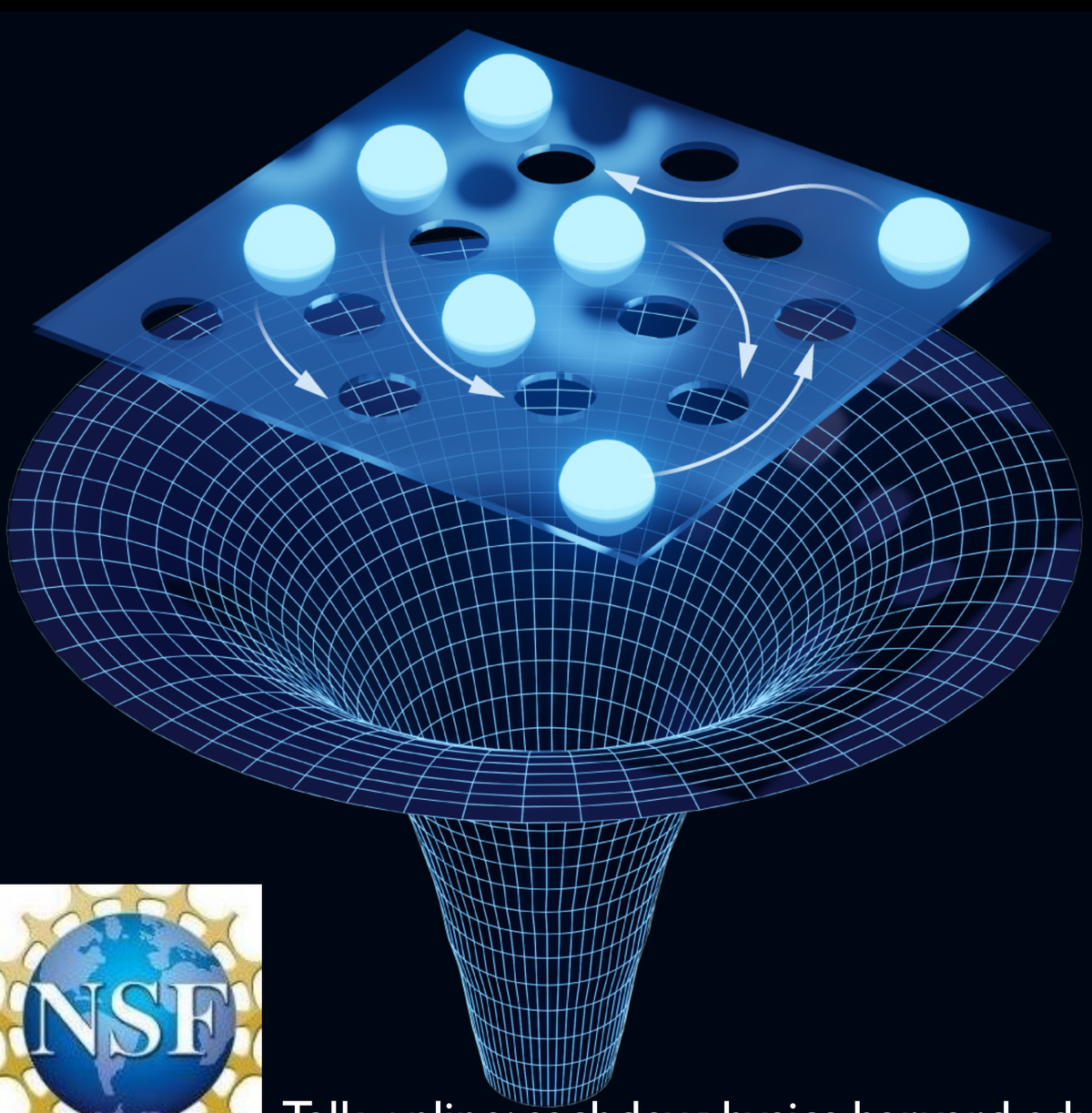
Quantum entanglement in nature:

superconductors and black holes



Institute Lecture
Indian Institute of Technology
Delhi
January 3, 2024

Subir Sachdev

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 ? (1870)

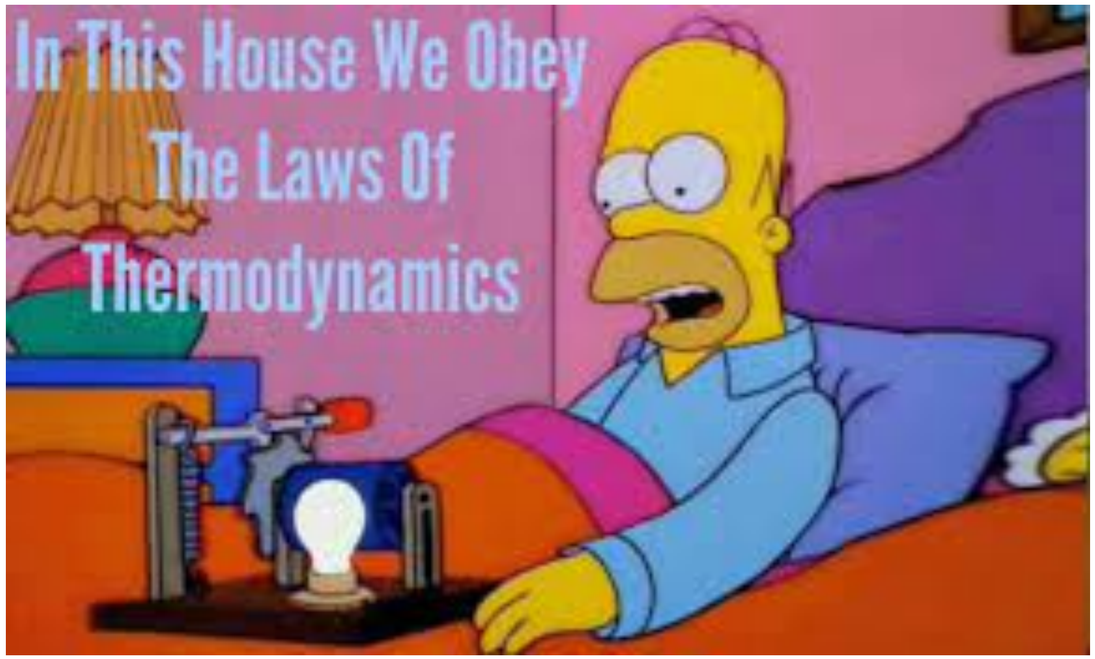
Clausius (1865):

Second Law of Thermodynamics:

Every macroscopic system has an

“entropy” which cannot decrease.

➡ No perpetual motion machines!



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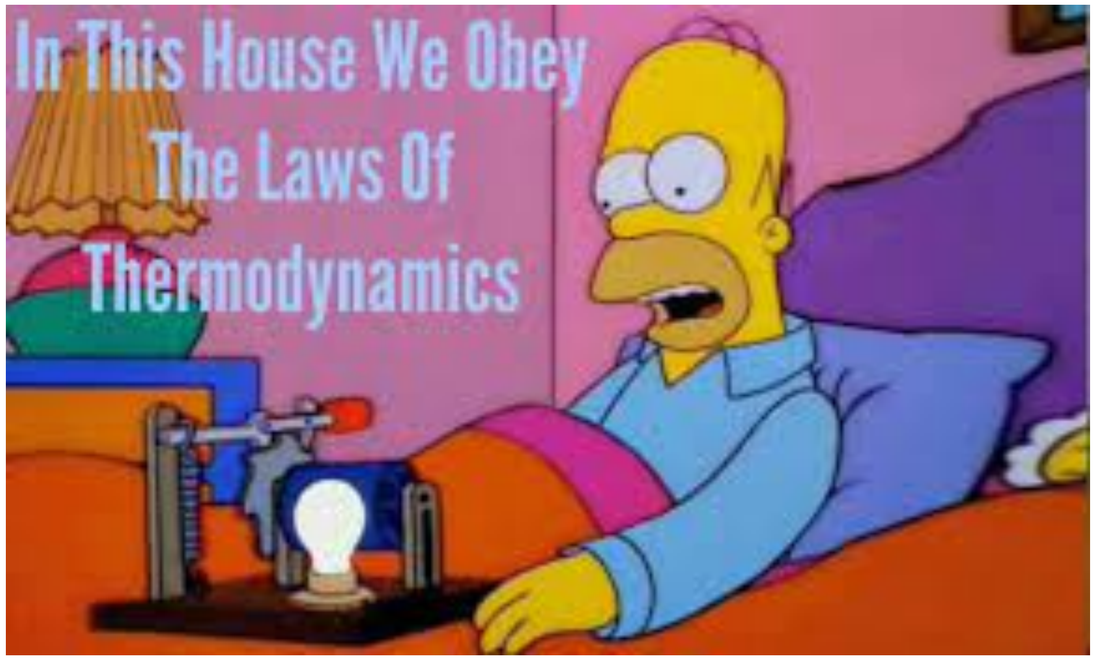

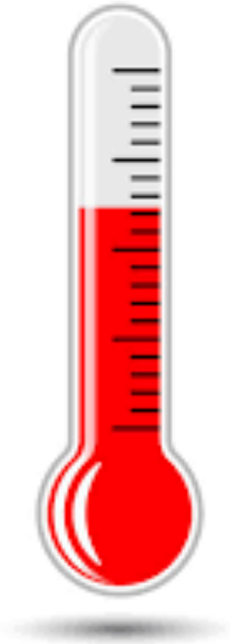

Temperature

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

Statistical interpretation of entropy (1870)

$$S = k_B \log W$$

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

$$S = k_B \log W$$

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

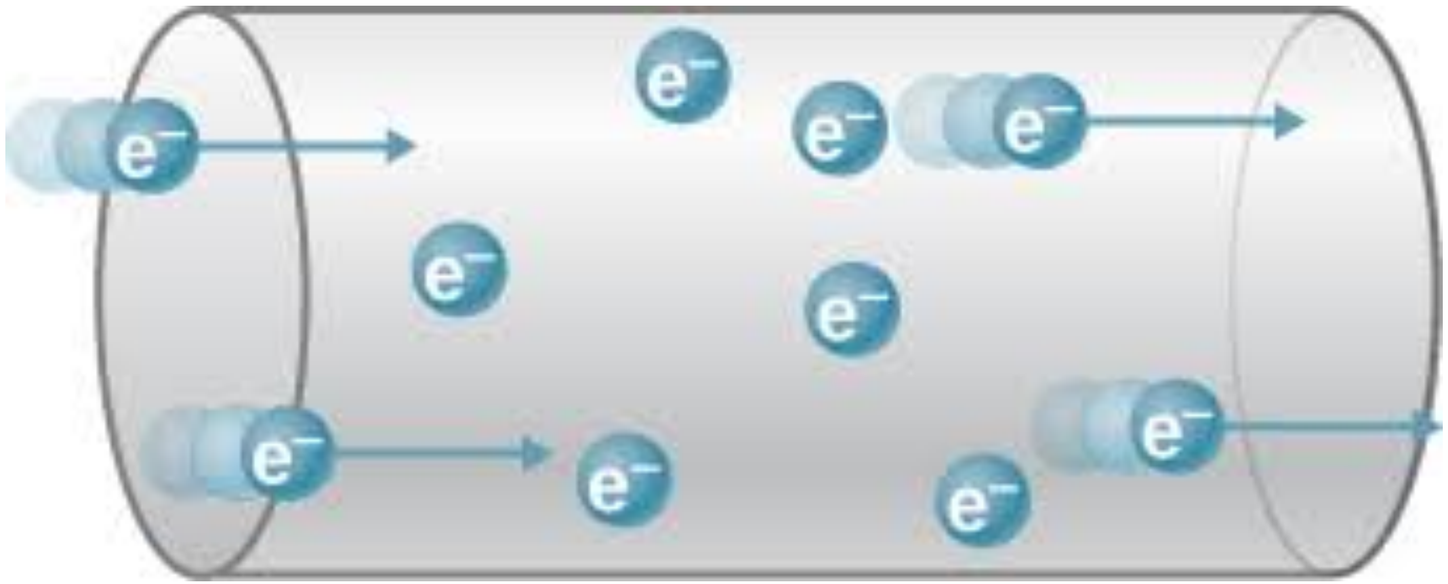
Ordinary conductors (metals) and superconductors (1911- today)

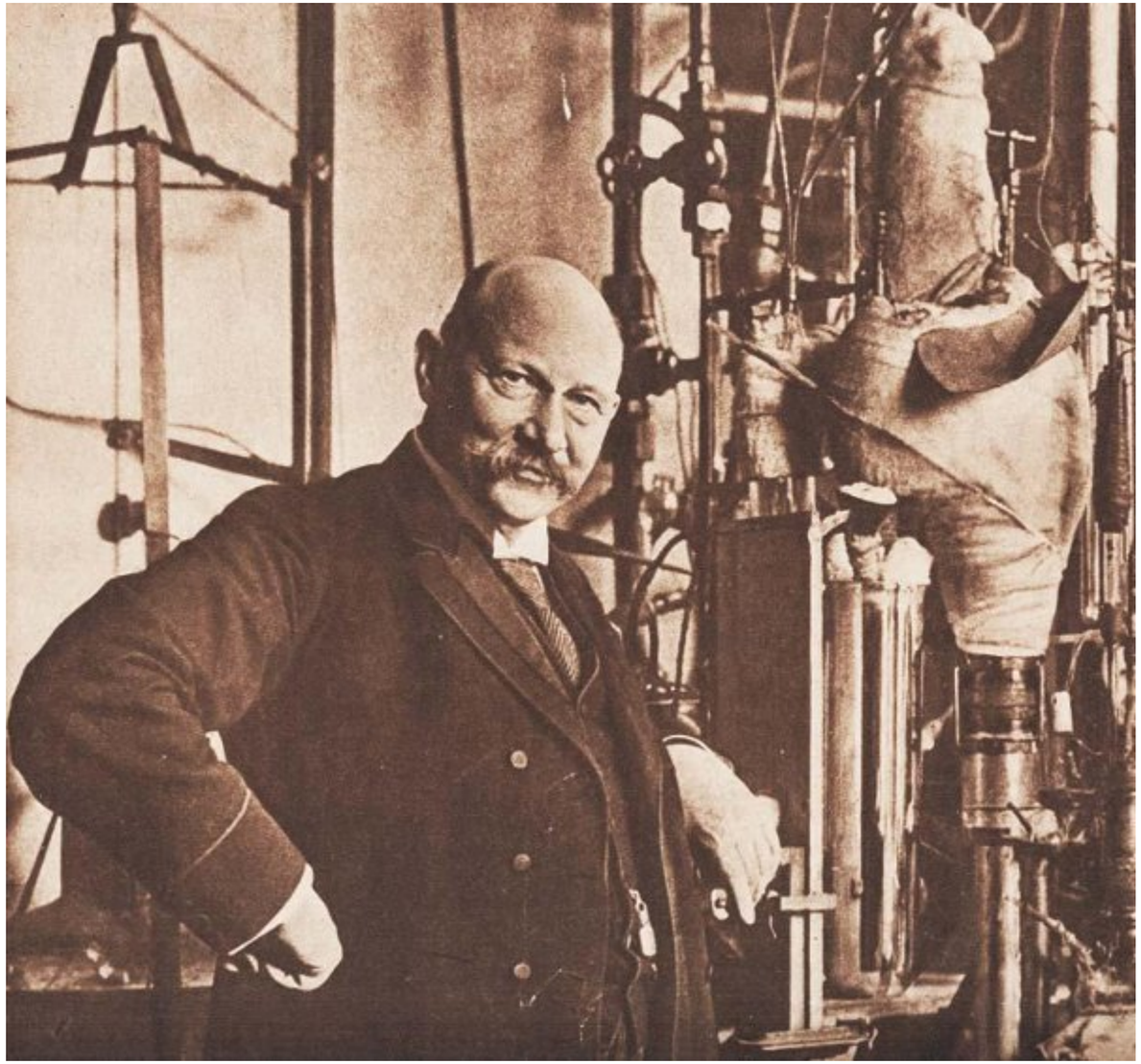
CONDUCTOR

SEMICONDUCTOR

SUPERCONDUCTOR

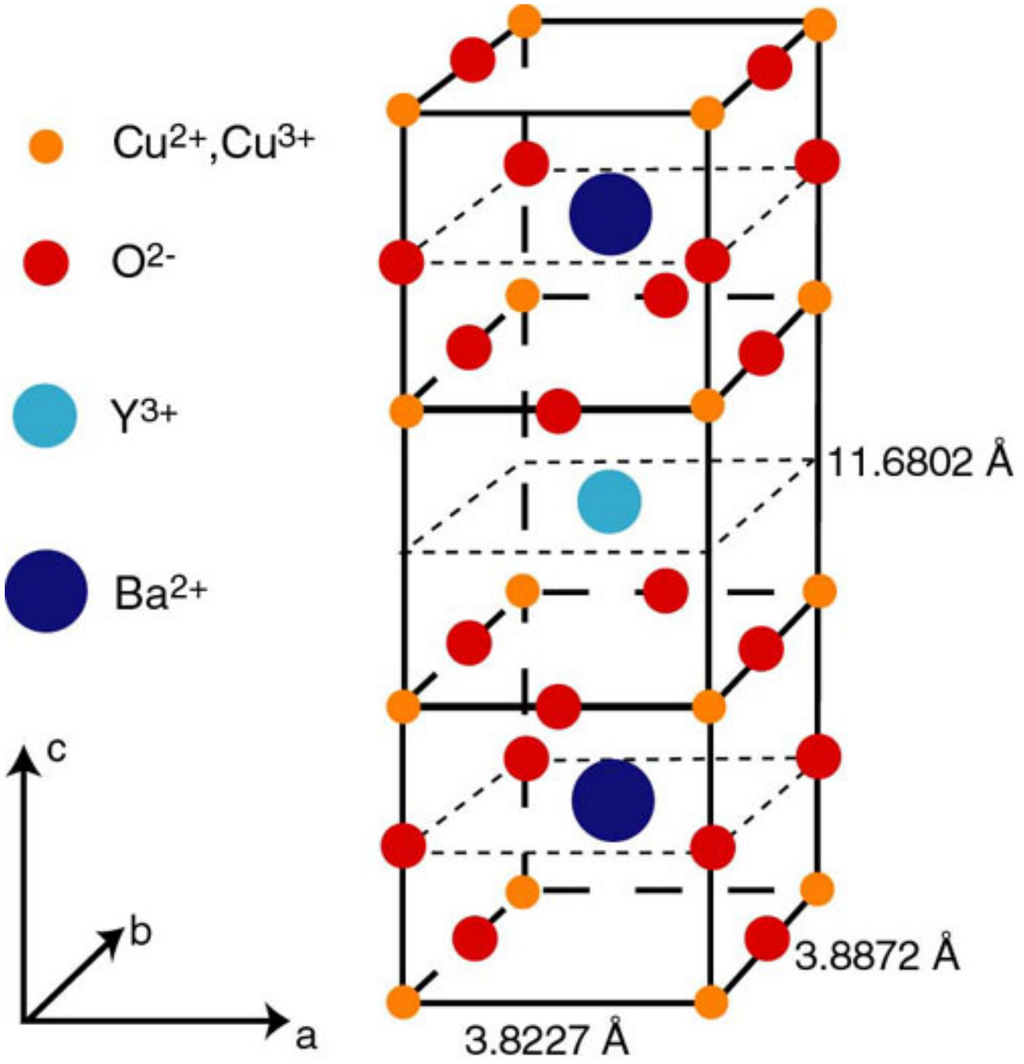
Copper: ordinary metal quantum matter



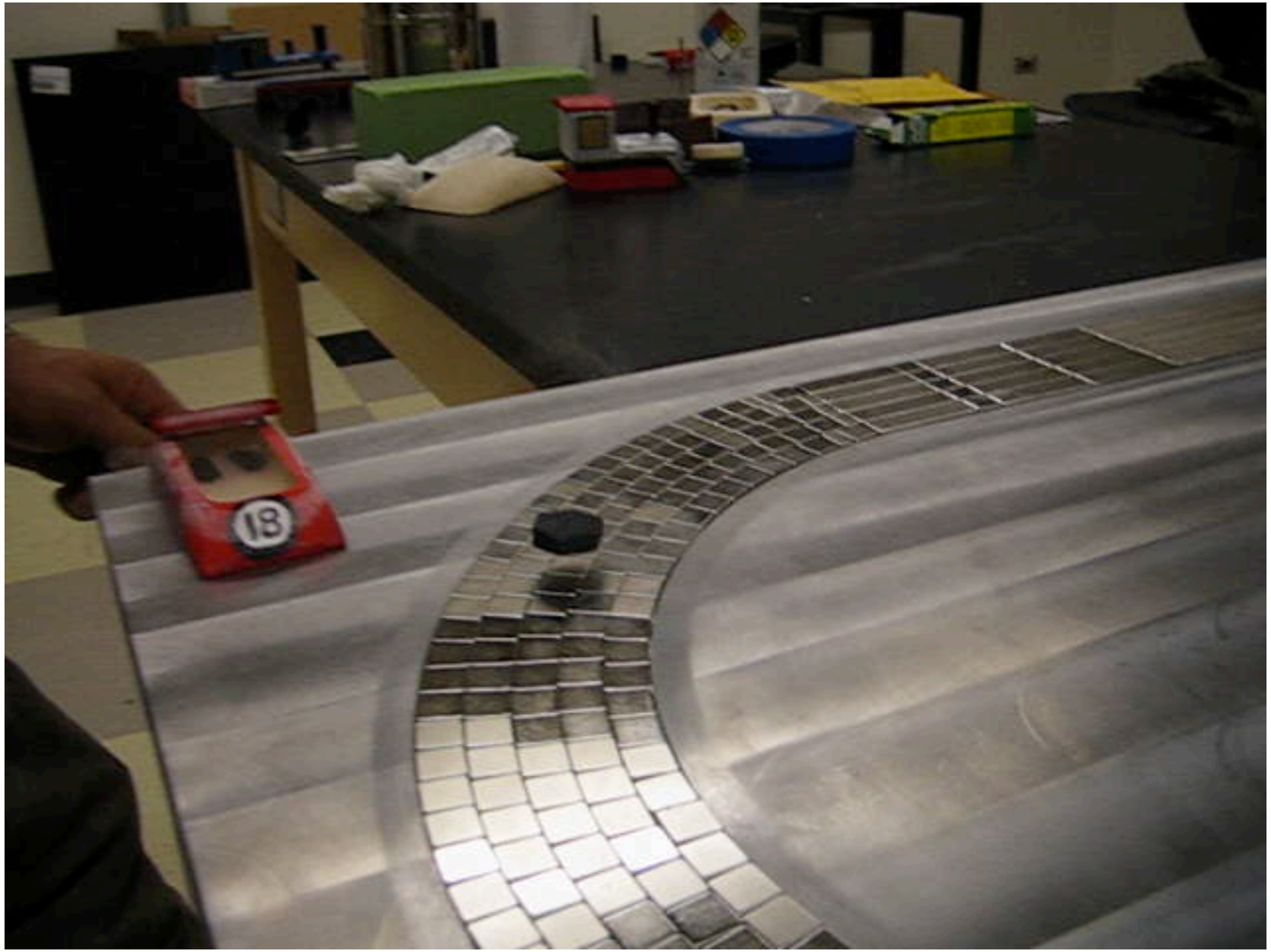


Kamerlingh Onnes 1911:
Mercury is a superconductor below -269 °C

Cuprate high temperature superconductors



$YBa_2Cu_3O_{6+x}$



Nd-Fe-B magnets, YBaCuO superconductor

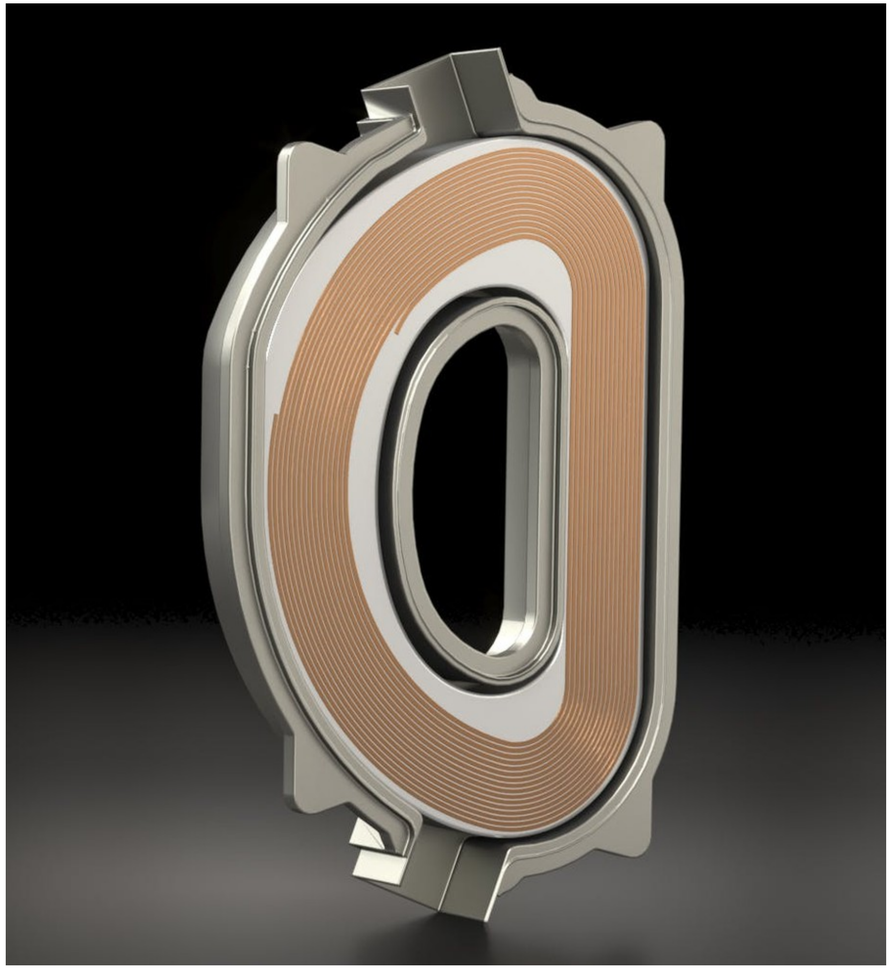
Julian Hetel and Nandini Trivedi, Ohio State University

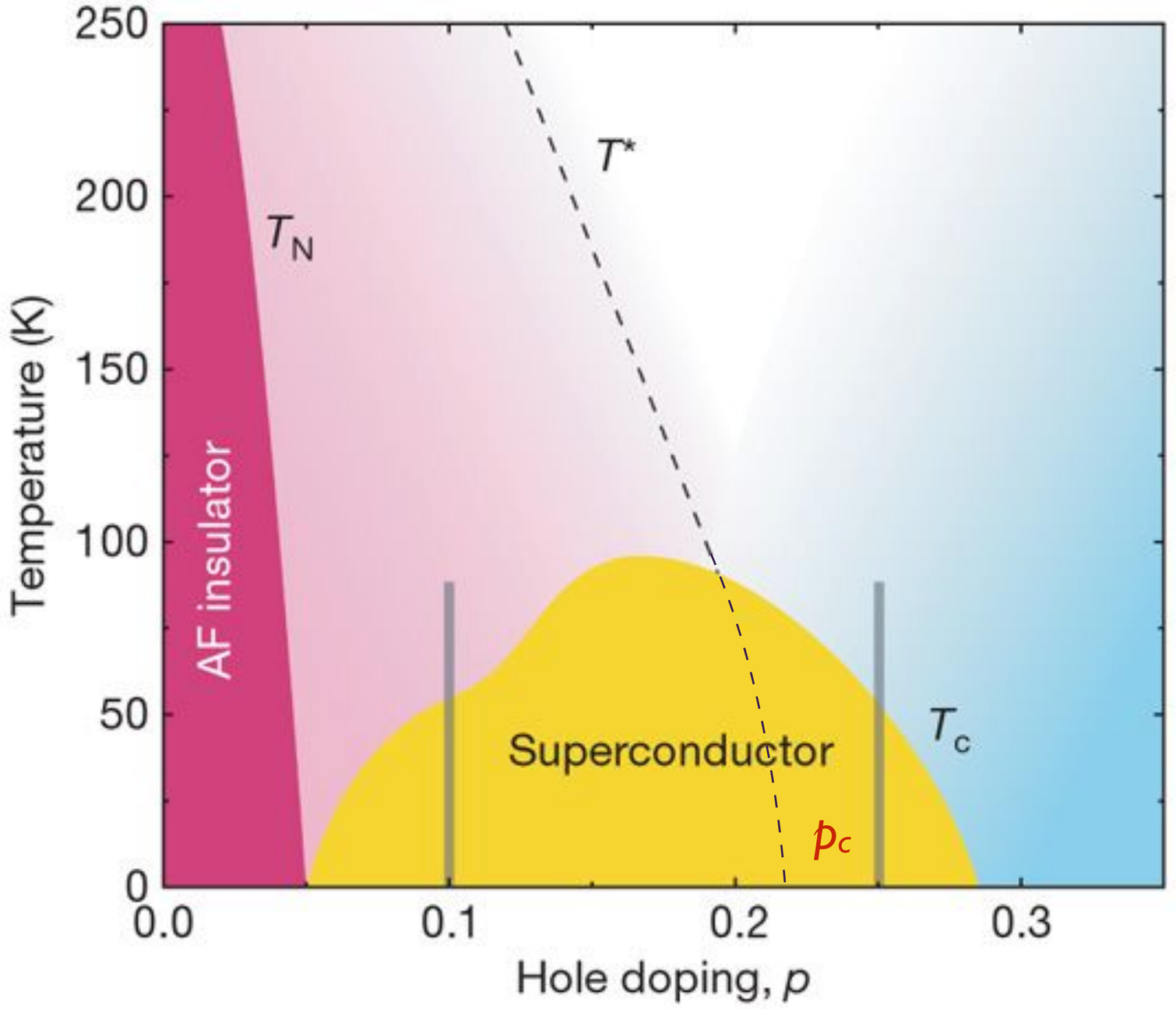
HTS Magnets: Enabling Technology

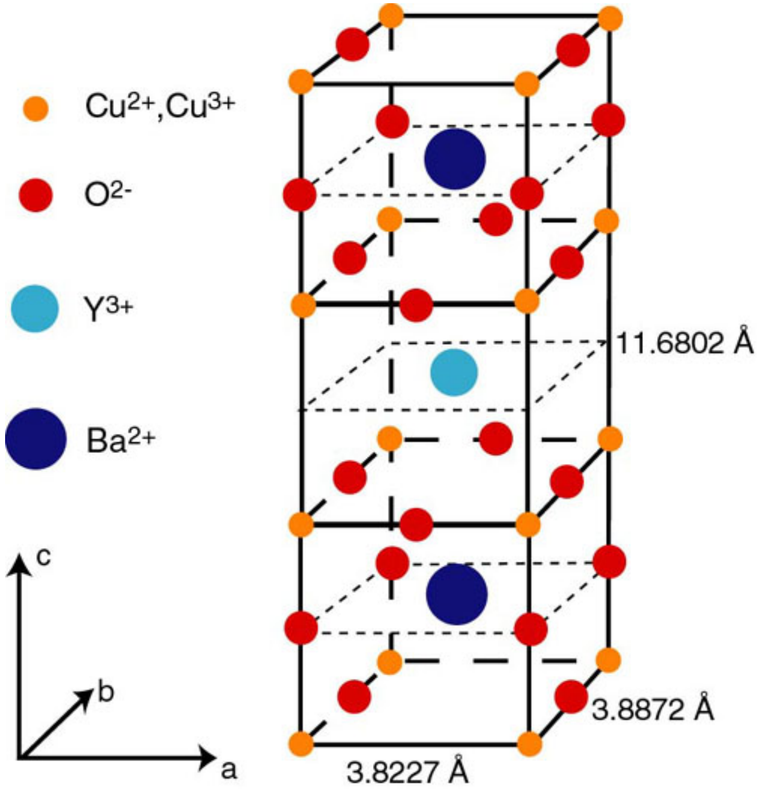
The surest path to limitless, clean, fusion energy

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

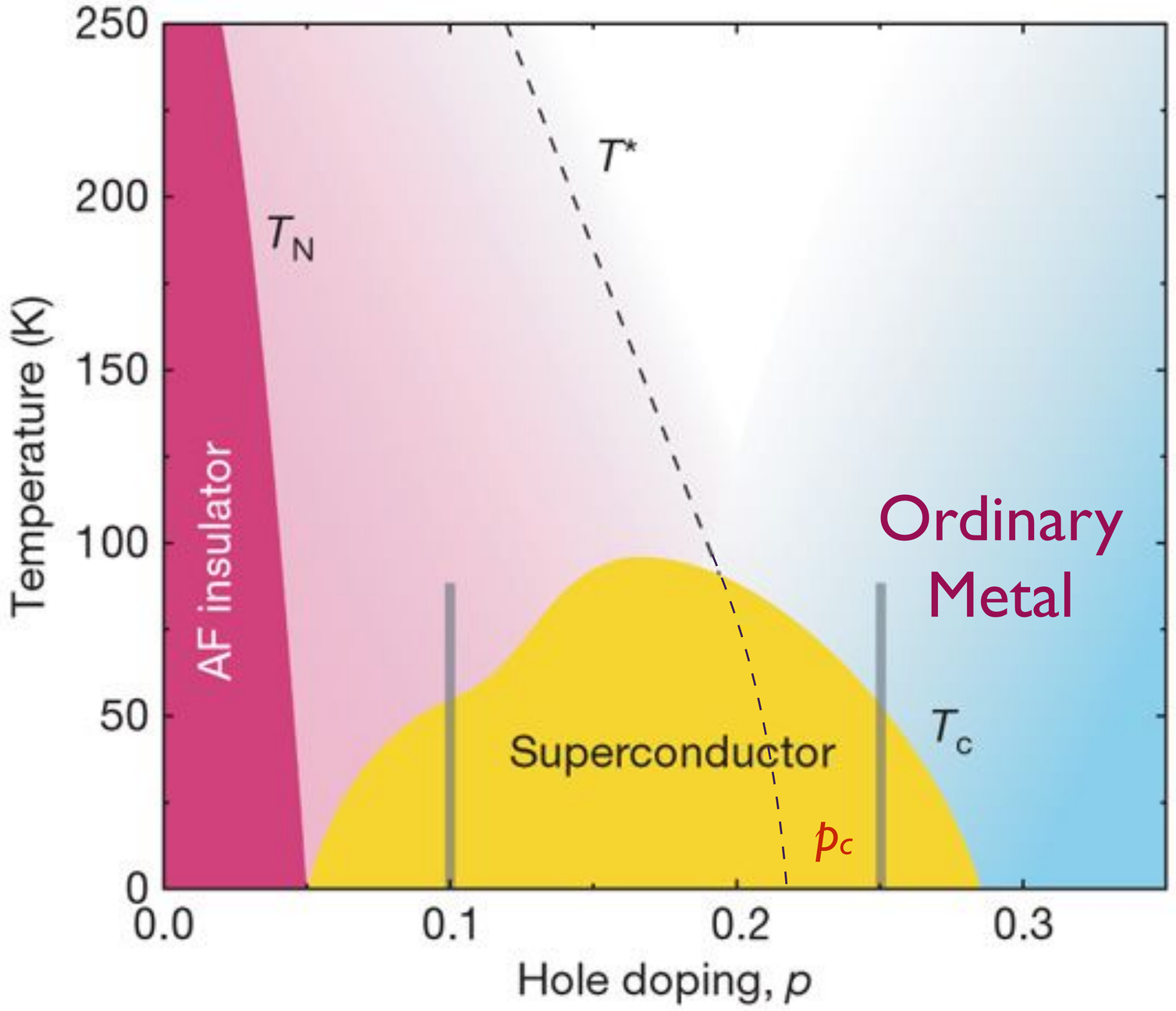
Commonwealth Fusion Systems




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


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

$YBa_2Cu_3O_{6+x}$


250
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T_N
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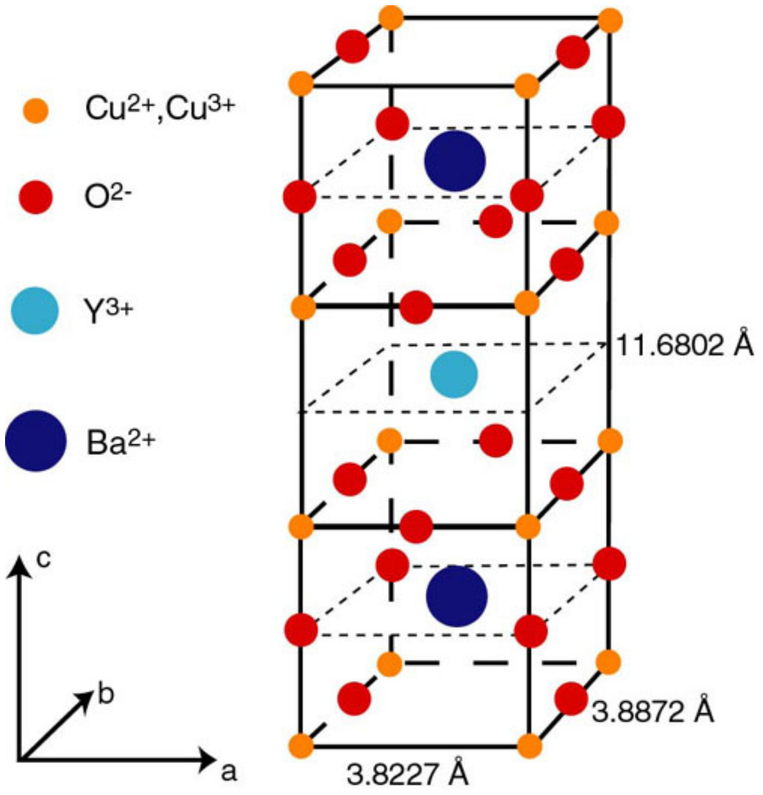
Ordinary
Metal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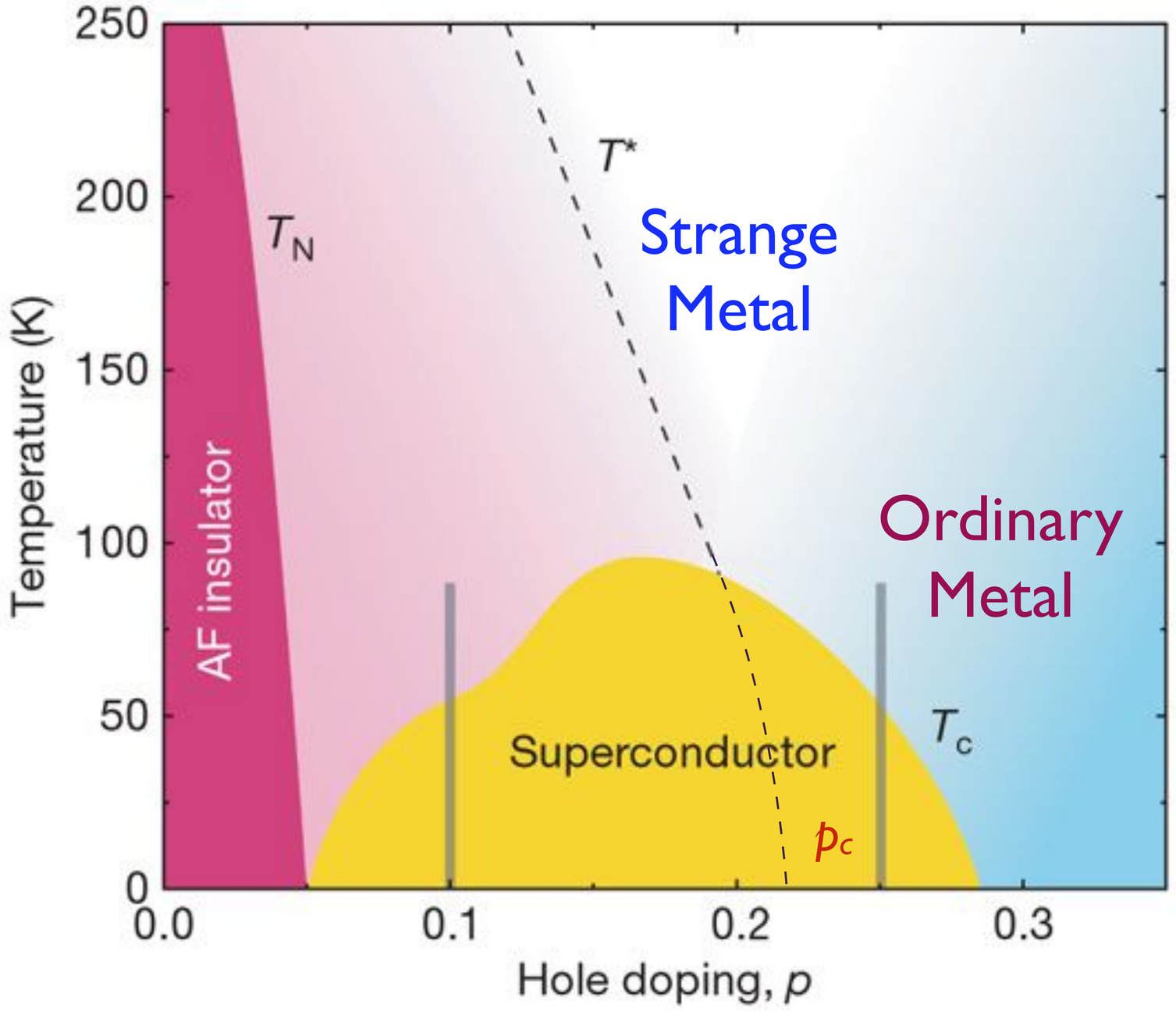
250
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Temperature (K)
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Hole doping, p
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AF insulator
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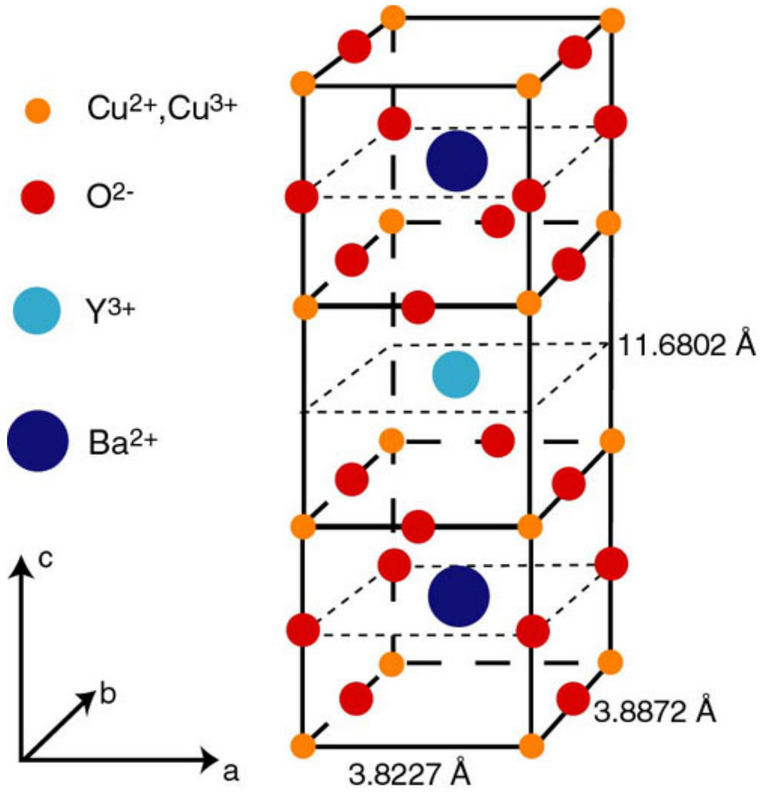
Cu^{2+},Cu^{3+}
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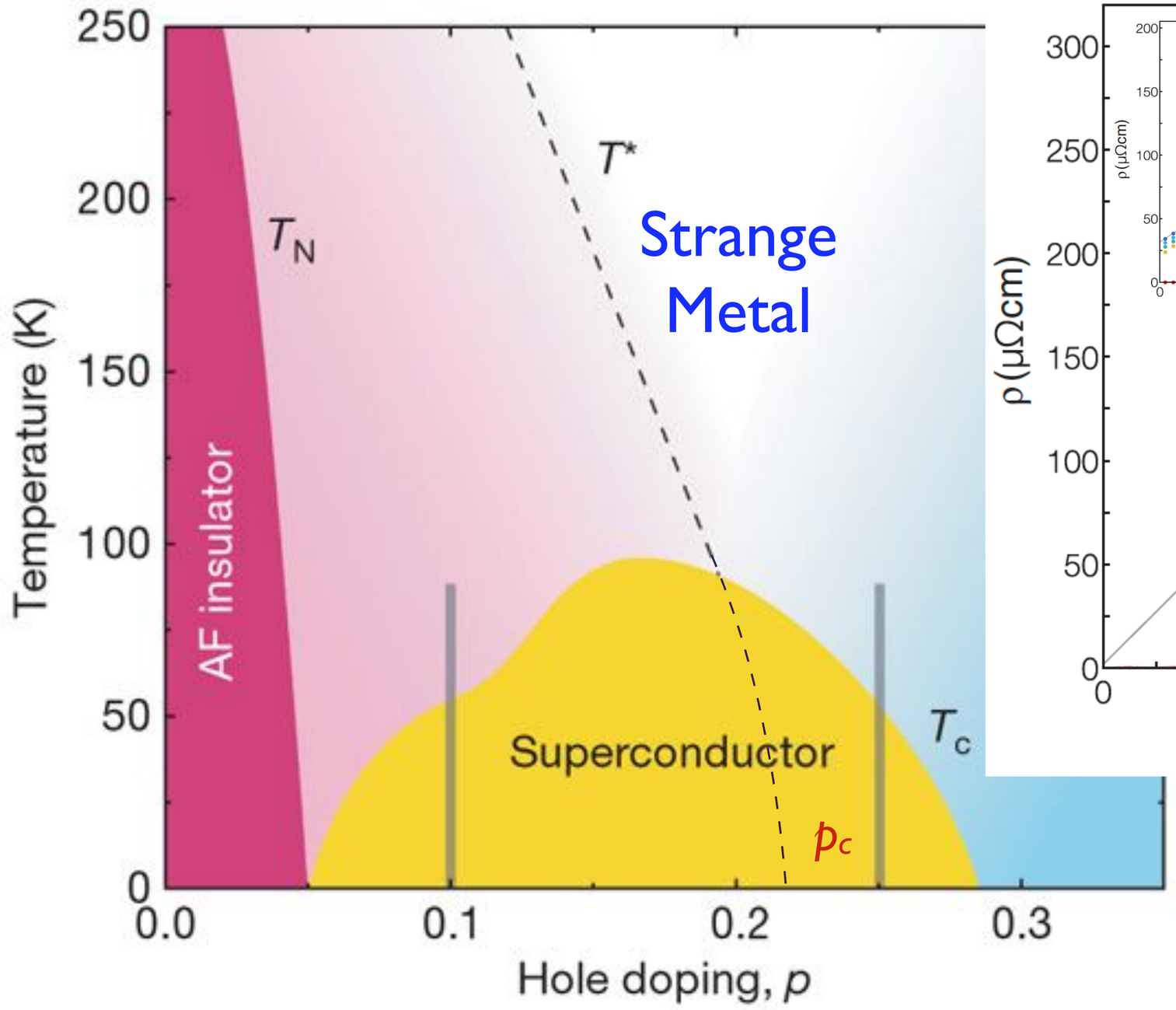
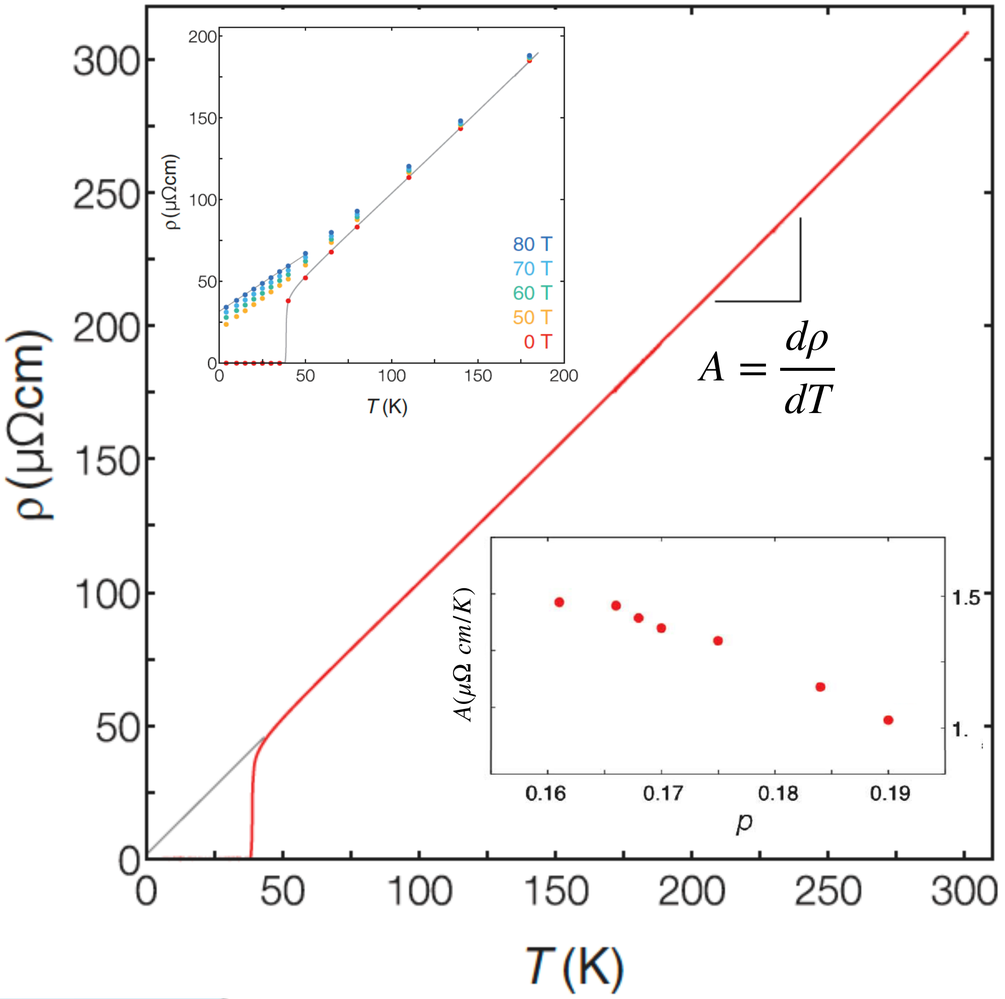


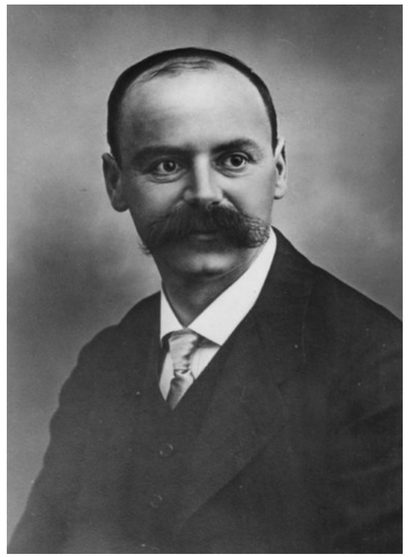


LSCO: Giraldo-Gallo et al. 2018

Black holes (1916-today)

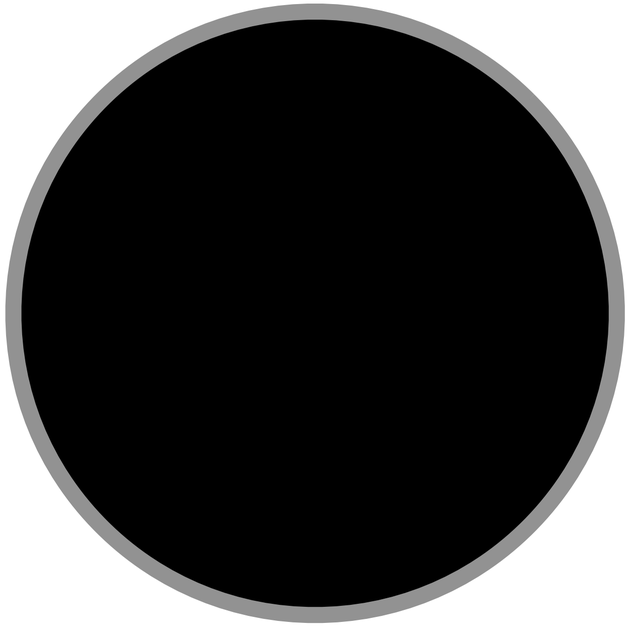
Black Holes

Objects so dense that light is gravitationally bound to them.



Karl Schwarzschild (1916)

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

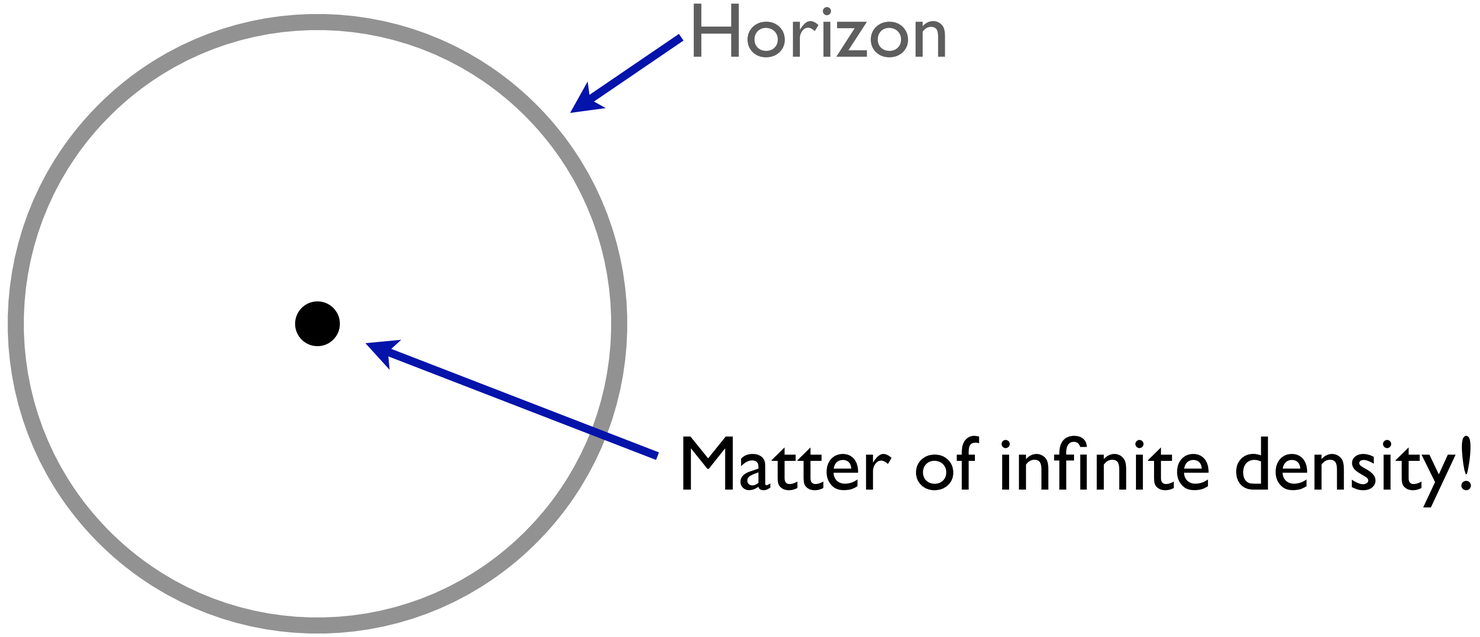


G Newton's constant, c velocity of light, M mass of black hole

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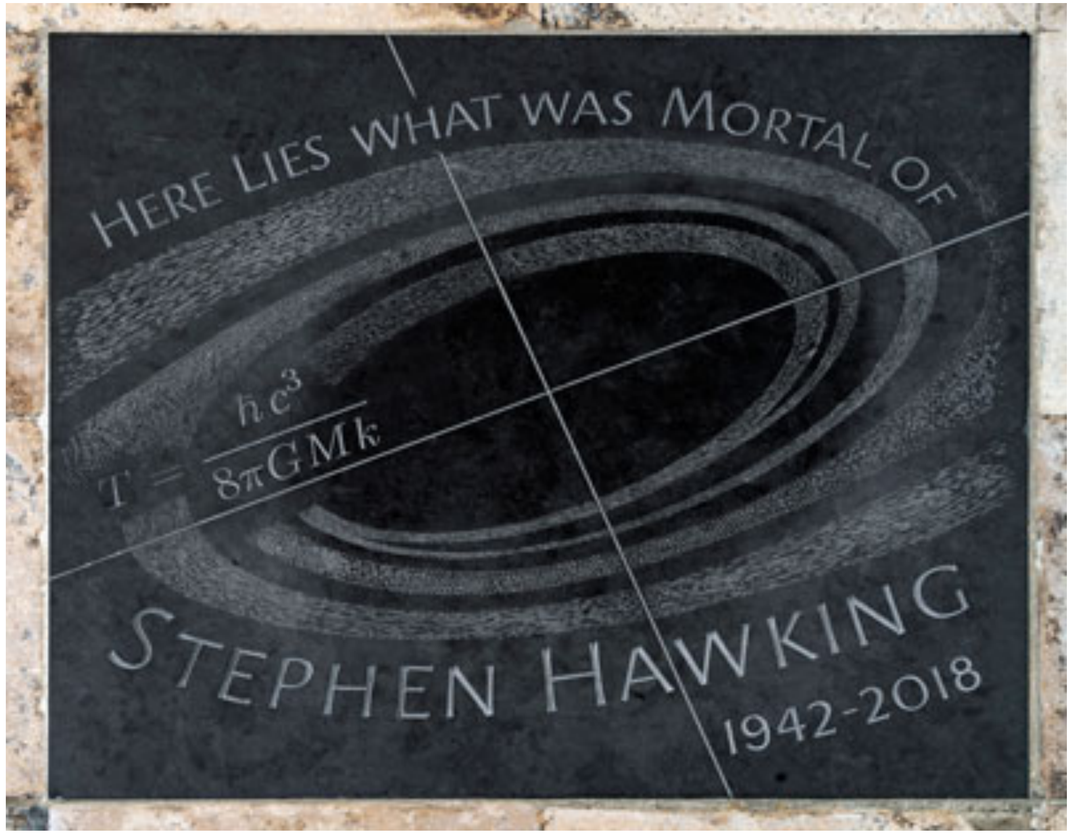
This singularity convinced many early on that black holes were unphysical solutions of Einstein's equations, and did not exist in our universe.

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

What is inside a black hole ???

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



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

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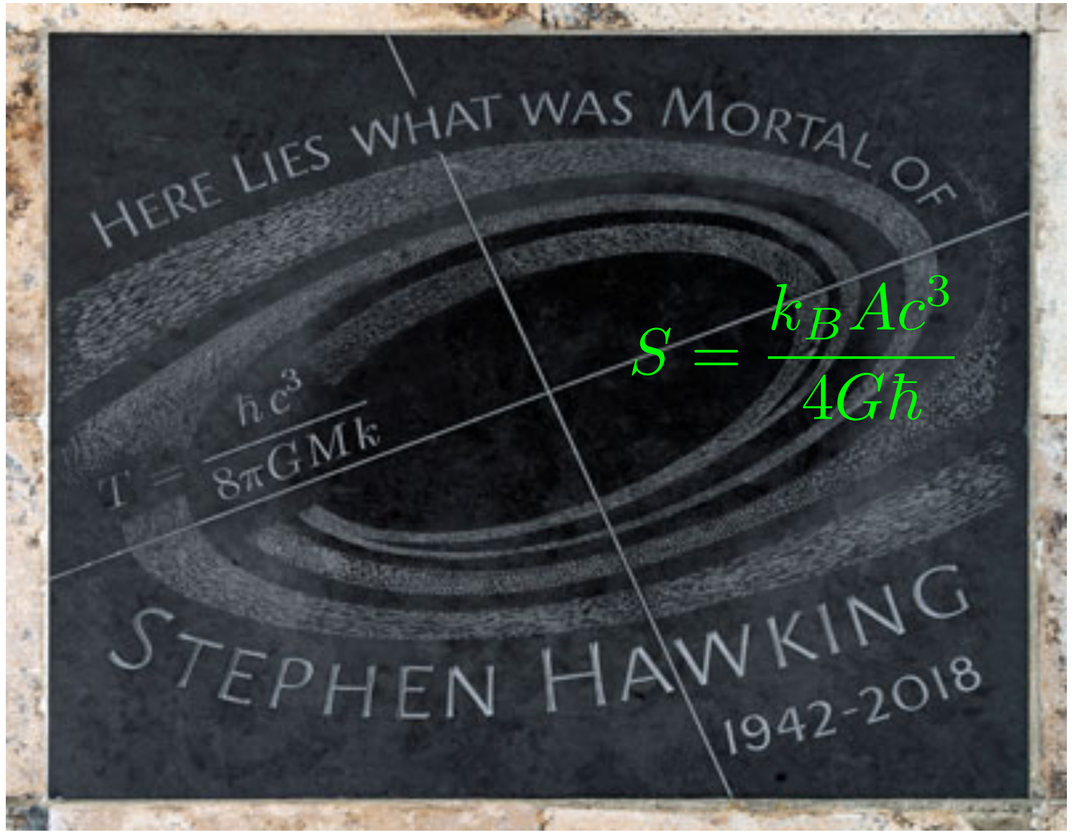


$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

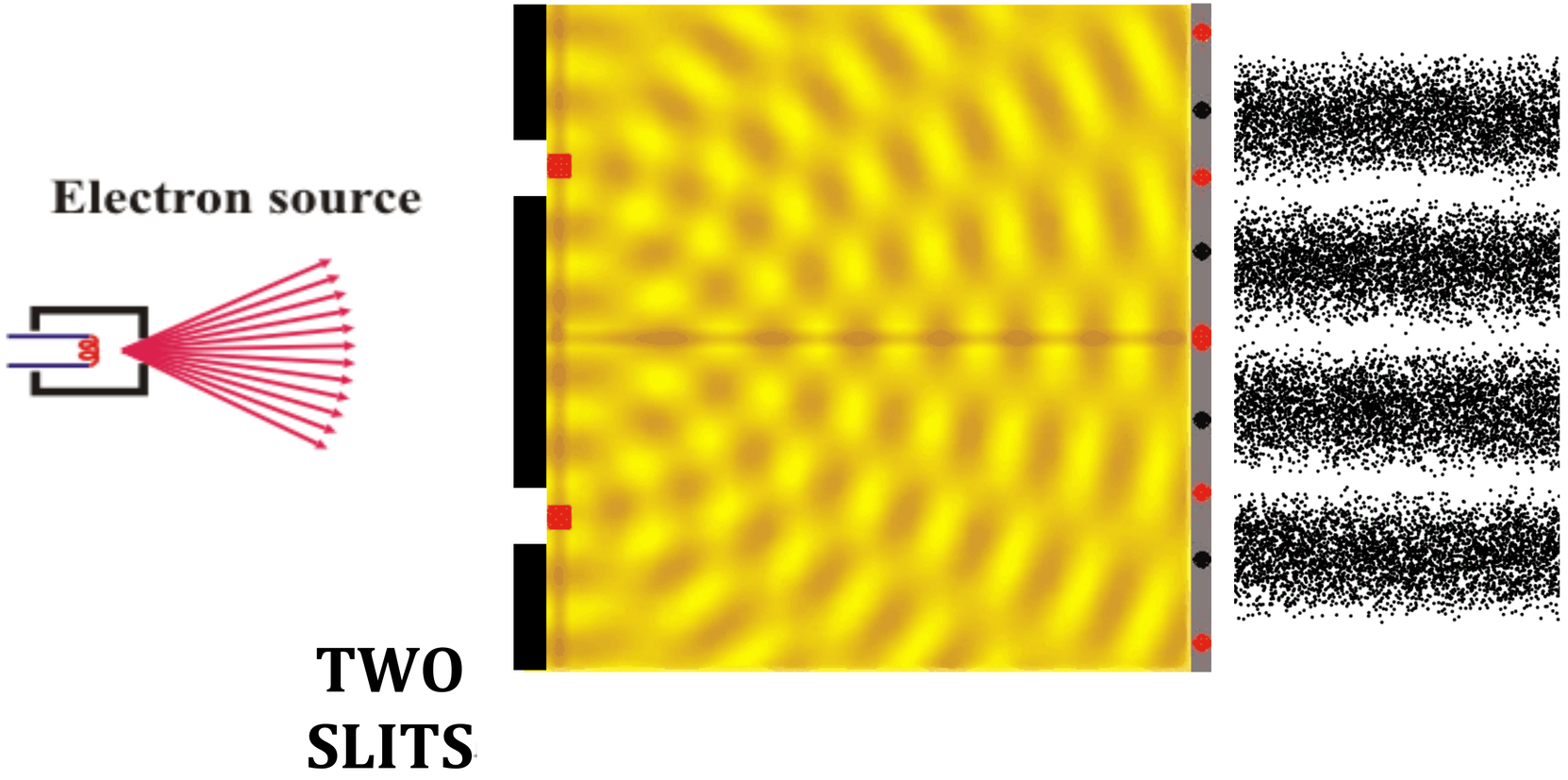
$$S = \frac{k_B A c^3}{4G\hbar}$$

What is quantum entanglement? (1935-2015)

"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.

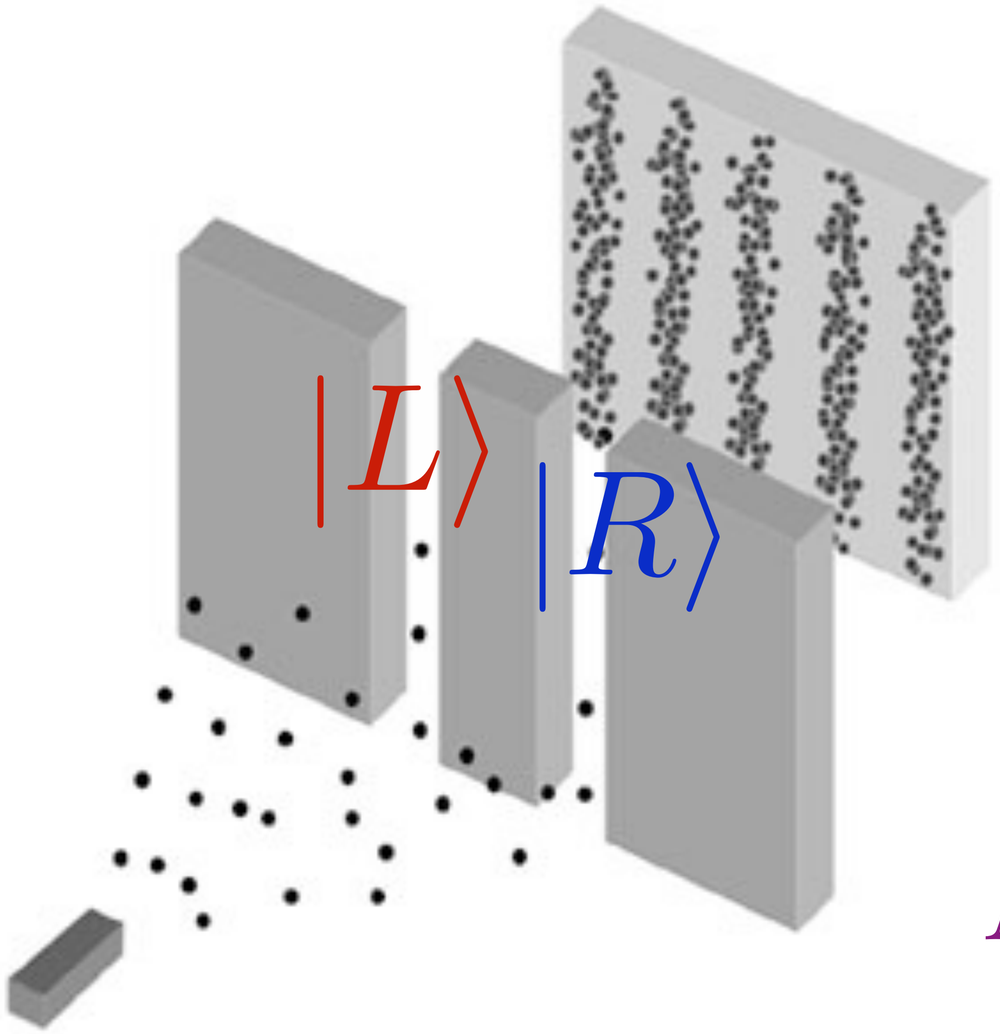
The double slit experiment



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

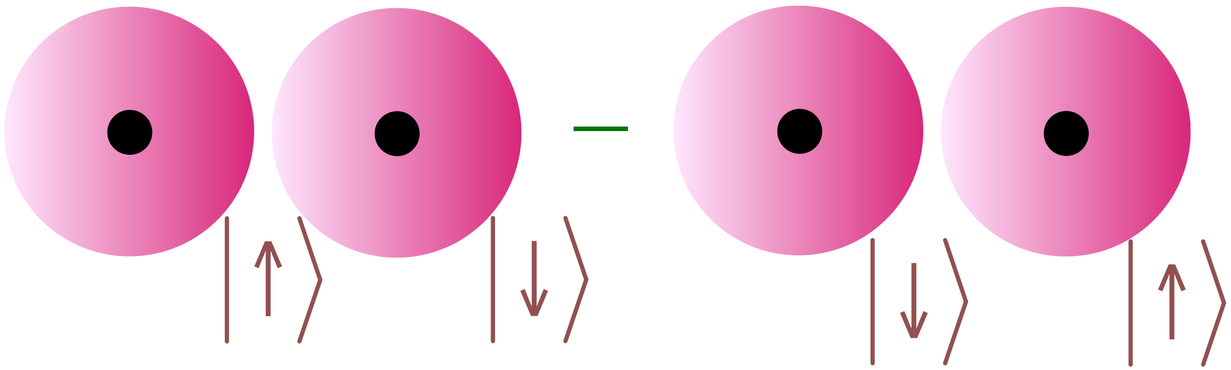
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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

(Received March 25, 1935)

Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



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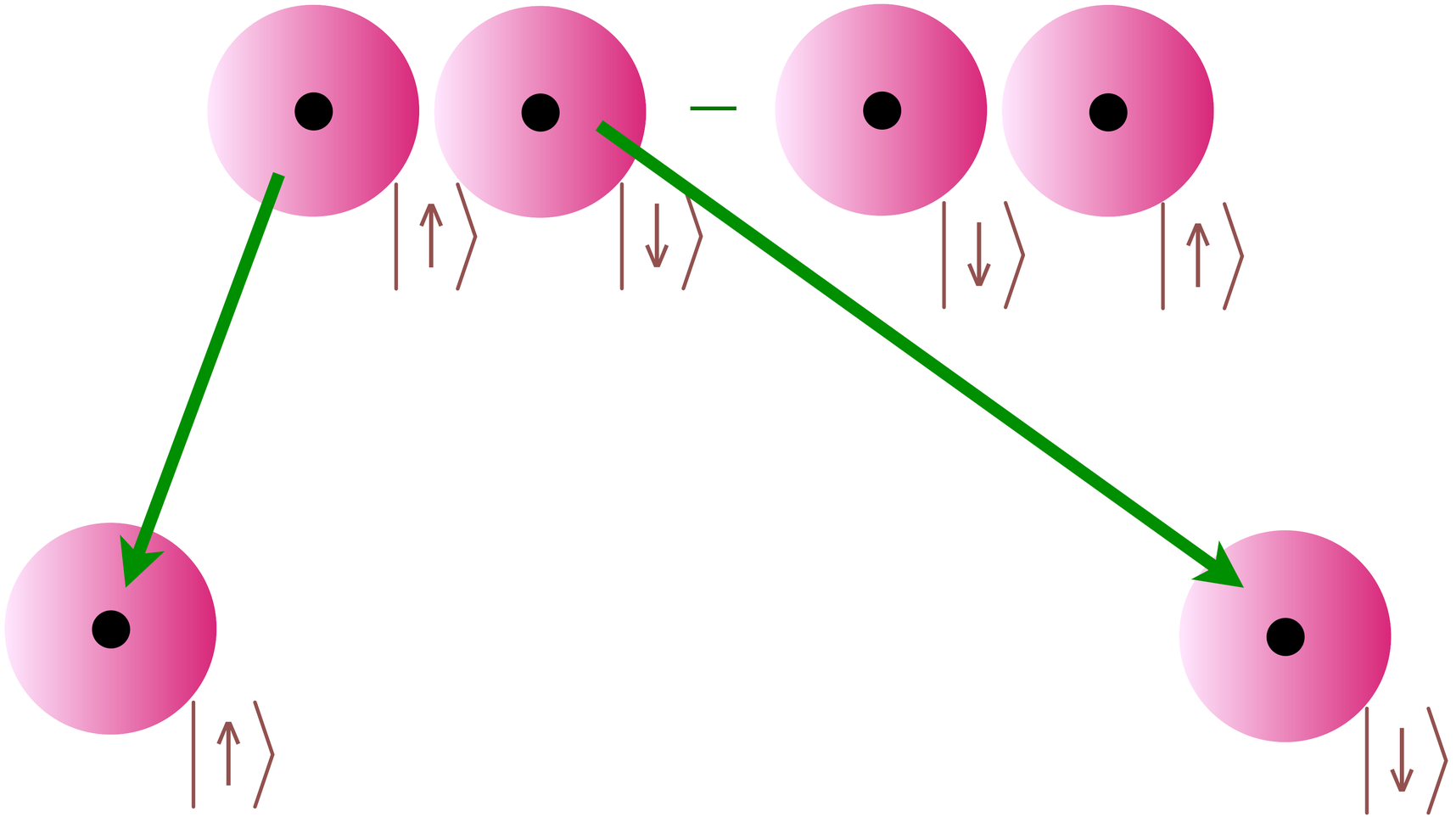

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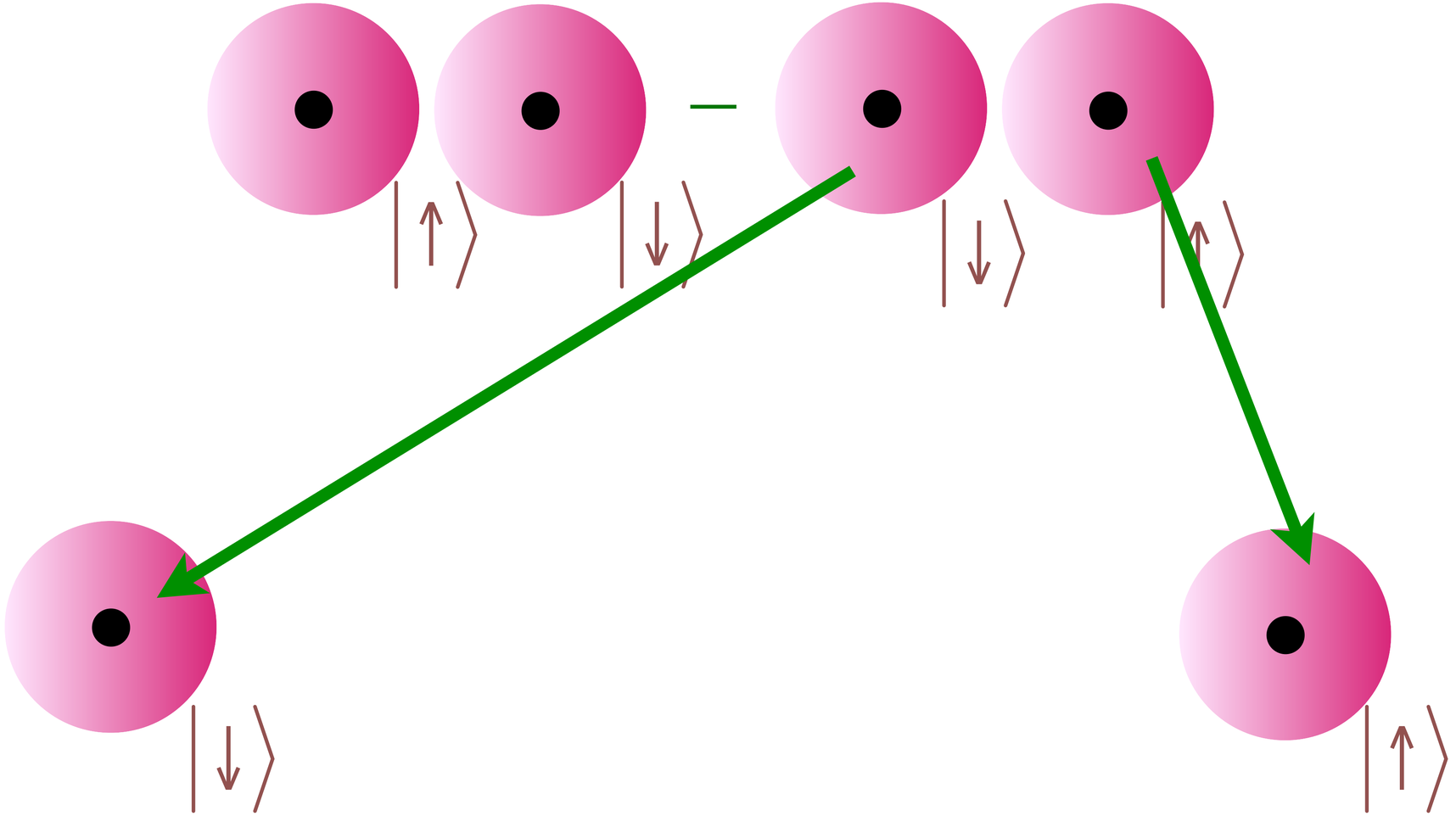

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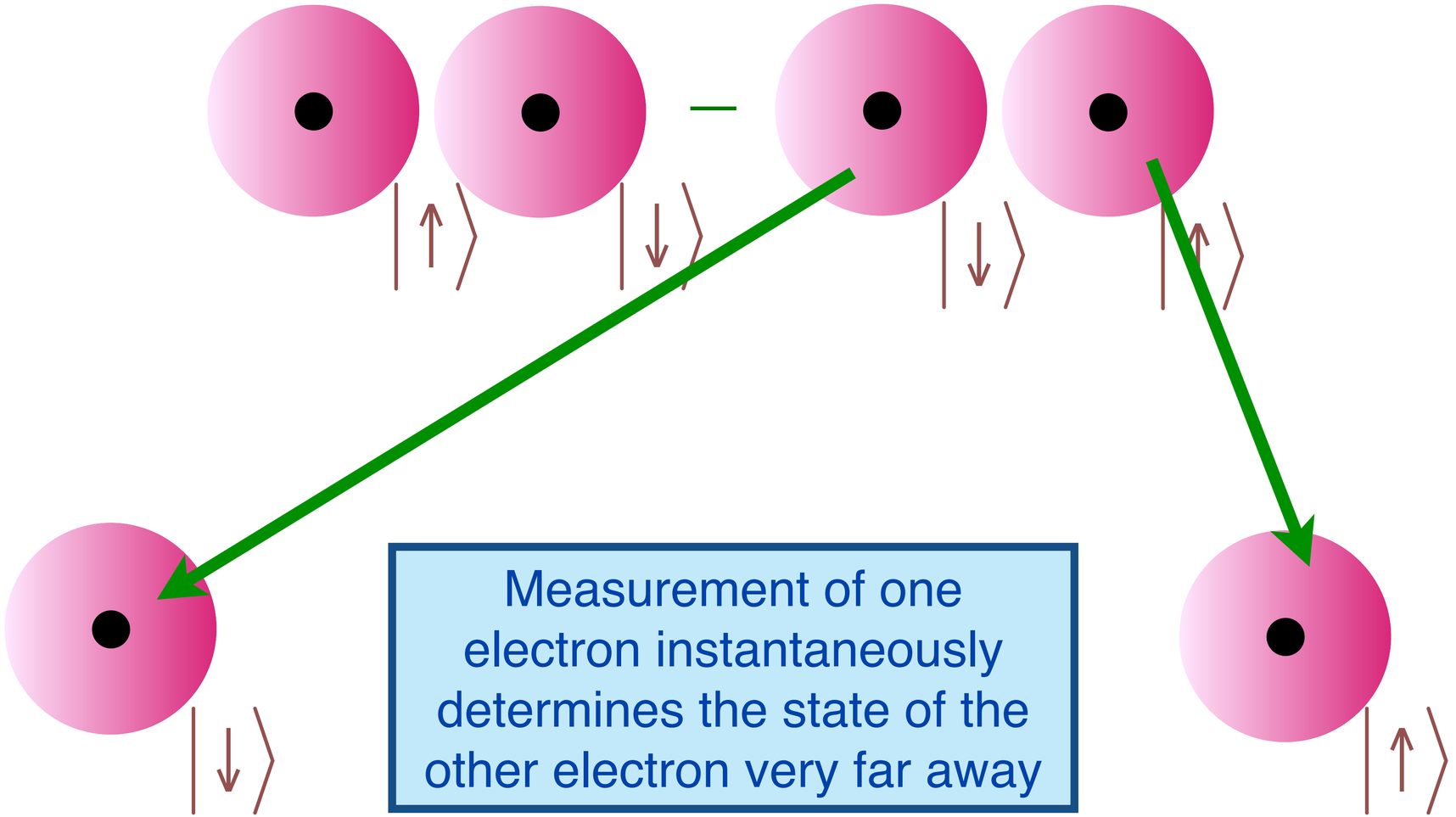

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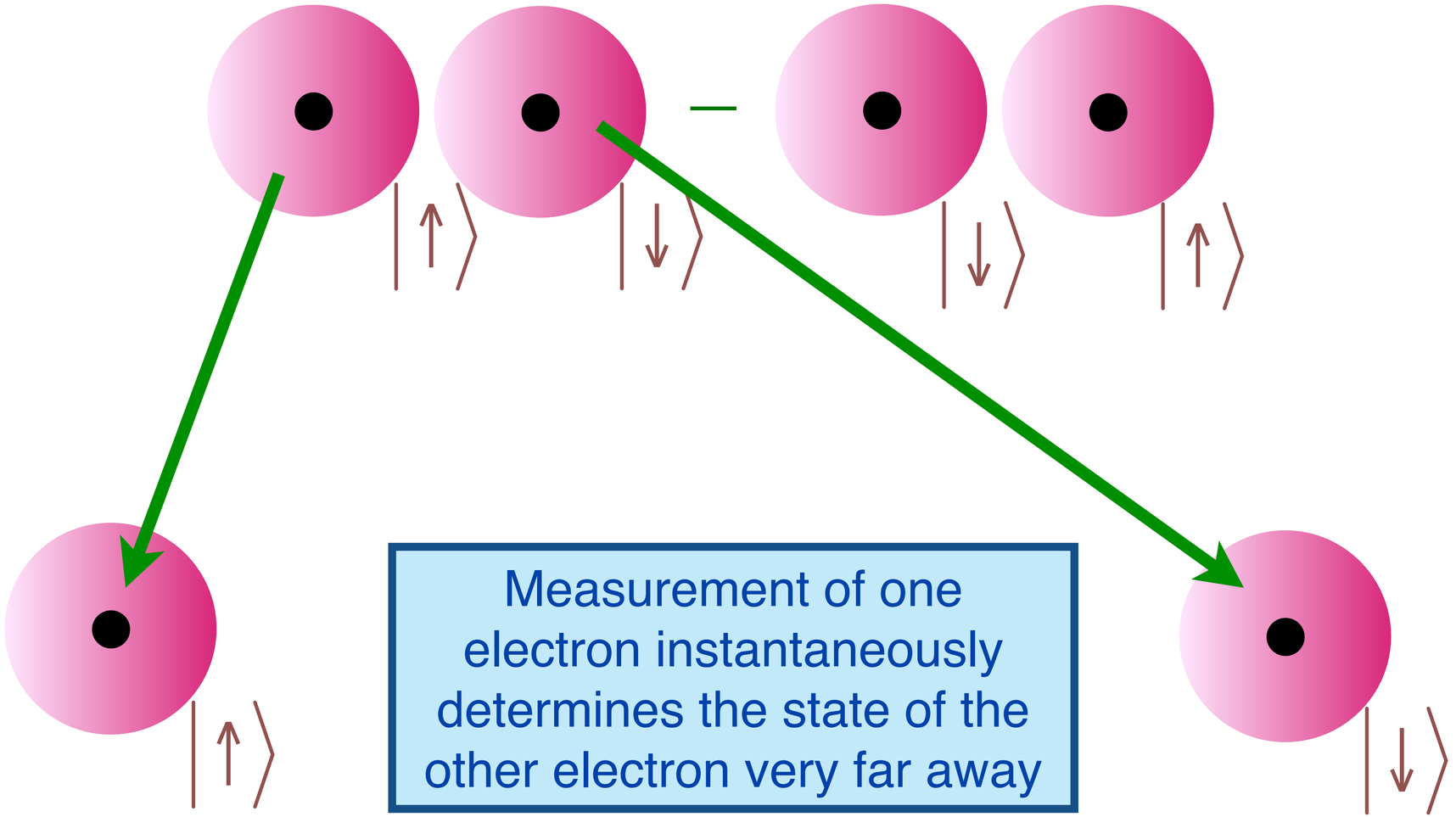

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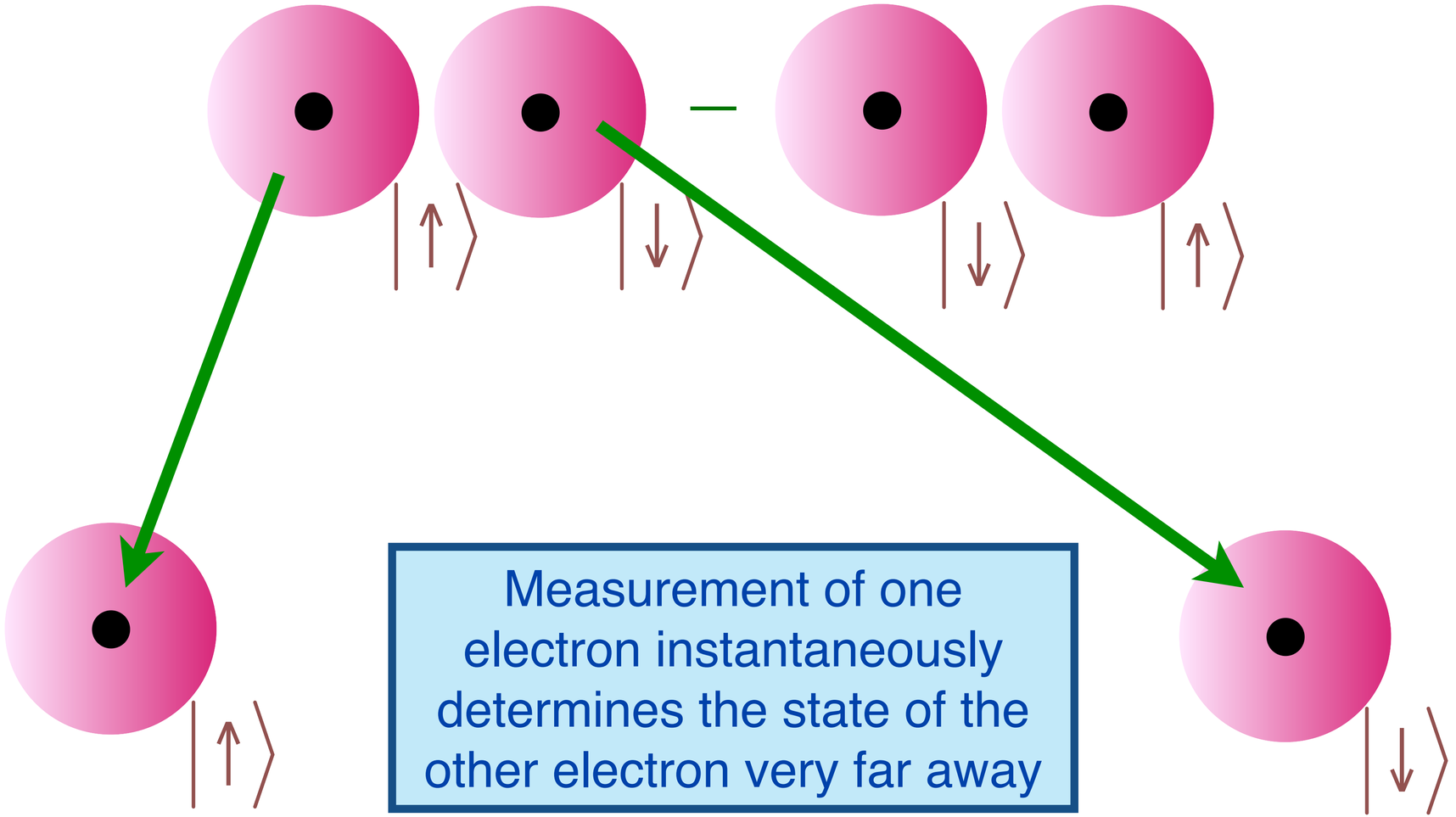
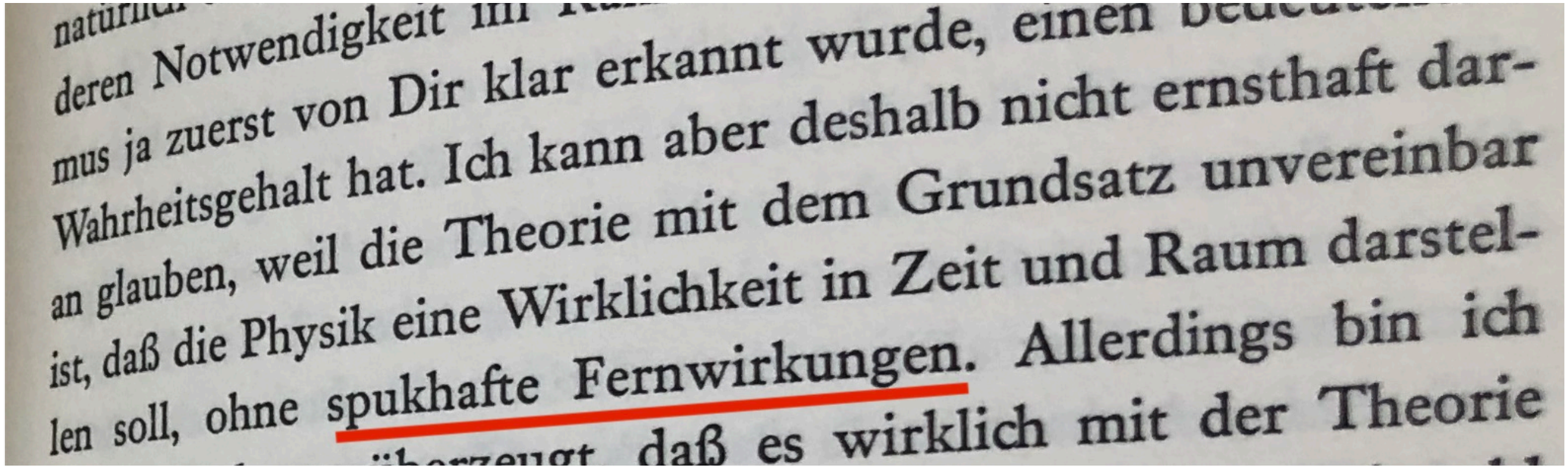


Spooky action at a distance !


deren Notwendigkeit
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
daß es wirklich mit der Theorie

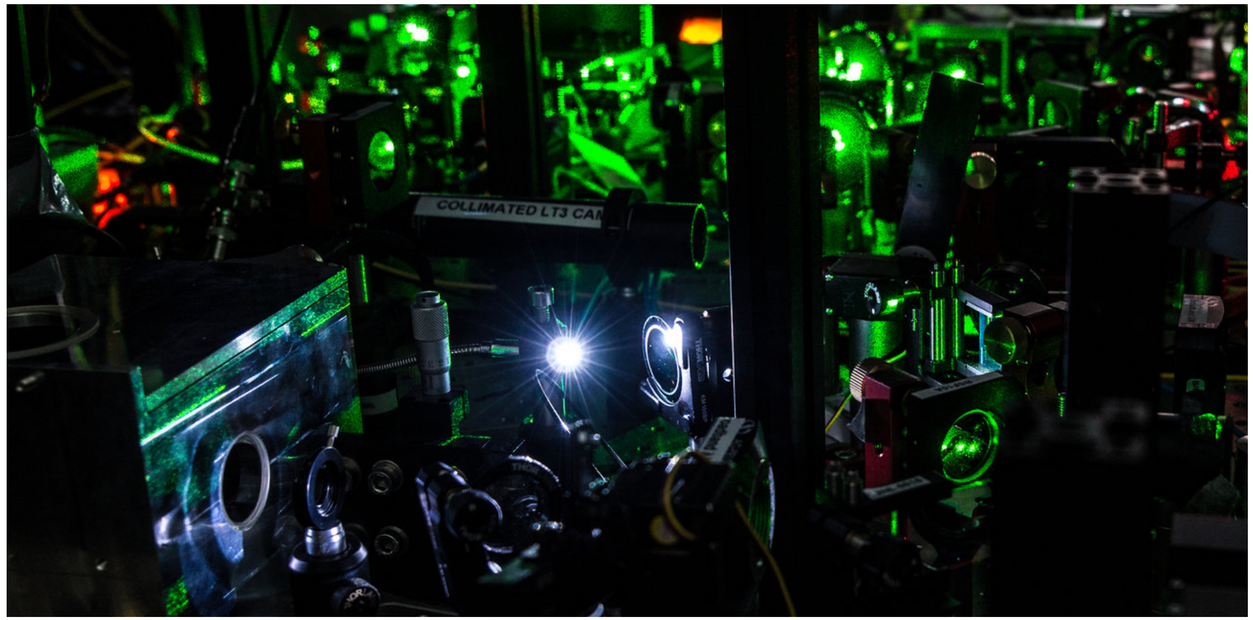
I cannot seriously believe in it because the theory cannot be reconciled with the idea that physics should represent a reality in time and space, free from spooky actions at distance

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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to solve open problems in the theory of
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A solvable model of quantum entanglement
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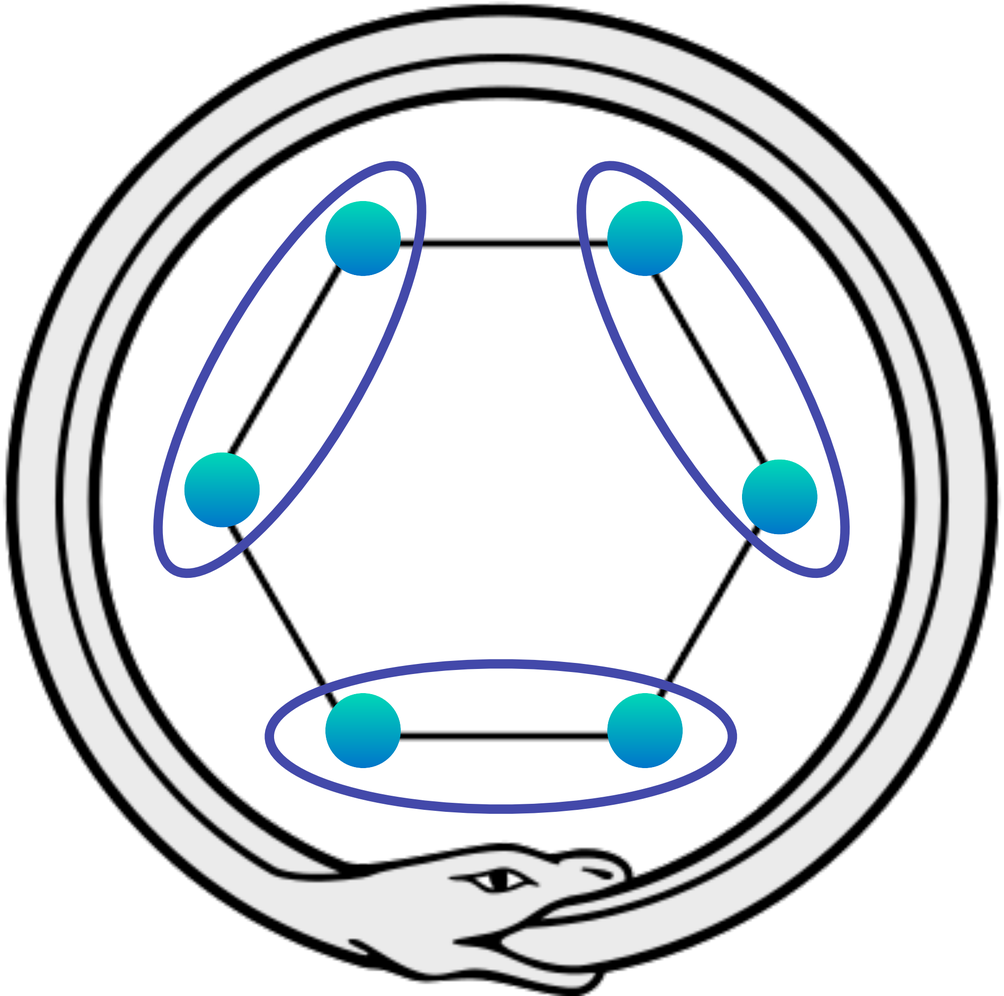
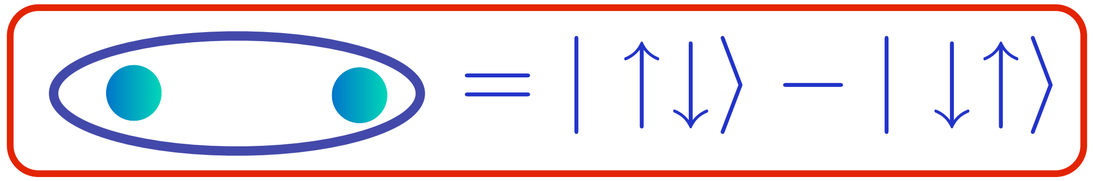
The Sachdev-Ye-Kitaev model
of many-particle entanglement

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 *





Benzene

*Wikipedia

Kekule's spooky dream (1865)

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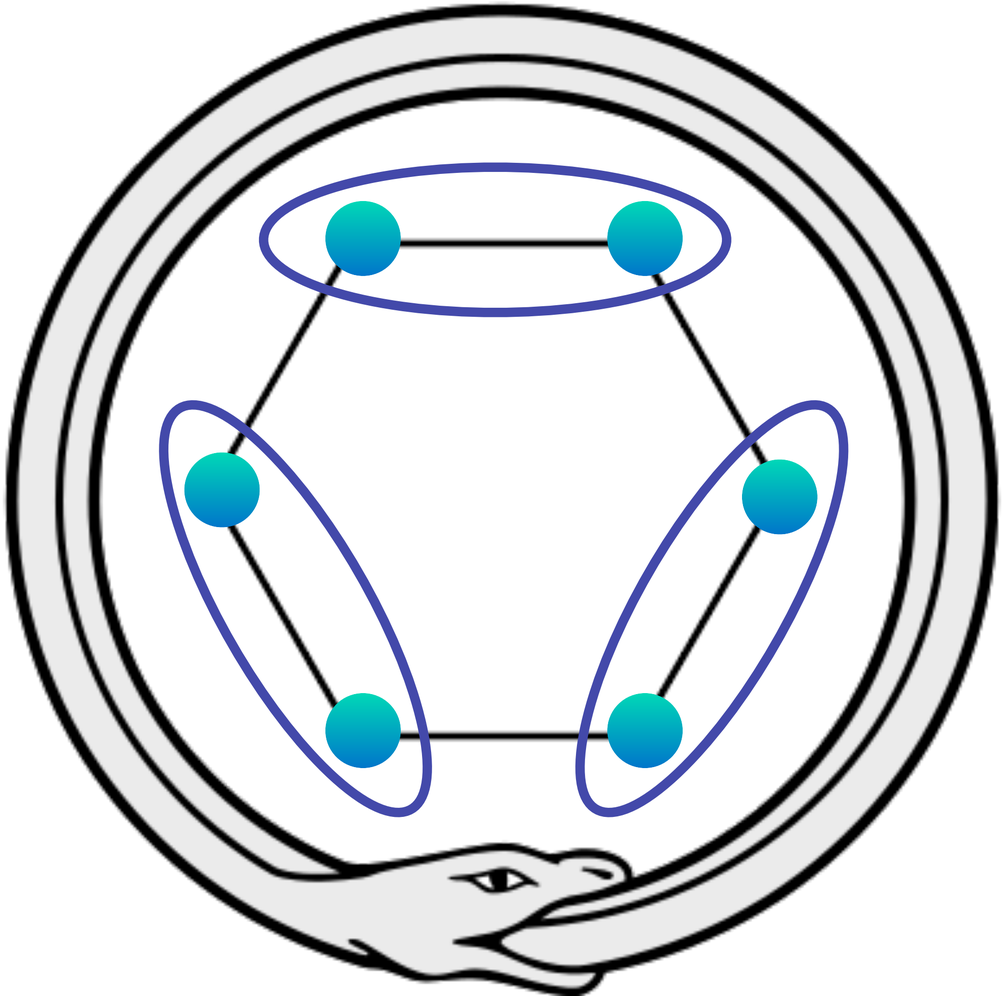
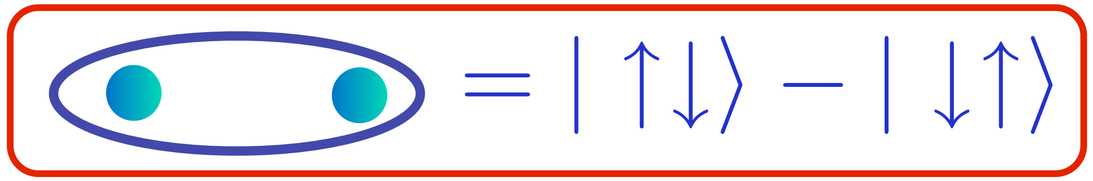
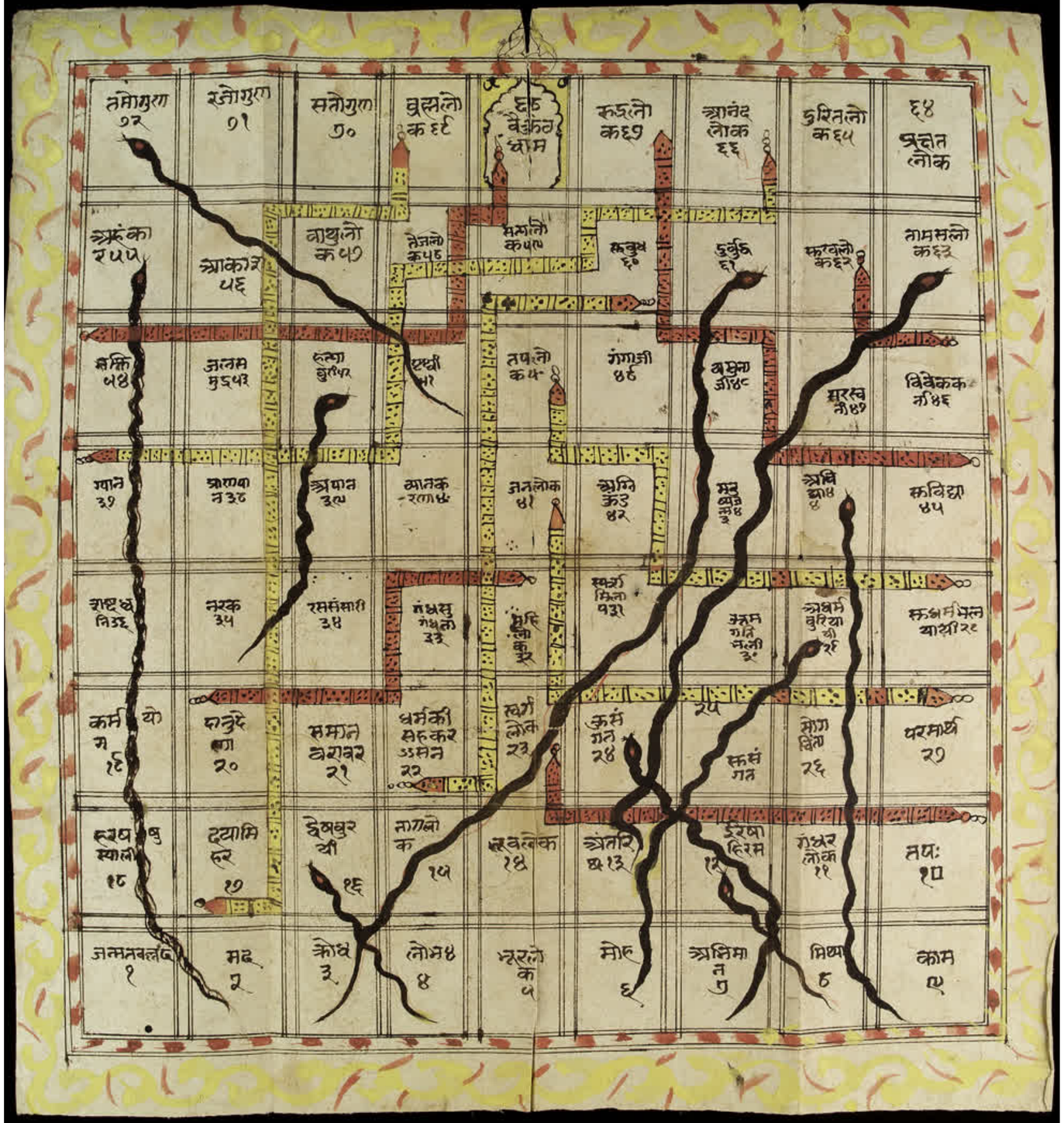




Benzene

*Wikipedia



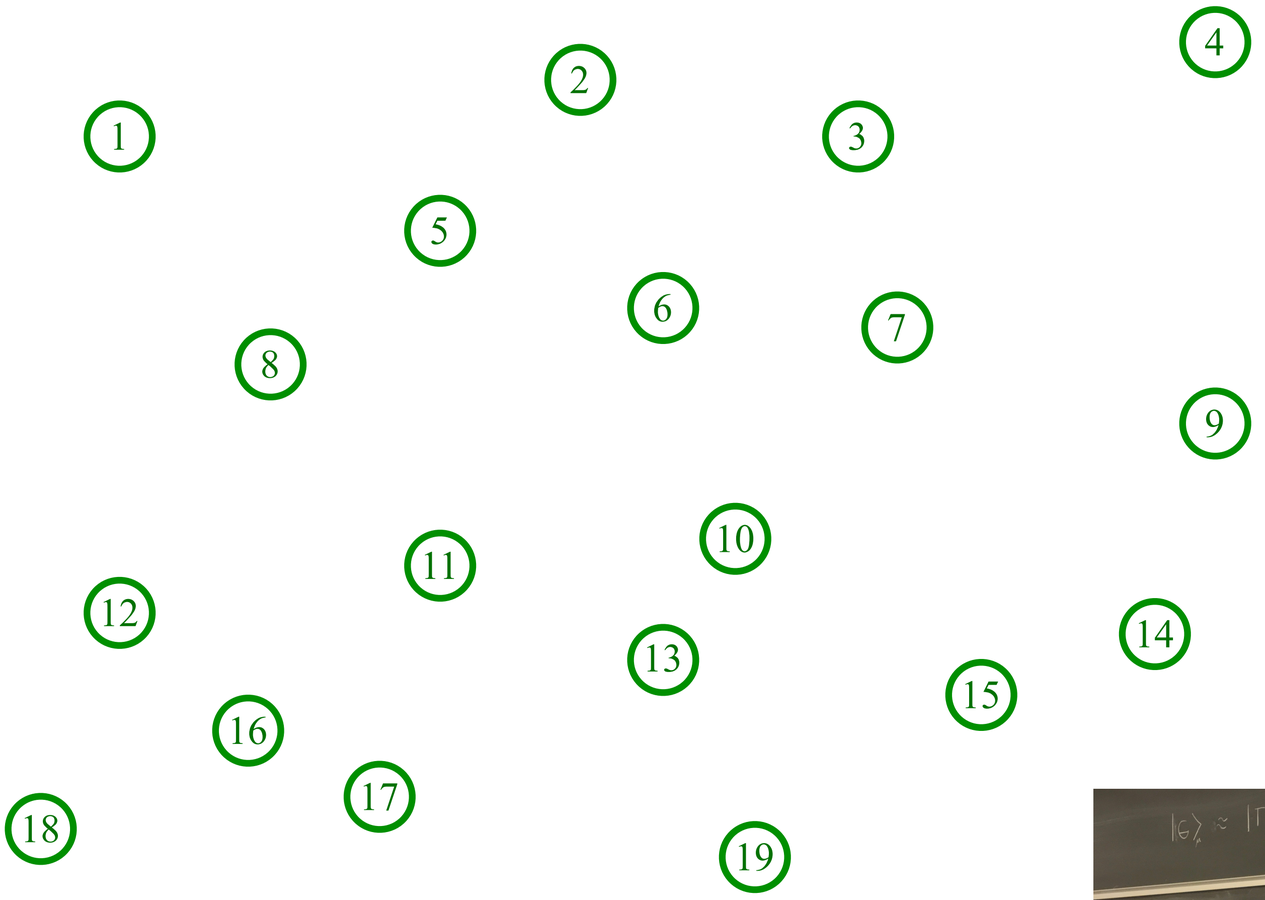
My spooky dream*

Ancient Indian game of Snakes and Ladders

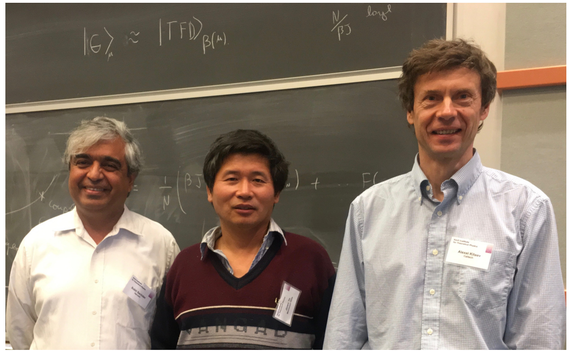
*Not true

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

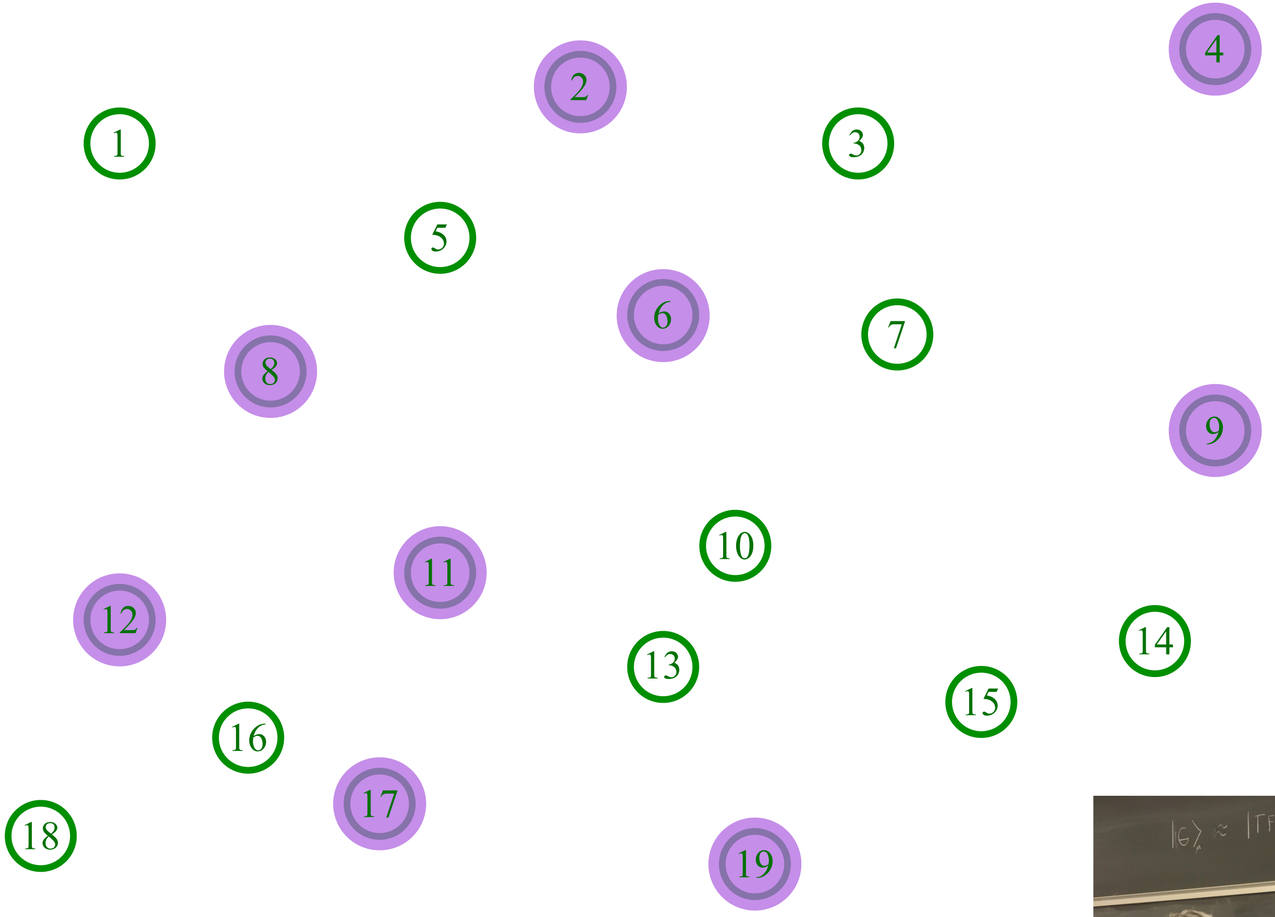


Pick a set of random positions

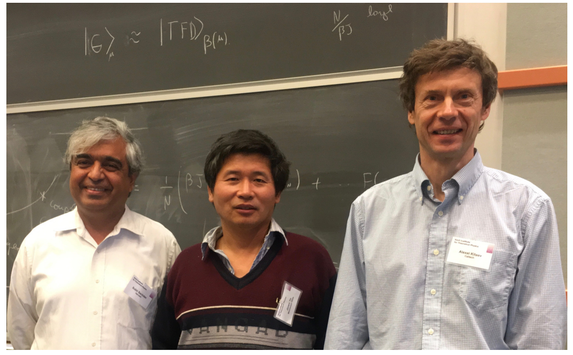


The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)



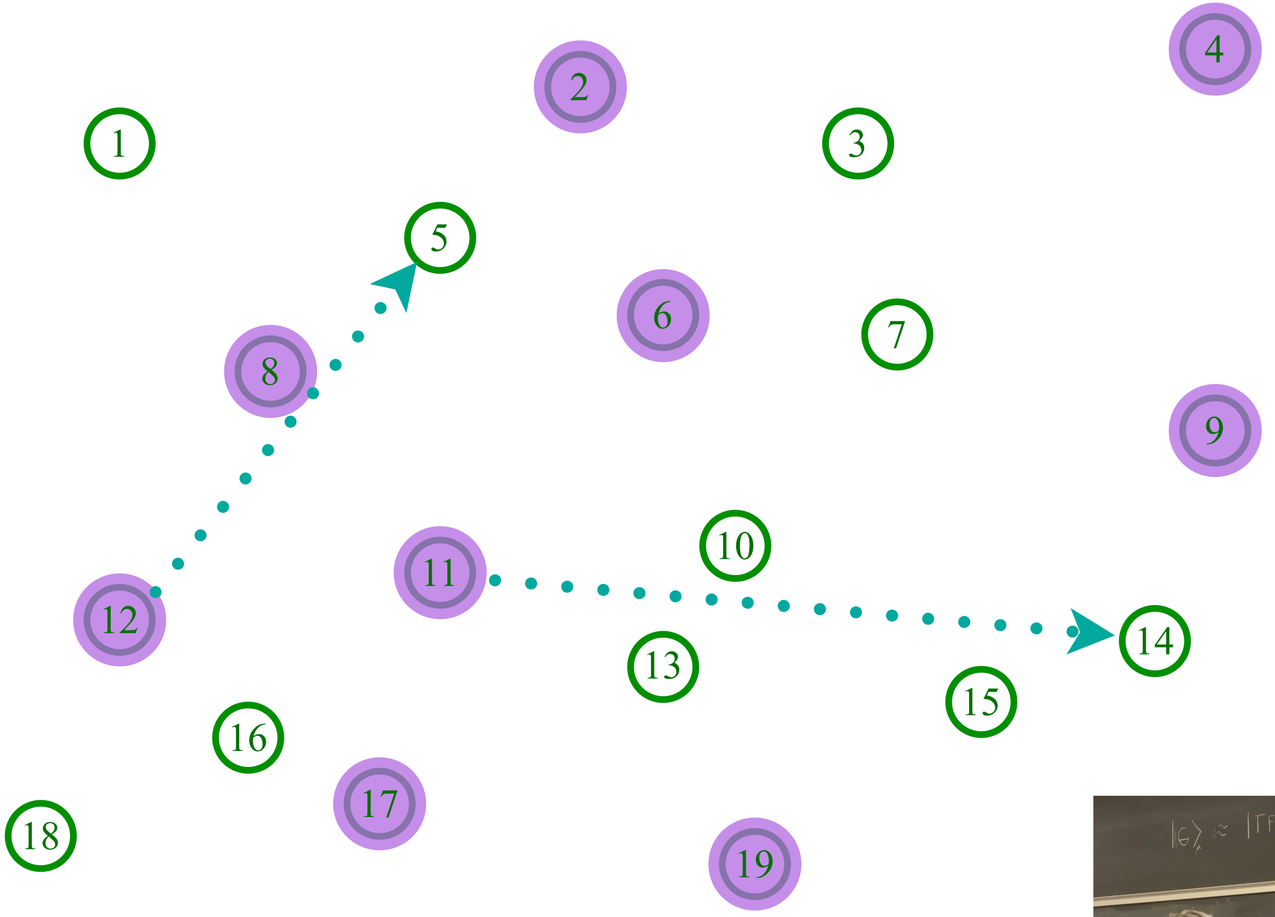
Place electrons randomly on some sites



The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

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



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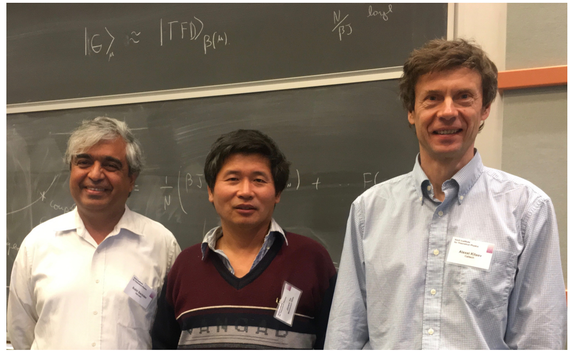

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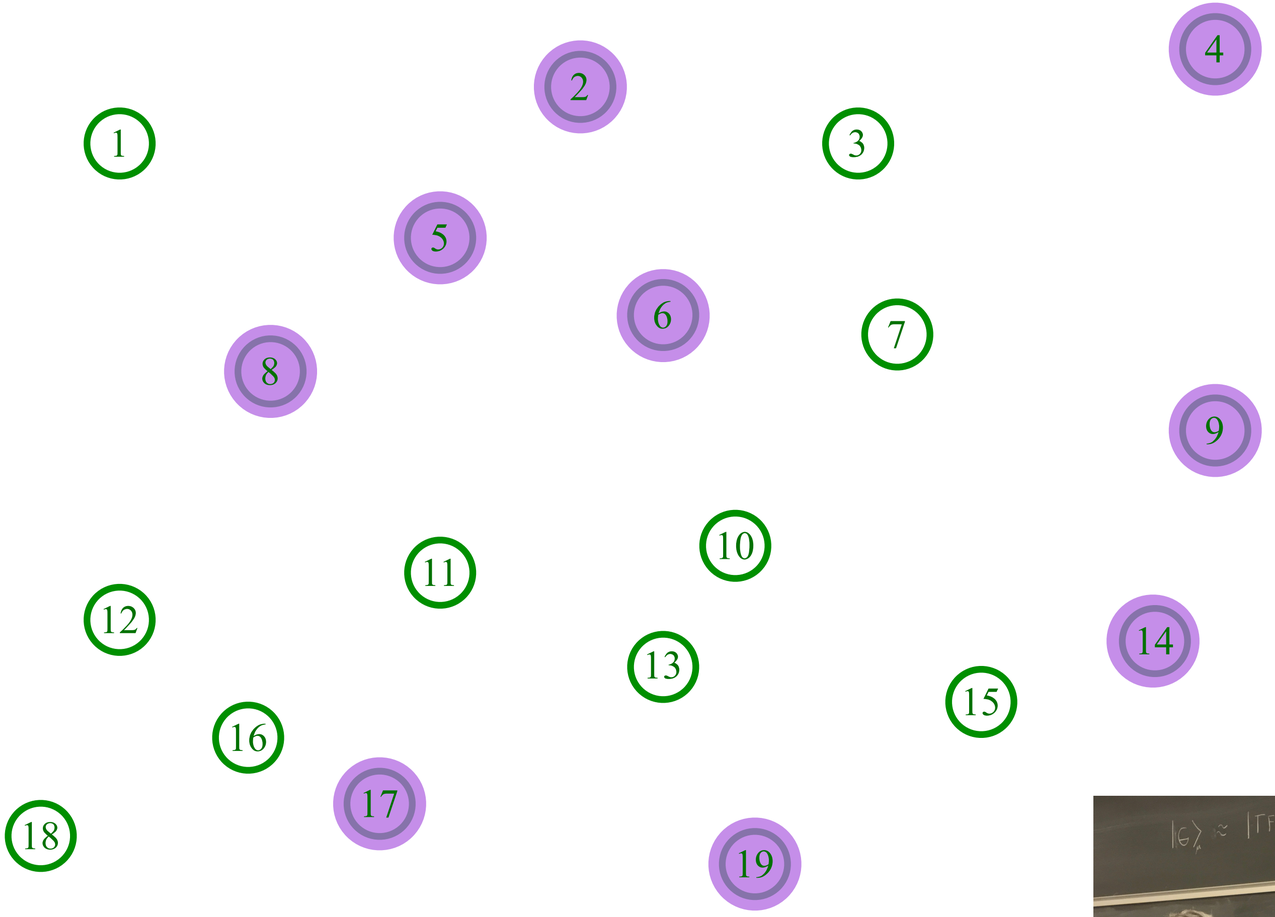
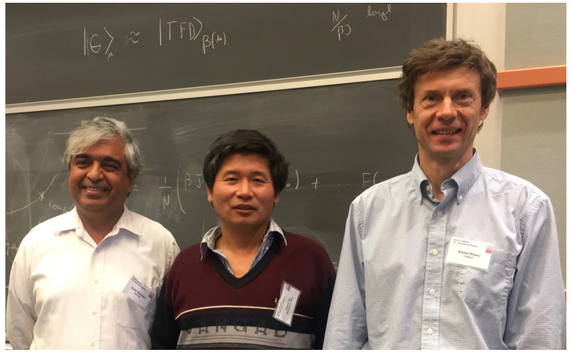
Sachdev, Ye (1993); Kitaev (2015)

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



Entangle electrons pairwise randomly



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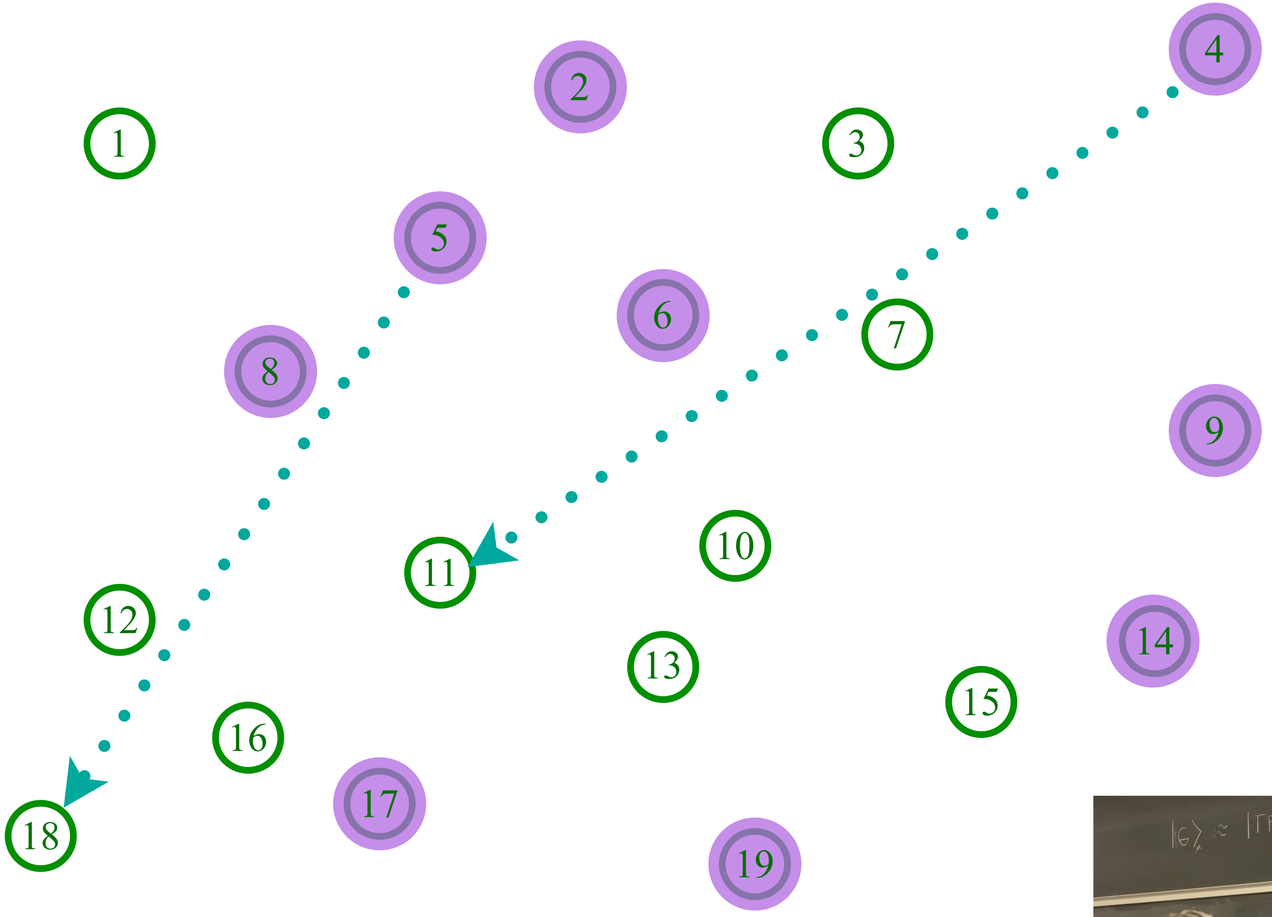

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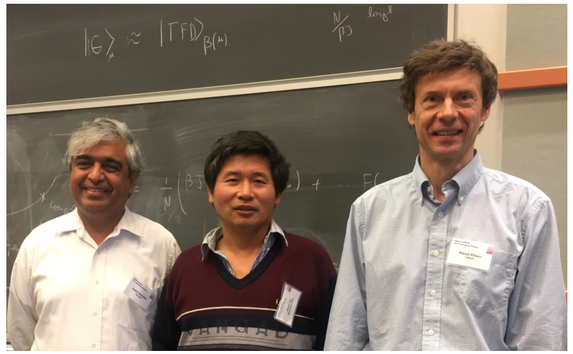

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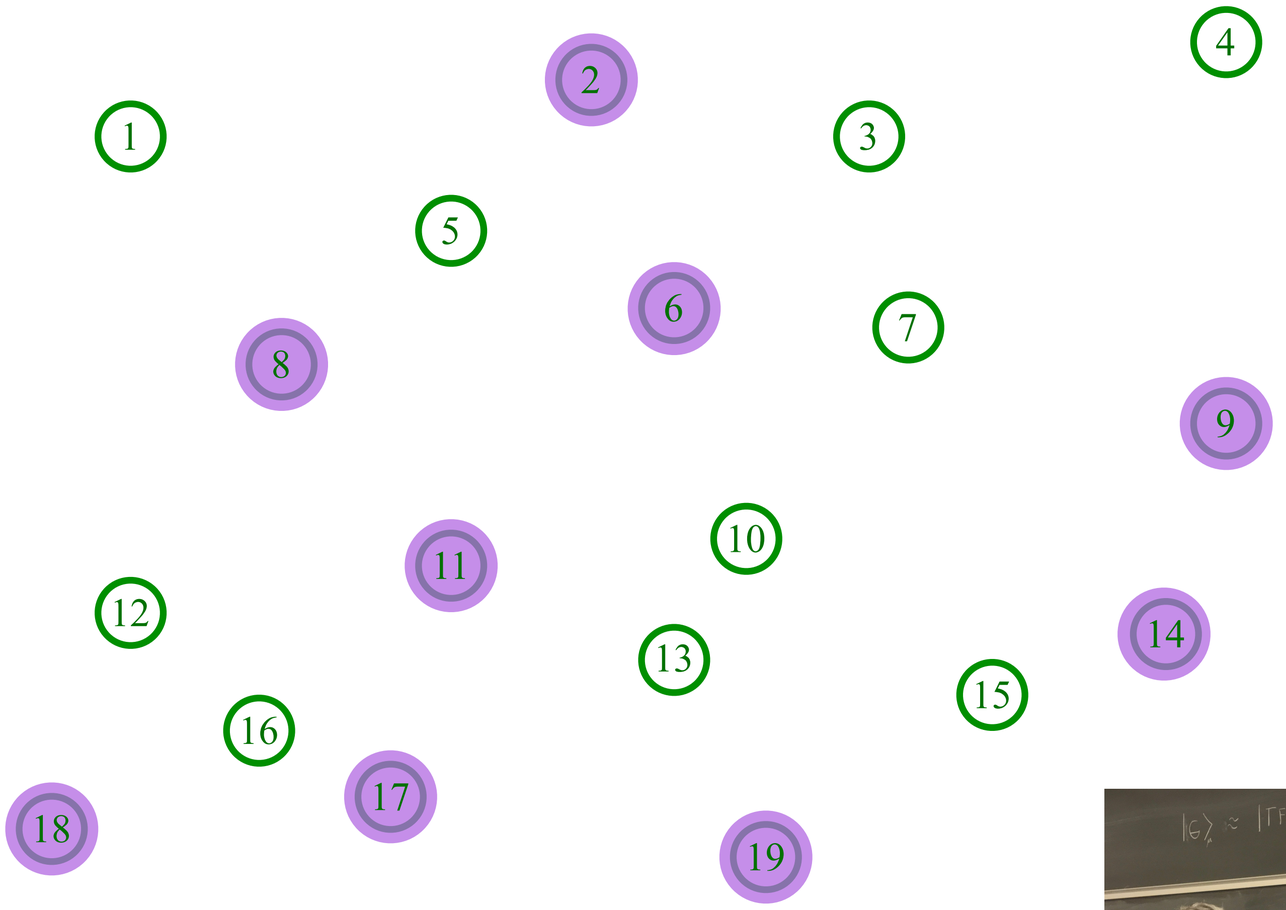

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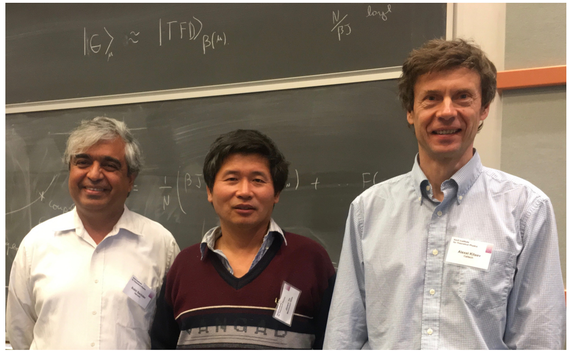

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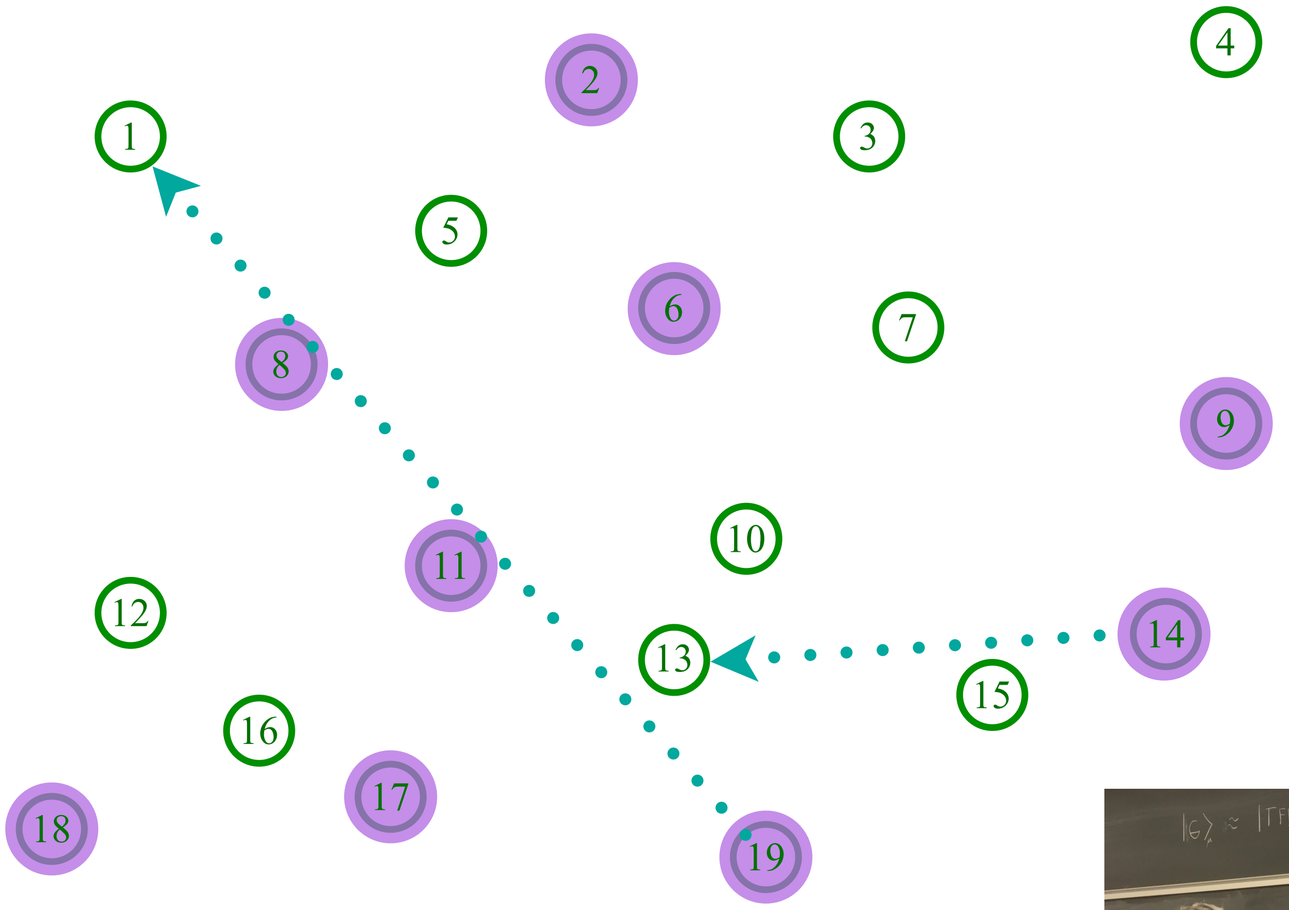

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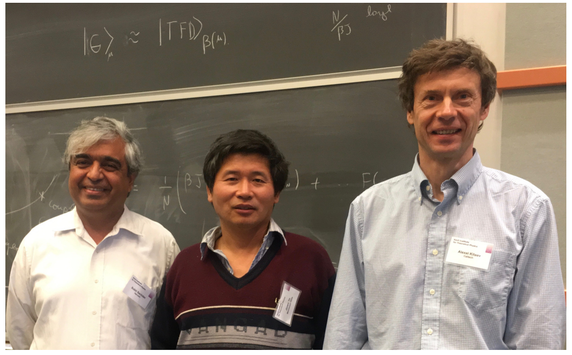

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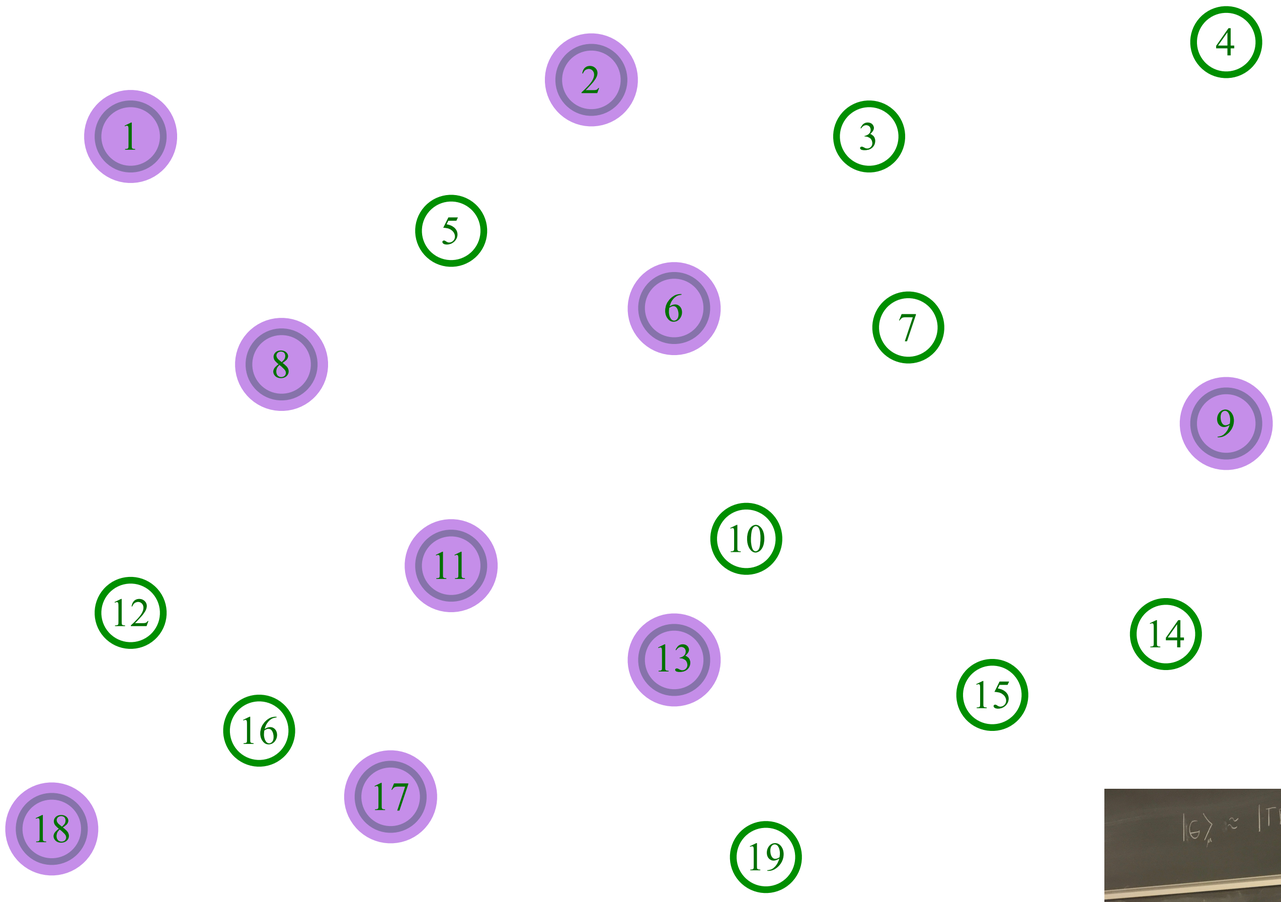

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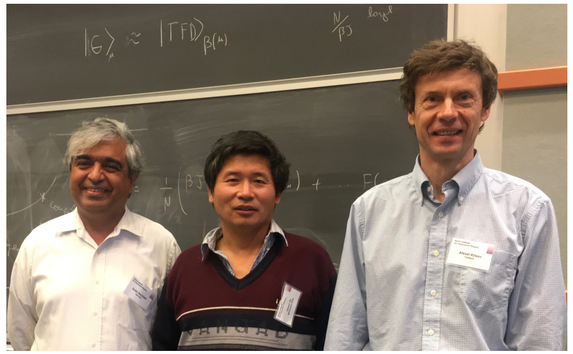

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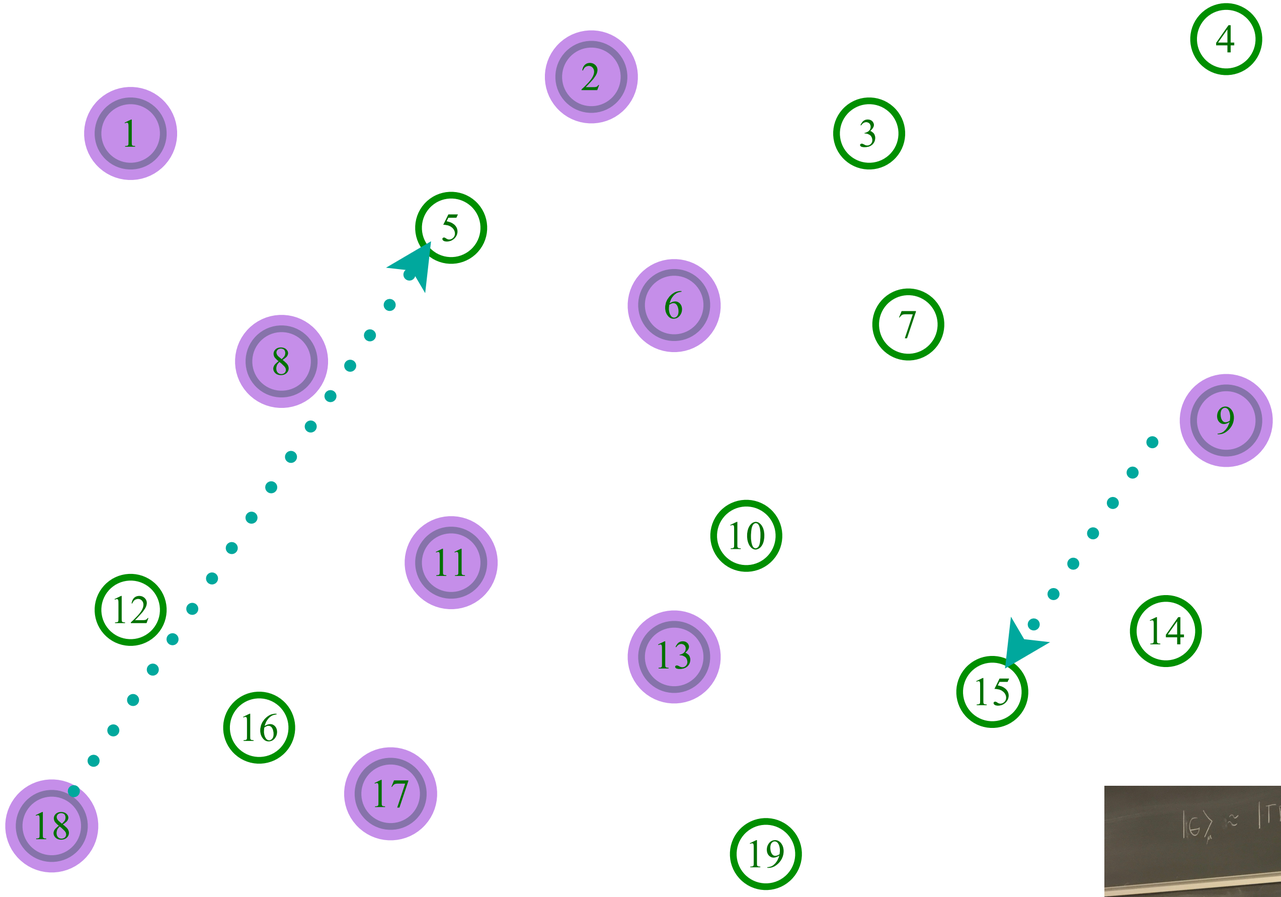

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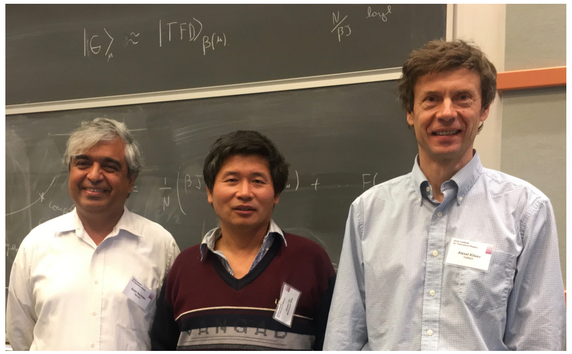

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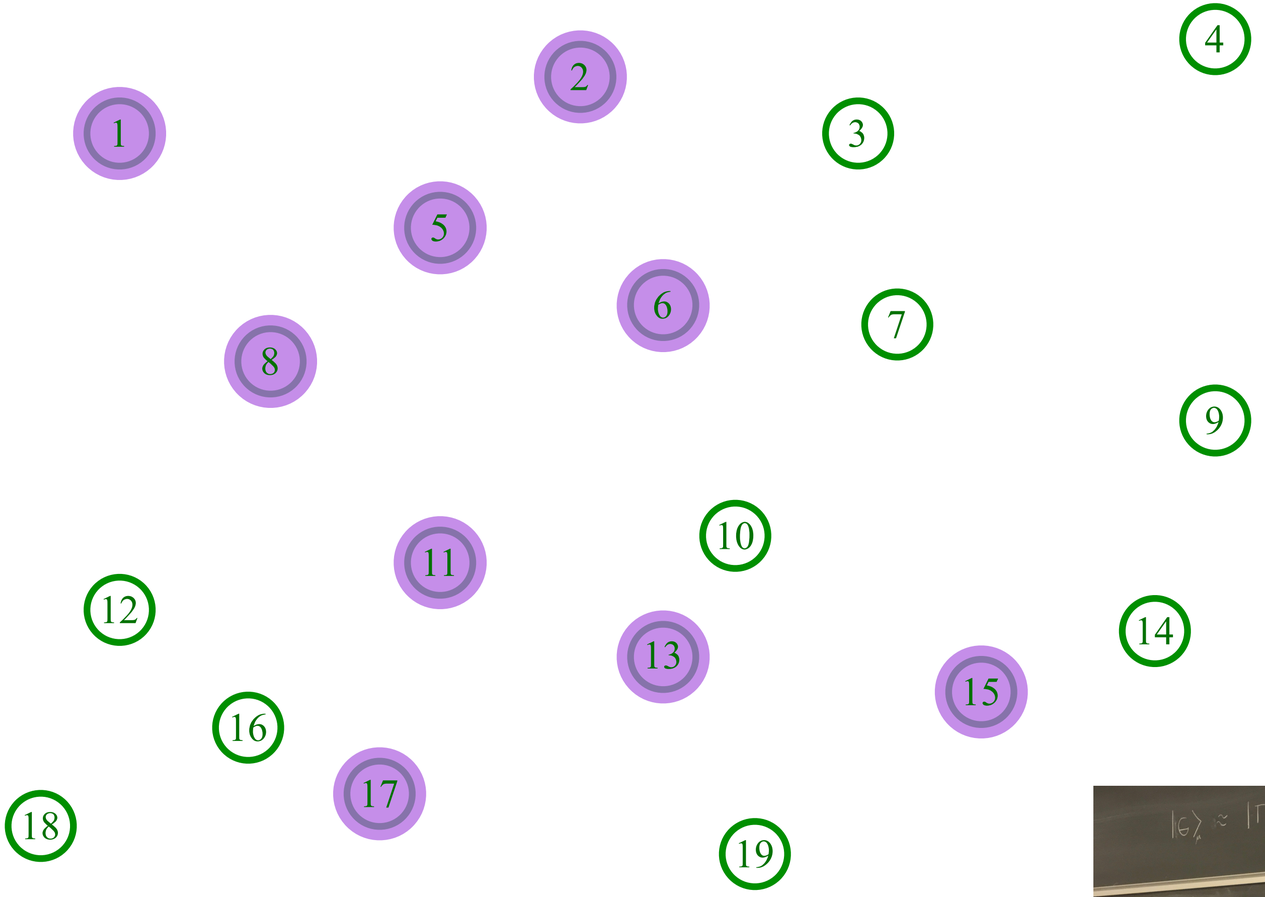

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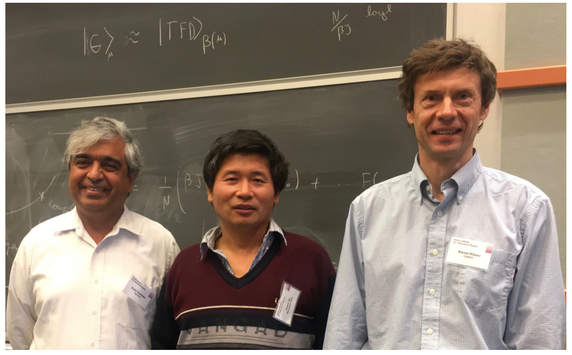

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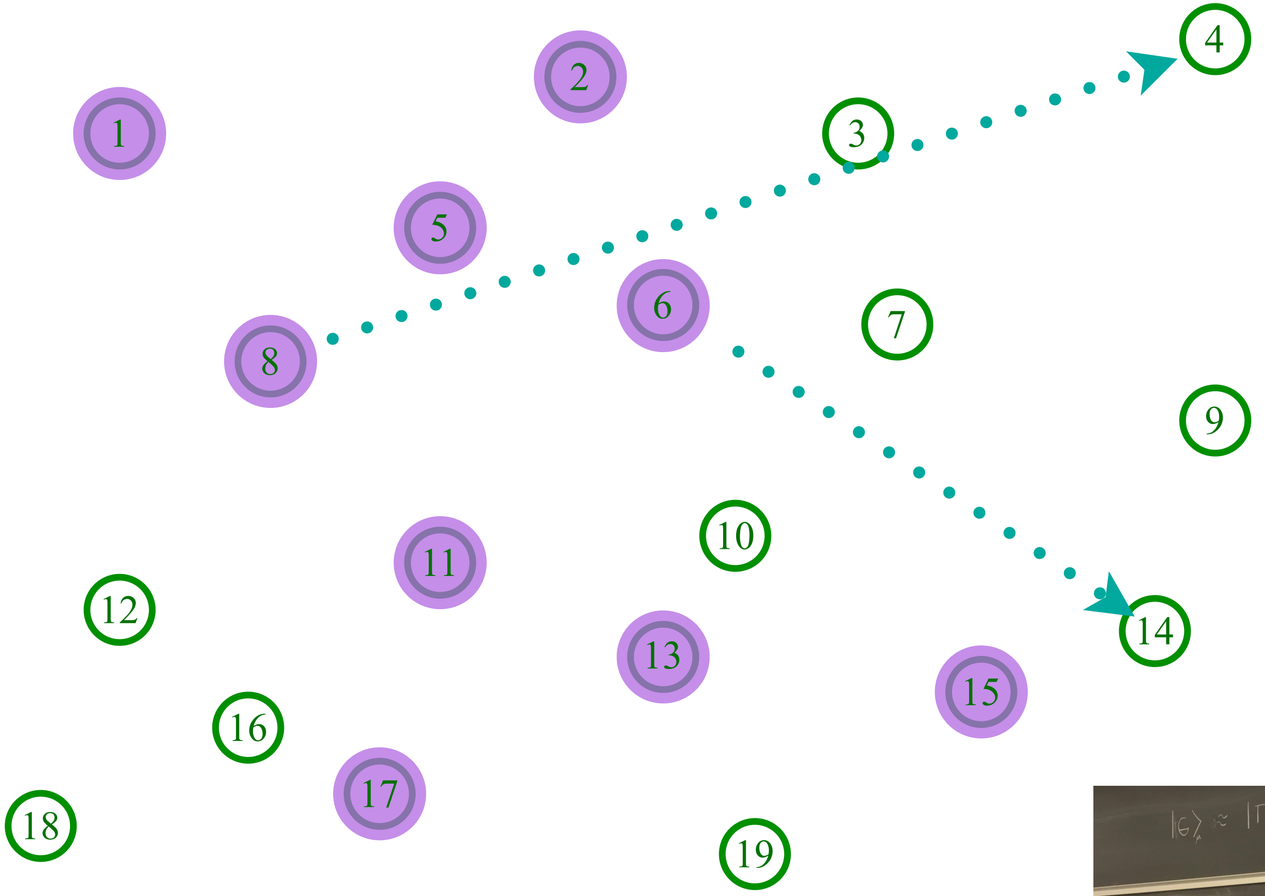

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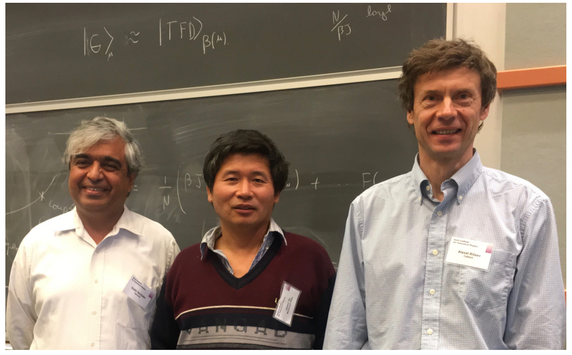

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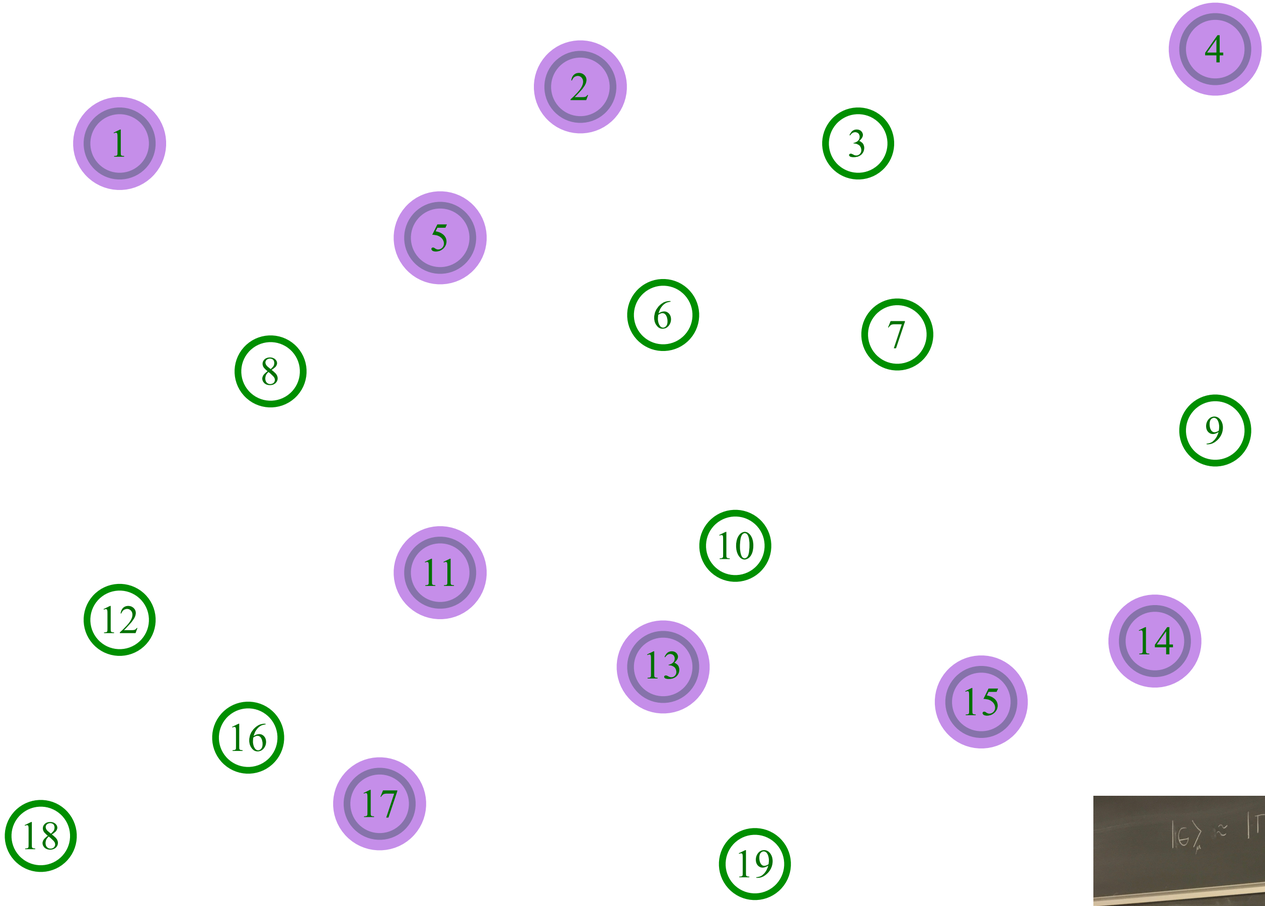

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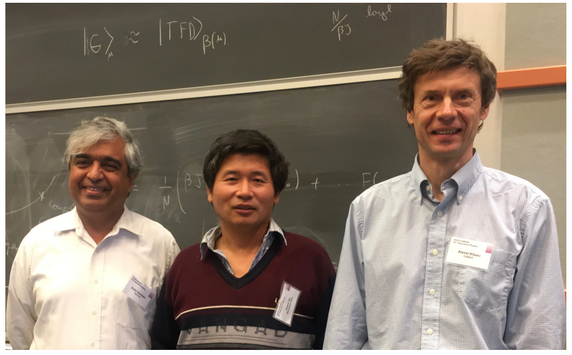


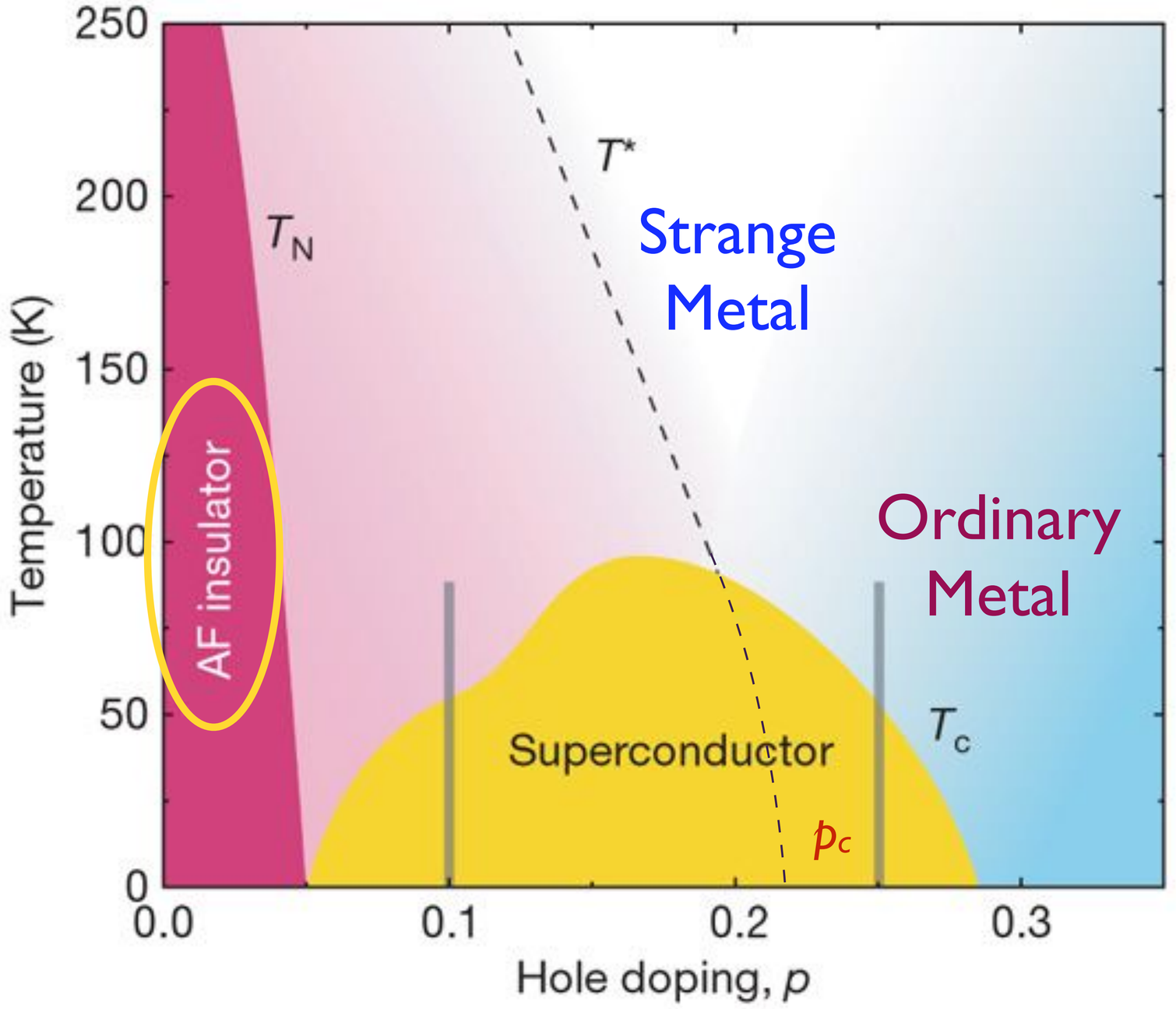
The Sachdev-Ye-Kitaev (SYK) model

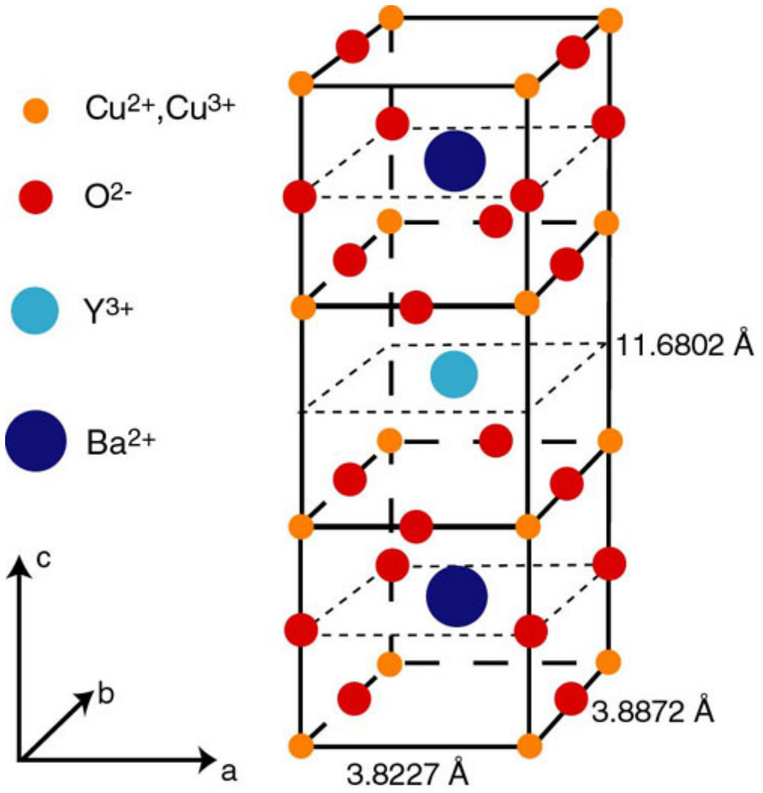
Sachdev, Ye (1993); Kitaev (2015)

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"

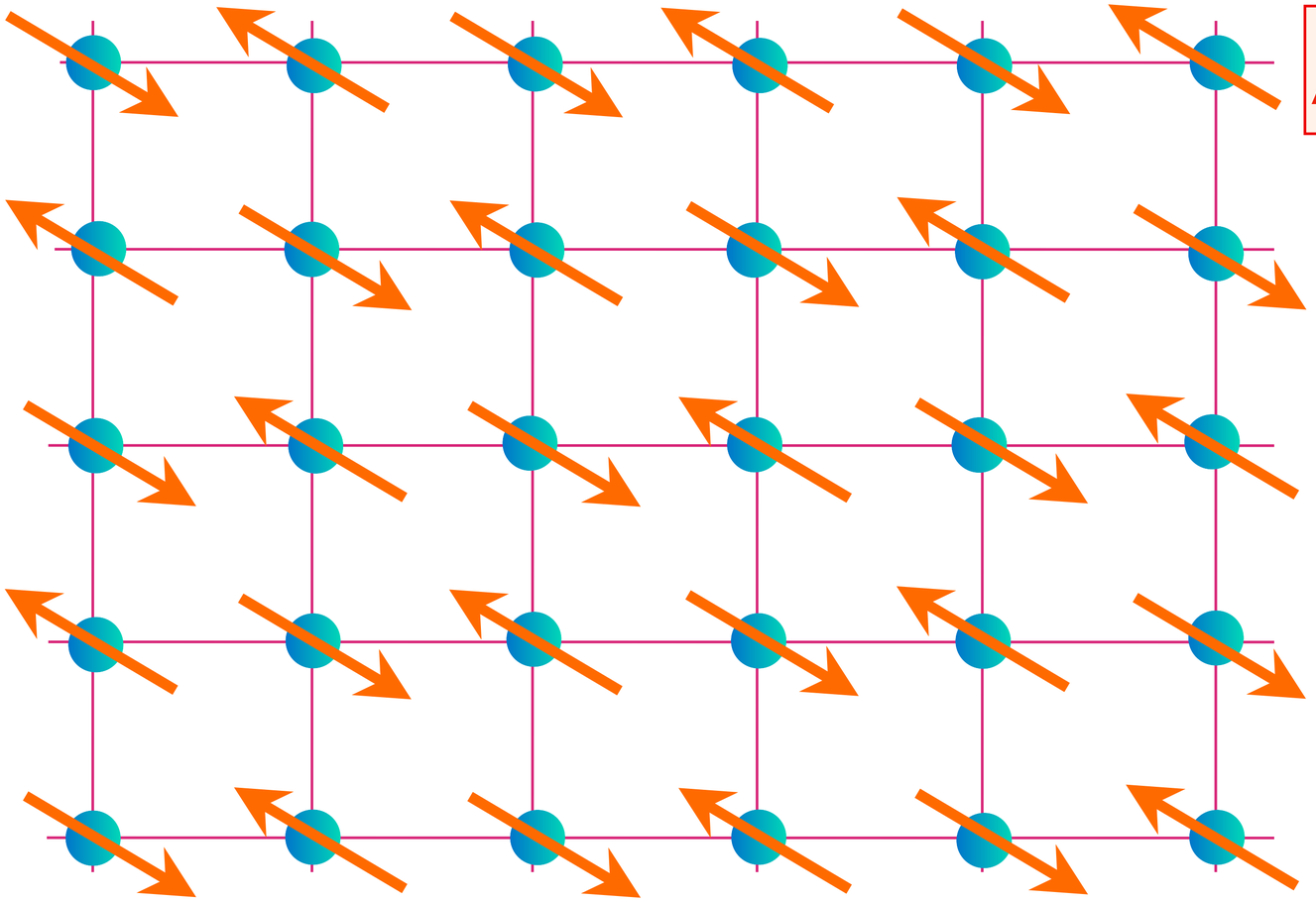
Quantum entanglement and superconductivity


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


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

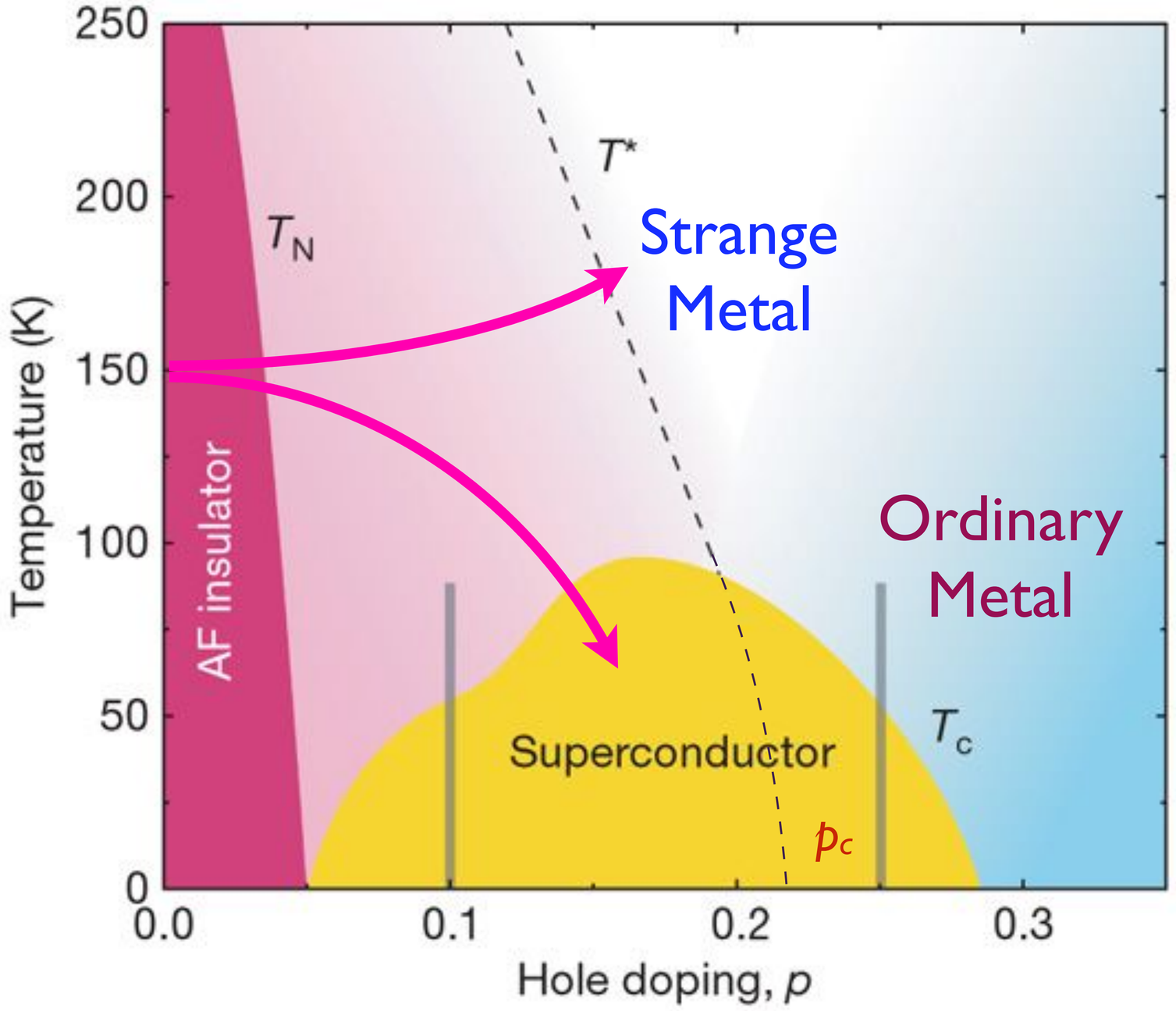
$YBa_2Cu_3O_{6+x}$

The dance of electrons on Cu atoms in YBCO



Antiferromagnetism

All nearest-neighbor pairs of electrons have opposite spins


250
200
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Temperature (K)
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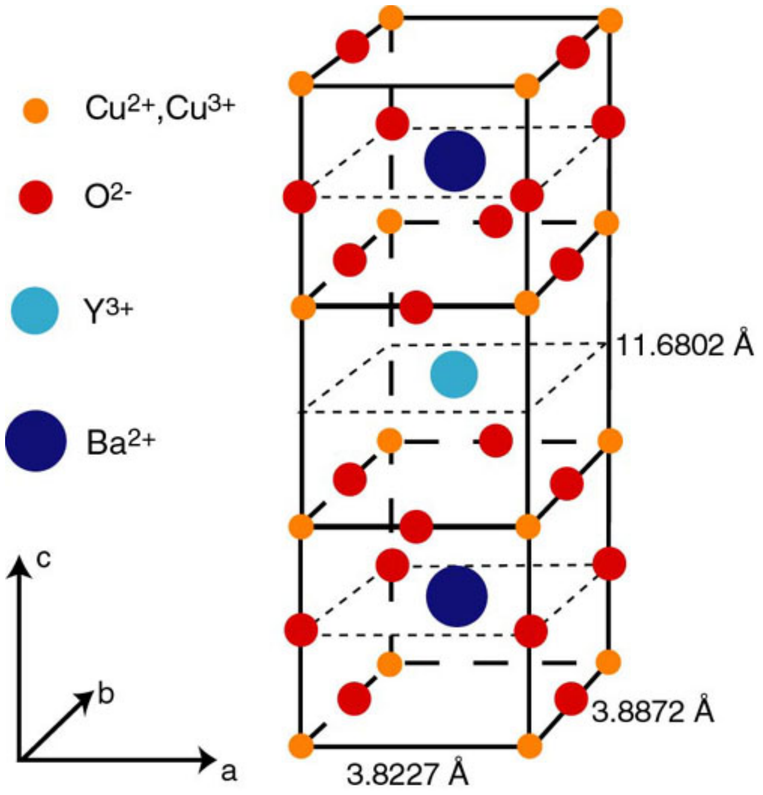
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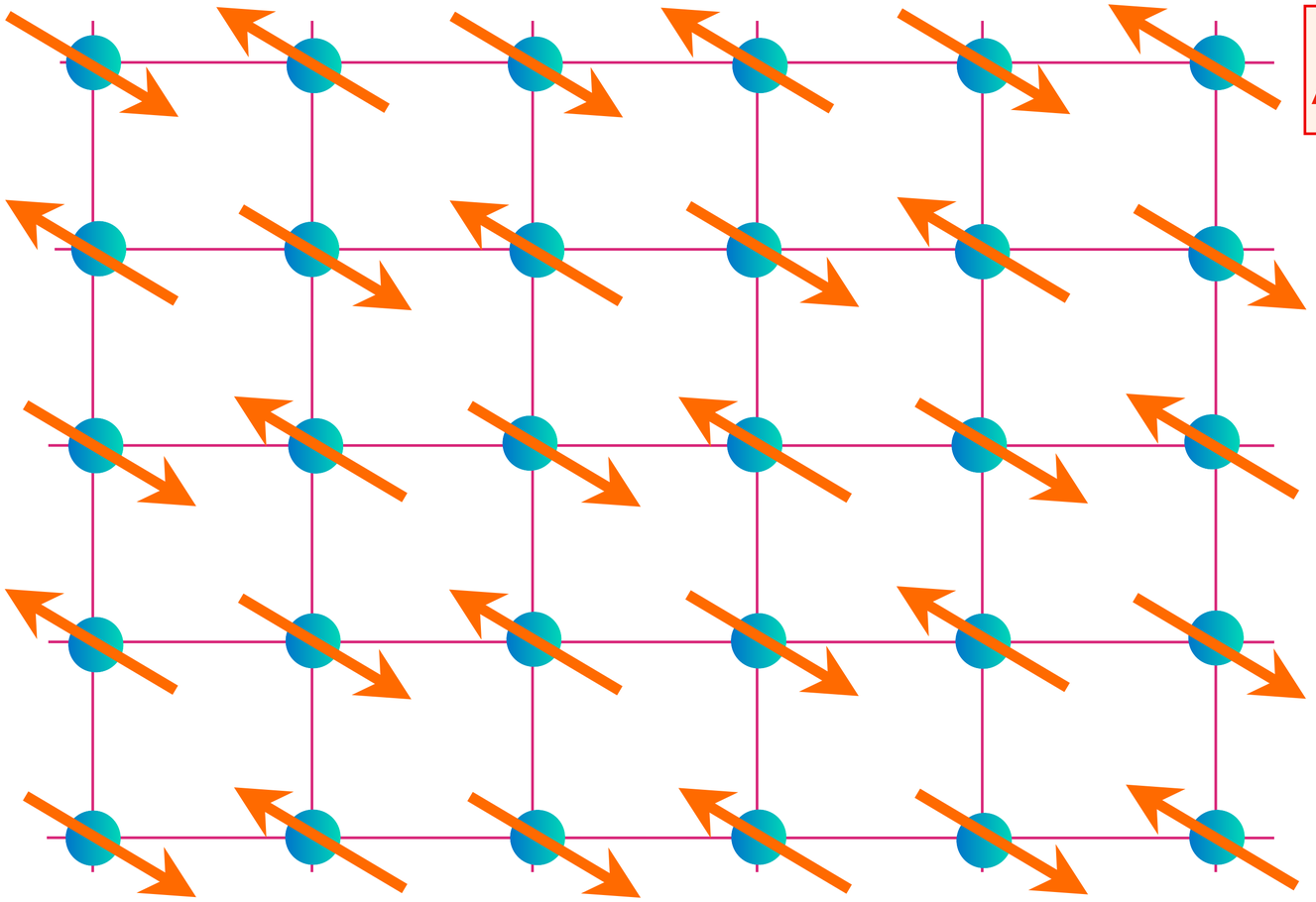

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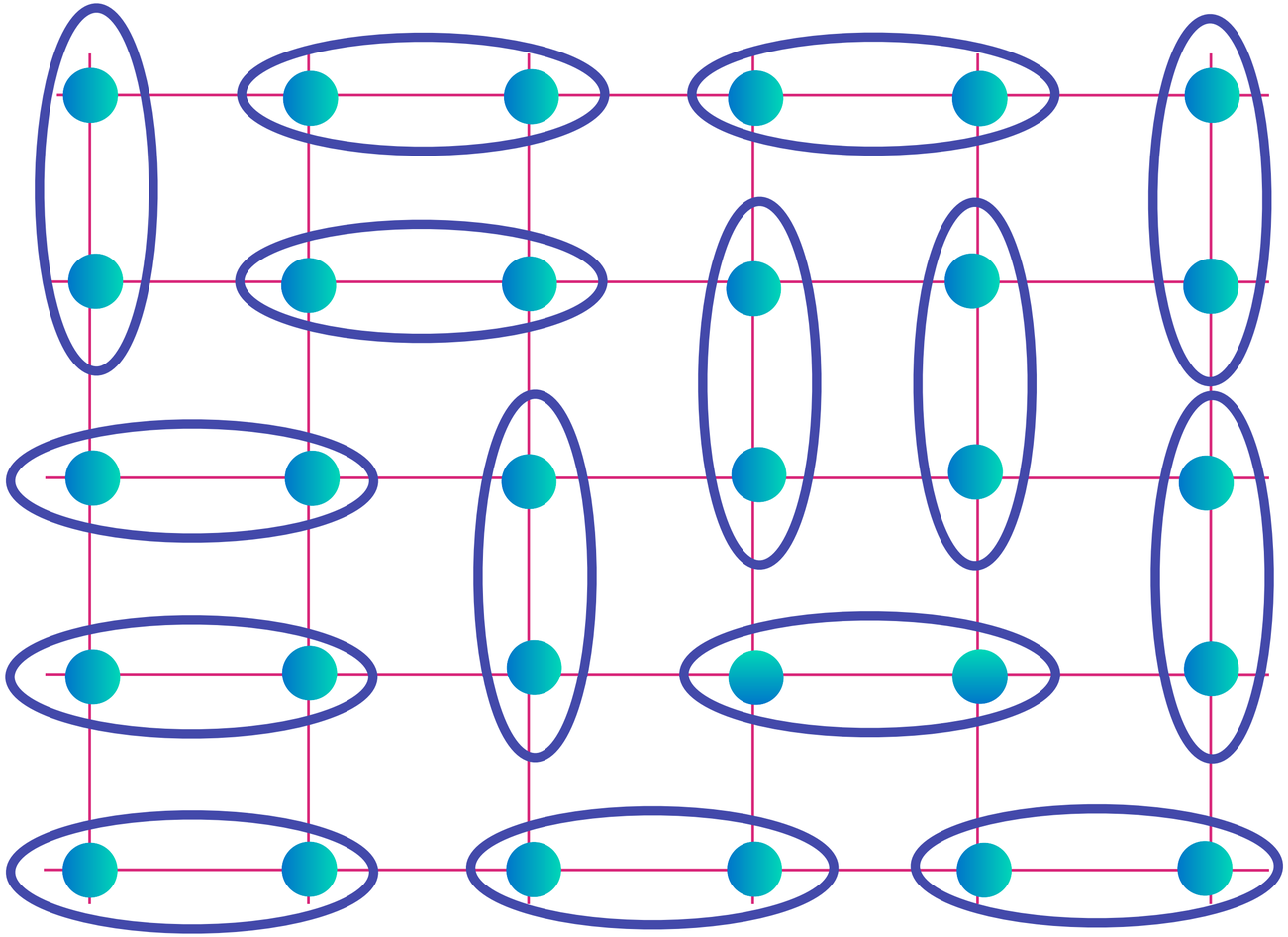
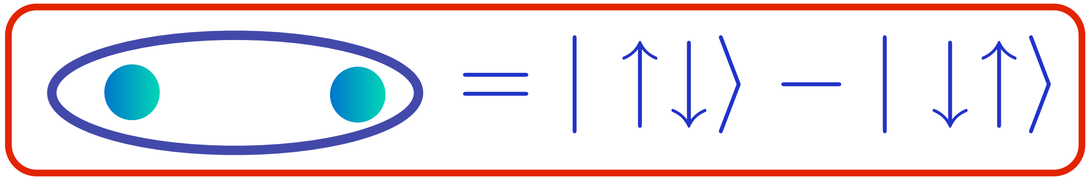


Baskaran+Anderson (1987)

Spin liquid

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



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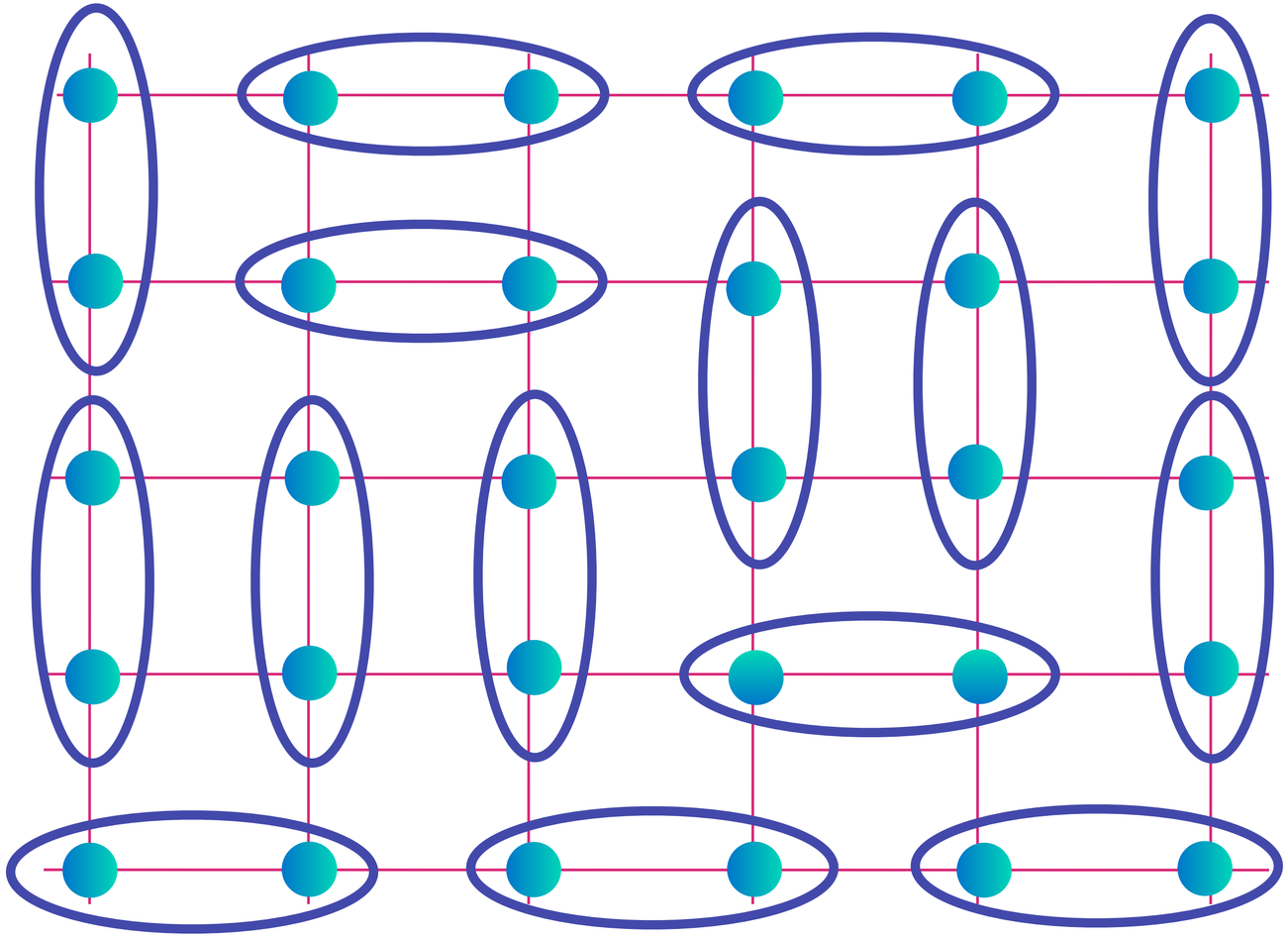

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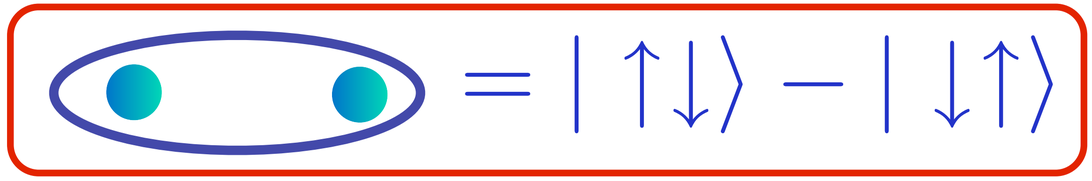

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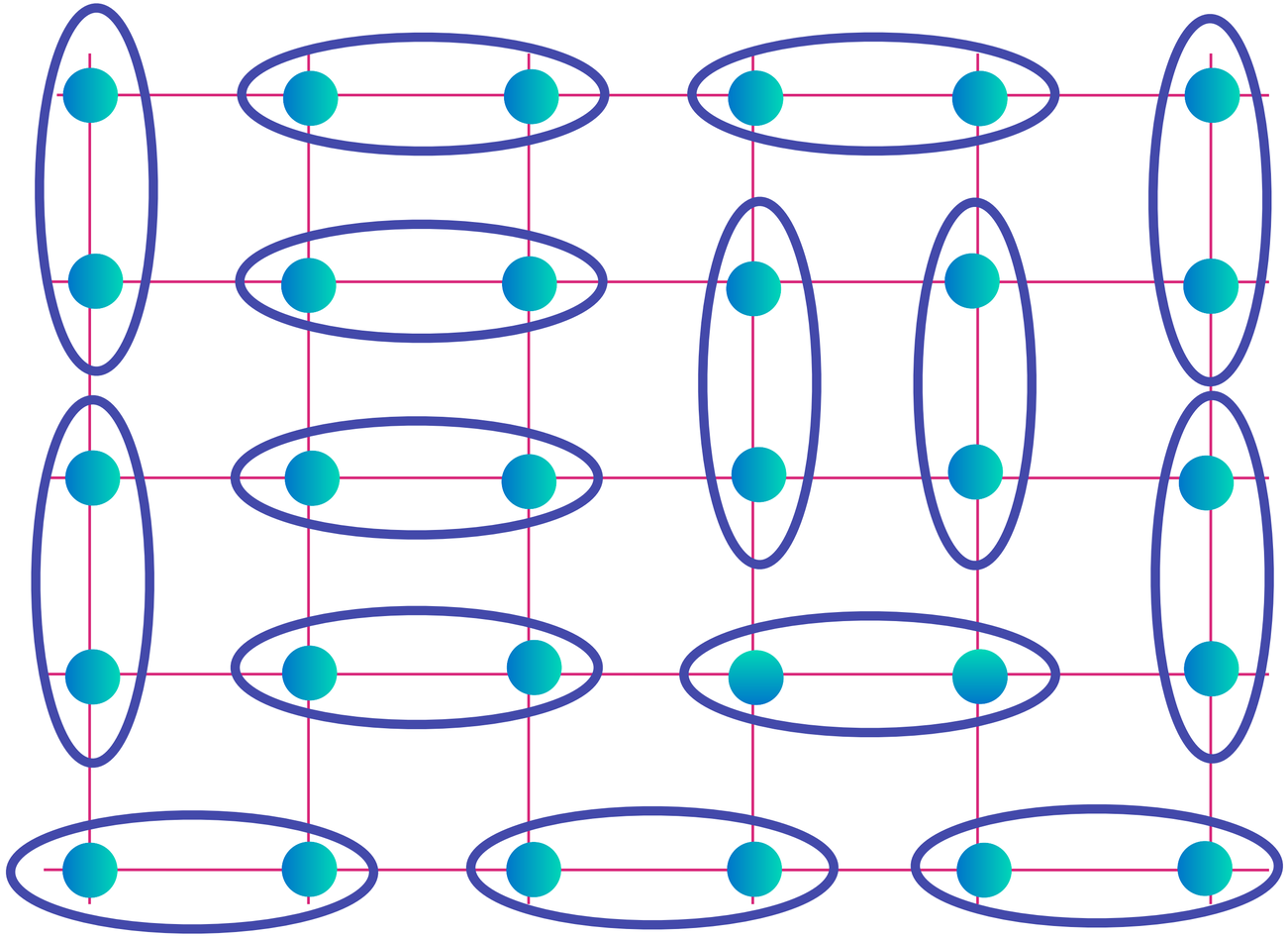

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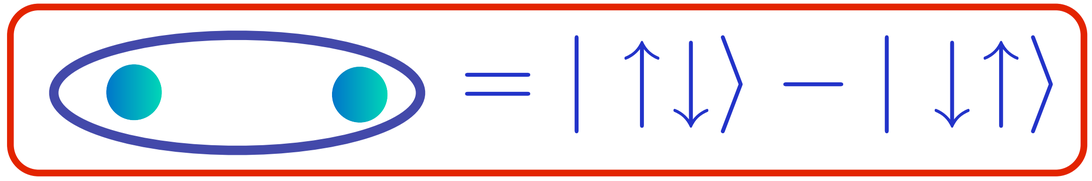

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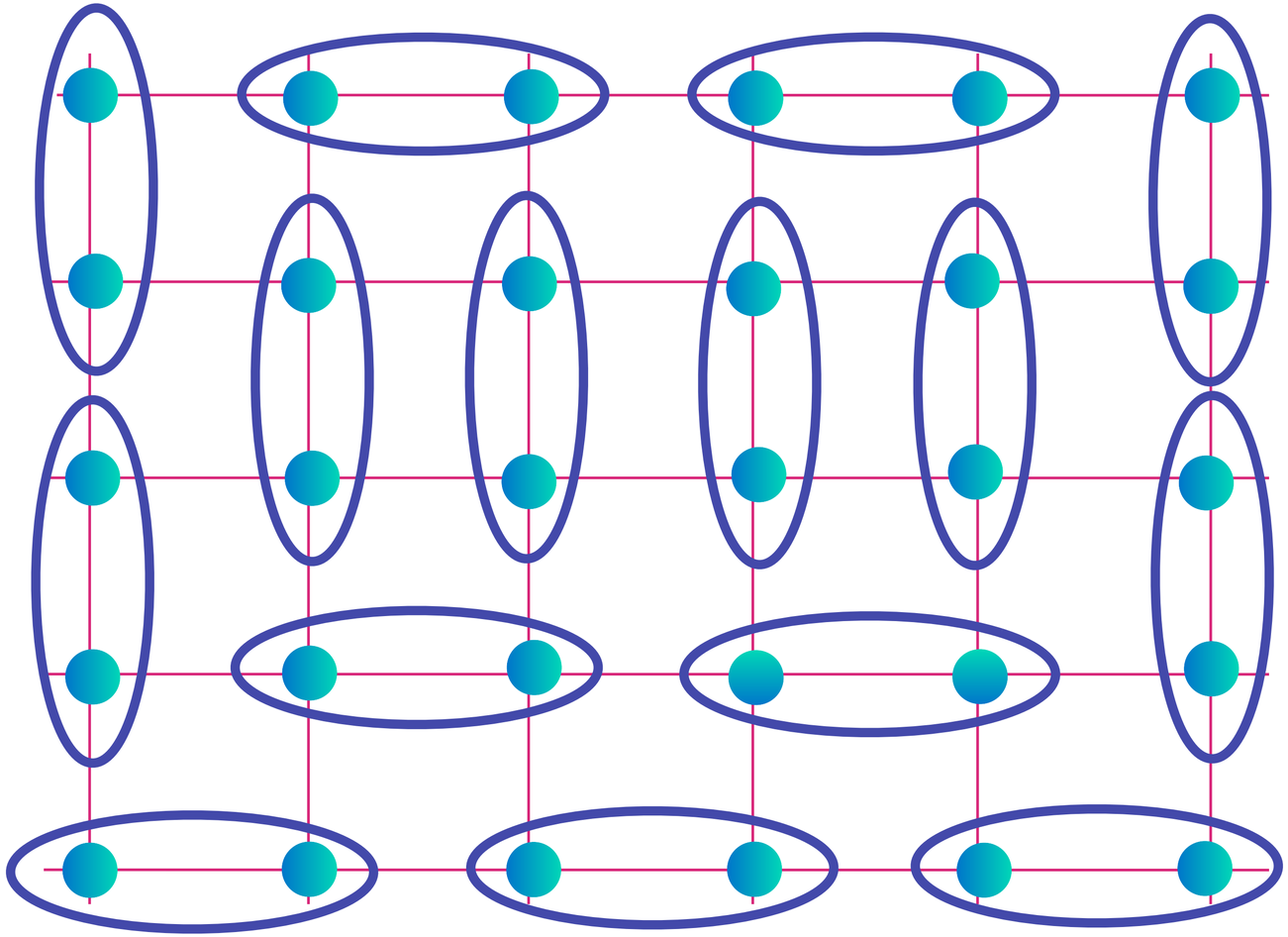

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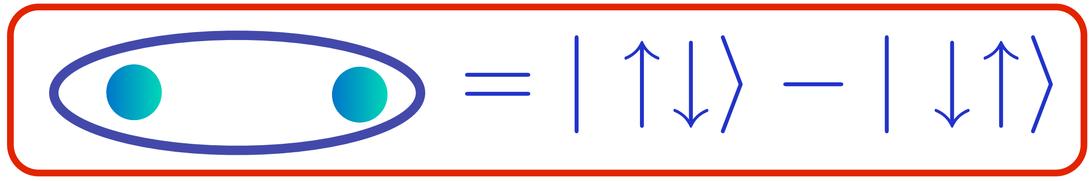

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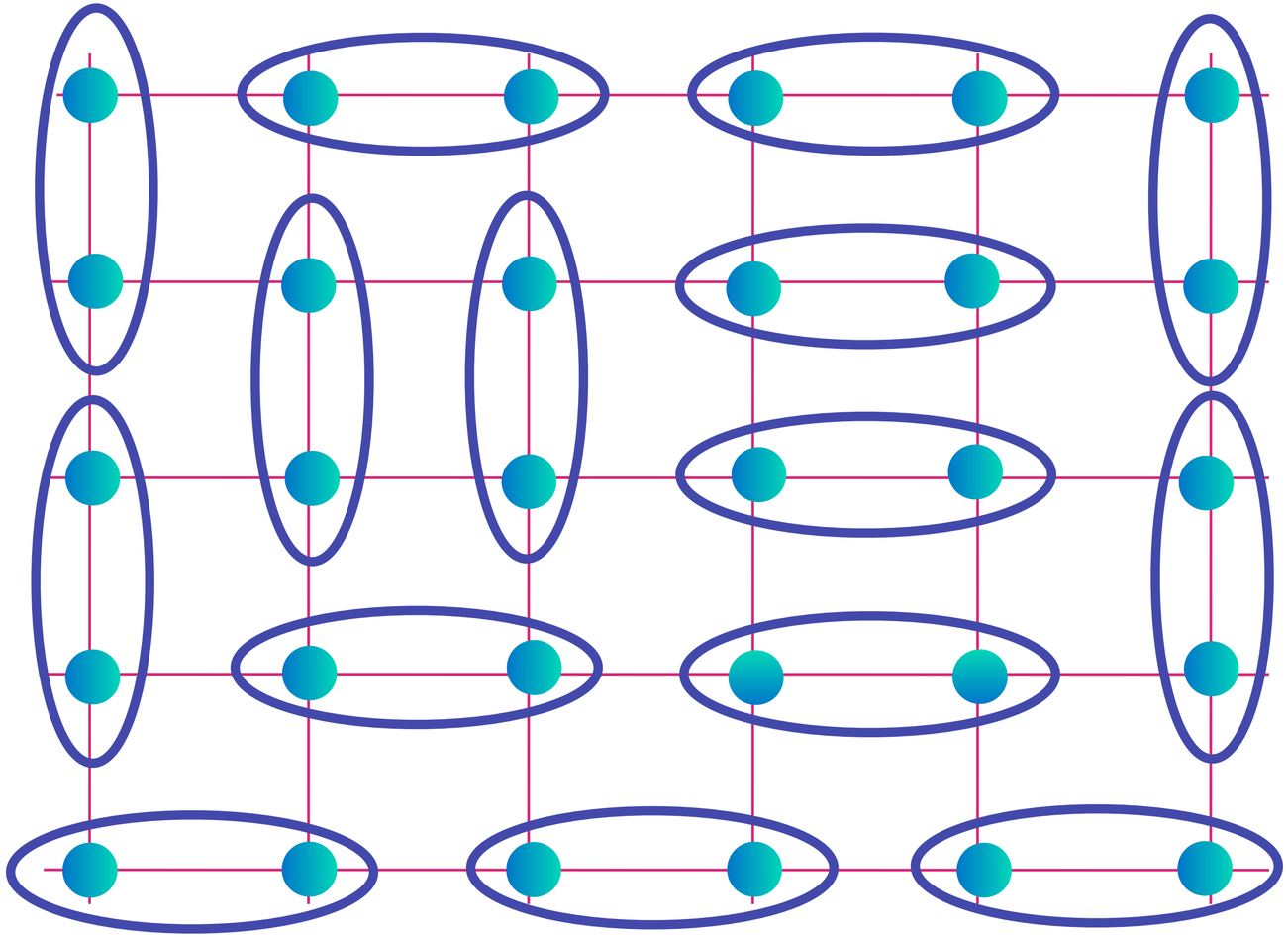

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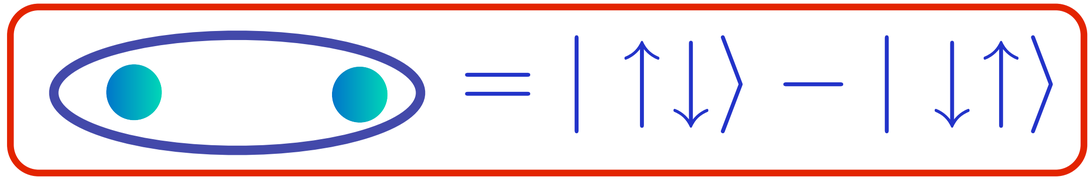

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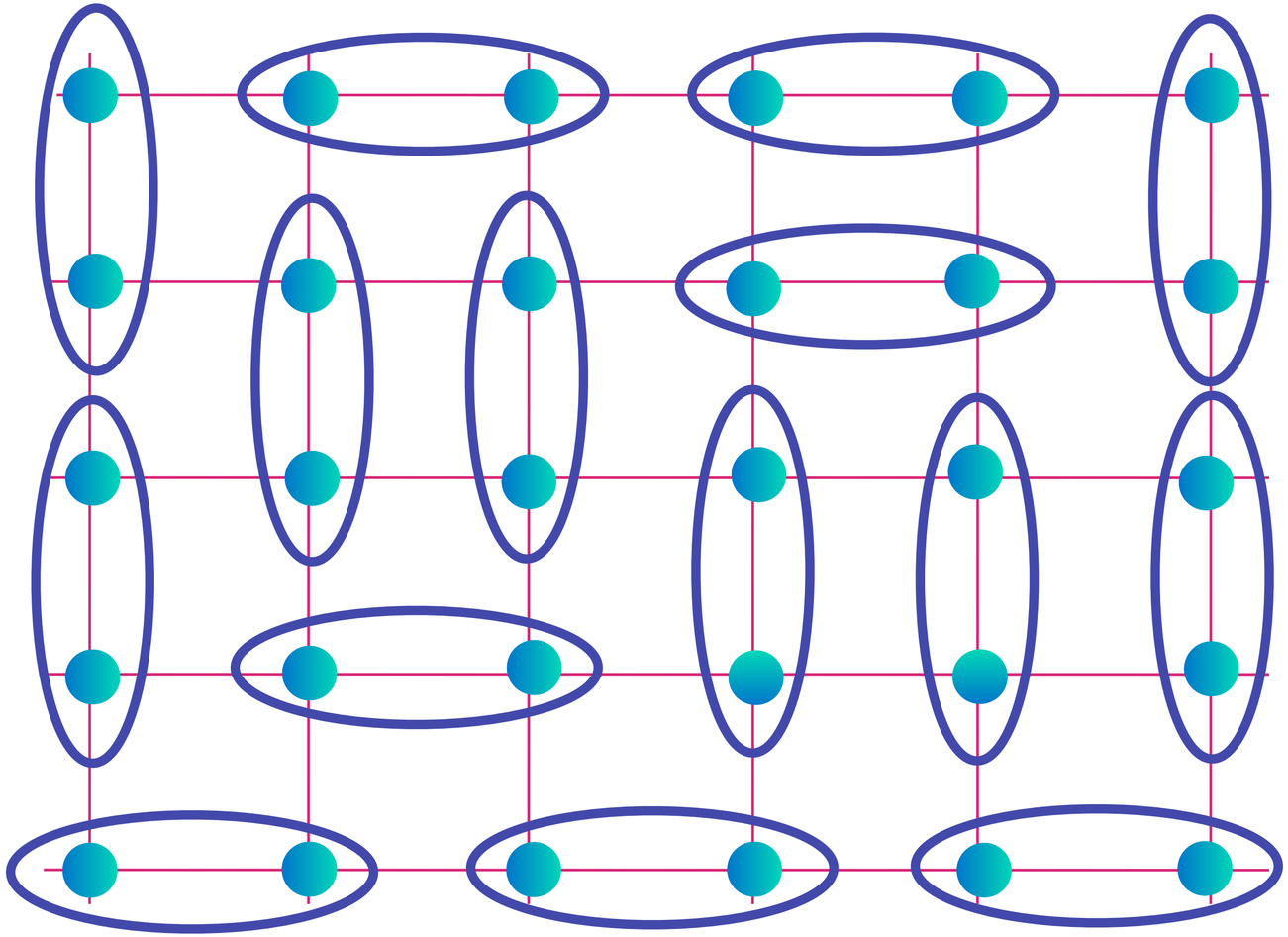

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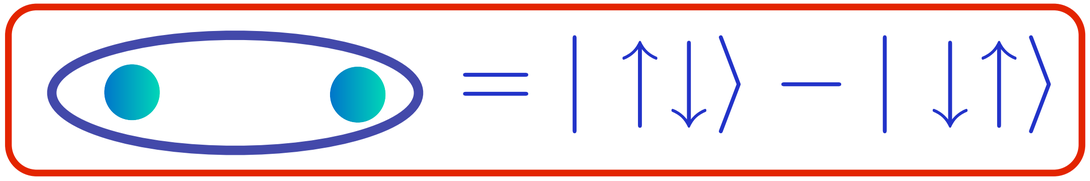

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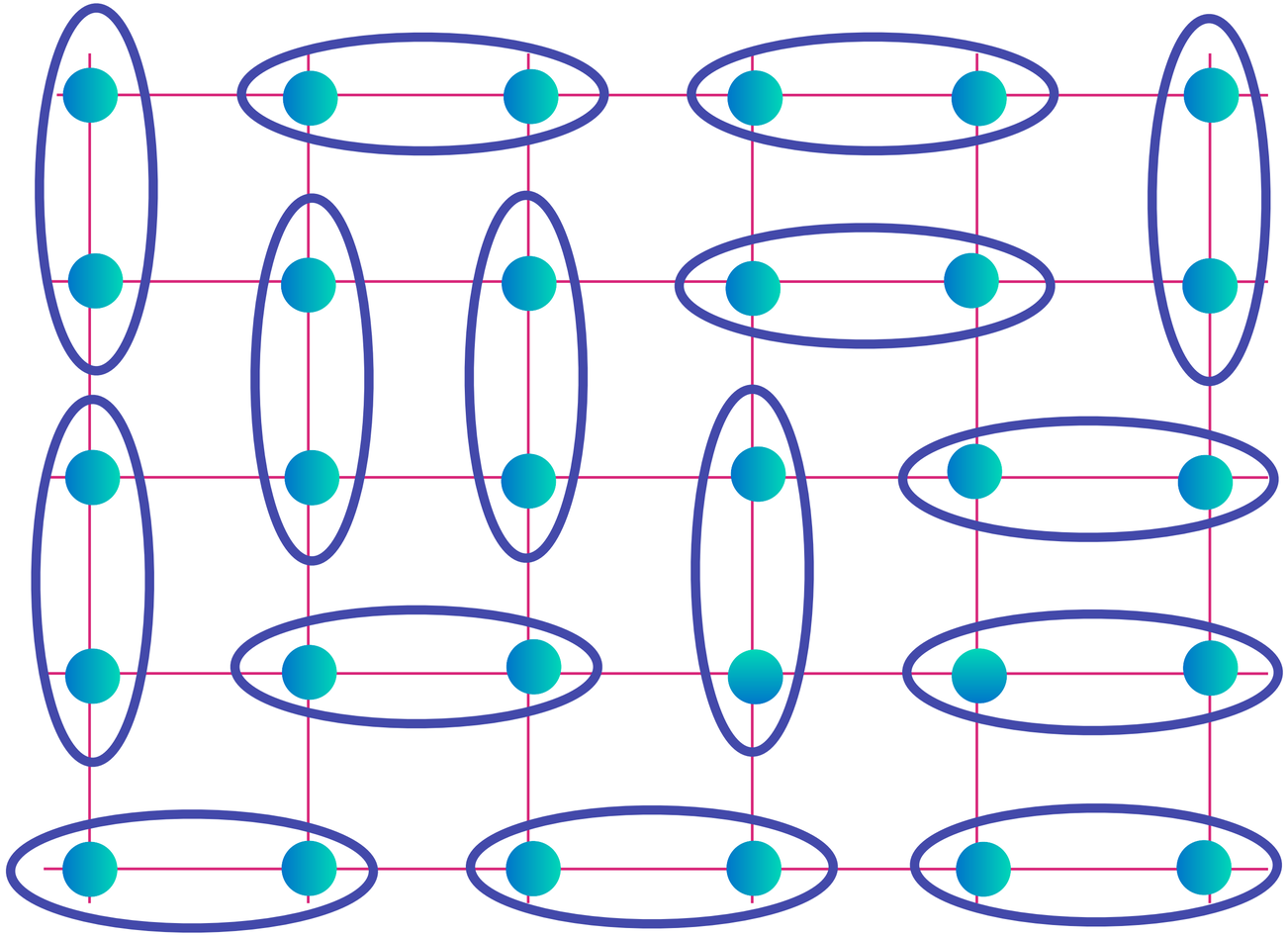

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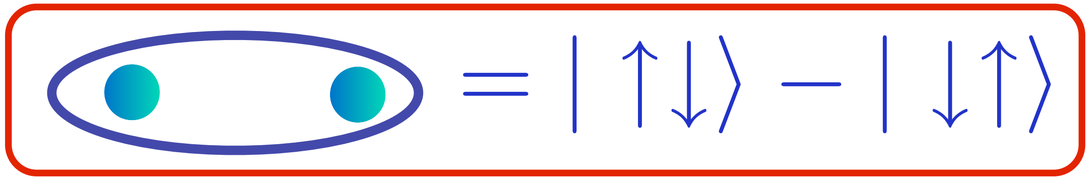

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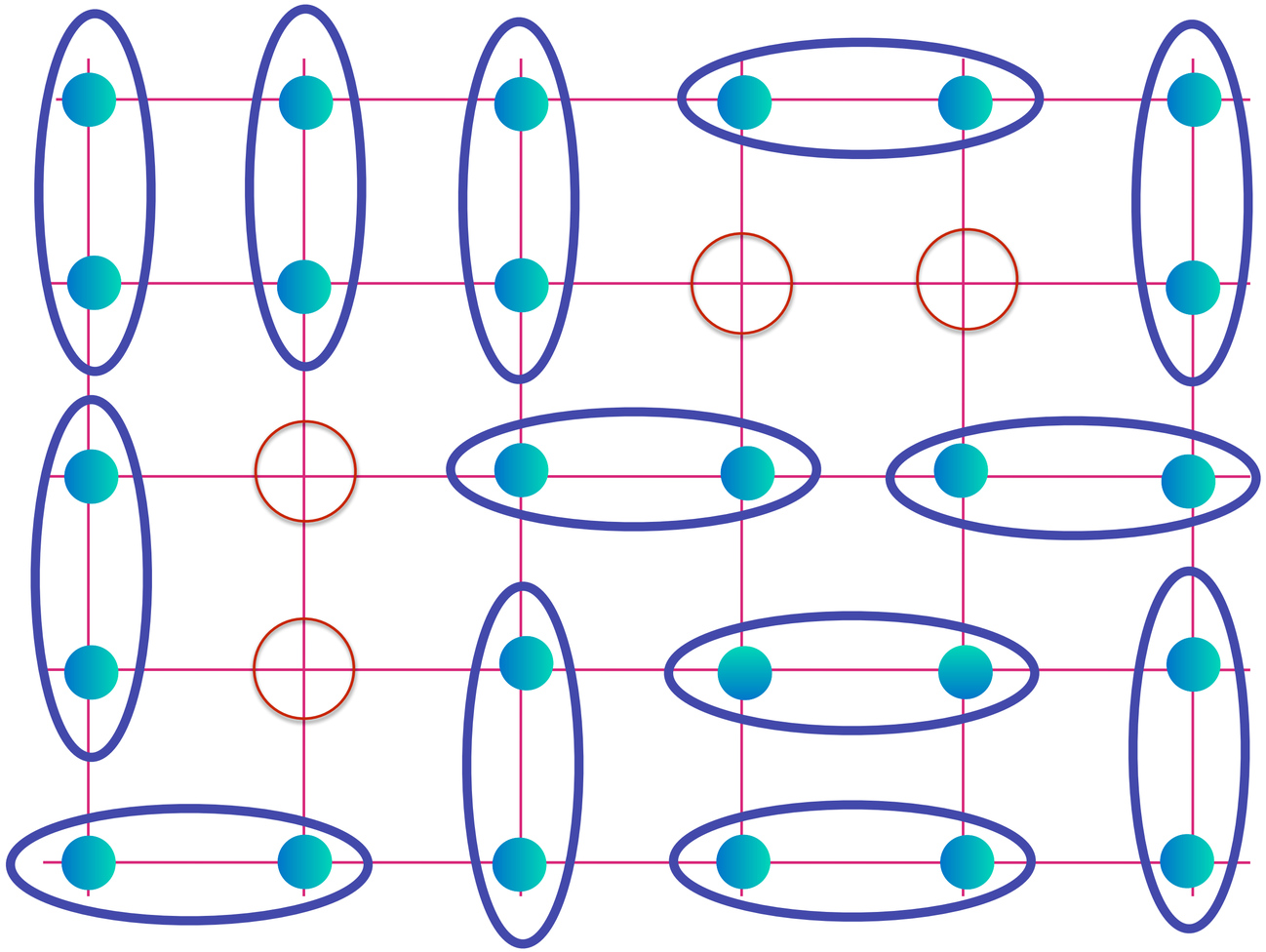

$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Superconductivity

Bose condensation of electron pairs

S.N. Bose (1924)

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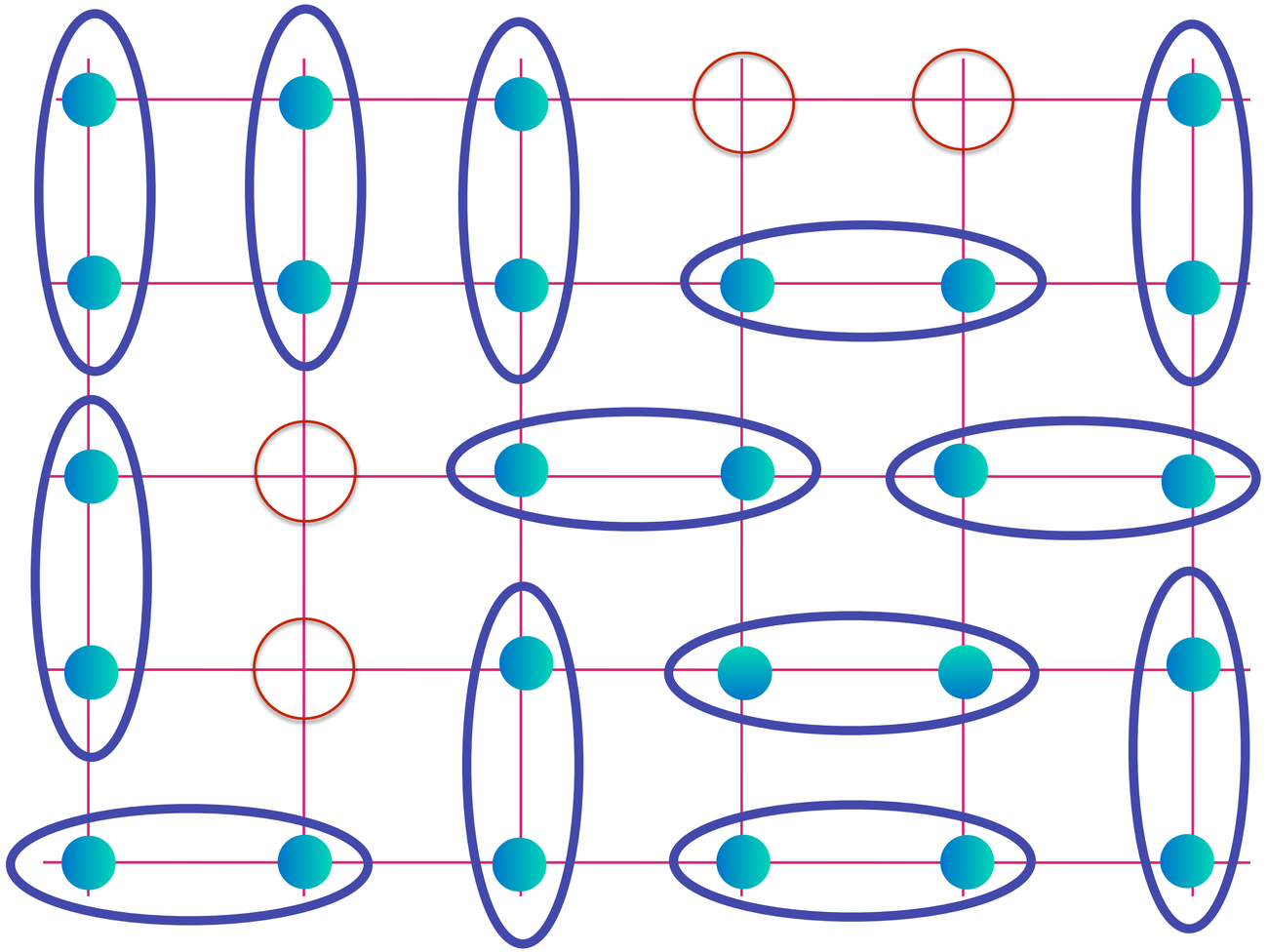

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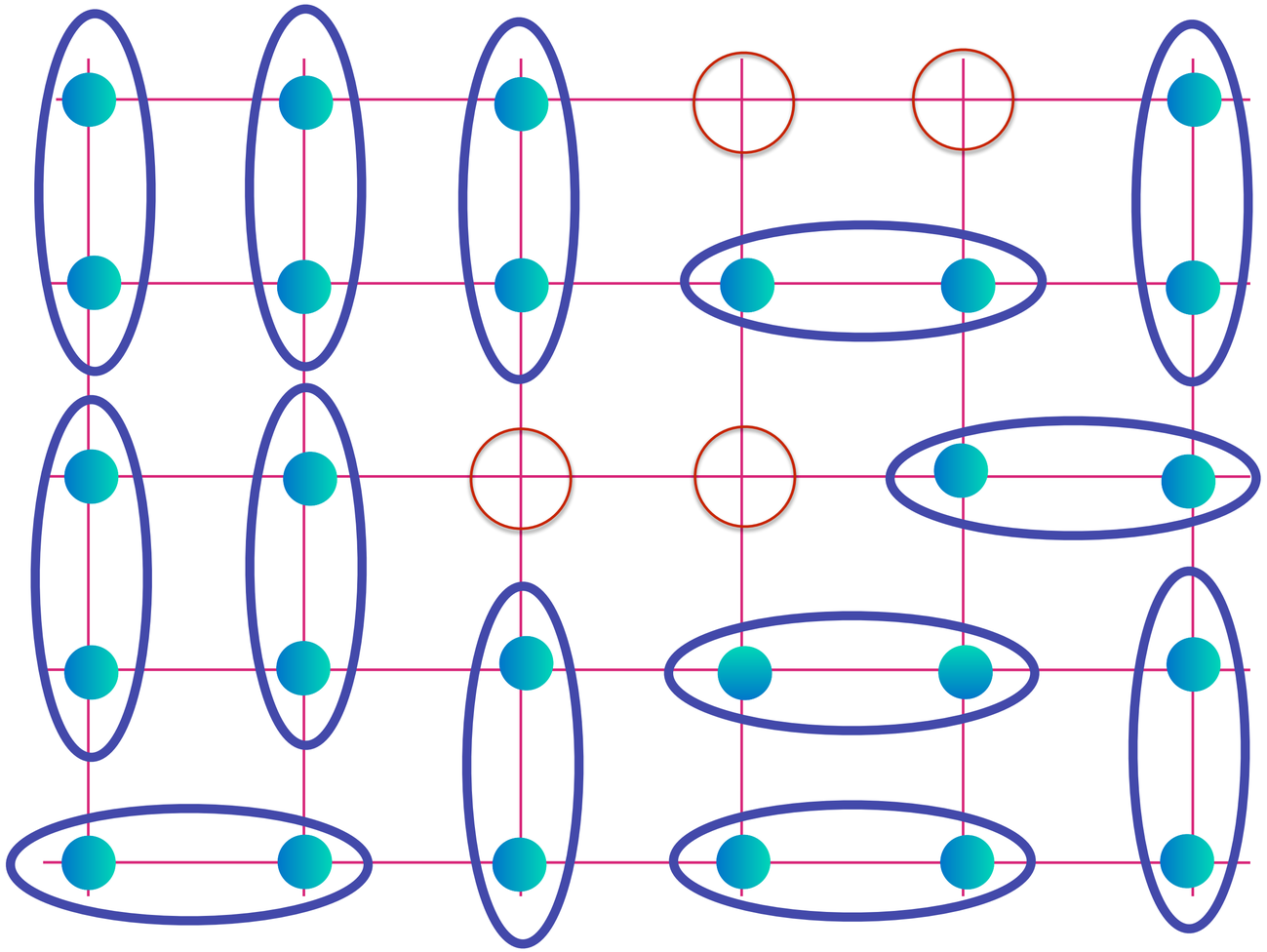

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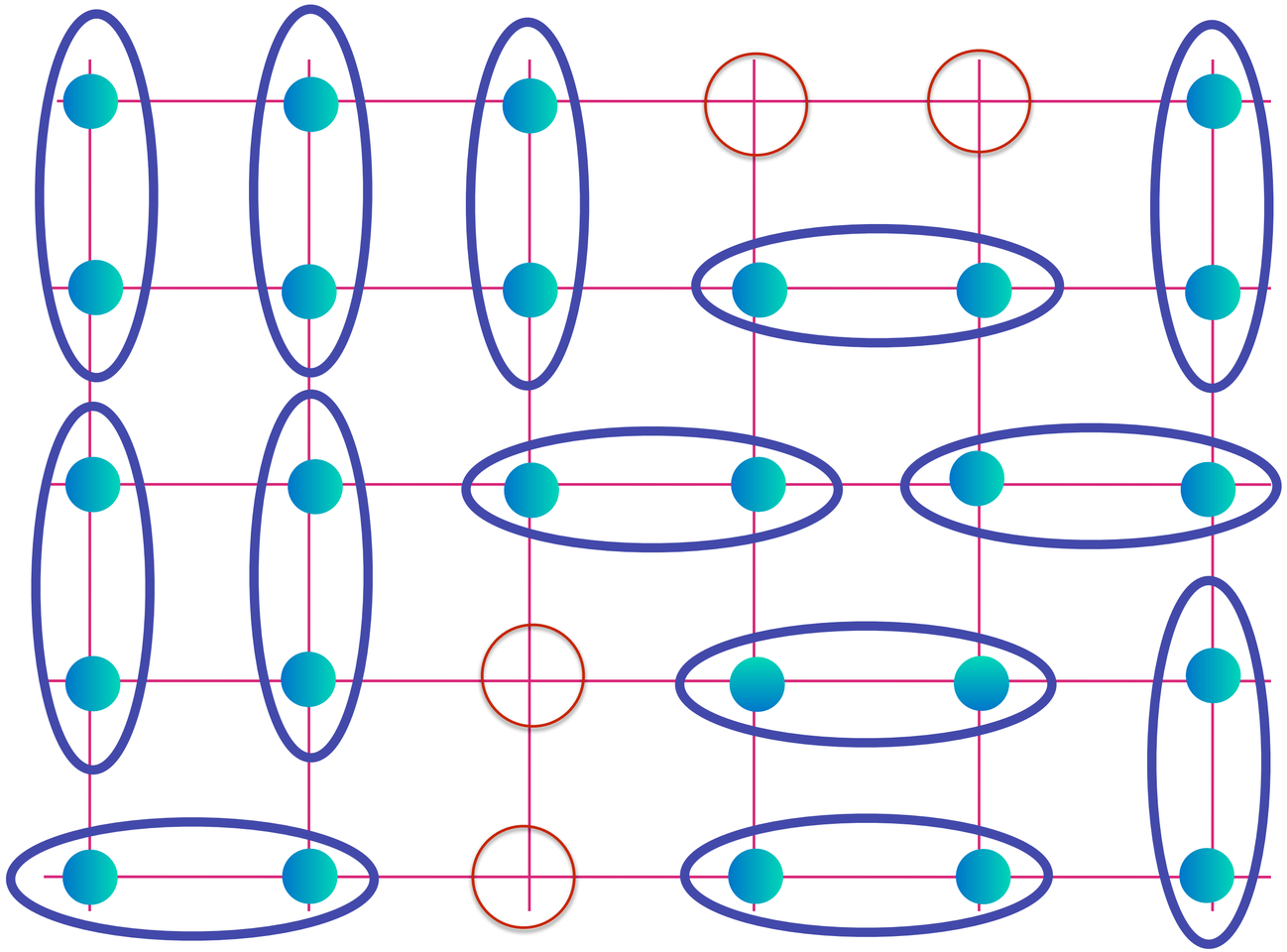

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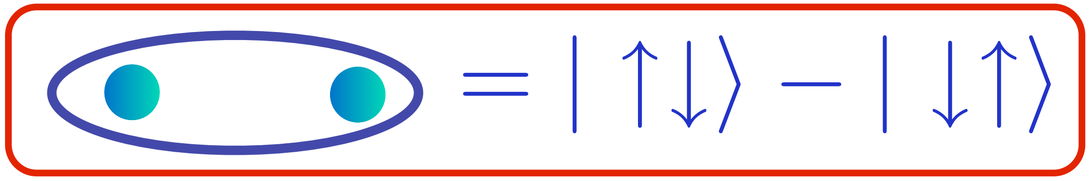

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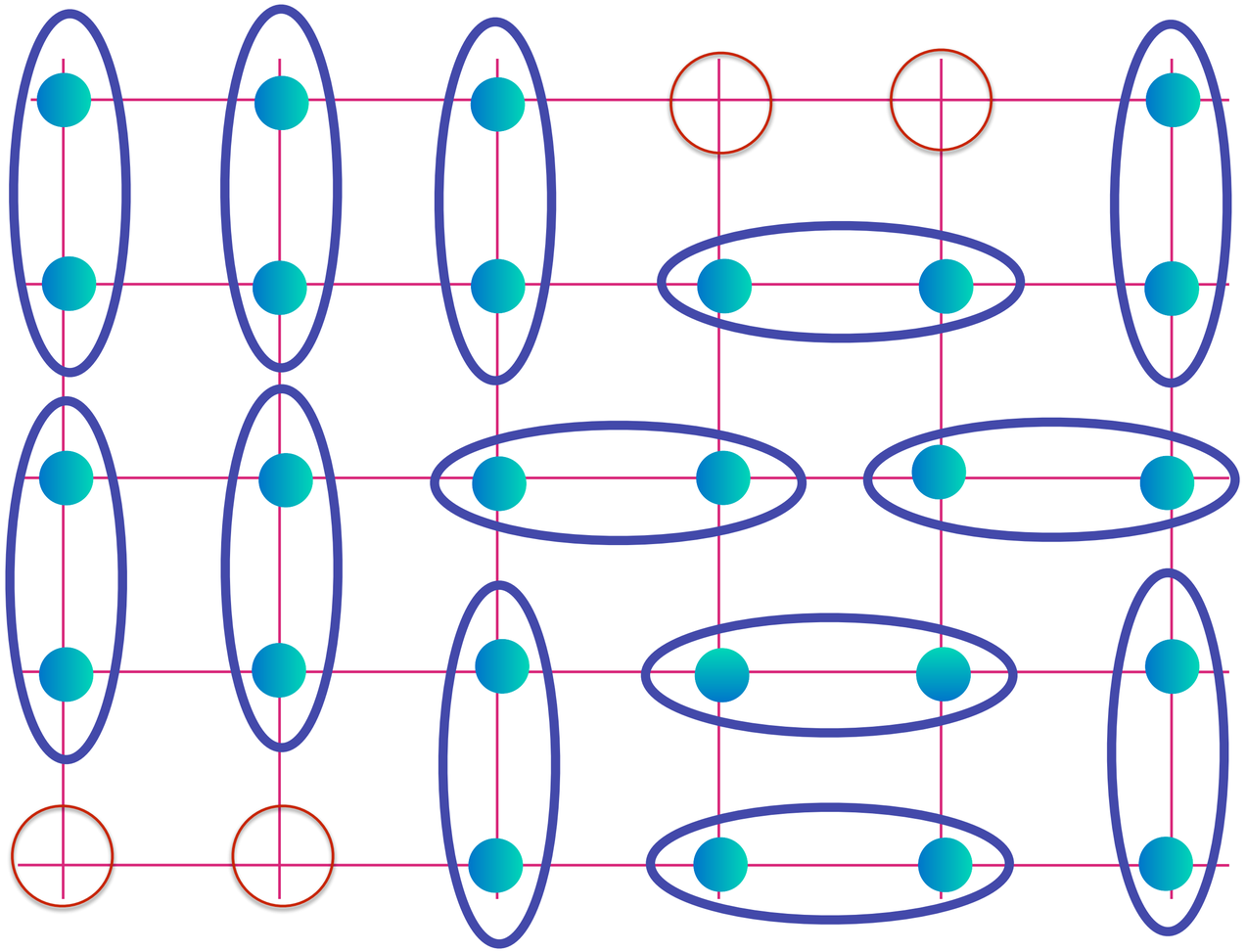

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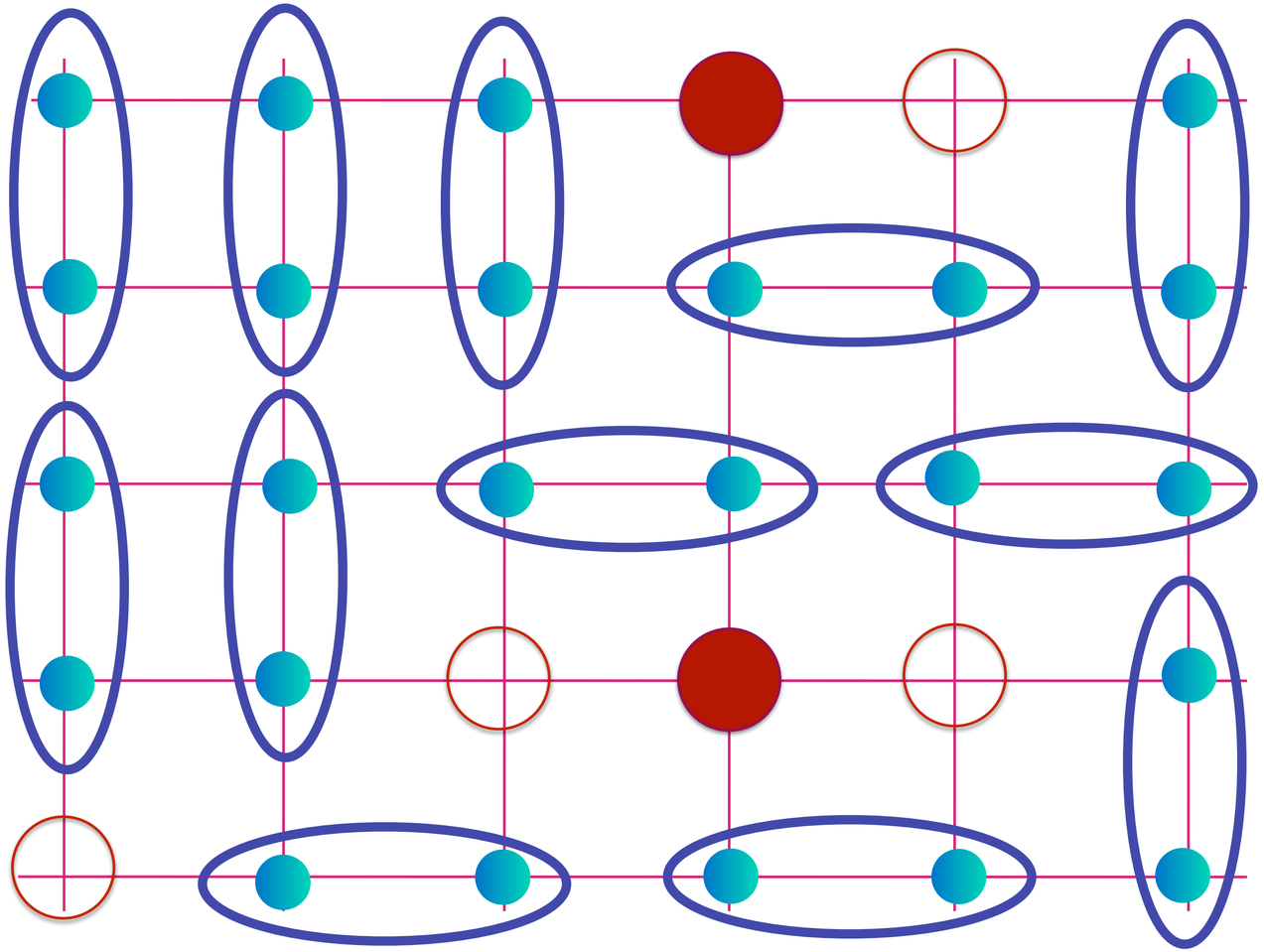

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Strange metal

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

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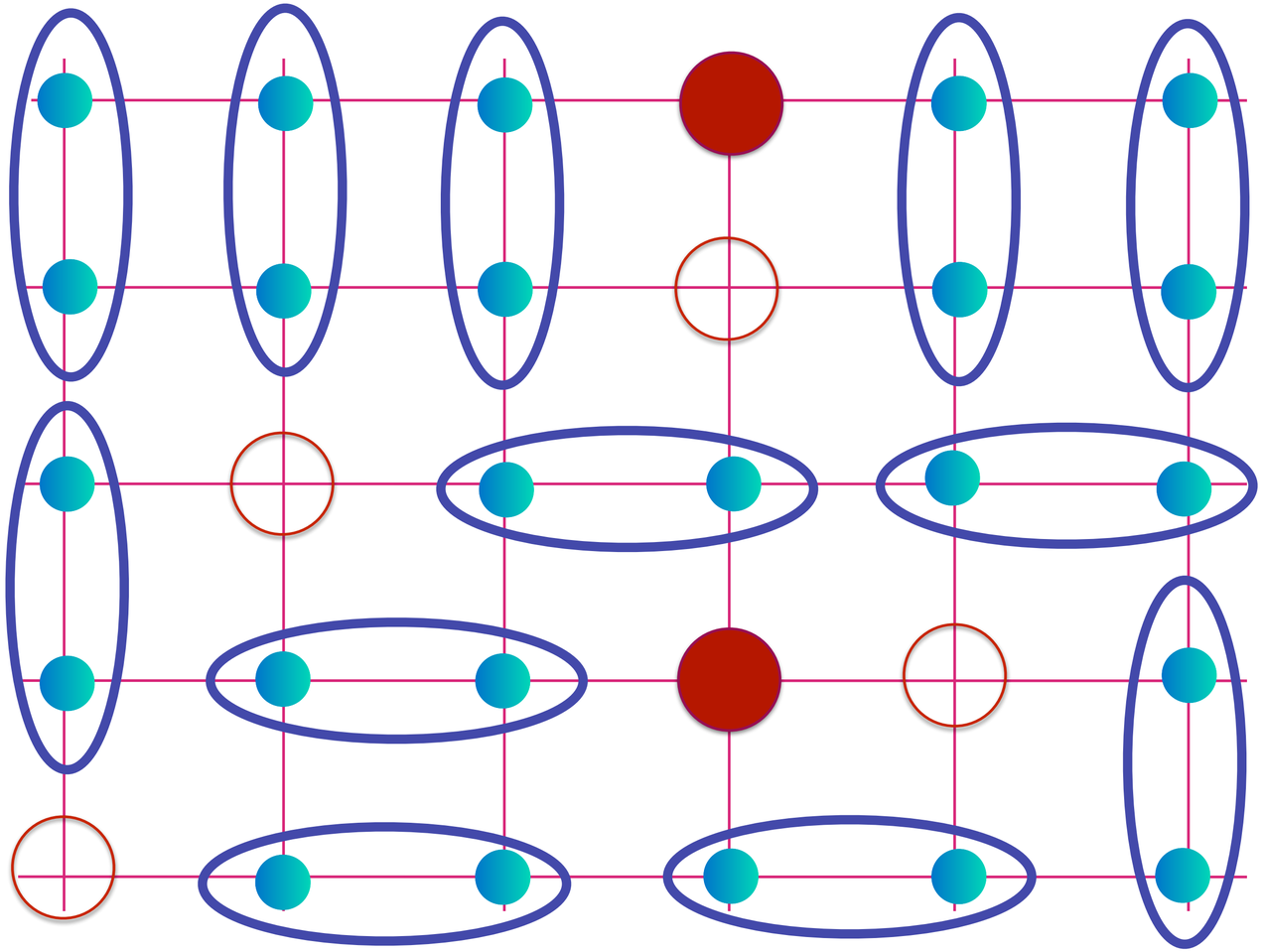

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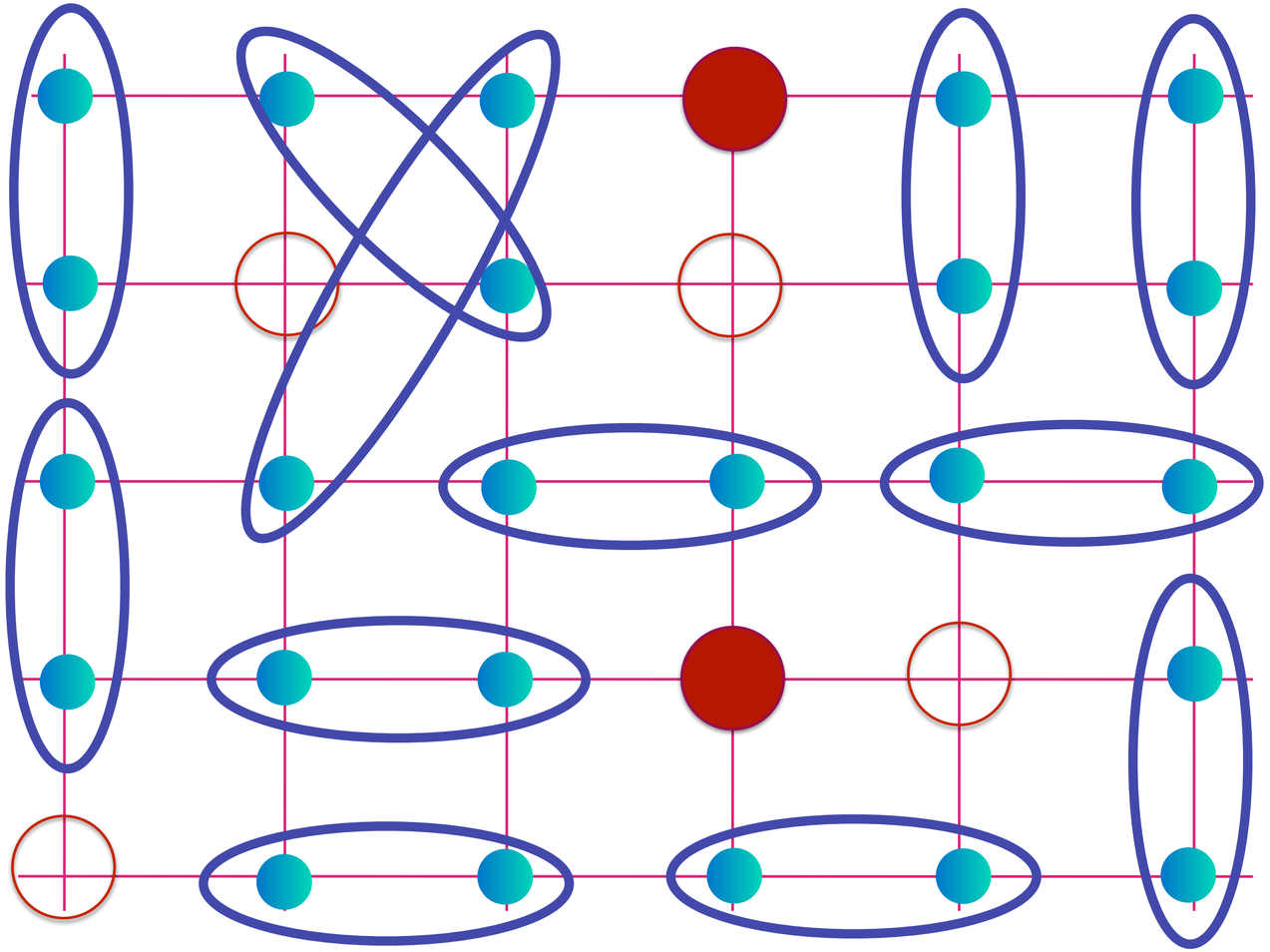

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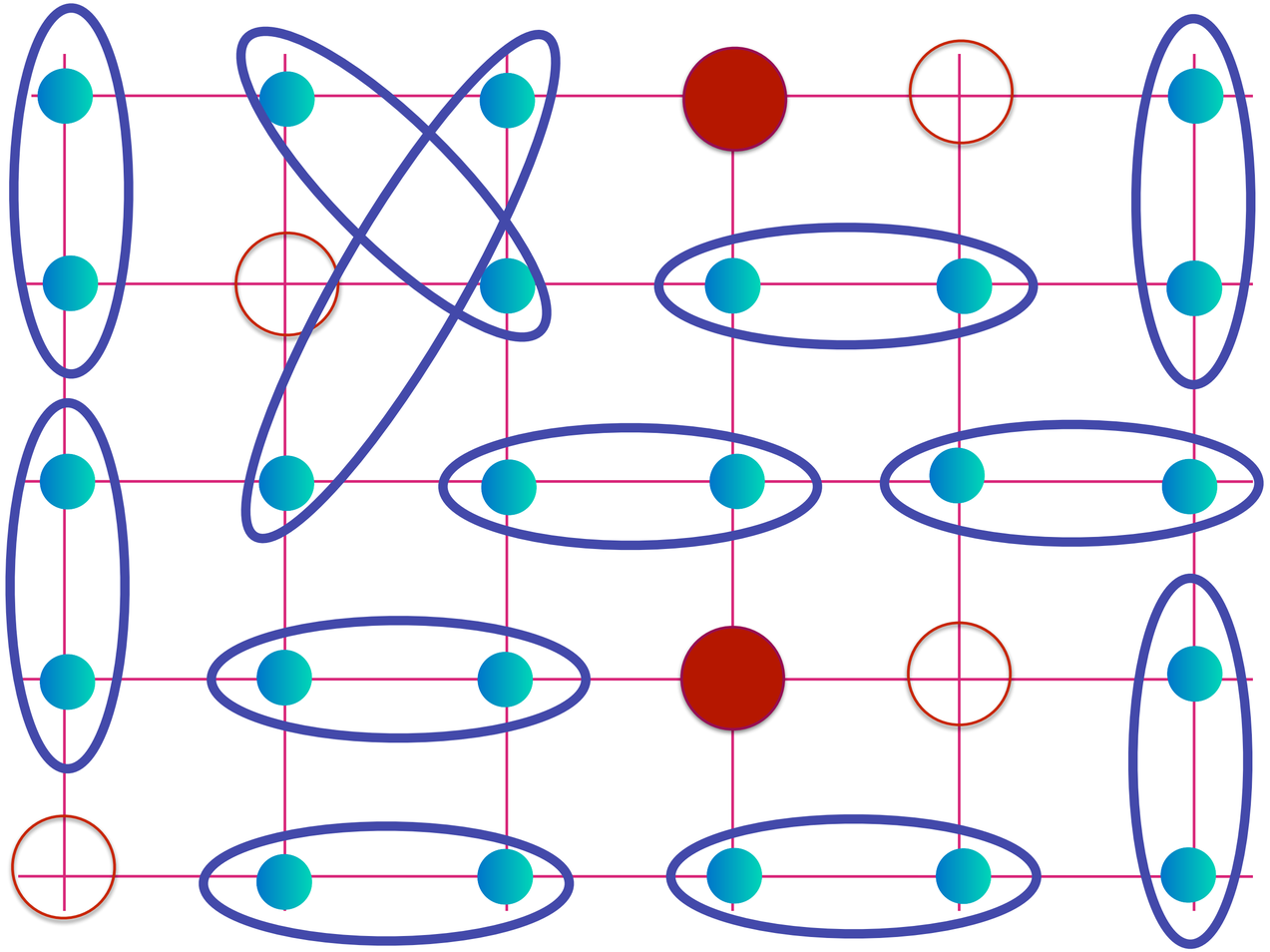

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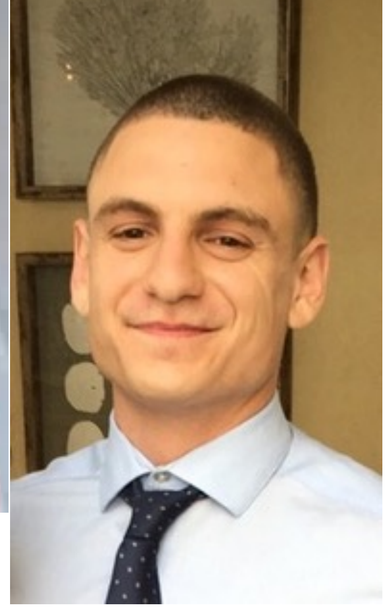
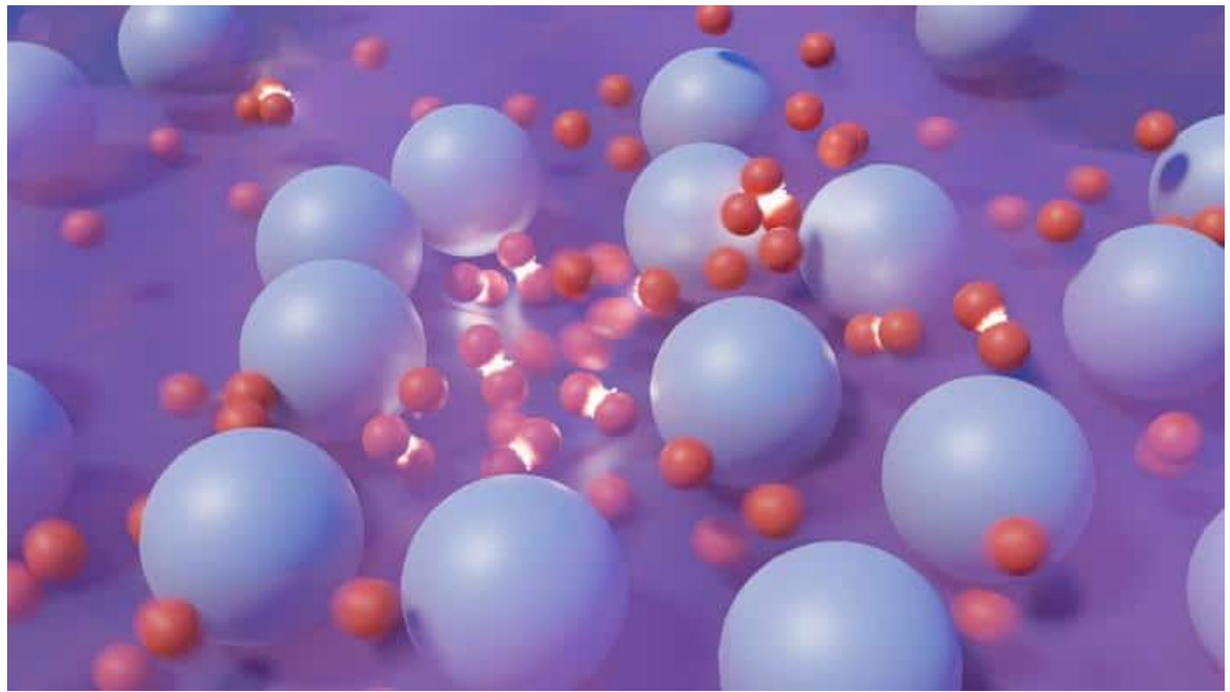
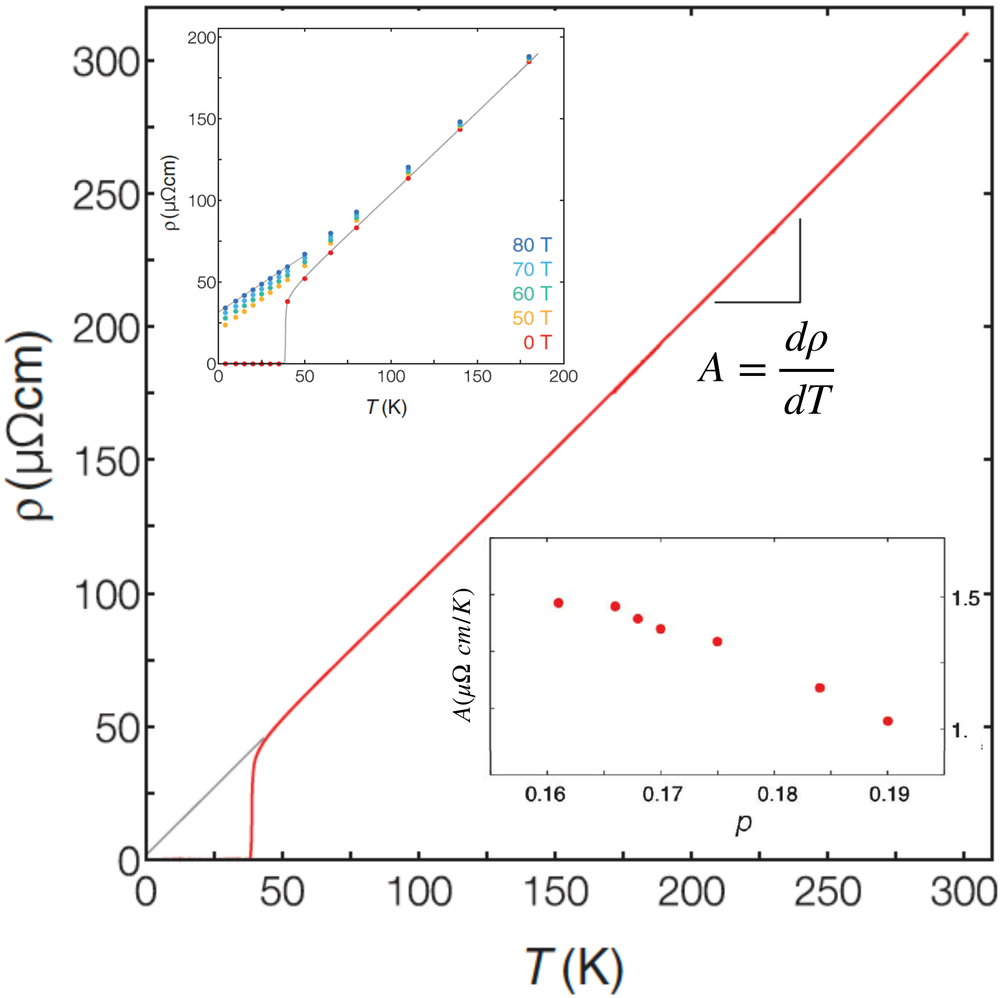
Aavishkar Patel
Flatiron Institute

Haoyu Guo
Cornell



Ilya Esterlis
Wisconsin



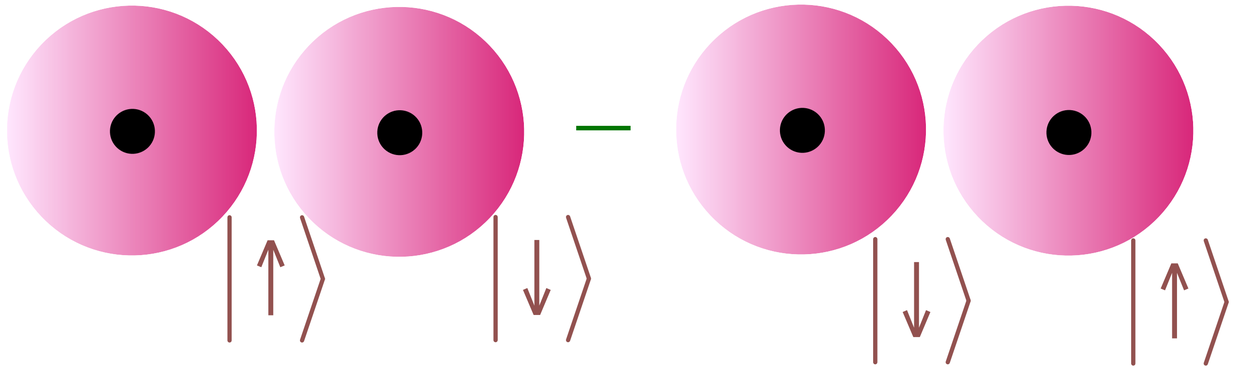


LSCO: Giraldo-Gallo et al. 2018

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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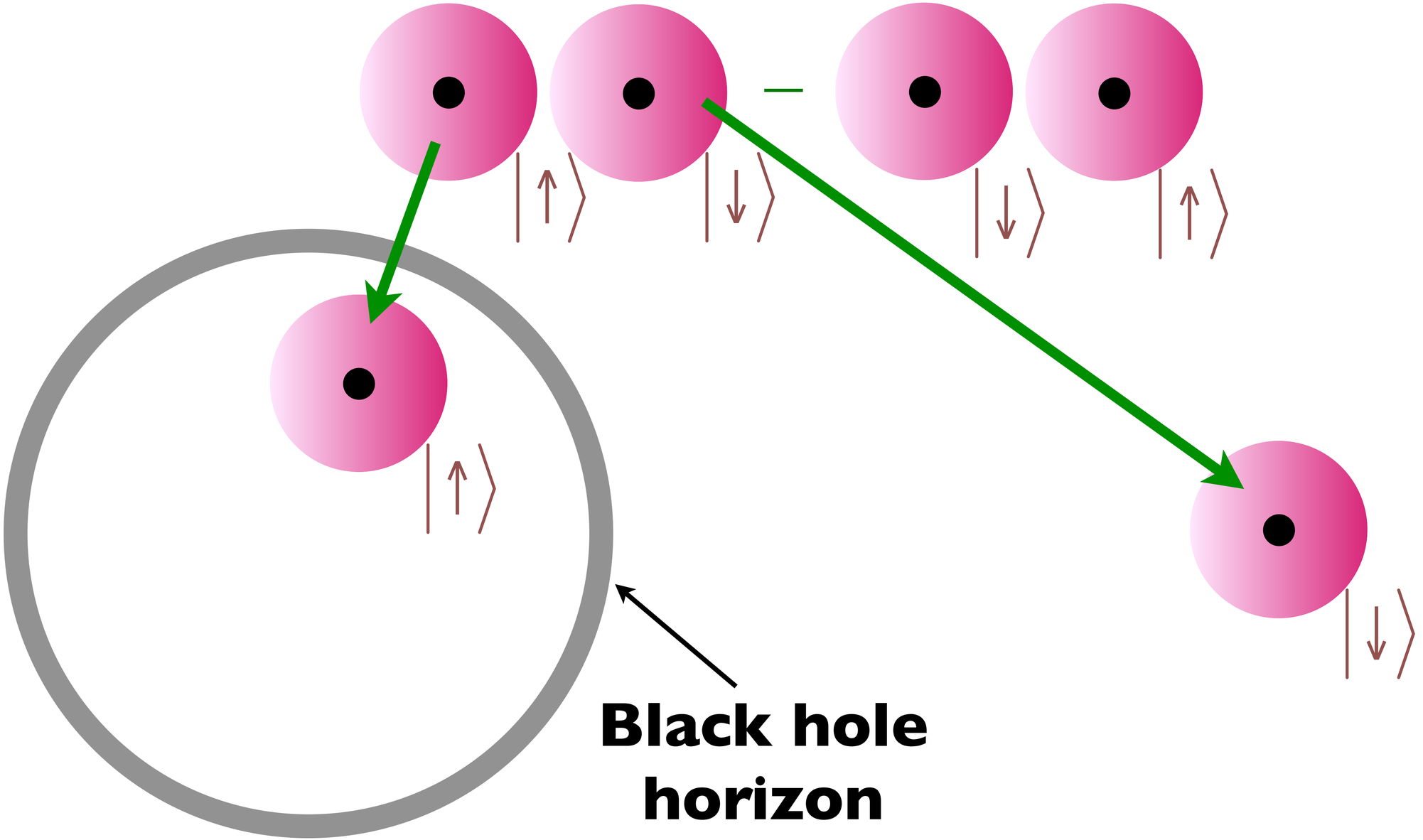

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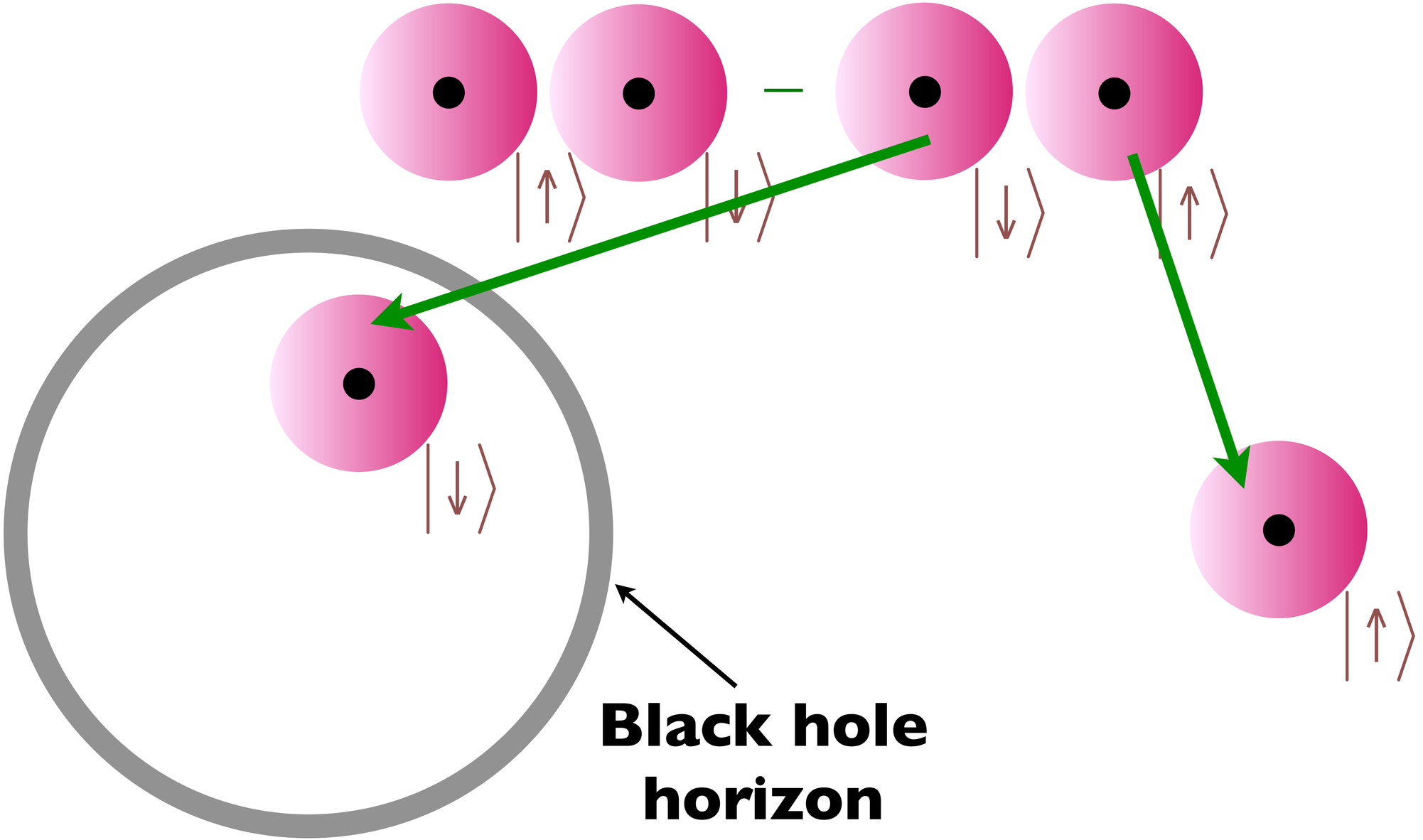
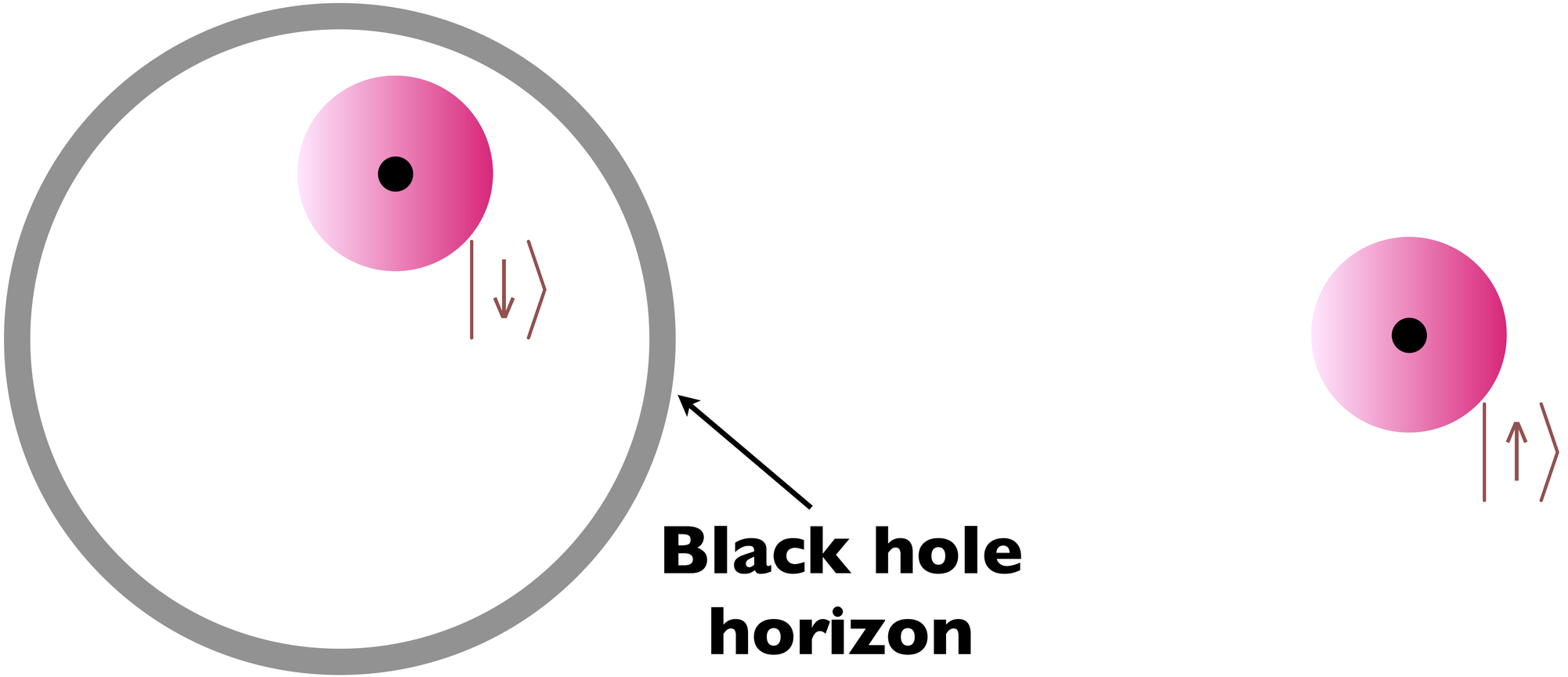


Quantum Entanglement across a black hole horizon

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



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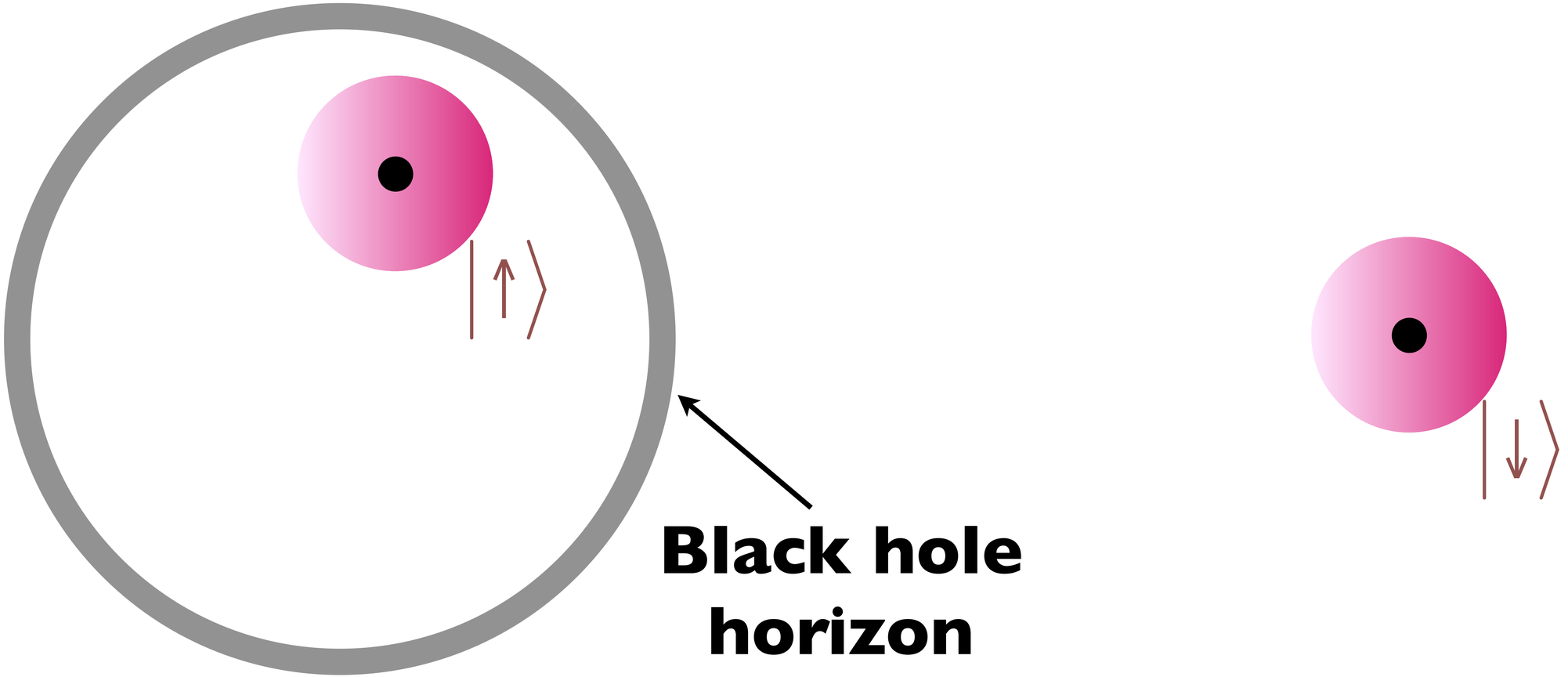
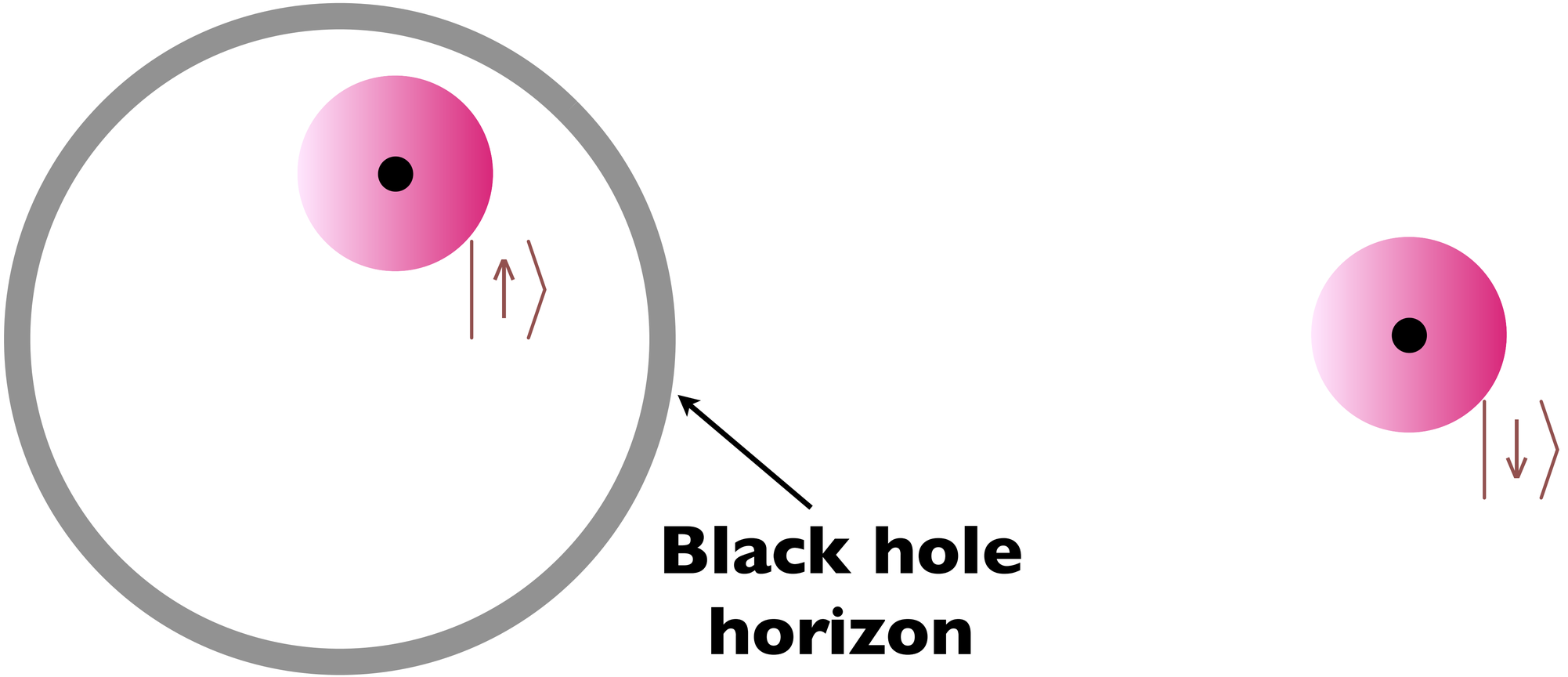


Quantum Entanglement across a black hole horizon

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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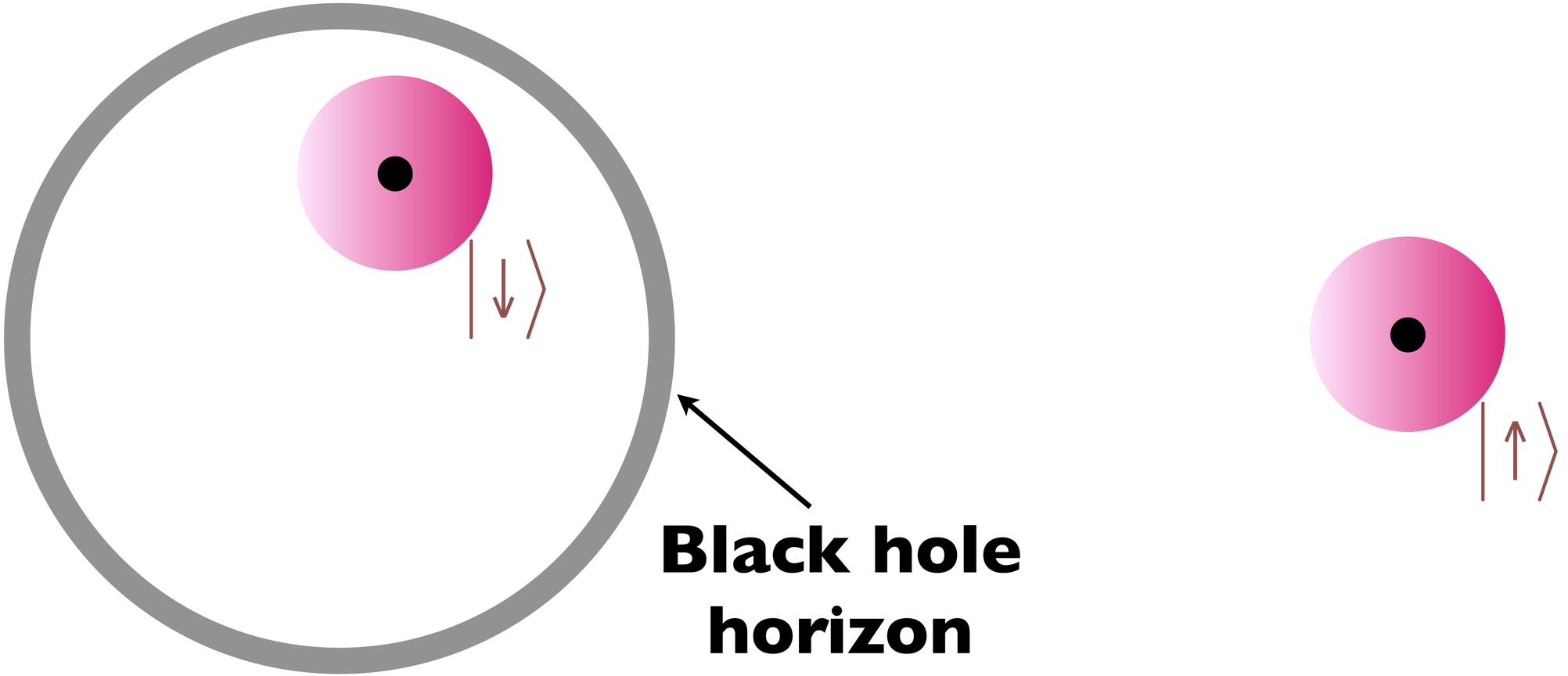
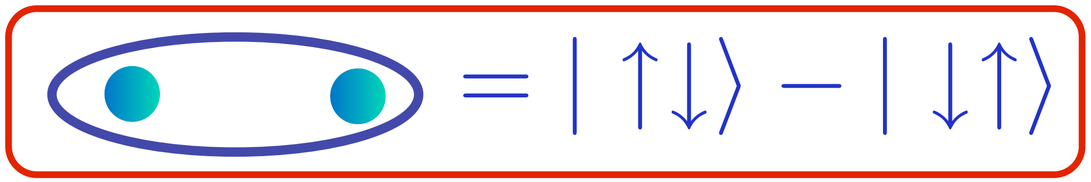
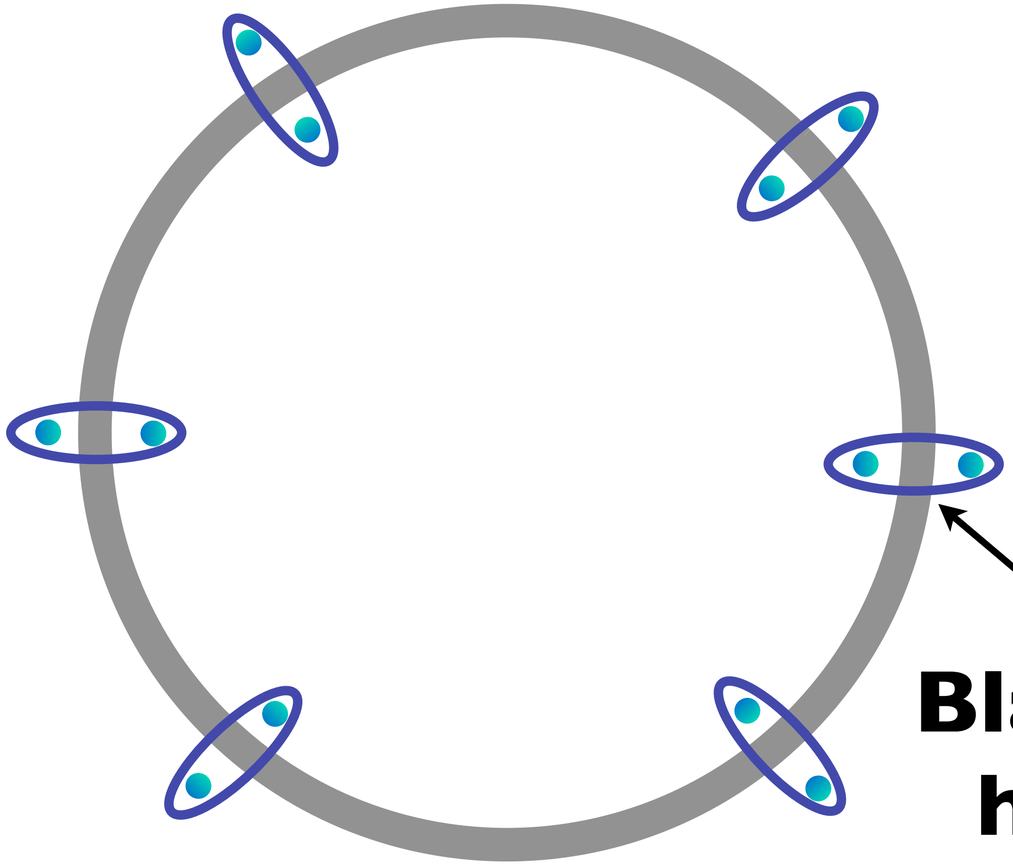


Quantum Entanglement across a black hole horizon

Quantum entanglement on the surface





Black hole horizon

By computations *outside* the black hole, Hawking obtained

$$S = \frac{k_B A c^3}{4G\hbar}$$

where A is area of the black hole horizon.

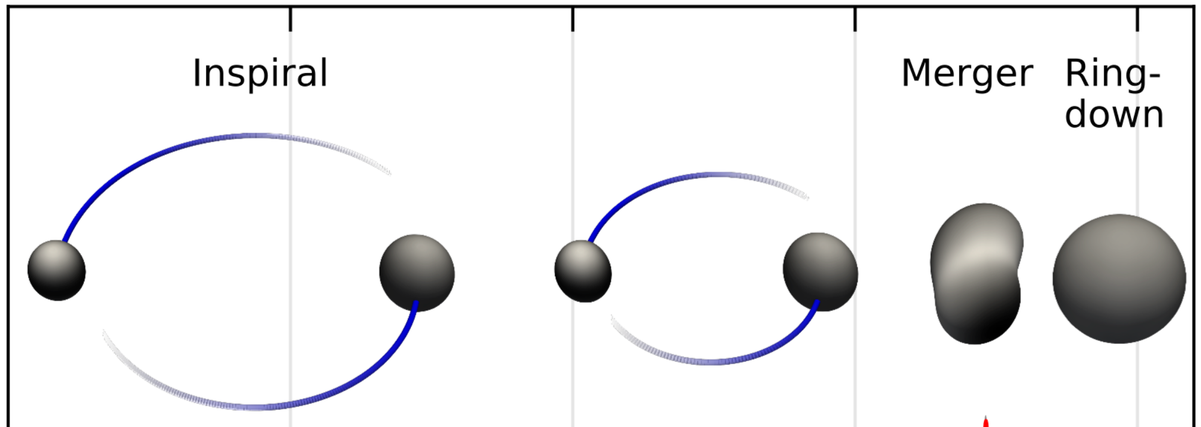
All other systems have entropy proportional to their volume.

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. $S = A k_B c^3/(4G\hbar)$.

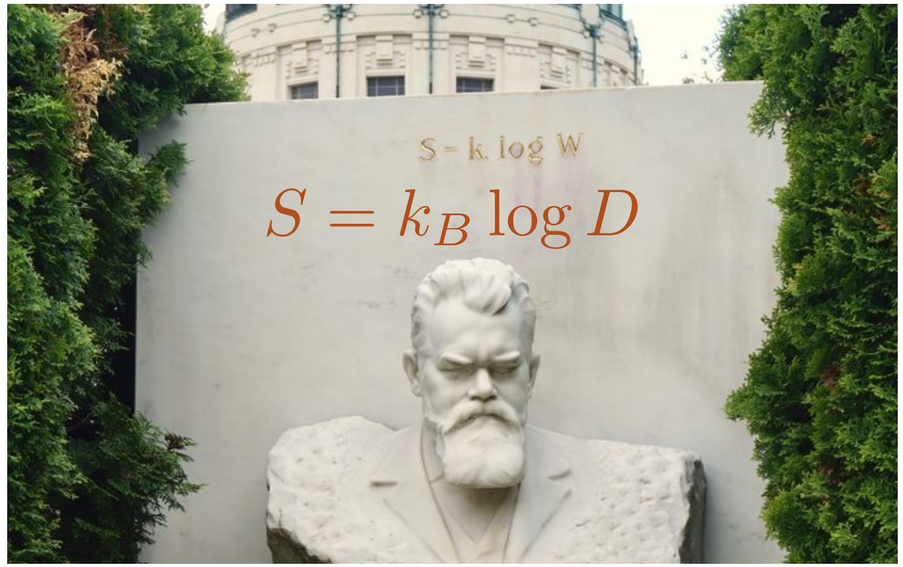
- They relax to thermal equilibrium in a time $\sim 8\pi GM/c^3 = \hbar/(k_B T_H)$, the Planckian time also found in strange metals, which suggests a connection to the SYK model!

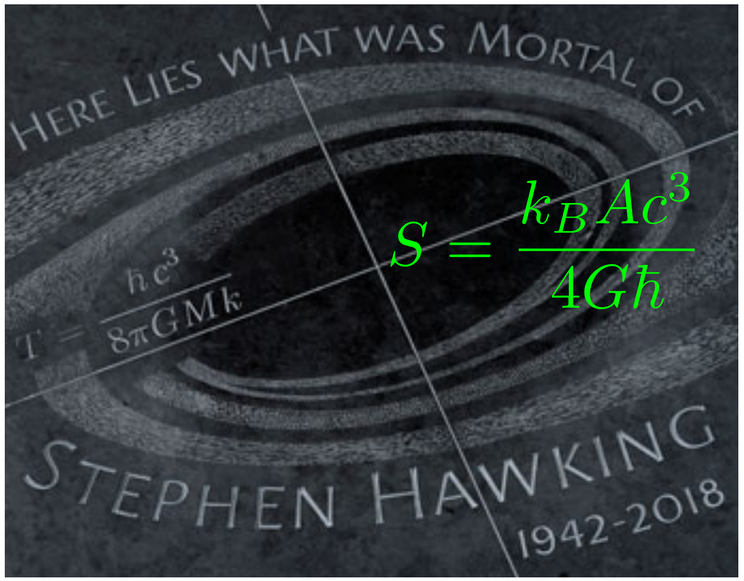


J. D. Bekenstein, PRD **7**, 2333 (1973)
S. W. Hawking, Nature **248**, 30 (1974)
C.V. Vishveshwara, Nature **227**, 936 (1970)

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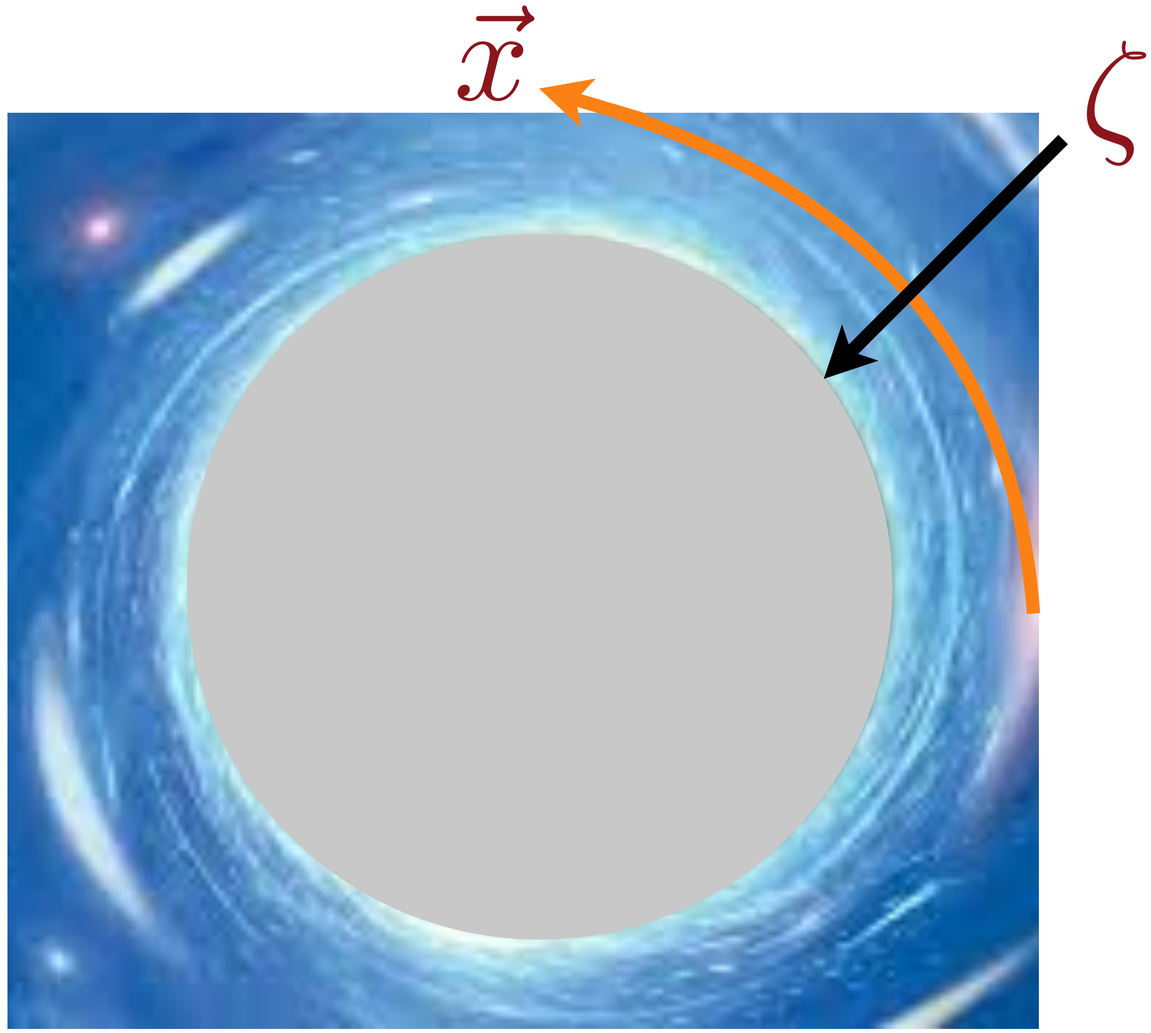
- Answer from string theory for 'supersymmetric' charged black holes: $D(E) = e^S \delta(E)$ *i.e.* all the states required by Hawking's entropy have exactly the same energy.

Strominger, Vafa (1996)

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



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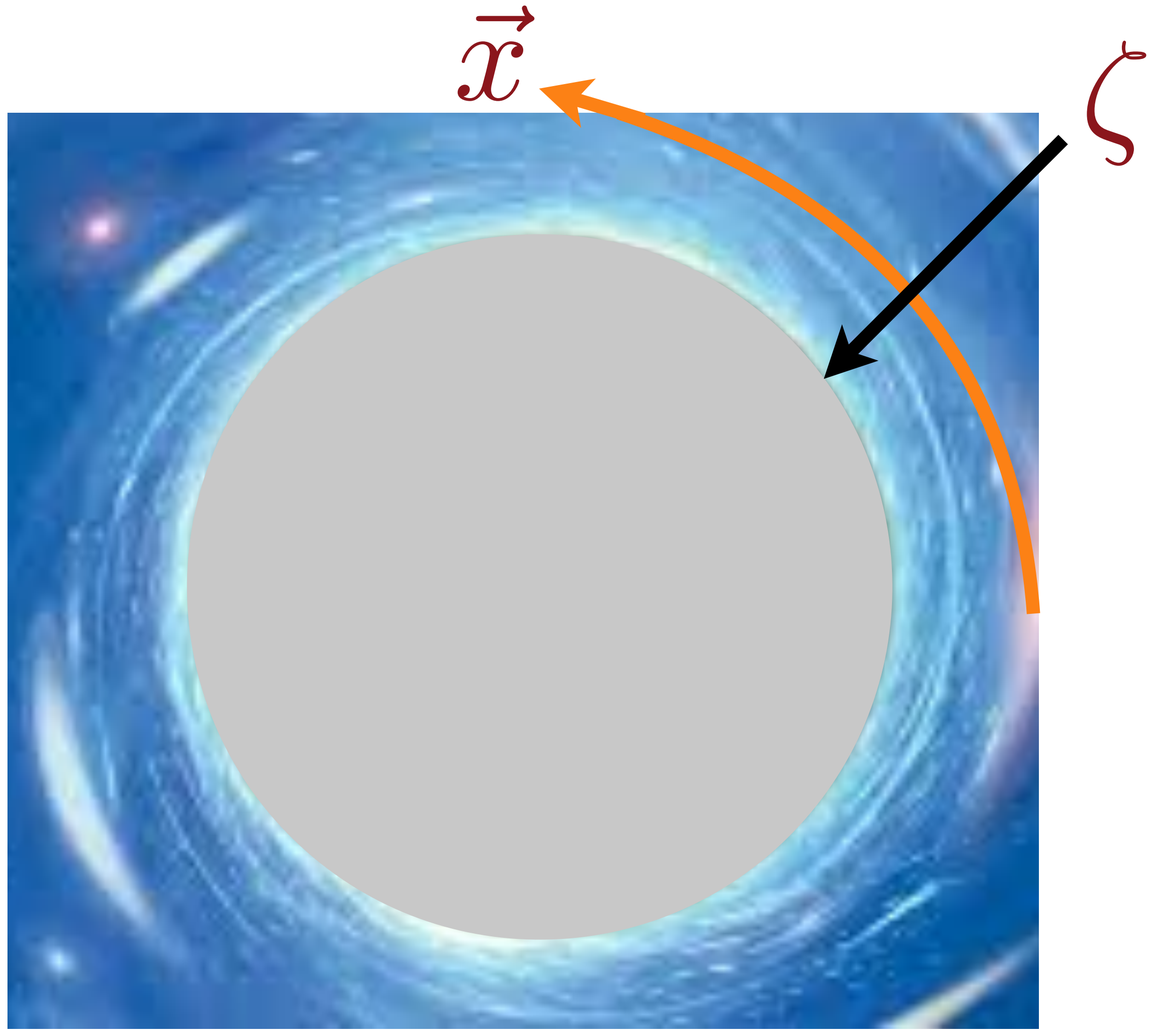
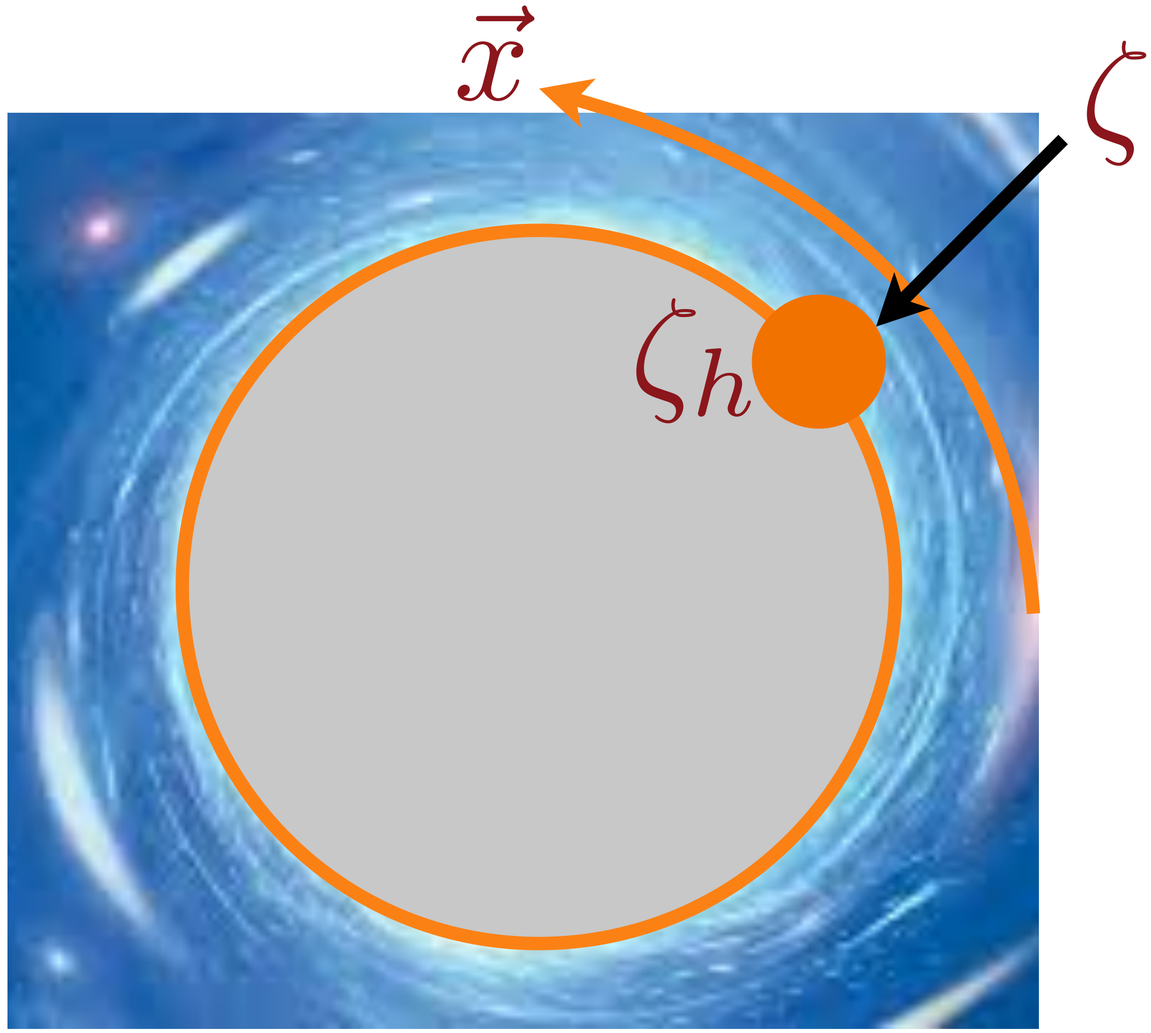


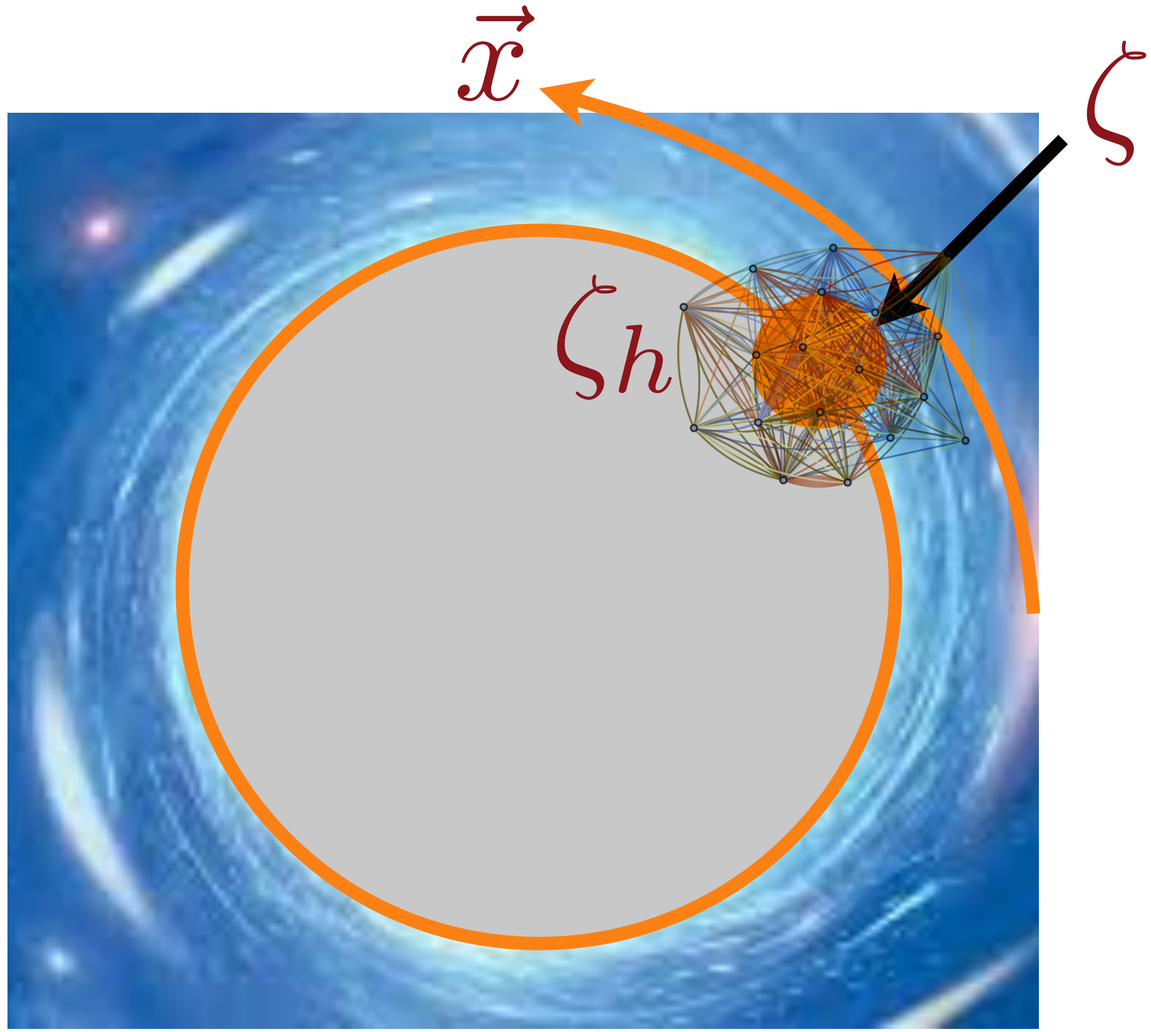
Zooming into the near-horizon region of a charged black hole at low temperature, yields a theory in one space (ζ) and one time dimension

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 allow black hole solutions with a net charge



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)

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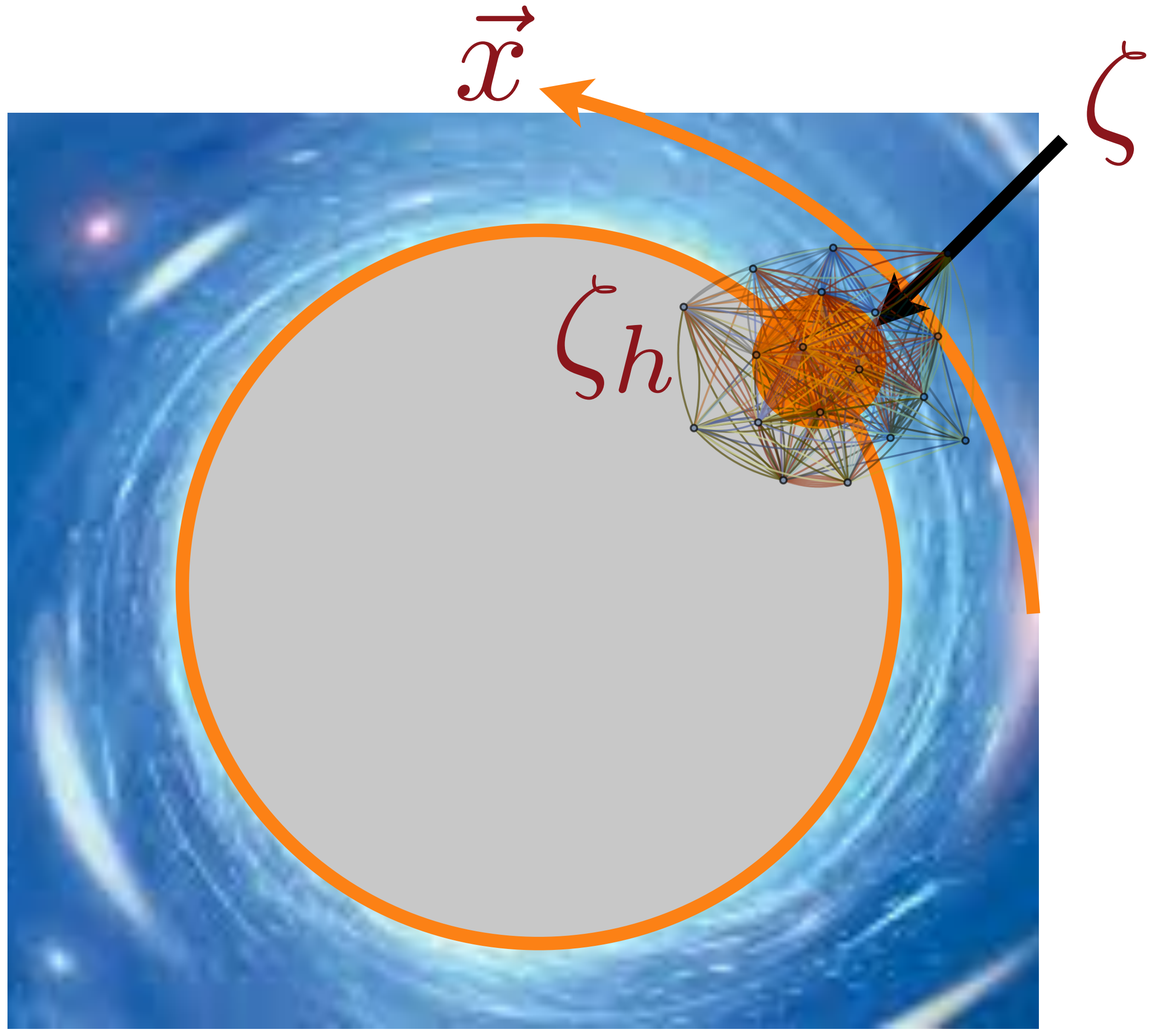

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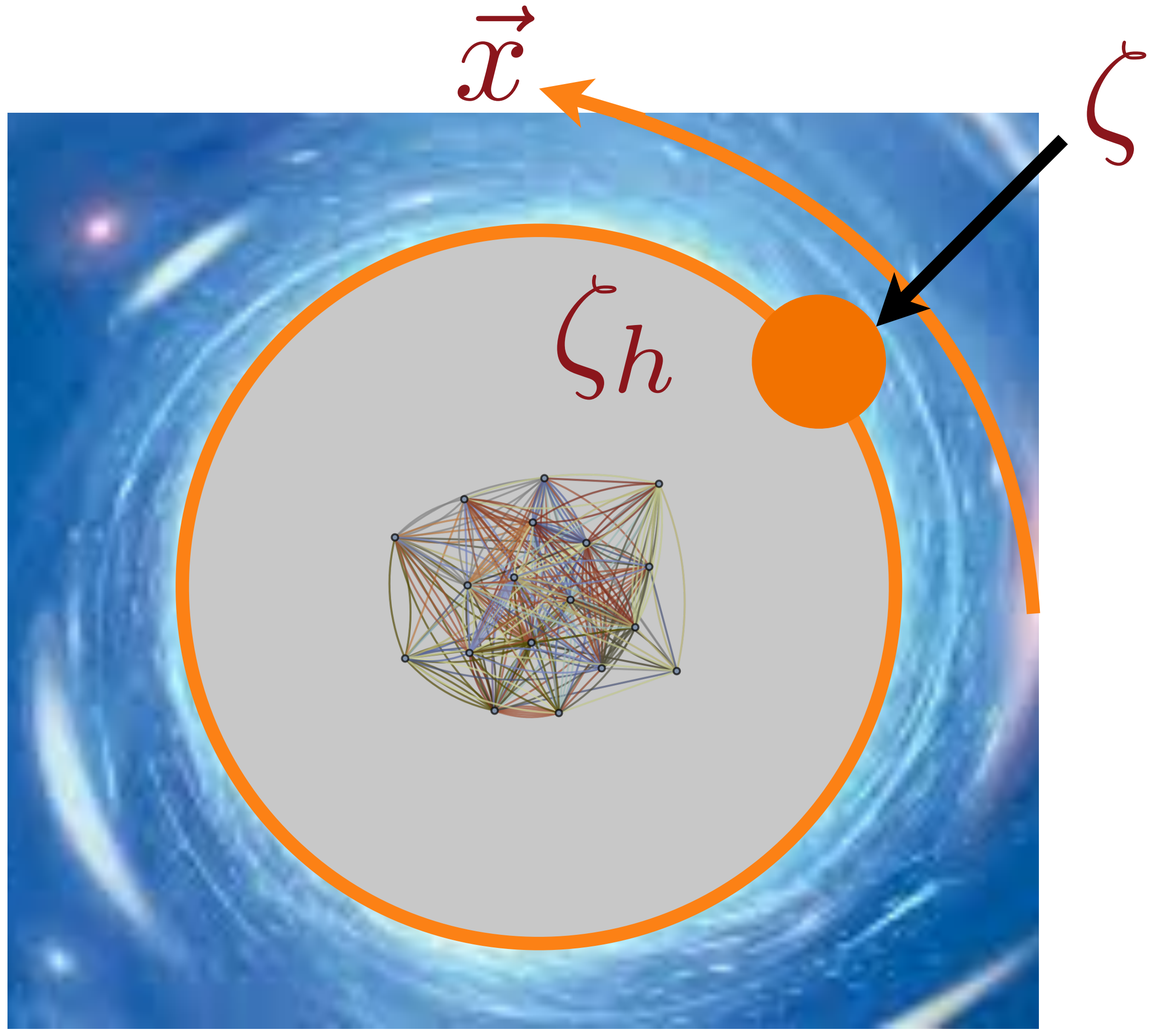

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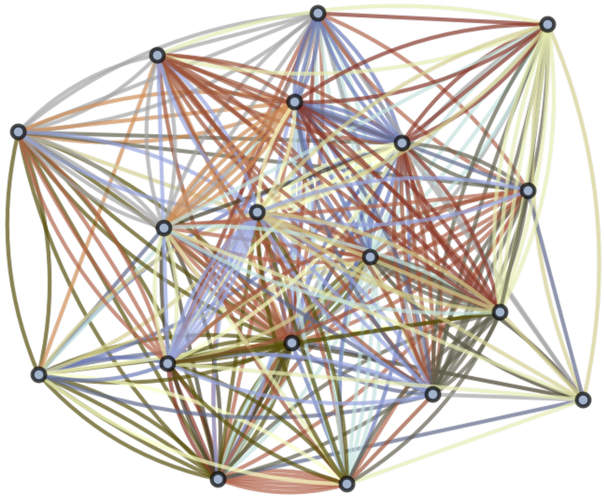
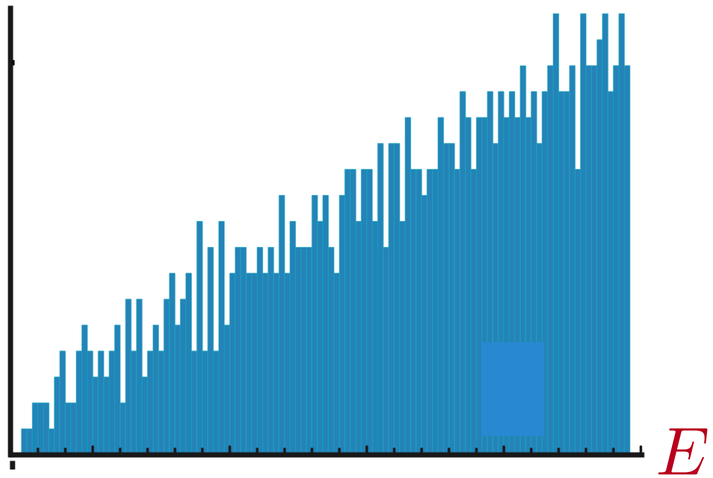
The Sachdev-Ye-Kitaev (SYK) model



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

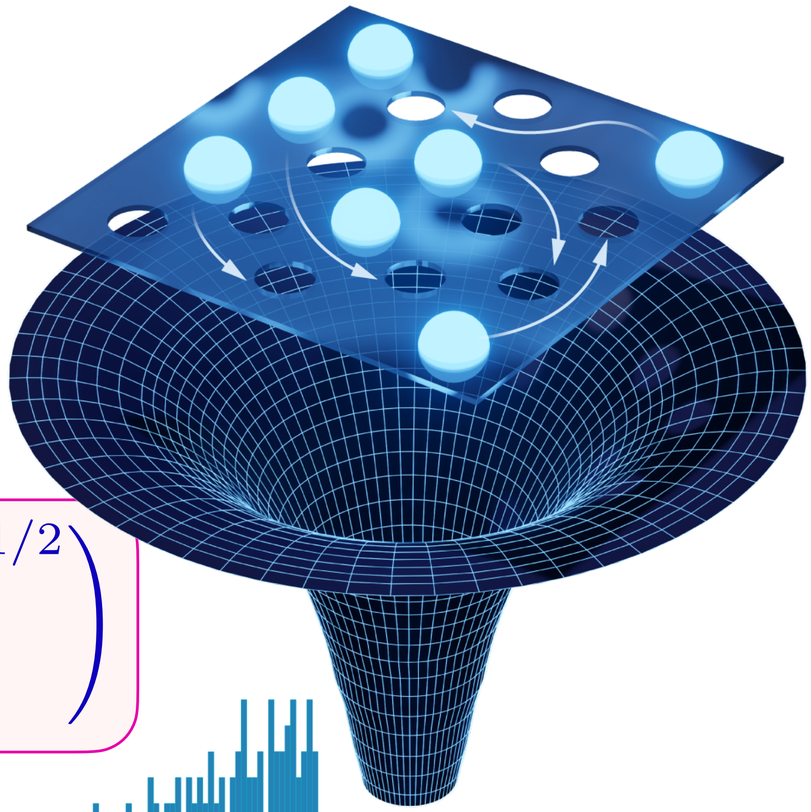
$$D(E) \sim \frac{1}{N} \exp\left(N s_0\right) \sinh\left(\left[2N\gamma E\right]^{1/2}\right)$$

where $s_0 = 0.46484769917080510749....$



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



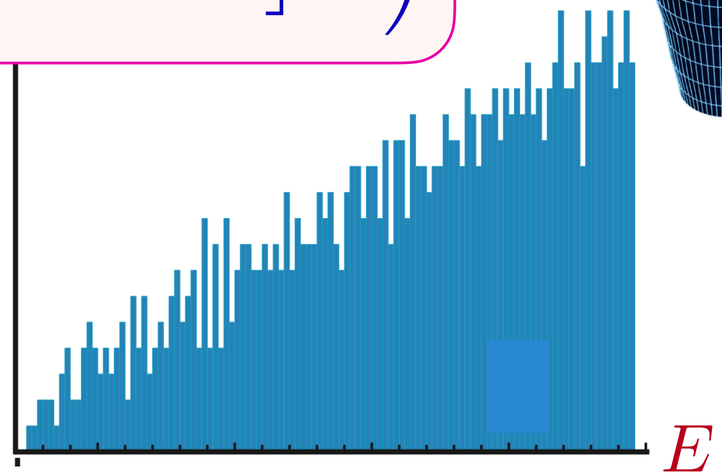
- For generic charged black holes in 3+1 dimensions with horizon area A at $T = 0$ and fixed charge $\mathcal{Q}$ ($A = 2G\mathcal{Q}^2/c^4$), the density of quantum states at small energy E is

Bekenstein-Hawking

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

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)

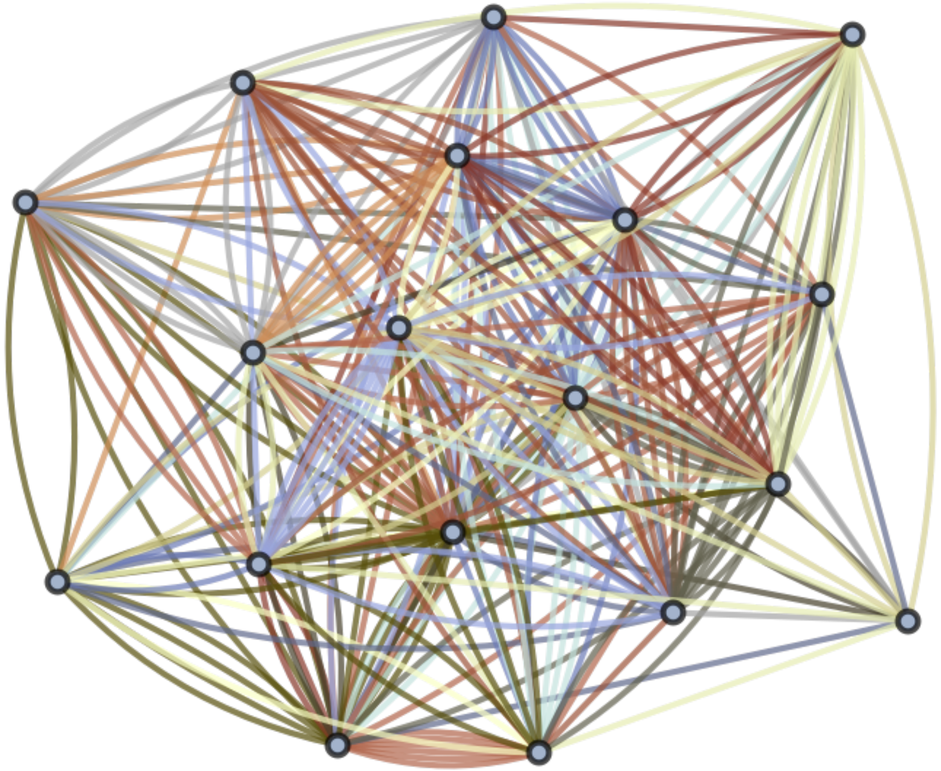
Superconductivity (1911)

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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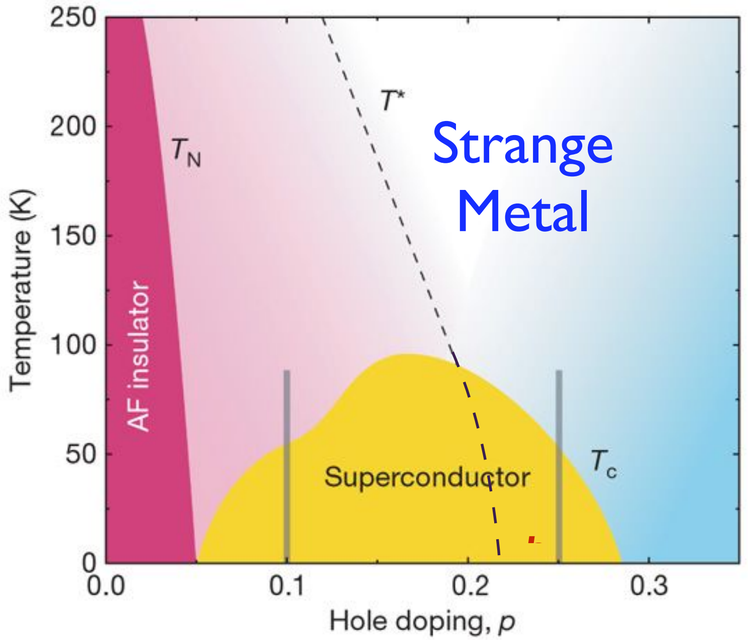
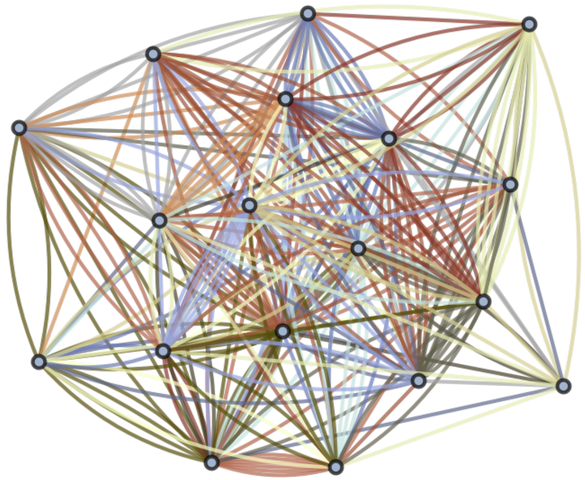


In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)



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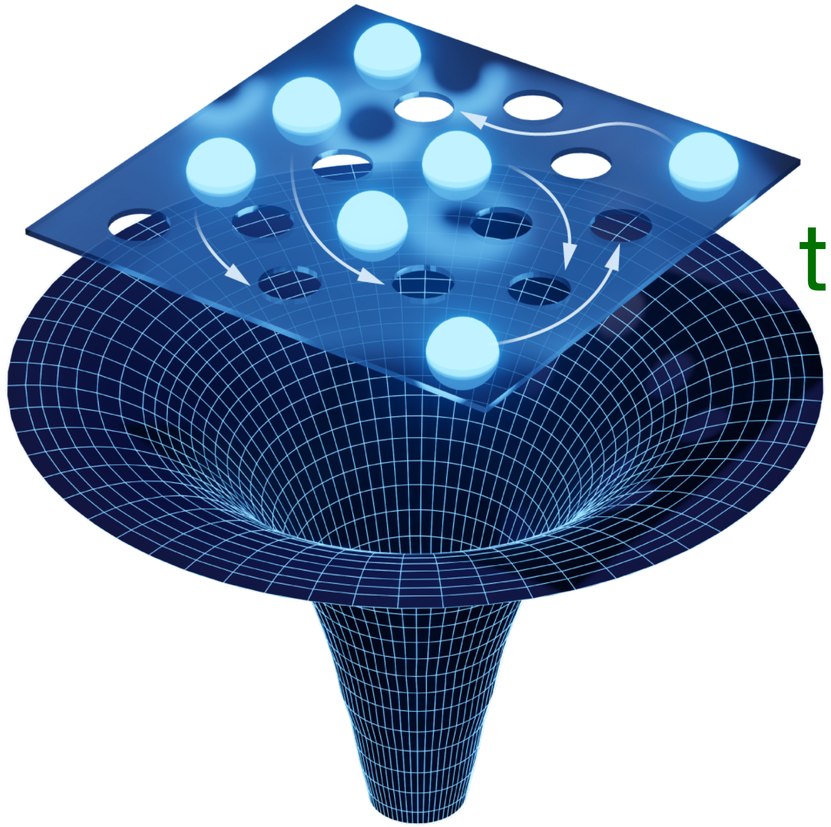

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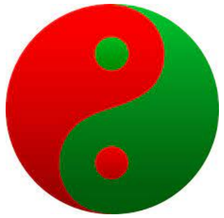

In a *dual* set of variables it describes the interior of ***charged black holes***

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