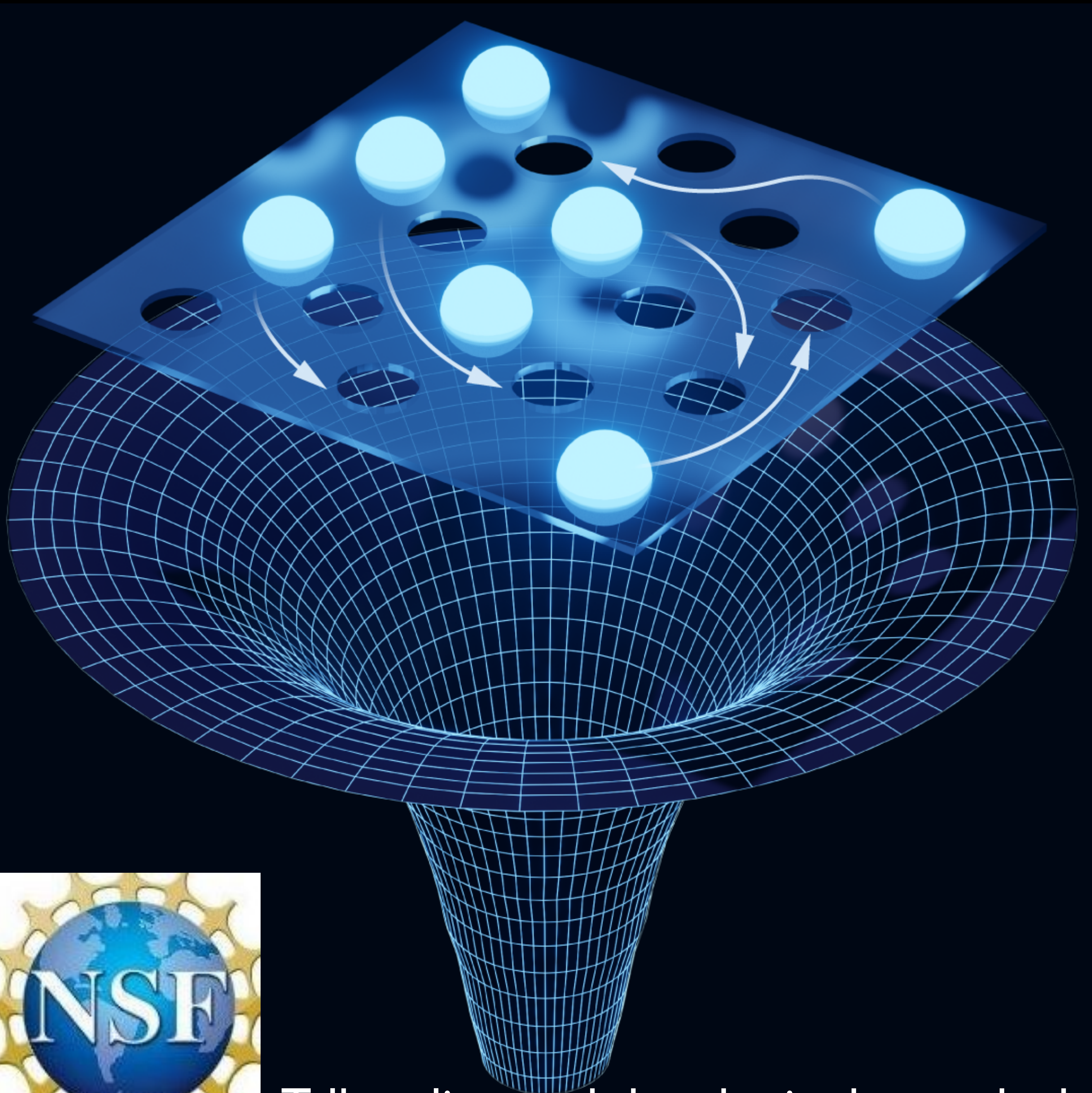


Quantum entanglement in nature: superconductors and black holes

Indian Academy of Sciences Public Lecture

National College, Bengaluru

December 28, 2023

Subir Sachdev

PHYSICS

VE RI TAS

HARVARD

Talk online: sachdev.physics.harvard.edu

Great discoveries in physics

Entropy (1870)

Superconductivity (1911)

Black holes (1916)

Quantum entanglement (1935)

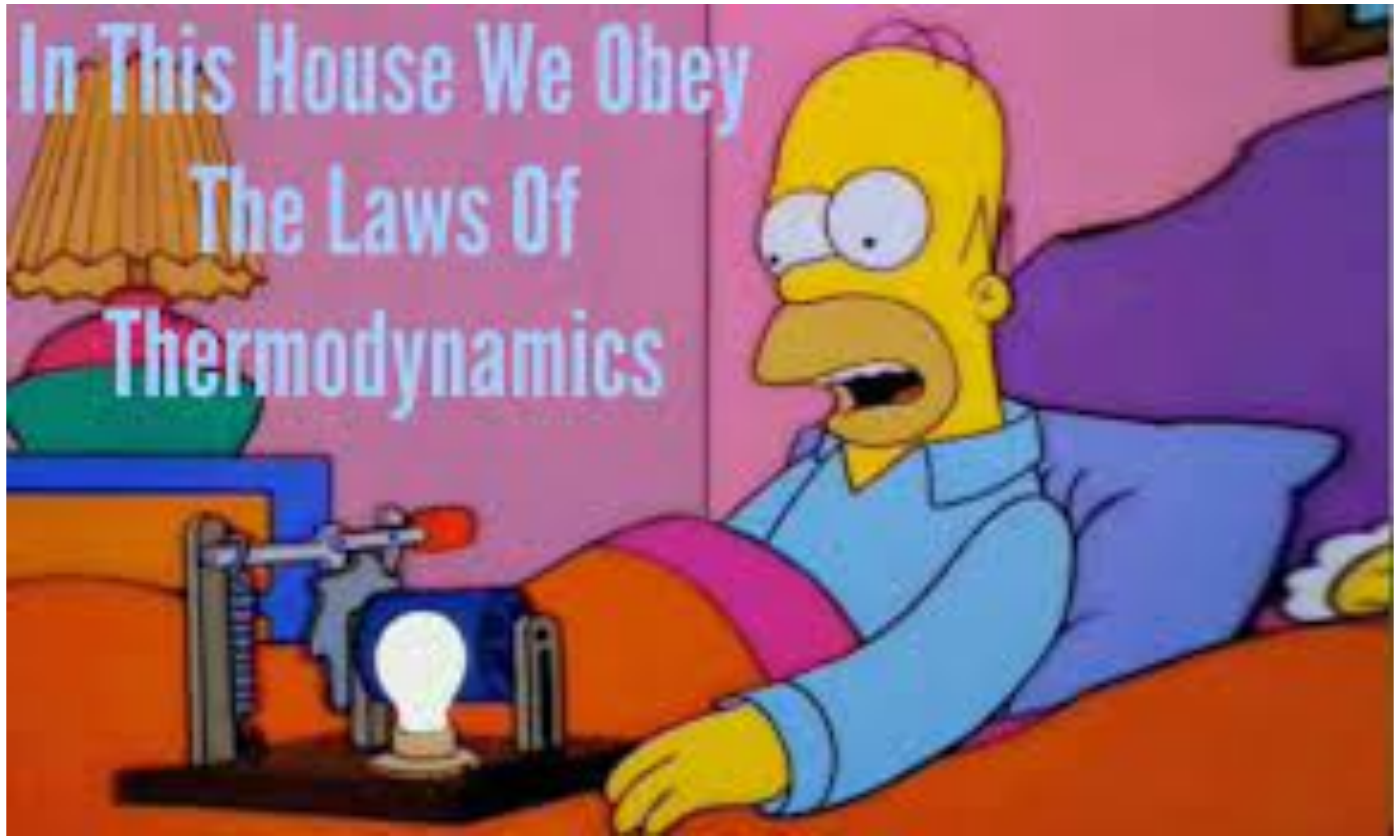
What is entropy and temperature ?

Clausius (1865):

Second Law of Thermodynamics:

Every macroscopic system has an "entropy" which cannot decrease.

➜ No perpetual motion machines!



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Every macroscopic system has an "entropy" which cannot decrease.

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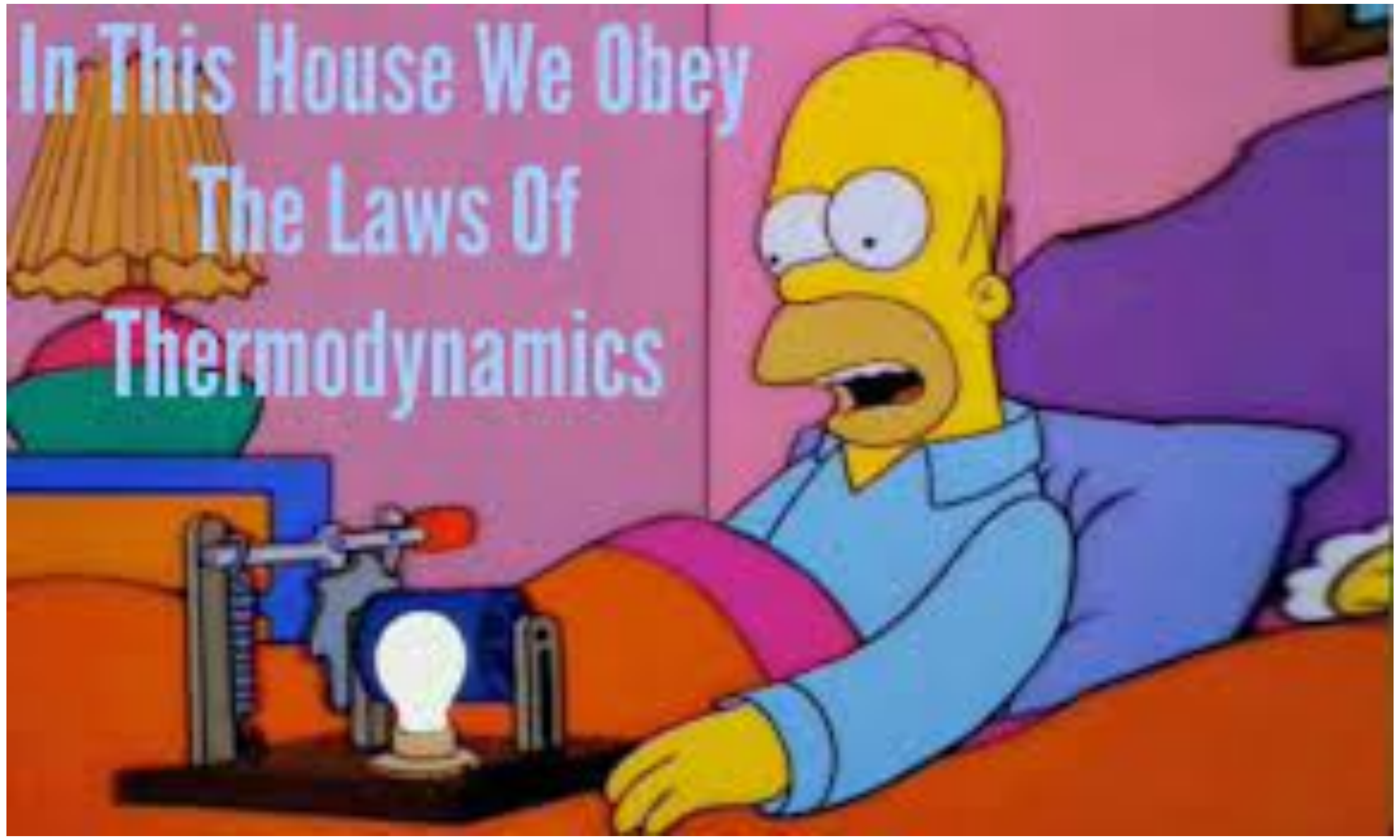
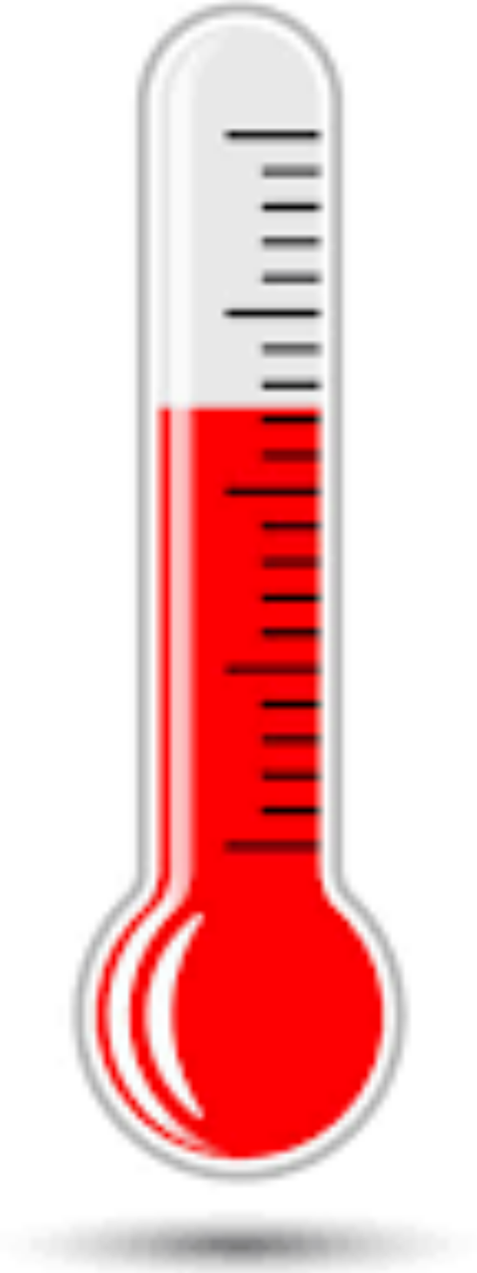
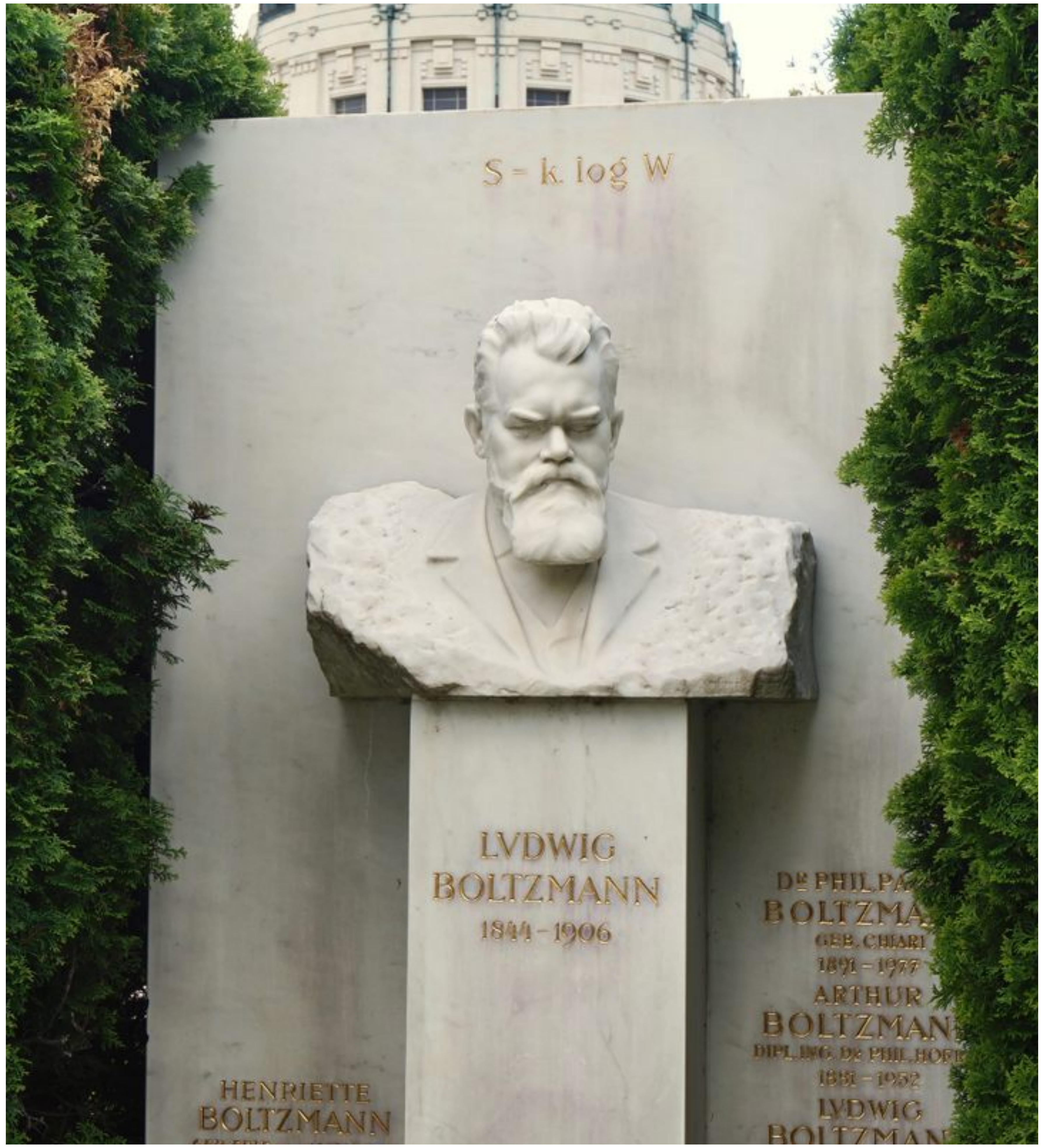




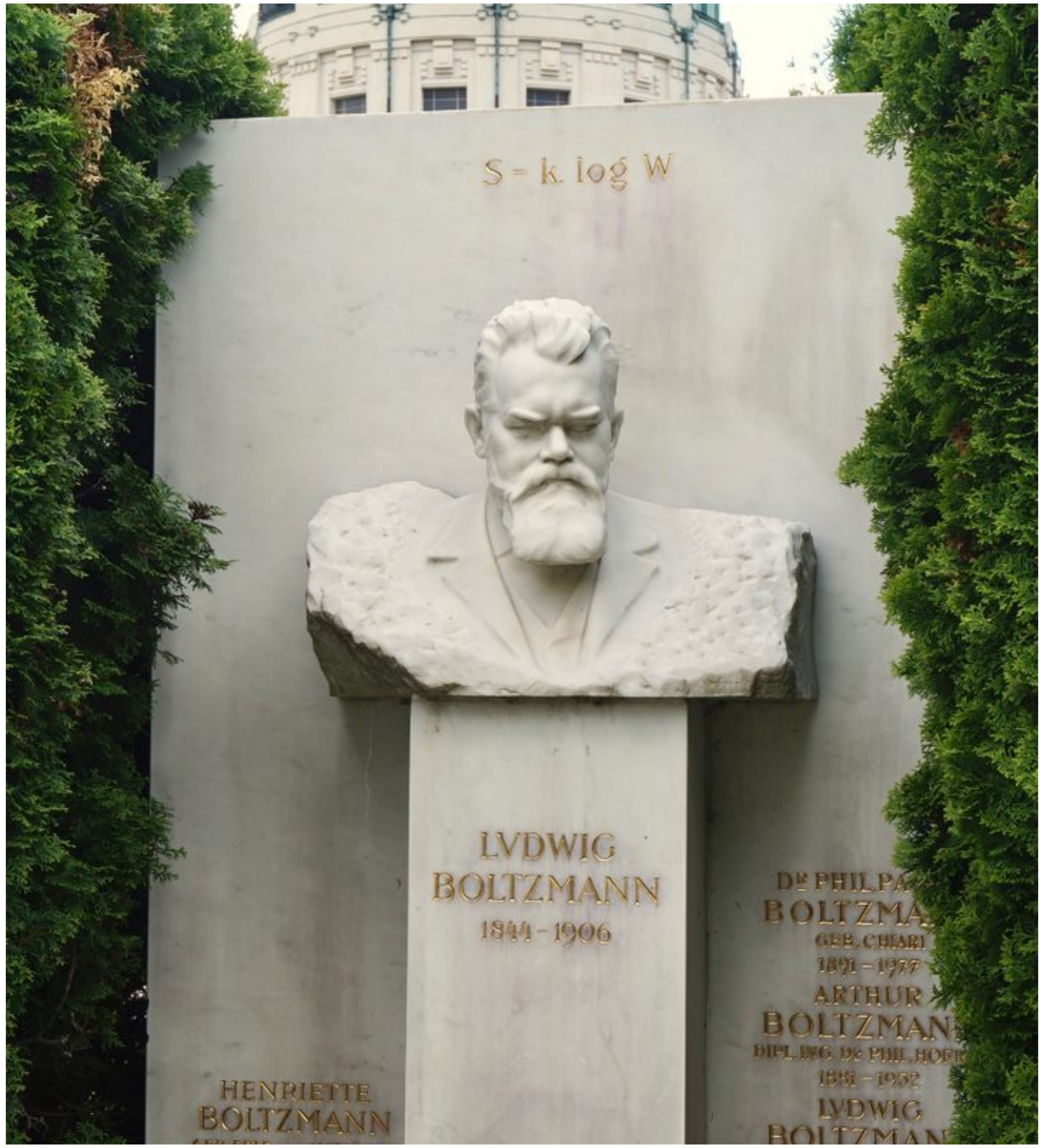
Temperature



Ludwig Boltzmann
20 February 1844 - September 5, 1906
Vienna, Austria

Statistical interpretation of entropy (1870)

$$S = k_B \log W$$



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20 February 1844 - September 5, 1906
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Statistical interpretation of entropy (1870)

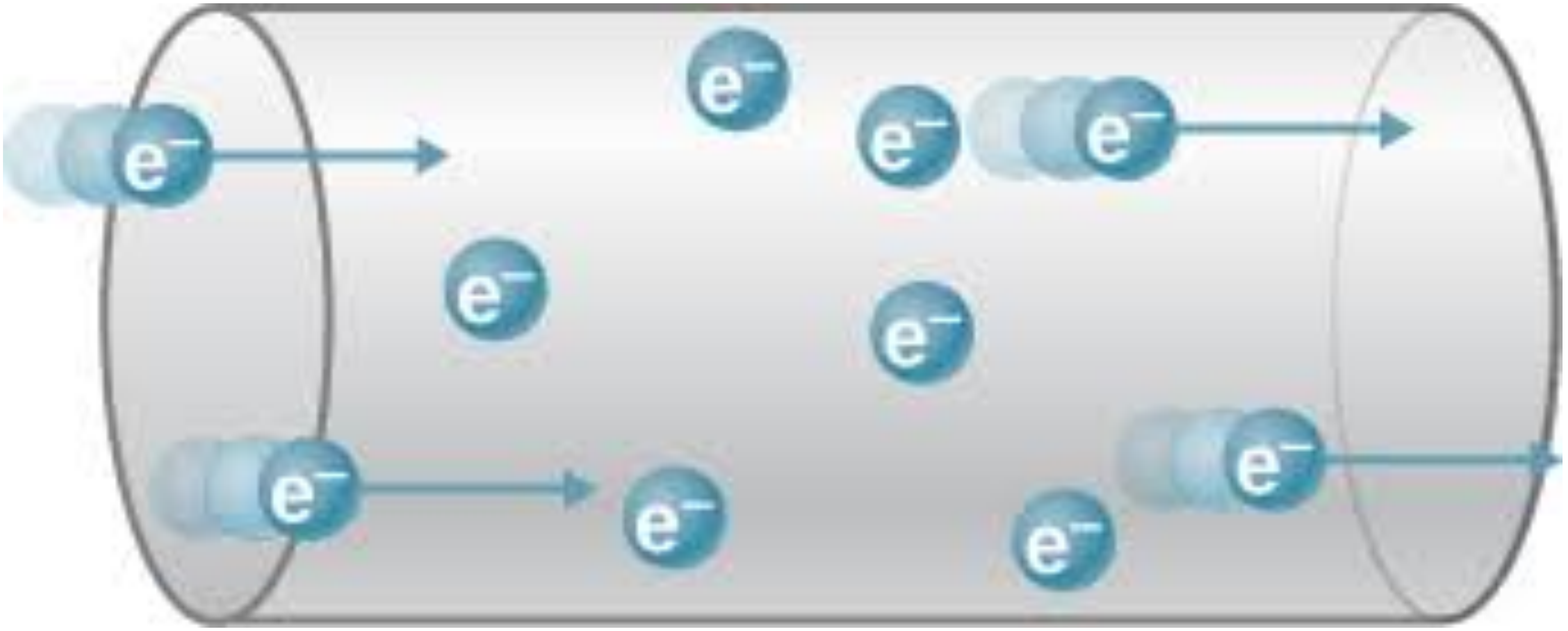
$$S = k_B \log W$$

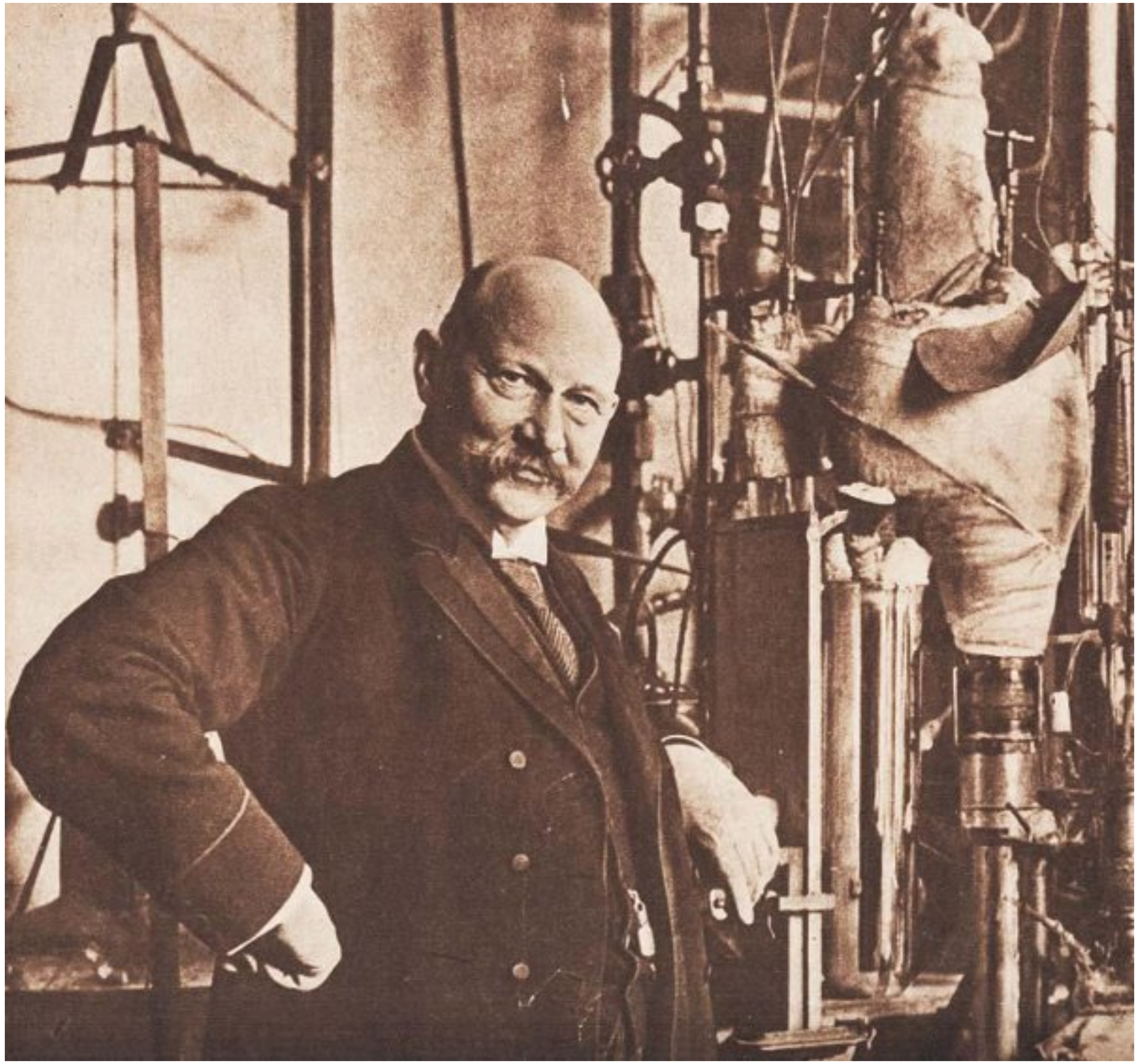
$$\frac{1}{T} = \frac{dS}{dE}$$

Ordinary conductors (metals) and superconductors

CONDUCTOR SEMICONDUCTOR SUPERCONDUCTOR

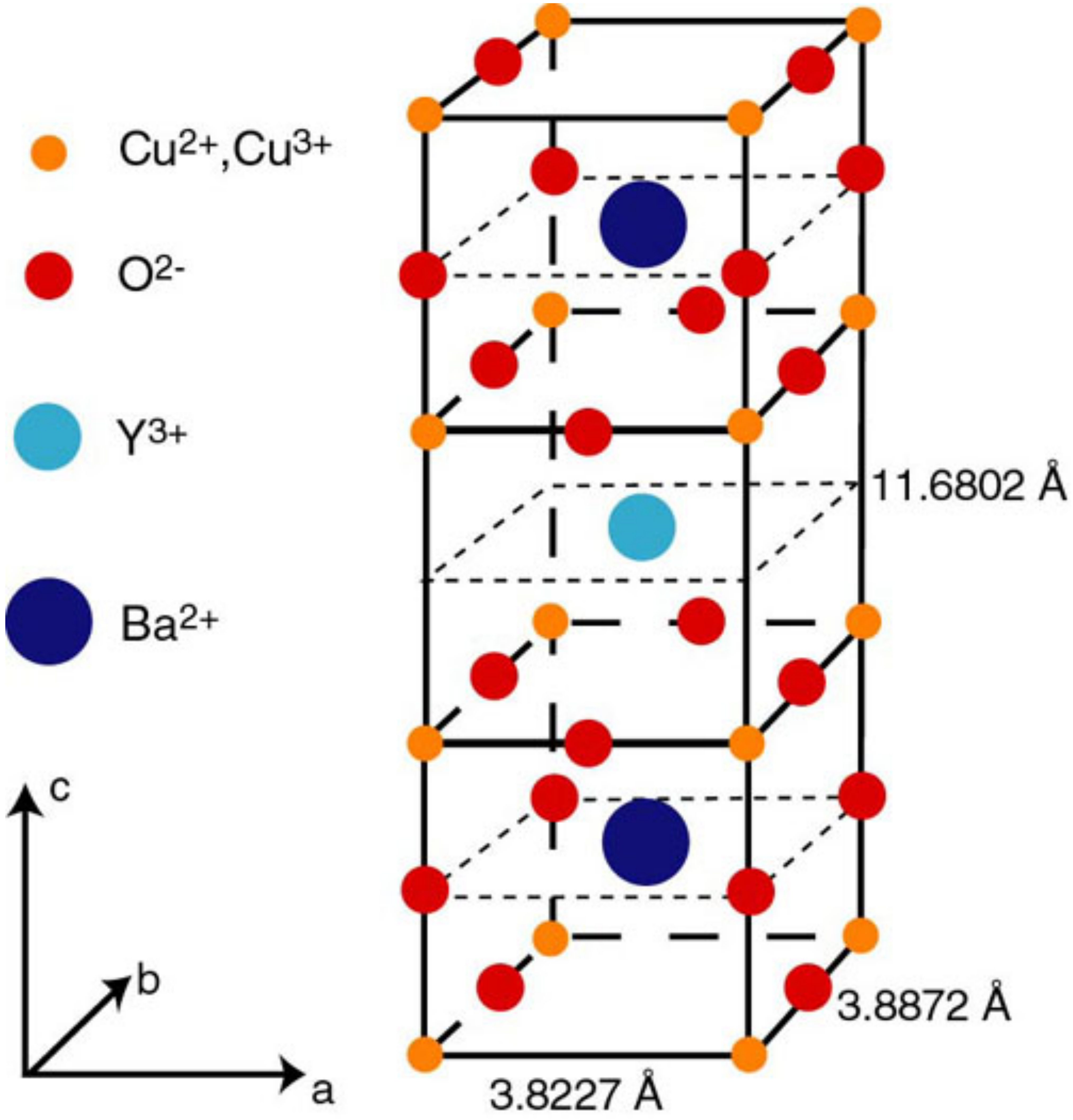
Copper: ordinary metal quantum matter



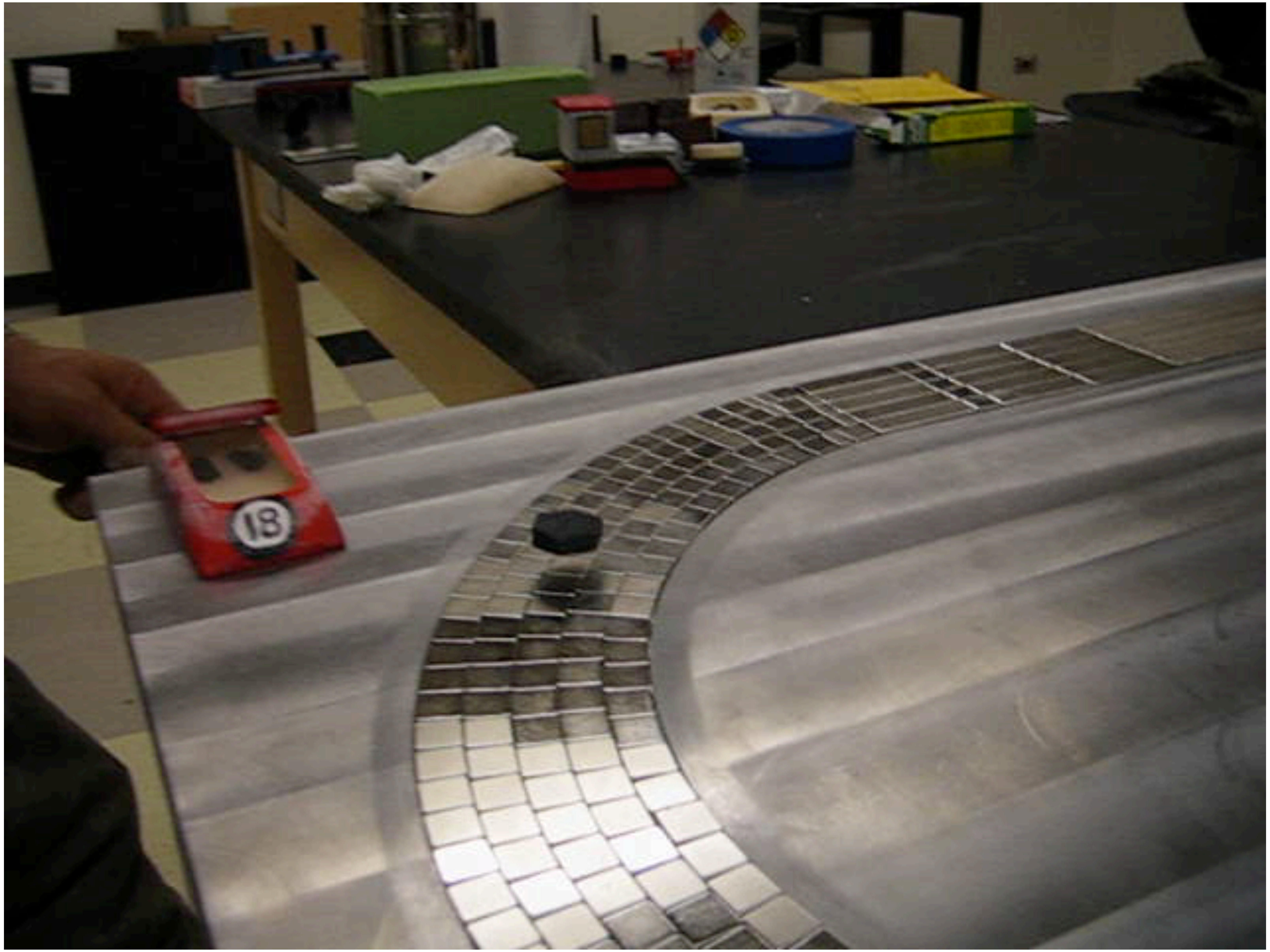


Kamerlingh Onnes 1911:
Mercury is a superconductor below -269 °C

Cuprate high temperature superconductors



$YBa_2Cu_3O_{6+x}$



Nd-Fe-B magnets, YBaCuO superconductor

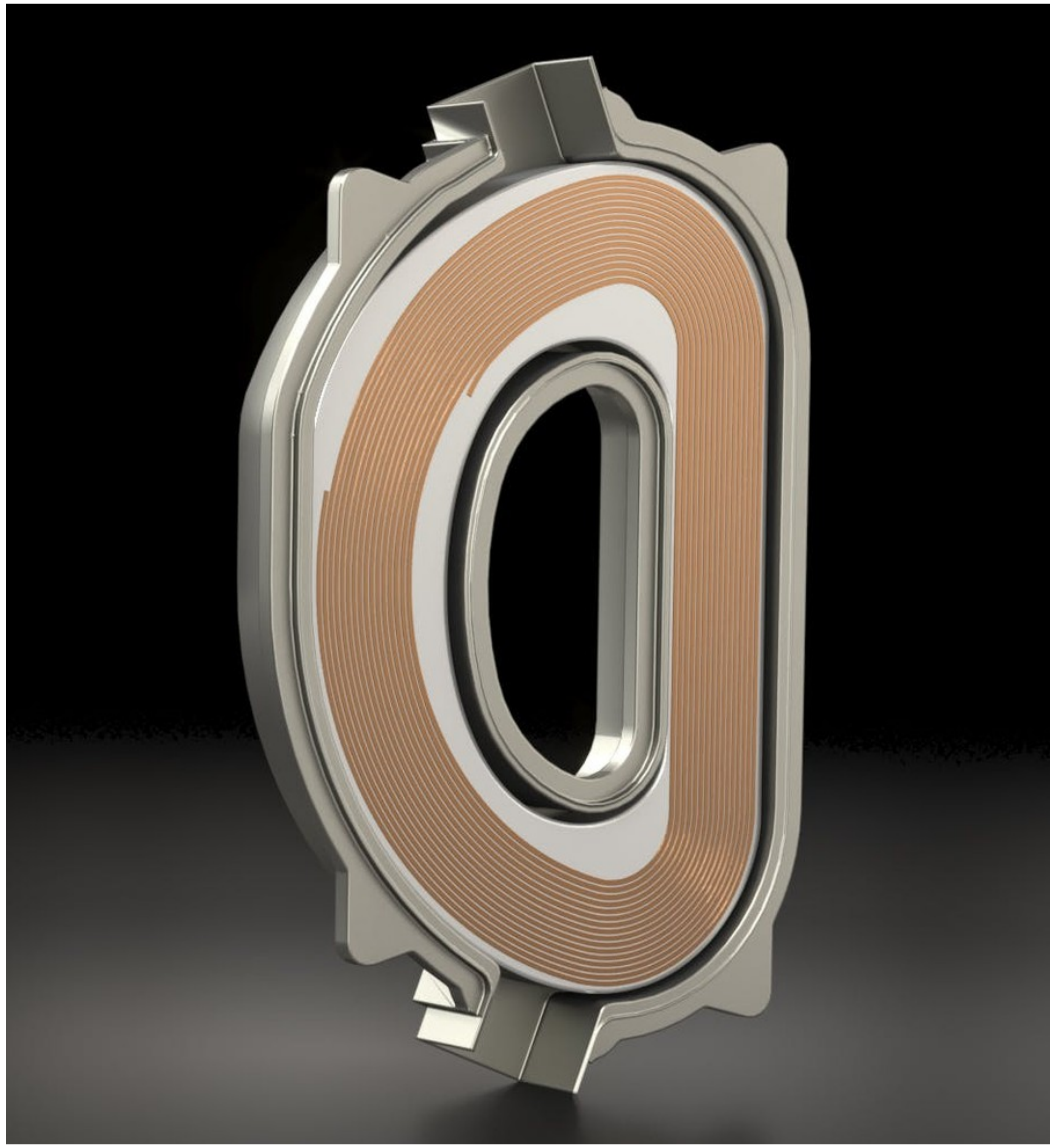
Julian Hetel and Nandini Trivedi, Ohio State University

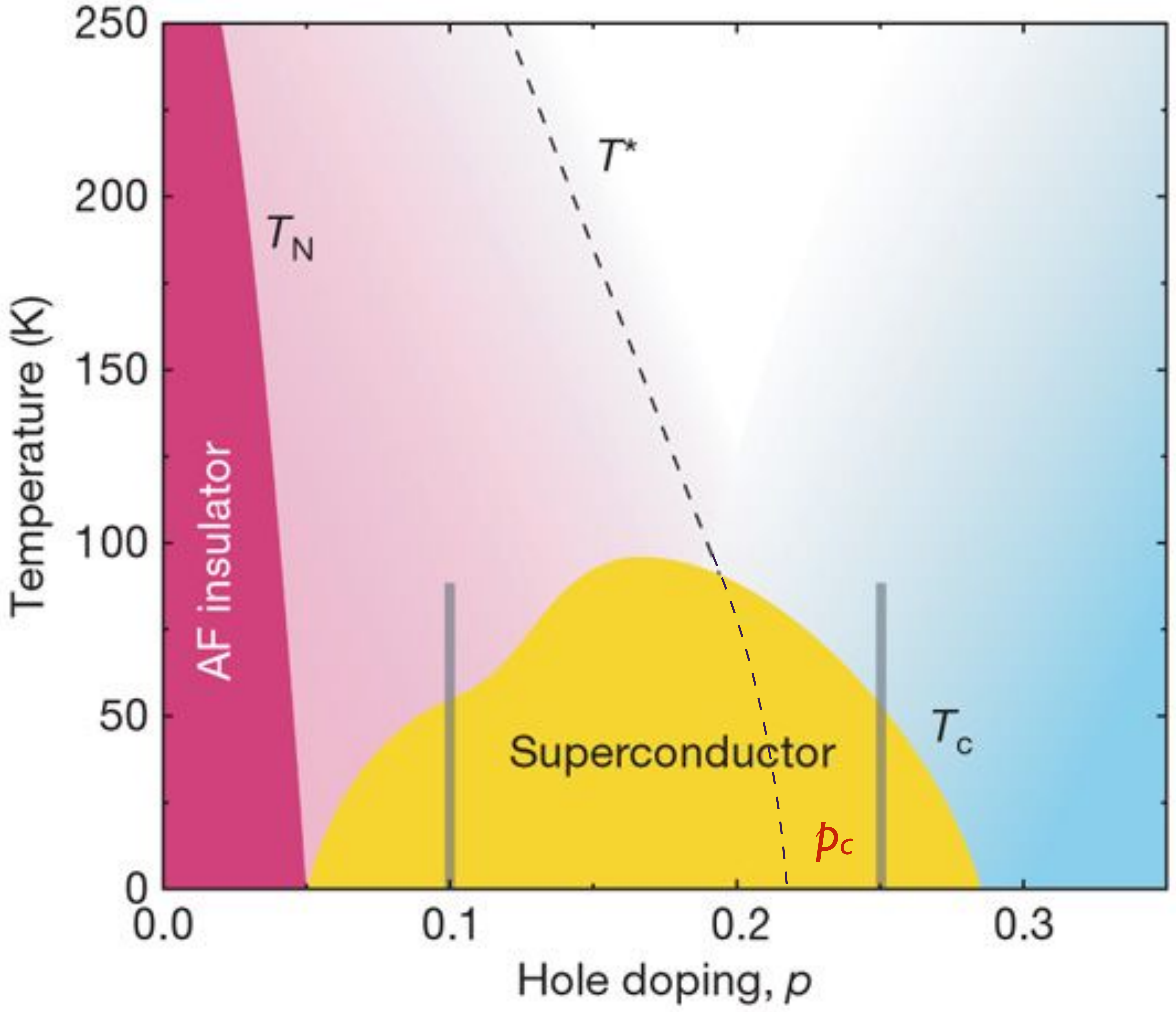
HTS Magnets: Enabling Technology

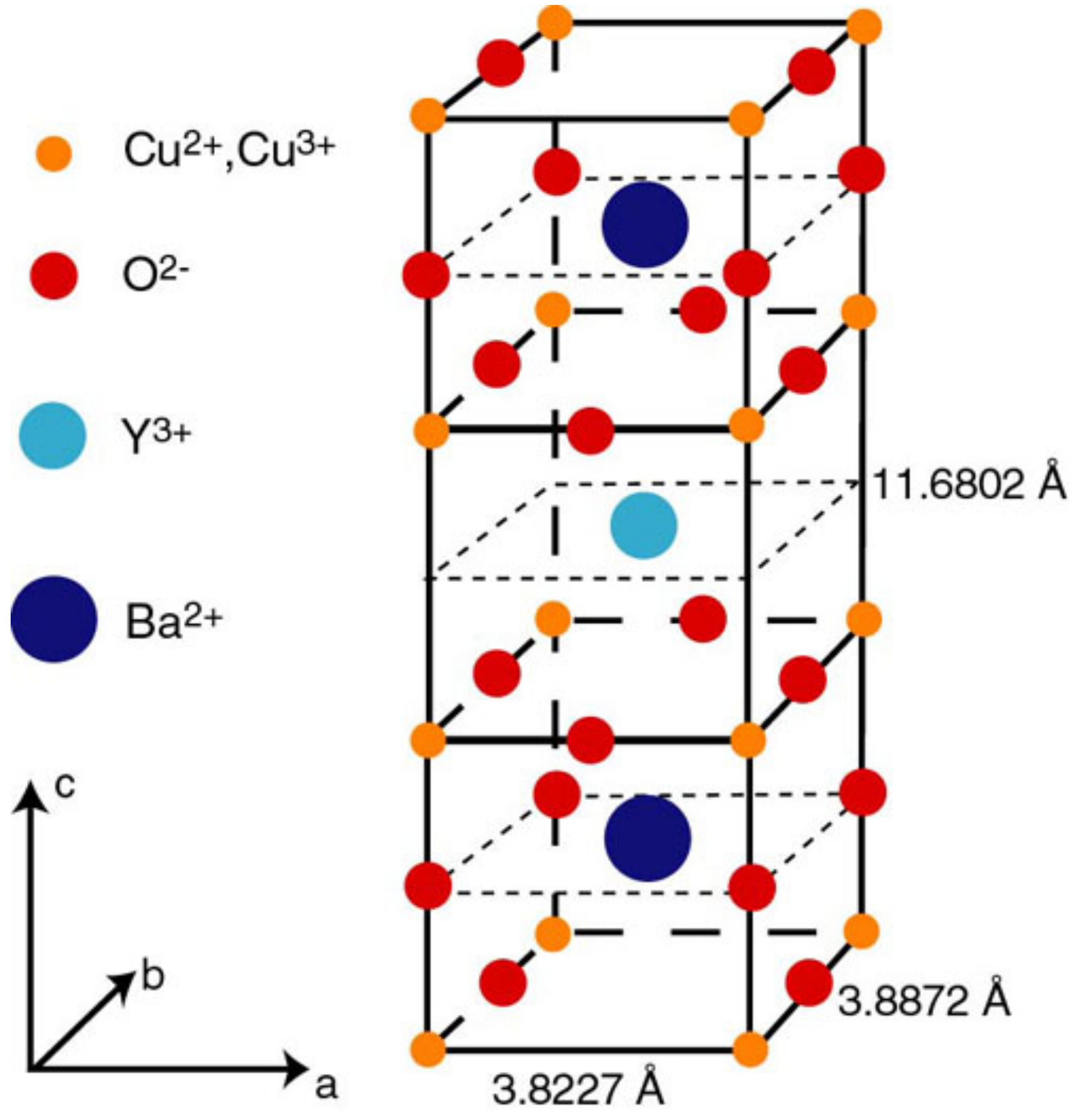
The surest path to limitless, clean, fusion energy

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

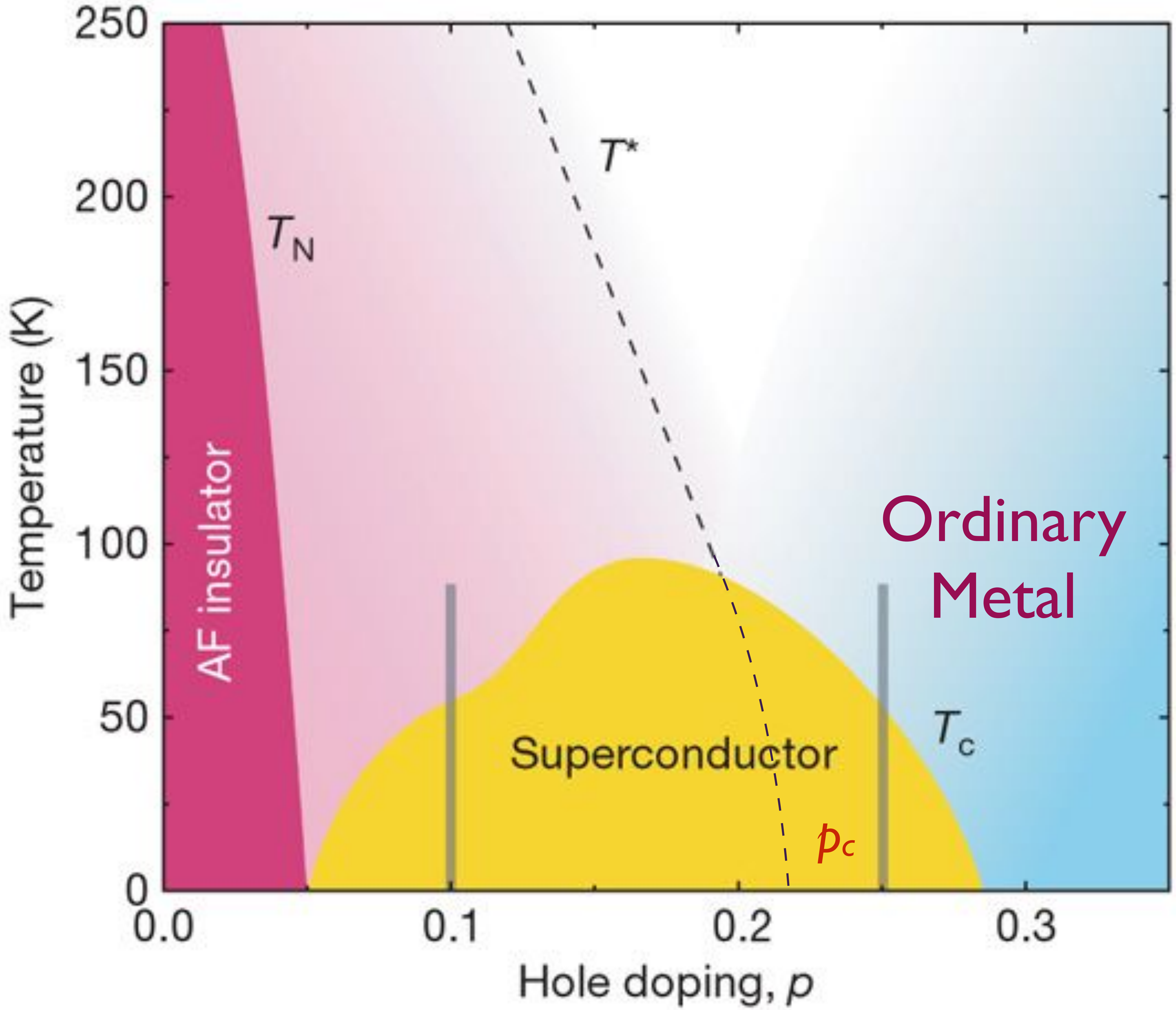
Commonwealth Fusion Systems




250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T*
Superconductor
T_c
p_c


Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å

$YBa_2Cu_3O_{6+x}$


250
200
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Temperature (K)
0.0
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AF insulator
T_N
T*
Ordinary
Metal
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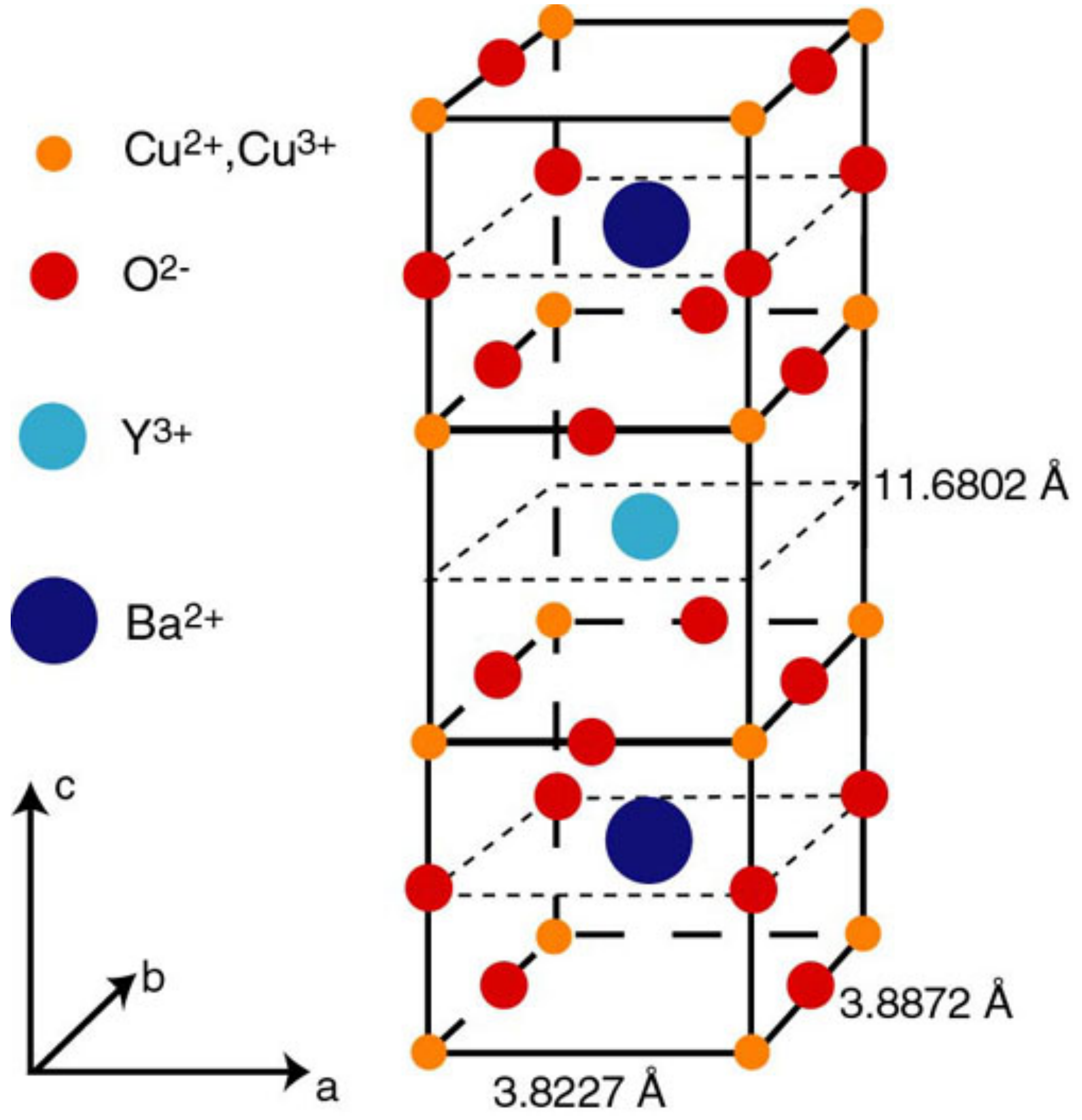
T_c
p_c


Cu2+,Cu3+
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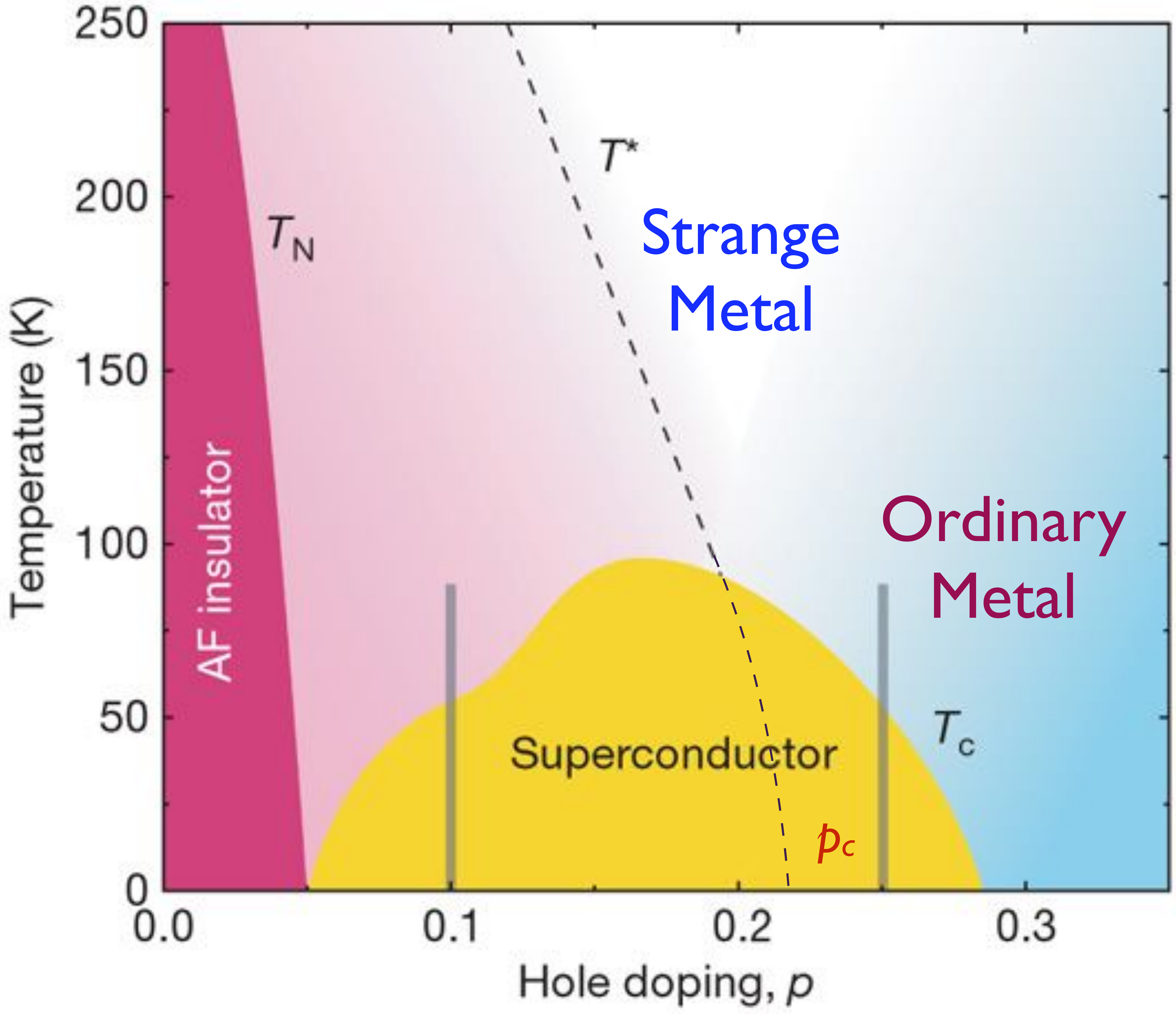
250
200
150
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Temperature (K)
0.0
0.1
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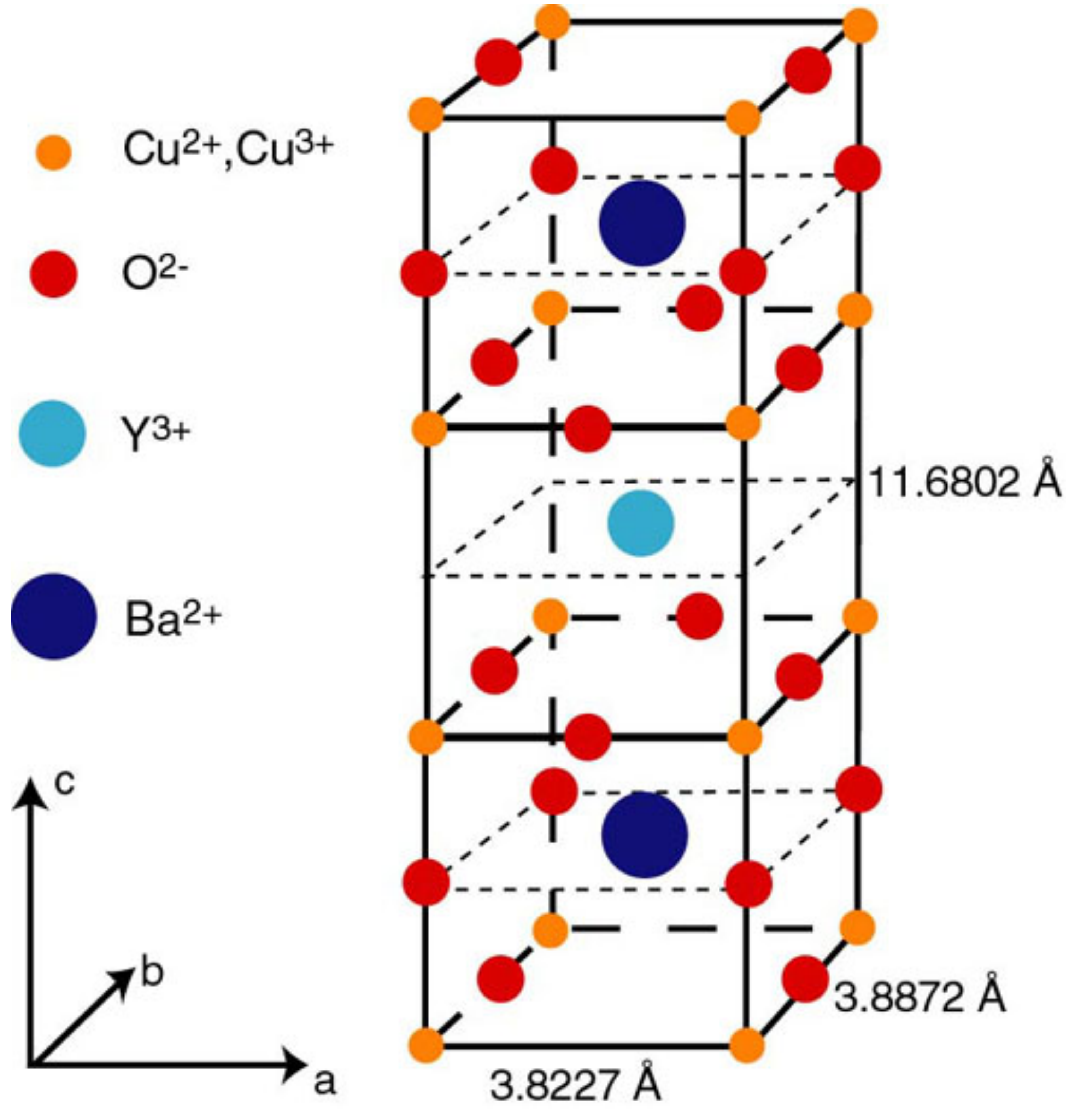
Cu^{2+},Cu^{3+}
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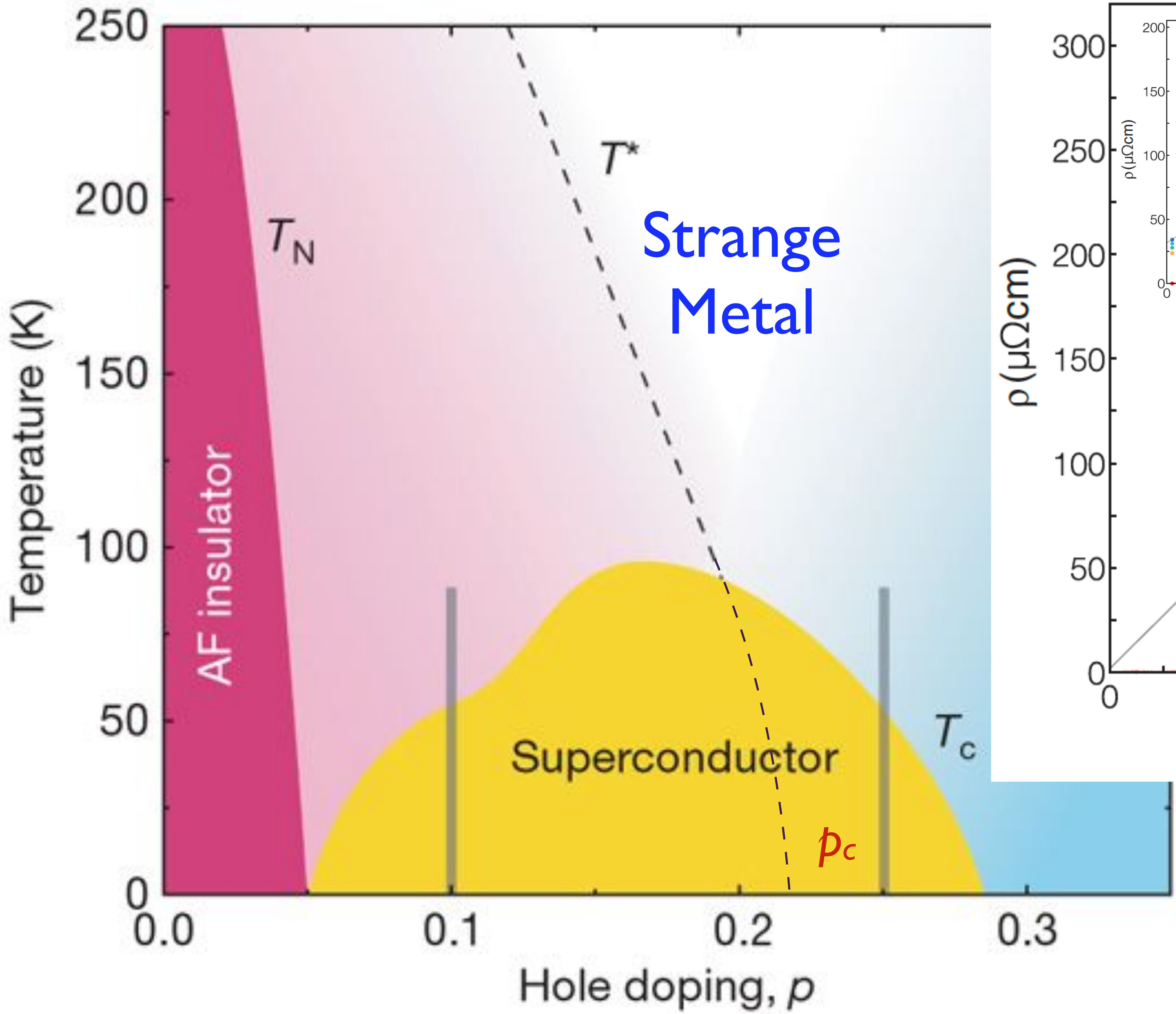
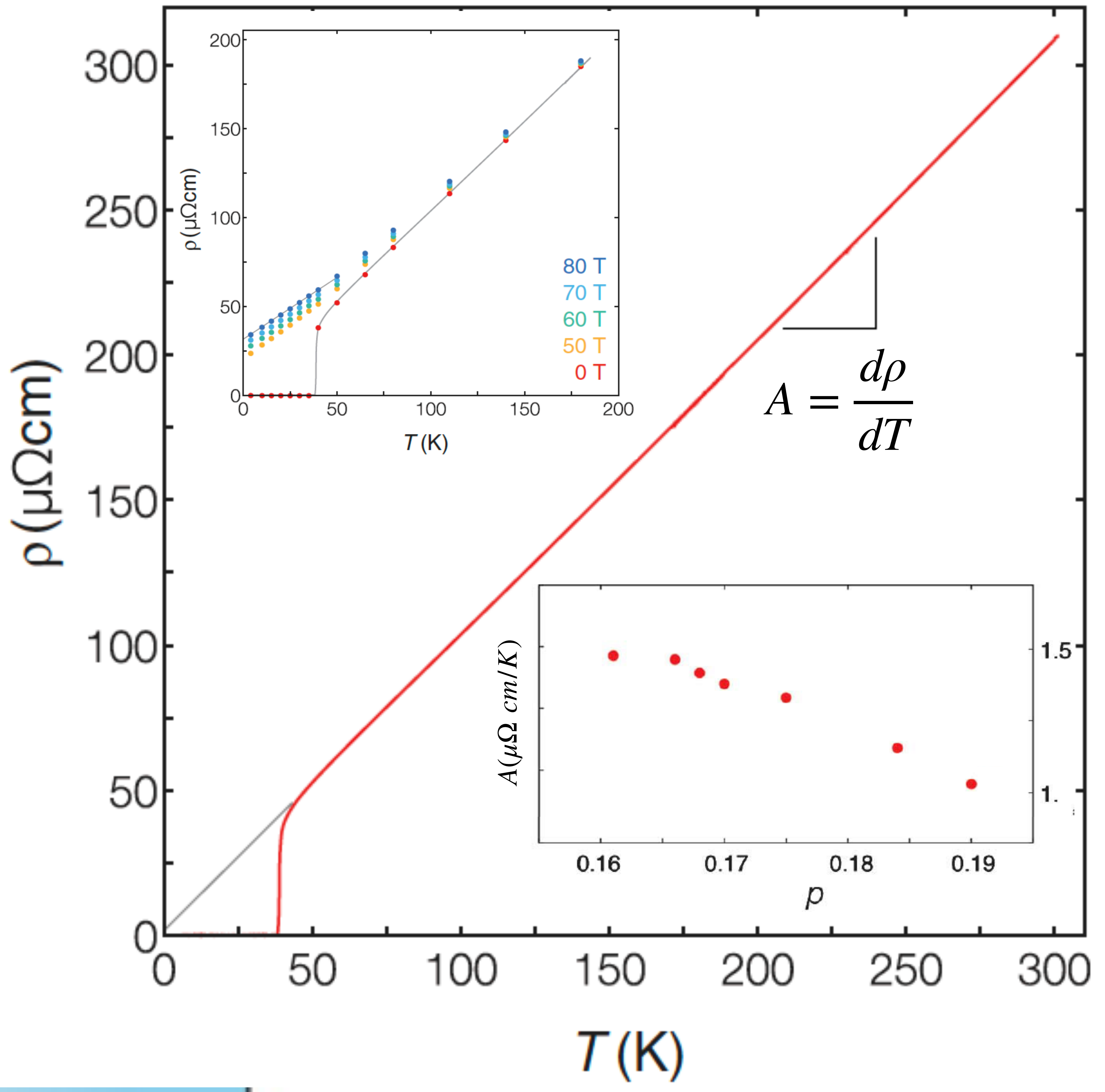


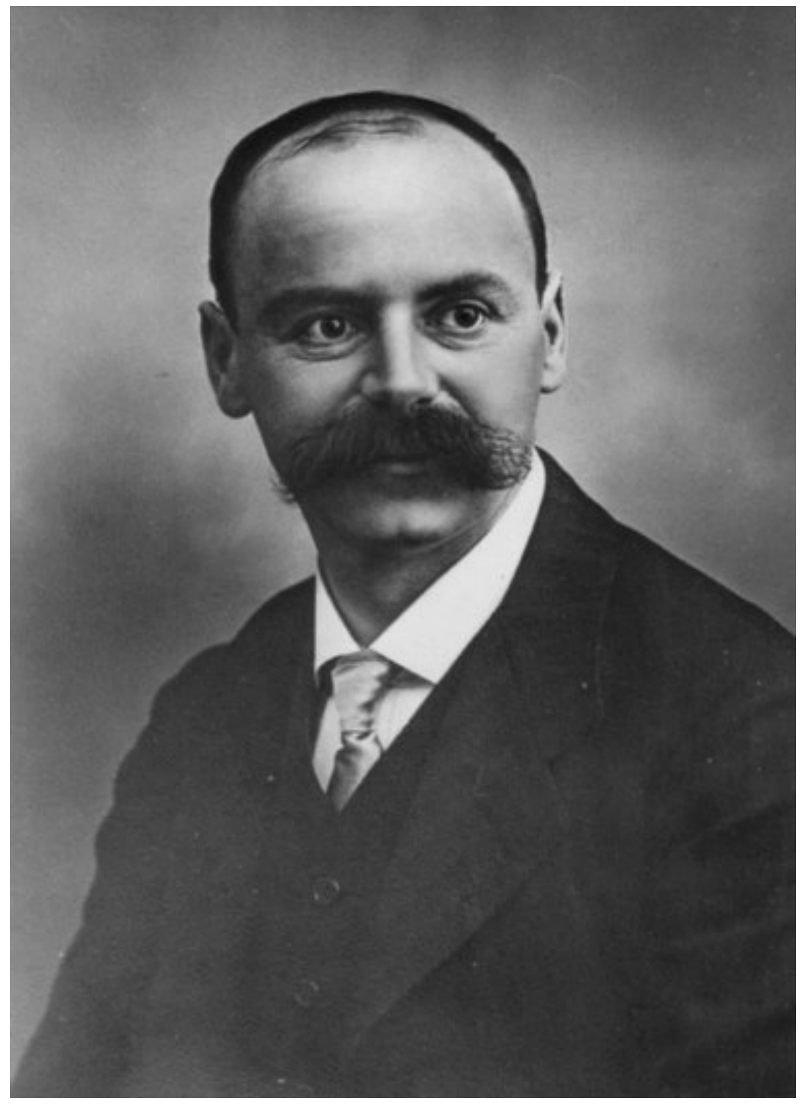


LSCO: Giraldo-Gallo et al. 2018

Black holes

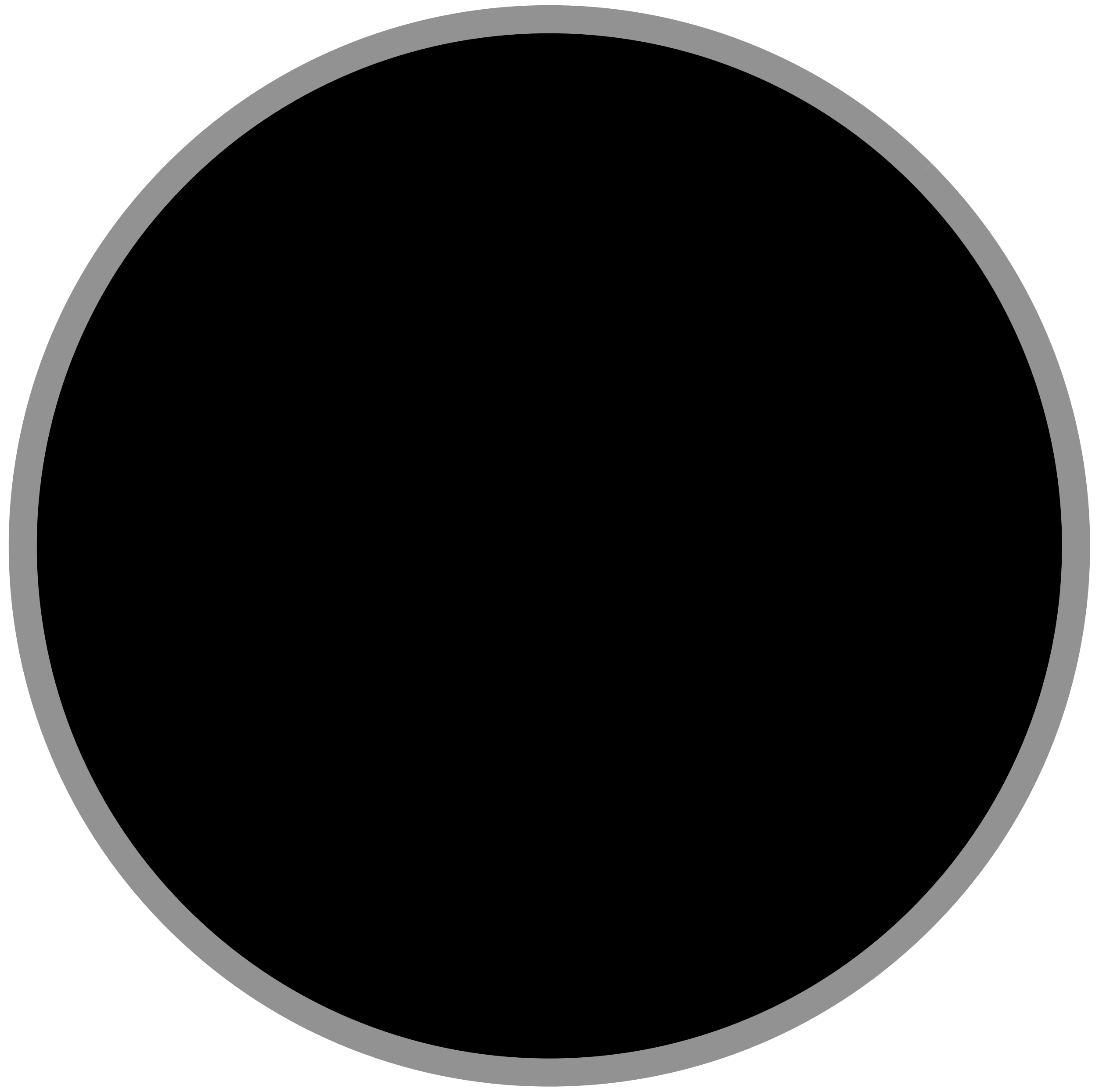
Black Holes

Objects so dense that light is gravitationally bound to them.



Karl Schwarzschild (1916)

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

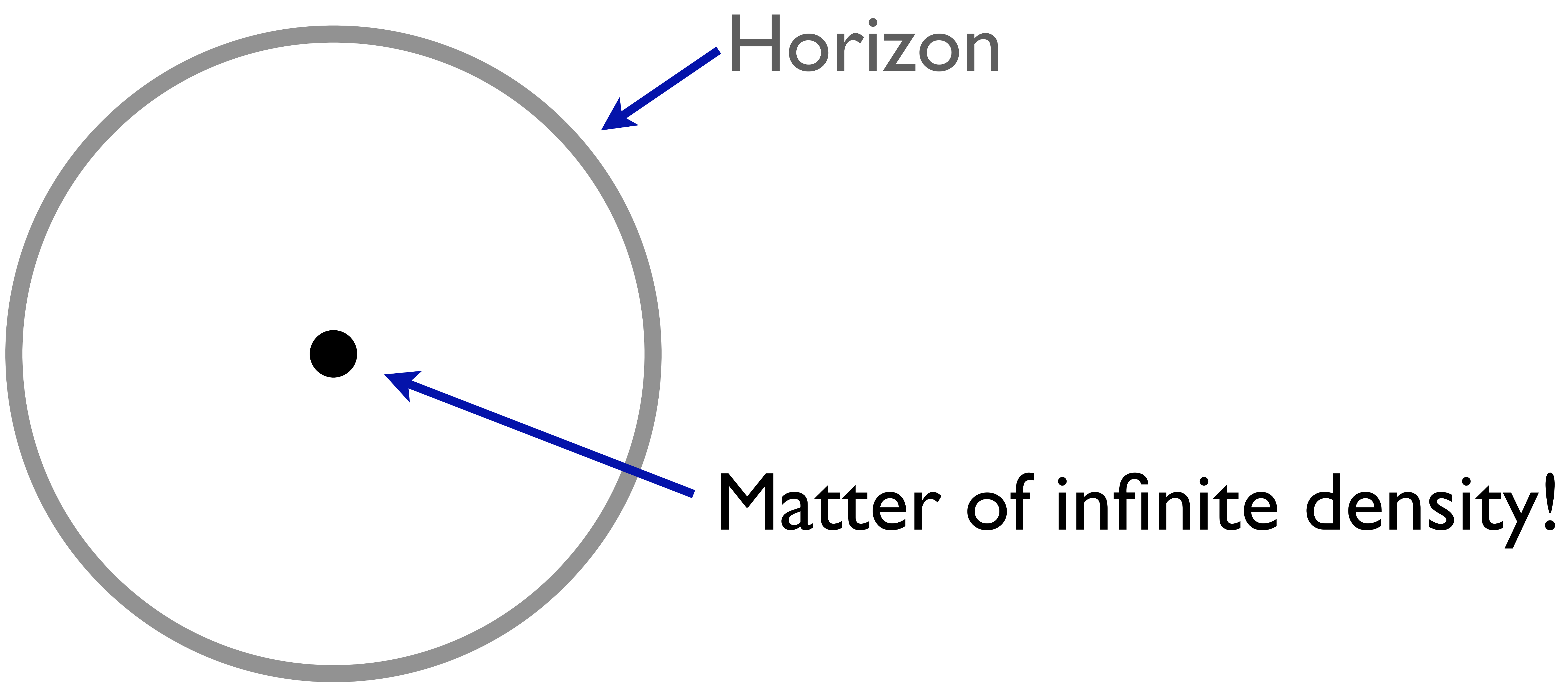


G Newton's constant, c velocity of light, M mass of black hole

For $M =$ earth's mass, $R \approx 9\, mm$!

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.



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.

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

$$R = 1.3 \times 10^{11}\mathrm{m}$$
$$\approx \text{earth's orbit}$$

Event Horizon Telescope
May 12, 2022

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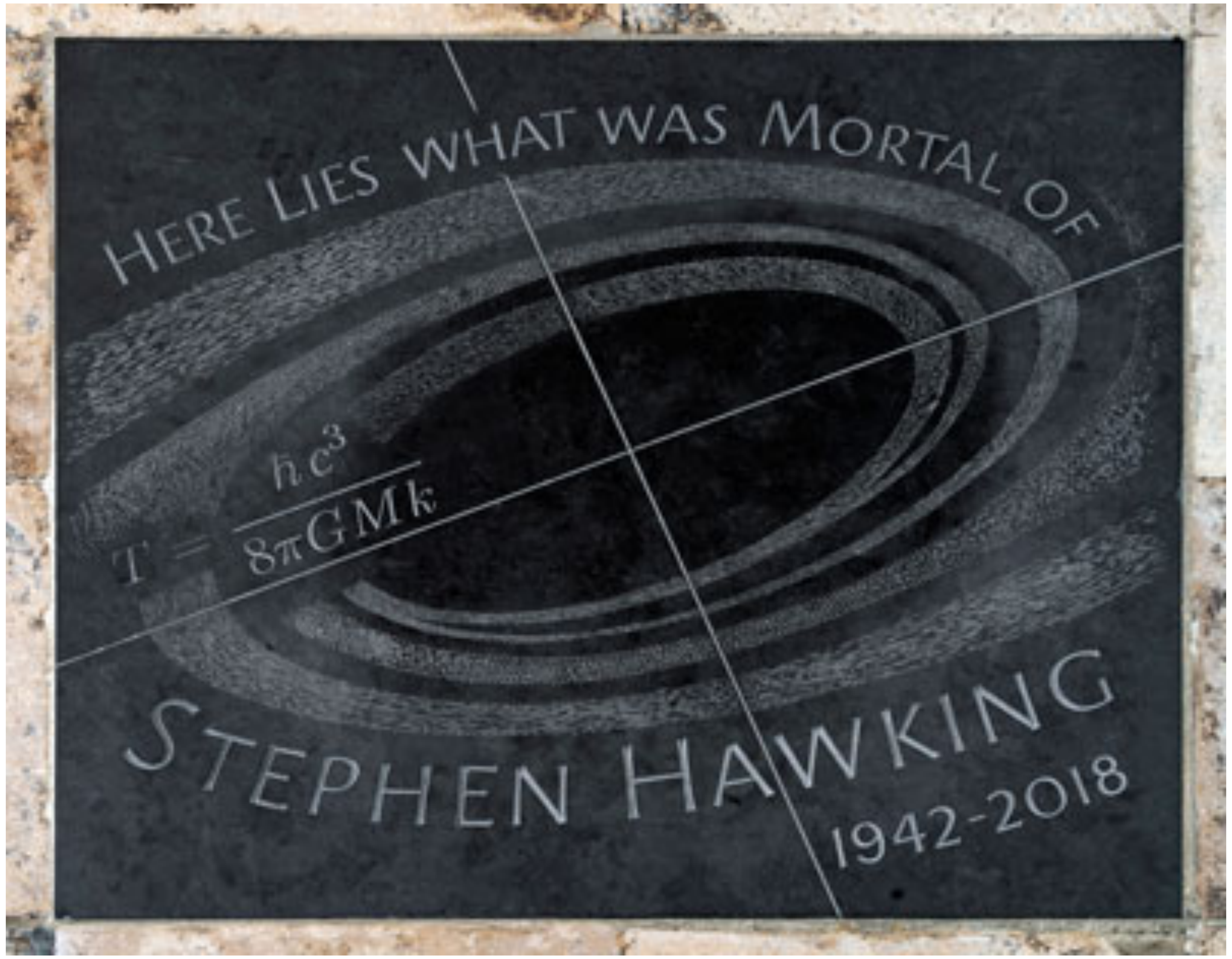
In any case, it was clear that quantum theory should be applied to the collapsed matter, but no one knew how to.

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



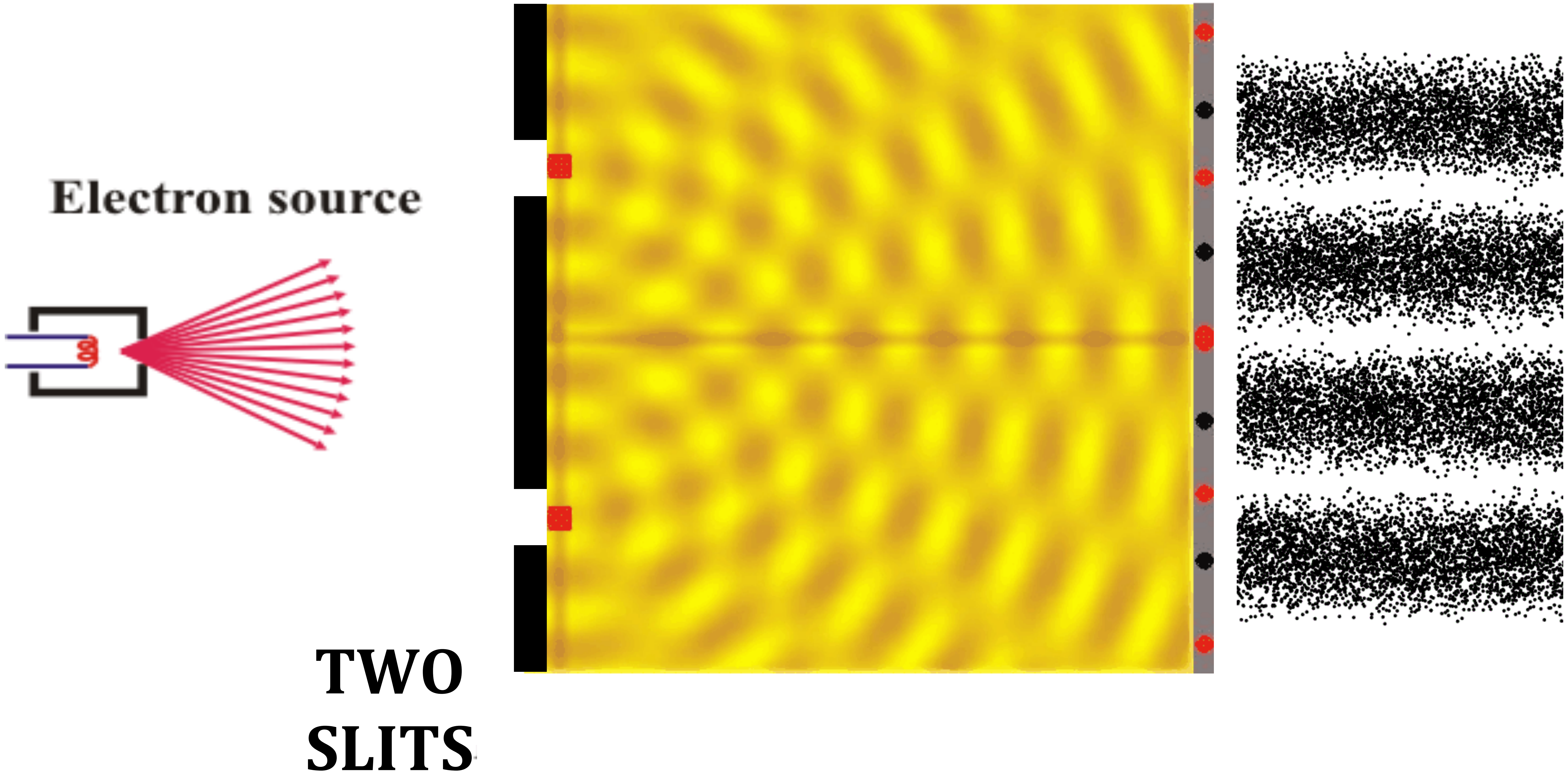
$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

What is
quantum entanglement?

"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.

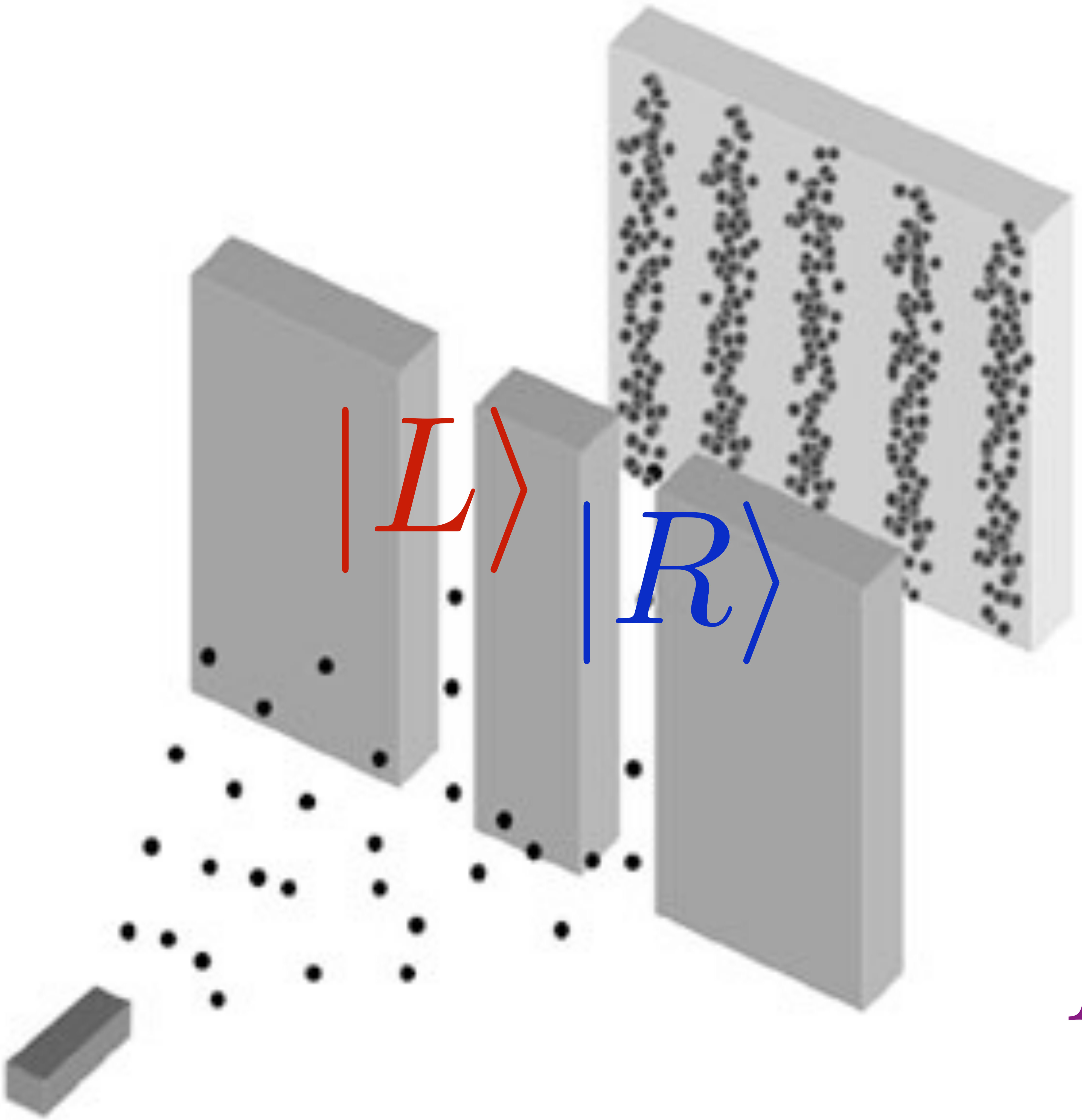
The double slit experiment



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

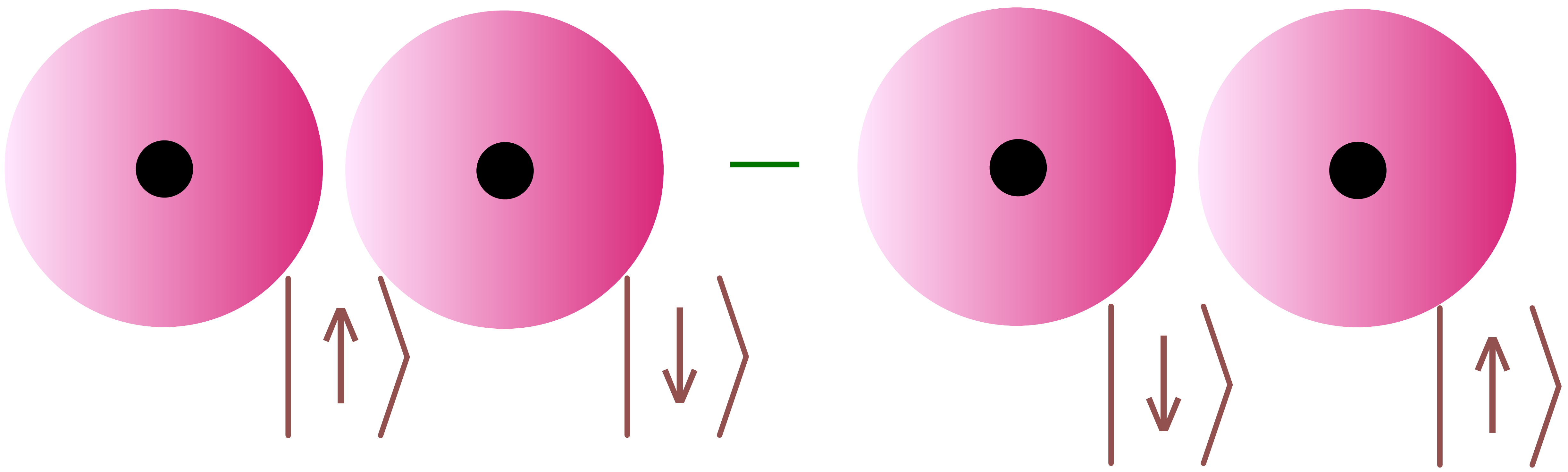
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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

(Received March 25, 1935)

Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



Quantum Entanglement

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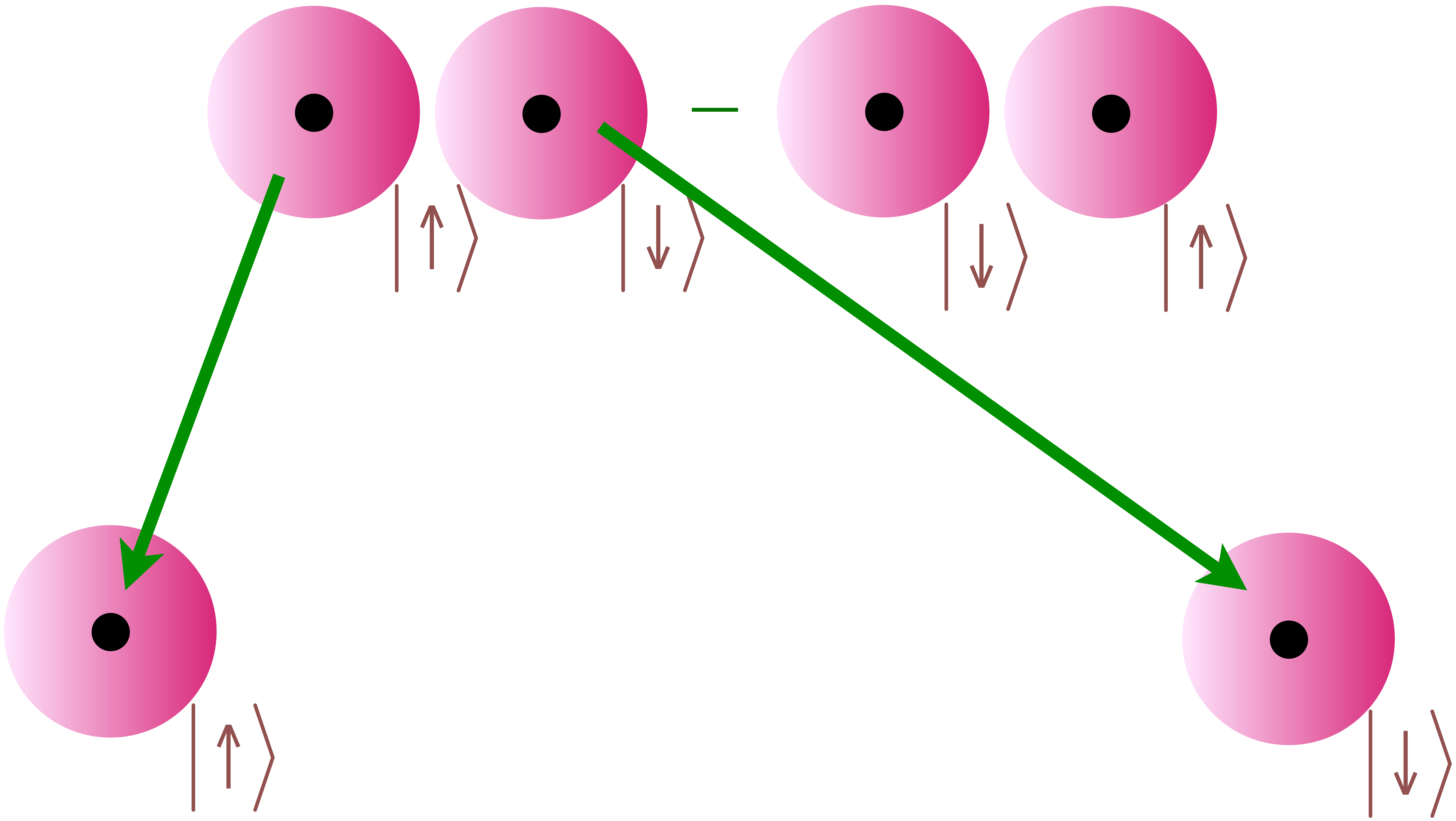

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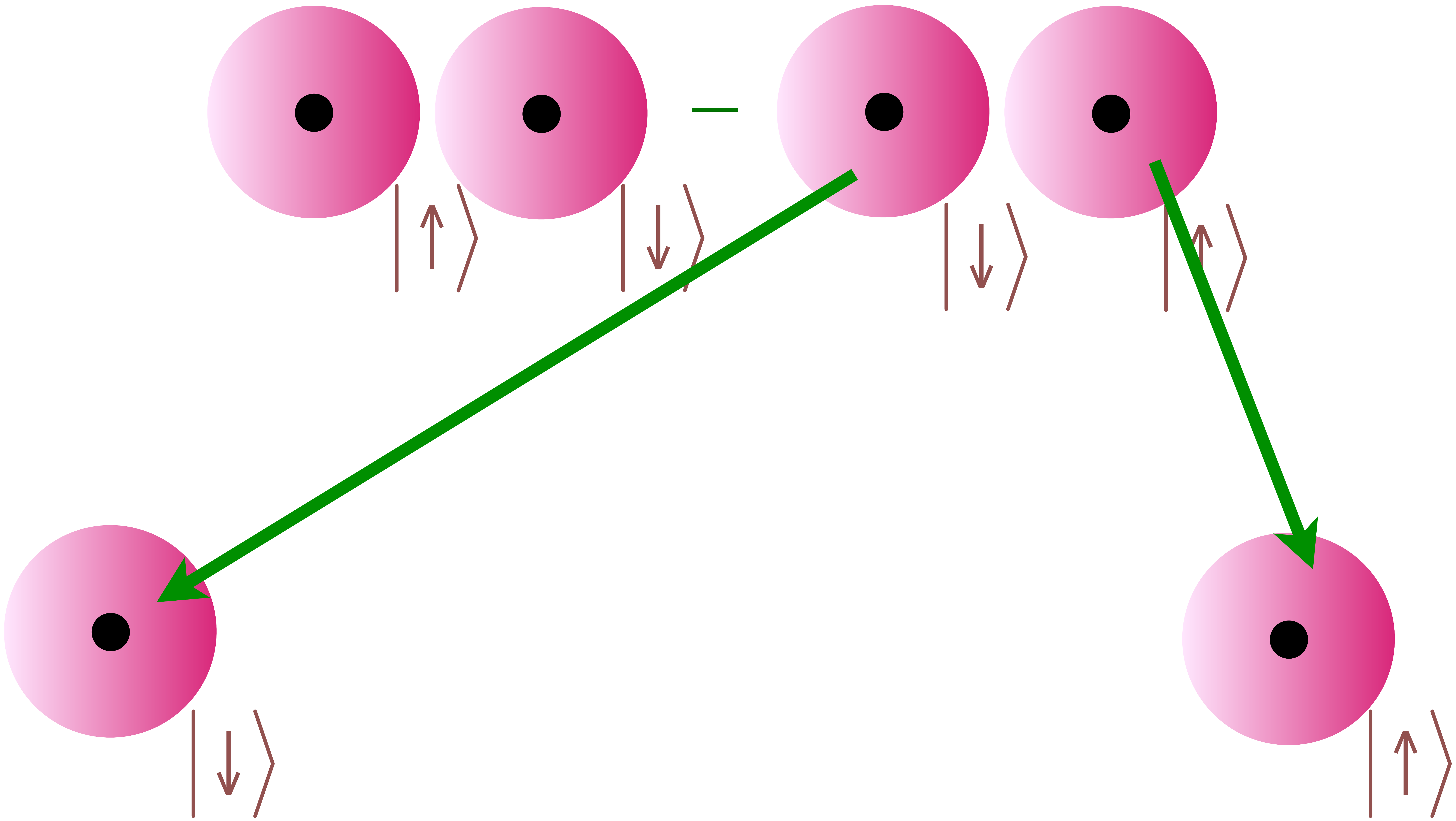

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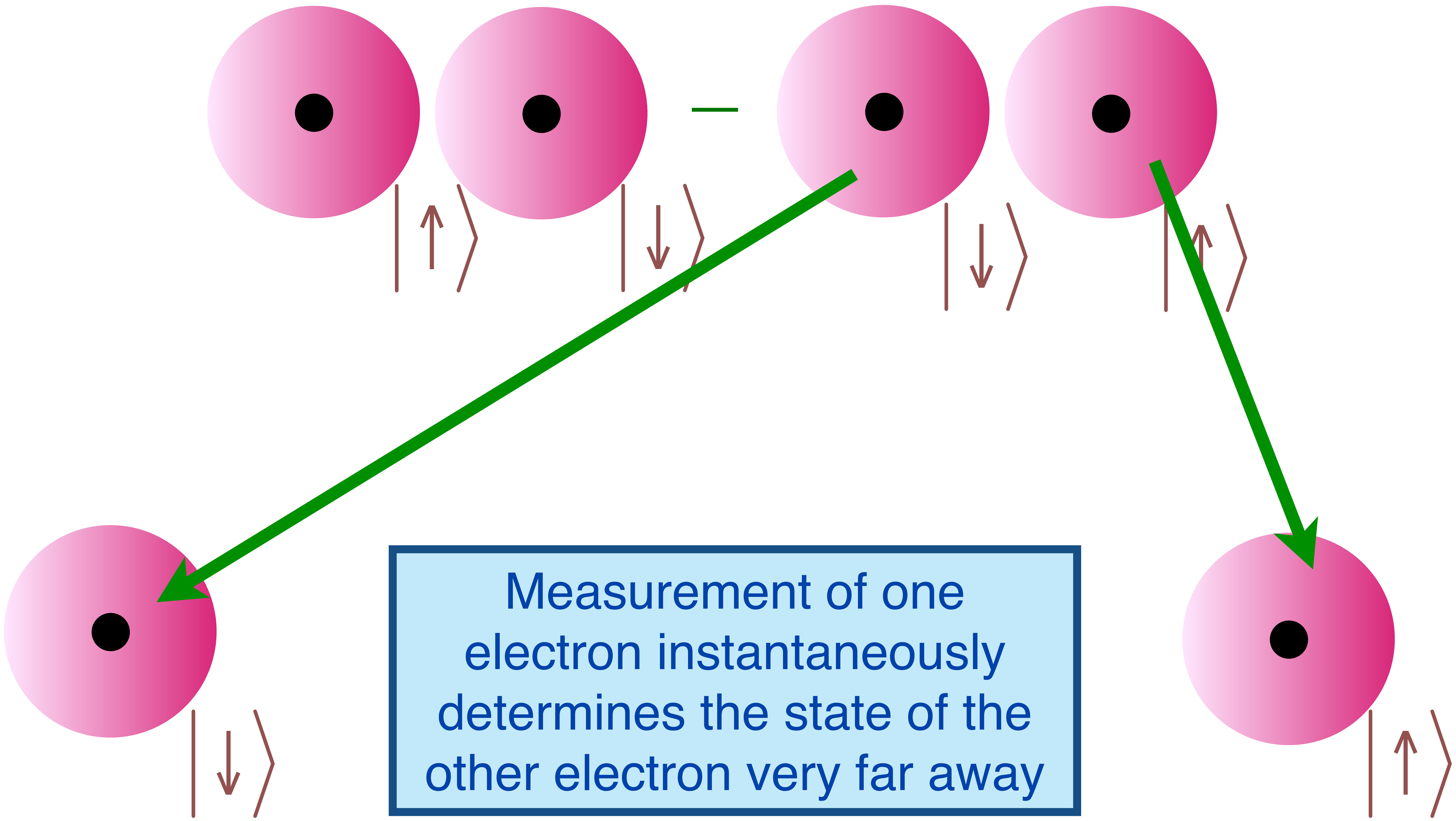

Measurement of one electron instantaneously determines the state of the other electron very far away

Quantum Entanglement

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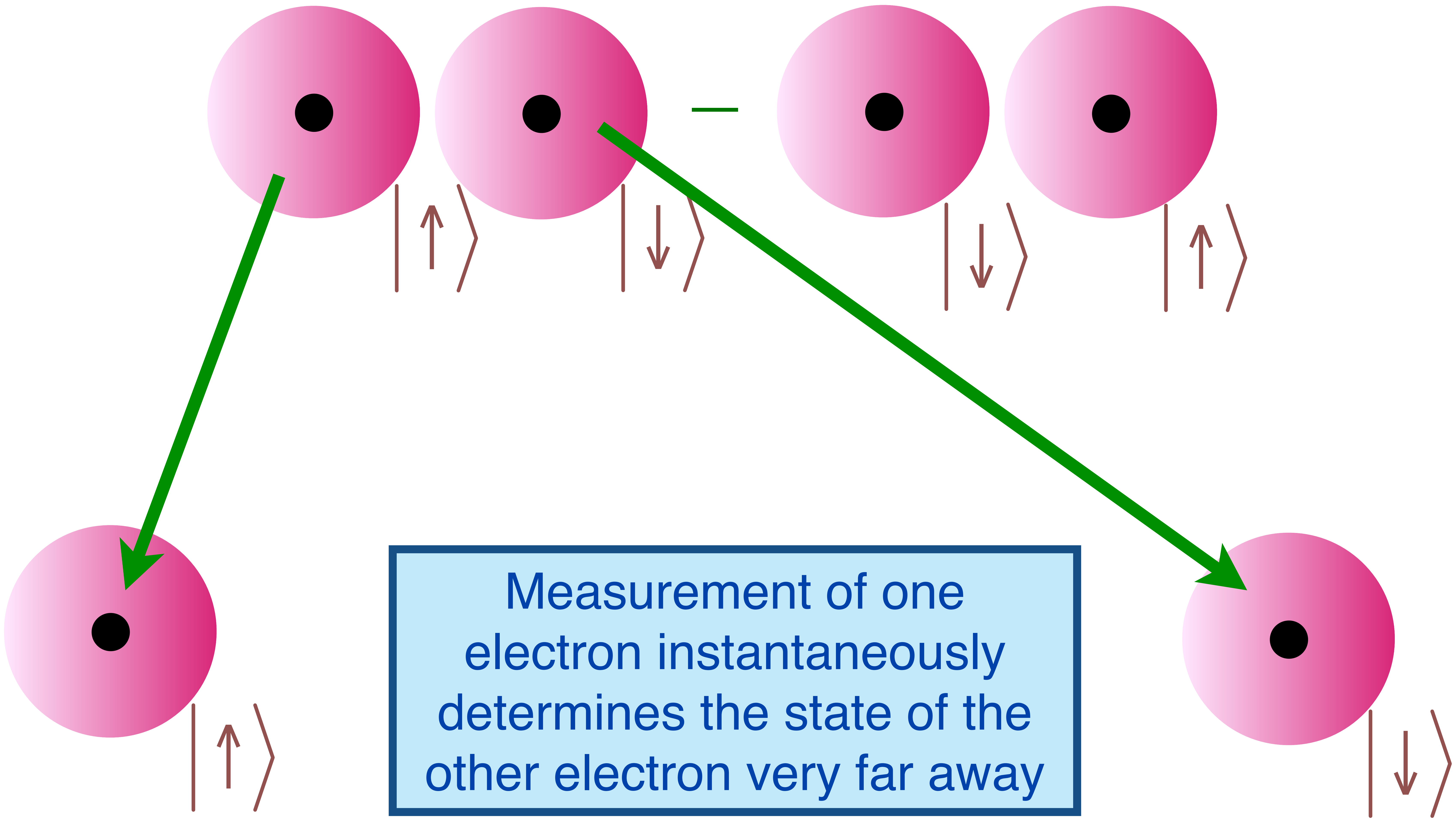

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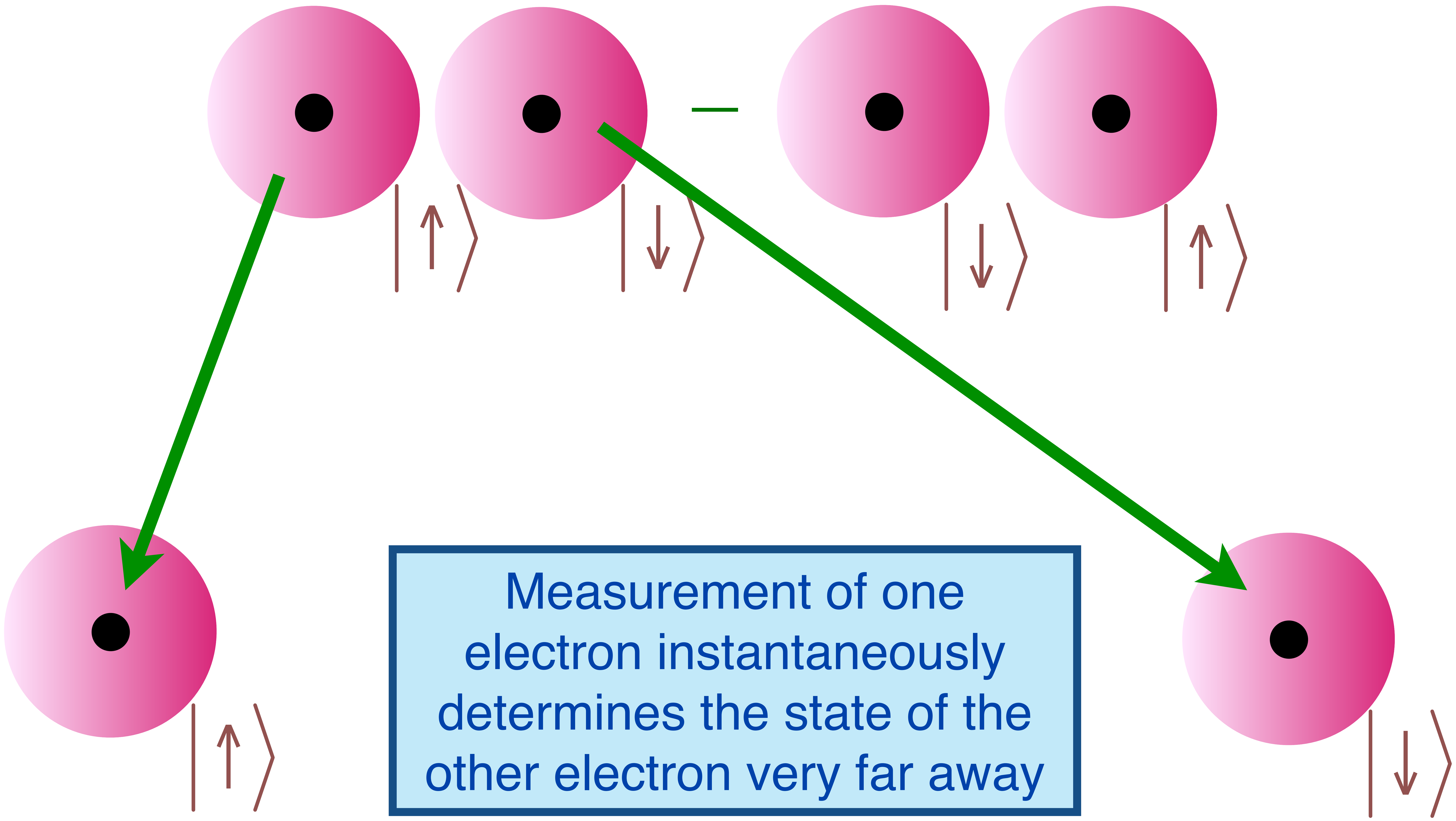
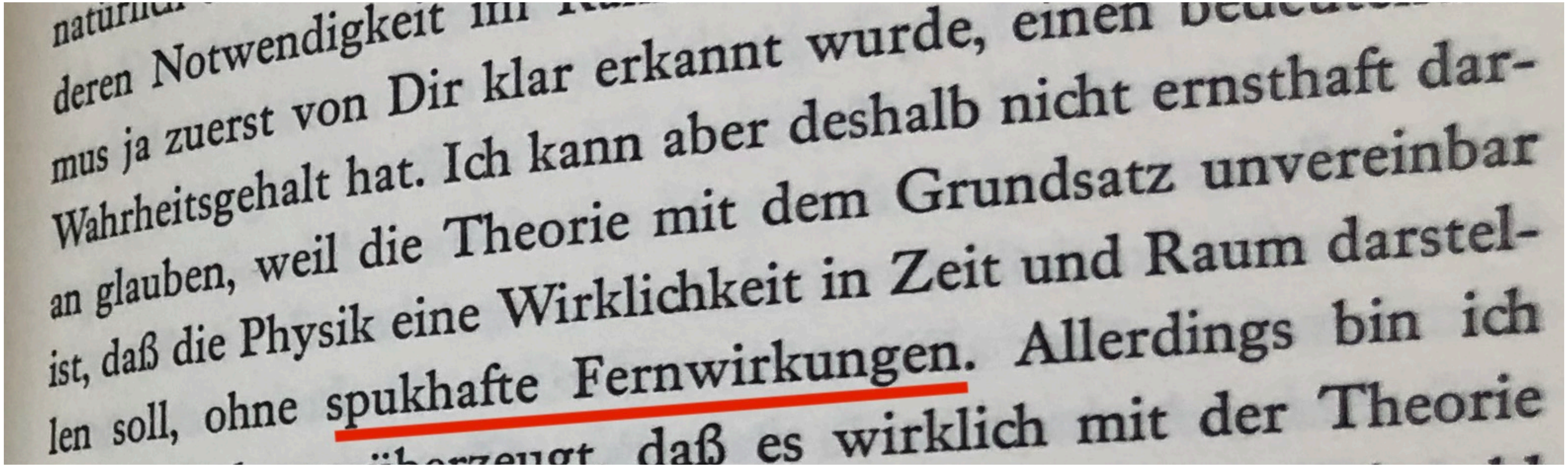


Measurement of one electron instantaneously determines the state of the other electron very far away

Spooky action at a distance !


deren Notwendigkeit im
mus ja zuerst von Dir klar erkannt wurde, einen
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

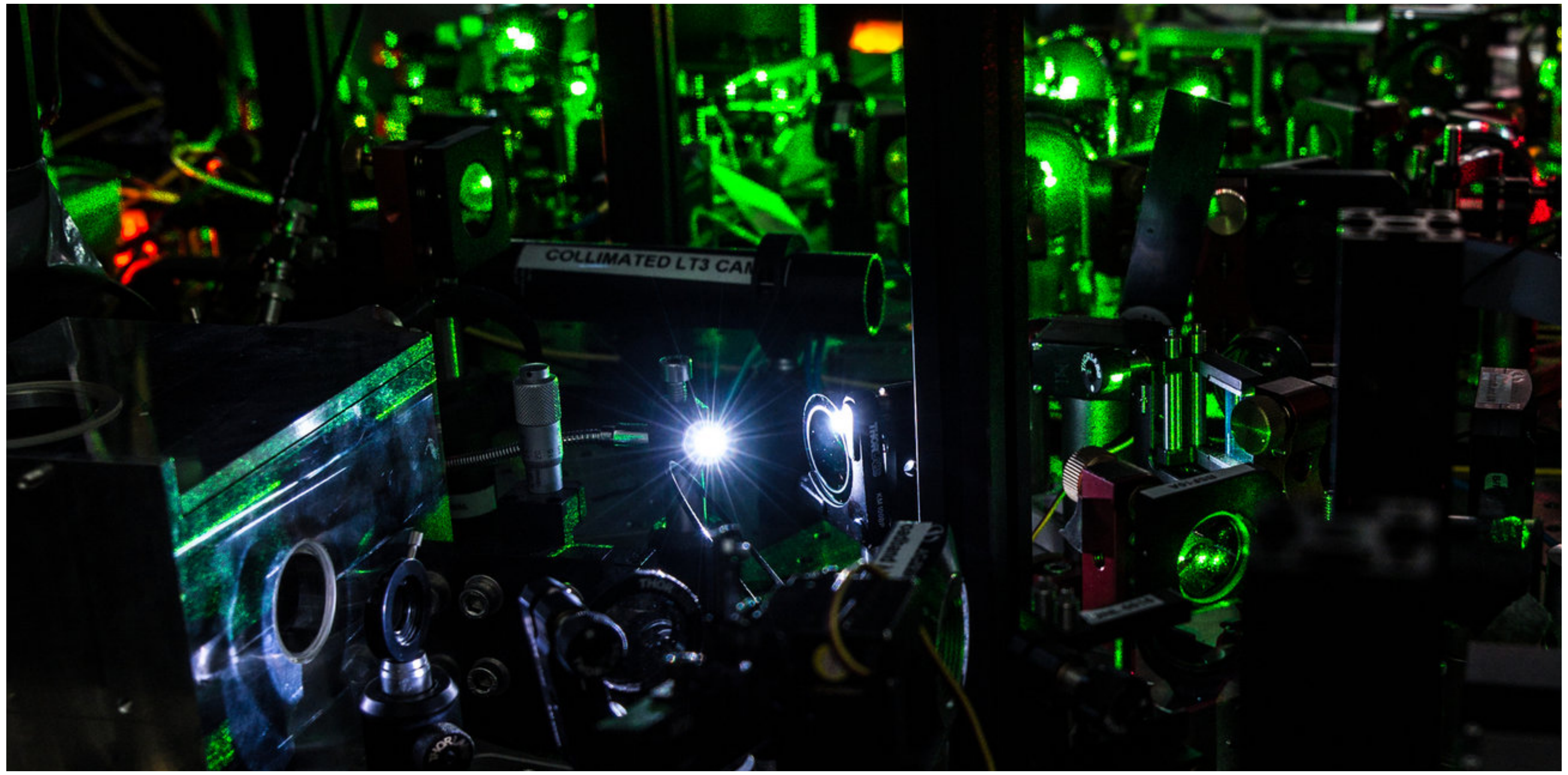
I cannot seriously believe in it because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at distance

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.

Great discoveries in physics

Entropy (1870)

Superconductivity (1911)

Black holes (1916)

Quantum entanglement (1935)

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

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

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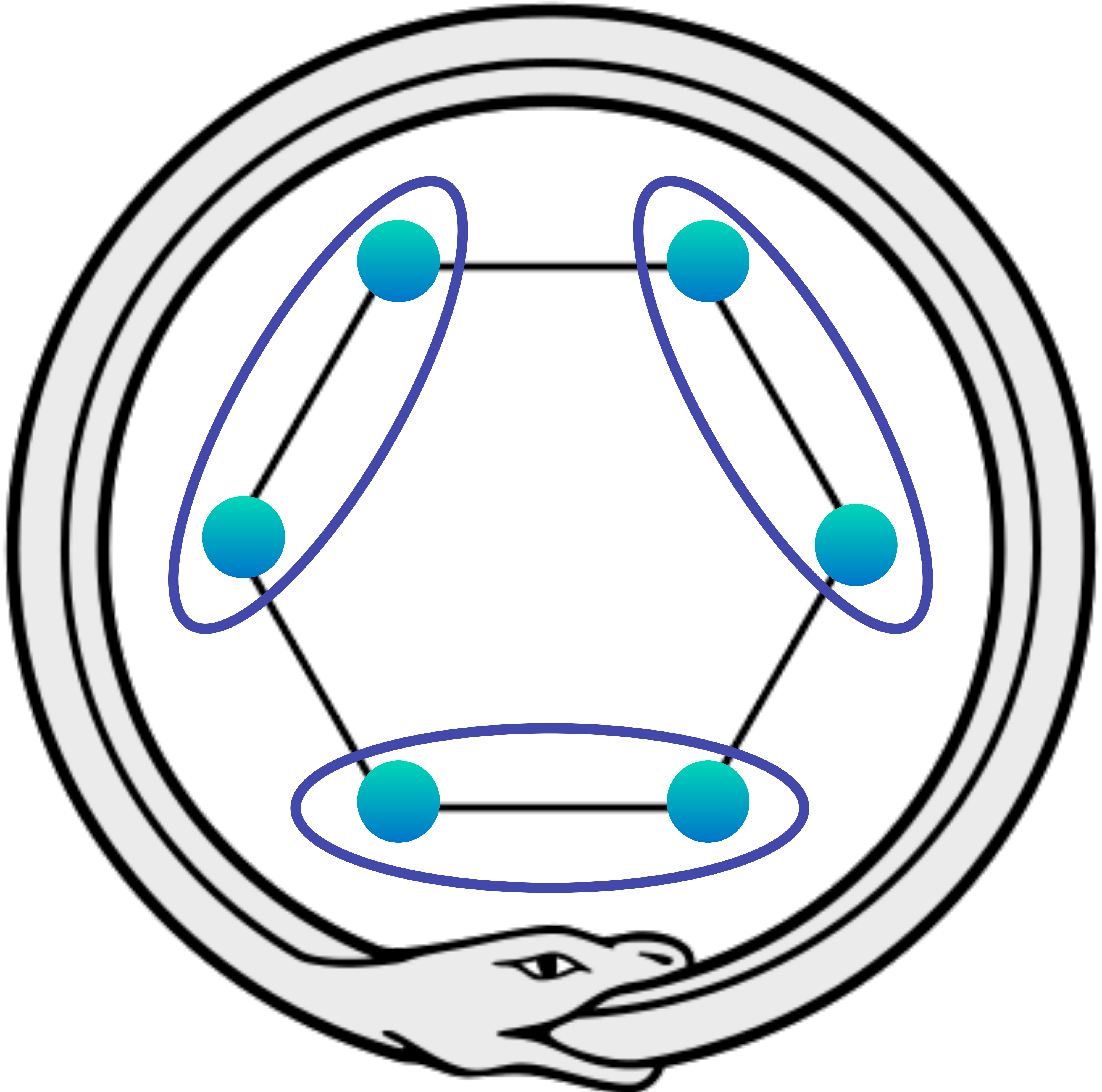
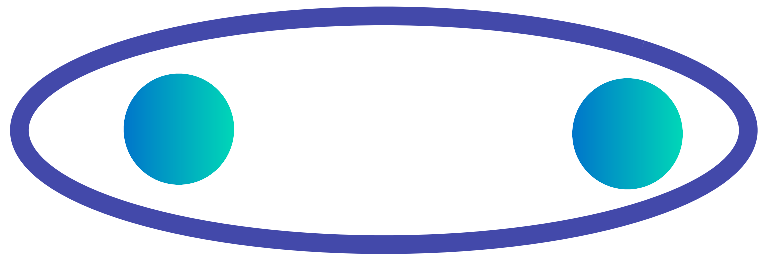
The Sachdev-Ye-Kitaev model of many-particle entanglement

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*





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

Benzene

*Wikipedia

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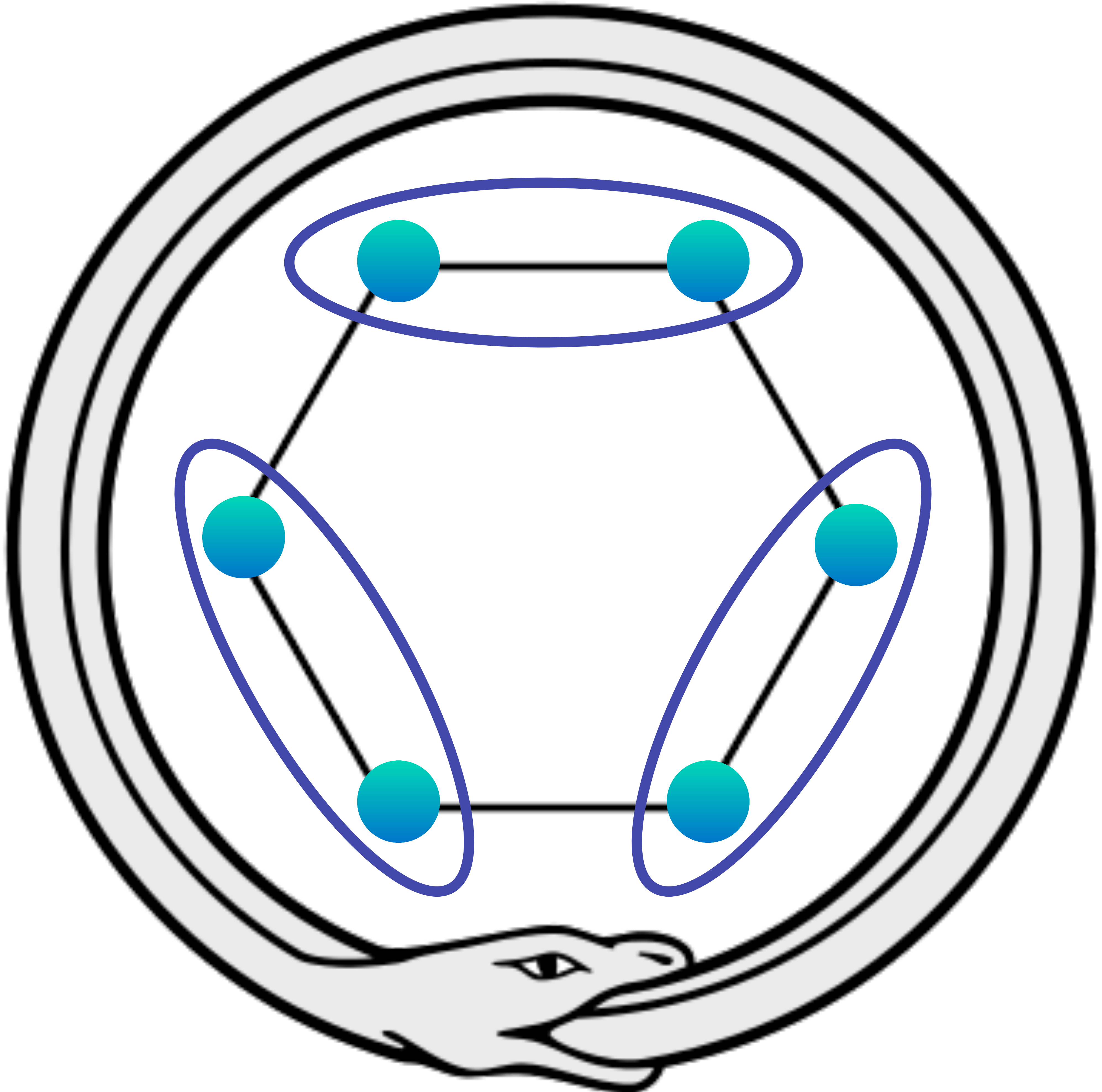

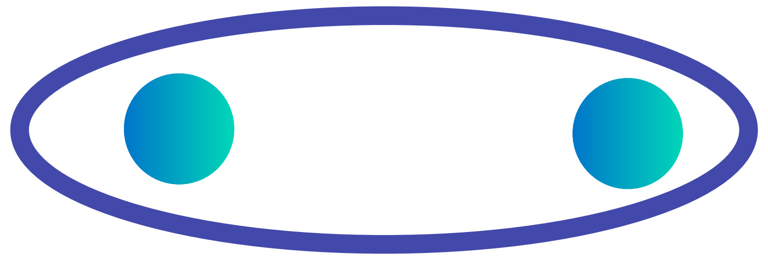

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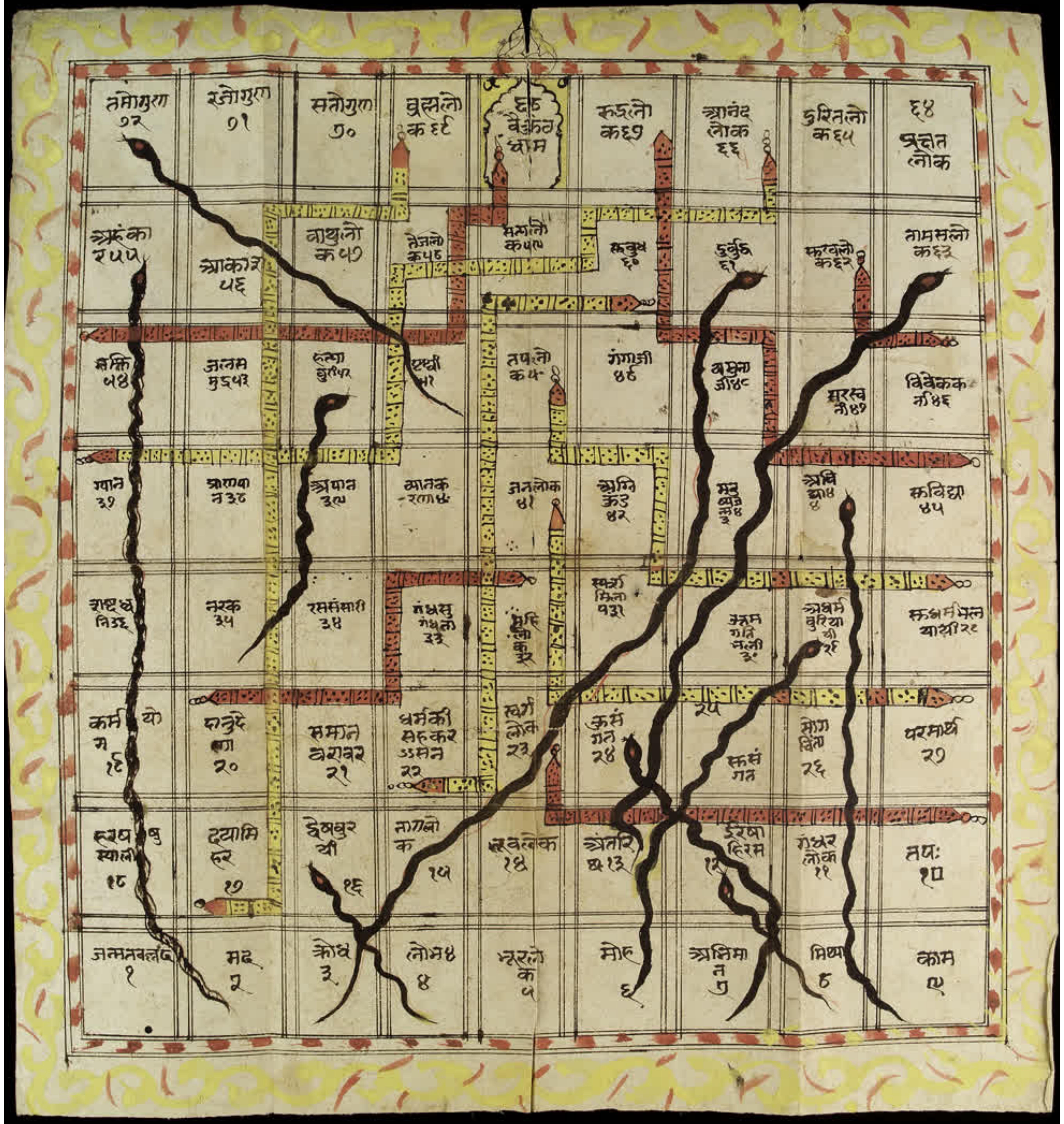
Benzene

*Wikipedia



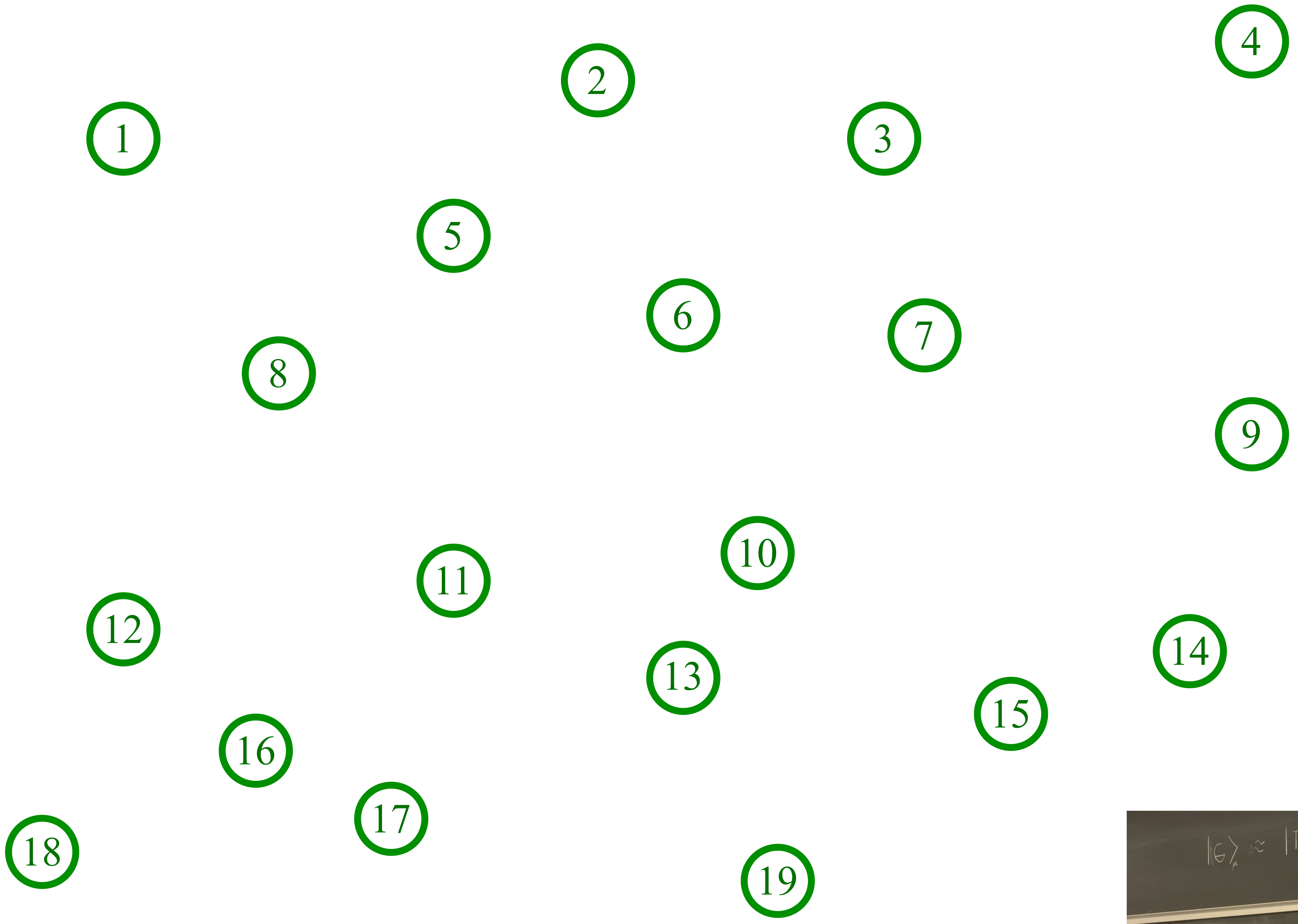
My spooky dream*

Ancient Indian game of Snakes and Ladders

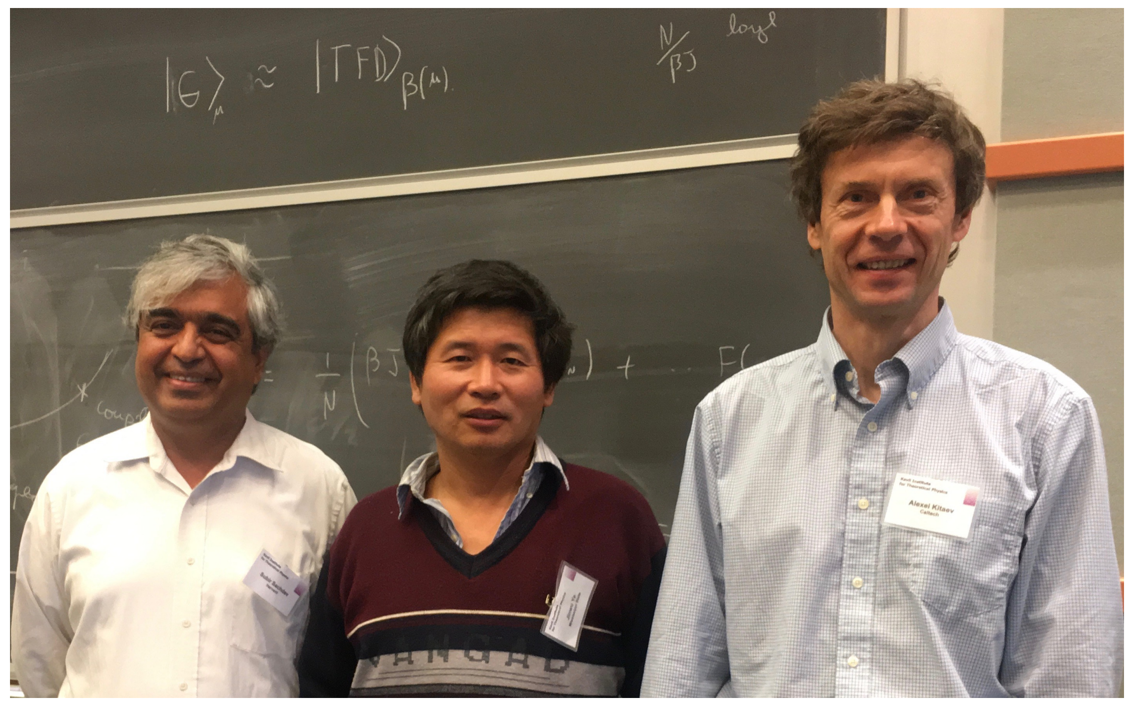
*Not true

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)



Pick a set of random positions



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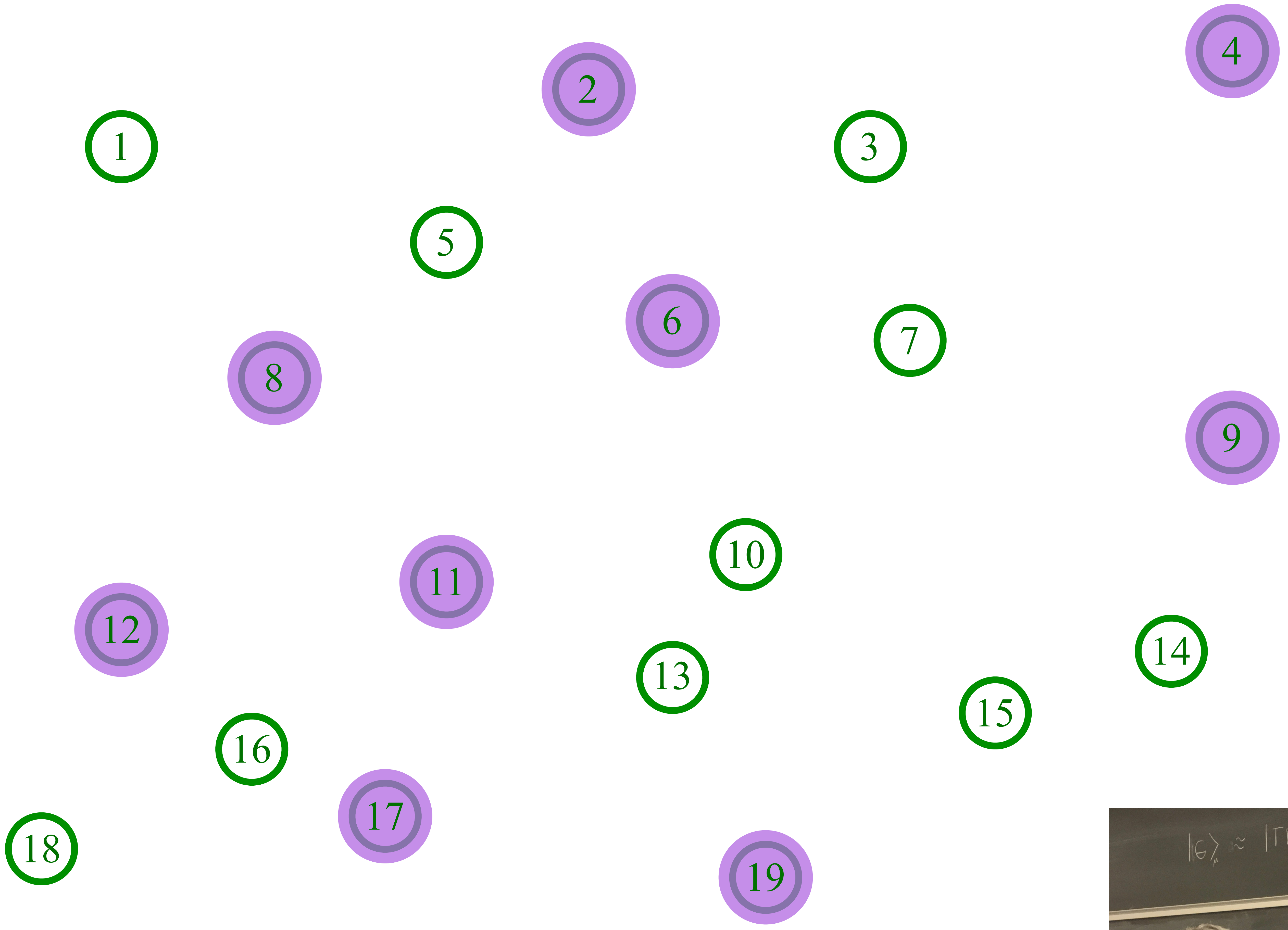
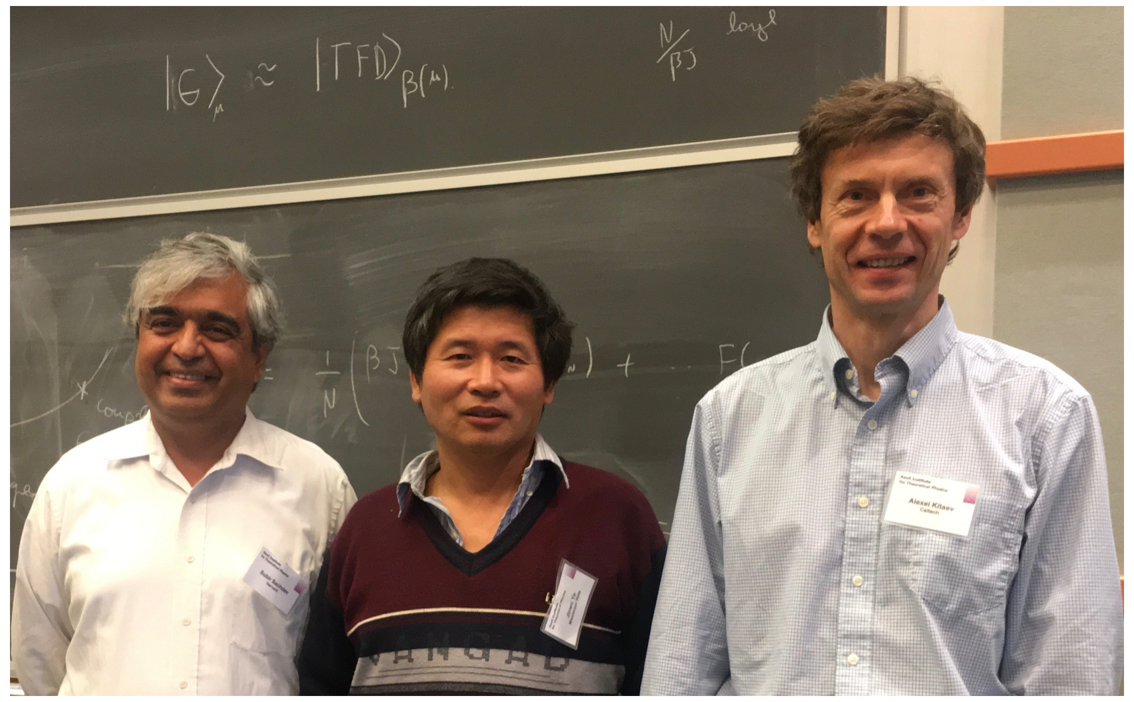


Place electrons randomly on some sites



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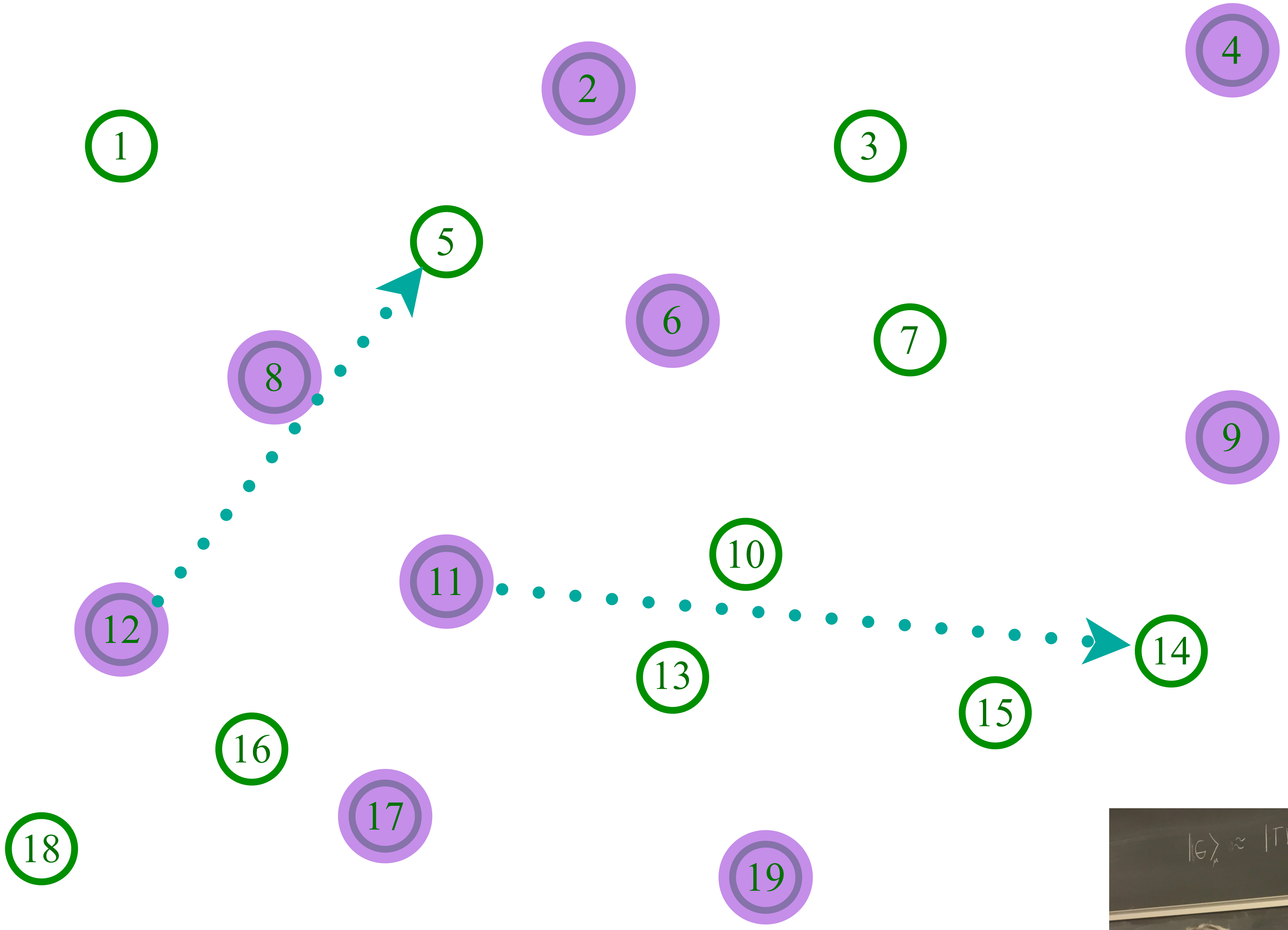
Sachdev, Ye (1993); Kitaev (2015)

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



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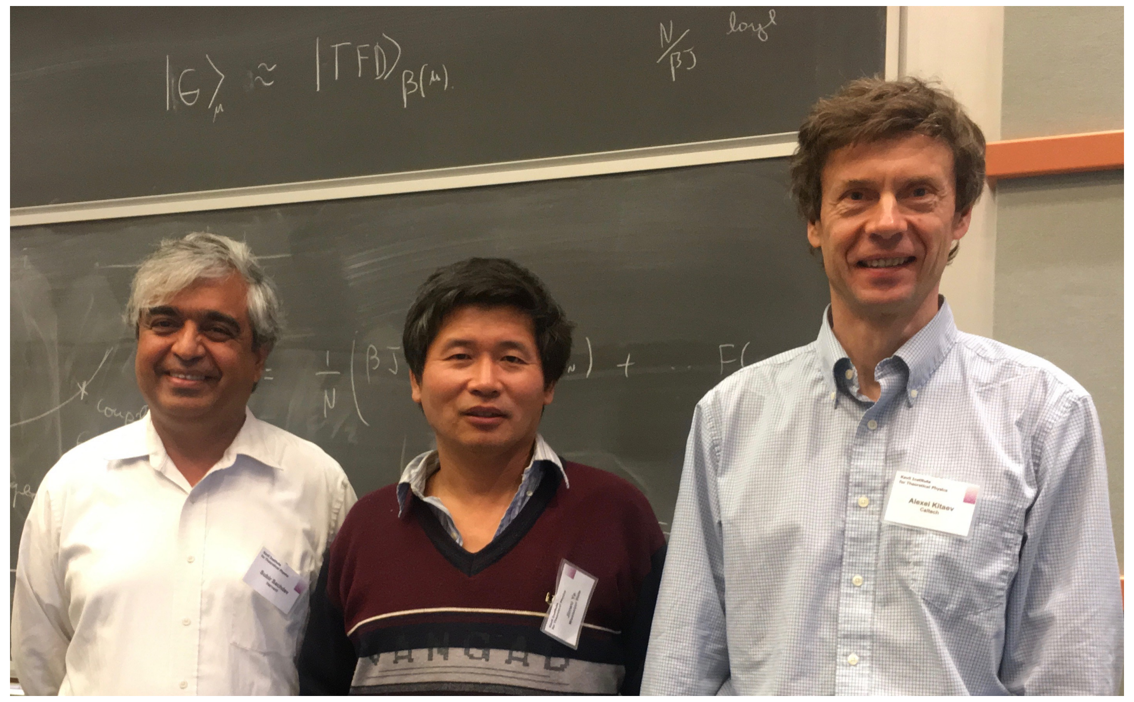

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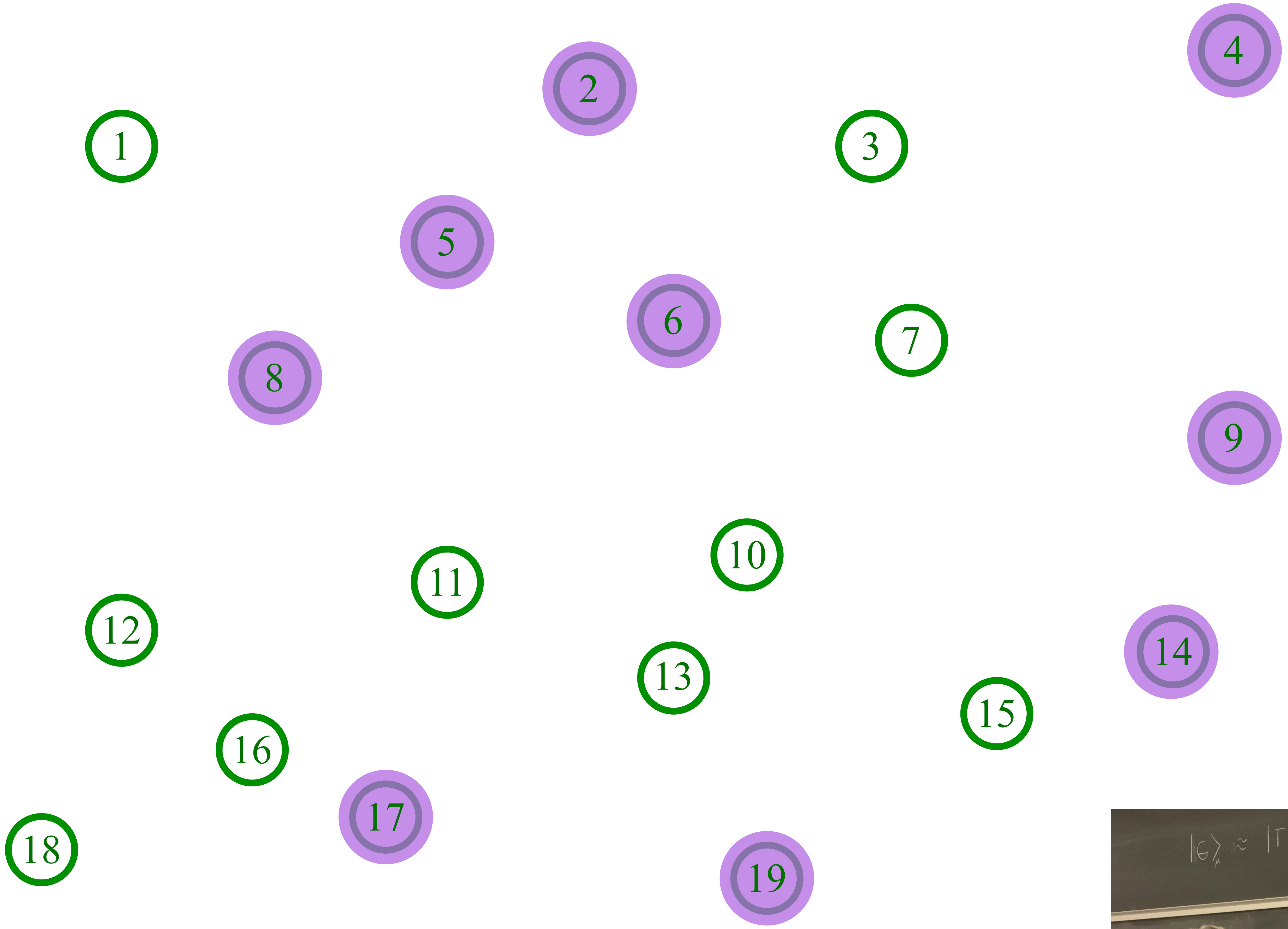
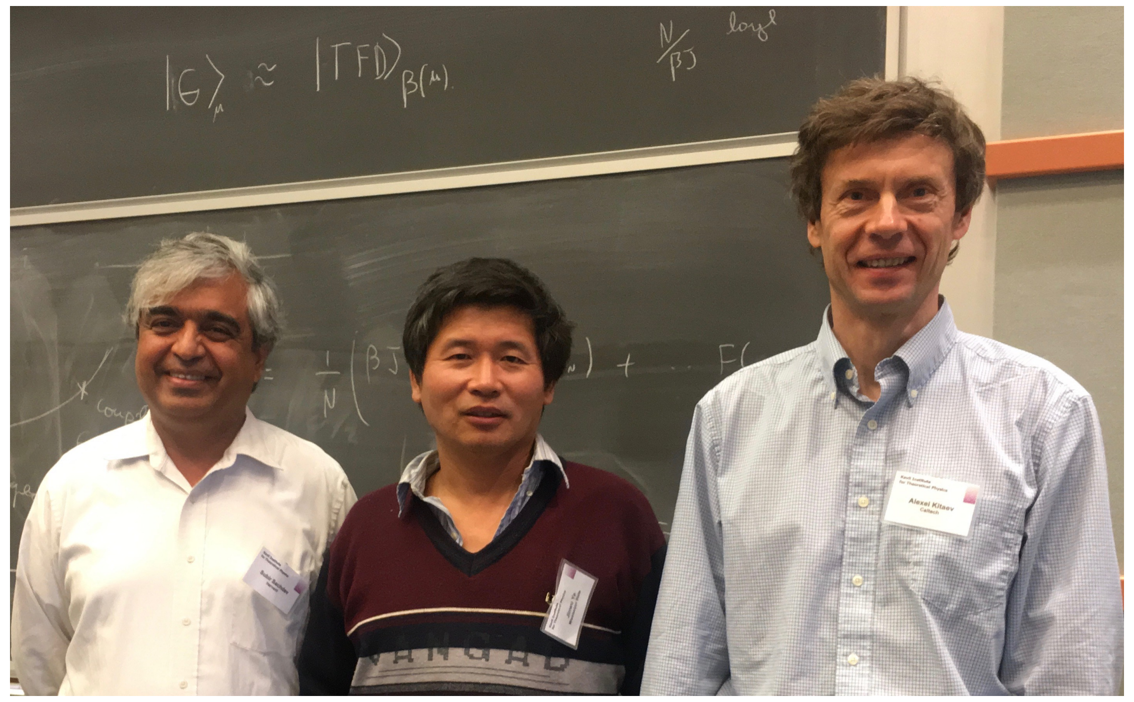


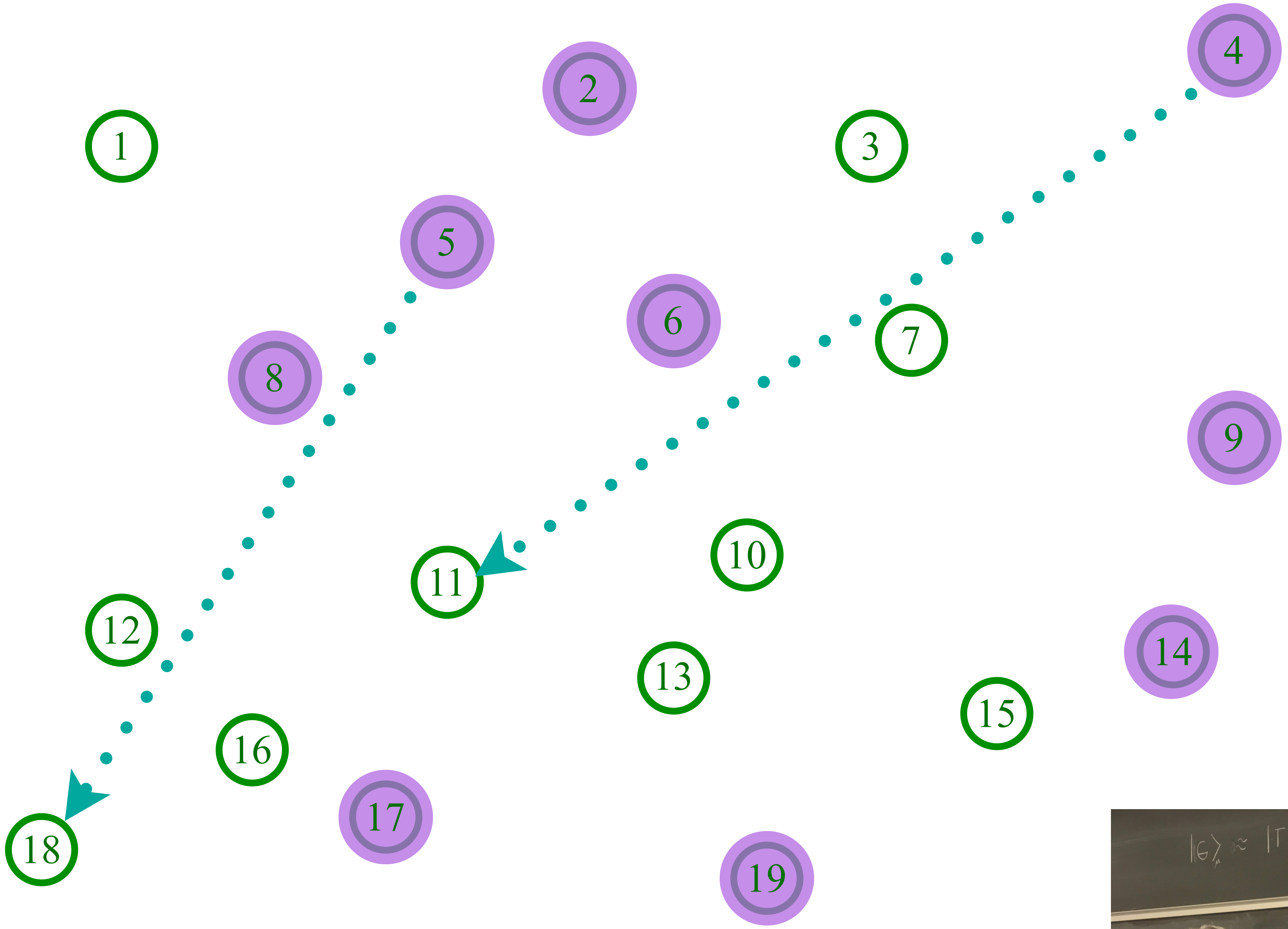
Entangle electrons pairwise randomly



The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



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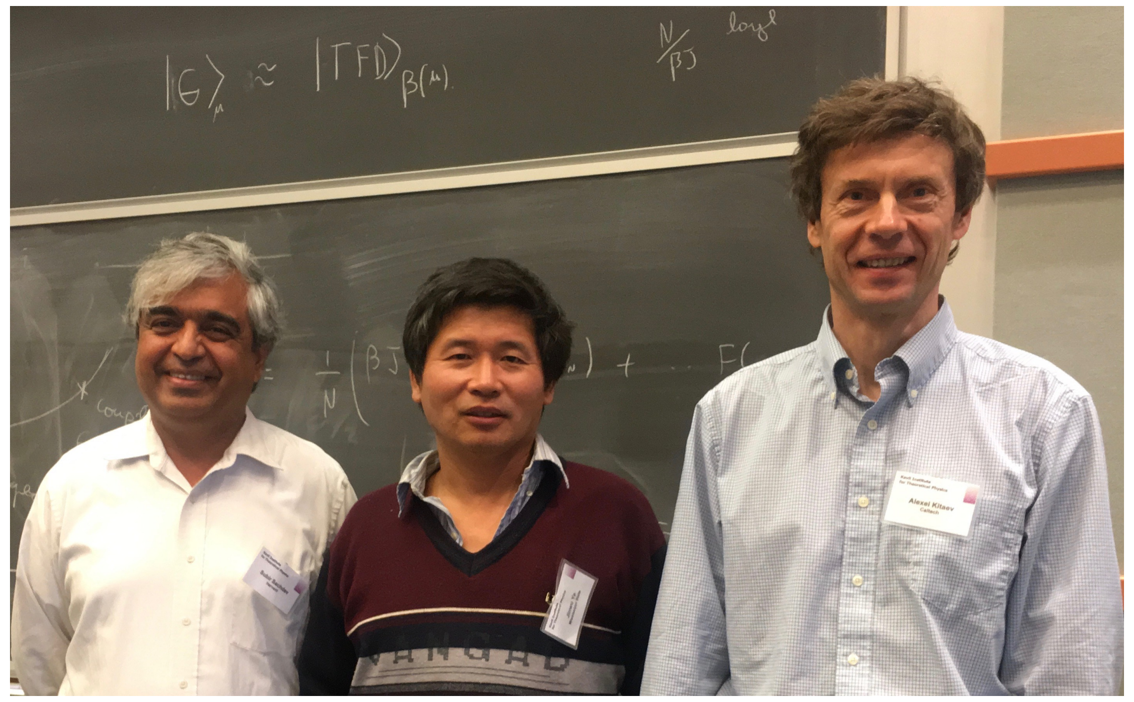

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Sachdev, Ye (1993); Kitaev (2015)

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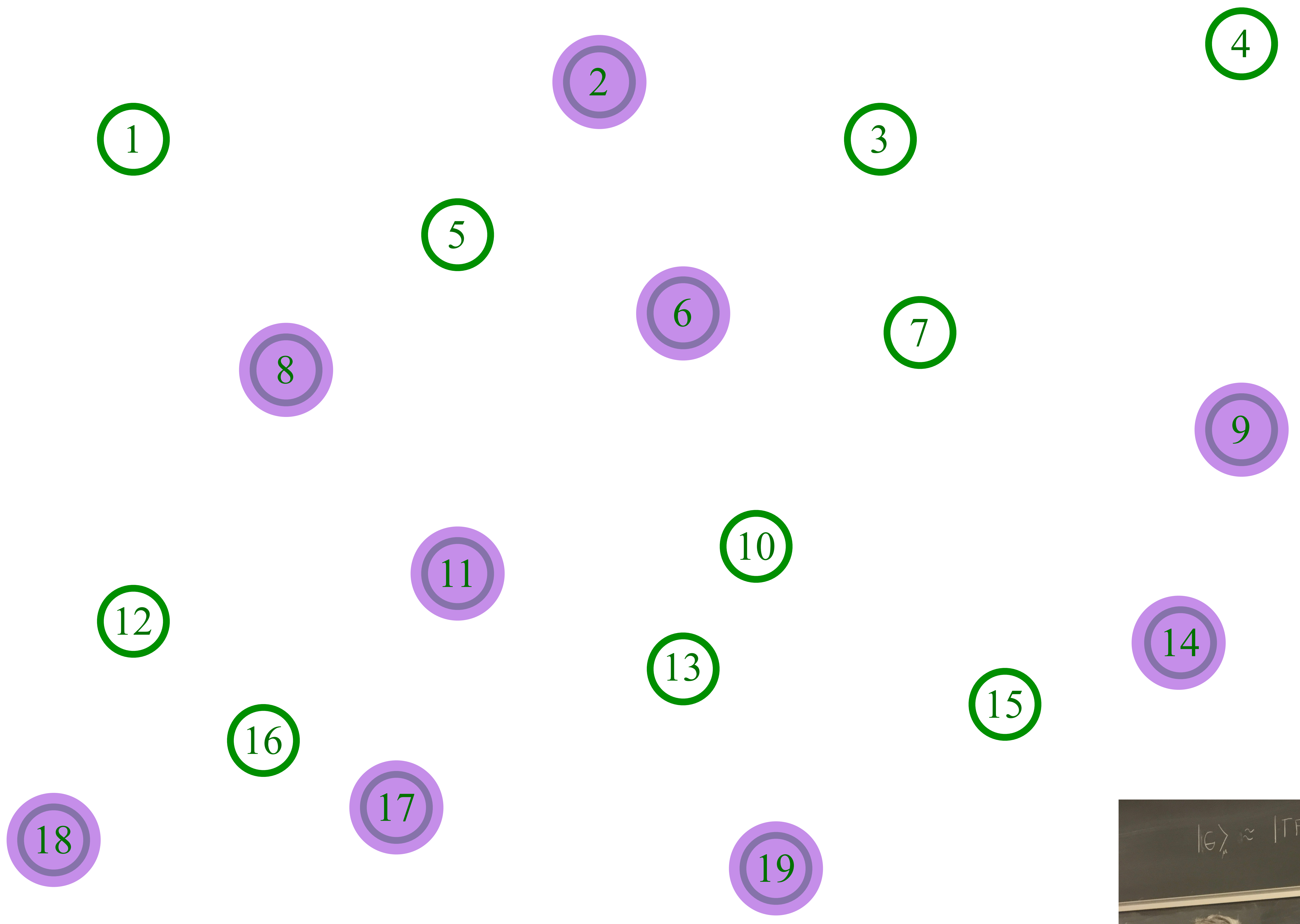

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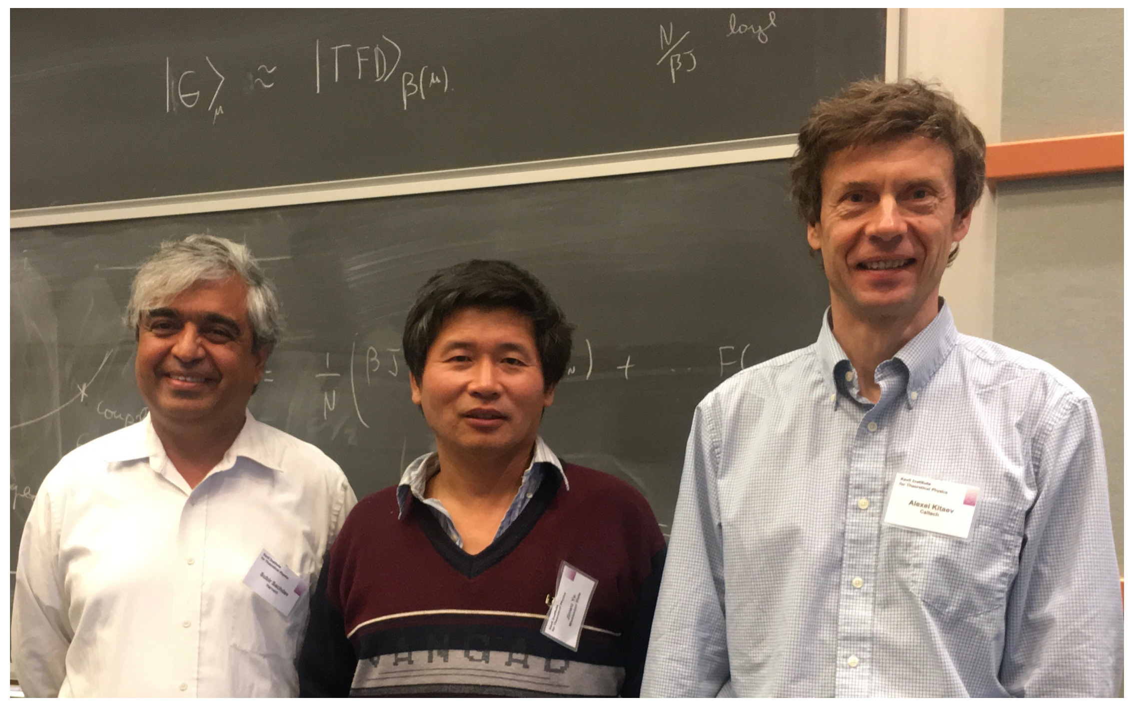

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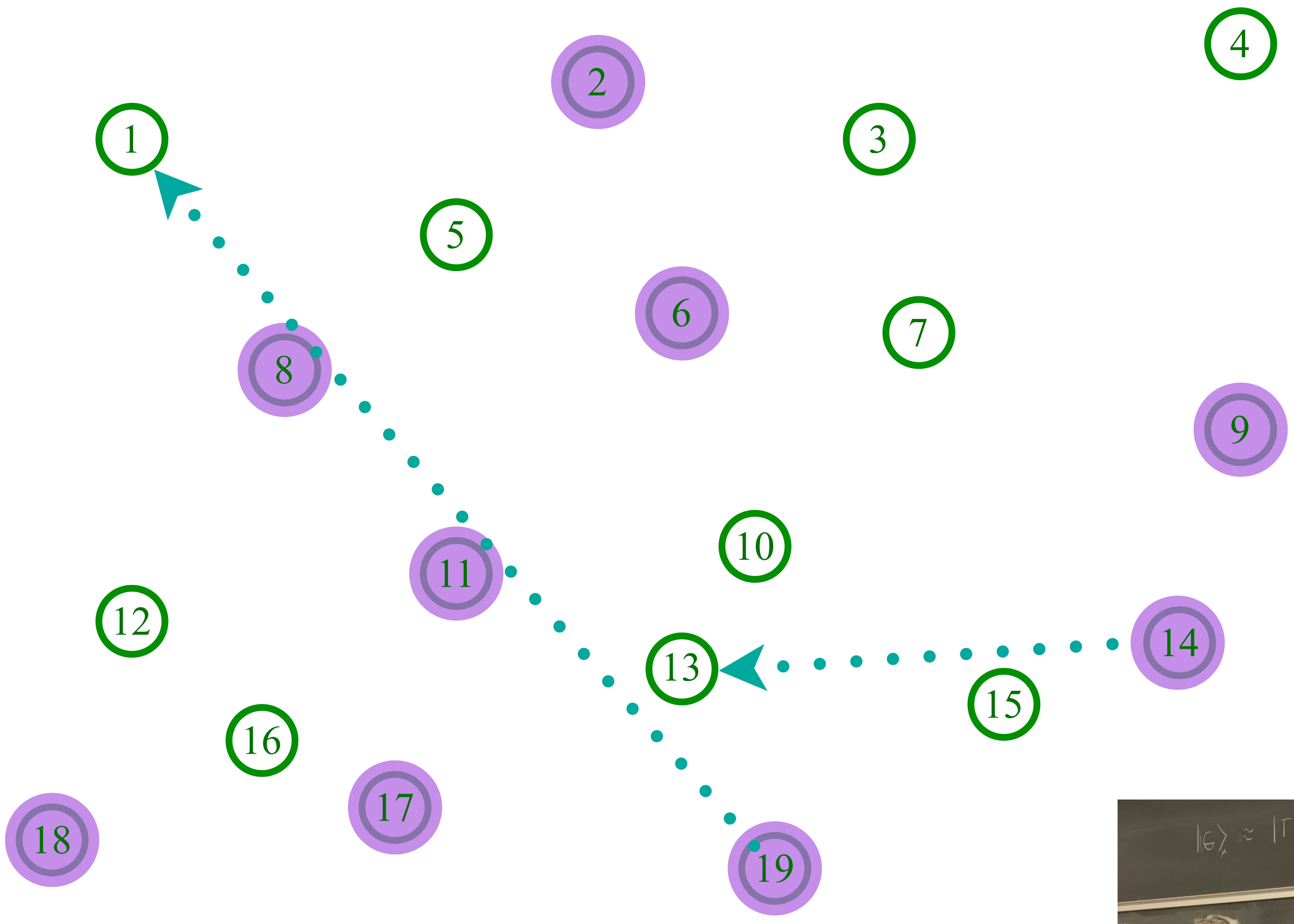
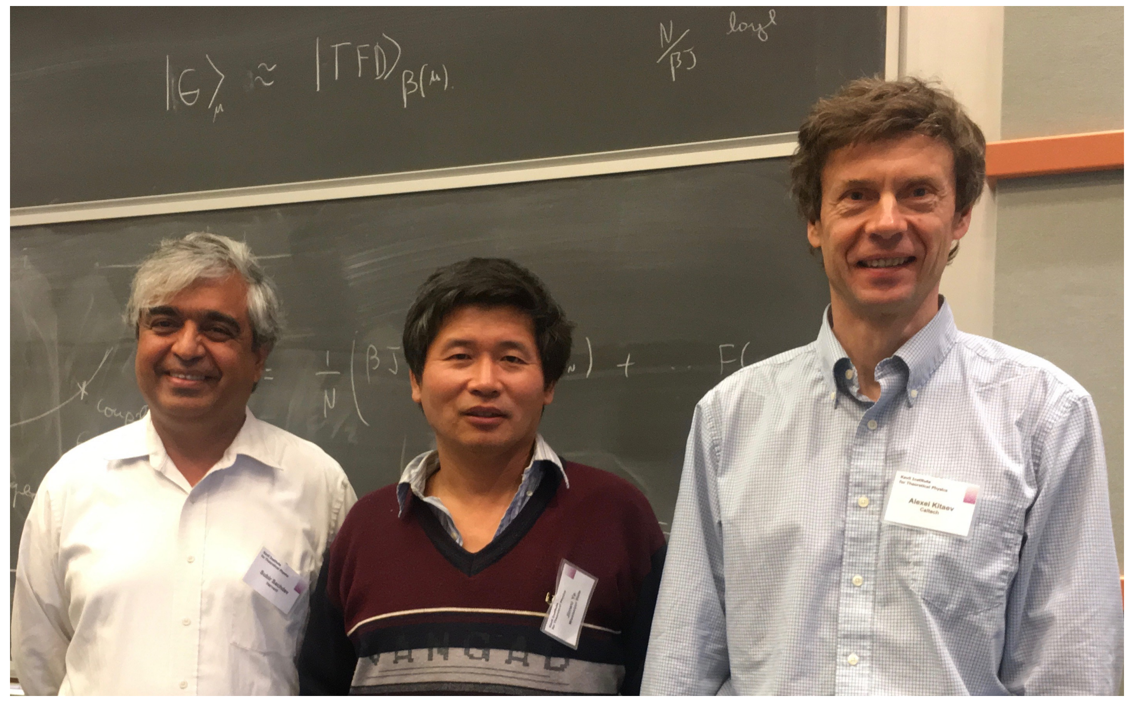
$$U_{14,19;1,13}$$



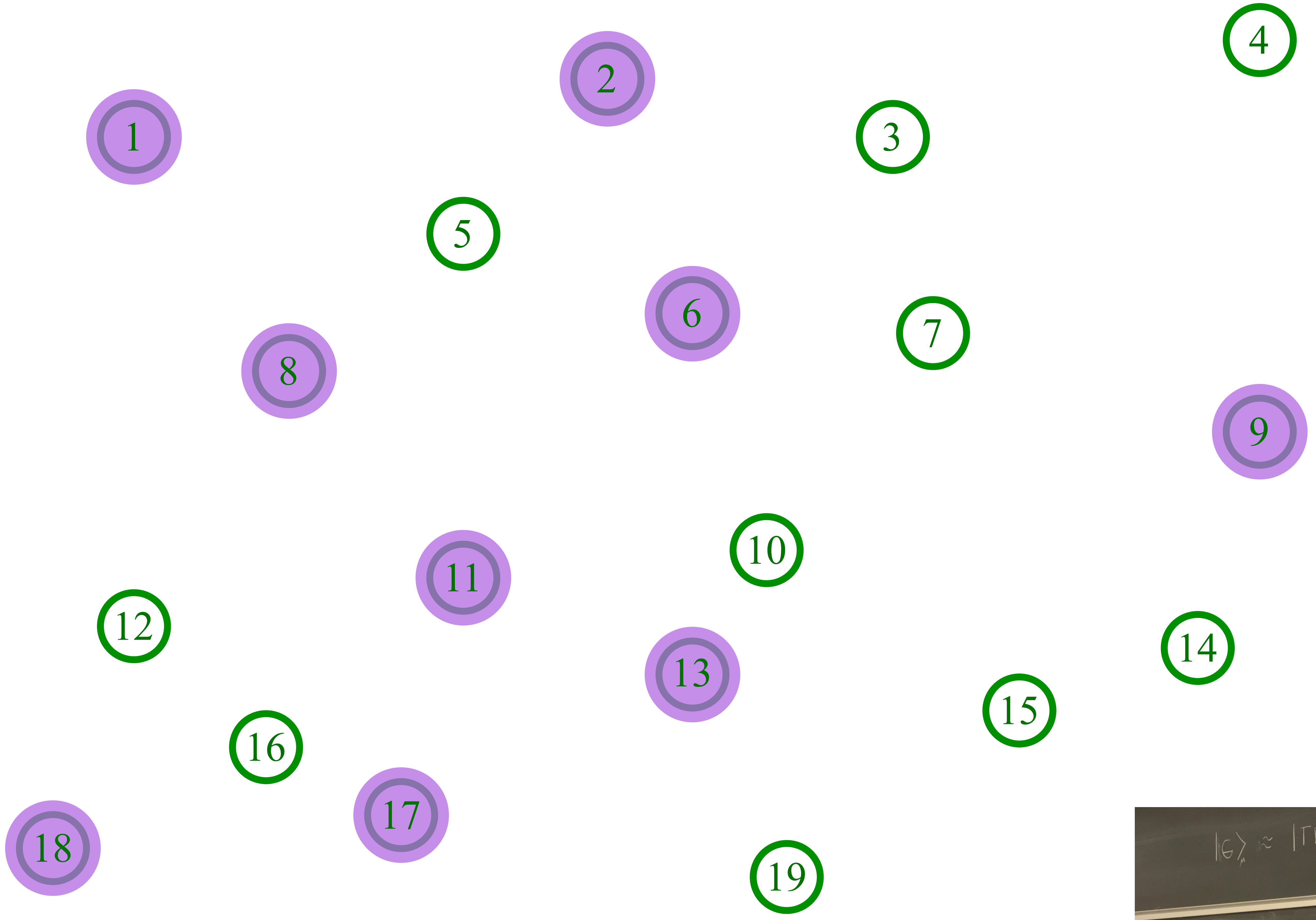
Entangle electrons pairwise randomly



The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



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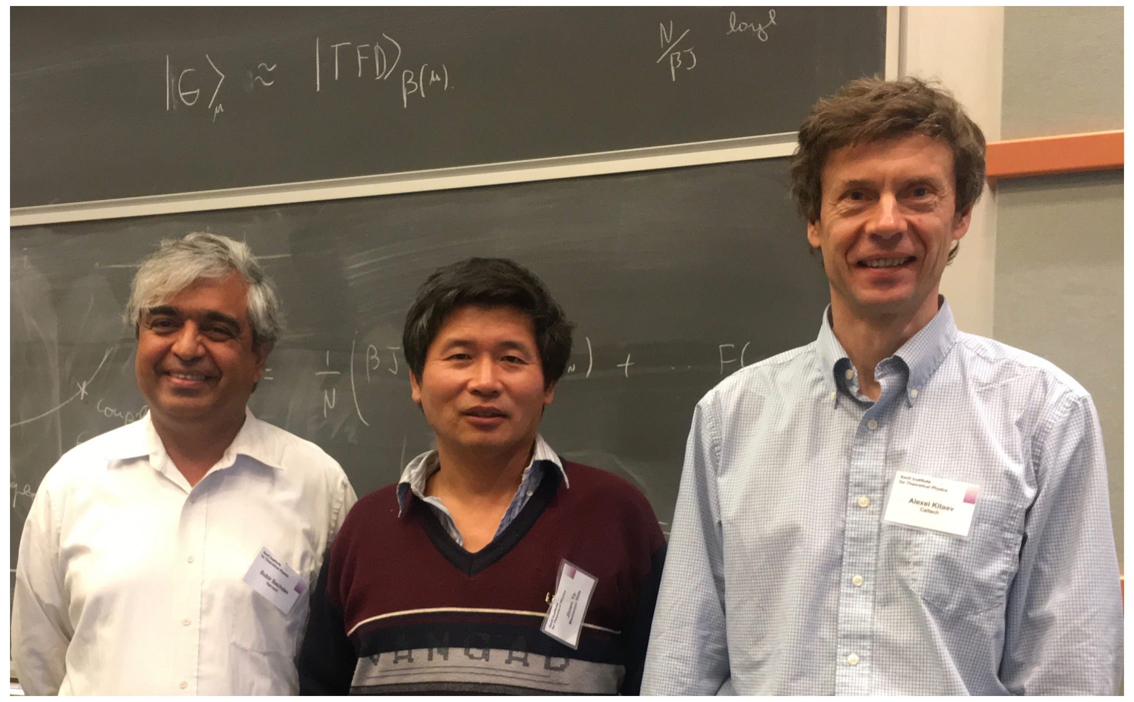

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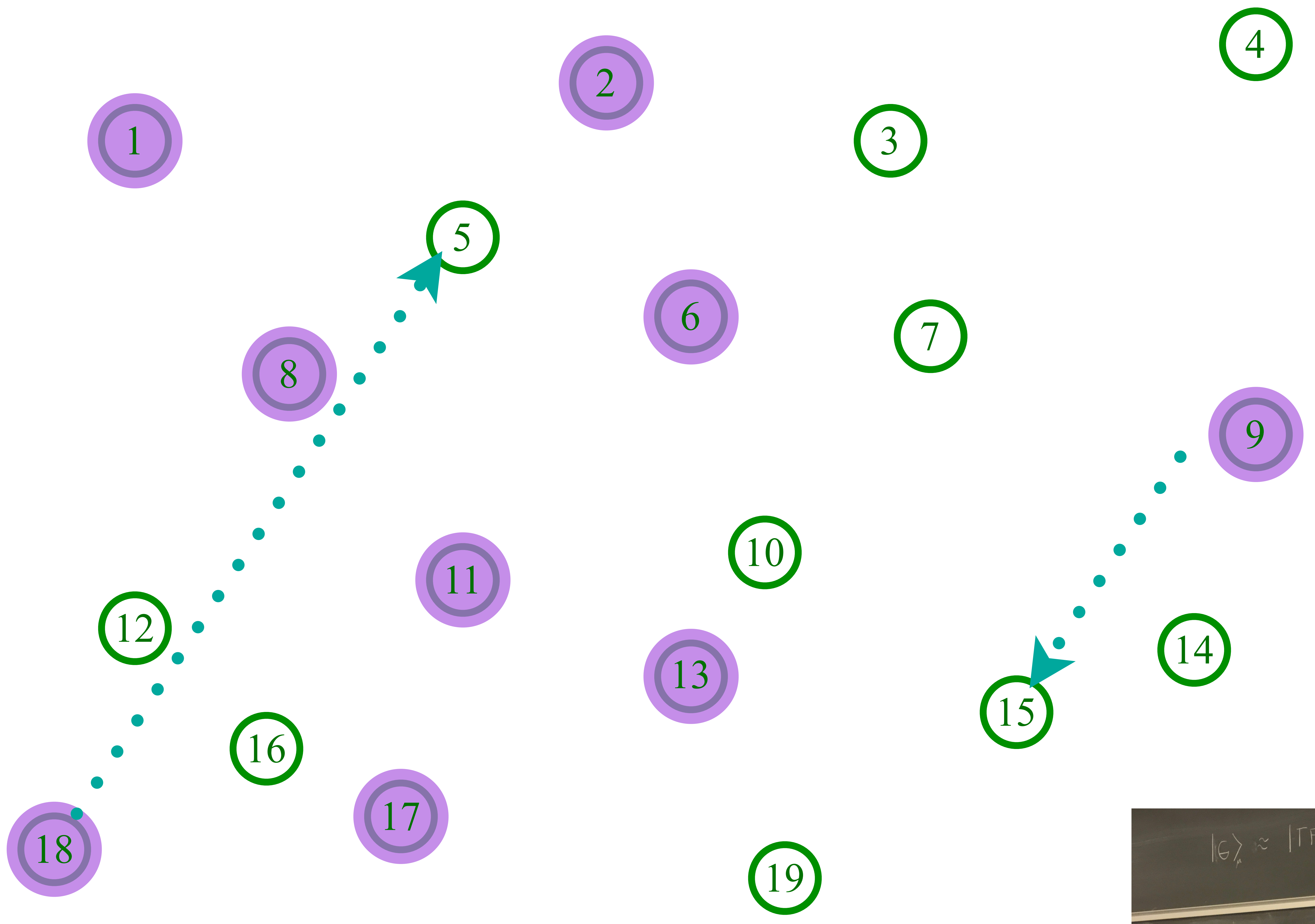

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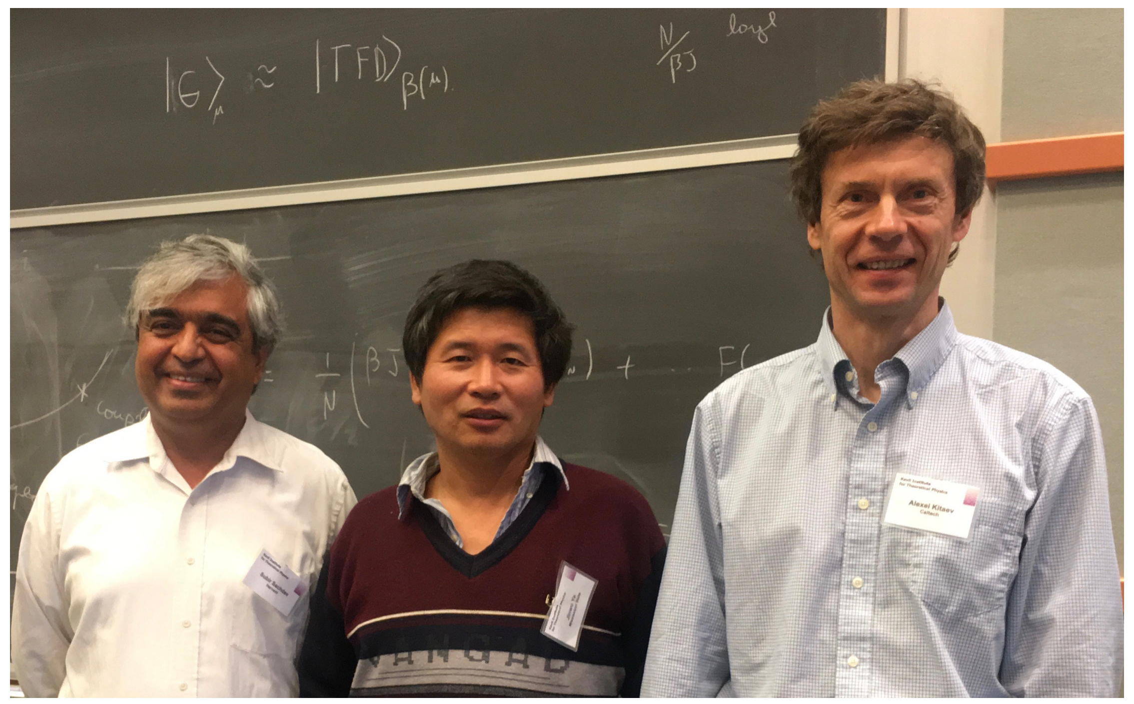

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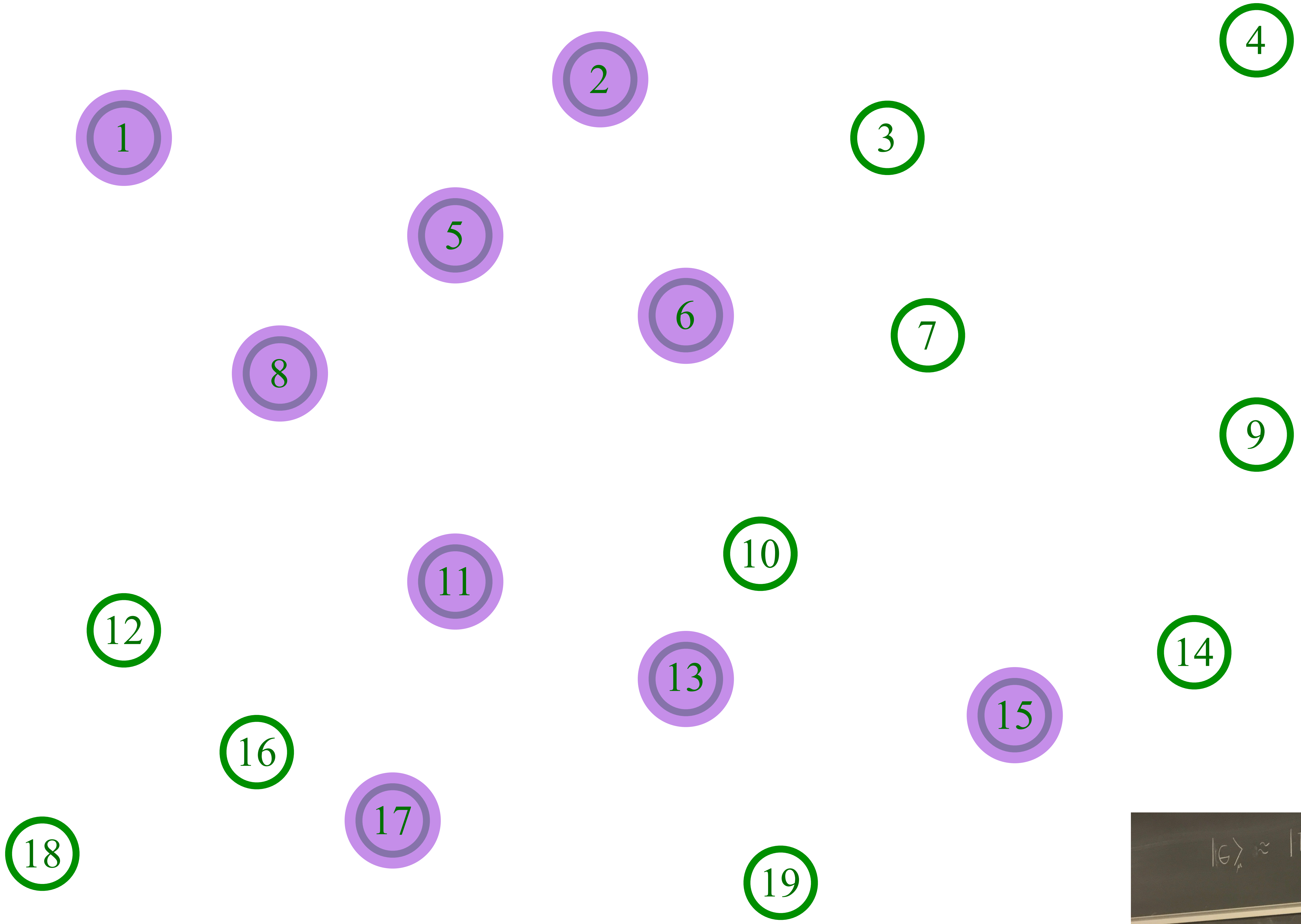

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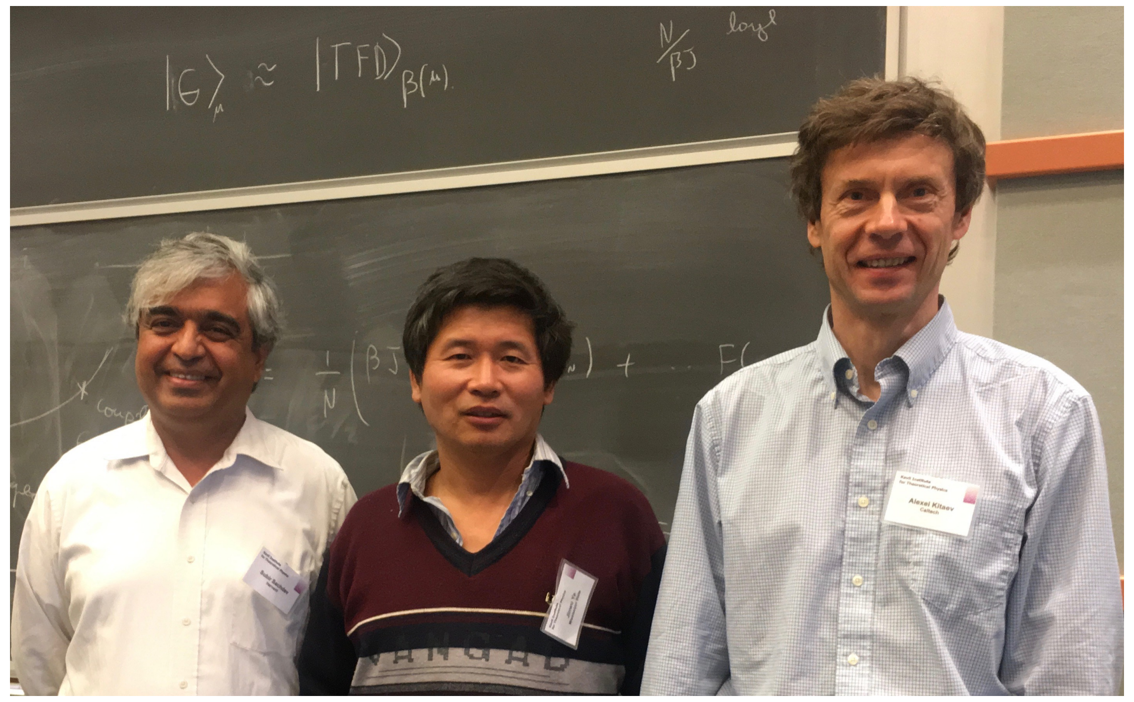
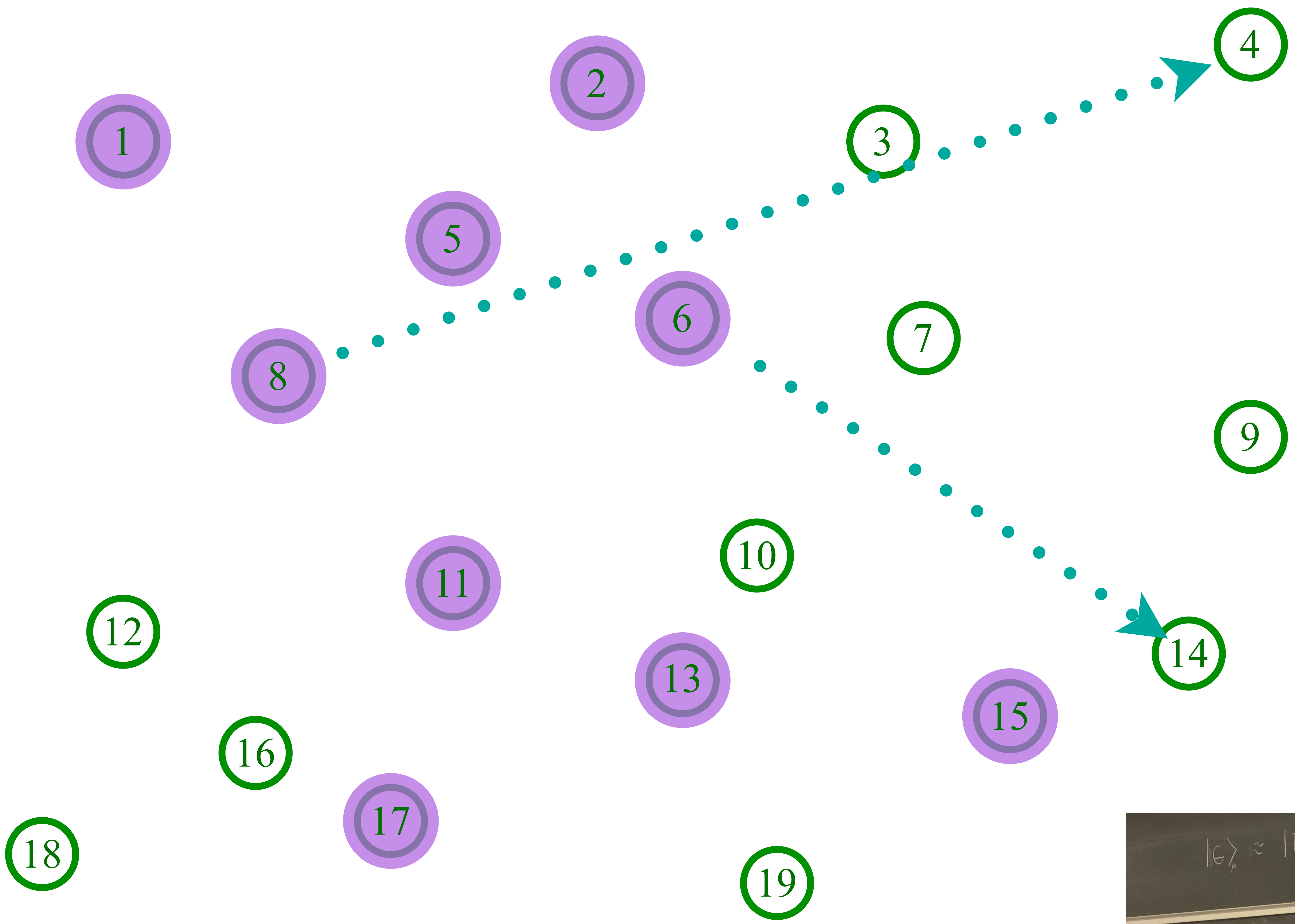


The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



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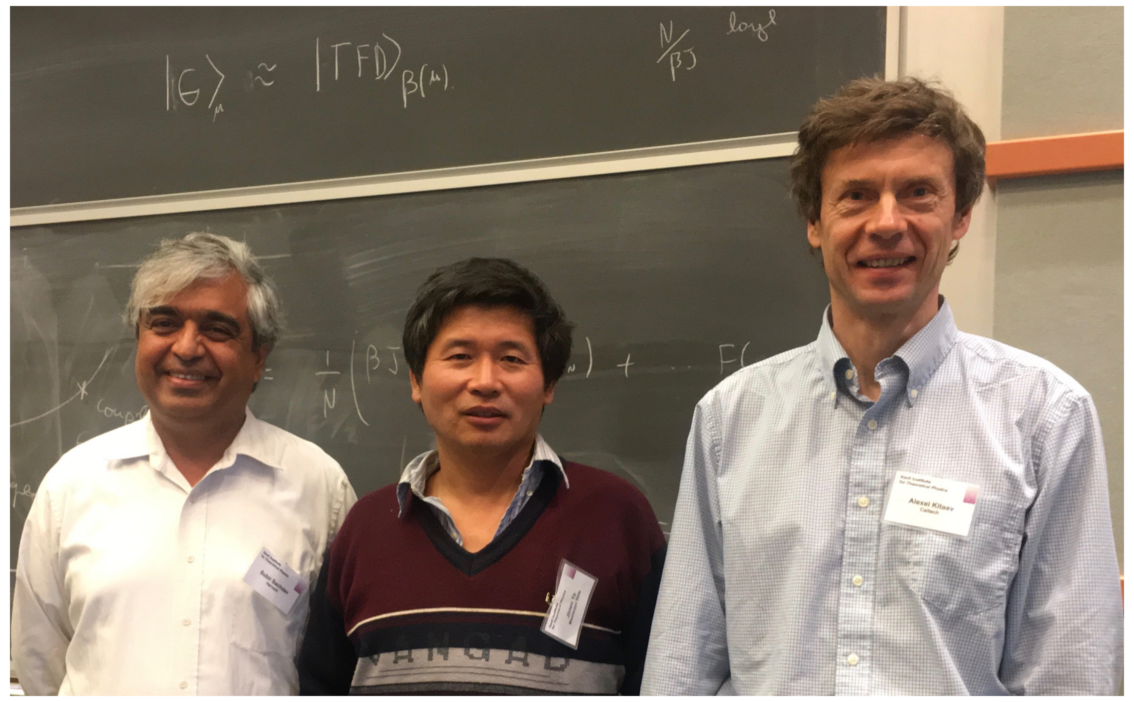

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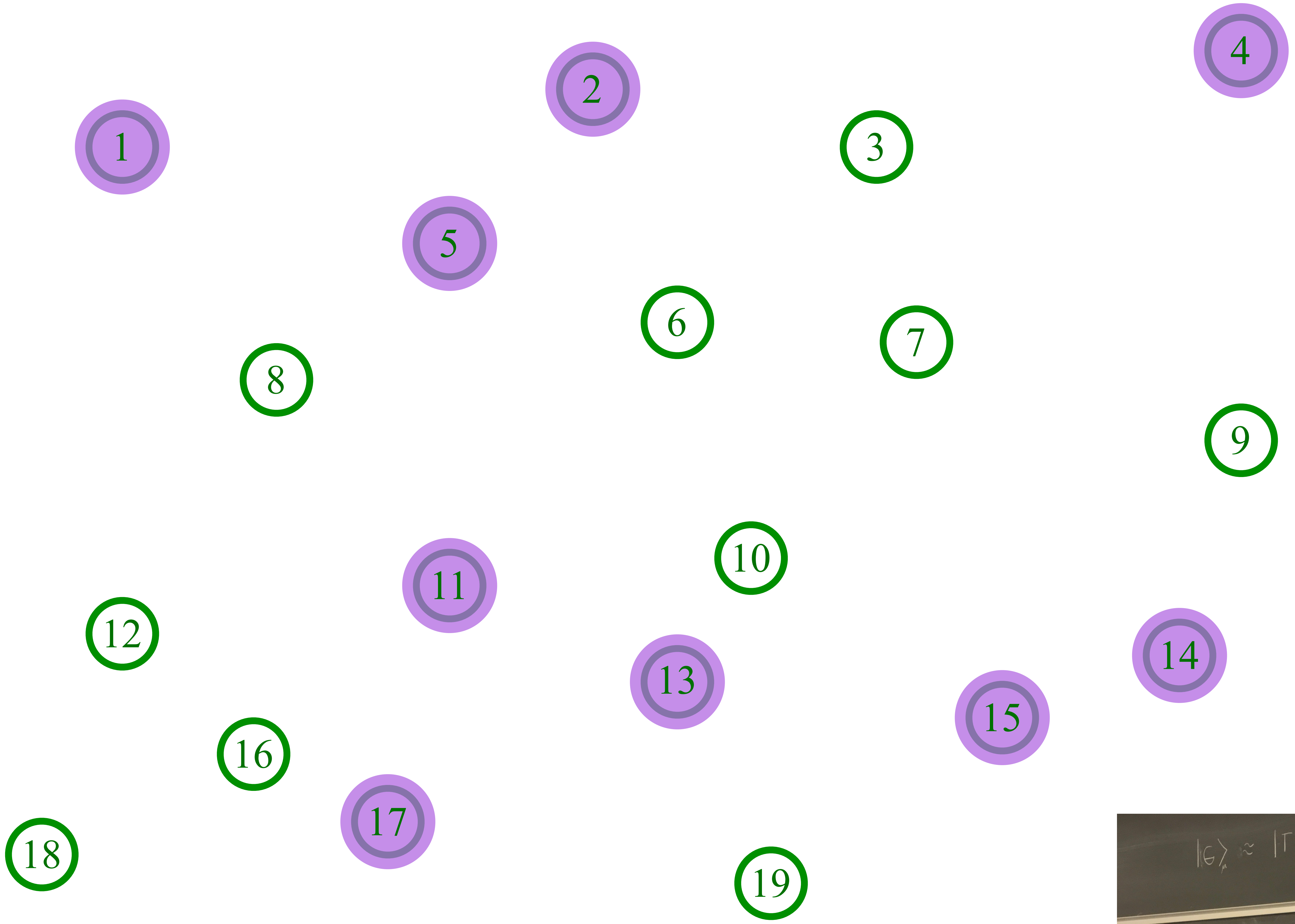

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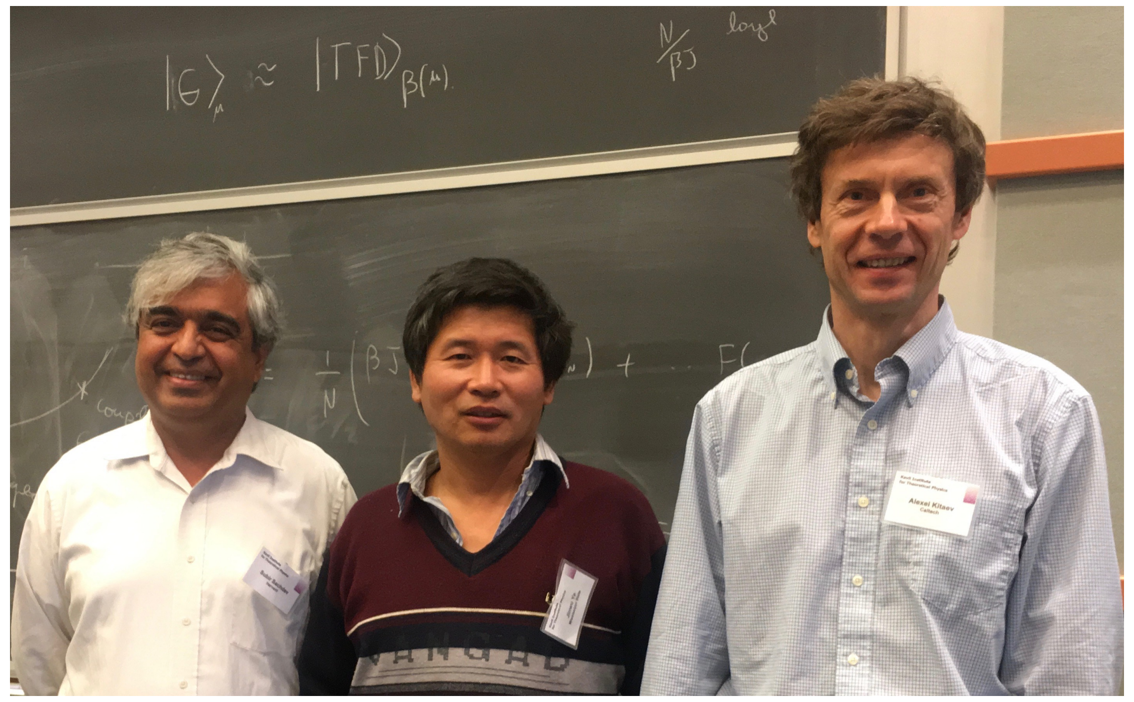


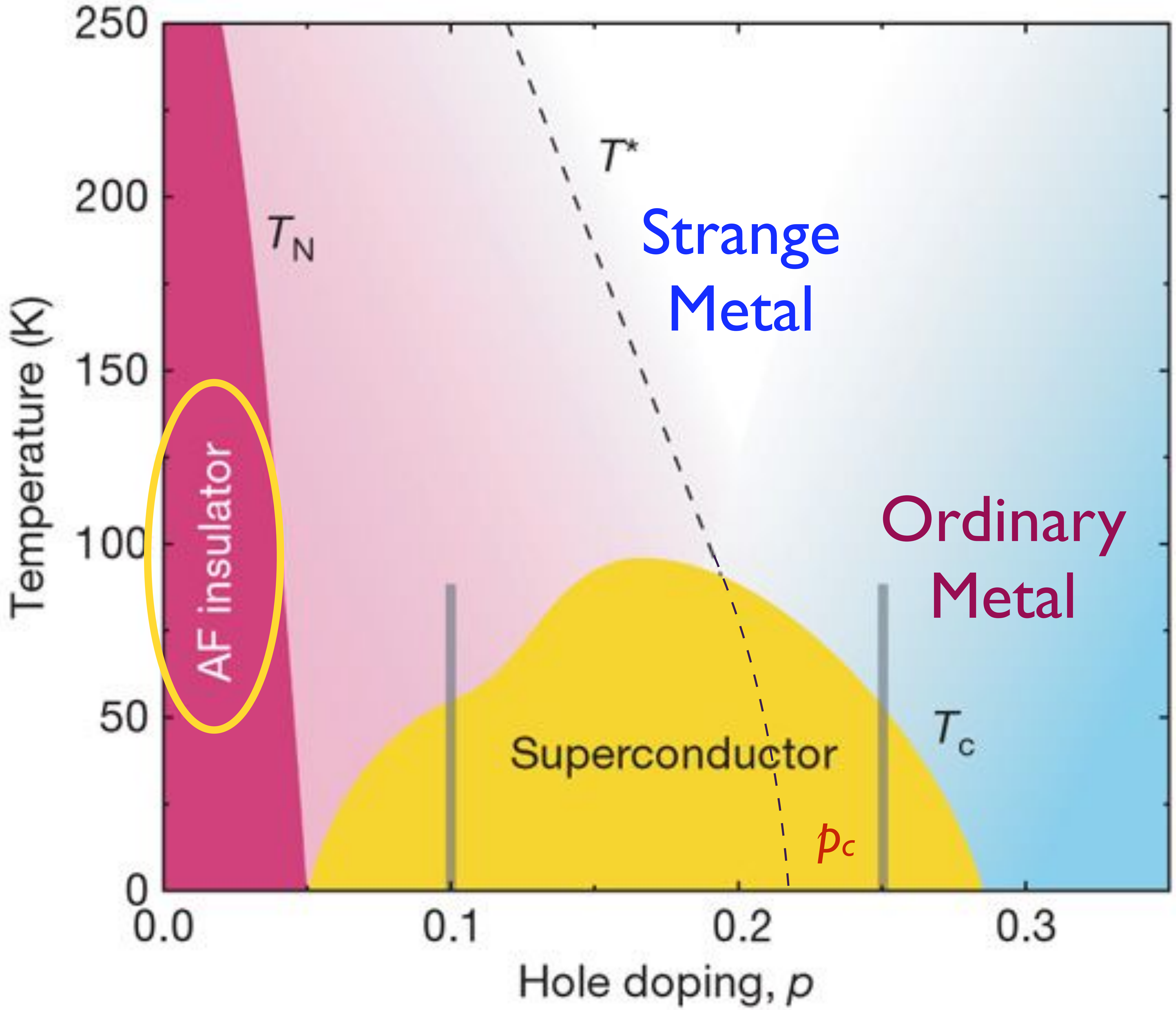
The Sachdev-Ye-Kitaev (SYK) model

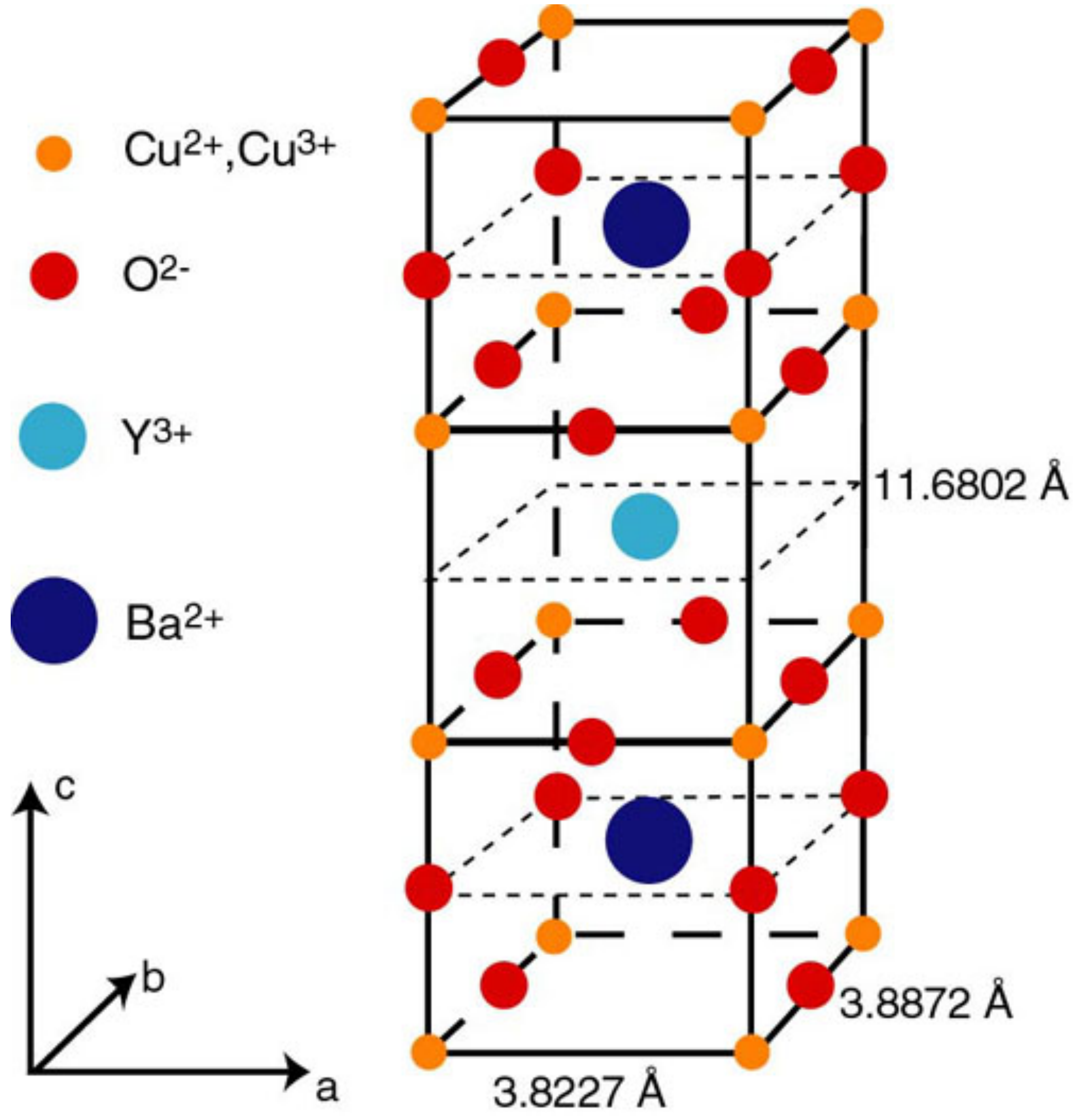
Sachdev, Ye (1993); Kitaev (2015)

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"

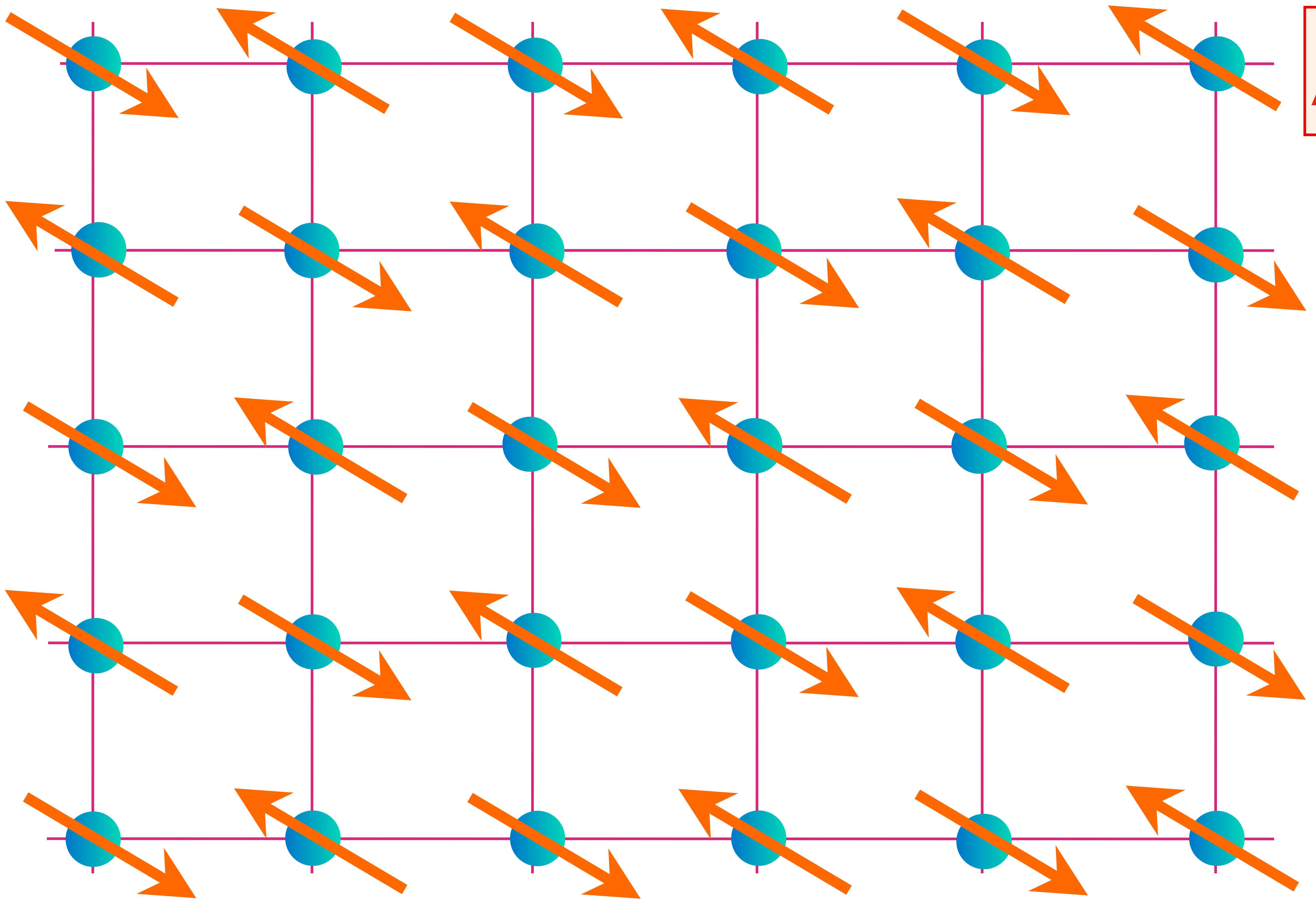
Quantum entanglement and superconductivity


250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
T_N
T^*
Strange
Metal
Ordinary
Metal
AF insulator
Superconductor
T_c
p_c


Cu^{2+},Cu^{3+}
O^{2-}
Y^{3+}
Ba^{2+}
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å

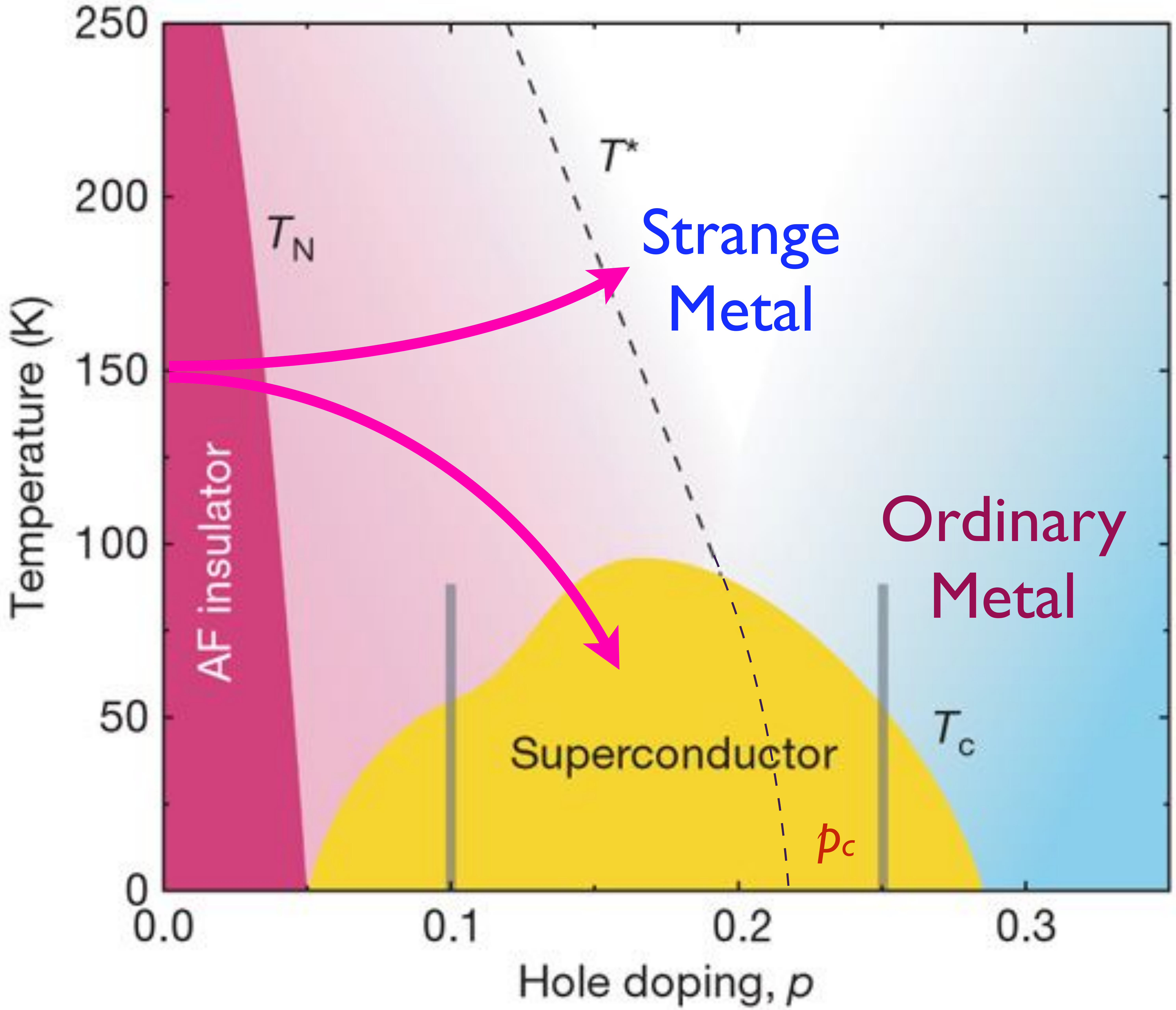
$YBa_2Cu_3O_{6+x}$

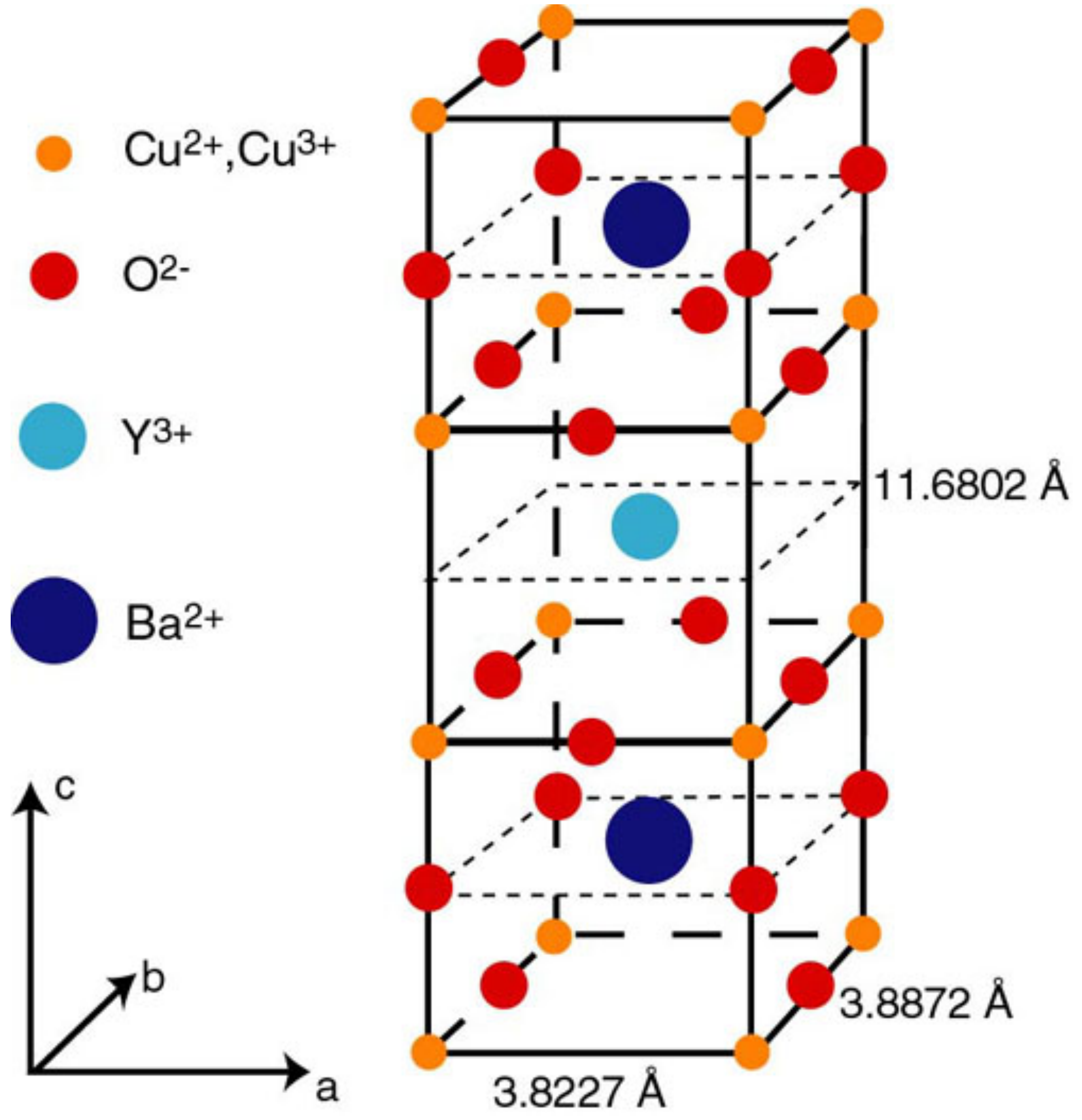
The dance of electrons on Cu atoms in YBCO



Antiferromagnetism

All nearest-neighbor pairs of electrons have opposite spins


250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Strange Metal
Ordinary Metal
Superconductor
T_c
p_c


Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å

$YBa_2Cu_3O_{6+x}$

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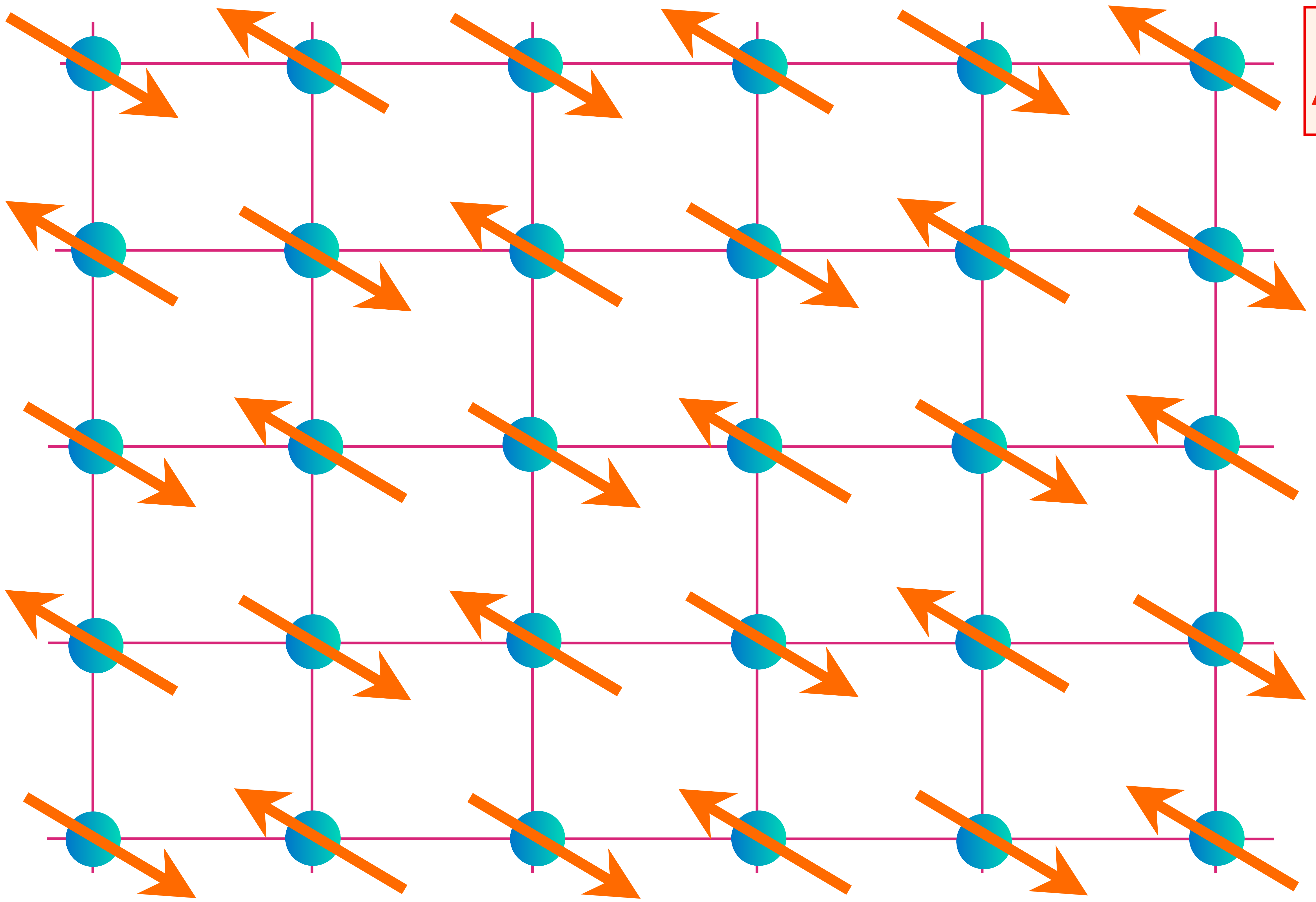

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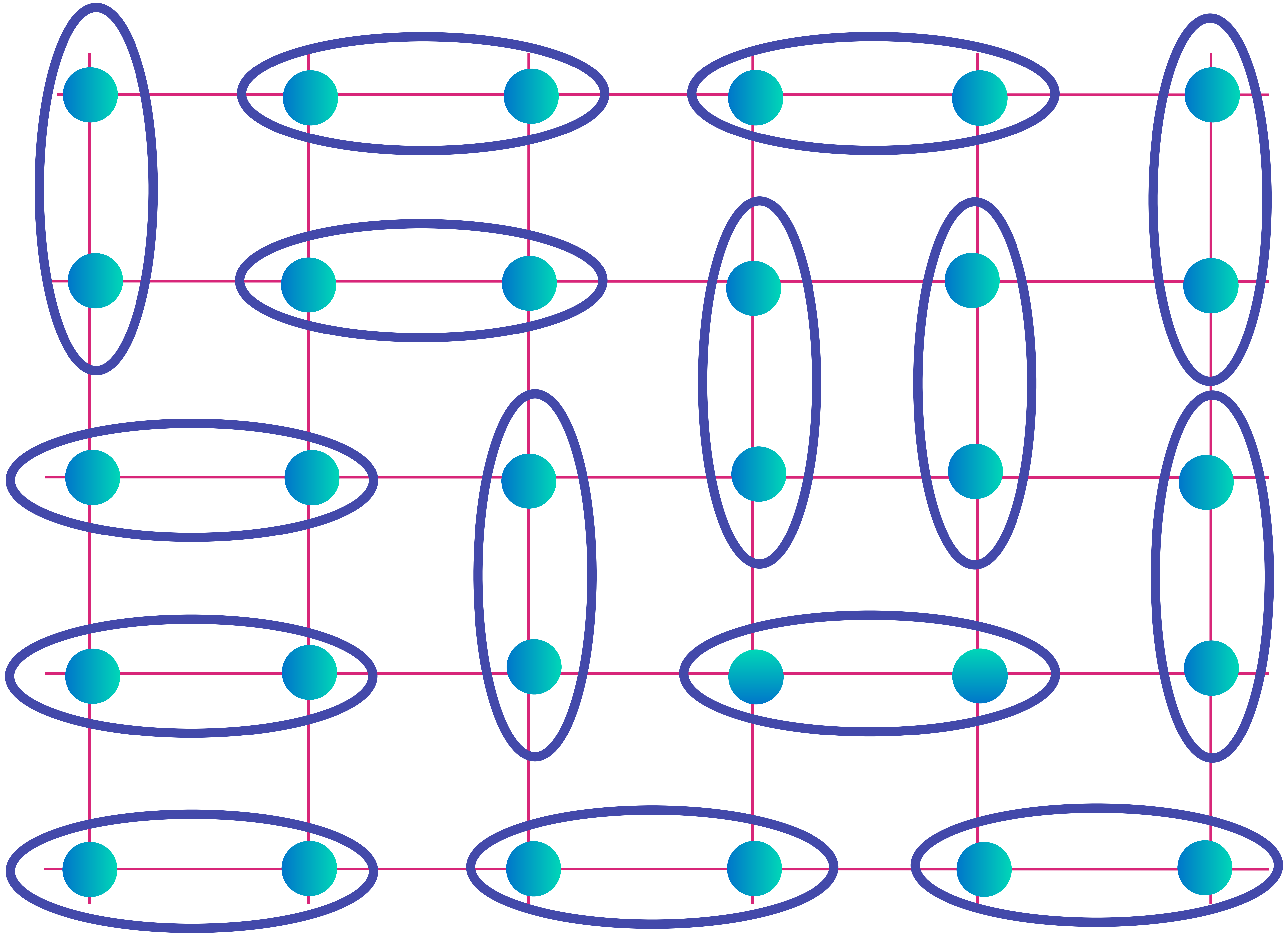
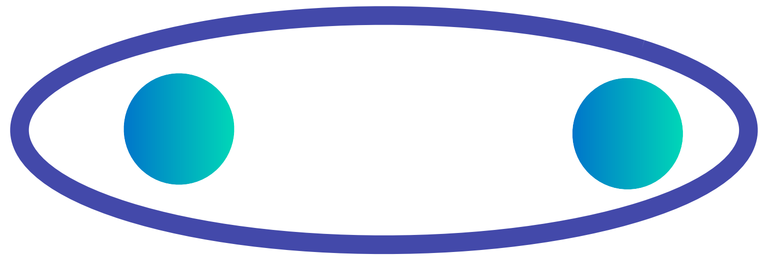
Baskaran+Anderson (1987)



Spin liquid

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

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

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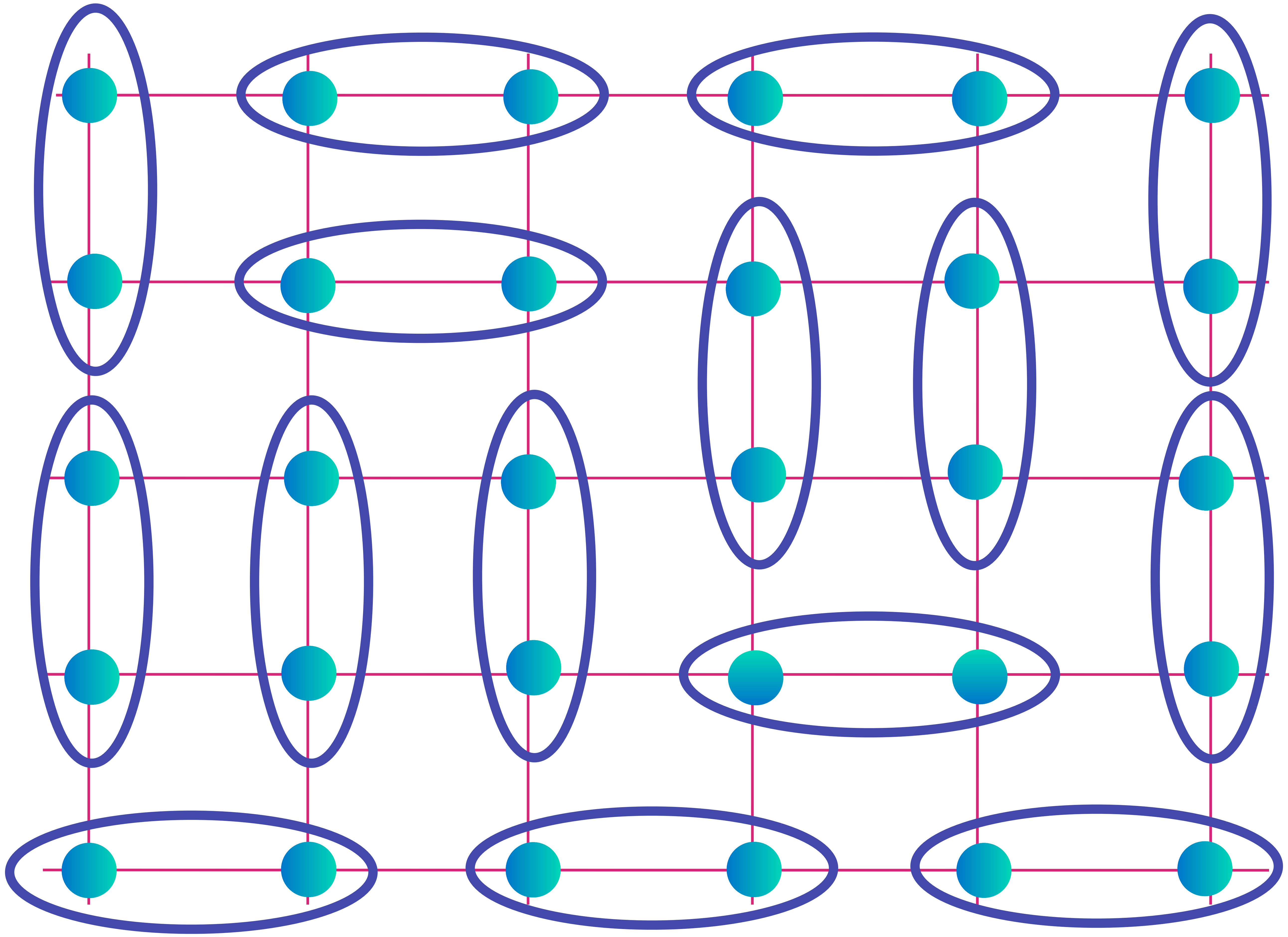

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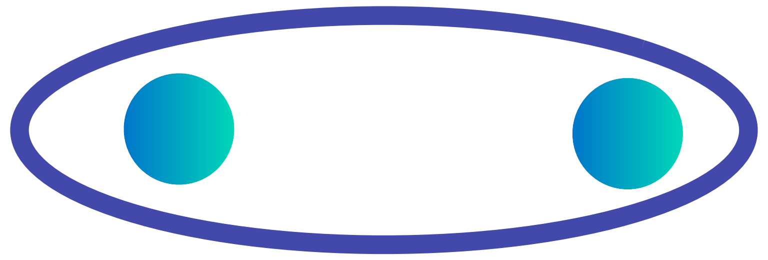

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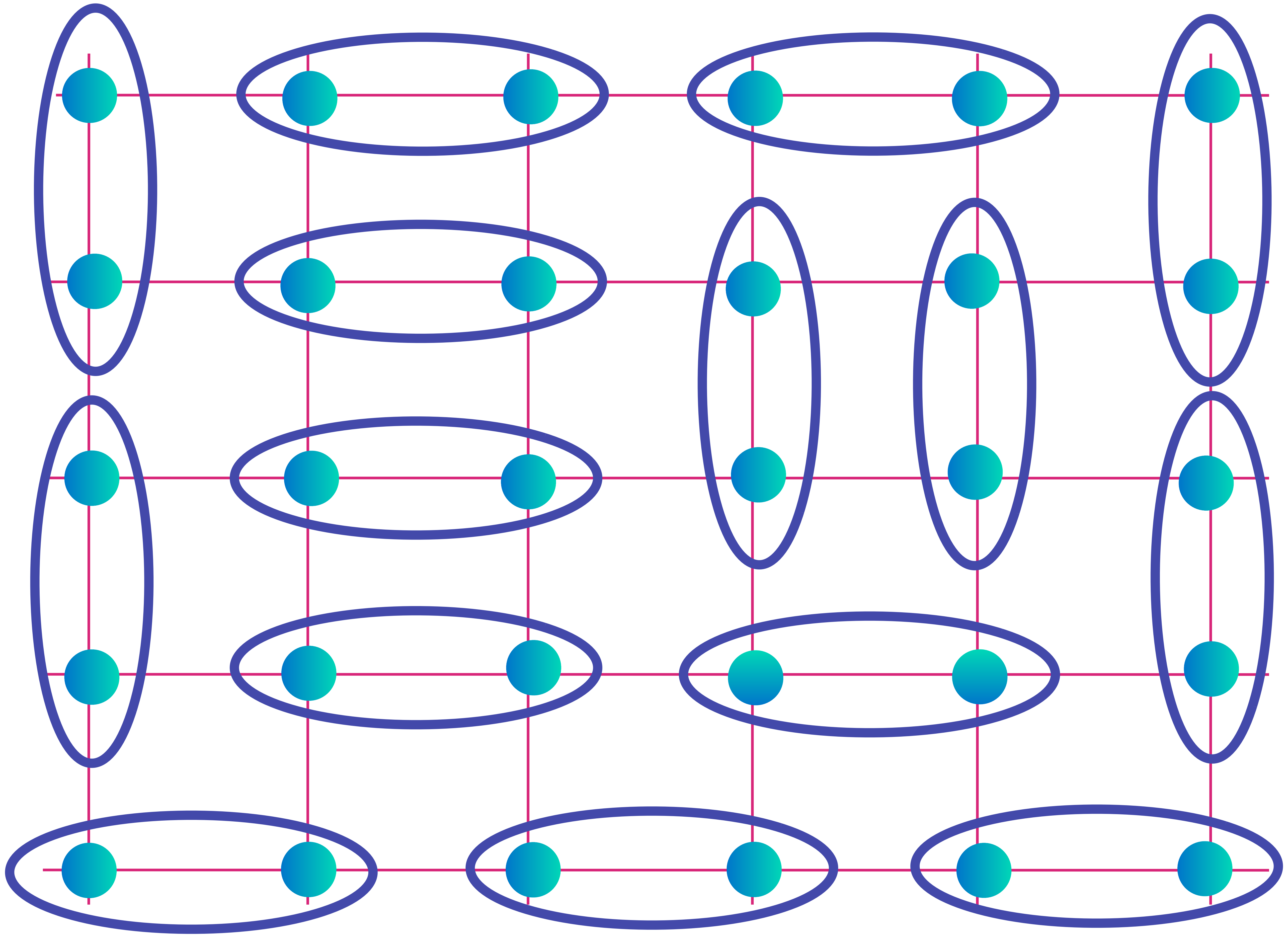

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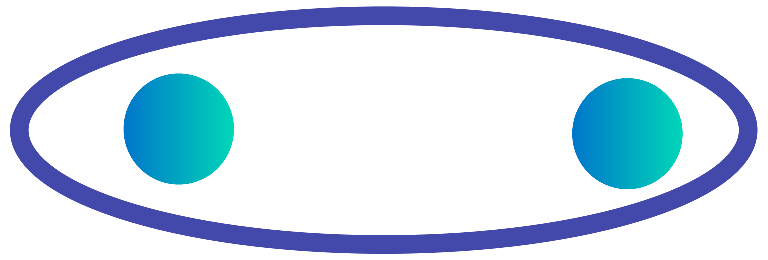 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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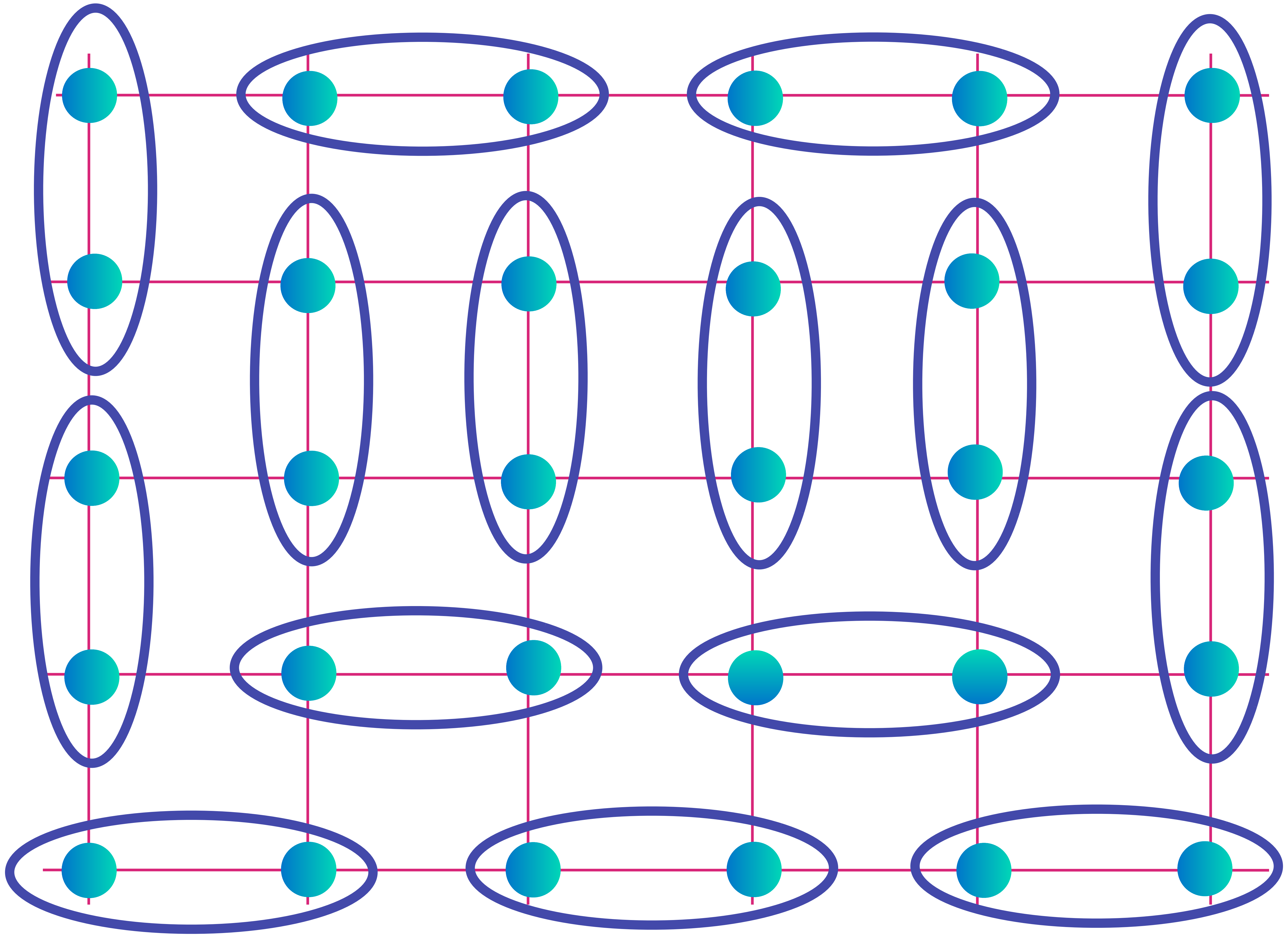

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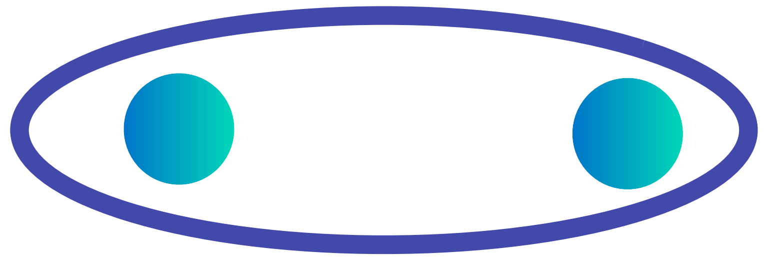 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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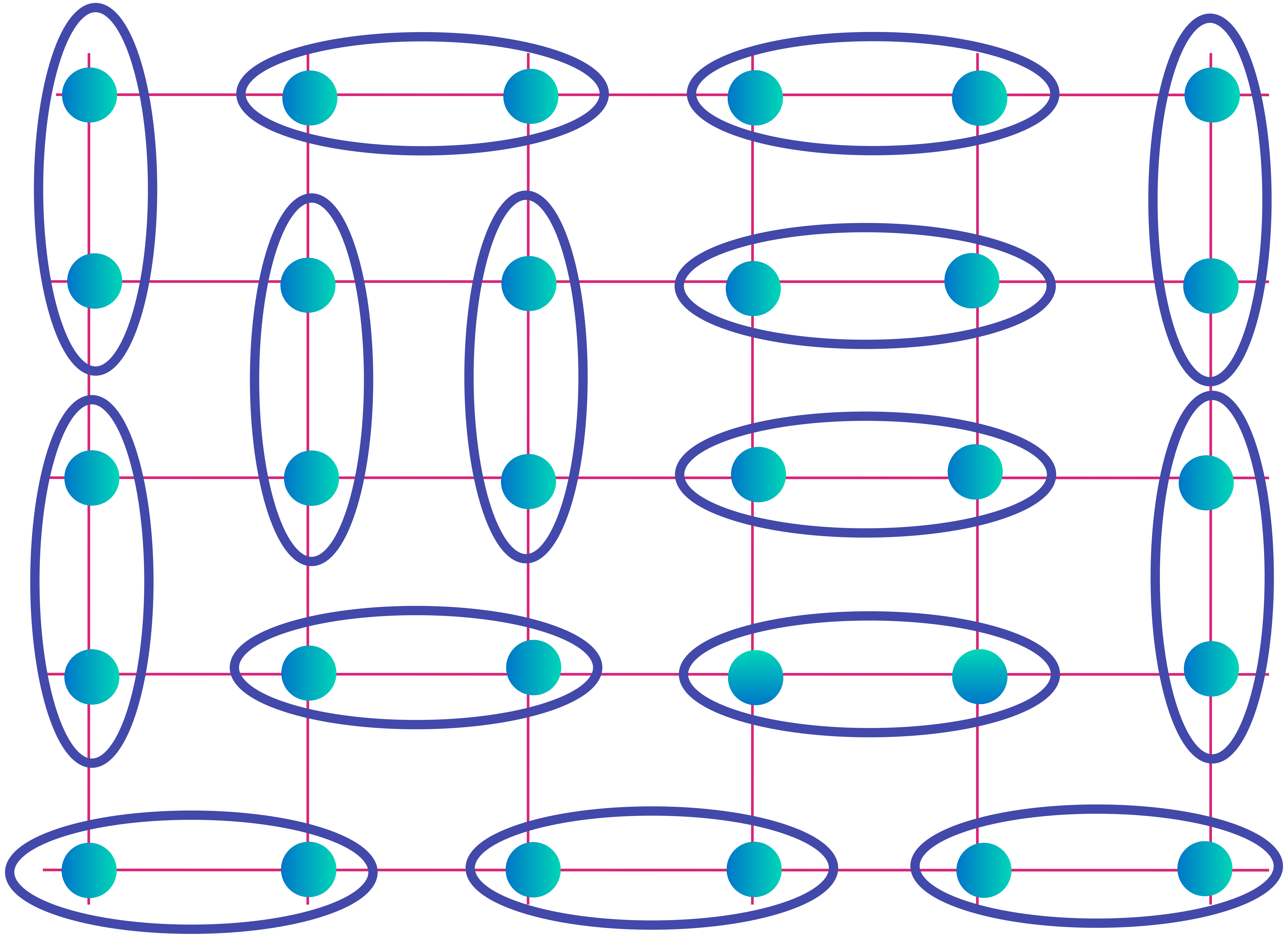

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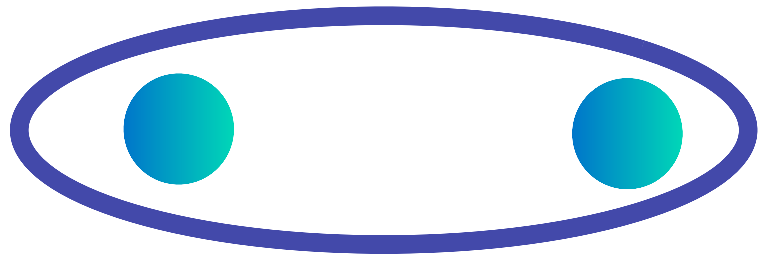 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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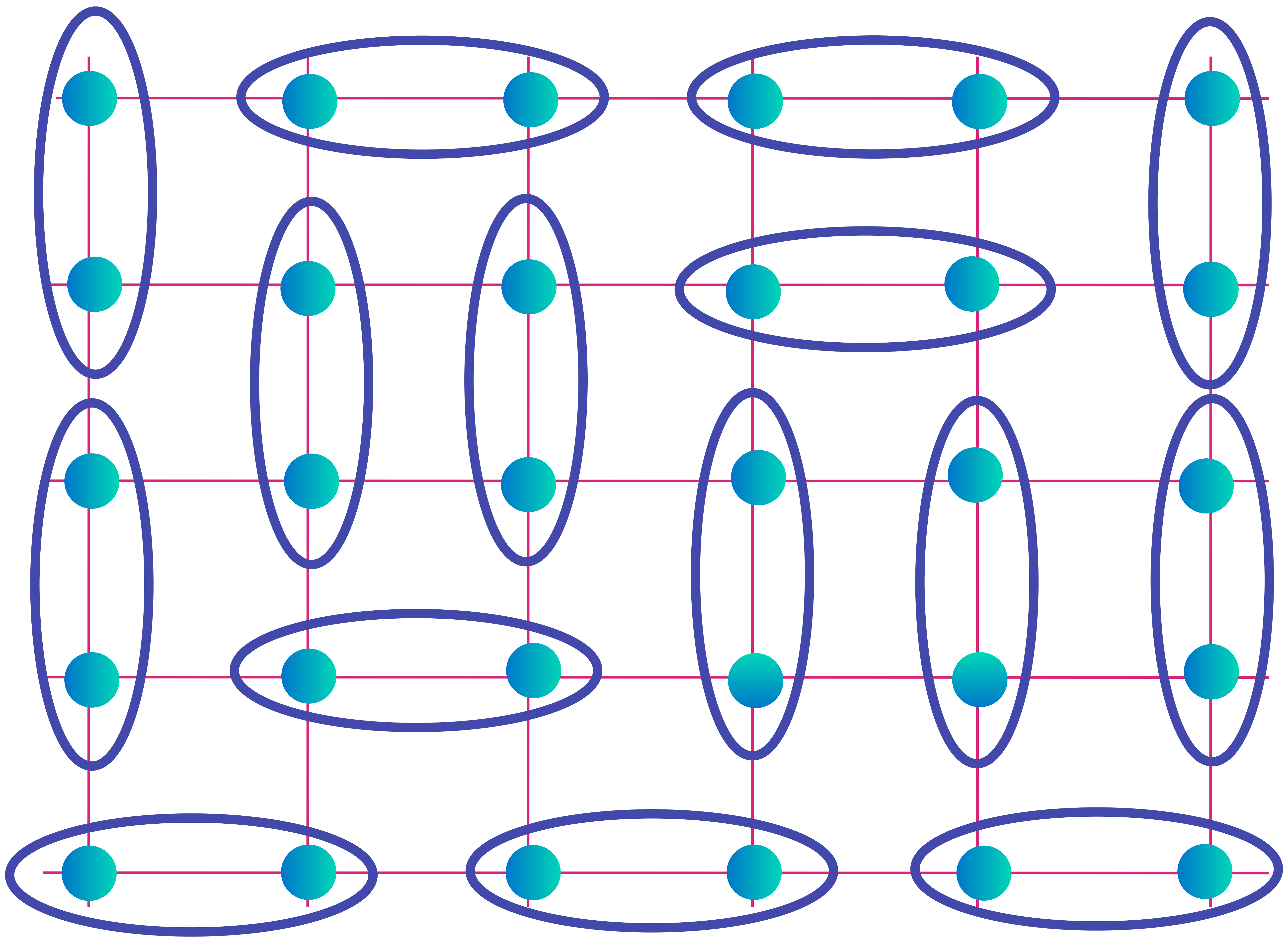

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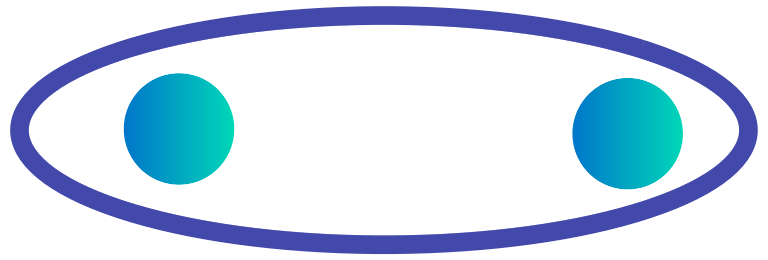 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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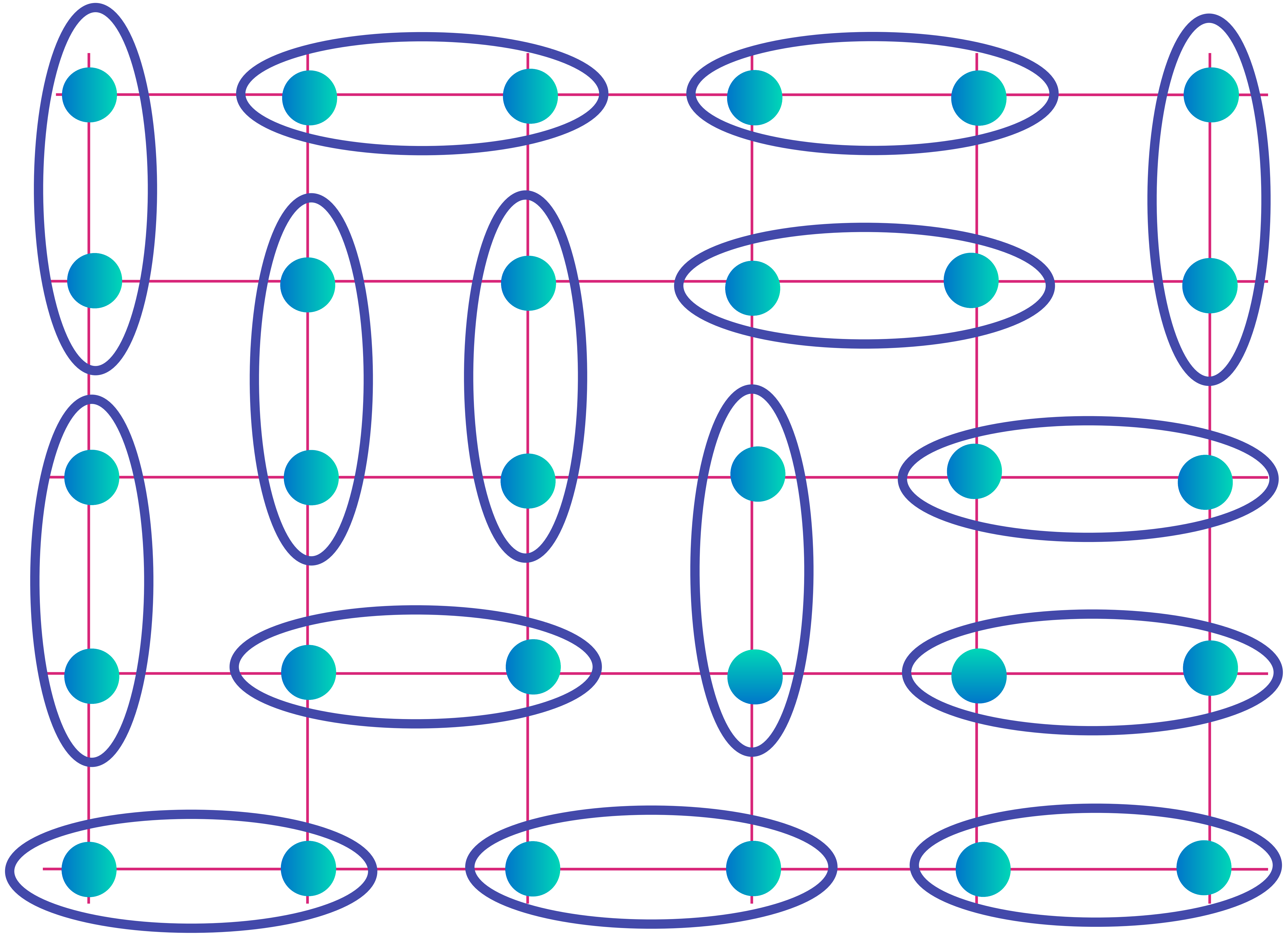

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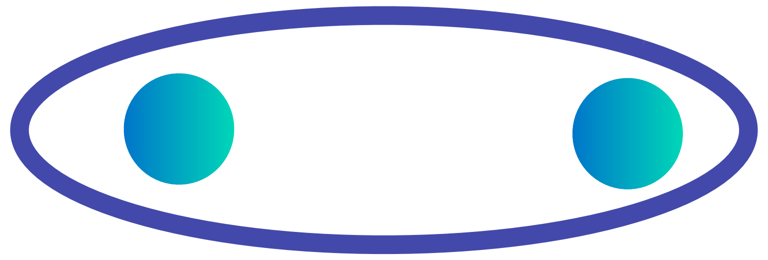

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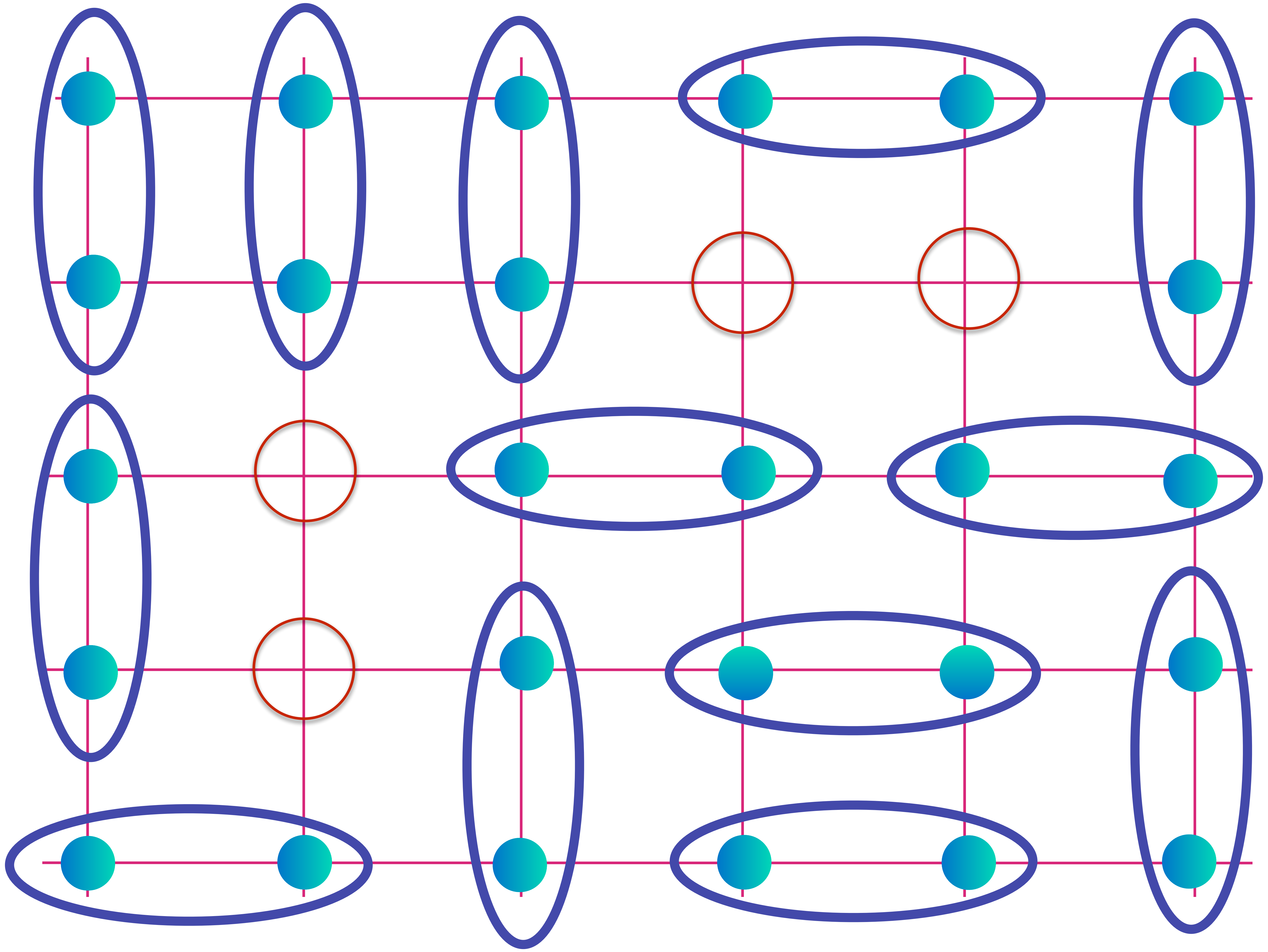
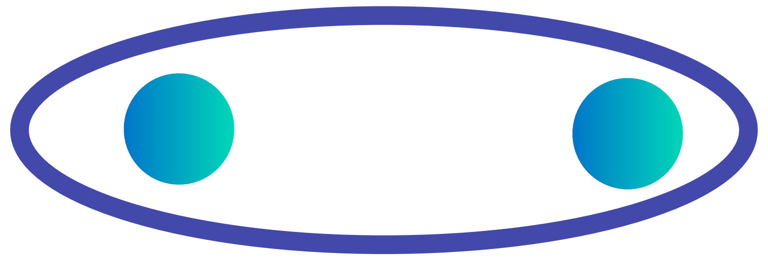


Superconductivity

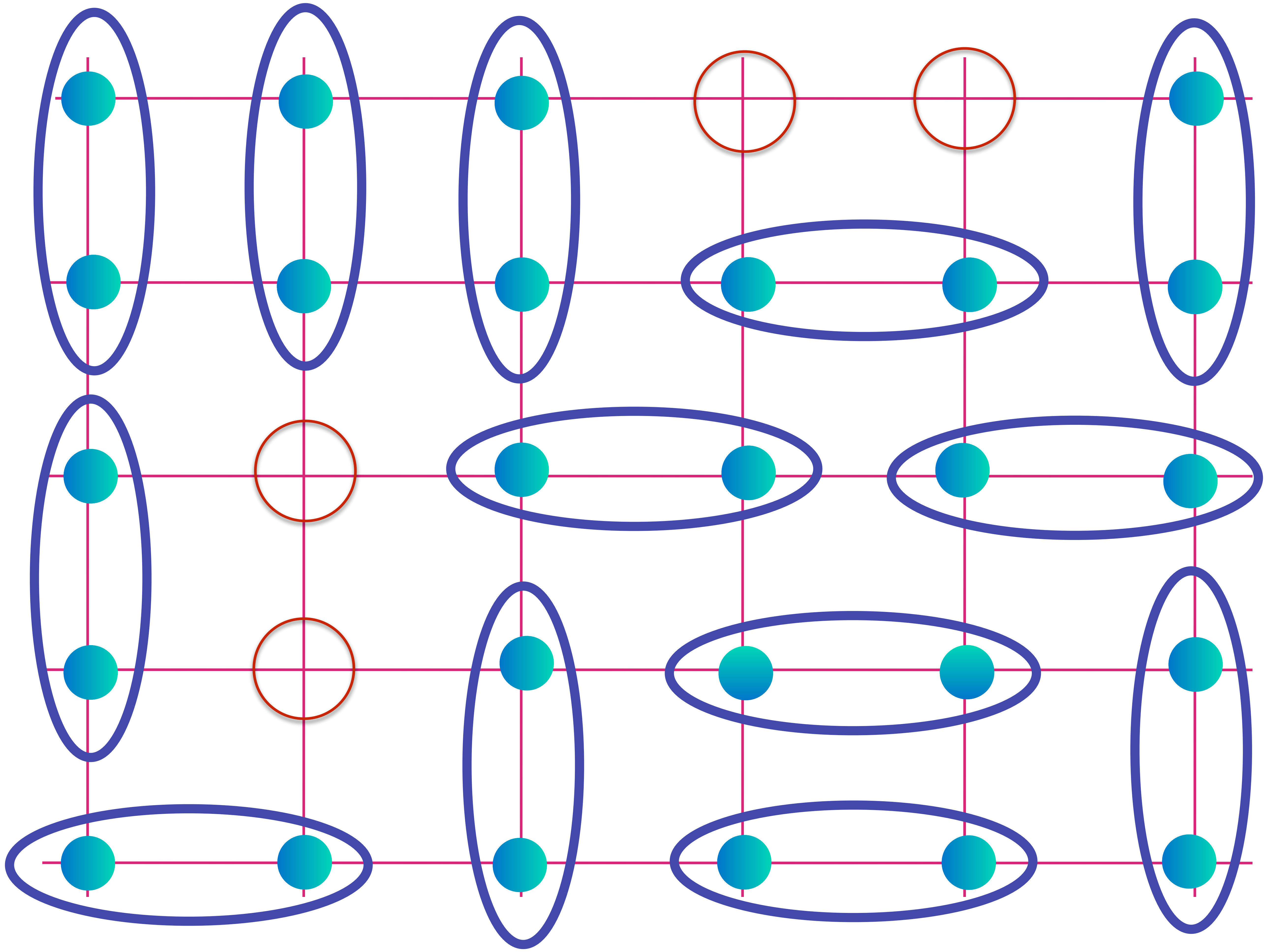
Bose condensation of electron pairs



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

S.N. Bose (1924)

The dance of electrons on Cu atoms in YBCO



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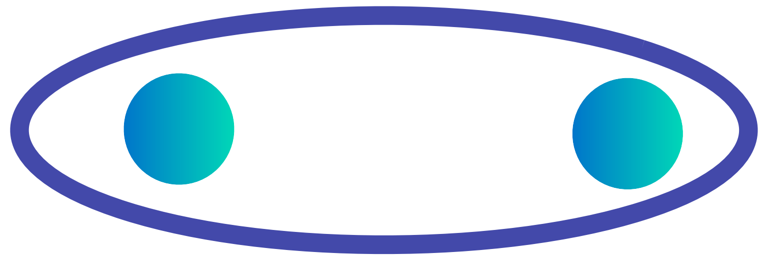

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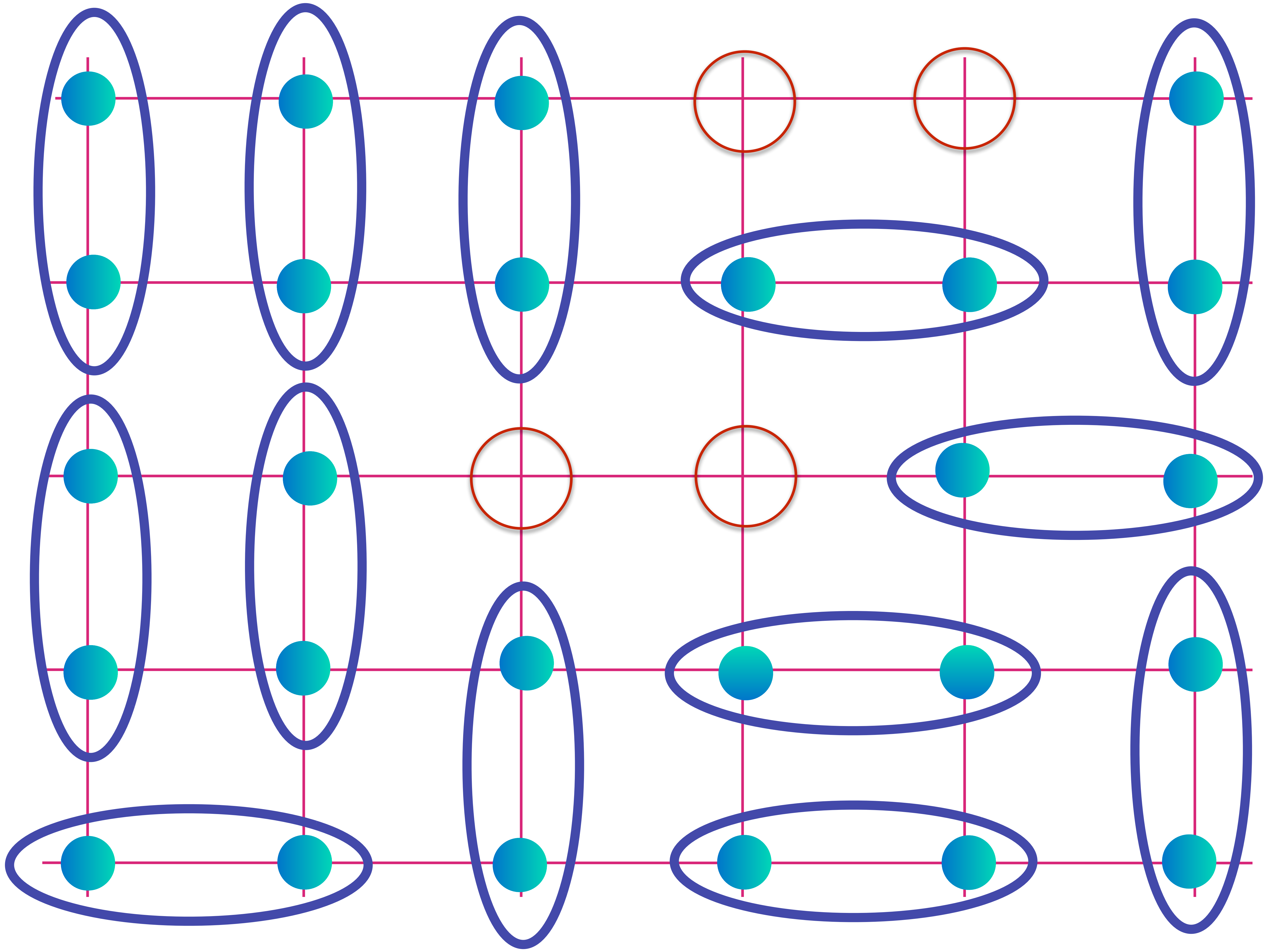

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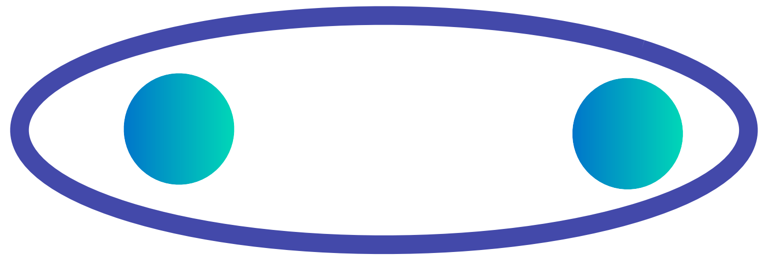 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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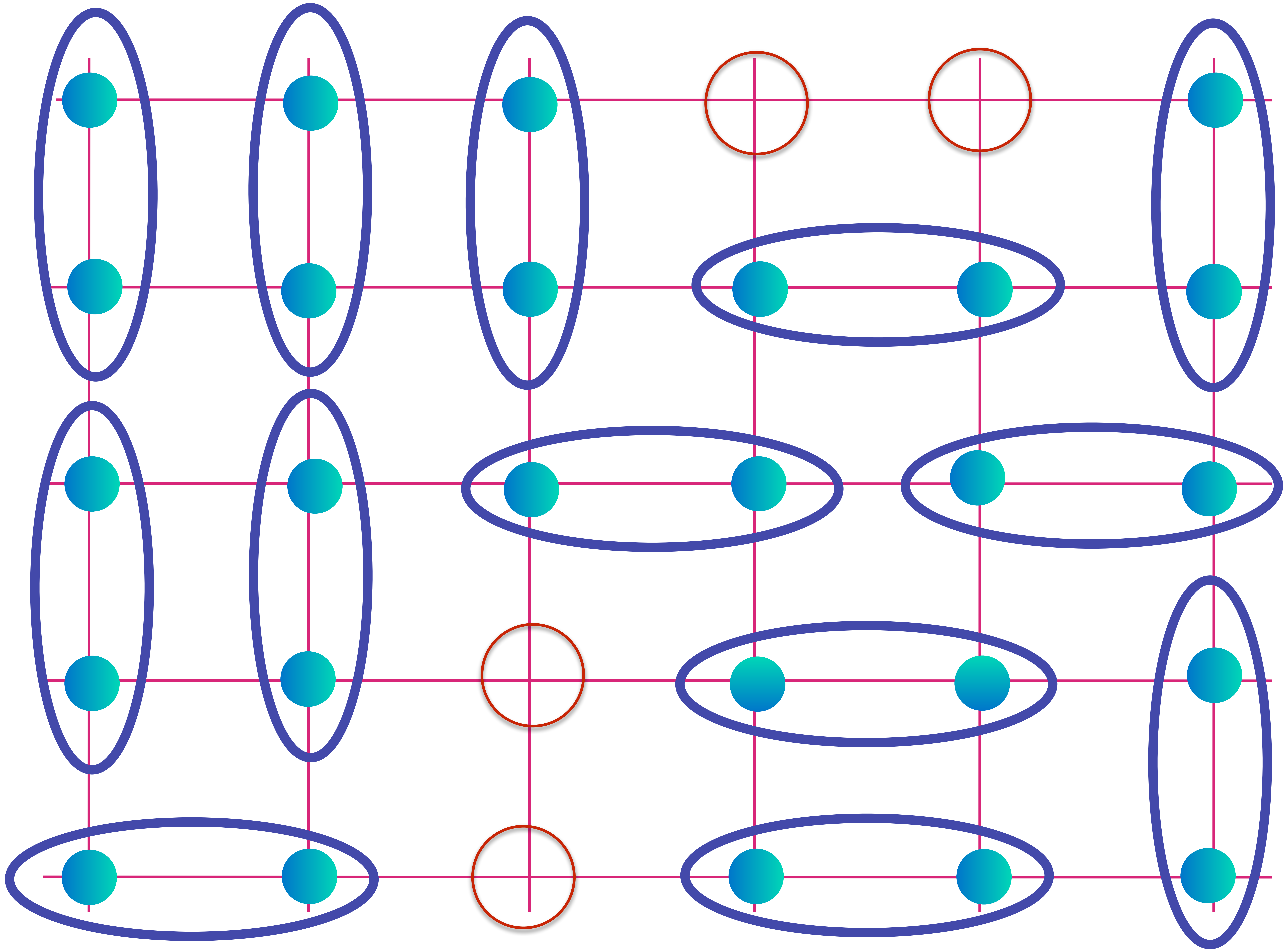

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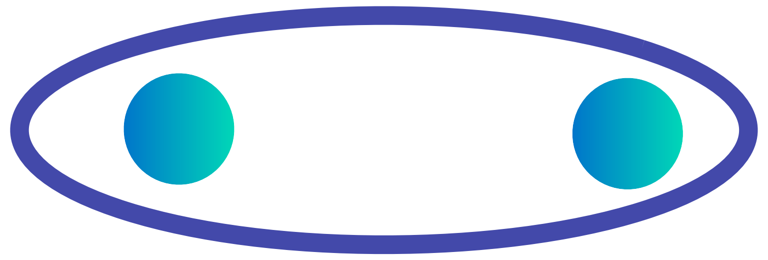 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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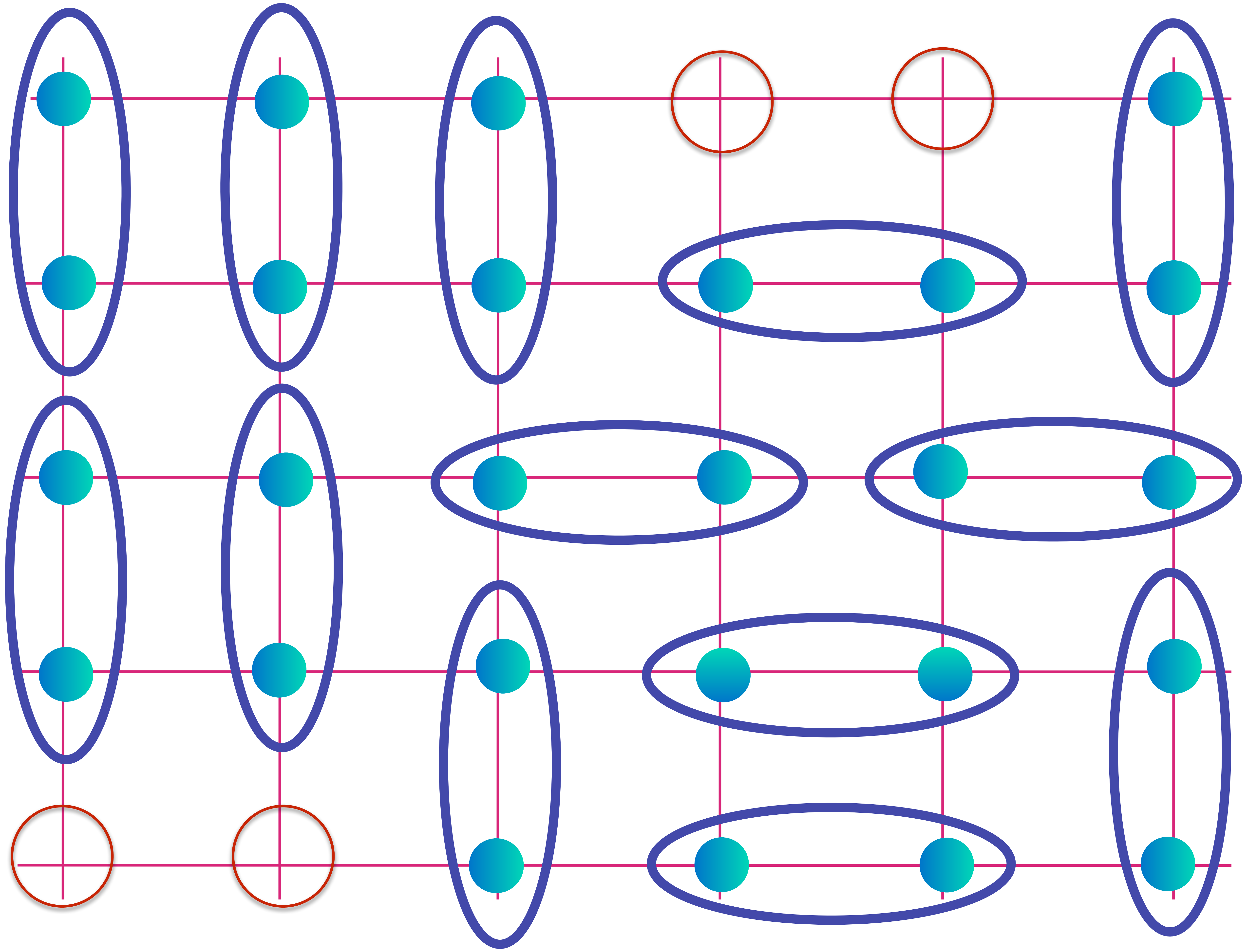

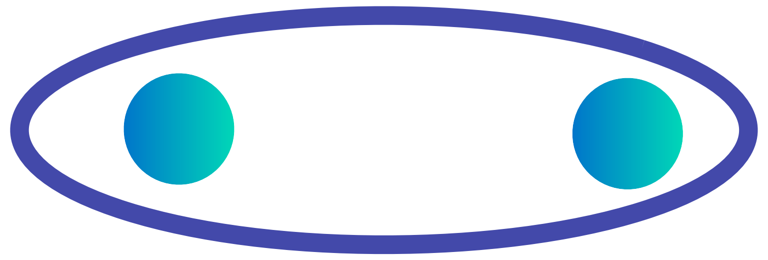 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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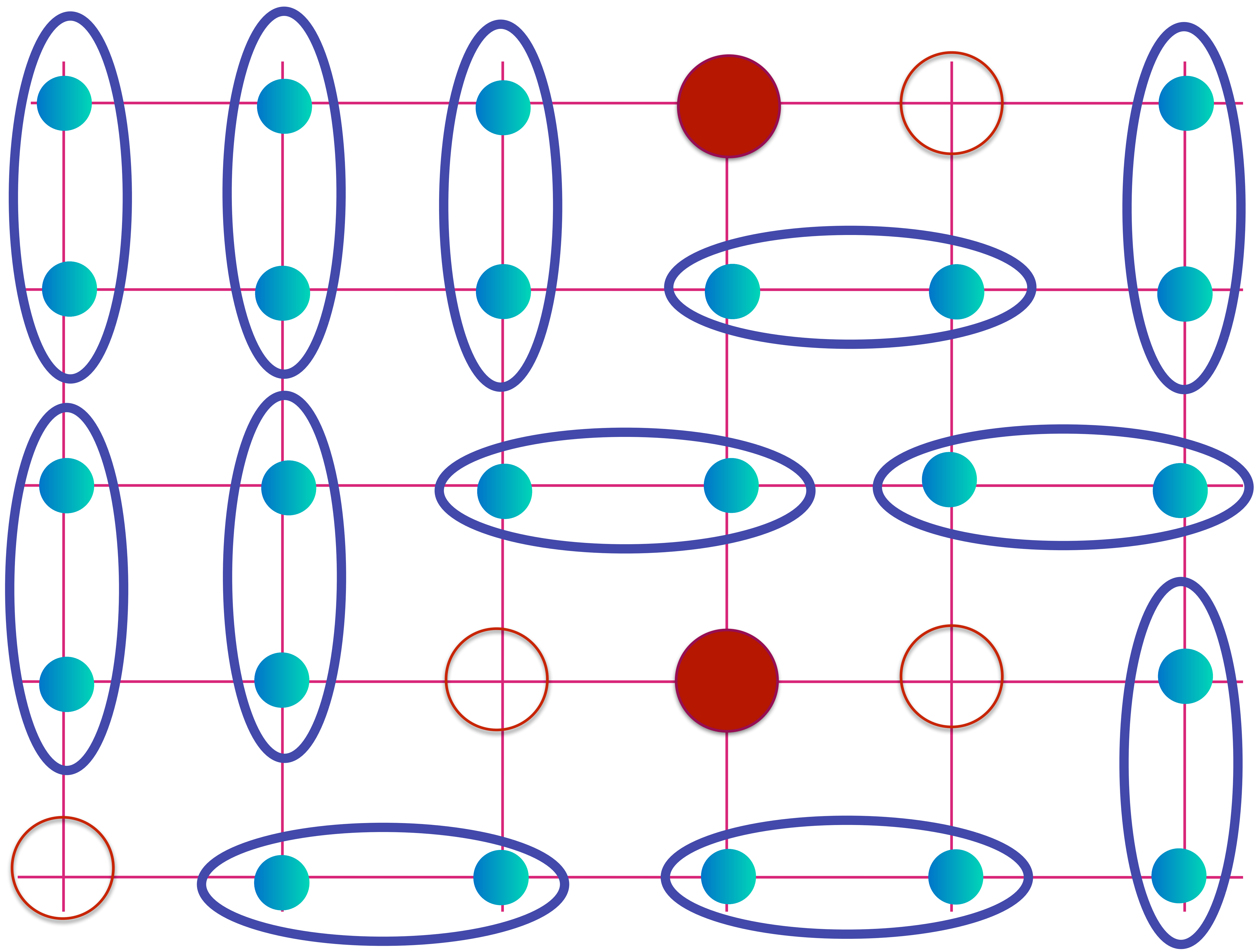
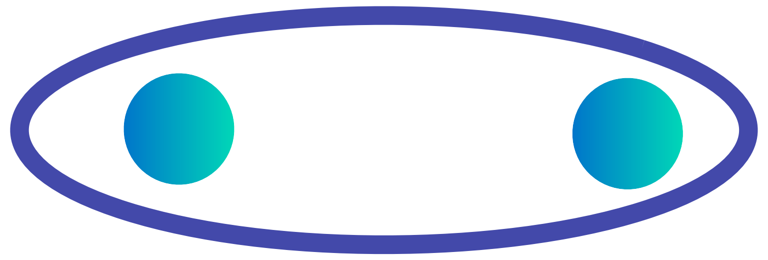


Strange metal

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



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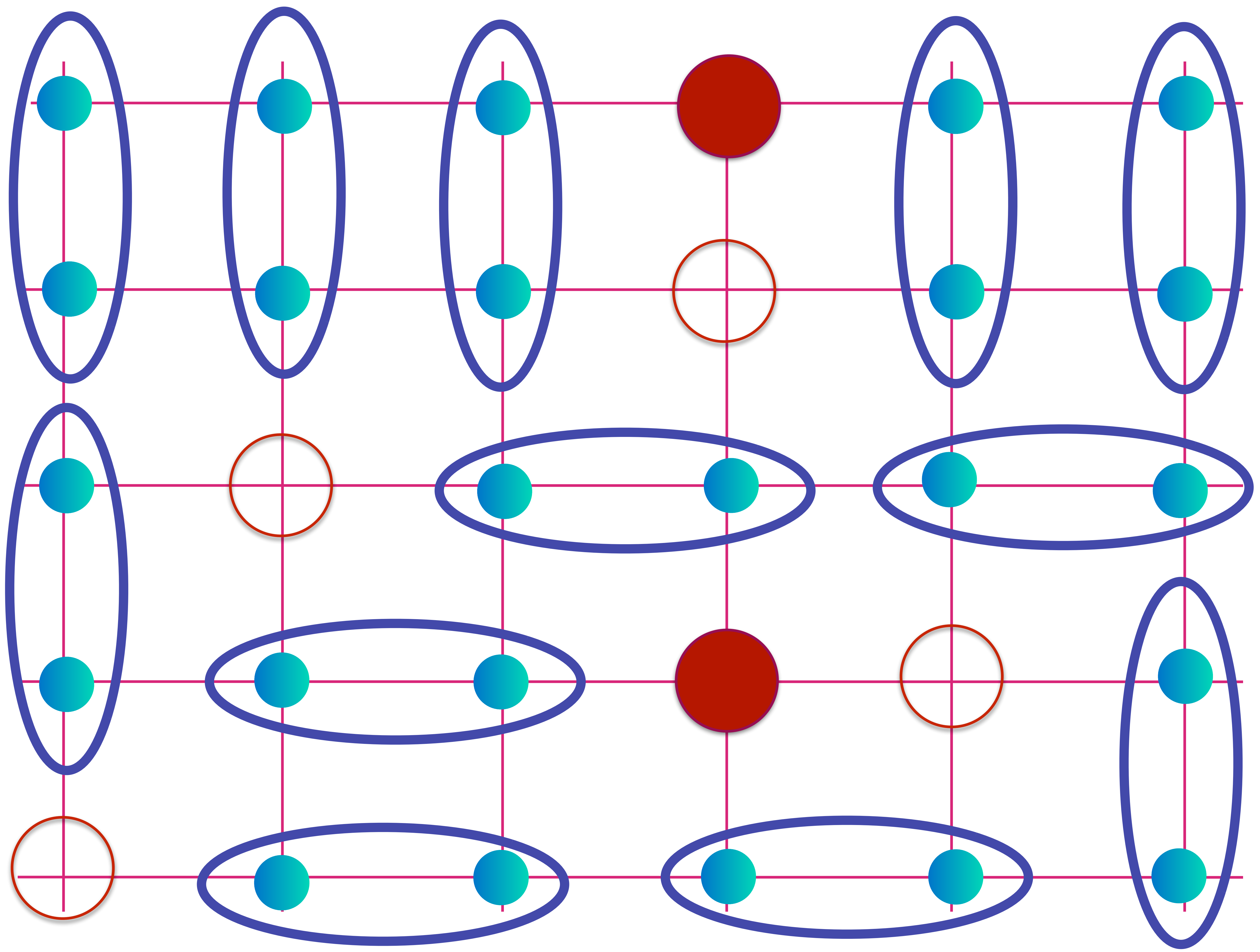

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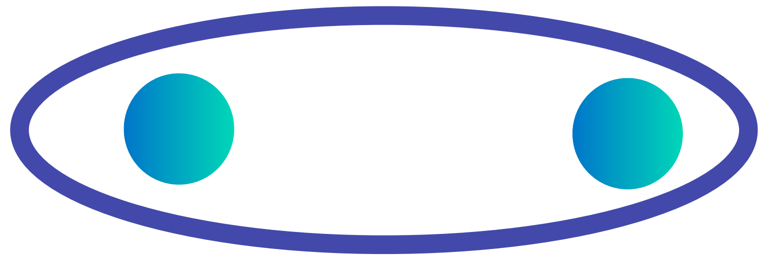

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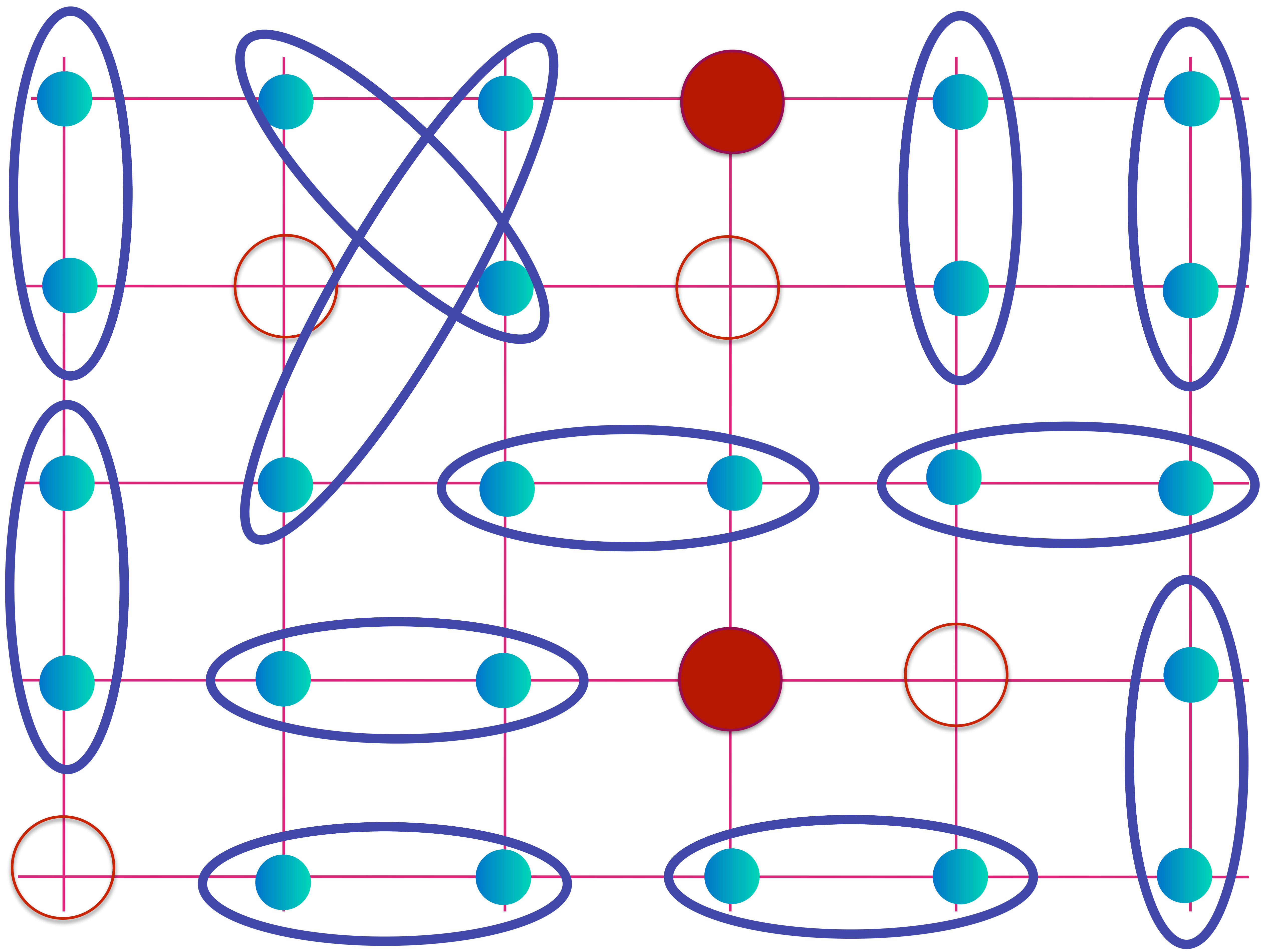

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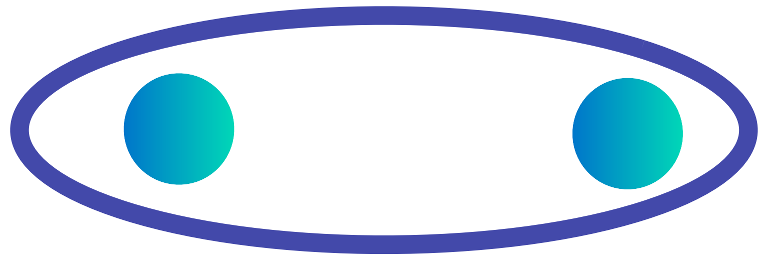

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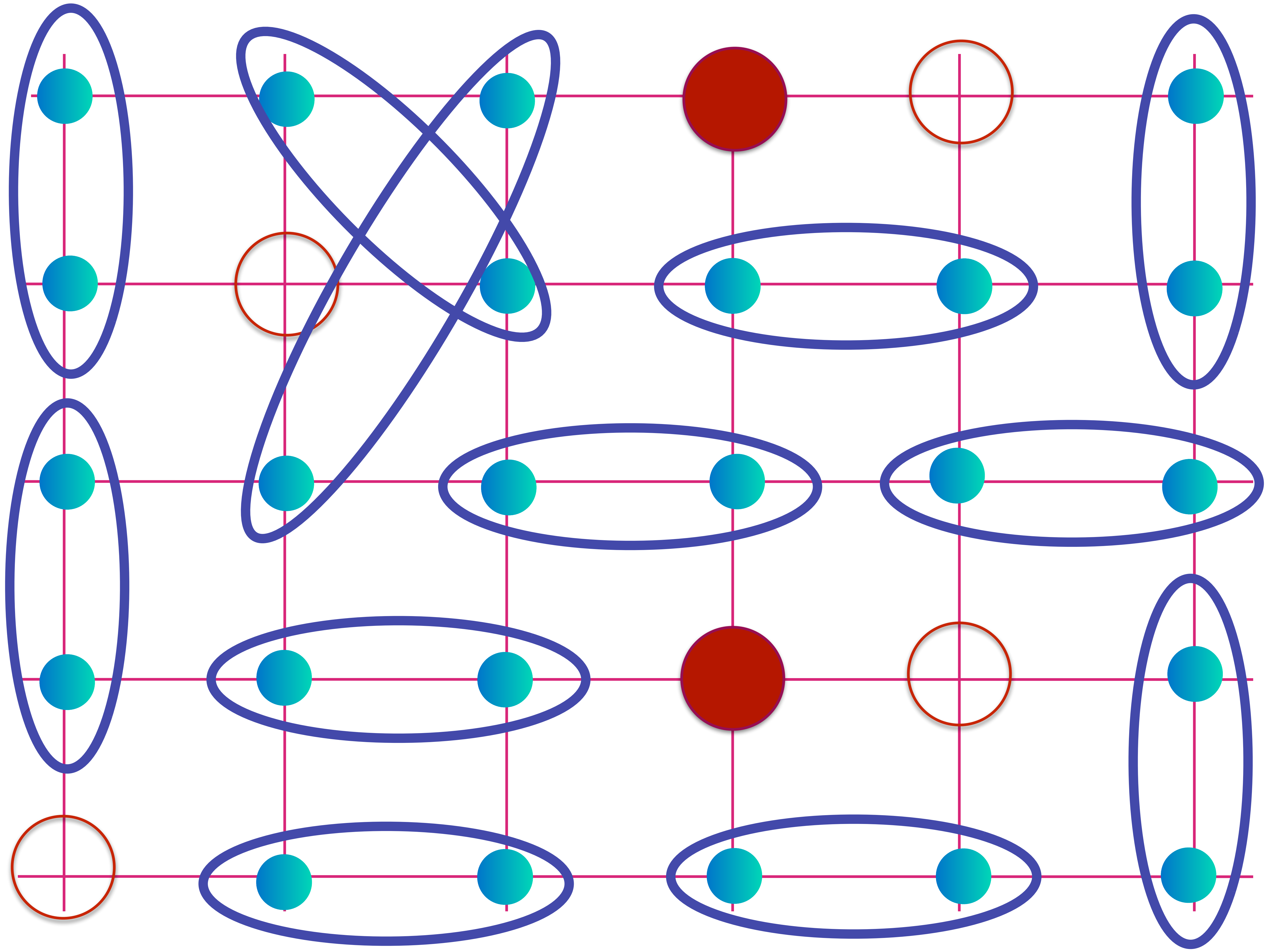

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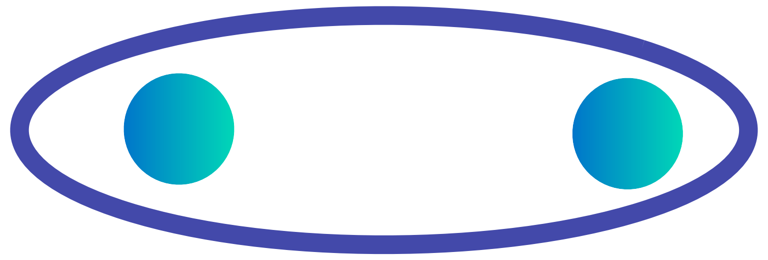

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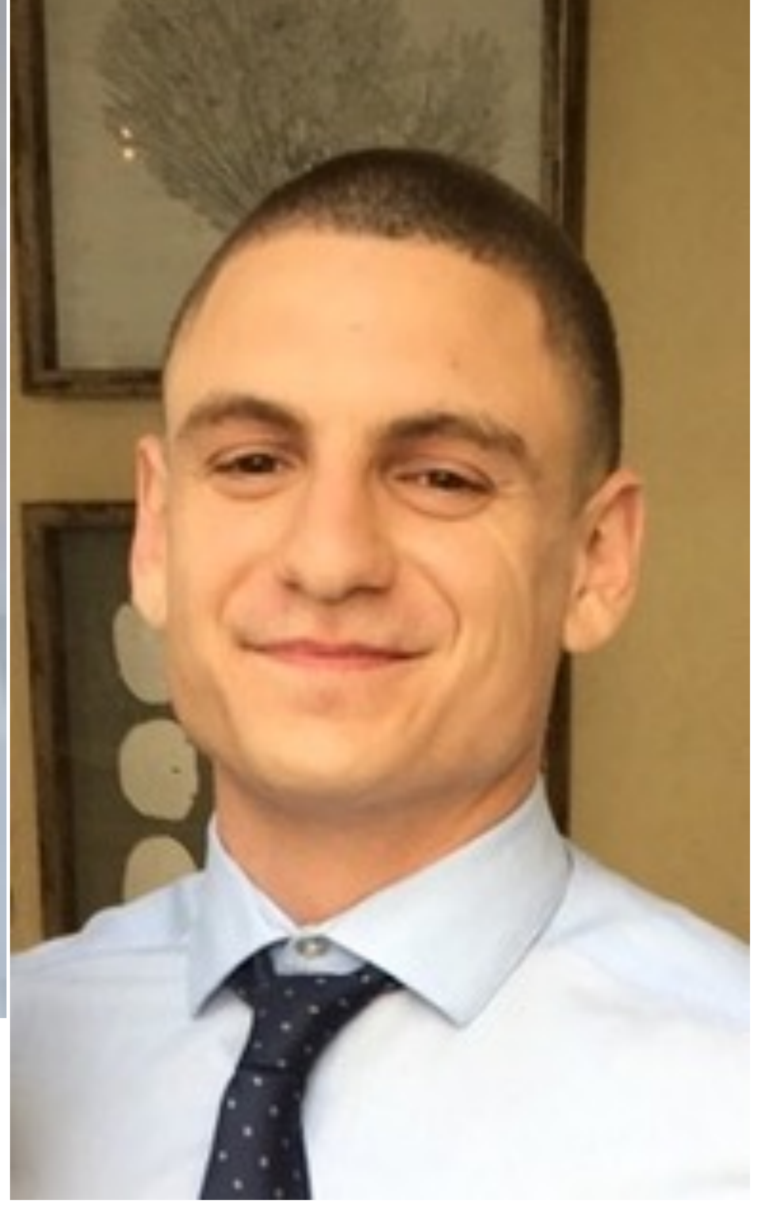
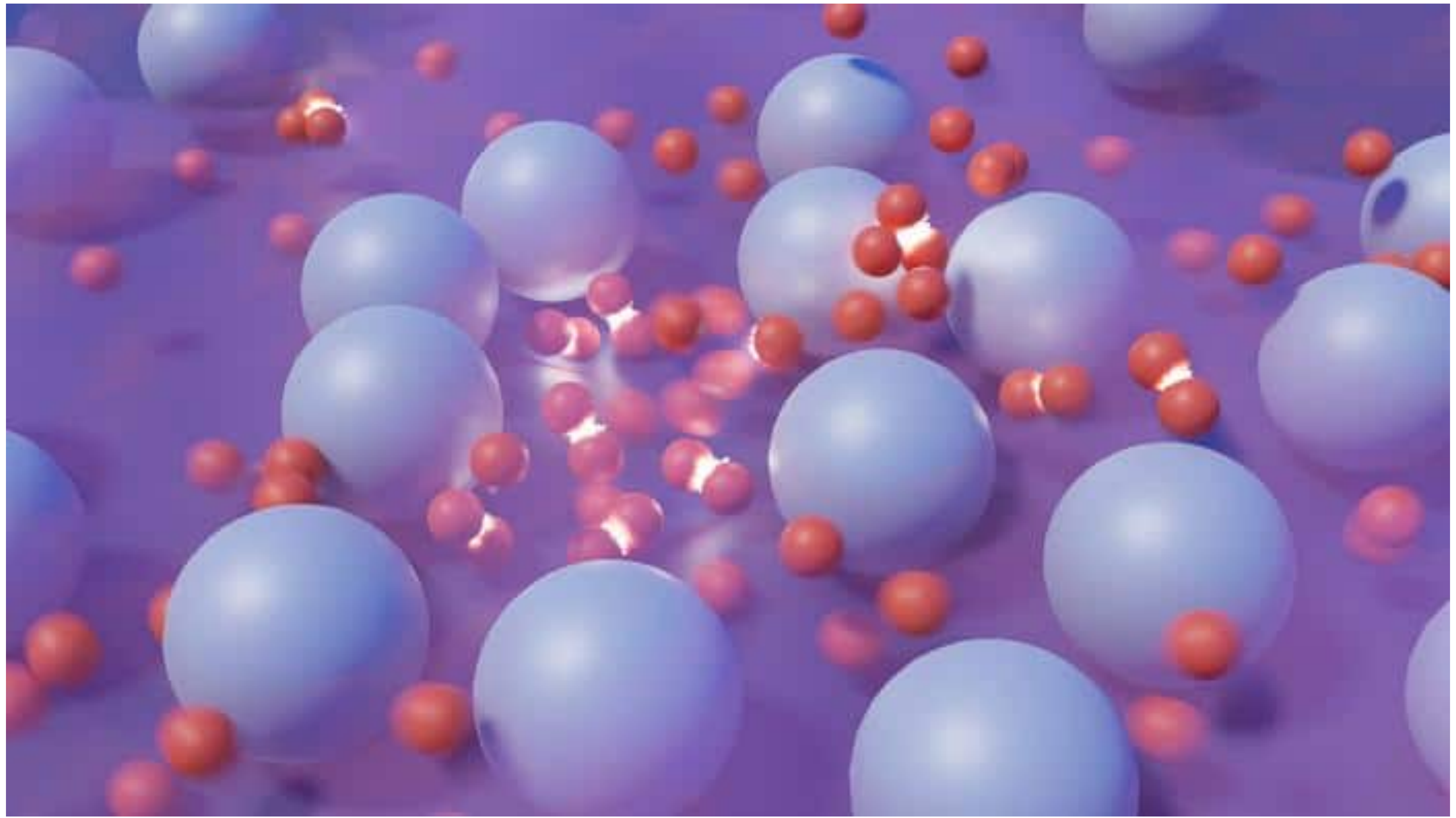
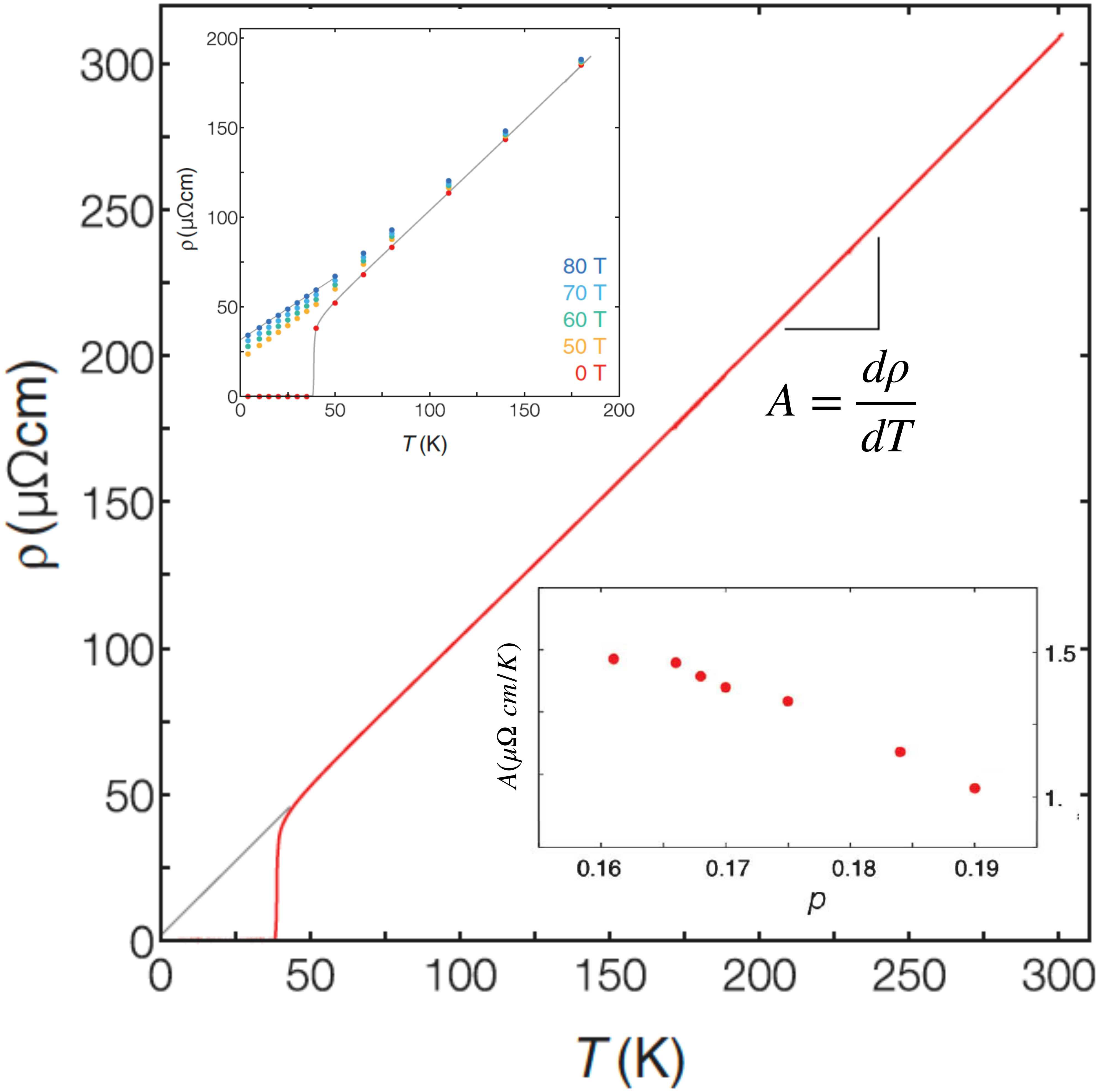


Aavishkar Patel
Flatiron Institute

Haoyu Guo
Cornell

Ilya Esterlis
Wisconsin



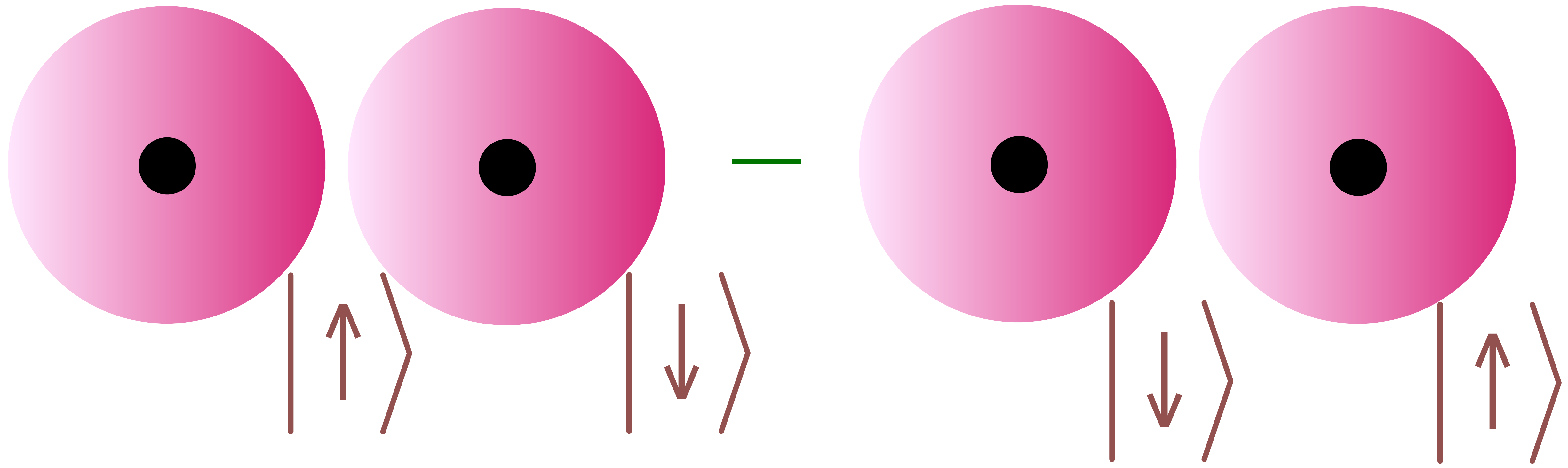


LSCO: Giraldo-Gallo et al. 2018

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

Quantum entanglement,
the SYK model,
and black holes
holes

Quantum Entanglement across a black hole horizon



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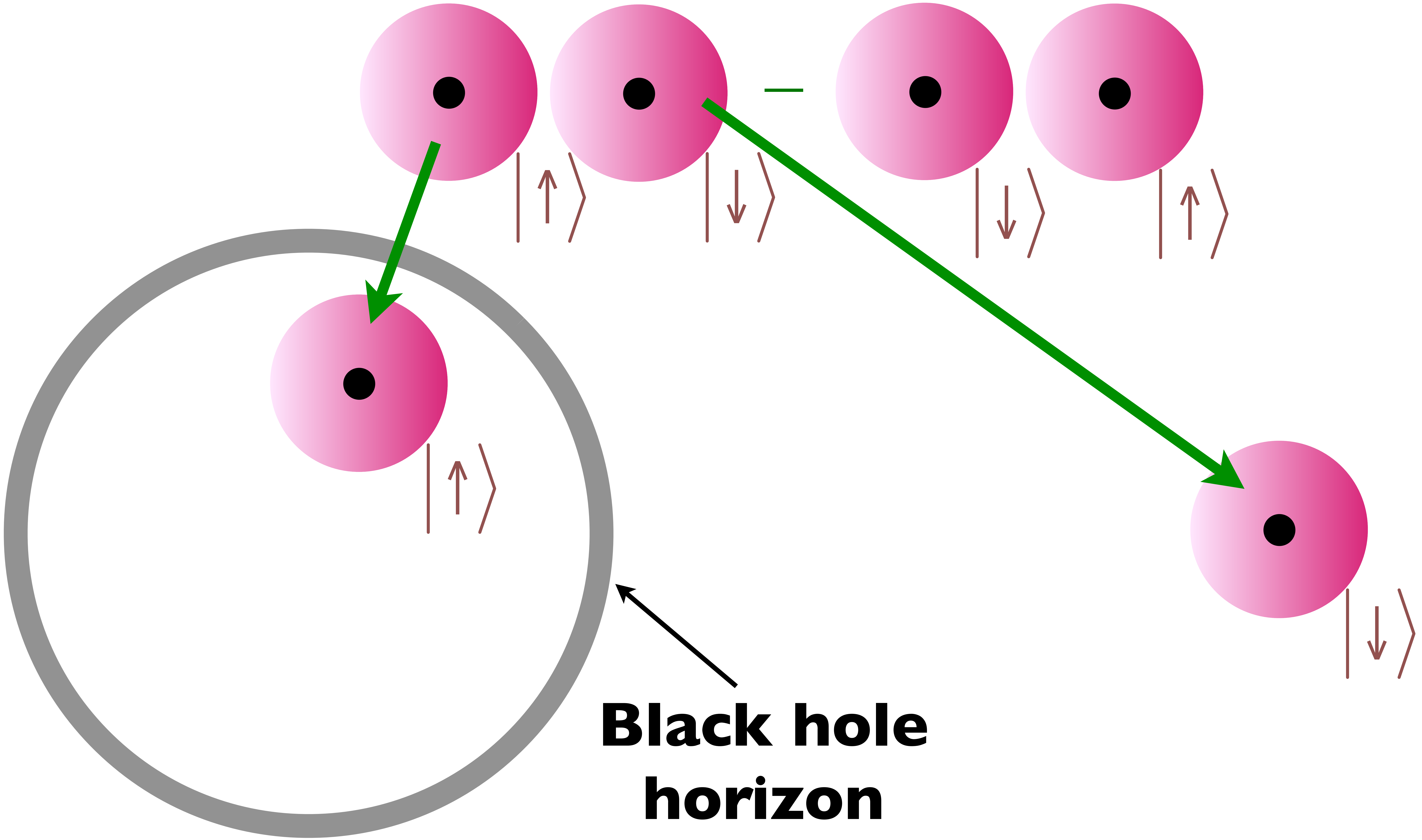
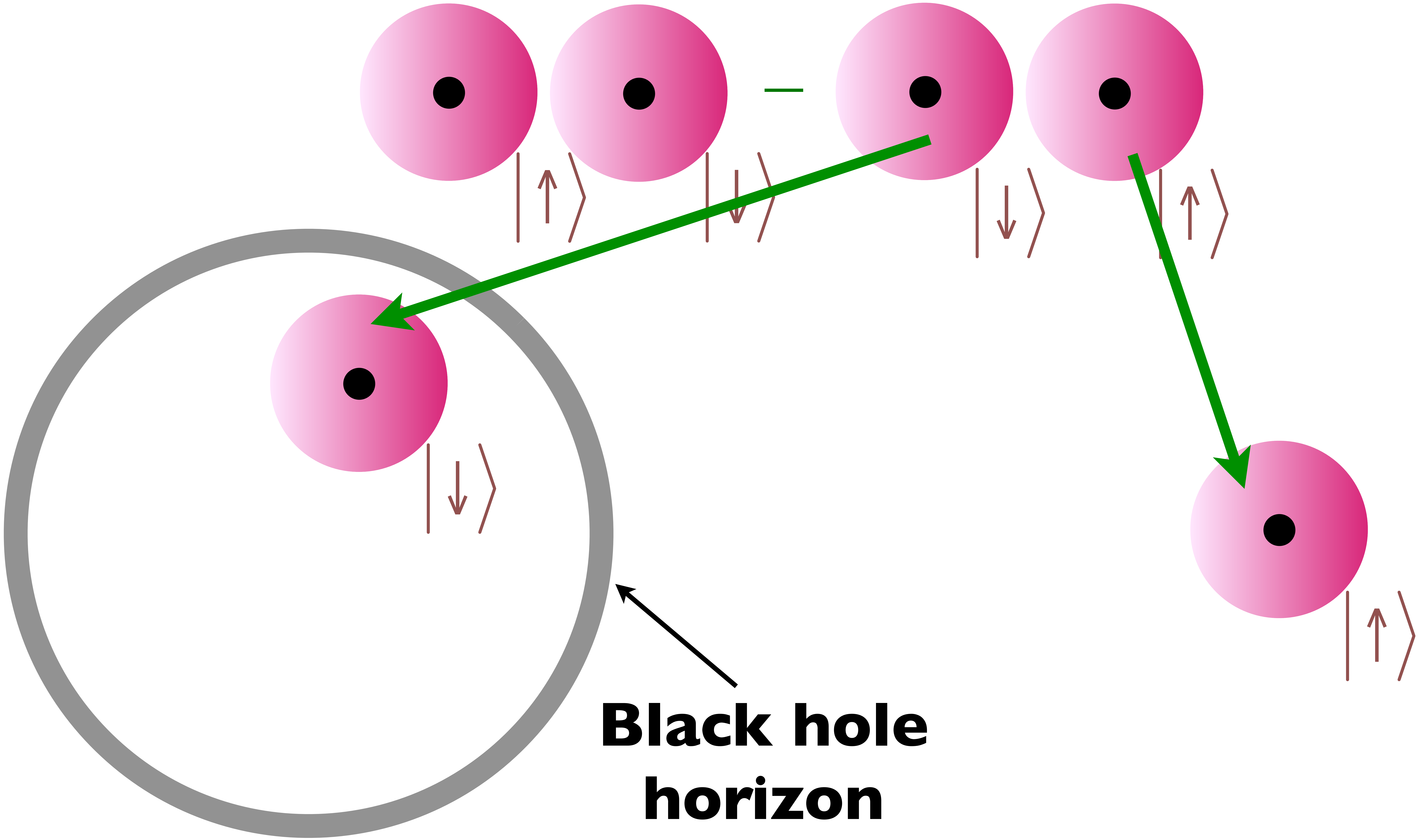
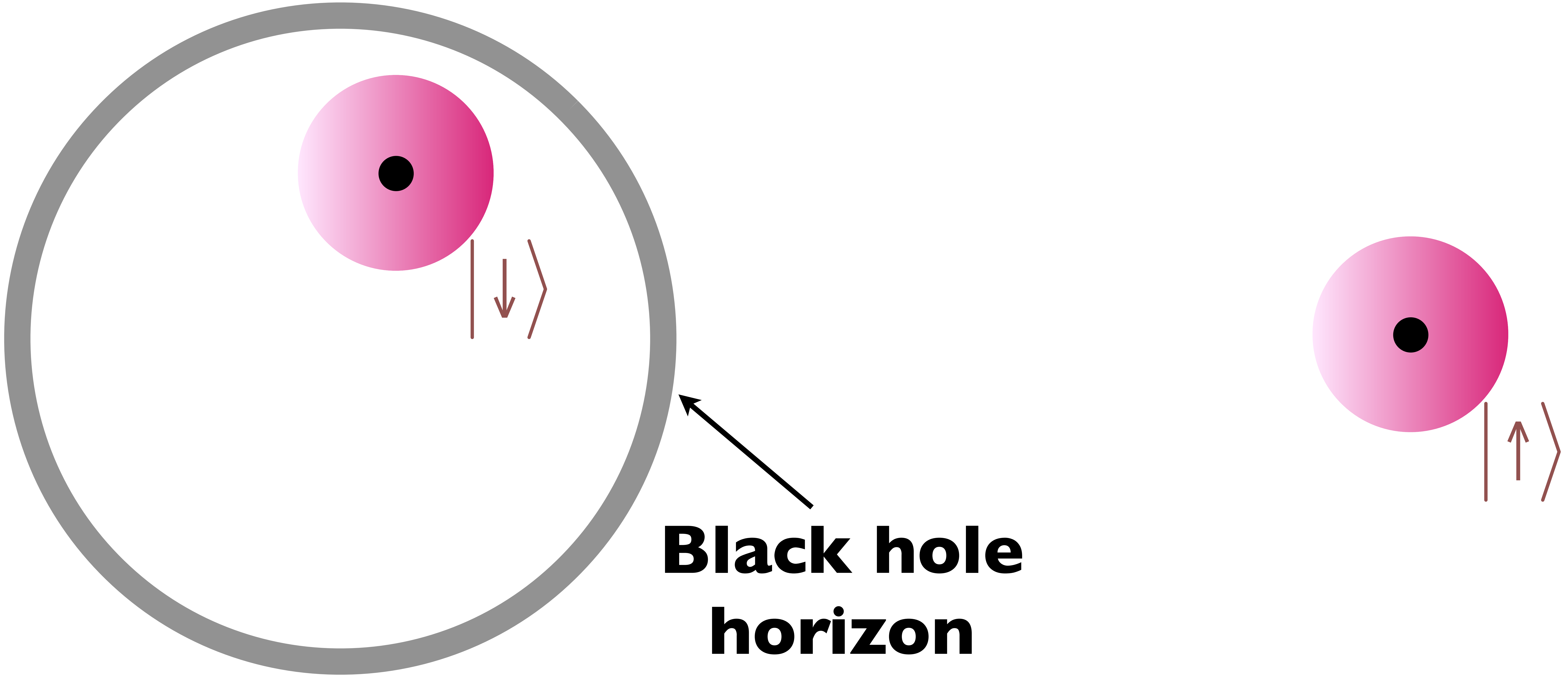


Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

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



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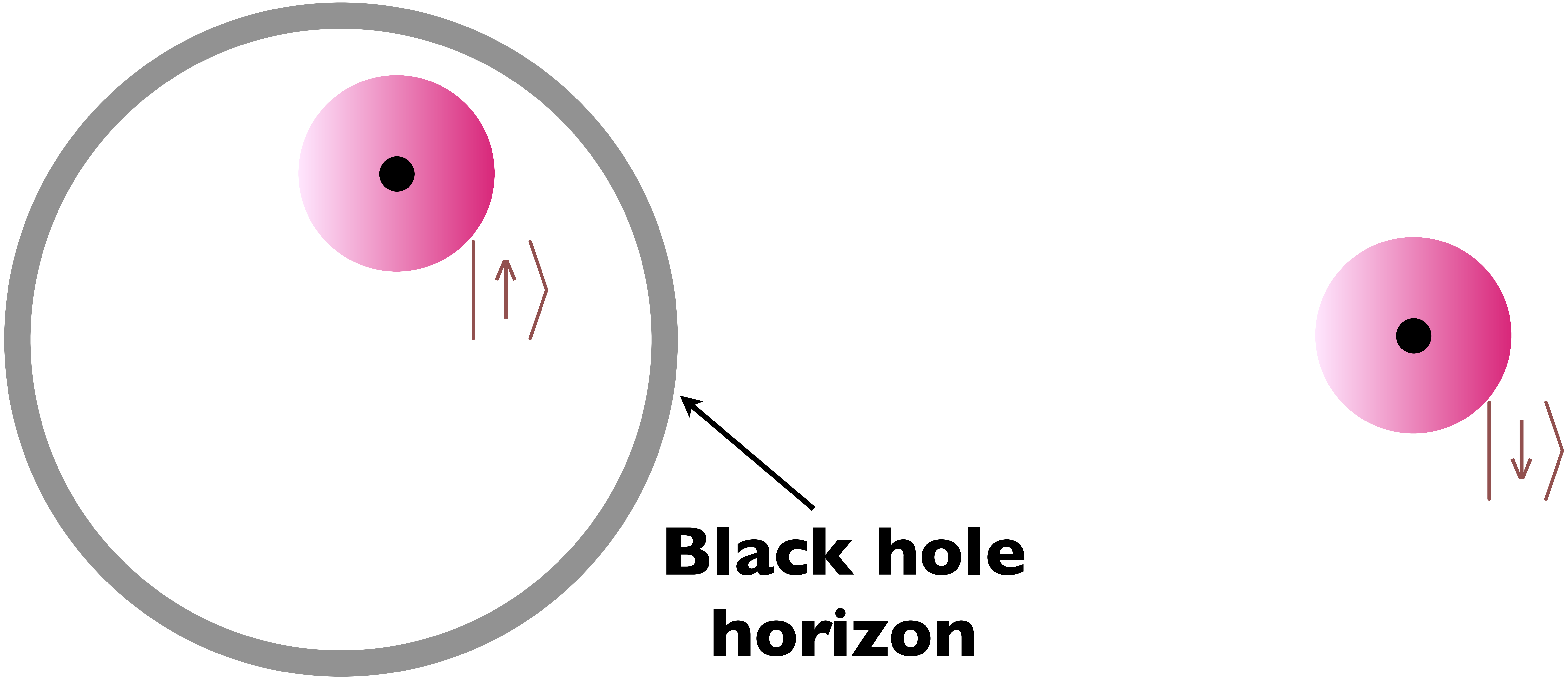
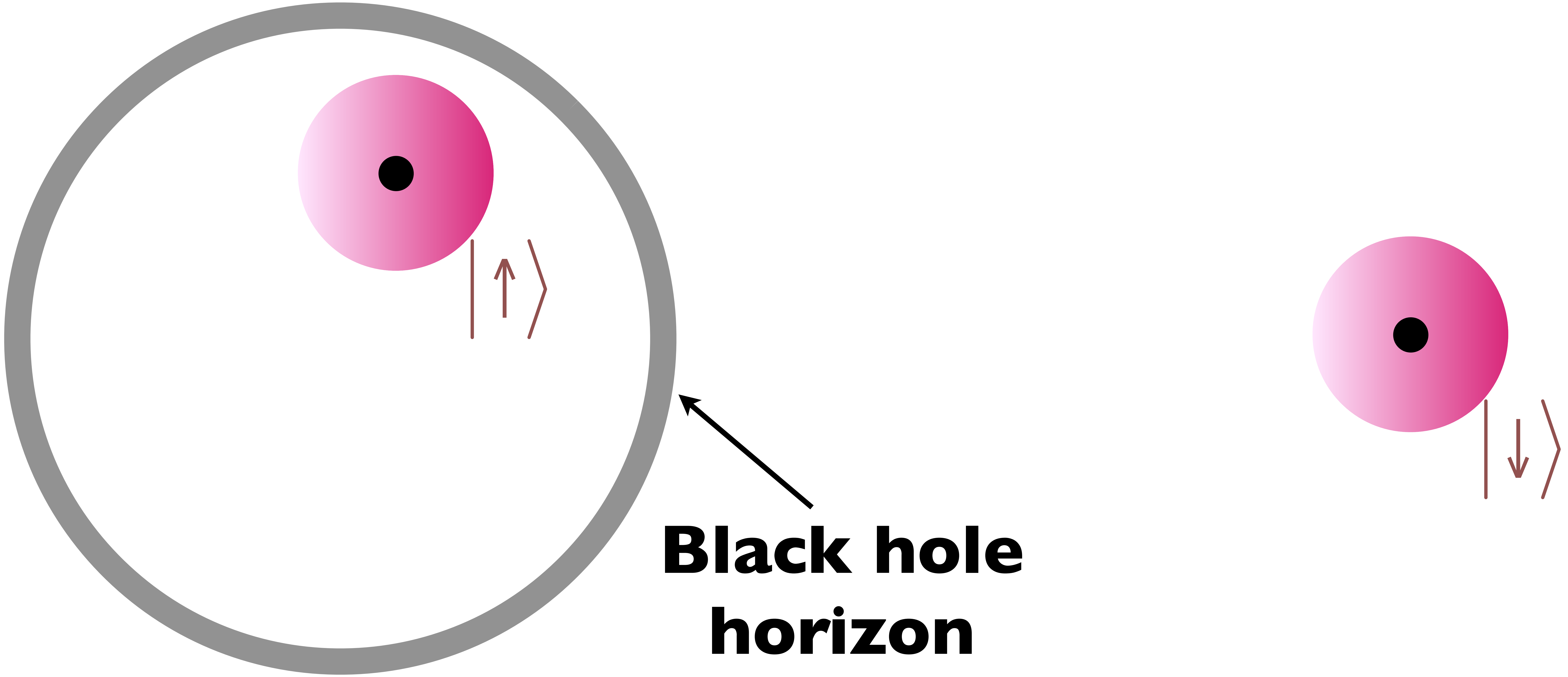


Quantum Entanglement across a black hole horizon

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.



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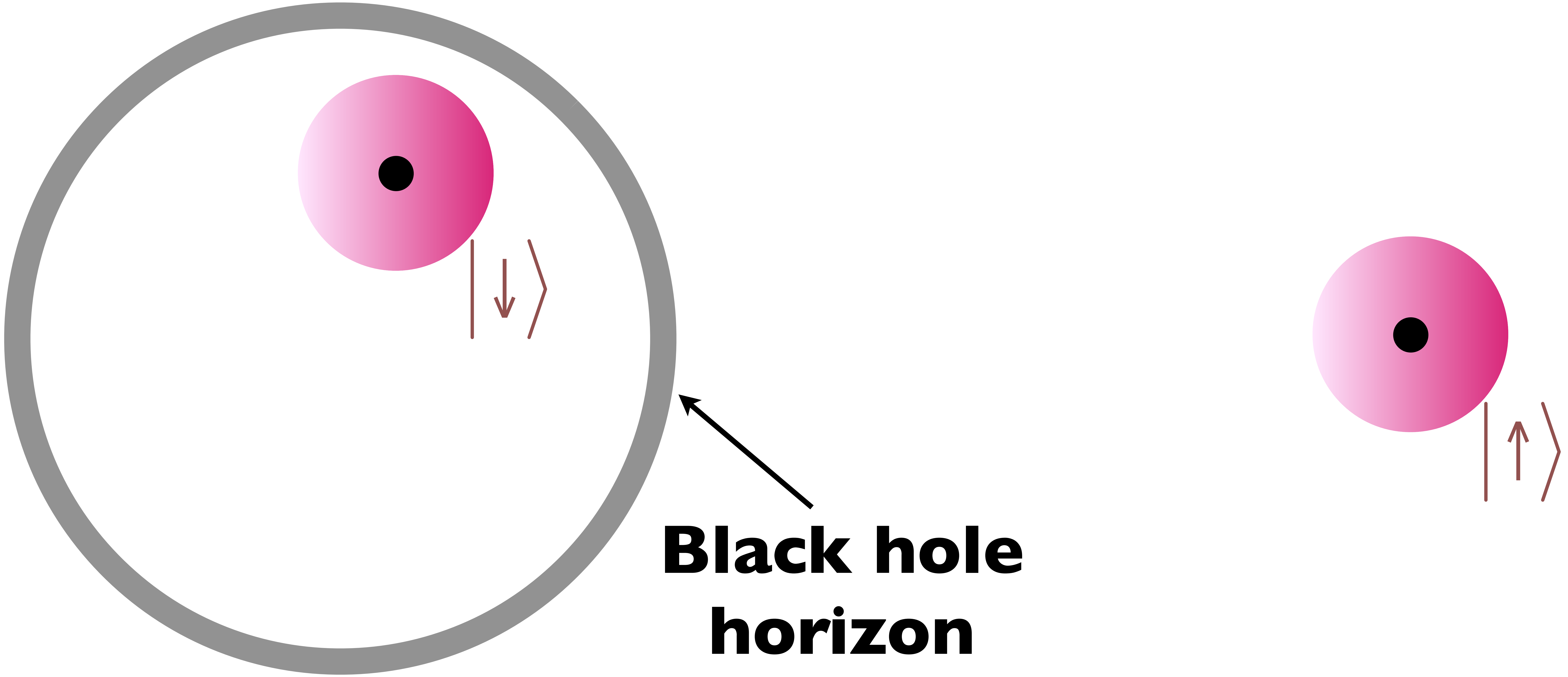
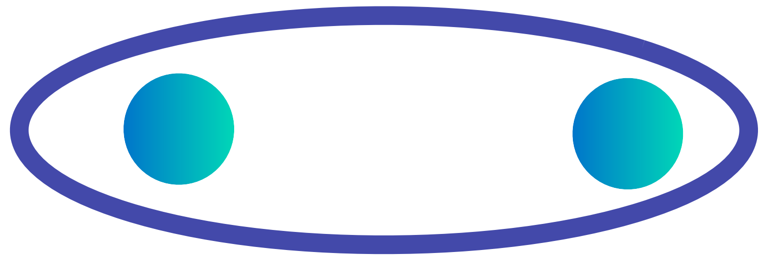
Hawking (1975): Black holes have a temperature and an entropy!

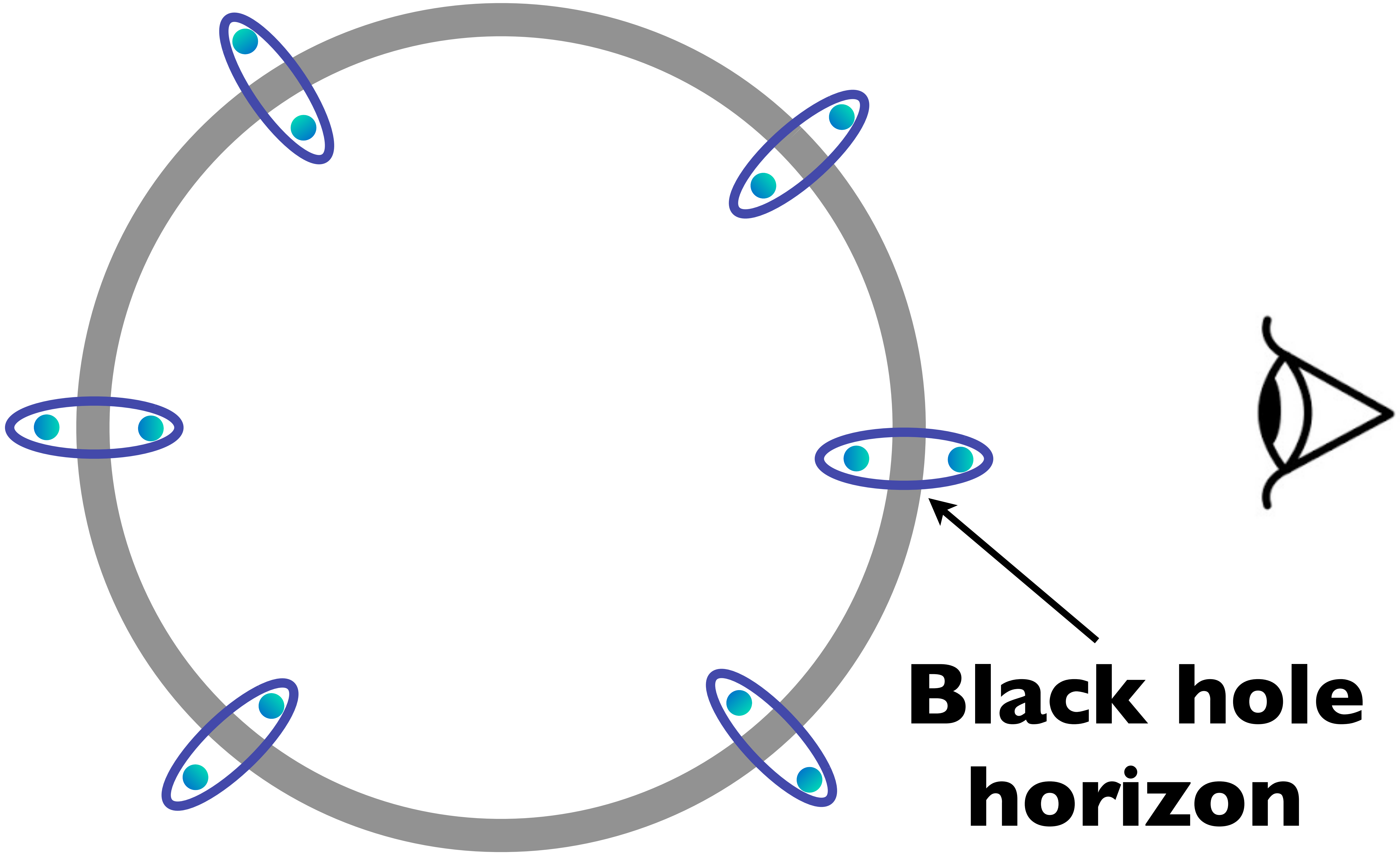
To an outside observer, the state of the electron inside the black hole cannot be known, and so the outside electron is in a random state.



Quantum Entanglement across a black hole horizon

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.

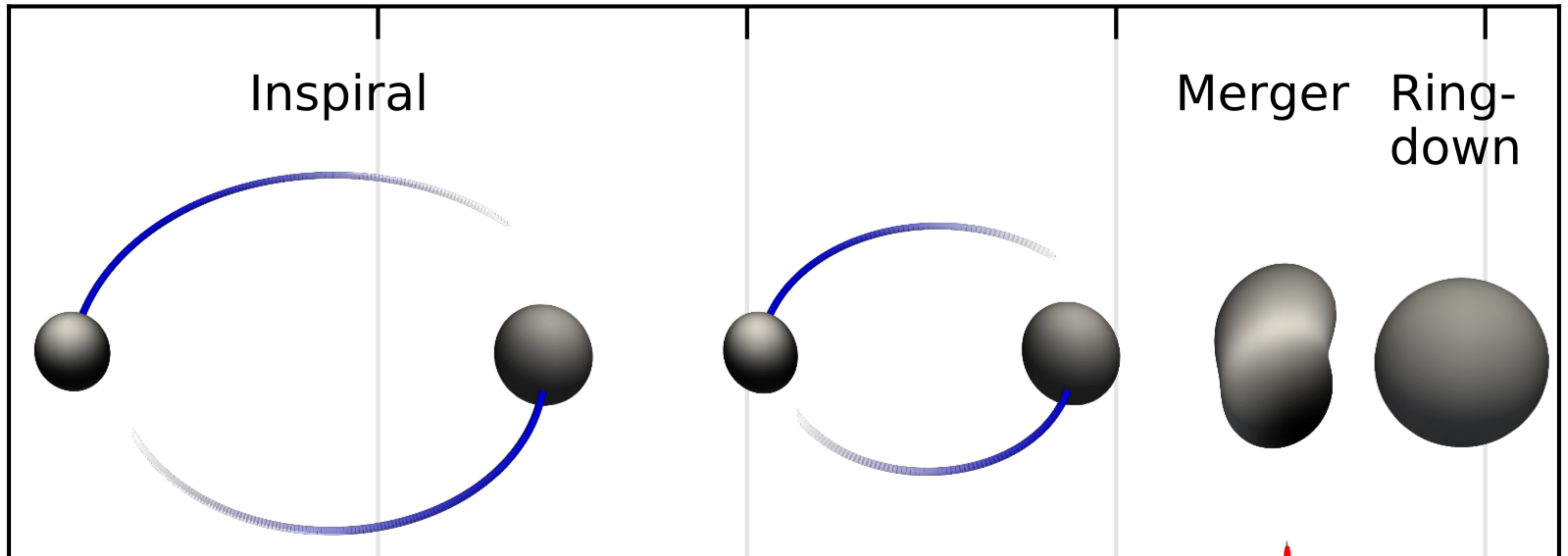
All other systems have entropy proportional to their volume.

Quantum black holes

- Black holes have an entropy and a temperature, $T_H = \hbar c^3/(8\pi G M k_B)$.

- The entropy is proportional to their surface area. $S = A k_B c^3/(4G\hbar)$.

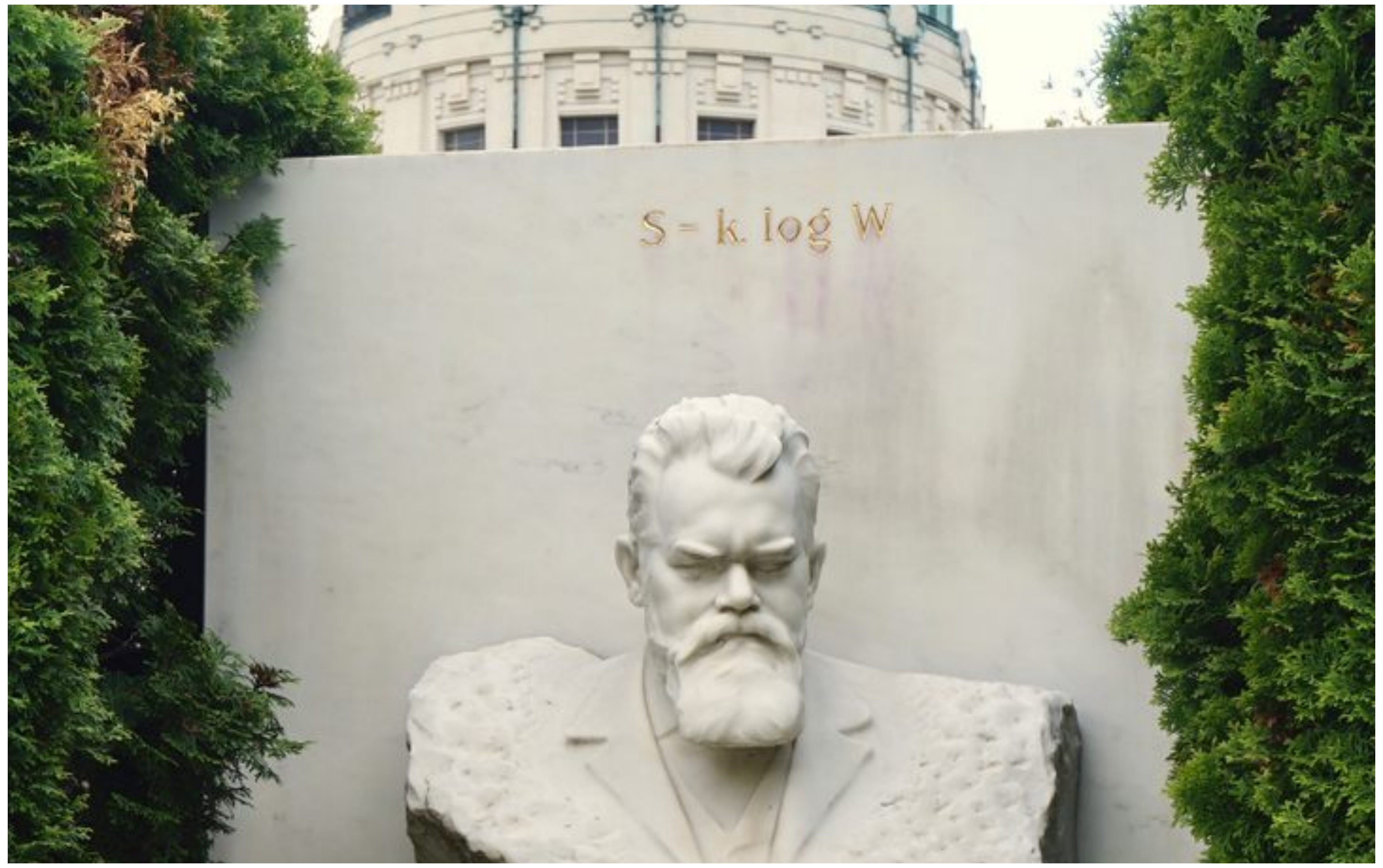
- They relax to thermal equilibrium in a time $\sim 8\pi G M/c^3 = \hbar/(k_B T_H)$, the Planckian time also found in strange metals, which suggests a connection to the SYK model!

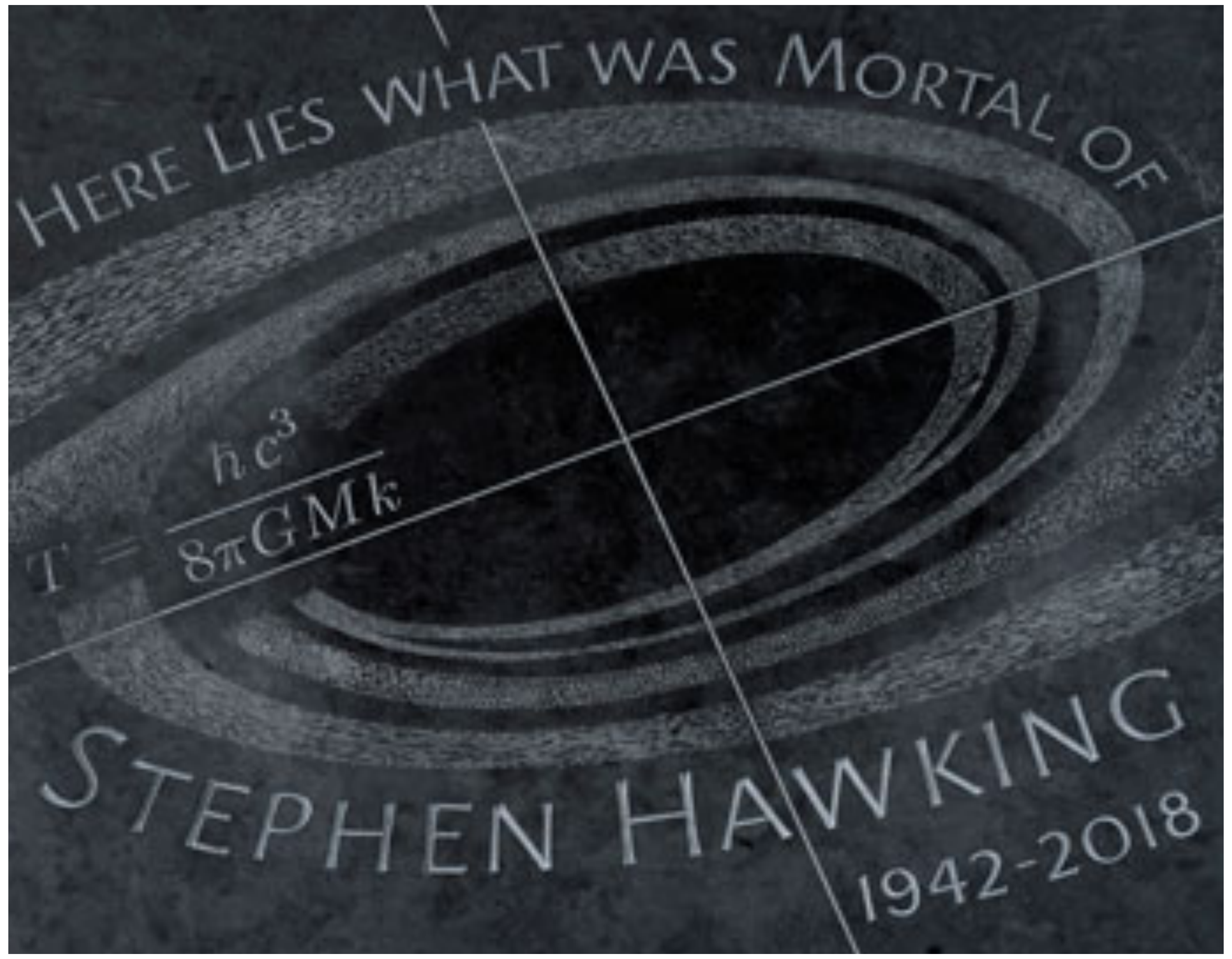


J. D. Bekenstein, PRD **7**, 2333 (1973)
S. W. Hawking, Nature **248**, 30 (1974)
C.V. Vishveshwara, Nature **227**, 936 (1970)

Quantum Black Holes

- Can we find a quantum theory for the collapsed matter at the center of the black hole, whose *density of quantum states* $D(E)$ [the quantum analog of Boltzmann's W] matches Hawking's entropy, in accordance with Boltzmann's principles of statistical mechanics, $S(E) = k_B \log D(E)$?





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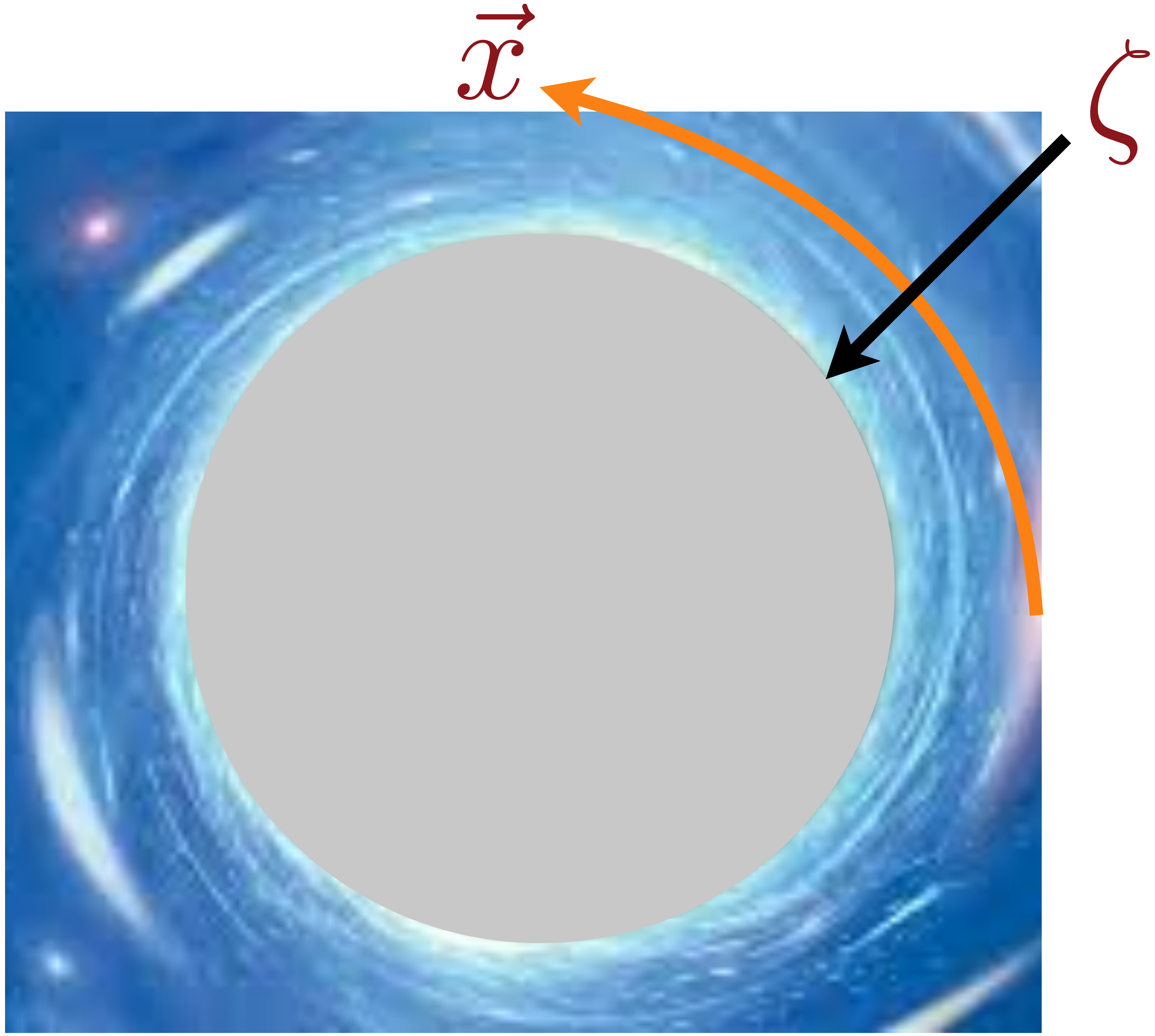
- Answer from string theory for 'supersymmetric' charged black holes: $D(E) = e^S \delta(E)$ *i.e.* all the states required by Hawking's entropy have exactly the same energy.

Strominger, Vafa (1996)

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



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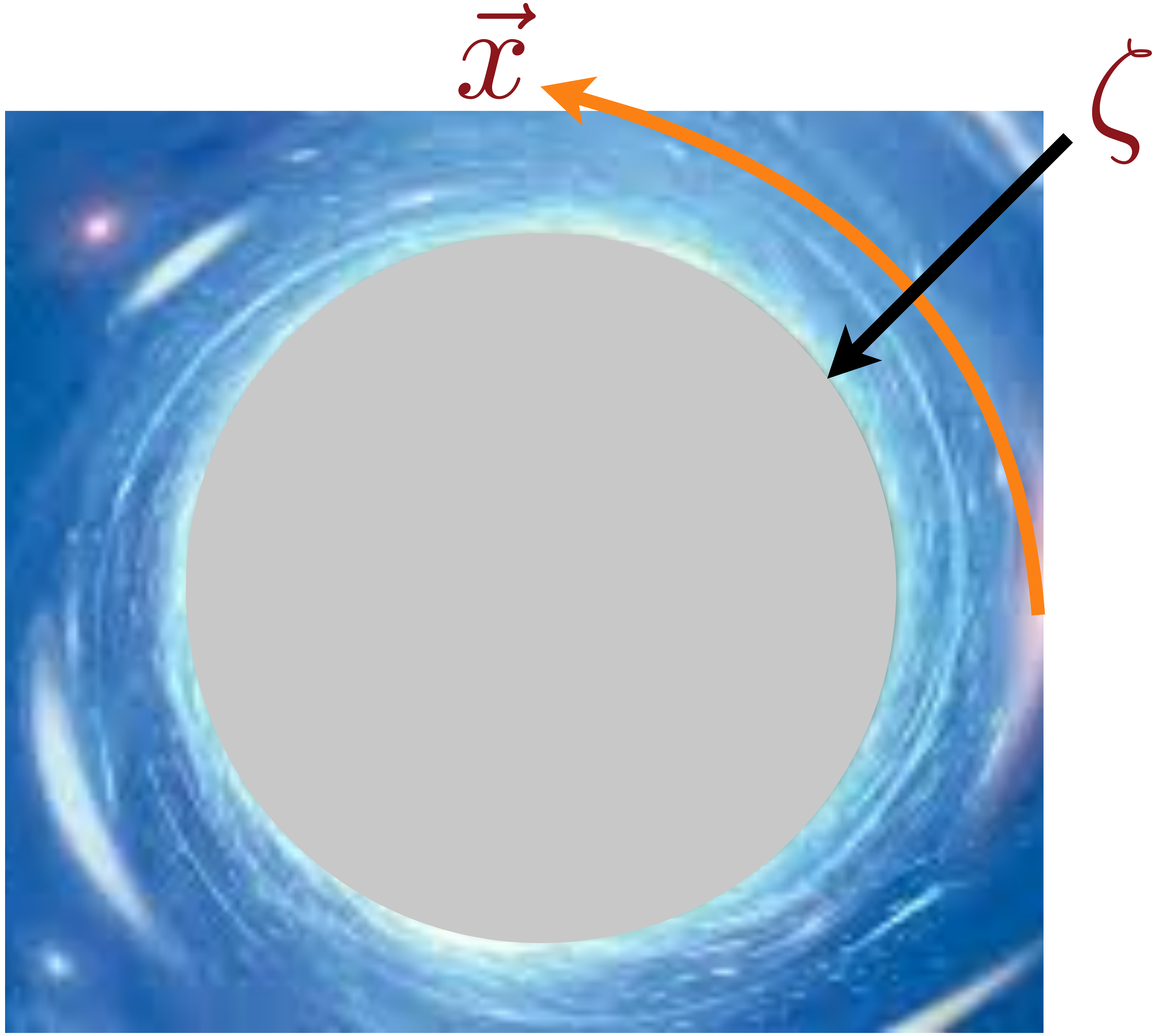
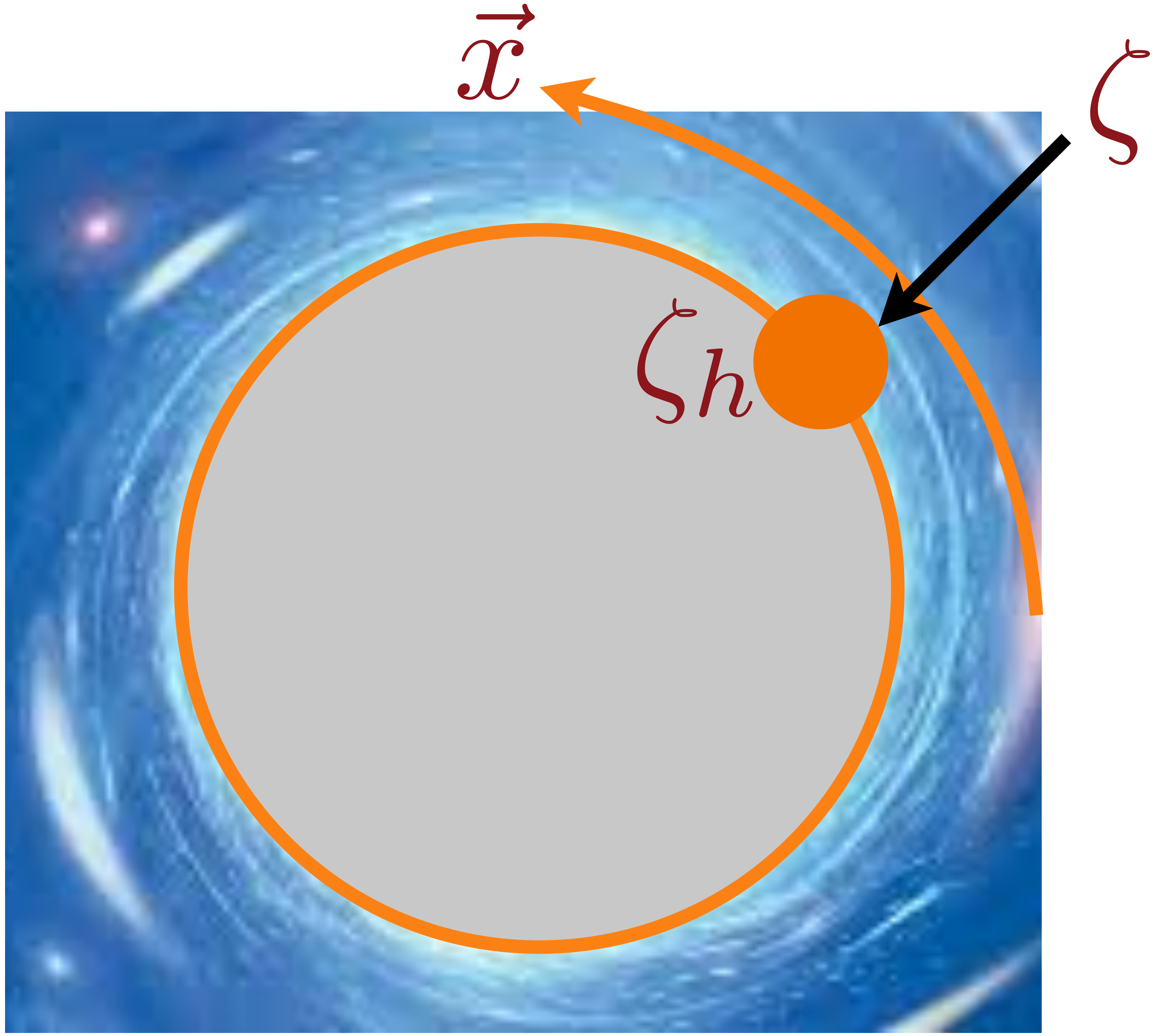


Zooming into the
near-horizon region
of a charged black hole
at low temperature,
yields a theory
in one space (ζ) and
one time dimension

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



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
and Einstein's general relativity
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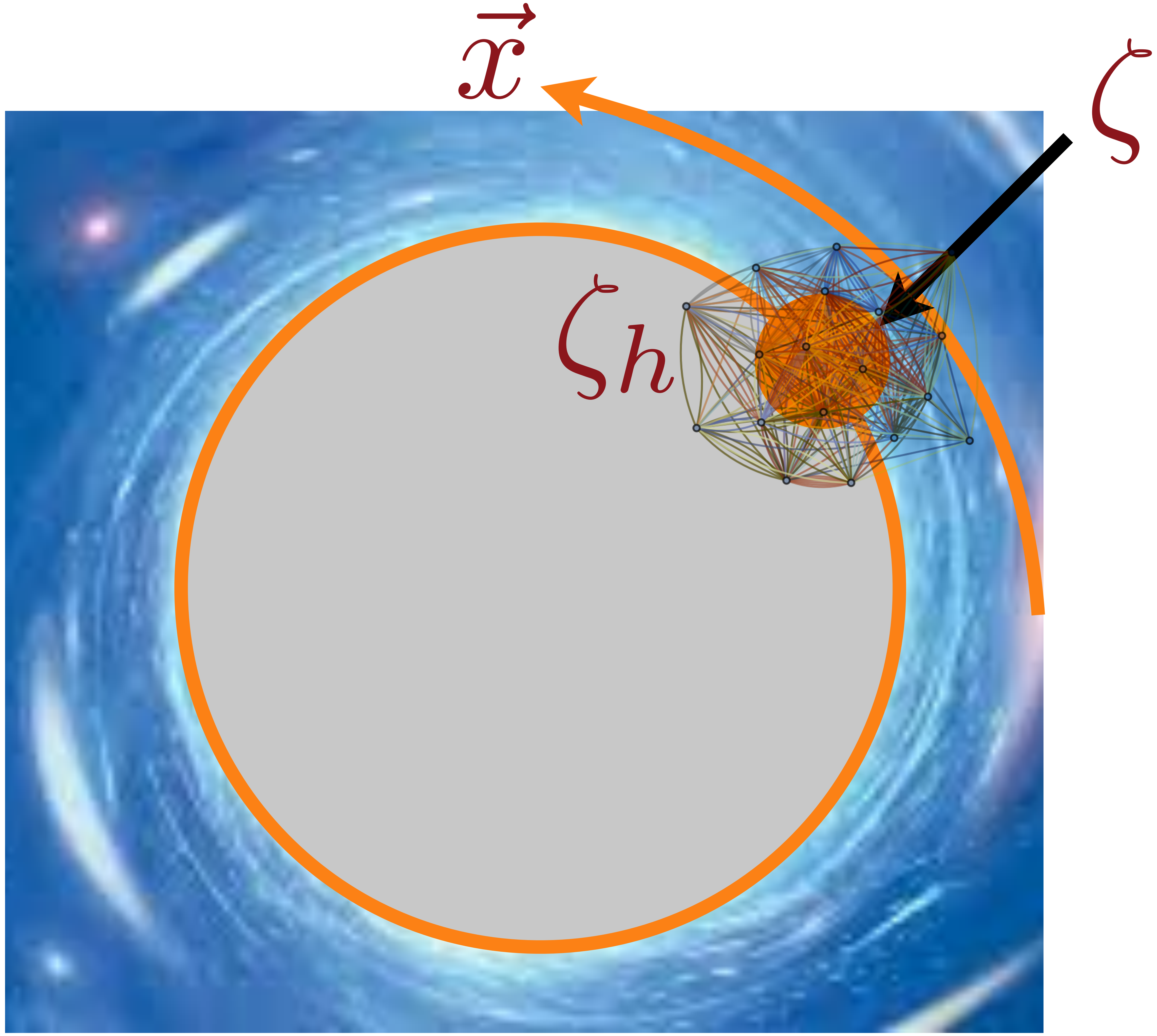
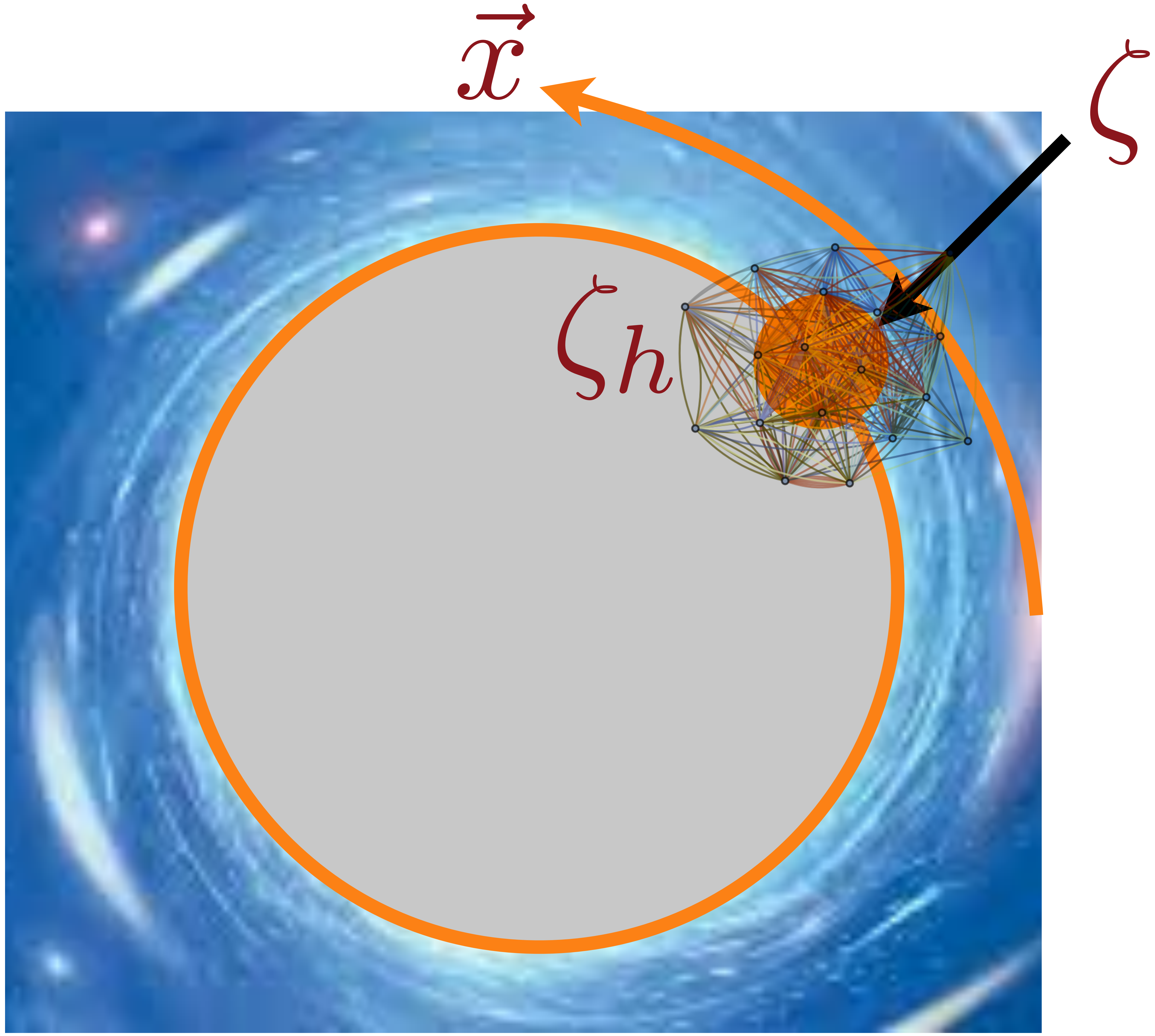


The quantum versions of Maxwell's and Einstein's equations in this two-dimensional spacetime are also the equations describing electron entanglement in the SYK model!

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

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



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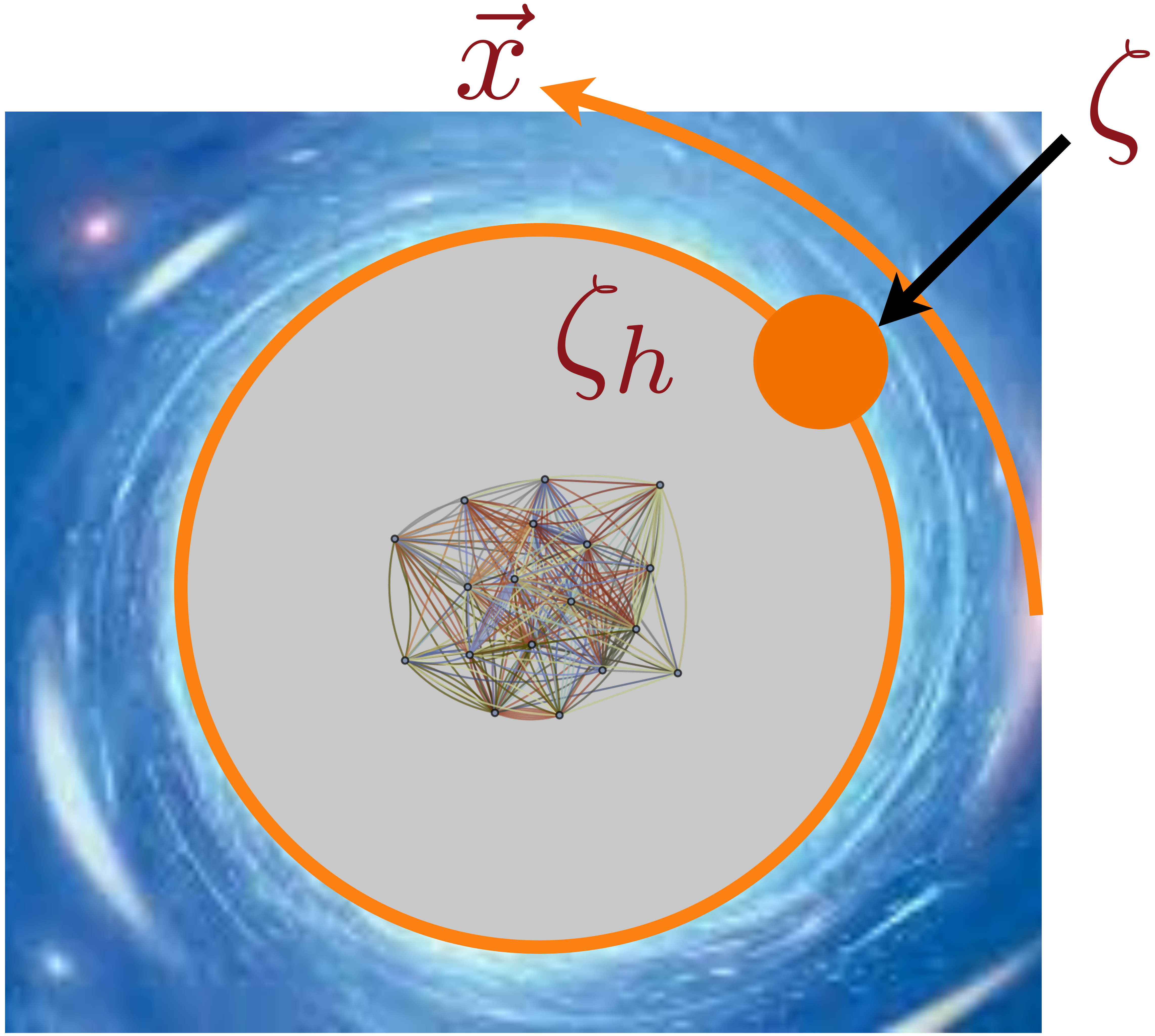

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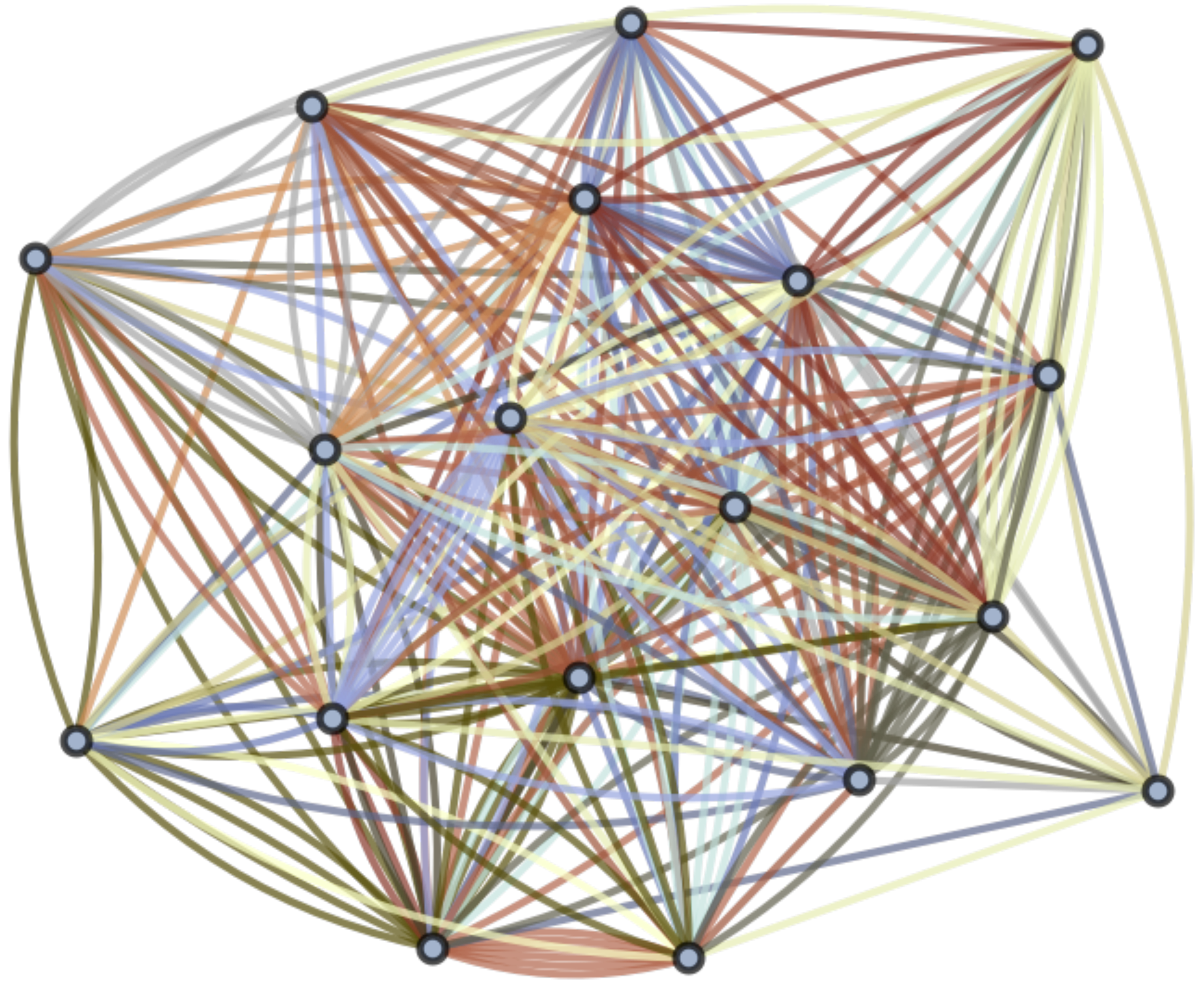
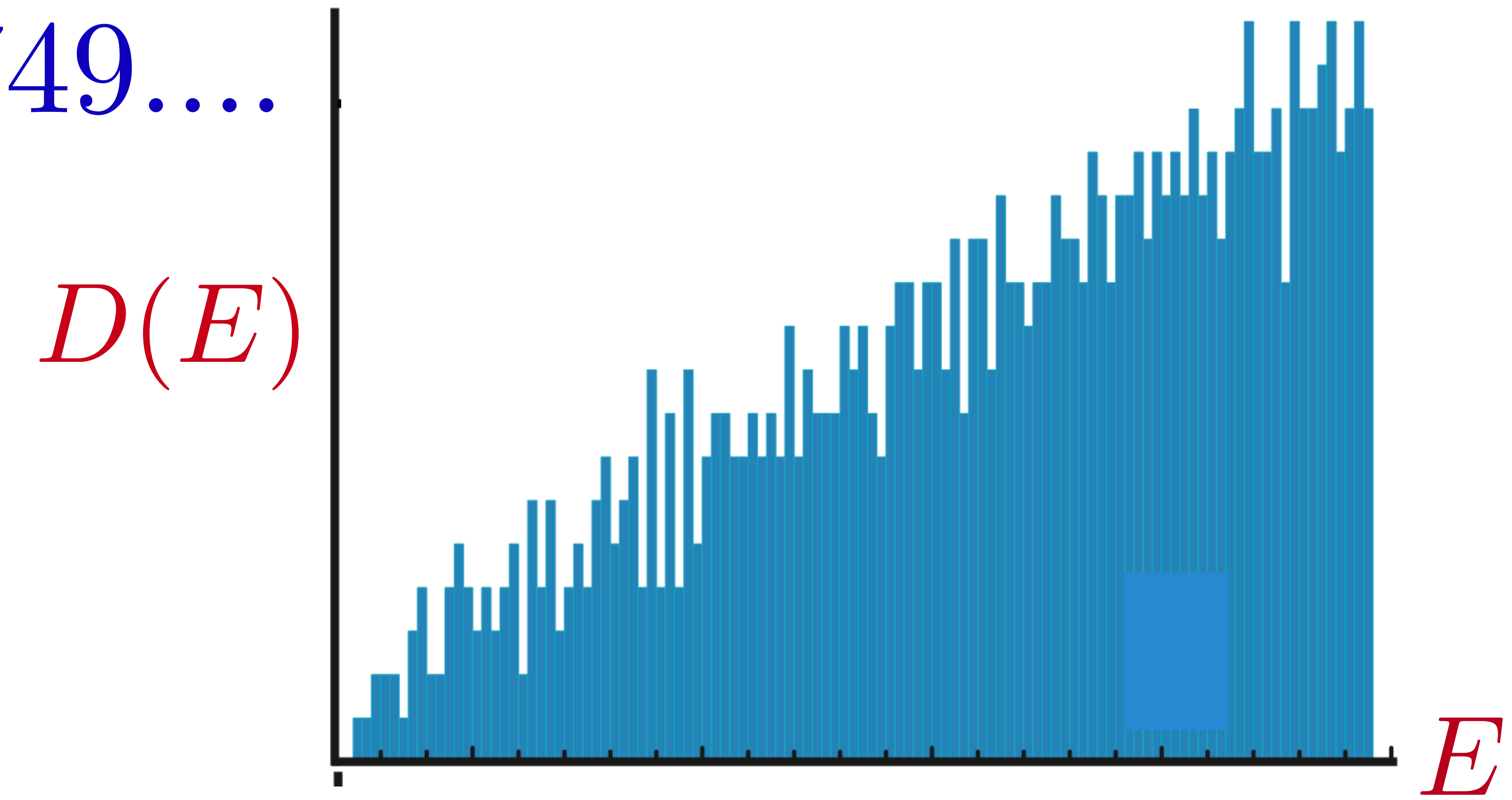
The Sachdev-Ye-Kitaev (SYK) model



- Density of quantum states of the SYK model with N sites

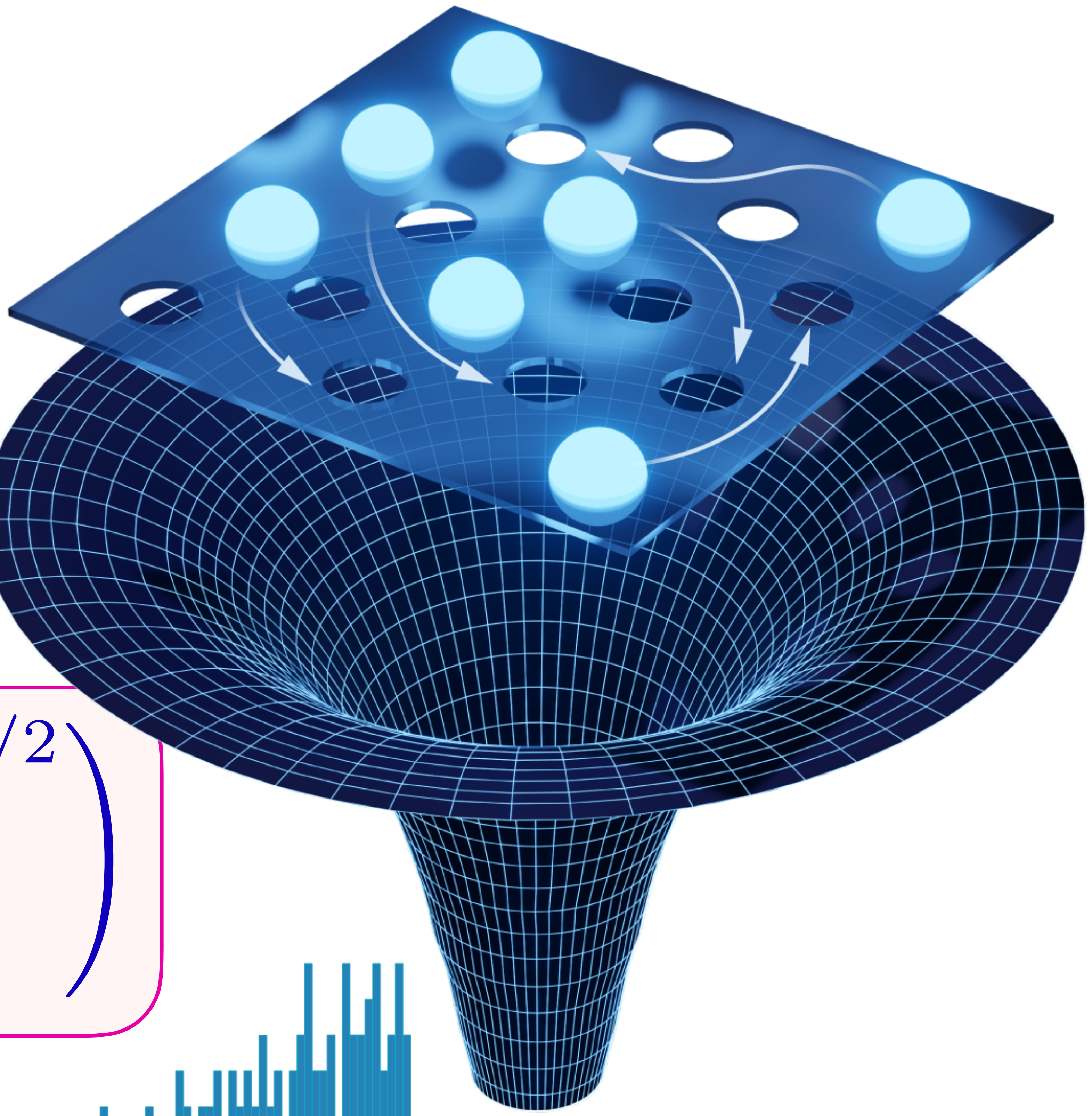
$$D(E) \sim \frac{1}{N} \exp\left(N s_0\right) \sinh\left(\left[2N\gamma E\right]^{1/2}\right)$$

where $s_0 = 0.4648476991708051 0749\ldots.$



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



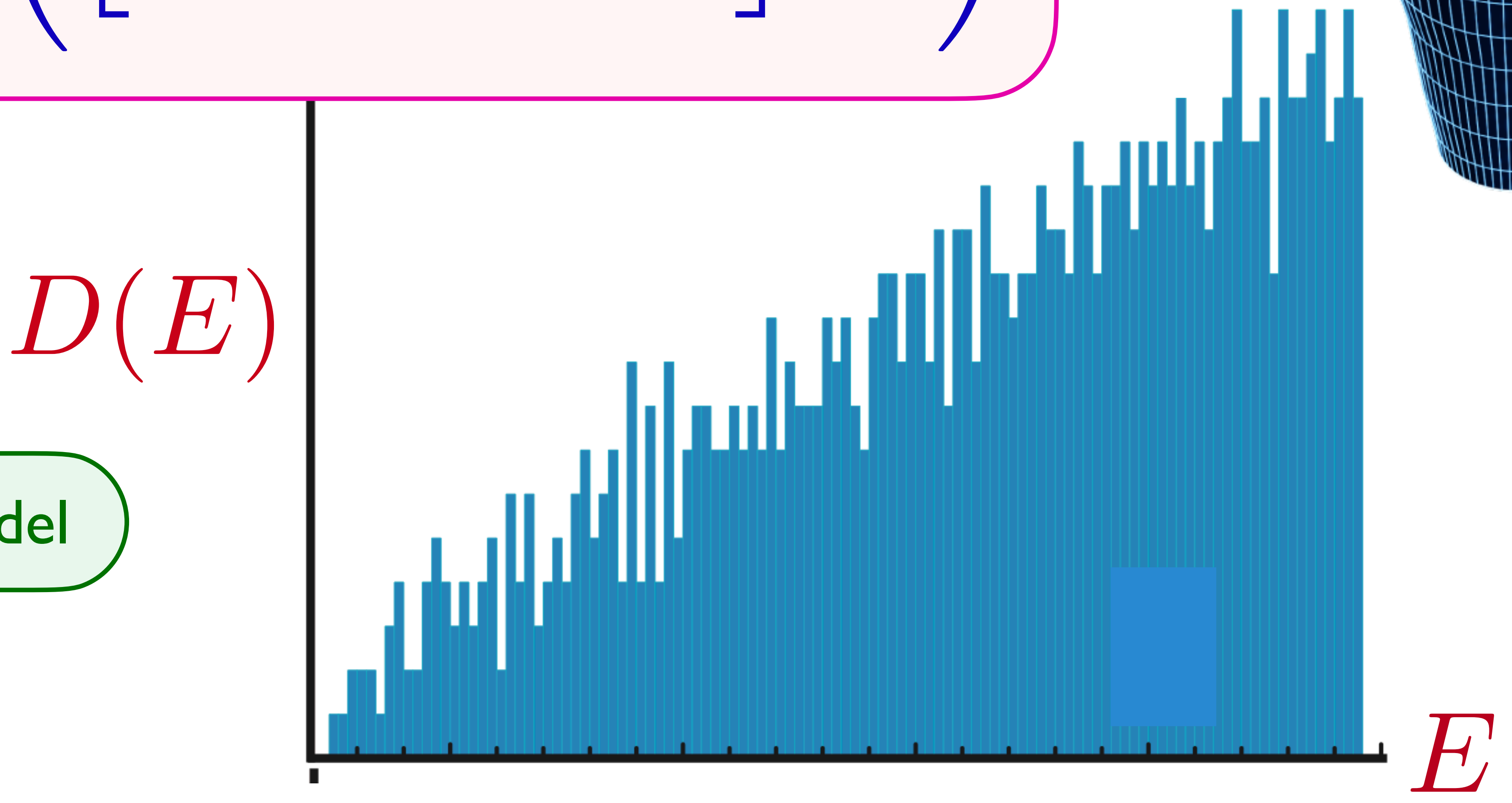
- For generic charged black holes in 3+1 dimensions with horizon area A at $T = 0$ and fixed charge $\mathcal{Q}$ ($A = 2G\mathcal{Q}^2/c^4$), the density of quantum states at small energy E is

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

Bekenstein-Hawking

Iliesiu, Murthy, Turiaci (2022)

Developments from the SYK model



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

Recap

Great discoveries in physics

Entropy (1870)

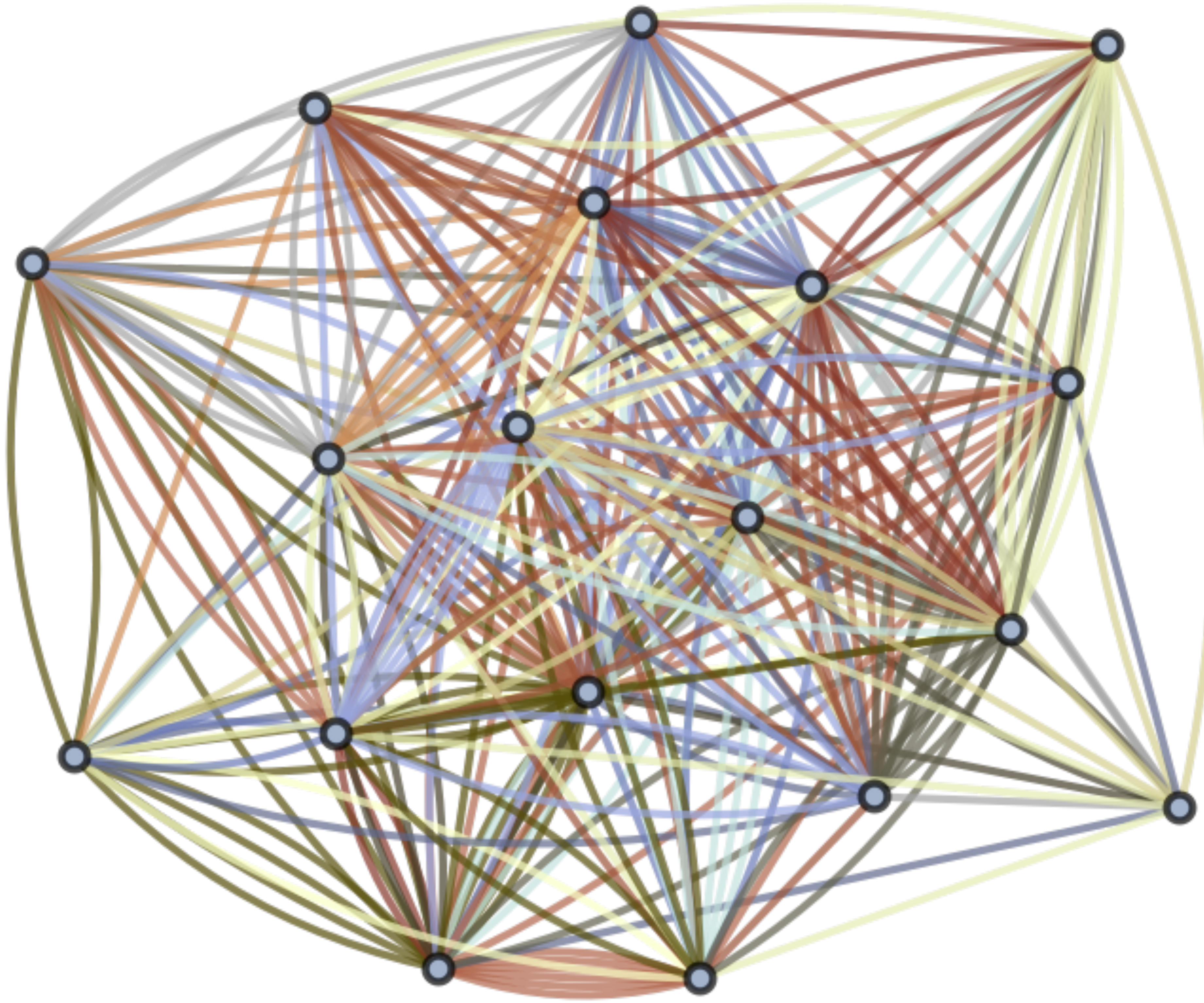
Superconductivity (1911)

Black holes (1916)

Quantum entanglement (1935)

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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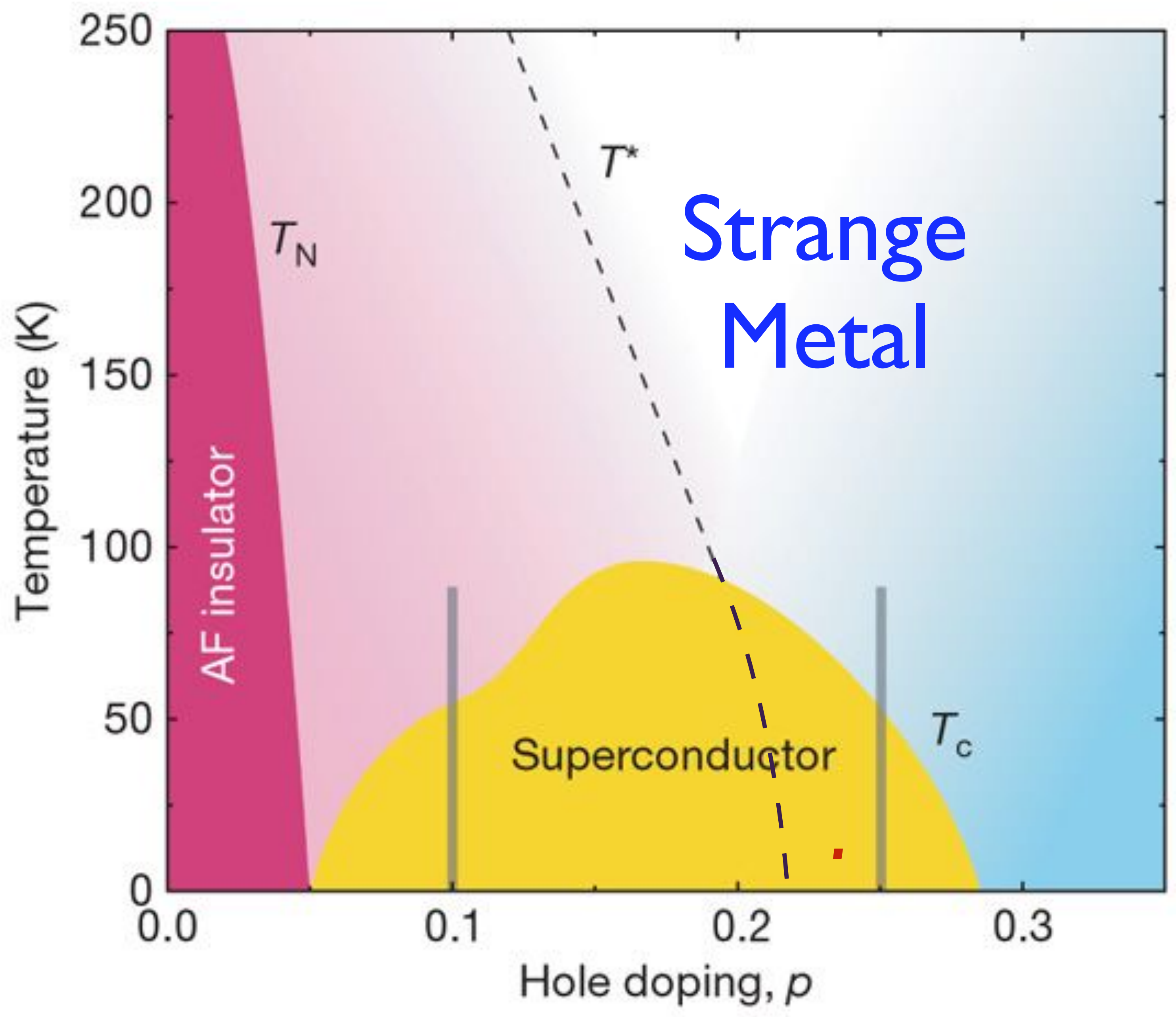
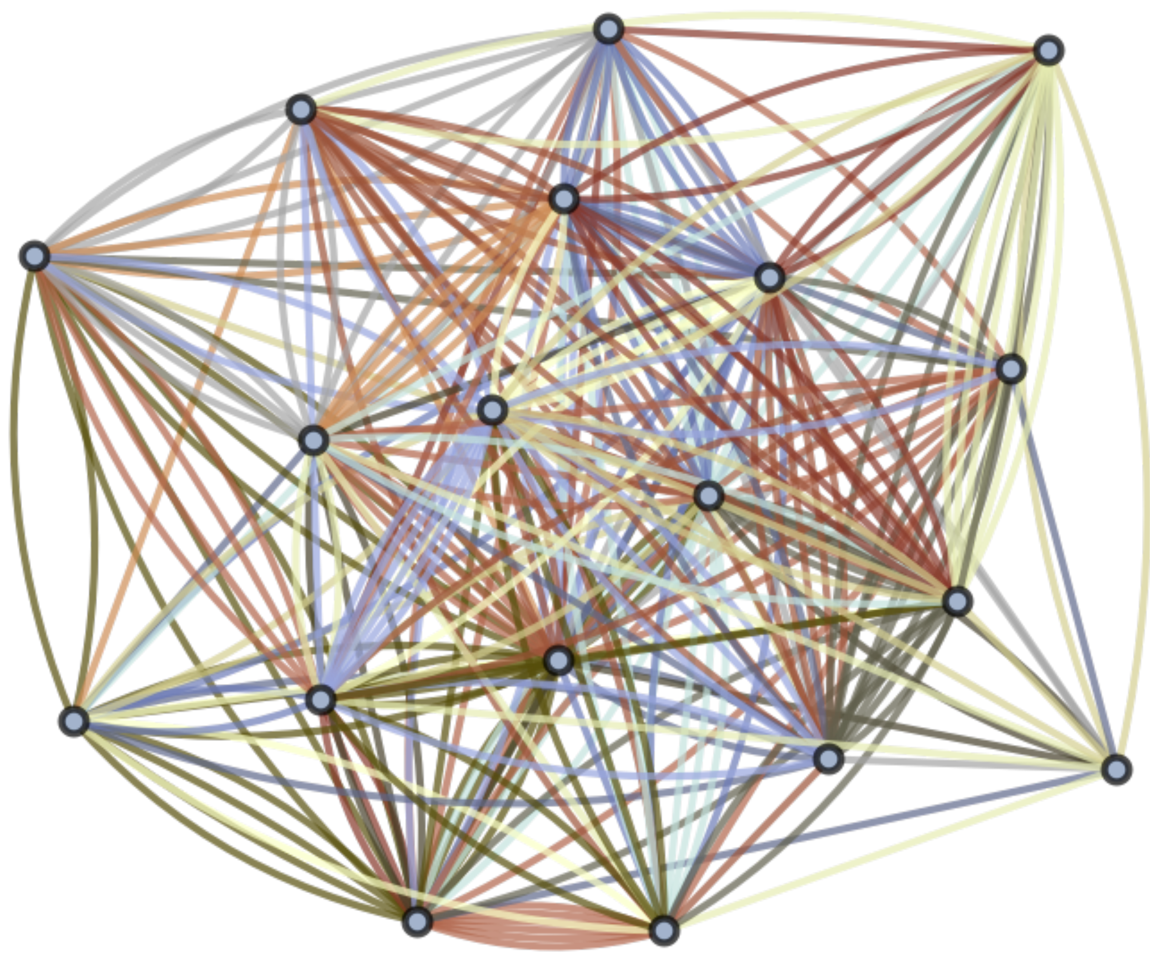


In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)



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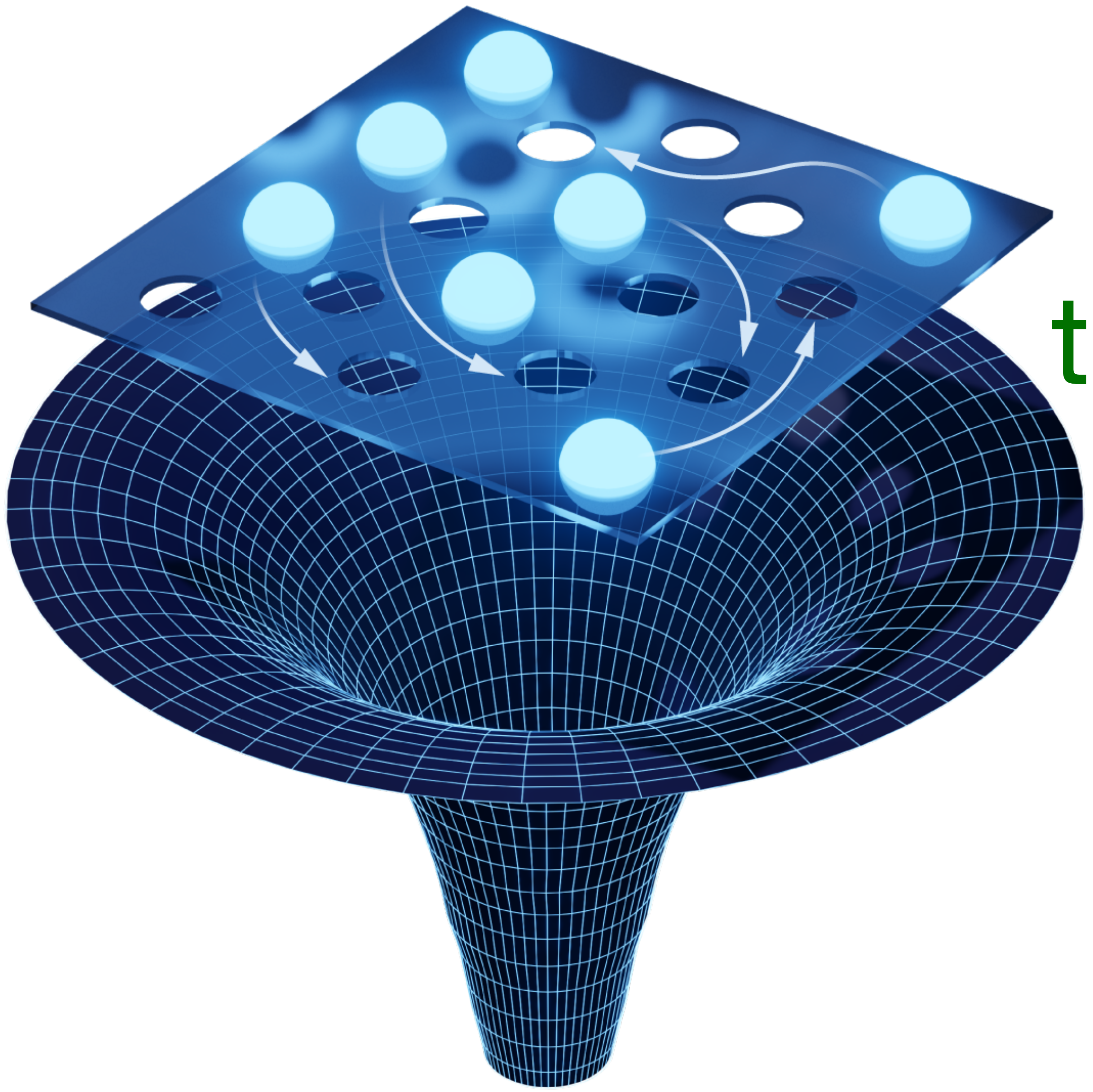

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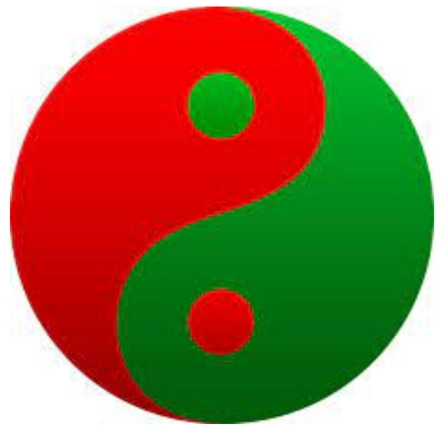

In a *dual* set of variables it describes the interior of ***charged black holes***

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