Strange metals and black holes

Homi Bhabha Memorial Public Lecture
Indian Institute of Science Education and Research, Pune
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Talk online: sachdev.physics.harvard.edu

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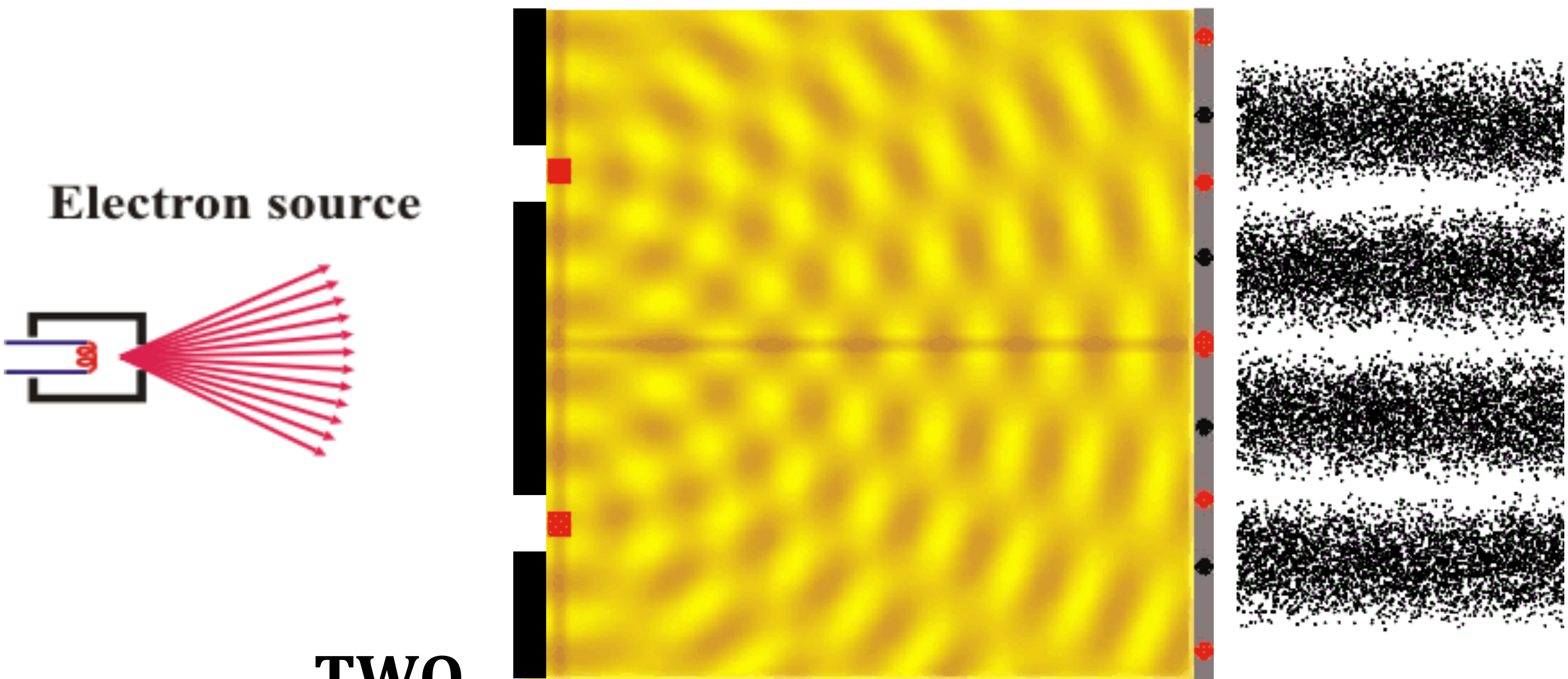
Quantum entanglement

The double slit experiment

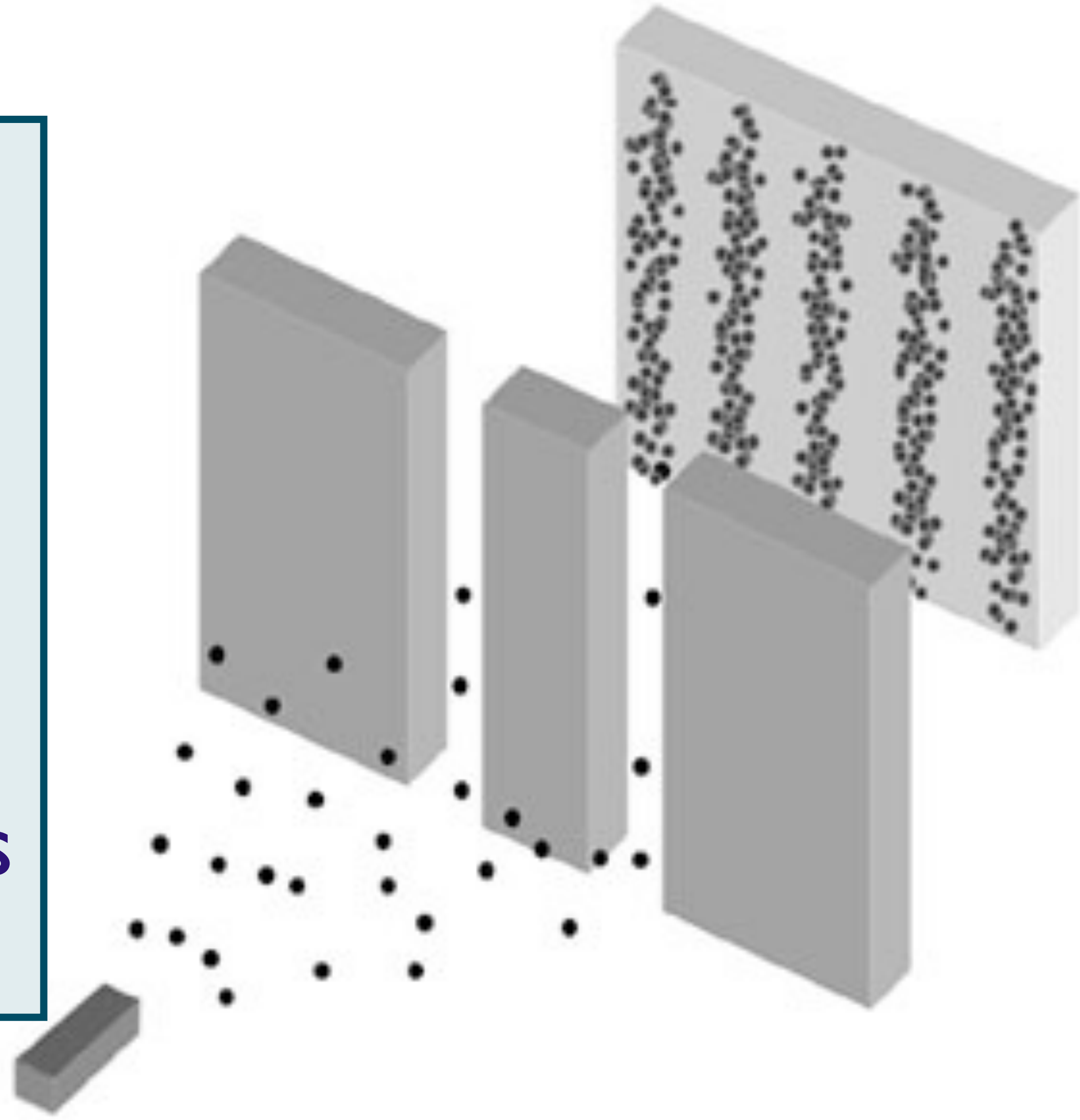


Unlike water waves, electrons arrive one-by-one (so is an electron a particle ?)

Interference of electrons

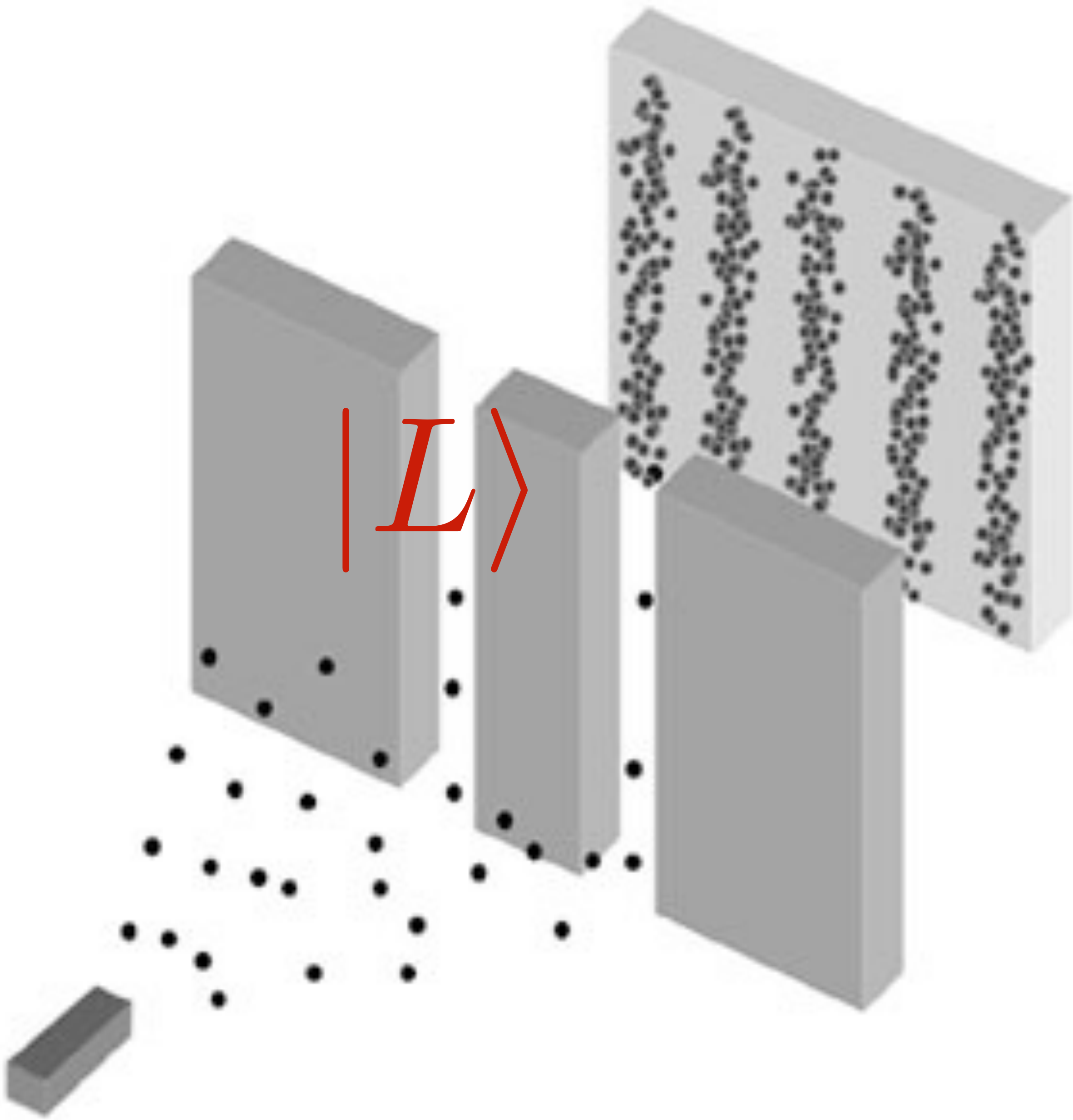
The double slit experiment

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



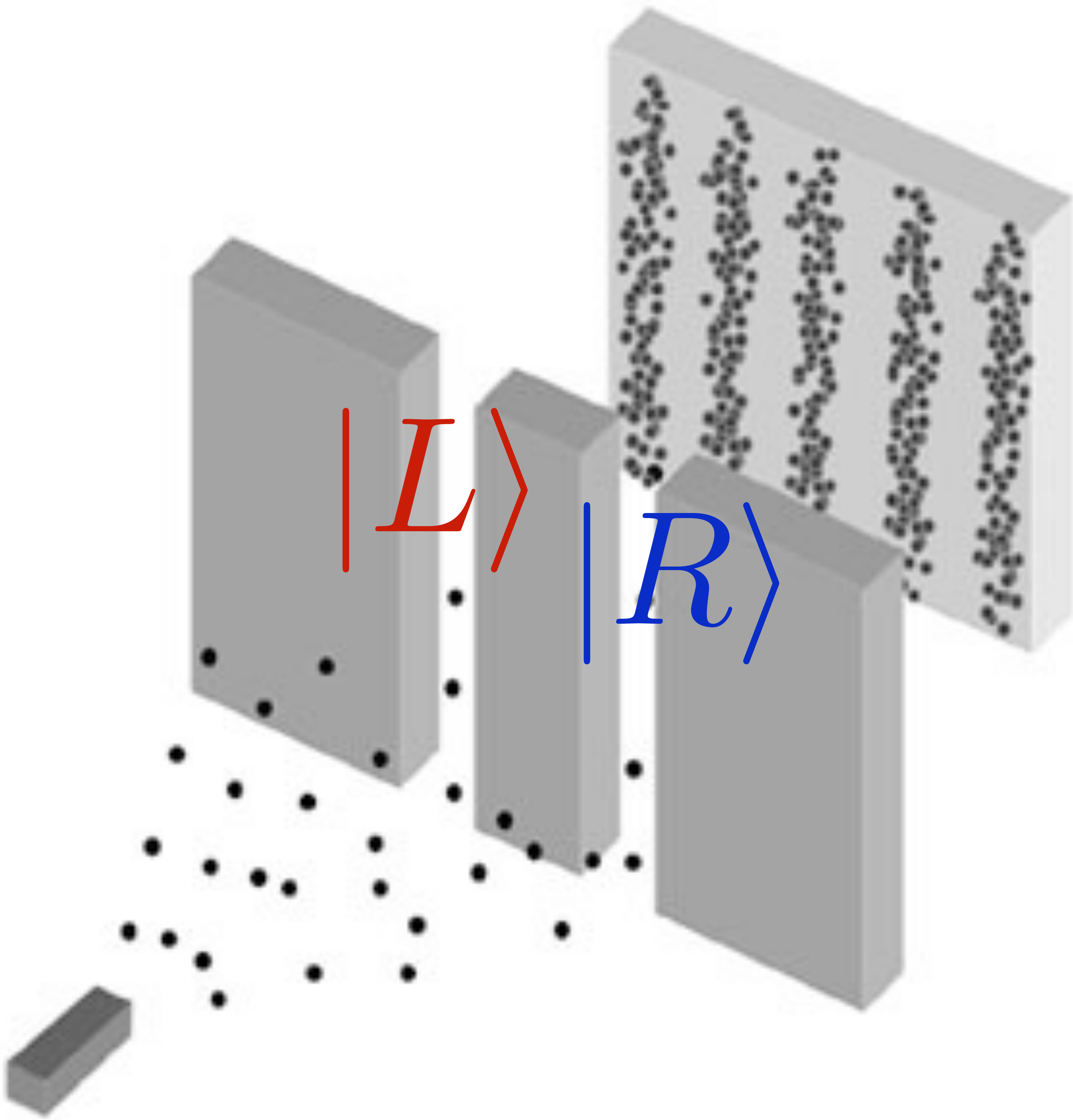
Interference of electrons

The double slit experiment



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

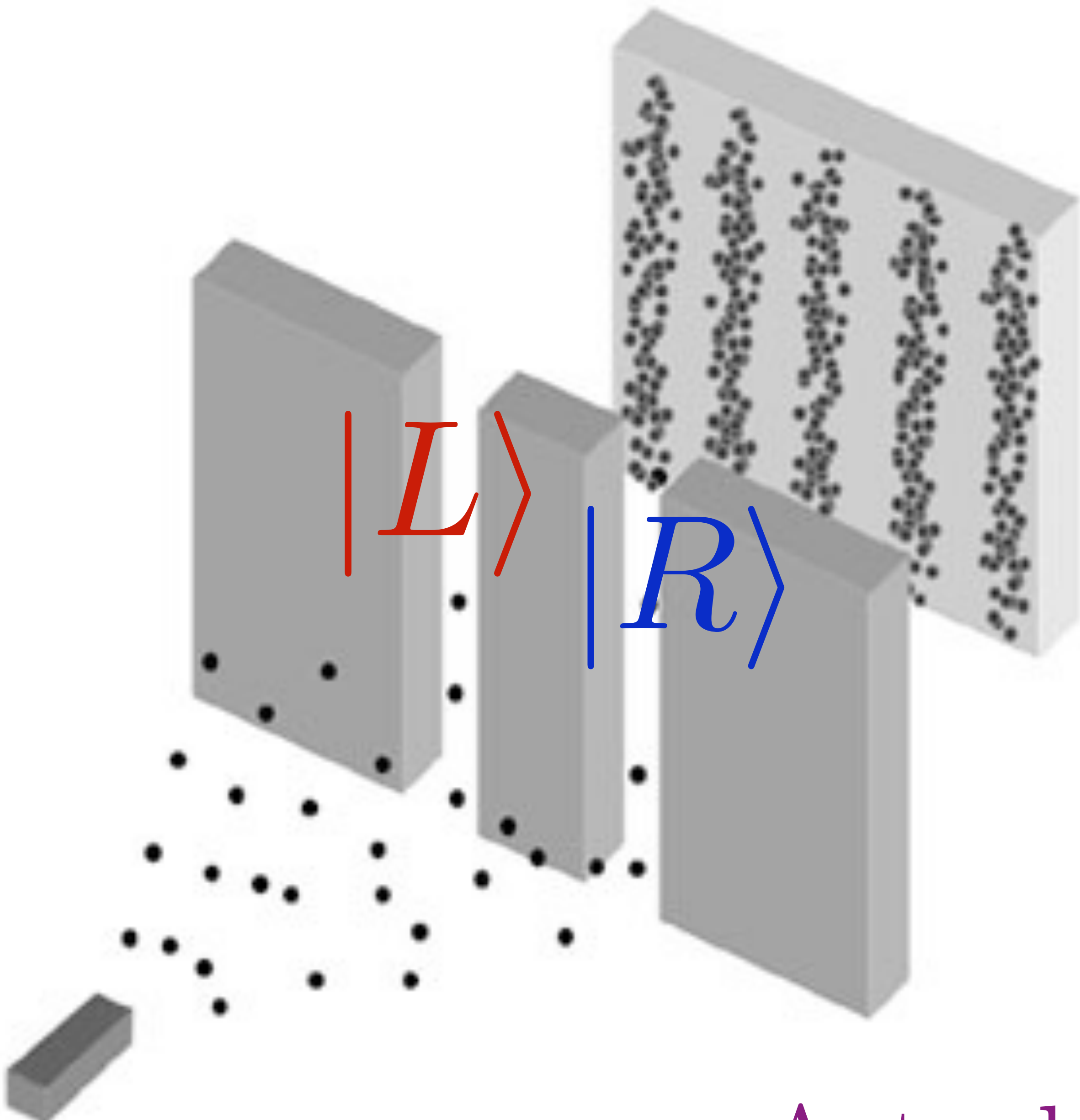
The double slit experiment



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

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

The double slit experiment



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

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

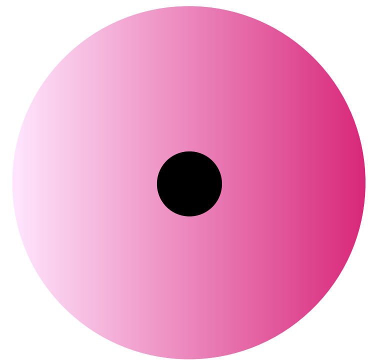
Actual state of *each* electron is

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

Quantum Entanglement: quantum superposition with more than one particle

Quantum Entanglement: quantum superposition with more than one particle

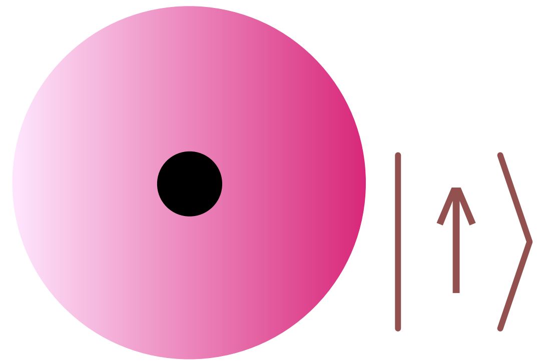
Hydrogen atom:



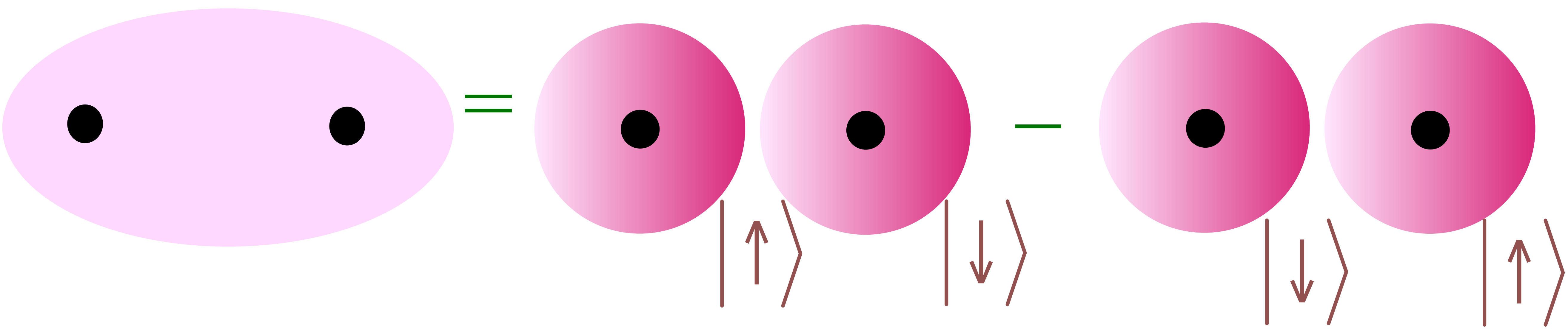
$$|\uparrow\rangle$$

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

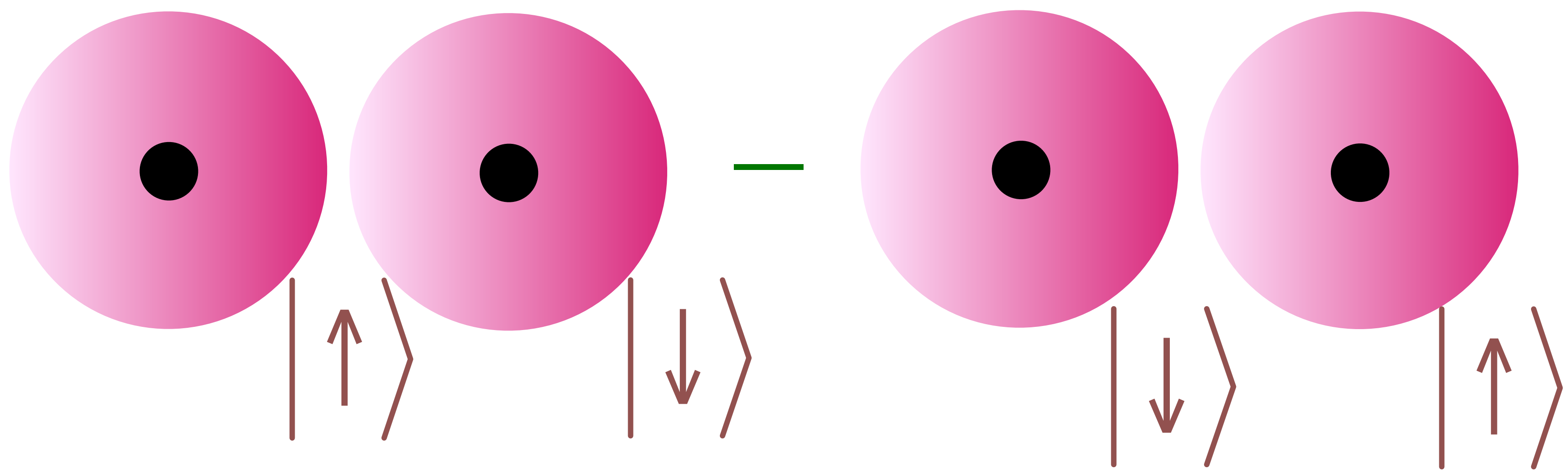


Hydrogen molecule:



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

Quantum Entanglement: quantum superposition with more than one particle



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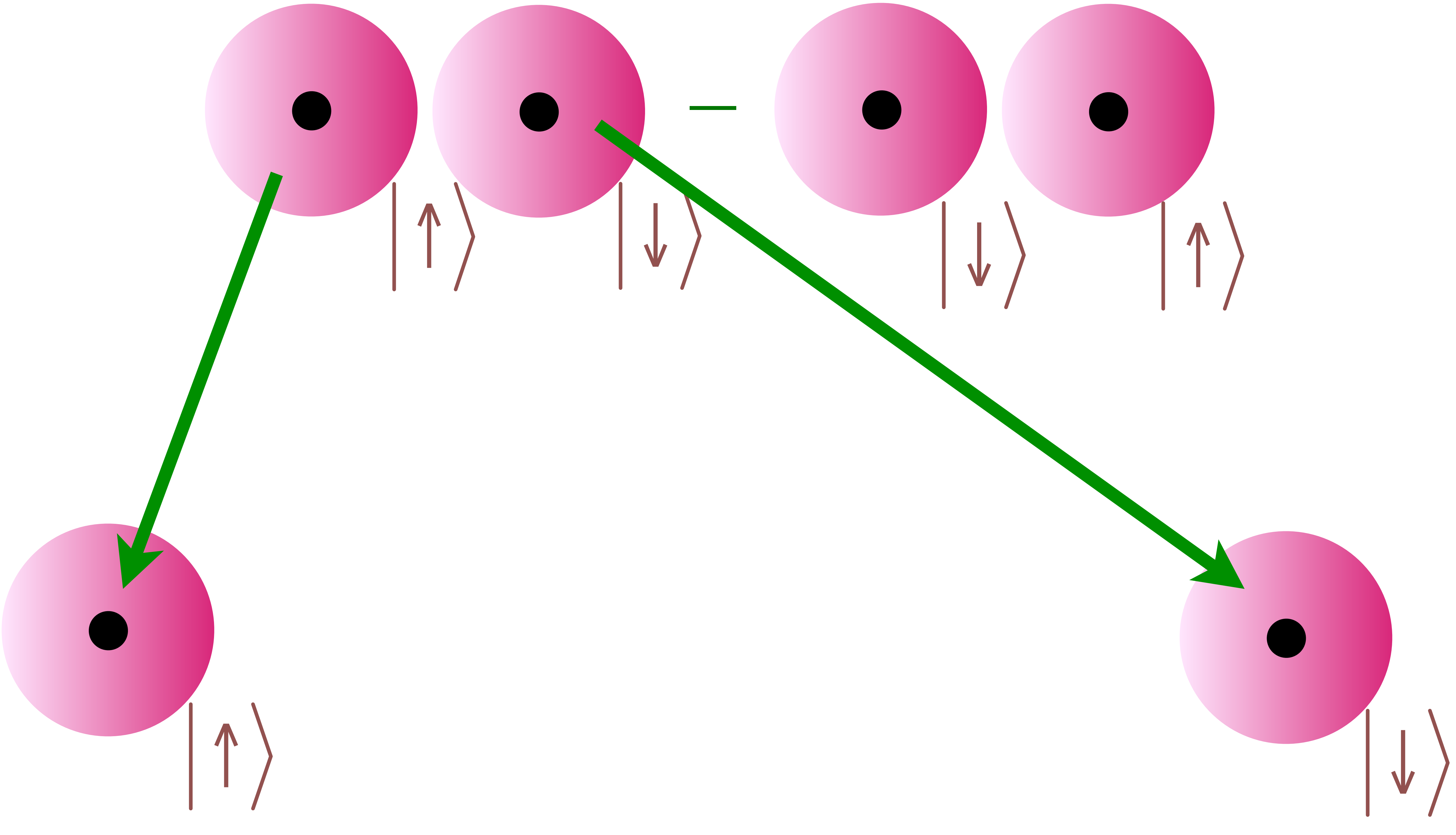

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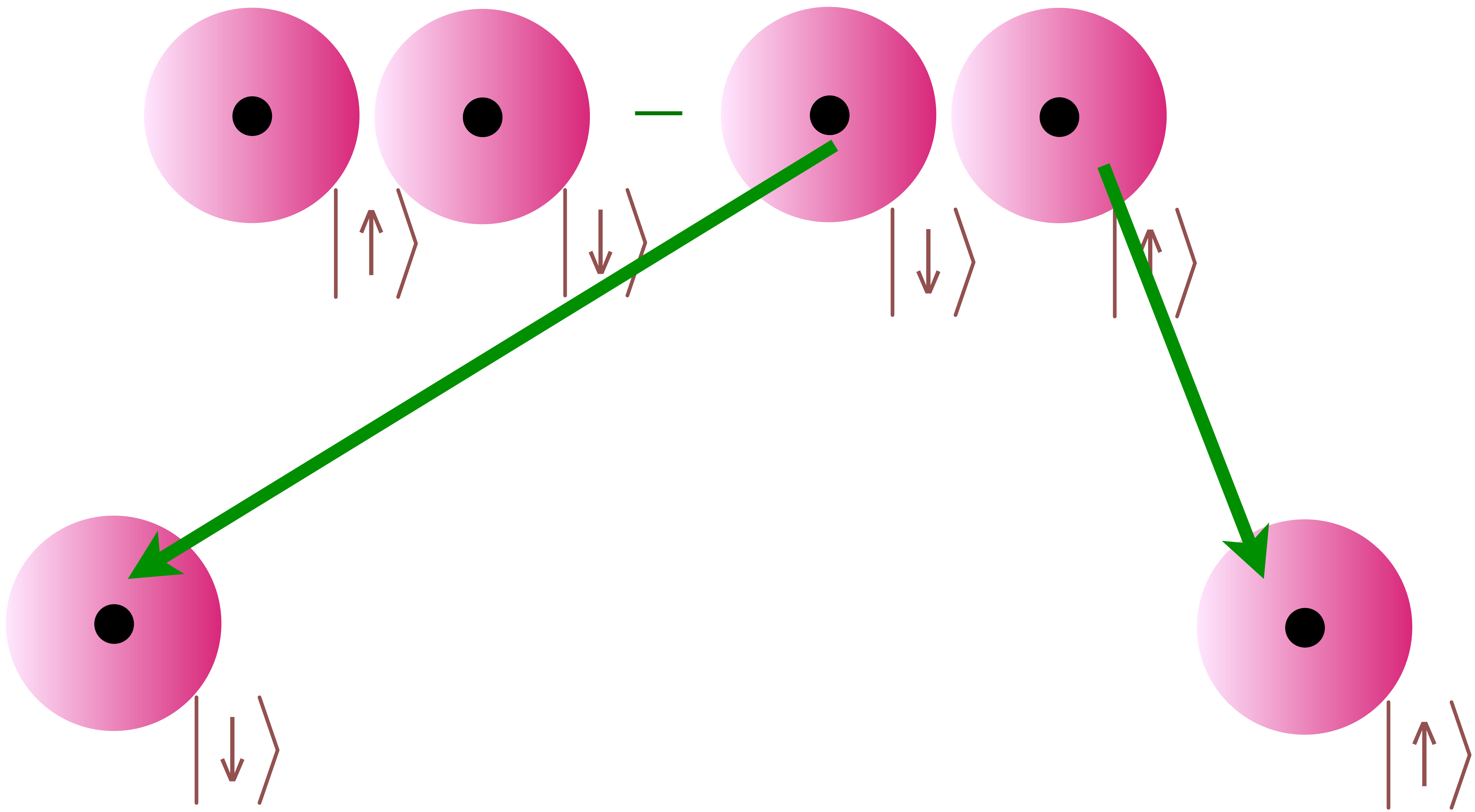

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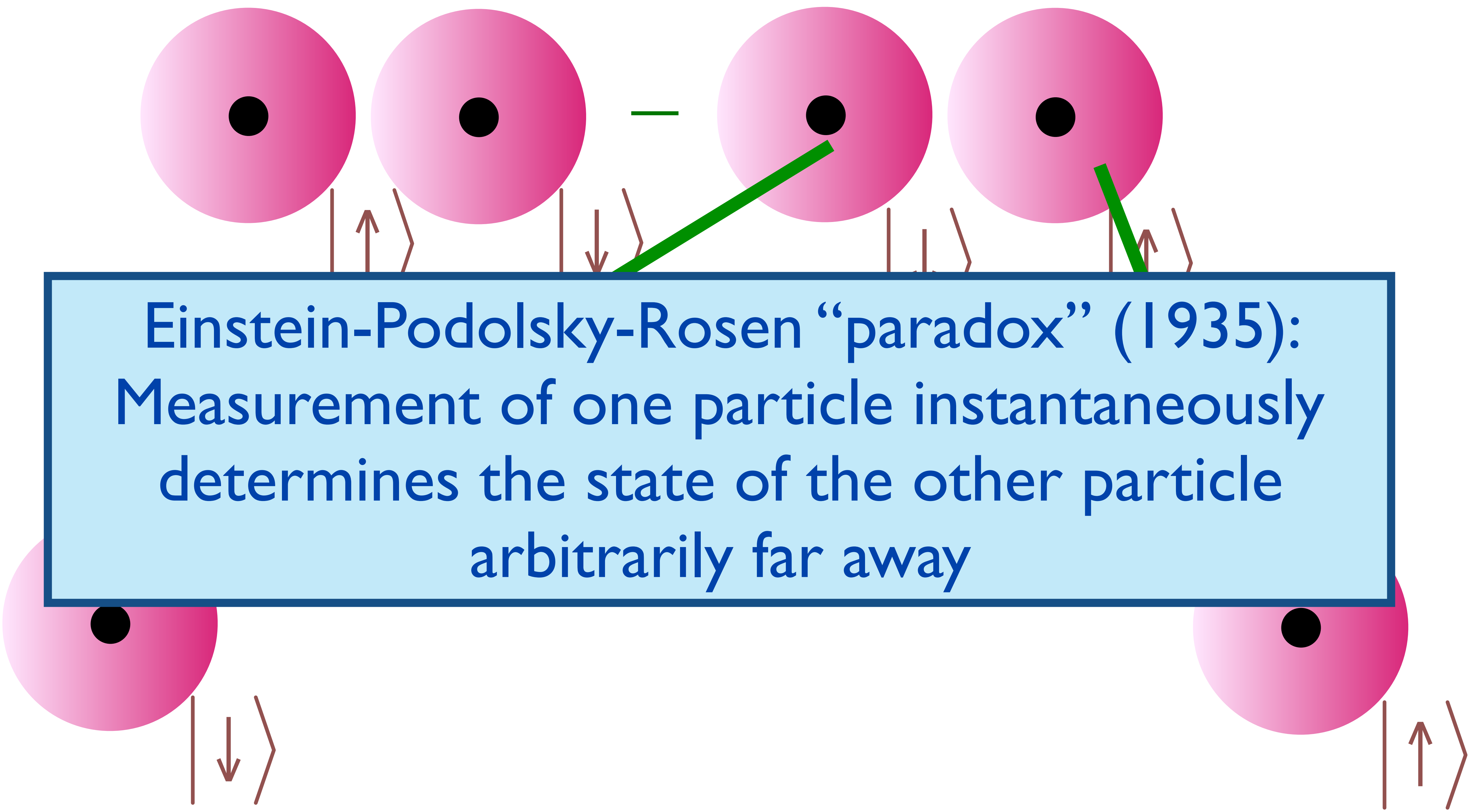


Einstein-Podolsky-Rosen "paradox" (1935): Measurement of one particle instantaneously determines the state of the other particle arbitrarily far away

Quantum entanglement

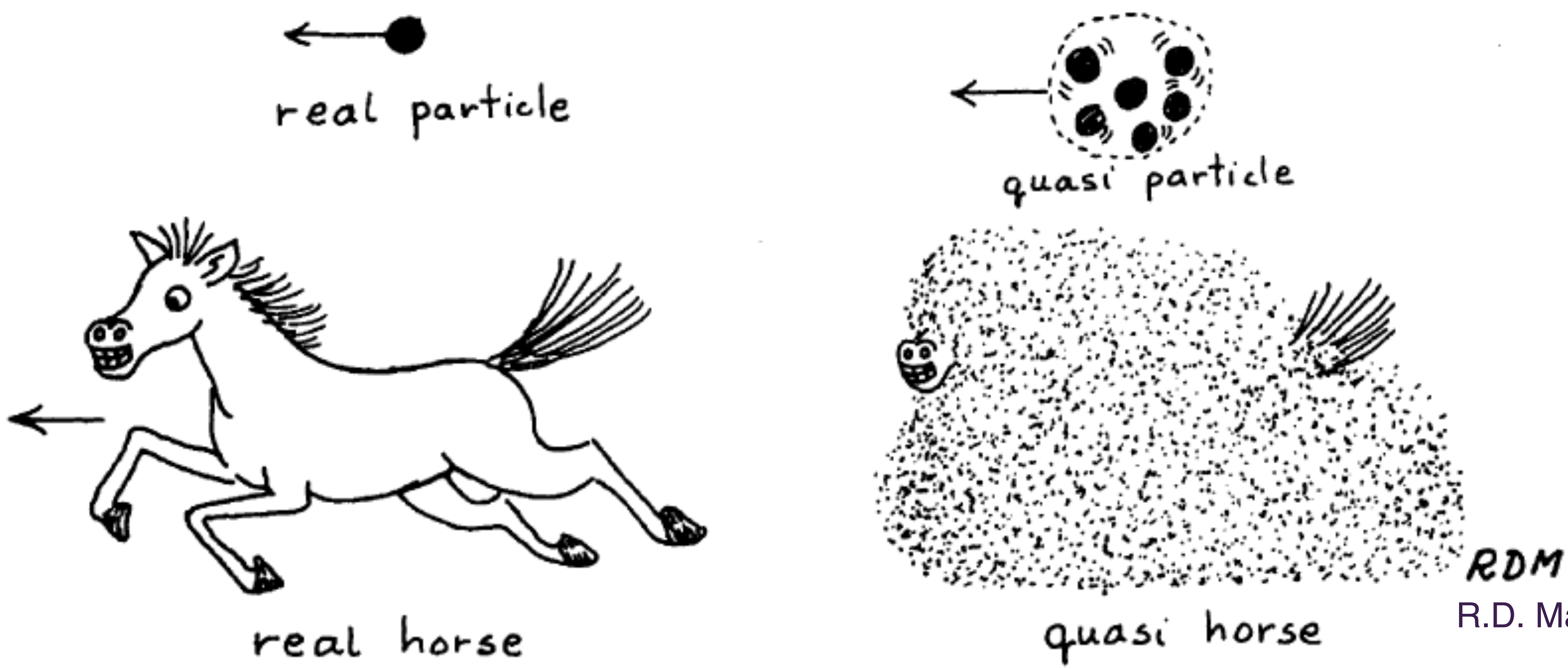
Quantum entanglement

Strange metals

Ordinary metals

Ordinary metals are shiny, and they conduct heat and electricity efficiently. Each atom donates electrons which are delocalized throughout the entire crystal

Almost all many-electron systems are described by the quasiparticle concept: a quasiparticle is an "excited lump" in the many-electron state which responds just like an ordinary particle.

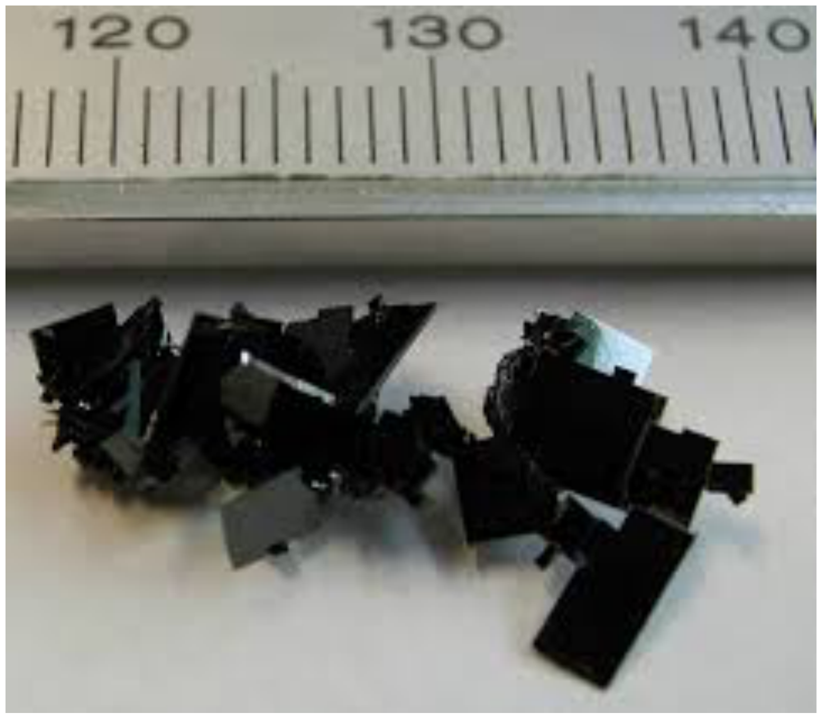


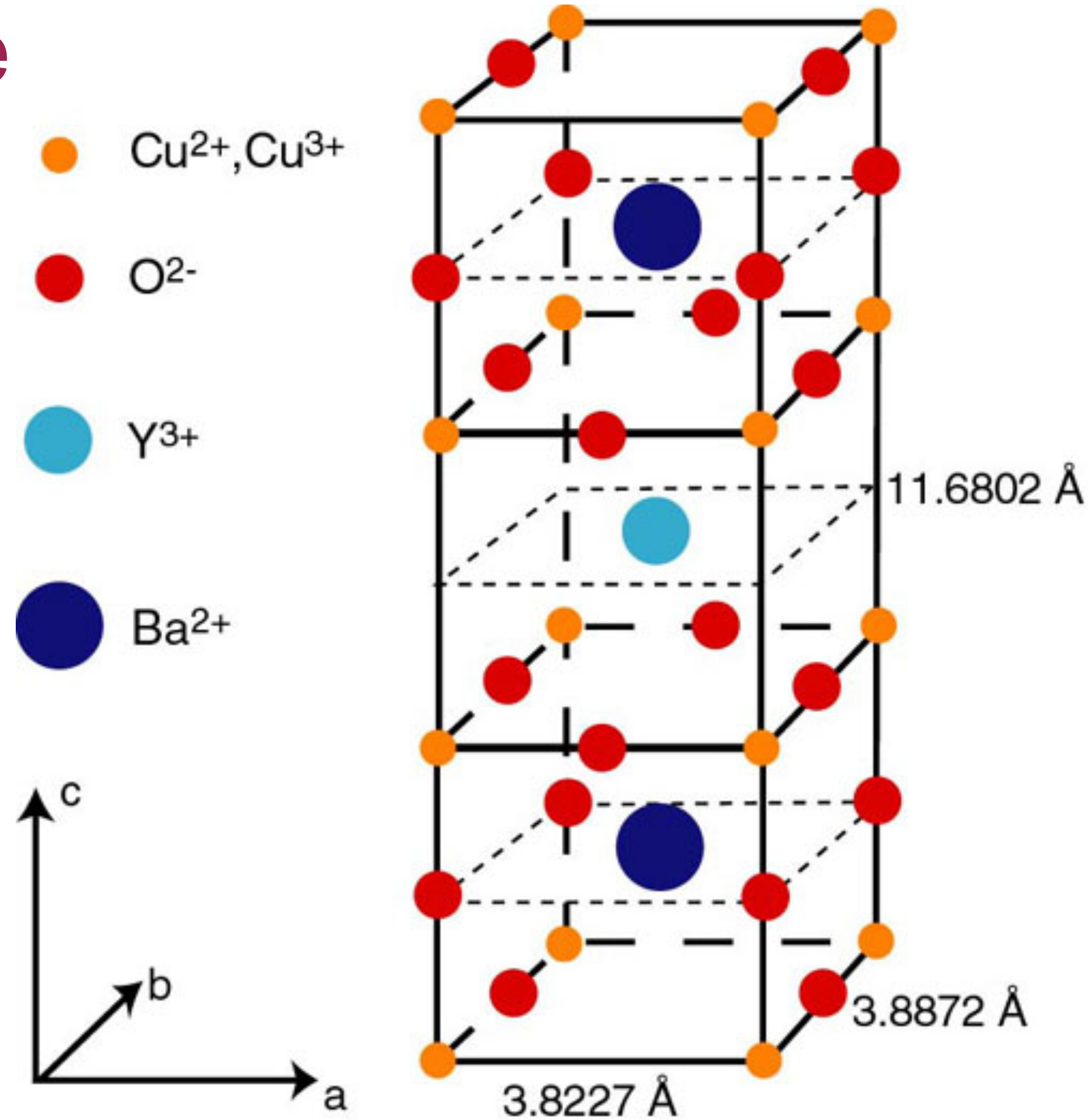
R.D. Mattuck

Almost all many-electron systems are described by the quasiparticle concept: a quasiparticle is an "excited lump" in the many-electron state which responds just like an ordinary particle.

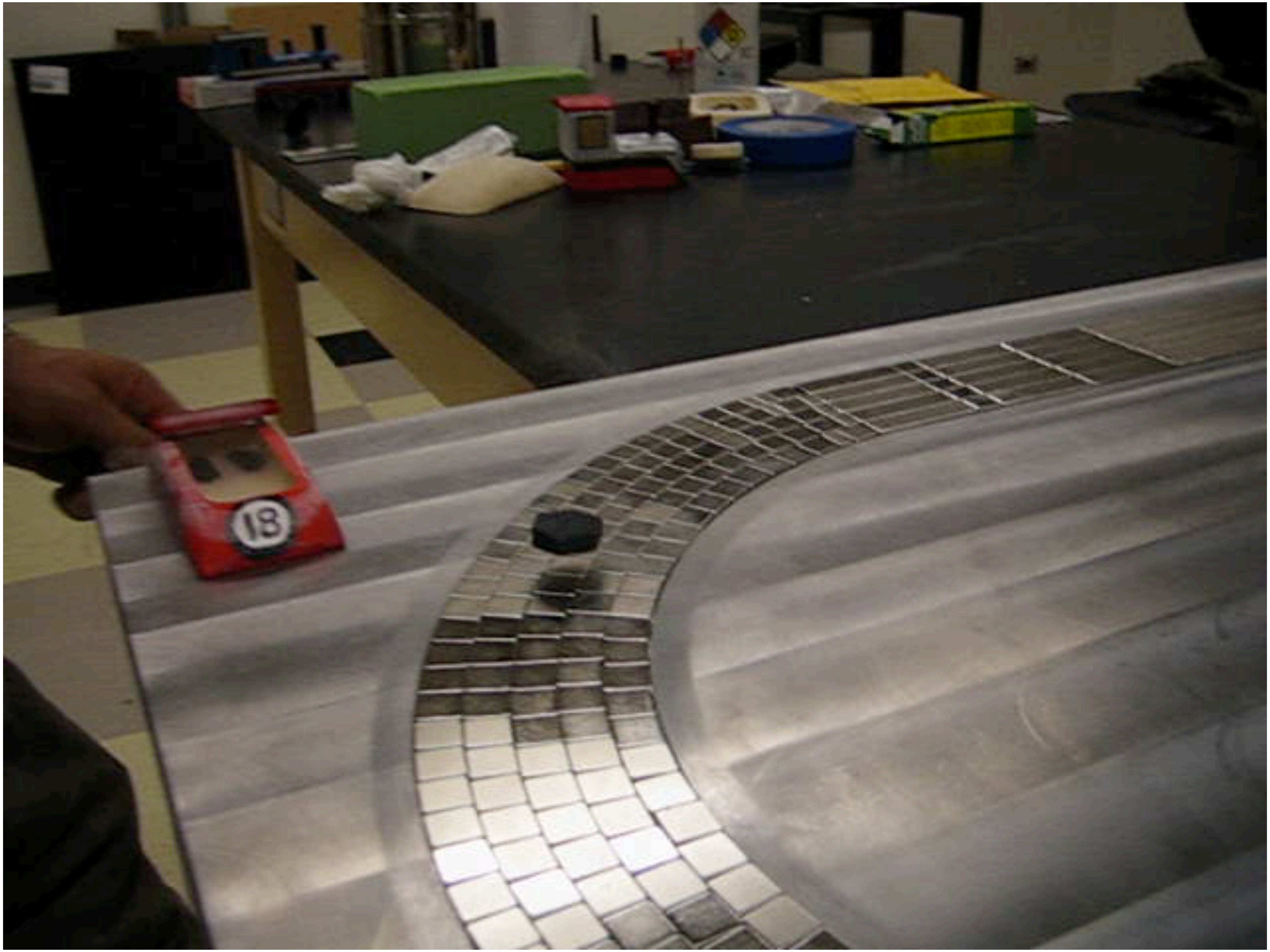
Quasiparticles eventually collide with each other. Such collisions eventually leads to thermal equilibration in a chaotic quantum state, but the equilibration takes a long time.

High temperature superconductors





$YBa_2Cu_3O_{6+x}$

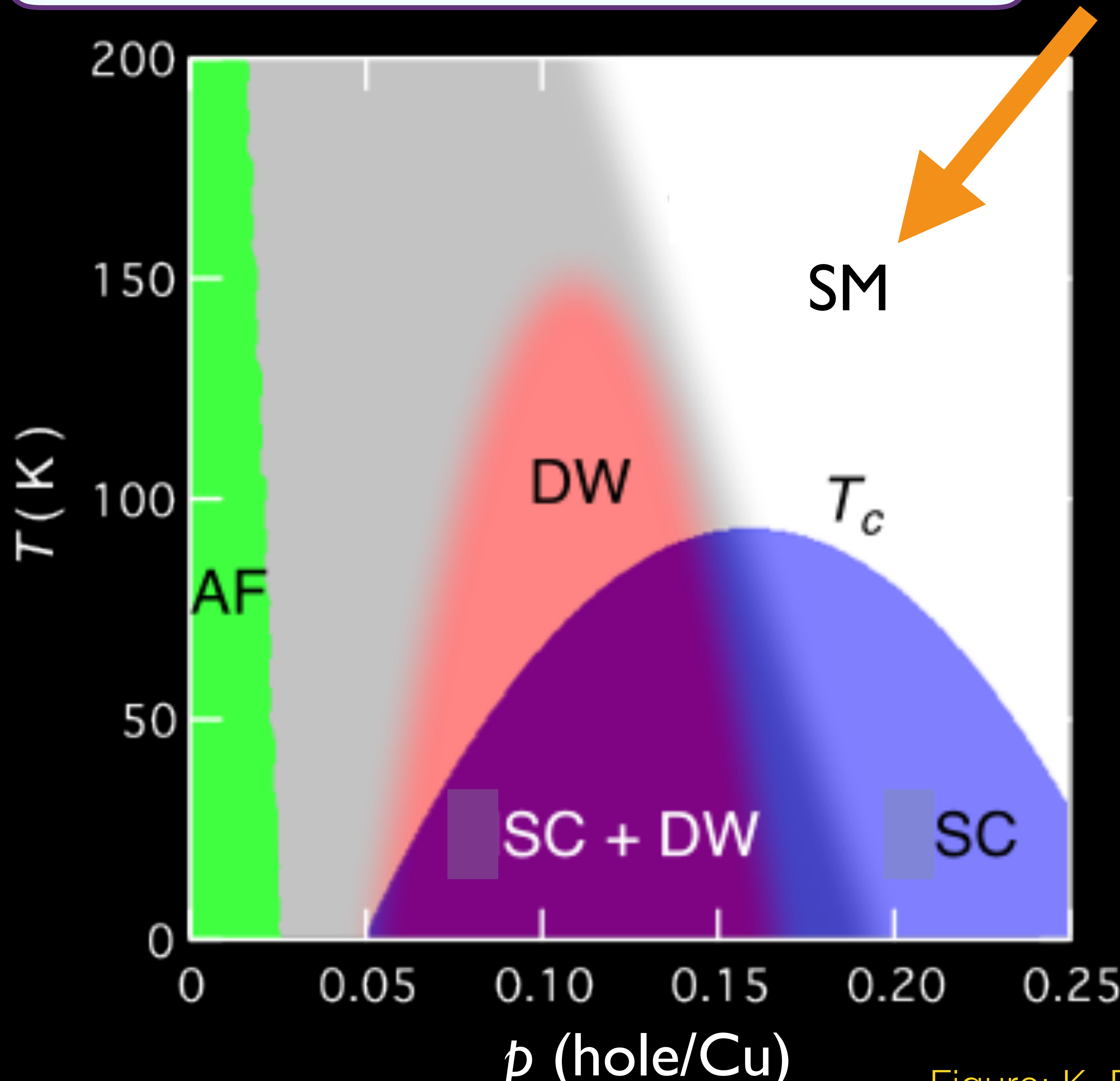


Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

Quantum matter <u>without</u> quasiparticles

Strange metal



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

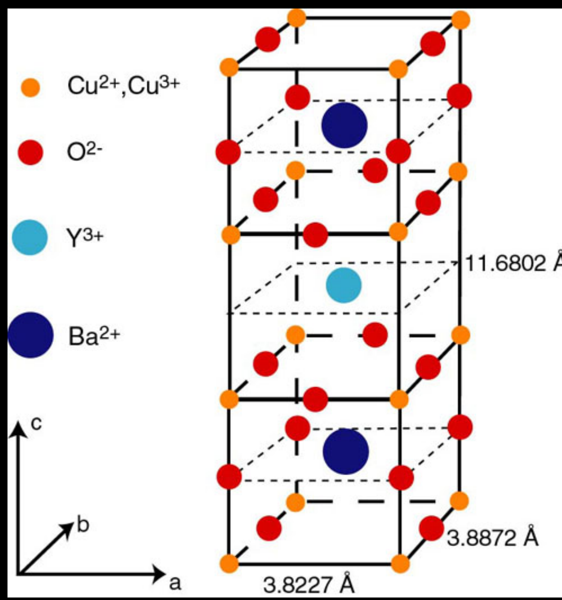


Figure: K. Fujita and J. C. Seamus Davis

“Strange”,

“Bad”,

or “Incoherent”,

metal has a resistivity, ρ, which obeys

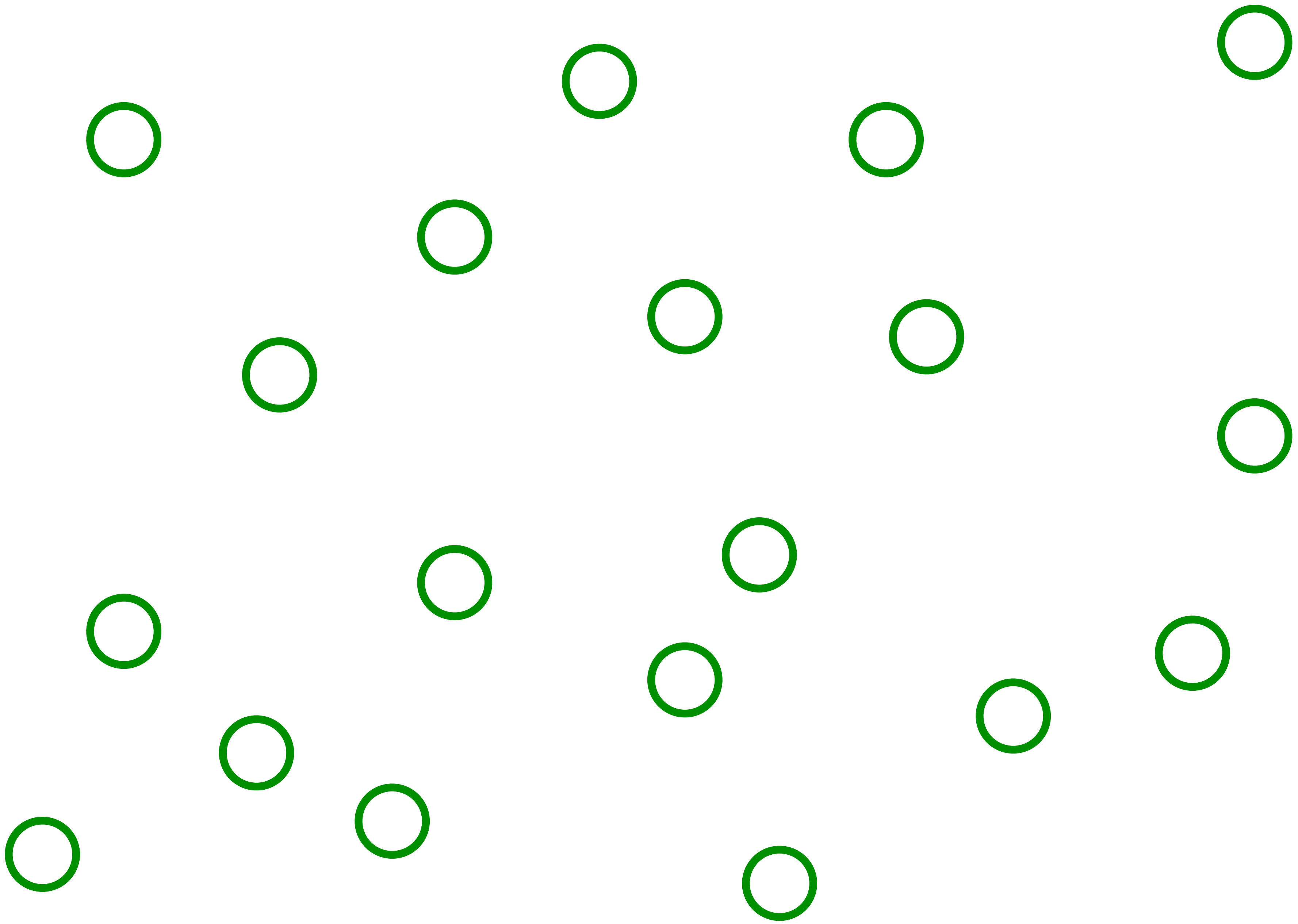
$$\rho \sim T,$$

and

$$\rho \gg h/e^2$$

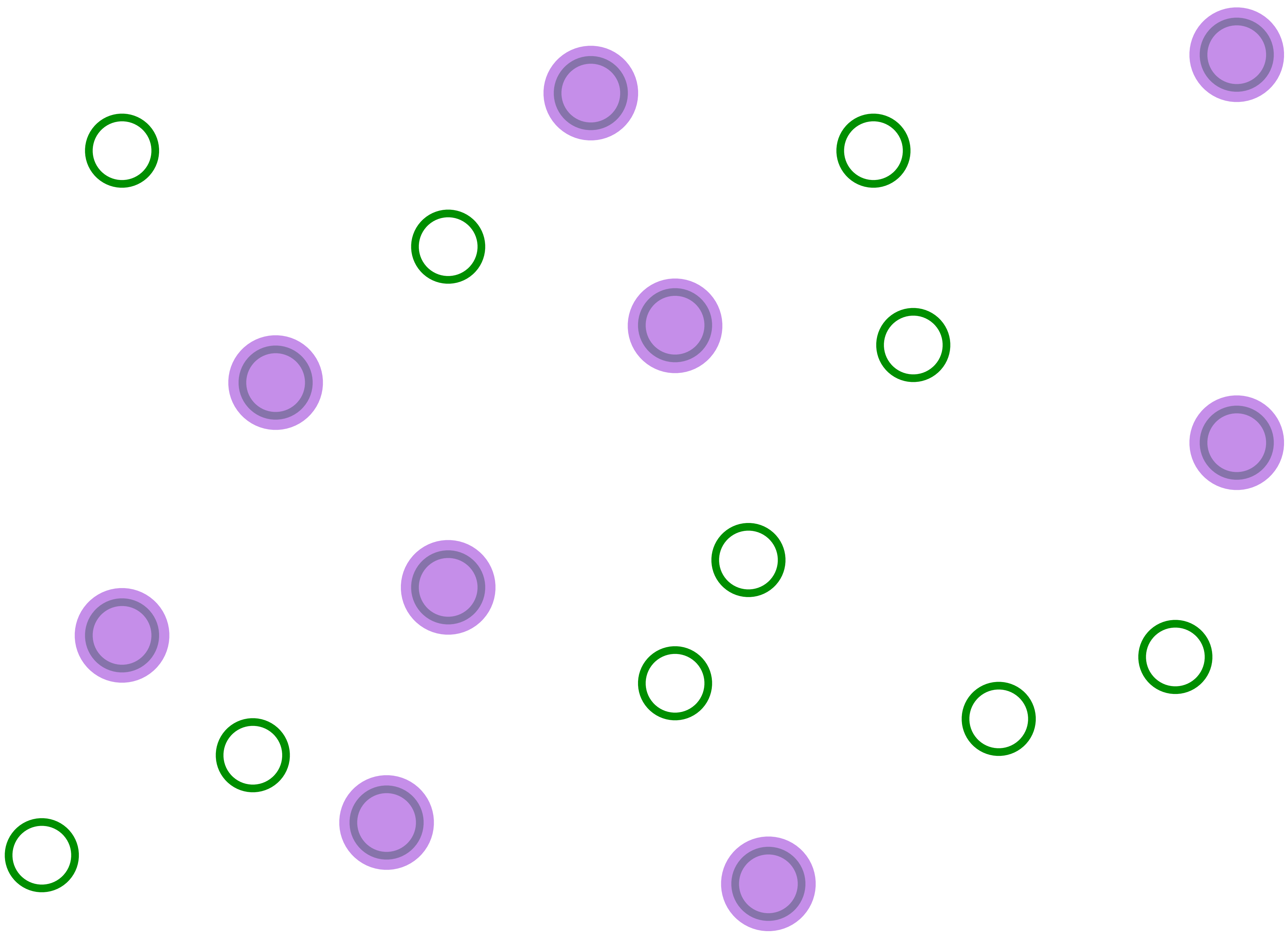
(in two dimensions),
where h/e^2 is the quantum unit of resistance.

The Sachdev-Ye-Kitaev (SYK) model



Pick a set of random positions

The Sachdev-Ye-Kitaev (SYK) model



Place electrons randomly on some sites

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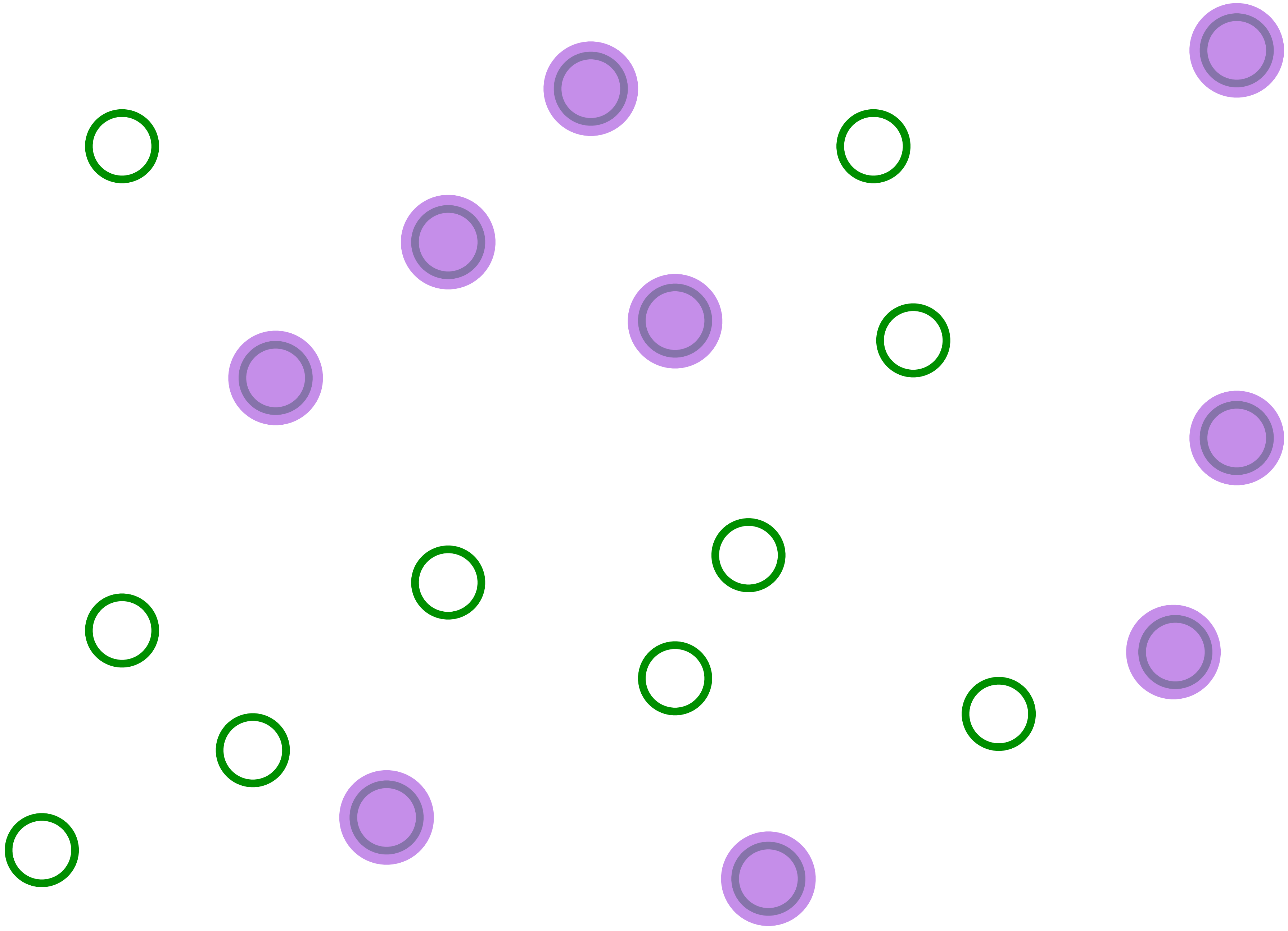

Entangle electrons pairwise randomly

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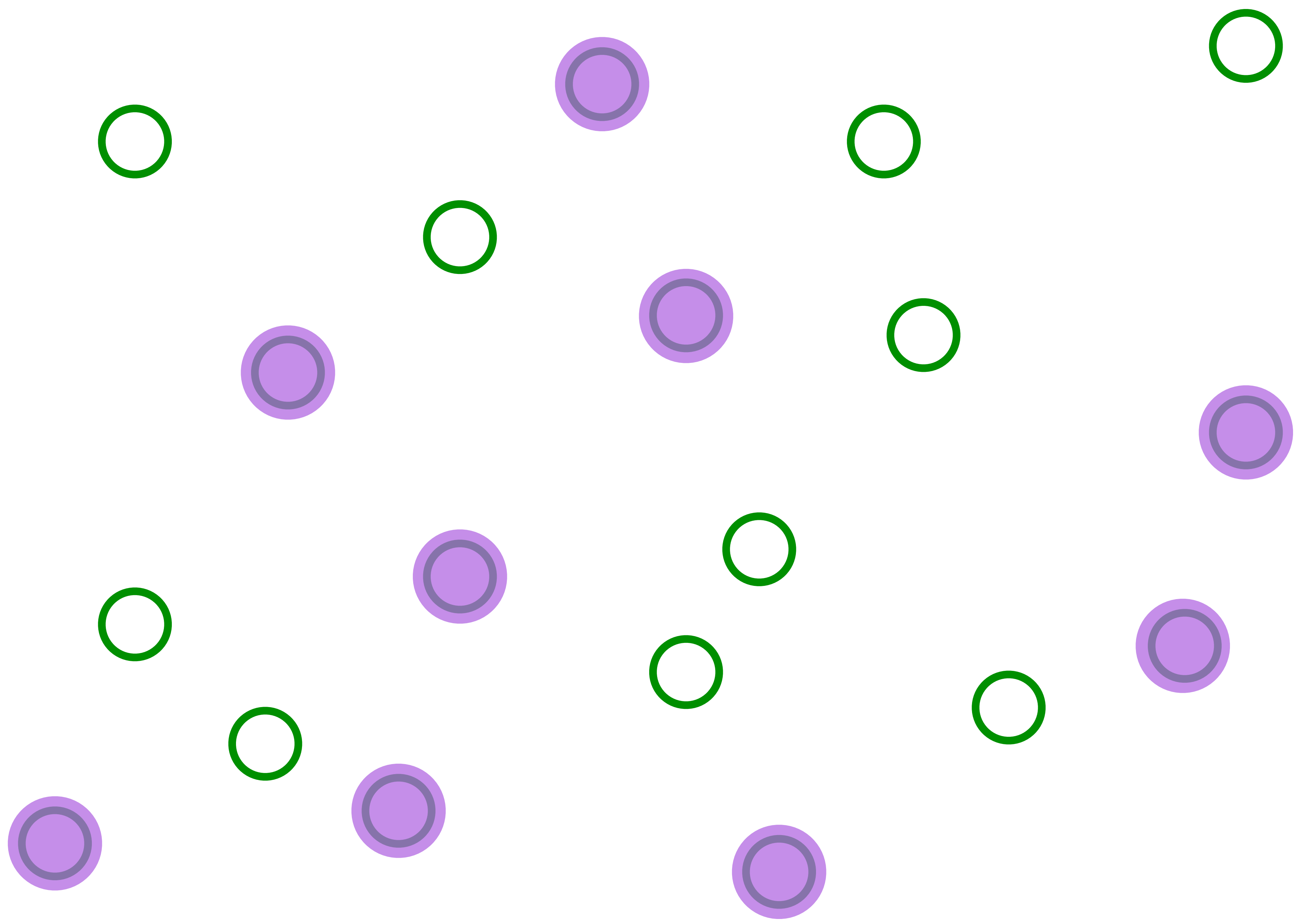

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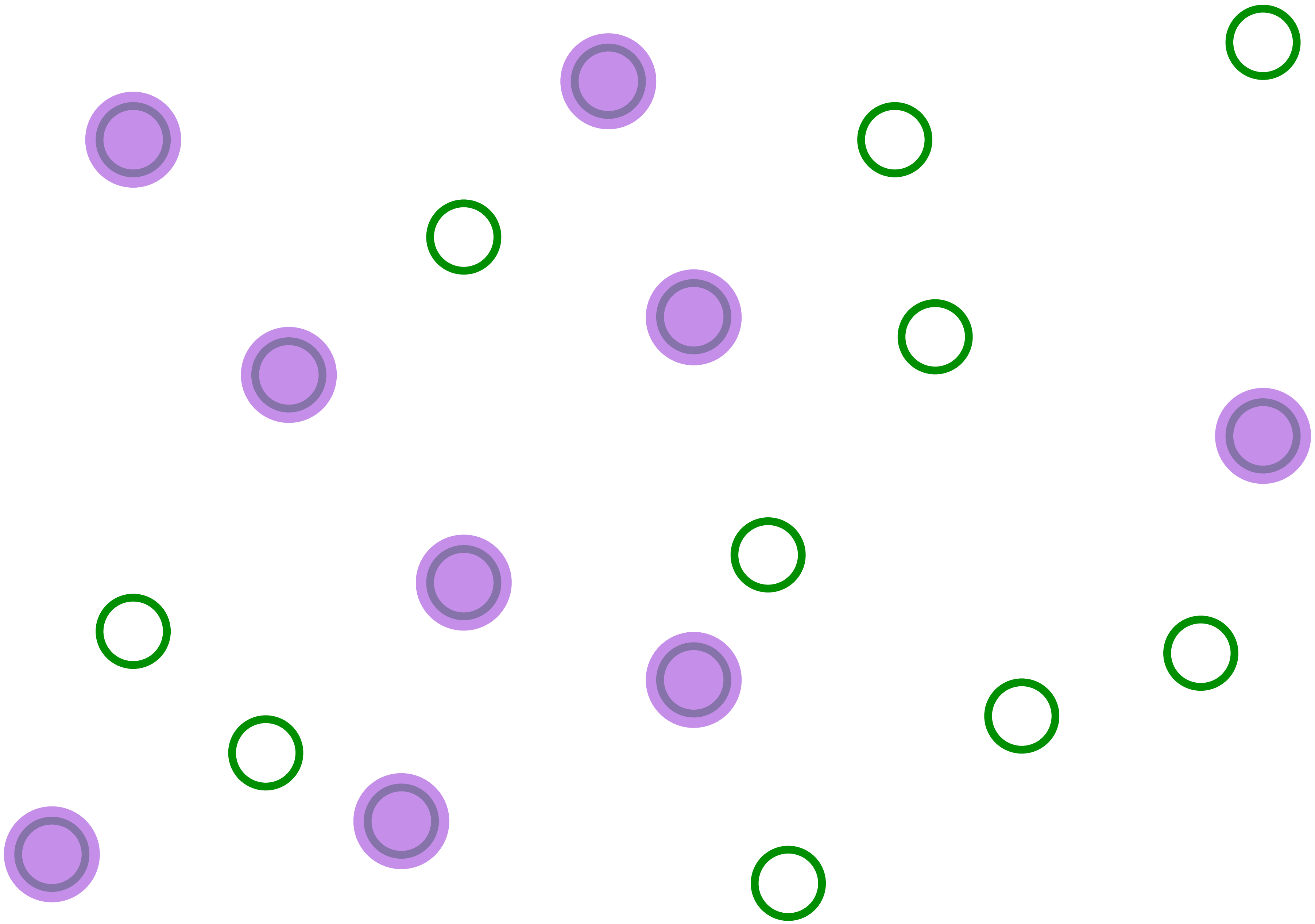

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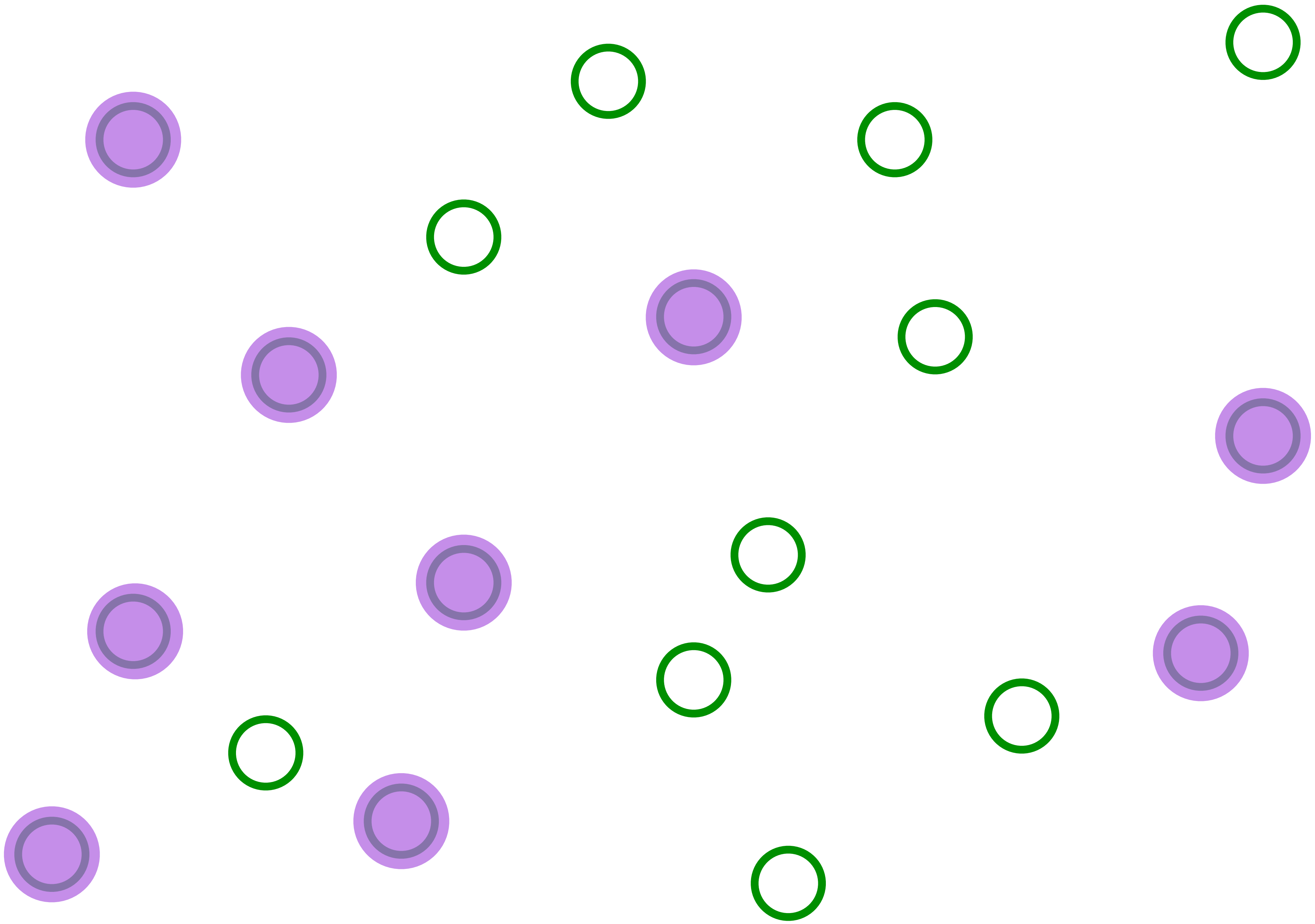

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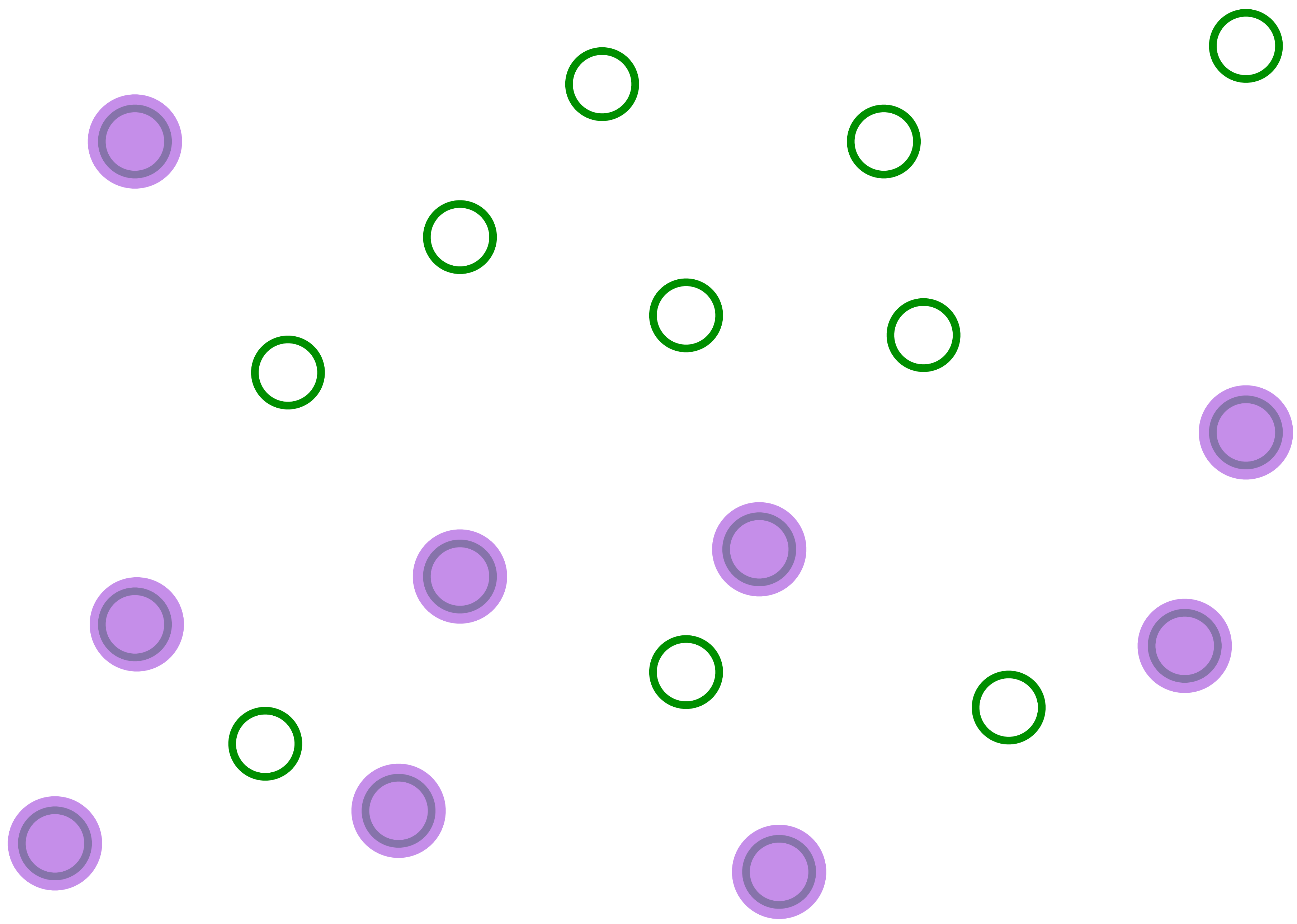

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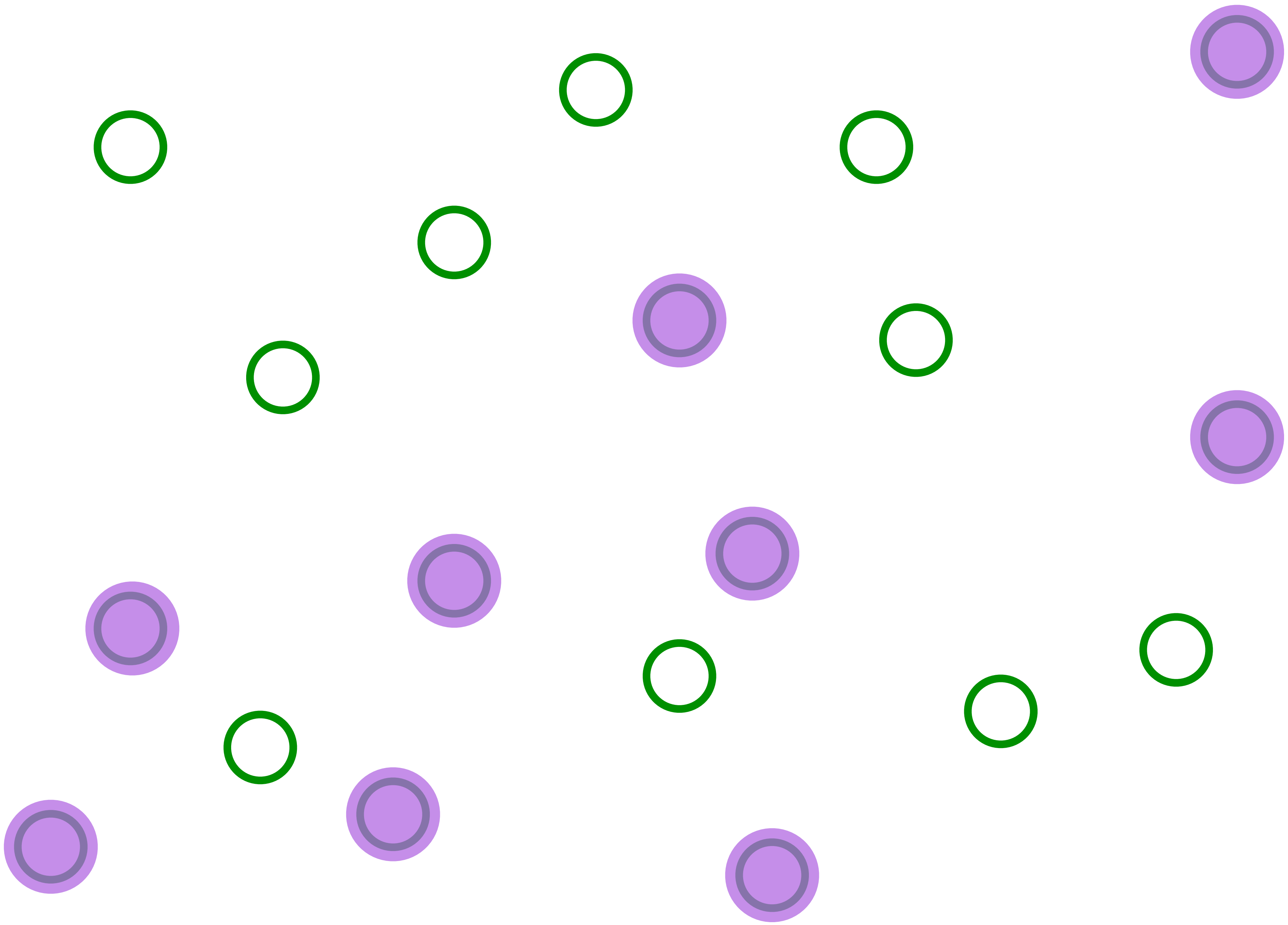

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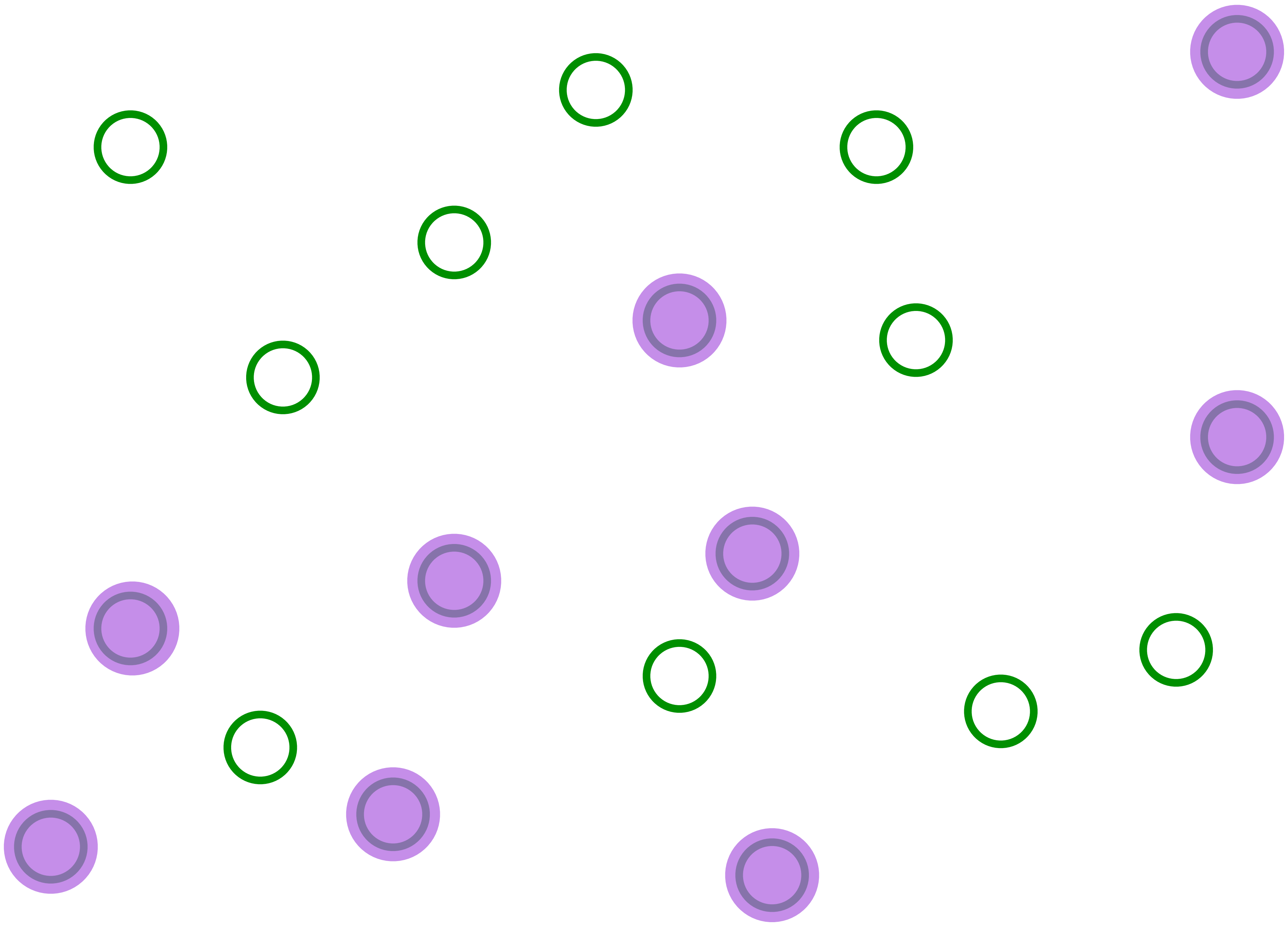
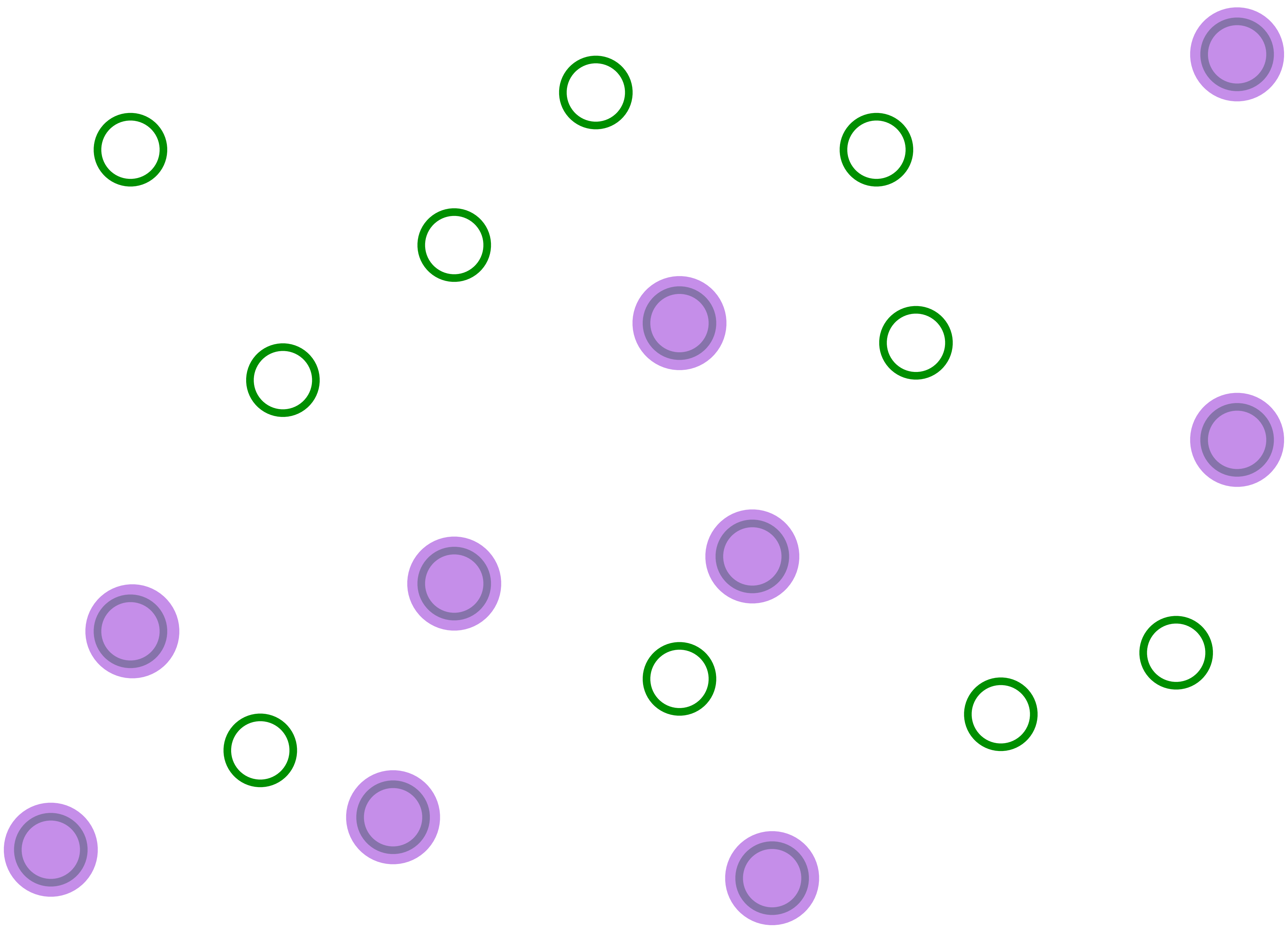


The SYK model has "nothing but entanglement"

The Sachdev-Ye-Kitaev (SYK) model

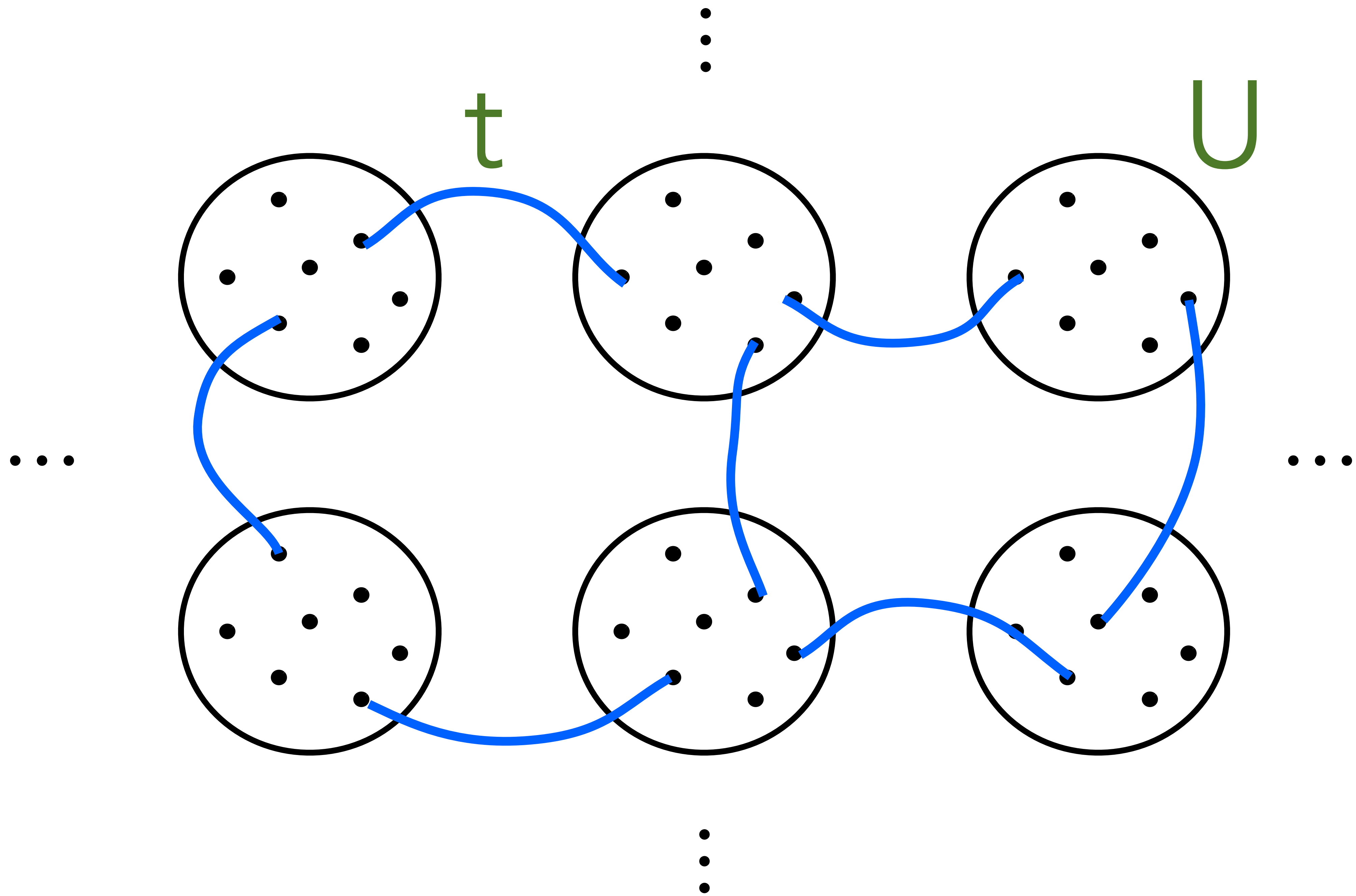


This describes both a strange metal and a black hole!

A strongly correlated metal built from Sachdev-Ye-Kitaev models

Xue-Yang Song, Chao-Ming Jian, and L. Balents, arXiv:1705.00117

See also A. Georges and O. Parcollet PRB **59**, 5341 (1999)



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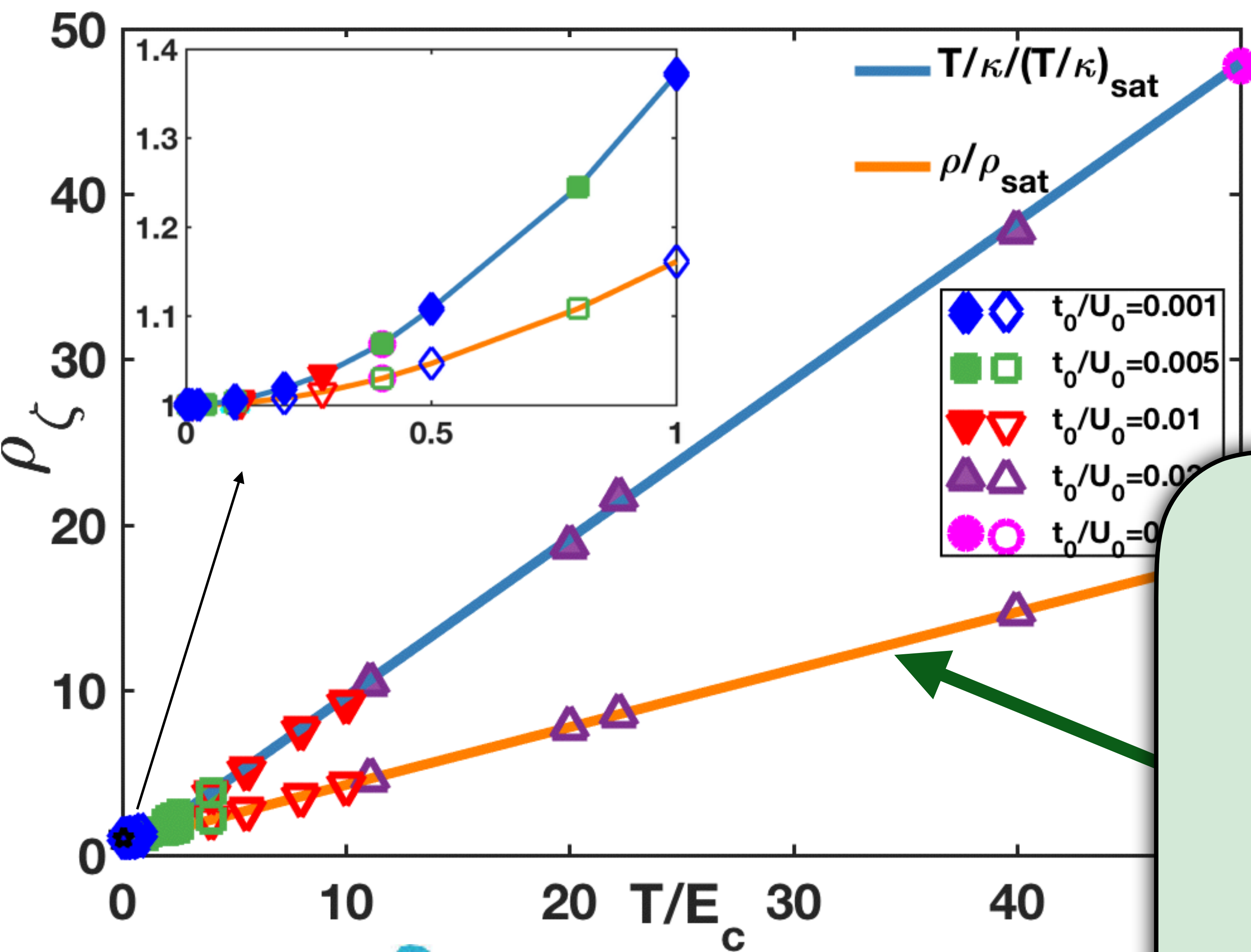


Low 'coherence' scale

$$E_c \sim \frac{t^2}{U}$$

For $E_c < T < U$, the resistivity, ρ, and entropy density, s, are

$$\rho \sim \frac{h}{e^2}\left(\frac{T}{E_c}\right), \quad s = s_0$$

Quantum matter without quasiparticles

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

Quantum matter without quasiparticles

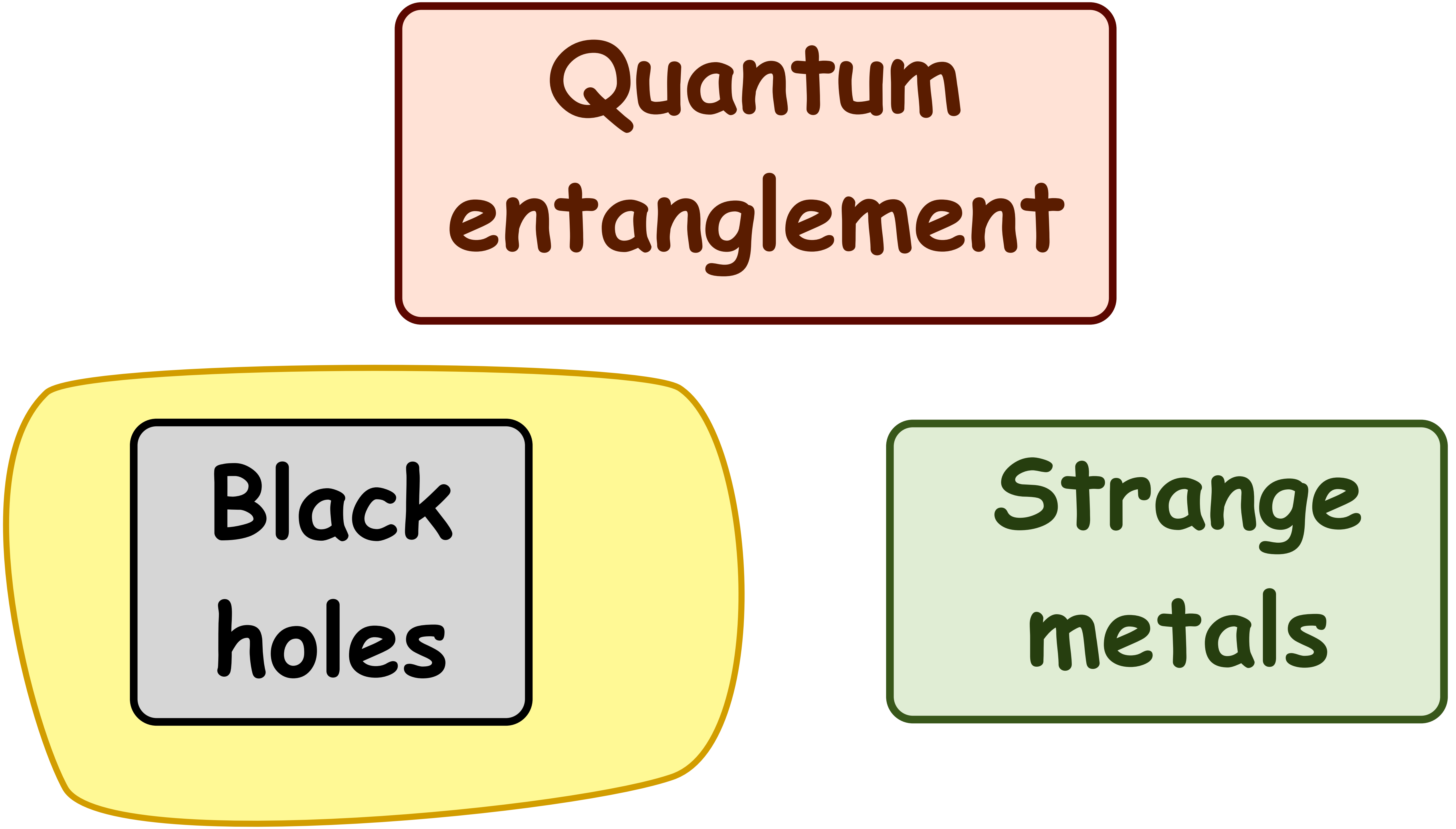
The complex quantum entanglement in the strange metal does not allow for any quasiparticle excitations.

Thermal equilibration into a chaotic quantum state happens very rapidly in systems without quasiparticle excitations: it happens in a shortest possible time of order $\frac{\hbar}{k_B T}$

(SS 1999, Maldacena, Shenker, Stanford 2015)

Quantum entanglement

Strange metals

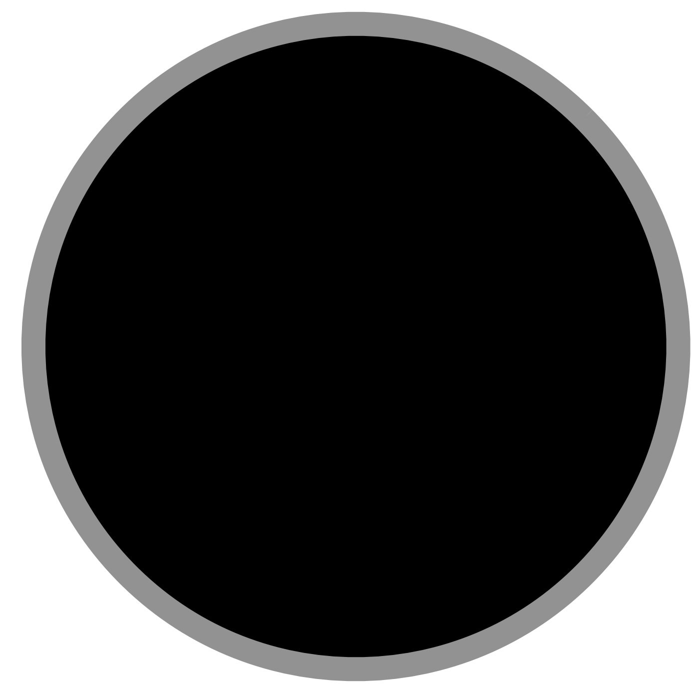


Quantum entanglement
Black holes
Strange metals

Black Holes

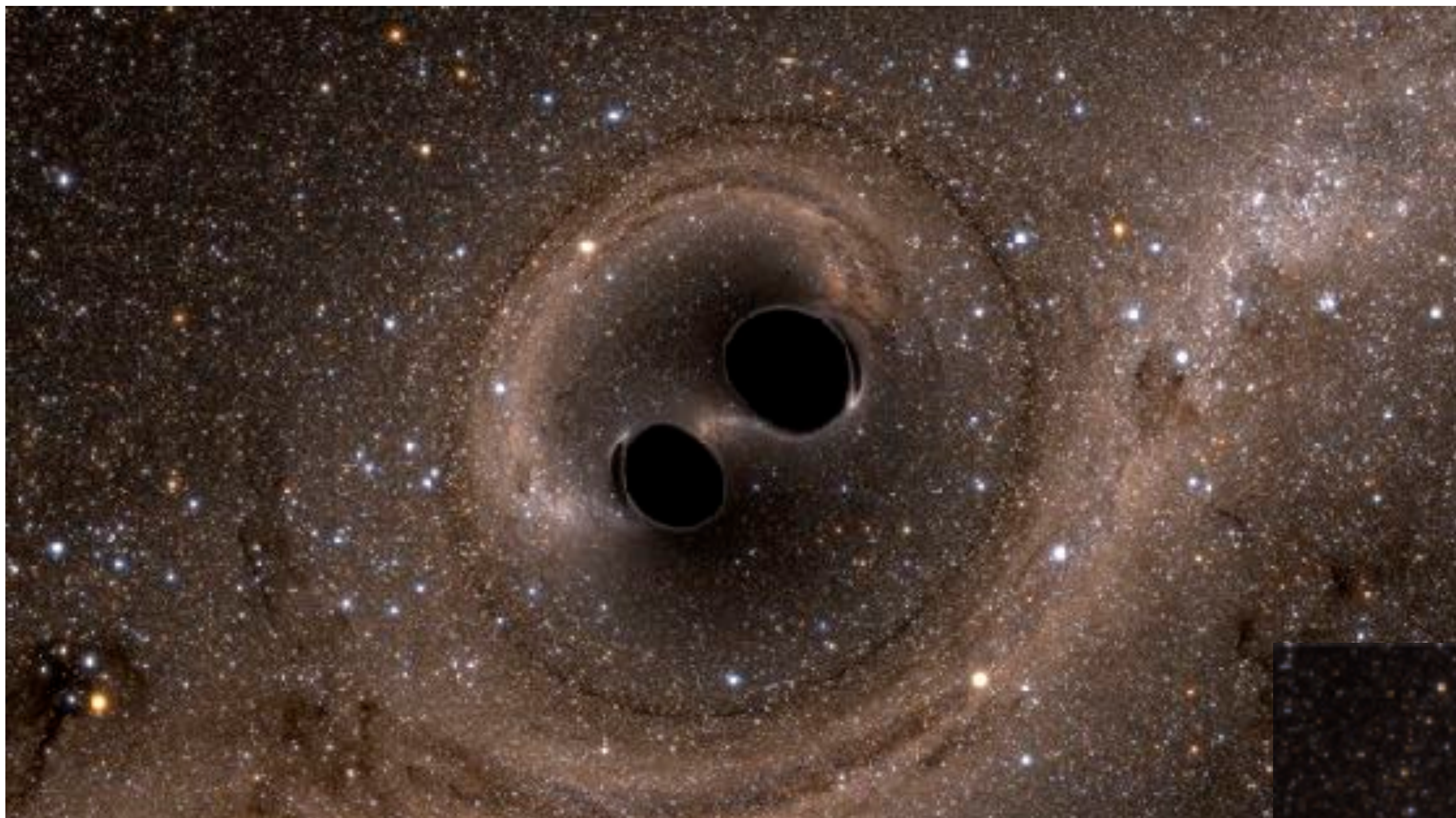
Objects so dense that light is gravitationally bound to them.

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

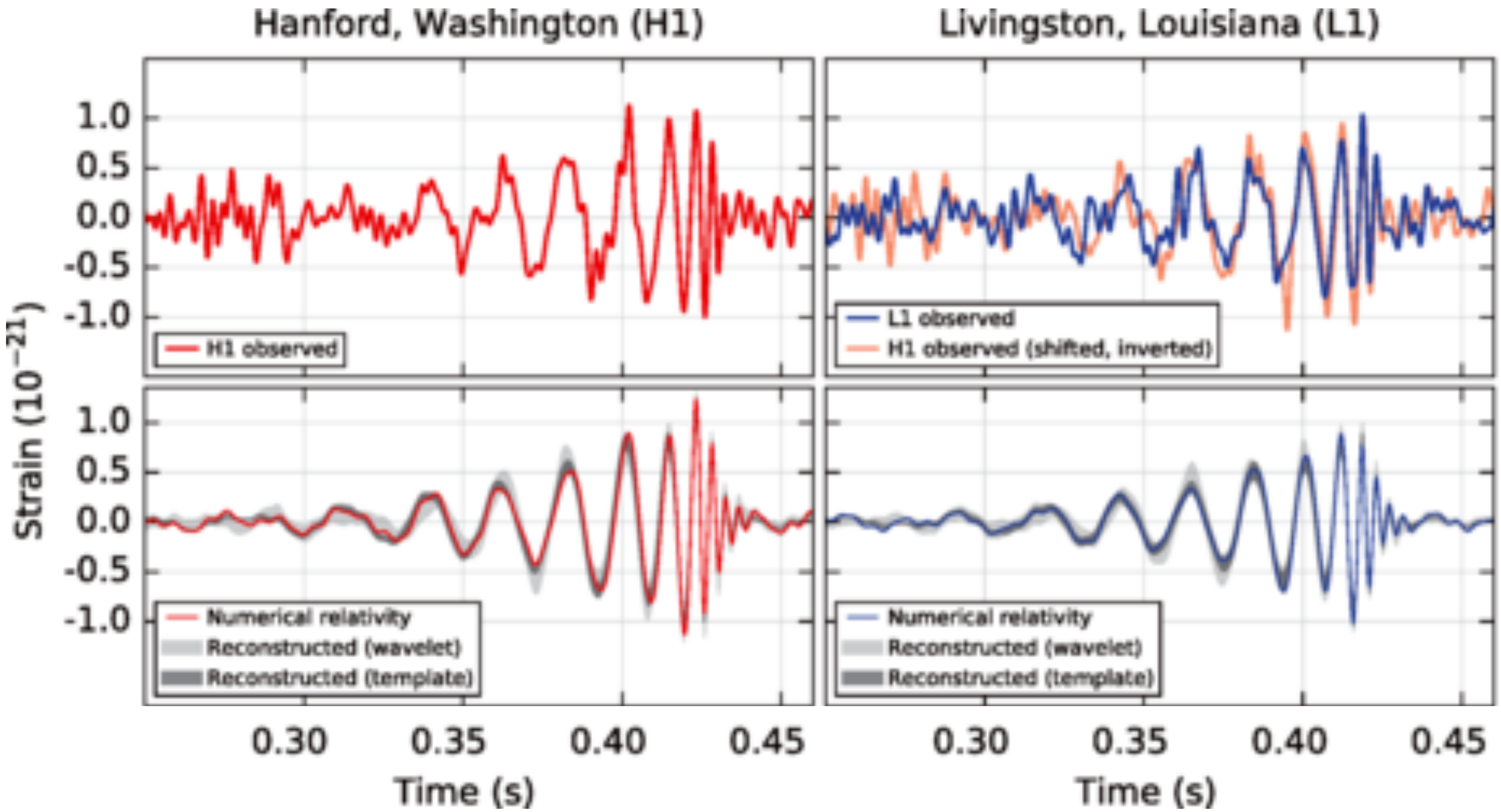


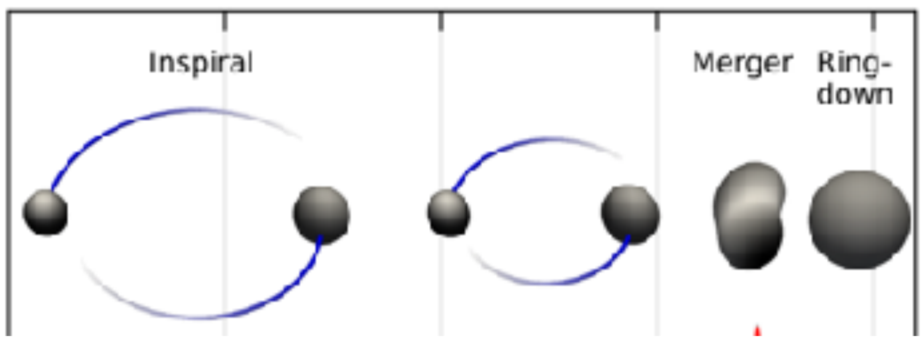
$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

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



0.1 seconds later !





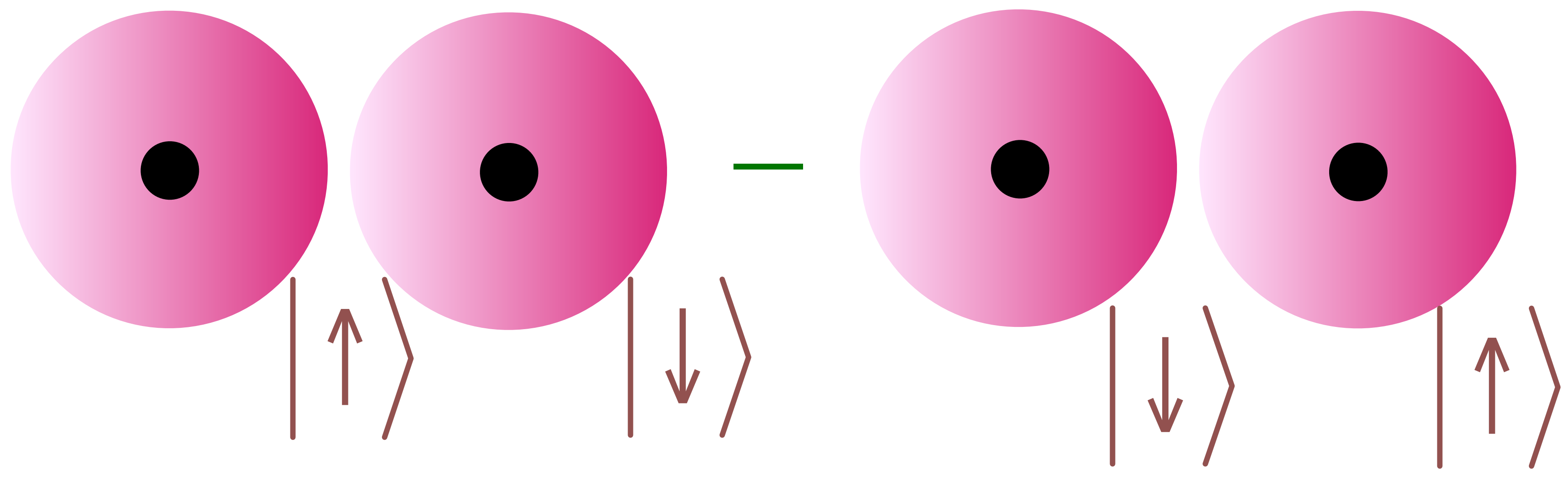
LIGO
September 14, 2015

- The ring-down is predicted by General Relativity to happen in a time $\dfrac{8\pi GM}{c^3} \sim 8$ milliseconds.

Black Holes + Quantum theory

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

Quantum Entanglement across a black hole horizon



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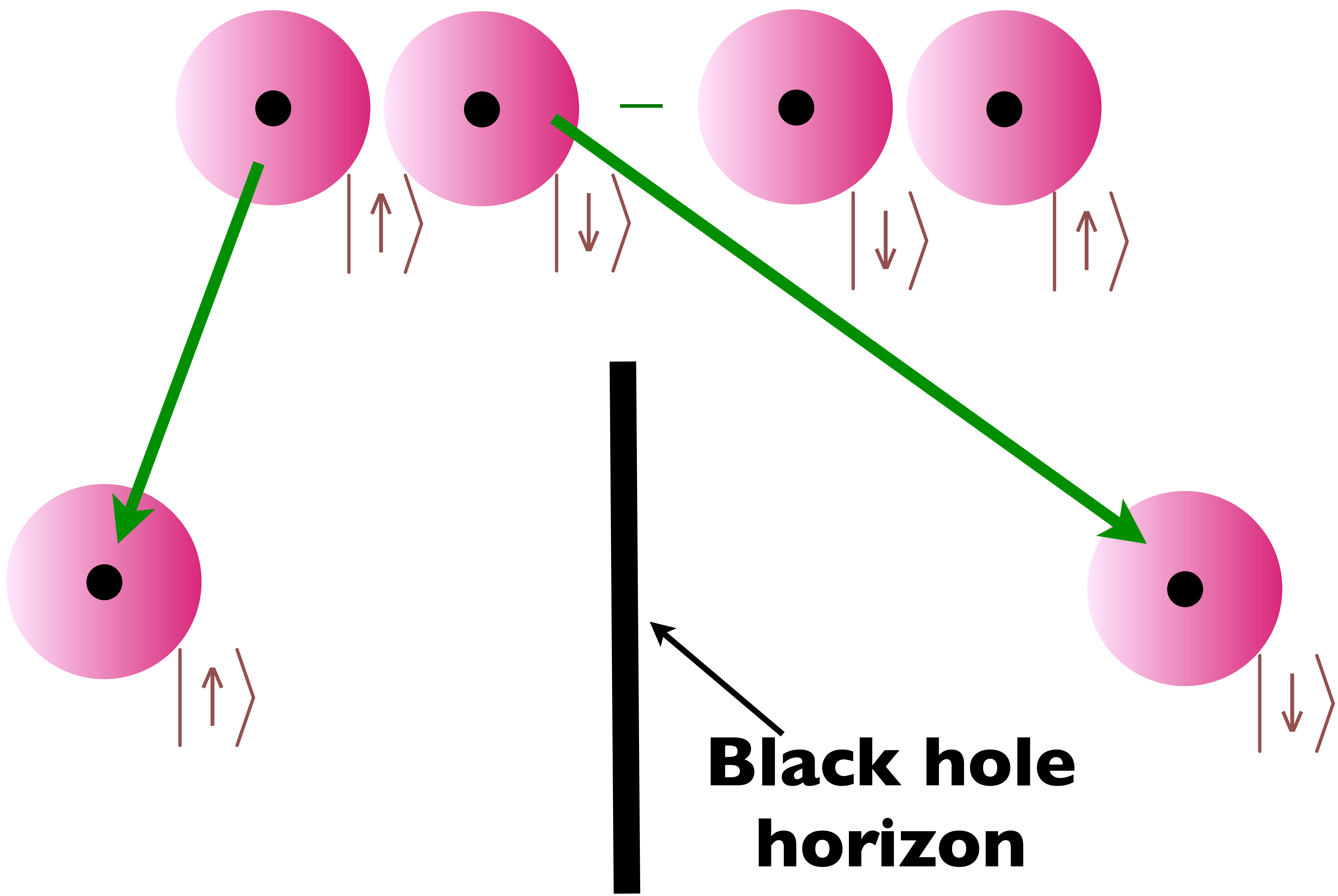

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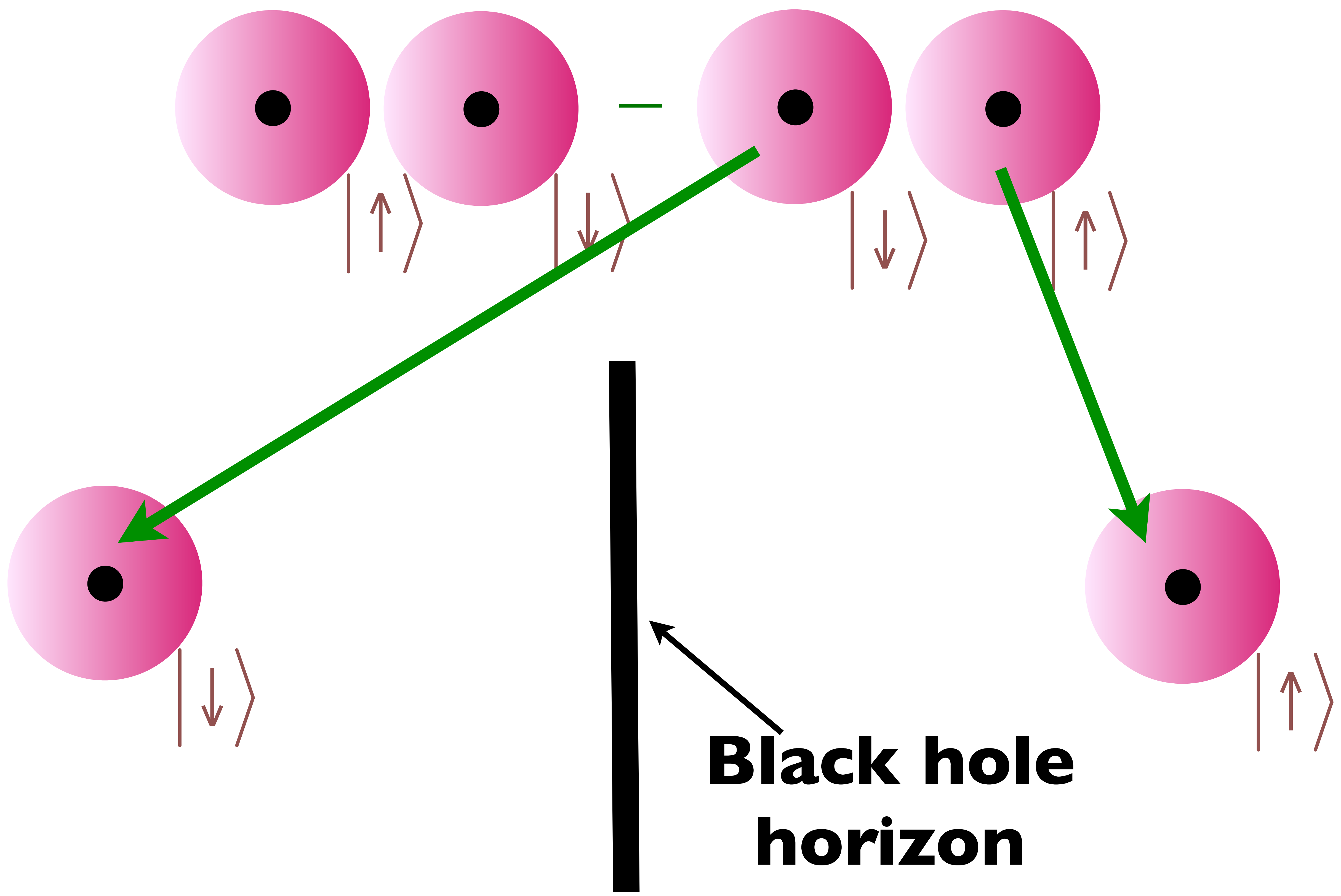
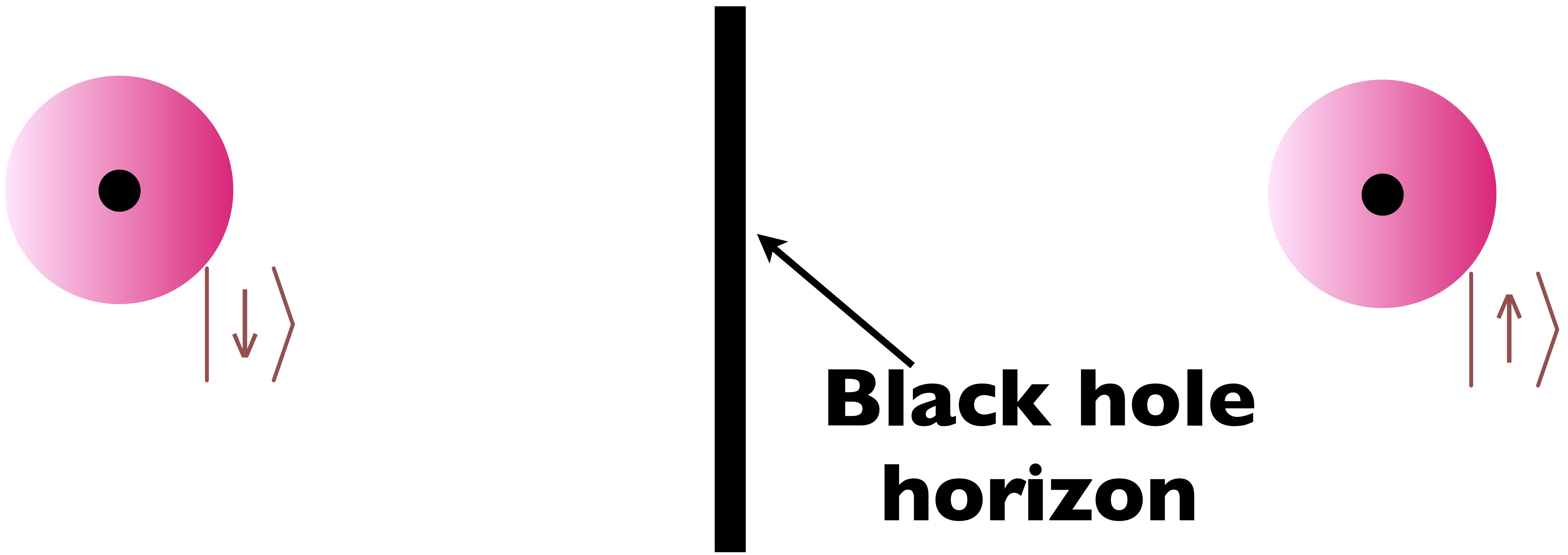


Quantum Entanglement across a black hole horizon

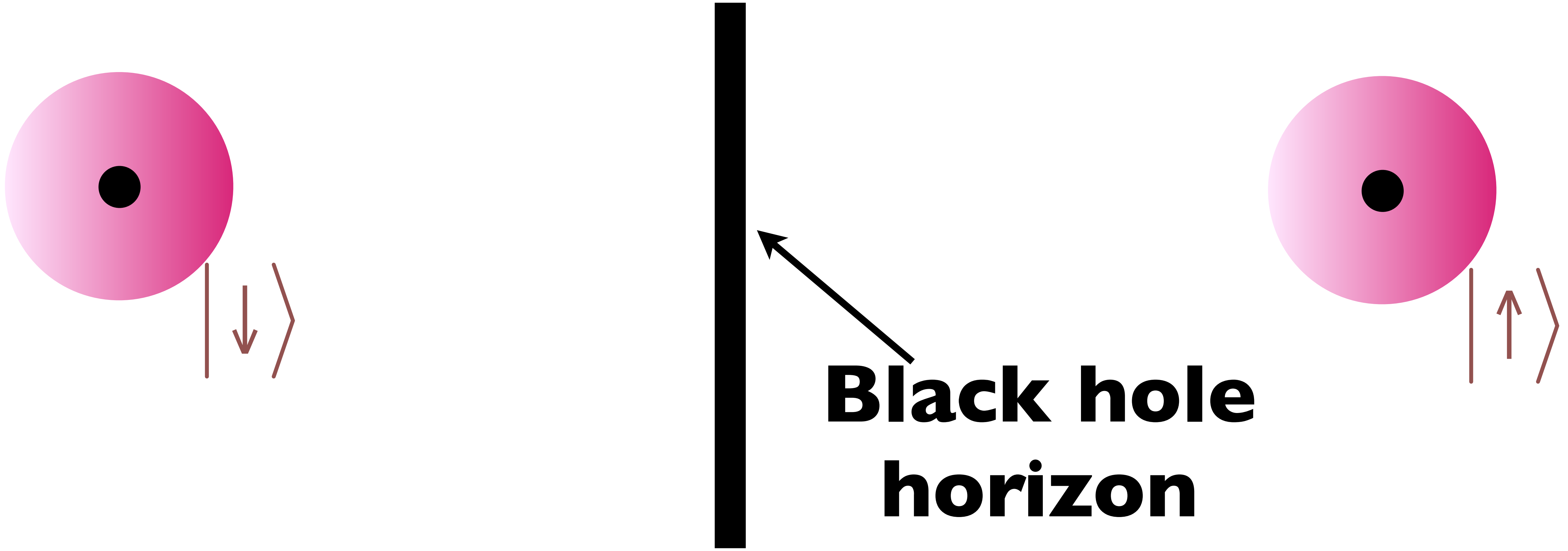
There is long-range quantum entanglement between the inside and outside of a black hole

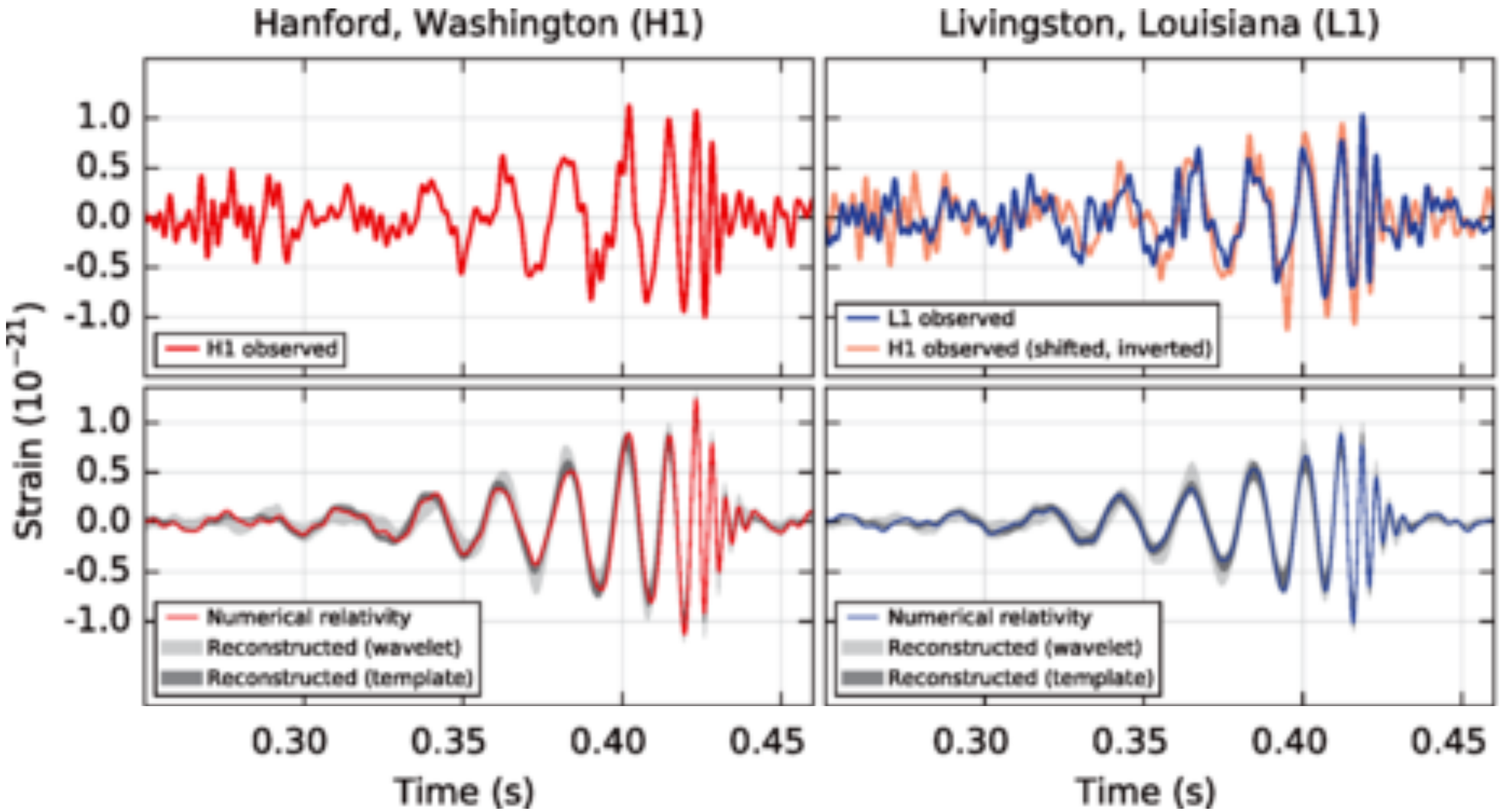


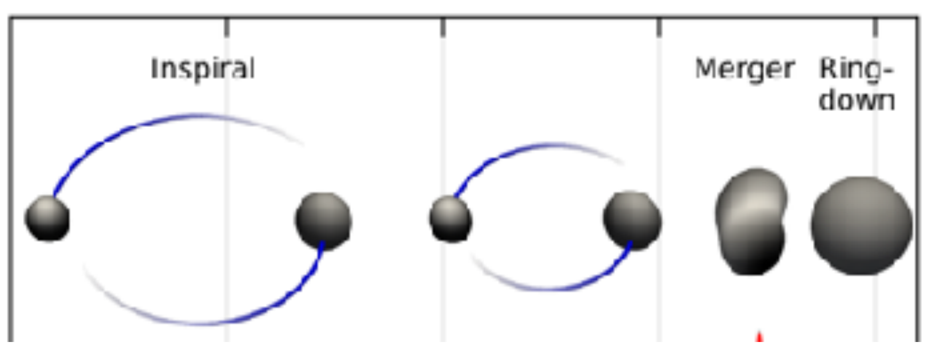
Quantum Entanglement across a black hole horizon

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

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

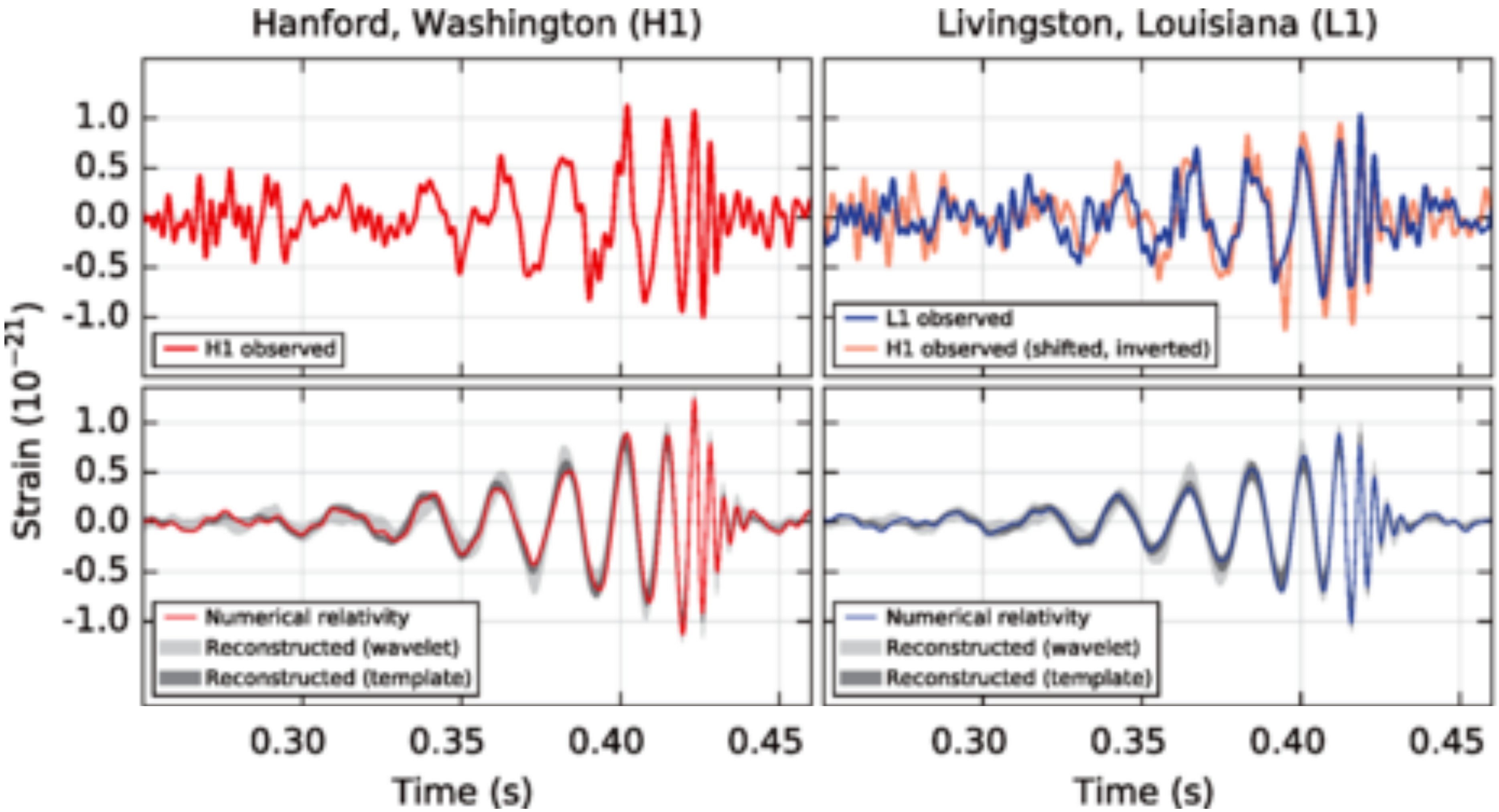


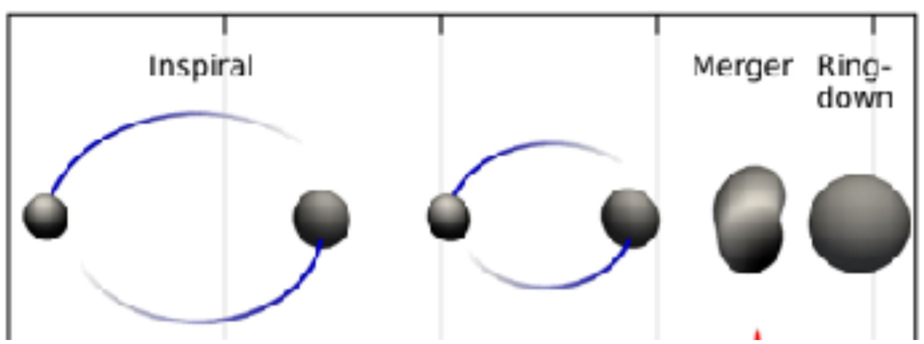




LIGO
September 14, 2015

- The ring-down is predicted by General Relativity to happen in a time $\dfrac{8\pi GM}{c^3} \sim 8$ milliseconds.





LIGO
September 14, 2015

- The ring-down is predicted by General Relativity to happen in a time $\frac{8\pi GM}{c^3}$ ~ 8 milliseconds. Curiously this happens to equal $\frac{\hbar}{k_B T_H}$: so the ring down can also be viewed as the approach of a quantum system to thermal equilibrium at the fastest possible rate!

Quantum entanglement

Black holes

Strange metals

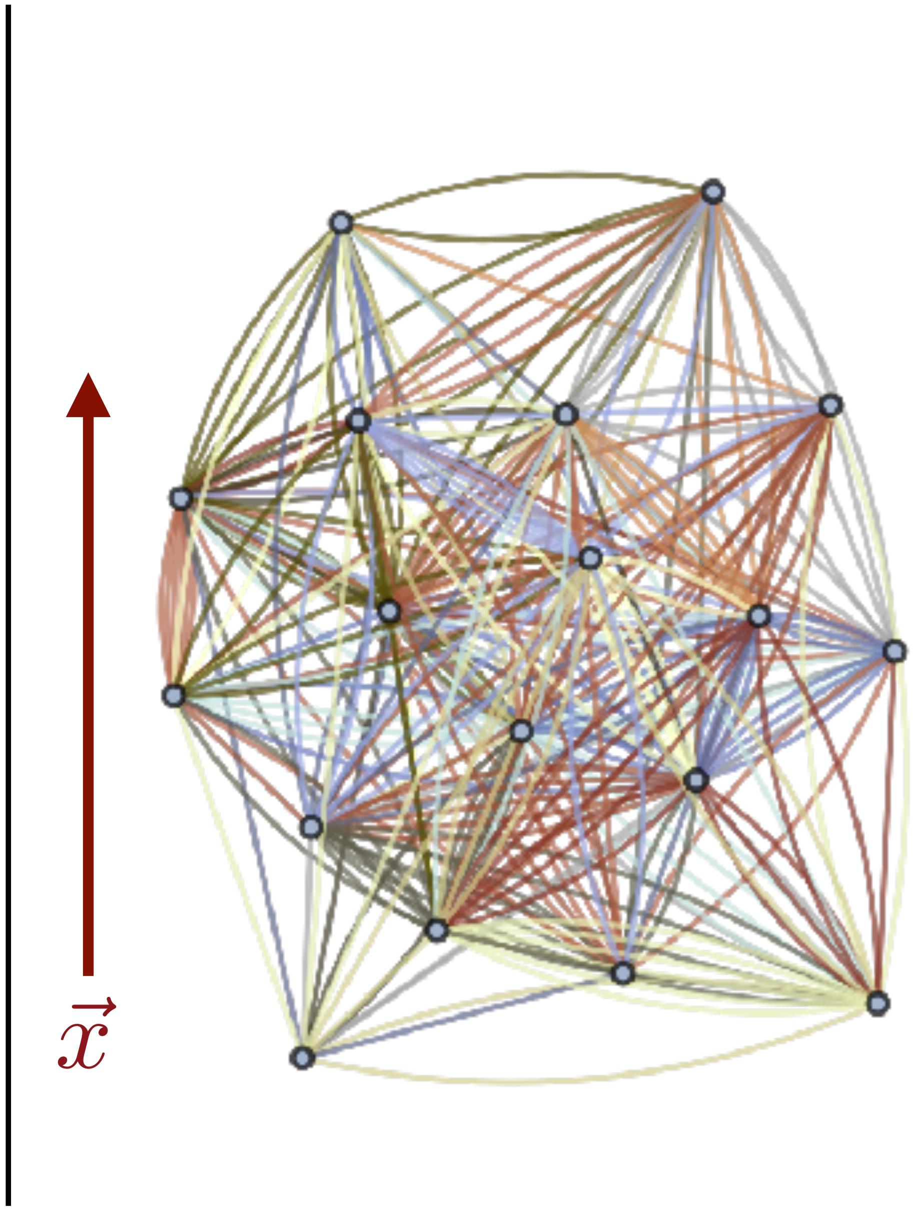
Quantum entanglement

Black holes

Strange metals

The SYK model is both a strange metal and a black hole!

SYK and black holes



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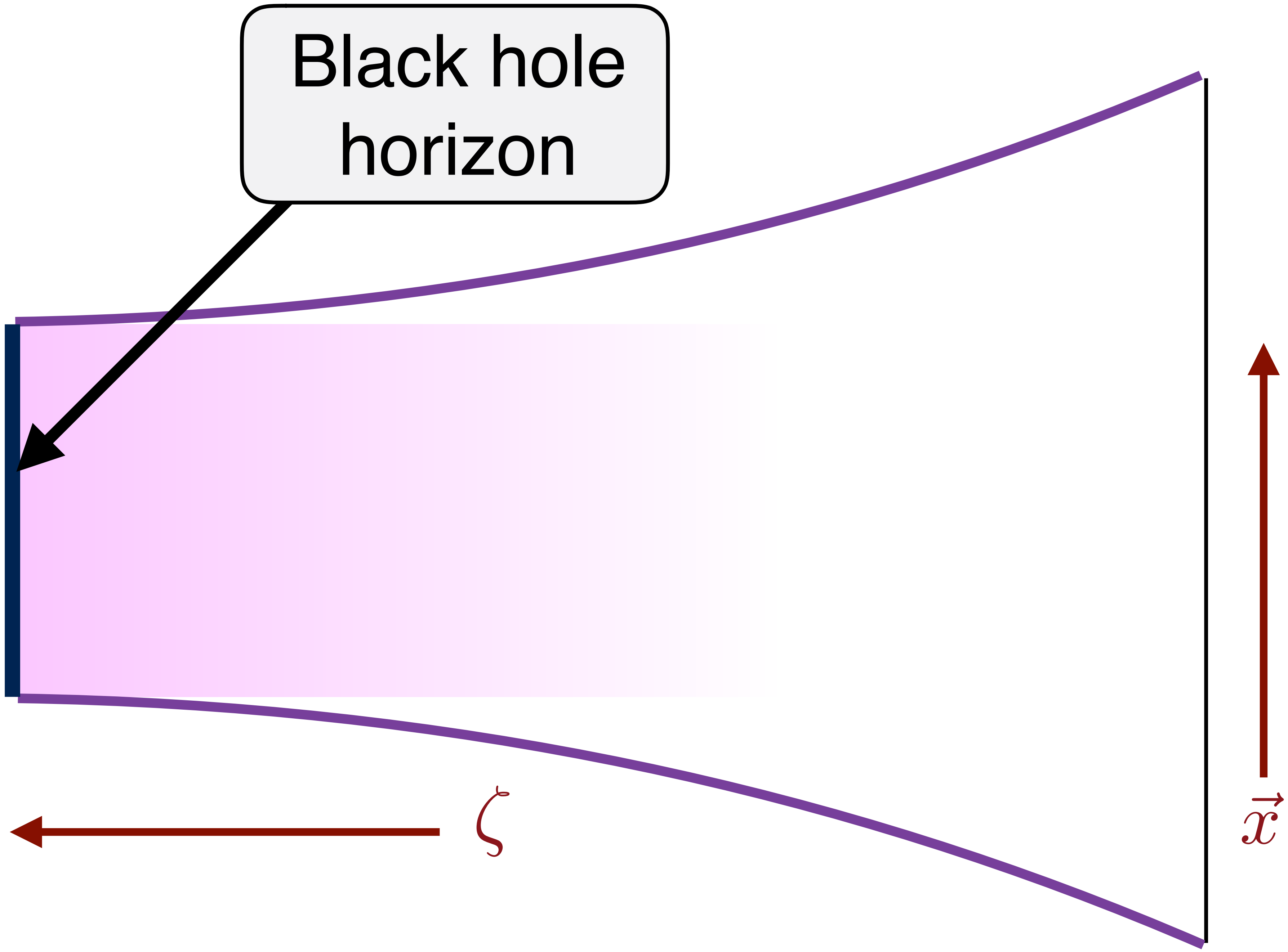
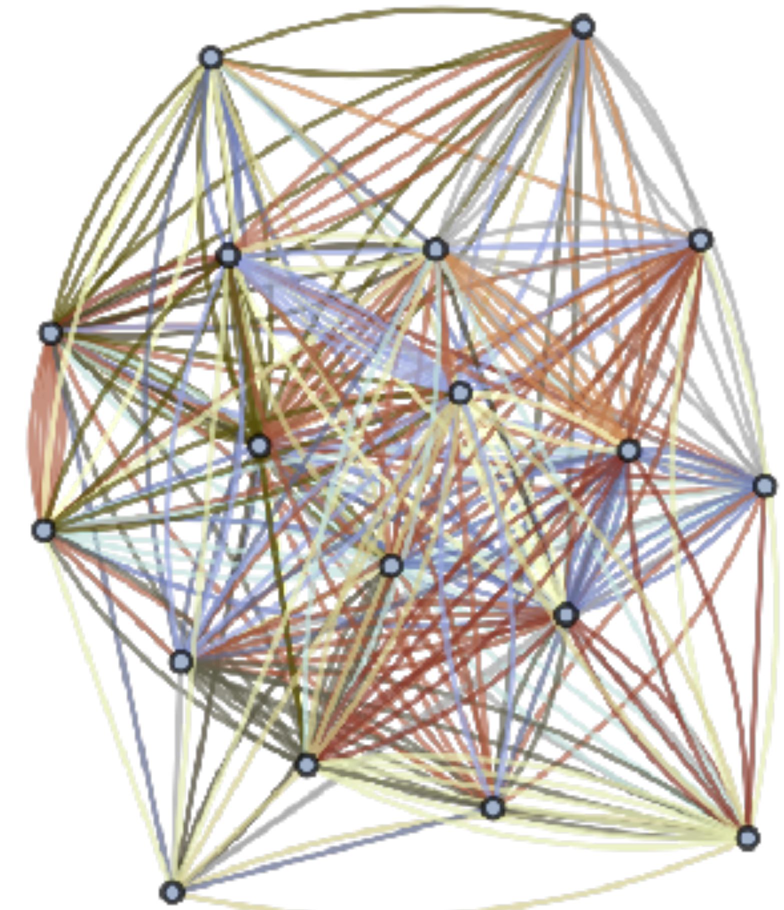
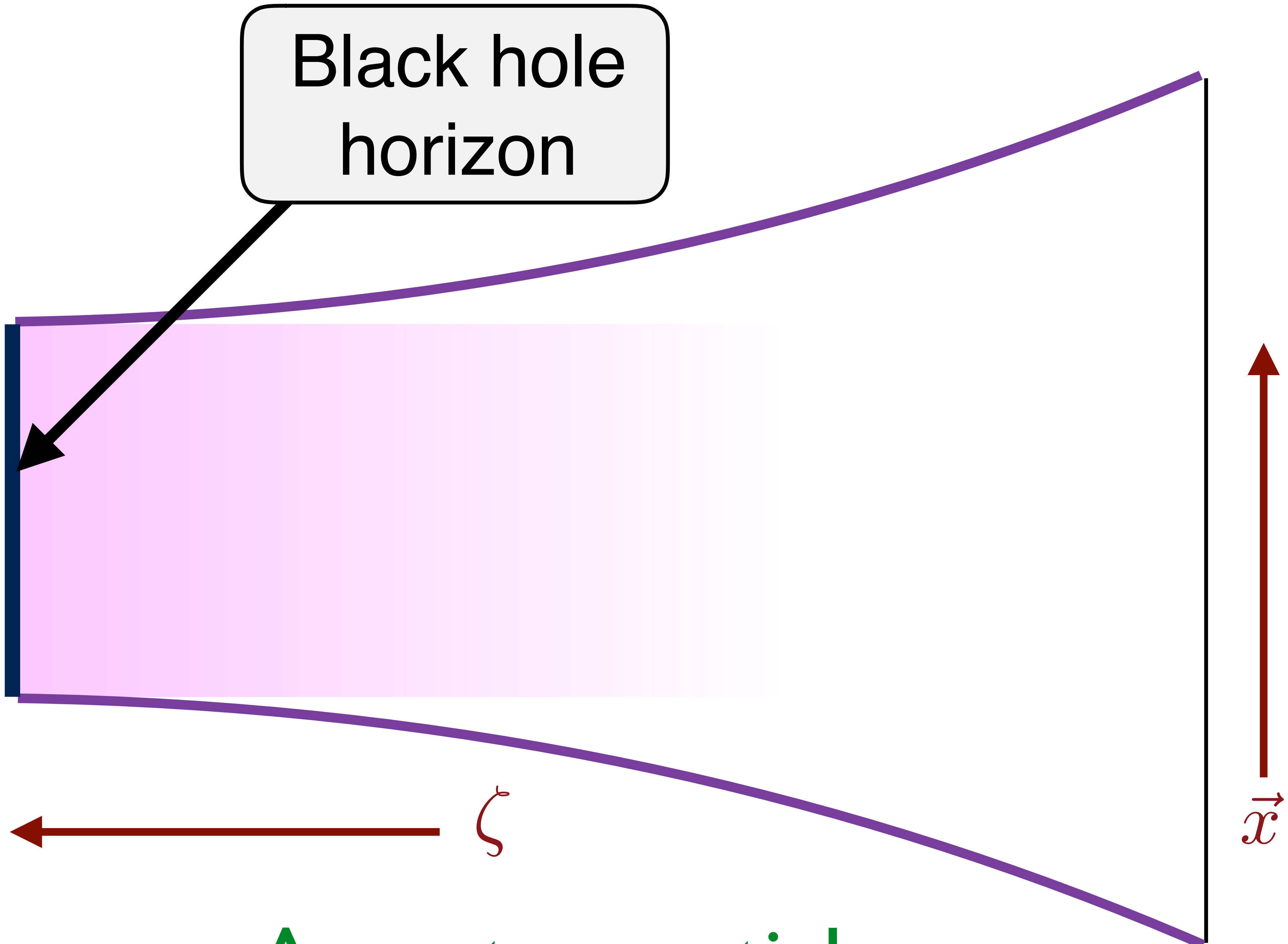
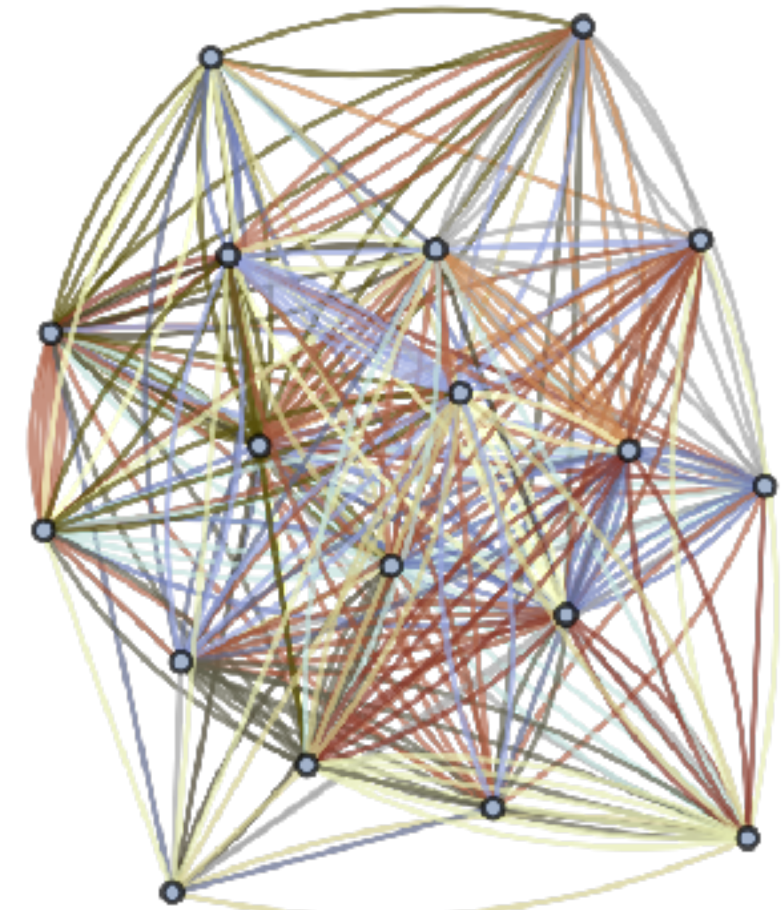




The SYK model has "dual" description in which an extra spatial dimension, ζ, emerges. The curvature of this "emergent" spacetime is described by Einstein's theory of general relativity

SYK and black holes

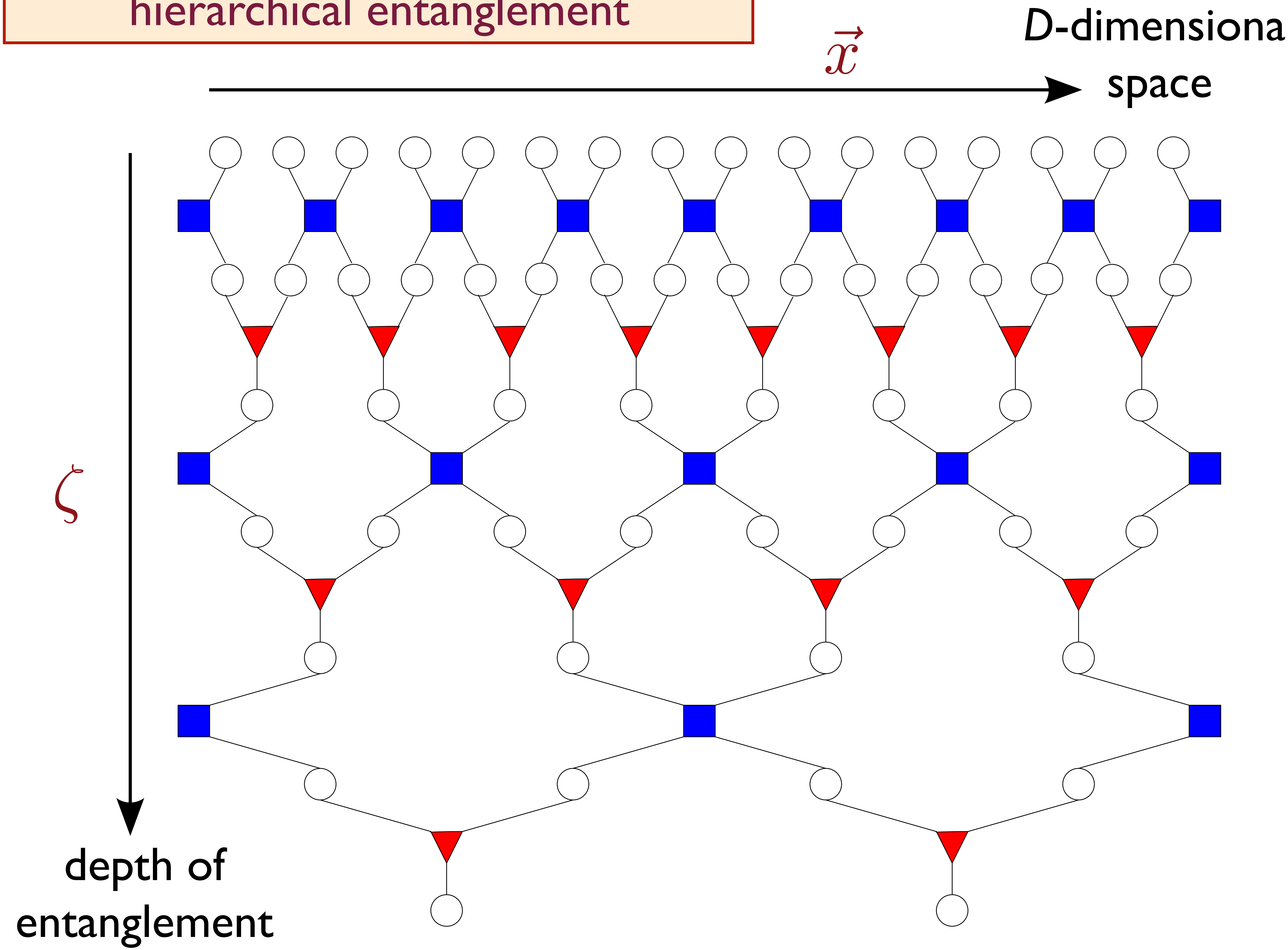


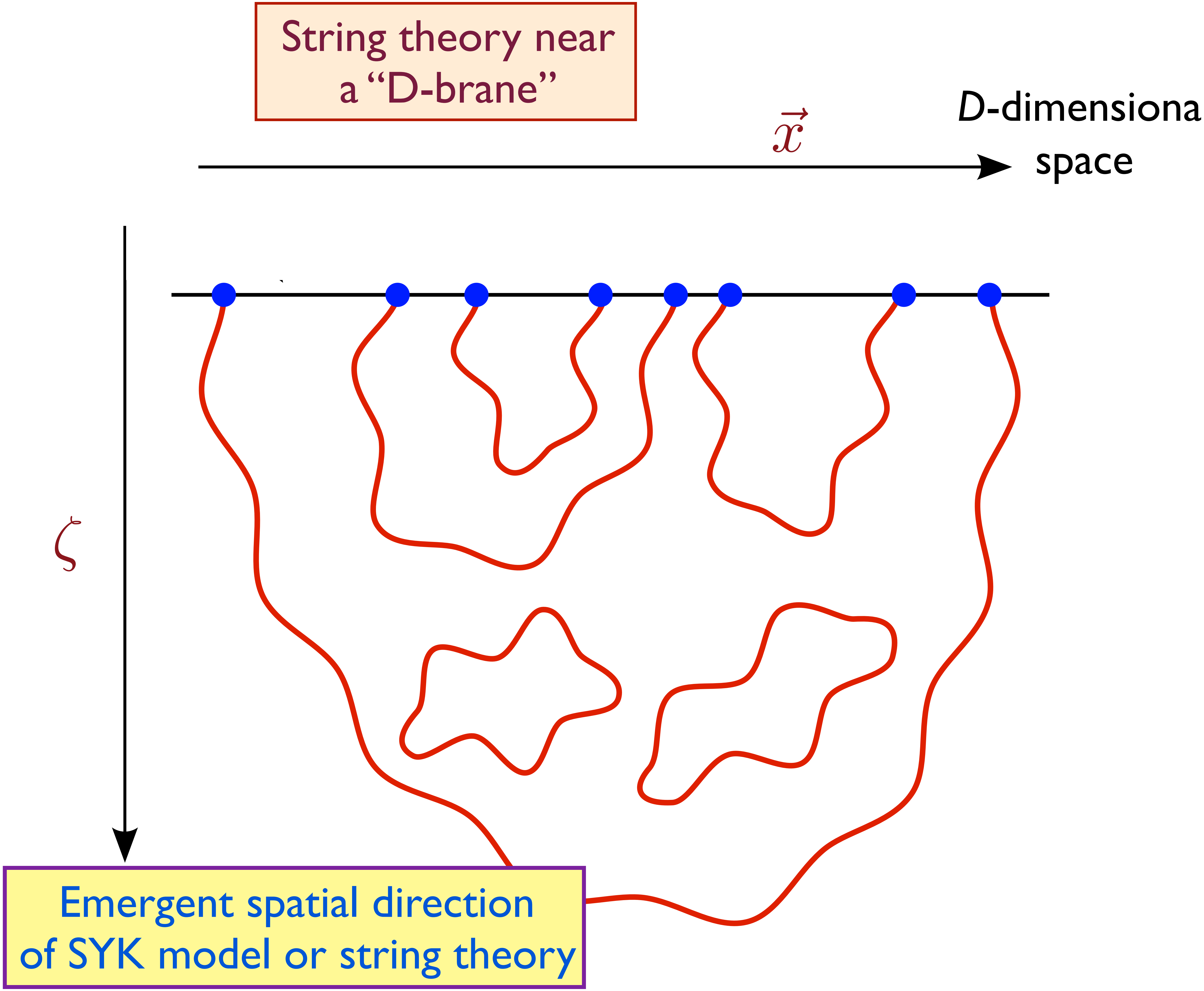


An extra spatial dimension emerges from quantum entanglement!

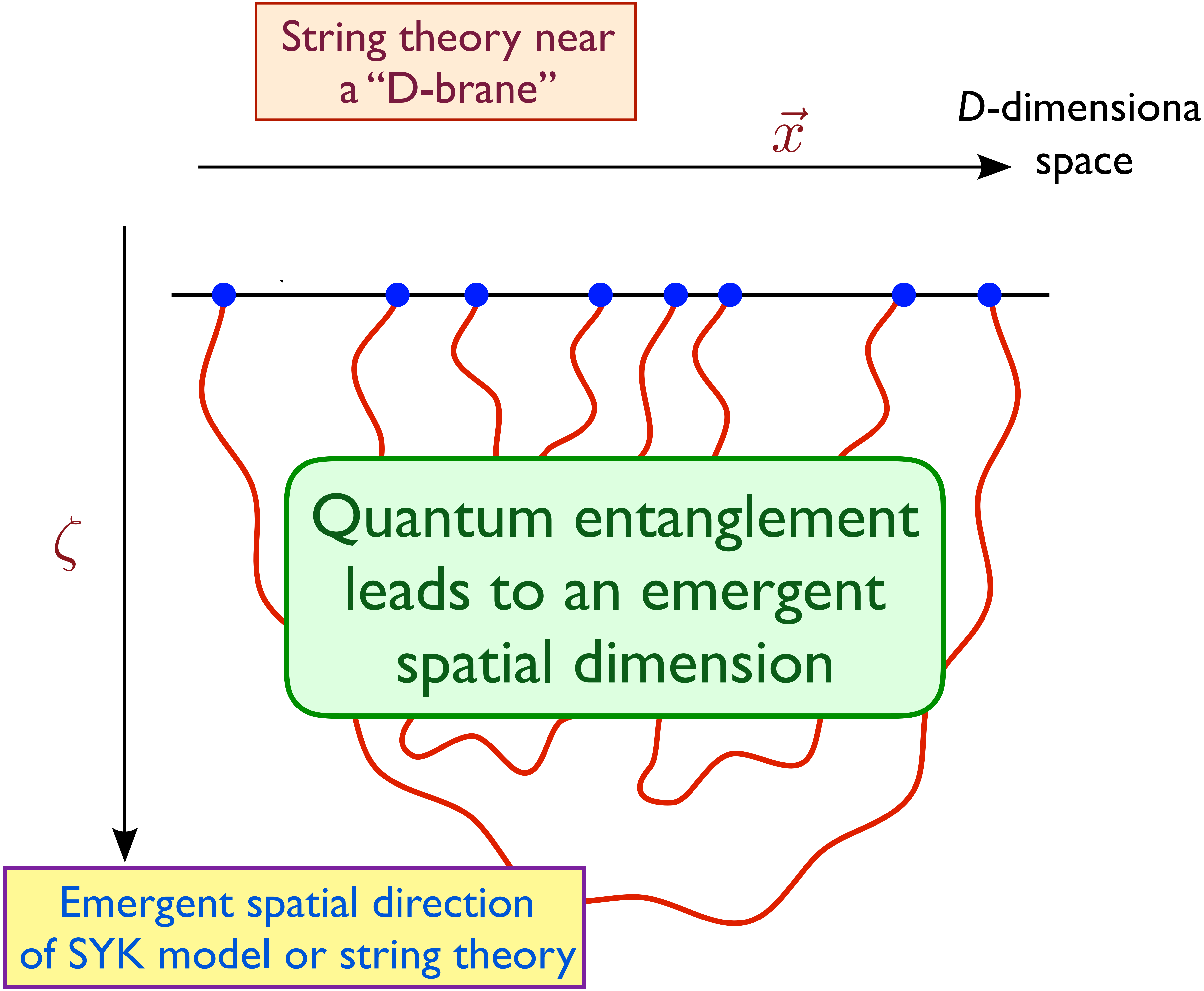
SS 2010; A. Kitaev, 2015

Tensor network of hierarchical entanglement





String theory near a “D-brane”
$\vec{x}$
D-dimensional space
ζ
Emergent spatial direction of SYK model or string theory



String theory near a “D-brane”
$\vec{x}$
D-dimensional space
ζ
Quantum entanglement leads to an emergent spatial dimension
Emergent spatial direction of SYK model or string theory

Quantum entanglement

Black holes

Strange metals

The SYK model is both a strange metal and a black hole!

Quantum matter <u>without</u> quasiparticles:

- No quasiparticle decomposition of low-lying states.
- Thermalization and many-body chaos in the shortest possible time of order $\hbar/(k_B T)$.

Quantum matter without quasiparticles:

- No quasiparticle decomposition of low-lying states.
- Thermalization and many-body chaos in the shortest possible time of order $\hbar/(k_B T)$.
- These are also characteristics of black holes in quantum gravity.