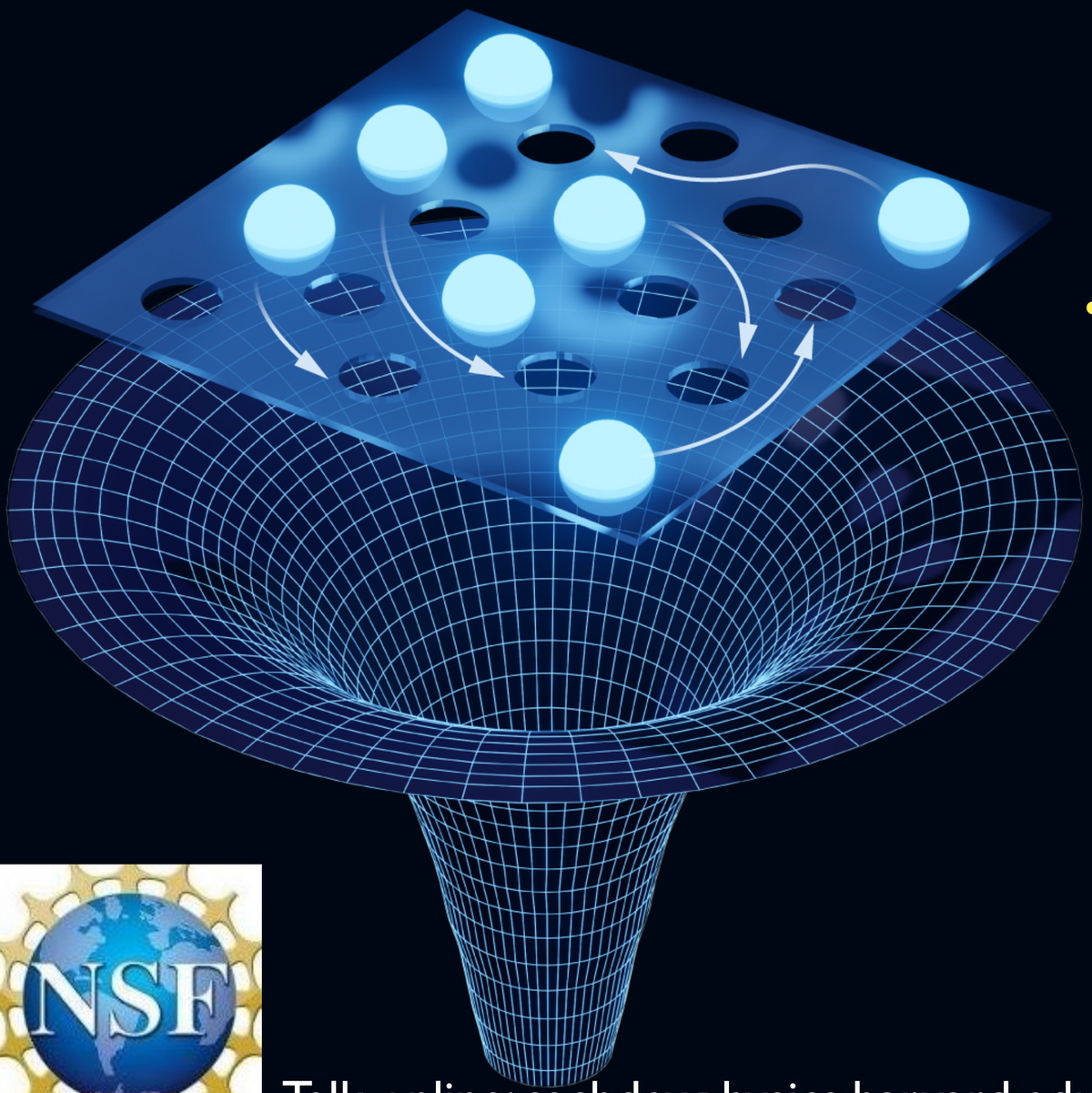


When nature entangles millions of particles: from quantum materials to black holes

Hong Kong University,
March 14, 2023

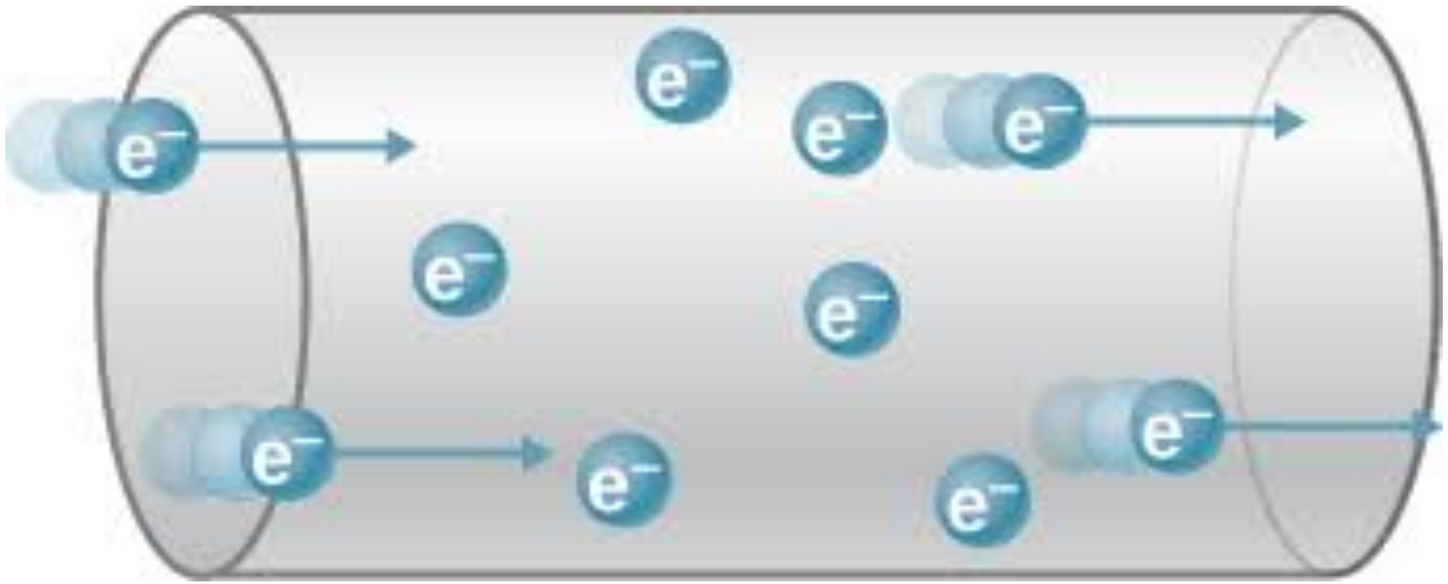
Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
VE RI TAS
HARVARD

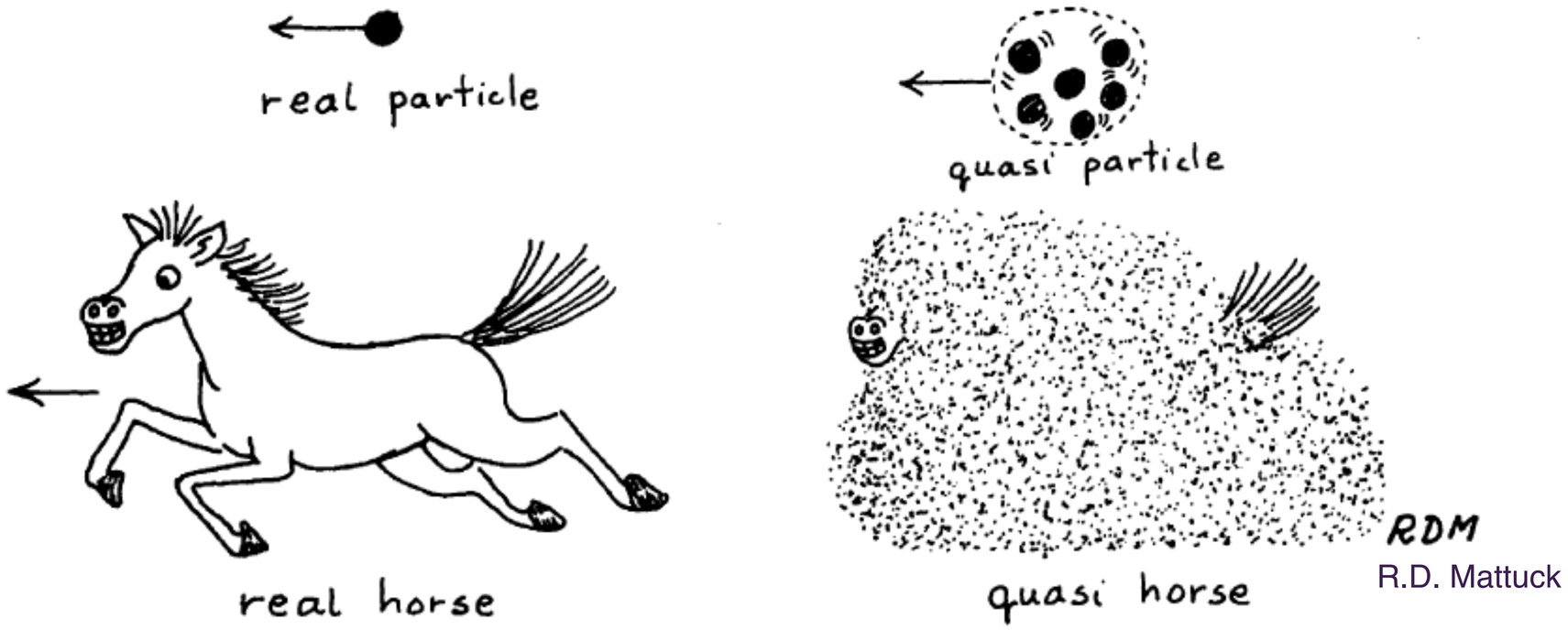
Quantum matter: ordinary metals, and strange metals

Copper: ordinary metal quantum matter



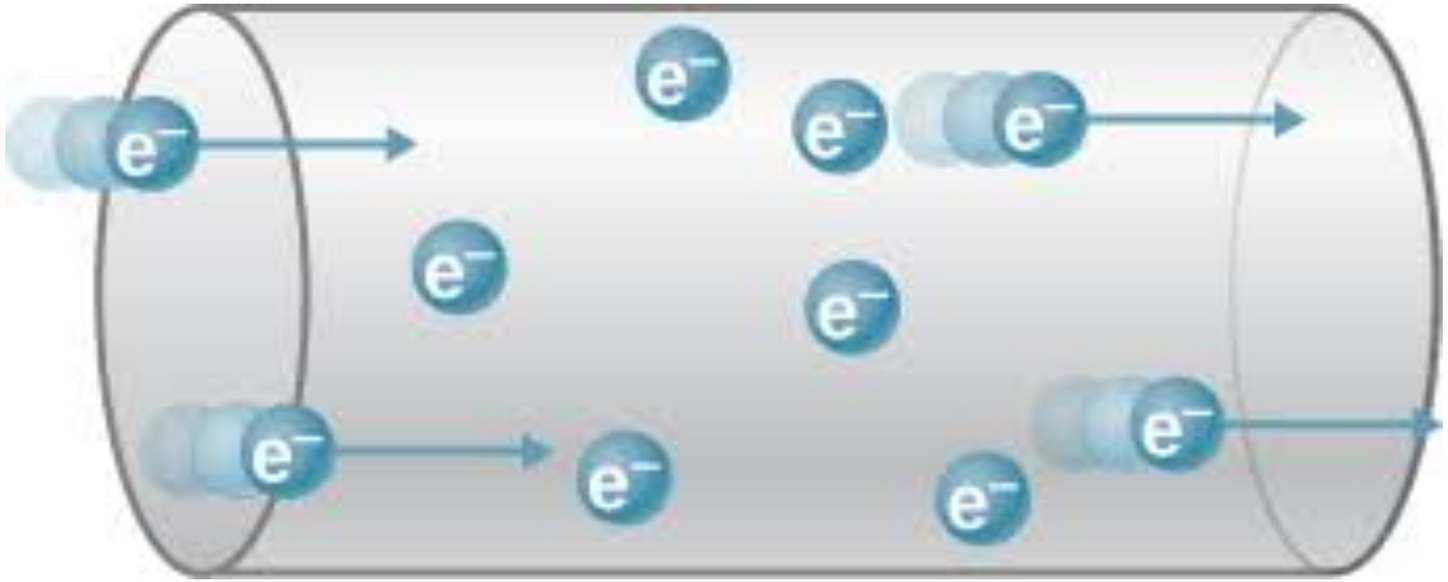
Almost all many-electron systems are described by the quasiparticle concept:

a quasiparticle is an "excited lump" in the many-electron state which responds just like an ordinary particle.

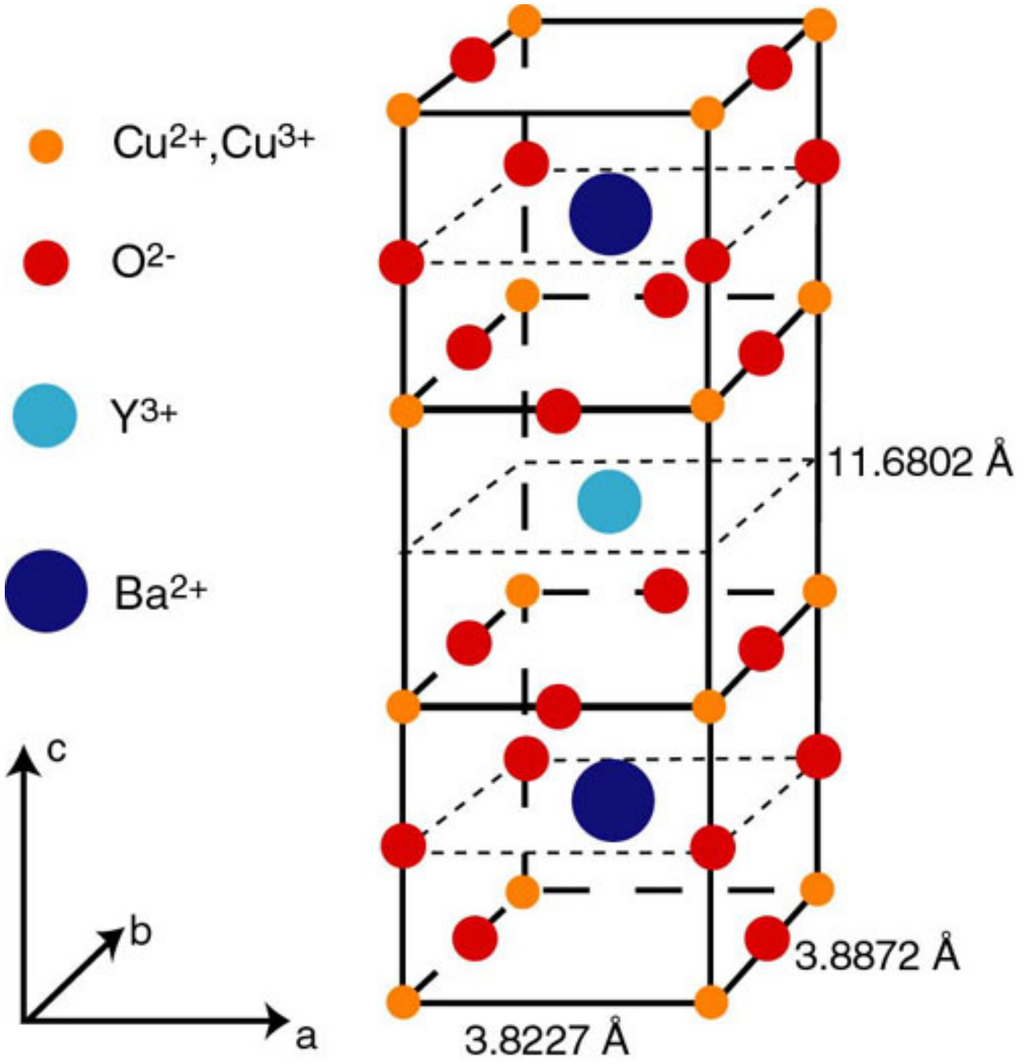


R.D. Mattuck

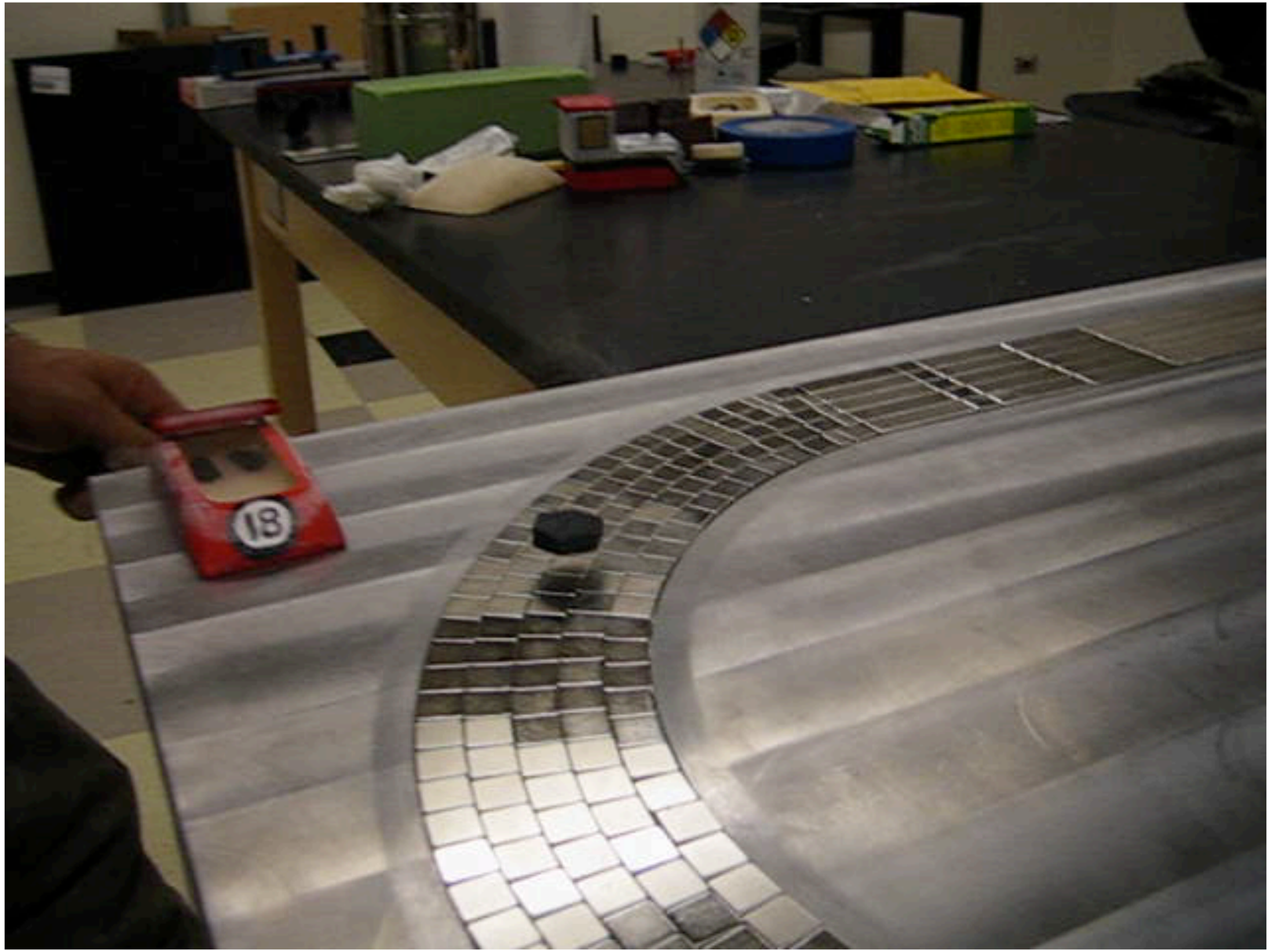
Current flow with quasiparticles in Copper



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

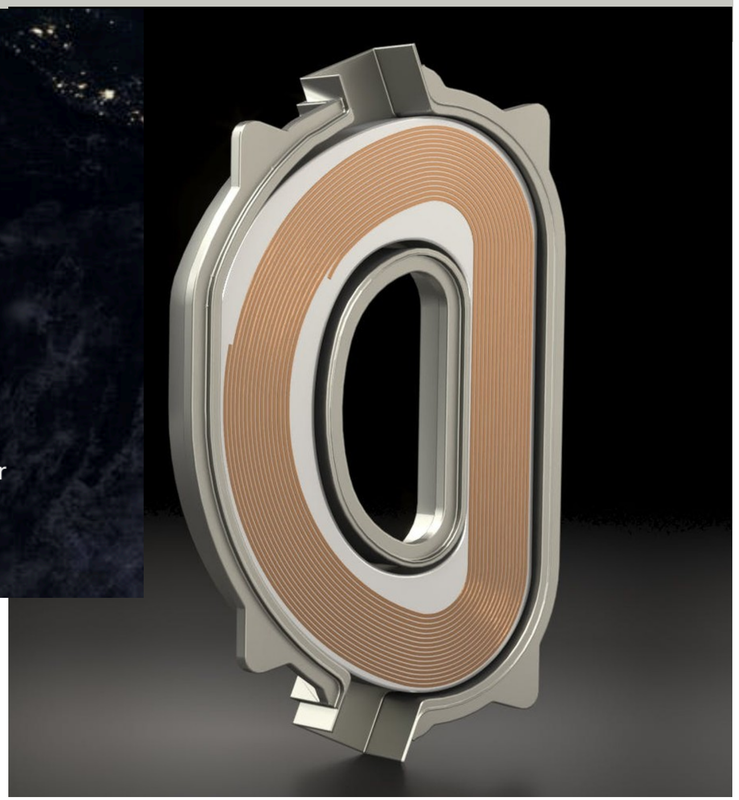
The fastest path to commercial fusion energy combining proven science with revolutionary magnet technology.

Limitless

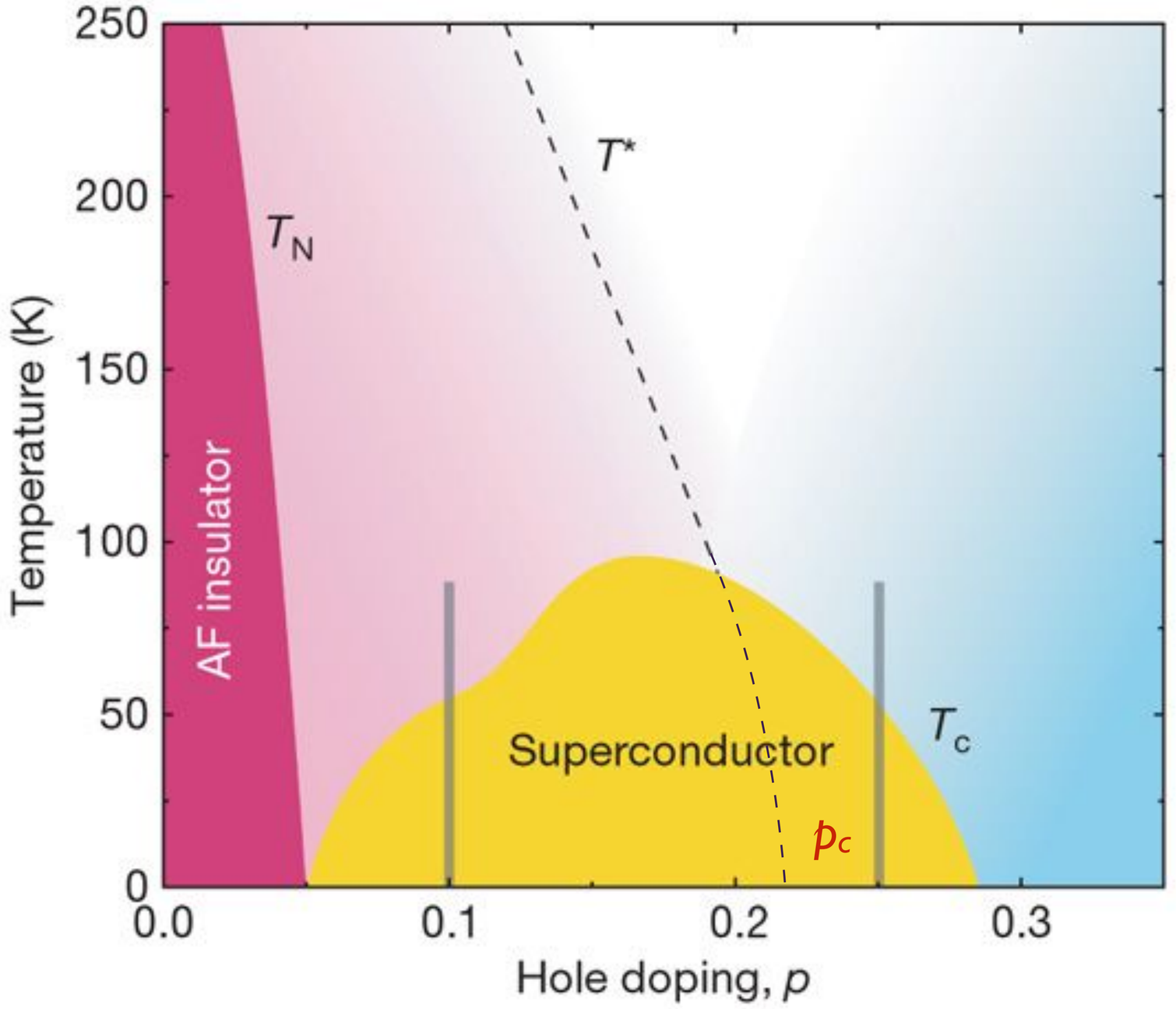
One glass of water will provide enough fusion fuel for one person's lifetime.

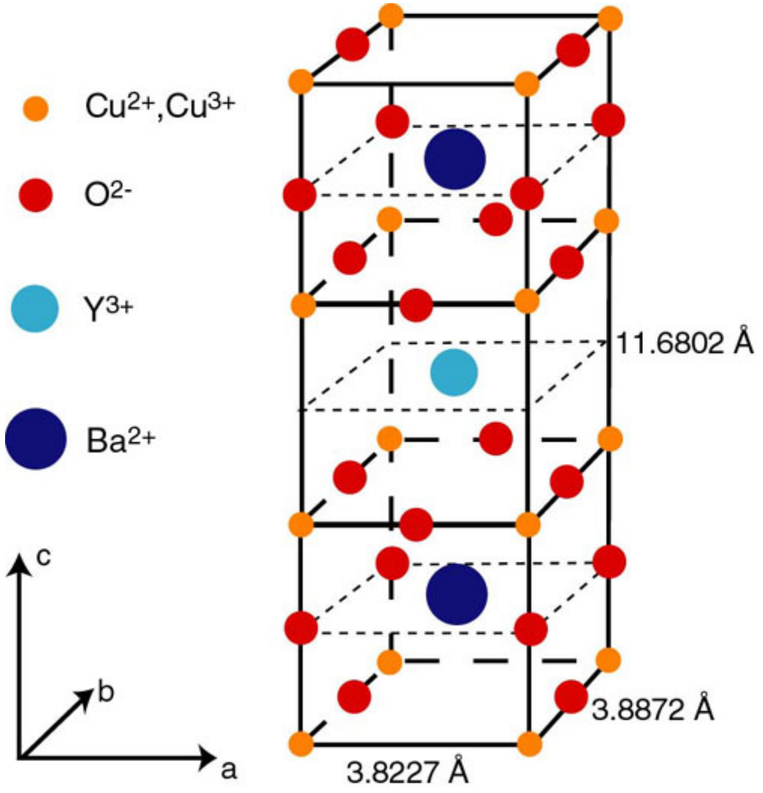
Clean

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

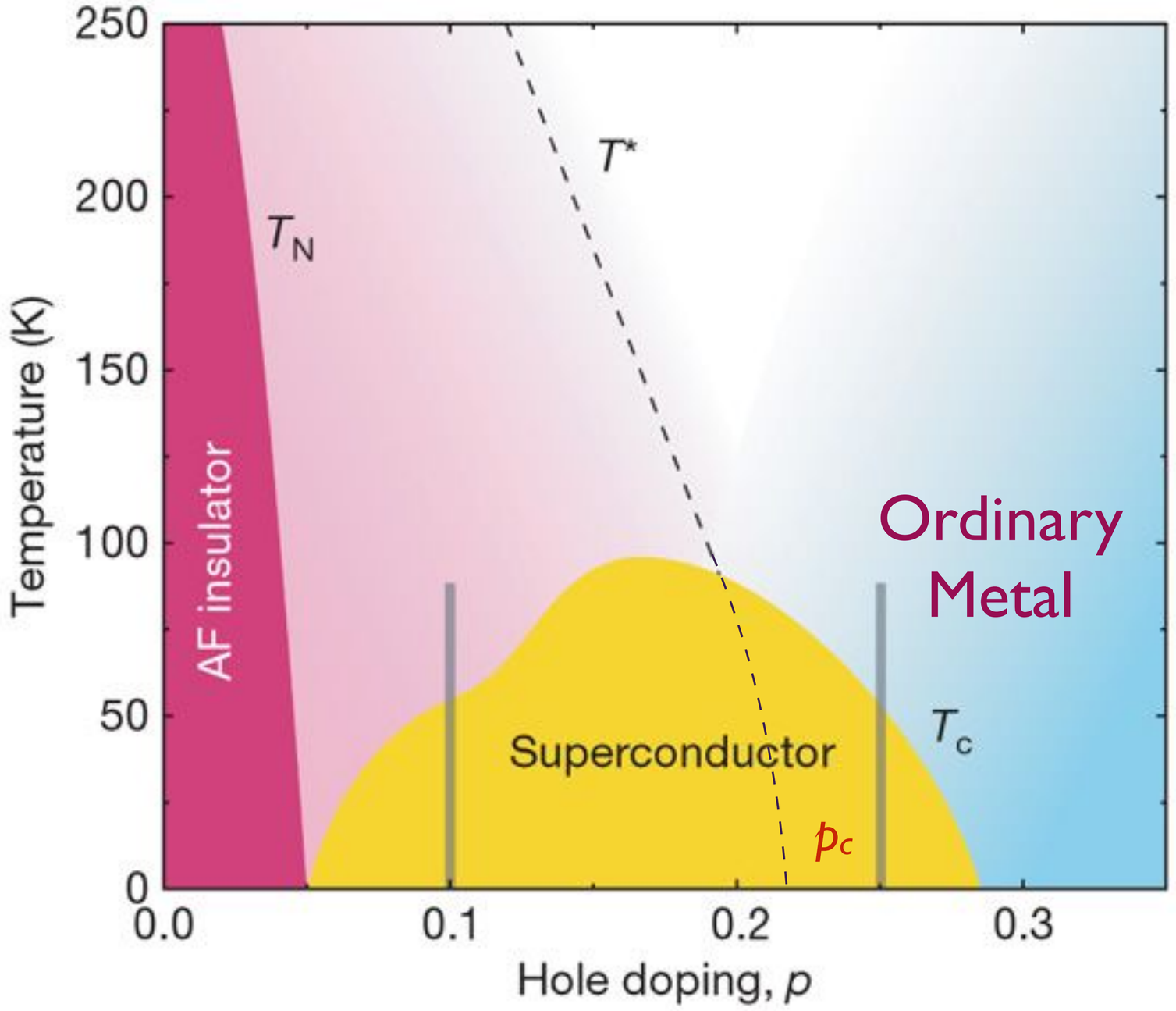


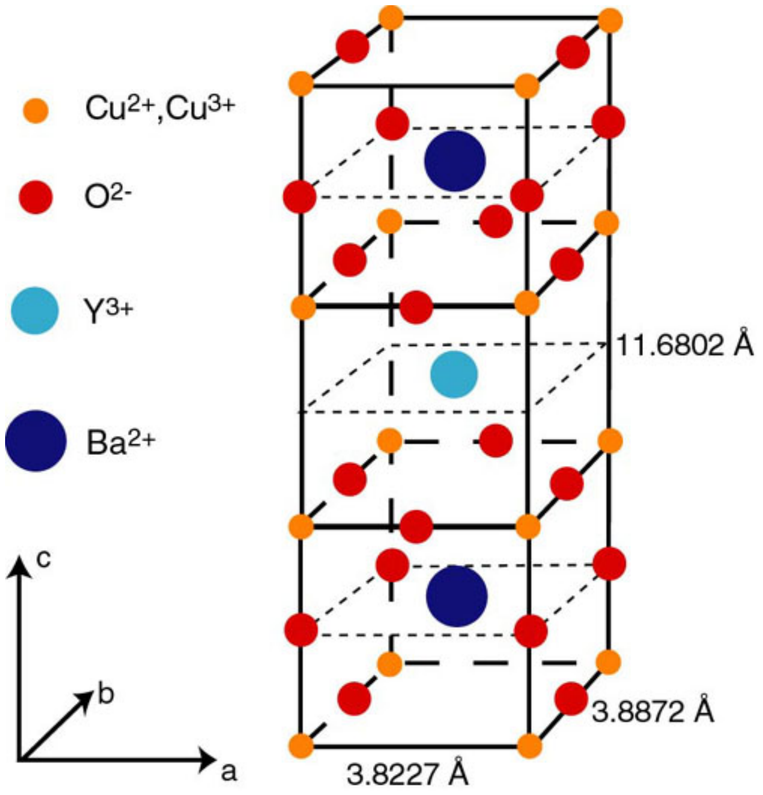
Commonwealth Fusion Systems


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


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

$YBa_2Cu_3O_{6+x}$


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
Ordinary
Metal


Cu2+,Cu3+
O2-
Y3+
Ba2+
c
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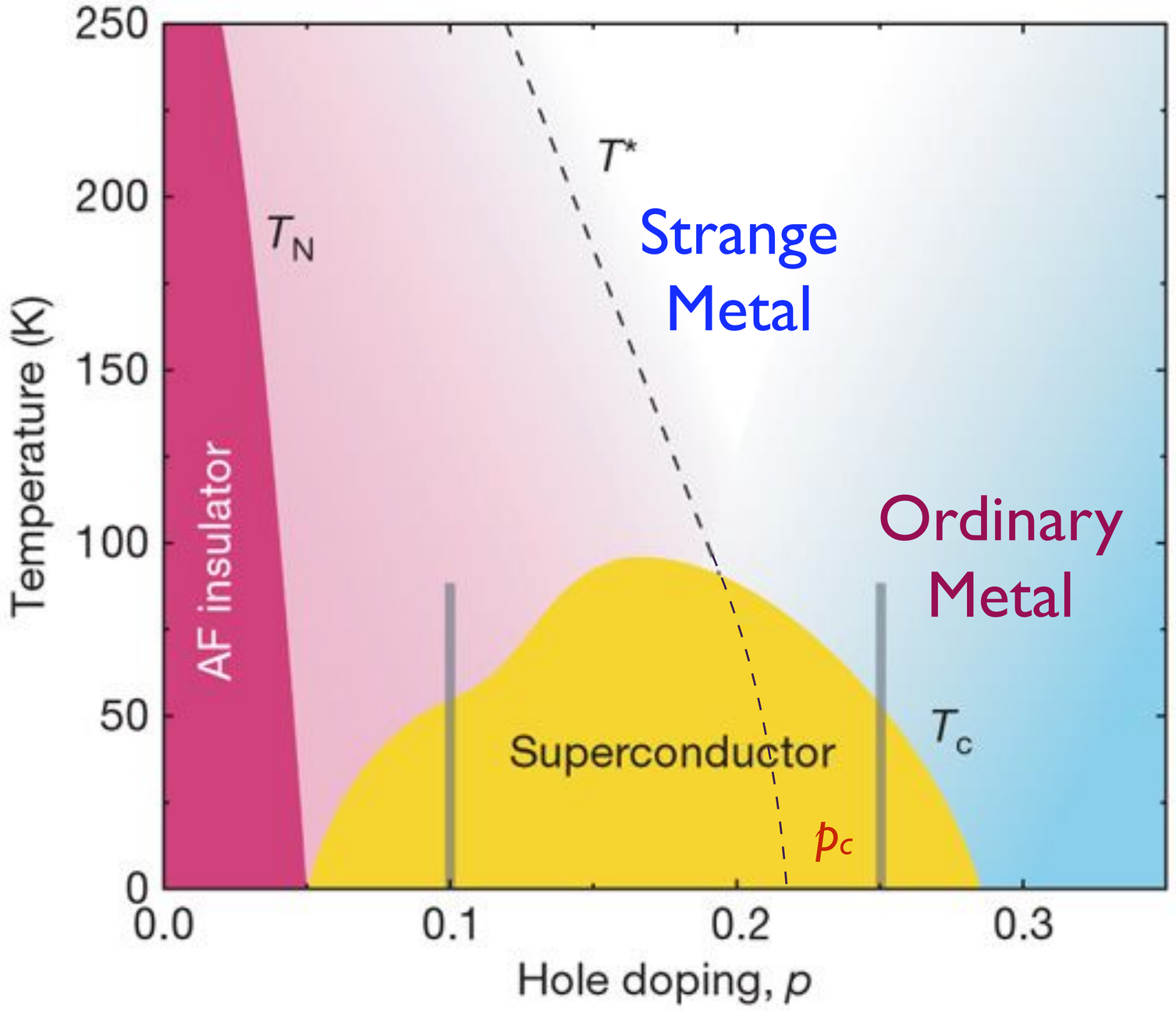
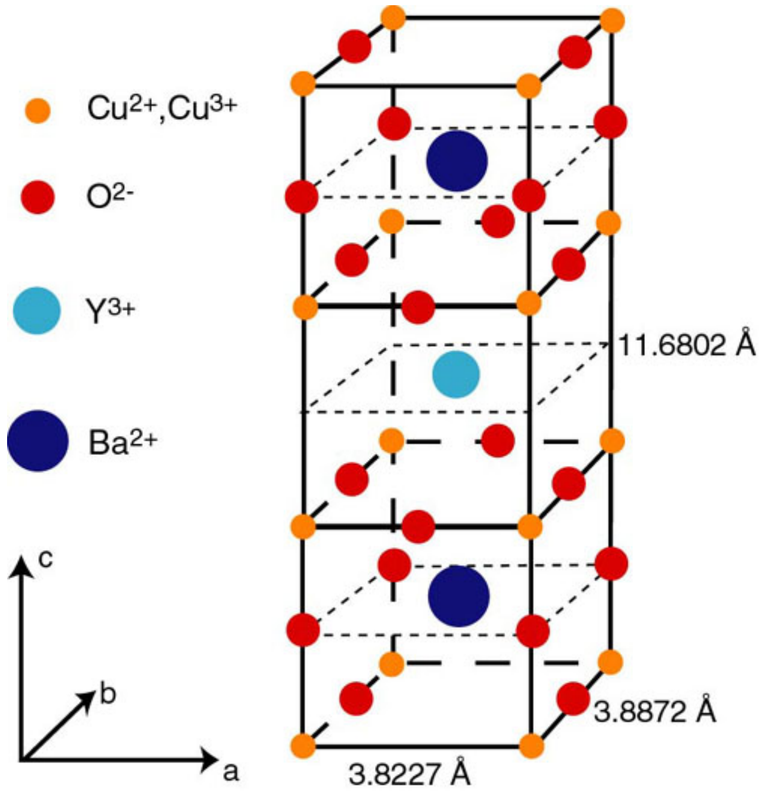

250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
T_N
T^*
AF insulator
Strange
Metal
Ordinary
Metal
Superconductor
T_c
p_c


Cu^{2+},Cu^{3+}
O^{2-}
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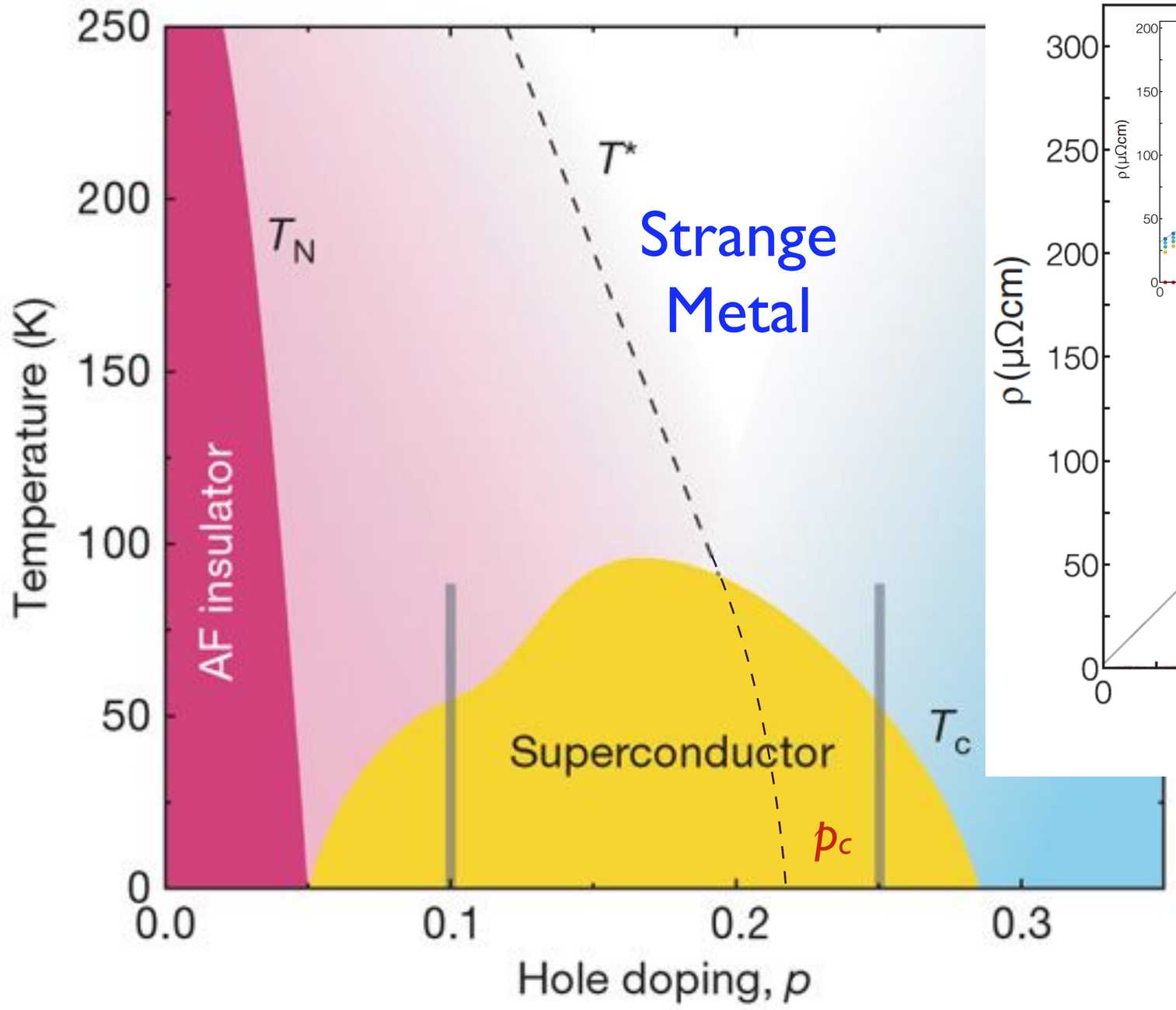
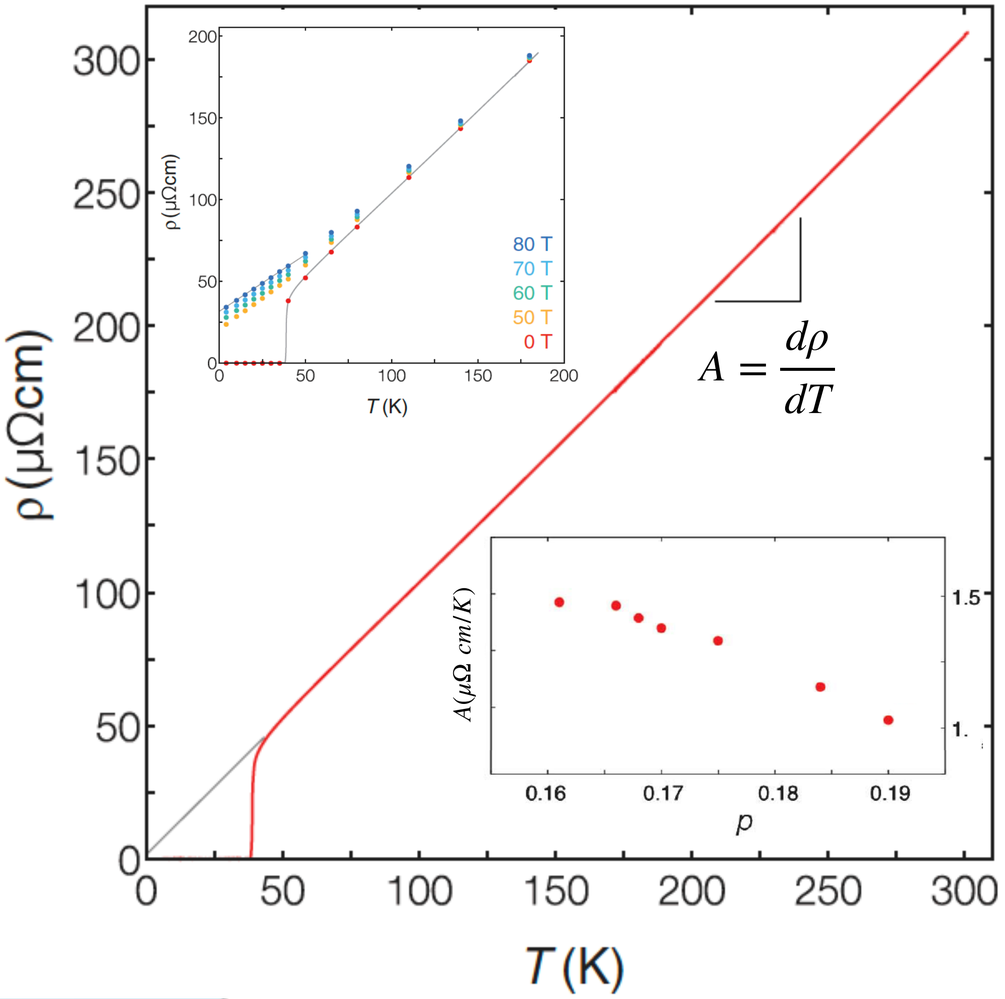
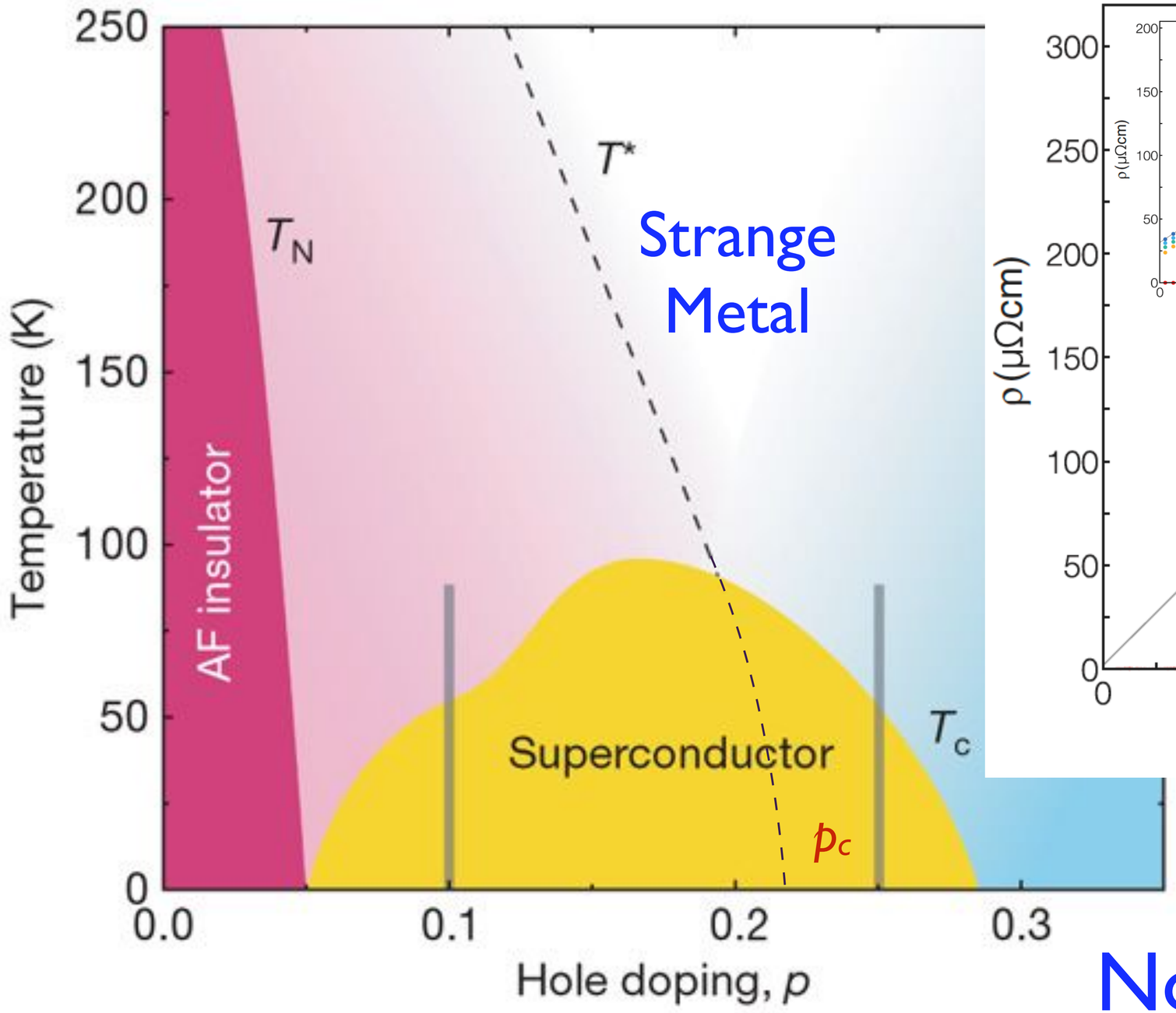
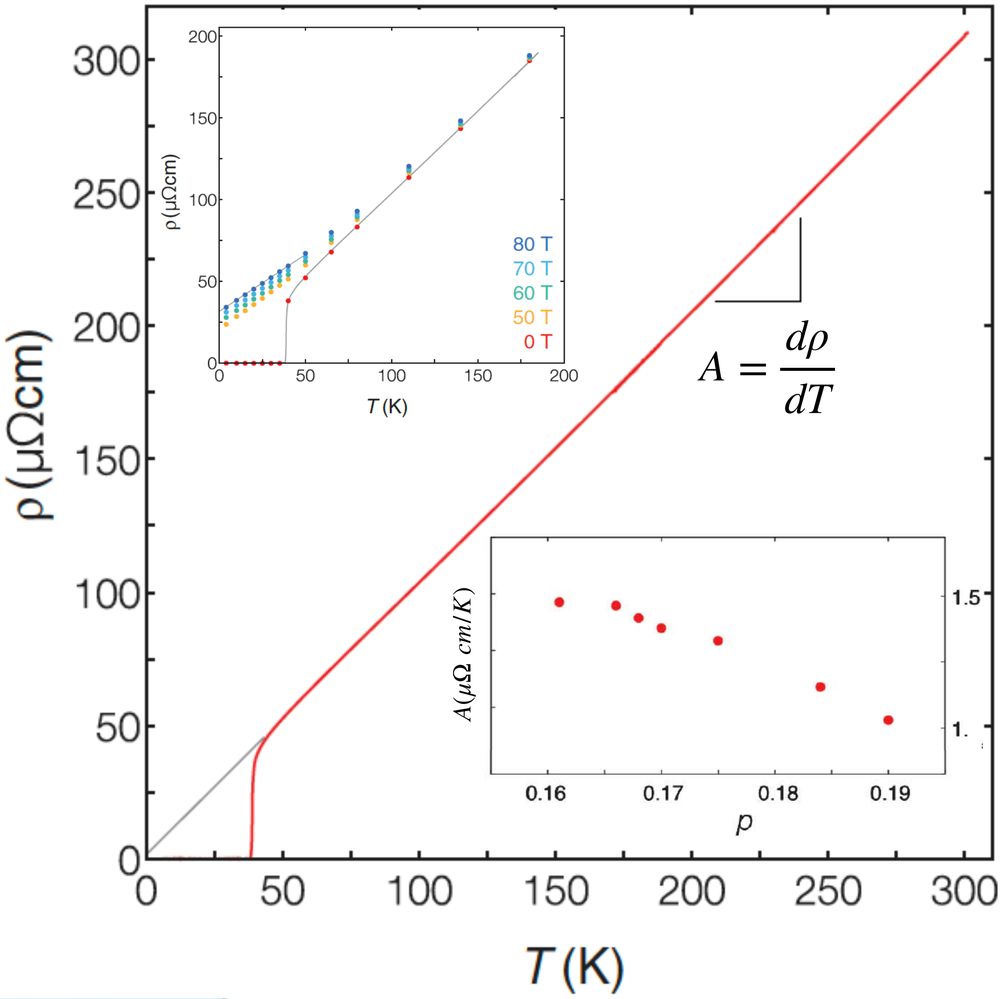




LSCO: Giraldo-Gallo et al. 2018





LSCO: Giraldo-Gallo et al. 2018

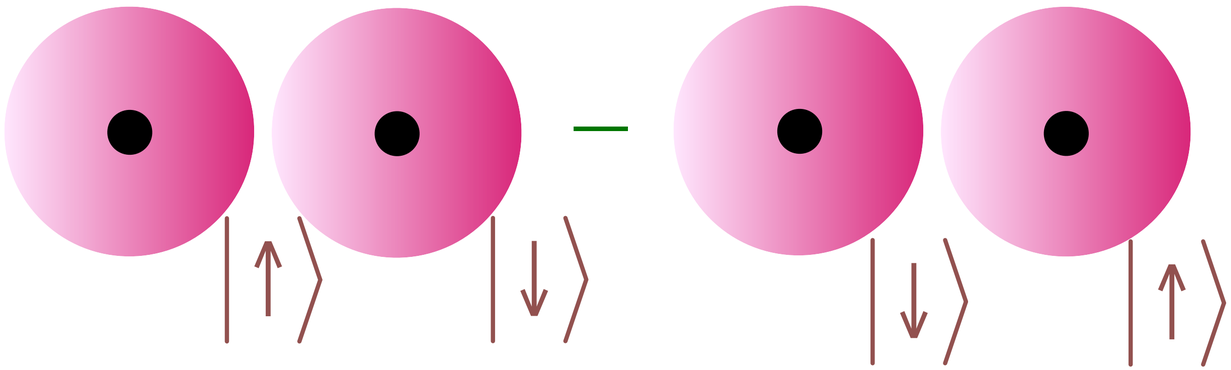
No quasiparticles ???

The Sachdev-Ye-Kitaev model of quantum matter without quasiparticles

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.

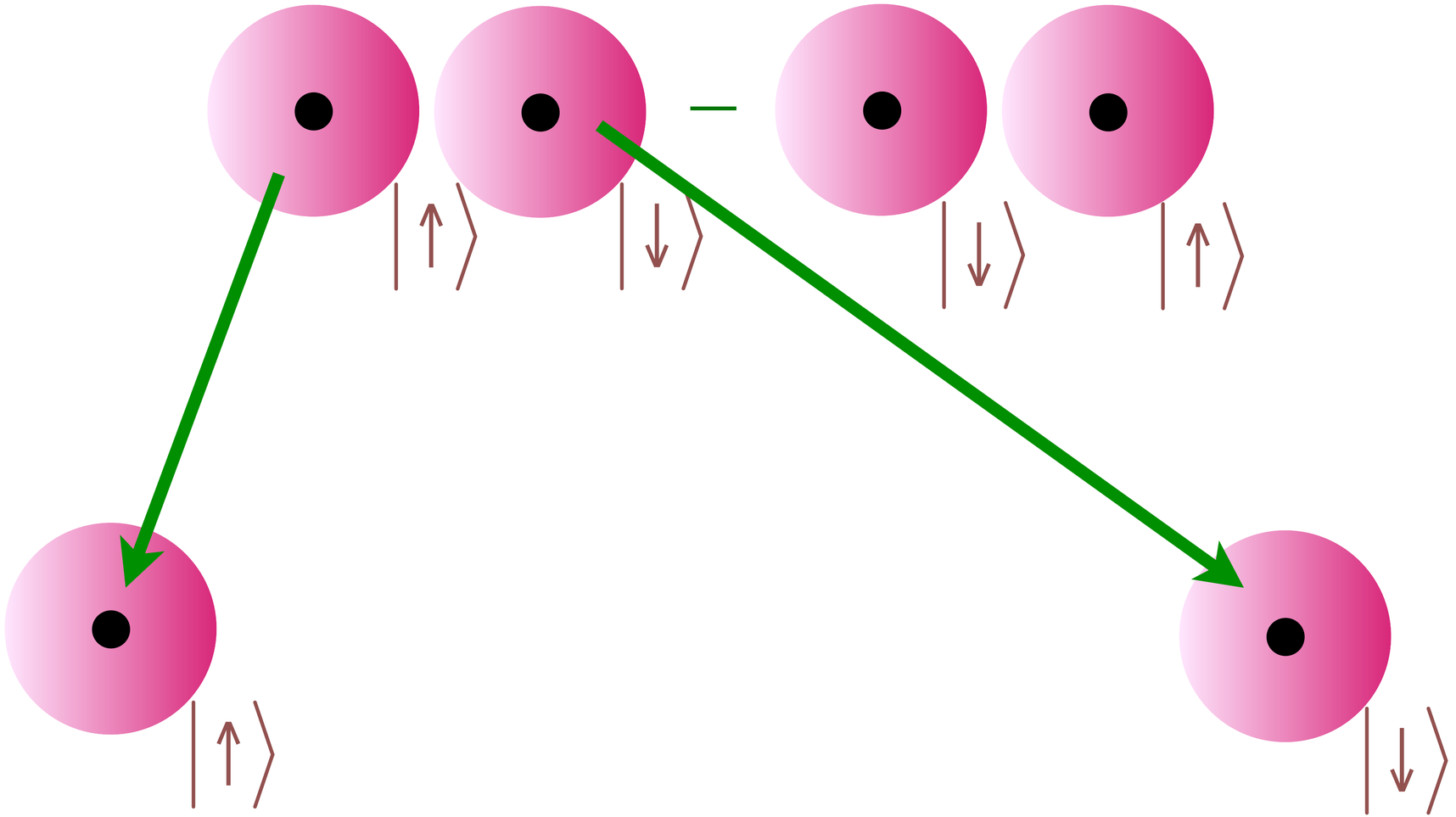
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



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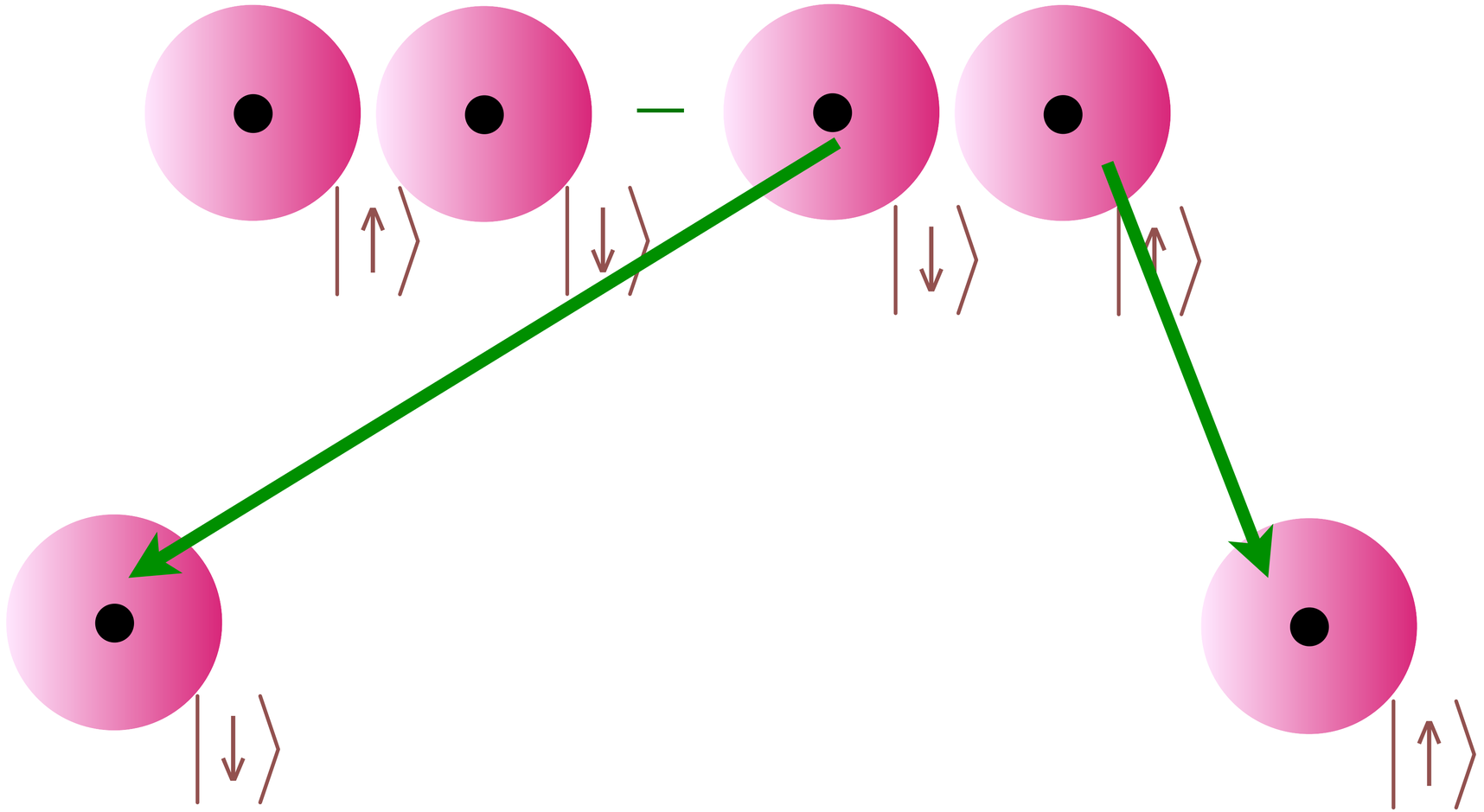

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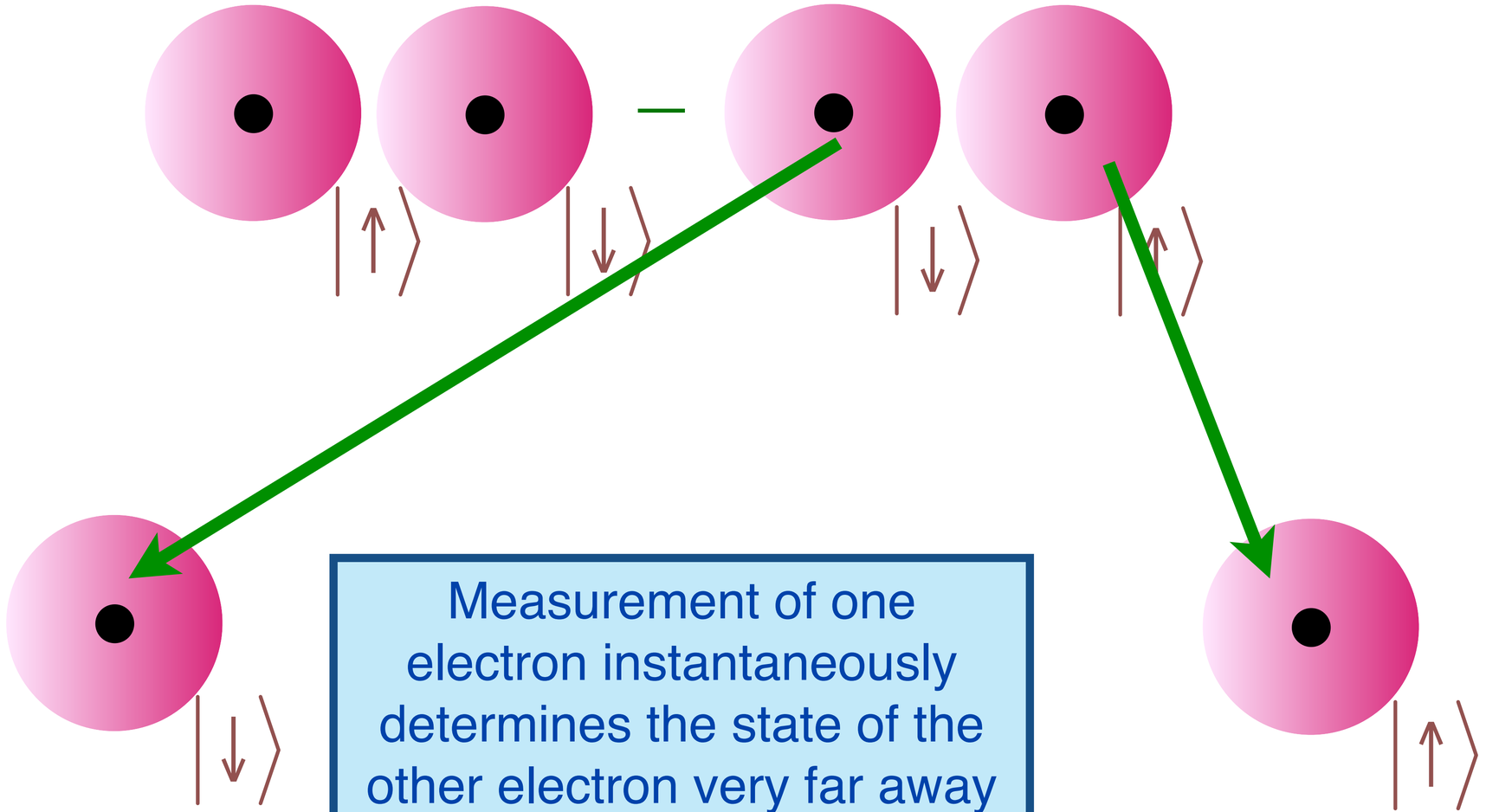

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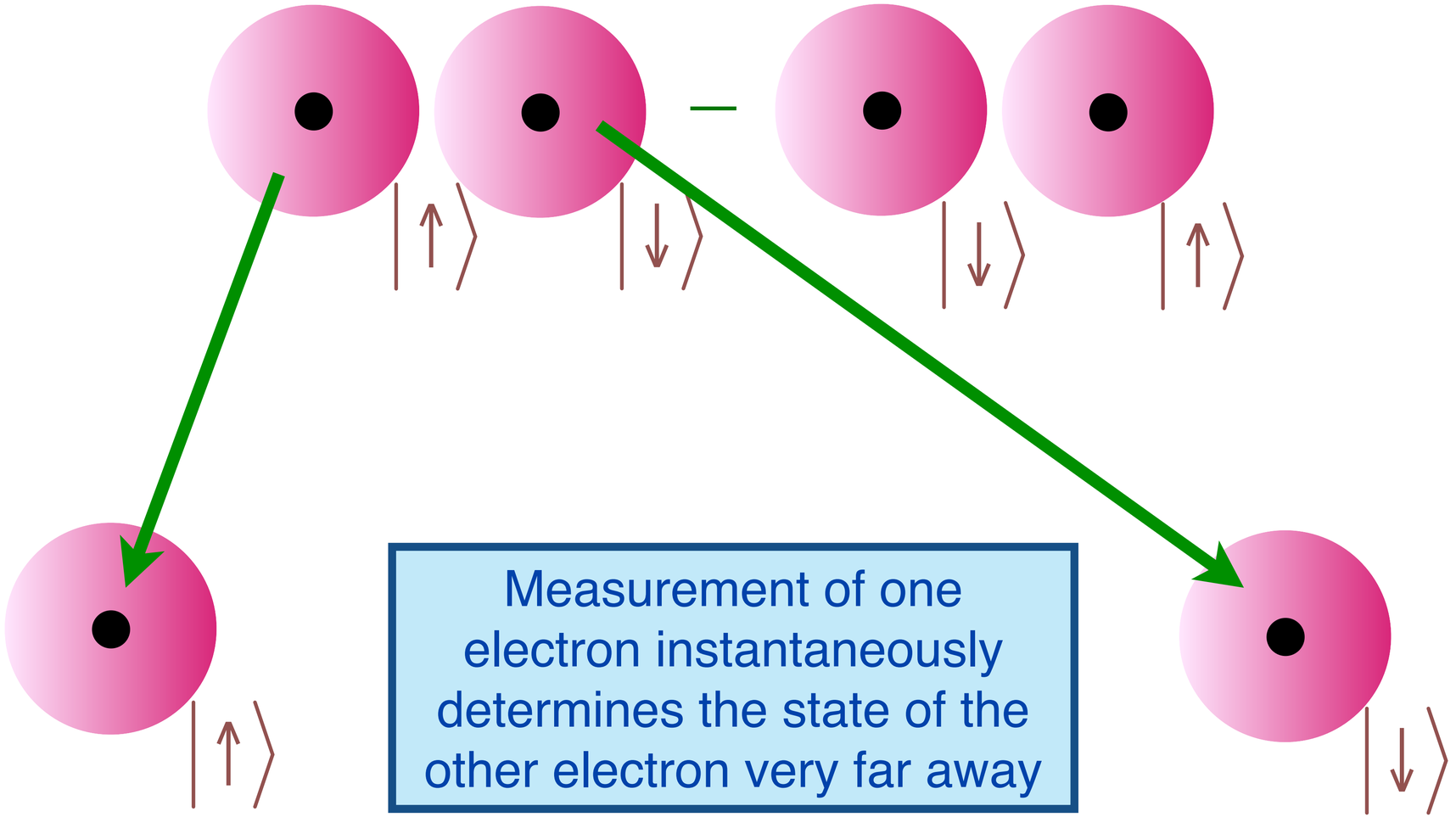

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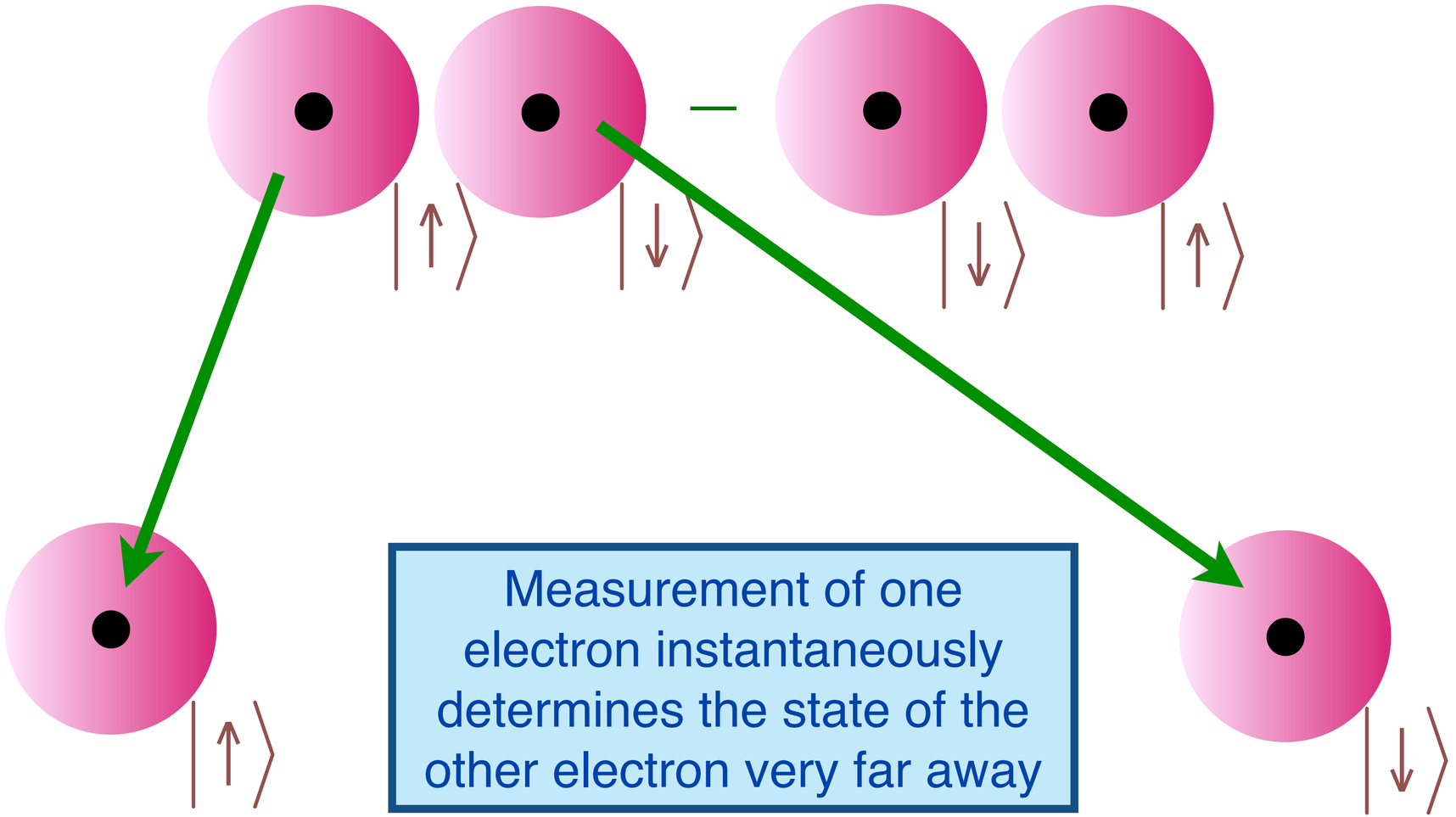
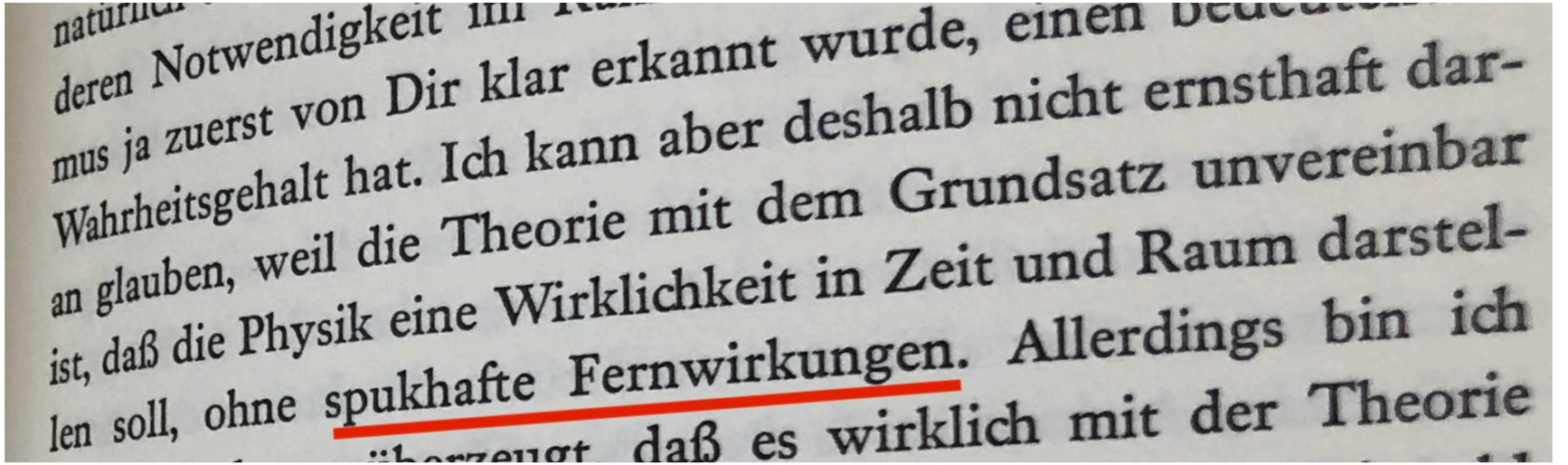


Spooky action at a distance !


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

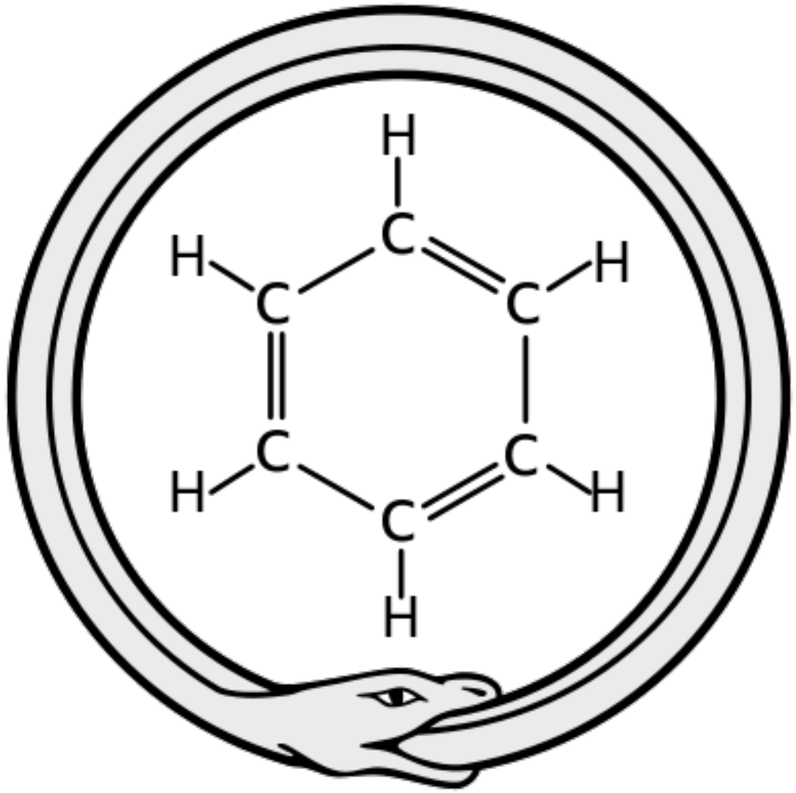
Albert Einstein to Max Born, 3 March 1947

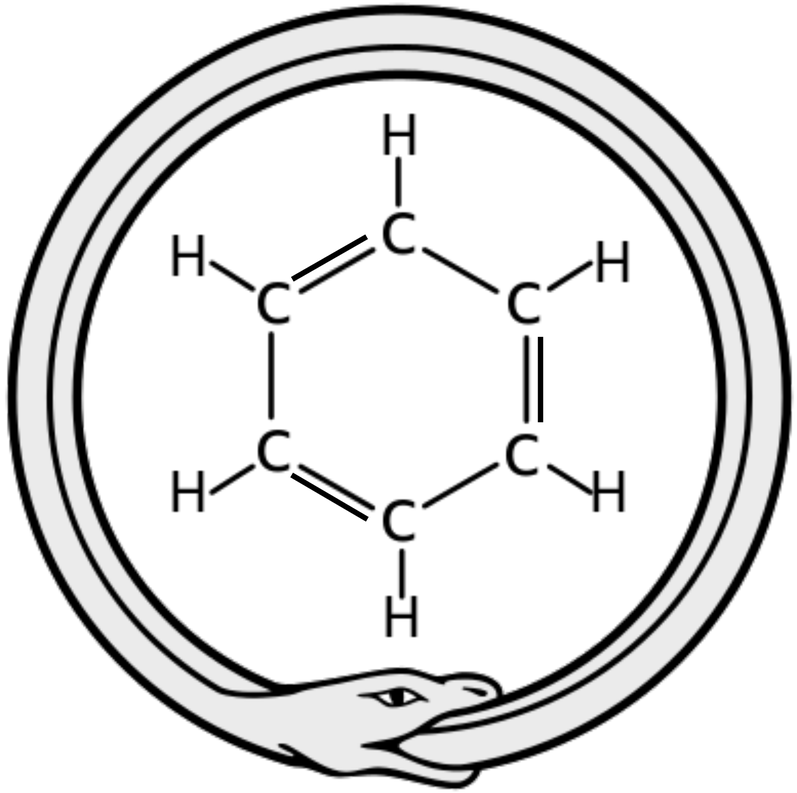
How about quantum entanglement of $3, 4, 5, \ldots \infty$ particles?

August Kekule, theory of the benzene molecule, 1865

Kekule's spooky dream

Here 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*





*Wikipedia

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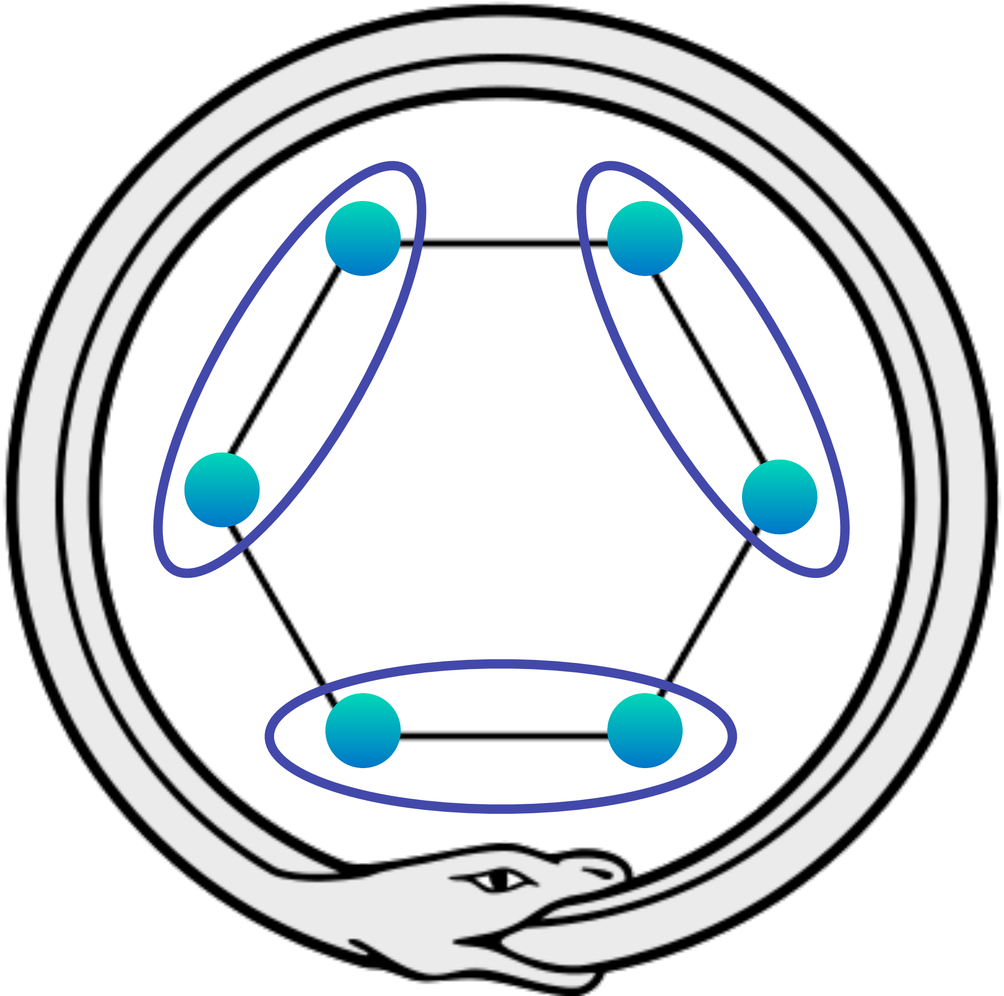

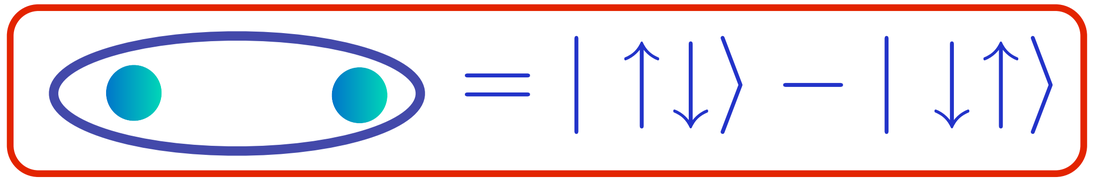

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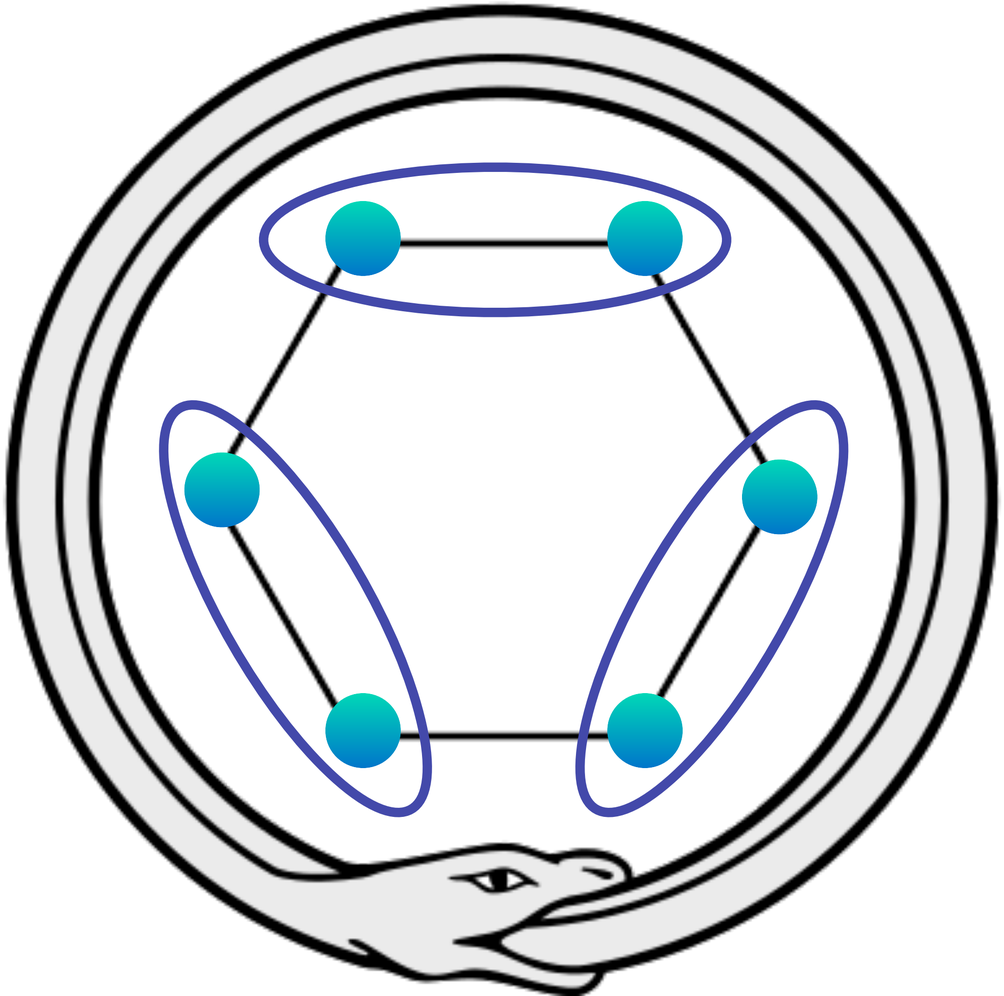

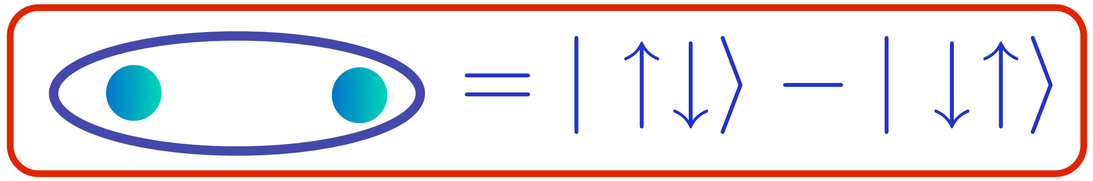

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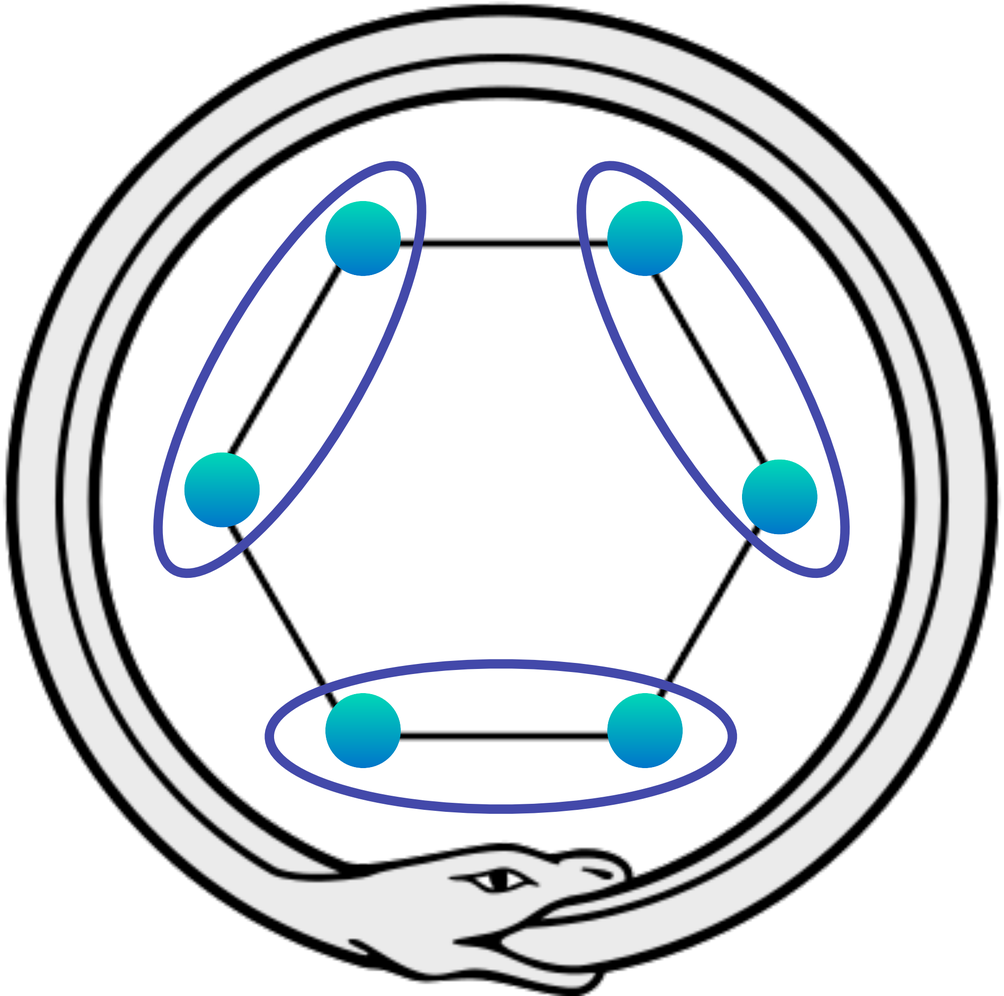

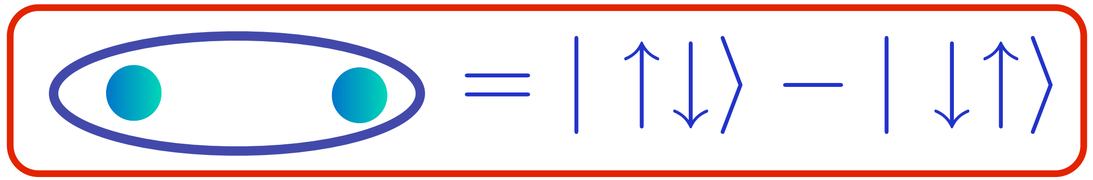

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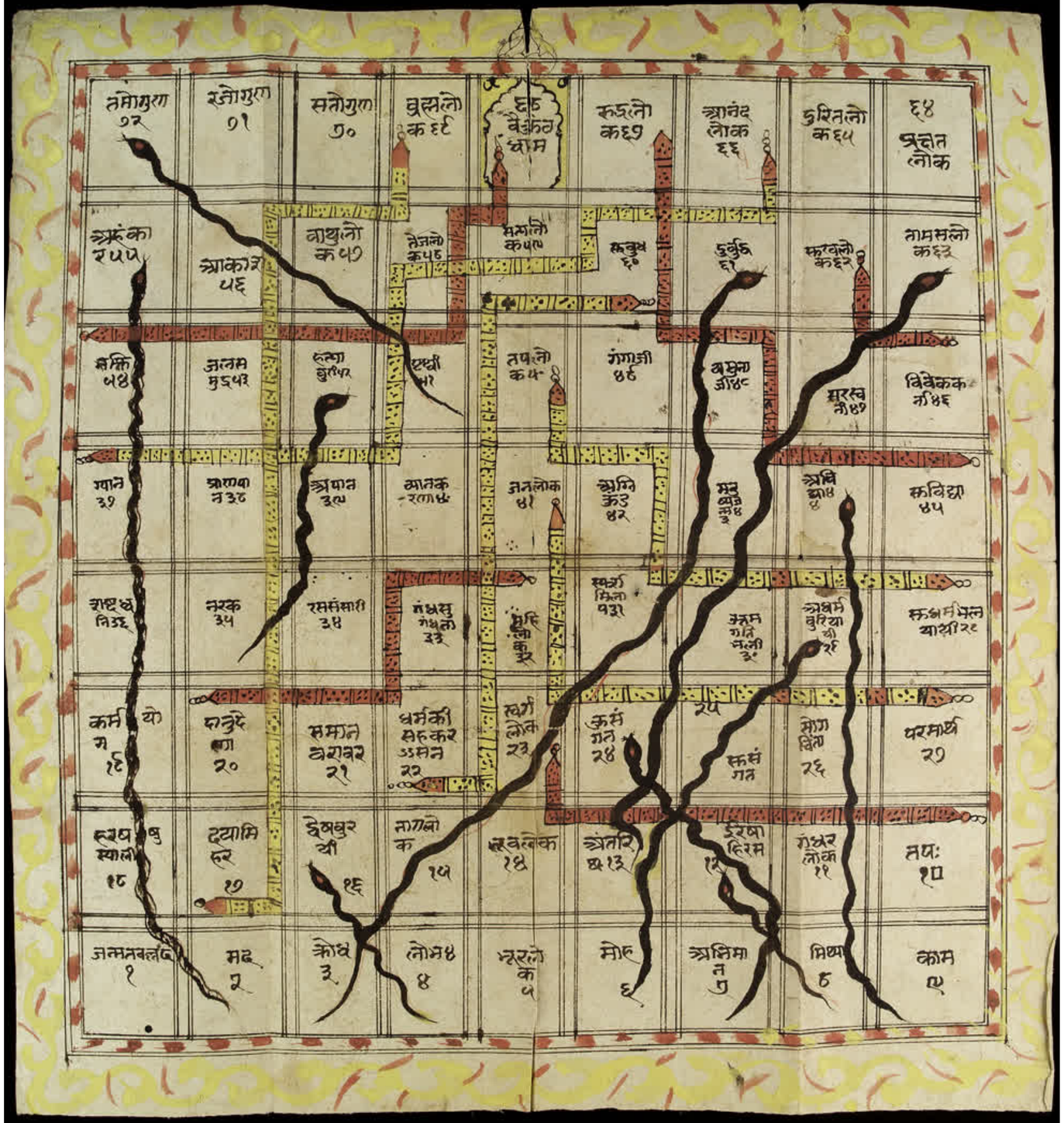


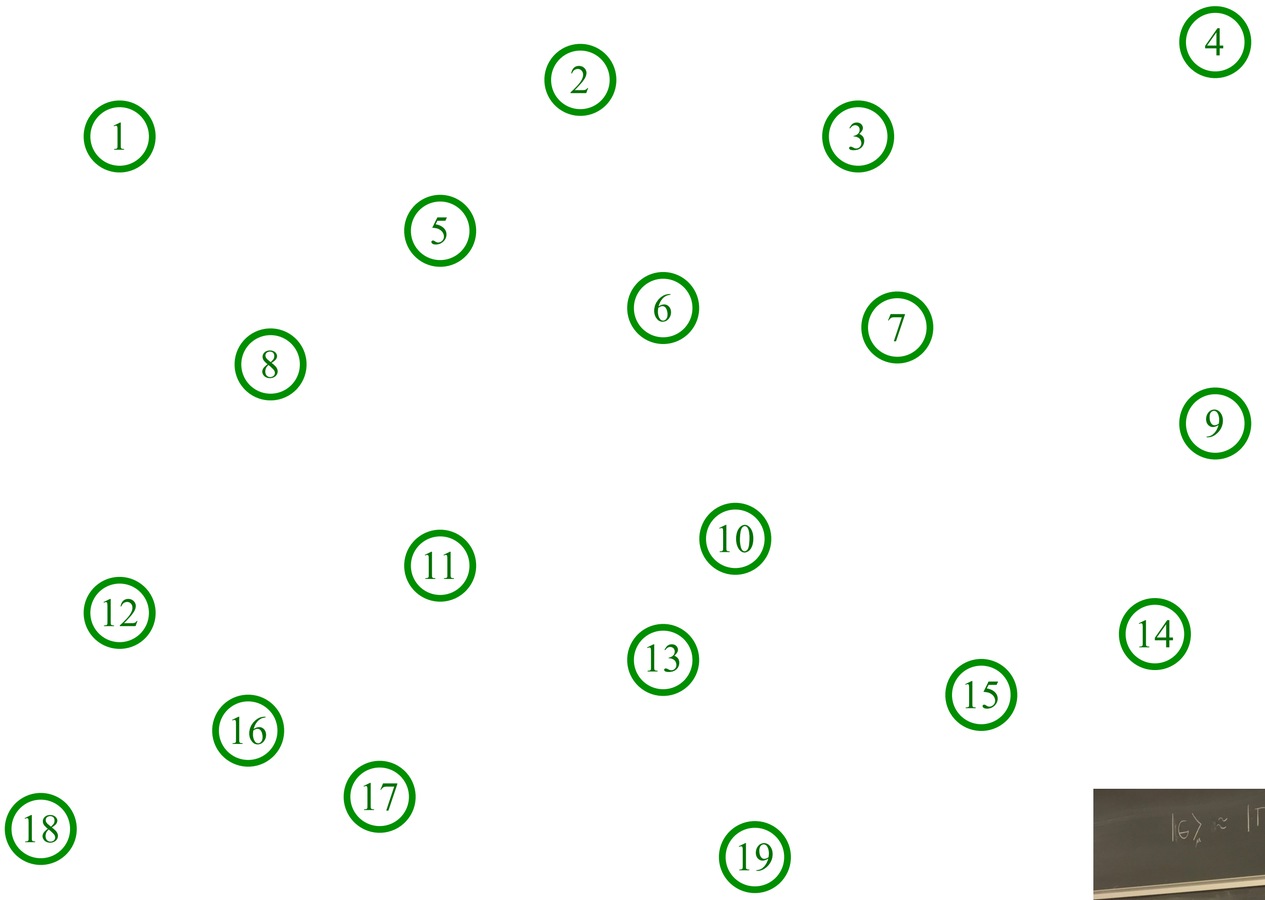
My spooky dream*

Ancient Indian game of Snakes and Ladders

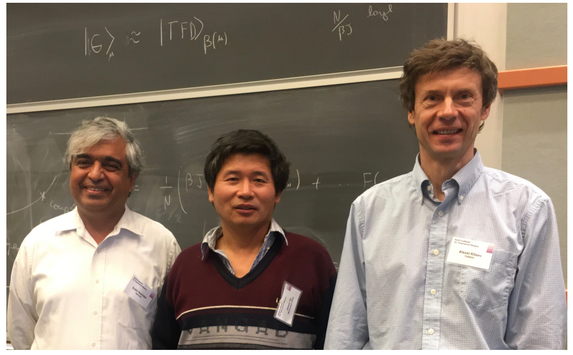
*Not true

The SYK model

Sachdev, Ye (1993); Kitaev (2015)

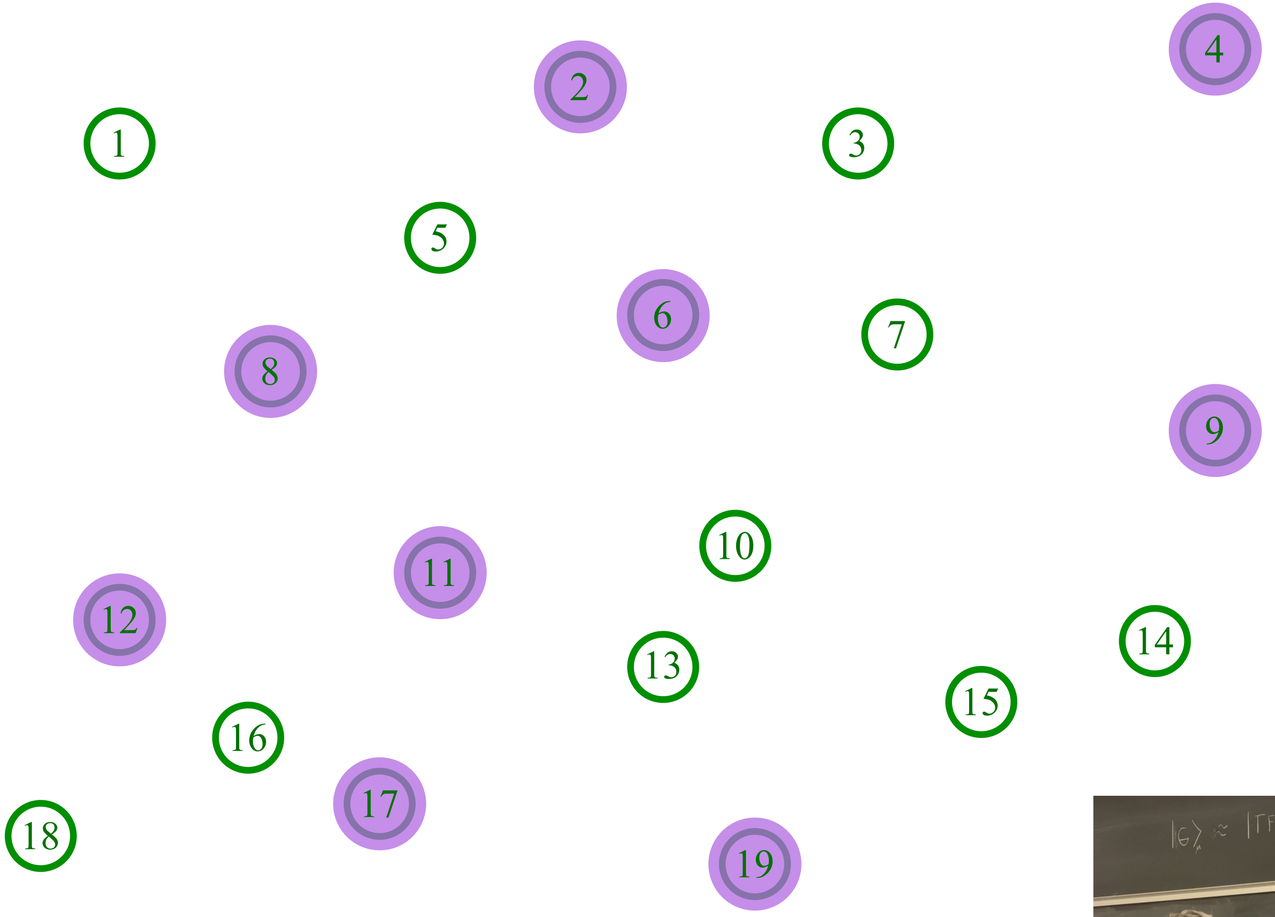


Pick a set of random positions

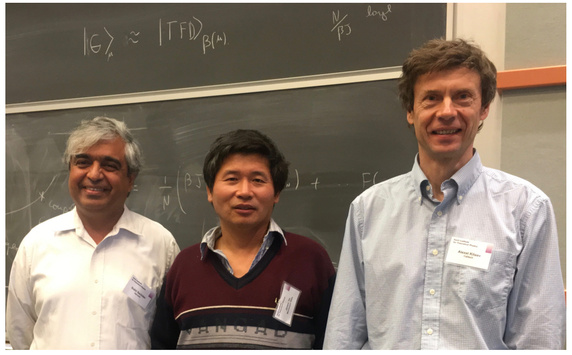


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



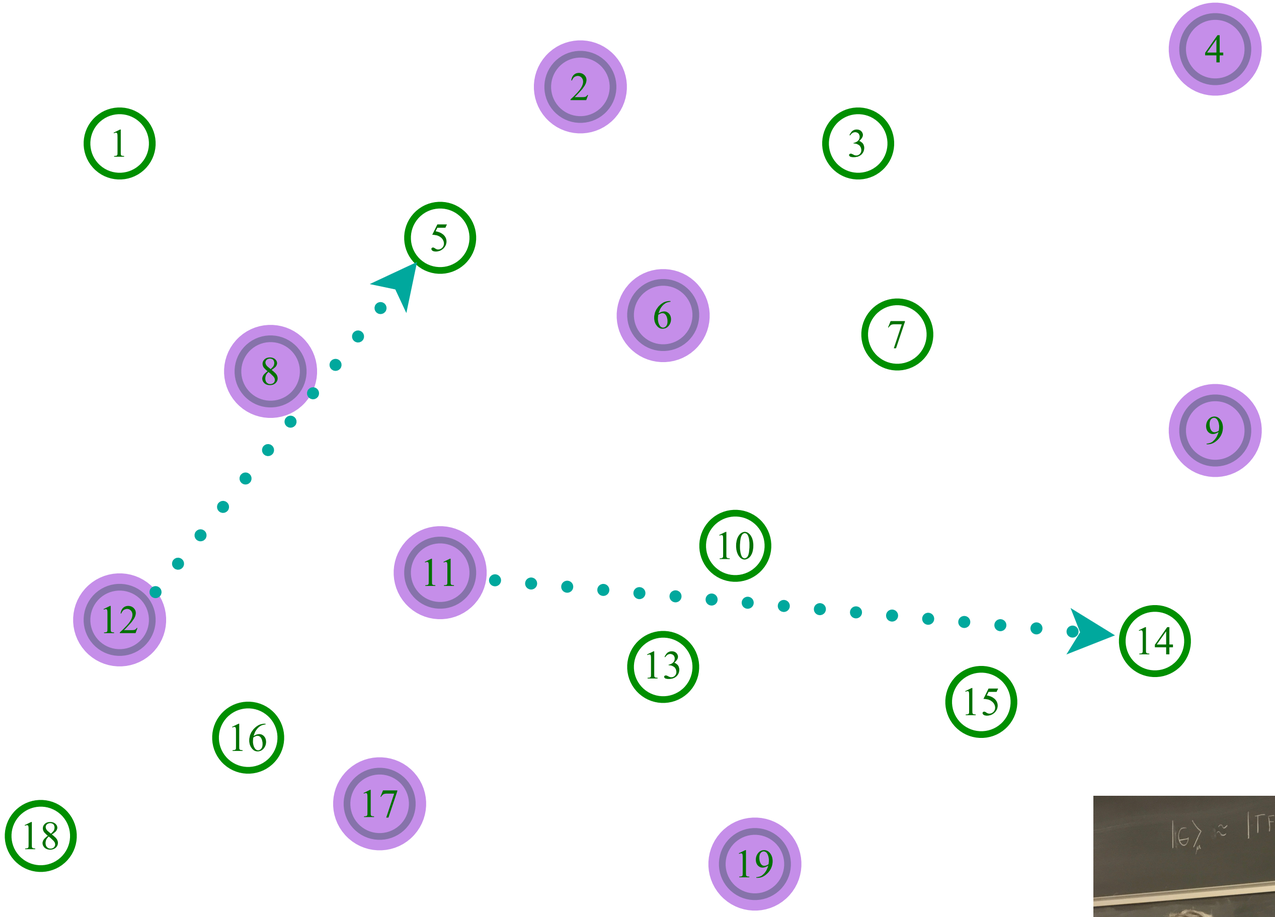
Place electrons randomly on some sites



The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



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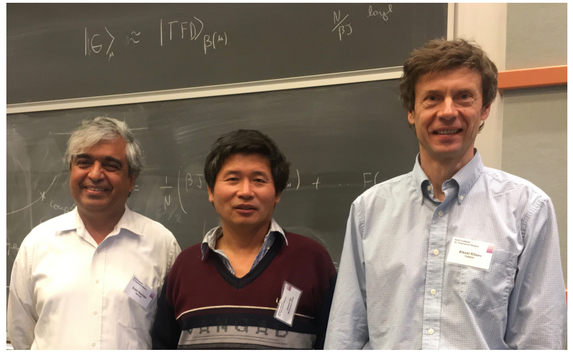

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Sachdev, Ye (1993); Kitaev (2015)

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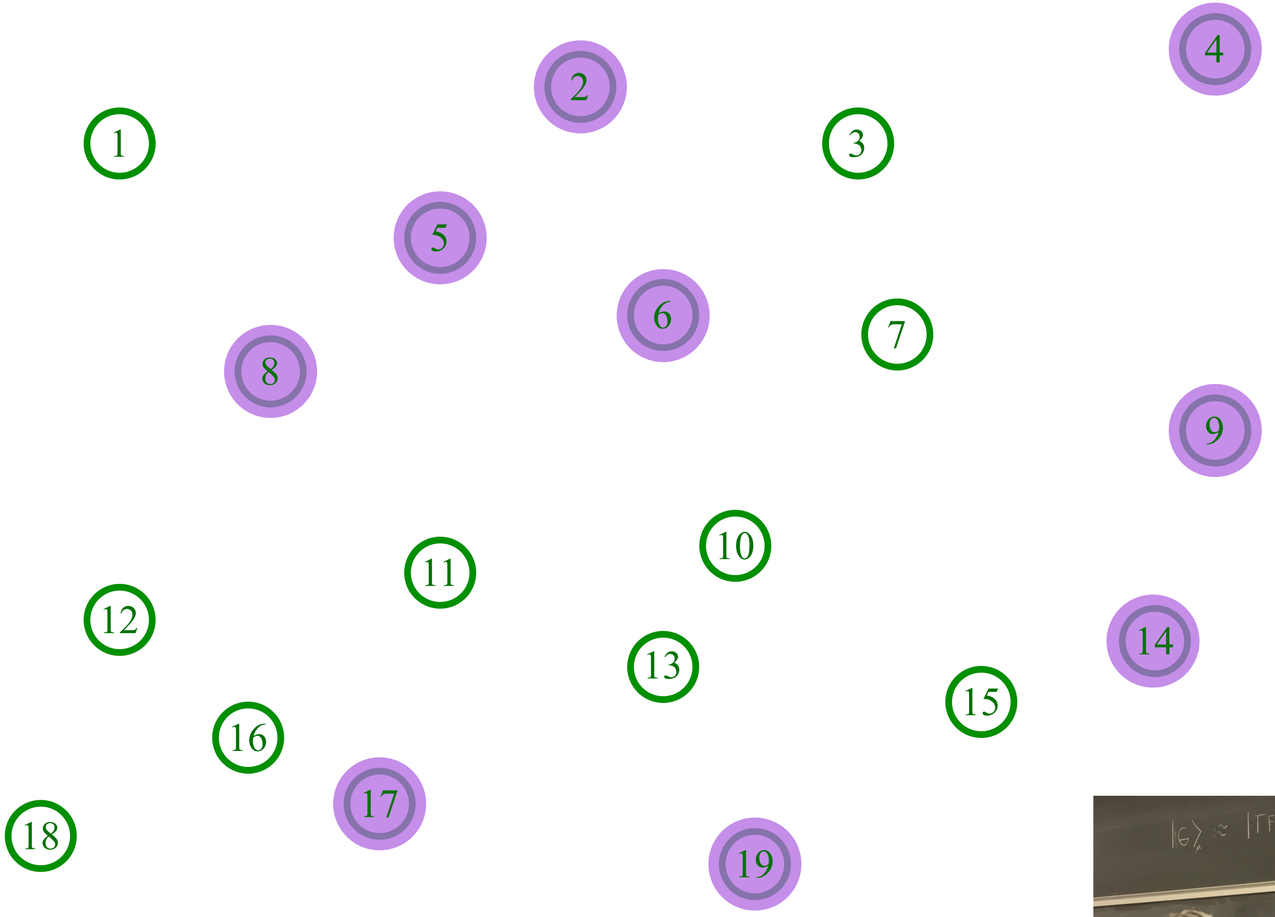
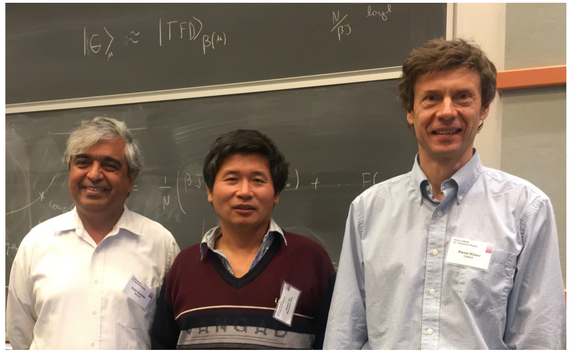


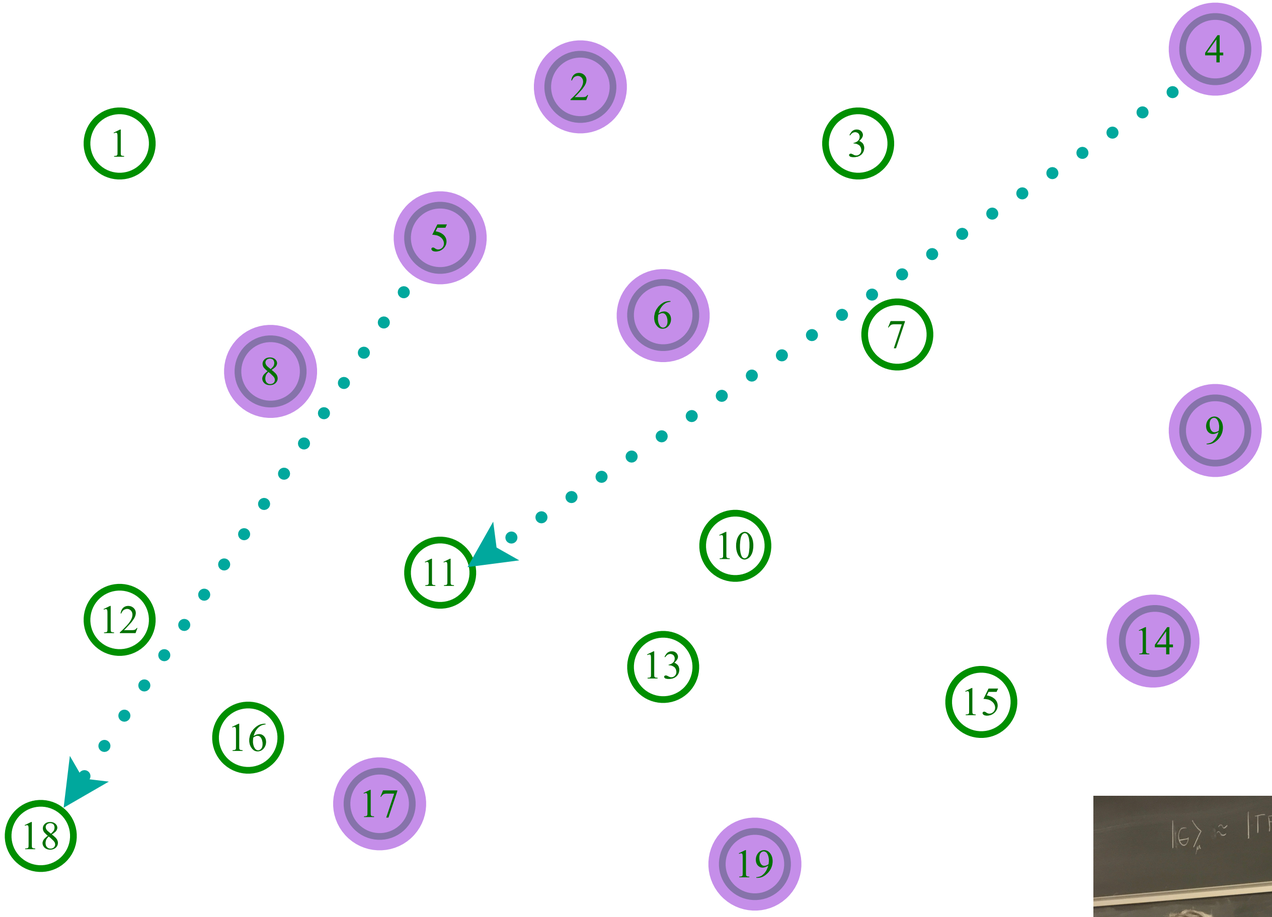
Entangle electrons pairwise randomly



The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



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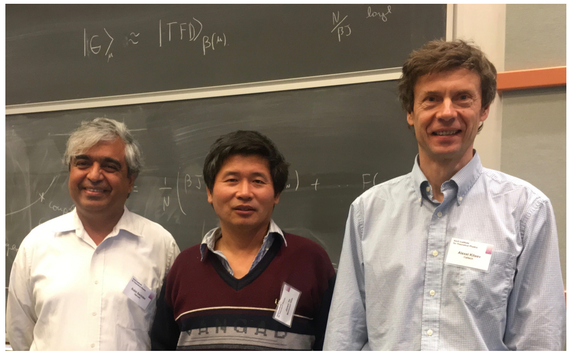

The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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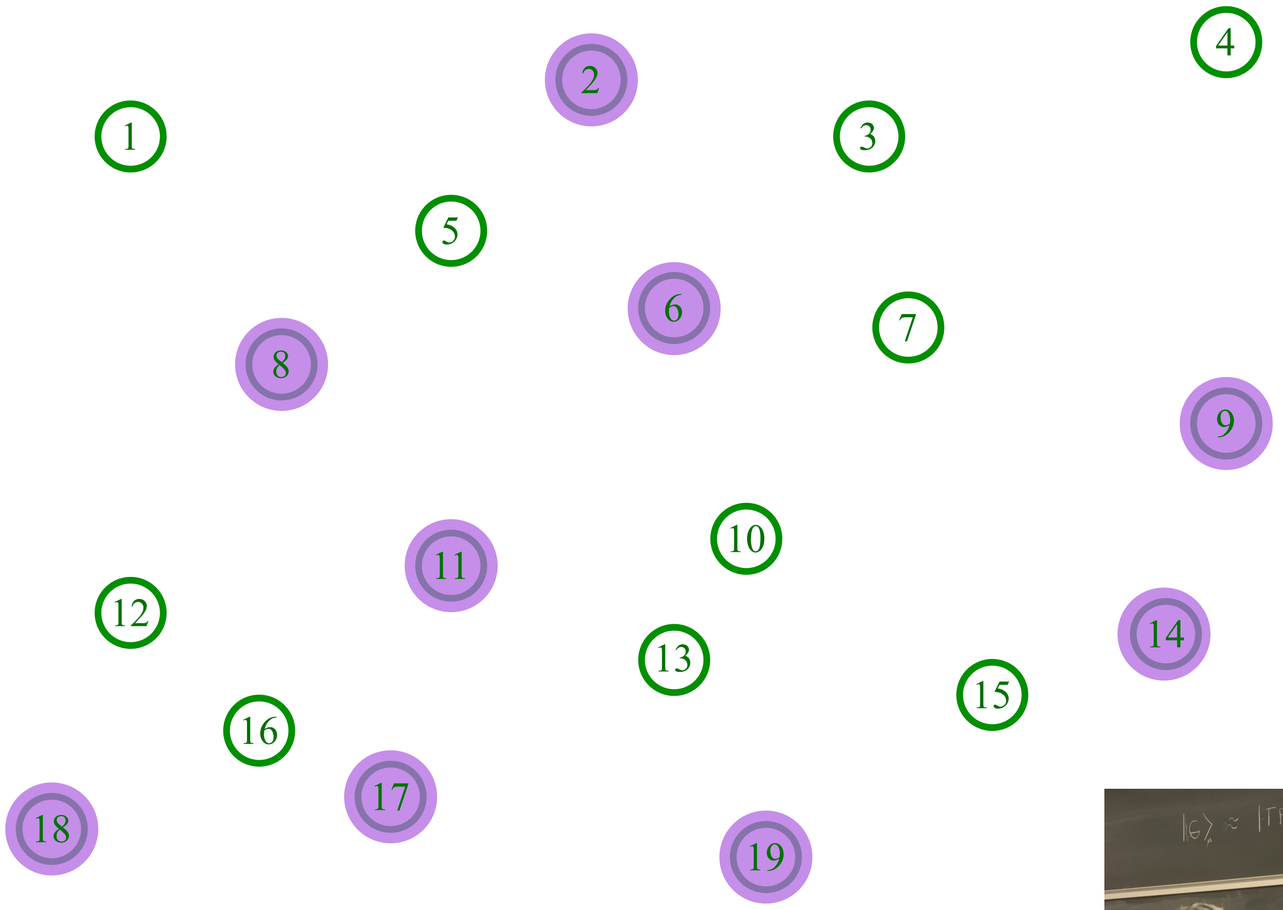

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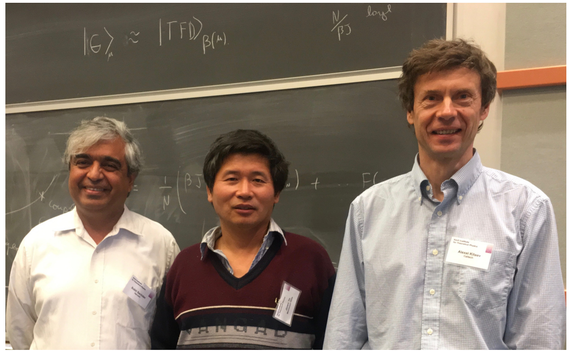
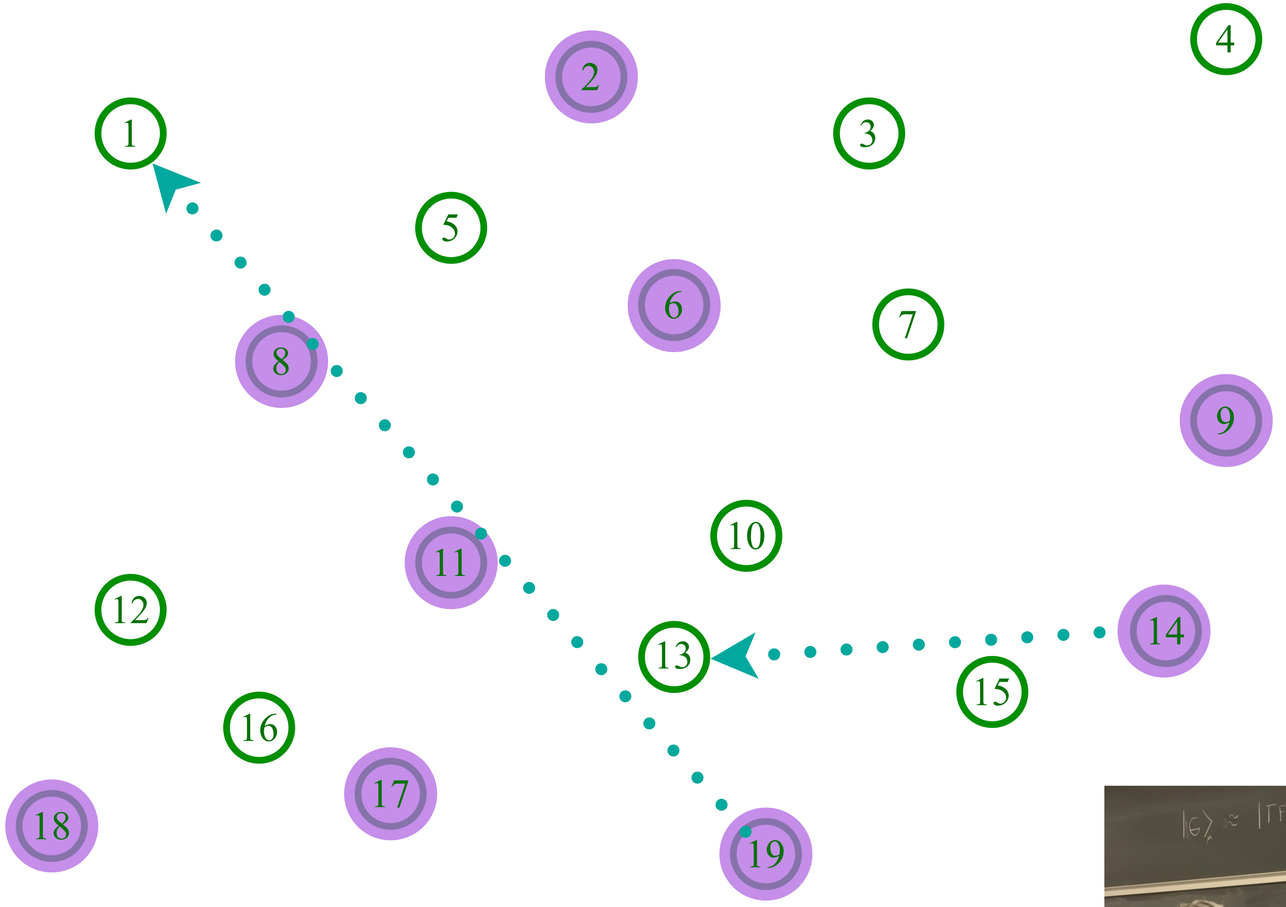


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



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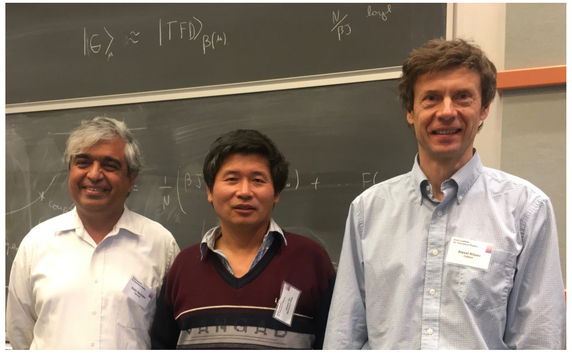

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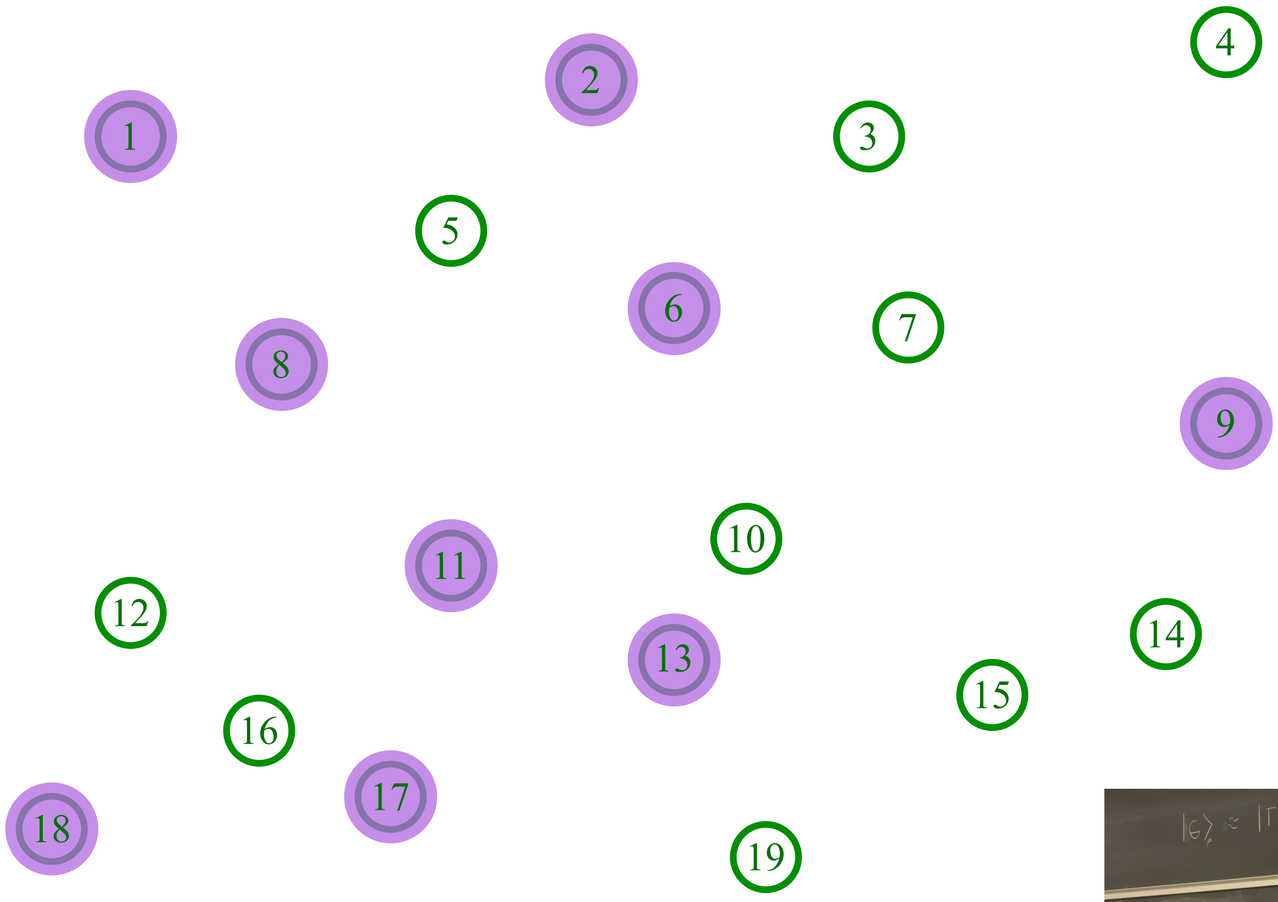
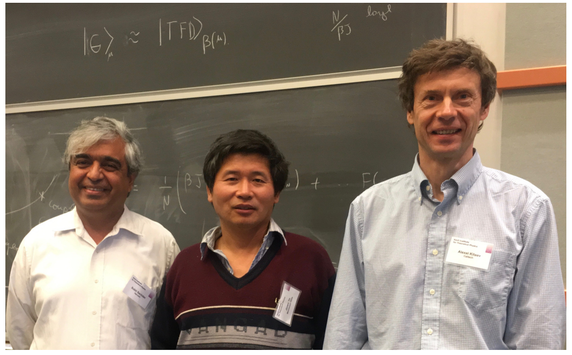


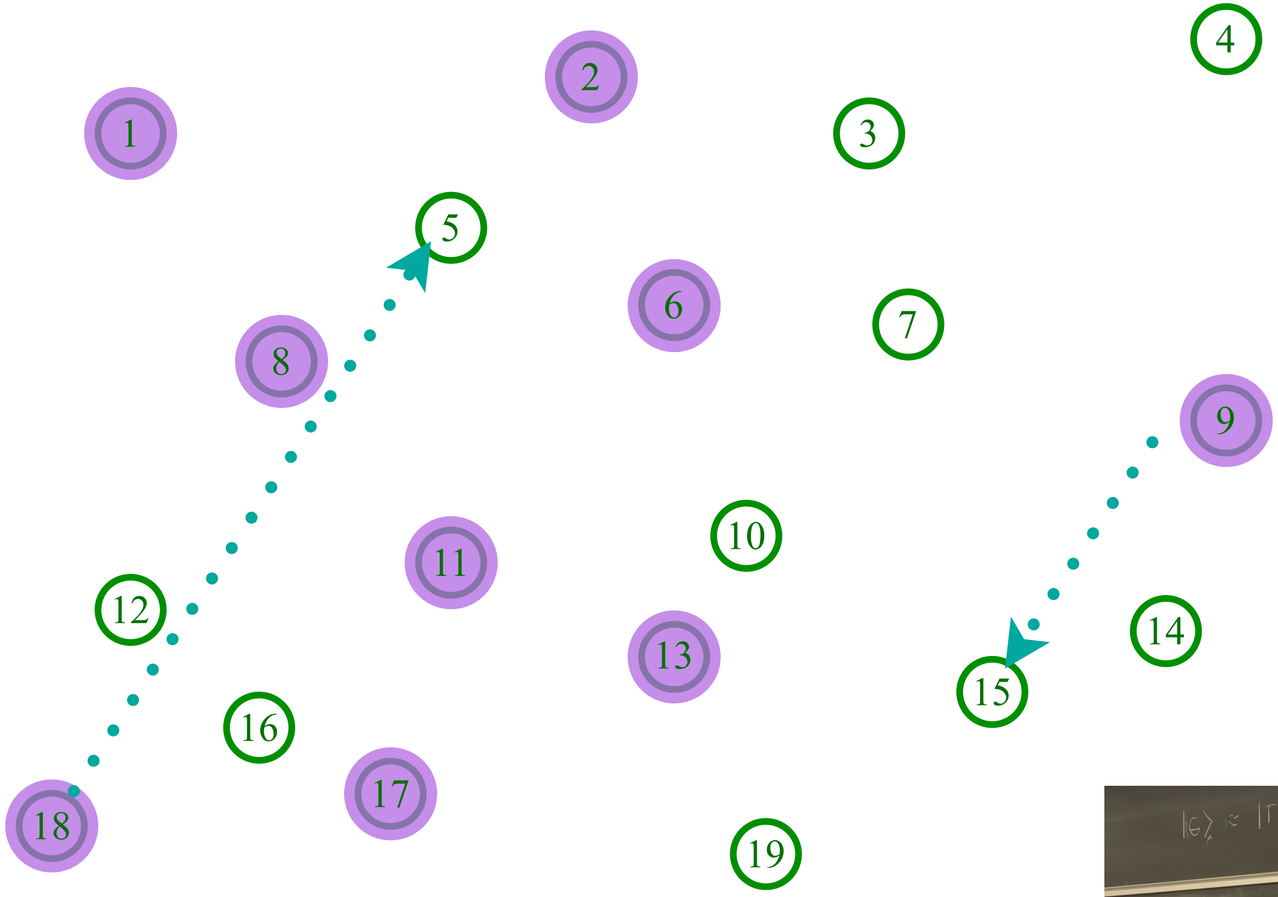
Entangle electrons pairwise randomly



The SYK model

Sachdev, Ye (1993); Kitaev (2015)

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



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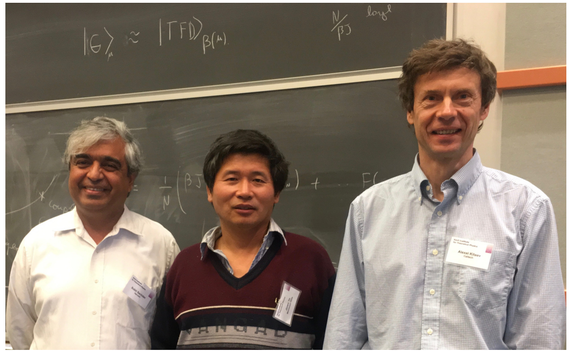

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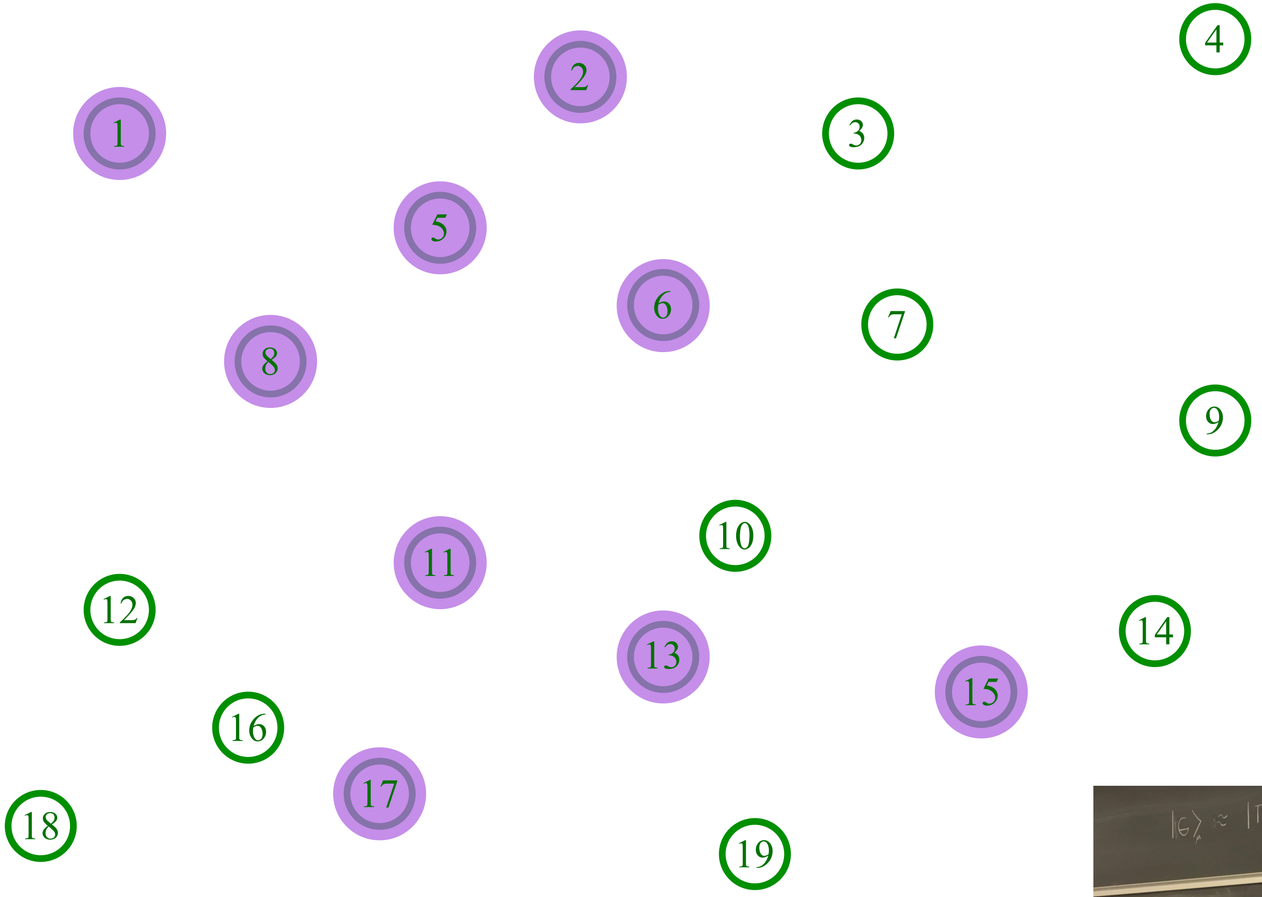

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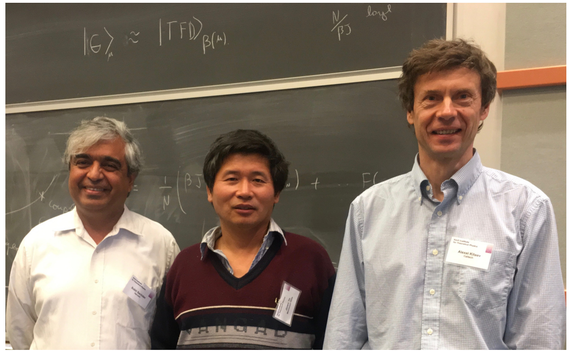

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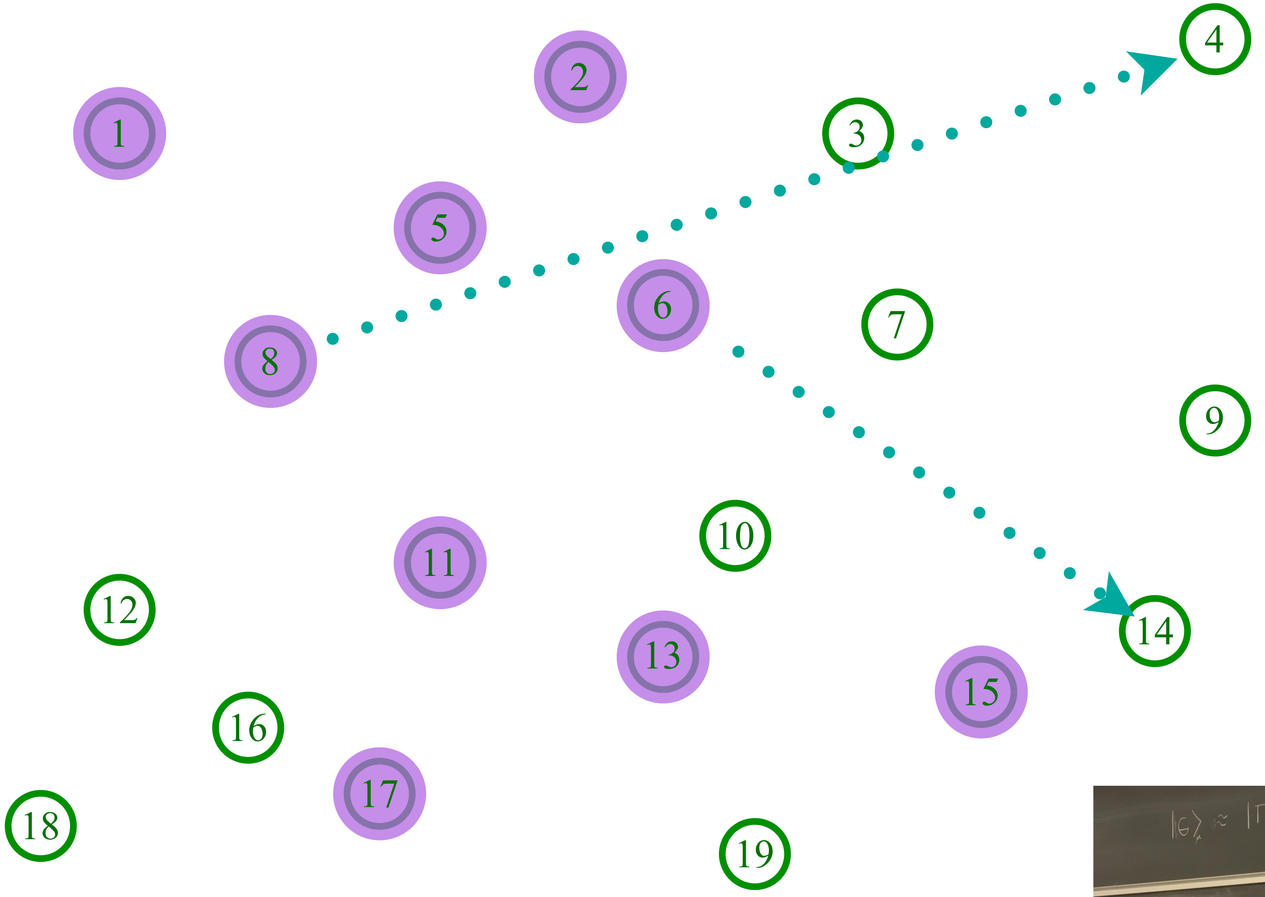

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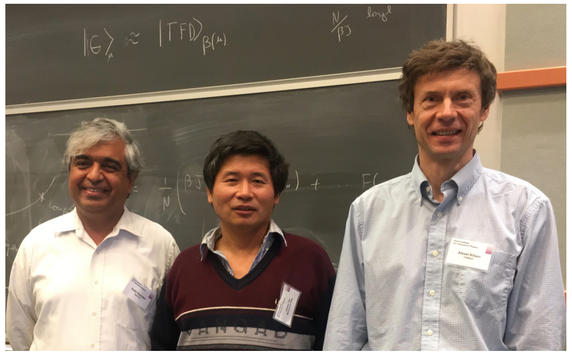

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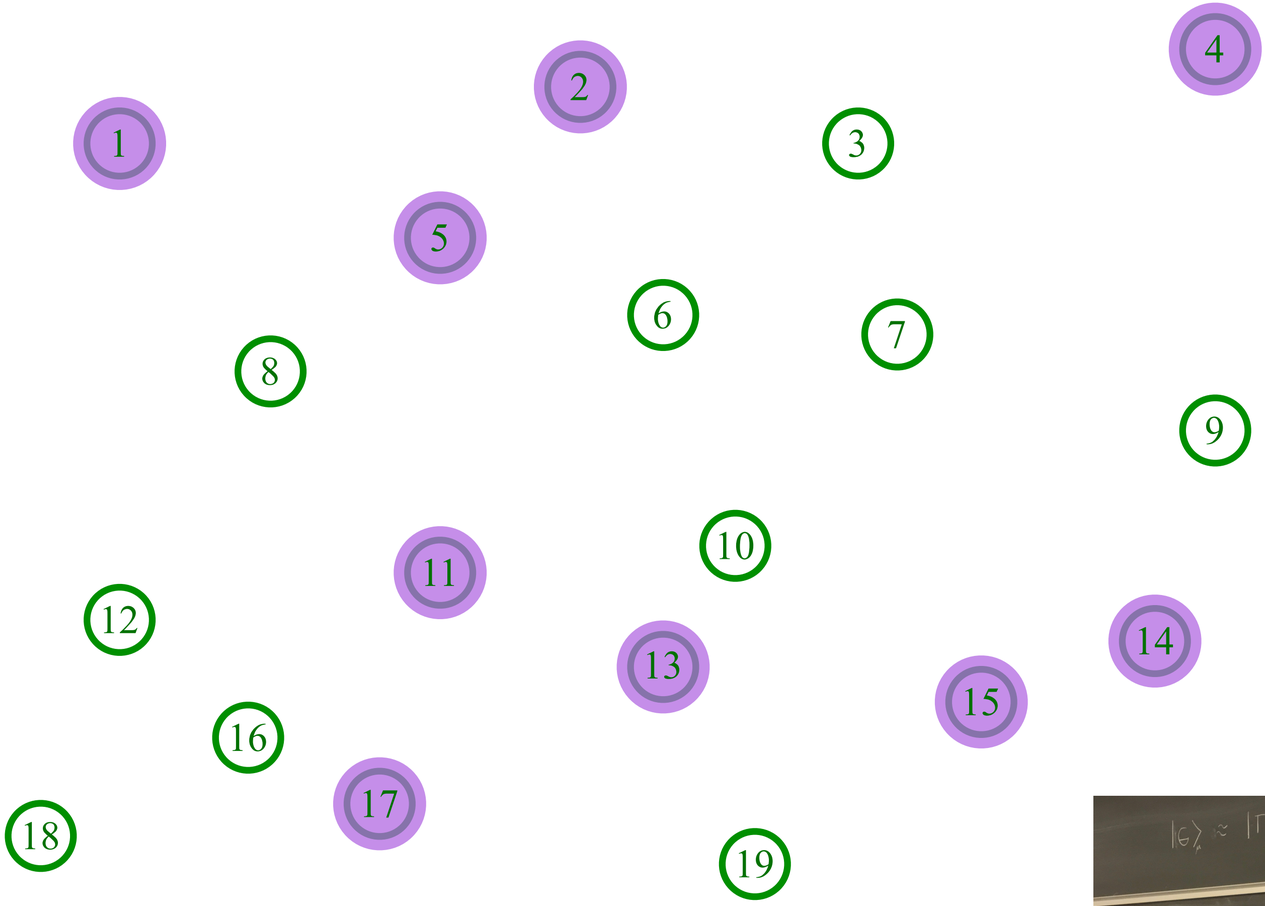

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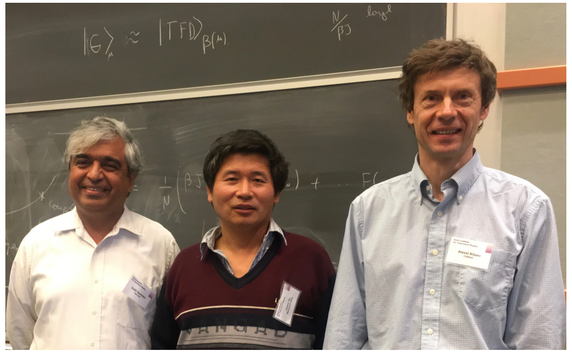


The SYK model

(See also: the "2-Body Random Ensemble" in nuclear physics; did not obtain the large N limit;
T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

$$\mathcal{H} = \frac{1}{(2N)^{3/2}} \sum_{\alpha,\beta,\gamma,\delta=1}^{N} U_{\alpha\beta;\gamma\delta}\, c_\alpha^\dagger c_\beta^\dagger c_\gamma c_\delta - \mu \sum_\alpha c_\alpha^\dagger c_\alpha$$

$$c_\alpha c_\beta + c_\beta c_\alpha = 0 \quad , \quad c_\alpha c_\beta^\dagger + c_\beta^\dagger c_\alpha = \delta_{\alpha\beta}$$

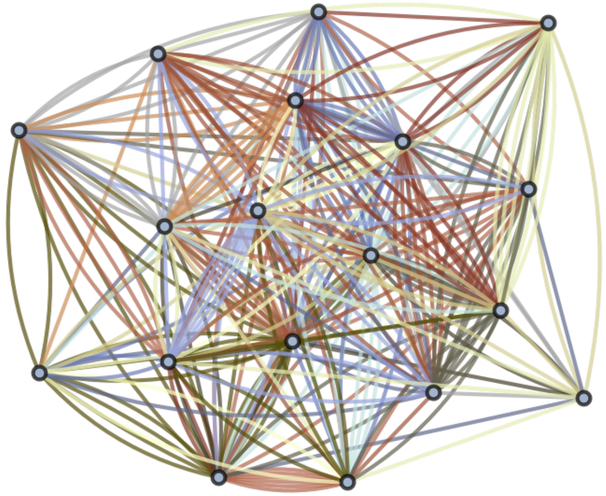
$$\mathcal{Q} = \frac{1}{N} \sum_\alpha c_\alpha^\dagger c_\alpha \, ; \quad [\mathcal{H}, \mathcal{Q}] = 0 \, ; \quad 0 \leq \mathcal{Q} \leq 1$$

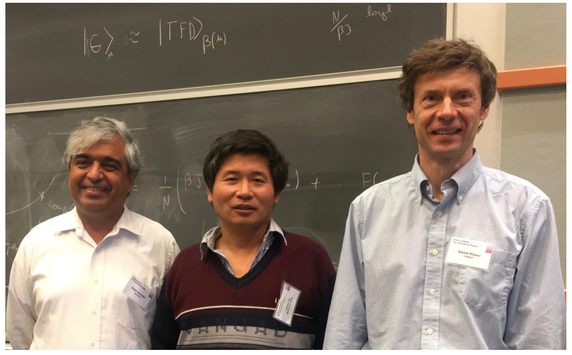
$U_{\alpha\beta;\gamma\delta}$ are independent random variables with $\overline{U_{\alpha\beta;\gamma\delta}} = 0$ and $\overline{|U_{\alpha\beta;\gamma\delta}|^2} = U^2$

$N \to \infty$ yields critical strange metal.

S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)





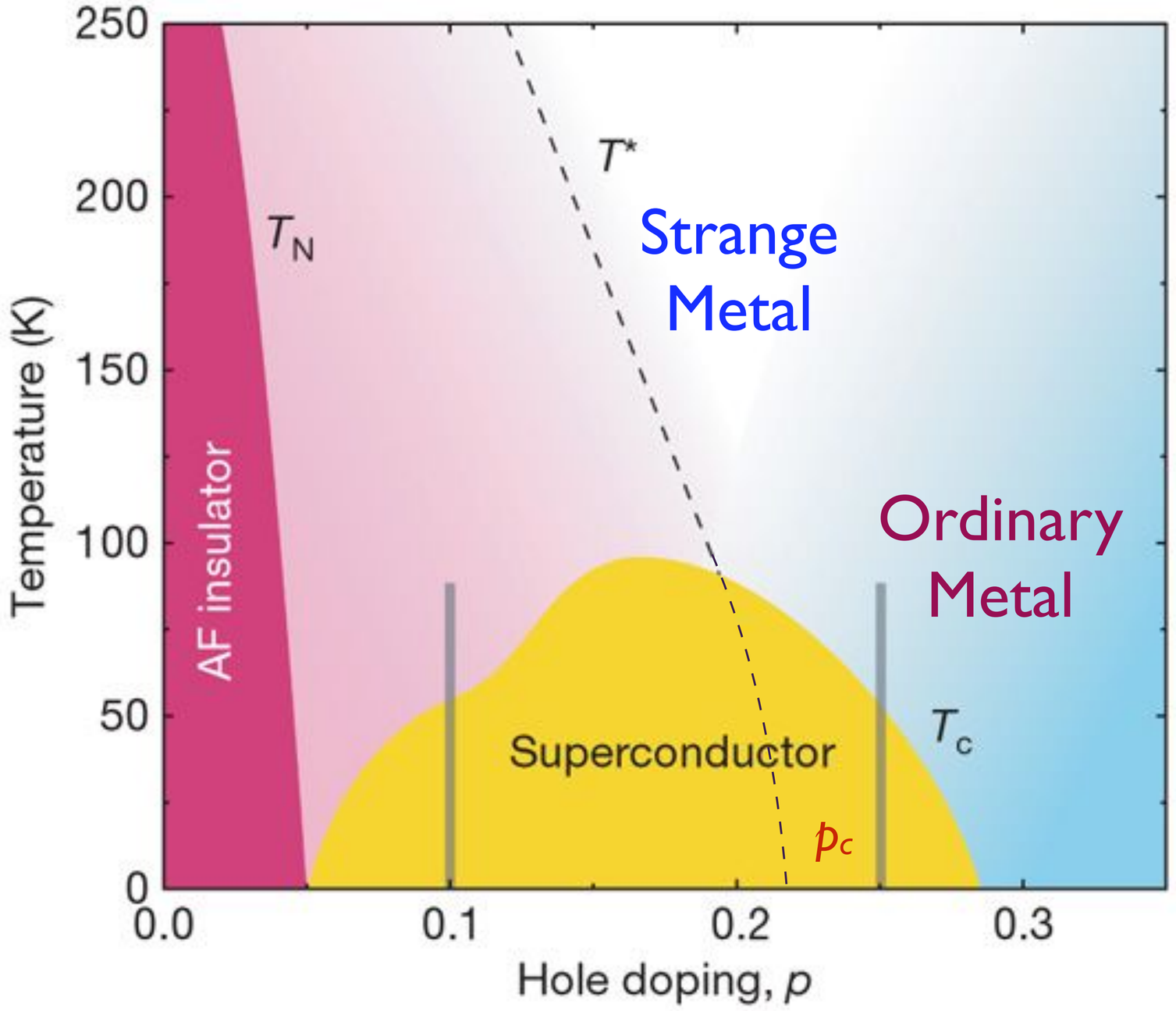
The Sachdev-Ye-Kitaev (SYK) model

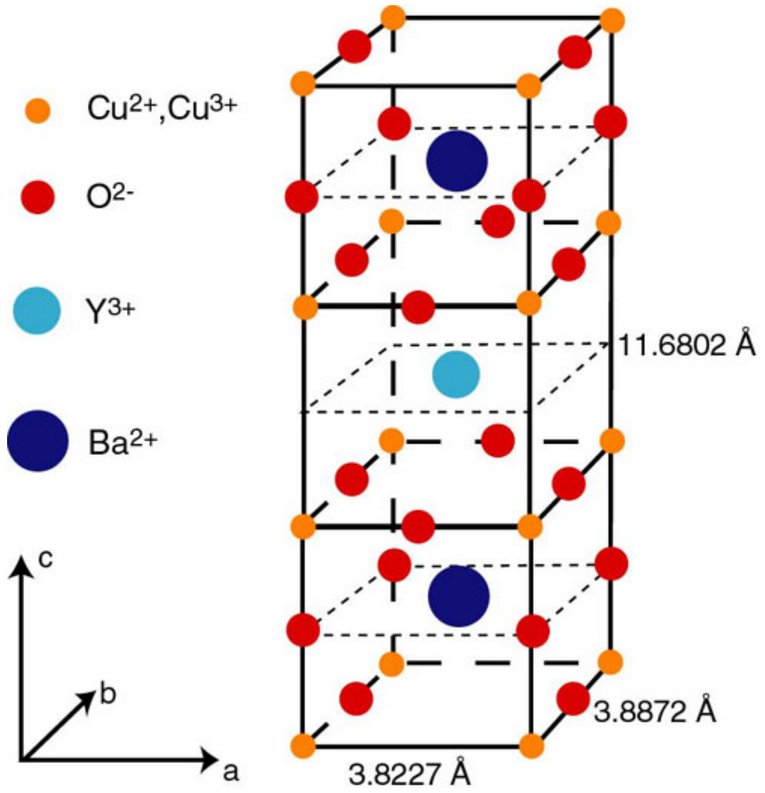
Sachdev, Ye (1993); Kitaev (2015)

A solvable model of multi-particle quantum entanglement.

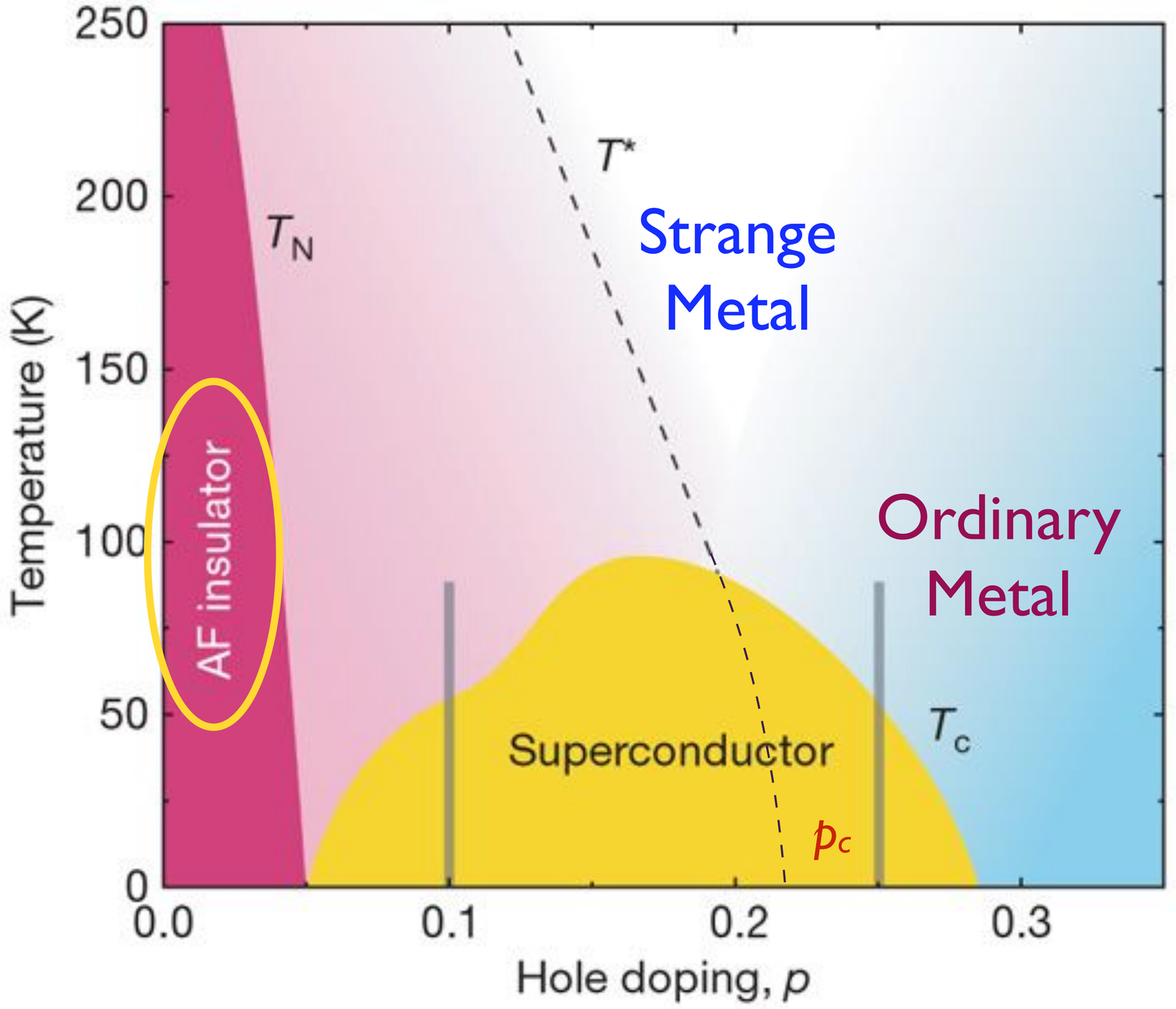
Yields a metal in which current is carried not by individual electrons, but by an entangled "quantum soup"

Spin liquids, fractionalization, and superconductivity


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

$YBa_2Cu_3O_{6+x}$


250
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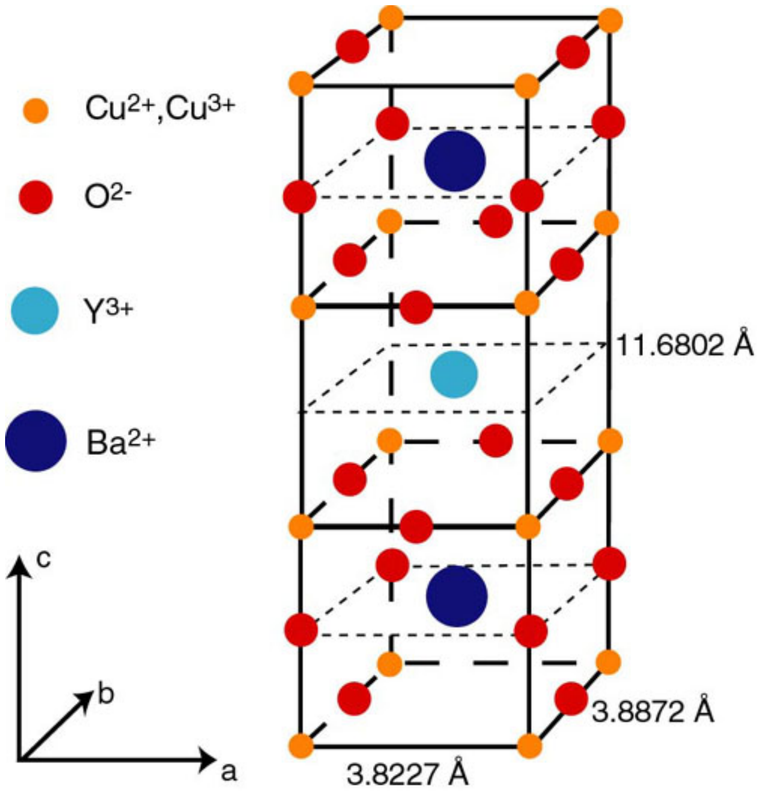
Cu2+,Cu3+
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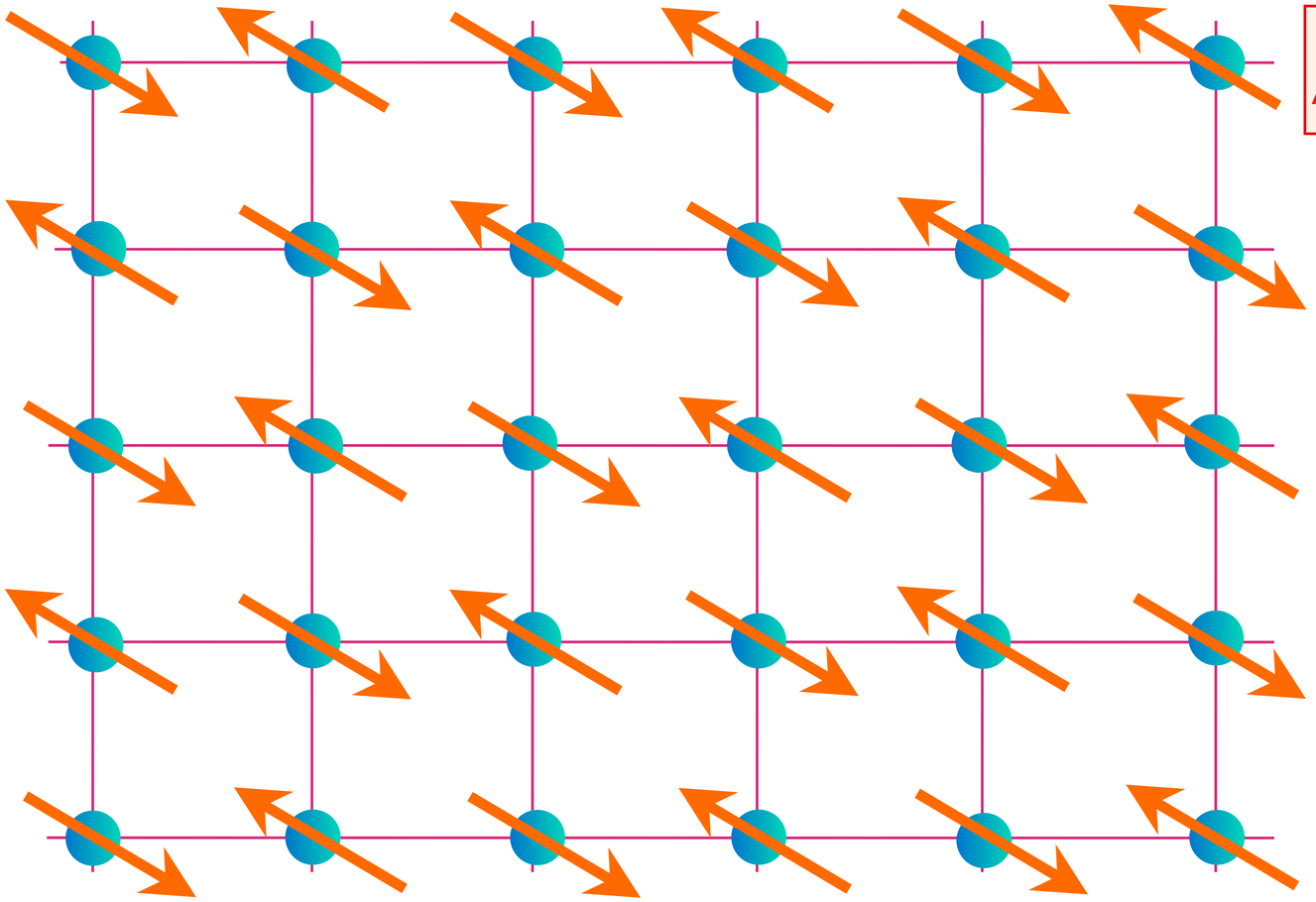
The dance of electrons on Cu atoms in YBCO



Antiferromagnetism

All nearest-neighbor pairs of electrons have opposite spins

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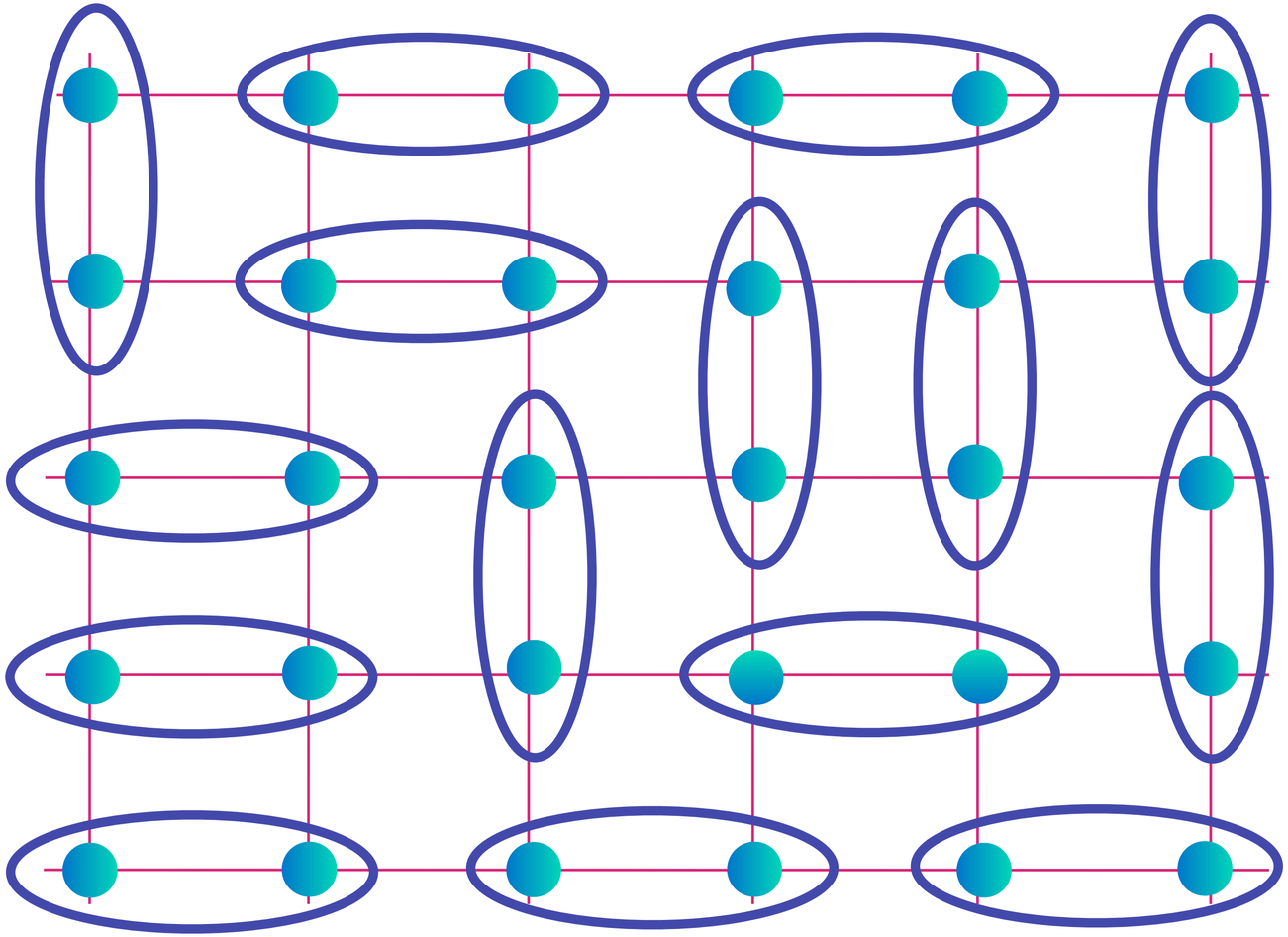
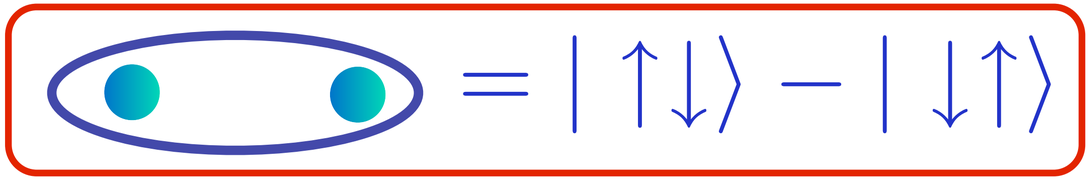


P.W. Anderson (1973)

Spin liquid

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



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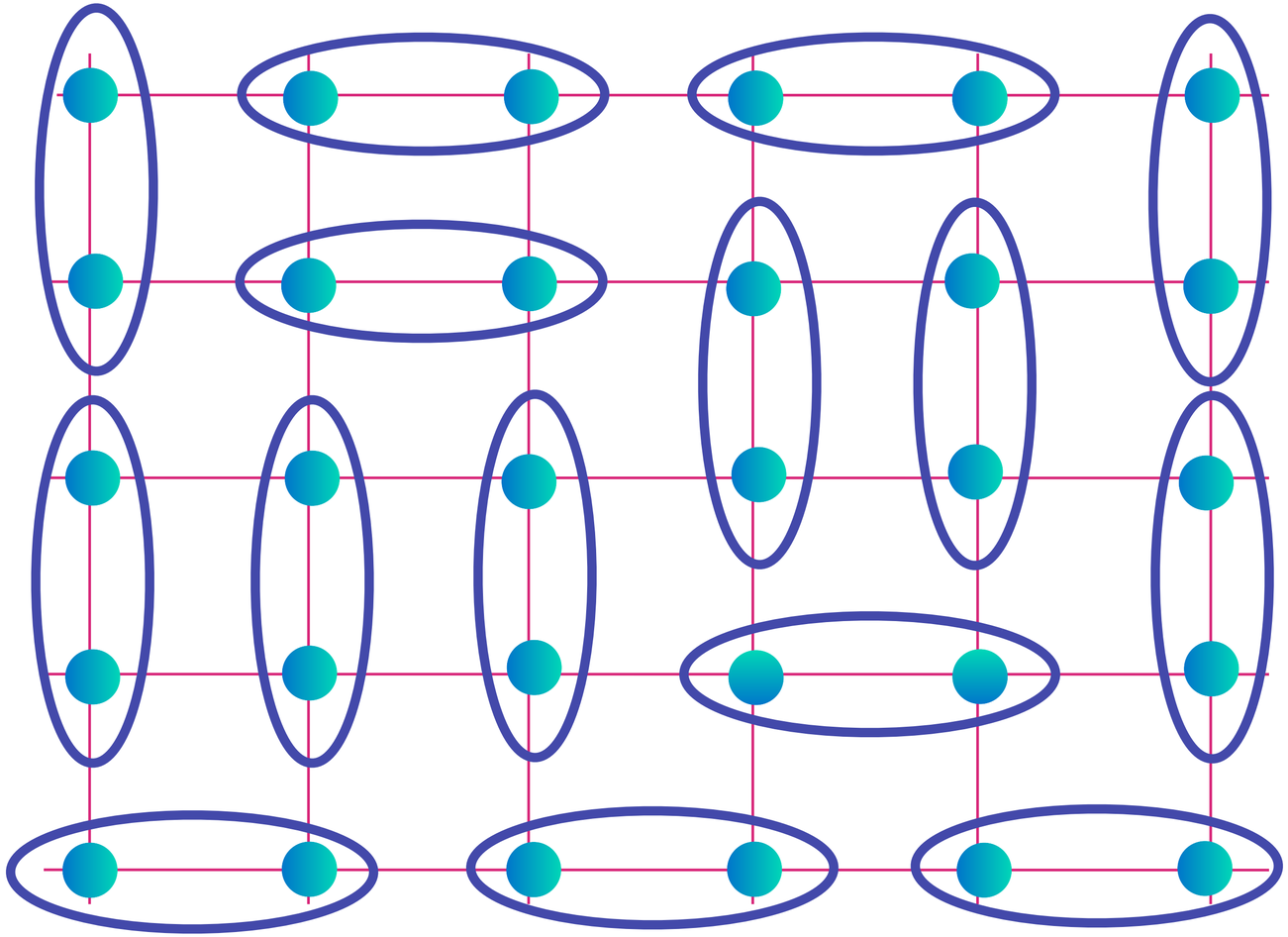

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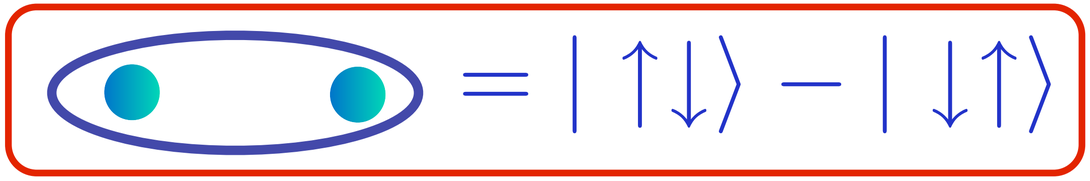

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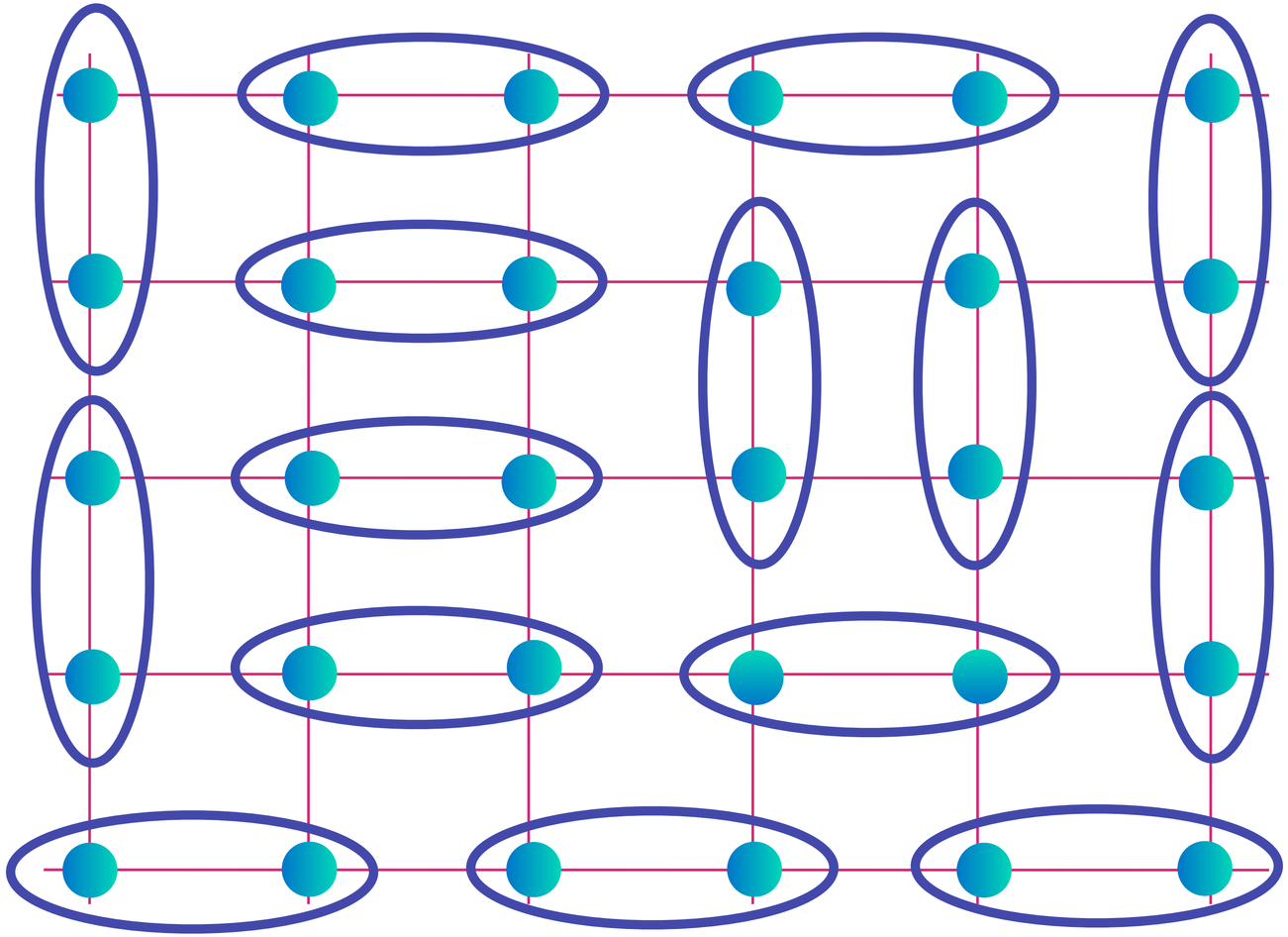

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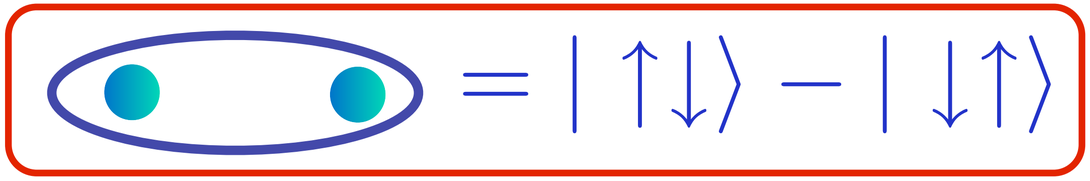

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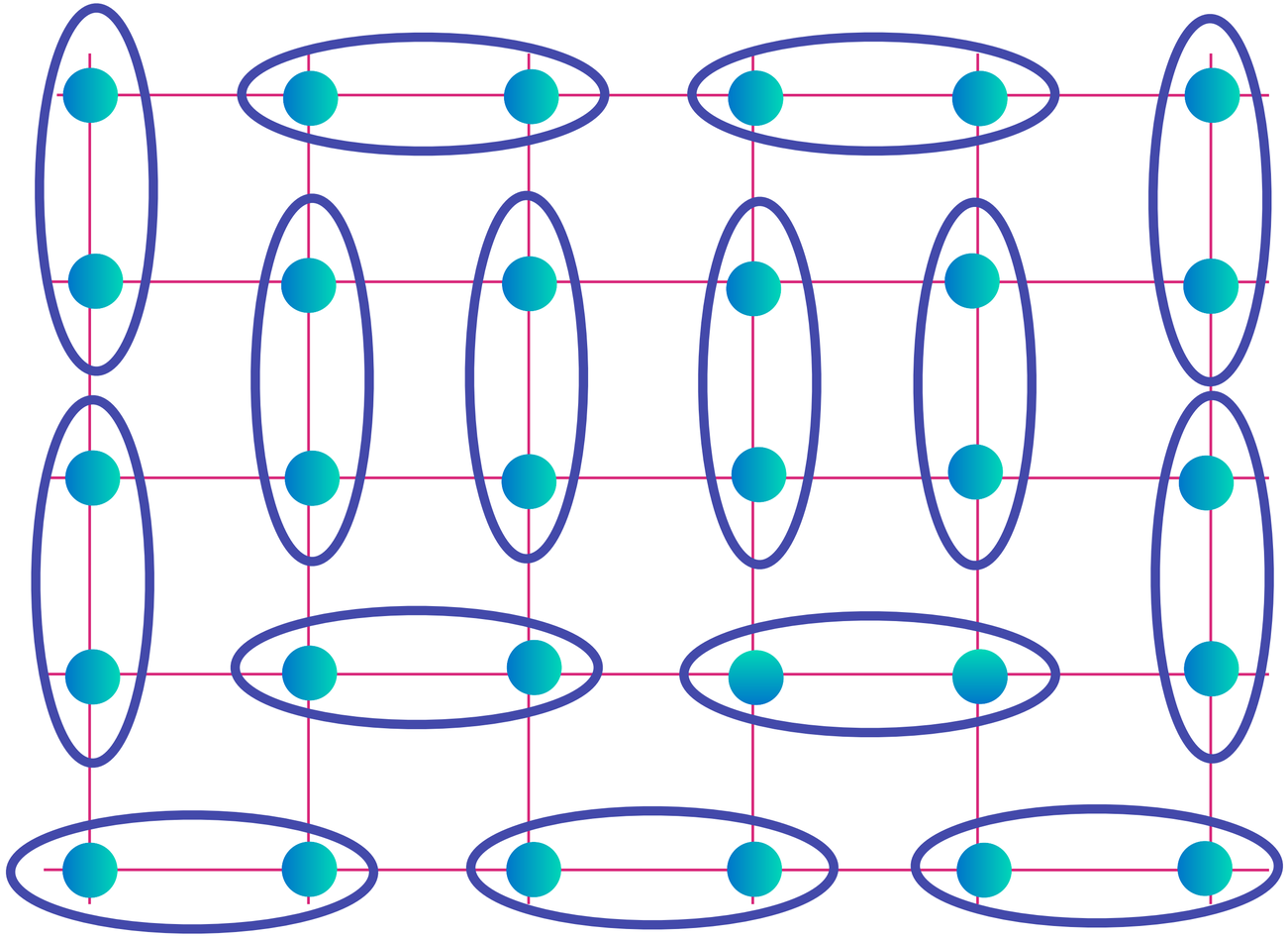

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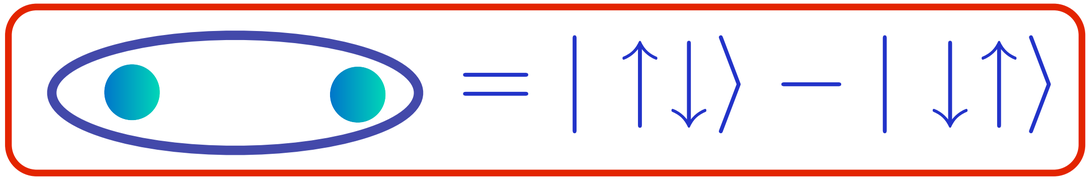

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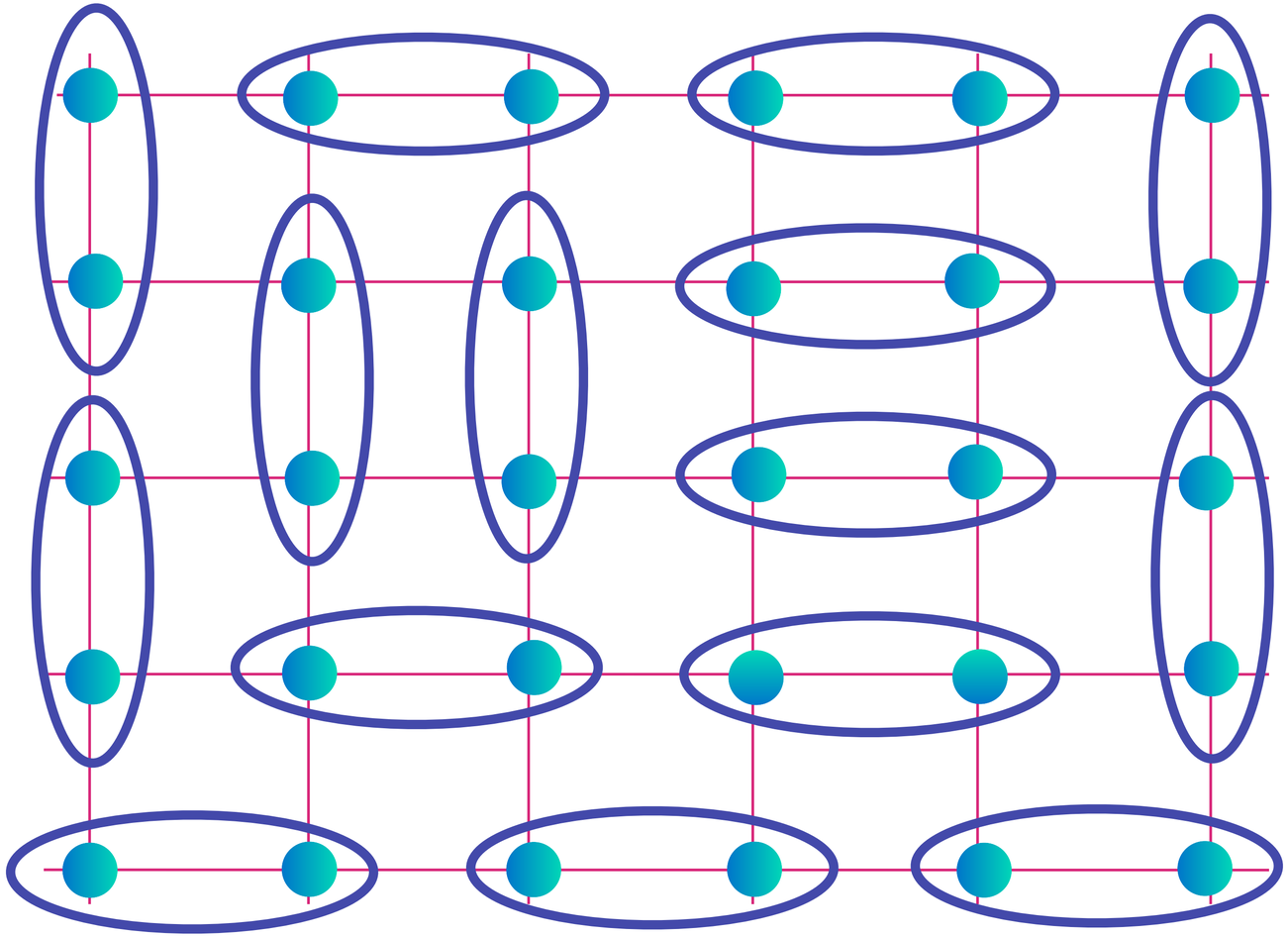

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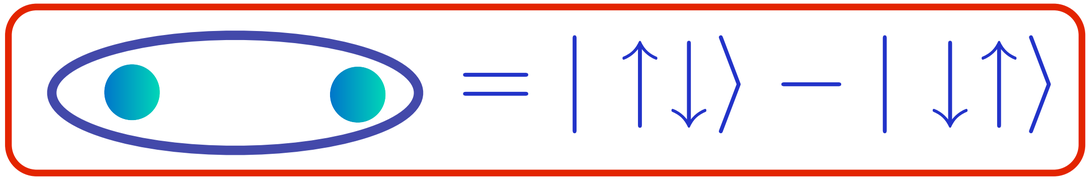

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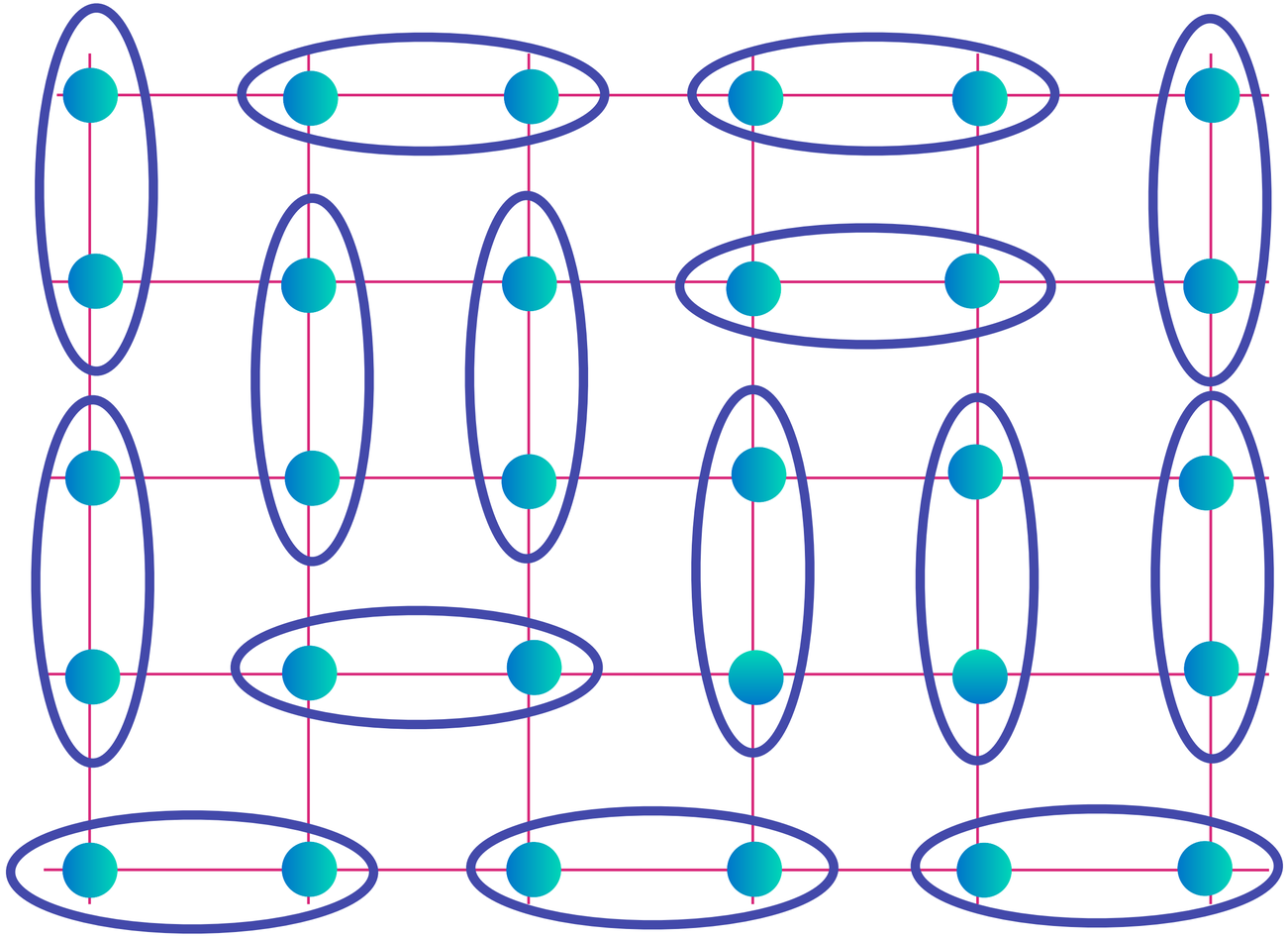

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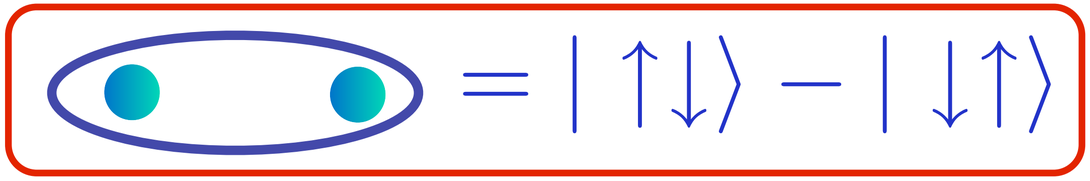

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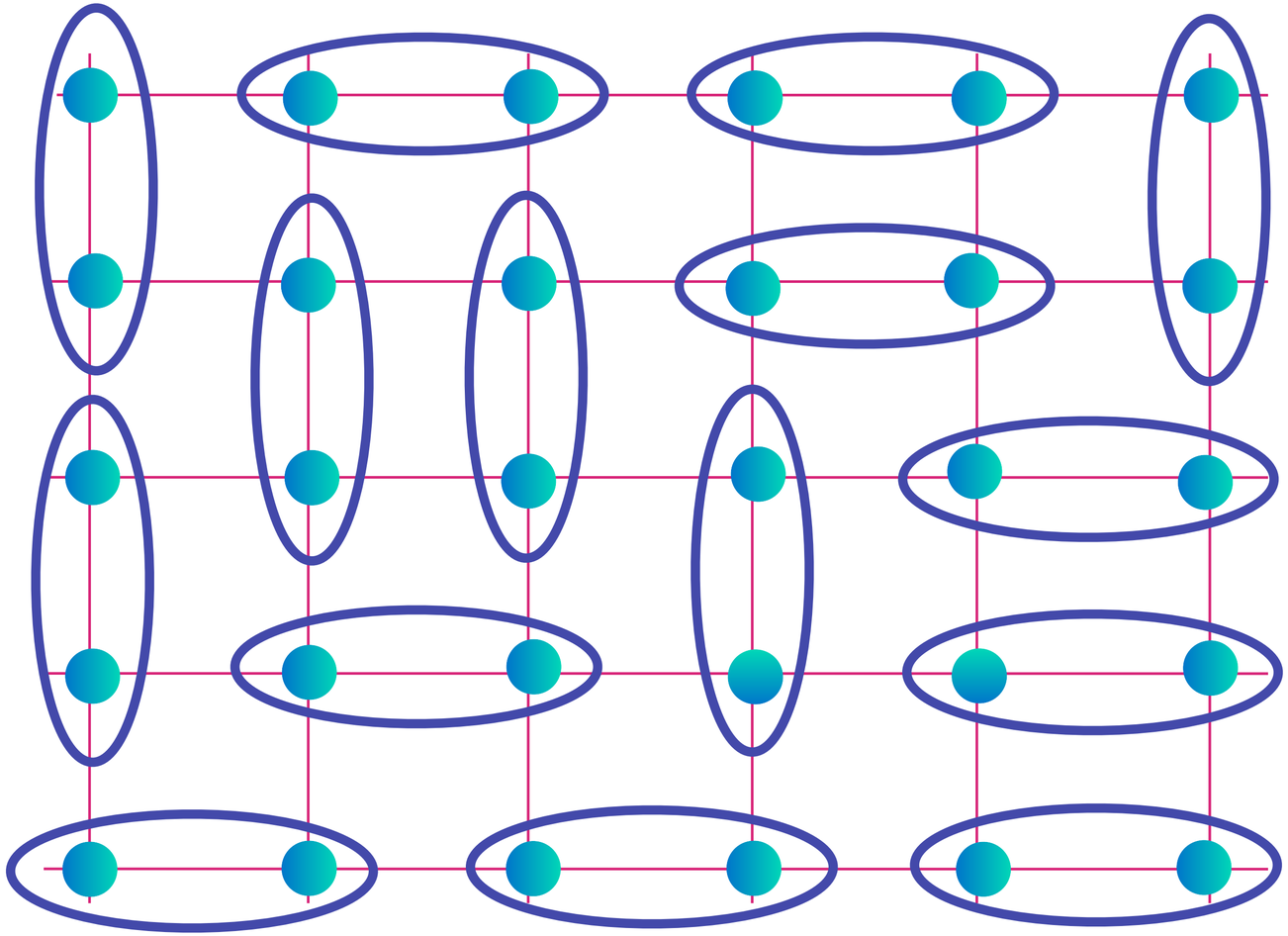

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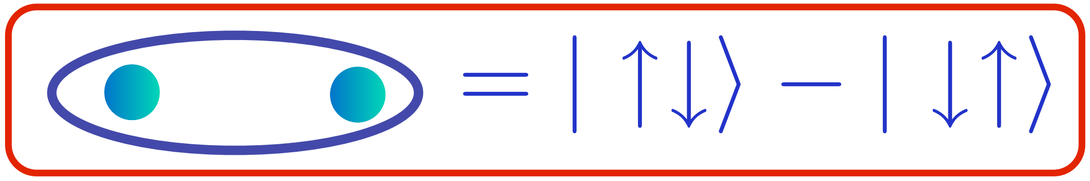

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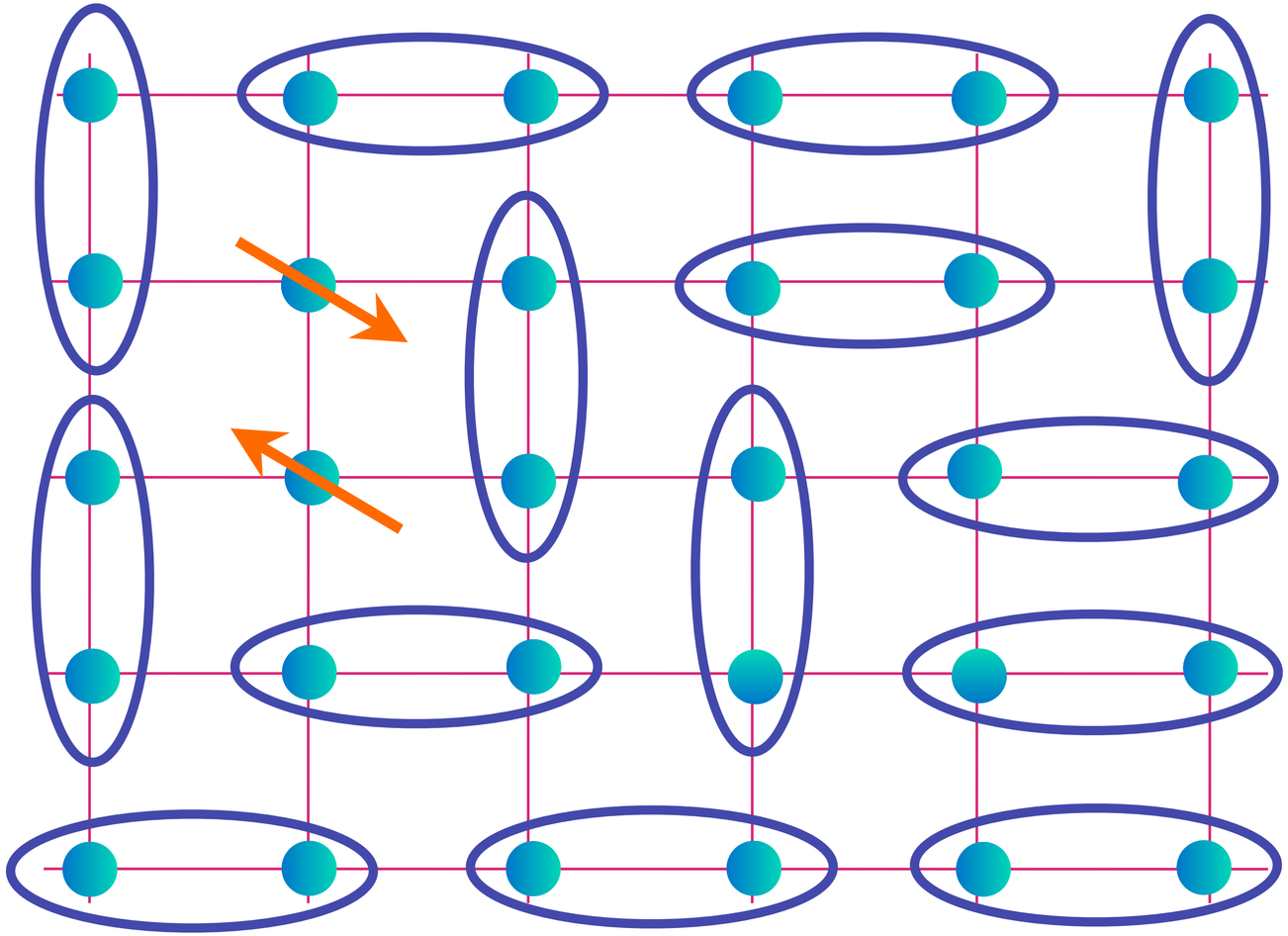
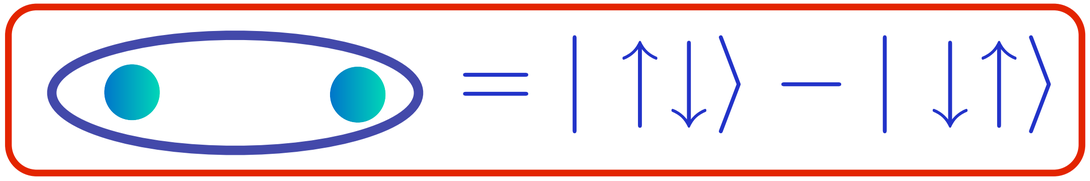


Kivelson (1987)

Fractionalization

A spinon:
an emergent particle which carries spin 1/2 but no charge



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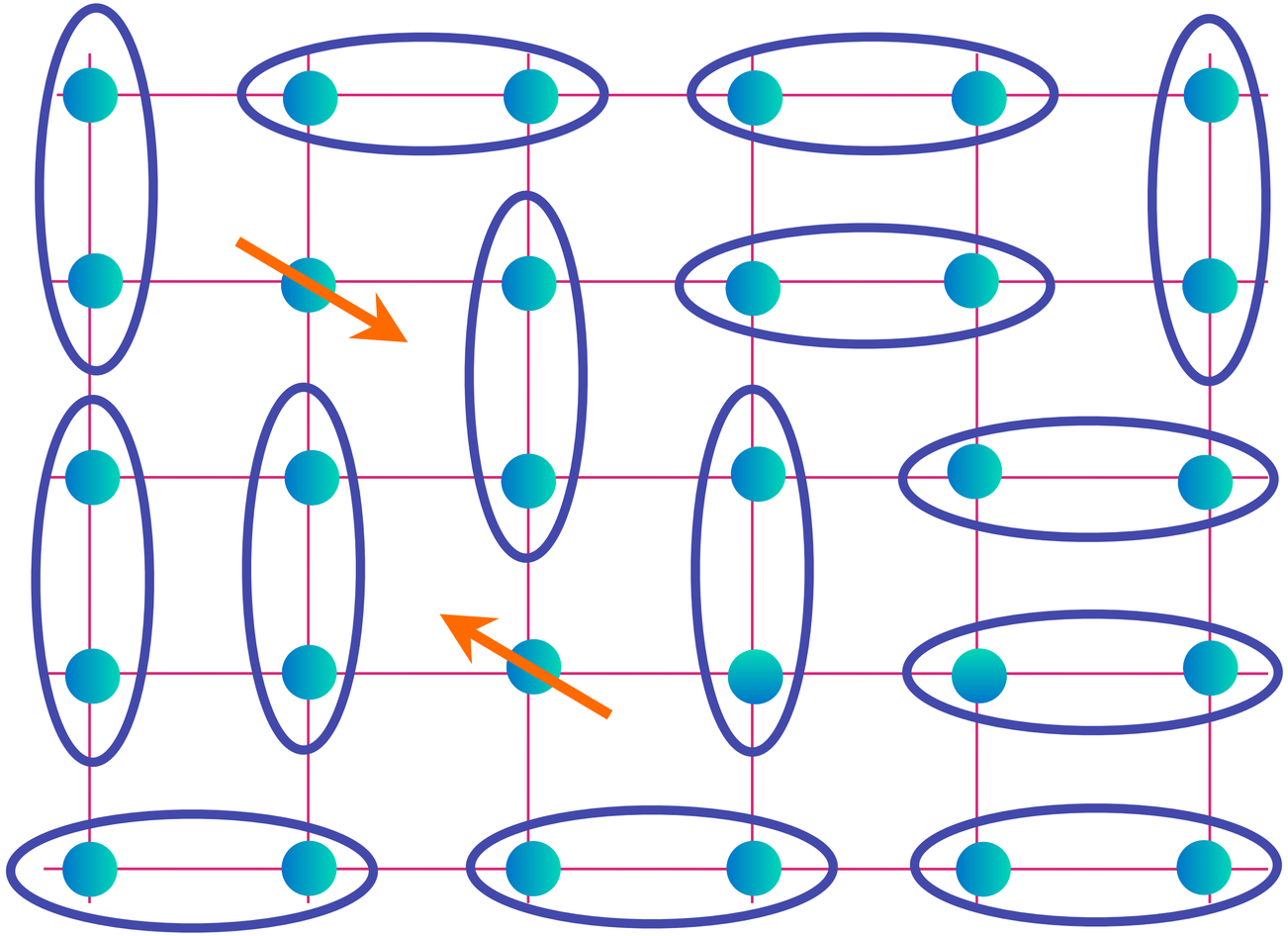

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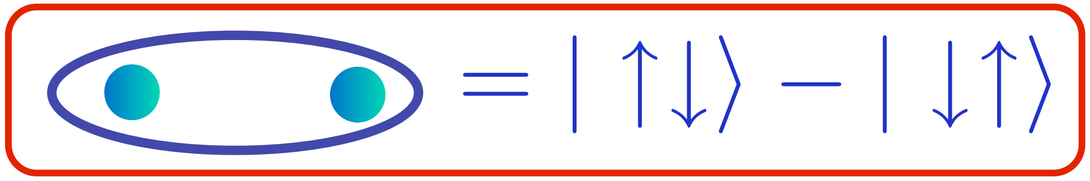

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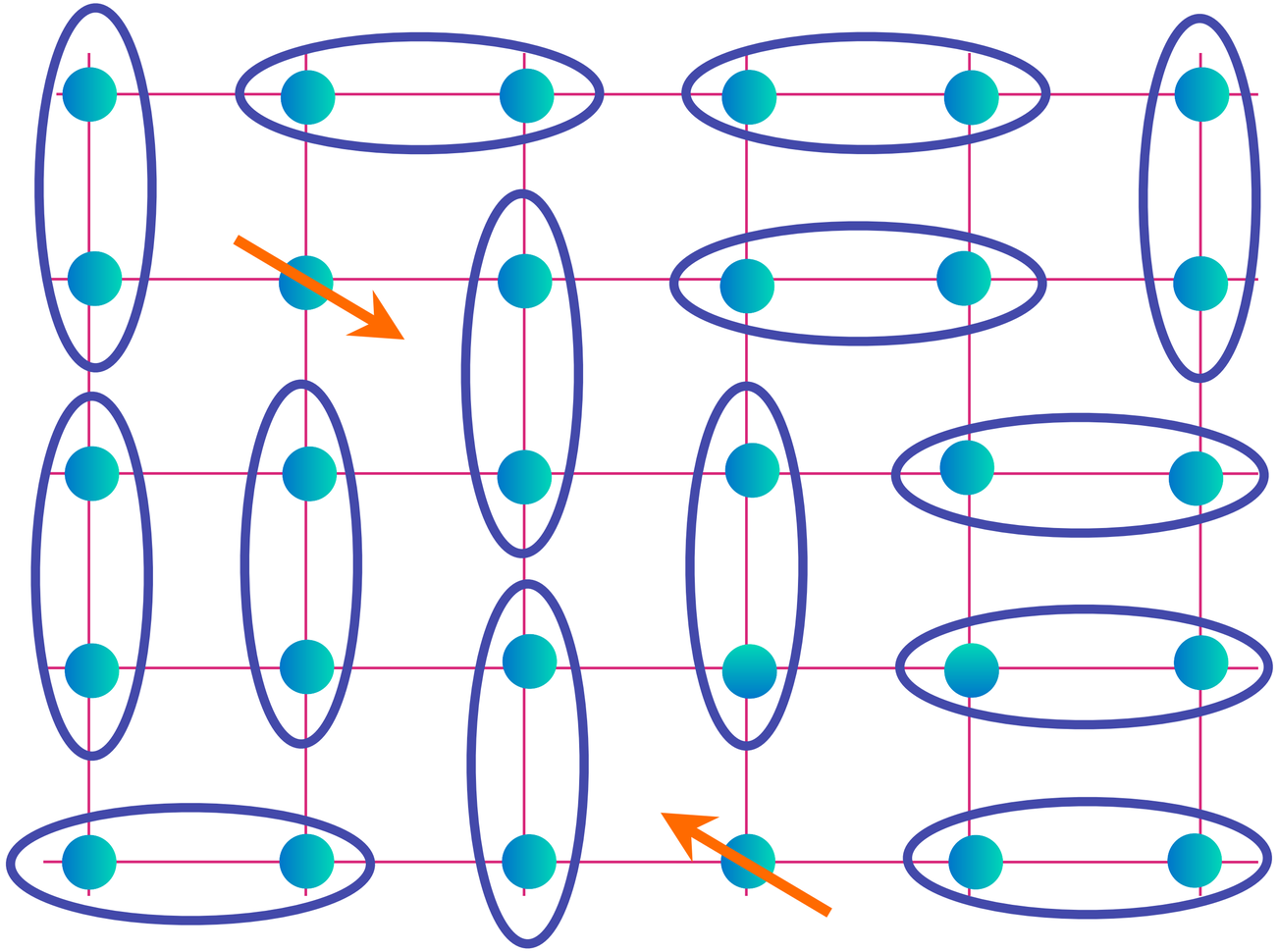

$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

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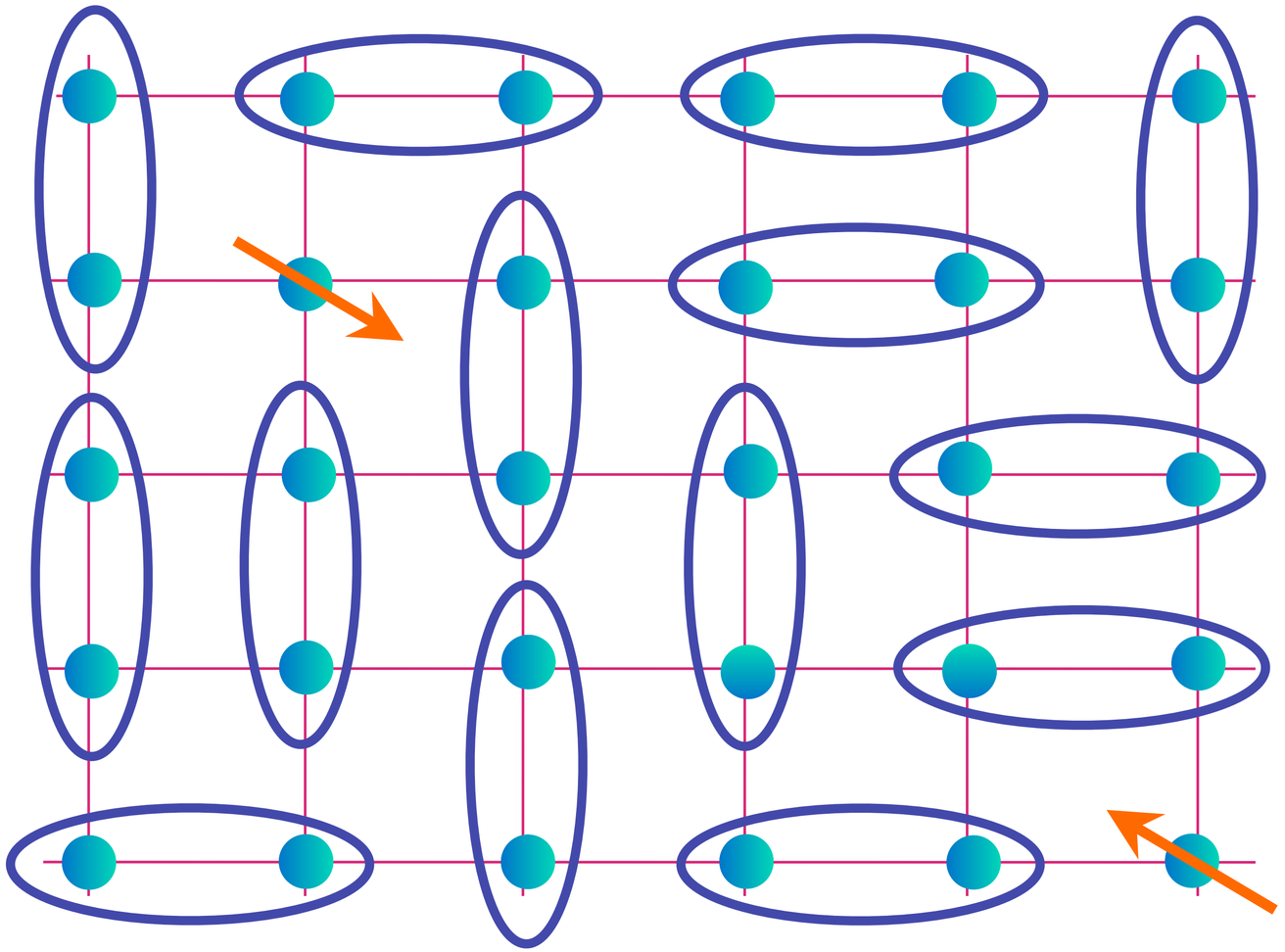

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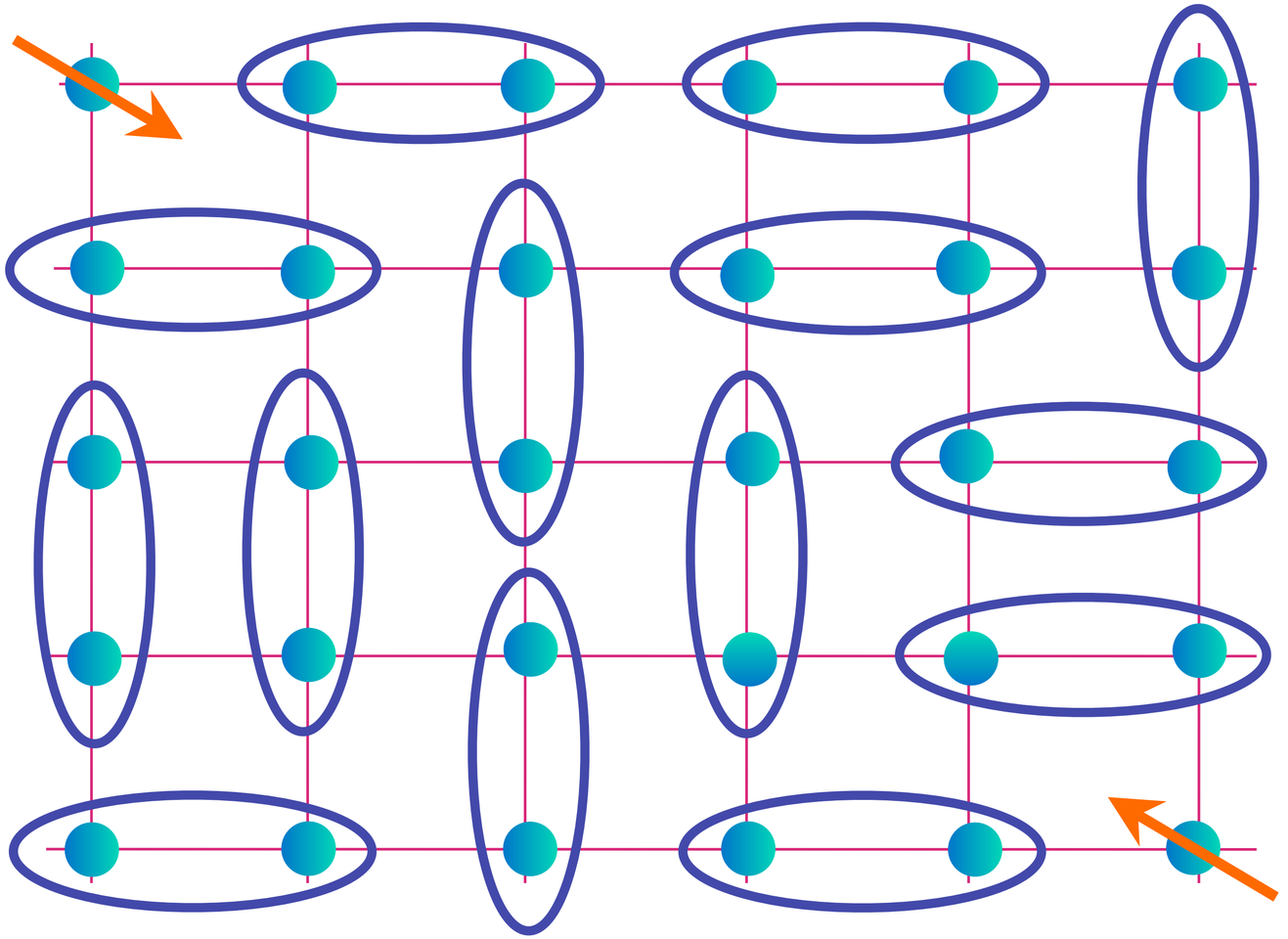

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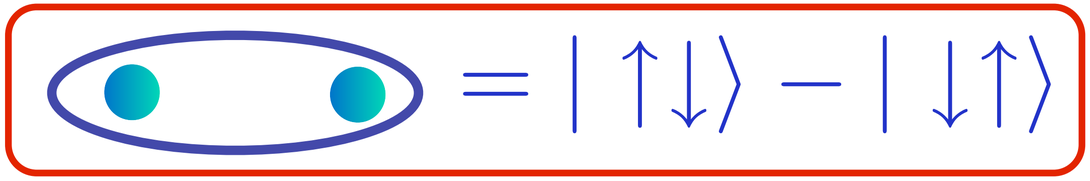

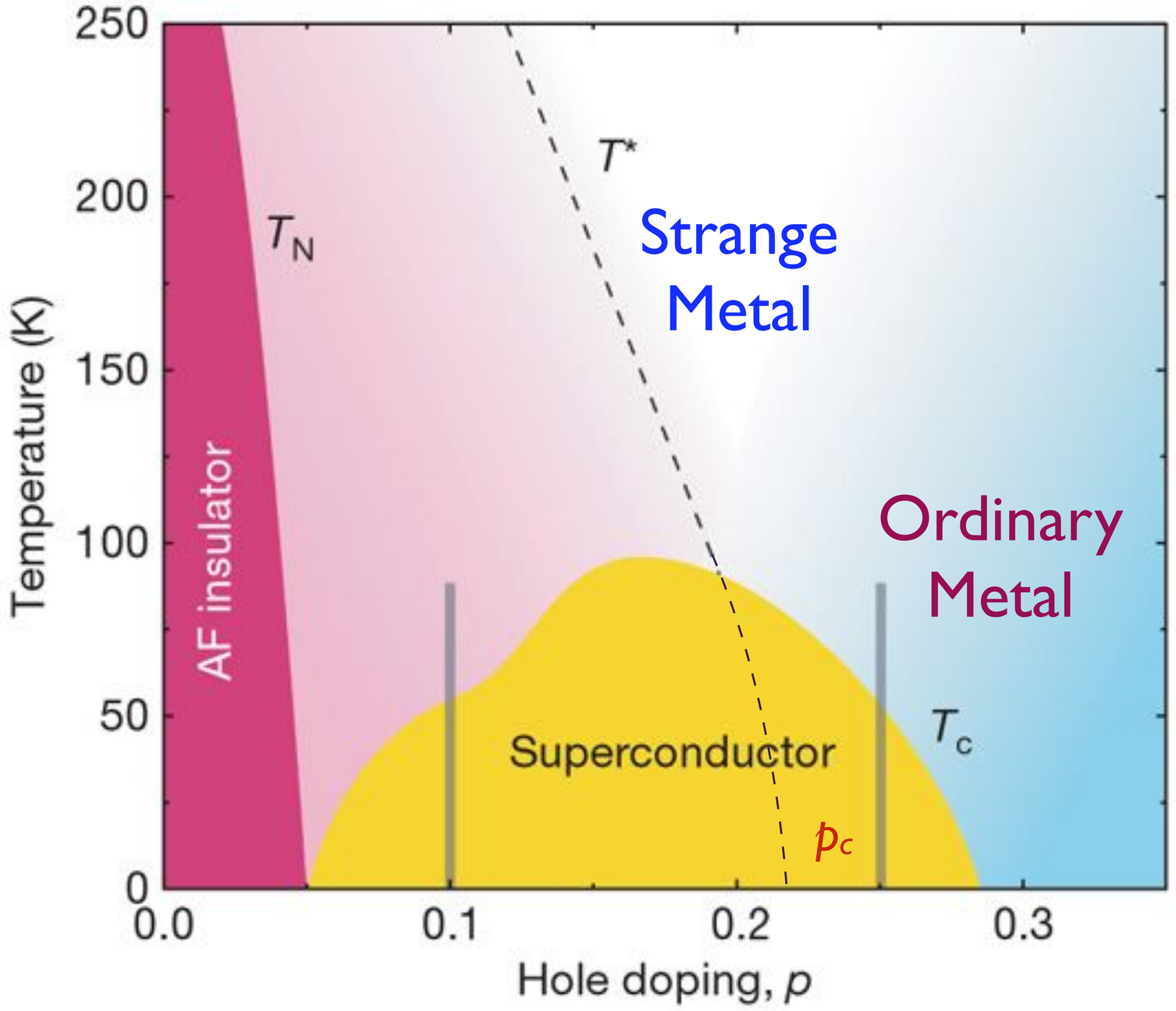
250
200
150
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50
0
Temperature (K)
0.0
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Hole doping, p
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AF insulator
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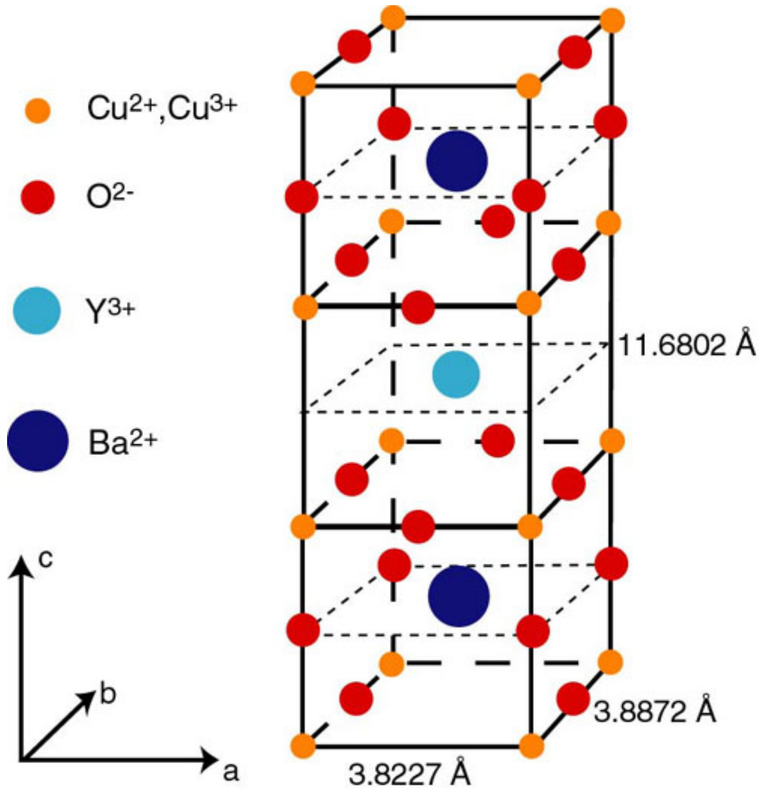
Cu^{2+},Cu^{3+}
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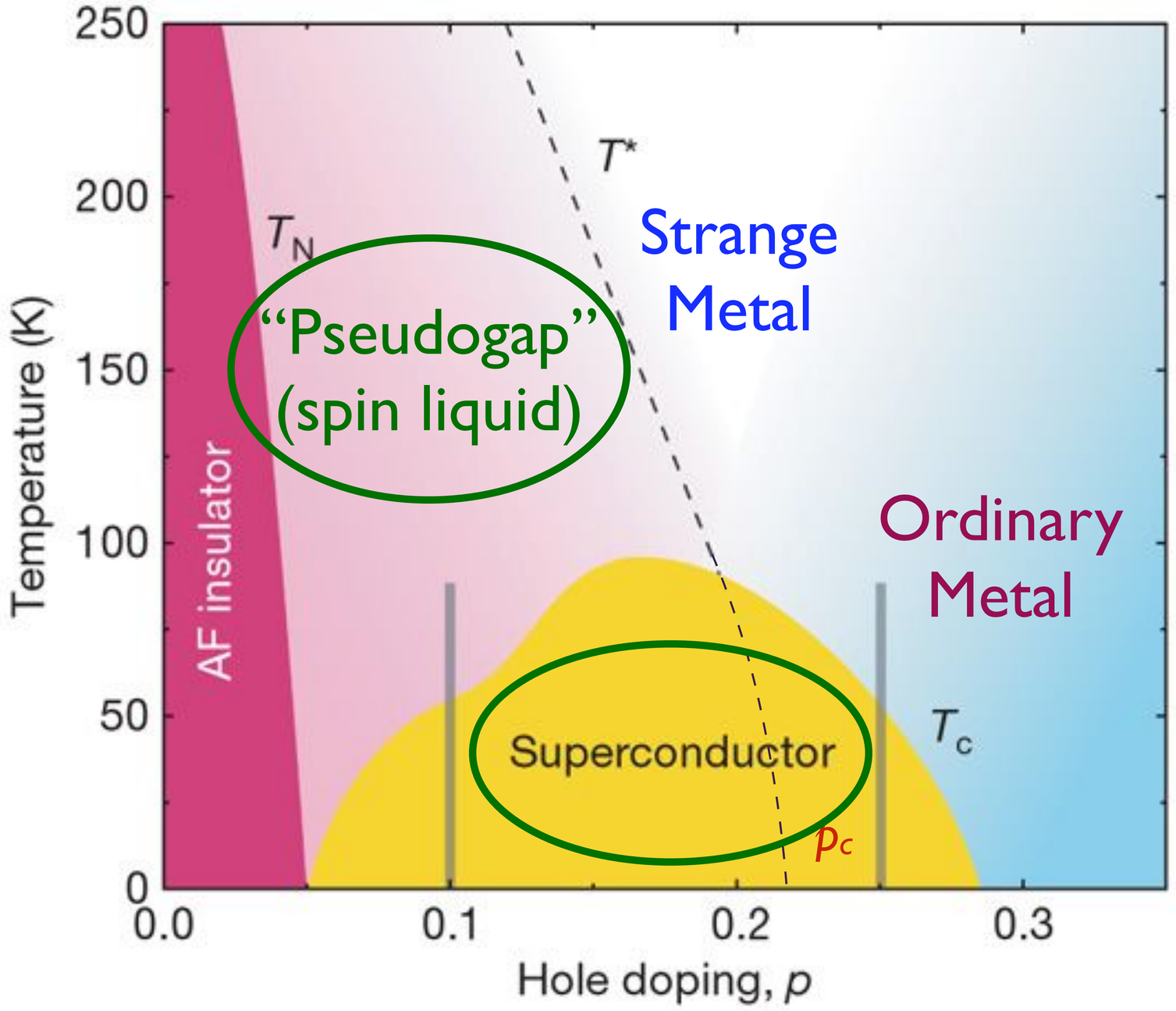
250
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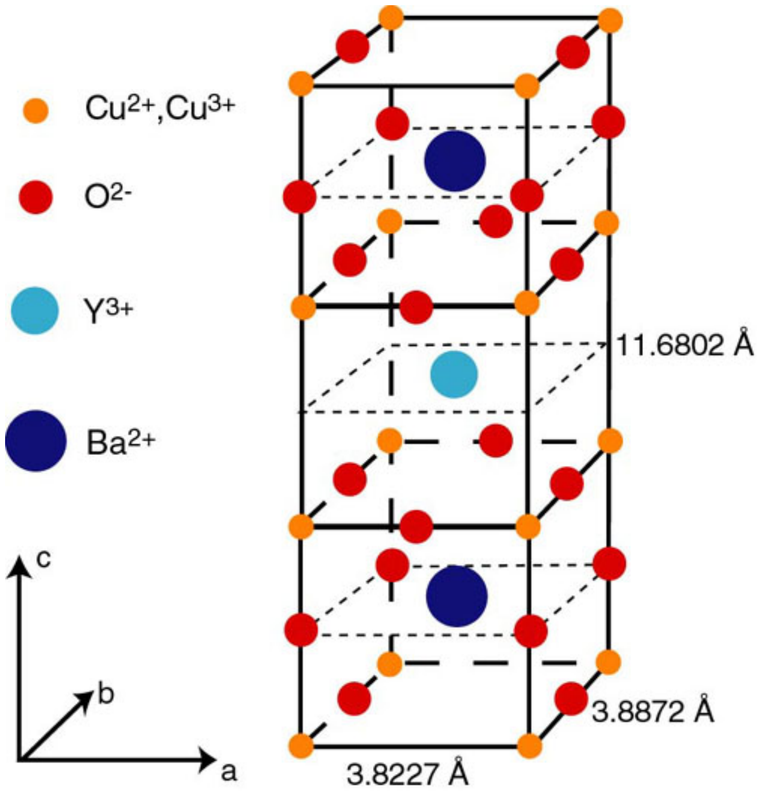
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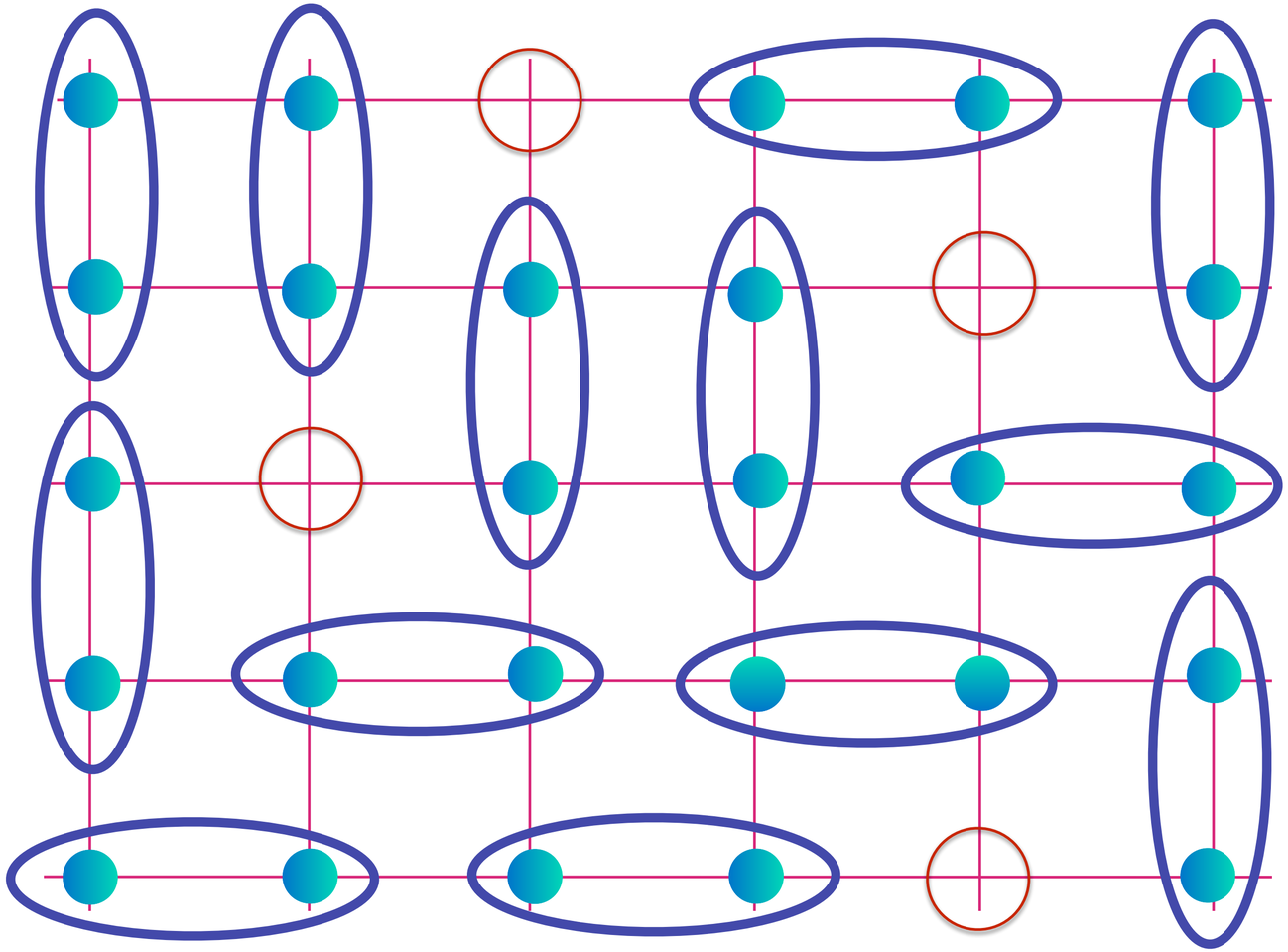
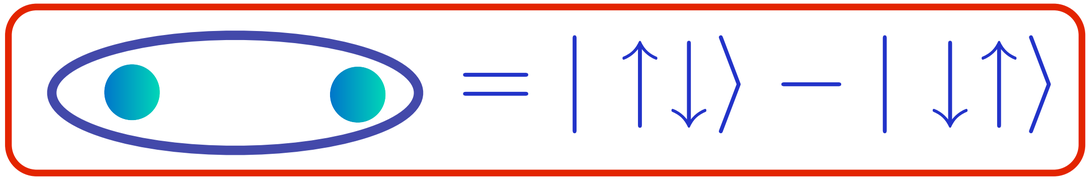


Pseudogap

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



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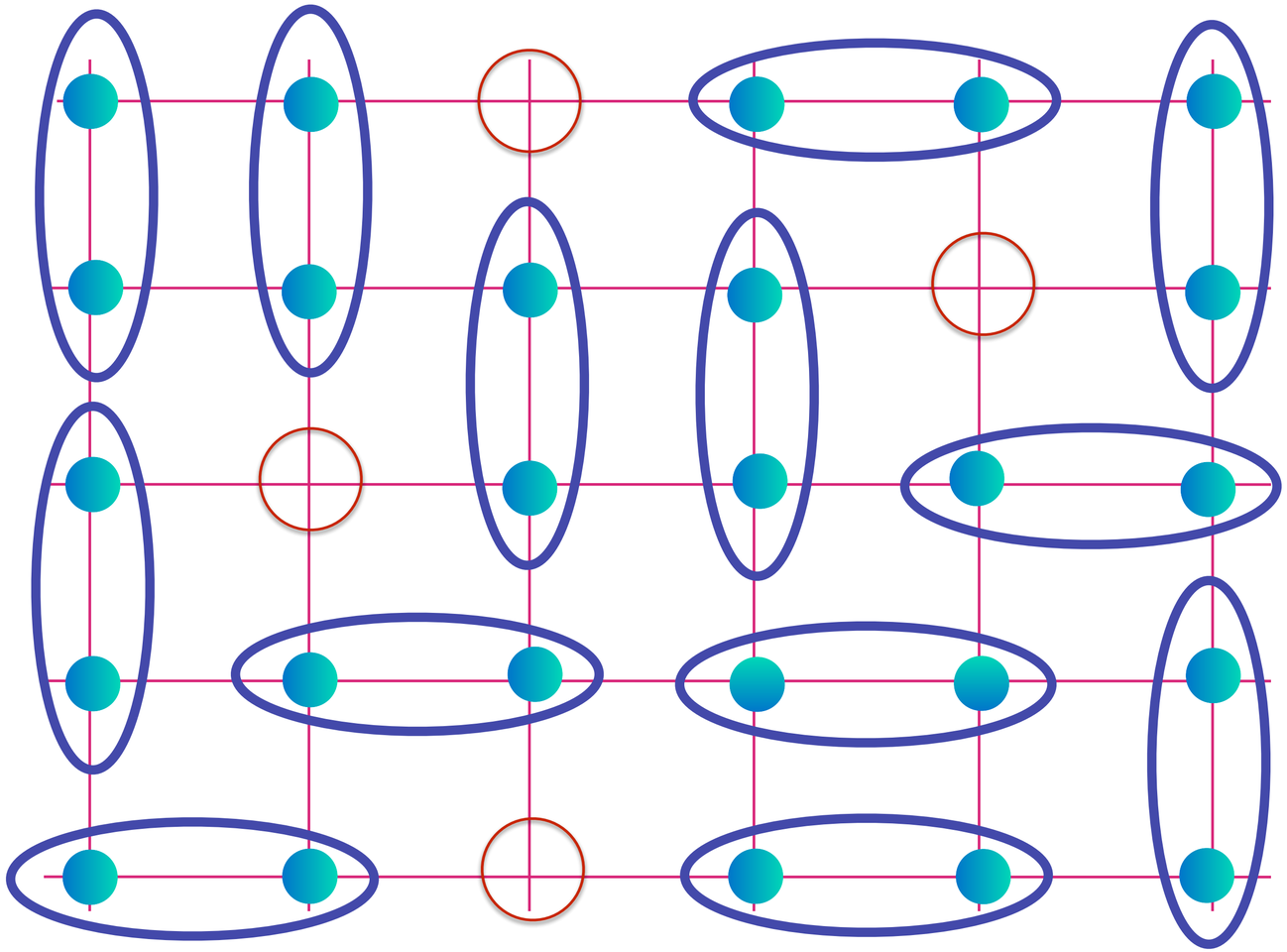

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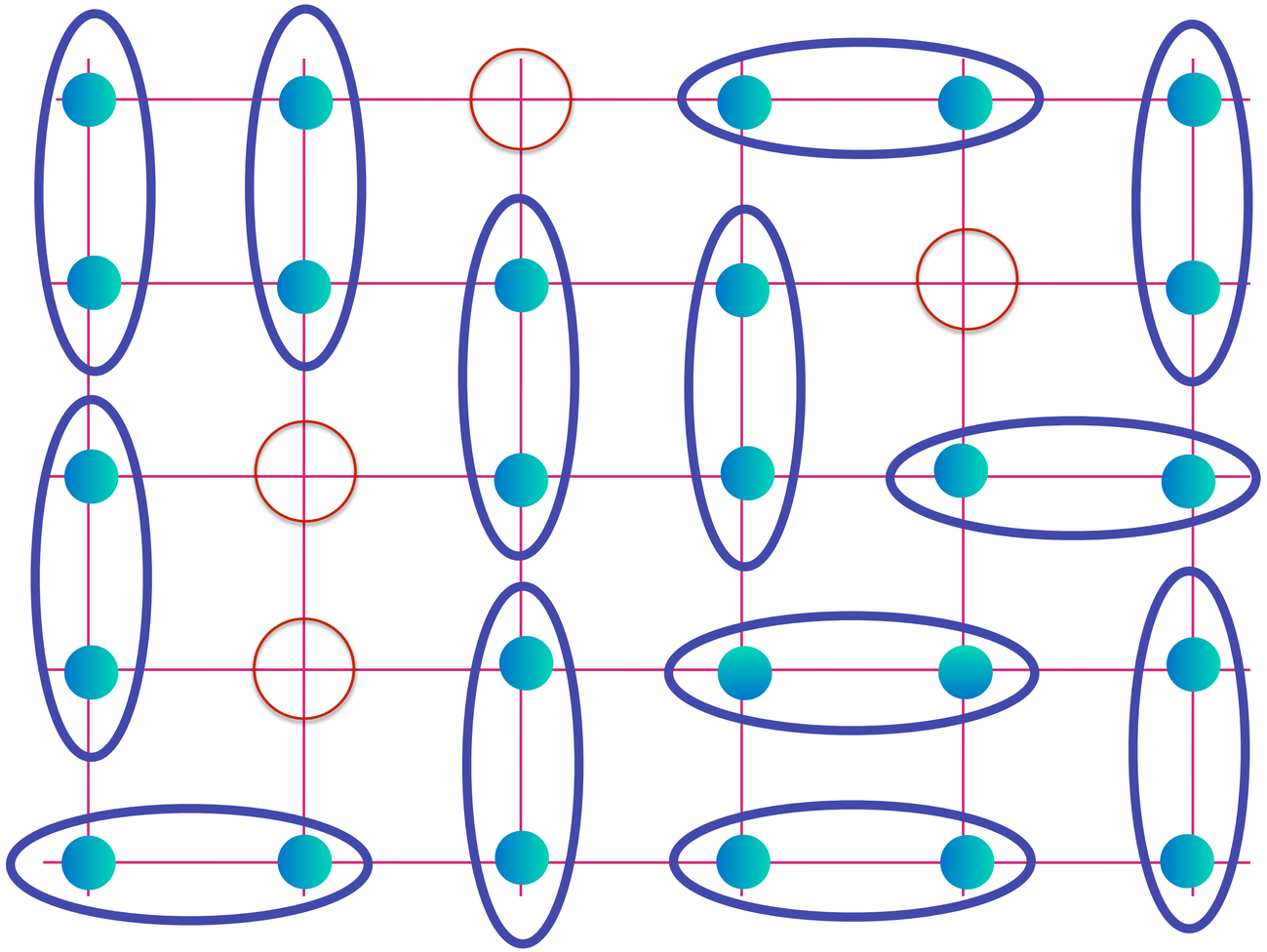

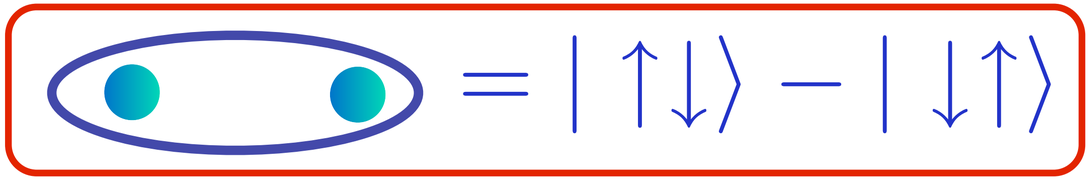

Pseudogap

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

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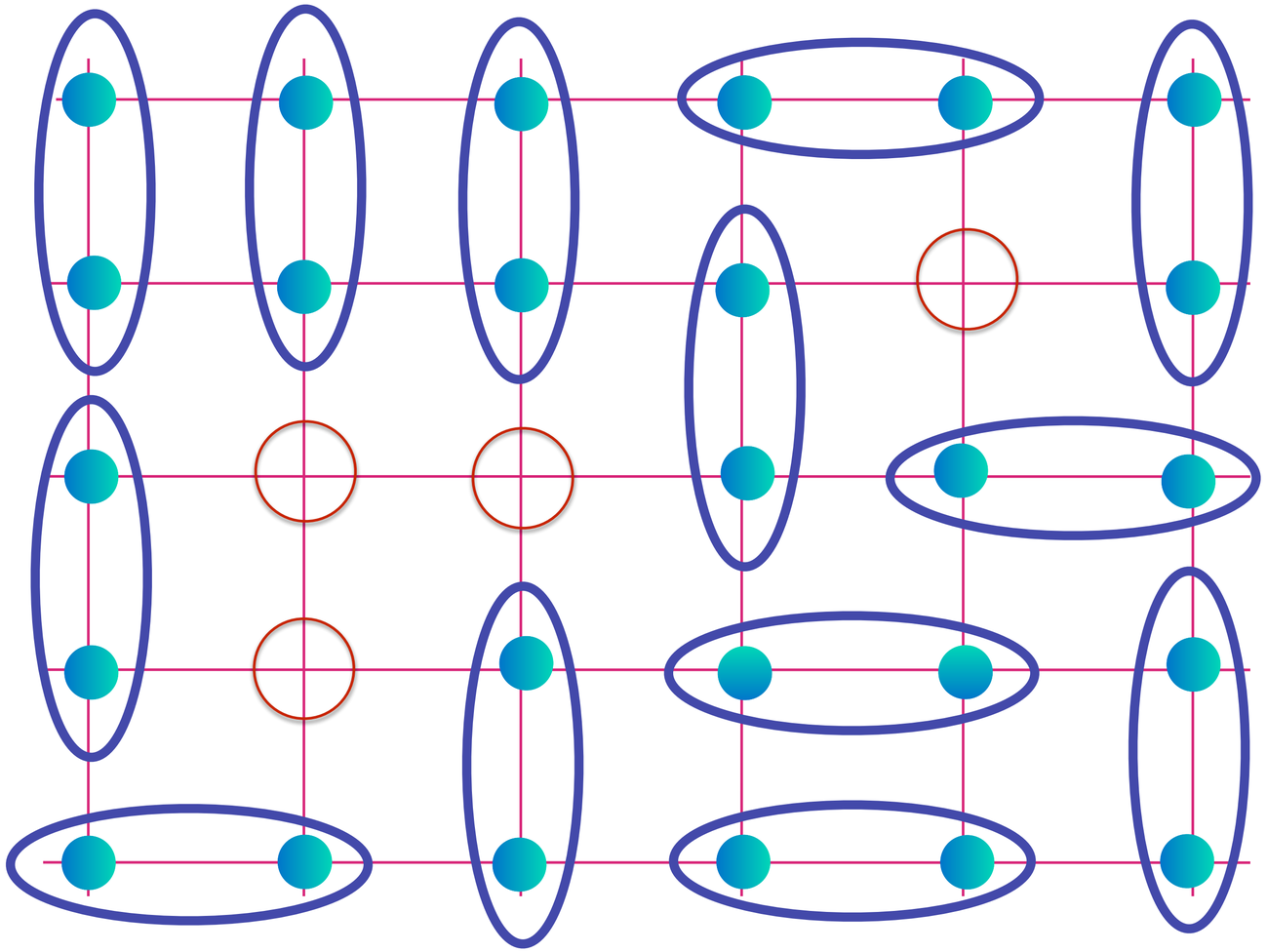

$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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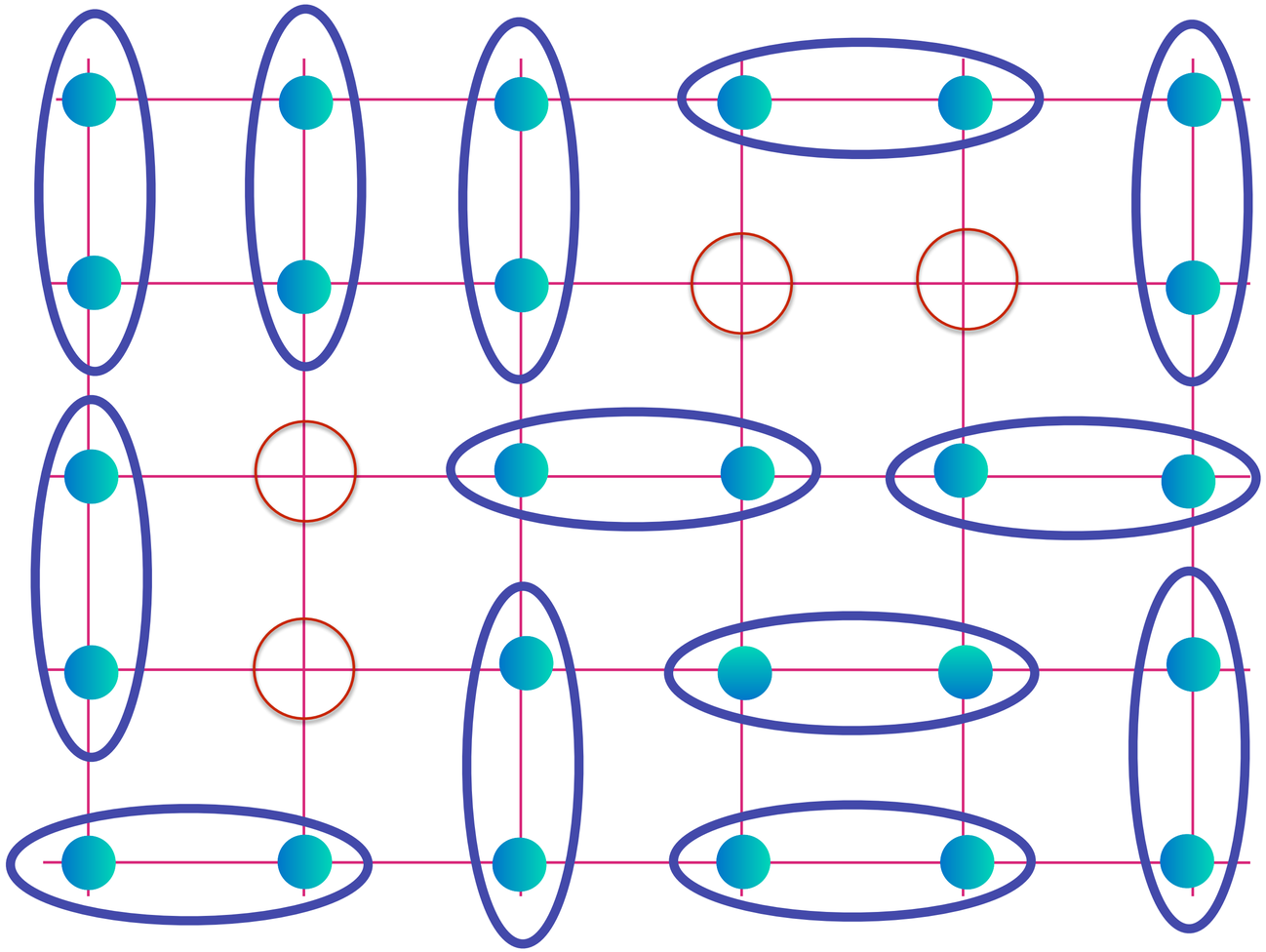

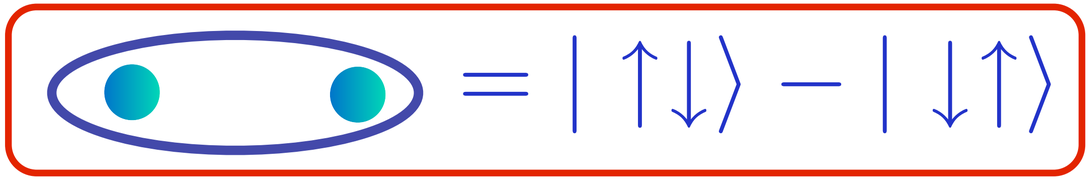

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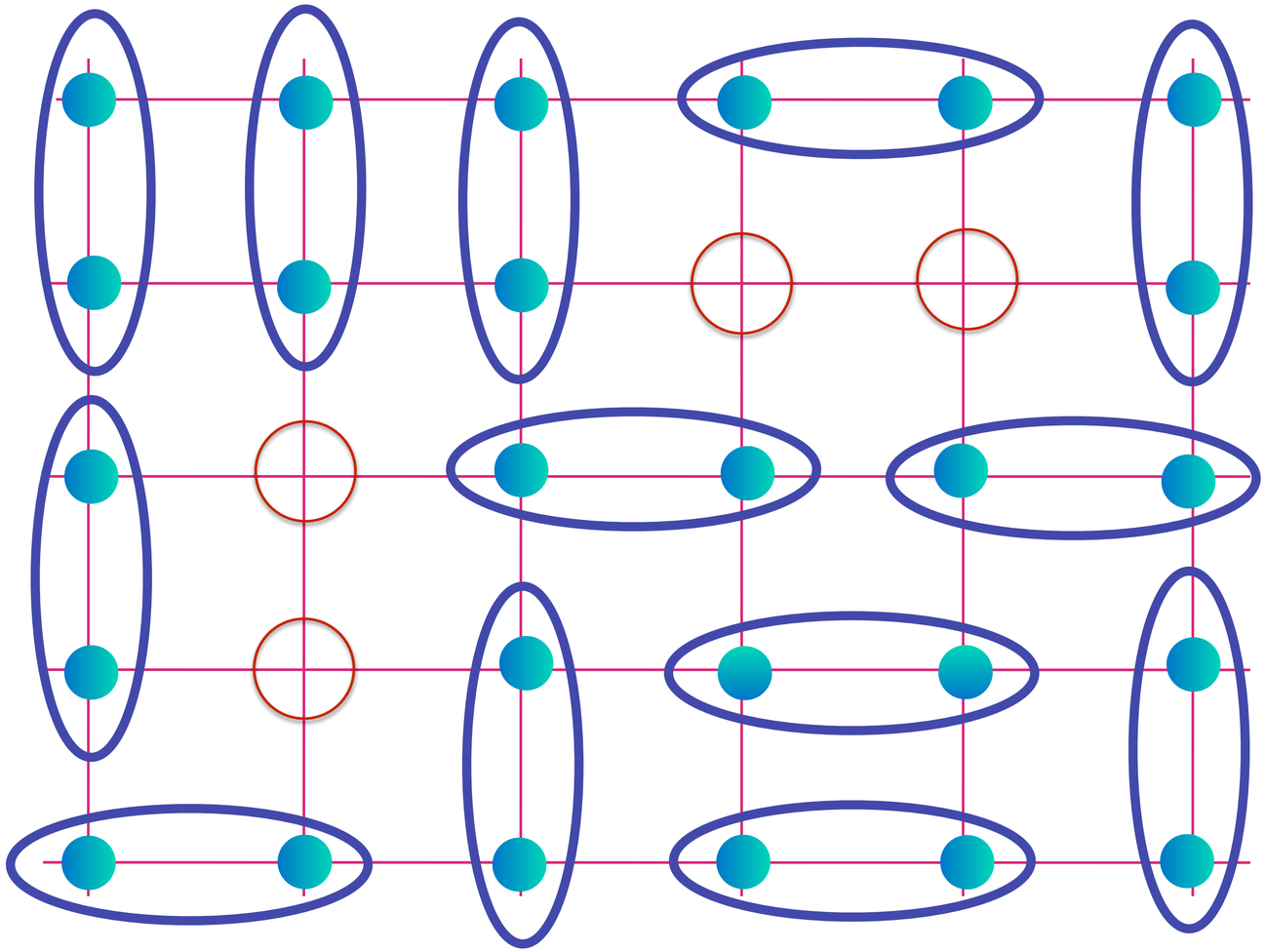
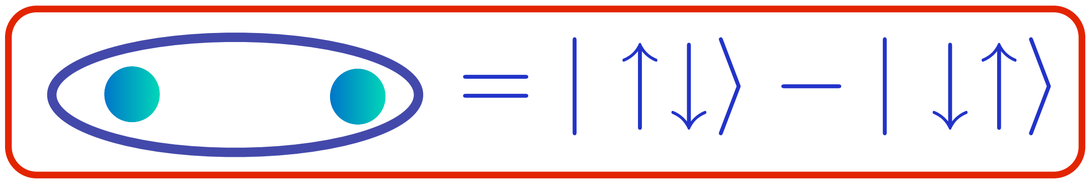


Superconductivity

Mobile
entangled
electron pairs



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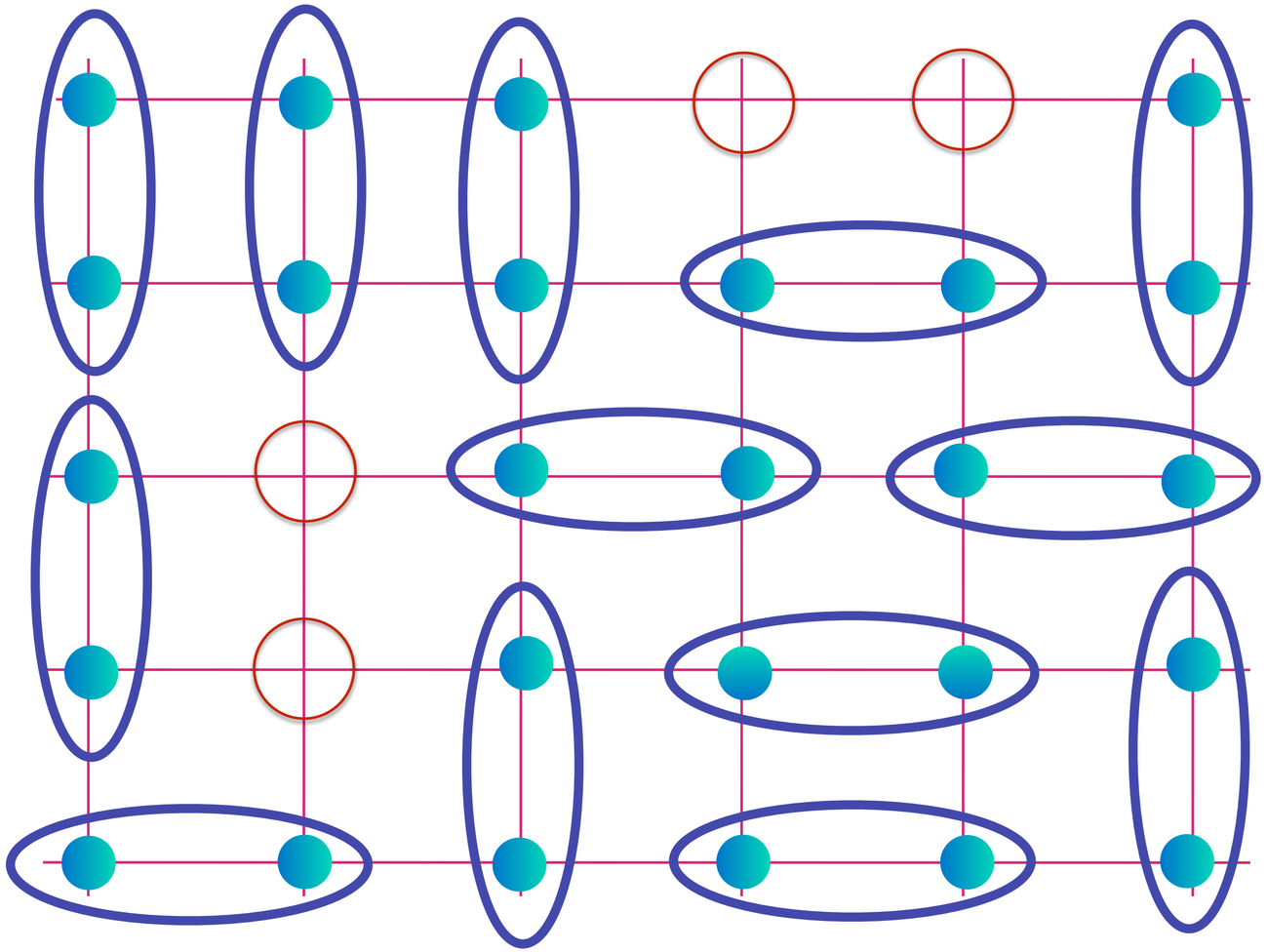

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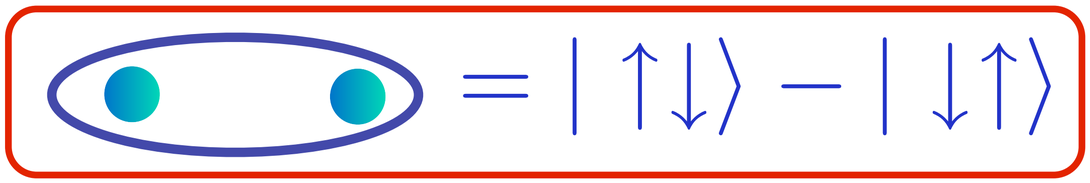

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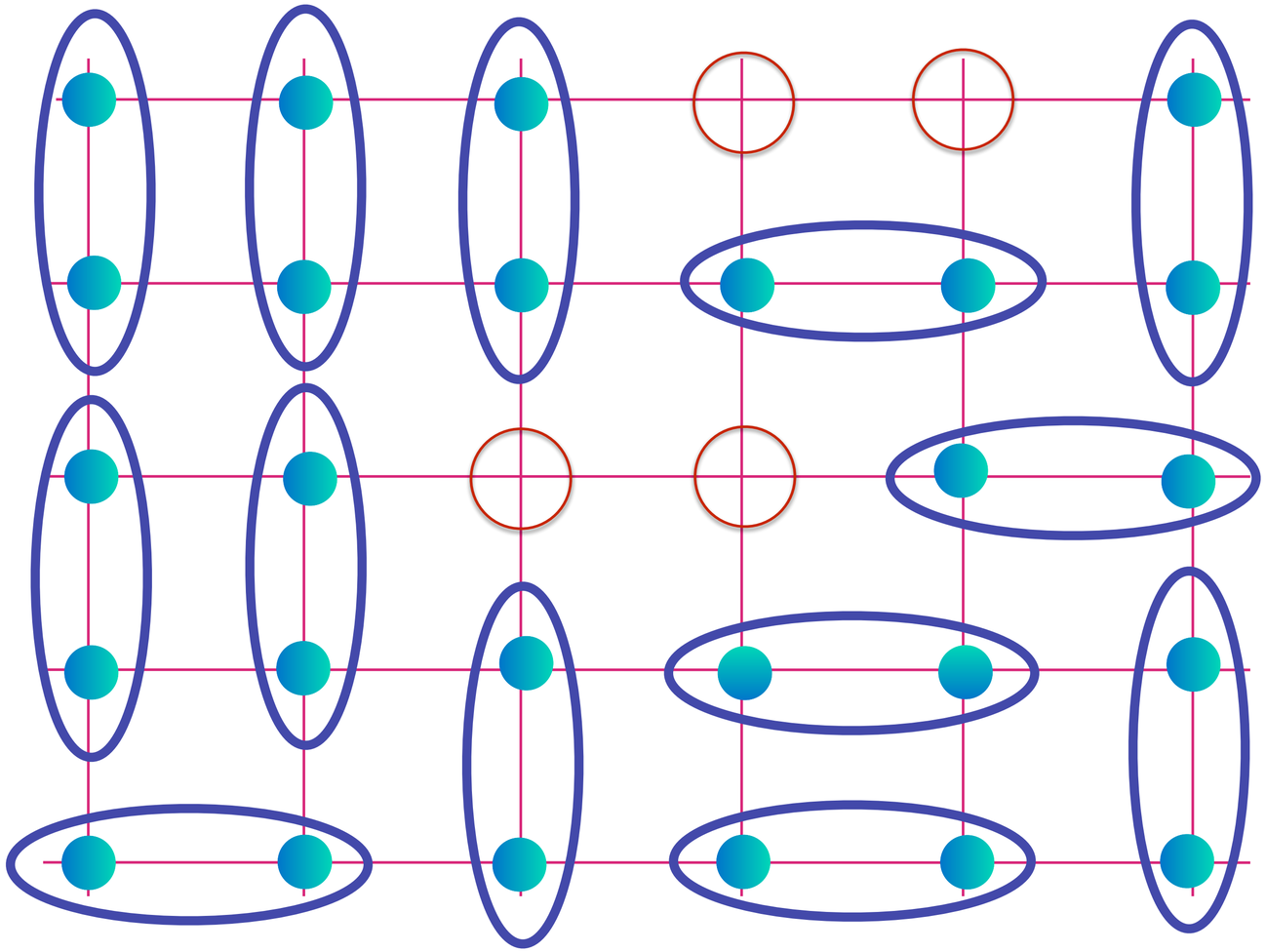

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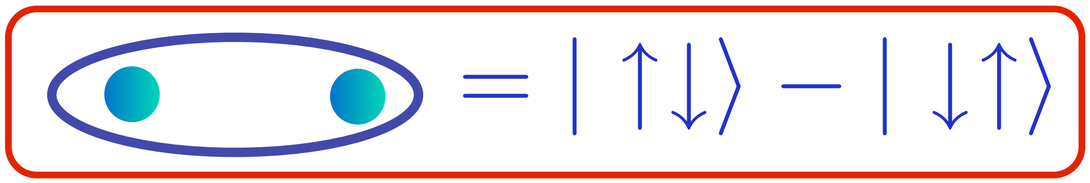

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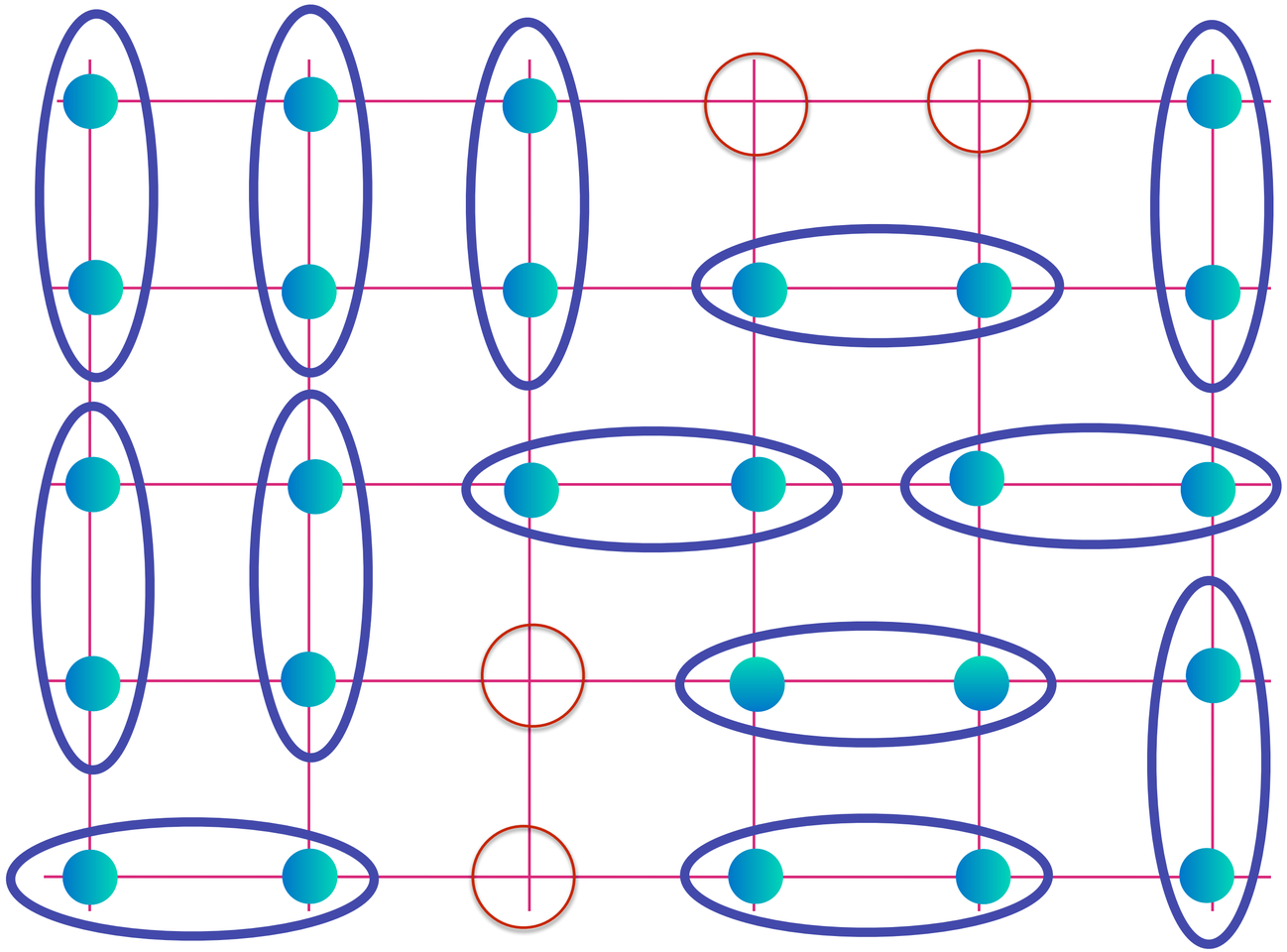

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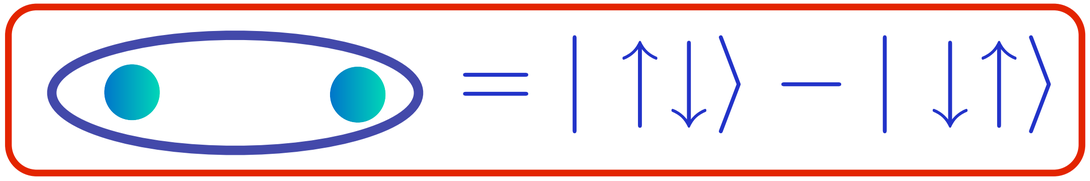

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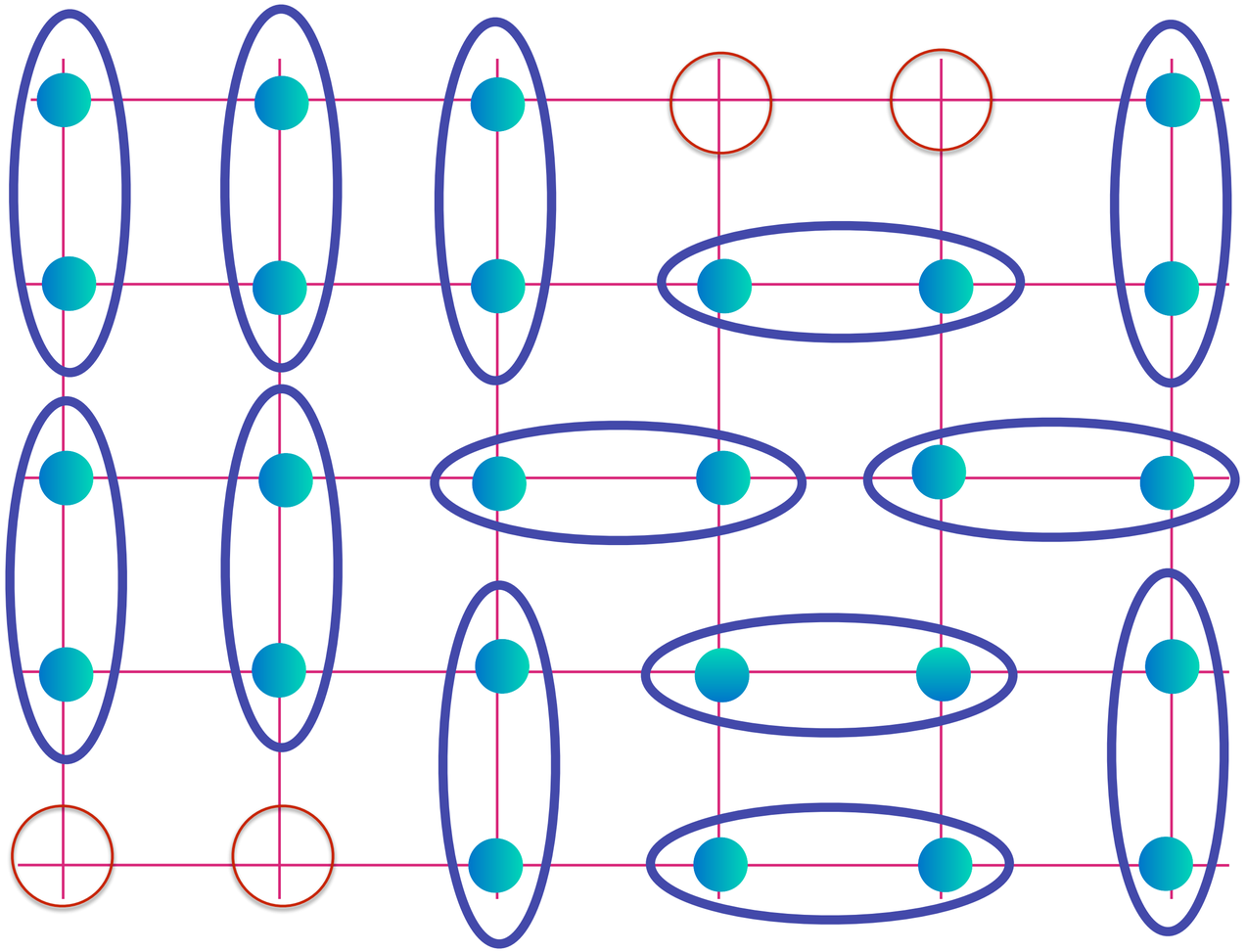

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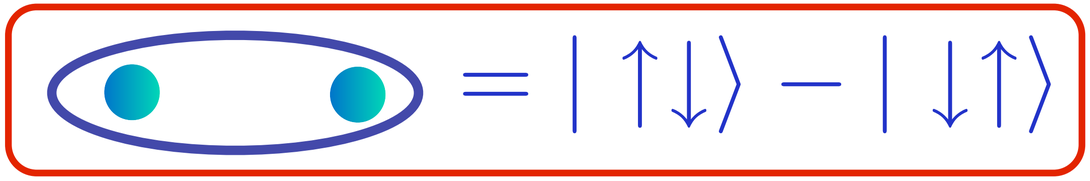
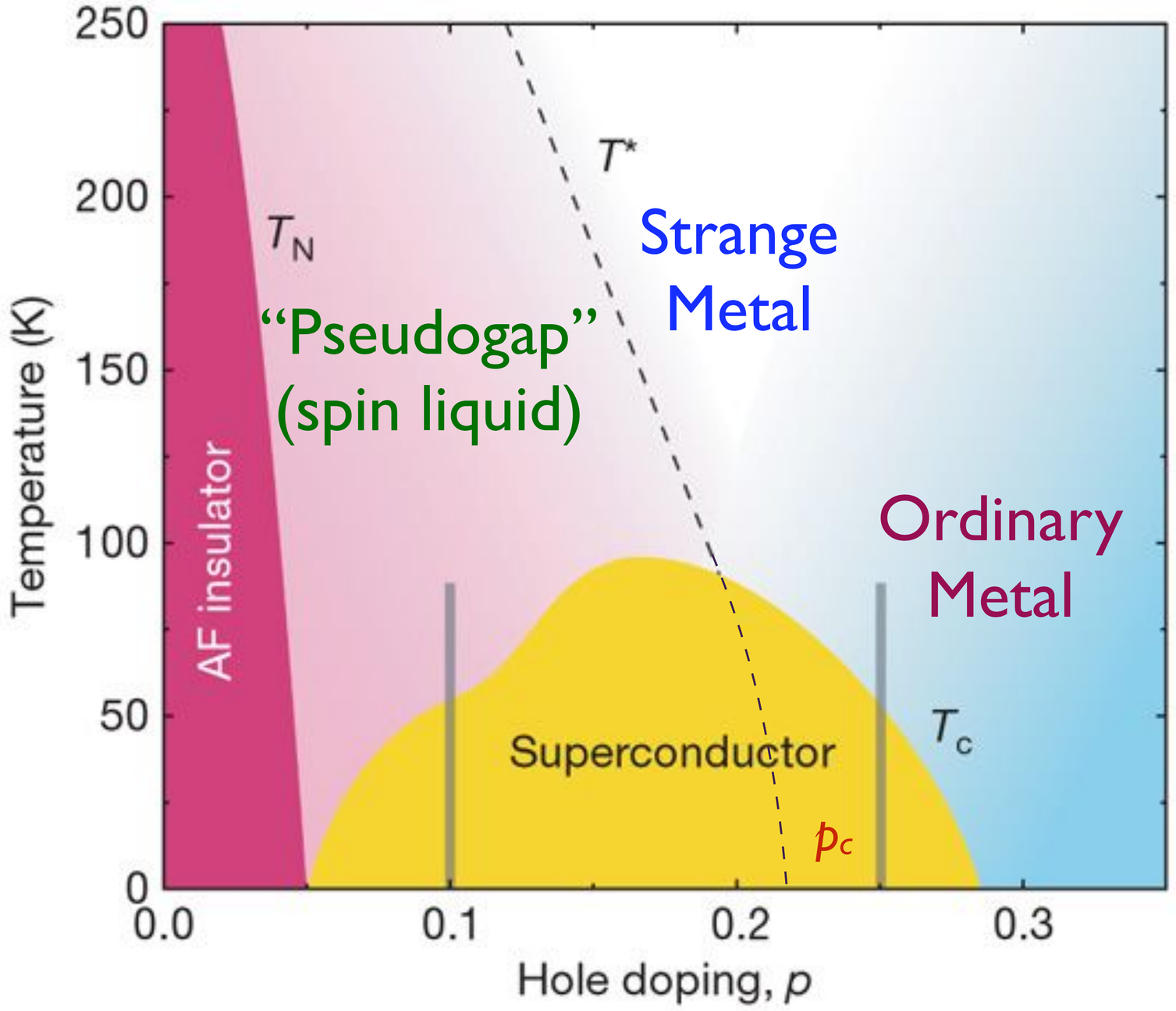
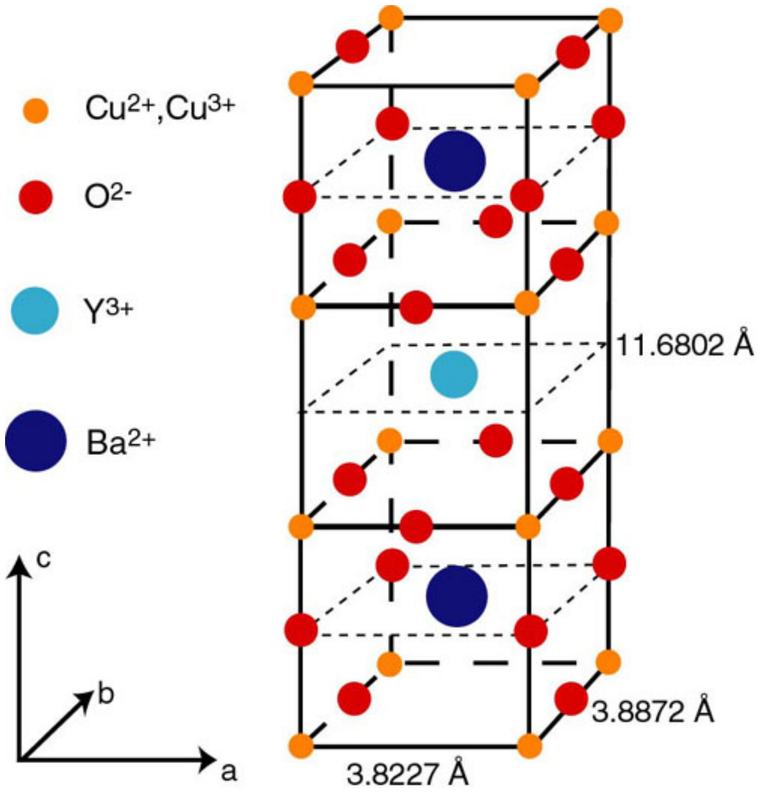
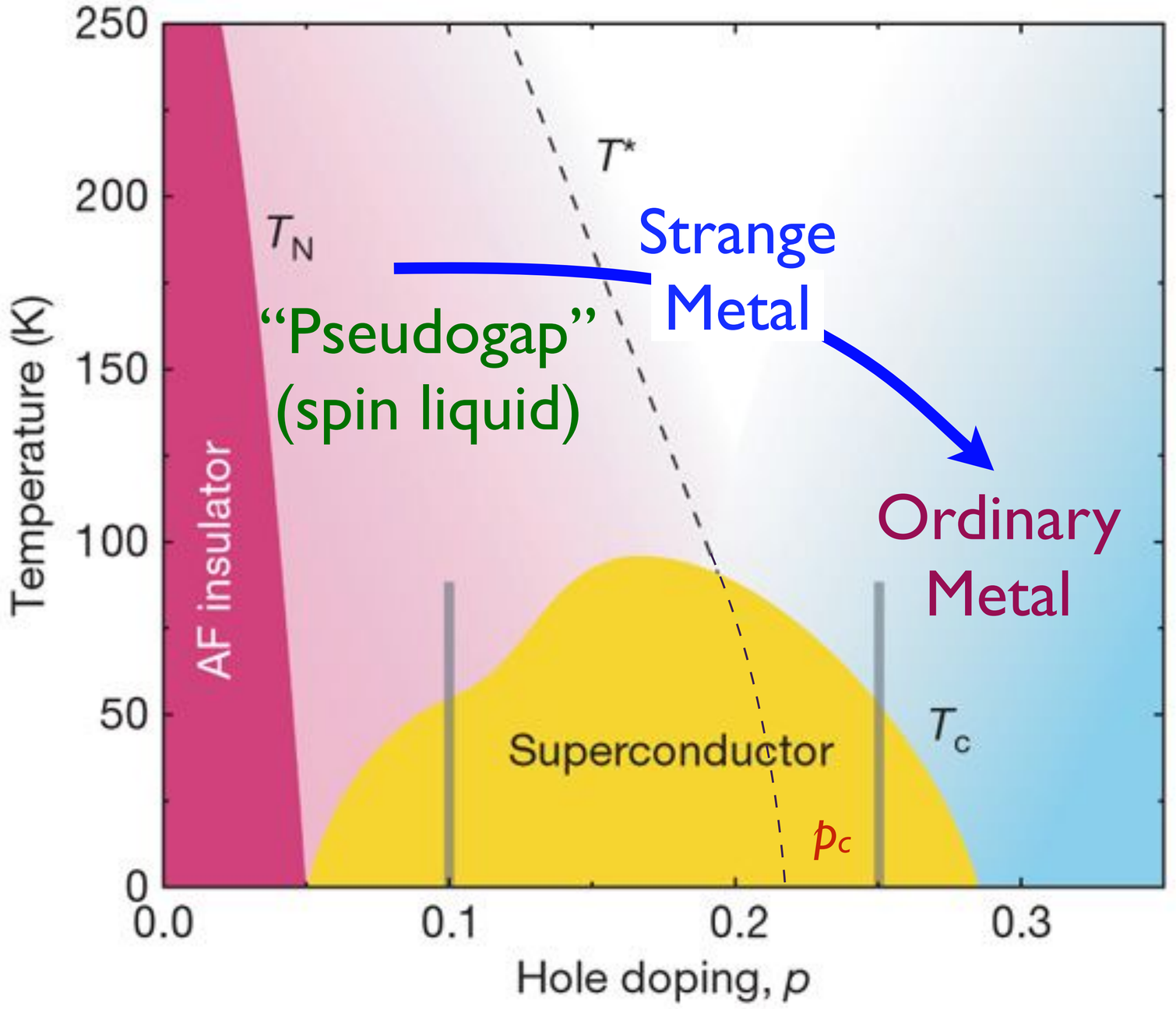


From the SYK model to a theory of strange metals


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

$YBa_2Cu_3O_{6+x}$



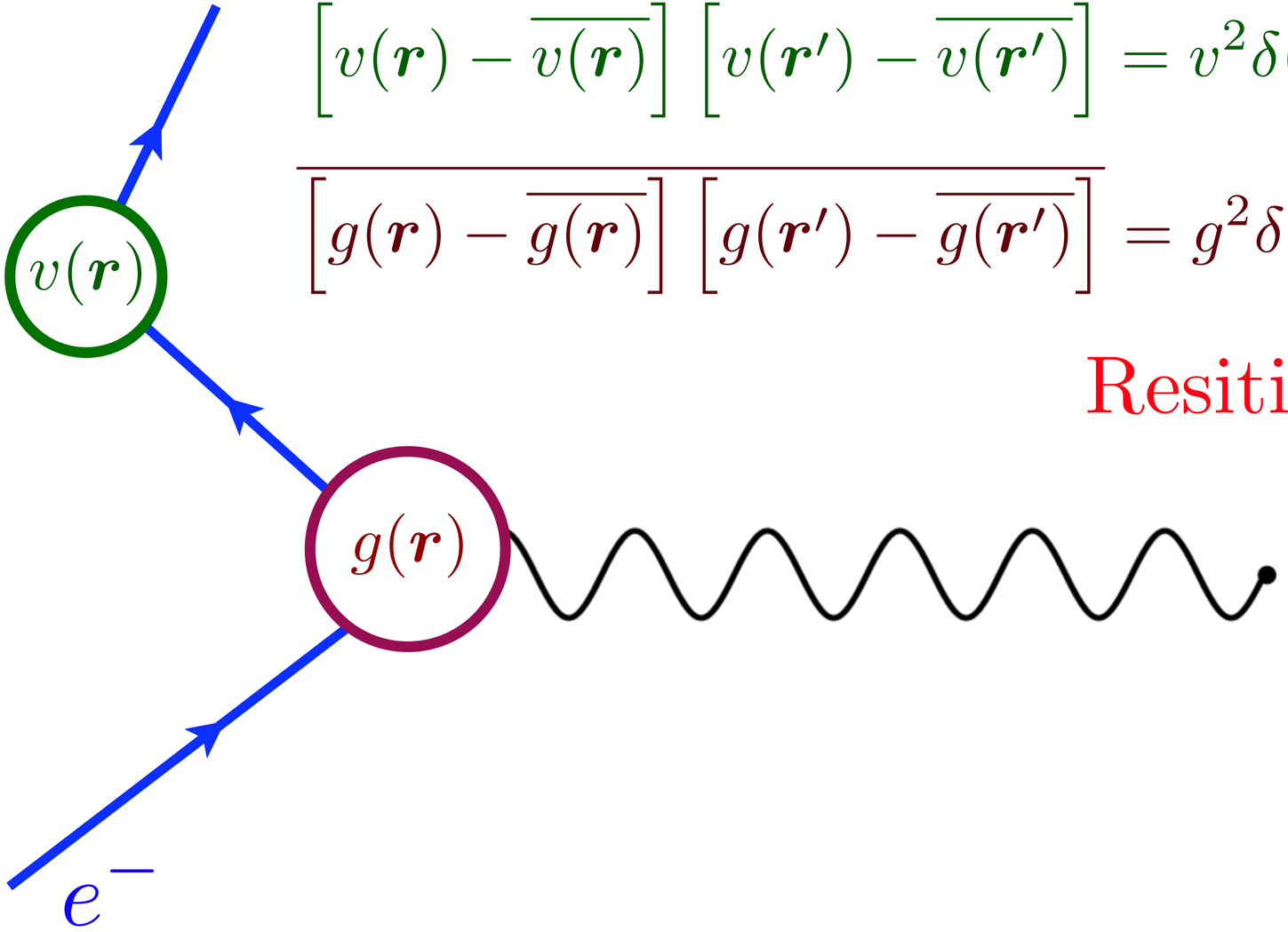
Strange Metal

Arises from the evolution of quantum entanglement between the spin liquid and the ordinary metal

The dance of electrons on Cu atoms in YBCO

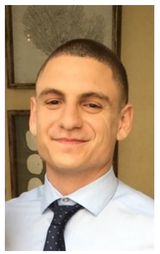
$$\overline{\Big[v(\boldsymbol{r}) - \overline{v(\boldsymbol{r})}\Big]\,\Big[v(\boldsymbol{r}') - \overline{v(\boldsymbol{r}')}\Big]} = v^2\delta(\boldsymbol{r}-\boldsymbol{r}')$$

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



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





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

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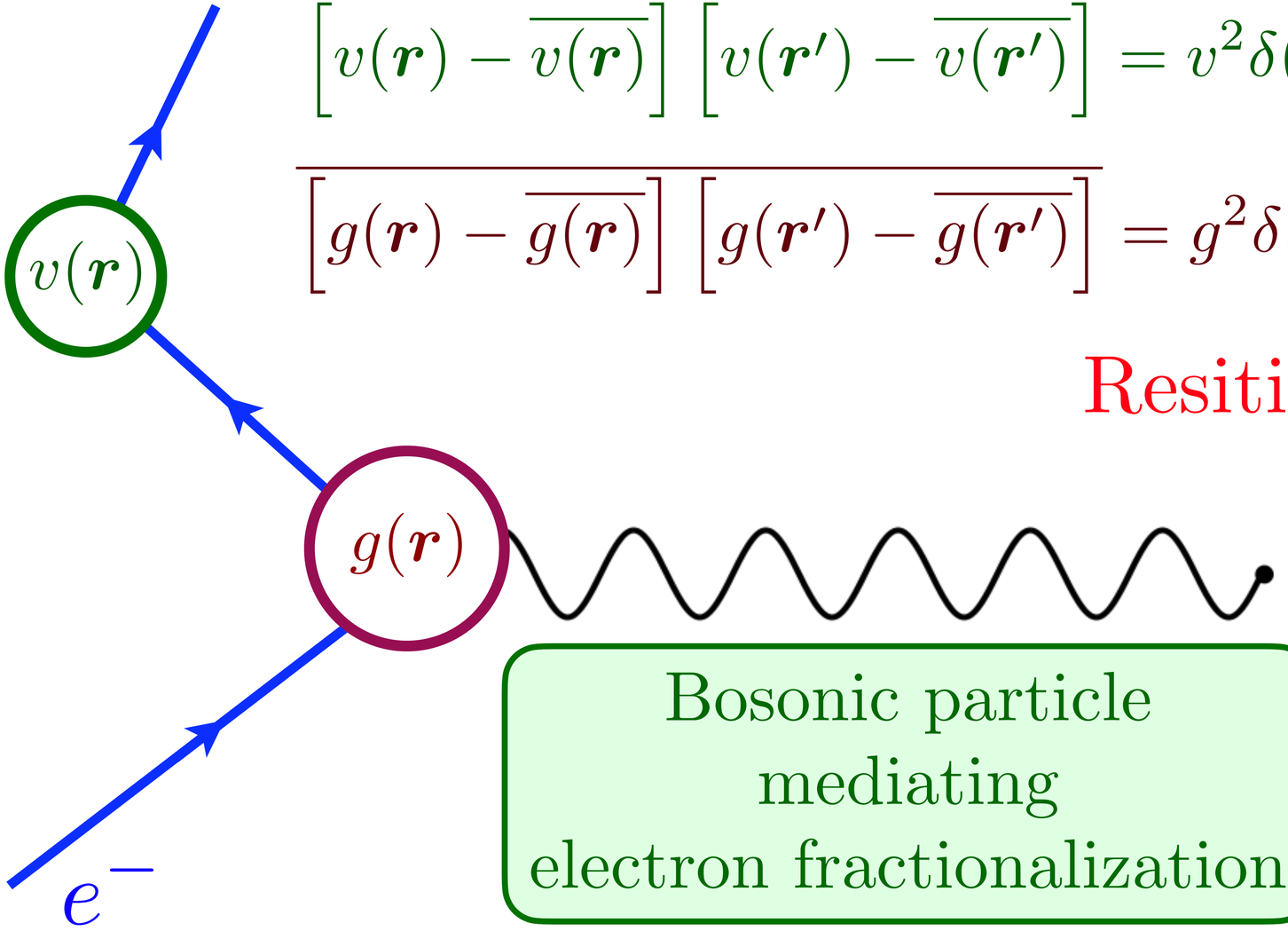
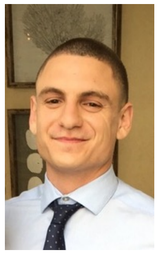


Bosonic particle
mediating
electron fractionalization





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The many faces of multi-particle entanglement

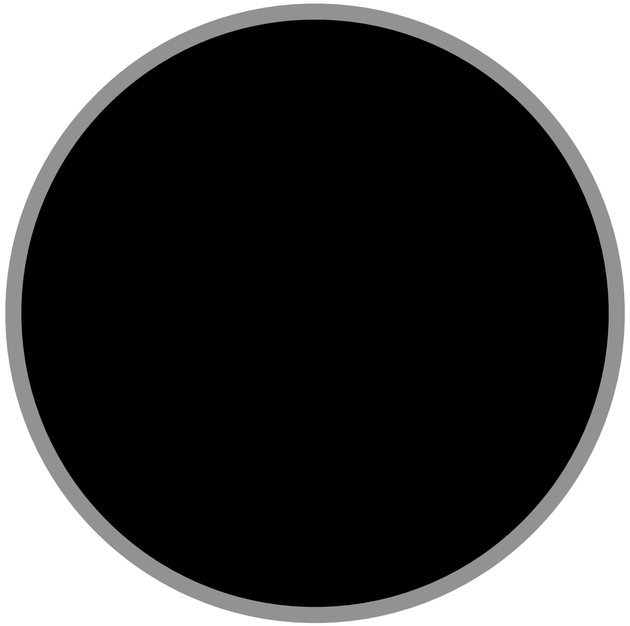
- Absence of quasiparticles, as in the SYK model and the strange metal
- Fractionalization and new emergent particles, as in spin liquids.
- Higher temperature superconductivity (?)

Black holes

Black Holes

Objects so dense that light is gravitationally bound to them.

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



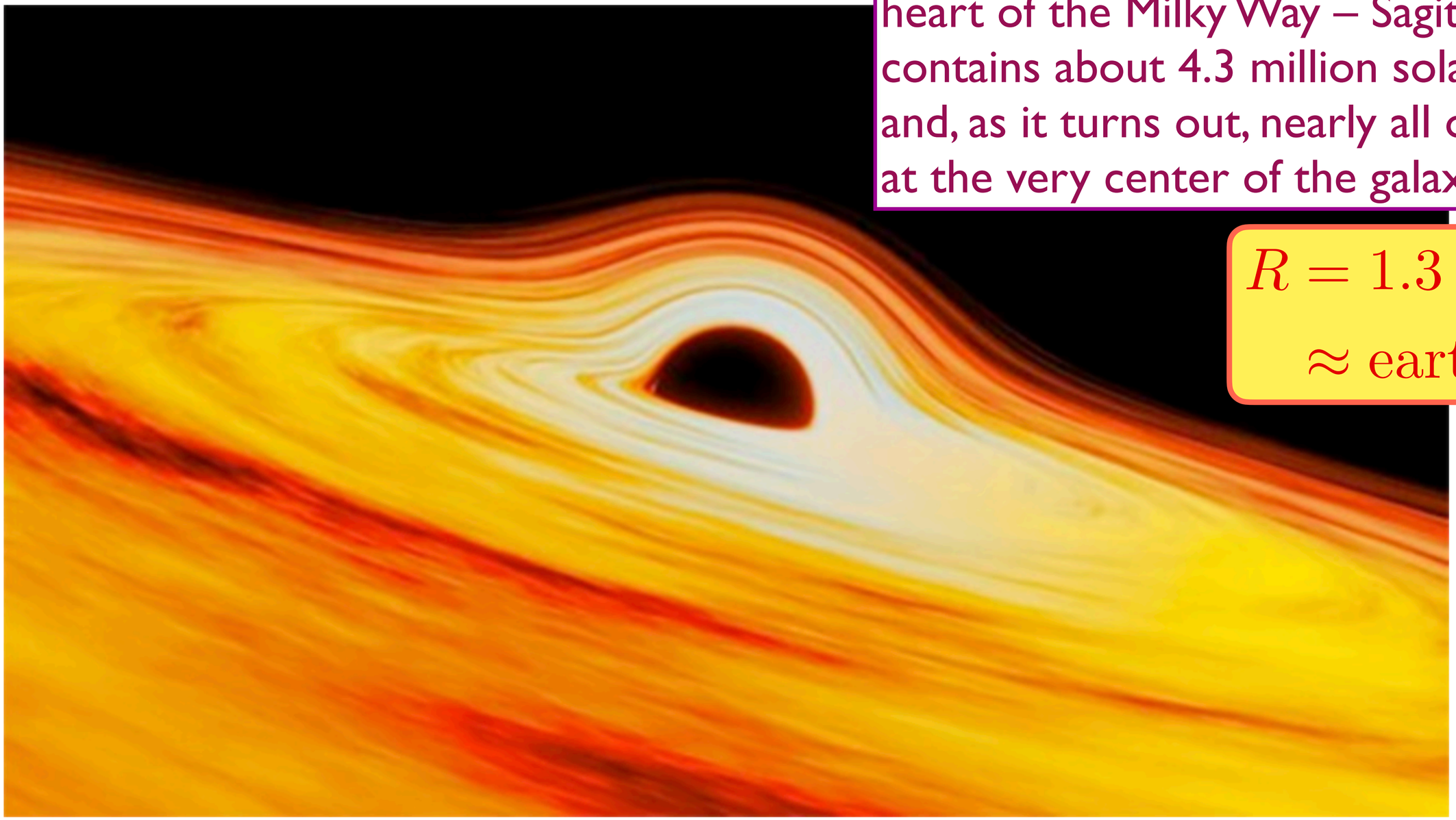
G Newton's constant, c velocity of light, M mass of black hole

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, and, as it turns out, nearly all of the mass at the very center of the galaxy.

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

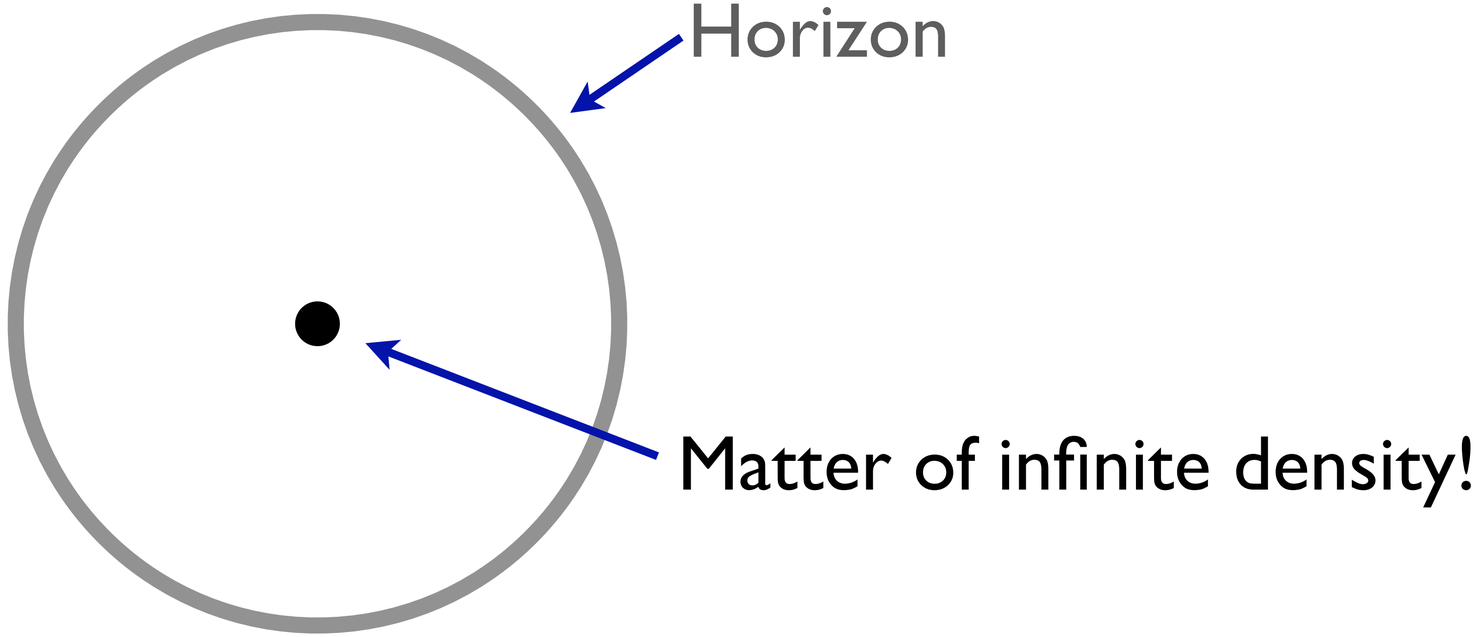
$$\approx \text{earth's orbit}$$



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.



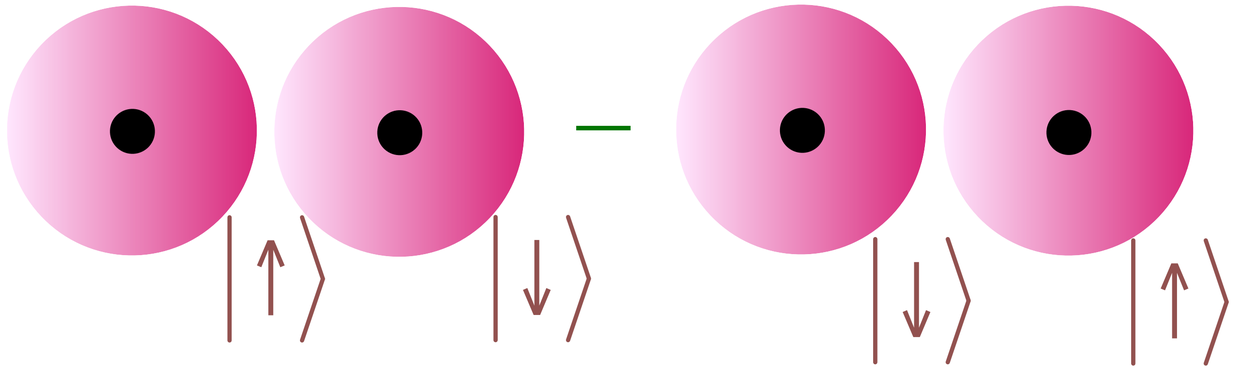
What is inside a black hole ???

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

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

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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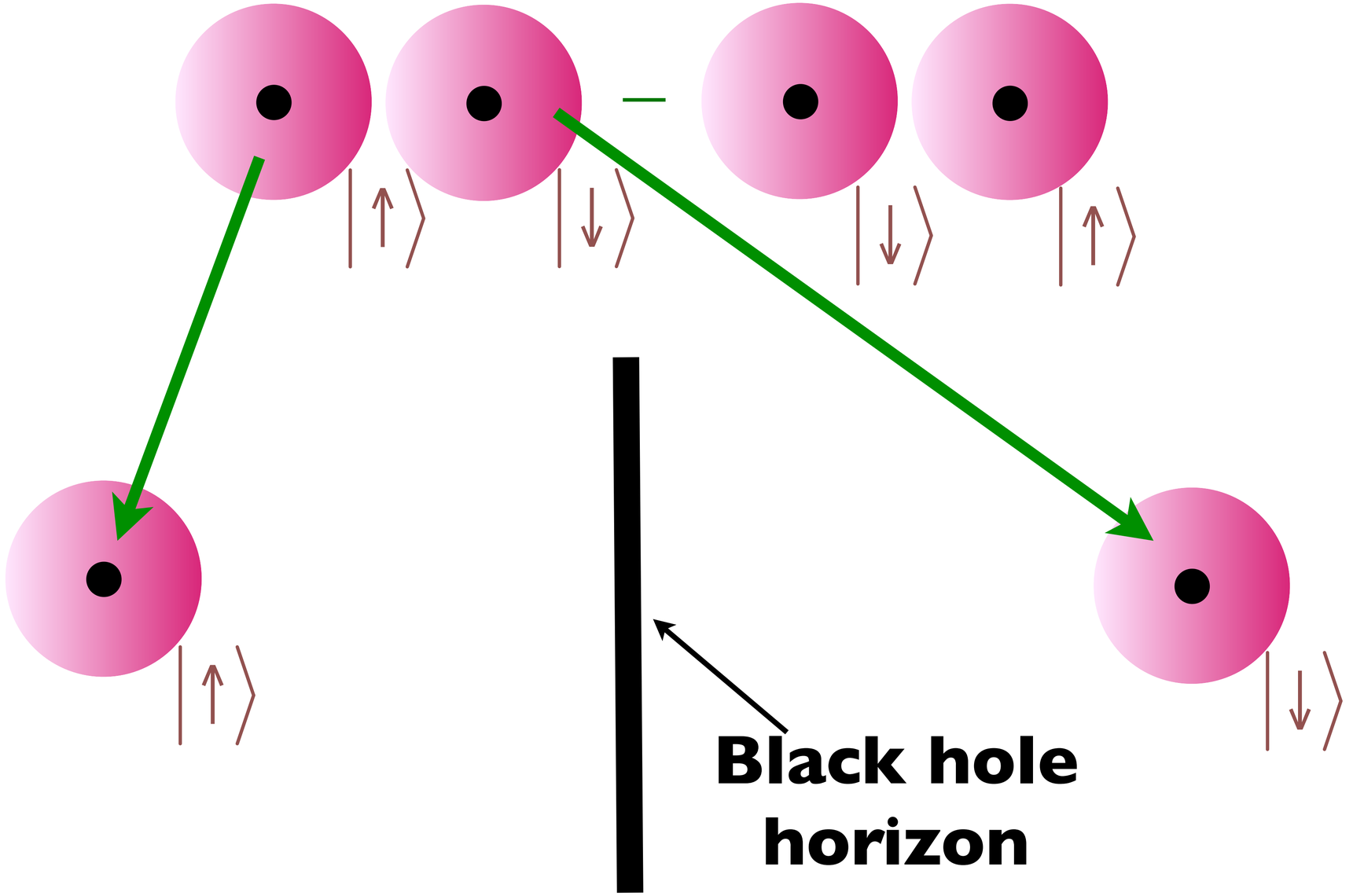

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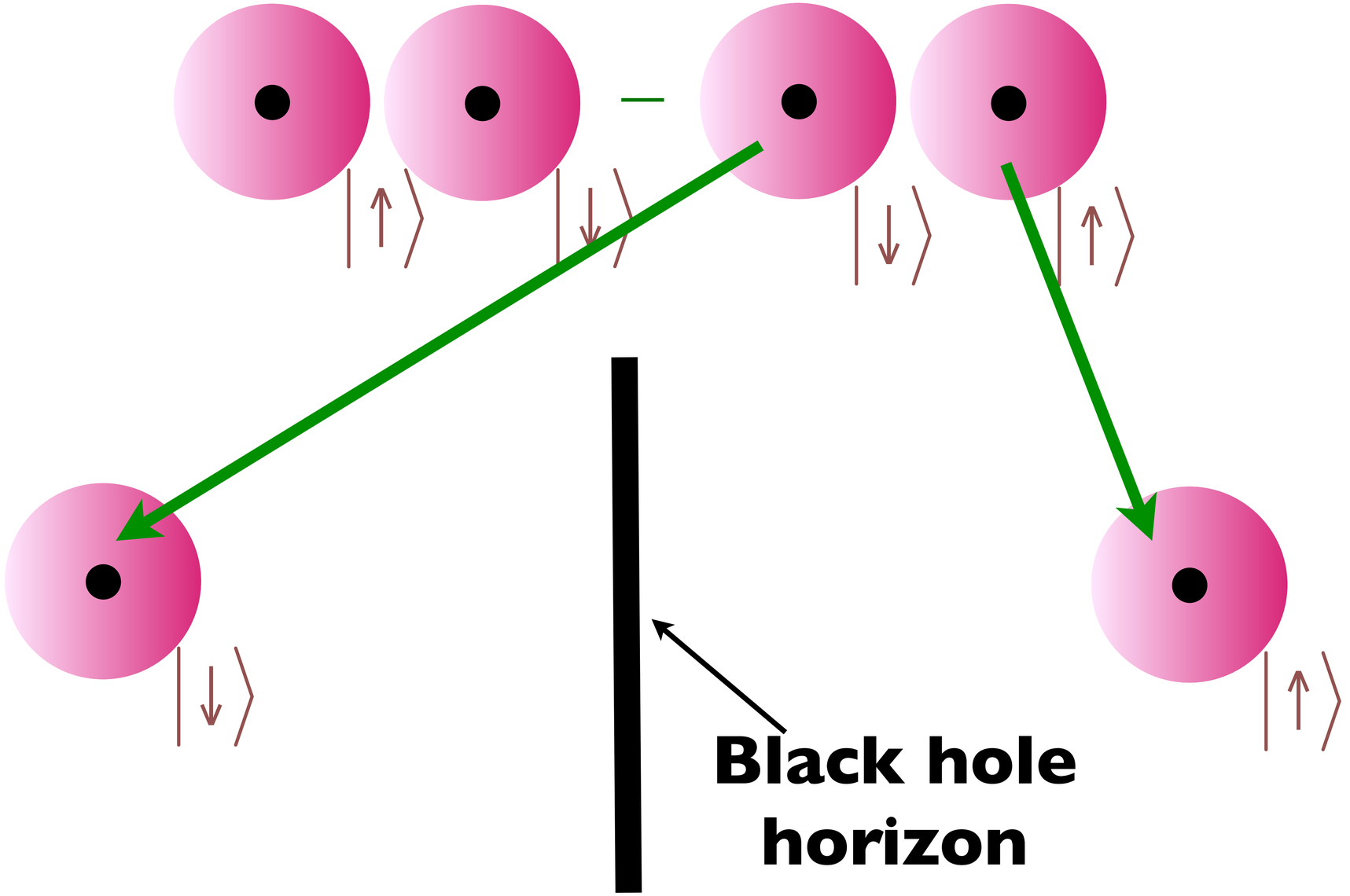
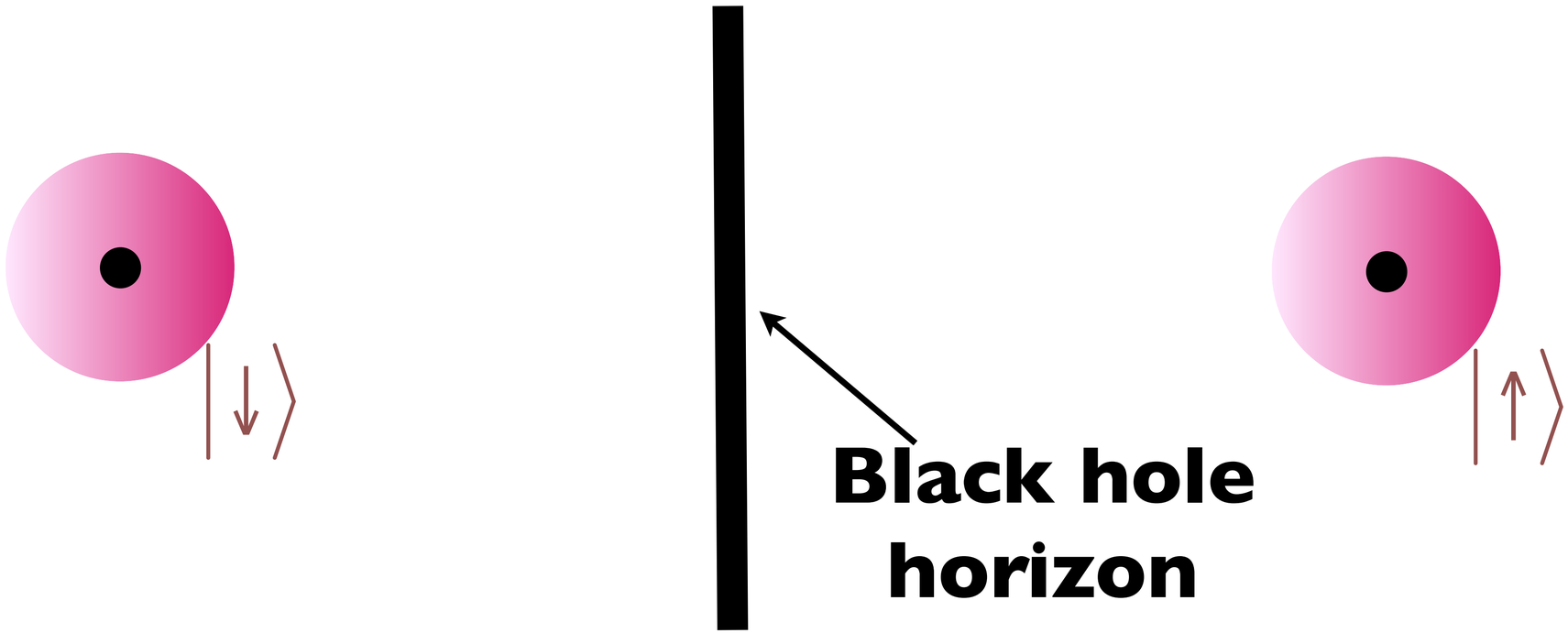


Quantum Entanglement across a black hole horizon

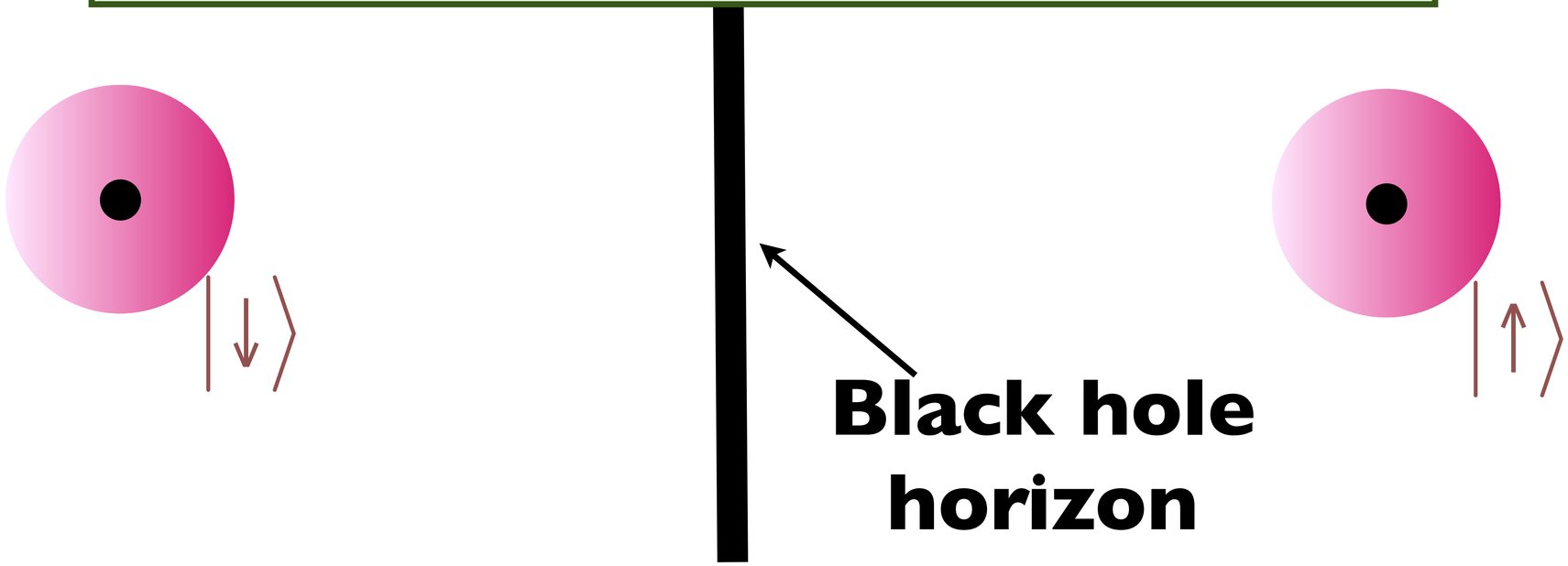
There is quantum entanglement between the inside and outside of a black hole



Quantum Entanglement across a black hole horizon

Hawking (1975) used other arguments to show that black hole horizons have a temperature and an entropy

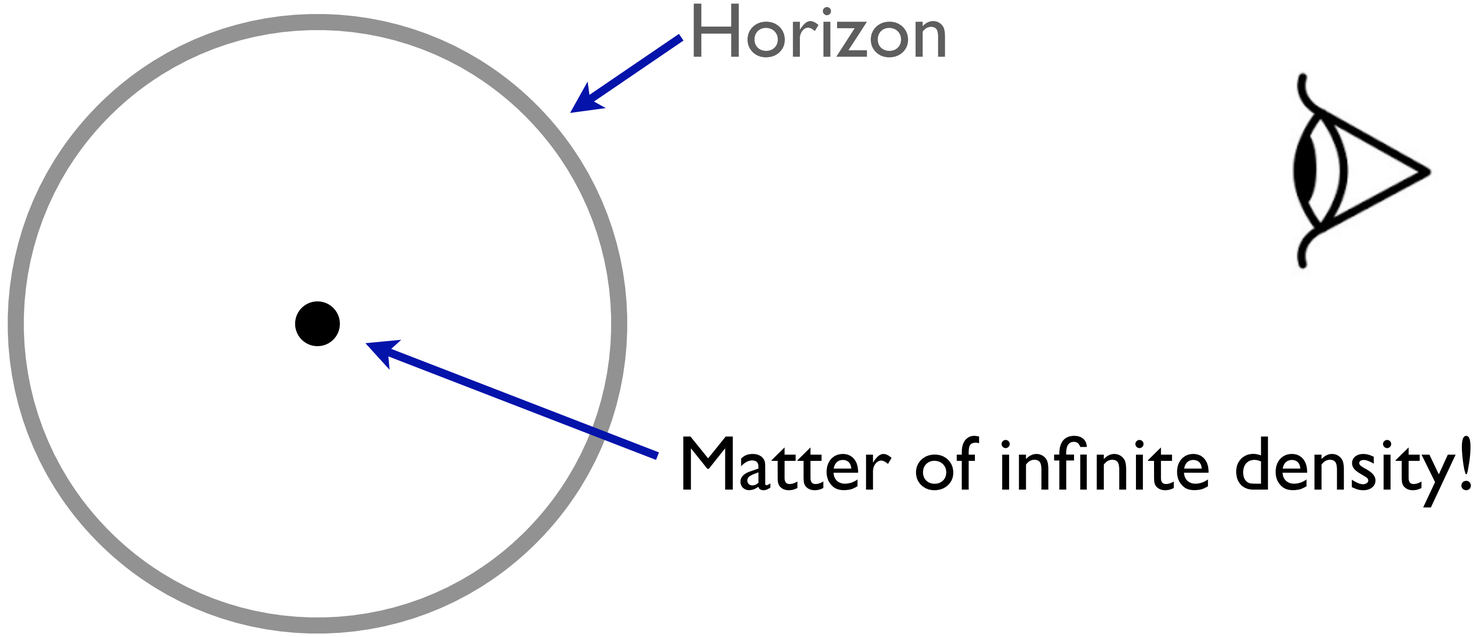
(The entanglement reasoning: to an outside observer, the state of the electron inside the black hole cannot be known, and so the outside electron is in a random state.)



Quantum Black Holes

Hawking obtained the black hole entropy by semiclassical computations for an observer *outside* the black hole horizon.

This allowed Hawking to avoid the contradictions associated with the singularity at the center of the black hole.



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

Statistical interpretation of entropy (1870)

$$S = k_B \log W$$

Density of quantum states $D(E) = \exp(S(E)/k_B)$

Quantum Black Holes

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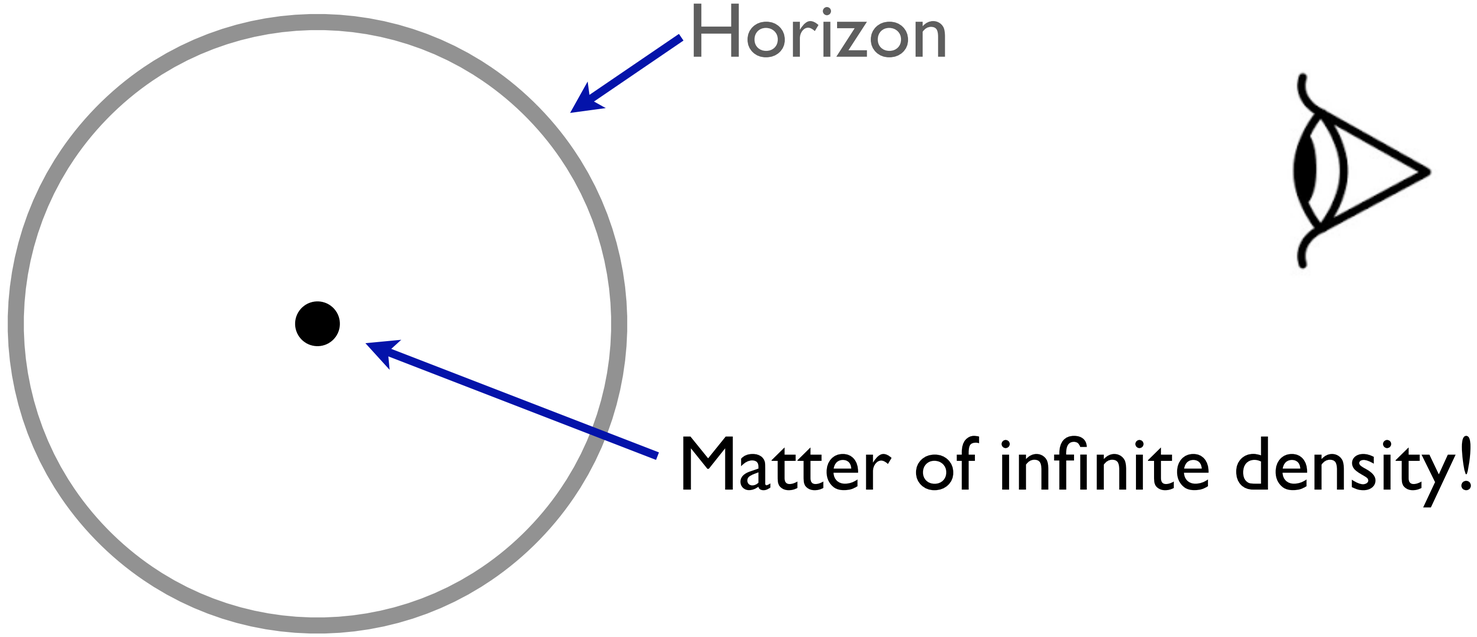


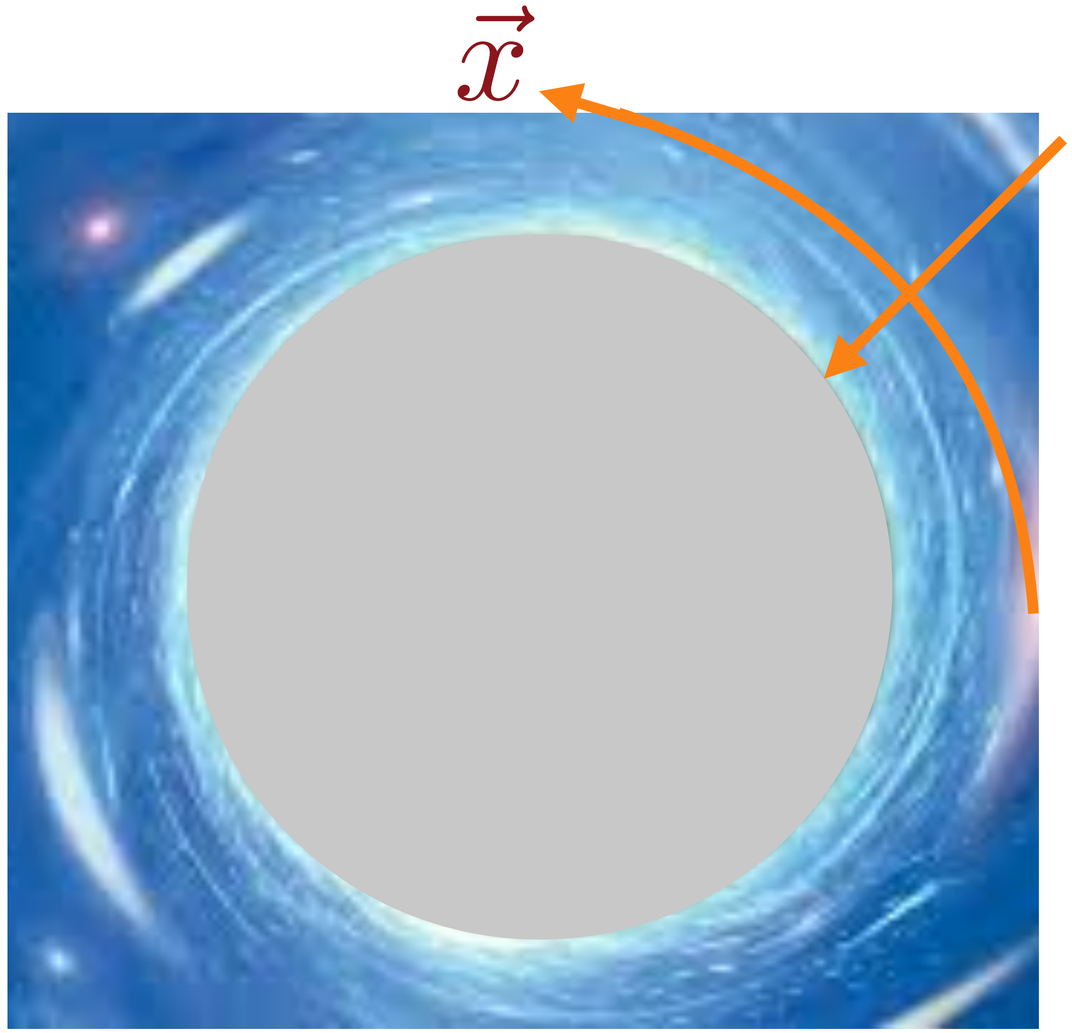
Quantum Black Holes

Hawking obtained the black hole entropy by semiclassical computations for an observer *outside* the black hole horizon.

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

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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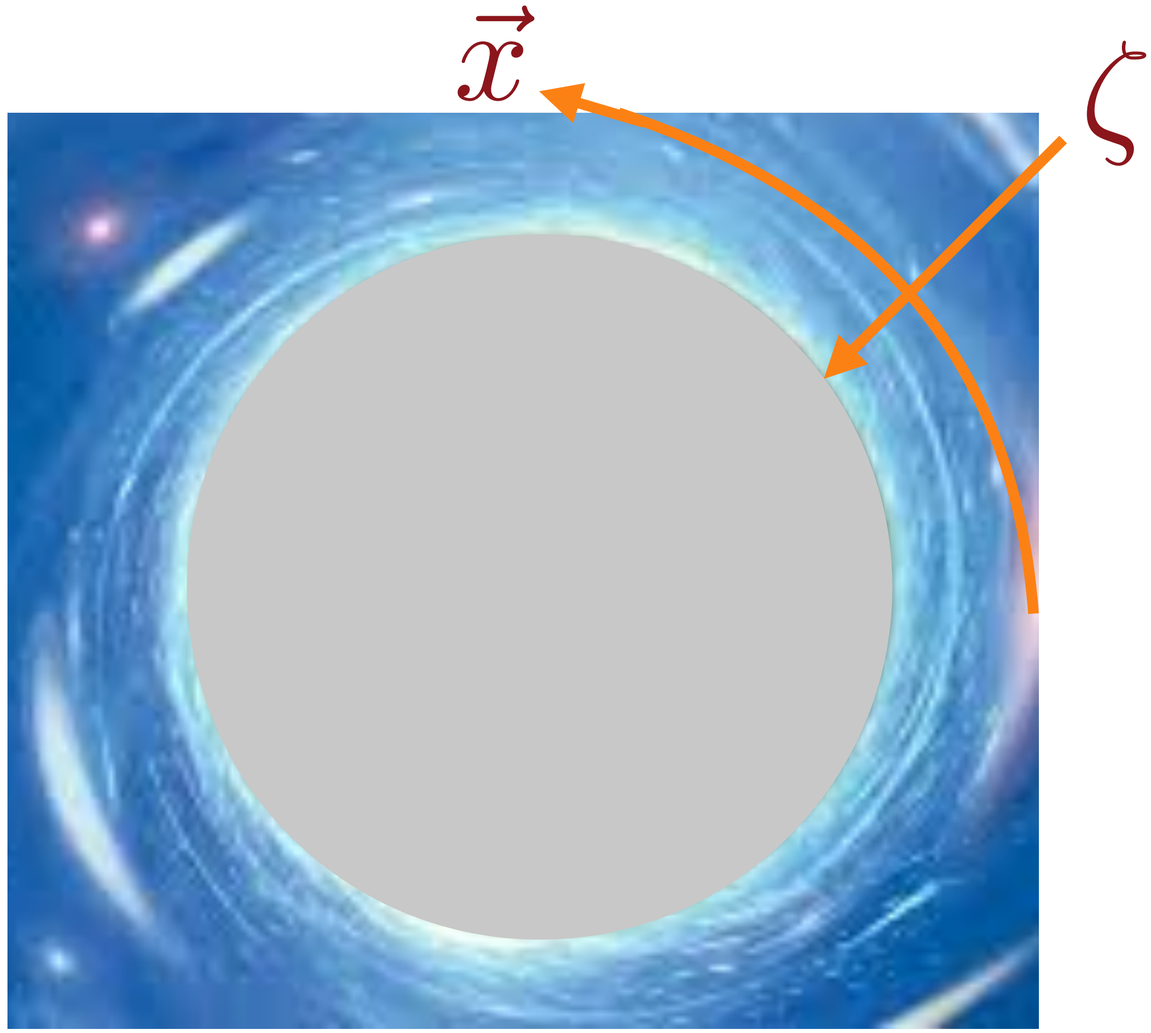
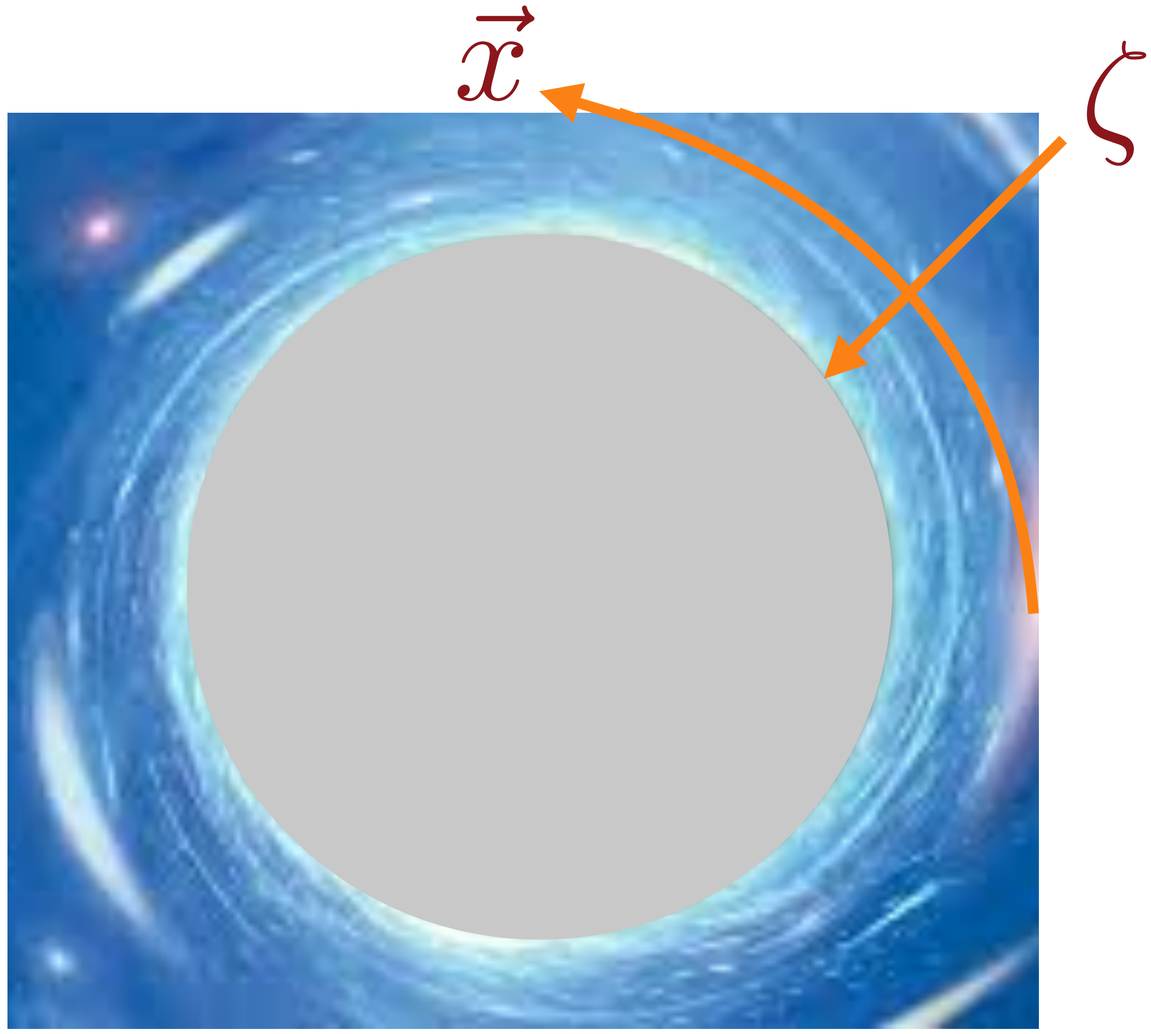


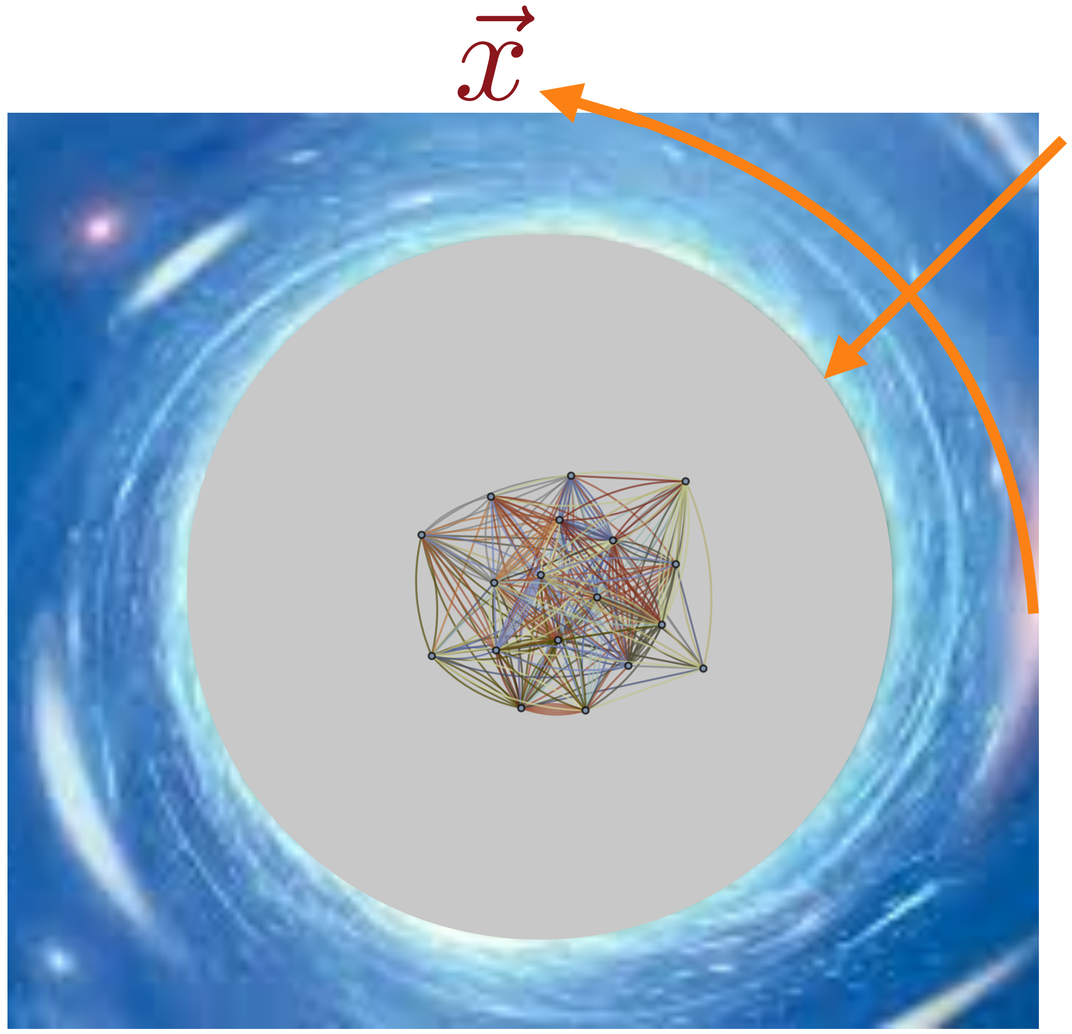
Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space (ζ) and one time dimension

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



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!

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

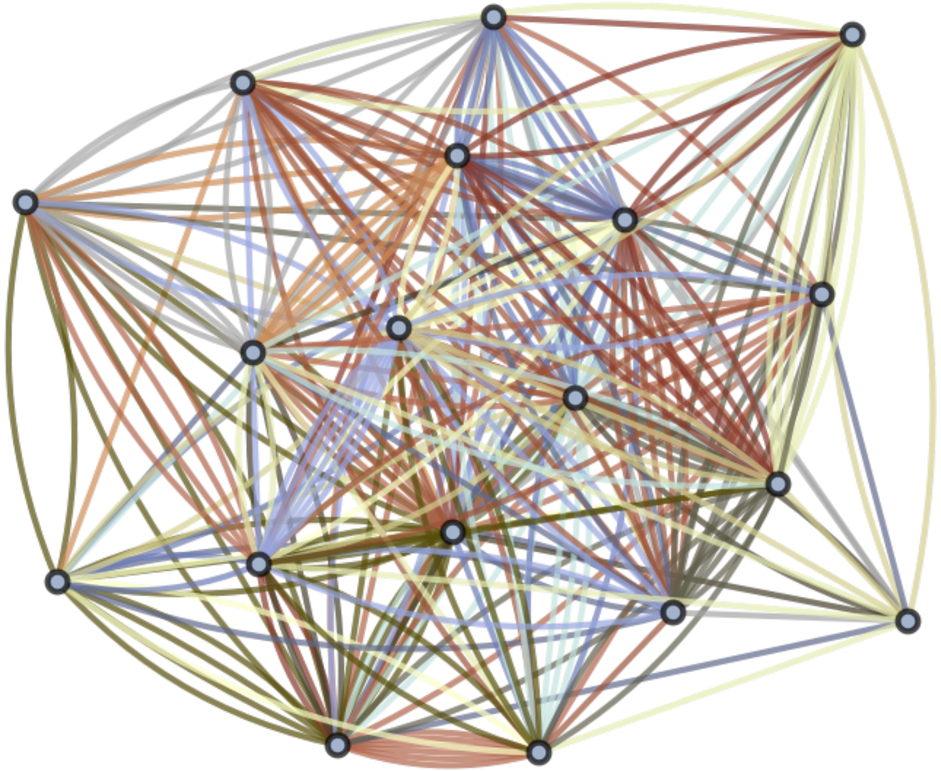


The SYK provides the needed realization of the black hole interior, and its density of quantum states matches gravitational entropy computations for charged black holes !

Recap

The Sachdev-Ye-Kitaev (SYK) model

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



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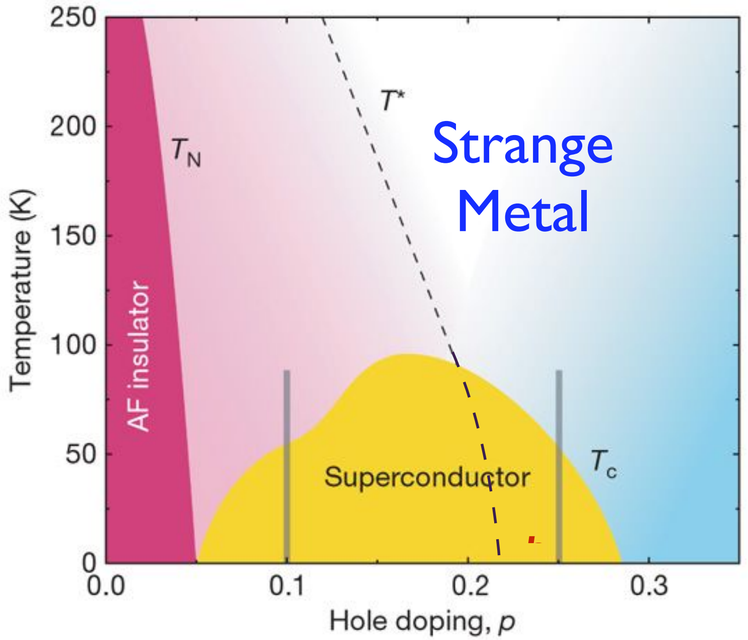
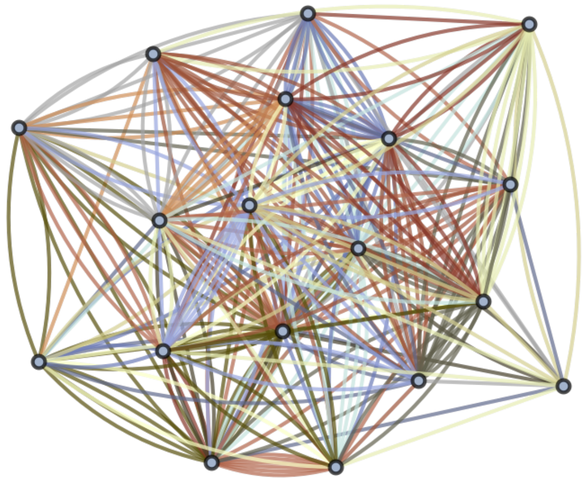


In one set of variables, it helps describe the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)



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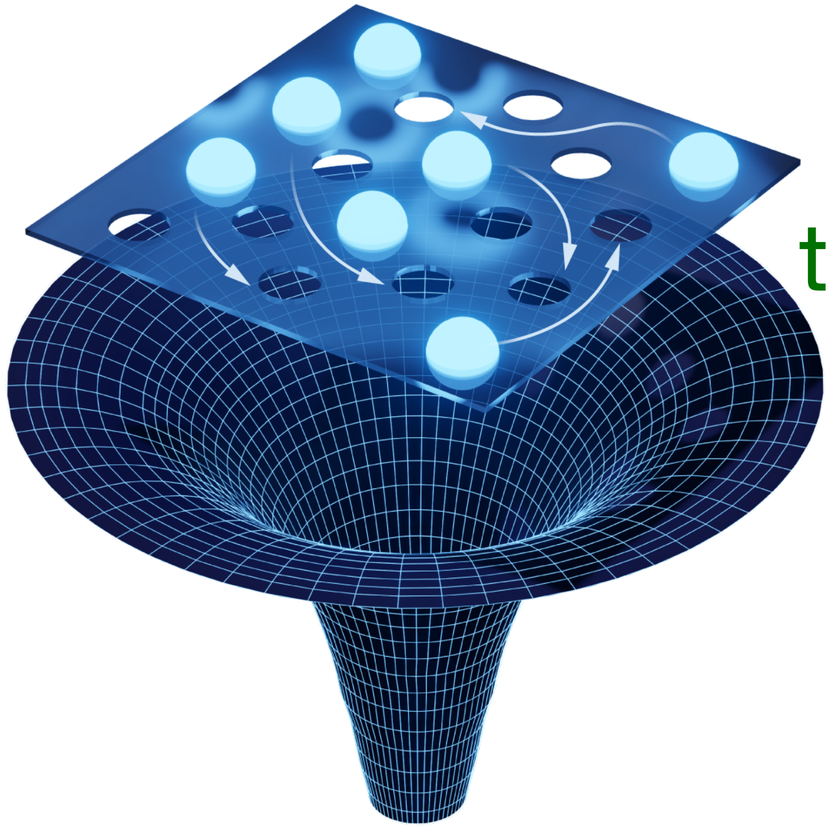

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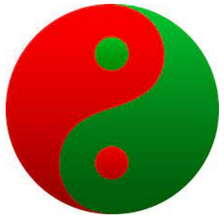
Sachdev, Ye (1993)



In a *dual* set of variables it describes

charged black holes

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

The many faces of multi-particle entanglement

- Absence of quasiparticles, as in the SYK model and the strange metal
- Fractionalization and new emergent particles, as in spin liquids.
- Higher temperature superconductivity (?)

The many faces of multi-particle entanglement

- Absence of quasiparticles, as in the SYK model and the strange metal
- Fractionalization and new emergent particles, as in spin liquids.
- Higher temperature superconductivity (?)
- A quantum theory of the interior of a black hole.