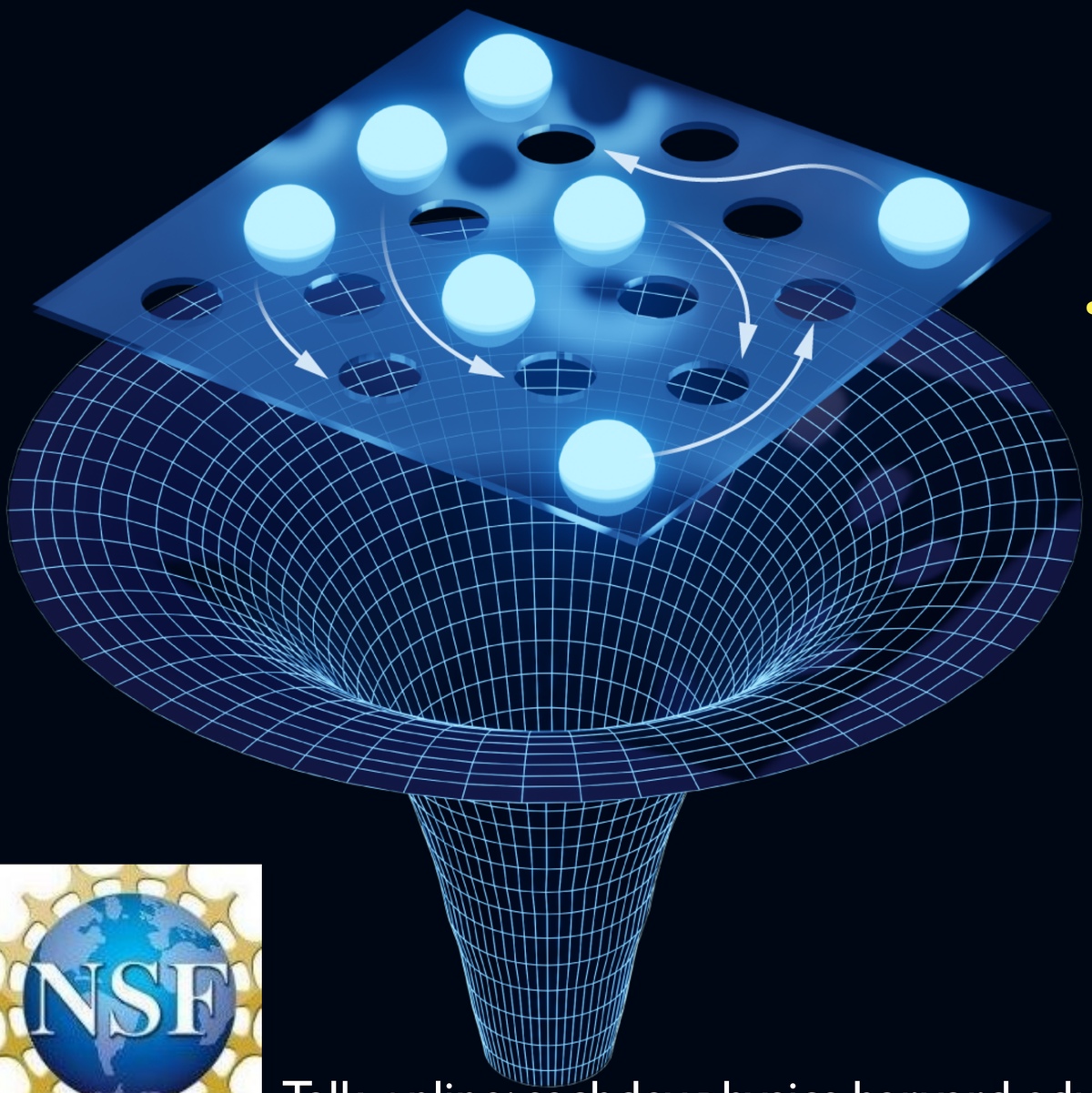


When nature entangles millions of particles: from quantum materials to black holes

Physics Club
IISER Tirupati
April 10, 2023

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
VE RI TAS
HARVARD

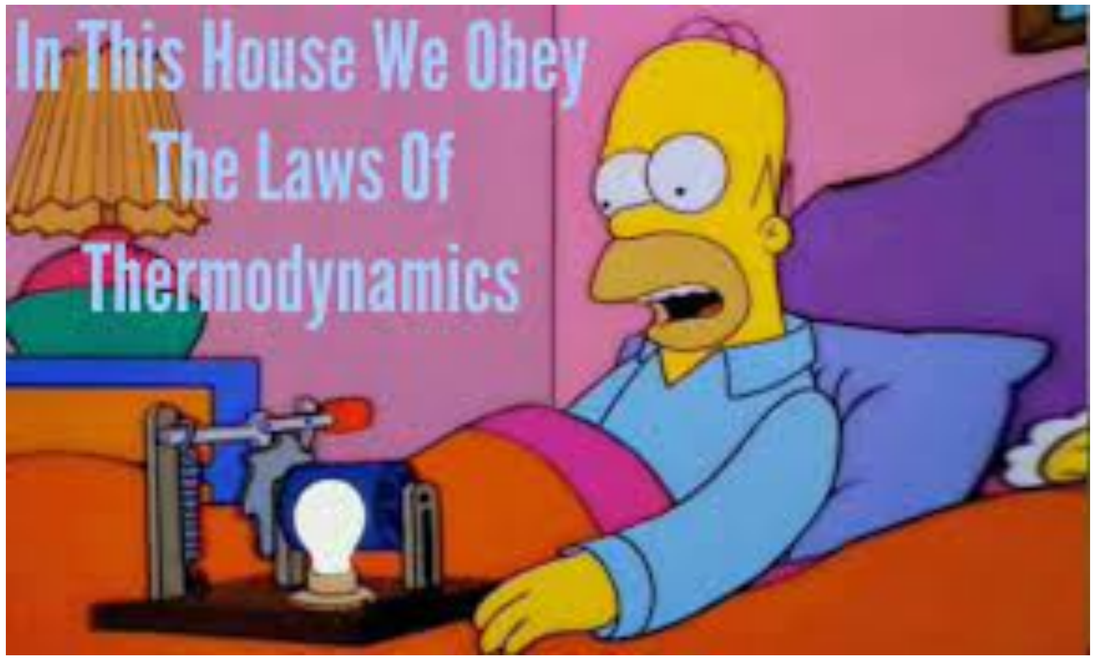
What is entropy and temperature ?

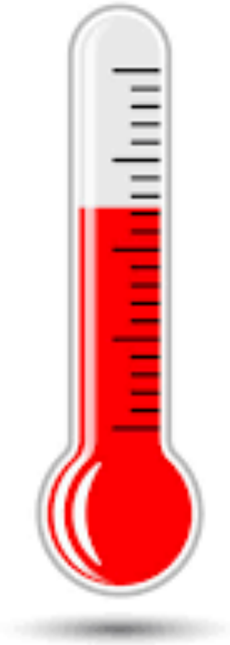
Clausius (1865):

Second Law of Thermodynamics:

Every macroscopic system has an “entropy” which cannot decrease.

➡ No perpetual motion machines!





Temperature

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

Statistical interpretation of entropy (1870)

$$S = k_B \log W$$

Density of quantum states $D(E)$

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

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Density of quantum states $D(E)$

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

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

What is quantum entanglement?

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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

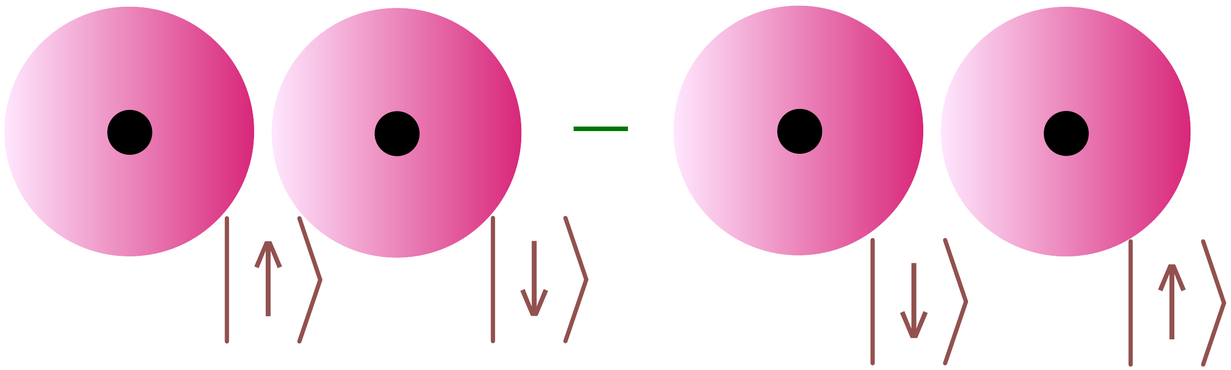
A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(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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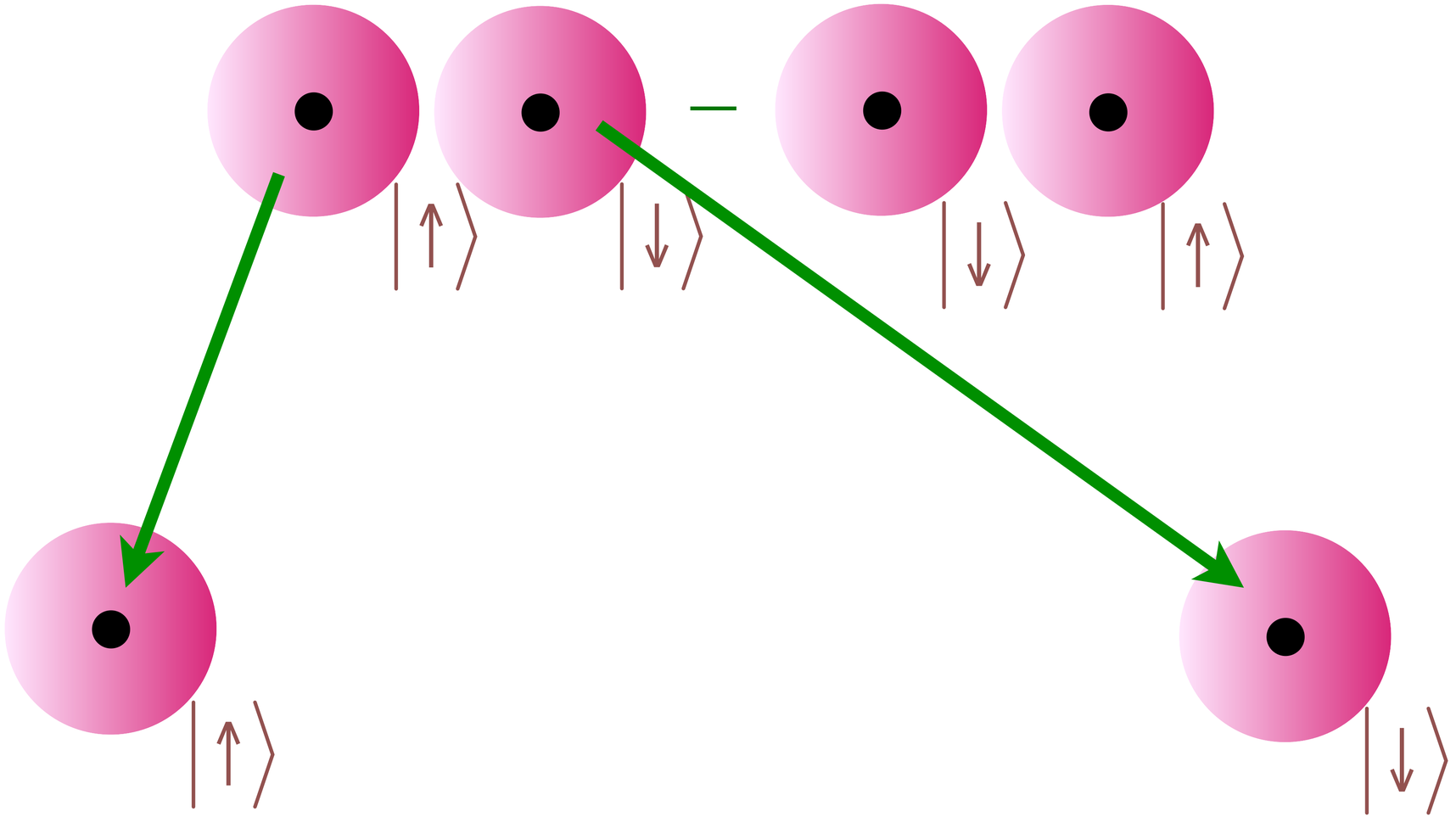

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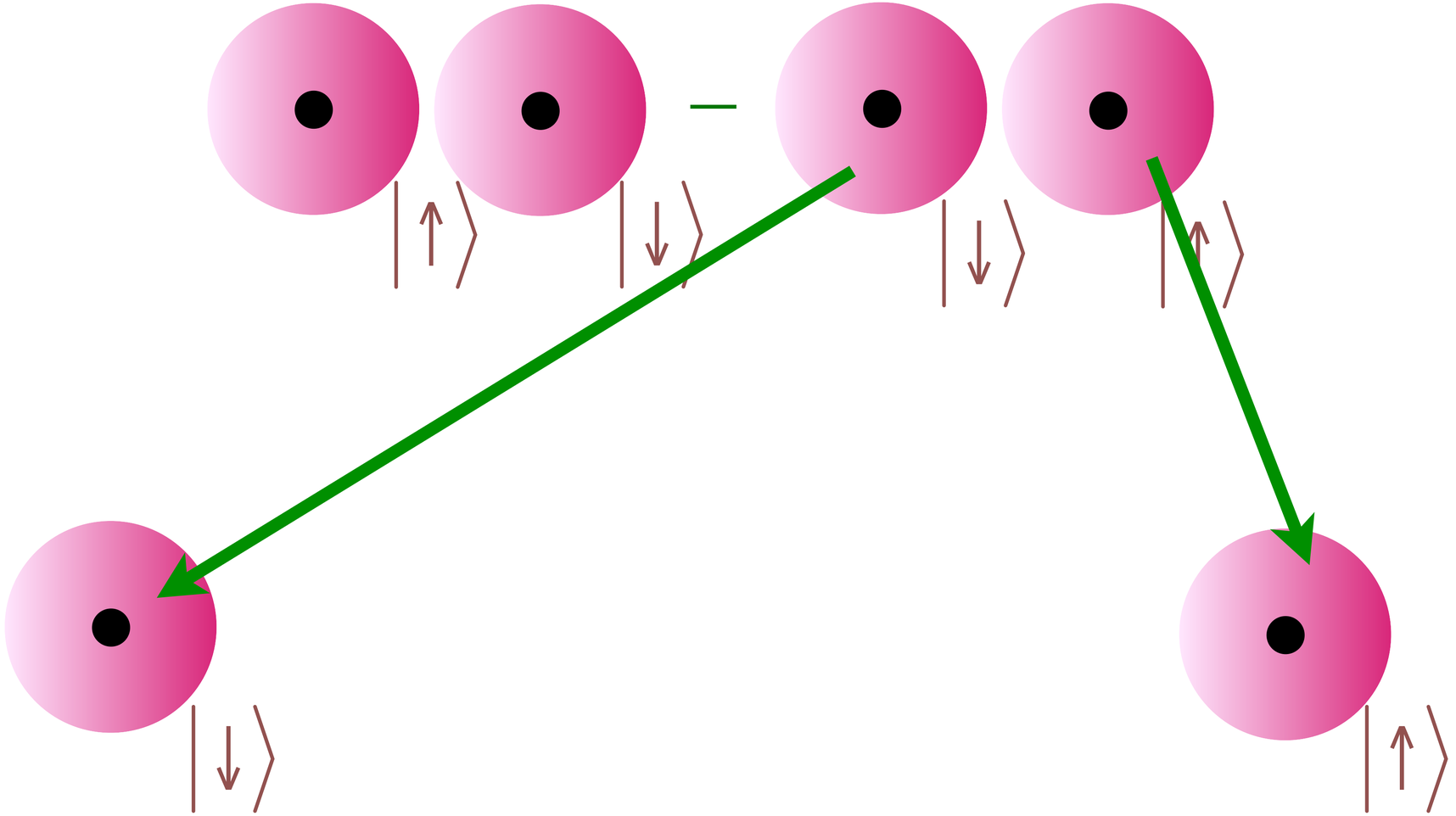

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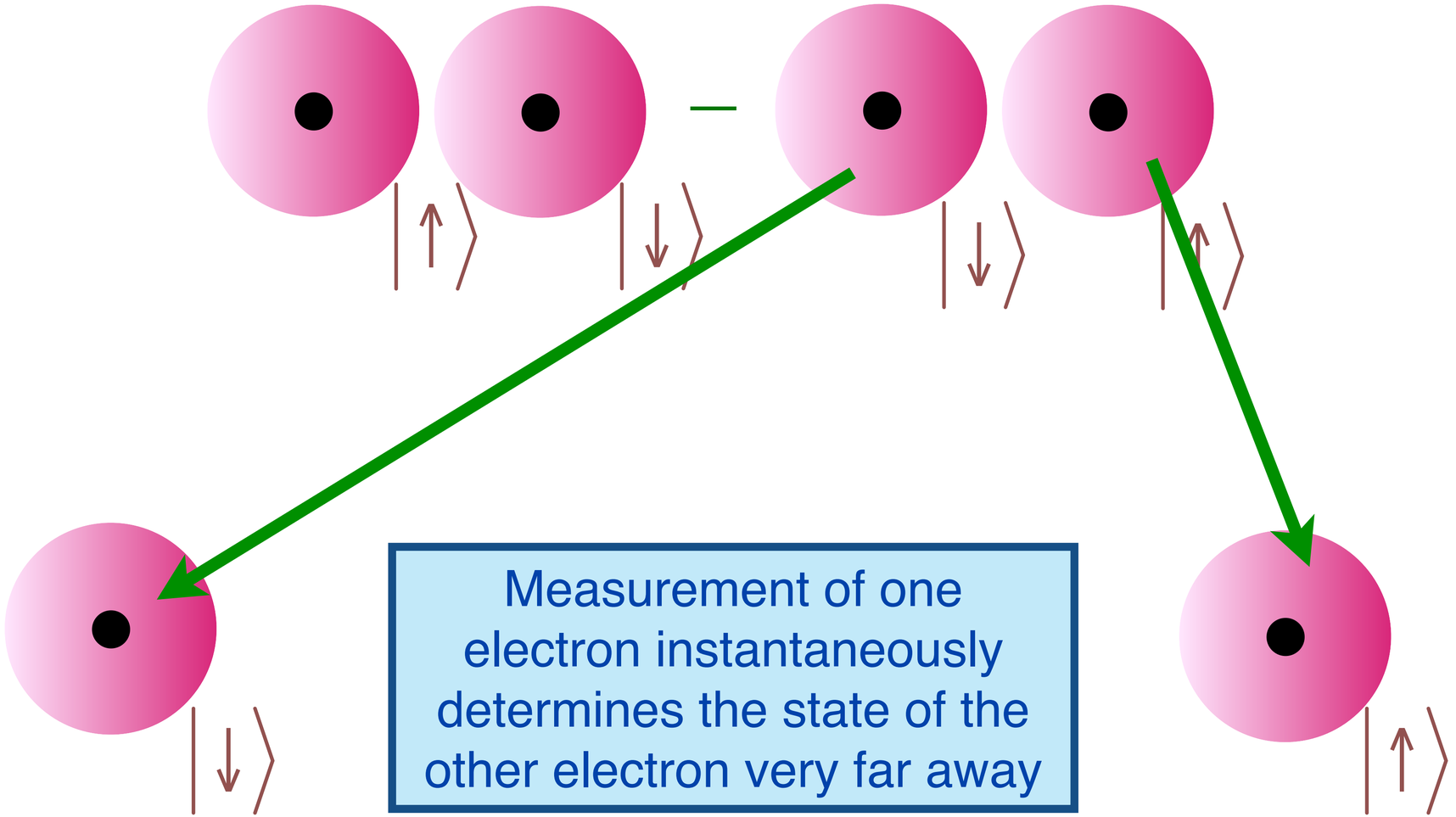

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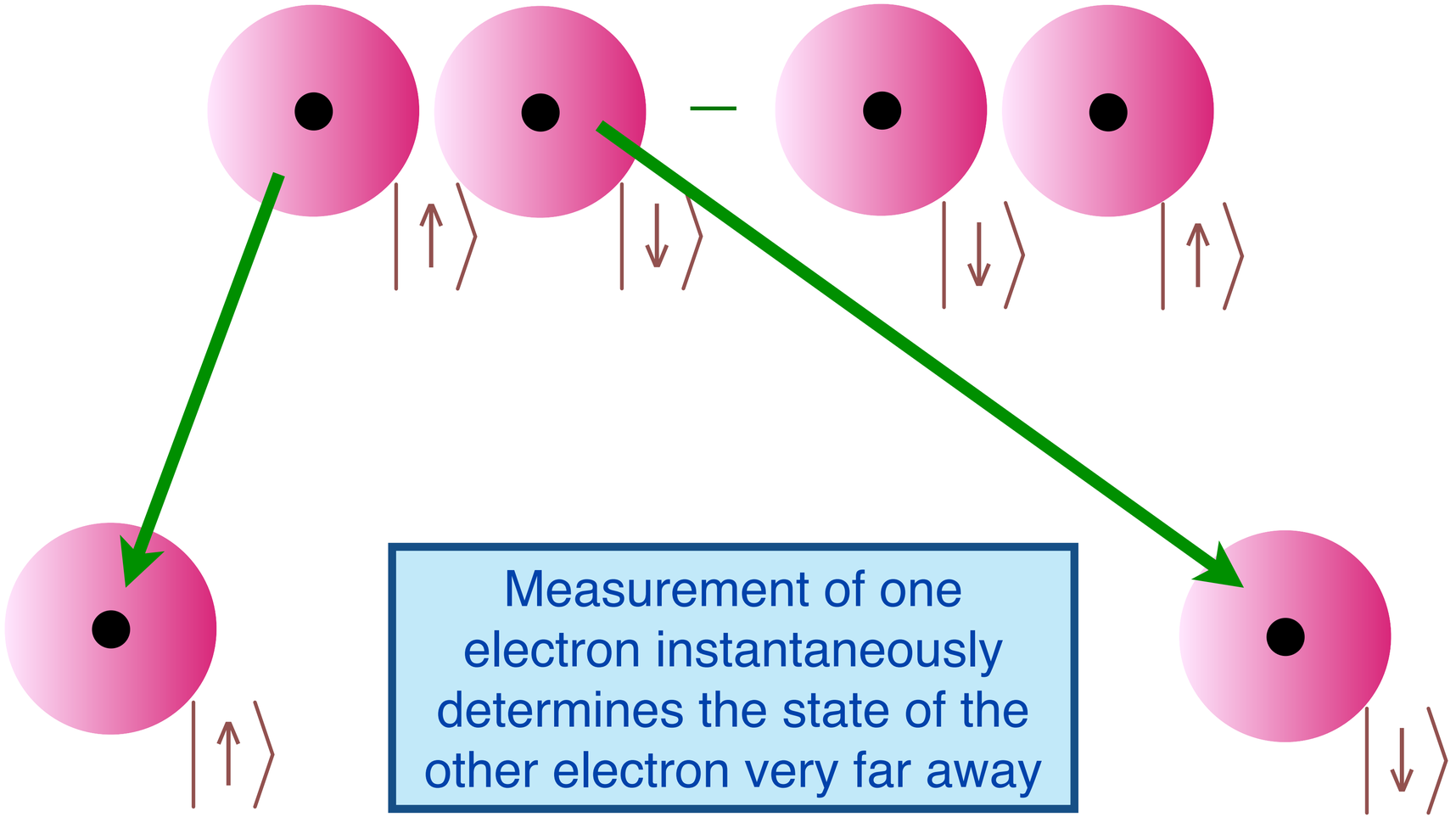

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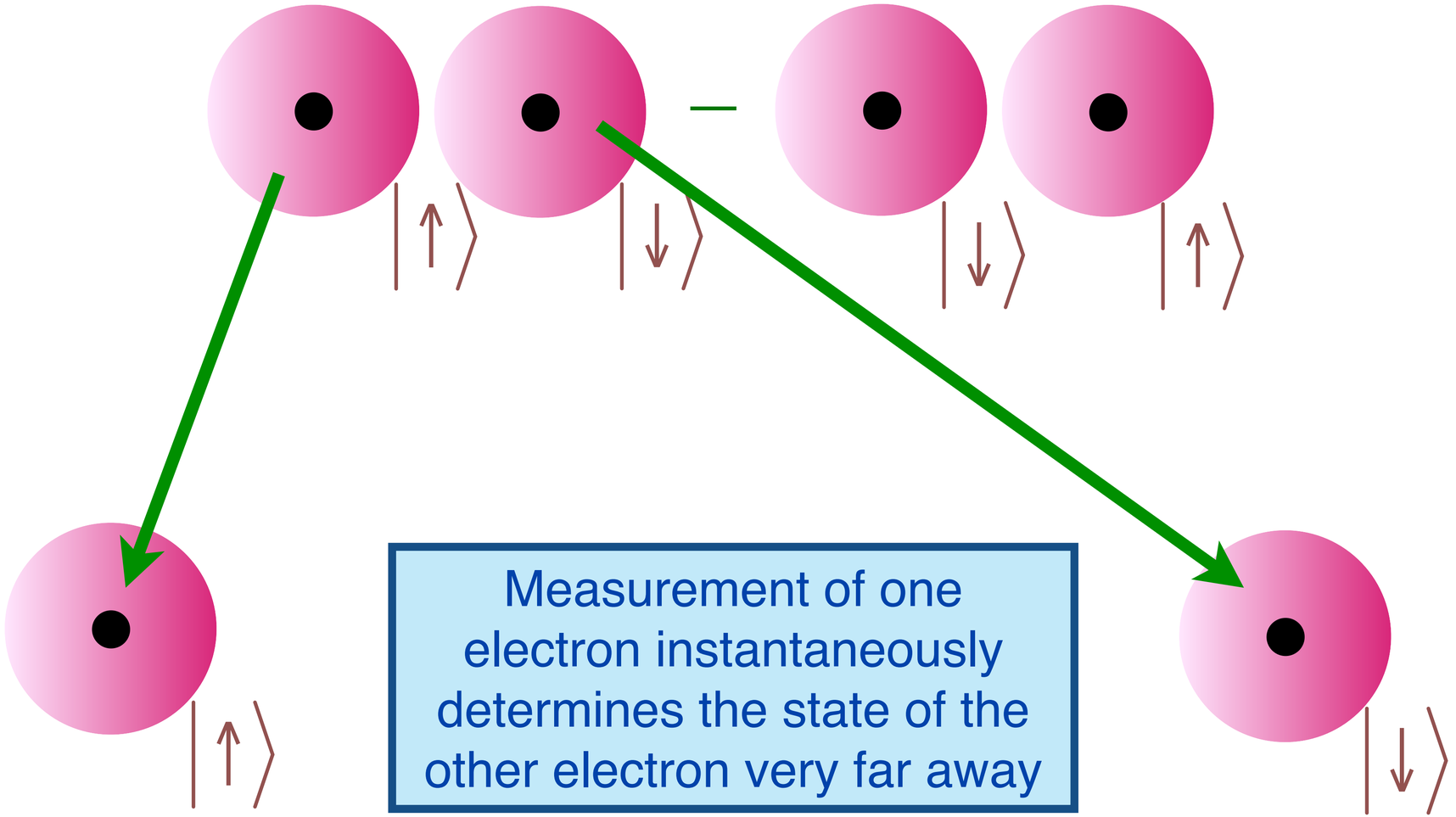
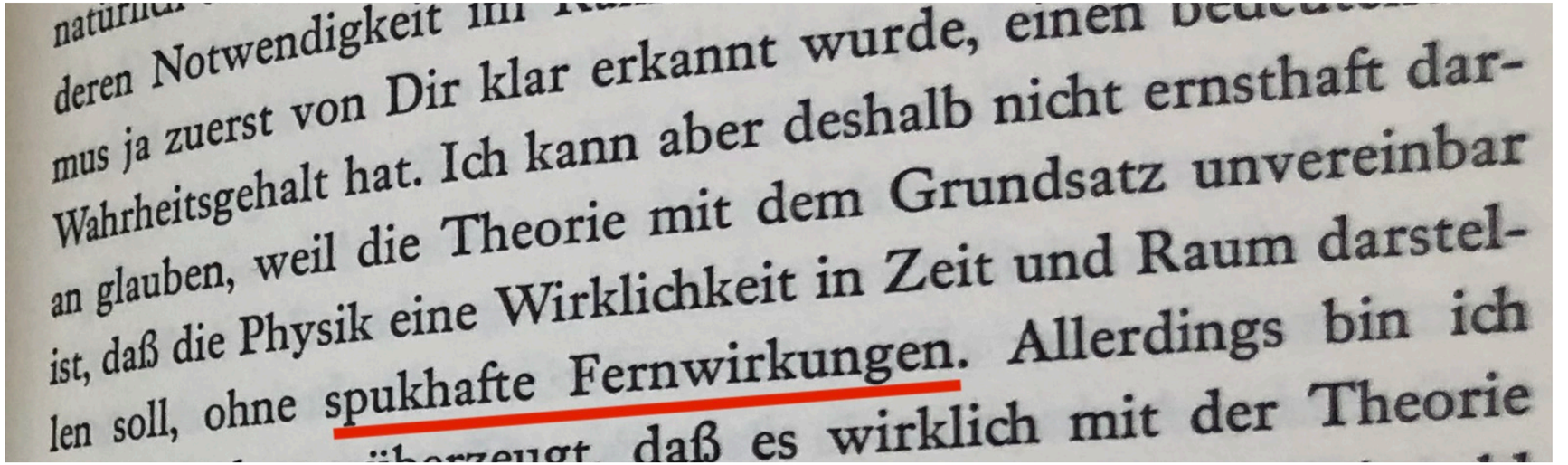


Spooky action at a distance !


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

amount of validity in the
recognise clearly as necessary given the framework
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
of doing 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

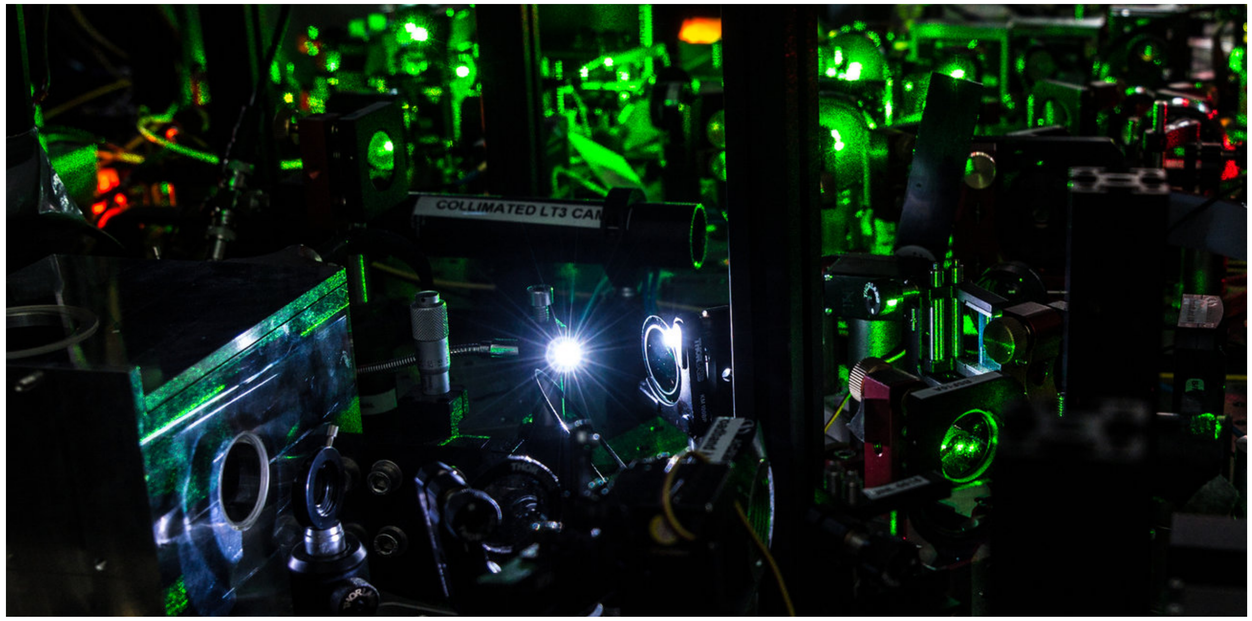
Albert Einstein to Max Born, 3 March 1947

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.



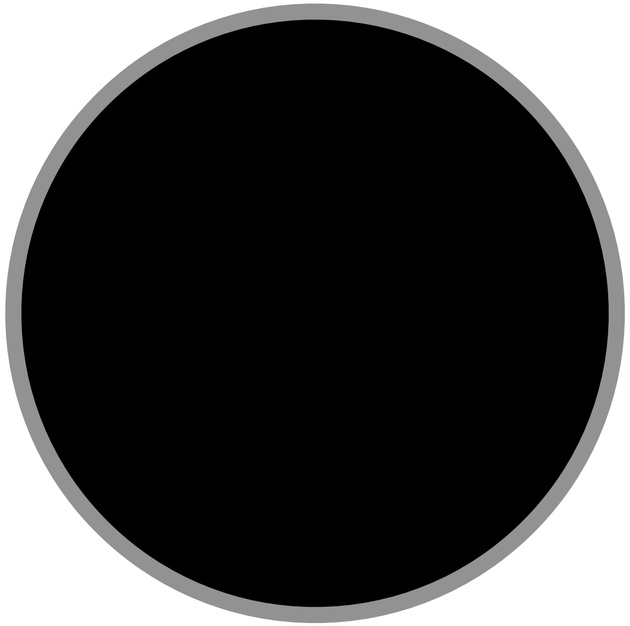
Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

Black holes

Black Holes

Objects so dense that light is gravitationally bound to them.

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



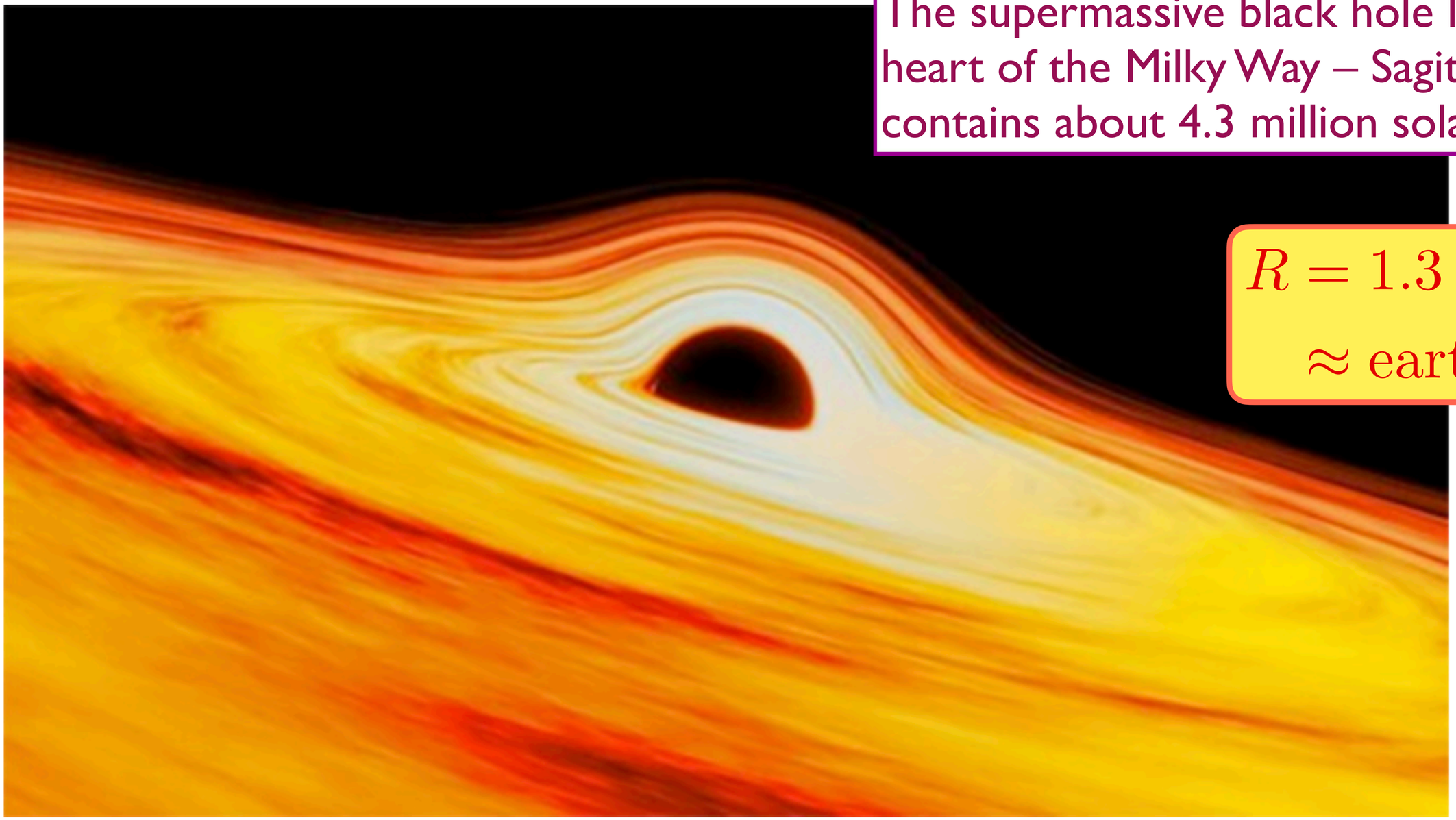
G Newton's constant, c velocity of light, M mass of black hole

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

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

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

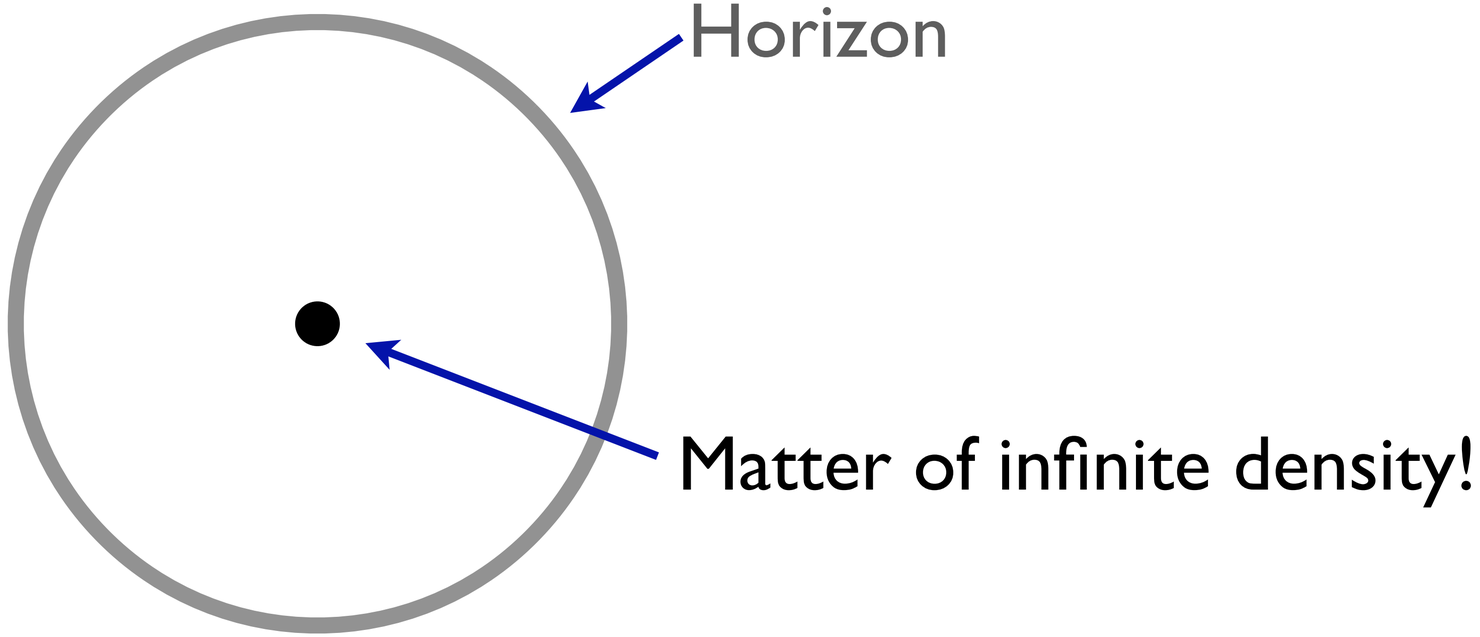
$$\approx \text{earth's orbit}$$



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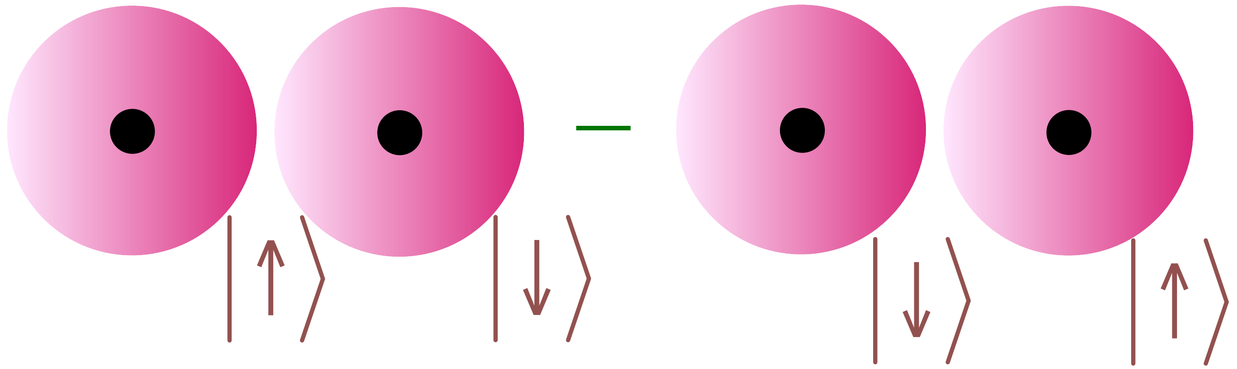
This singularity convinced many early on that black holes were unphysical solutions of Einstein's equations, and did not exist in our universe.

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



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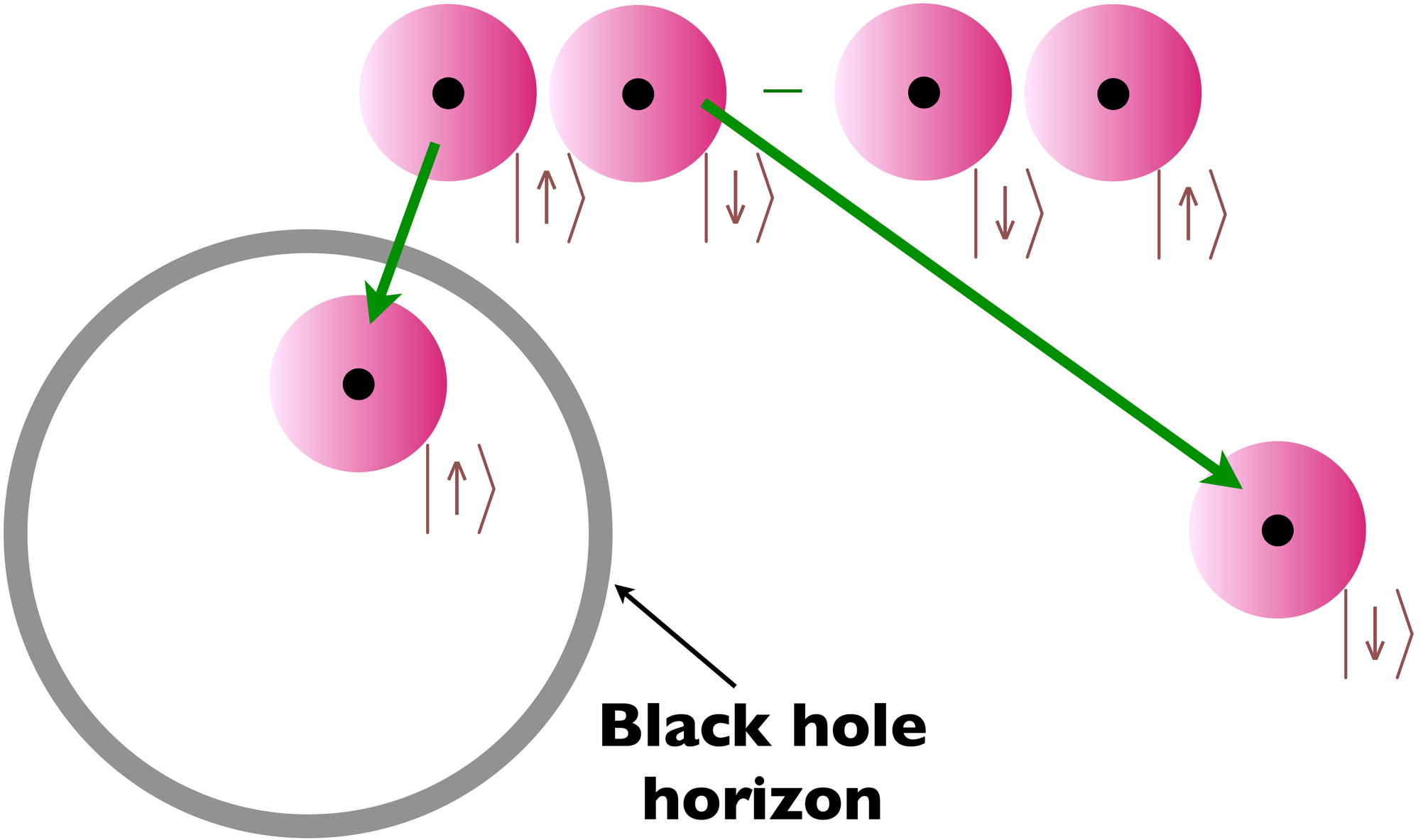

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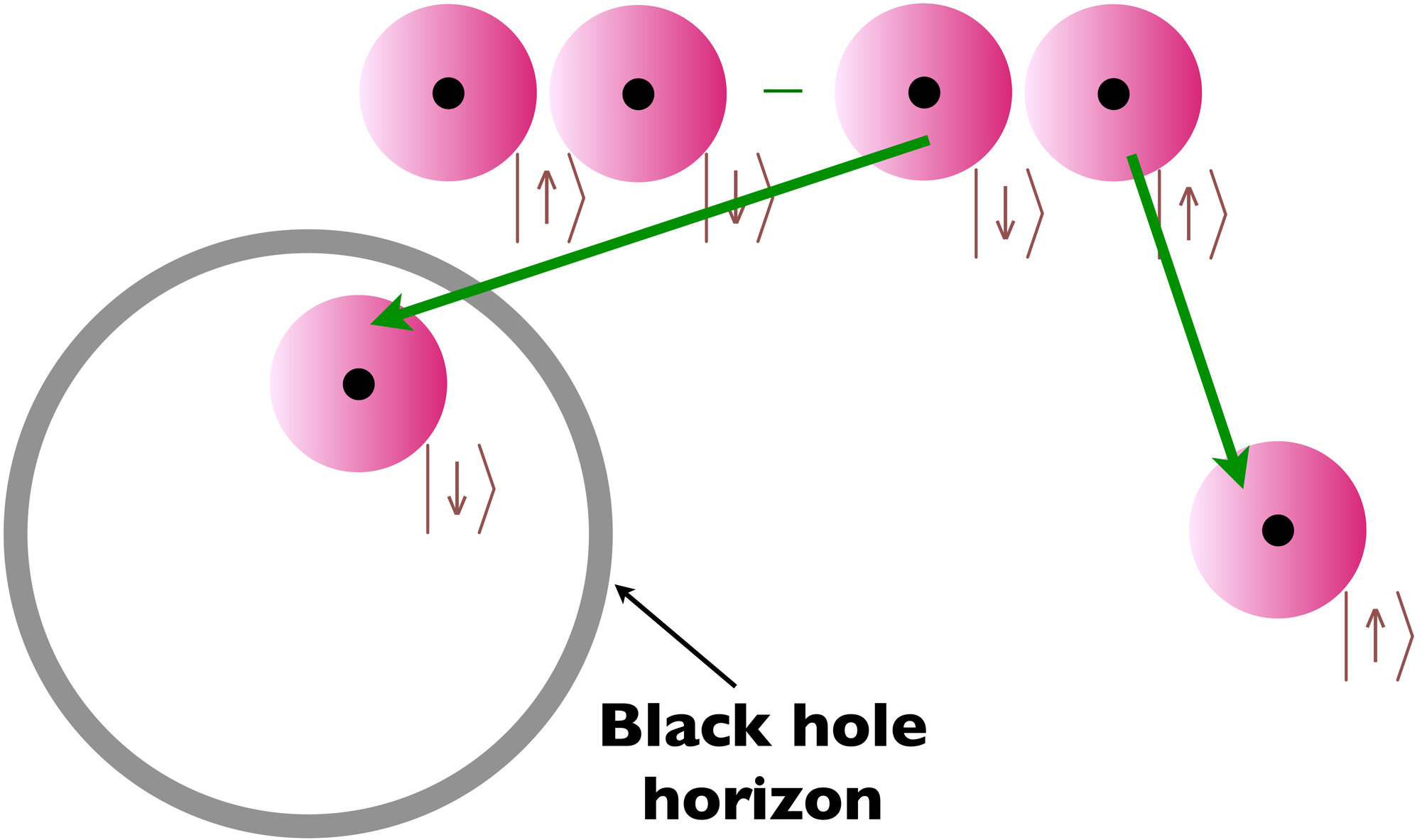
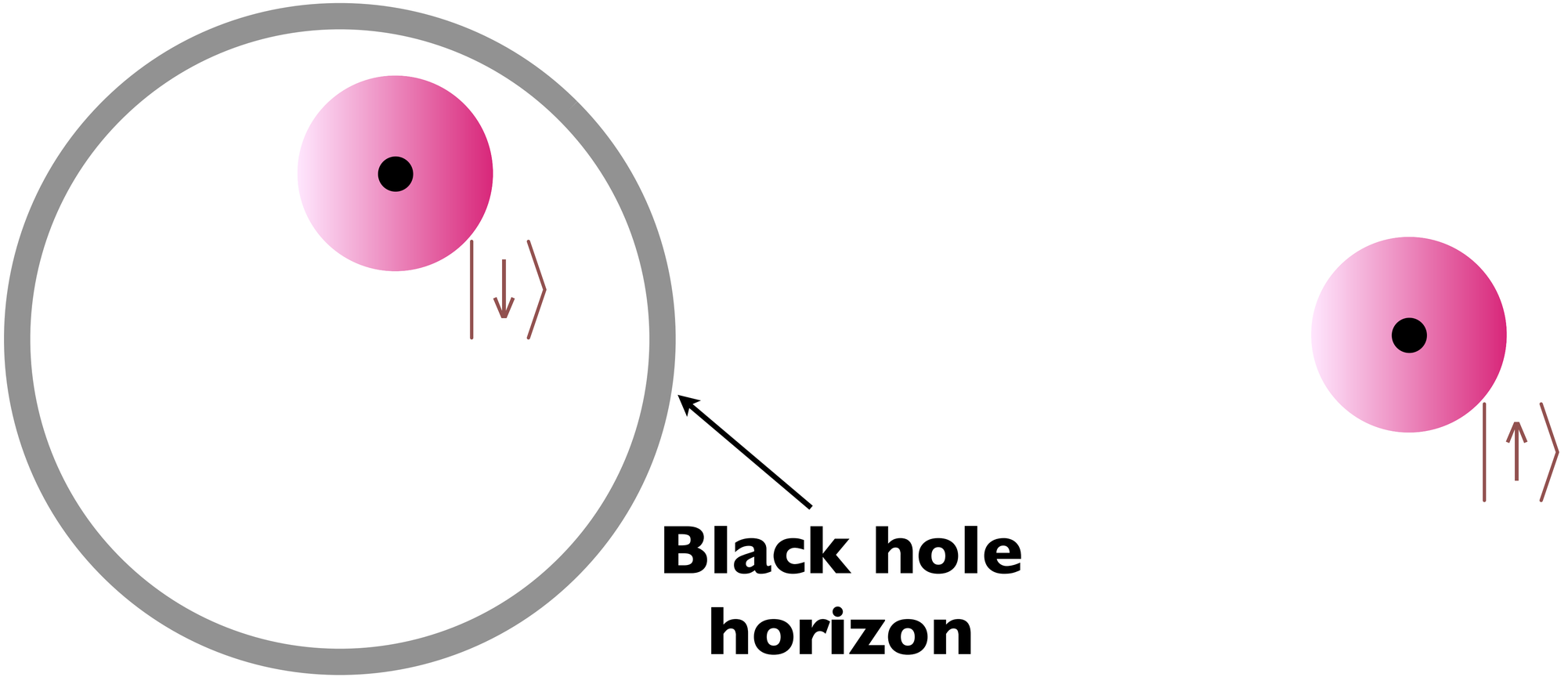


Quantum Entanglement across a black hole horizon

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



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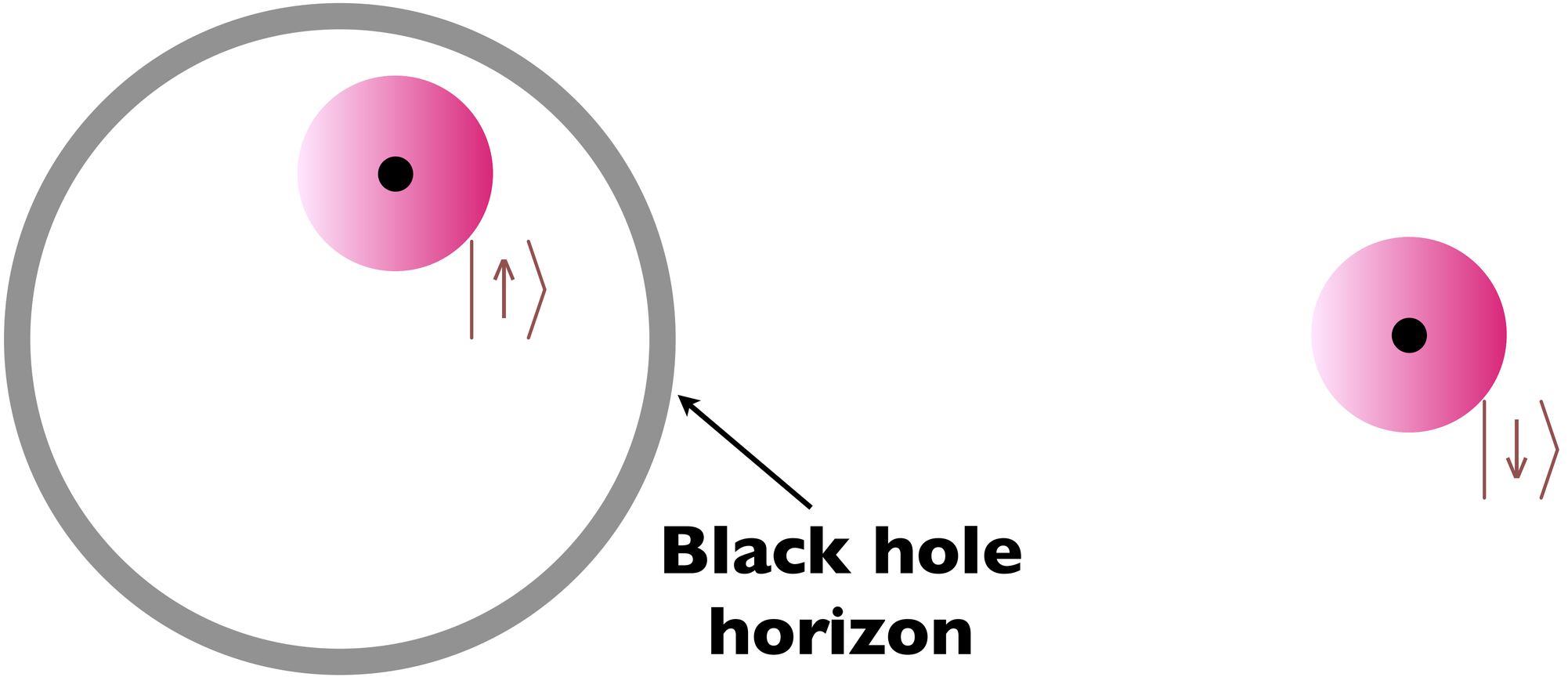
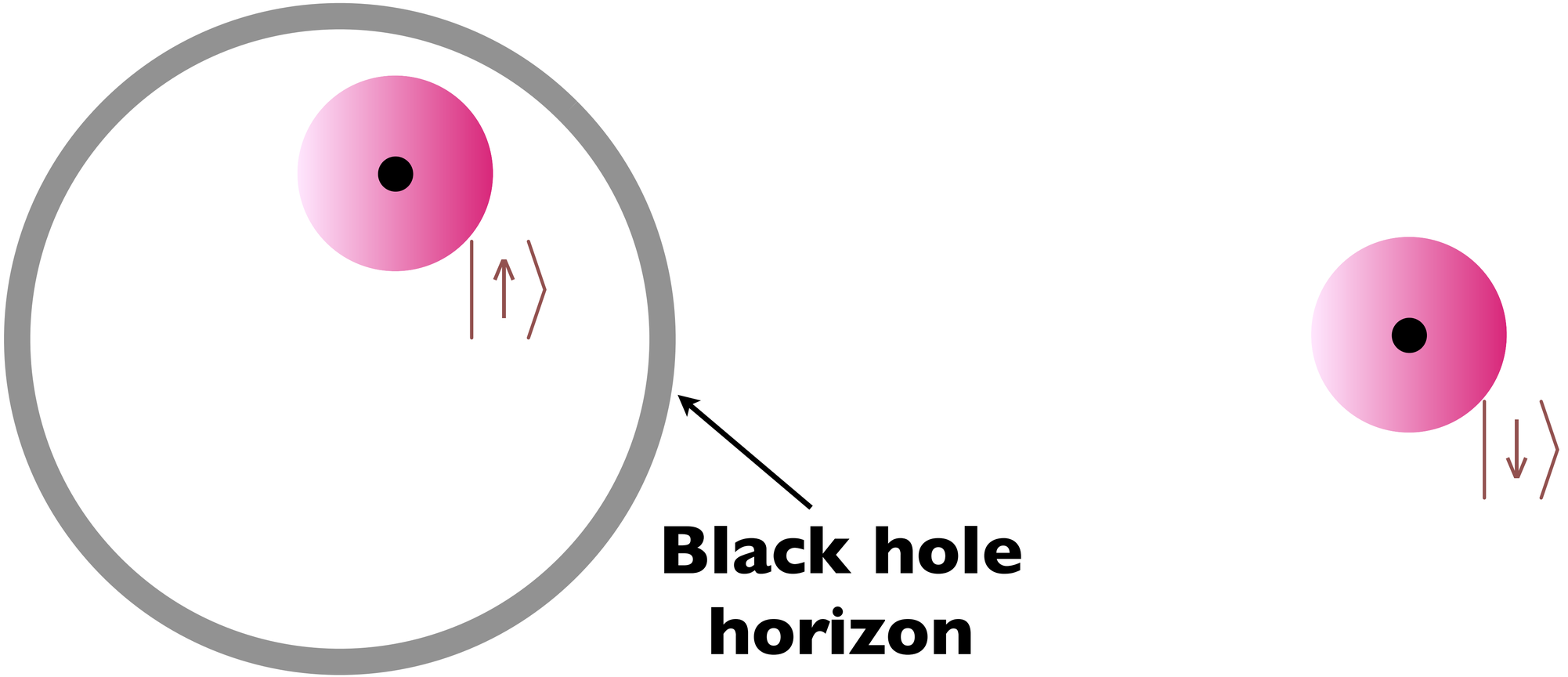


Quantum Entanglement across a black hole horizon

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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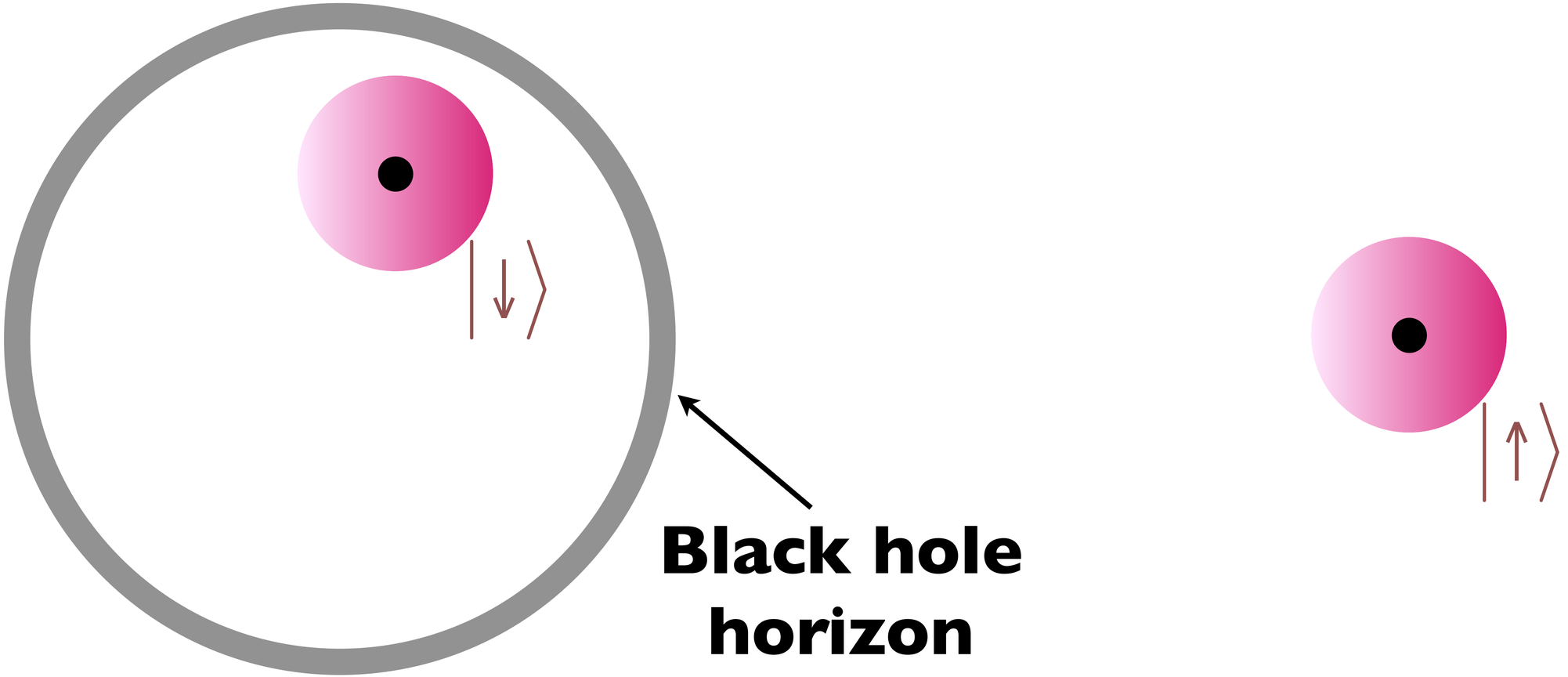
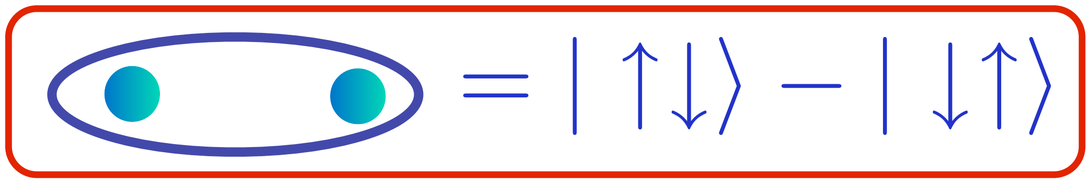
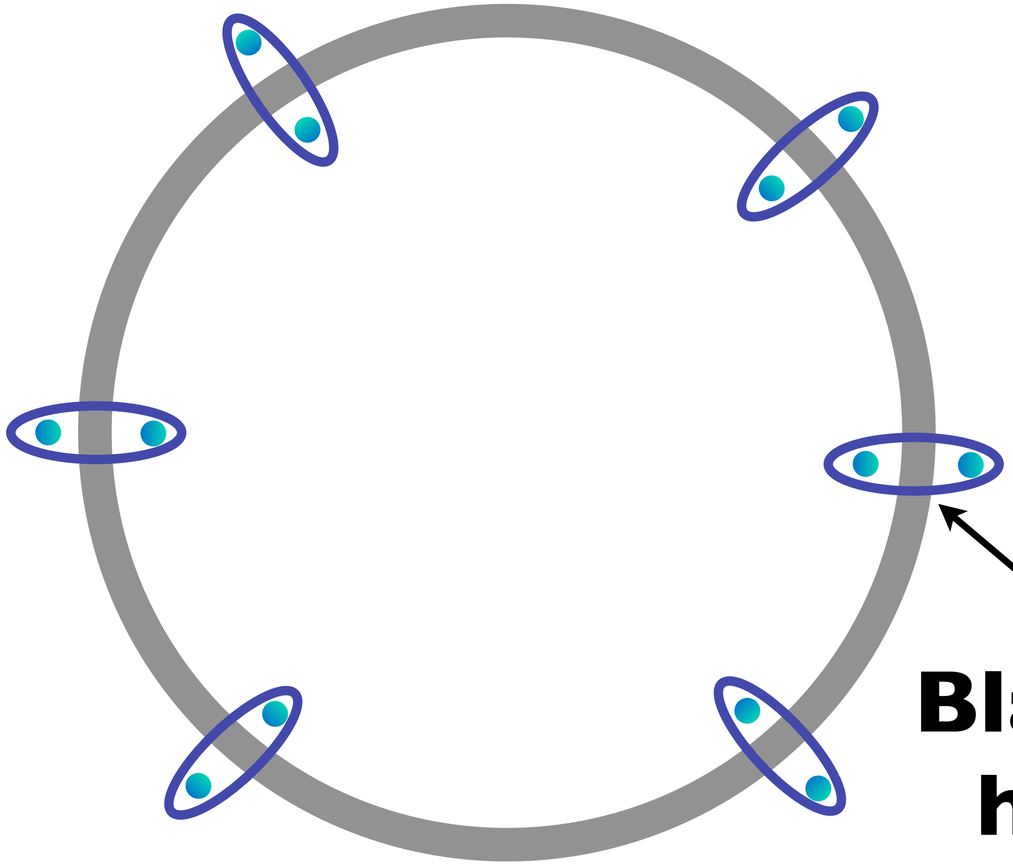


Quantum Entanglement across a black hole horizon

Quantum entanglement on the surface





Black hole horizon

By computations *outside* the black hole, Hawking obtained

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

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

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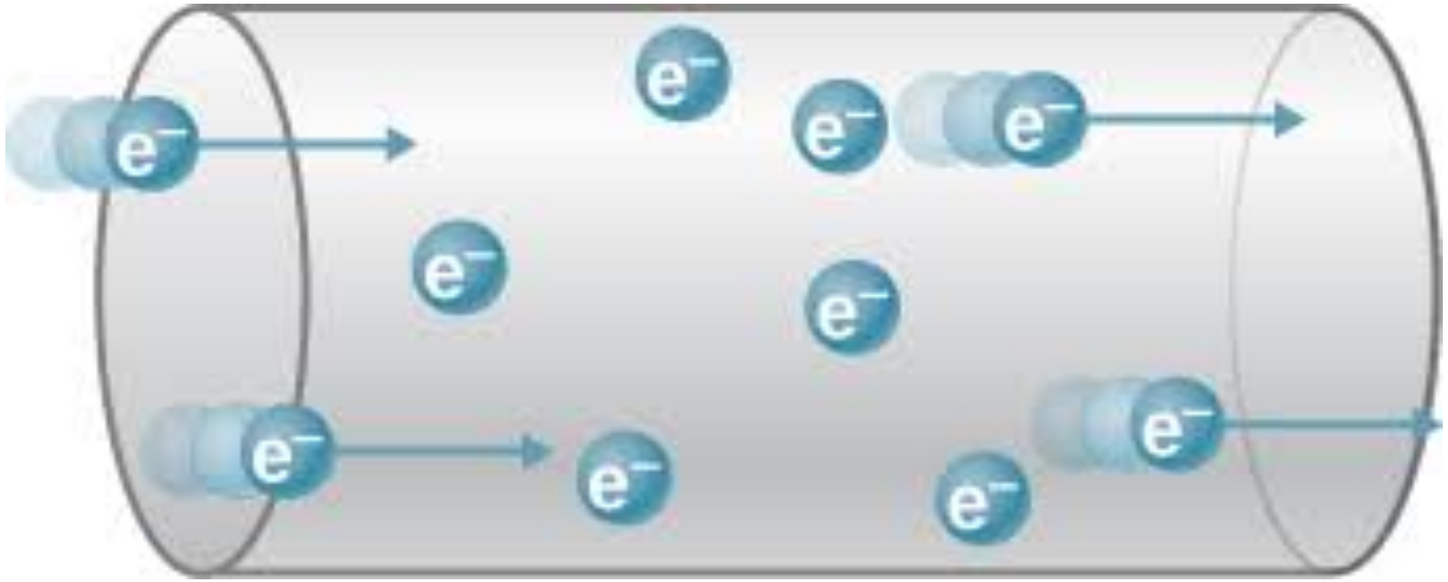
- Answer from string theory for 'supersymmetric' charged black holes: $D(E) = e^S \delta(E)$ *i.e.* all the states required by Hawking's entropy have exactly the same energy.

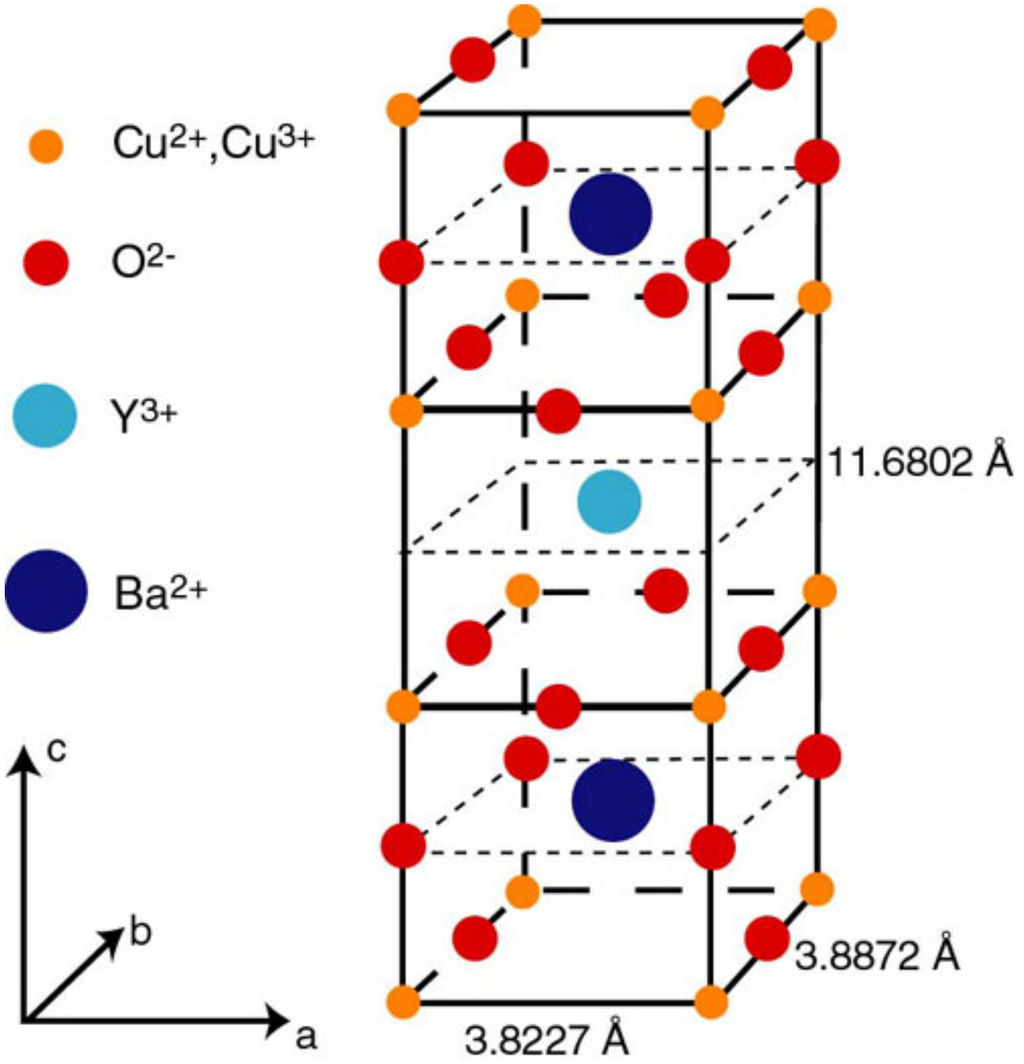
Strominger, Vafa (1996)

Quantum matter: ordinary metals, and strange metals

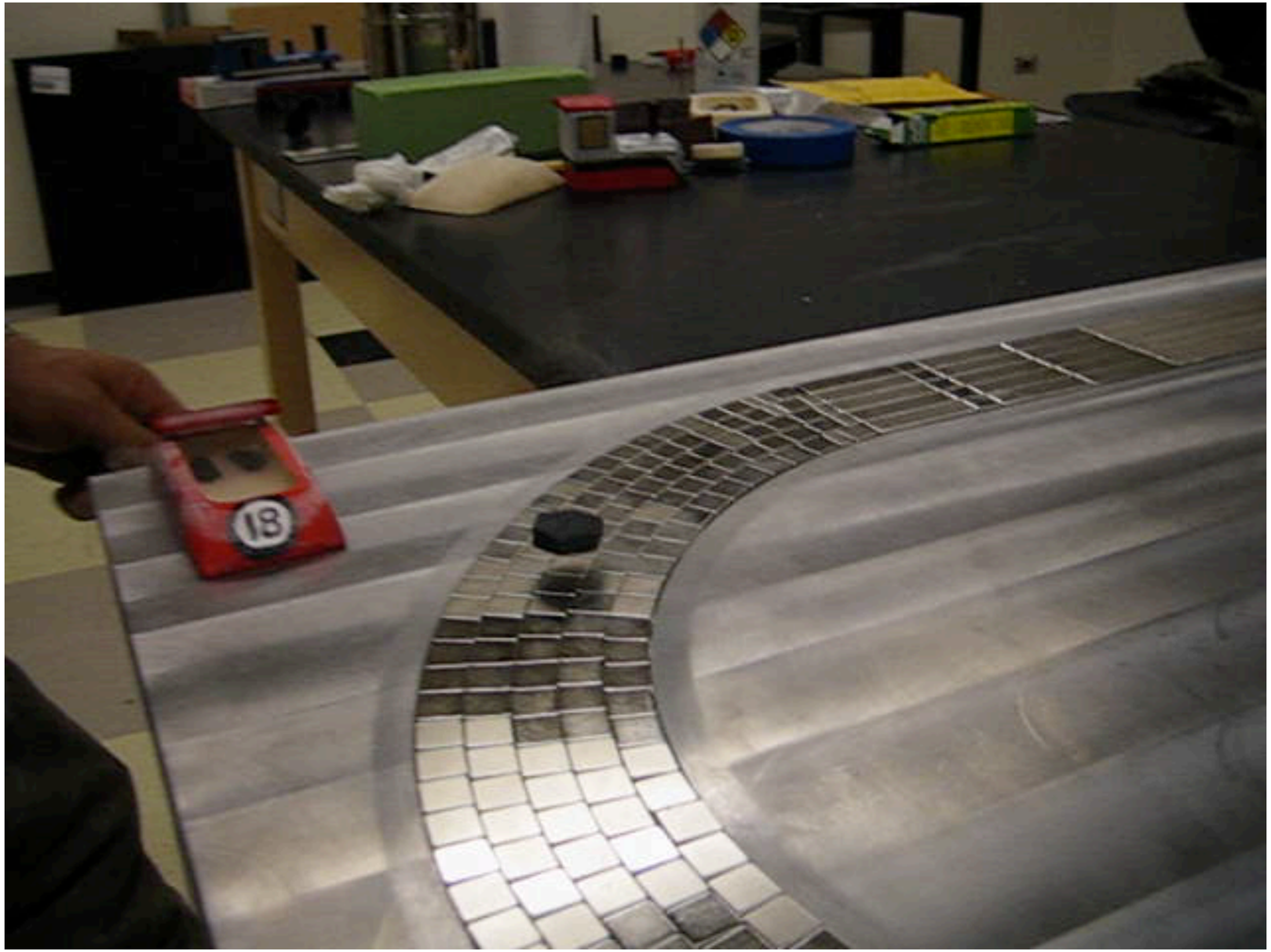
Copper: ordinary metal quantum matter



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

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

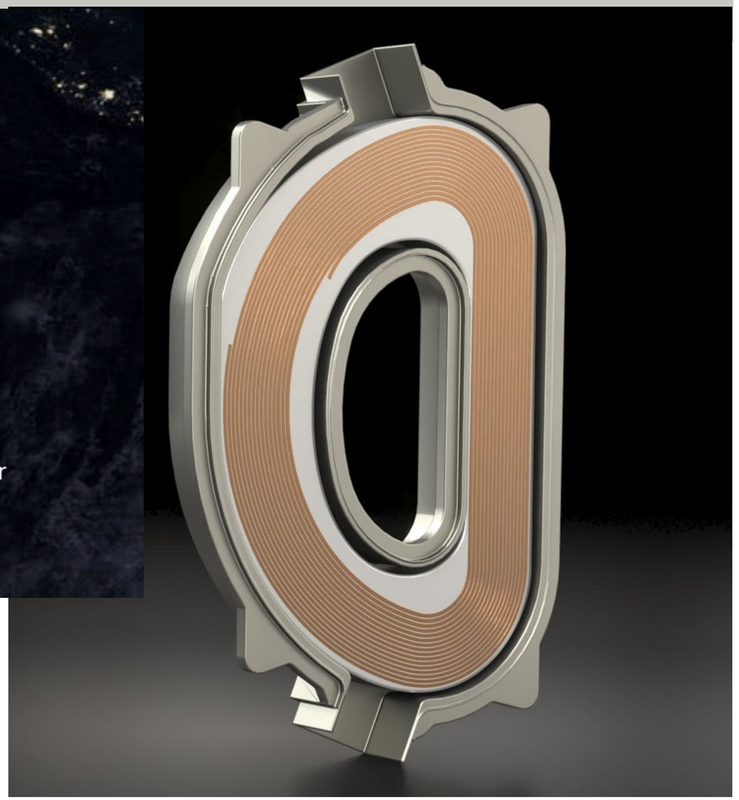
The fastest path to commercial fusion energy combining proven science with revolutionary magnet technology.

Limitless

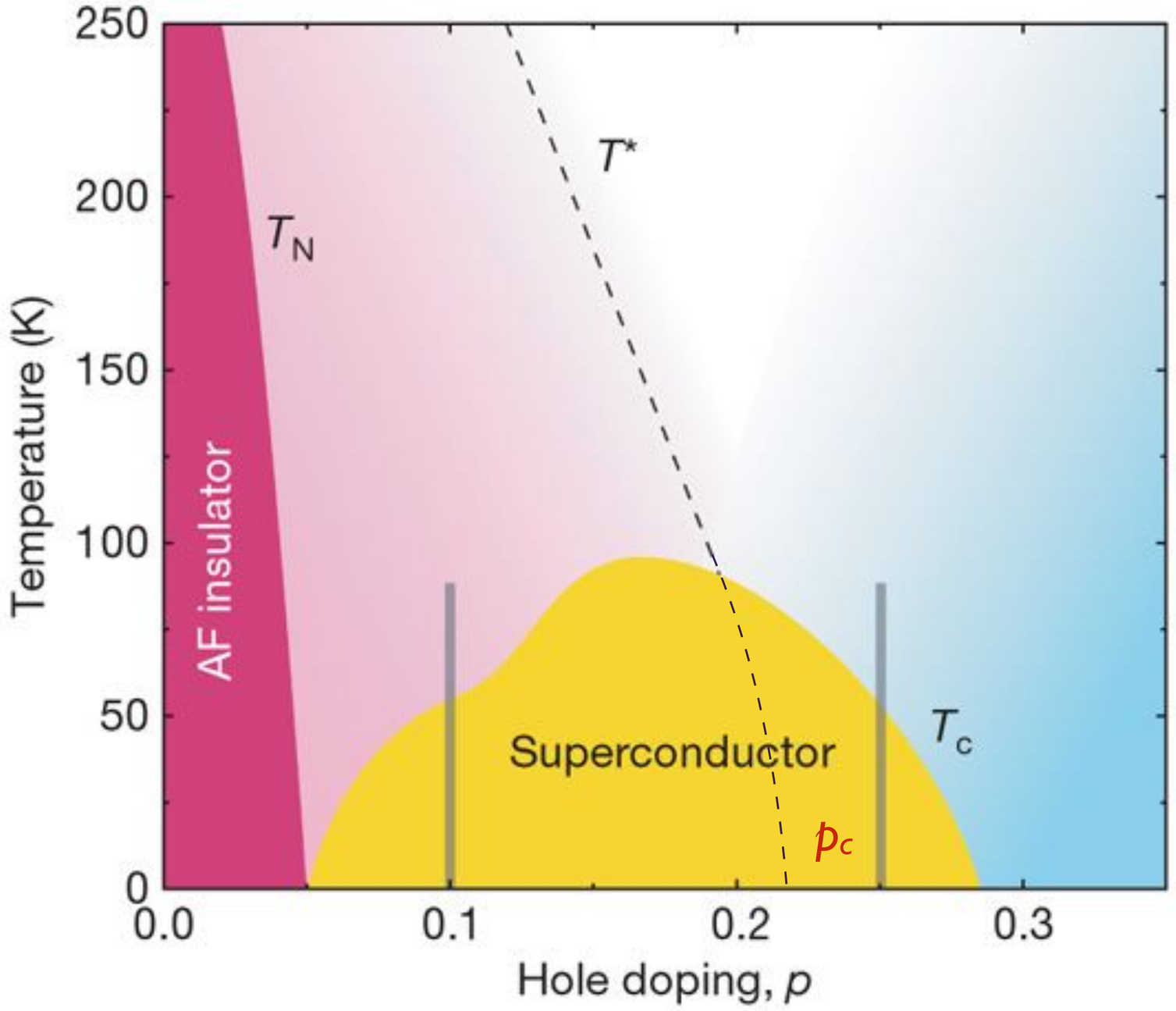
One glass of water will provide enough fusion fuel for one person's lifetime.

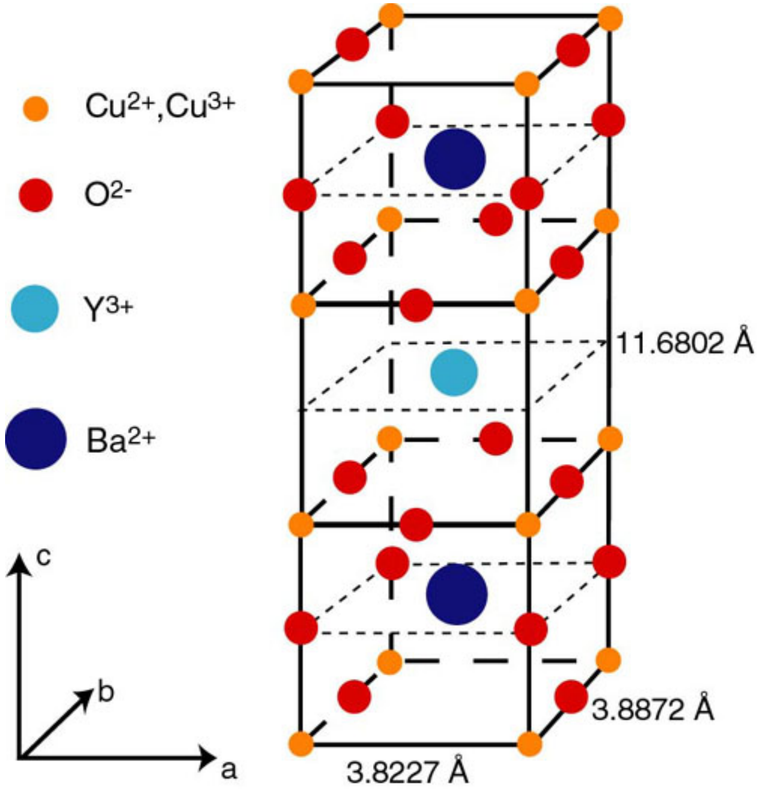
Clean

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

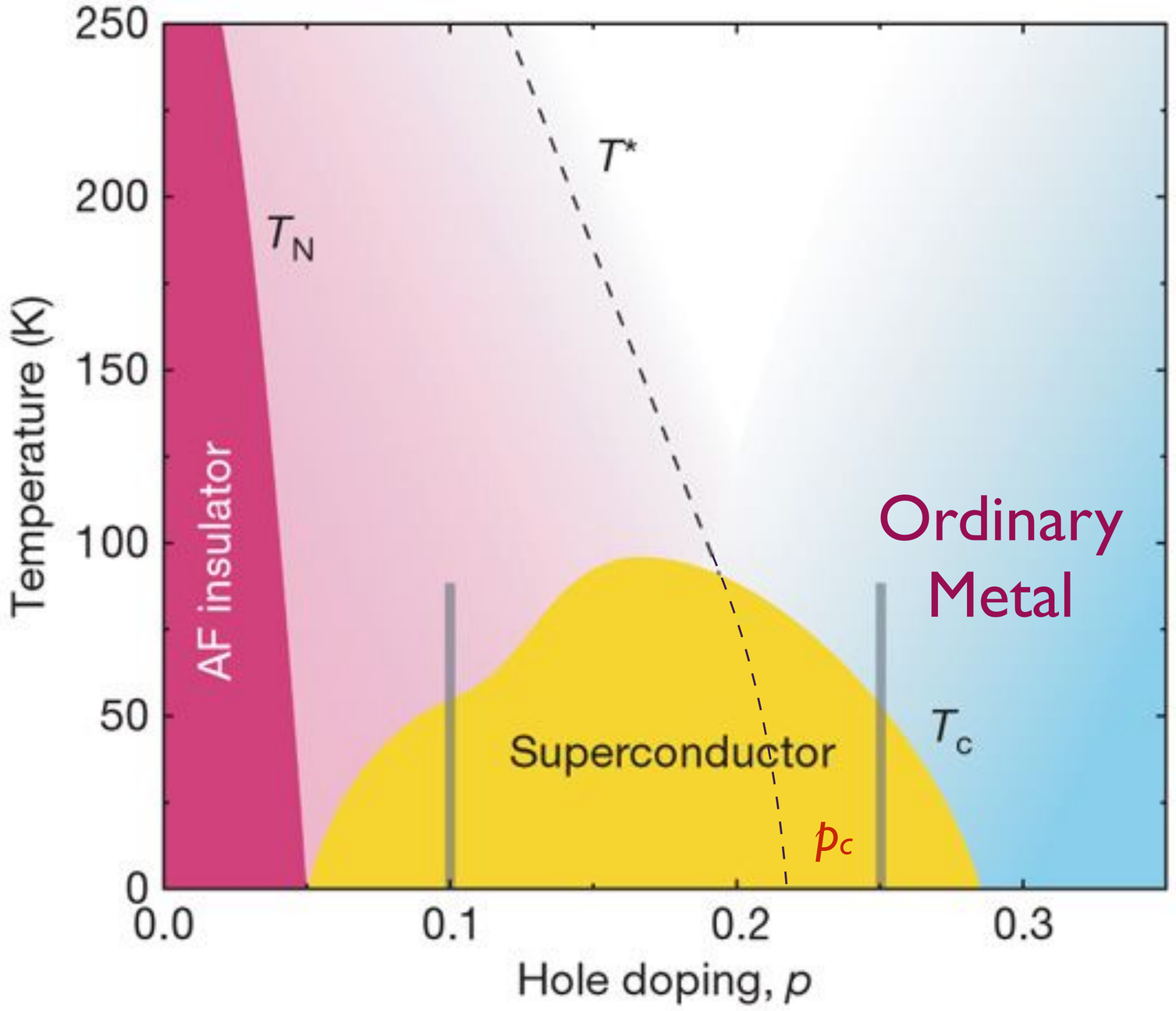


Commonwealth Fusion Systems


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


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

$YBa_2Cu_3O_{6+x}$


250
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0.0
0.1
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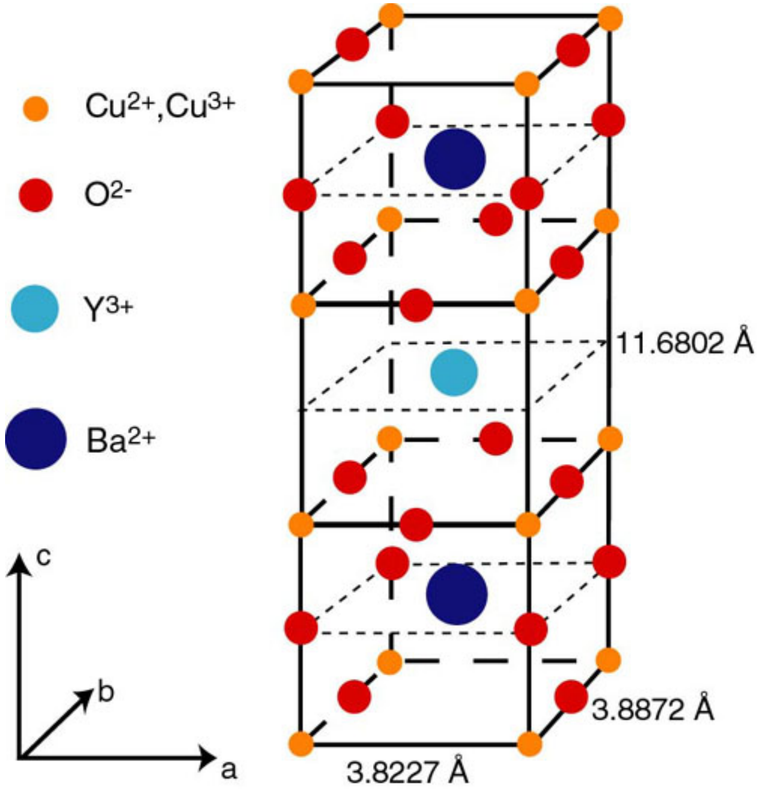
Hole doping, p
AF insulator
T_N
T^*
Superconductor
T_c
p_c
Ordinary
Metal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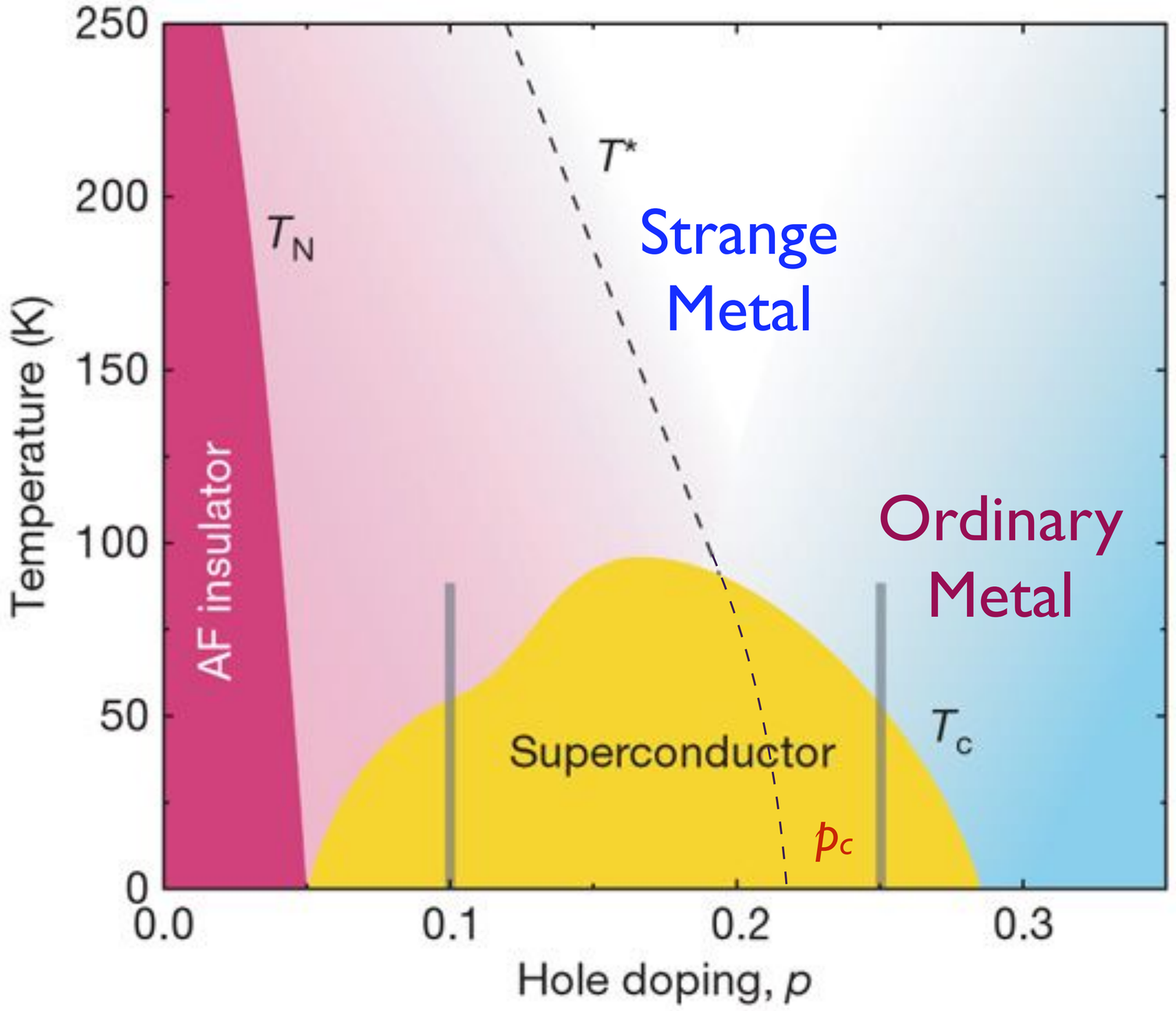
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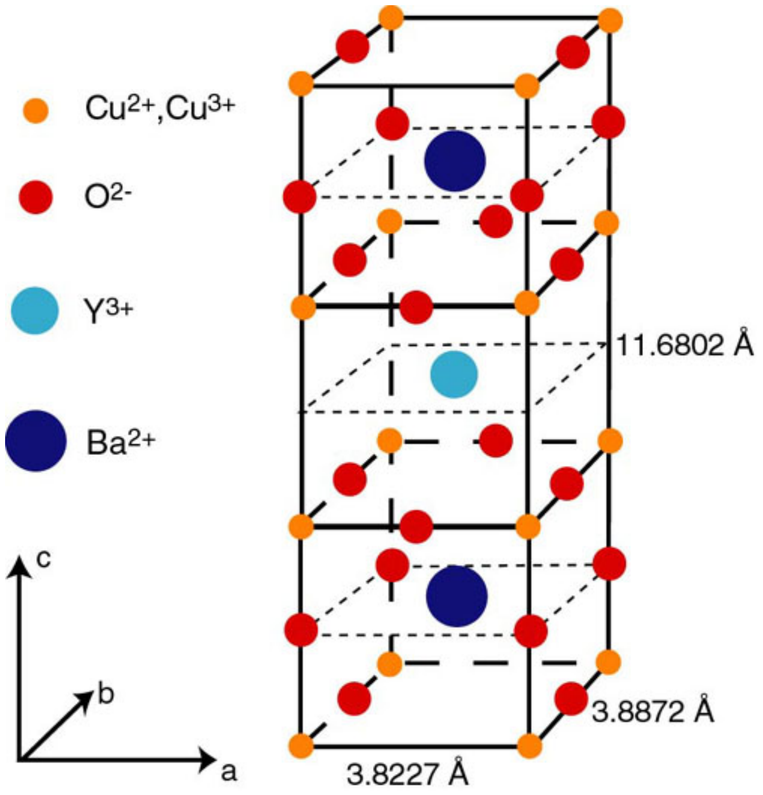
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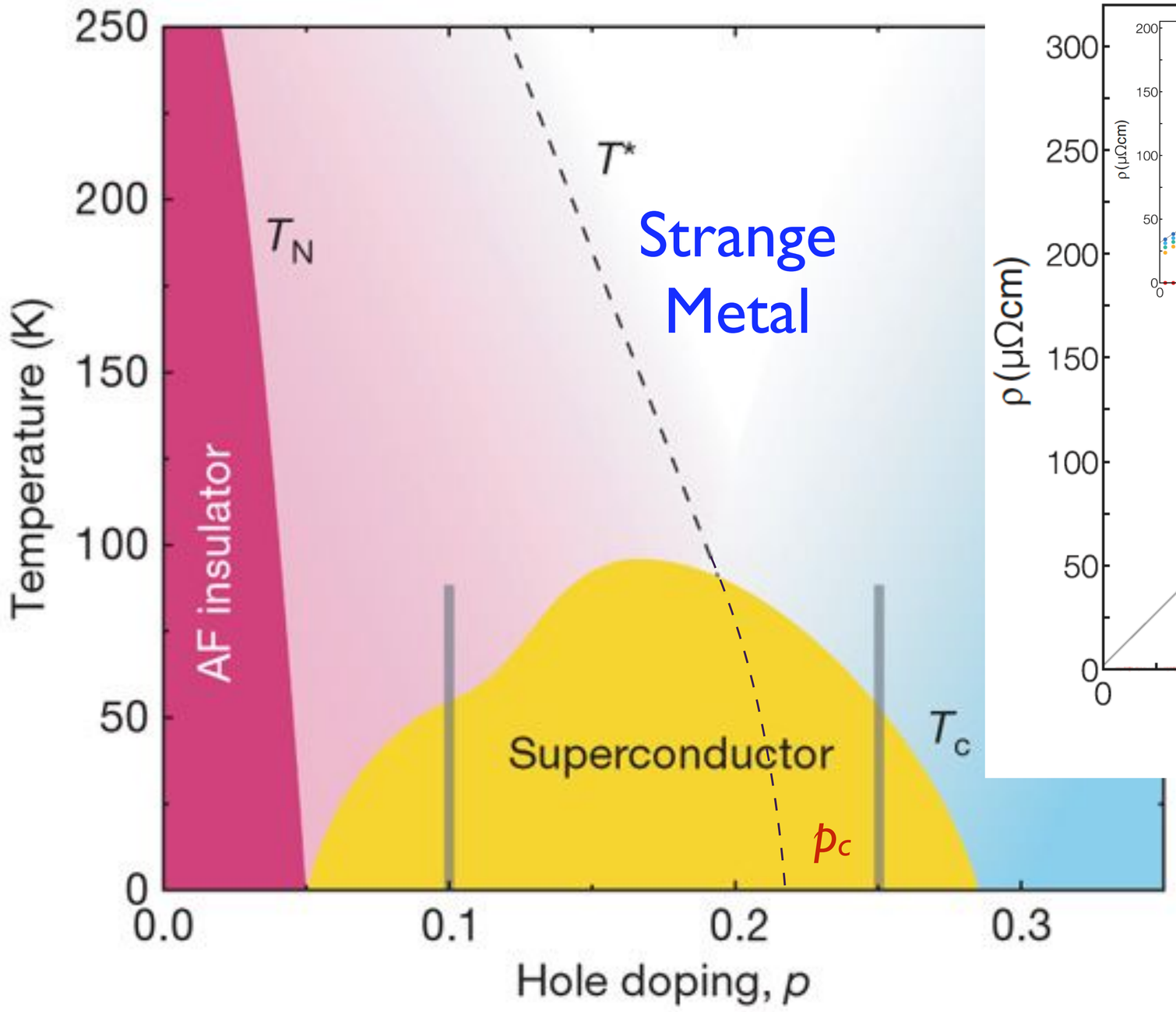
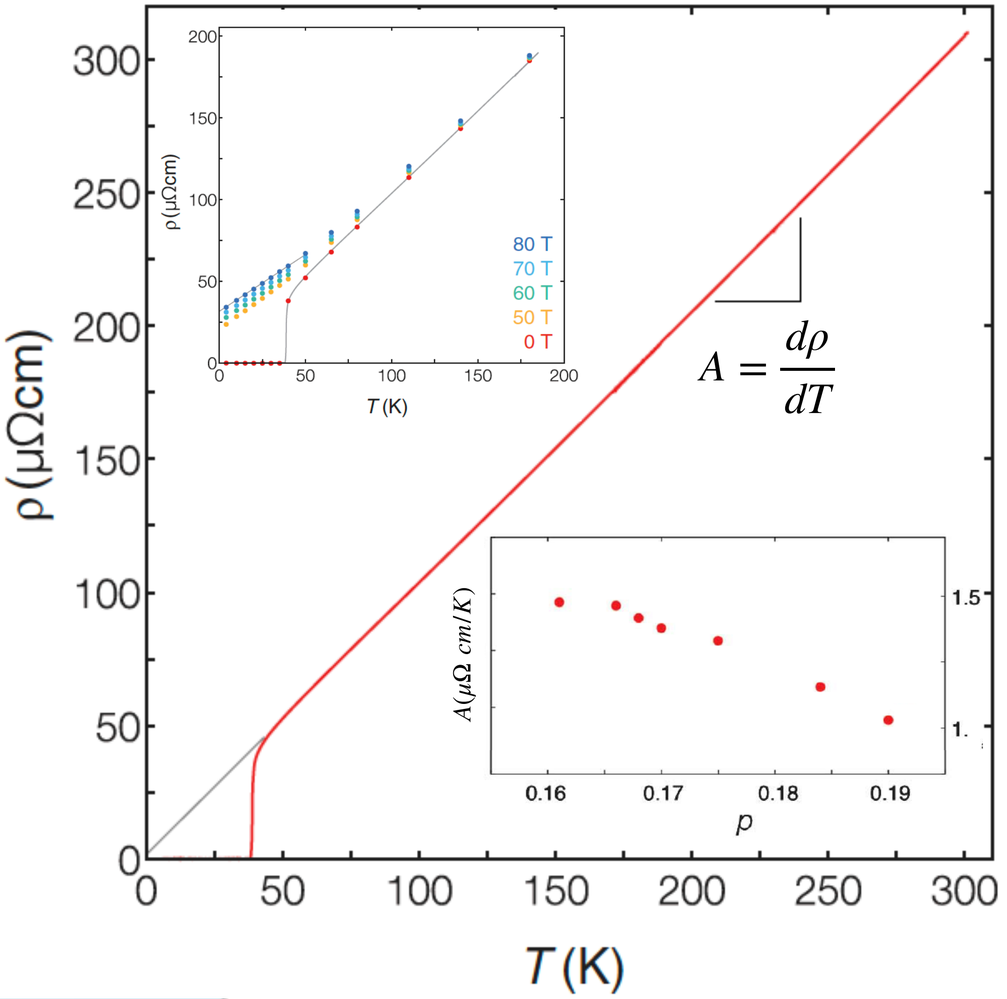
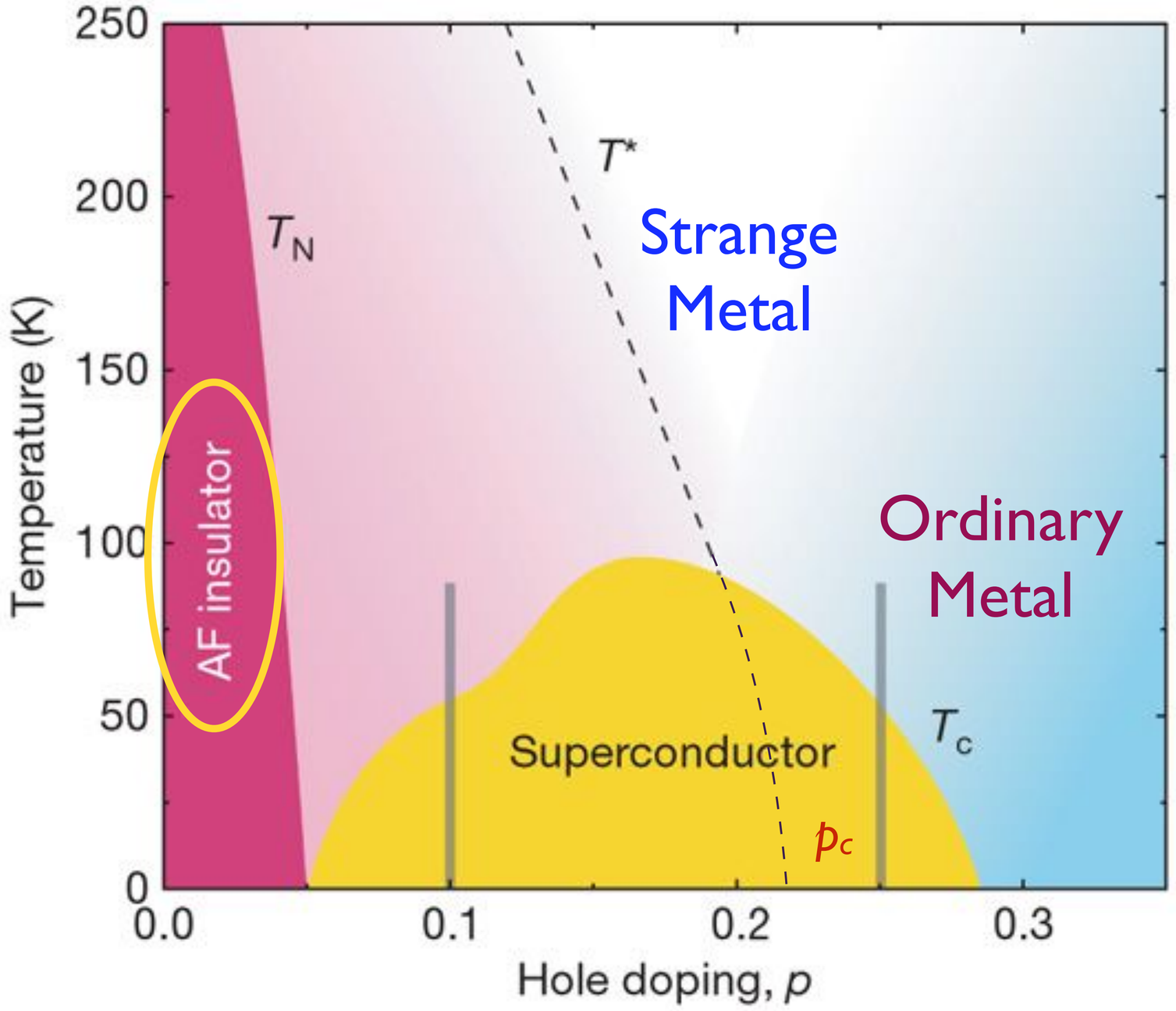




LSCO: Giraldo-Gallo et al. 2018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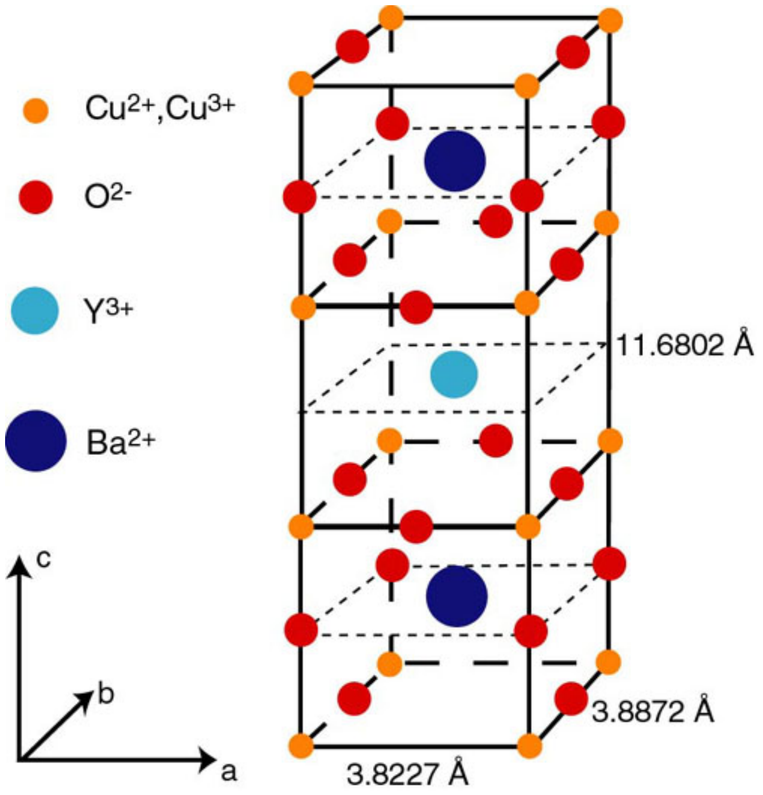
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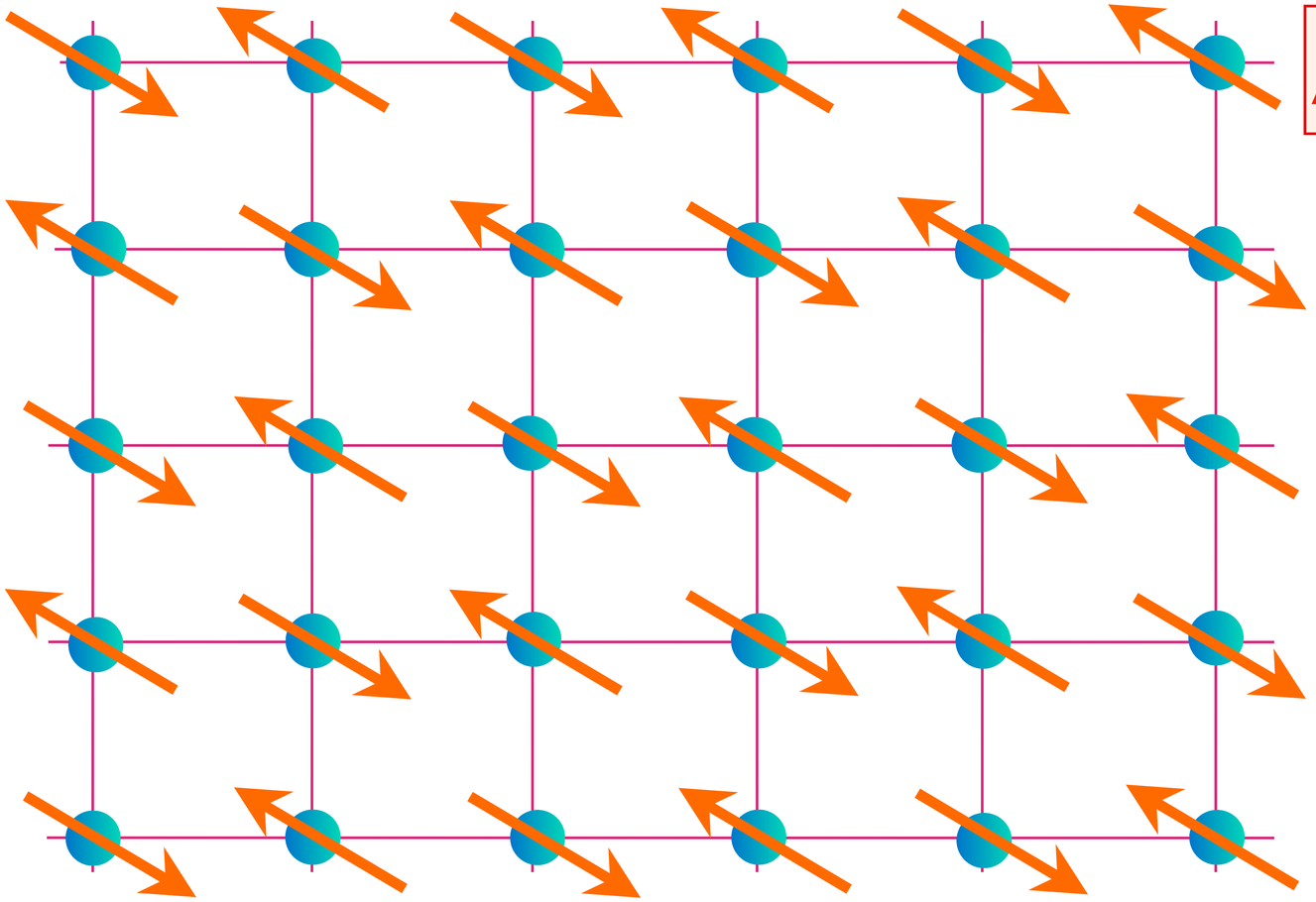
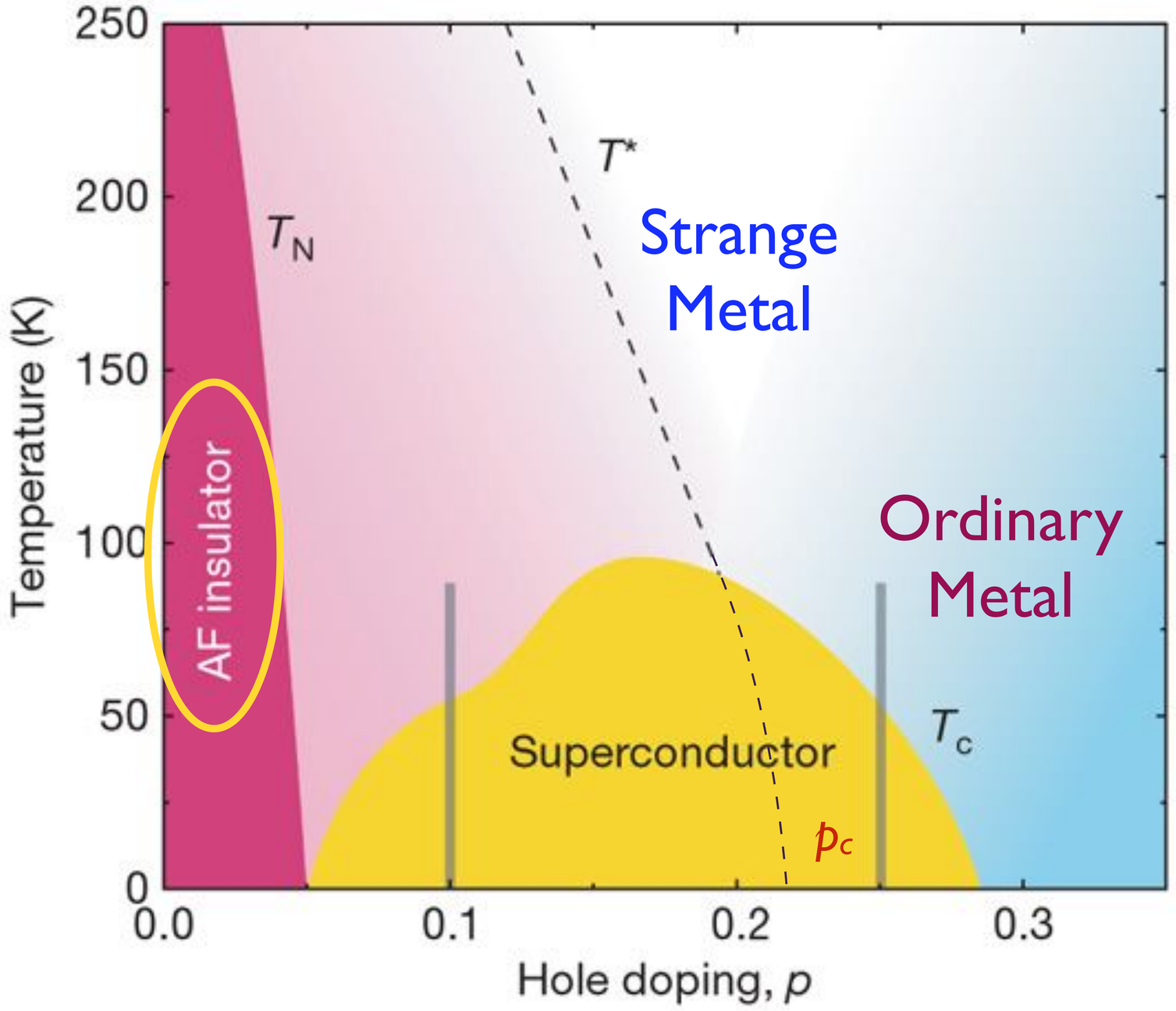
$YBa_2Cu_3O_{6+x}$

The dance of electrons on Cu atoms in YBCO



Antiferromagnetism

All nearest-neighbor pairs of electrons have opposite spins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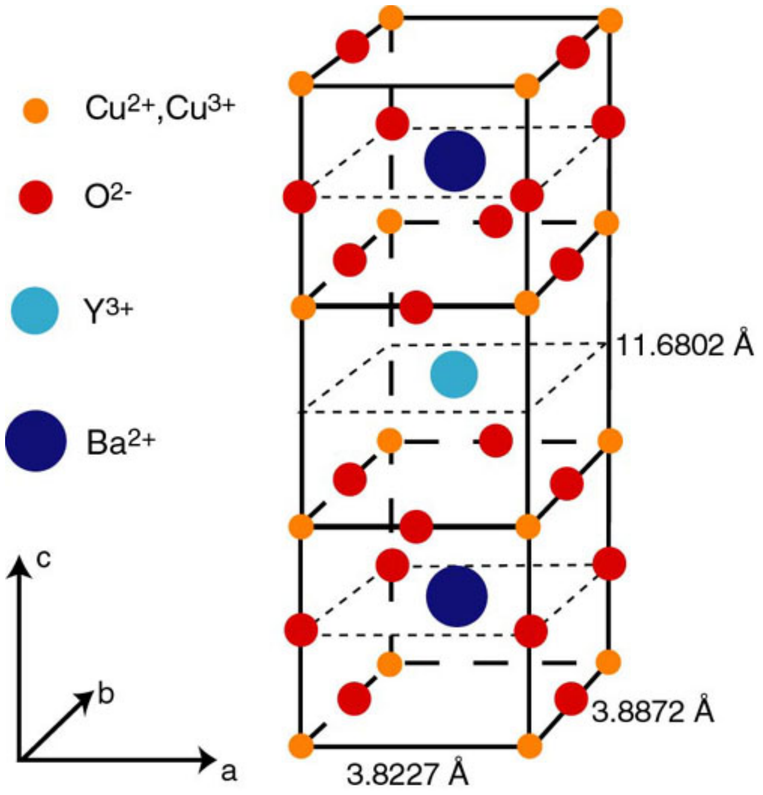
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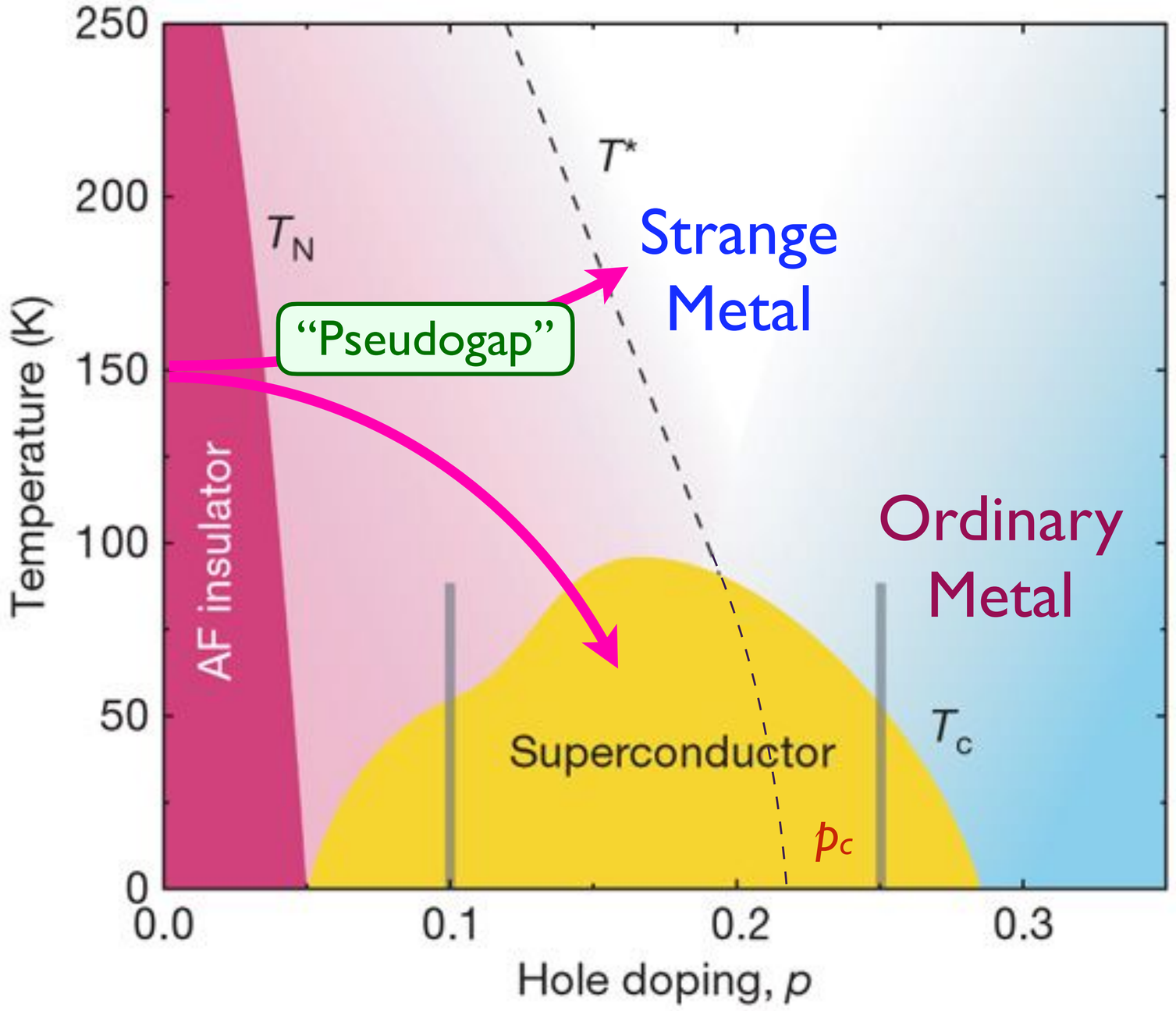
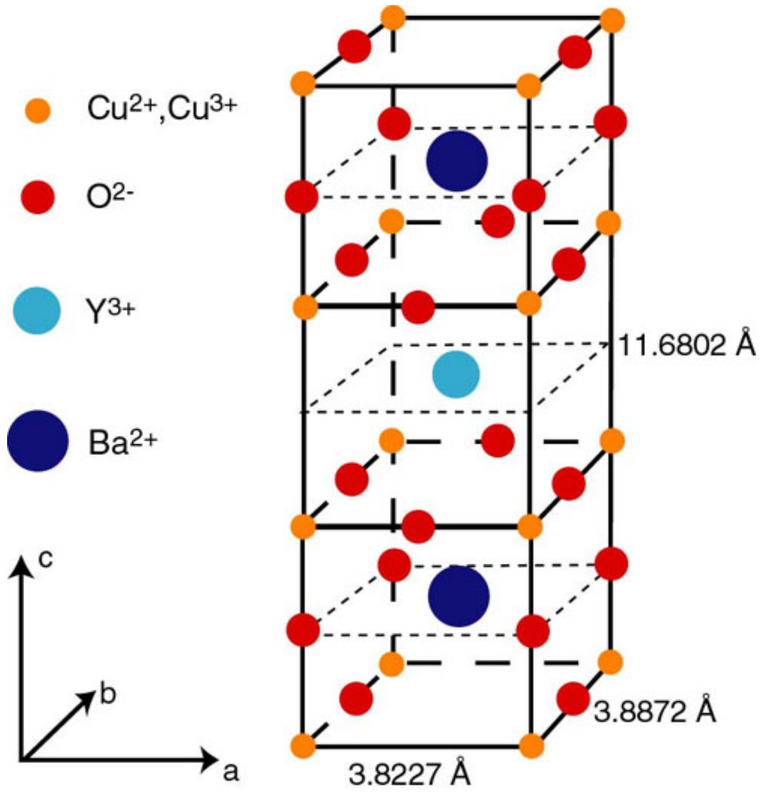
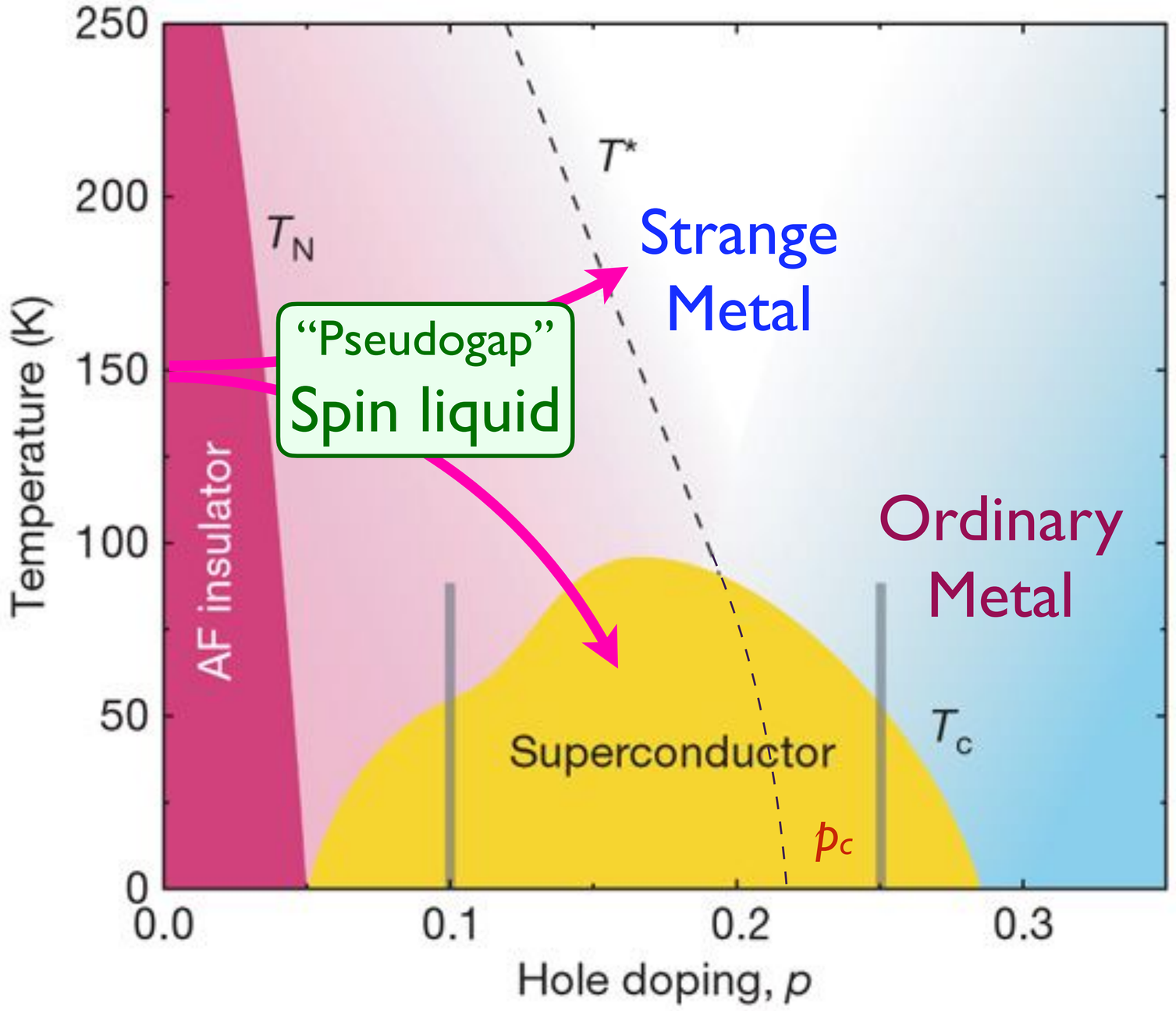

250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
T_N
T^*
"Pseudogap"
Strange Metal
Ordinary Metal
AF insulator
Superconductor
T_c
p_c


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

$YBa_2Cu_3O_{6+x}$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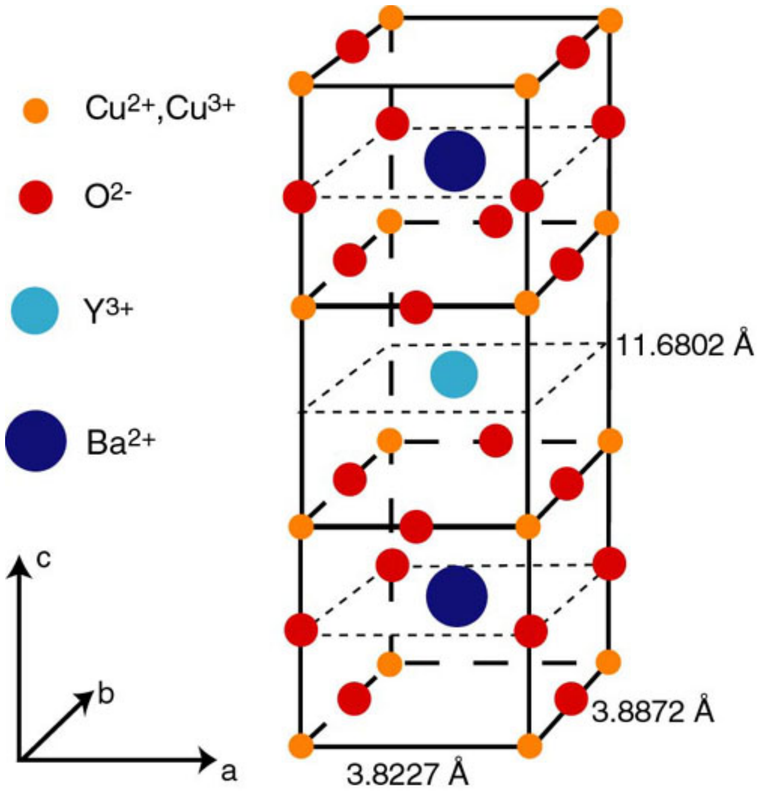
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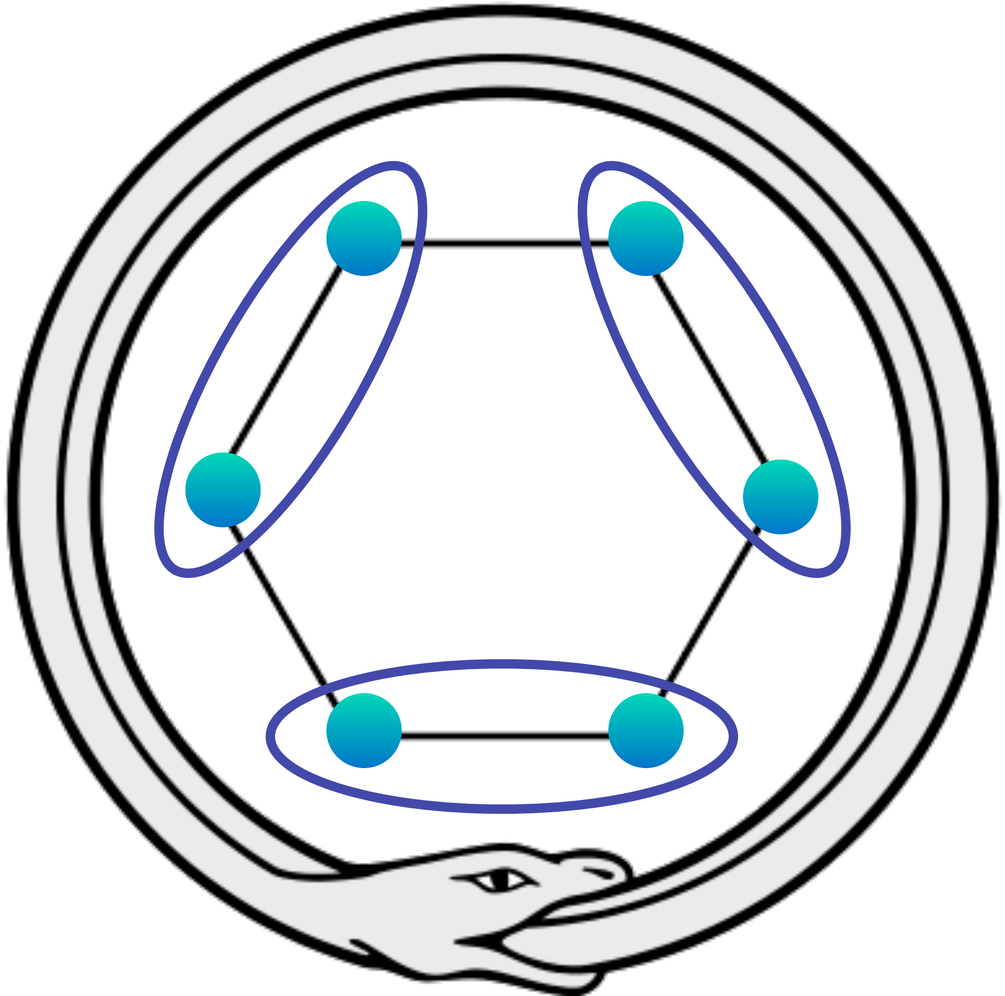
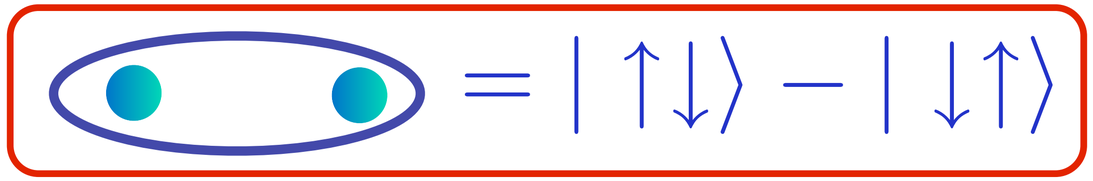
Kekule's spooky dream (1865)

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

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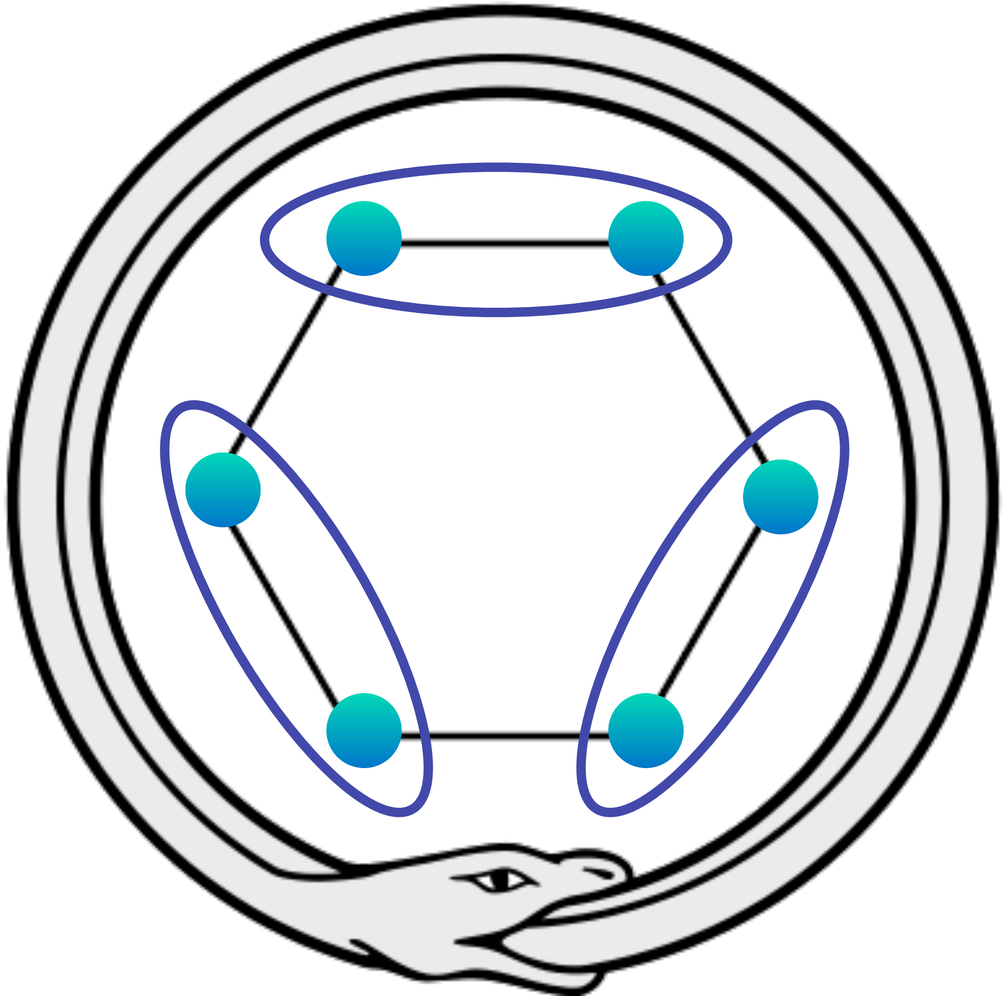
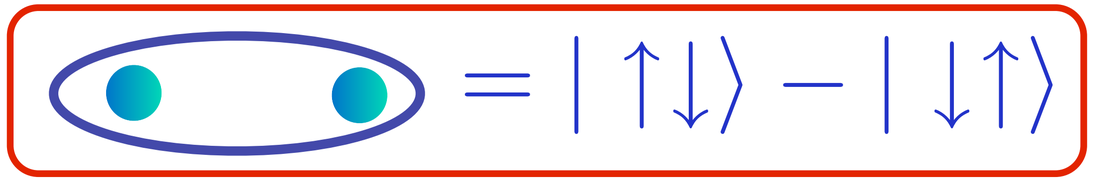
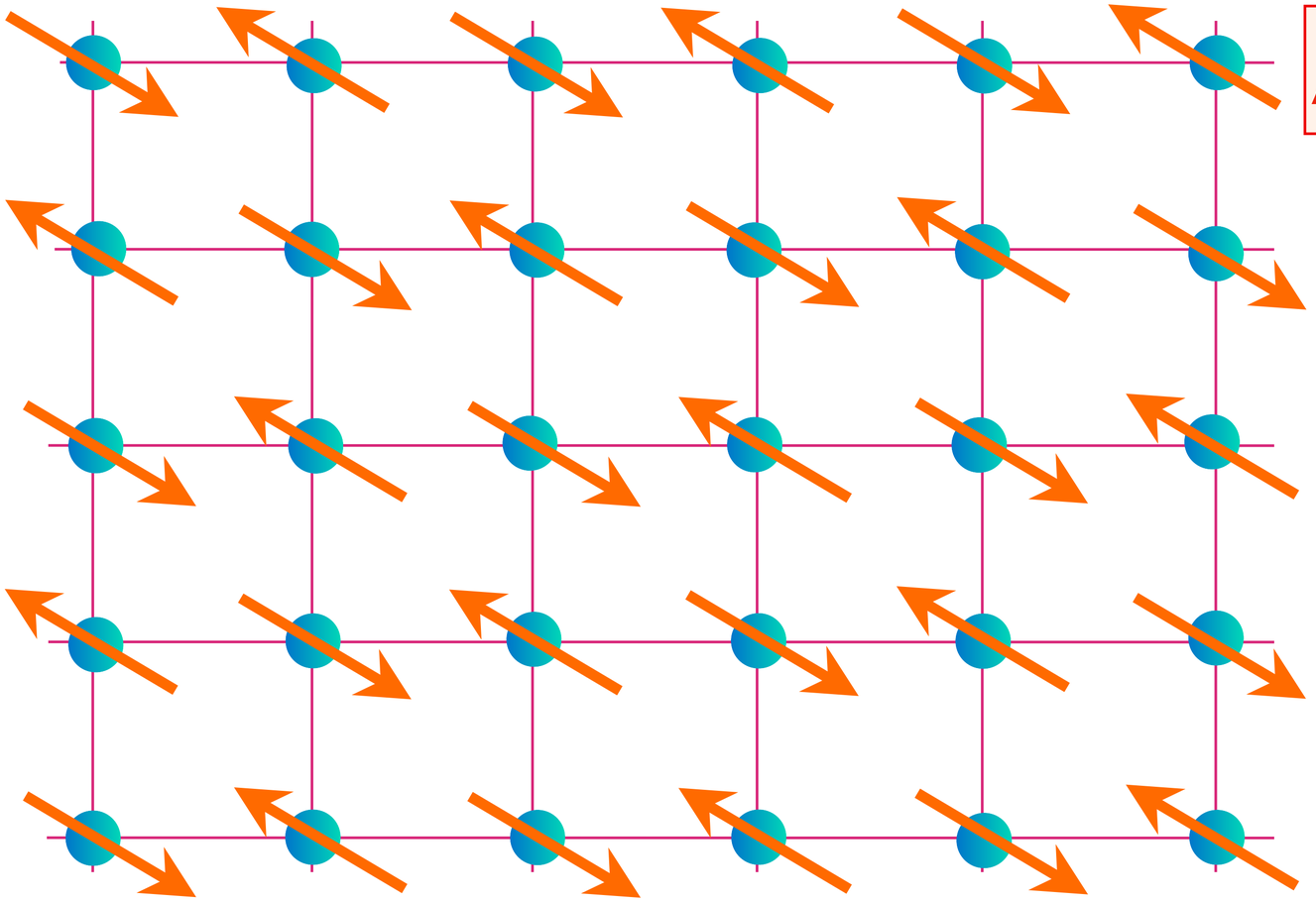




Benzene

*Wikipedia

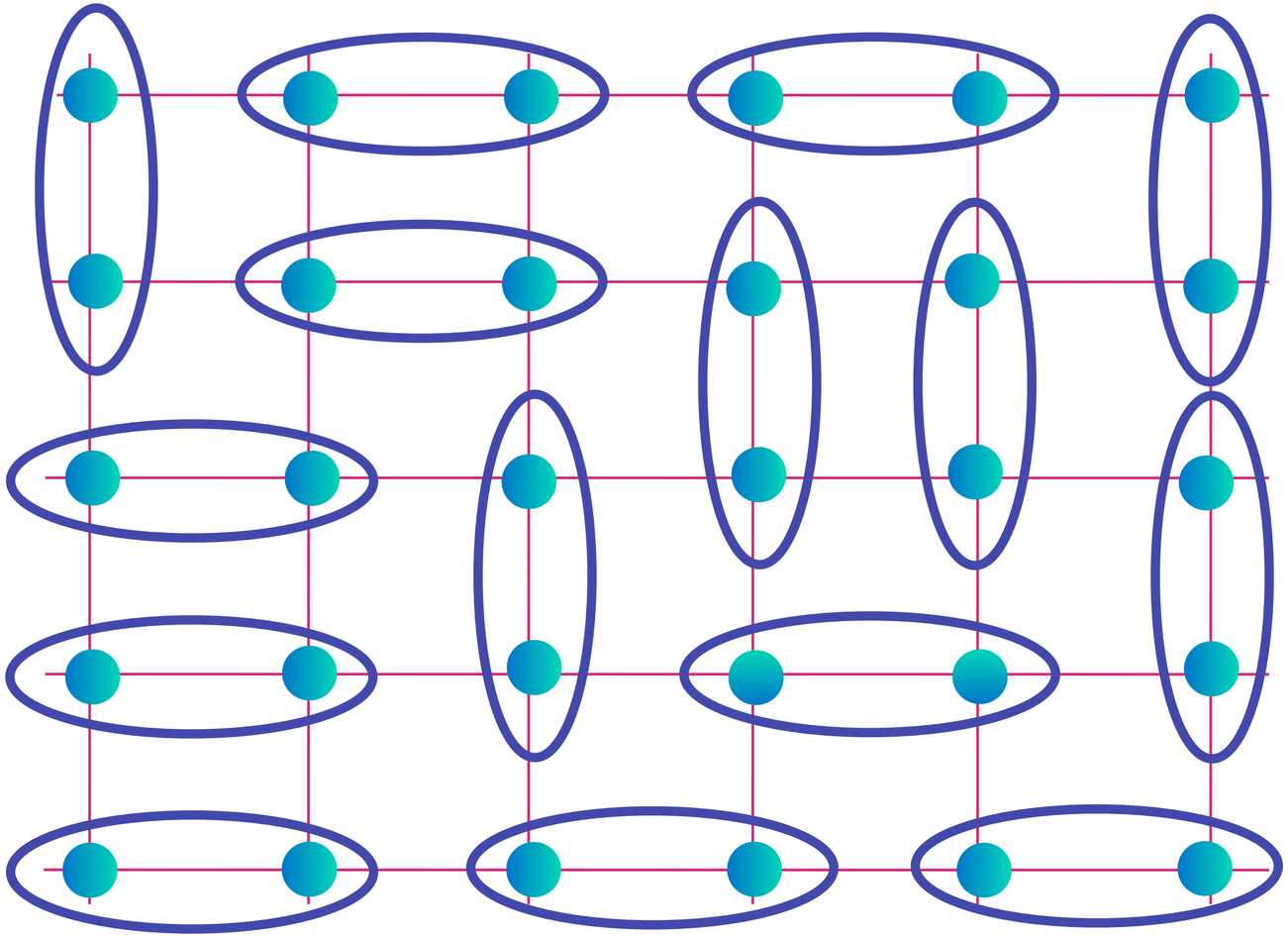
The dance of electrons on Cu atoms in YBCO



Antiferromagnetism

All nearest-neighbor pairs of electrons have opposite spins

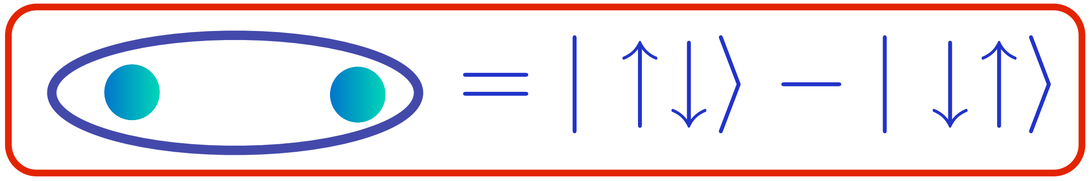
The dance of electrons on Cu atoms in YBCO



P.W. Anderson (1973)

Spin liquid

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



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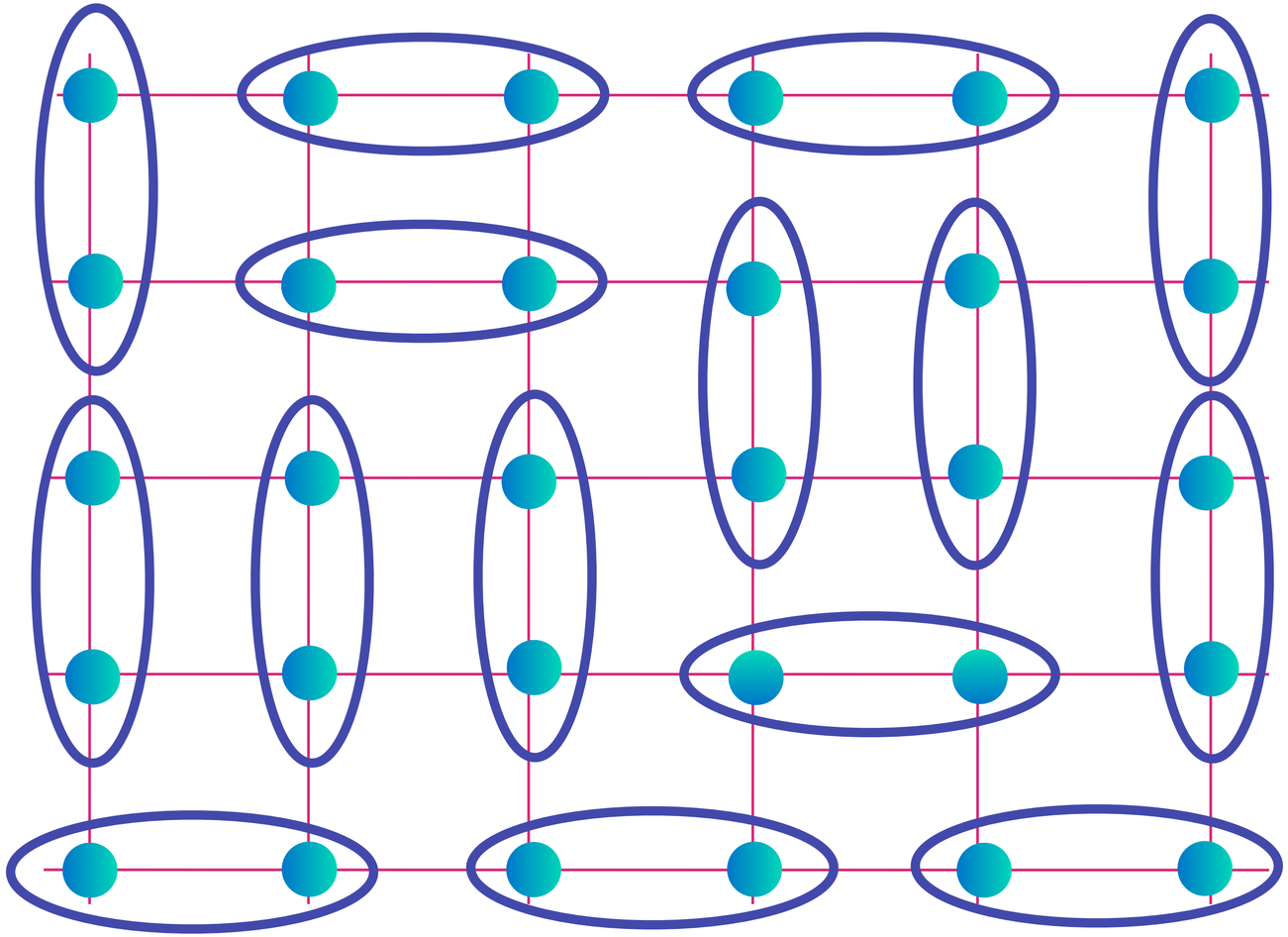

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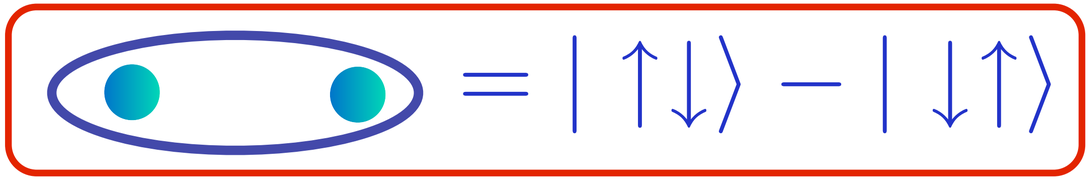

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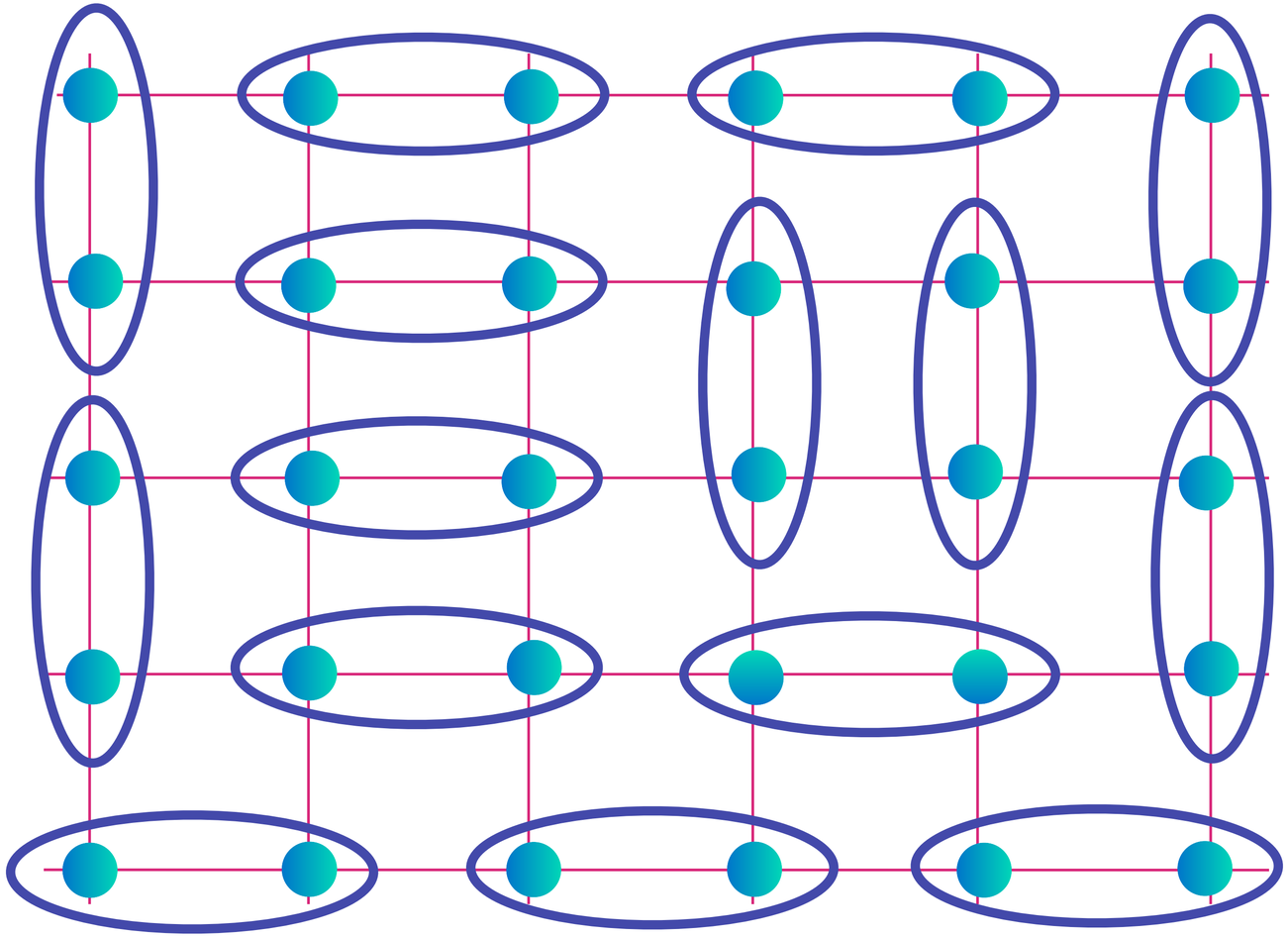

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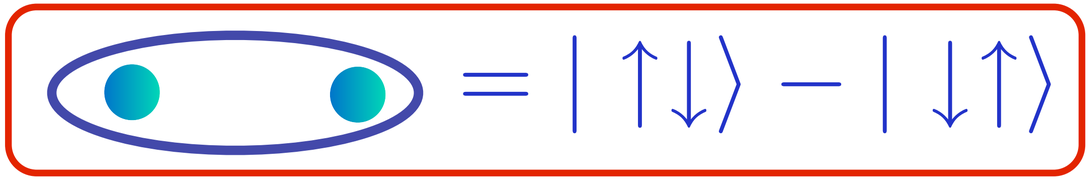

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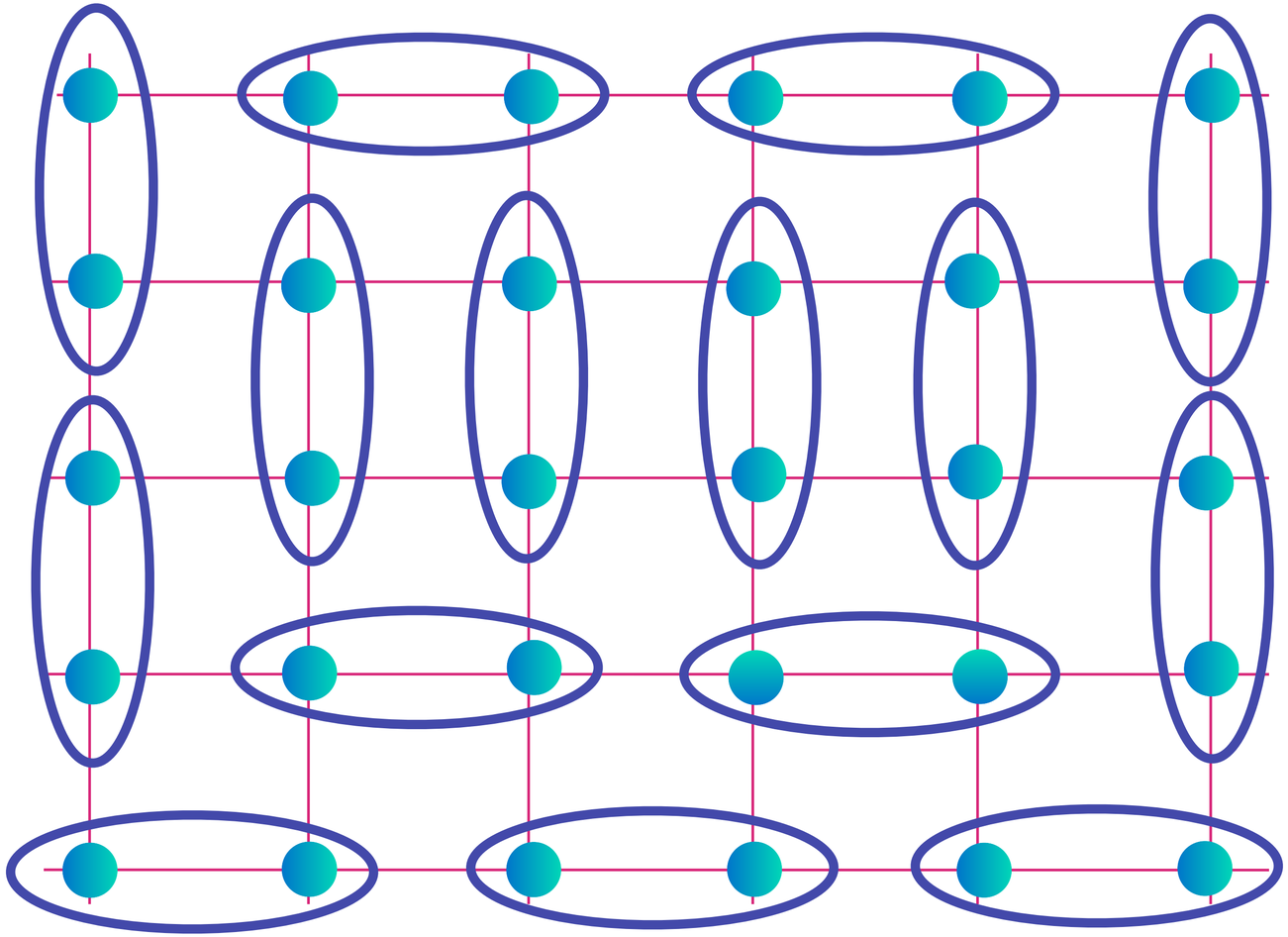

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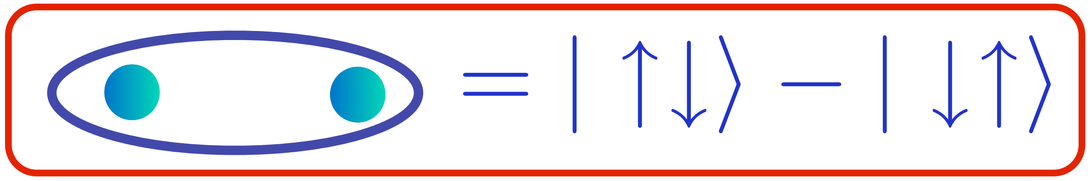

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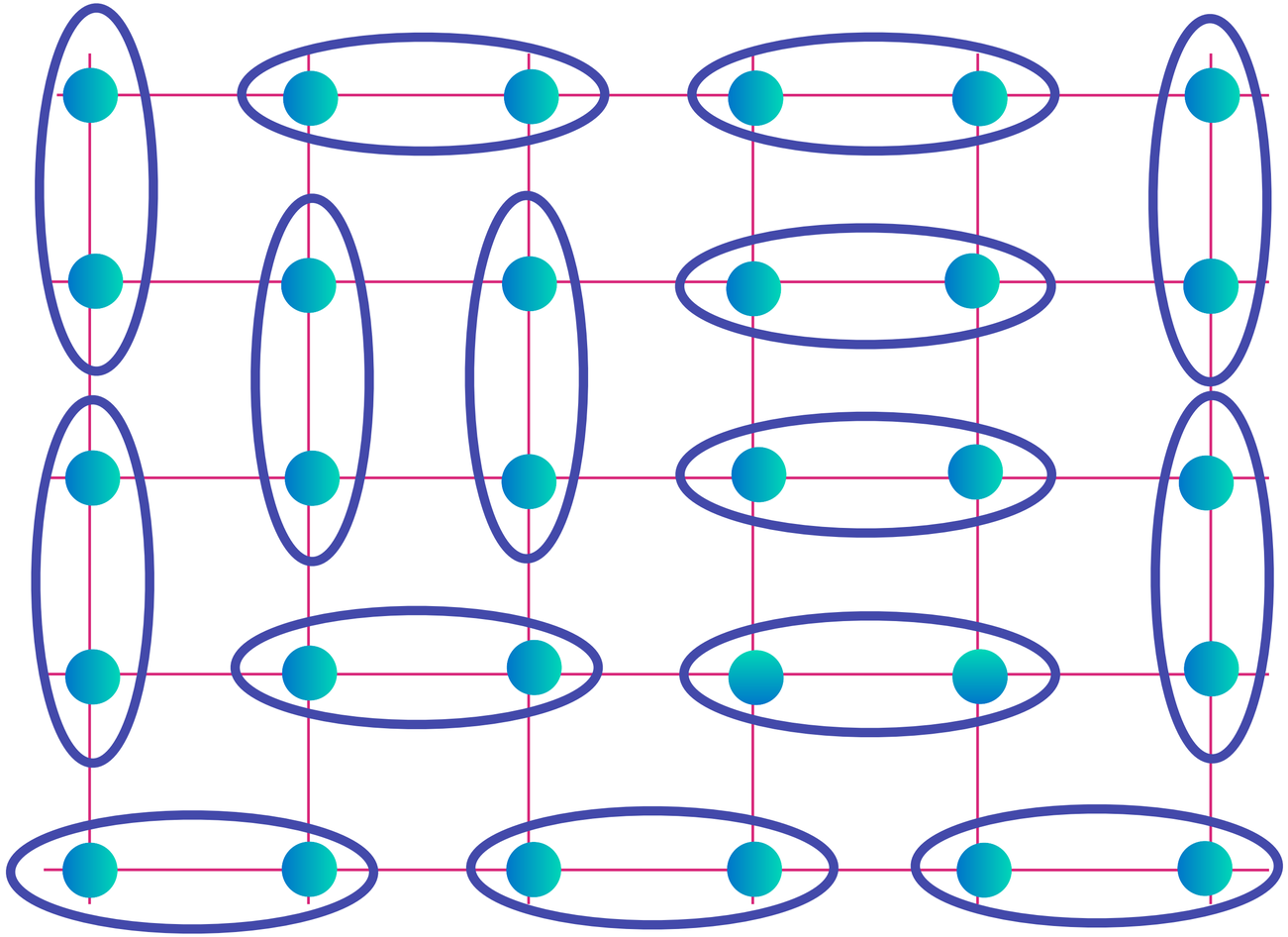

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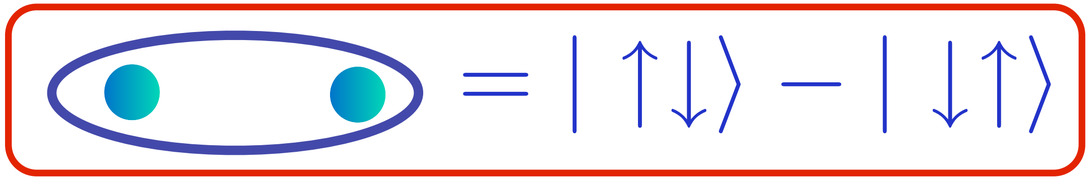

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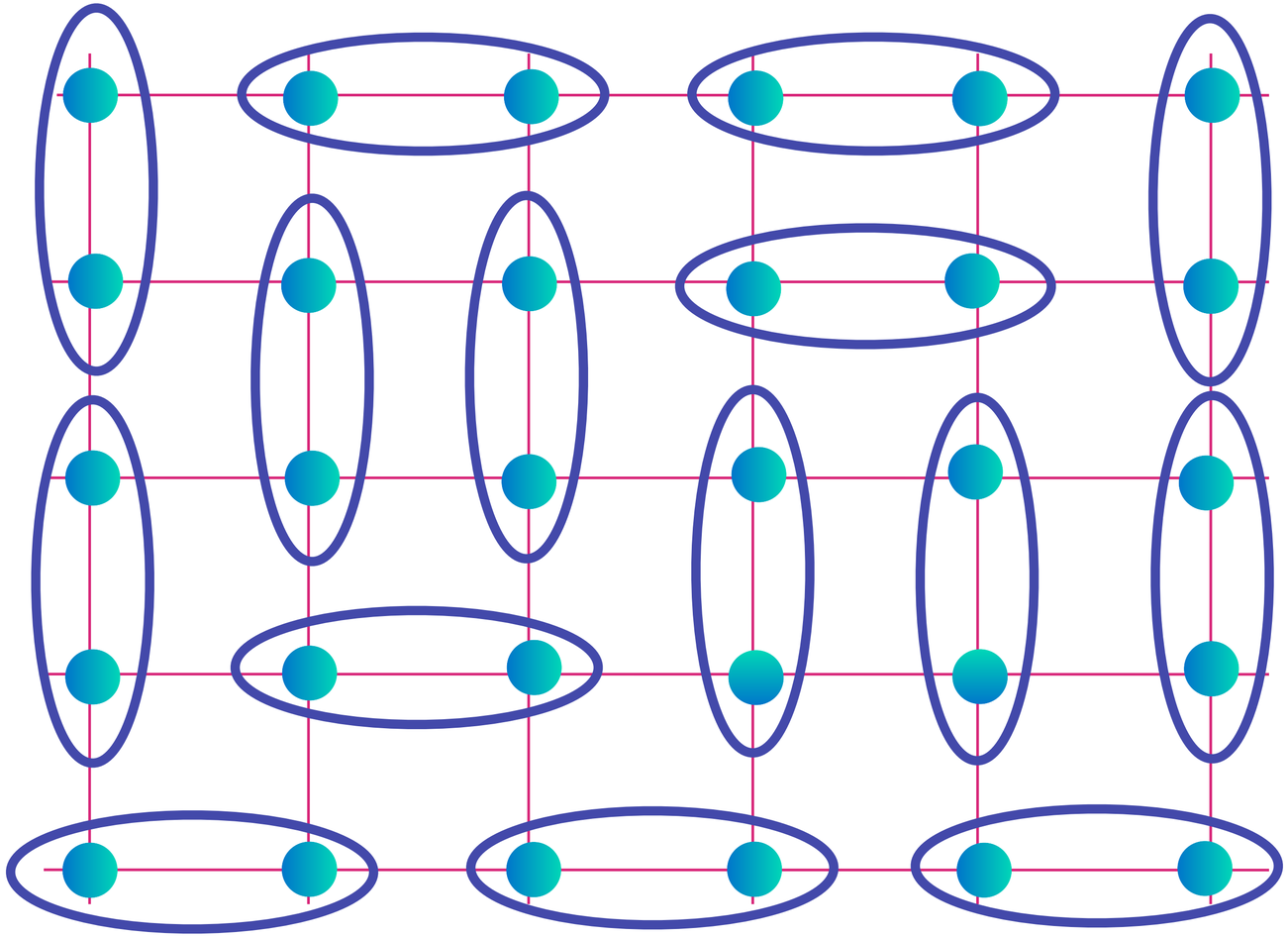

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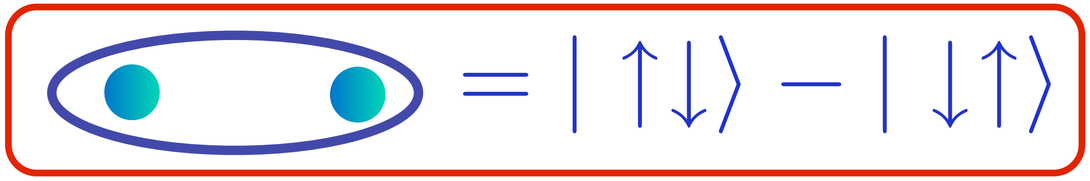

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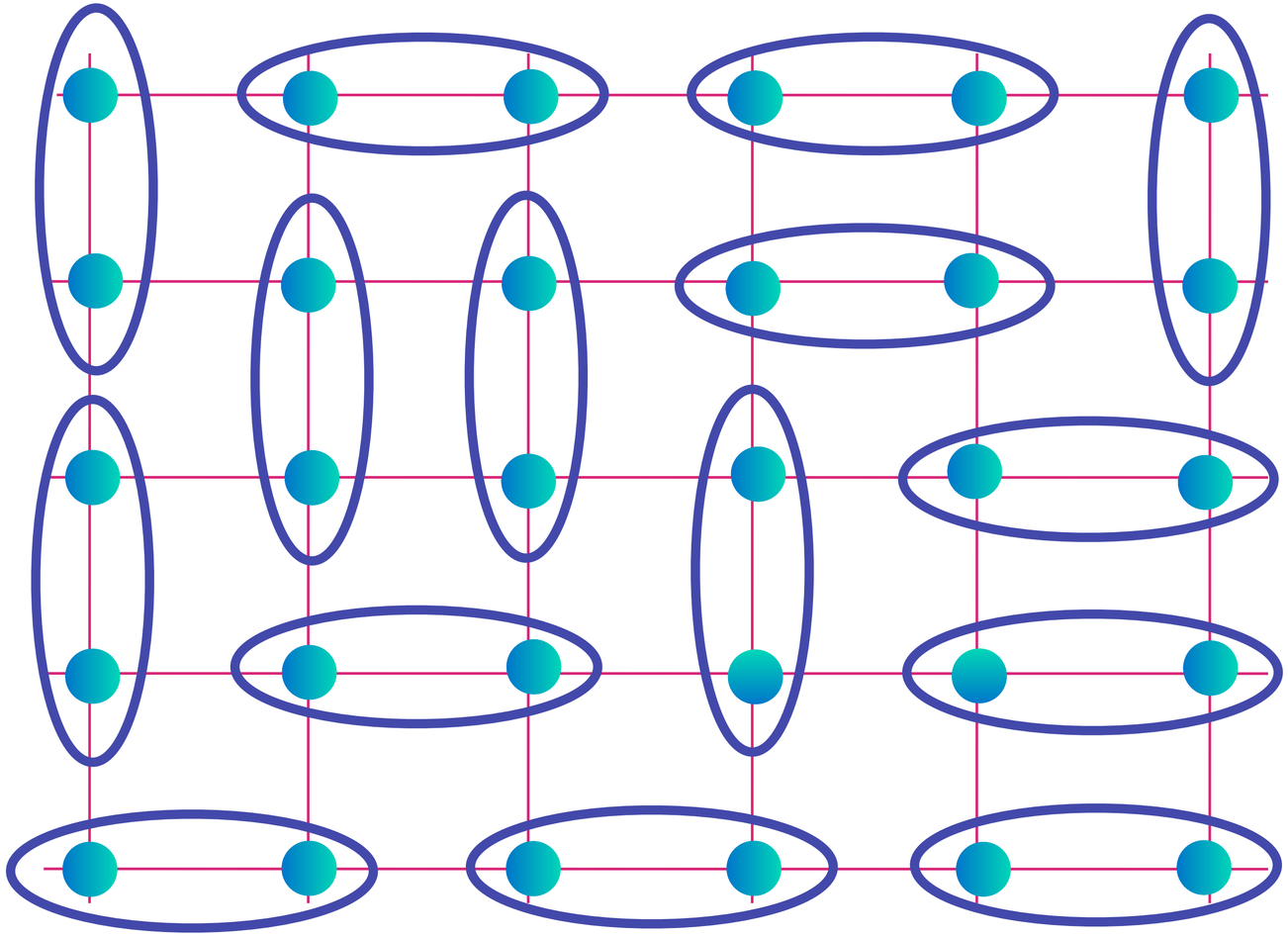

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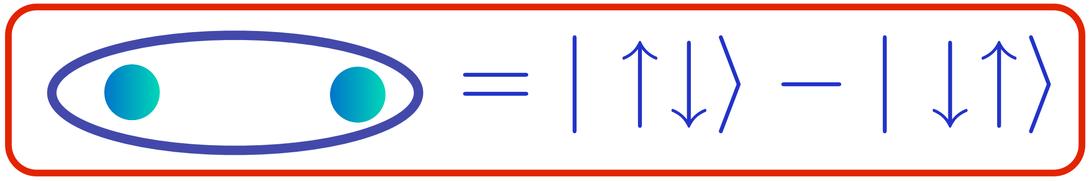

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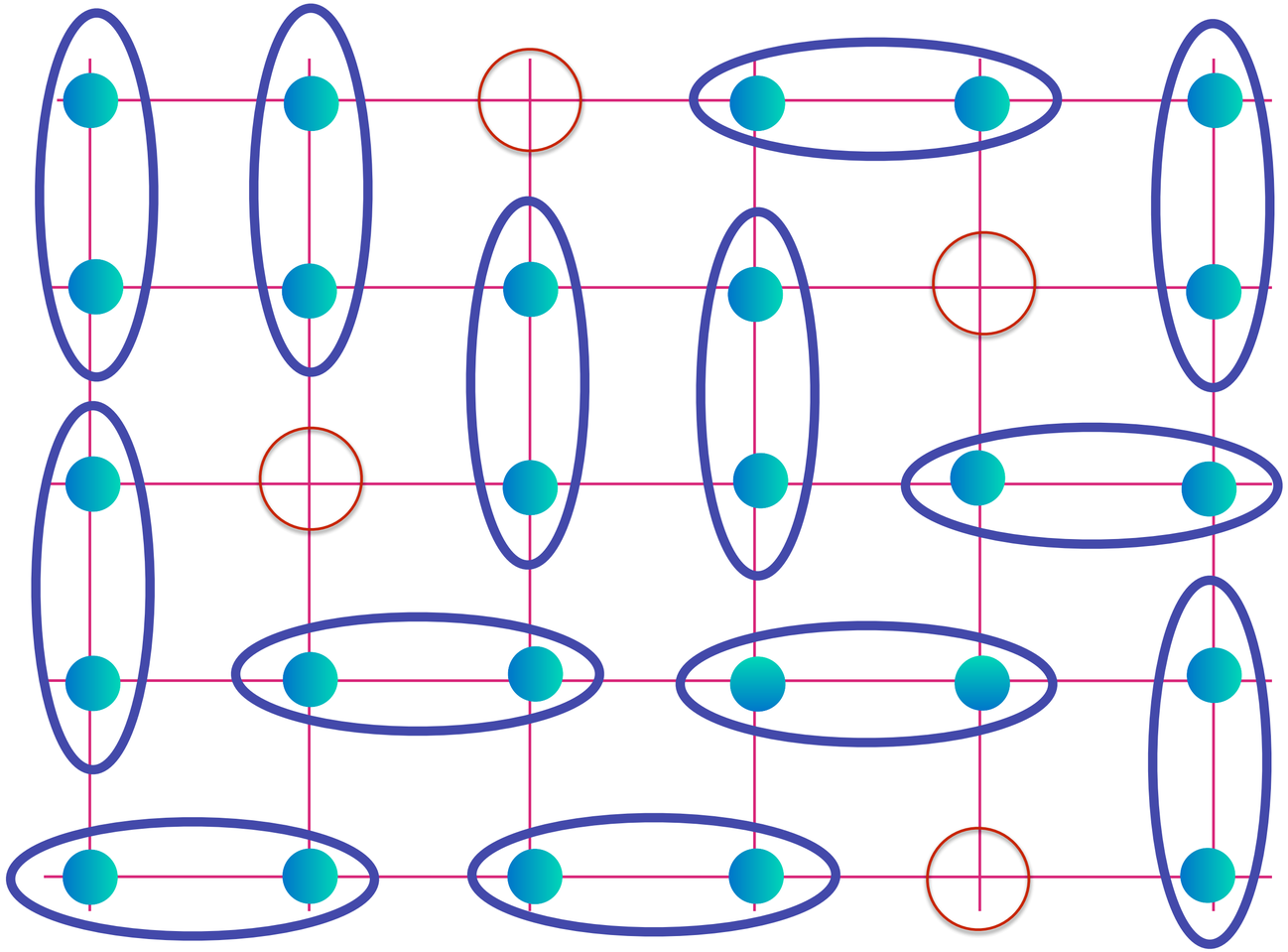

$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Pseudogap

Small density of mobile “holes” in a sea of entangled electron pairs

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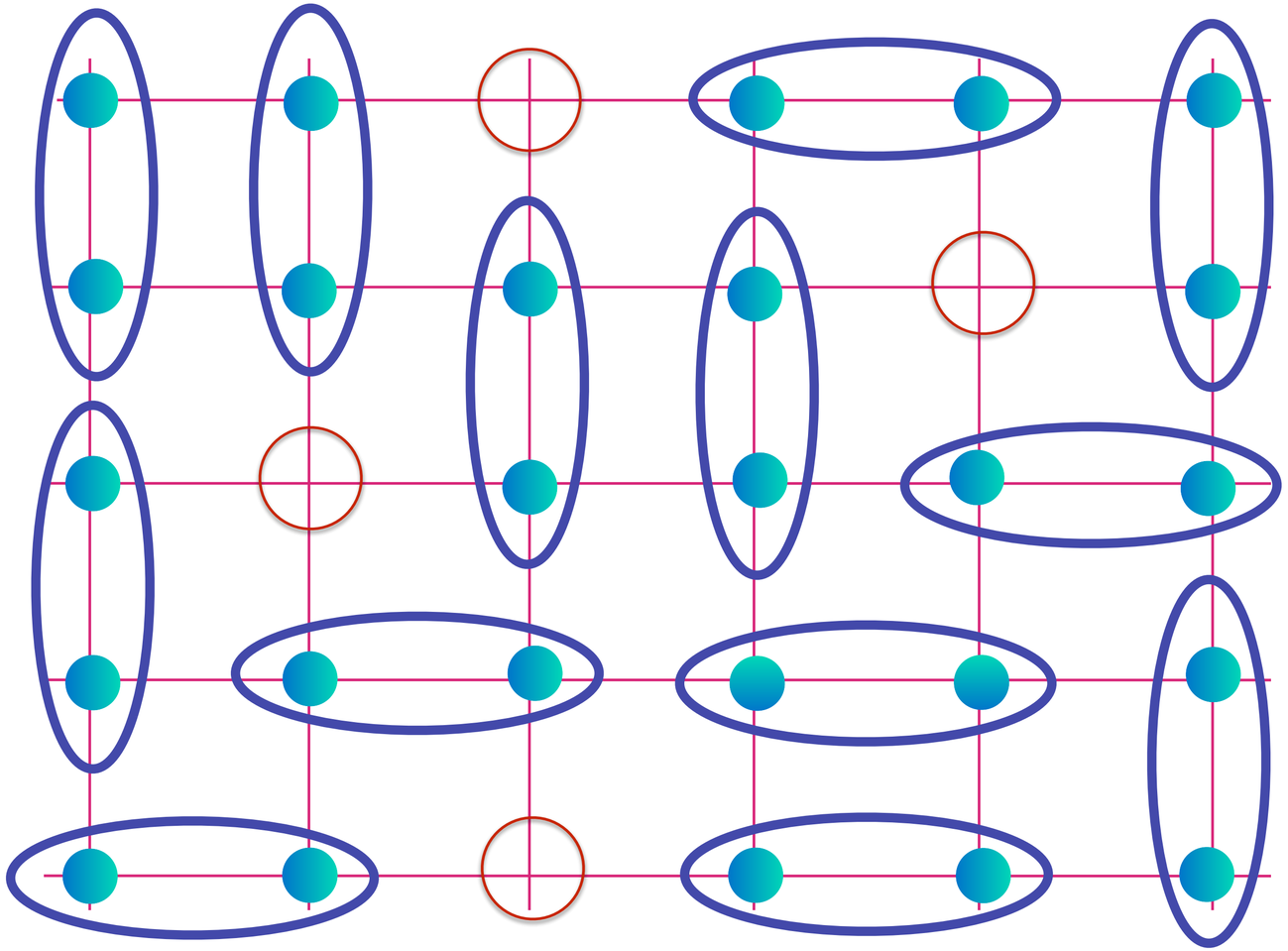

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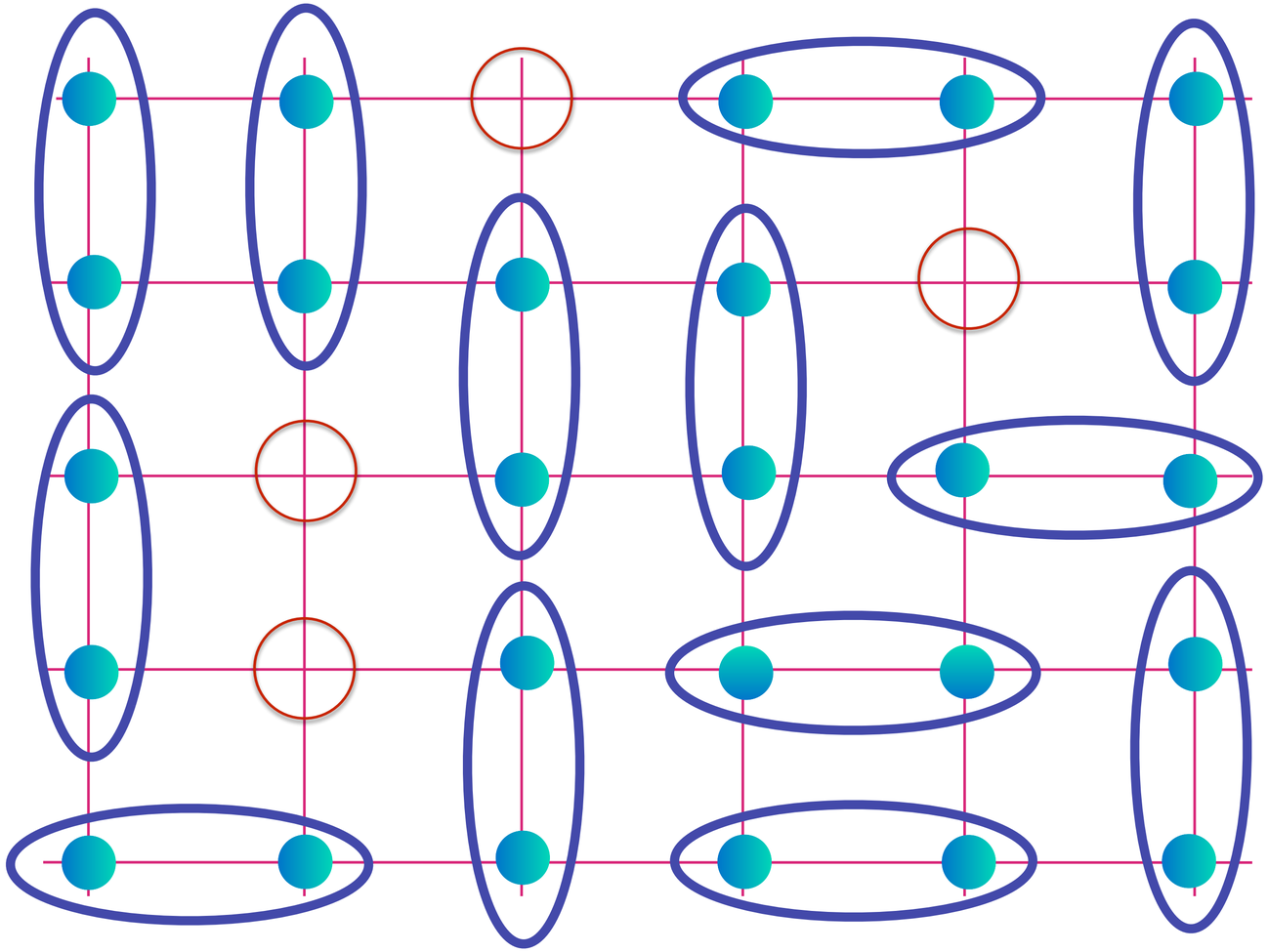

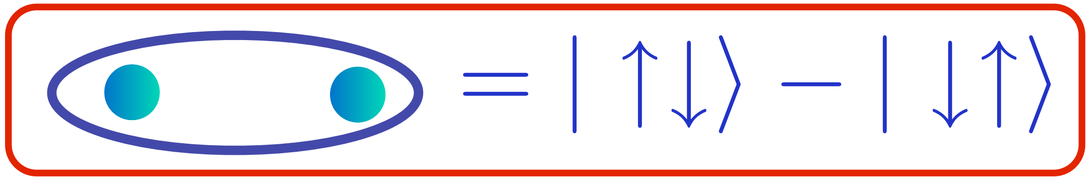

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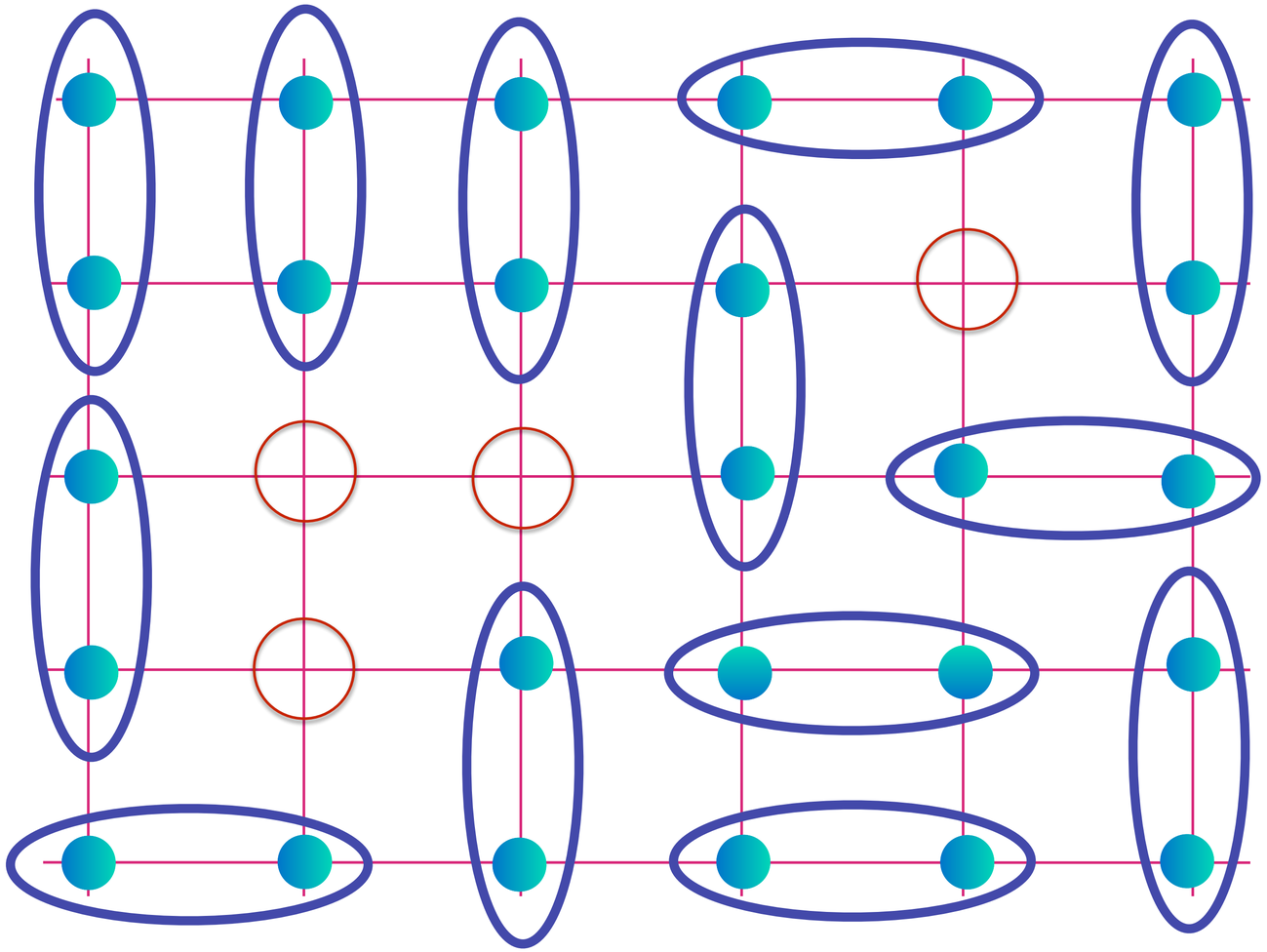

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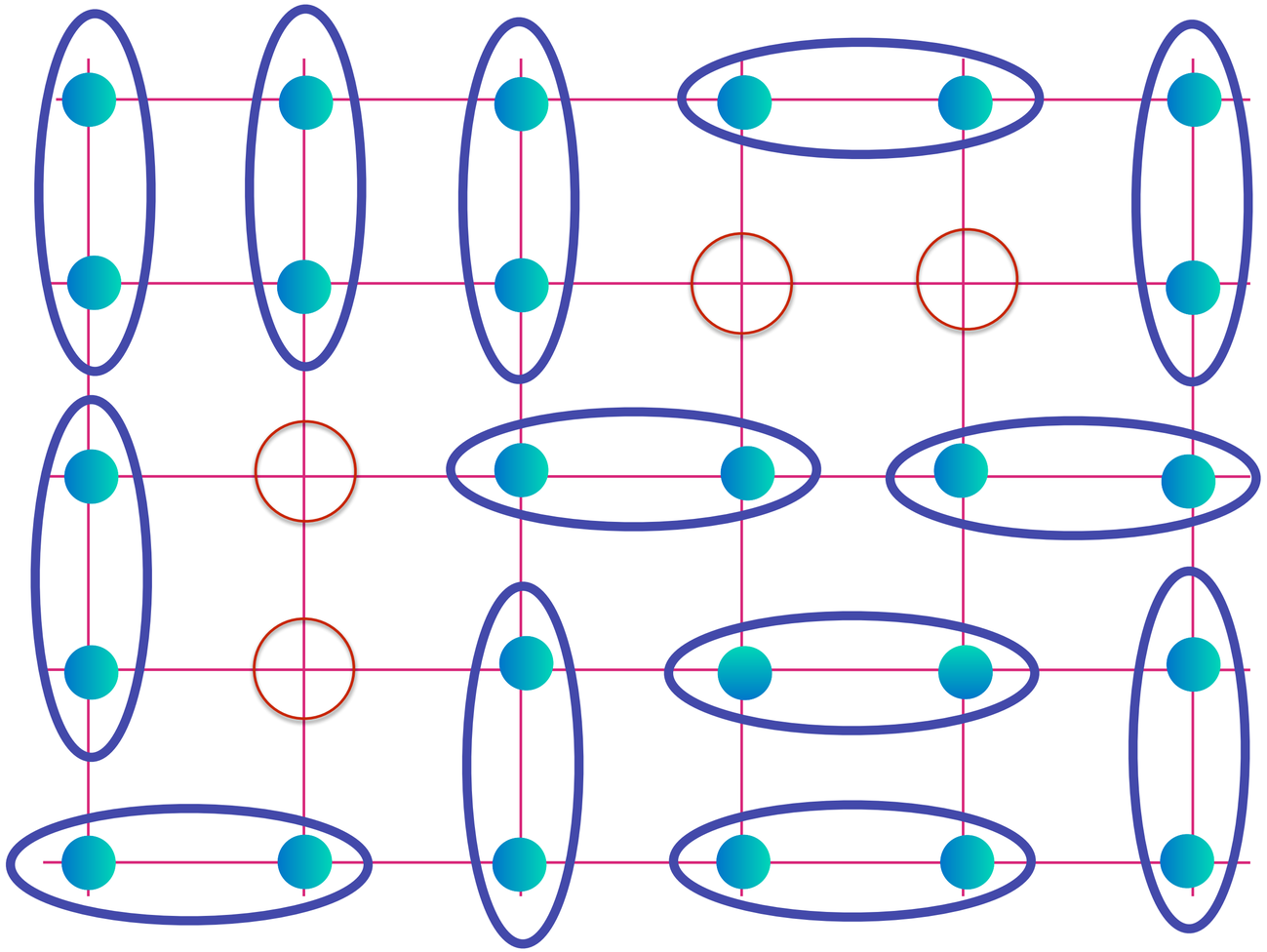

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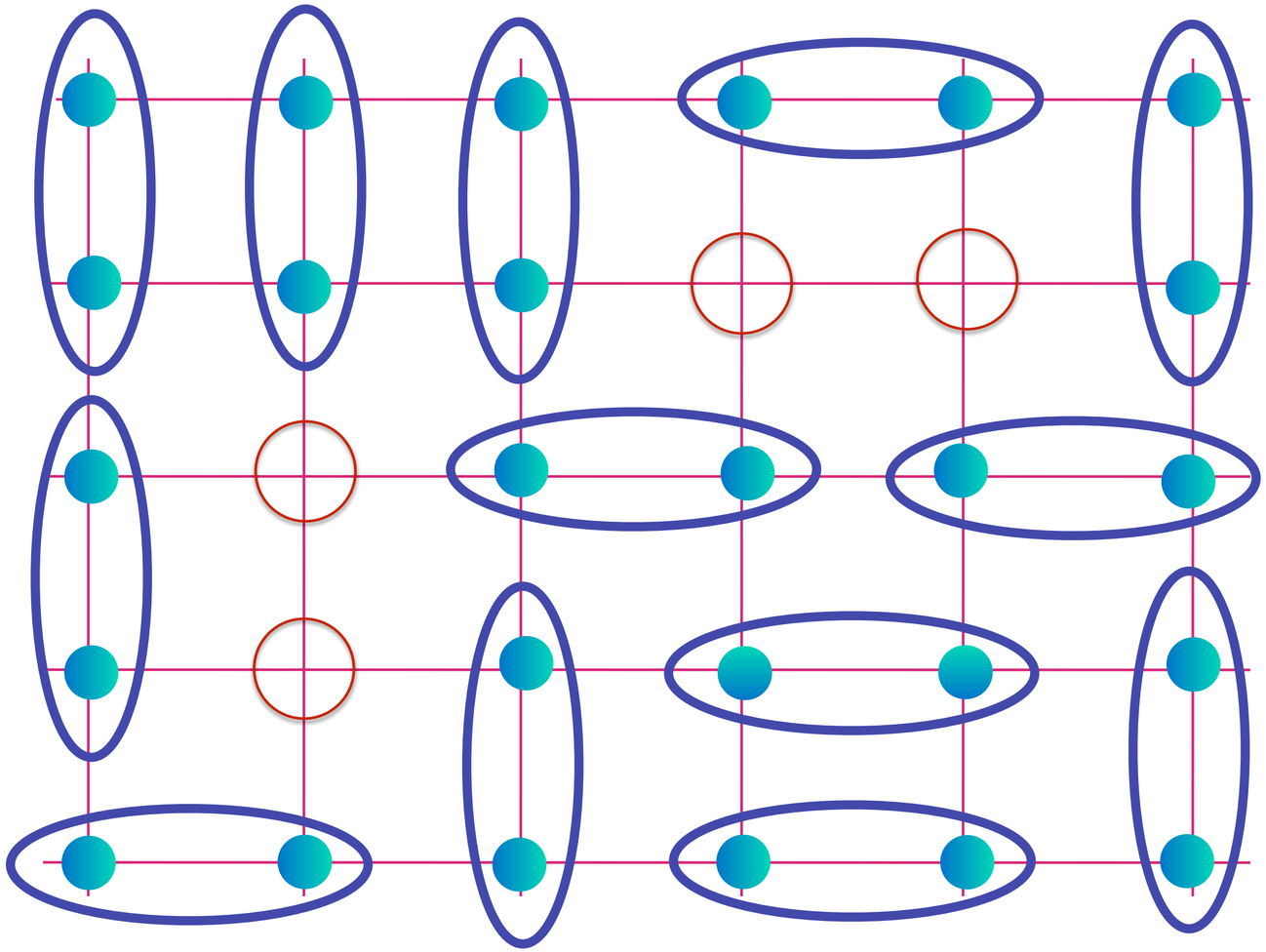
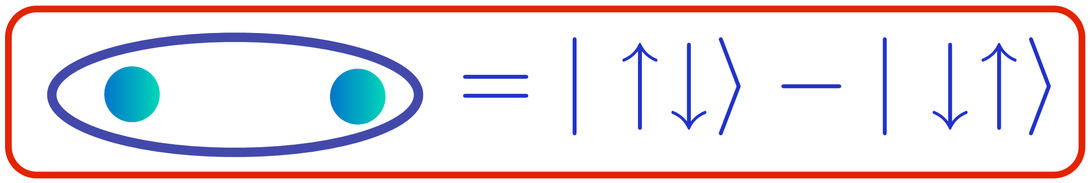


Superconductivity

Mobile
entangled
electron pairs



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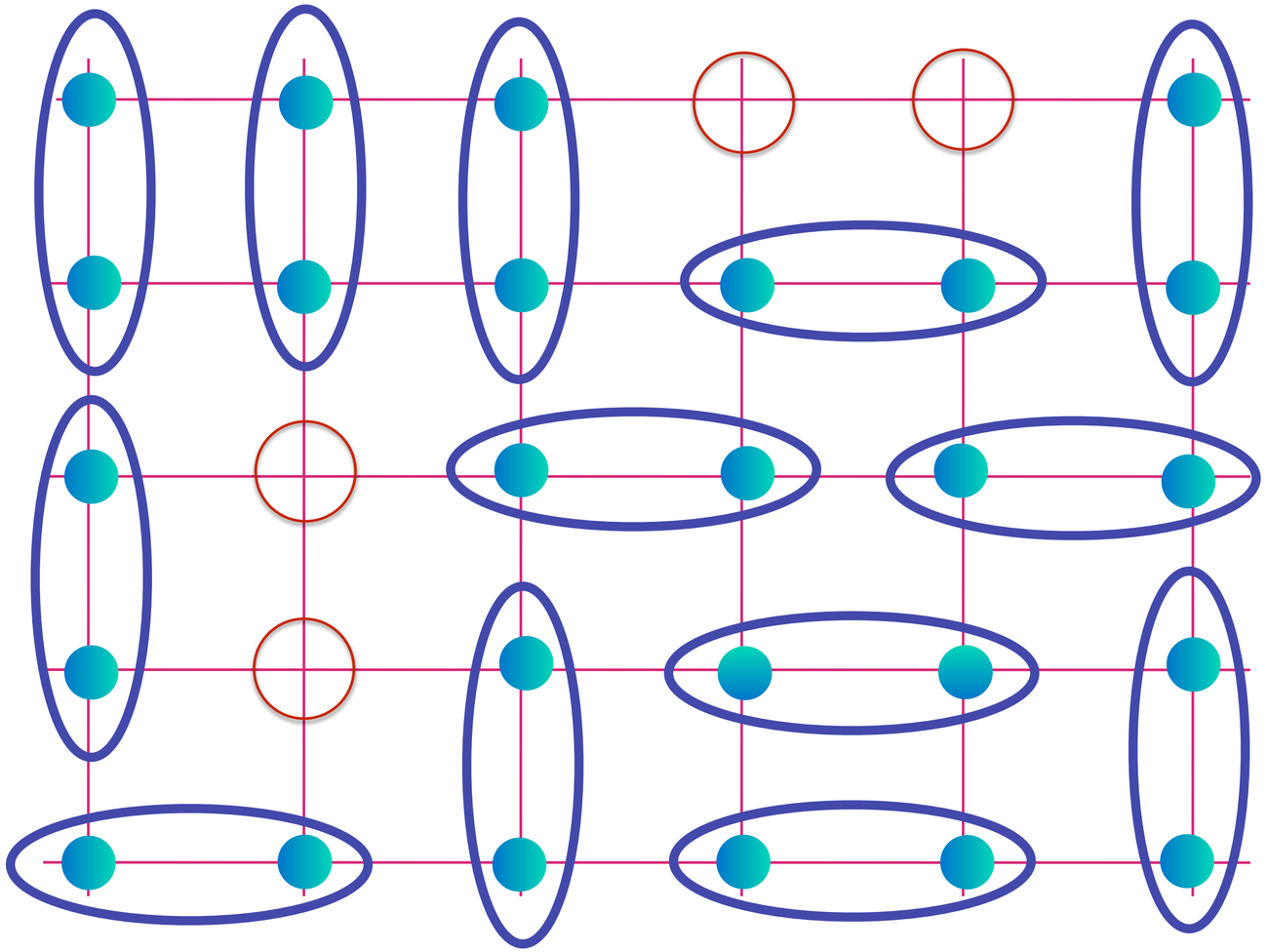

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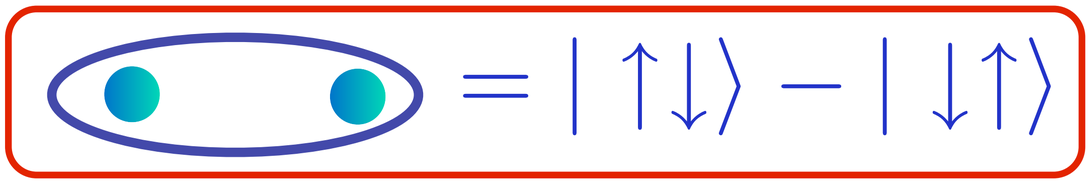

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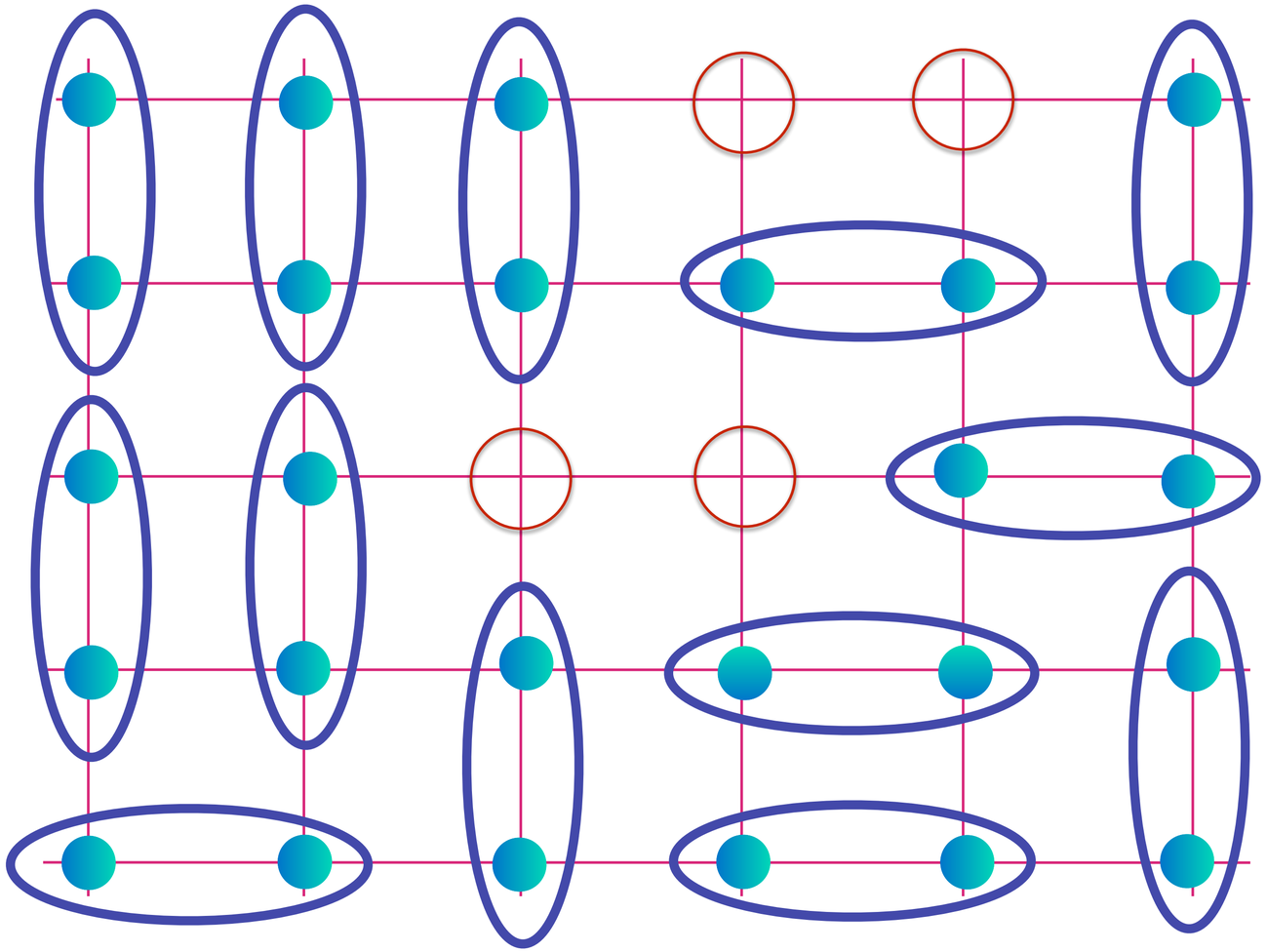

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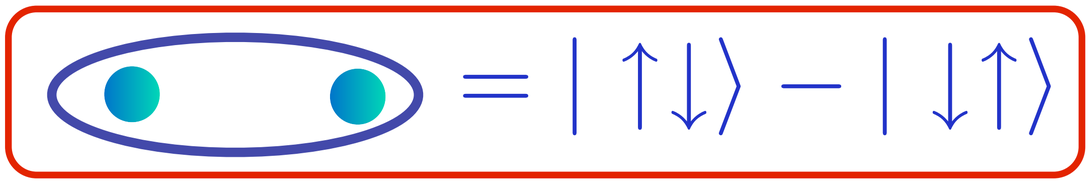

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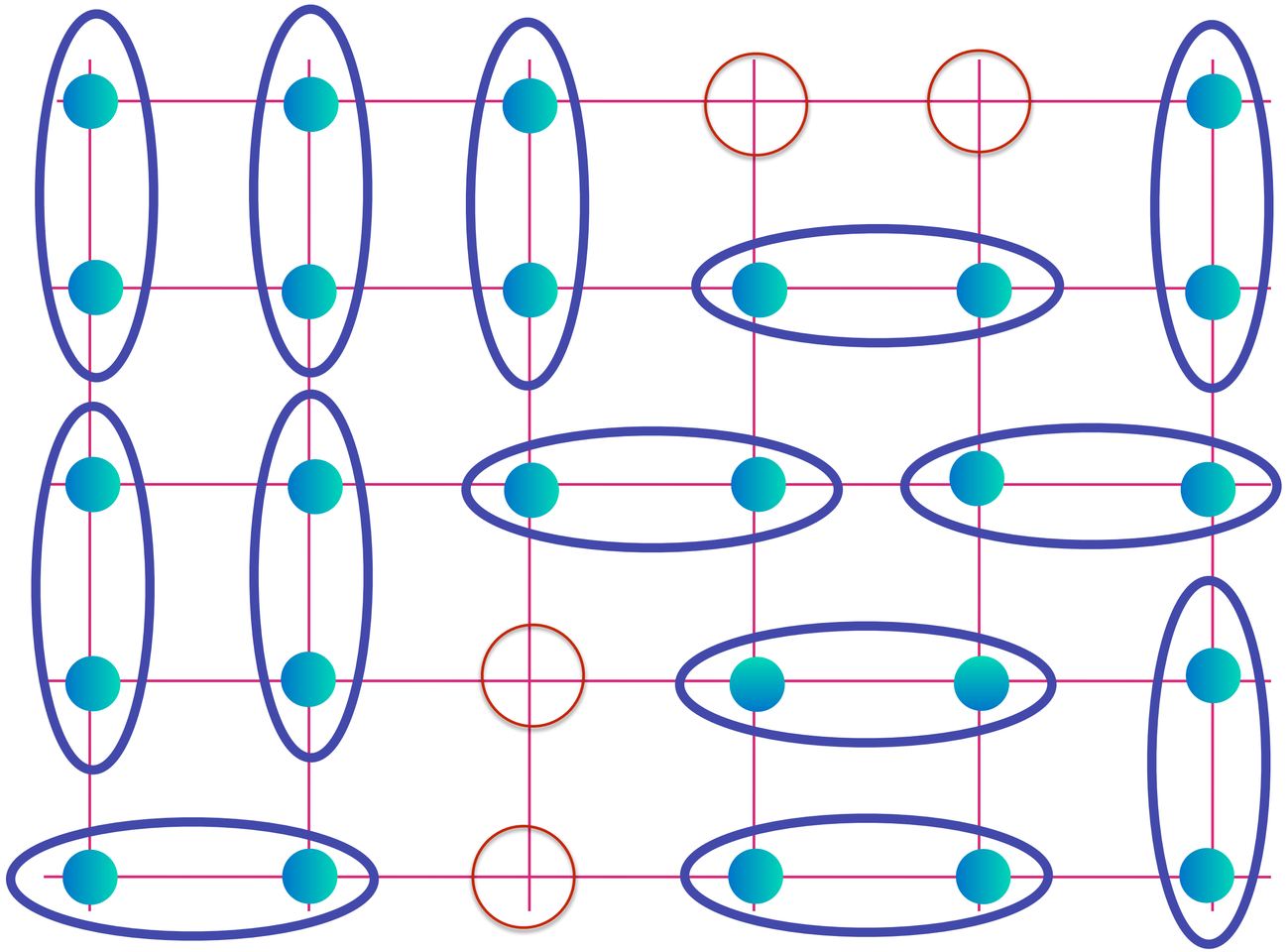

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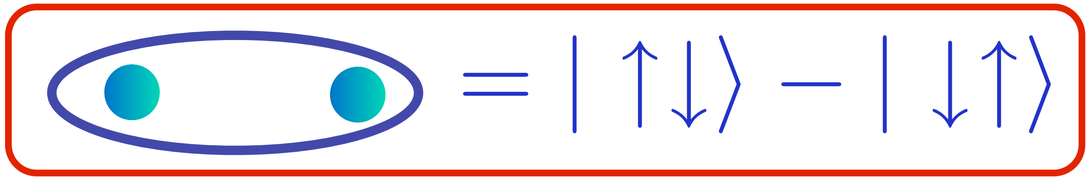

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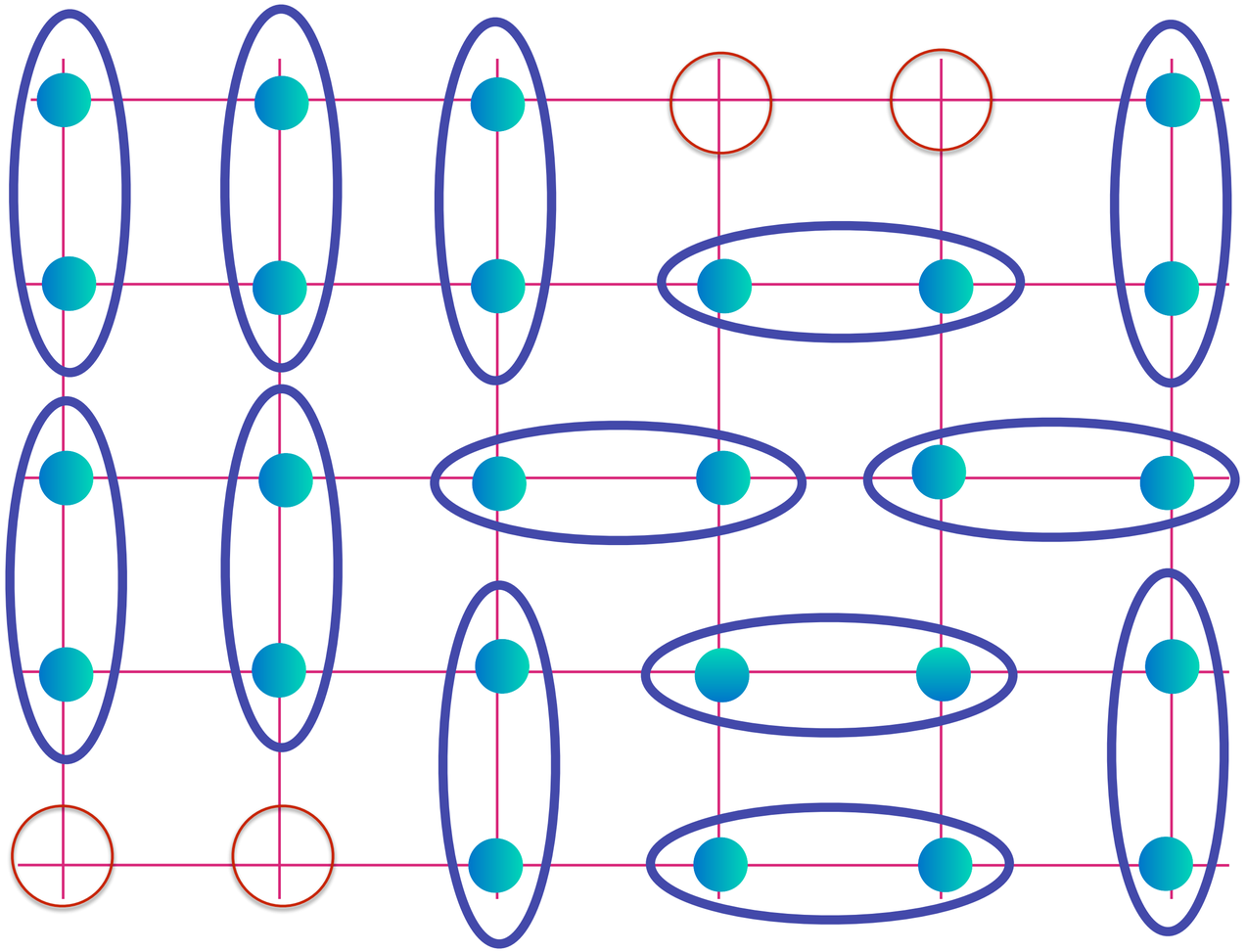

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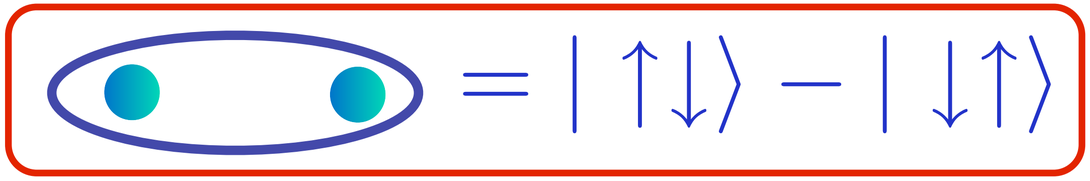

Needed:
A solvable model of quantum entanglement
of $3, 4, 5, \ldots \infty$ particles

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

Kekule's spooky dream (1865)

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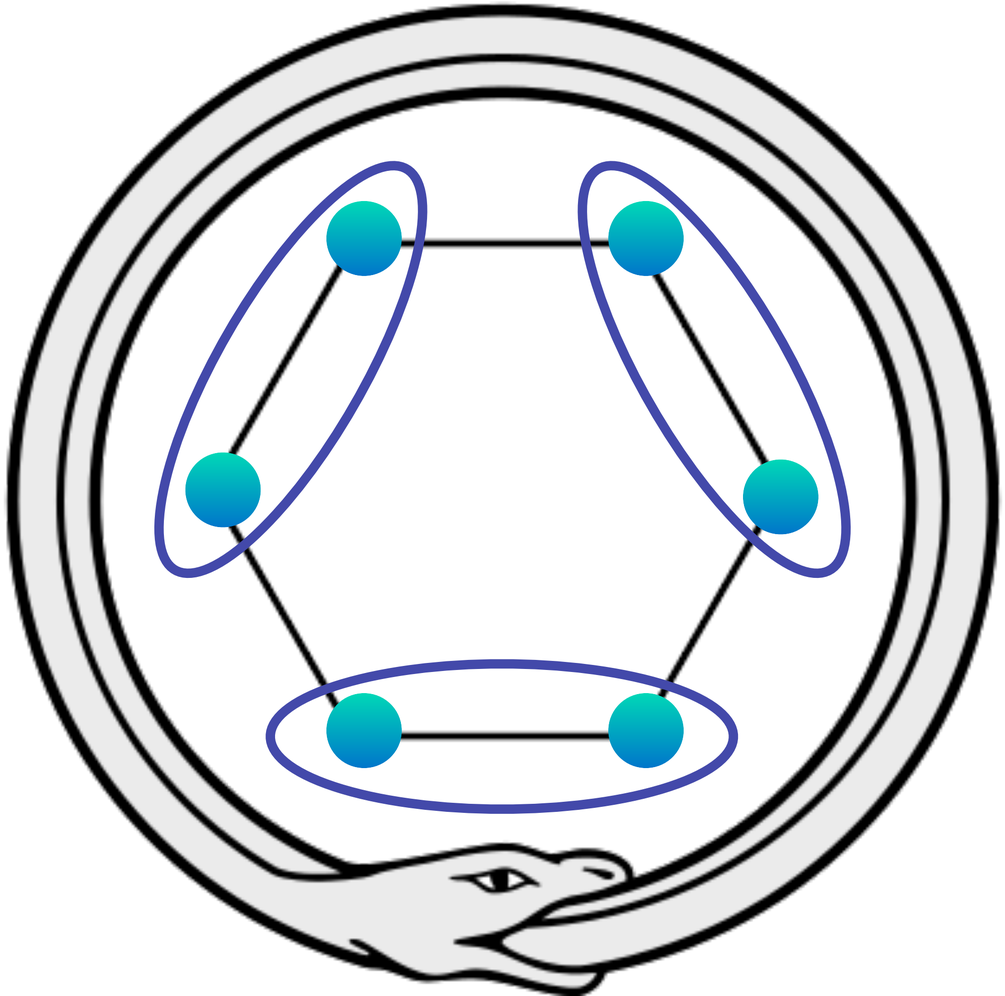

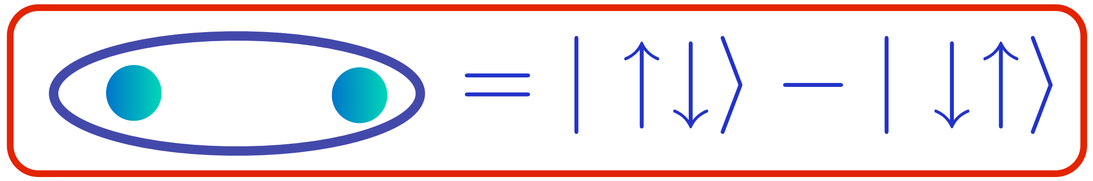

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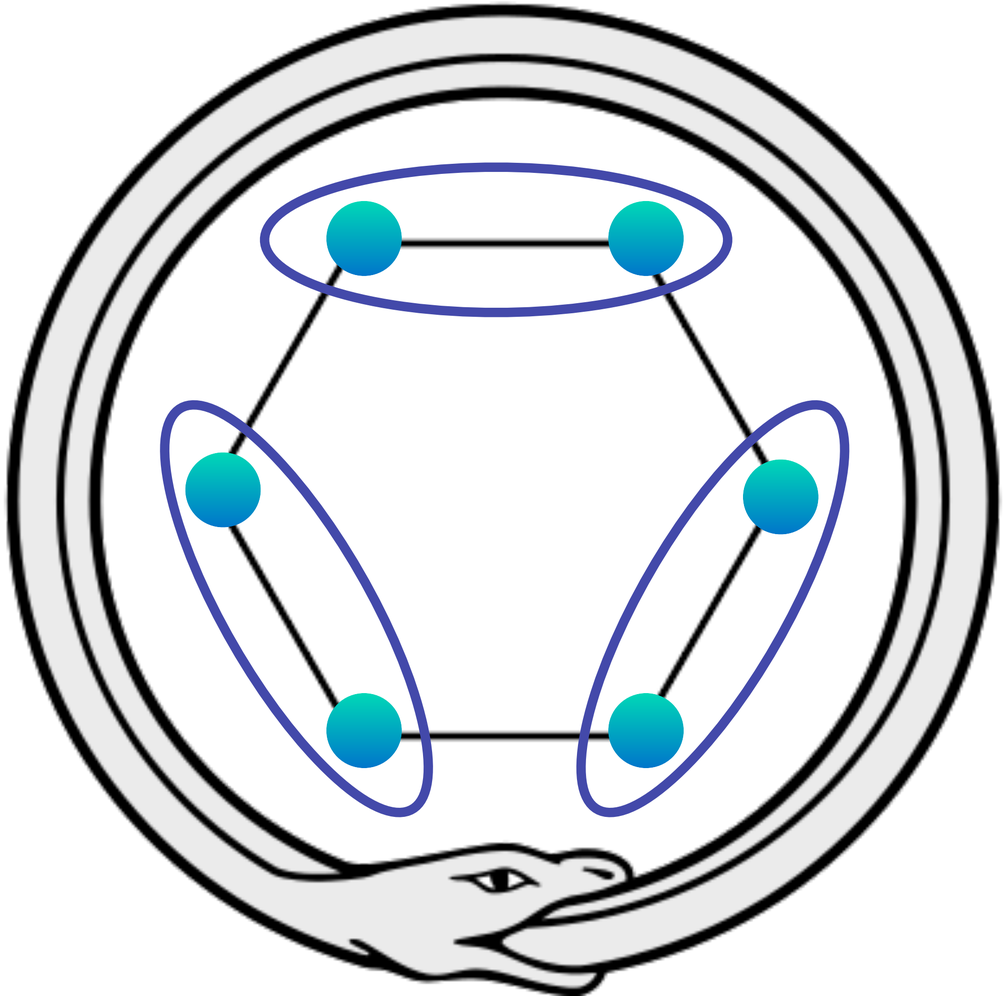

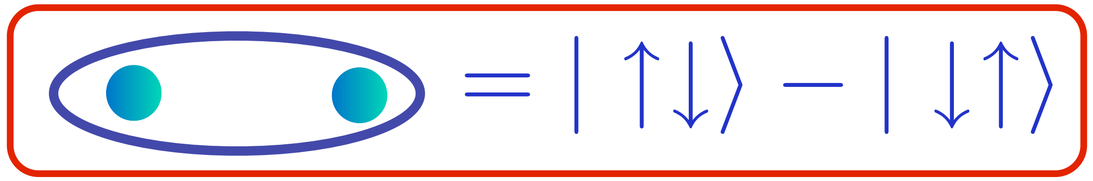

Benzene

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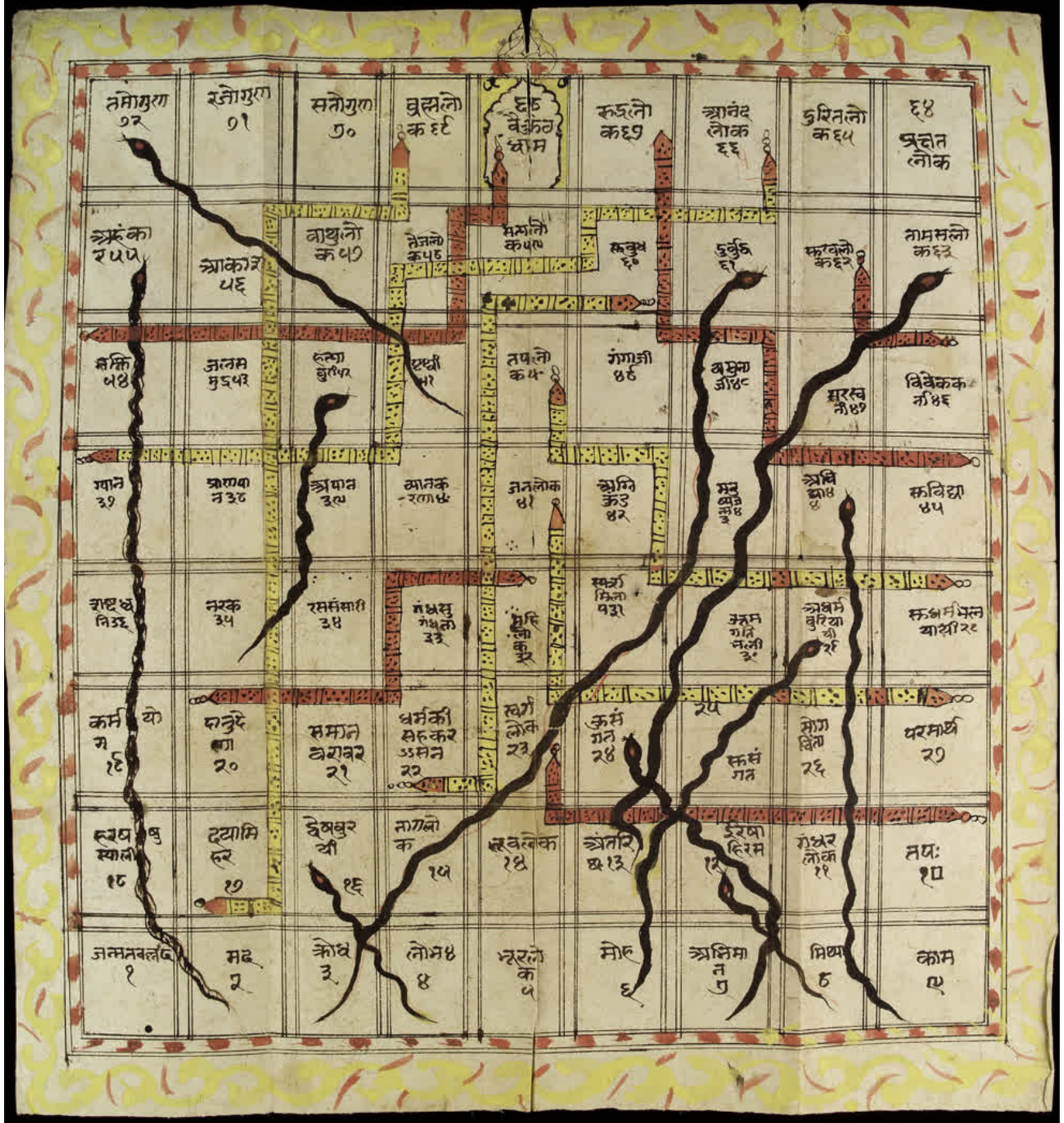


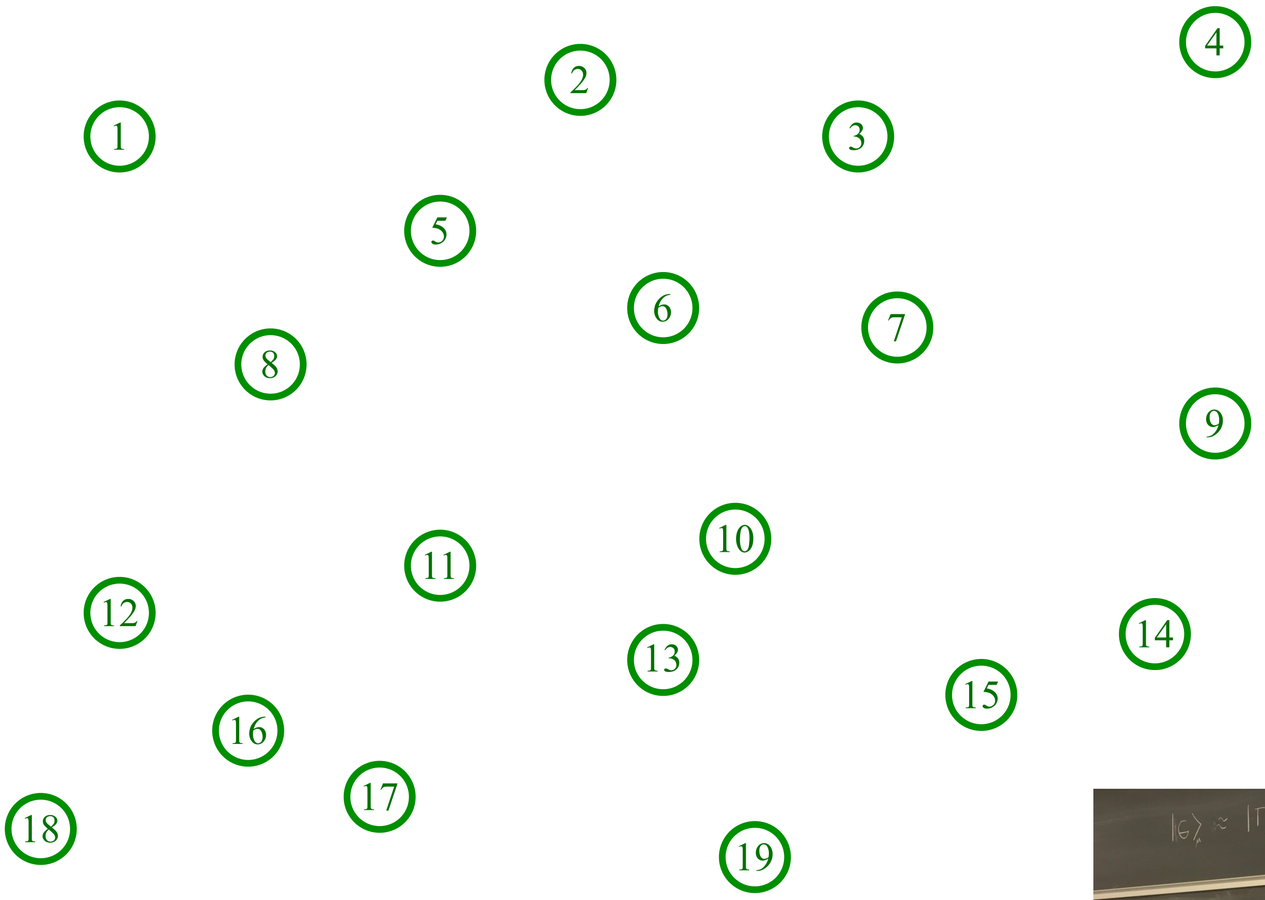
My spooky dream*

Ancient Indian game of Snakes and Ladders

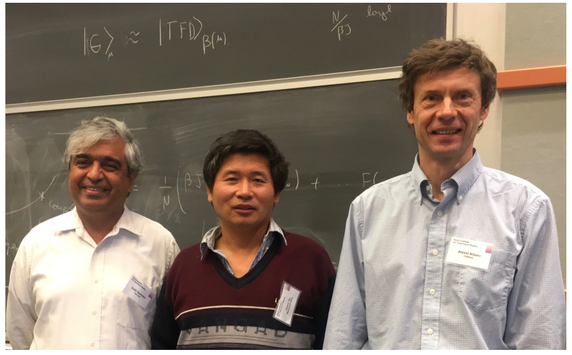
*Not true

The SYK model

Sachdev, Ye (1993); Kitaev (2015)



Pick a set of random positions



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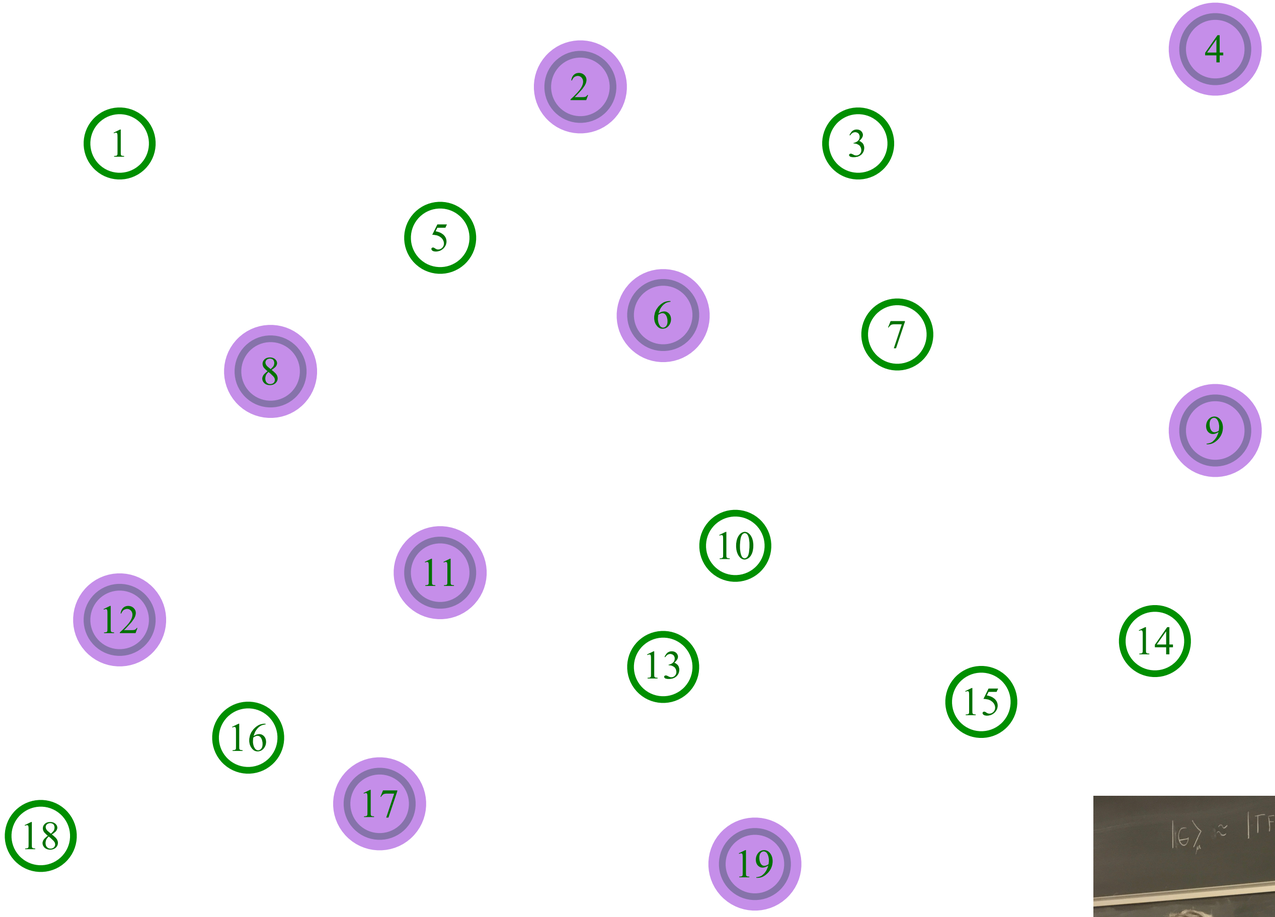
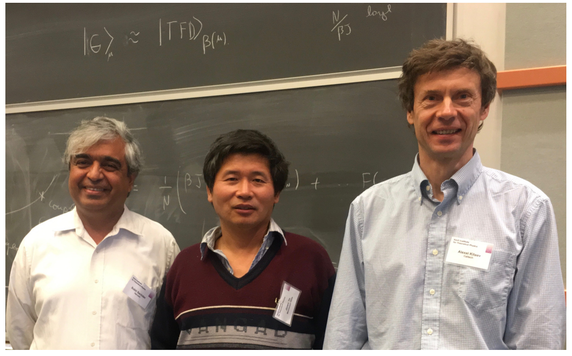


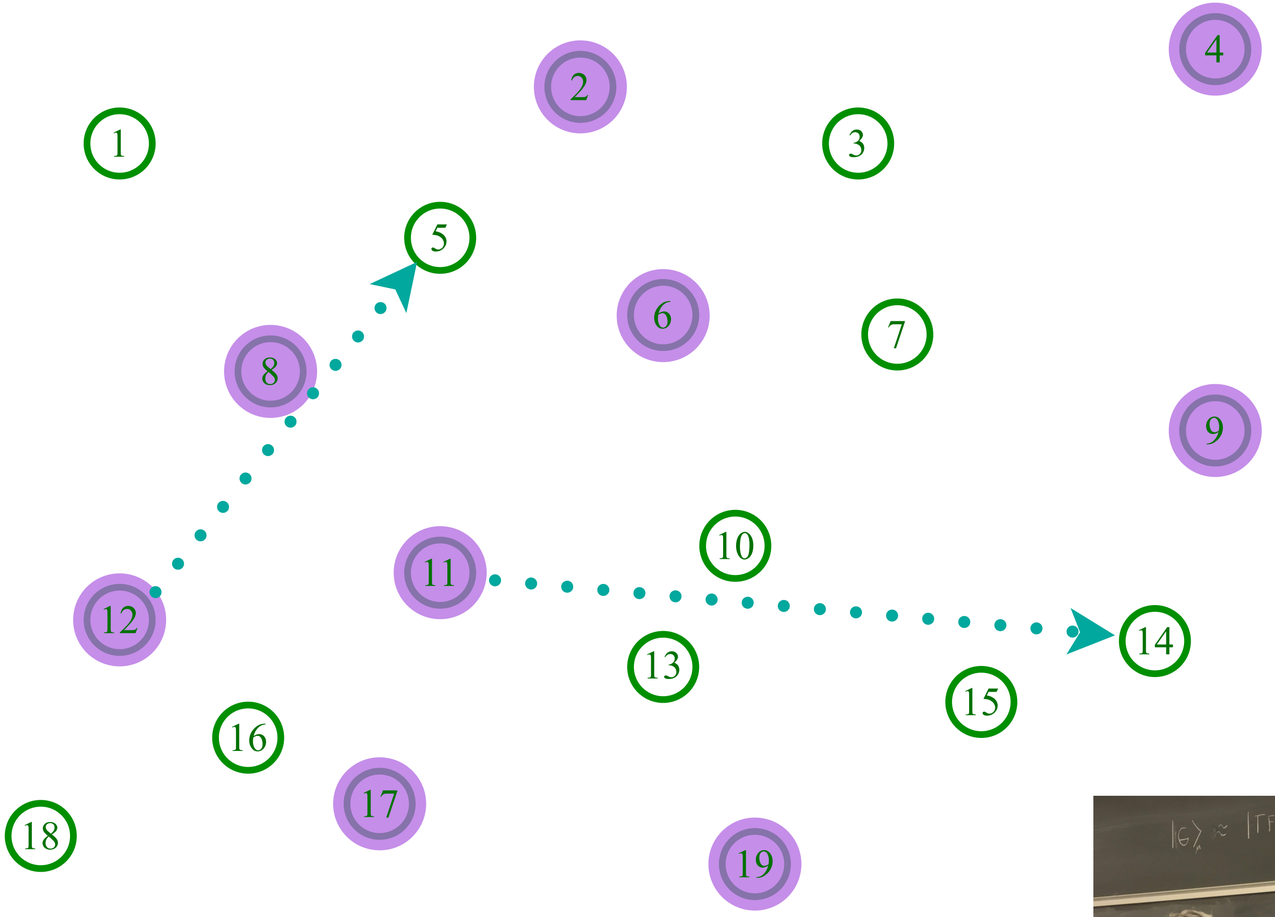
Place electrons randomly on some sites



The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



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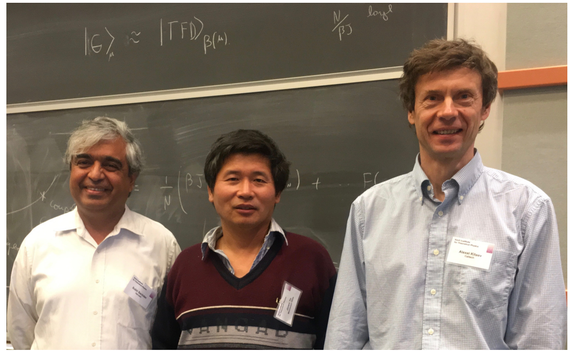
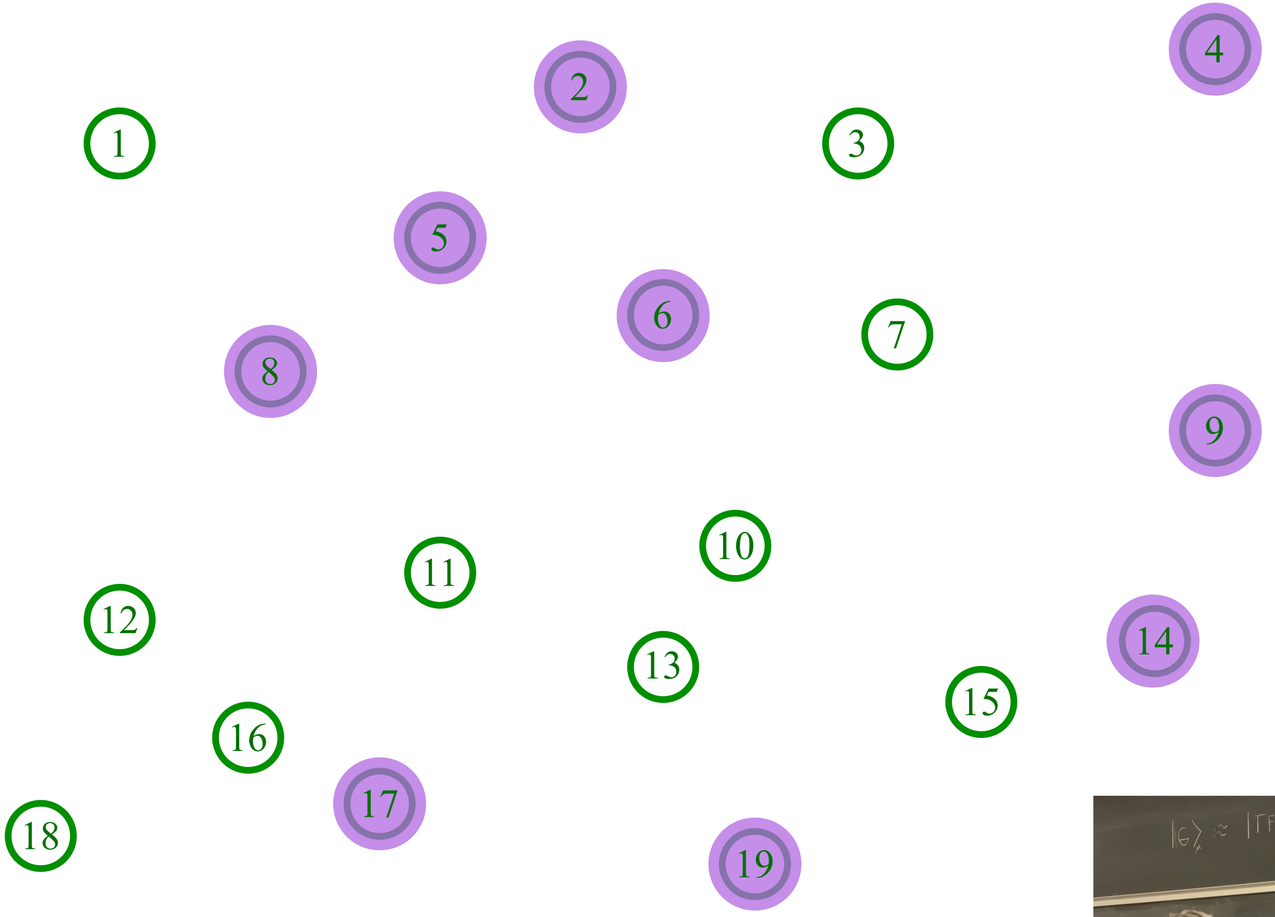


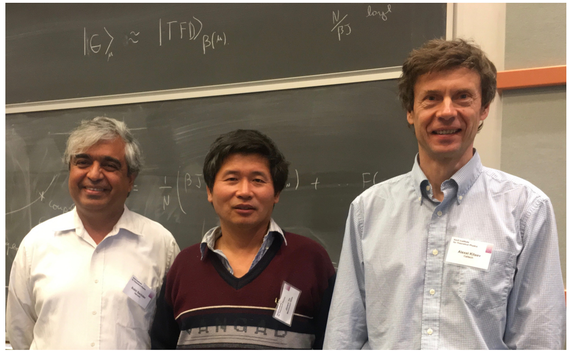
The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



Entangle electrons pairwise randomly



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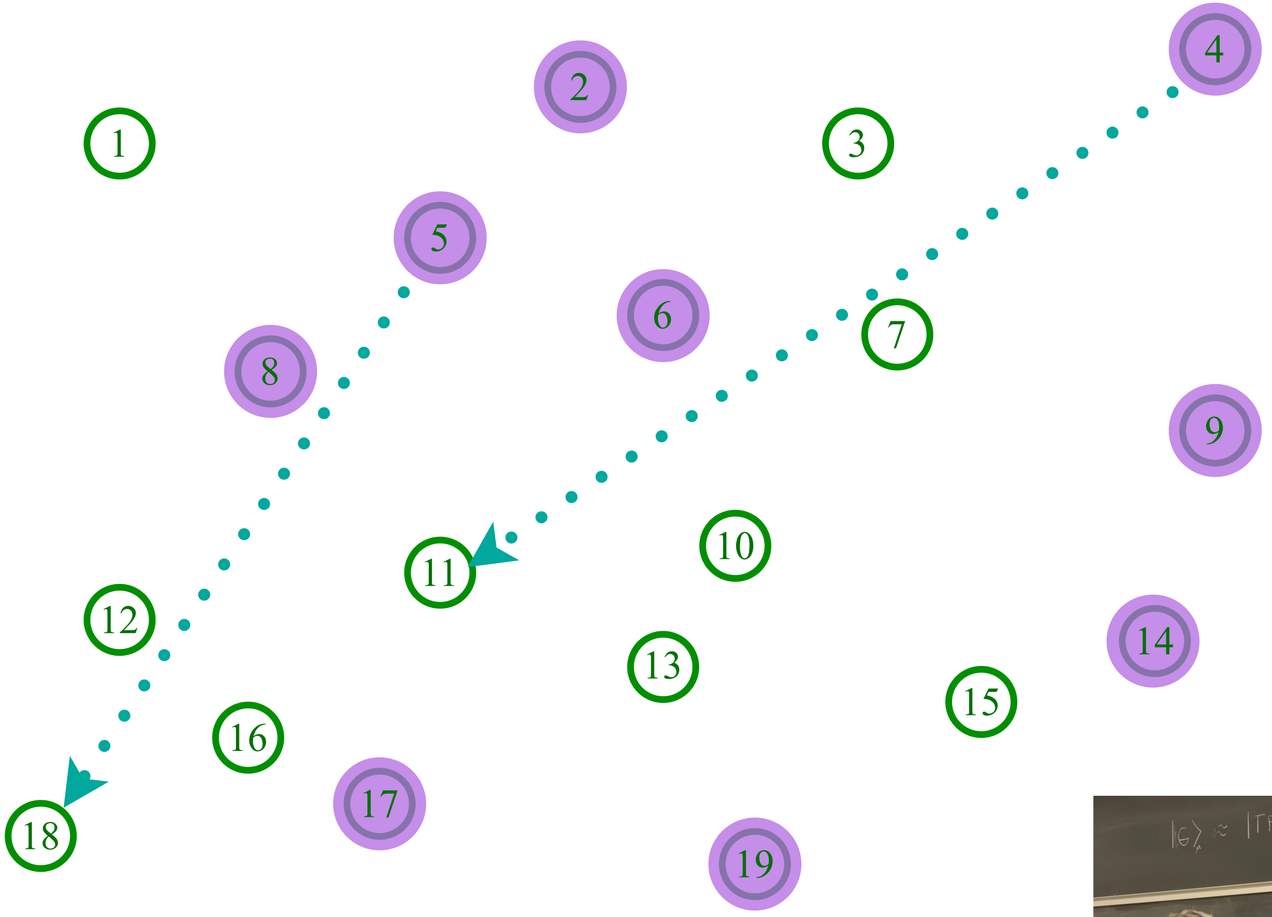
Sachdev, Ye (1993); Kitaev (2015)

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



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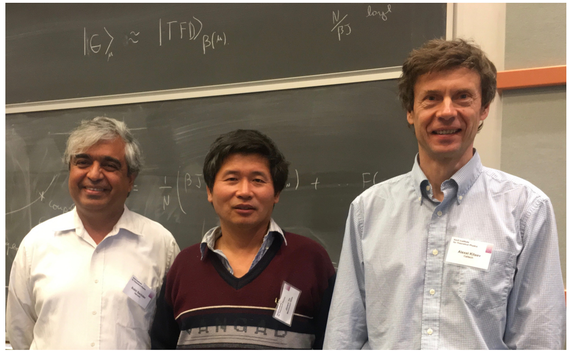

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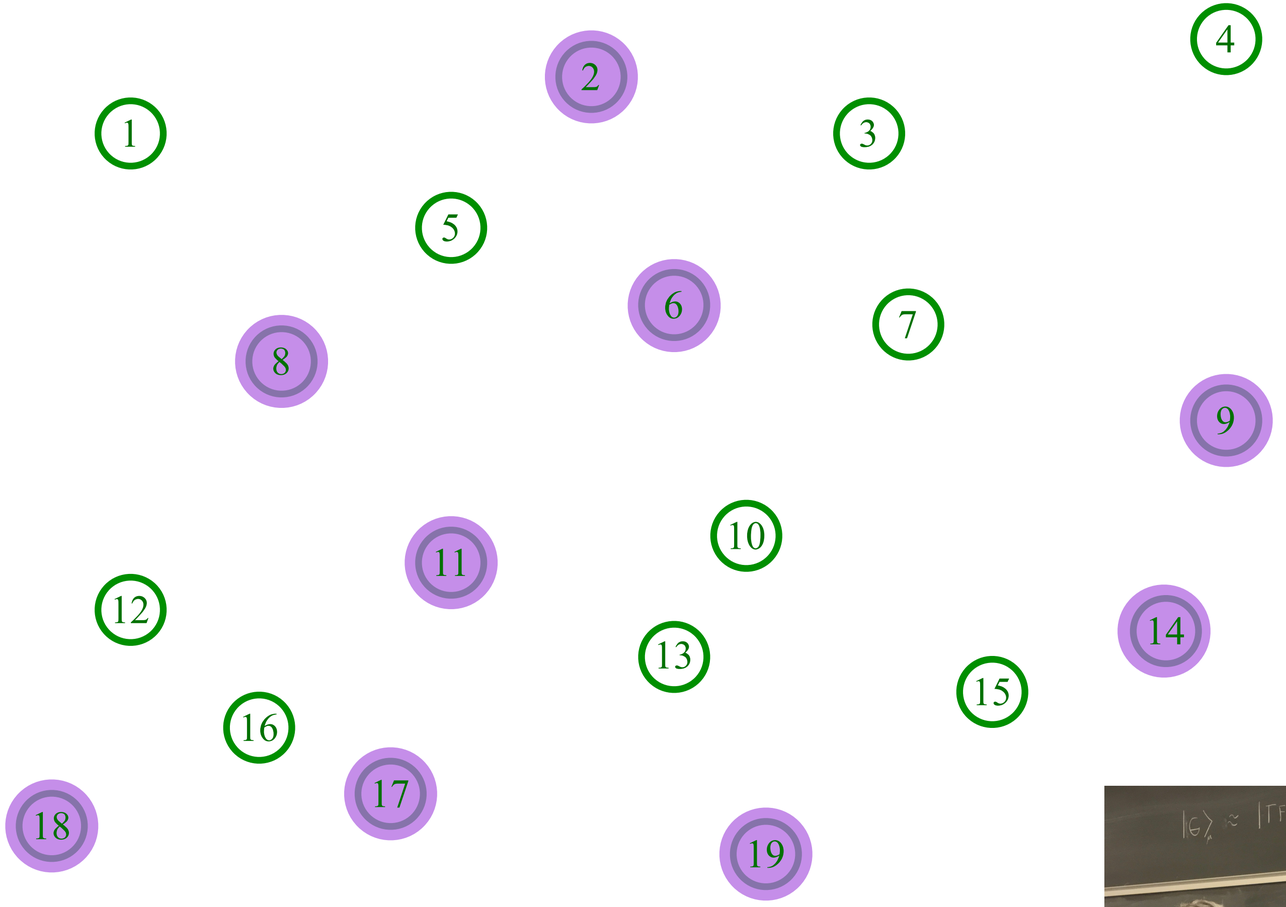

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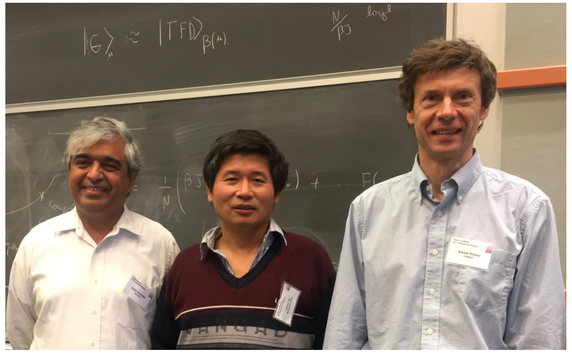
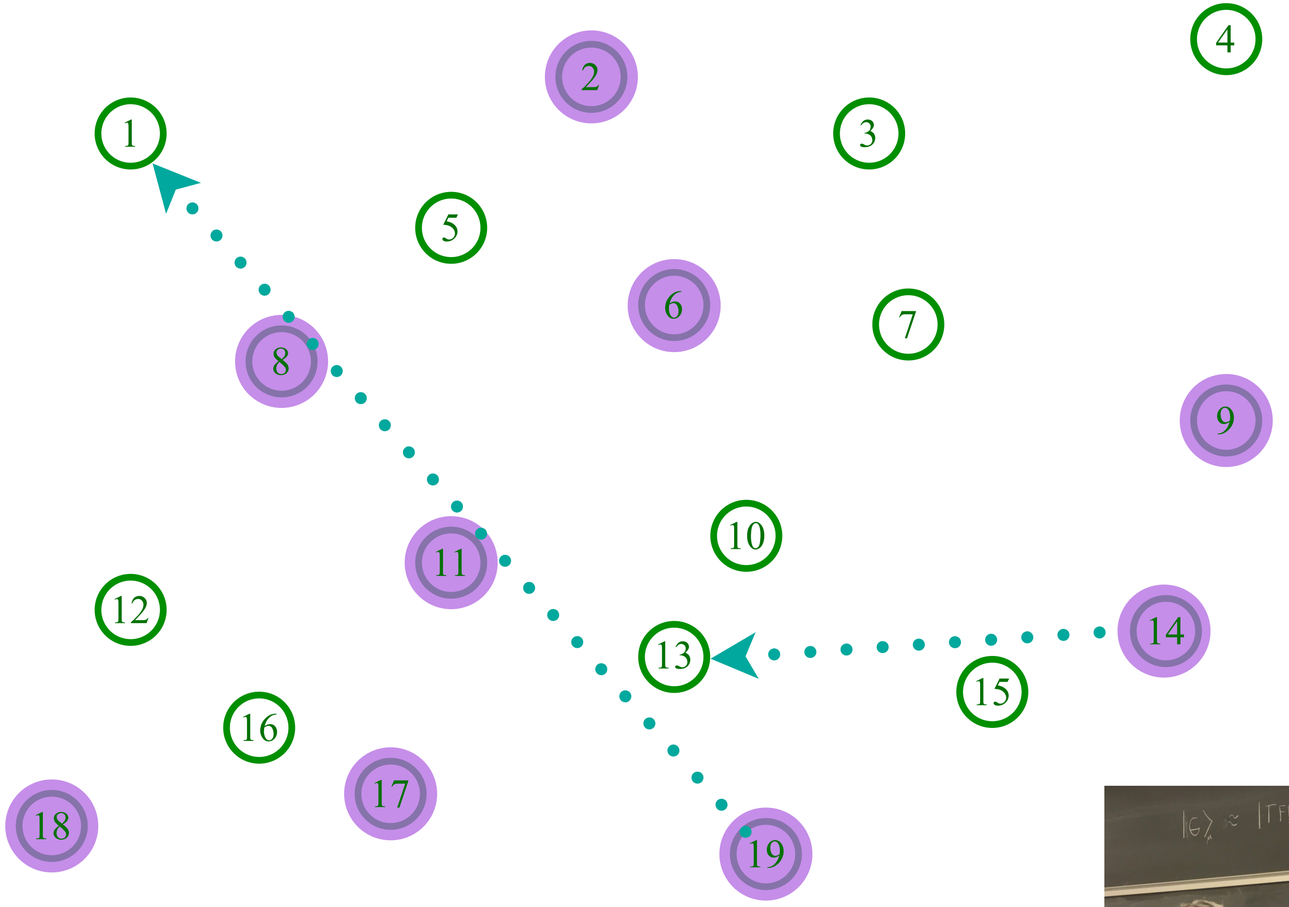


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



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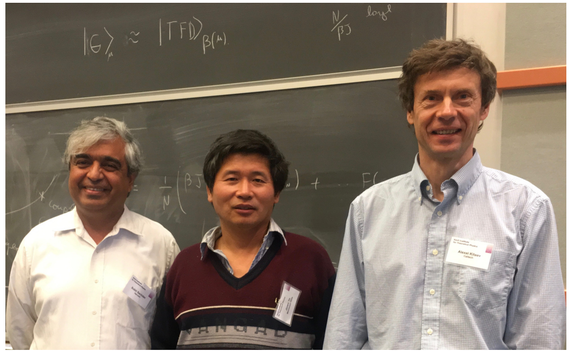

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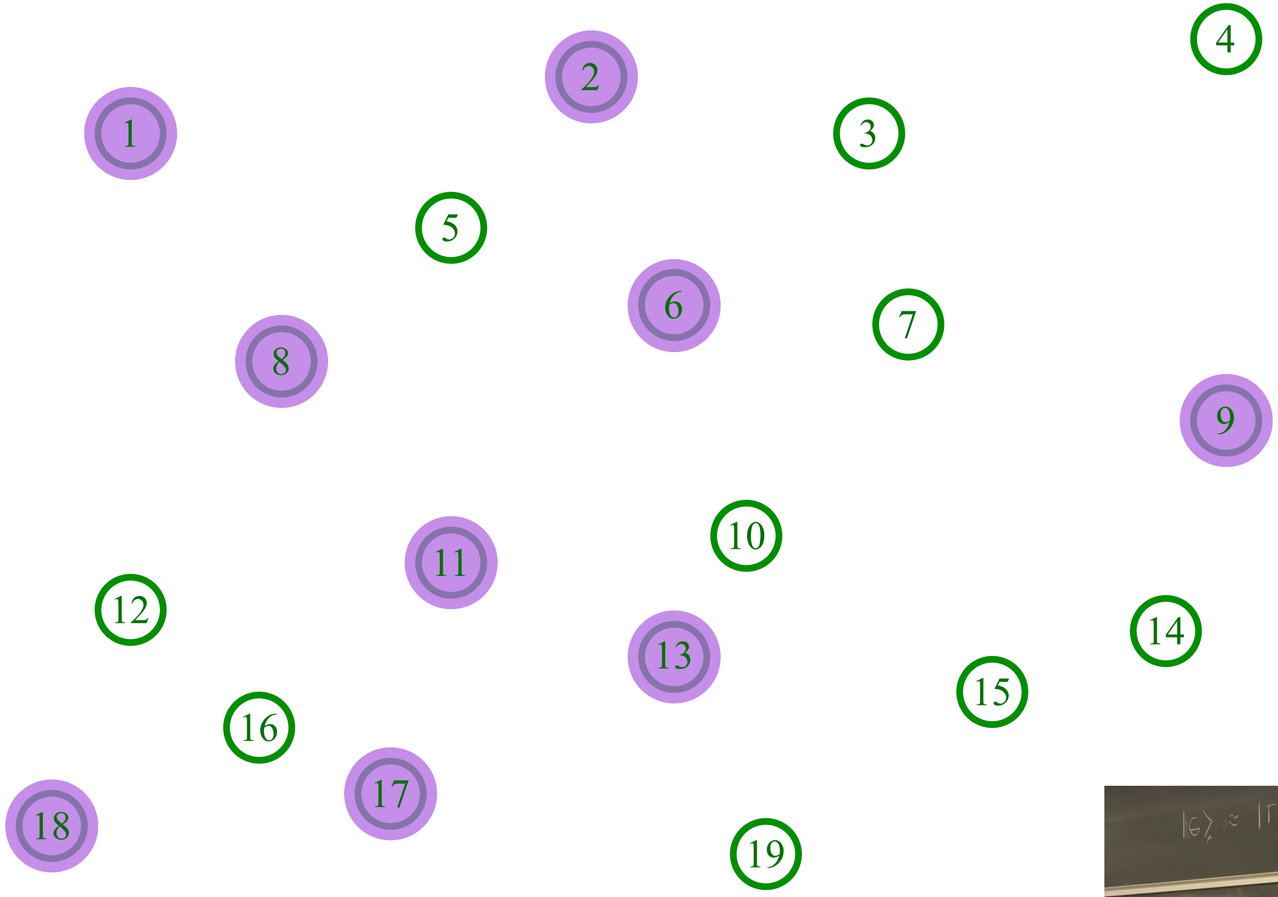

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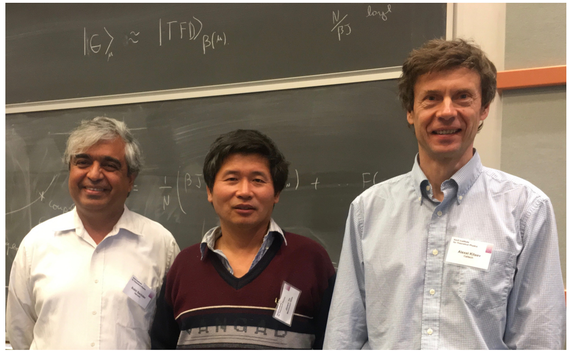

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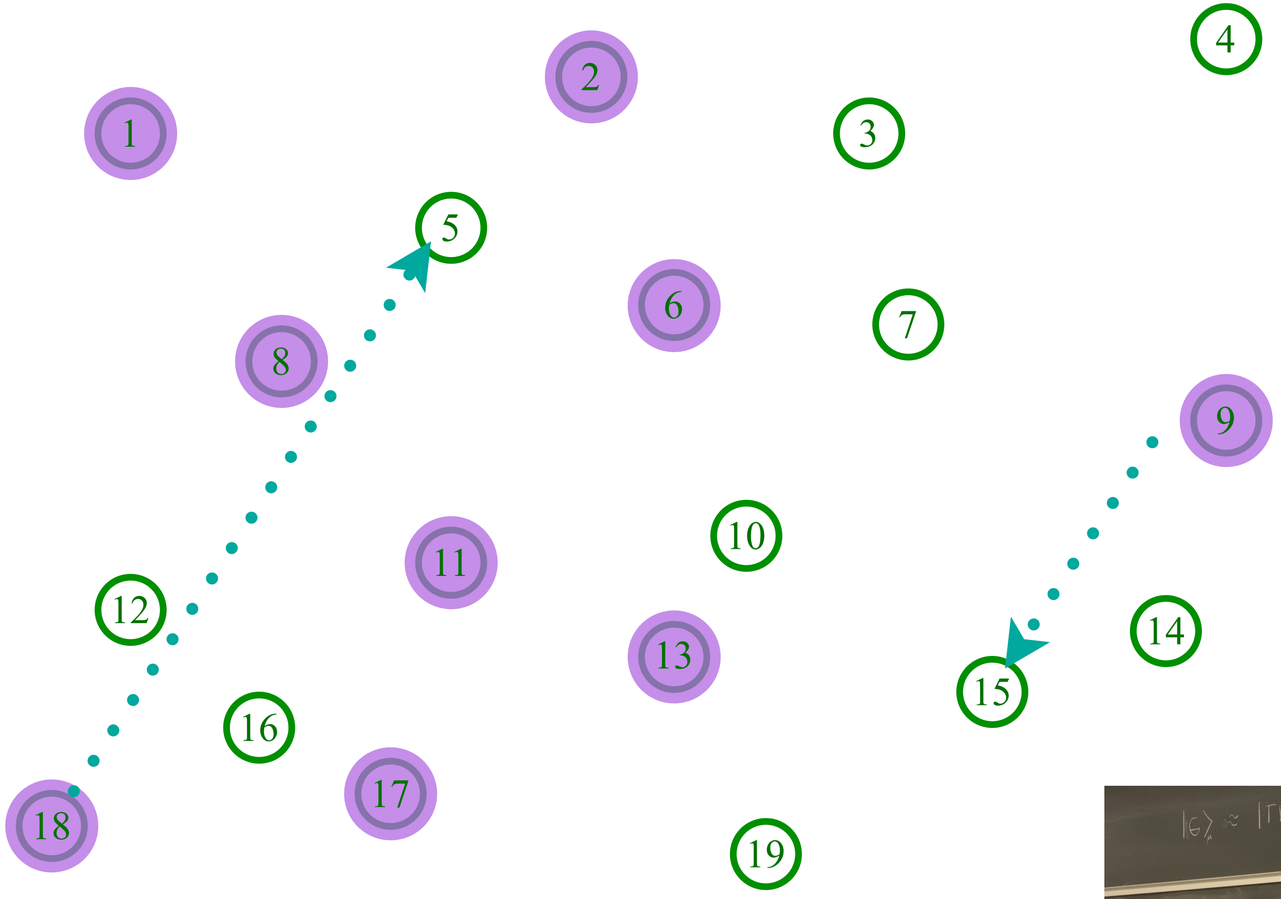
Sachdev, Ye (1993); Kitaev (2015)

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



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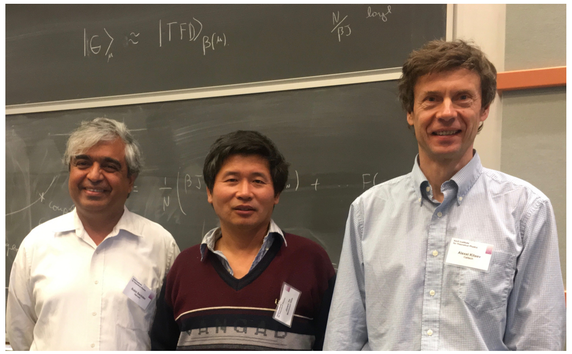

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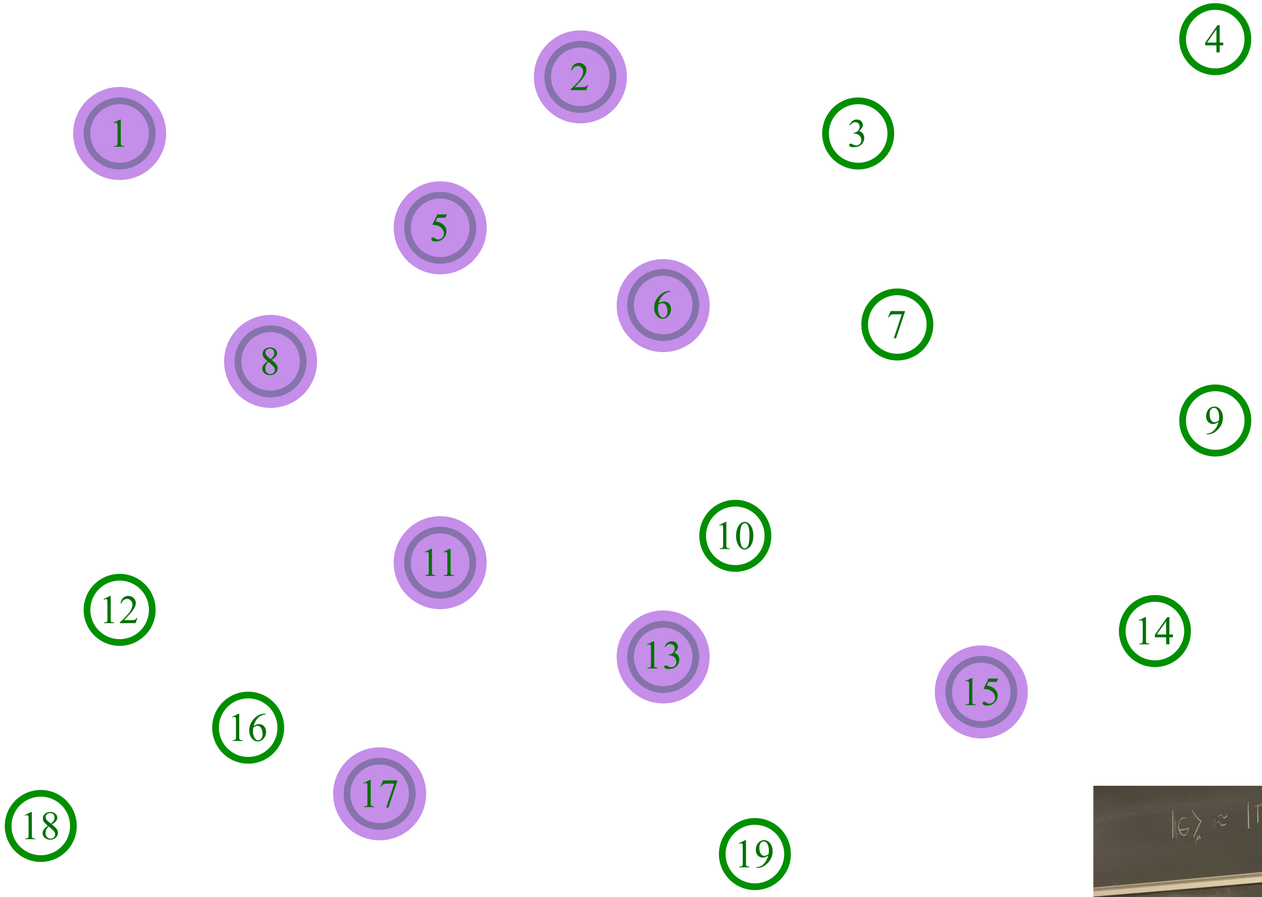

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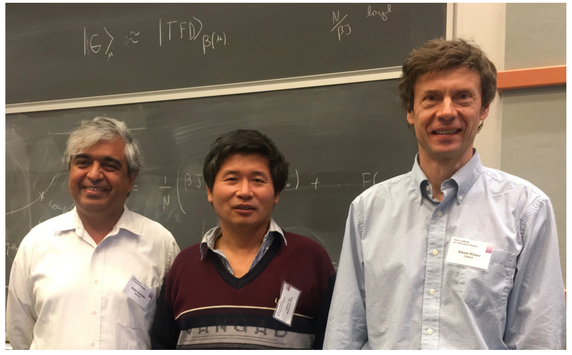
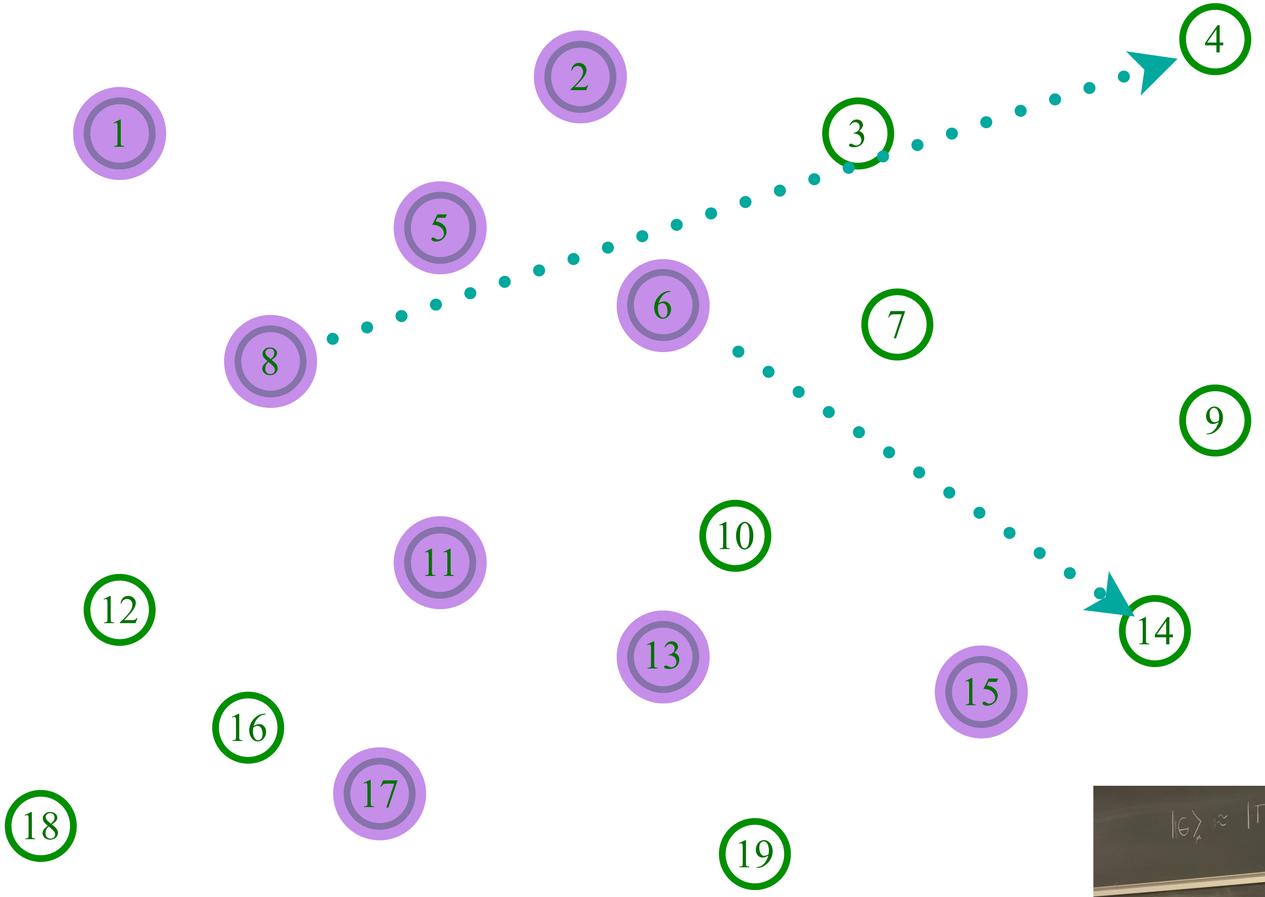


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



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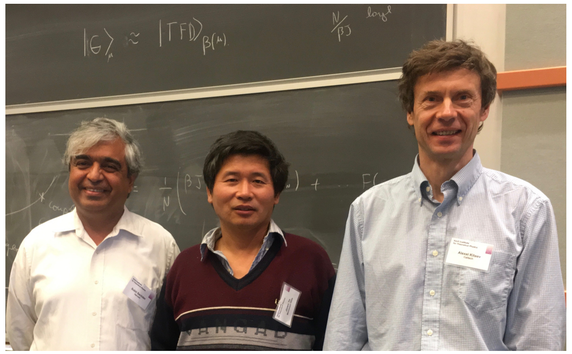

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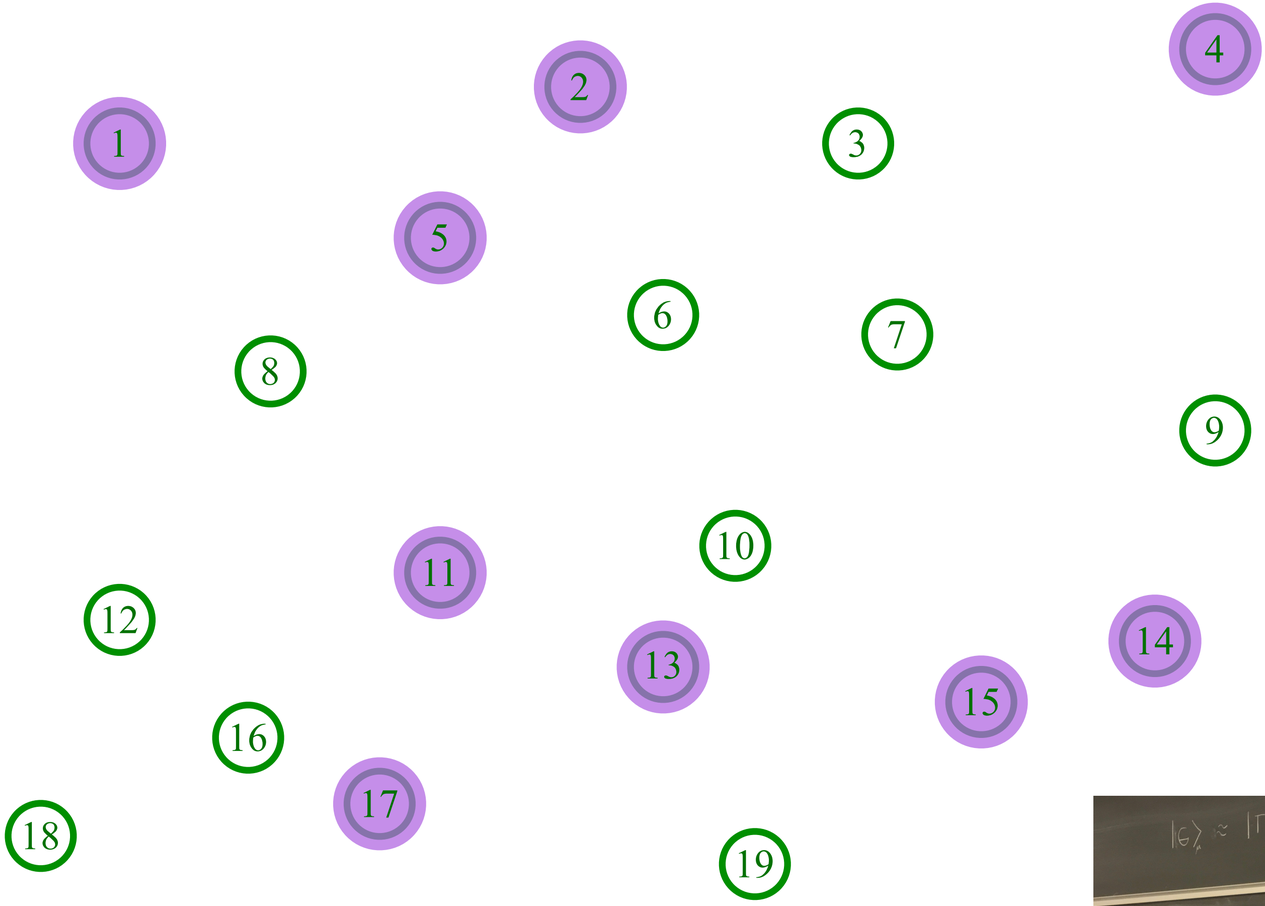

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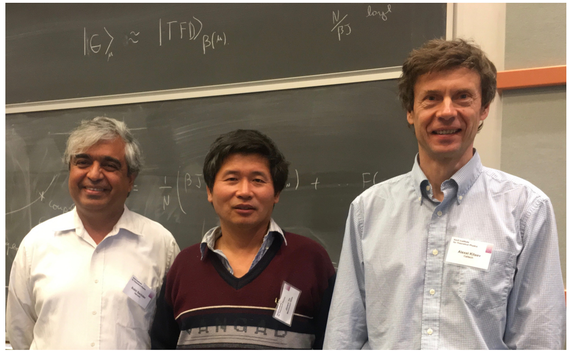


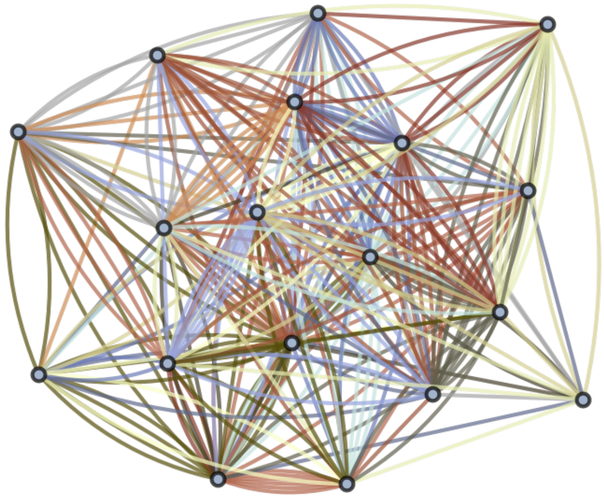
The Sachdev-Ye-Kitaev (SYK) model

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"

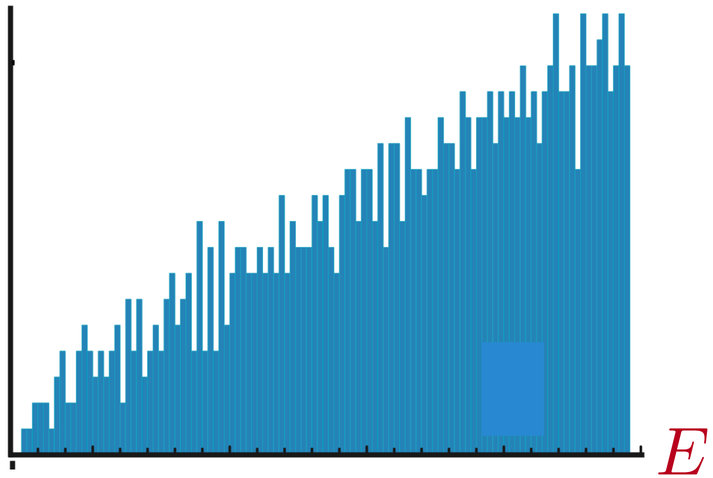
The Sachdev-Ye-Kitaev (SYK) model



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

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

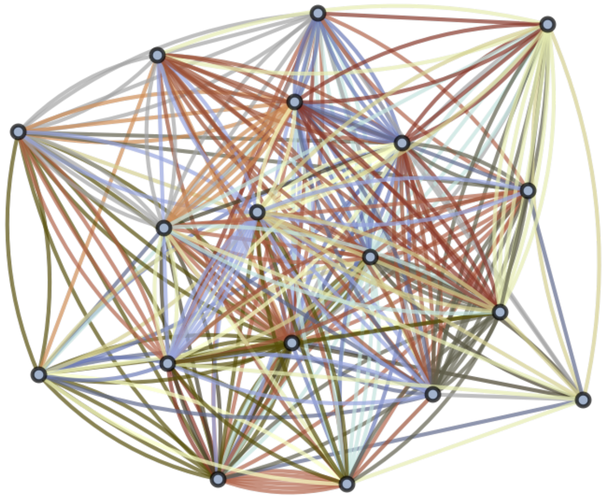
where $s_0 = 0.46484769917080510749....$



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

The Sachdev-Ye-Kitaev (SYK) model

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



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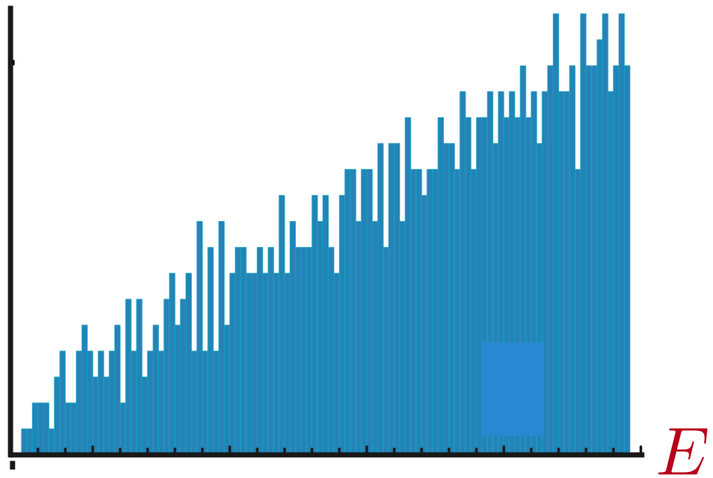

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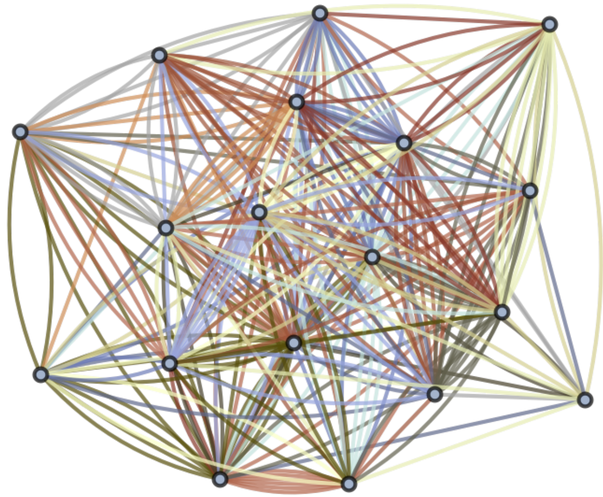

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J. S. Cotler et al.,
JHEP 05 (2017) 118

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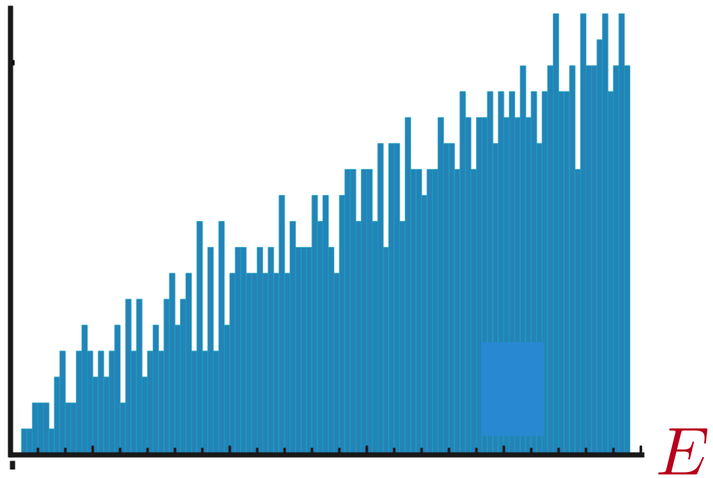

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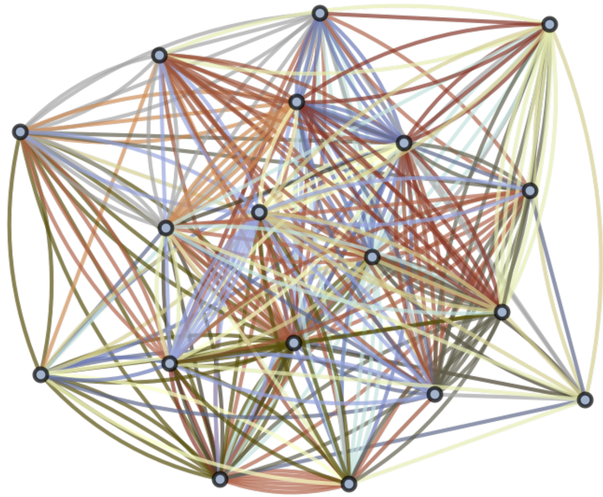

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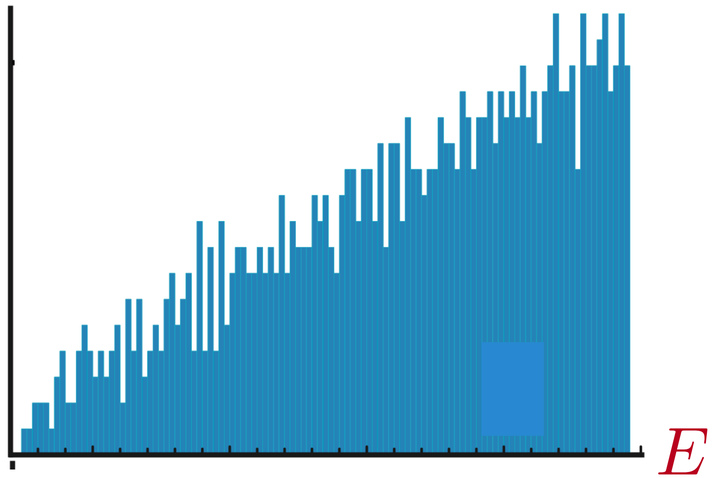
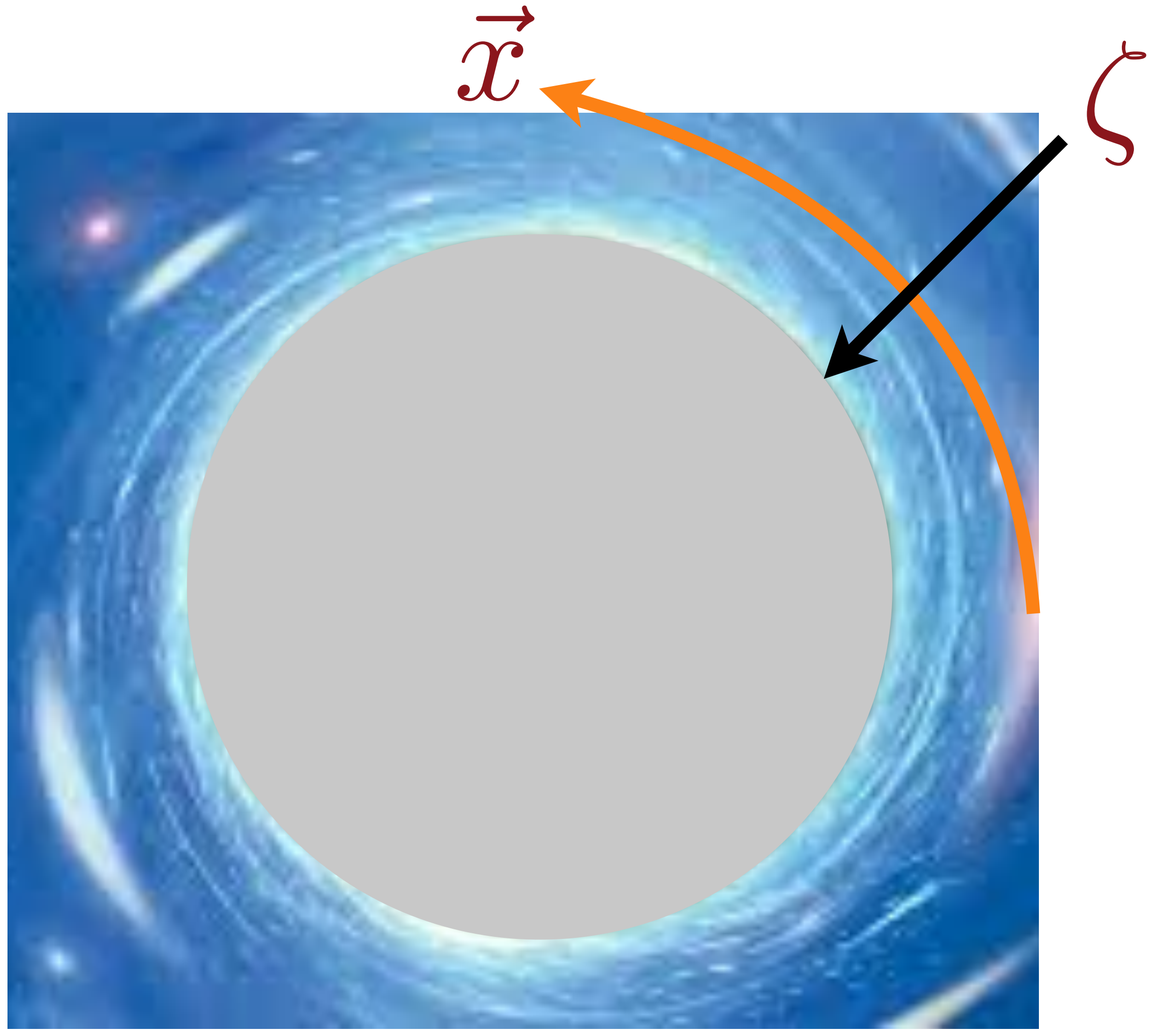
Yingfei Gu, A. Kitaev, S. Sachdev, and
G. Tarnopolsky, JHEP 02 (2020) 157



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

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



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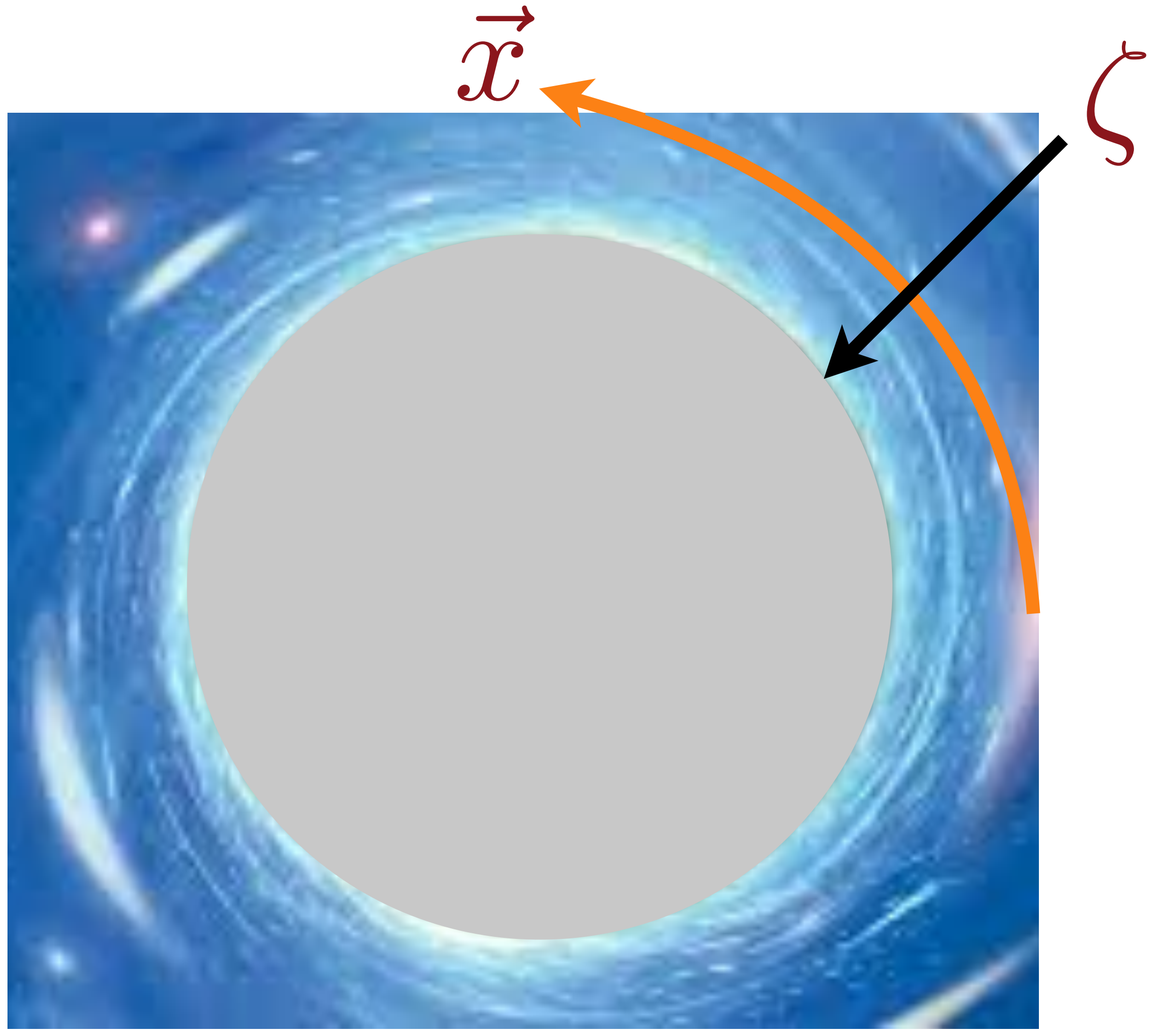

Zooming into the near-horizon region of a charged black hole at low temperature, yields a theory in one space (ζ) and one time dimension

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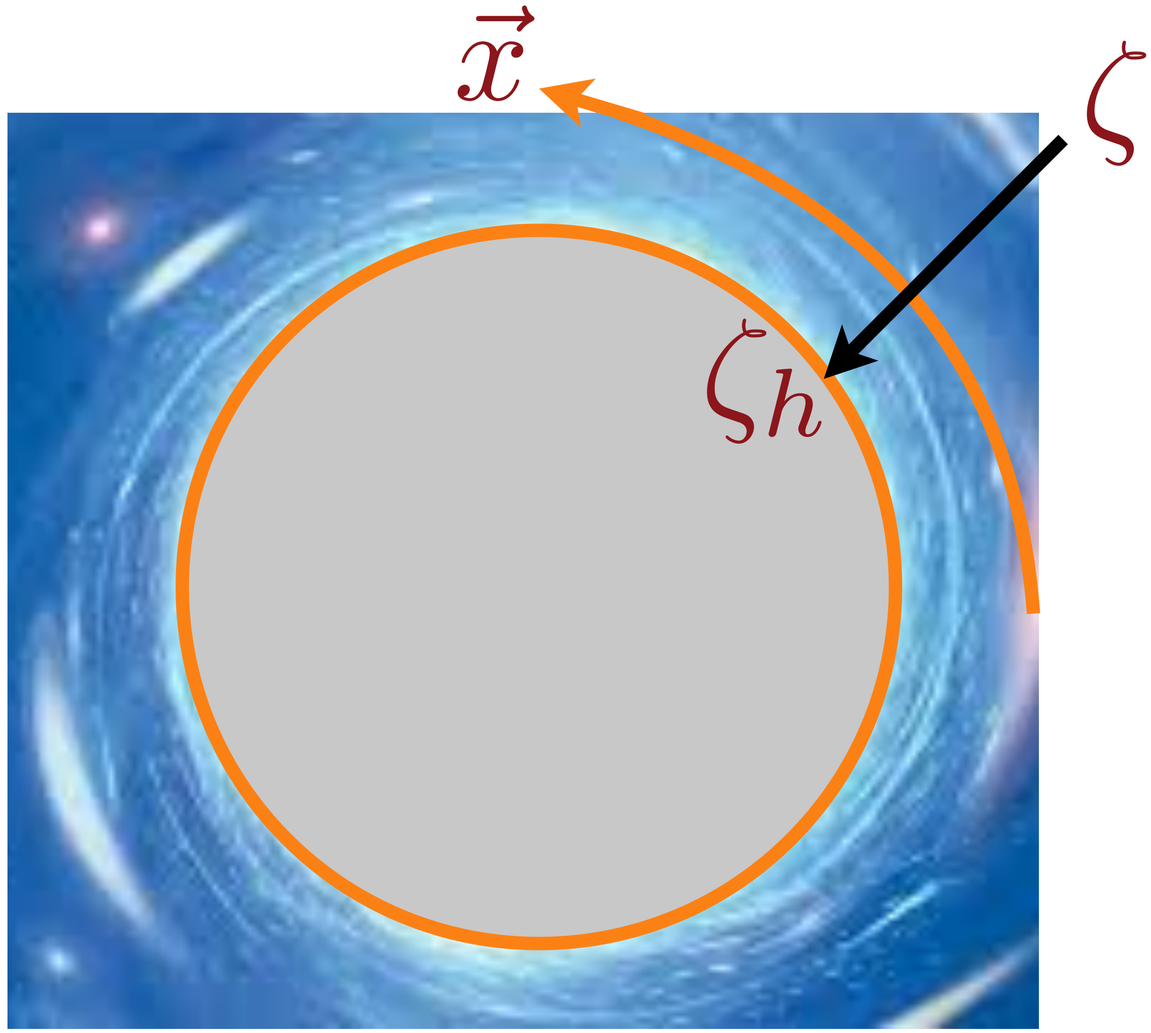
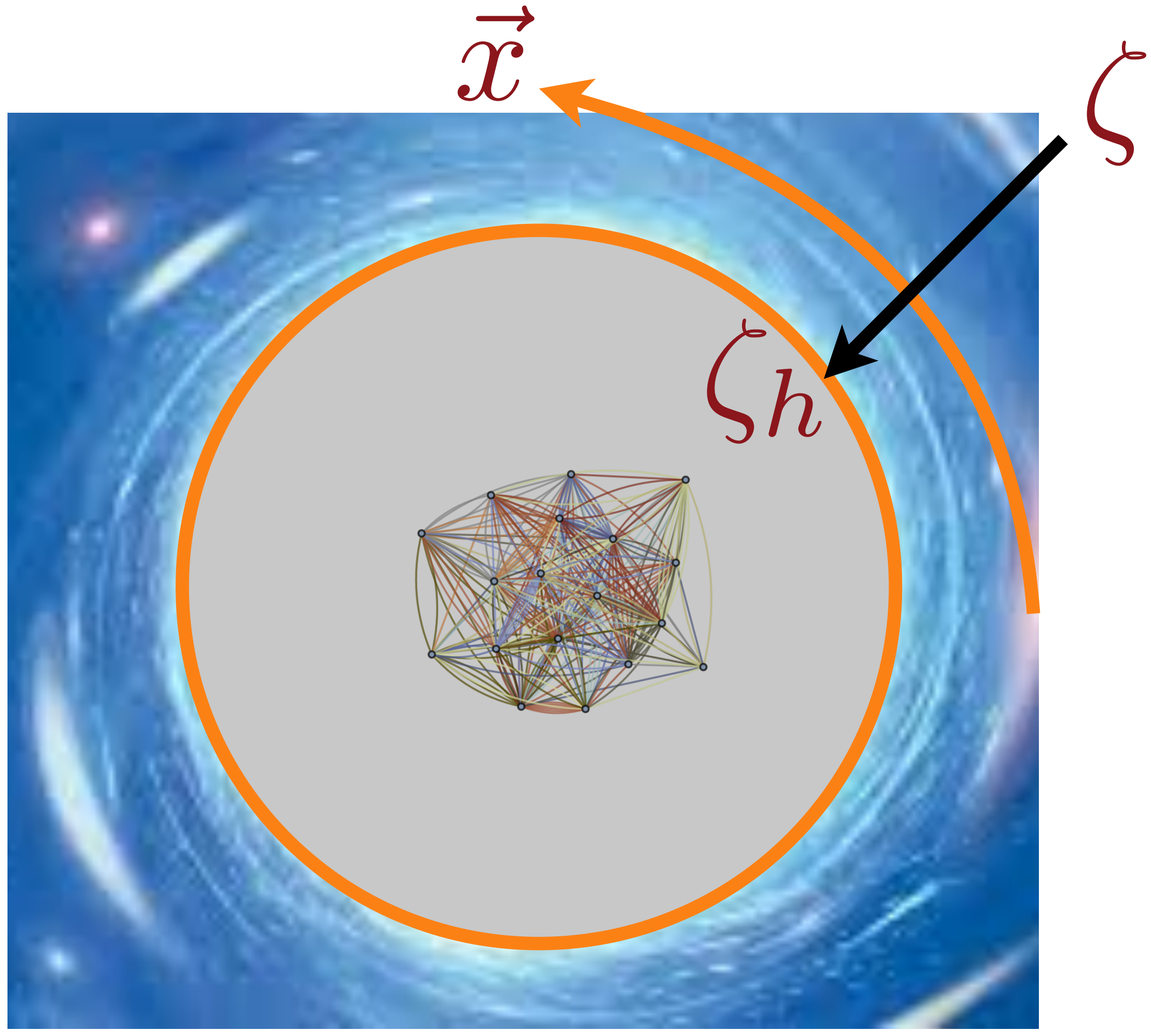


So we need only consider complex entanglement at one spatial "point" on the horizon ($\zeta = \zeta_h$), just as is described by the SYK model

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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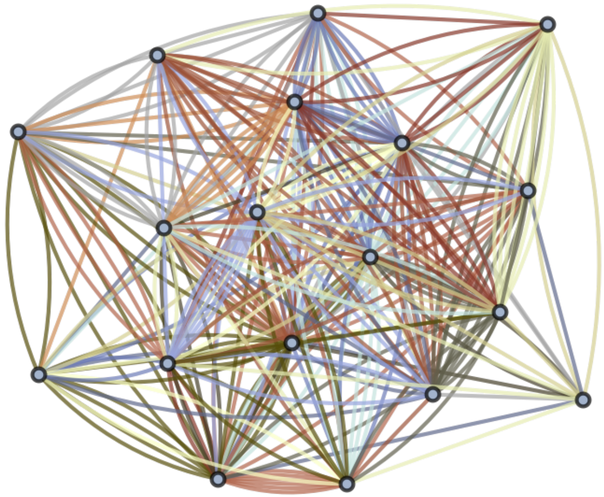

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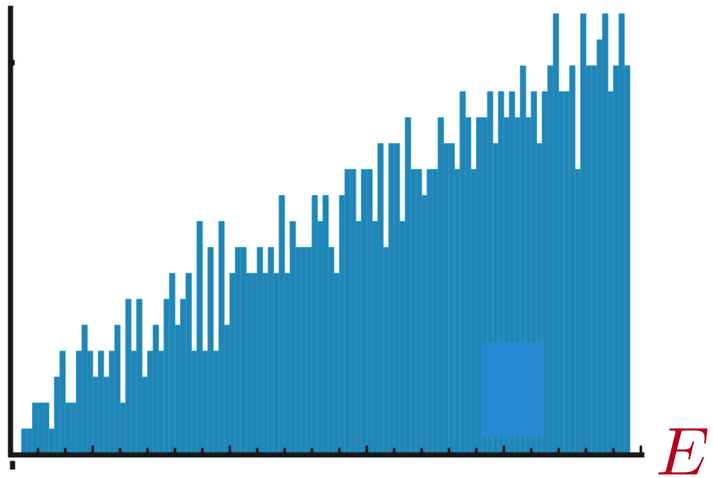
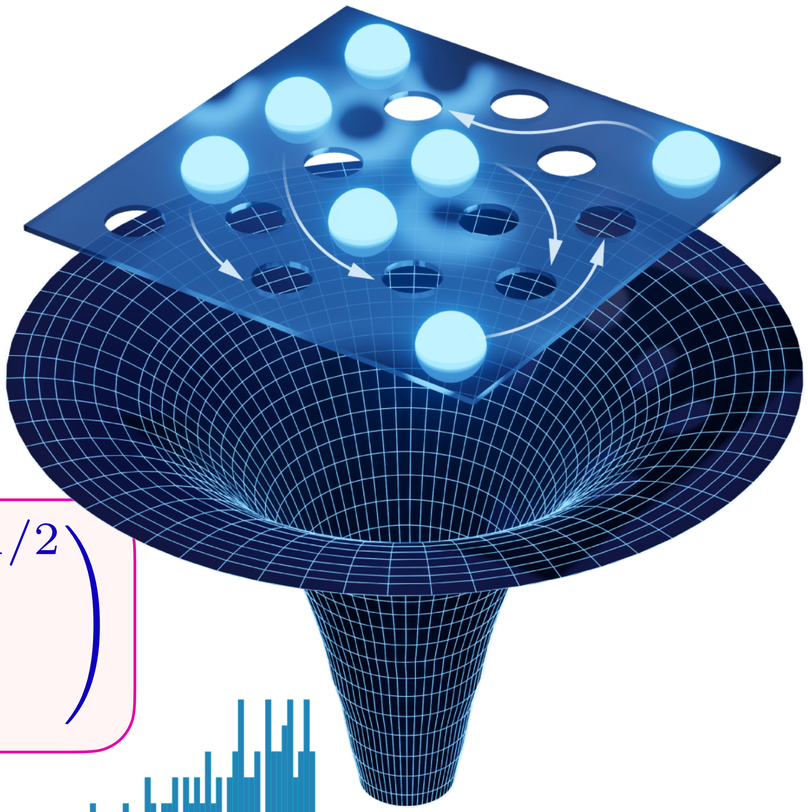


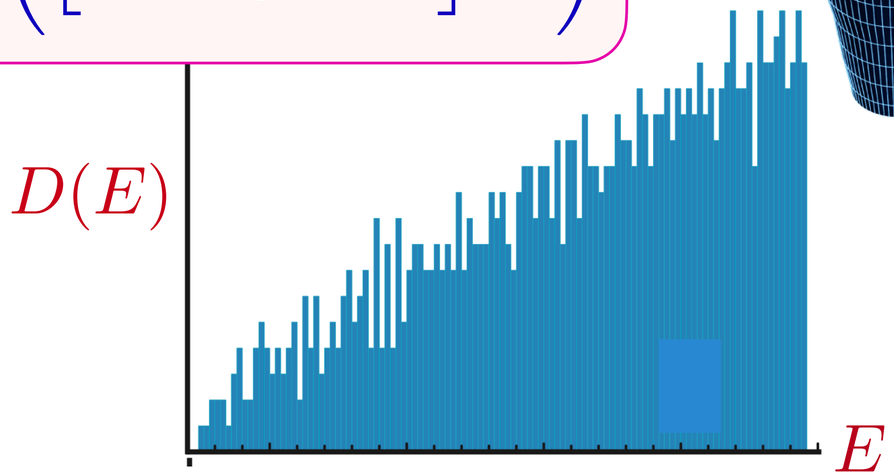
D. Chowdhury, A. Georges, O. Parcollet, and S. S., Rev. Mod. Phys. **94**, 035004 (2022)

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 $\mathcal{Q}$ ($A = 2G\mathcal{Q}^2/c^4$), the density of quantum states at small energy E is

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





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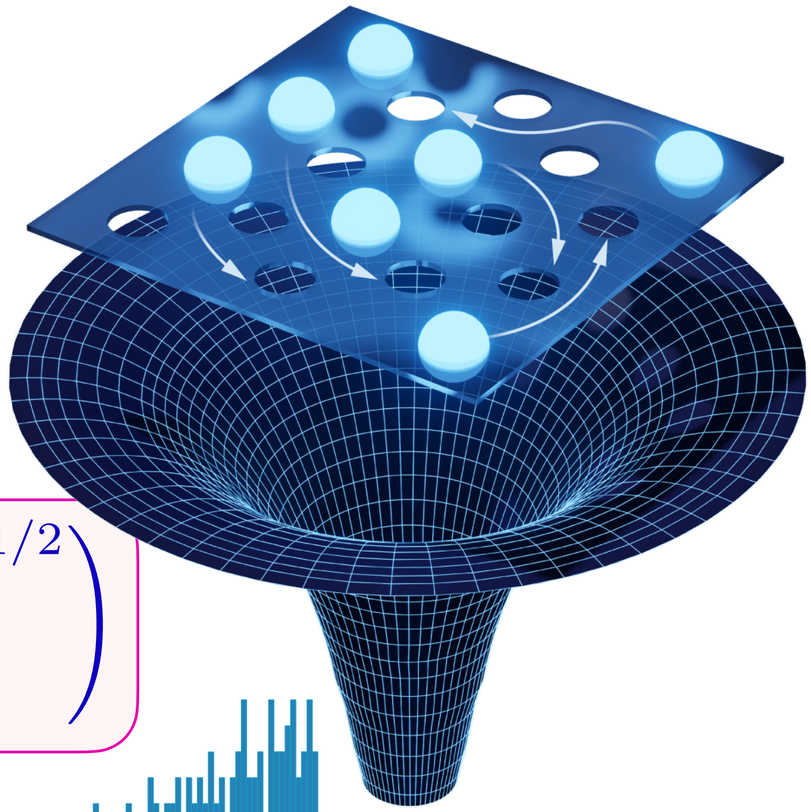

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Bekenstein-Hawking

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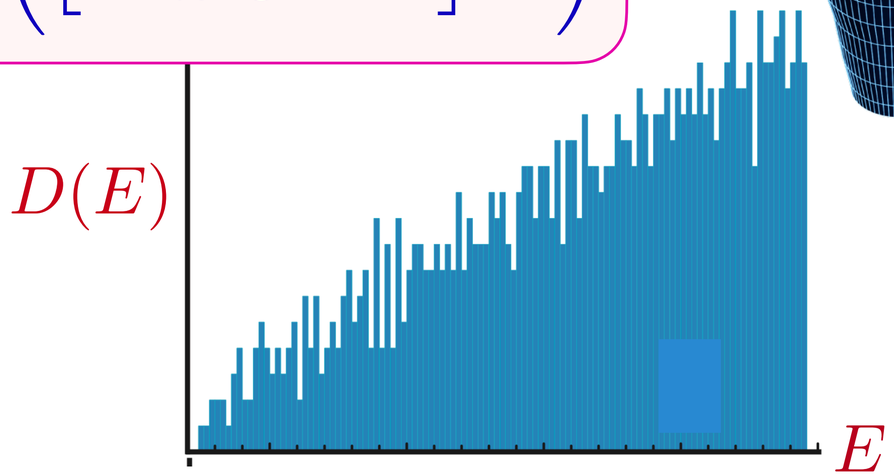

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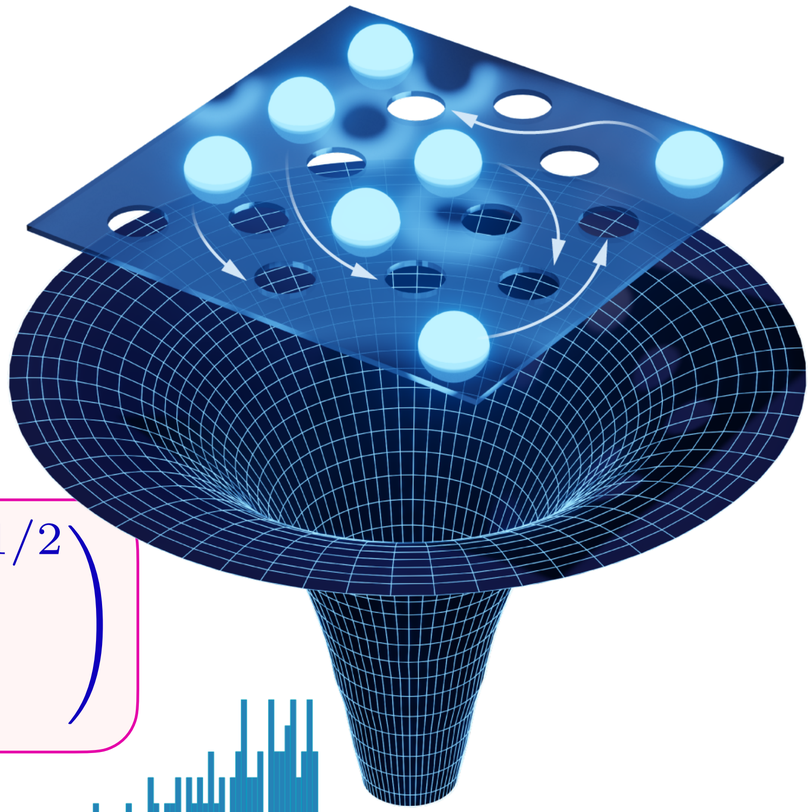

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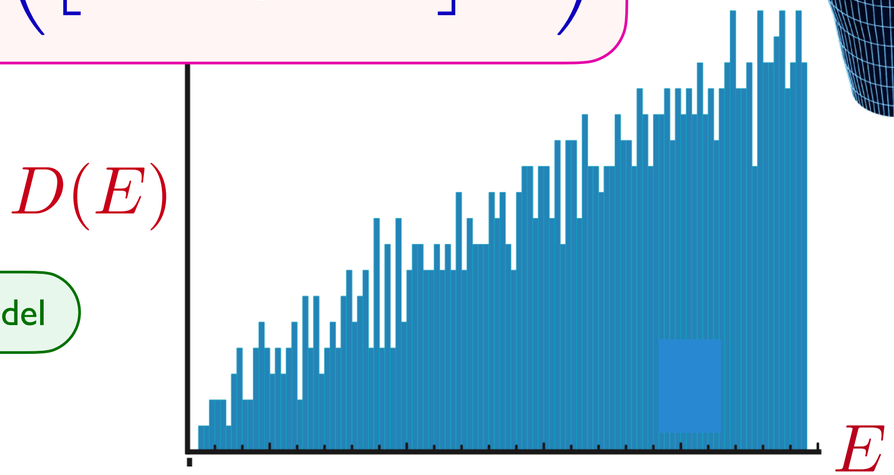
Developments from the SYK model



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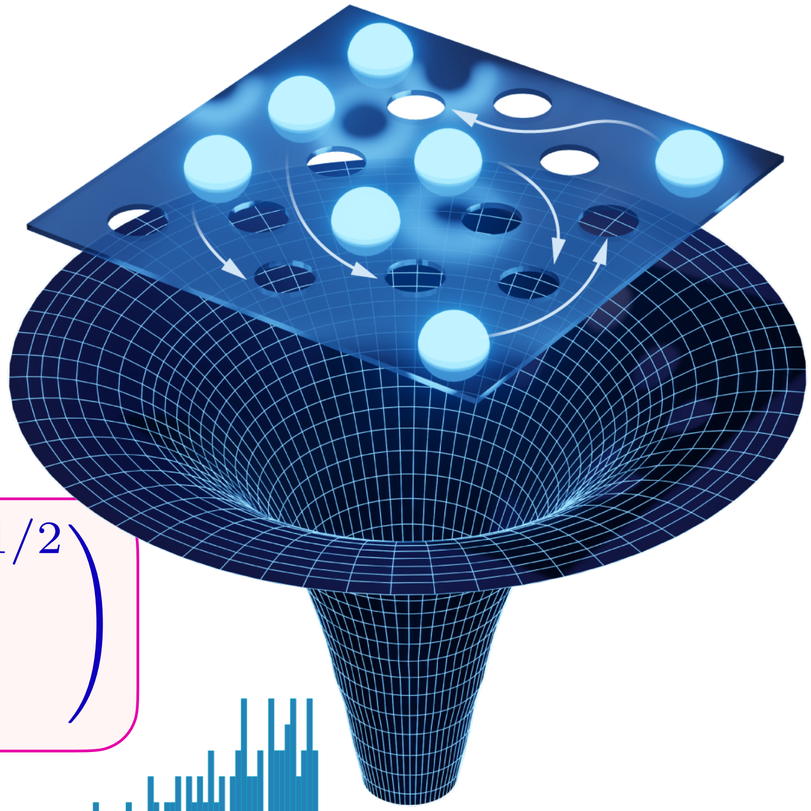

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Iliesiu, Murthy, Turiaci (2022)

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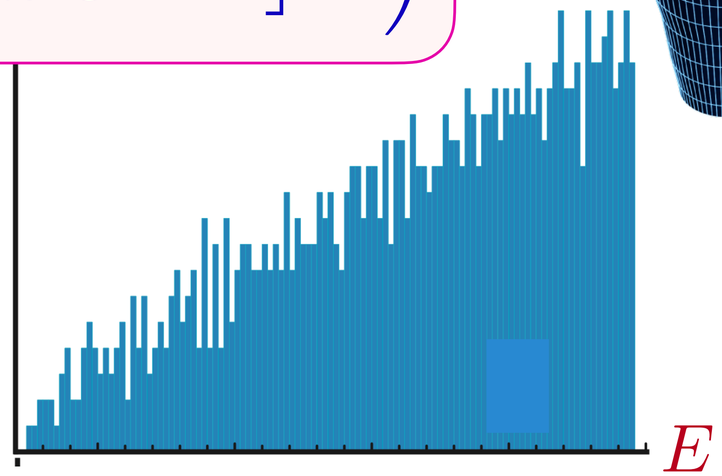


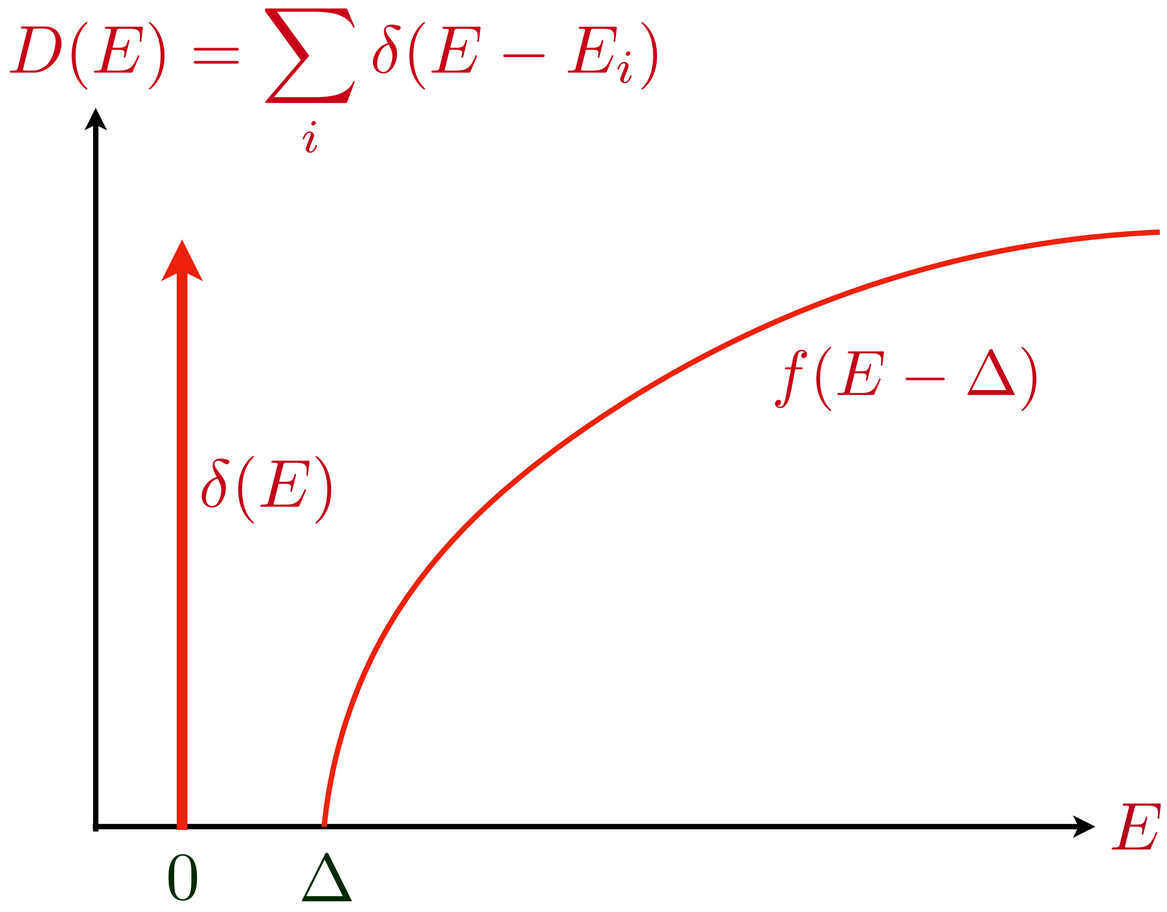
D. Chowdhury, A. Georges, O. Parcollet, and S. S., Rev. Mod. Phys. **94**, 035004 (2022)

String theory of charged black holes

- With sufficient low energy supersymmetry, string theory yields:

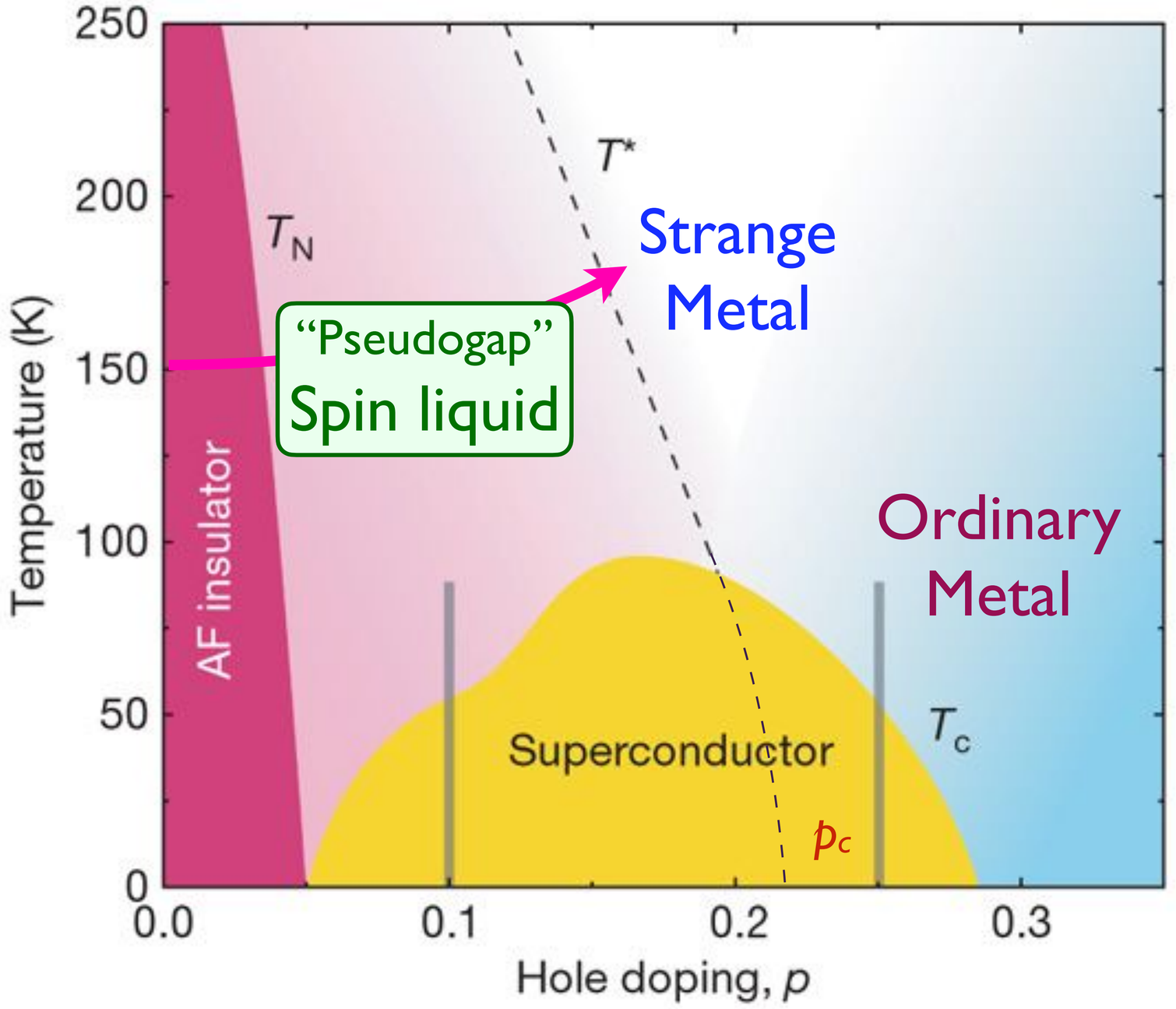
$$D(E) = \exp\left(\frac{A_0 c^3}{4\hbar G}\right)\delta(E) + \theta(E-\Delta)f(E-\Delta) + \ldots$$

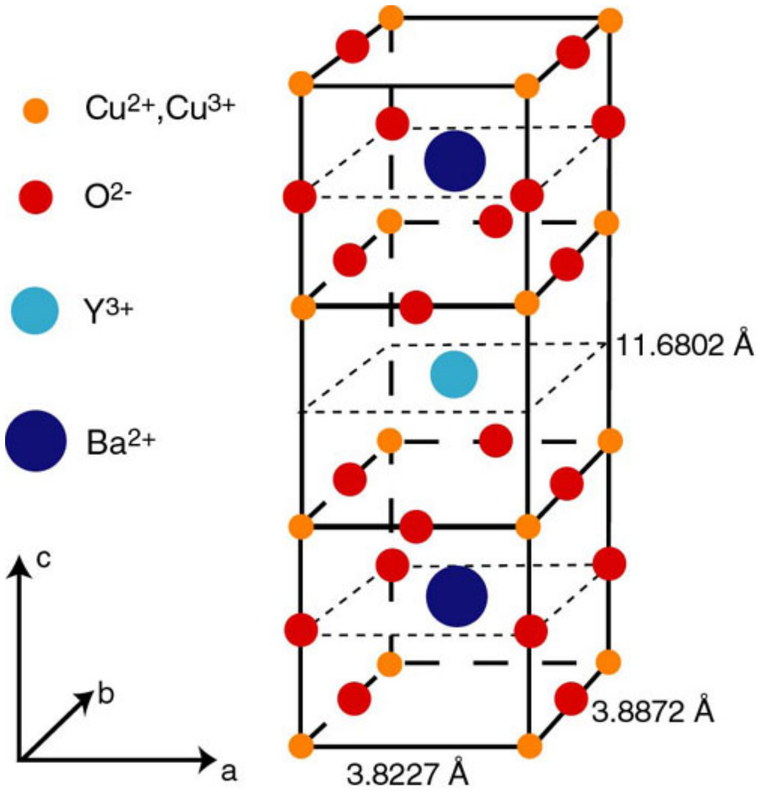
There are exponentially many degenerate BPS ground states, and an energy gap Δ above the ground state.



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

From the SYK model to a theory of strange metals


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


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

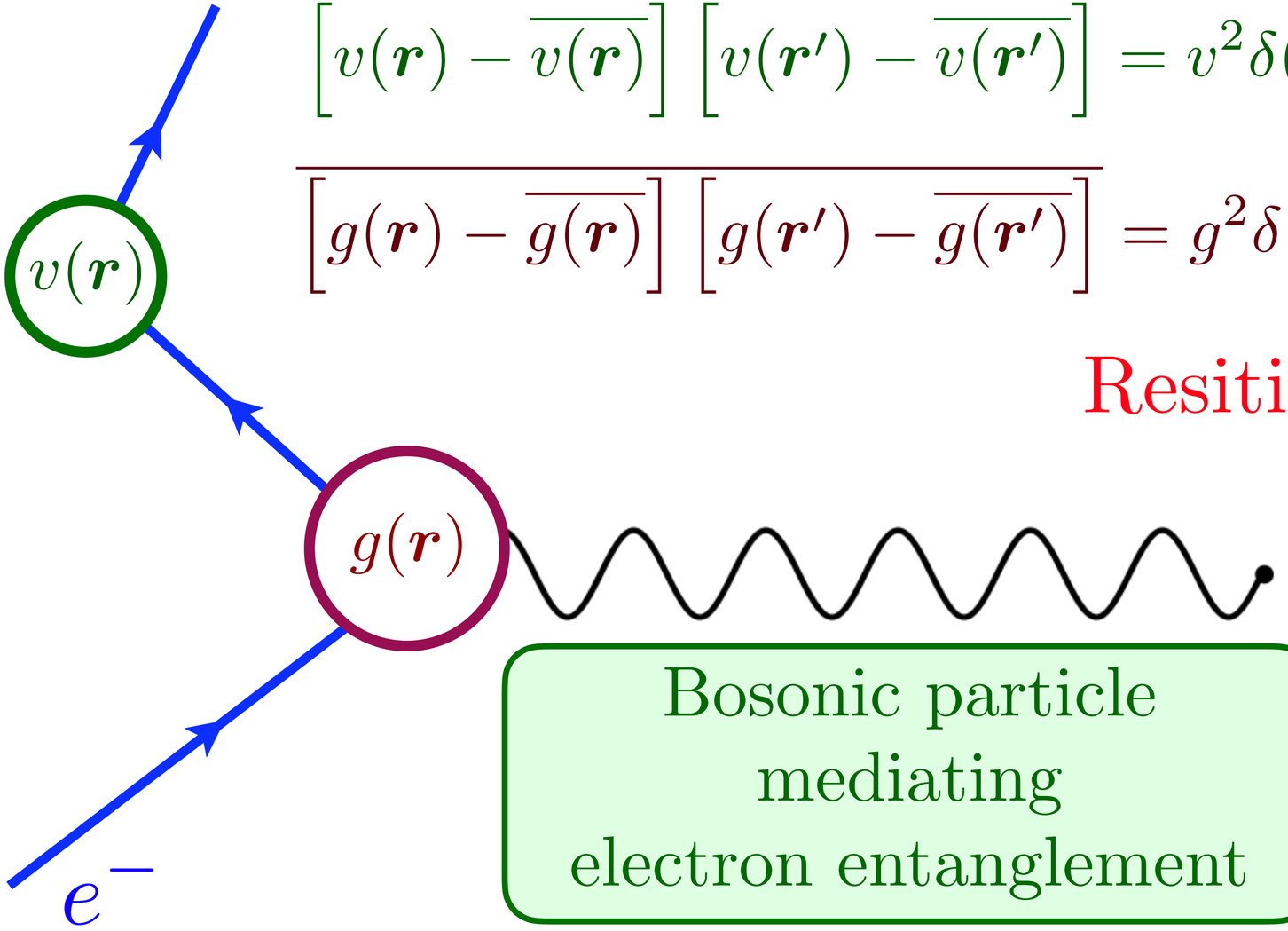
$YBa_2Cu_3O_{6+x}$

The dance of electrons on Cu atoms in YBCO

$$\overline{\Big[v(\boldsymbol{r}) - \overline{v(\boldsymbol{r})}\Big]\,\Big[v(\boldsymbol{r}') - \overline{v(\boldsymbol{r}')}\Big]} = v^2\delta(\boldsymbol{r}-\boldsymbol{r}')$$

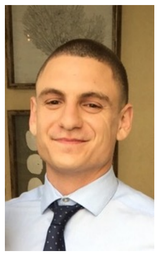
$$\overline{\Big[g(\boldsymbol{r}) - \overline{g(\boldsymbol{r})}\Big]\,\Big[g(\boldsymbol{r}') - \overline{g(\boldsymbol{r}')}\Big]} = g^2\delta(\boldsymbol{r}-\boldsymbol{r}')$$

Resitivity $\rho(T) \sim v^2 + g^2 T$



Bosonic particle
mediating
electron entanglement



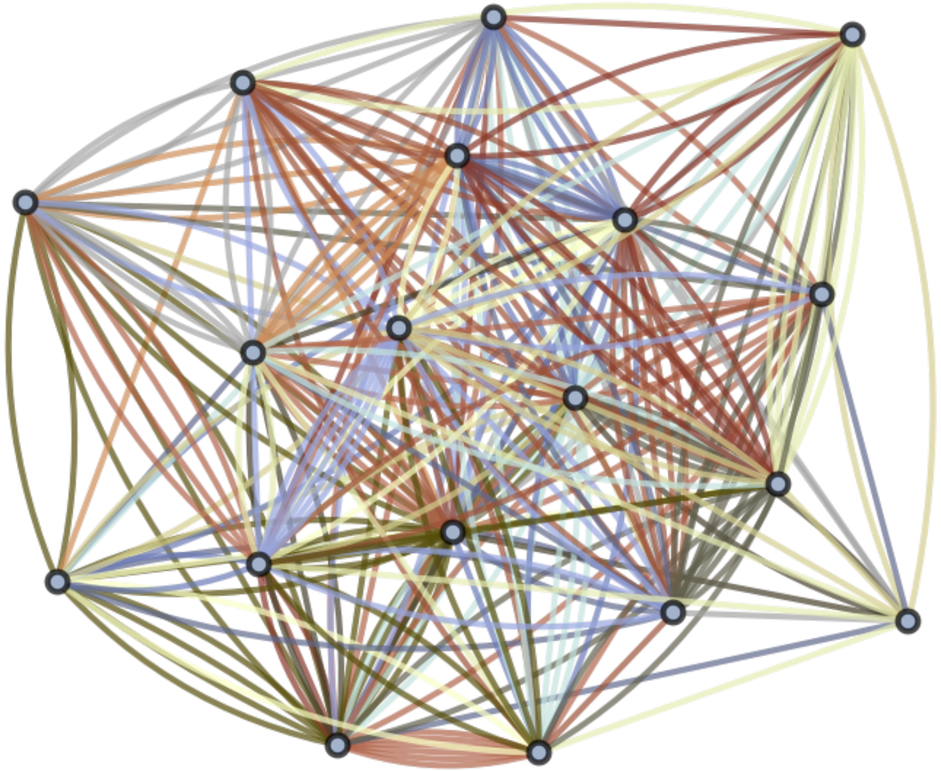


Aavishkar Patel, Haoyu Guo, Ilya Esterlis, S.S. arXiv: 2203.04990, *Science*, to appear

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

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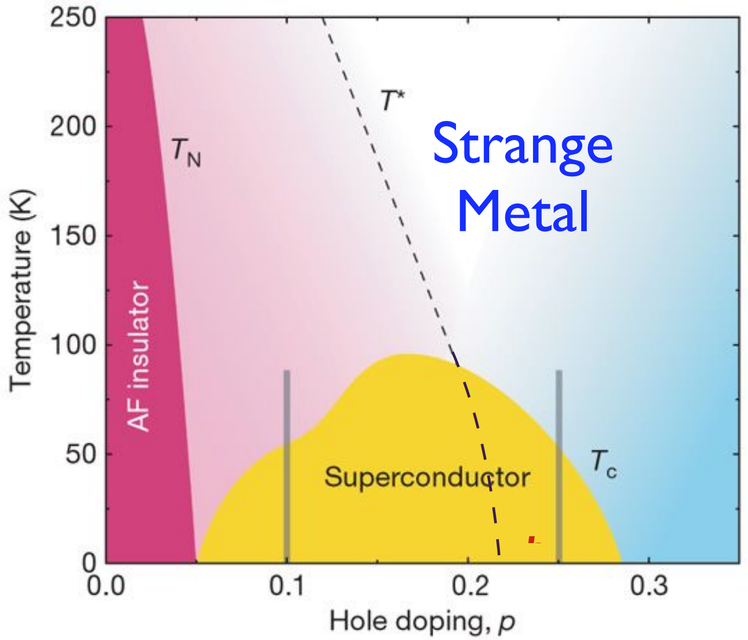
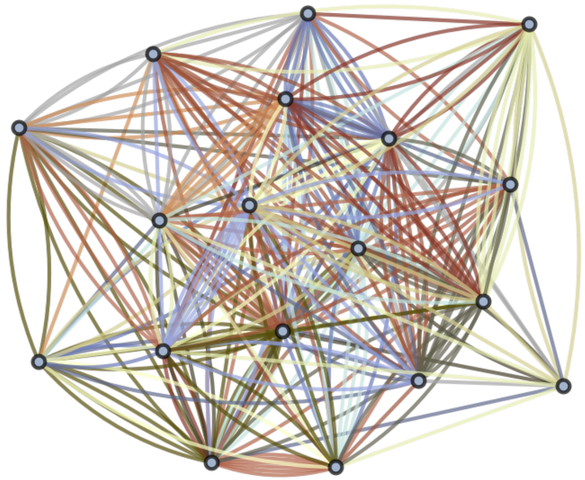


In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)



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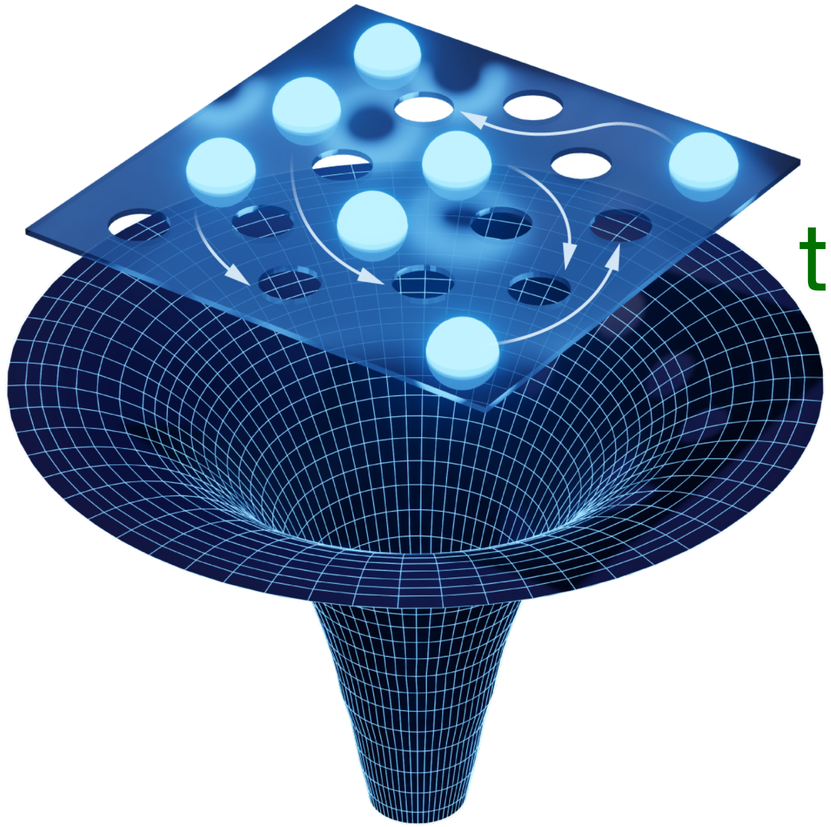

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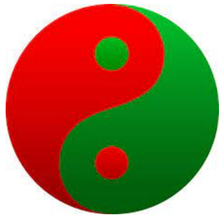
Sachdev, Ye (1993)



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

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