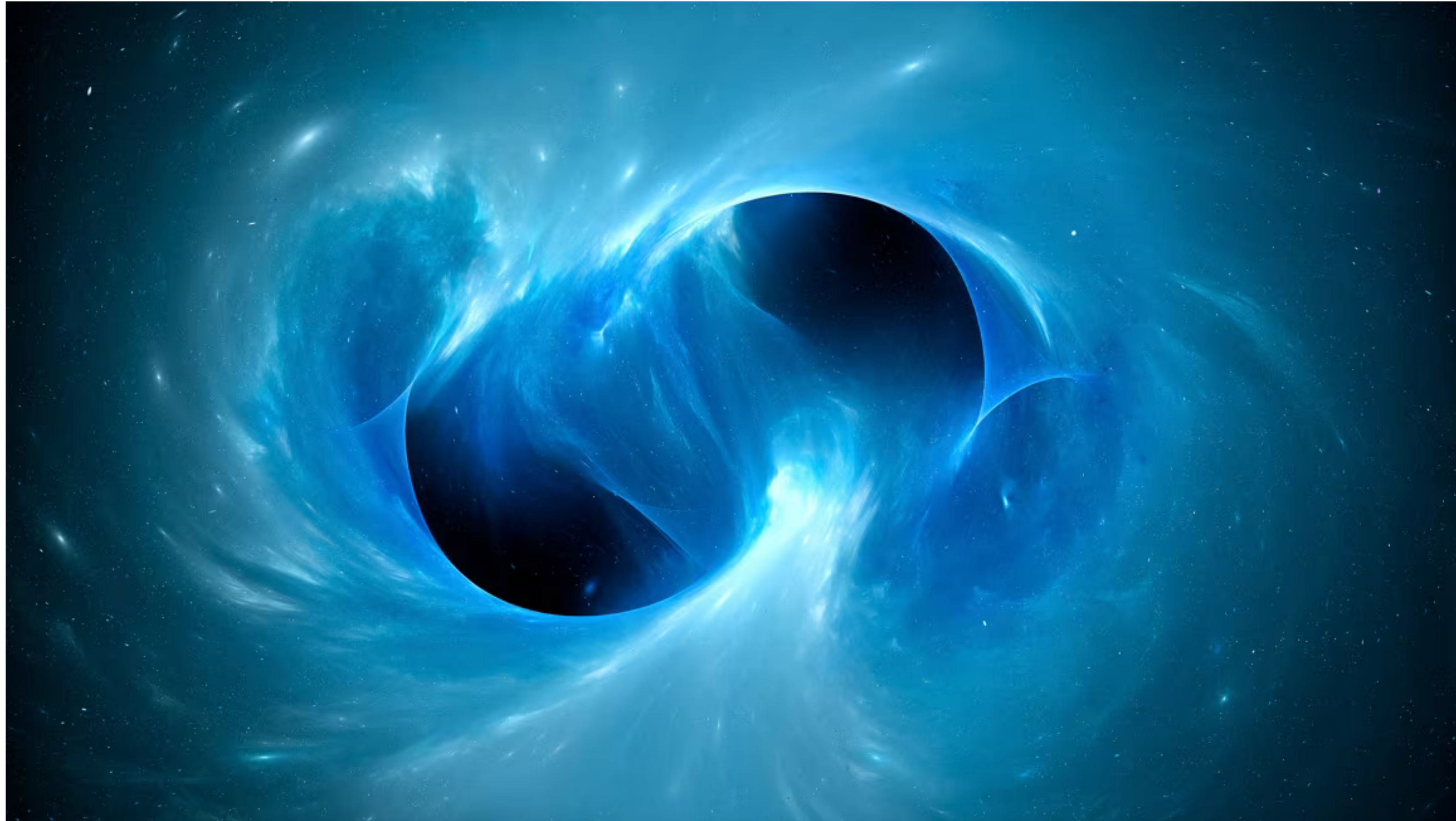
By computations *outside*
the black hole,
Hawking obtained
the black hole entropy

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

where A is area of the
black hole horizon.

All other systems have
entropy proportional to
their volume.

Quantum Entanglement across a black hole horizon



Sakkmesterke/Science Photo Library RF/Getty Images

$$\tau_{\text{ring-down}} \sim \frac{\hbar}{k_B T}$$

Planckian dynamics of
quasi-normal modes!

C.V. Vishveshwara
Nature **227**, 936 (1970)

T is the Hawking
temperature of
the black hole

Quantum Entanglement across a black hole horizon

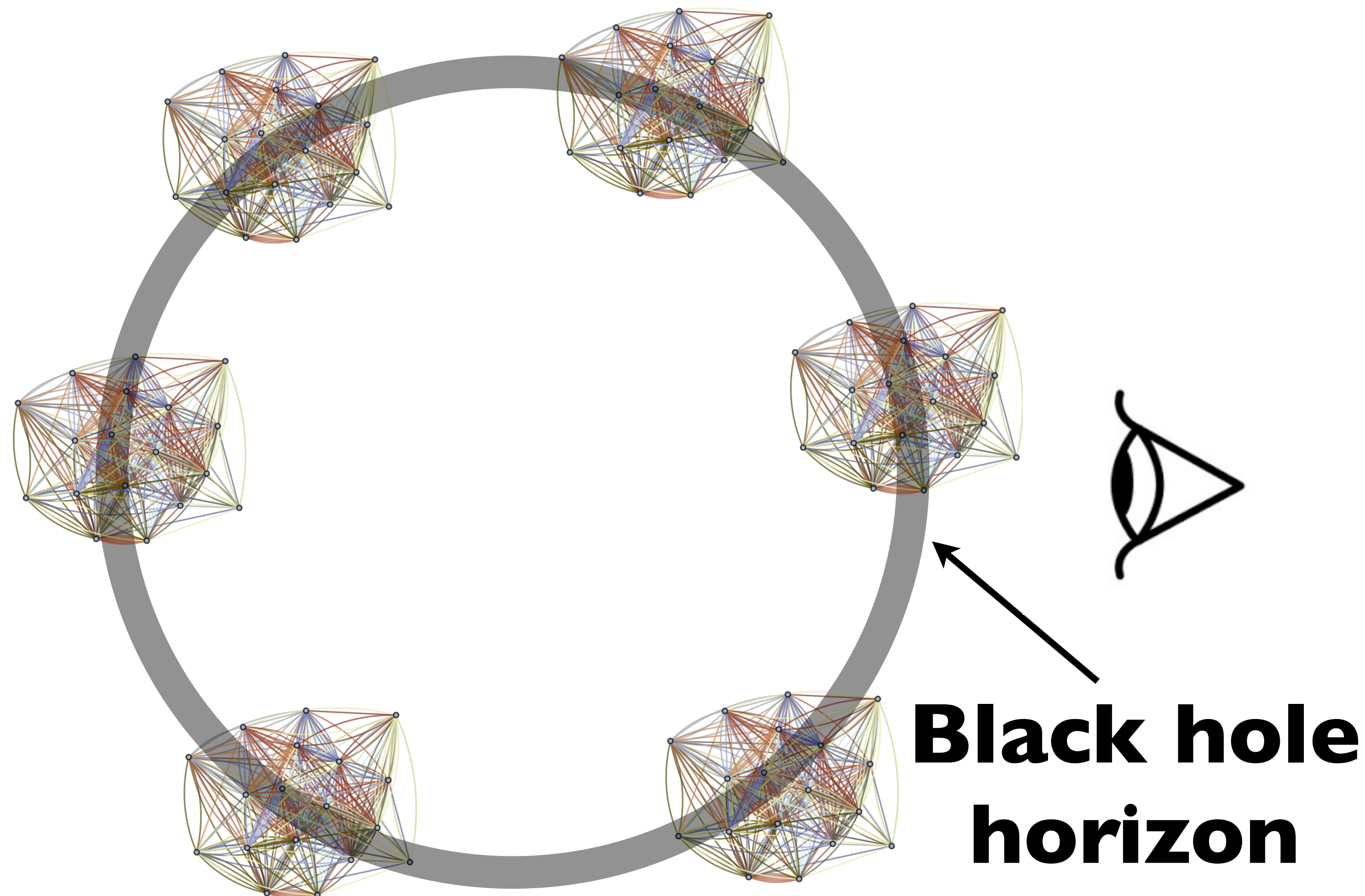
Quantum entanglement on the surface

S. Sachdev, PRL **105**, 151602 (2010)

Holographic Metals and the Fractionalized Fermi Liquid

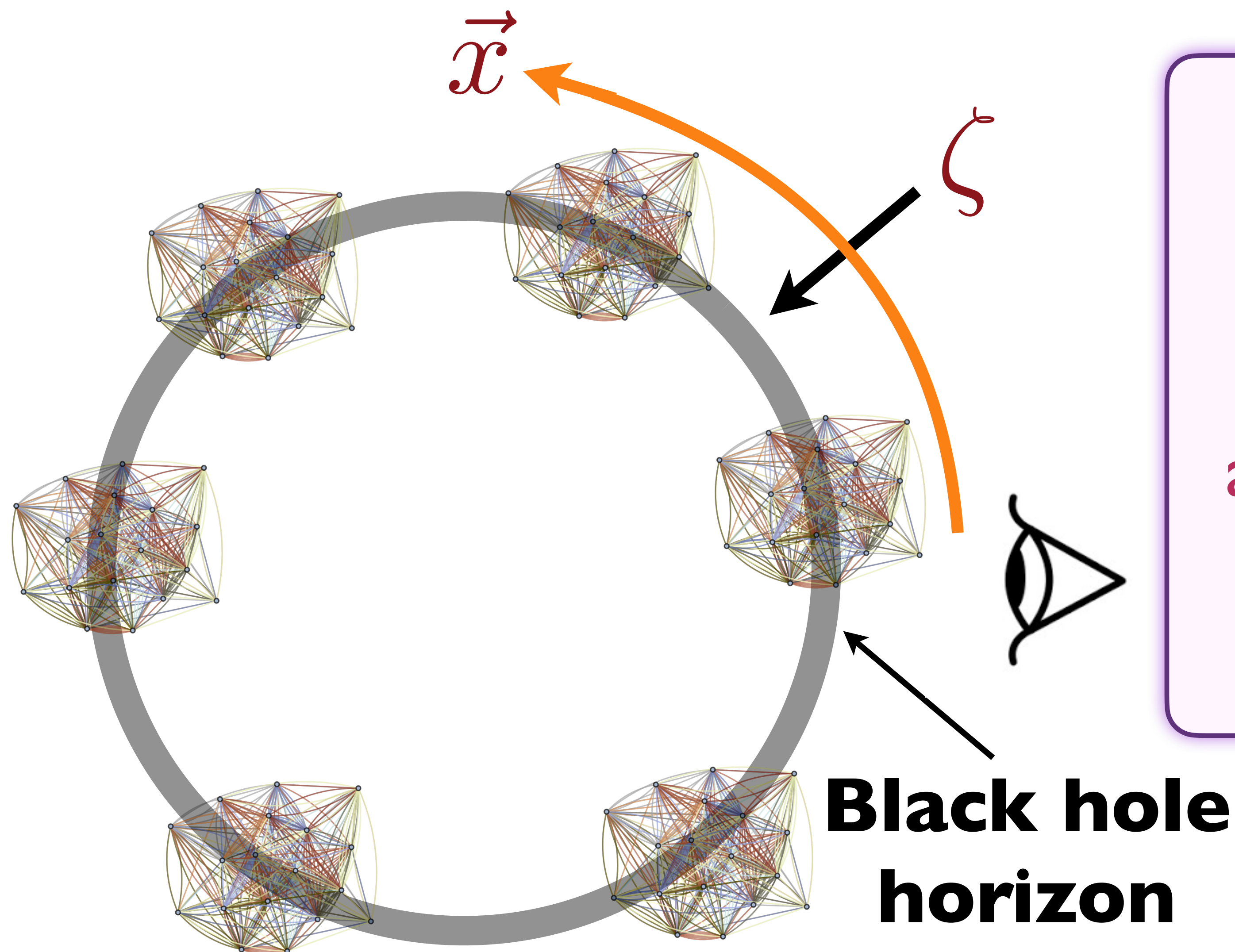
Subir Sachdev

“... This correspondence implies that certain mean-field gapless spin liquids are states of matter at nonzero density realizing the near-horizon, $AdS_2 \times R_2$ physics of Reissner- Nordström black holes.”





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



The quantum versions of
Maxwell's and Einstein's
equations in
 ζ space and time are
also the equations describing
electron entanglement
in the SYK model!

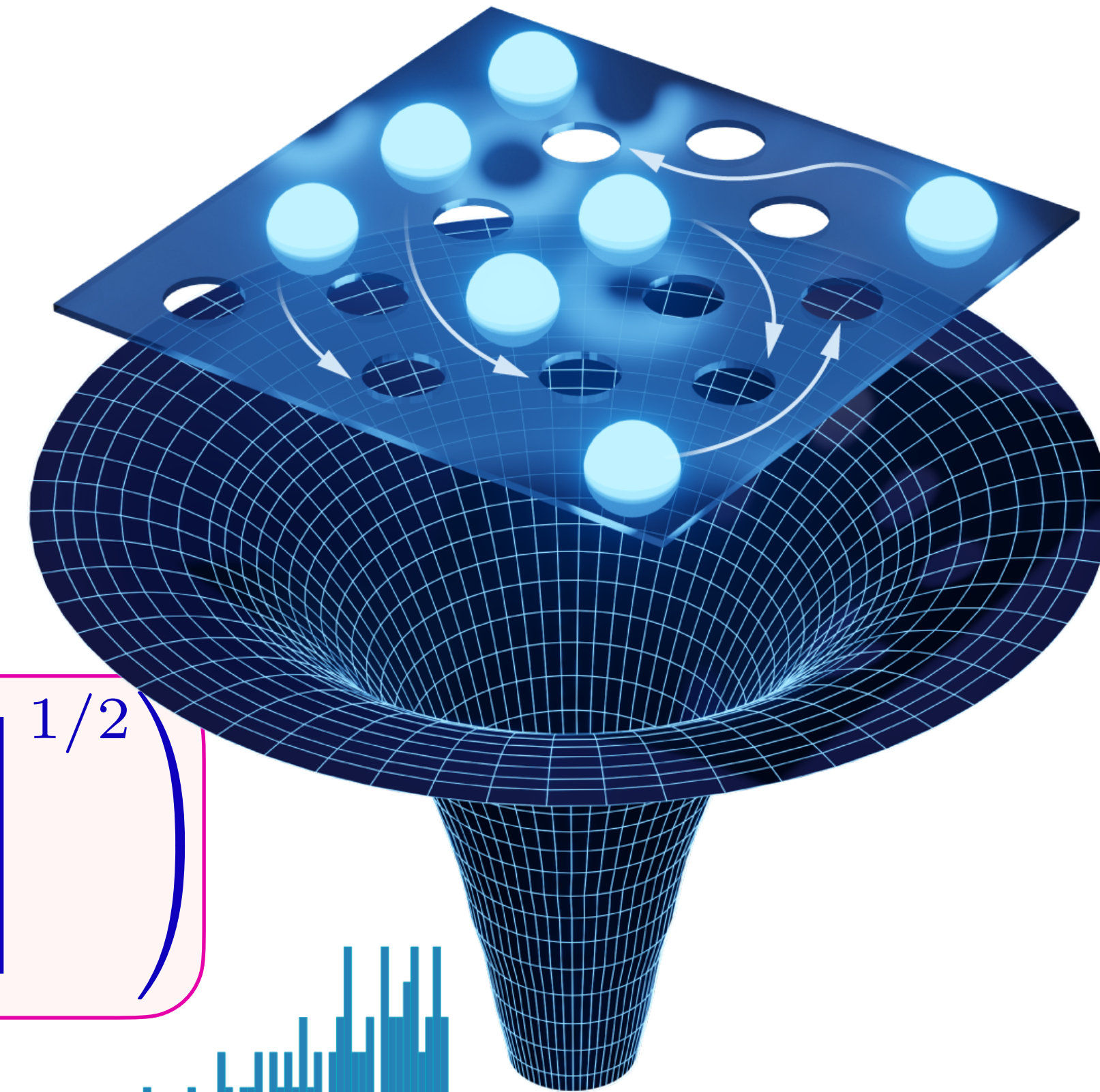
Kitaev (2015), Maldacena Stanford (2015)

D. Chowdhury, A. Georges, O. Parcollet, and S. S.,
Rev. Mod. Phys. **94**, 035004 (2022)

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

- For generic charged black holes in 3+1 dimensions with horizon area A_0 at $T = 0$ and fixed charge Q ($A_0 = 2GQ^2/c^4$), the density of quantum states at small energy E is

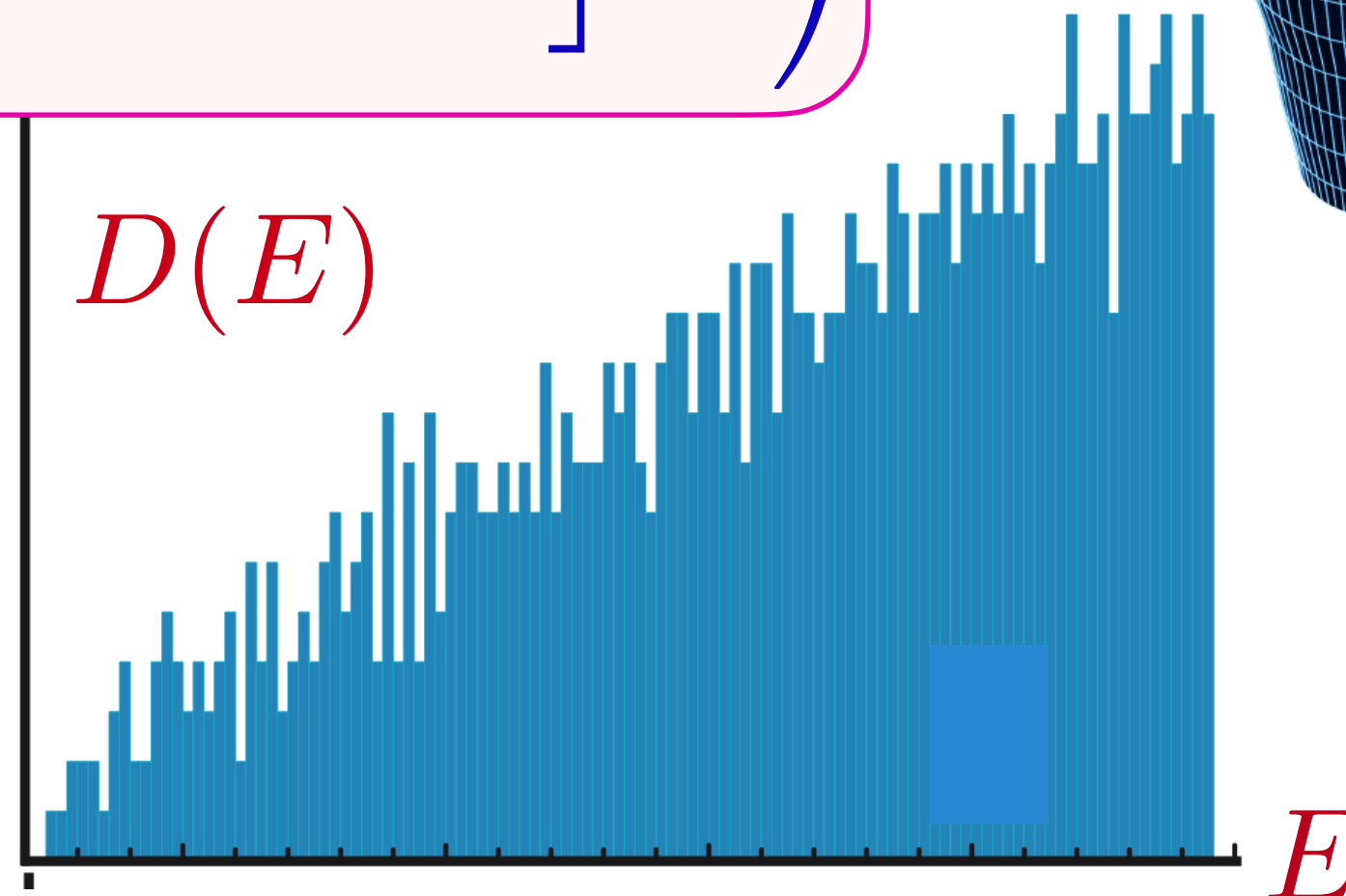
$$D(E) \sim \left(\frac{A_0 c^3}{\hbar G} \right)^{-347/90} \exp \left(\frac{A_0 c^3}{4\hbar G} \right) \sinh \left(\left[\frac{\sqrt{\pi} A_0^{3/2} c^2}{\hbar^2 G} E \right]^{1/2} \right)$$



Bekenstein-Hawking

Iliesiu, Murthy, Turiaci (2022)

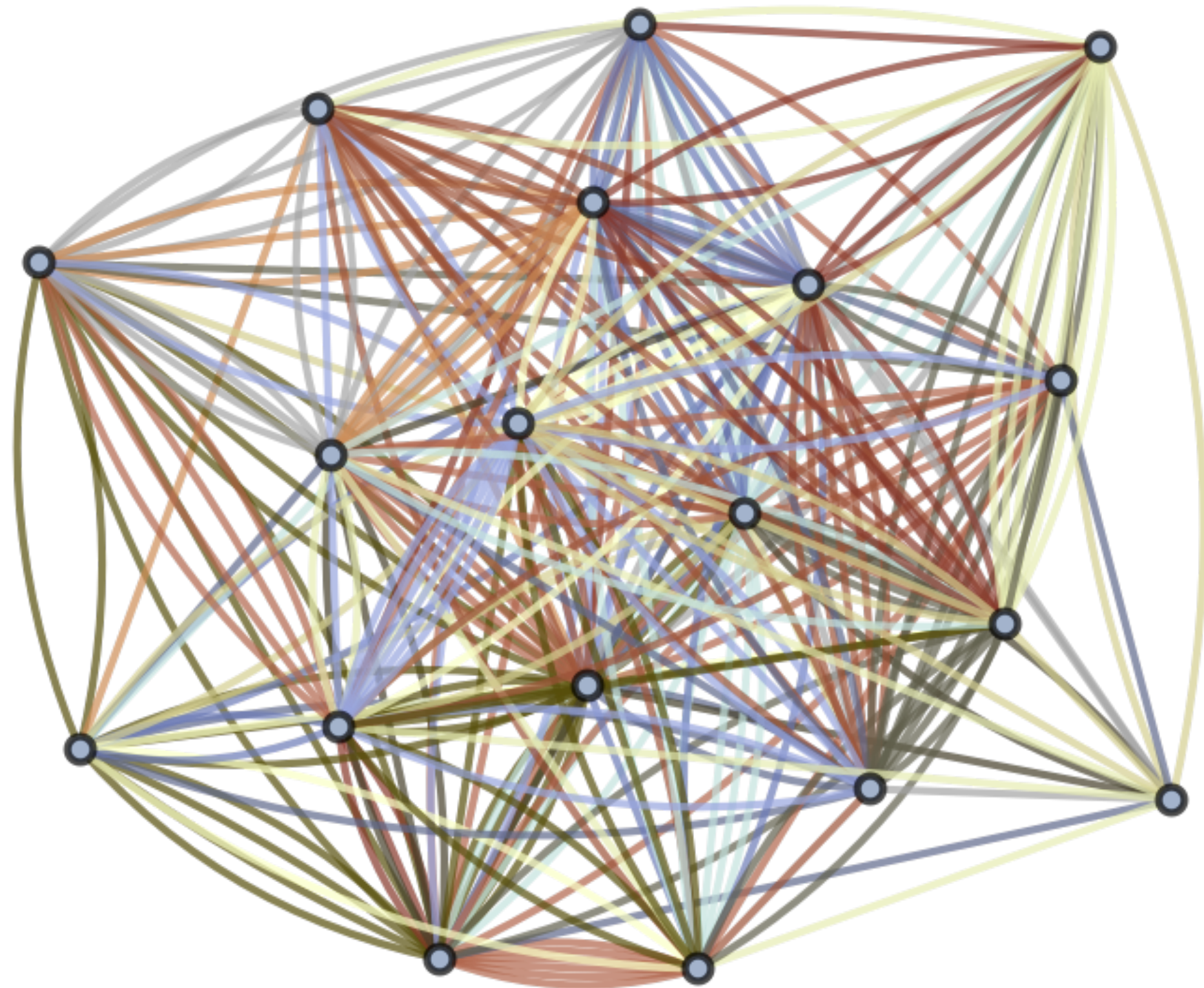
Developments from the SYK model



Similar remarks apply to rotating neutral black holes.

The Sachdev-Ye-Kitaev (SYK) model

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

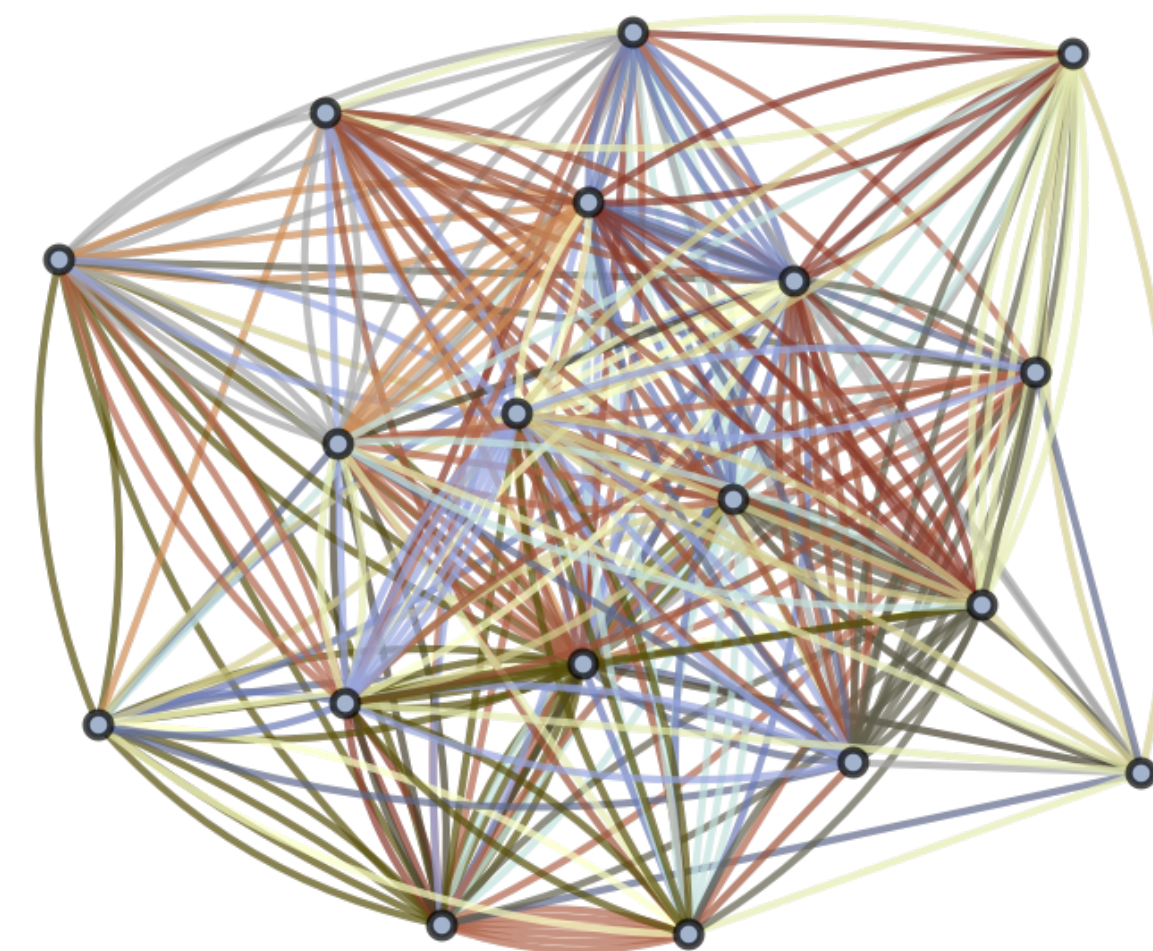
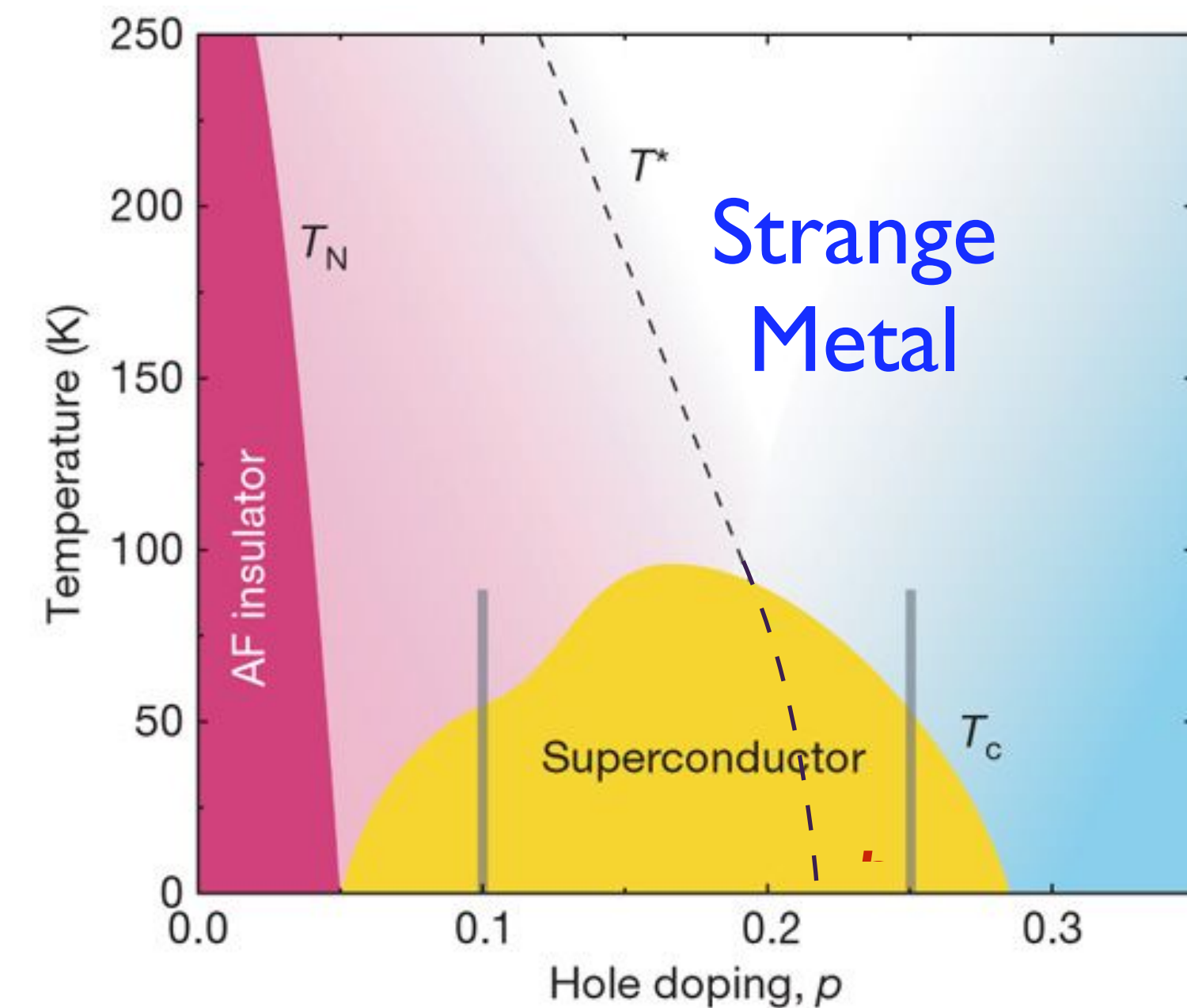


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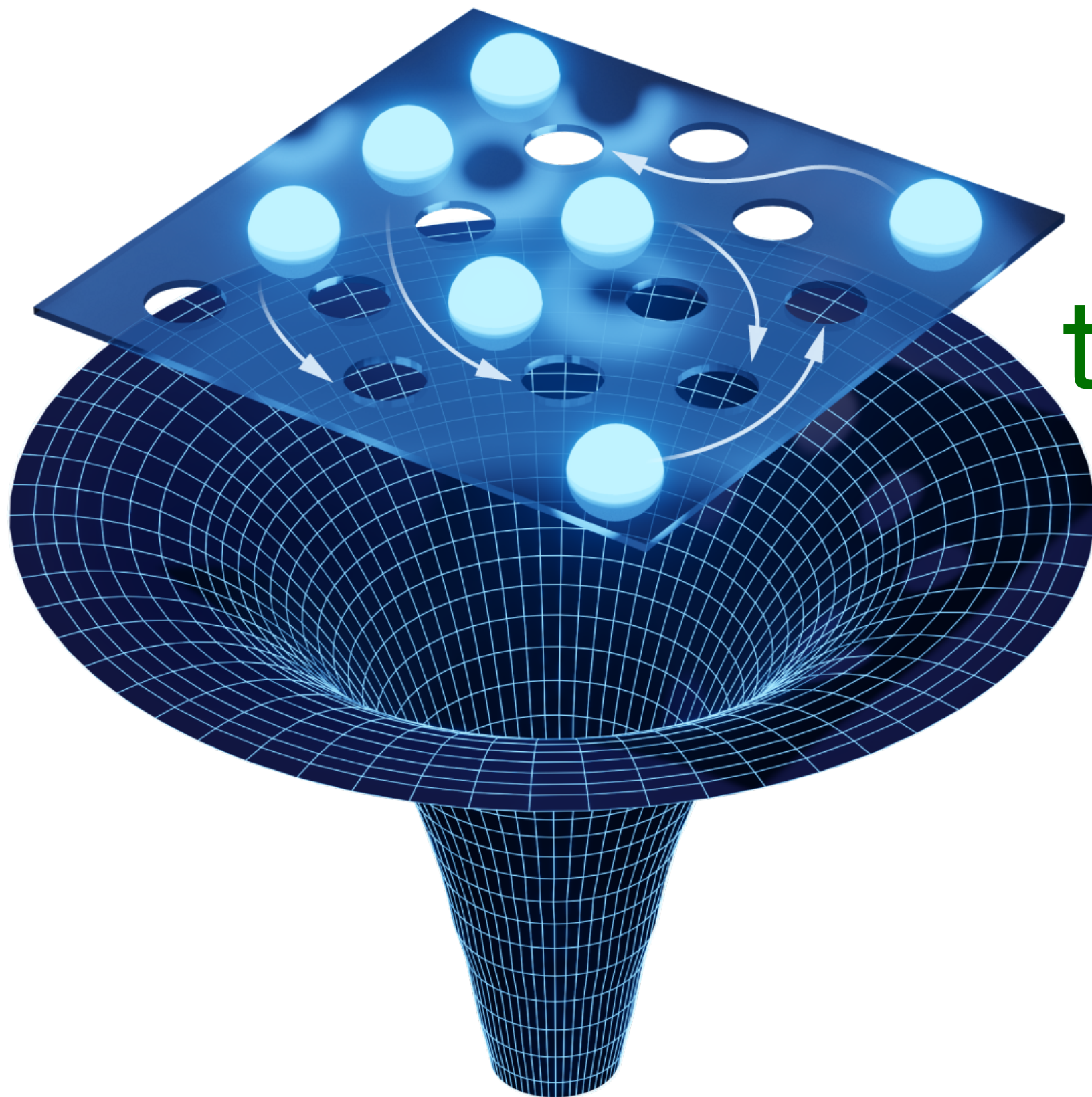
In one set of variables, it helps describe the *strange* electrical properties of YBCO

Sachdev, Ye (1993)



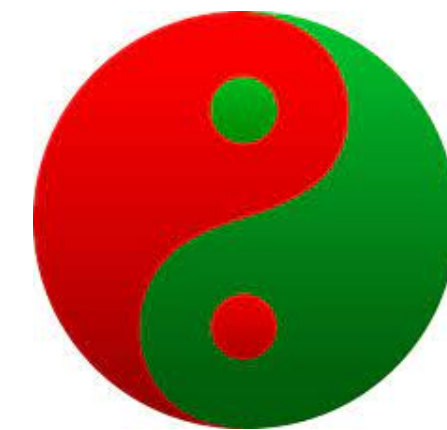
The Sachdev-Ye-Kitaev (SYK) model

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



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)