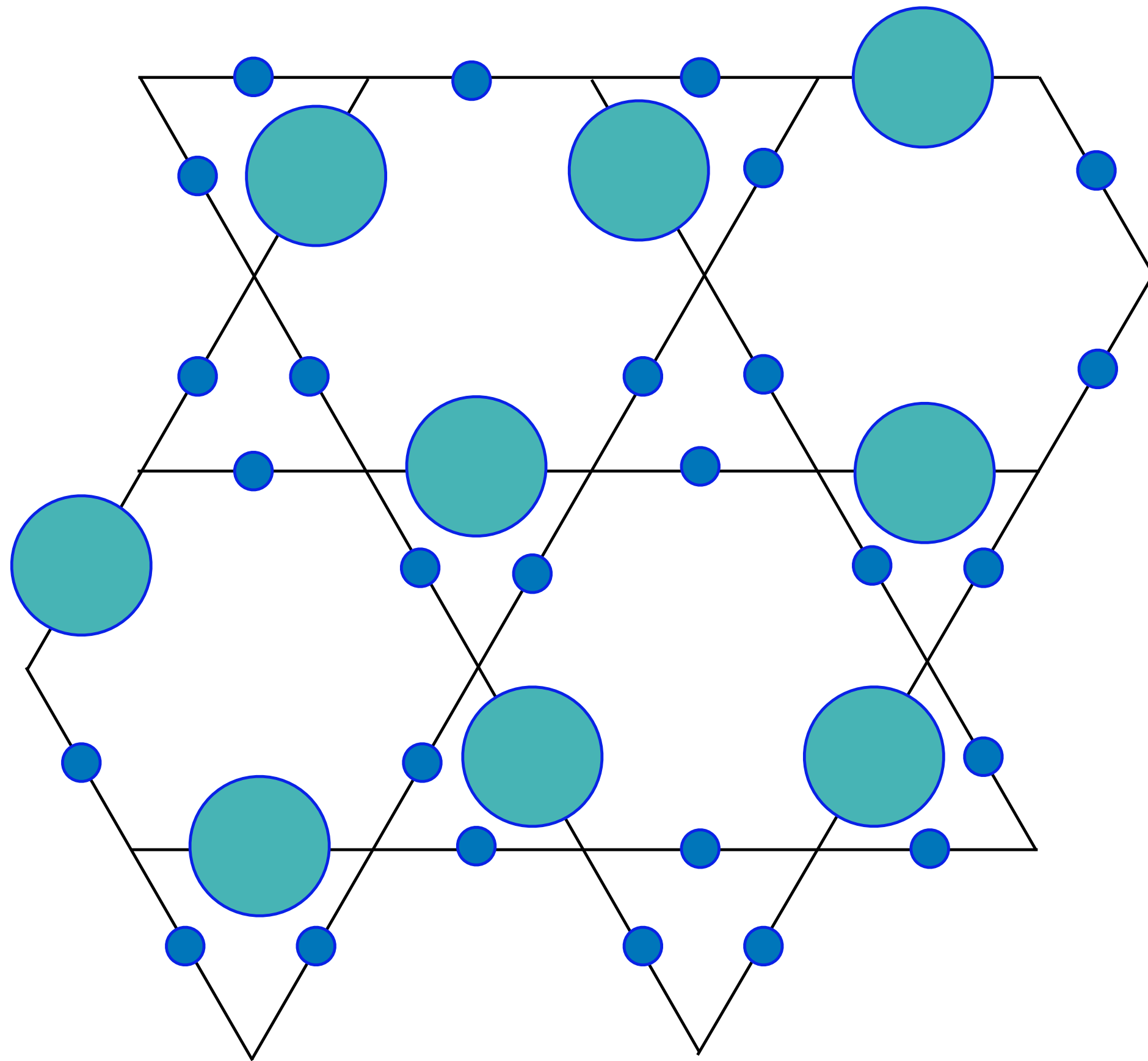


100 years of many-particle quantum mechanics: from Bose and Fermi to quantum materials and devices.



HUN-REN Wigner
Research Centre for Physics
Budapest
October 7, 2025

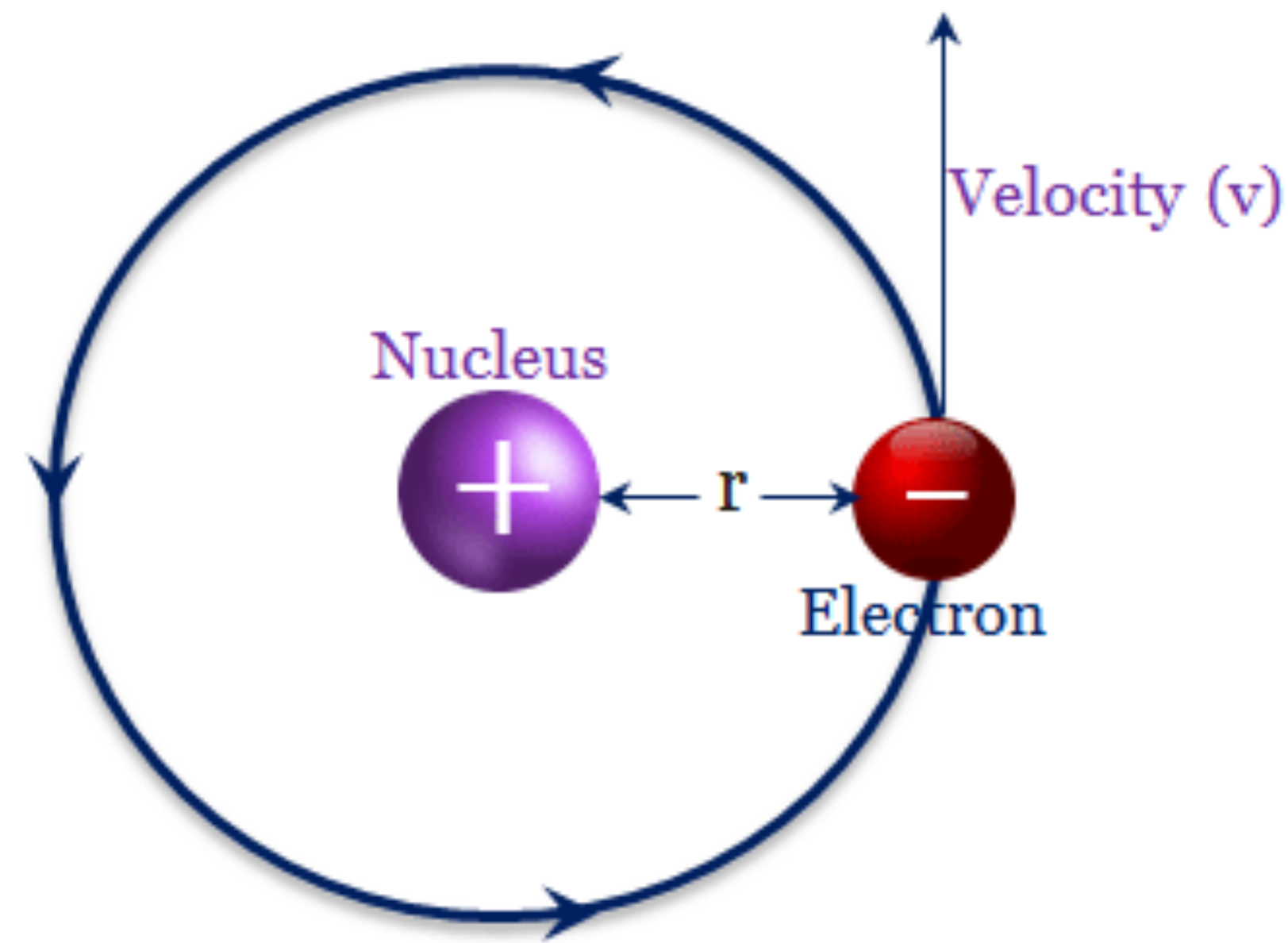
Subir Sachdev



HARVARD

Quantum mechanics
to
quantum materials:
the first 100 years

Hydrogen atom

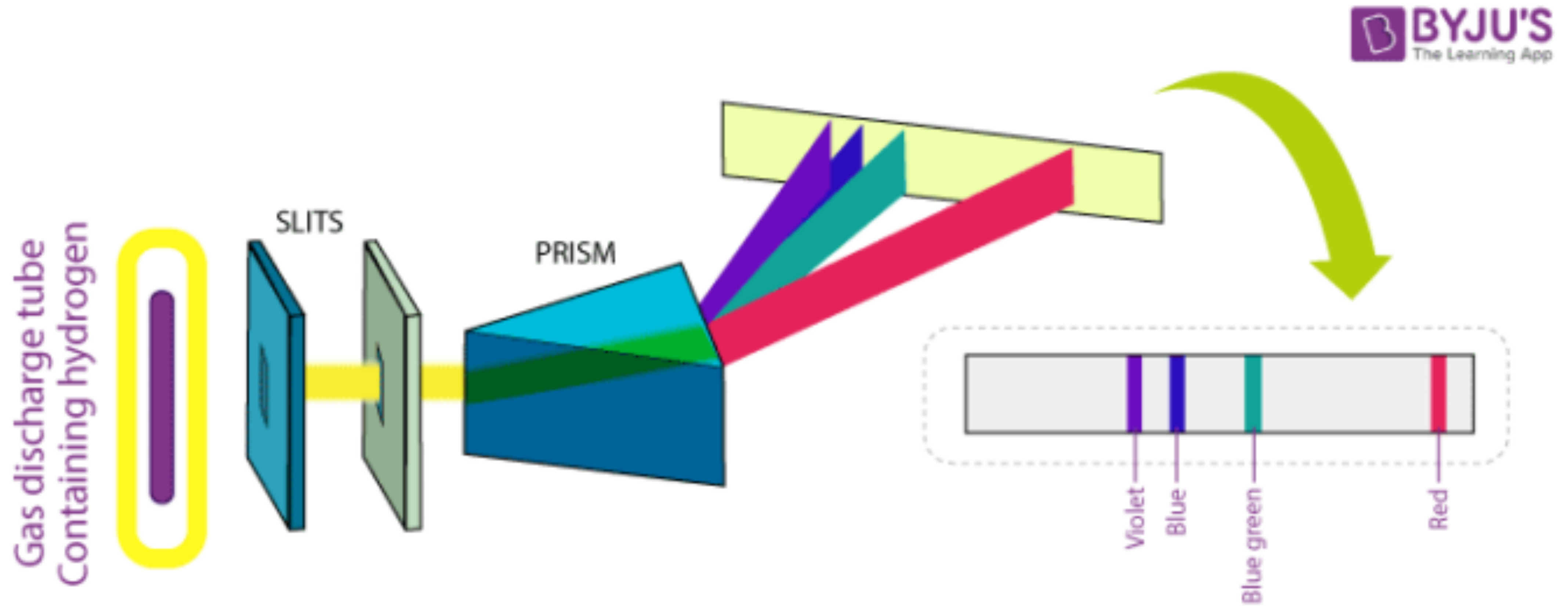


$\Rightarrow 10^{-10}$ meters $\Leftarrow$

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

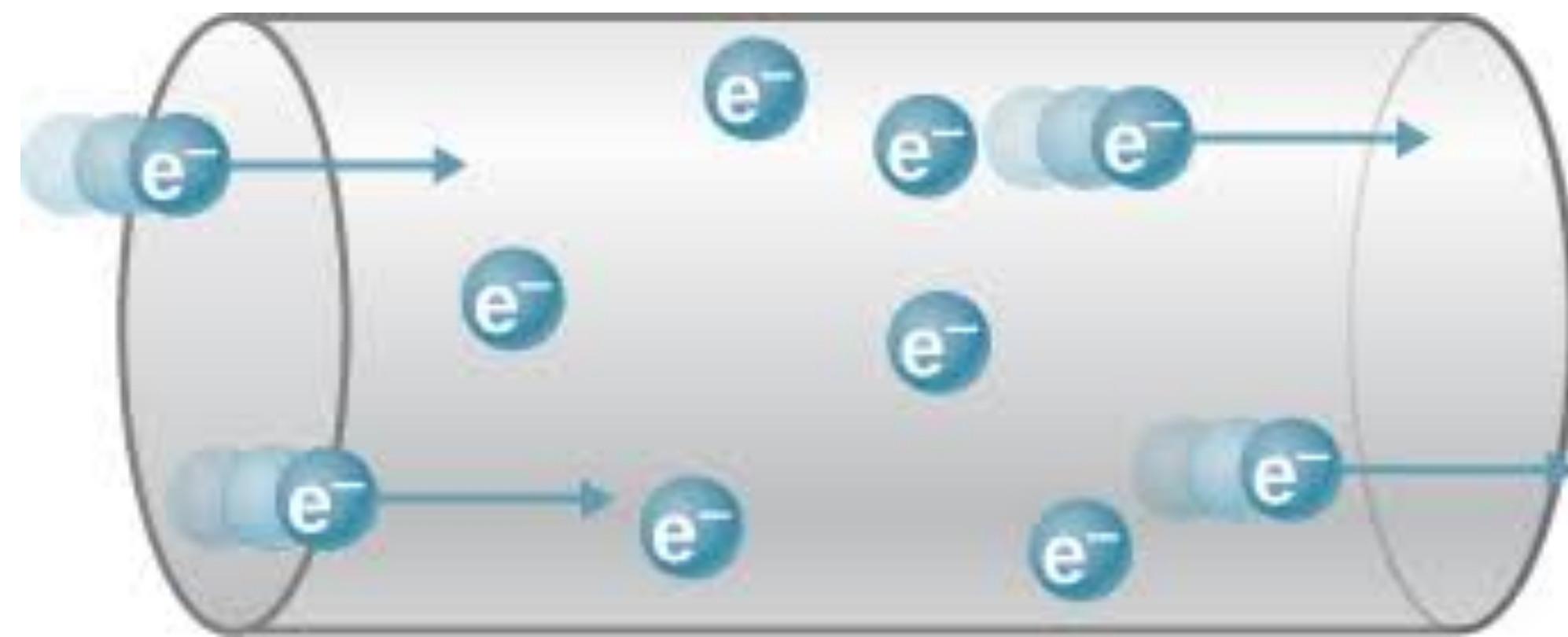
It is described by the quantum theory of Schrödinger and Heisenberg (1925).

- 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): Pairs of electrons behave like **bosons**, and this is the explanation for superconductivity.

- Today: Many particles exhibit many *emergent phenomena*, related to **quantum entanglement**. These are crucial to understanding modern quantum materials, such as the high temperature superconductors.

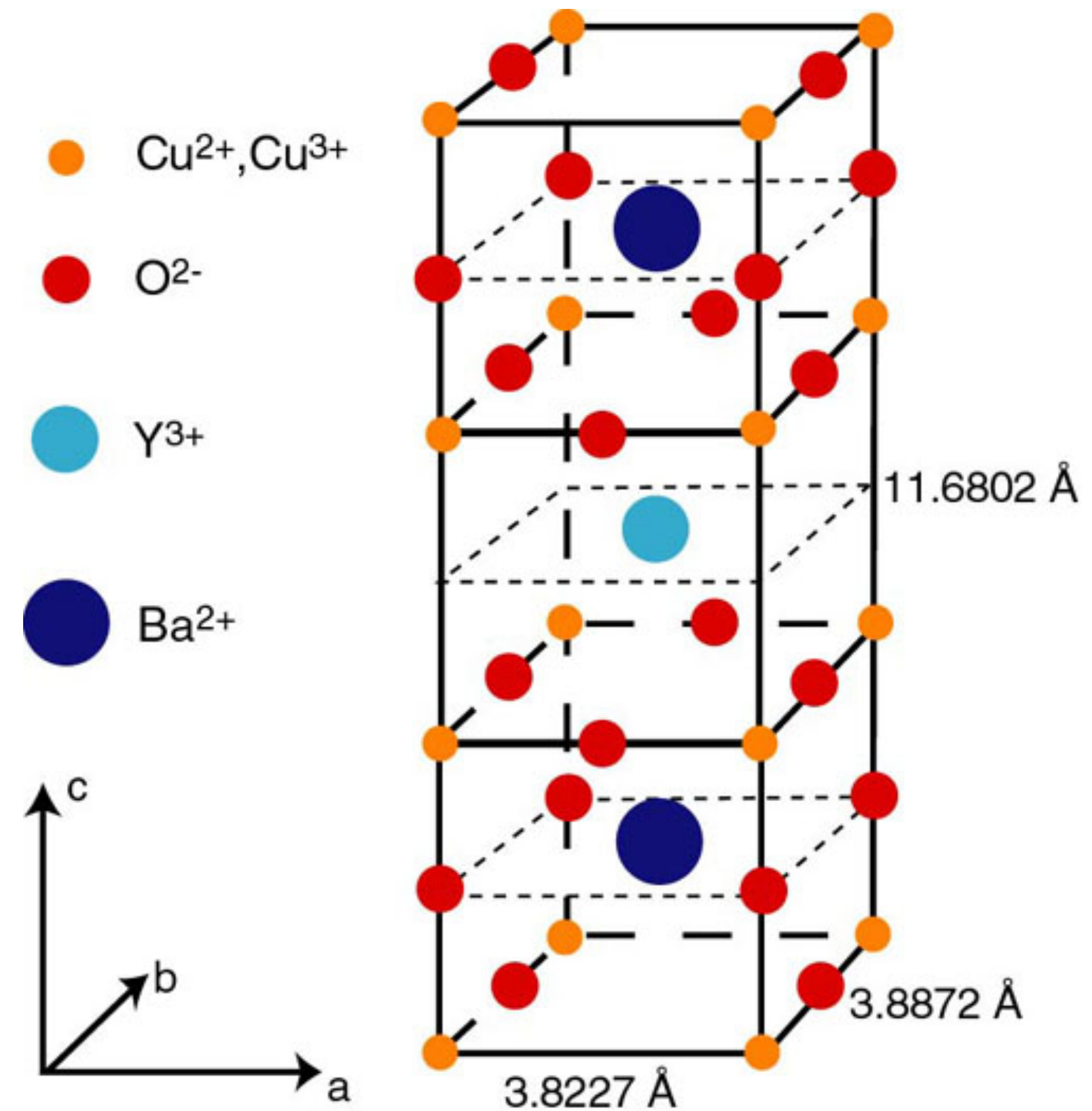
- Today: Many particles exhibit many *emergent phenomena*, related to **quantum entanglement**. These are crucial to understanding modern quantum materials, such as the high temperature superconductors.
- Ideas on multi-particle entanglement in quantum materials have strongly influenced quantum computing, especially quantum error correction (and vice versa).

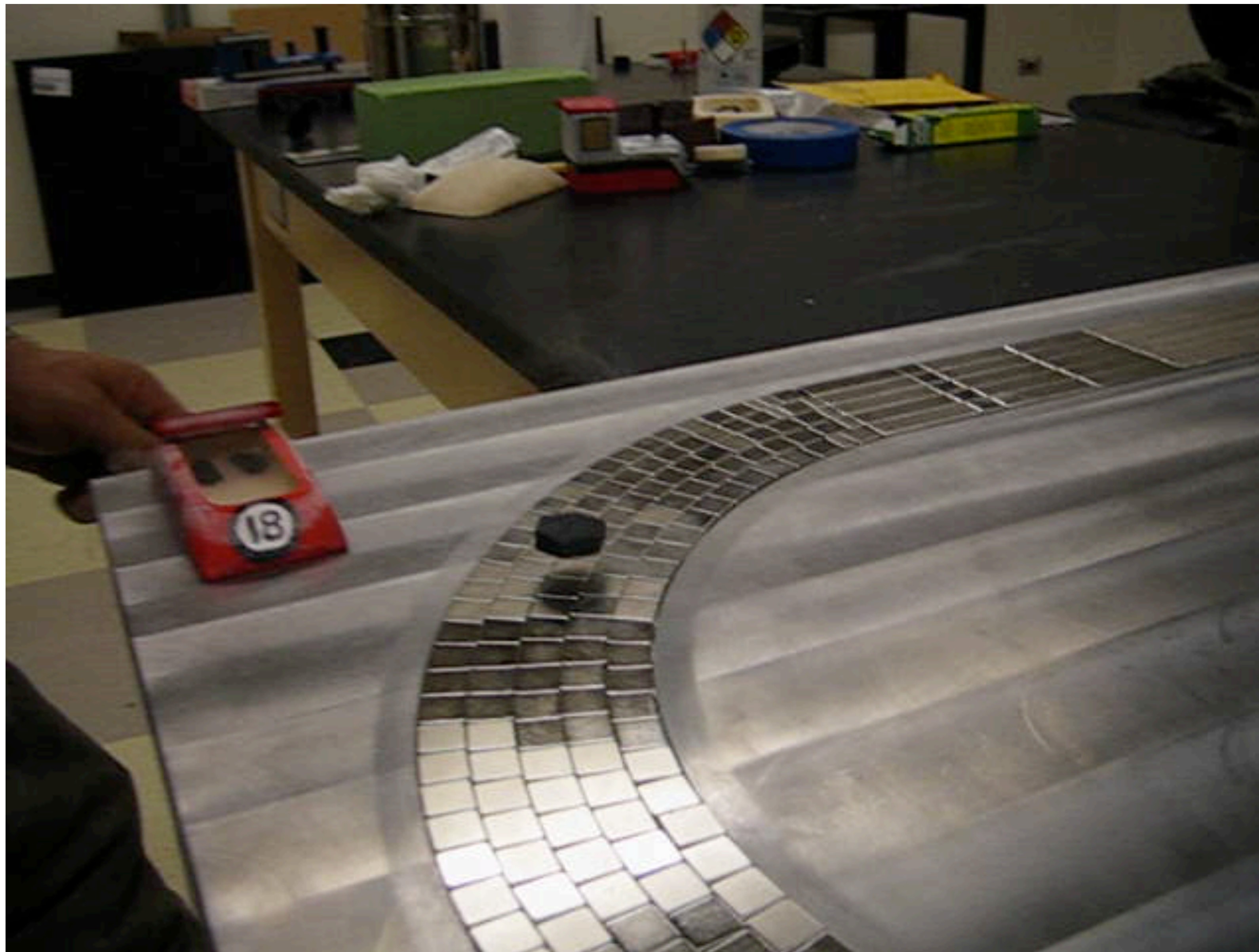
Superconductors



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

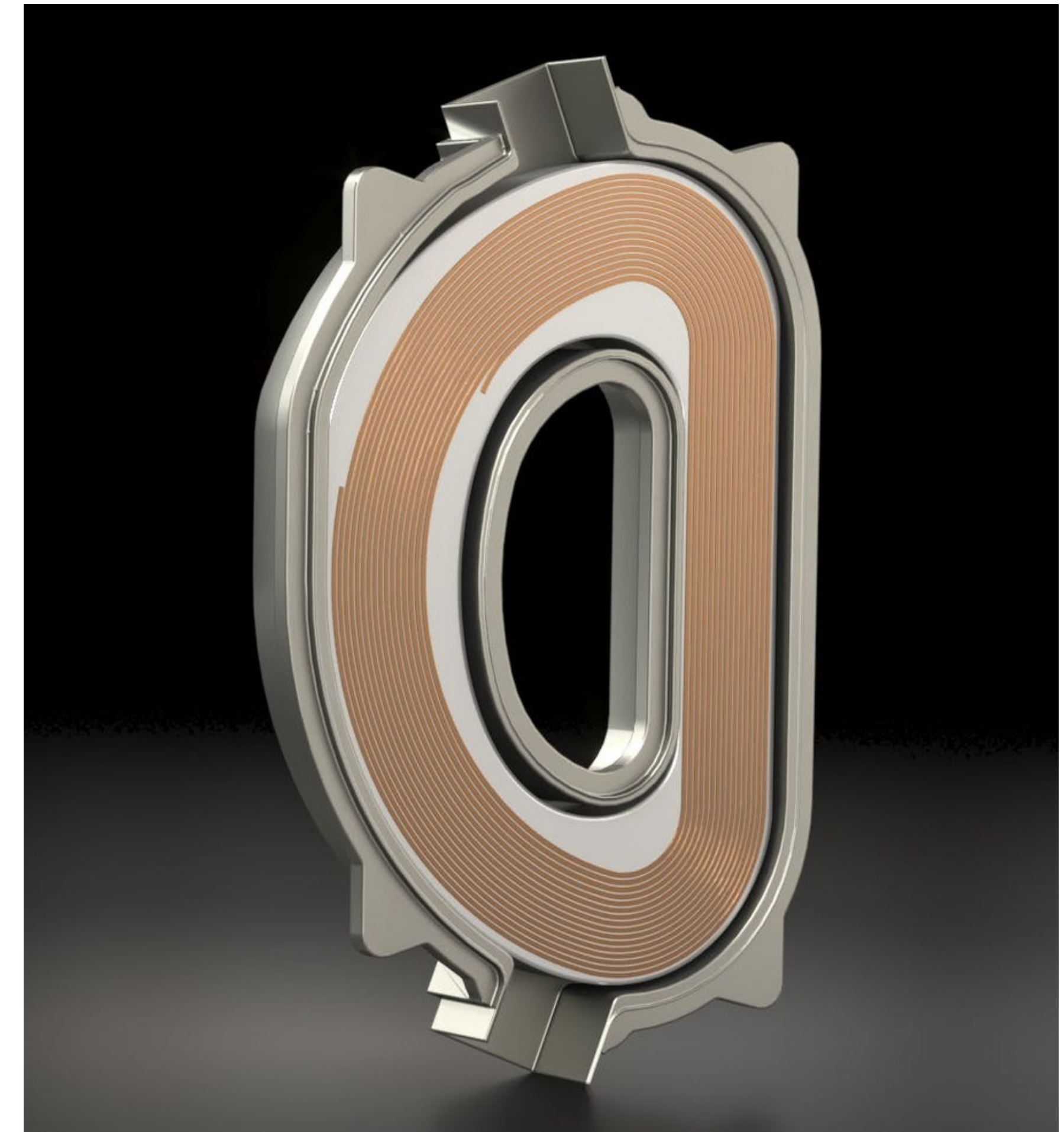
HTS Magnets: Enabling Technology

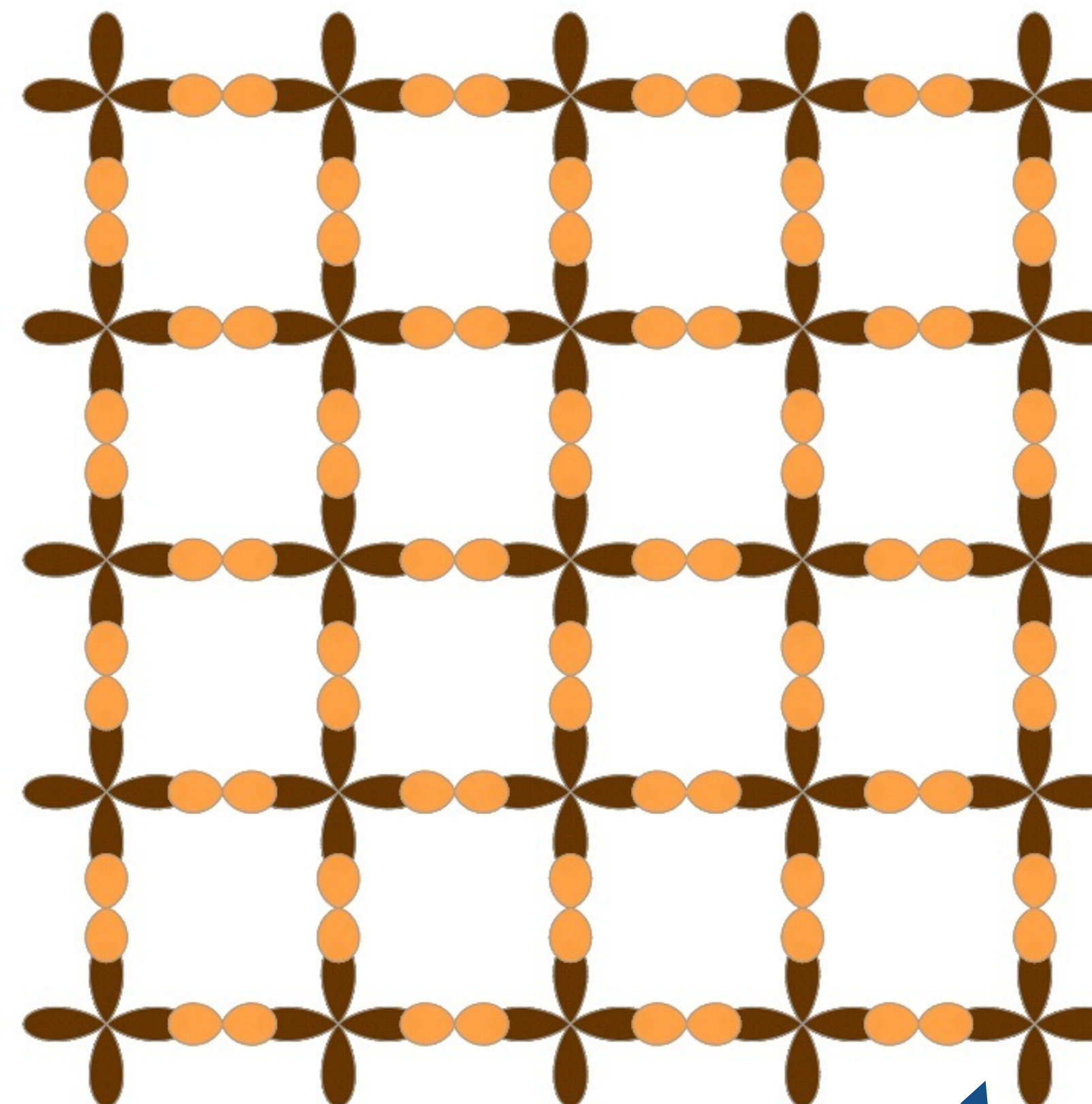
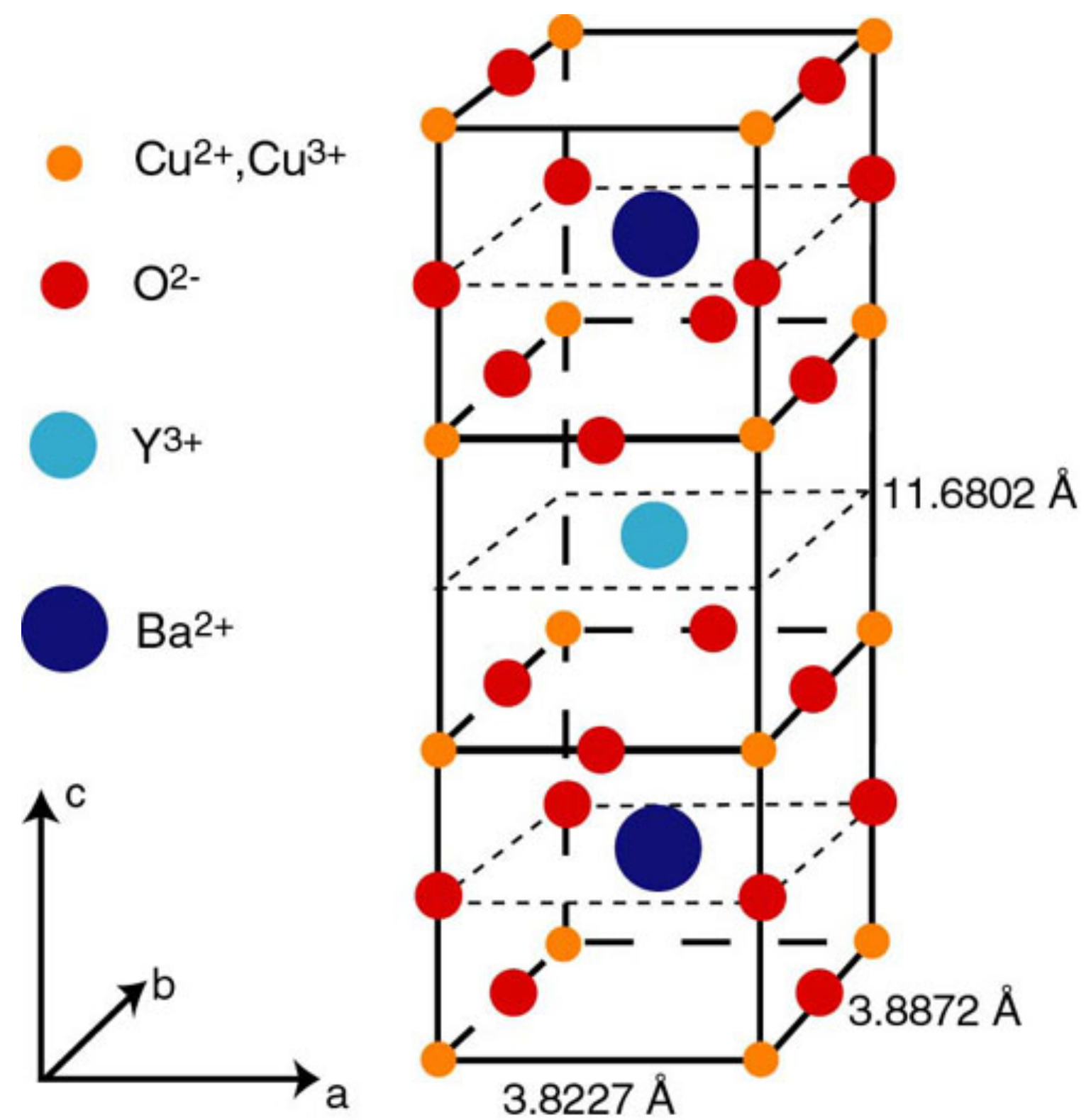
The surest path to limitless,
clean, fusion energy

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

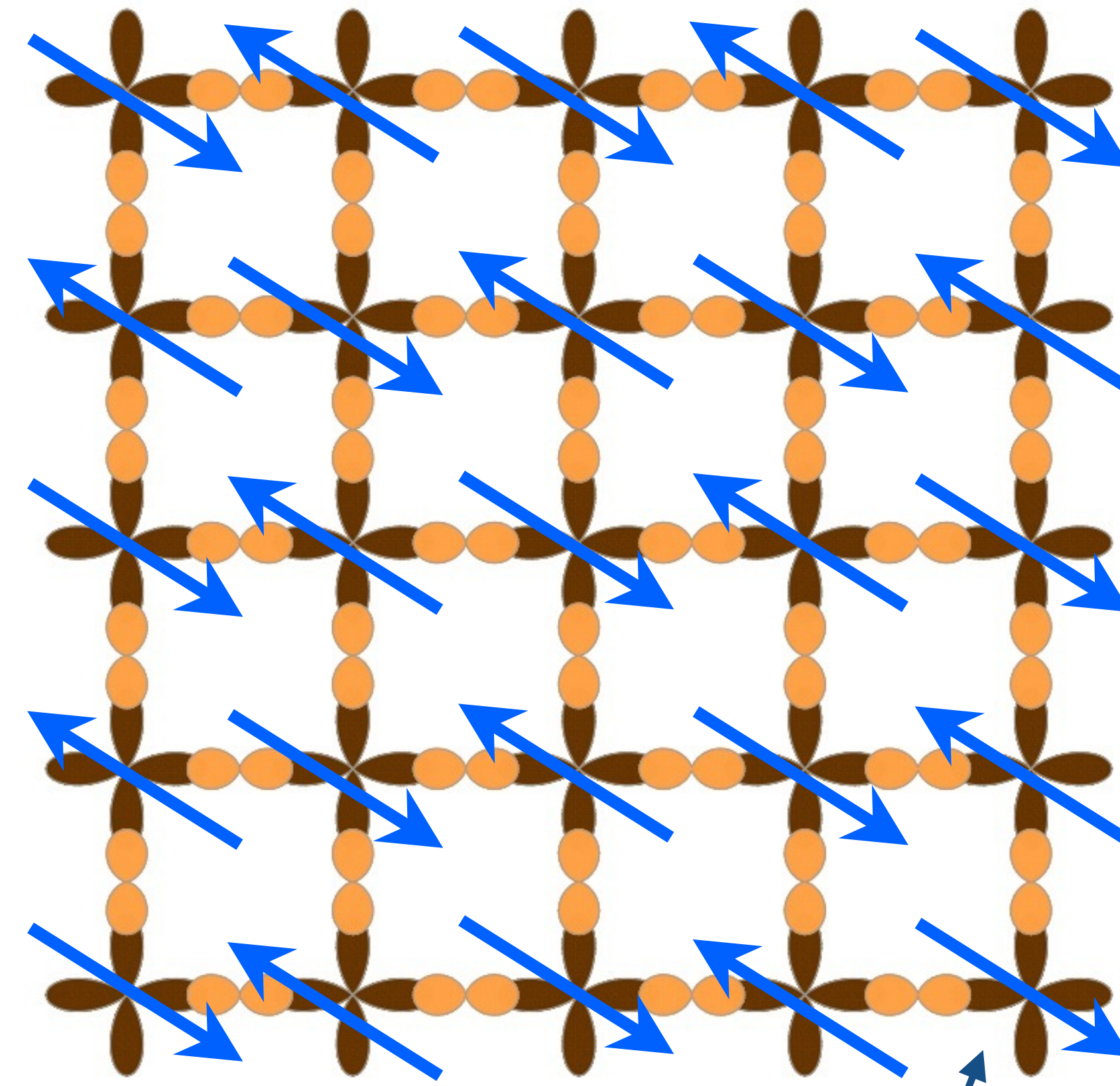
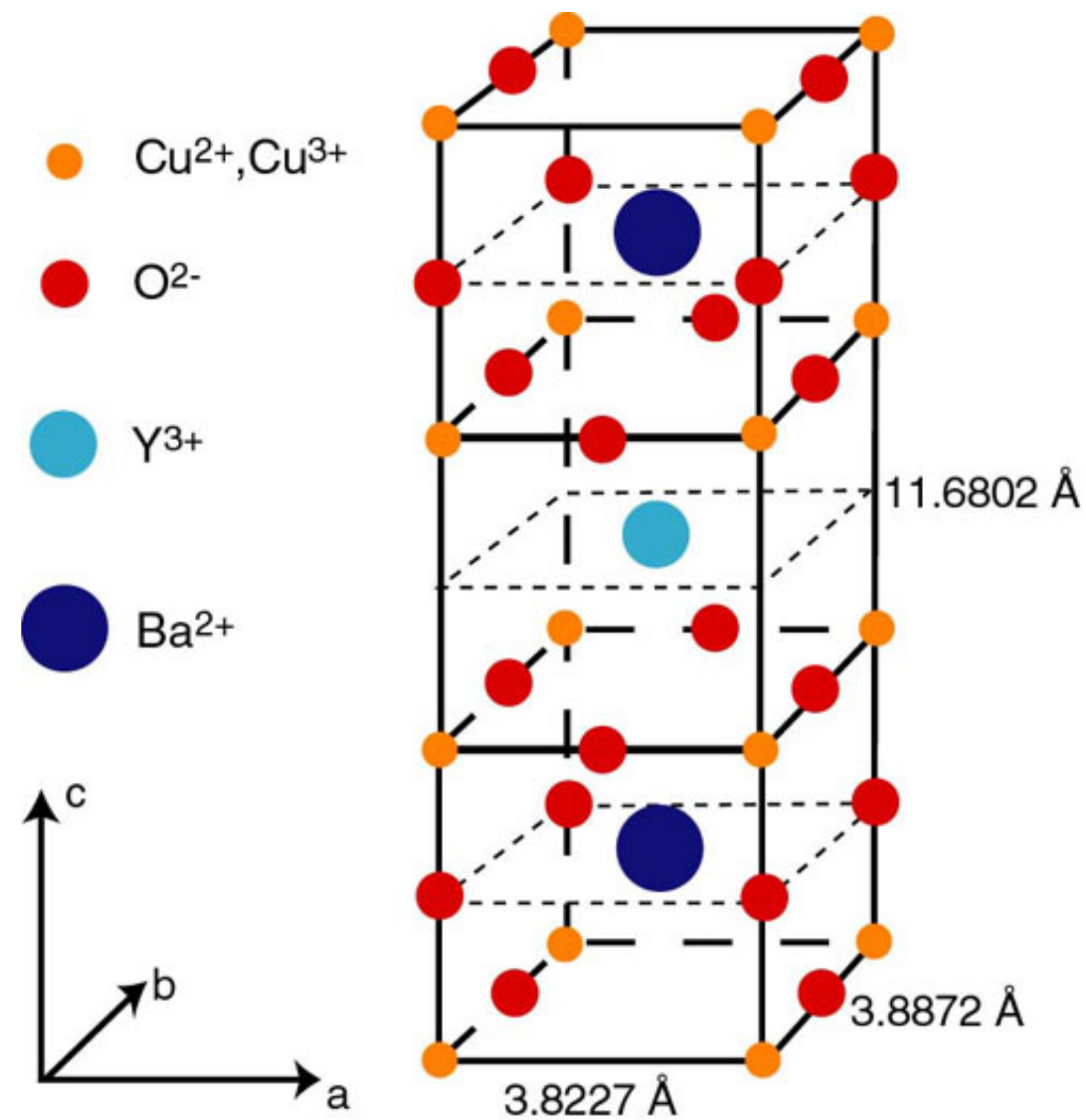


Commonwealth
Fusion Systems





Cu



Cu

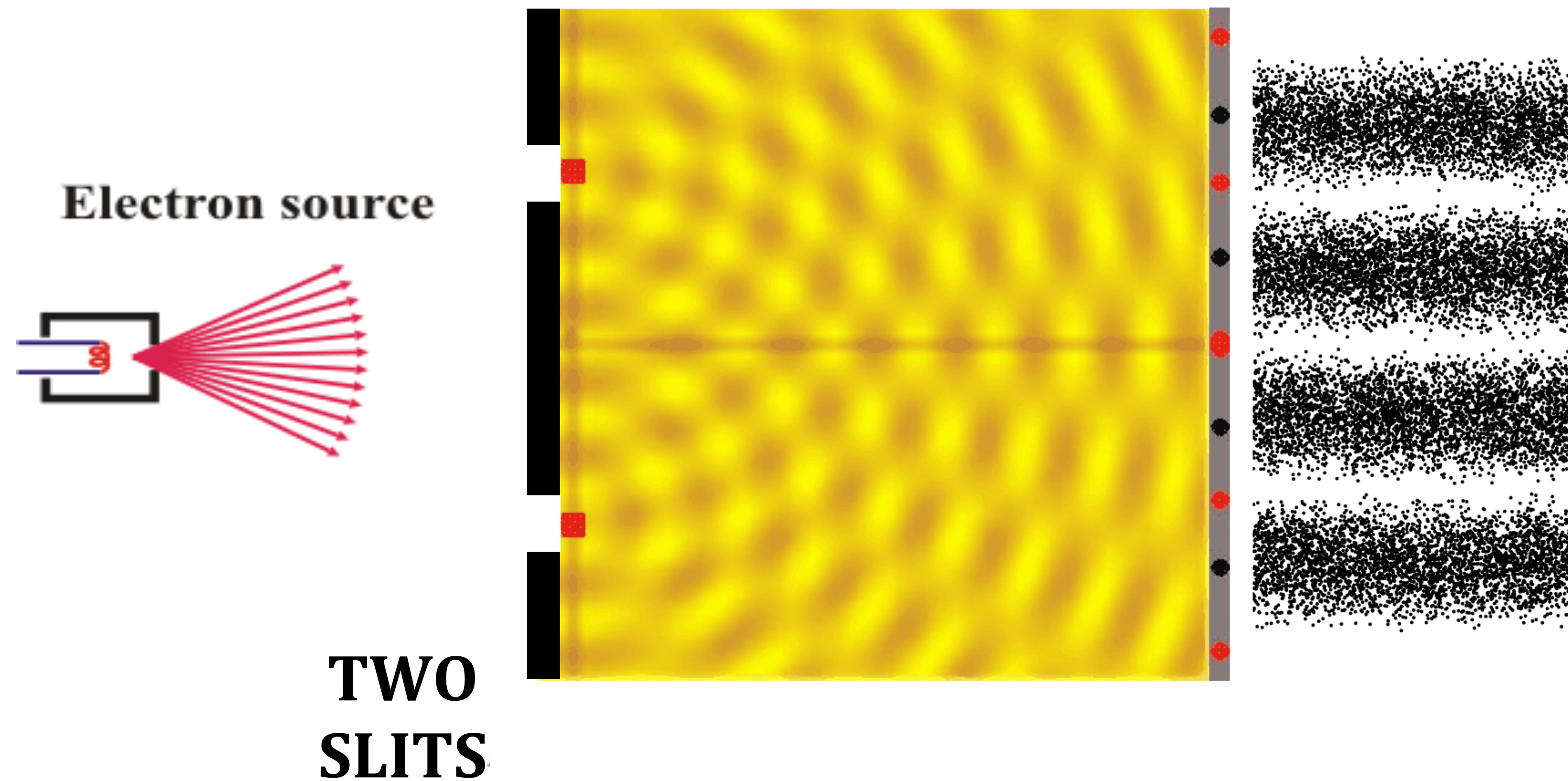


P.W.Anderson and G. Baskaran (1988): The key to high temperature superconductivity is the formation of a “resonating valence bond state”
 (a type of **quantum spin liquid**) which entangles the electrons on Cu

Quantum entanglement

Principles of Quantum Mechanics: I. Quantum Superposition

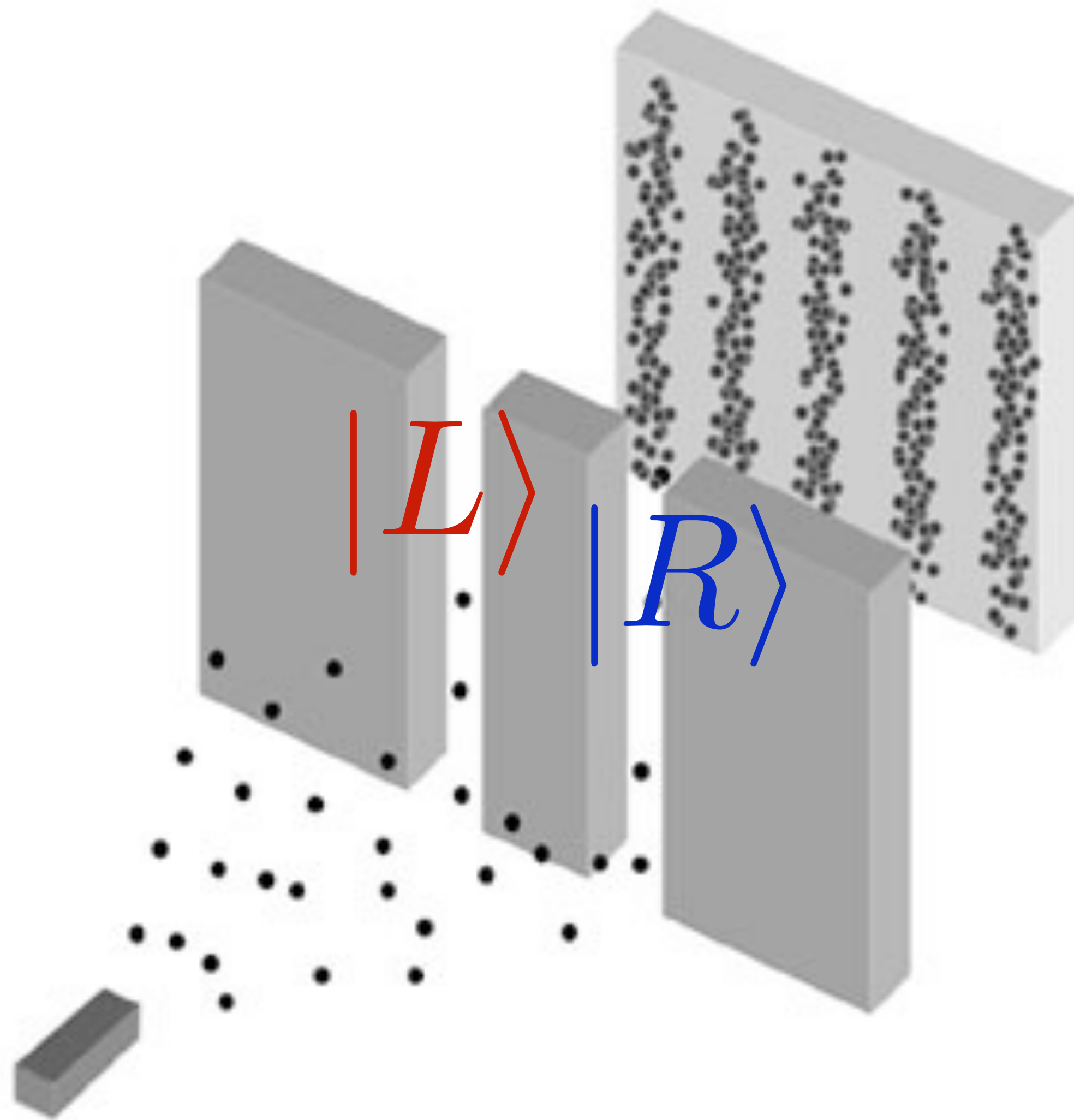
The double slit experiment



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
 $|L\rangle + |R\rangle$

MAY 15, 1935

PHYSICAL REVIEW

VOLUME 47

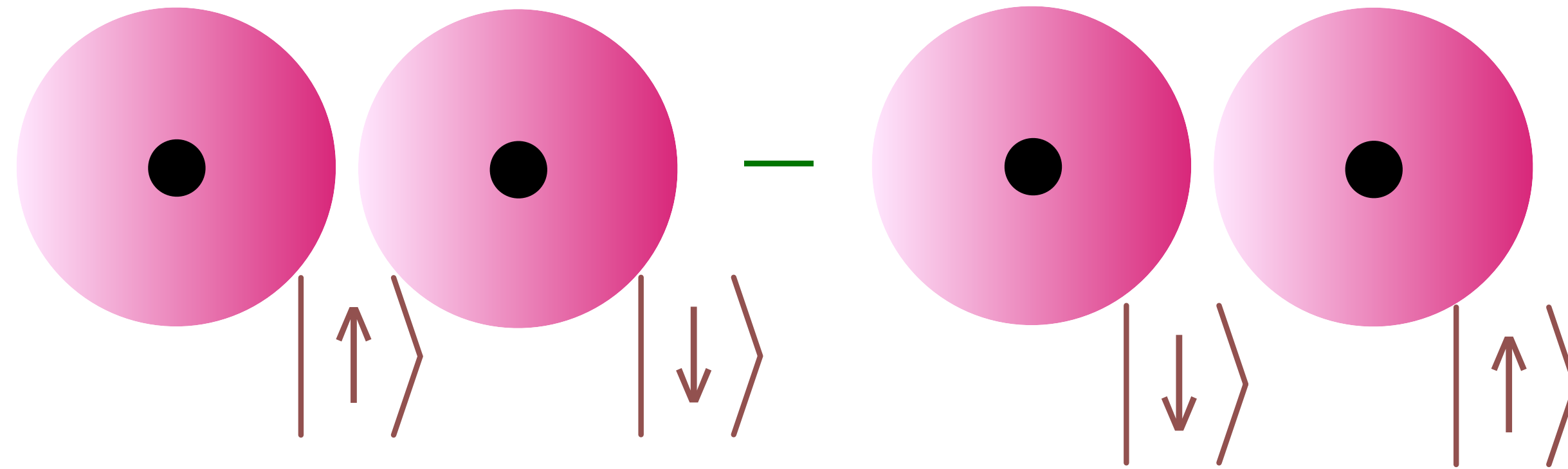
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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

(Received March 25, 1935)

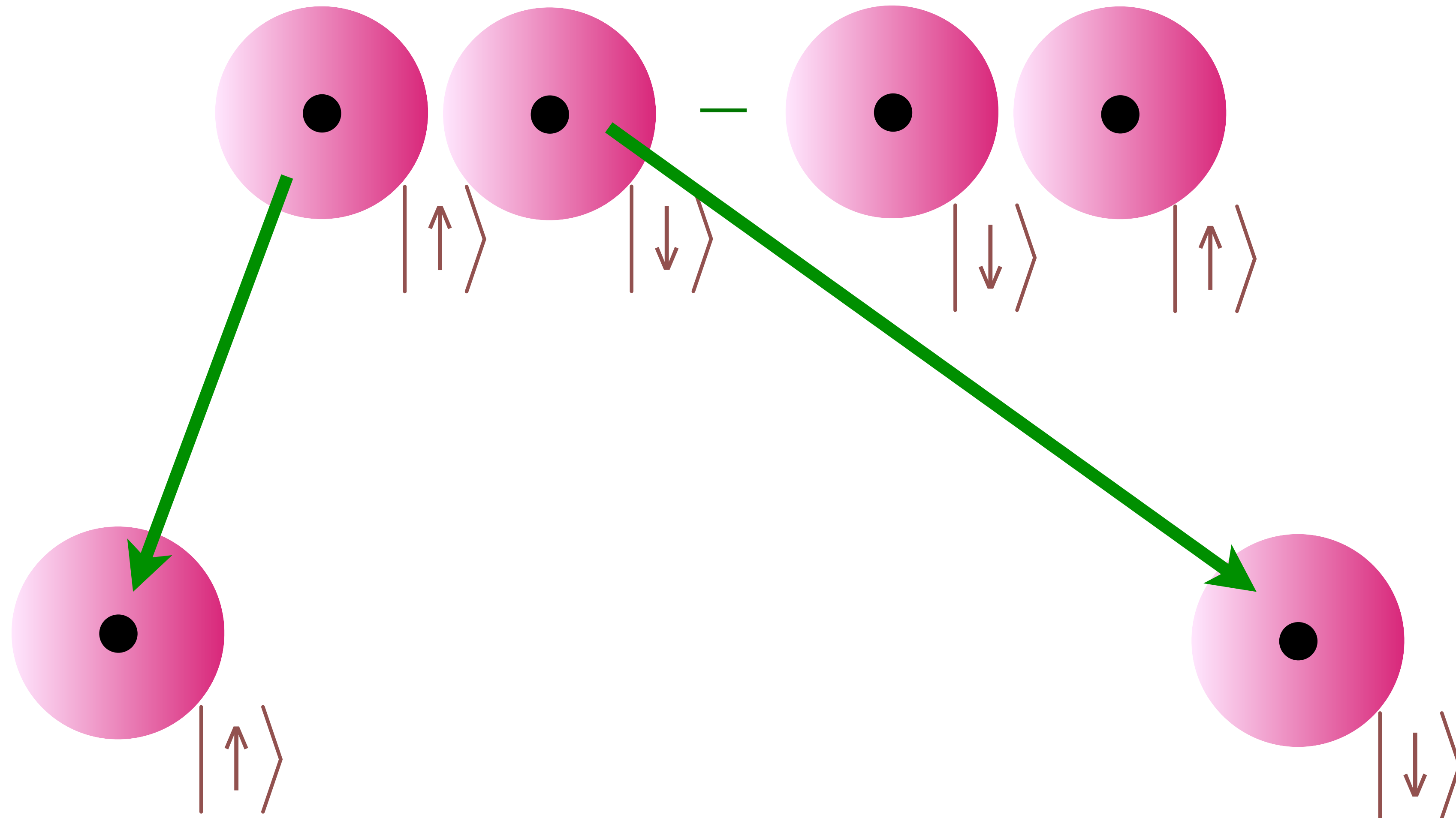
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



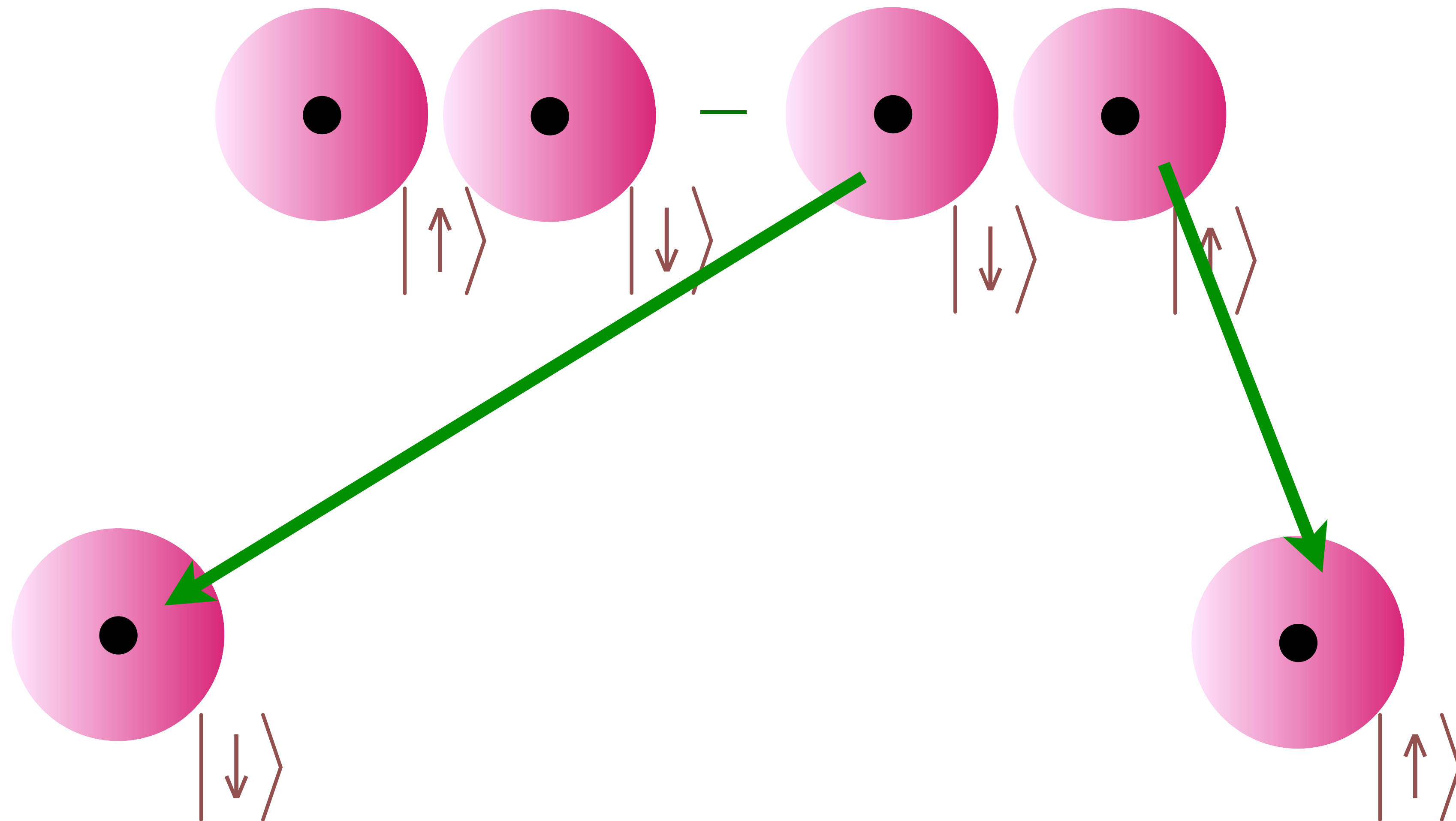
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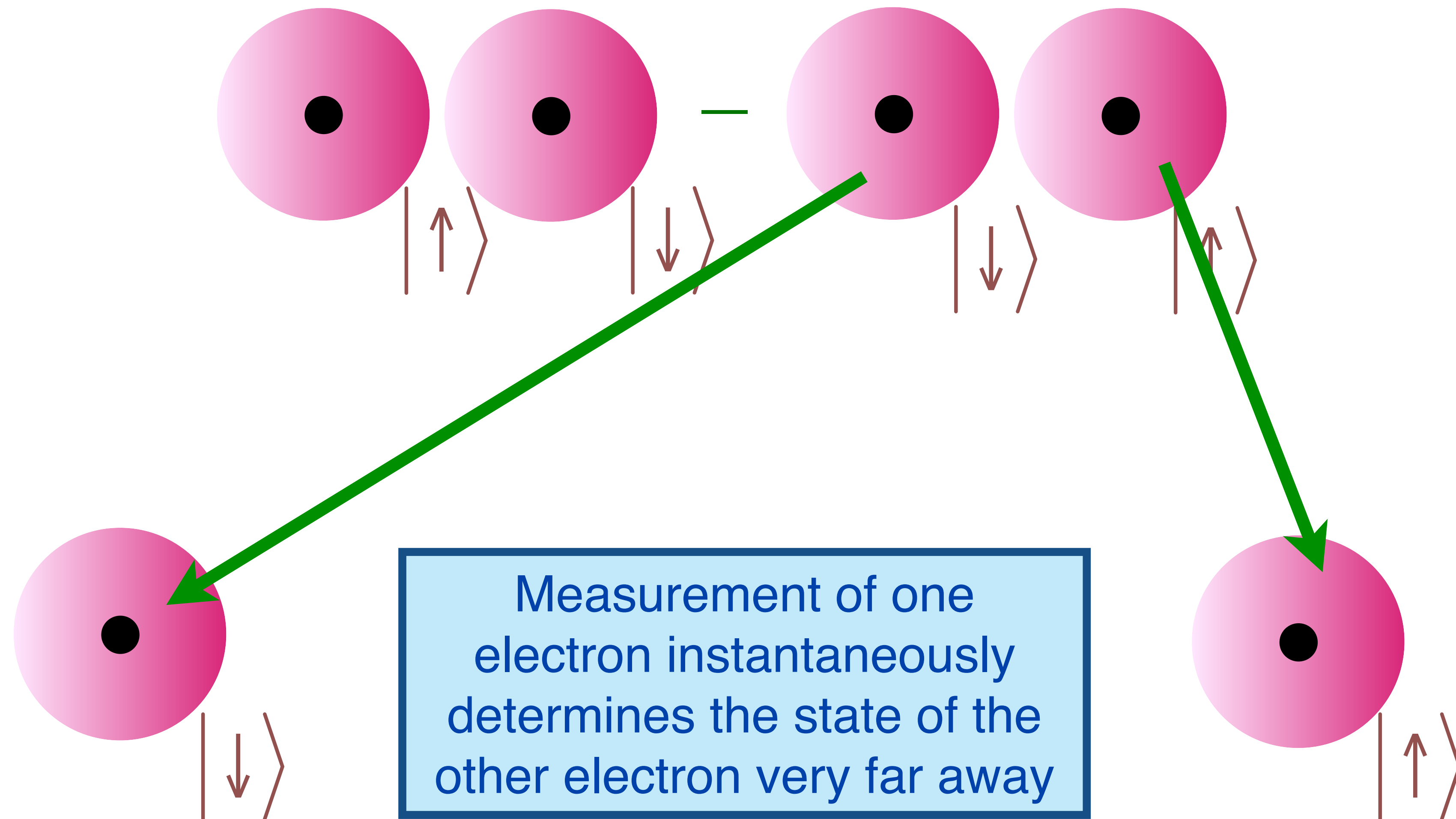
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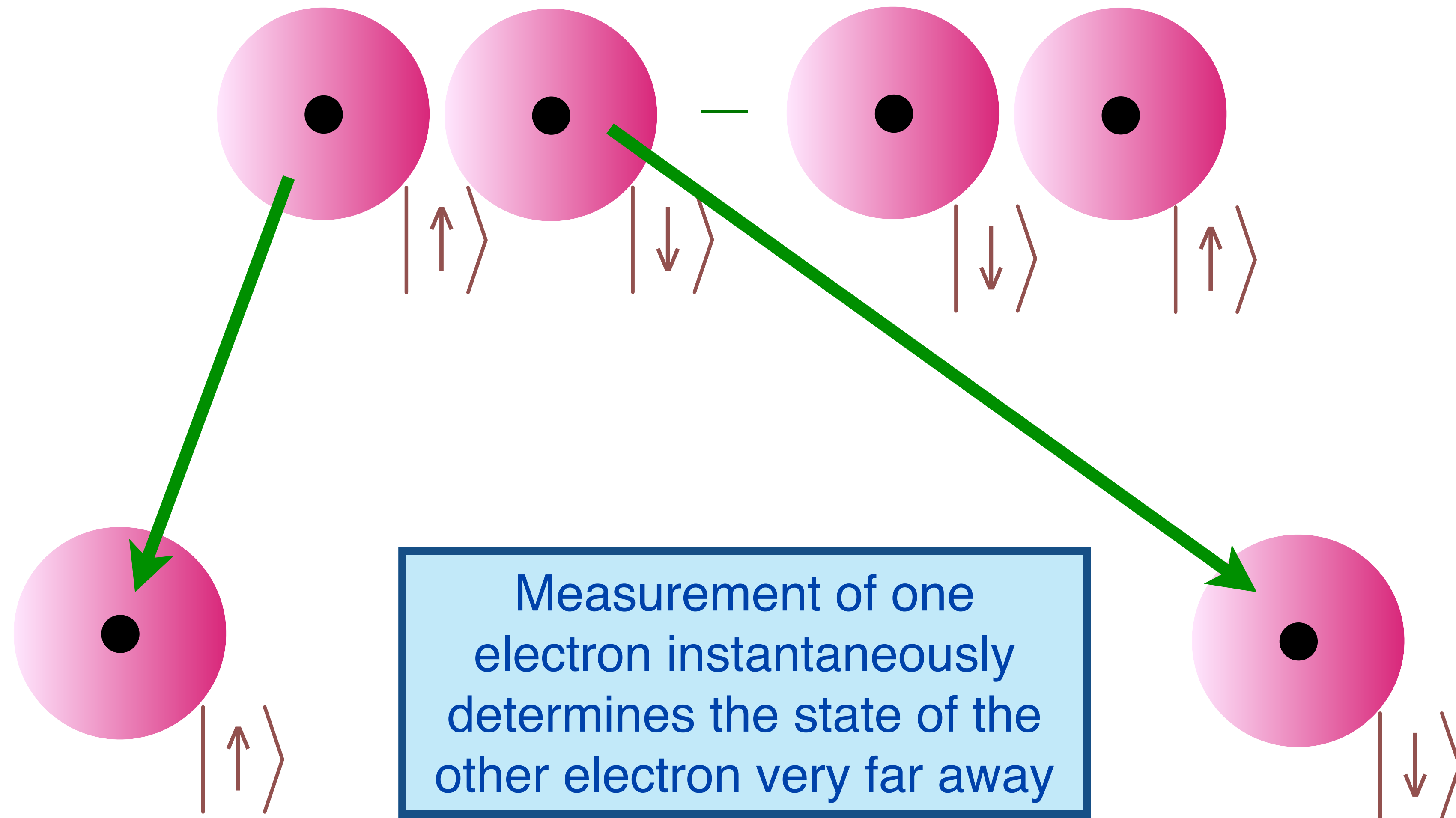
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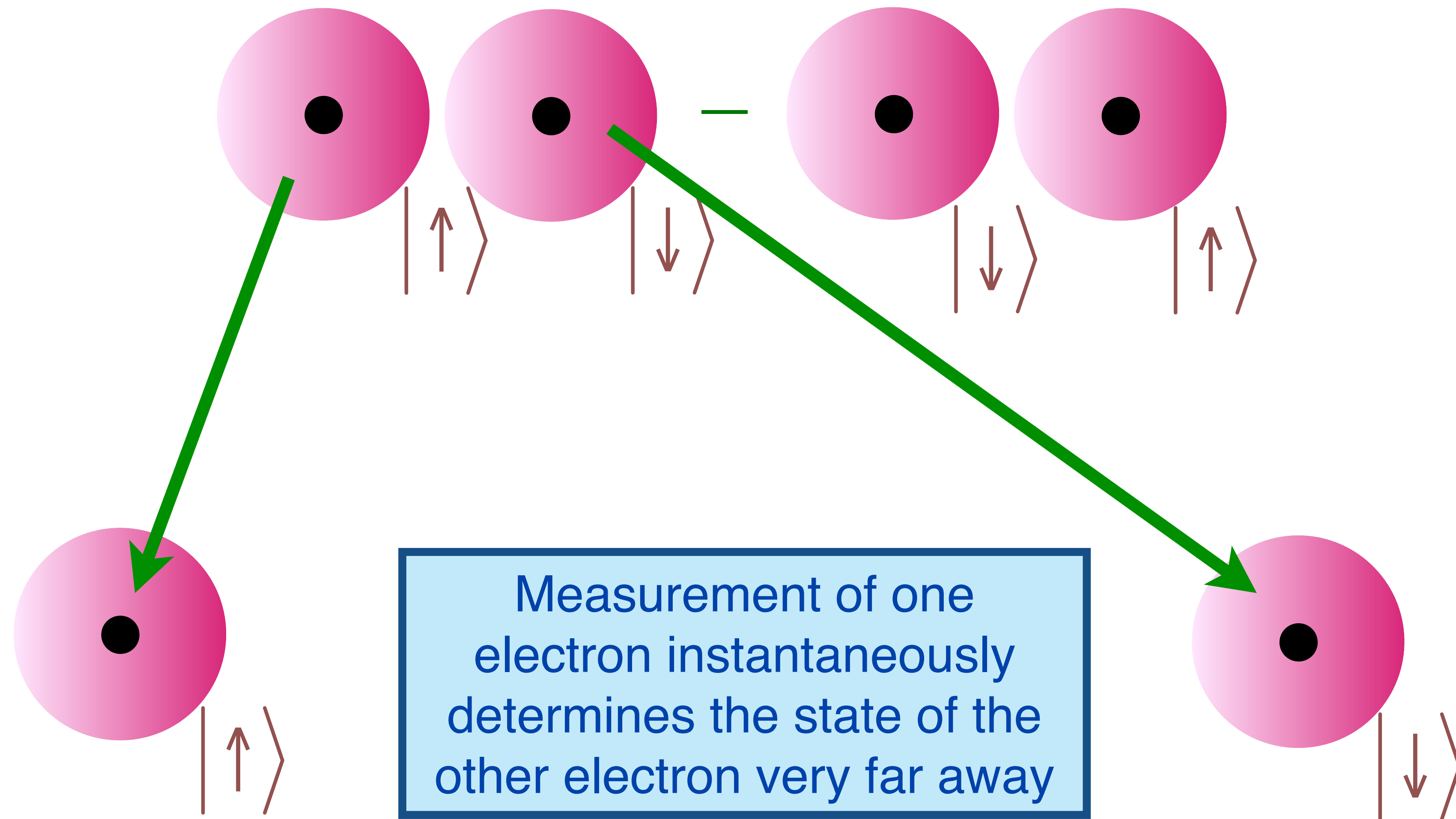
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



Spooky action at a distance !

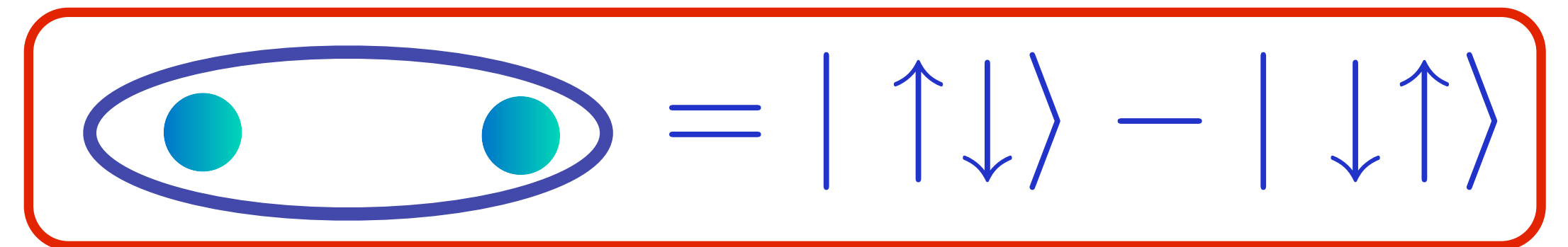
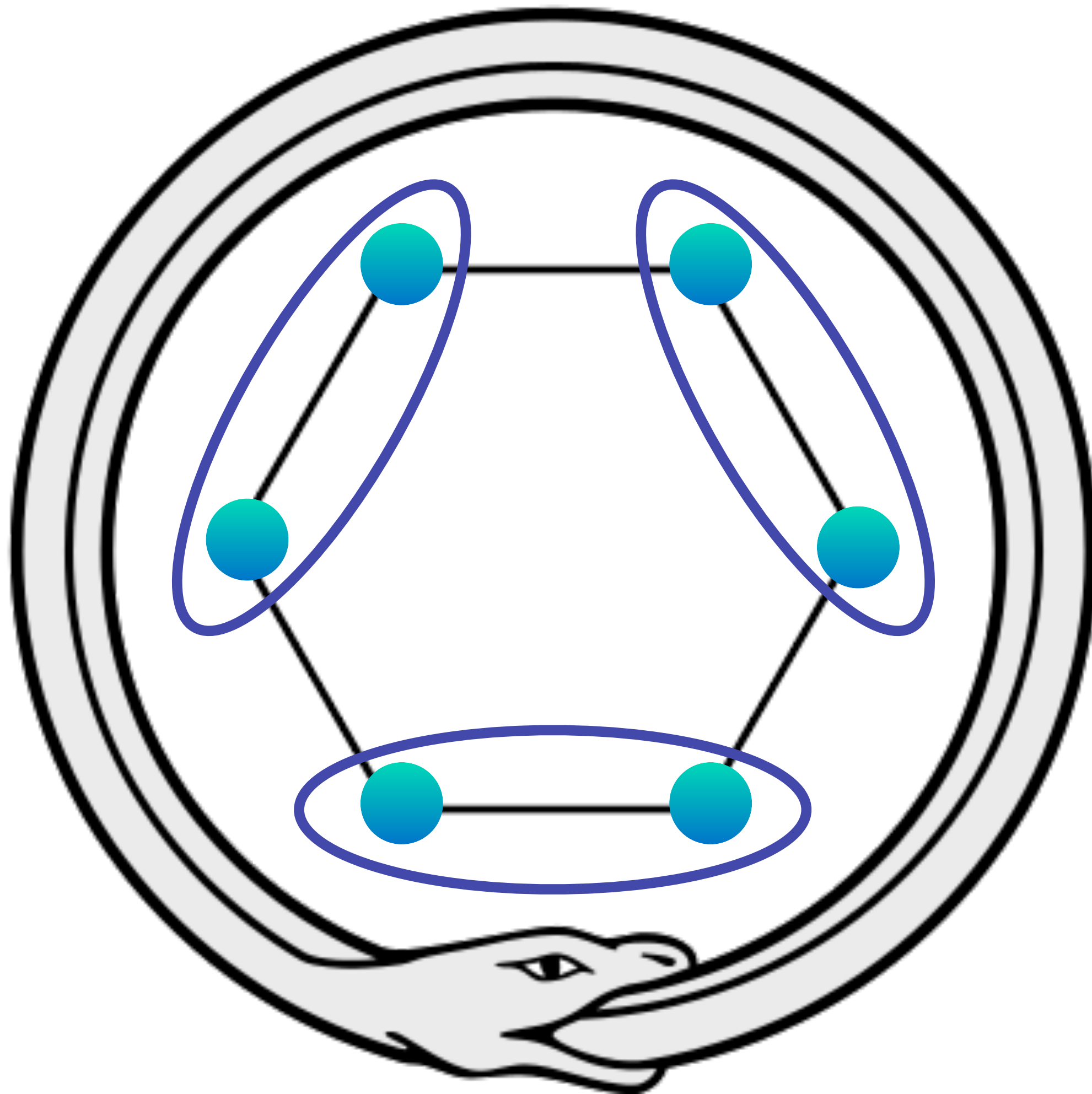
natürlicher
deren Notwendigkeit im Raum
mus ja zuerst von Dir klar erkannt wurde, einen Bedeutung
Wahrheitsgehalt hat. Ich kann aber deshalb nicht ernsthaft dar-
an glauben, weil die Theorie mit dem Grundsatz unvereinbar
ist, daß die Physik eine Wirklichkeit in Zeit und Raum darstel-
len soll, ohne spukhafte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

Kekulé's spooky dream (1865)

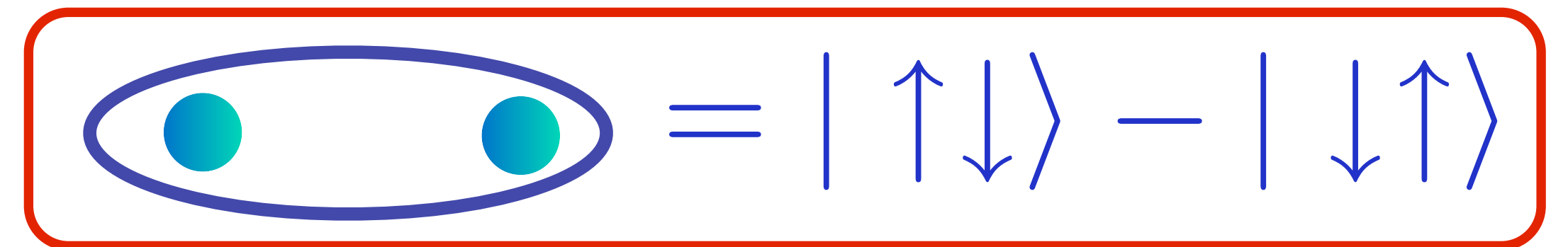
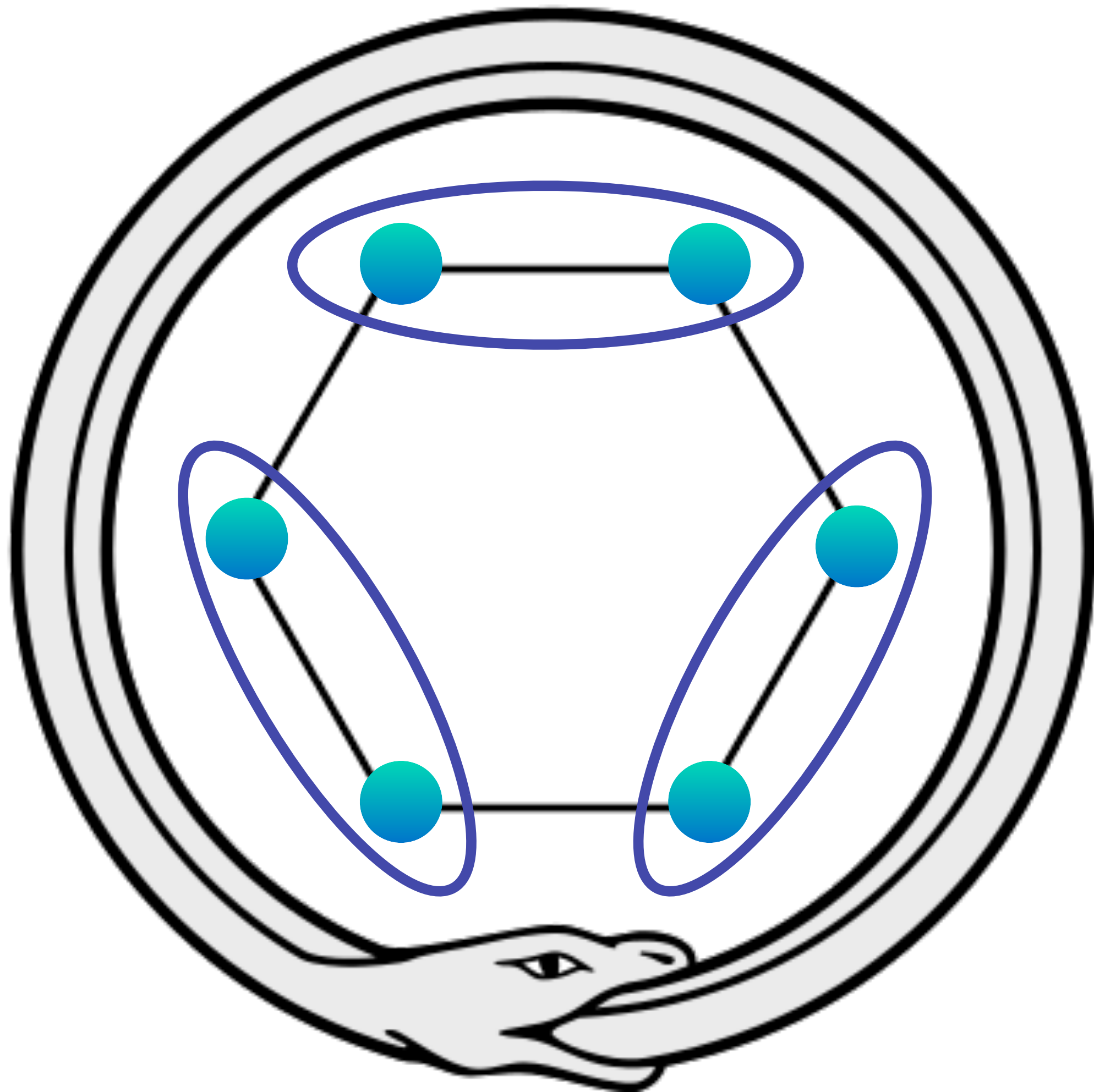
Kekulé spoke of the creation of the theory. He said that he had discovered the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail^{*}



Benzene

Kekulé's spooky dream (1865)

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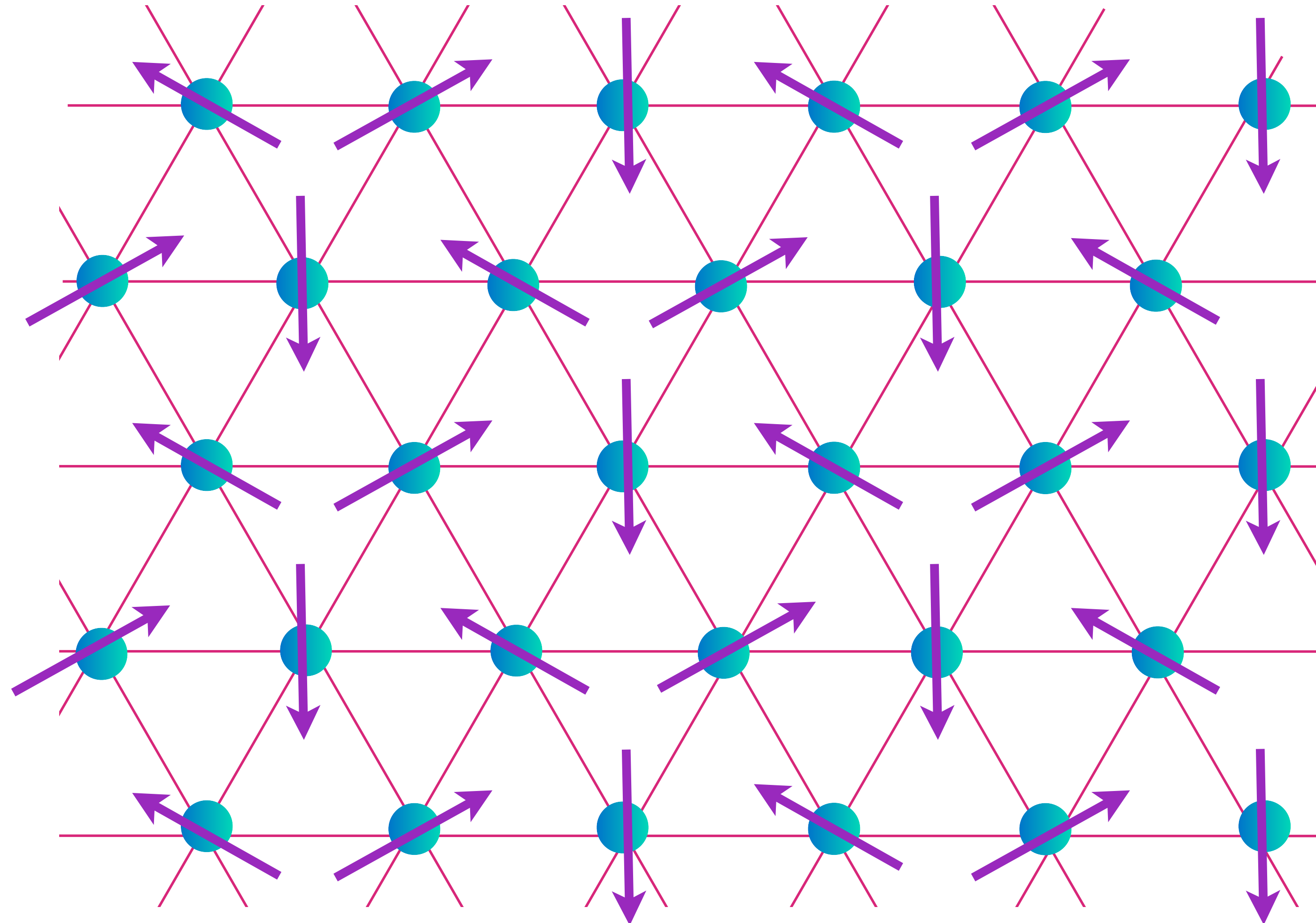
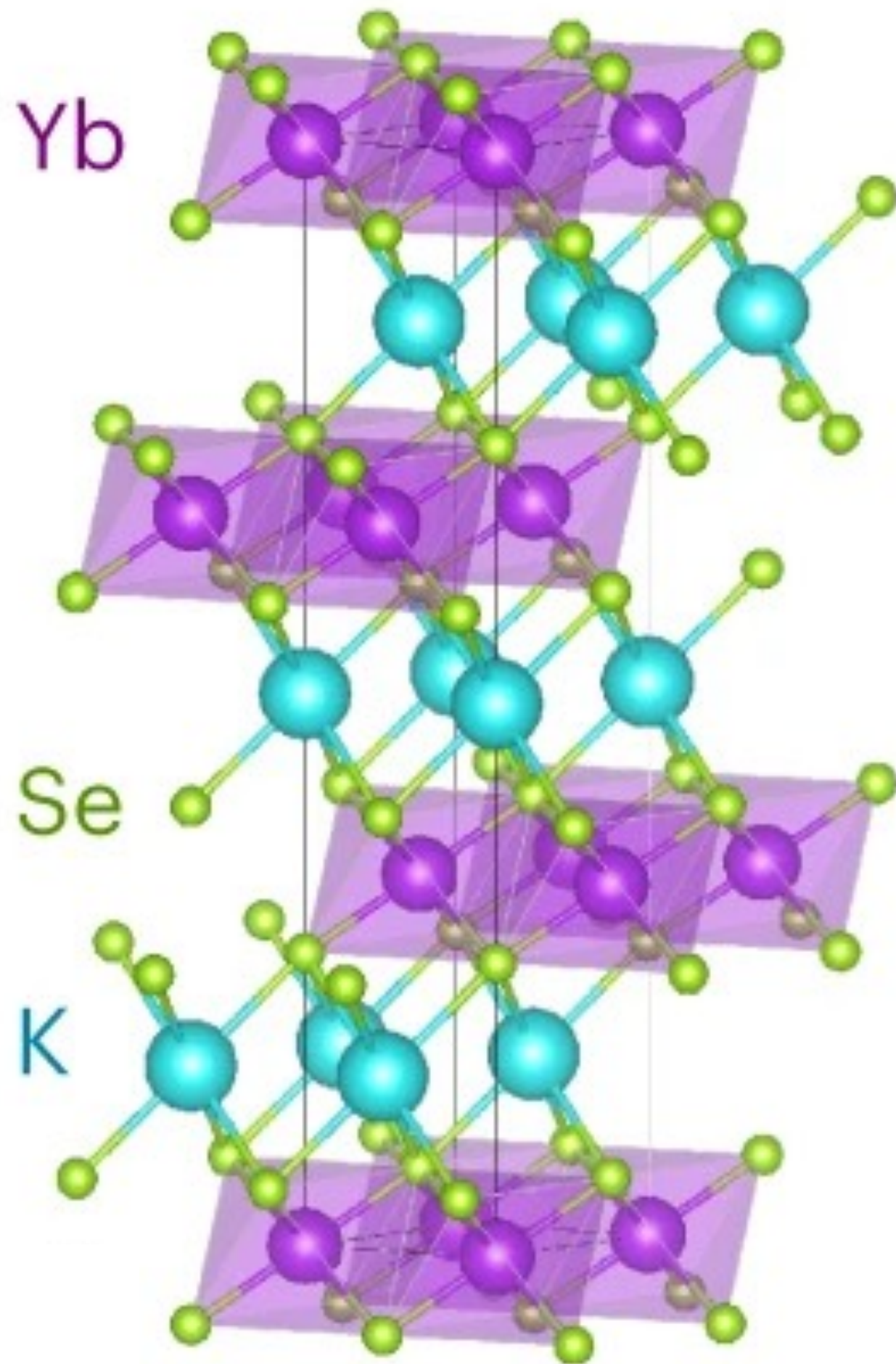


Benzene

Quantum spin liquids and quantum error correction

Triangular lattice antiferromagnet

KYbSe₂

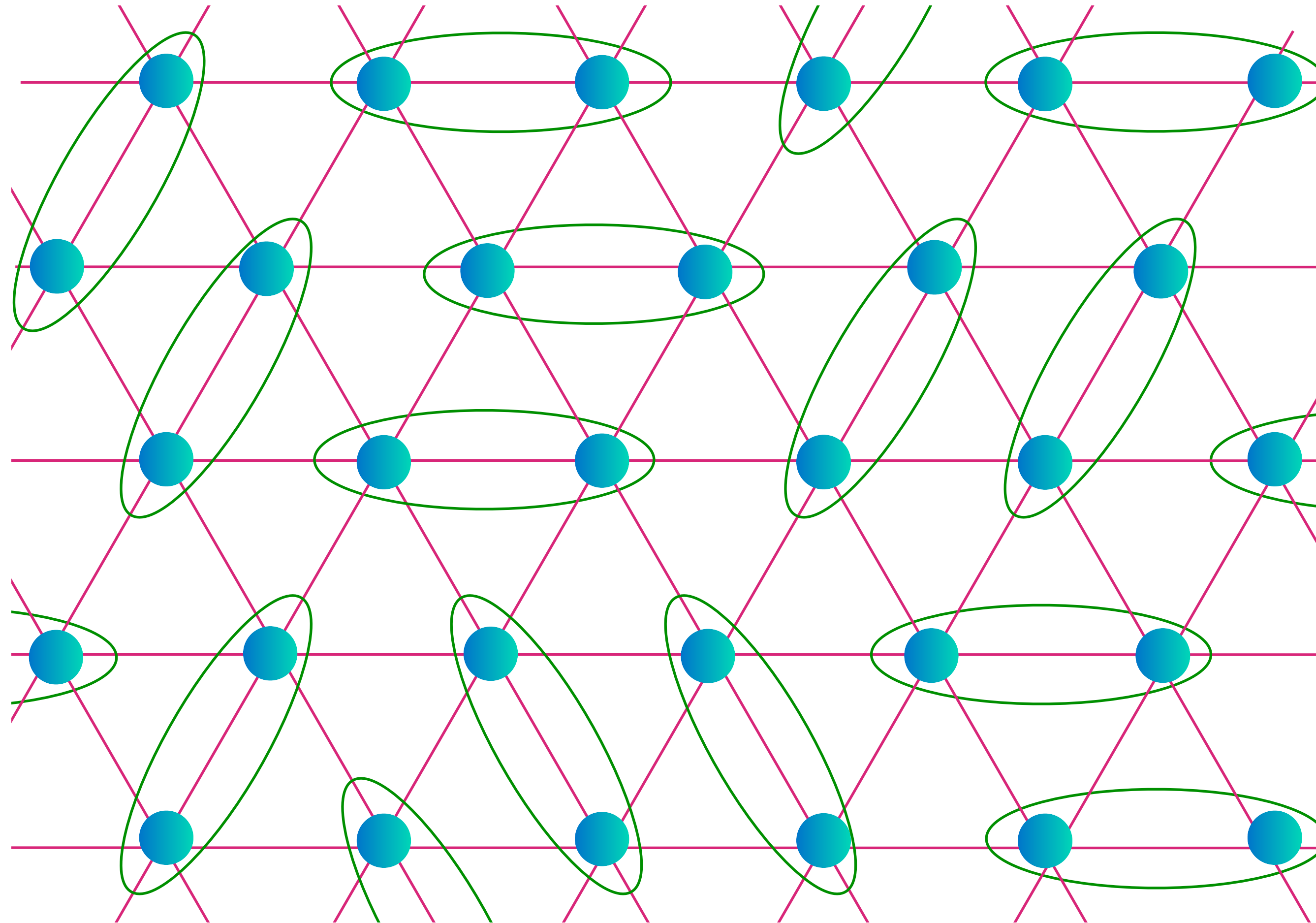


Nearest-neighbor model has ordered spins

Spin liquid: resonating valence bonds

Patrik Fazekas
Hungarian Academy of Sciences

$$\text{[Diagram of two blue dots in a green oval]} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



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

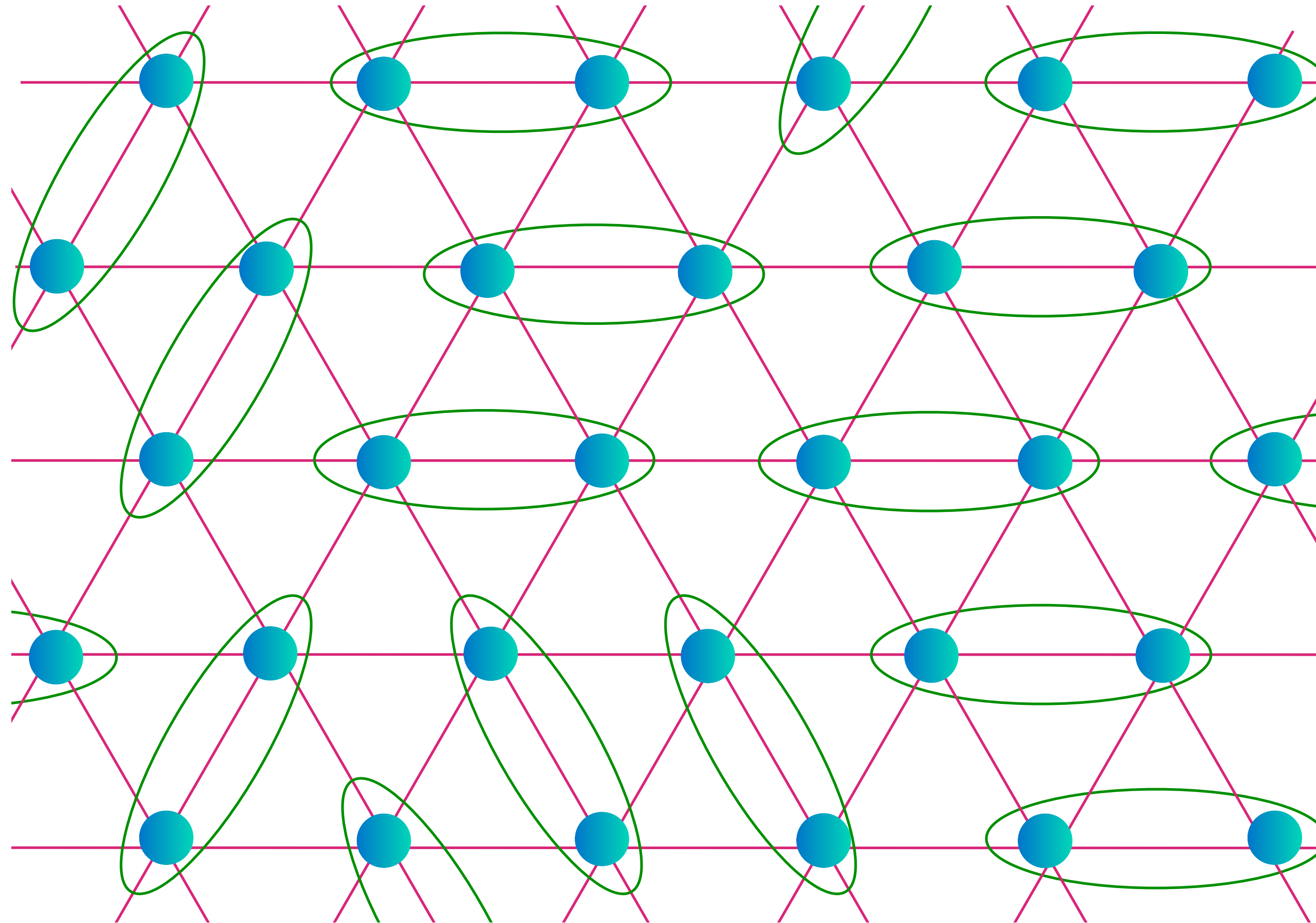
$\mathcal{D} \rightarrow$ dimer covering
of lattice

Patrik Fazekas and P. W. Anderson, *Philos. Mag.* **30**, 23 (1974).

Spin liquid: resonating valence bonds

Patrik Fazekas
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$$\text{green oval with two blue dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



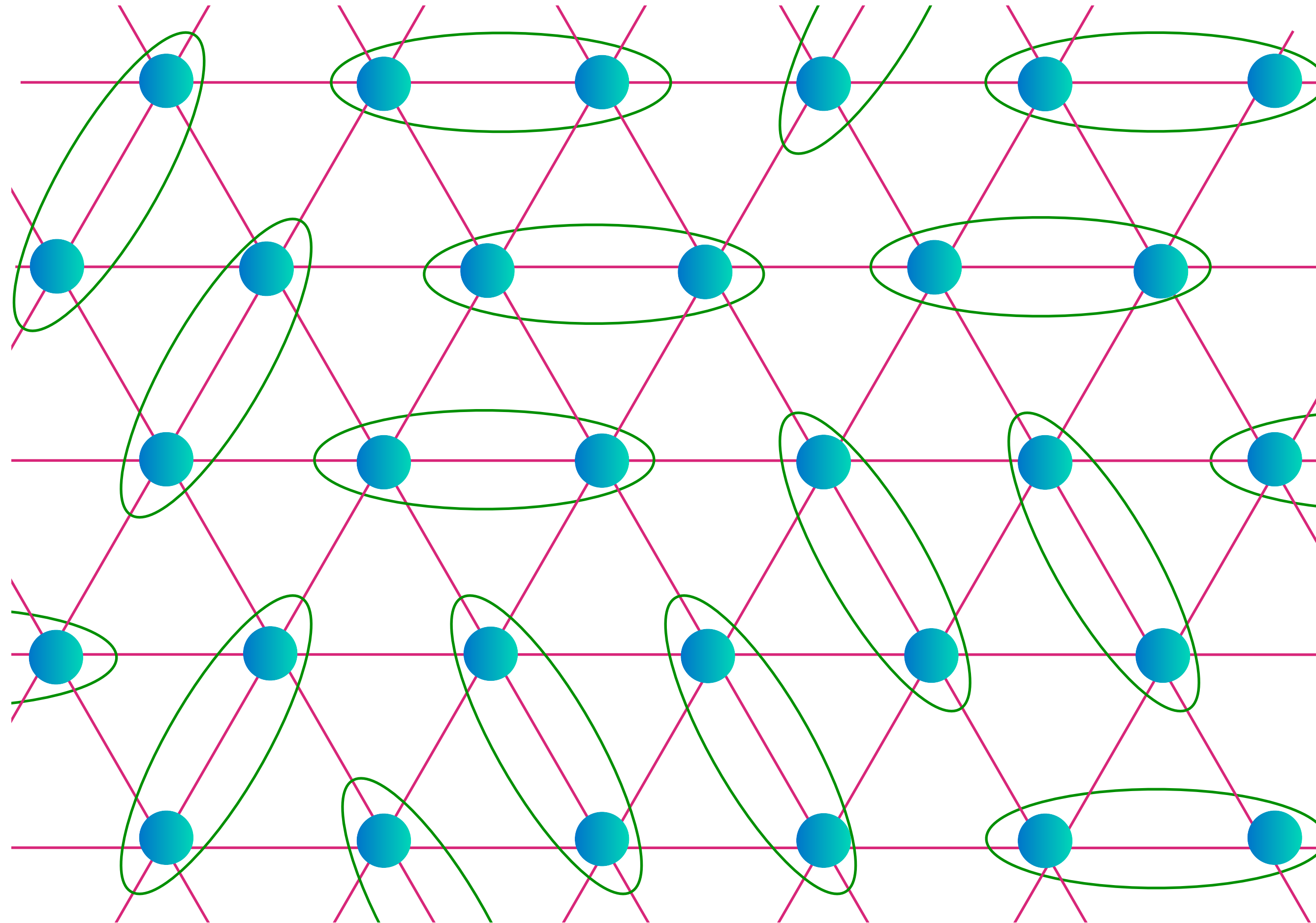
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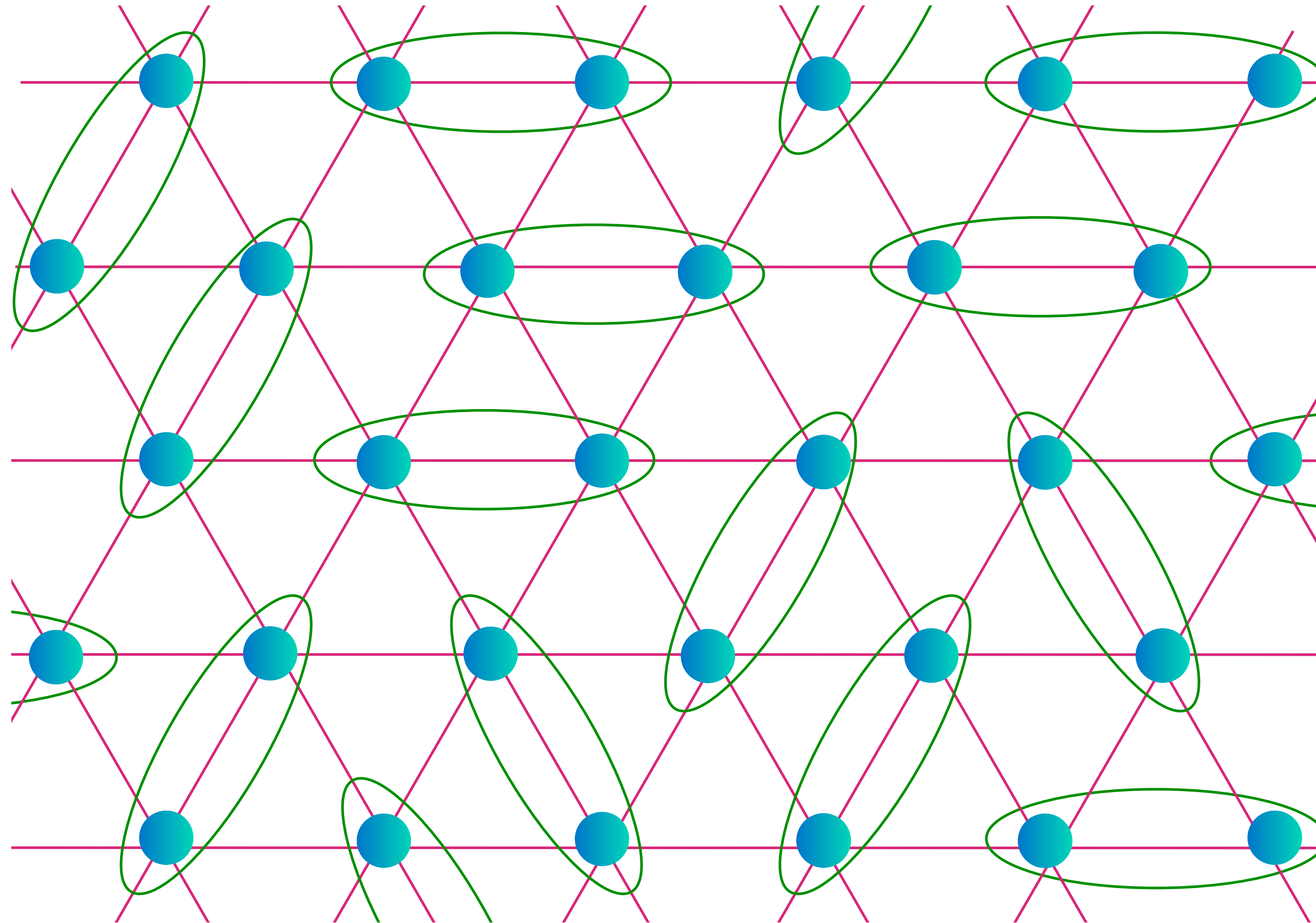
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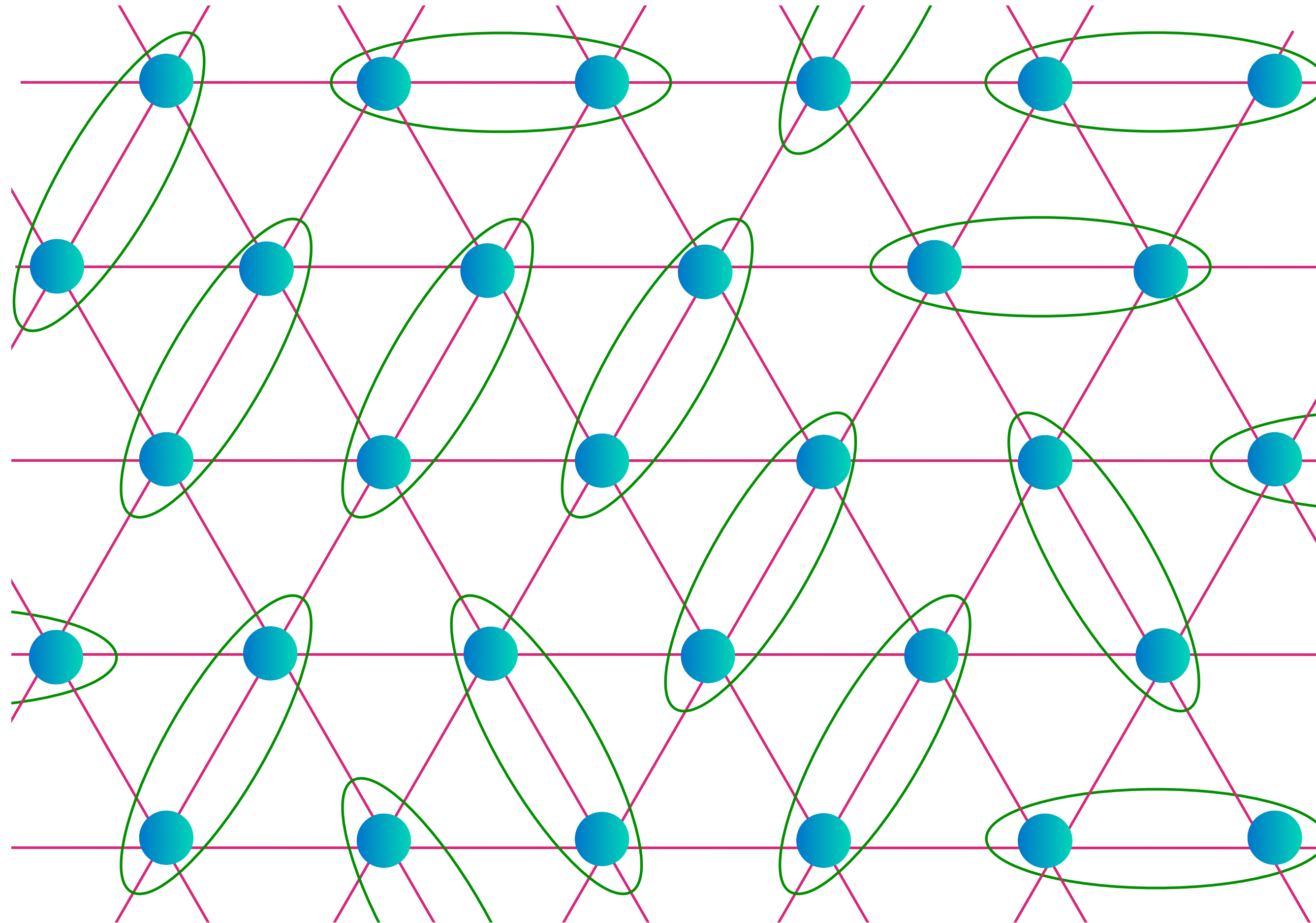
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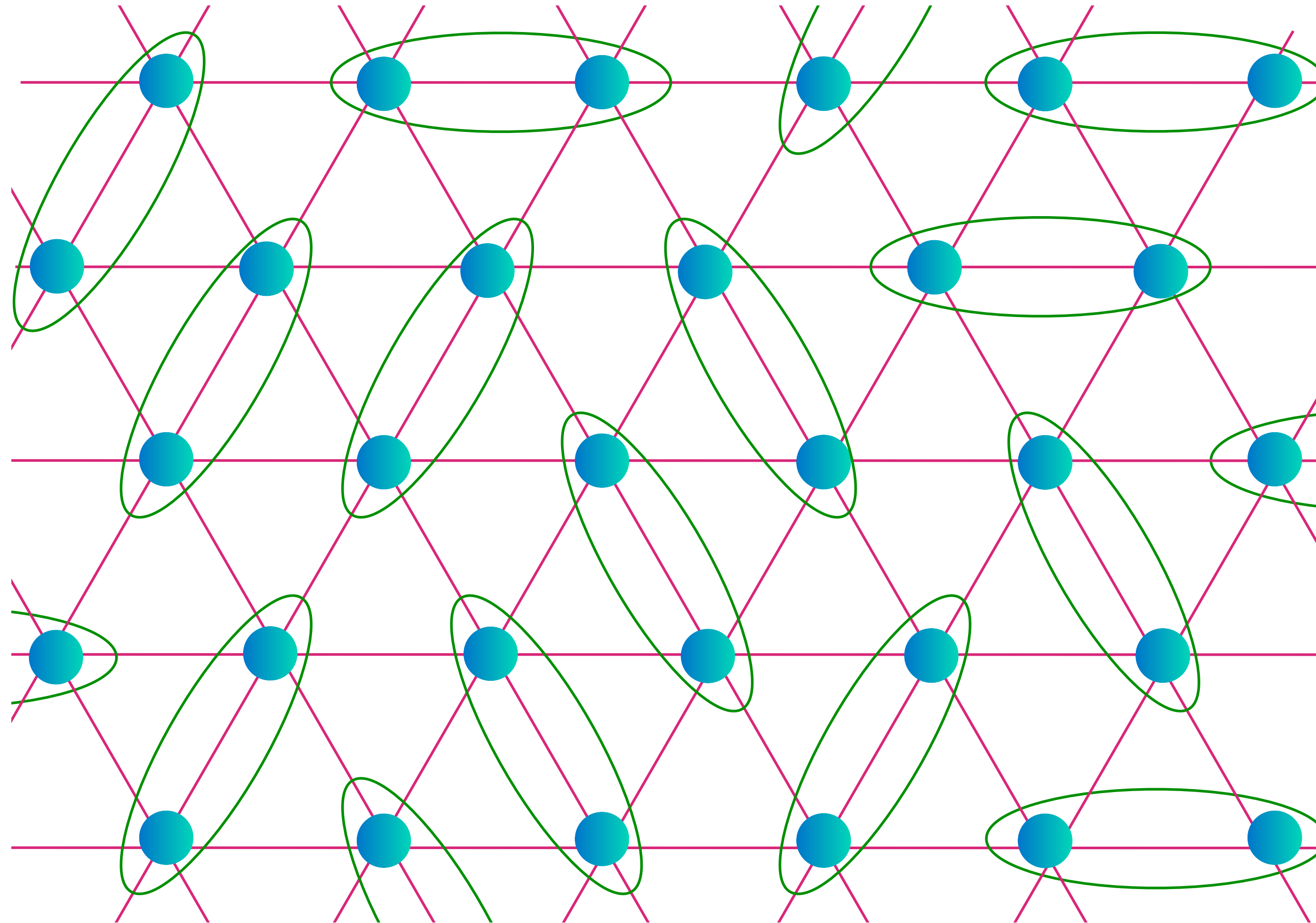
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$\mathcal{D} \rightarrow$ dimer covering
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Spin liquid: resonating valence bonds

Patrik Fazekas
Hungarian Academy of Sciences

$$\text{oval with two dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



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

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

Spin liquid: resonating valence bonds

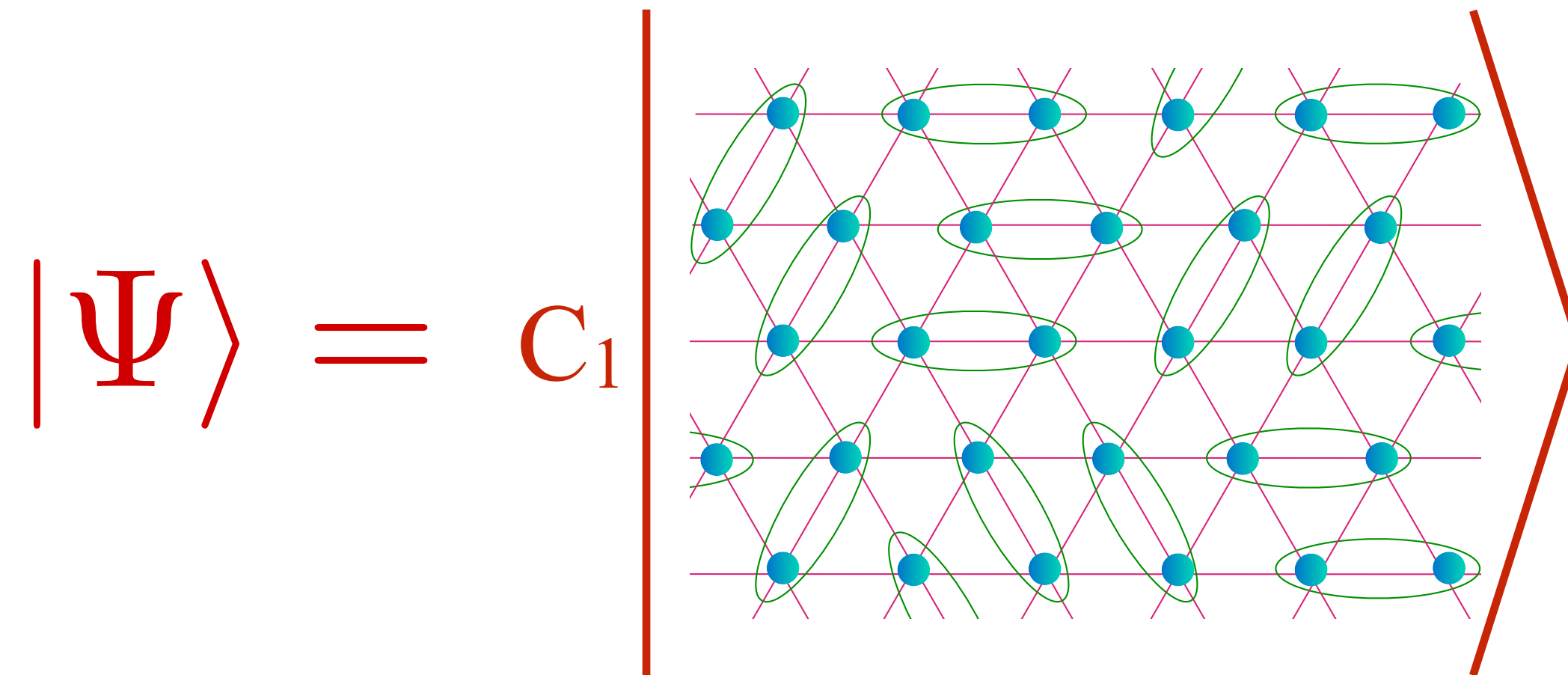
$$\text{green oval with two blue dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$$|\Psi\rangle = C_1 \left[\text{diagram 1} \right] + C_2 \left[\text{diagram 2} \right] + C_3 \left[\text{diagram 3} \right] + C_4 \left[\text{diagram 4} \right] + C_5 \left[\text{diagram 5} \right] + \dots$$

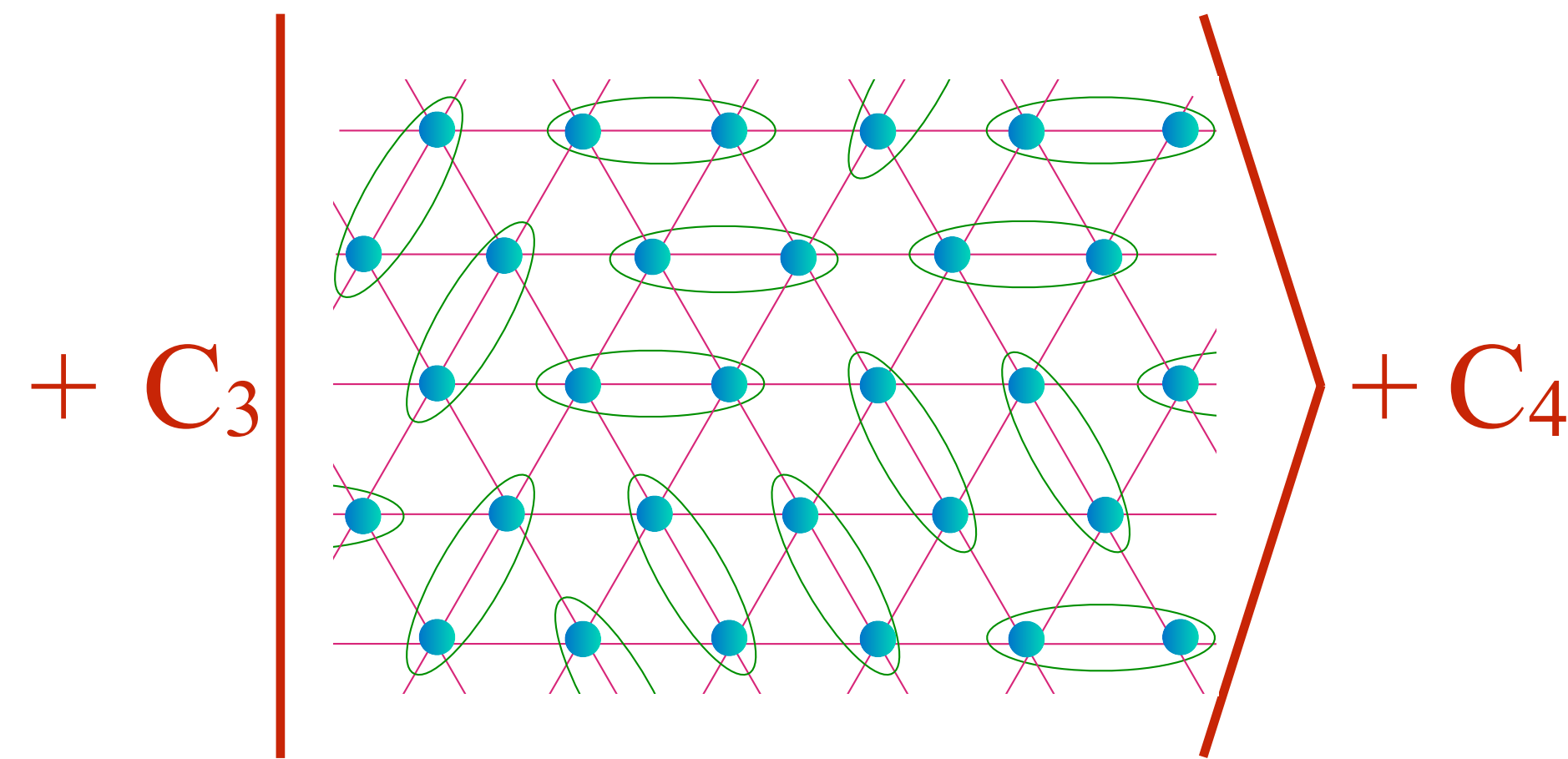
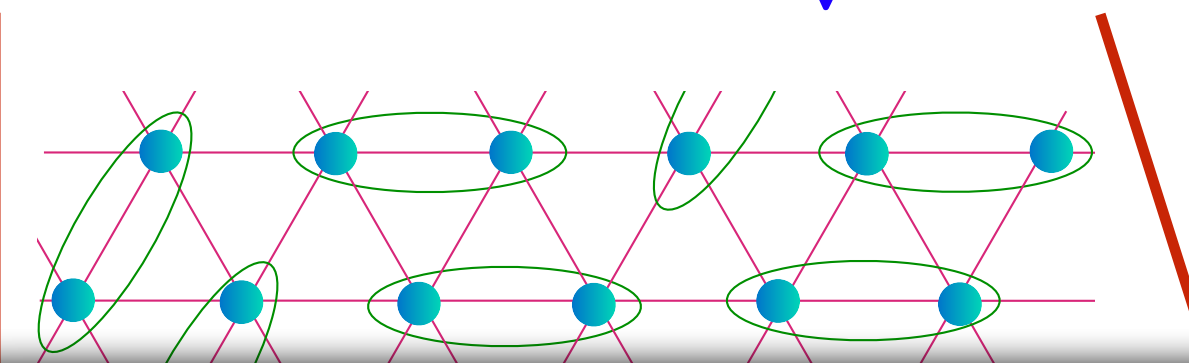
The diagrams show a 4x6 grid of blue dots (spins) on a triangular lattice. Green ovals represent valence bonds between pairs of spins. In each diagram, the pattern of green ovals is different, illustrating the concept of resonating valence bonds. The diagrams are enclosed in large red brackets, and the coefficients C_1 through C_5 are written in red. The entire expression is for the wavefunction $|\Psi\rangle$.

Spin liquid: resonating valence bonds

$$\text{green oval with two blue dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



+

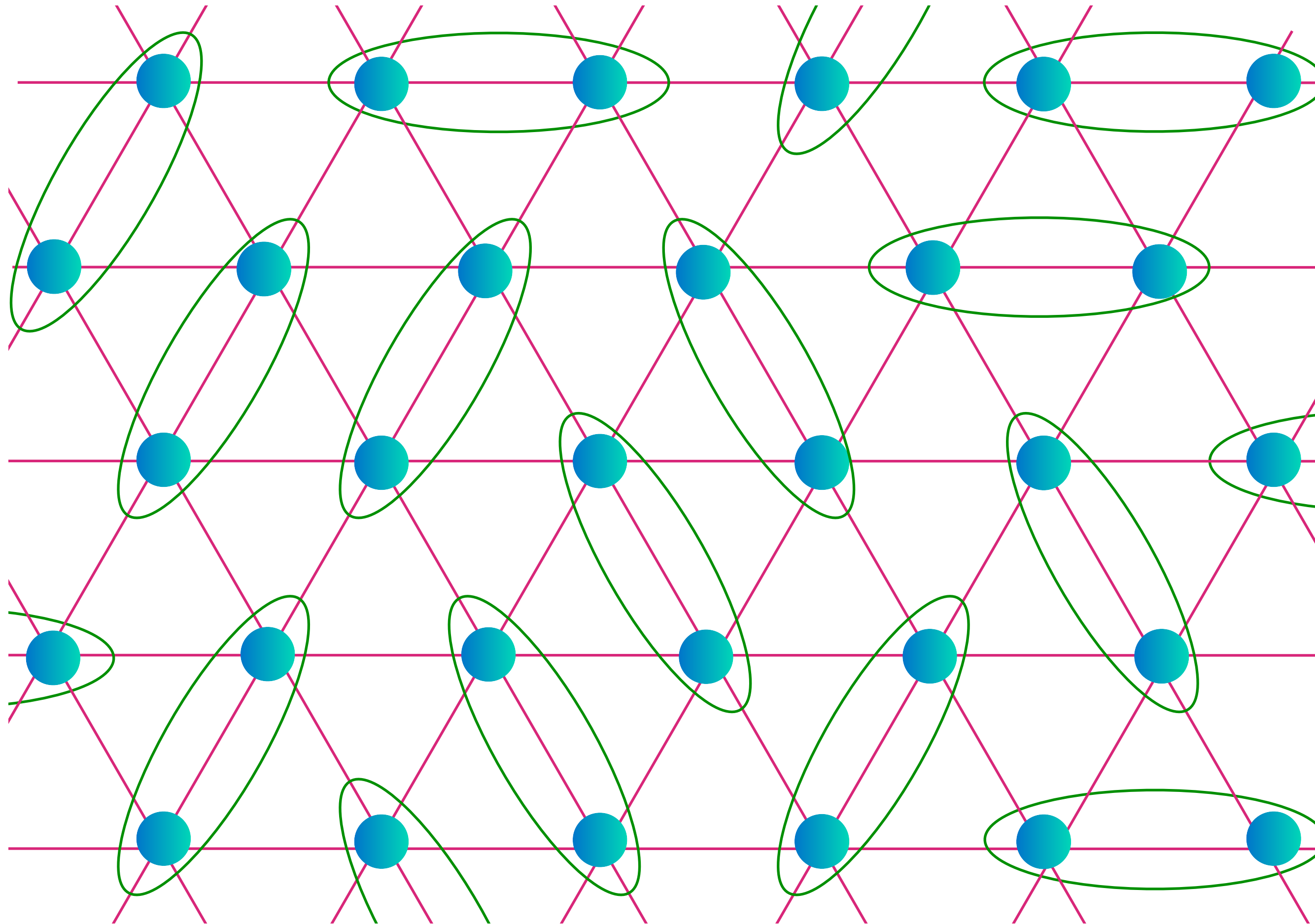


Key feature: fractionalization.
Excitations are particle-like,
but cannot be created
by local operators.
The excitations are classified
under distinct
anyon sectors.

Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

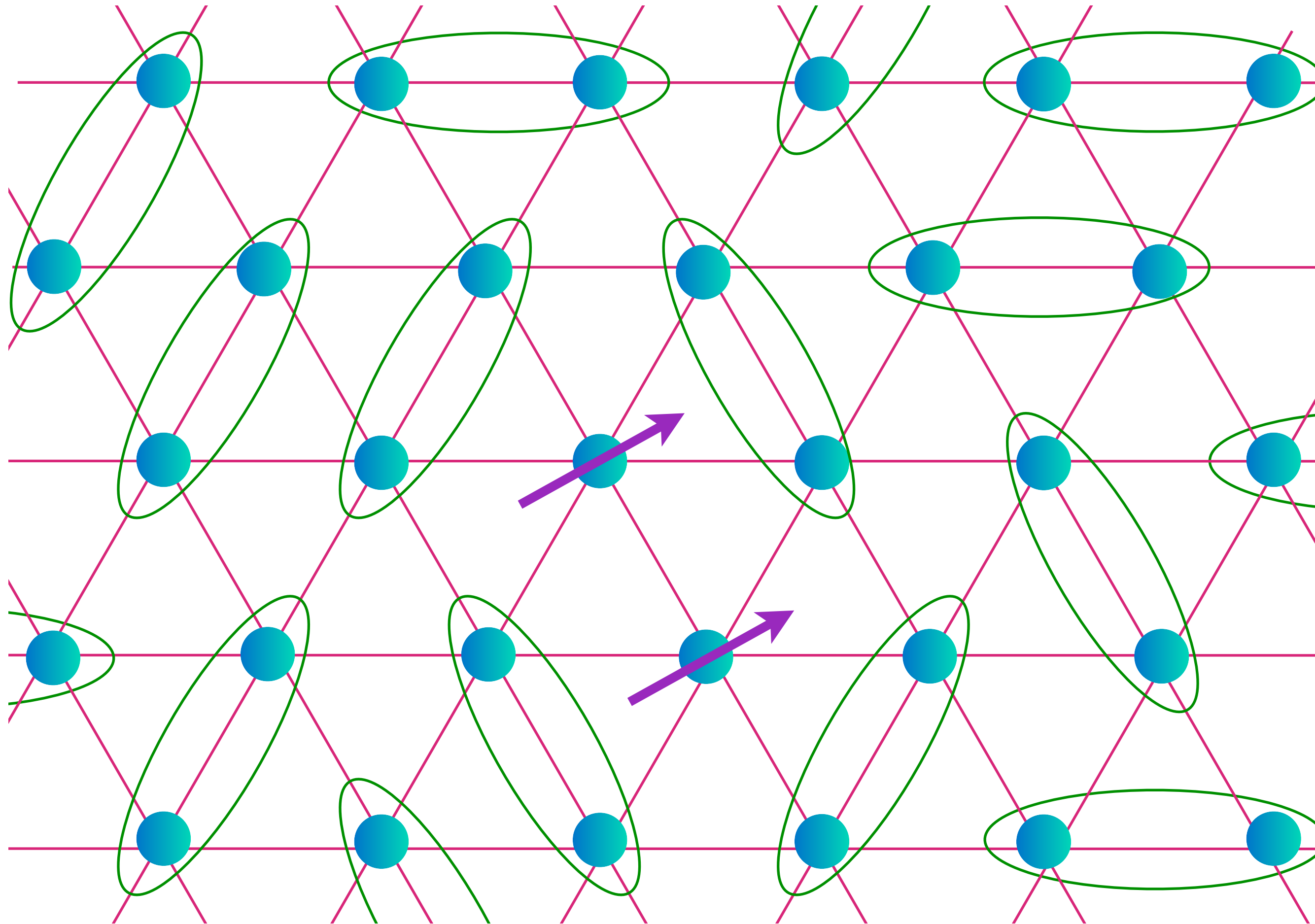
$$\text{[Diagram of two blue dots in a green oval]} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

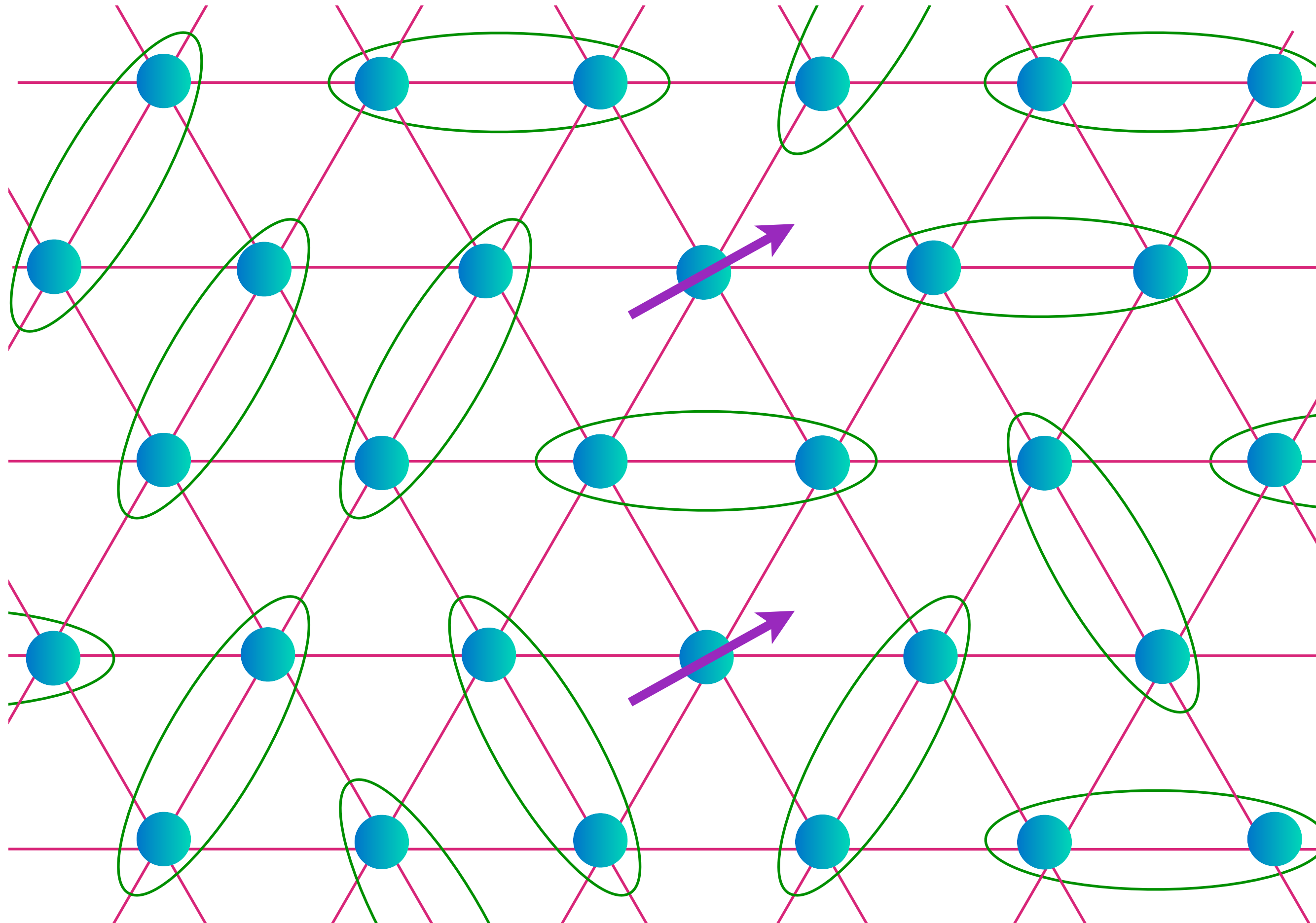
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Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

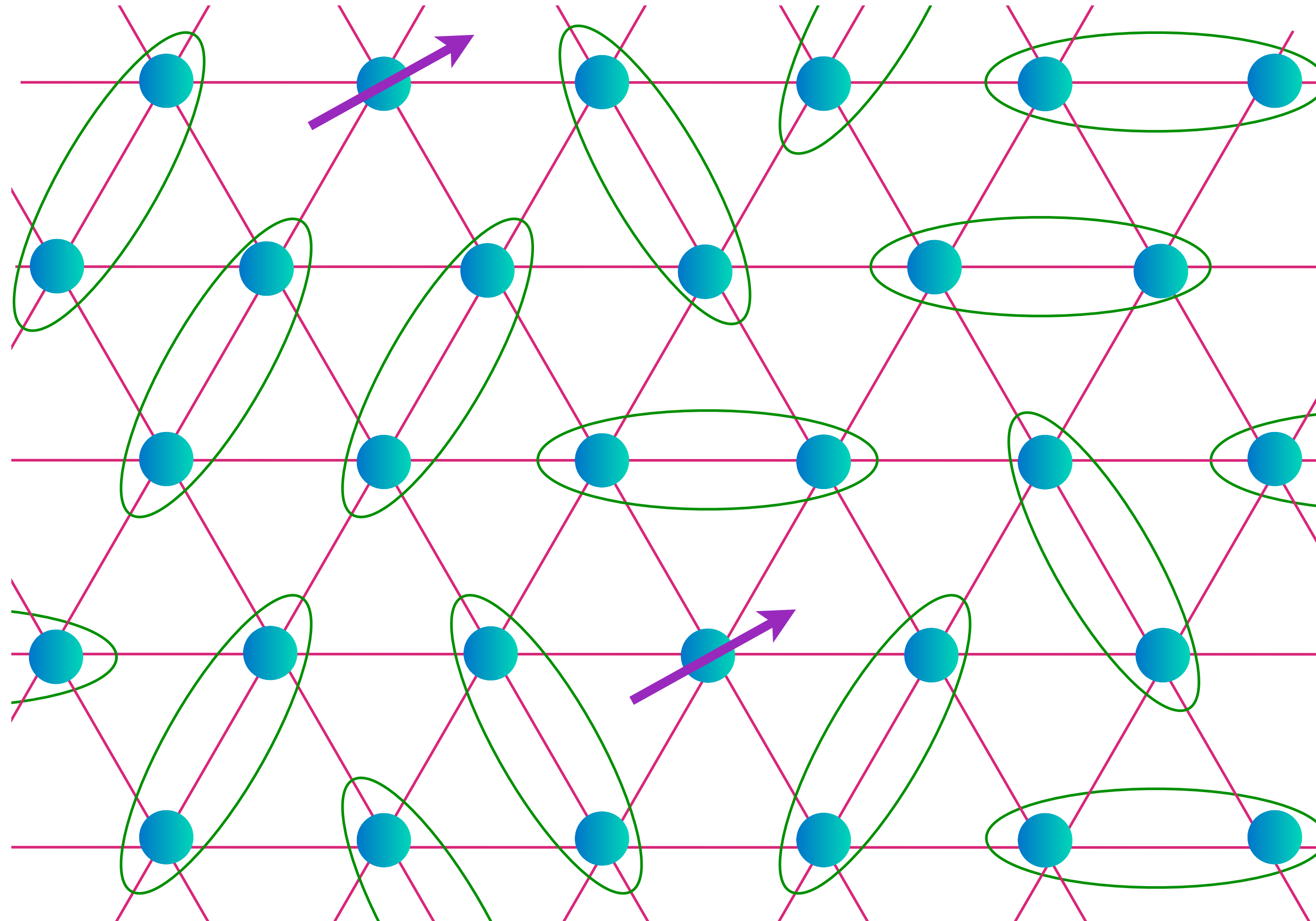
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Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

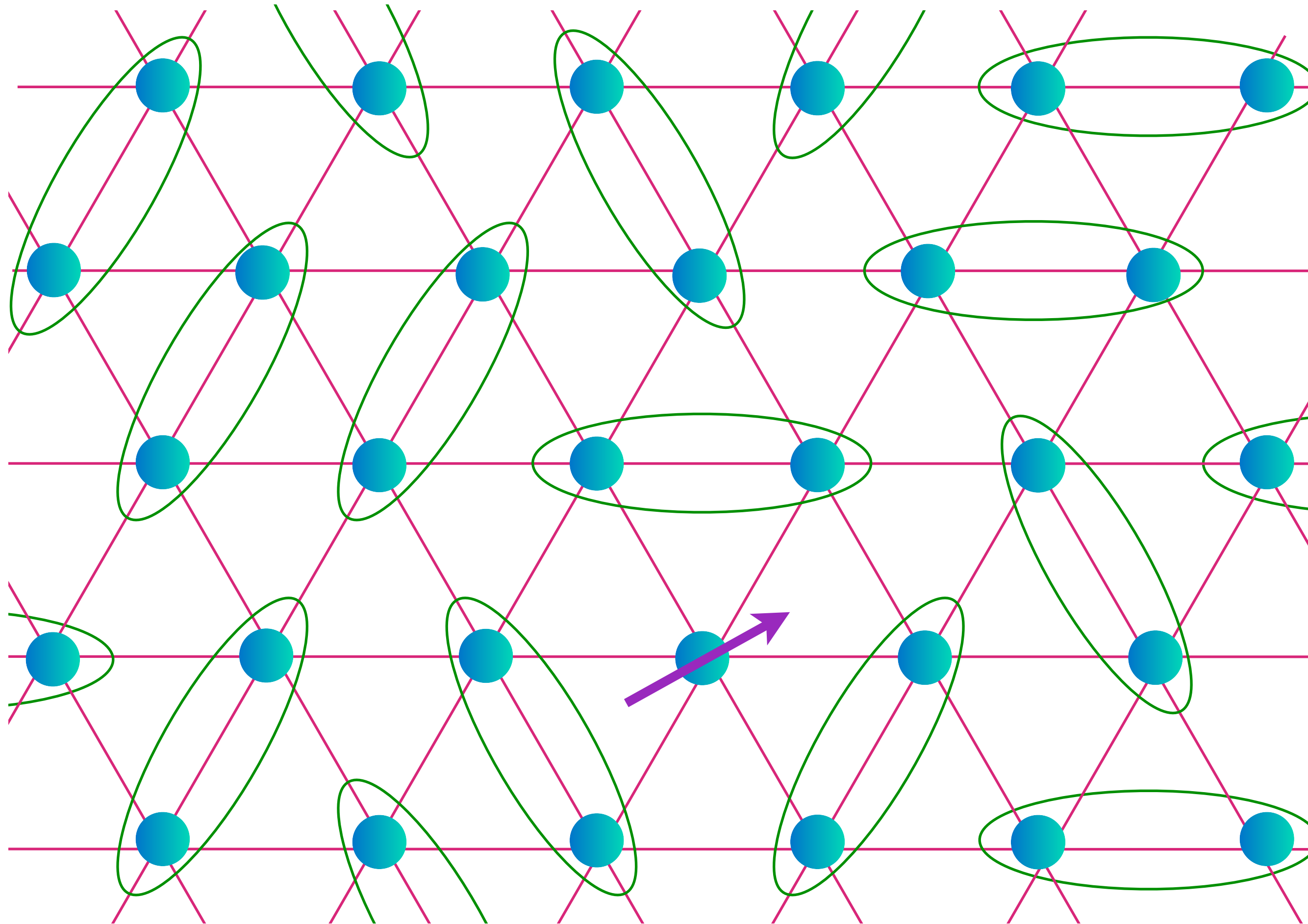
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Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

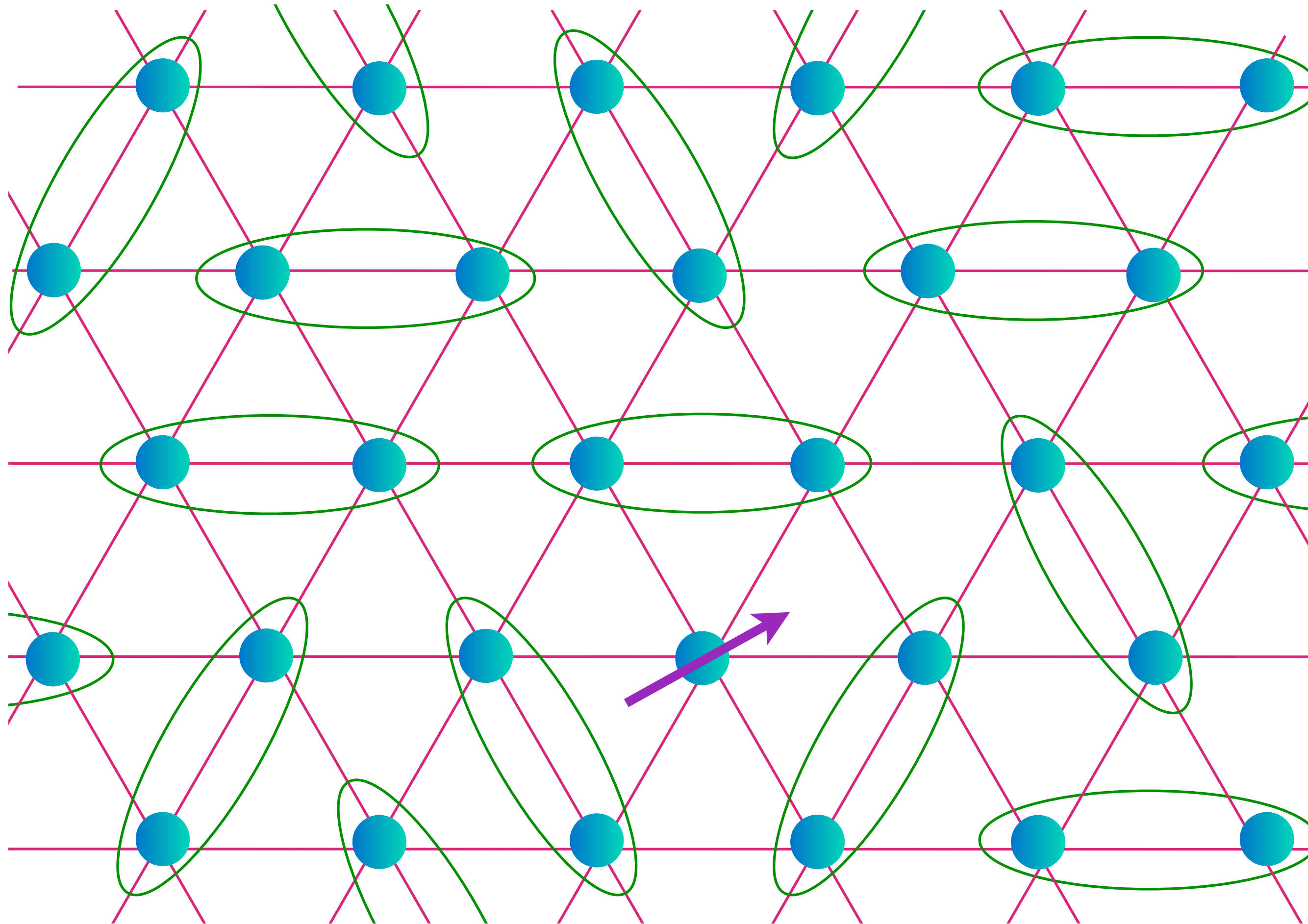
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Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

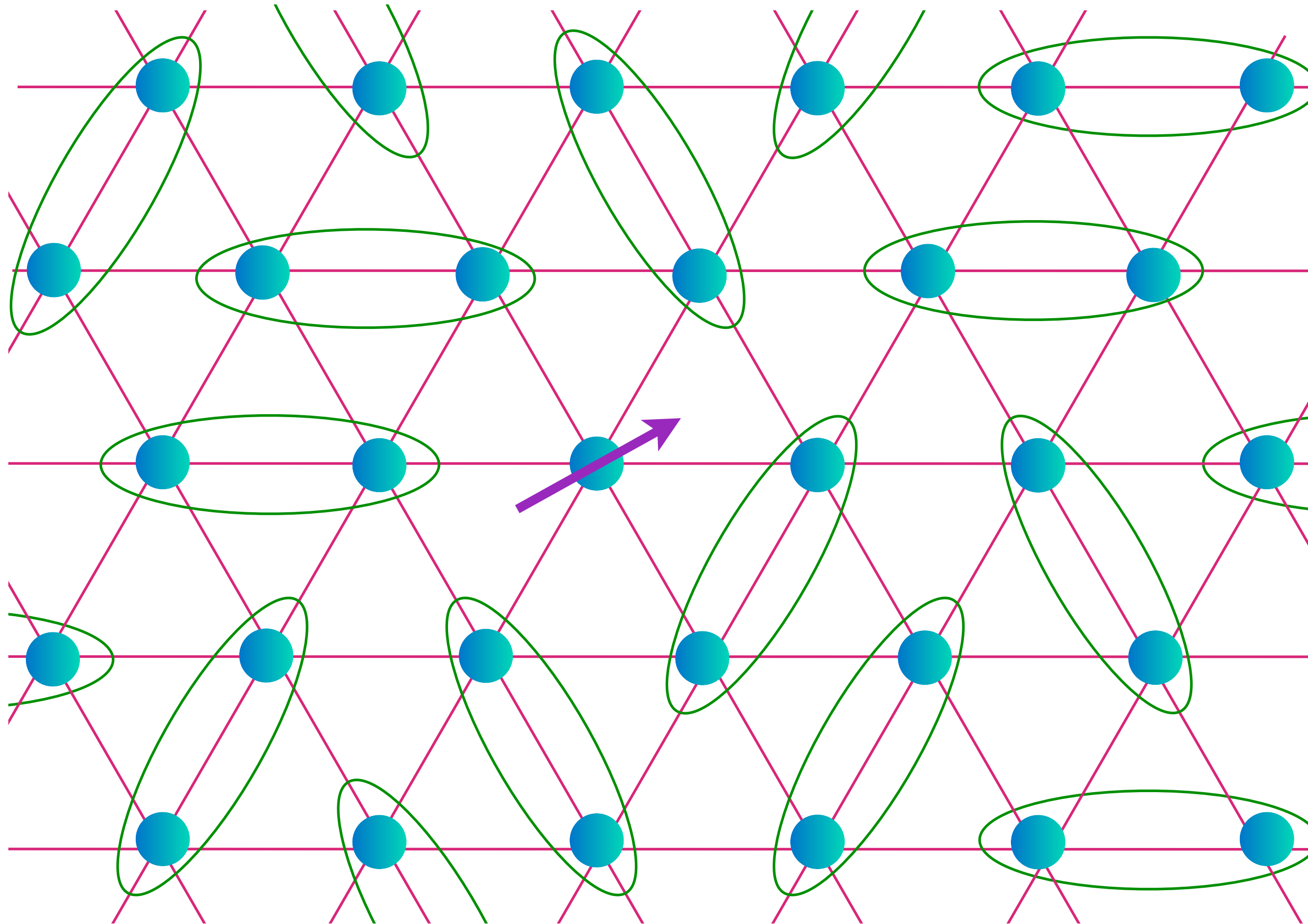
$$\text{green oval with two blue dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

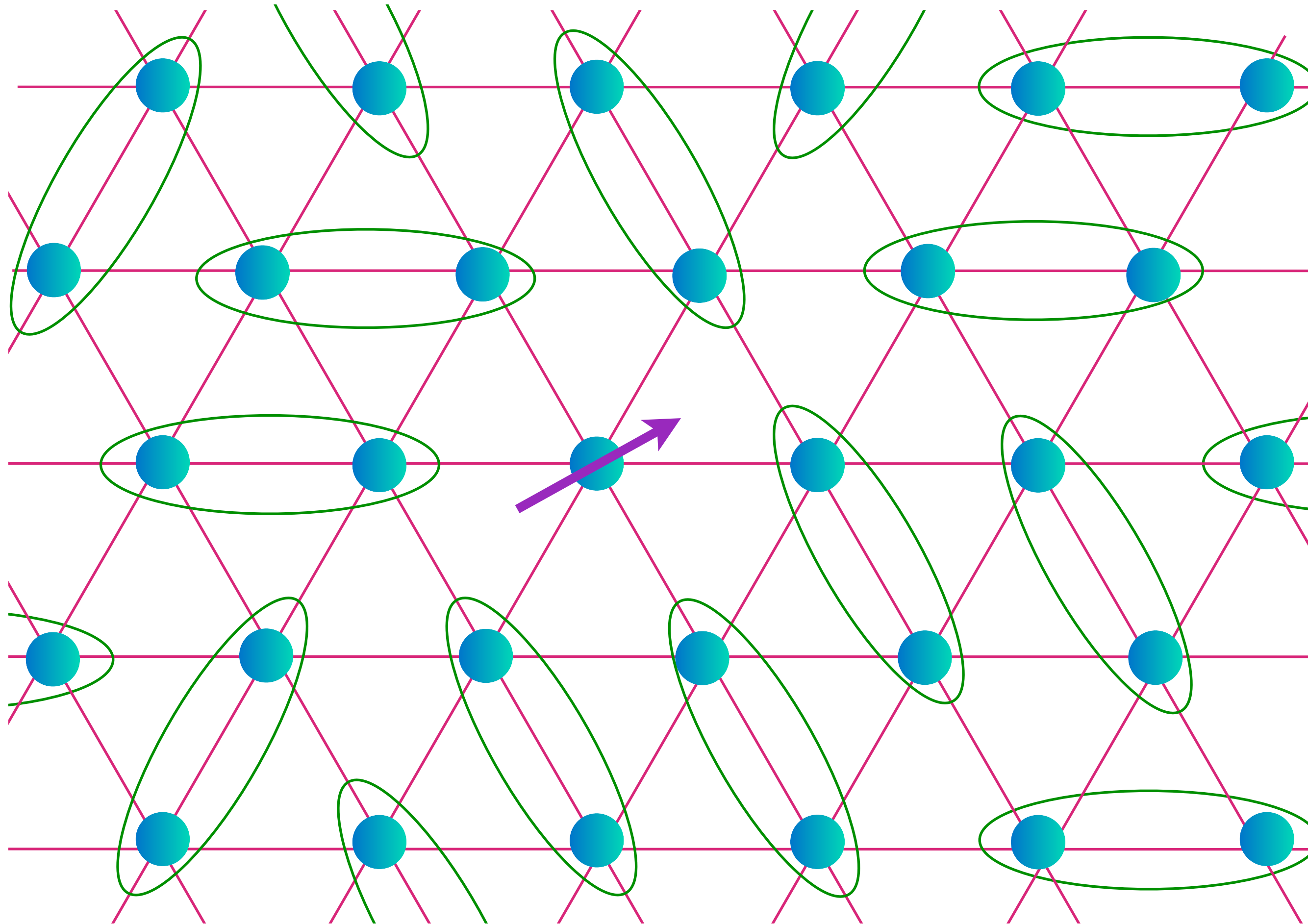
$$\text{green oval with two blue dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

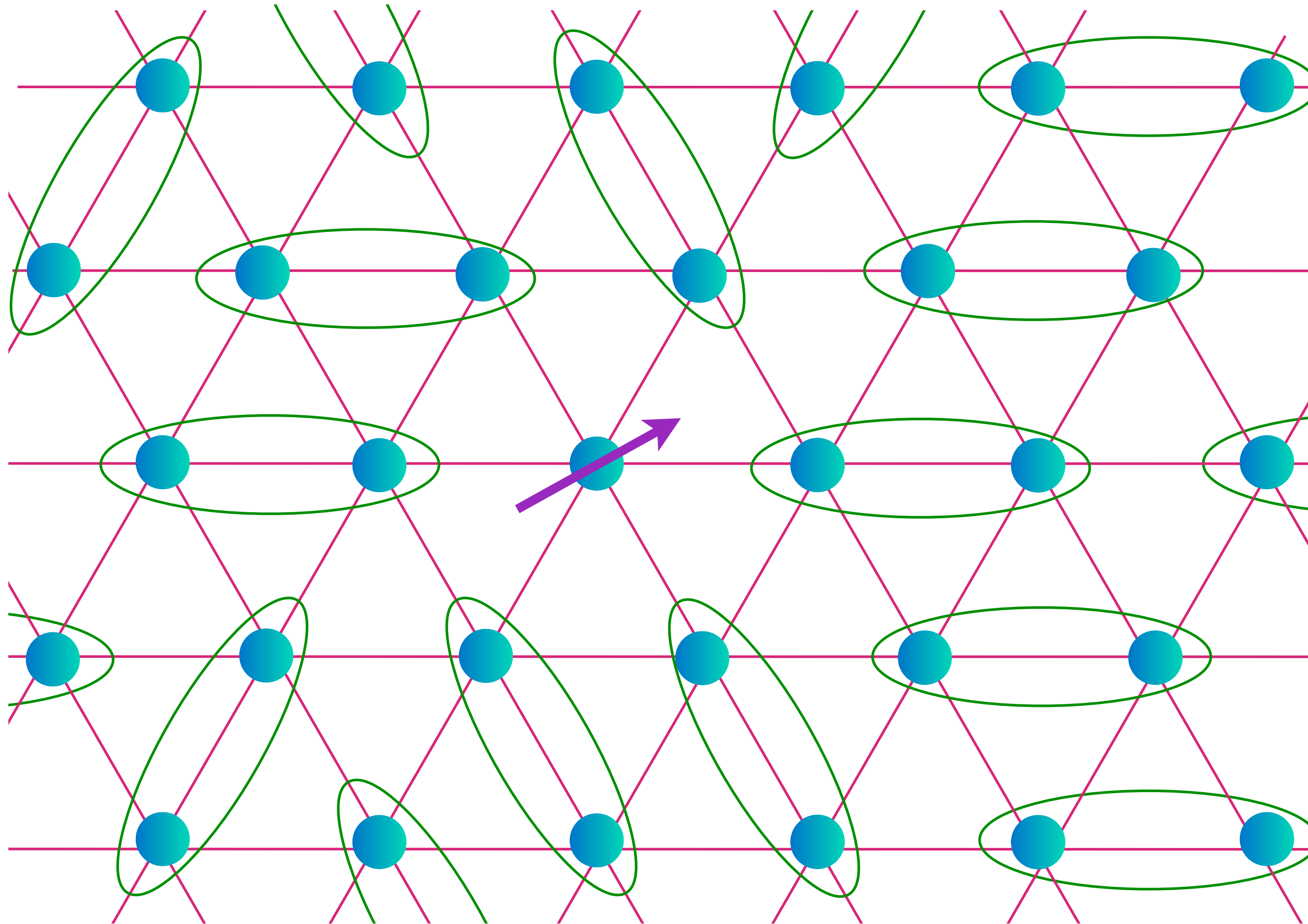
$$\text{green oval with two blue dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



Spin liquid: resonating valence bonds

Fractionalized excitations: a “spinon”

$$\text{[Diagram of two blue dots in a green oval]} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$



Spin liquid: resonating valence bonds

$$\text{green oval with two blue dots} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$$|\Psi\rangle = C_1 \left[\text{diagram 1} \right] + C_2 \left[\text{diagram 2} \right] + C_3 \left[\text{diagram 3} \right] + C_4 \left[\text{diagram 4} \right] + C_5 \left[\text{diagram 5} \right] + \dots$$

The diagrams show a 4x6 grid of blue dots (spins) on a triangular lattice. Each dot is enclosed in a green oval representing a valence bond. The orientation of the green ovals varies between the diagrams, illustrating different configurations of resonating valence bonds. The entire expression is enclosed in large red brackets, with red coefficients C_1 through C_5 and a red ellipsis.

Another anyon—involves subtle changes in sign of superposition

$$\text{blue circle pair in green oval} = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$$|\Psi\rangle = C_1 \left[\text{Diagram 1} \right] + C_2 \left[\text{Diagram 2} \right] + C_3 \left[\text{Diagram 3} \right] + C_4 \left[\text{Diagram 4} \right] + C_5 \left[\text{Diagram 5} \right] + \dots$$

The diagrams show a 4x6 grid of blue circles (spins) on a pink triangular lattice. A horizontal dashed green line is drawn between the second and third rows. A green star marks the intersection of the dashed line and the third vertical line from the left. In each diagram, the blue circles are paired into dimers (green ovals) in a different configuration. The sequence of diagrams shows a progression of dimer configurations across the green line.

$$C_n \Rightarrow C_n (-1)^{\text{Number of dimers across green line}}$$

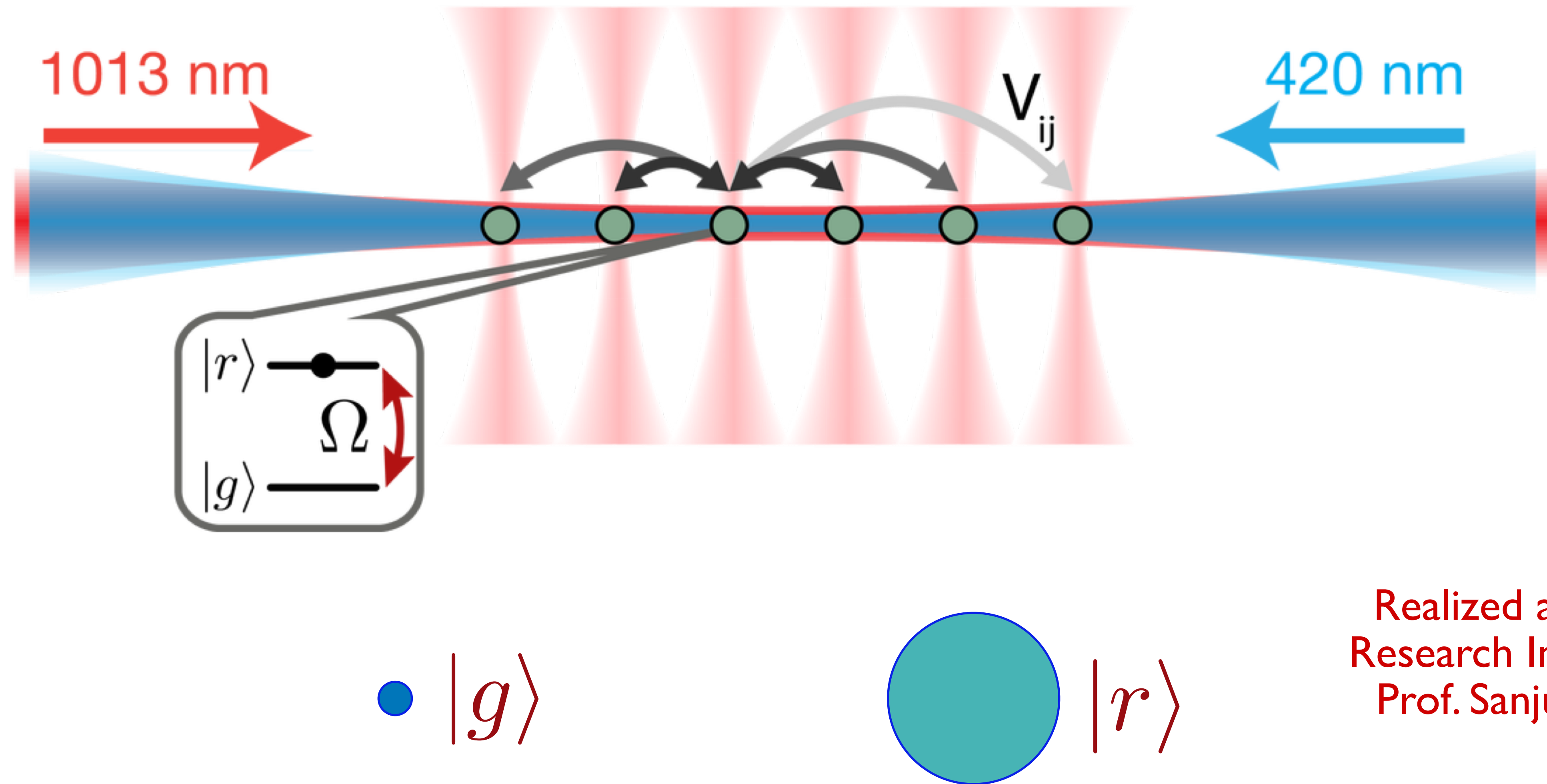
Read and Sachdev (1990):

Determined the anyon structure of the resonating valence bond spin liquid.

The anyon structure of this spin liquid is the same as
Kitaev's *toric code* (1997).

Kitaev (1997): Place the quantum information in a superposition
of anyon sectors for fault-tolerant quantum computation.

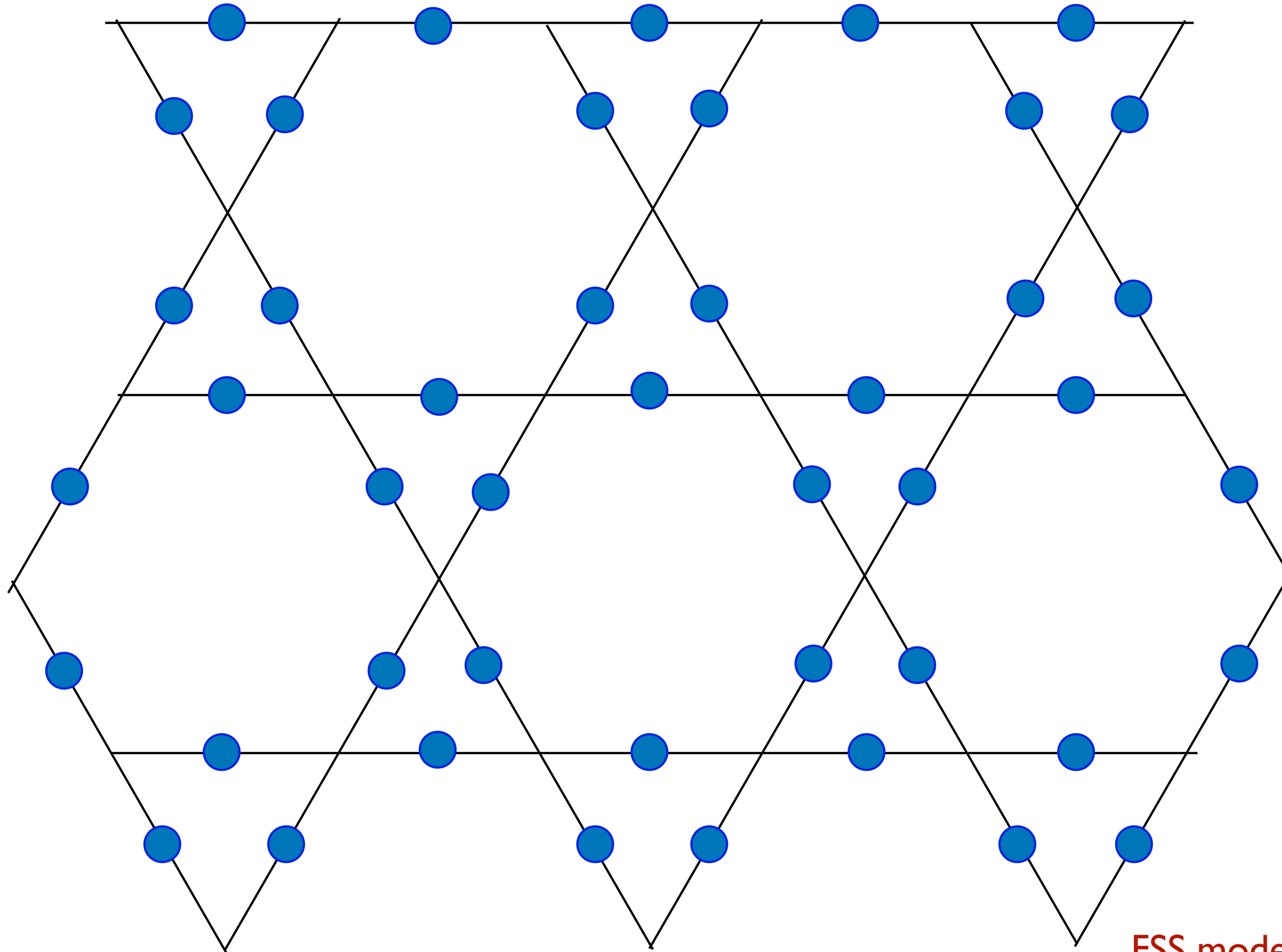
Qubits using Rydberg atoms in optical tweezers



Realized at Raman
Research Institute by
Prof. Sanjukta Roy

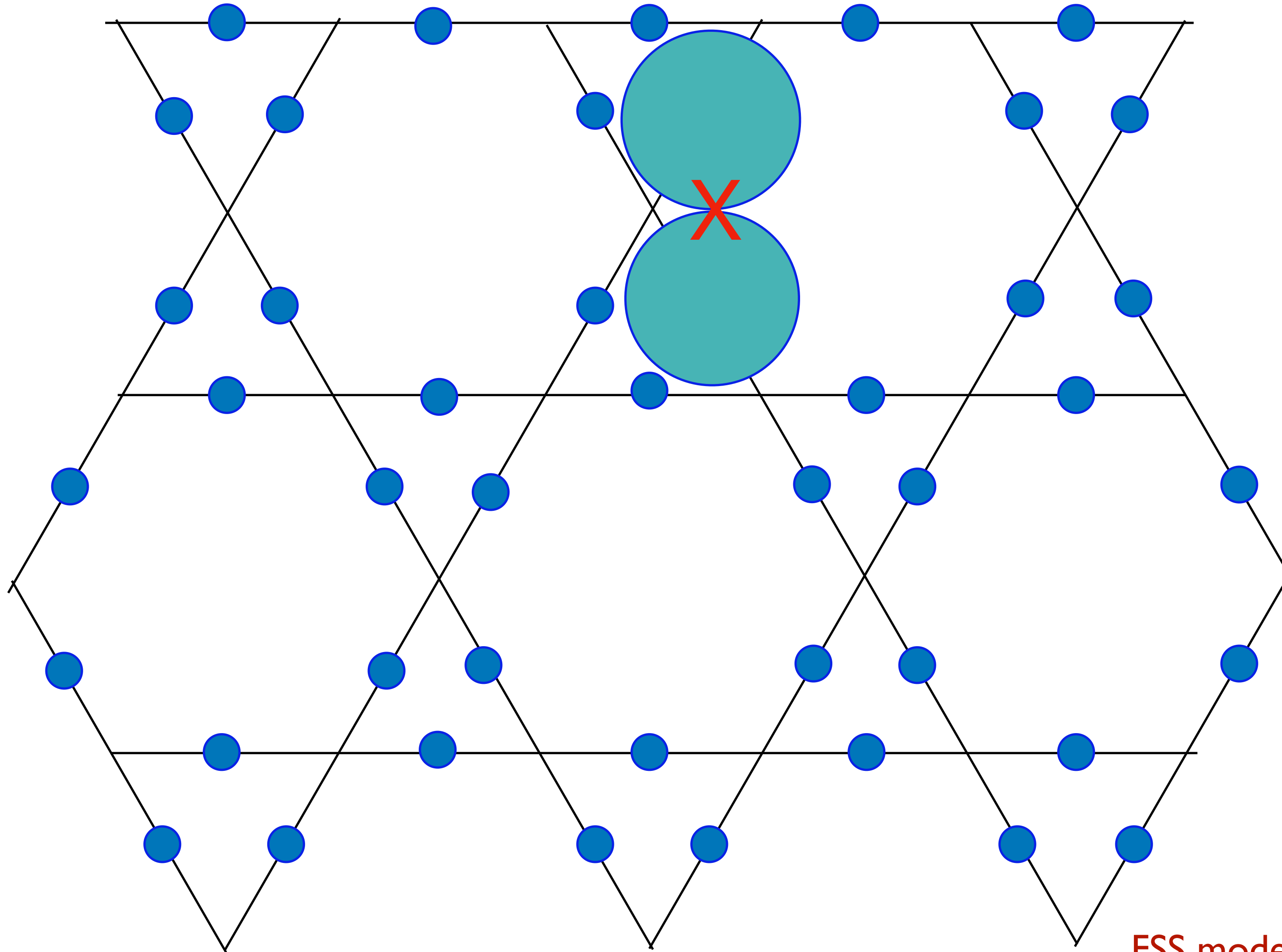
S. Ebadi, Tout T. Wang, H. Levine, A. Keesling, G. Semeghini, A. Omran, D. Bluvstein,
R. Samajdar, H. Pichler, Wen Wei Ho, Soonwon Choi, S. Sachdev, M. Greiner, V. Vuletić,
and M. D. Lukin, Nature **595**, 227 (2021)

Entangling Rydberg atom qubits



FSS model:
S. Sachdev, K. Sengupta, and S.M. Girvin, PRB **66**, 075128 (2002)
P. Fendley, K. Sengupta, S. Sachdev, PRB **69**, 075106 (2004)

Entangling Rydberg atom qubits



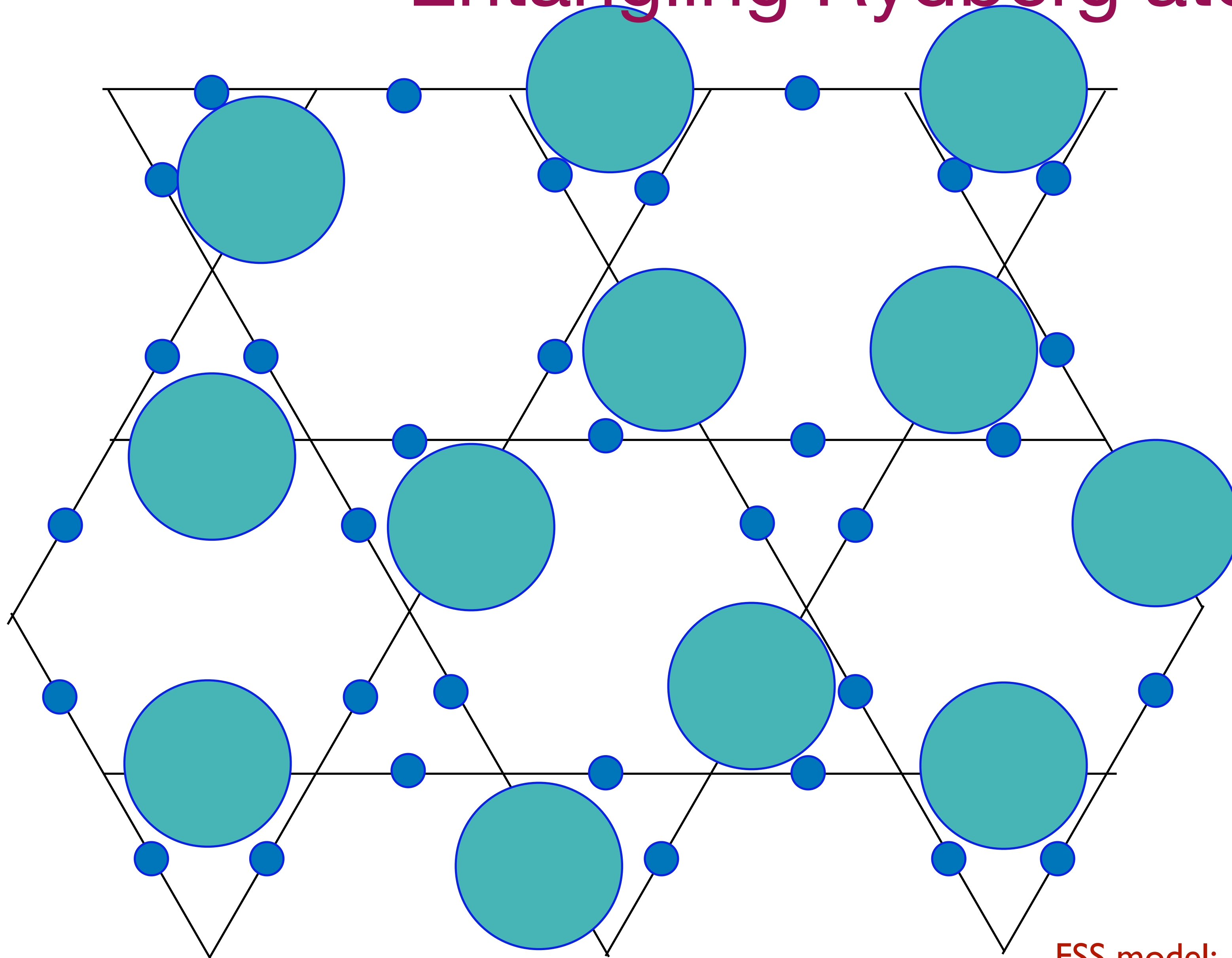
NOT
ALLOWED

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ALLOWED

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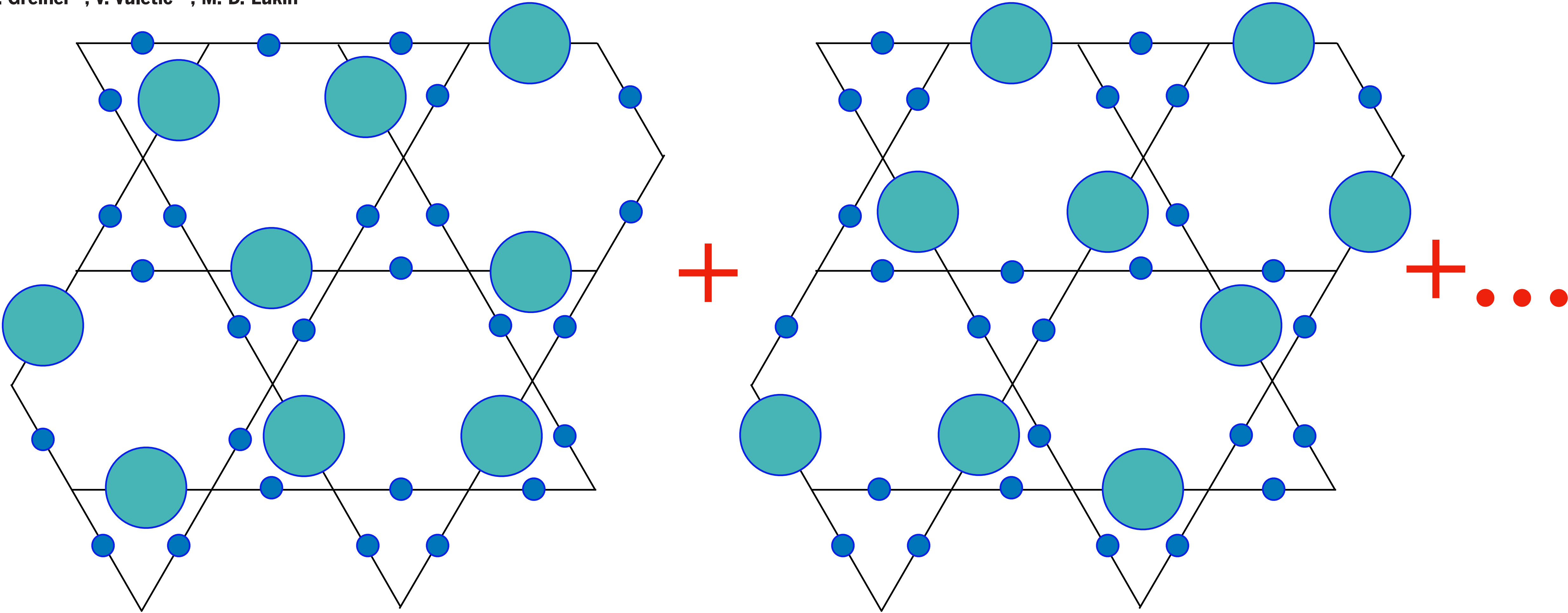
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Probing topological spin liquids on a programmable quantum simulator

Science **374**, 1242–1247 (2021)

G. Semeghini¹, H. Levine¹, A. Keesling^{1,2}, S. Ebadi¹, T. T. Wang¹, D. Bluvstein¹, R. Verresen¹,
H. Pichler^{3,4}, M. Kalinowski¹, R. Samajdar¹, A. Omran^{1,2}, S. Sachdev^{1,5}, A. Vishwanath^{1*},
M. Greiner^{1*}, V. Vuletić^{6*}, M. D. Lukin^{1*}



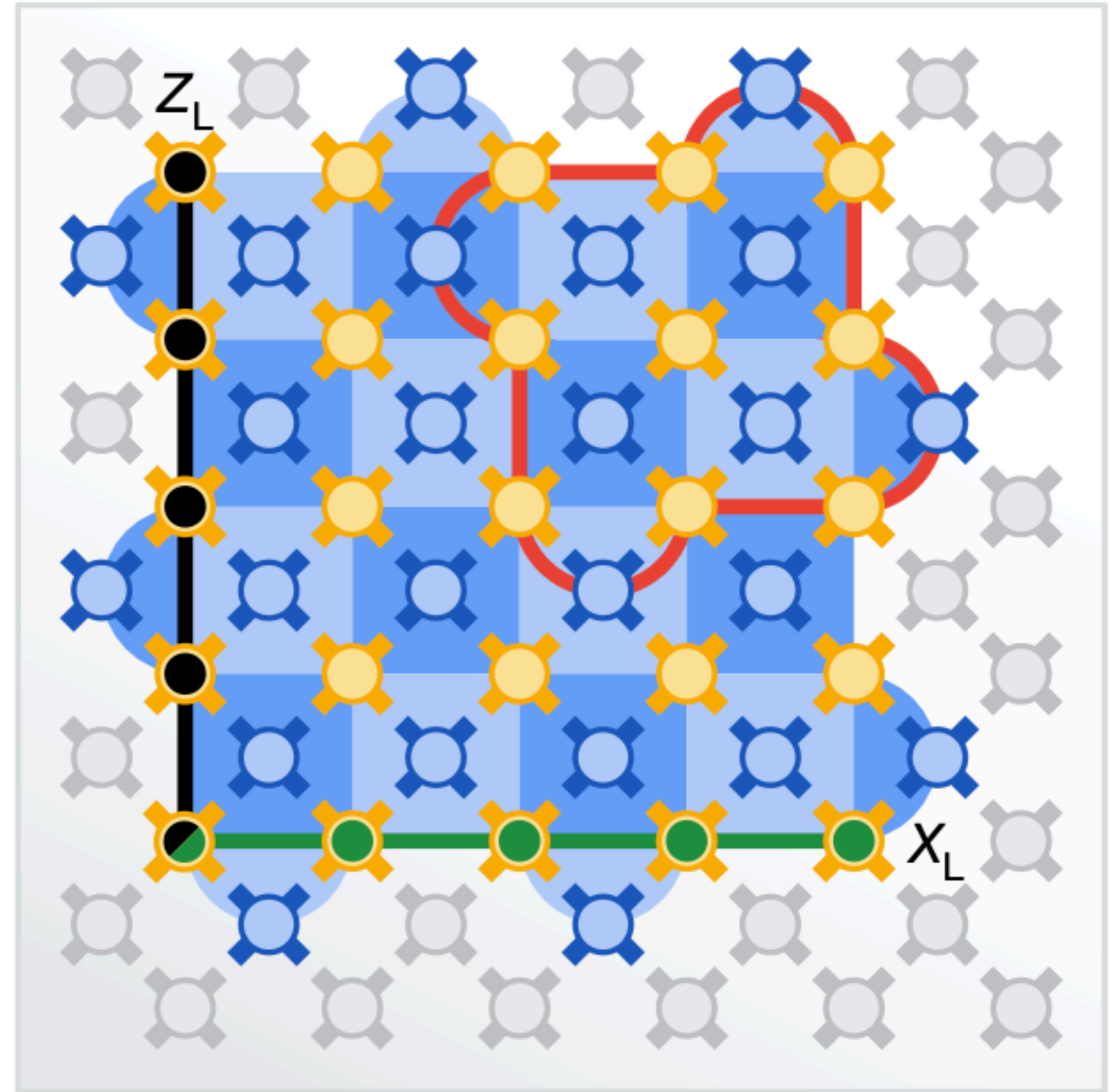
Entanglement similar to that in a RVB spin liquid

Suppressing quantum errors by scaling a surface code logical qubit

Google Quantum AI*

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“Surface code” is closely related to the “toric code”



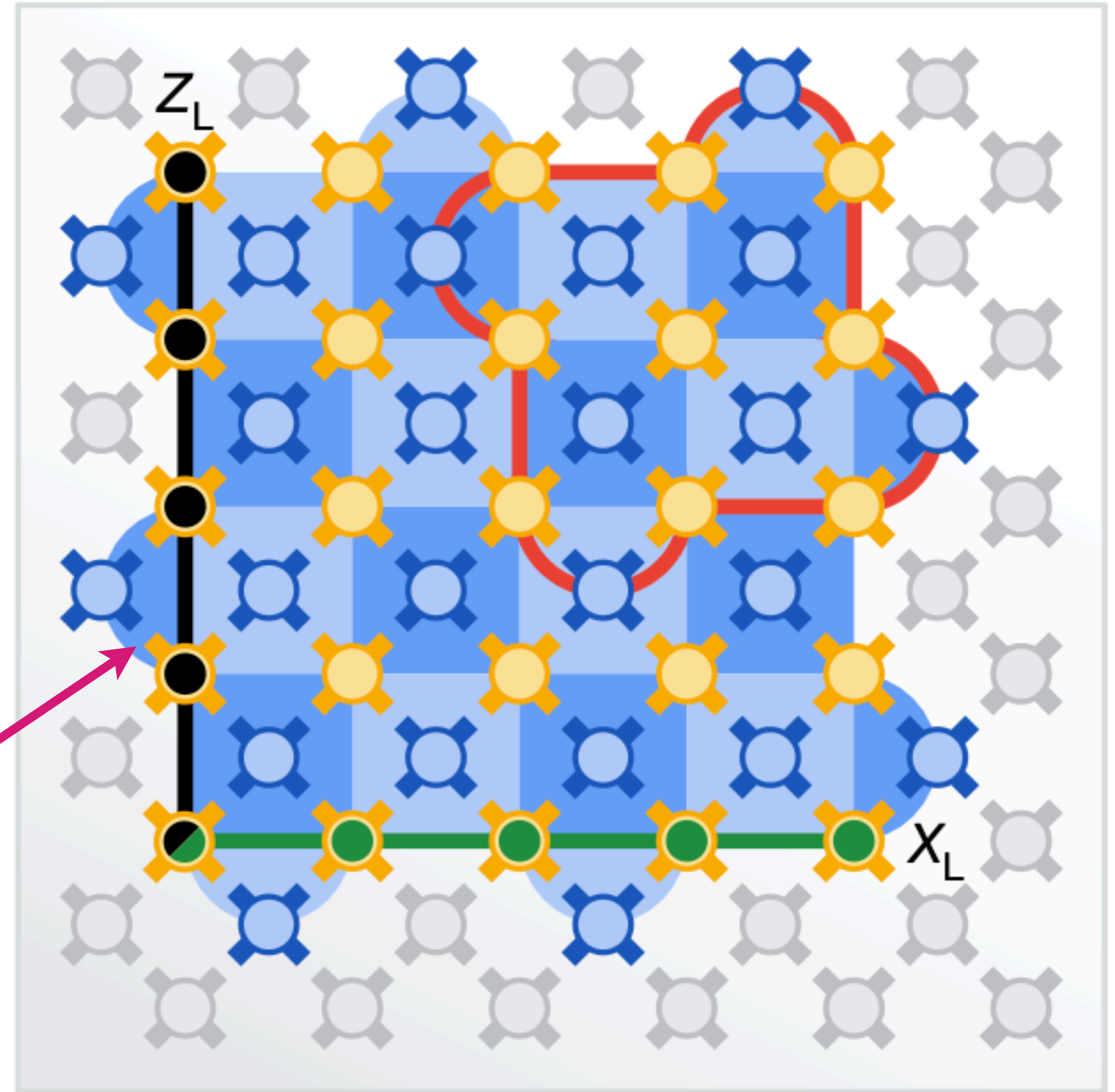
Suppressing quantum errors by scaling a surface code logical qubit

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“Surface code” is closely related to the “toric code”

Nobel Prize today for one of these superconducting junctions !



Although it has had a dramatic impact on theory/experiments on
fault-tolerant quantum computations,
the theory of spin liquids with well-defined anyons
does *not* solve the problem of
high temperature superconductivity in the cuprates

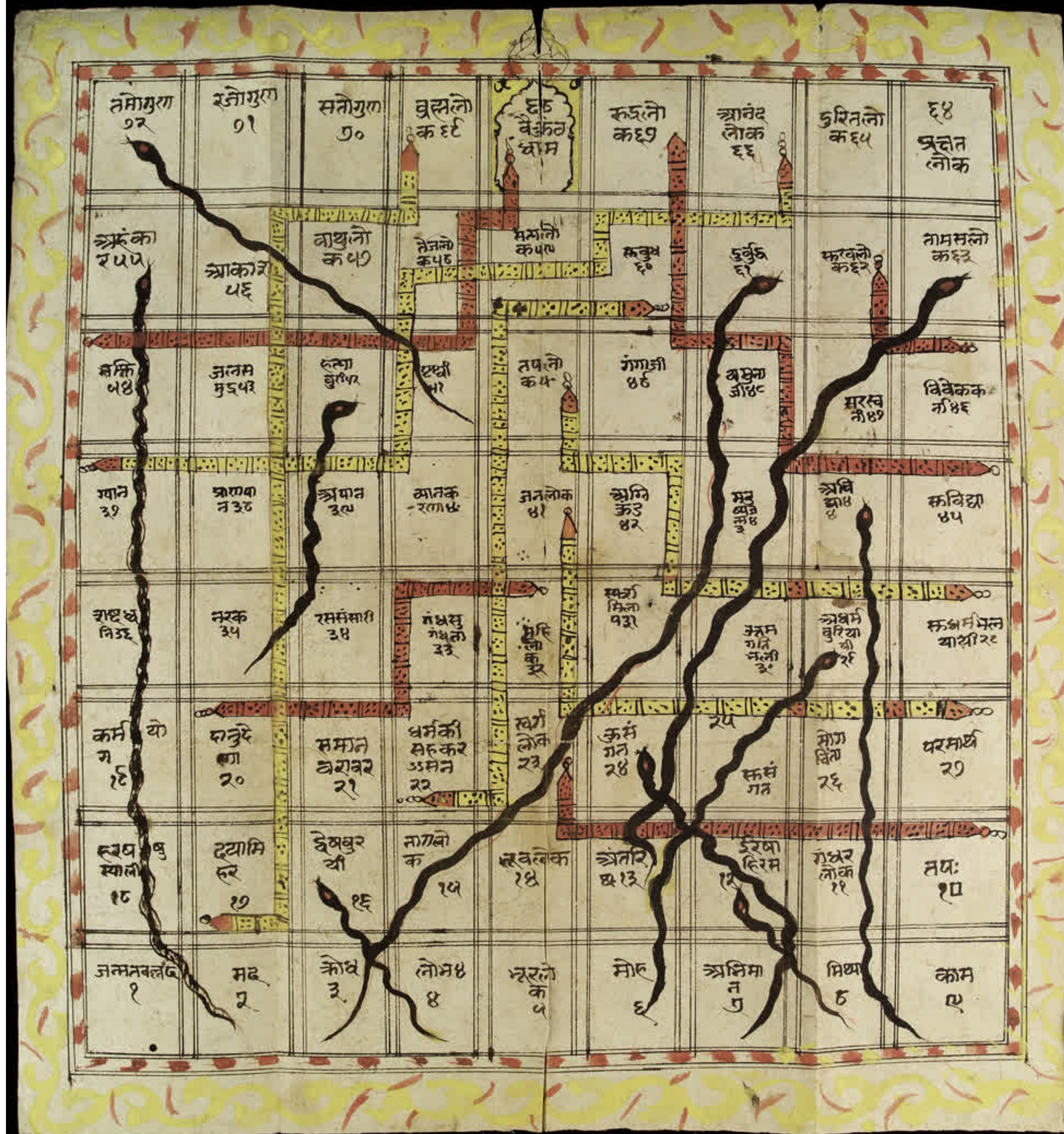
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**The Sachdev-Ye-Kitaev model
of entanglement of mobile fermions**

My
spooky
dream*

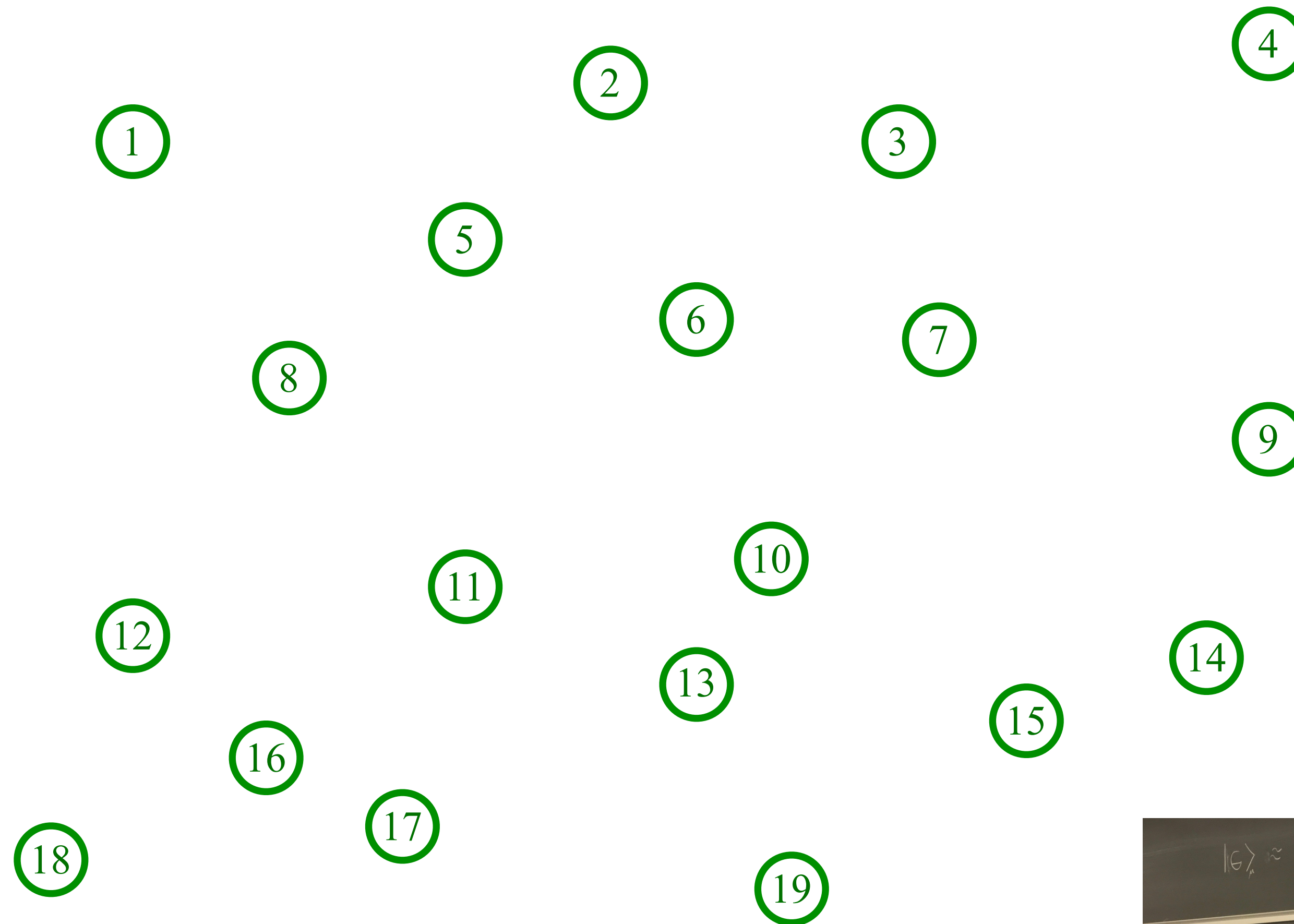
Ancient
Indian
game of
Snakes
and
Ladders

*Not true

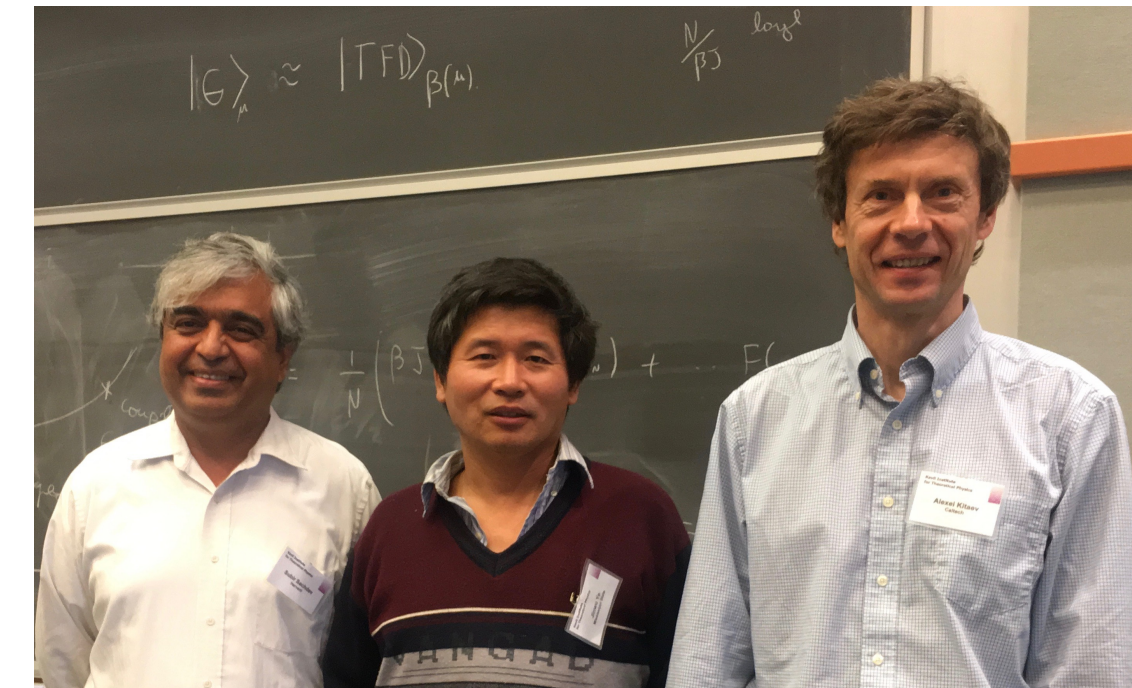


The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

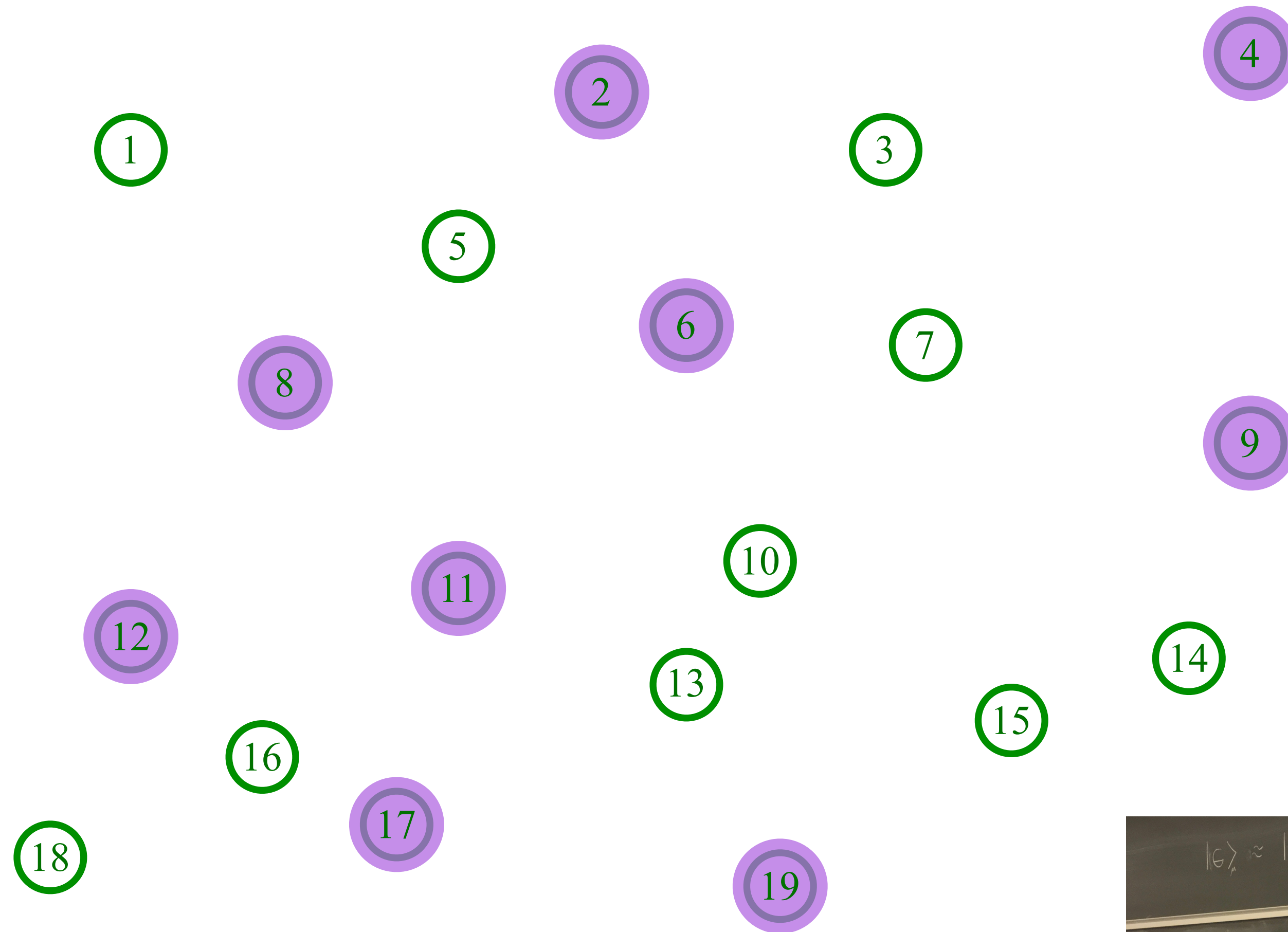


Pick a set of random positions

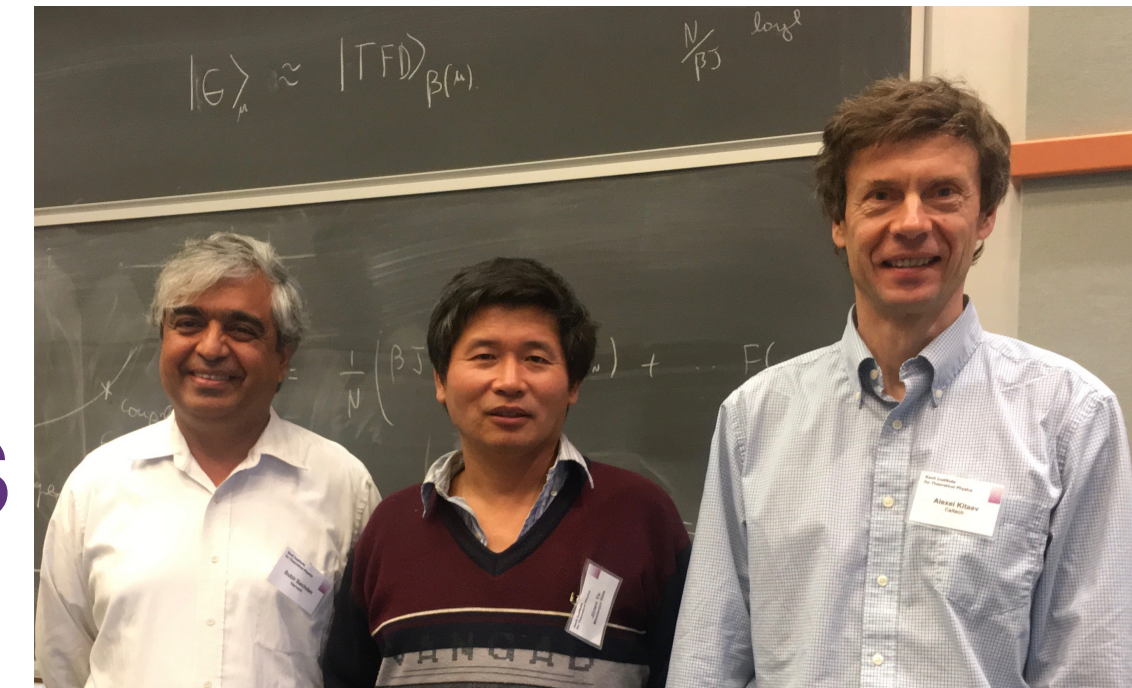


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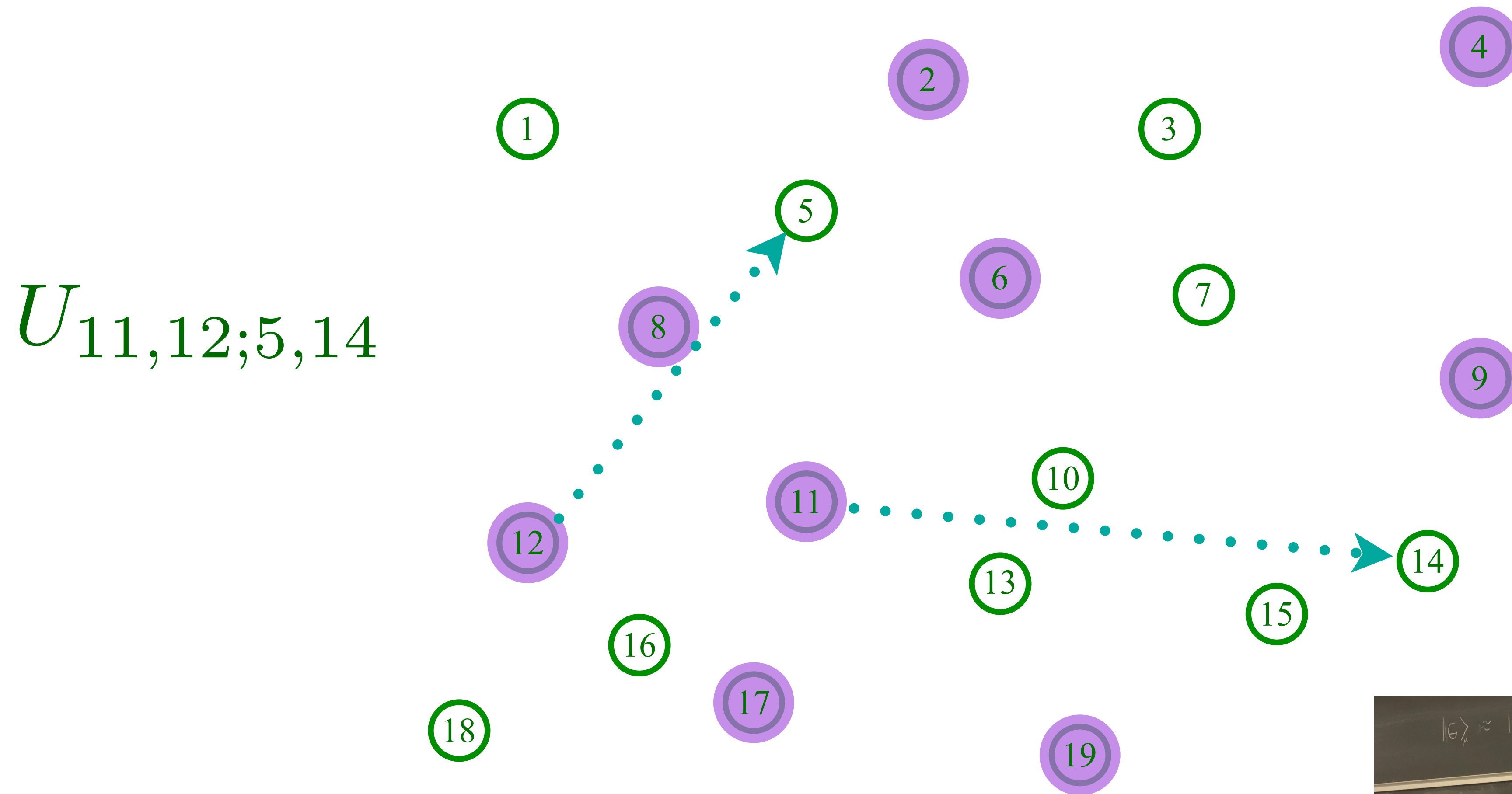


Place electrons randomly on some sites

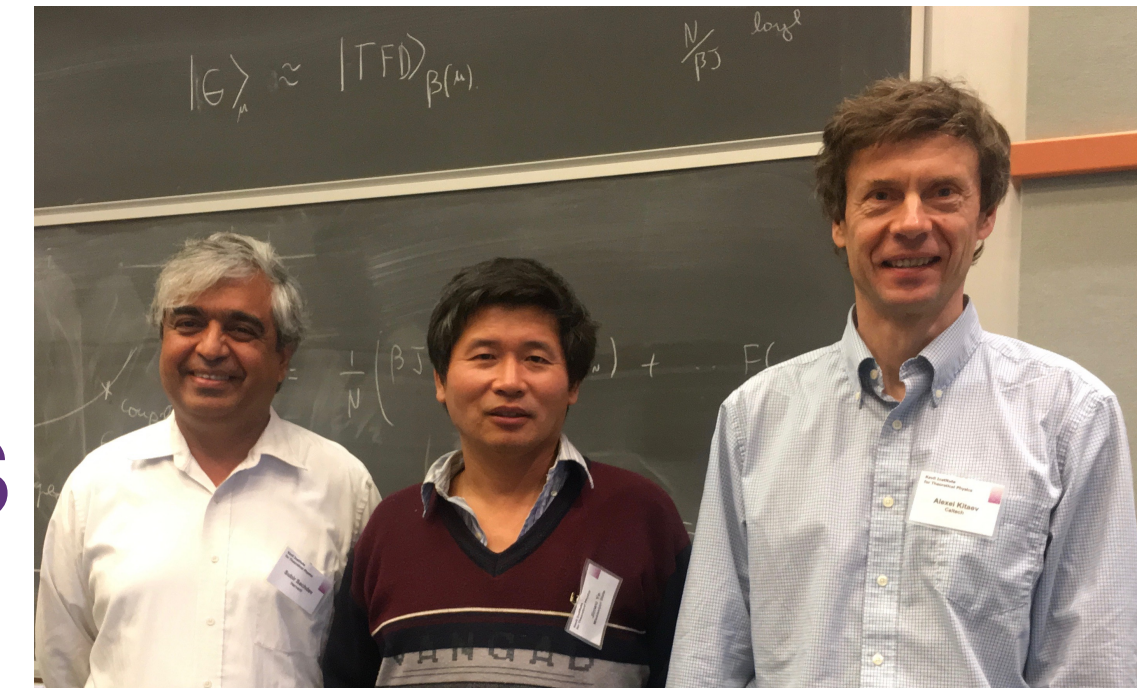


The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)



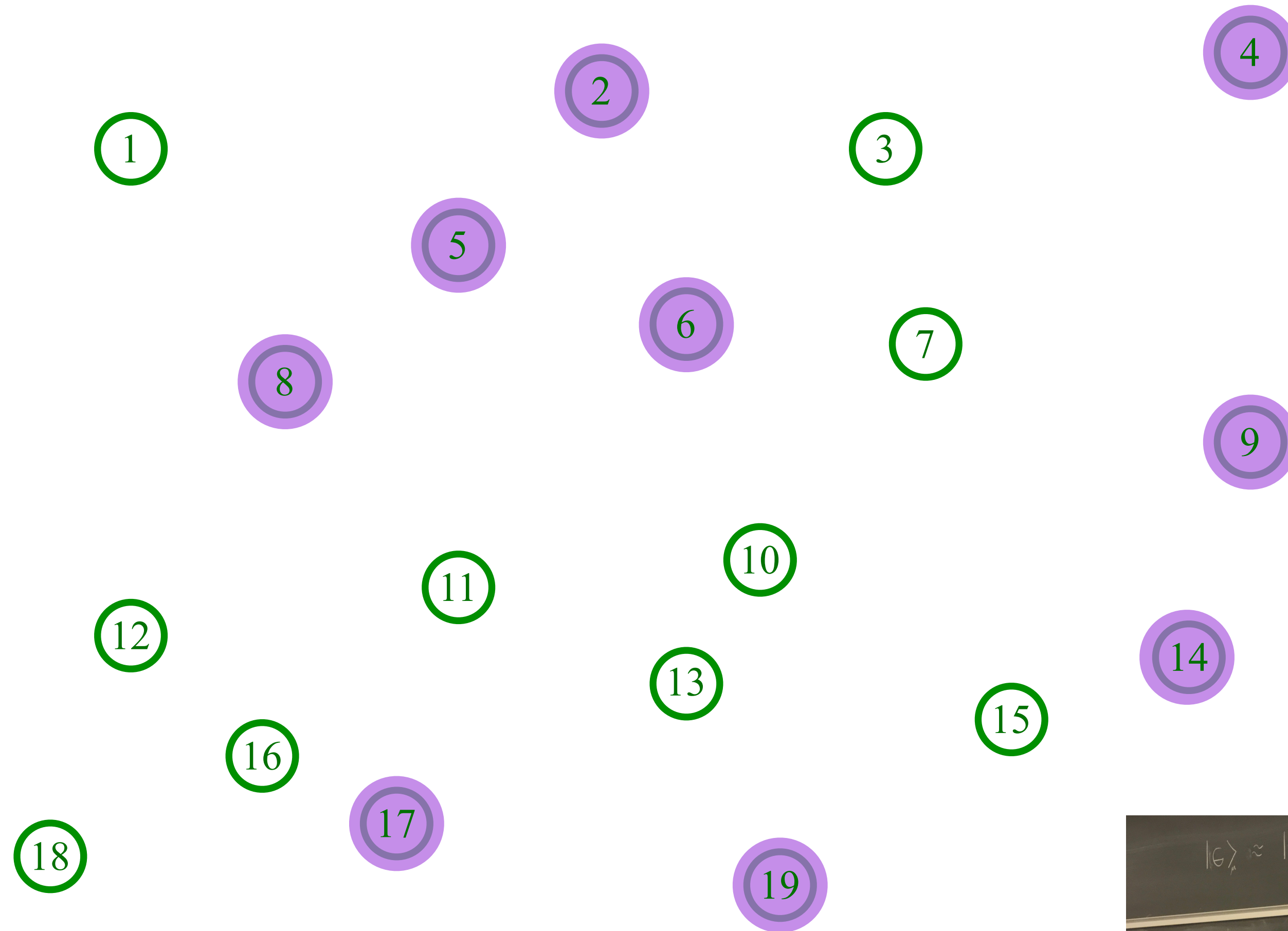
Place electrons randomly on some sites



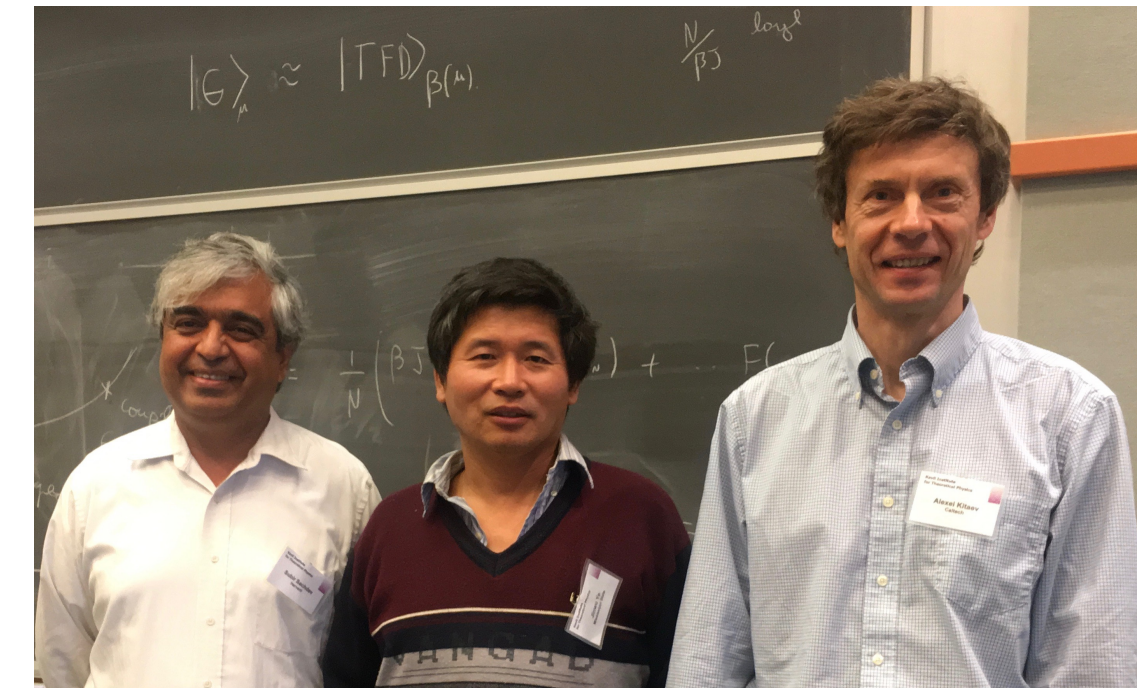
The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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

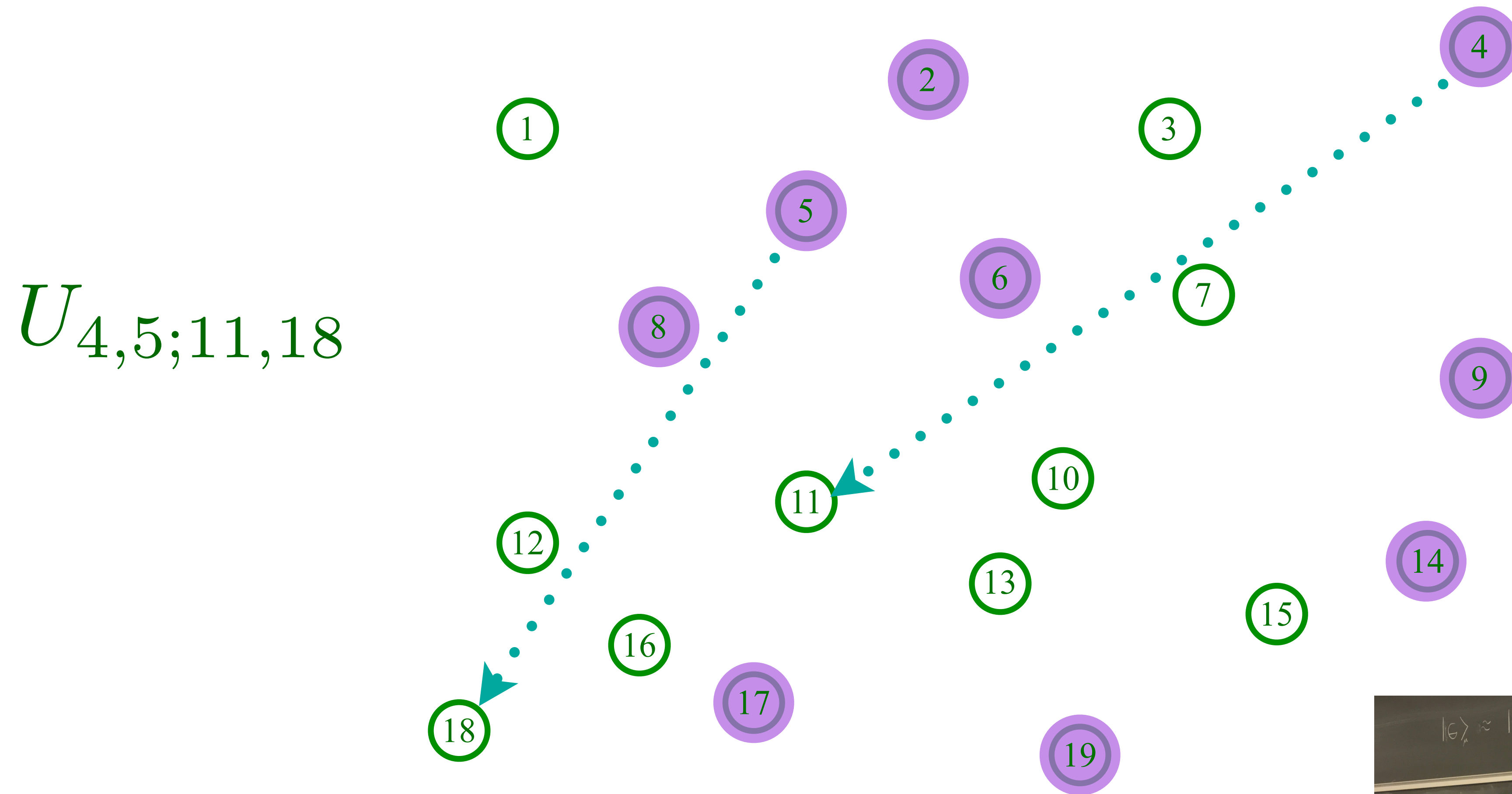


Entangle electrons pairwise randomly

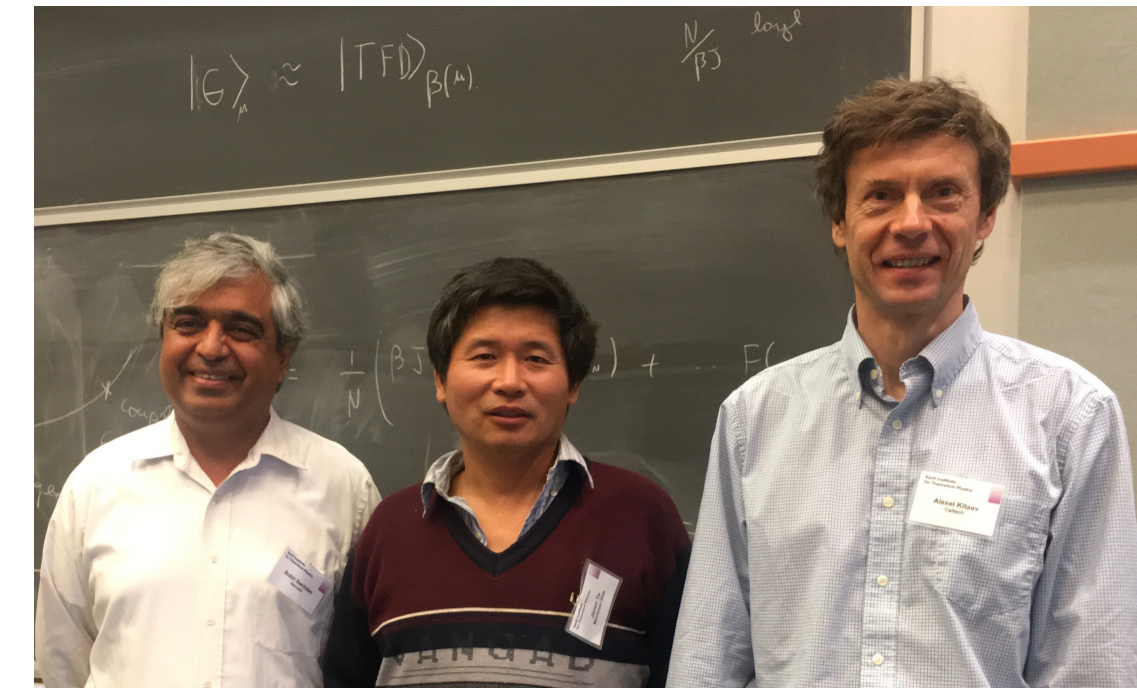


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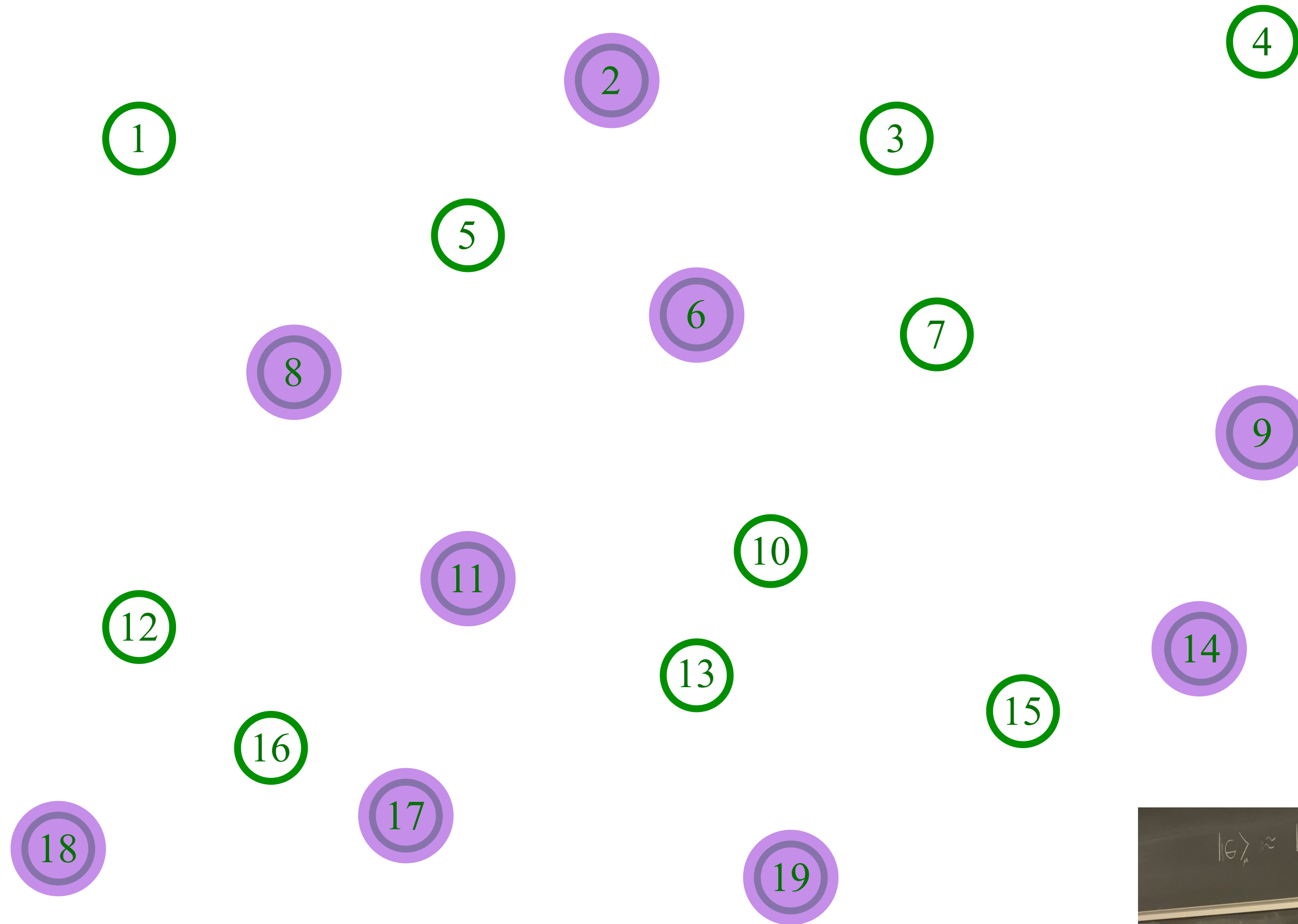
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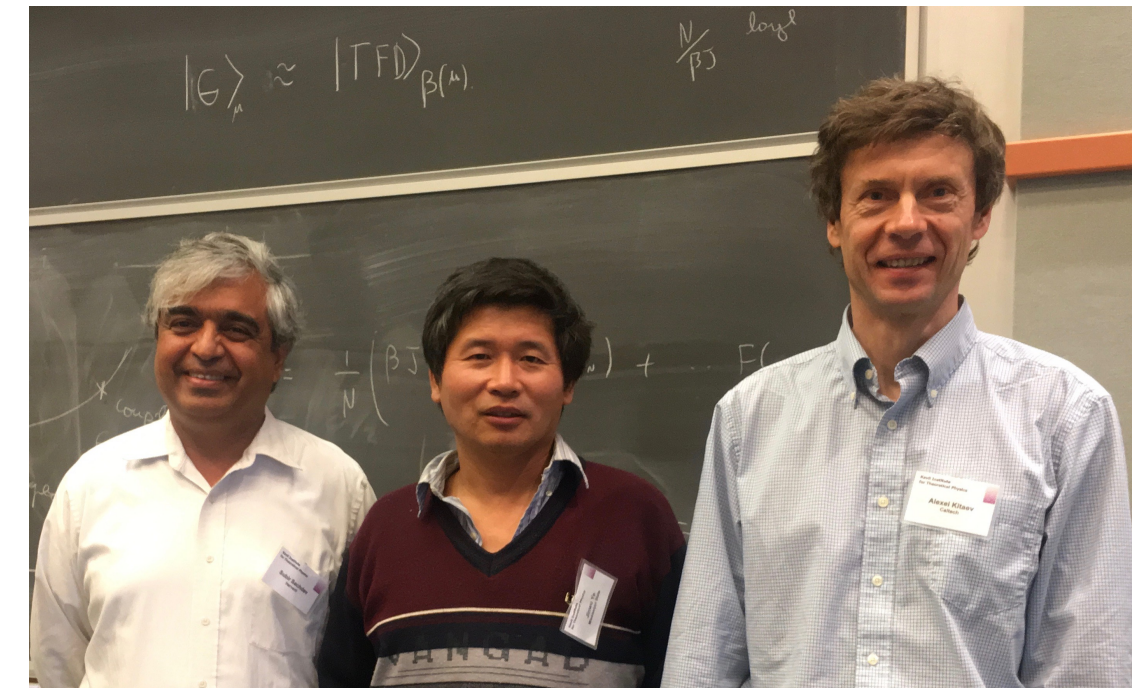
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Sachdev, Ye (1993); Kitaev (2015)

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

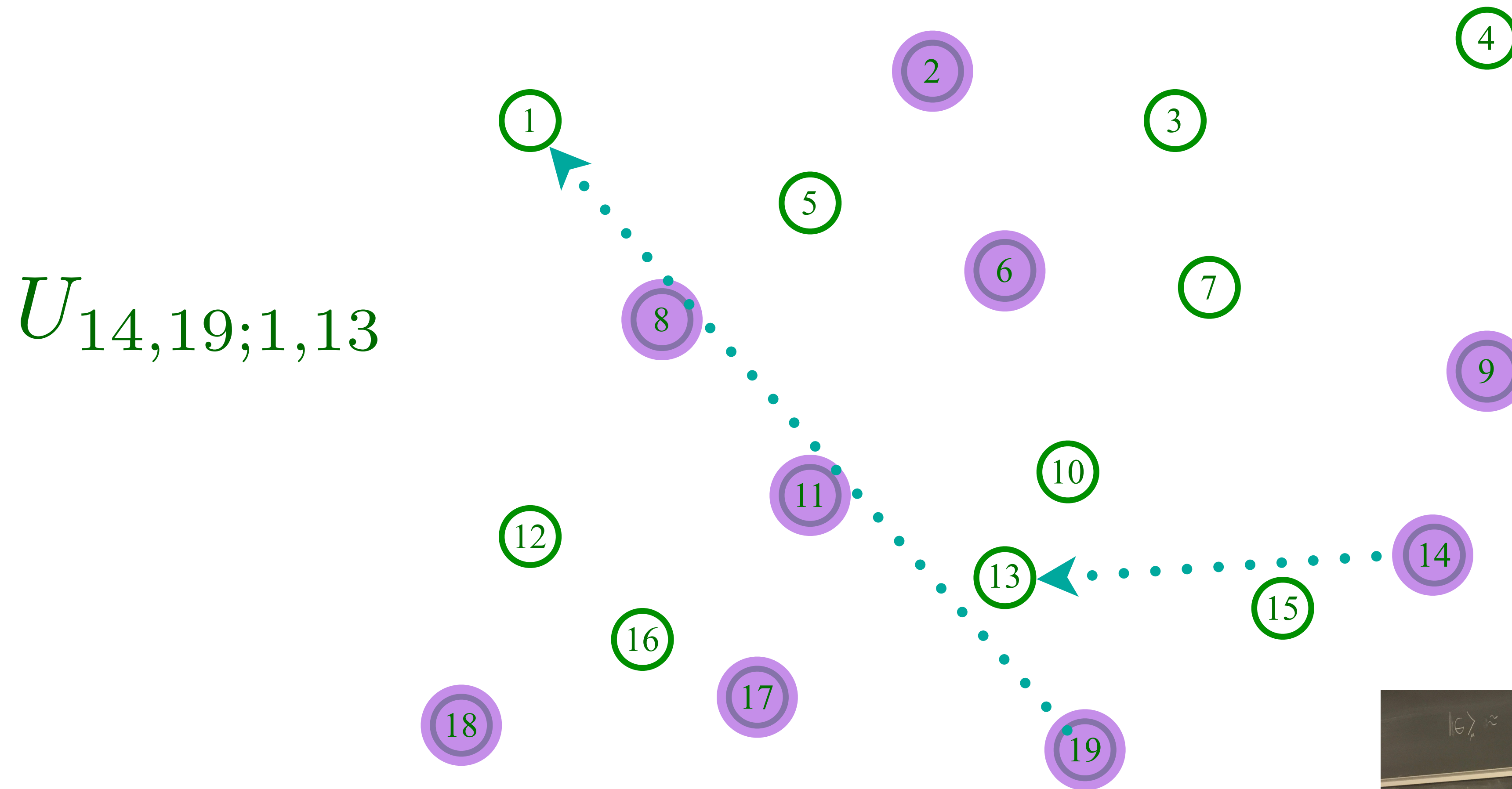


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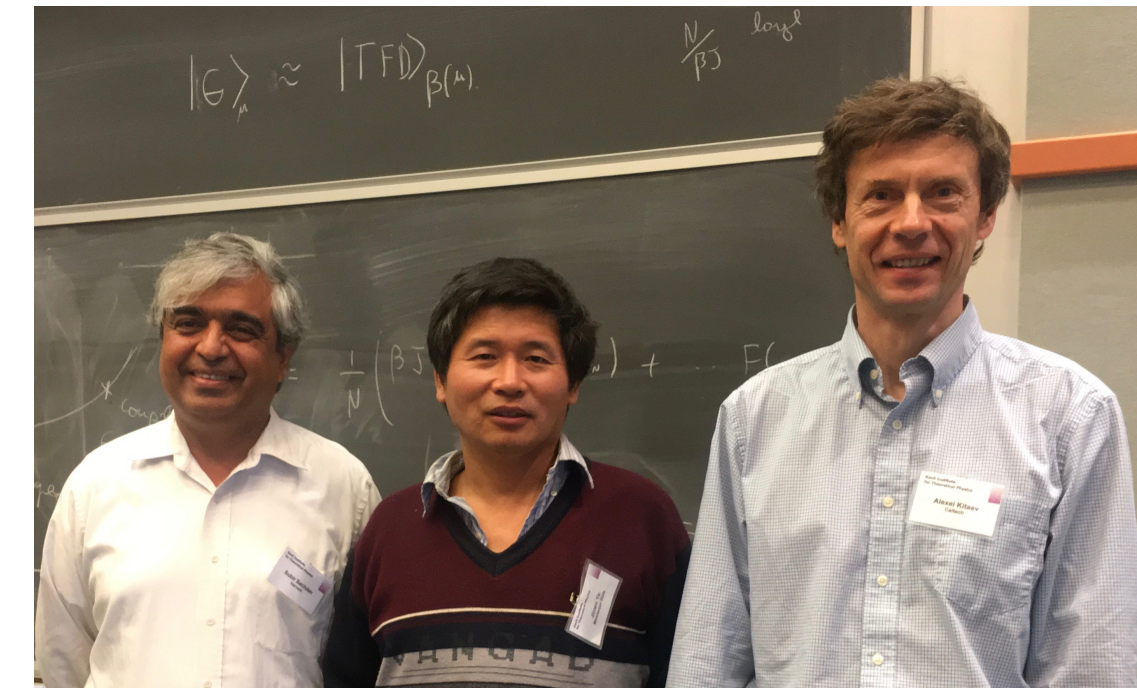


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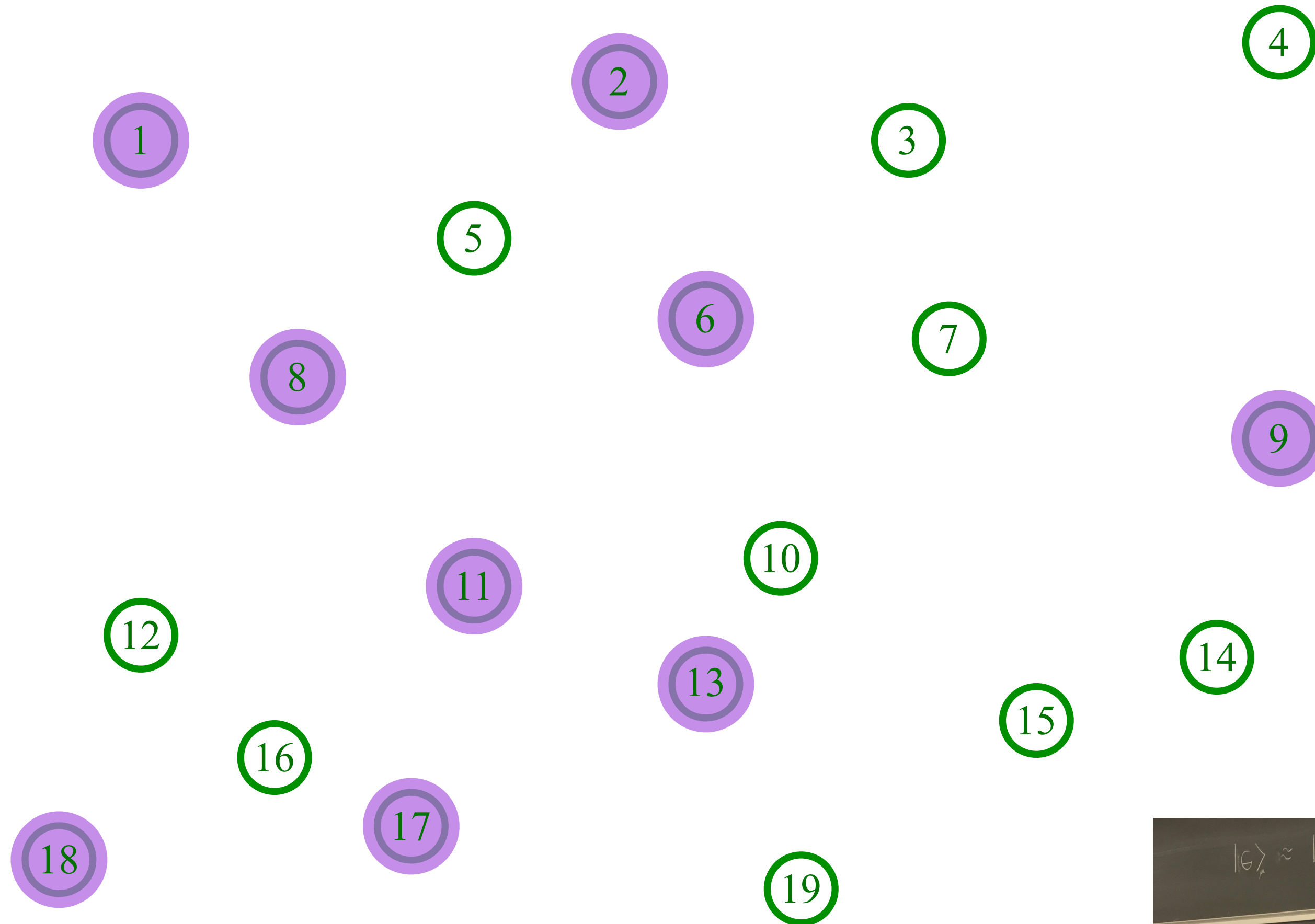
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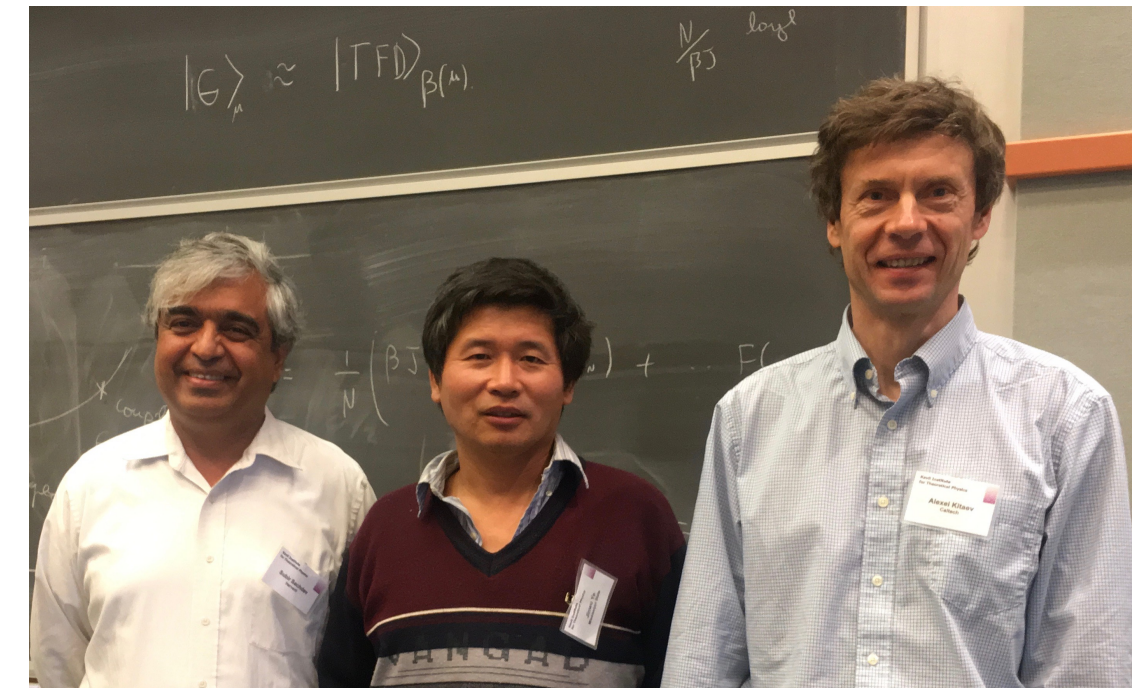
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Sachdev, Ye (1993); Kitaev (2015)

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

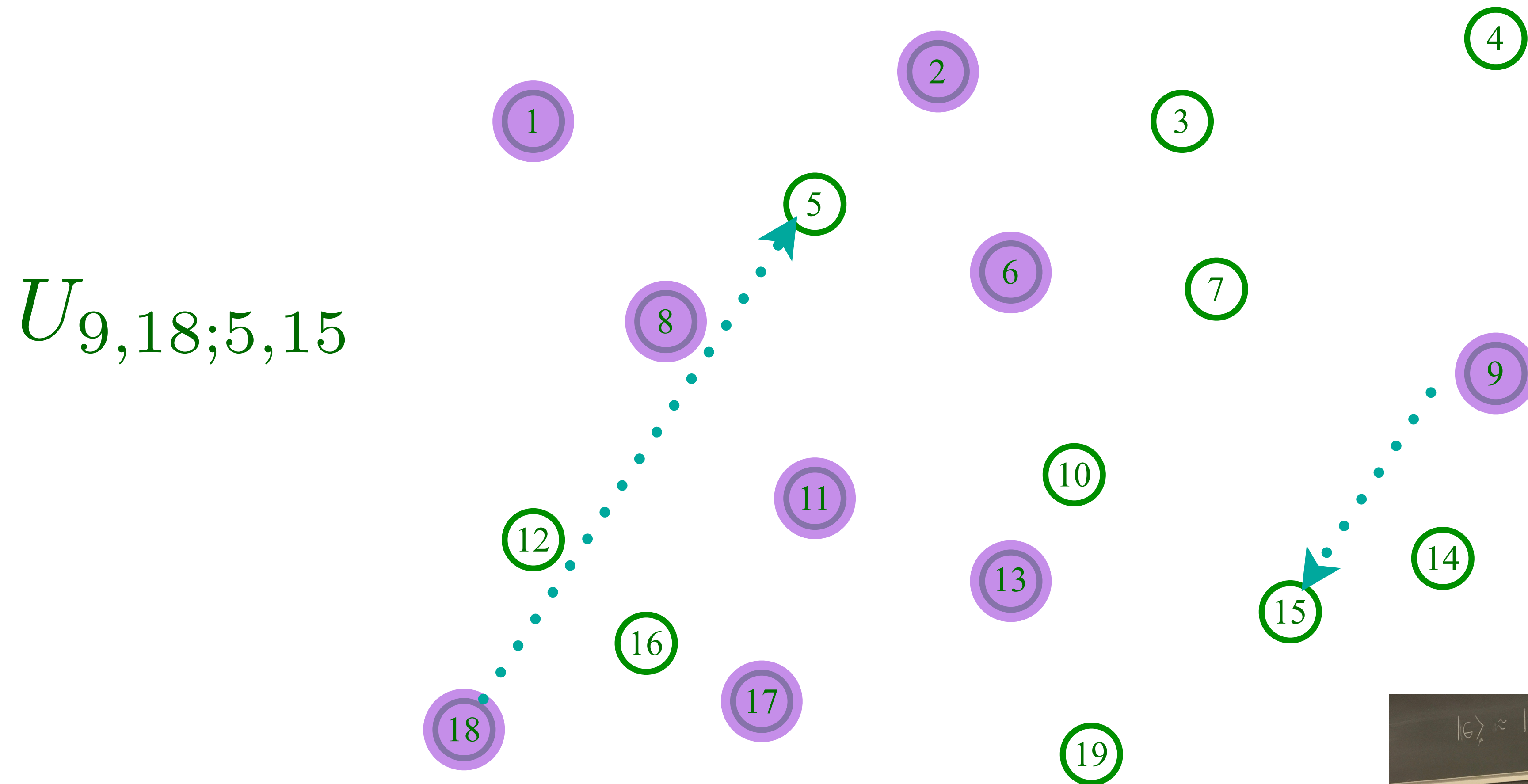


Entangle electrons pairwise randomly

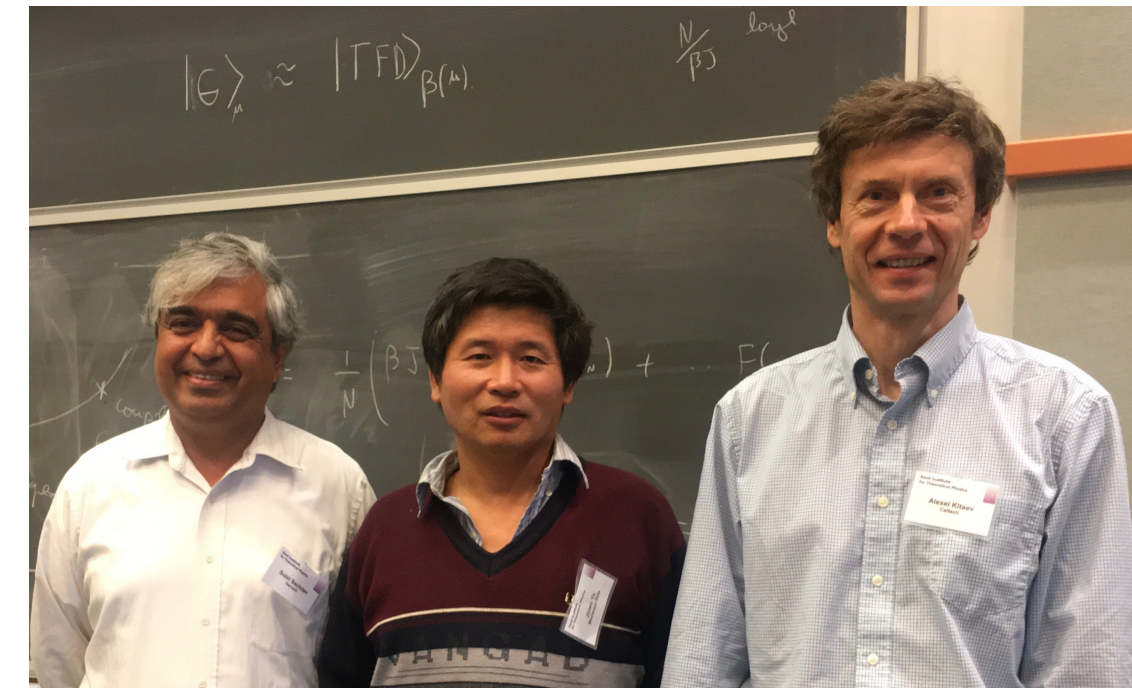


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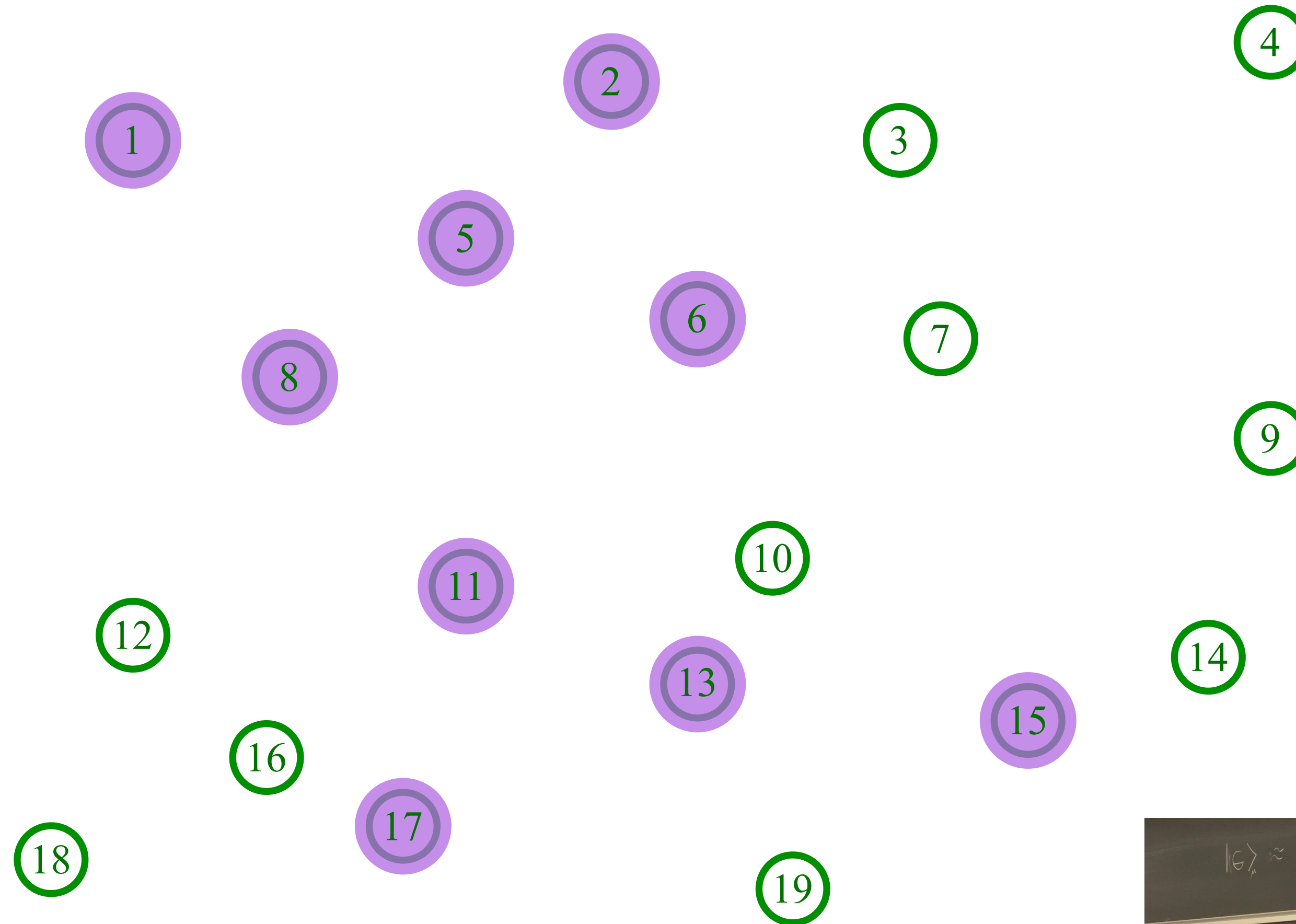
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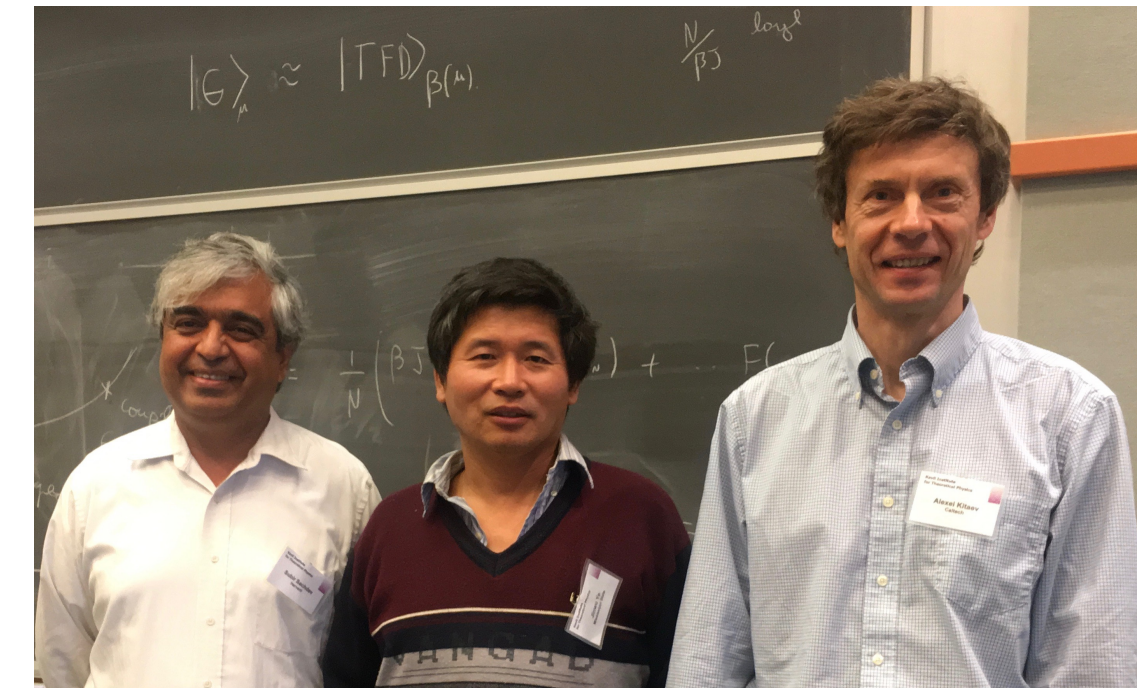
The Sachdev-Ye-Kitaev (SYK) model

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

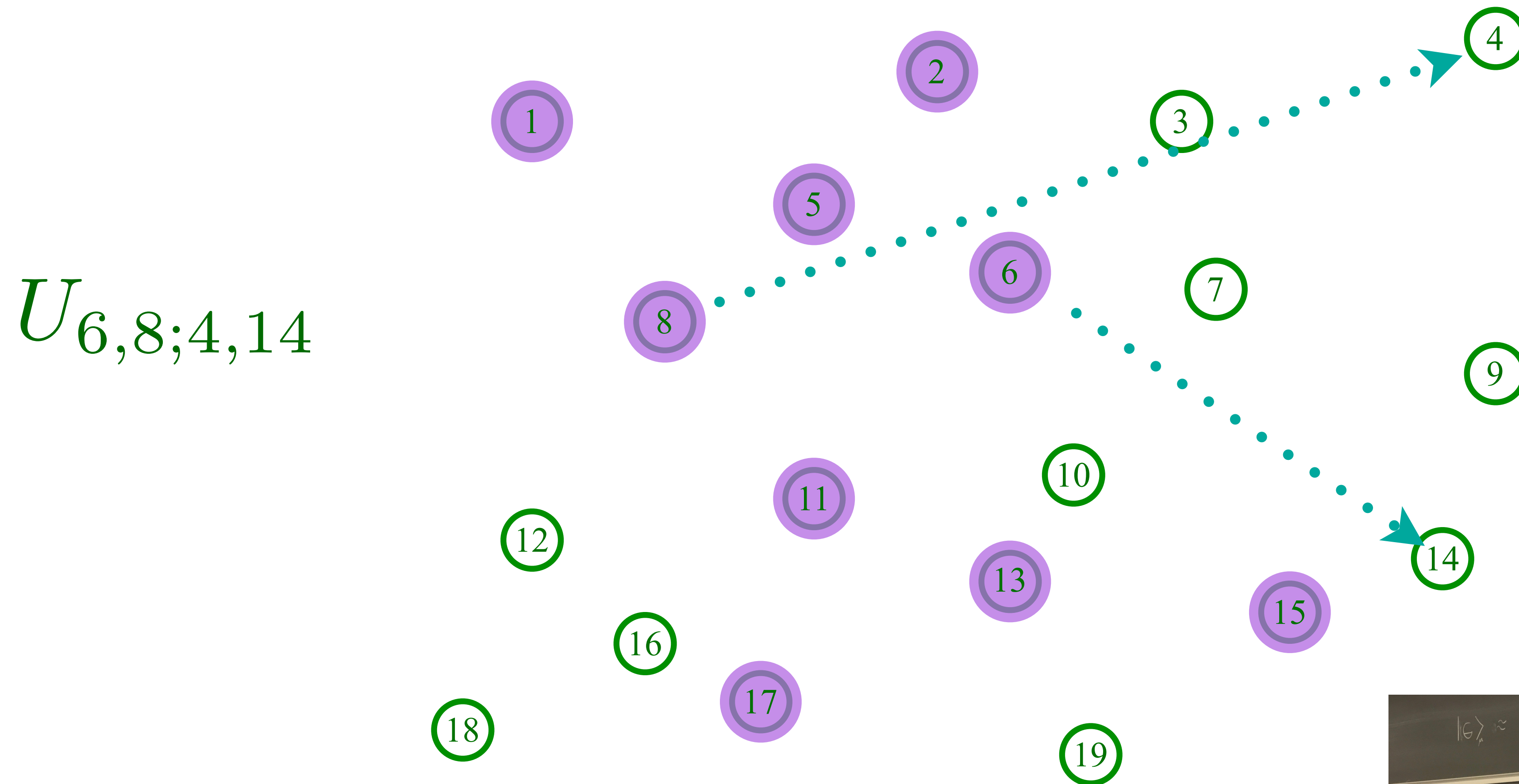


Entangle electrons pairwise randomly

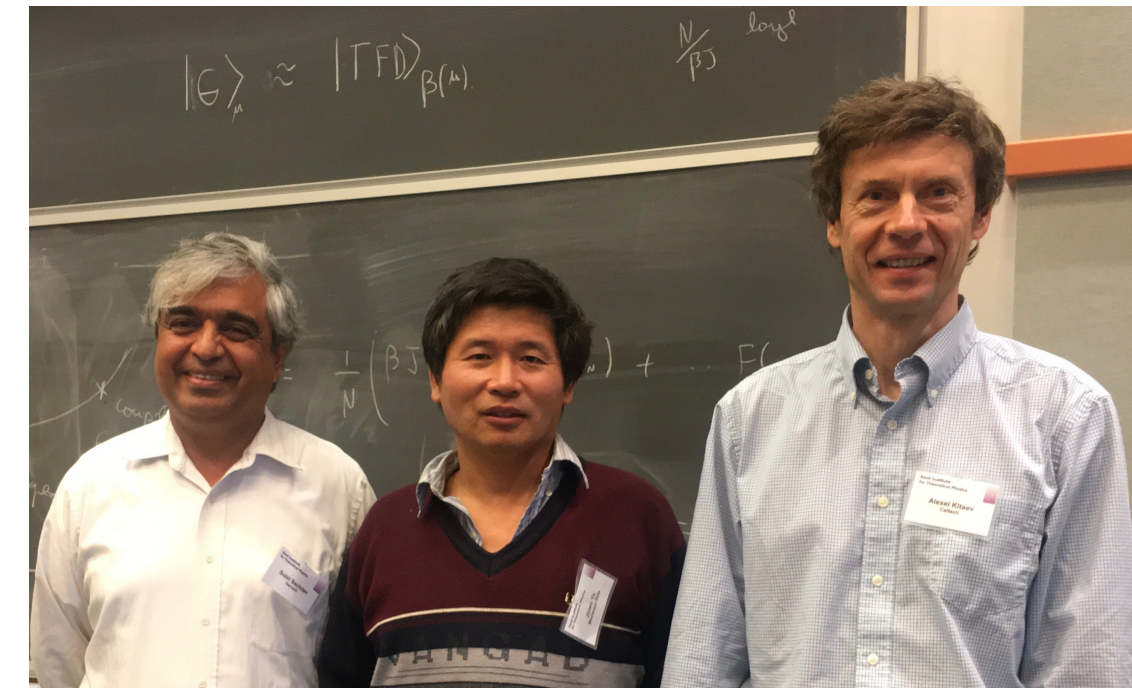


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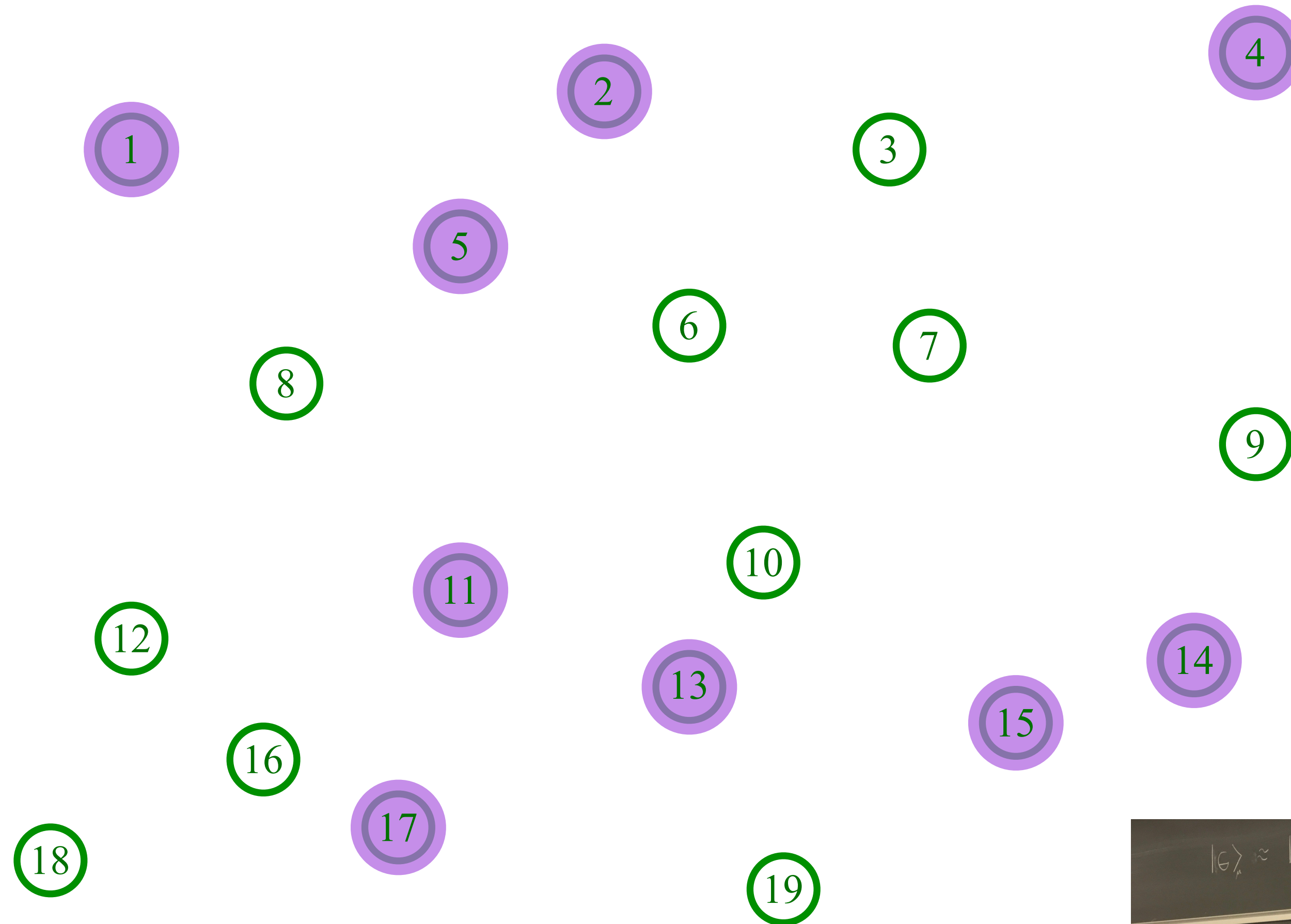
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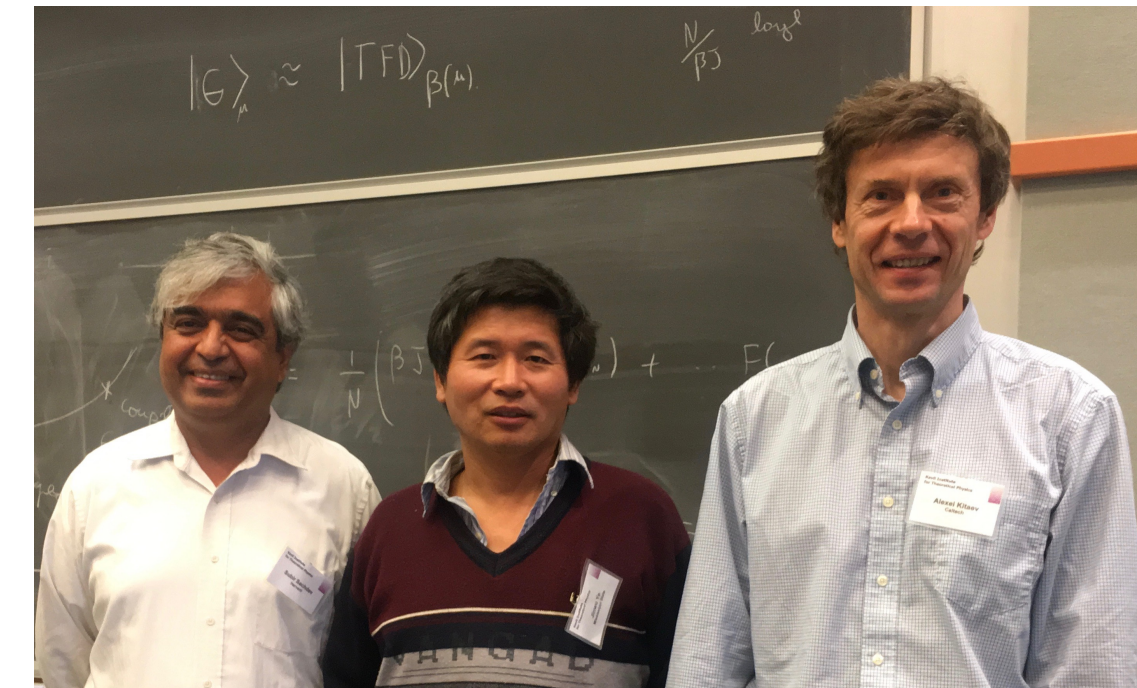
The Sachdev-Ye-Kitaev (SYK) model

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)

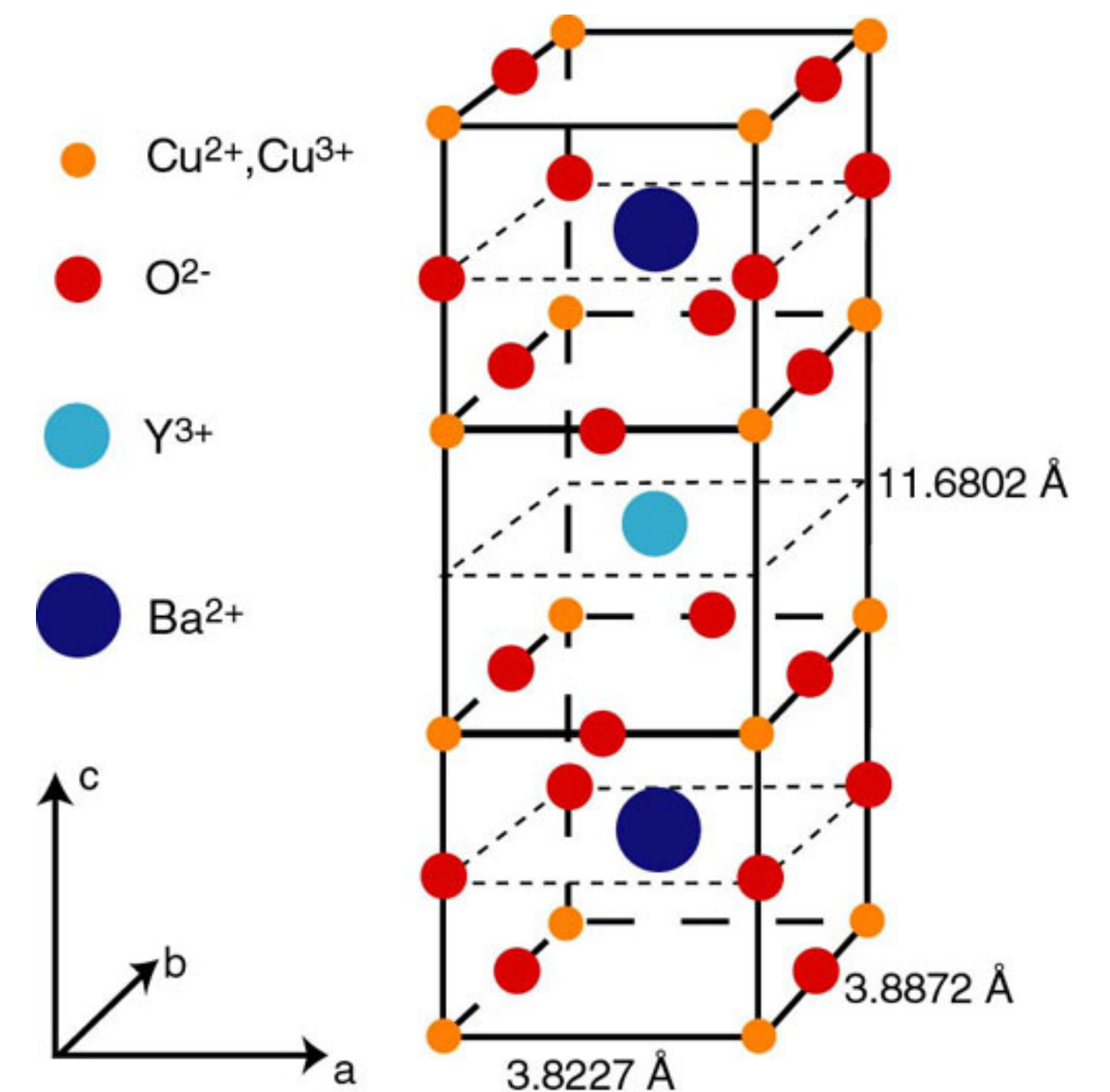
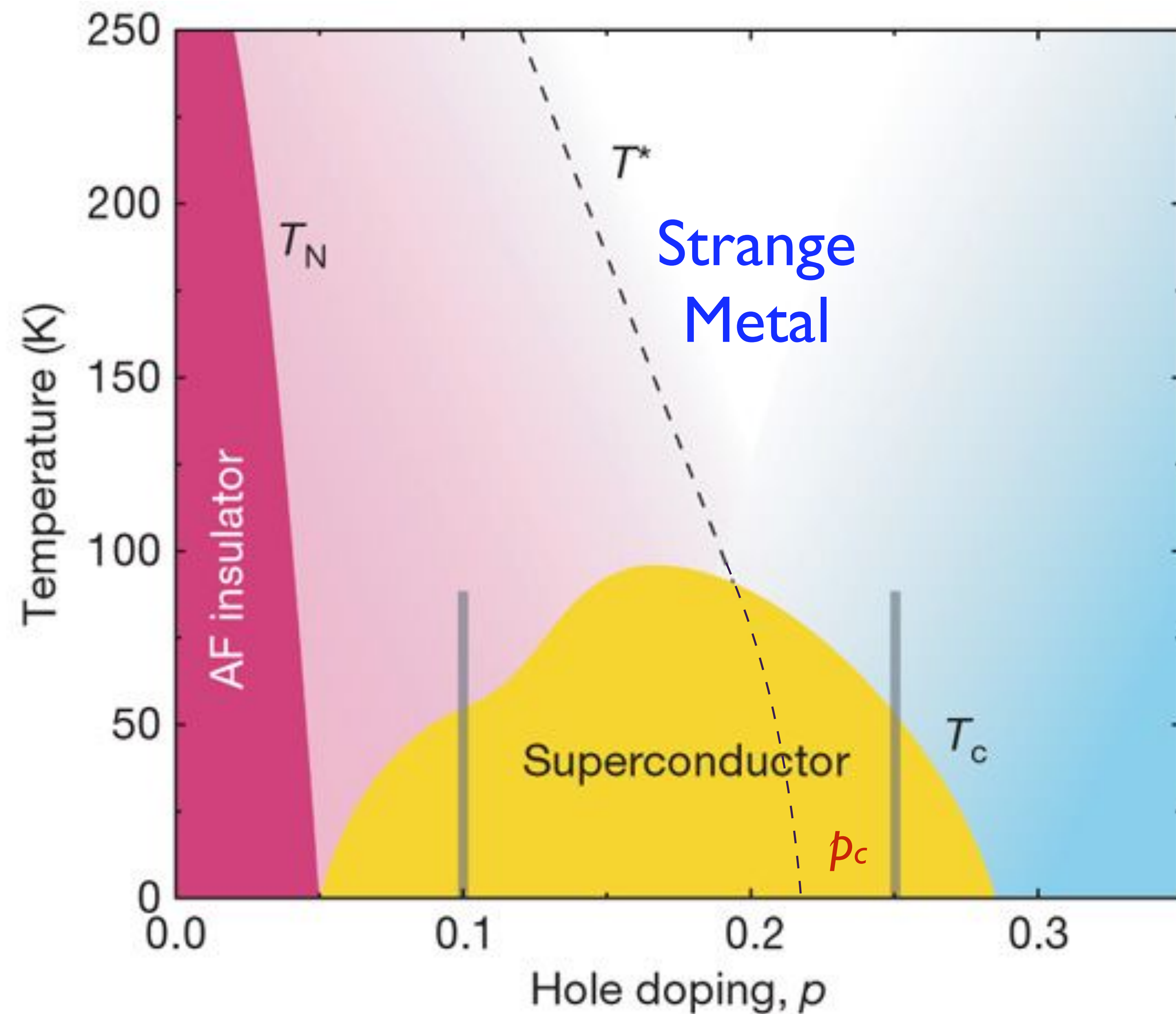
Yields a quantum state whose excitations are not particle-like i.e. no bosons, fermions, anyons....

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

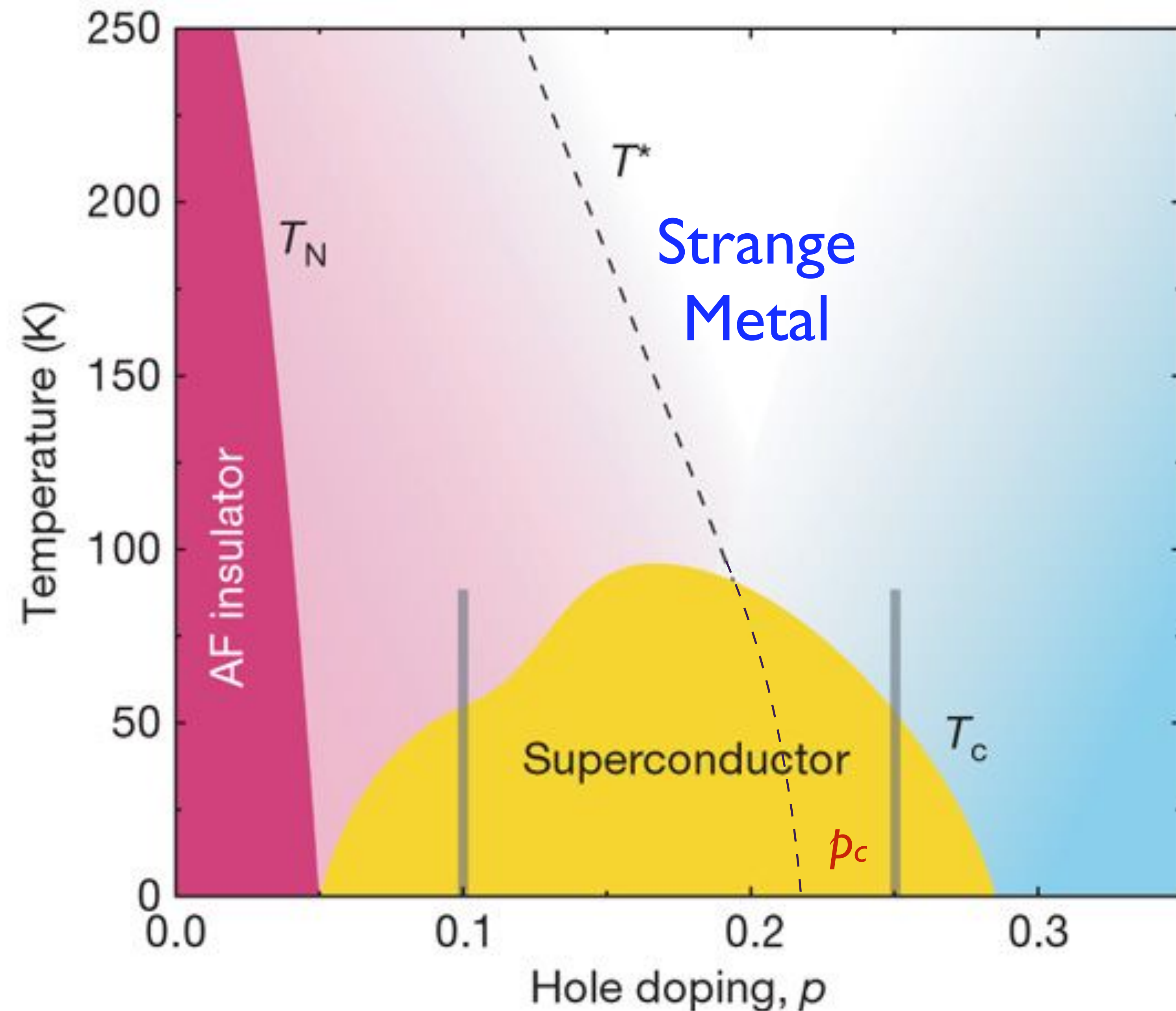
The relaxation time, τ , when perturbed at a frequency ω is given by

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

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



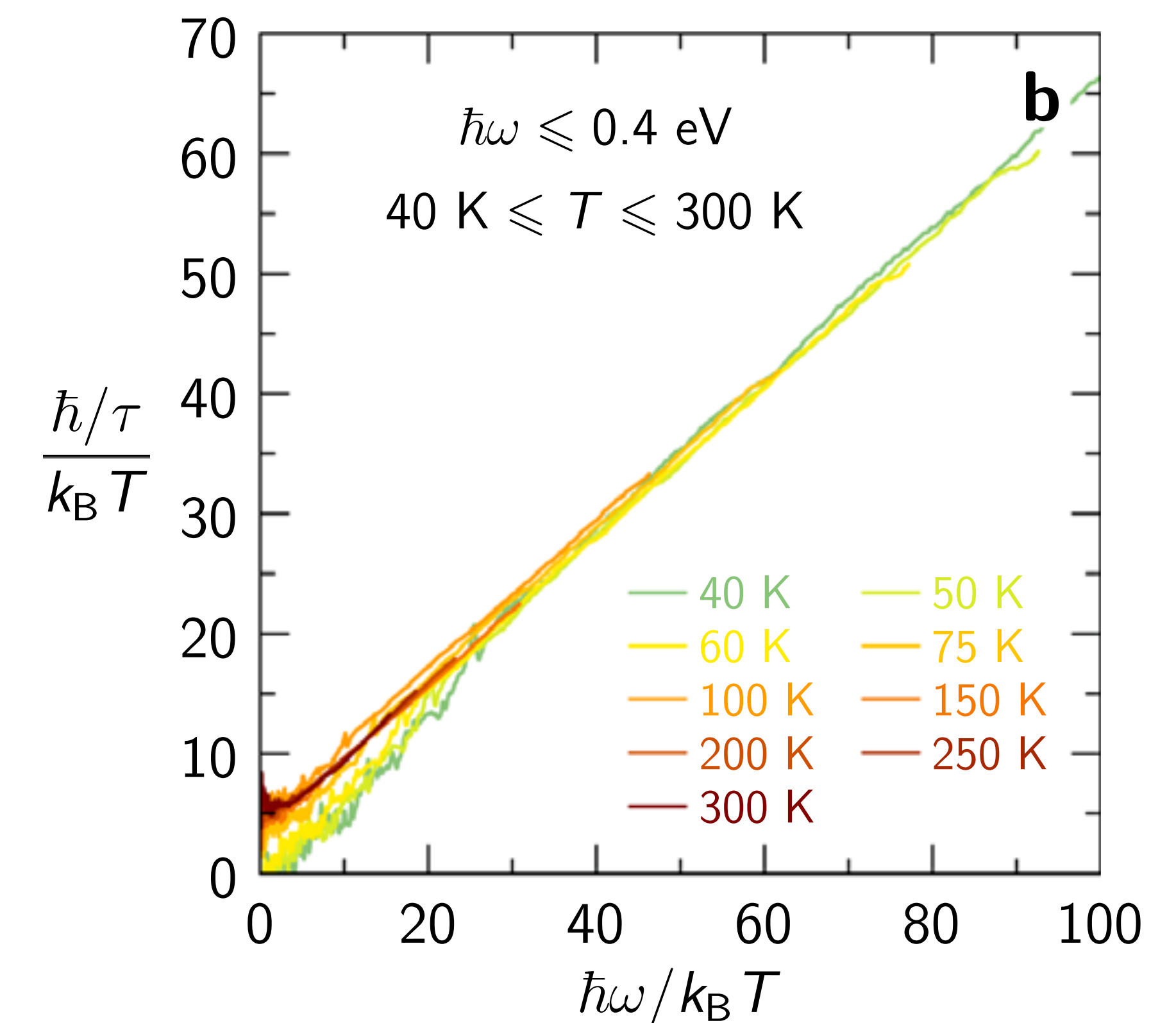
The “strange metal” has
no particle-like/anyon
excitations
and is described by
a SYK-type theory



Planckian dynamics !

Electron scattering time τ
from optical conductivity

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



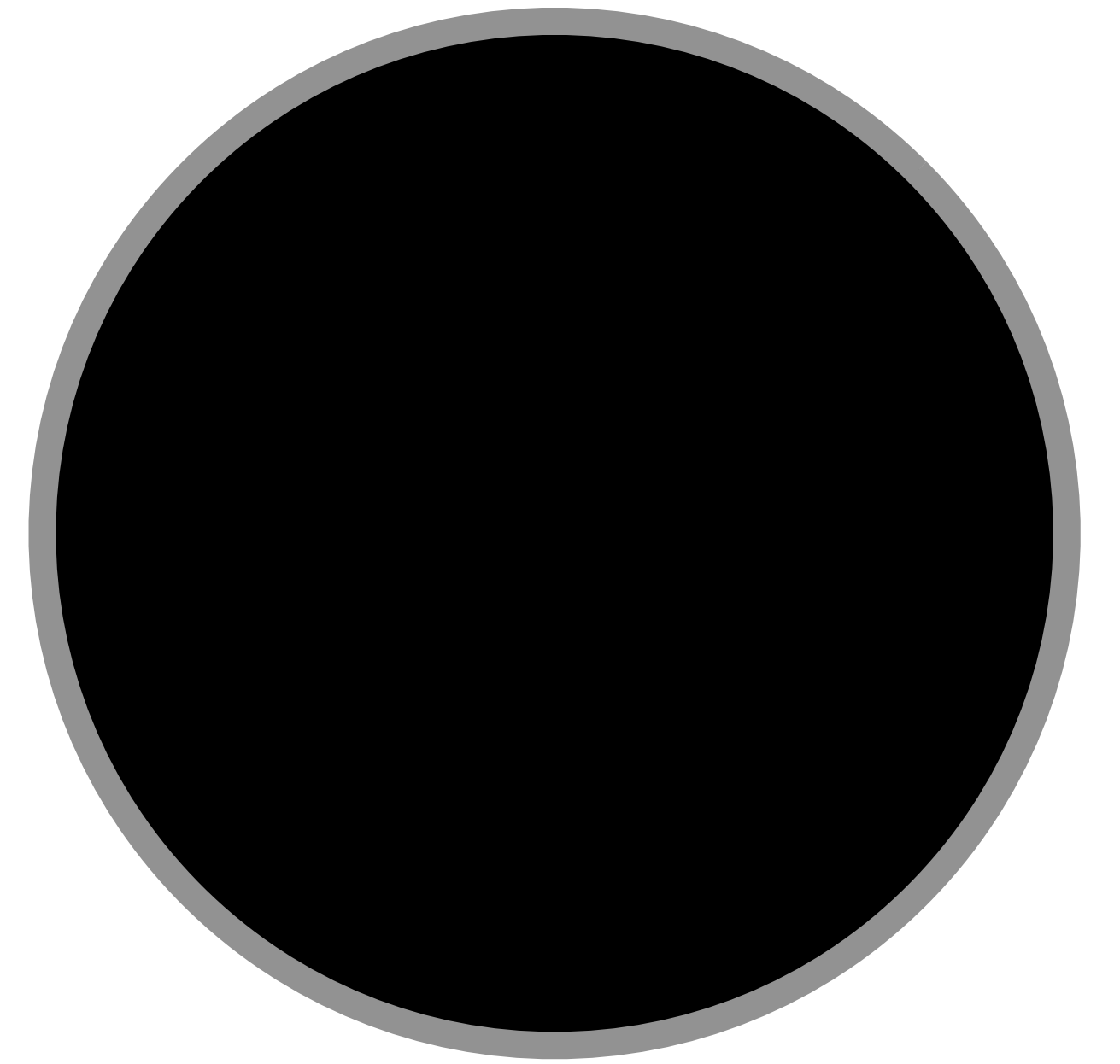
Quantum entanglement,
the SYK model,
and black holes

Black Holes

Objects so dense that light is gravitationally bound to them.



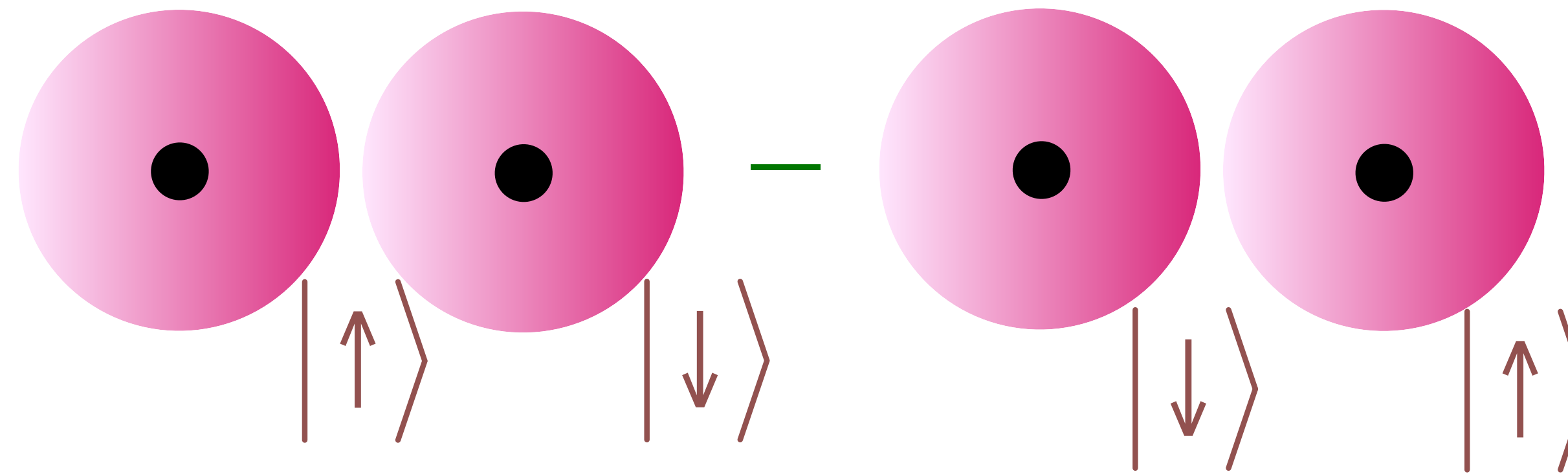
Horizon radius $R = \frac{2GM}{c^2}$



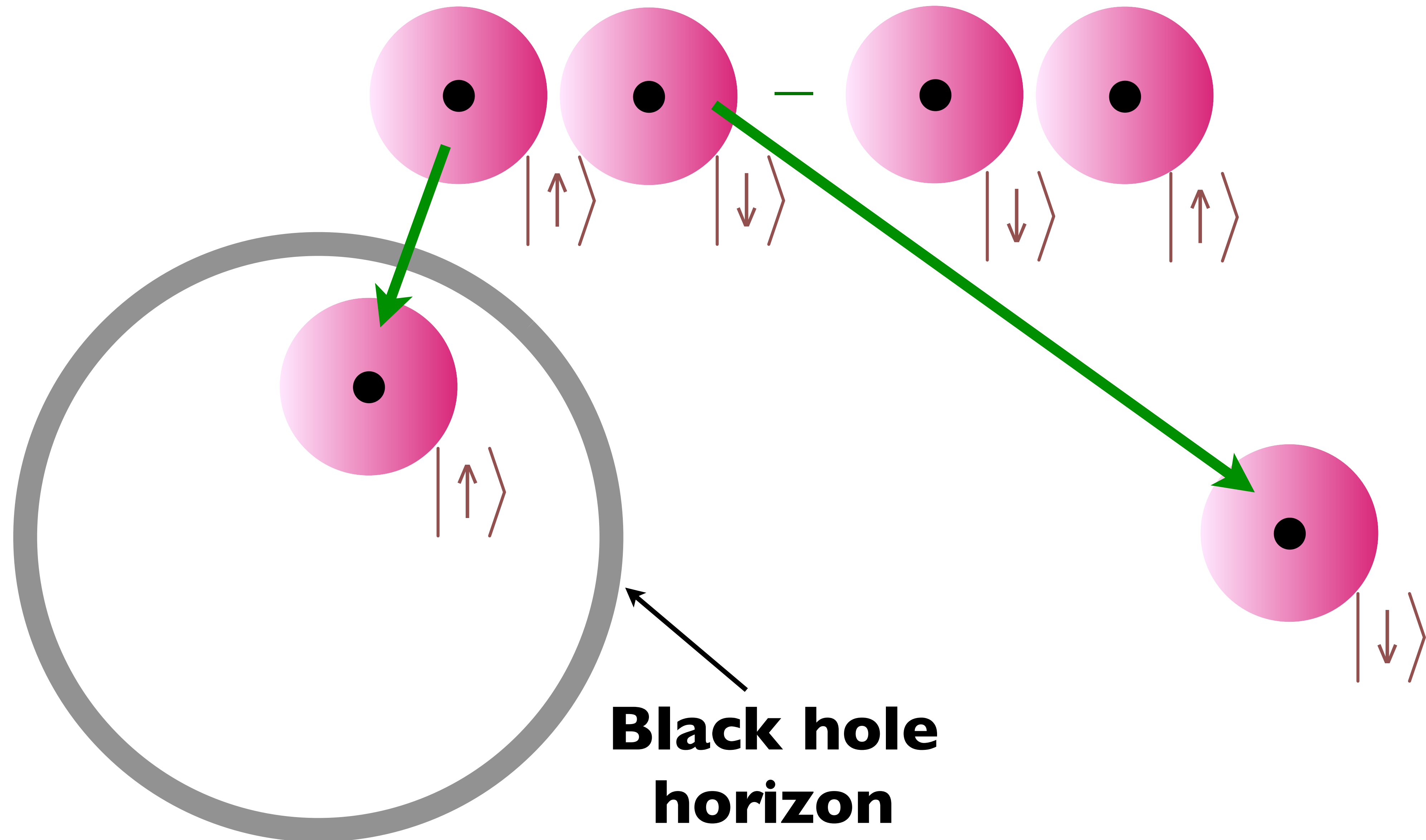
Karl Schwarzschild (1916)

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

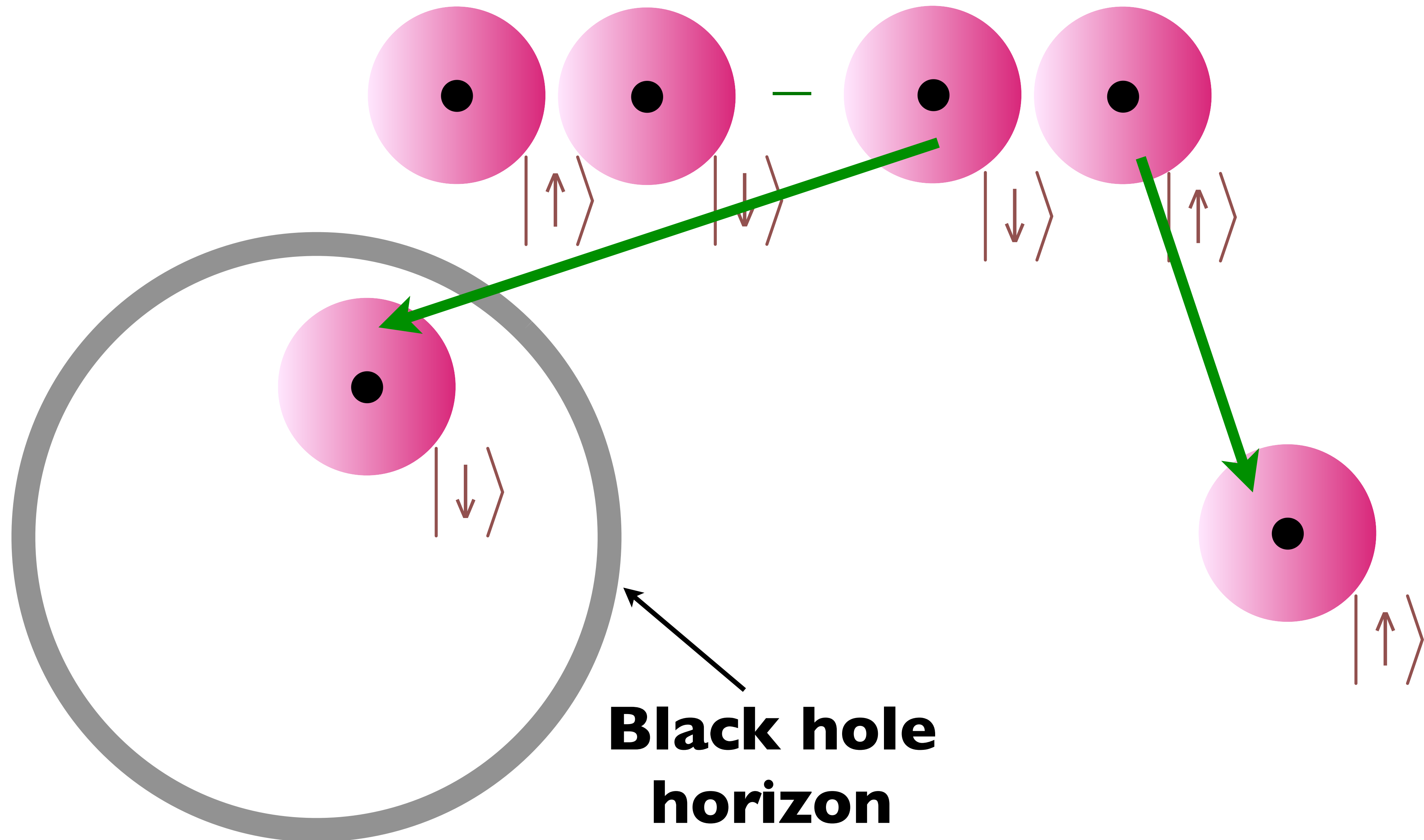
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

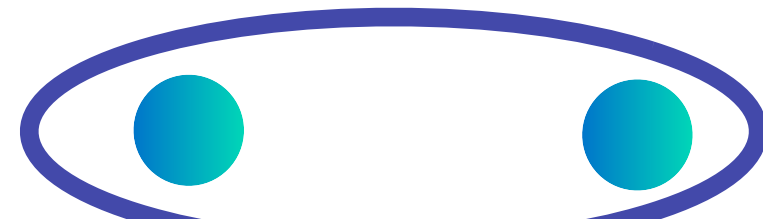


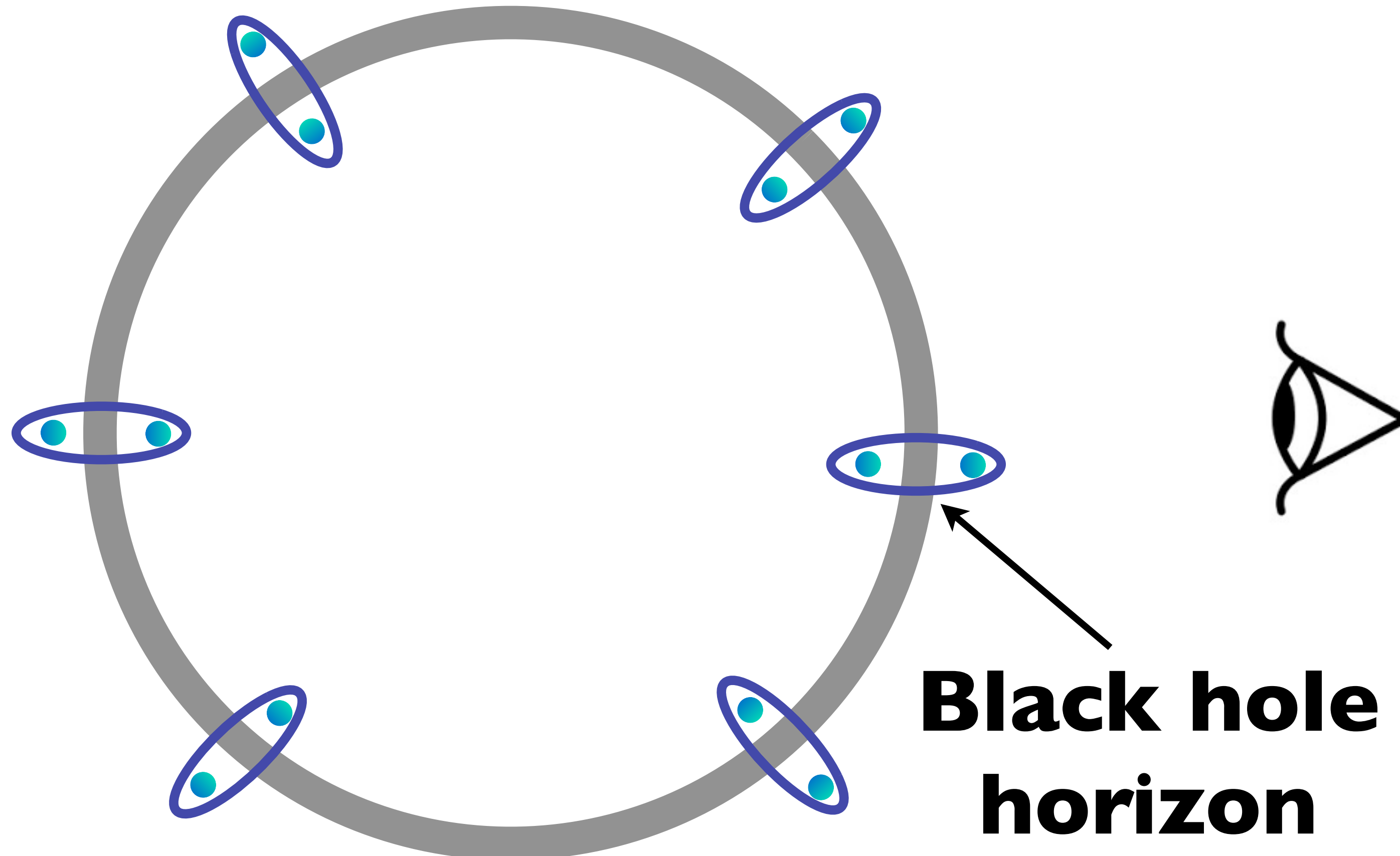
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

Quantum entanglement
on the surface


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



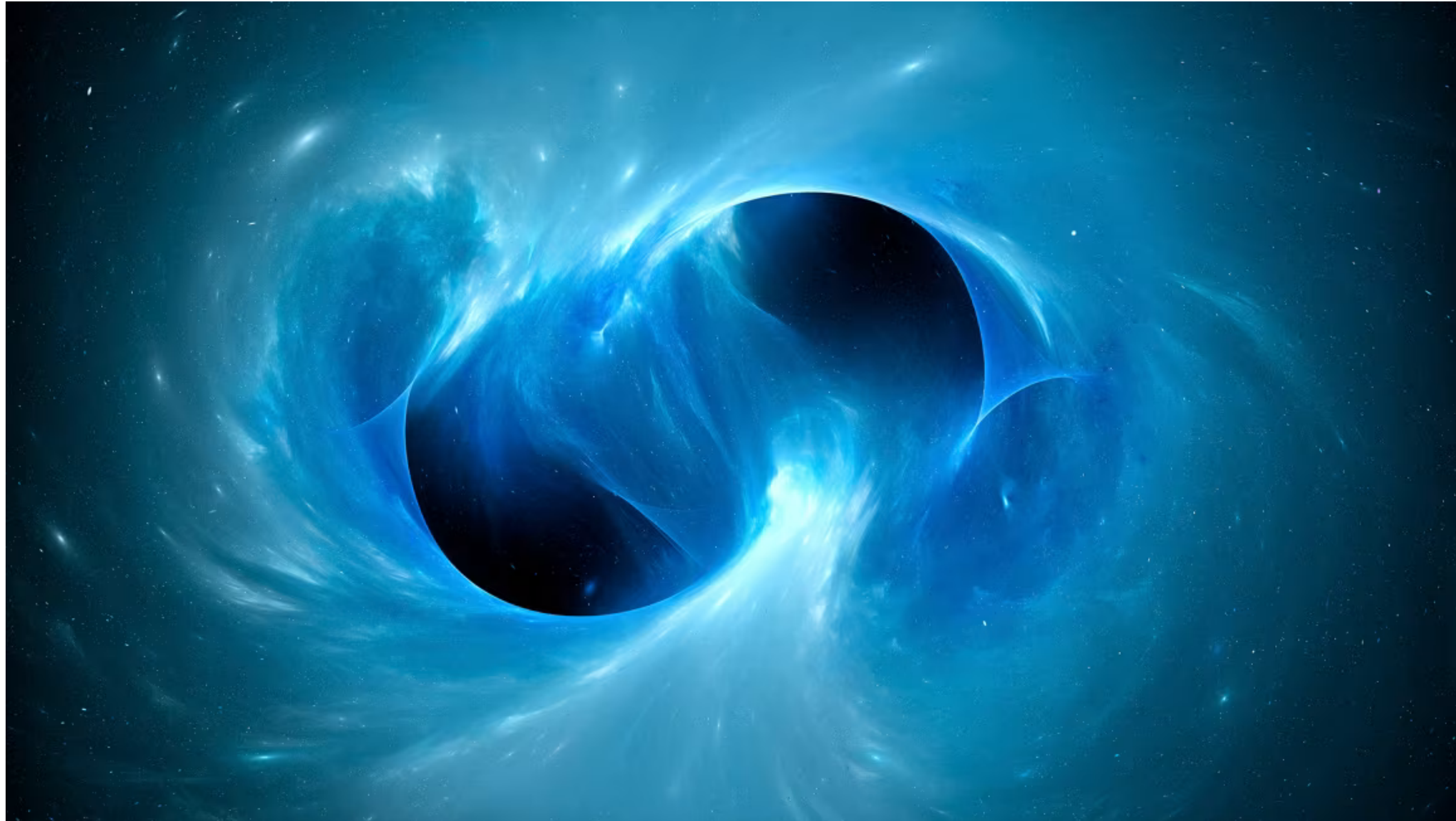
By computations *outside*
the black hole,
Hawking obtained
the black hole entropy

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

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

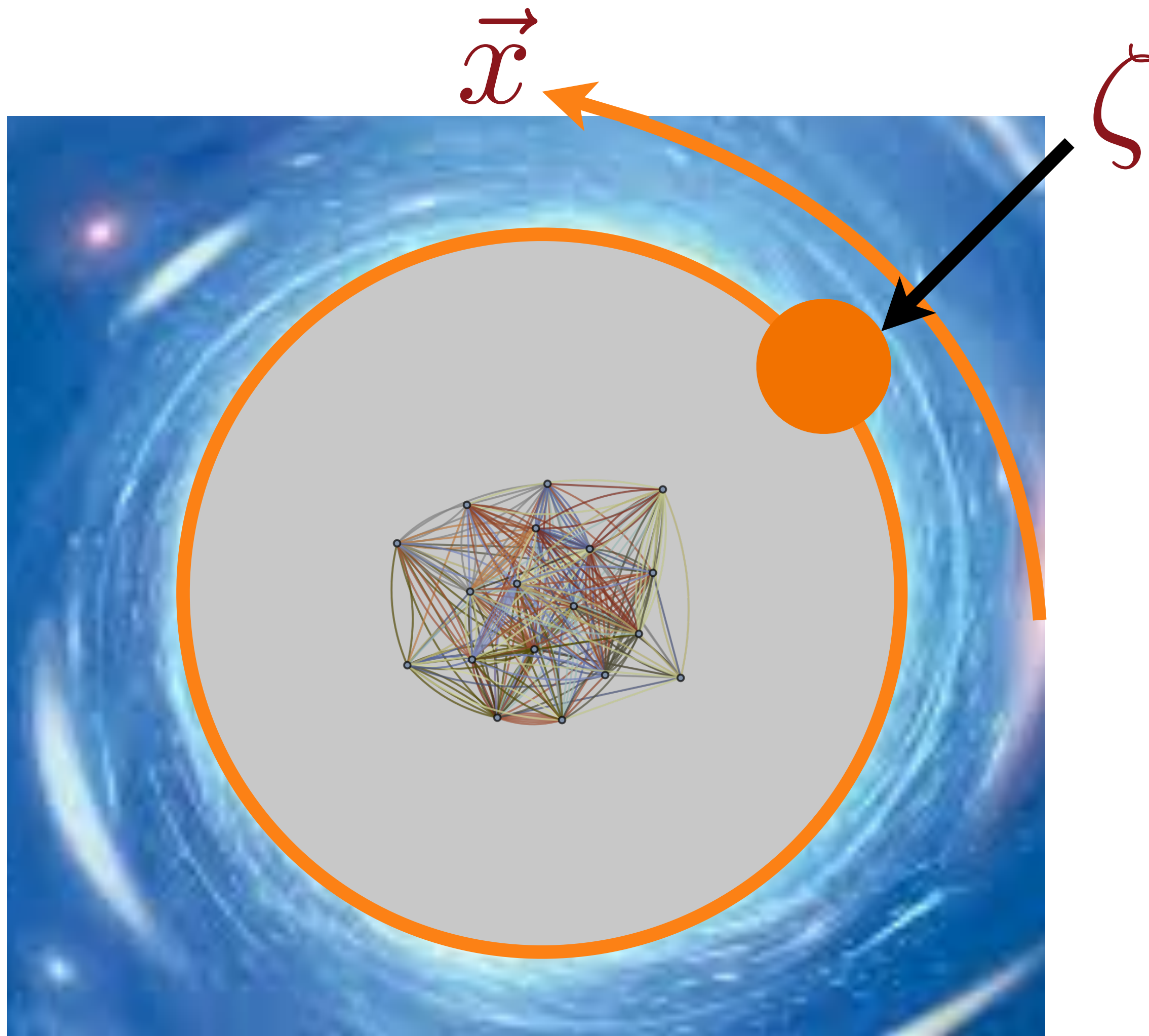
$$\tau_{\text{ring-down}} \sim \frac{\hbar}{k_B T}$$

Planckian dynamics!

T is the Hawking temperature of the black hole



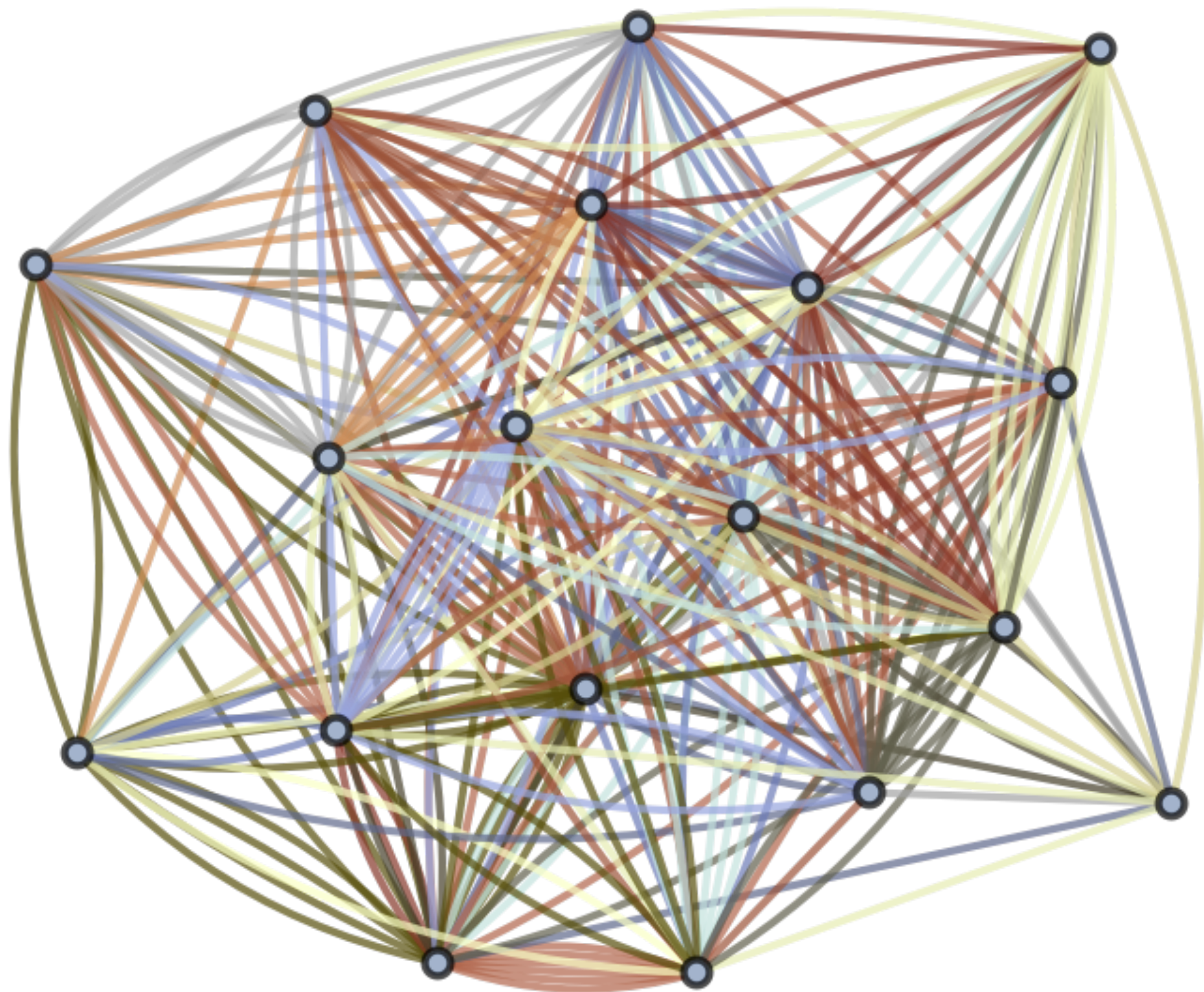
Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



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

The Sachdev-Ye-Kitaev (SYK) model

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

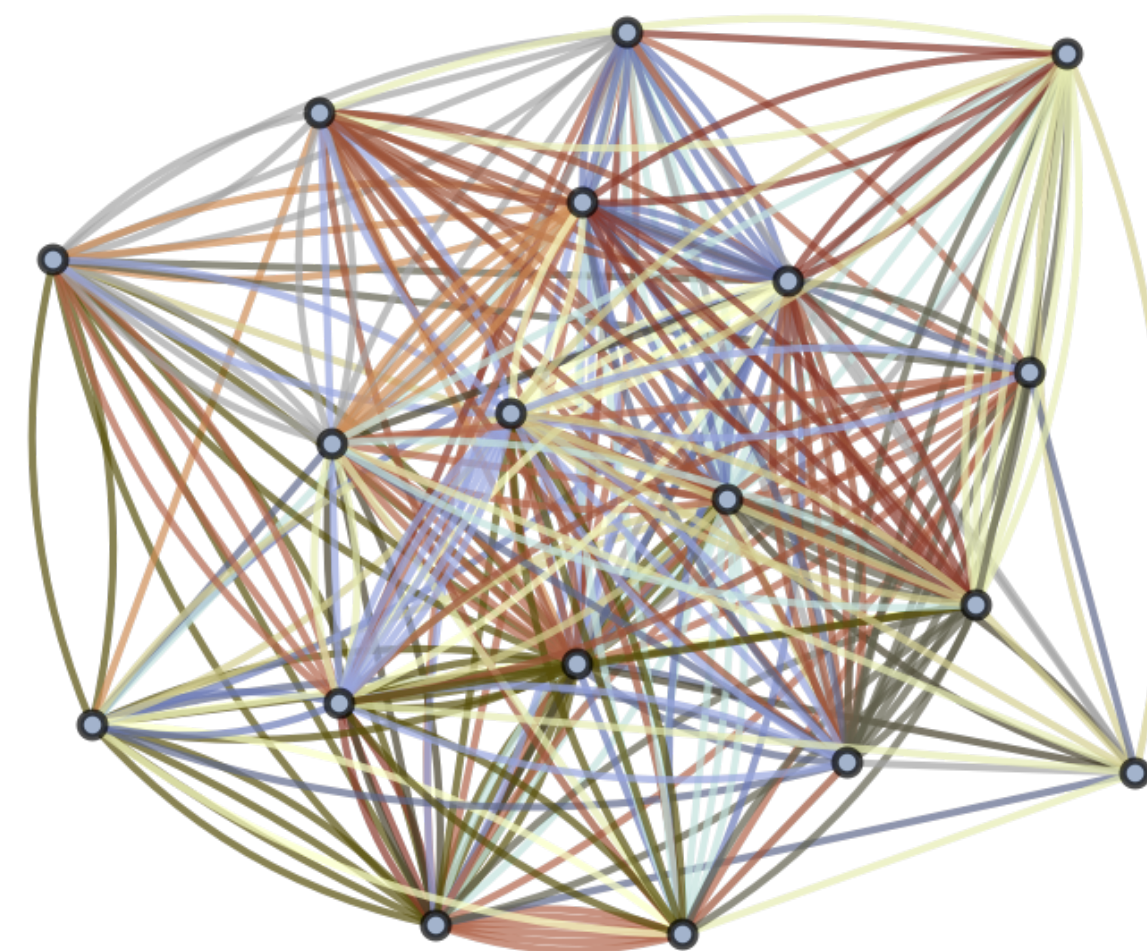
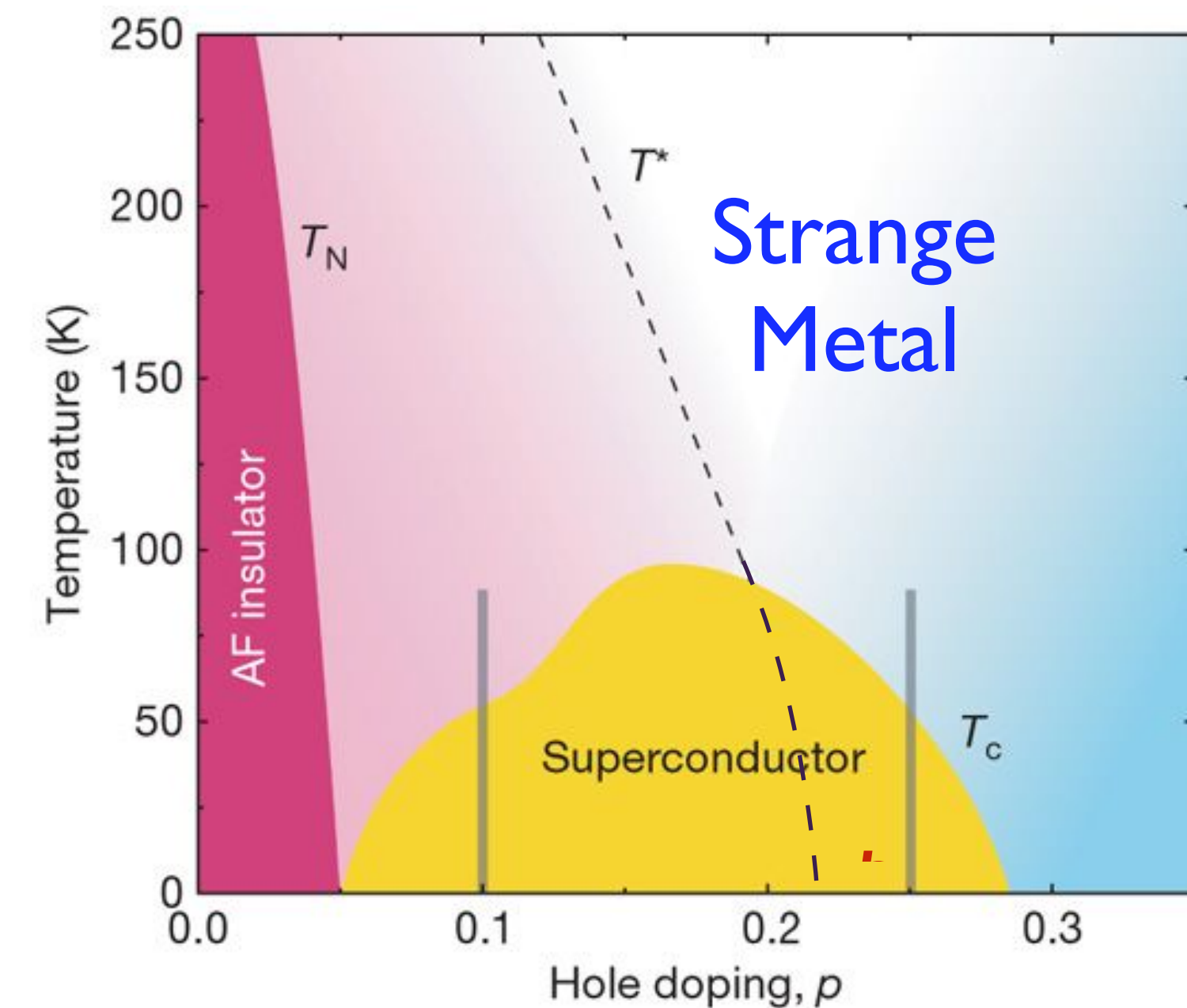


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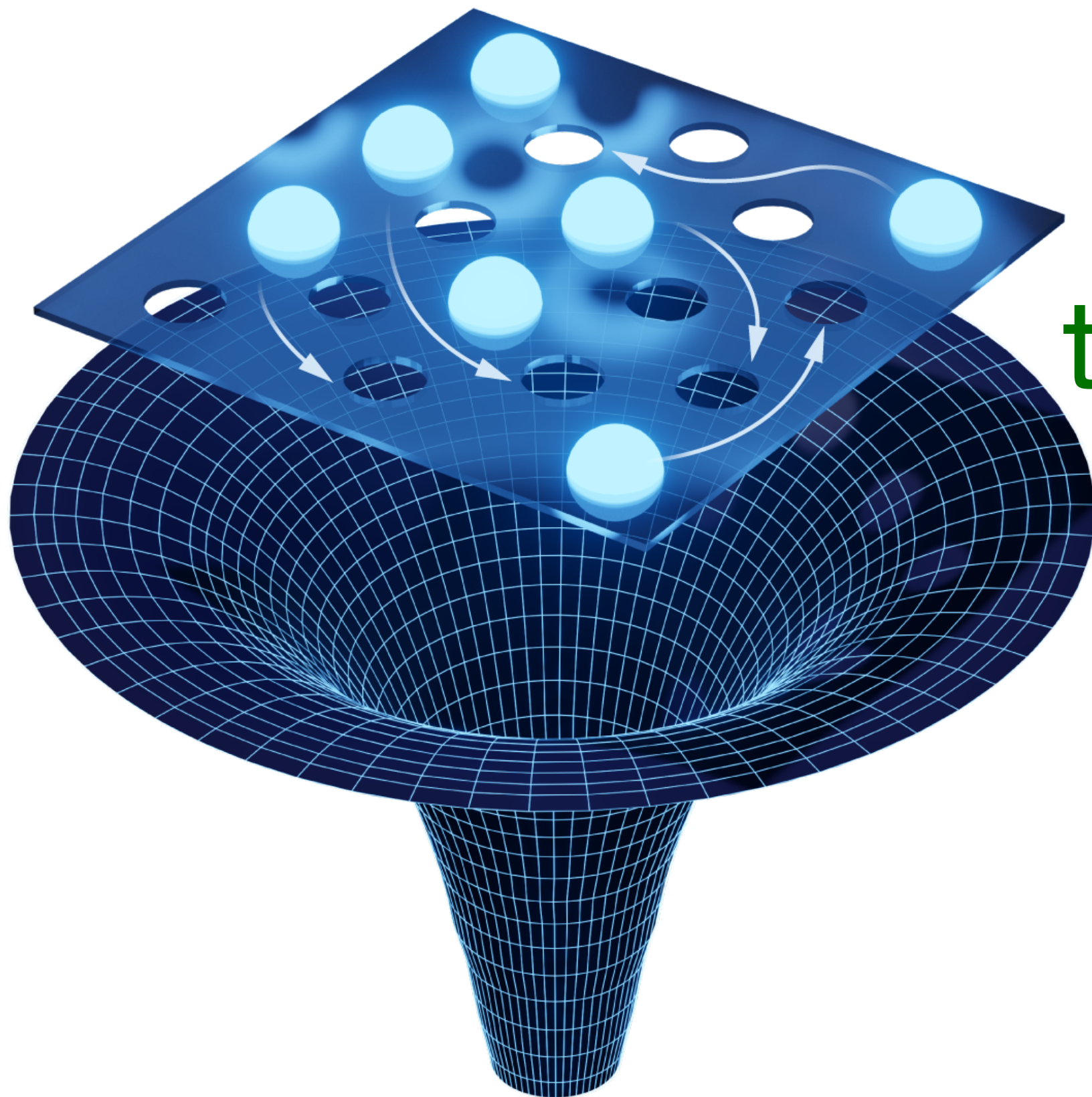
In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)



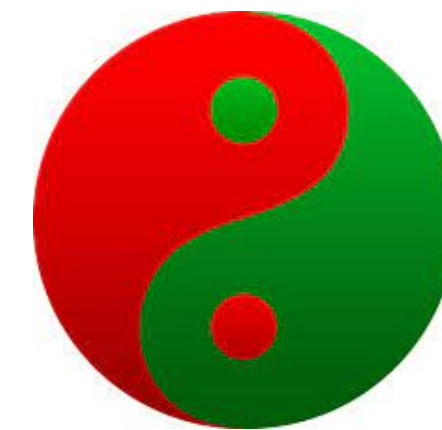
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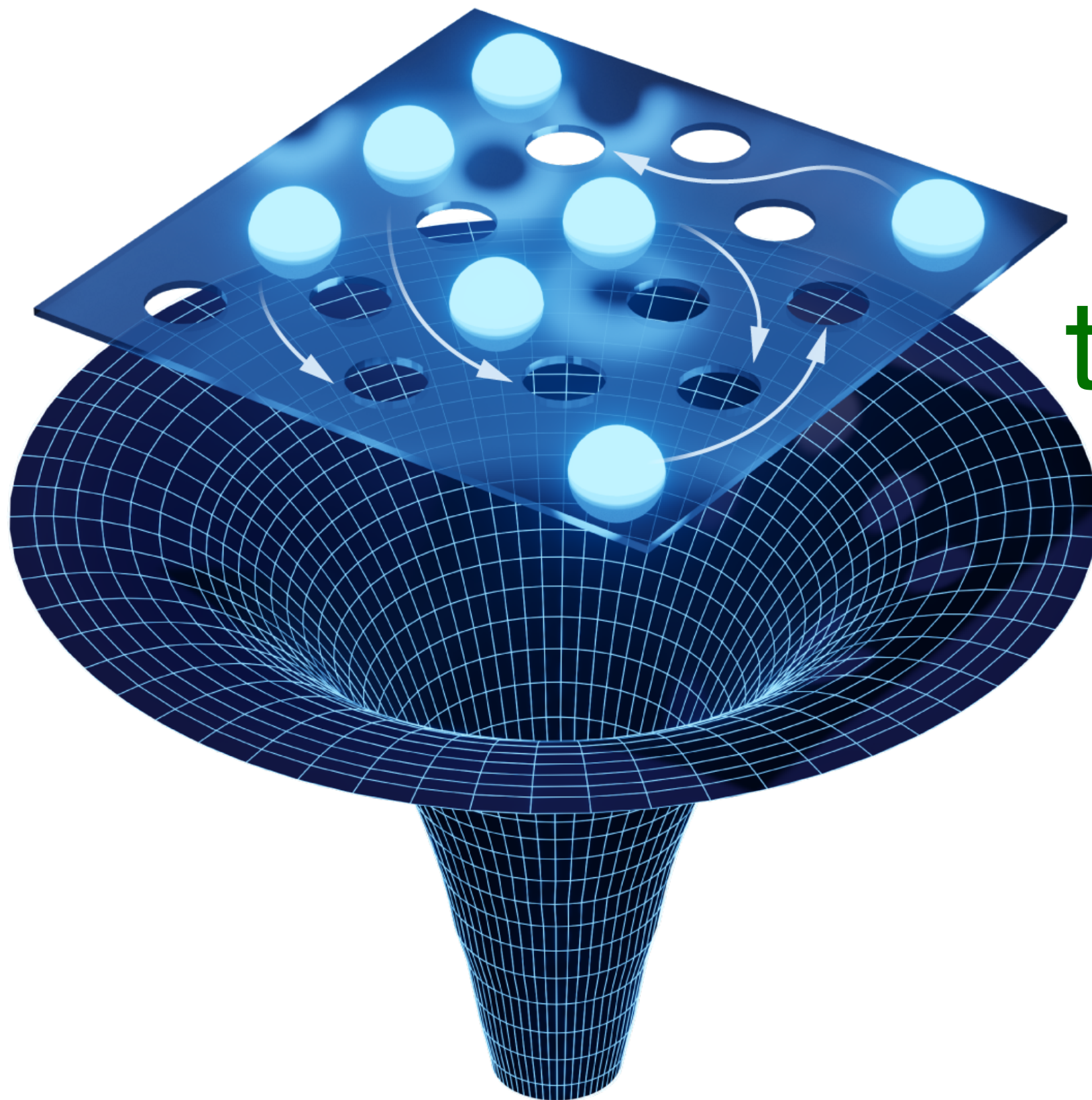


In a ***dual*** set of variables it describes the interior of ***charged black holes***

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

The Sachdev-Ye-Kitaev (SYK) model

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



In a recent paper, we showed that the complex quantum entanglement in the SYK model lead to a quantum advantage?

Can the complex quantum entanglement in the SYK model lead to a quantum advantage?

In the interior of *charged black holes*