

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

Dayalbagh Educational Institute, Agra
January 1, 2021

Subir Sachdev



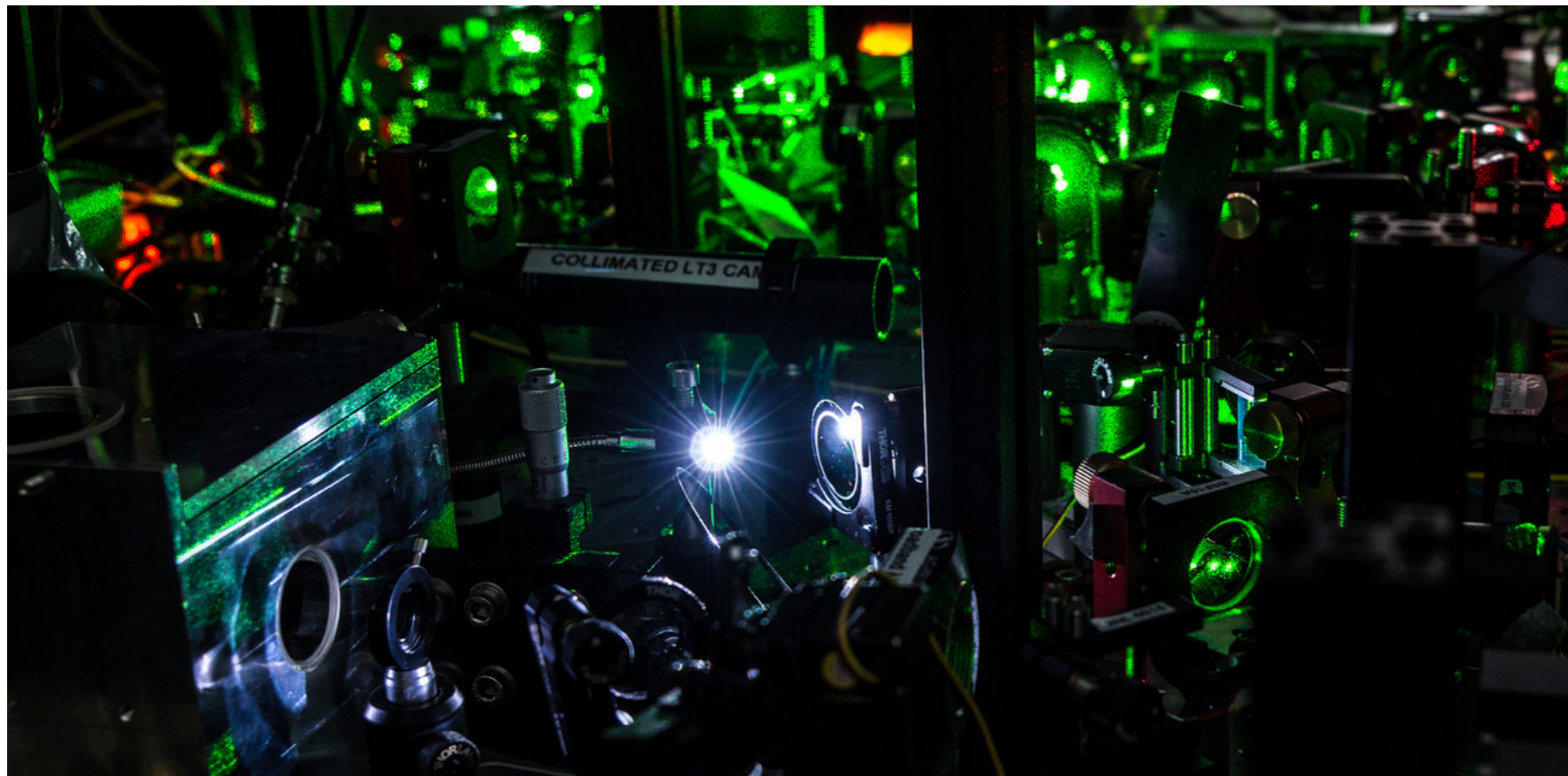
Talk online: sachdev.physics.harvard.edu

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.

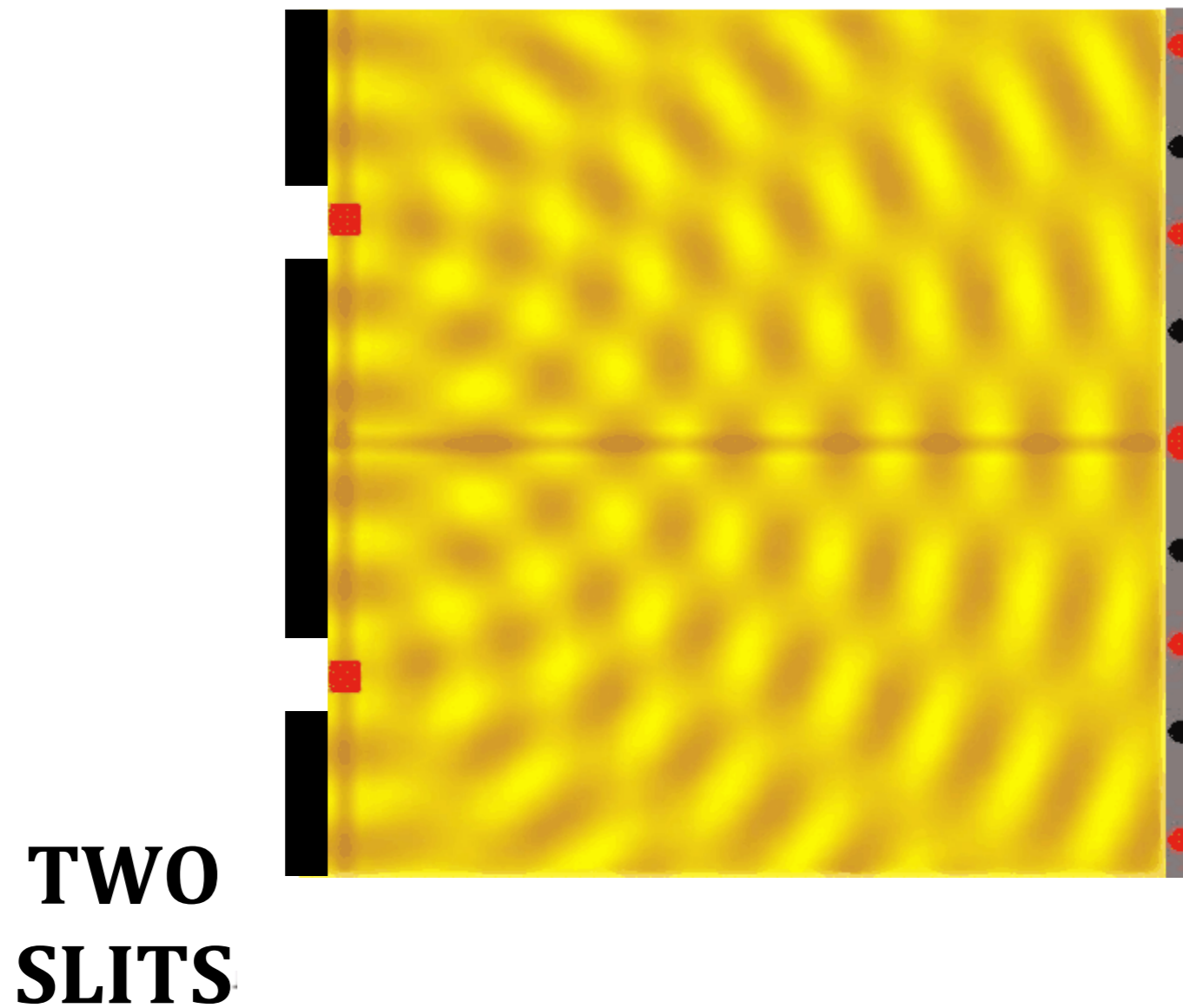


Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

Quantum entanglement

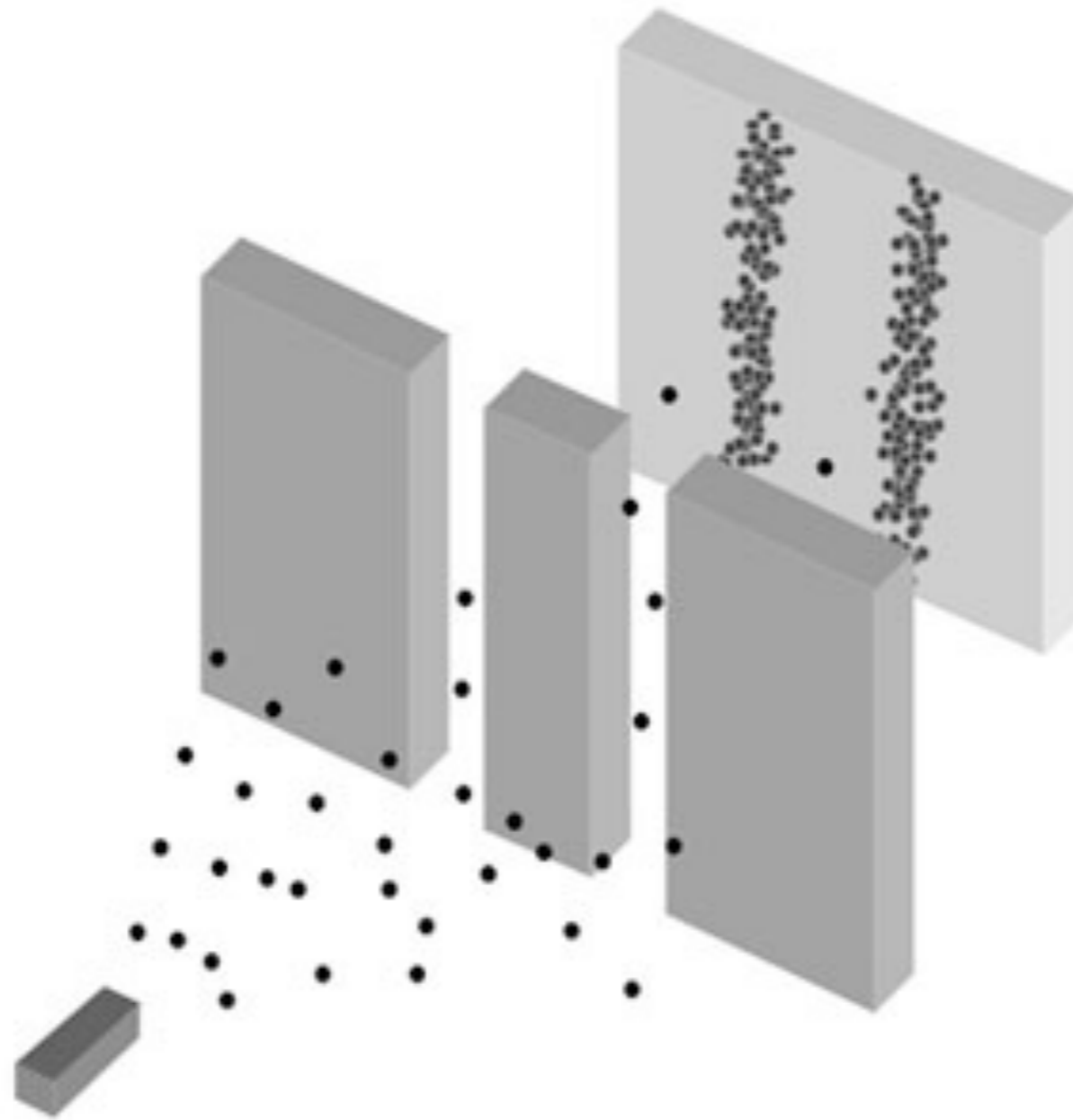
Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment



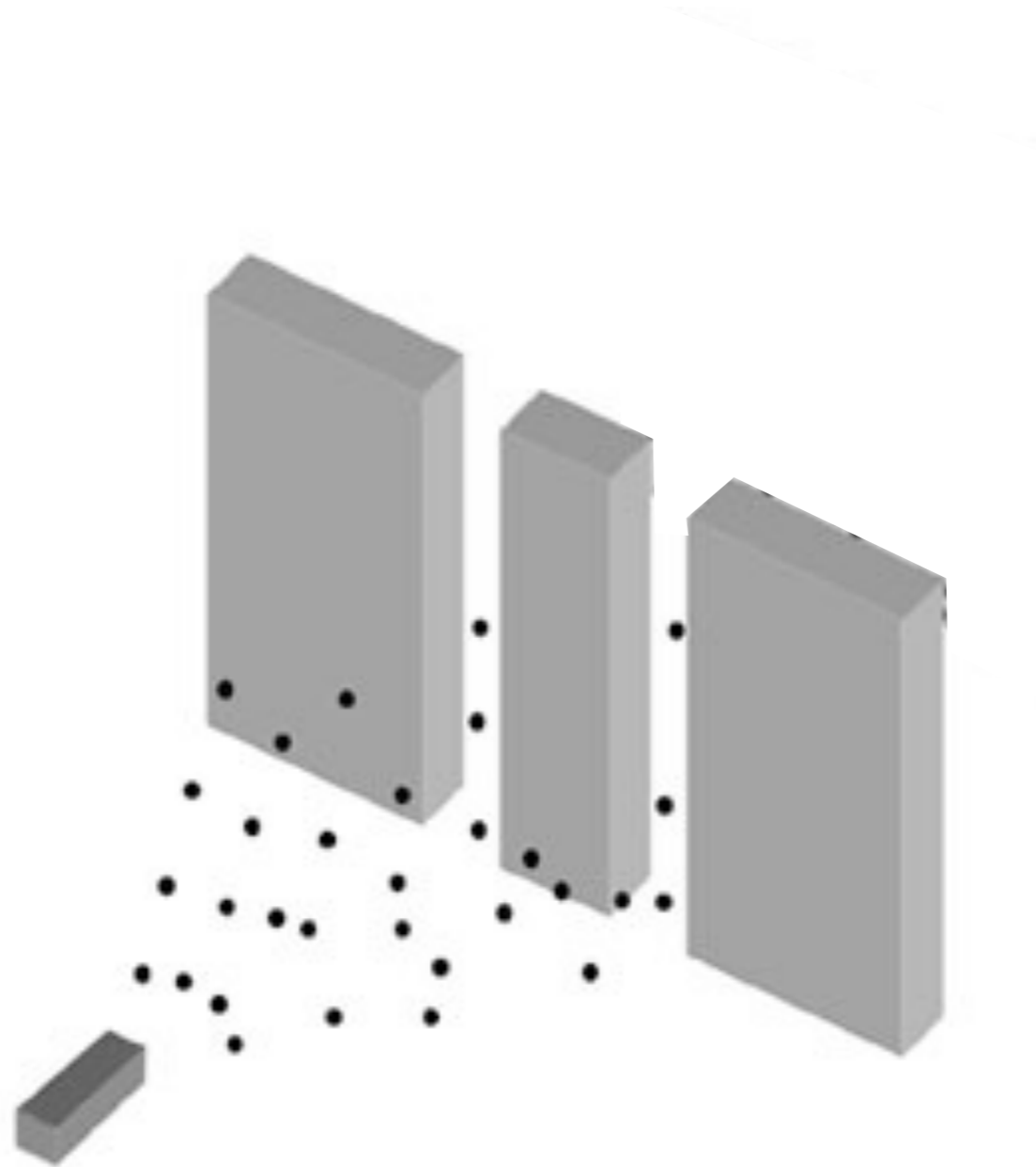
Interference of water waves

The double slit experiment



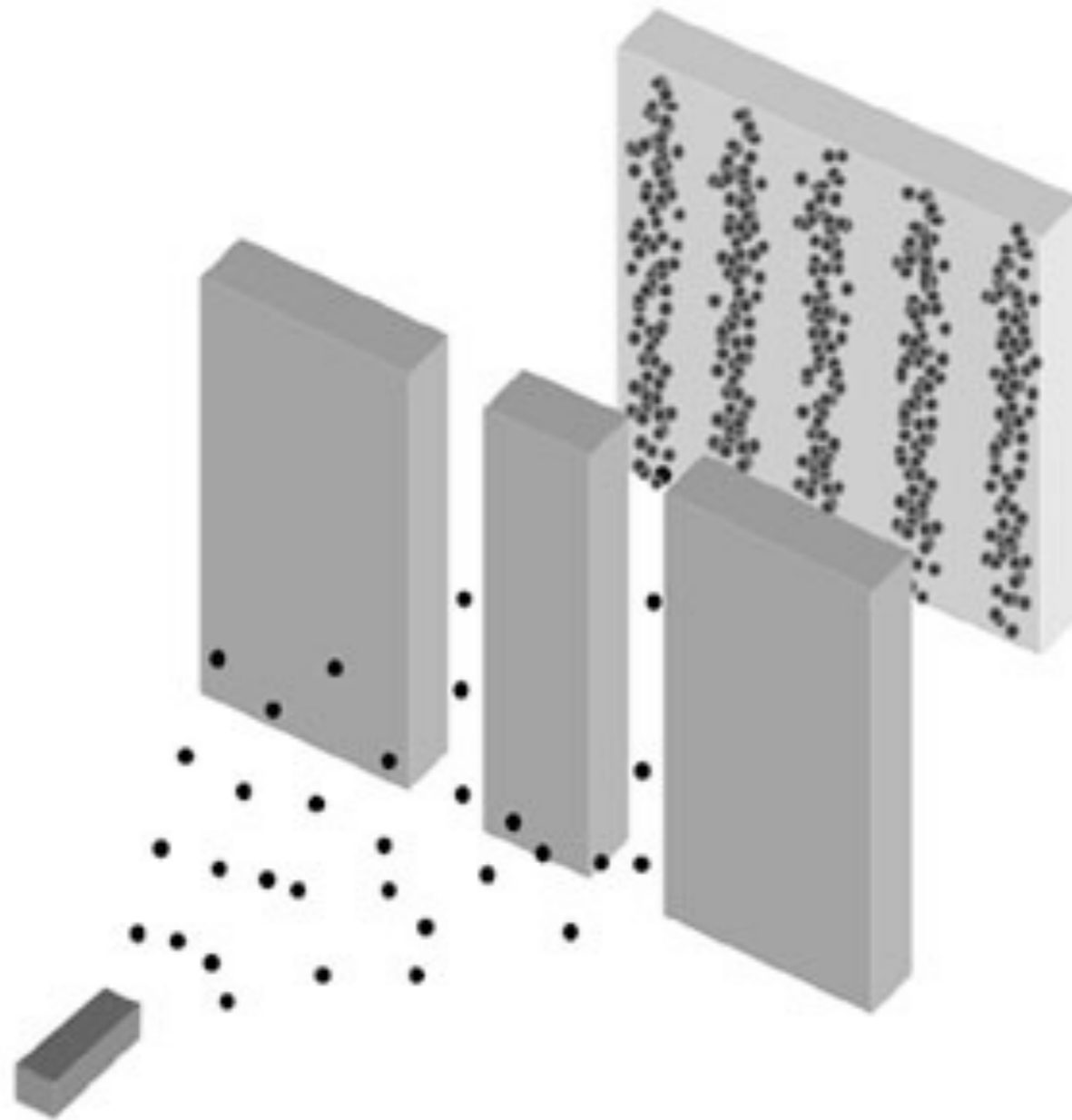
Bullets

The double slit experiment



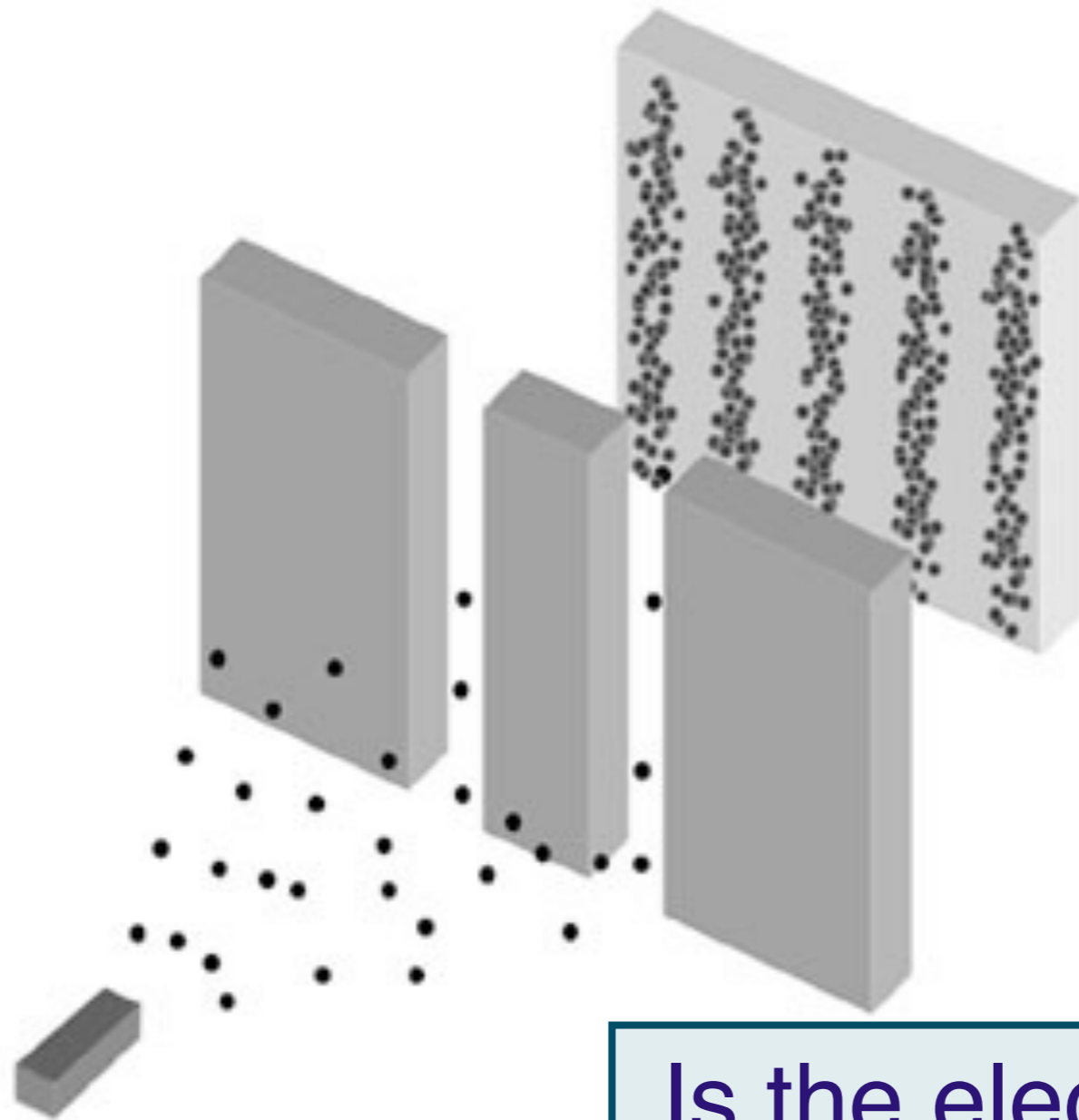
Send electrons through the slits

The double slit experiment



Interference of electrons

The double slit experiment

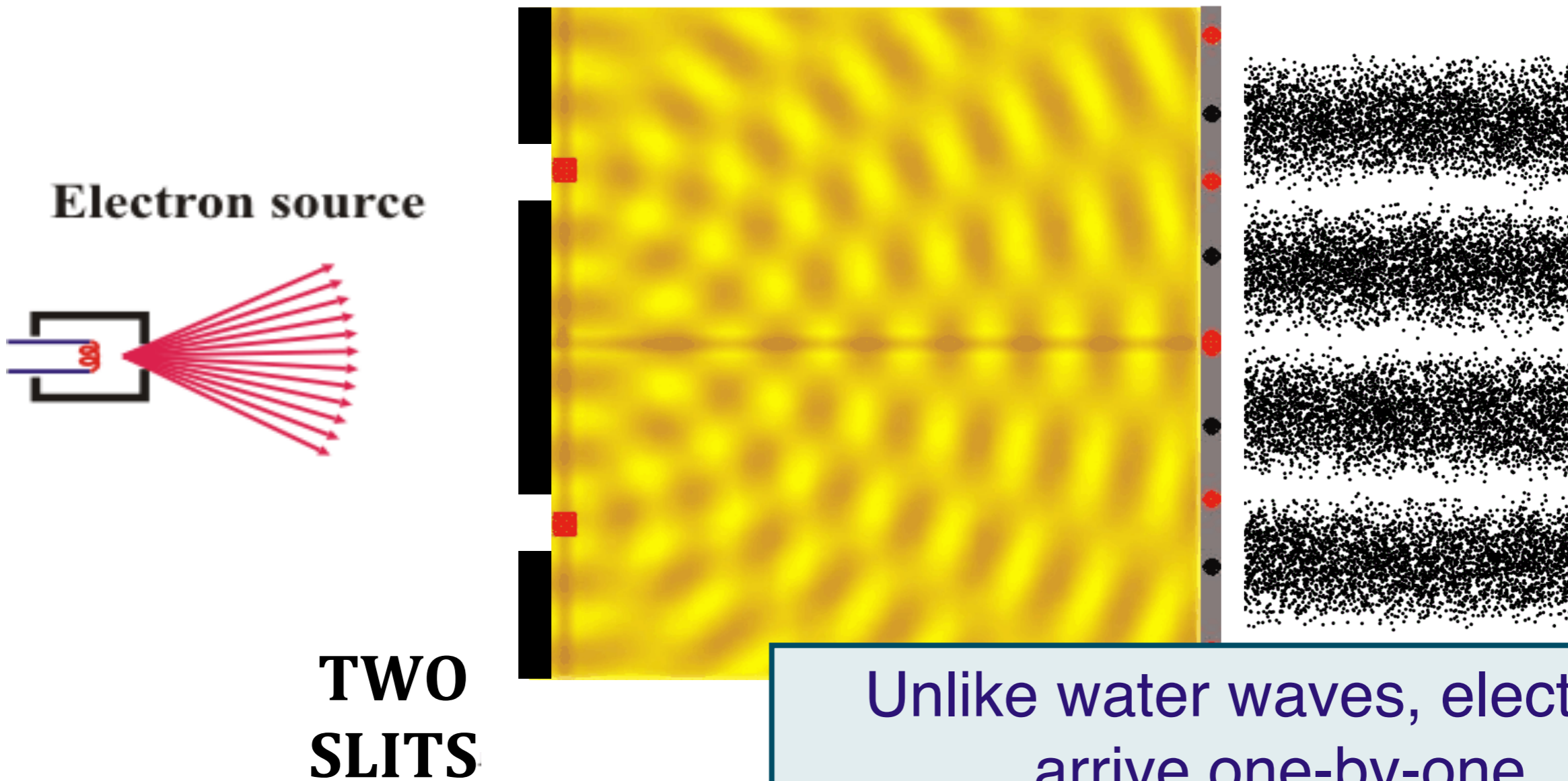


Is the electron a wave ?

Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

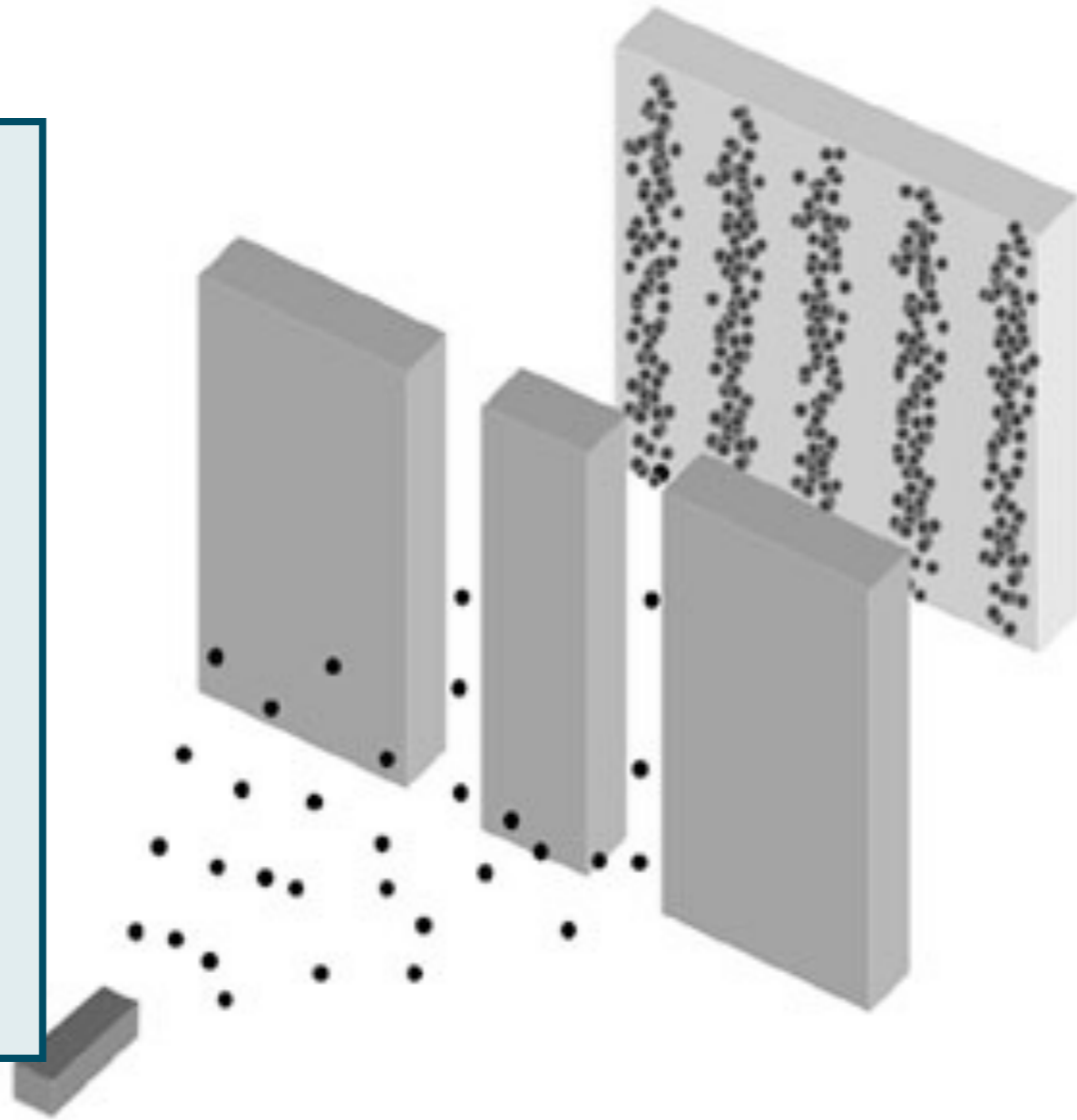


Unlike water waves, electrons arrive one-by-one (so is it like a particle ?)

Interference of electrons

The double slit experiment

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

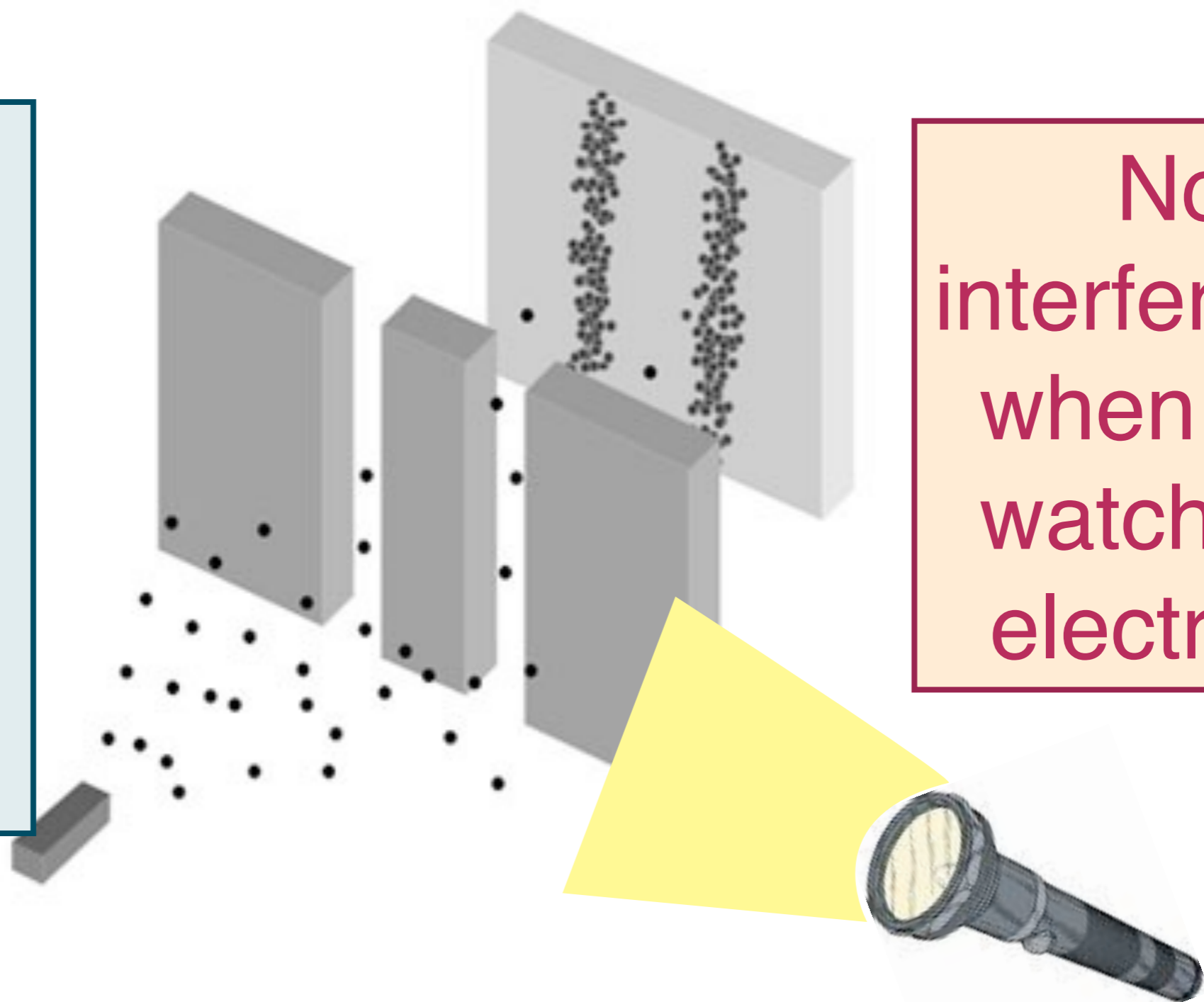


Interference of electrons

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

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



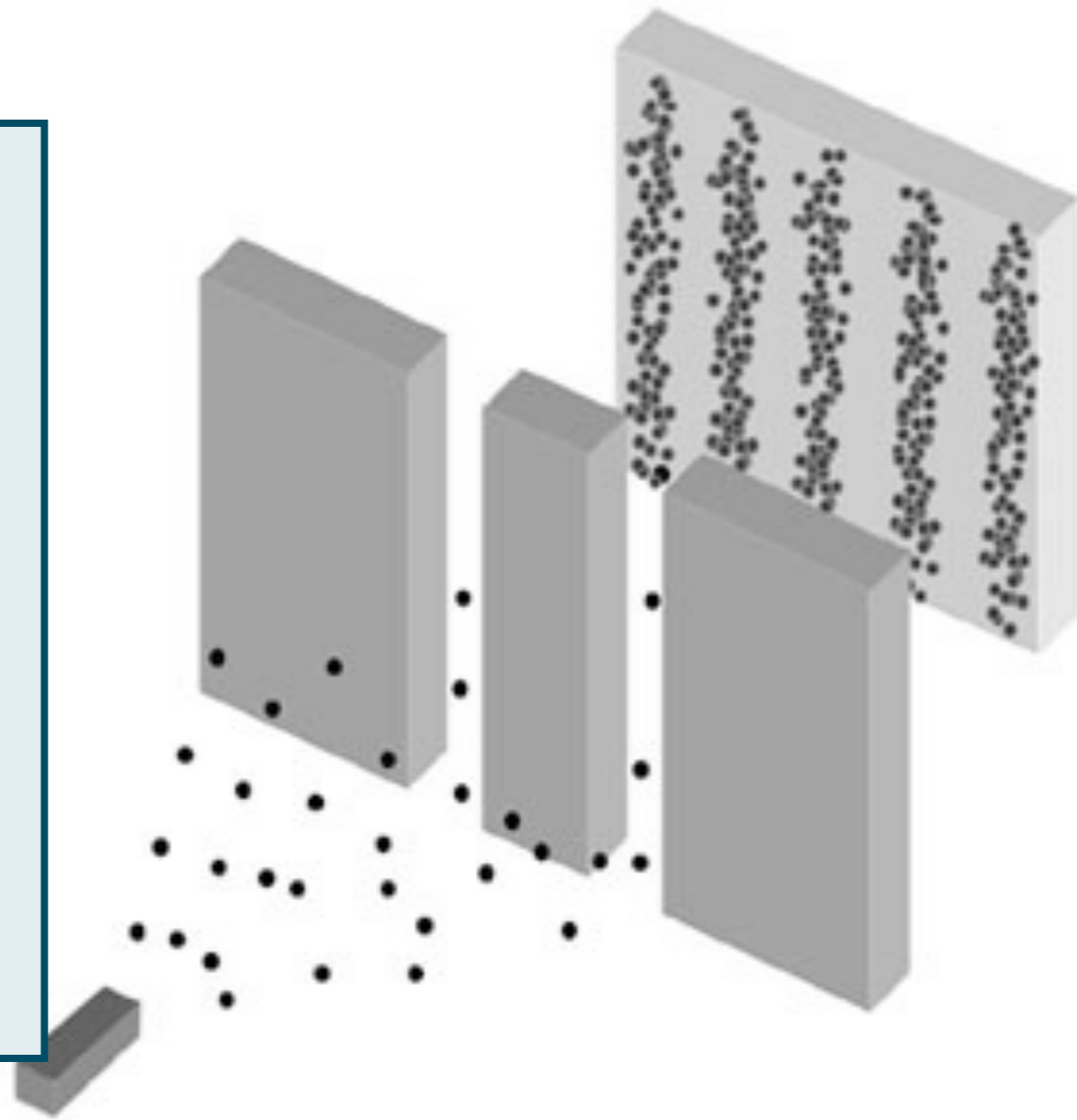
No interference when you watch the electrons

Interference of electron

Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment

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

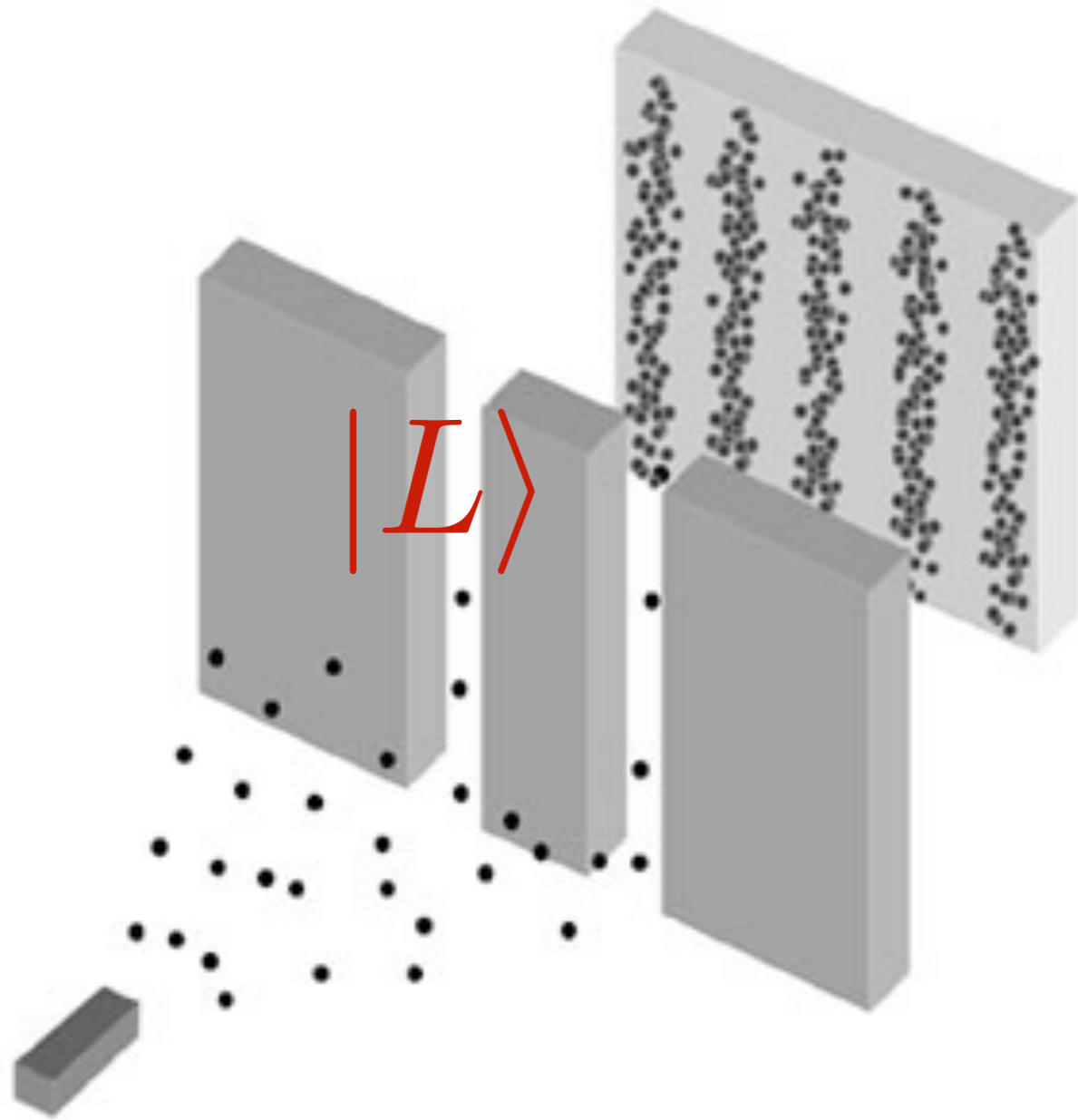


Each electron passes through both slits !

Interference of electrons

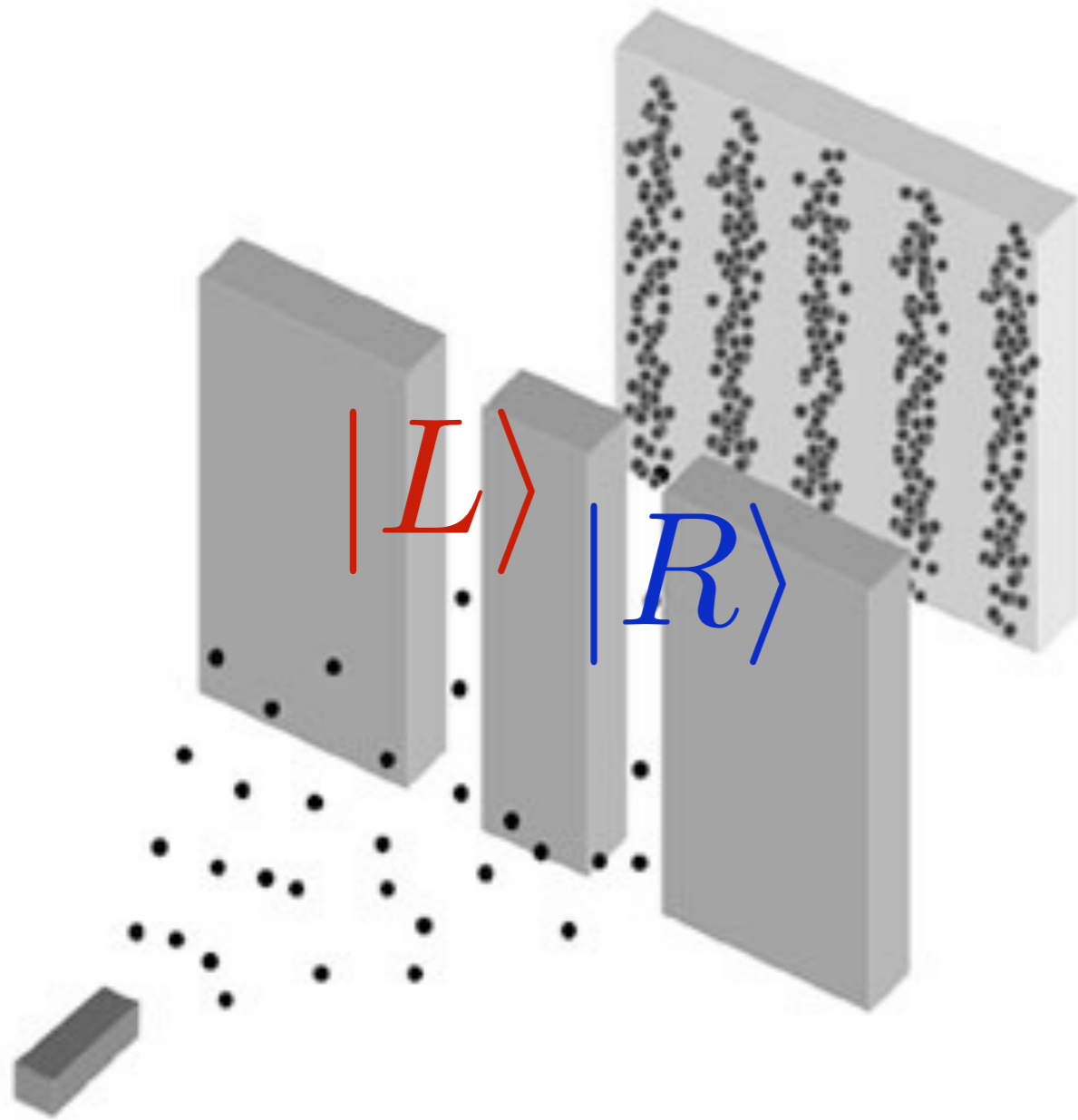
Principles of Quantum Mechanics: I. Quantum Superposition

The double slit experiment



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

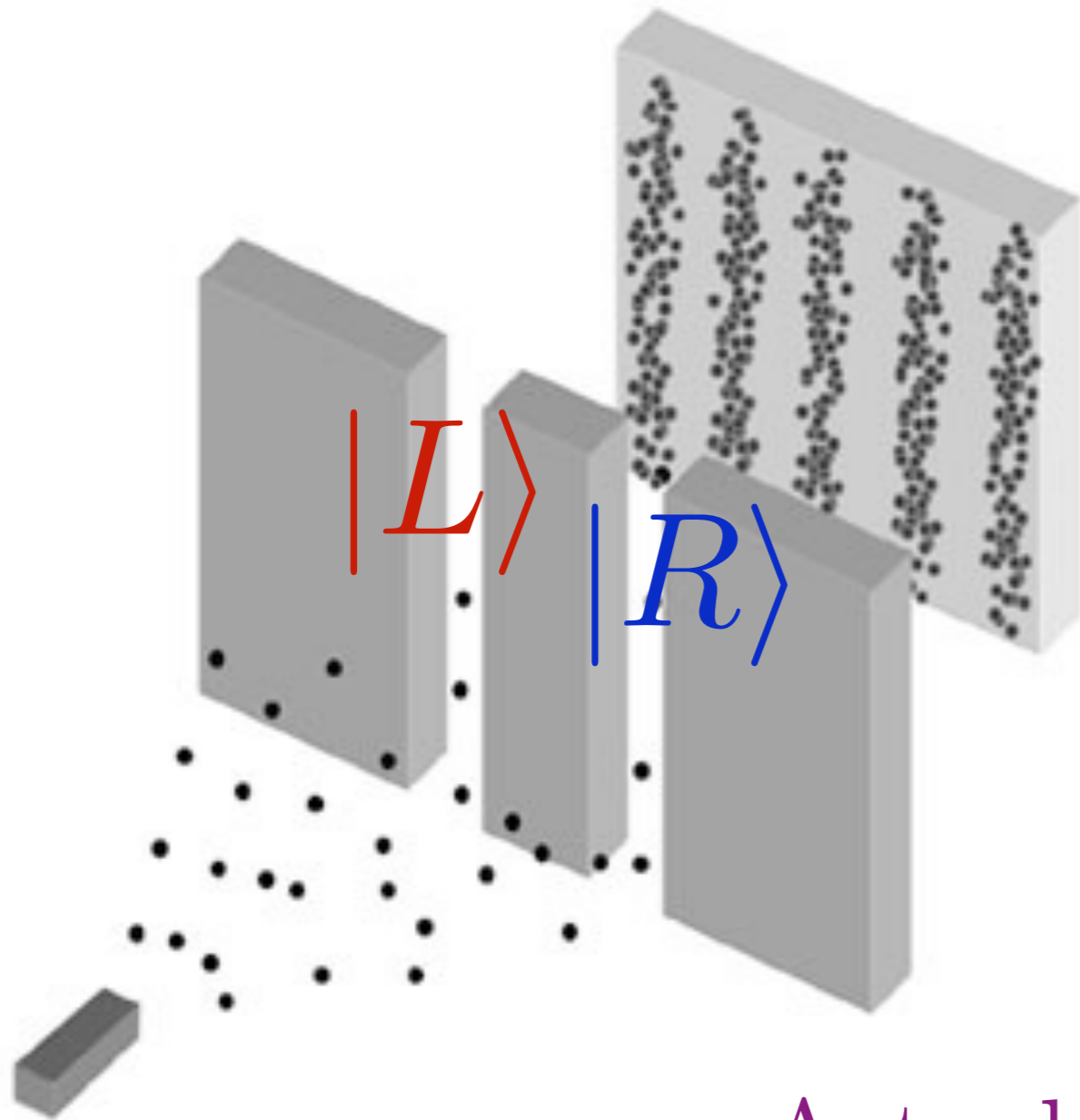
The double slit experiment



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

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

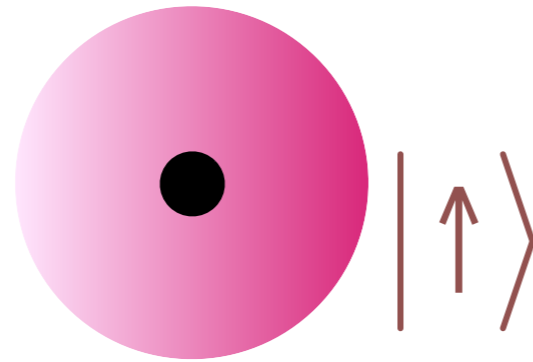
Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition
with more than one particle

Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

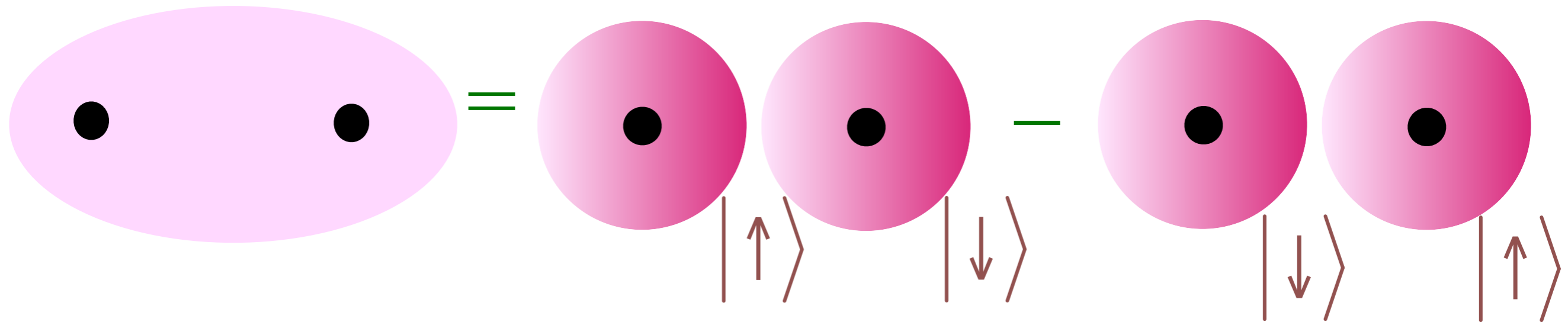


Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle



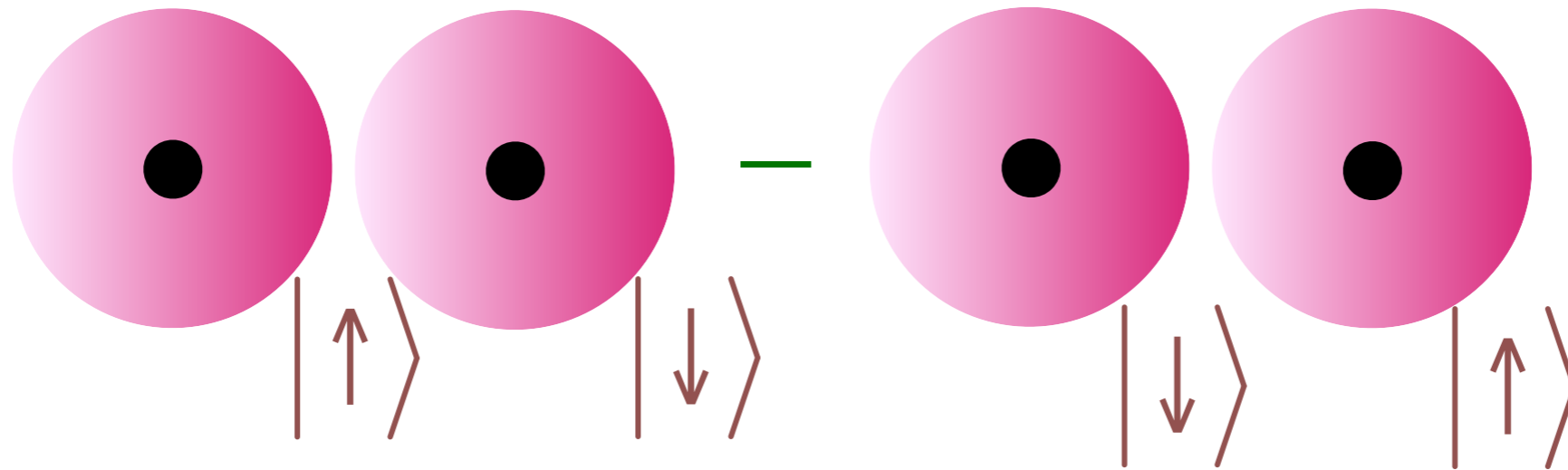
Hydrogen molecule:



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

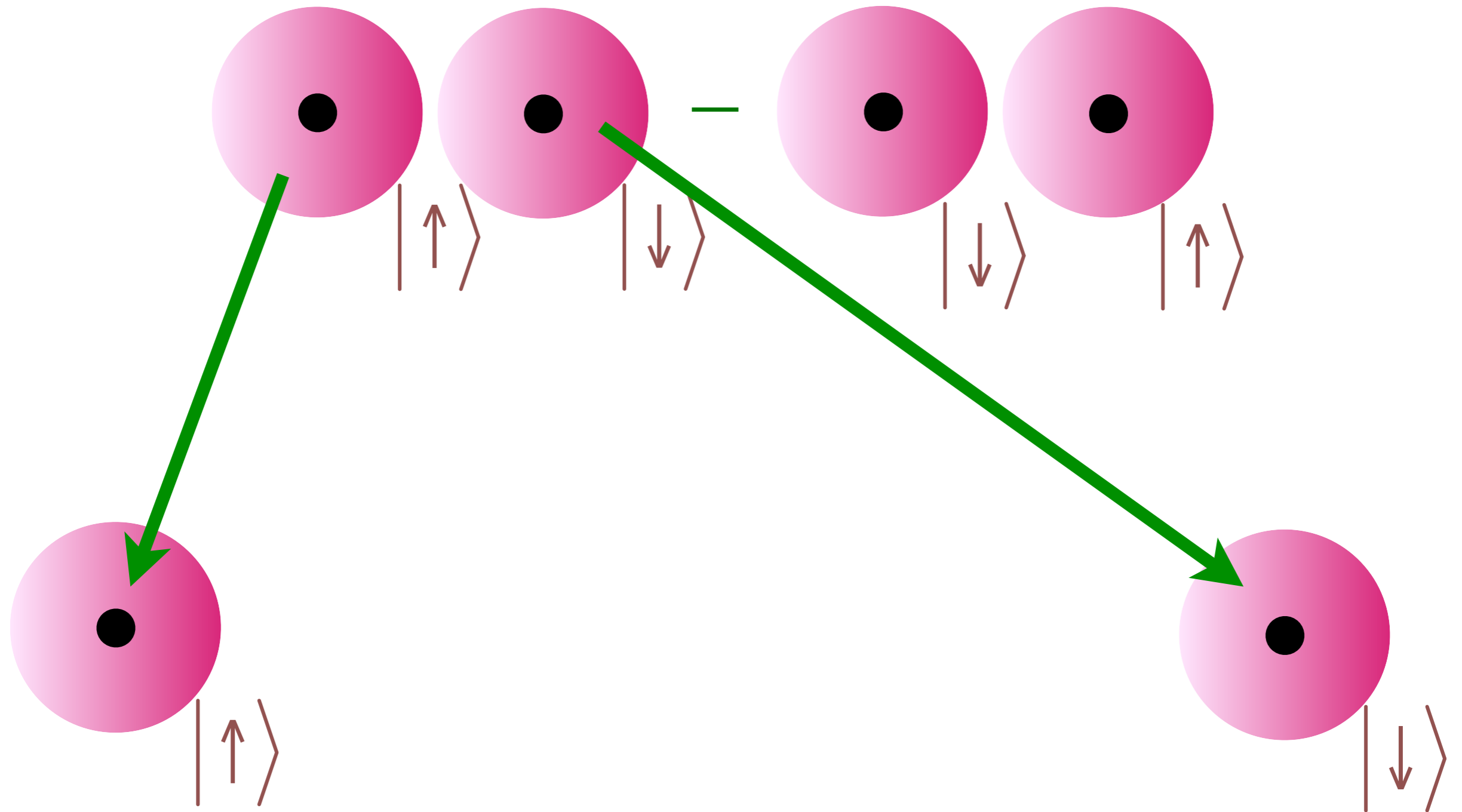
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Quantum Entanglement: quantum superposition
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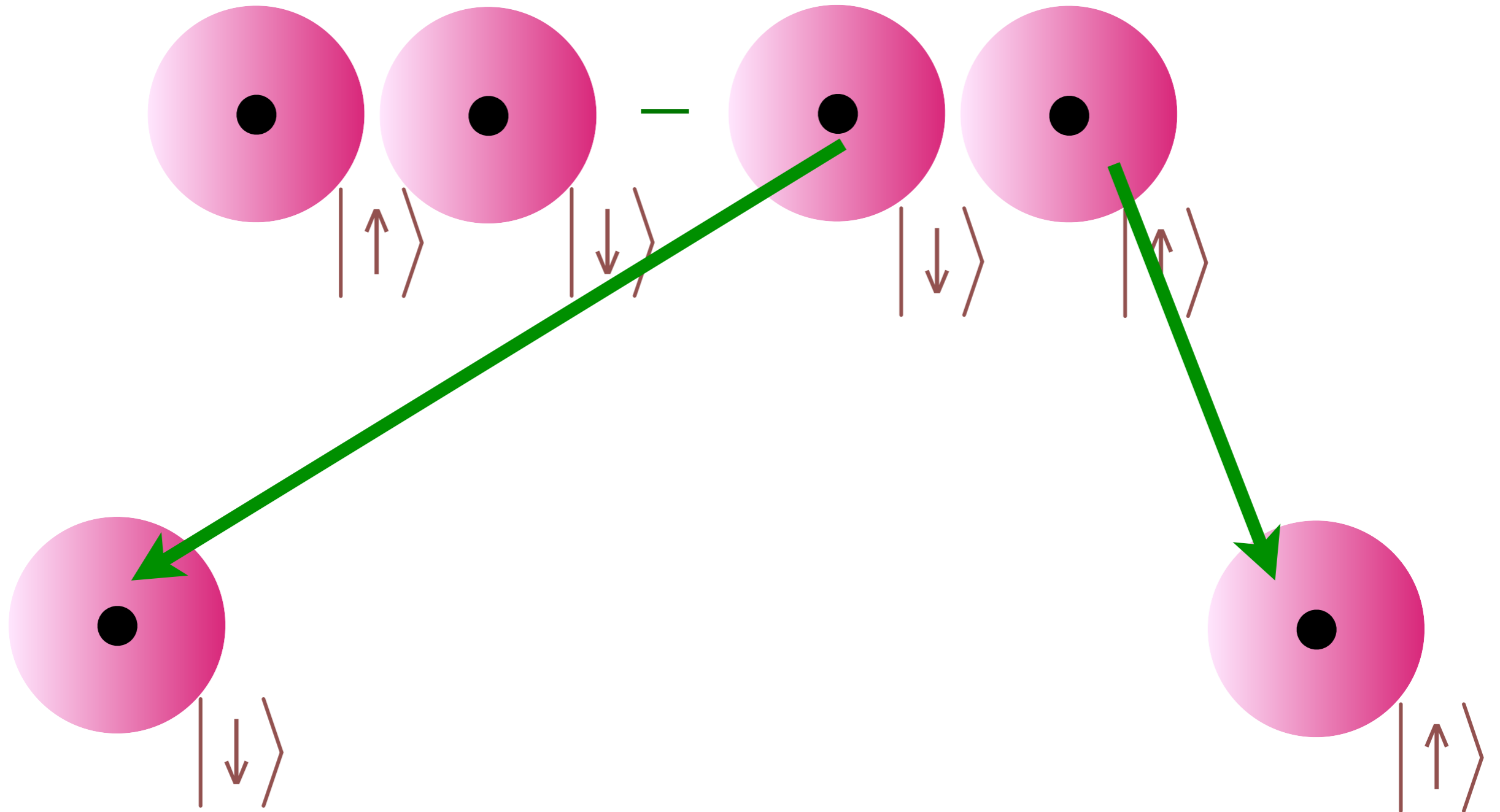
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Quantum Entanglement: quantum superposition with more than one particle



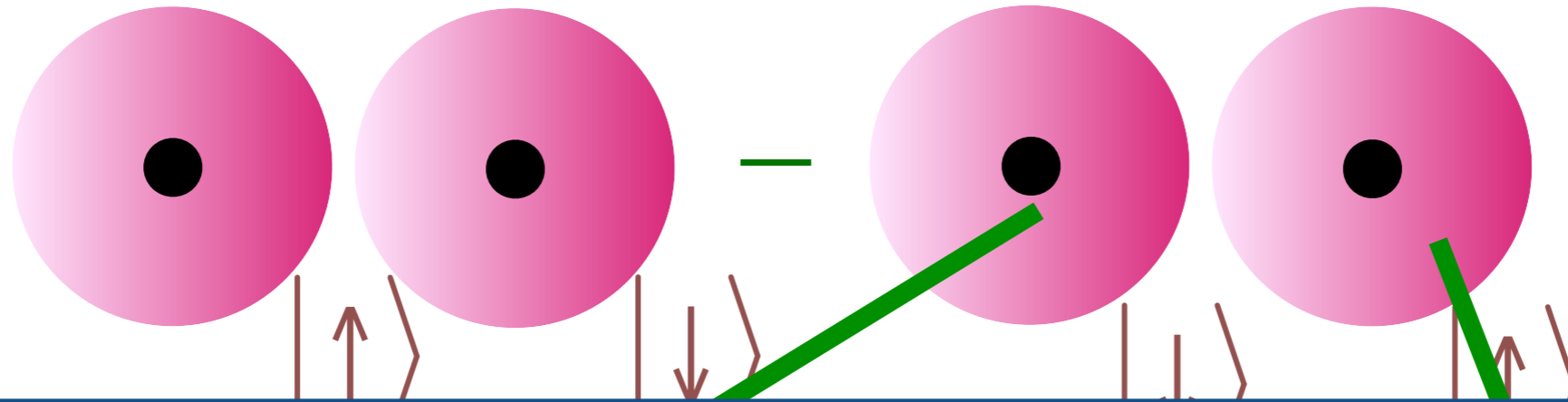
Principles of Quantum Mechanics: II. Quantum Entanglement

Quantum Entanglement: quantum superposition with more than one particle

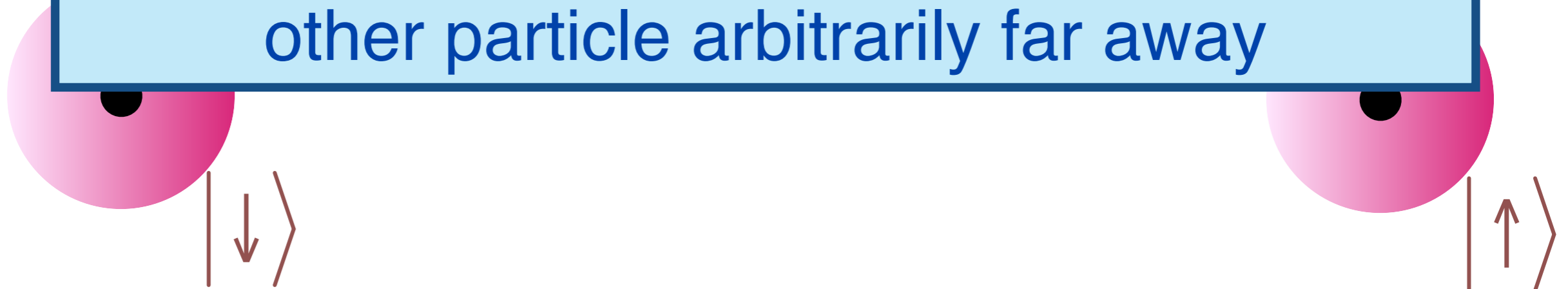


Principles of Quantum Mechanics: II. Quantum Entanglement

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**

**Quantum
entanglement**

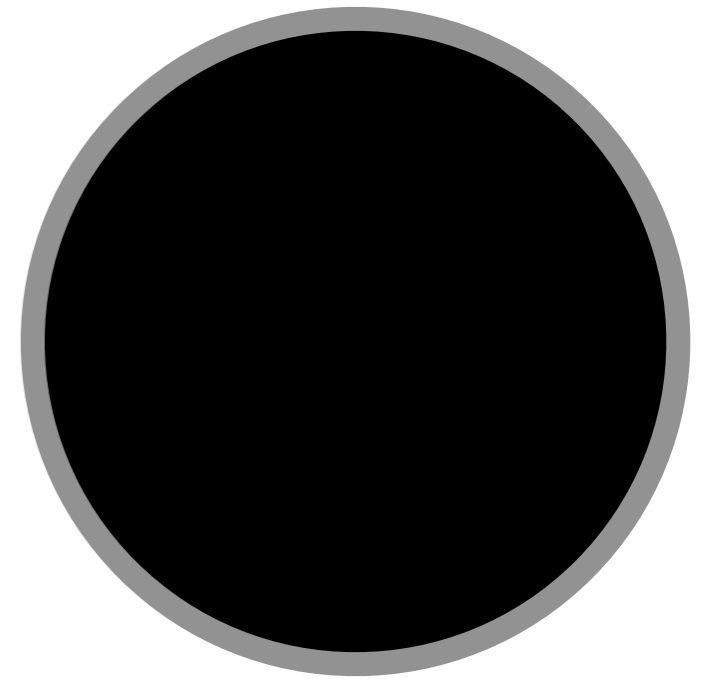
**Black
holes**

Black Holes

Objects so dense that light is gravitationally bound to them.

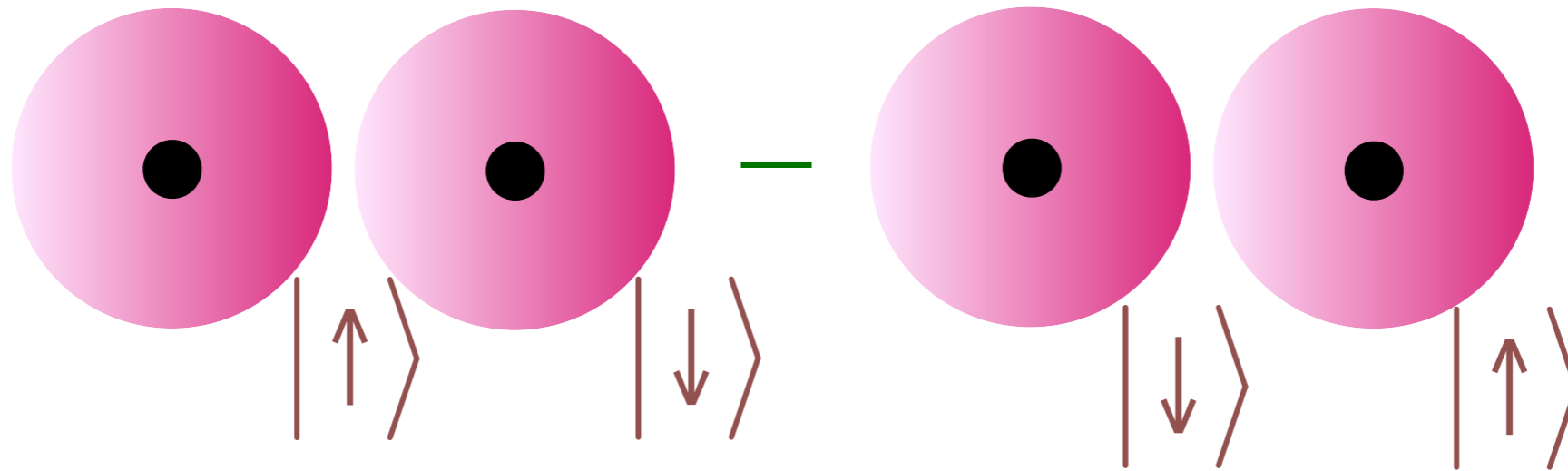
In Einstein's theory, the region inside the black hole **horizon** is disconnected from the rest of the universe.

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

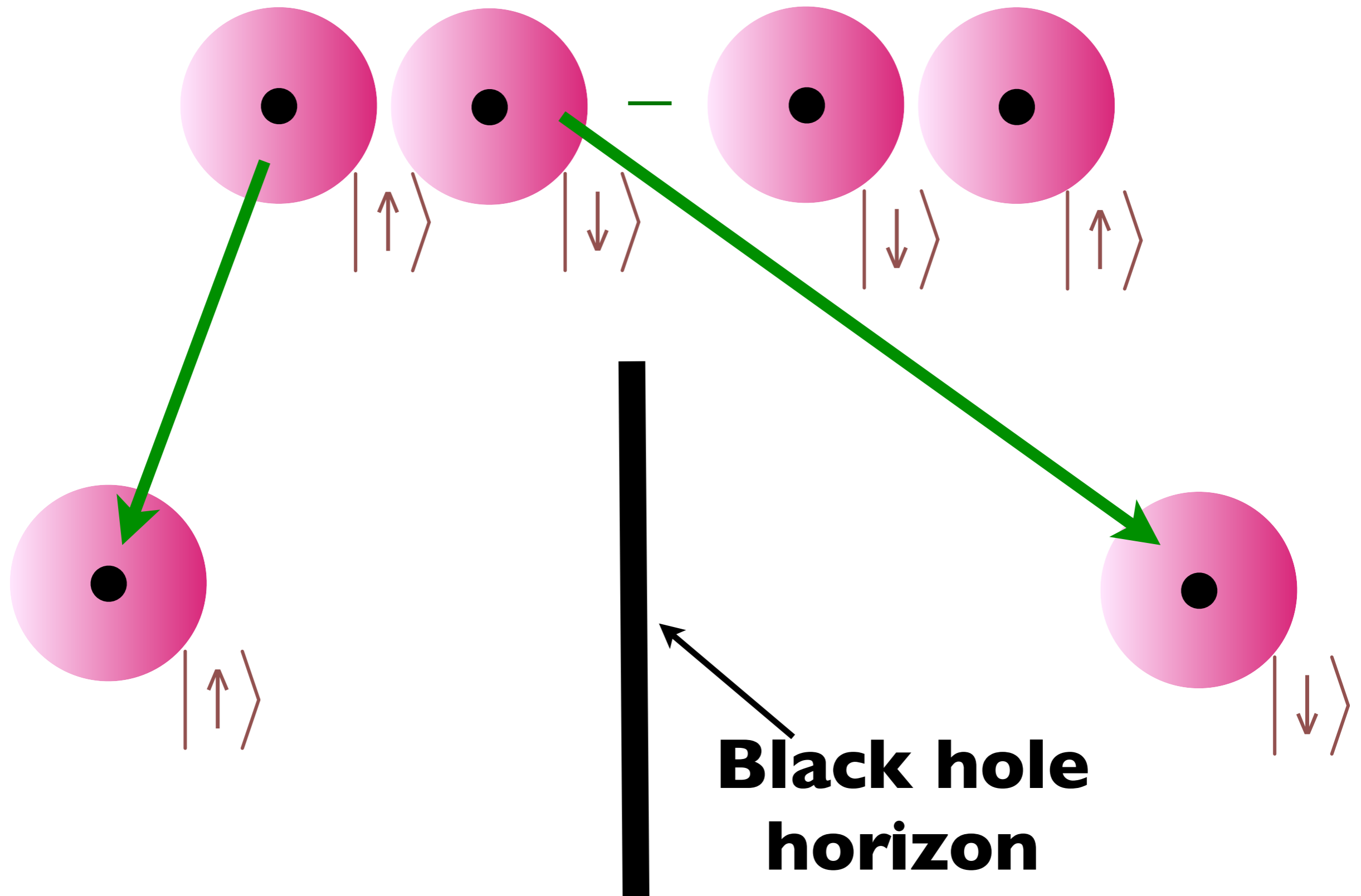


G Newton's constant, c velocity of light, M mass of black hole

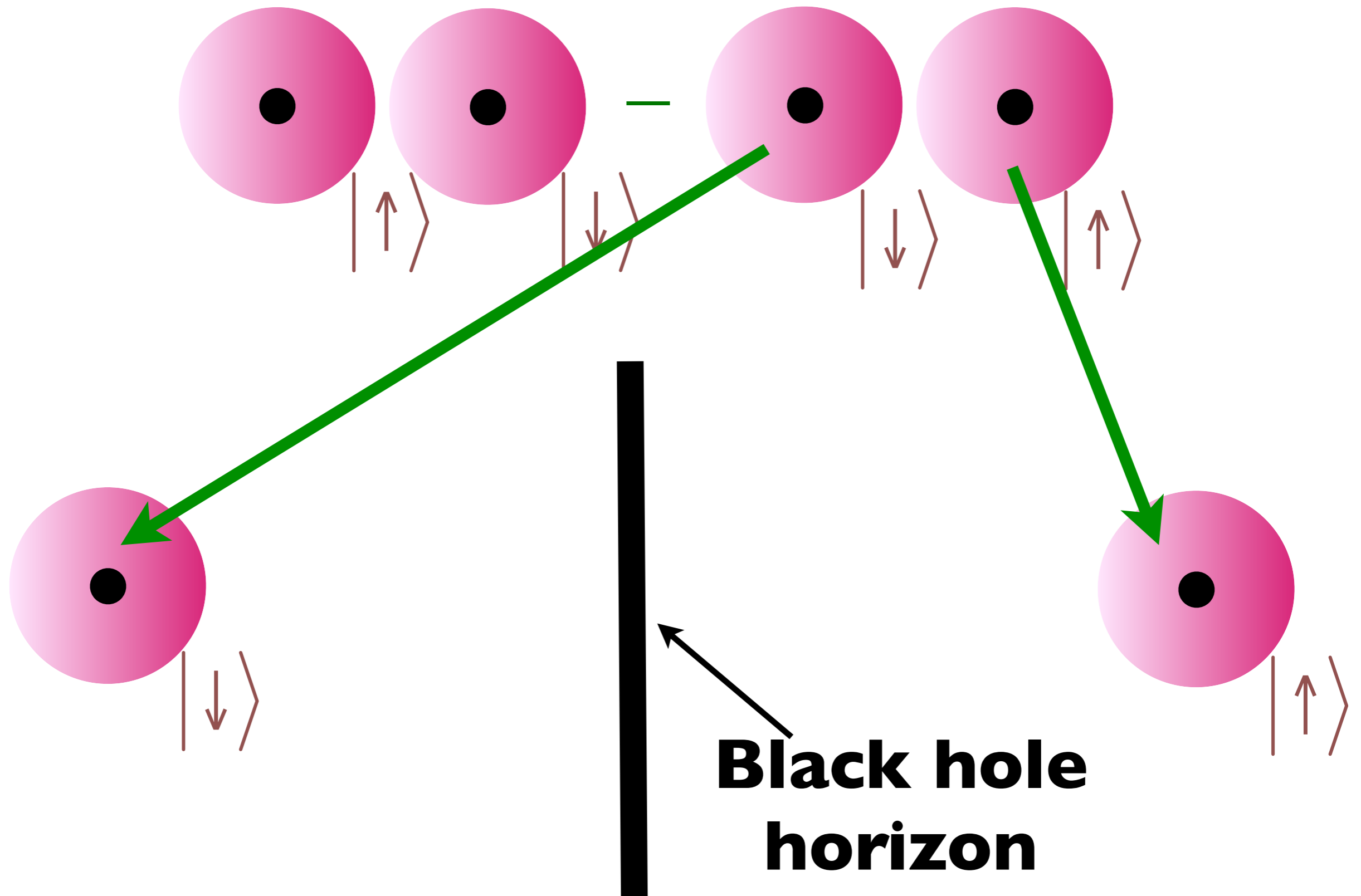
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

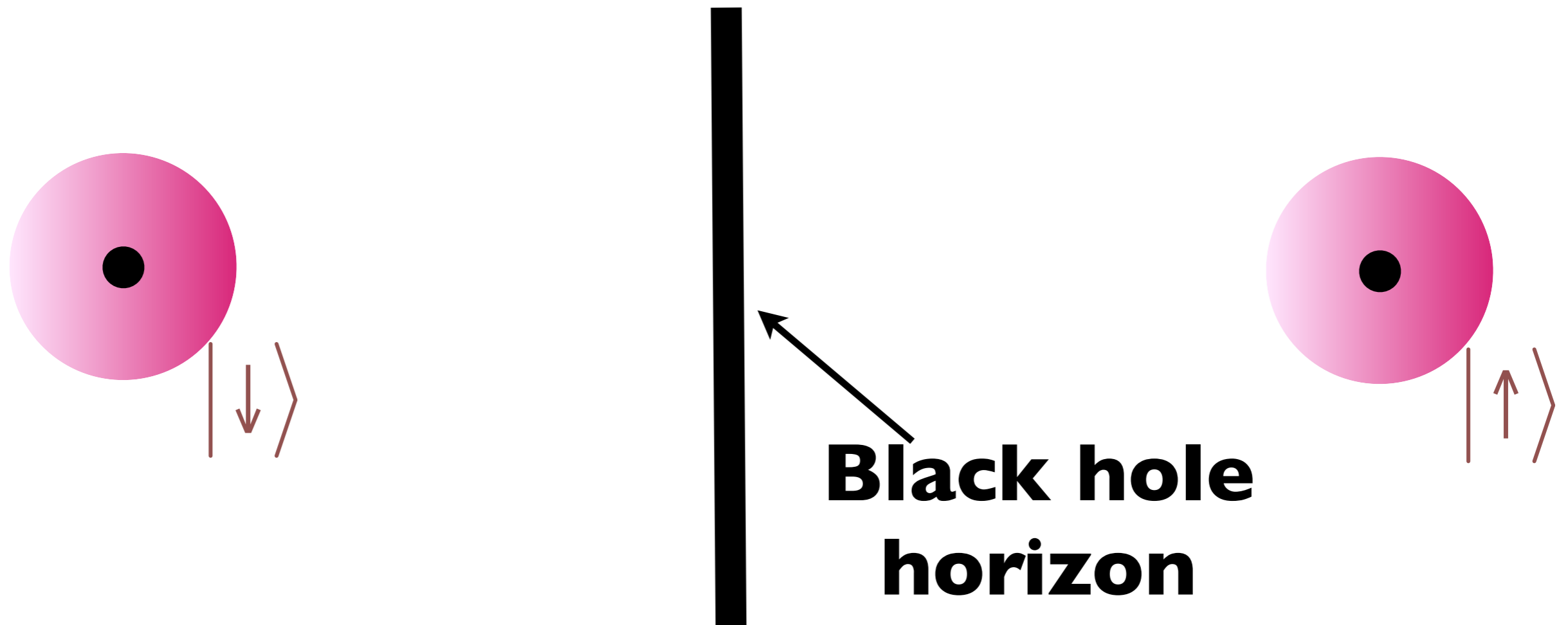


Quantum Entanglement across a black hole horizon



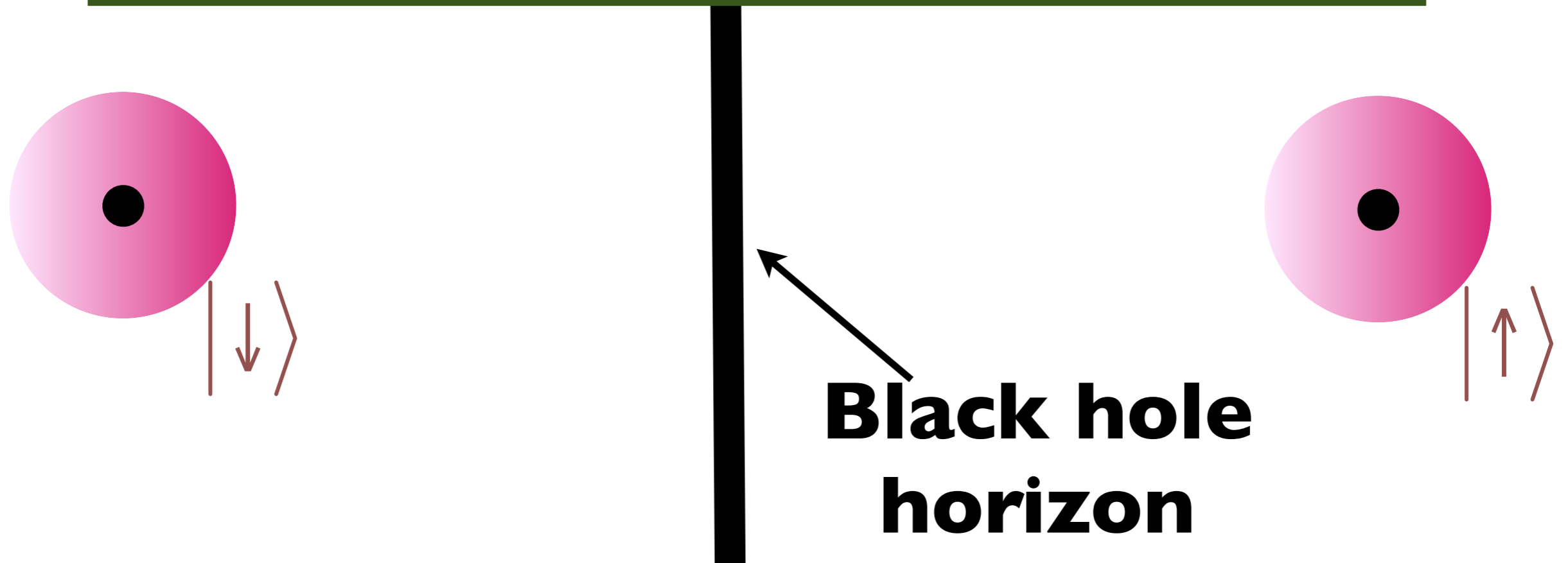
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

Hawking 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)



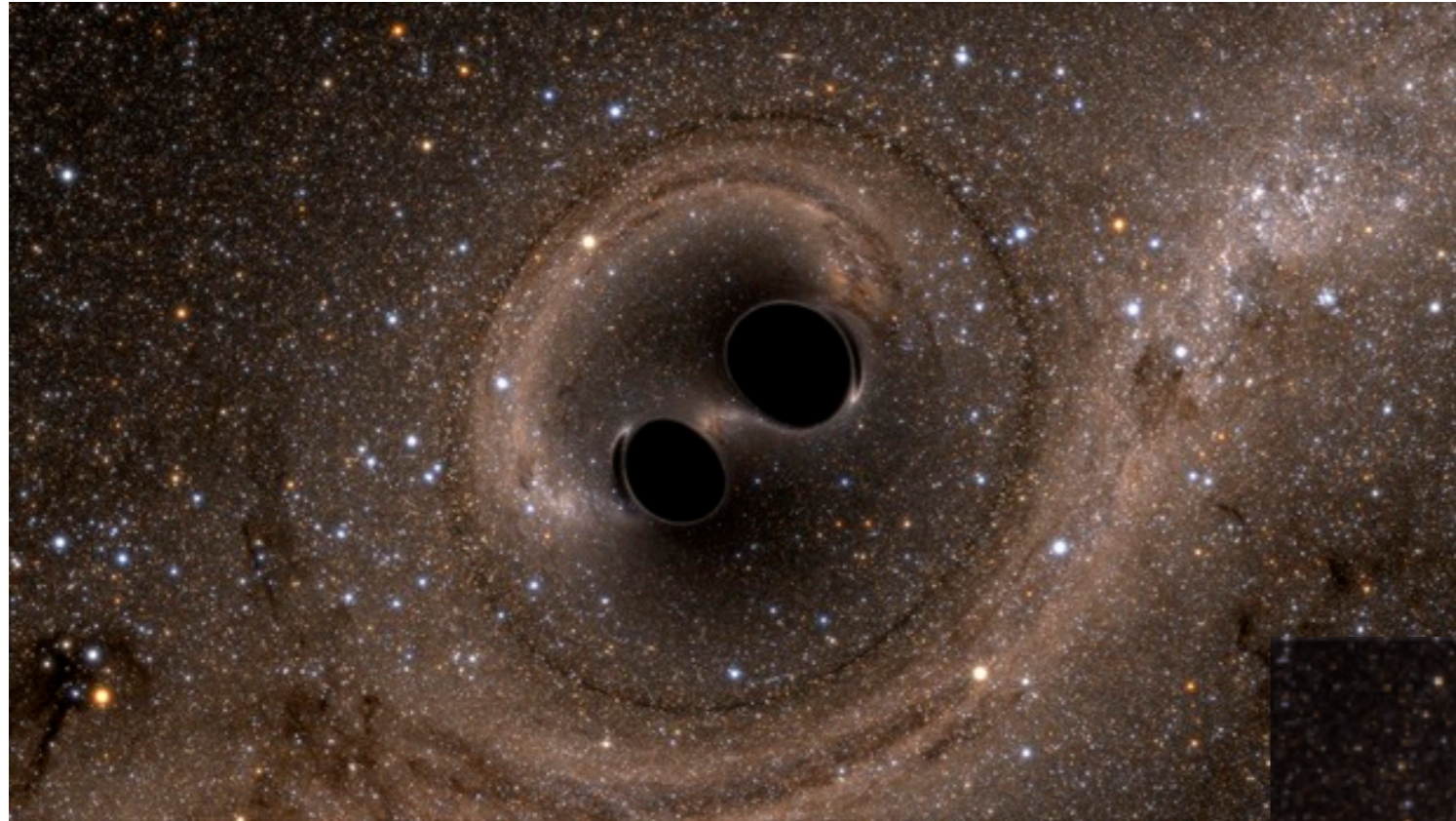
Quantum Black holes

- Black holes have an entropy and a temperature, T_H
- The entropy is proportional to their surface area.

J. D. Bekenstein, PRD **7**, 2333 (1973)
S.W. Hawking, Nature **248**, 30 (1974)

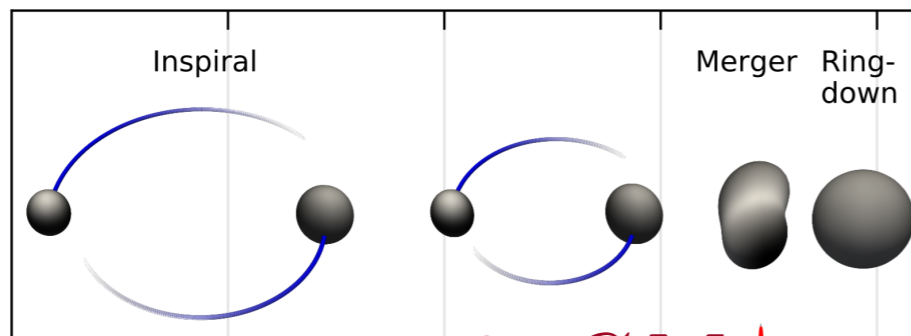
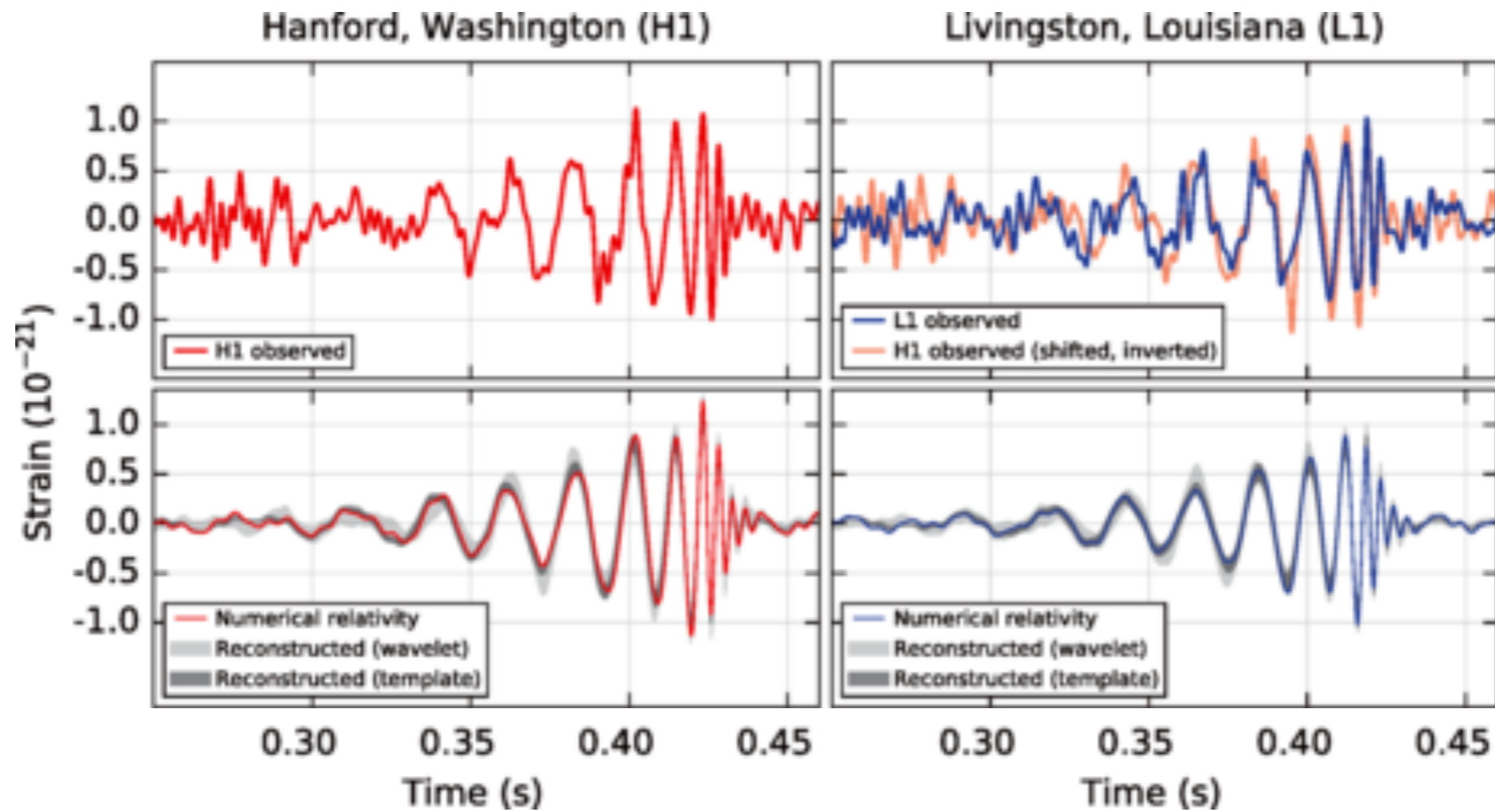


On September 14, 2015, LIGO detected the merger of two black holes, each weighing about 30 solar masses, with radii of about 100 km, 1.3 billion light years away



0.1 seconds later !





LIGO
September 14, 2015

- The ring-down time $\frac{8\pi GM}{c^3} \sim 8$ milliseconds. Curiously, for essentially all types of black holes, the ring-down time equals

$$\frac{\hbar}{k_B T_H}$$

\hbar Planck's constant, k_B Boltzmann's constant

Quantum Black holes

- Black holes have an entropy and a temperature, T_H
- The entropy is proportional to their surface area.
- They relax to thermal equilibrium in a Planckian time $\sim \hbar/(k_B T_H)$.

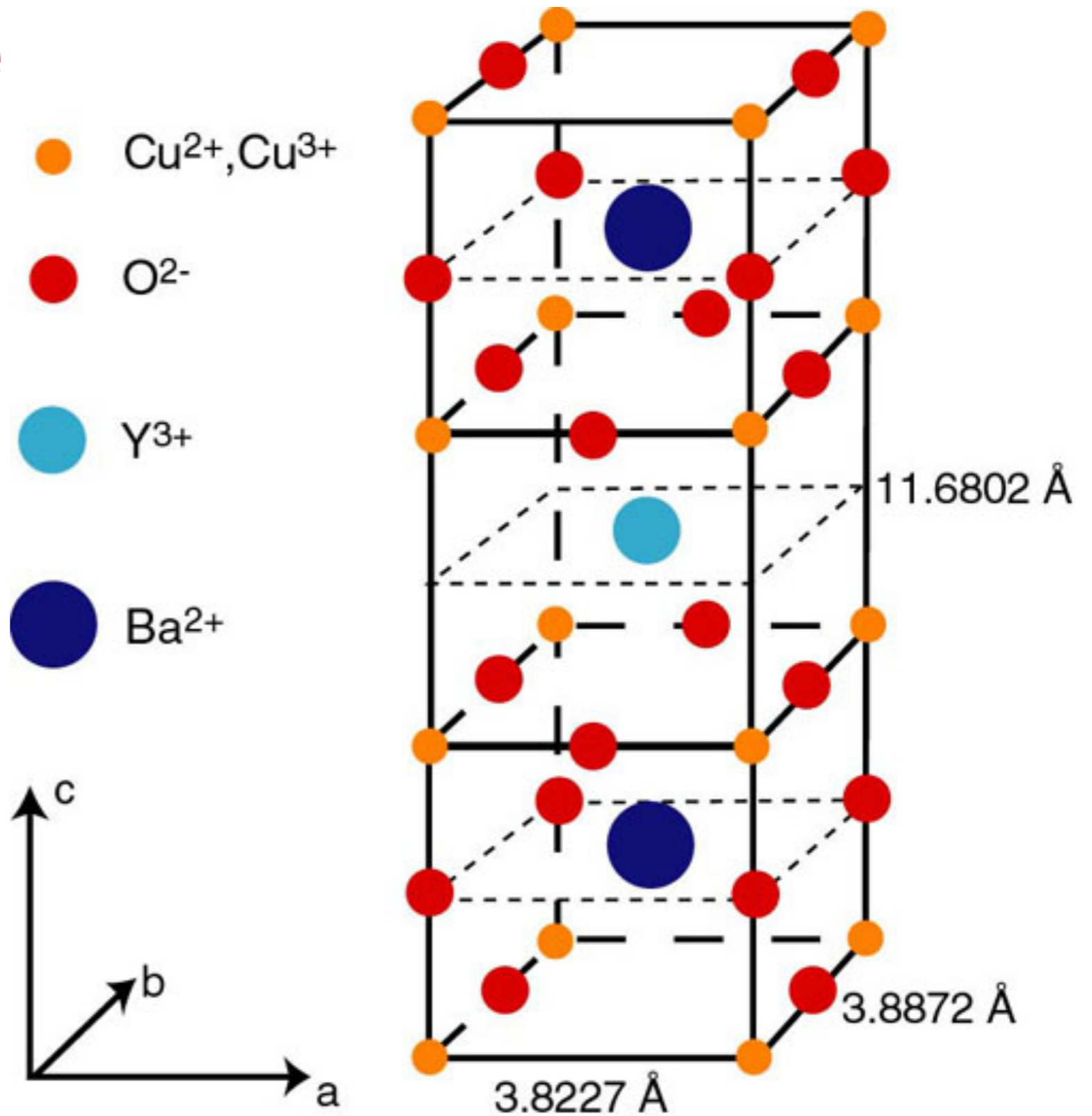


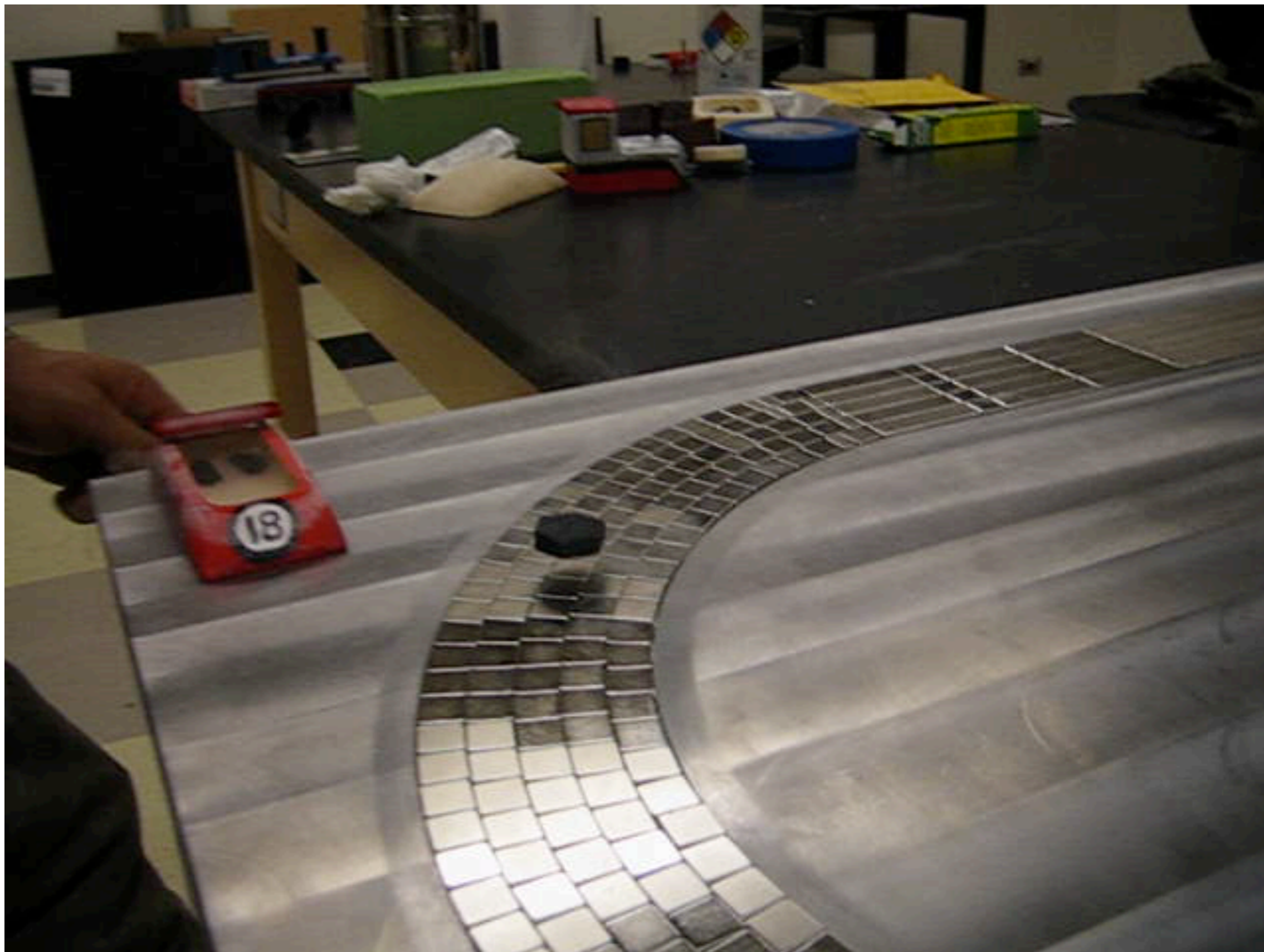
**Quantum
entanglement**

**Black
holes**

Superconductors

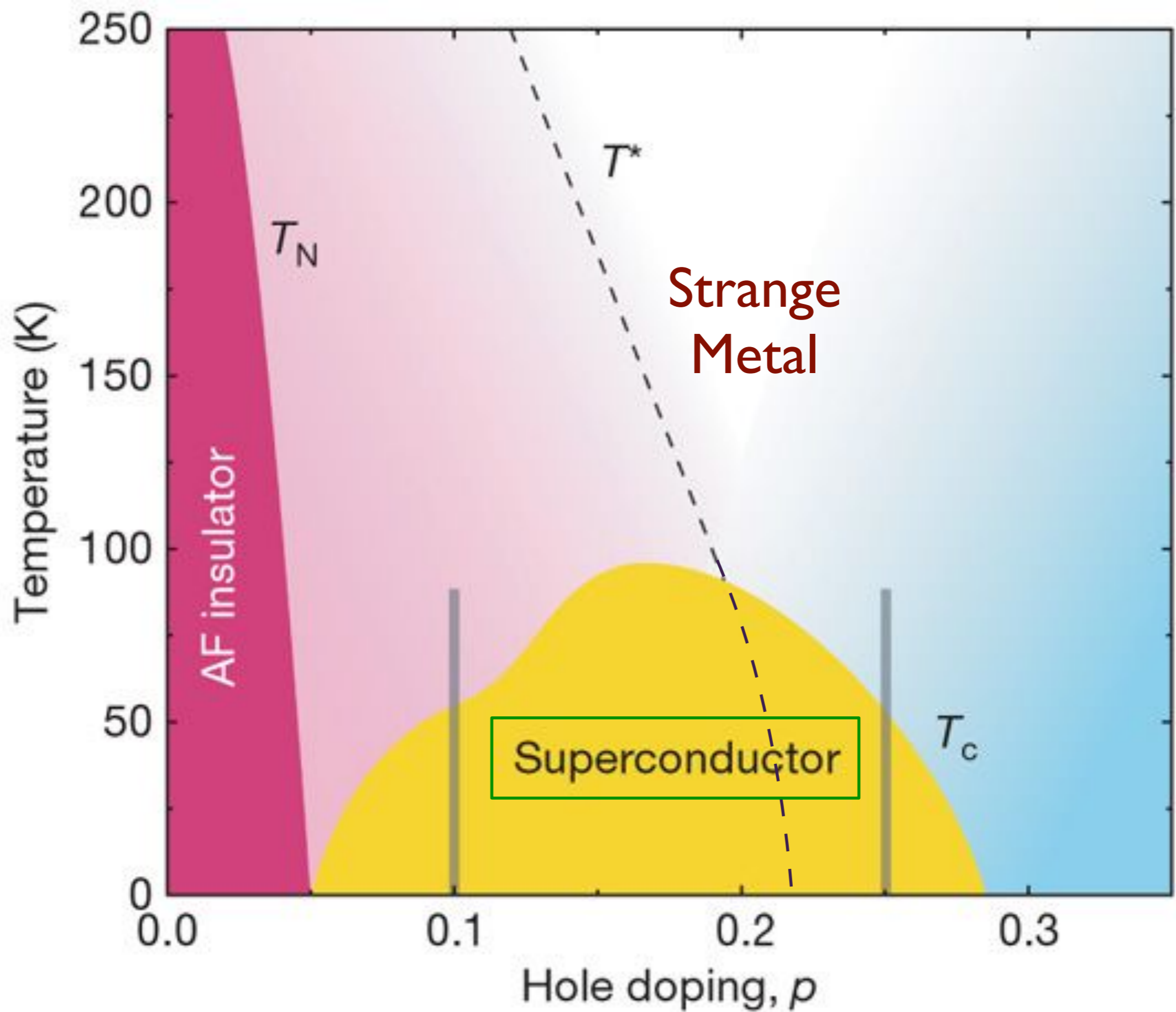
High temperature superconductors

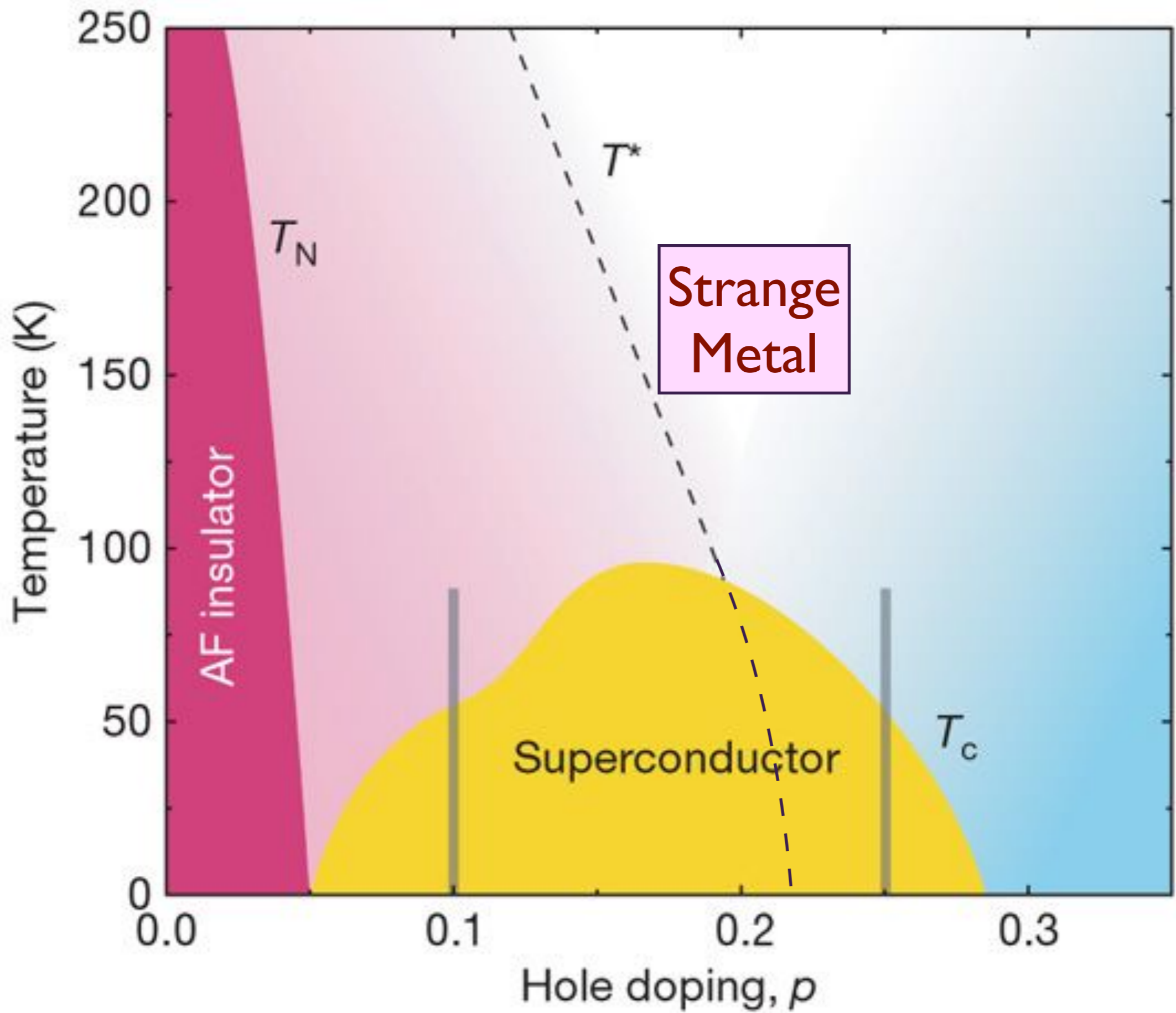




Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University



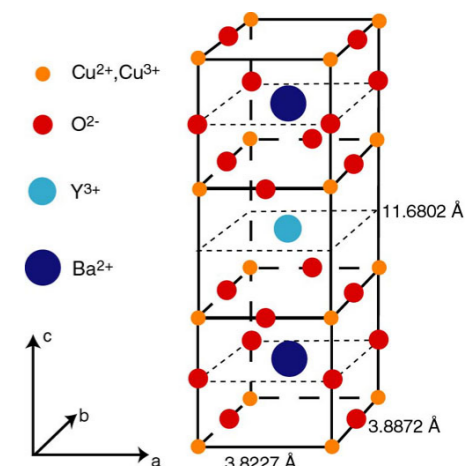


Material		n (10^{27} m^{-3})	m^* (m_0)	A_1 / d (Ω / K)	$h / (2e^2 T_F)$ (Ω / K)	α
Bi2212	$p = 0.23$	6.8	8.4 ± 1.6	8.0 ± 0.9	7.4 ± 1.4	1.1 ± 0.3
Bi2201	$p \sim 0.4$	3.5	7 ± 1.5	8 ± 2	8 ± 2	1.0 ± 0.4
LSCO	$p = 0.26$	7.8	9.8 ± 1.7	8.2 ± 1.0	8.9 ± 1.8	0.9 ± 0.3
Nd-LSCO	$p = 0.24$	7.9	12 ± 4	7.4 ± 0.8	10.6 ± 3.7	0.7 ± 0.4
PCCO	$x = 0.17$	8.8	2.4 ± 0.1	1.7 ± 0.3	2.1 ± 0.1	0.8 ± 0.2
LCCO	$x = 0.15$	9.0	3.0 ± 0.3	3.0 ± 0.45	2.6 ± 0.3	1.2 ± 0.3
TMTSF	$P = 11 \text{ kbar}$	1.4	1.15 ± 0.2	2.8 ± 0.3	2.8 ± 0.4	1.0 ± 0.3

Slope of T -linear resistivity vs Planckian limit in seven materials.

$$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$

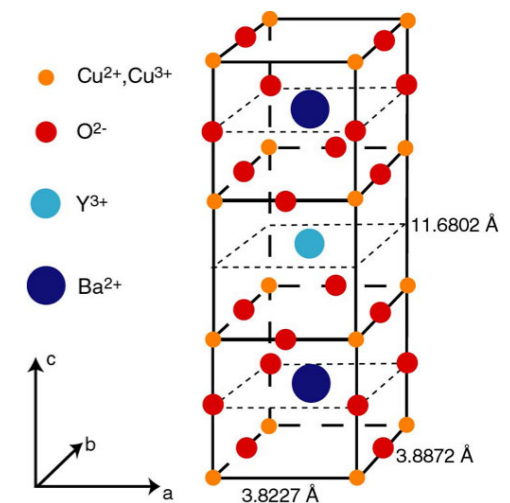
Current flow without quasiparticles



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Slope of T -linear resistivity vs Planckian limit in seven materials.

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Remarkably similar universality in strange metals and black holes!

**Quantum
entanglement**

**Black
holes**

Superconductors

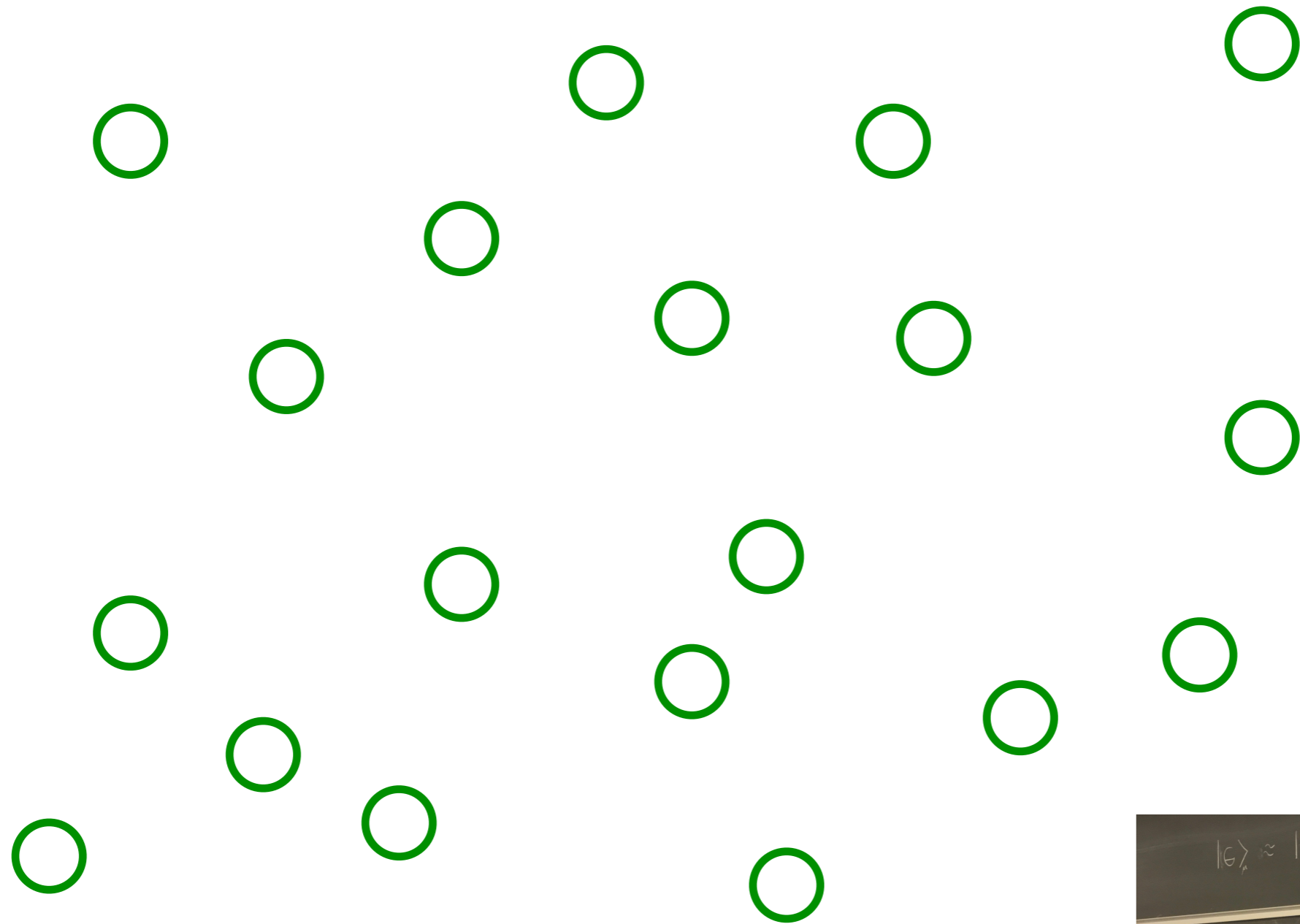
**Quantum
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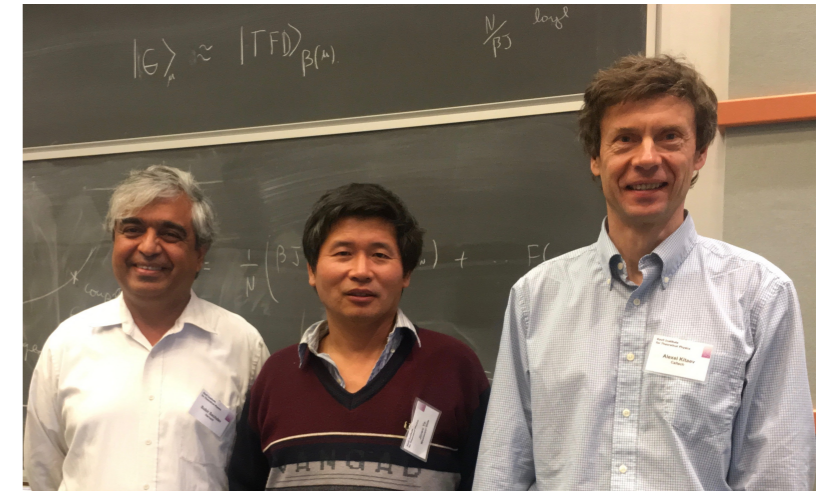
Superconductors

**A "toy model" which describes both
a superconductor and a black hole!**

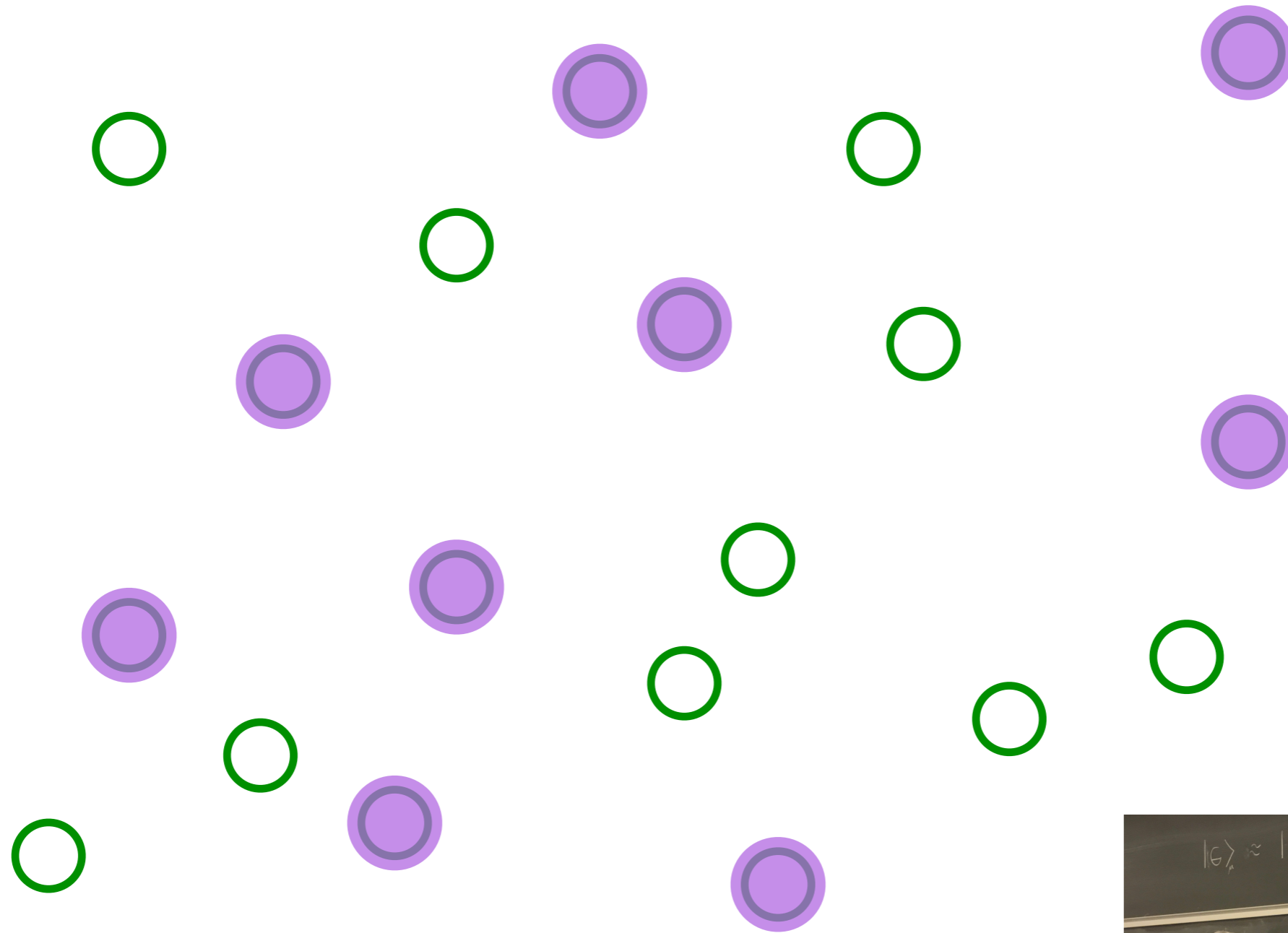
The Sachdev-Ye-Kitaev (SYK) model



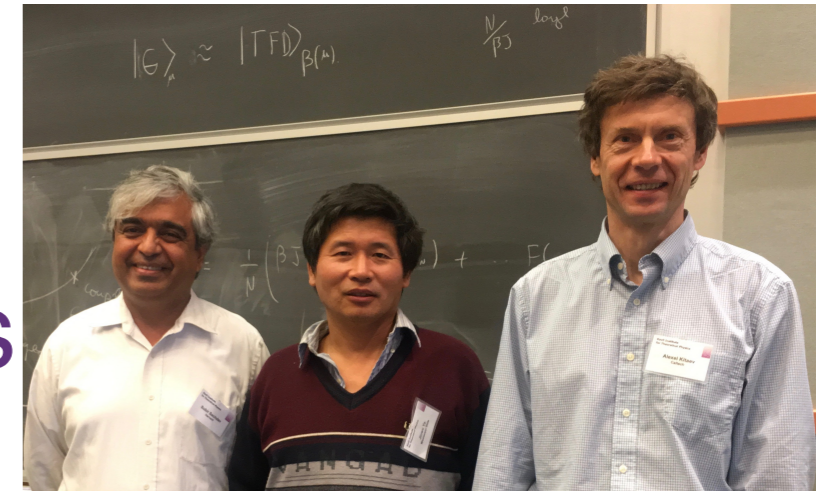
Pick a set of random positions



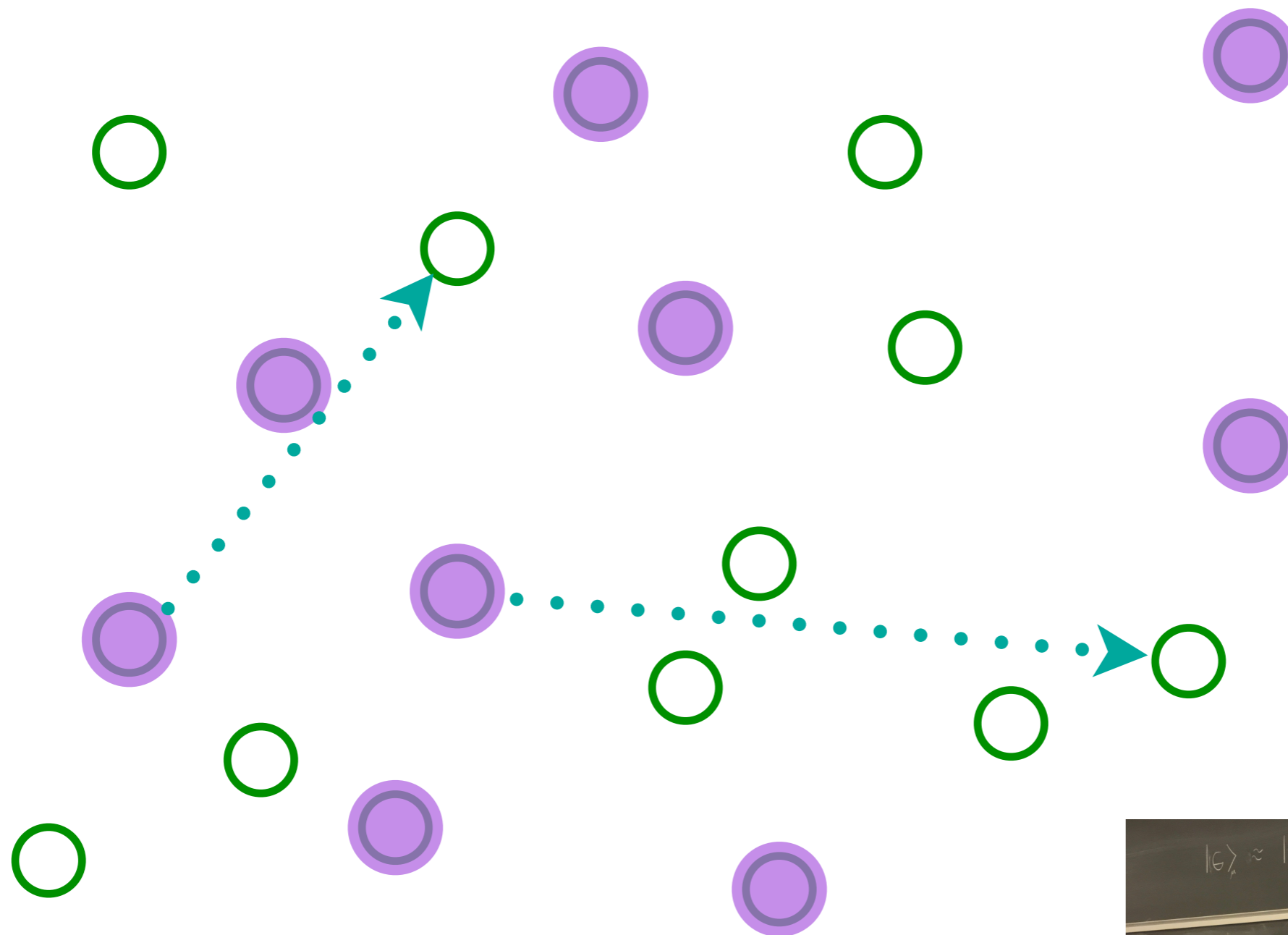
The SYK model



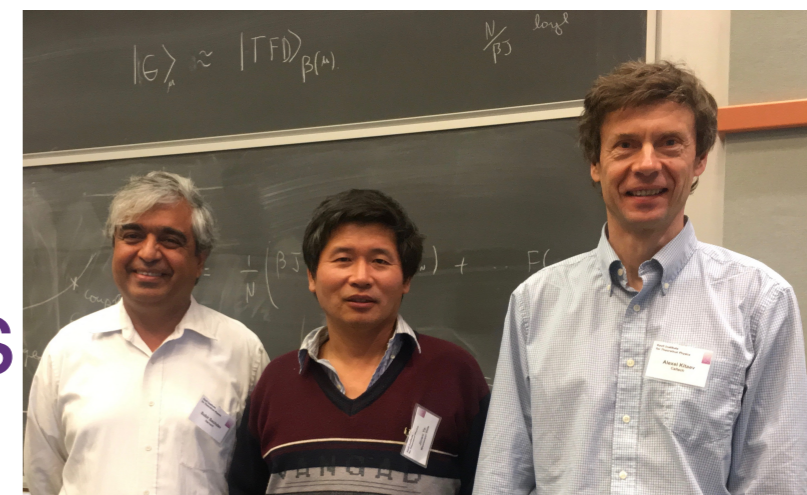
Place electrons randomly on some sites



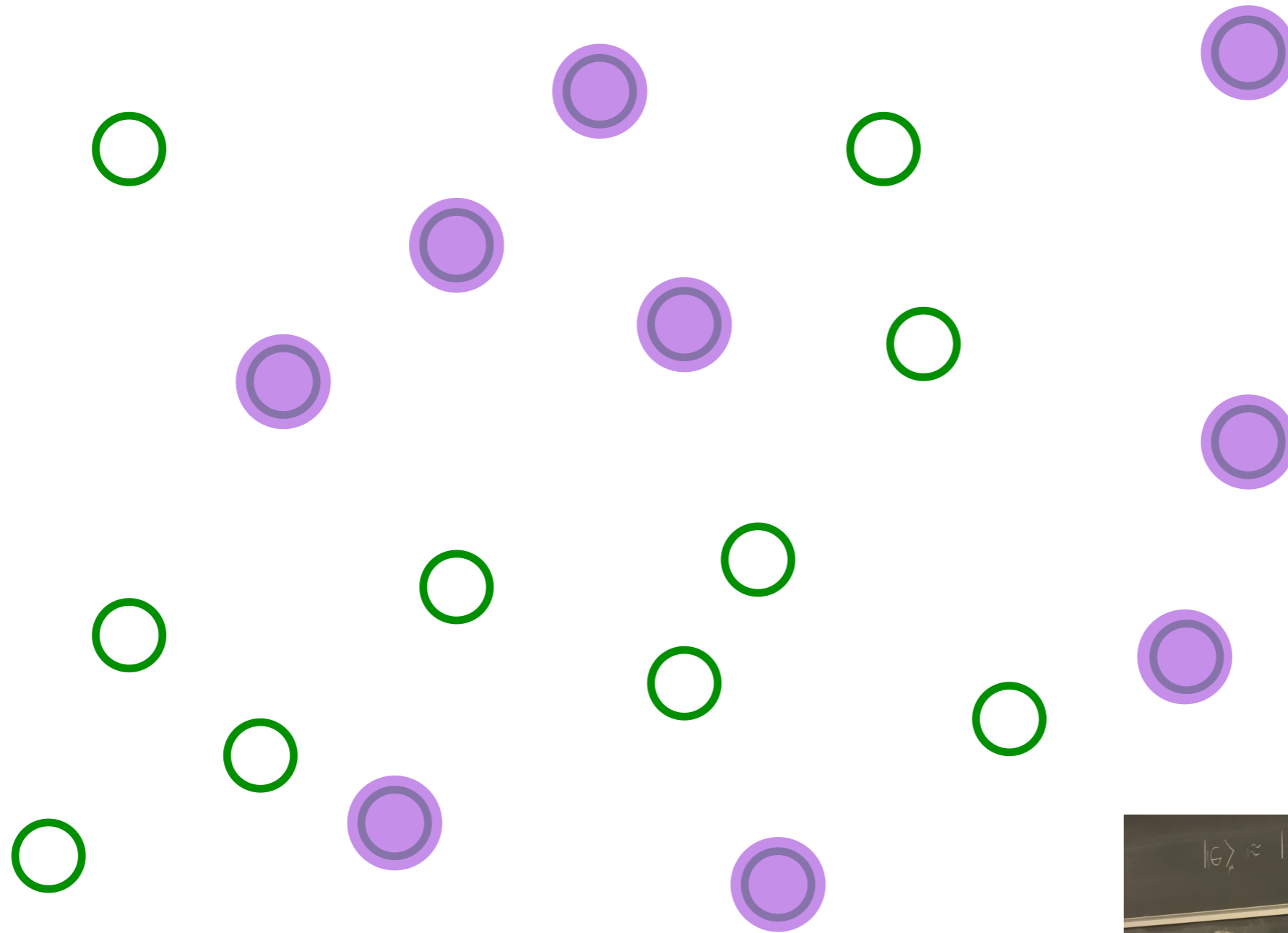
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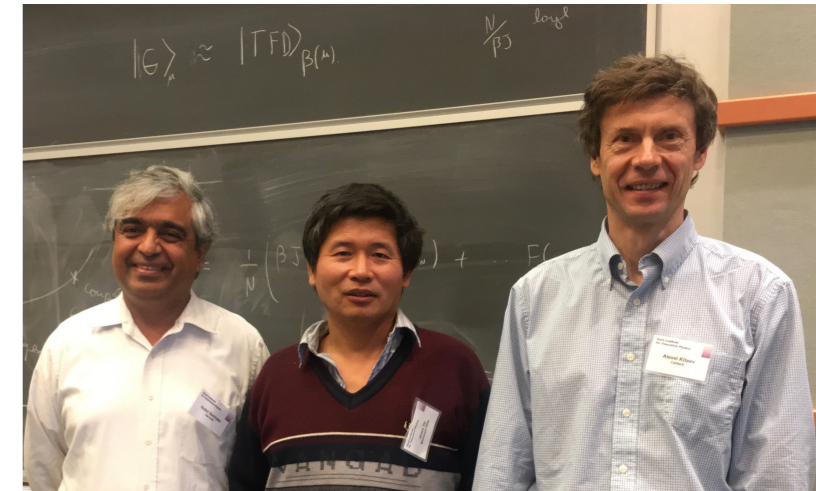
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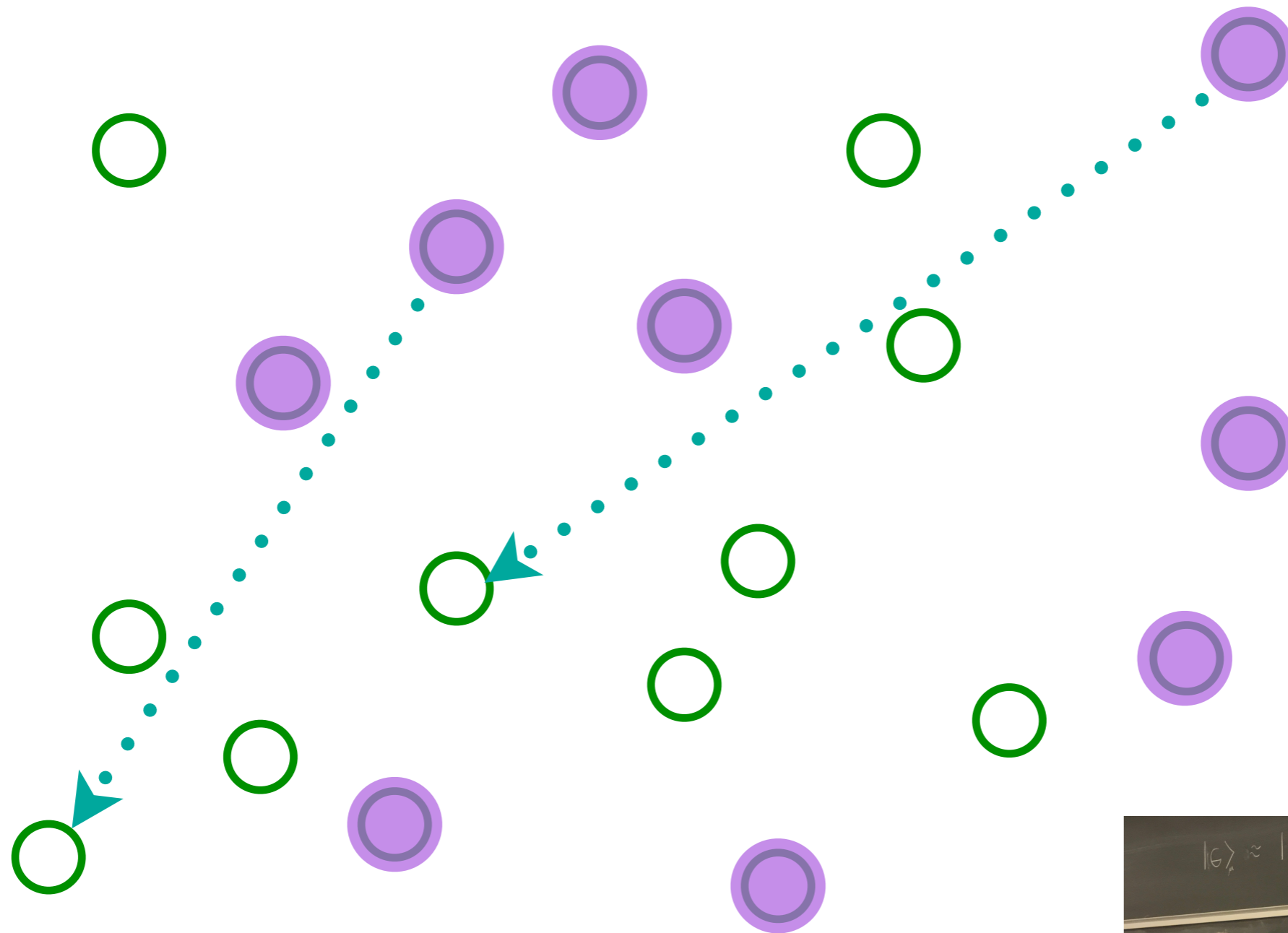
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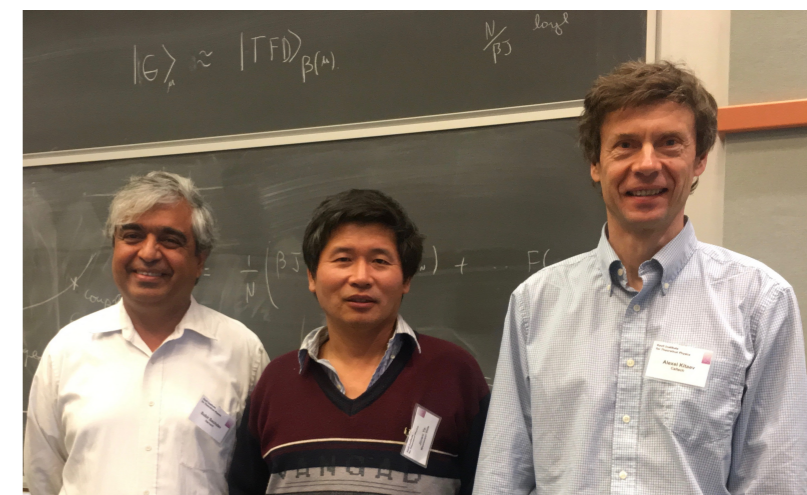
Entangle electrons pairwise randomly



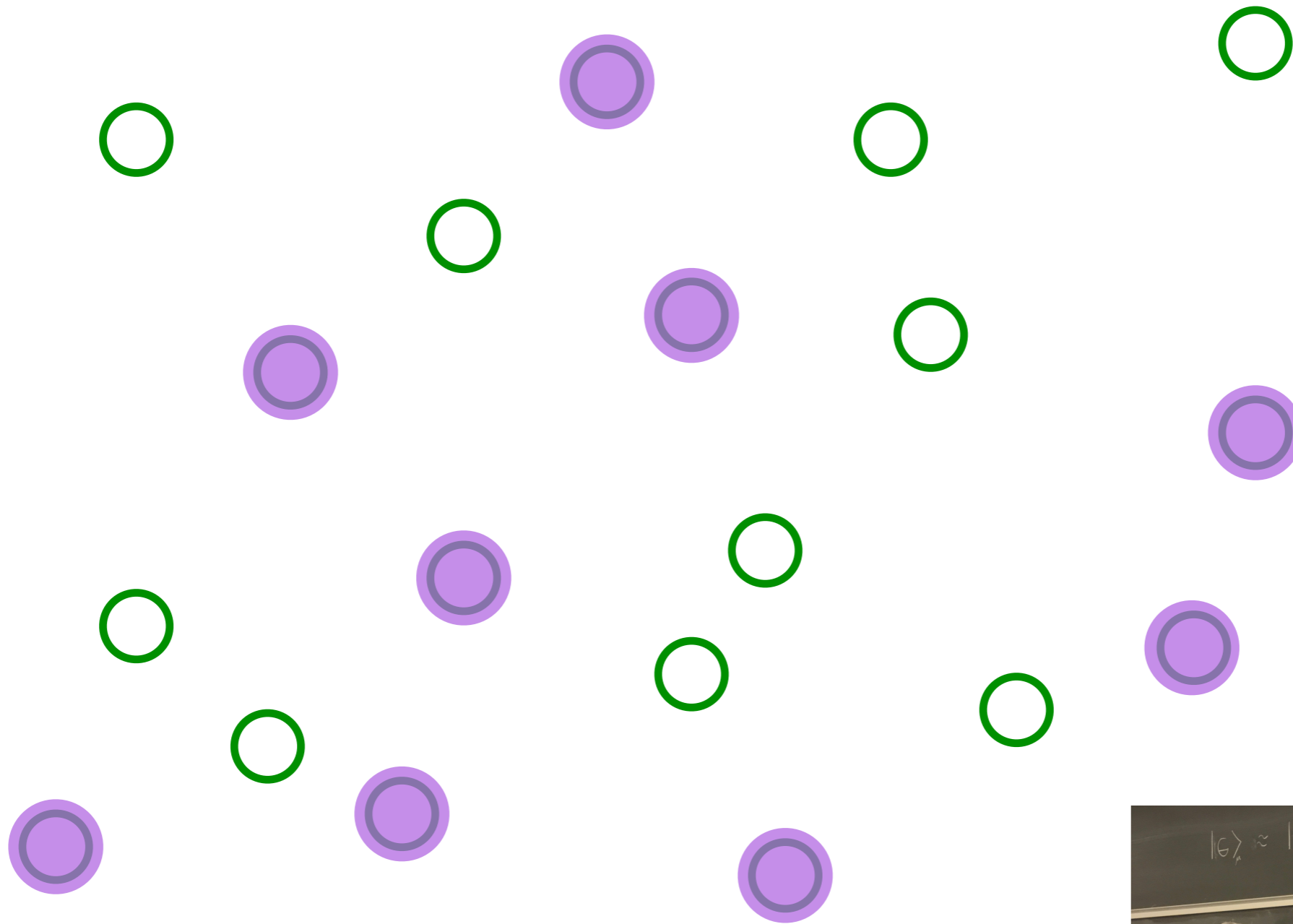
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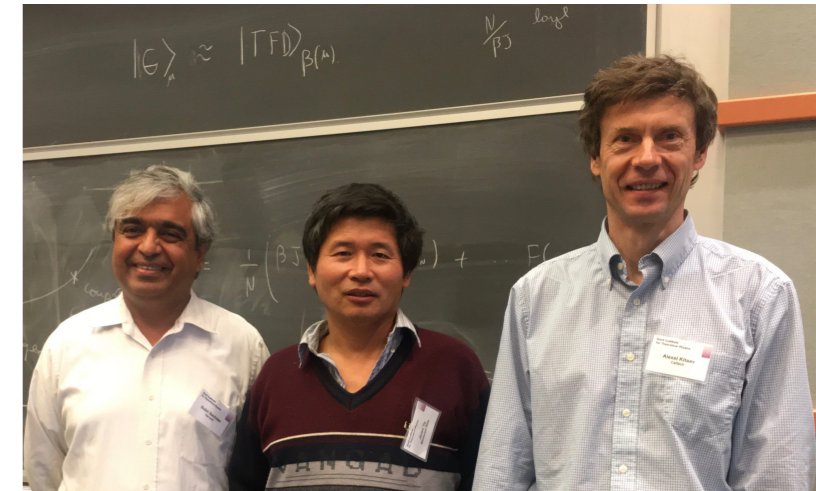
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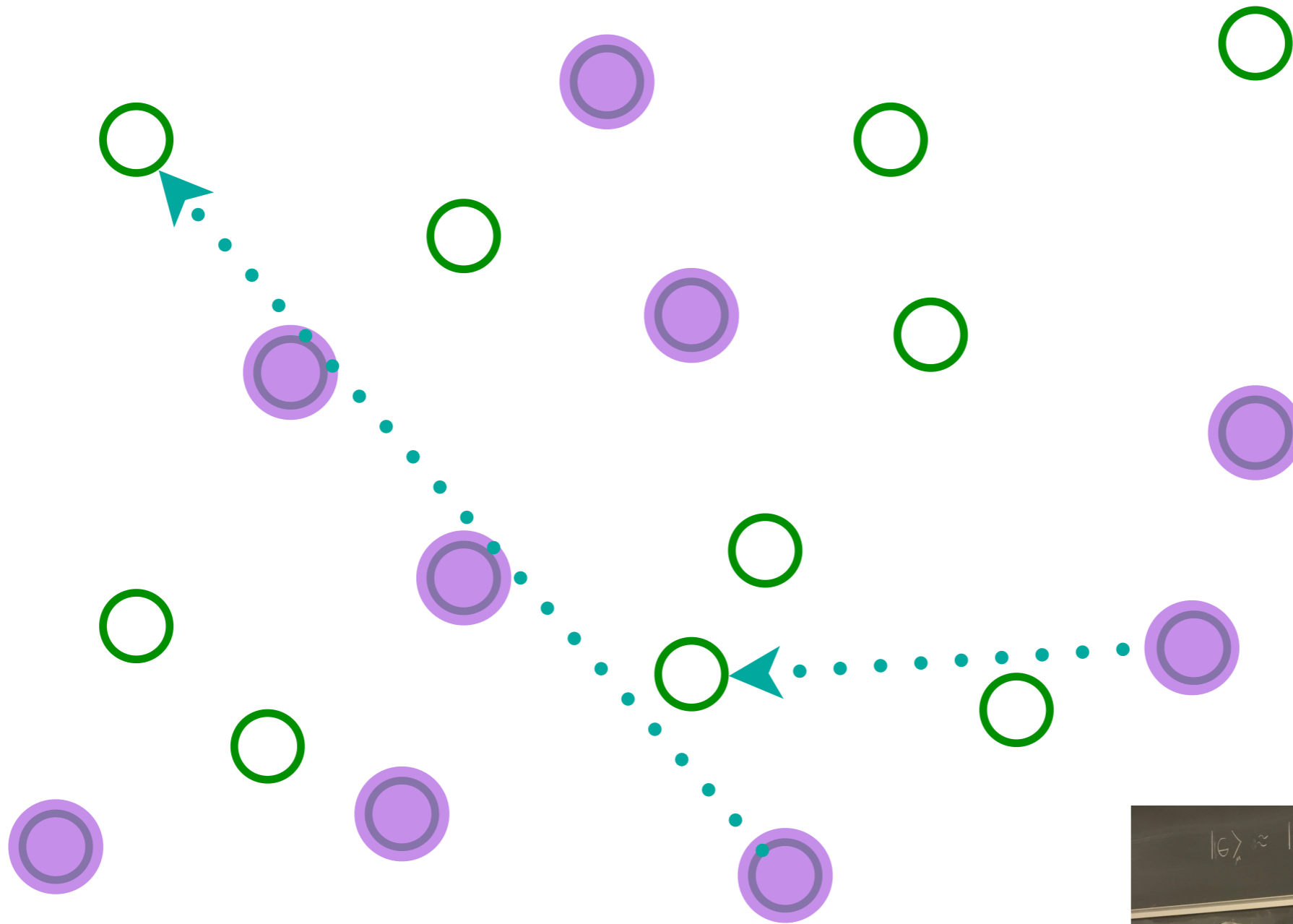
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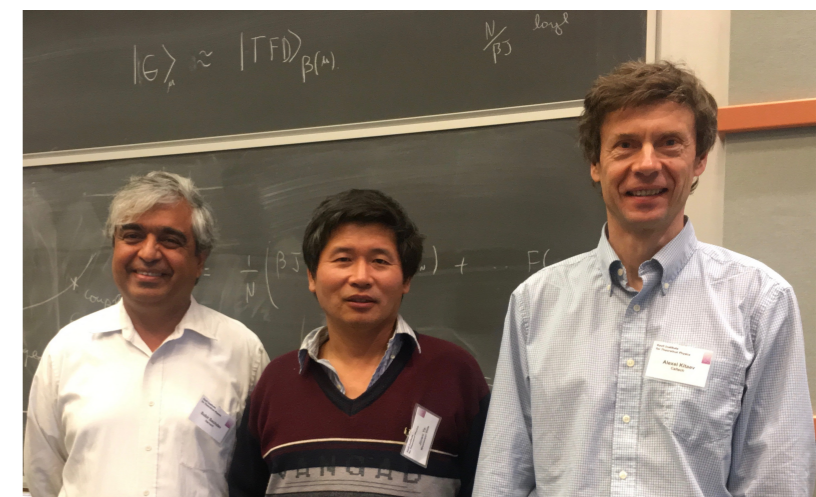
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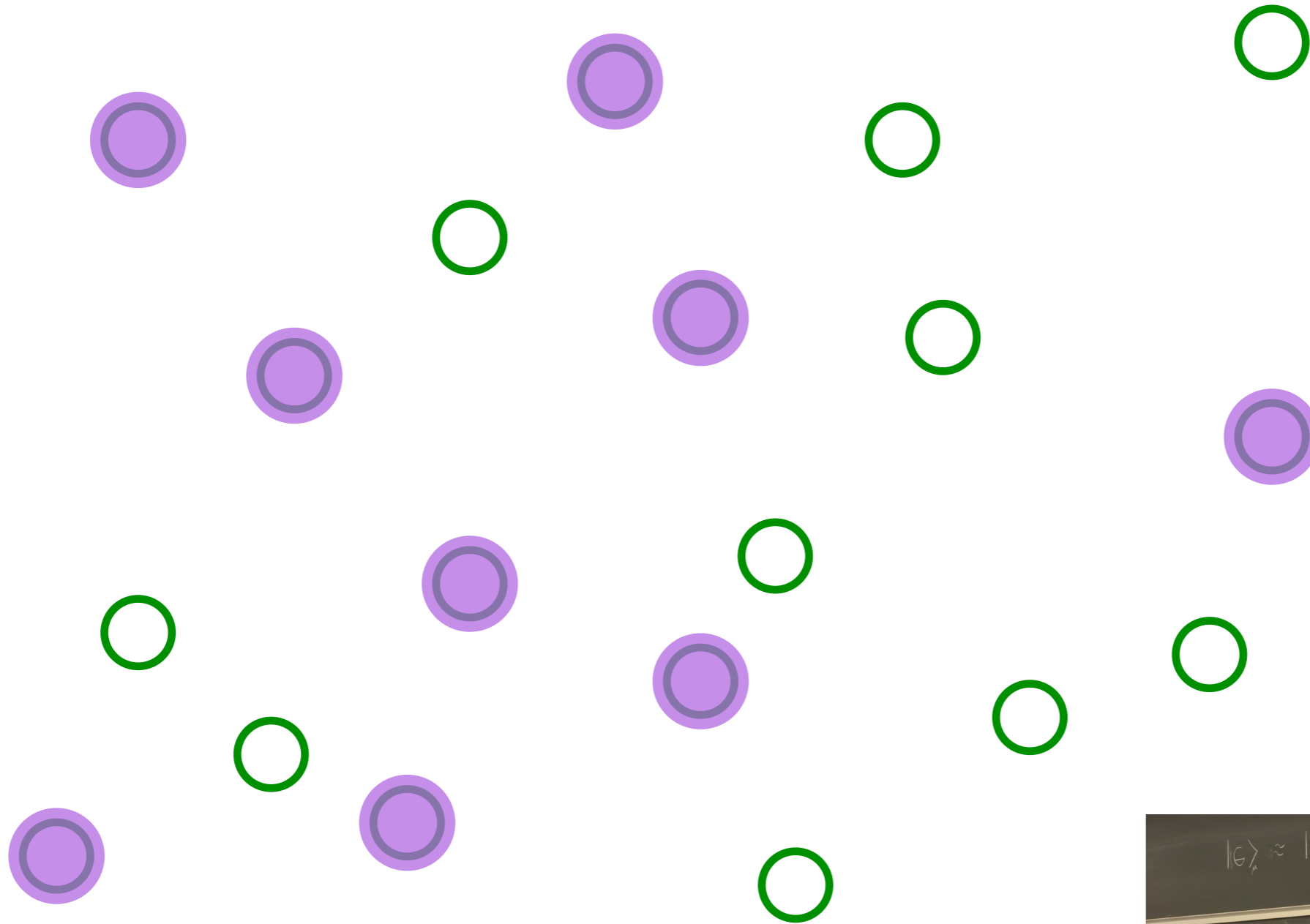
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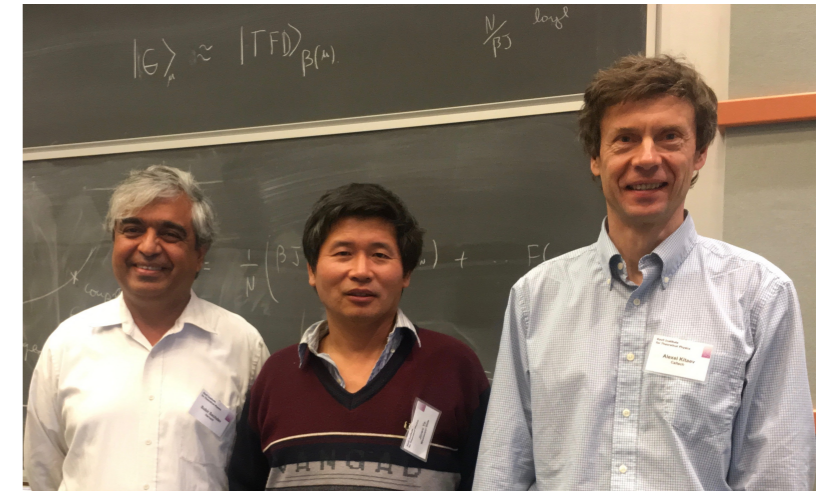
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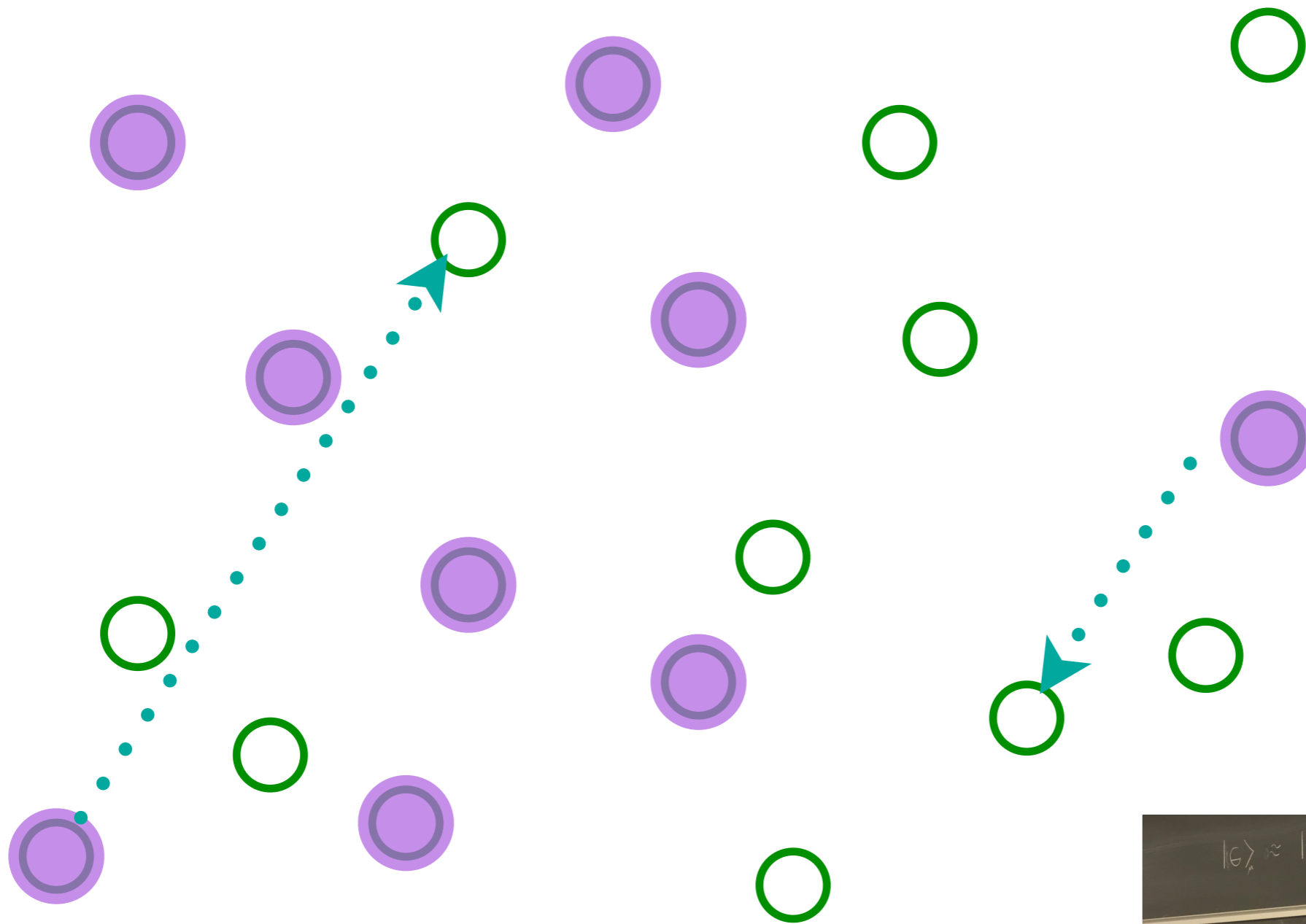
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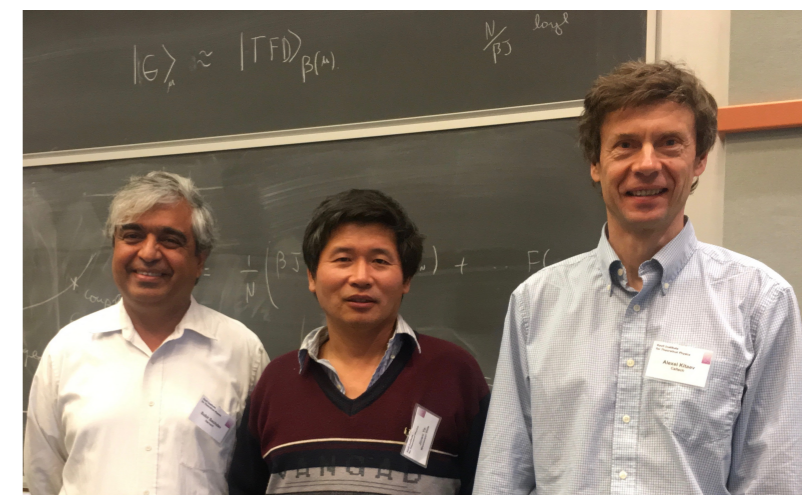
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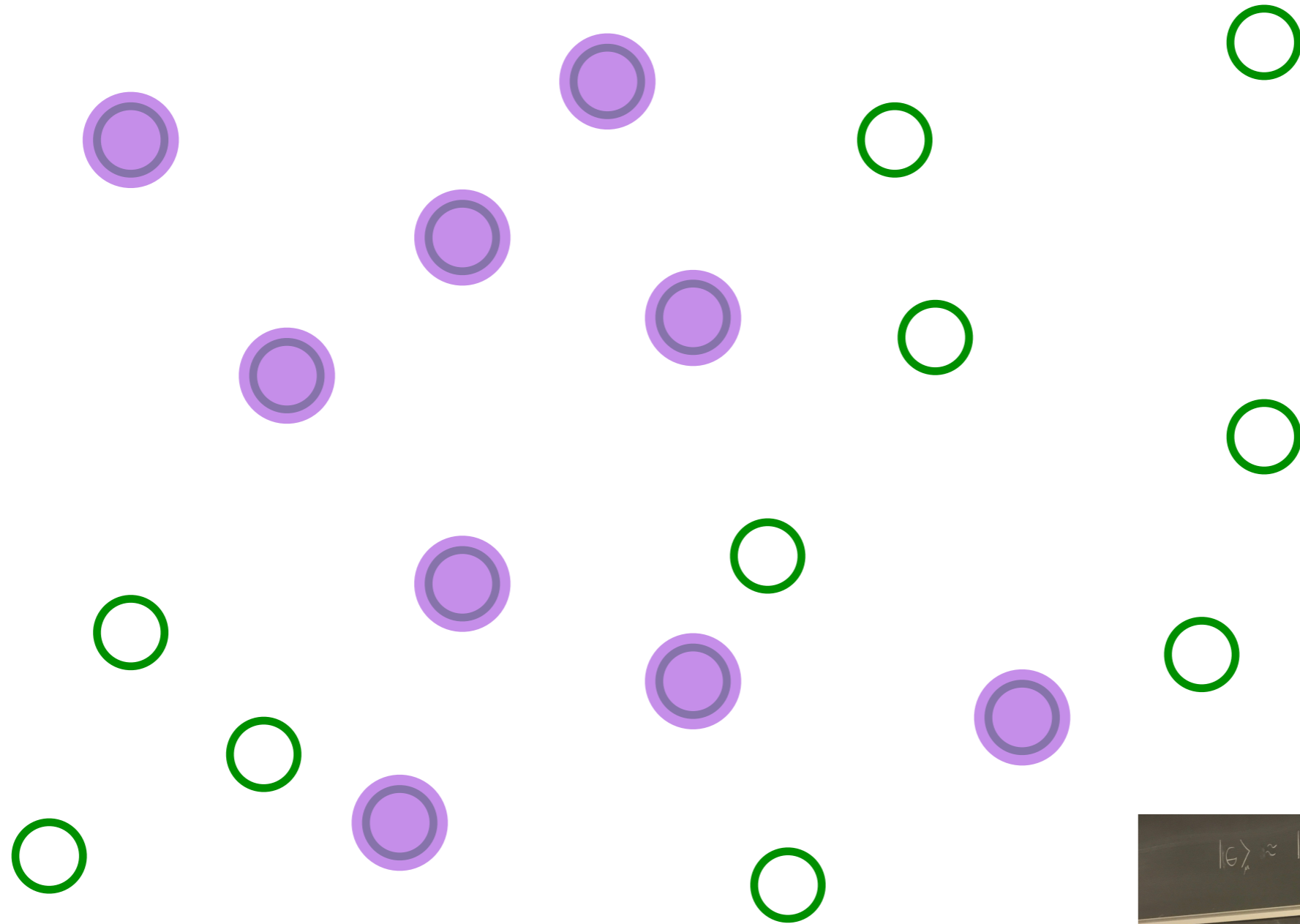
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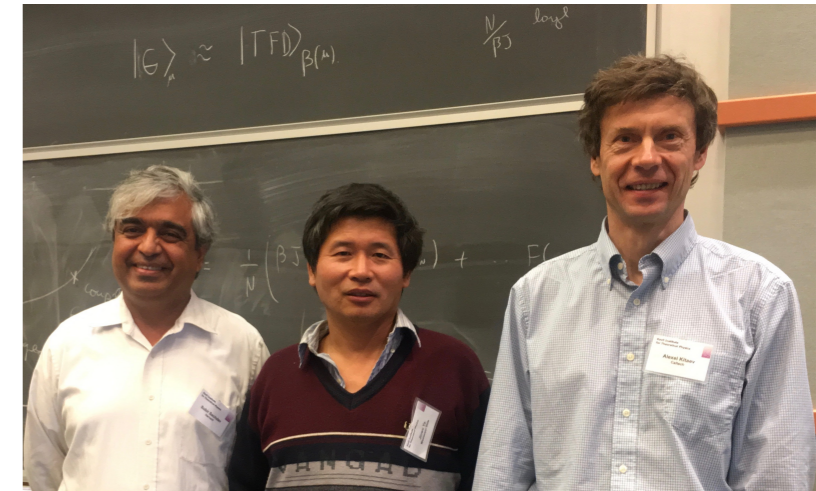
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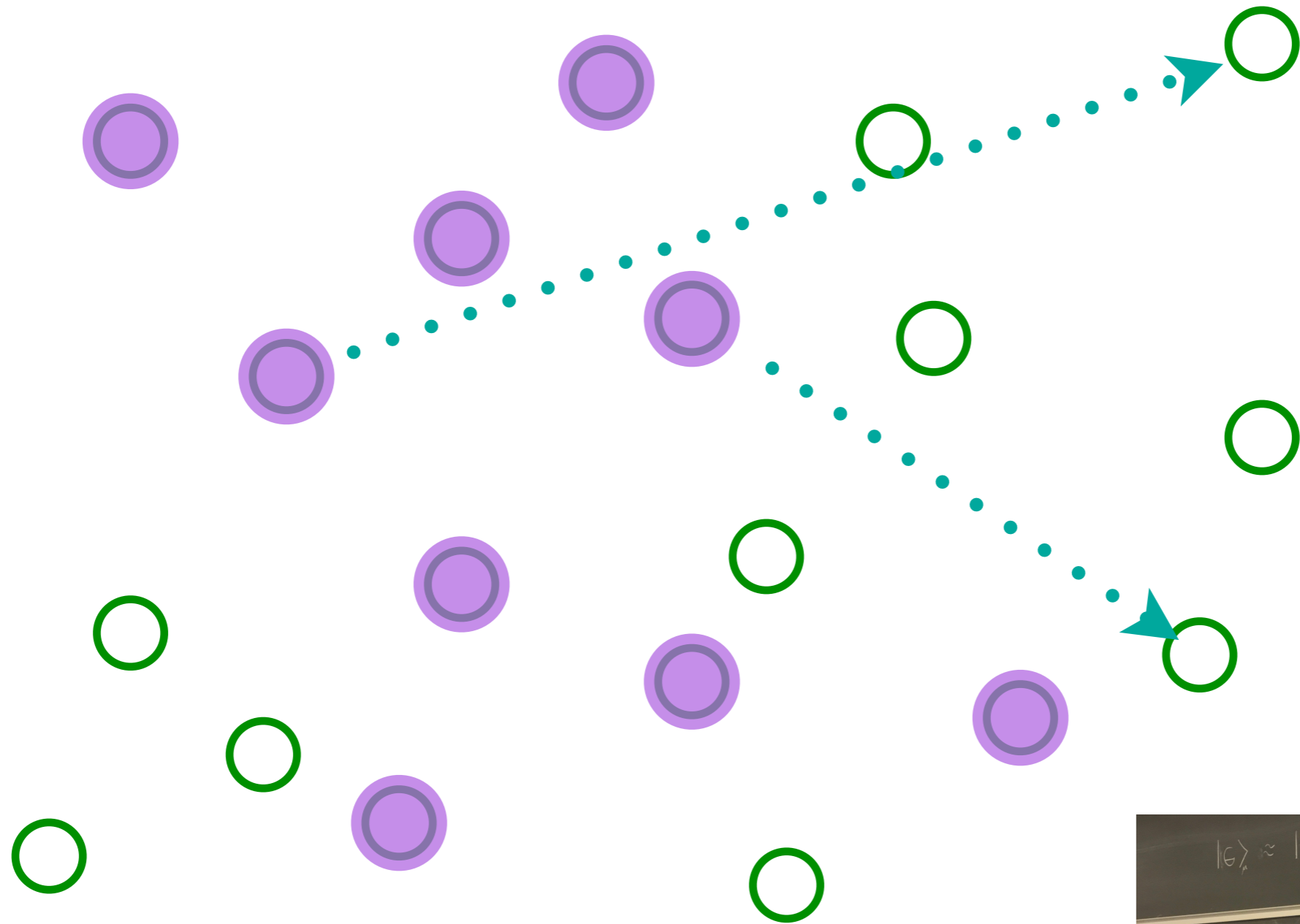
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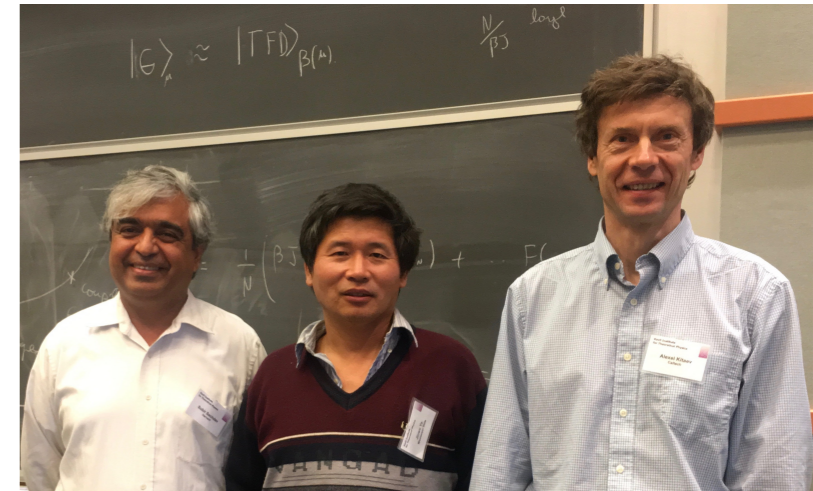
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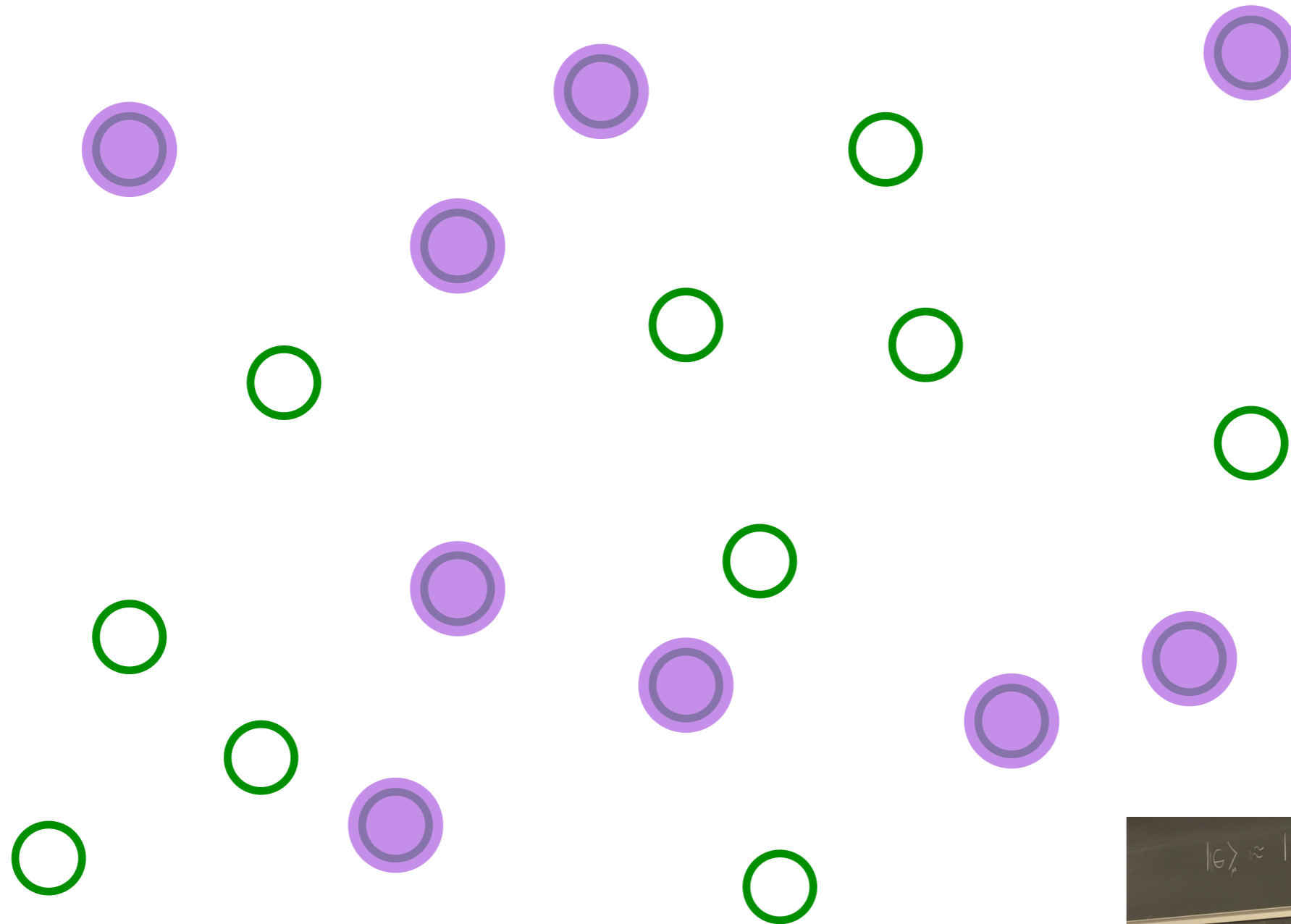
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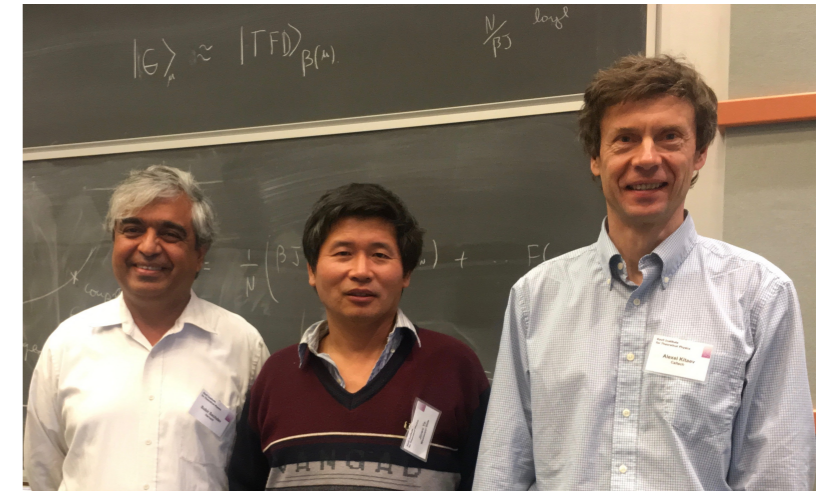
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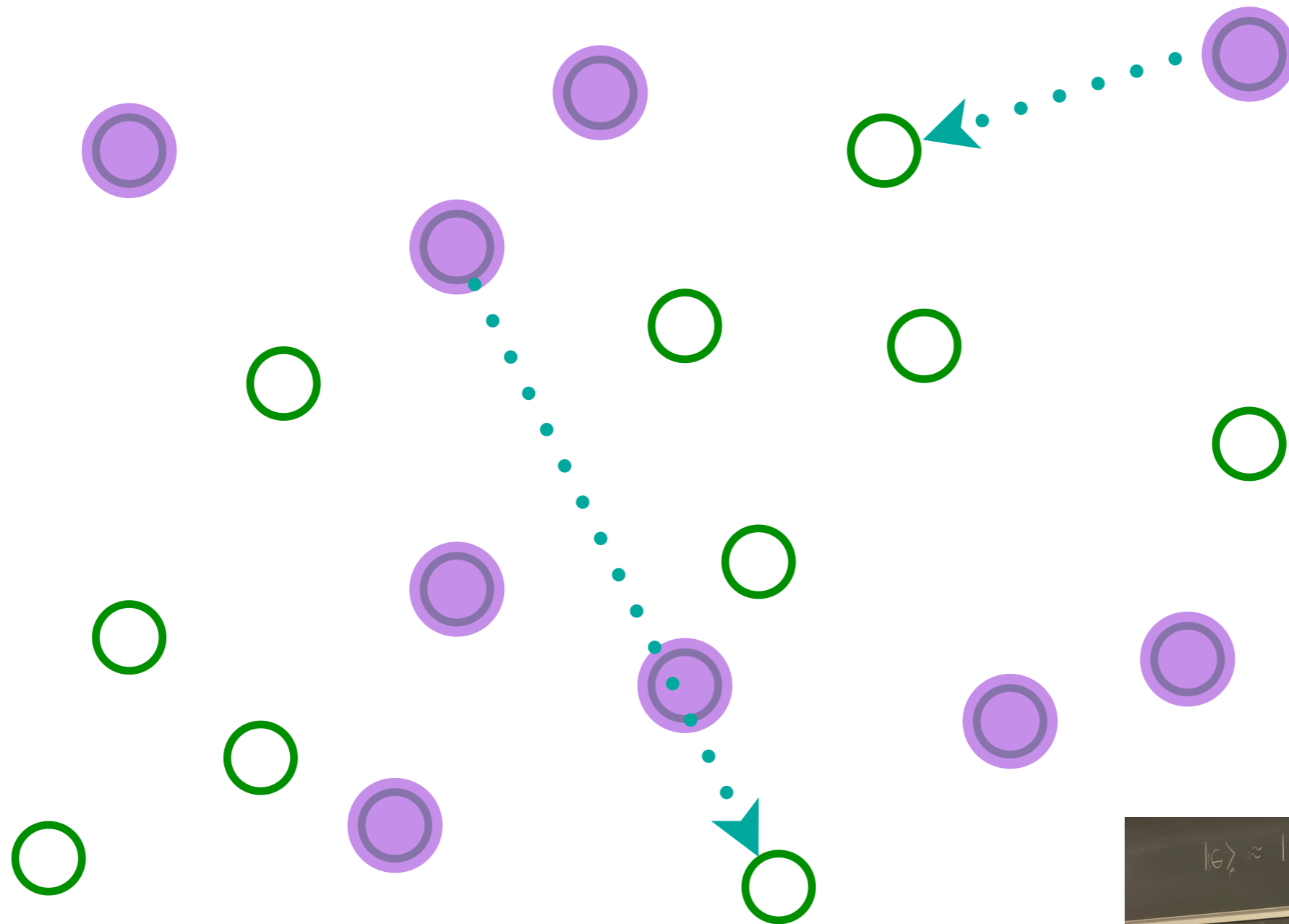
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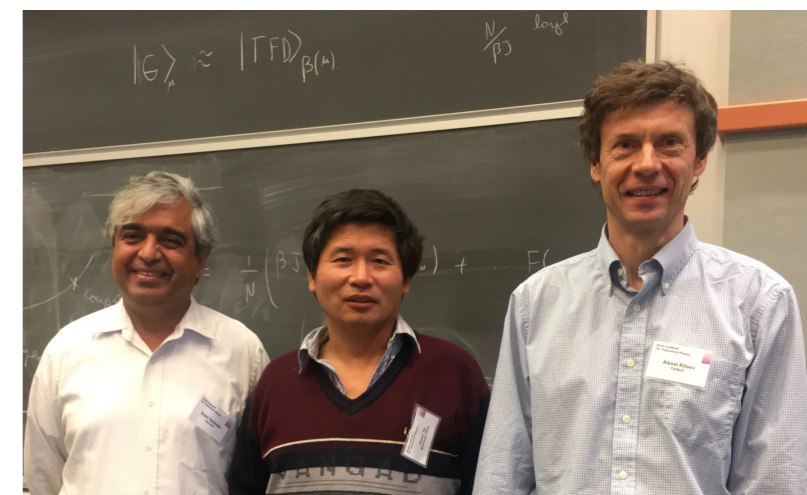
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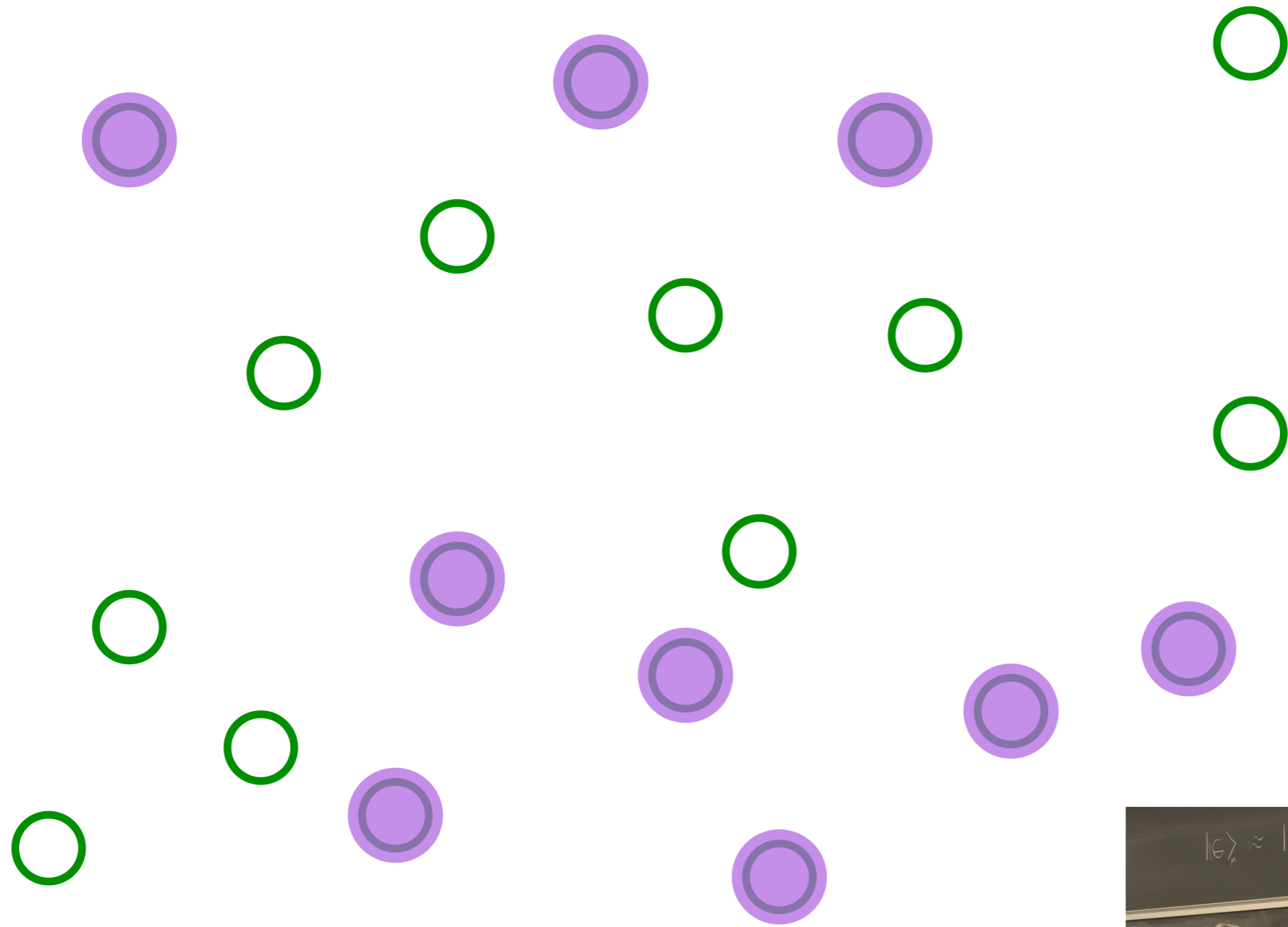
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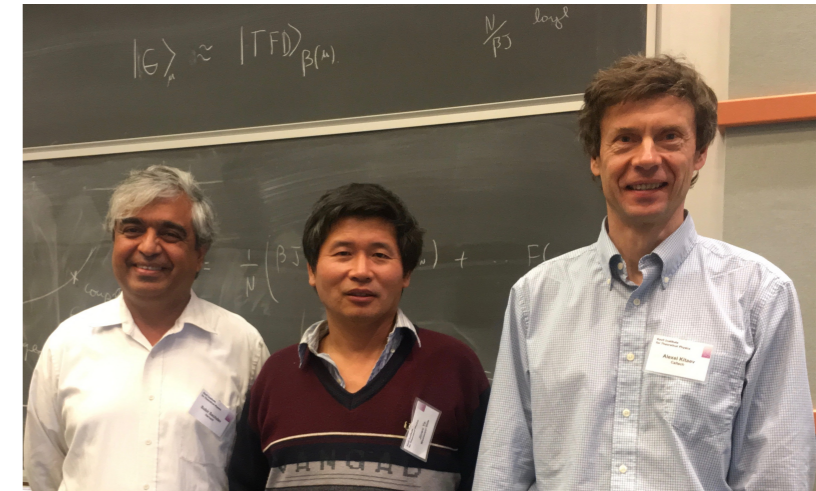
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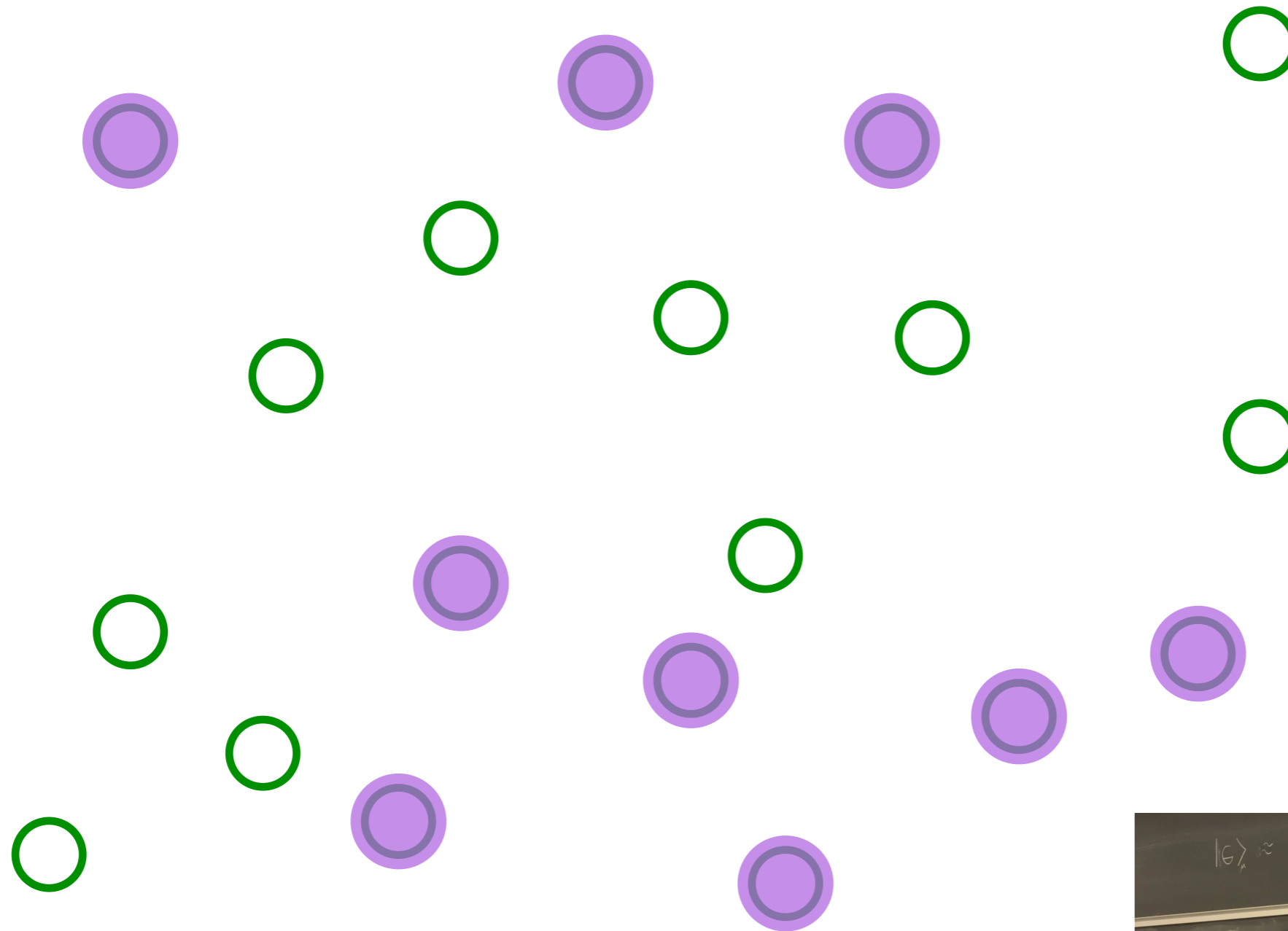
The SYK model



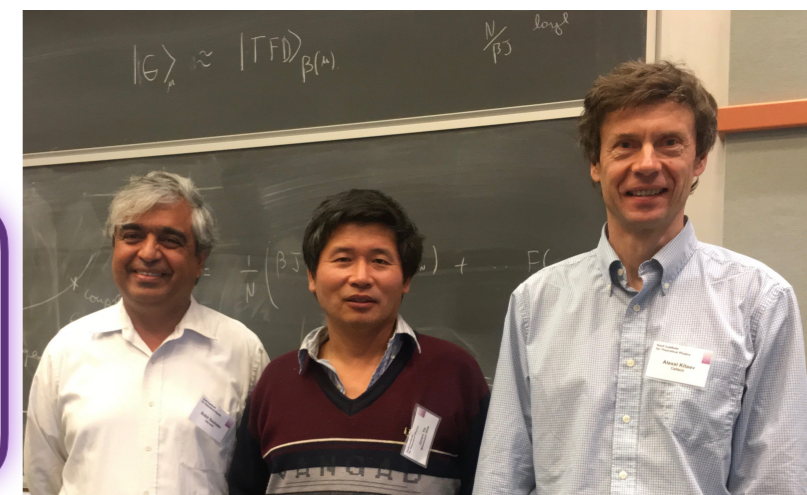
Entangle electrons pairwise randomly



The SYK model

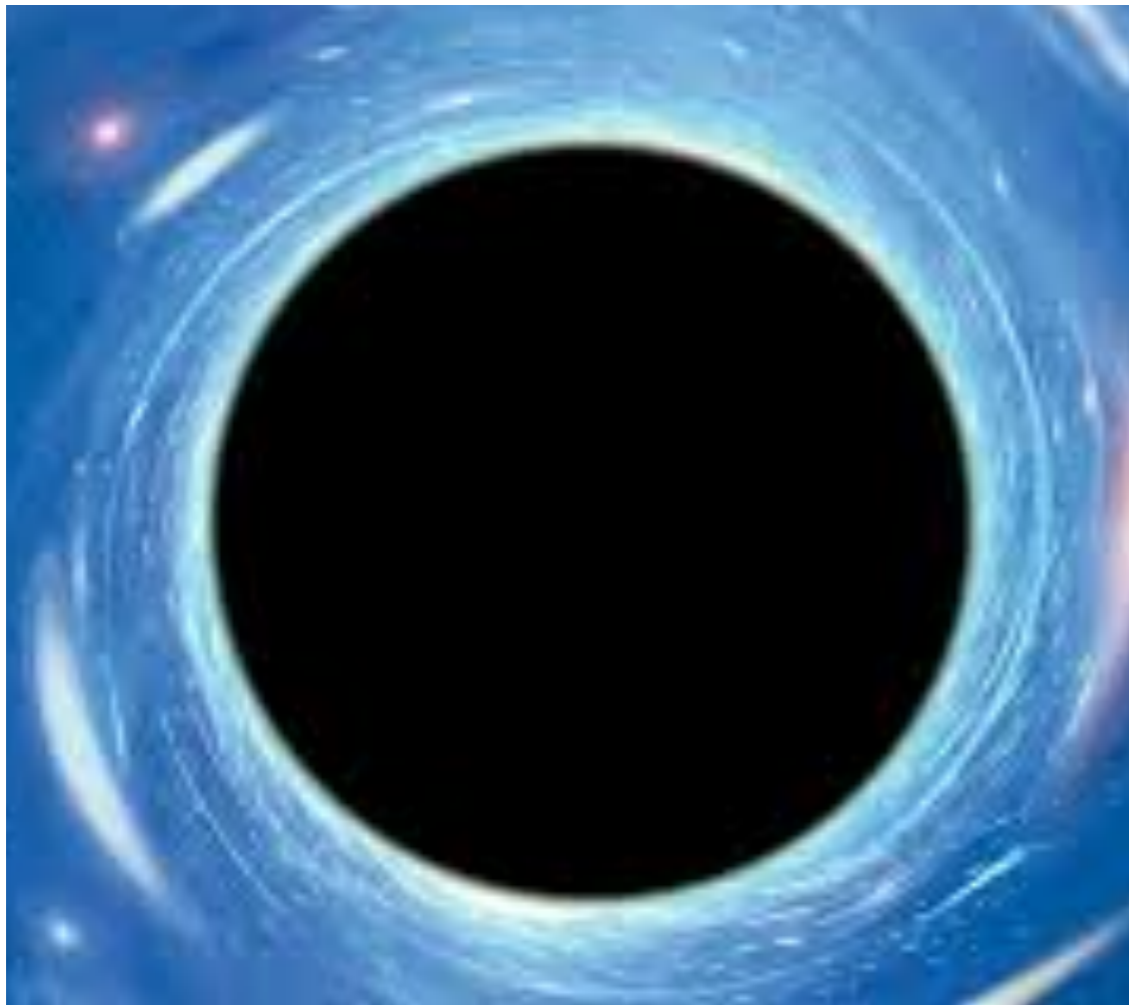


**This describes both a
superconductor and a black hole!**



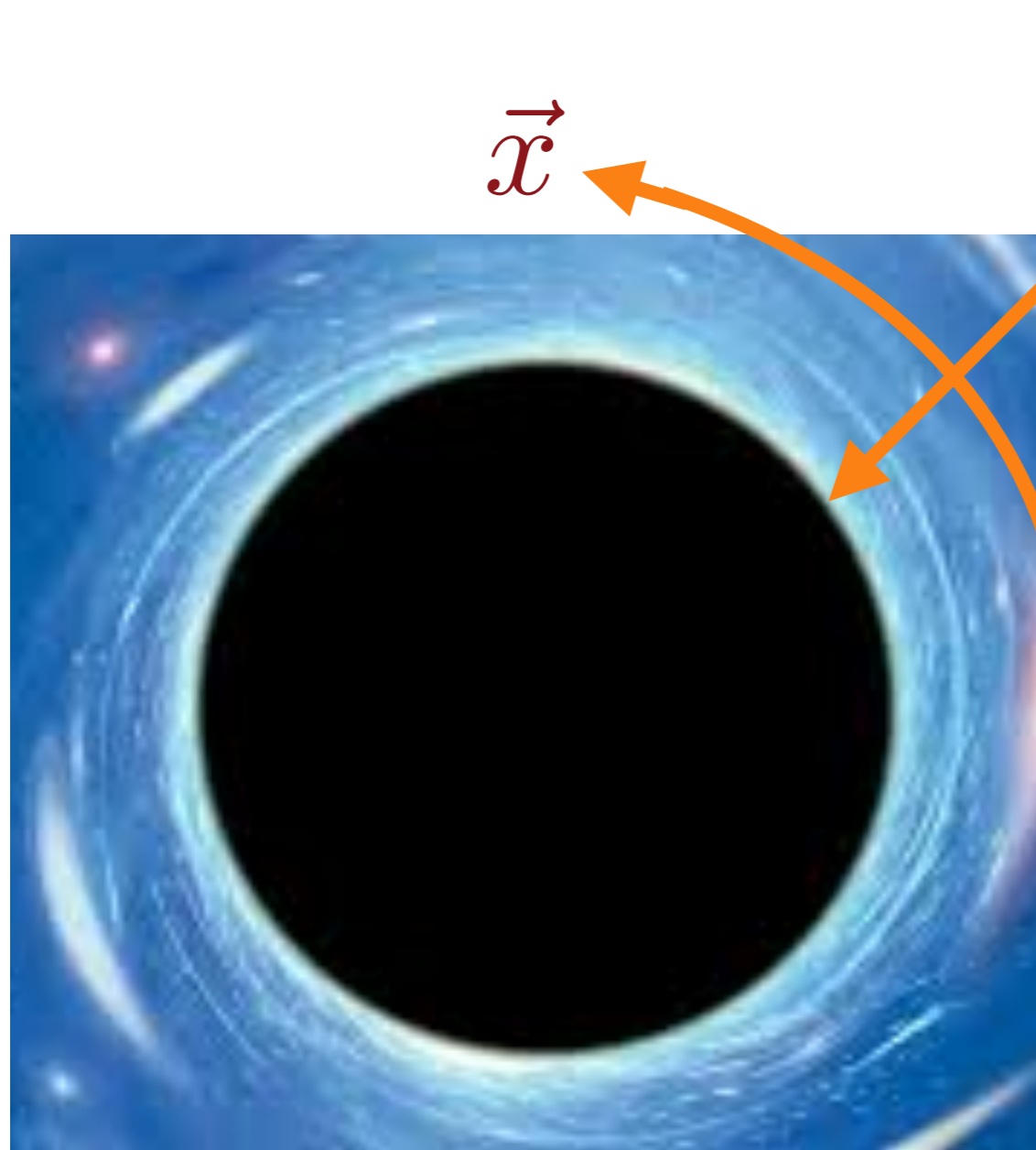


Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge





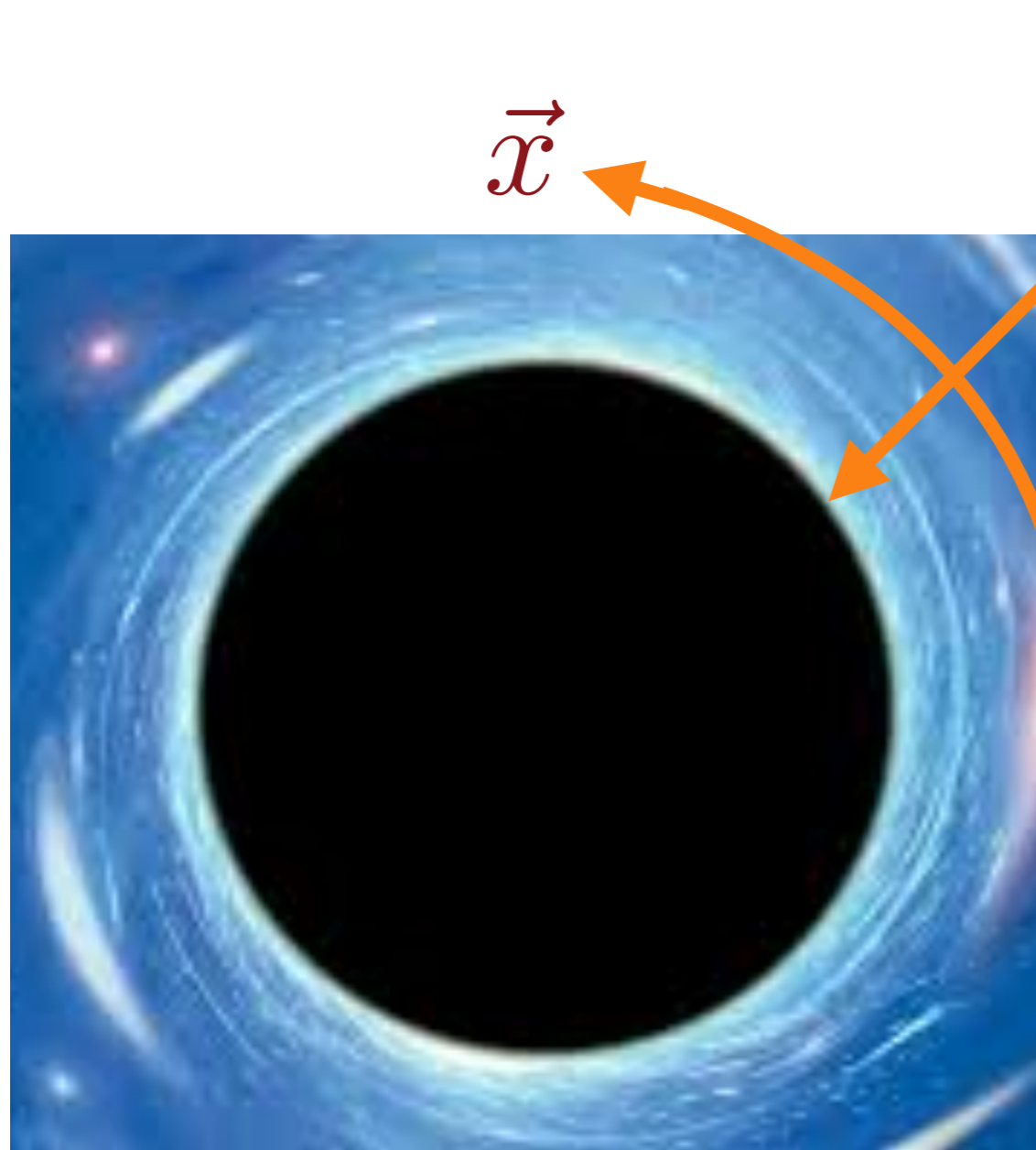
Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



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



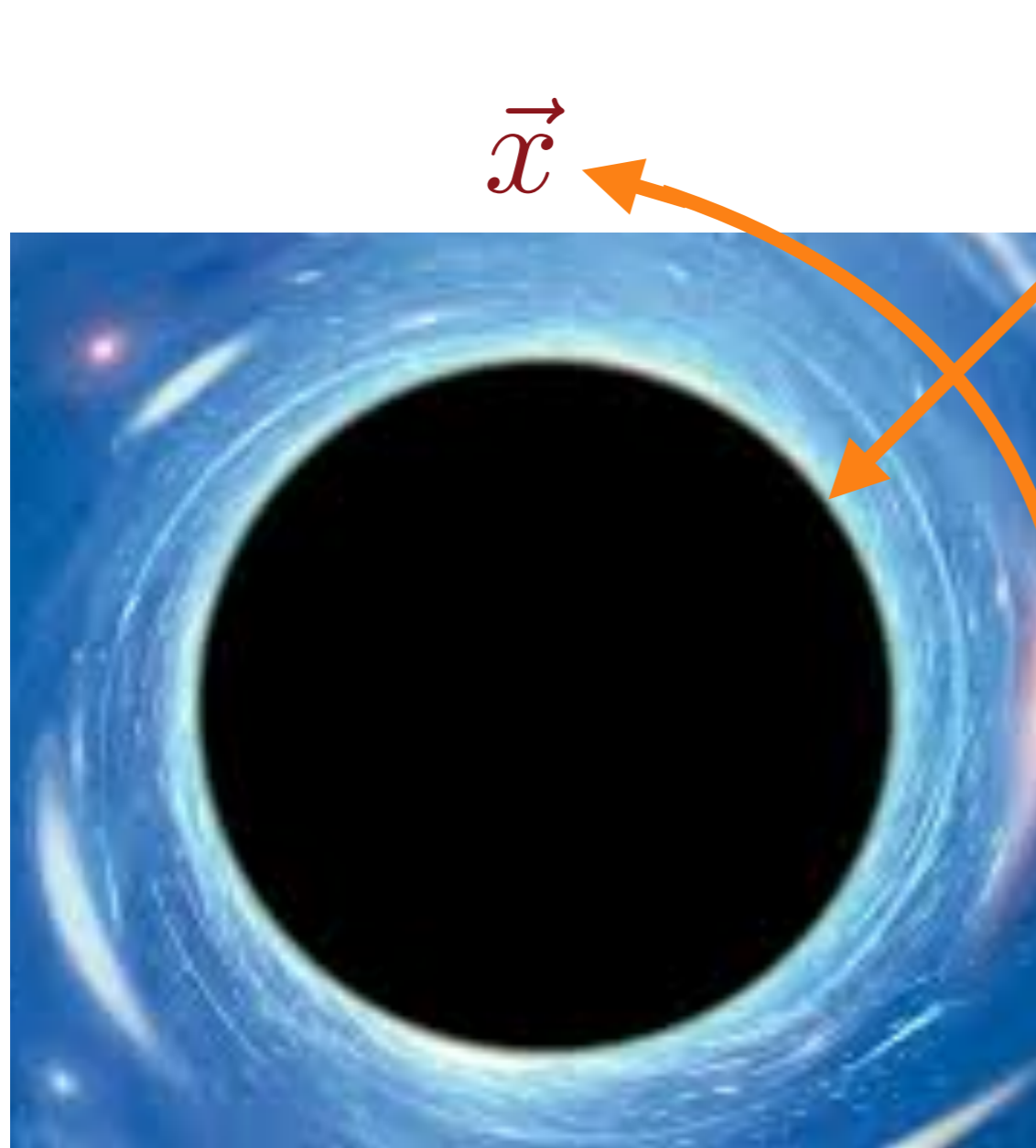
Maxwell's electromagnetism
and Einstein's general relativity
allow black hole solutions with a net charge



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"

**Quantum
entanglement**

**Black
holes**

Superconductors

**A "toy model" which describes both
a superconductor and a black hole!**