Spooky action at a distance: in the lab and in black holes

Stonebridge at Montgomery
November 6, 2021

Subir Sachdev

INSTITUTE FOR ADVANCED STUDY

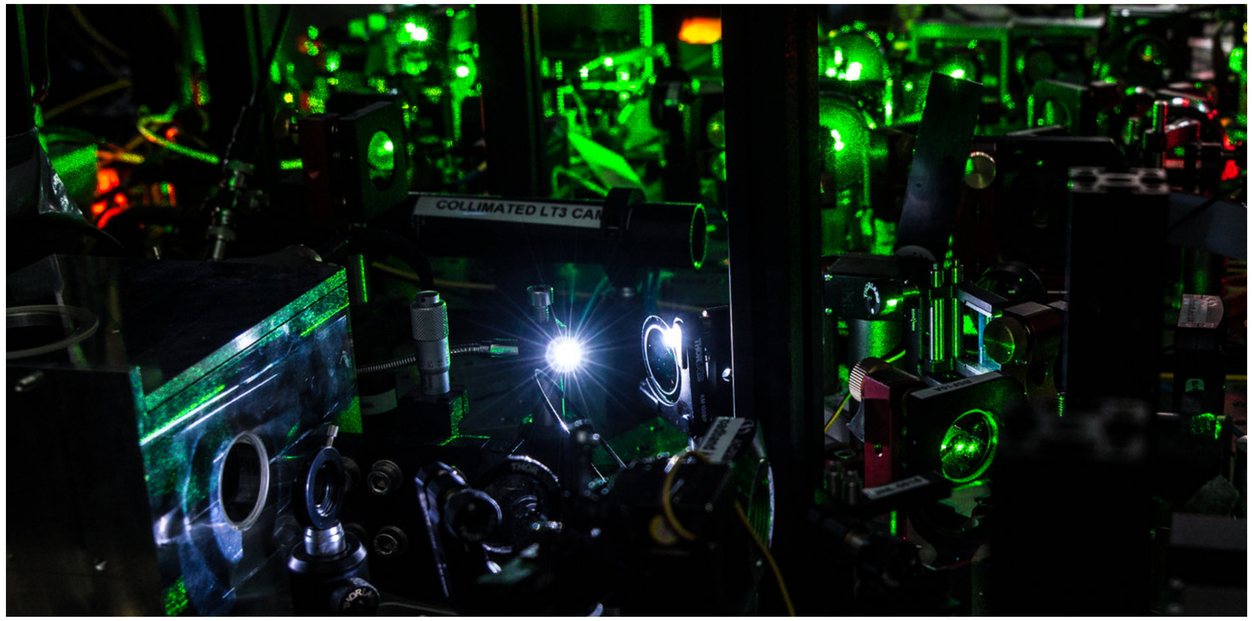
HARVARD

The New York Times

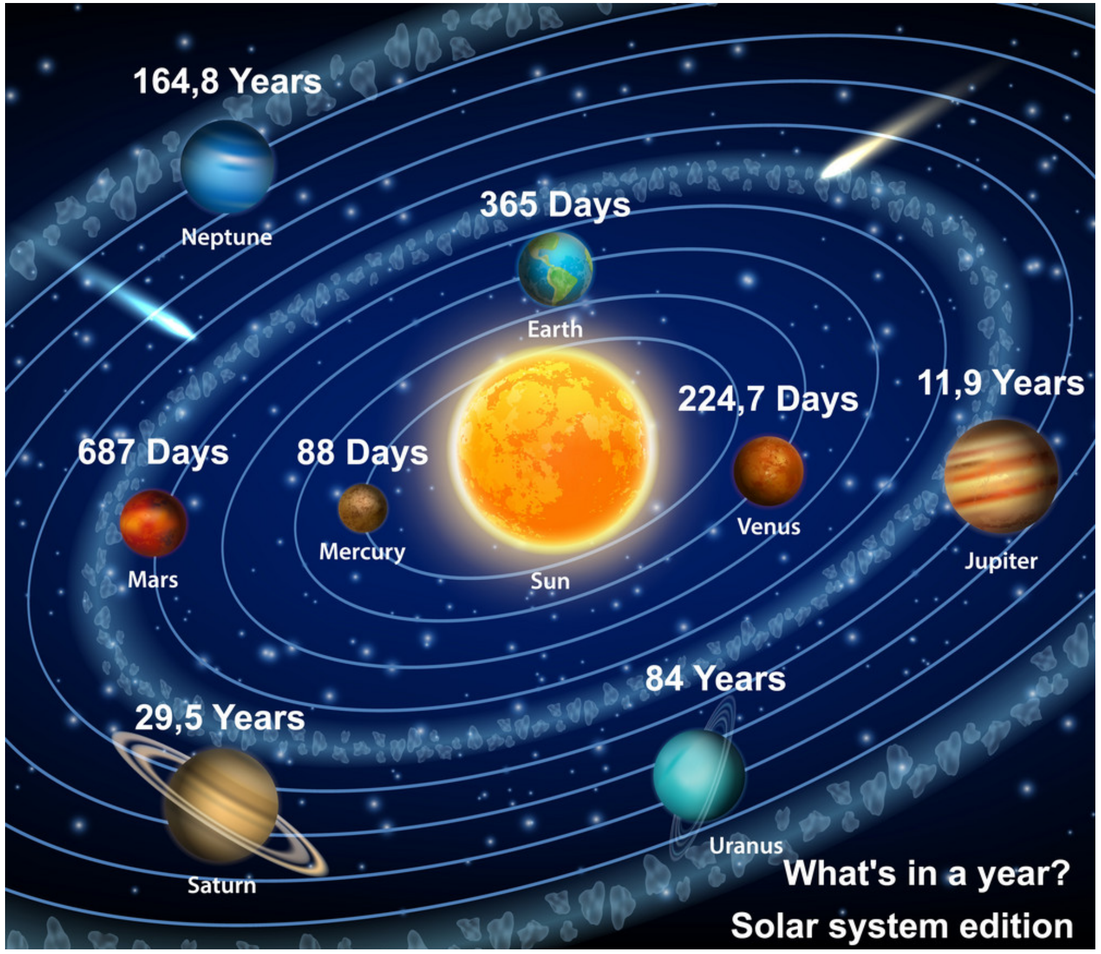
Sorry, Einstein. Quantum Study Suggests ‘Spooky Action’ Is Real.

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

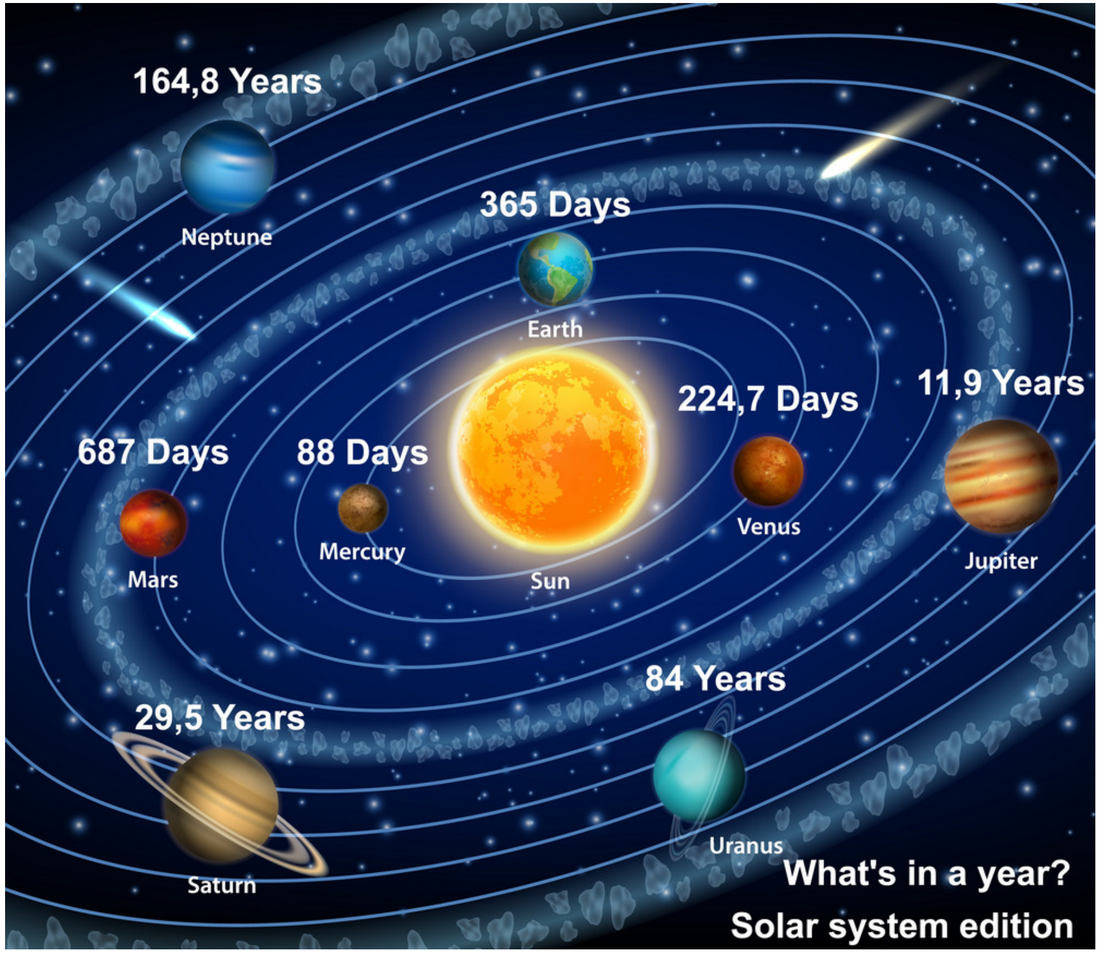
In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other’s behavior.



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.



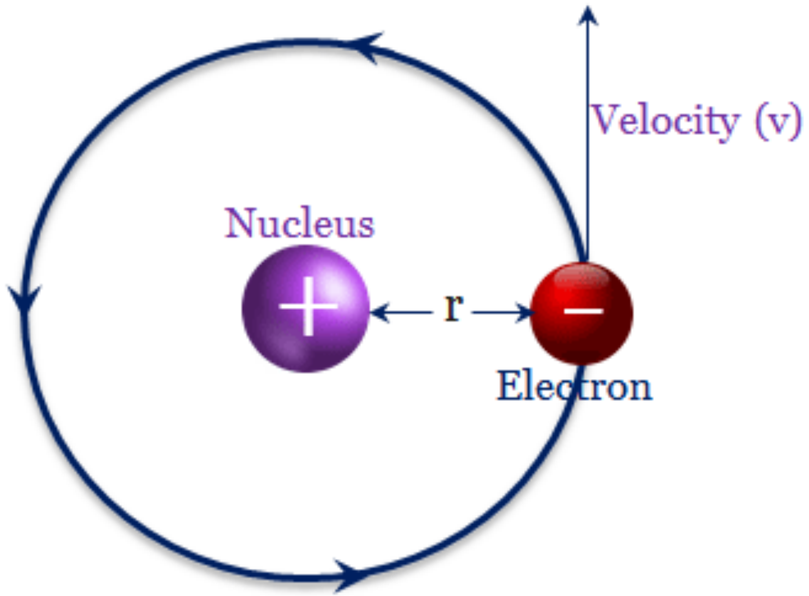
Newton showed (1687) that the same laws of motion applied on planetary length scales ($\sim$ 1 trillion meters) and the length scale of an apple tree (1 meter).



Newton showed (1687) that the same laws of motion applied on planetary length scales ($\sim$ 1 trillion meters) and the length scale of an apple tree (1 meter).

What happens on smaller distances ?

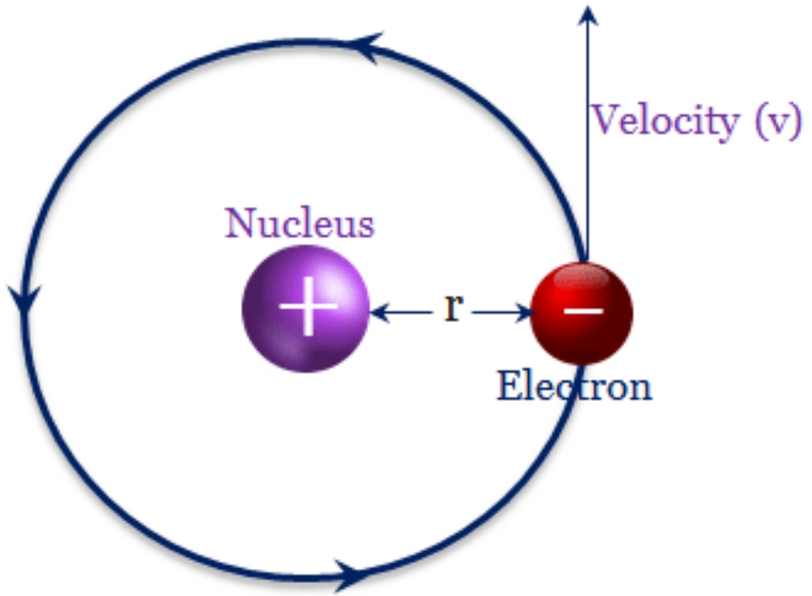
Hydrogen atom



$\Rightarrow 10^{-10}$ meters $\Leftarrow$

The motion of the electron around the proton is *not* described by the same theory as the motion of the planets around the sun.

Hydrogen atom

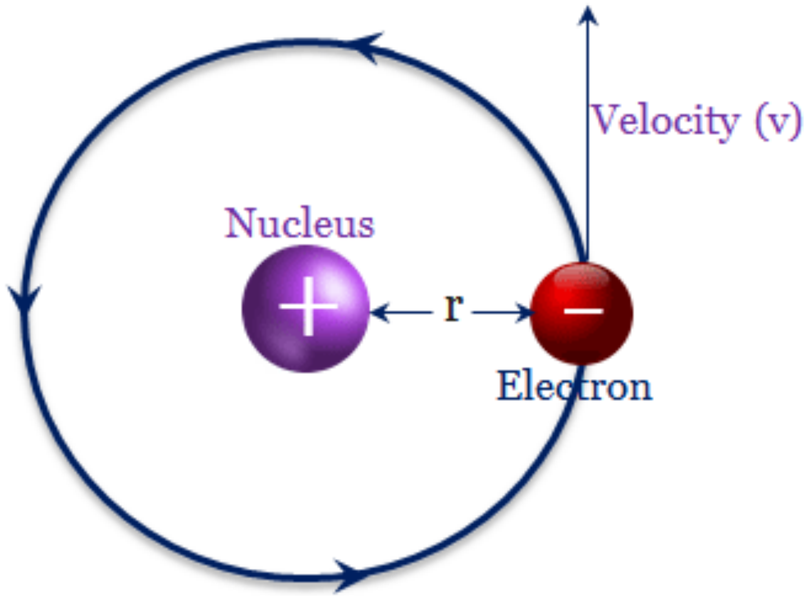


$\Rightarrow 10^{-10}$ meters $\Leftarrow$

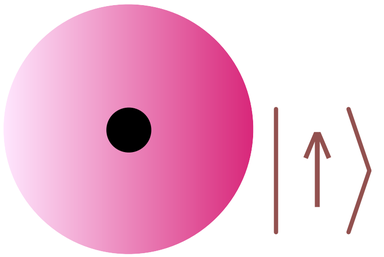
The motion of the electron around the proton is *not* described by the same theory as the motion of the planets around the sun.

It is described by the quantum theory of Schrödinger and Heisenberg (1925).

Hydrogen atom



$=$

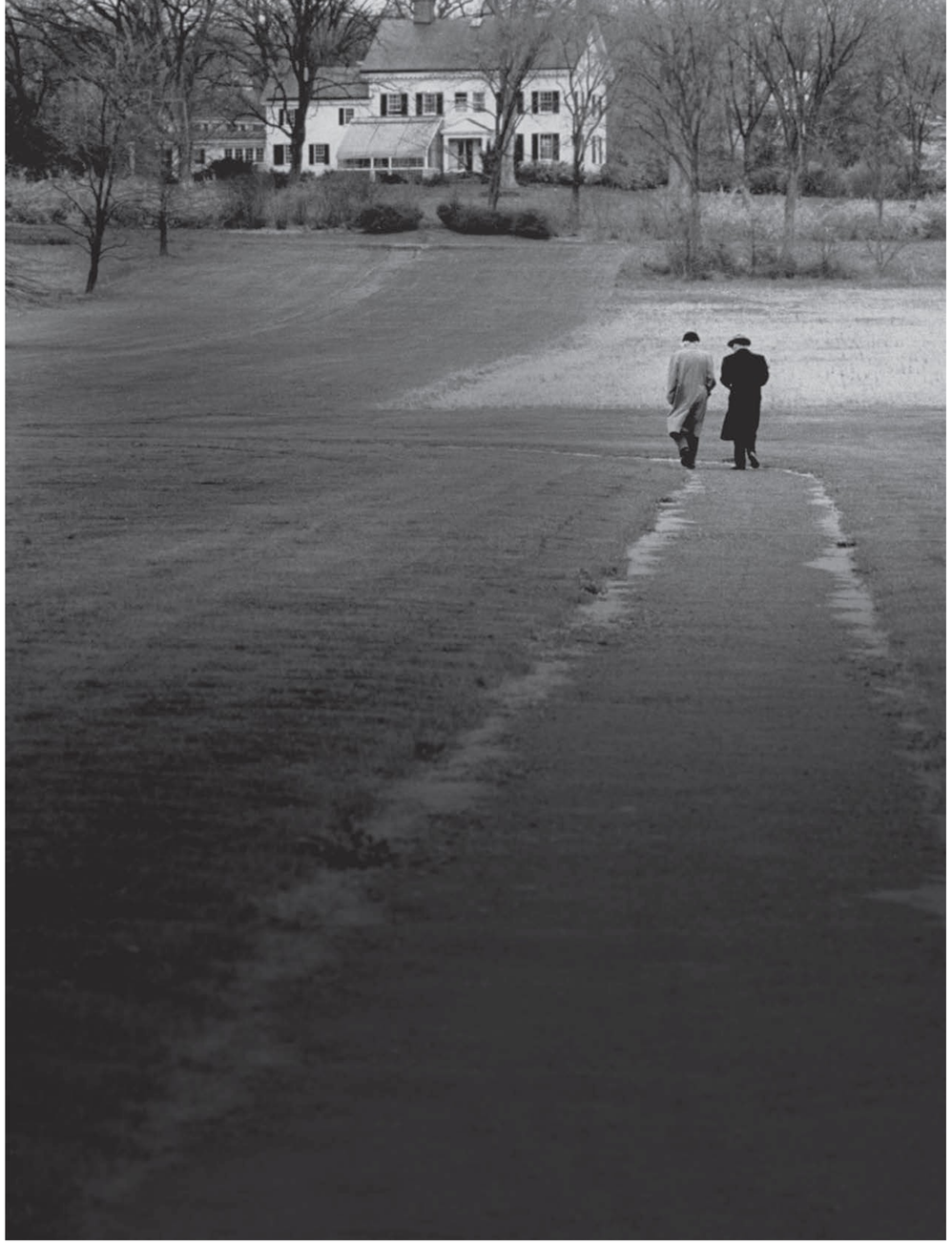


$\Rightarrow 10^{-10}$ meters $\Leftarrow$

The motion of the electron around the proton is *not* described by the same theory as the motion of the planets around the sun.

The electron also spins on its own axis $|\uparrow\rangle$ or $|\downarrow\rangle$

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.



Albert Einstein and Kurt Godel, 1954

View near our window,
Godel Lane, Princeton, Nov 6, 2021

View near
our window,
Godel Lane,
Princeton,
Nov 6, 2021

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)

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

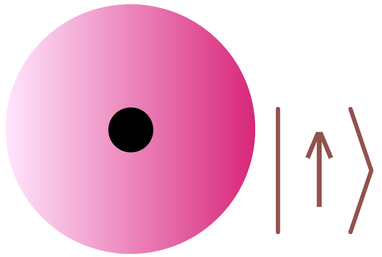
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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

(Received March 25, 1935)

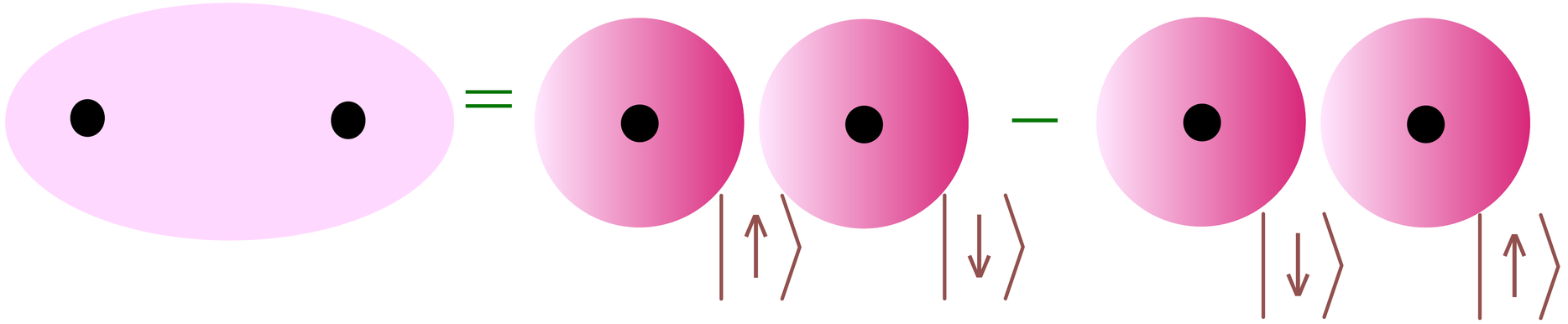
Molecules

Hydrogen atom:



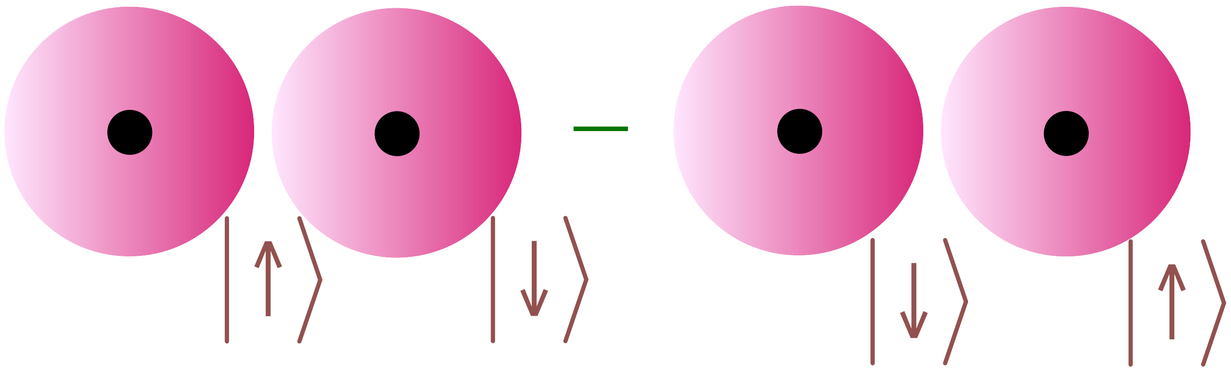
Covalent bond

Hydrogen molecule:



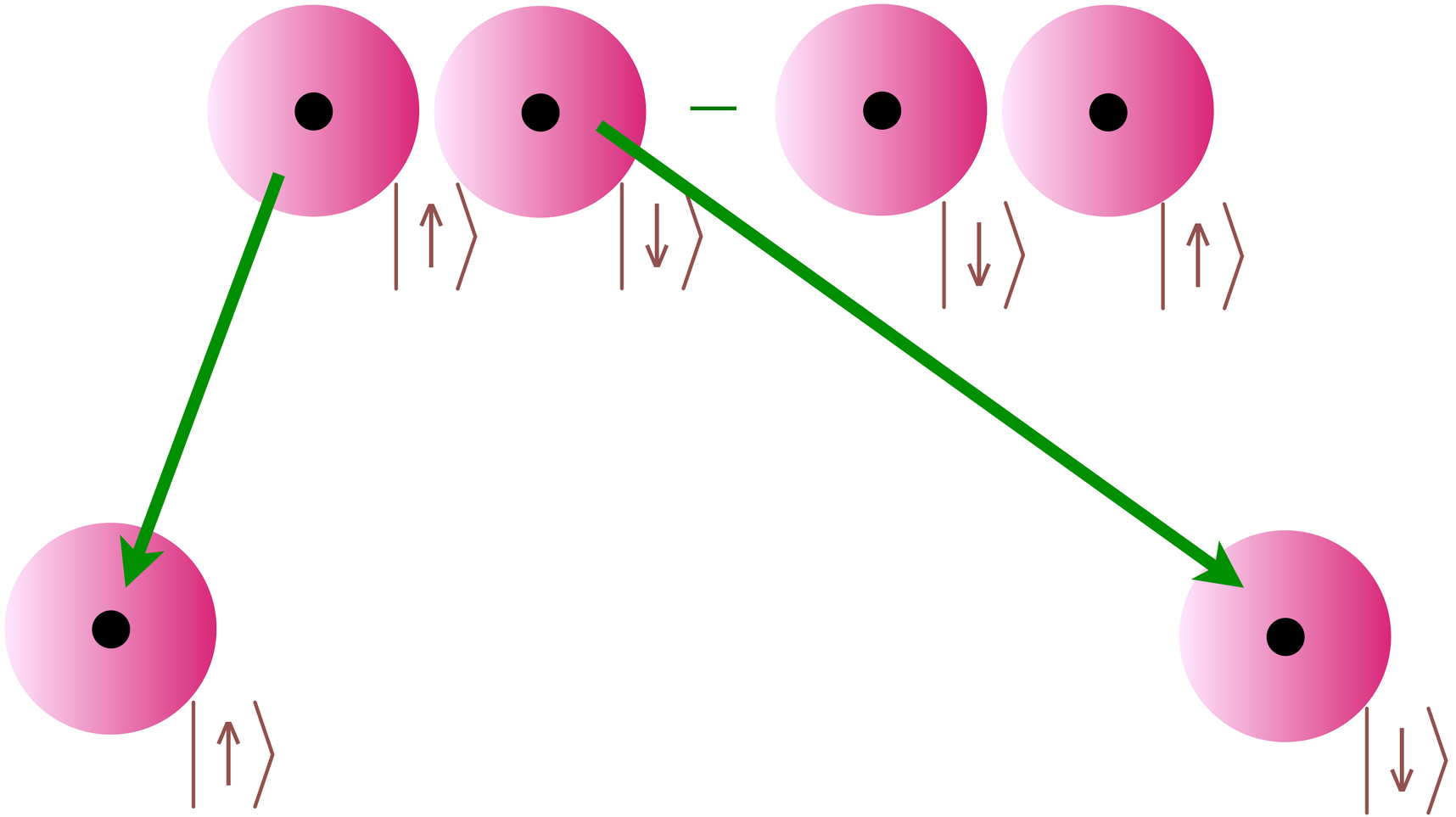
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



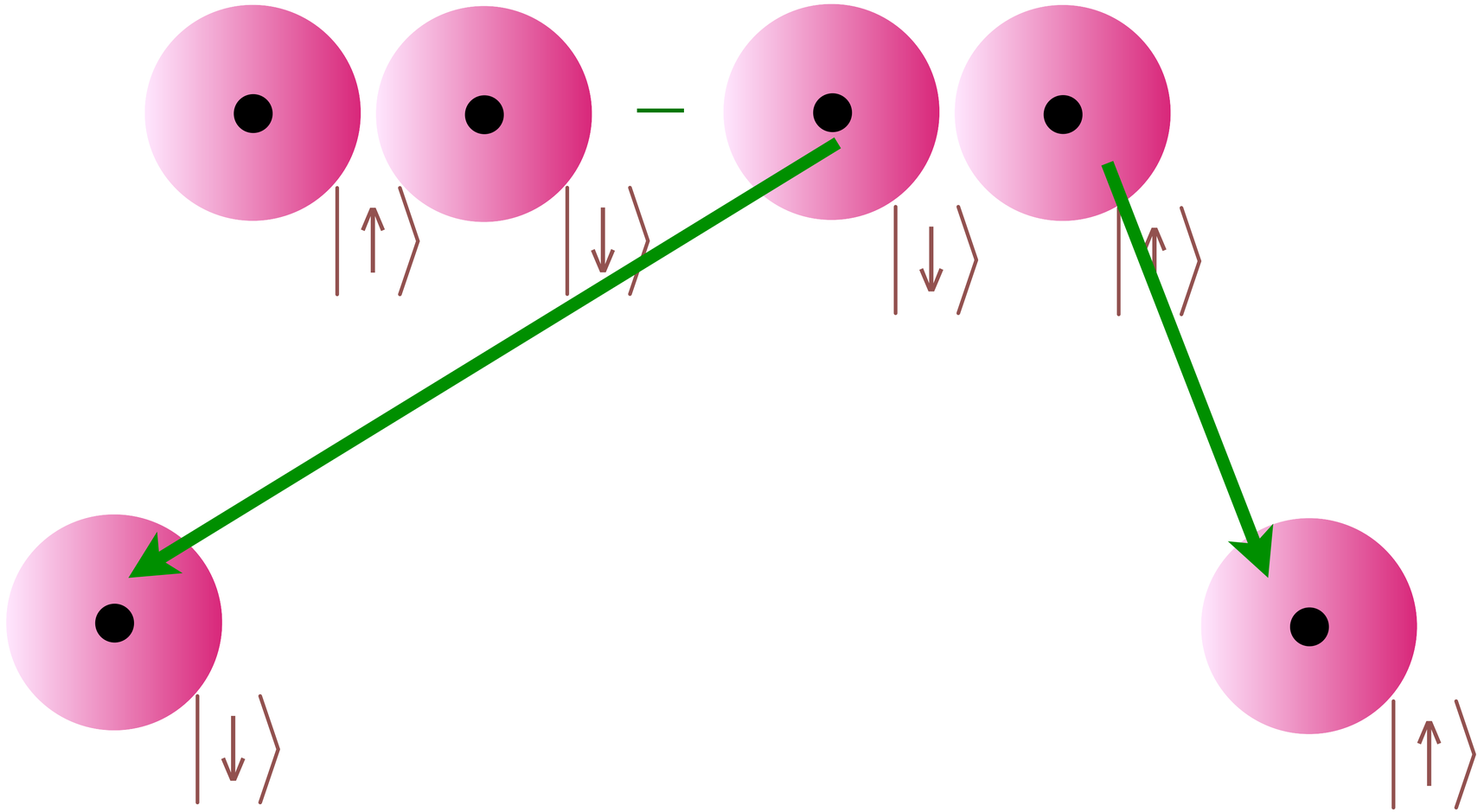
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



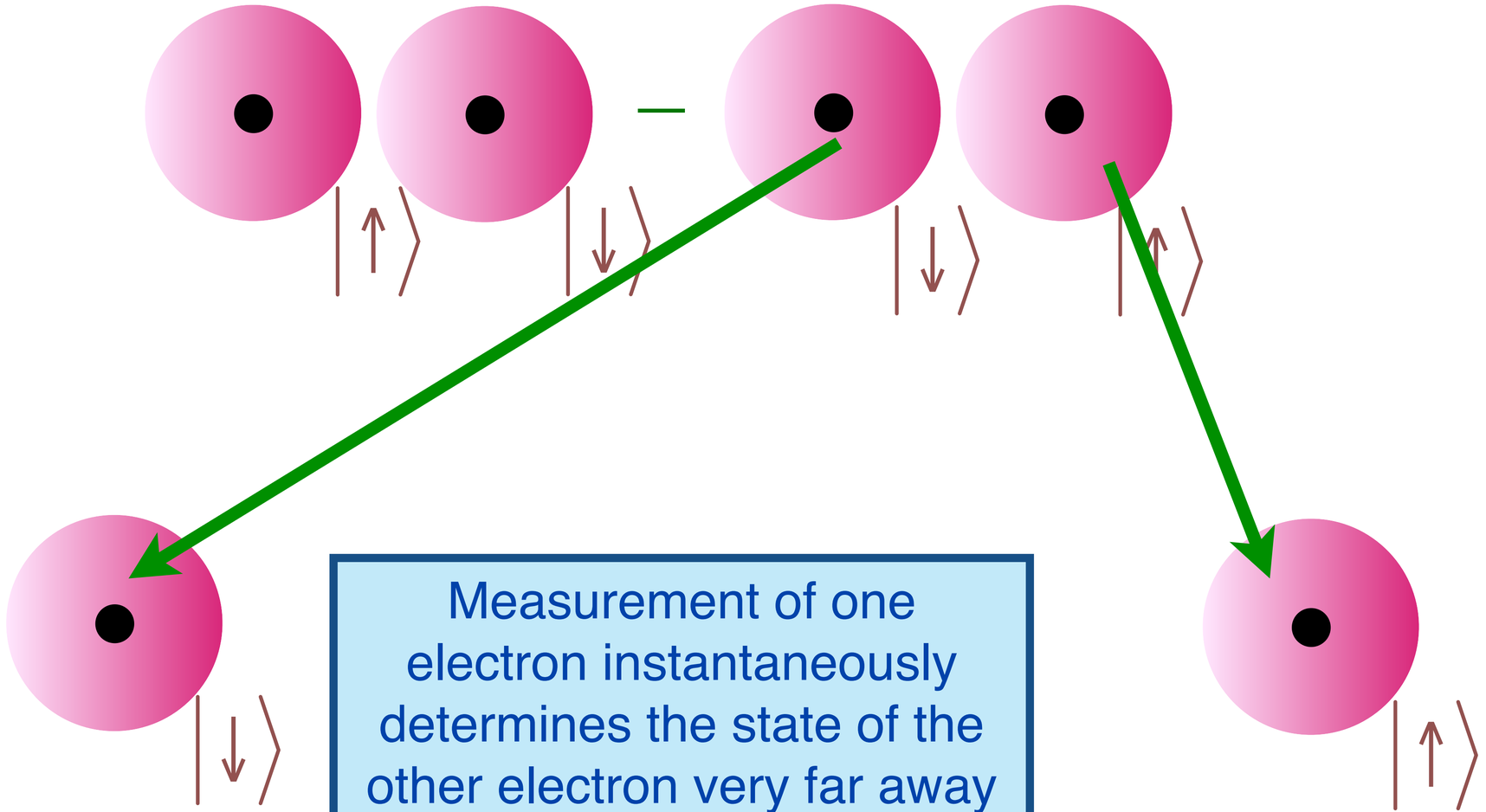
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



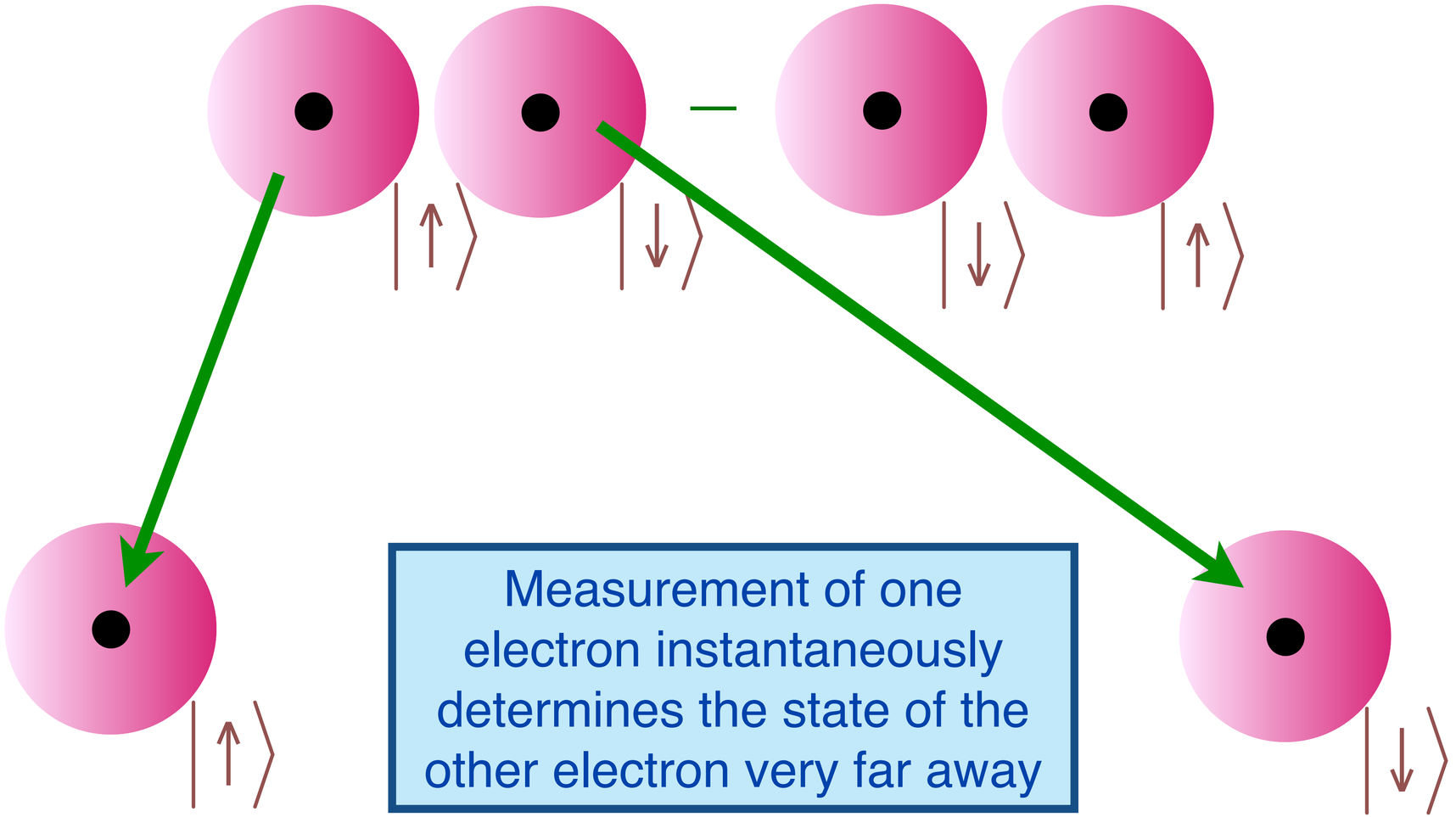
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



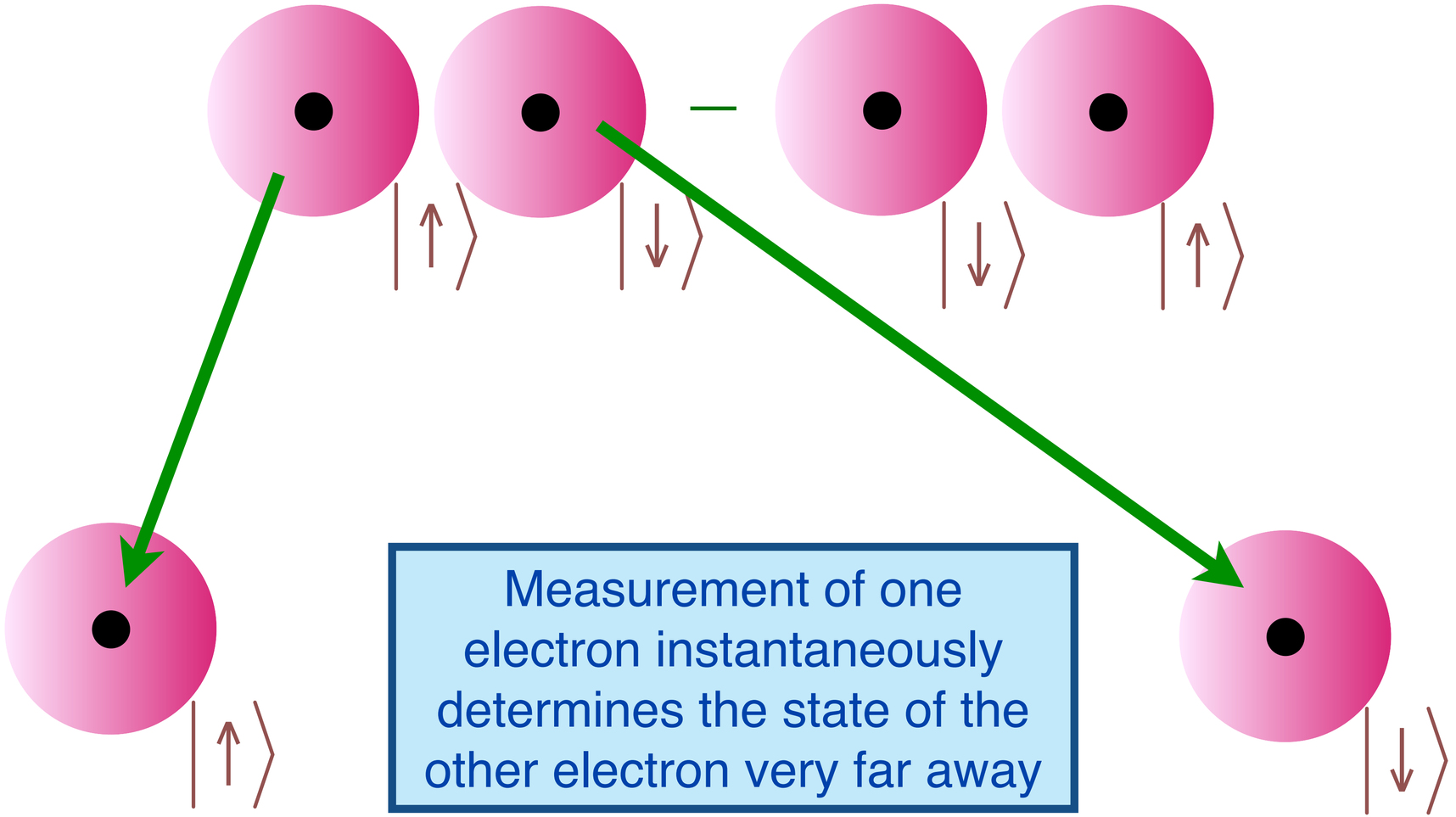
Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



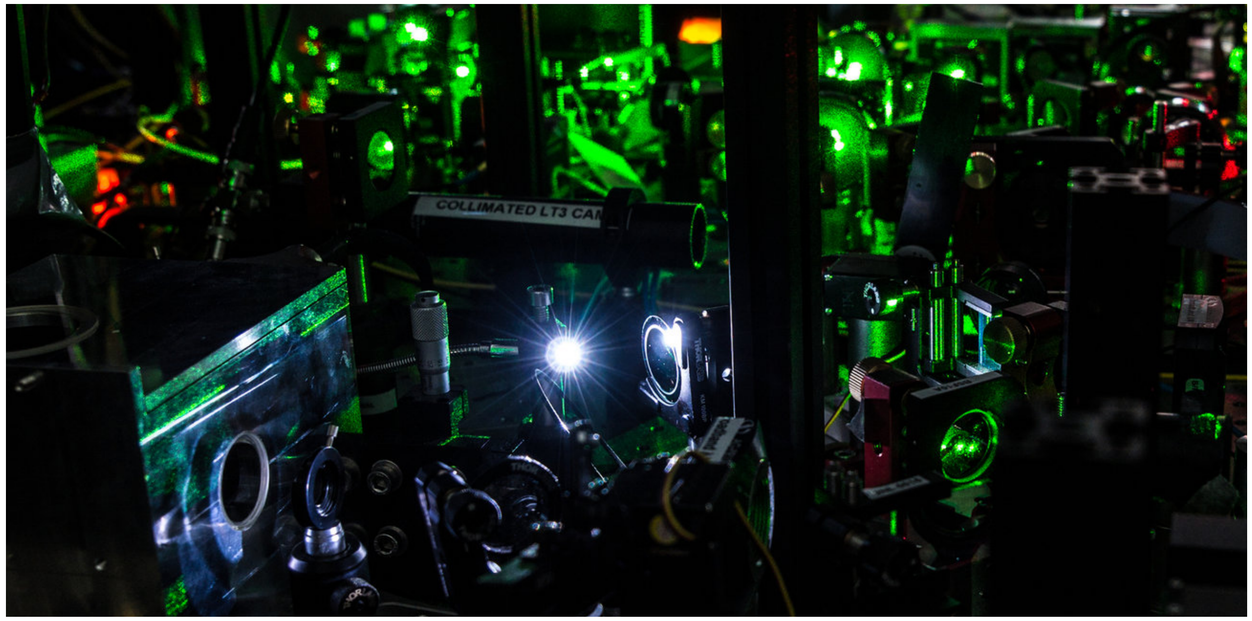
Spooky action at a distance !

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.

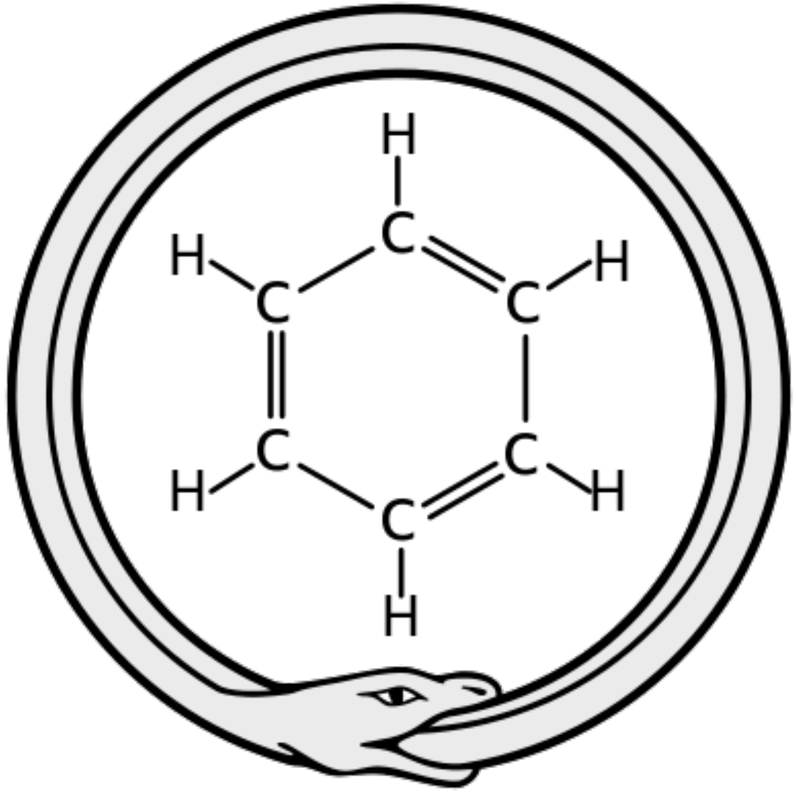


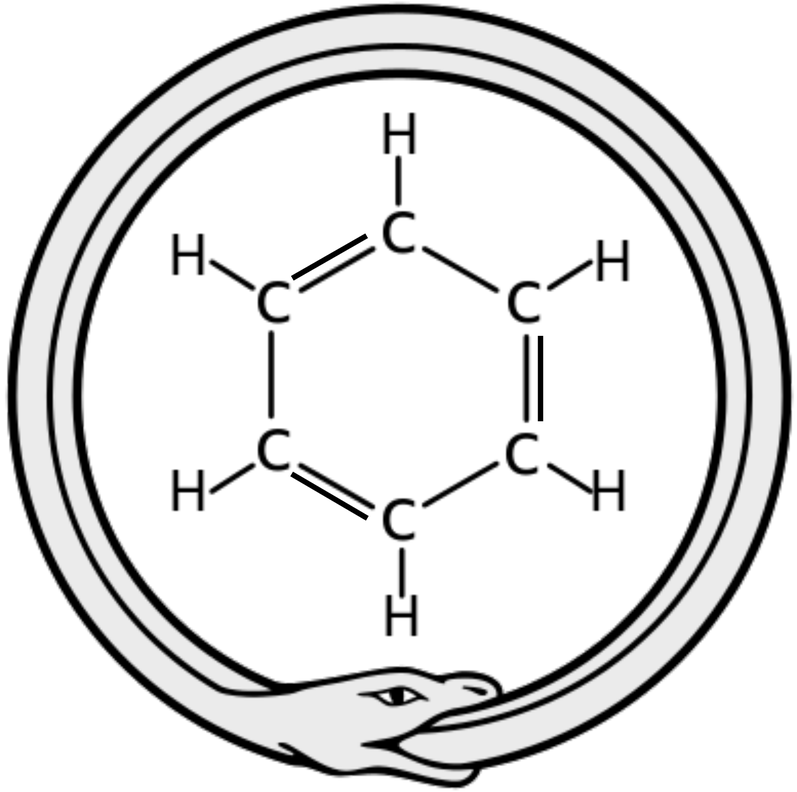
Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

August Kekule, theory of the benzene molecule, 1865

Kekule's 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 (this is an ancient symbol known as the ouroboros).



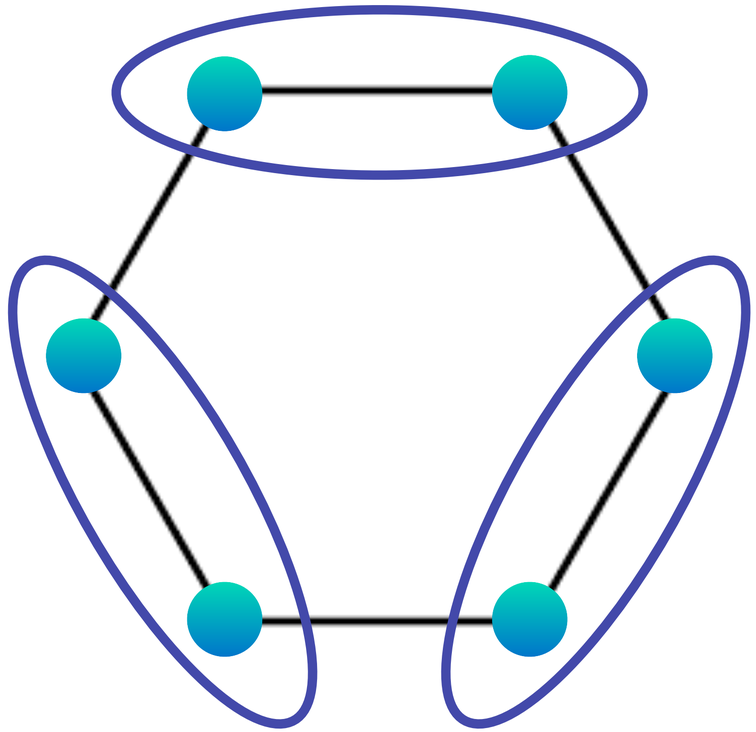


The most remarkable new idea in the quantum theory is the
principle of superposition:
a physical system can be in a
superposition of two (or more) distinct states.

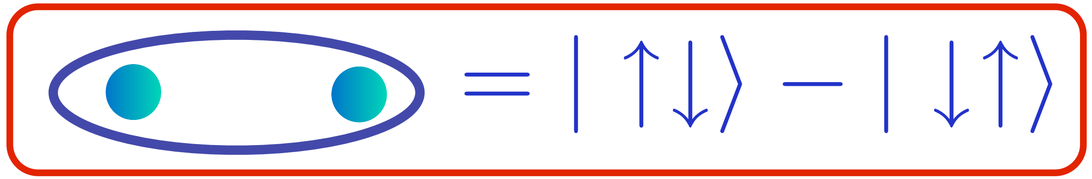
The most remarkable new idea in the quantum theory is the *principle of superposition*:
a physical system can be in a
superposition of two (or more) distinct states.

Benzene

Benzene has a
superposition of
covalent bonds,
each of which
is a superposition
of a pair of electrons!



"Resonating"
covalent
bonds



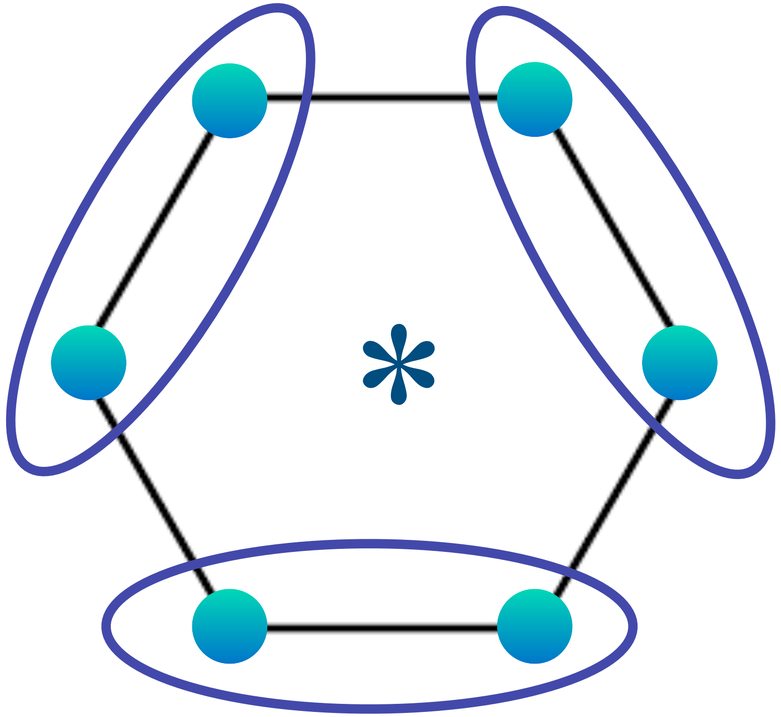
The most remarkable new idea in the quantum theory is the

principle of superposition:

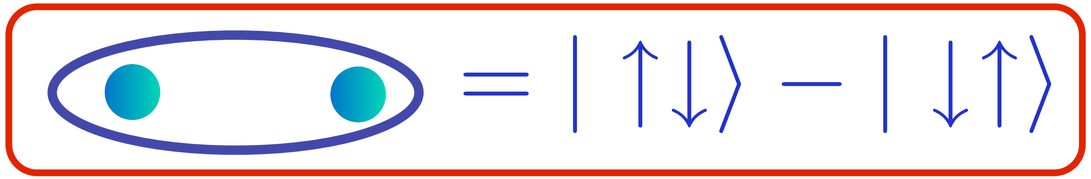
a physical system can be in a
superposition of two (or more) distinct states.

Benzene

Benzene has a
superposition of
covalent bonds,
each of which
is a superposition
of a pair of electrons!



"Resonating"
covalent
bonds



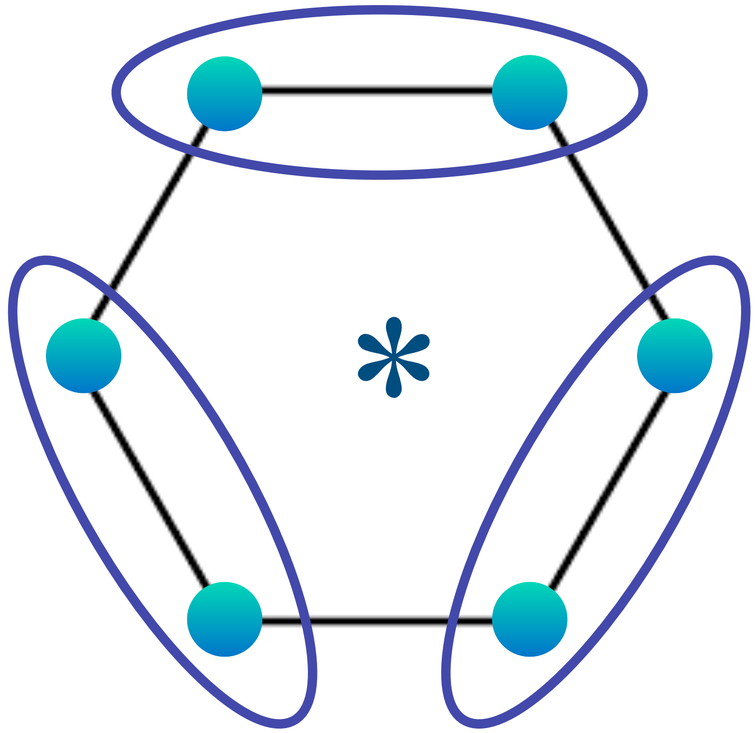
The most remarkable new idea in the quantum theory is the

principle of superposition:

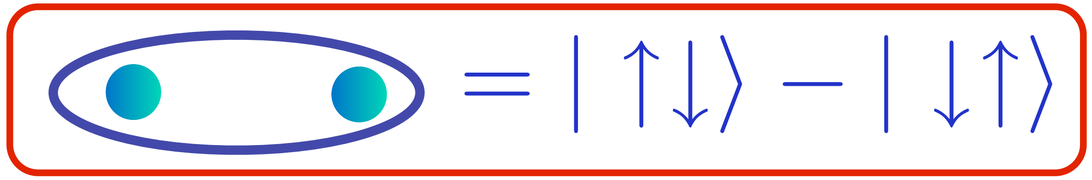
a physical system can be in a
superposition of two (or more) distinct states.

Benzene

Benzene has a
superposition of
covalent bonds,
each of which
is a superposition
of a pair of electrons!

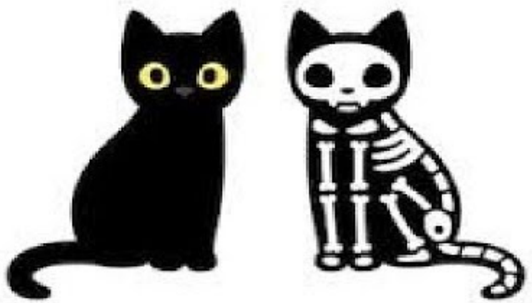


"Resonating"
covalent
bonds



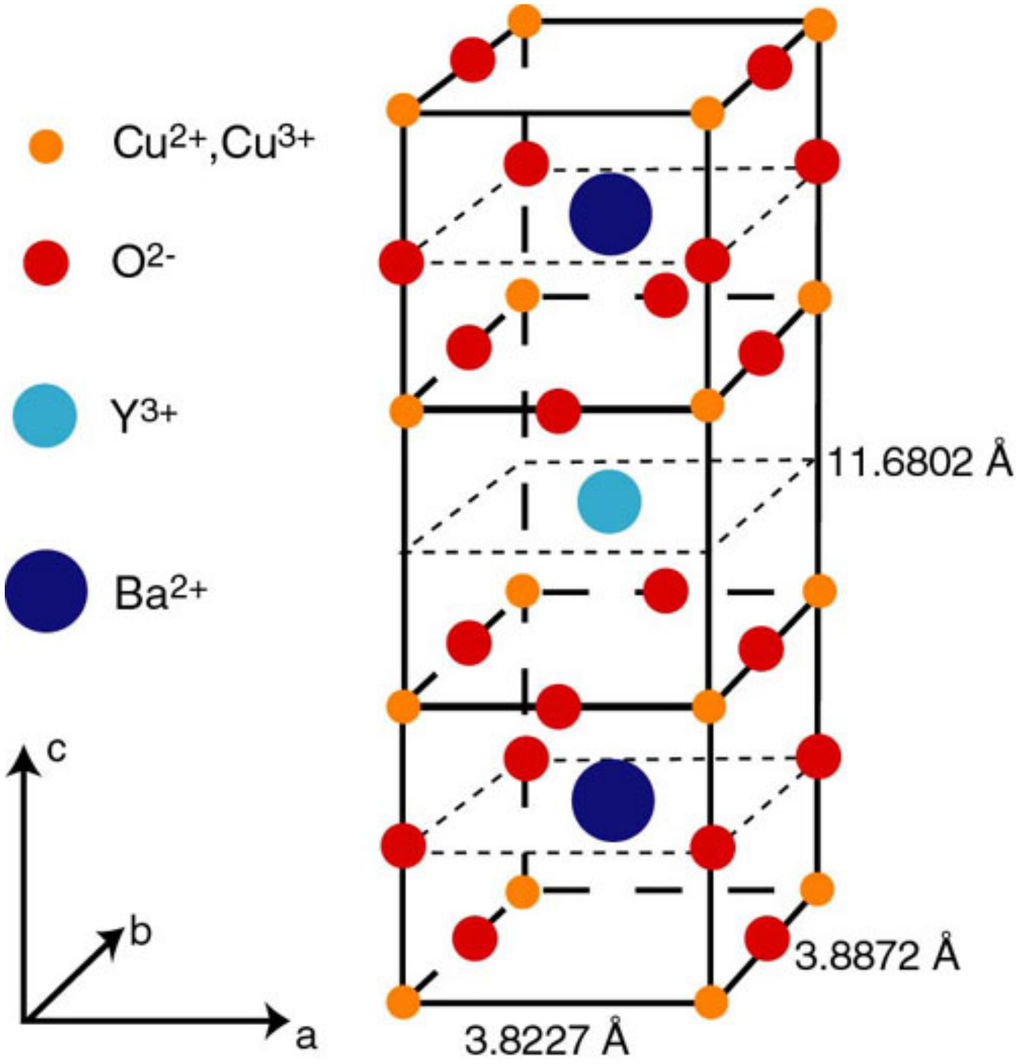
The most remarkable new idea in the quantum theory is the *principle of superposition*:
a physical system can be in a
superposition of two (or more) distinct states.

Schrodinger's Cat

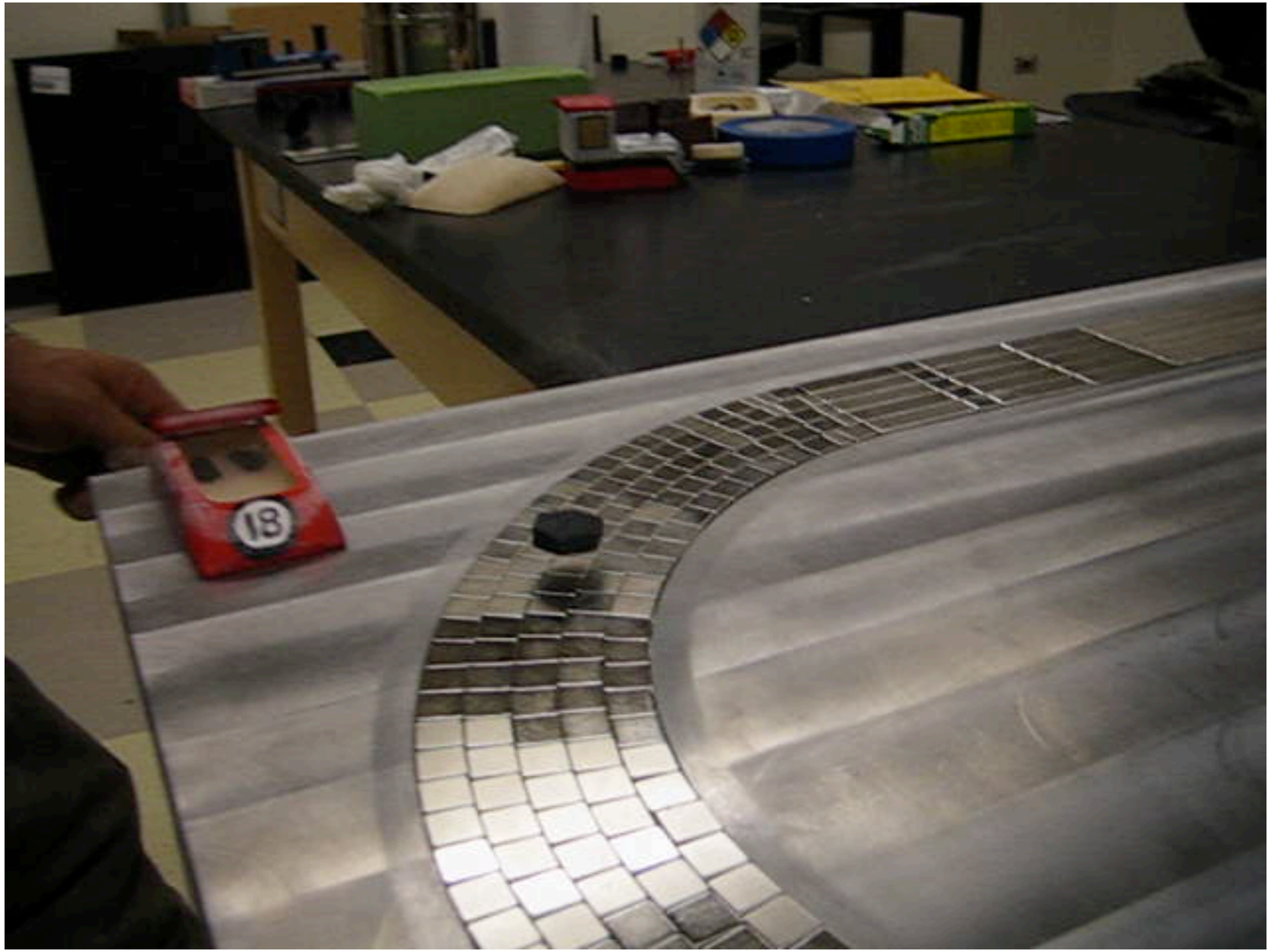


$$\frac{1}{\sqrt{2}}|\text{live cat}\rangle + \frac{1}{\sqrt{2}}|\text{dead cat}\rangle$$

High temperature superconductors



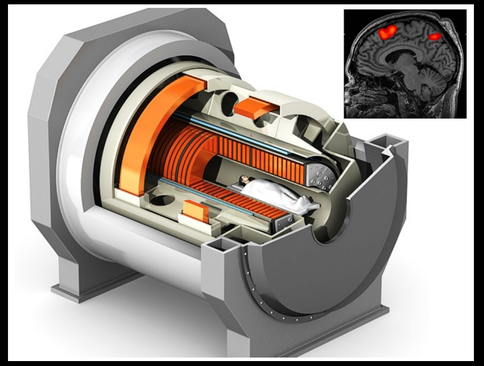
$$YBa_2Cu_3O_{6+x}$$



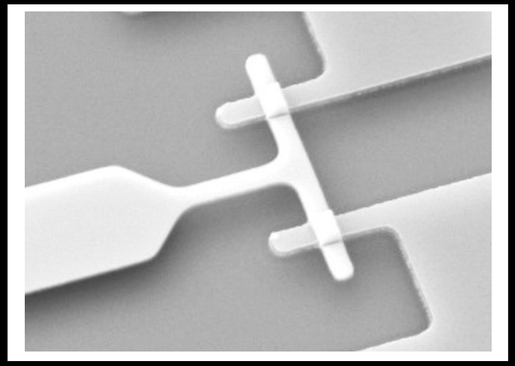
Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

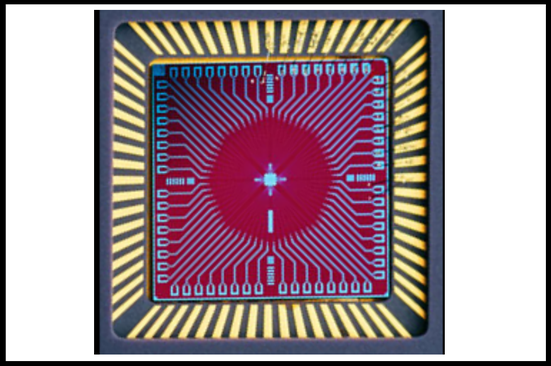
SUPERCONDUCTIVITY: SCIENTIFIC APPLICATIONS



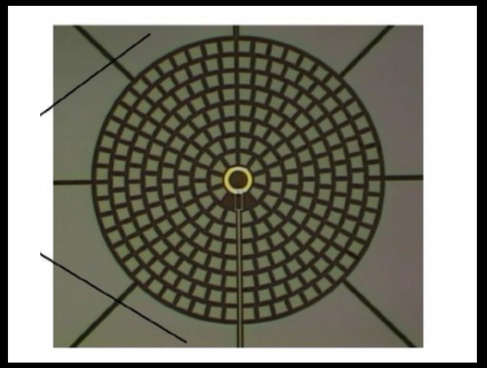
FUNCTIONAL MRI



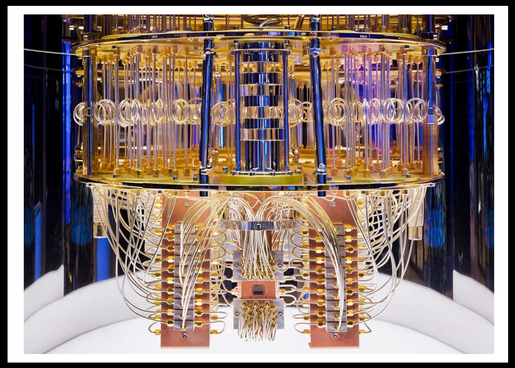
SQUID SENSORS



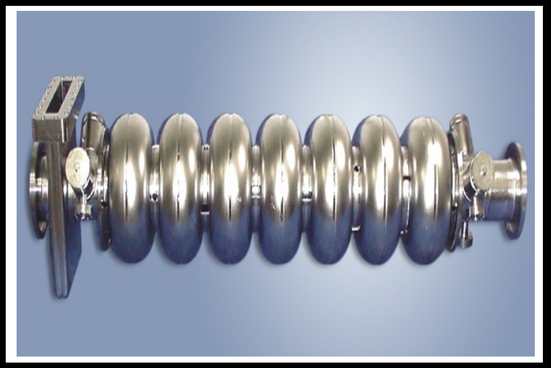
SINGLE PHOTON IMAGING



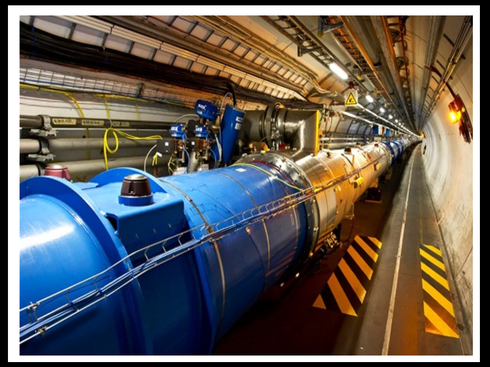
TRANS. EDGE BOLOMETER



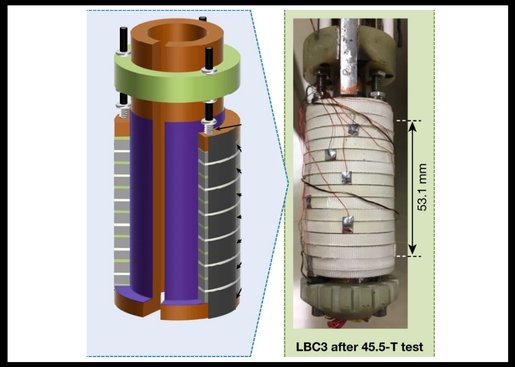
QUANTUM INFO. TECH.



HIGH ENERGY PHYSICS



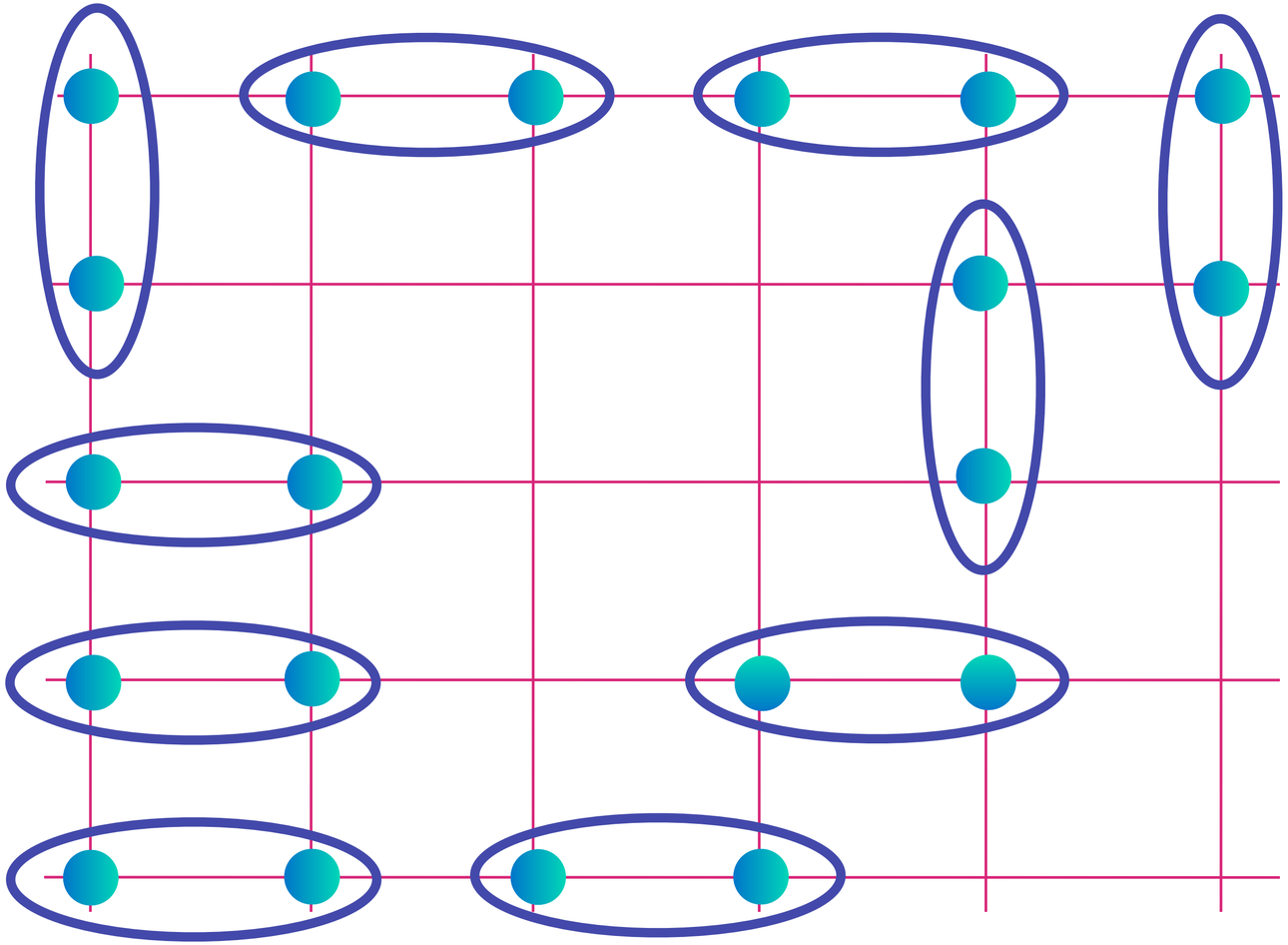
ACCELERATORS

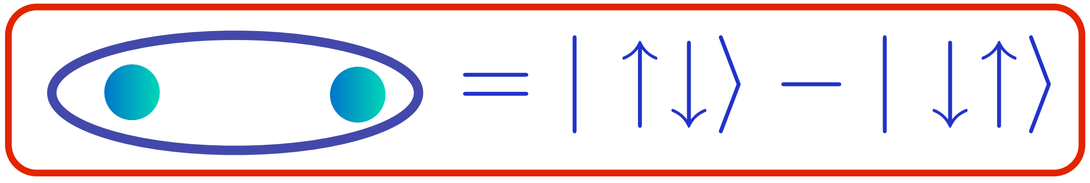


50+ TESLA MAGNETS

TOKOMAK FUSION

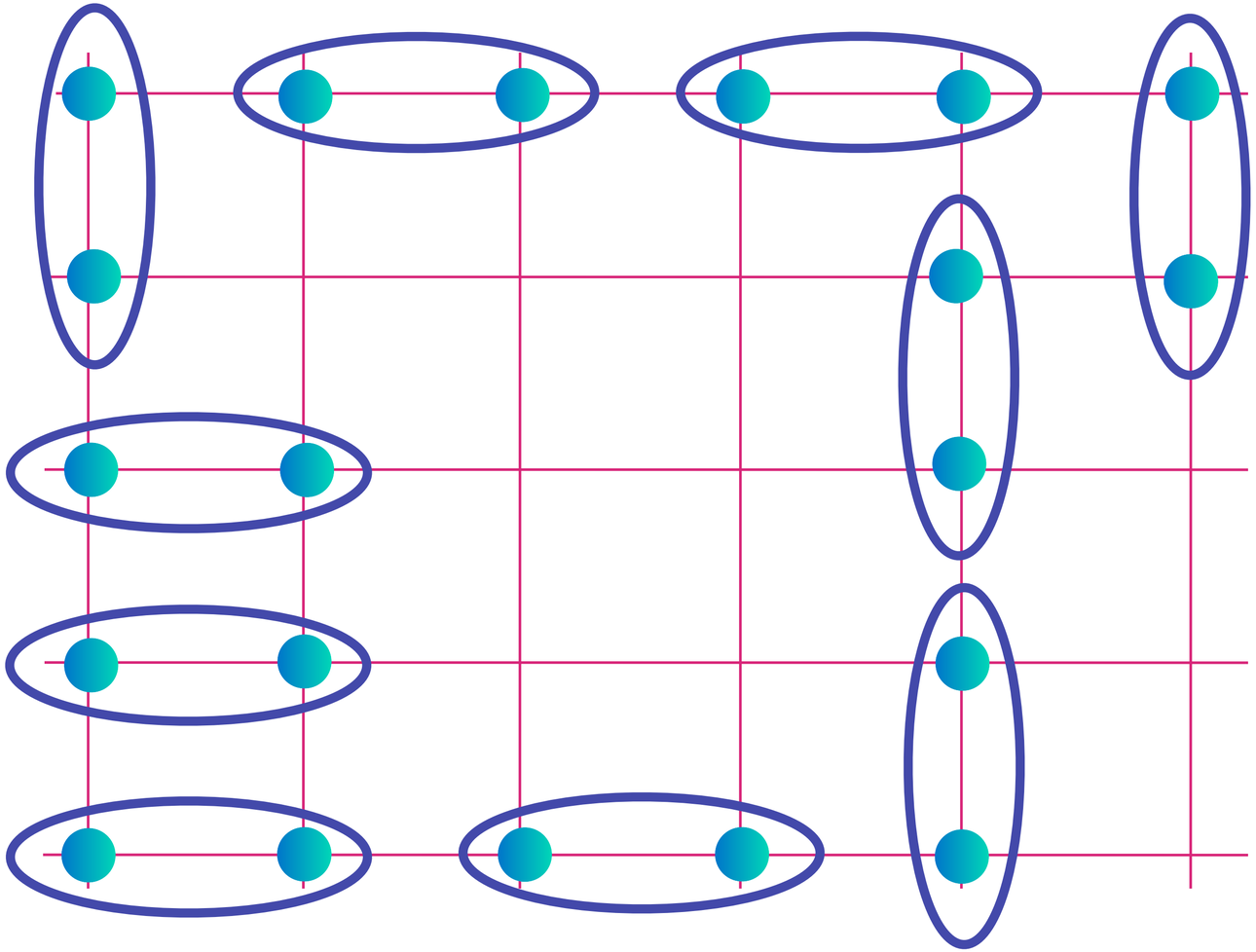
The dance of electrons on Cu atoms in YBCO





Electrons entangle "en masse" by exchanging partners, and there is long-range quantum entanglement

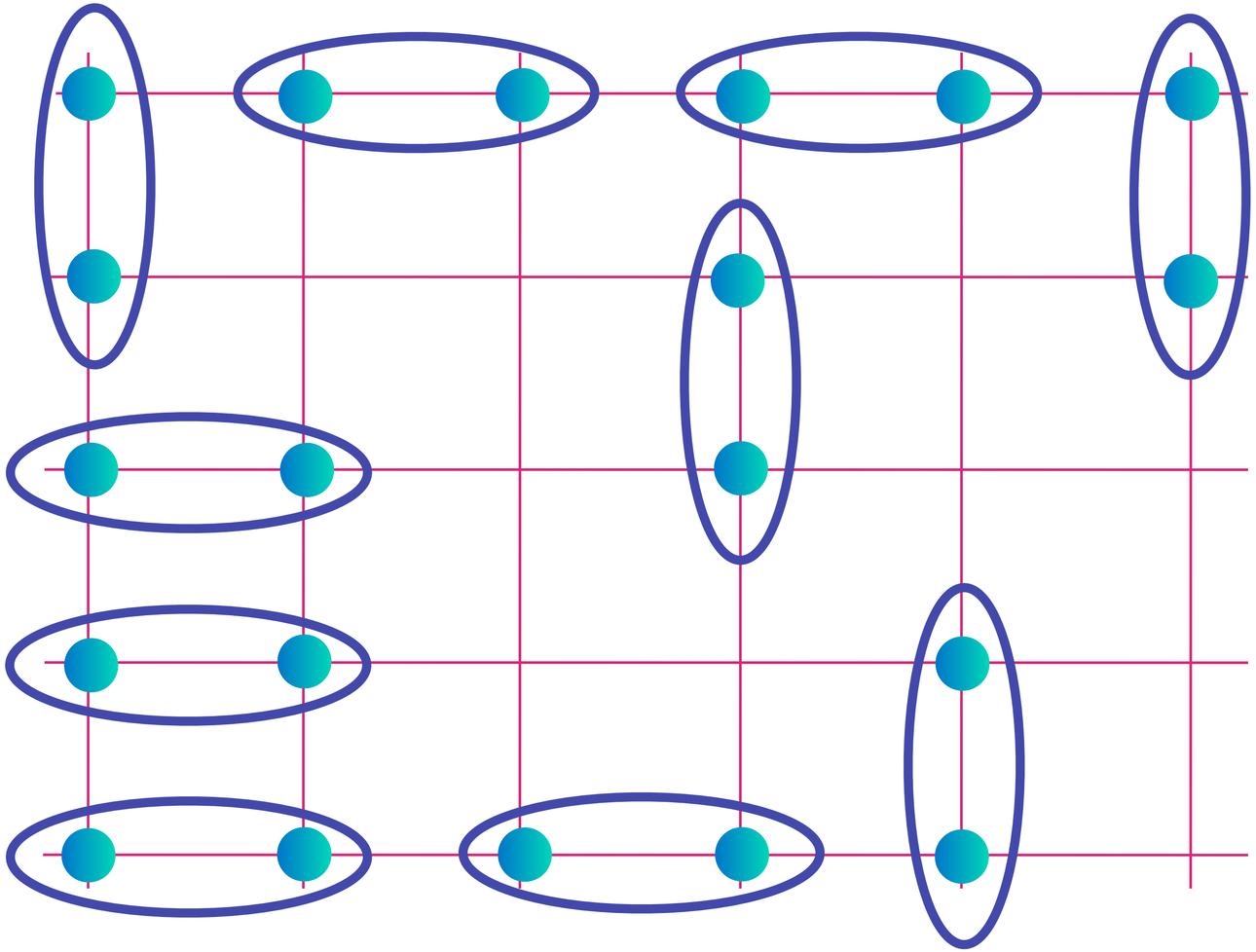
The dance of electrons on Cu atoms in YBCO



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

Electrons
entangle
"en masse"
by
exchanging
partners,
and there is
long-range
quantum
entanglement

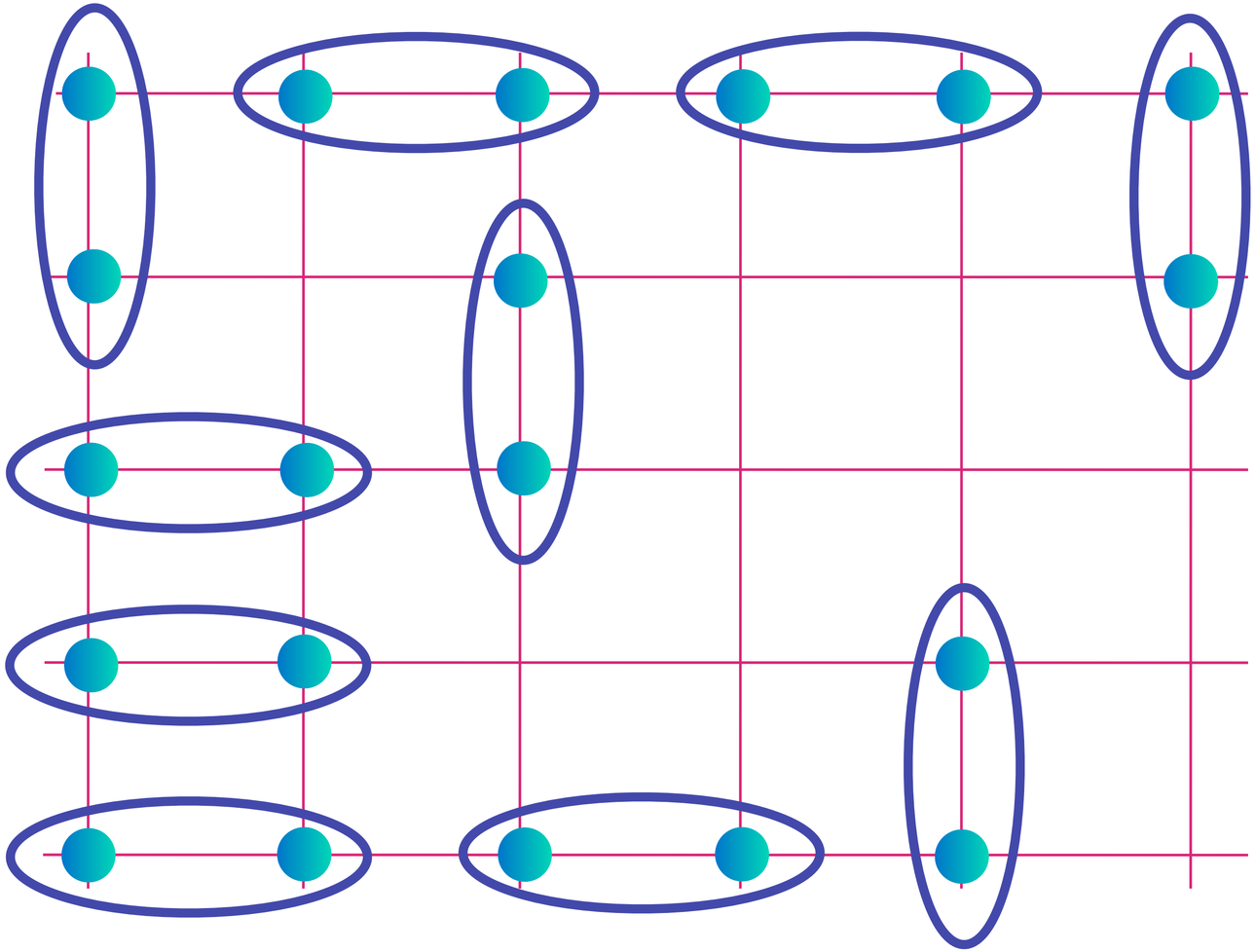
The dance of electrons on Cu atoms in YBCO



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

Electrons entangle "en masse" by exchanging partners, and there is long-range quantum entanglement

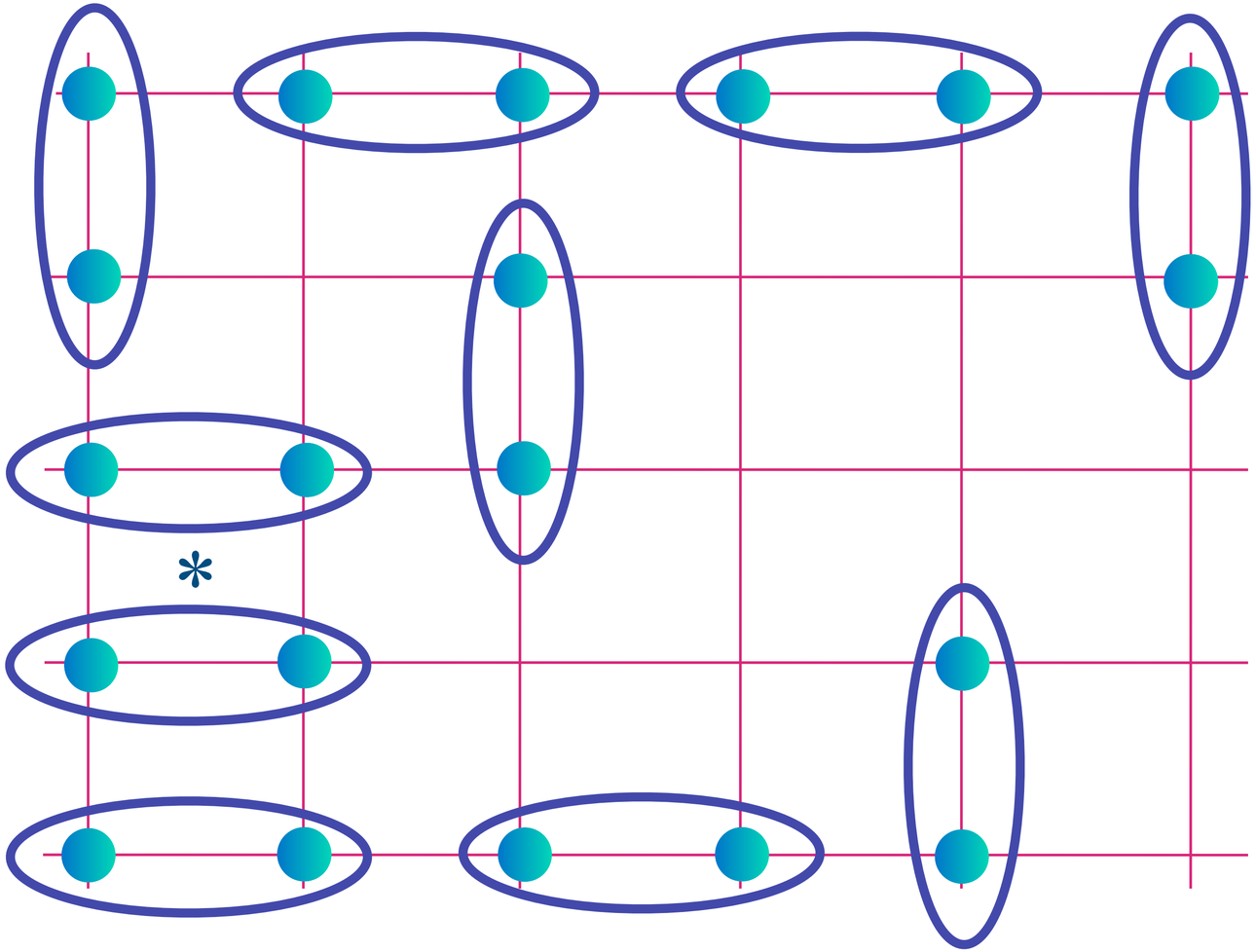
The dance of electrons on Cu atoms in YBCO



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

Electrons entangle "en masse" by exchanging partners, and there is long-range quantum entanglement

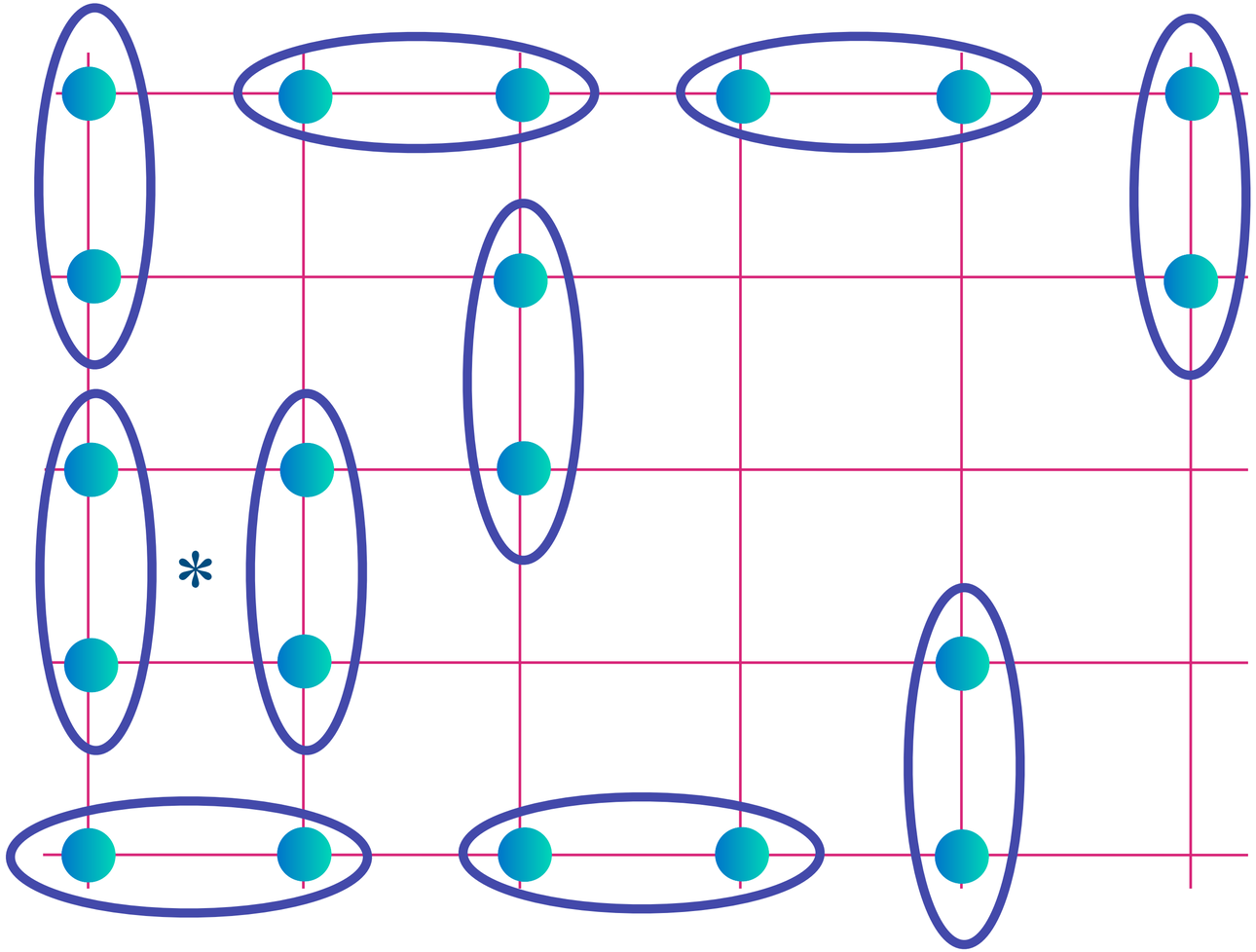
The dance of electrons on Cu atoms in YBCO



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

Electrons entangle "en masse" by exchanging partners, and there is long-range quantum entanglement

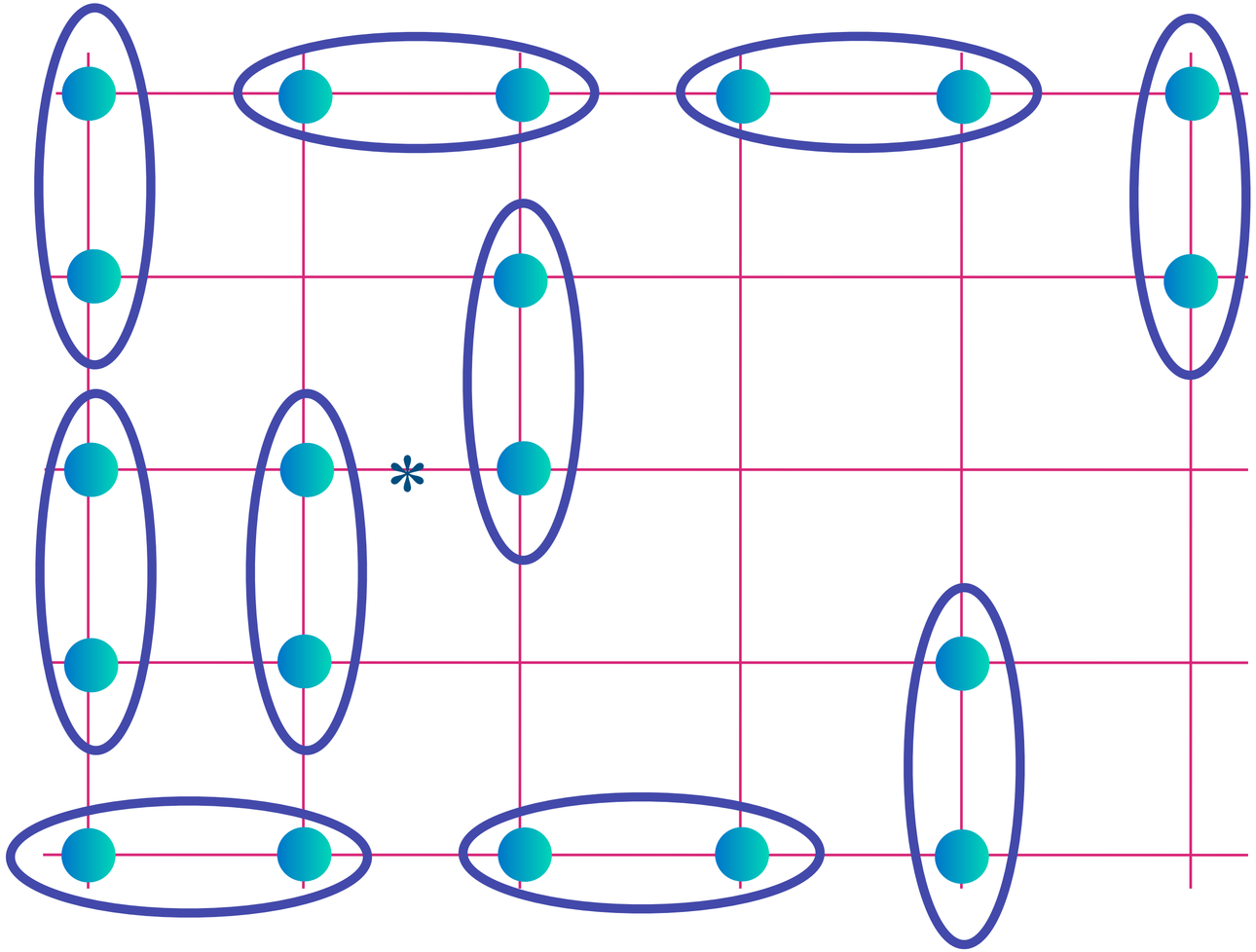
The dance of electrons on Cu atoms in YBCO



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

Electrons
entangle
"en masse"
by
exchanging
partners,
and there is
long-range
quantum
entanglement

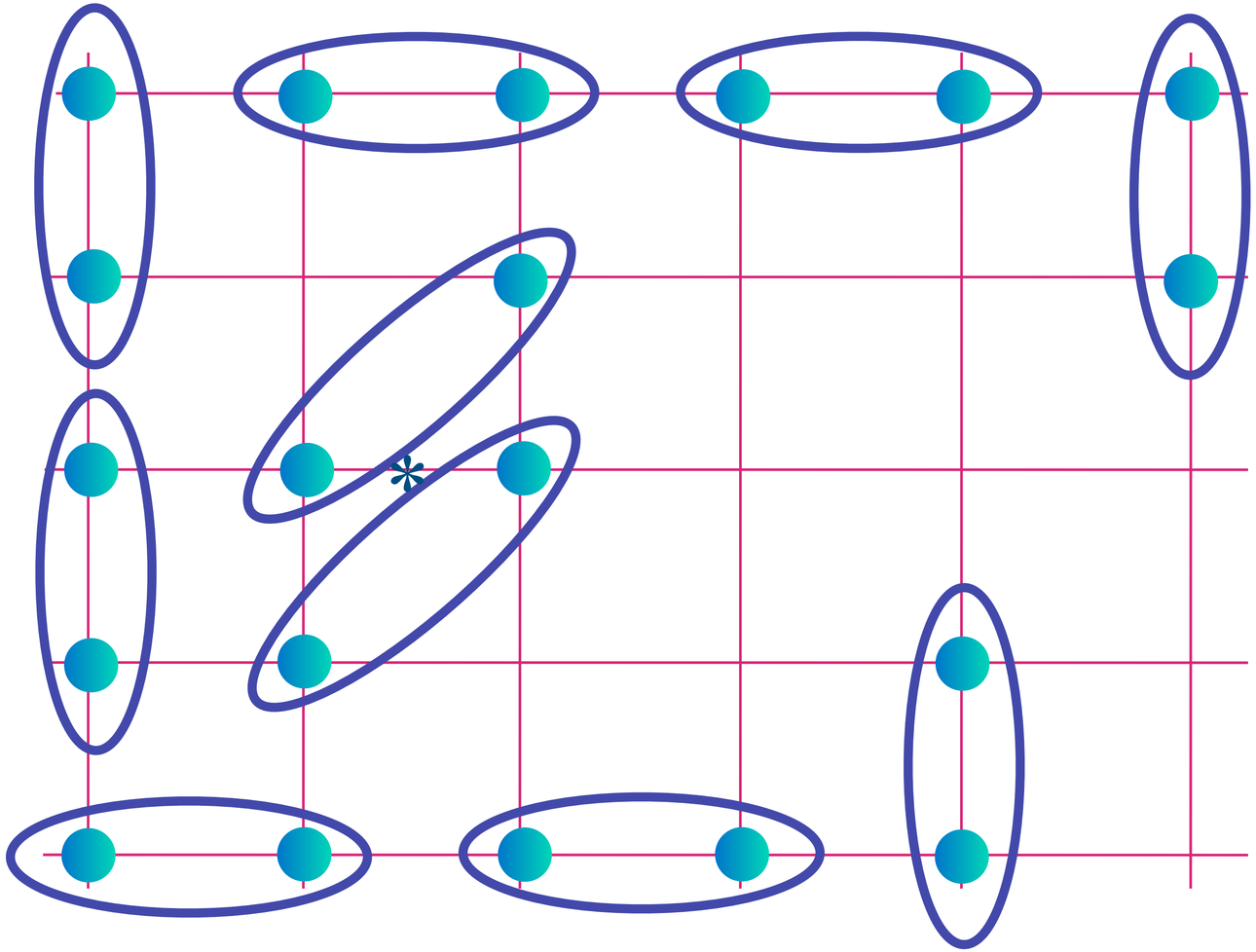
The dance of electrons on Cu atoms in YBCO



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

Electrons entangle "en masse" by exchanging partners, and there is long-range quantum entanglement

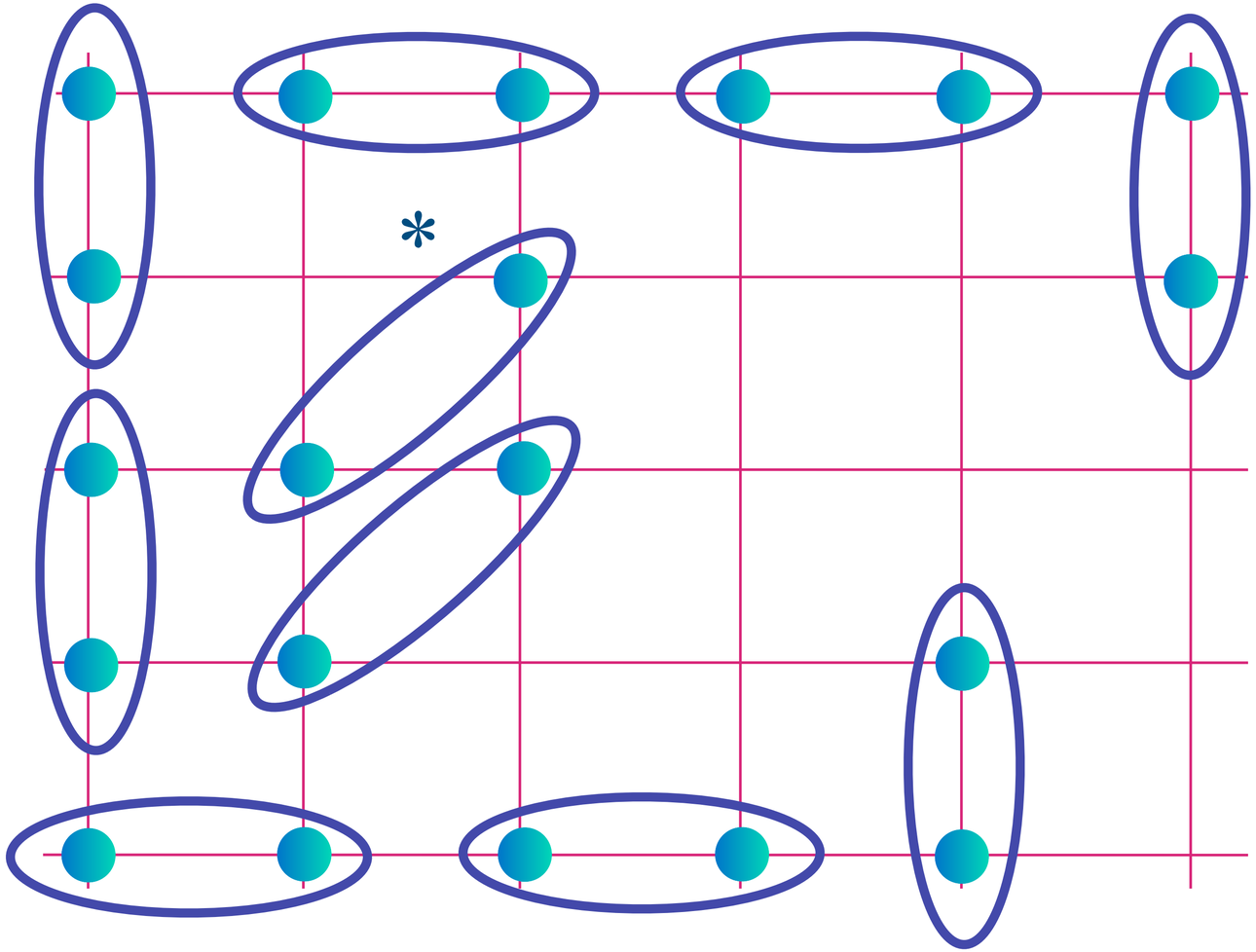
The dance of electrons on Cu atoms in YBCO



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

Electrons entangle "en masse" by exchanging partners, and there is long-range quantum entanglement

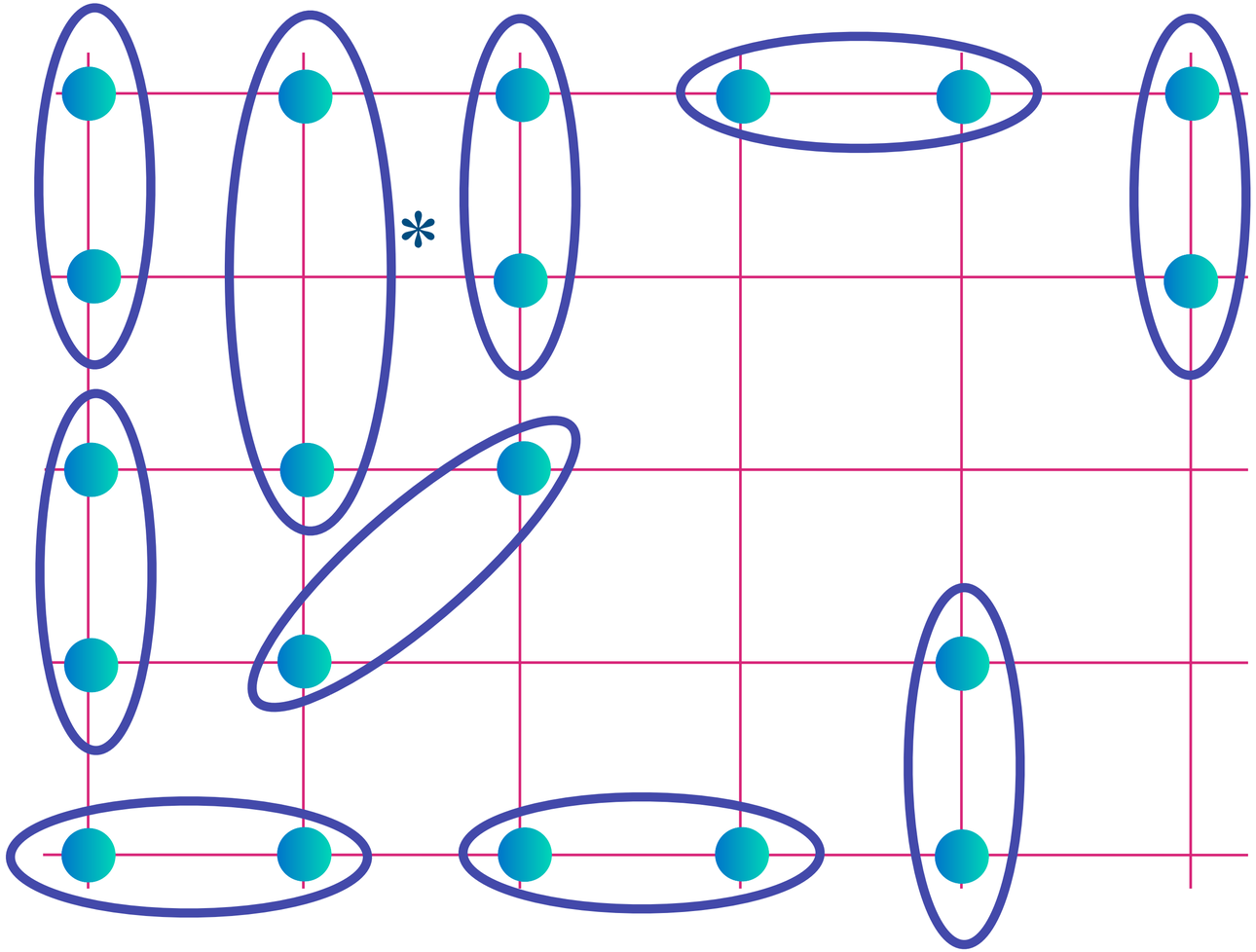
The dance of electrons on Cu atoms in YBCO



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

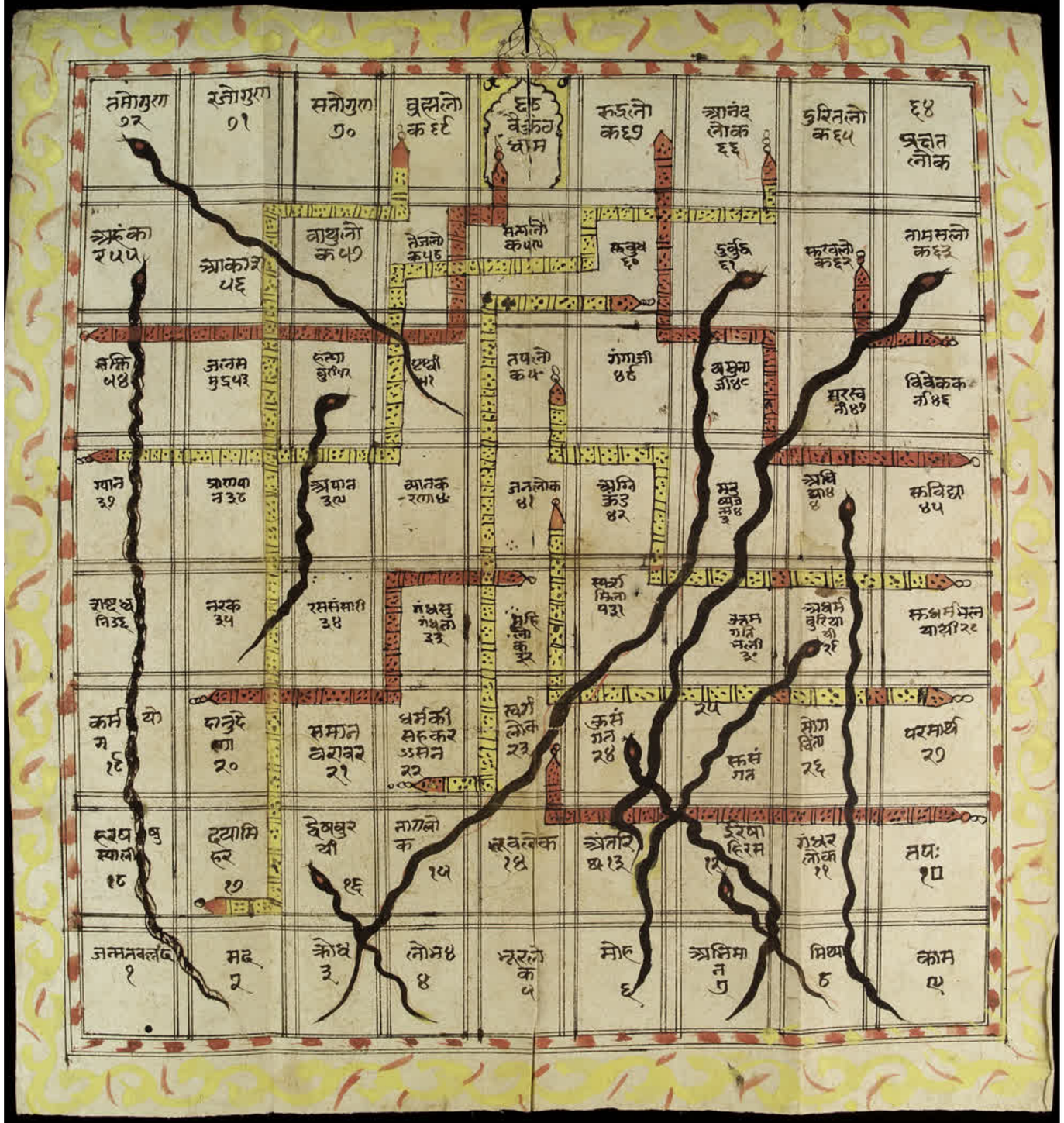
Electrons
entangle
"en masse"
by
exchanging
partners,
and there is
long-range
quantum
entanglement

The dance of electrons on Cu atoms in YBCO



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

Electrons
entangle
"en masse"
by
exchanging
partners,
and there is
long-range
quantum
entanglement



My dream*

Snakes and ladders

*Not true

The Sachdev-Ye-Kitaev (SYK) model

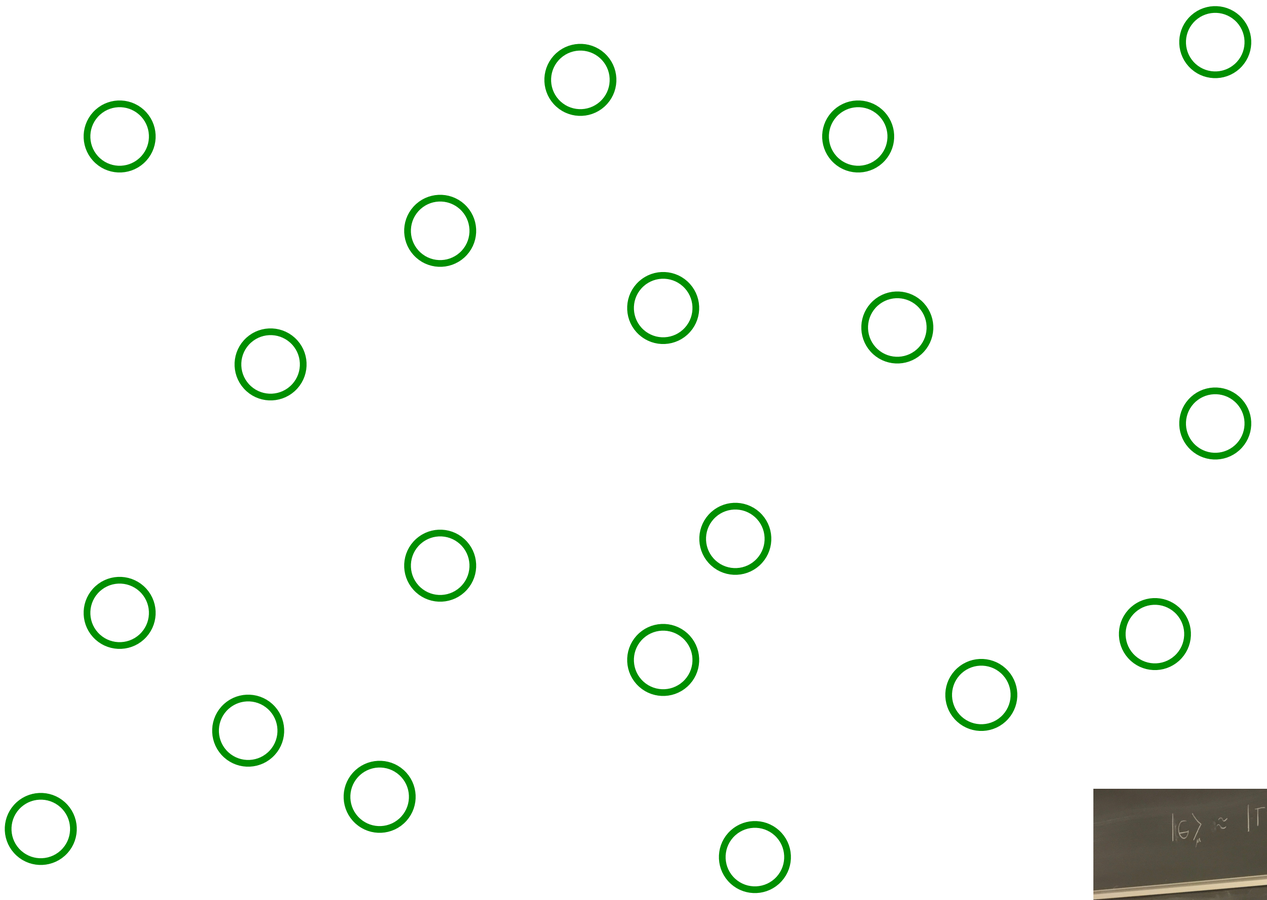
The SYK model has a scale-invariant entanglement structure:
i.e. electrons are entangled
at all distances !

It describes
the ***strange*** electrical properties of YBCO

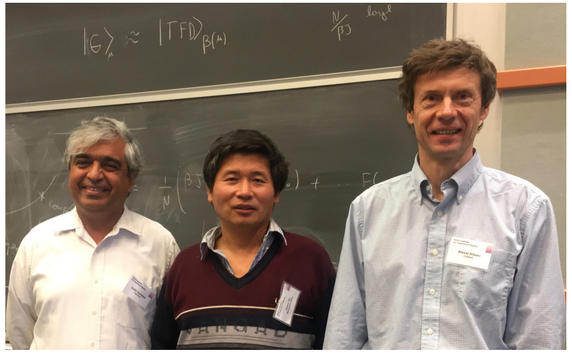
Sachdev, Ye (1993)

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

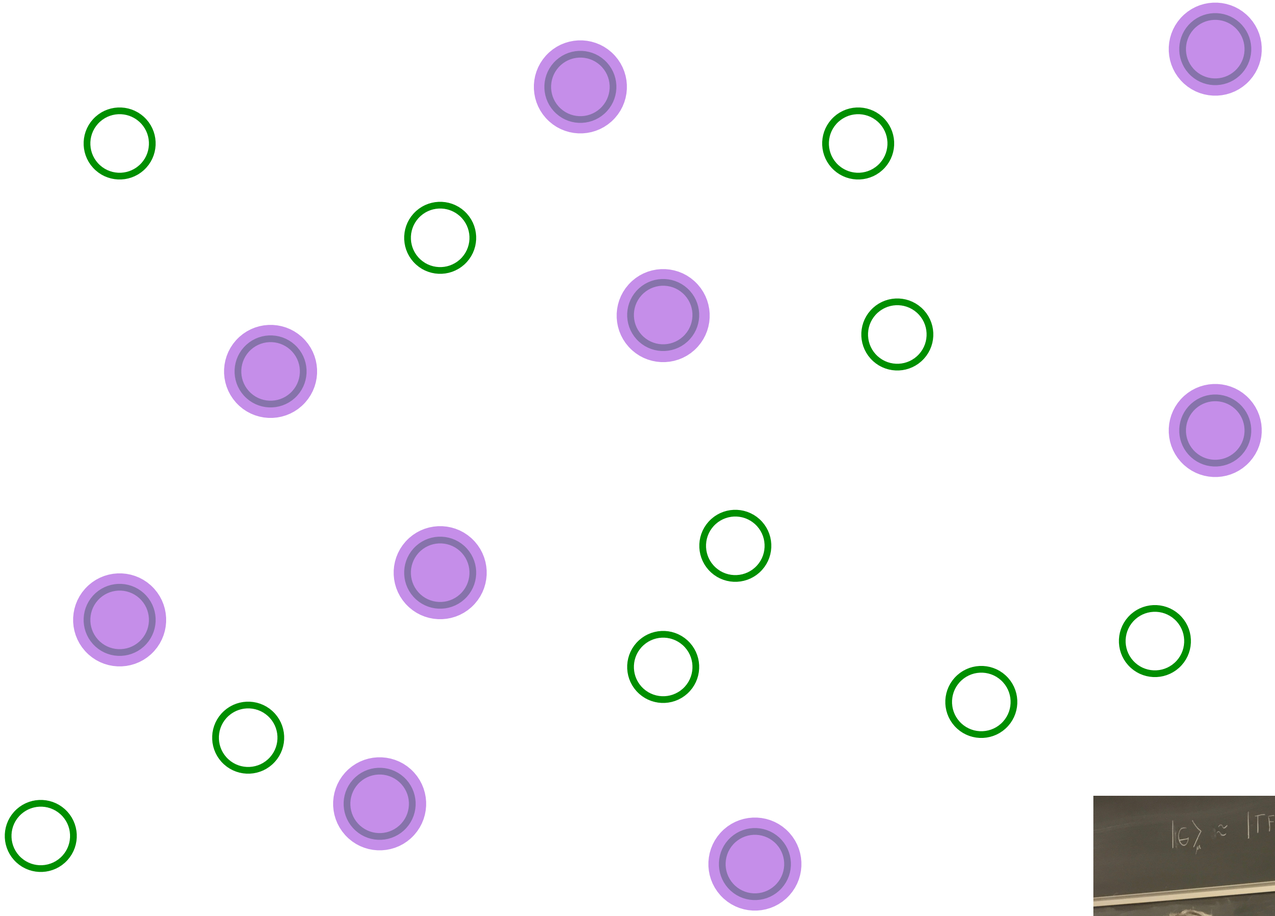


Pick a set of random positions

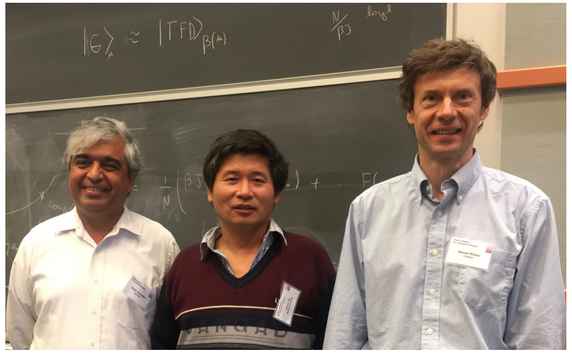


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

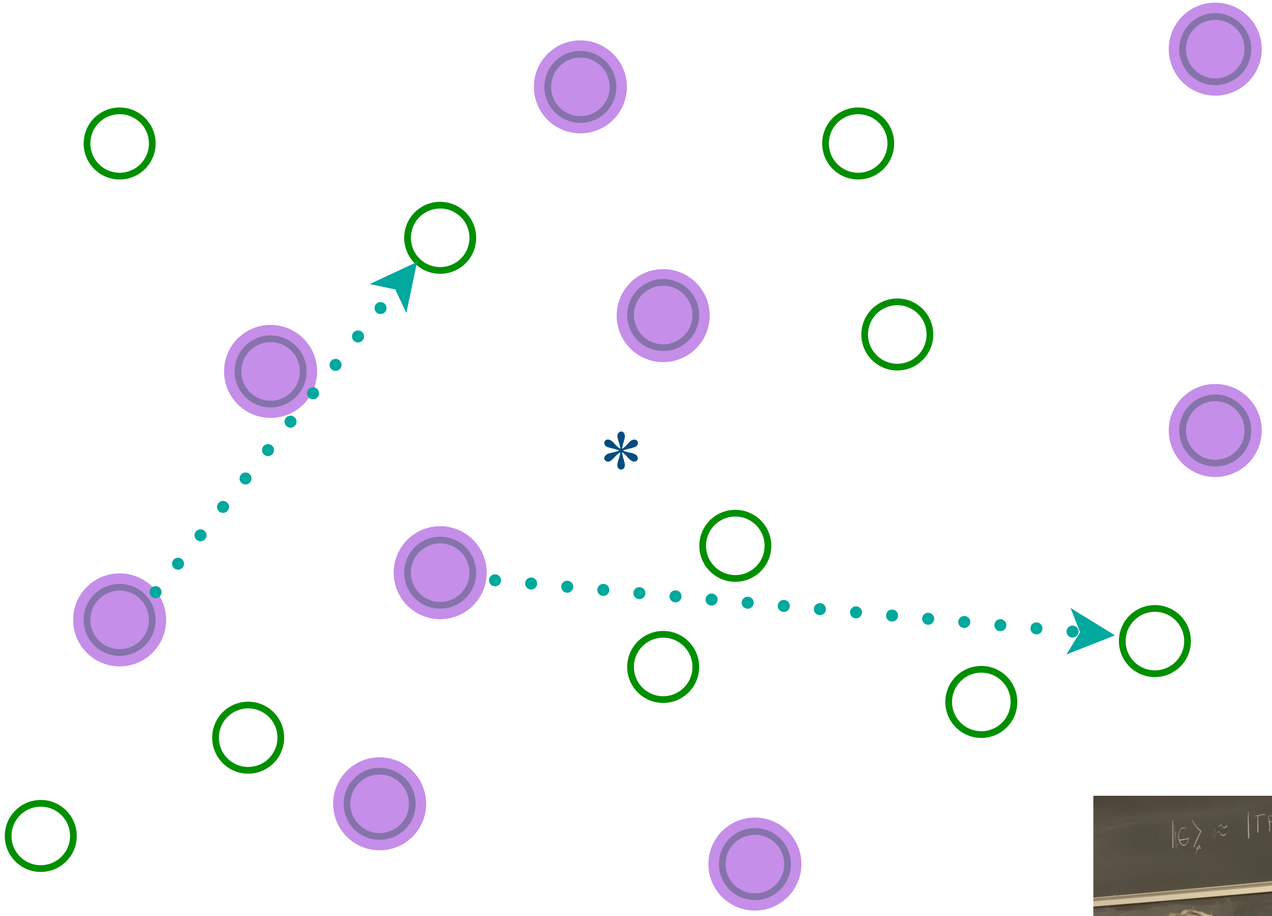


Place electrons randomly on some sites

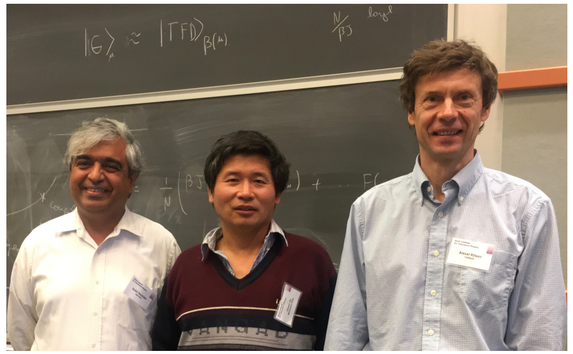


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

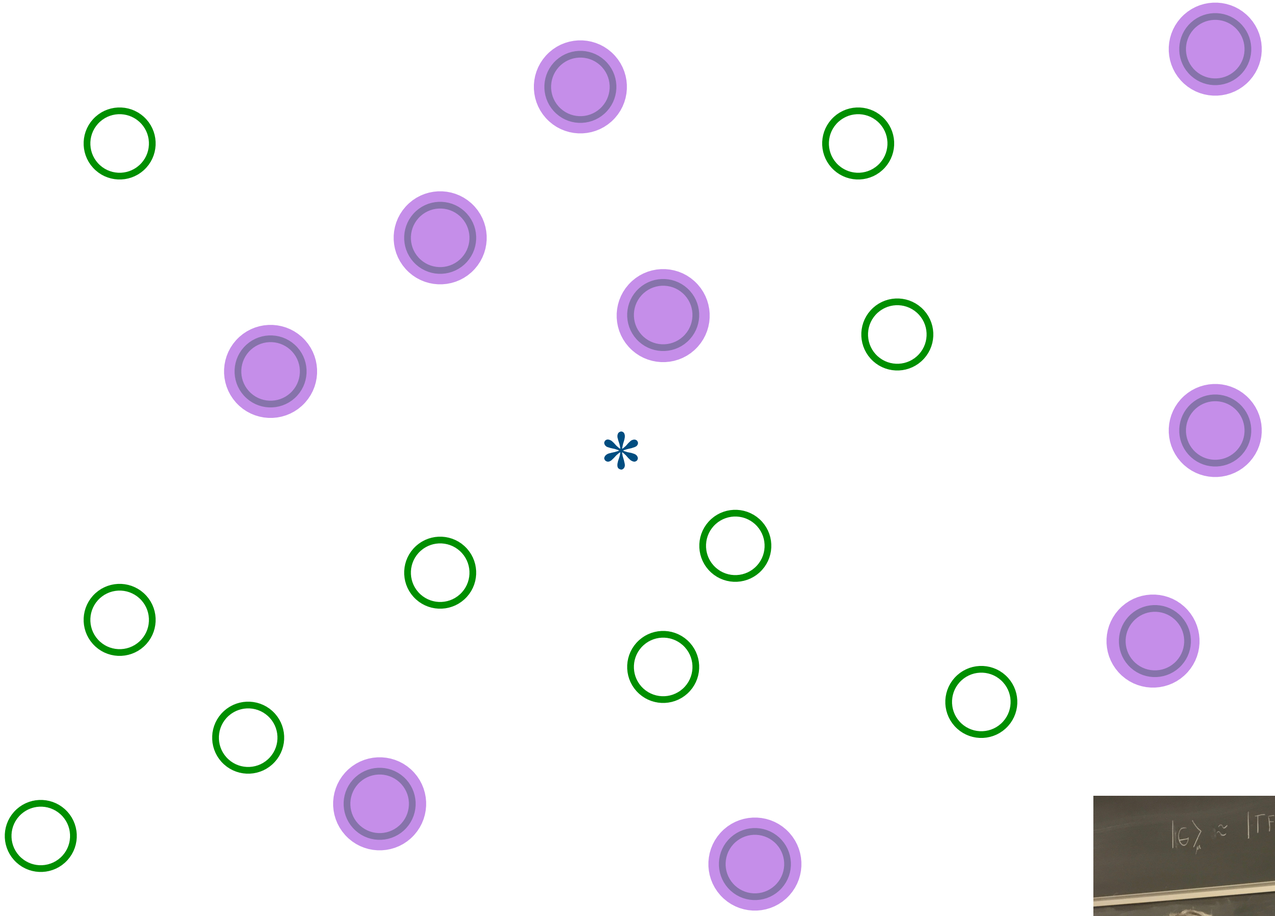


Place electrons randomly on some sites

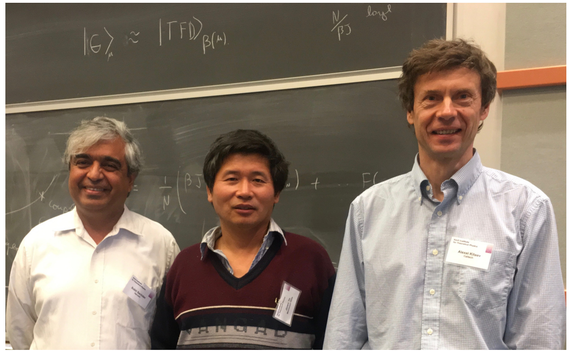


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

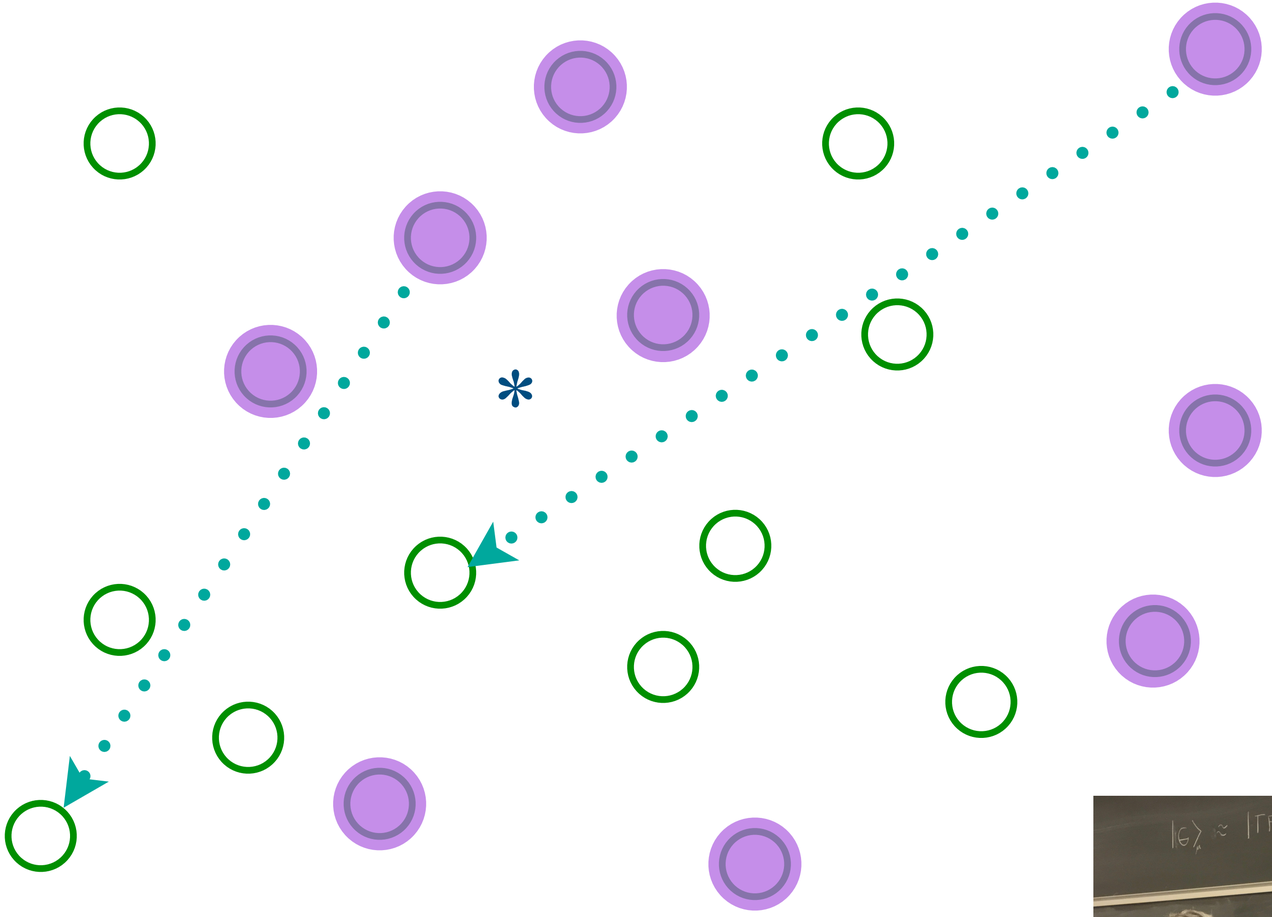


Entangle electrons pairwise randomly

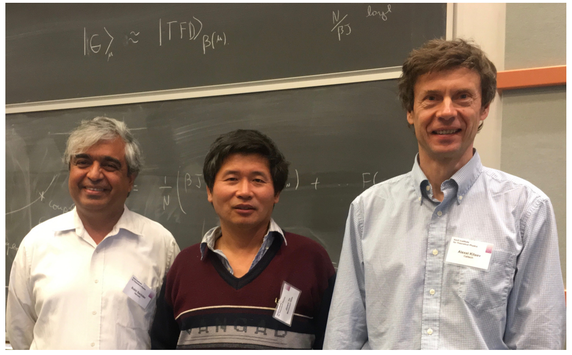


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

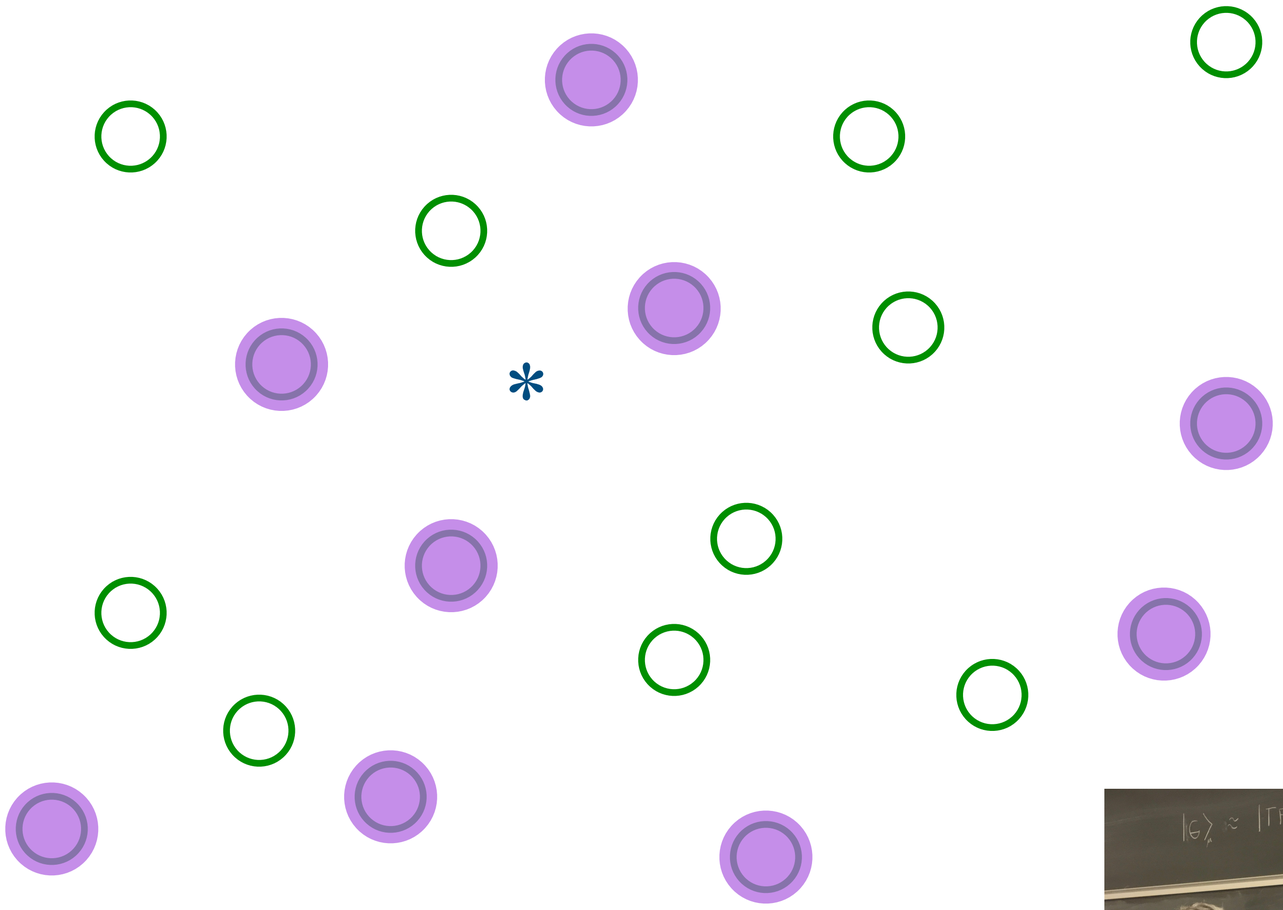


Entangle electrons pairwise randomly

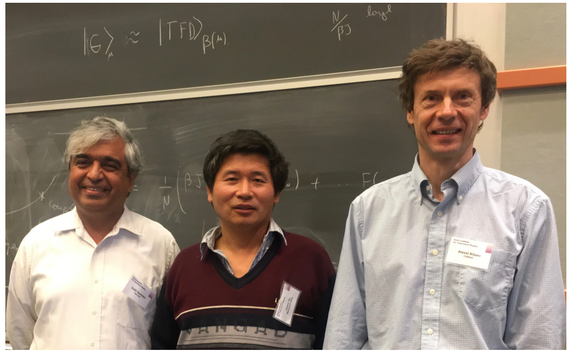


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

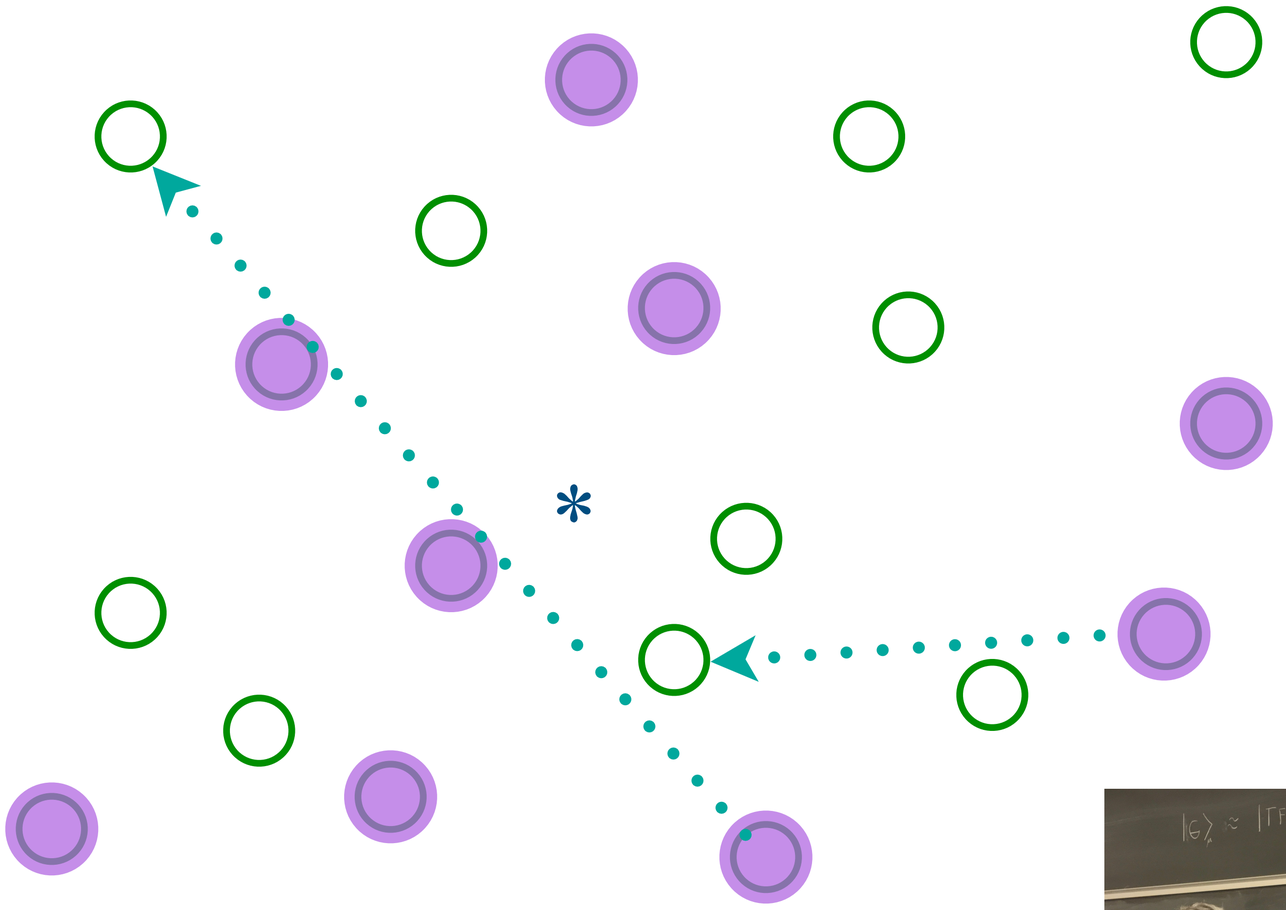


Entangle electrons pairwise randomly

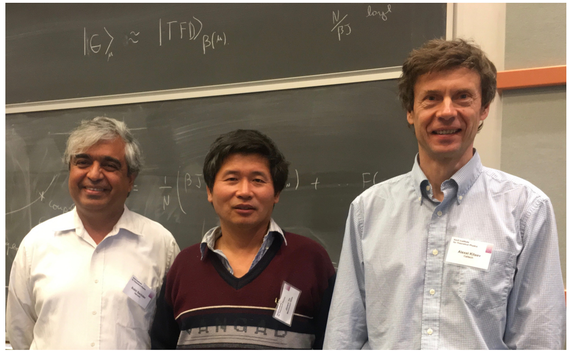


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

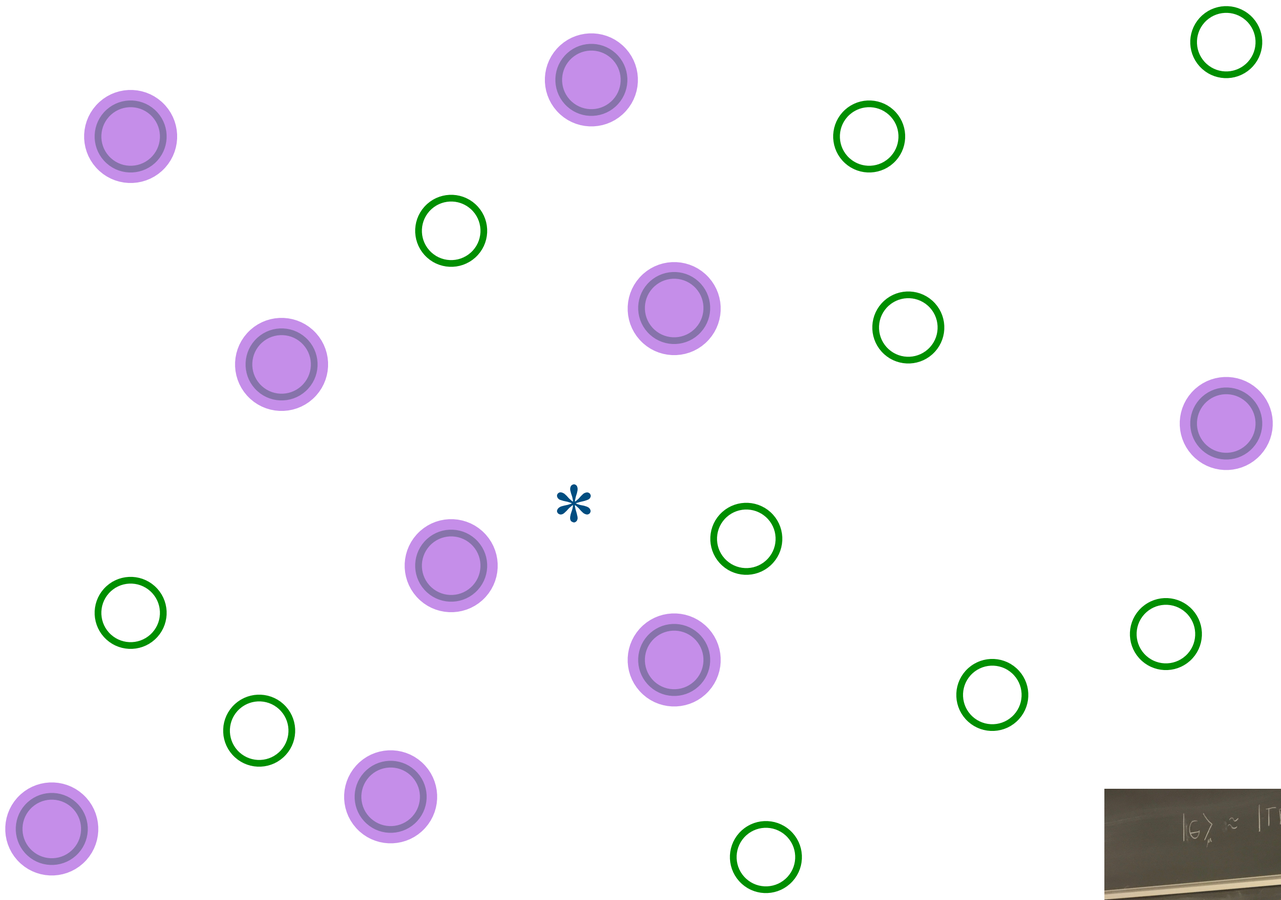


Entangle electrons pairwise randomly

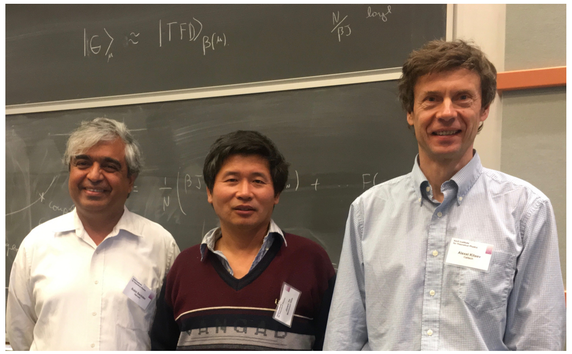


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

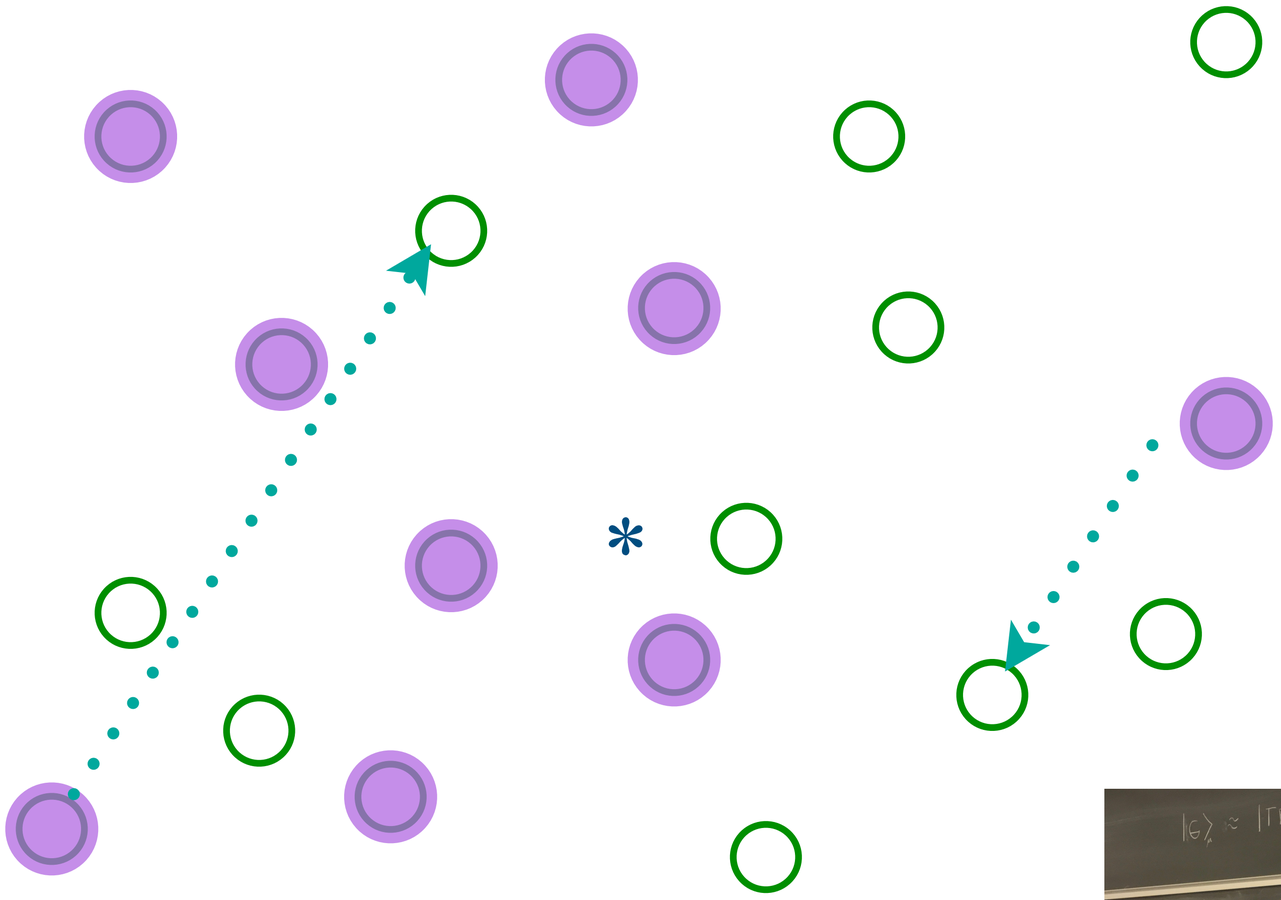


Entangle electrons pairwise randomly

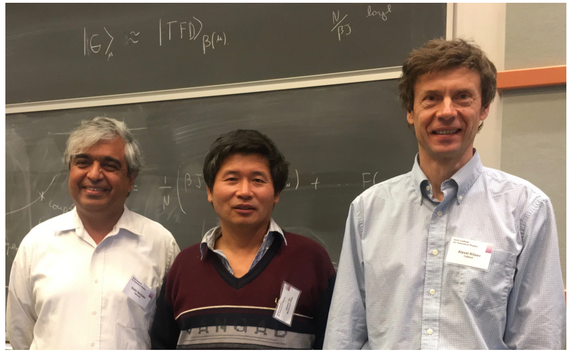


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

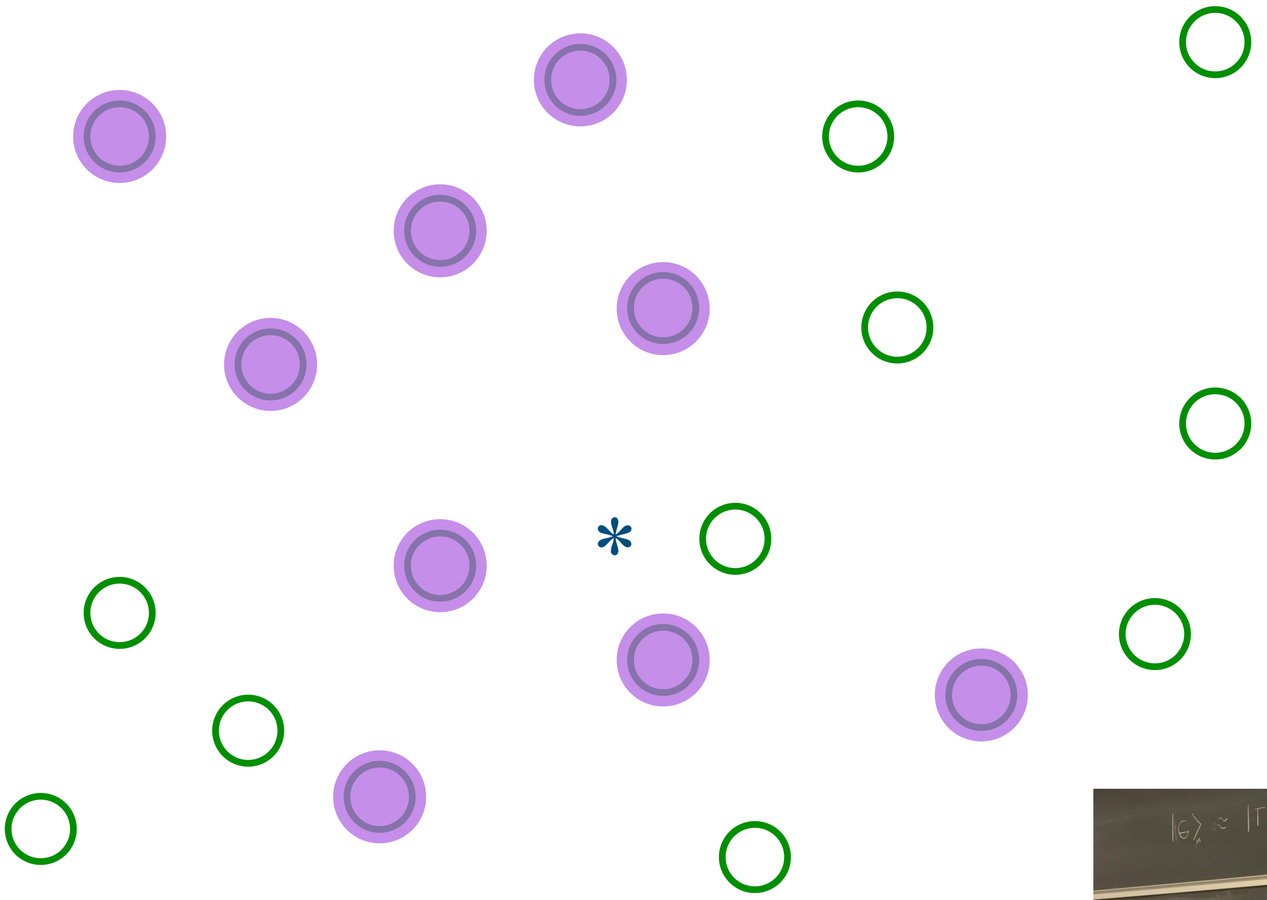


Entangle electrons pairwise randomly

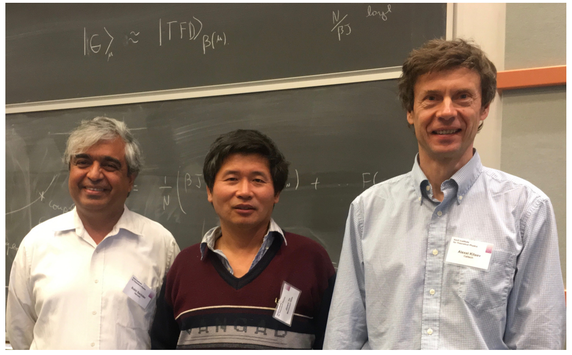


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

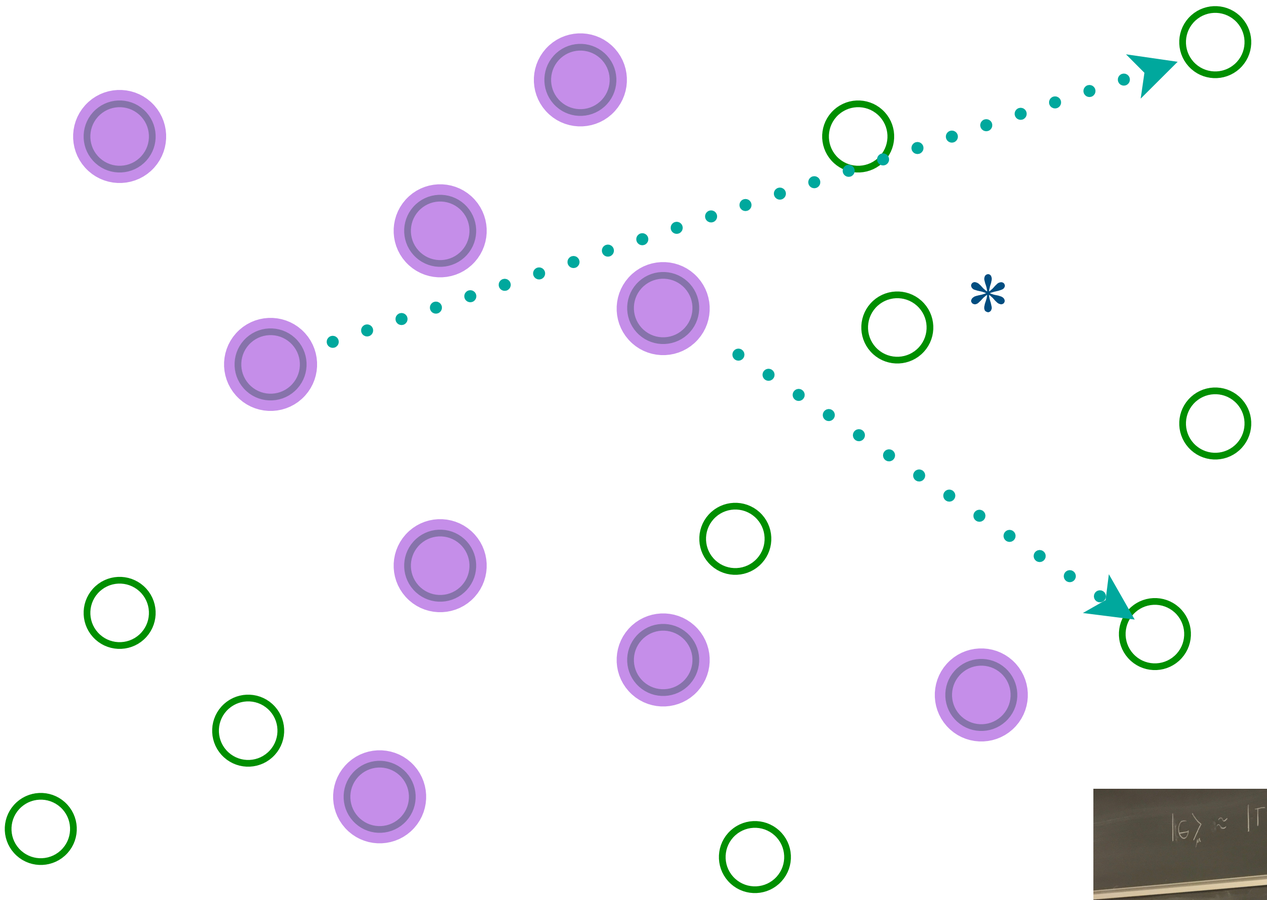


Entangle electrons pairwise randomly

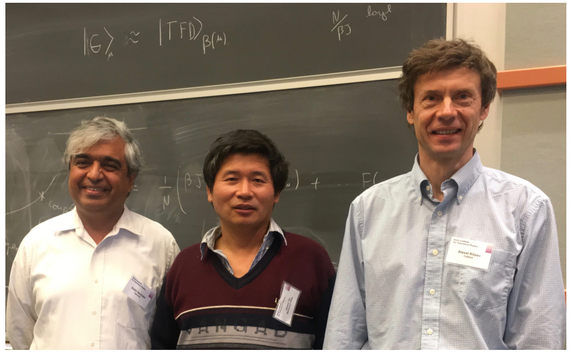


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

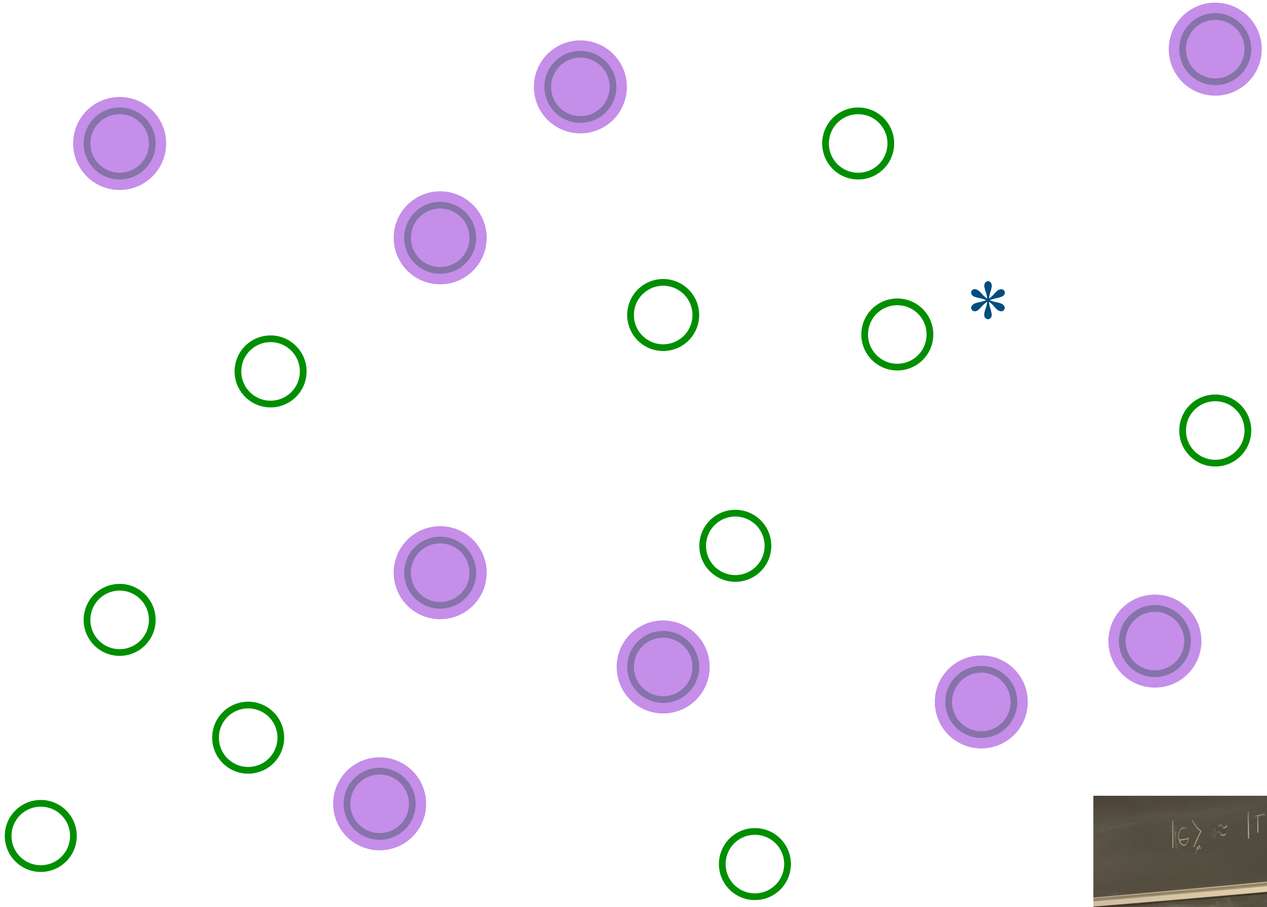


Entangle electrons pairwise randomly

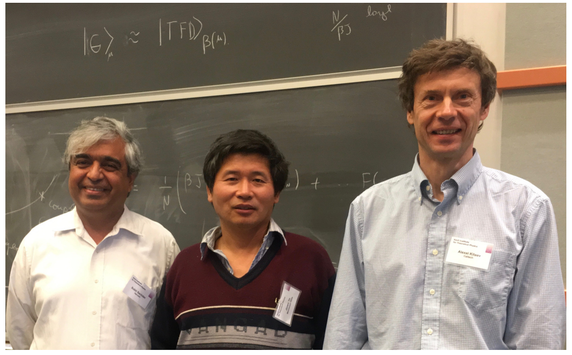


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

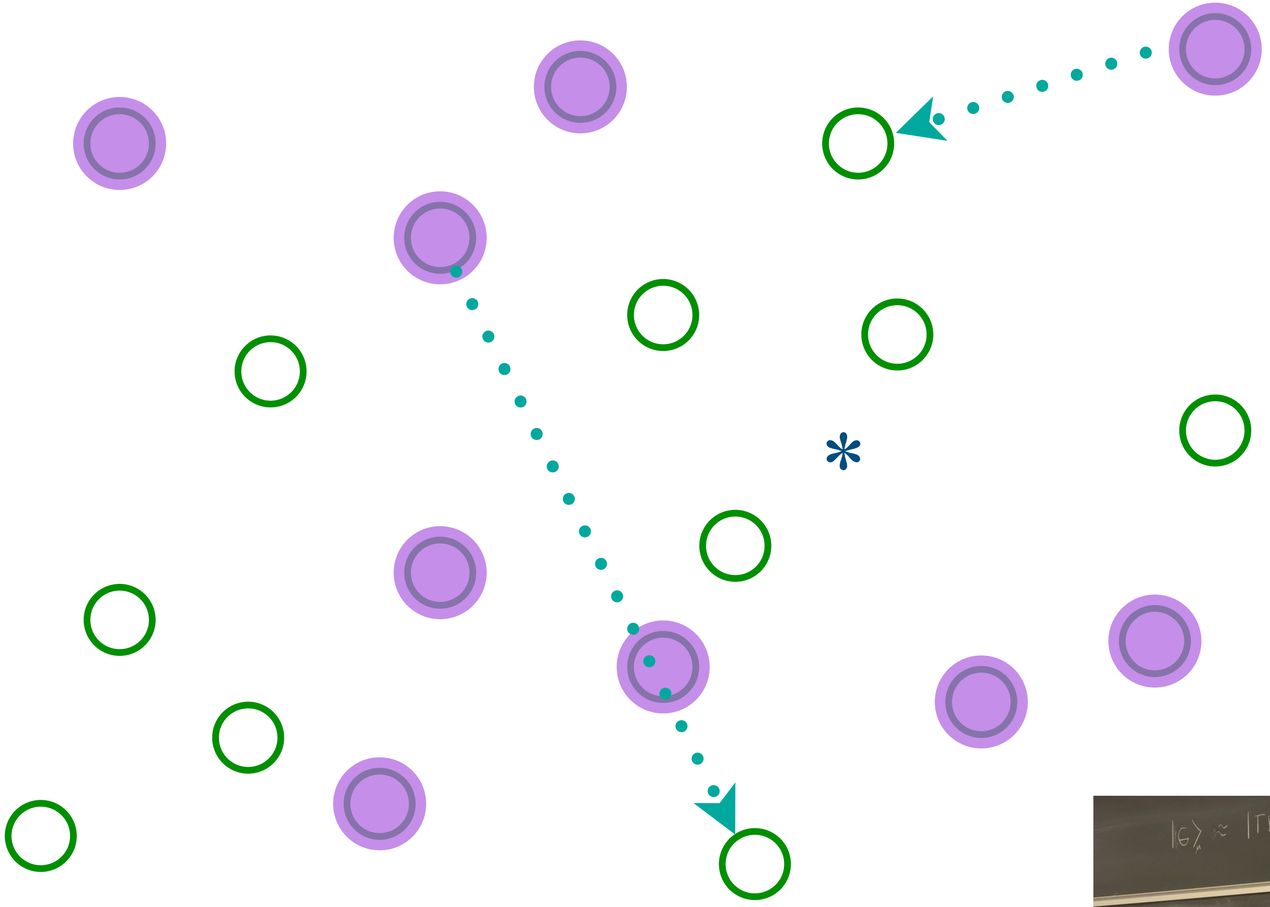


Entangle electrons pairwise randomly

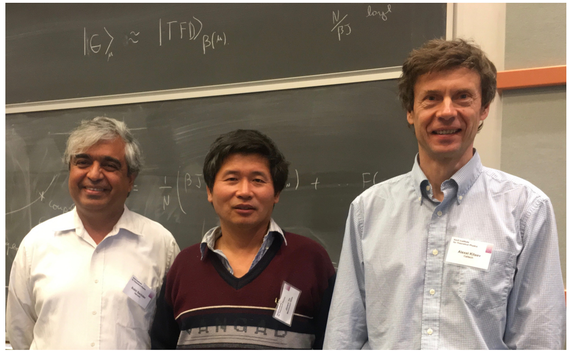


The SYK model

Sachdev, Ye (1993); Kitaev (2015)

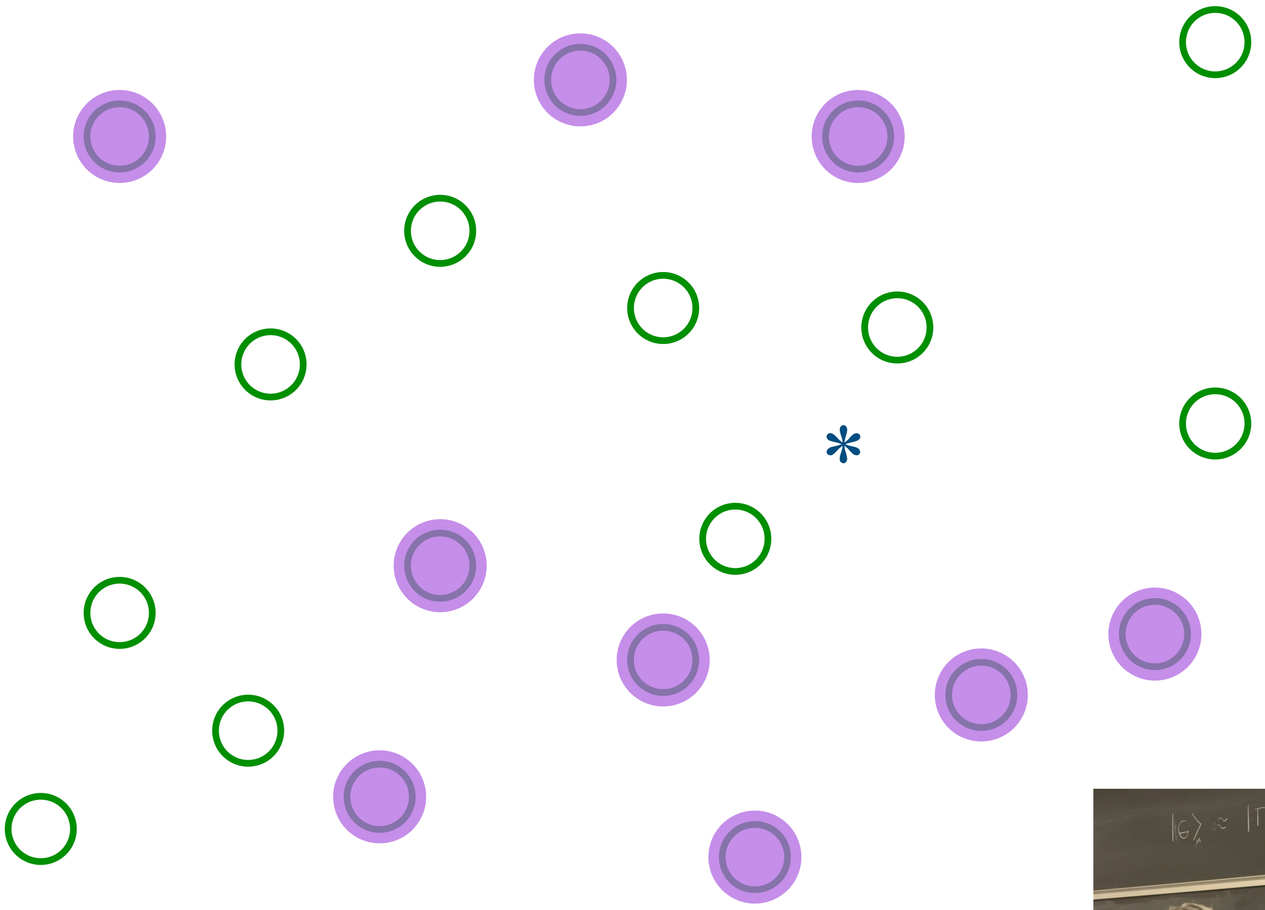


Entangle electrons pairwise randomly

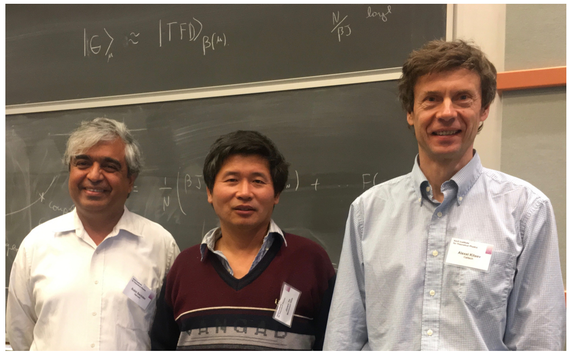


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



Entangle electrons pairwise randomly

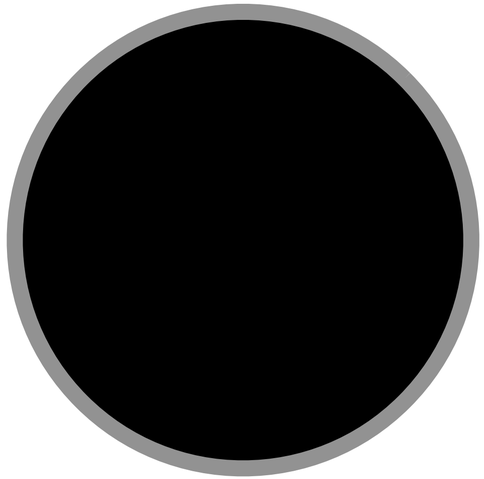


Complex quantum entanglement in black holes

Black Holes

Objects so dense that light is gravitationally bound to them.

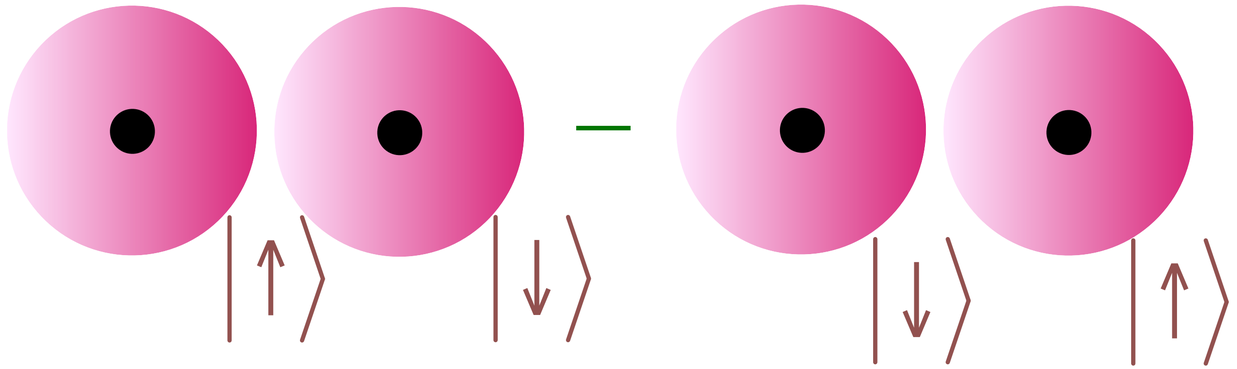
$$\text{Horizon radius } R = \frac{2GM}{c^2}$$



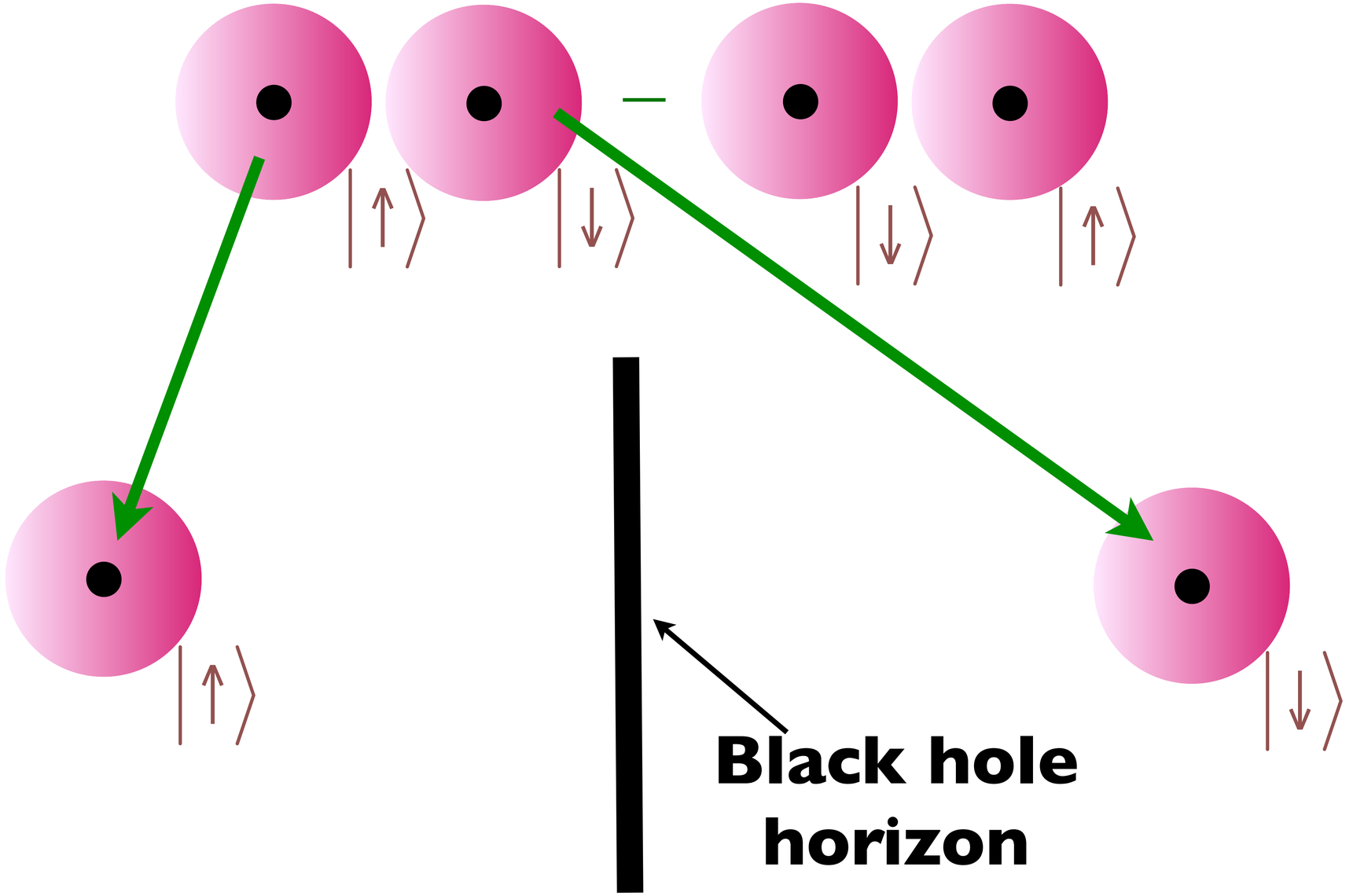
G Newton's constant, c velocity of light, M mass of black hole

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

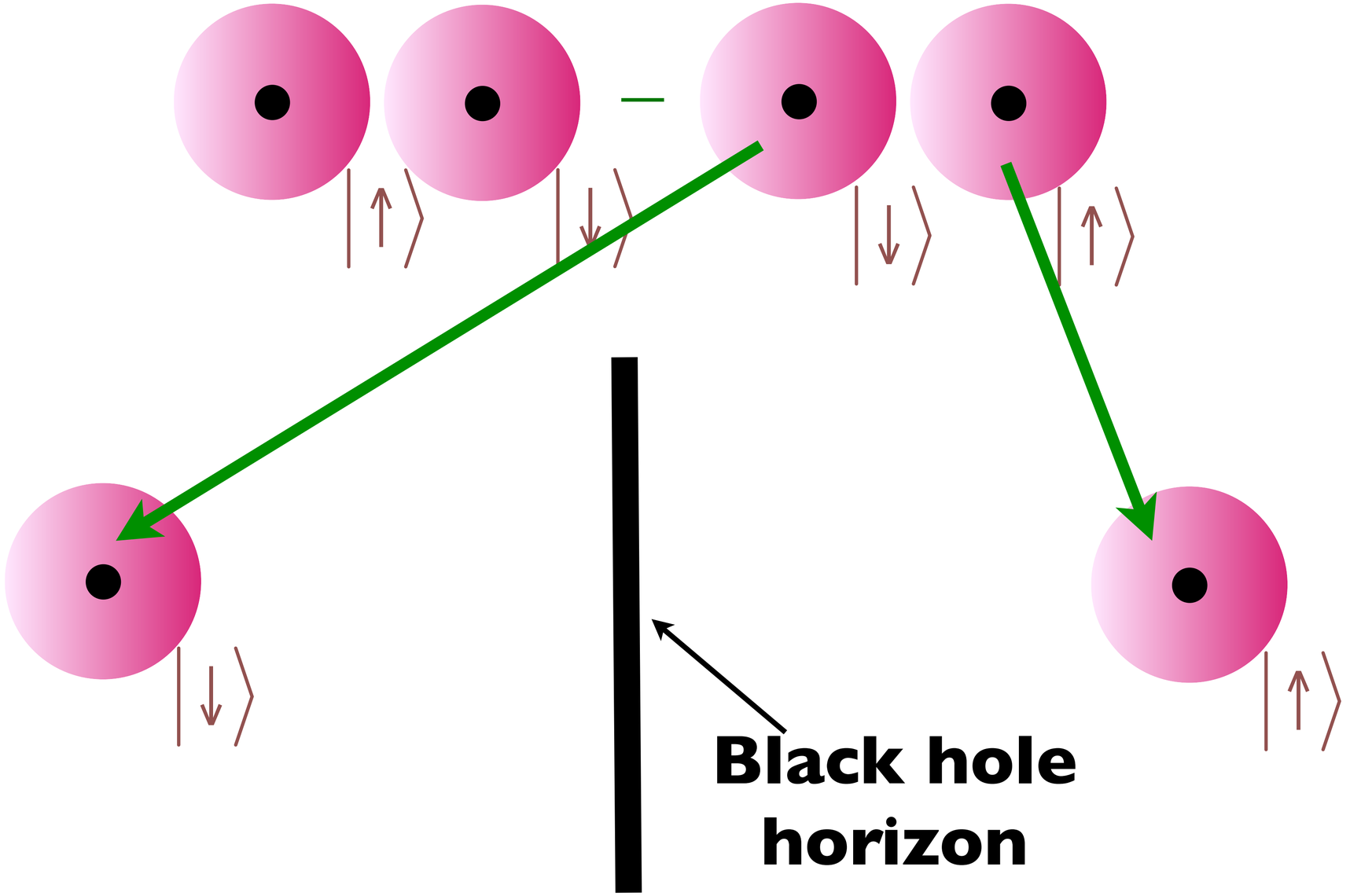
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

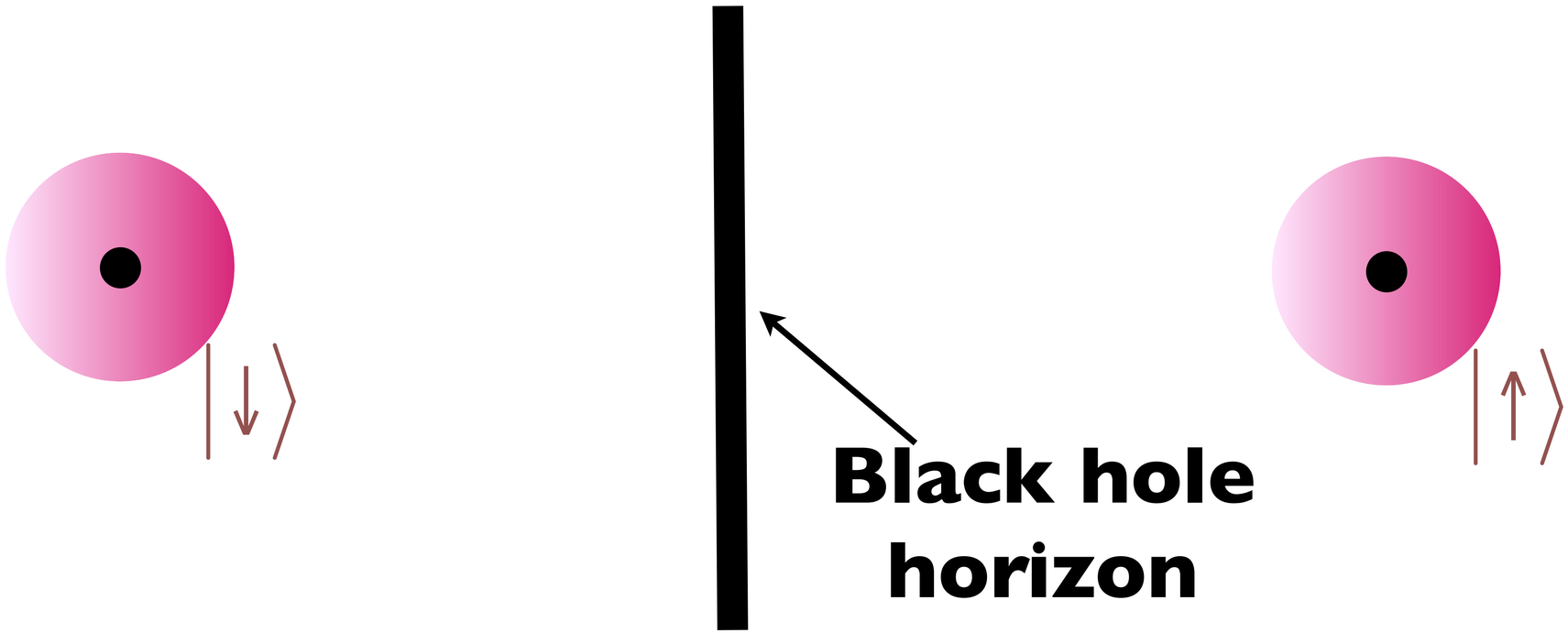


Quantum Entanglement across a black hole horizon



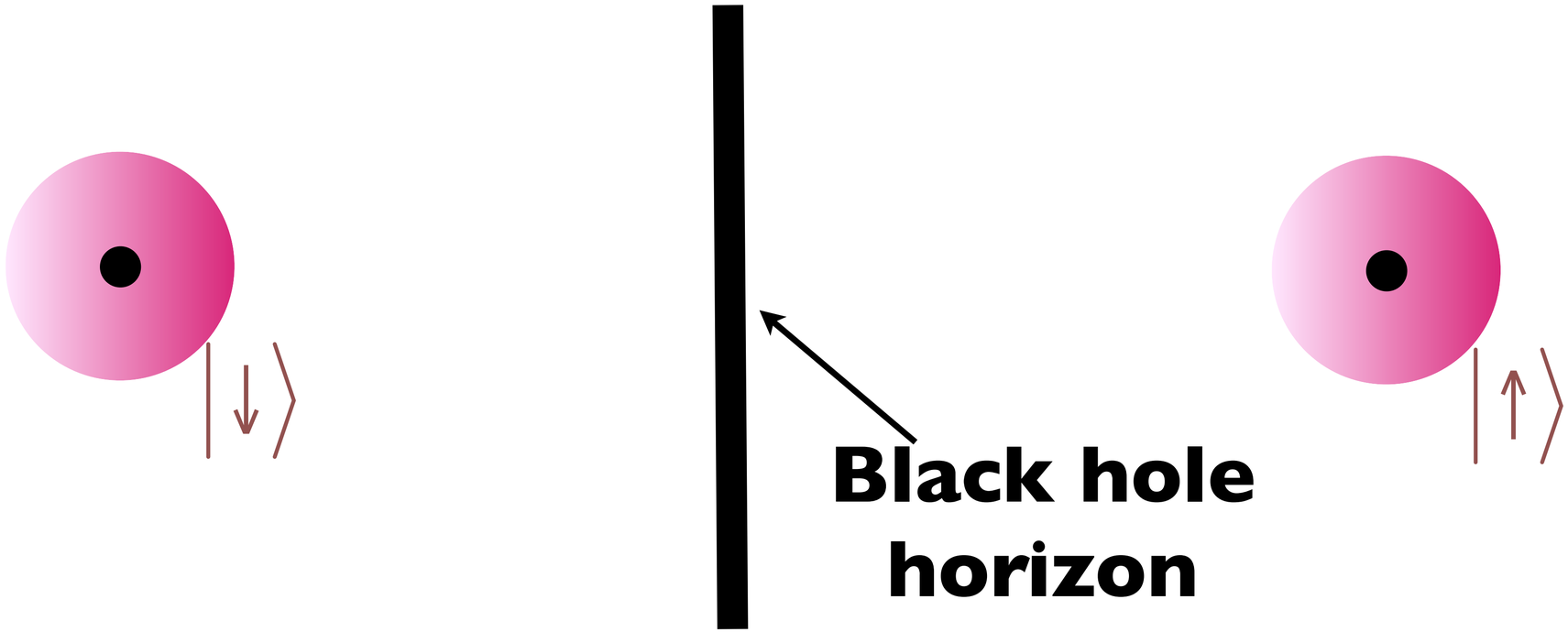
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

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



The Sachdev-Ye-Kitaev (SYK) model

The SYK model has a scale-invariant entanglement structure:
i.e. electrons are entangled
at all distances !

It describes
the ***strange*** electrical properties of YBCO

Sachdev, Ye (1993)

The Sachdev-Ye-Kitaev (SYK) model

The SYK model has a scale-invariant entanglement structure:
i.e. electrons are entangled
at all distances !

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

Sachdev, Ye (1993)

In a *dual* set of variables it describes certain

black holes

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

Quantum theory of electrons,
one at a time:
metals and insulators

Quantum entanglement of
electron pairs:
superconductivity

Quantum entanglement of 2,3,4,……∞ electrons: strange metal of YBCO

Complex quantum entanglement in black holes