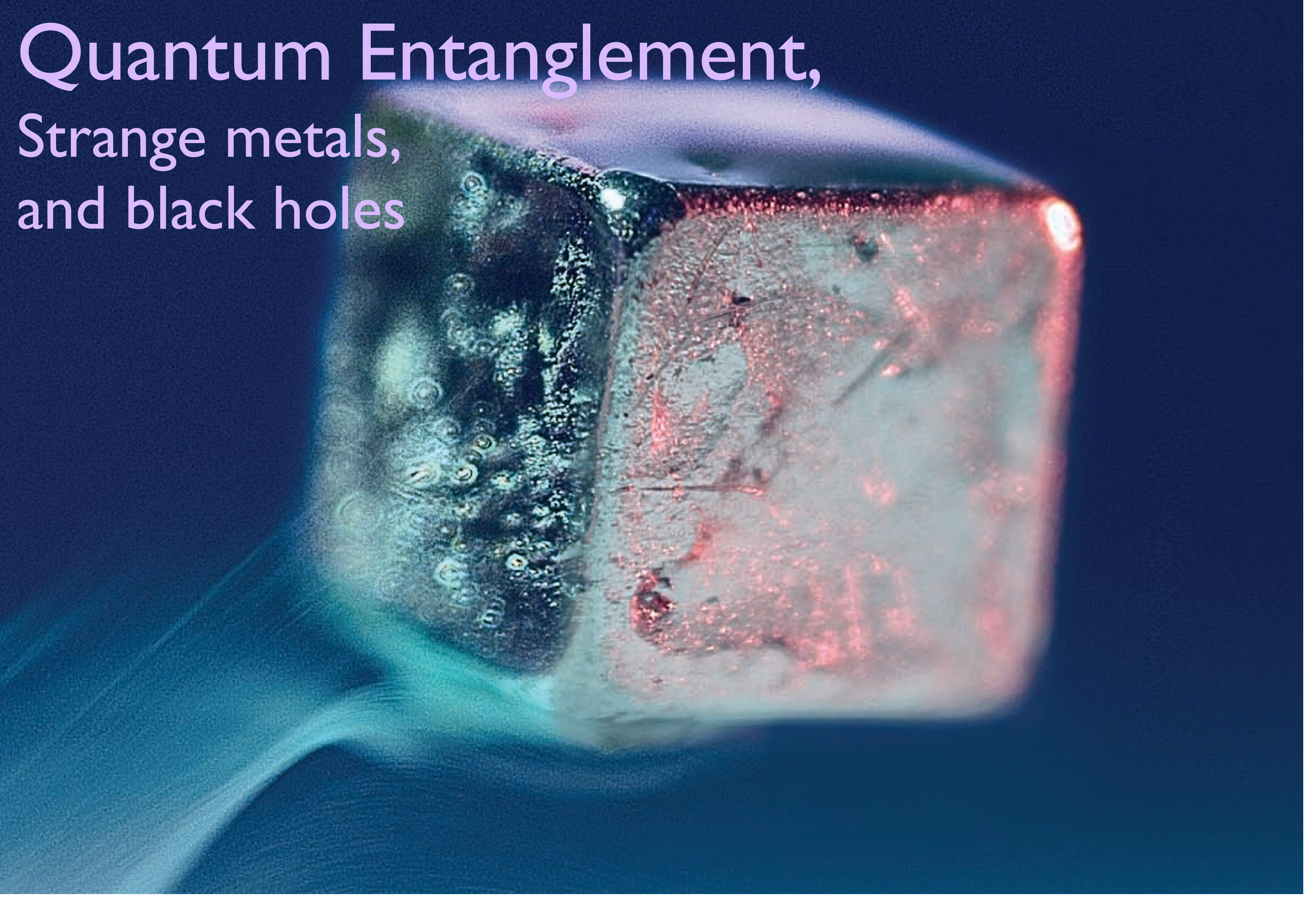
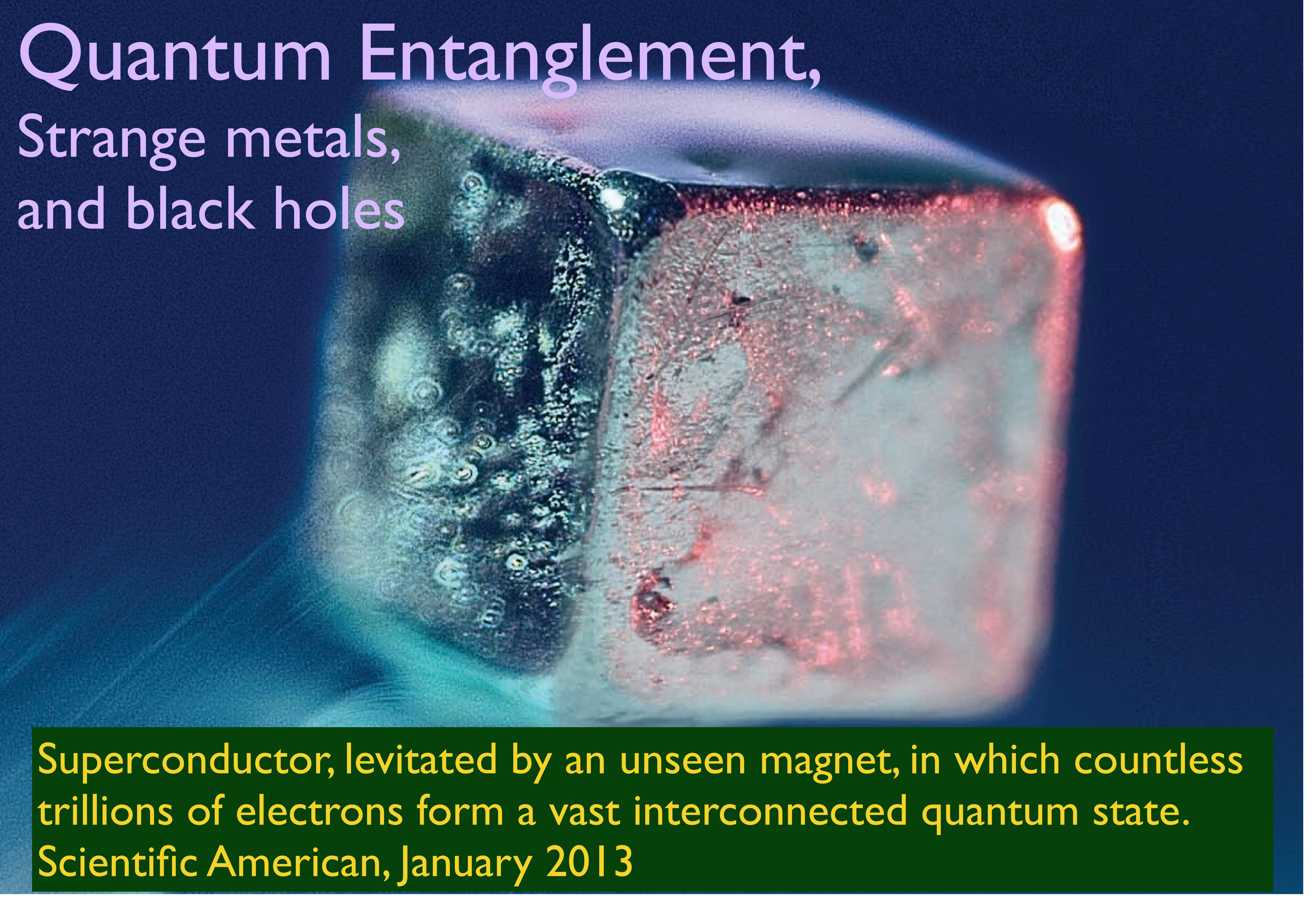
Quantum Entanglement,
Strange metals, and black holes



Subir Sachdev, Harvard University

Quantum Entanglement,
Strange metals,
and black holes



Superconductor, levitated by an unseen magnet, in which countless trillions of electrons form a vast interconnected quantum state.
Scientific American, January 2013

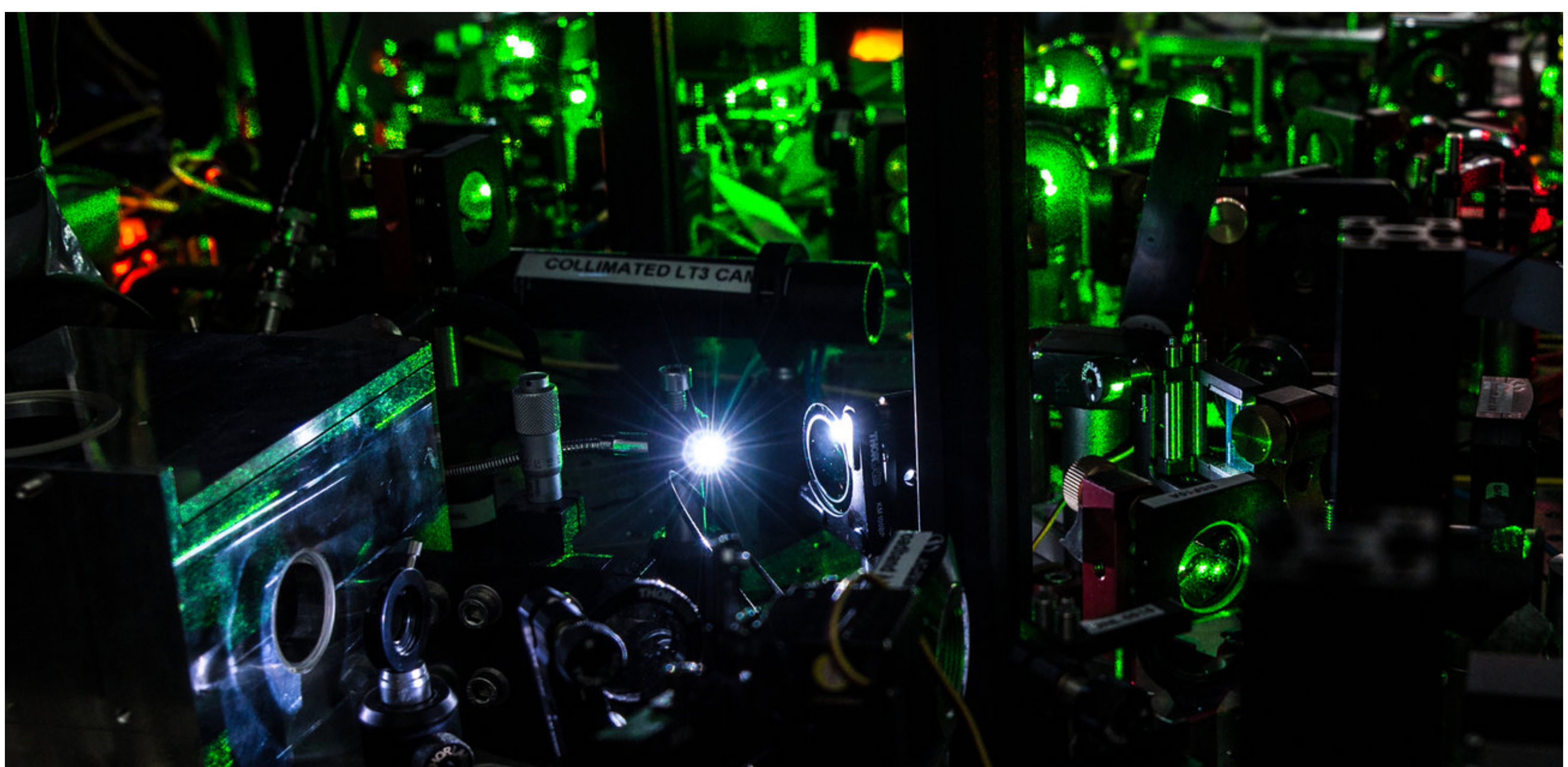
Subir Sachdev, Harvard University

The New York Times

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

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

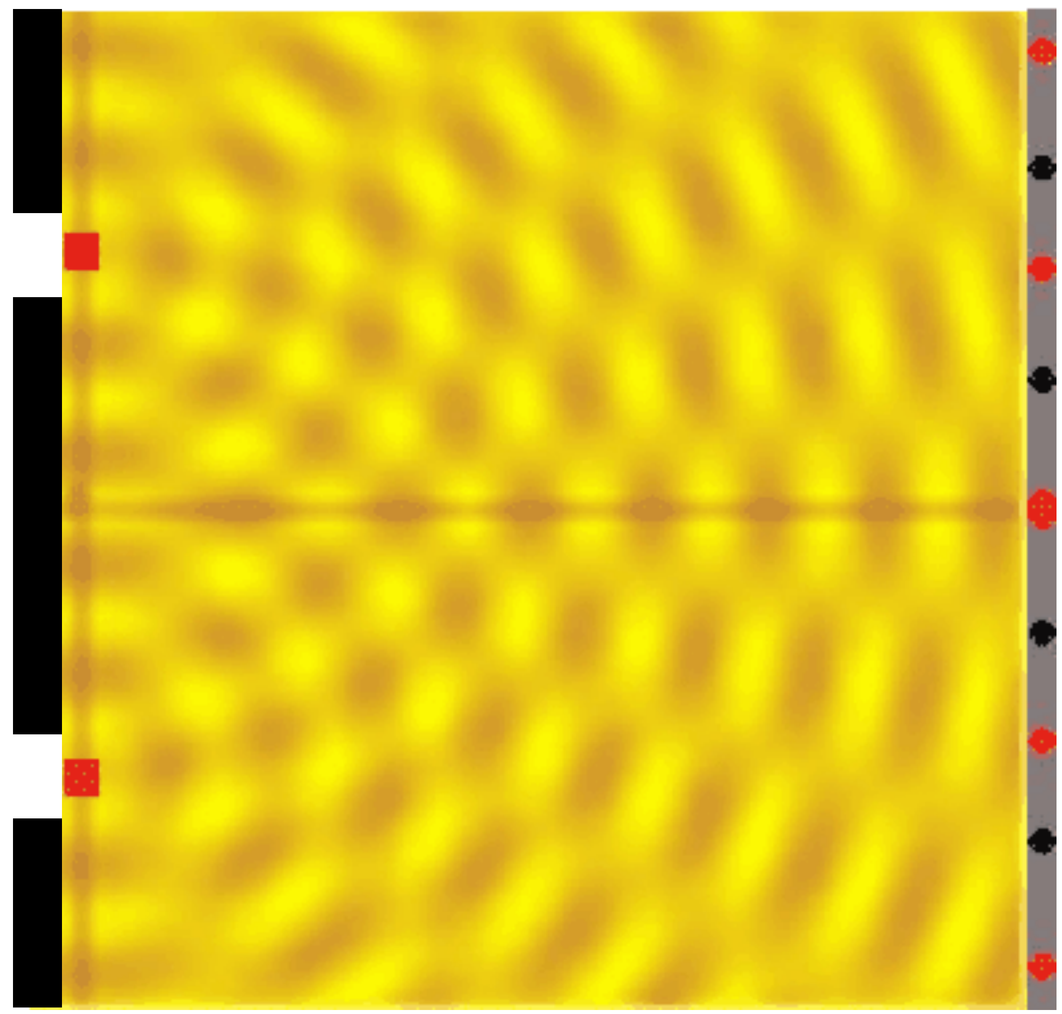
In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other’s behavior.



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.

Quantum entanglement

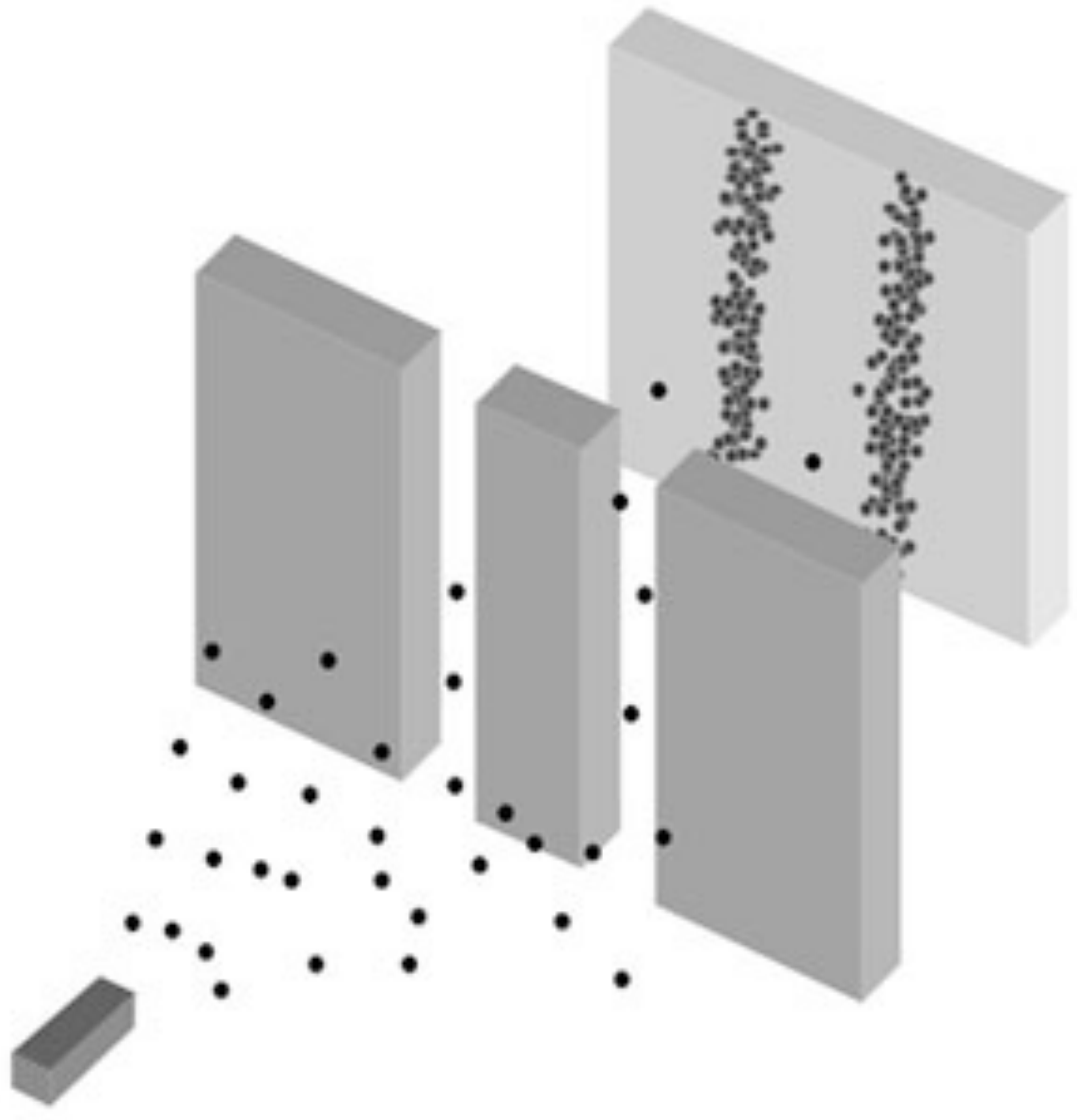
The double slit experiment



TWO SLITS

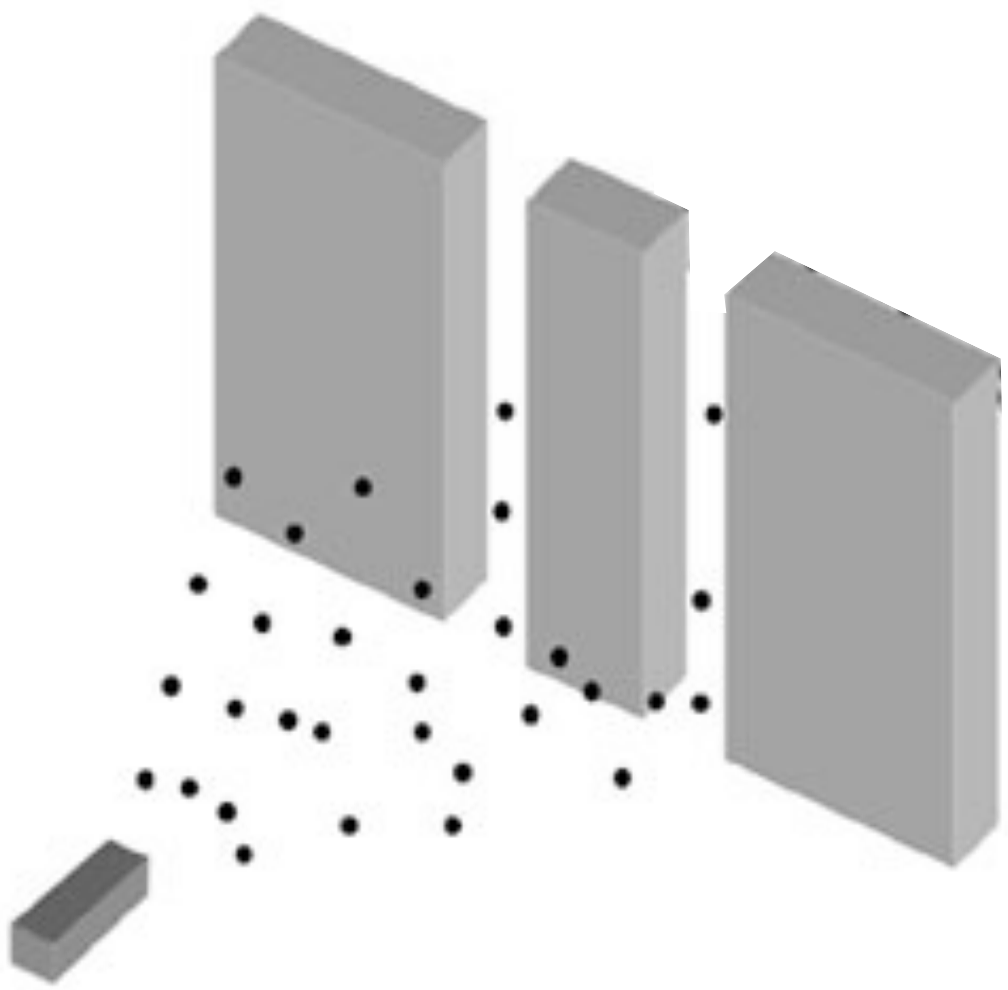
Interference of water waves

The double slit experiment



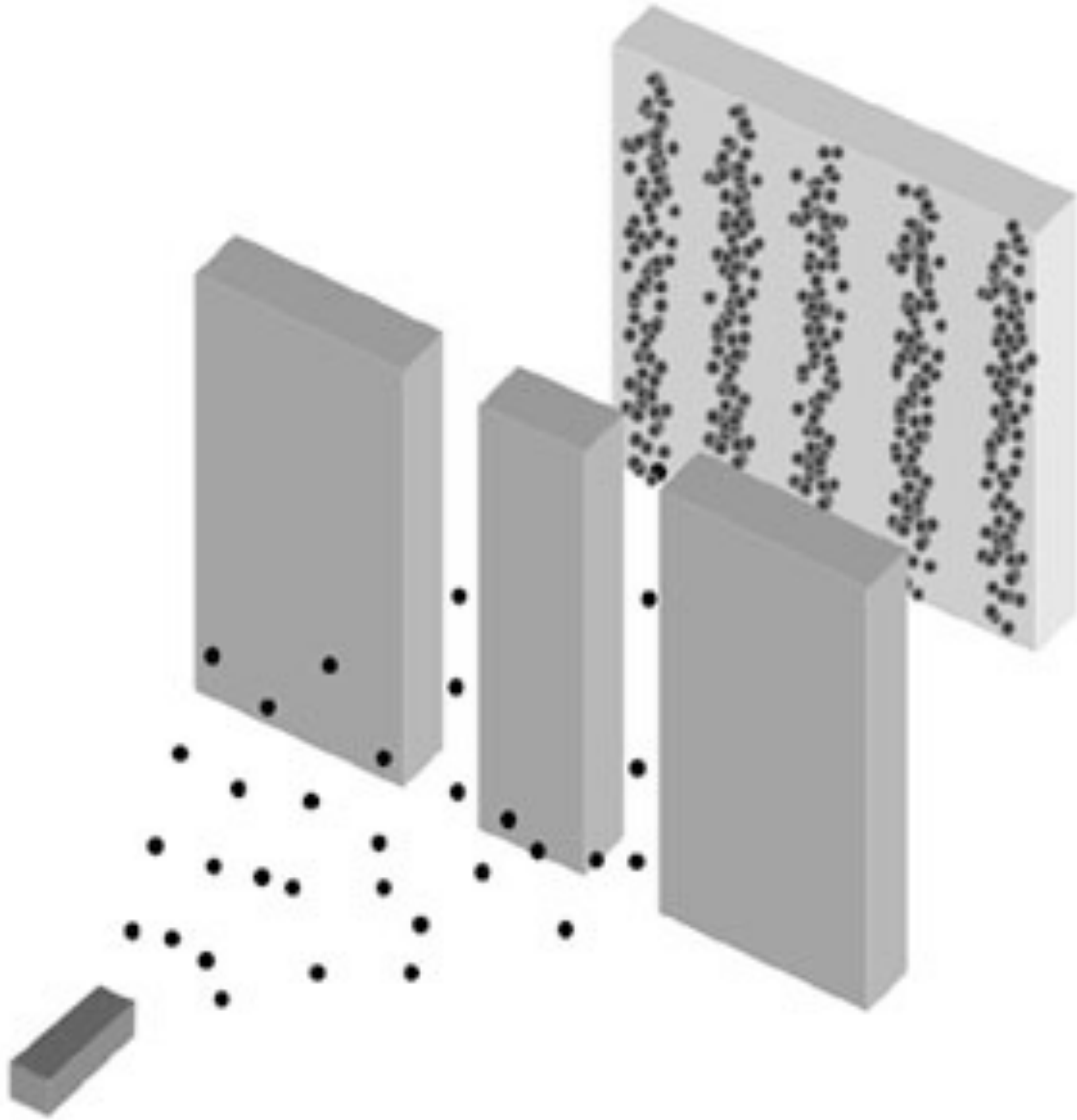
Bullets

The double slit experiment



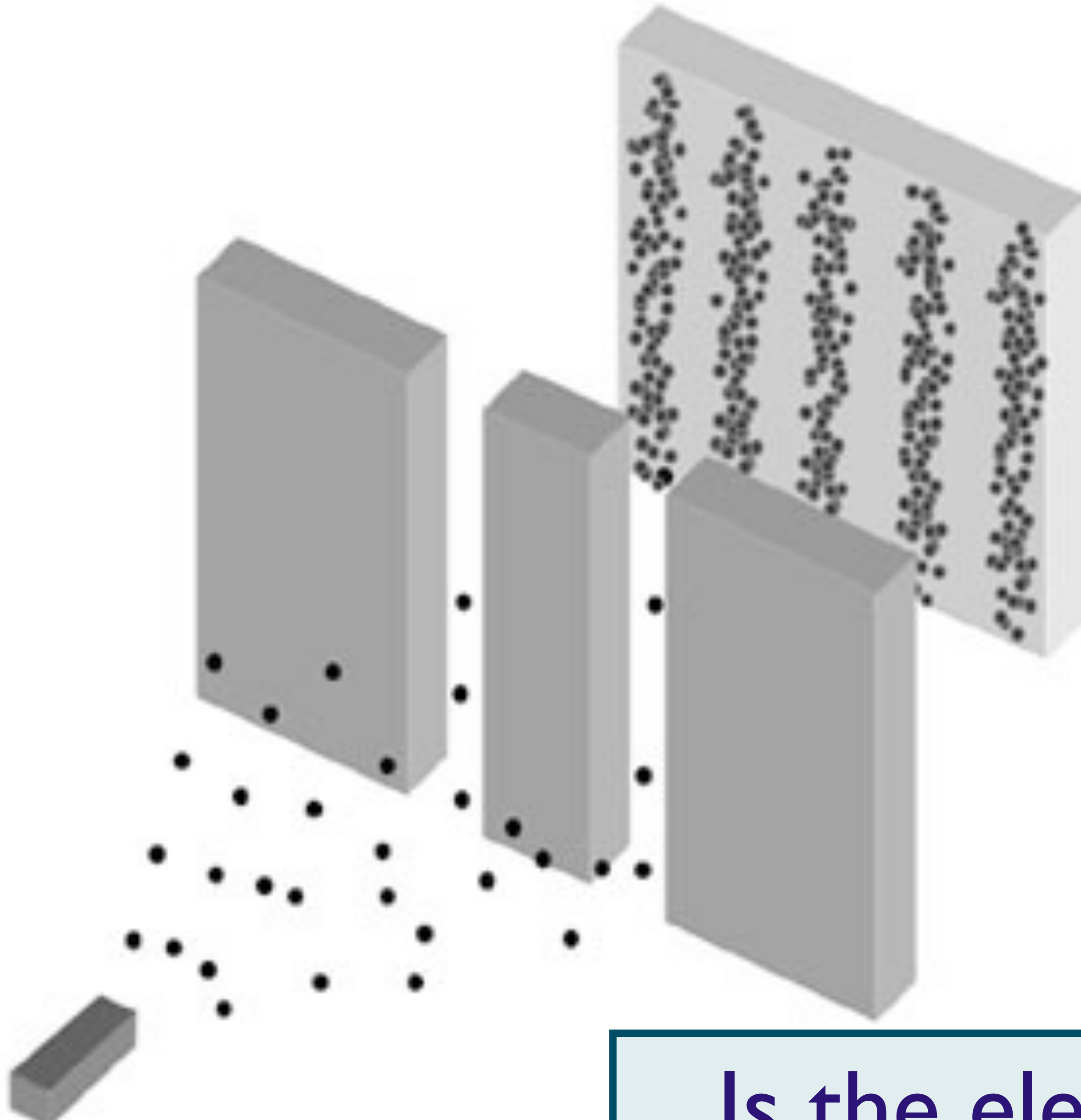
Send electrons through the slits

The double slit experiment



Interference of electrons

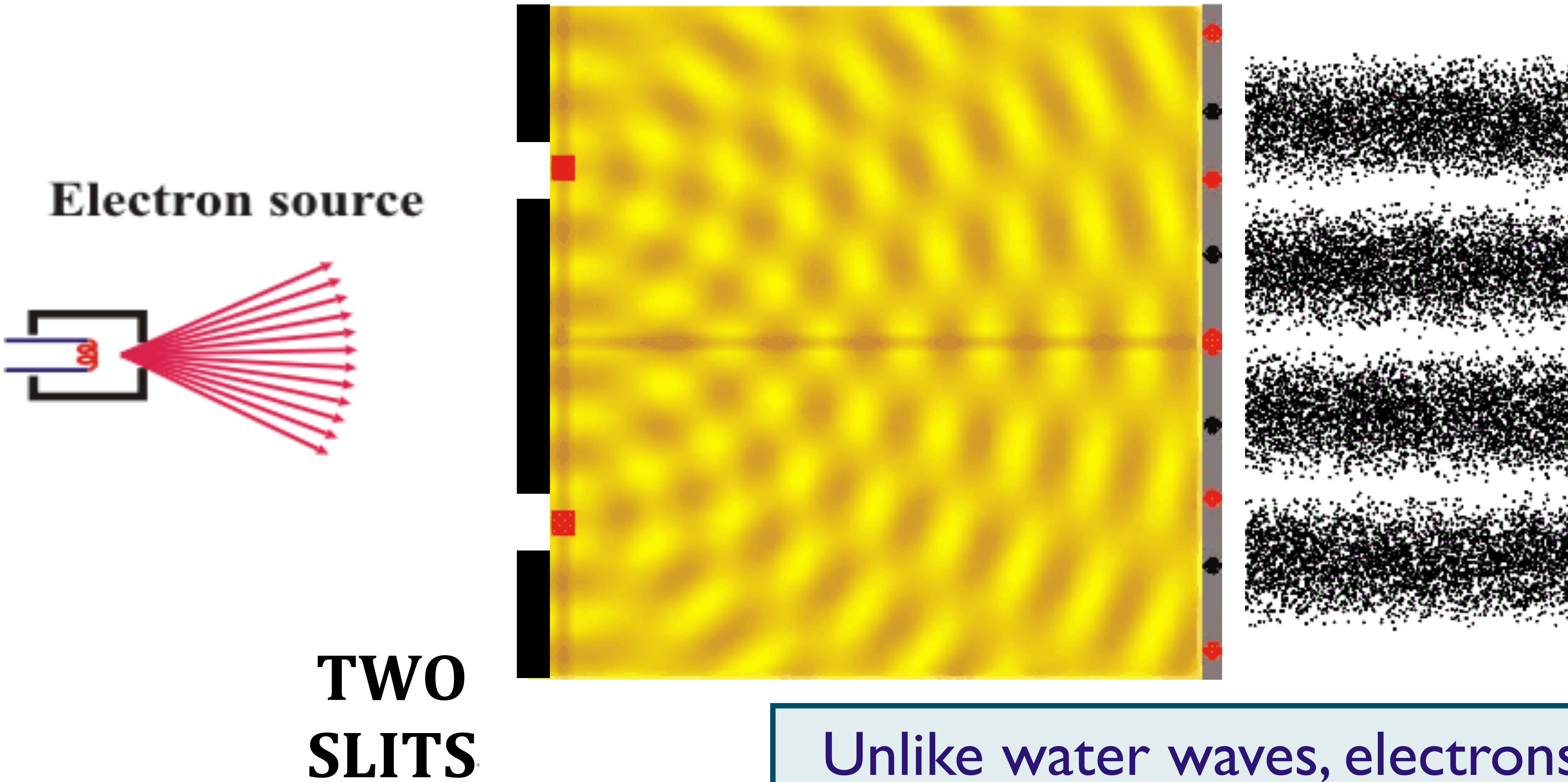
The double slit experiment



Is the electron a wave ?

Interference of electrons

The double slit experiment

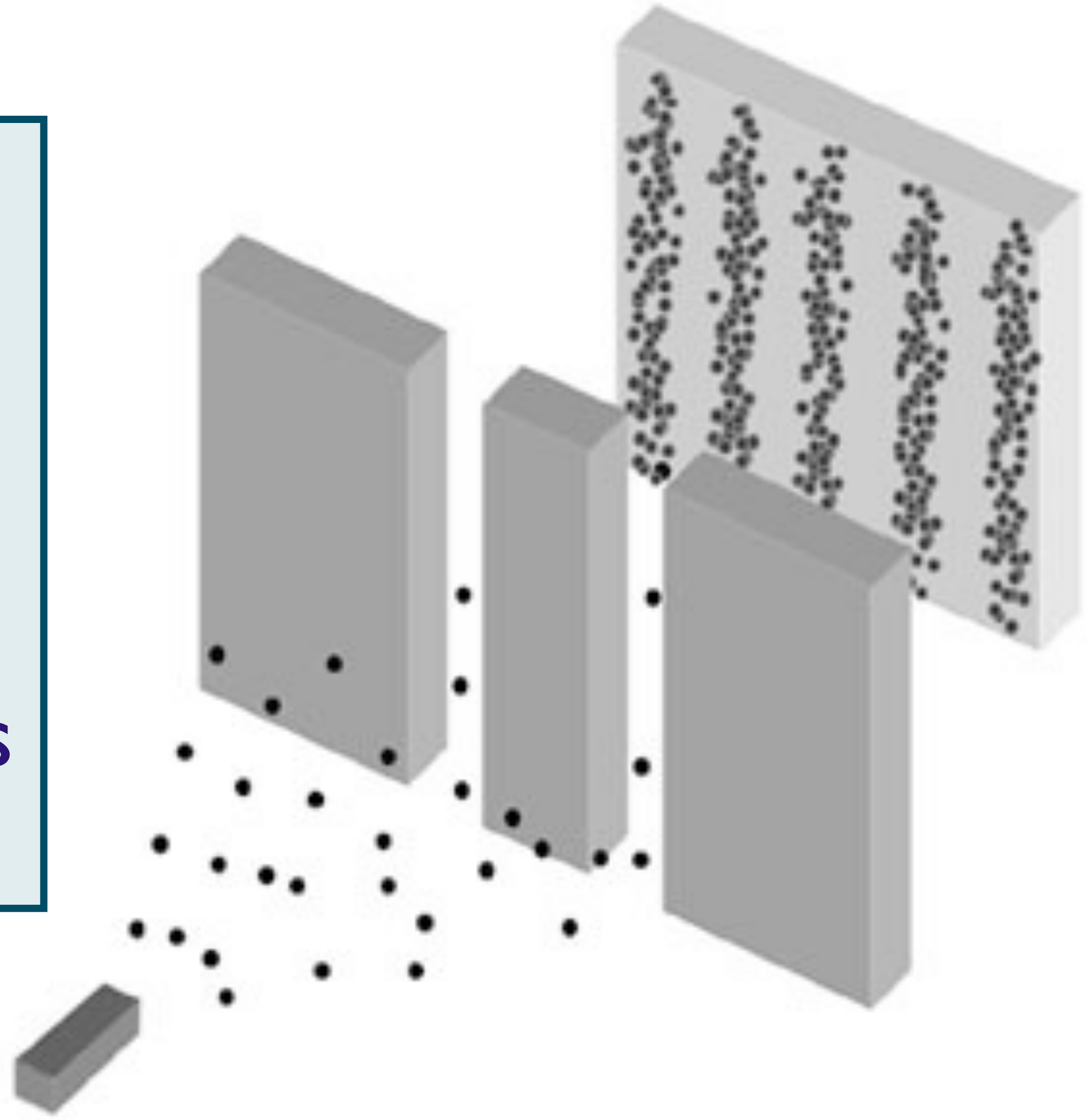


Unlike water waves, electrons arrive one-by-one (so is it like a particle ?)

Interference of electrons

The double slit experiment

But if it is like a particle, which slit does each electron pass through ?



Interference of electrons

The double slit experiment

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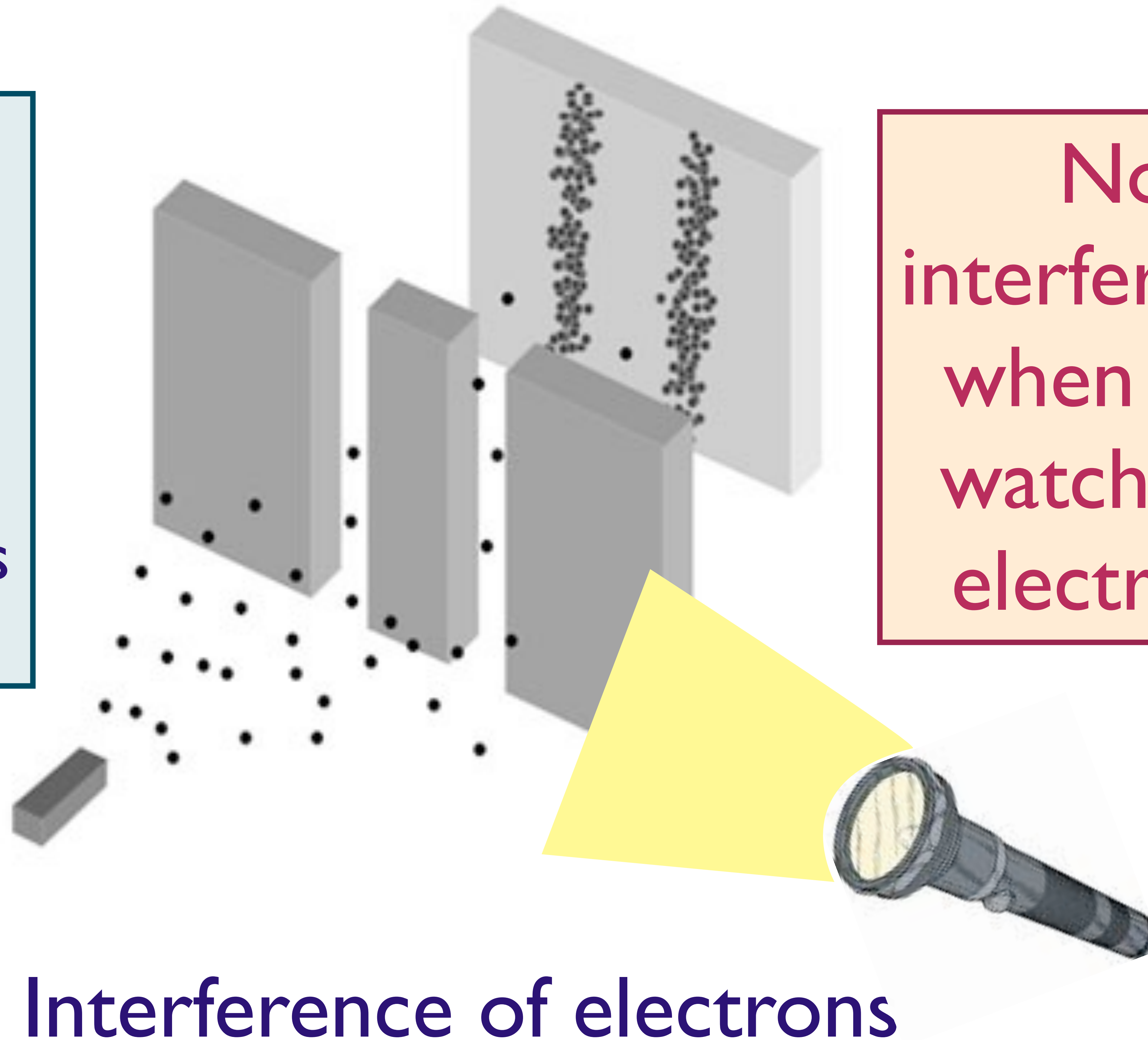
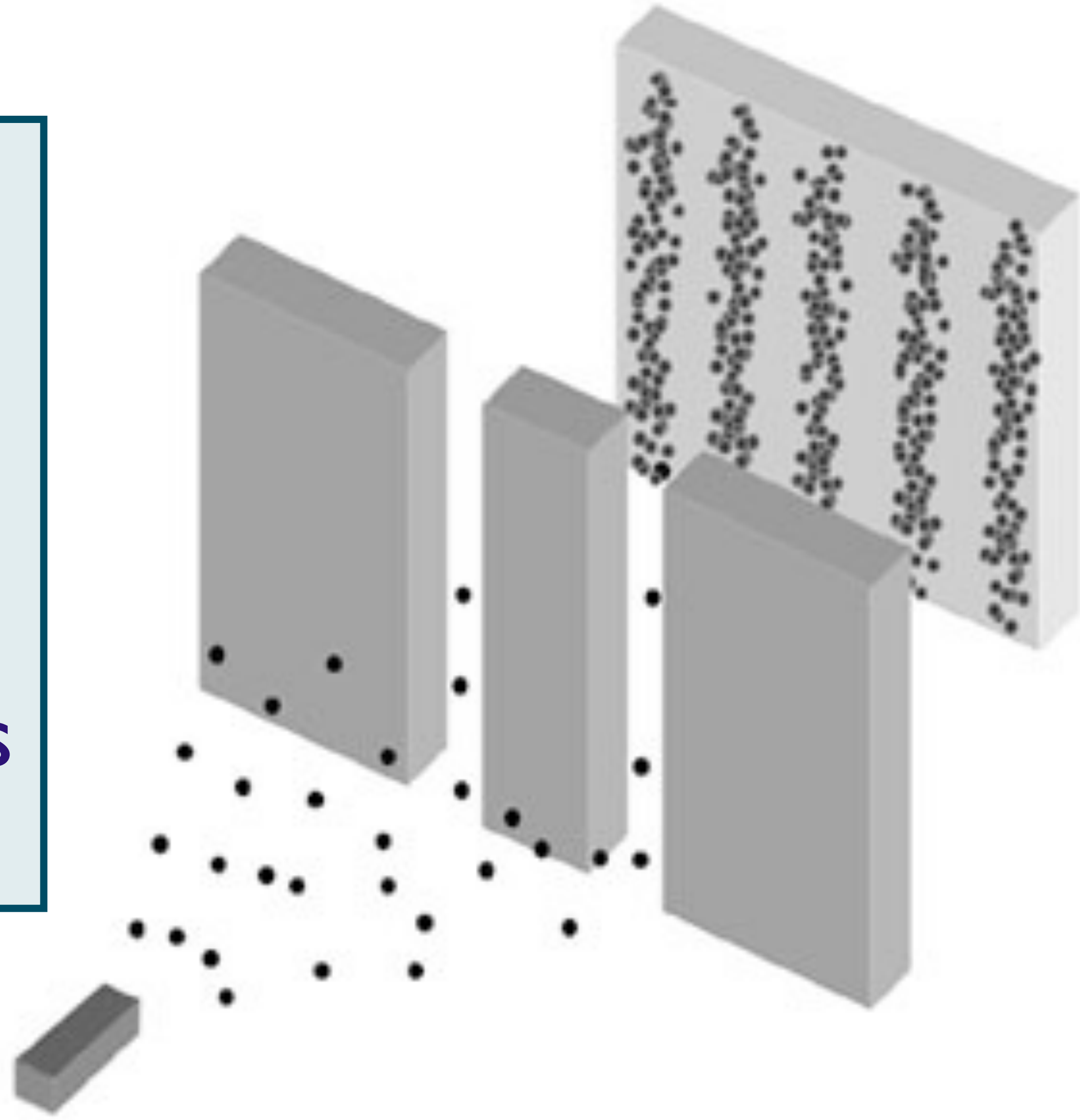


No interference when you watch the electrons

Interference of electrons

The double slit experiment

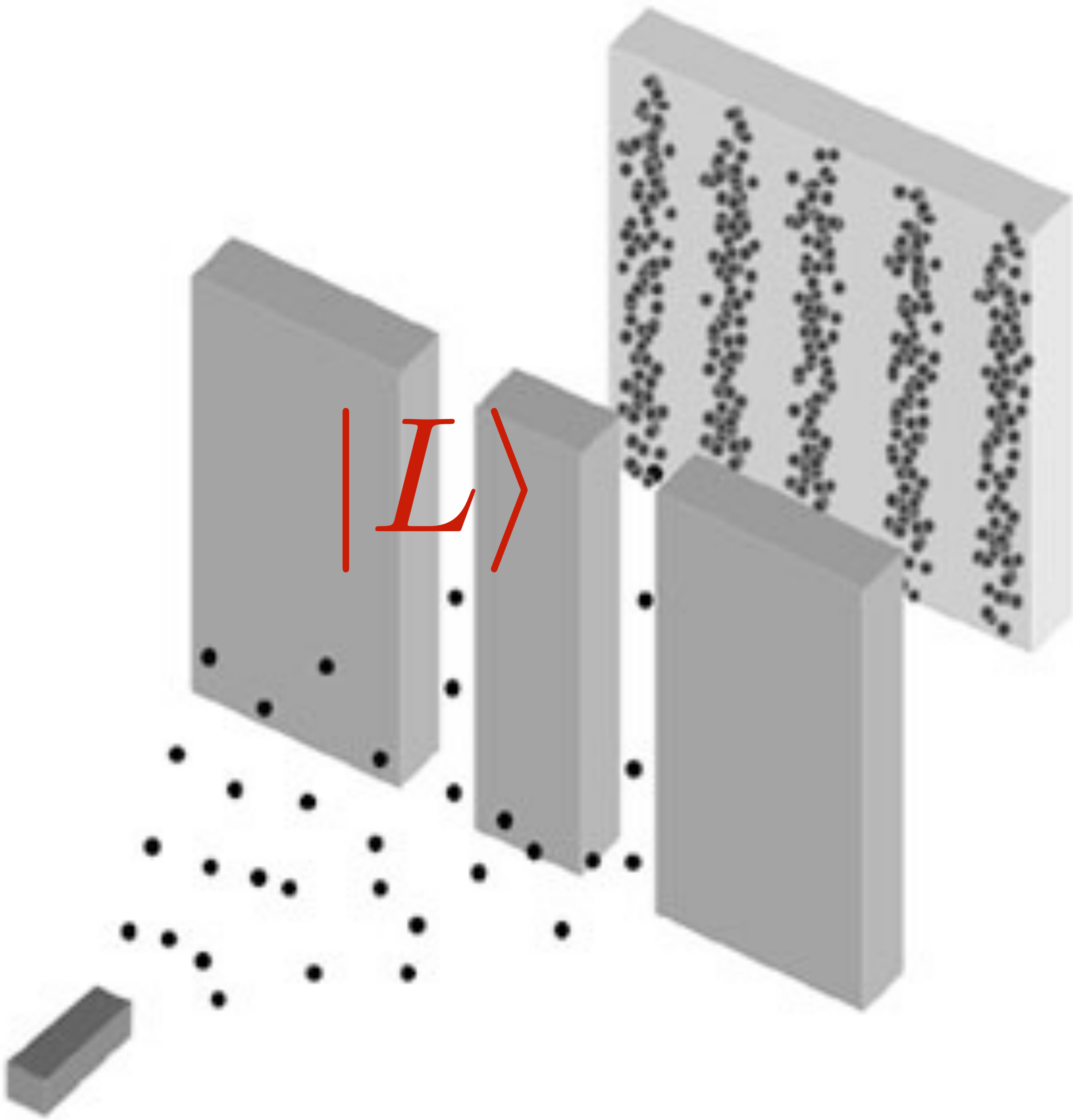
But if it is like a particle, which slit does each electron pass through ?



Each electron passes through both slits !

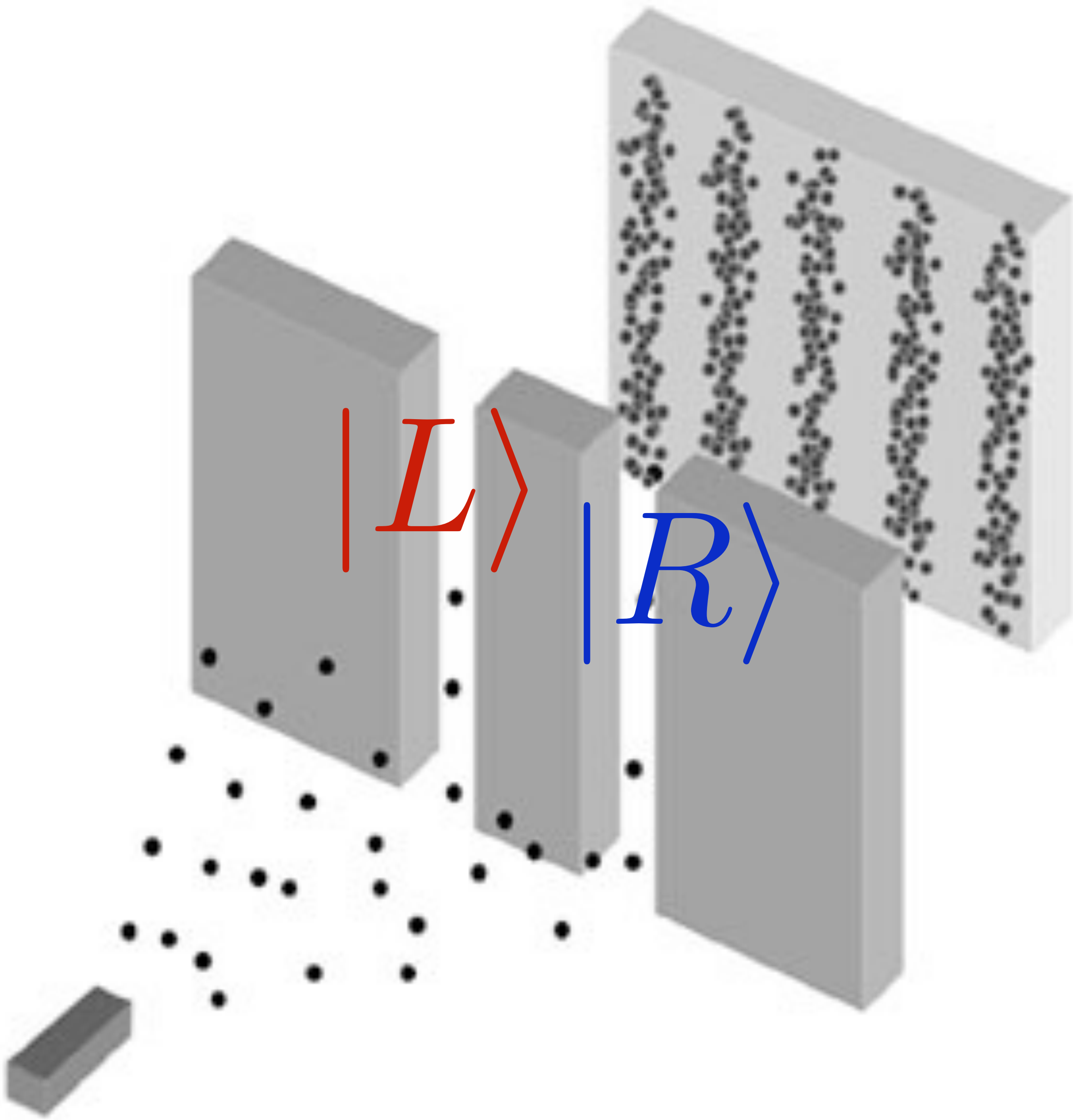
Interference of electrons

The double slit experiment



Let $|L\rangle$ represent the state with the electron in the left slit

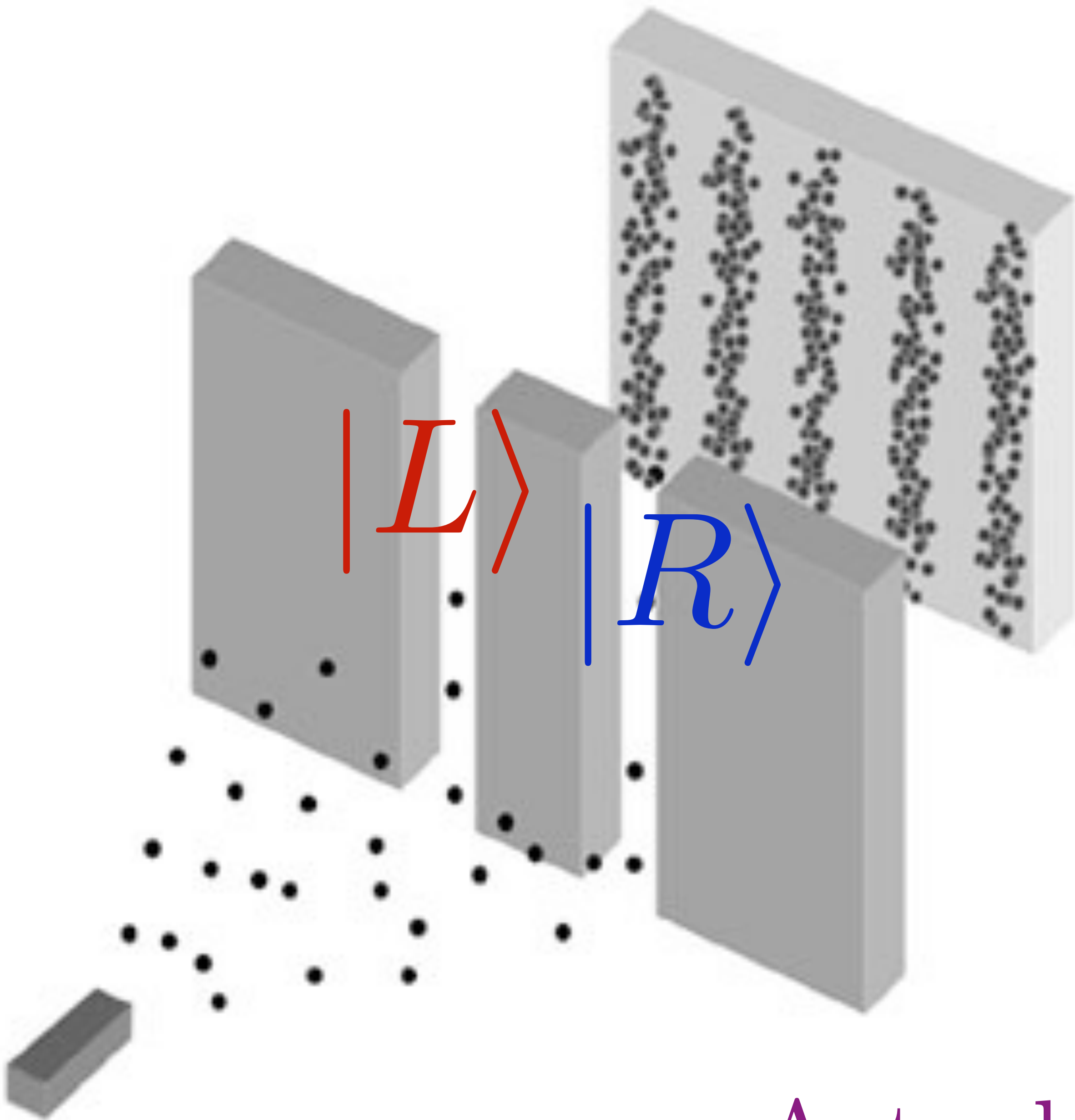
The double slit experiment



Let $|L\rangle$ represent the state with the electron in the left slit

And $|R\rangle$ represents the state with the electron in the right slit

The double slit experiment



Let $|L\rangle$ represent the state with the electron in the left slit

And $|R\rangle$ represents the state with the electron in the right slit

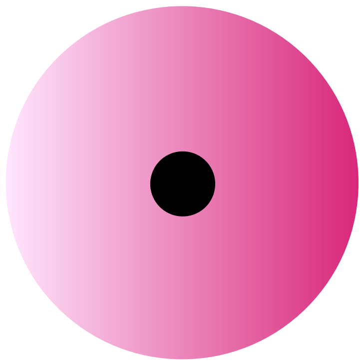
Actual state of *each* electron is

$$|L\rangle + |R\rangle$$

Quantum Entanglement: quantum superposition with more than one particle

Quantum Entanglement: quantum superposition with more than one particle

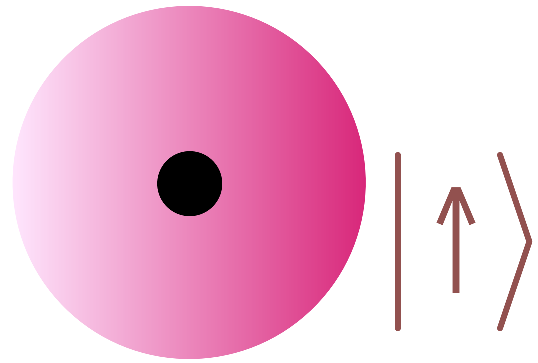
Hydrogen atom:



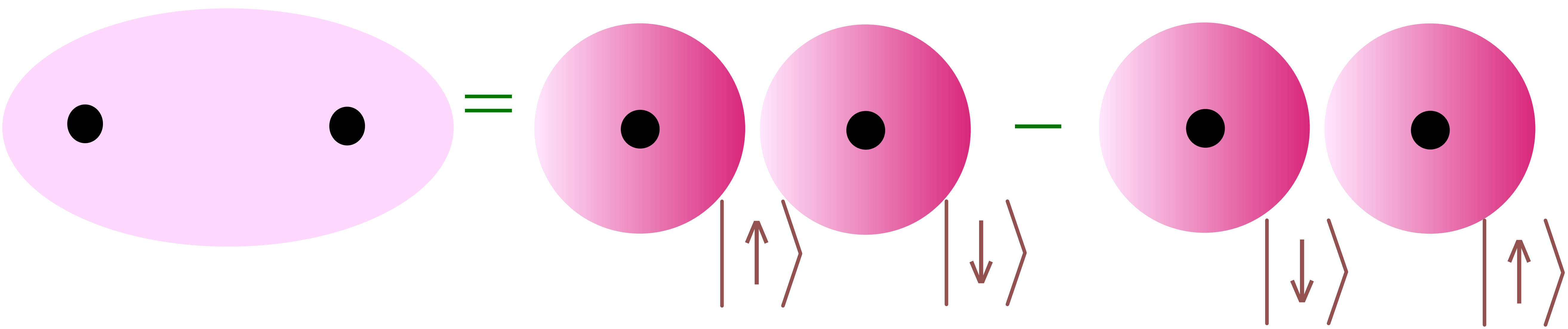
$|\uparrow\rangle$

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

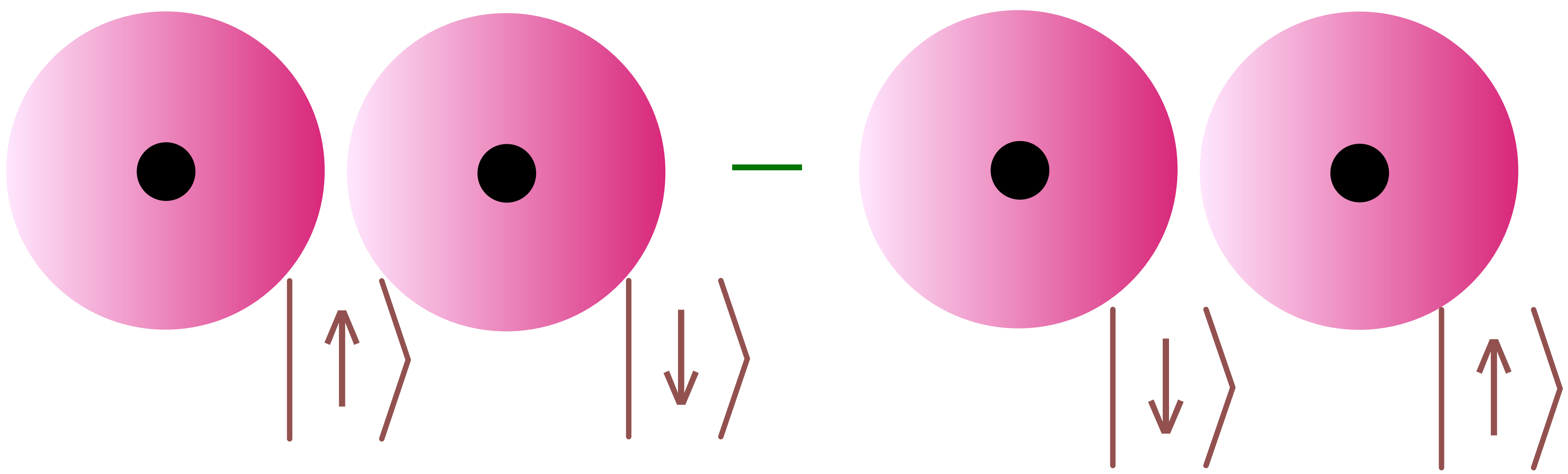


Hydrogen molecule:

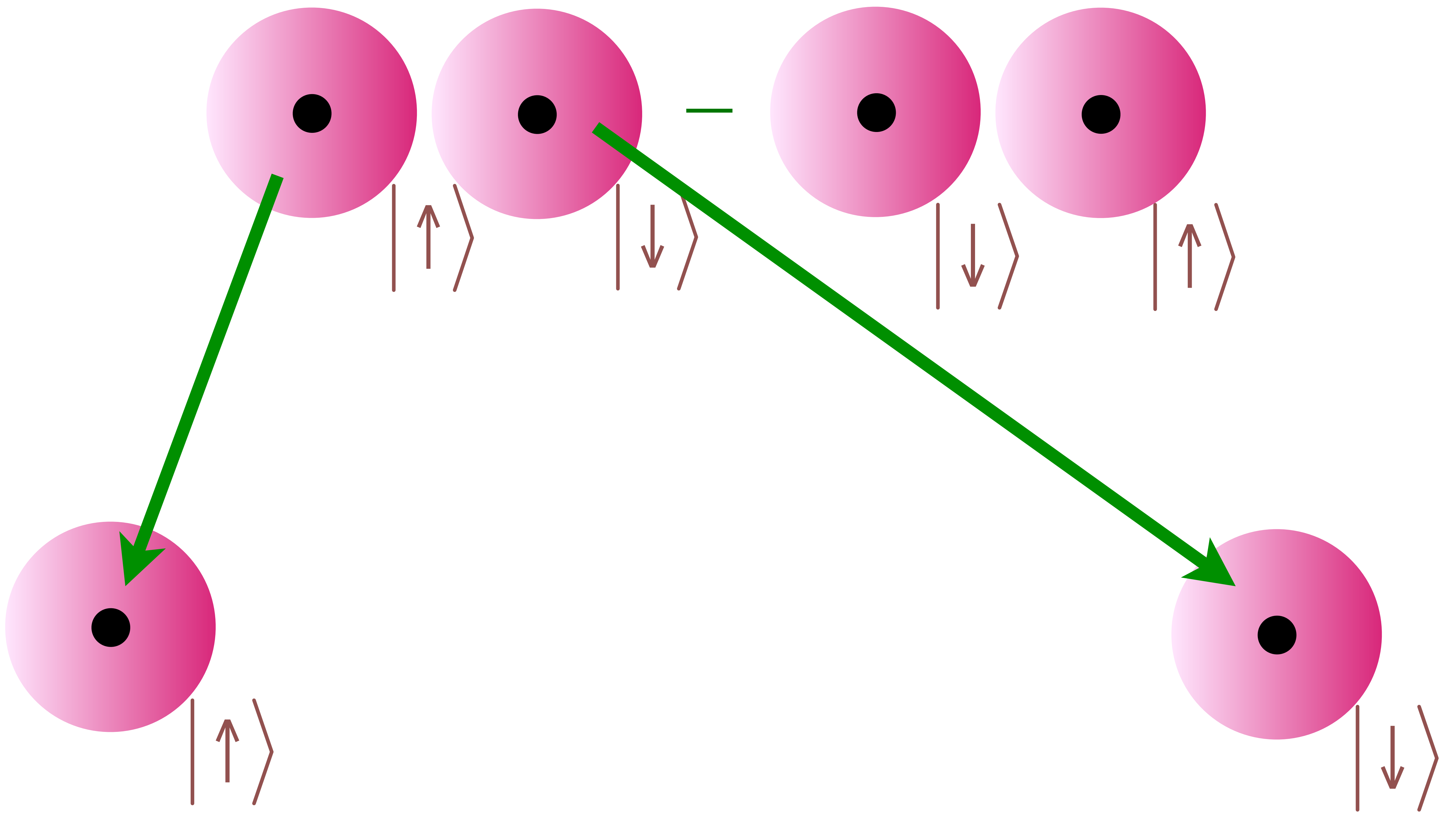


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

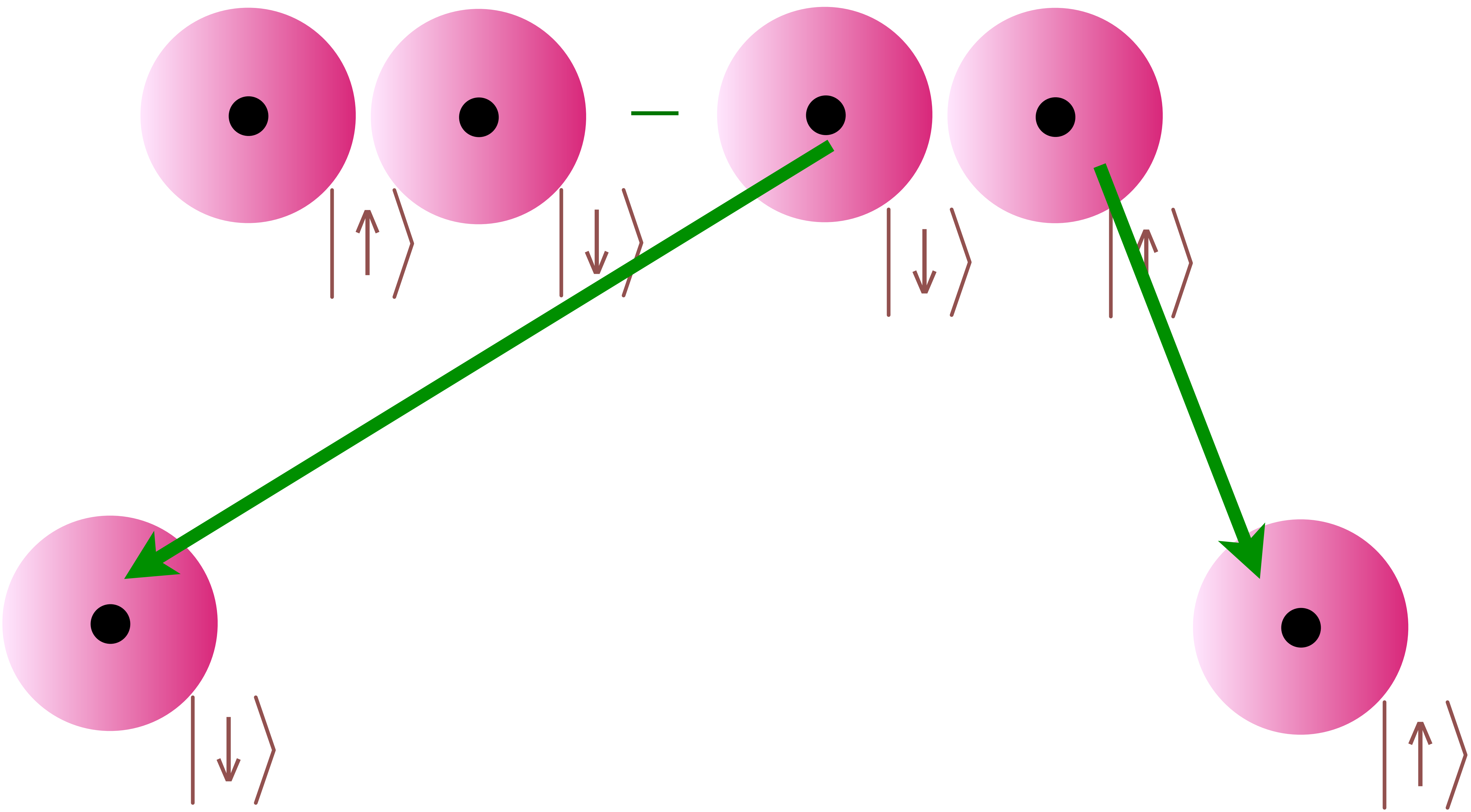
Quantum Entanglement: quantum superposition with more than one particle



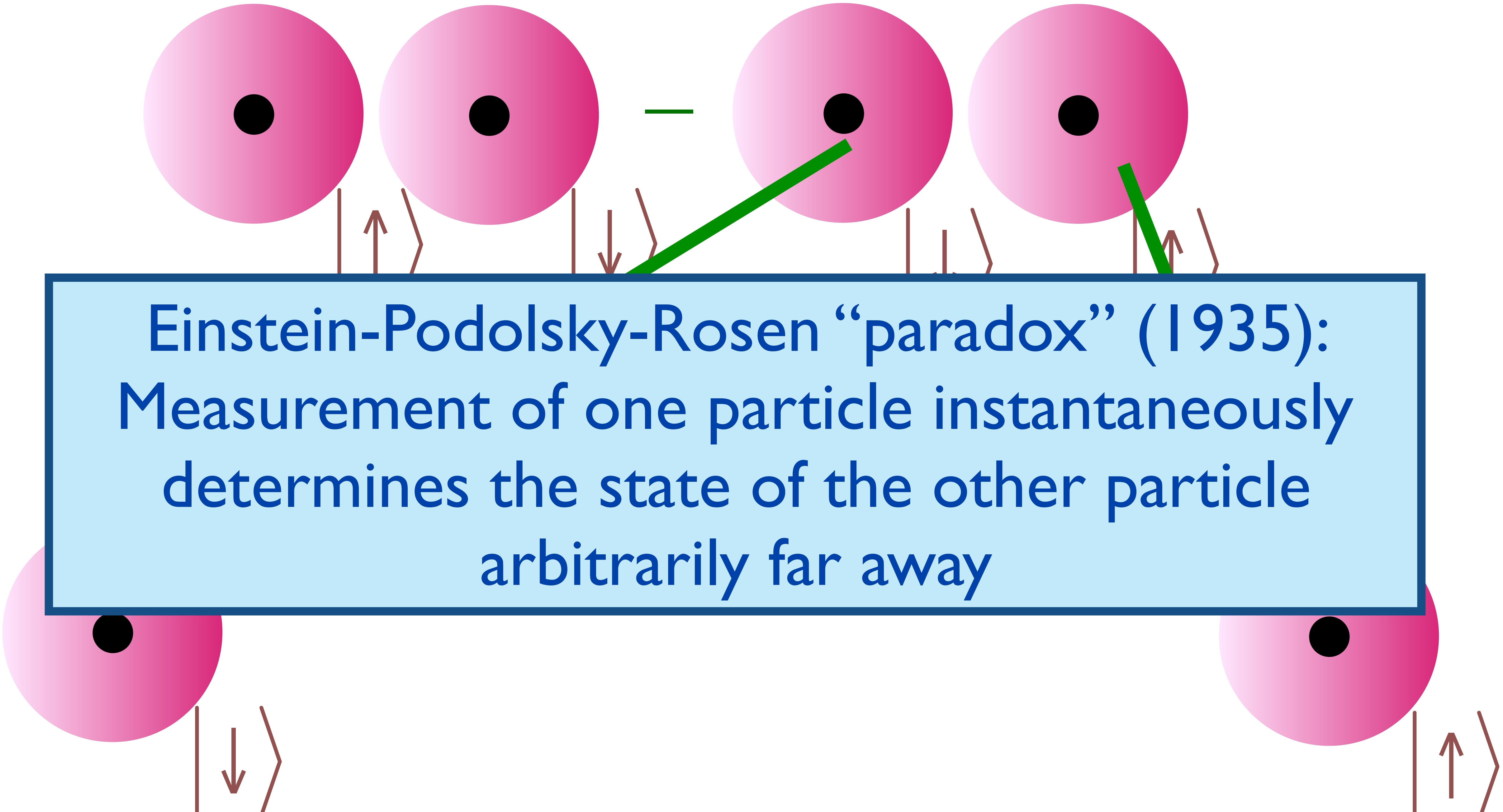
Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



Einstein-Podolsky-Rosen "paradox" (1935):
Measurement of one particle instantaneously determines the state of the other particle arbitrarily far away

Quantum entanglement

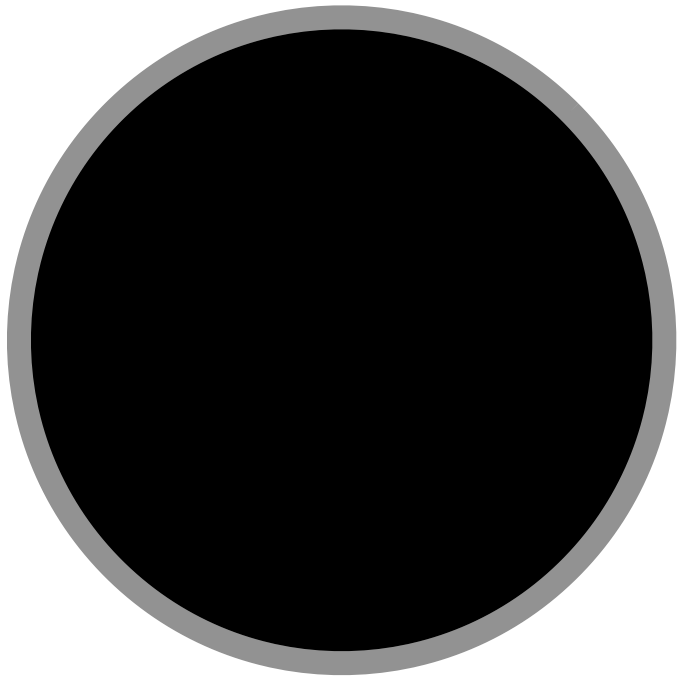
Quantum entanglement

Black holes

Black Holes

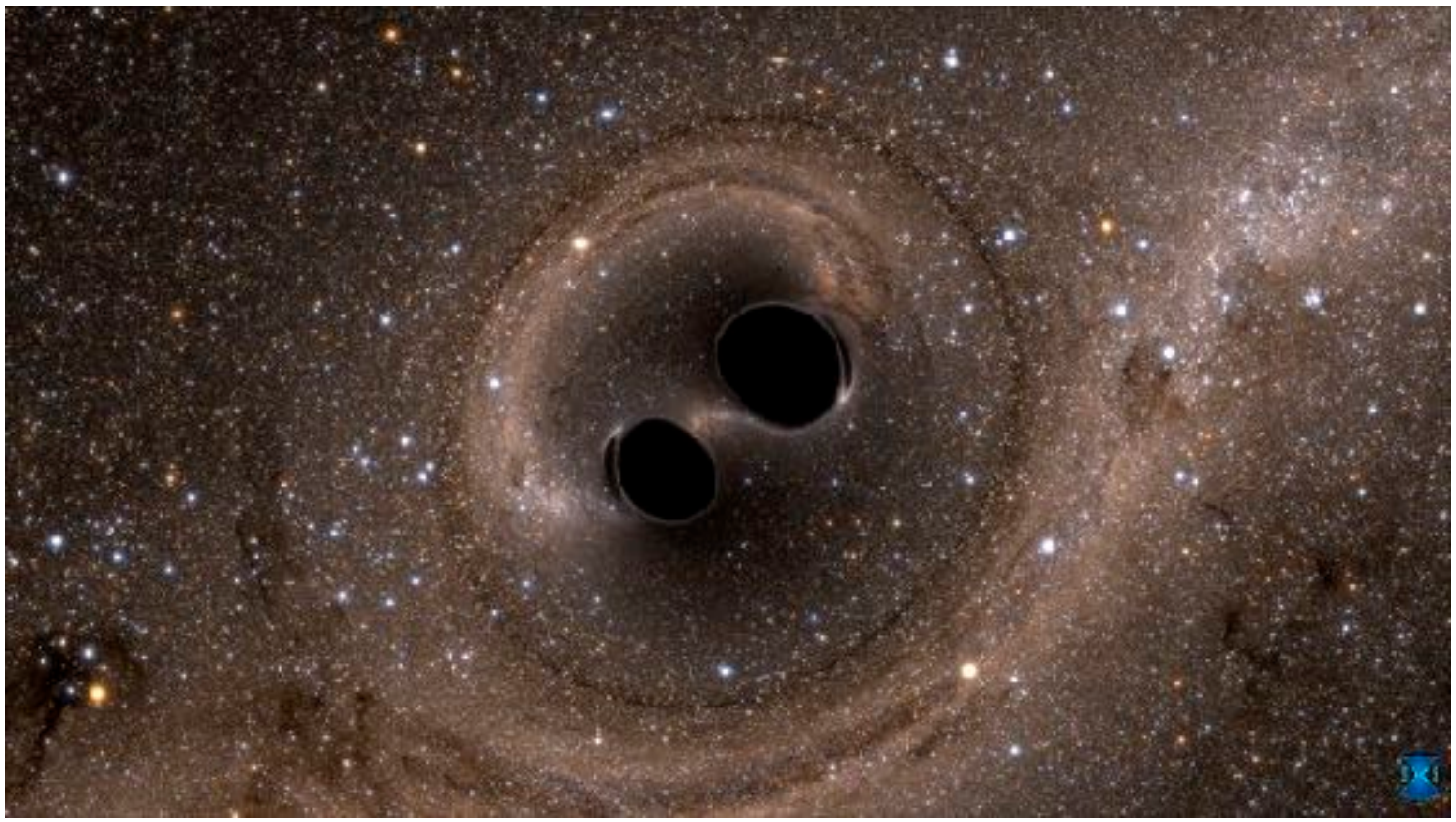
Objects so dense that light is gravitationally bound to them.

In Einstein's theory, the region inside the black hole **horizon** is disconnected from the rest of the universe.



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

On September 14, 2015, LIGO detected the merger of two black holes, each weighing about 30 solar masses, with radii of about 100 km, 1.3 billion light years away



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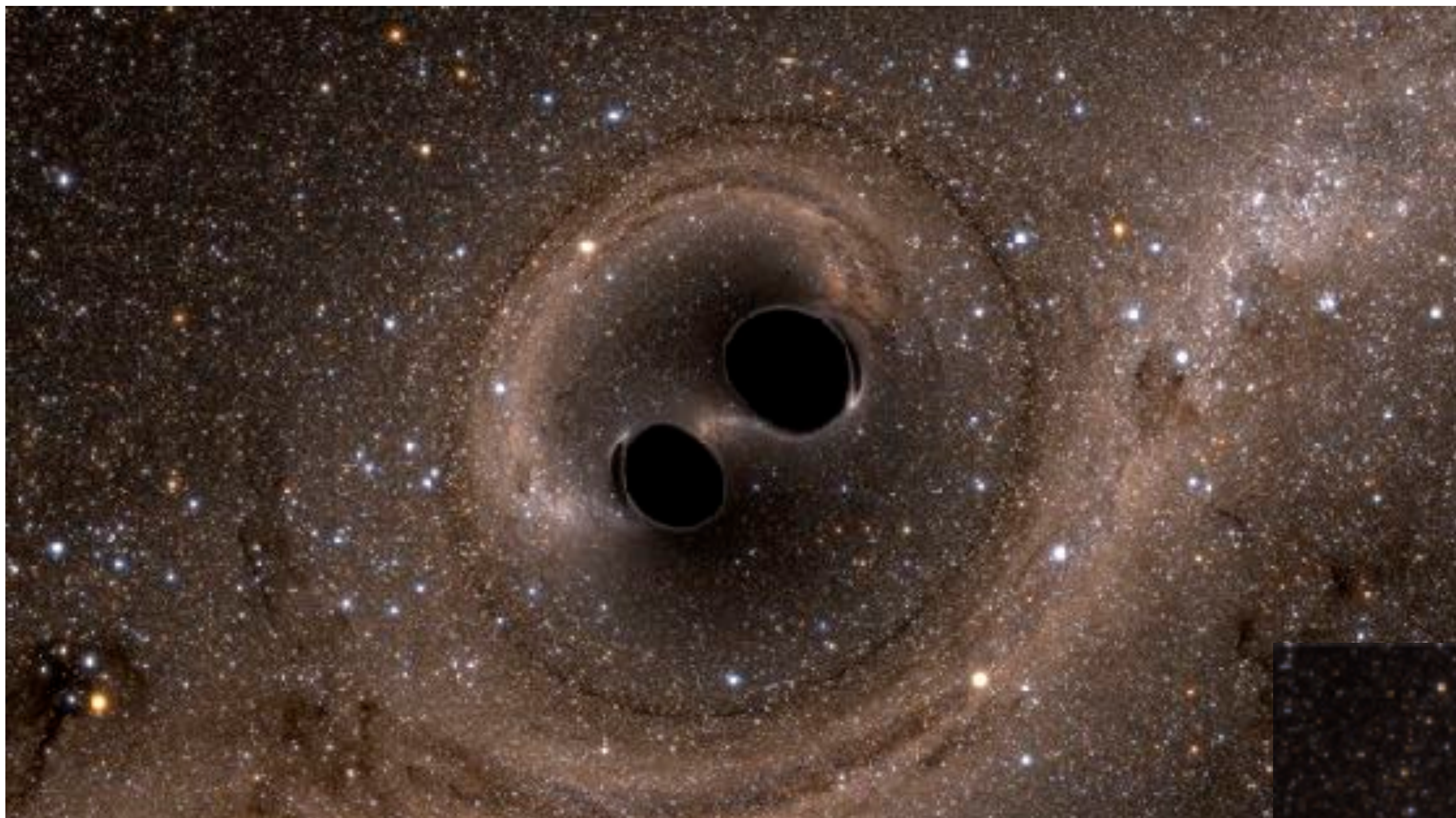
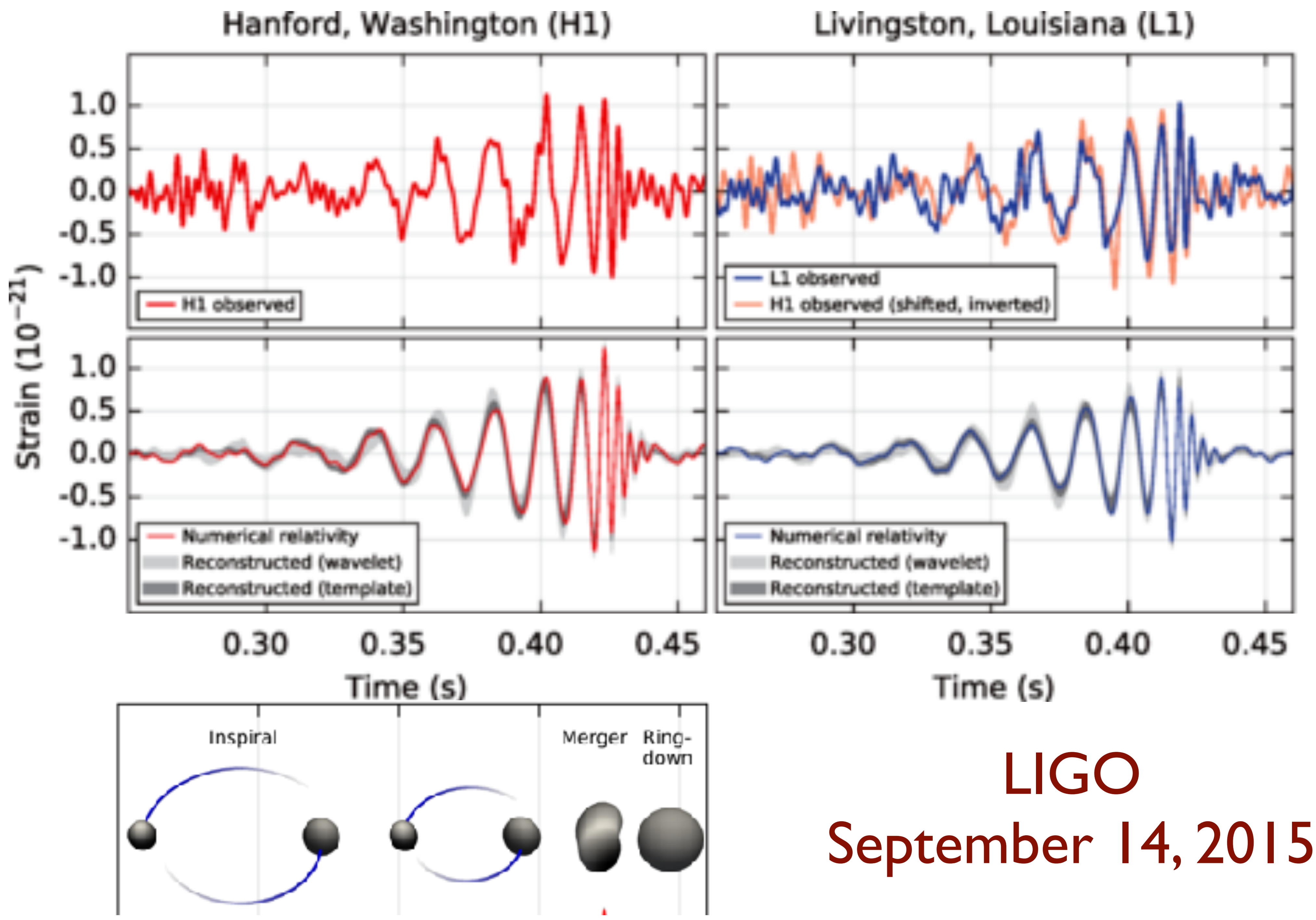


0.1 seconds later !

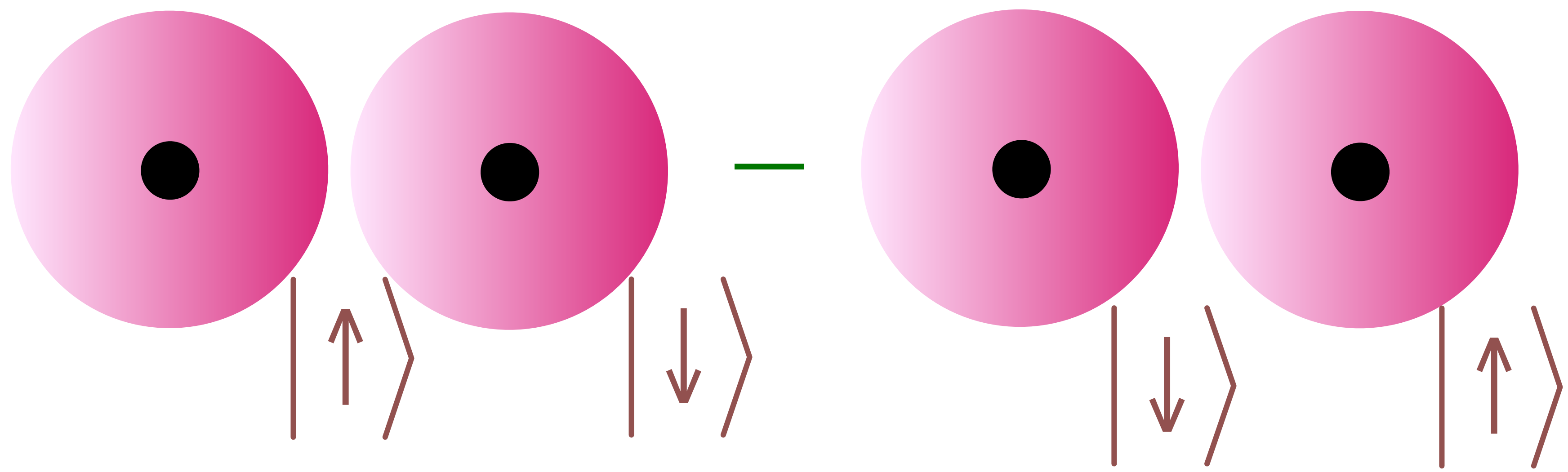


LIGO
September 14, 2015

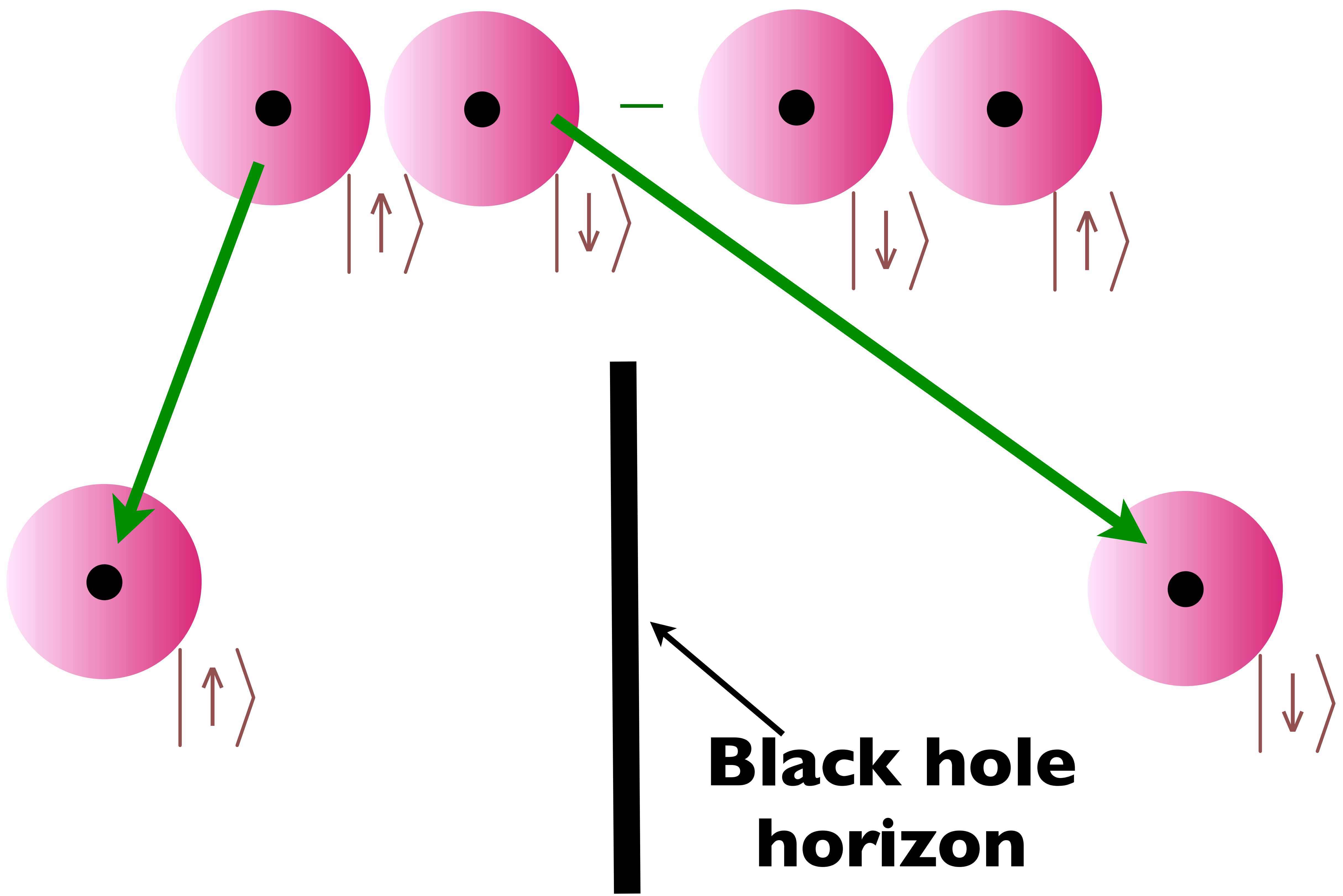
Black Holes + Quantum theory

Around 1974, Bekenstein and Hawking showed that the application of the quantum theory across a black hole horizon led to many astonishing conclusions

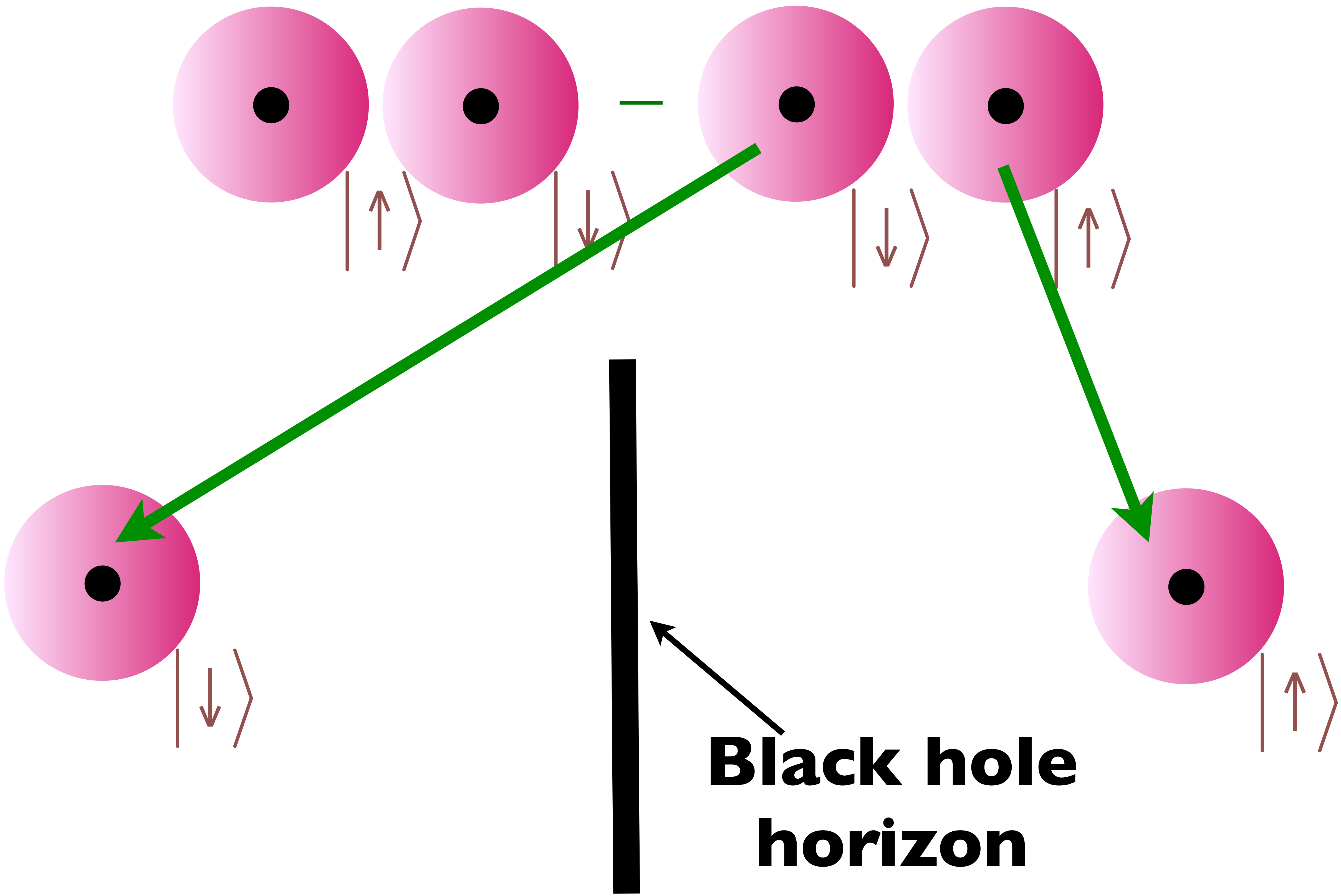
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

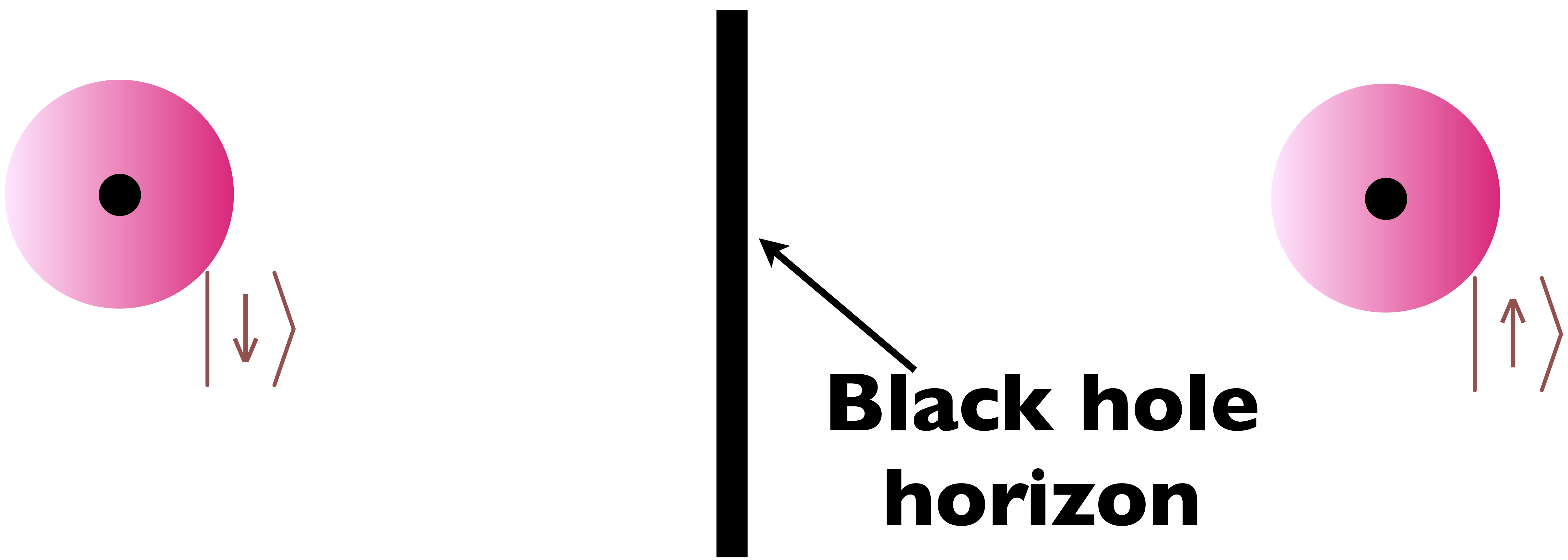


Quantum Entanglement across a black hole horizon



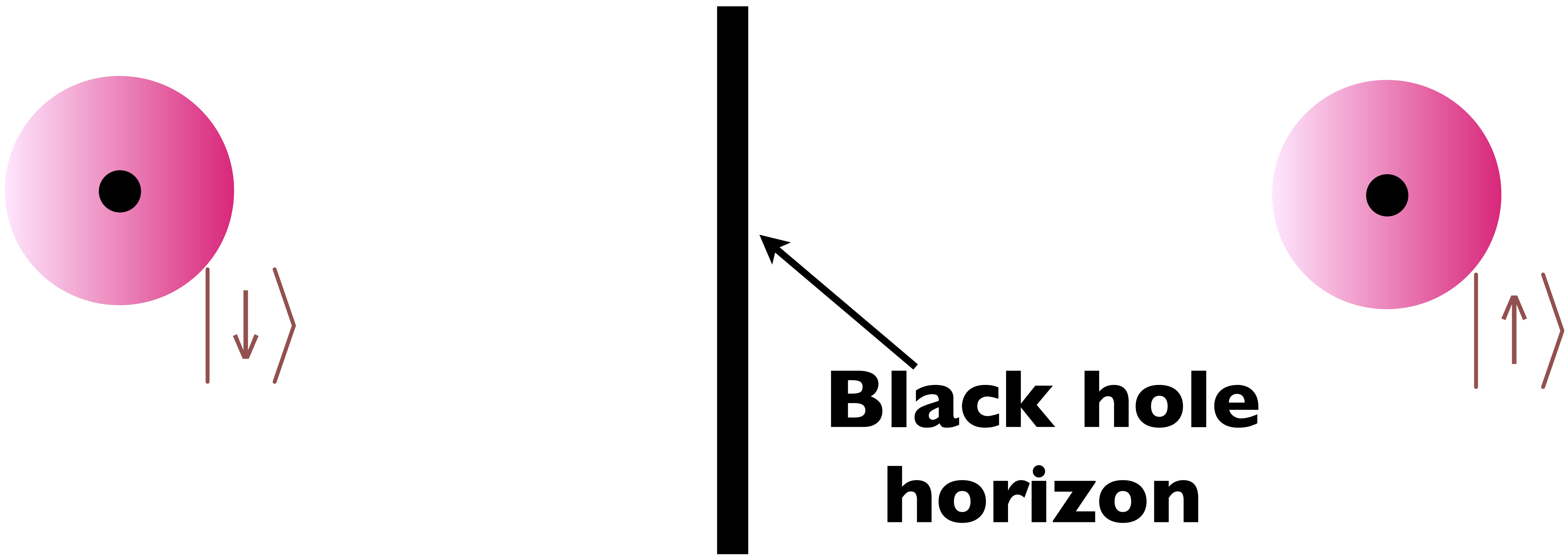
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

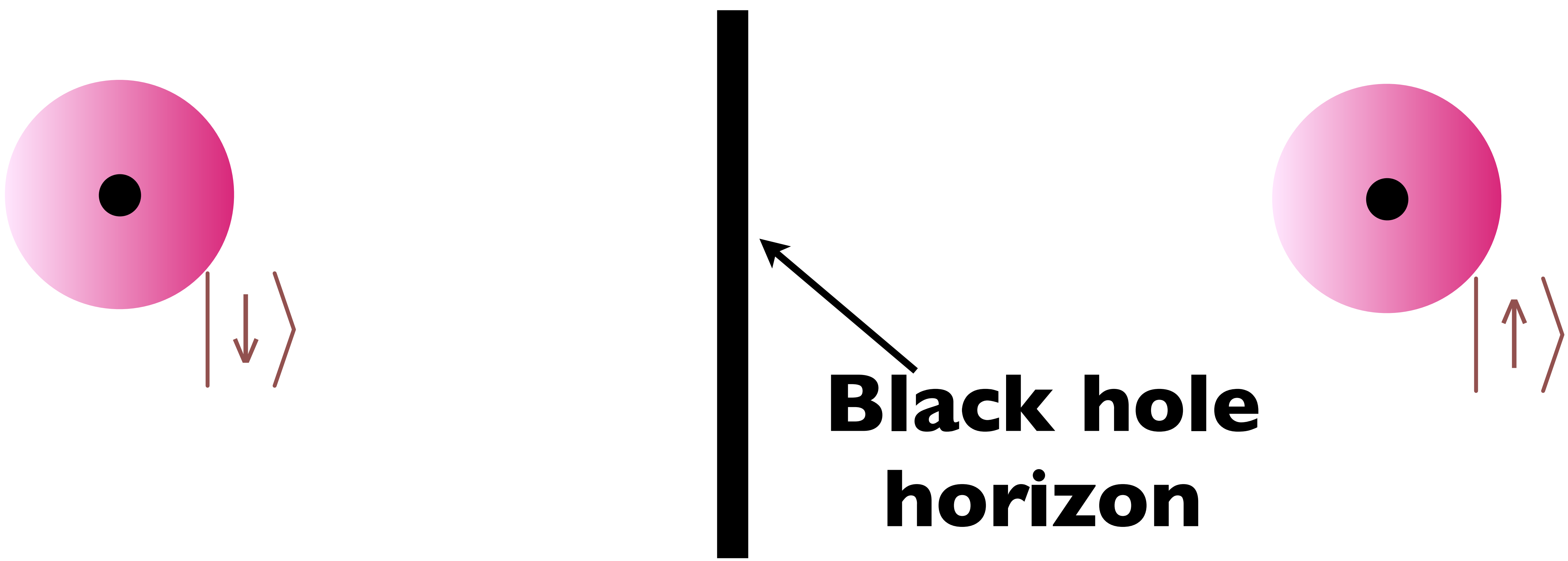
Hawking used this to show that black hole horizons have an entropy and a temperature

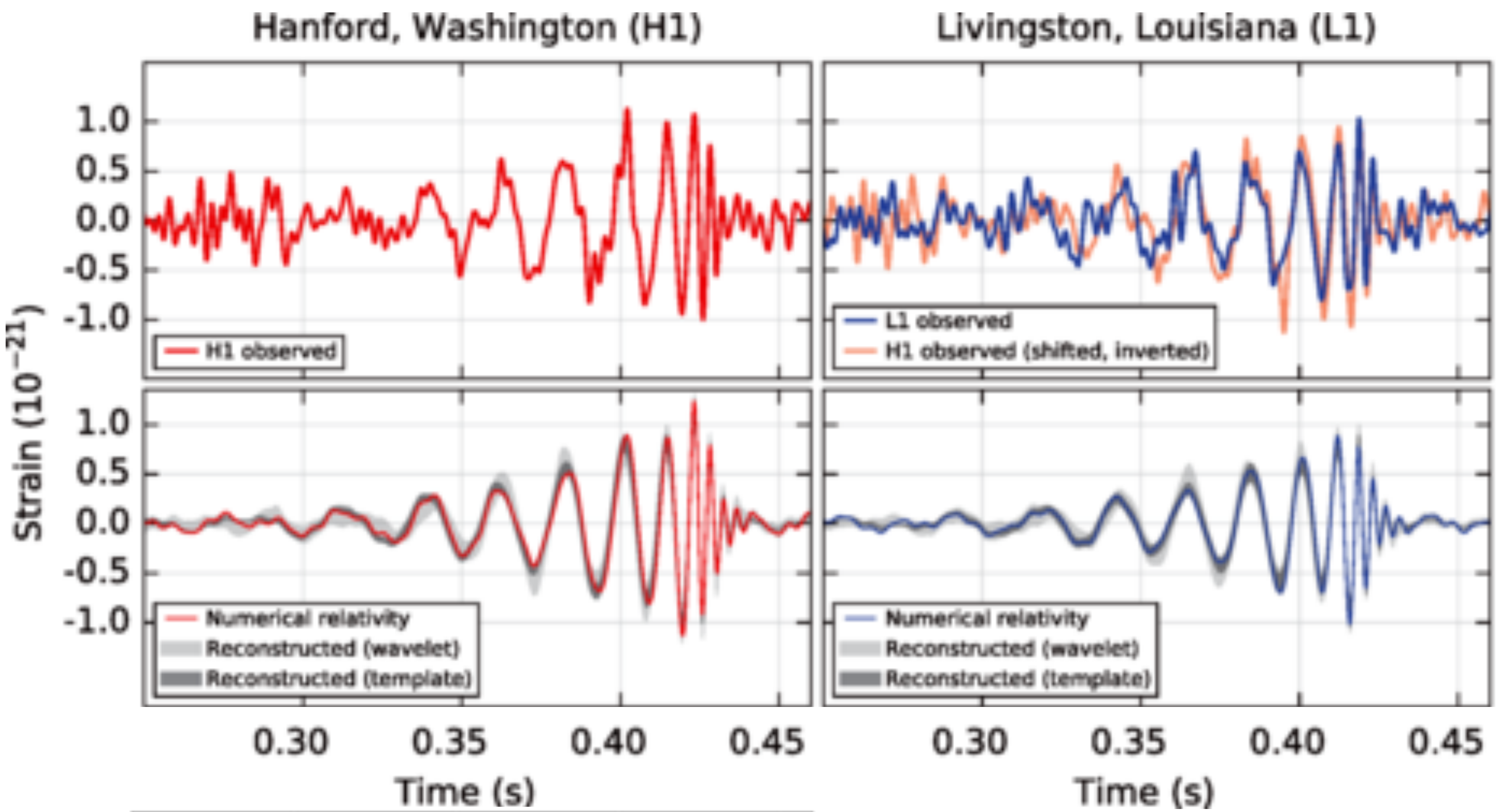


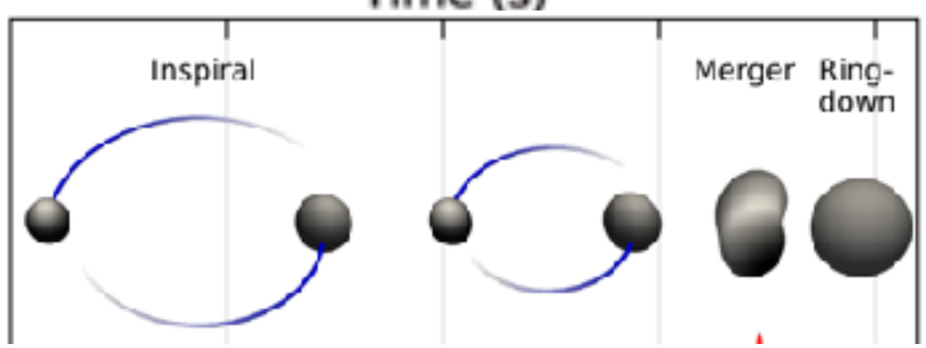
Quantum Entanglement across a black hole horizon

Hawking used this to show that black hole horizons have an entropy and a temperature

(because to an outside observer, the state of the electron inside the black hole is an unknown)







LIGO
September 14, 2015

- The Hawking temperature, T_H influences the radiation from the black hole at the very last stages of the ring-down (not observed so far). The ring-down (approach to thermal equilibrium) happens very rapidly in a time $\sim \dfrac{\hbar}{k_B T_K} \sim 8$ milliseconds.

Quantum entanglement

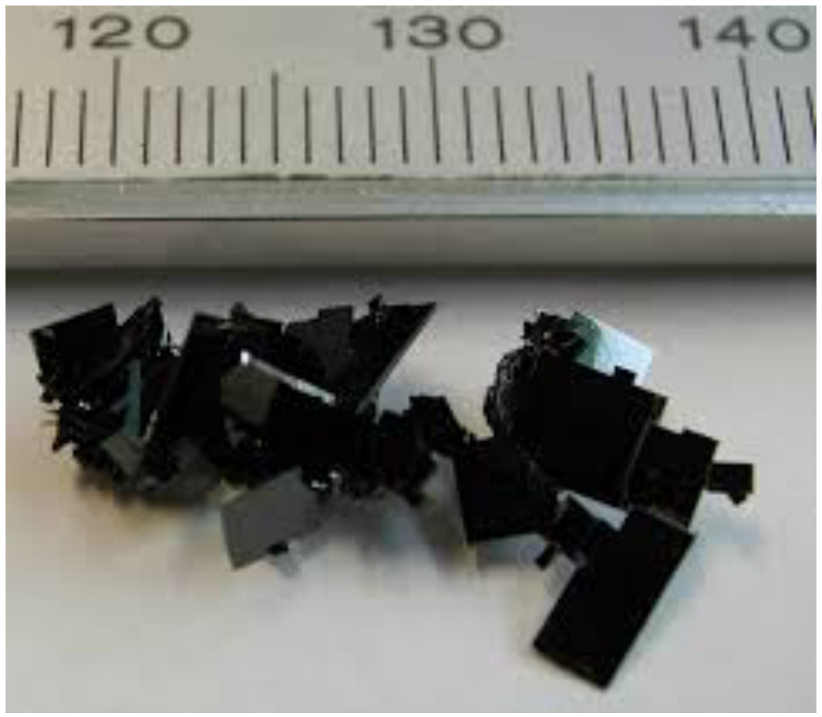
Black holes

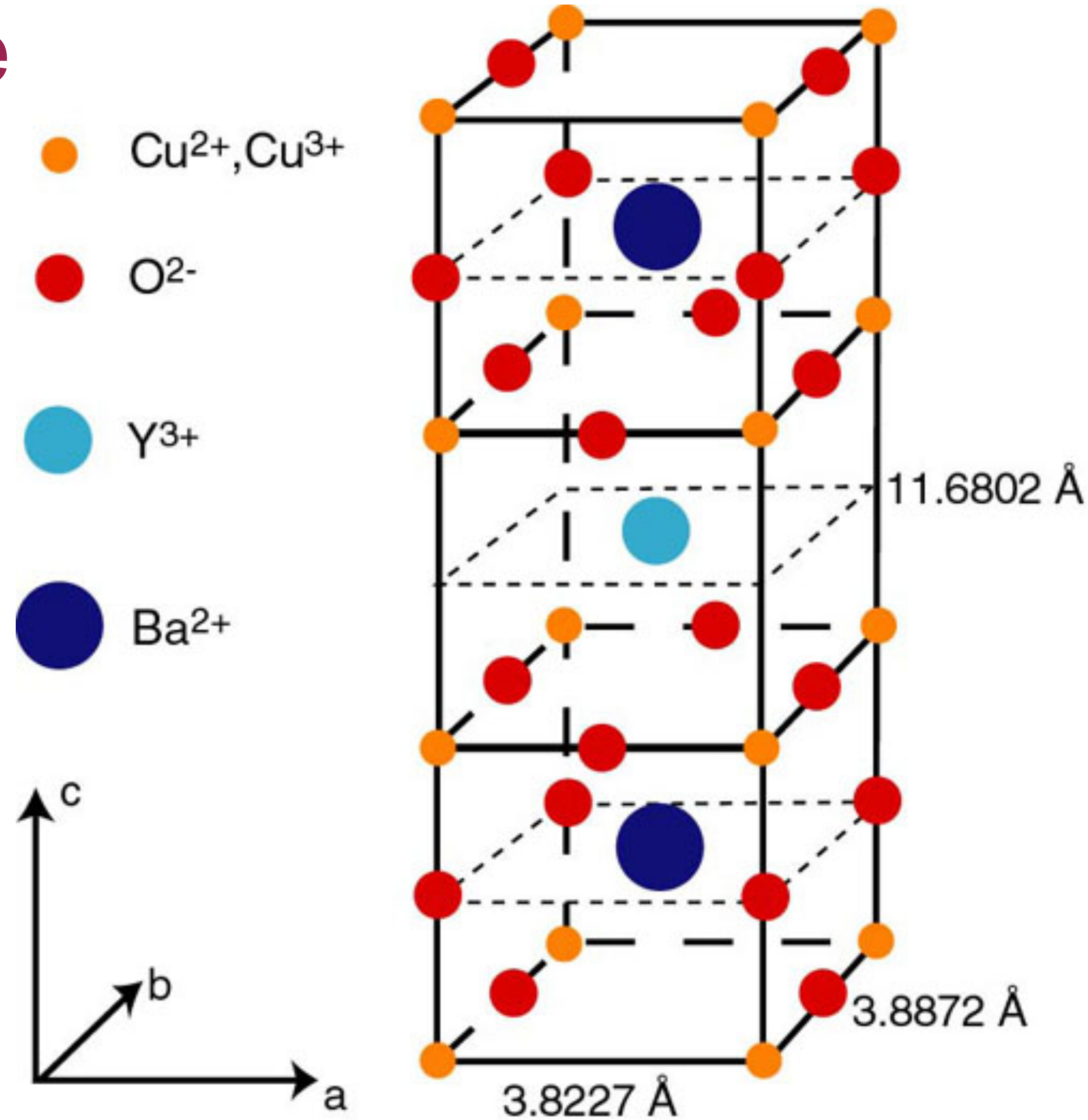
Quantum entanglement

Black holes

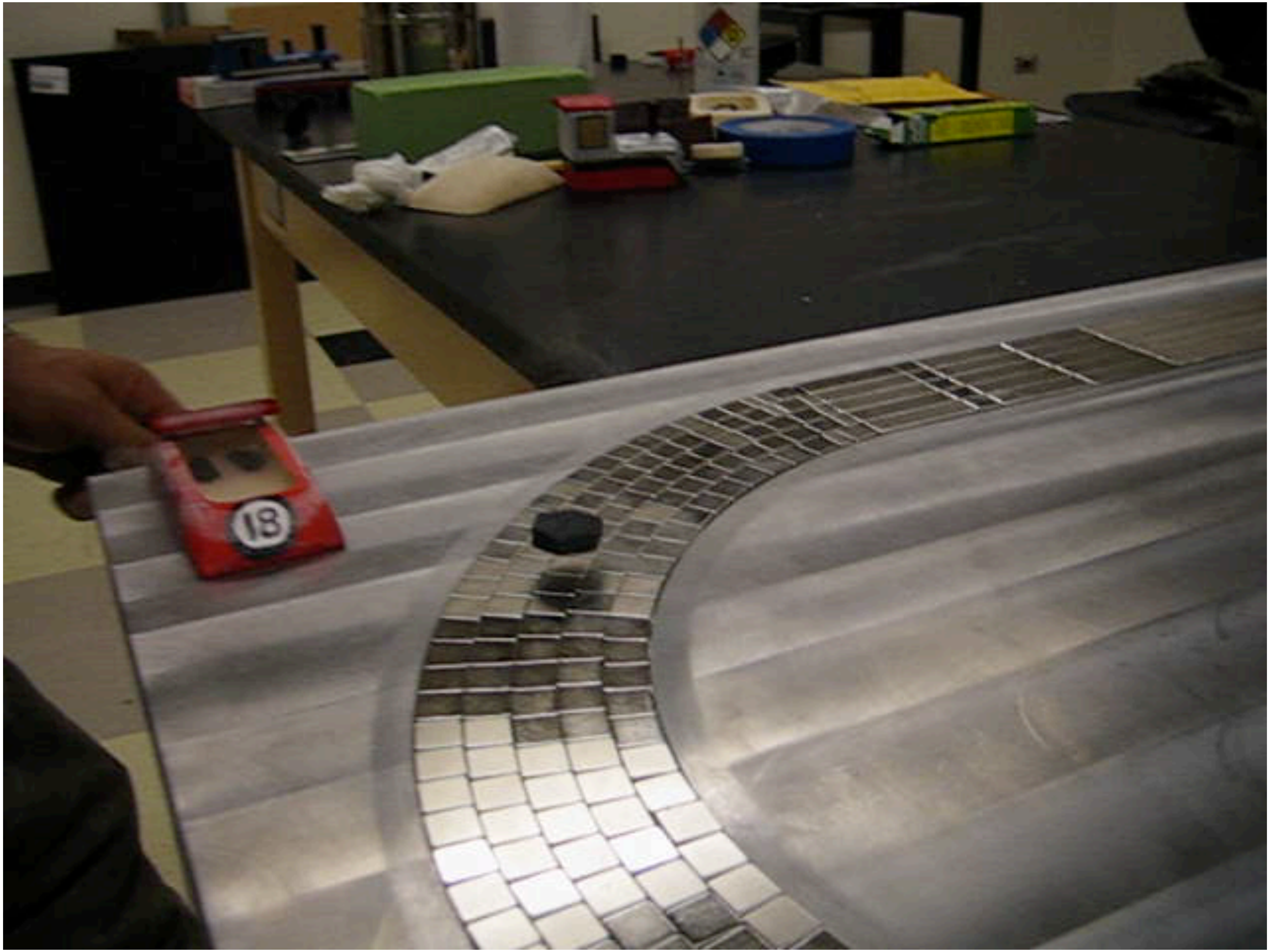
Strange metals

High temperature superconductors





$$YBa_2Cu_3O_{6+x}$$



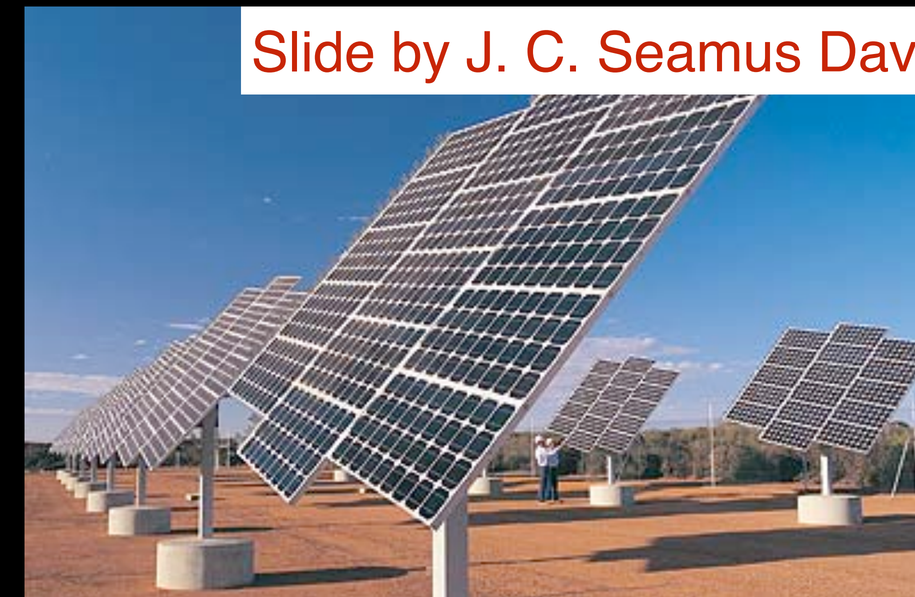
Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

Slide by J. C. Seamus Davis

Power Efficiency/Capacity/Stability

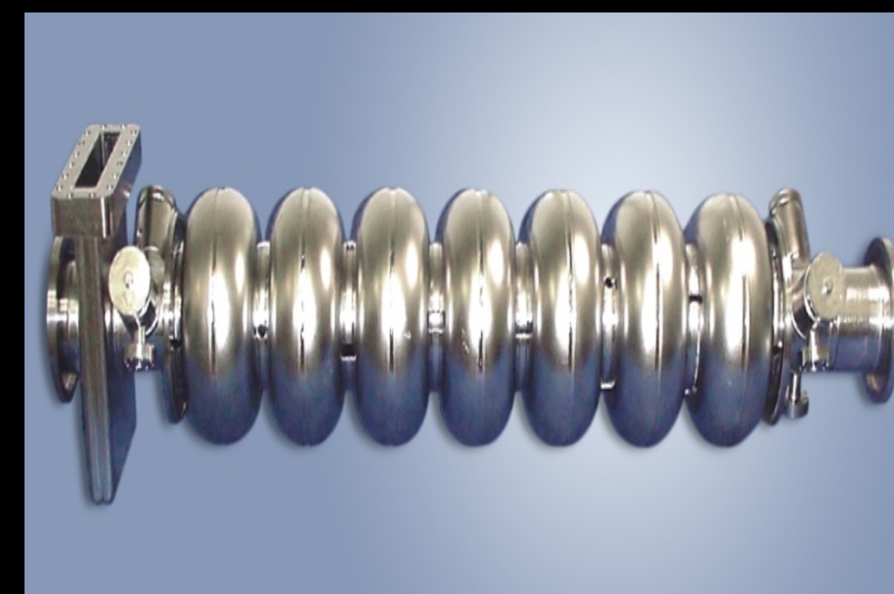
Power Bottlenecks



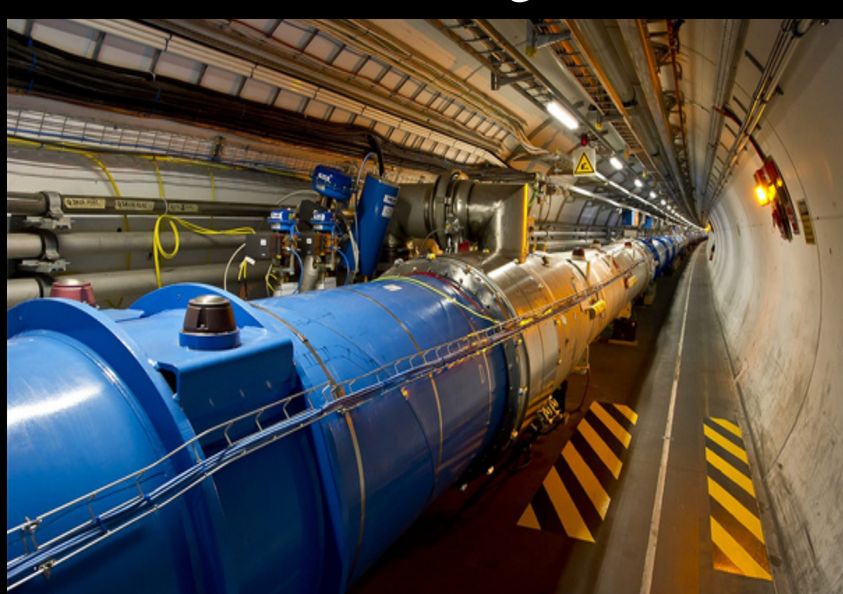
Accommodate Renewable Power

Efficient Rotating Machines

Information Technology



Next Generation HEP

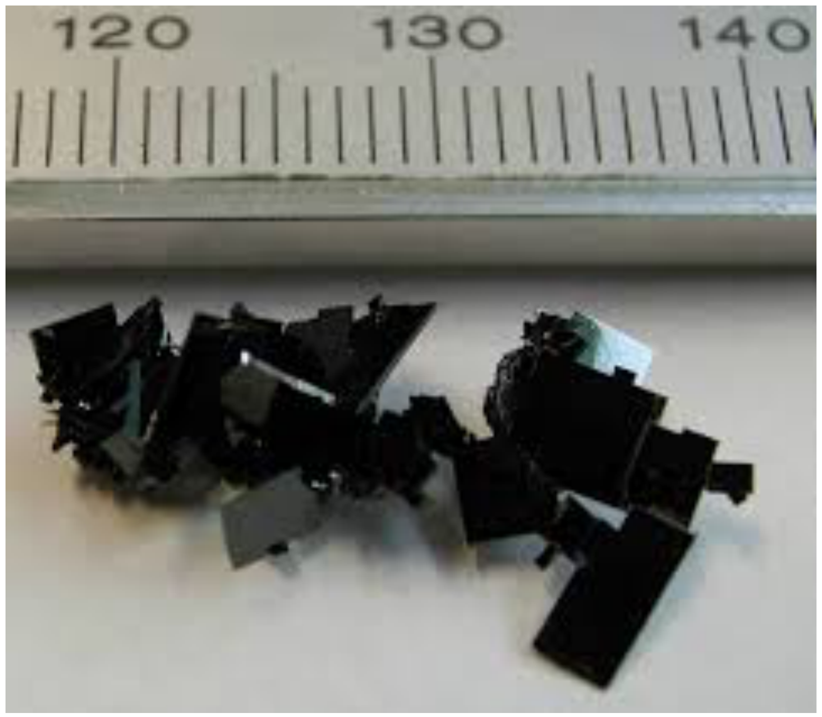


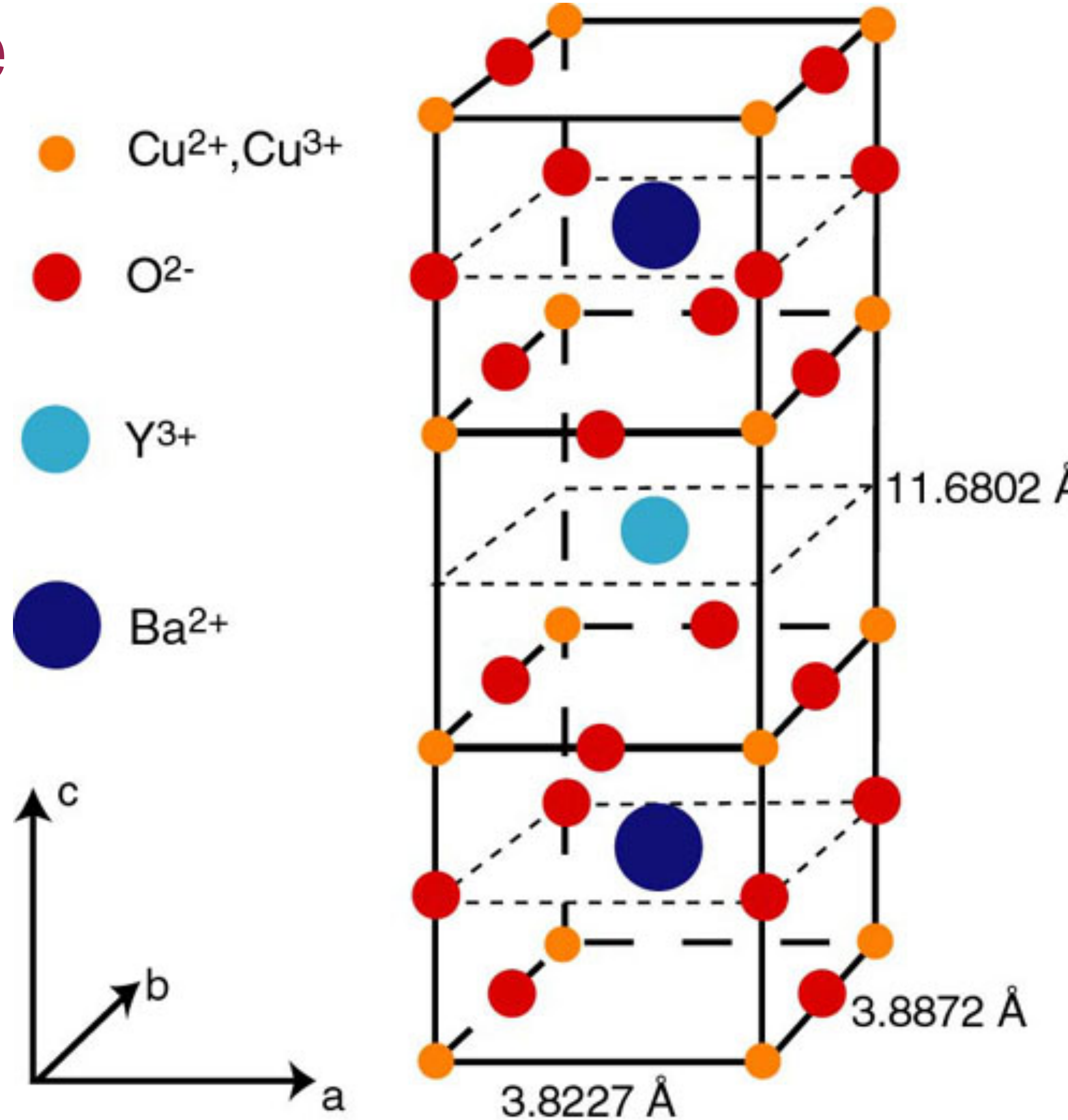
Ultra-High Magnetic Fields

Medical

Transport

High temperature superconductors





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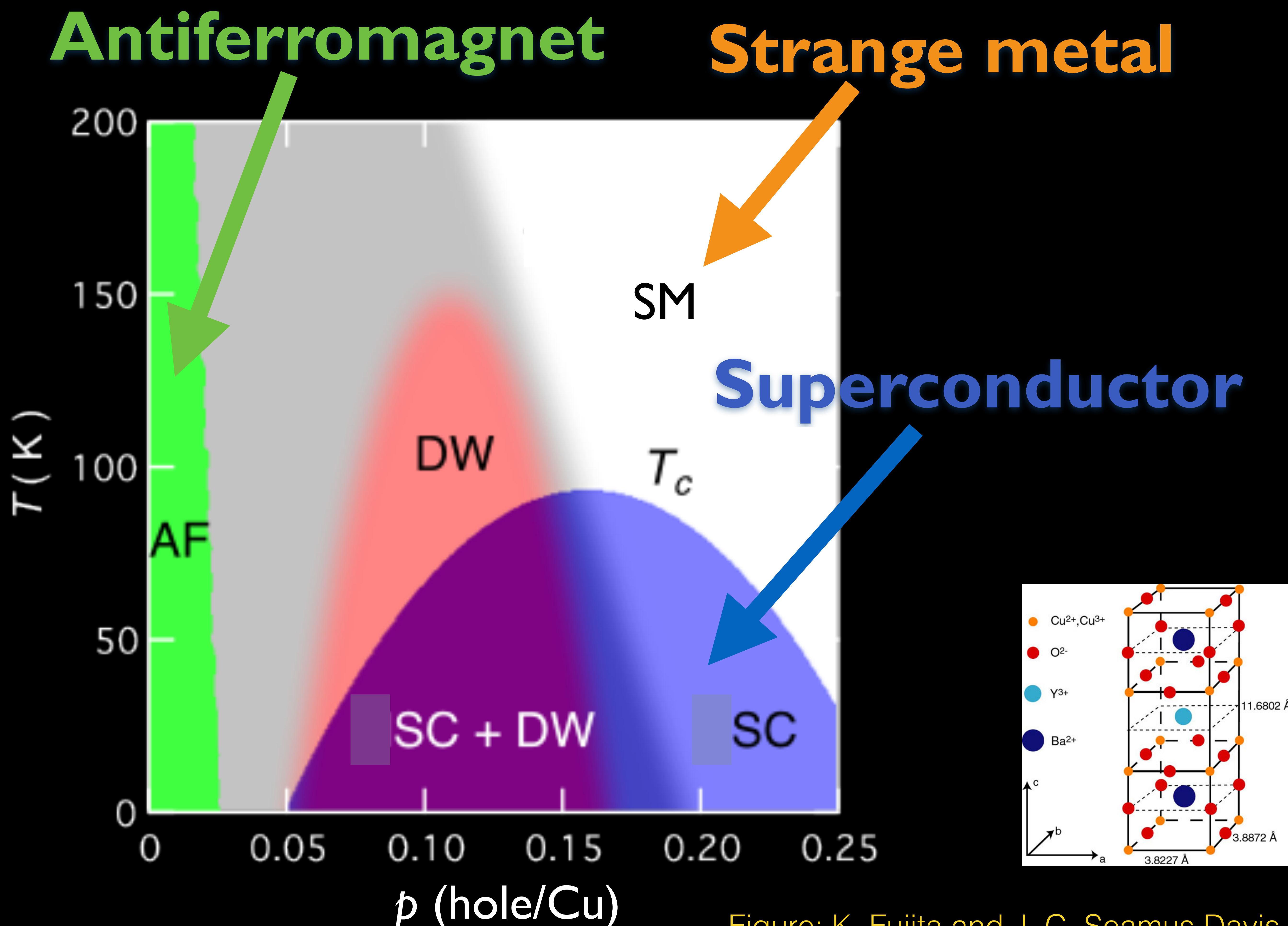
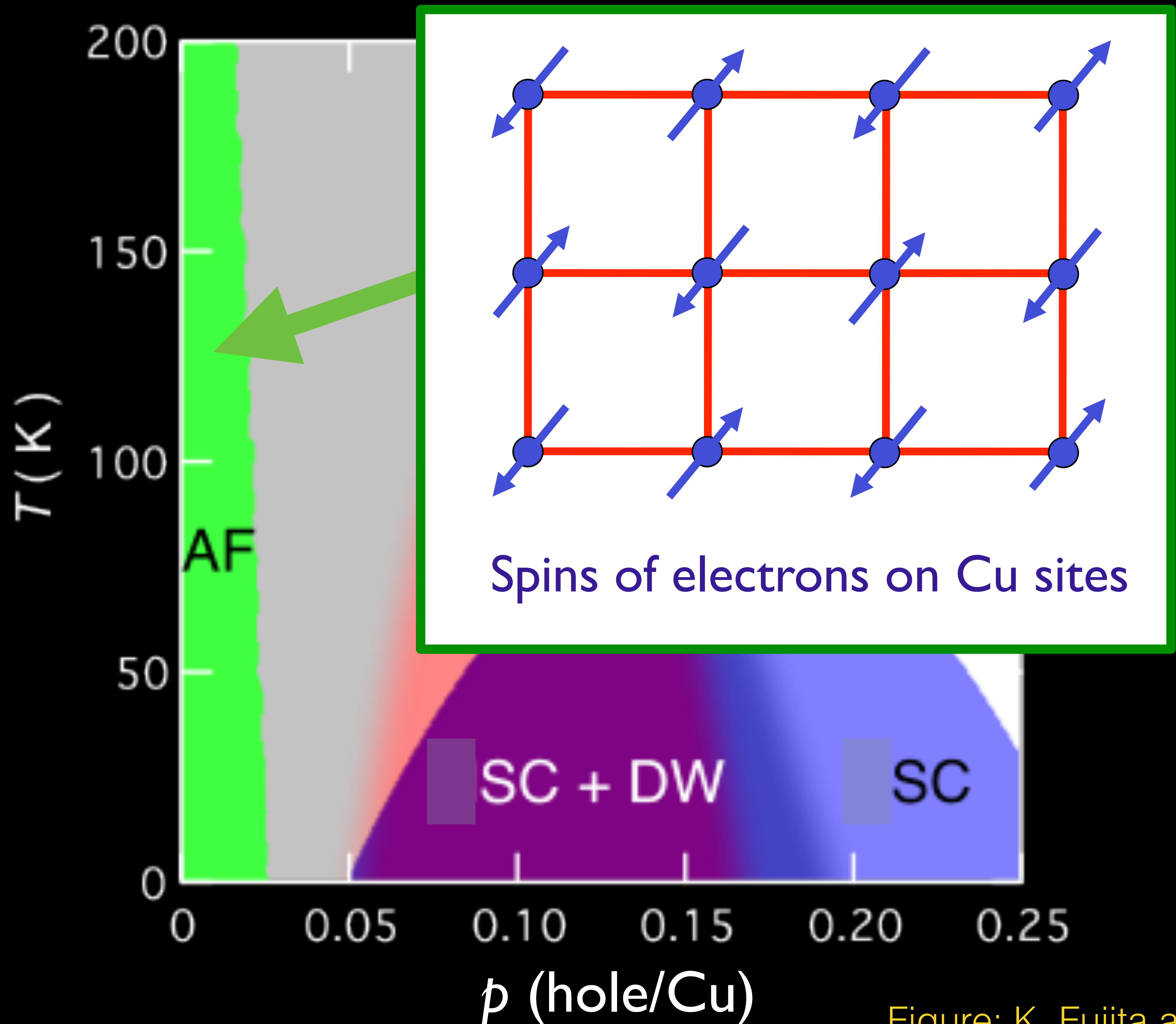


Figure: K. Fujita and J. C. Seamus Davis

Antiferromagnet



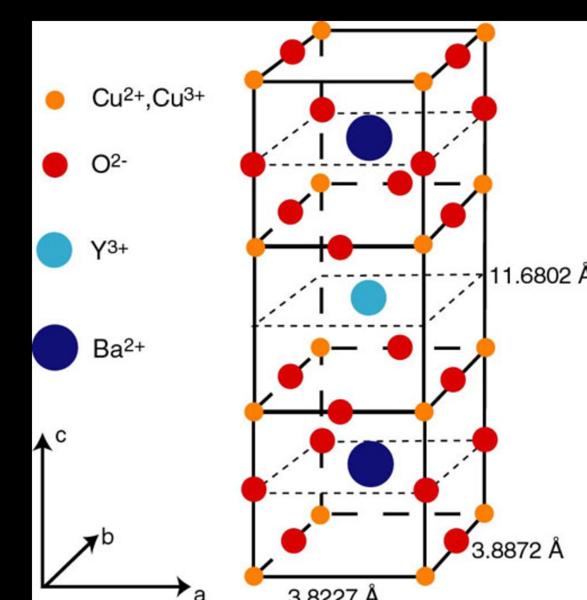
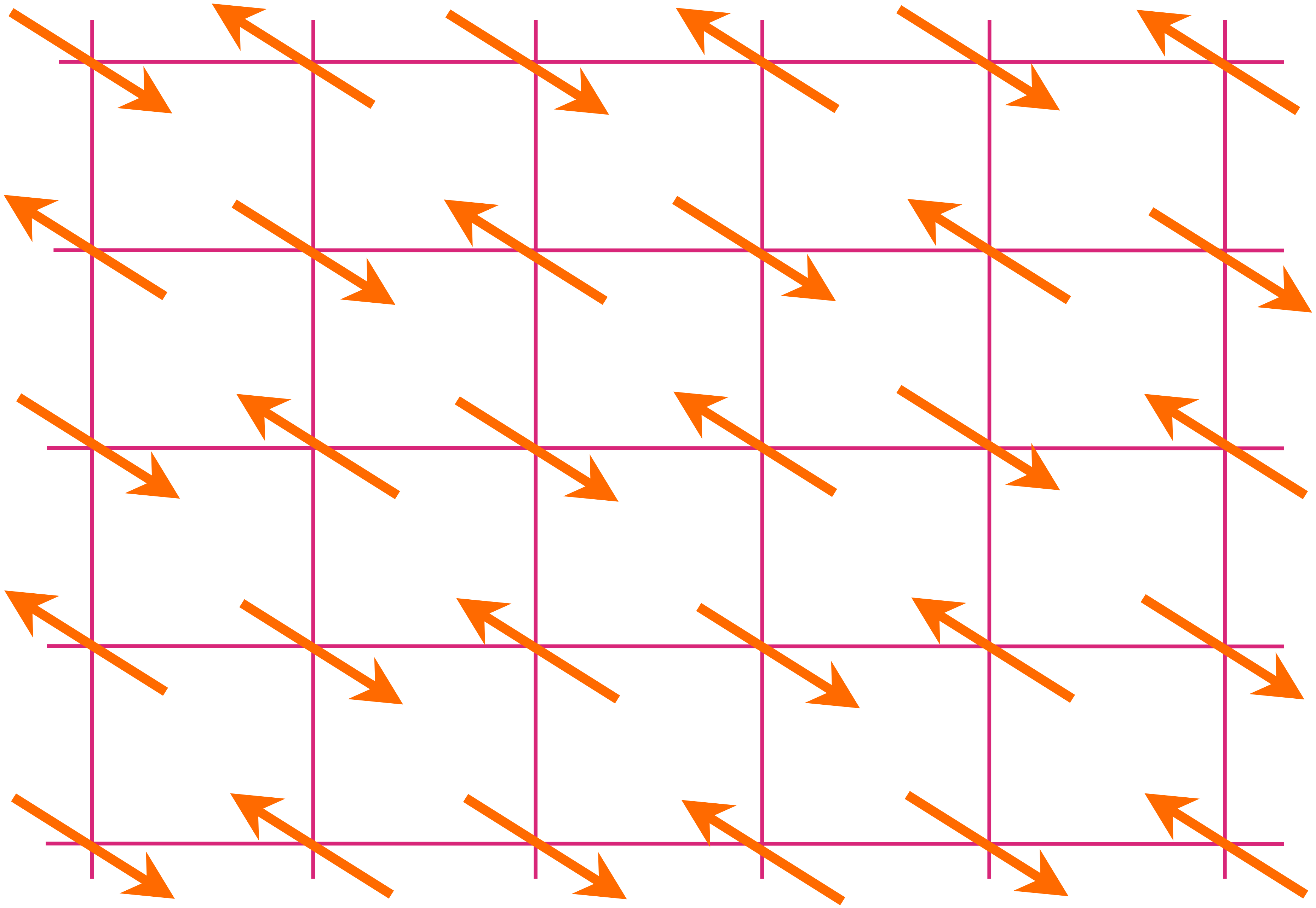
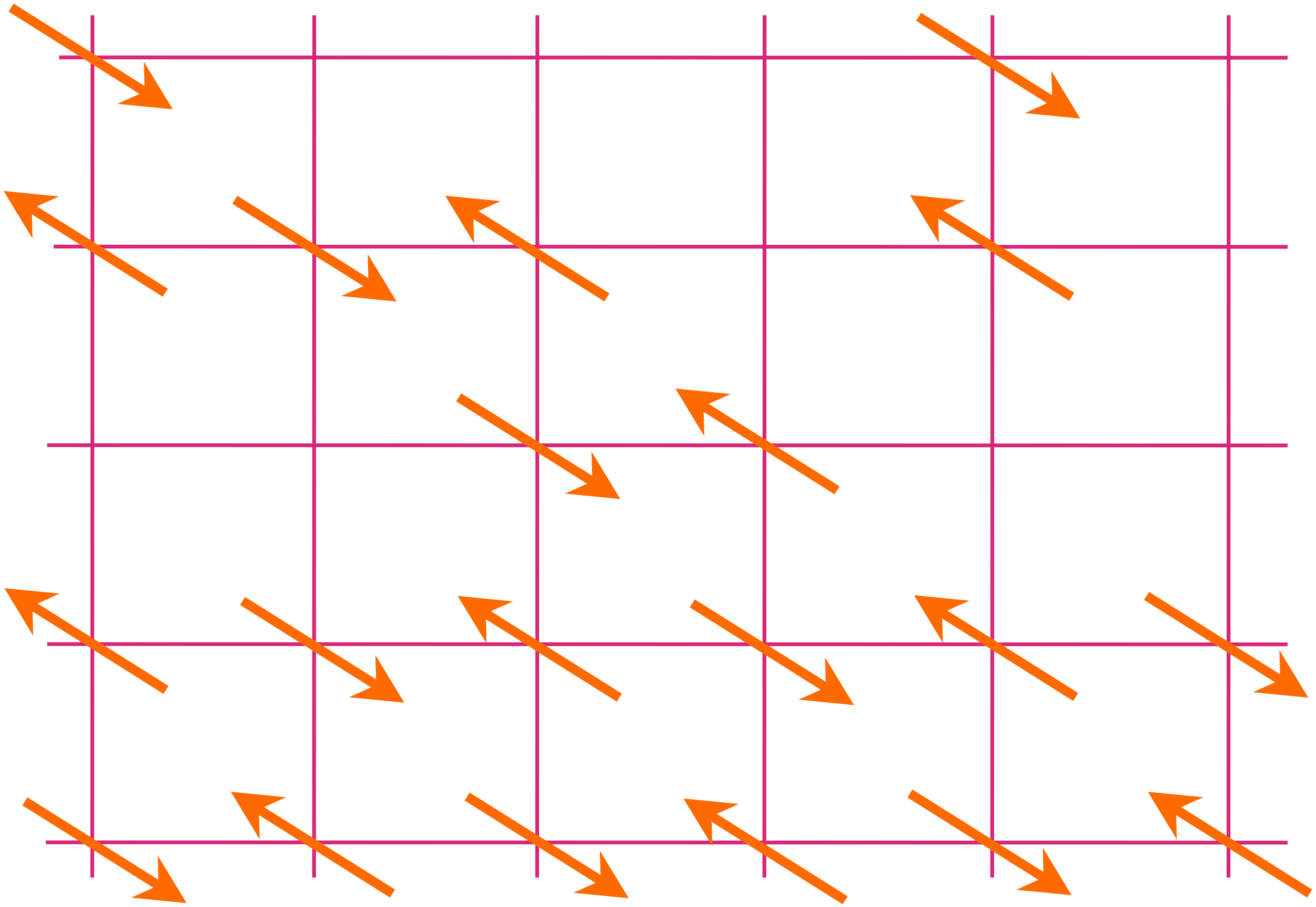


Figure: K. Fujita and J. C. Seamus Davis

Square lattice of Cu sites

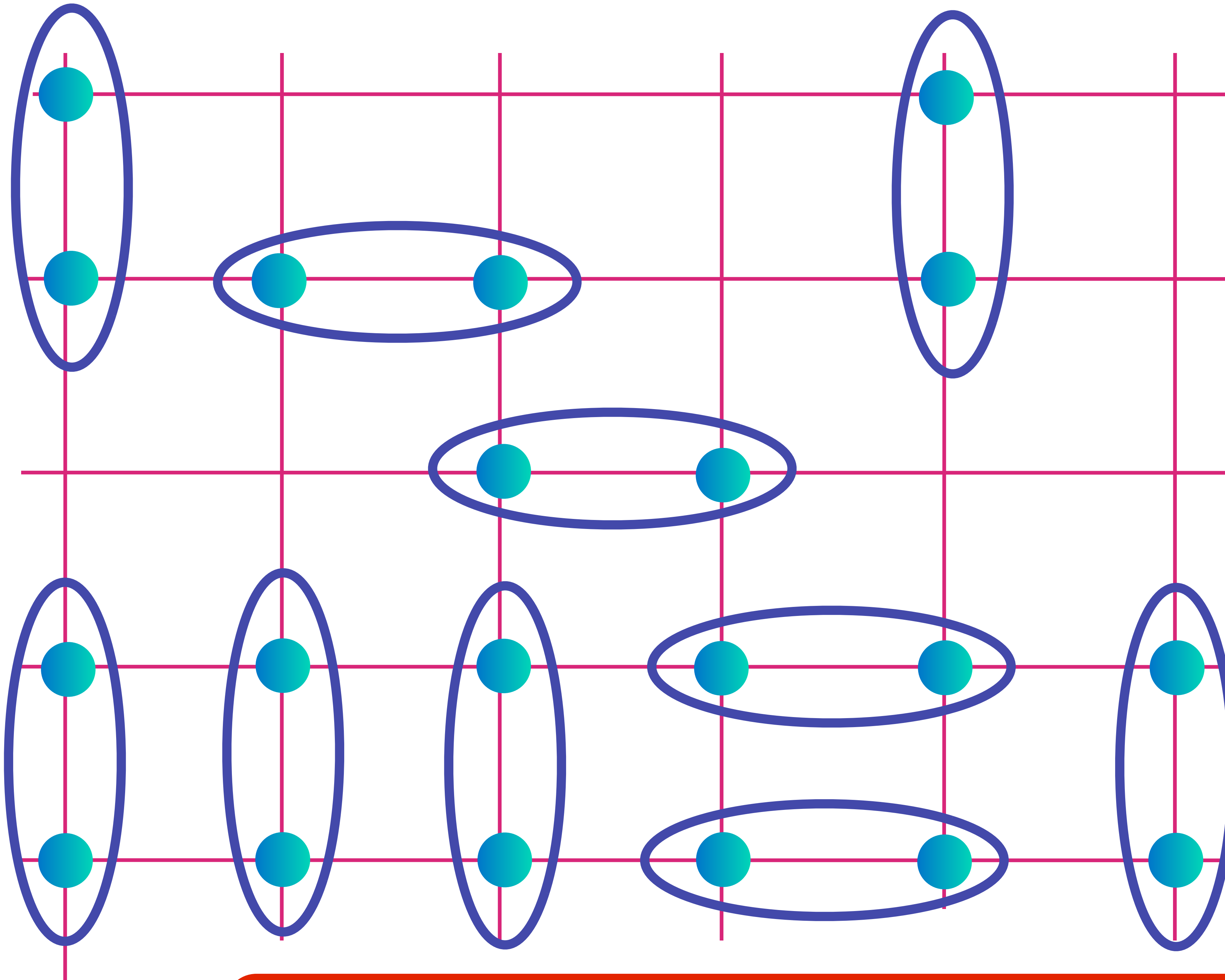


Square lattice of Cu sites

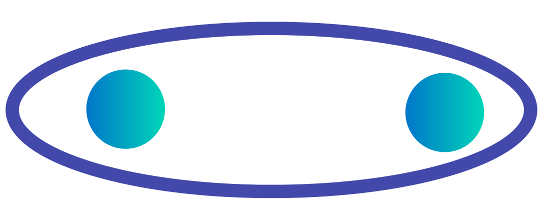


Remove density
p electrons

Square lattice of Cu sites

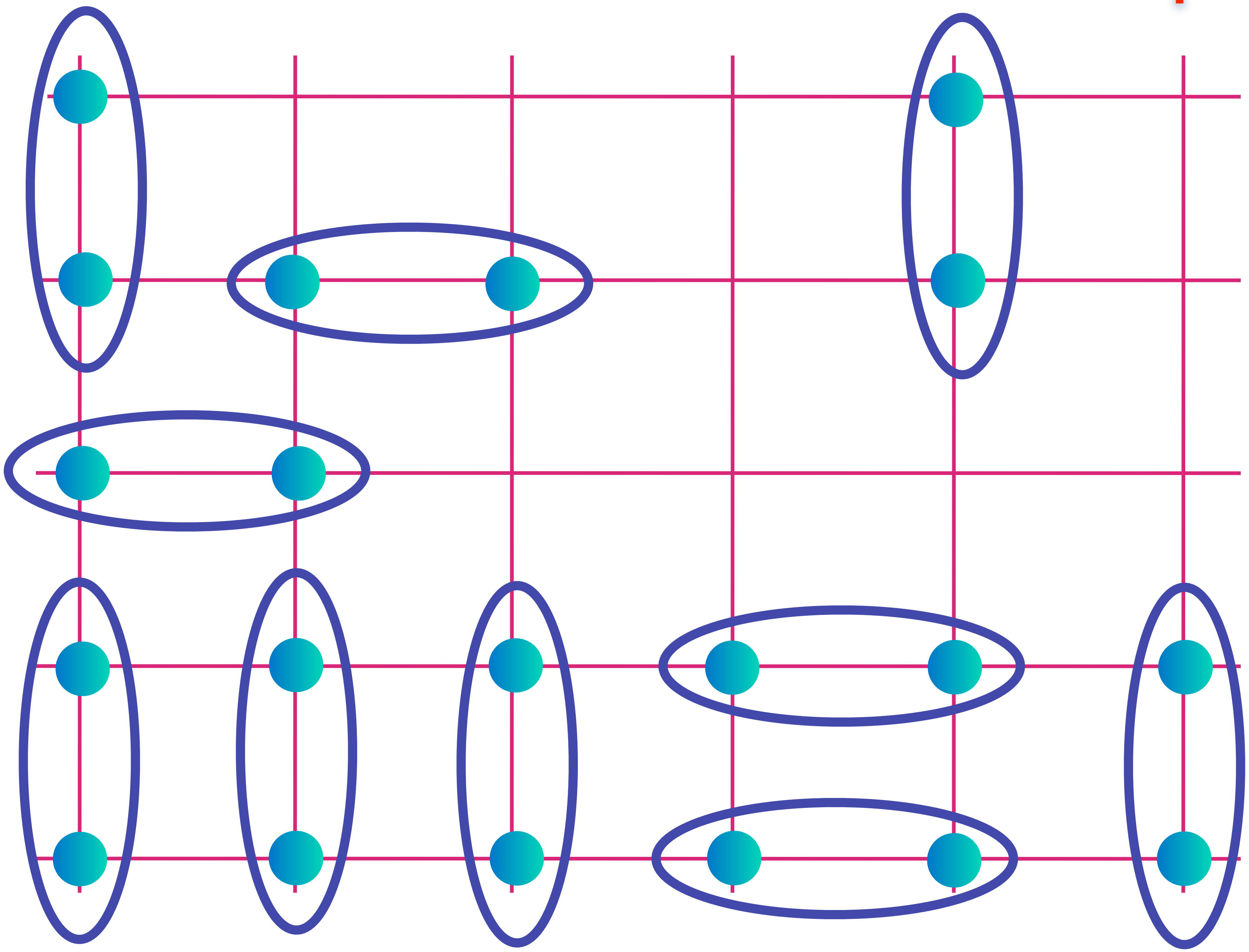


Electrons entangle in ("Cooper") pairs into chemical bonds

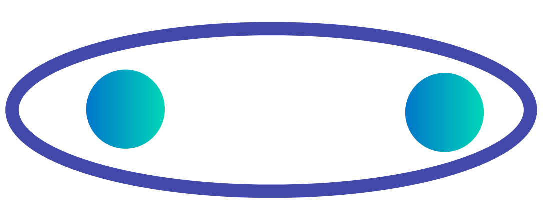
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Square lattice of Cu sites

Superconductivity



Cooper pairs form quantum superpositions at different locations: "Bose-Einstein condensation" in which all pairs are "everywhere at the same time"

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

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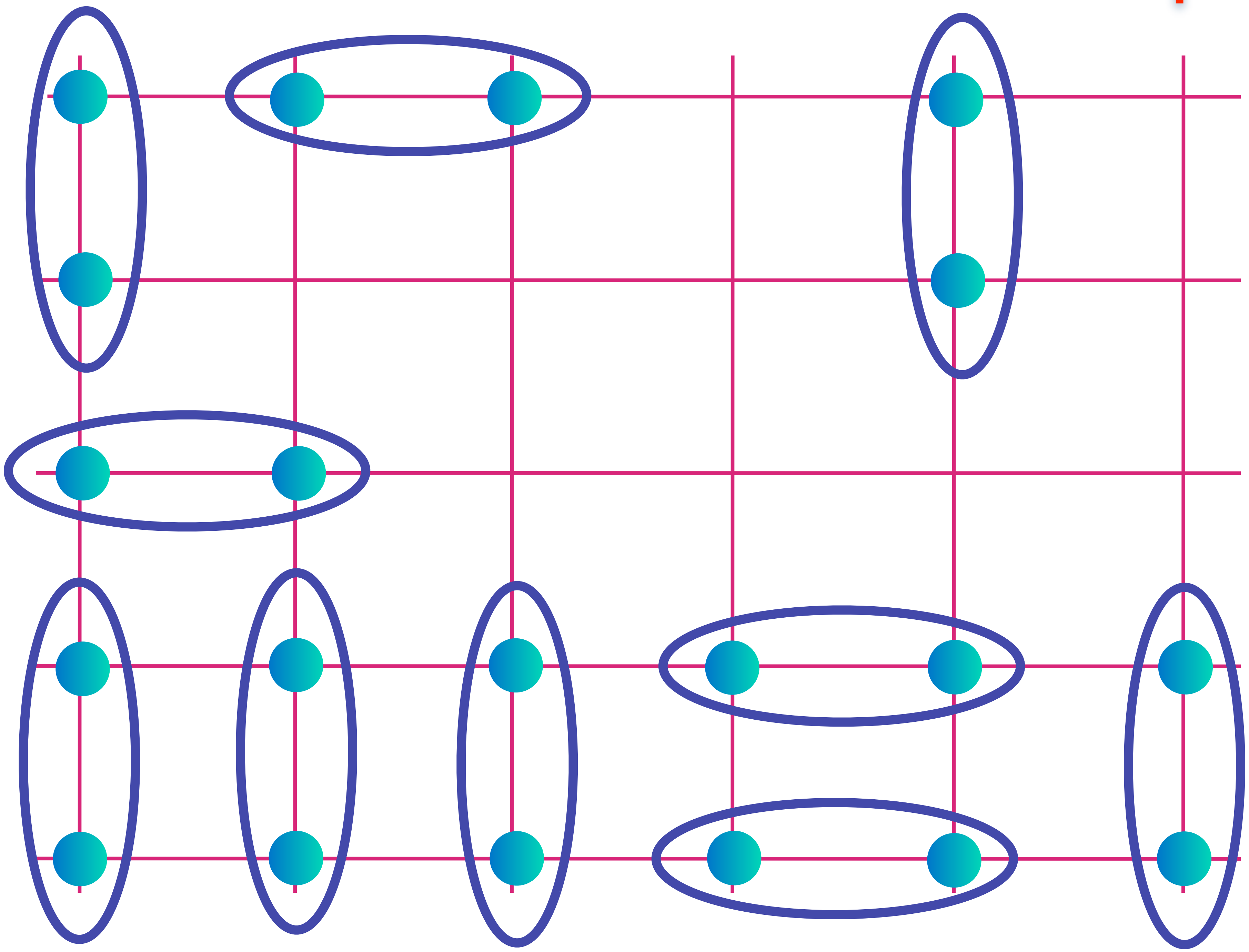

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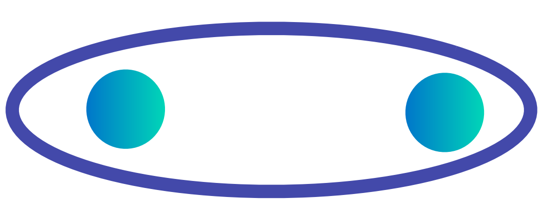

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Square lattice of Cu sites

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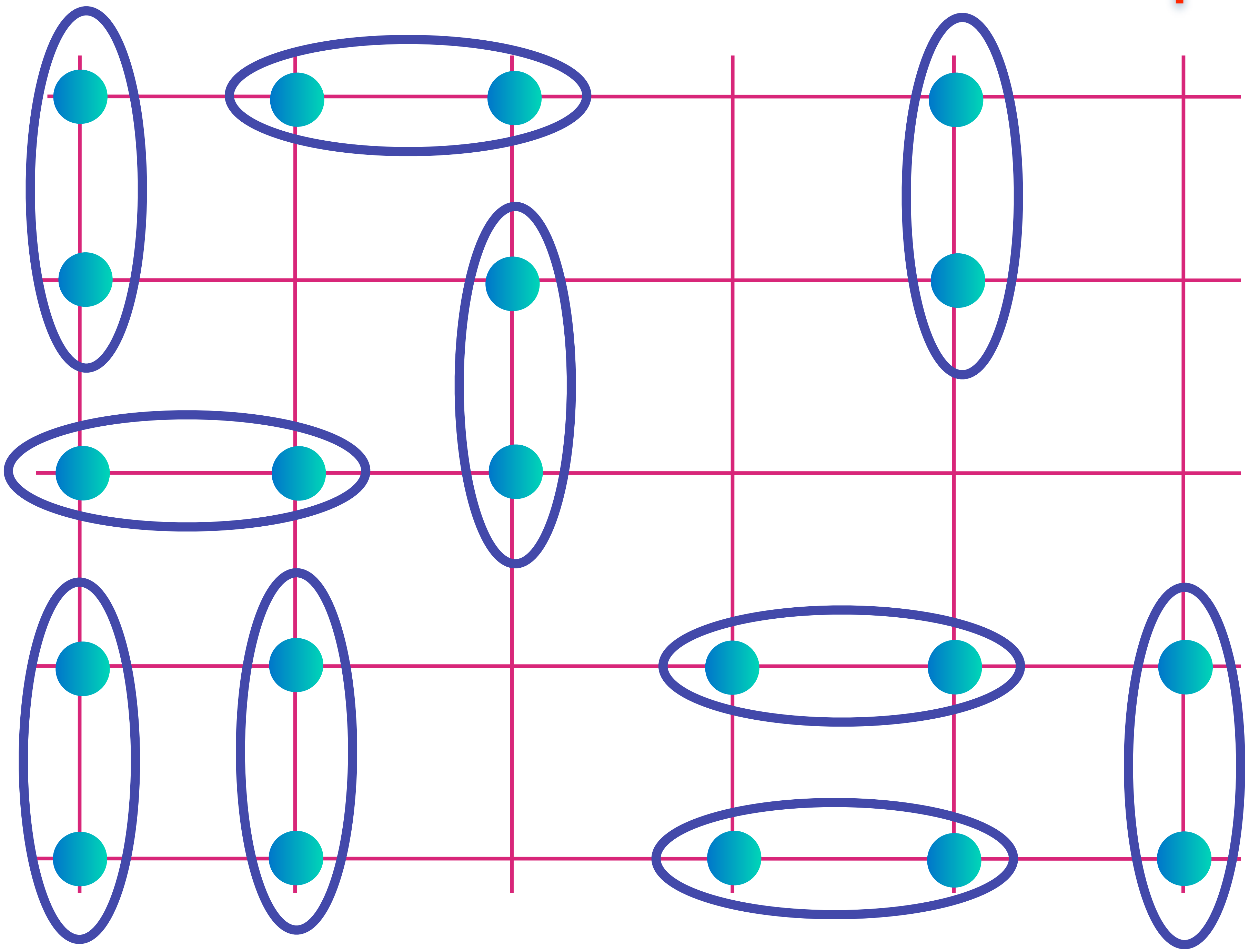

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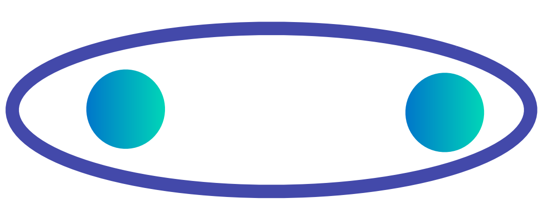 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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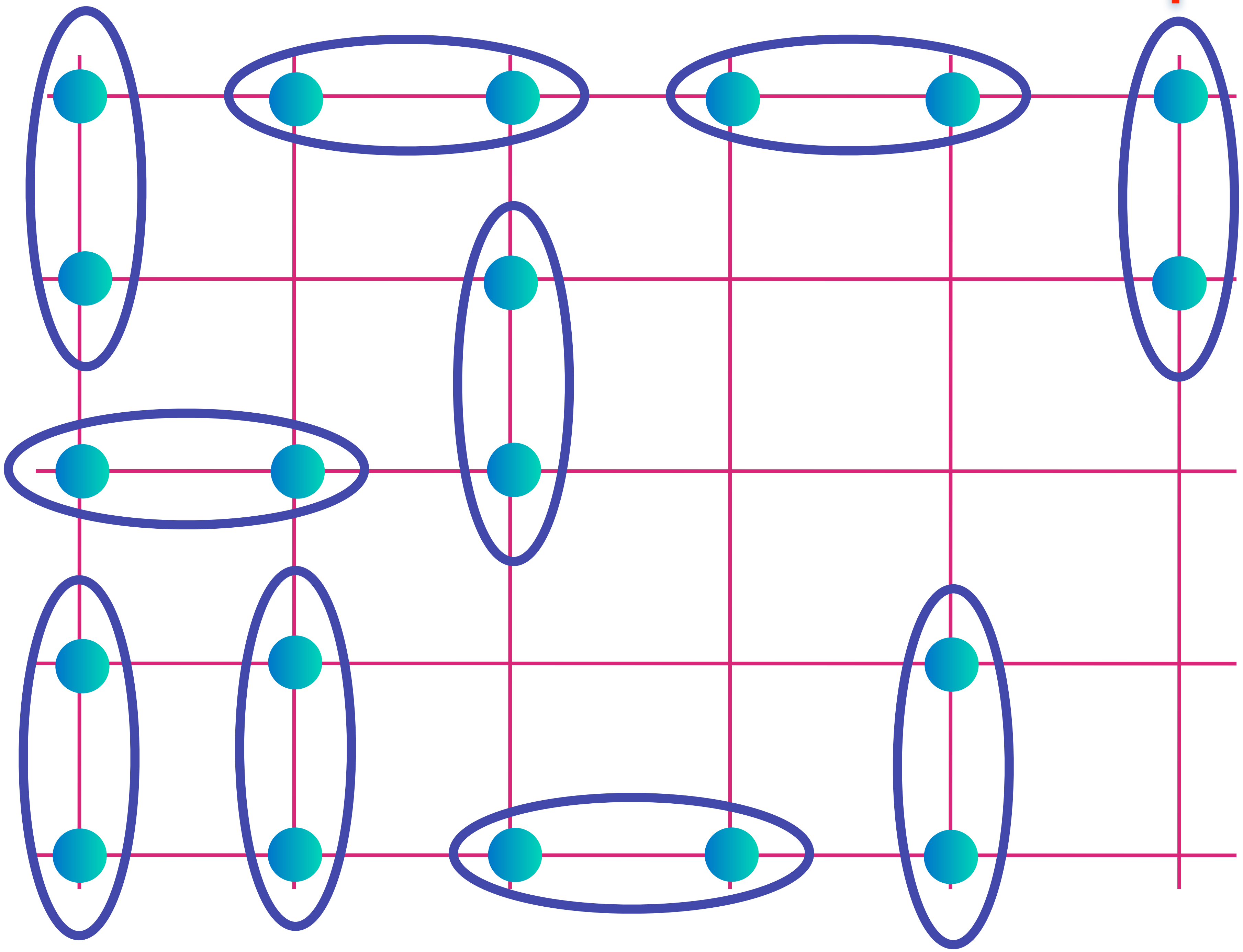

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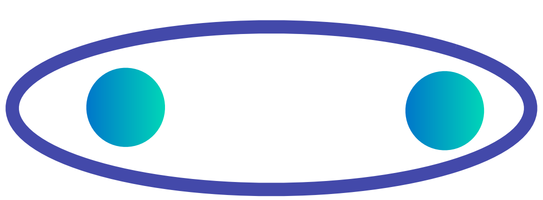
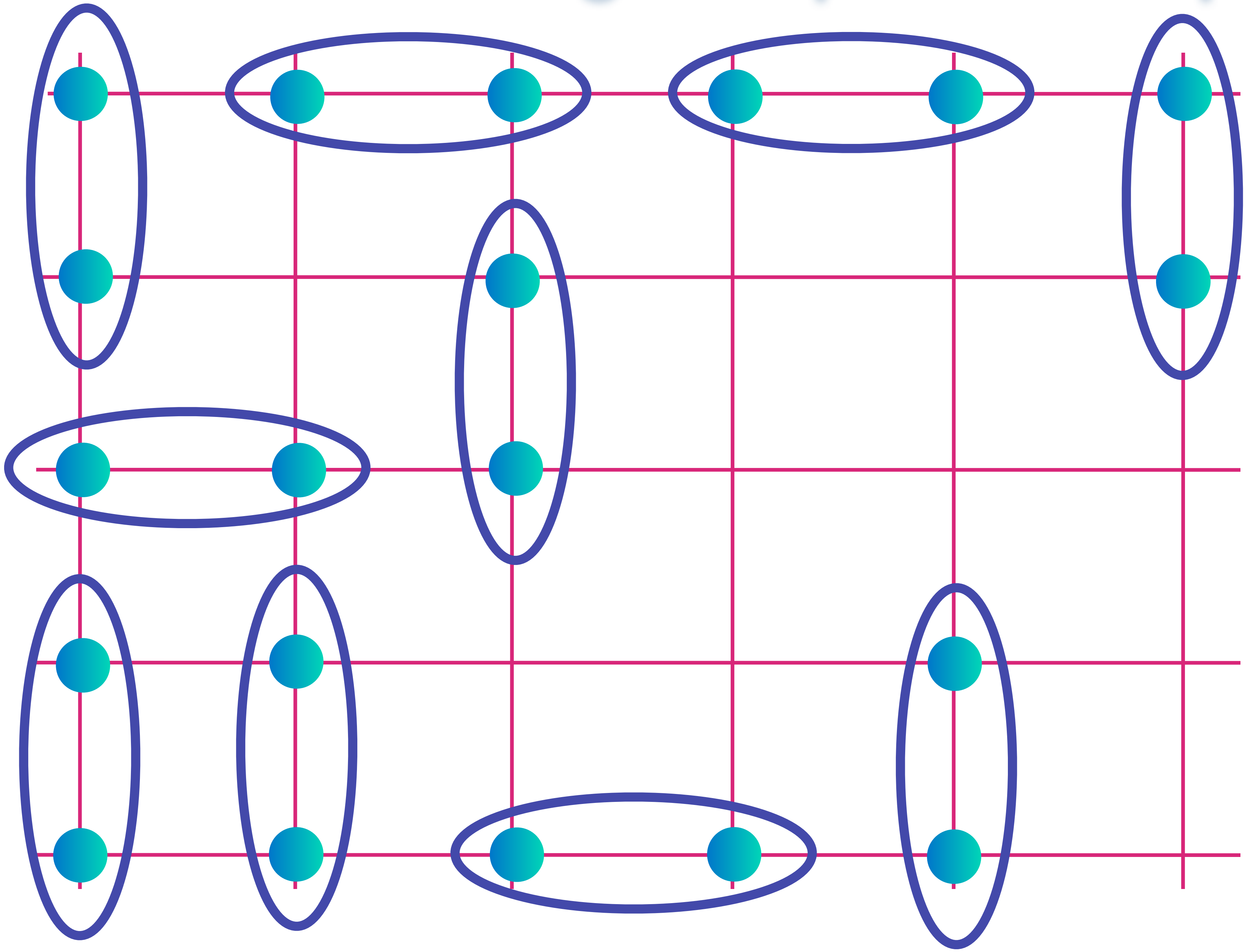


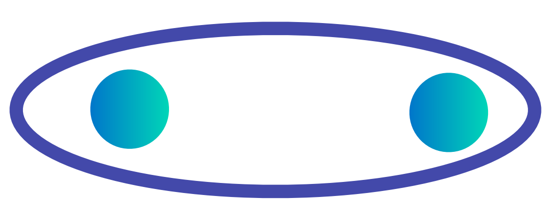
$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Square lattice of Cu sites

High temperature superconductivity !



Electrons <u>entangle</u> by exchanging partners, and there is <u>long-range quantum entanglement</u> in the strange metal.



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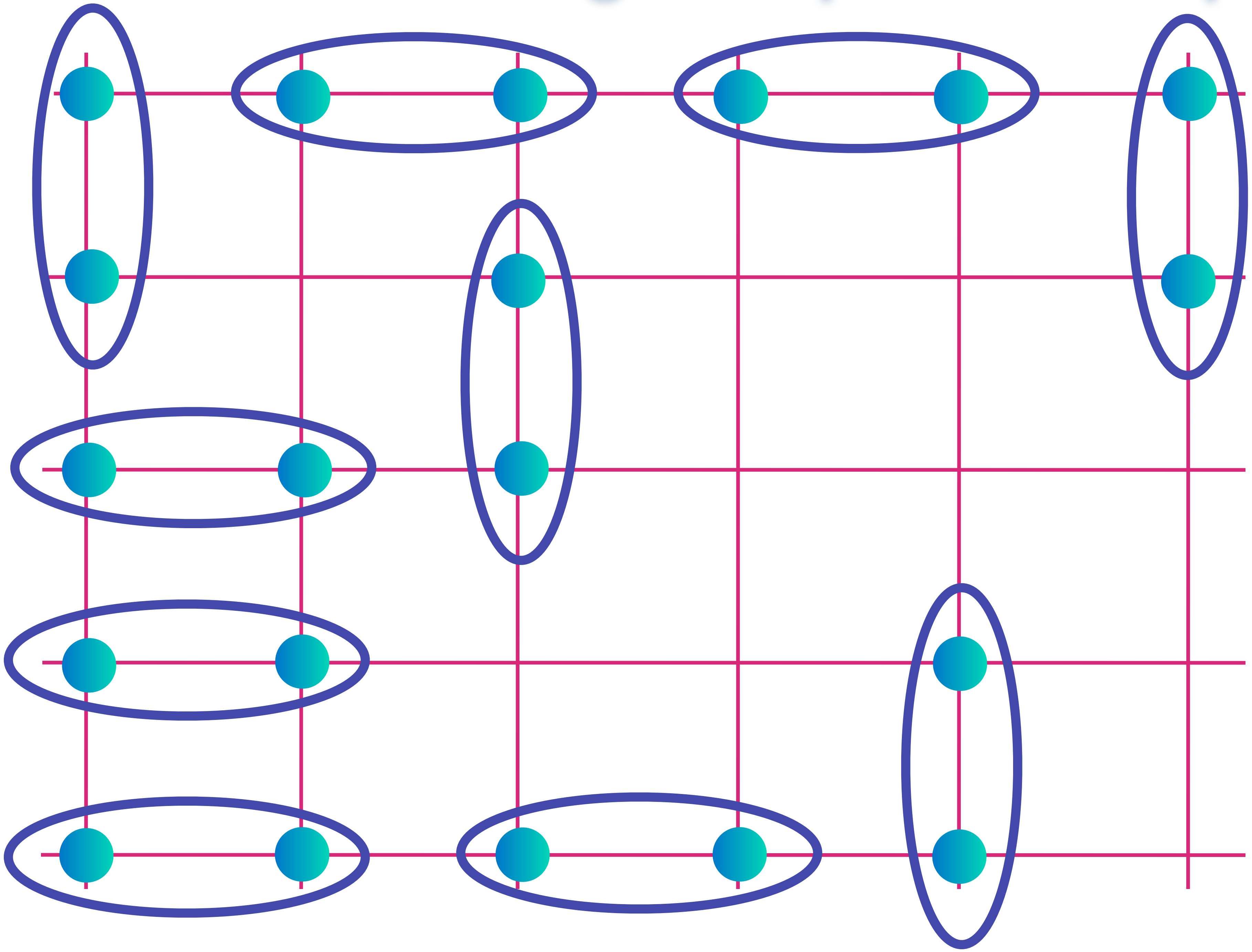
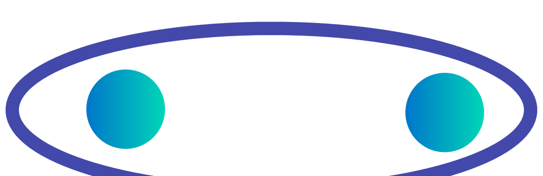


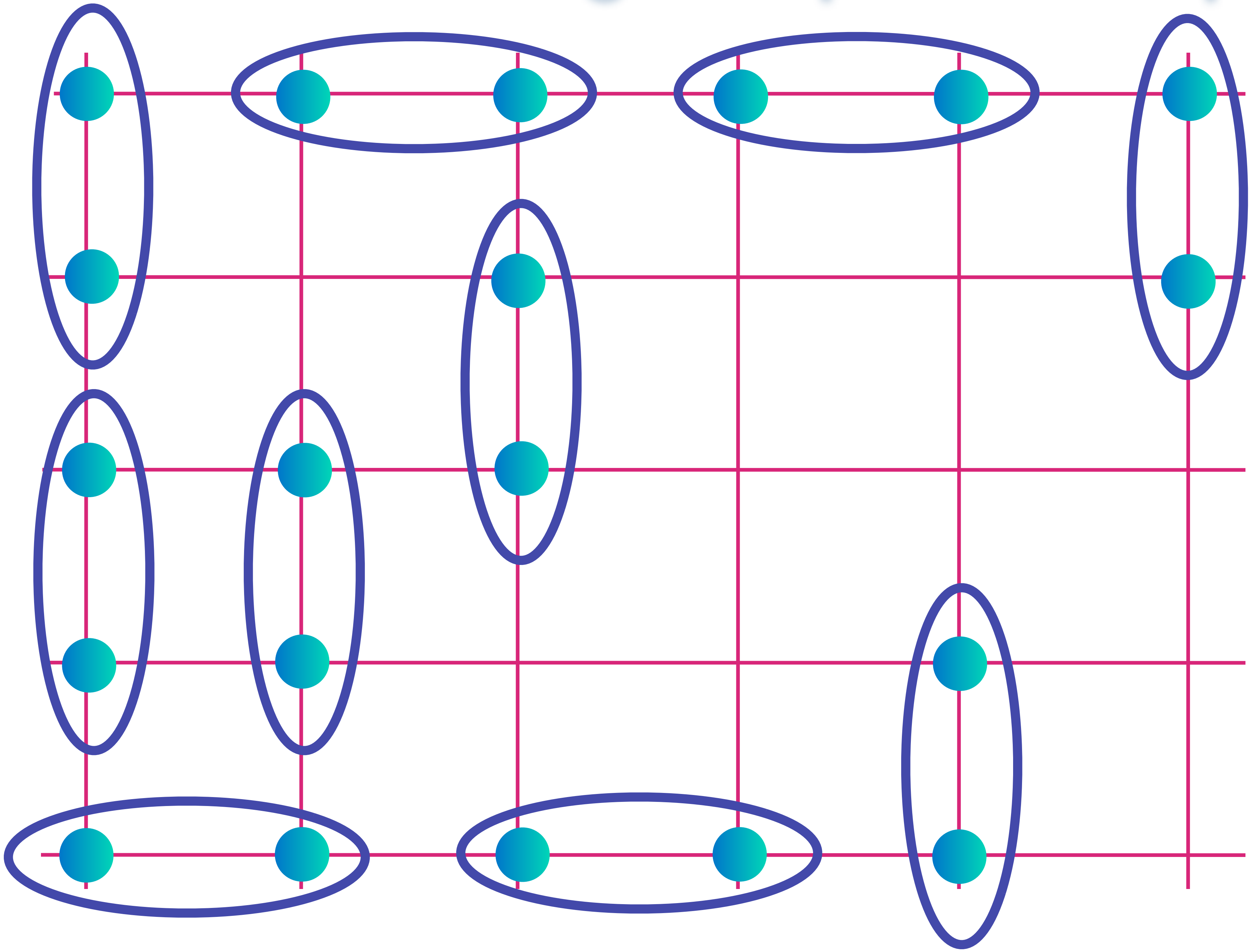
Electrons entangle by exchanging partners, and there is long-range quantum entanglement in the strange metal.



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

Square lattice of Cu sites

High temperature superconductivity !



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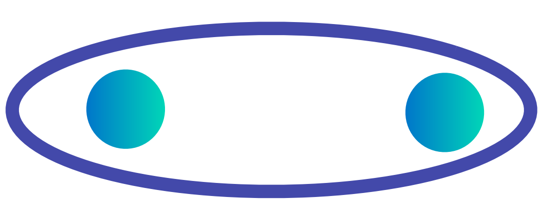

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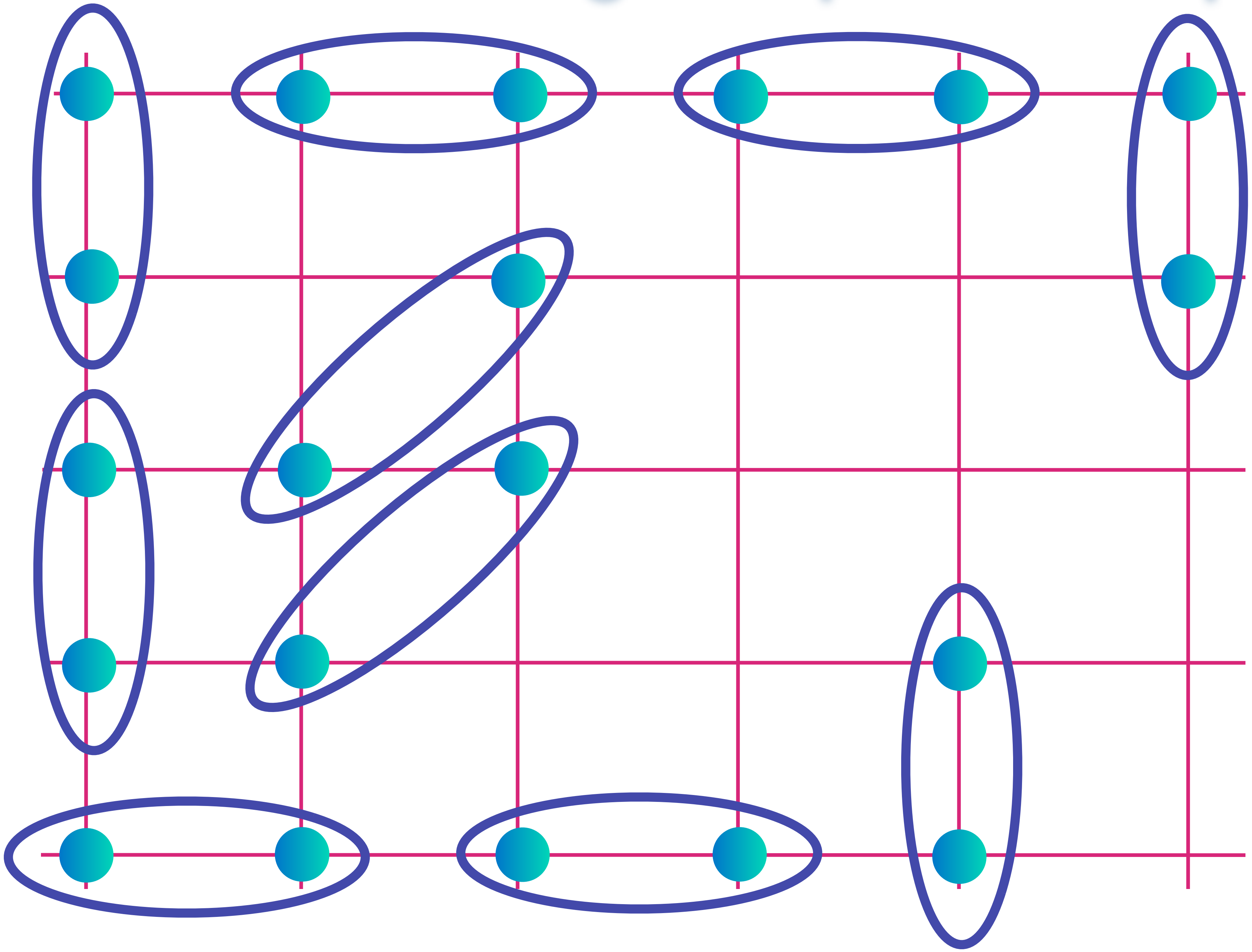

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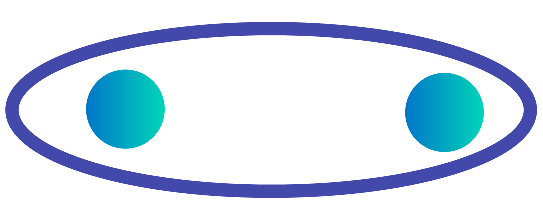

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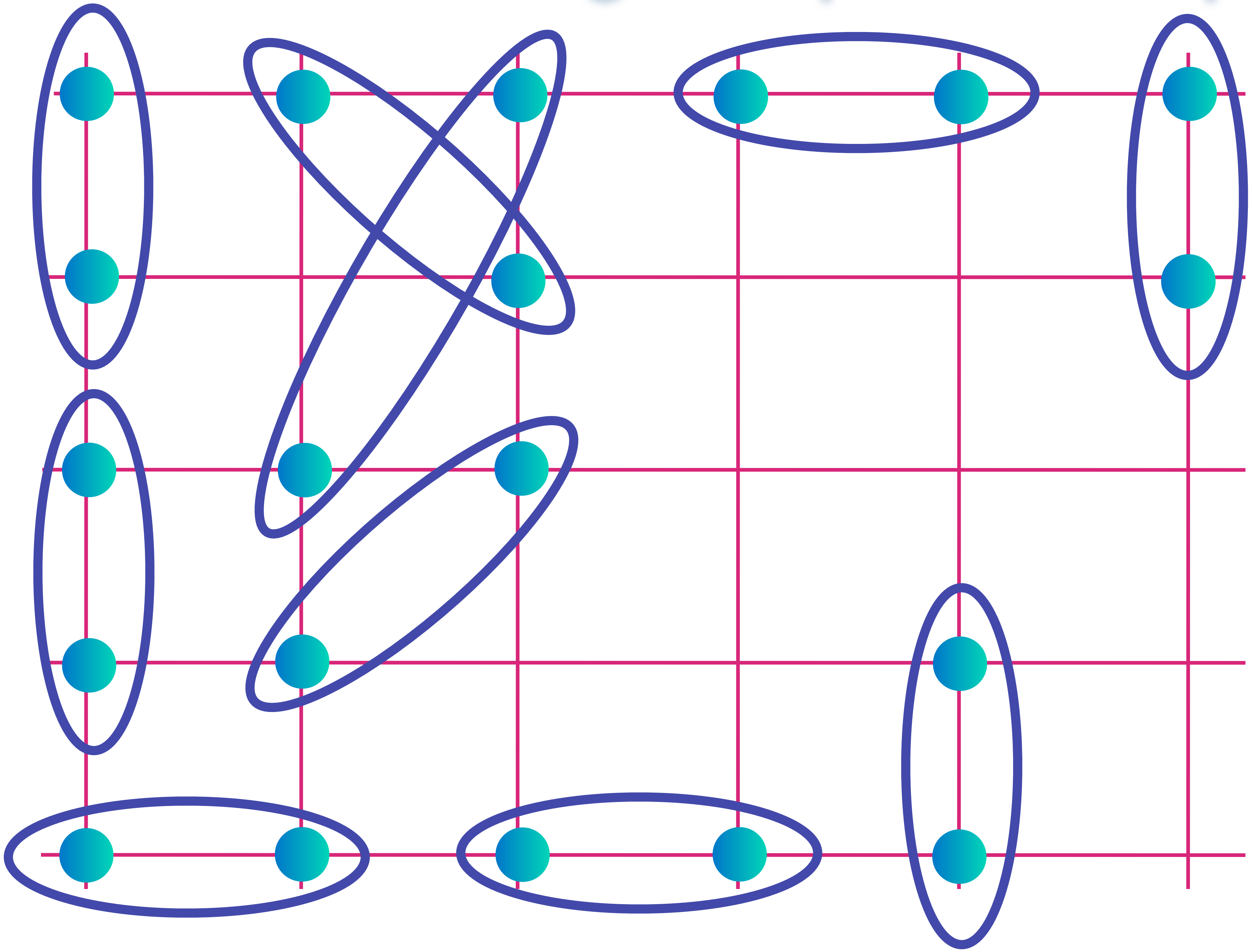

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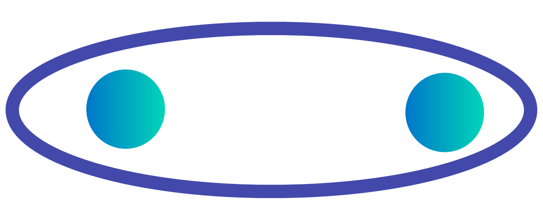

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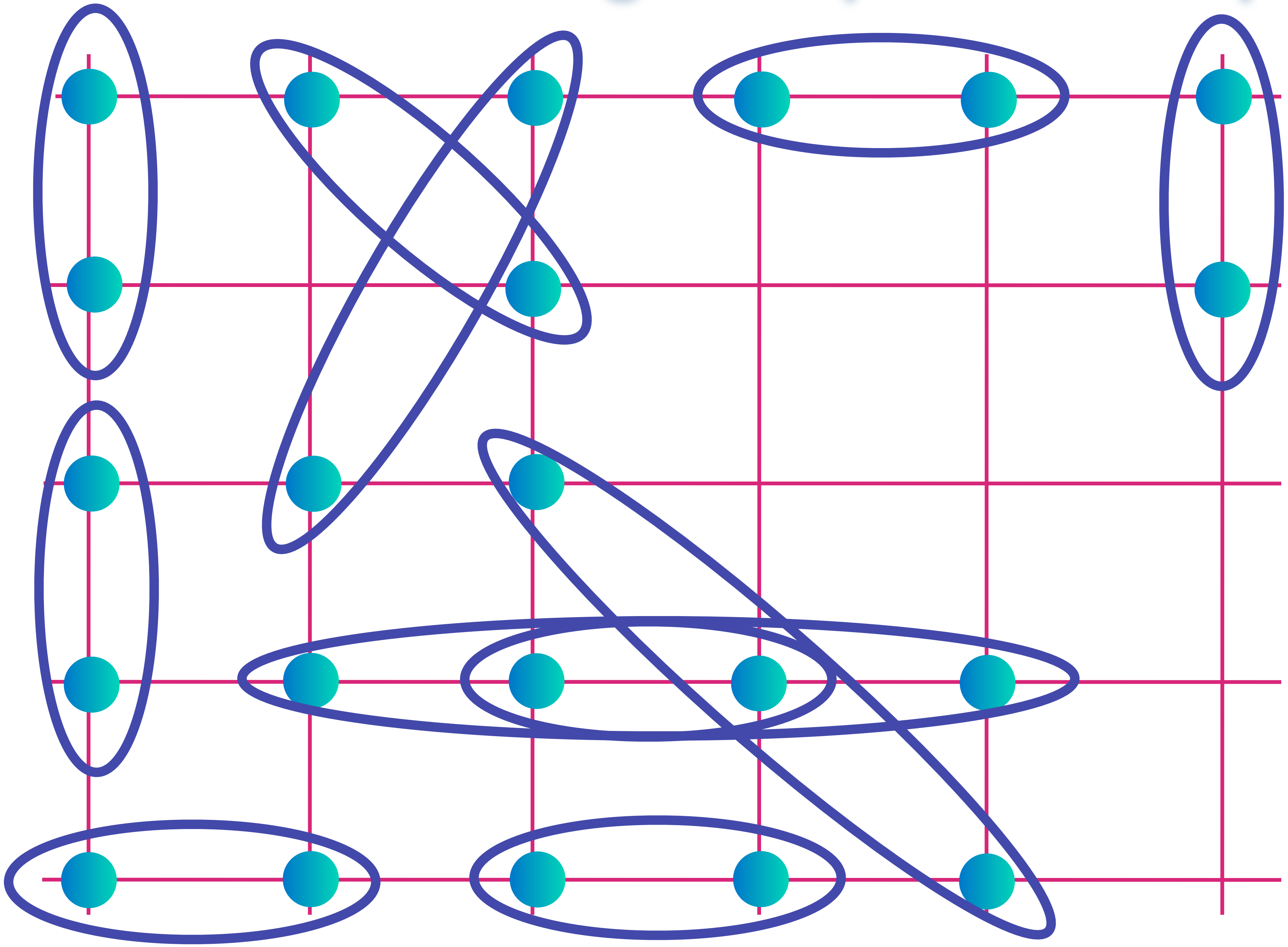

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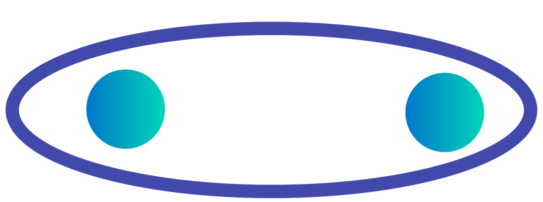 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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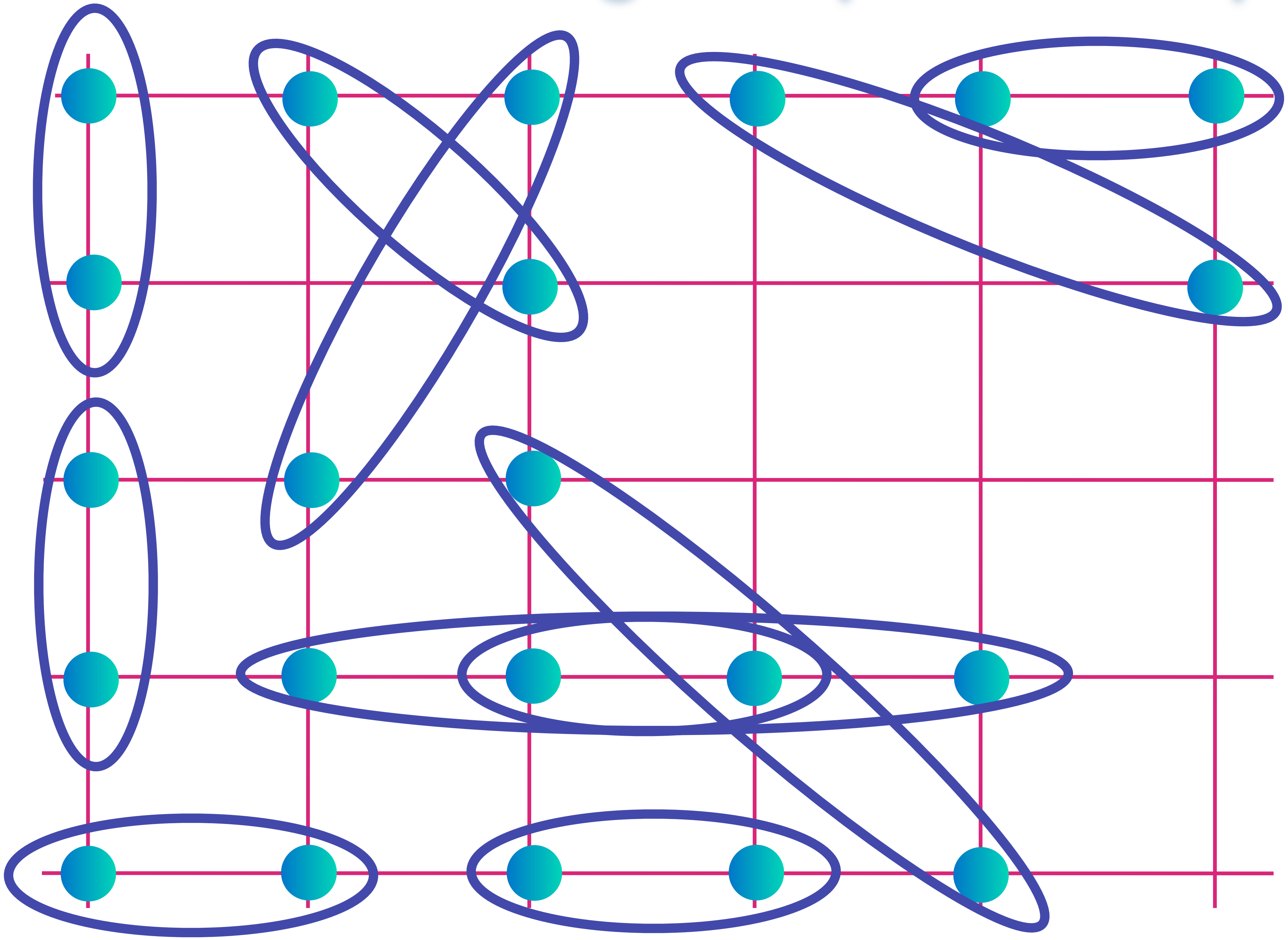

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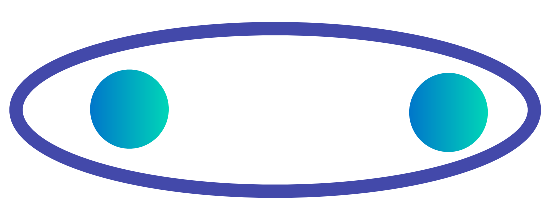
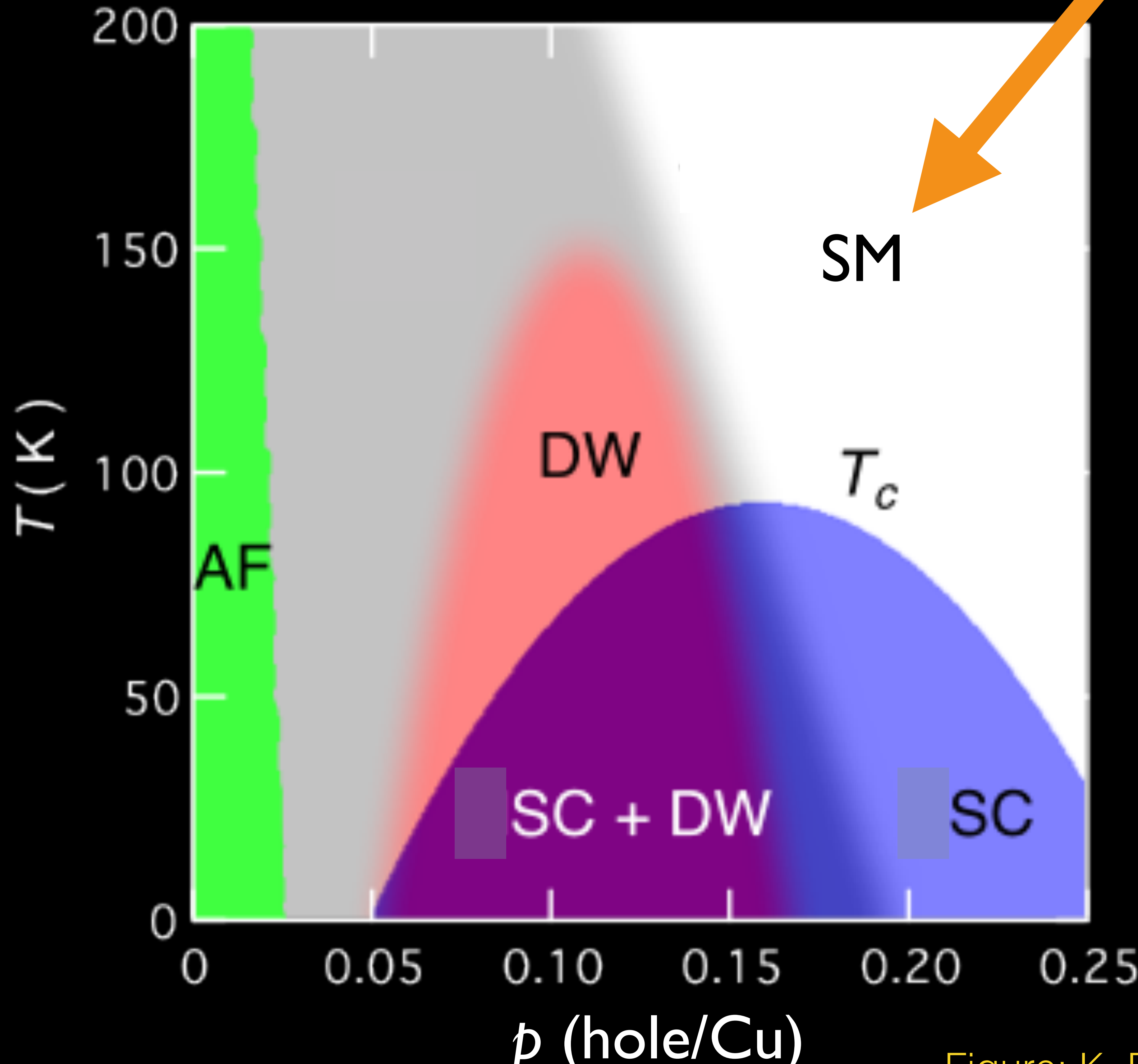
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Strange metal



Entangled electrons lead to “strange” temperature dependence of resistivity and other properties

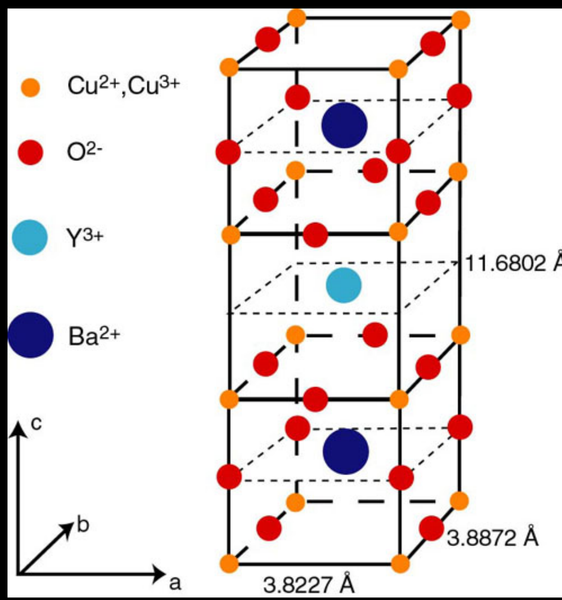
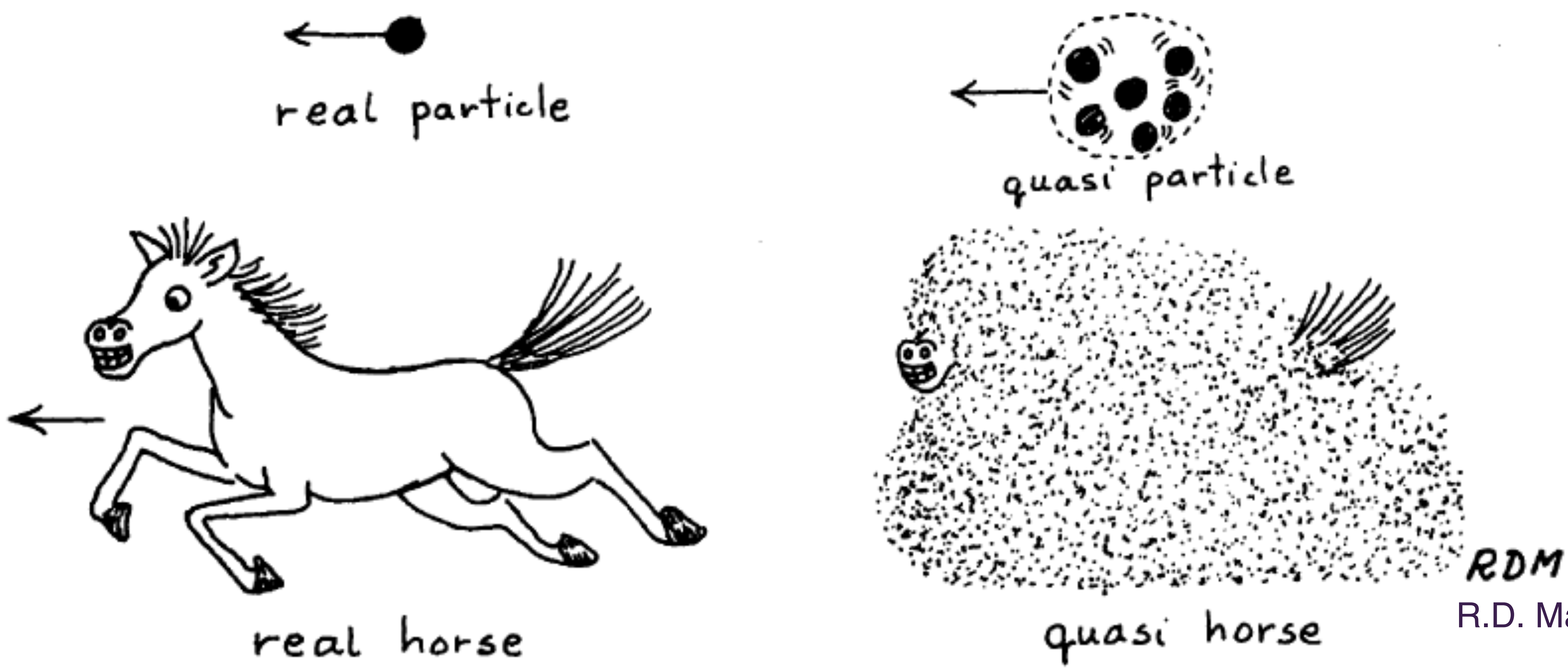


Figure: K. Fujita and J. C. Seamus Davis

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

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.

Quasiparticles eventually collide with each other. Such collisions eventually leads to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time.

Quantum matter without quasiparticles

The complex quantum entanglement in the strange metal does not allow for any quasiparticle excitations.

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$$\tau_\varphi \geq C \frac{\hbar}{k_B T} \qquad \text{(SS, 1999)}$$

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- In the strange metal the above inequalities become equalities as $T \to 0$.

Quantum entanglement

Black holes

Strange metals

Quantum entanglement

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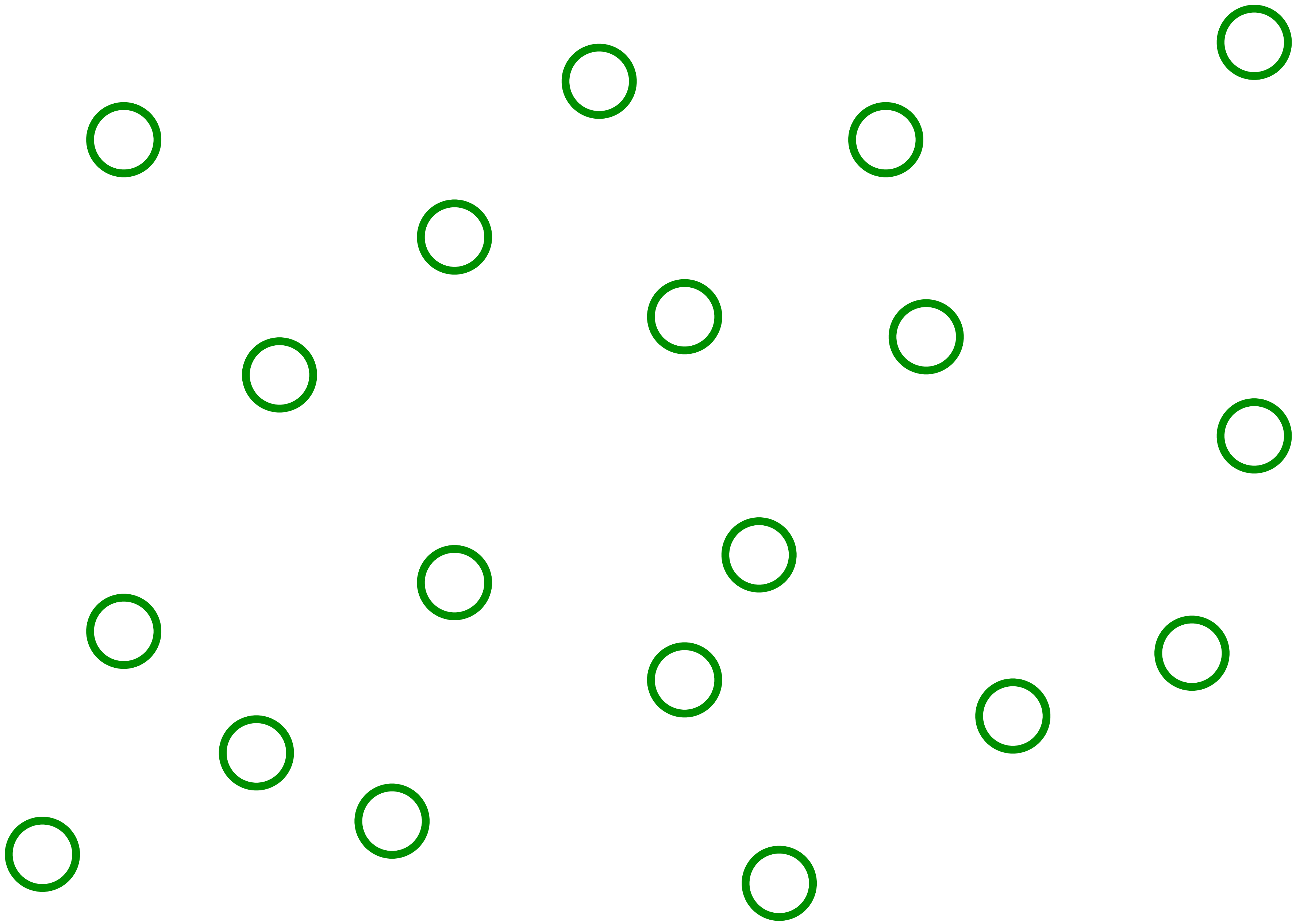
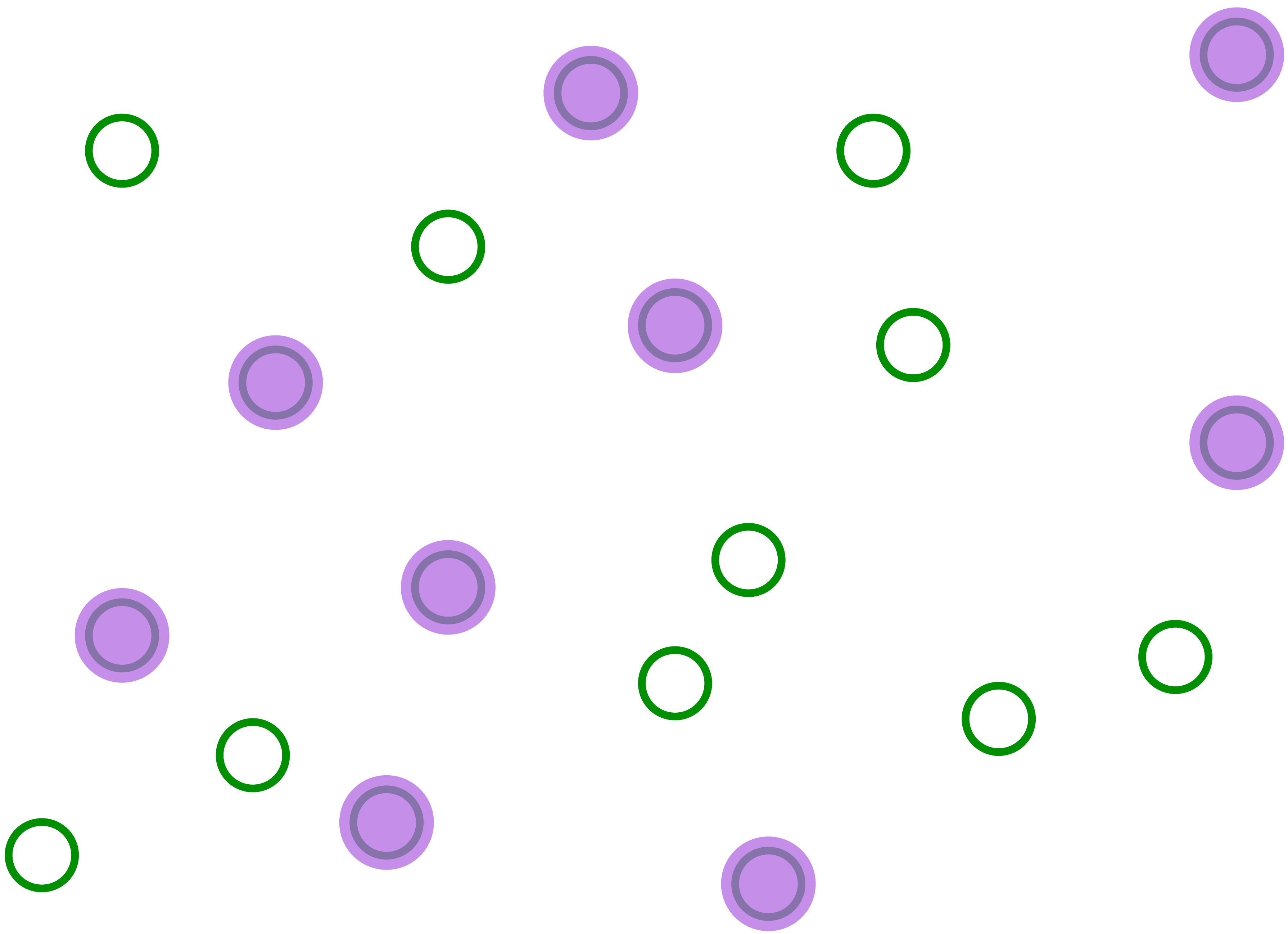
A "toy model" which is both a strange metal and a black hole!

The Sachdev-Ye-Kitaev (SYK) model



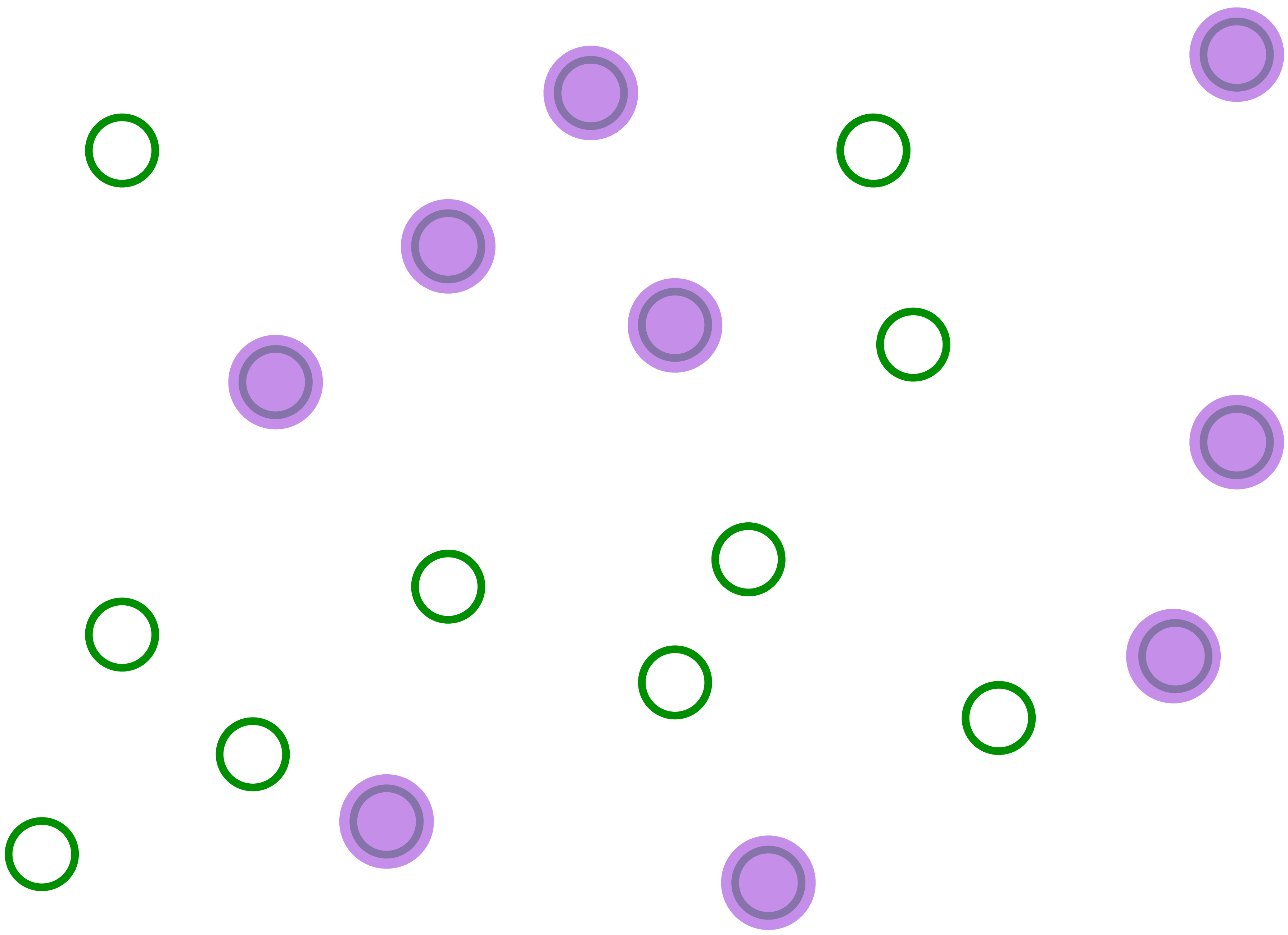
Pick a set of random positions

The Sachdev-Ye-Kitaev (SYK) model



Place electrons randomly on some sites

The Sachdev-Ye-Kitaev (SYK) model



Entangle electrons pairwise randomly

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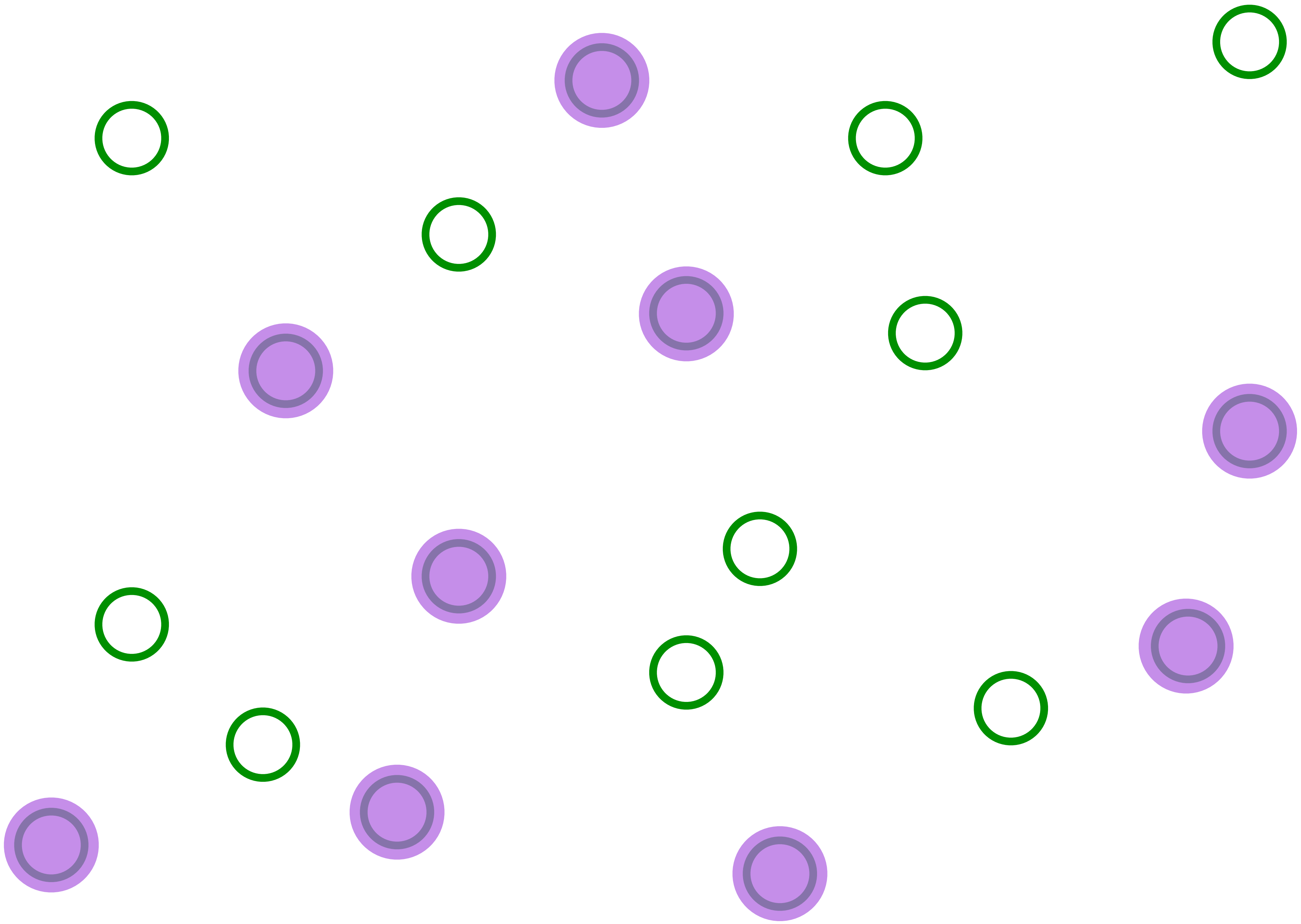

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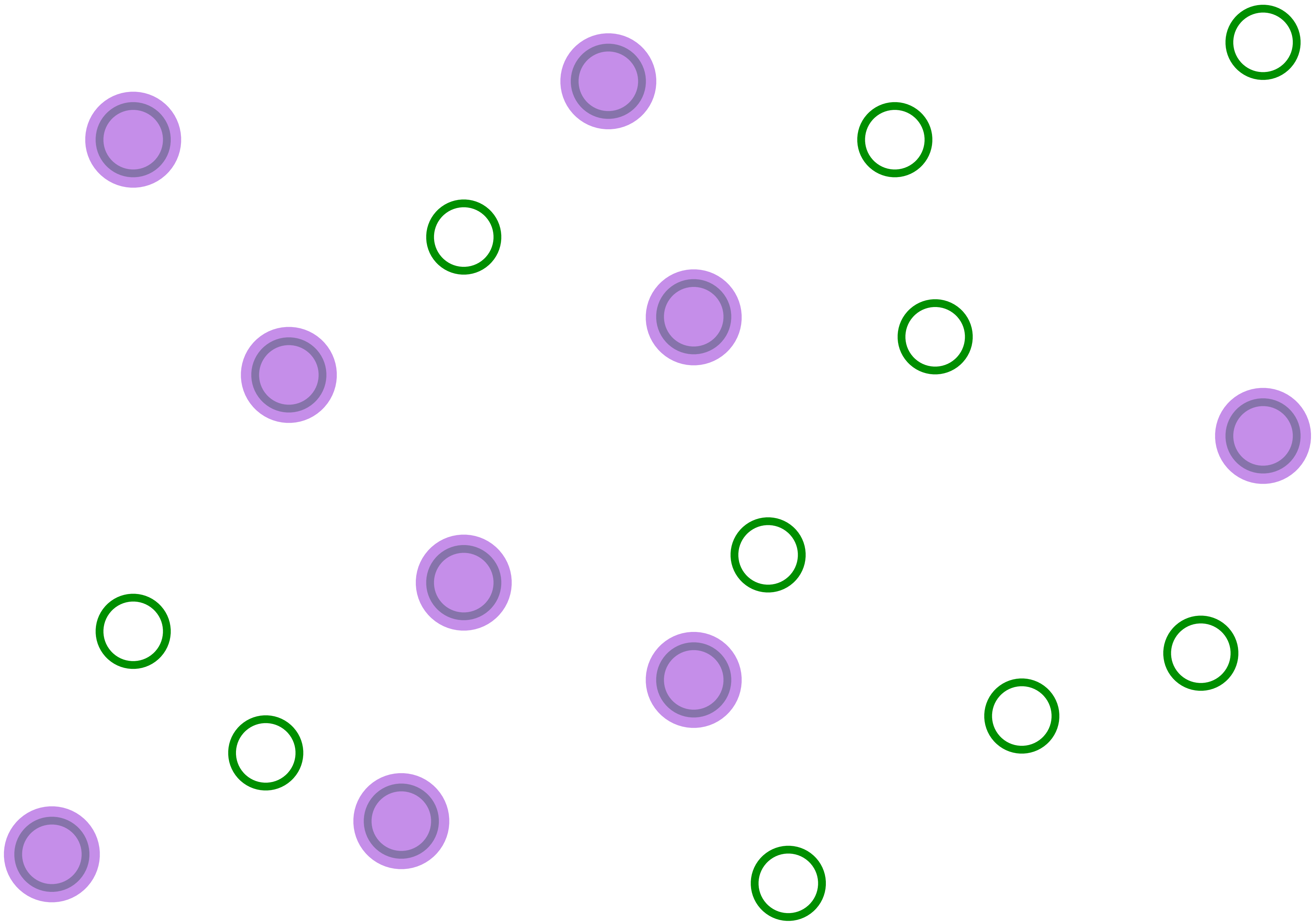

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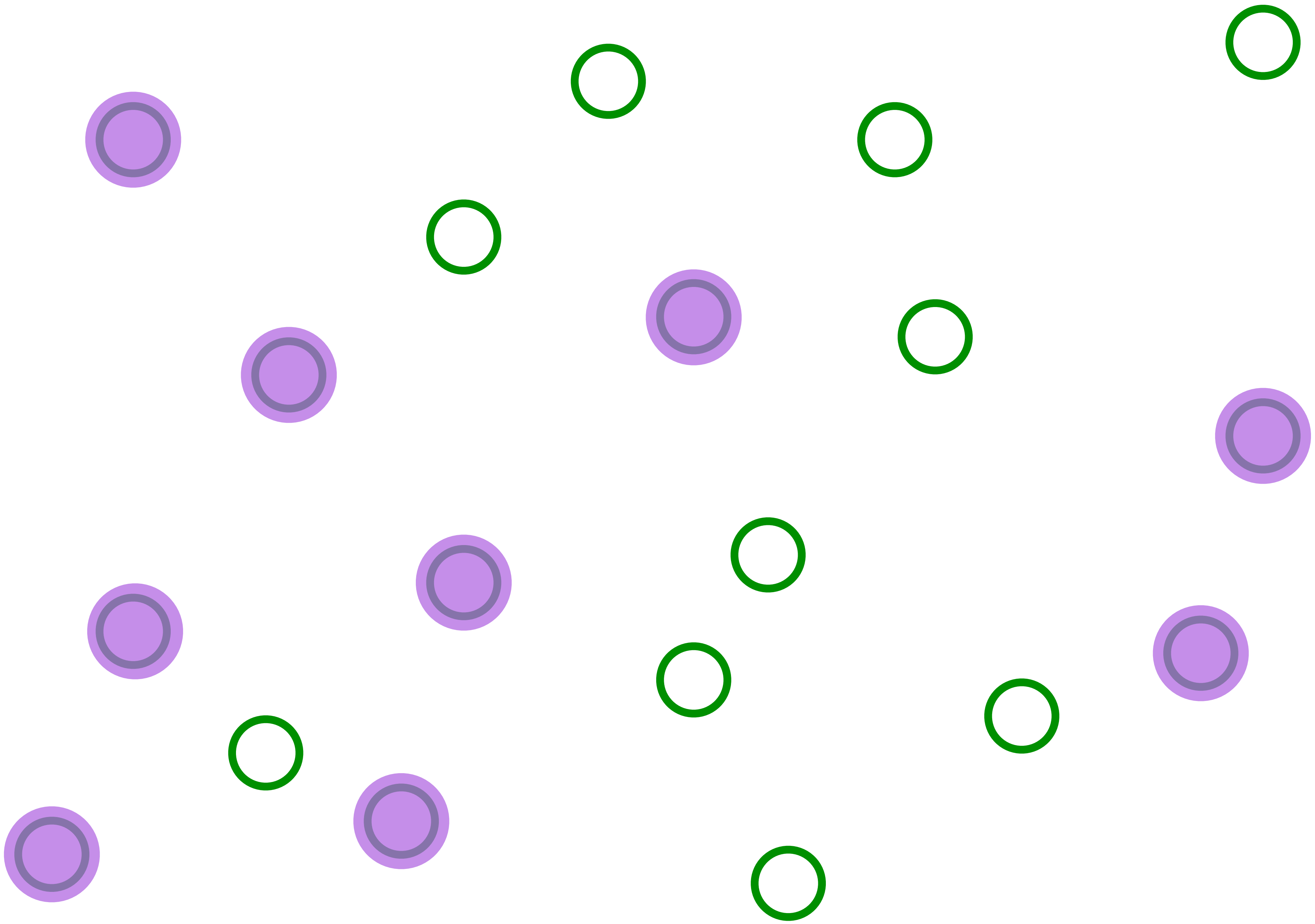

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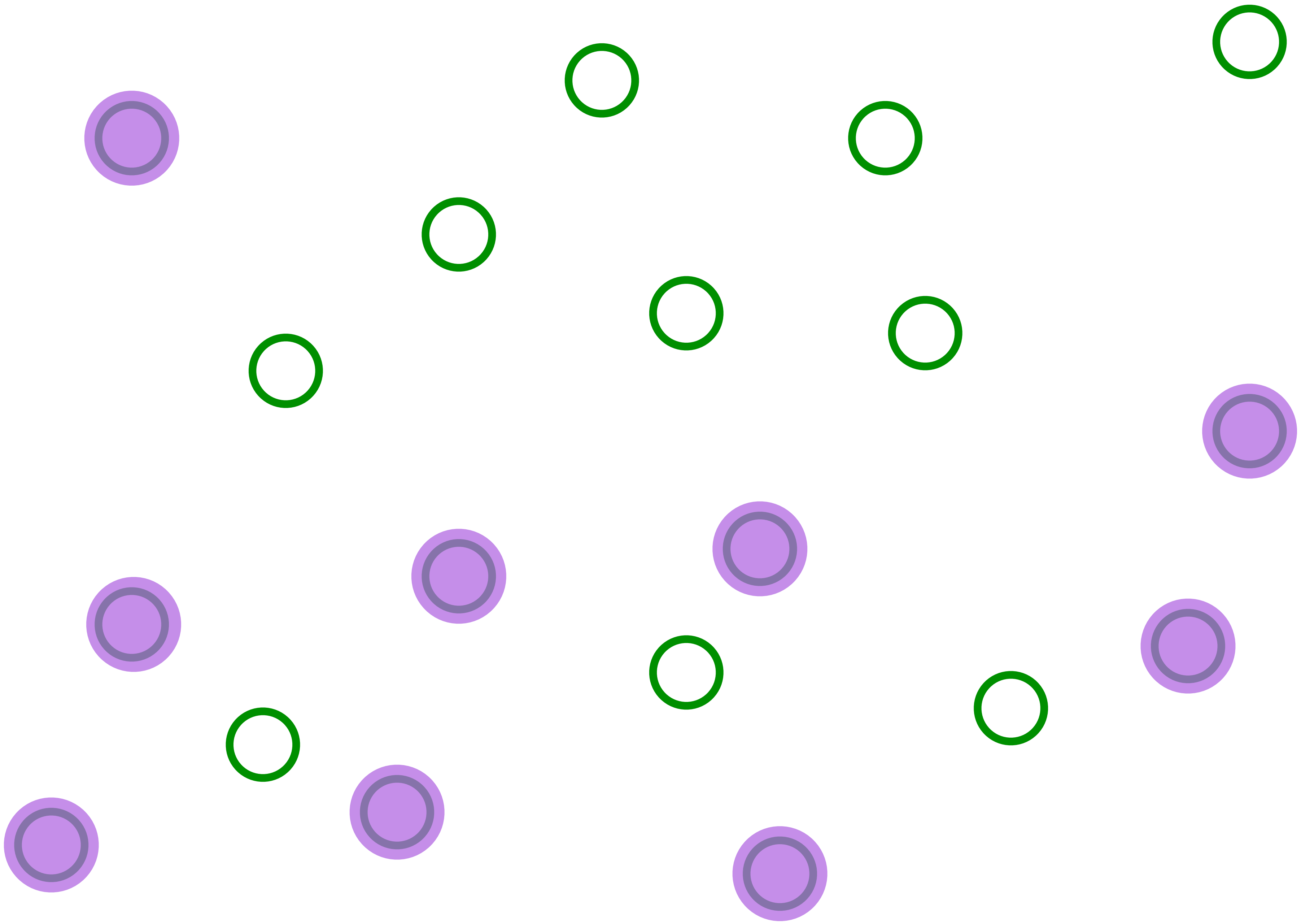

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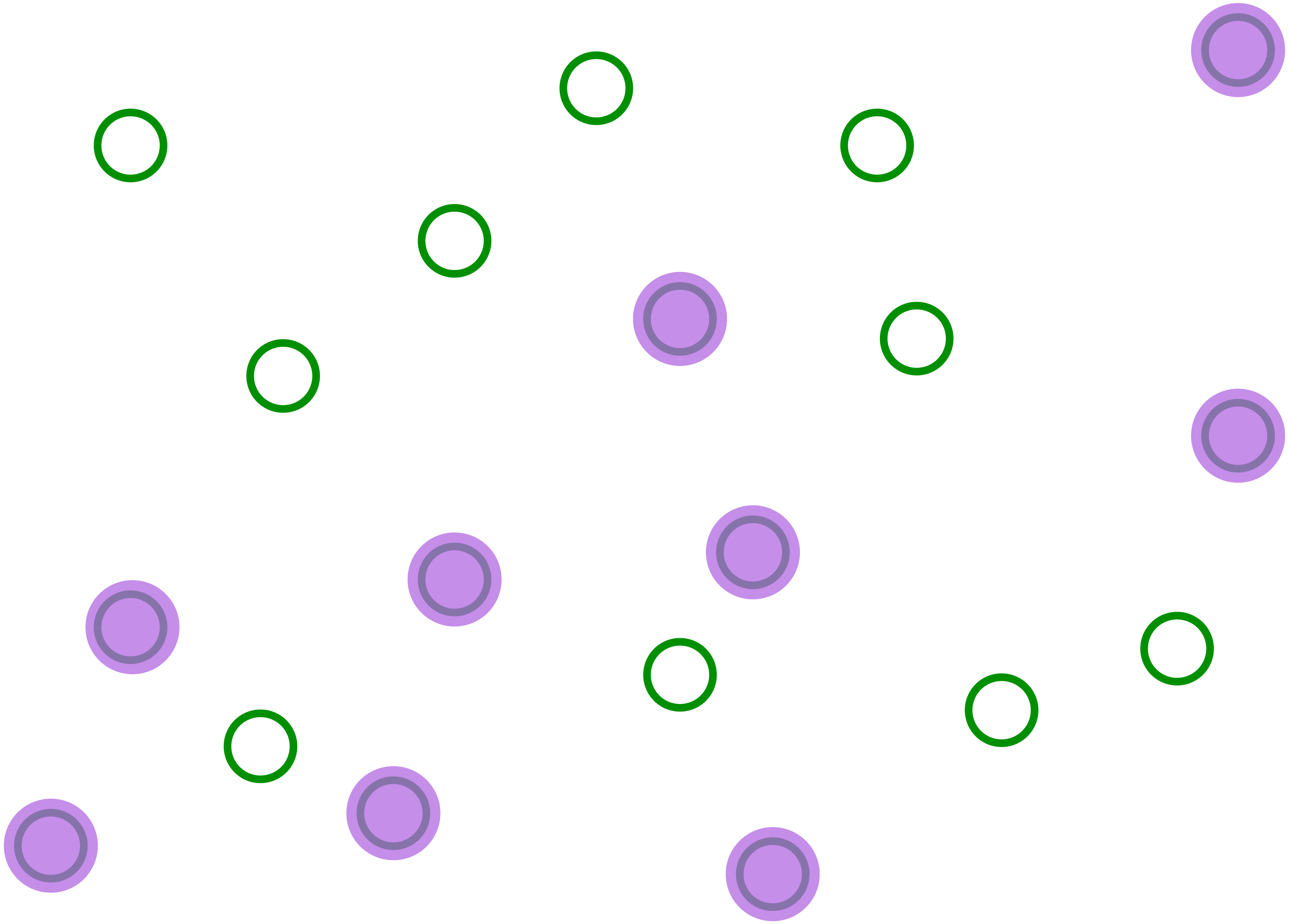

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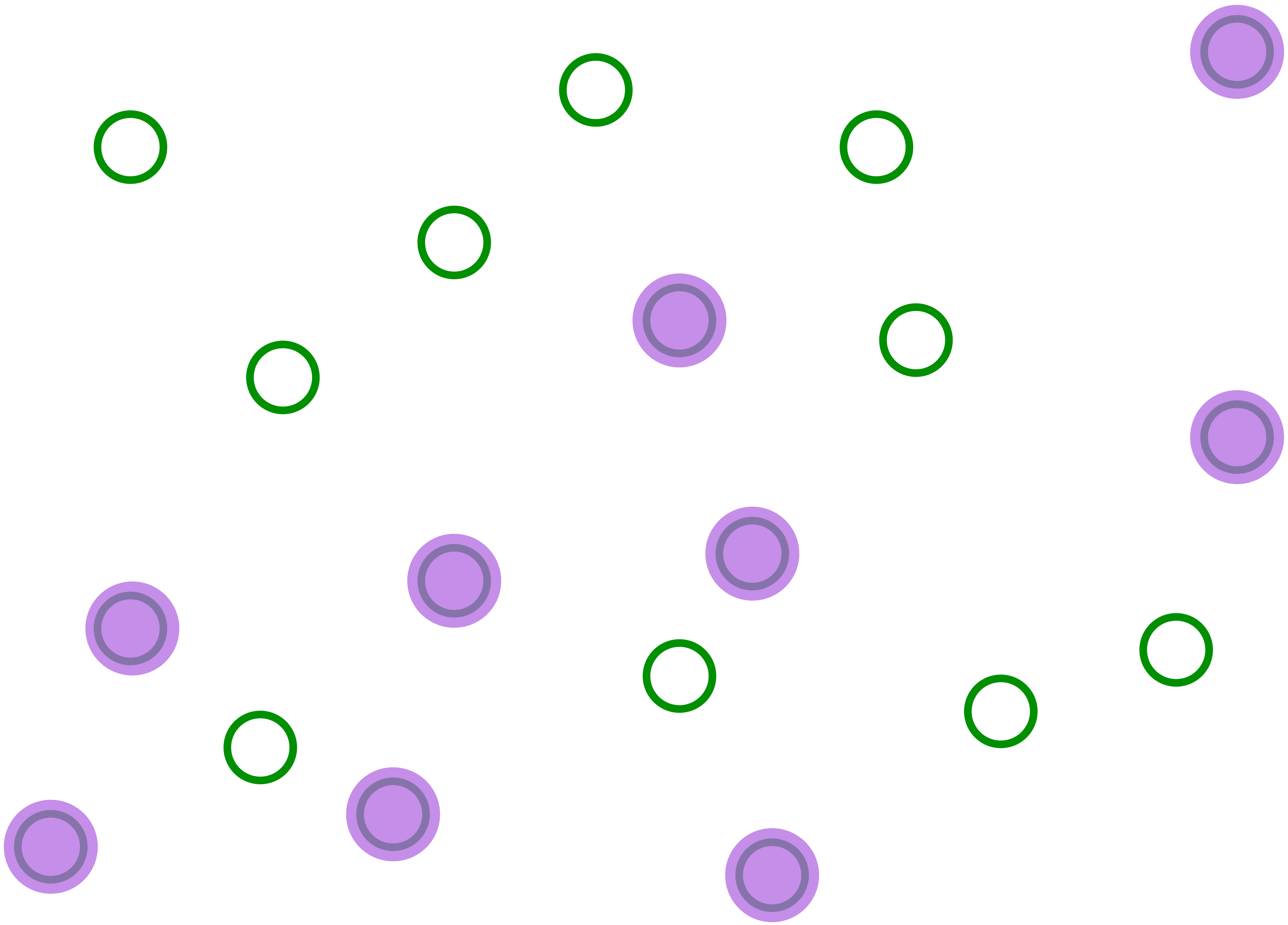
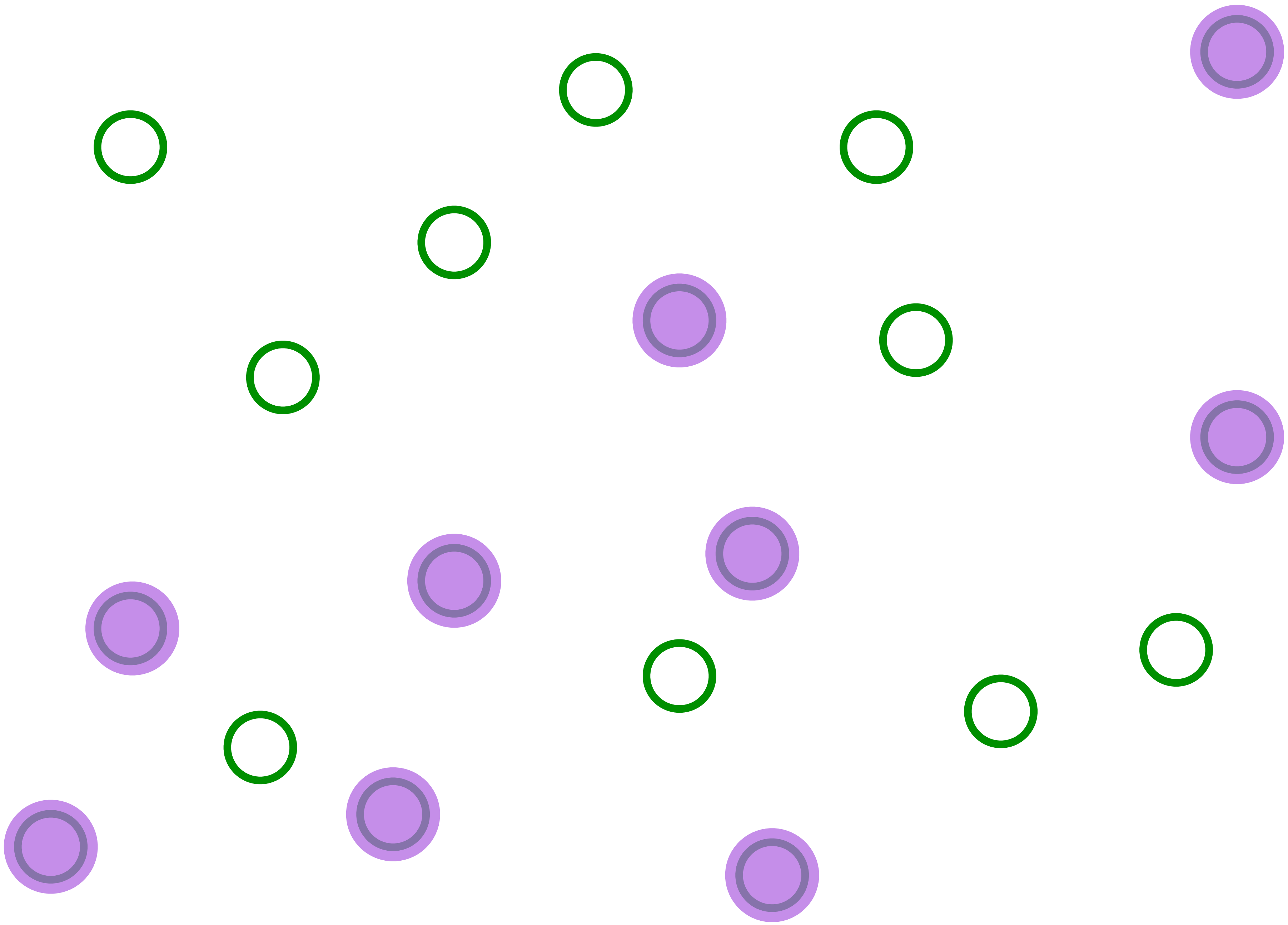


The SYK model has “nothing but entanglement”

The Sachdev-Ye-Kitaev (SYK) model



This describes both a strange metal and a black hole!

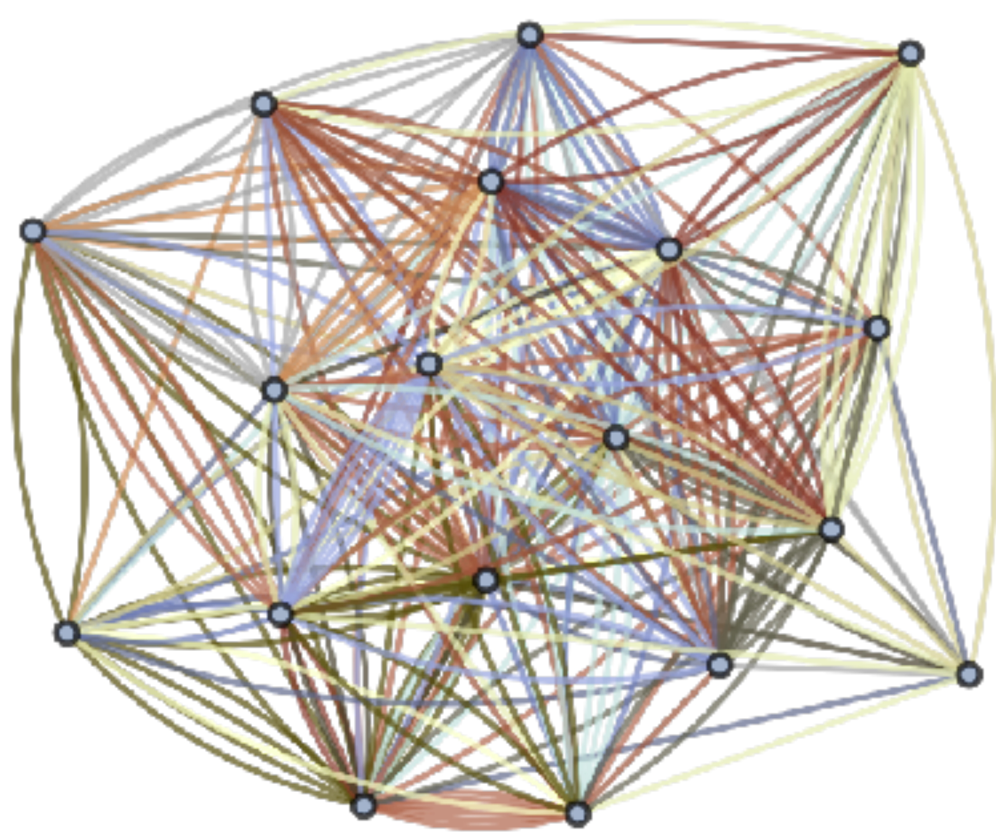
SYK model

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell - \mu \sum_i c_i^\dagger c_i$$

$$c_i c_j + c_j c_i = 0 \quad , \quad c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$$\mathcal{Q} = \frac{1}{N} \sum_i c_i^\dagger c_i$$

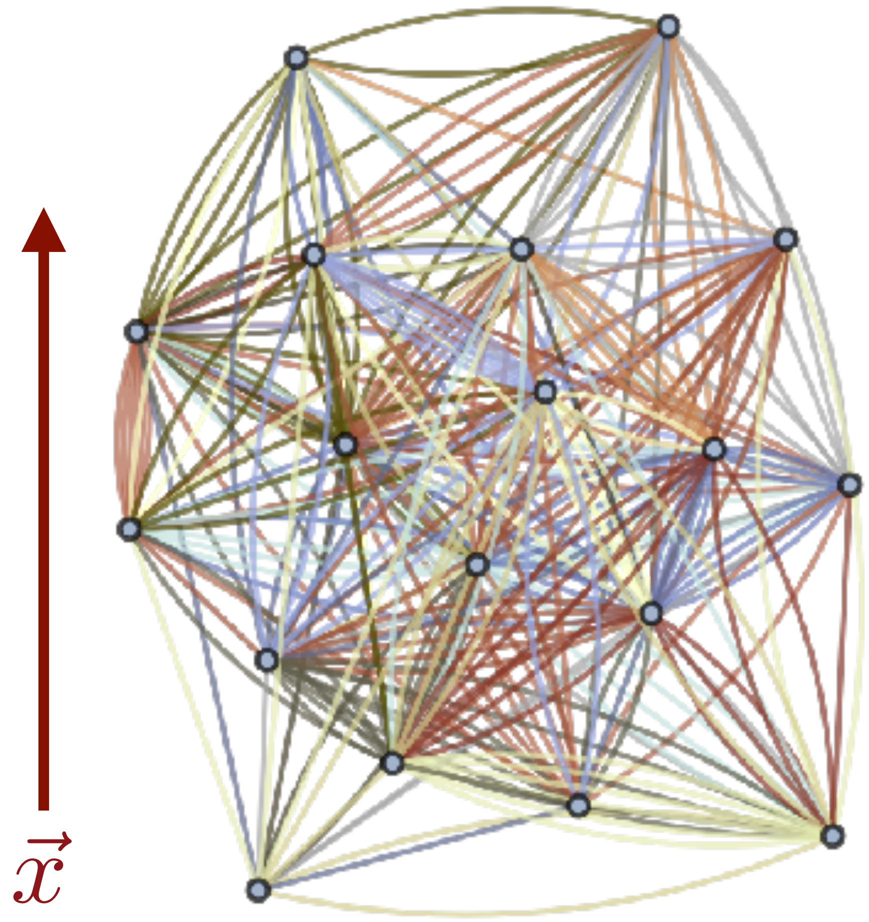
$J_{ij;k\ell}$ are independent random variables with $\overline{J_{ij;k\ell}} = 0$ and $\overline{|J_{ij;k\ell}|^2} = J^2$
$N \to \infty$ yields critical strange metal.



SS and J. Ye 1993

A. Kitaev, (2015) ; SS 2015

SYK and black holes



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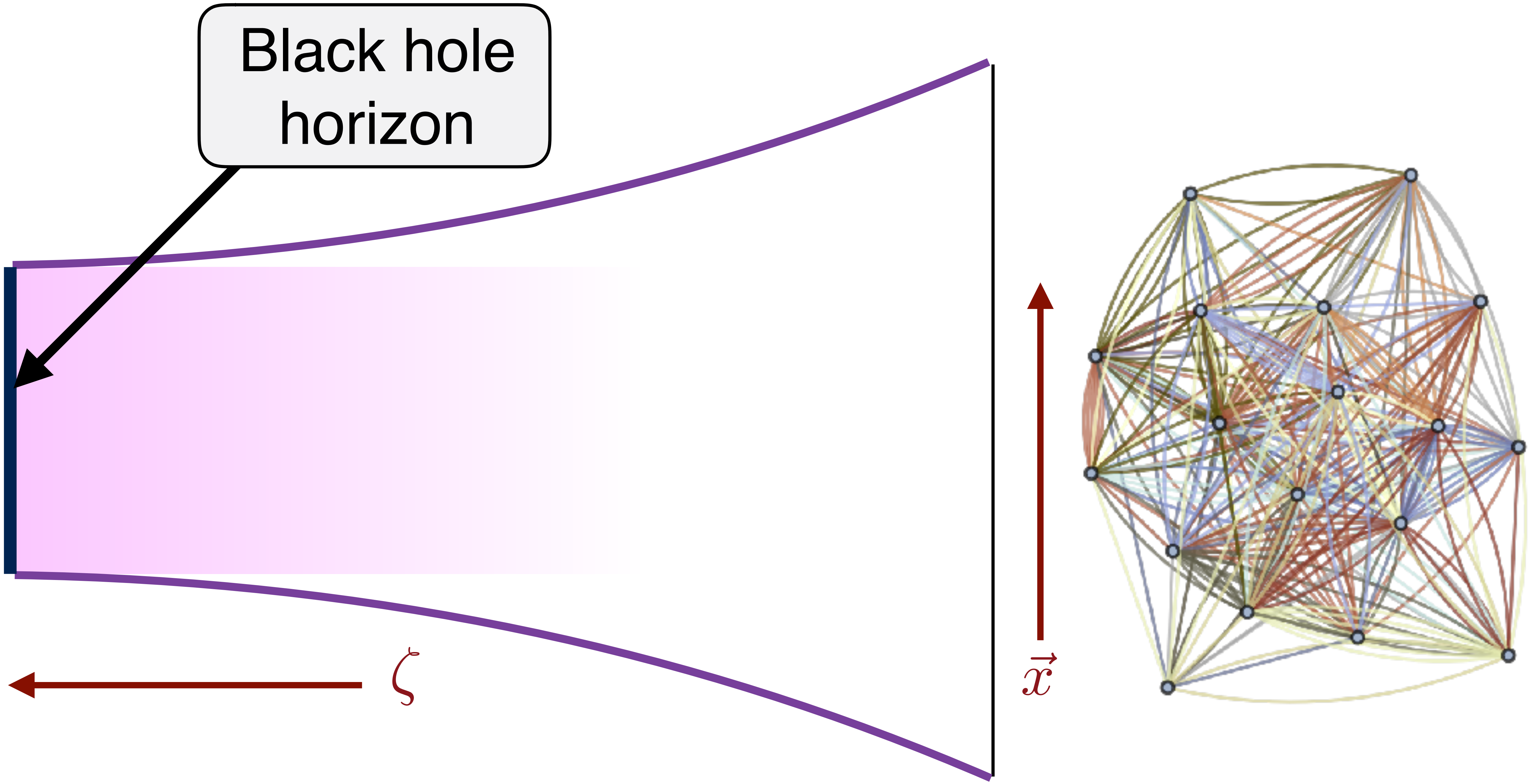
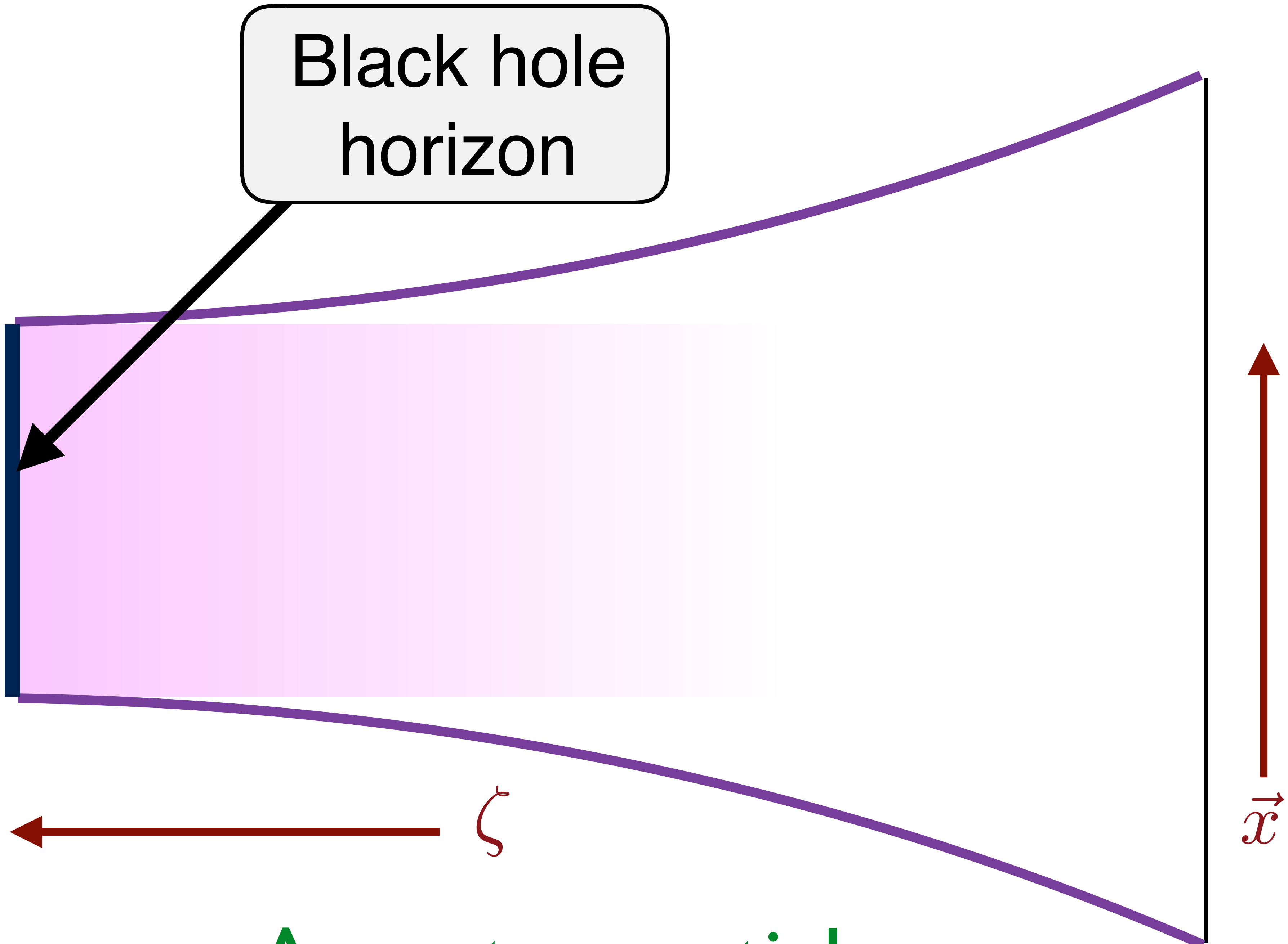
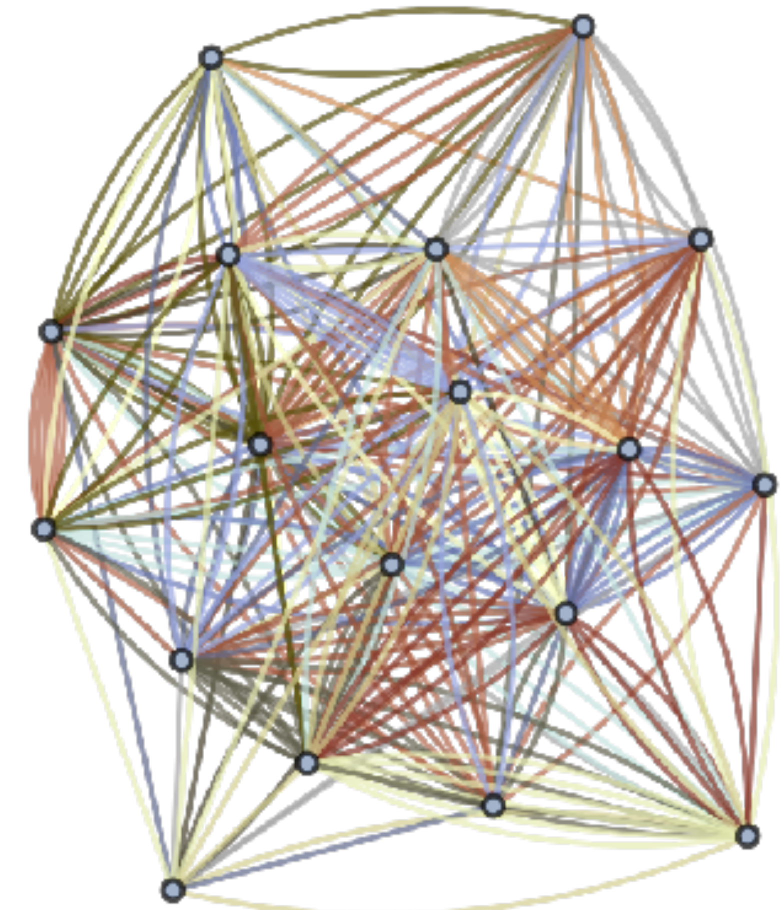


The SYK model has "dual" description
in which an extra spatial dimension, ζ, emerges.
The curvature of this "emergent" spacetime is described
by Einstein's theory of general relativity

SYK and black holes

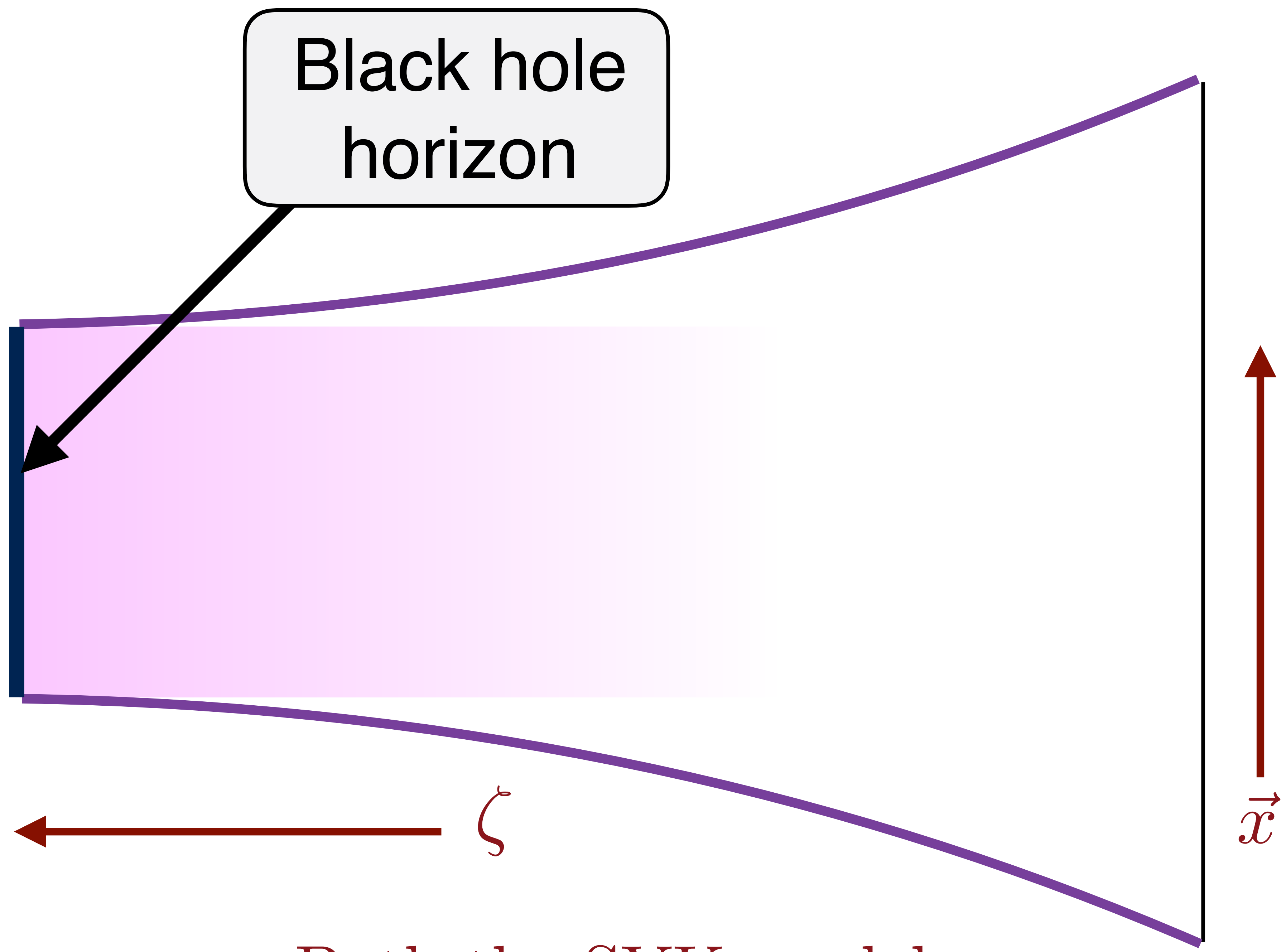


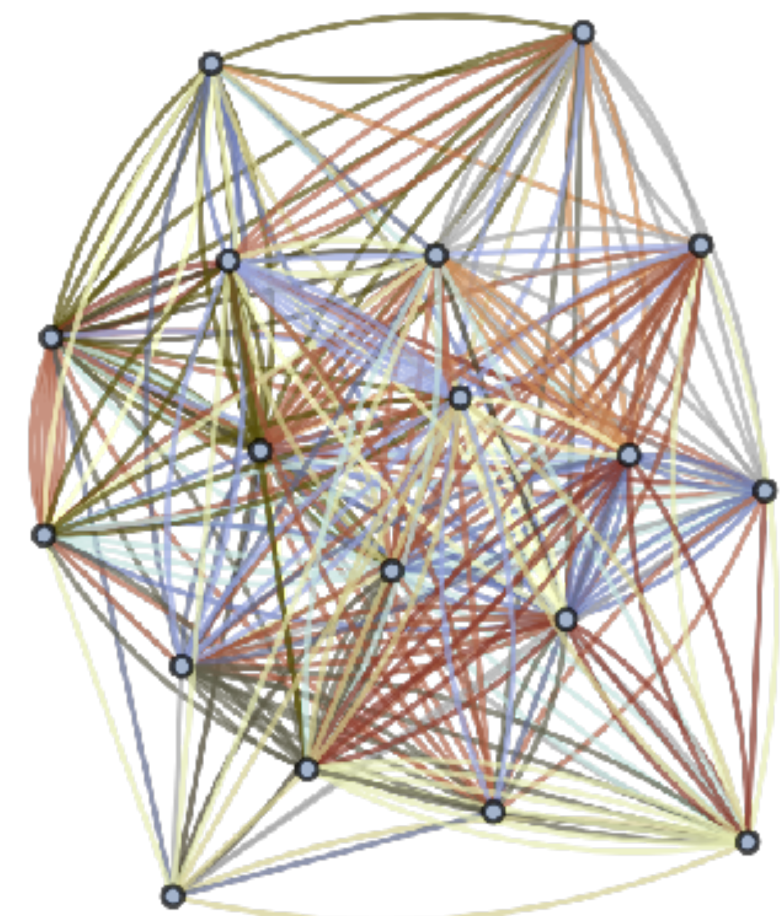


An extra spatial dimension emerges from quantum entanglement!

SS 2010; A. Kitaev, 2015

SYK and black holes

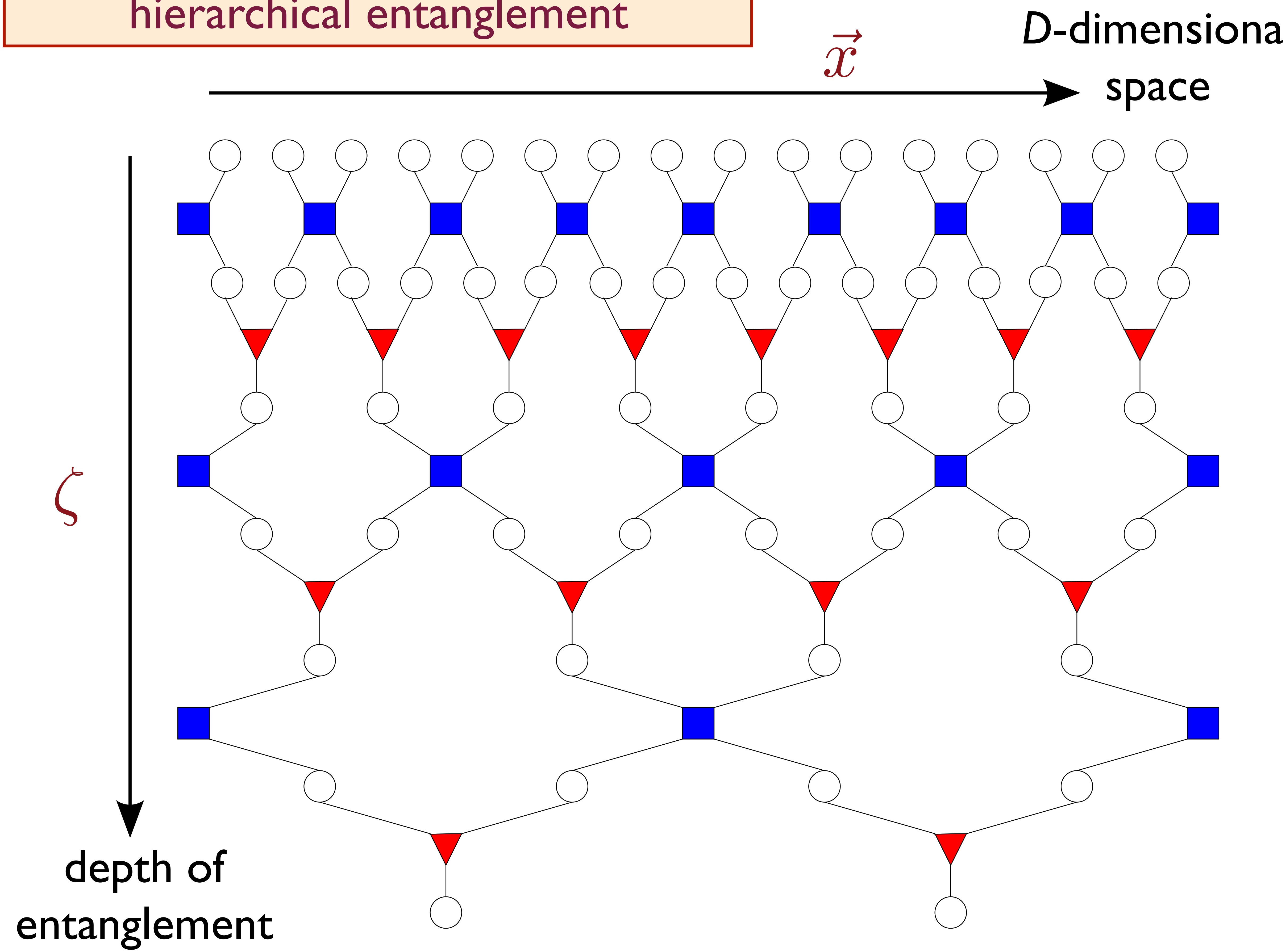


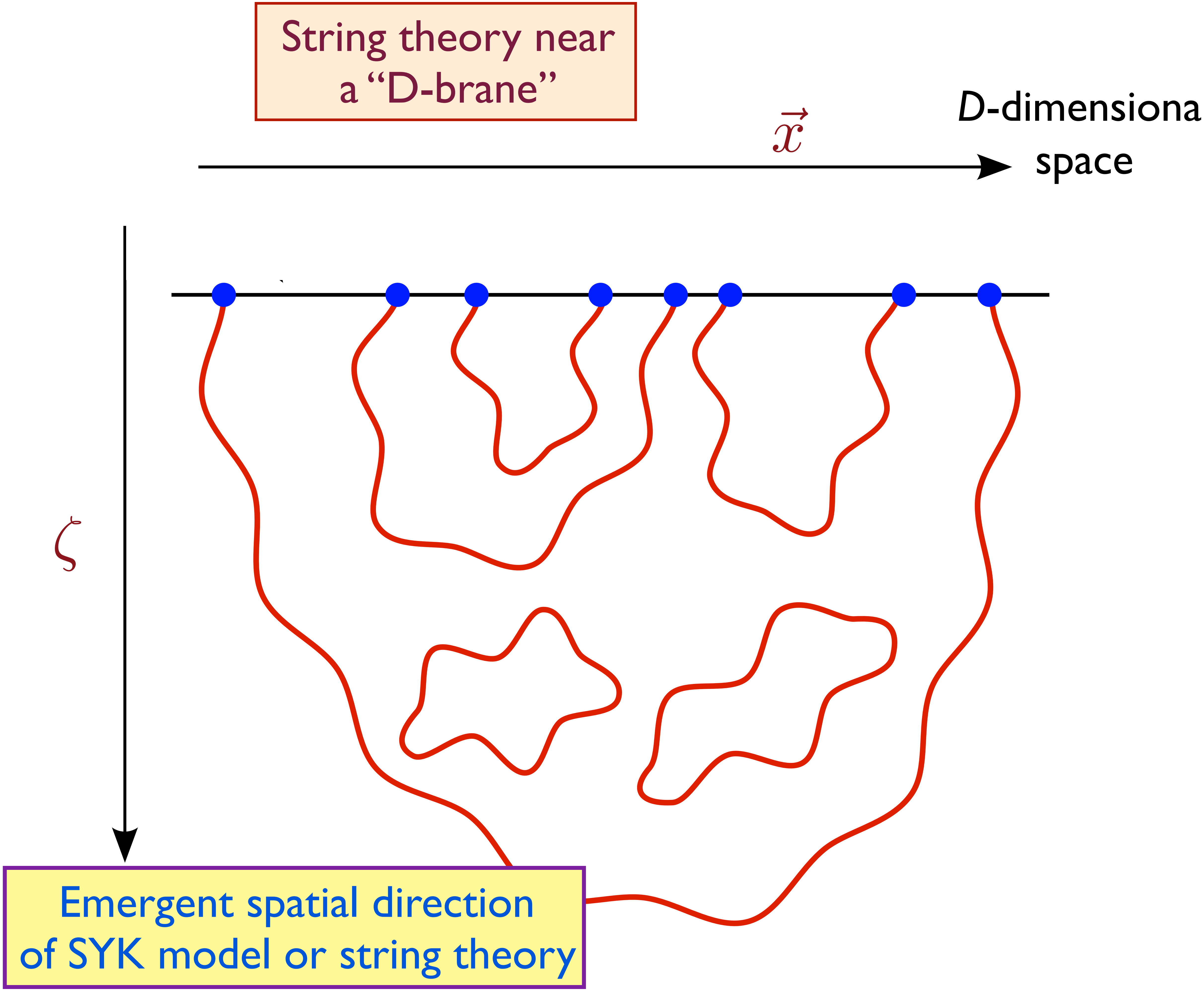


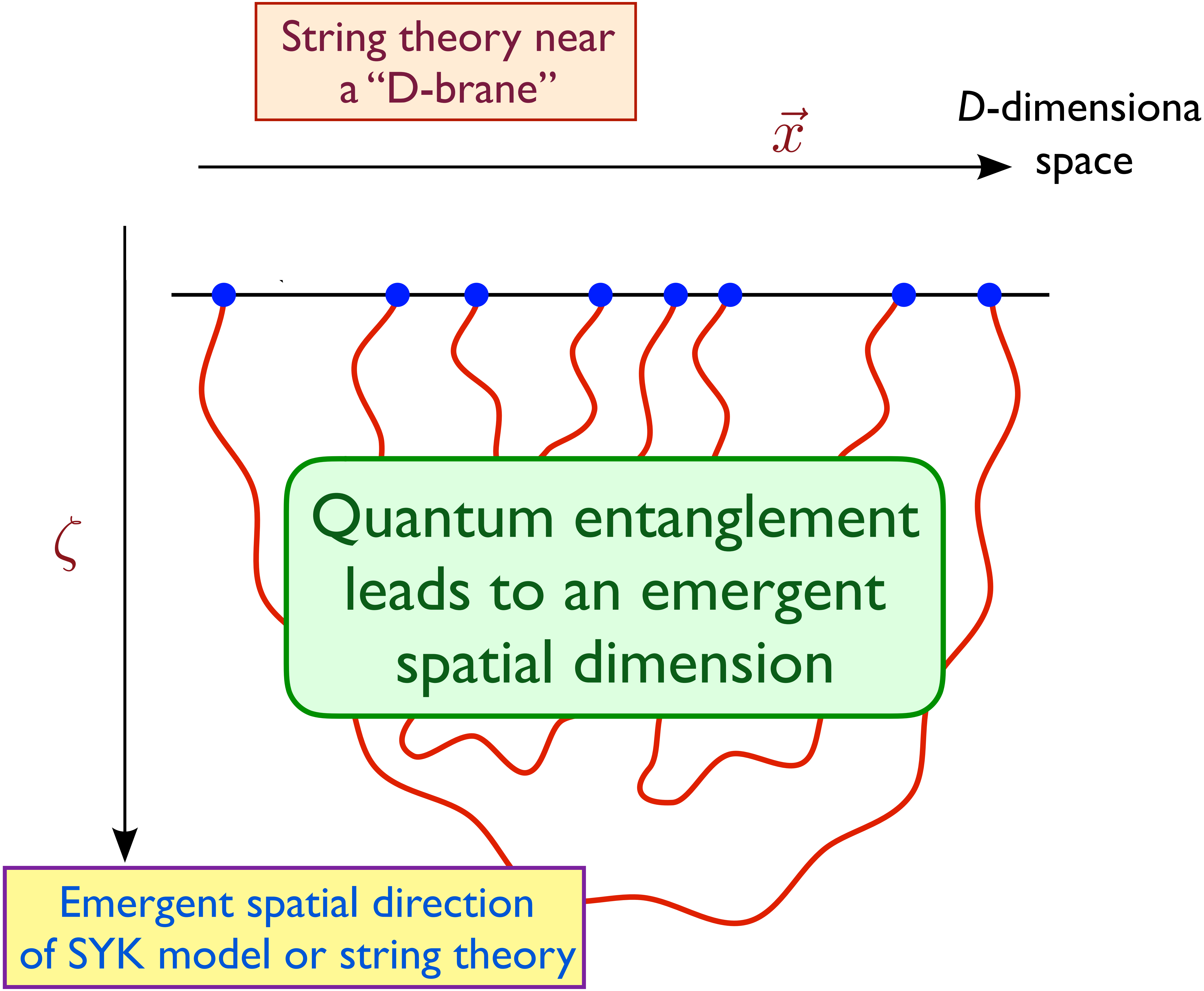
Both the SYK model
and the theory of gravity
have a time to quantum chaos $= \dfrac{\hbar}{2\pi k_B T}$

A. Kitaev, 2015
Maldacena, Stanford 2016

Tensor network of hierarchical entanglement




String theory near a “D-brane”
$\vec{x}$
D-dimensional space
ζ
Emergent spatial direction of SYK model or string theory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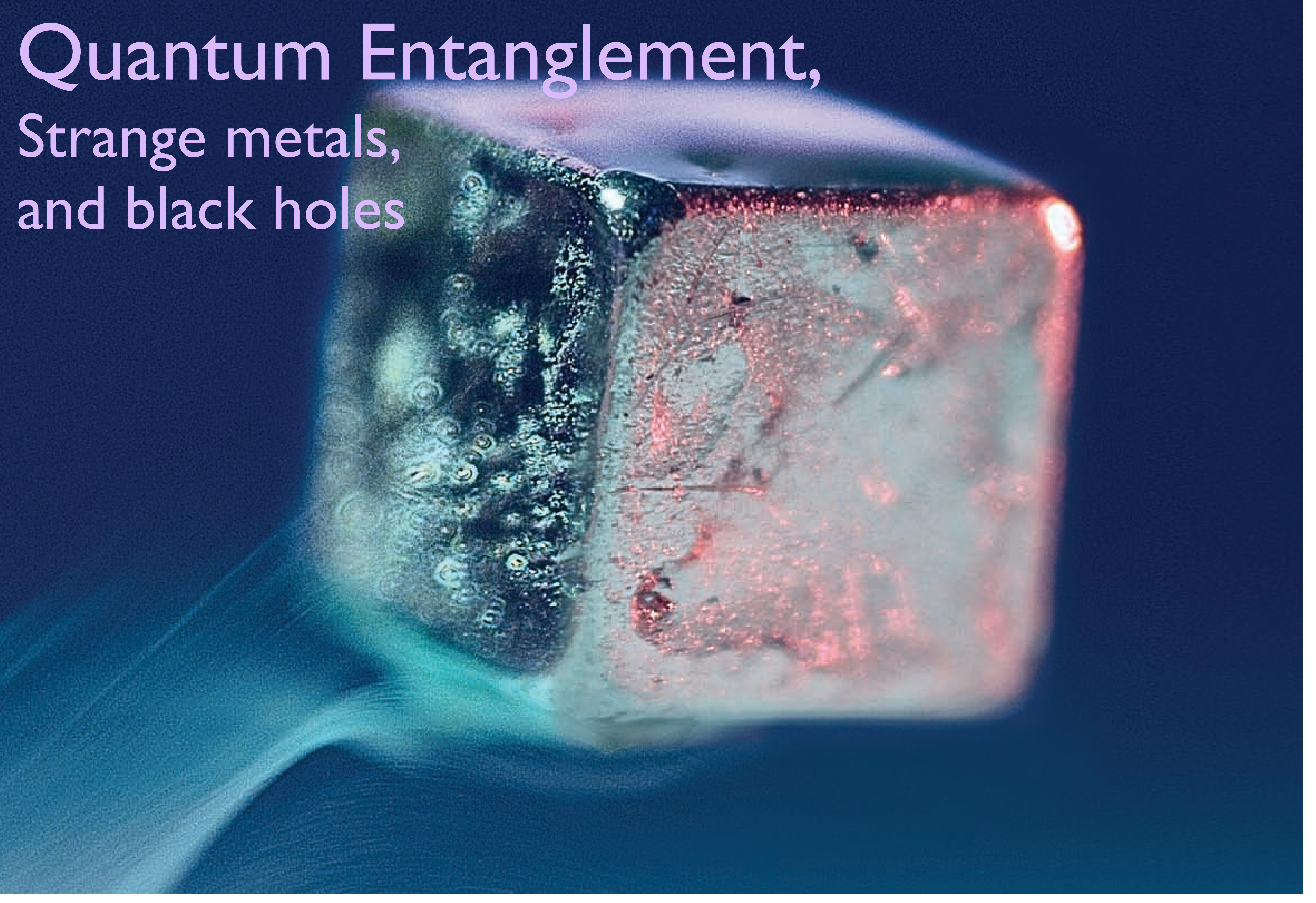
Quantum Entanglement,
Strange metals, and black holes



Subir Sachdev, Harvard University and TIFR