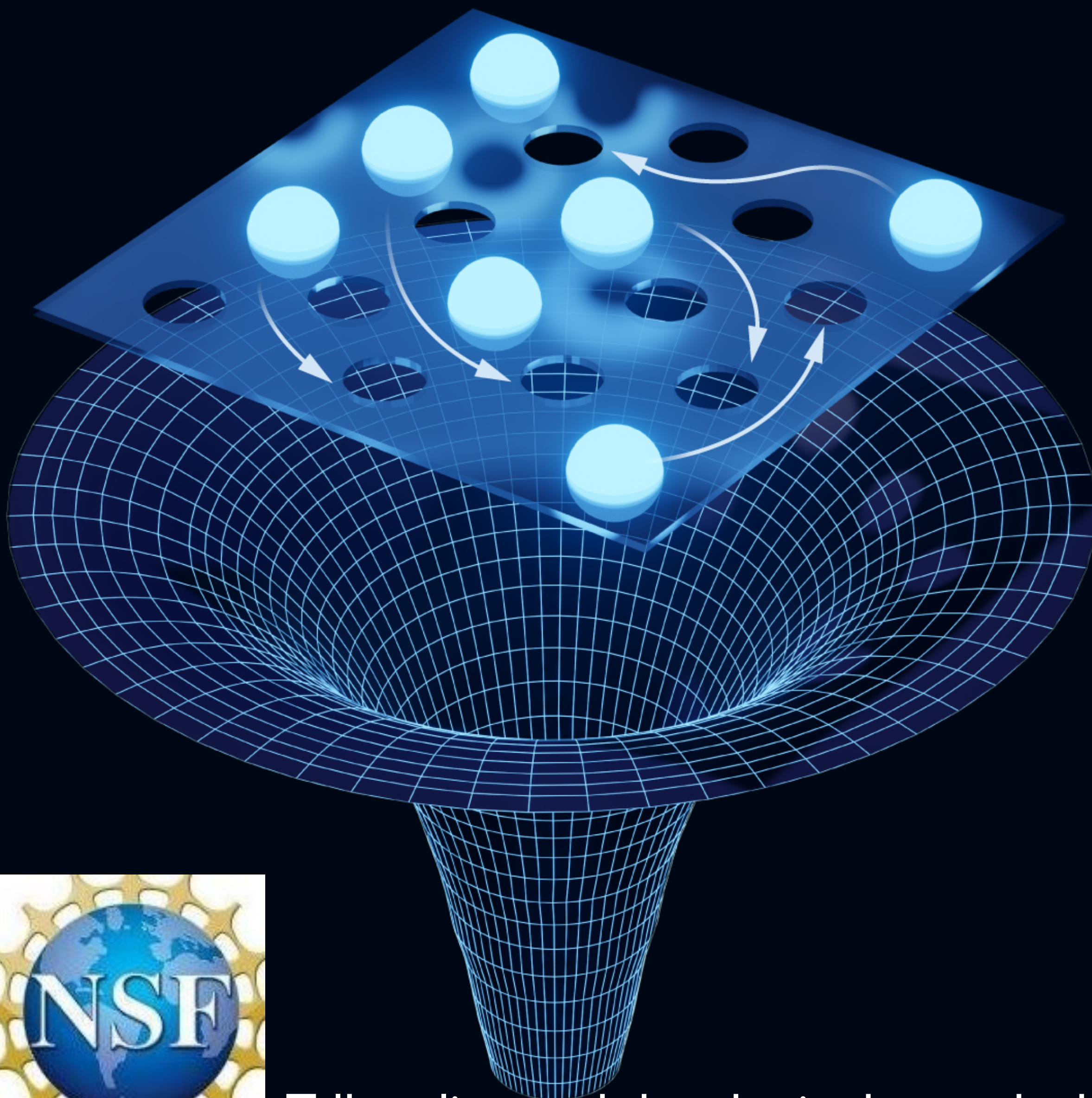


When nature entangles millions of particles: from quantum materials to black holes

Physics Club
IISER Tirupati
April 10, 2023

Subir Sachdev

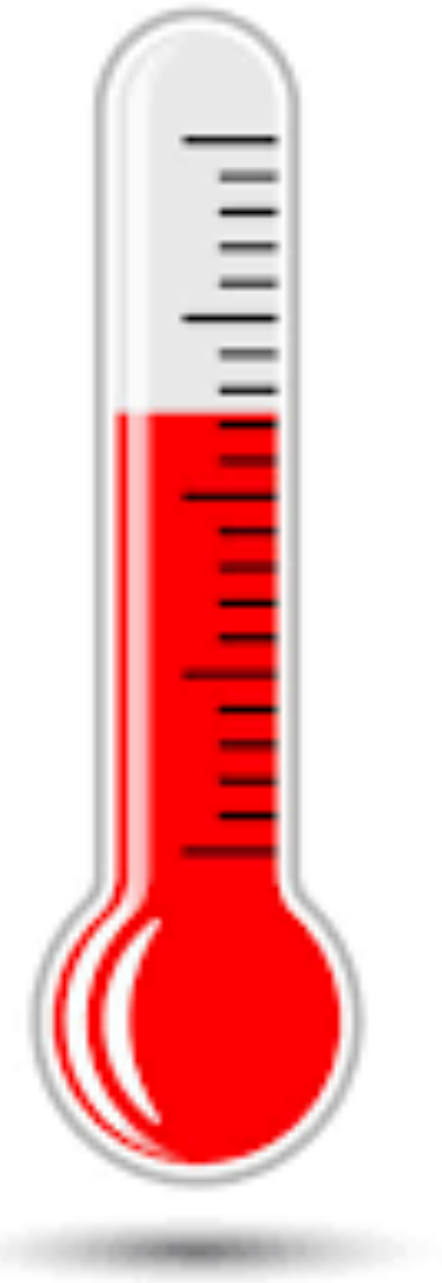


Talk online: sachdev.physics.harvard.edu



What is entropy
and temperature ?

Clausius (1865):
Second Law of Thermodynamics:
Every macroscopic system has an
“entropy” which cannot decrease.
➔ No perpetual motion machines!



Temperature

Statistical interpretation of entropy (1870)

$$S = k_B \log W$$

Density of quantum states $D(E)$

$$S(E) = k_B \log D(E)$$



Ludwig Boltzmann

20 February 1844 - September 5, 1906

Vienna, Austria

Statistical interpretation of entropy (1870)

$$S = k_B \log W$$

Density of quantum states $D(E)$

$$S(E) = k_B \log D(E)$$

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



Ludwig Boltzmann

20 February 1844 - September 5, 1906

Vienna, Austria

What is
quantum entanglement?

MAY 15, 1935

PHYSICAL REVIEW

VOLUME 47

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

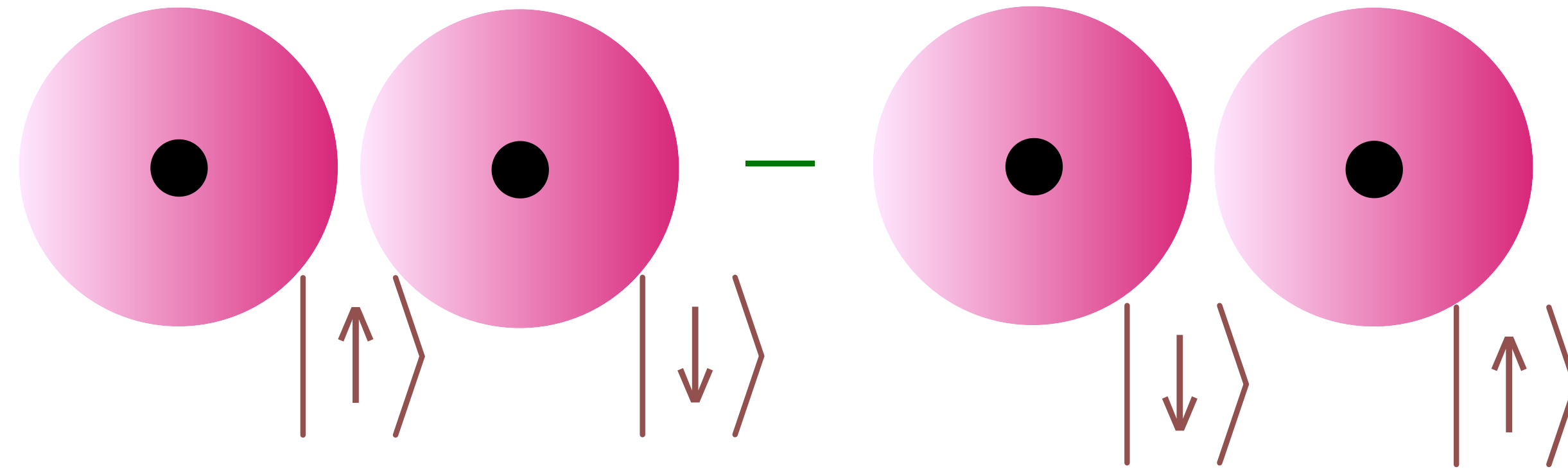
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

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.

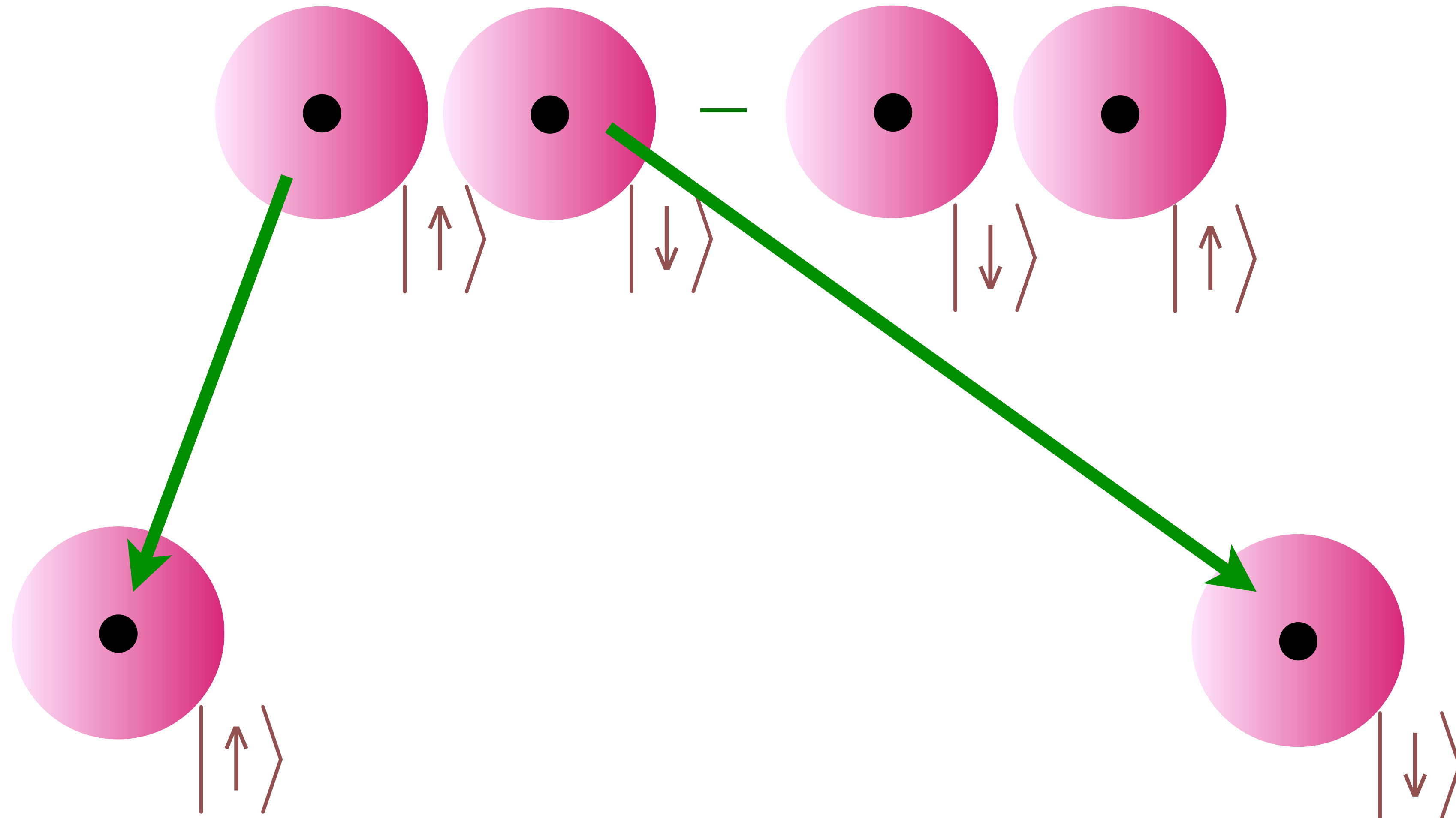
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



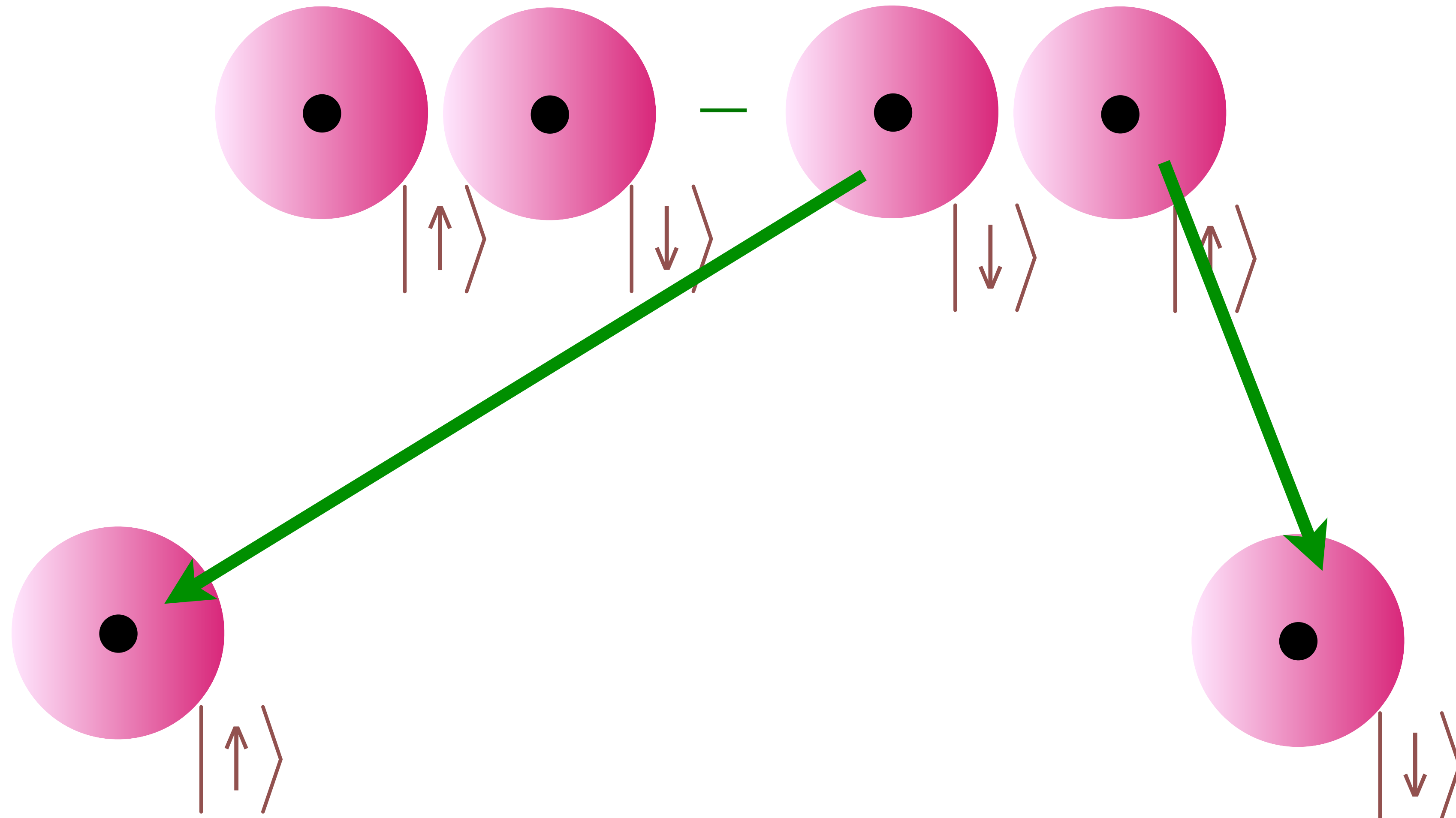
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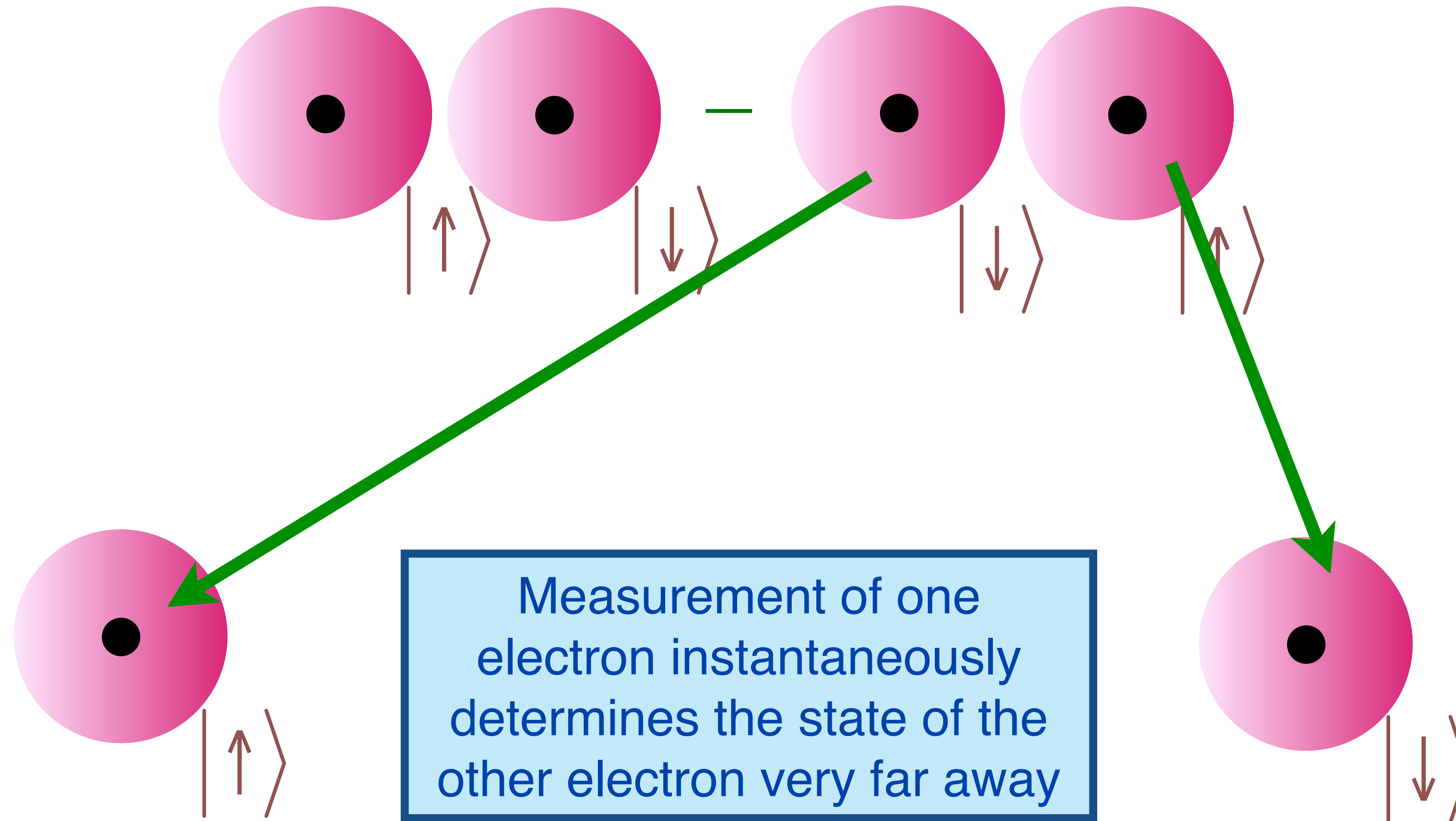
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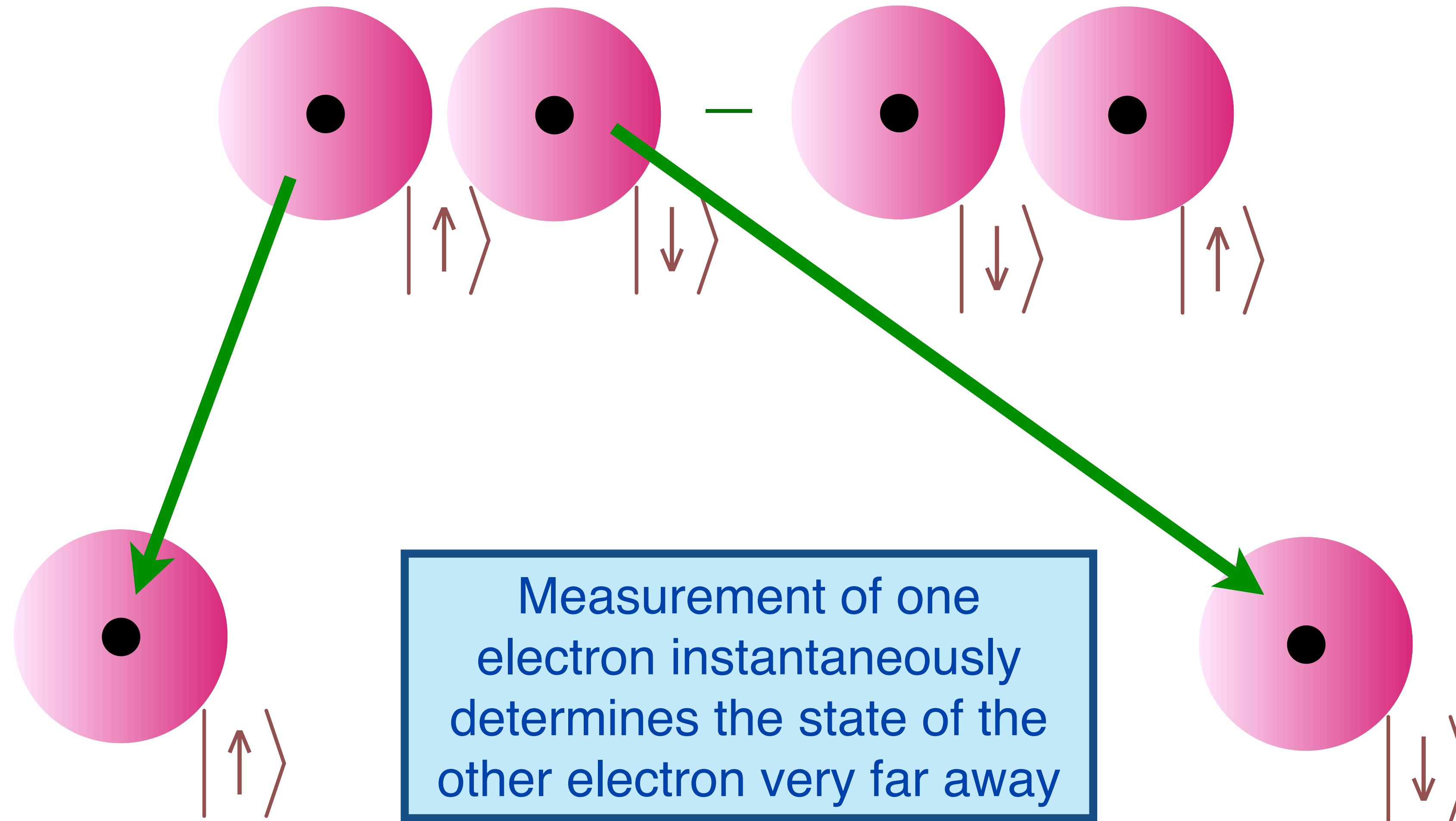
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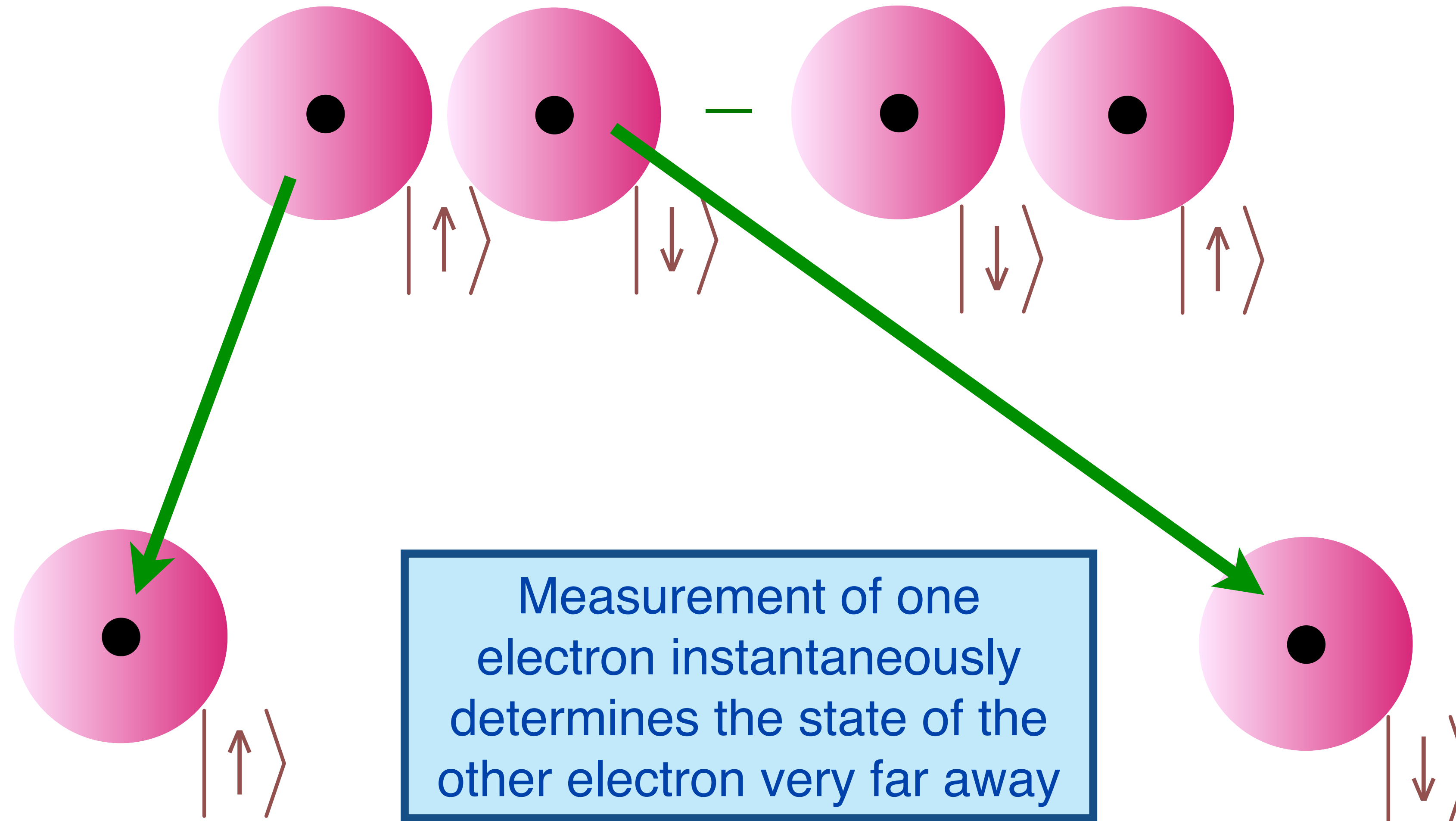
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Quantum Entanglement

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

amount of validity in the
recognise clearly as necessary given the framework of
malism. I cannot seriously believe in it because the theory cannot be rec-
onciled with the idea that physics should represent a reality in time and
space, free from spooky actions at a distance. I am, however, not yet
convinced that it can really be achieved with a continuous field
... this which so

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

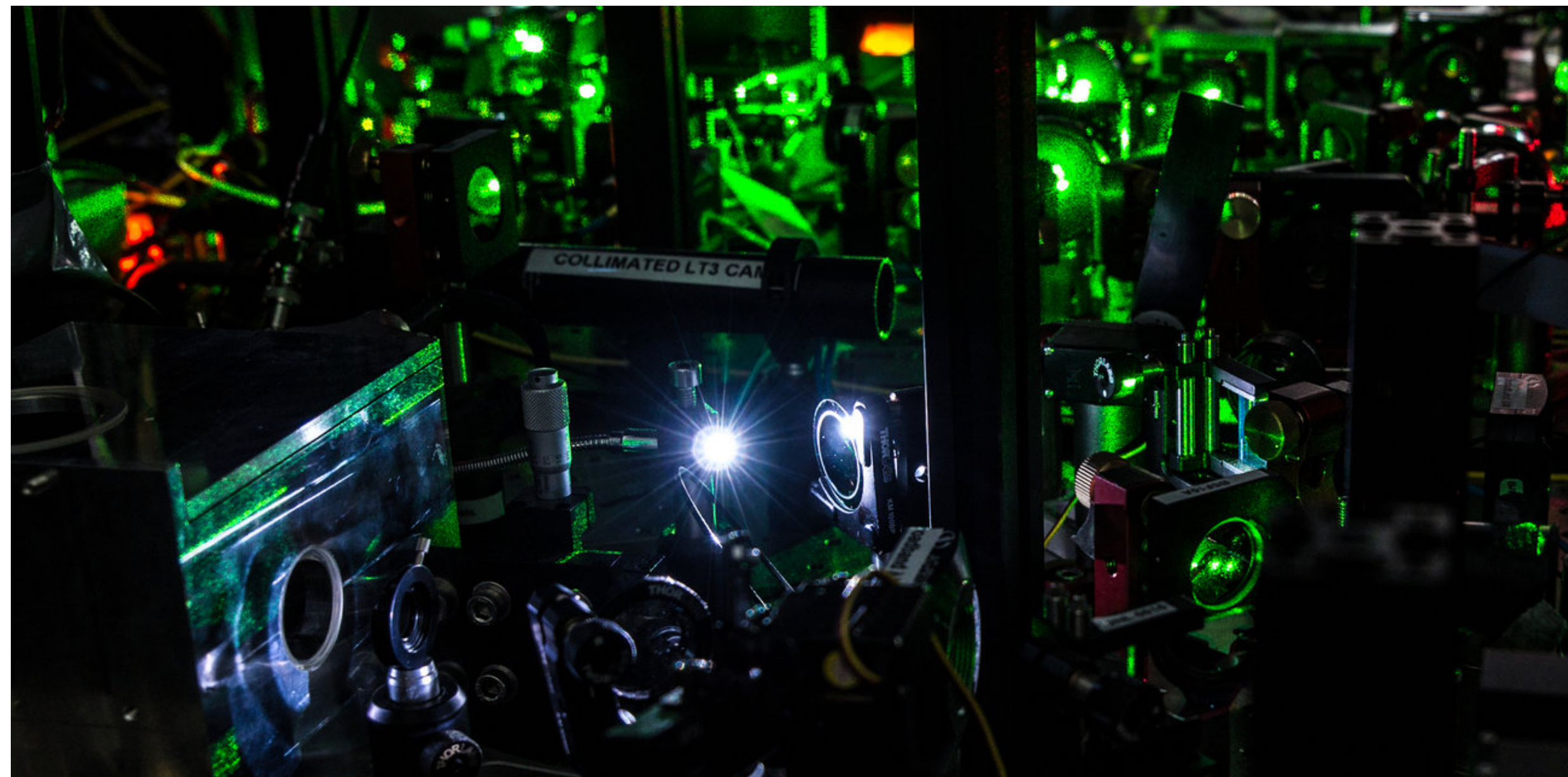
Albert Einstein to Max Born, 3 March 1947

The New York Times

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

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

In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other’s behavior.



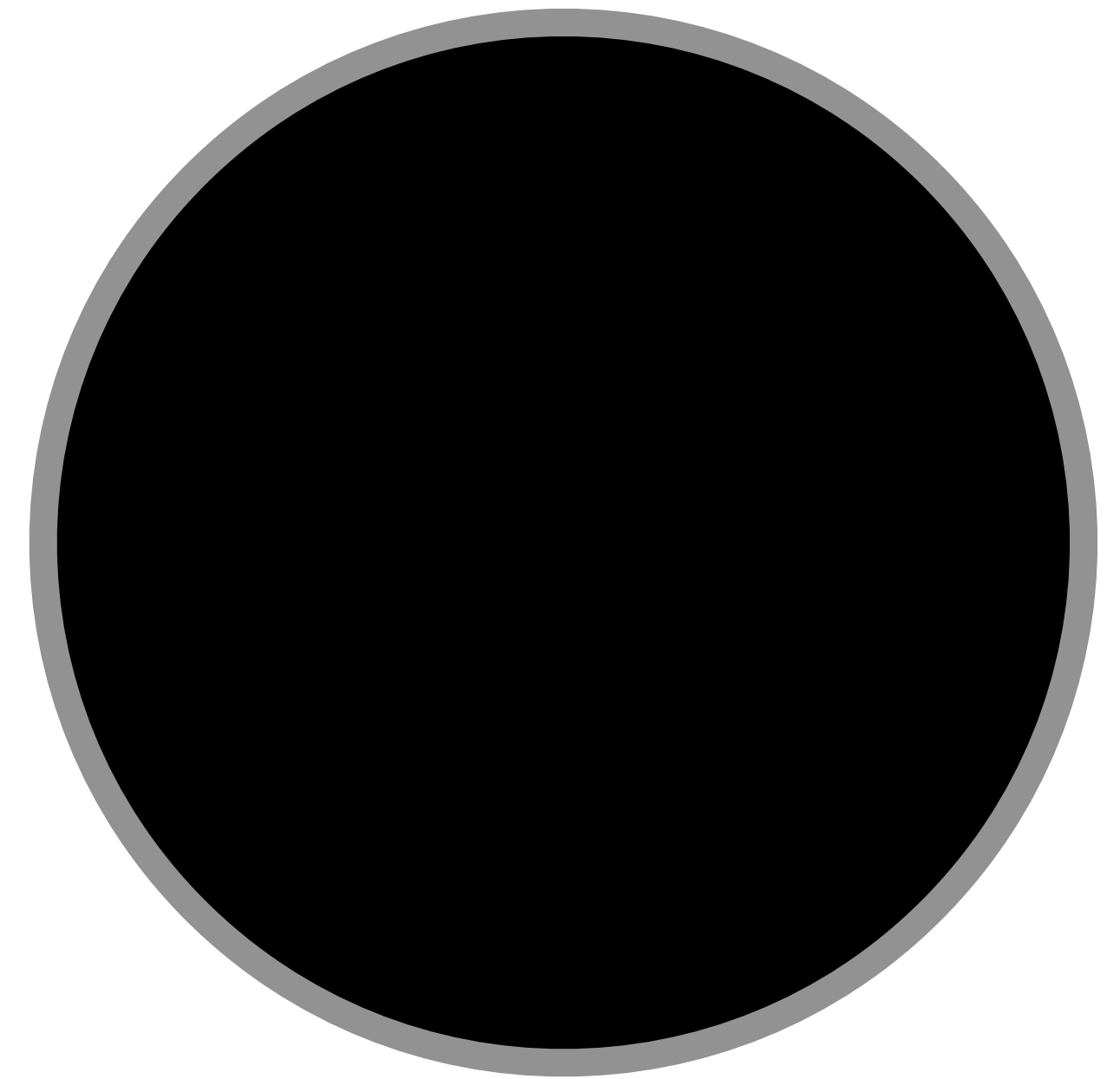
Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

**Black
holes**

Black Holes

Objects so dense that light is gravitationally bound to them.

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



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

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

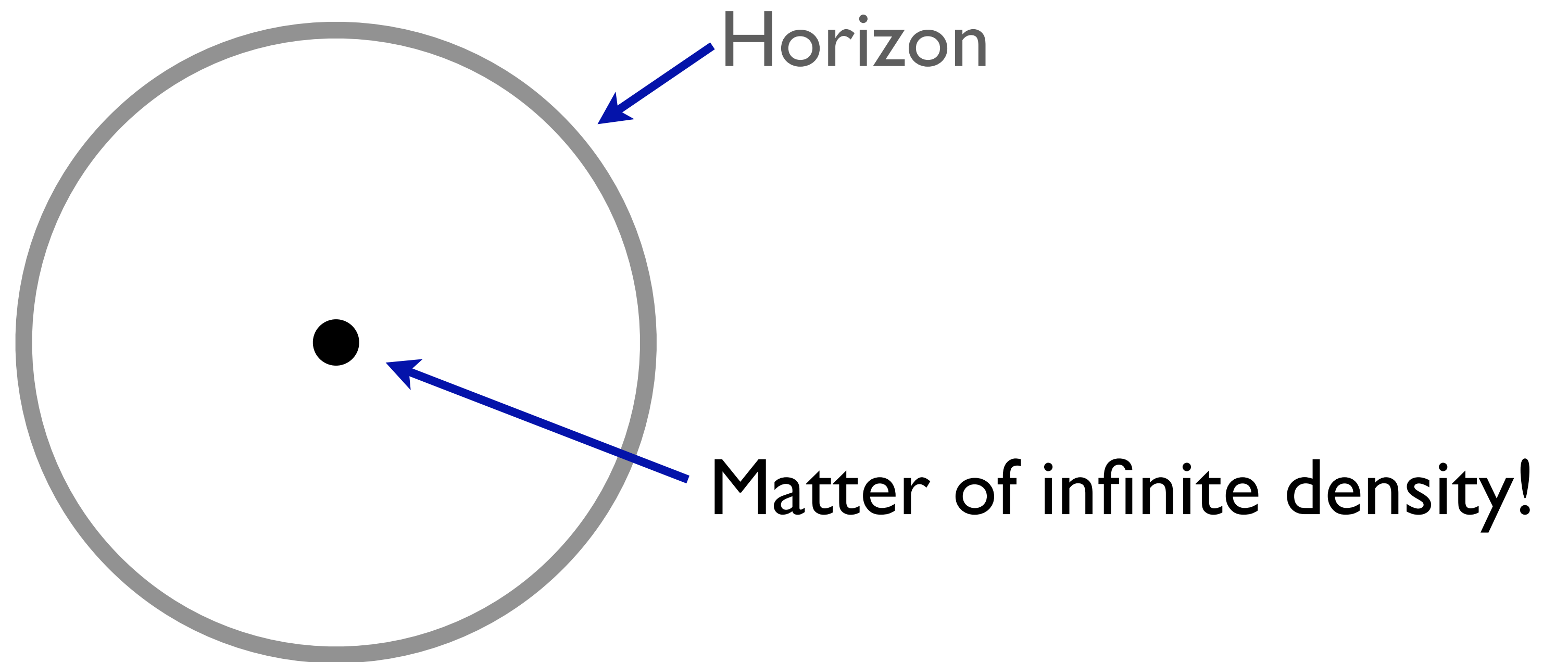
$$R = 1.3 \times 10^{11} \text{ m}$$

\approx earth's orbit

An artist's impression of Sagittarius A*, the supermassive black hole at the heart of the Milky Way. Image: International Gemini Observatory/NOIRLab/NSF/AURA/J. da Silva/(Spaceengine); M. Zamani (NSF's NOIRLab)

What is inside a black hole ???

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



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

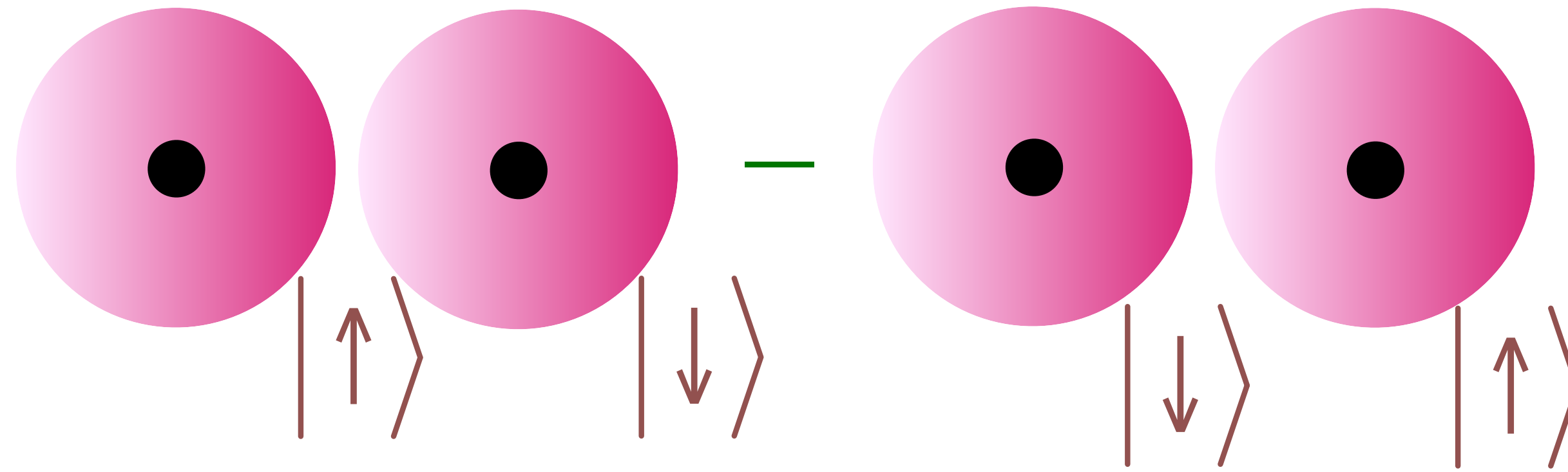
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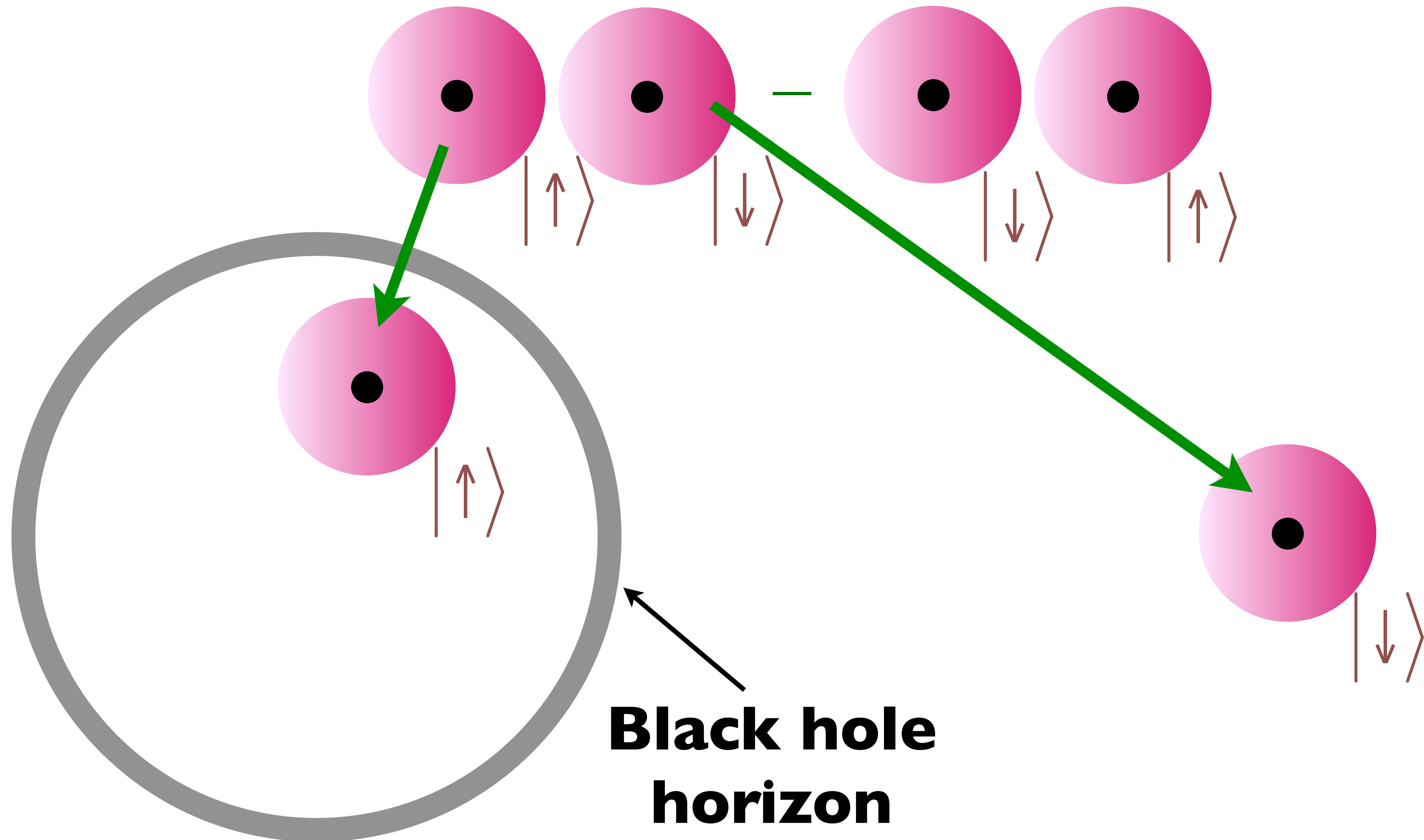
This singularity convinced many early on that black holes were unphysical solutions of Einstein's equations, and did not exist in our universe.

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

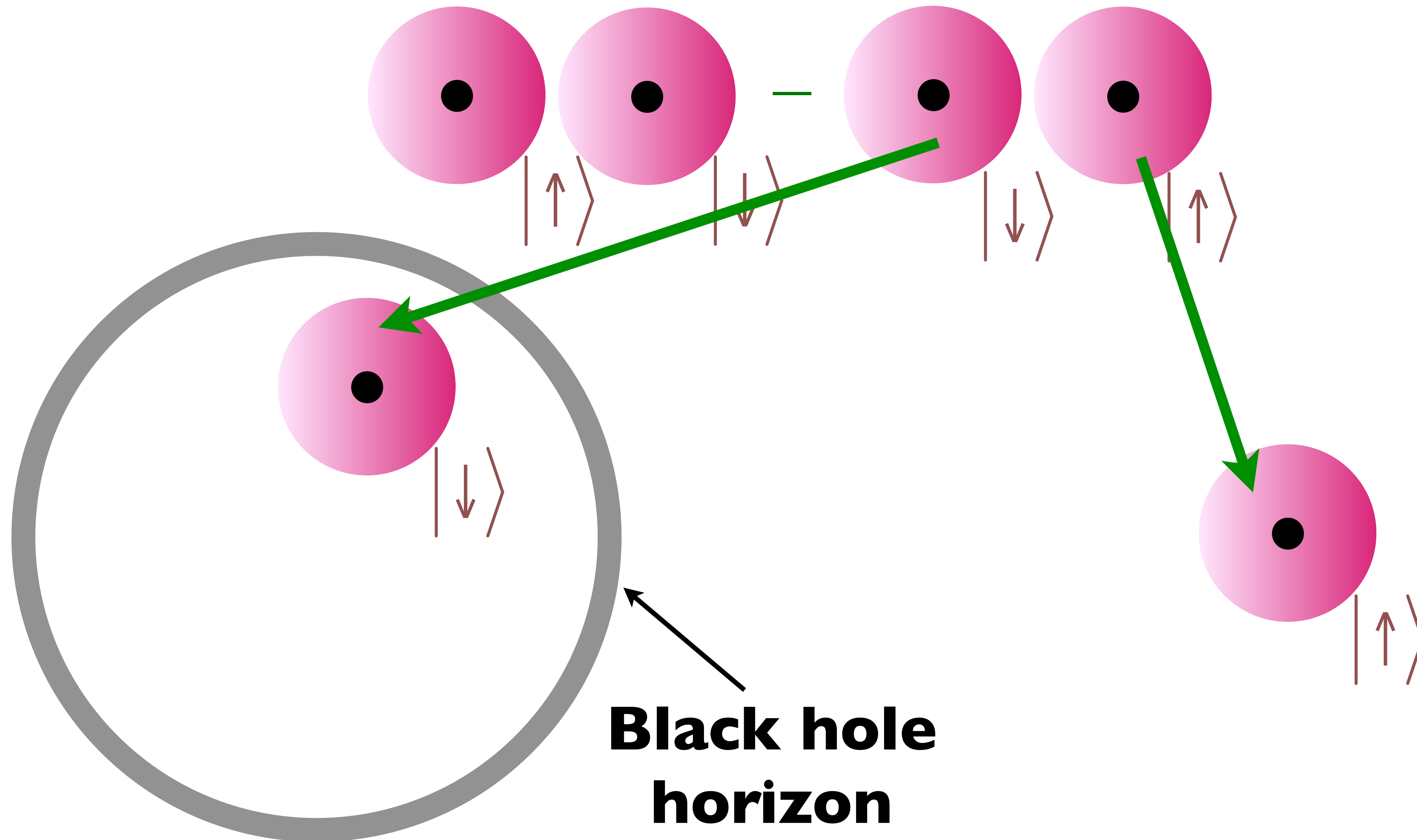
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

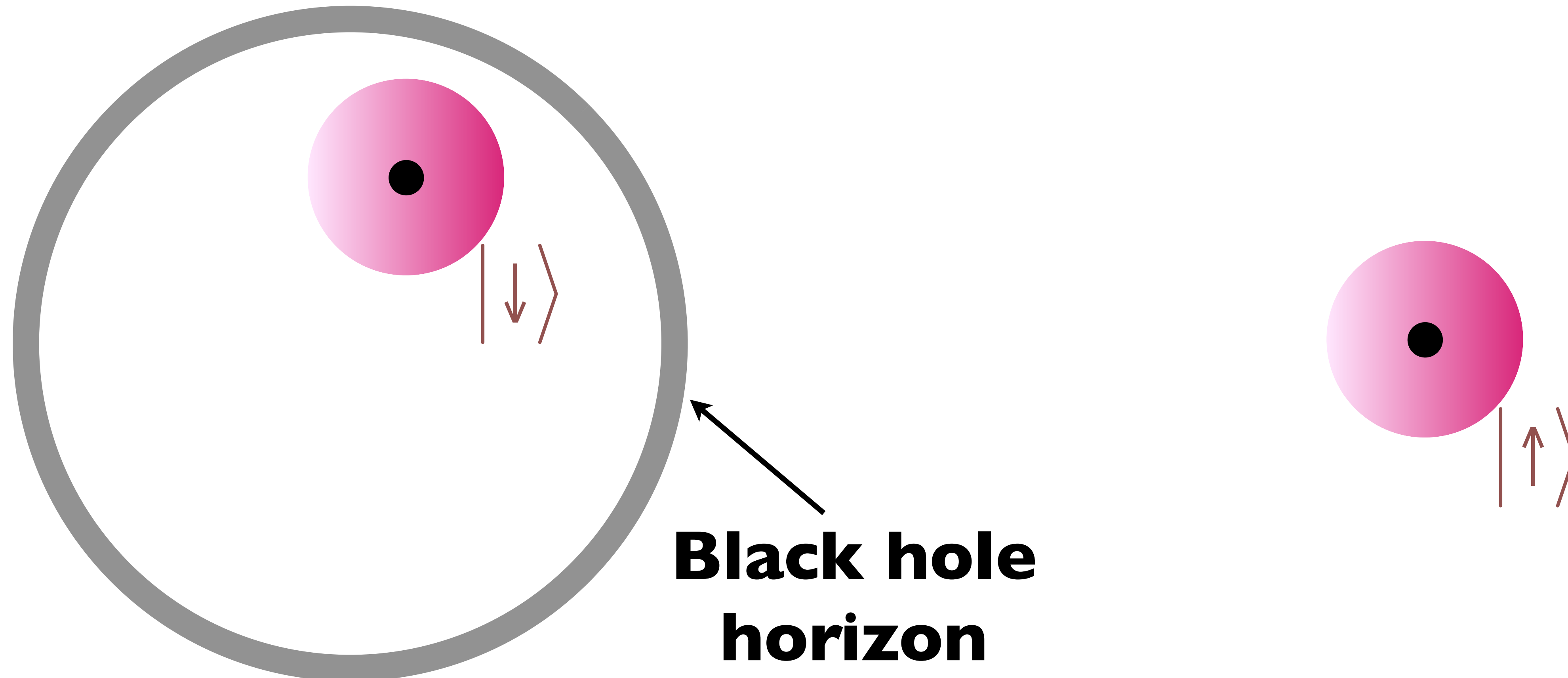


Quantum Entanglement across a black hole horizon



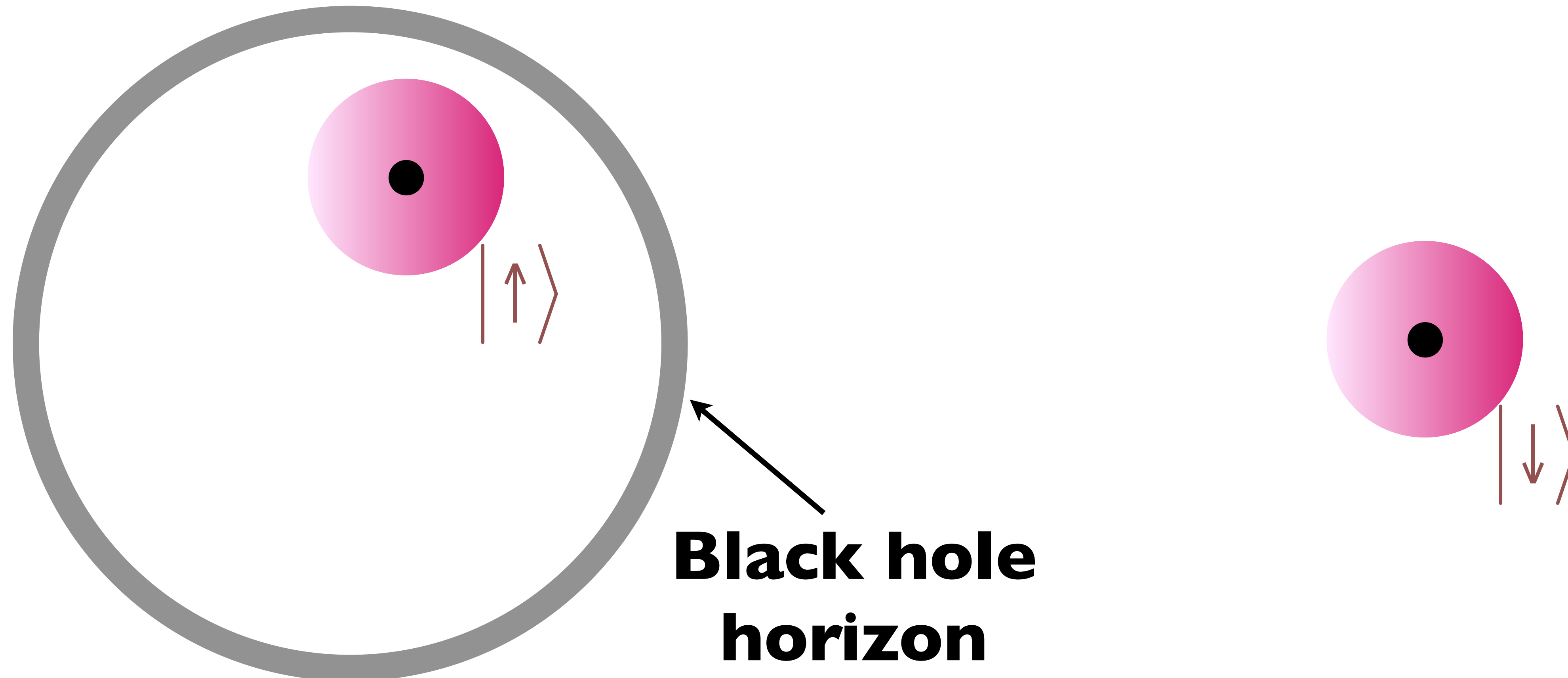
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

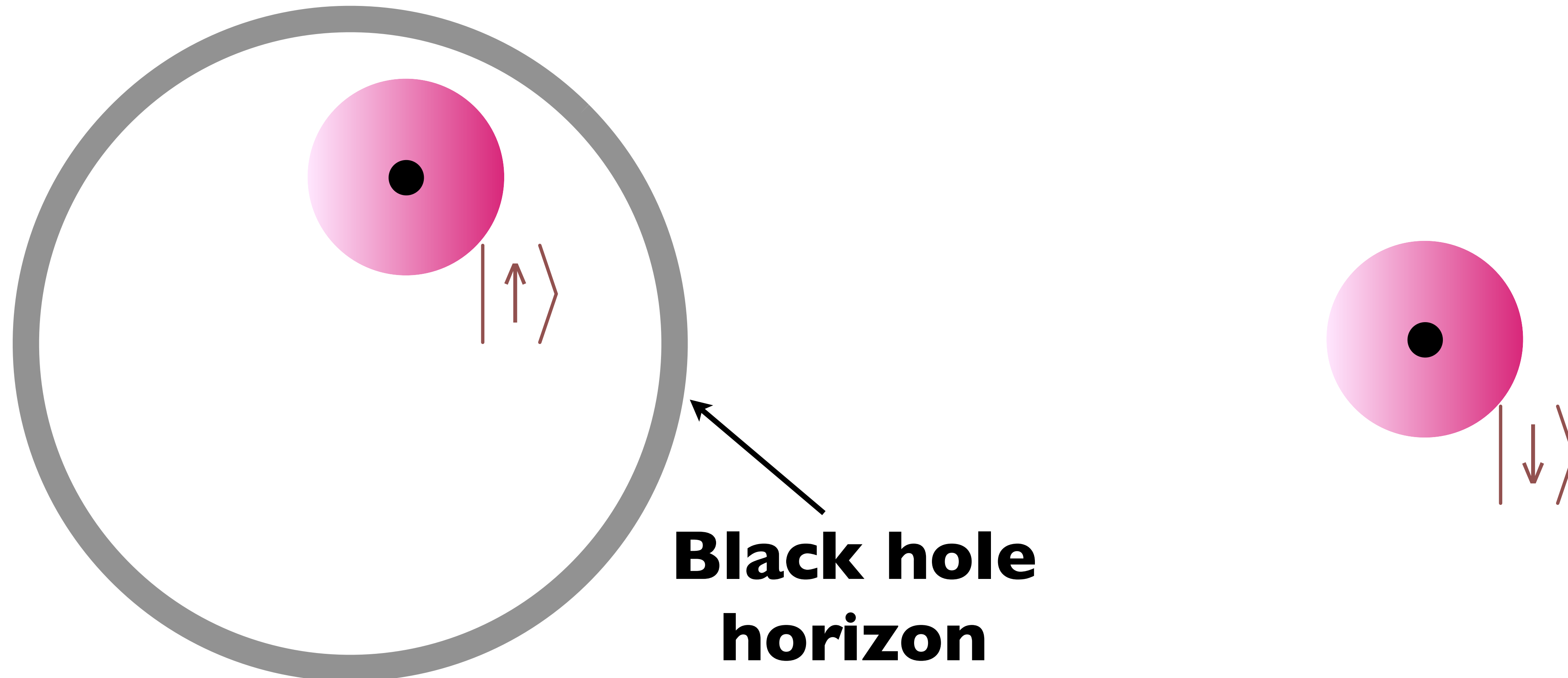
There is quantum entanglement between the inside and outside of a black hole



Quantum Entanglement across a black hole horizon

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

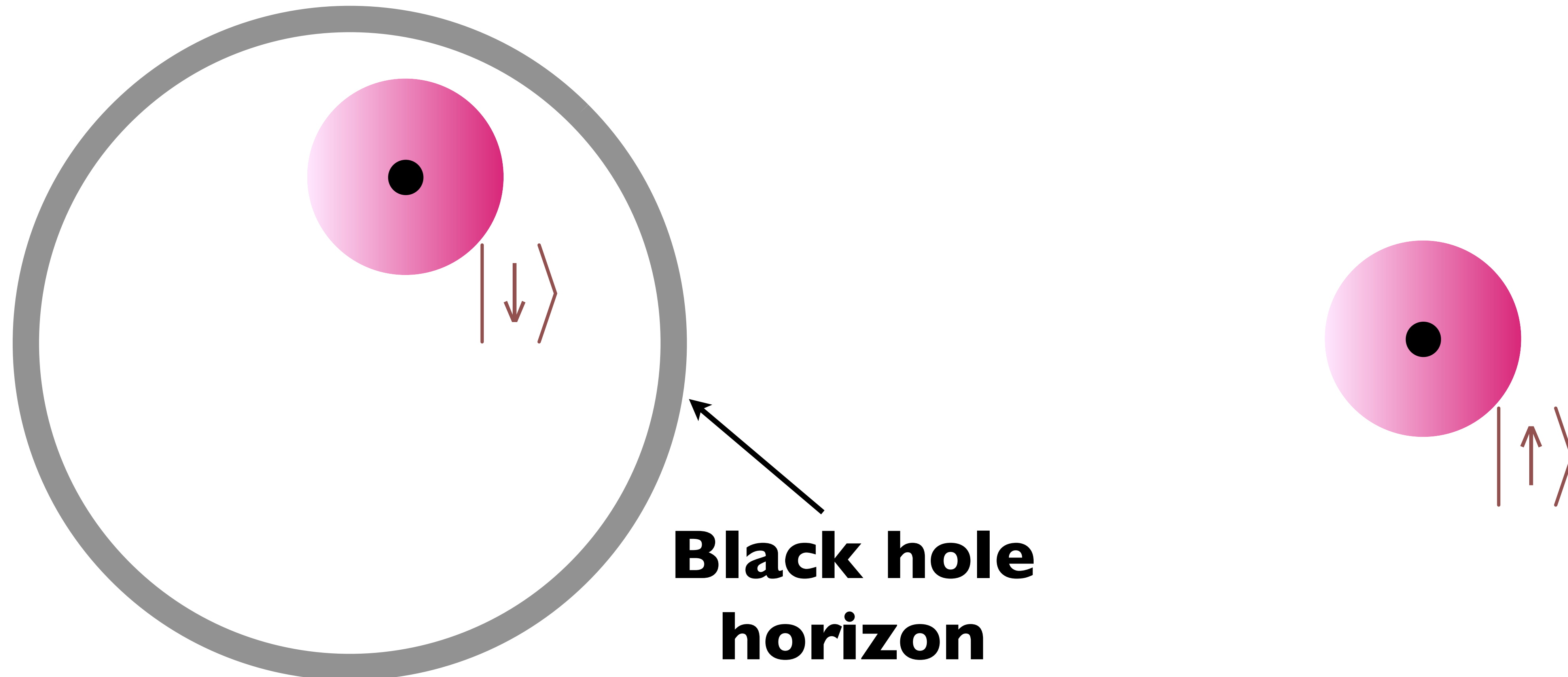
To an outside observer, the state of the electron inside the black hole cannot be known, and so the outside electron is in a random state.



Quantum Entanglement across a black hole horizon

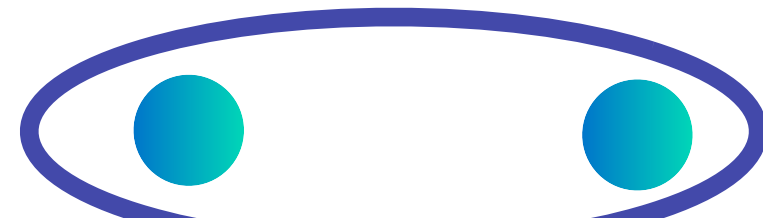
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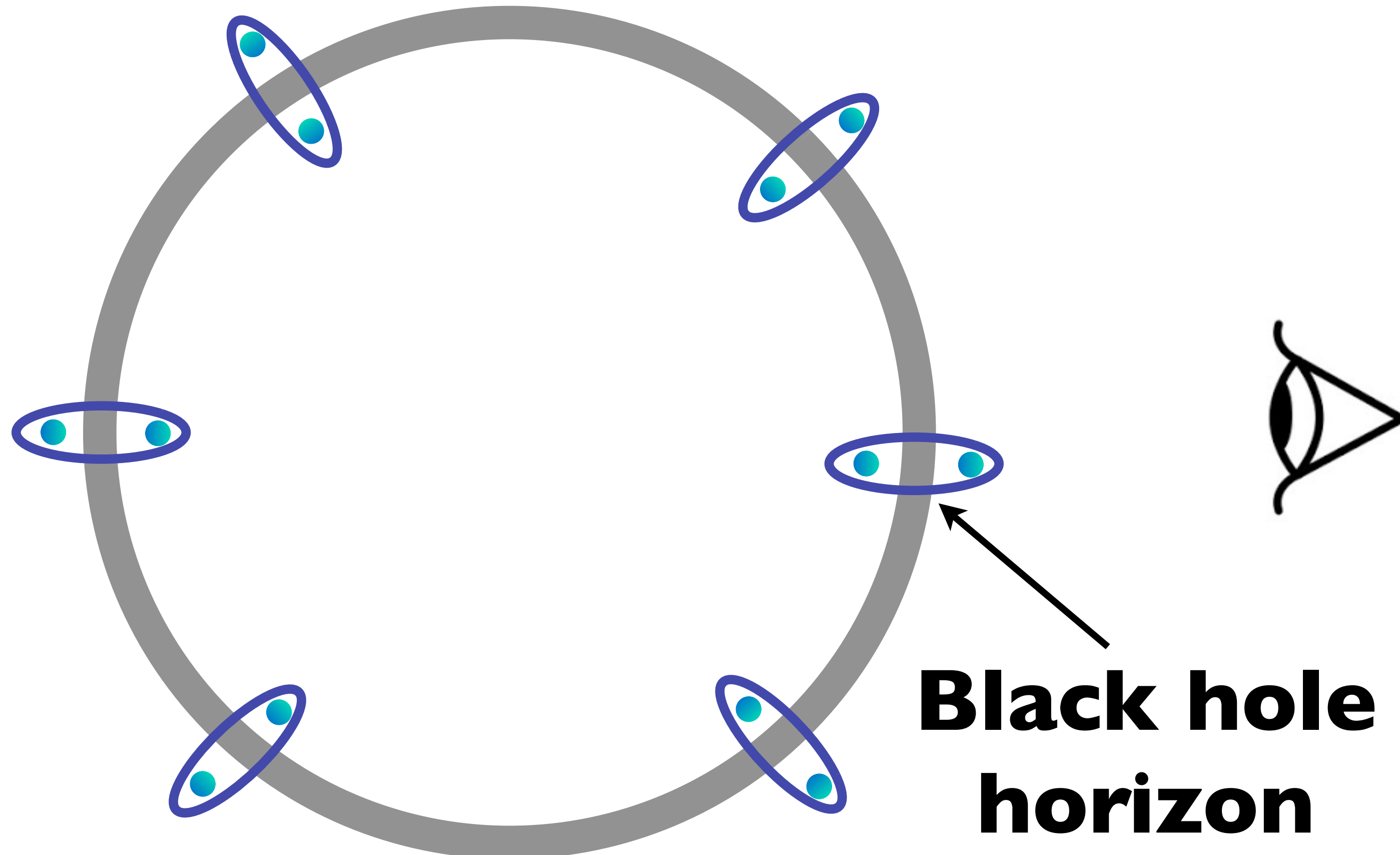
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Quantum Entanglement across a black hole horizon

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

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

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* $D(E)$ matches Hawking's entropy, in accordance with Boltzmann's principles of statistical mechanics?
- 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)

Needed:

A solvable model of quantum entanglement
of 3, 4, 5, ... ∞ particles

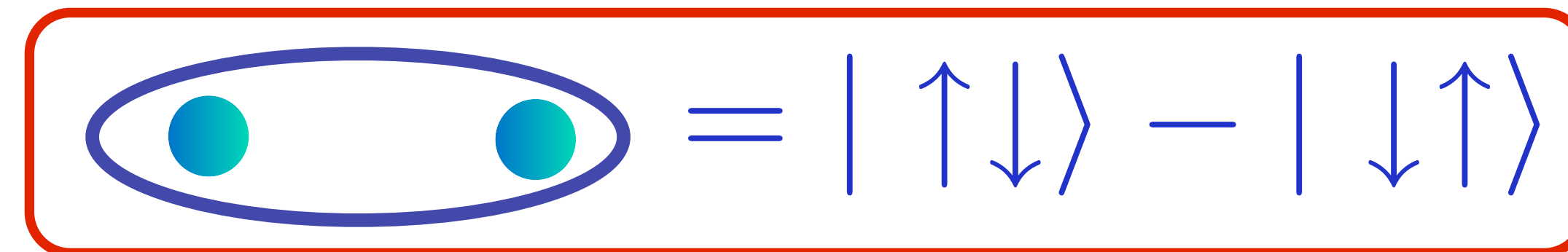
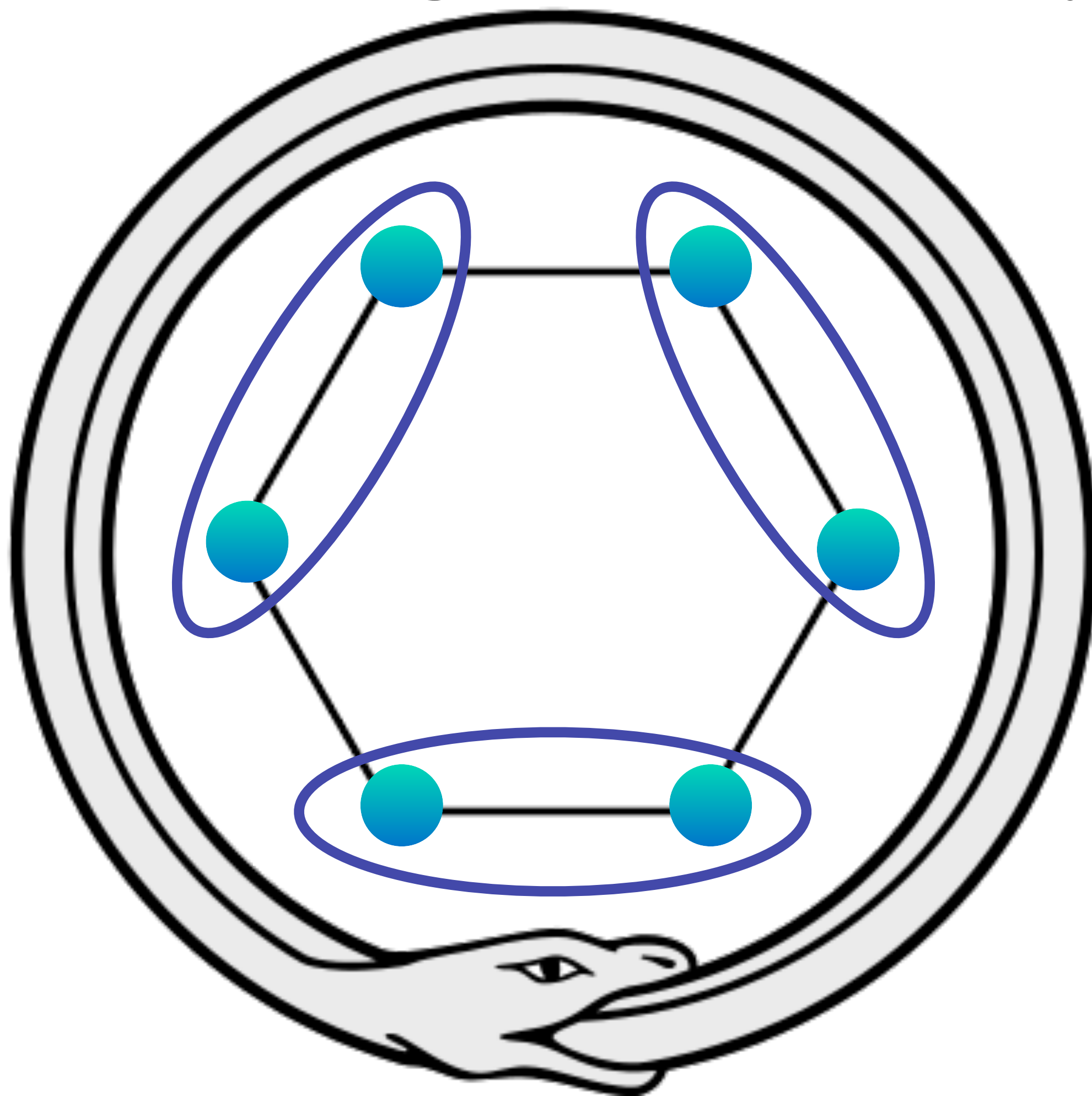
Needed:

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

Kekulé's spooky dream (1865)

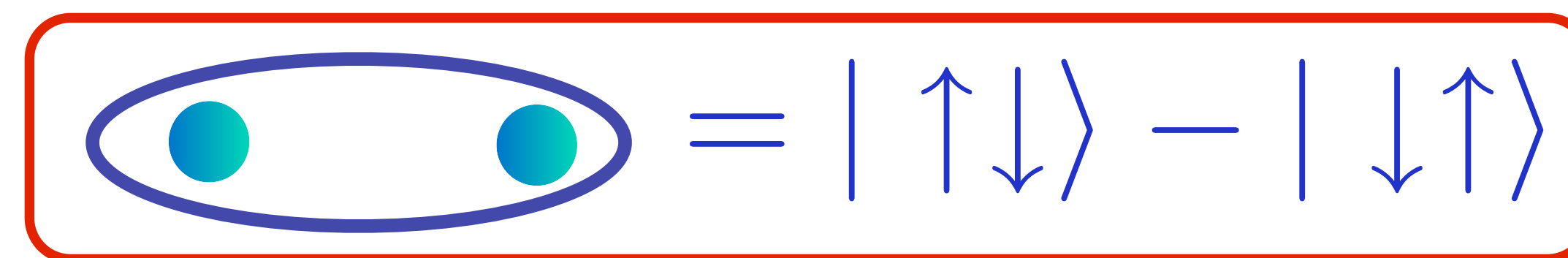
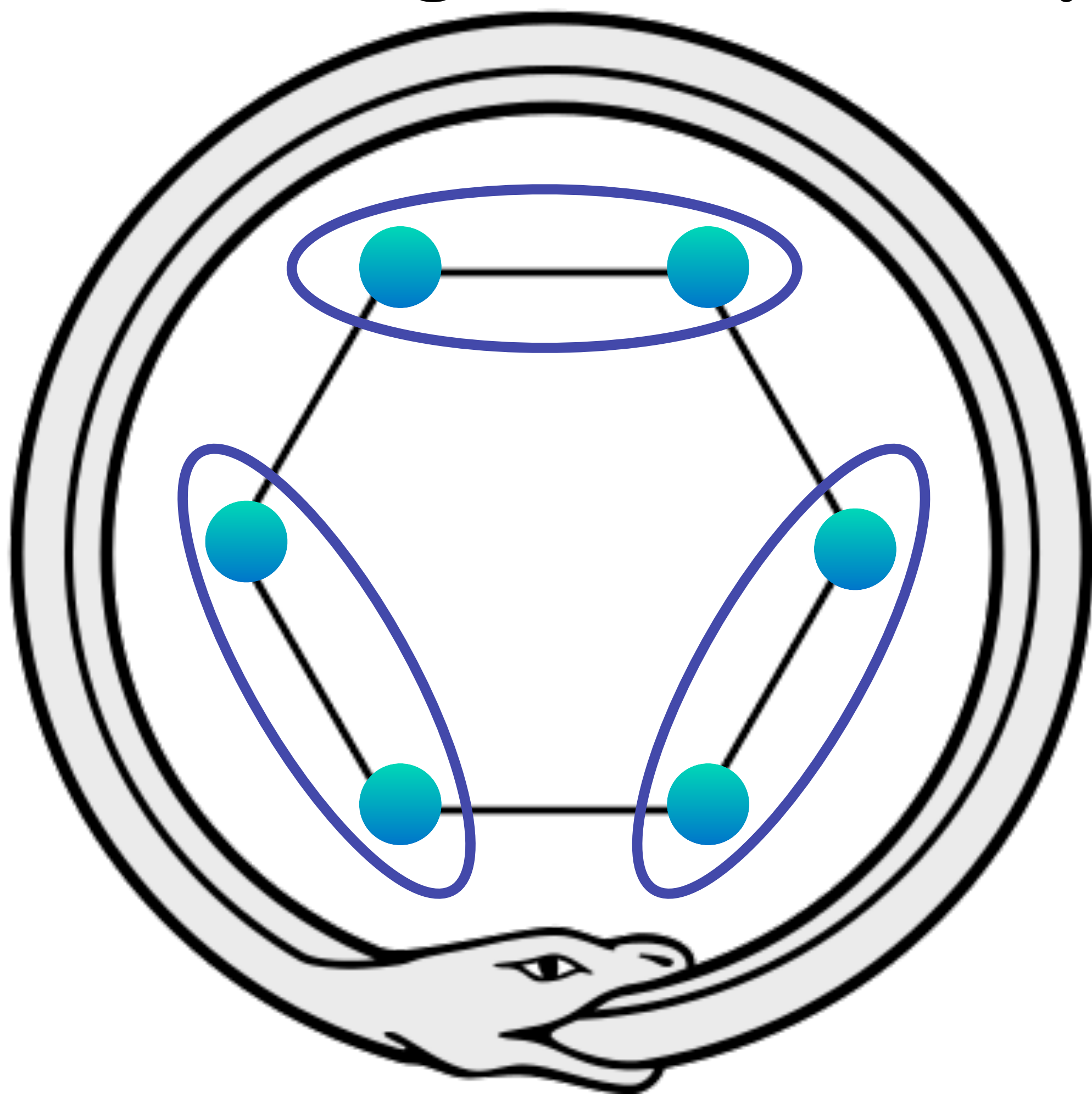
Kekulé spoke of the creation of the theory. He said that he had discovered the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail*



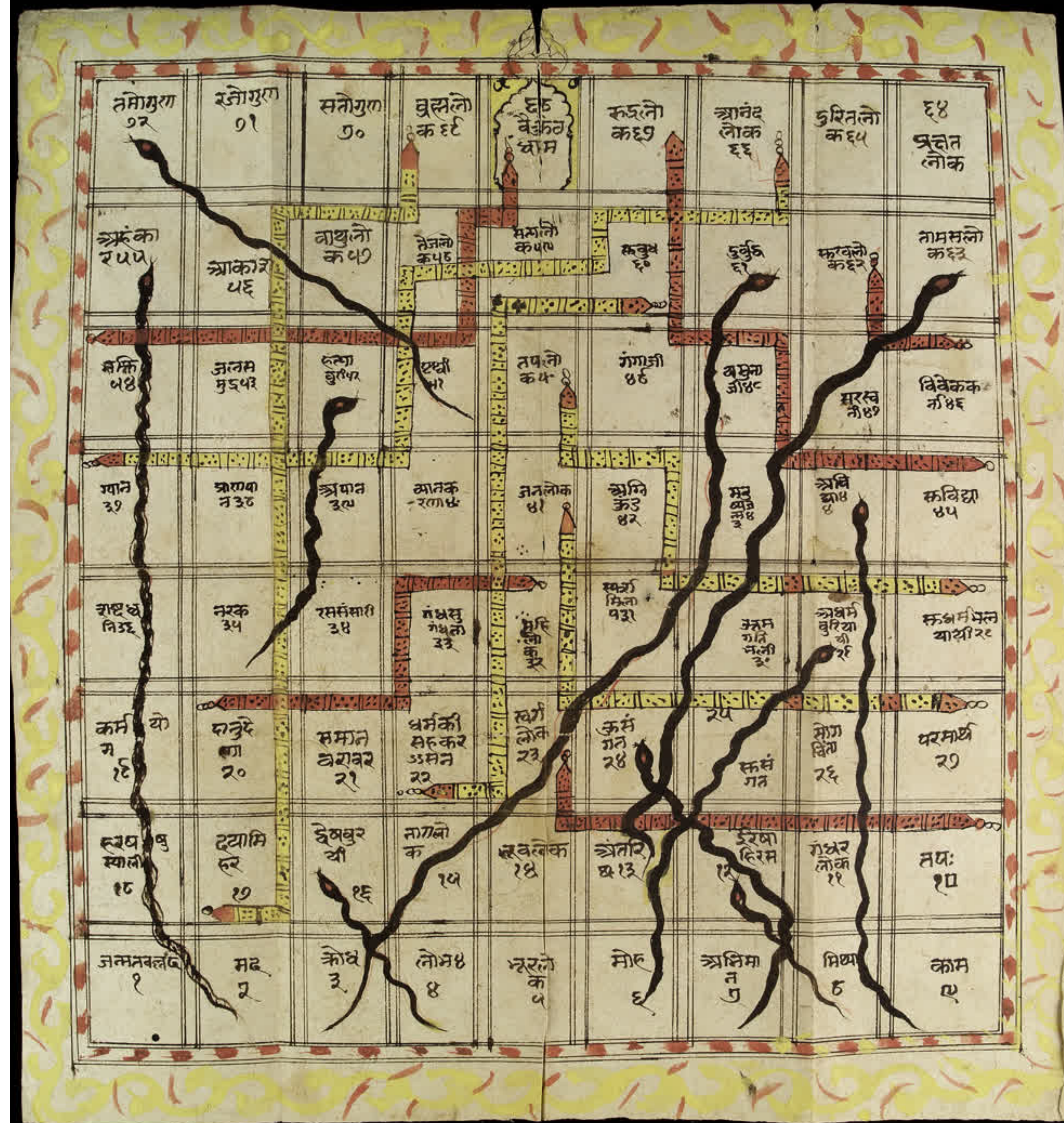
Benzene

Kekulé's spooky dream (1865)

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Benzene



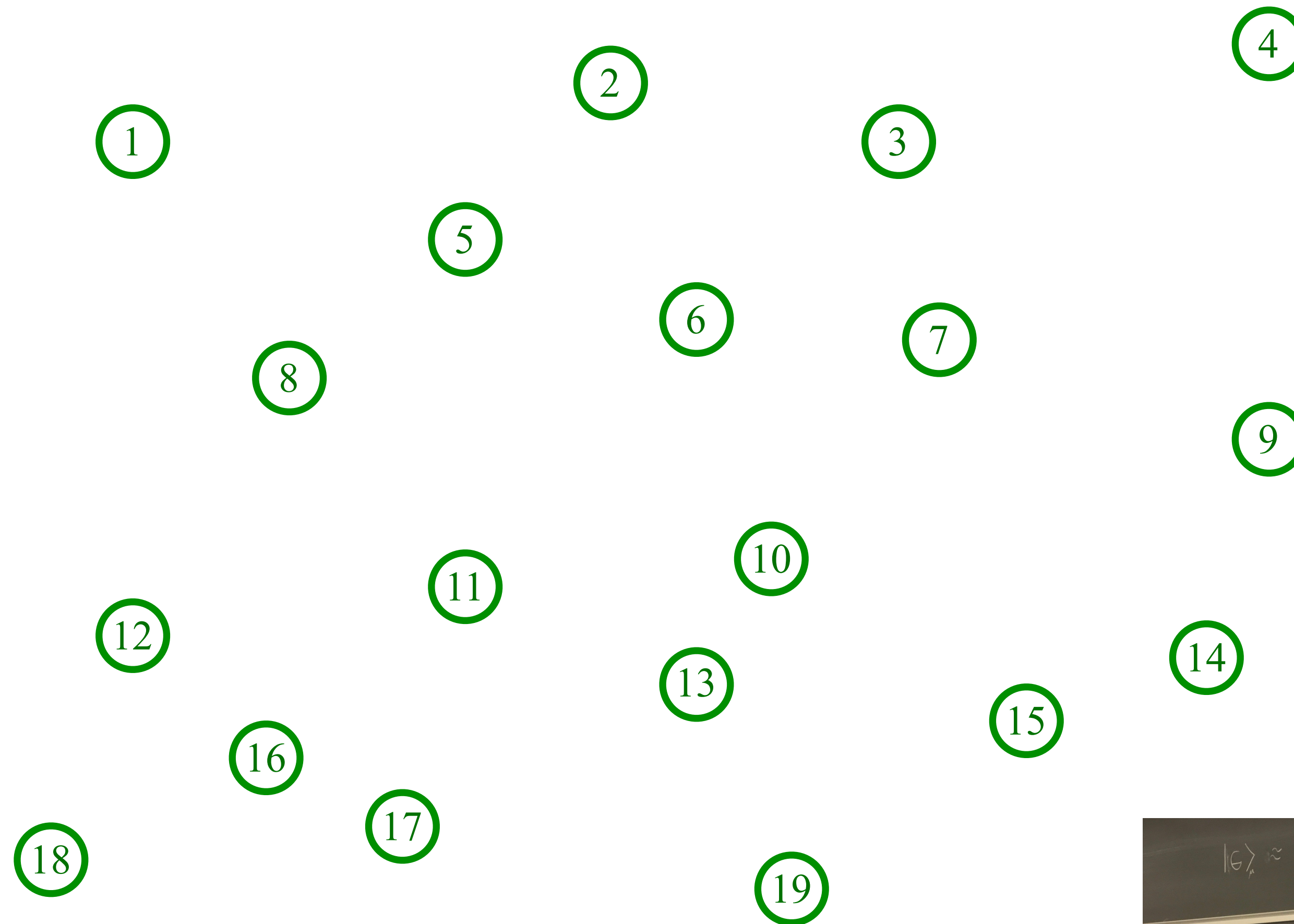
My
spooky
dream*

Ancient
Indian
game of
Snakes
and
Ladders

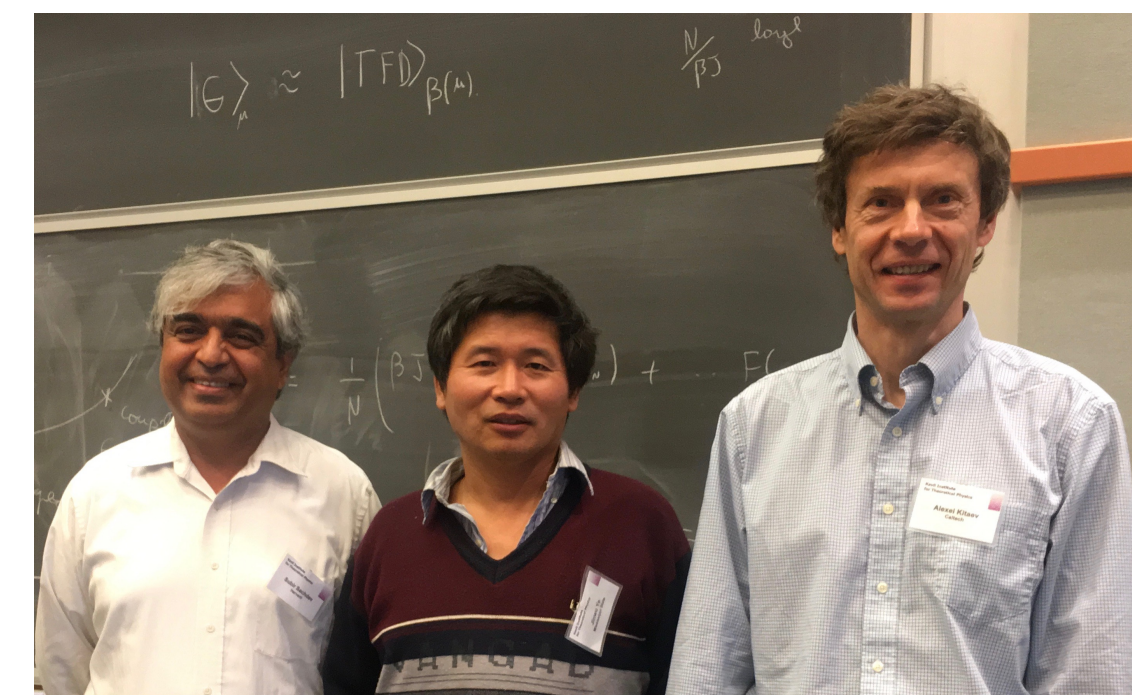
*Not true

The SYK model

Sachdev, Ye (1993); Kitaev (2015)

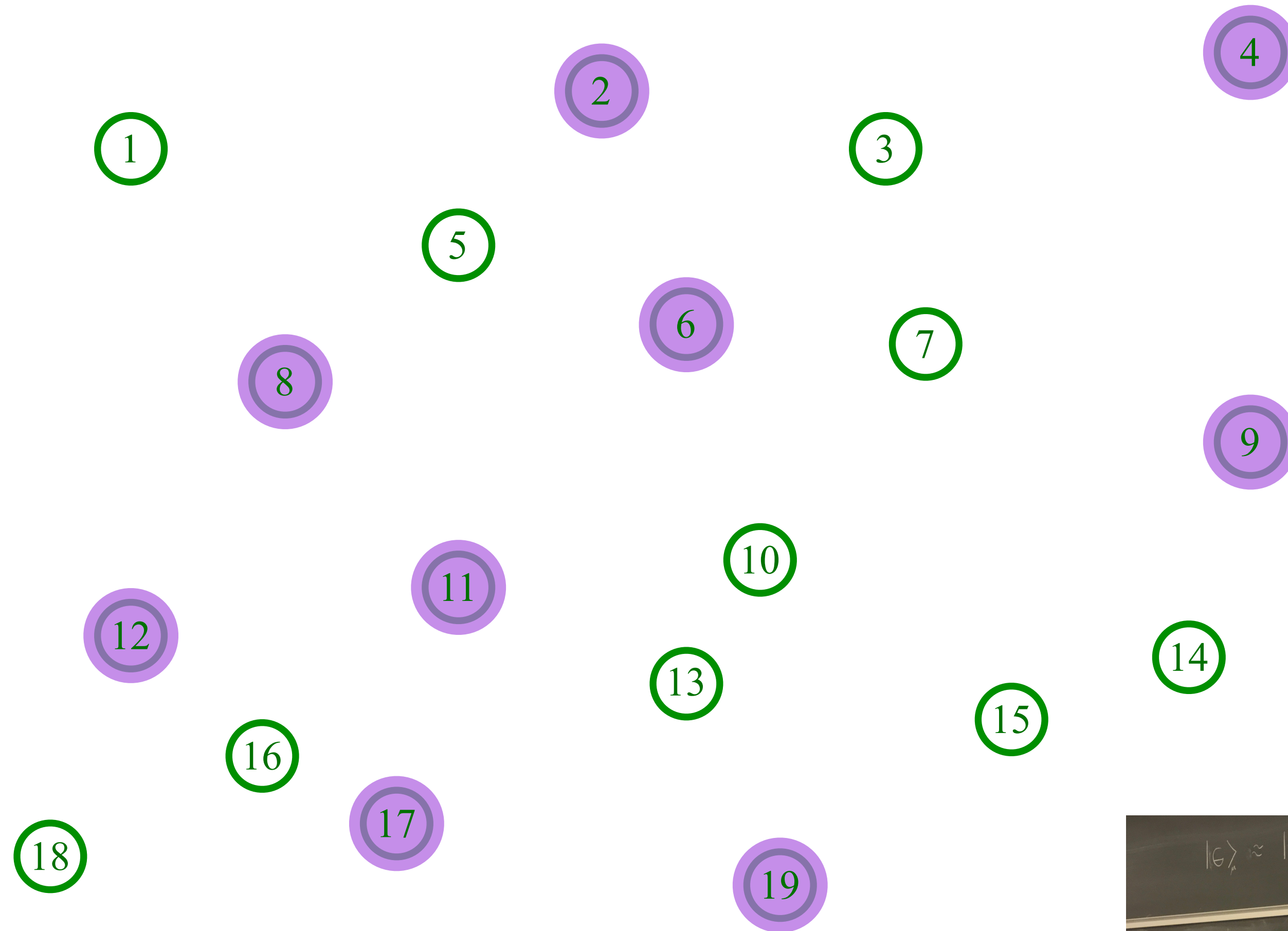


Pick a set of random positions

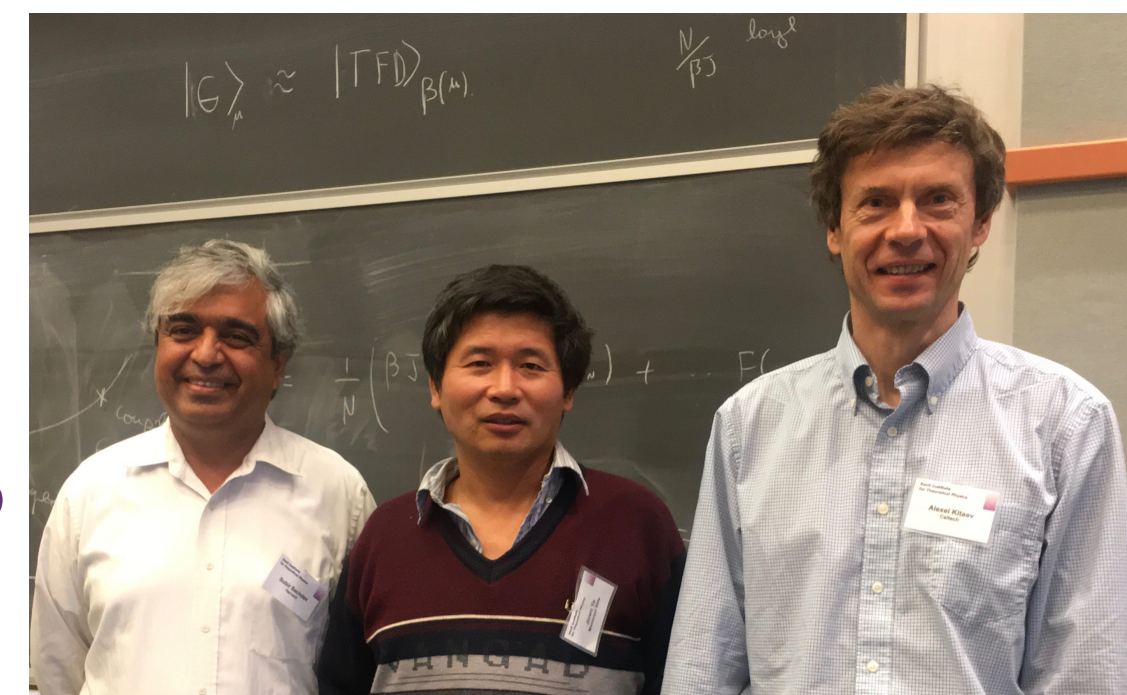


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

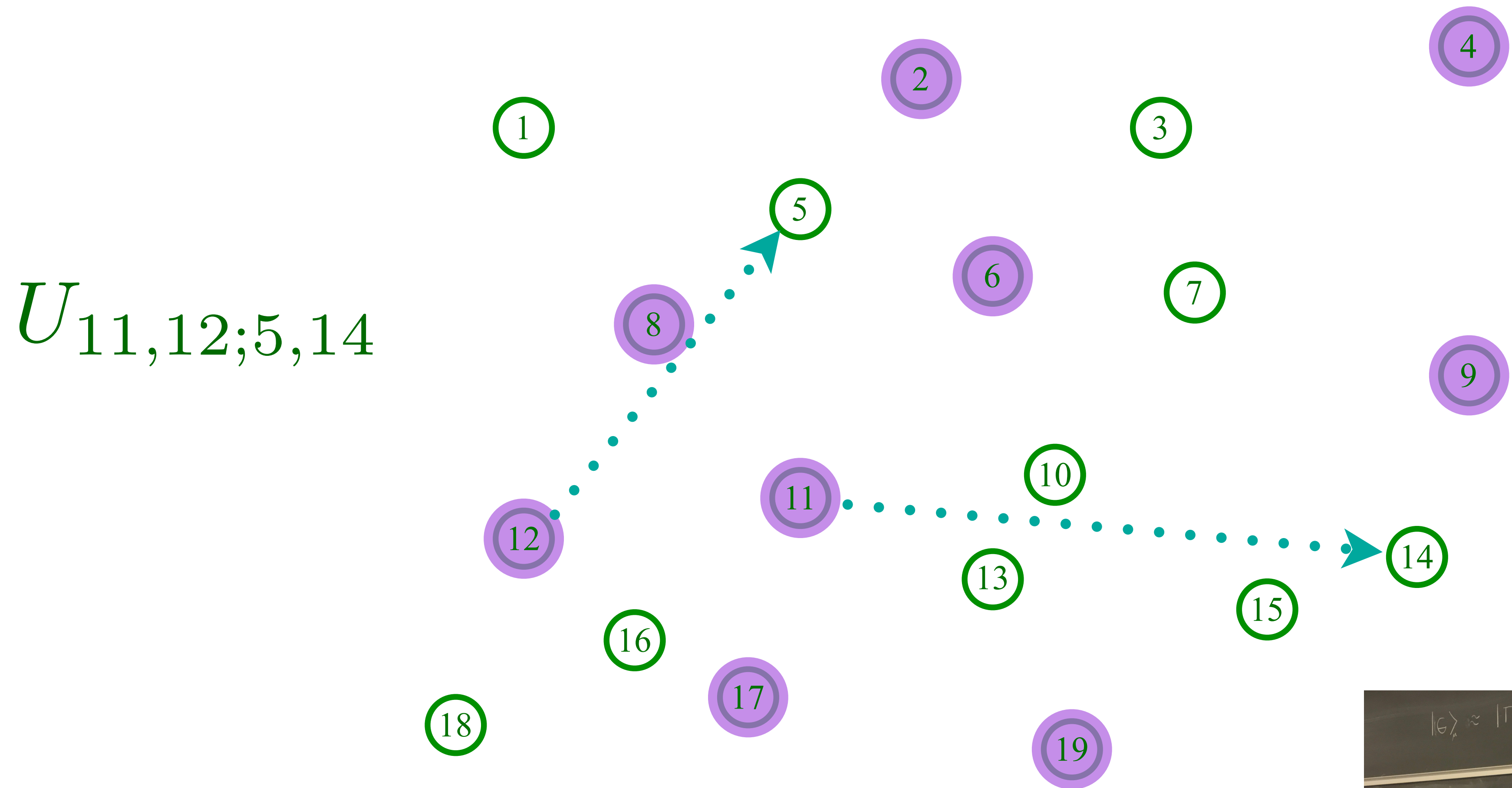


Place electrons randomly on some sites

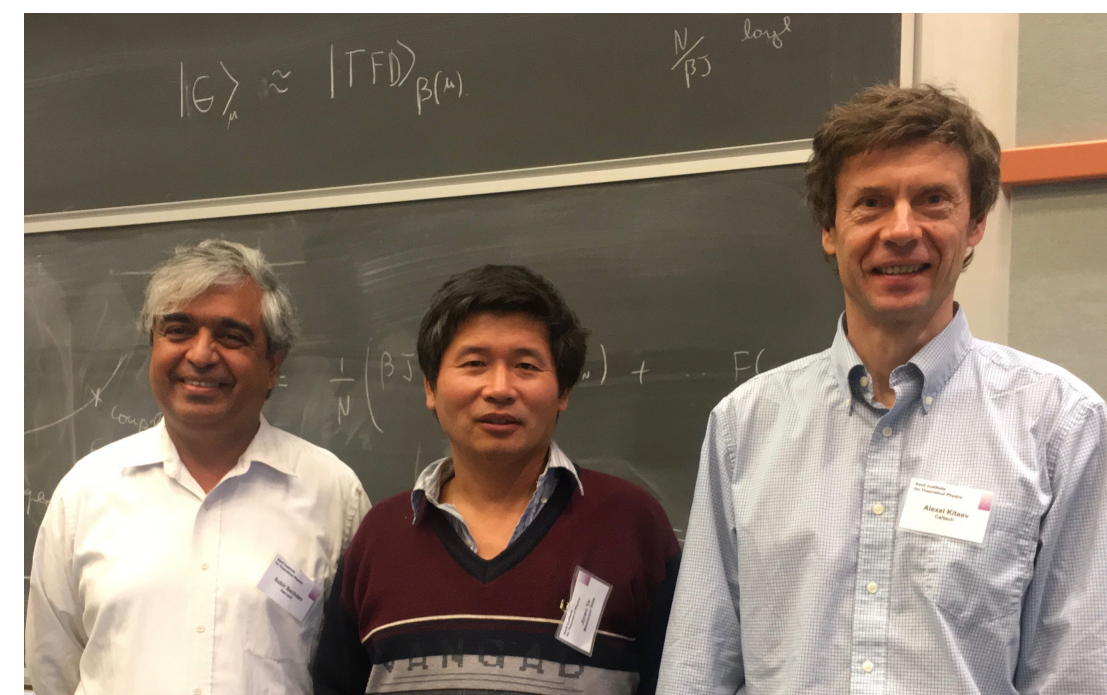


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



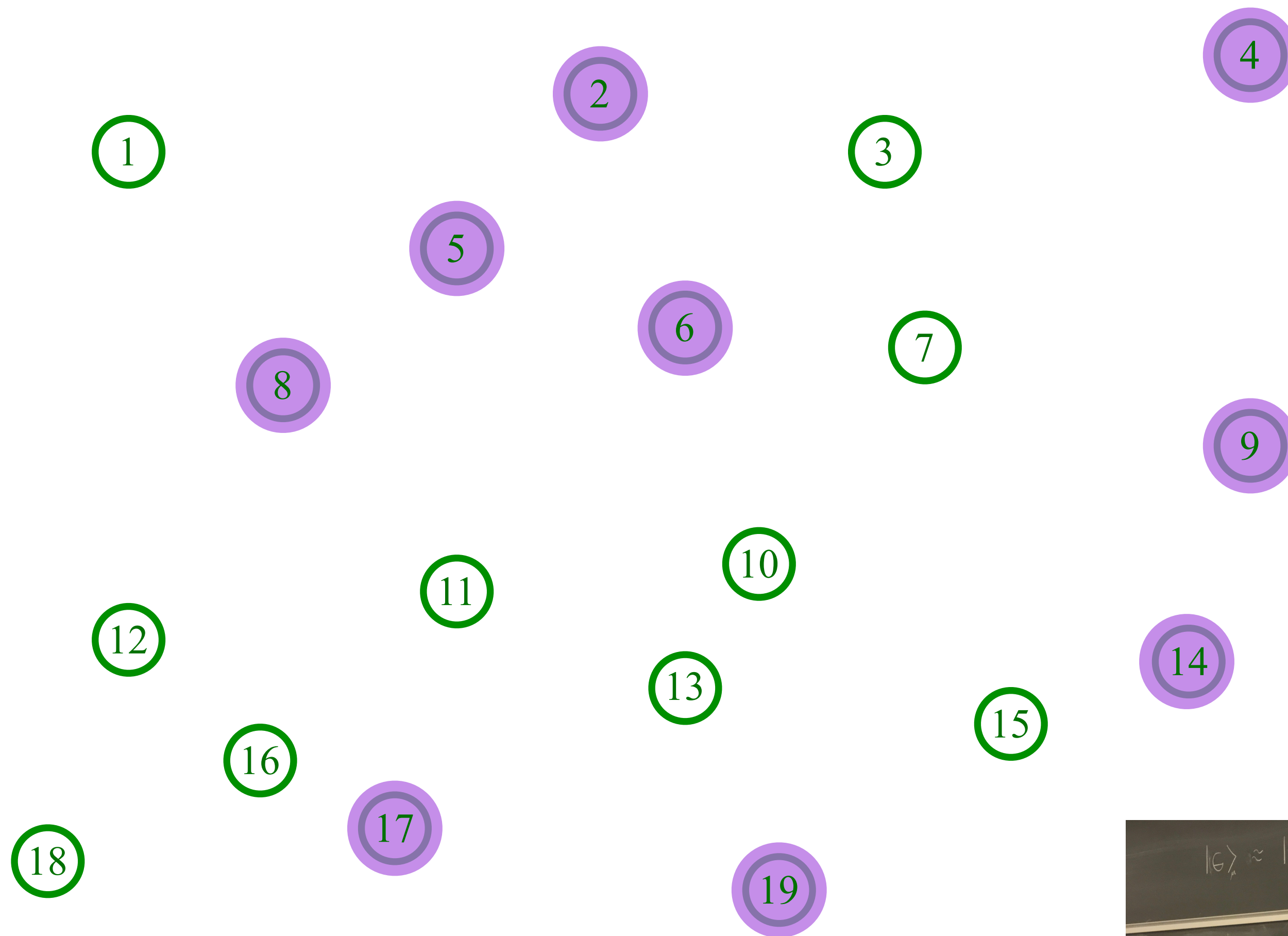
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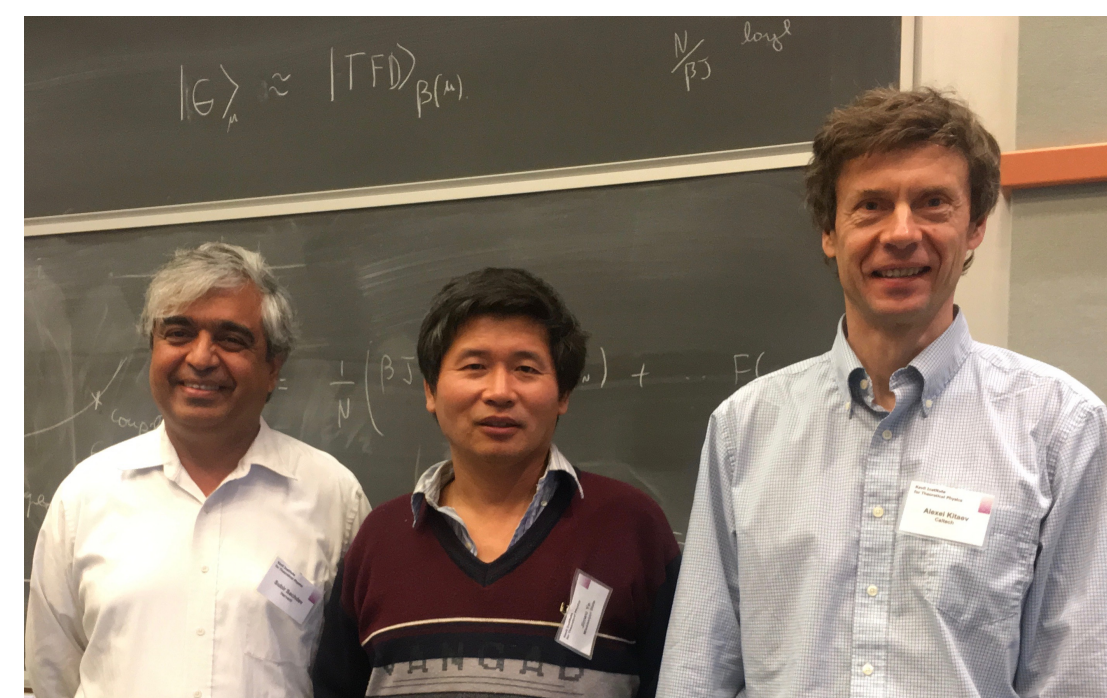
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



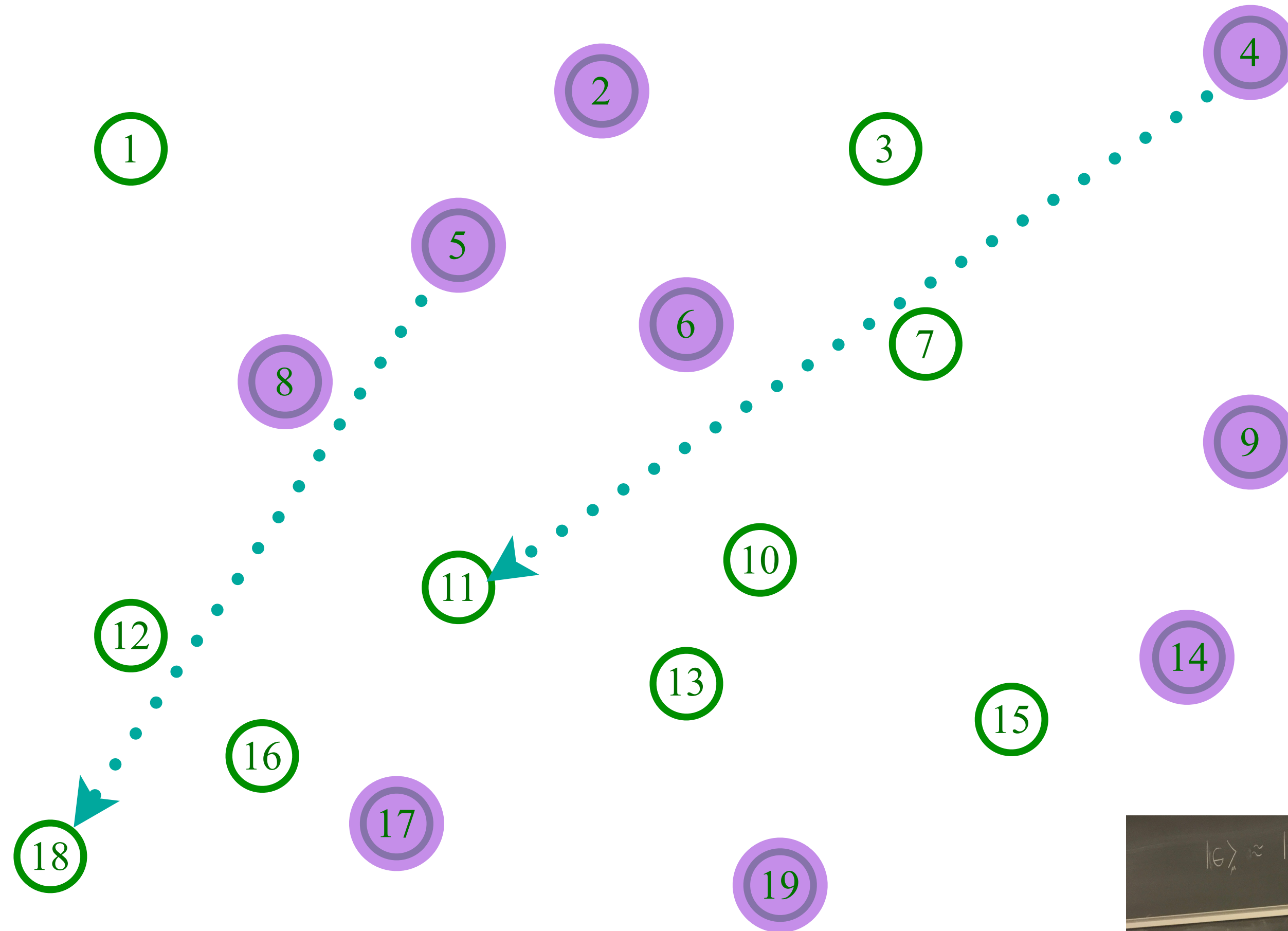
Entangle electrons pairwise randomly



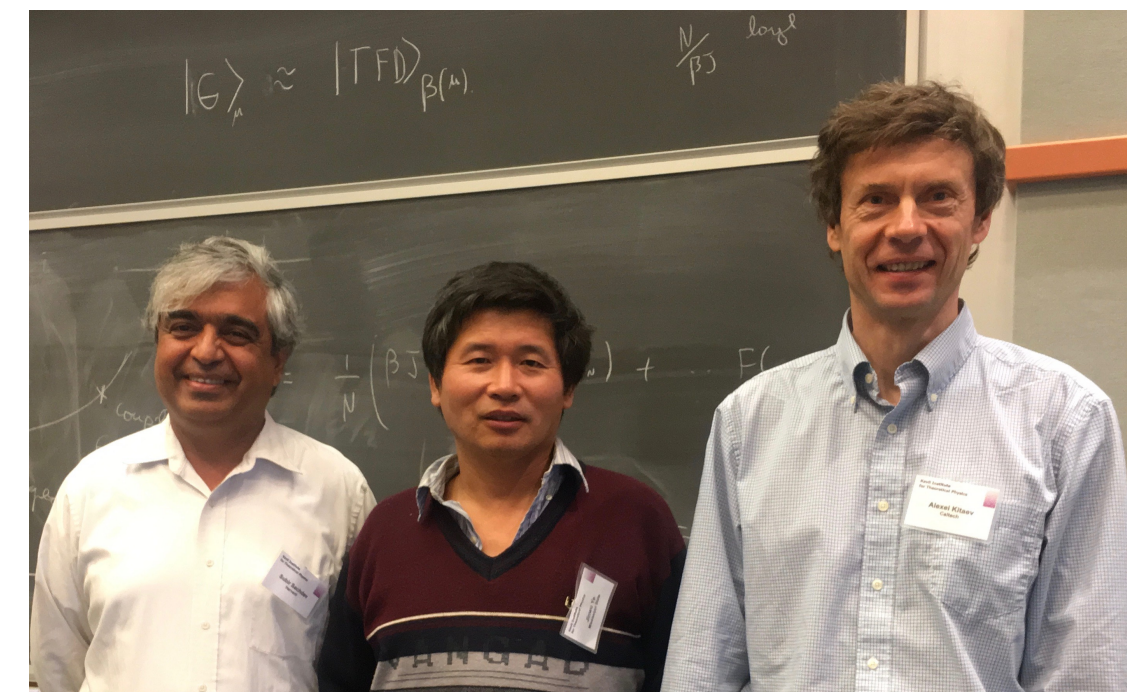
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



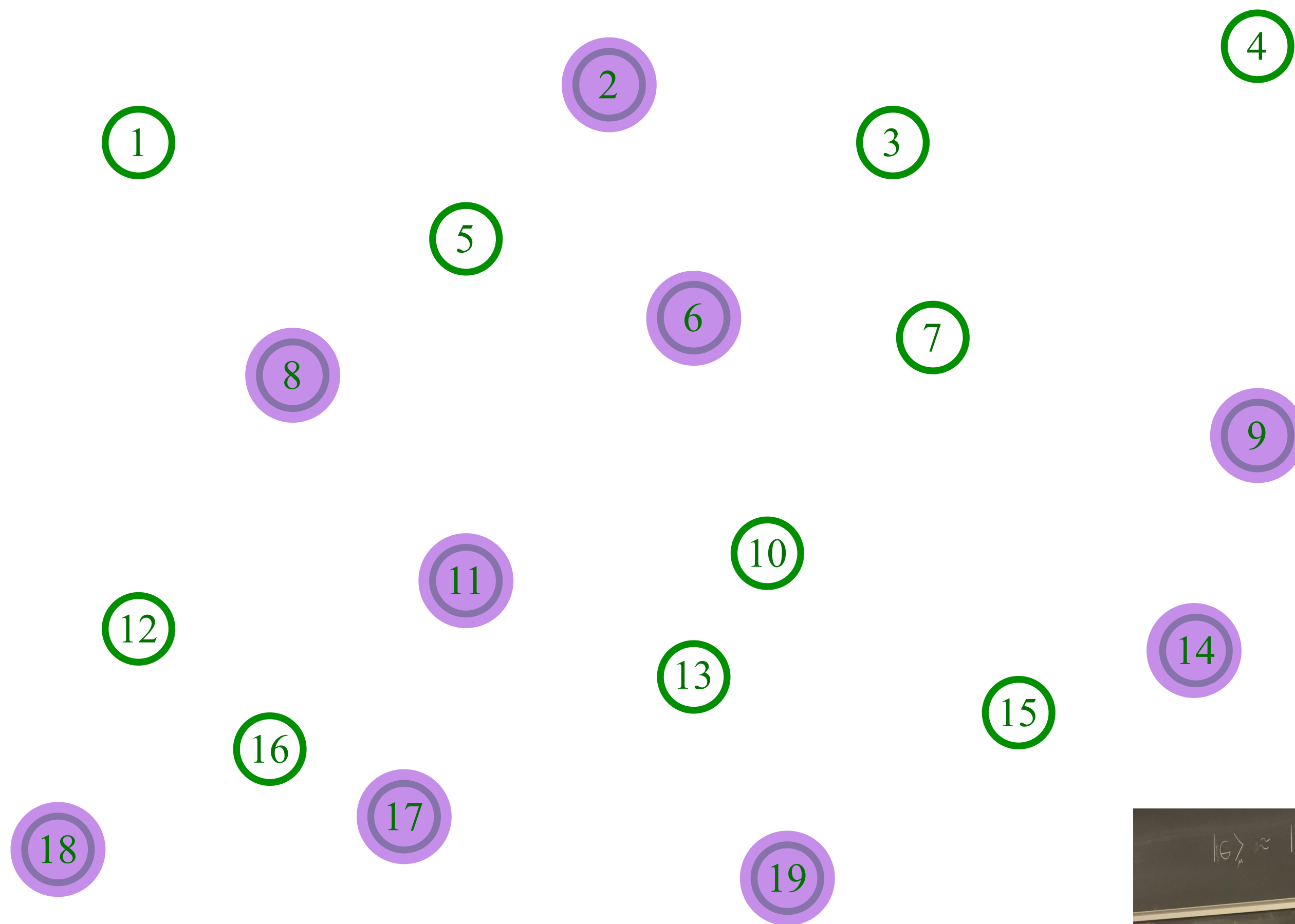
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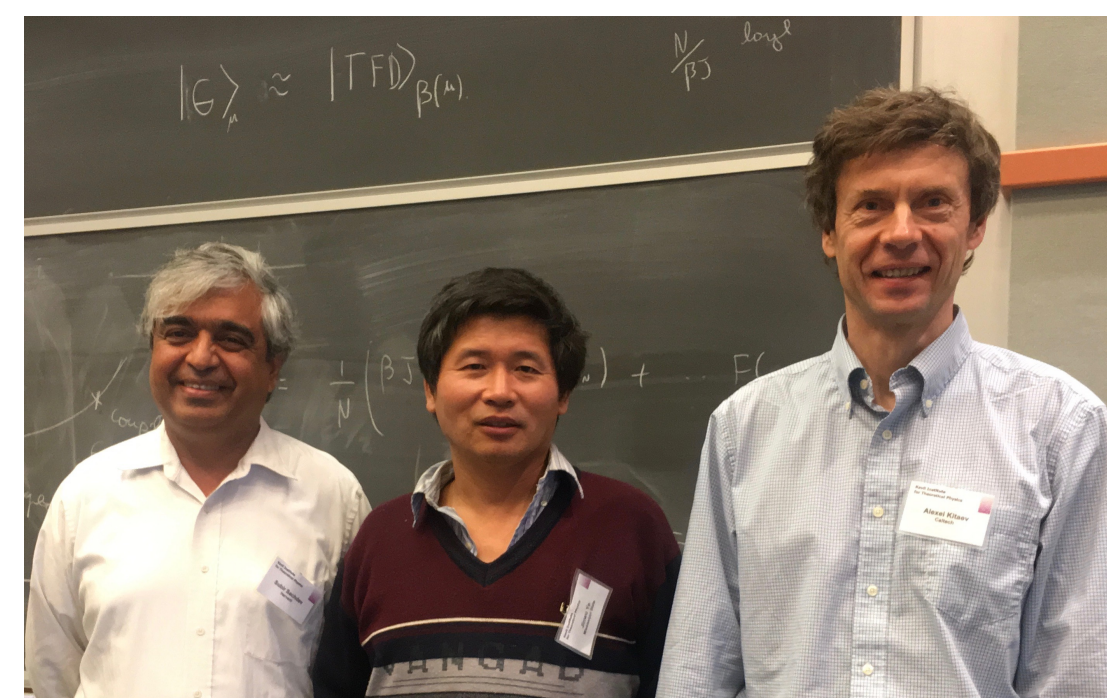
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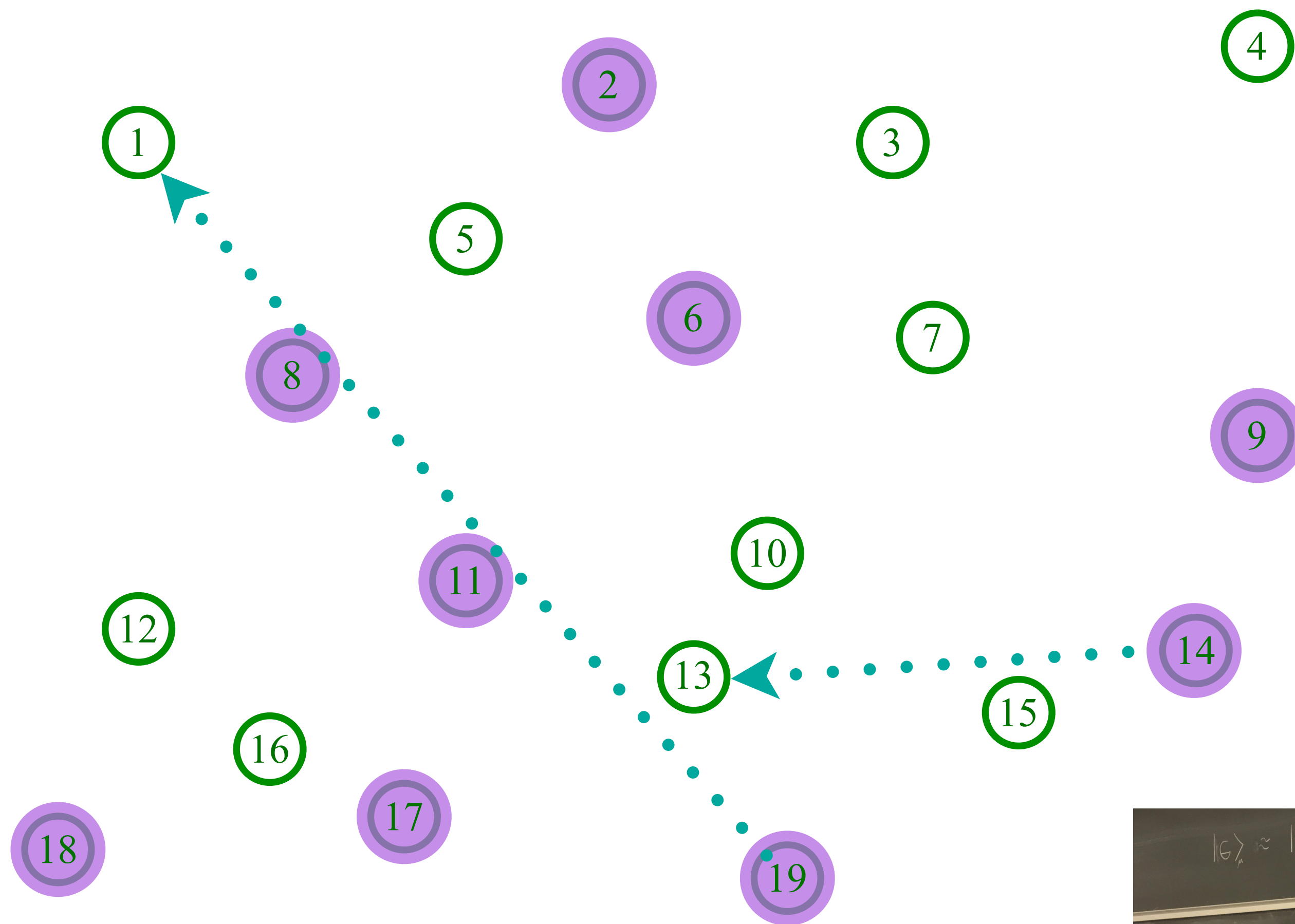
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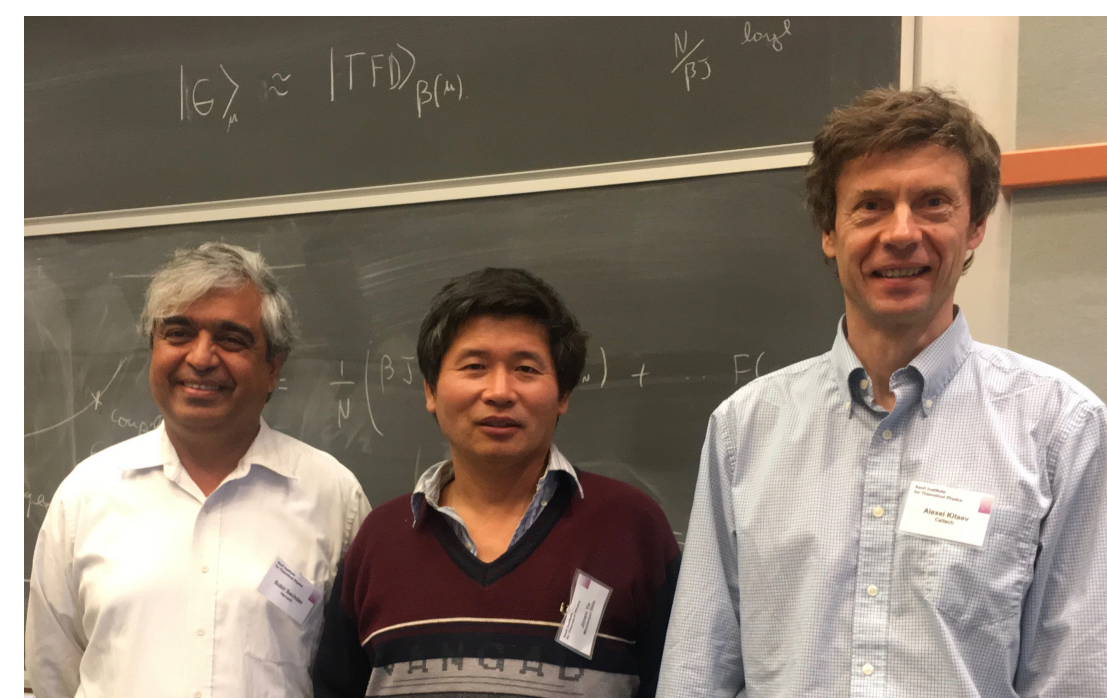
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



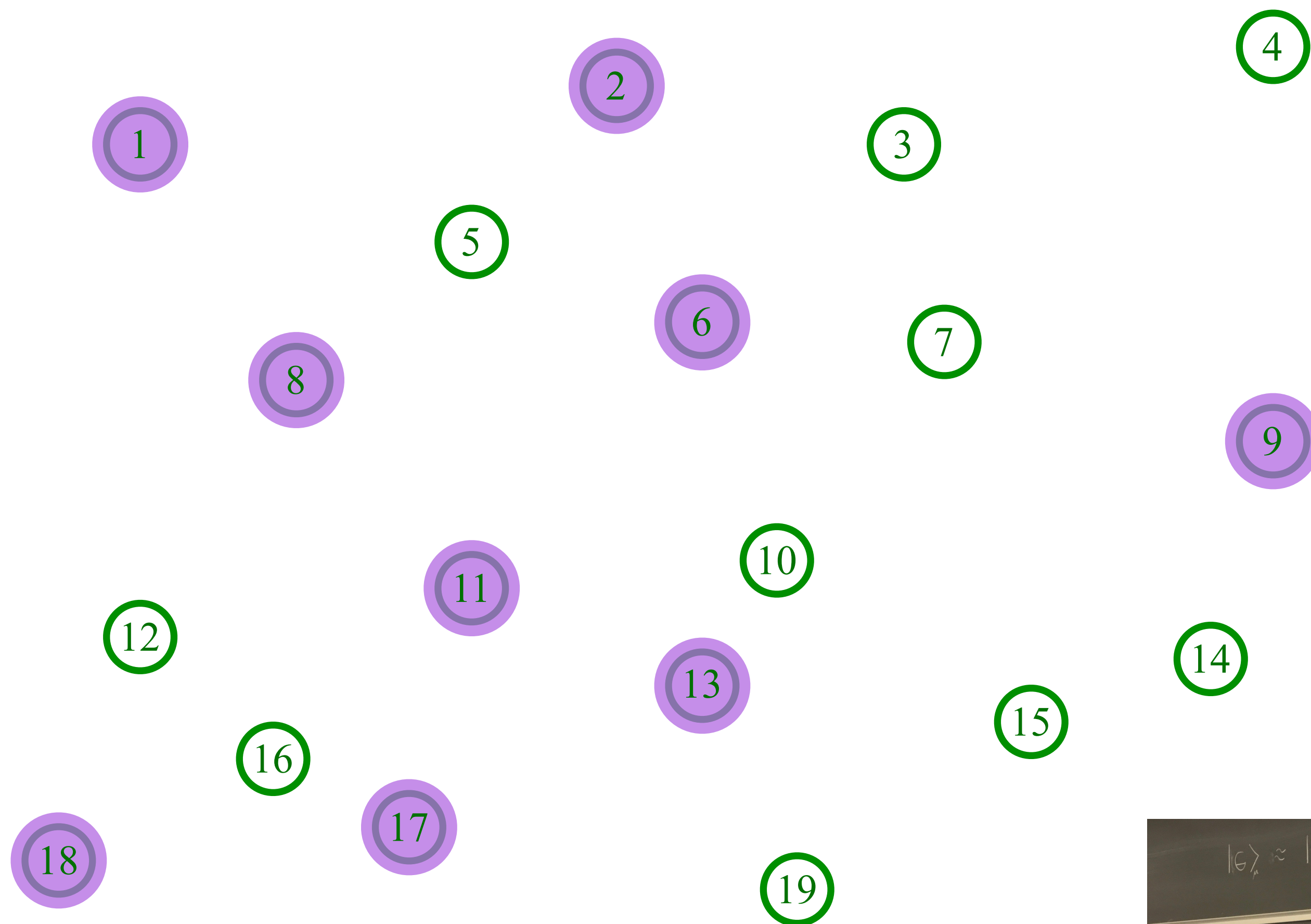
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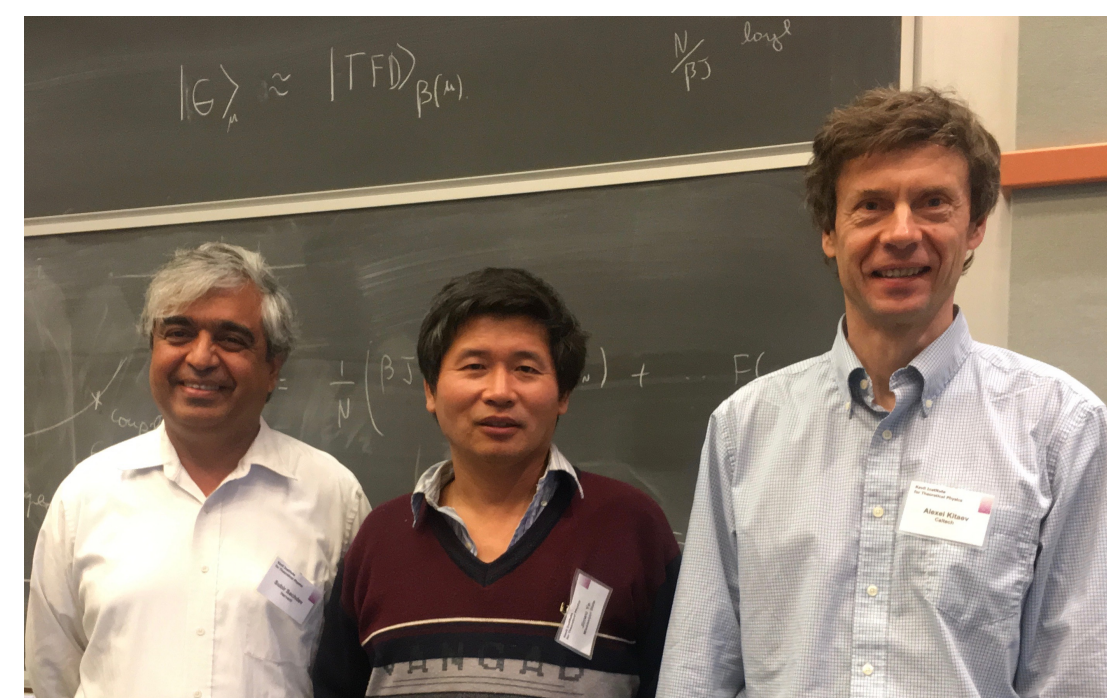
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Sachdev, Ye (1993); Kitaev (2015)

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



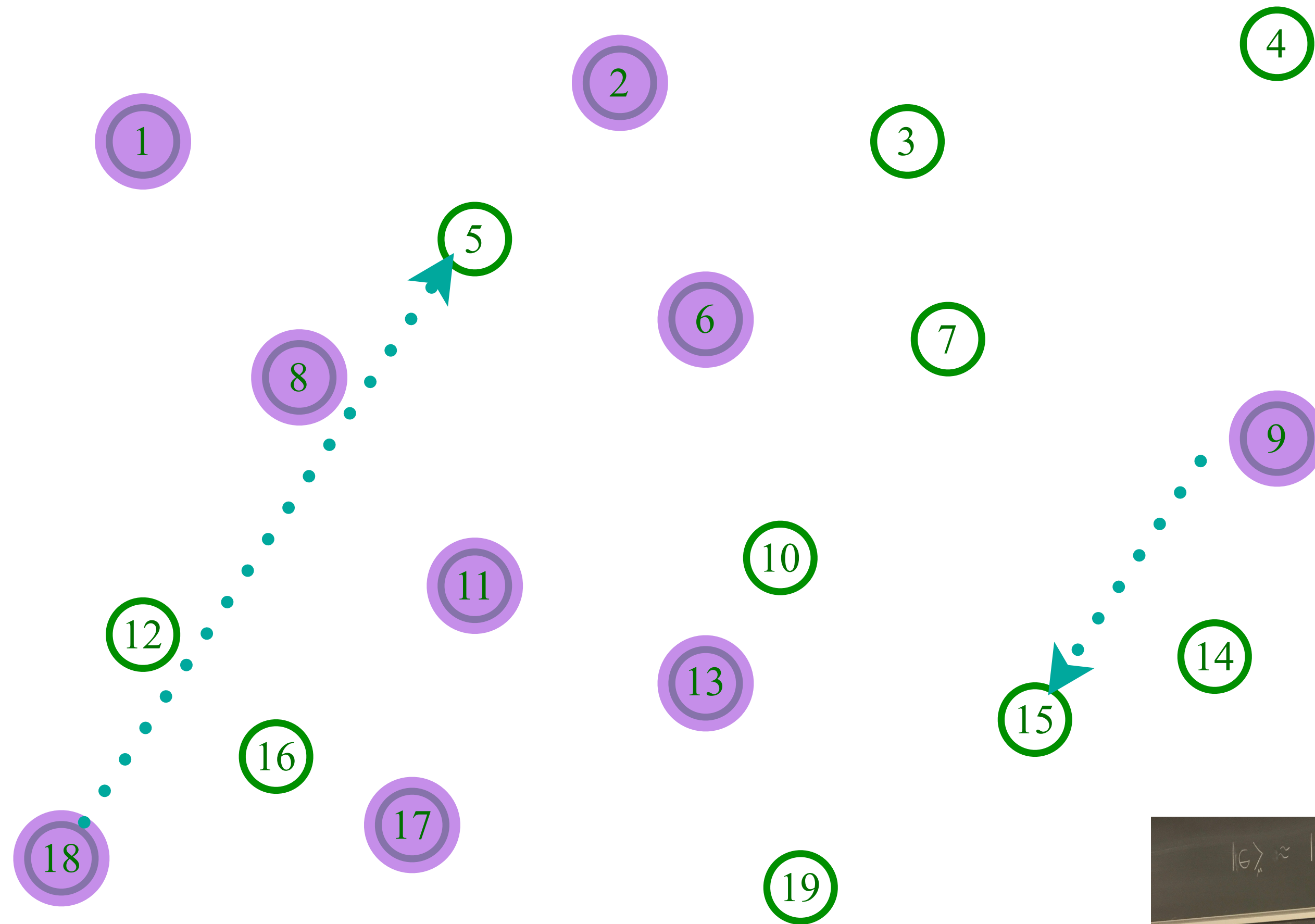
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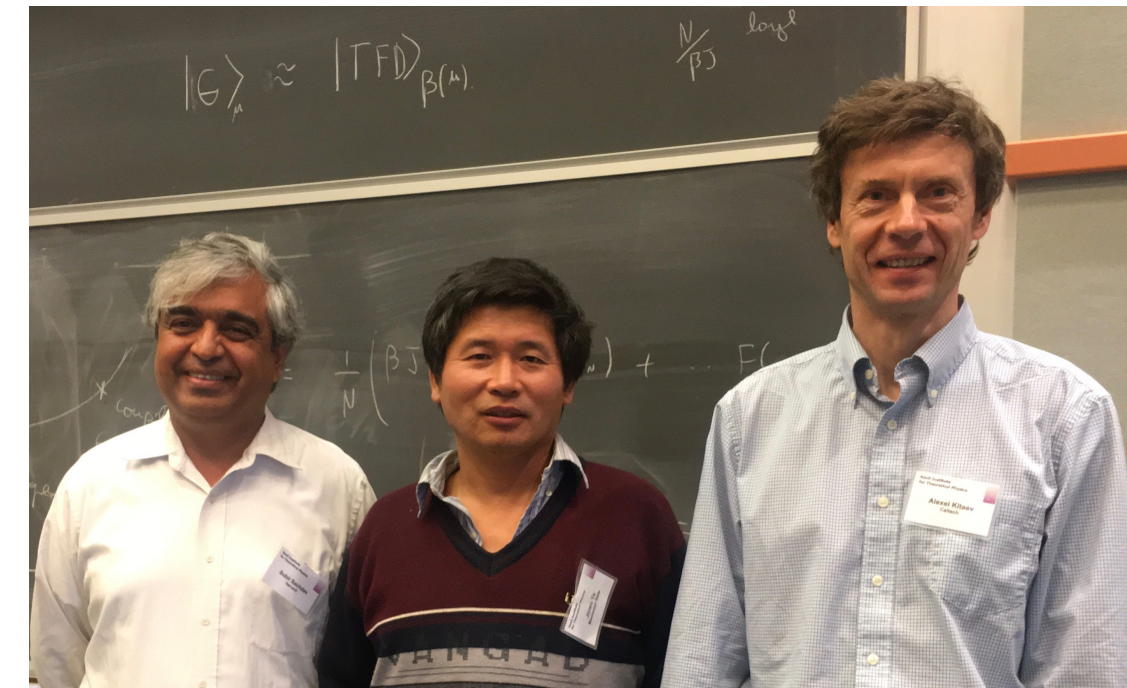
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



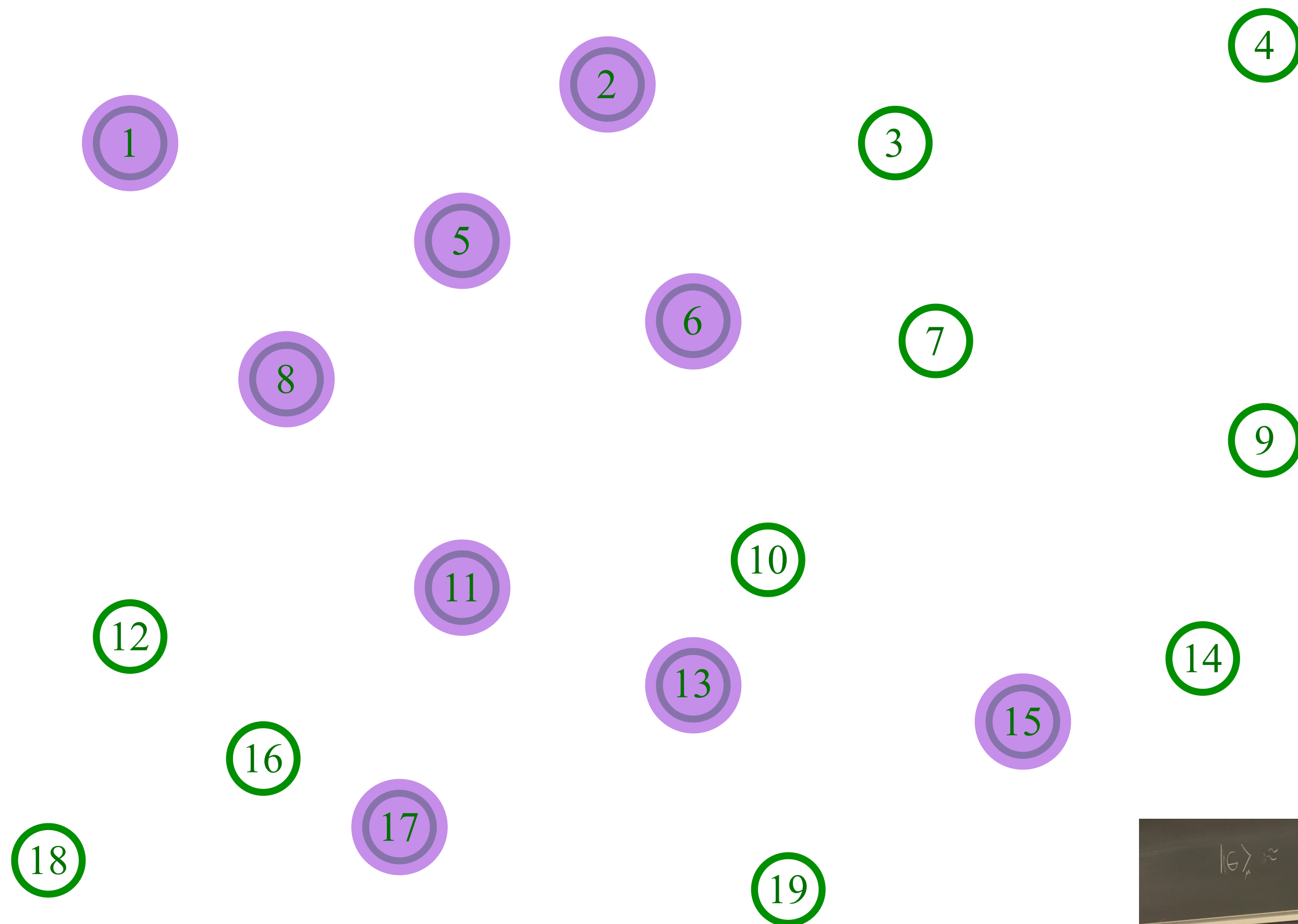
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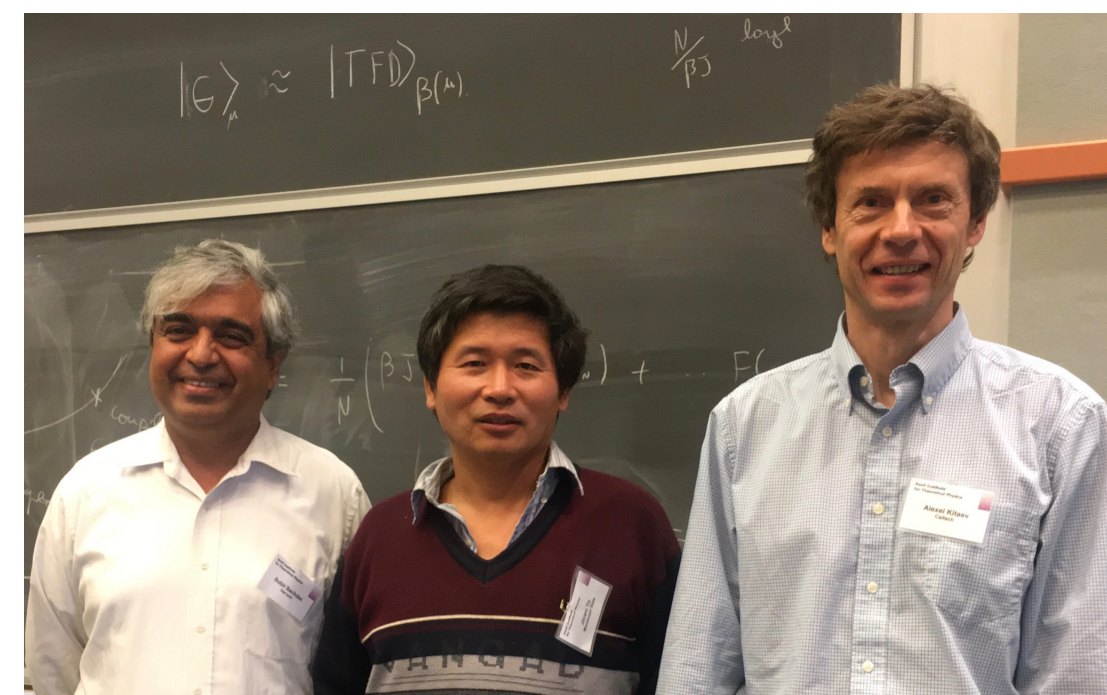
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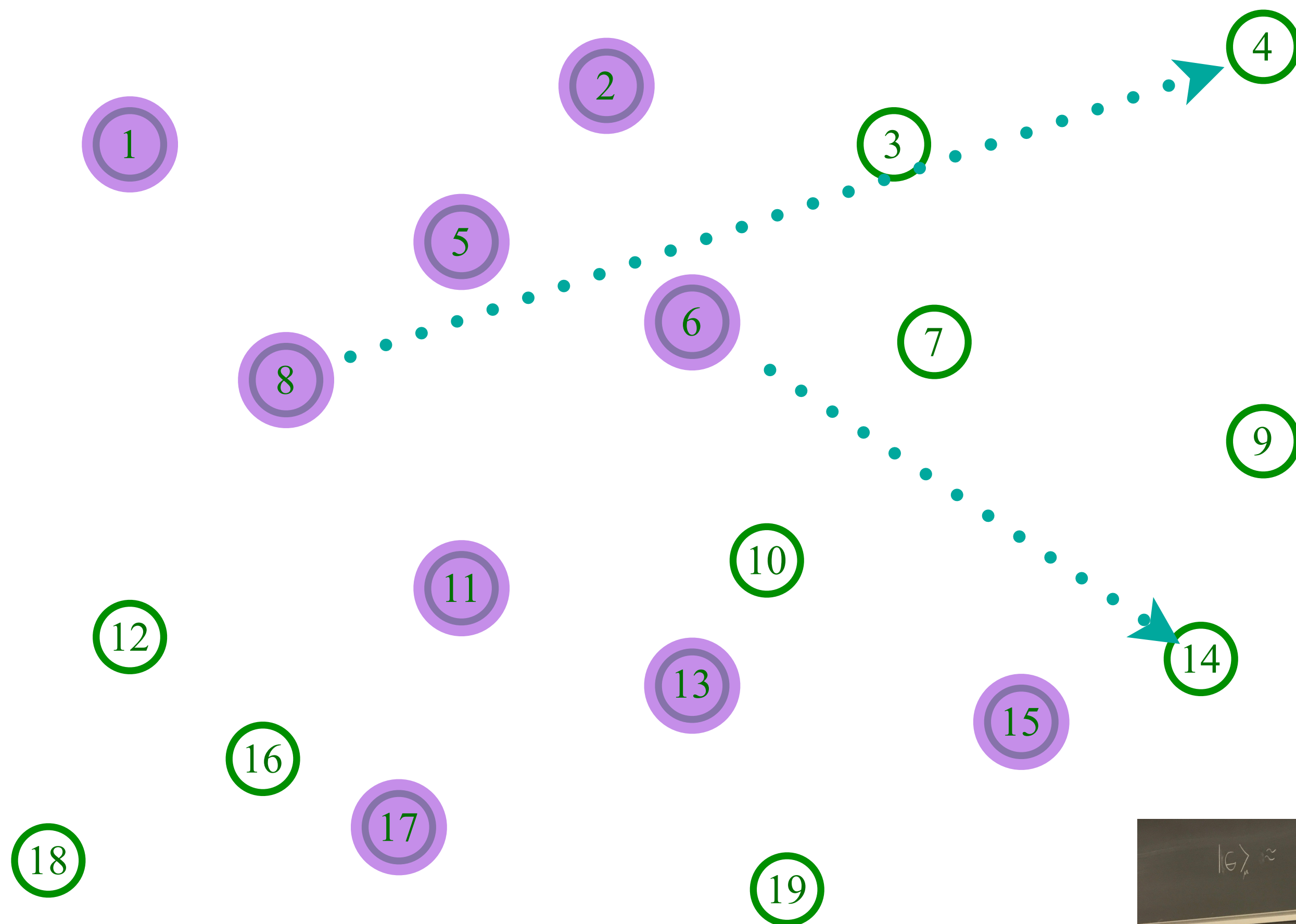
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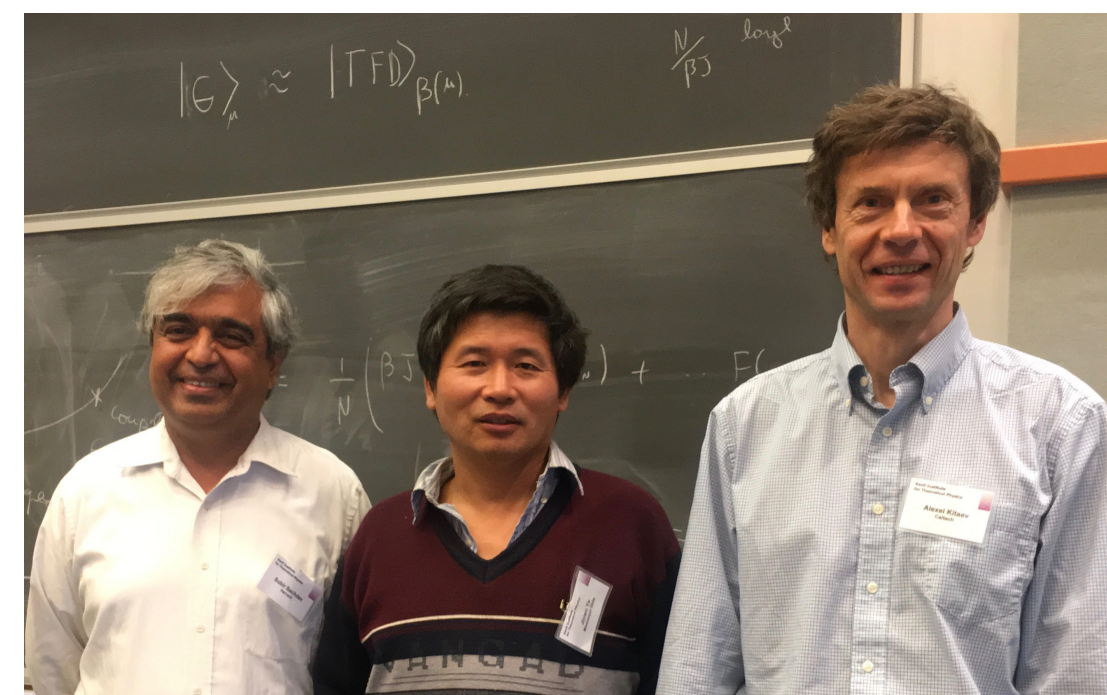
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



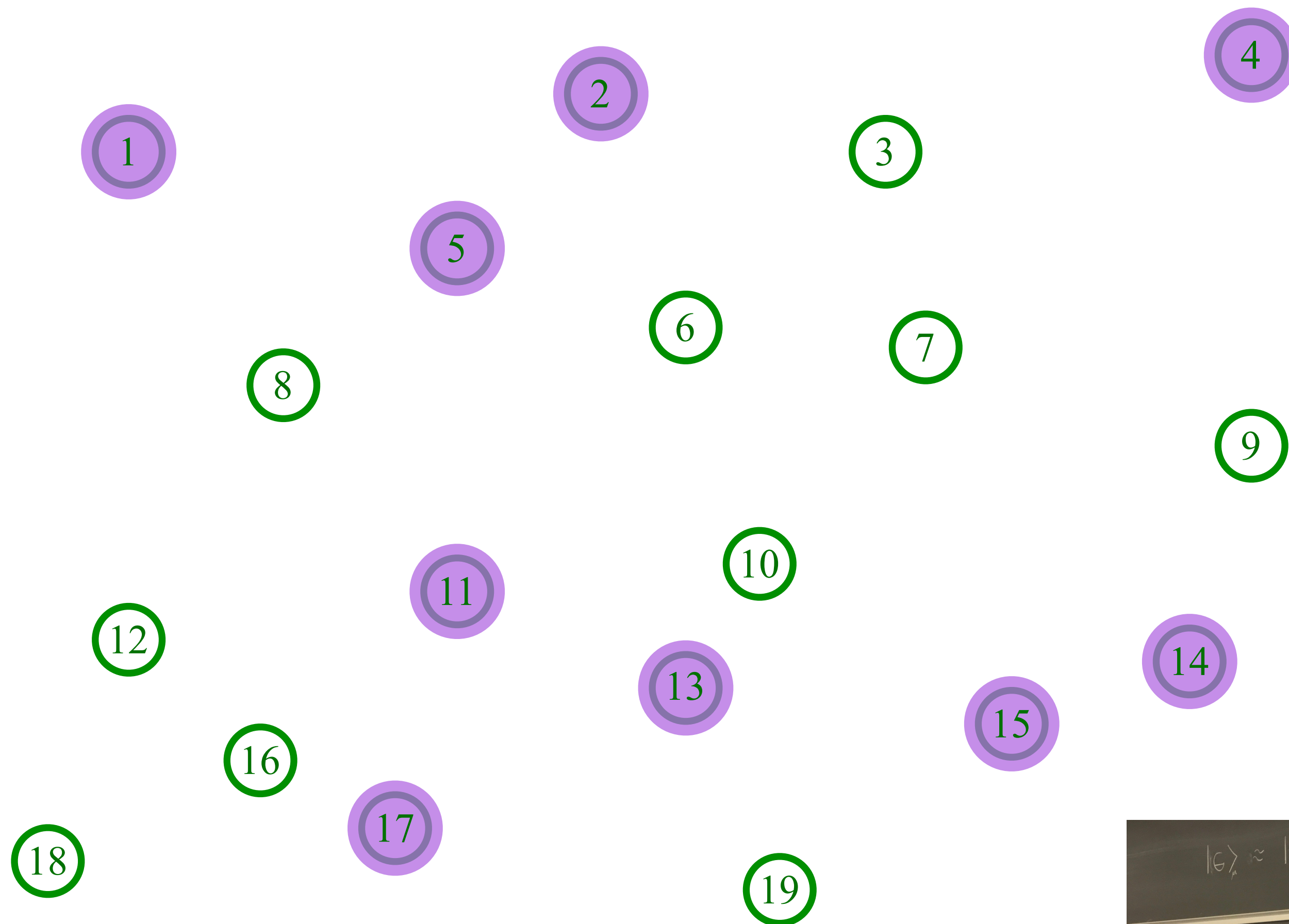
Entangle electrons pairwise randomly



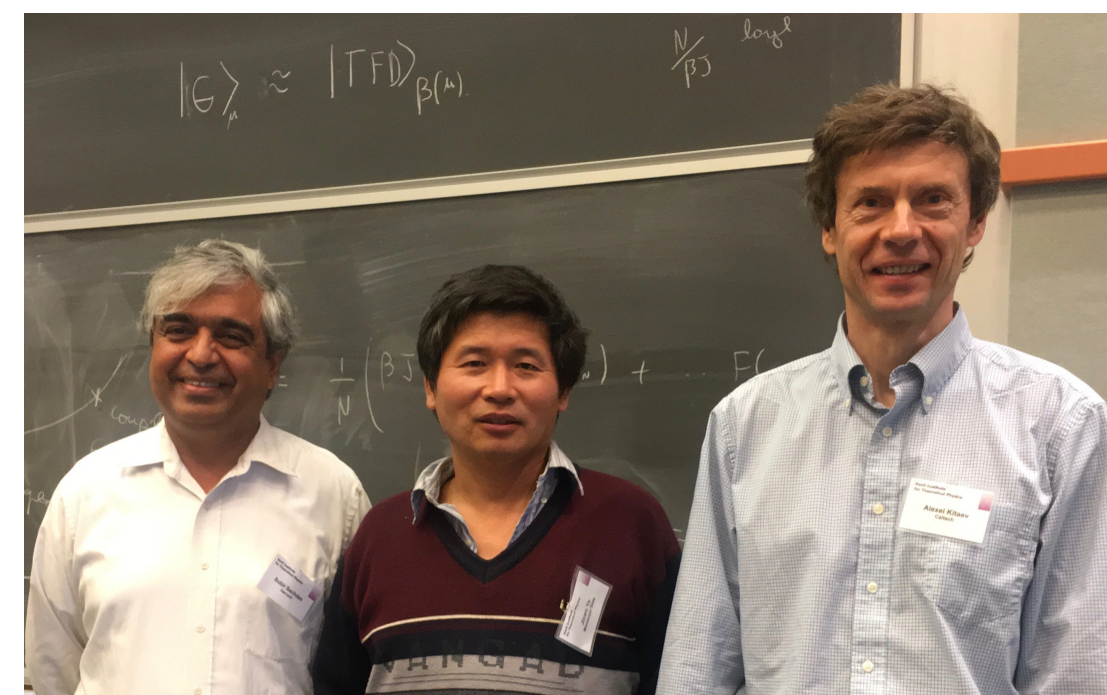
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



Entangle electrons pairwise randomly



The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

A solvable model of multi-particle
quantum entanglement.

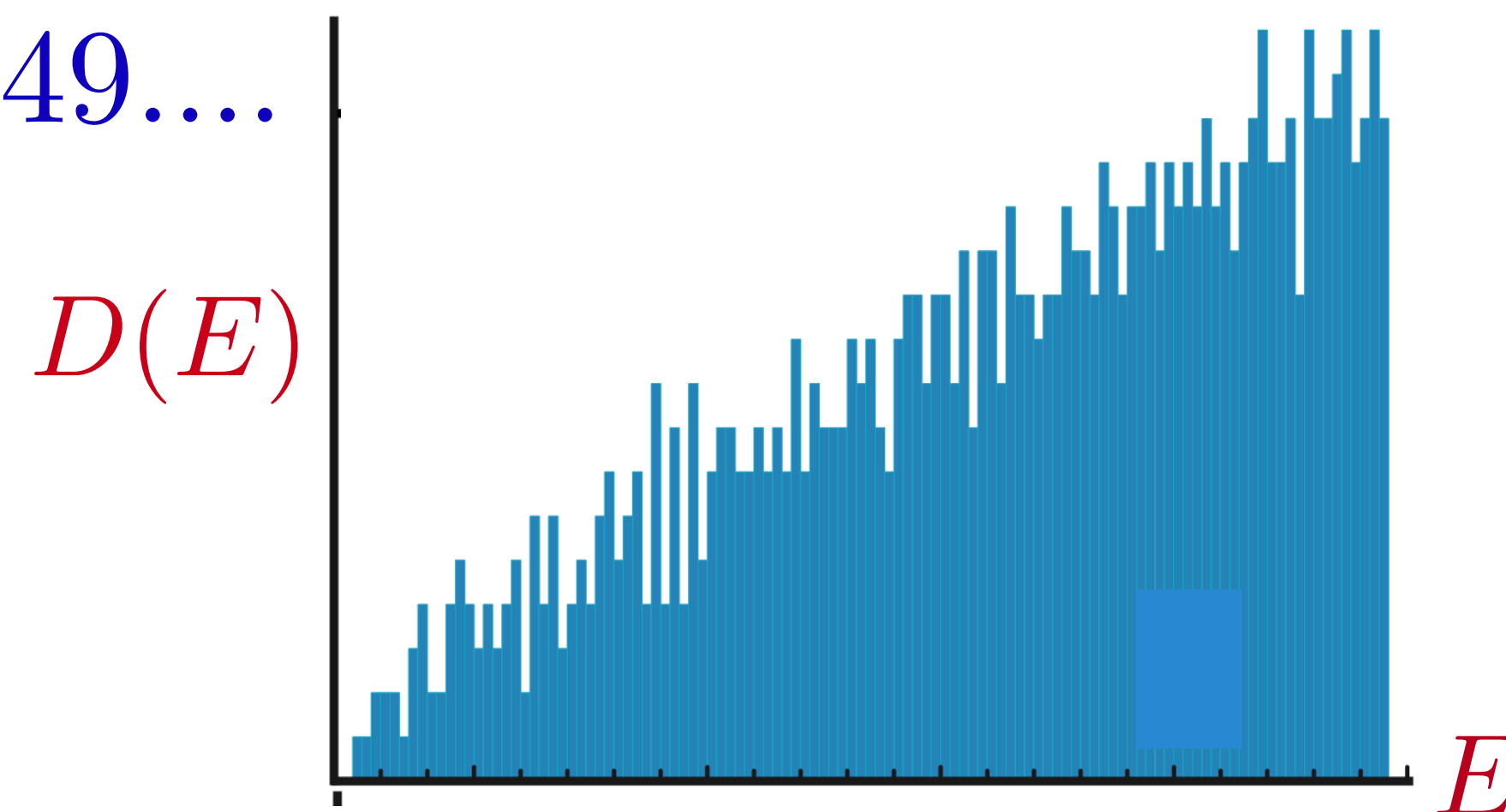
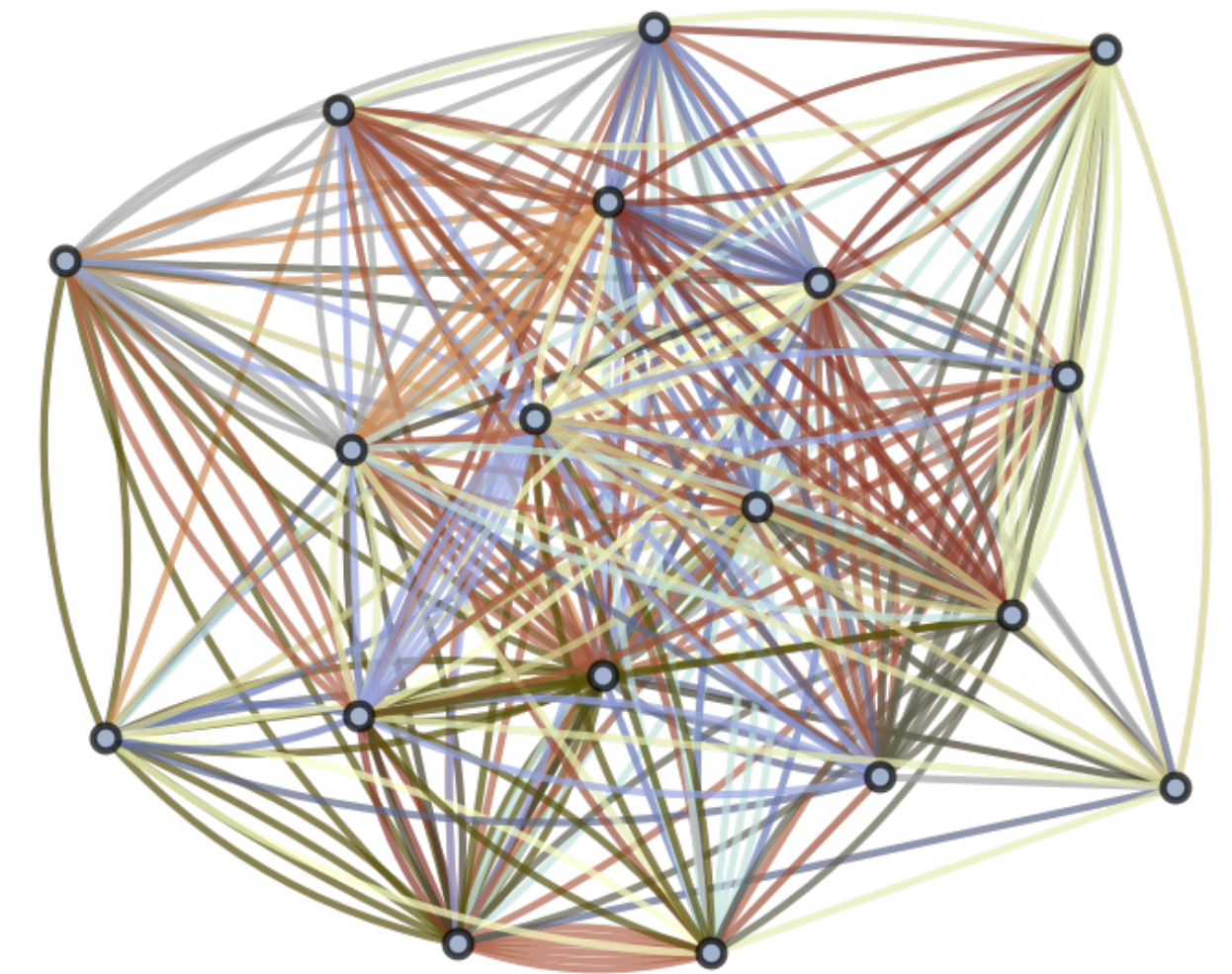
Yields a metal in which current is carried
not by individual electrons,
but by an entangled “quantum soup”

The Sachdev-Ye-Kitaev (SYK) model

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

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

where $s_0 = 0.46484769917080510749\dots$



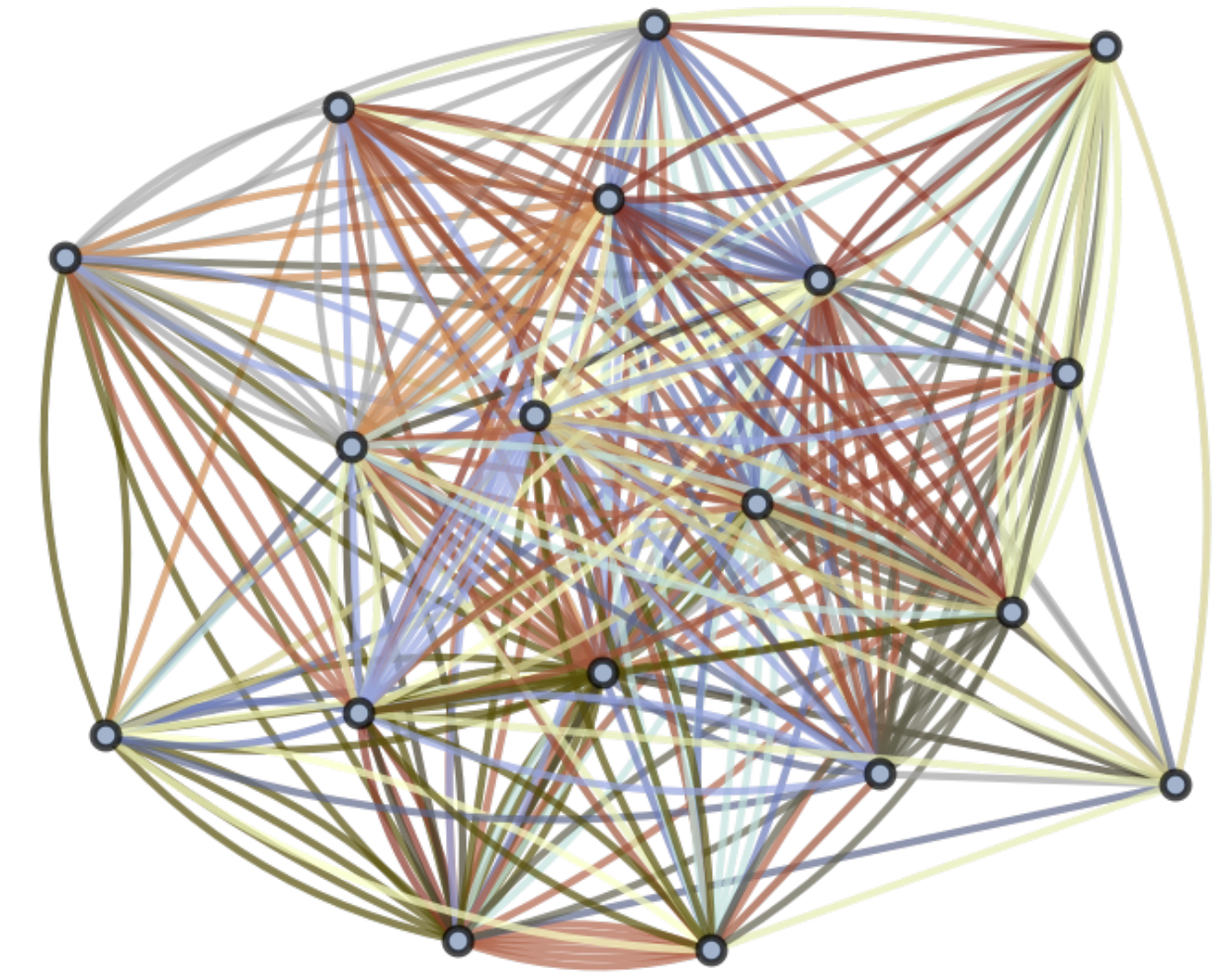
The Sachdev-Ye-Kitaev (SYK) model

A. Georges, O. Parcollet, and S. Sachdev,
PRB **63**, 134406 (2001)

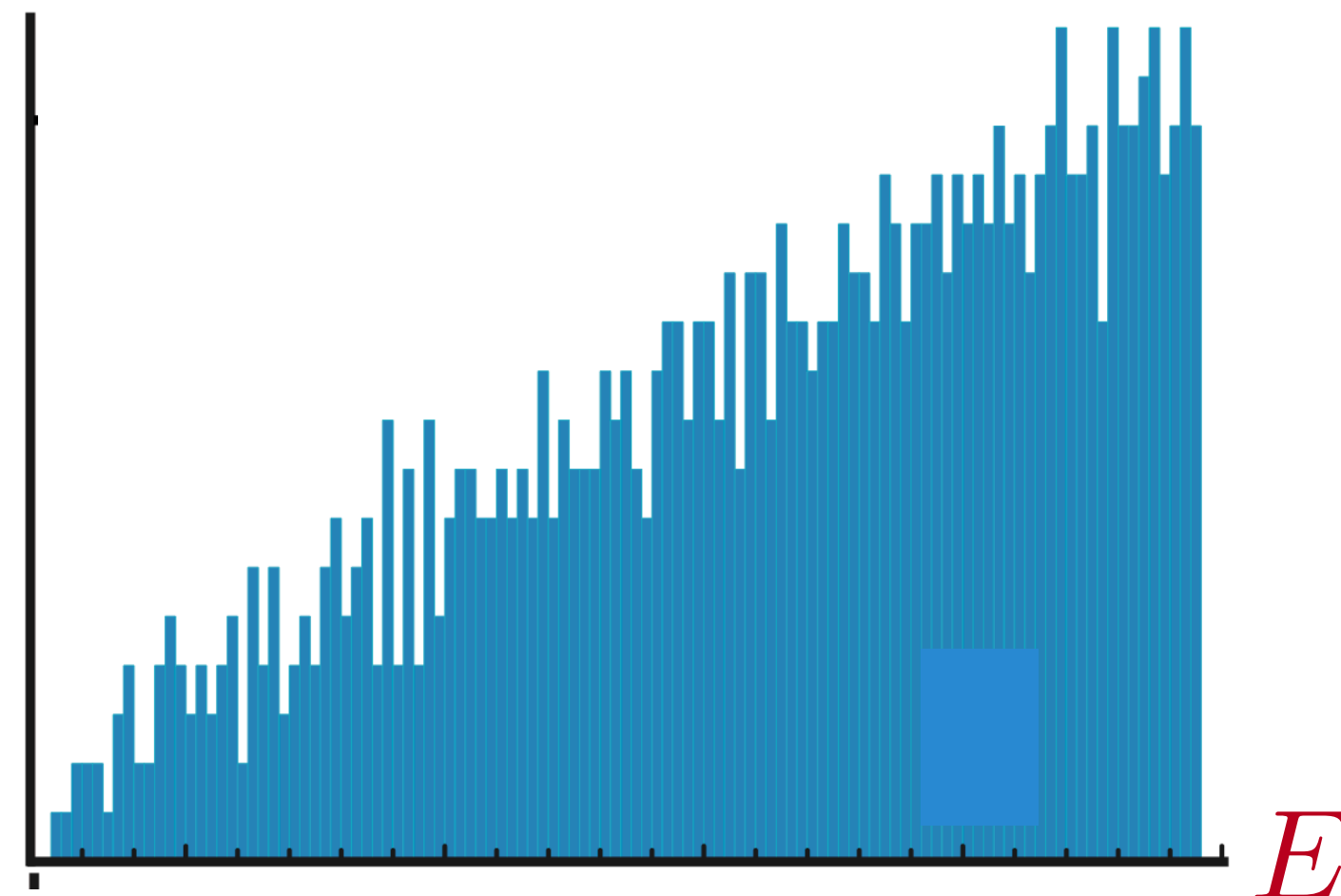
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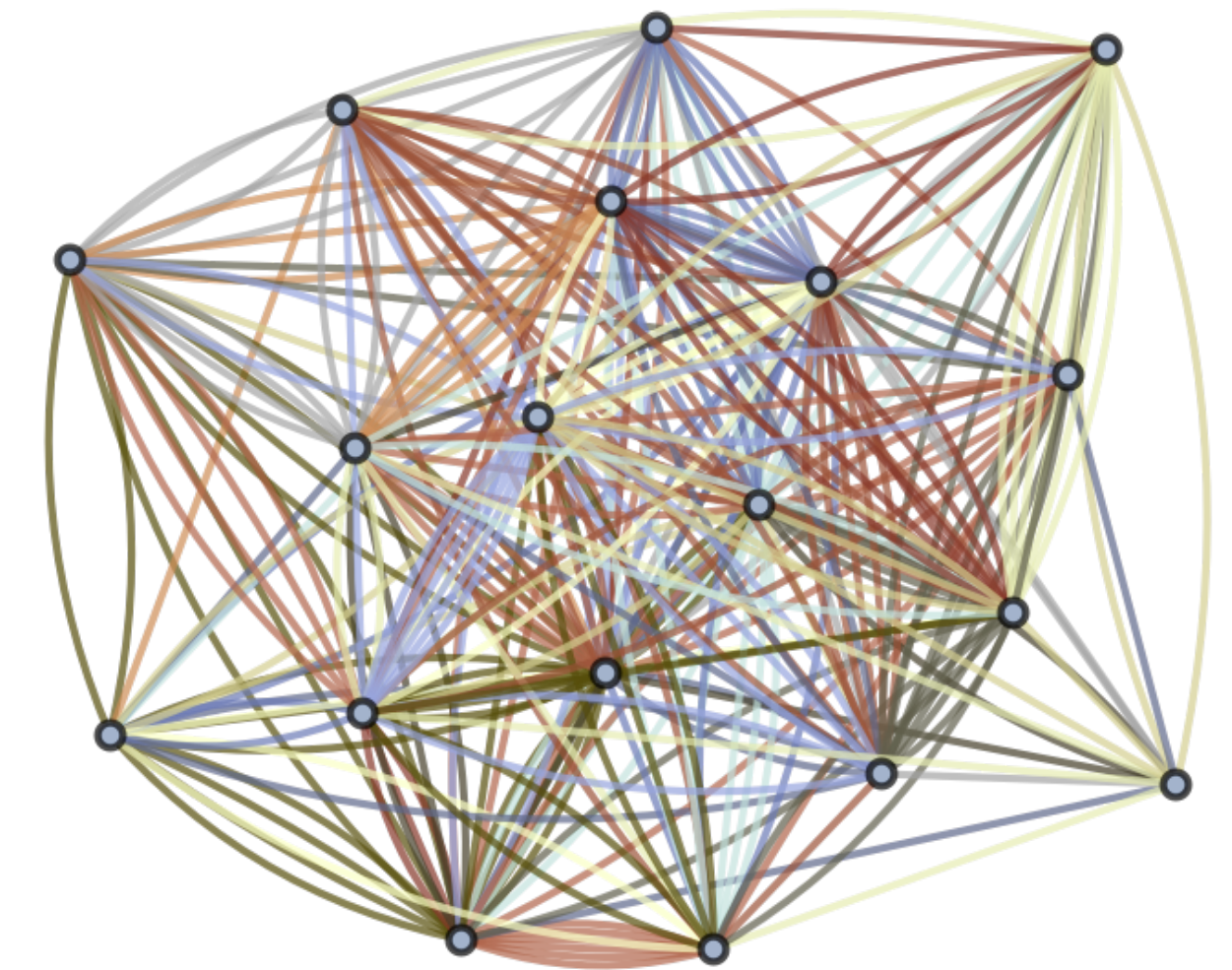


$D(E)$



The Sachdev-Ye-Kitaev (SYK) model

A. Georges, O. Parcollet, and S. Sachdev,
PRB **63**, 134406 (2001)



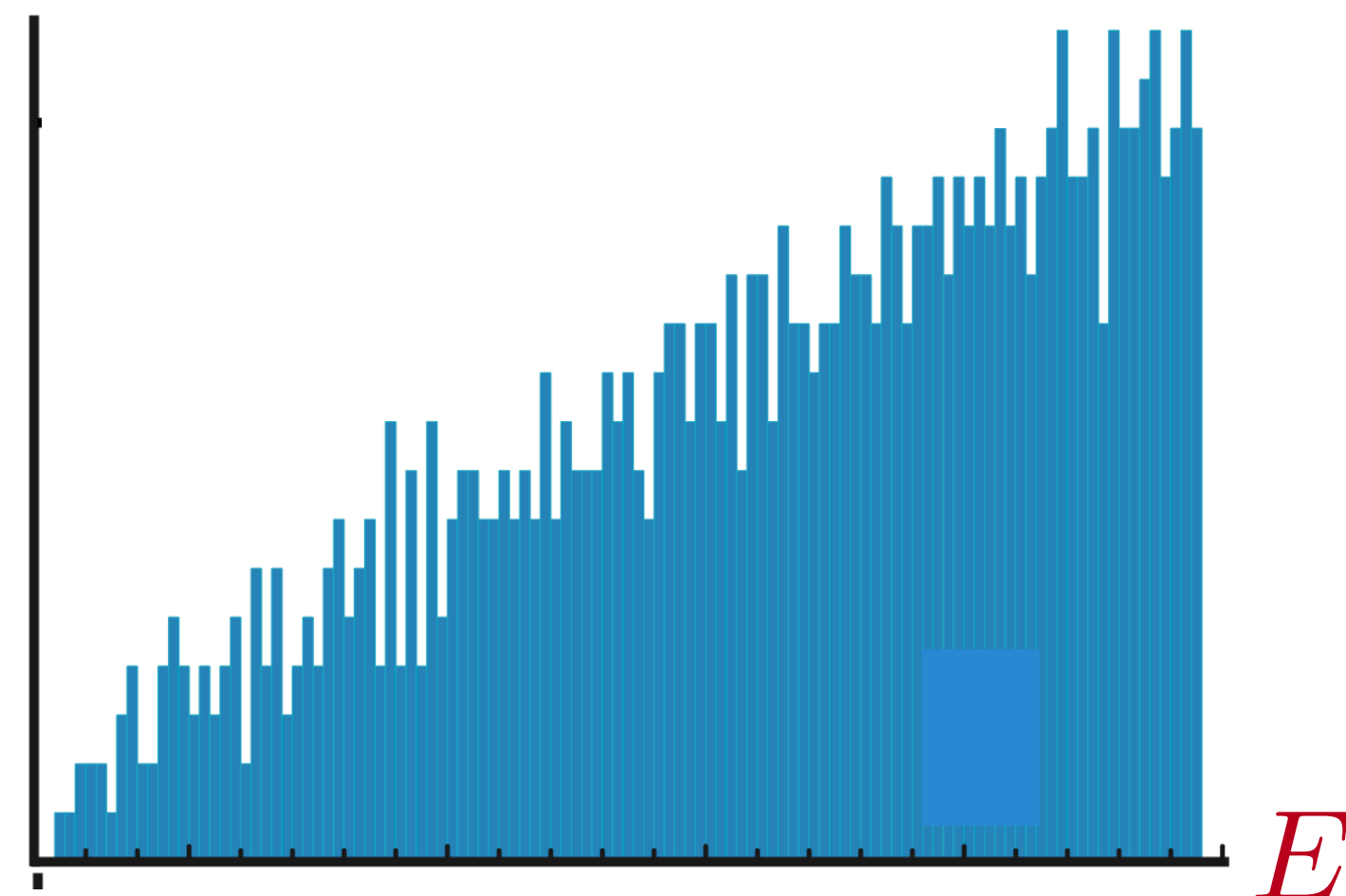
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J. S. Cotler et al.,
JHEP 05 (2017) 118

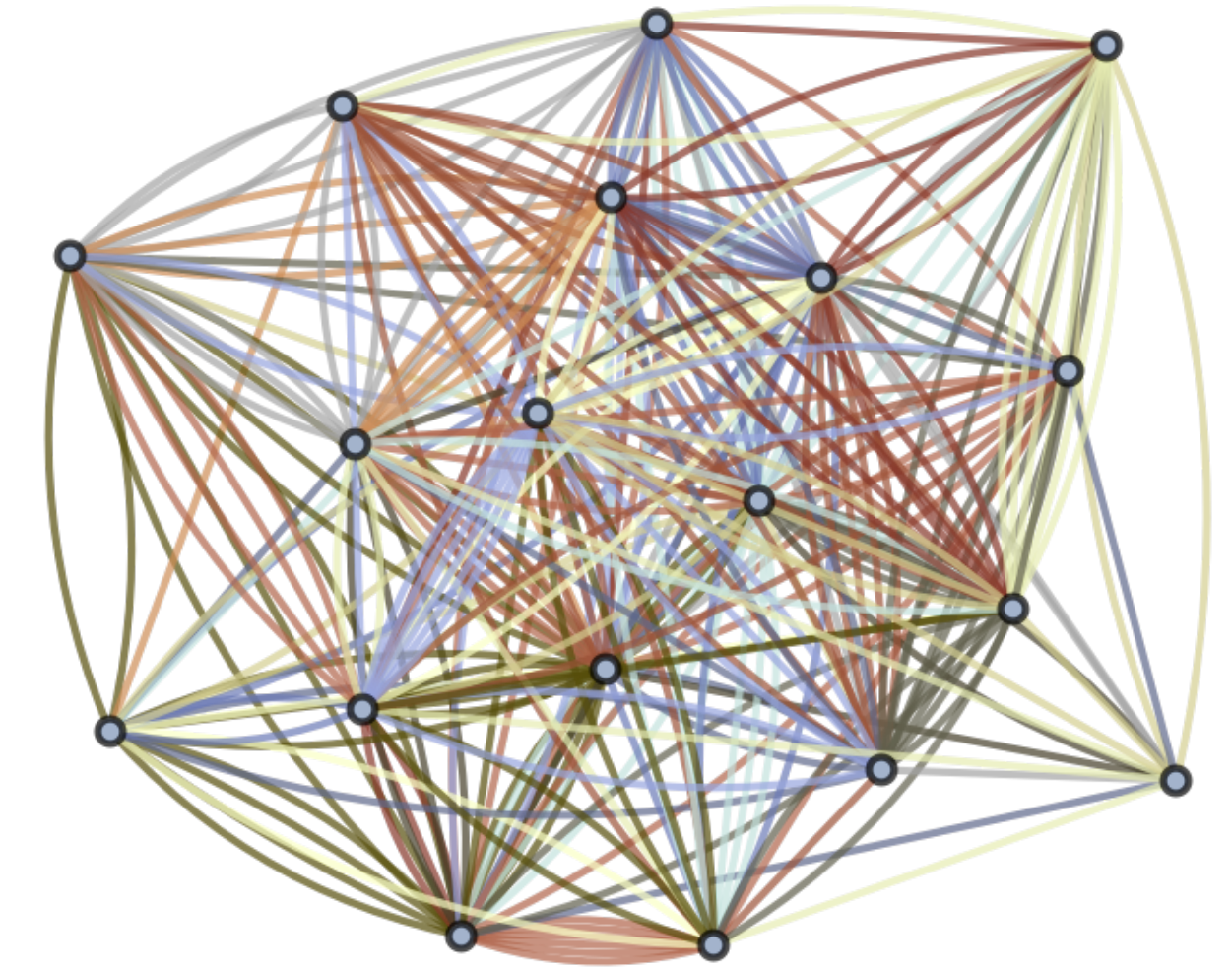
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$D(E)$



The Sachdev-Ye-Kitaev (SYK) model

A. Georges, O. Parcollet, and S. Sachdev,
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- Density of quantum states of the SYK model with N sites

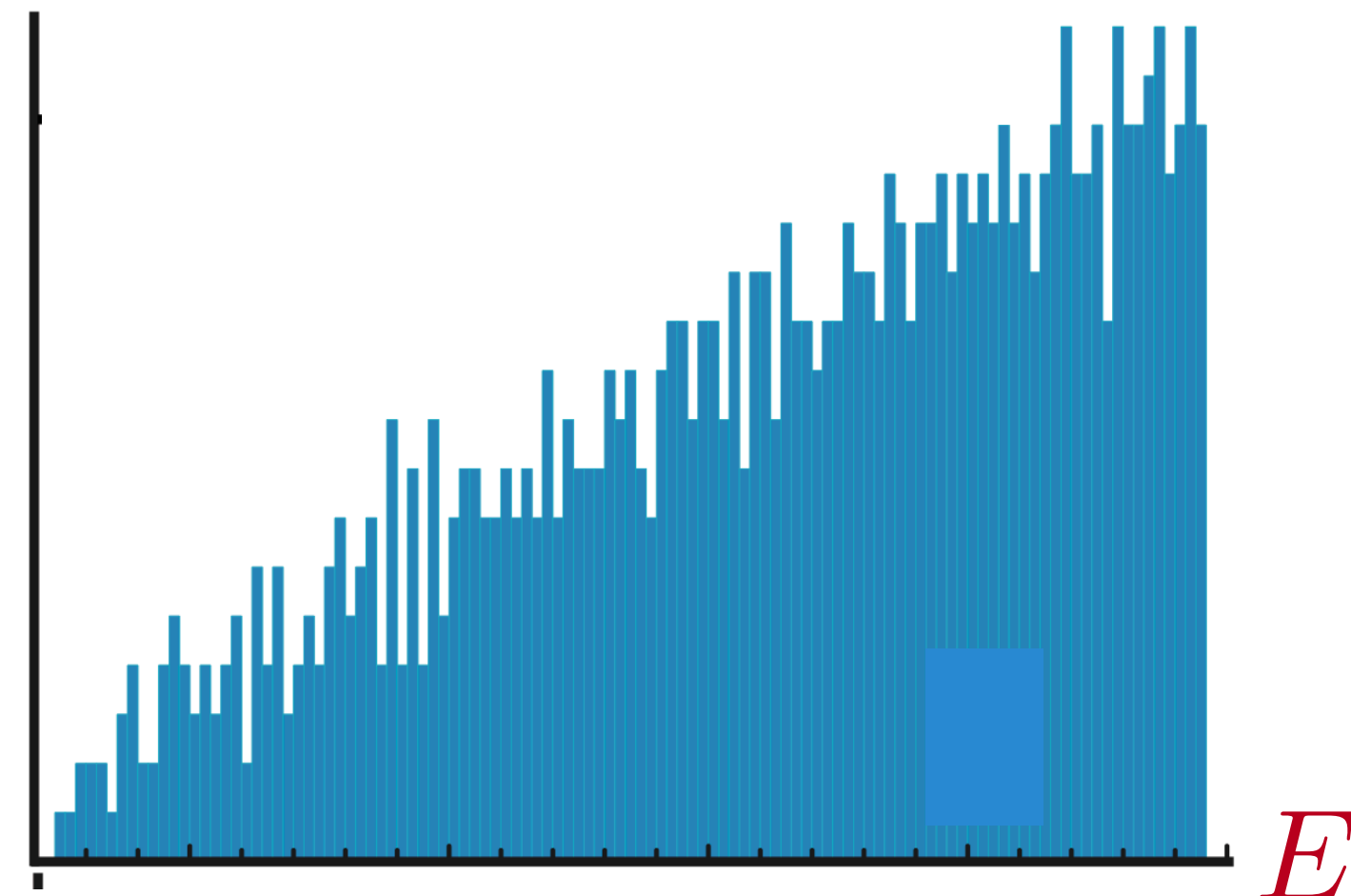
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J. S. Cotler et al.,
JHEP 05 (2017) 118

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Yingfei Gu, A. Kitaev, S. Sachdev, and
G. Tarnopolsky, JHEP 02 (2020) 157

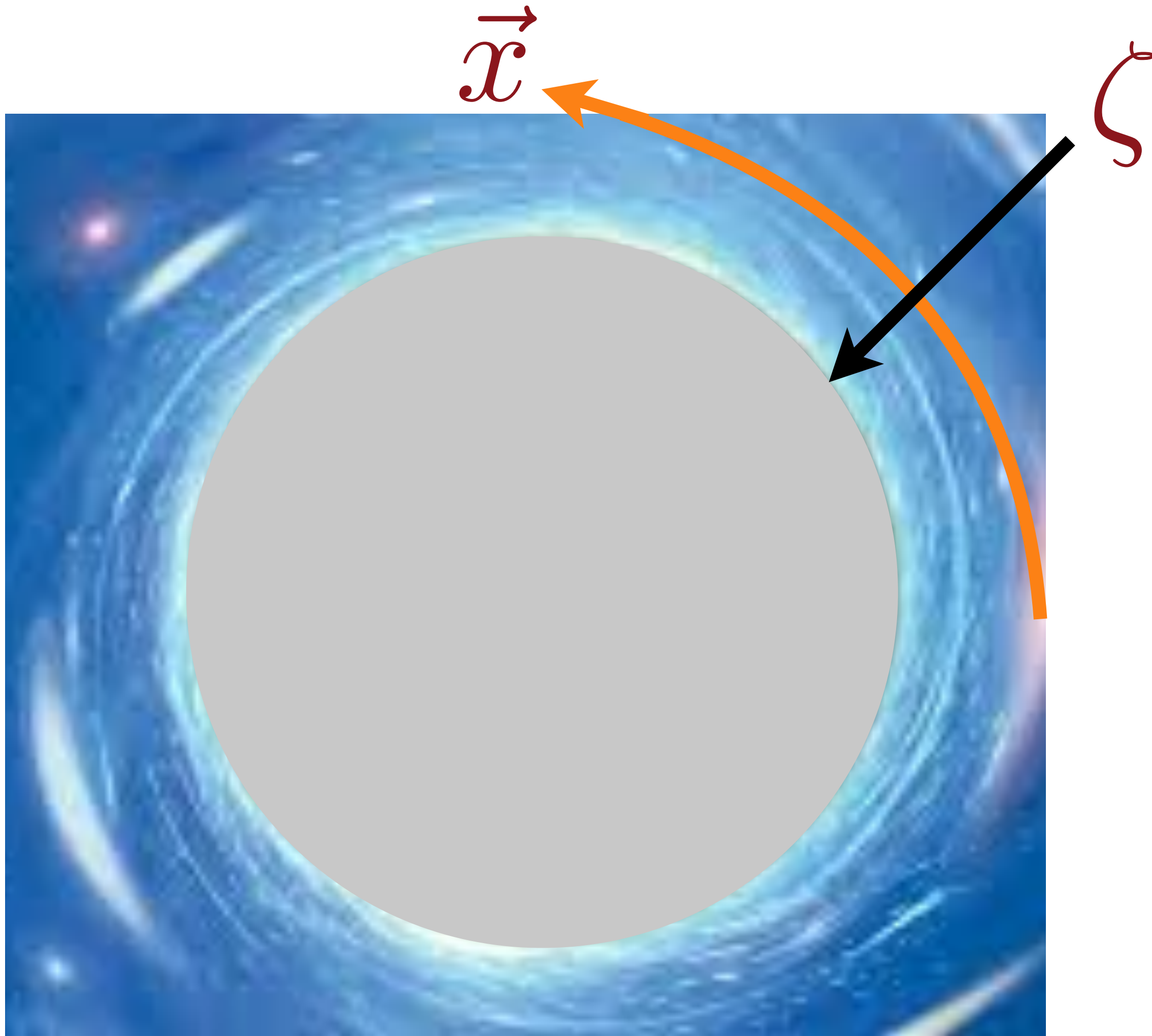
$D(E)$



From the SYK model
to a quantum theory of
charged black holes

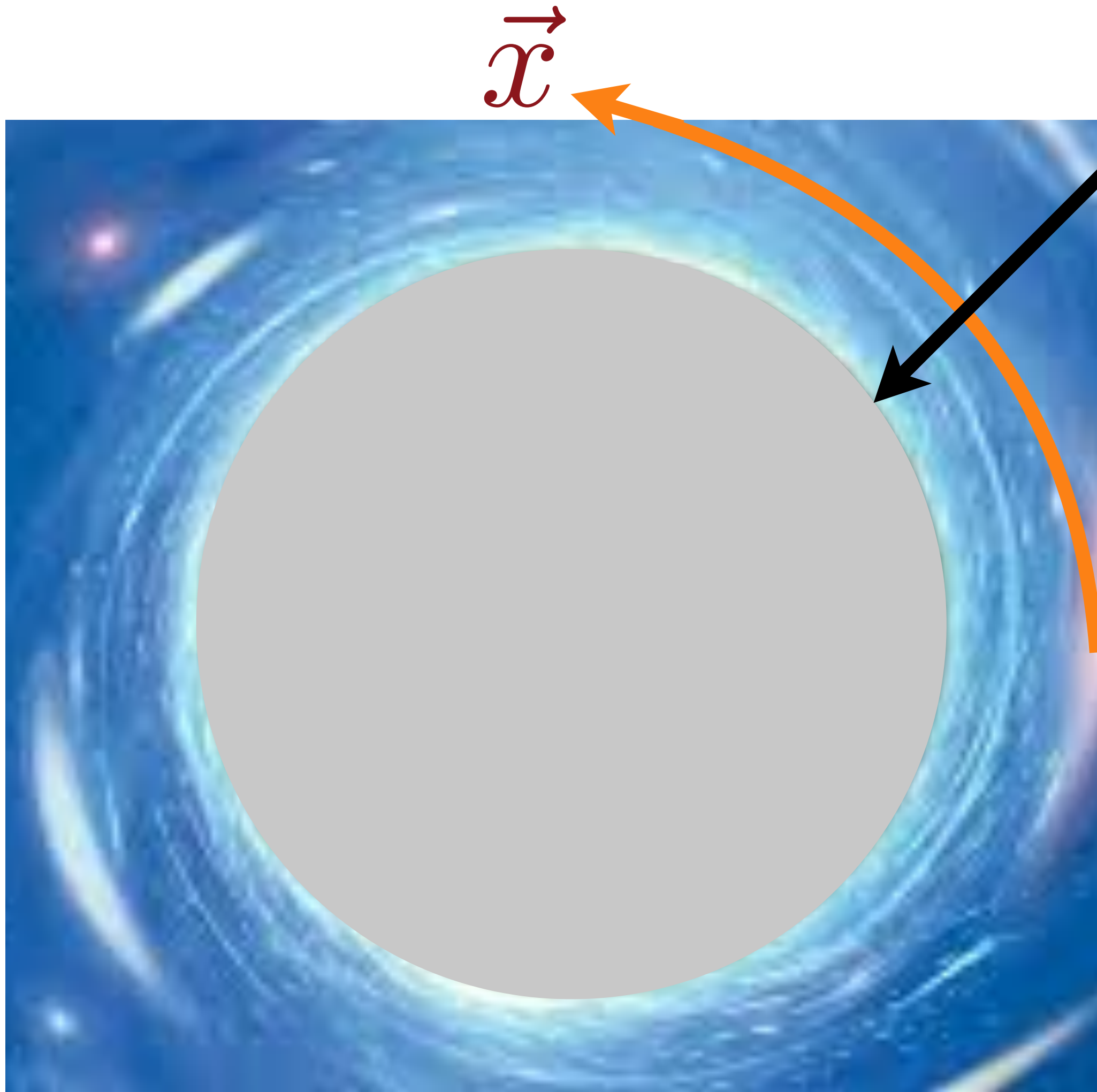


Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge





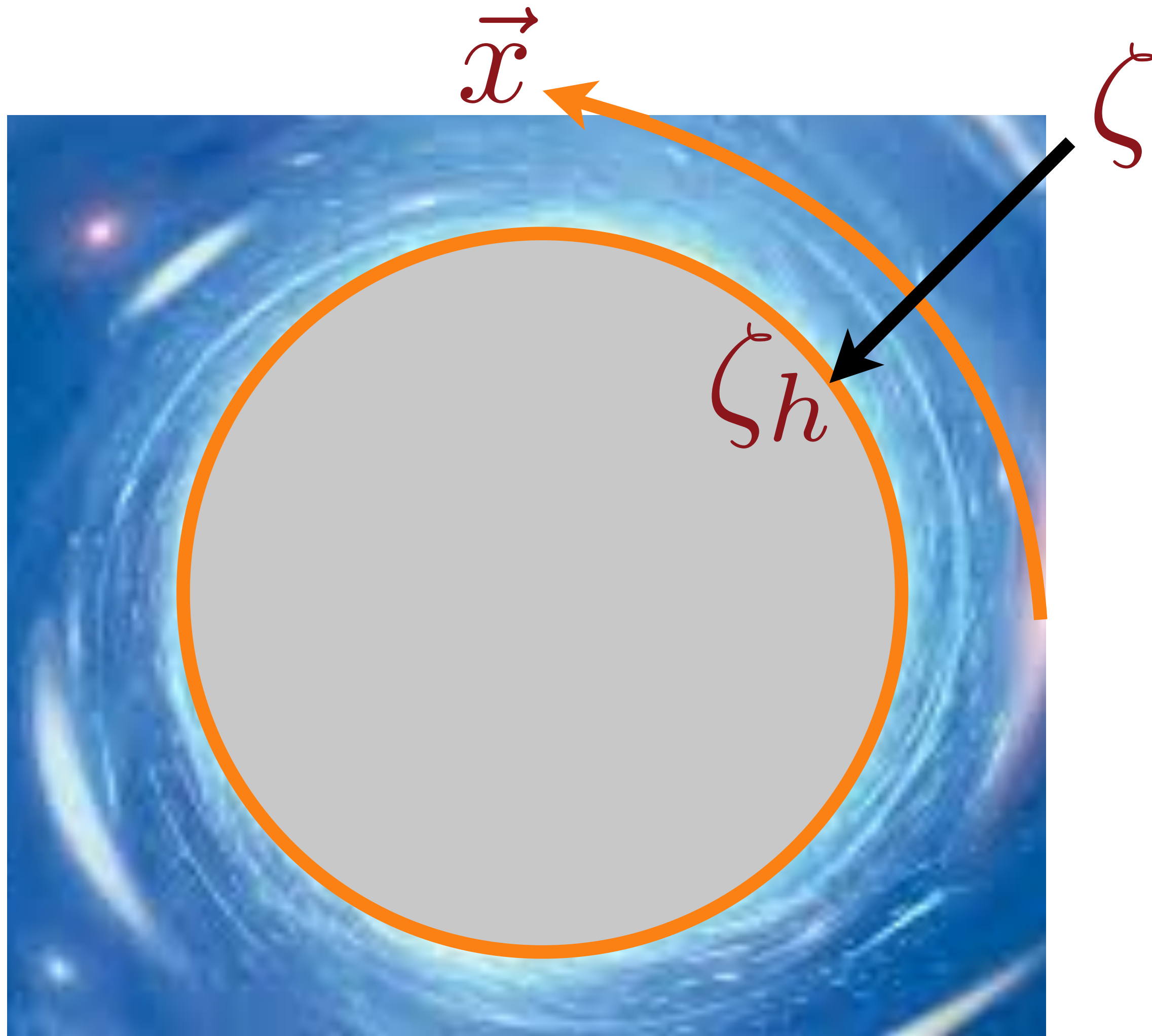
Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



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



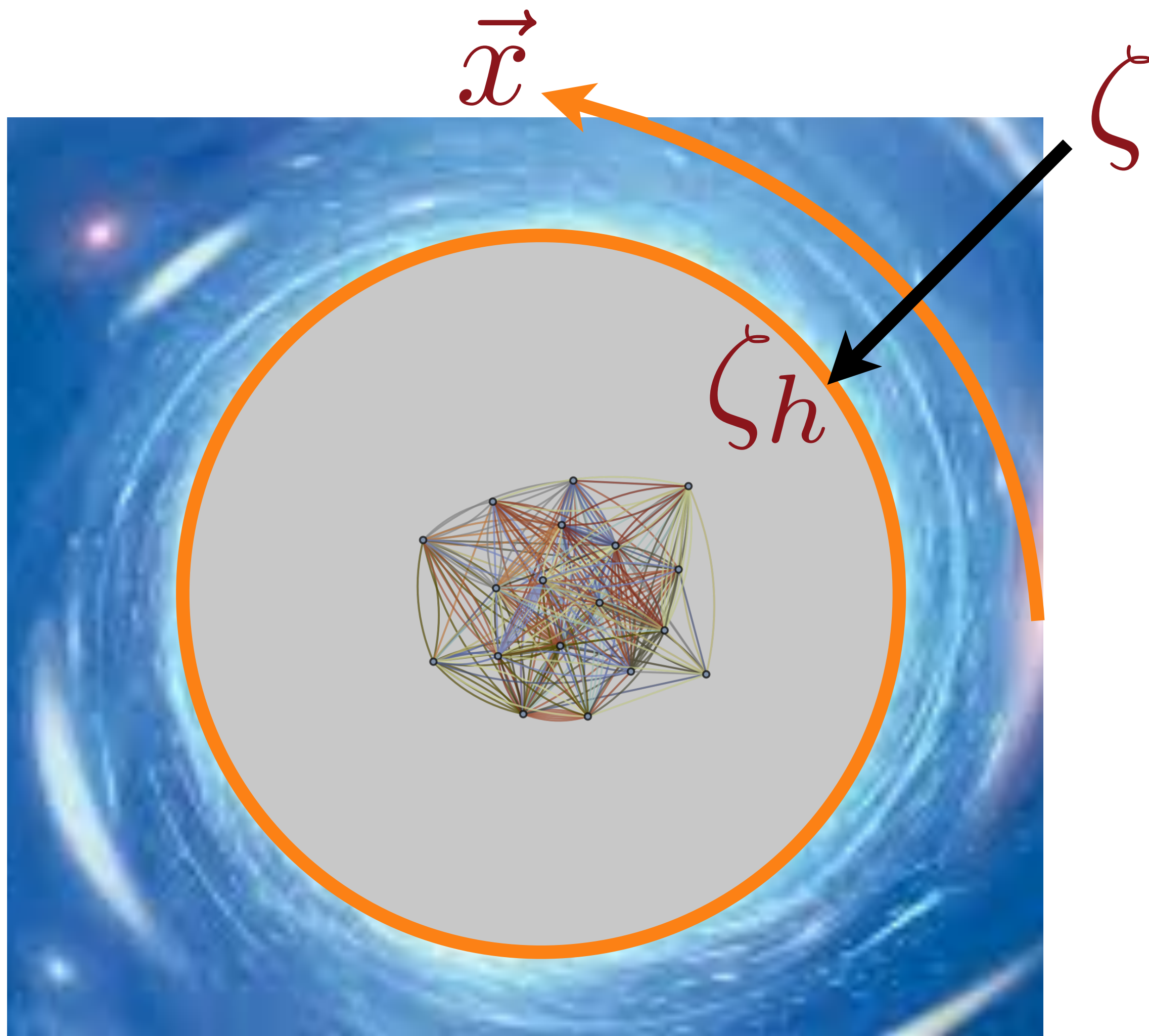
Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



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



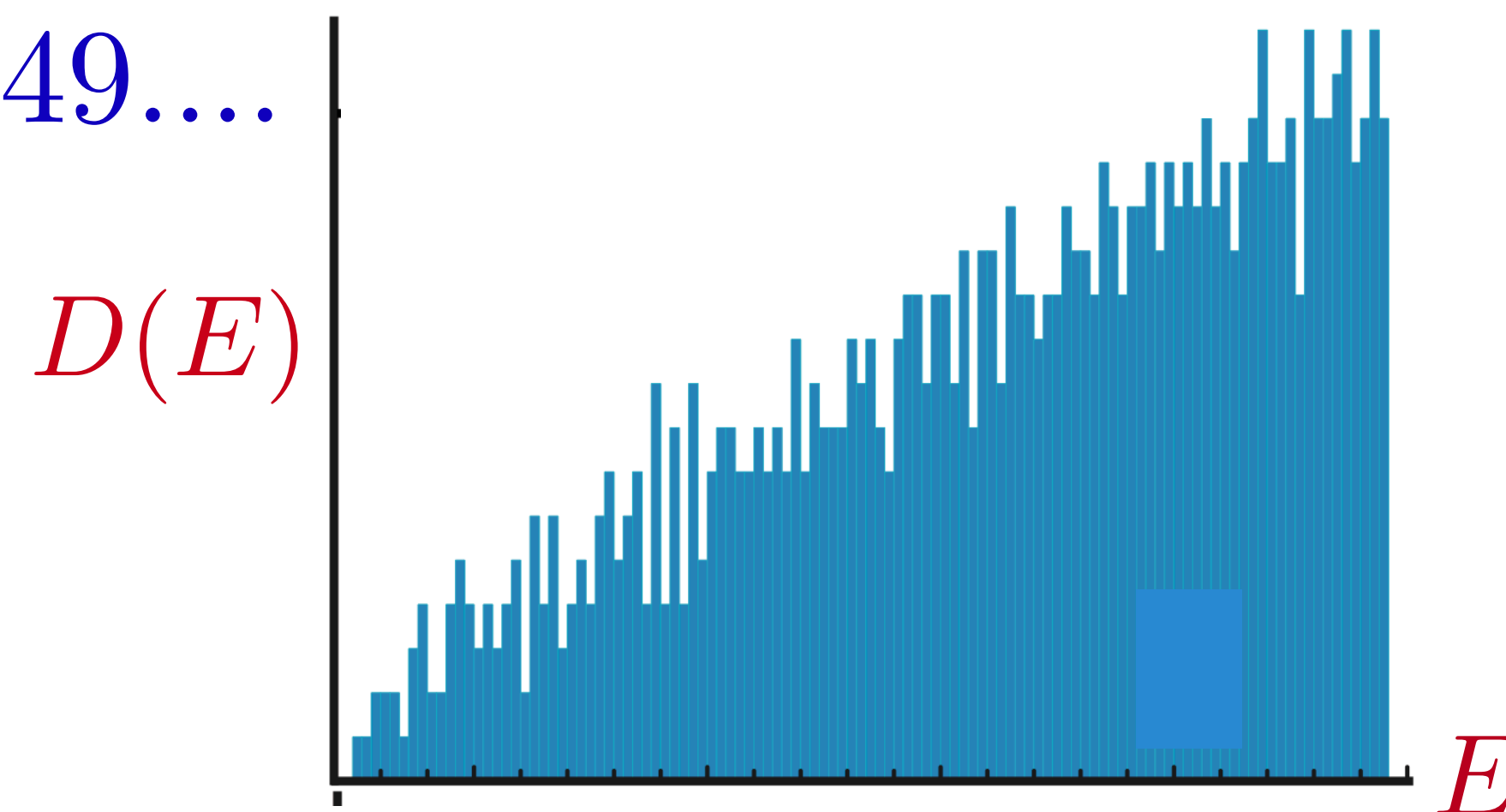
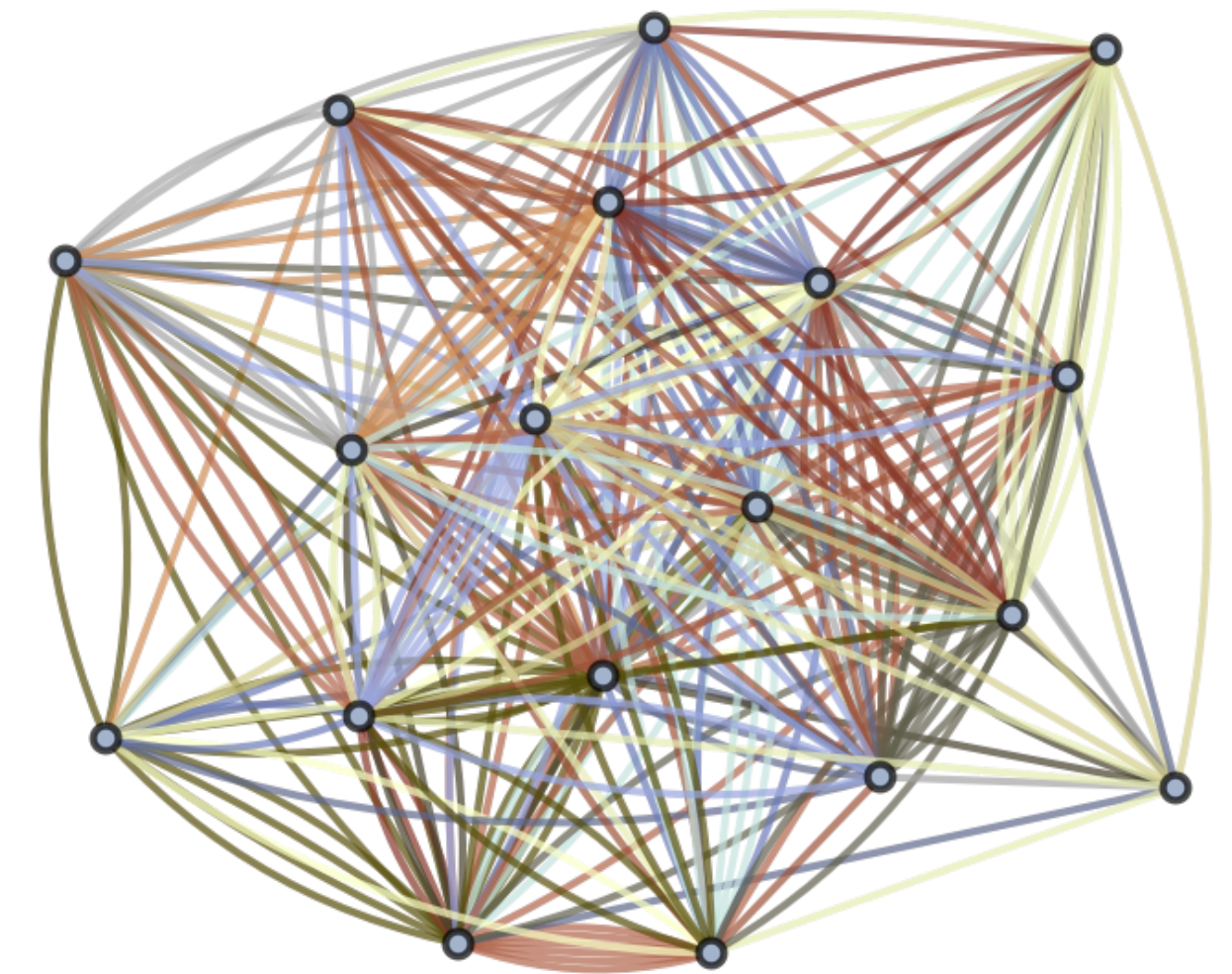
The quantum versions of
Maxwell's and Einstein's
equations in this
two-dimensional spacetime are
also the equations describing
electron entanglement in the
SYK model!

The Sachdev-Ye-Kitaev (SYK) model

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

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

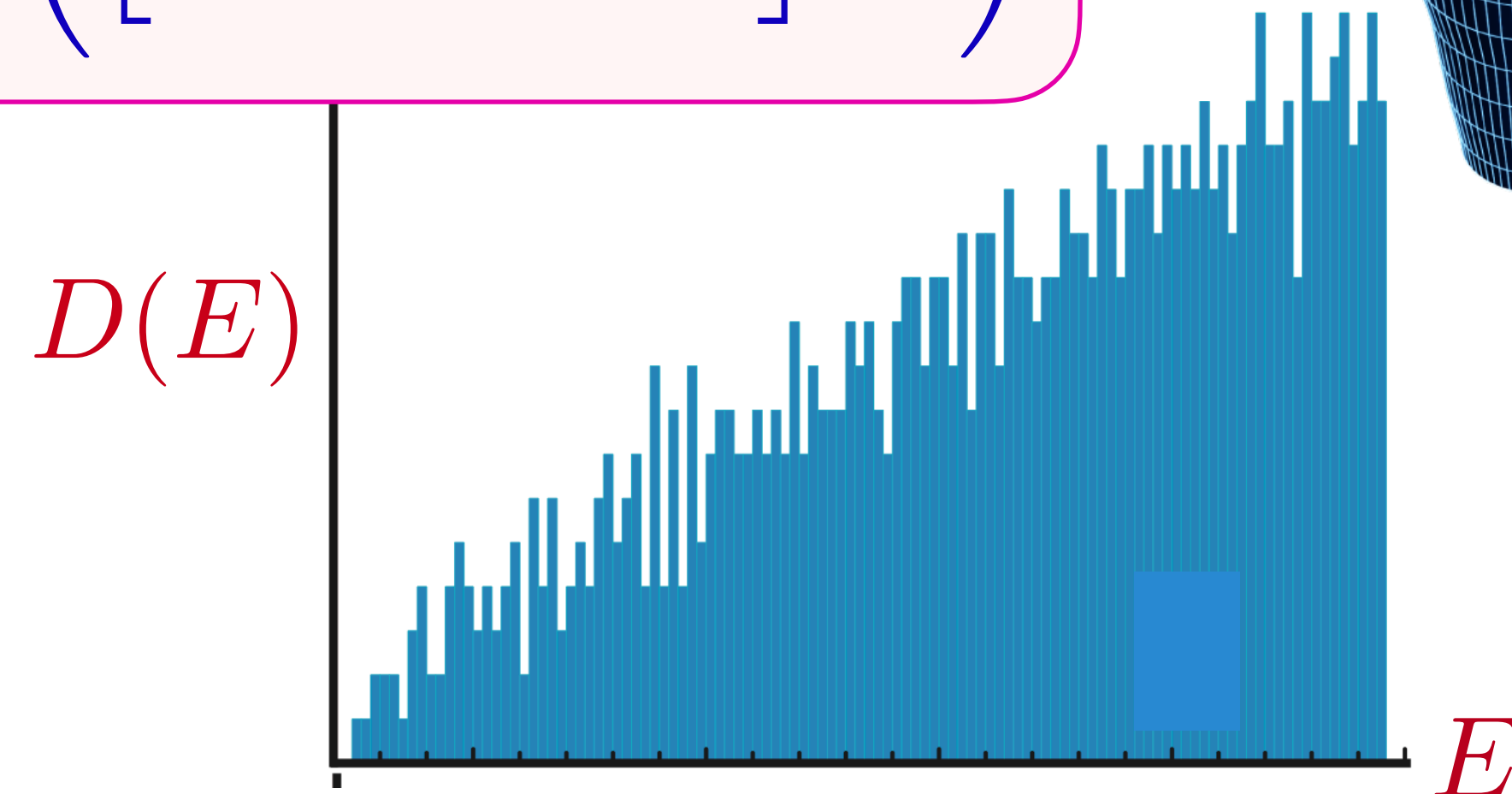
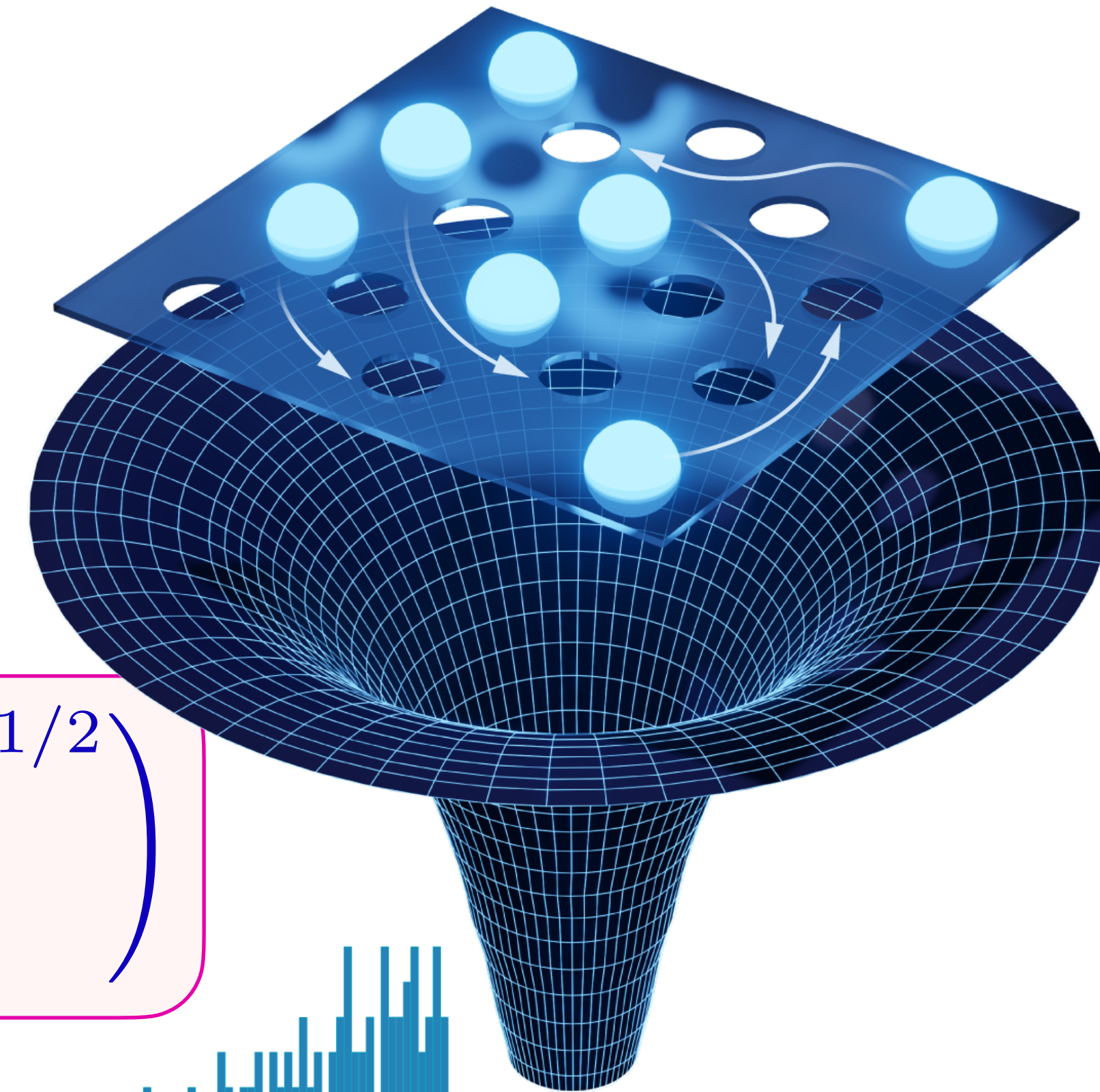
where $s_0 = 0.46484769917080510749\dots$



Quantum simulation of charged black holes by the SYK model

- For generic charged black holes in 3+1 dimensions with horizon area A at $T = 0$ and fixed charge, the density of quantum states at small energy E is

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

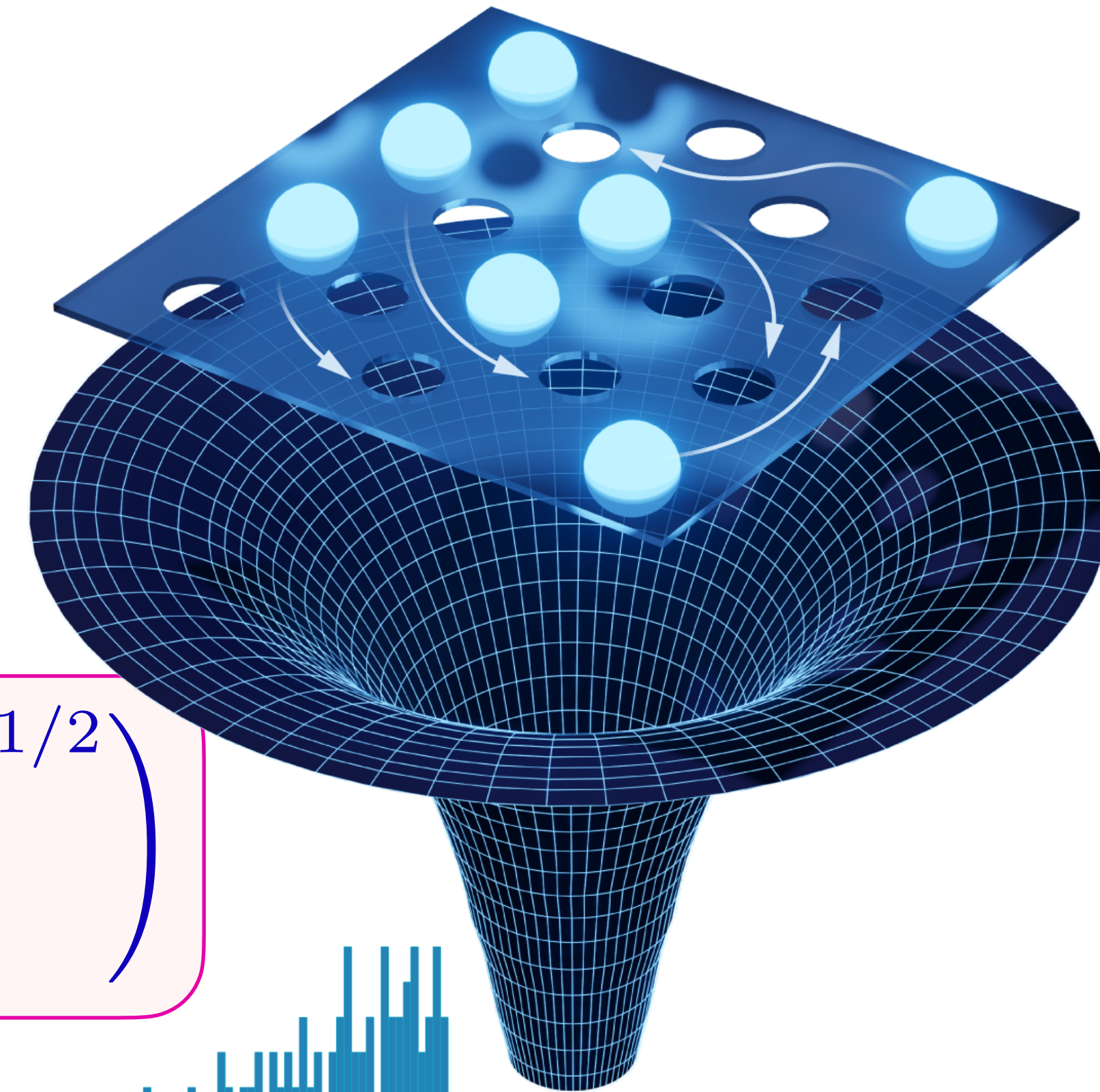


Quantum simulation of charged black holes by the SYK model

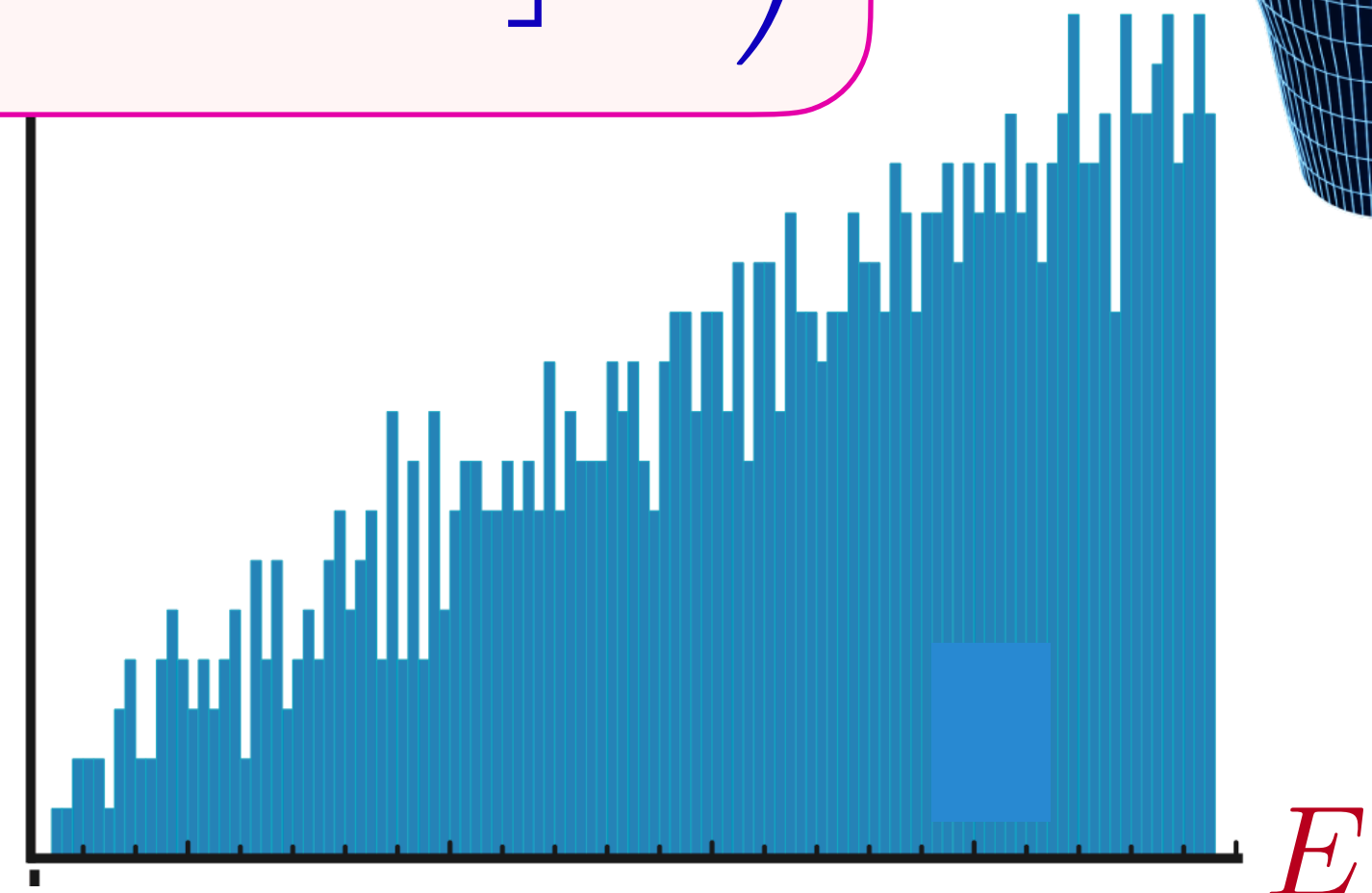
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Bekenstein-Hawking



$D(E)$



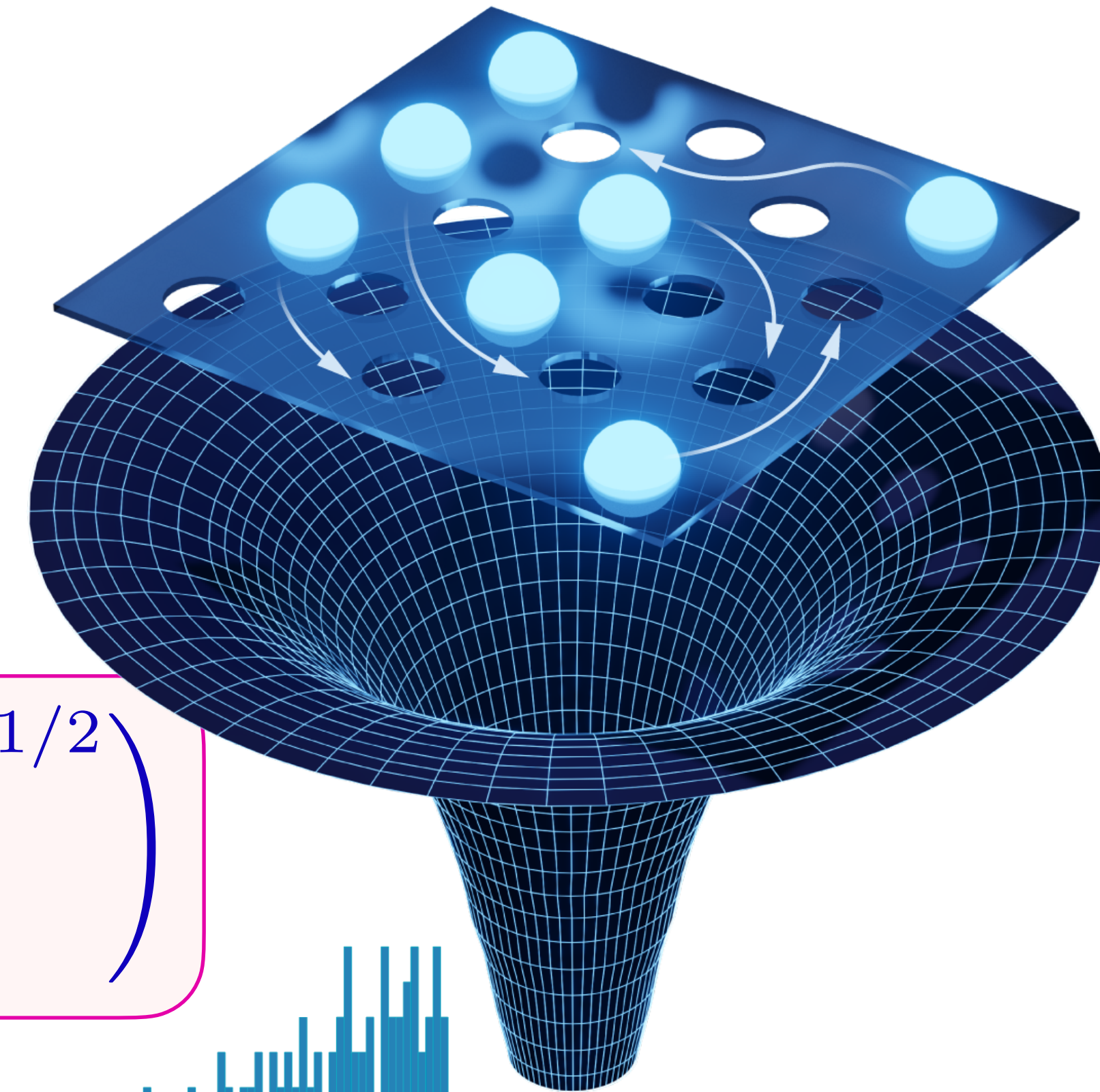
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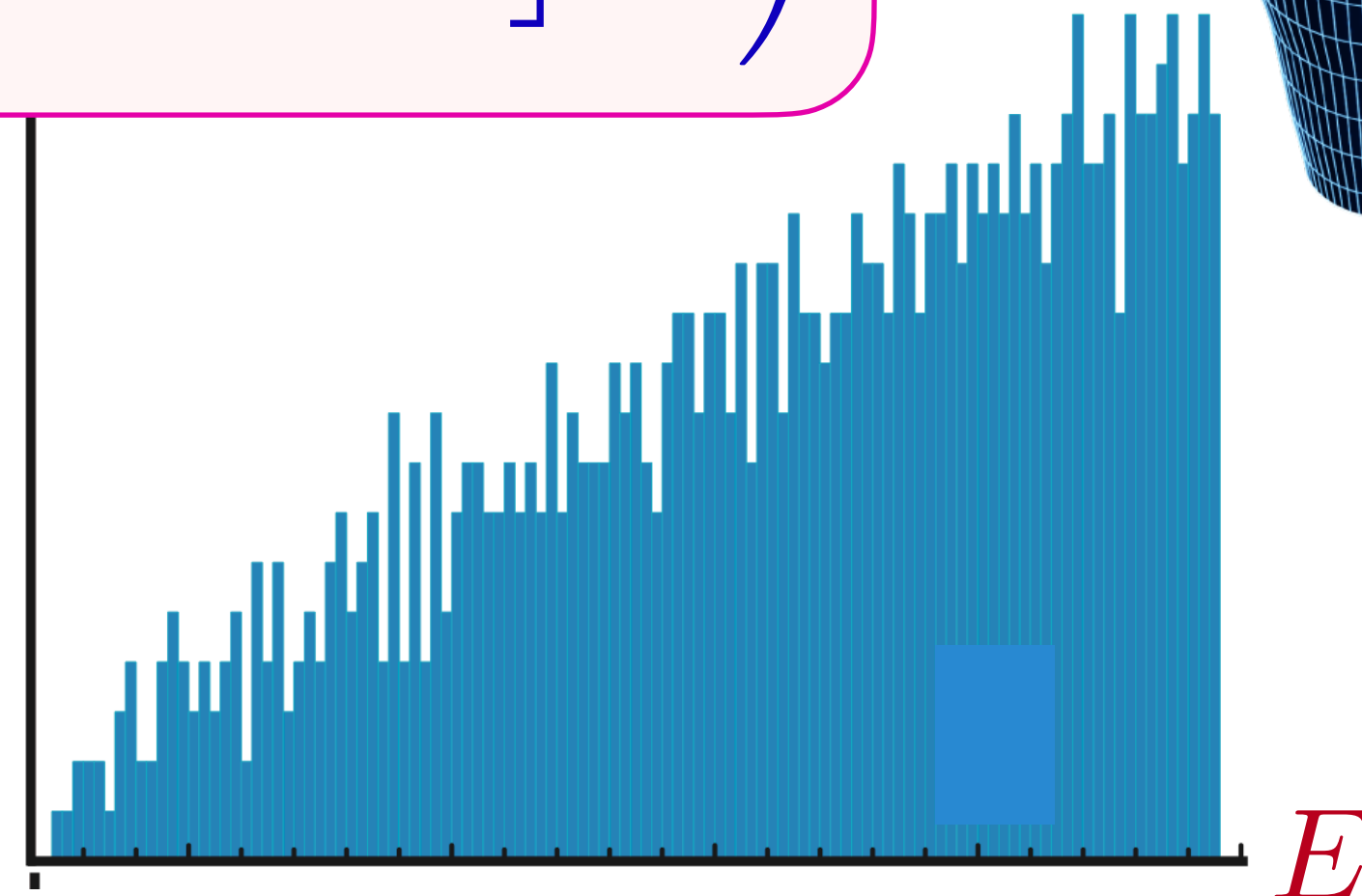
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Bekenstein-Hawking

Developments from the SYK model



$D(E)$



Quantum simulation of charged black holes by the SYK model

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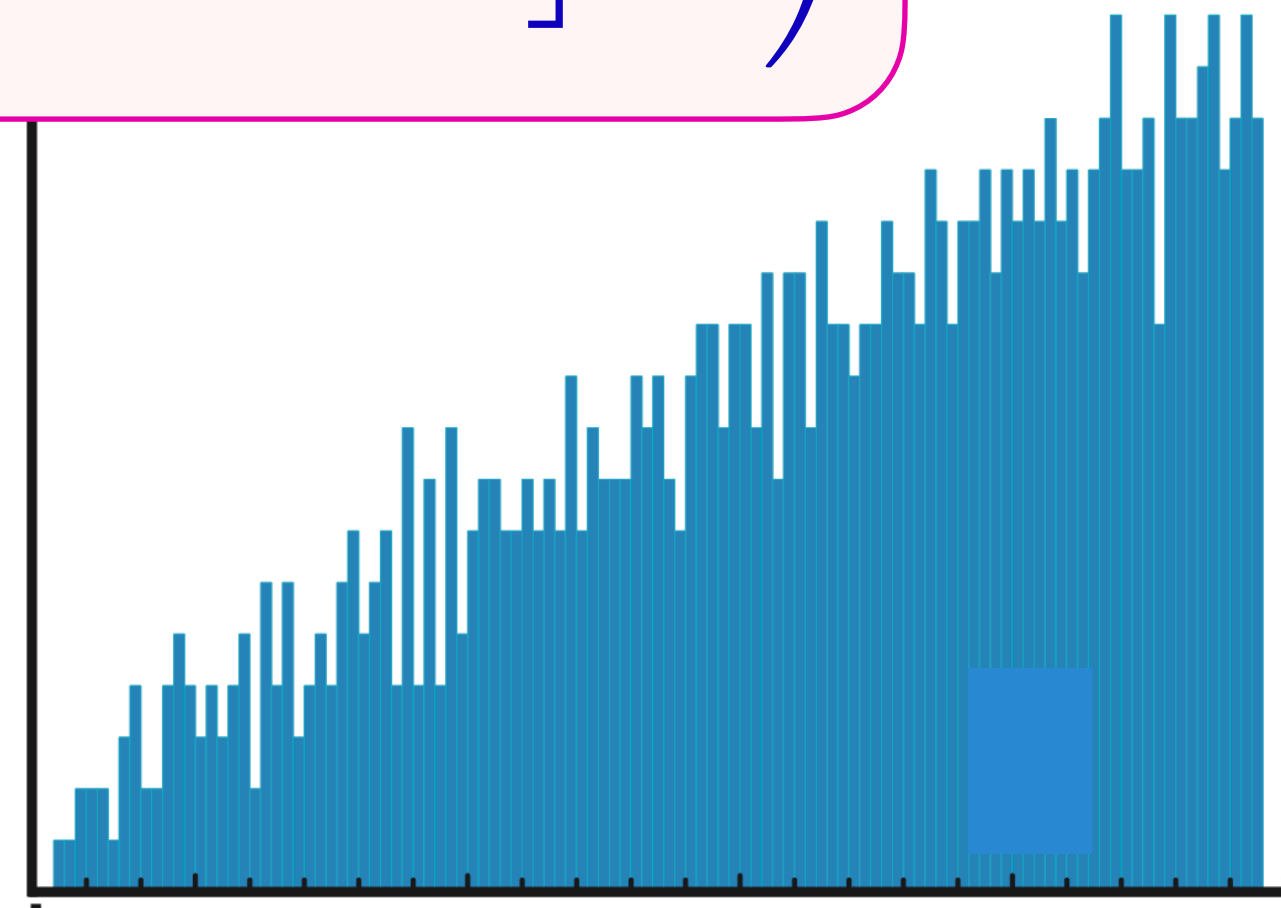
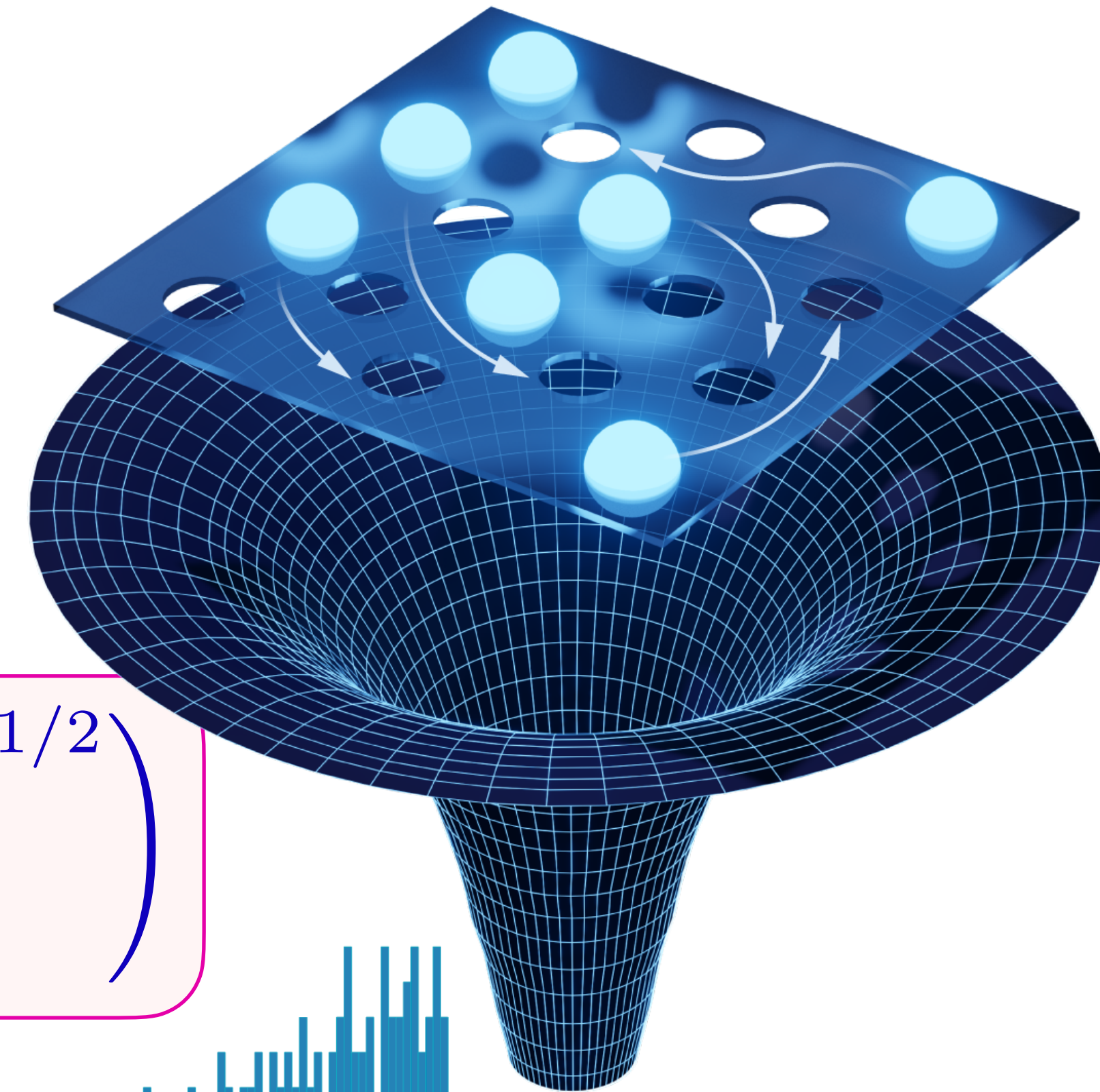
Iliesiu, Murthy, Turiaci (2022)

Bekenstein-Hawking

Developments from the SYK model

$D(E)$

E

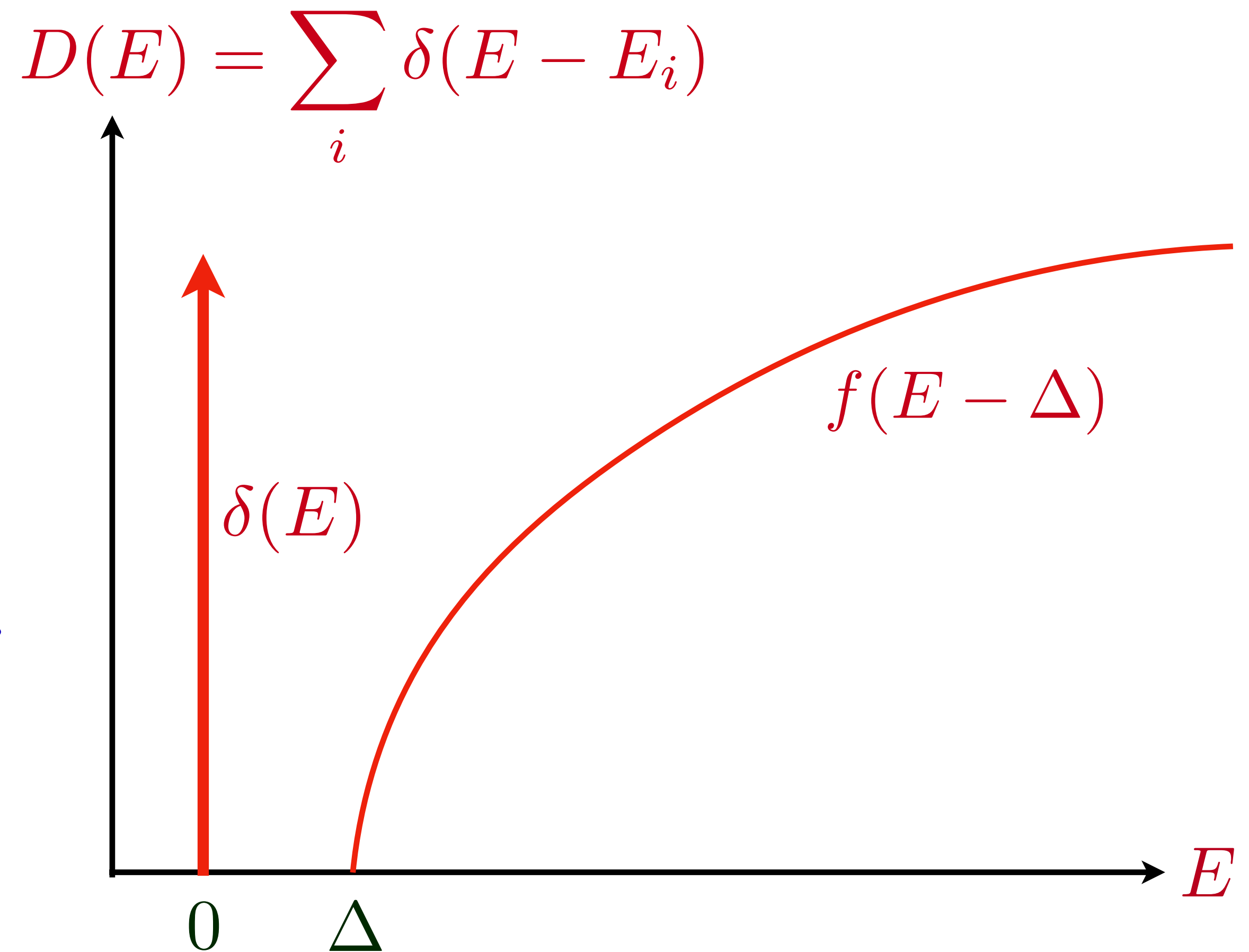


String theory of charged black holes

- With sufficient low energy supersymmetry, string theory yields:

$$D(E) = \exp\left(\frac{A_0 c^3}{4\hbar G}\right) \delta(E) + \theta(E - \Delta) f(E - \Delta) + \dots$$

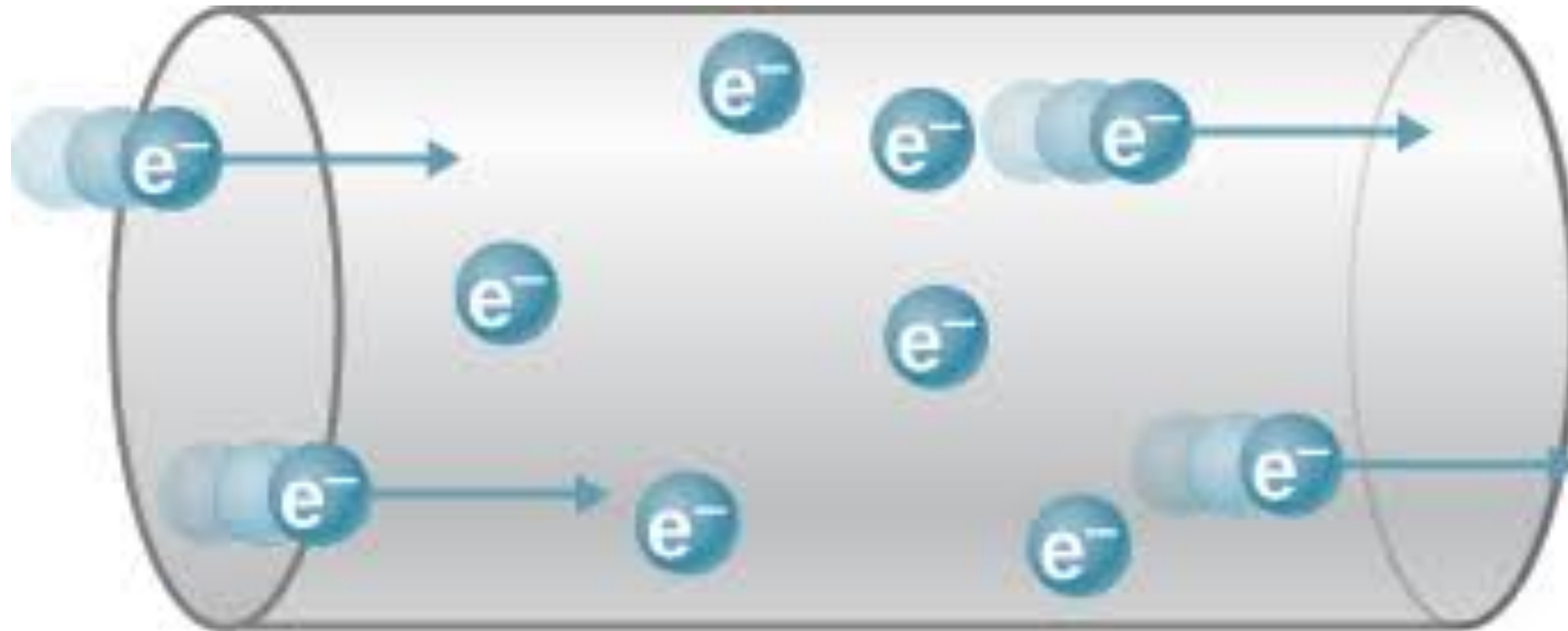
There are exponentially many degenerate BPS ground states, and an energy gap Δ above the ground state.



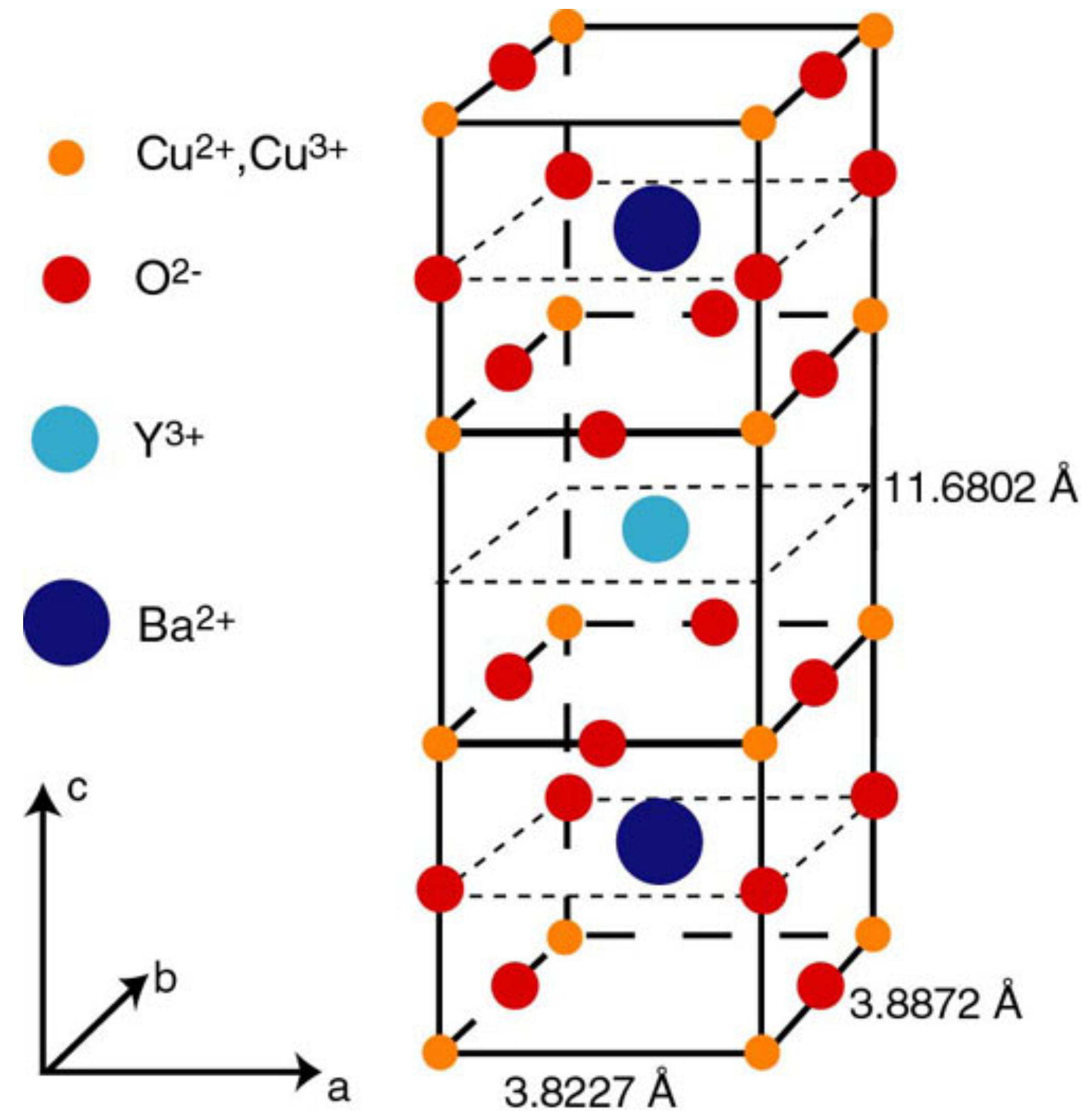
M. Heydeman, L.V. Iliesiu, G. J. Turiaci, and W. Zhao, 2020
L.V. Iliesiu, S. Murthy, G. J. Turiaci, 2022

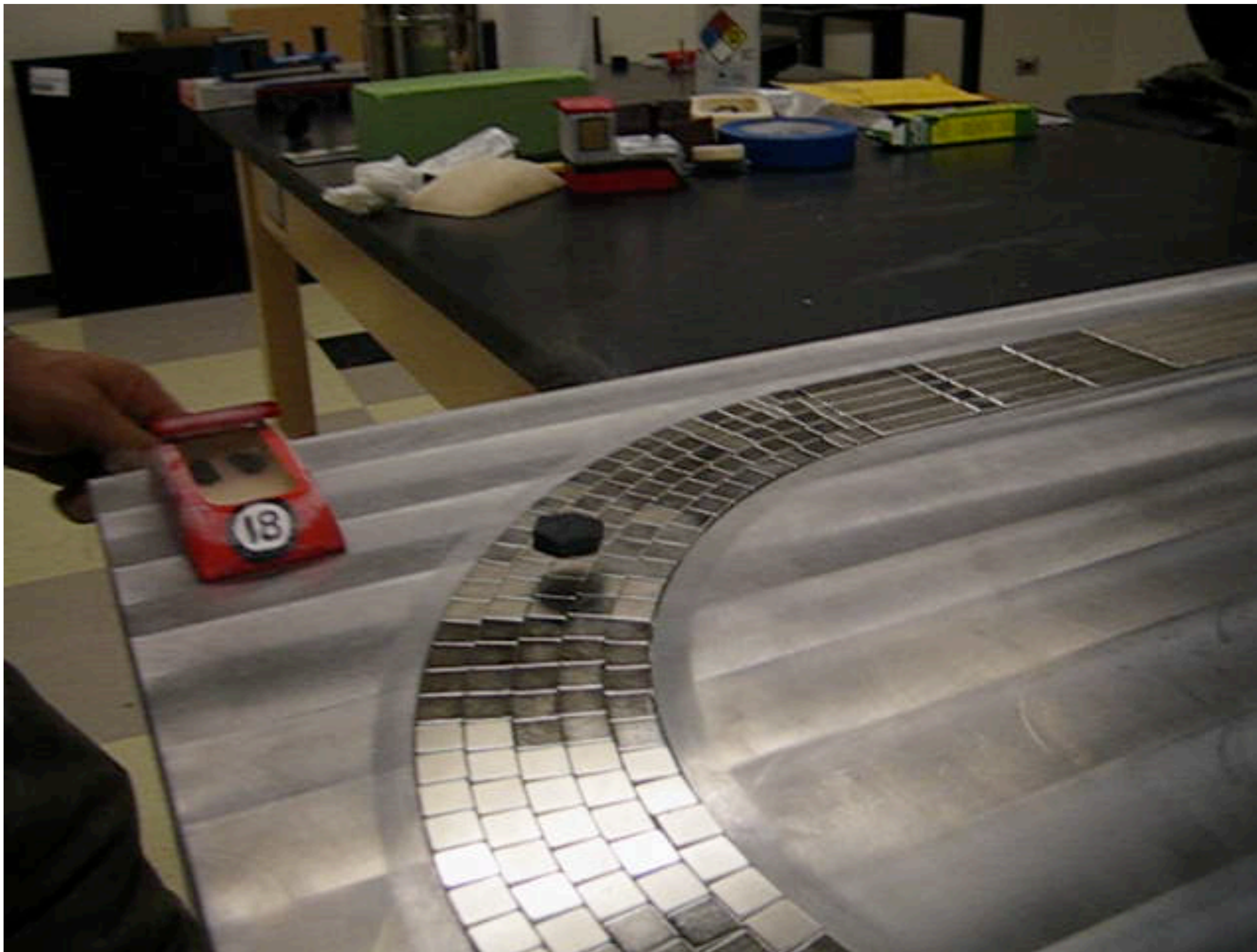
Quantum matter:
ordinary metals,
and
strange metals

Copper: ordinary metal quantum matter



Cuprate high temperature superconductors





Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

HTS Magnets: Enabling Technology

A new high temperature superconductor (HTS) recently reached industrial maturity: Rare Earth Barium Copper Oxide (REBCO). CFS is using HTS and has built its first-of-its-kind high-field large-bore superconducting magnet. HTS

magnets will allow for smaller, faster, and less expensive tokamaks using the science developed on Alcator C-Mod and other tokamaks.

The surest path to limitless, clean, fusion energy

● Surest

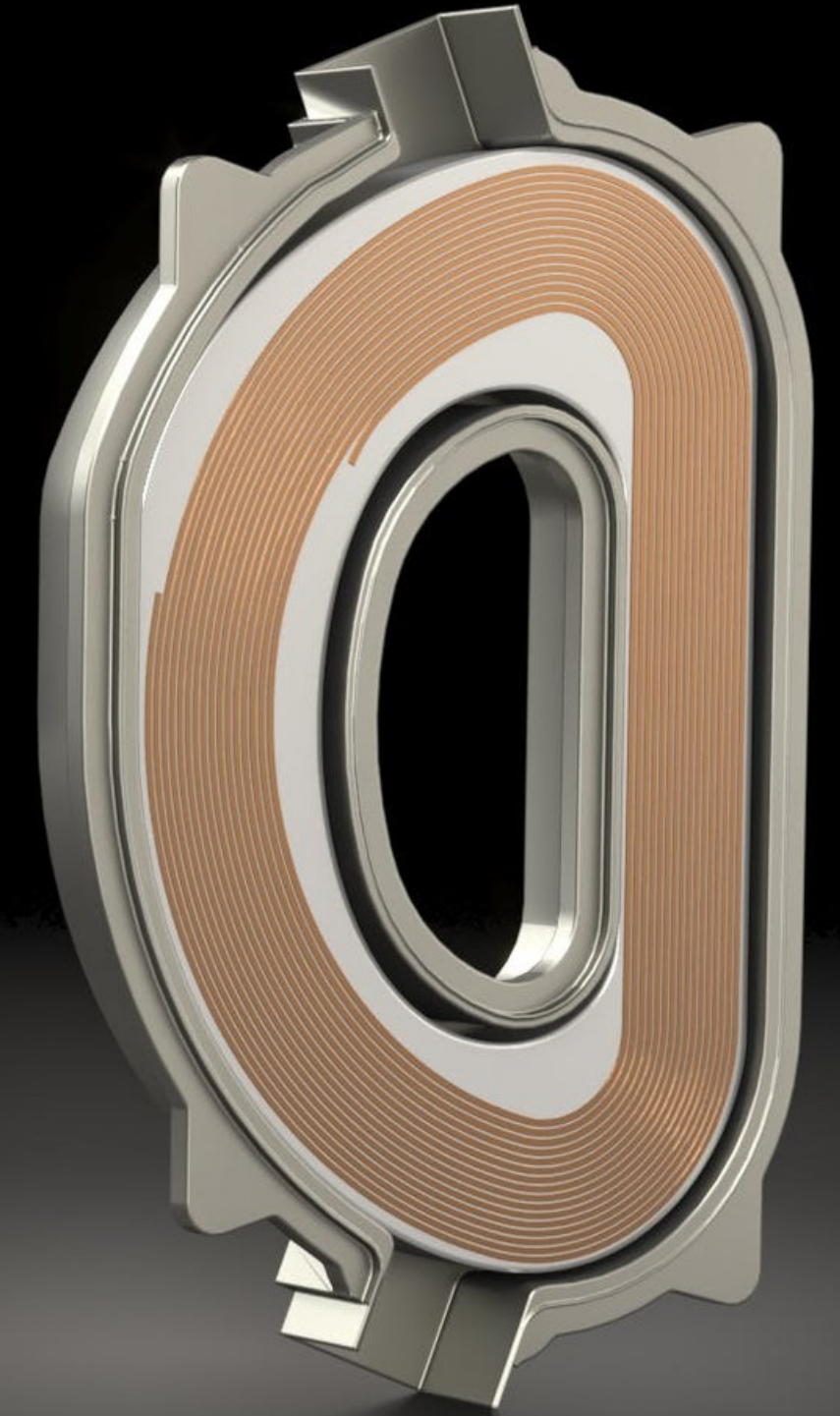
The fastest path to commercial fusion energy combining proven science with revolutionary magnet technology.

○ Limitless

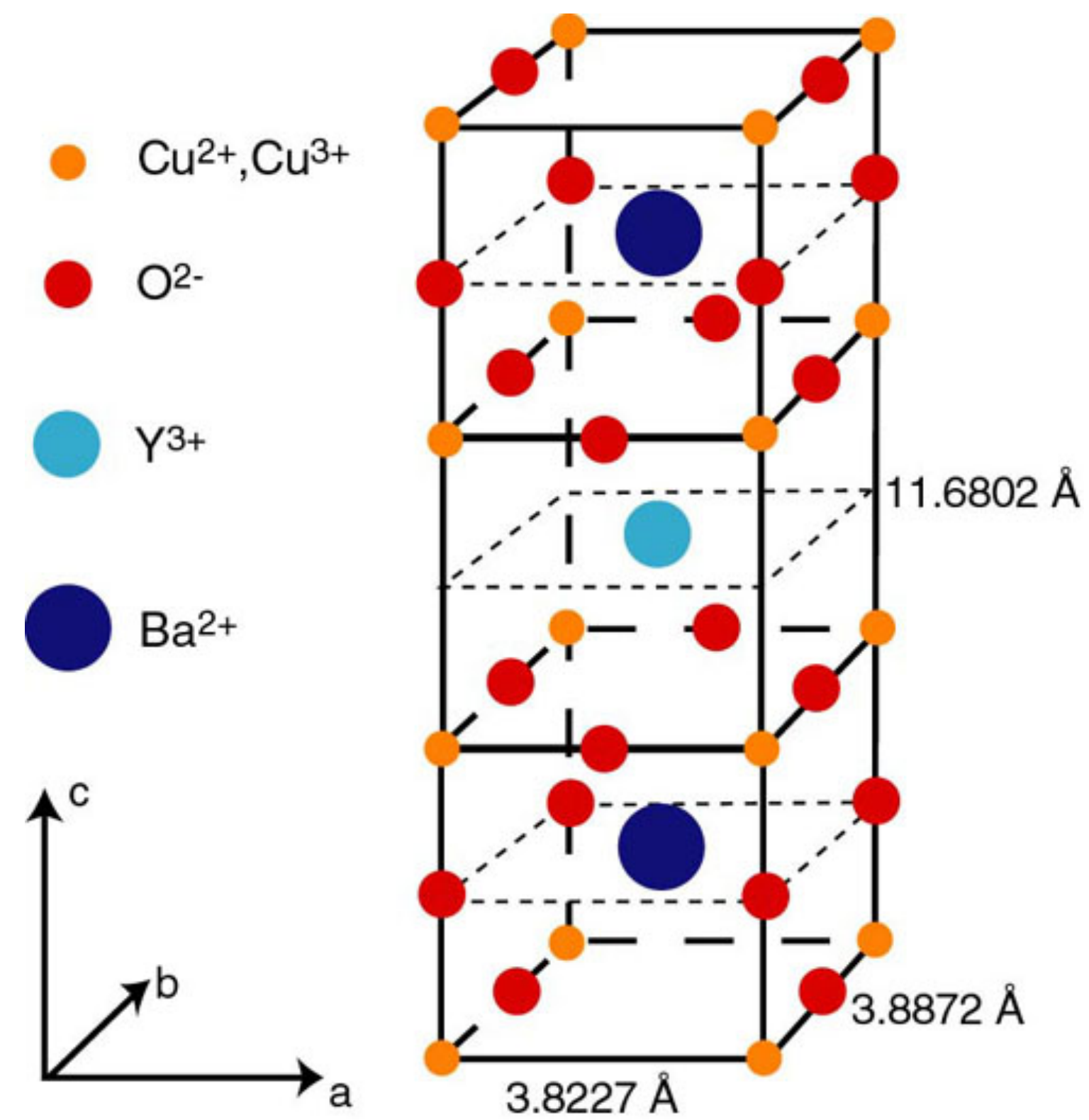
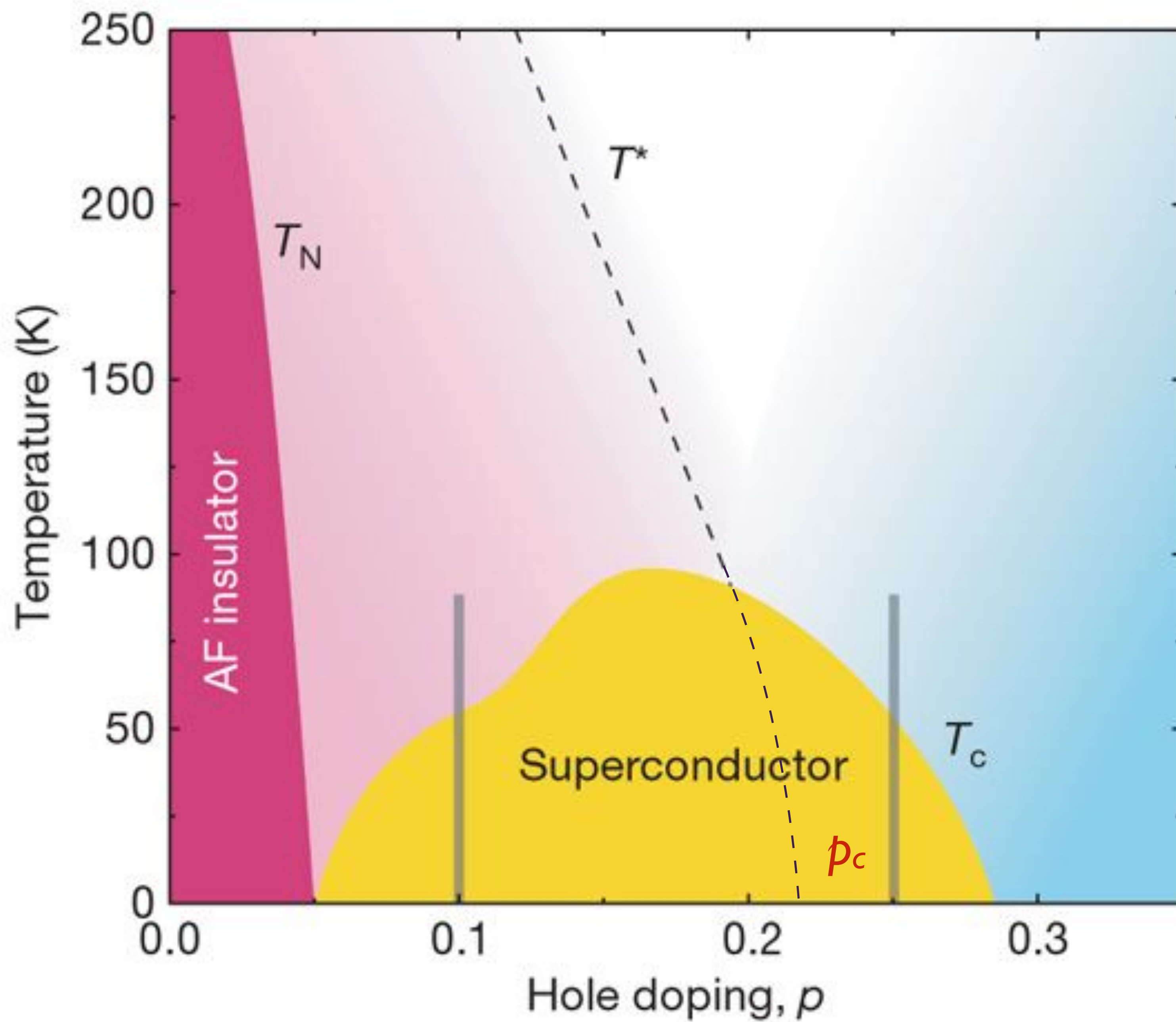
One glass of water will provide enough fusion fuel for one person's lifetime.

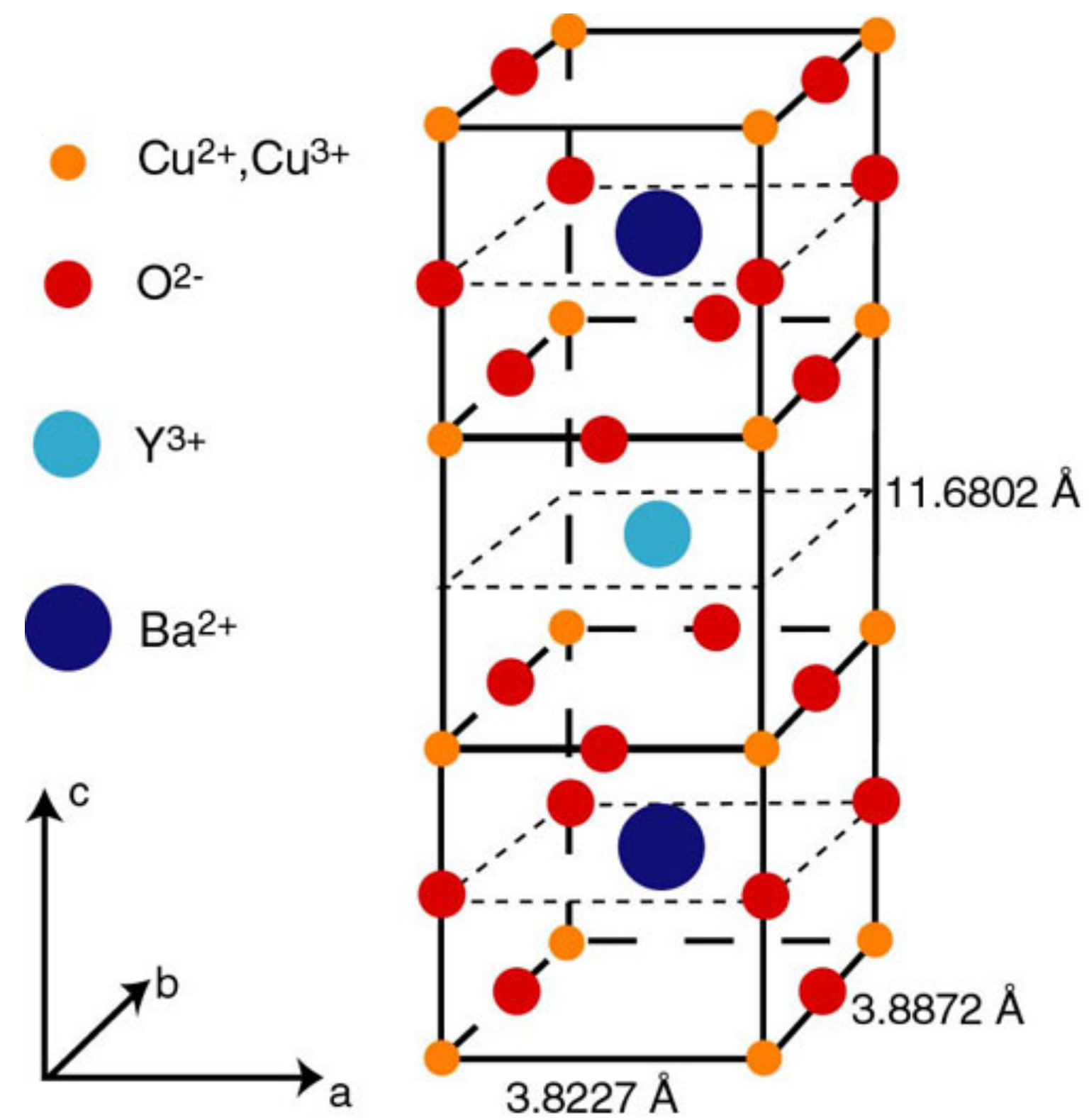
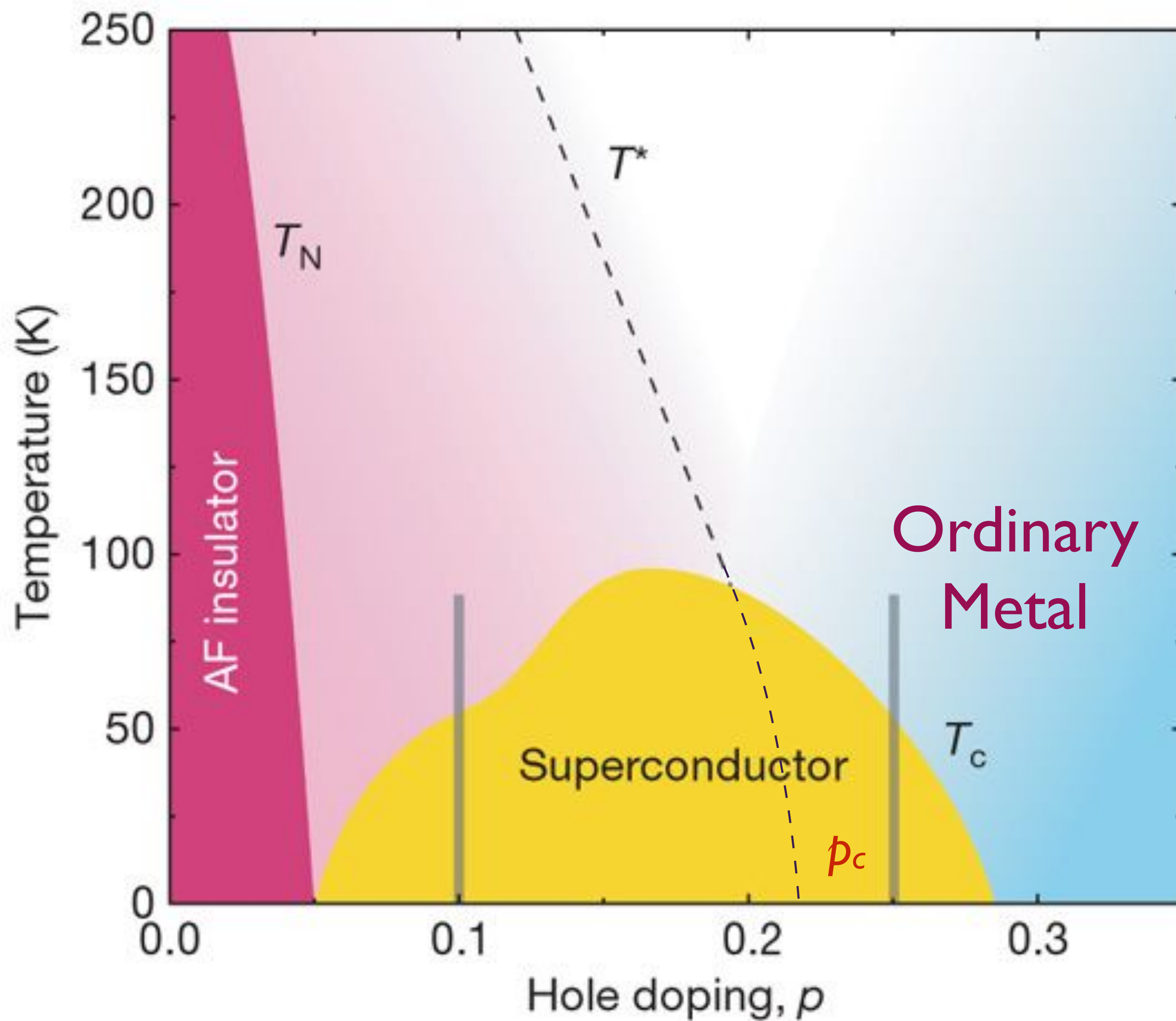
○ Clean

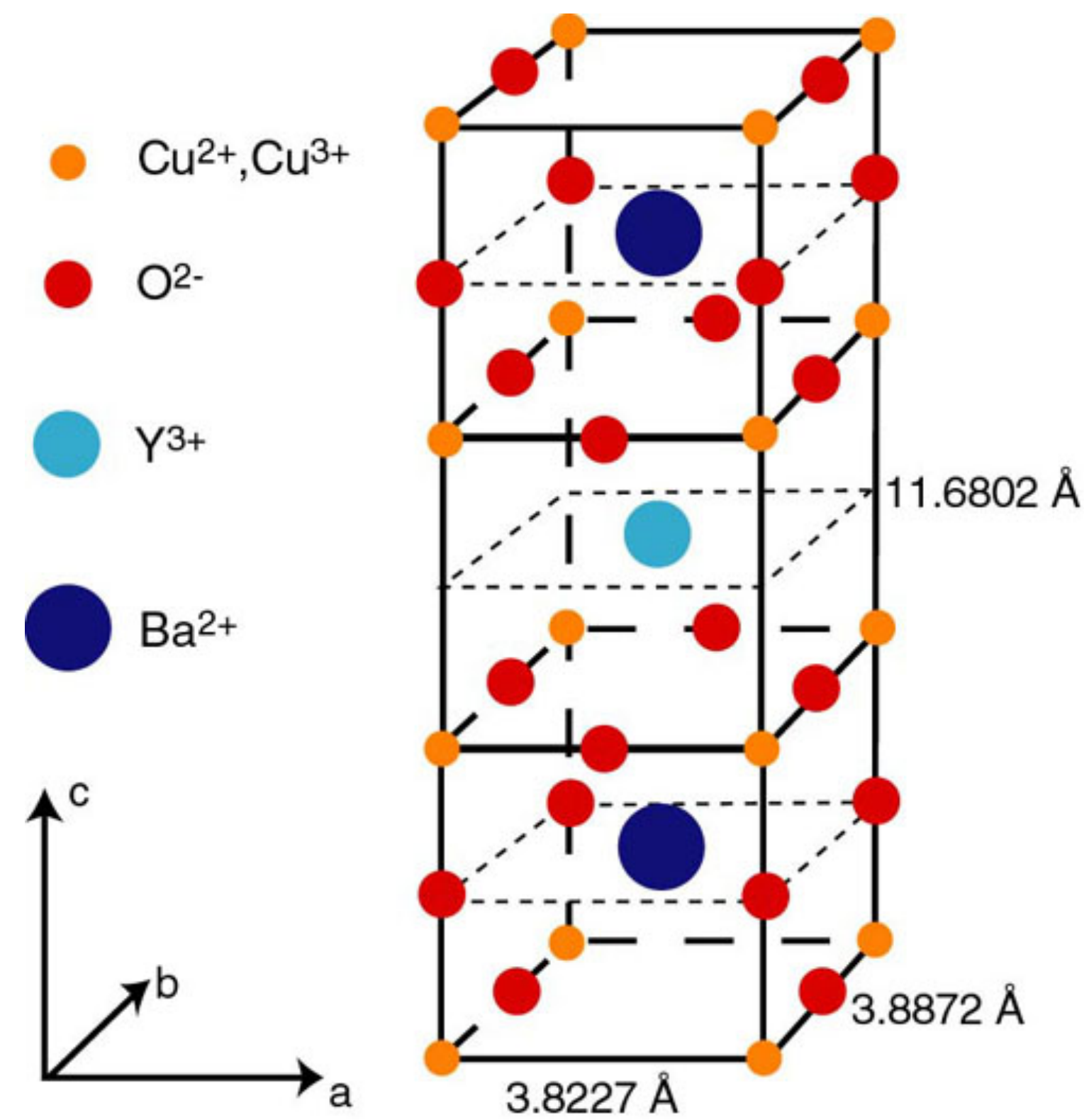
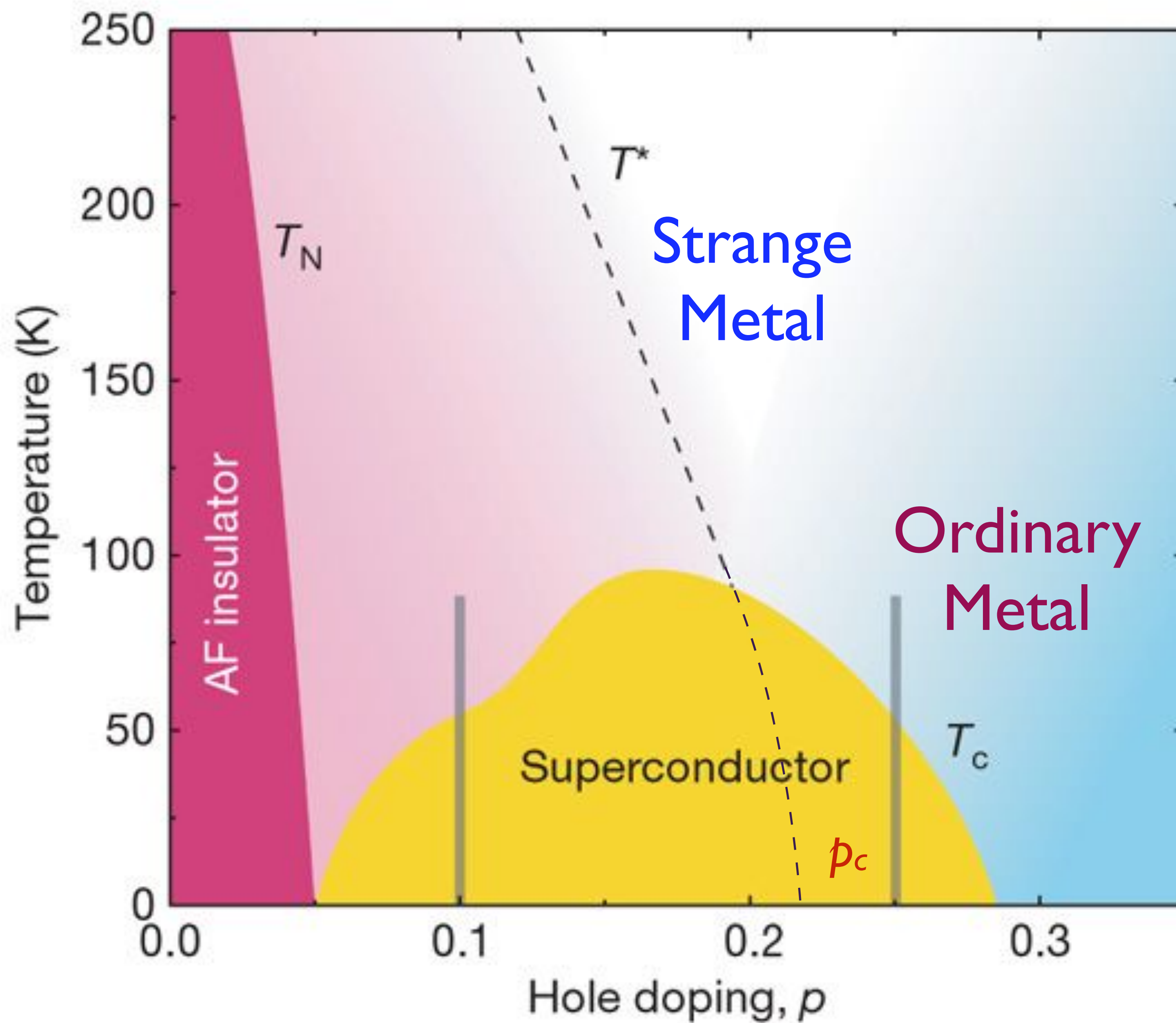
A new source of clean energy to meet our growing energy demands and combat climate change.

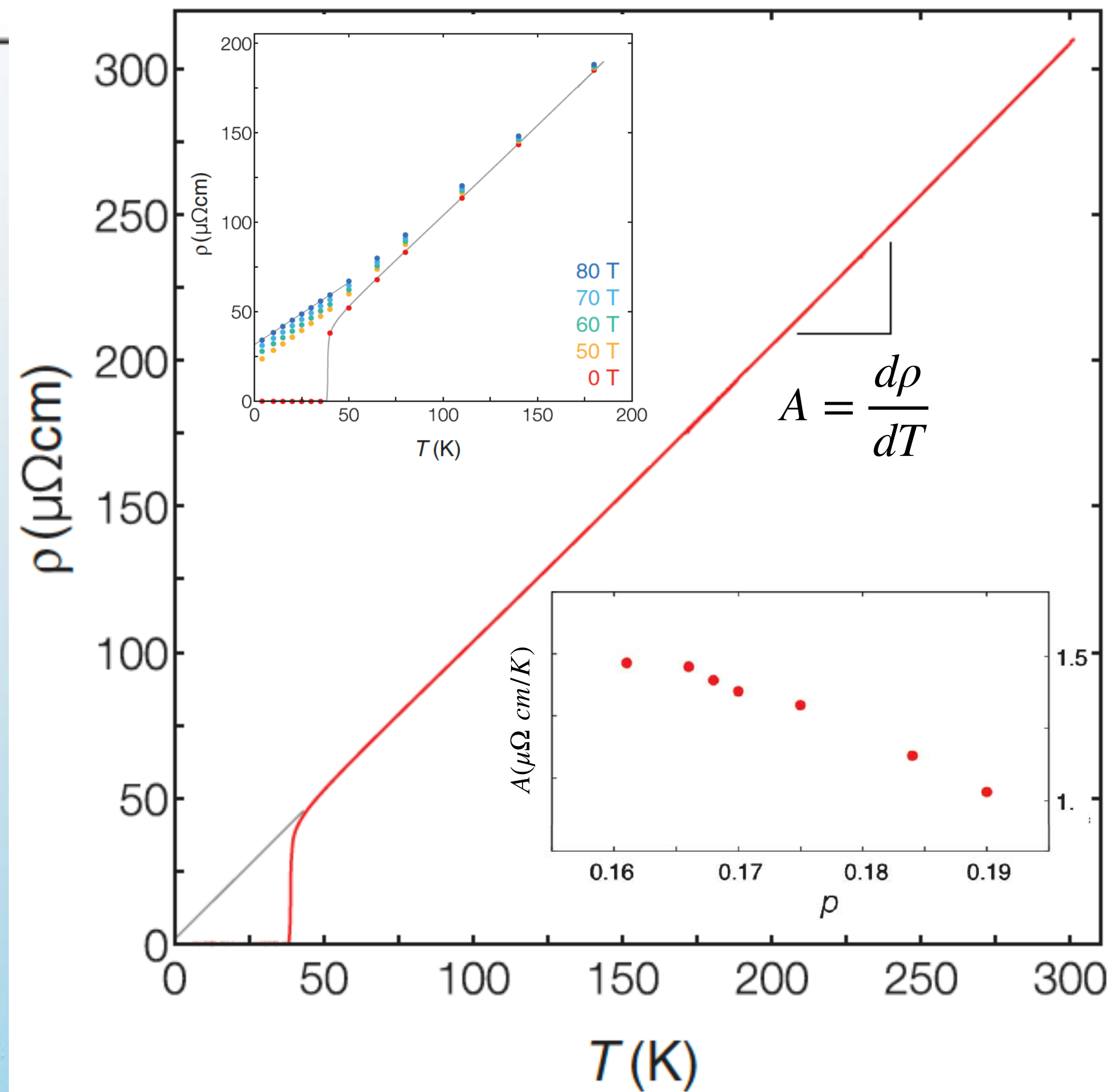
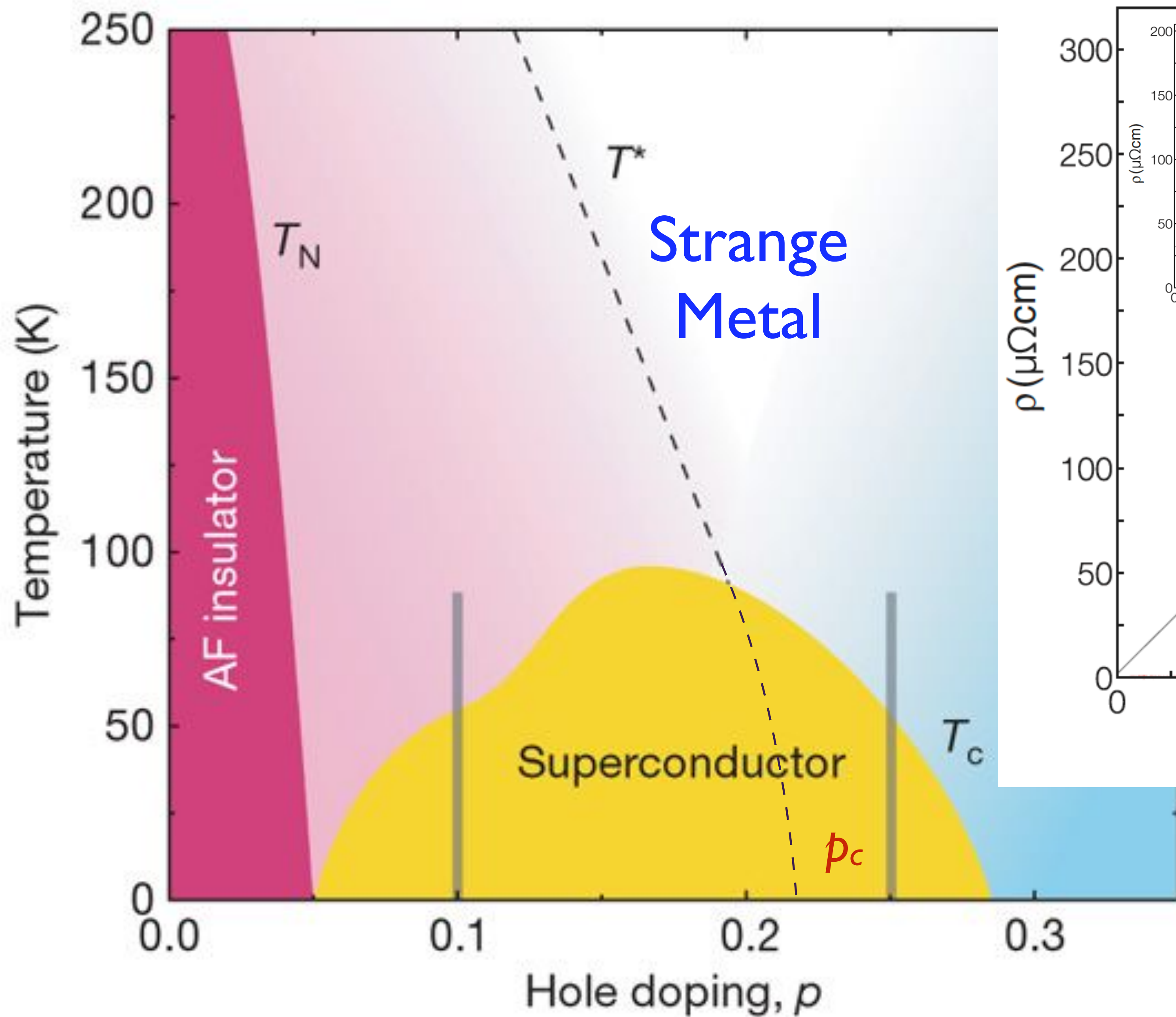


Commonwealth
Fusion Systems

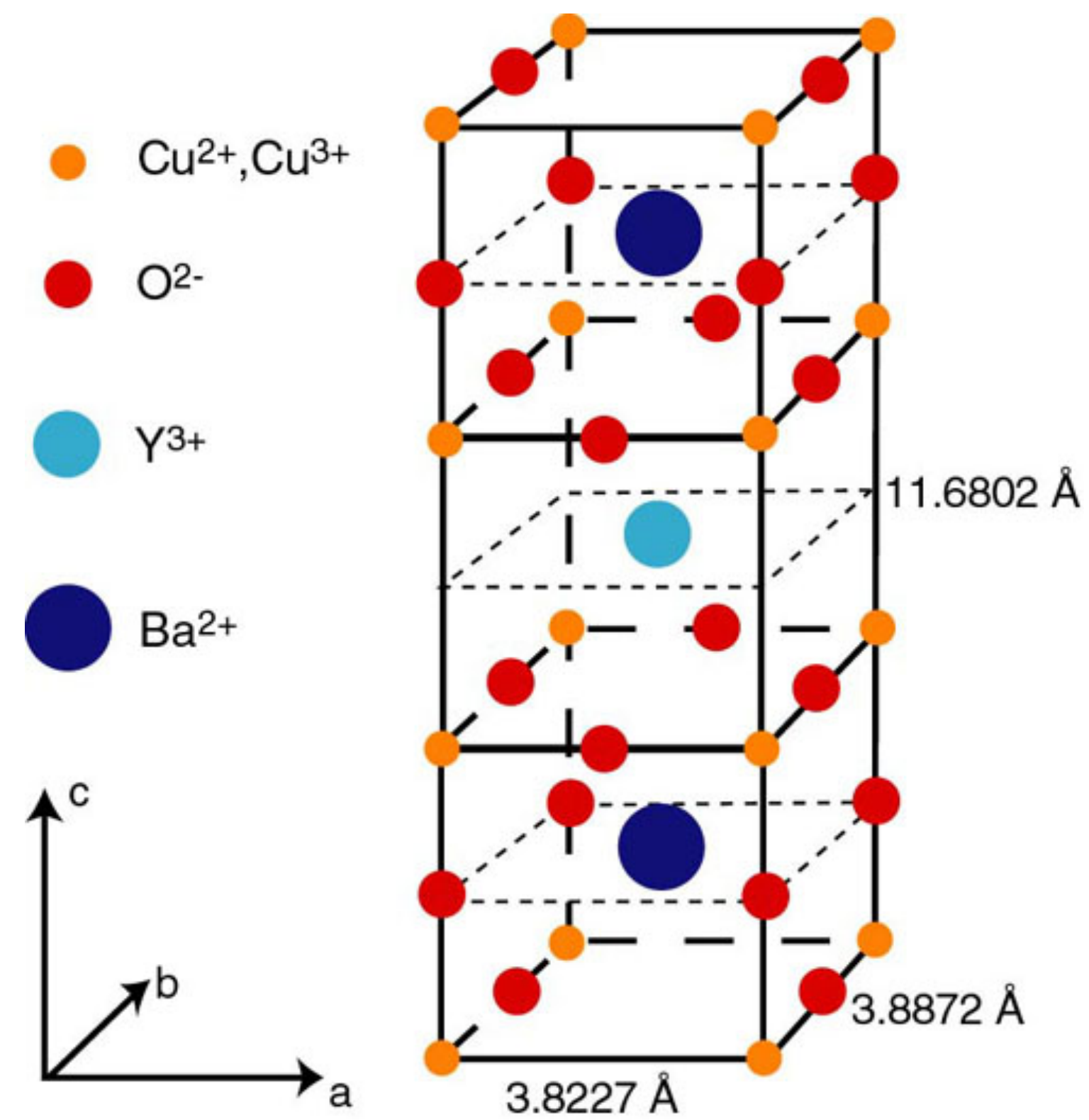
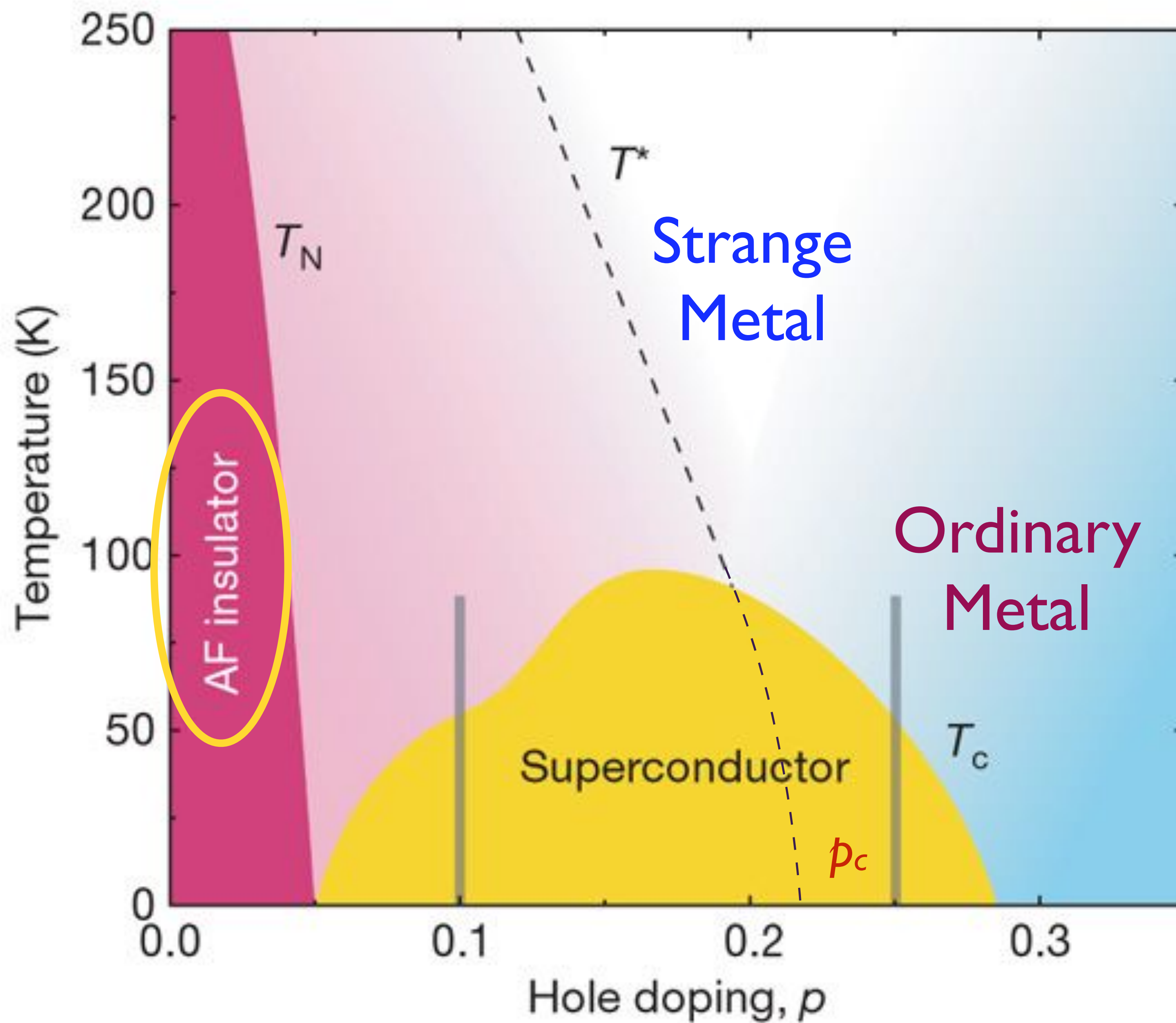




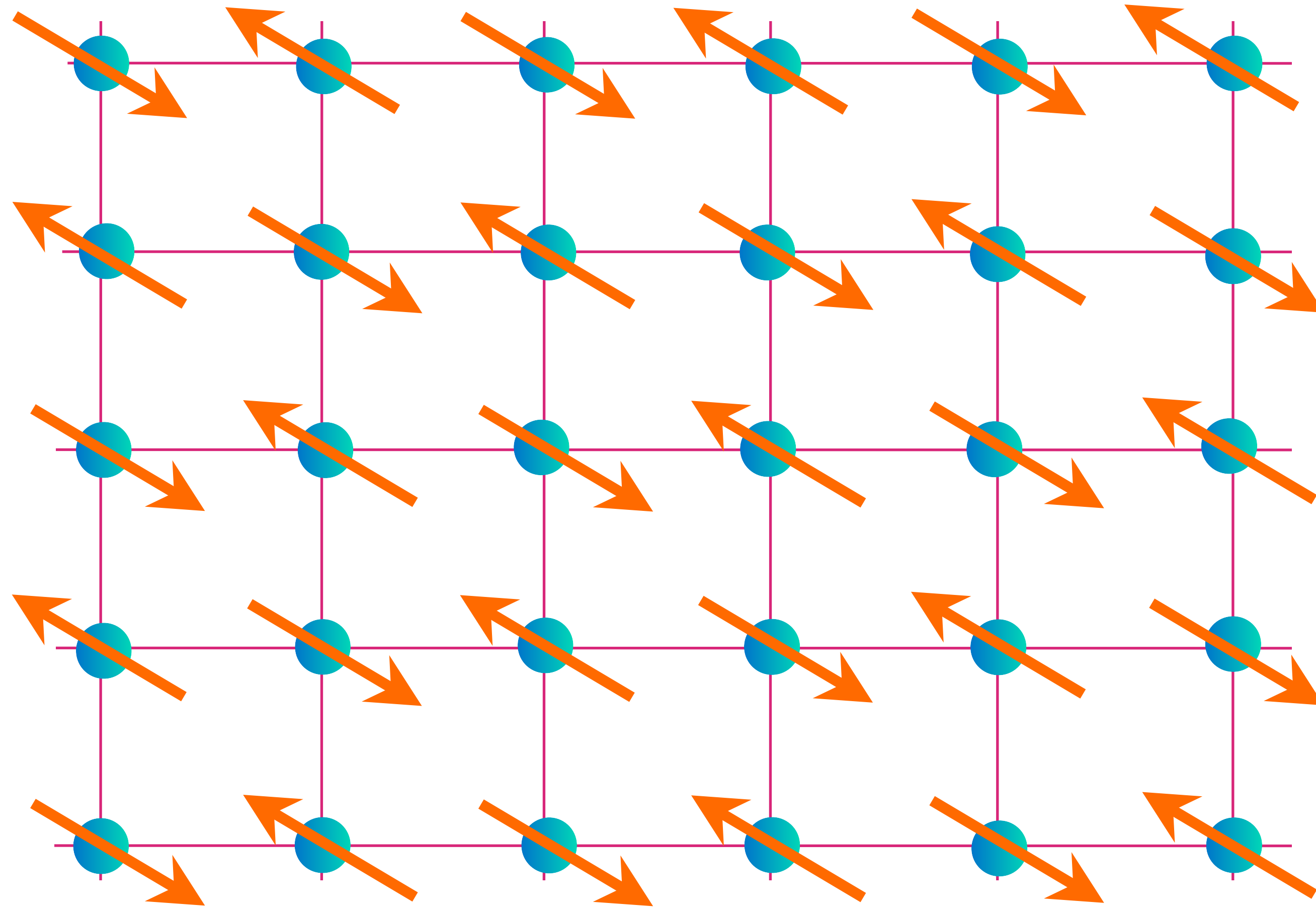




LSCO: Giraldo-Gallo et al. 2018

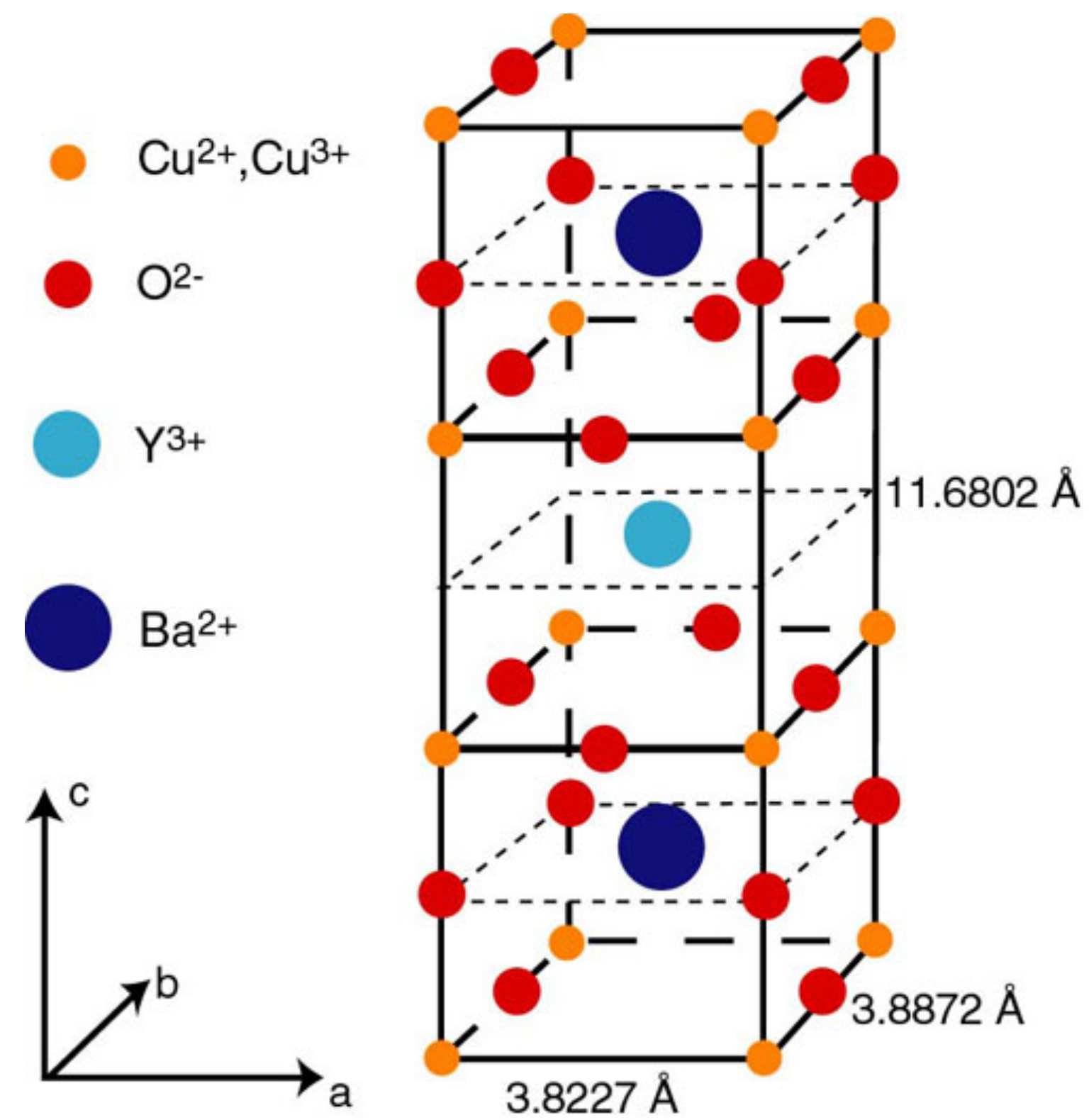
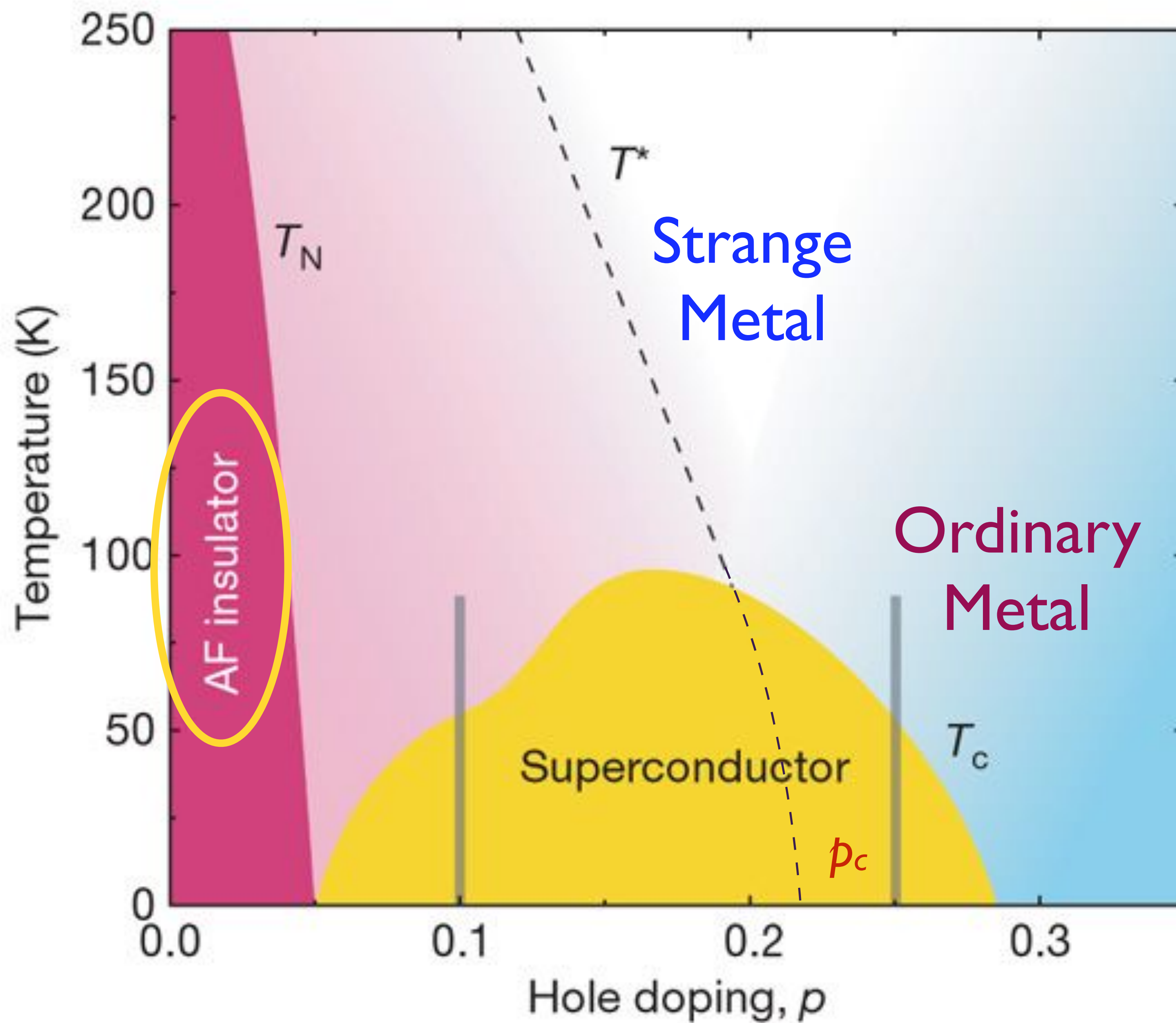


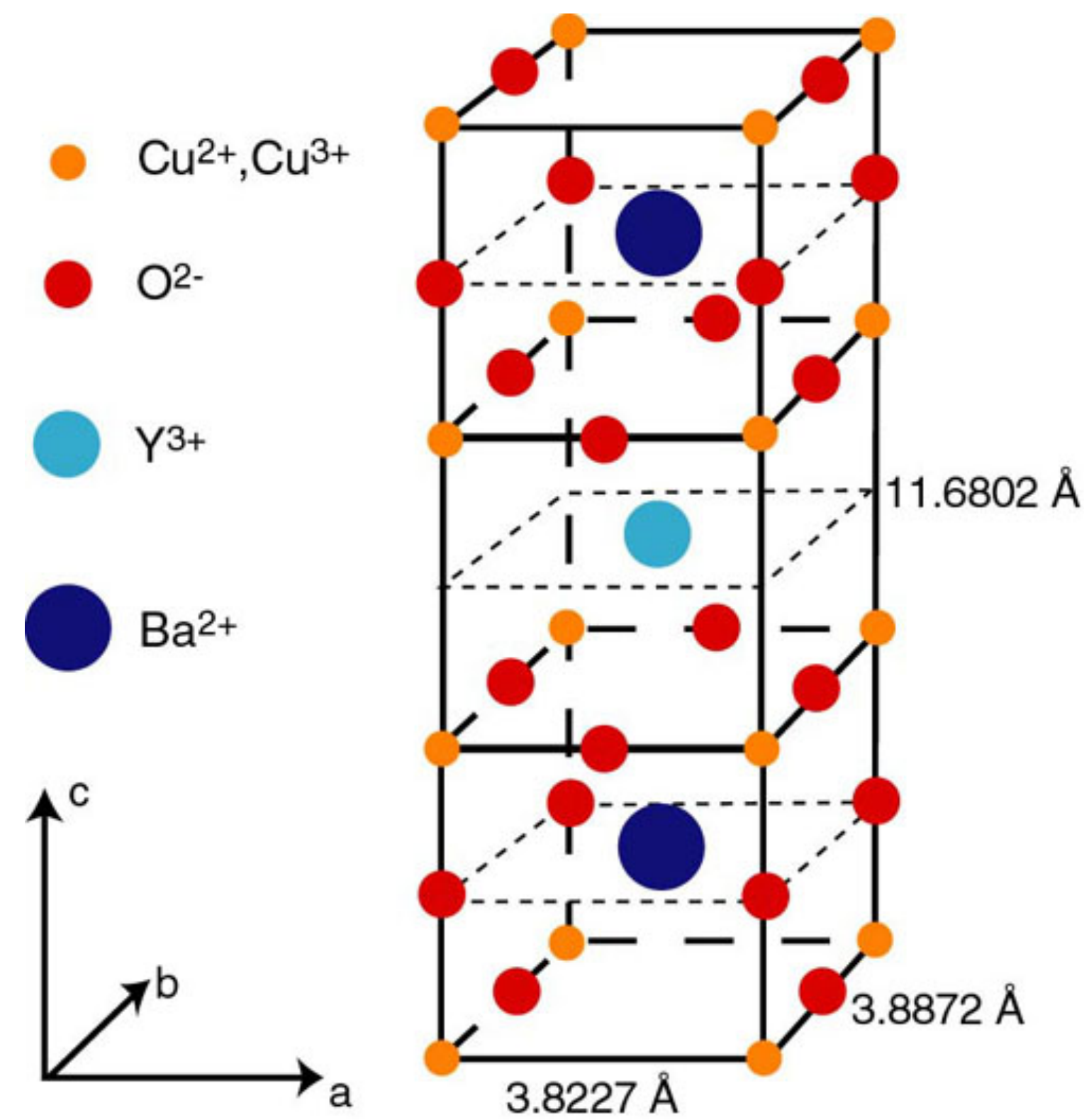
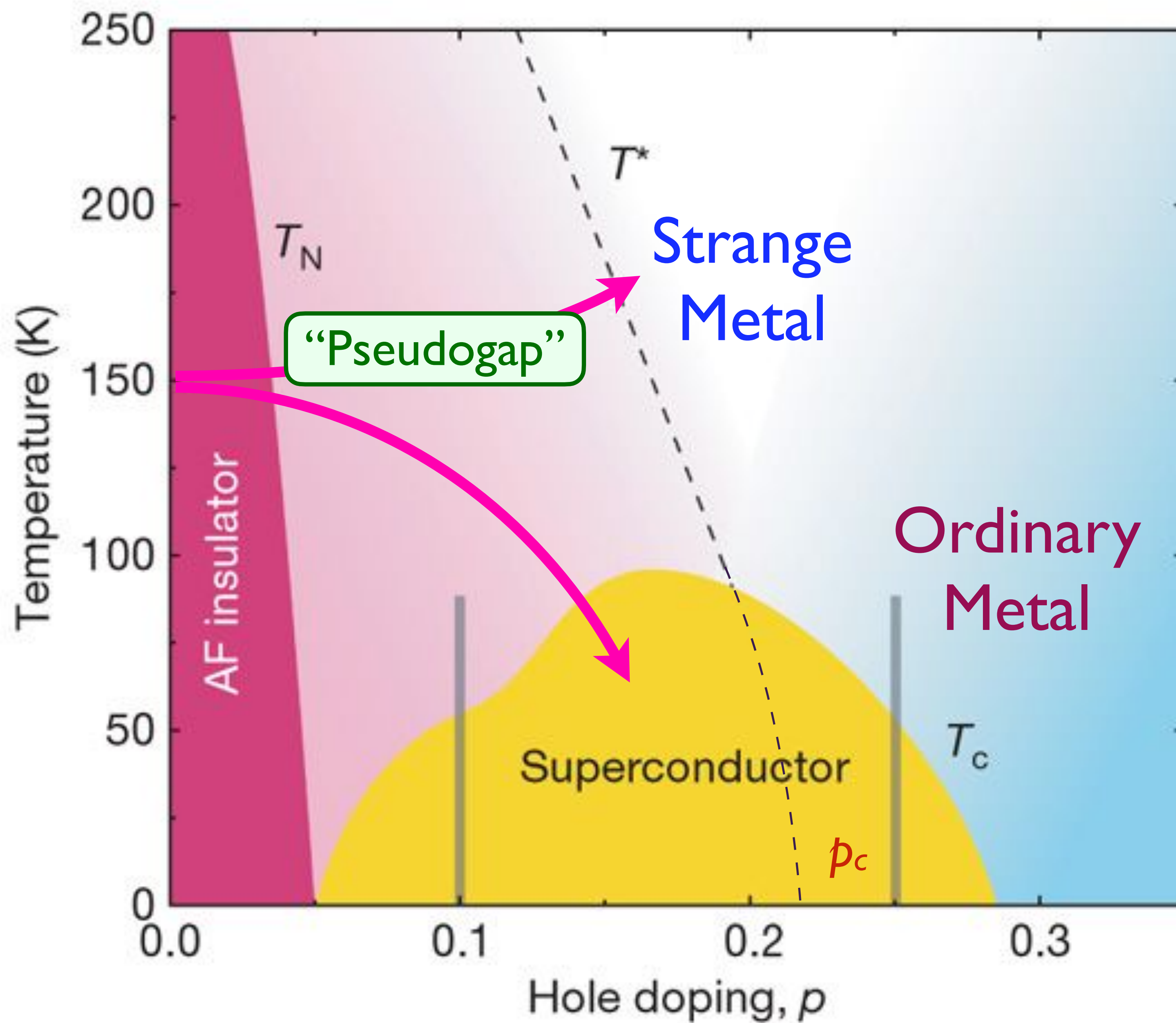
The dance of electrons on Cu atoms in YBCO

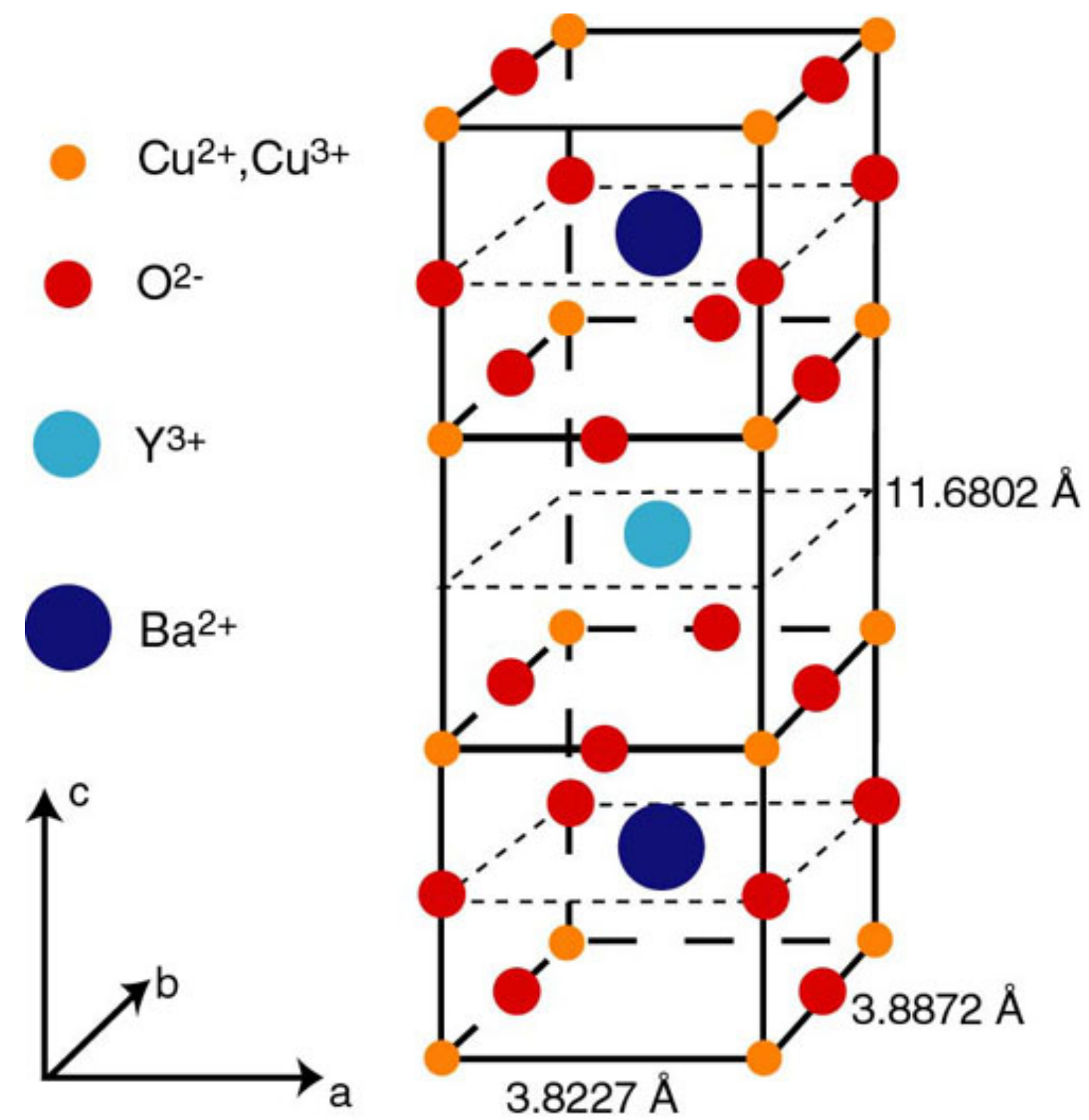
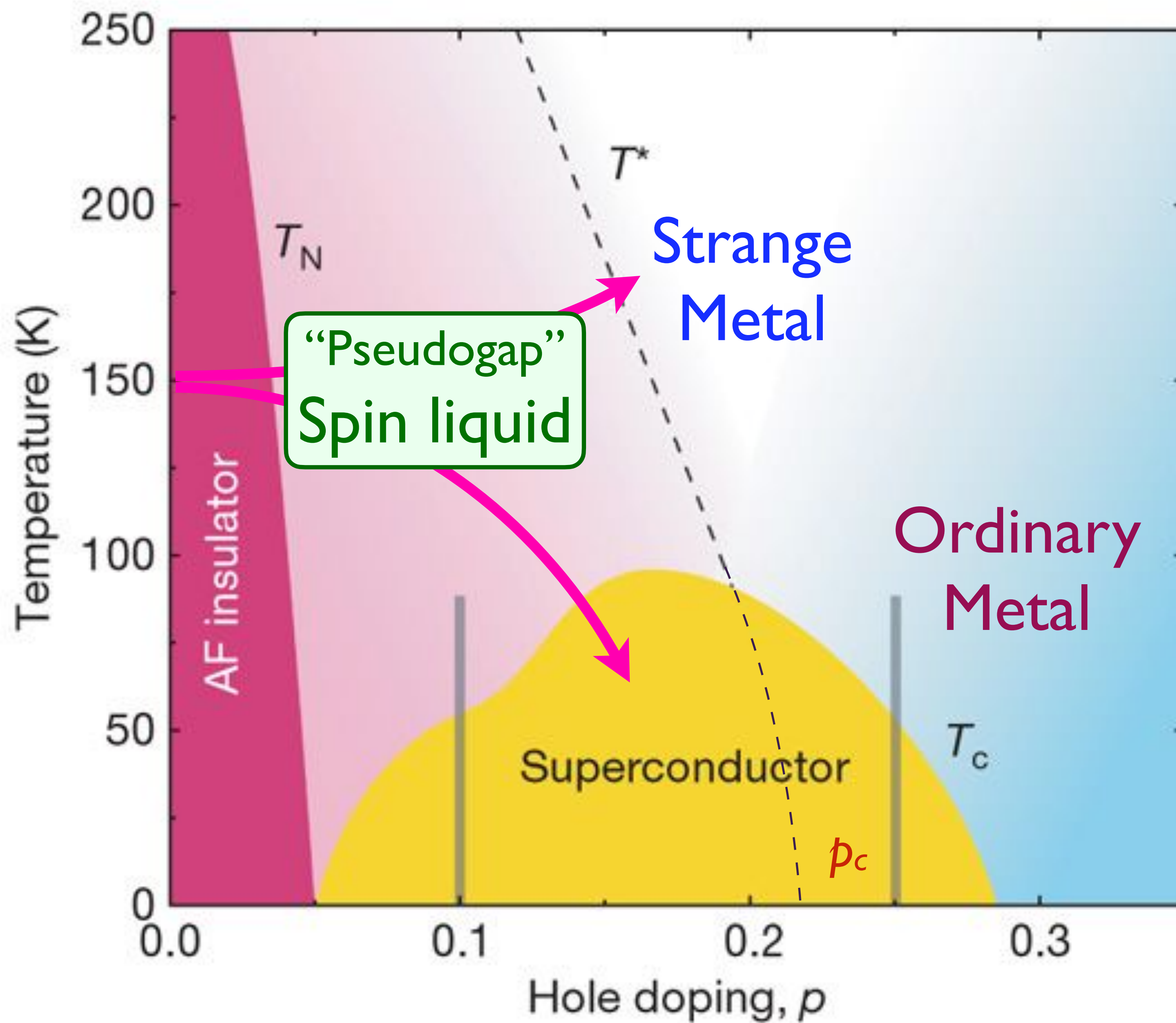


Antiferromagnetism

All nearest-neighbor pairs of electrons have opposite spins



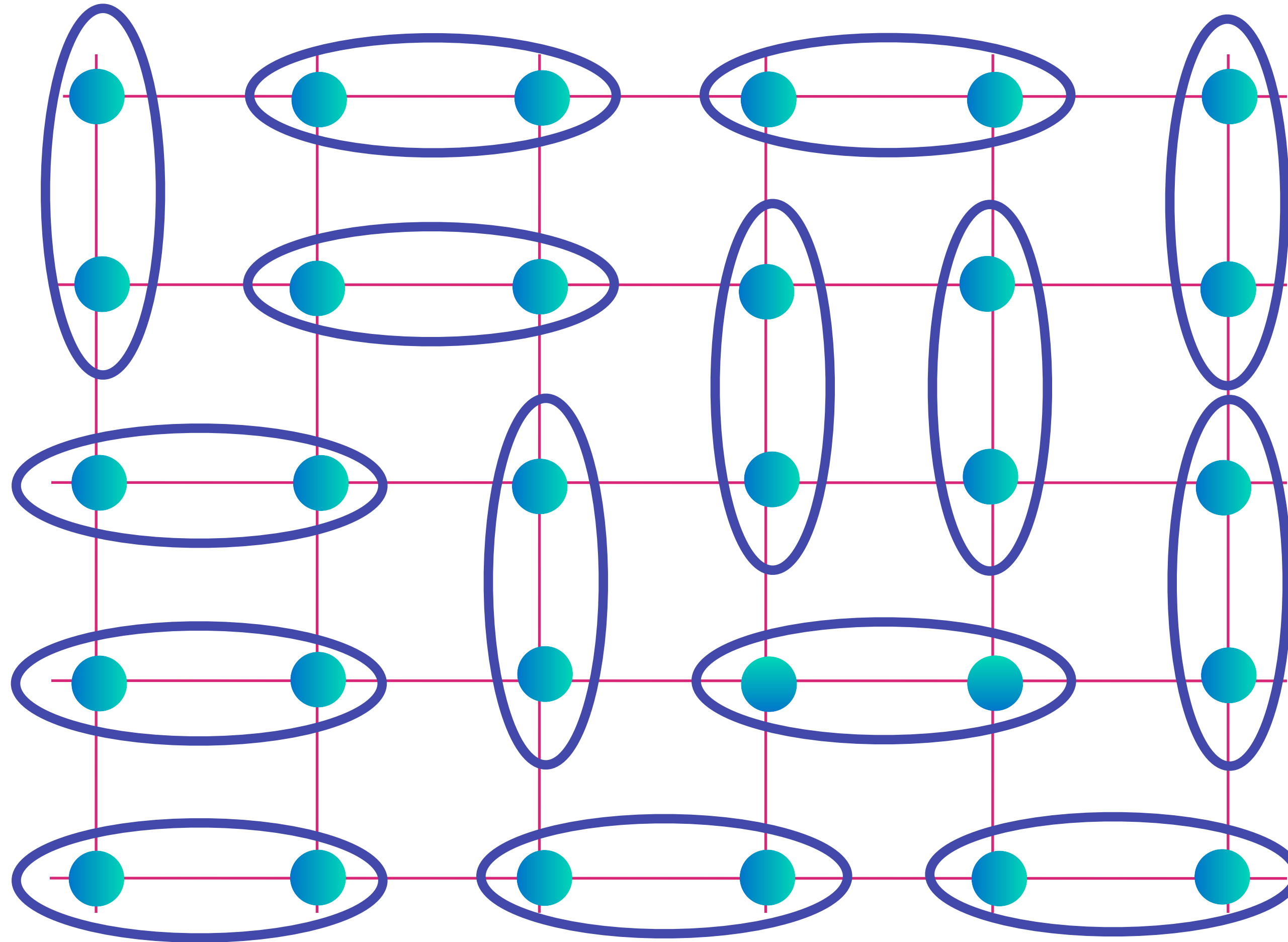




The dance of electrons on Cu atoms in YBCO

P.W. Anderson (1973)

Spin liquid



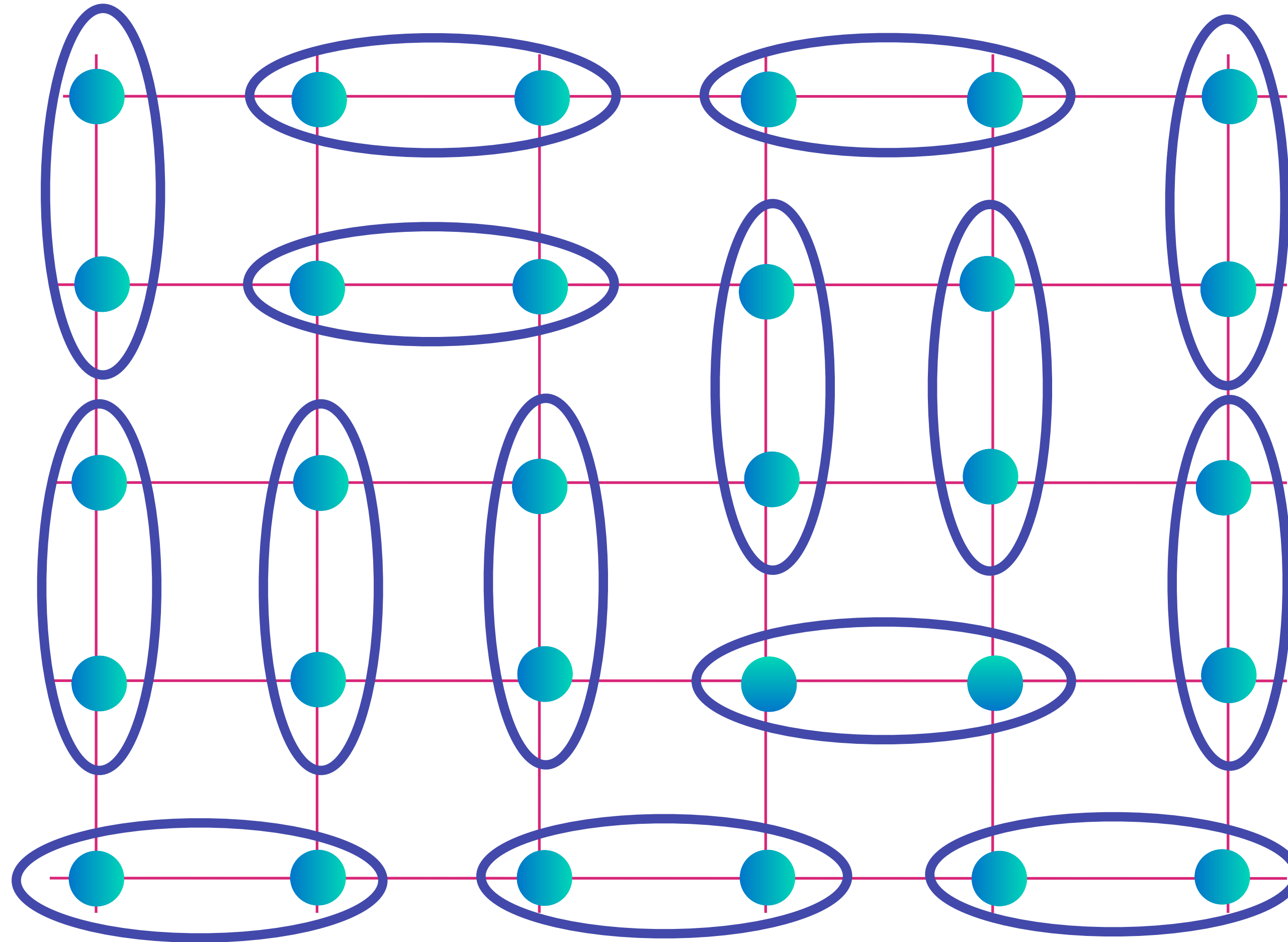
Electrons form entangled pairs, and the pairs entangle across the entire sample

$$\text{[Diagram of two electrons in an oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

The dance of electrons on Cu atoms in YBCO

P.W. Anderson (1973)

Spin liquid



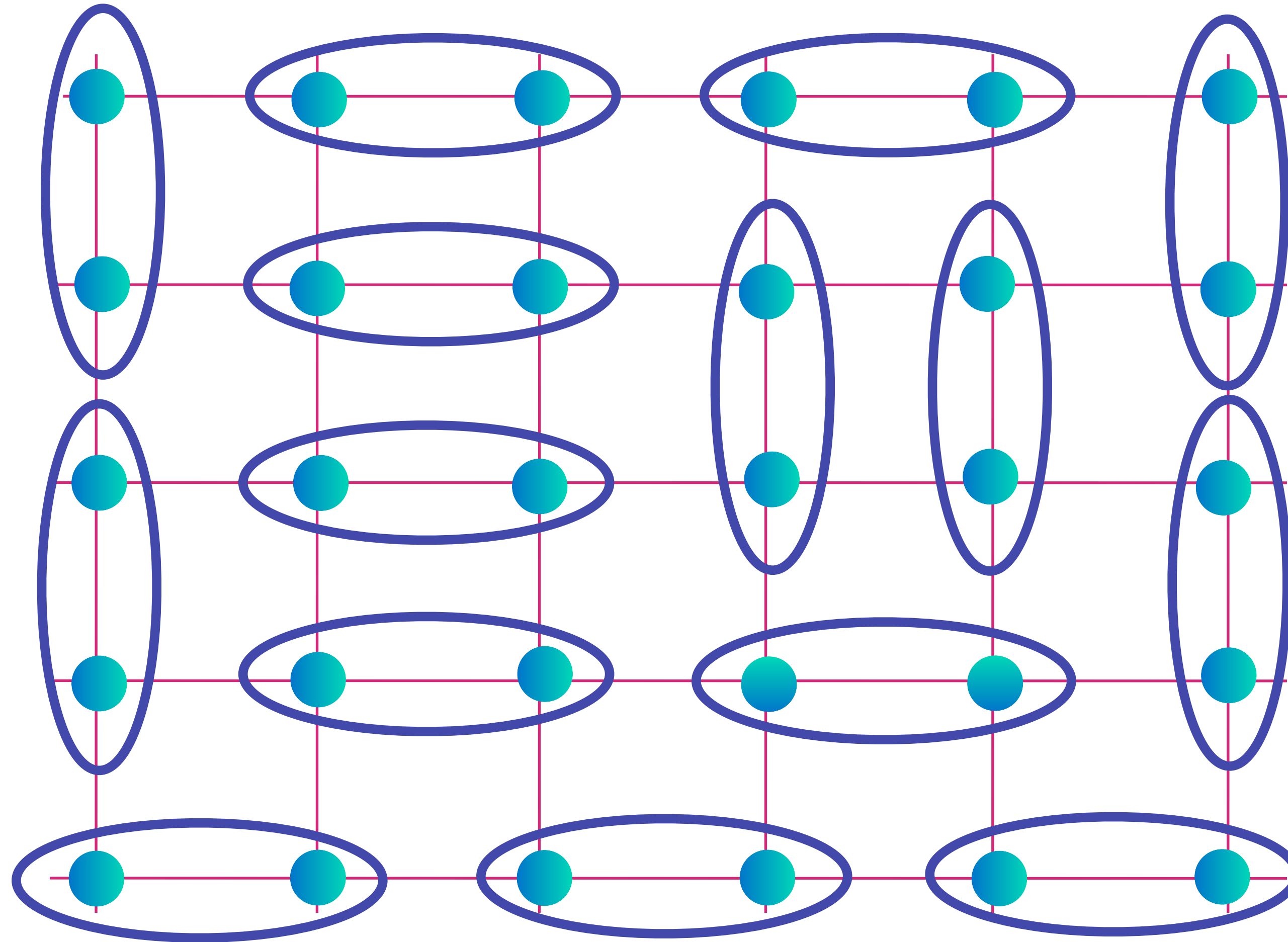
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$$\text{[Diagram of two teal dots in a blue oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

The dance of electrons on Cu atoms in YBCO

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Spin liquid



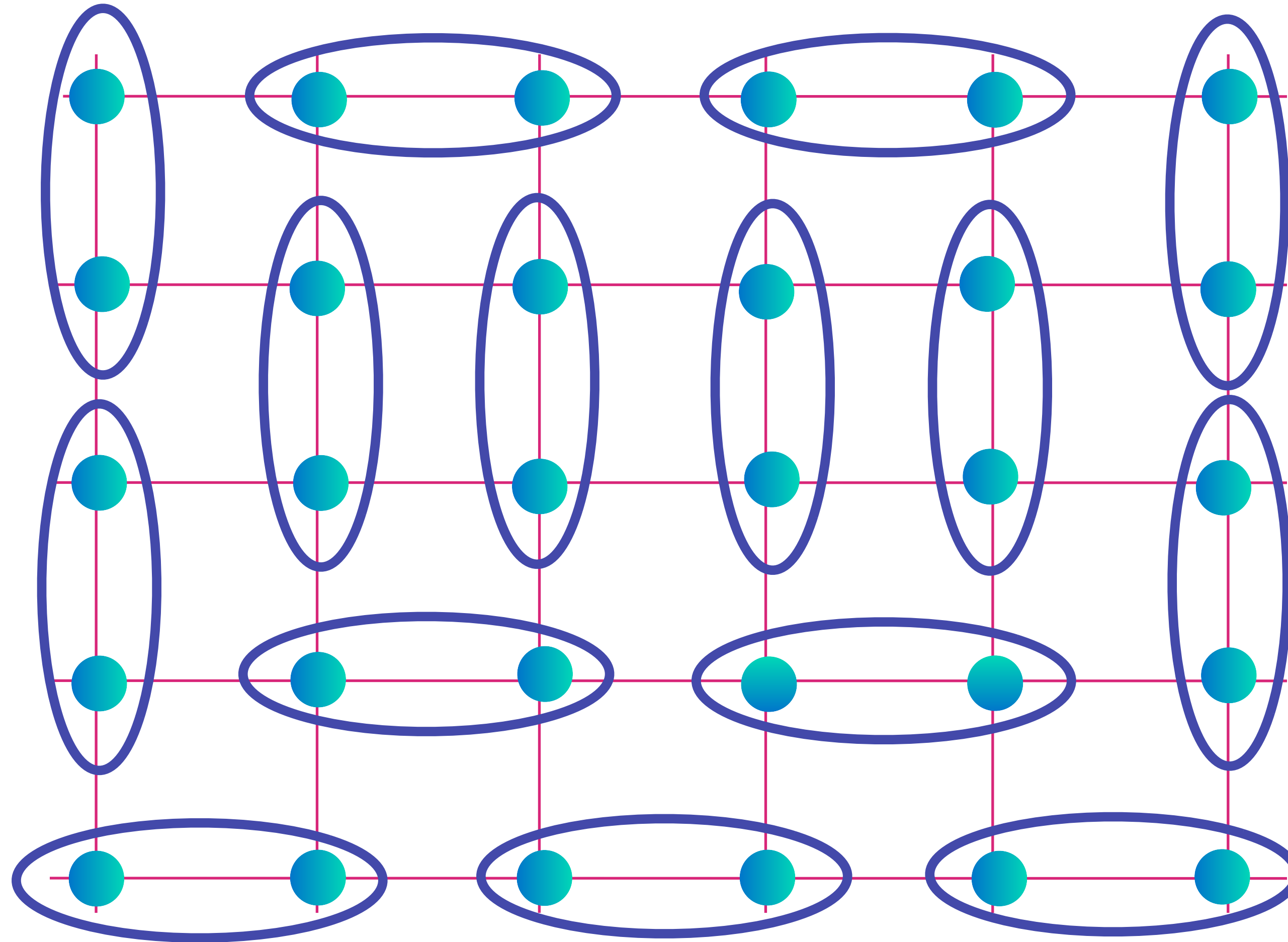
Electrons form entangled pairs, and the pairs entangle across the entire sample

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

The dance of electrons on Cu atoms in YBCO

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Spin liquid



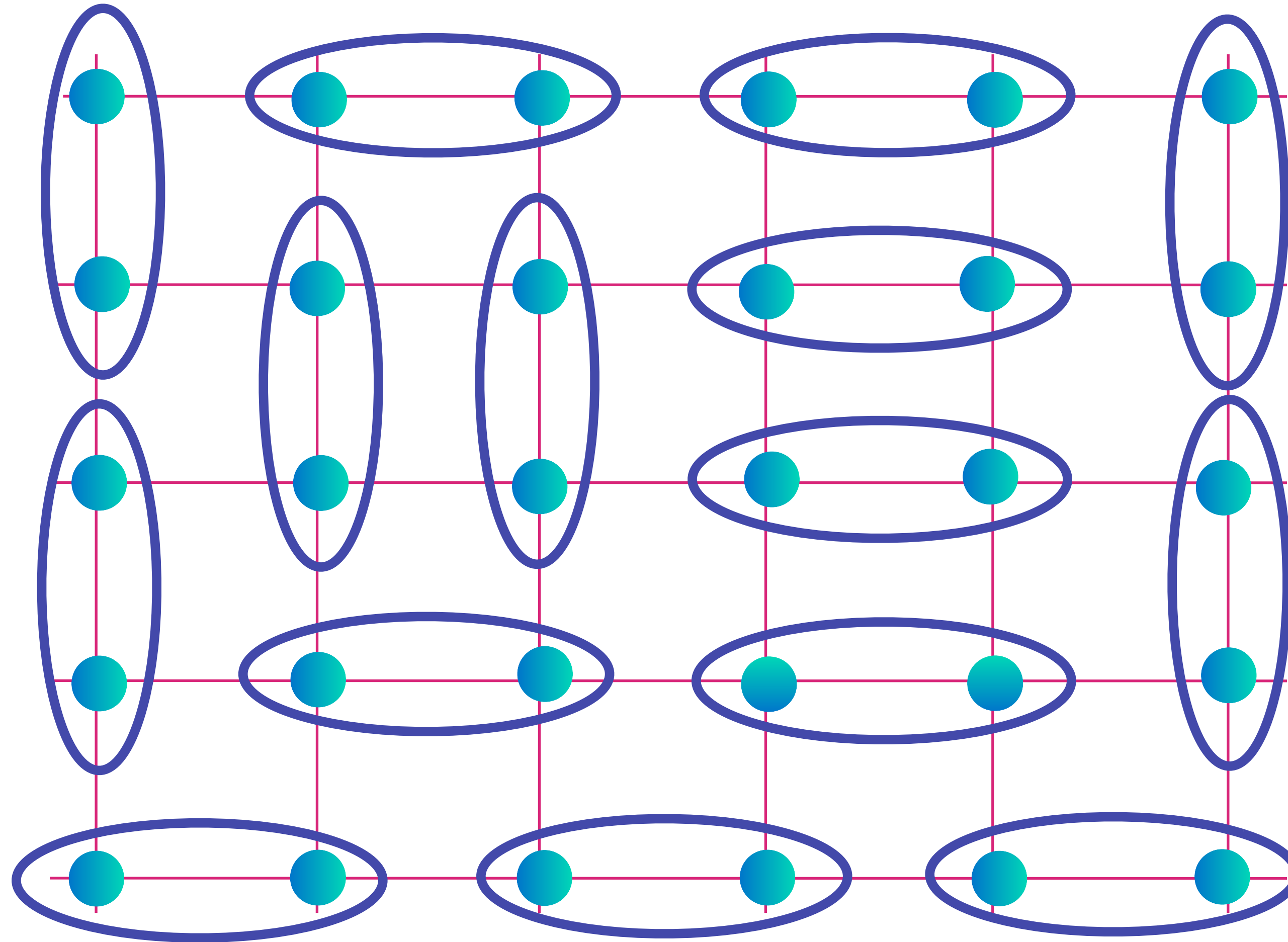
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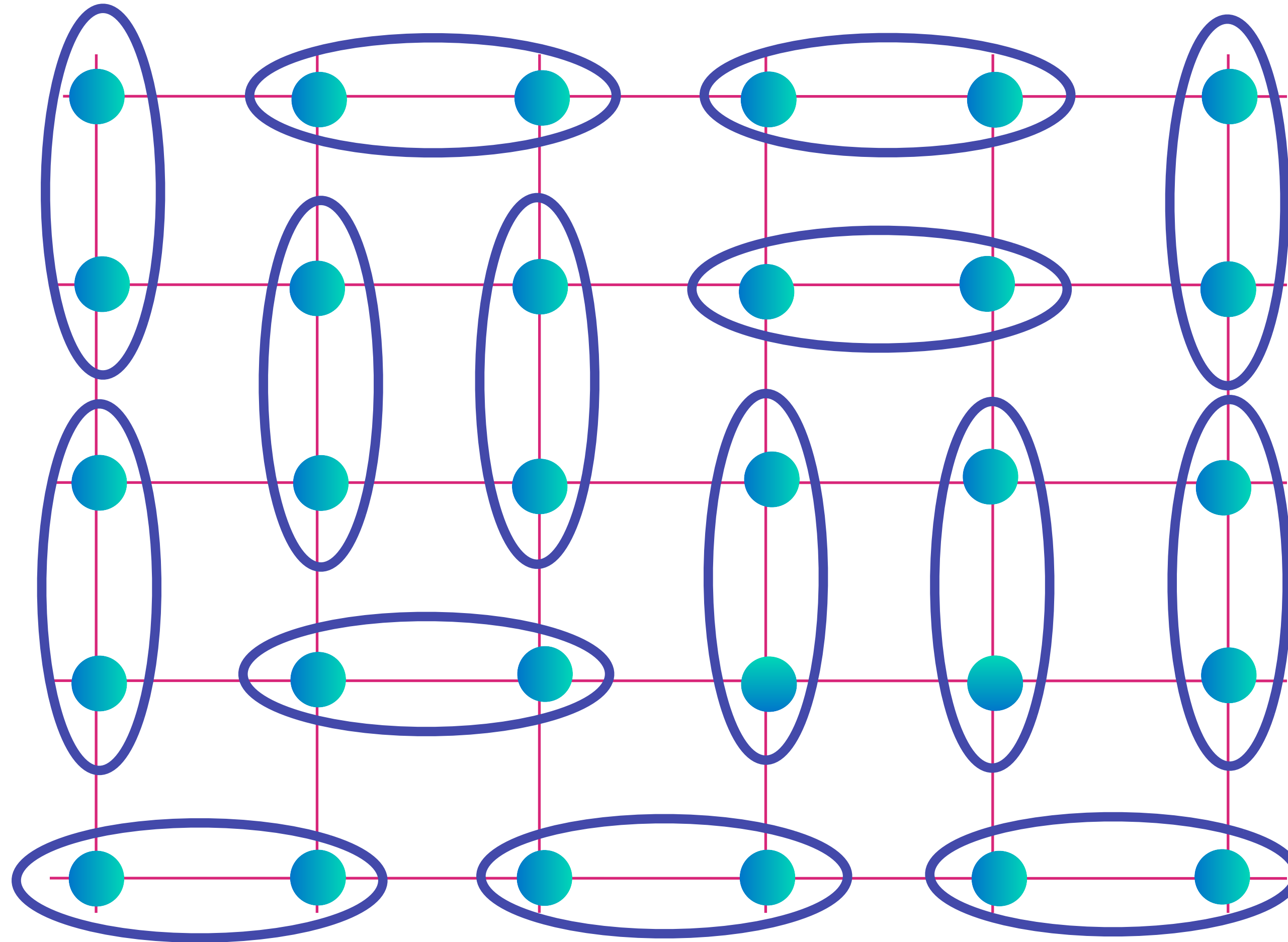
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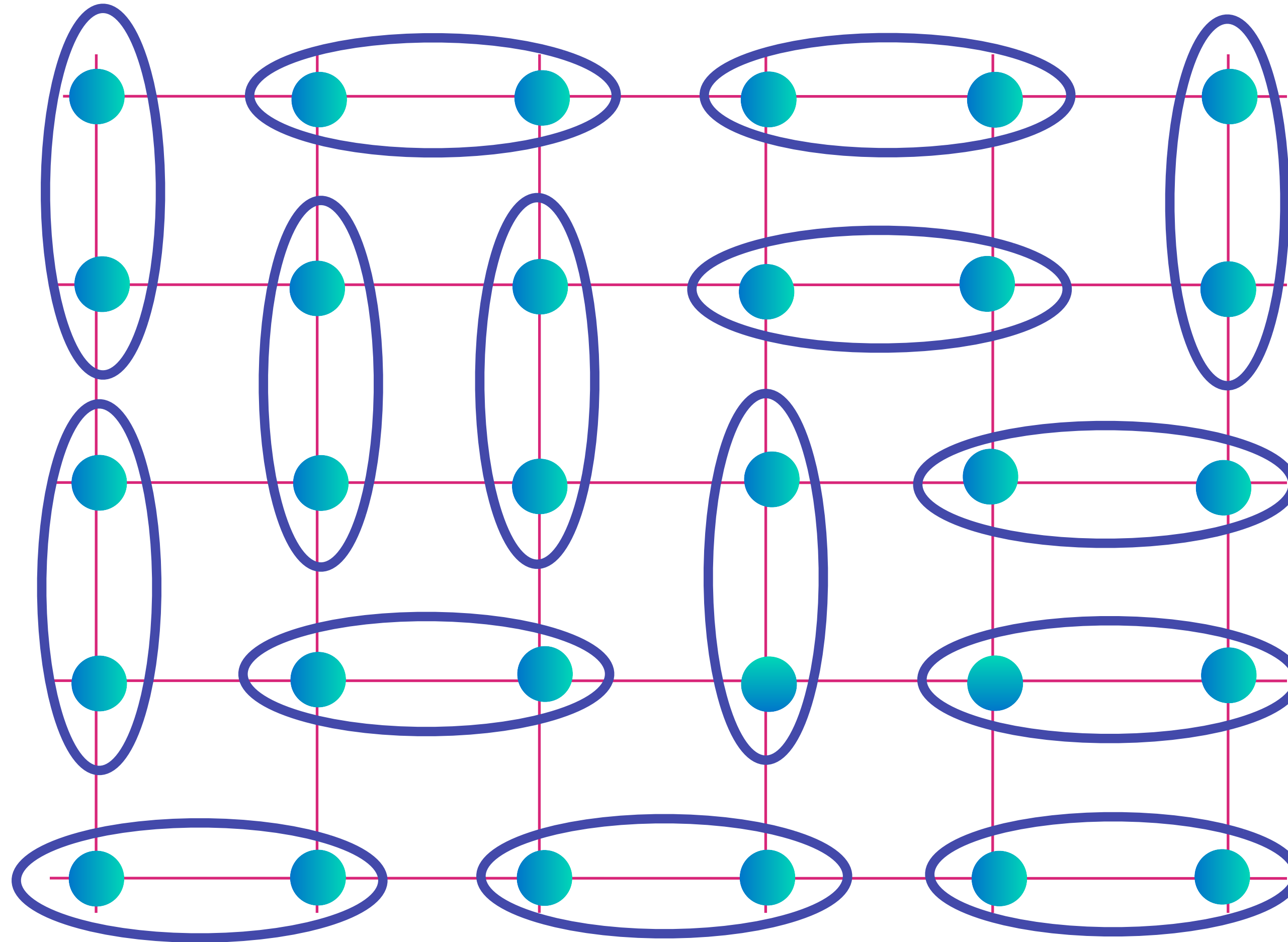
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The dance of electrons on Cu atoms in YBCO

P.W. Anderson (1973)

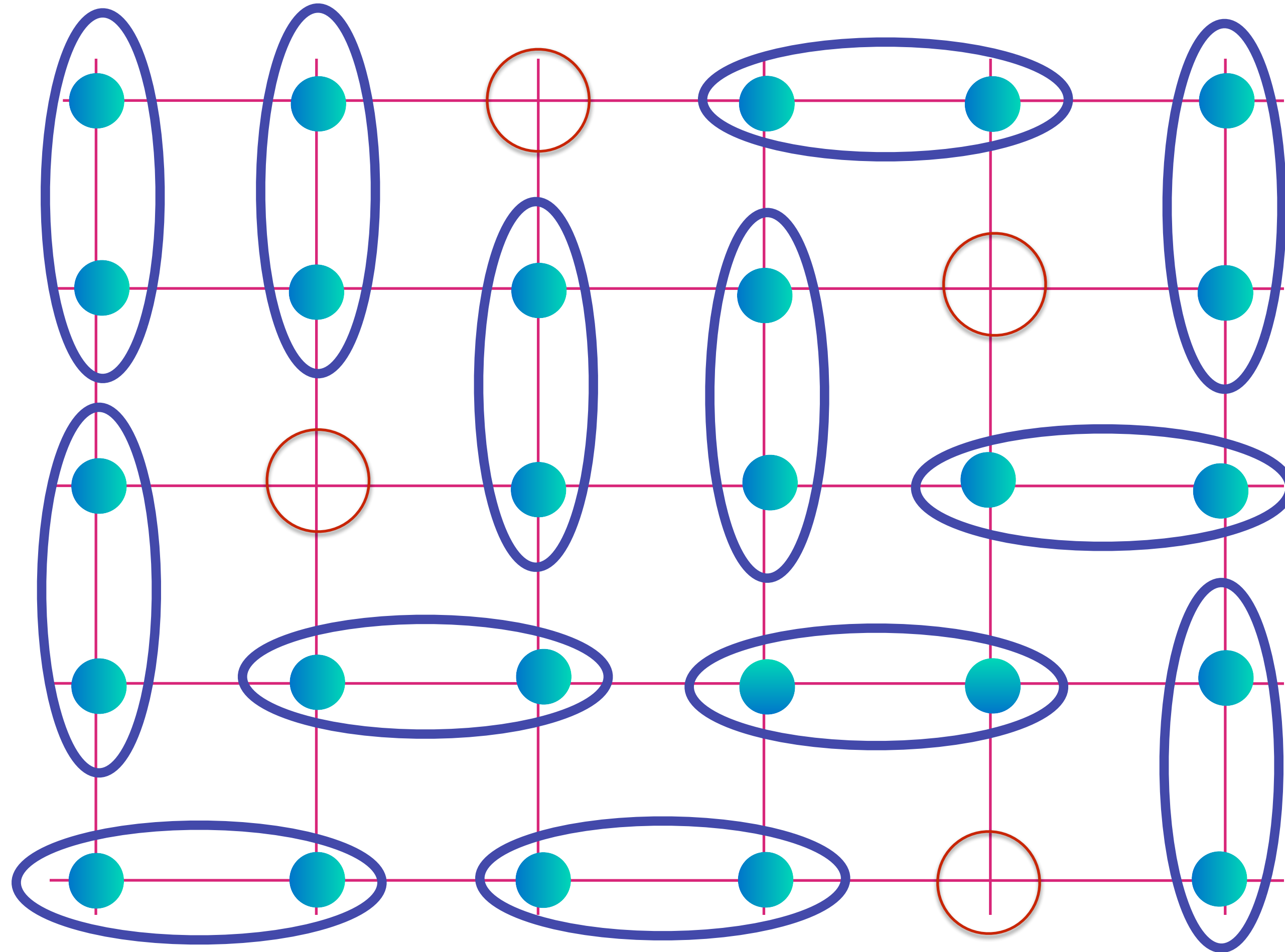
Spin liquid



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

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

The dance of electrons on Cu atoms in YBCO

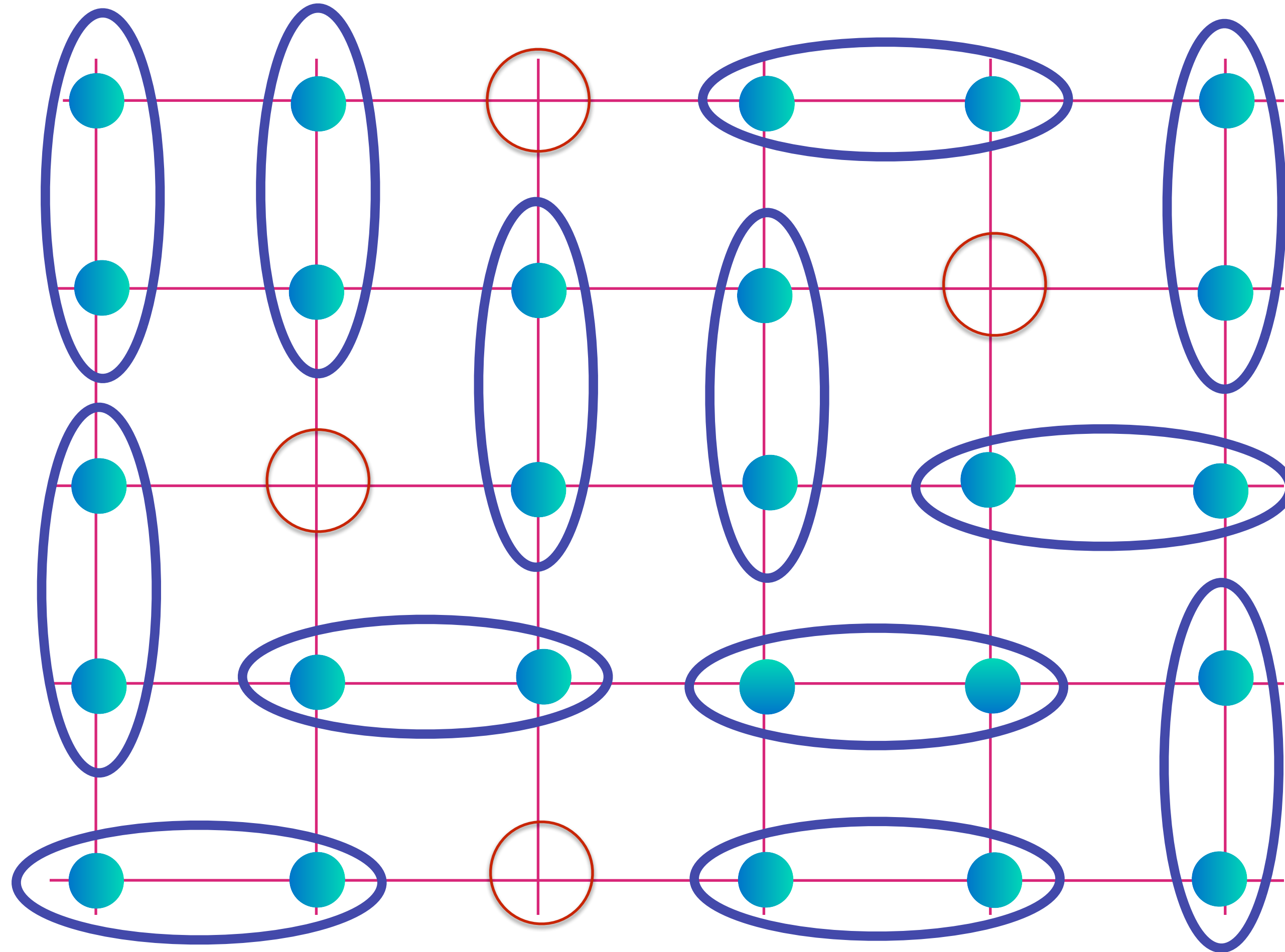


Pseudogap

Small density of mobile "holes" in a sea of entangled electron pairs

$$\text{[Blue Oval with 2 Teal Dots]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

The dance of electrons on Cu atoms in YBCO

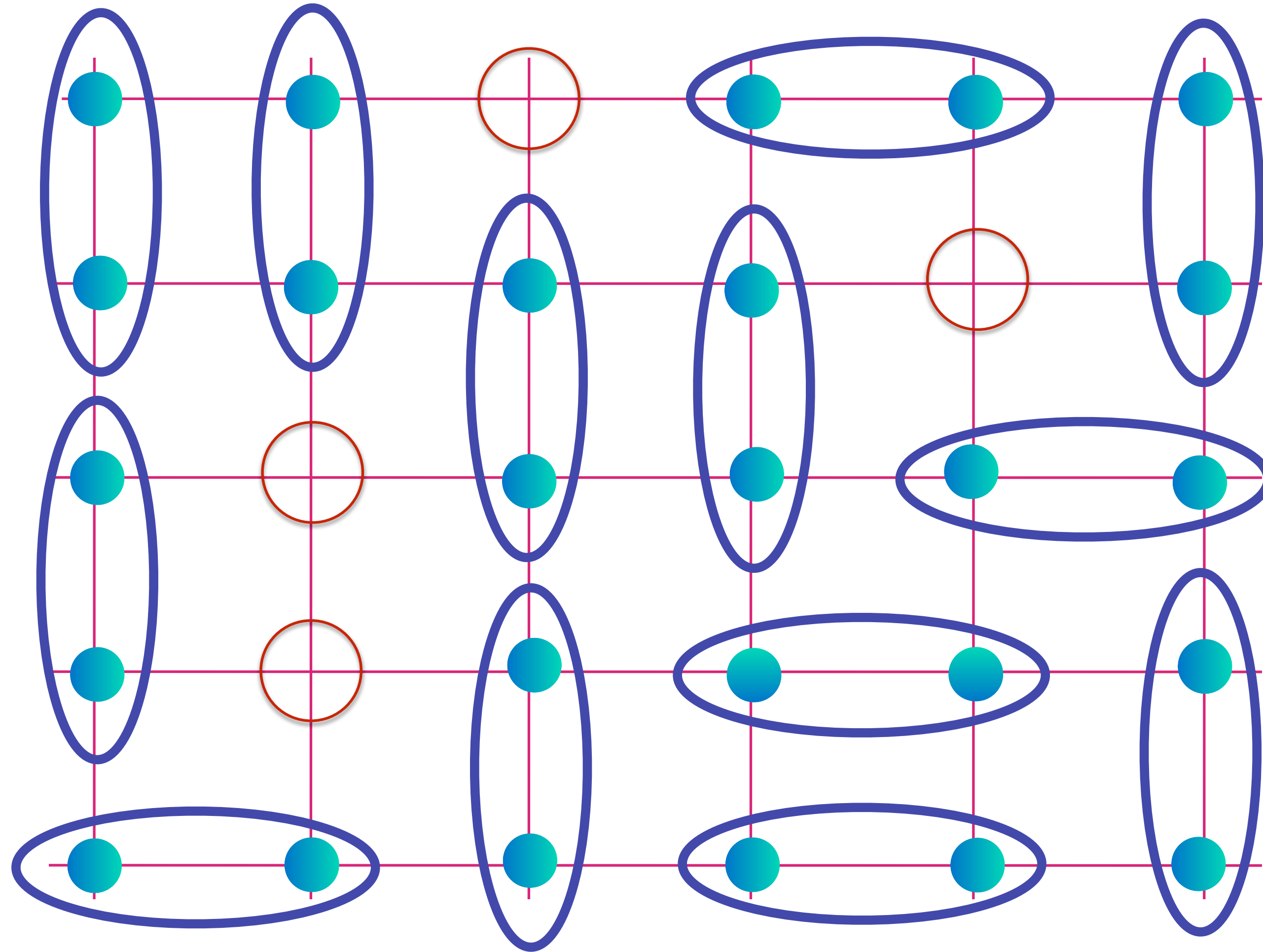


Pseudogap

Small density of mobile "holes" in a sea of entangled electron pairs

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

The dance of electrons on Cu atoms in YBCO

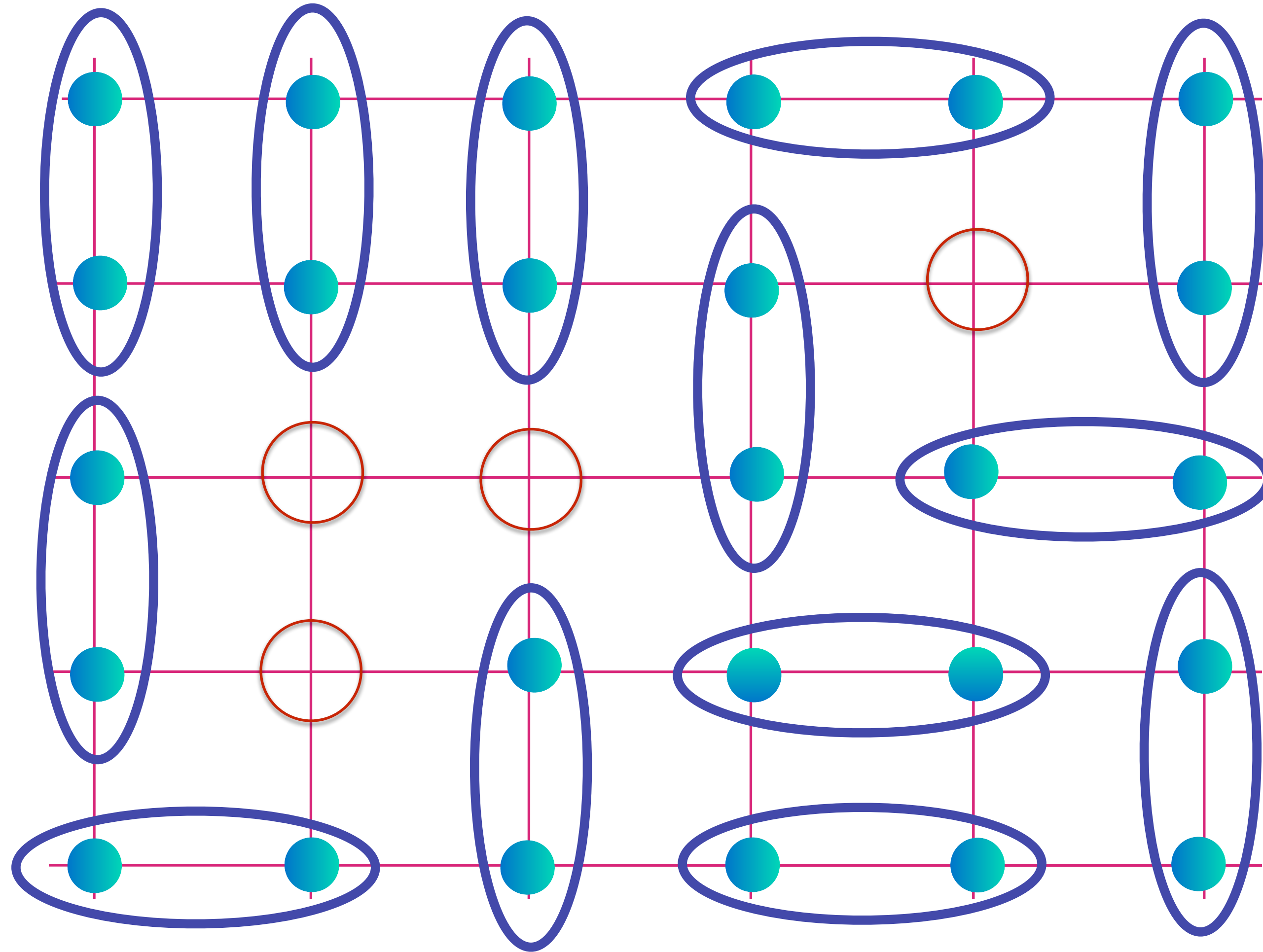


Pseudogap

Small density of mobile "holes" in a sea of entangled electron pairs

$$\text{[Diagram of a pair]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

The dance of electrons on Cu atoms in YBCO

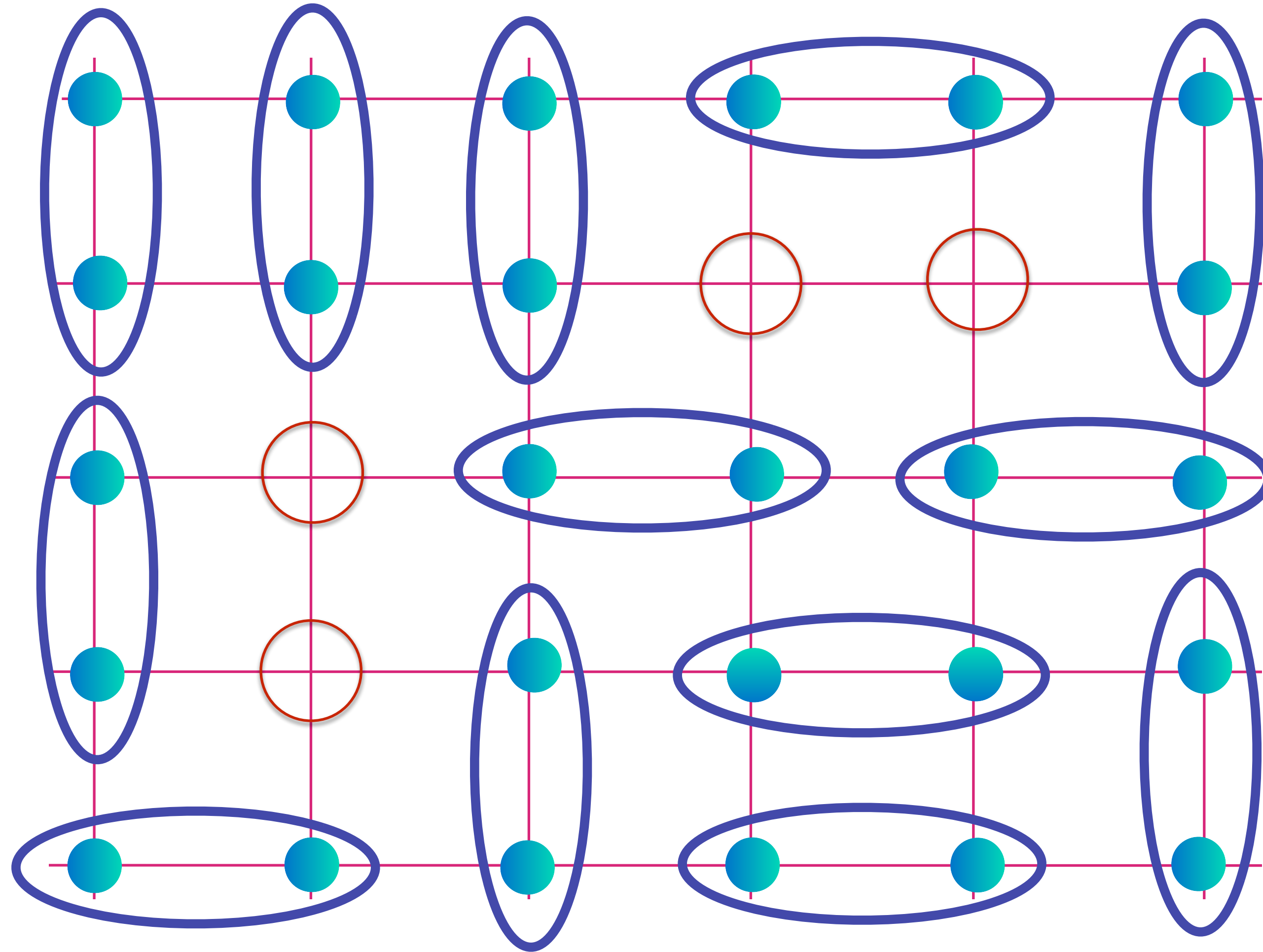


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The dance of electrons on Cu atoms in YBCO

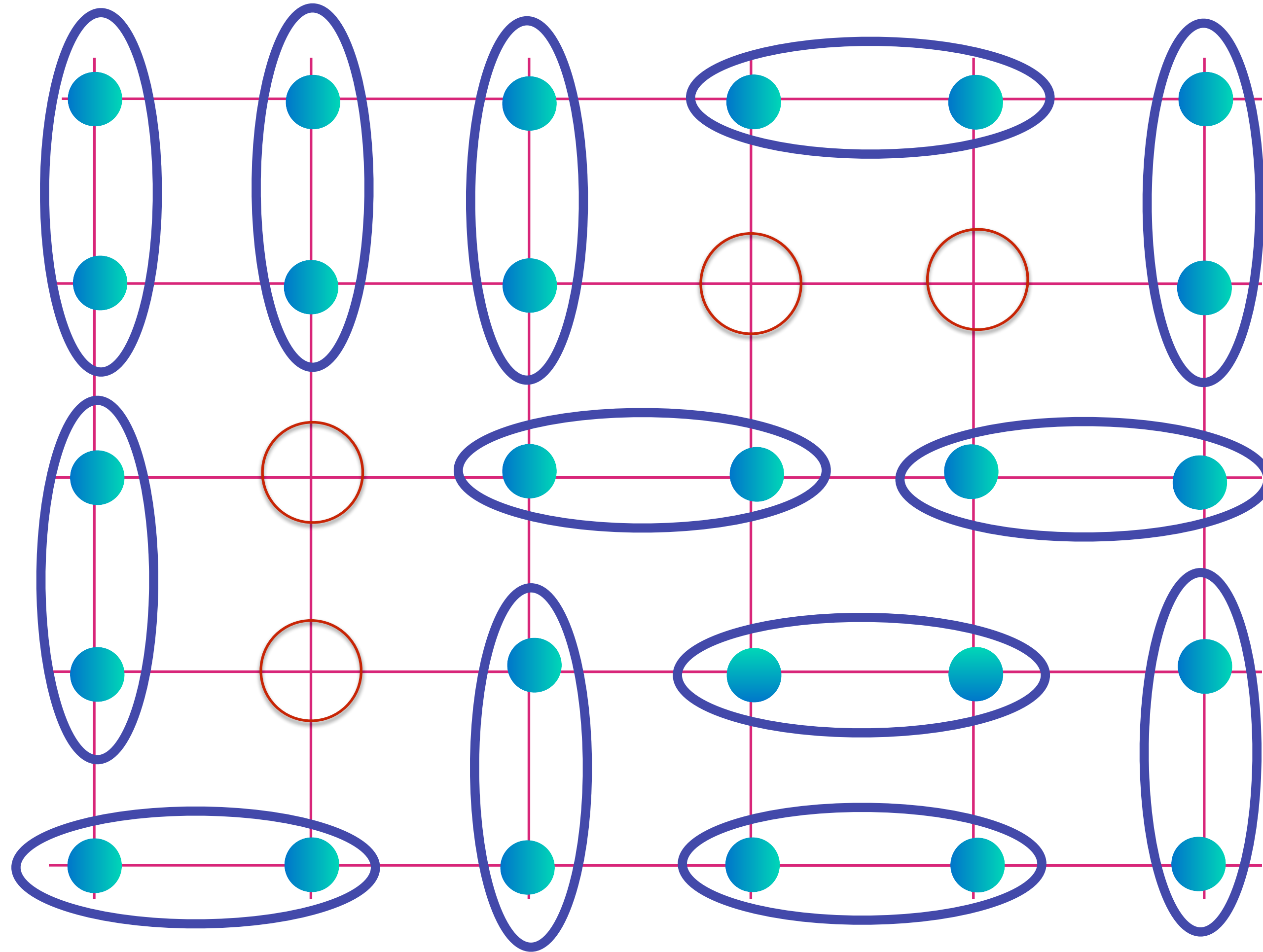


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The dance of electrons on Cu atoms in YBCO

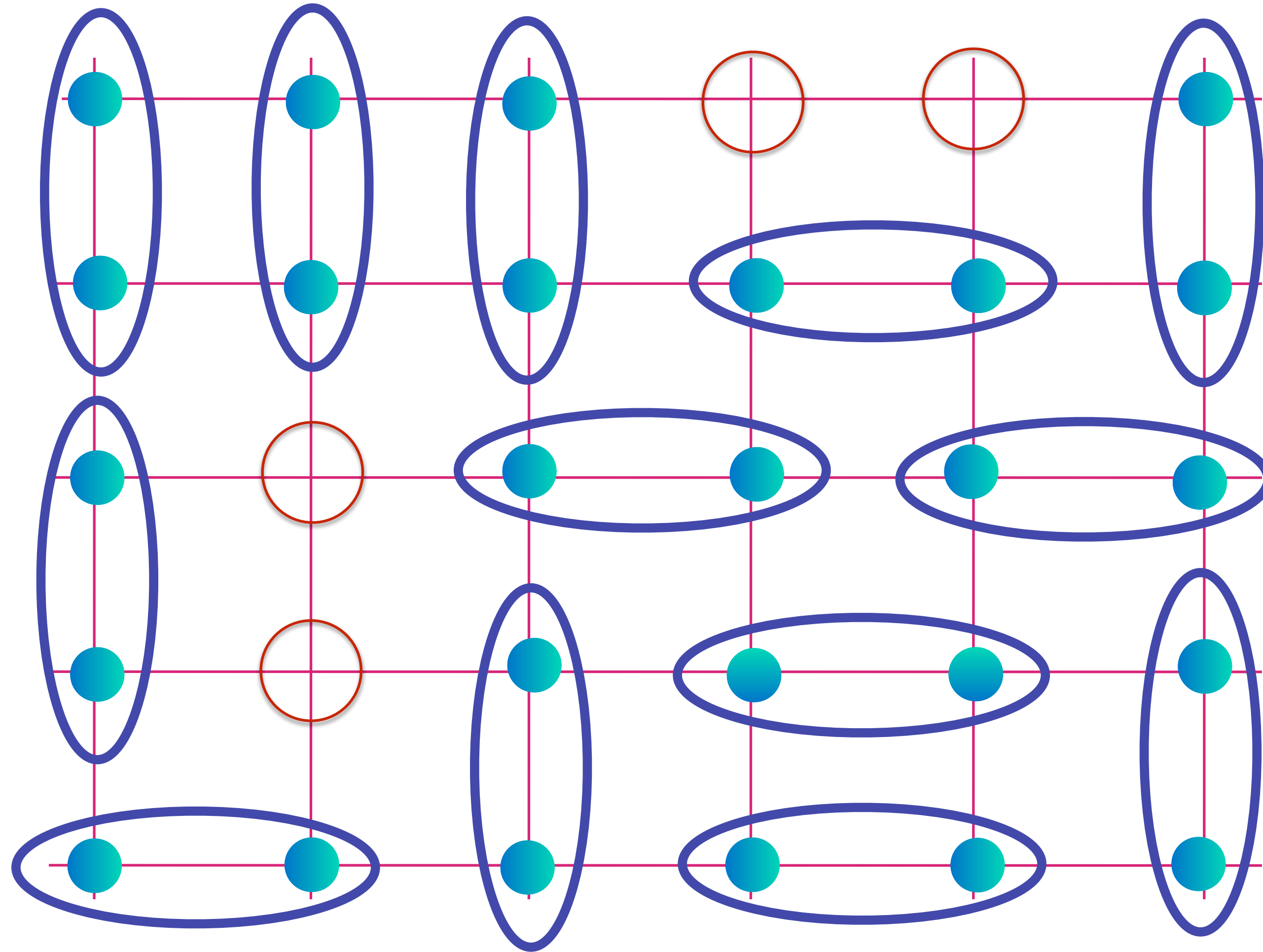


Superconductivity

Mobile
entangled
electron pairs

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

The dance of electrons on Cu atoms in YBCO

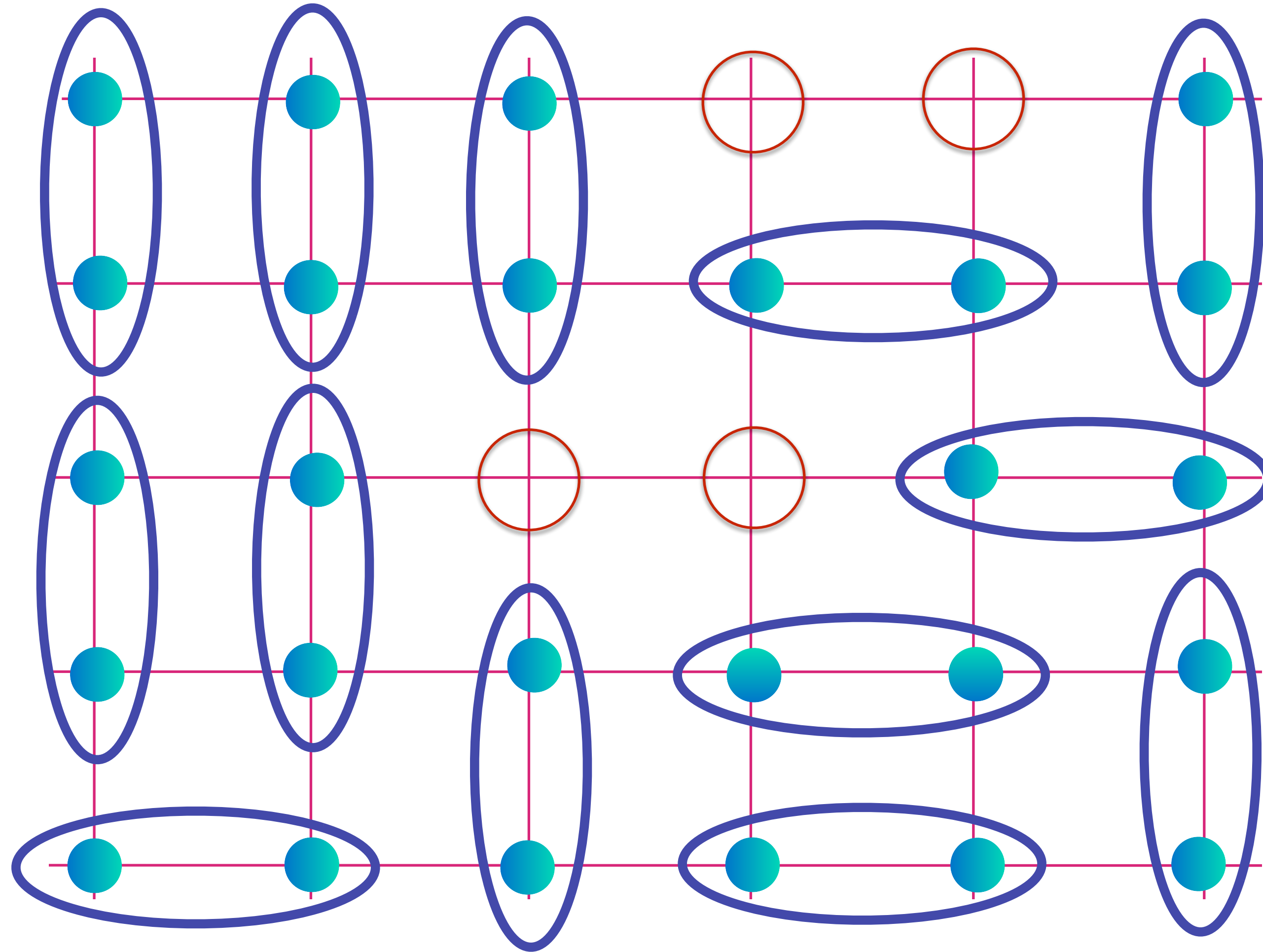


Superconductivity

Mobile
entangled
electron pairs

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

The dance of electrons on Cu atoms in YBCO

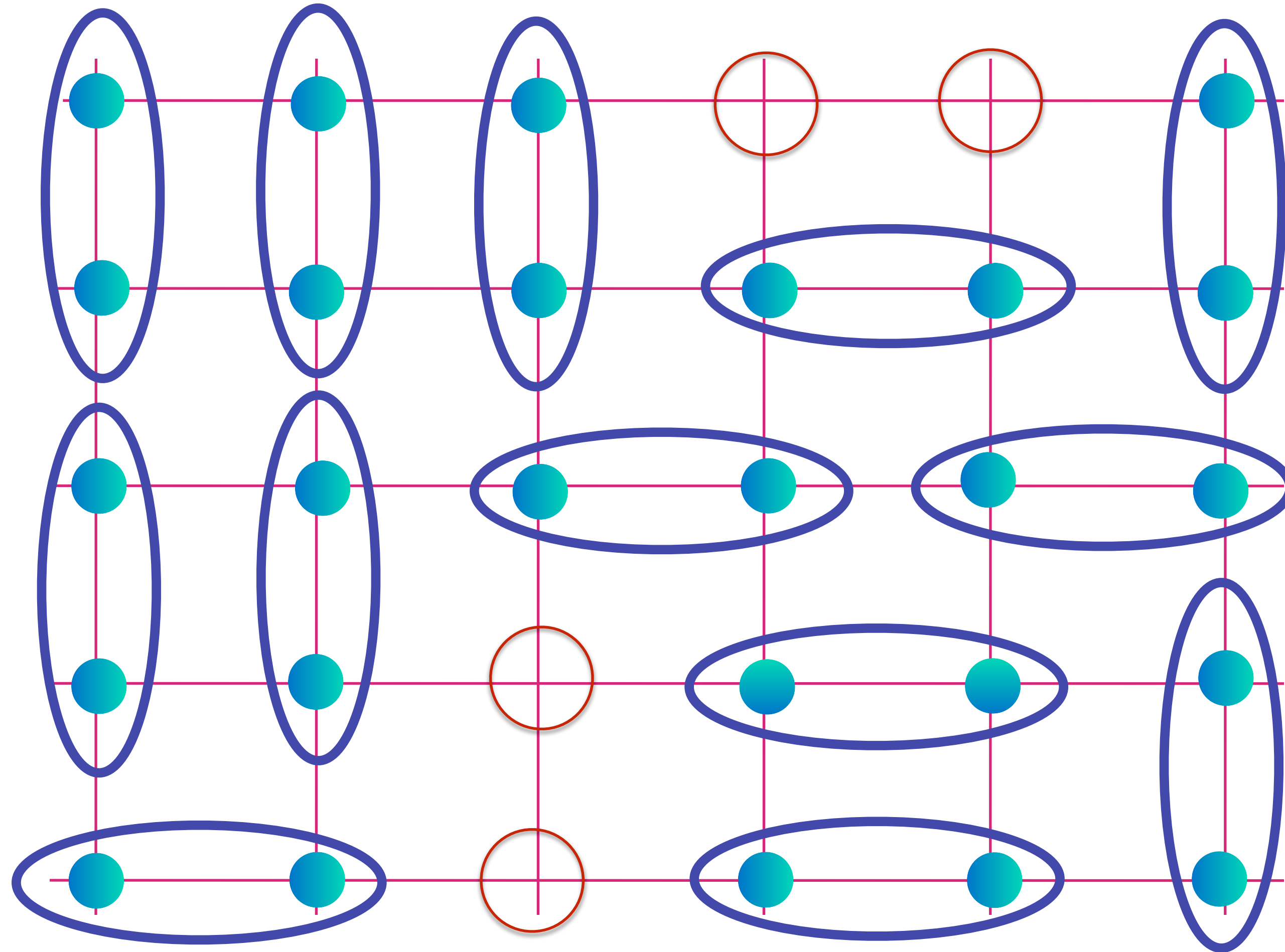


Superconductivity

Mobile
entangled
electron pairs

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

The dance of electrons on Cu atoms in YBCO

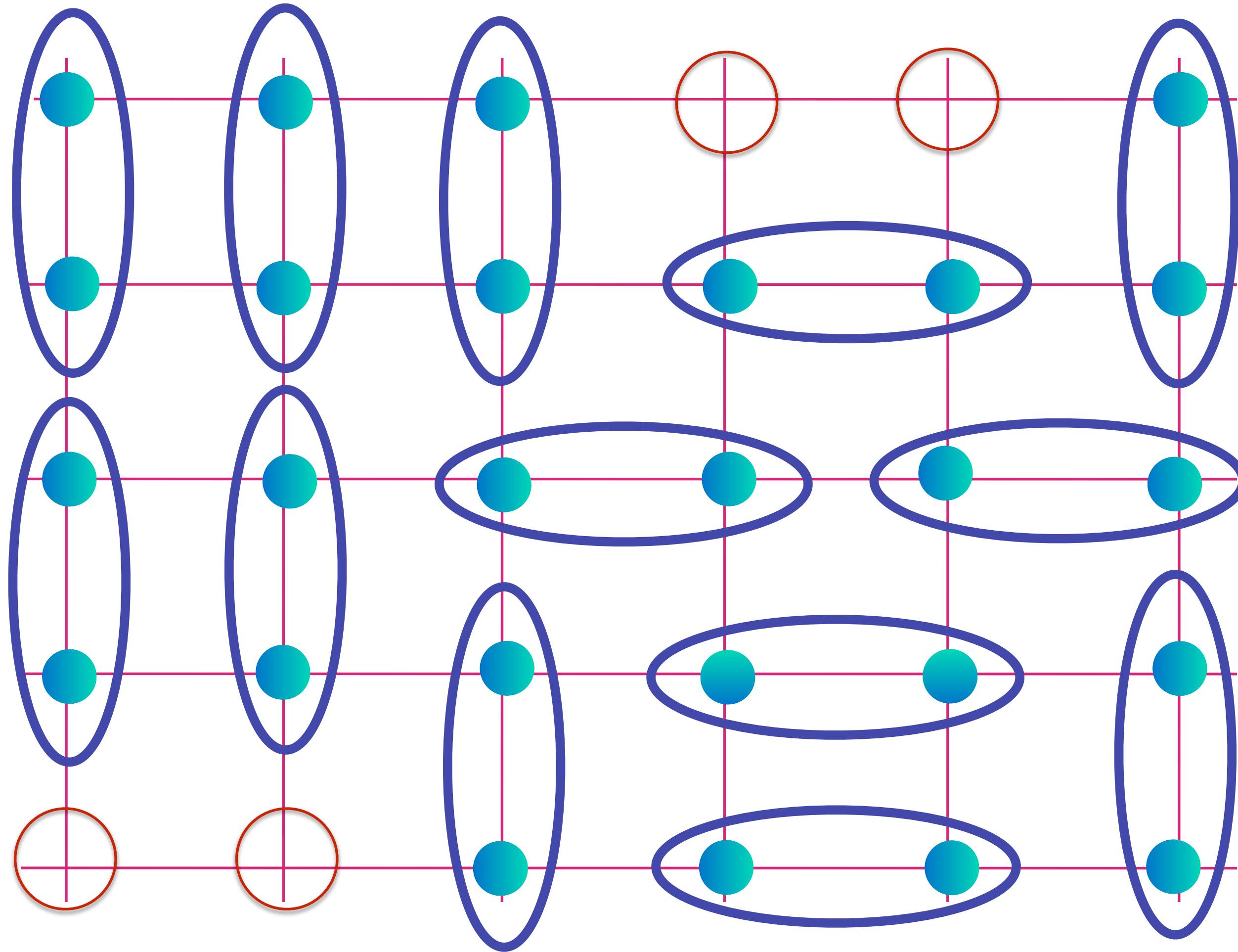


Superconductivity

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

The dance of electrons on Cu atoms in YBCO

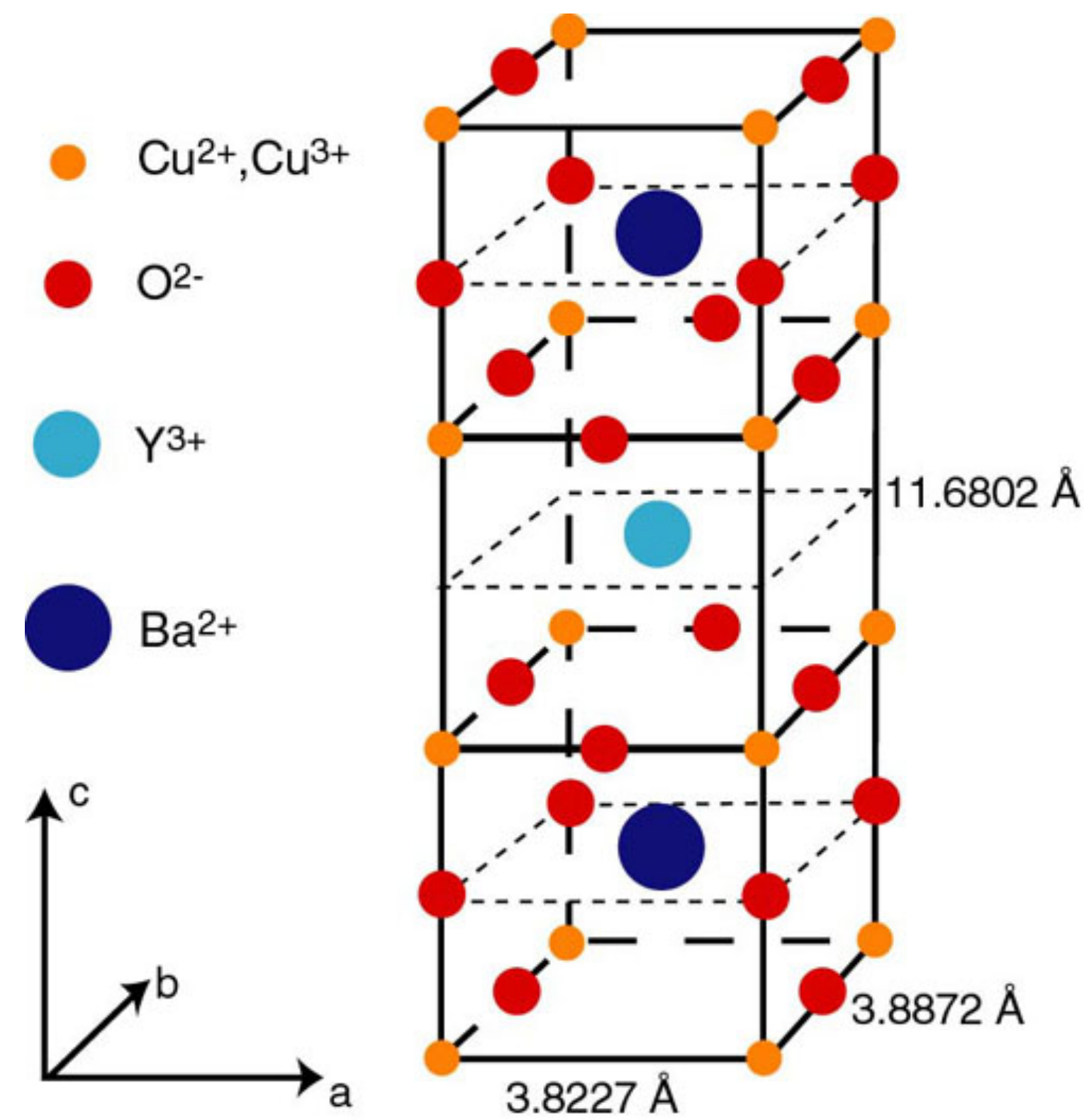
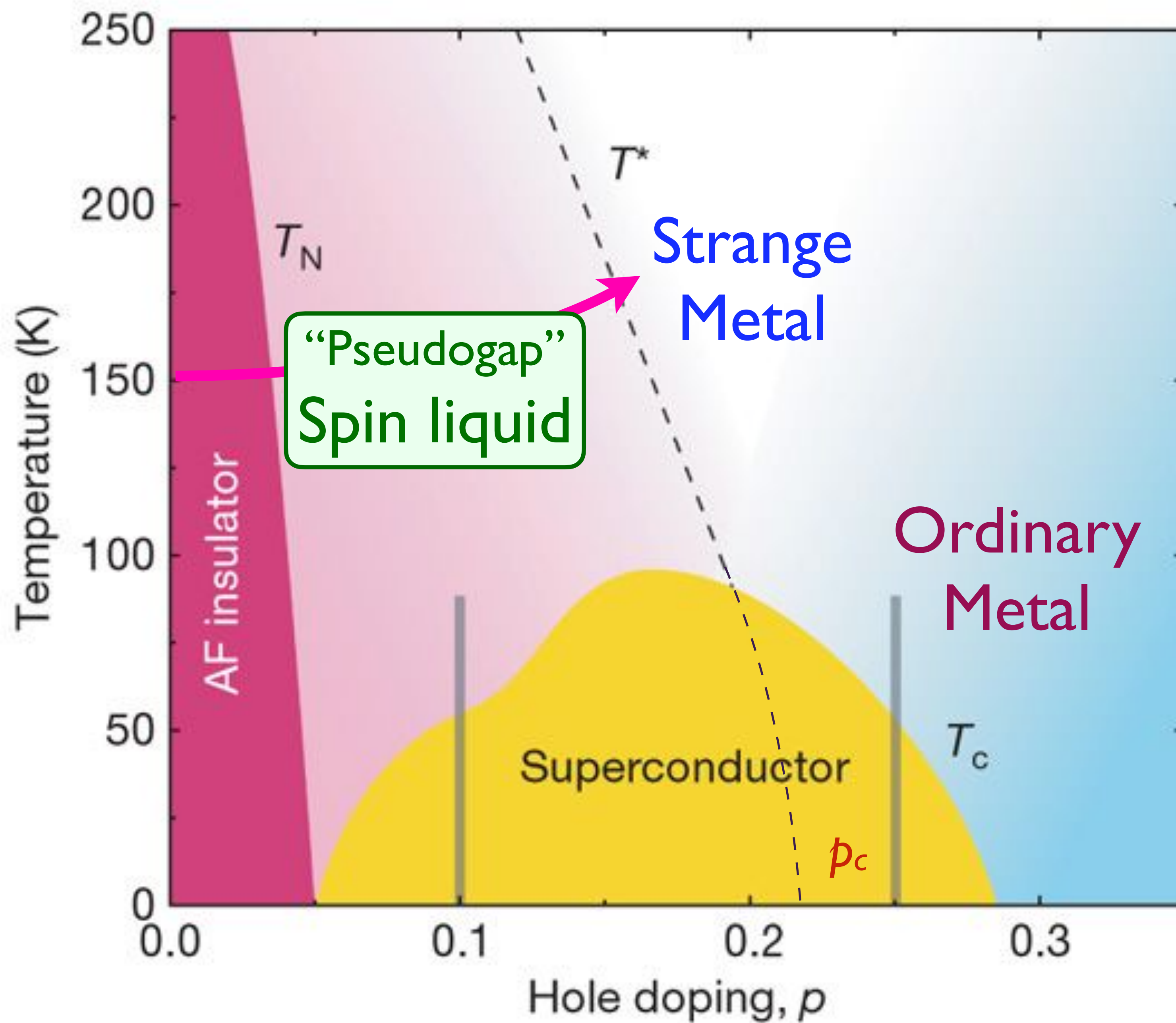


Superconductivity

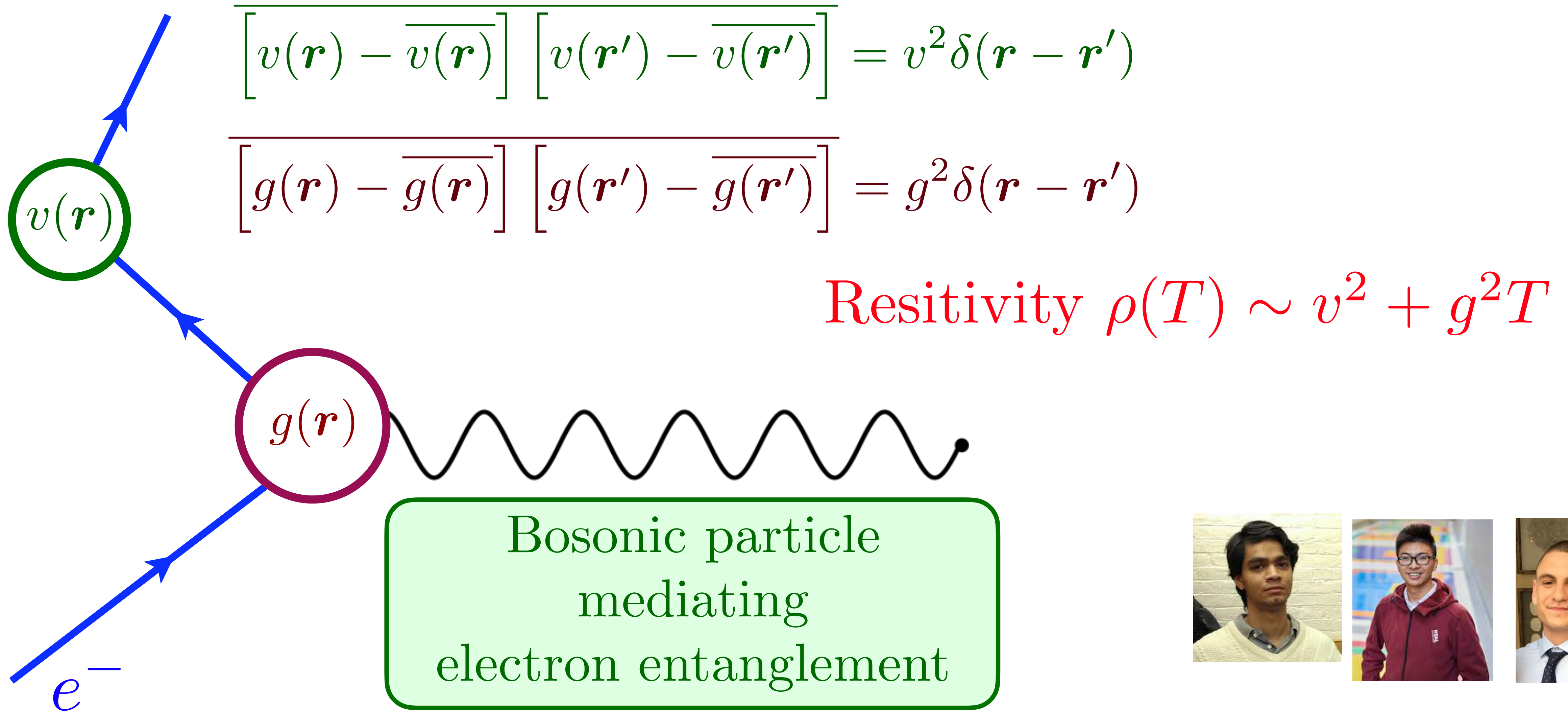
Mobile
entangled
electron pairs

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

From the SYK model
to a theory of
strange metals



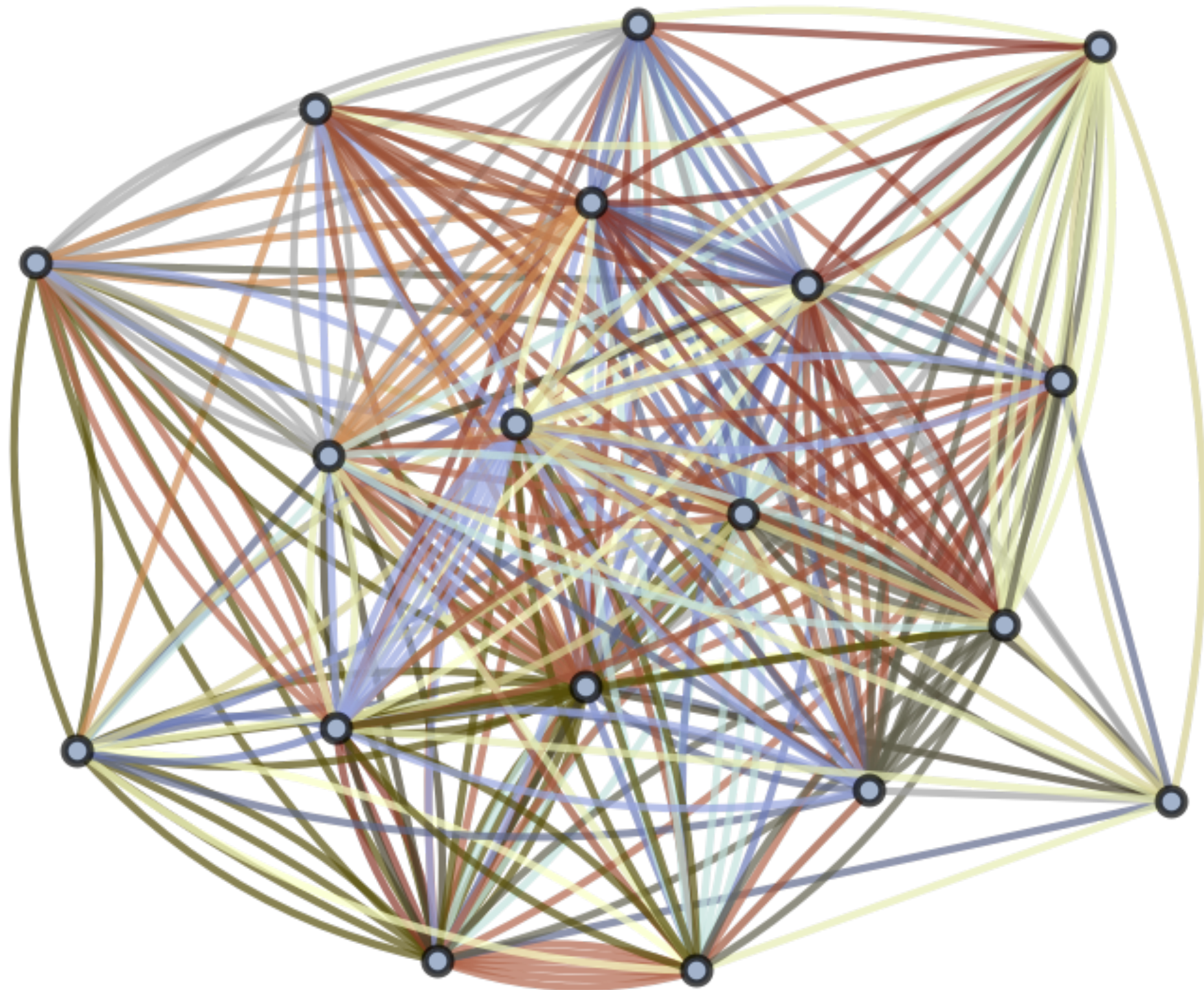
The dance of electrons on Cu atoms in YBCO



Recap

The Sachdev-Ye-Kitaev (SYK) model

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

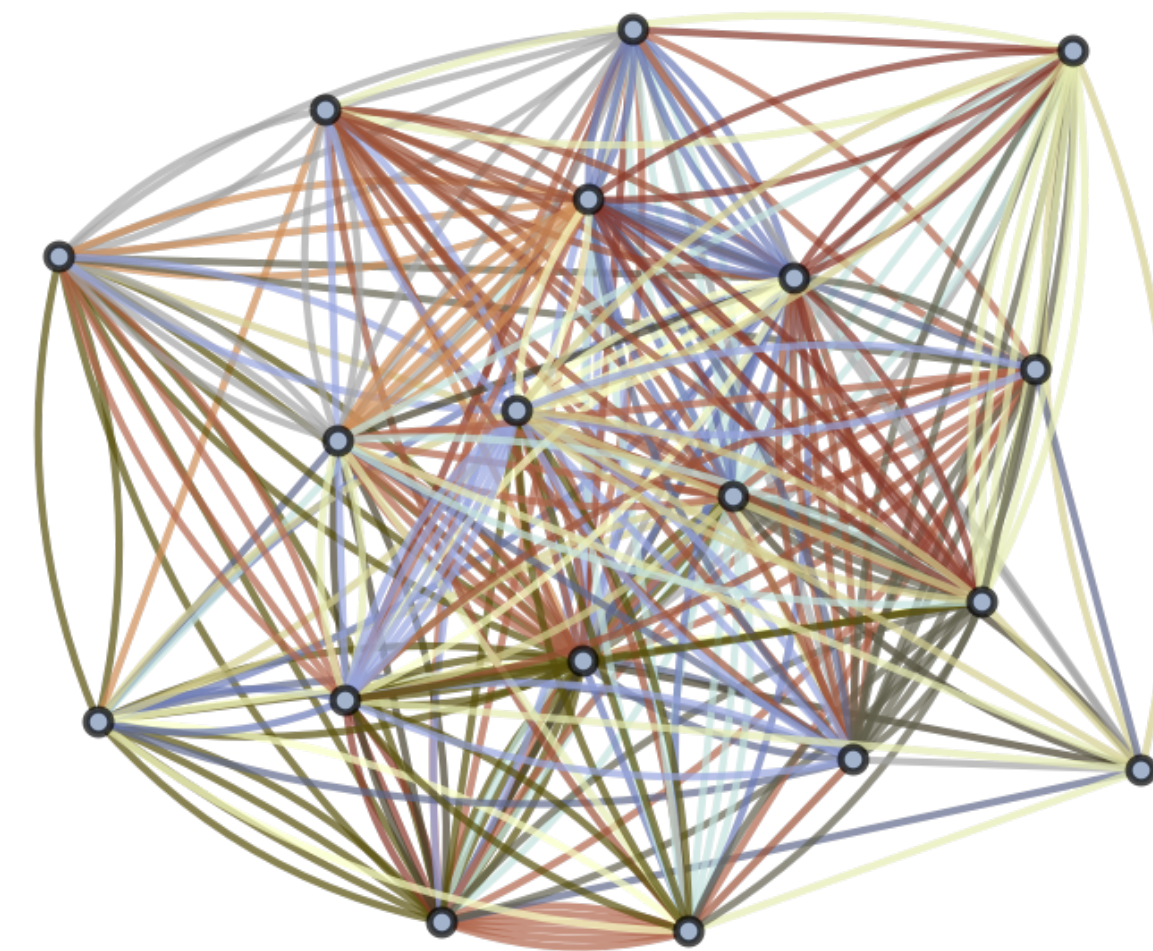
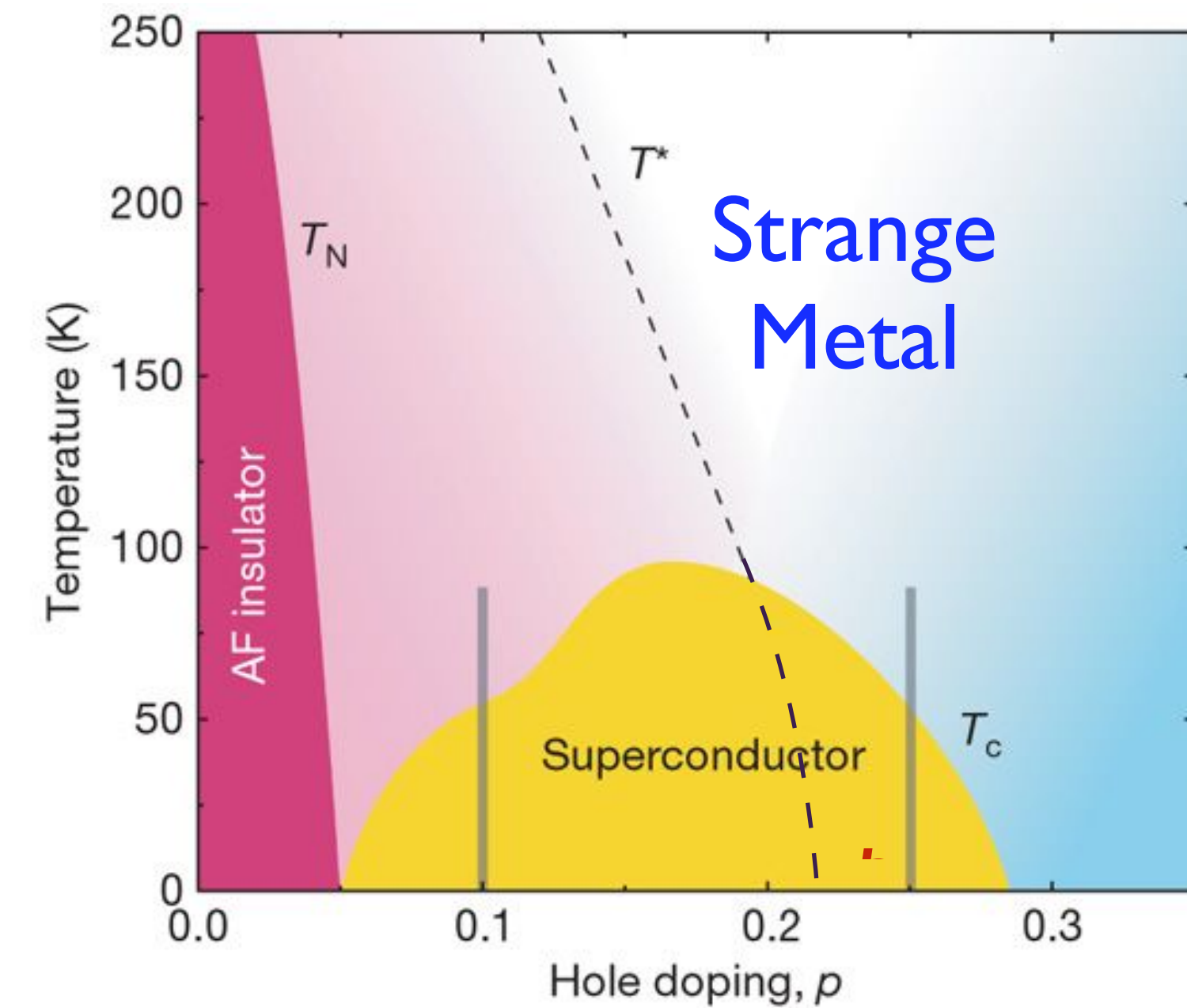


The Sachdev-Ye-Kitaev (SYK) model

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

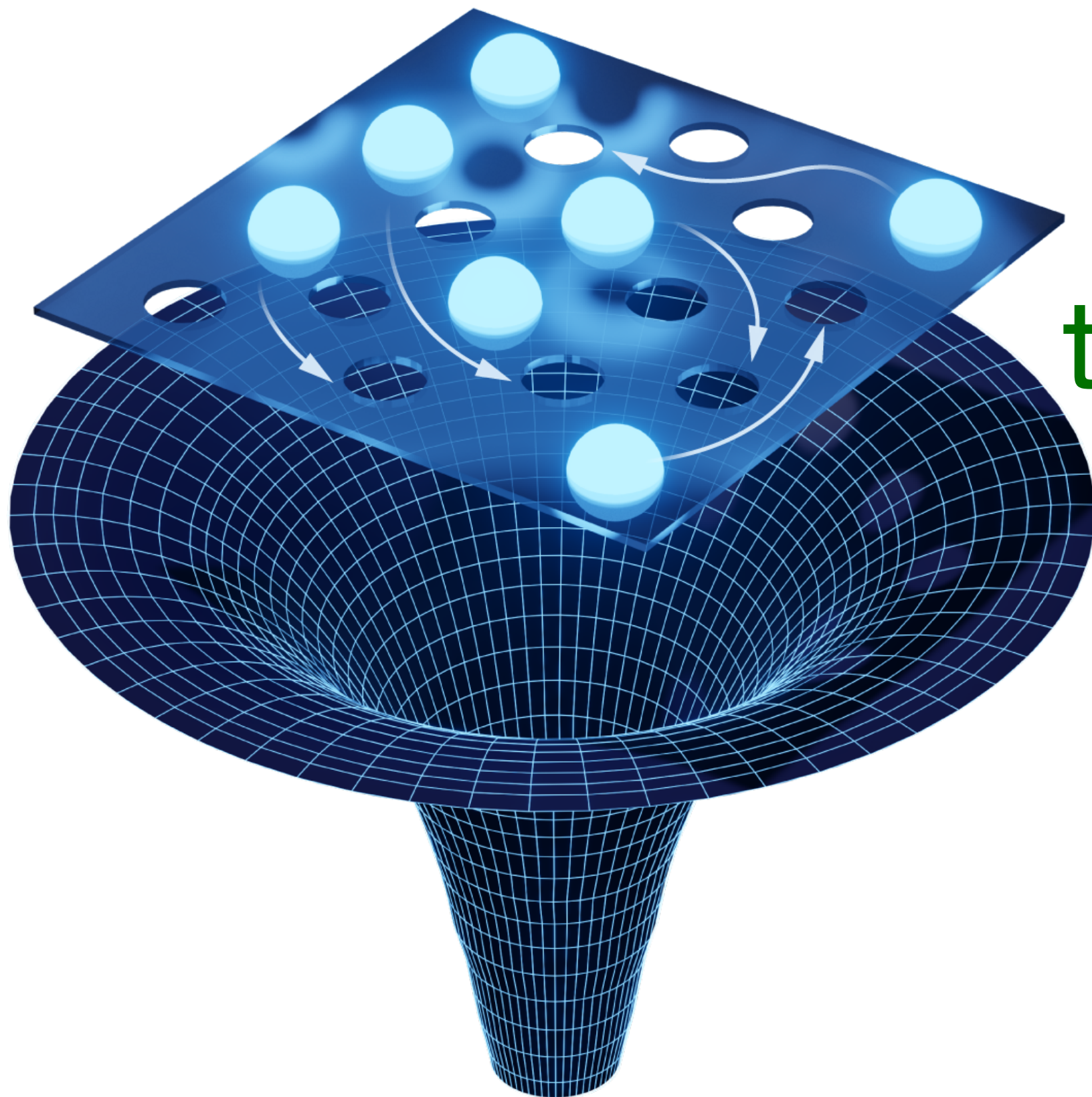
In one set of variables, it helps describe the *strange* electrical properties of YBCO

Sachdev, Ye (1993)



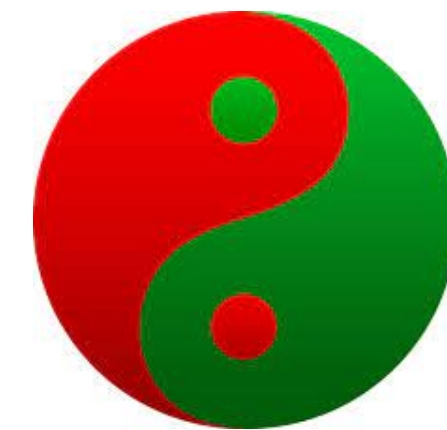
The Sachdev-Ye-Kitaev (SYK) model

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



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

Sachdev, Ye (1993)



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

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