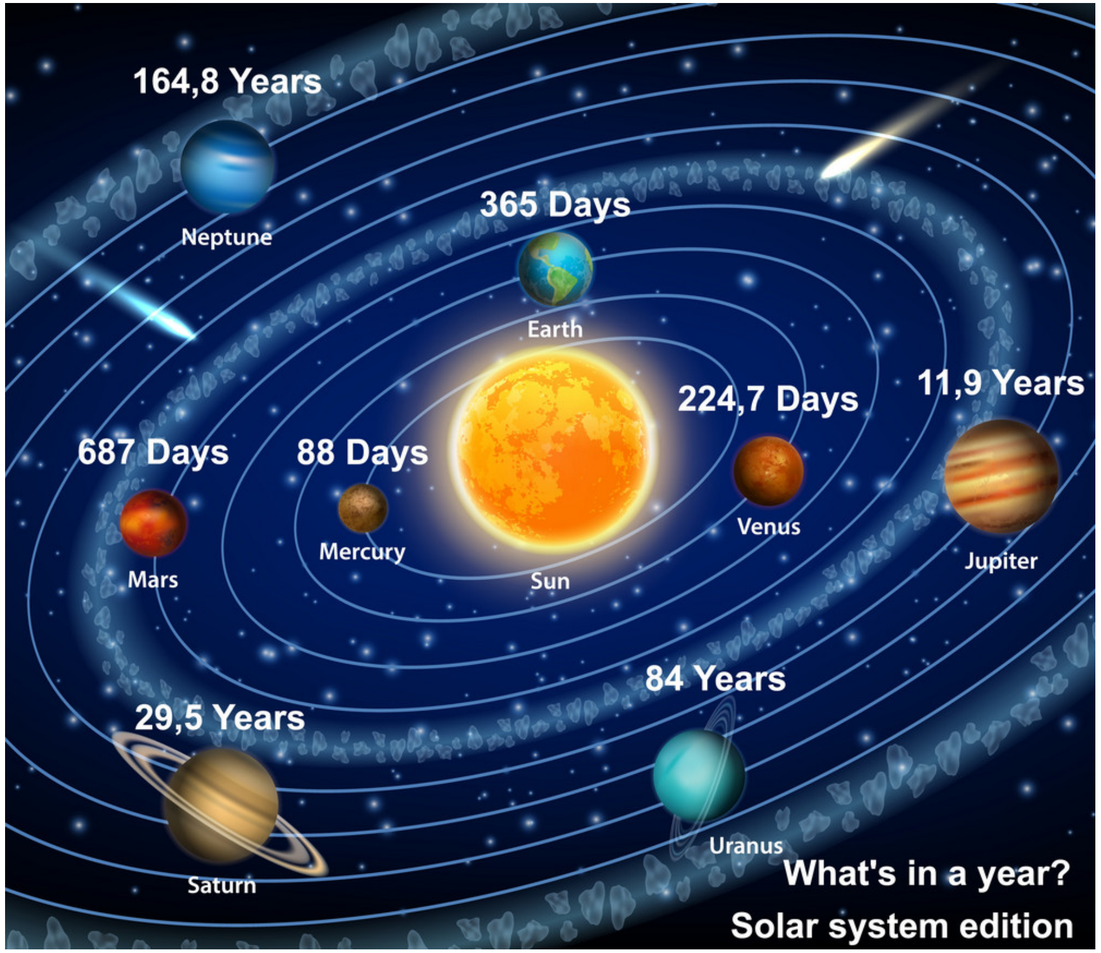
Quantum entanglement at all distances

Peterson Public Lecture
Kansas State University
April 26, 2022

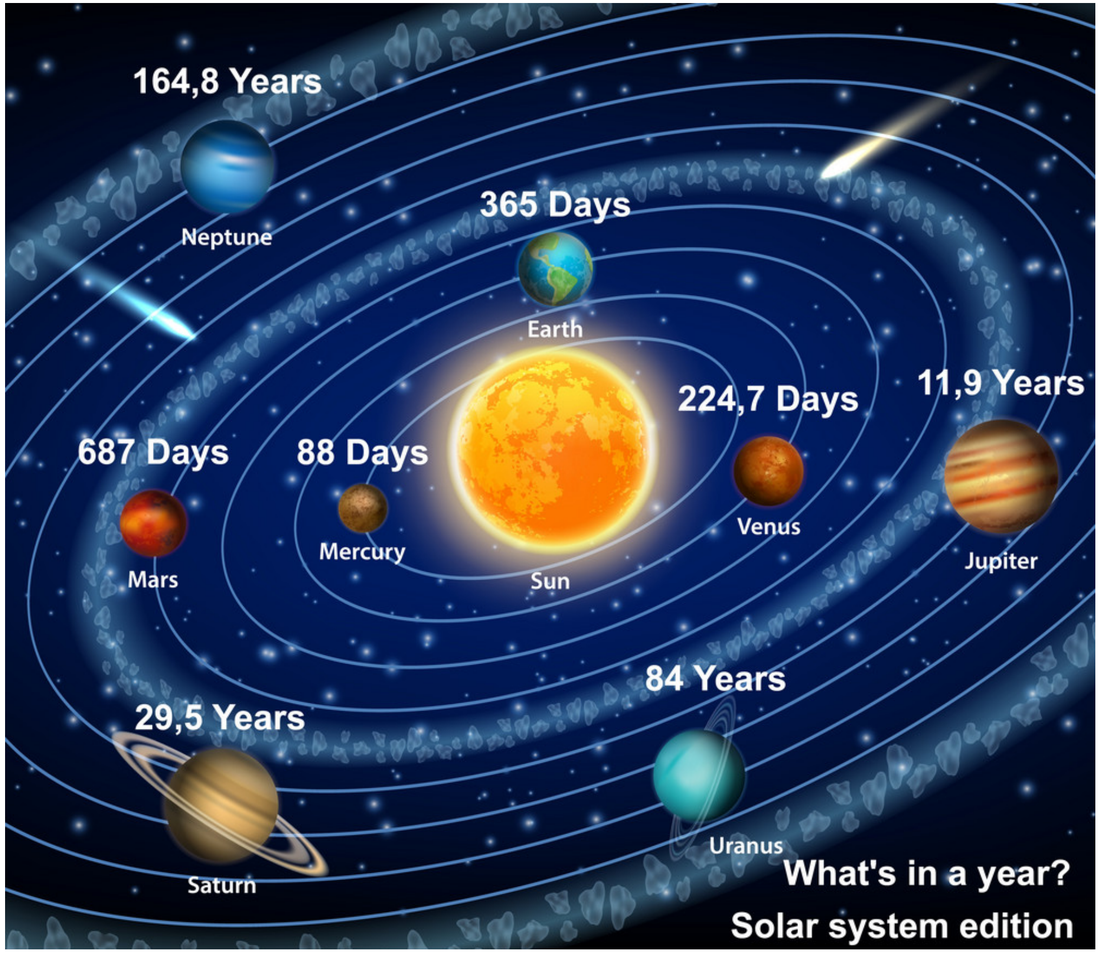
Subir Sachdev

INSTITUTE FOR ADVANCED STUDY

PHYSICS
HARVARD



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).



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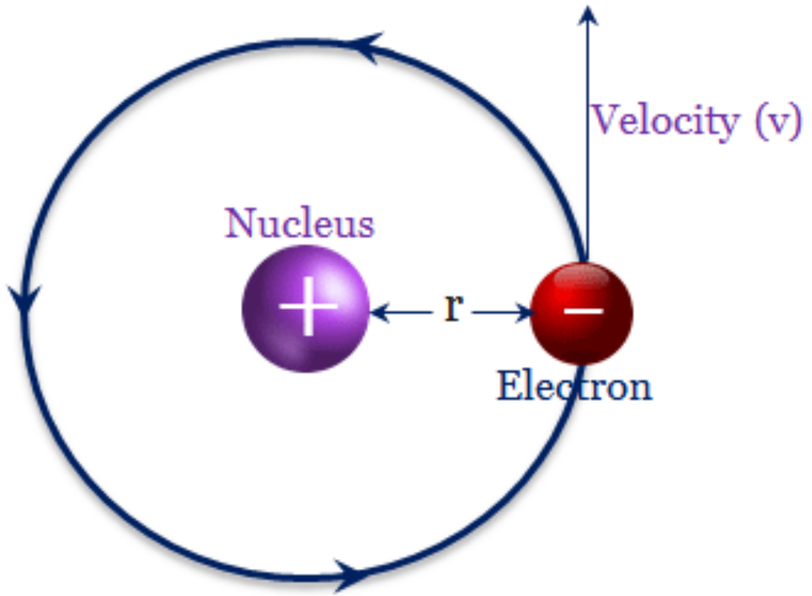
What happens on smaller distances ?

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.

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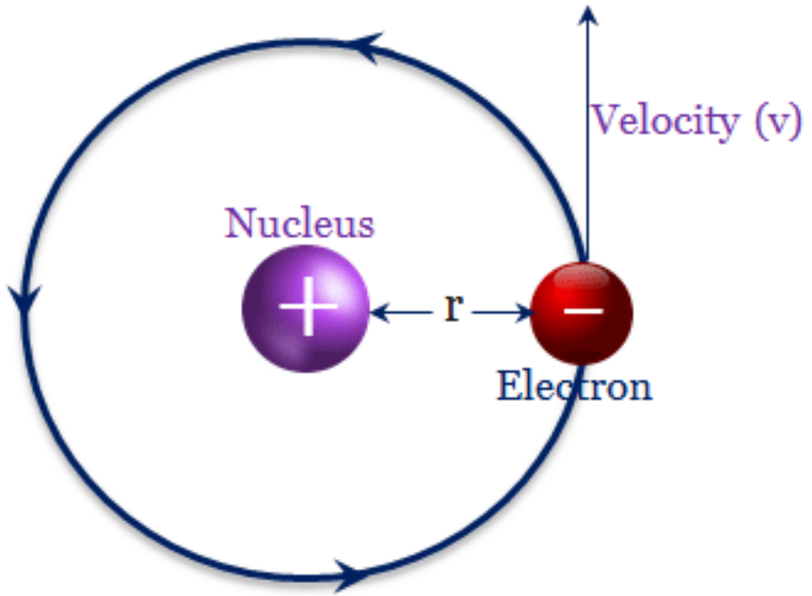

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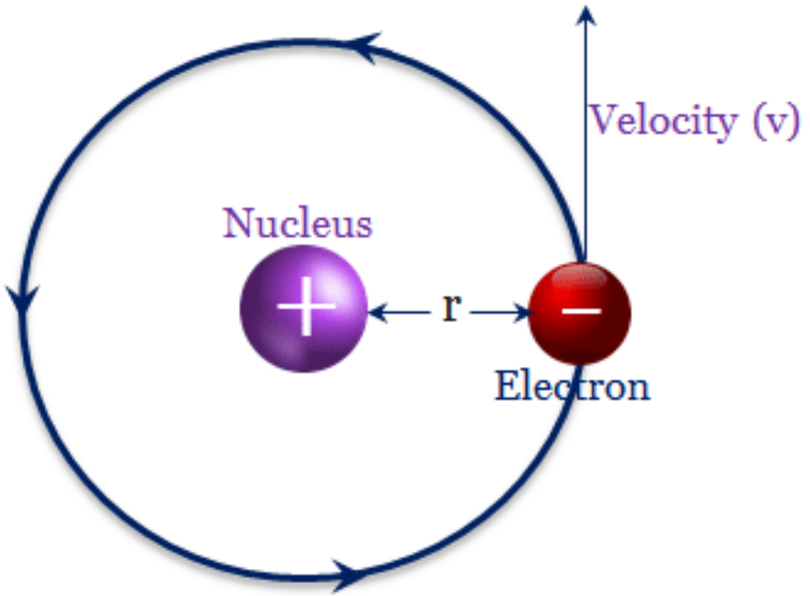
It is described by the quantum theory of Schrödinger and Heisenberg (1925).

Hydrogen atom



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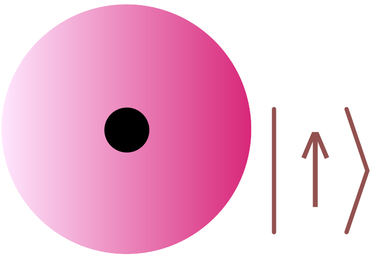


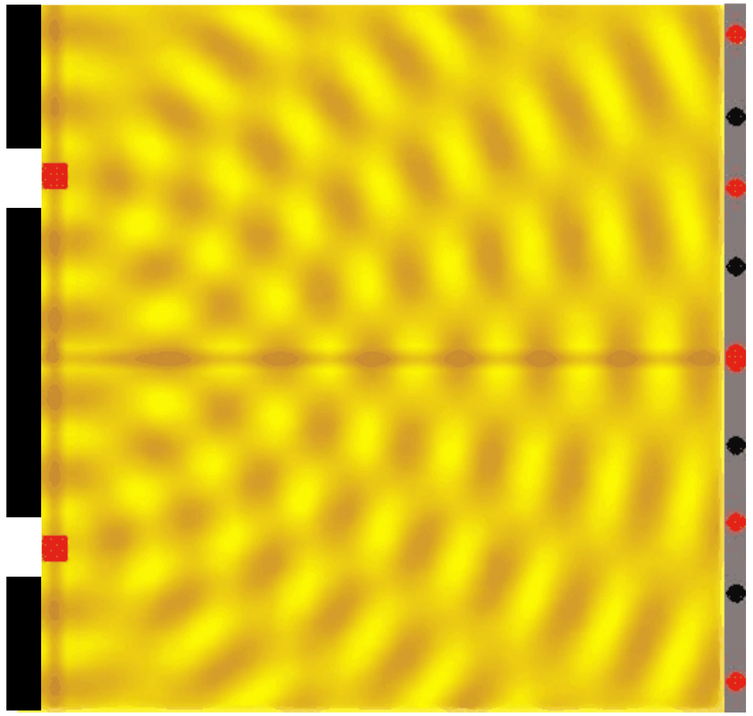
$\Rightarrow 10^{-10}$ meters $\Leftarrow$

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.

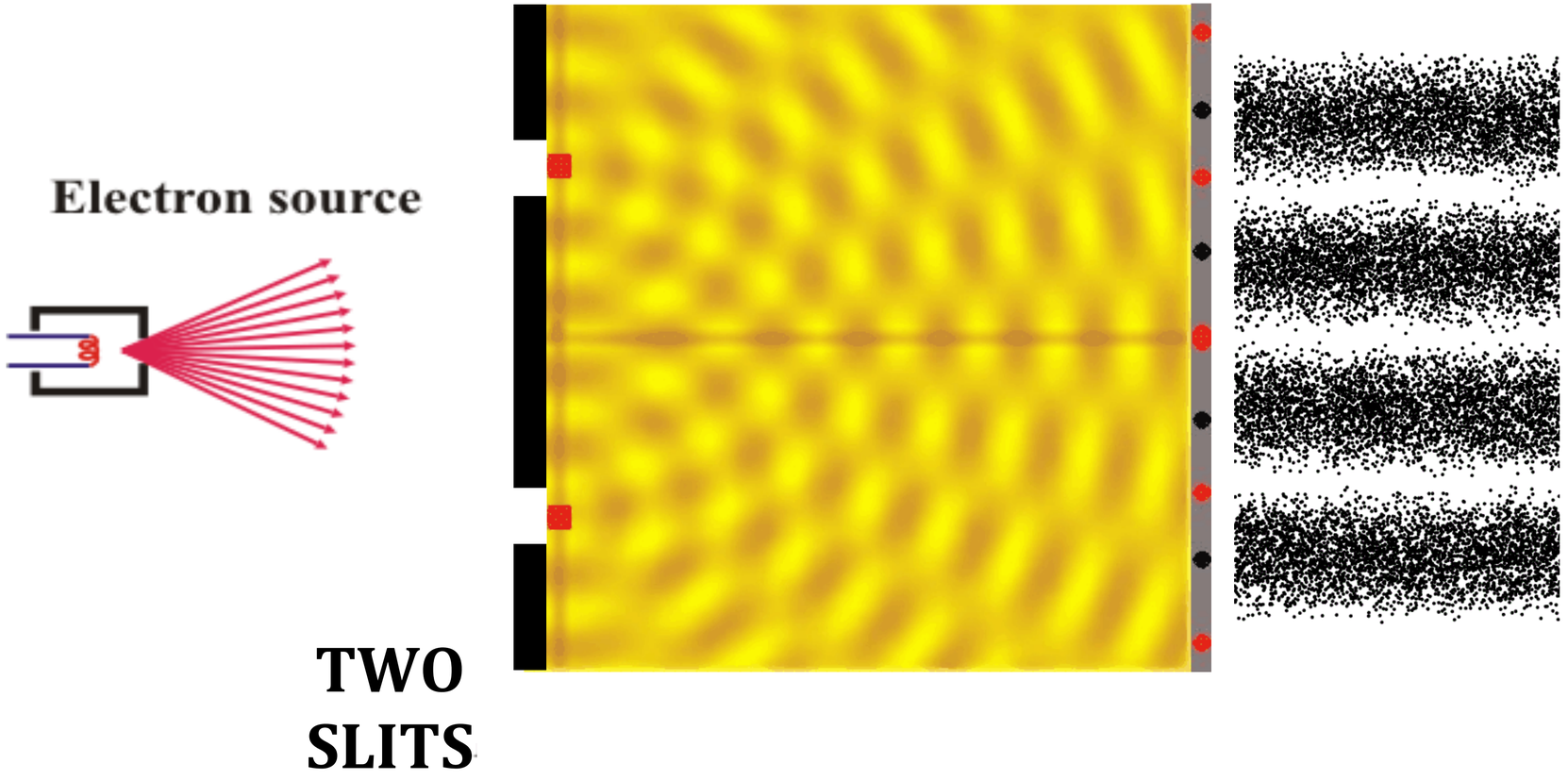
The double slit experiment



TWO SLITS

Interference of water waves

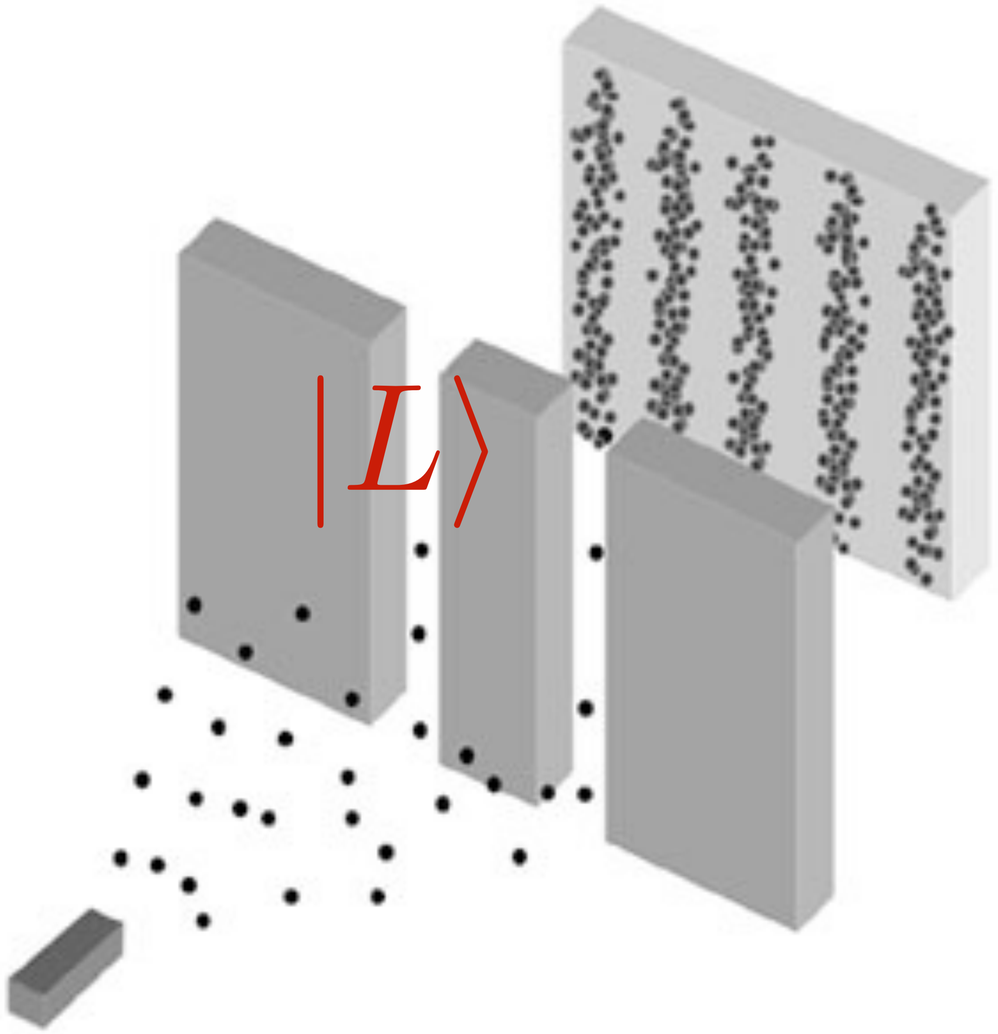
The double slit experiment



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

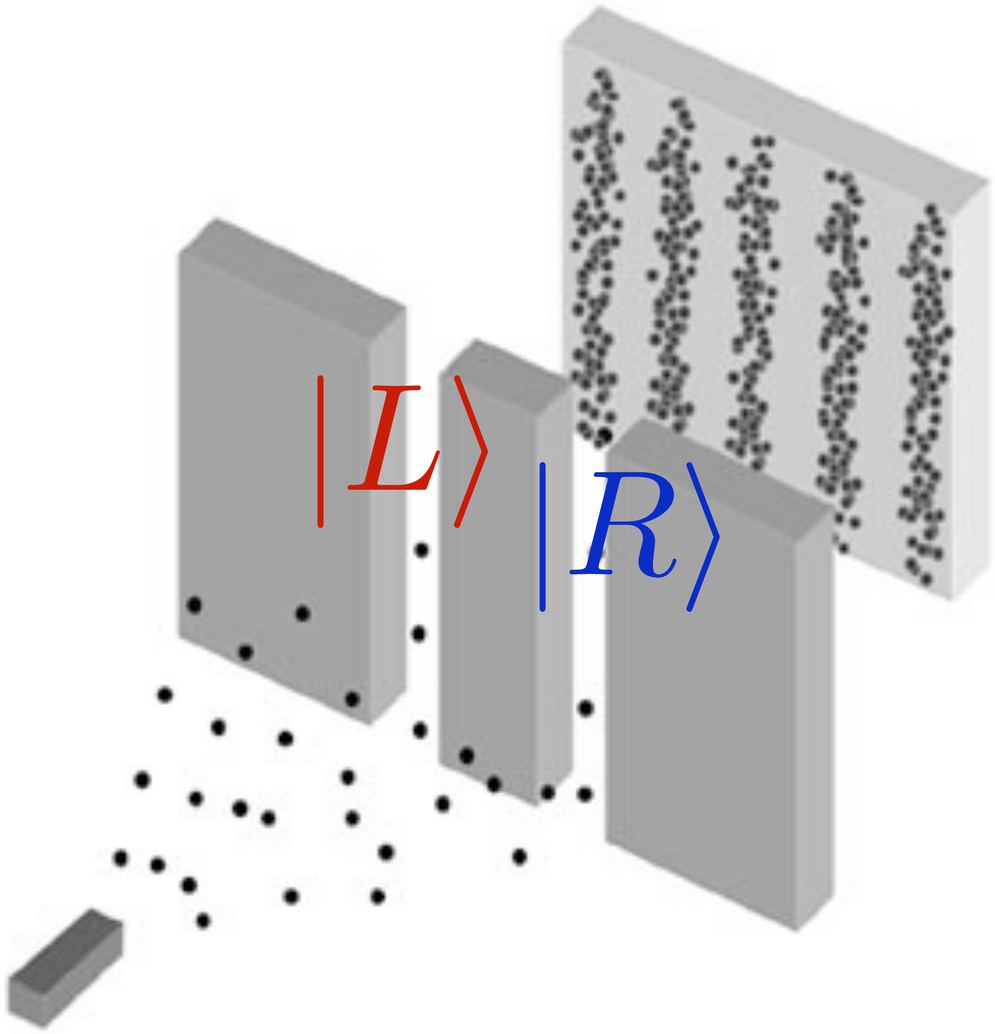
Interference of electrons

The double slit experiment



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

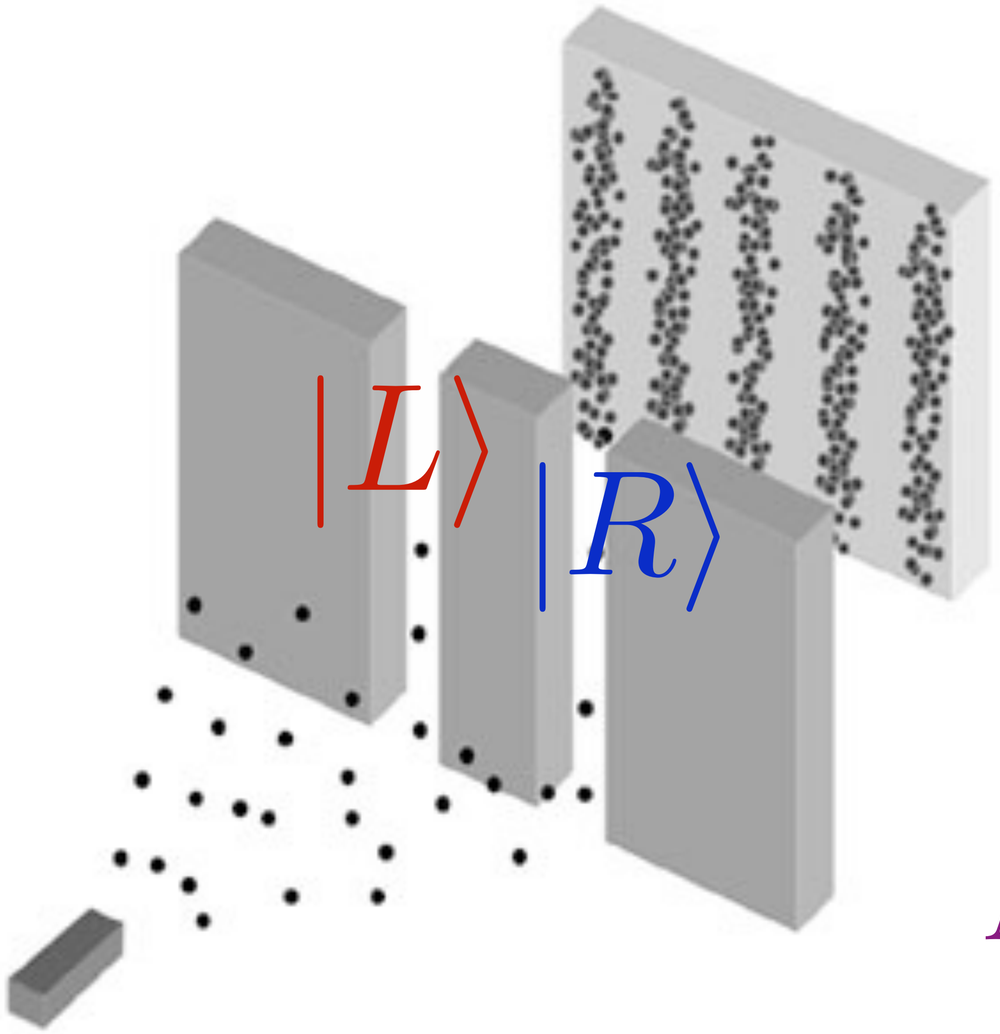
The double slit experiment



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



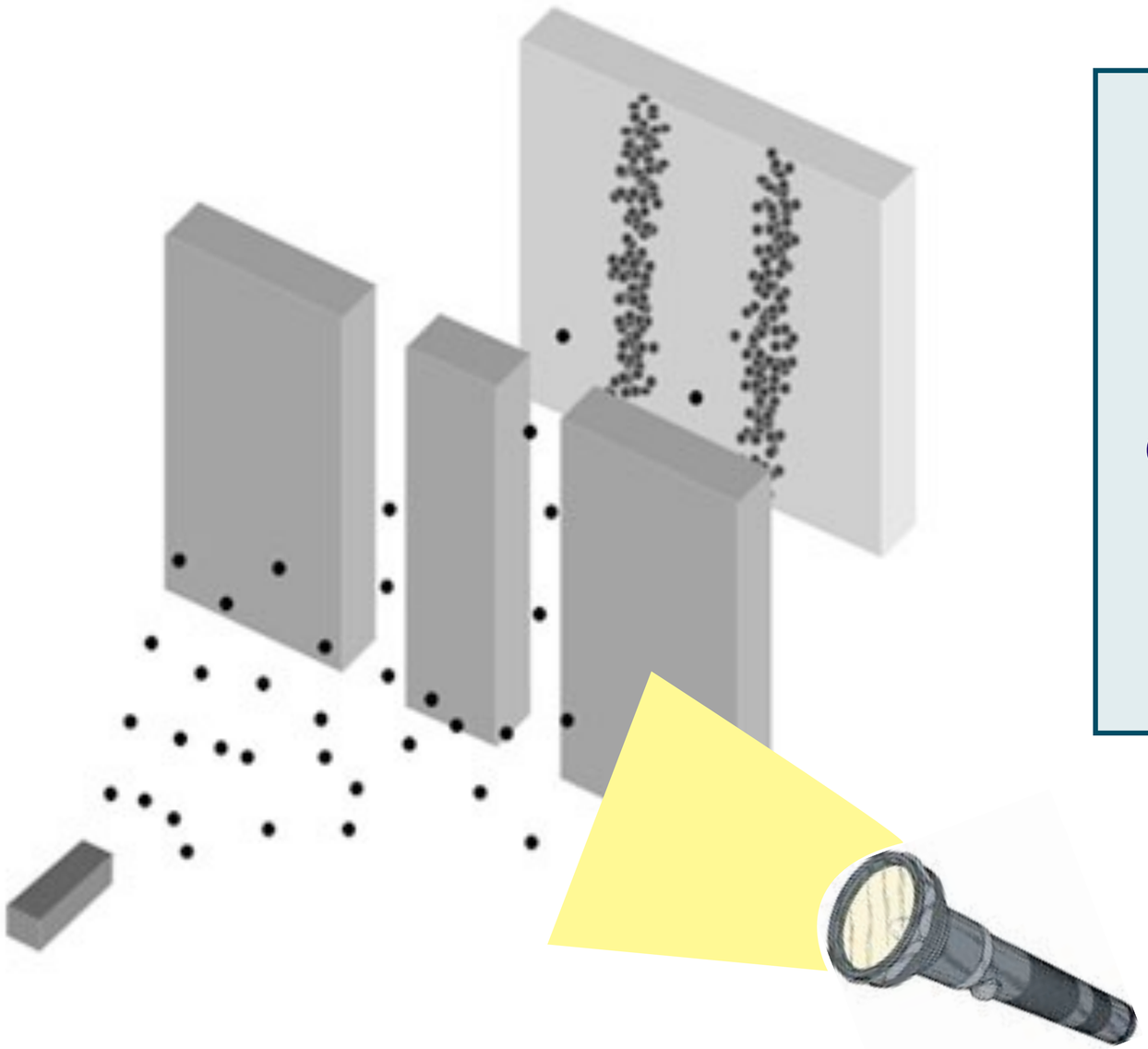
Let $|L\rangle$ represent the state with the electron in the left slit

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

Actual state of *each* electron is

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

The double slit experiment



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

No interference when you watch the electrons

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

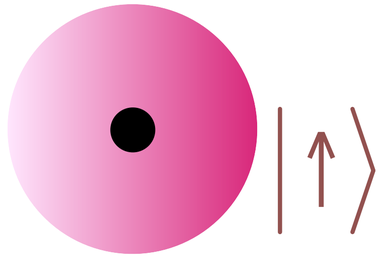
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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

(Received March 25, 1935)

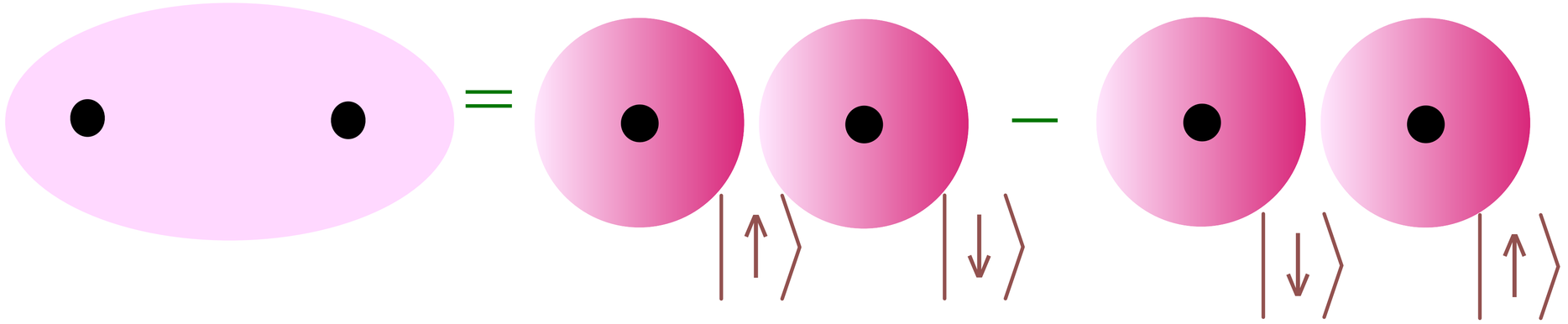
Molecules

Hydrogen atom:



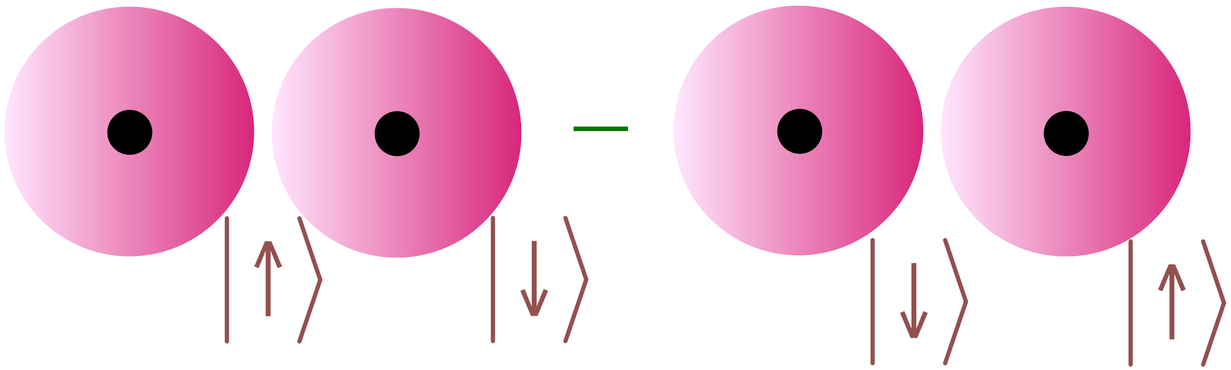
Covalent bond

Hydrogen molecule:



Quantum Entanglement

Einstein, Podolsky, Rosen (1935)



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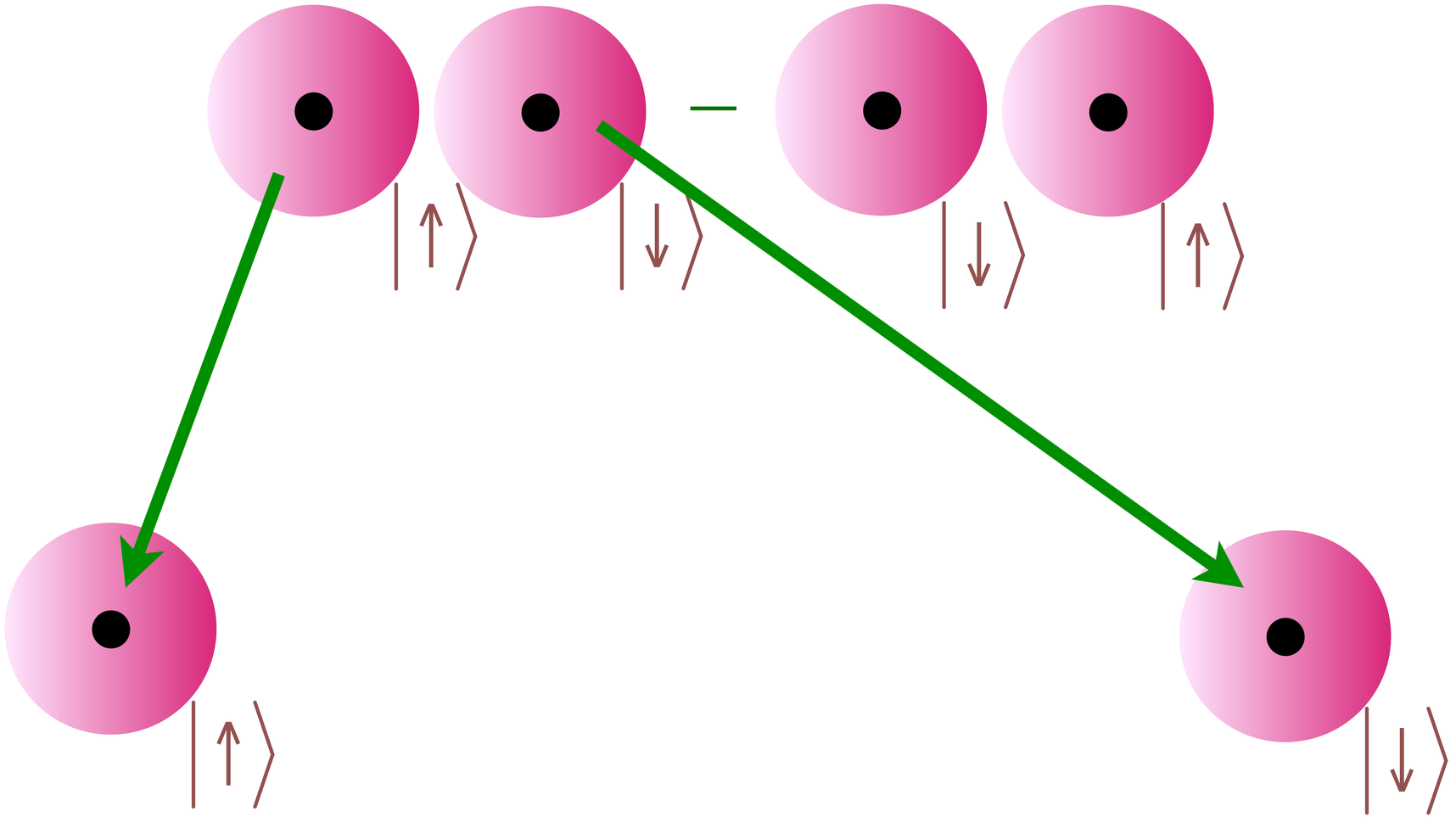

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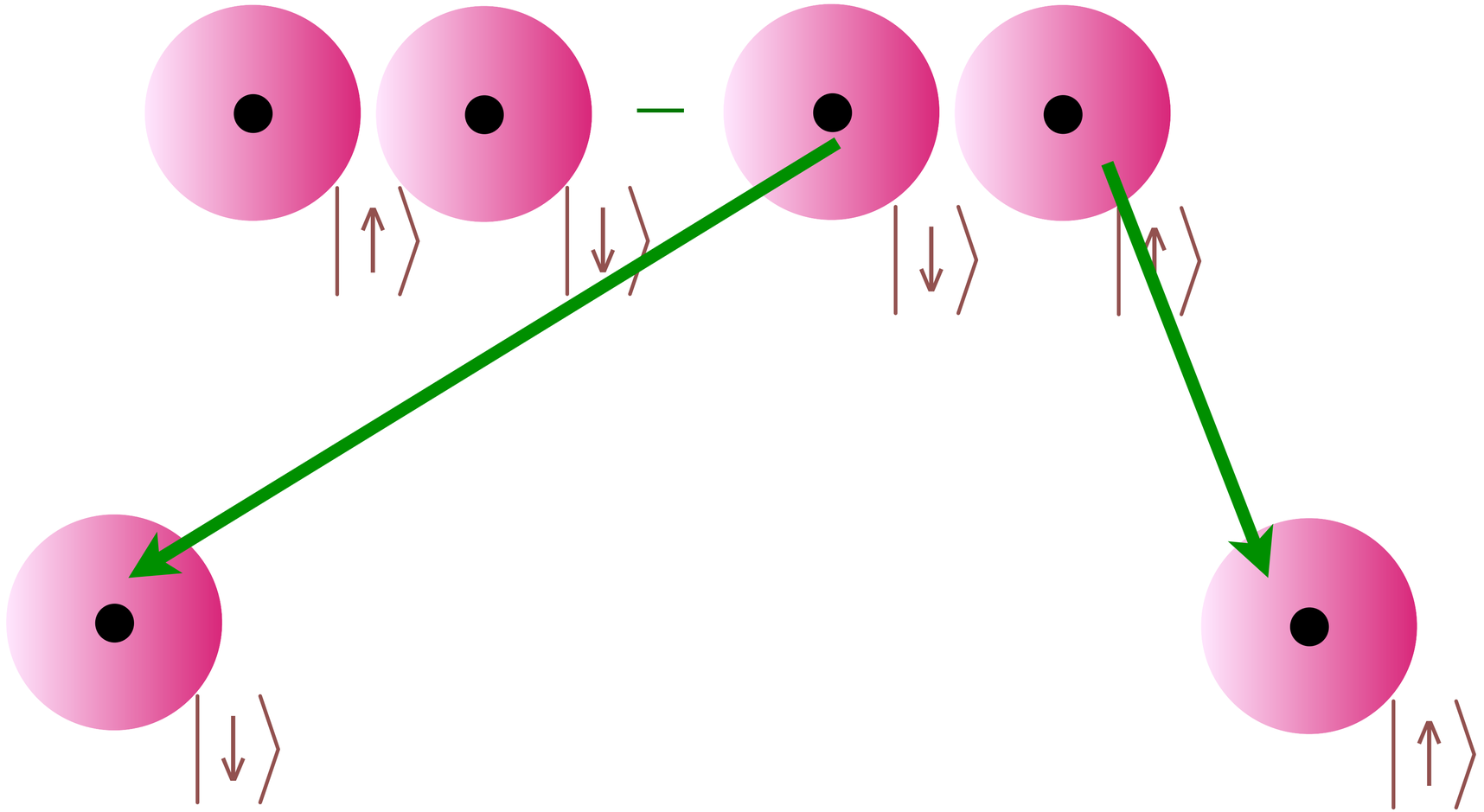

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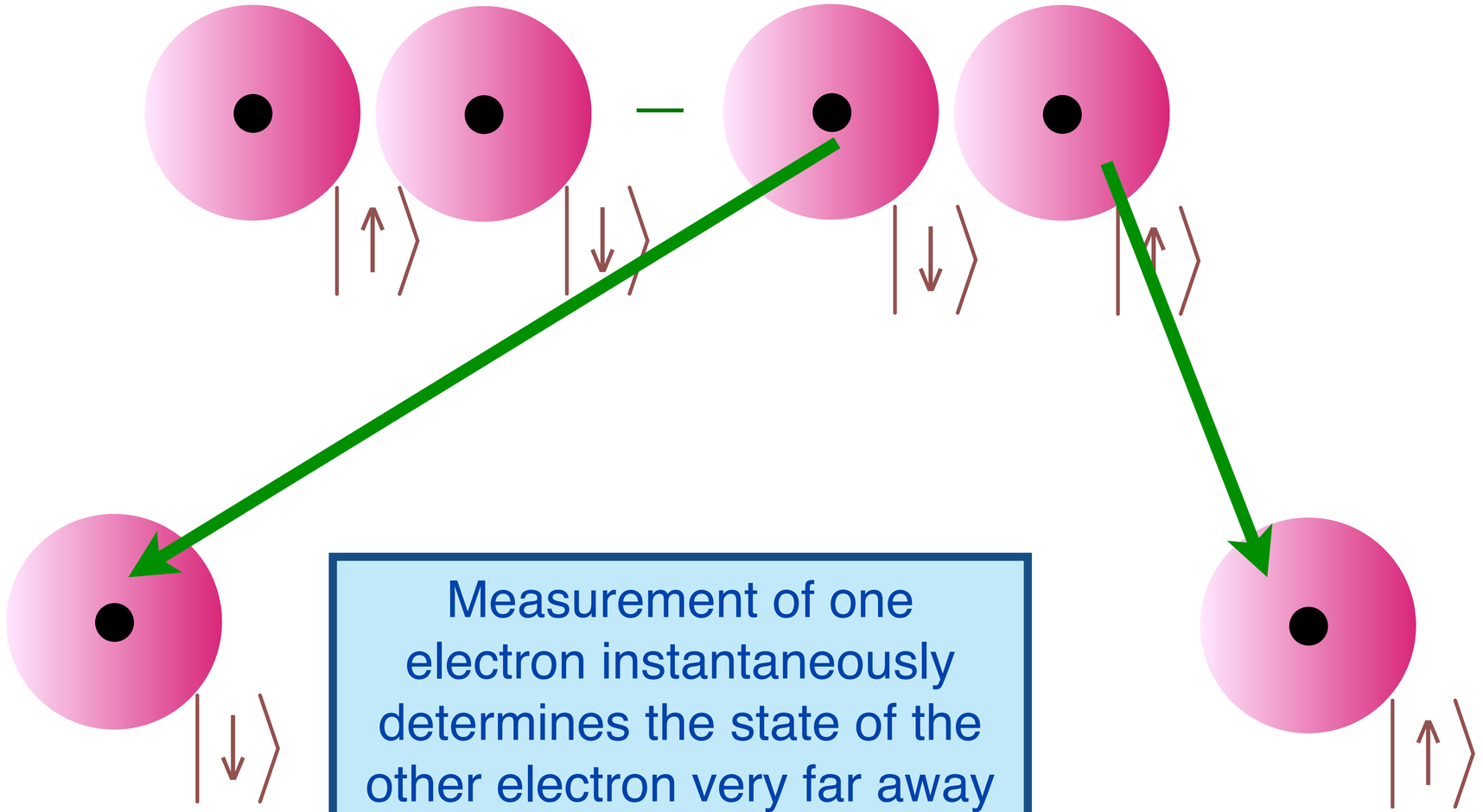

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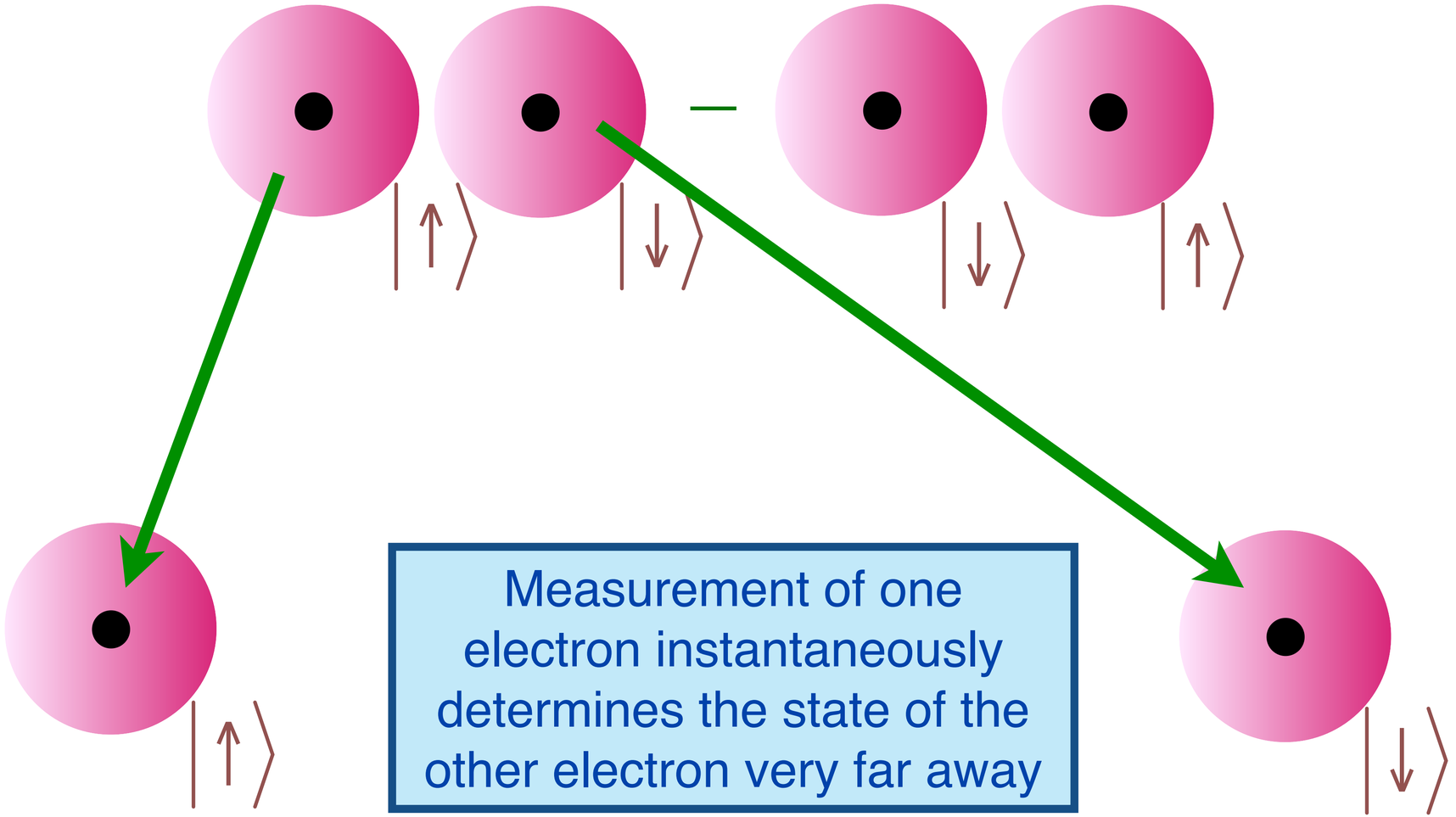

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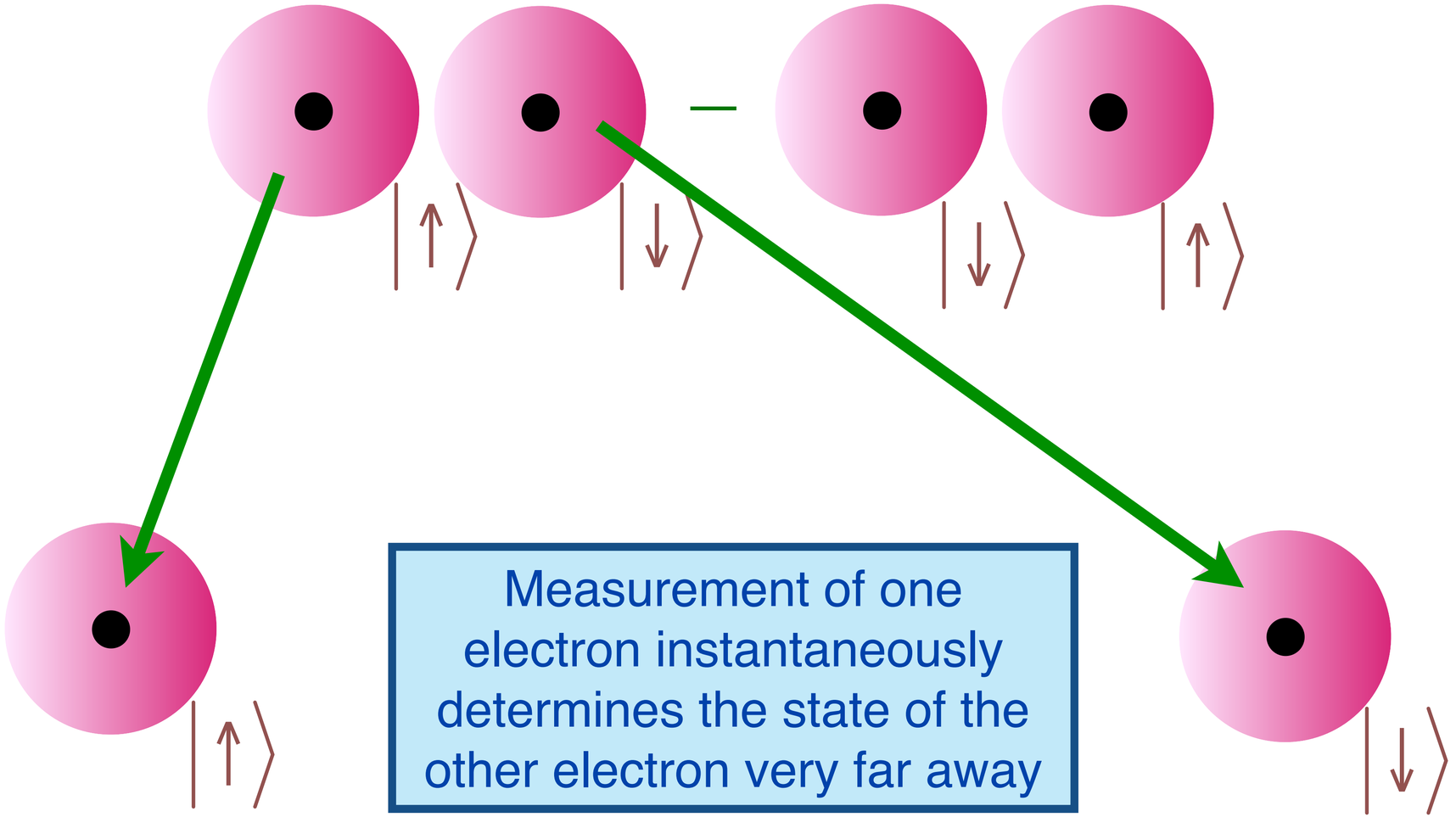


Spooky action at a distance !

Diskussionen; denn Hedi, als Quäkerin, legt Deine Aussprüche oft anders aus, als ich alter Heide (das heißt, ich bin das eigentlich garnicht, sondern recht fromm; nur im Vergleich zu Hedi). Grüß unsere Freunde in Princeton, Neumann, Ladenburg, Weyl und den bissigen Pauli. In alter Freundschaft

Dein Max Born

Unter den experimentellen Arbeiten meines Mitarbeiters Fürth war nur eine, deren Idee von mir ausgegangen ist, der photoelektrische Fouriertransformer. Er ist später von dem Edinburgher Zweig der Firma Ferranti weiter entwickelt worden, hat sich aber nicht in die Praxis eingeführt.

[84]

3. 3. 47

Lieber Born!

Wenn ich nicht ein ausgepichter alter Gauner wäre mit einem versteinerten schlechten Gewissen, dann hätt' ich es nicht so lange ausgehalten, ohne Dir zu schreiben. Darum, erstens hat Deiner Frau Gedicht über das indische Lebensideal tiefen Eindruck auf mich gemacht, so daß es mich nicht gewundert hätte, wenn es von dem alten Goethe geschrieben wäre; zweitens war ich sehr beeindruckt von dem Beitrag, den Du dem sonderbaren Schulmeister Schilpp für den mir gewidmeten Band gegeben hast. Es ist so viel Wärme darin und ein so deutlicher Beweis dafür, für wie sonderbar und versteinert Du meine Haltung der statistischen Quantentheorie gegenüber ansiehst. Endlich gefiel mir Deine Sorge für den Transport Deines chinesischen Schützlings besonders gut, der Dir – glücklicherweise ohne mein Dazwischentreten – glücklich und schweigsam entglitten ist. Ich hatte mit Weyl über den Fall beraten, und wir waren darin überein gekommen, daß wir das Problem nicht in der von Dir vorgeschlagenen Weise zu lösen imstande gewesen wären, und daß ich mich an den englischen Botschafter wenden

solle, der die Sache schandenhalber zu einem befriedigenden Abschluß bringen würde. Glücklicherweise verbummelte ich diesen Schritt einige Tage, worauf Dein erlösender Brief ankam.

Meine physikalische Haltung kann ich Dir nicht so begründen, daß Du sie irgendwie vernünftig finden würdest. Ich sehe natürlich ein, daß die prinzipiell statistische Behandlungsweise, deren Notwendigkeit im Rahmen des bestehenden Formalismus ja zuerst von Dir klar erkannt wurde, einen bedeutenden Wahrheitsgehalt hat. Ich kann aber deshalb nicht ernsthaft daran glauben, weil die Theorie mit dem Grundsatz unvereinbar ist, daß die Physik eine Wirklichkeit in Zeit und Raum darstellen soll, ohne spukhafte Fernwirkungen. Allerdings bin ich nicht fest davon überzeugt, daß es wirklich mit der Theorie eines kontinuierlichen Feldes gemacht werden kann, obwohl ich hierfür eine bisher recht vernünftig erscheinende Möglichkeit gefunden habe. Die rechnerischen Schwierigkeiten sind jedoch so groß, daß ich ins Gras beißen werde, bevor ich selbst eine sichere Überzeugung hierüber erlangt habe. Aber davon bin ich fest überzeugt, daß man schließlich bei einer Theorie landen wird, deren gesetzmäßig verbundene Dinge nicht Wahrscheinlichkeiten sondern gedachte Tatbestände sind, wie man es bis vor kurzem als selbstverständlich betrachtet hat. Zur Begründung dieser Überzeugung kann ich aber nicht logische Gründe, sondern nur meinen kleinen Finger als Zeugen beibringen, also keine Autorität, die außerhalb meiner Hand irgendwelchen Respekt einflößen kann.

Ich freue mich, daß Dein Leben und Deine Arbeit fruchtbar und befriedigend sind. Dies hilft einem hinweg über die Tollheiten der Menschen, die das Schicksal des sogenannten homo sapiens im Großen bestimmen. Es war ja wohl nie besser, aber man hat es in seiner Jämmerlichkeit nicht so deutlich gesehen, und die Folgen der Pfuscherei waren weniger katastrophal als unter den gegenwärtigen Umständen.

Sei mit den Deinen herzlich gegrüßt von Deinem

A. Einstein.

saying that it is even more difficult for scientists than for ordinary people to develop a conscience and a sense of right and wrong. In regard to Laue, I have also heard that his conduct was decent and courageous. One can only hope that he will survive the last, and presumably the most gruesome, period of the war.

I hope that you will write again from time to time. A letter from you gives us the very greatest pleasure. It causes long discussions; for Hedi, as a Quaker, often interprets your remarks very differently from the way I do, old heathen that I am (I am not one really, in fact I am quite devout; it is only in comparison with Hedi). Give my regards to our friends in Princeton – Neumann, Ladenburg, Weyl and the caustic Pauli.

In old friendship

Yours

Max Born

♦ Forth's experimental work contained only one idea of mine; this was the photoelectric Fourier transformer. Later on the Edinburgh branch of Ferranti developed this further, but it was not, however, introduced in practice.

84 *Dear Born*

3 March, 1947

If I were not a confirmed old rogue, with a fossilised bad conscience, I would not have been able to go for such a long time without writing to you. For firstly, your wife's poem about the Indian ideal of life made so deep an impression on me that I would not have been surprised if it had been written by old Goethe himself; secondly, I was very impressed with your contribution to that peculiar schoolmaster Schilpp's volume which is dedicated to me. It has so much warmth and proves so clearly that you consider my attitude towards statistical quantum mechanics to be strange and archaic. Finally, I particularly like your solicitude for your Chinese protégé's transportation; fortunately he has happily and silently slipped away from you without my intervention. I had consulted Weyl about him, and we both agreed that we would not have been able to solve the problem in the way you had suggested, and that I should

approach the English ambassador, who would bring the matter honourably to a satisfactory conclusion. Fortunately I avoided making this step for several days, and then your letter arrived, releasing me.

I cannot make a case for my attitude in physics which you would consider at all reasonable. I admit, of course, that there is a considerable amount of validity in the statistical approach which you were the first to recognise clearly as necessary given the framework of the existing formalism. 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 a distance. I am, however, not yet firmly convinced that it can really be achieved with a continuous field theory, although I have discovered a possible way of doing this which so far seems quite reasonable. The calculation difficulties are so great that I will be biting the dust long before I myself can be fully convinced of it. But I am quite convinced that someone will eventually come up with a theory whose objects, connected by laws, are not probabilities but considered facts, as used to be taken for granted until quite recently. I cannot, however, base this conviction on logical reasons, but can only produce my little finger as witness, that is, I offer no authority which would be able to command any kind of respect outside of my own hand.

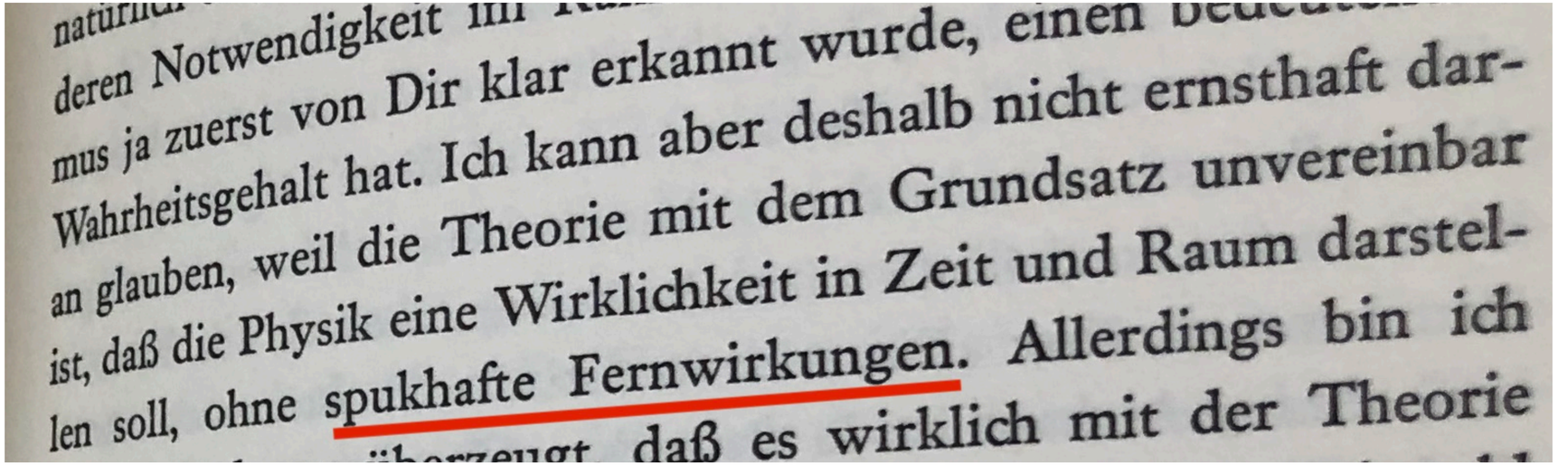
I am glad that your life and work are fruitful and satisfying. This helps one to bear the craziness of the people who determine the fate of *homo sapiens* (so-called) on the grand scale. Maybe it has never been any better, but one did not see it as clearly in all its wretchedness, nor were the consequences of the bungling quite as catastrophic as under present conditions.

Best wishes to you and your family

Yours

A. Einstein

♦ My wife's 'Indian Sonnets' have been published in an anthology of her poems,[33] 'Stille Gänge' [Silent Corridors]. 'Schoolmaster' Schilpp's volume is one of the series published in the United States called *The Library of Living Philosophers*, under this title: *Albert Einstein, Philosopher–Scientist*. Each volume of this collection begins with a short autobiography of the ...sopher concerned; this is followed by critical reviews of his ... different authors, and ends with the subject's reply to his ... had undertaken to write about Einstein's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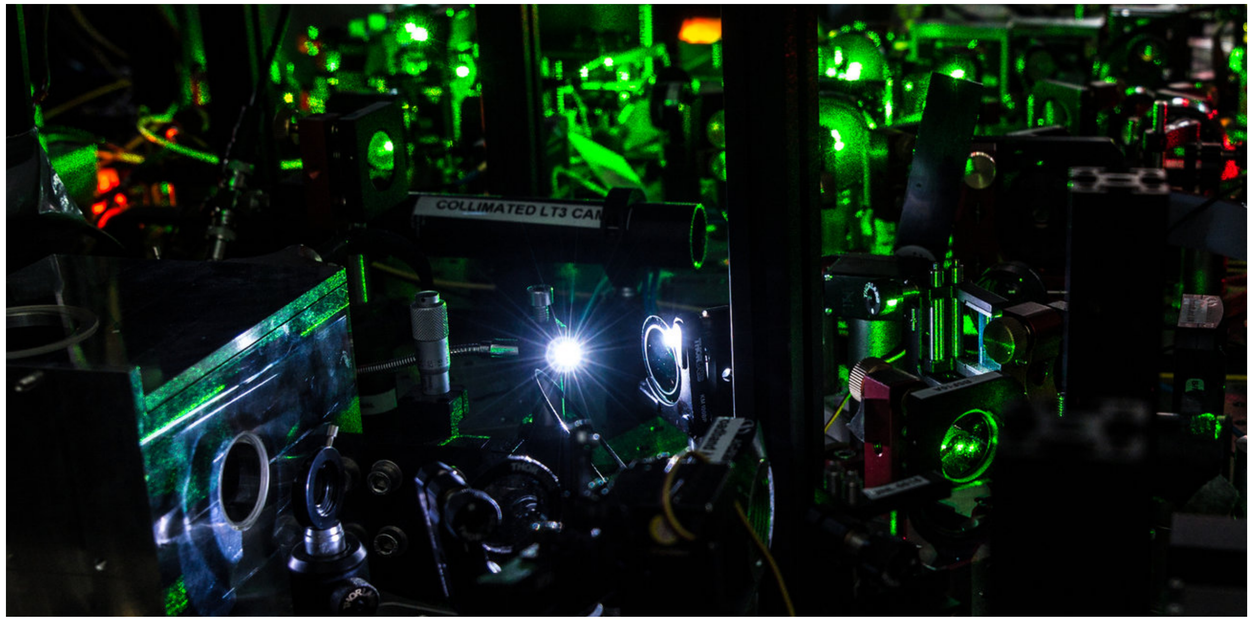
Albert Einstein to Max Born, 3 March 1947

The New York Times

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

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

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

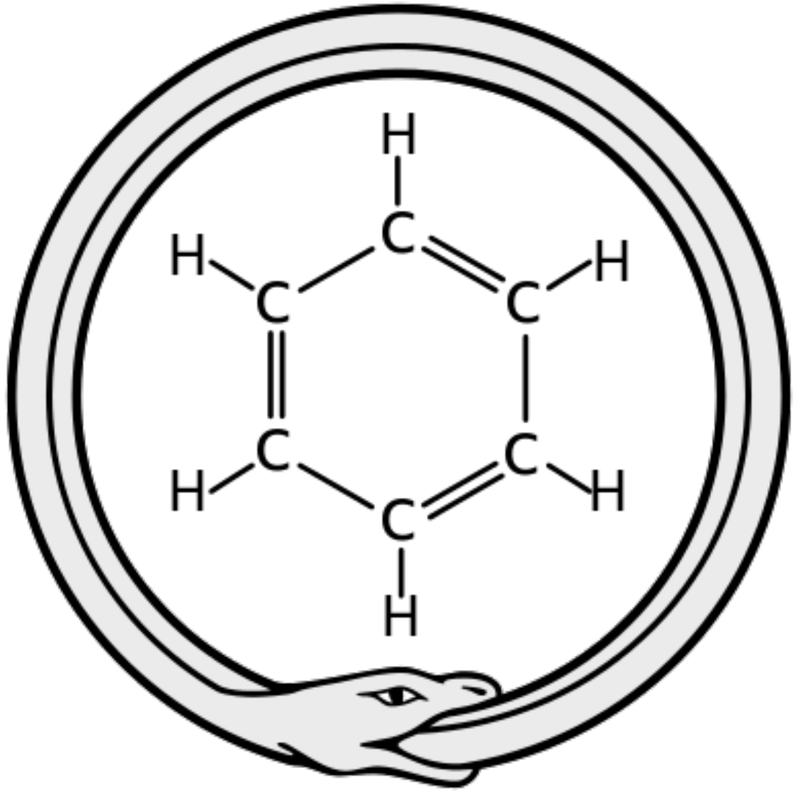


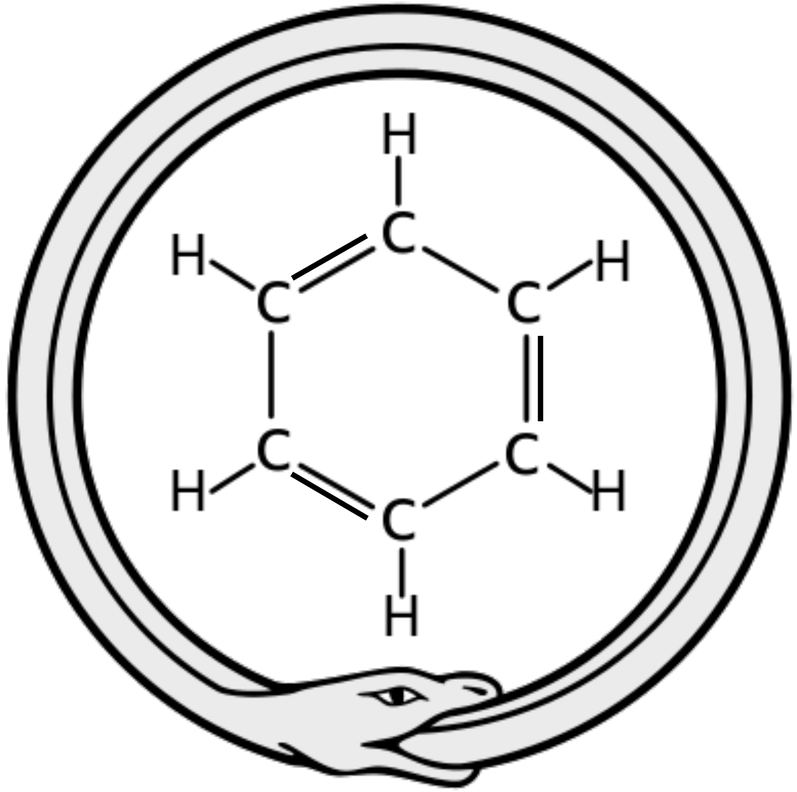
Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

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).*





*Wikipedia

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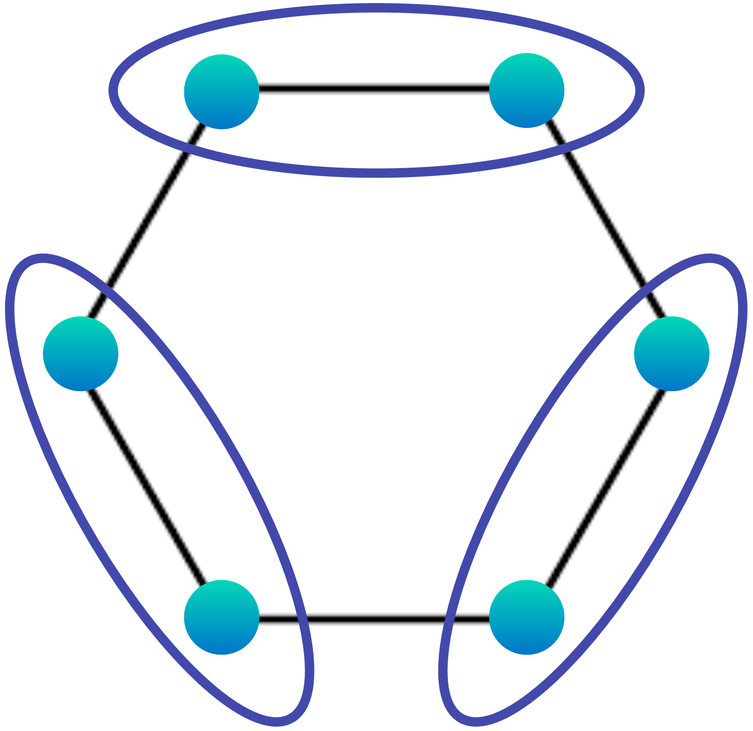
Benzene

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



"Resonating"
covalent
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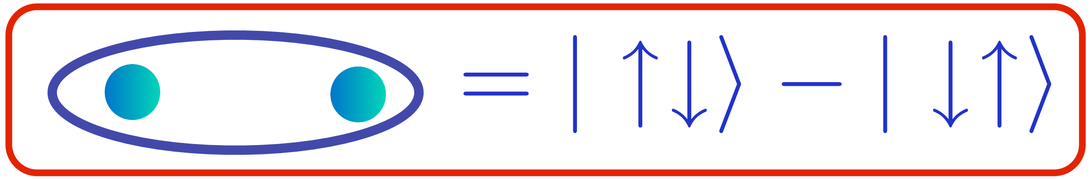

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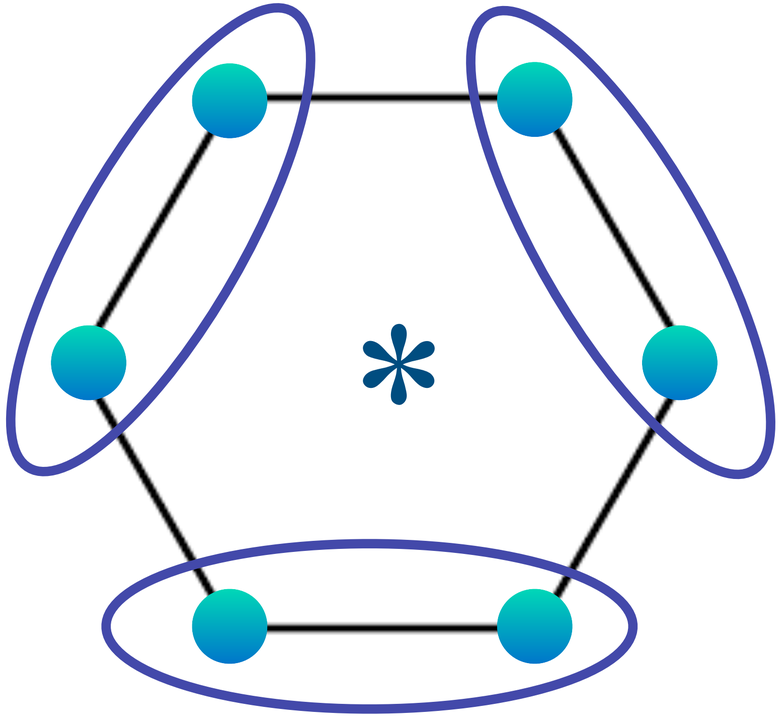

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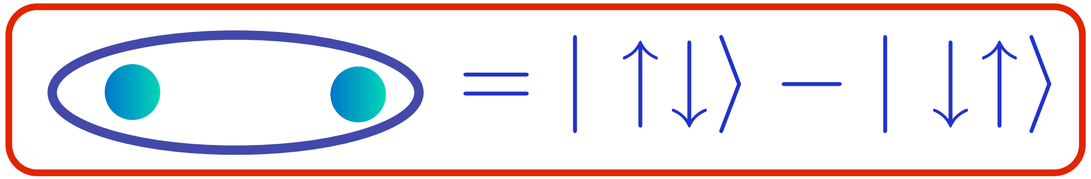

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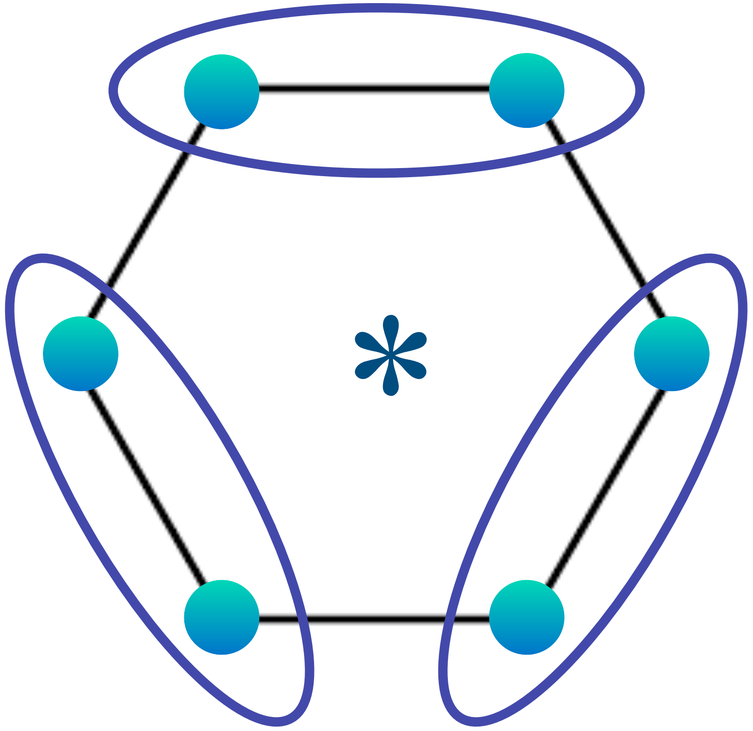

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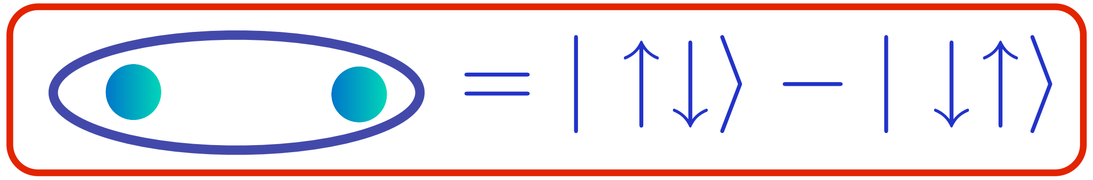

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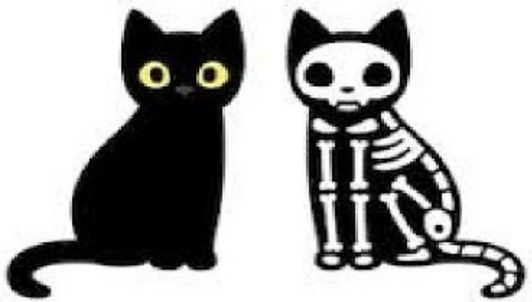
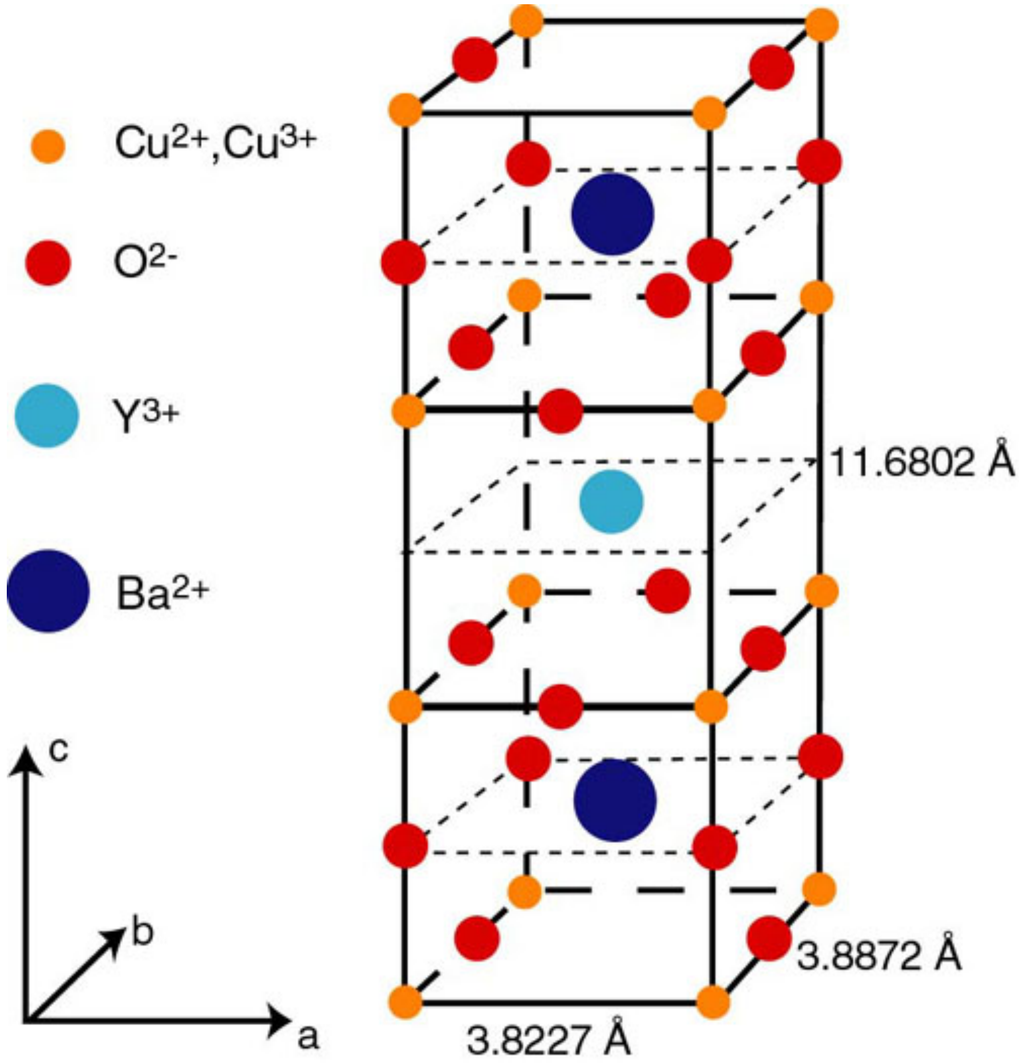
Schrodinger's Cat

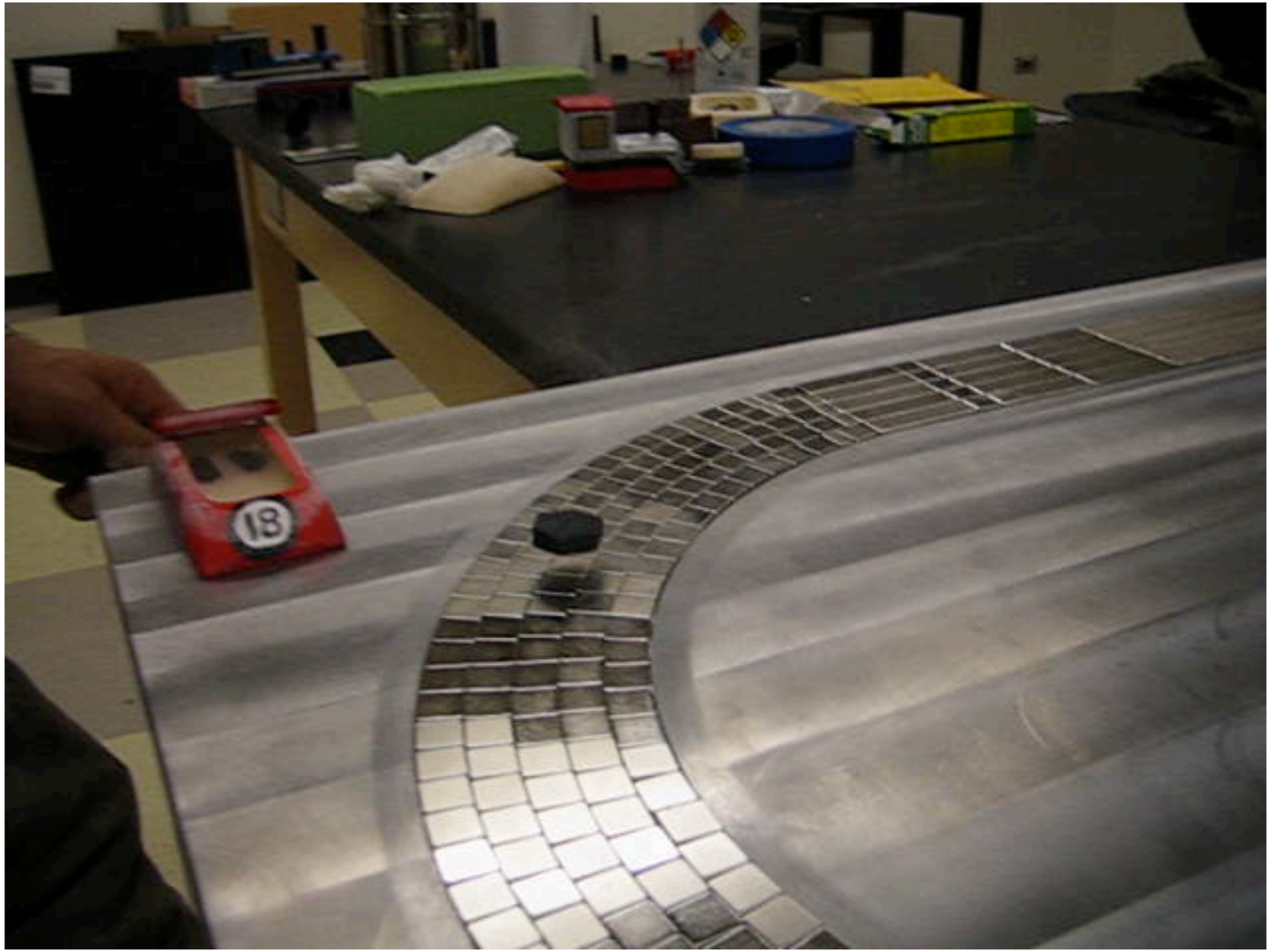


$$\frac{1}{\sqrt{2}}|\text{alive}\rangle + \frac{1}{\sqrt{2}}|\text{dead}\rangle$$

High temperature superconductors



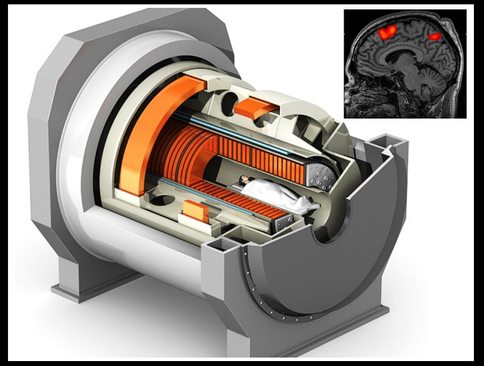
$$YBa_2Cu_3O_{6+x}$$



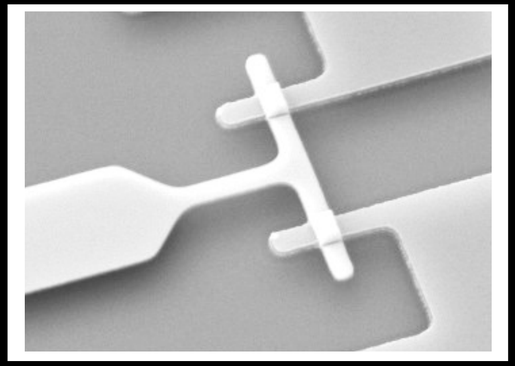
Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

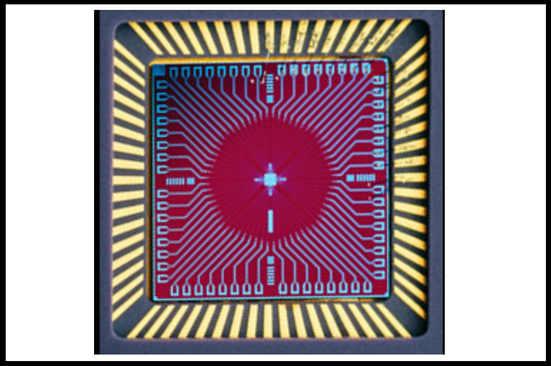
SUPERCONDUCTIVITY: SCIENTIFIC APPLICATIONS



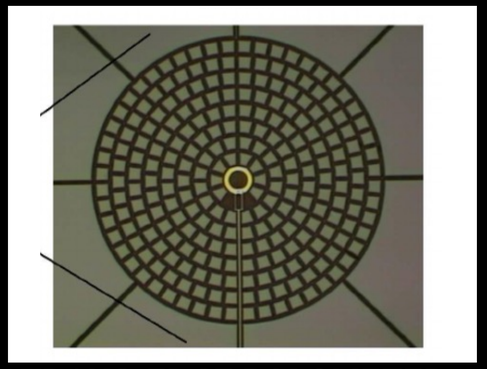
FUNCTIONAL MRI



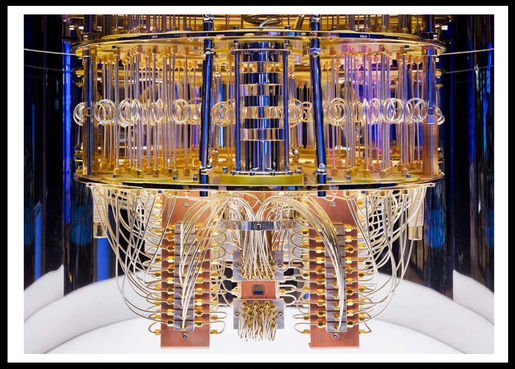
SQUID SENSORS



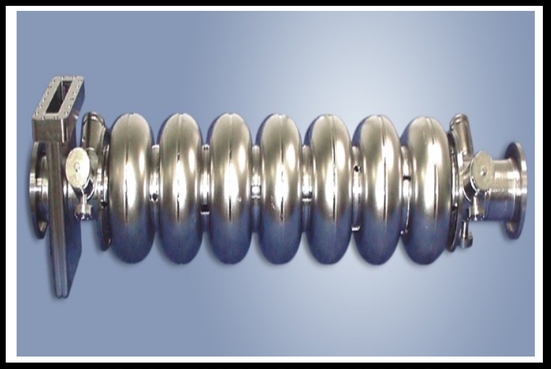
SINGLE PHOTON IMAGING



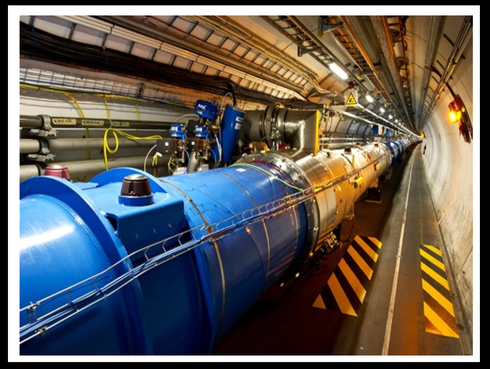
TRANS. EDGE BOLOMETER



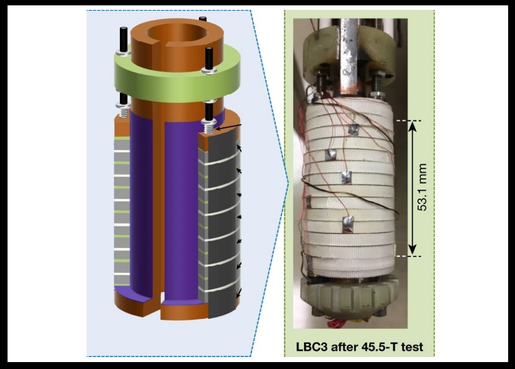
QUANTUM INFO. TECH.



HIGH ENERGY PHYSICS



ACCELERATORS



50+ TESLA MAGNETS

TOKOMAK FUSION

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

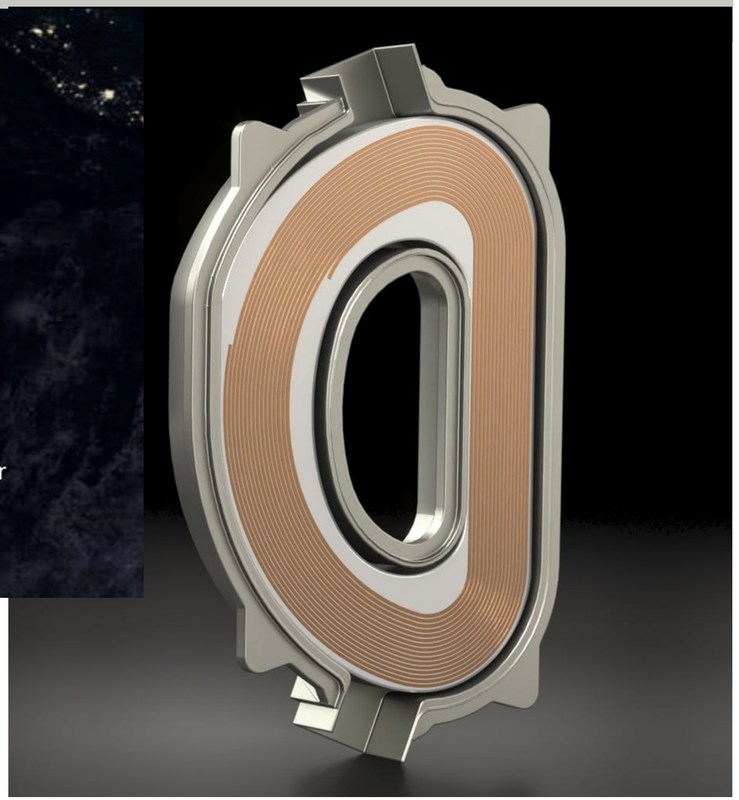
The fastest path to commercial fusion energy combining proven science with revolutionary magnet technology.

Limitless

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

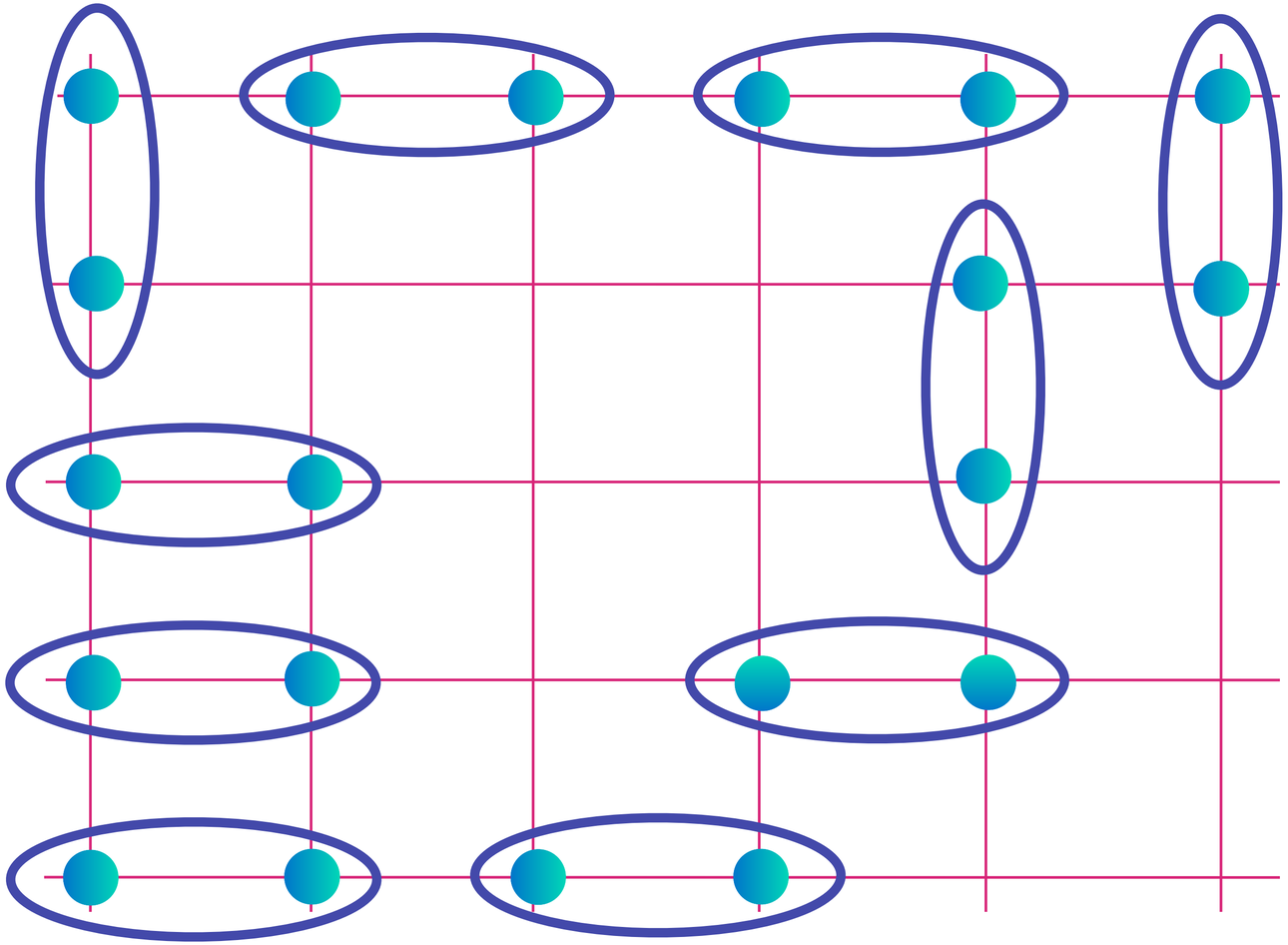
Clean

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



Commonwealth Fusion Systems

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

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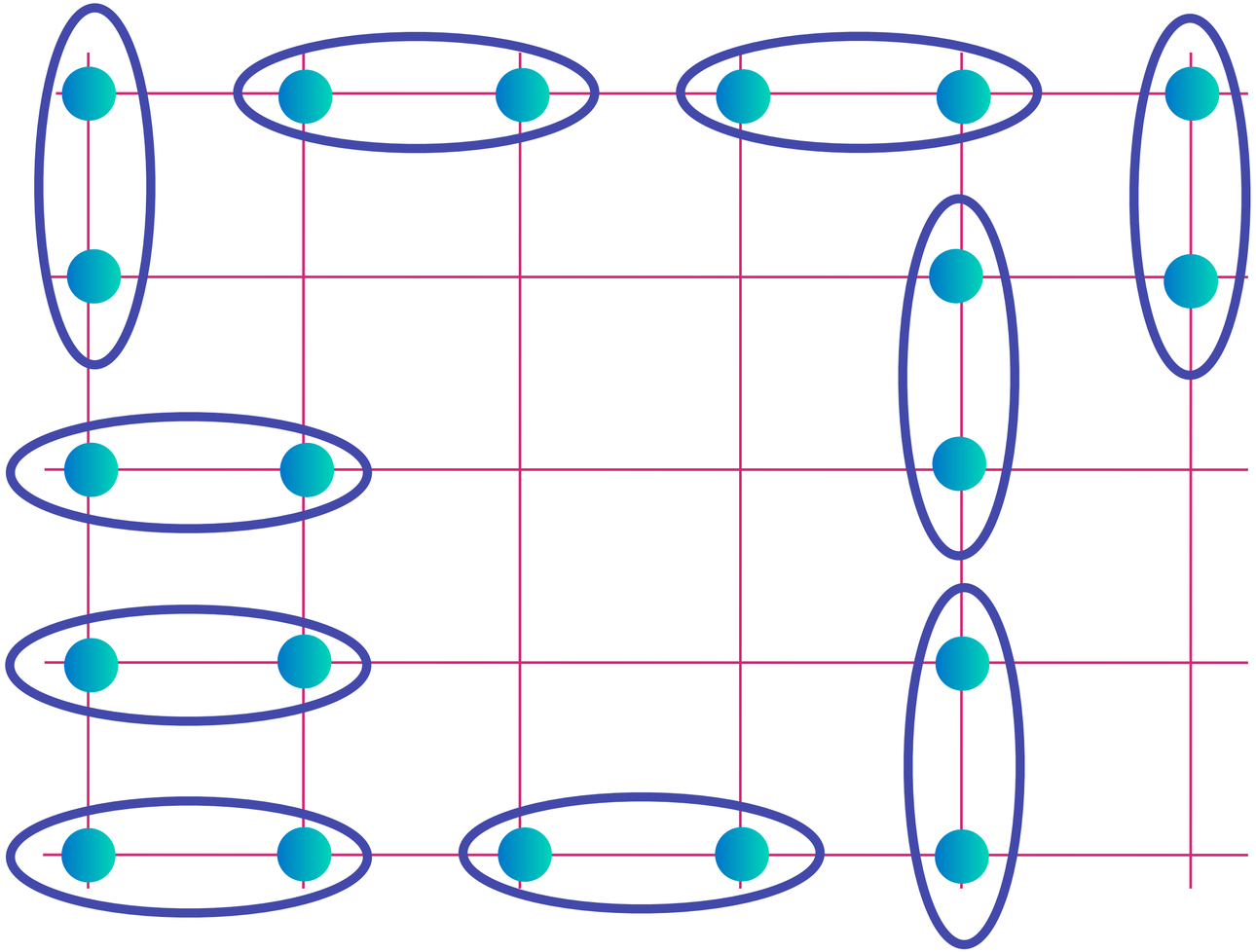

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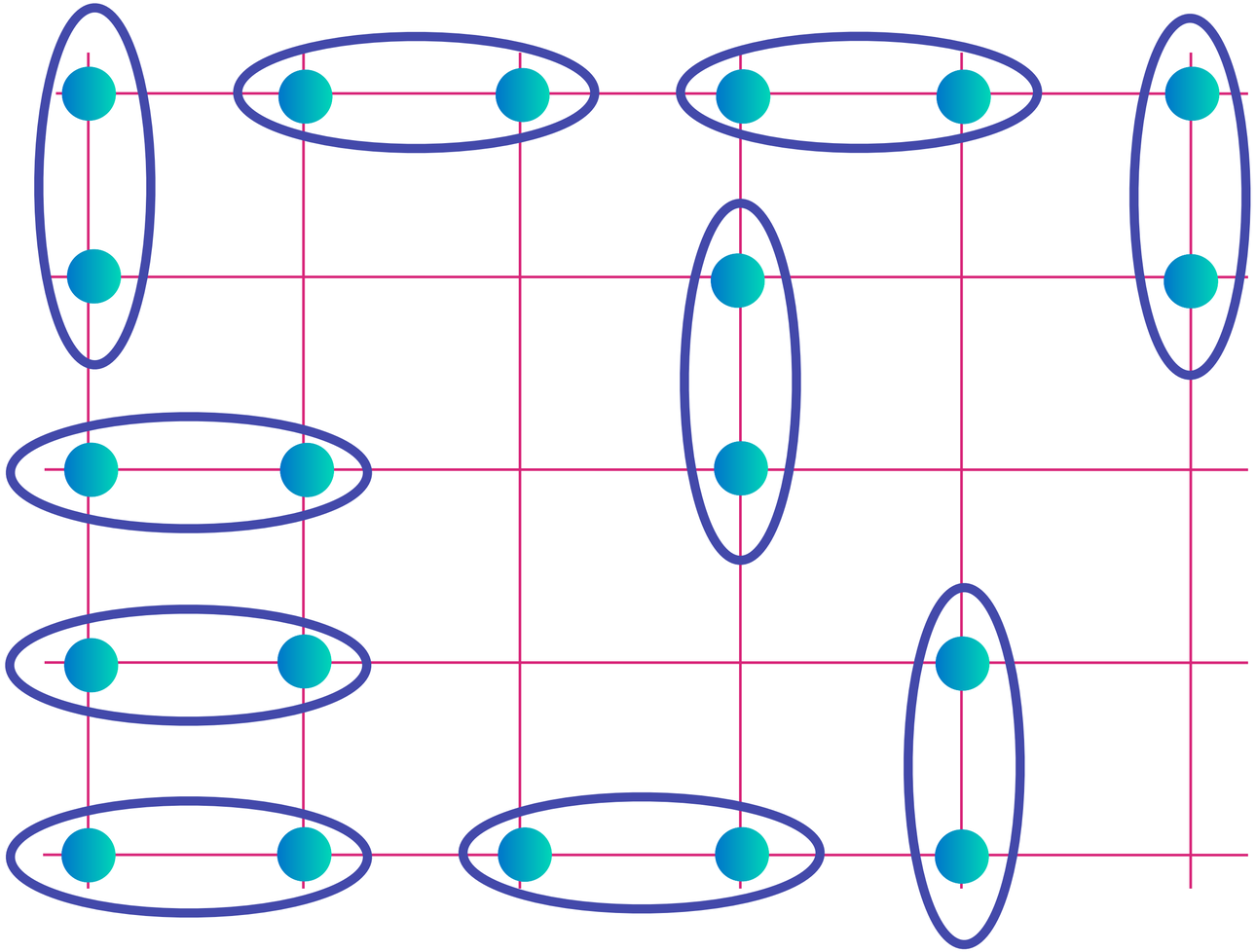

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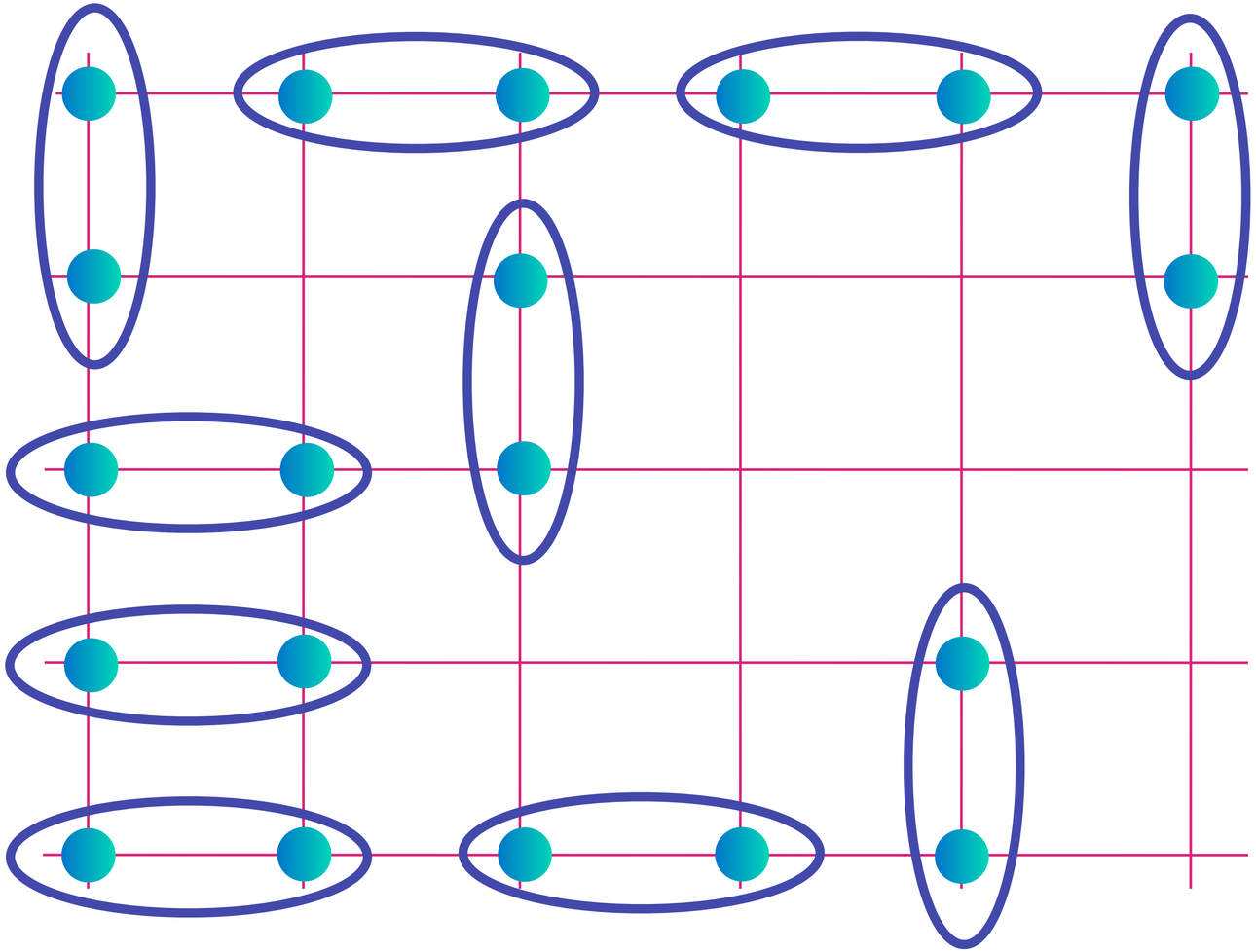

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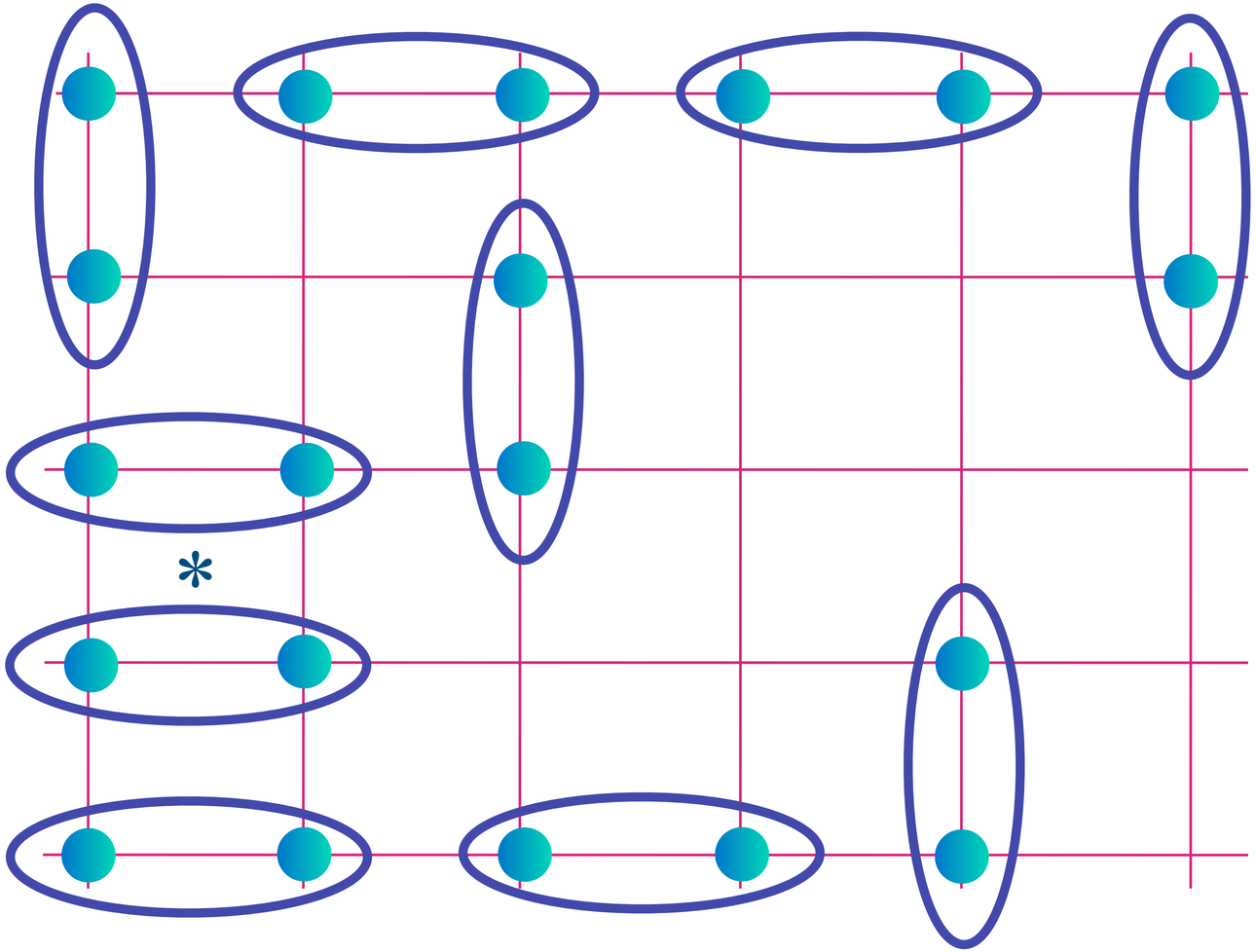

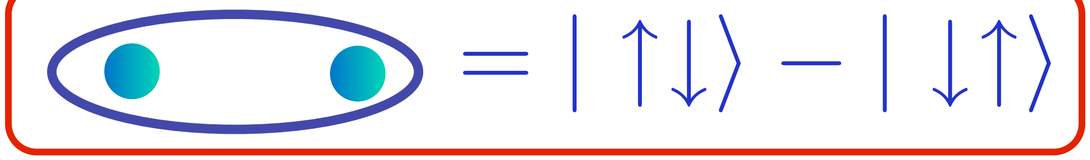

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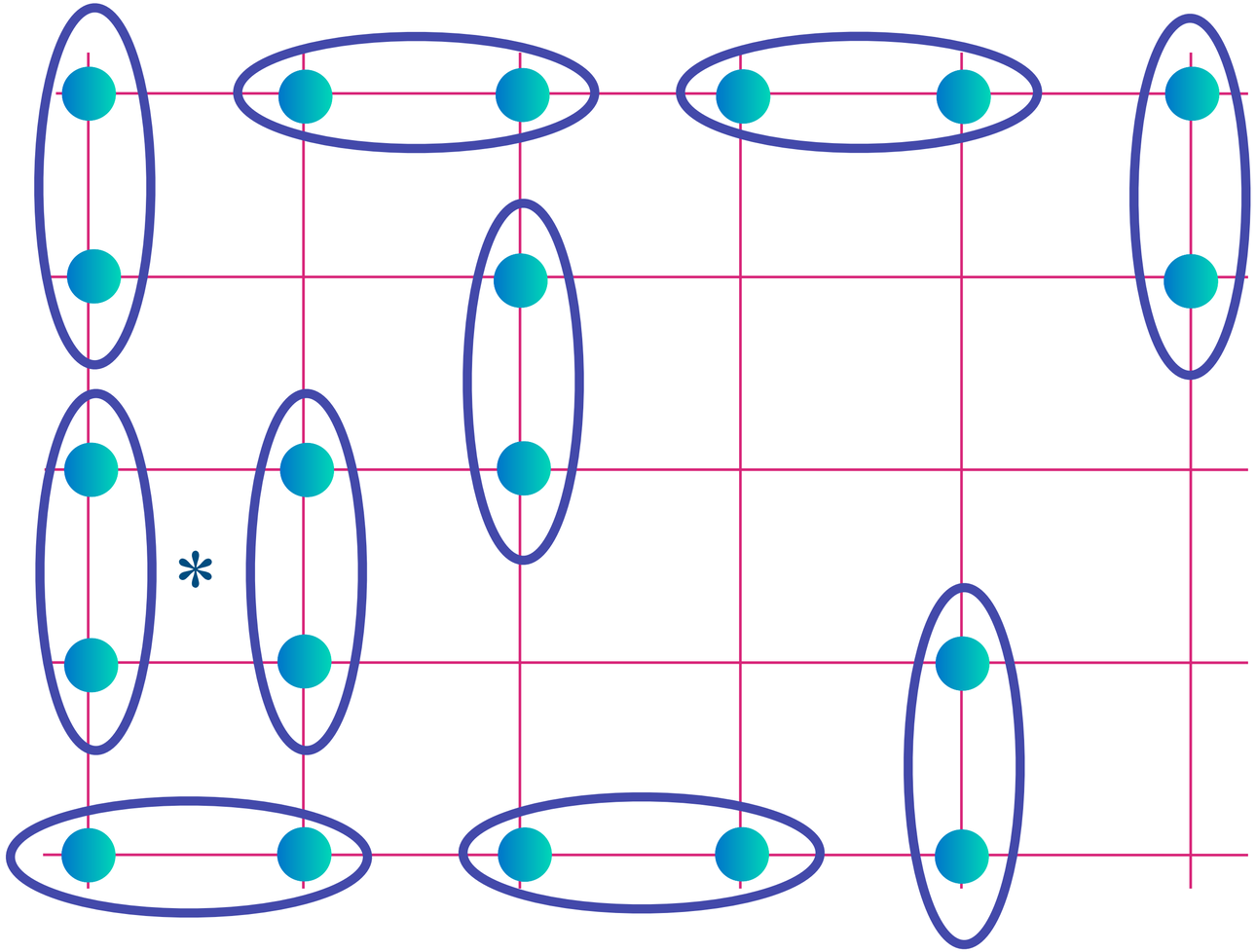

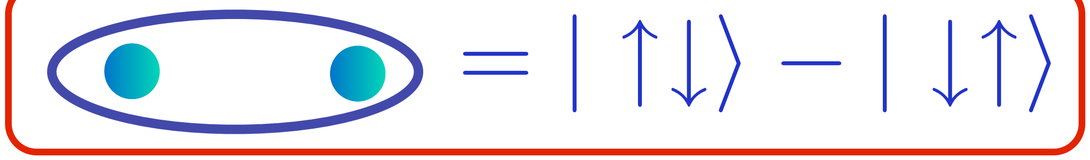

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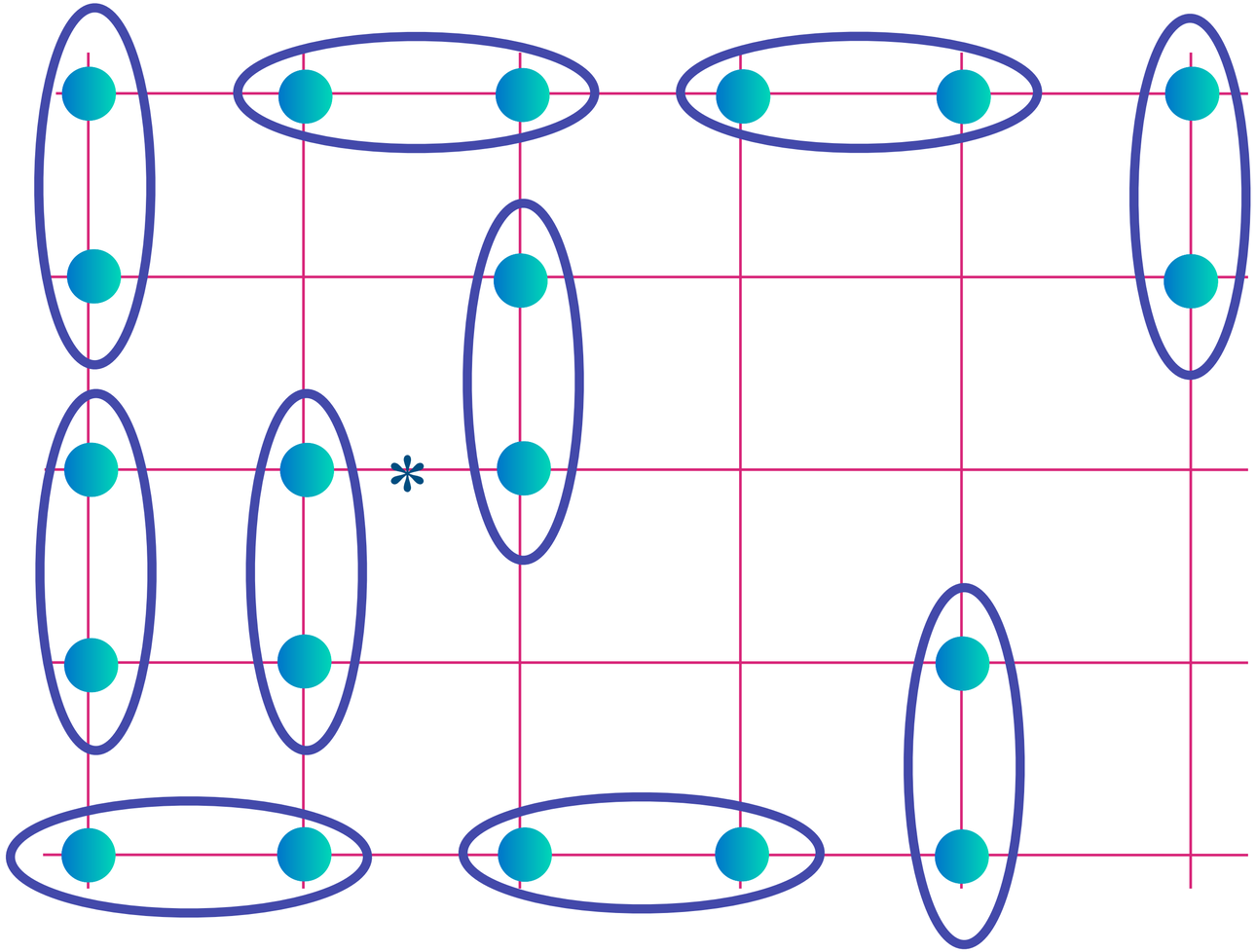

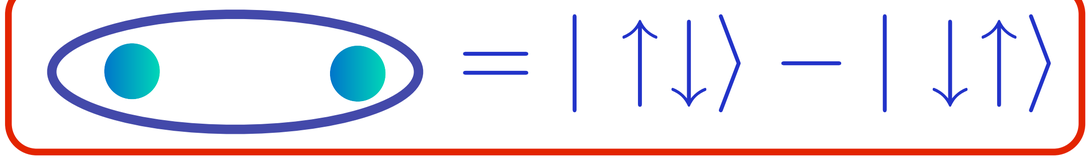

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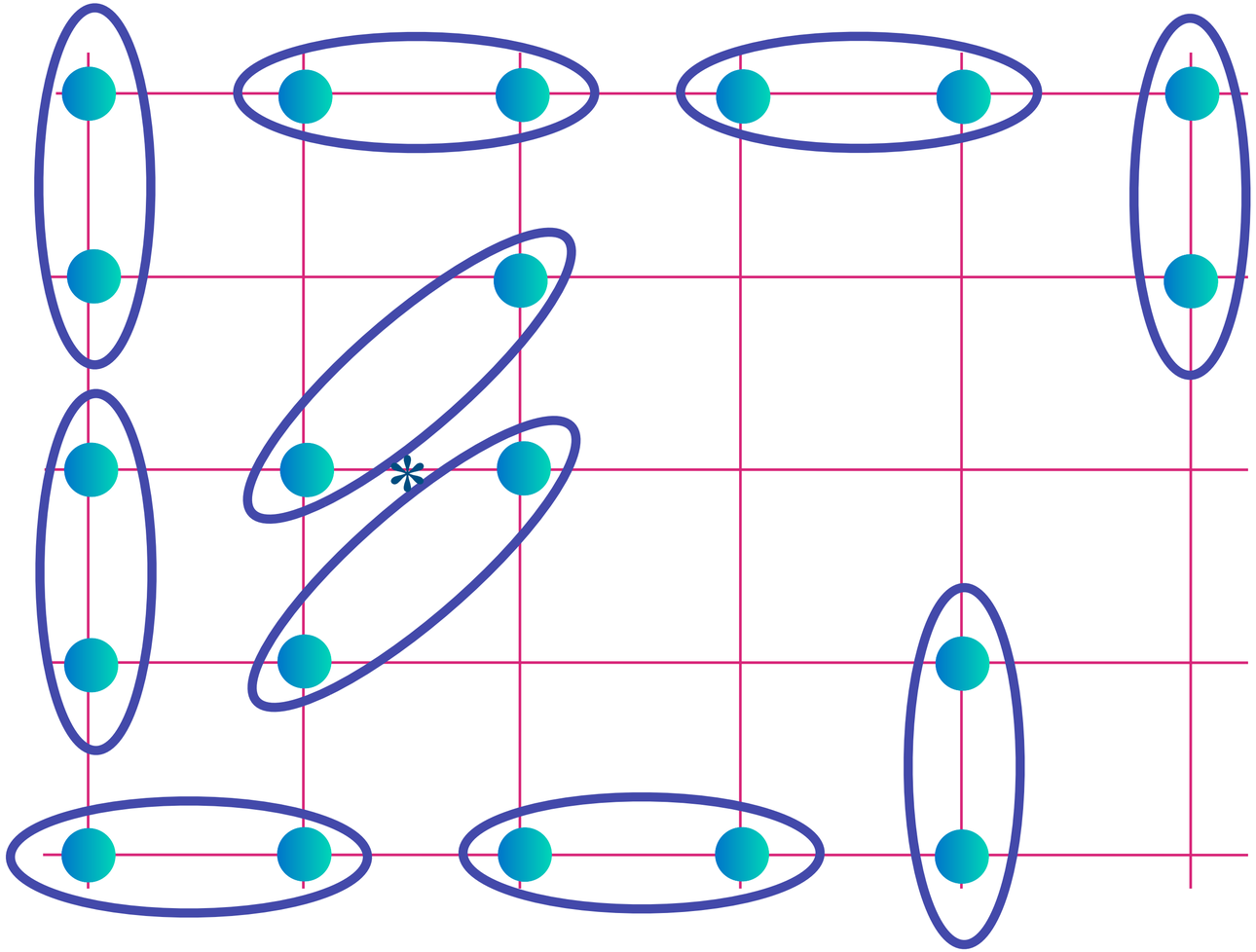

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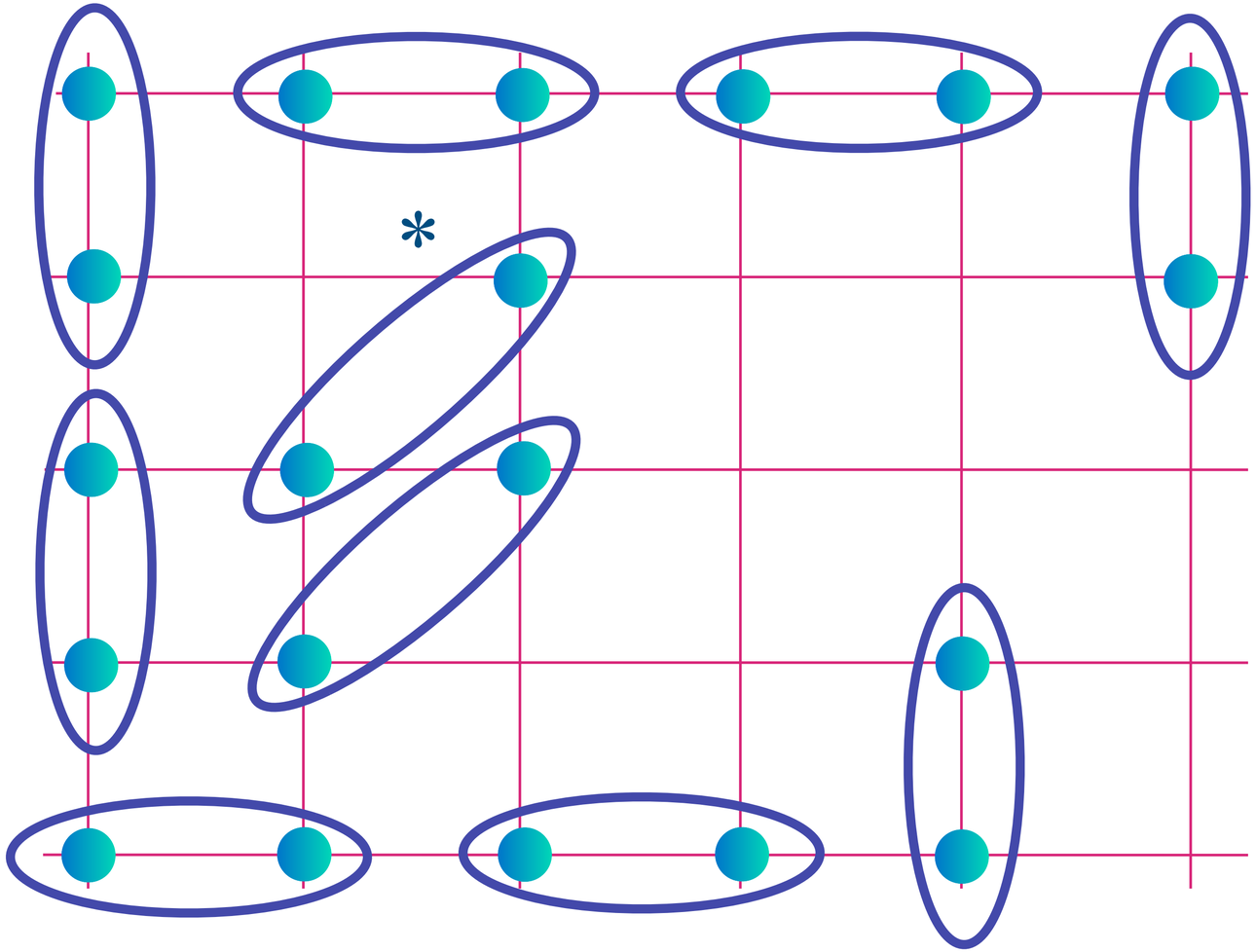

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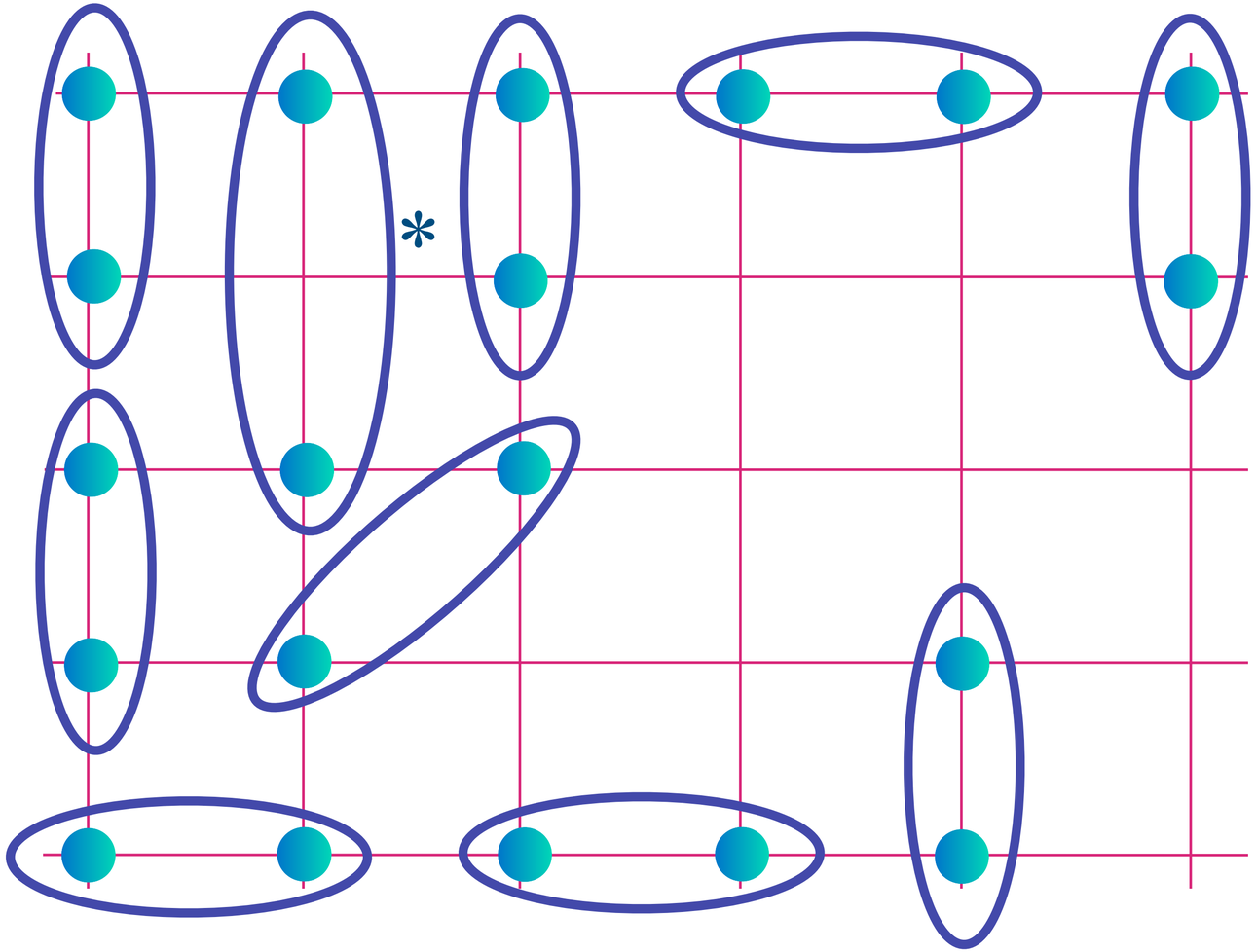
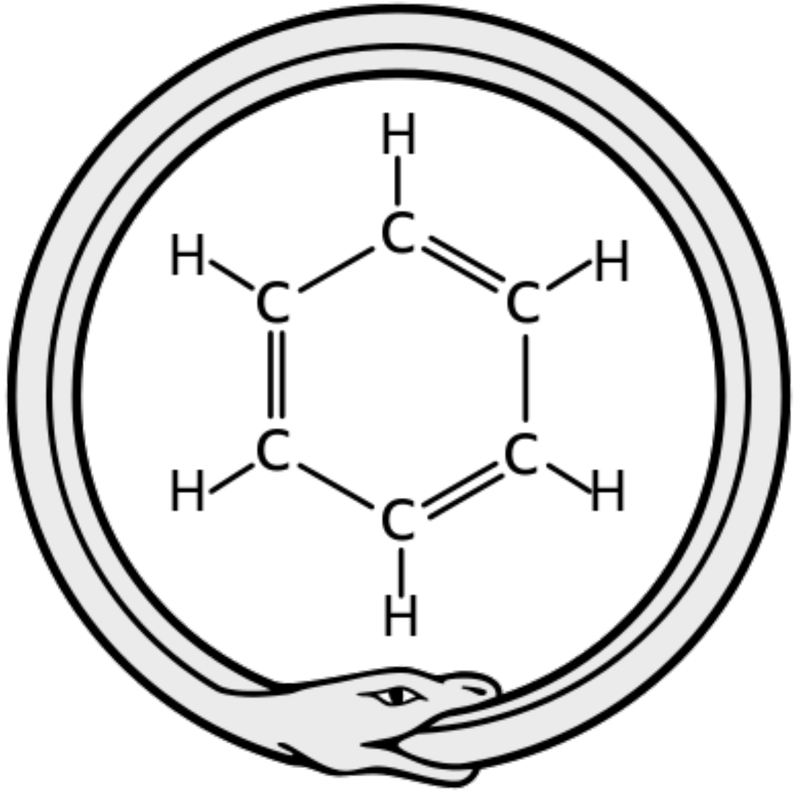


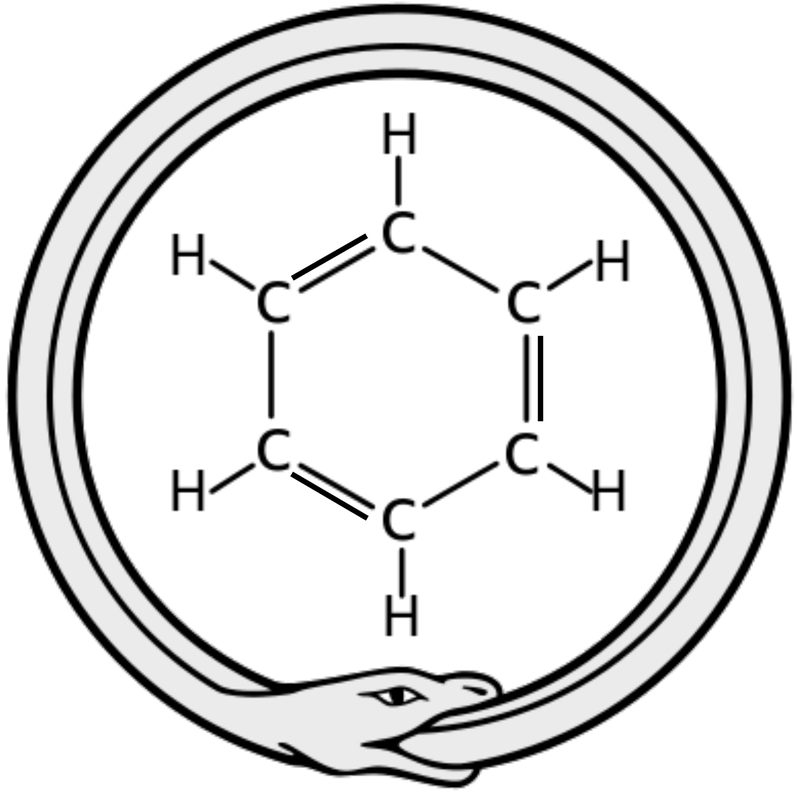
$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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

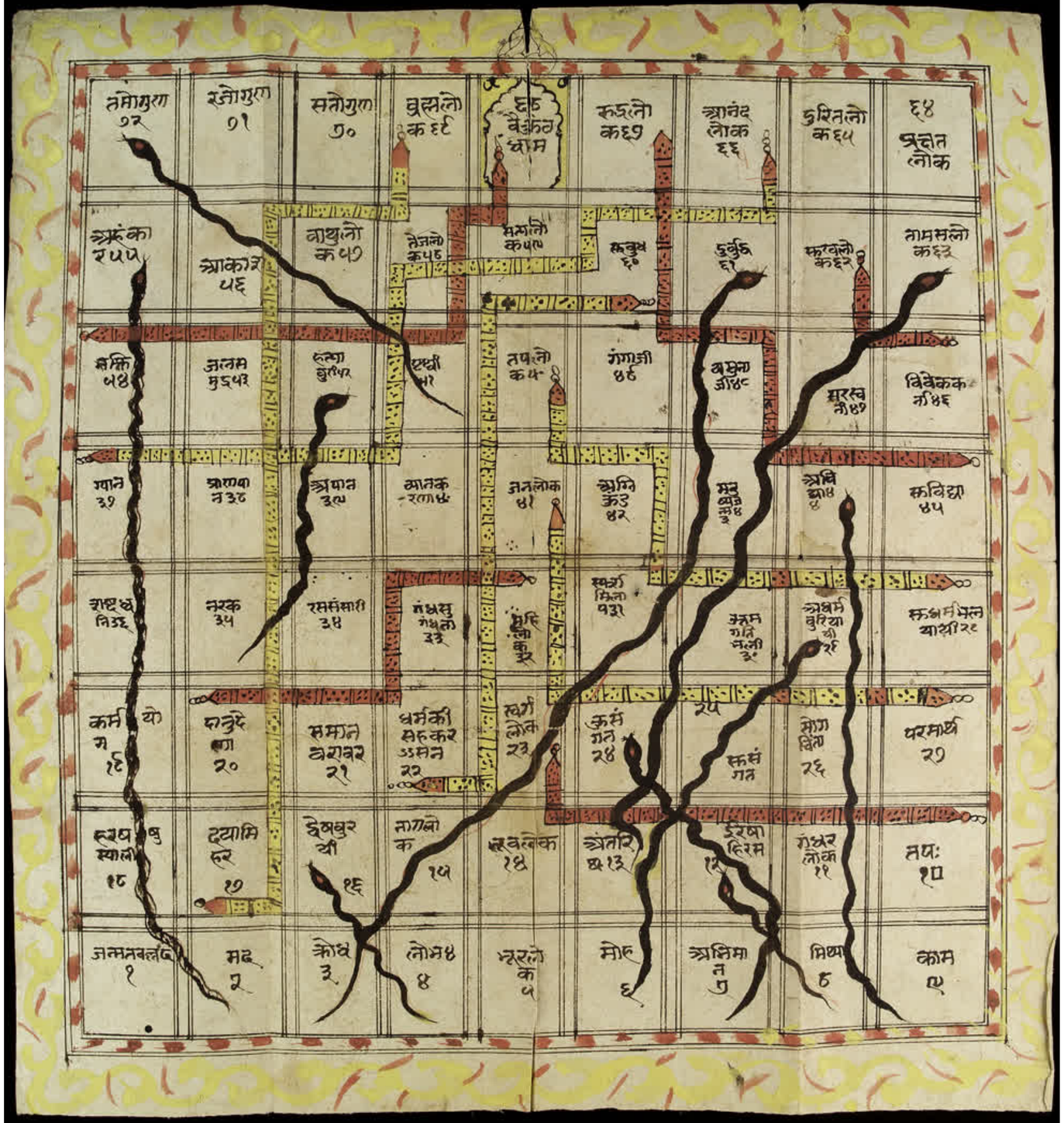
Kekule's dream

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).*





*Wikipedia



My dream*

Snakes and ladders

*Not true

The Sachdev-Ye-Kitaev (SYK) model

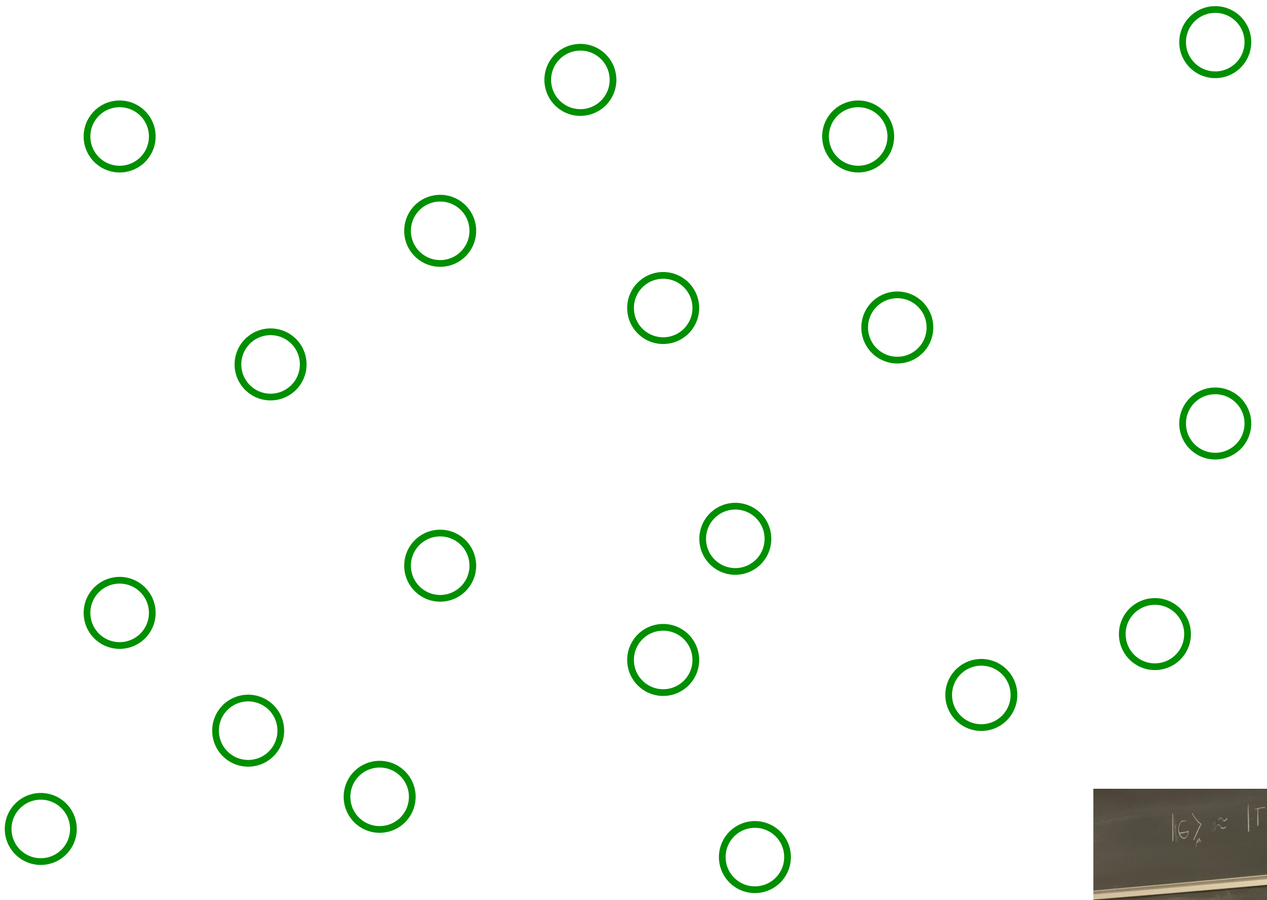
The SYK model has a scale-invariant entanglement structure:
i.e. electrons are entangled
at all distances !

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

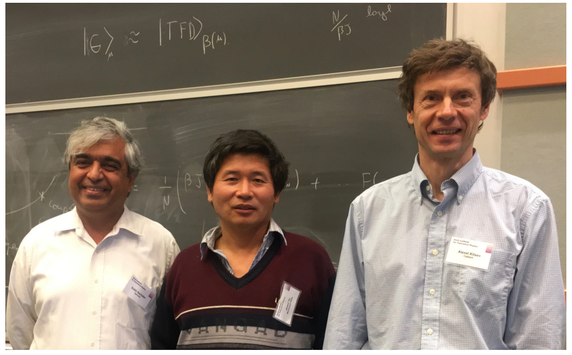
Sachdev, Ye (1993)

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

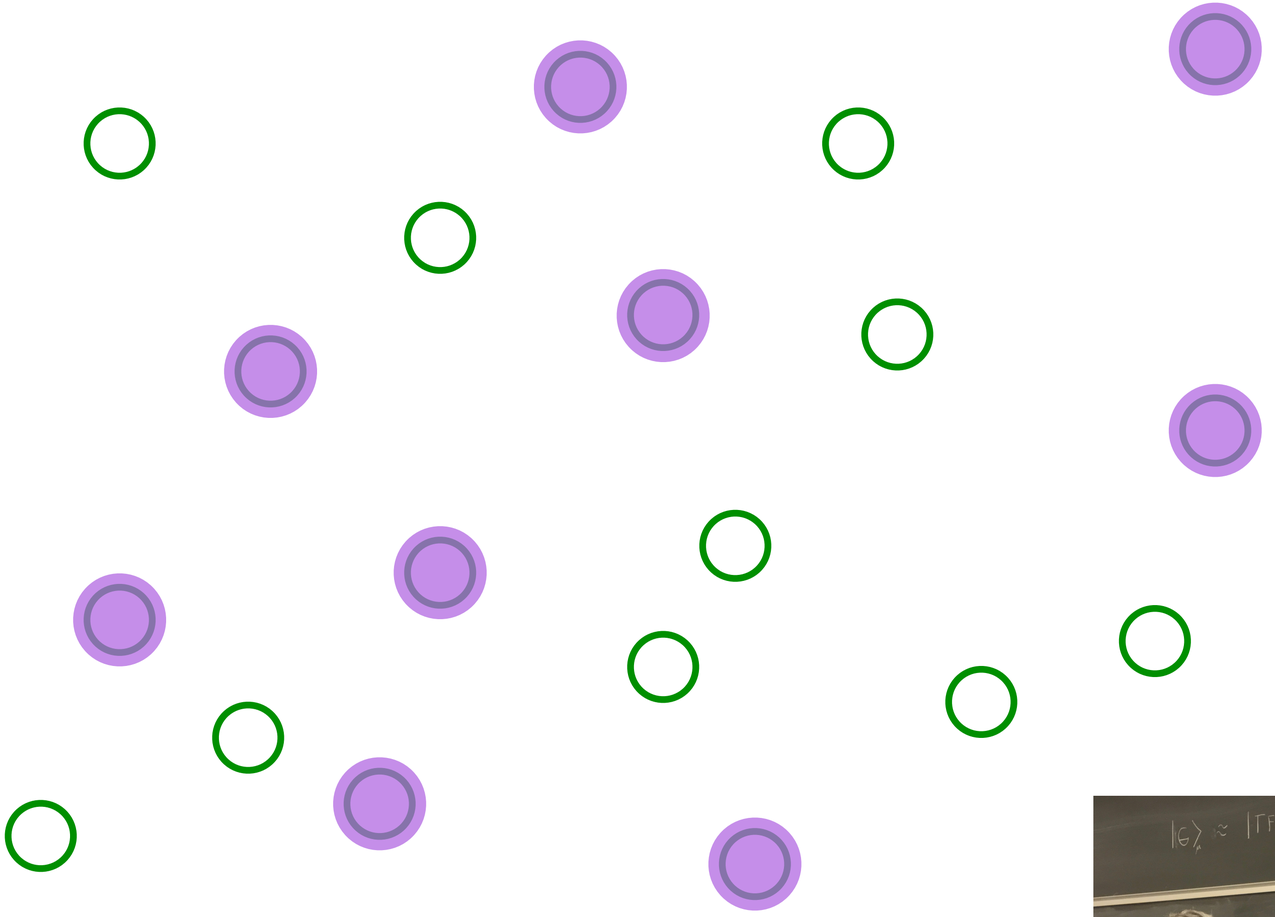


Pick a set of random positions

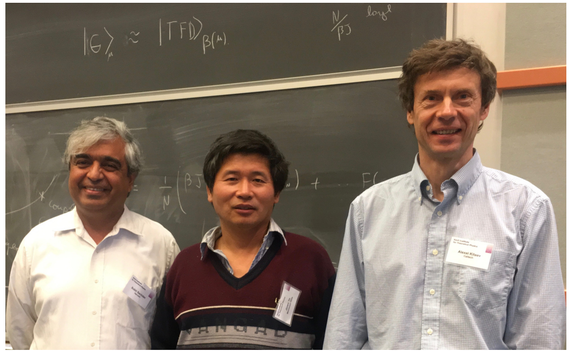


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



Place electrons randomly on some sites



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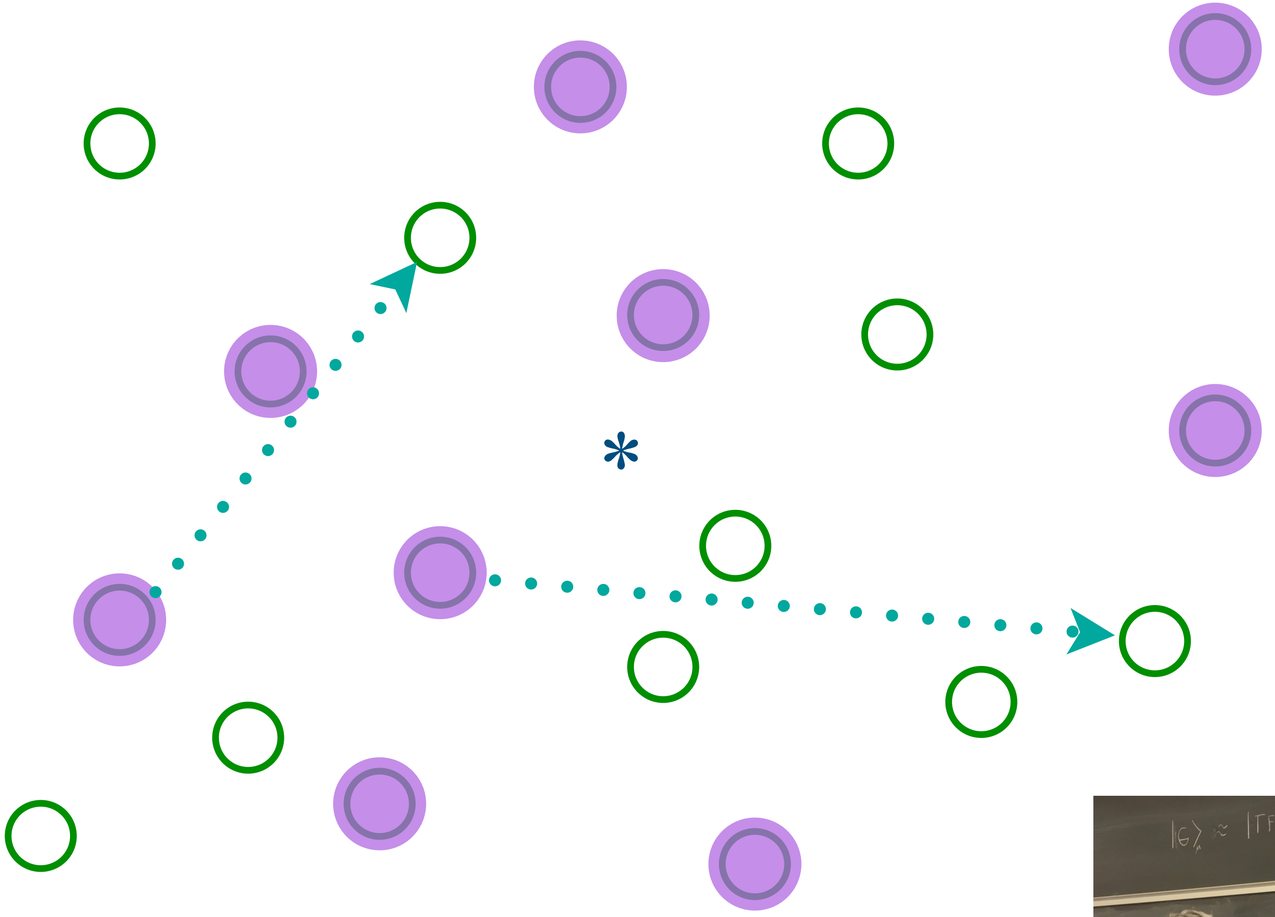

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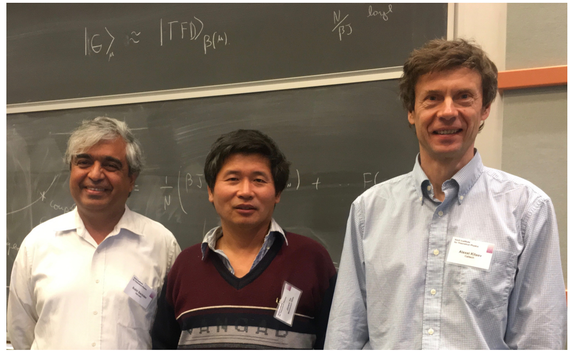

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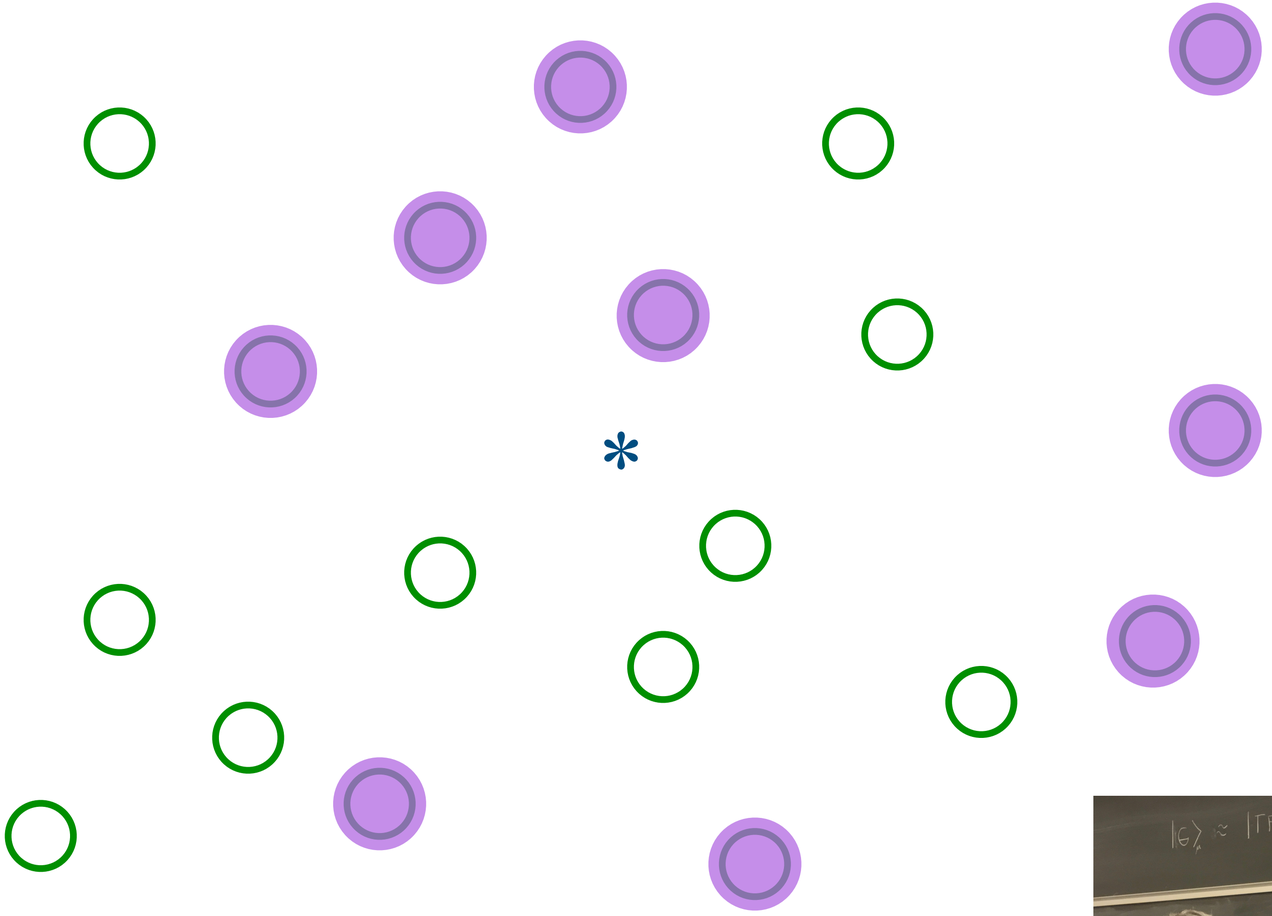
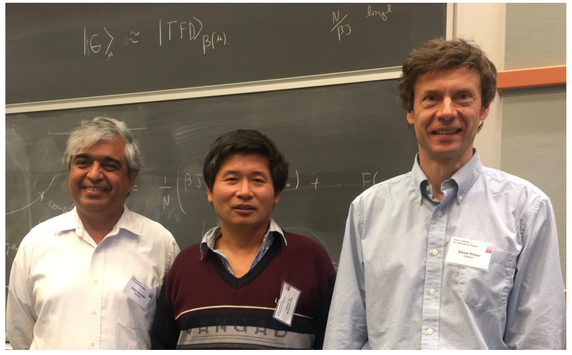


Entangle electrons pairwise randomly



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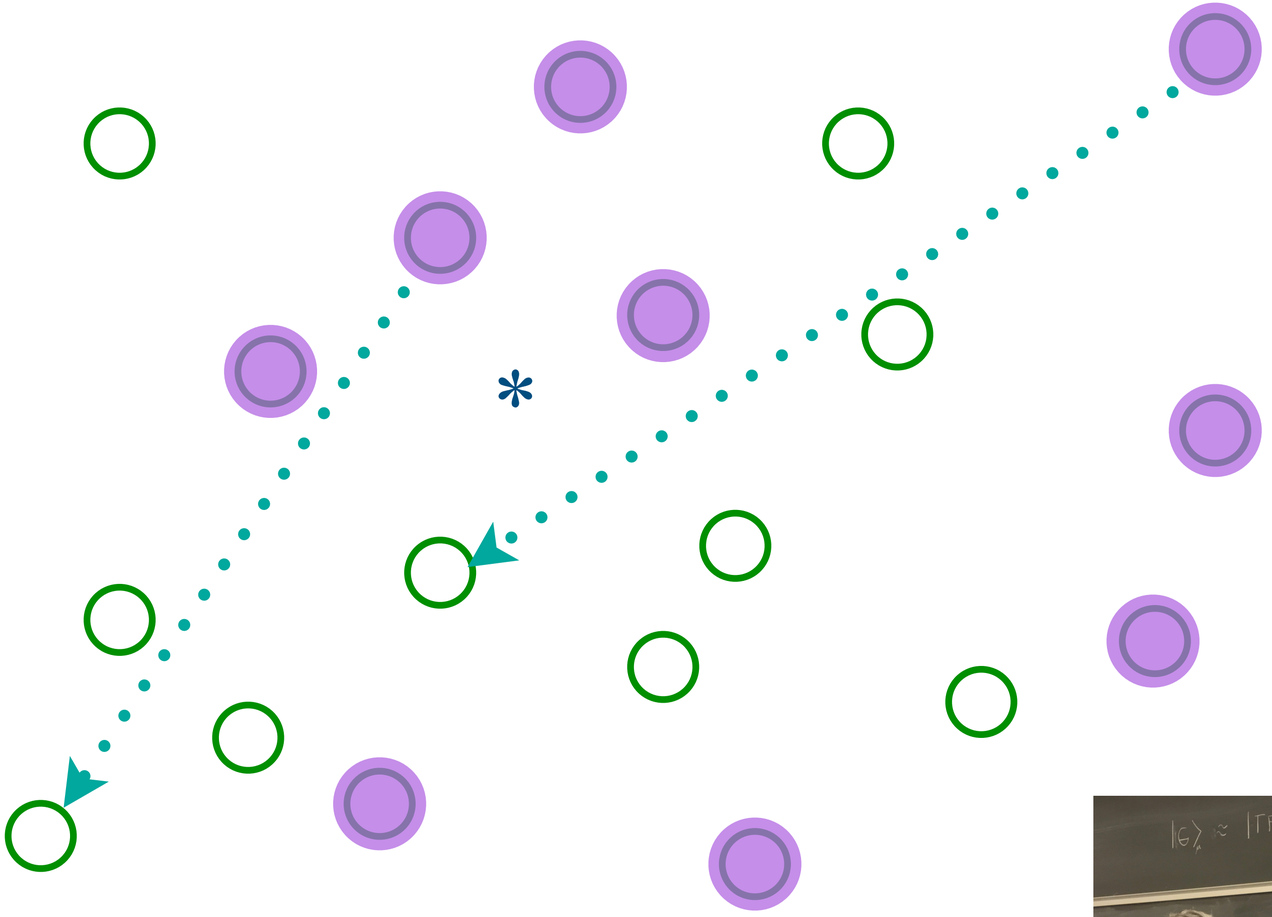

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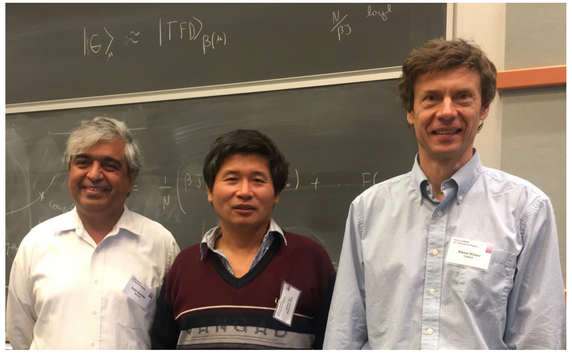

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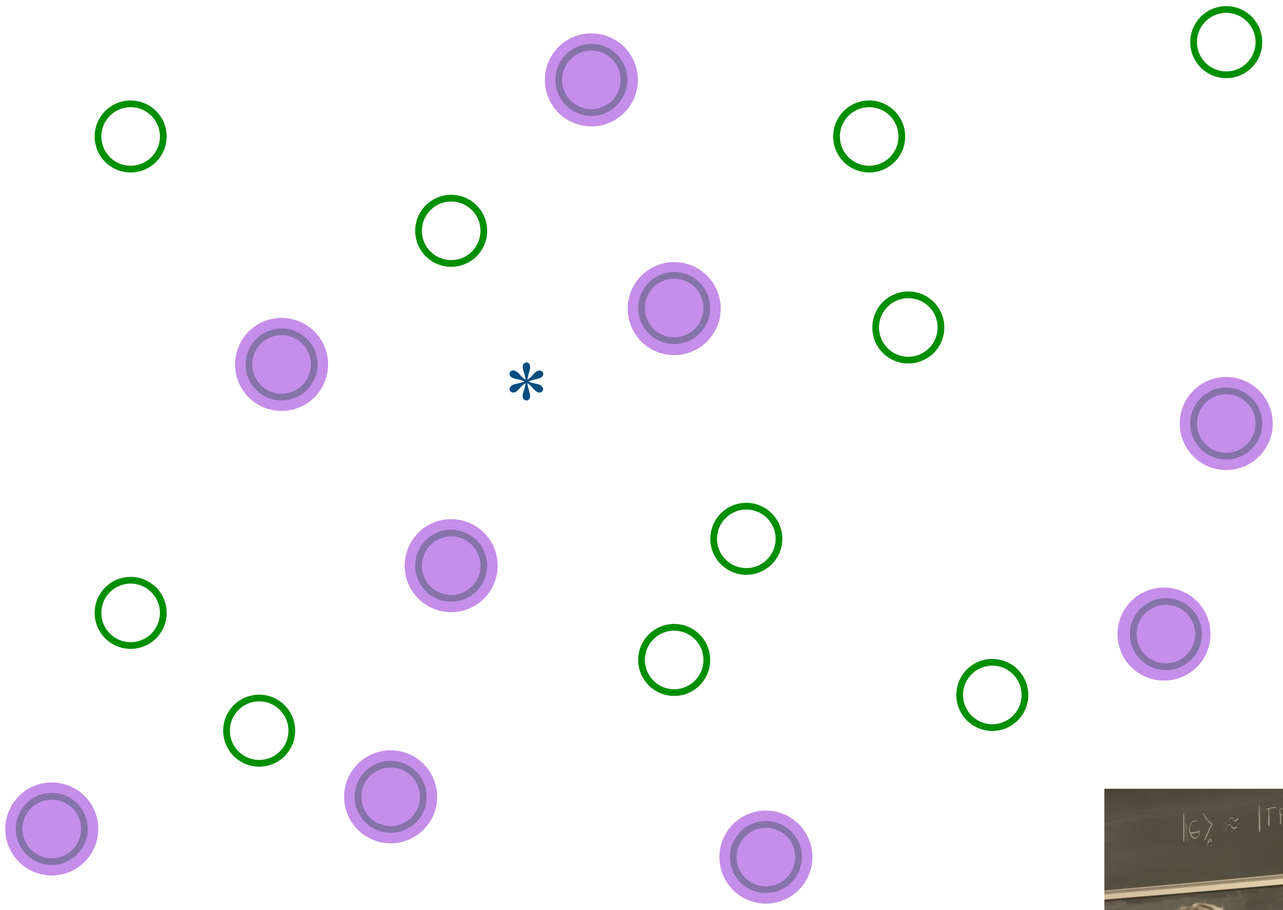

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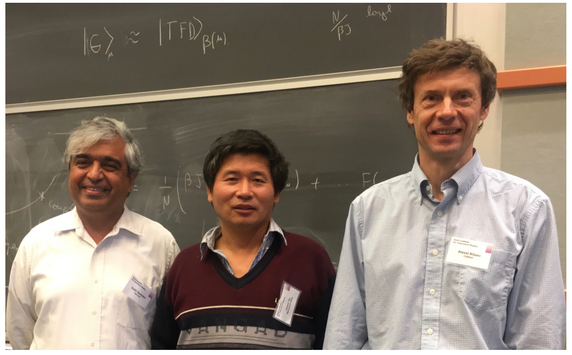

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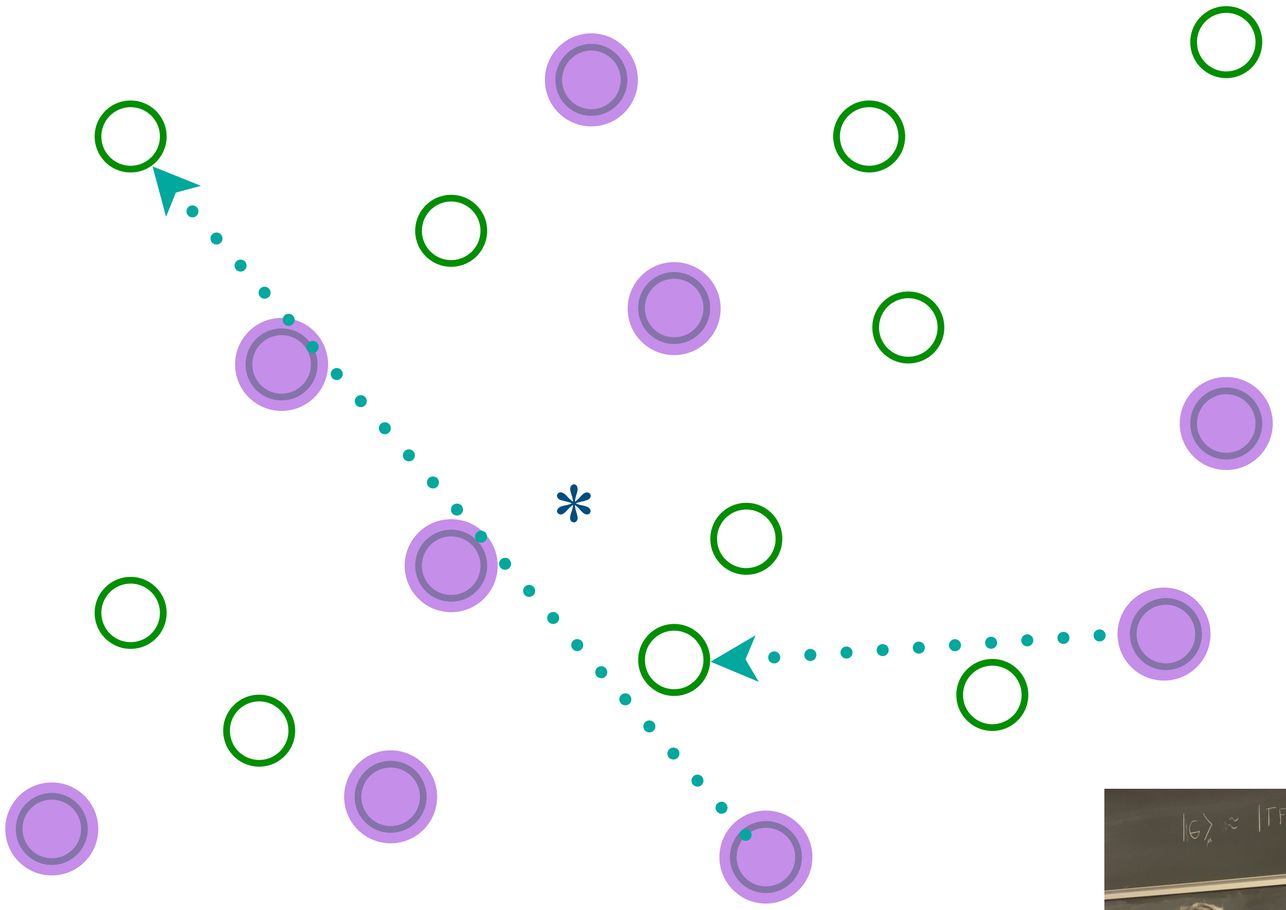

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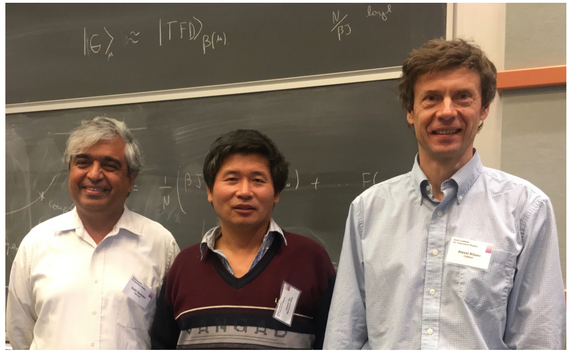

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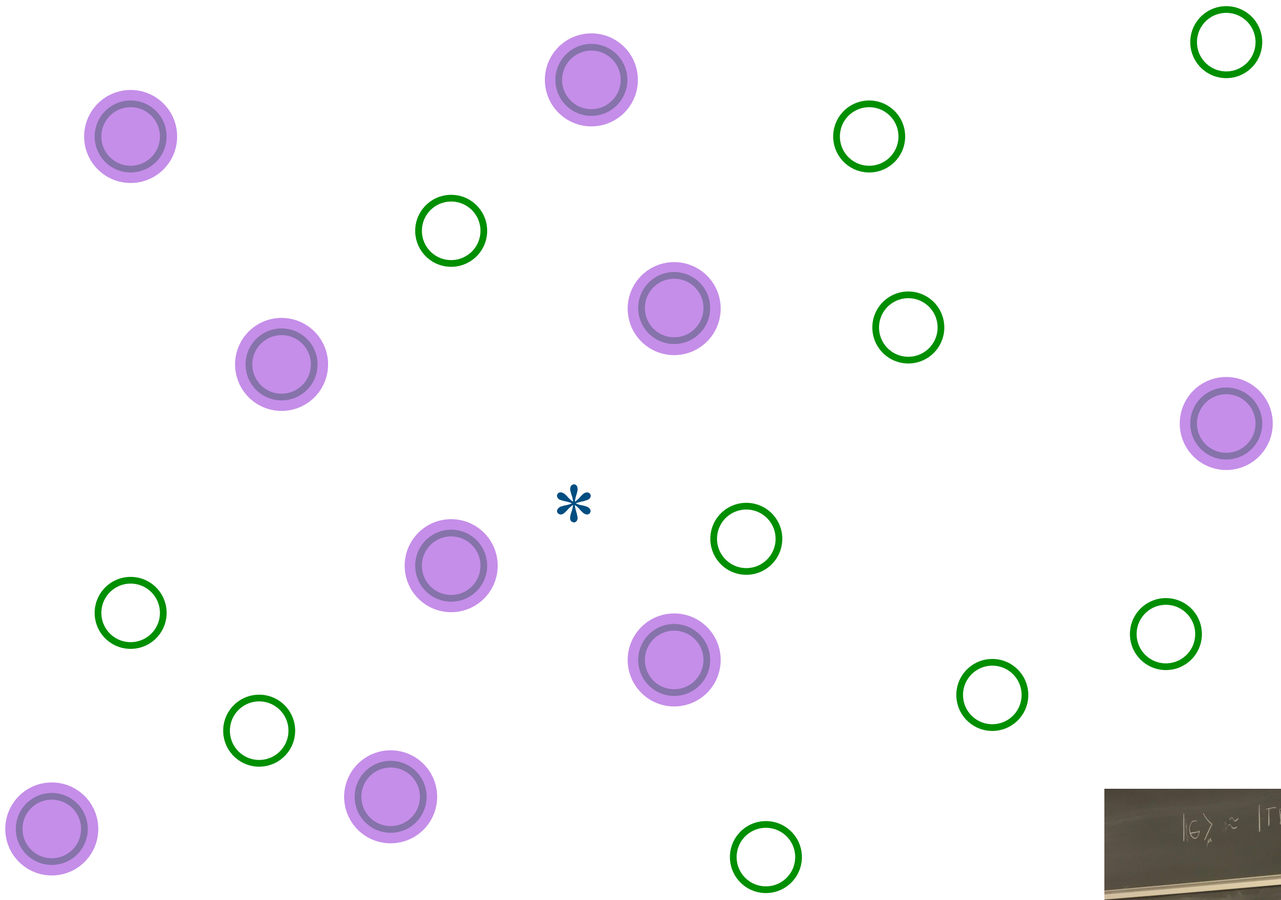

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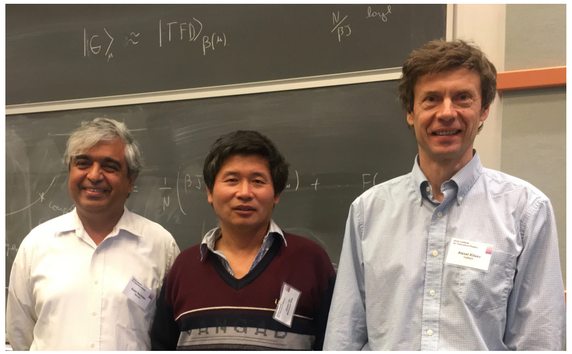

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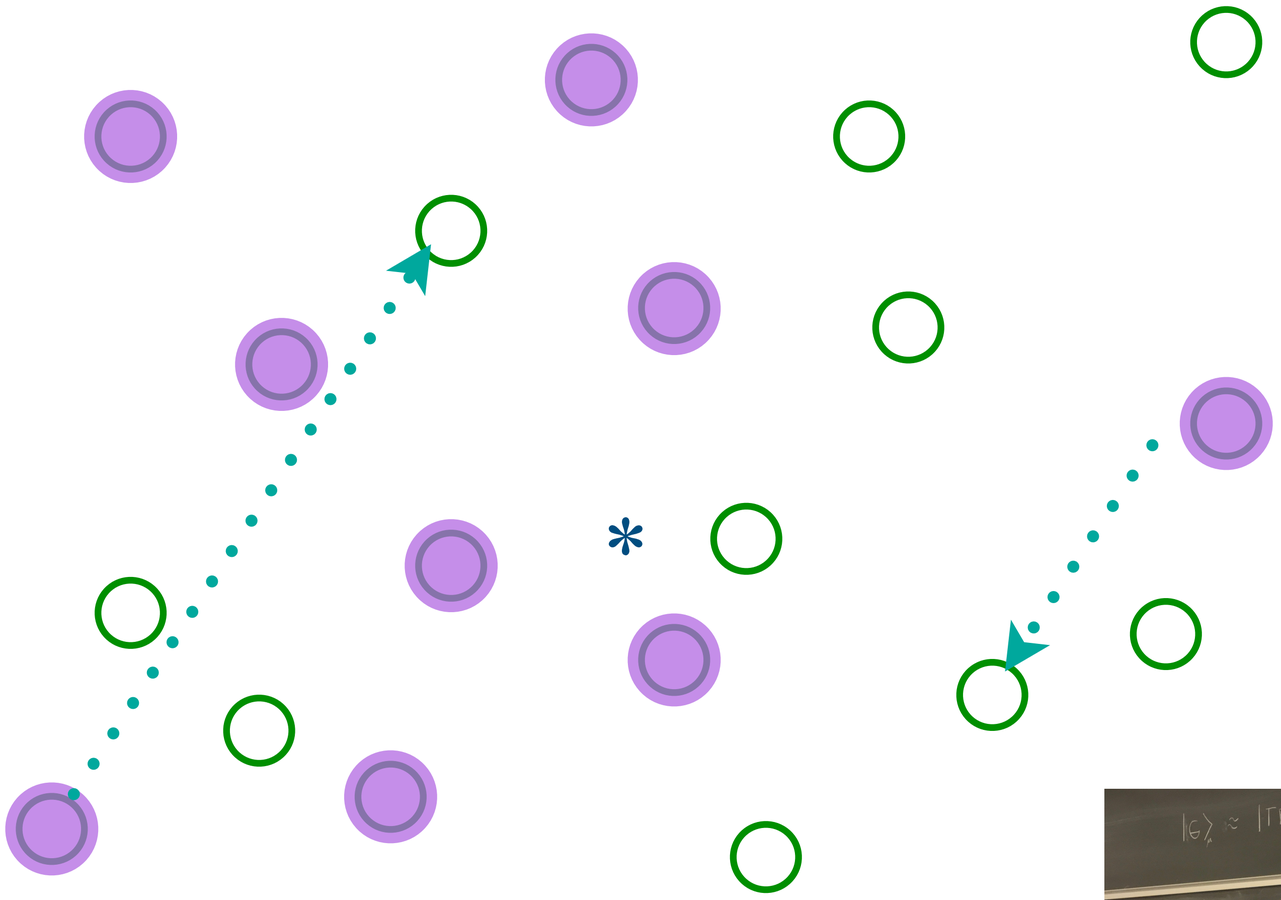

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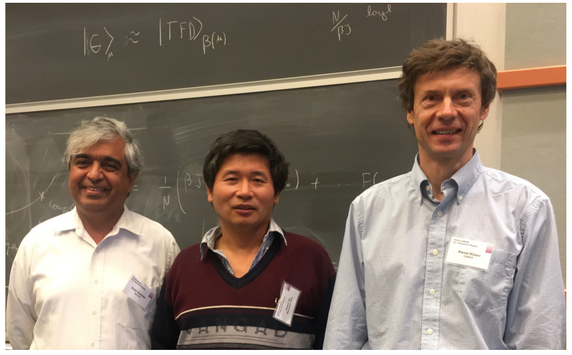

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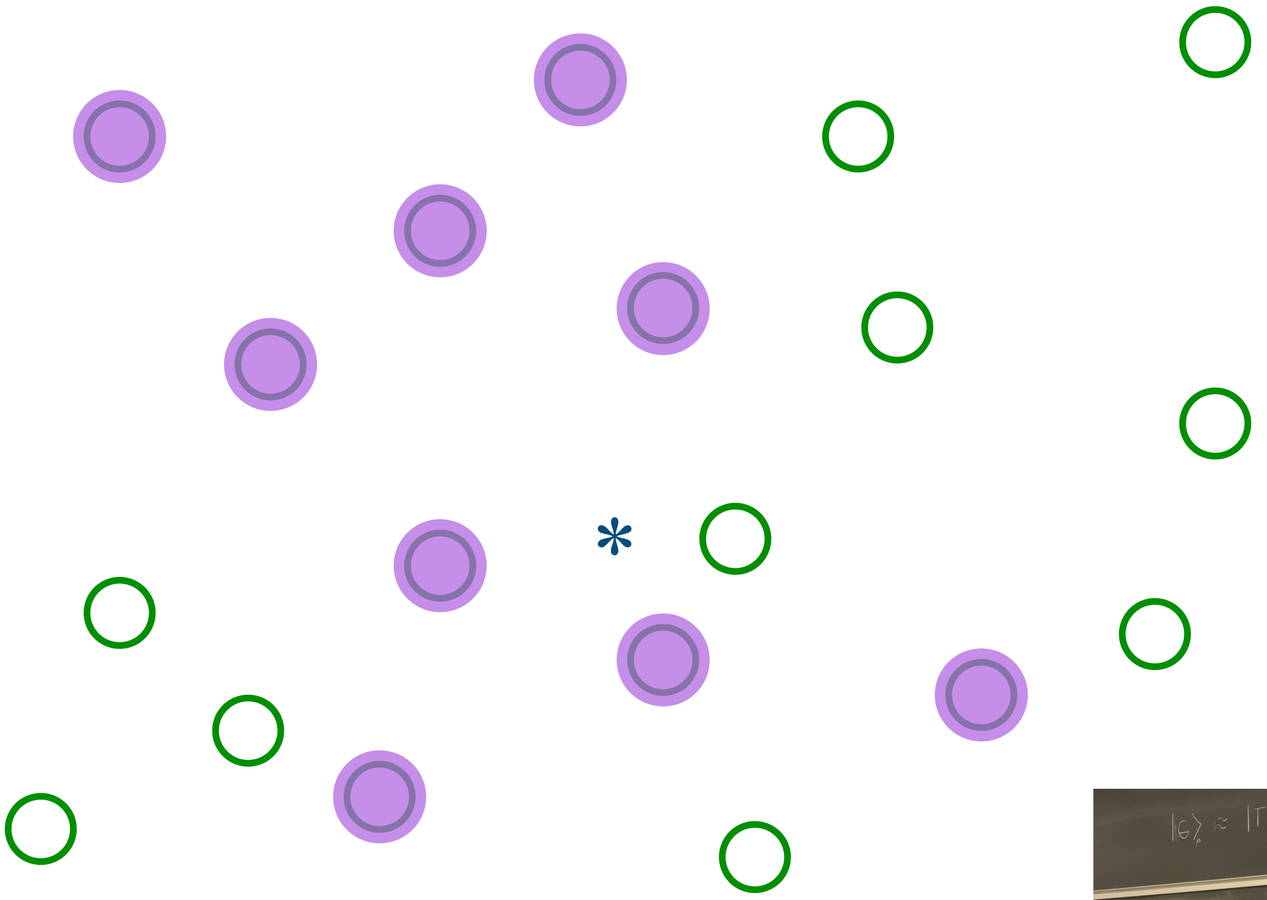

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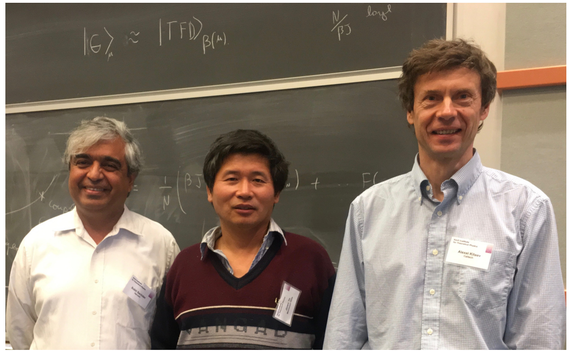

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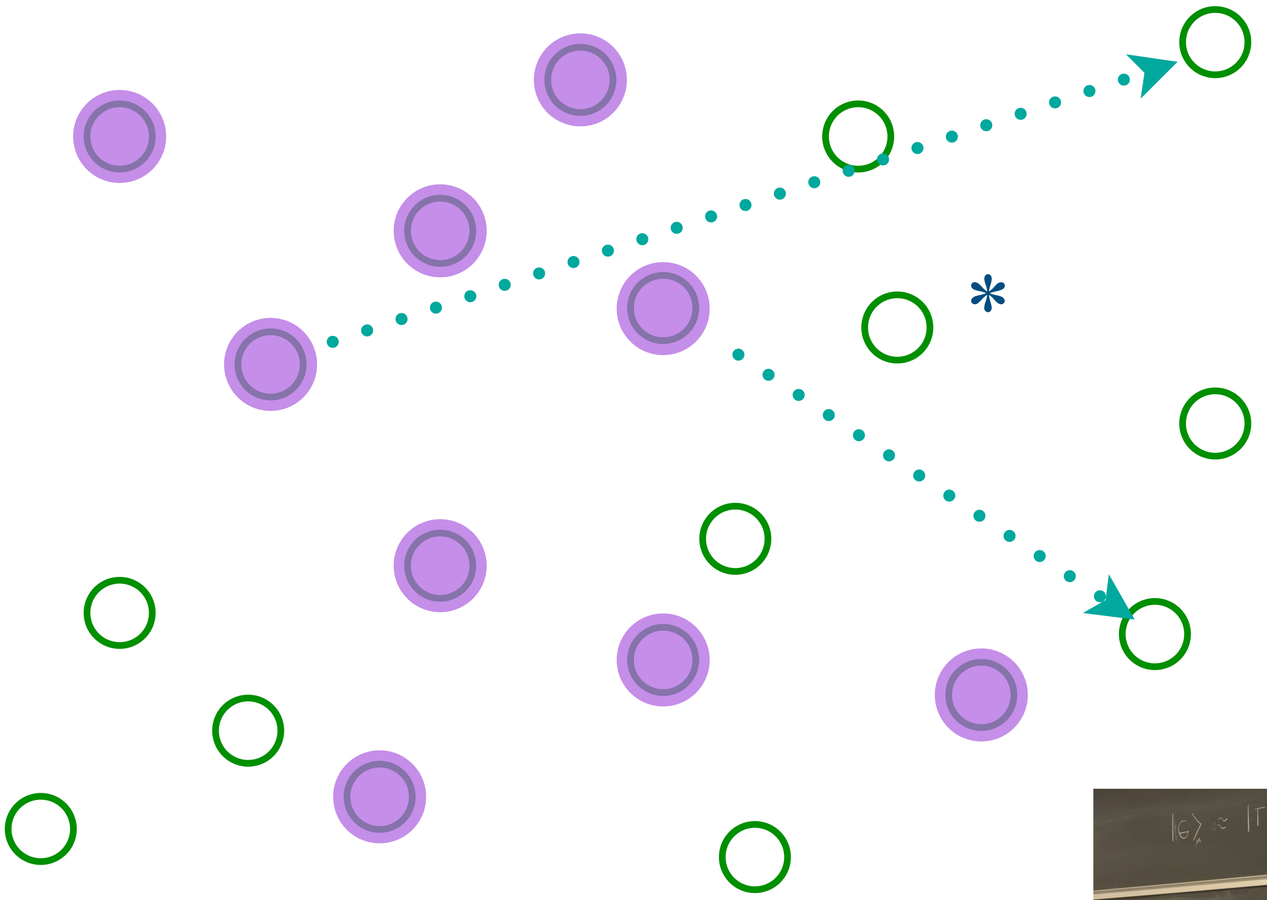

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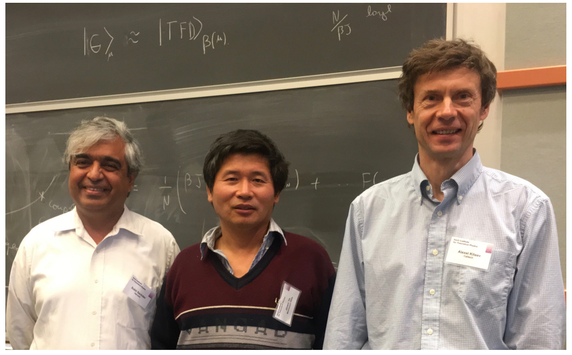

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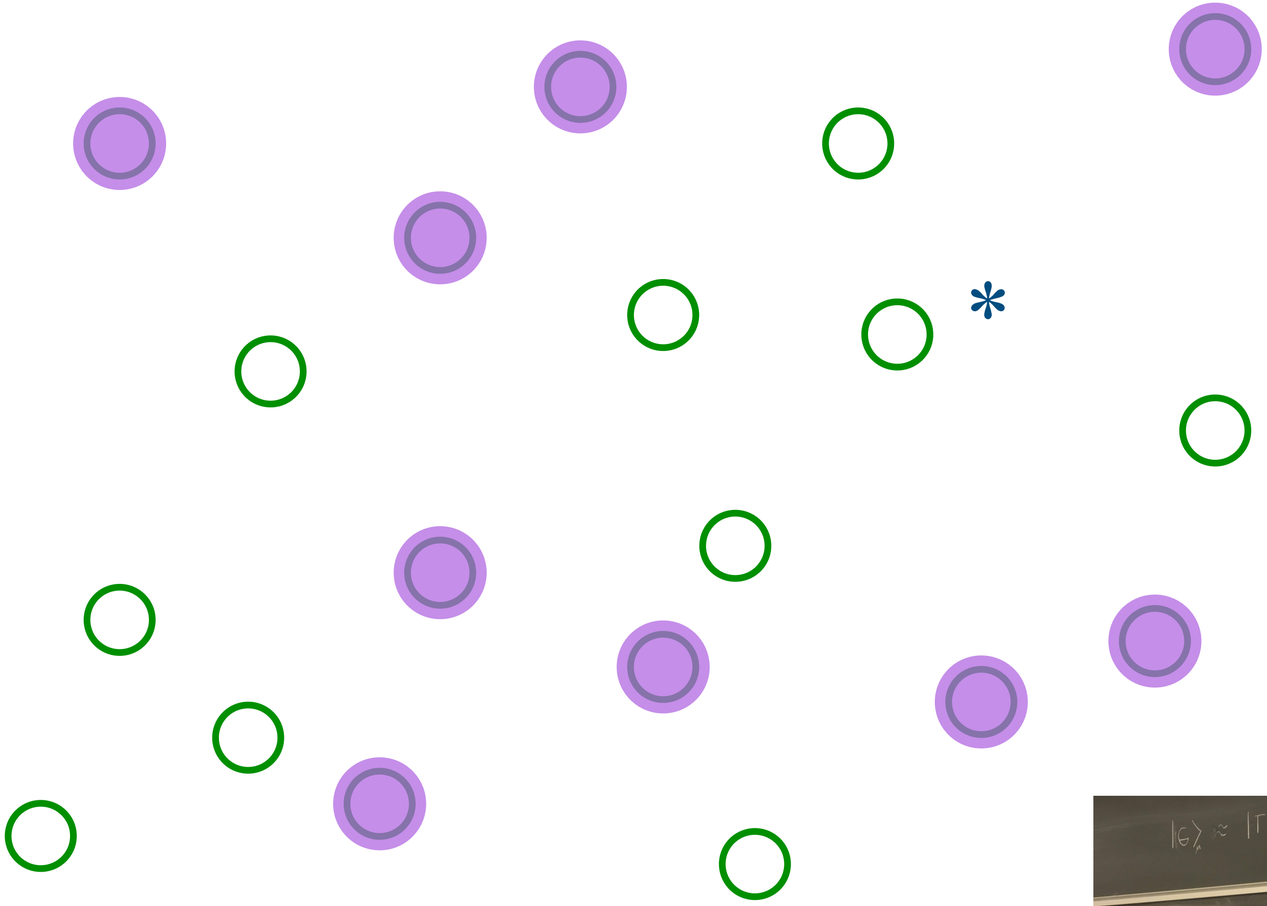

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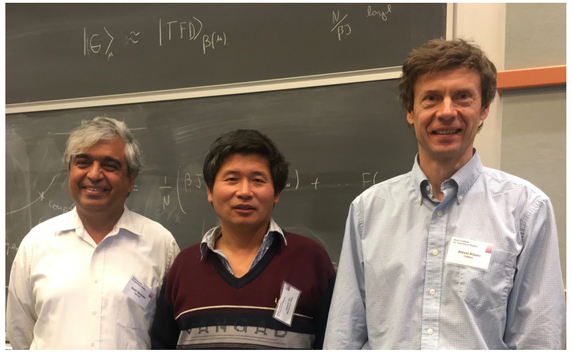
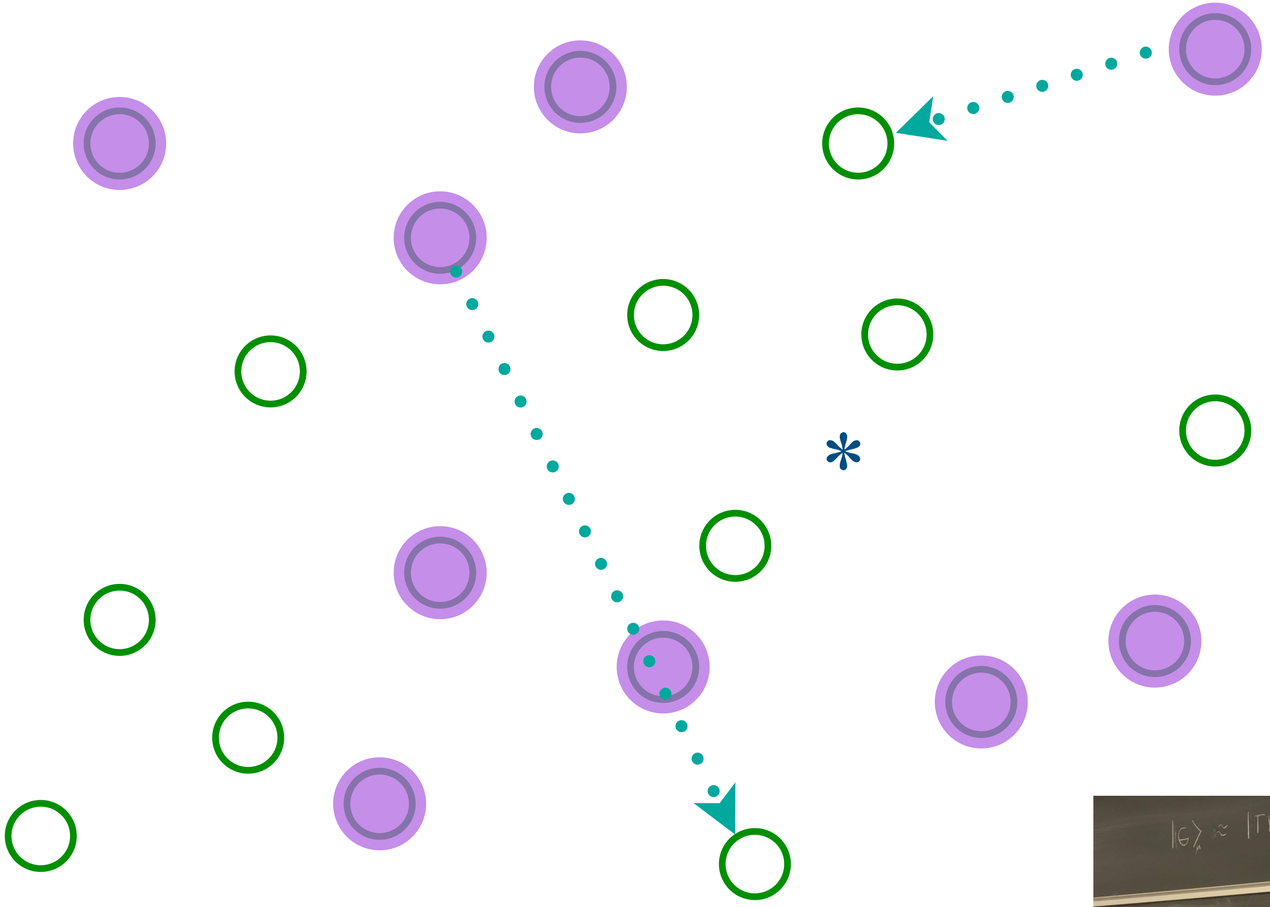
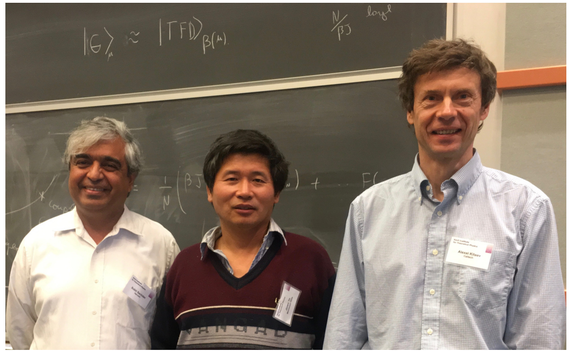


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



Entangle electrons pairwise randomly



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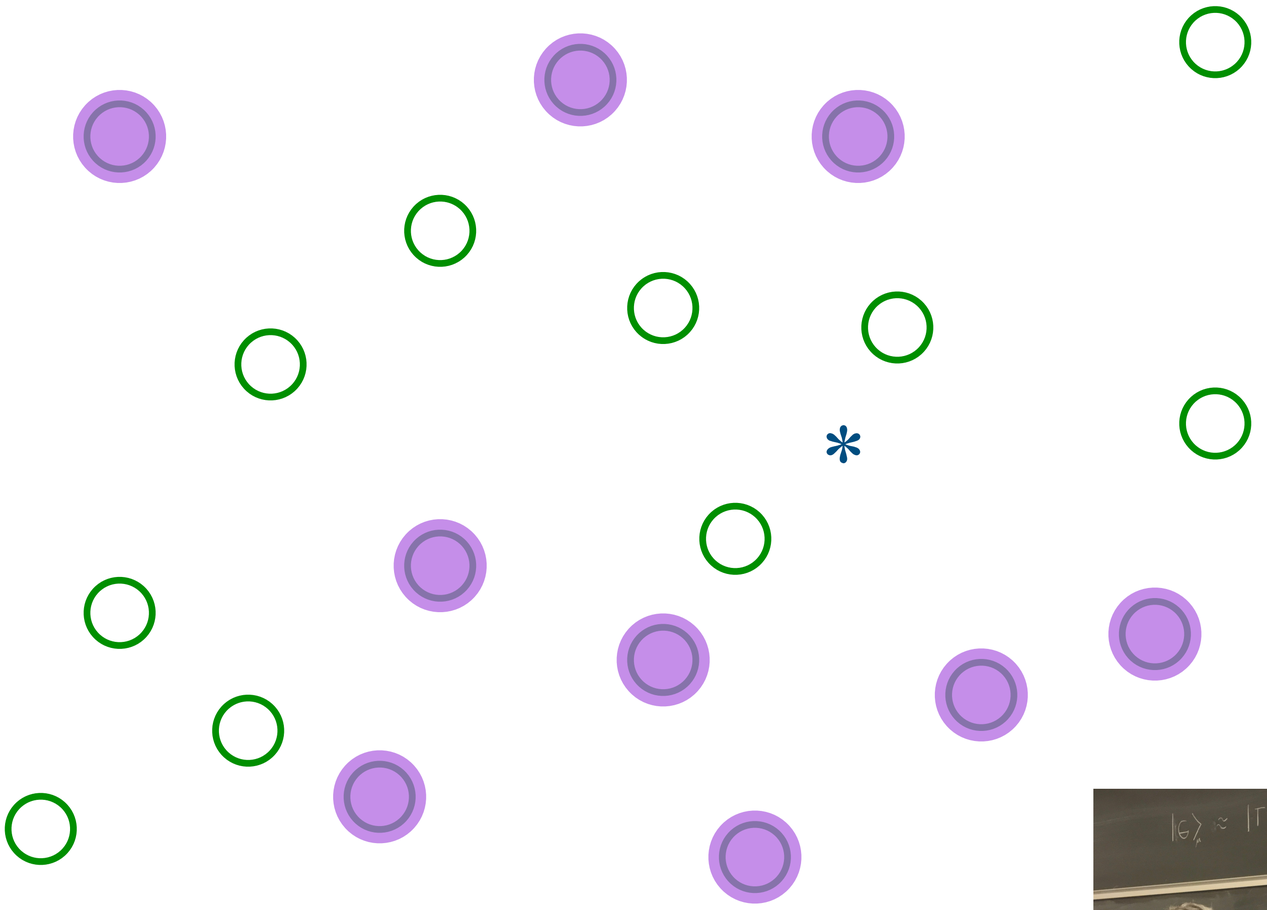

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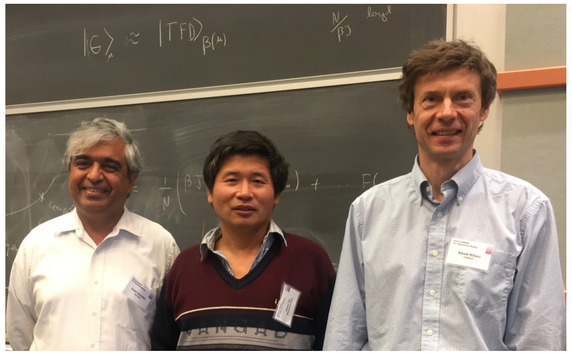
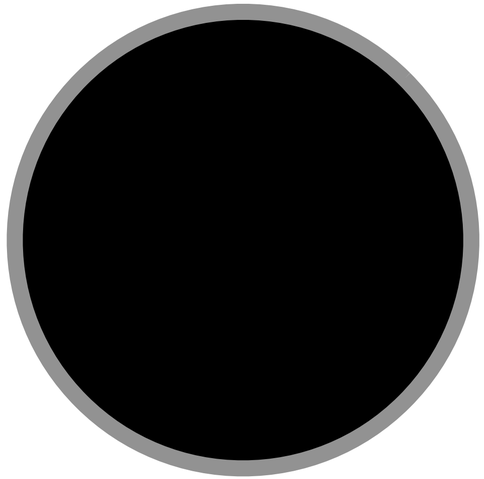


Complex quantum entanglement in black holes

Black Holes

Objects so dense that light is gravitationally bound to them.

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



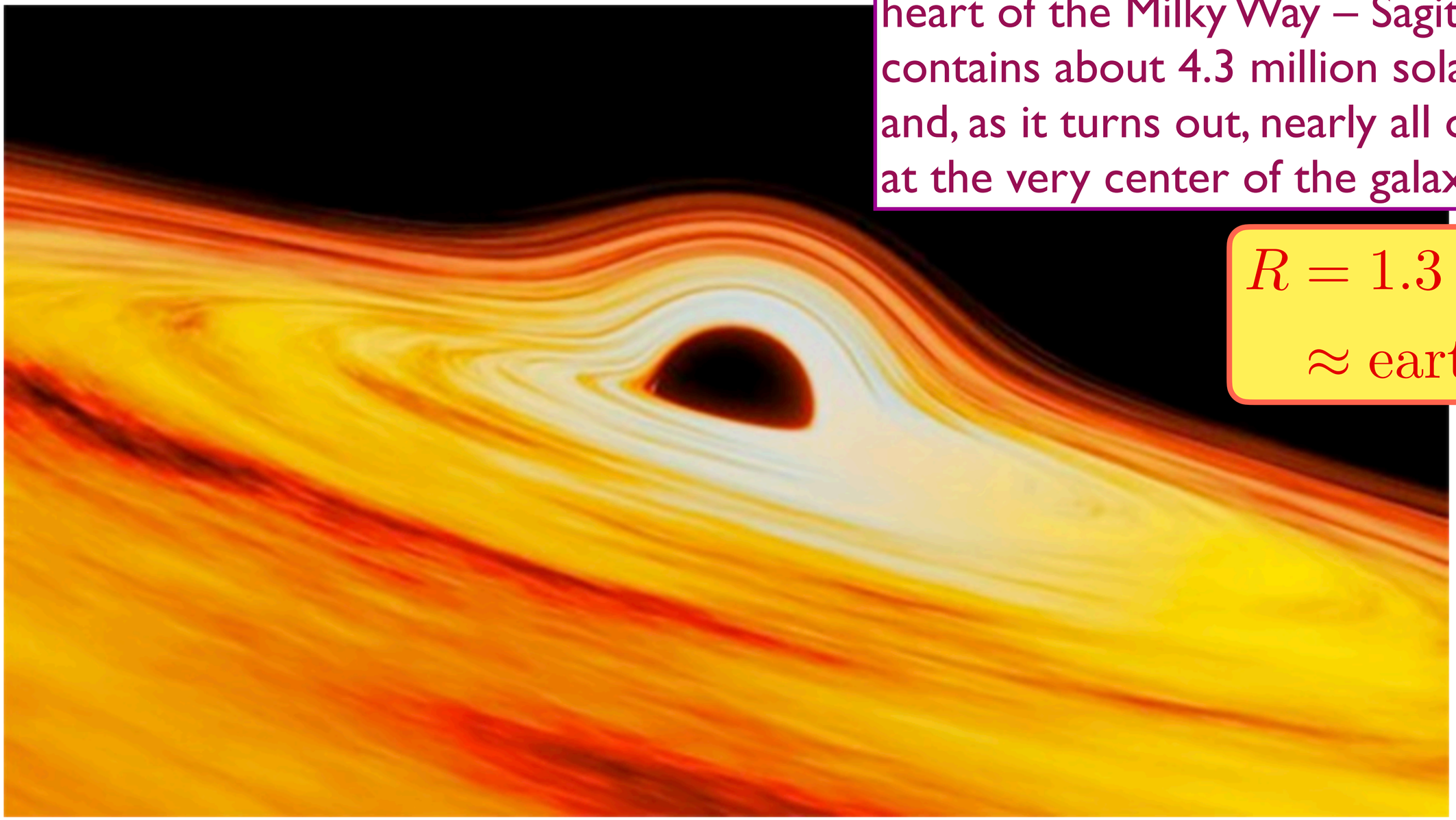
G Newton's constant, c velocity of light, M mass of black hole

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

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.

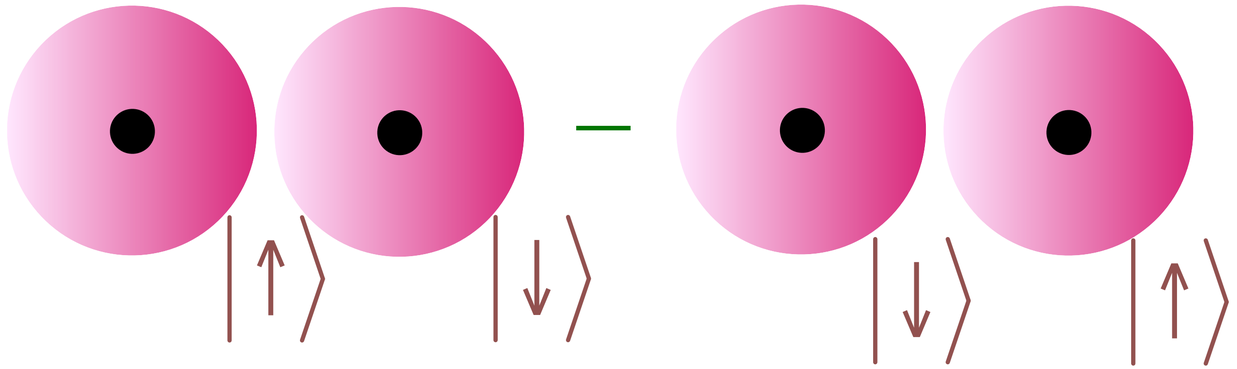
$$R = 1.3 \times 10^{11}\mathrm{m}$$

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



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)

Quantum Entanglement across a black hole horizon



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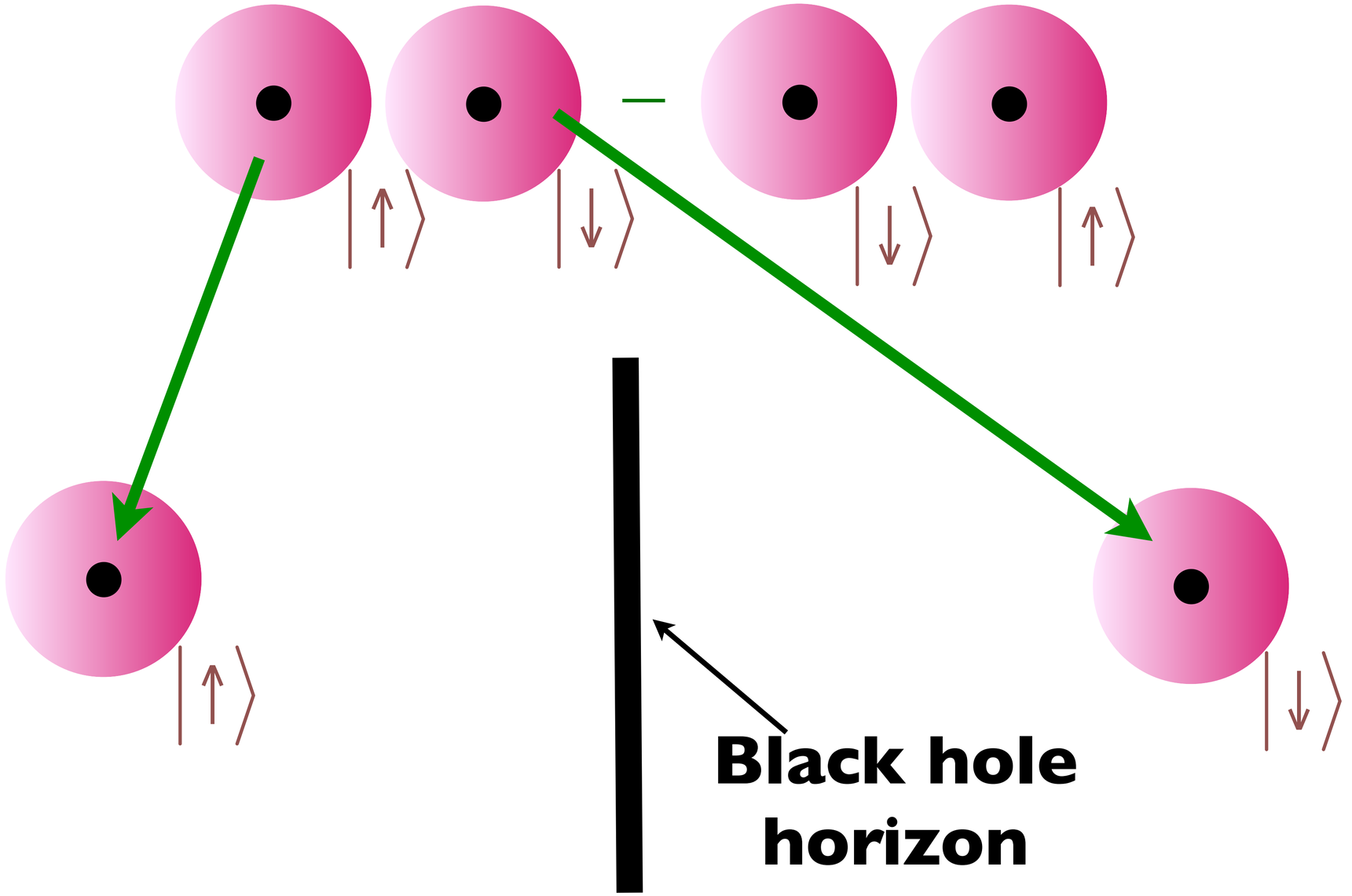
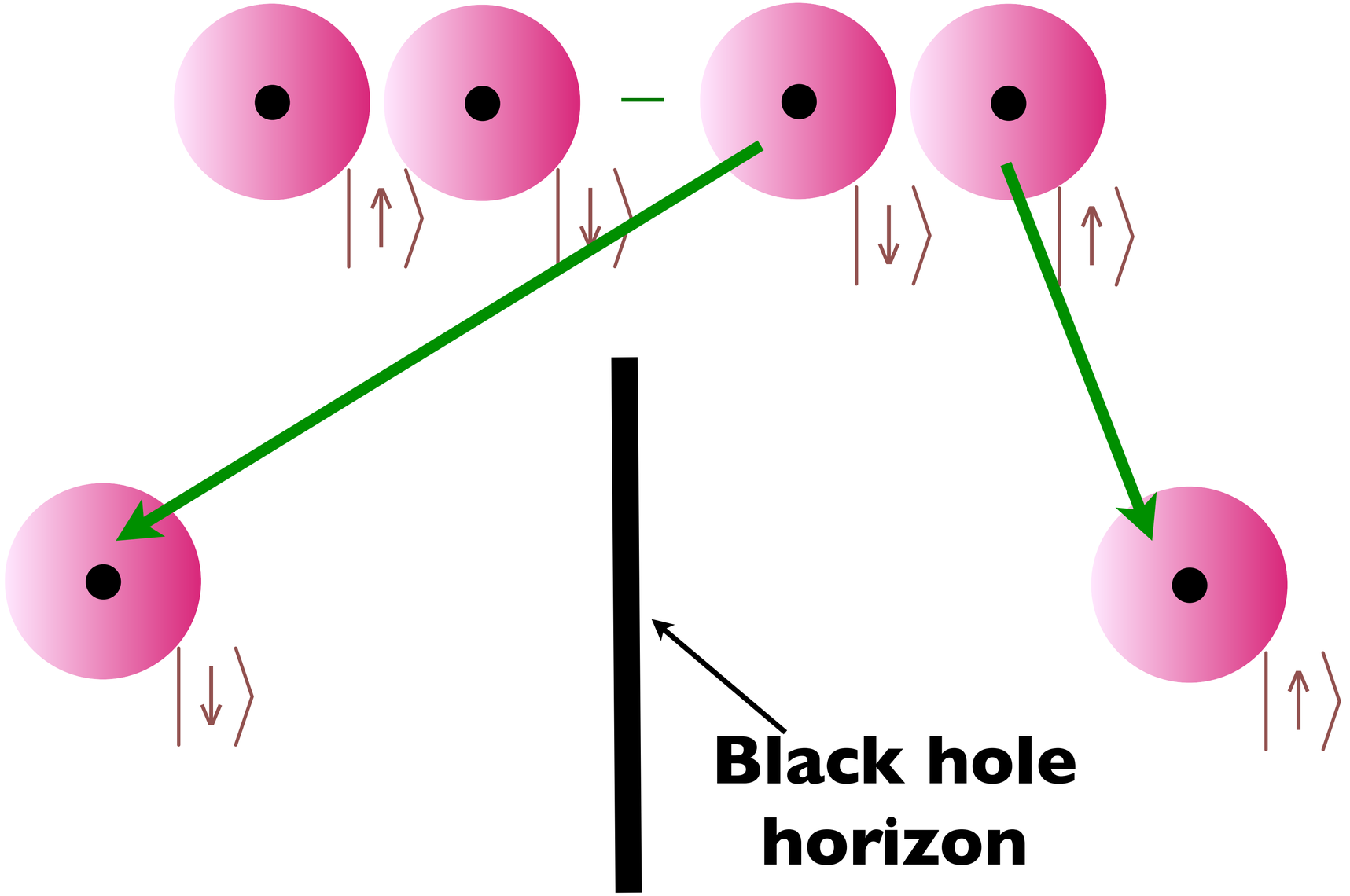
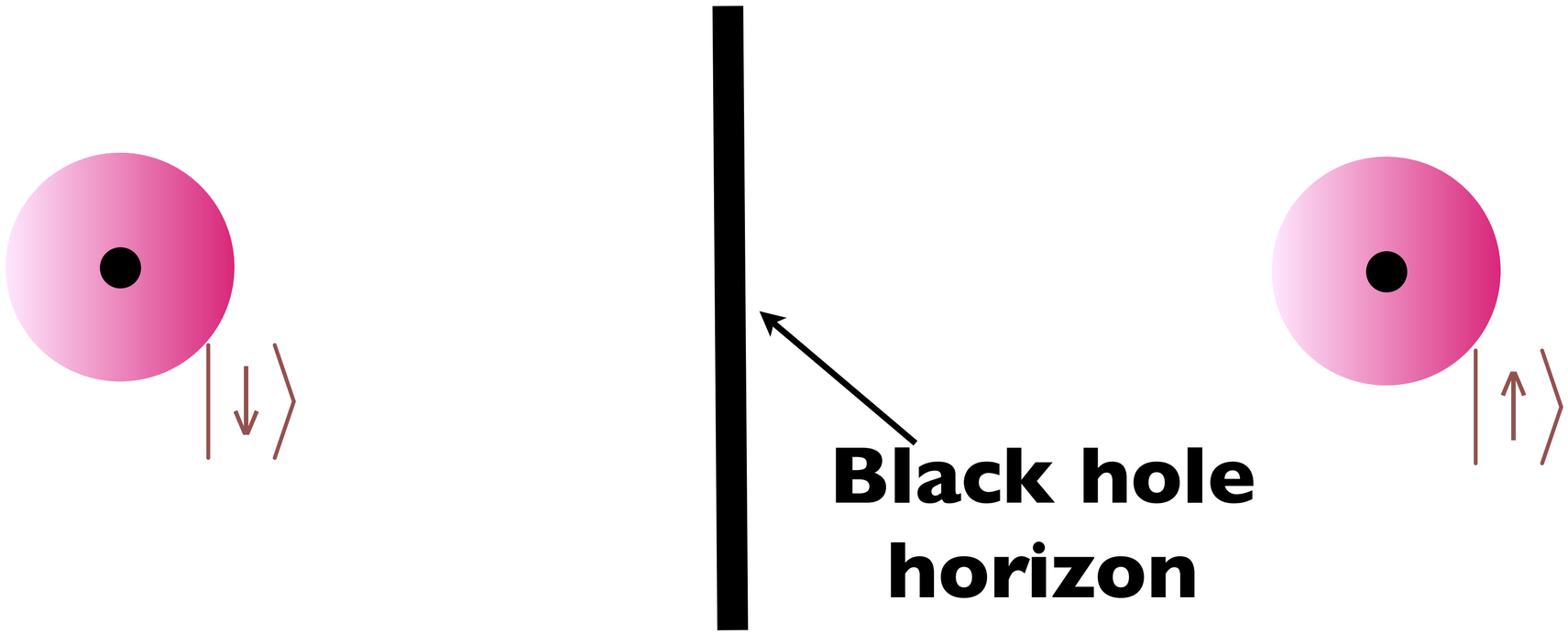


Quantum Entanglement across a black hole horizon



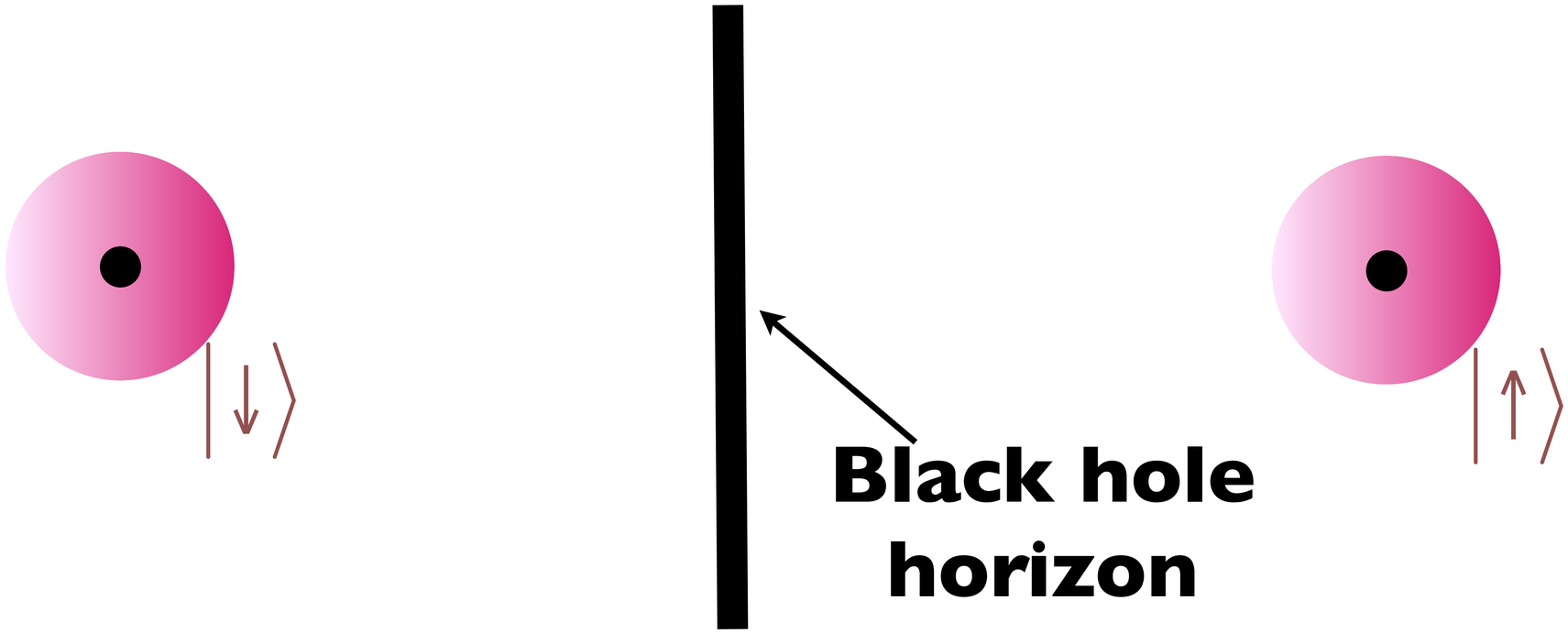
Quantum Entanglement across a black hole horizon

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



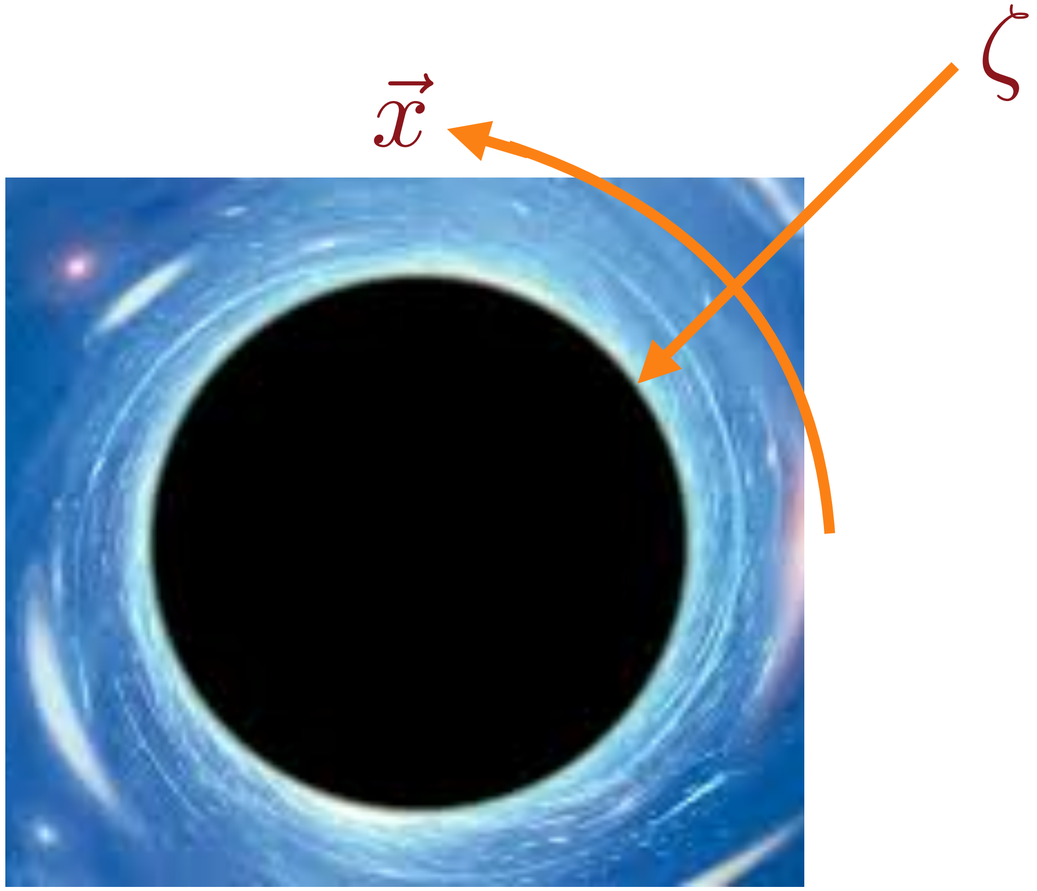
Quantum Entanglement across a black hole horizon

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.)



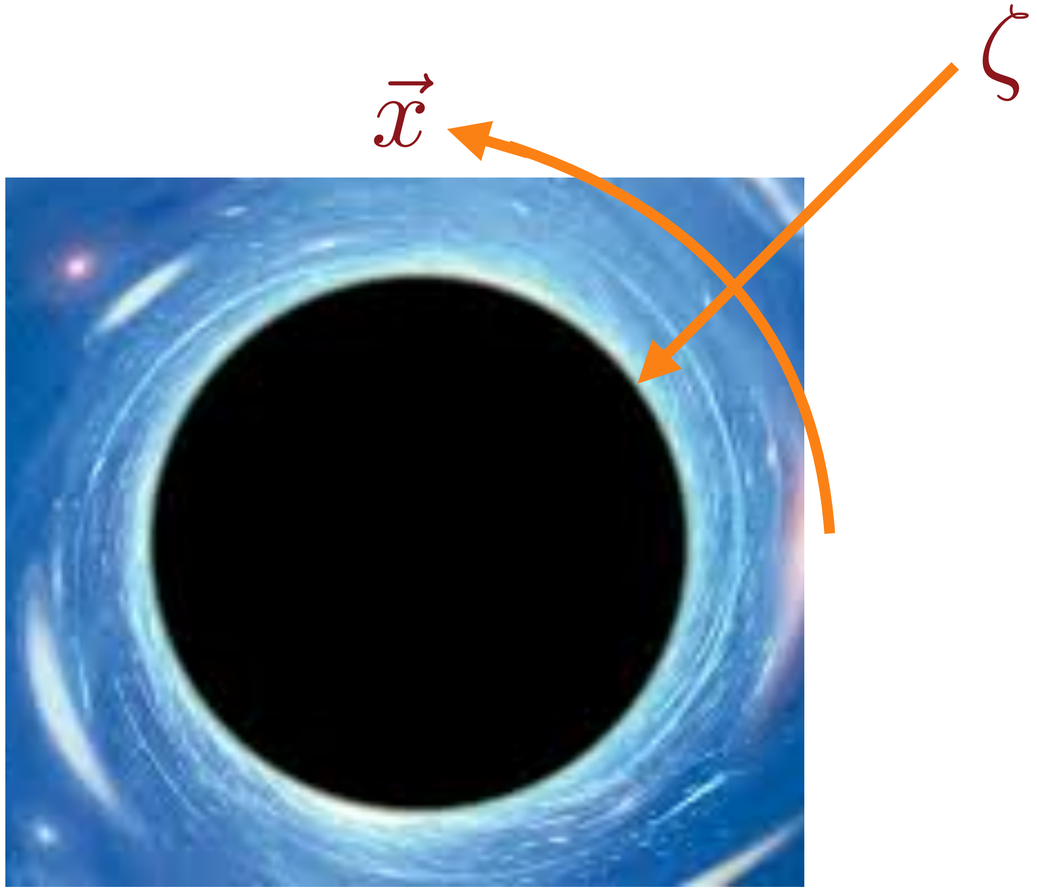
Maxwell's electromagnetism and Einstein's general relativity allow black hole solutions with a net charge

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



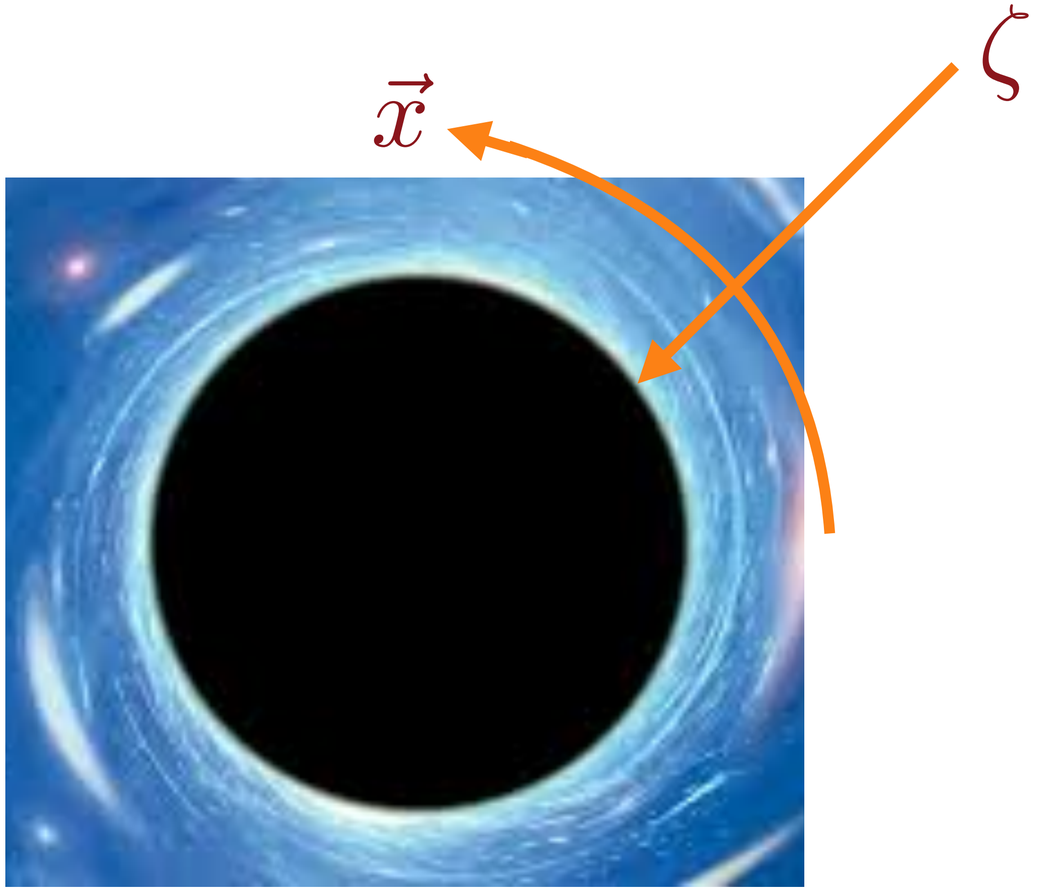
Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space (ζ) and one time dimension

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



This has led to a deeper understanding of entanglement in superconductors and of Hawking's black hole information "paradox"

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

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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