The New York Times

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

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

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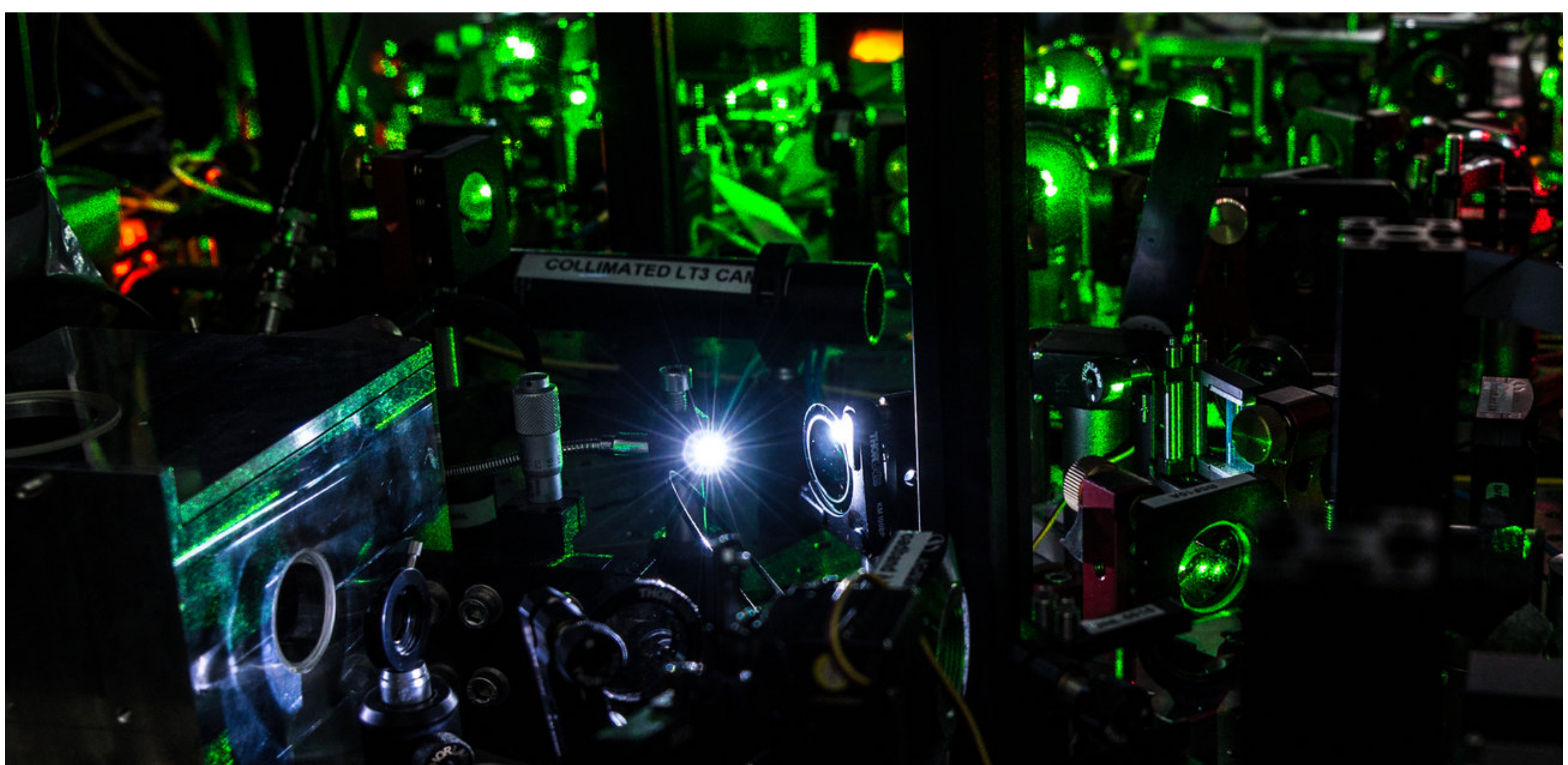

Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

Ultra-spooky action at a distance: from quantum materials in the lab to black holes

Simons Foundation, New York
January 21, 2020

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

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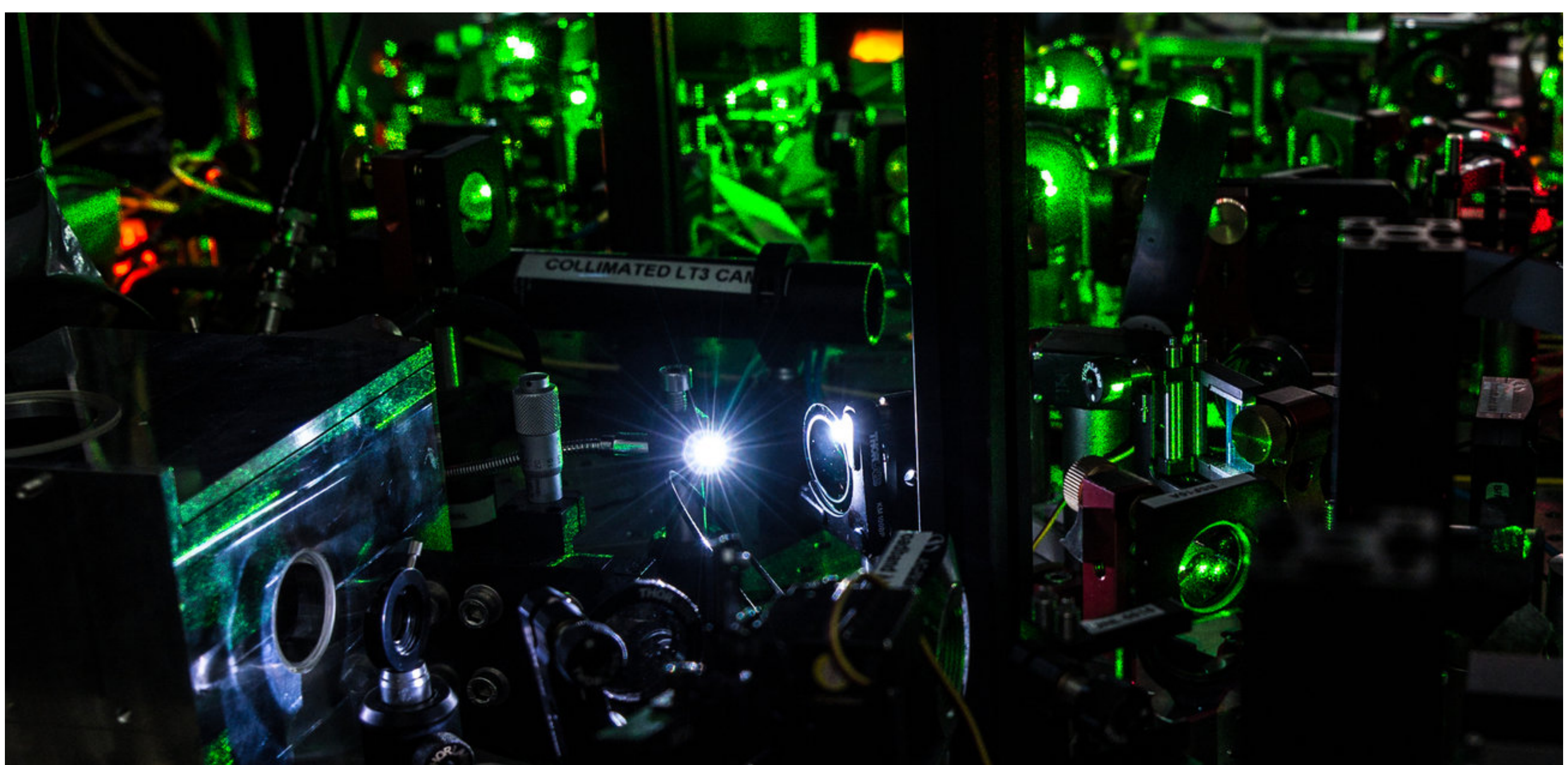

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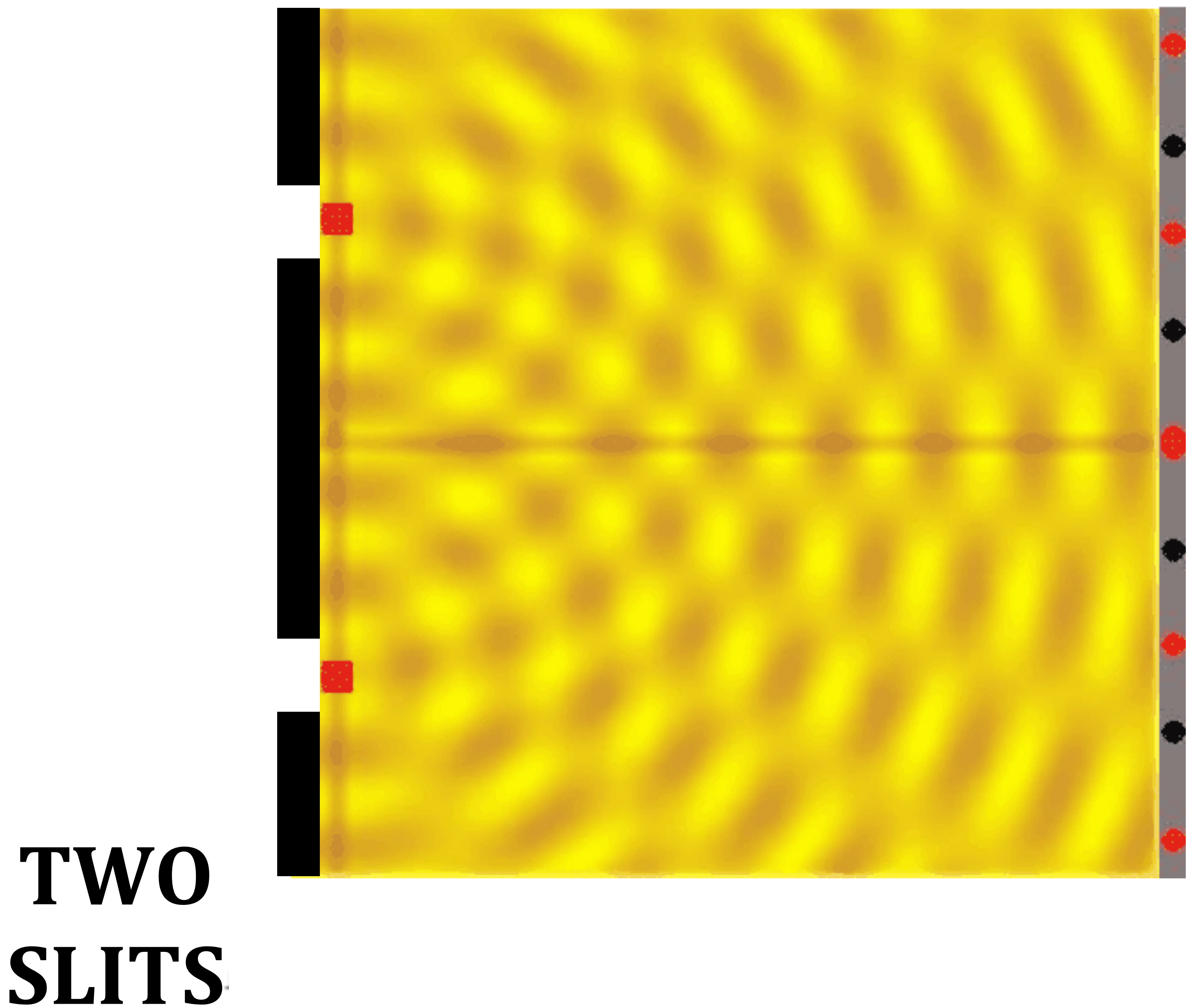
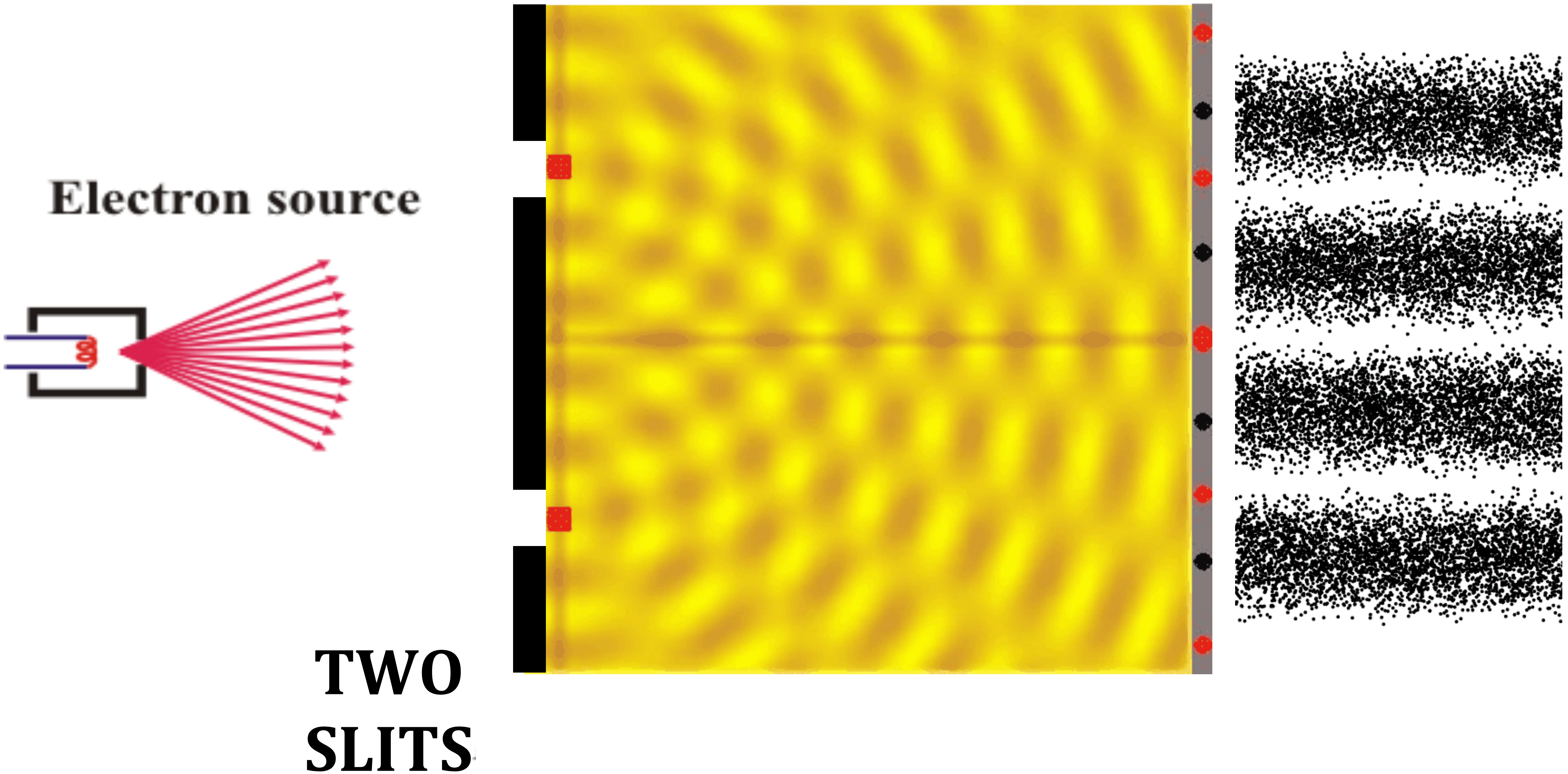
Quantum entanglement

The double slit experiment



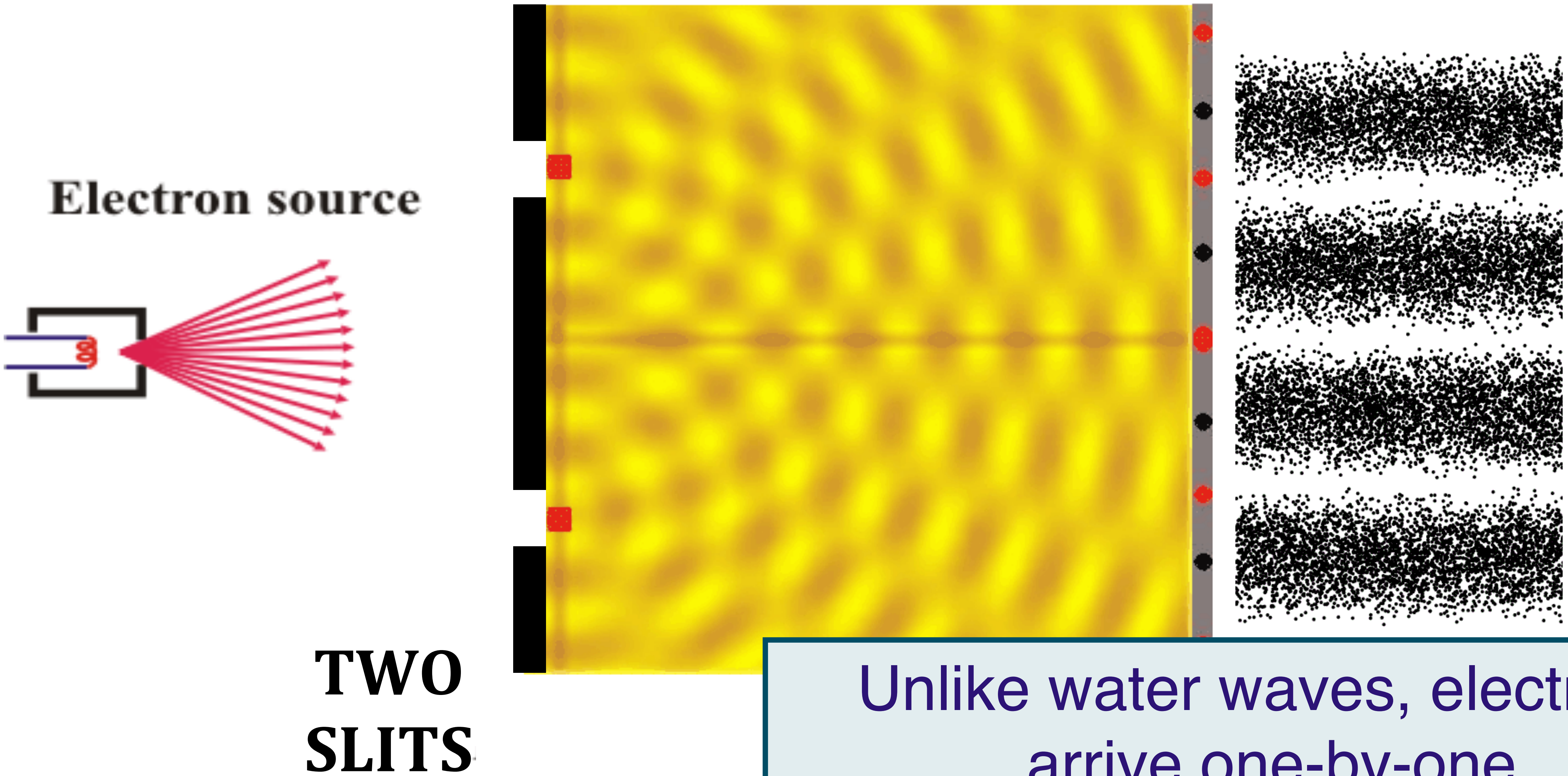
Interference of water waves

The double slit experiment



Interference of electrons

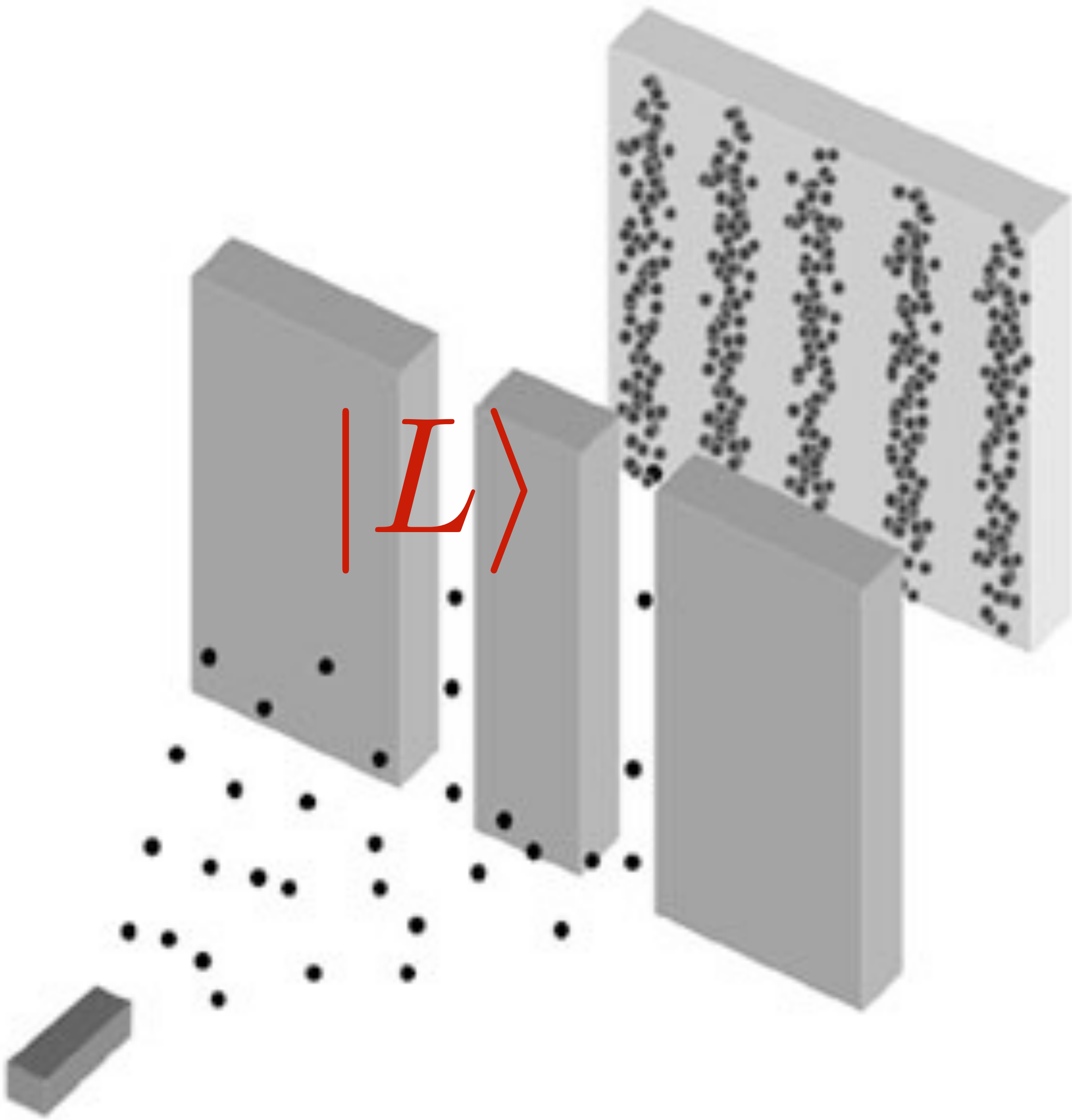
The double slit experiment



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

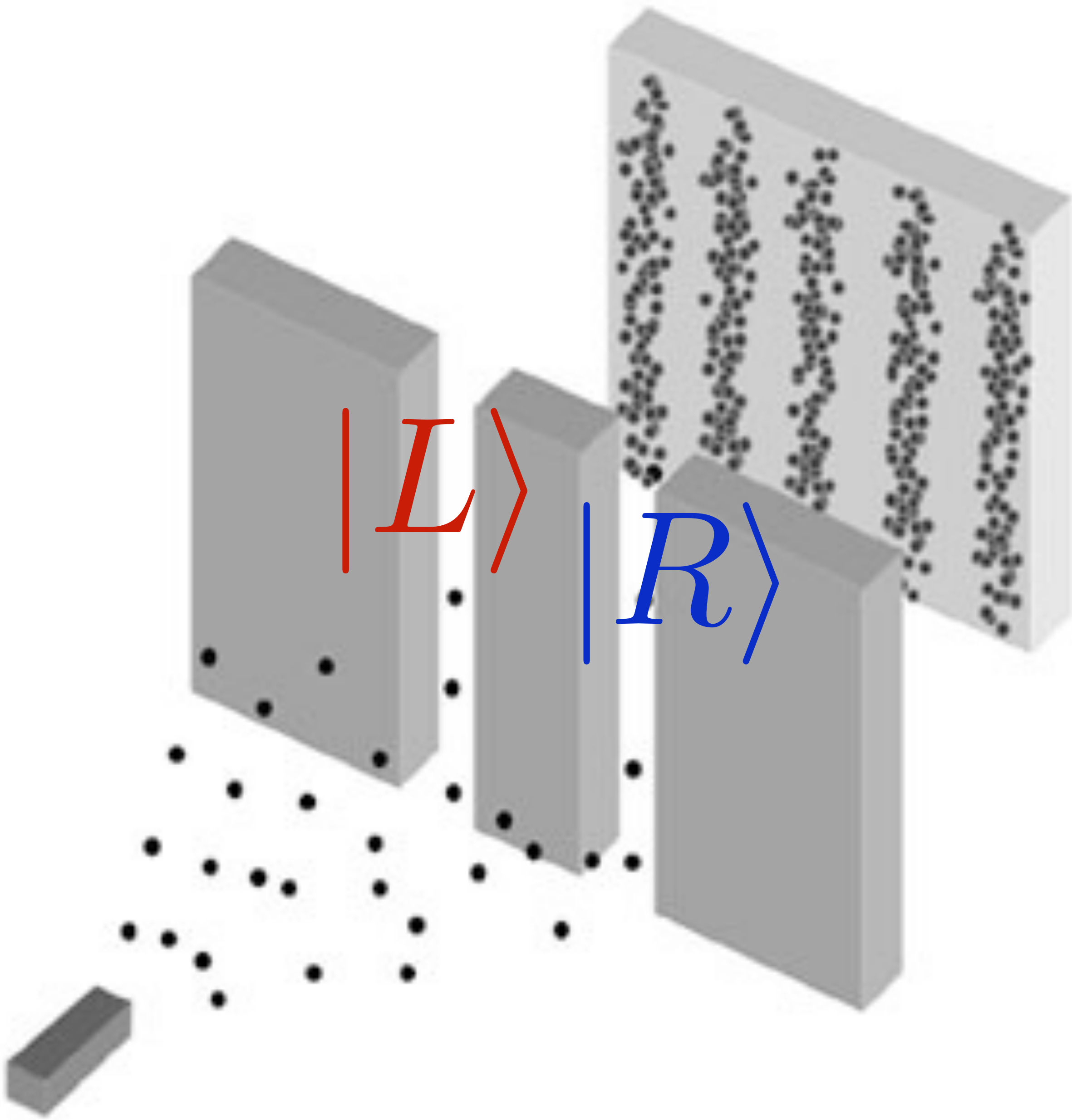
Interference of electrons

The double slit experiment



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

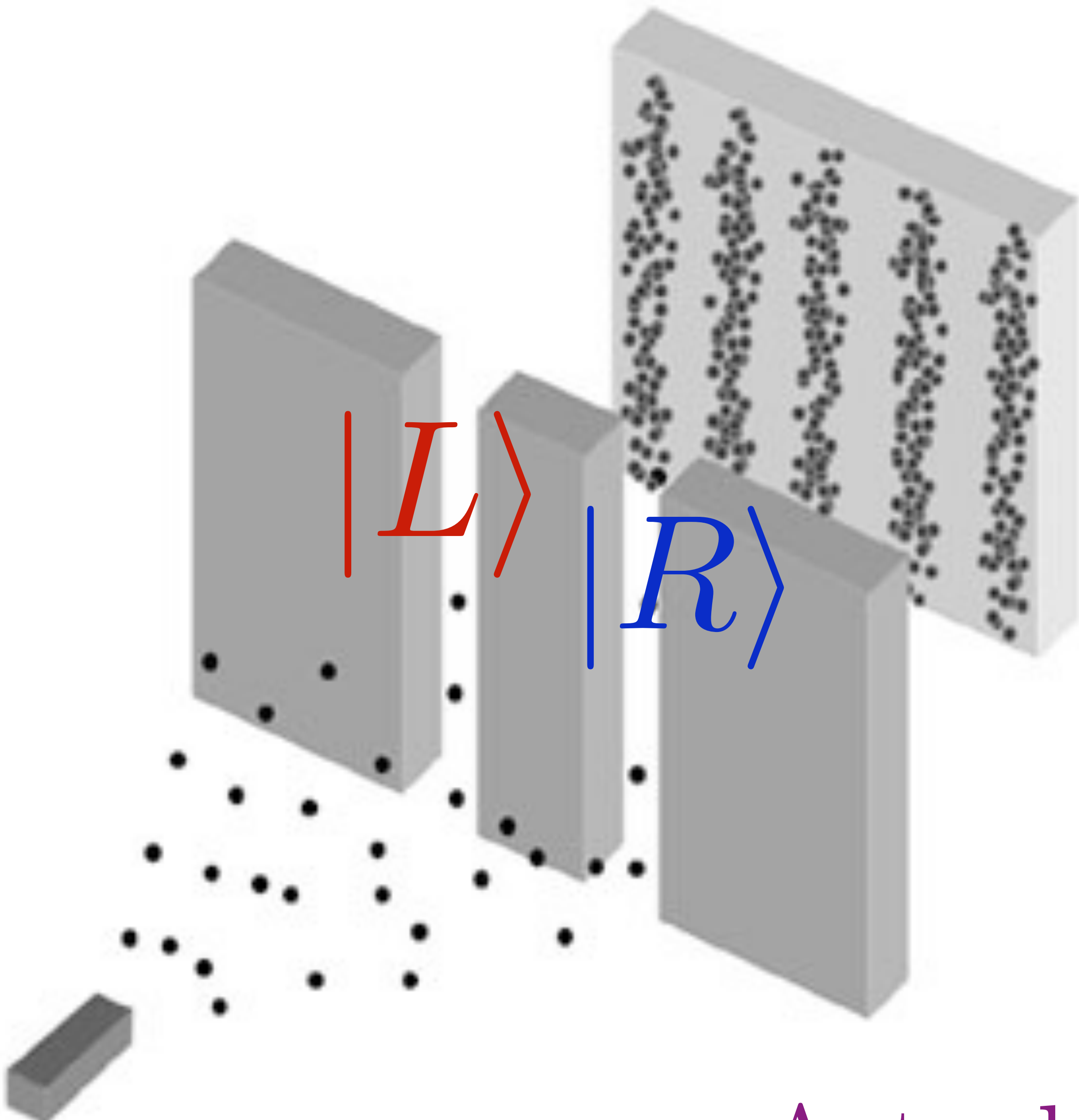
The double slit experiment



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

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

The double slit experiment



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

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

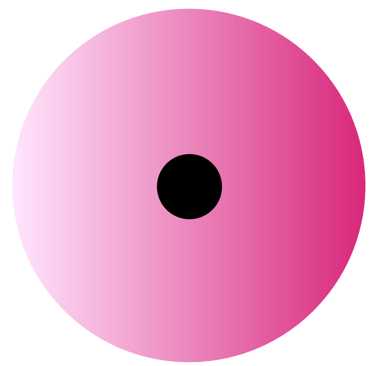
Actual state of *each* electron is

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

Quantum Entanglement: quantum superposition with more than one particle

Quantum Entanglement: quantum superposition with more than one particle

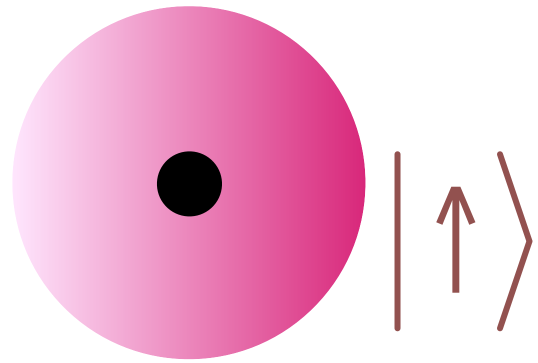
Hydrogen atom:



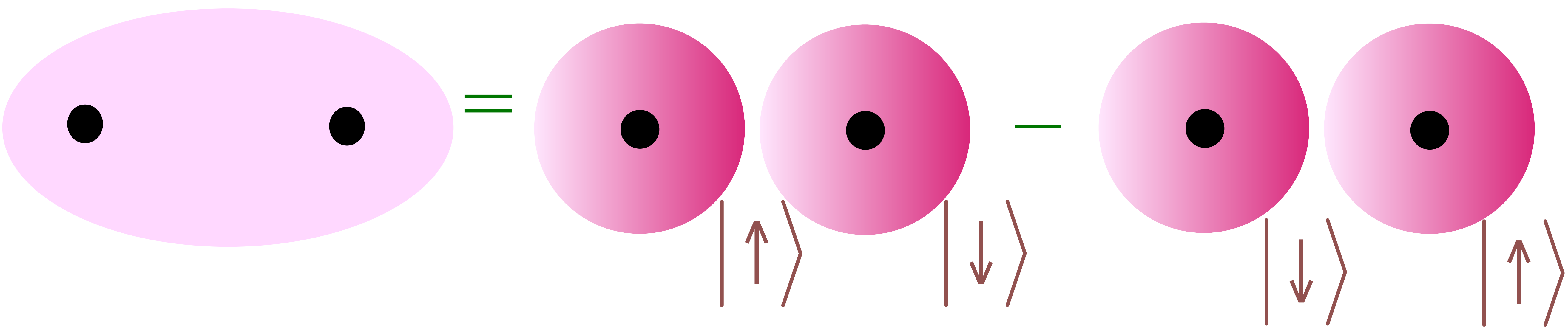
$|\uparrow\rangle$

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

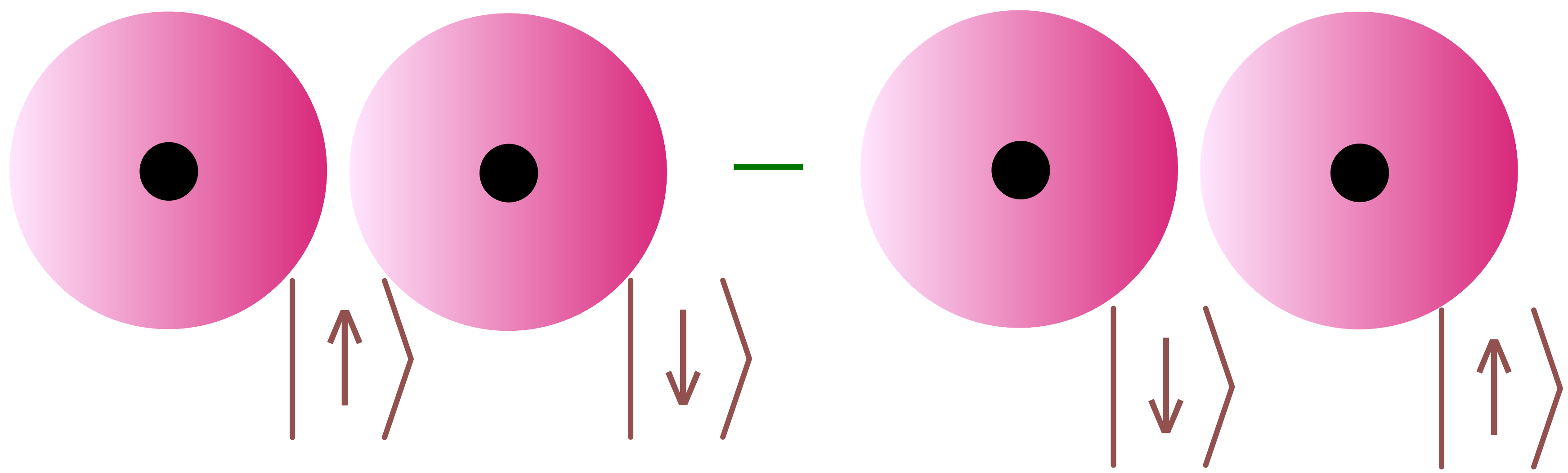


Hydrogen molecule:

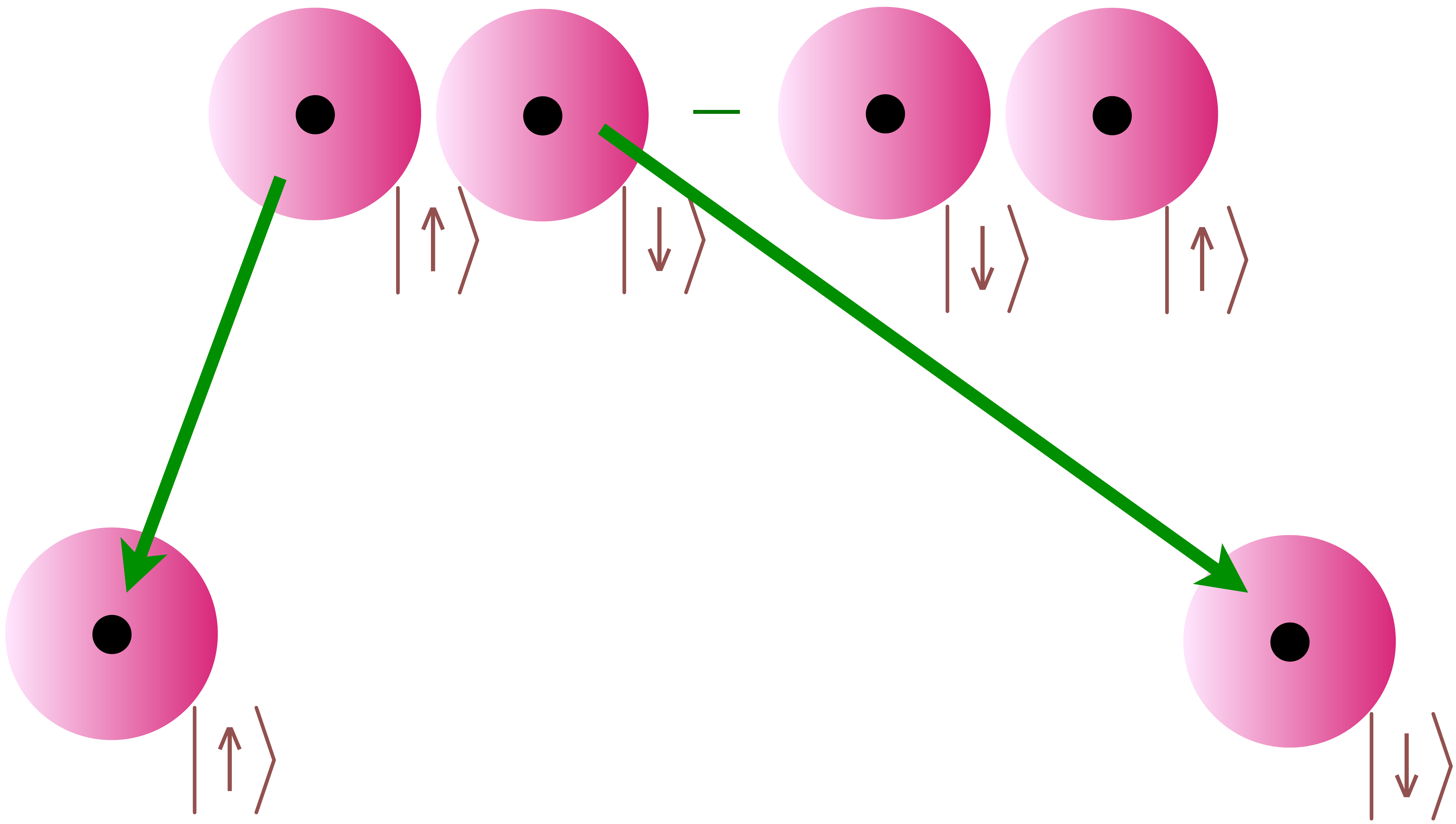


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

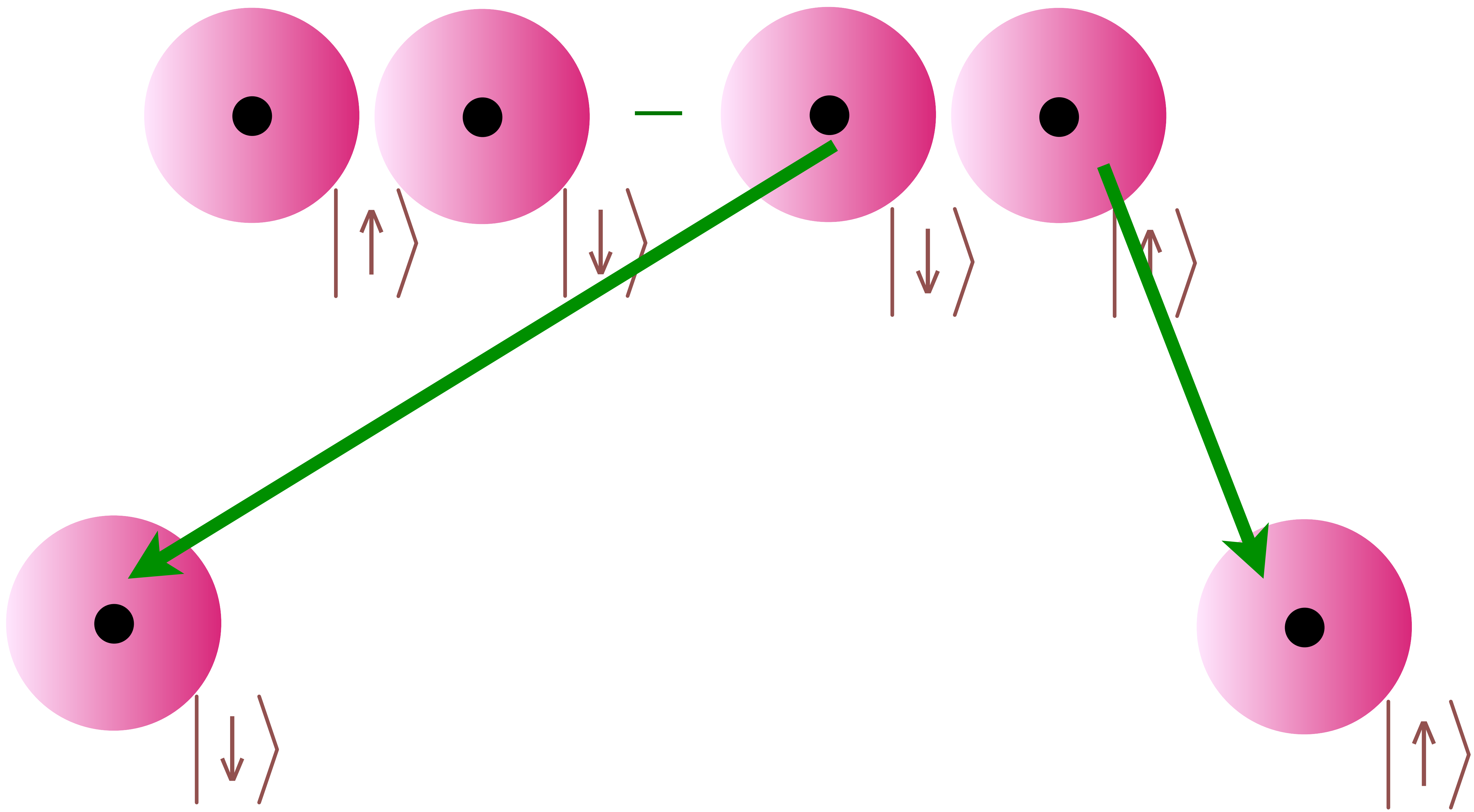
Quantum Entanglement: quantum superposition with more than one particle



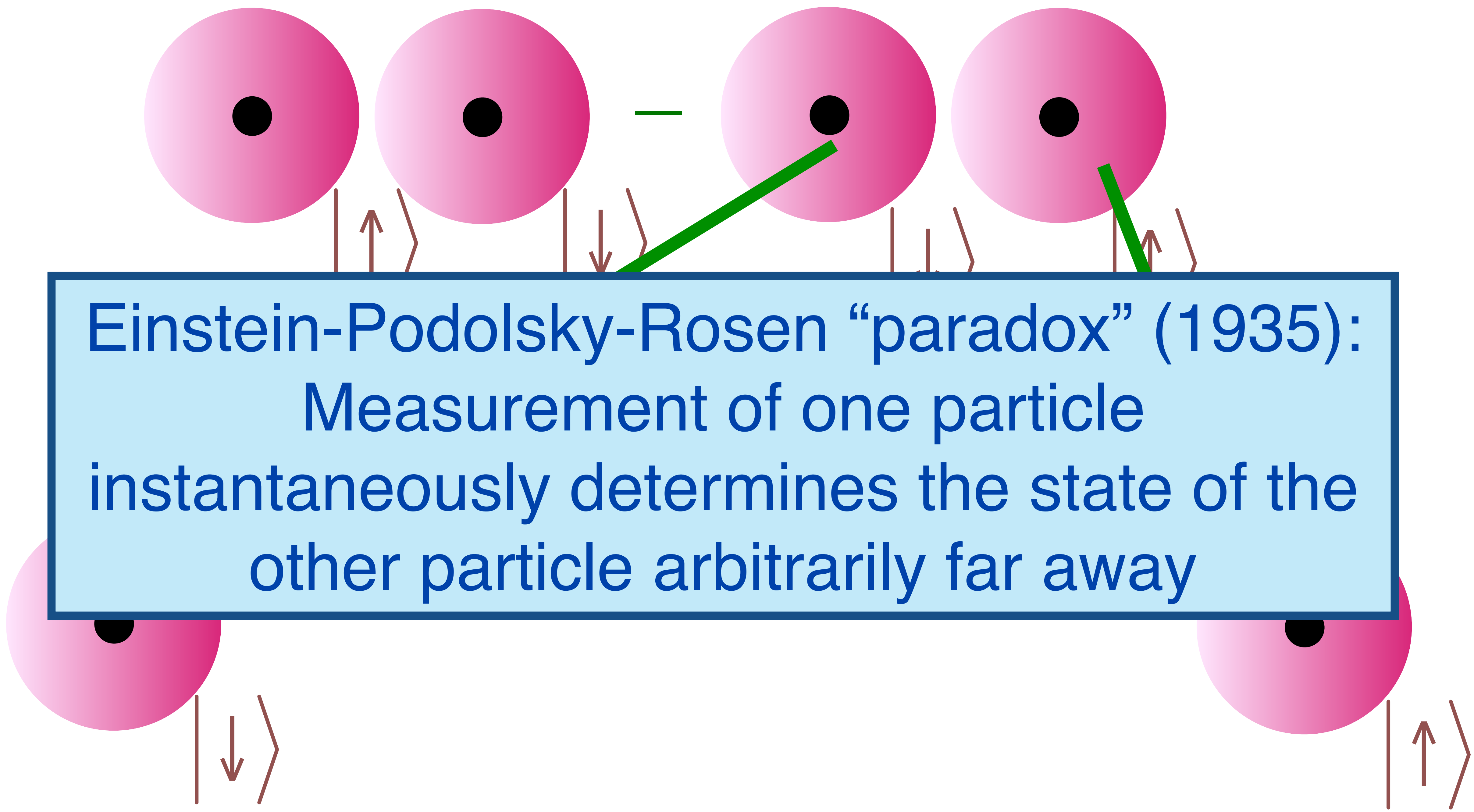
Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



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

Quantum entanglement

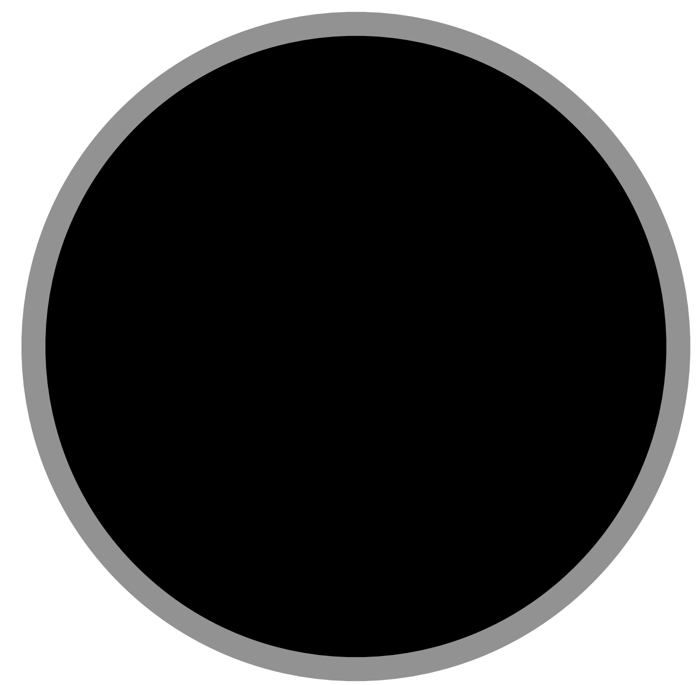
Quantum entanglement

Black holes

Black Holes

Objects so dense that light is gravitationally bound to them.

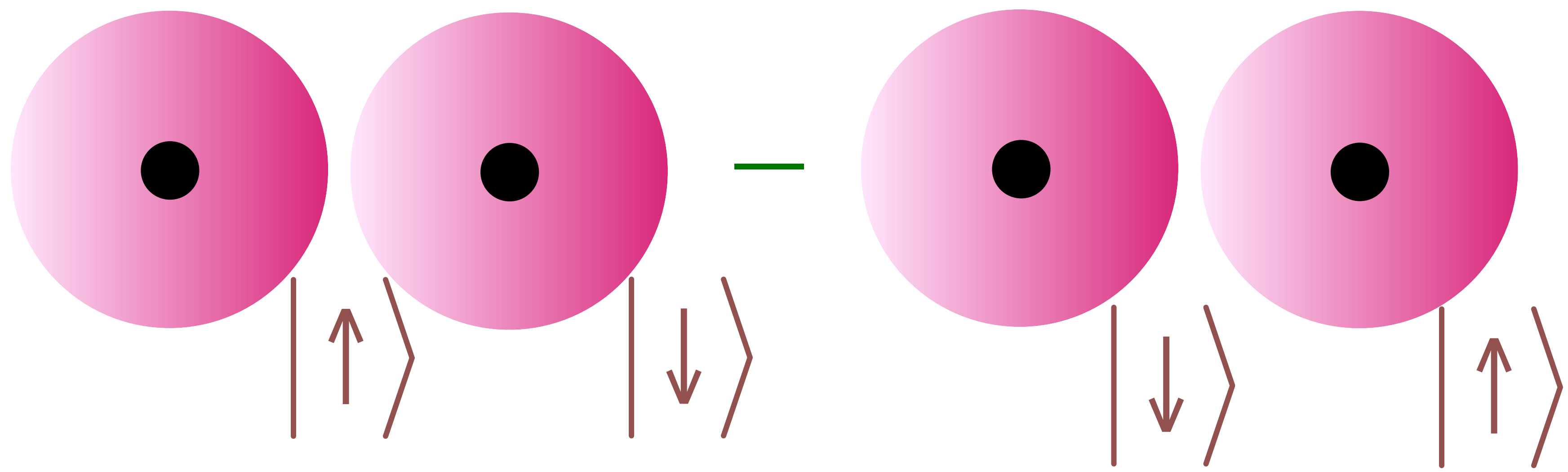
In Einstein's theory, the region inside the black hole **horizon** is disconnected from the rest of the universe.



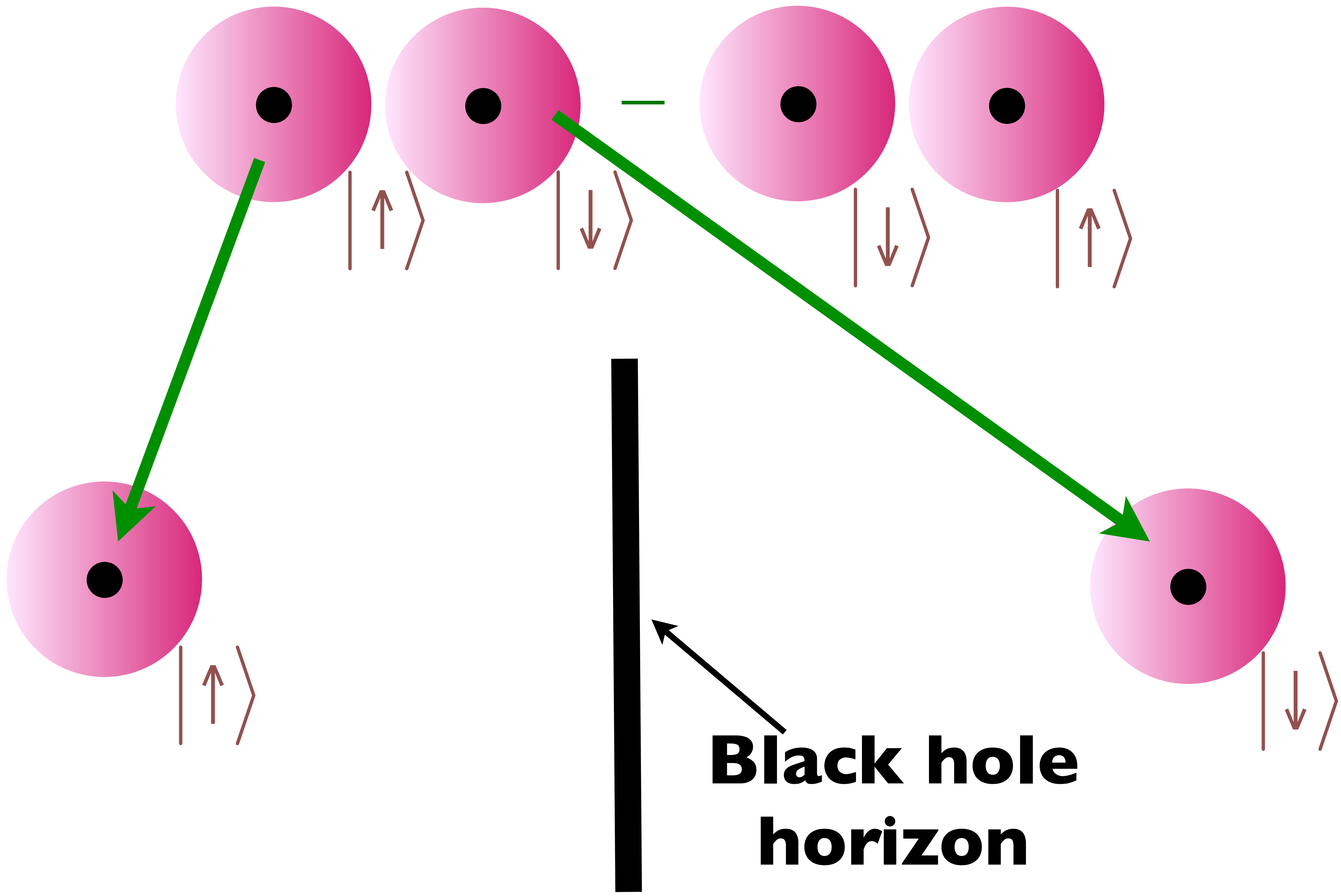
$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

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

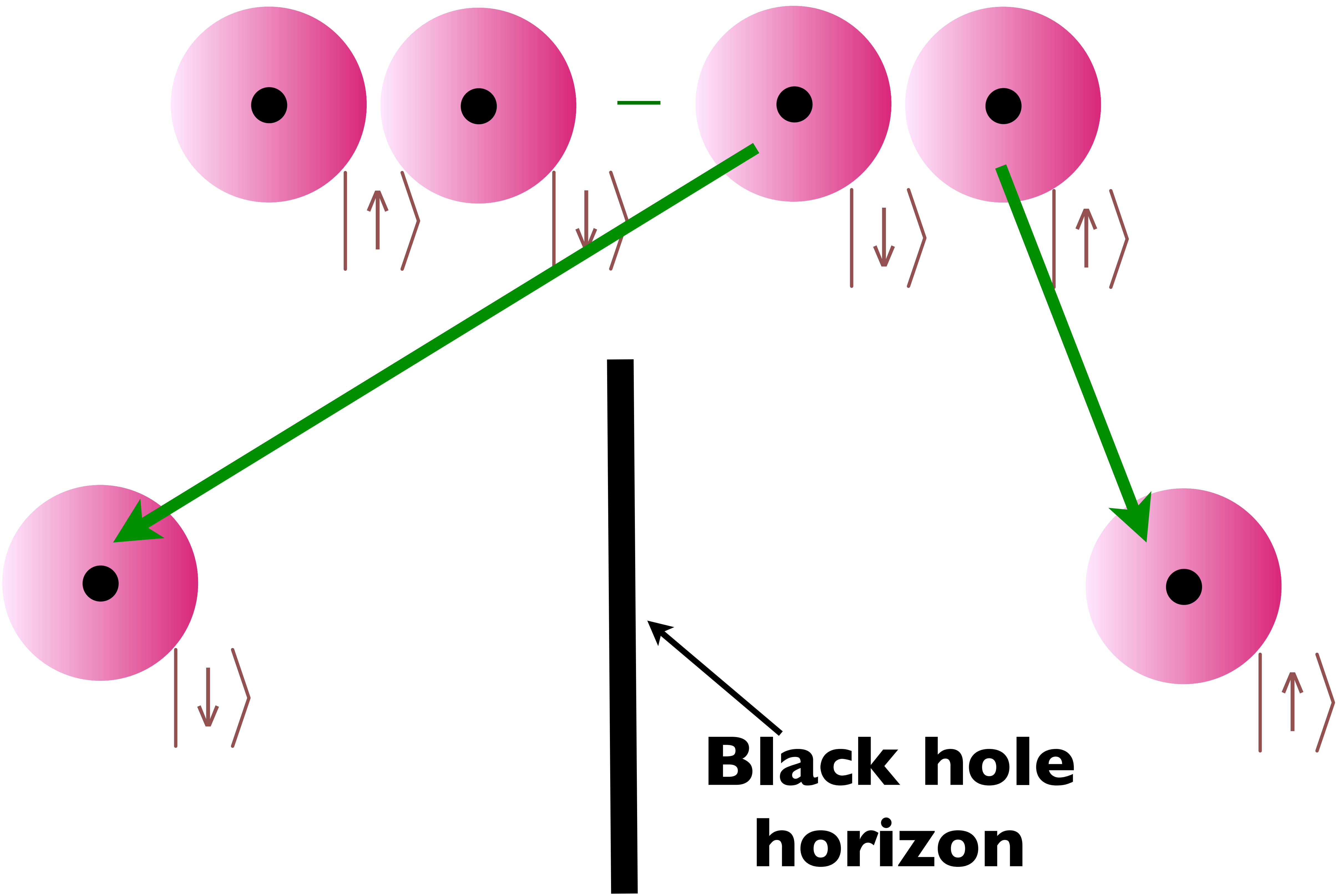
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

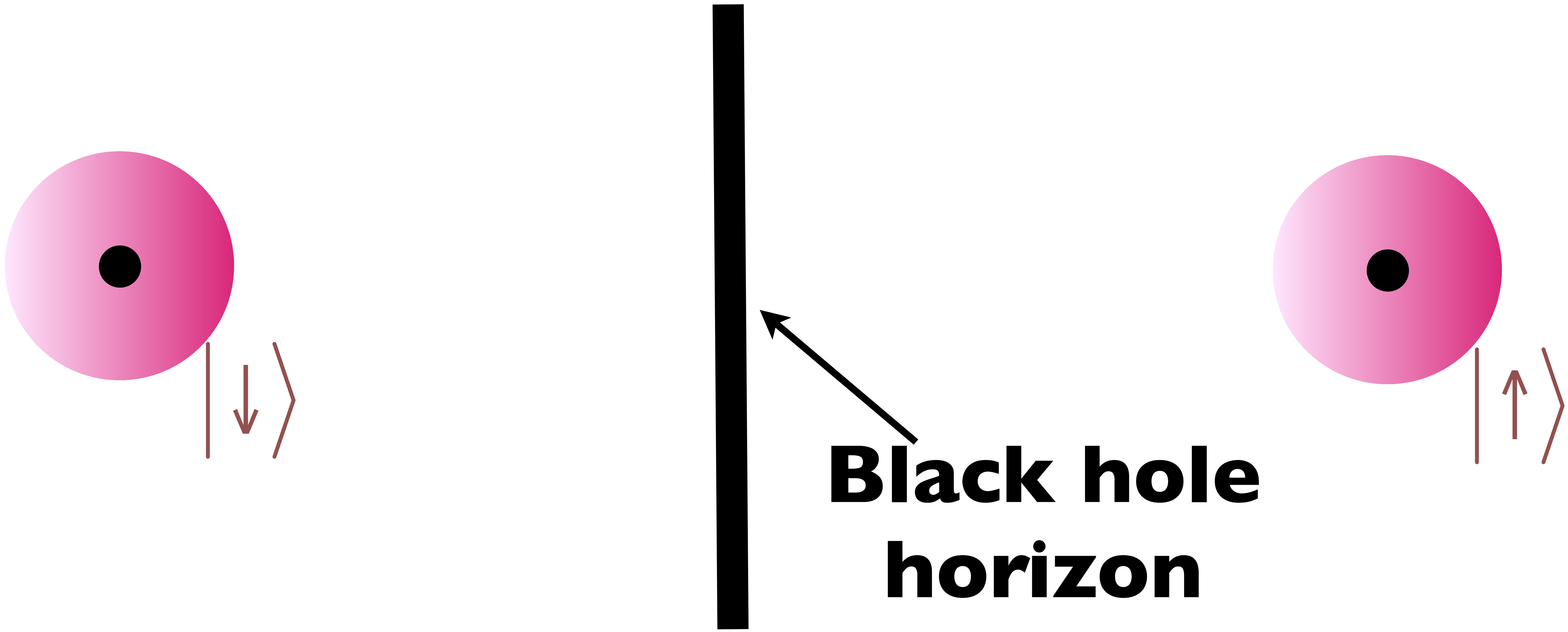


Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

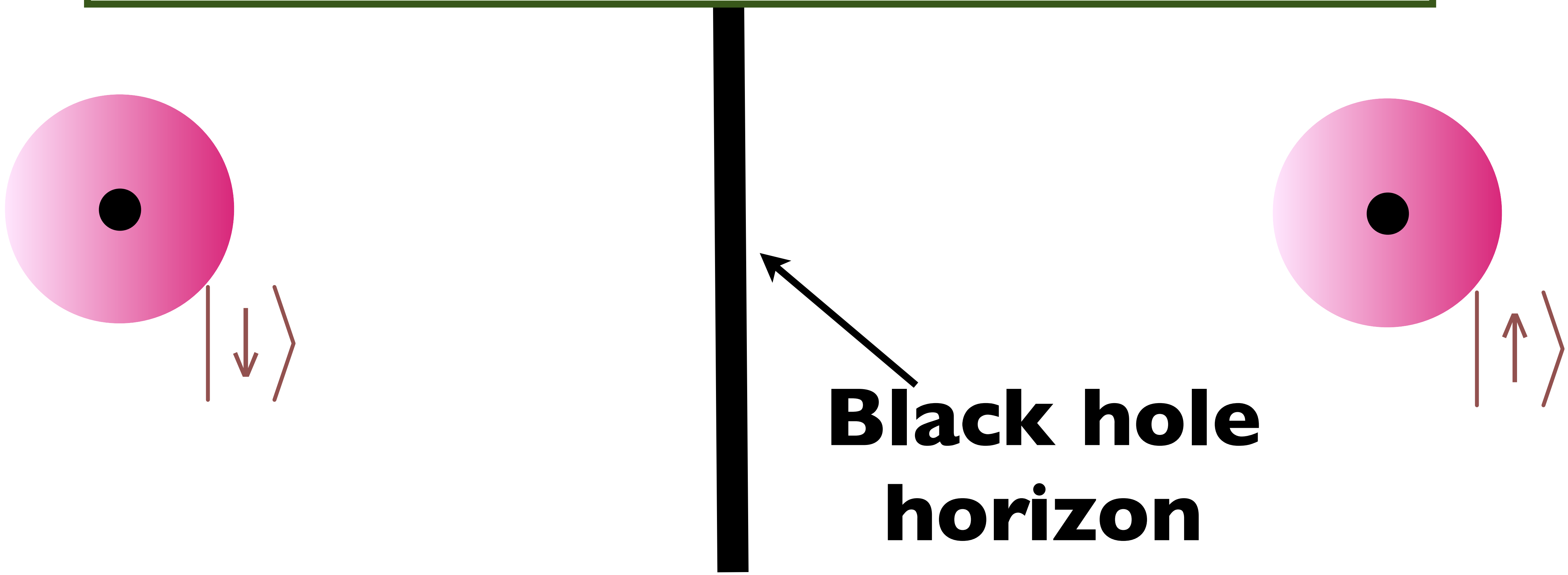
There is quantum entanglement between the inside and outside of a black hole



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)

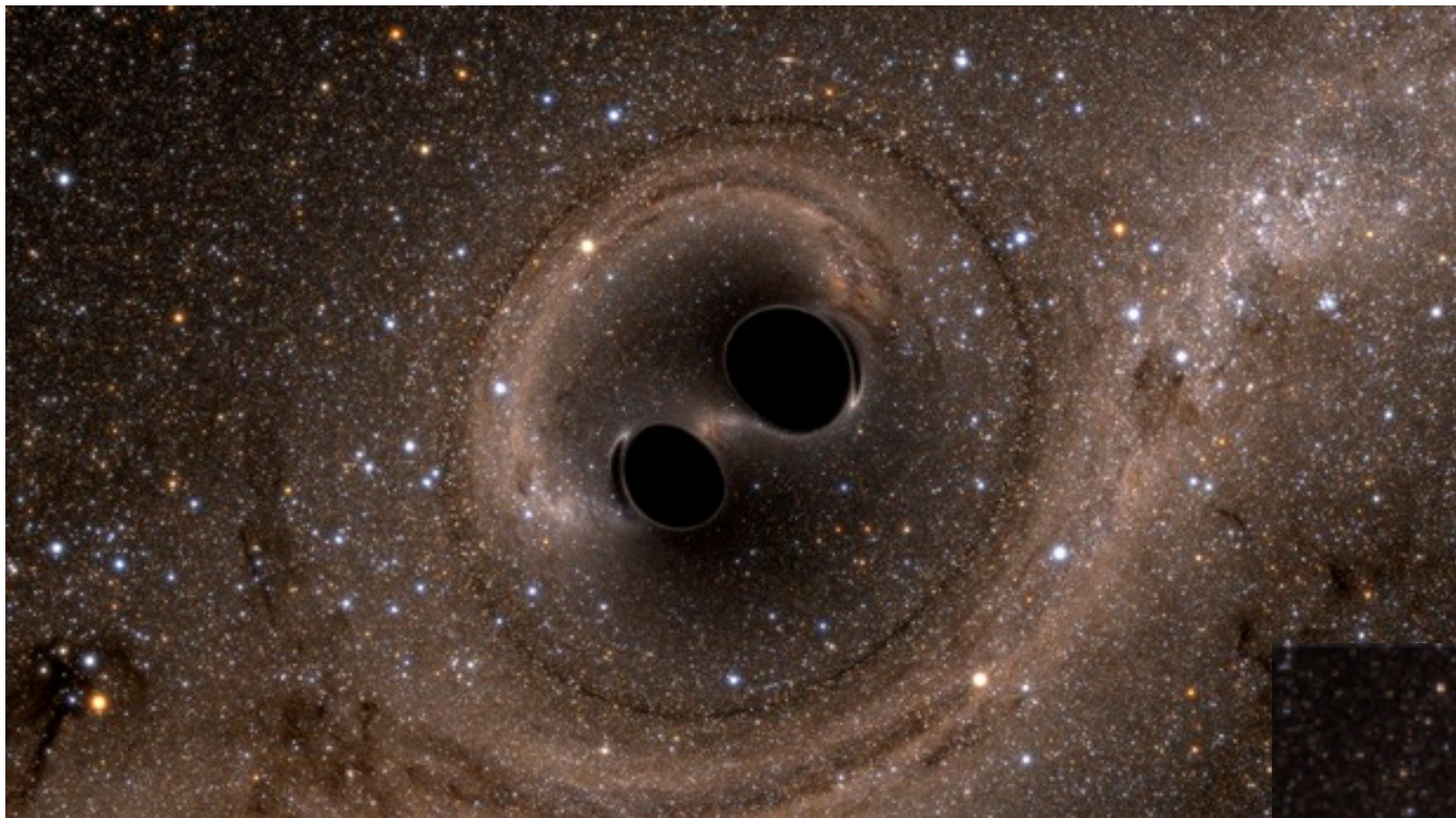


Quantum Black holes

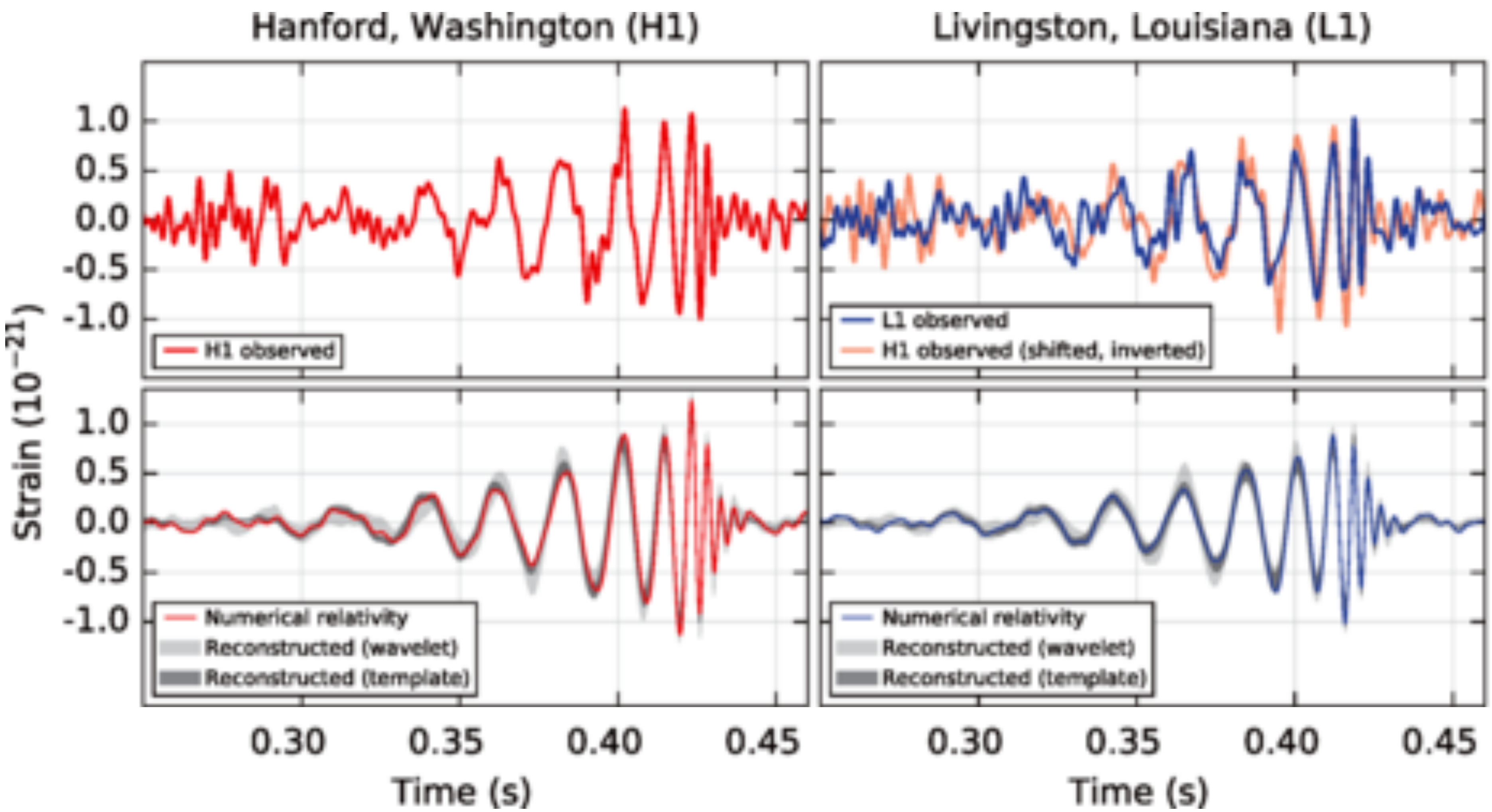
- Black holes have an entropy and a temperature, T_H
- The entropy is proportional to their surface area.

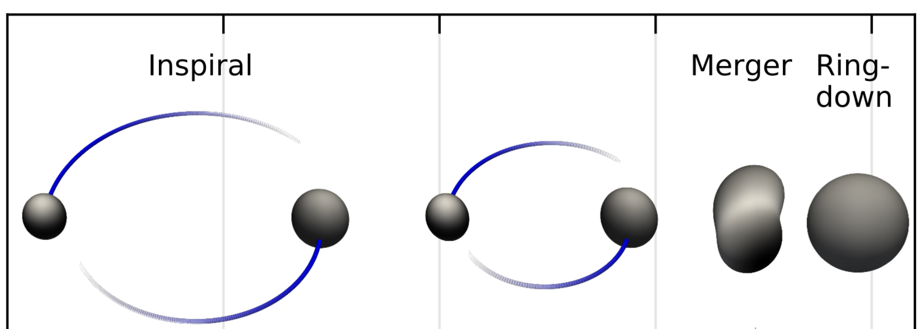
J. D. Bekenstein, PRD **7**, 2333 (1973)
S.W. Hawking, Nature **248**, 30 (1974)

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

$$\boxed{\frac{\hbar}{k_B T_H},} \qquad \hbar \text{ Planck's constant}, \quad k_B \text{ Boltzmann's constant}$$

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

Quantum entanglement

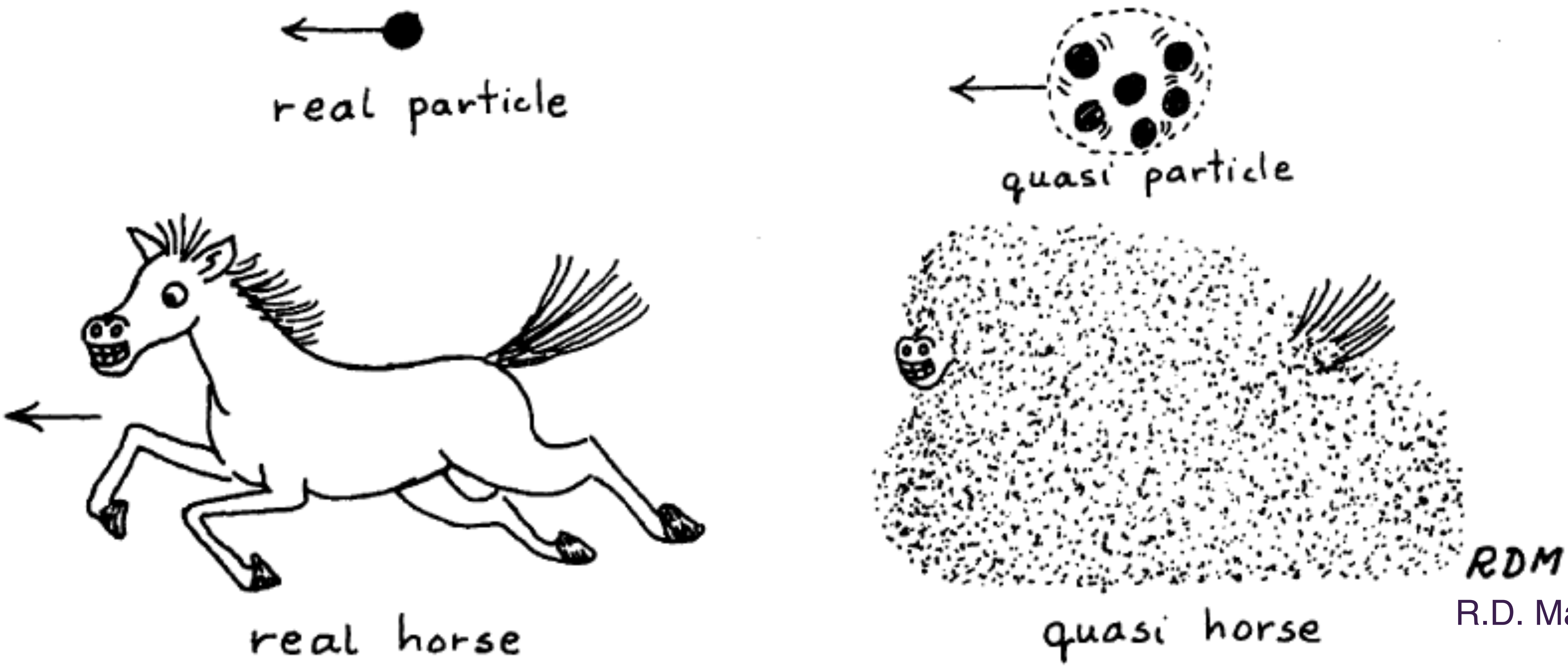
Black holes

Metals (ordinary and strange) and superconductors

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

Current flow with quasiparticles

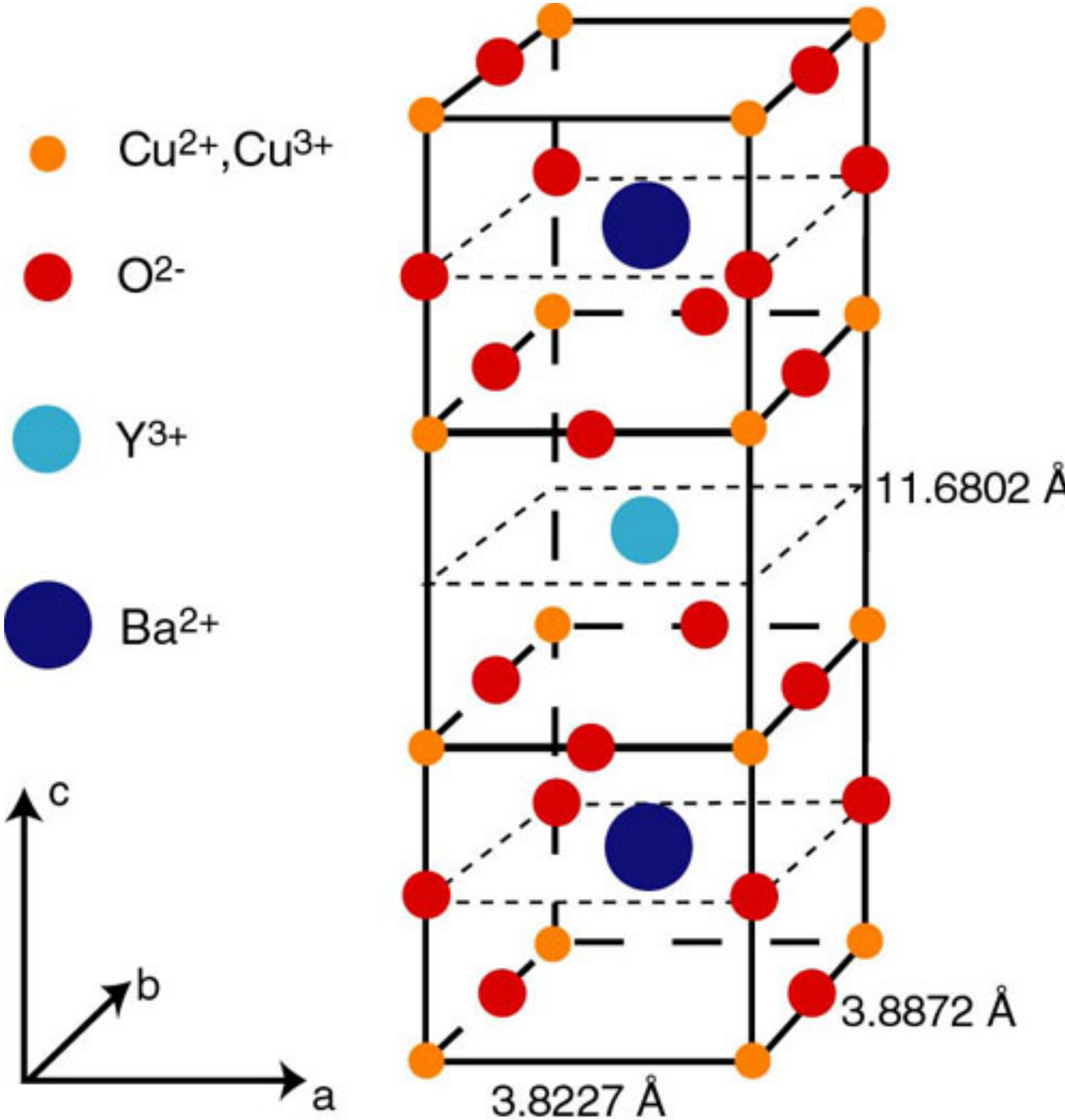
- The resistivity, ρ, of a metal from the flow of quasi-particles is

$$\rho = \frac{m^*}{ne^2}\frac{1}{\tau}$$

where m^* is the effective mass of a quasipartcle, n is the density of electrons, e is the charge of an electron, and τ is a quasiparticle scattering time. The theory of ordinary metals implies that as the temperature $T \to 0$

$$\tau \sim \frac{1}{T^2} \gg \frac{\hbar}{k_B T}$$

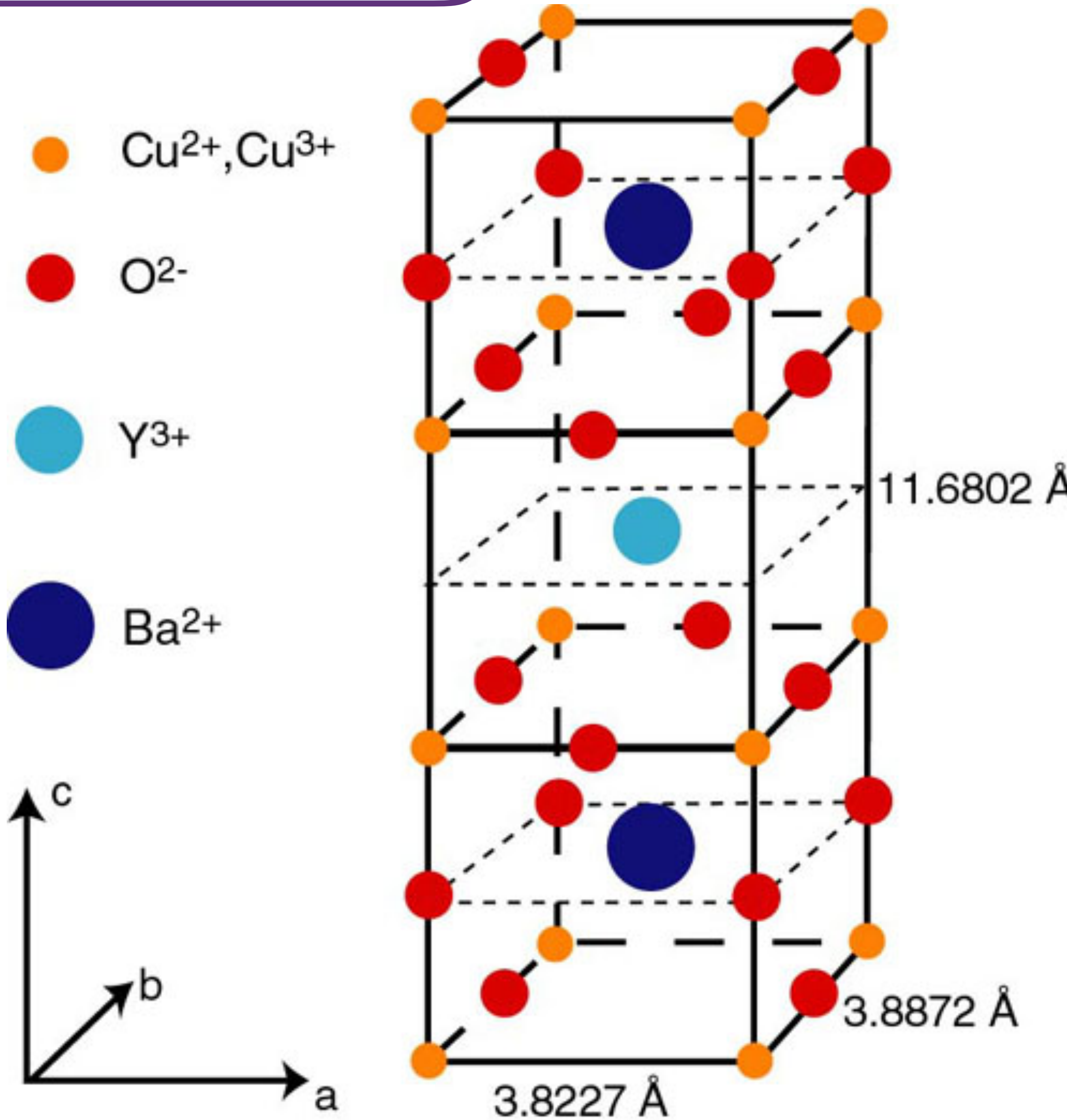
High temperature superconductors



$YBa_2Cu_3O_{6+x}$

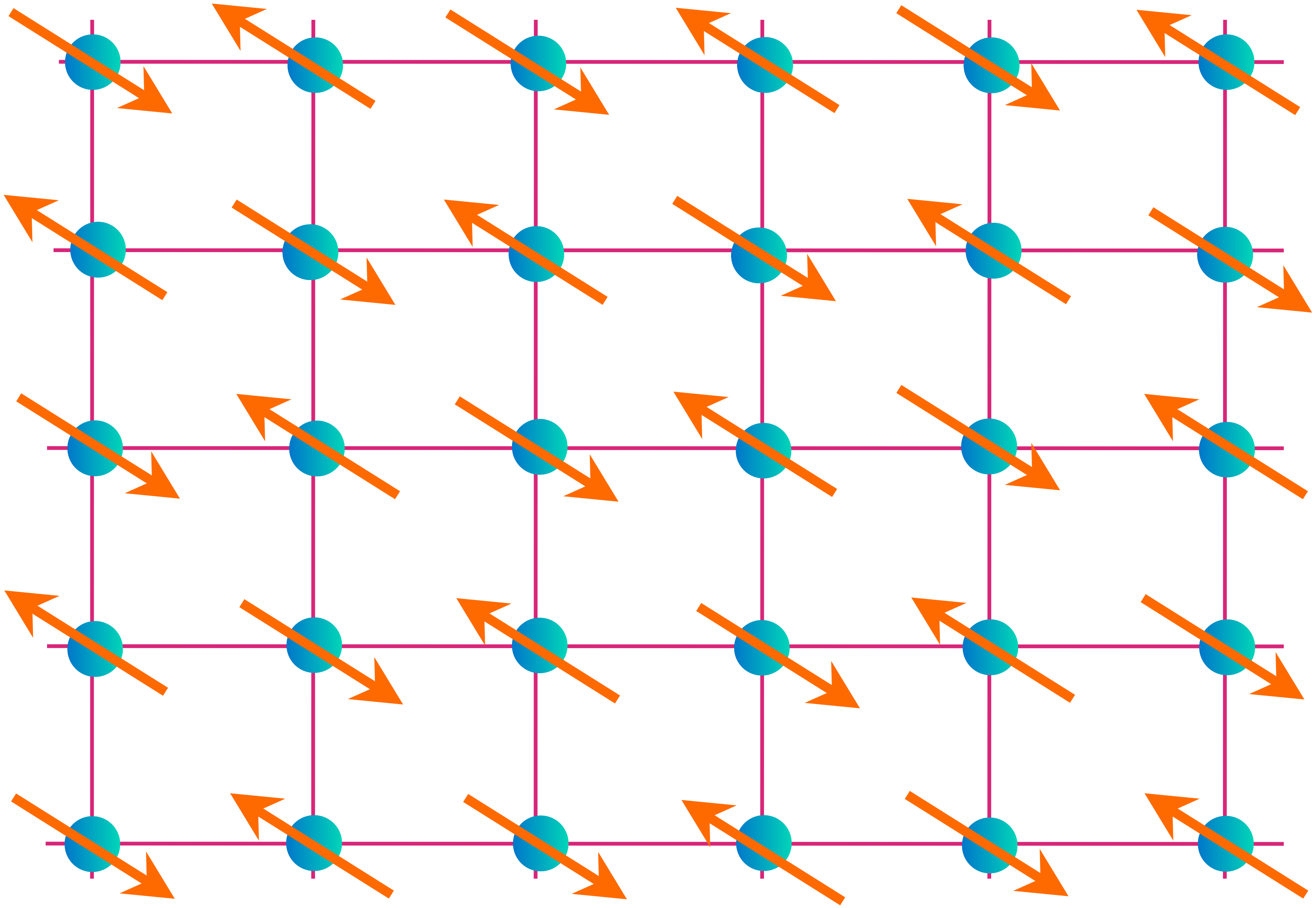
Ultra-quantum matter!

High temperature superconductors

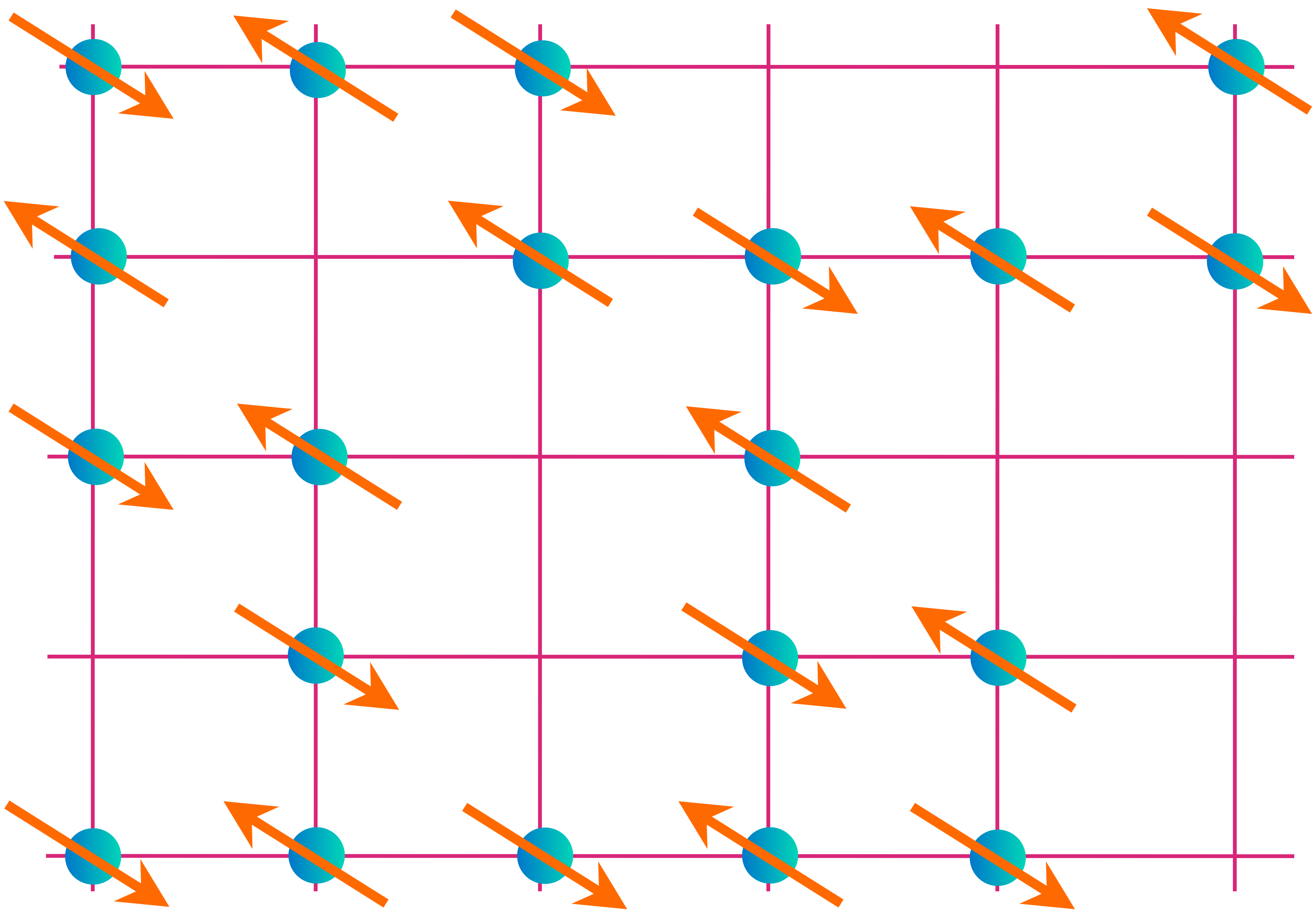


$$YBa_2Cu_3O_{6+x}$$

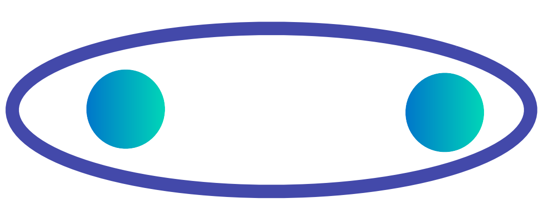
Square lattice of Cu sites



Square lattice of Cu sites at $p = p_c$

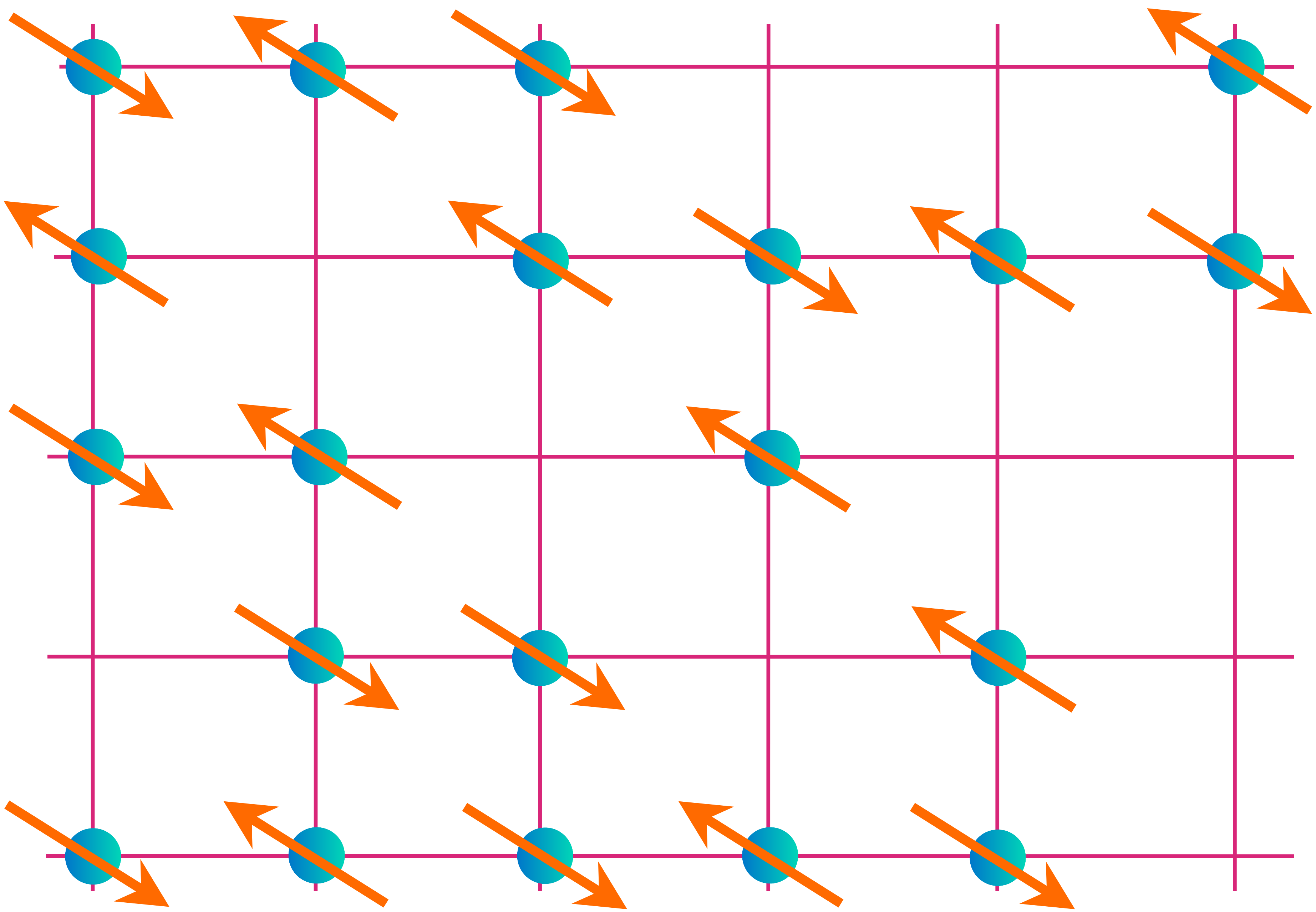


Remove fraction p electrons



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

Square lattice of Cu sites at $p=p_c$



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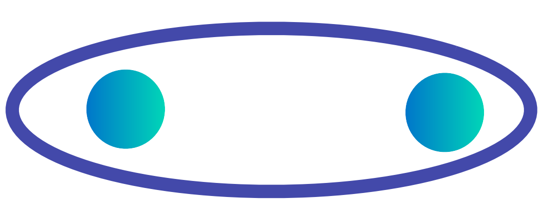 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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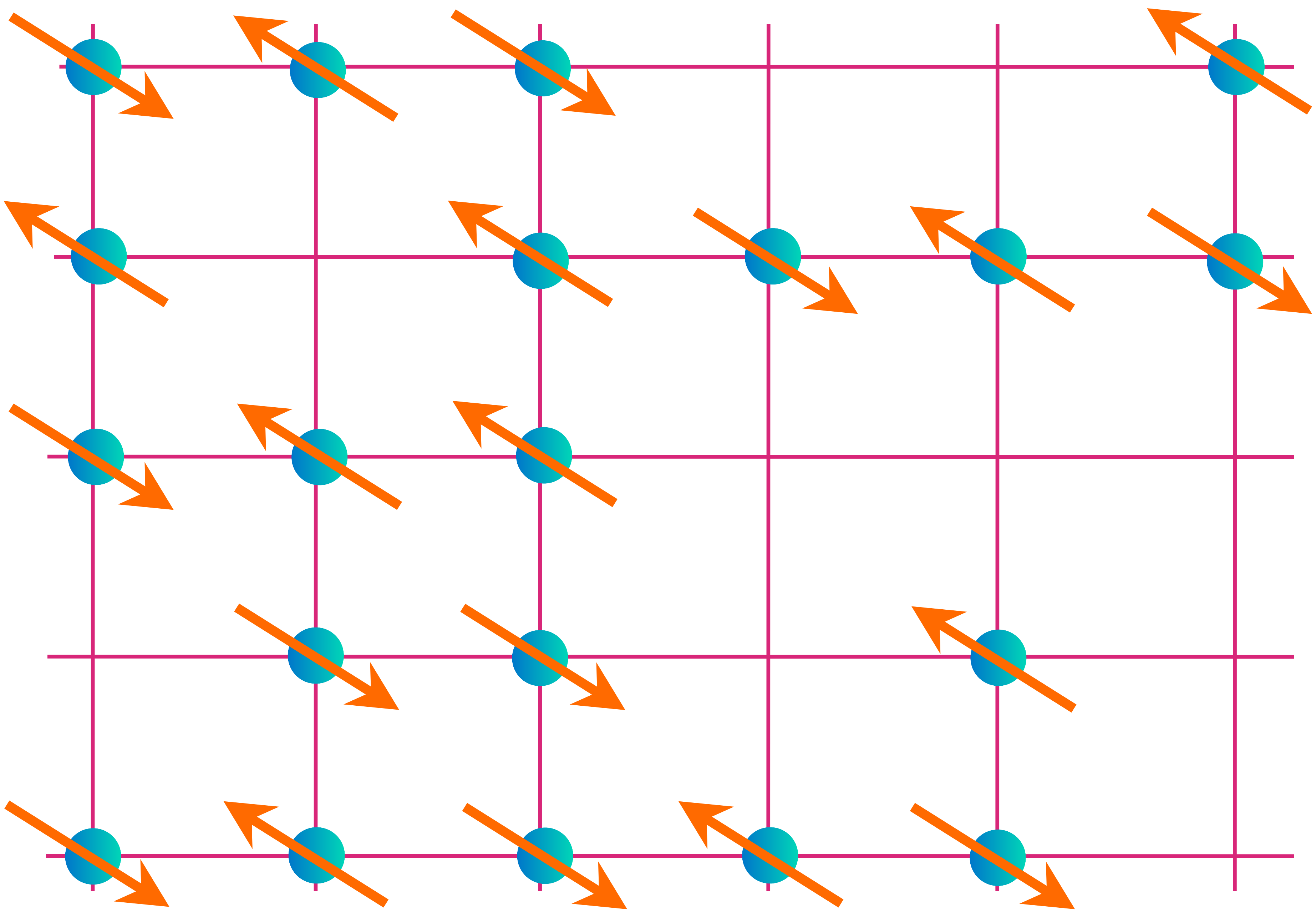

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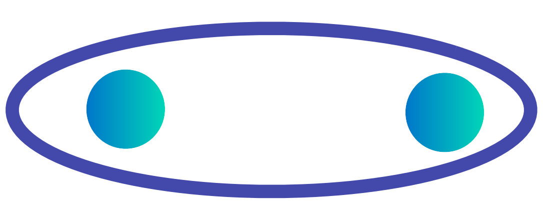

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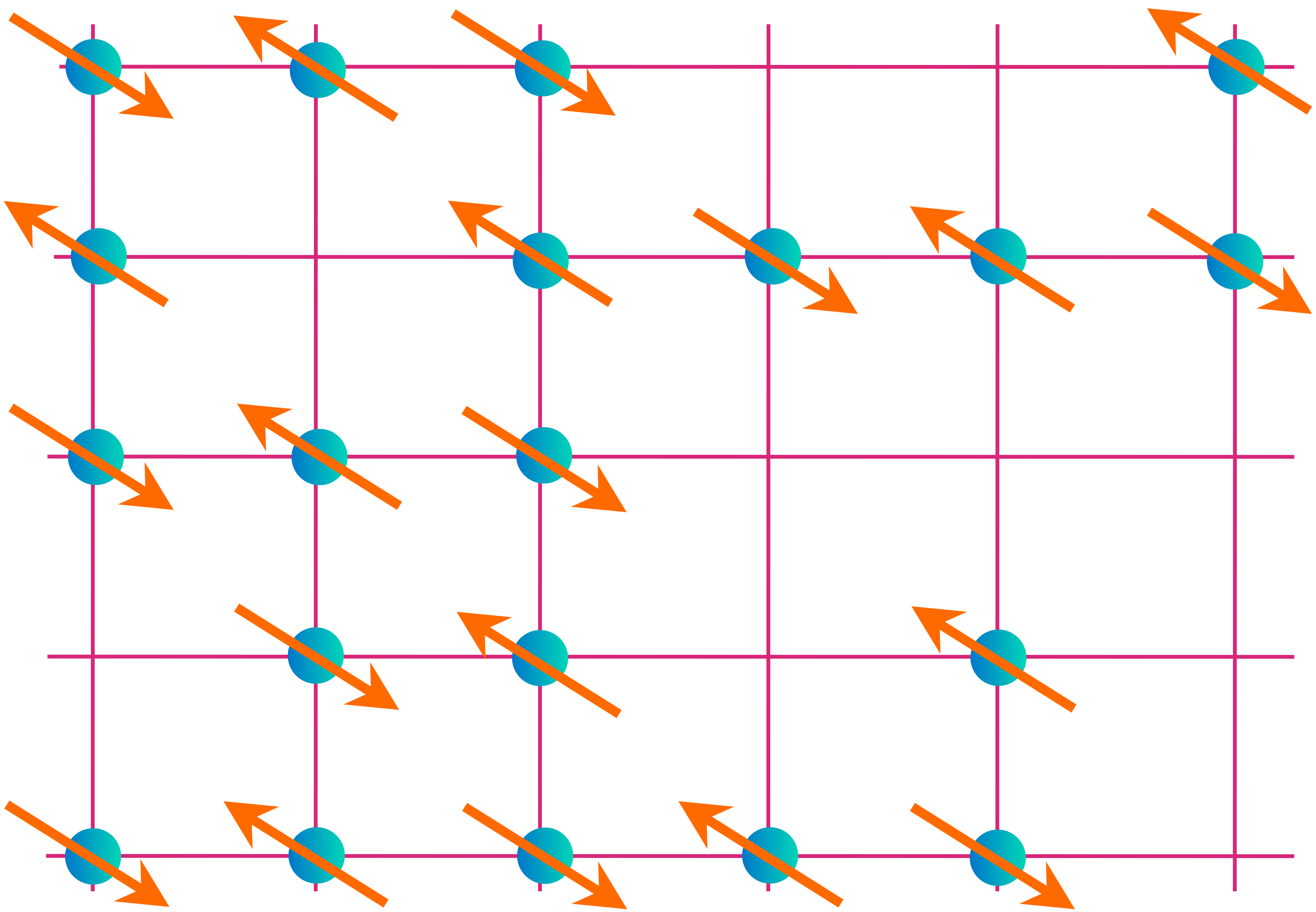

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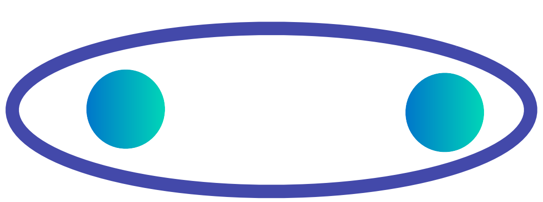

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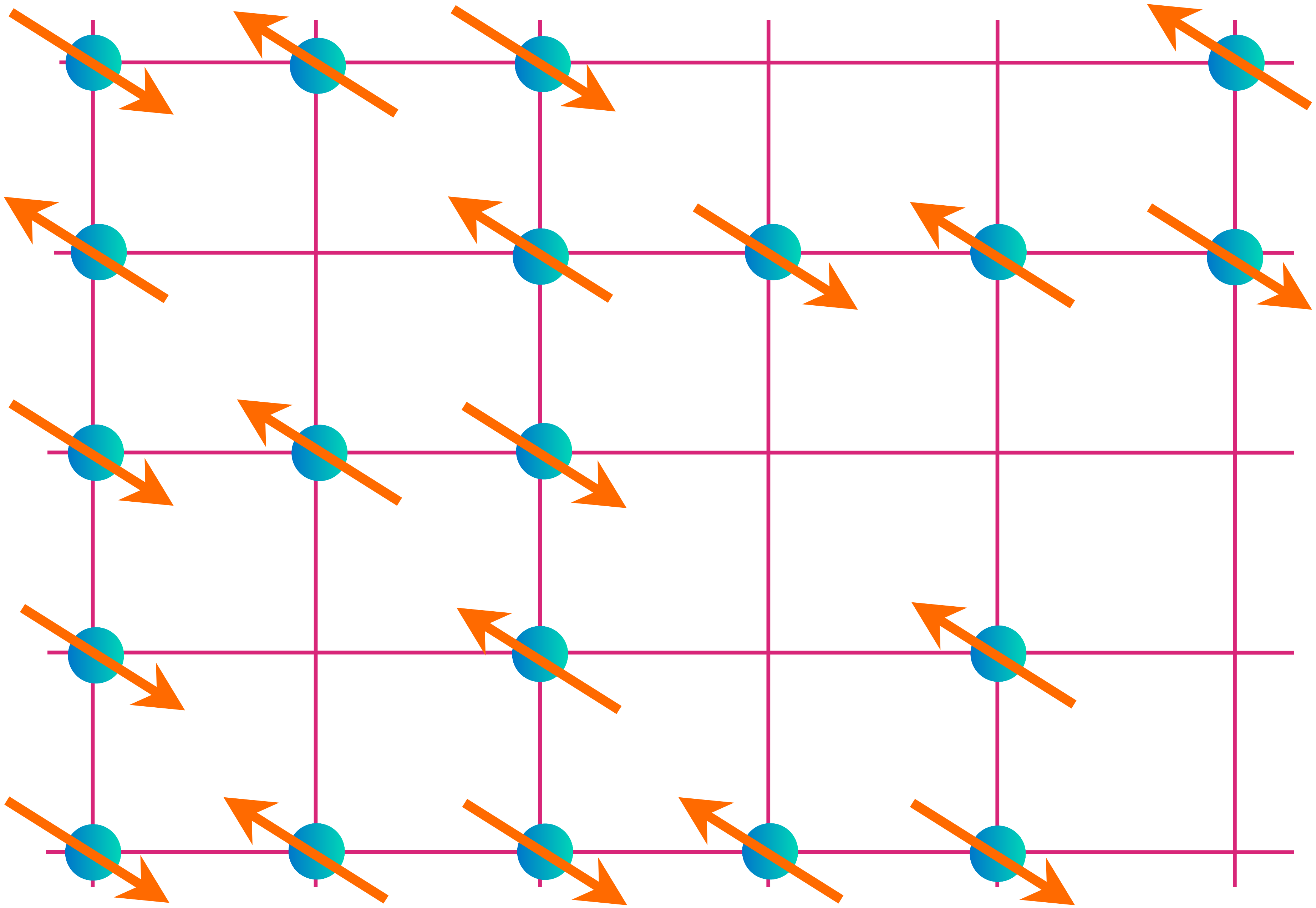

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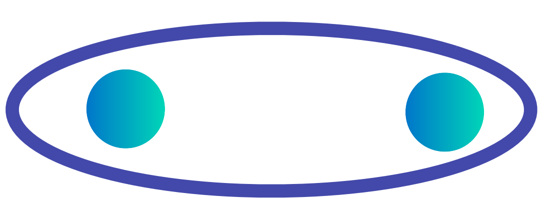

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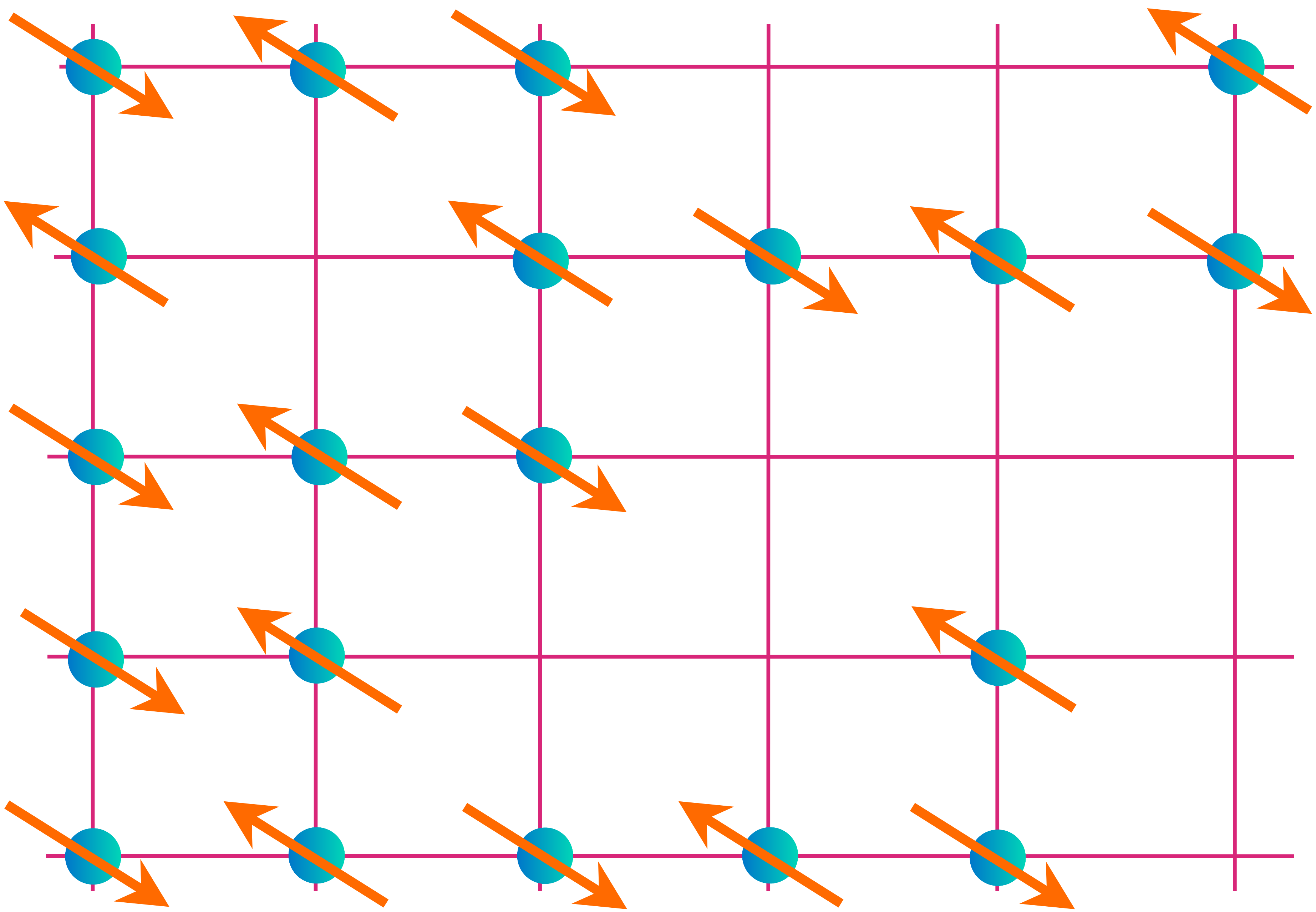

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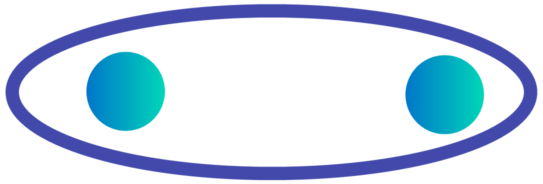 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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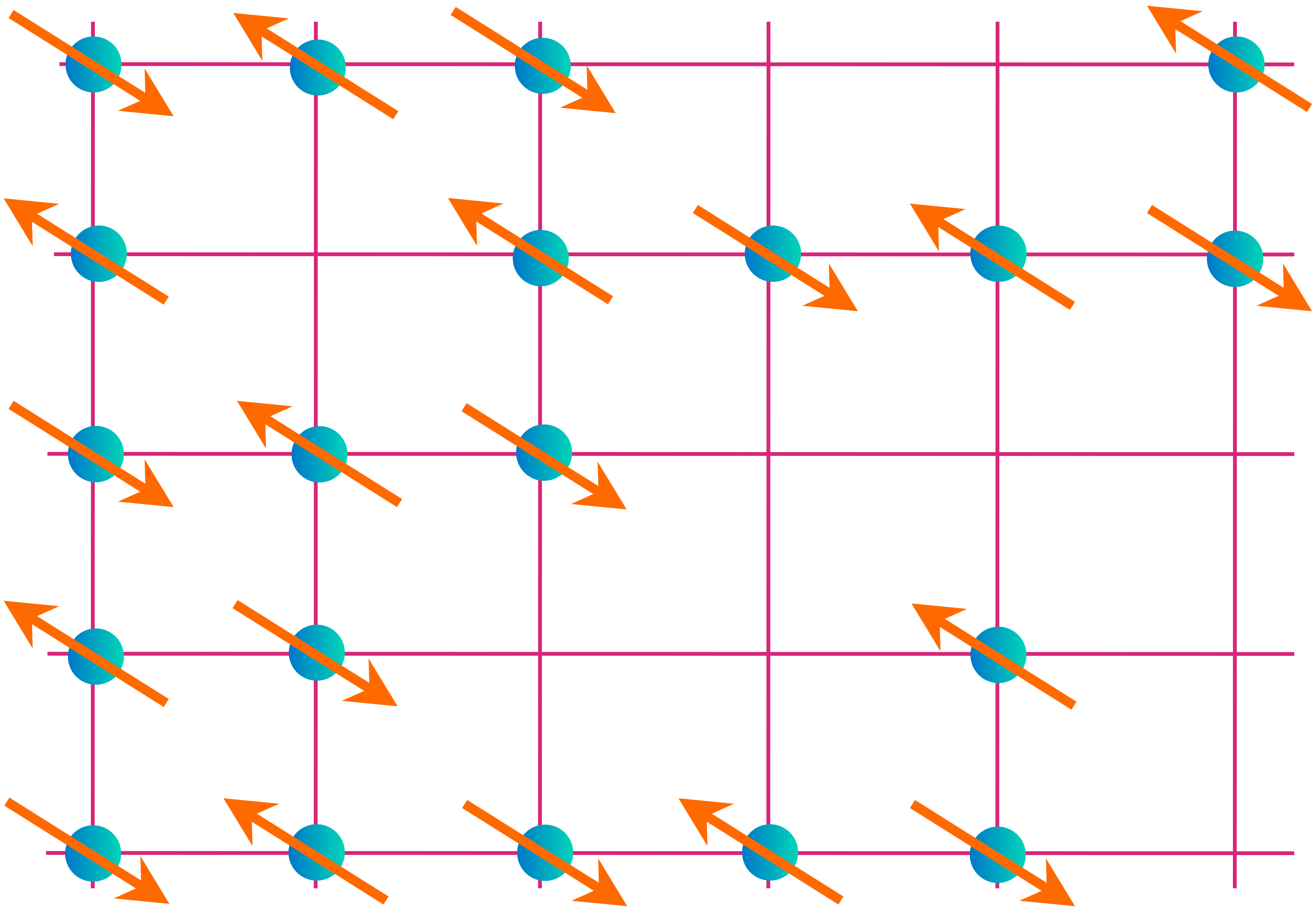

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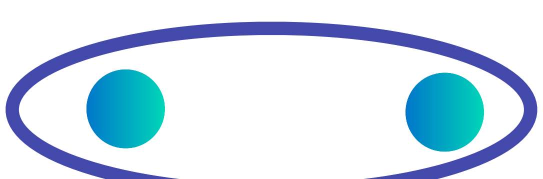

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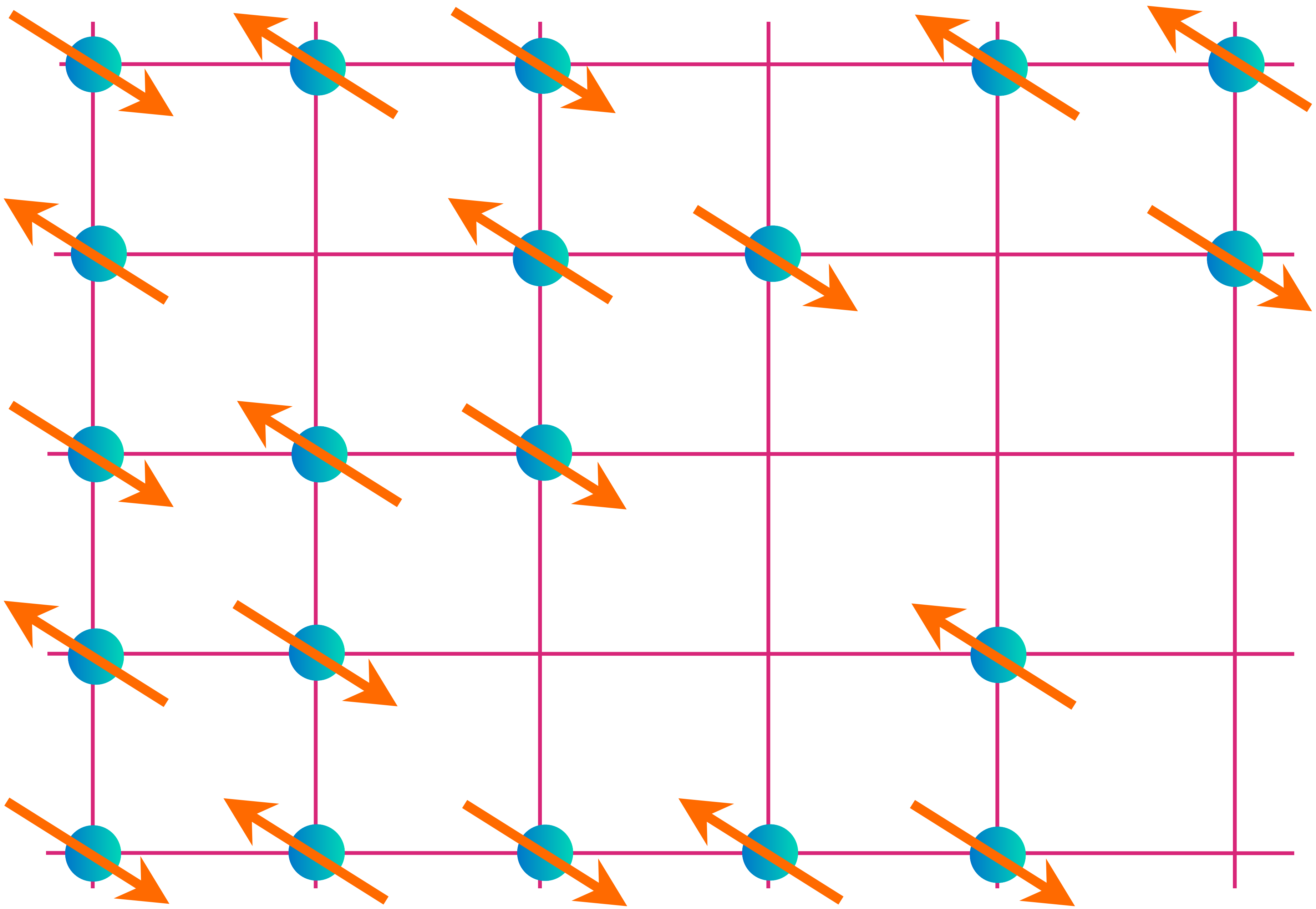

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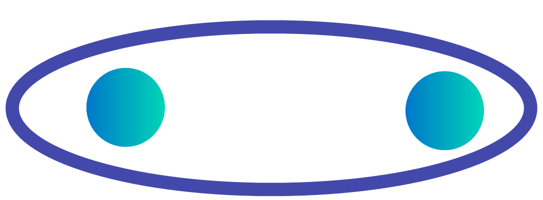

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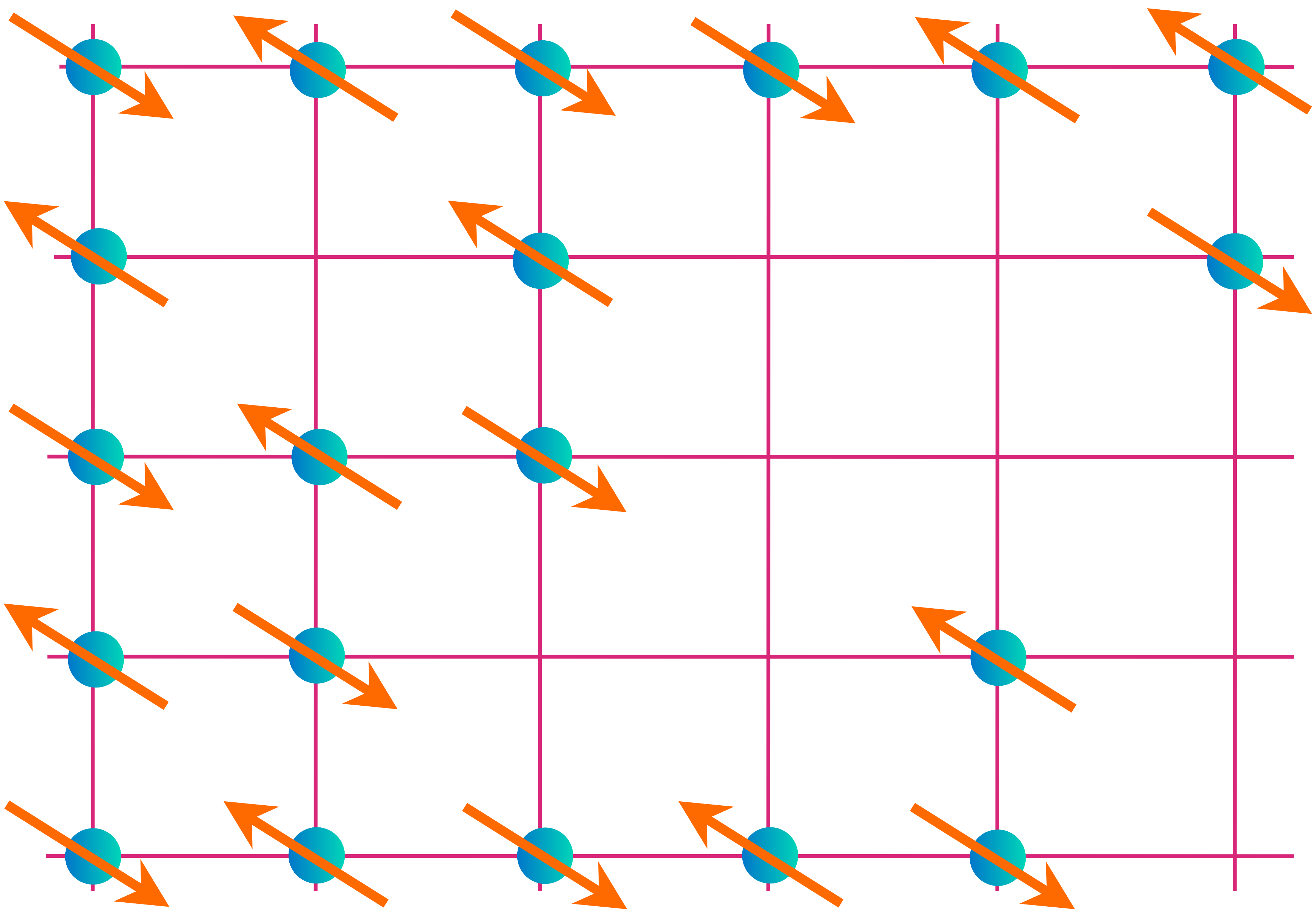

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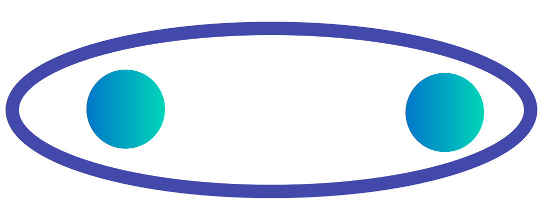 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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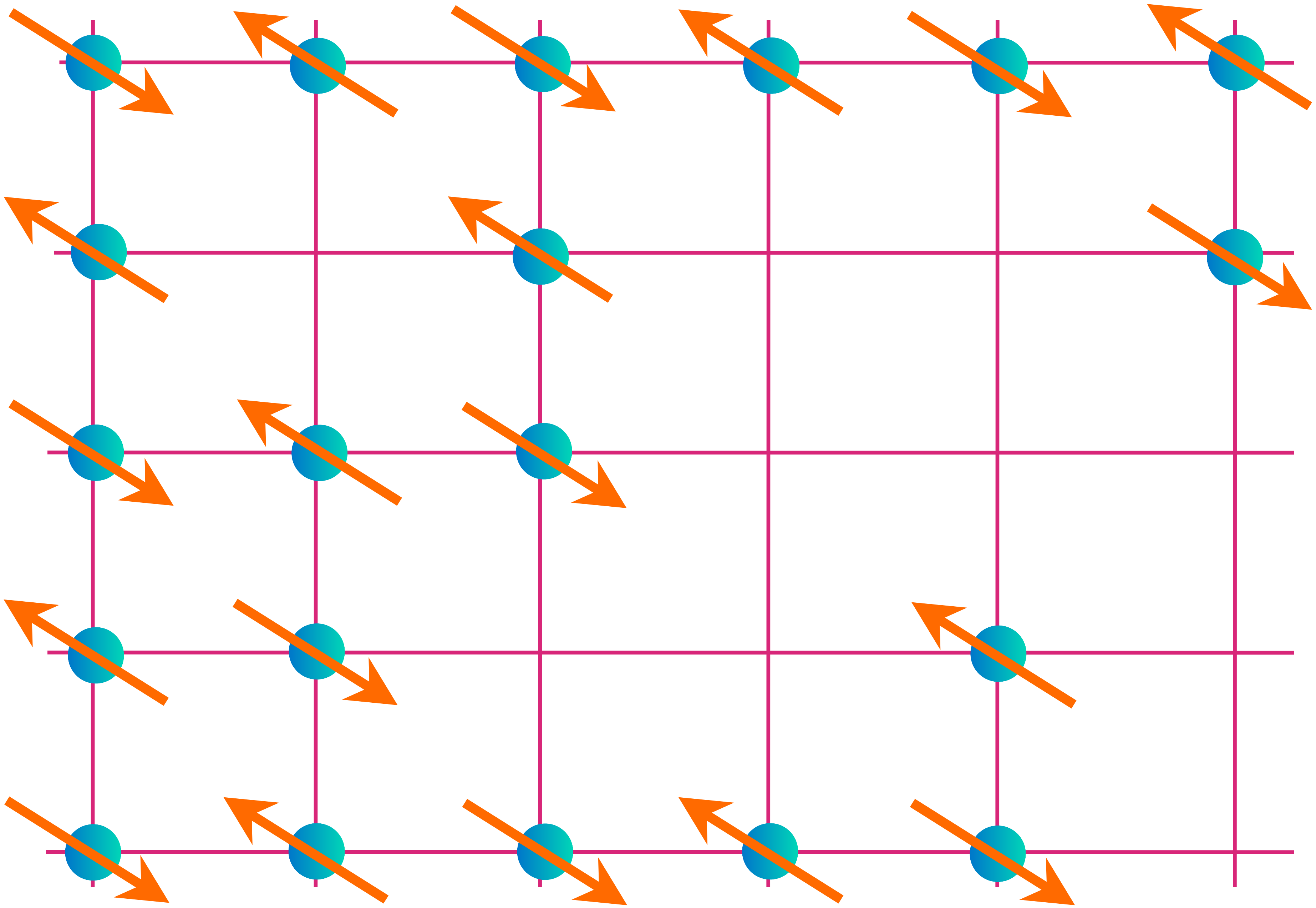

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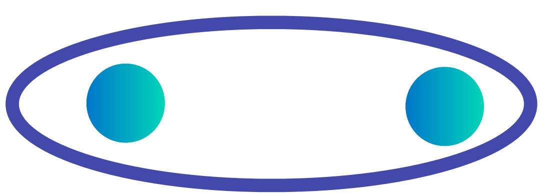

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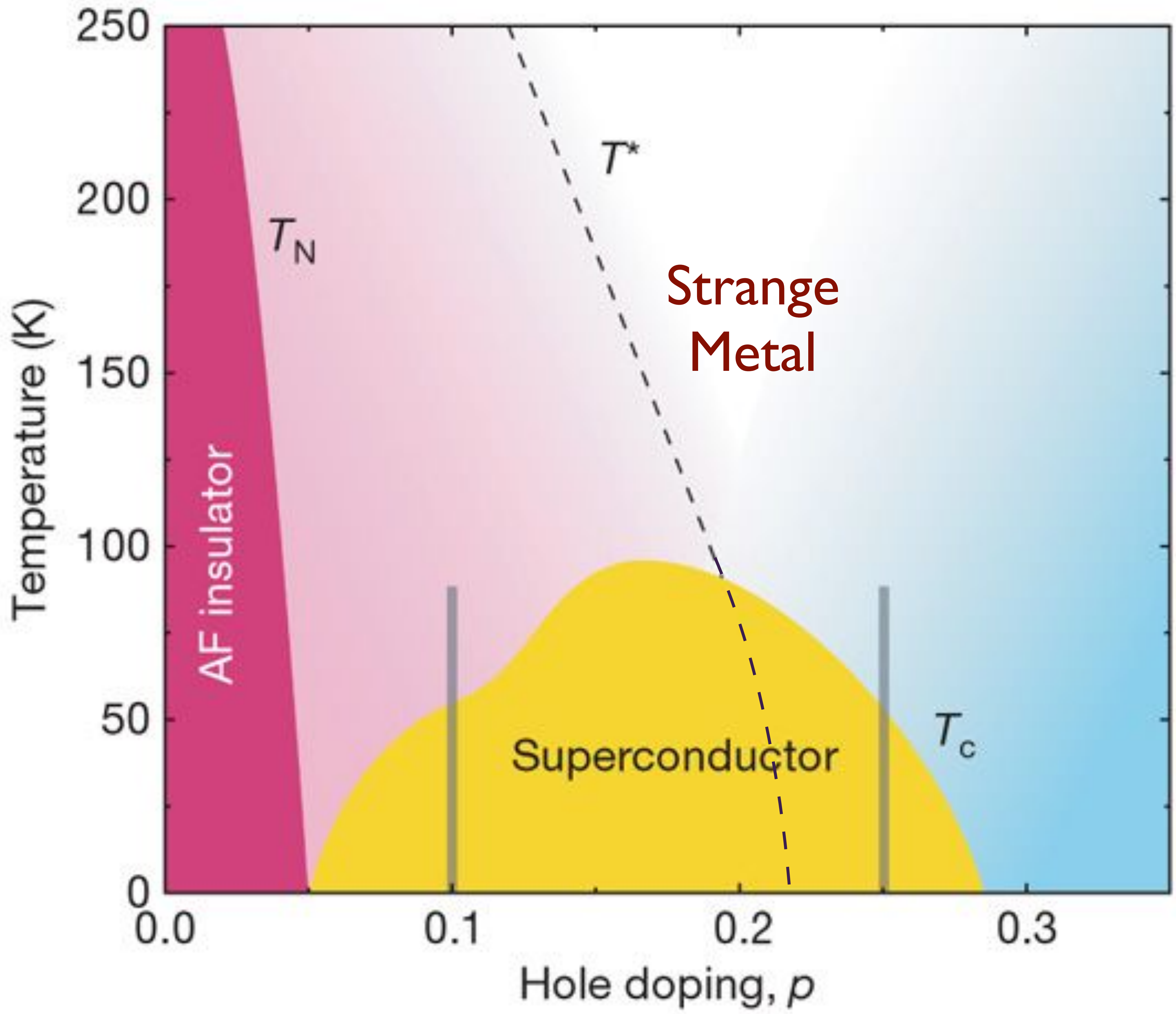
250
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Temperature (K)
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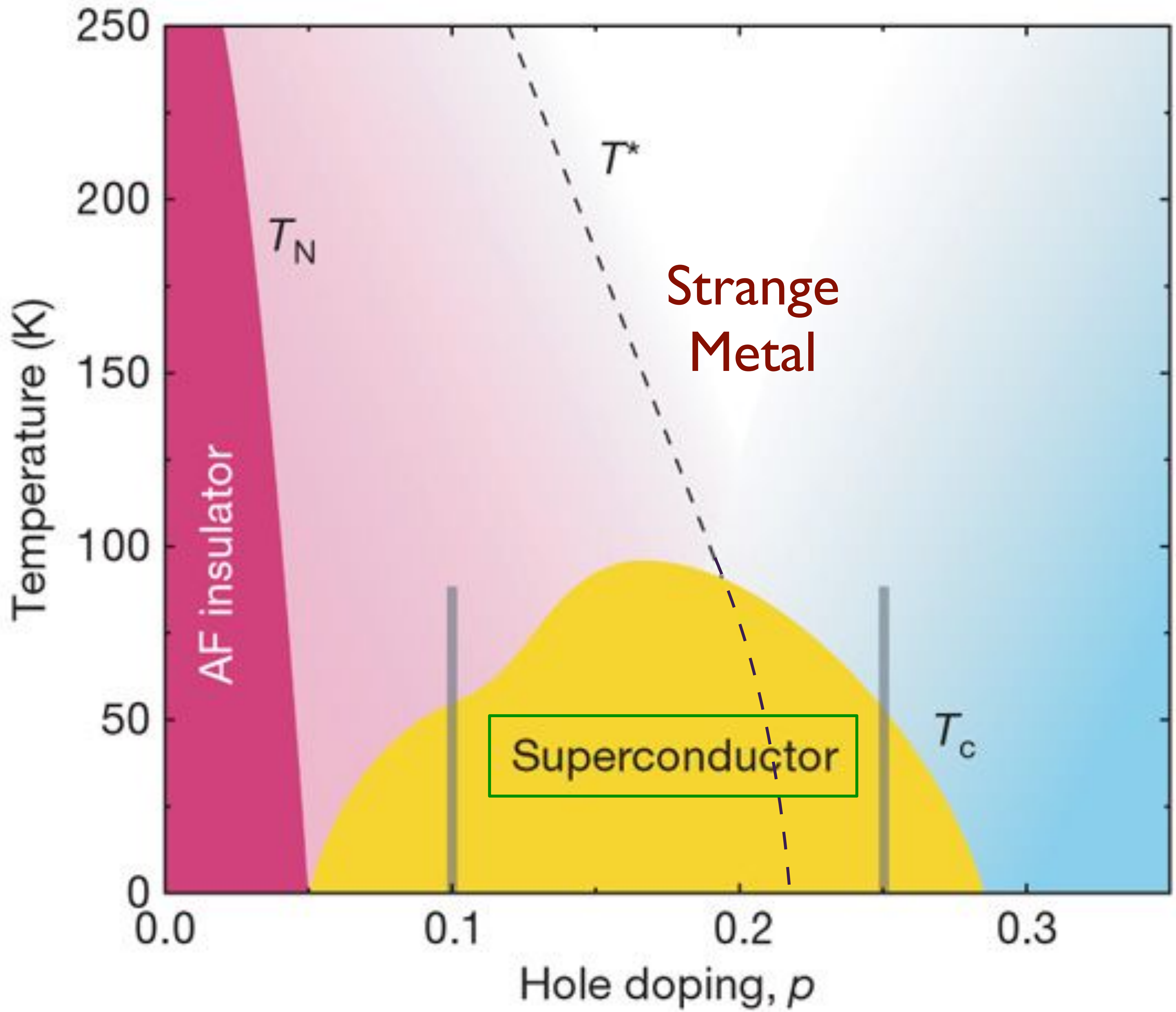
Hole doping, p
AF insulator
T_N
T^*
Strange
Metal
Superconductor
T_c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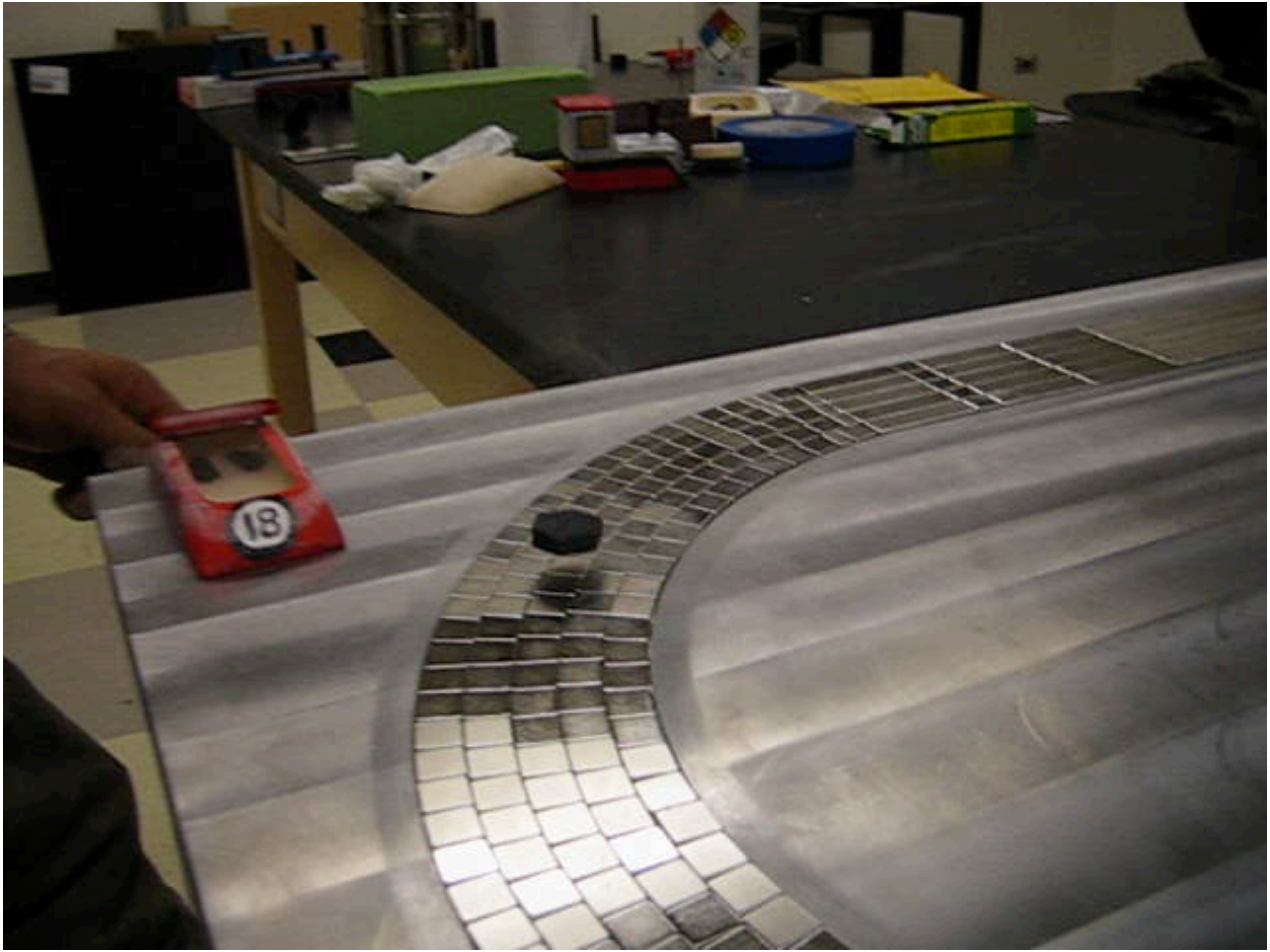


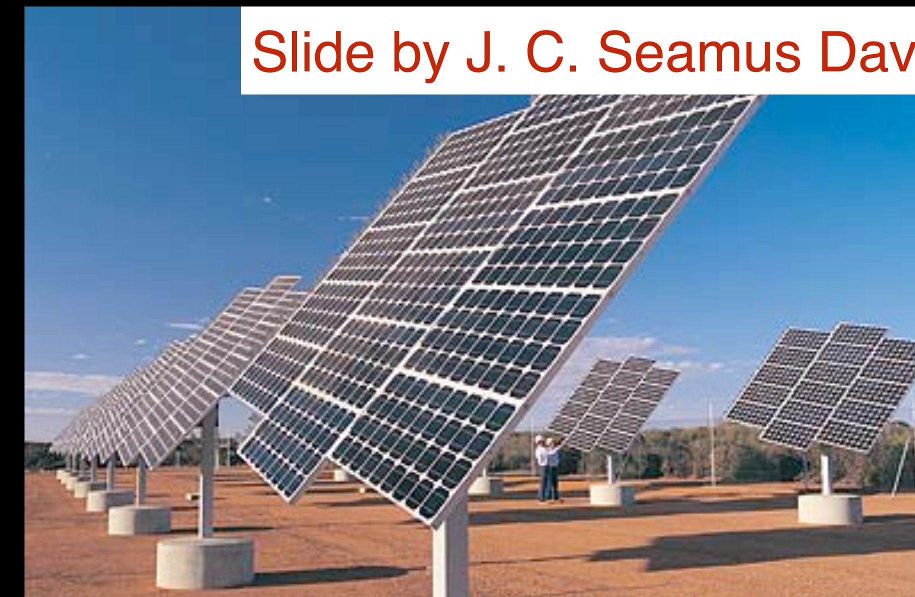
Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

Slide by J. C. Seamus Davis

Power Efficiency/Capacity/Stability

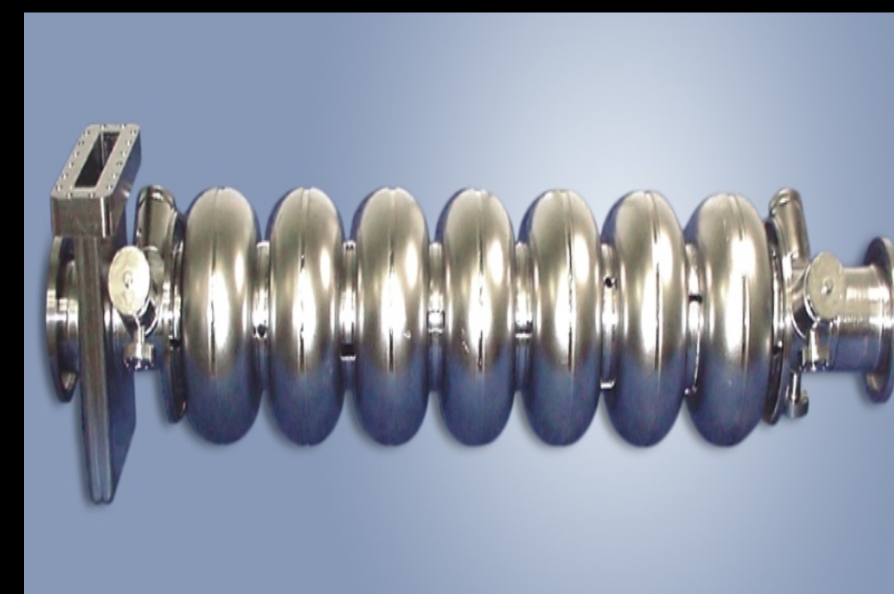
Power Bottlenecks



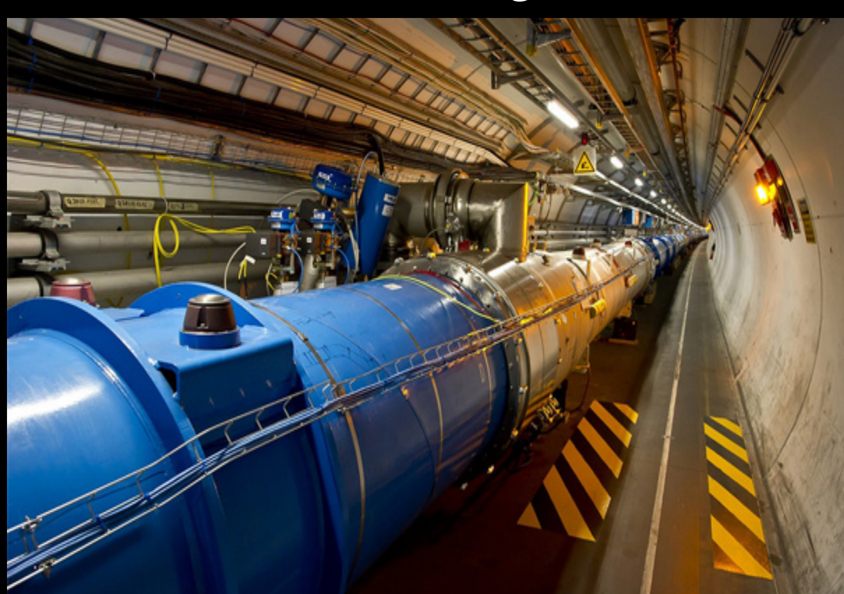
Accommodate Renewable Power

Efficient Rotating Machines

Information Technology



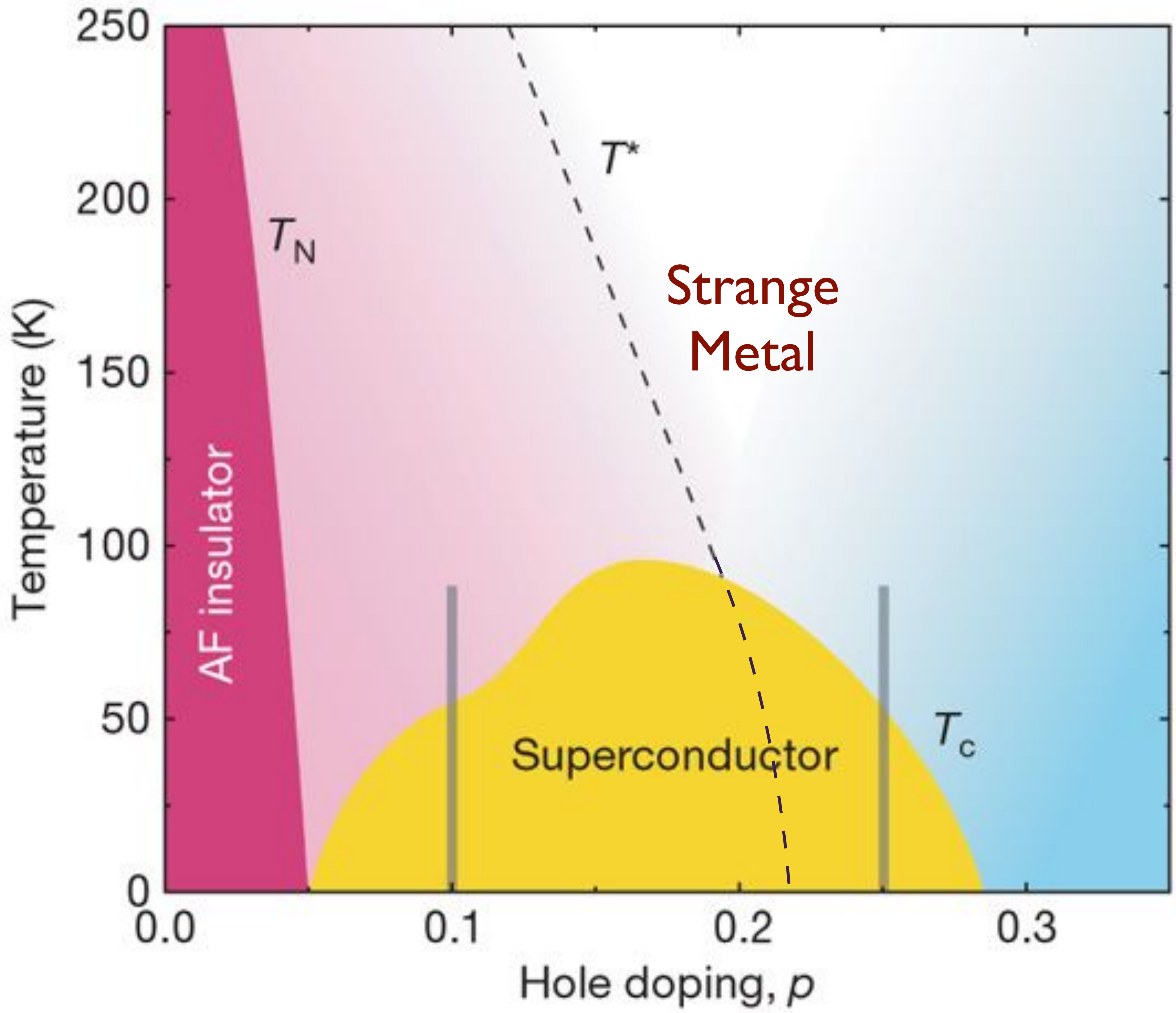
Next Generation HEP



Ultra-High Magnetic Fields

Medical

Transport



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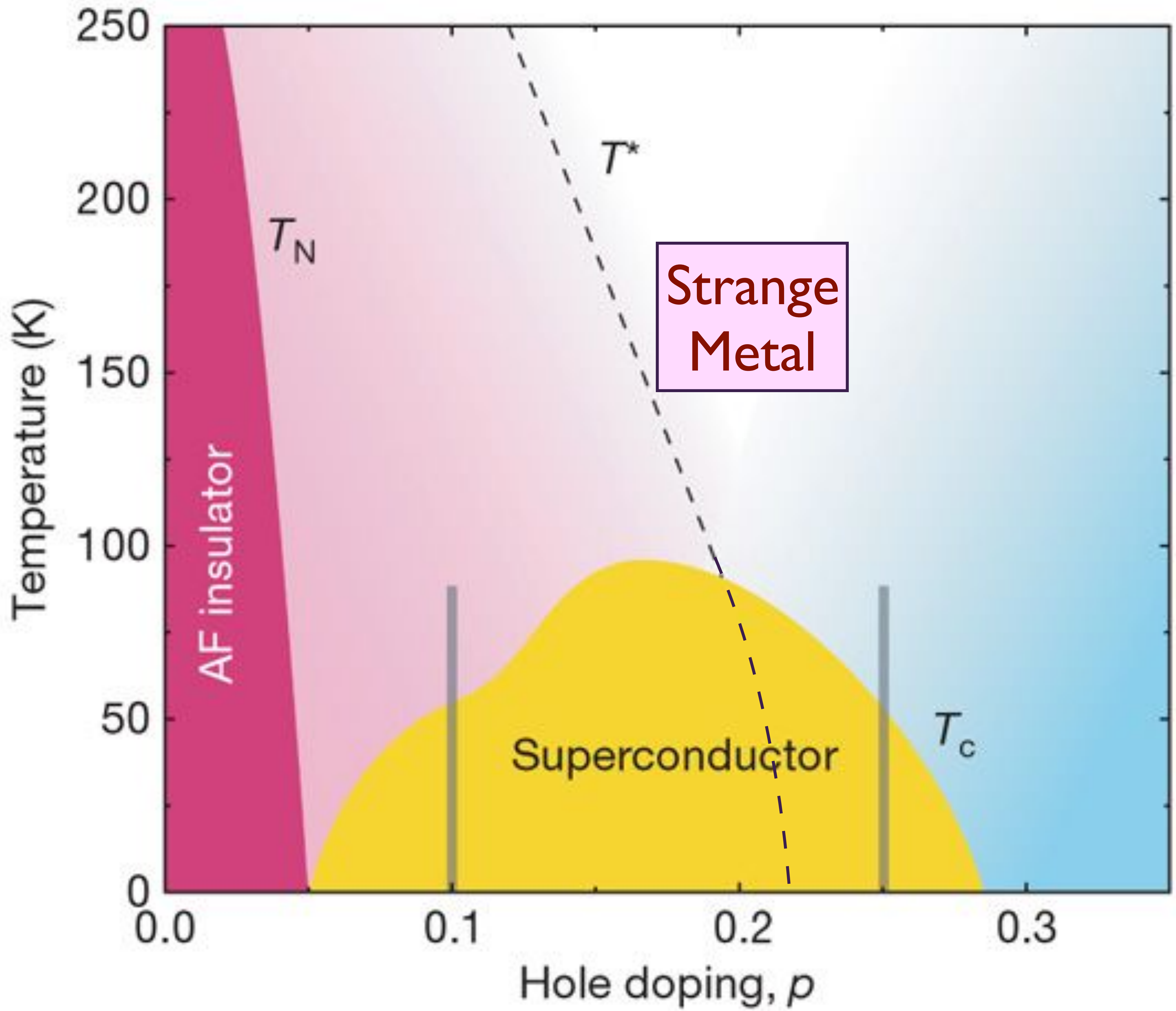
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T_N
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Strange Metal
Superconductor
T_c

Remarkable recent observation of 'Planckian' strange metal transport in cuprates, pnictides, magic-angle graphene, and ultracold atoms: the resistivity, ρ, is

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Current flow without quasiparticles

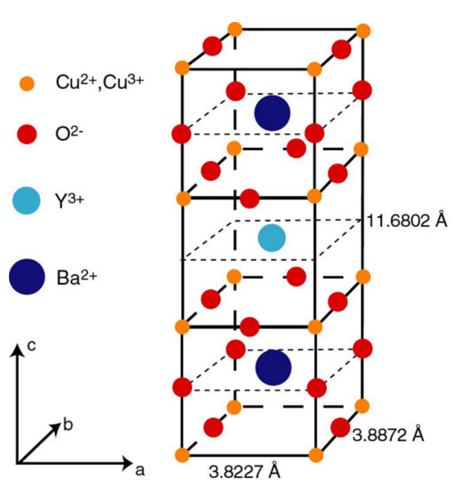
A. Legros, S. Benhabib, W. Tabis, F. Laliberté, M. Dion, M. Lizaire, B. Vignolle, D. Vignolles, H. Raffy, Z. Z. Li, P. Auban-Senzier, N. Doiron-Leyraud, P. Fournier, D. Colson, L. Taillefer, and C. Proust, Nature Physics **15**, 142 (2019)

Material		$\boldsymbol{n}$ (10^{27} m^{-3})	$\boldsymbol{m^*}$ (m_0)	$\boldsymbol{A_1 / d}$ ($\boldsymbol{\Omega}$ / K)	$h / (2e^2\, T_F)$ ($\boldsymbol{\Omega}$ / 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	$P = 11$ 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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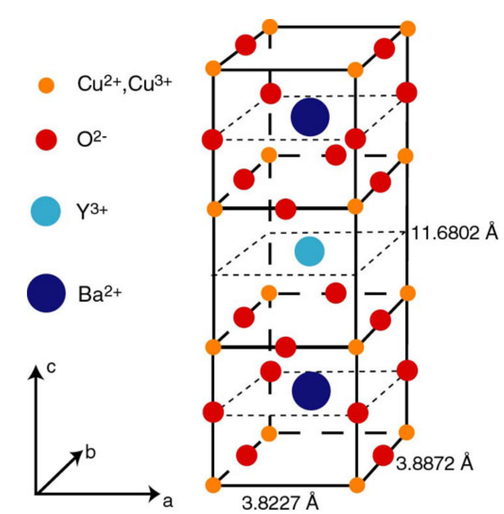
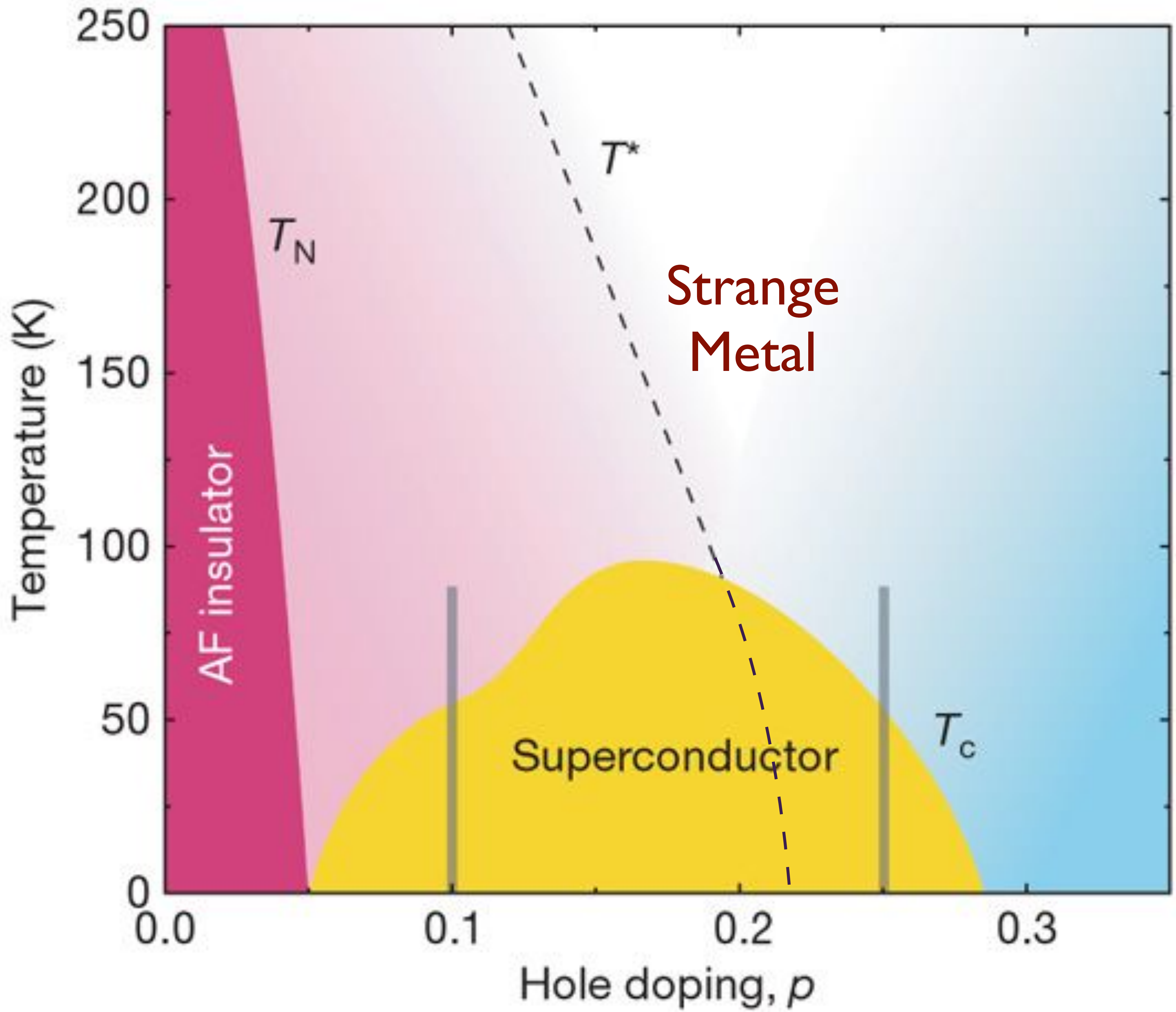
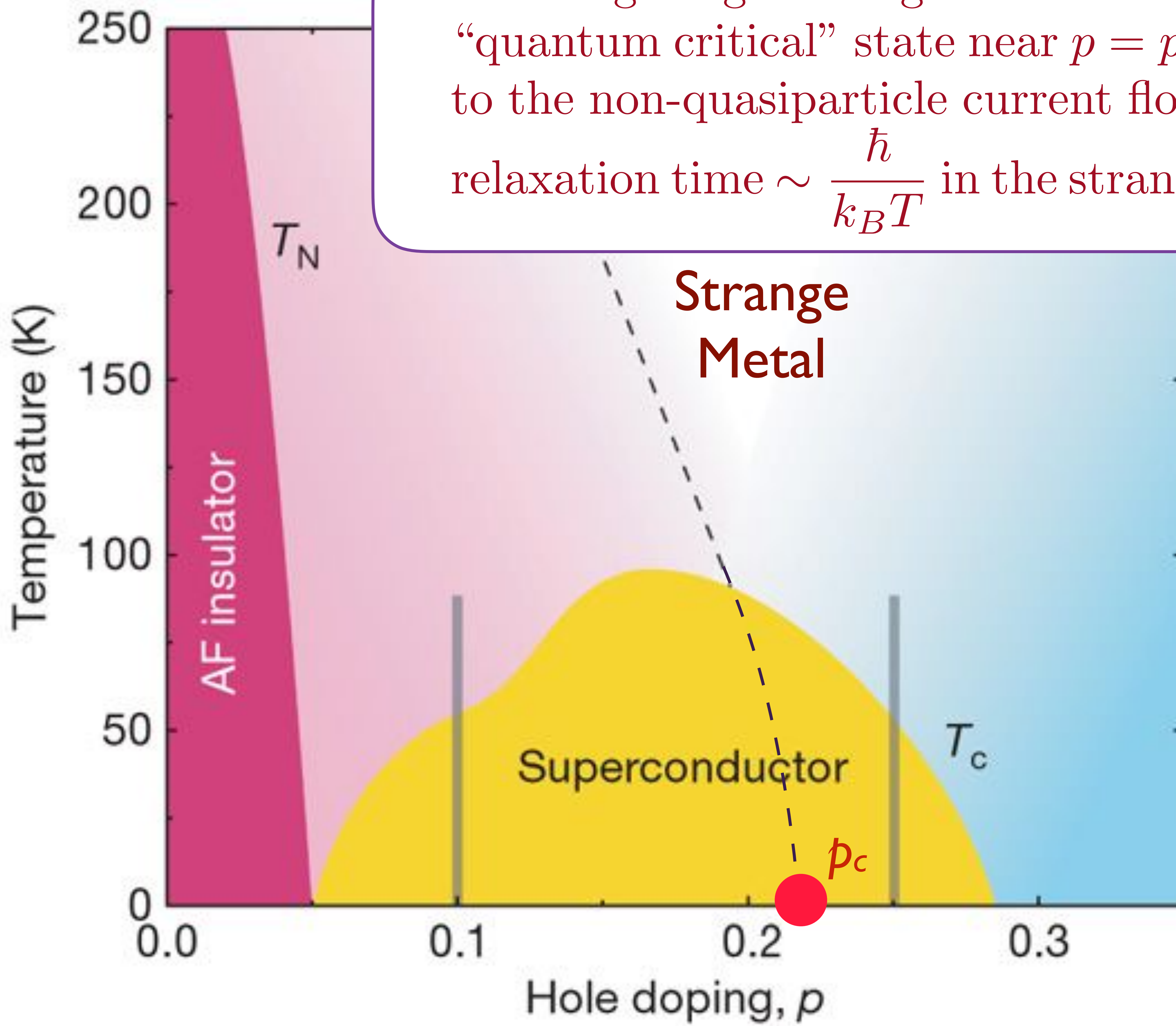
Remarkably similar universality in strange metals and black holes!



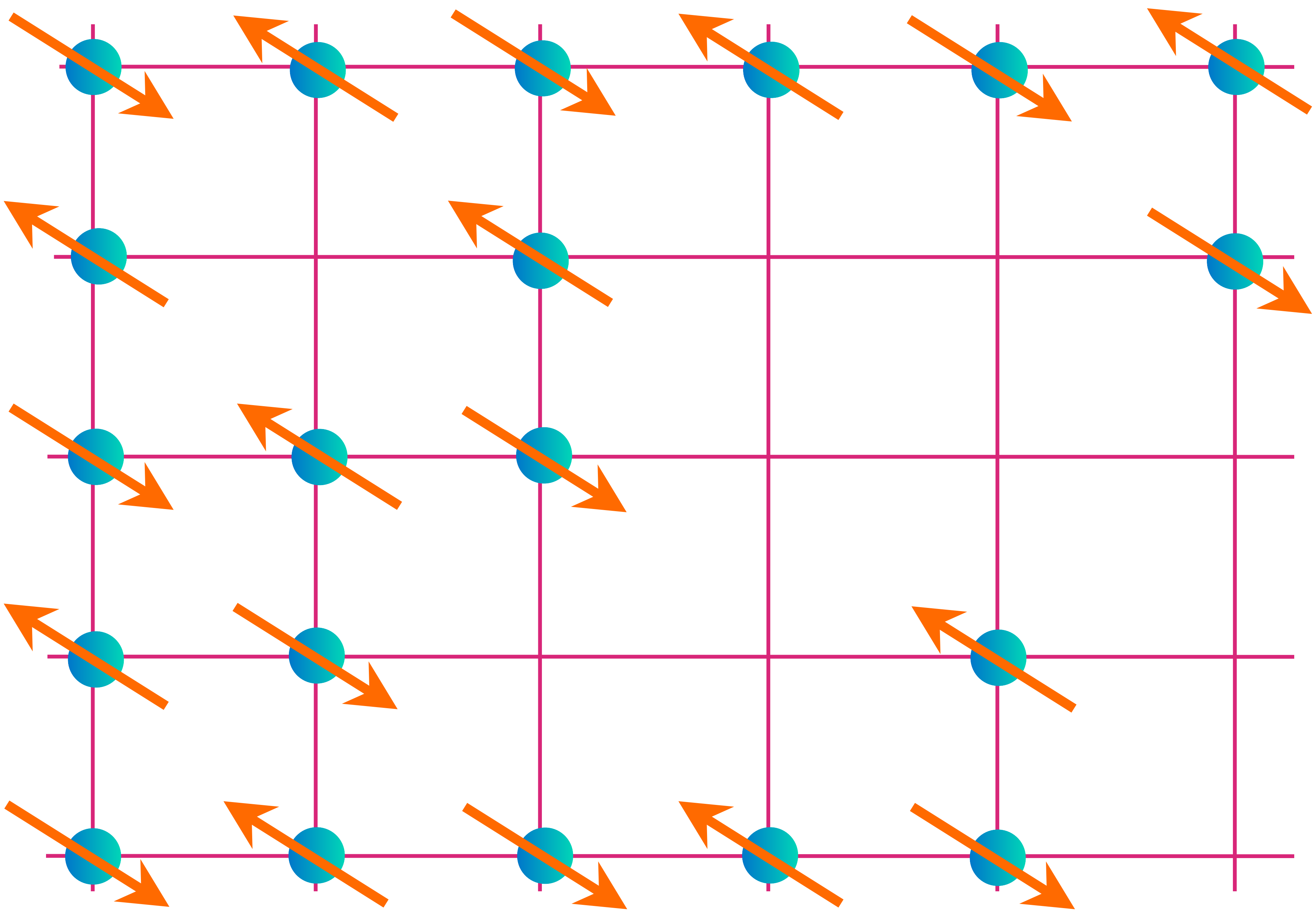


250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T*
Strange
Metal
Superconductor
T_c

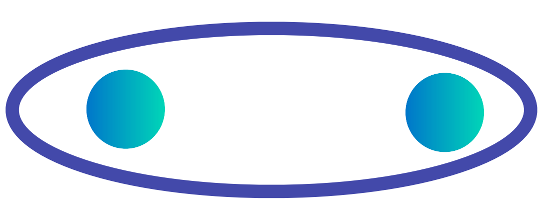
- The long-range entanglement in the "quantum critical" state near $p = p_c$ leads to the non-quasiparticle current flow with relaxation time $\sim \dfrac{\hbar}{k_B T}$ in the strange metal



Square lattice of Cu sites at $p = p_c$



Remove fraction p electrons



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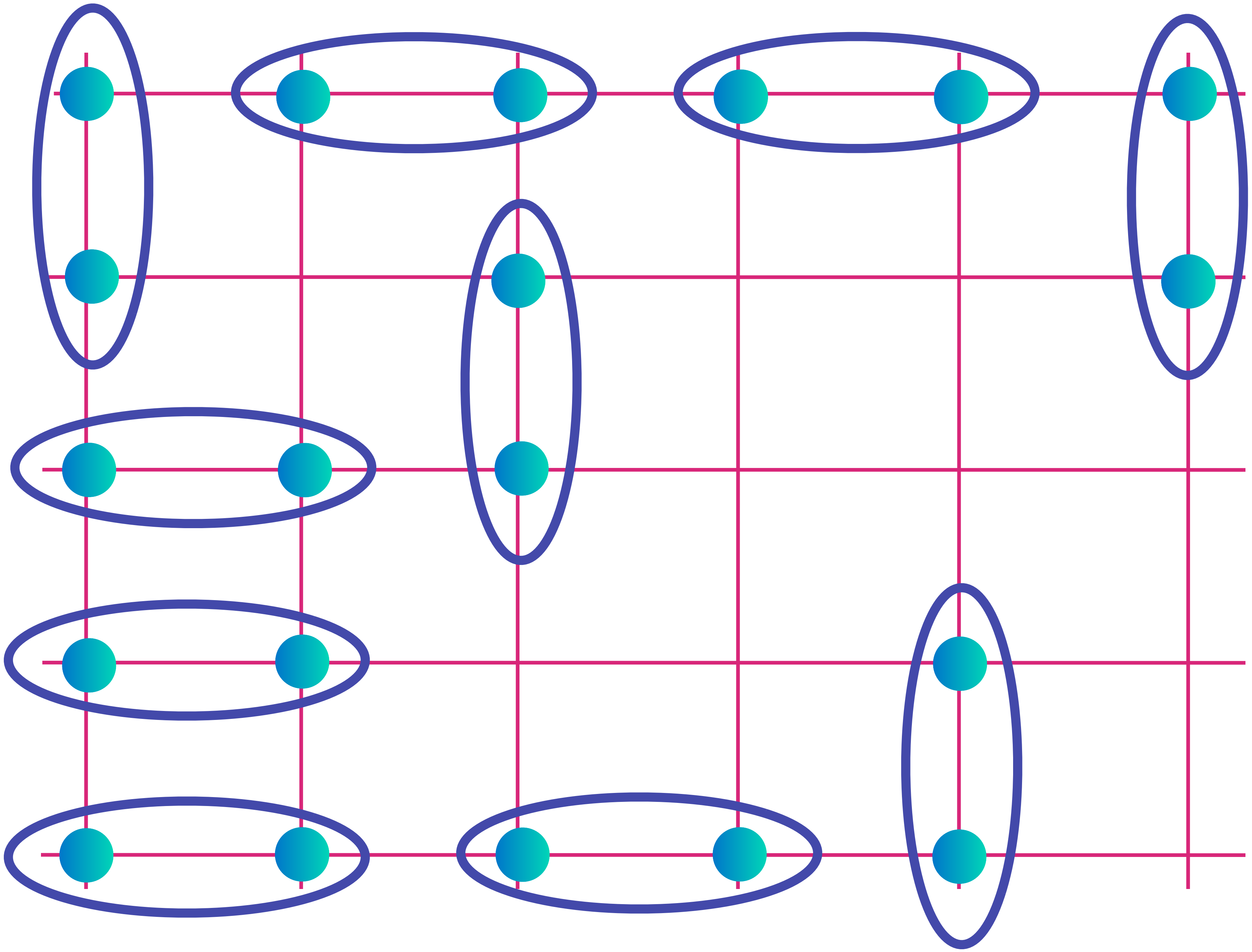
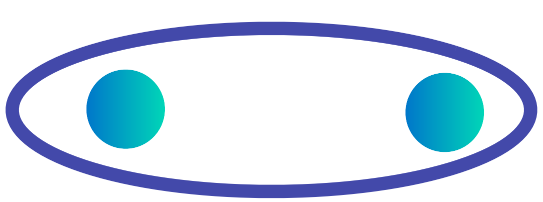


Electrons entangle in ("Cooper") pairs into chemical bonds



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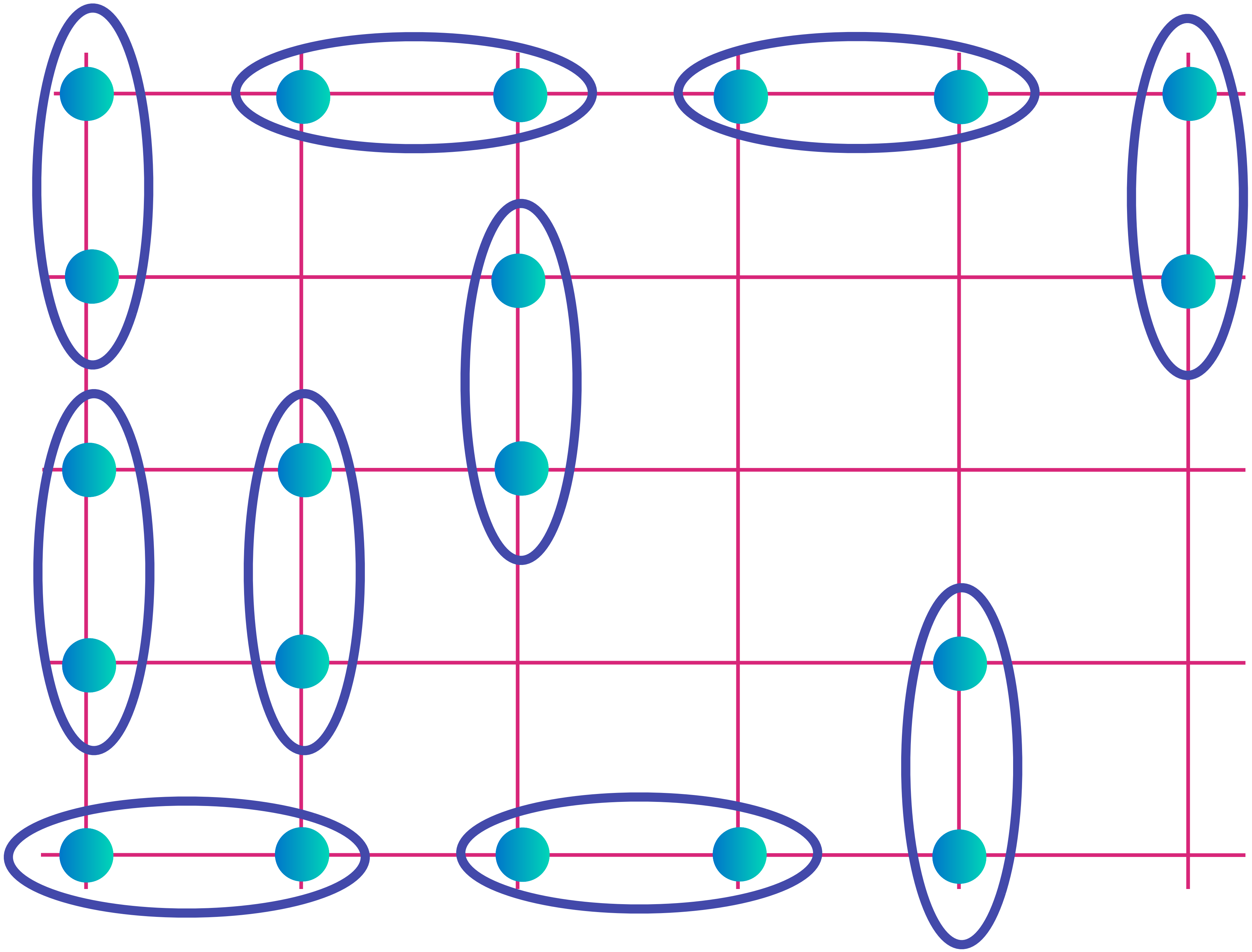
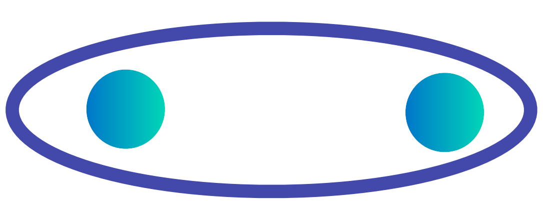


Electrons <u>entangle</u> "en masse" by exchanging partners, and there is <u>long-range quantum entanglement</u>



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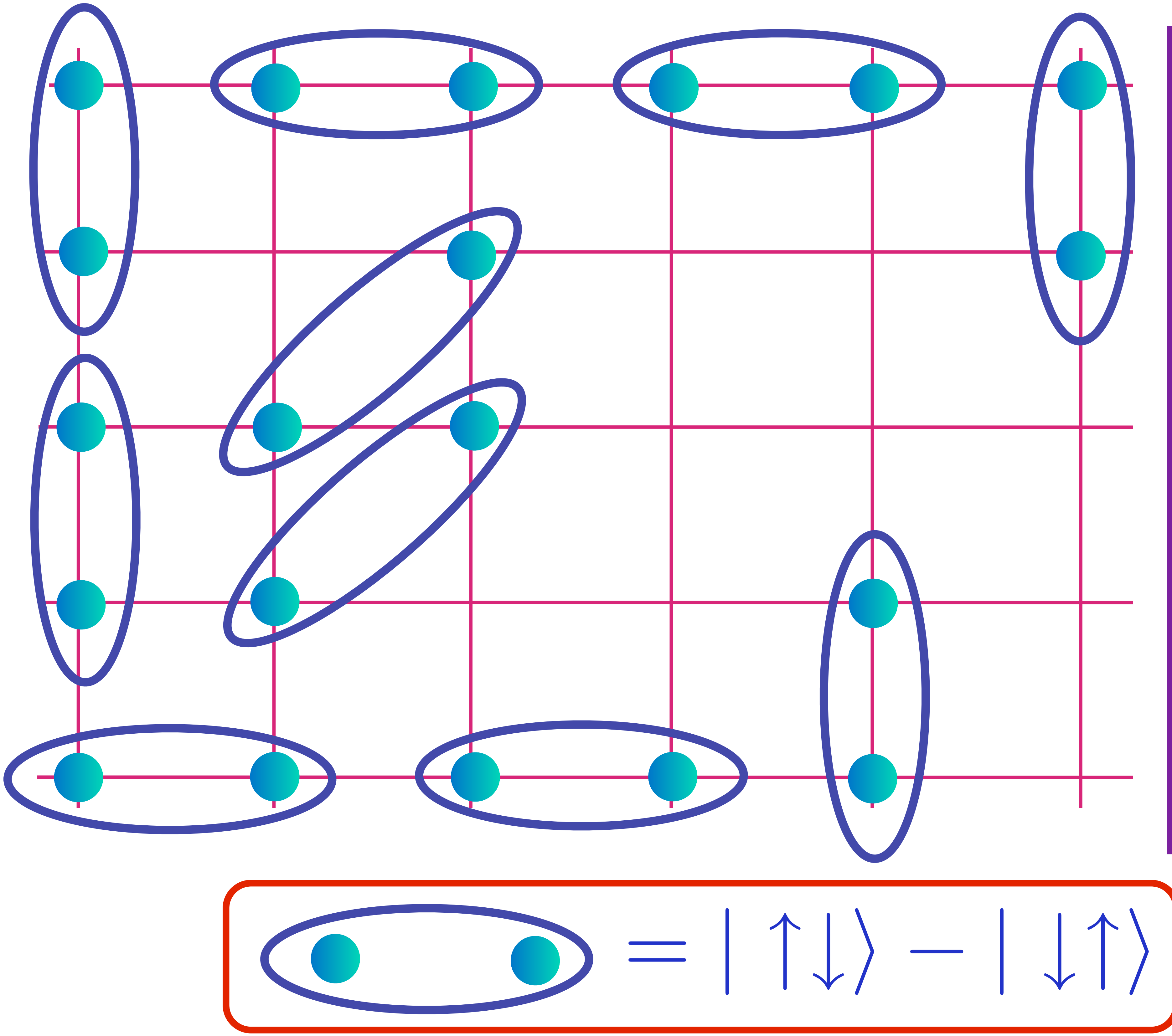

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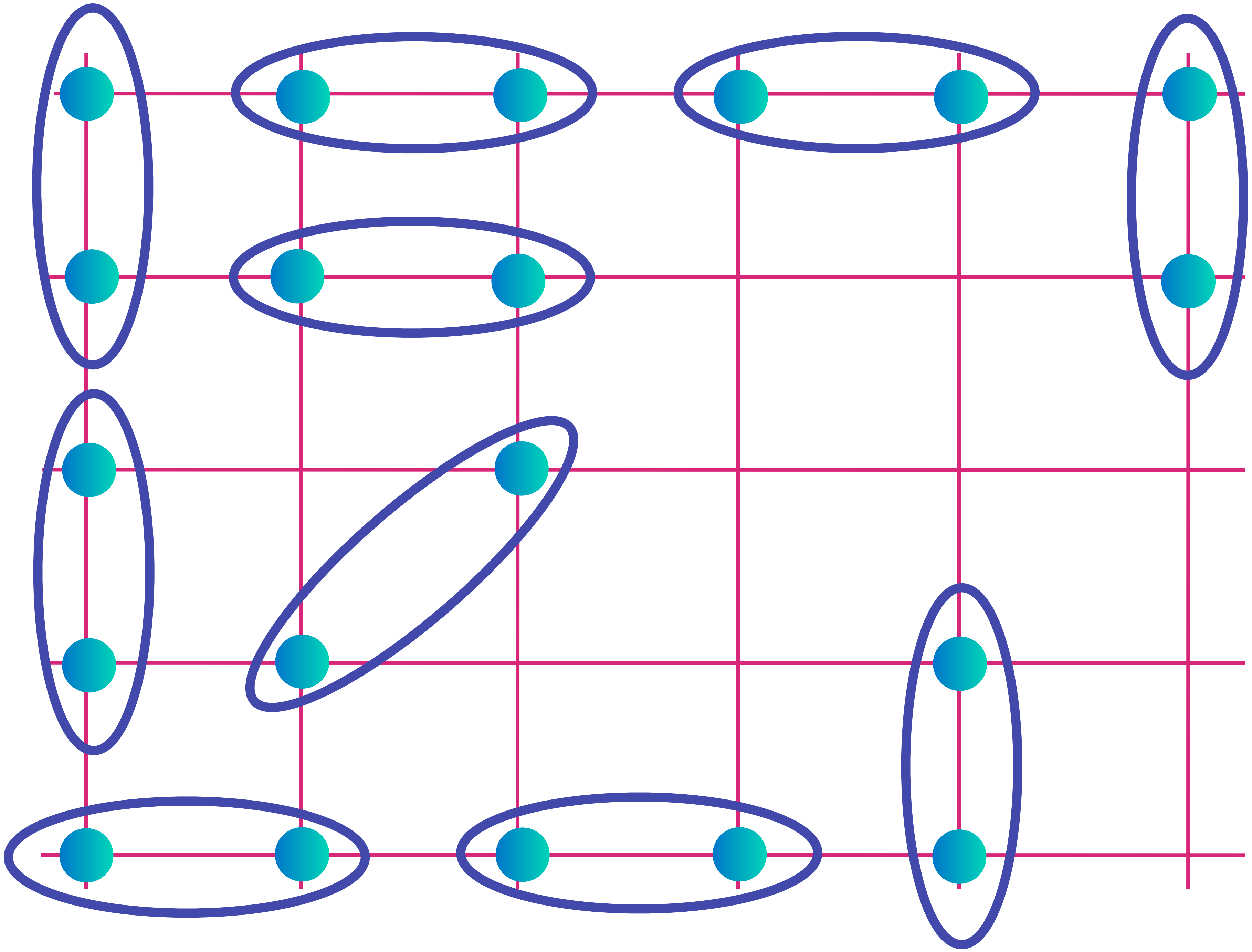

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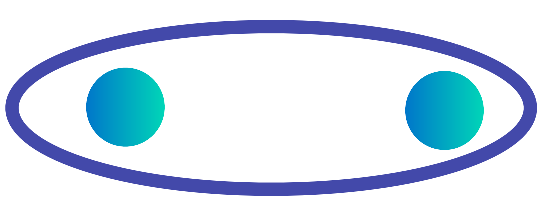

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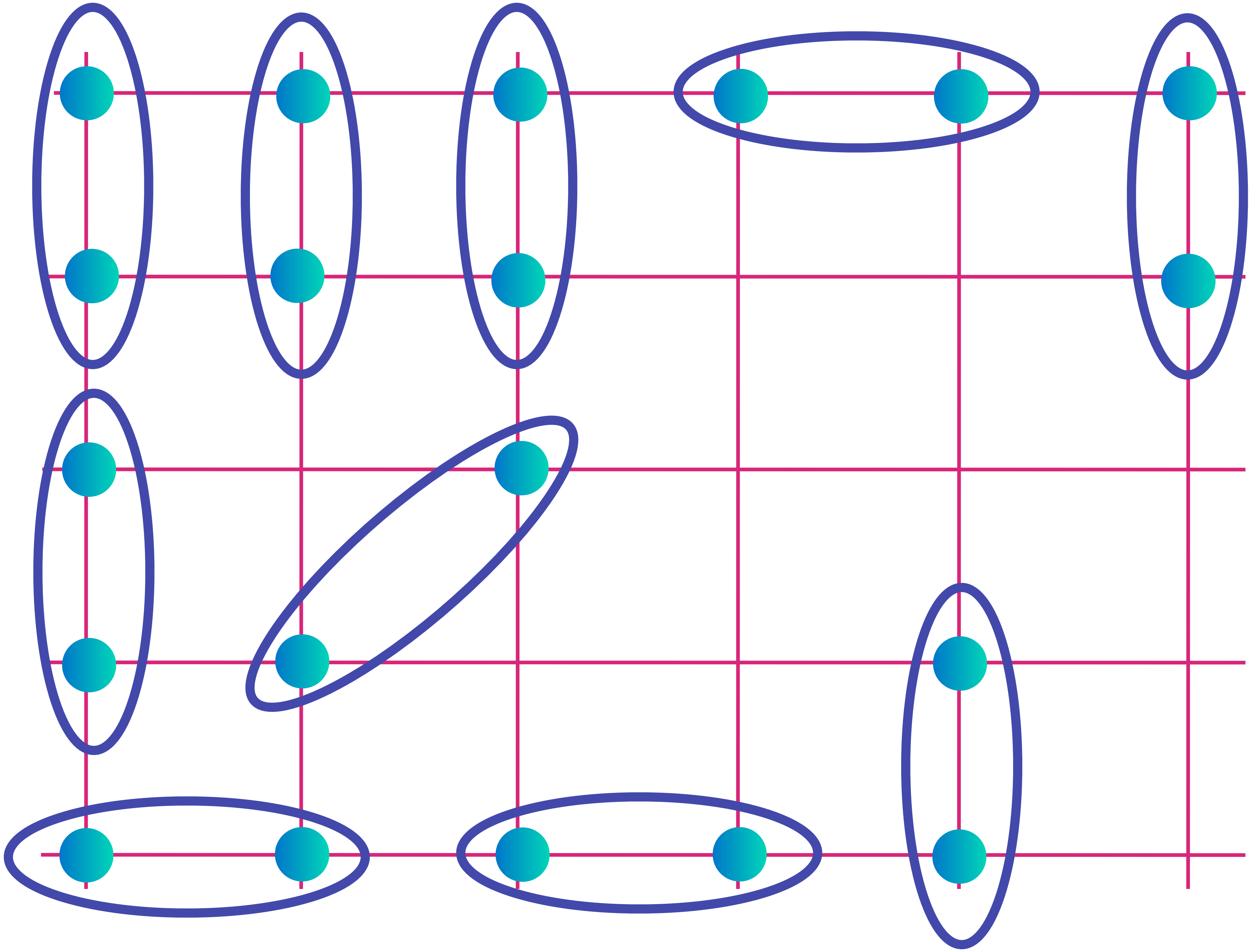

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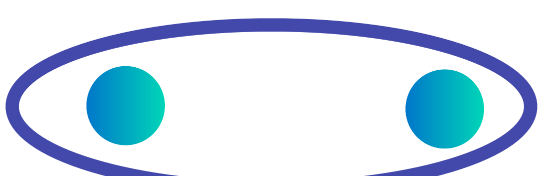
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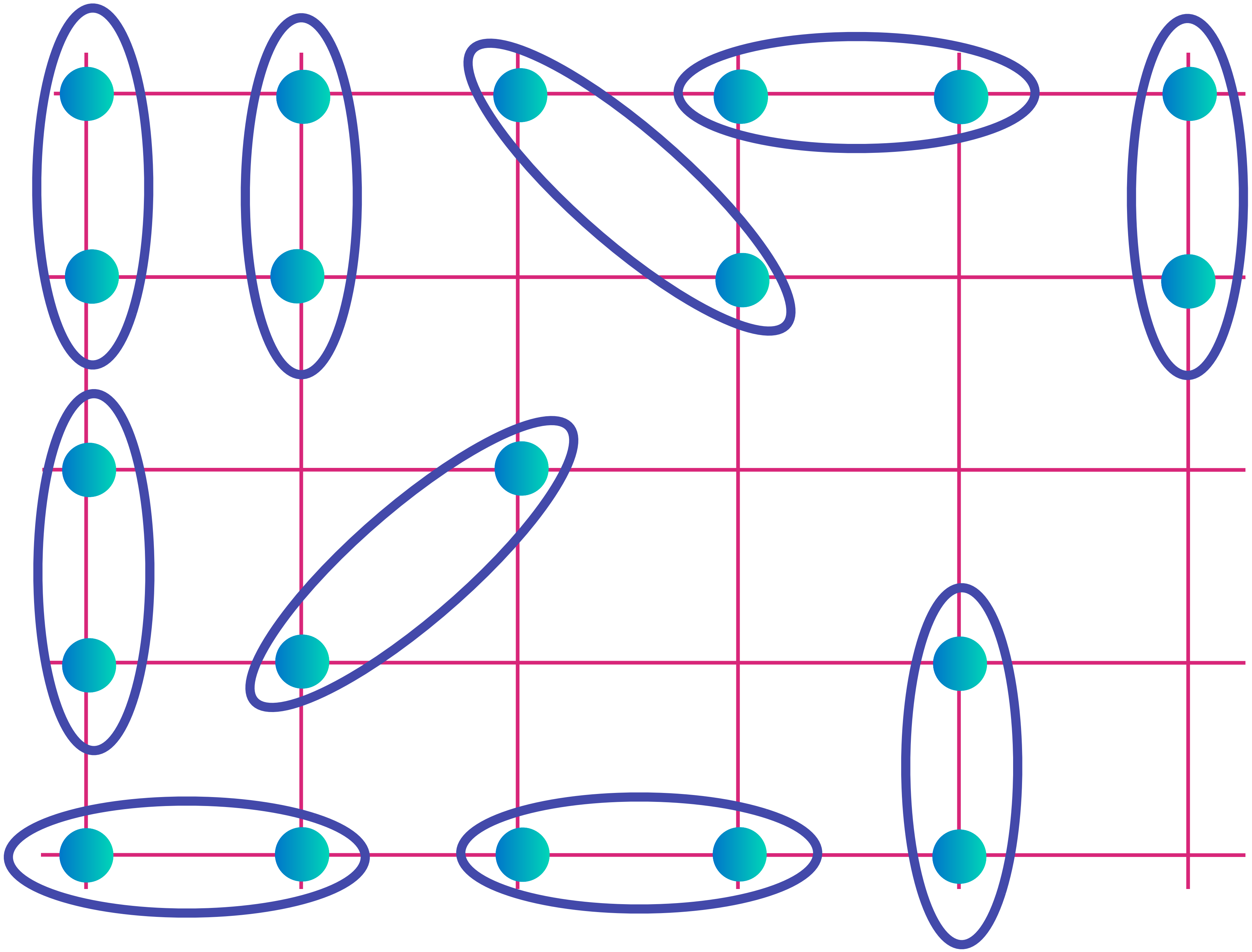

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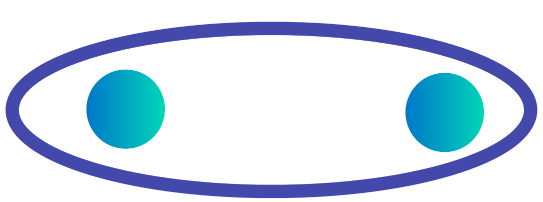

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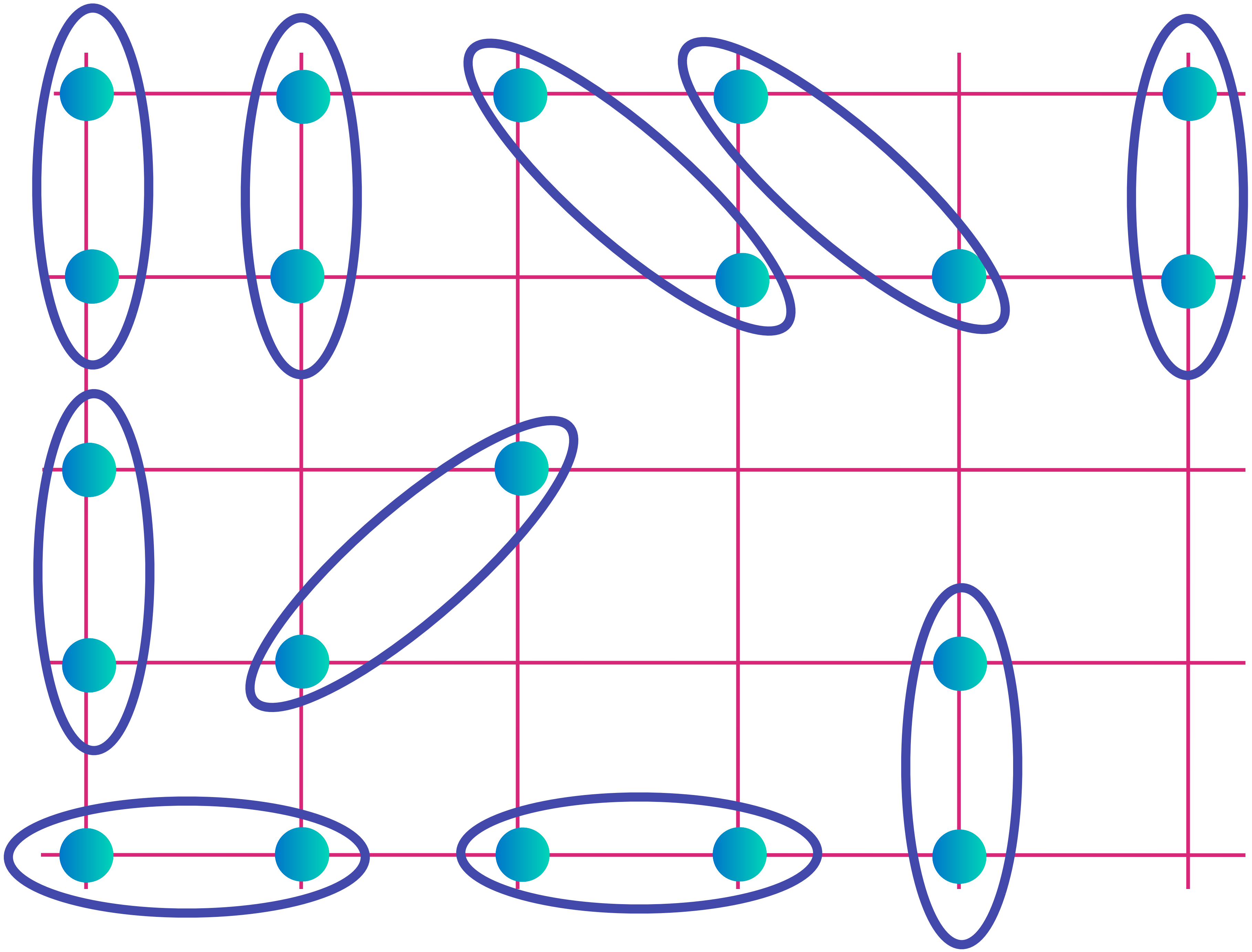

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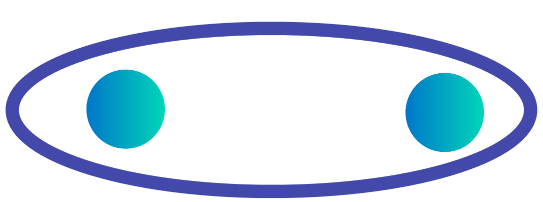

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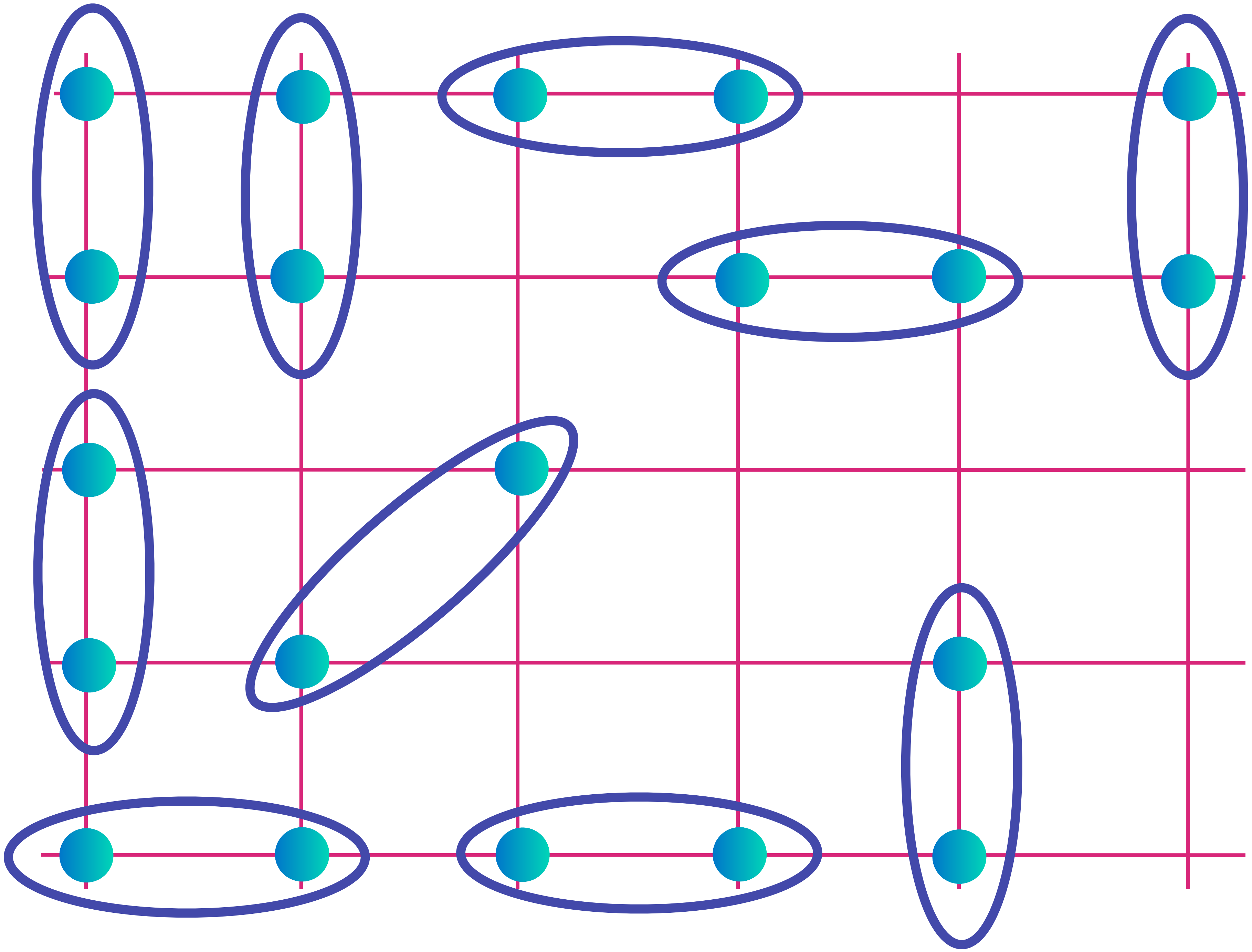

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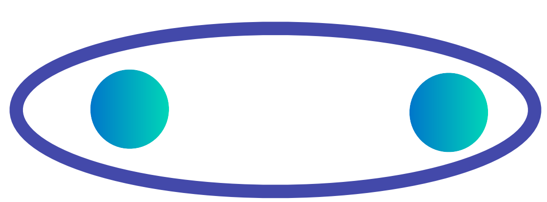

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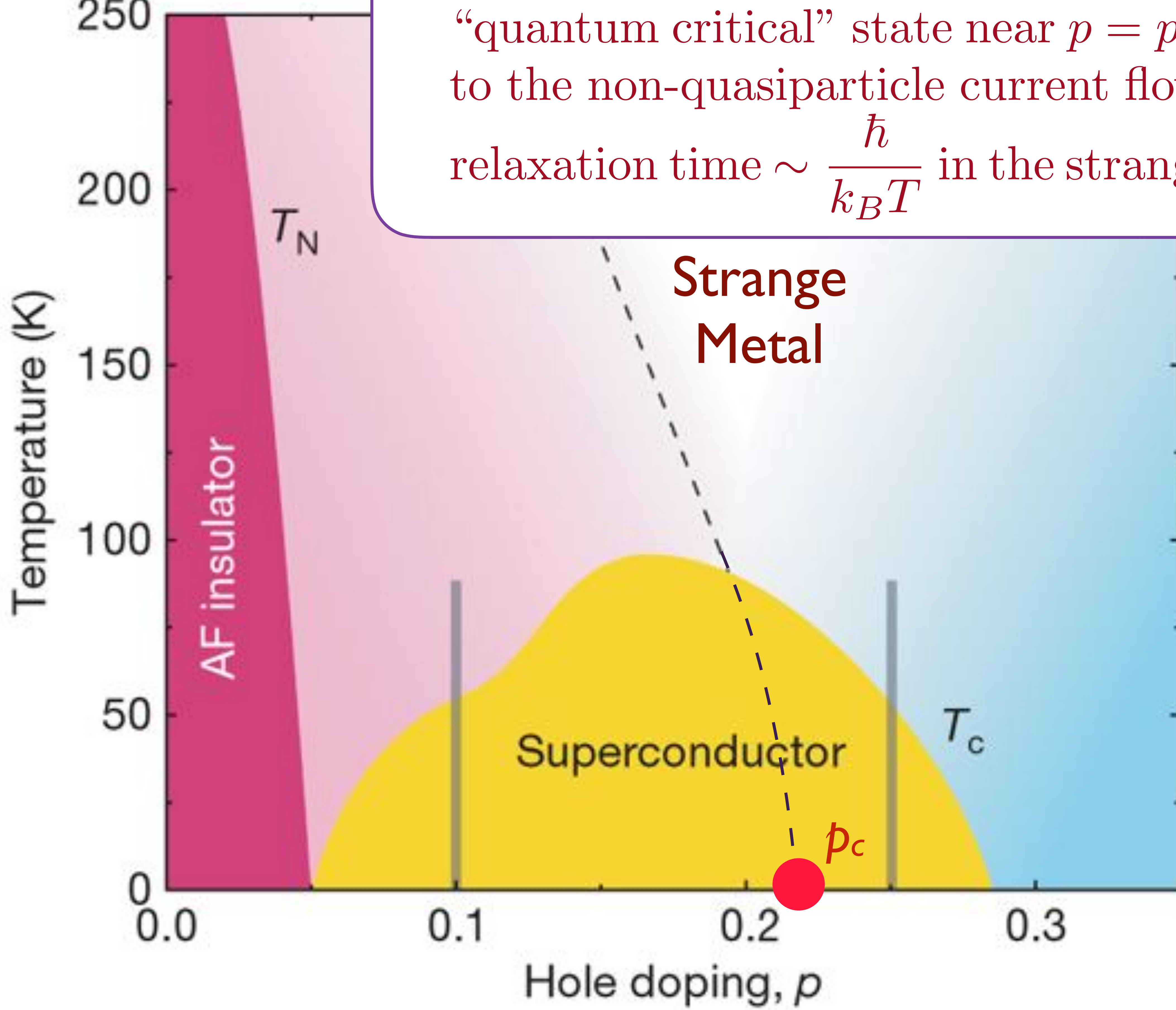

Quantum entanglement

Black holes

Metals (ordinary and strange) and superconductors

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 $\sim \hbar/(k_B T_H)$.

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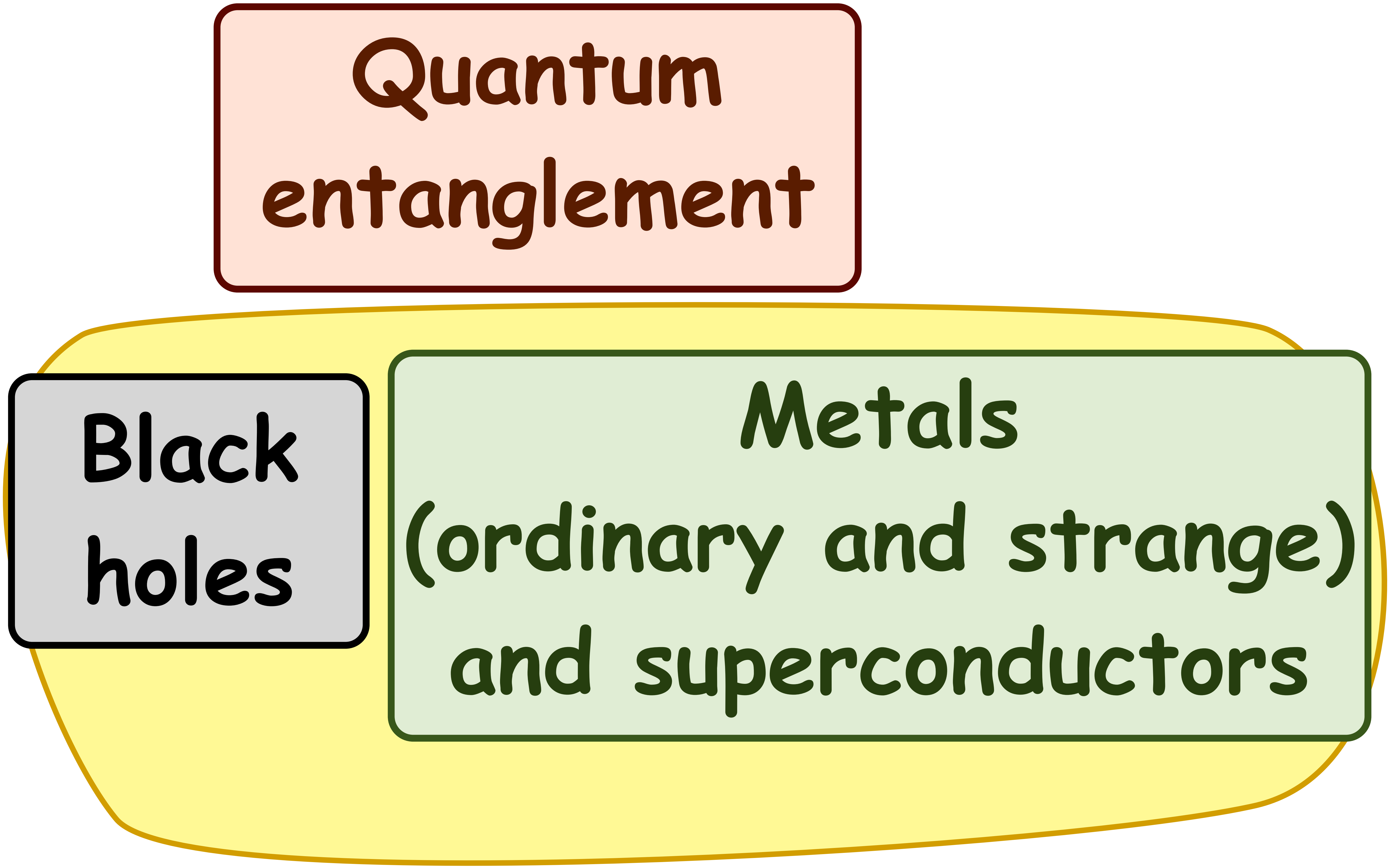
<u>Holography</u>:
Quantum black holes "look like" quantum-critical many-particle systems without quasiparticle excitations, residing "on" the surface of the black hole

J. Maldacena, IJTP **38**, 1113 (1999); S.S. Gubser, I.R. Klebanov, and A.M. Polyakov Phys. Lett. B **428**, 105 (1998); E. Witten, Adv. Theor. Math. Phys. **2**, 253 (1998)


Quantum entanglement
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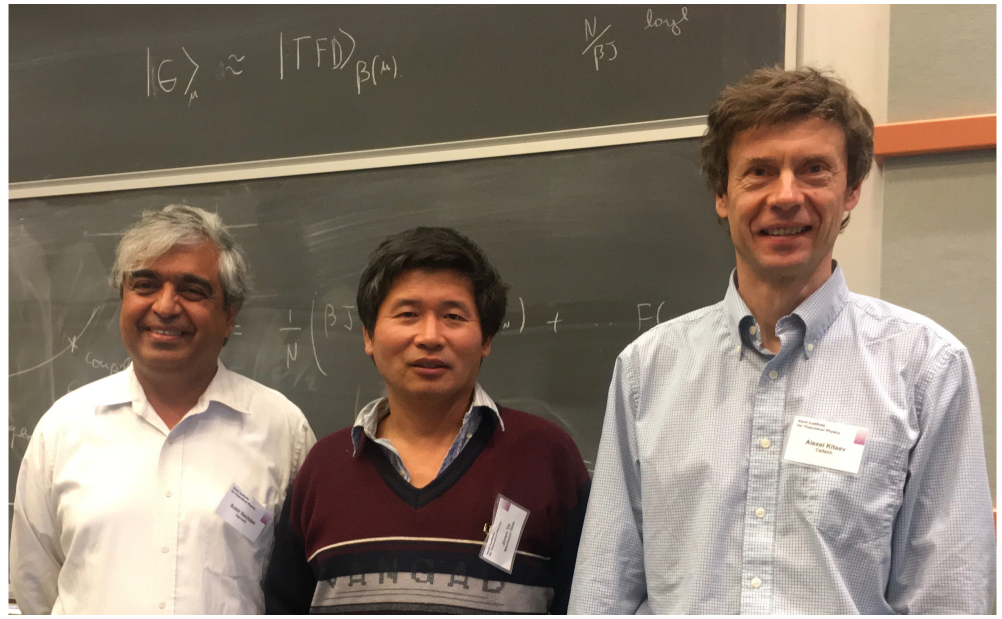
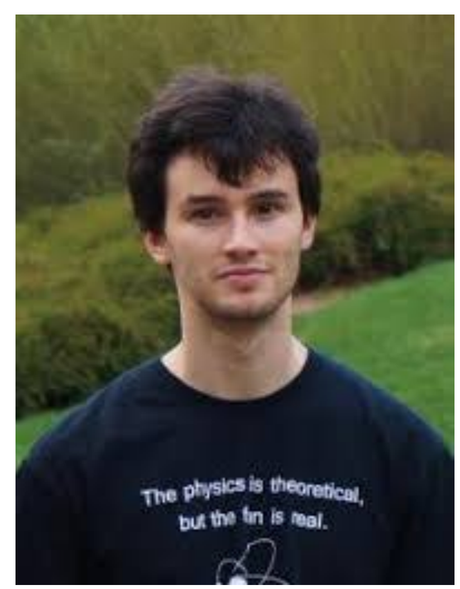
A “toy model” which describes both a strange metal and a black hole!

The Sachdev-Ye-Kitaev (SYK) model



S. Sachdev and J. Ye (1993); A. Kitaev (2015)

Variation described in
D. G. Joshi, Chenyuan Li, G. Tarnopolsky, A. Georges,
and S. Sachdev, arXiv:1912.08822



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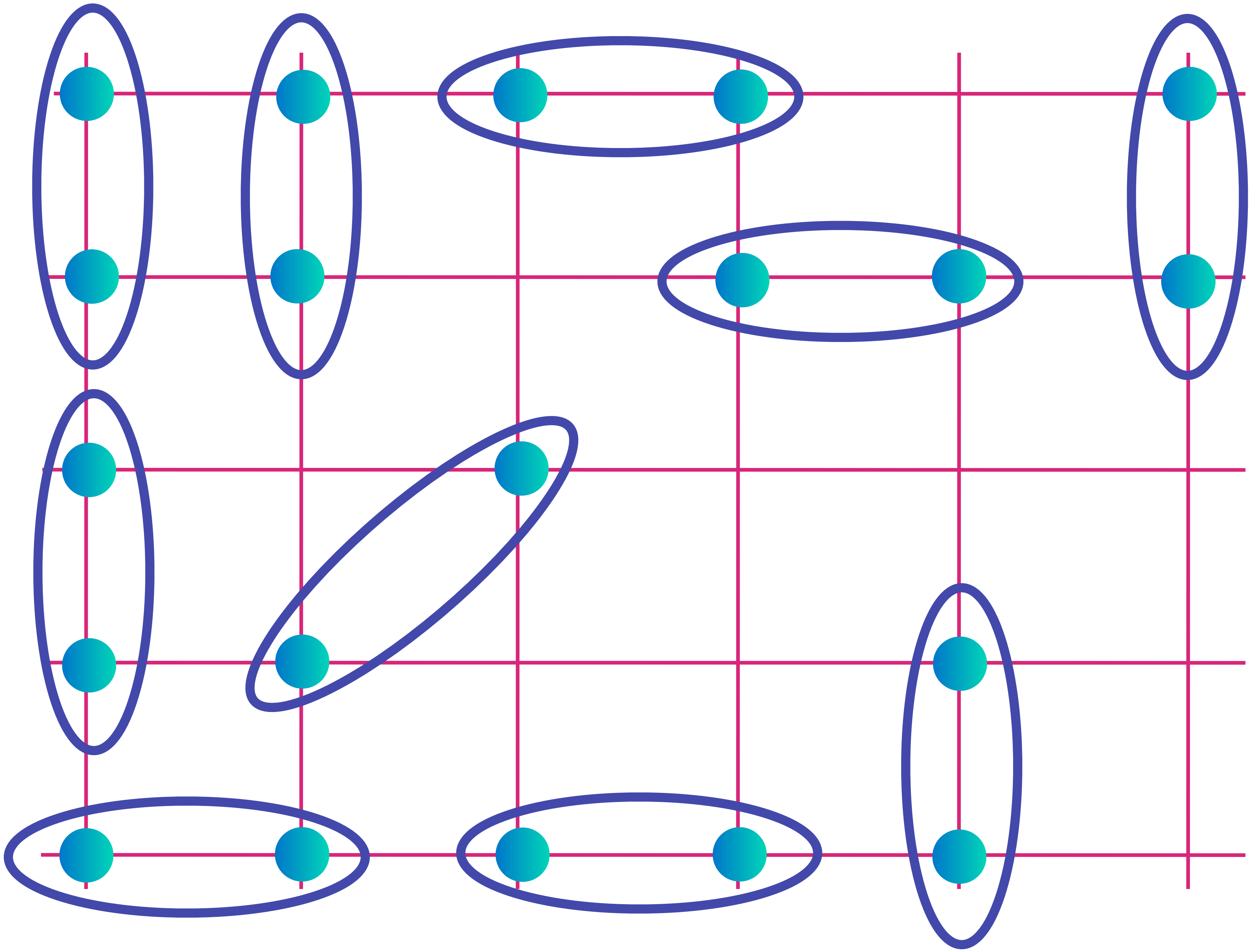

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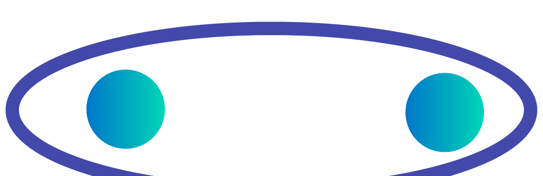

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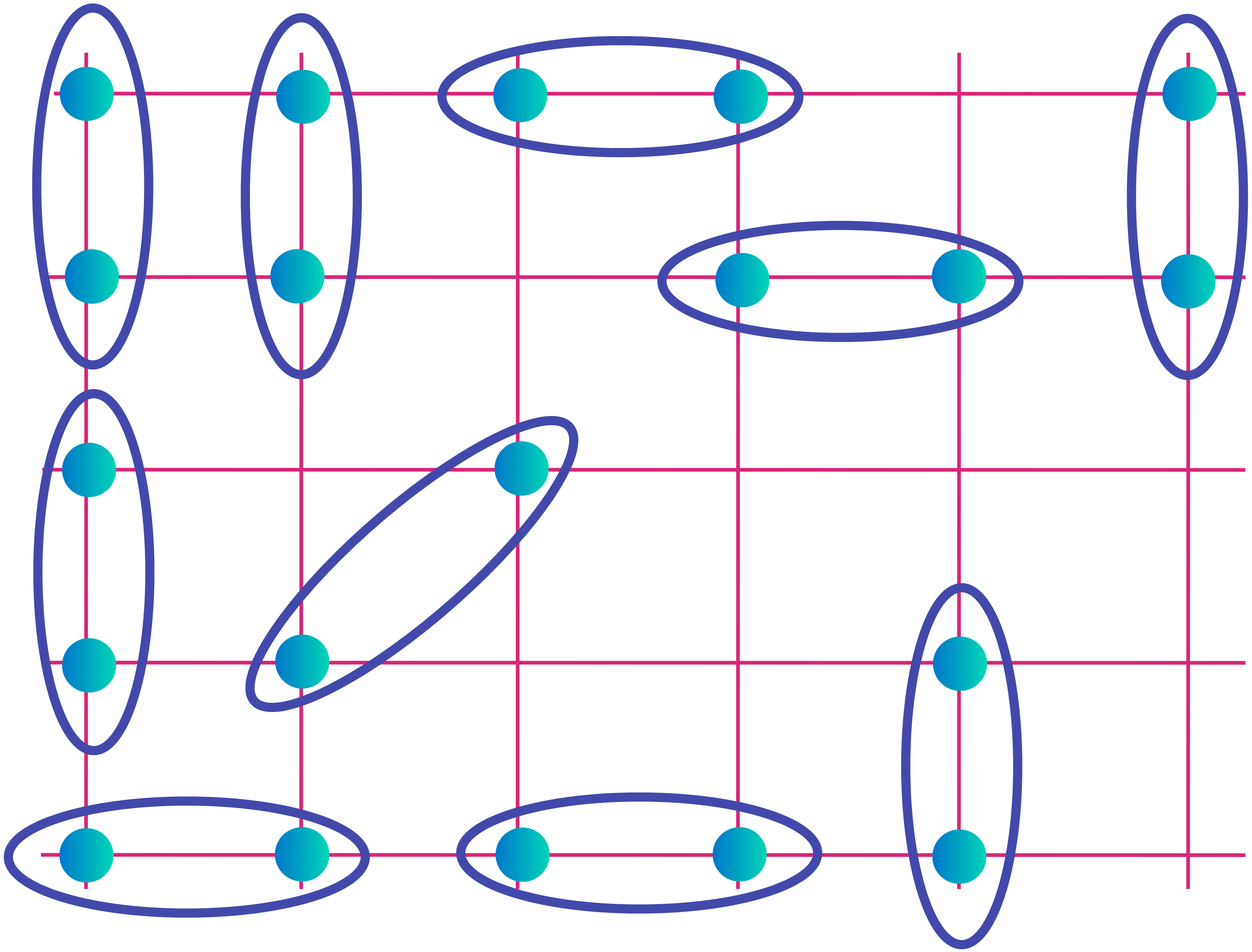
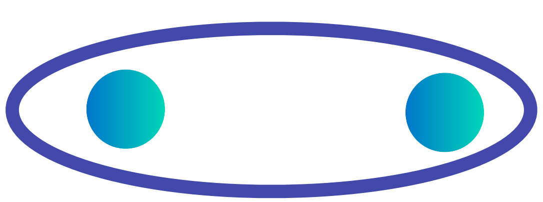


Allow electron motion and bond exchange between ANY pair of sites, all with a random amplitude



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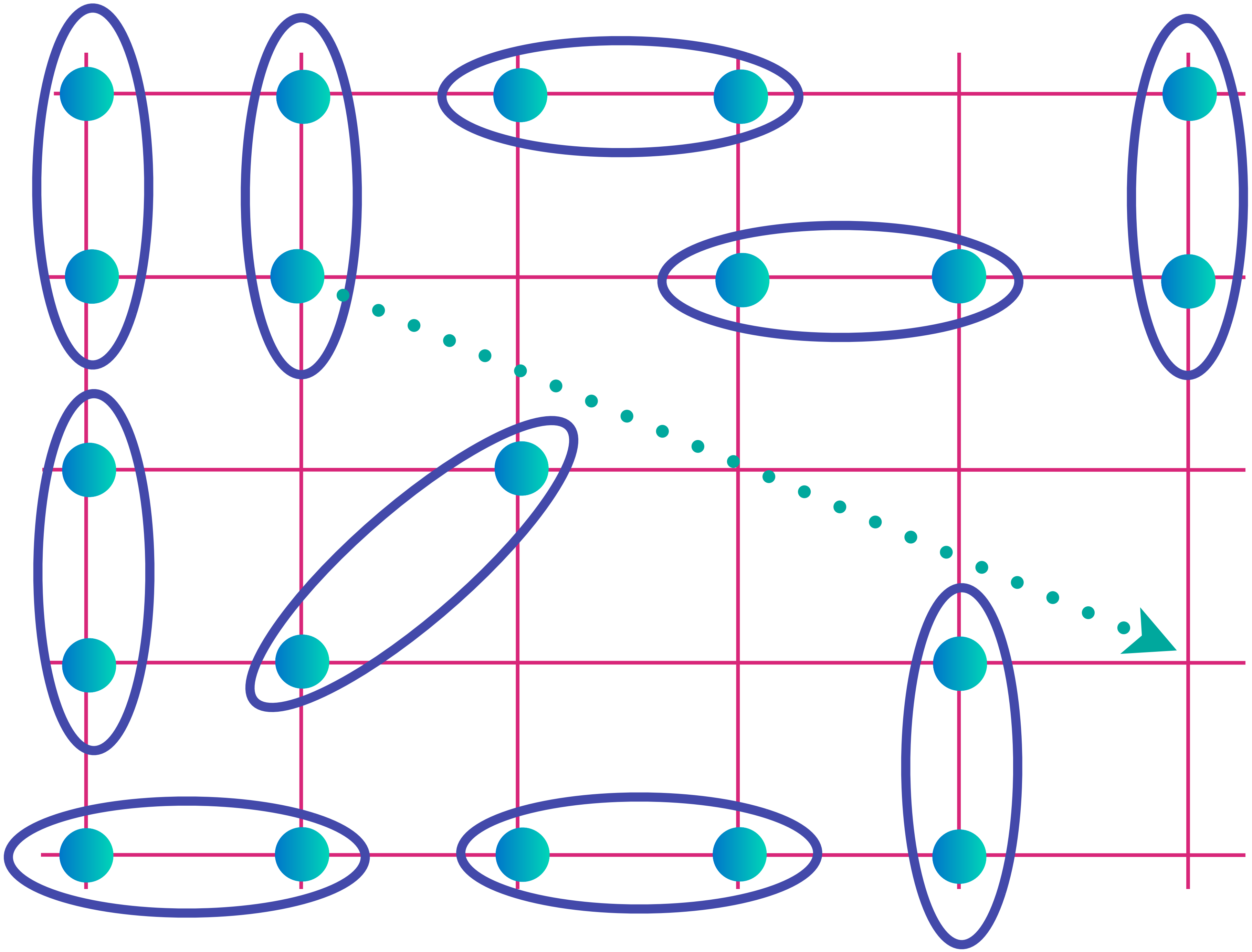

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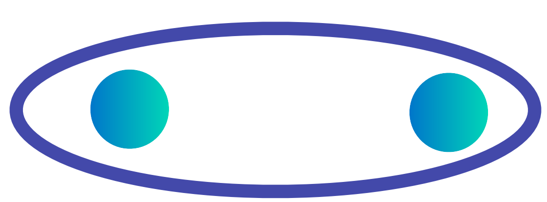
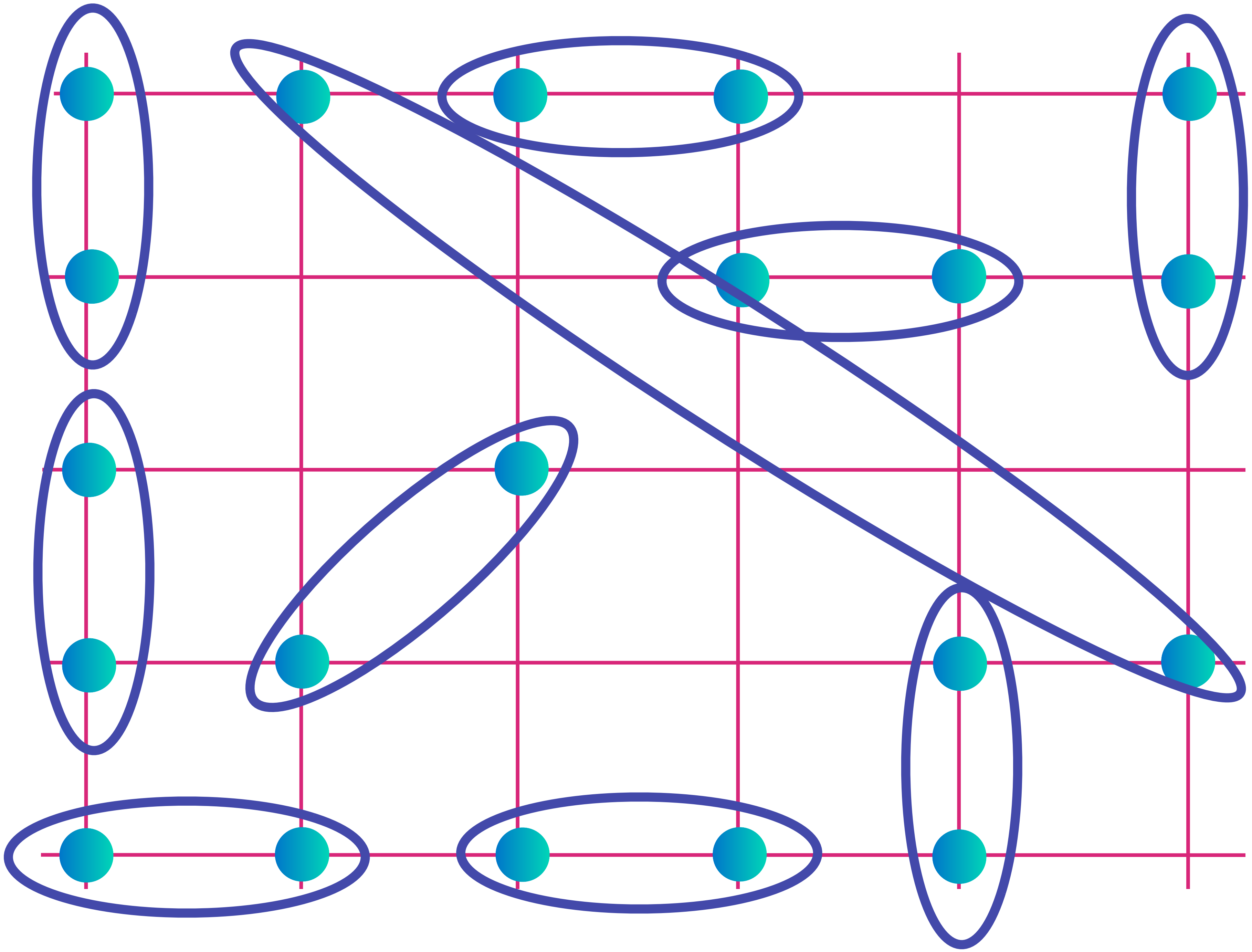
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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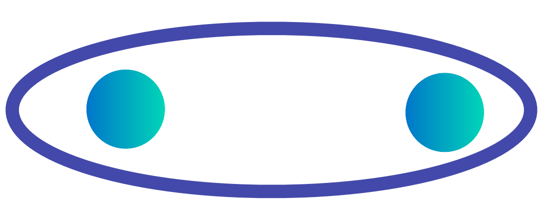
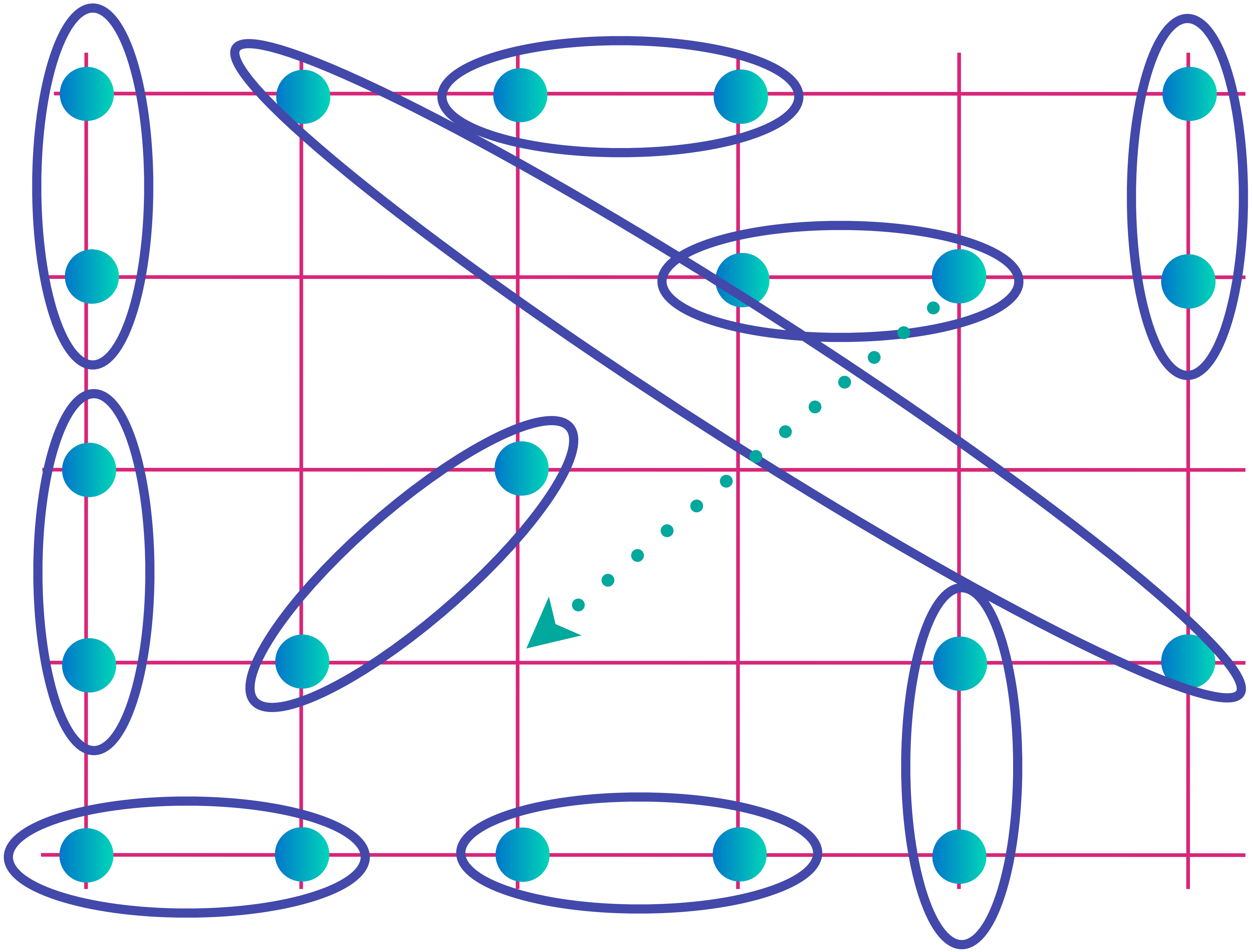
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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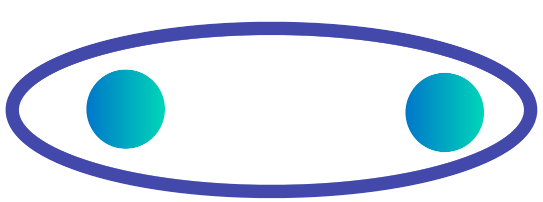
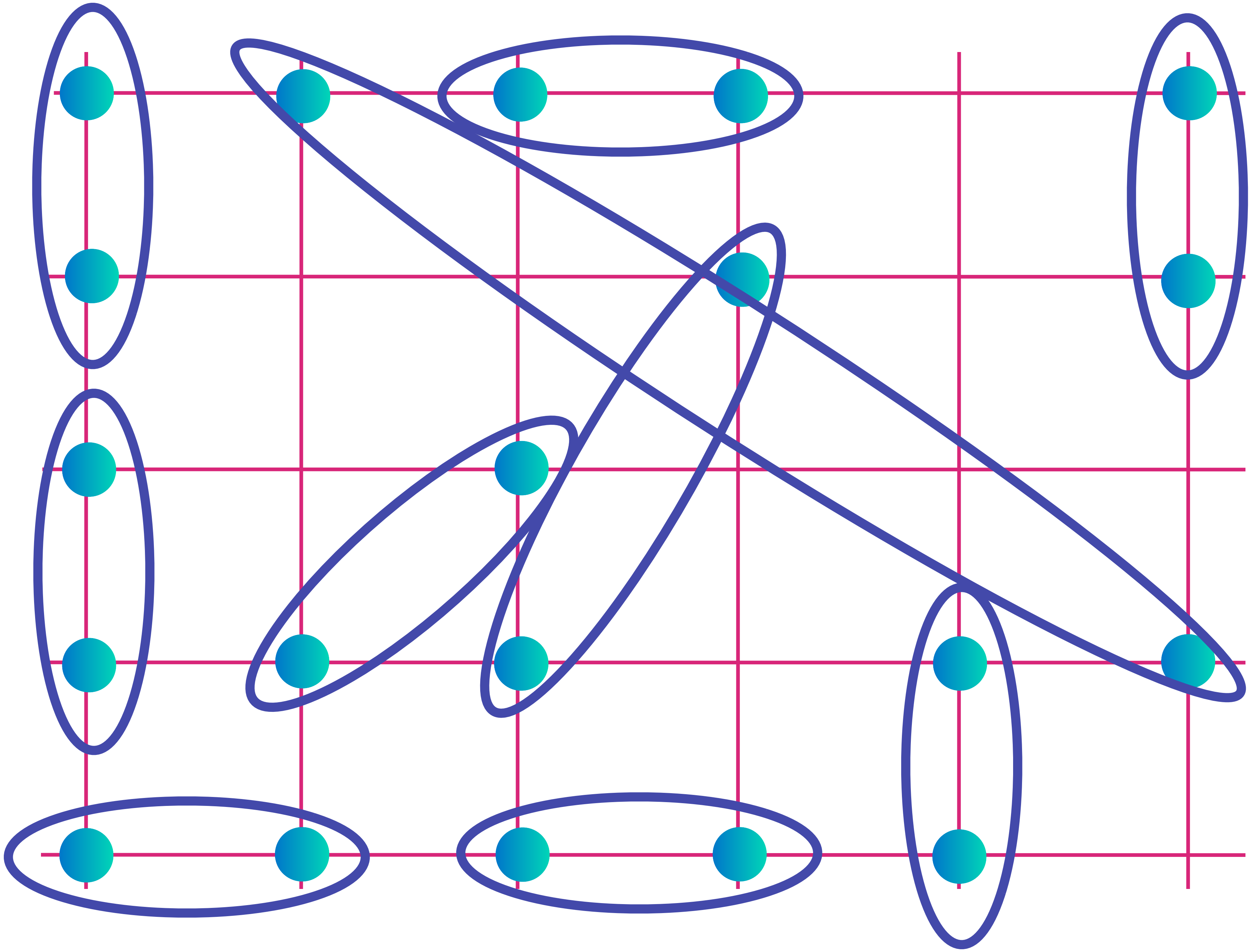
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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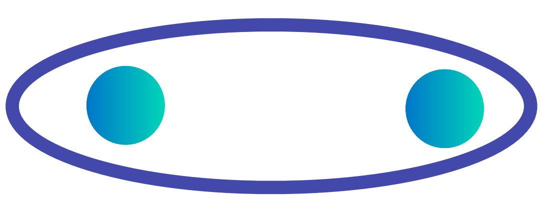
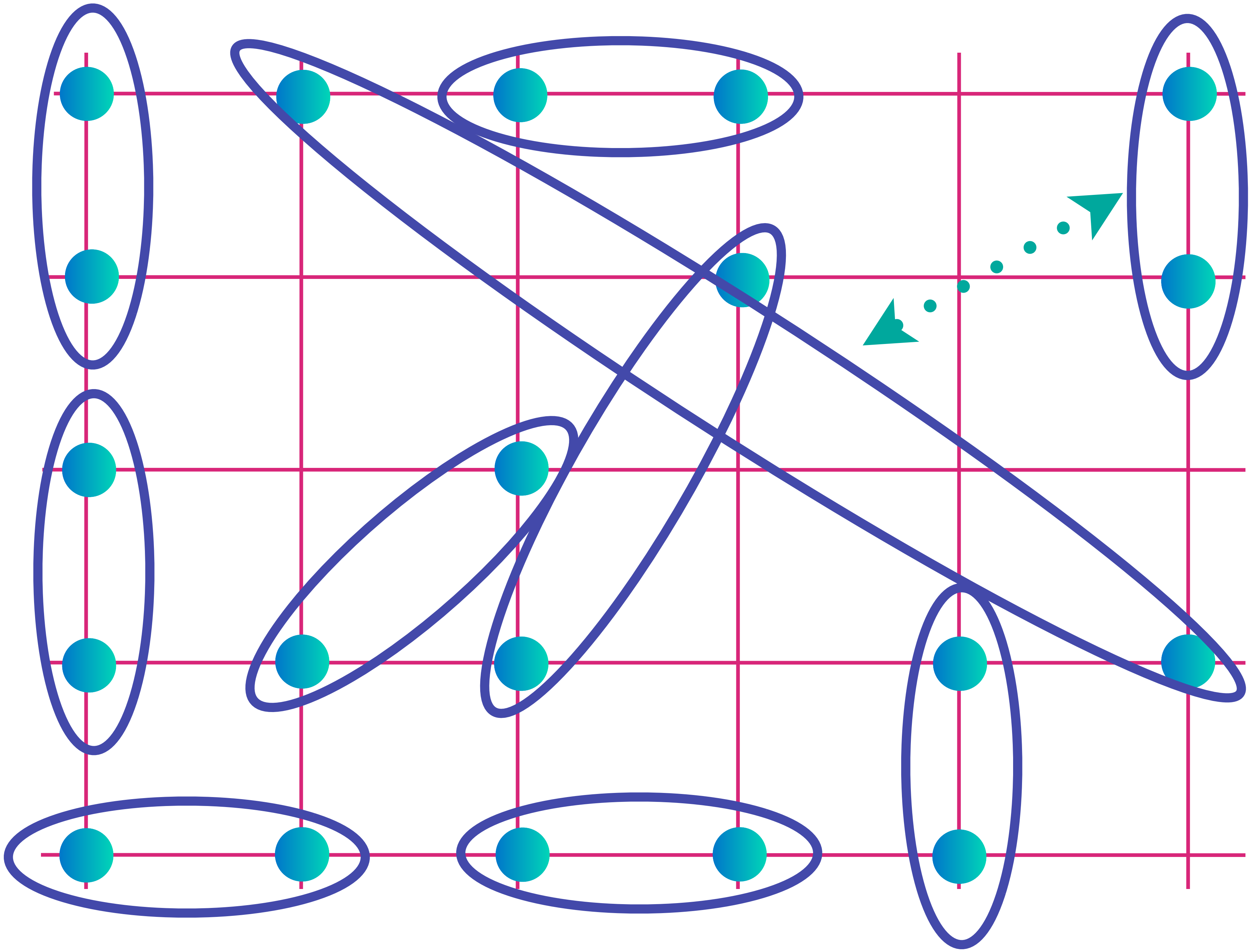
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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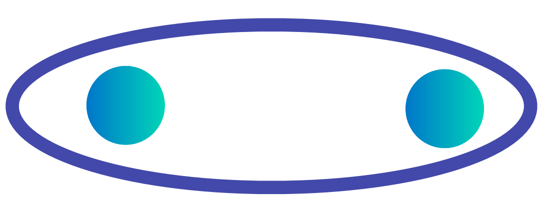
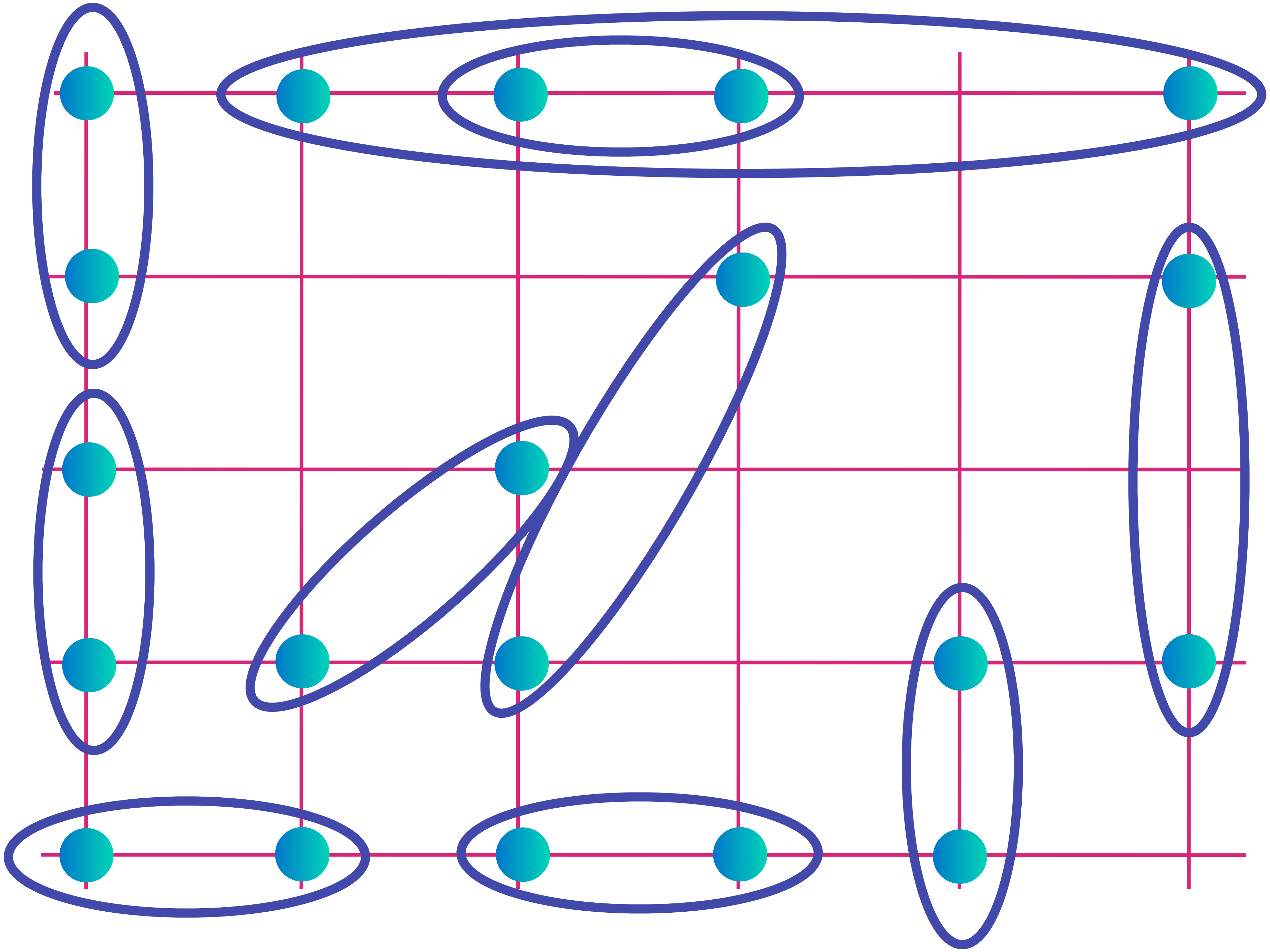
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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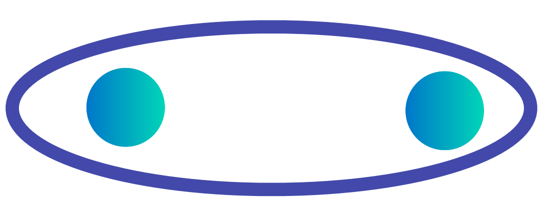
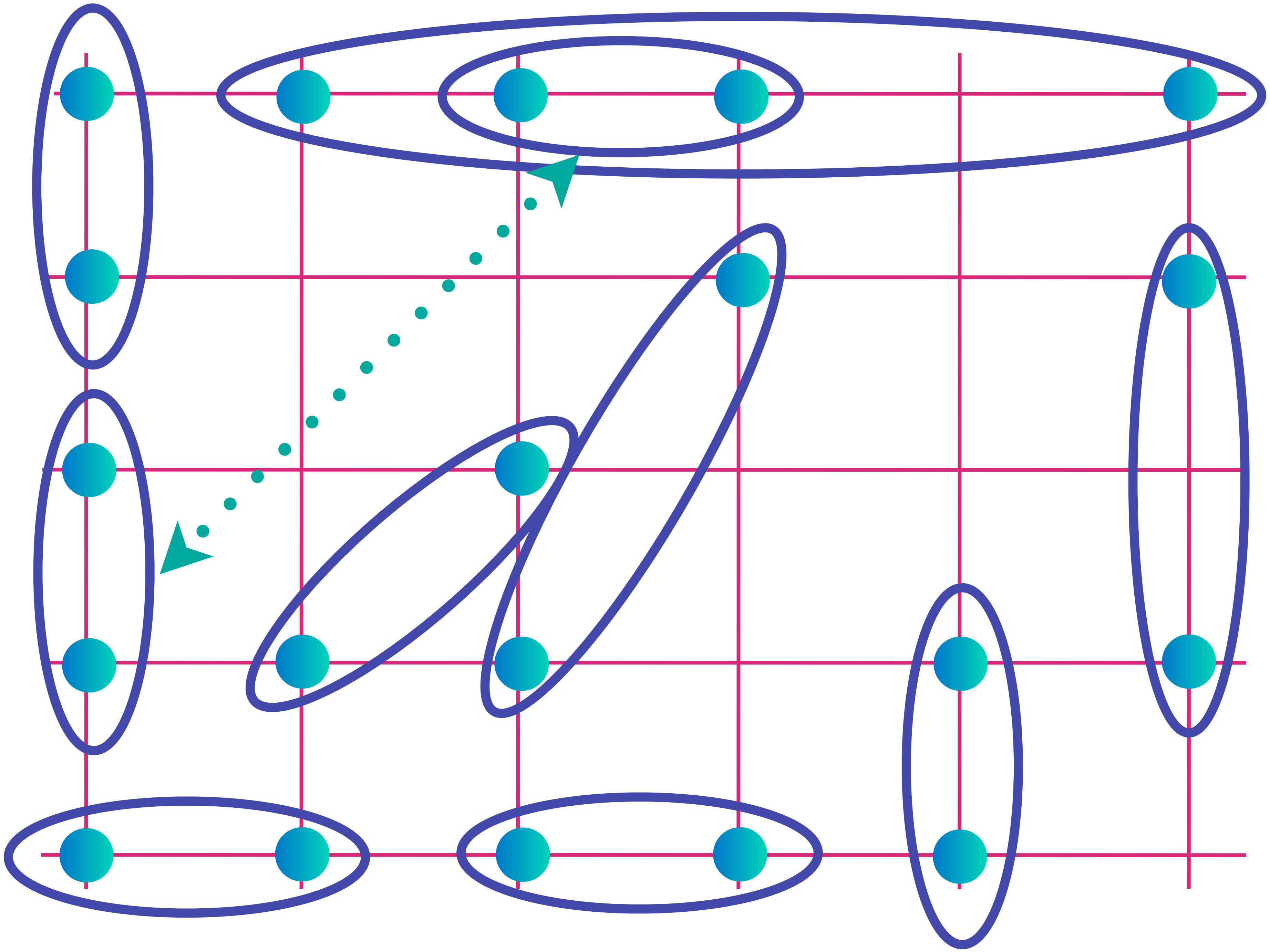
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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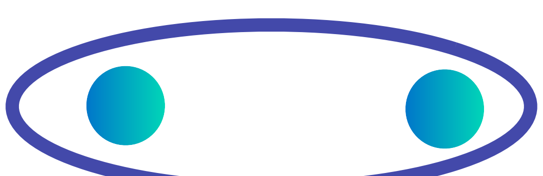
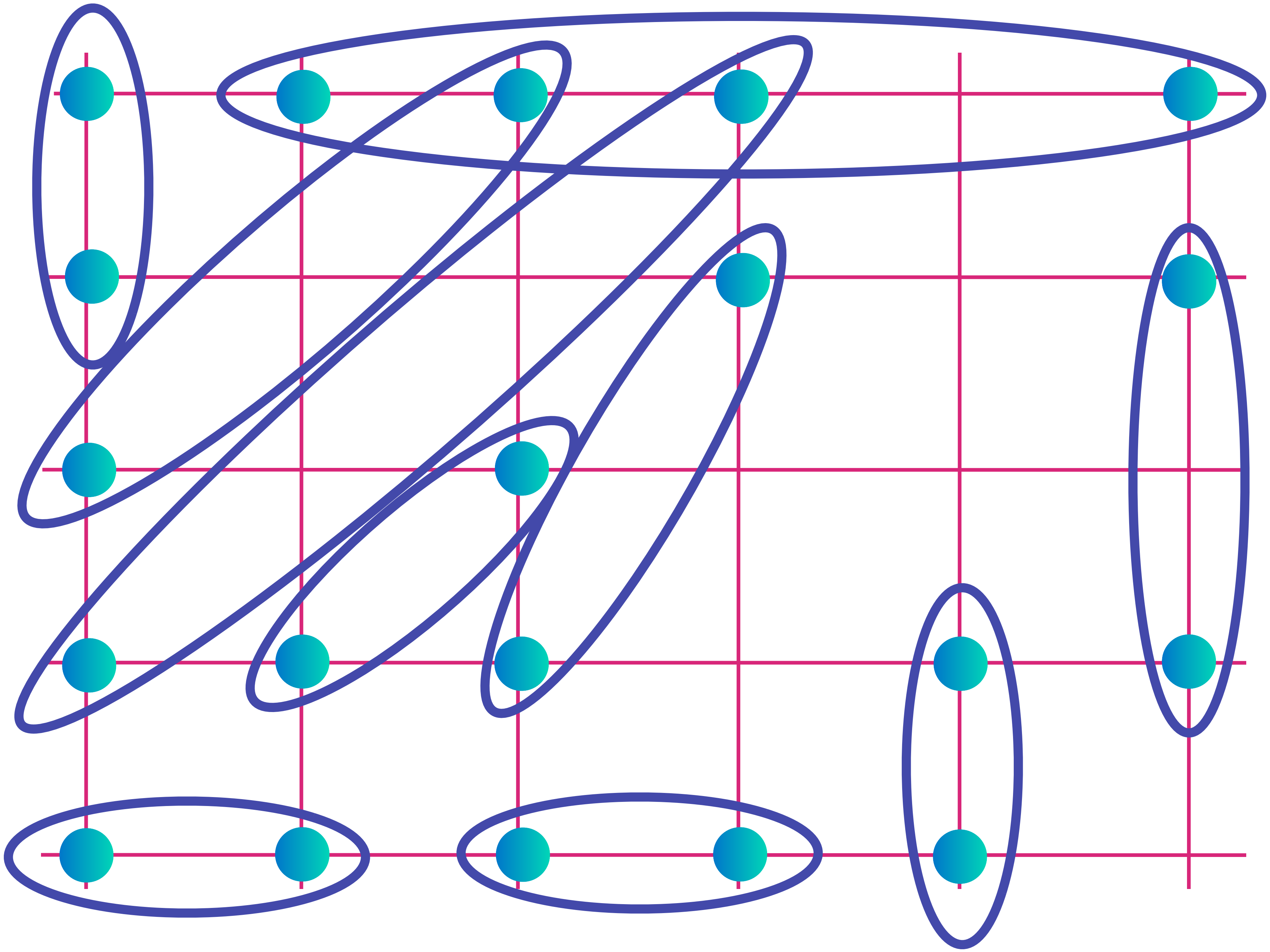
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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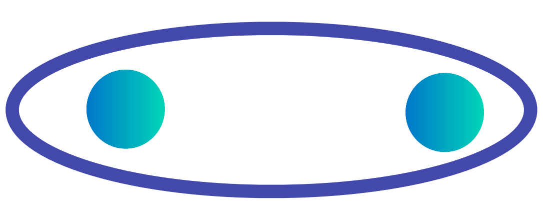

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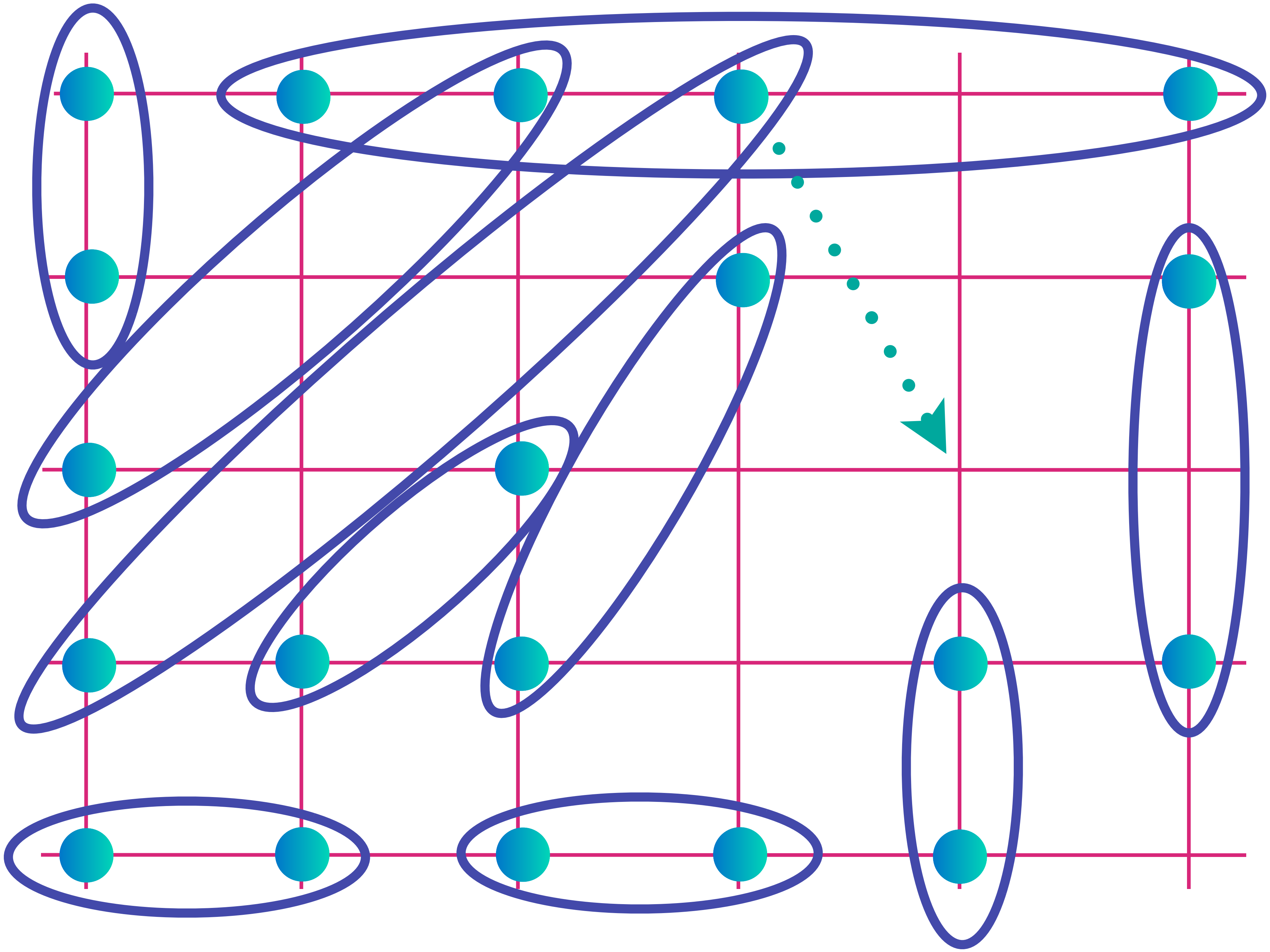

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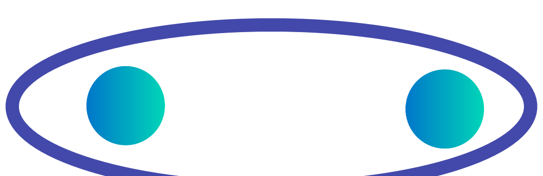
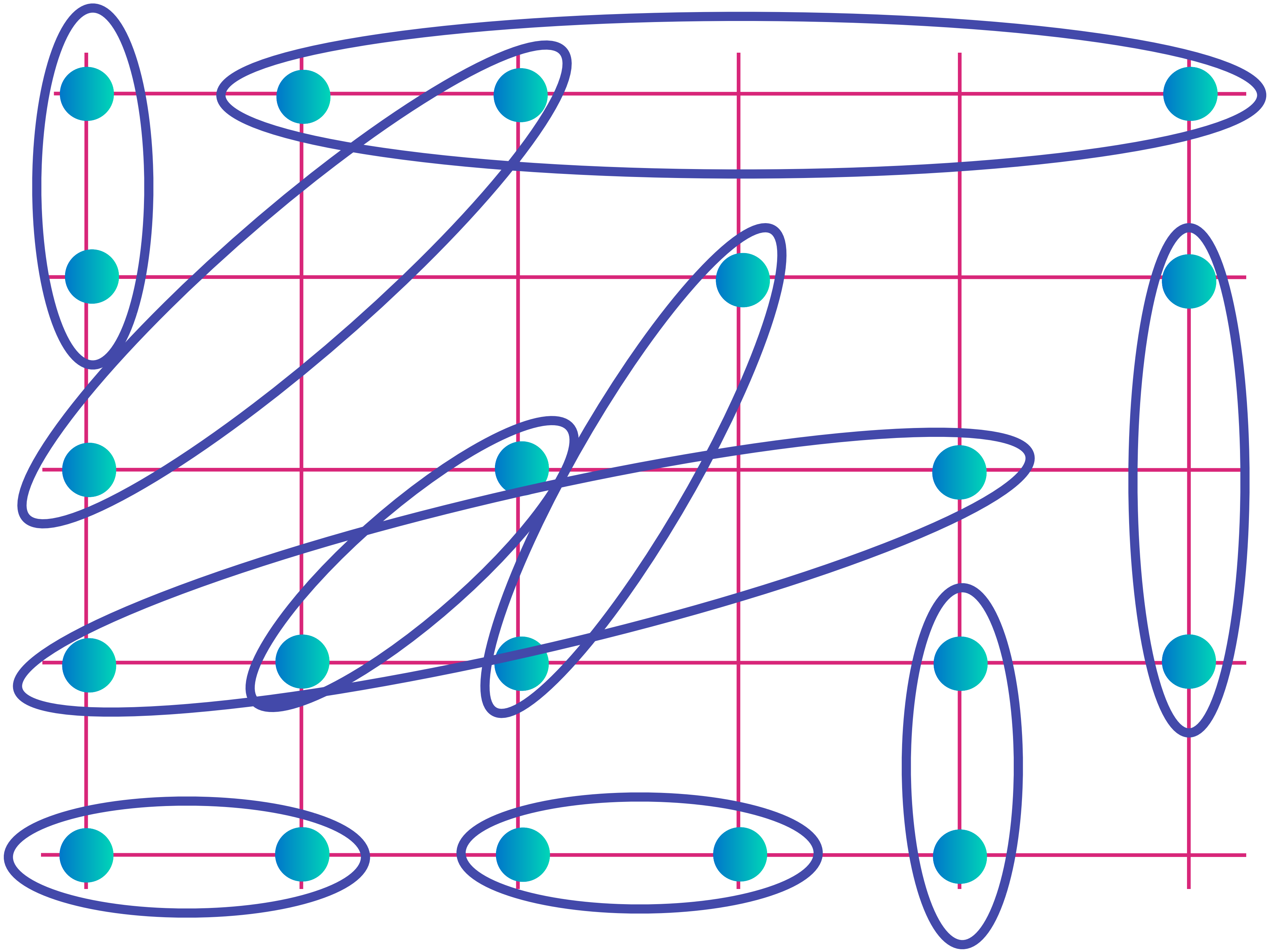
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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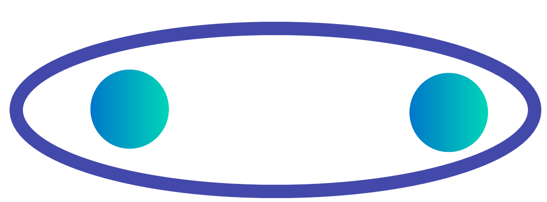
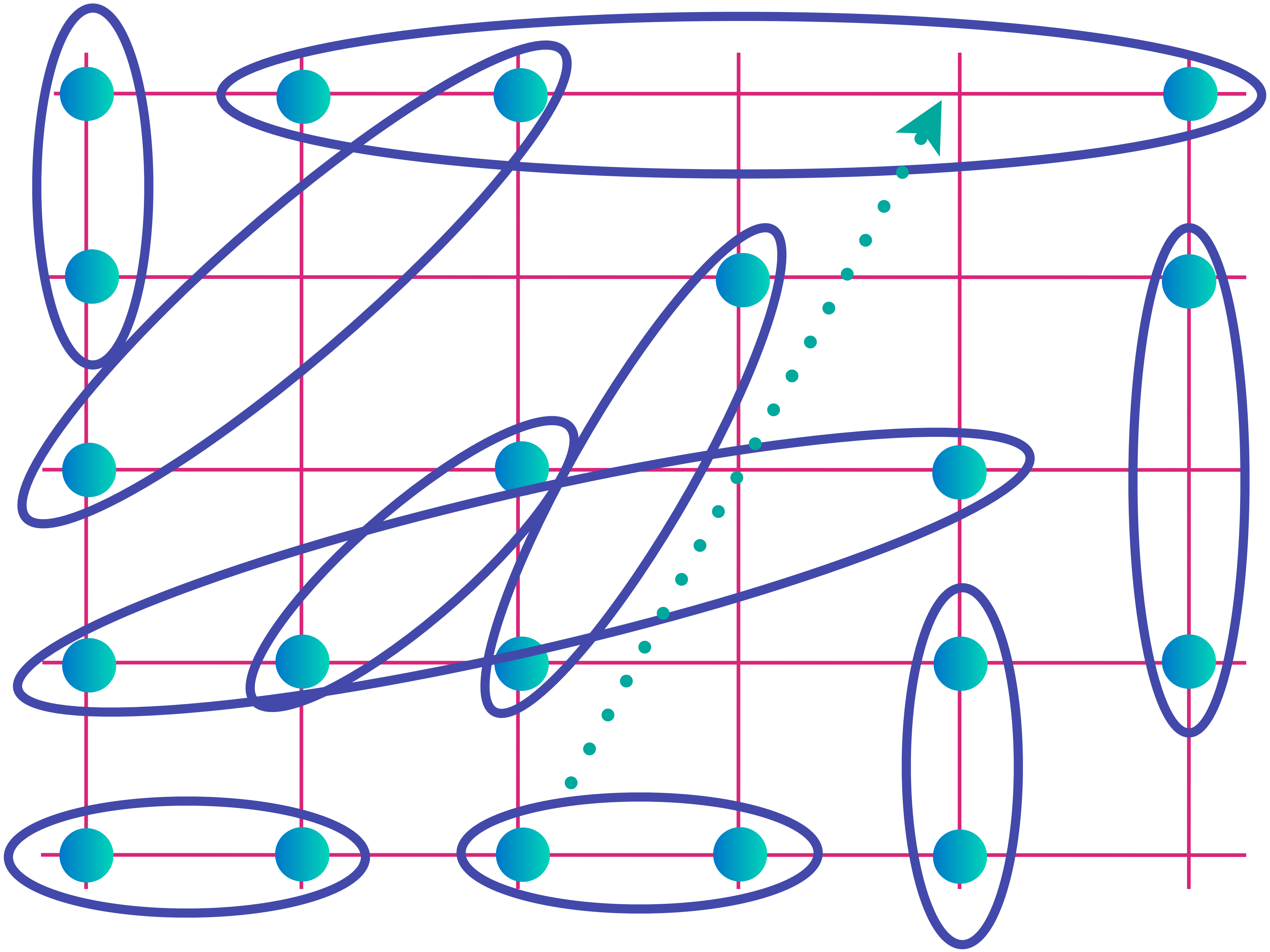
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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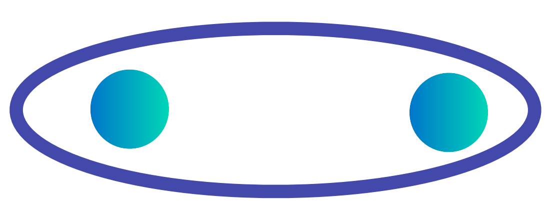
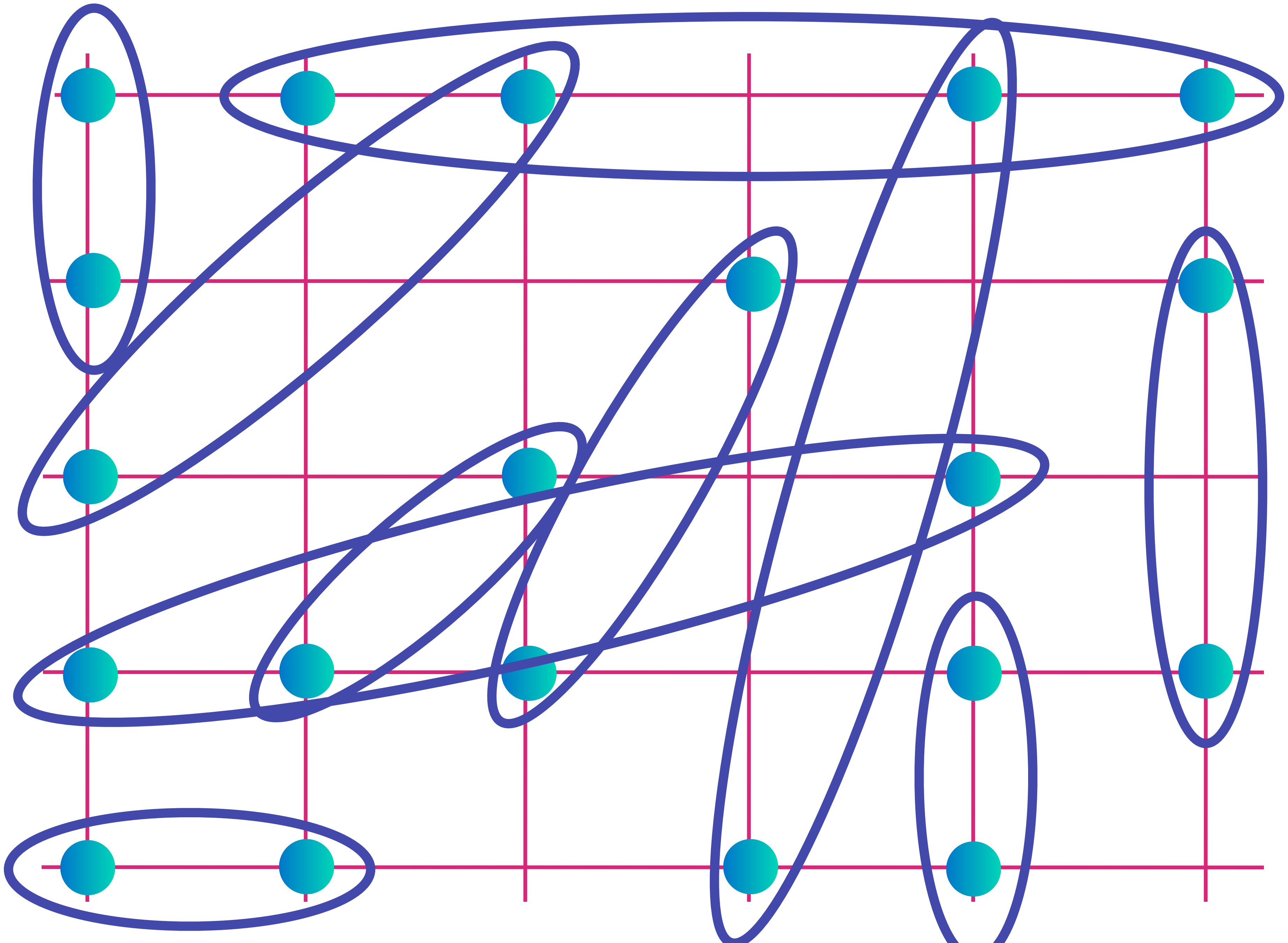
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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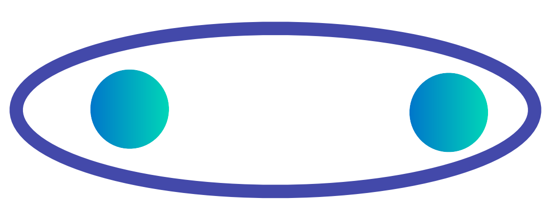
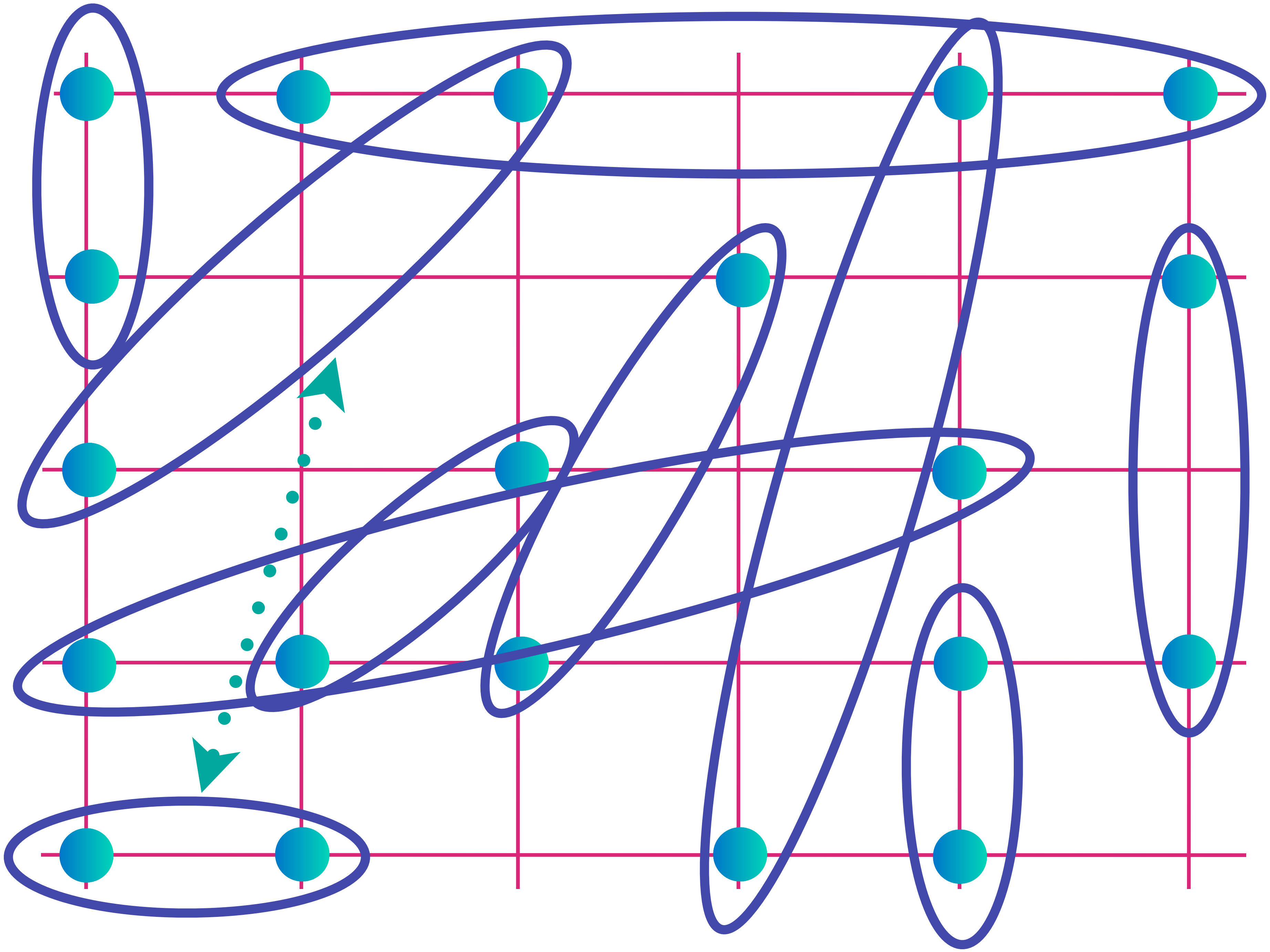
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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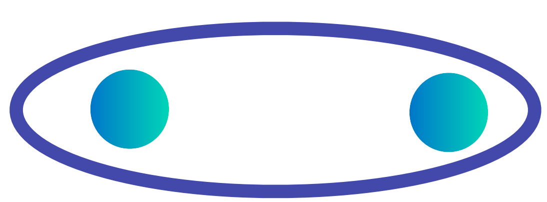
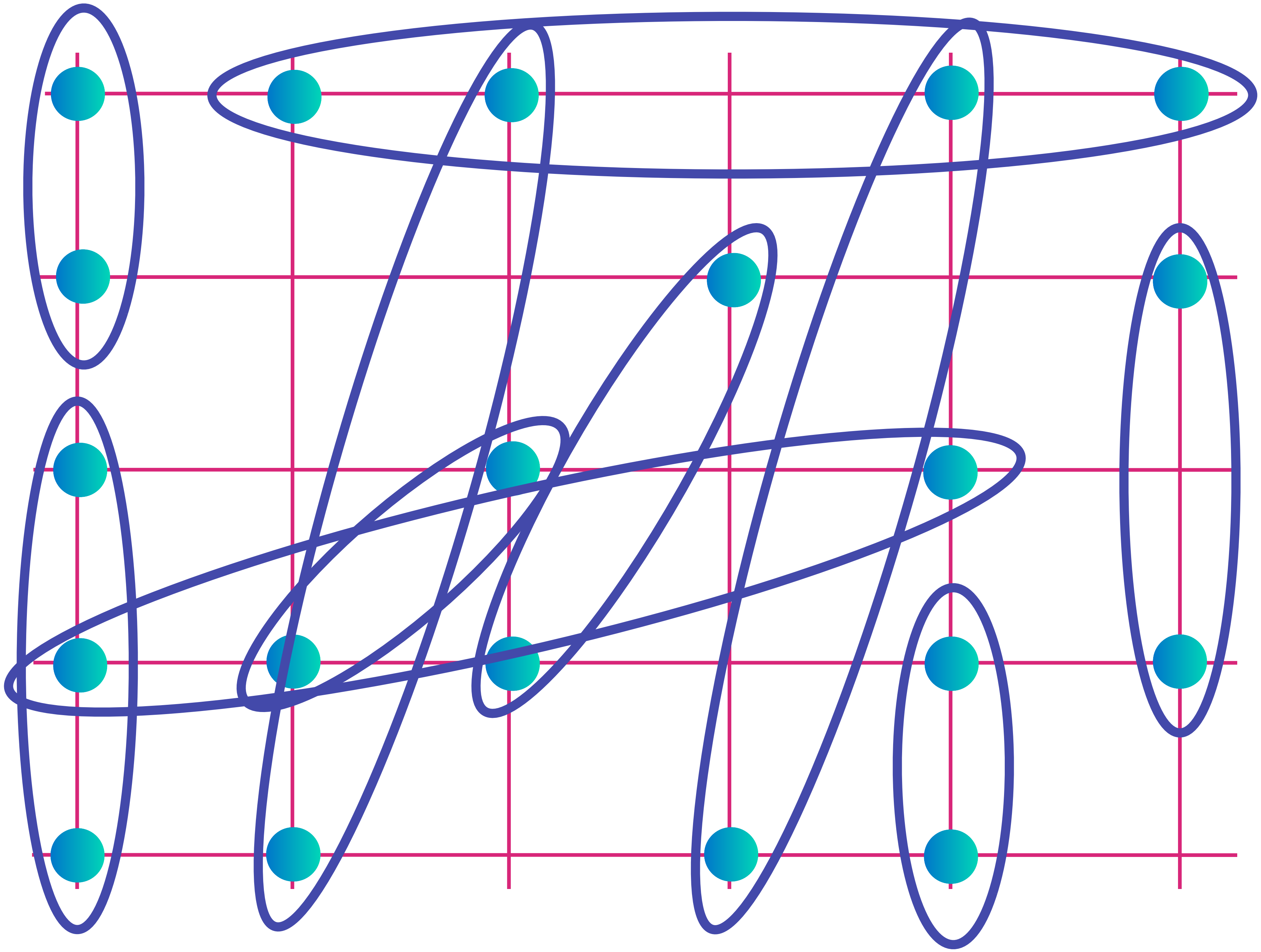
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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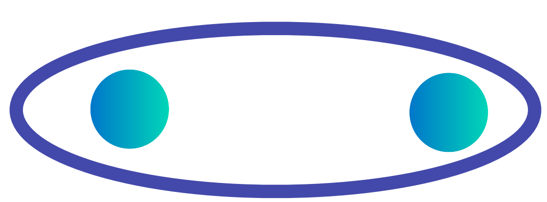
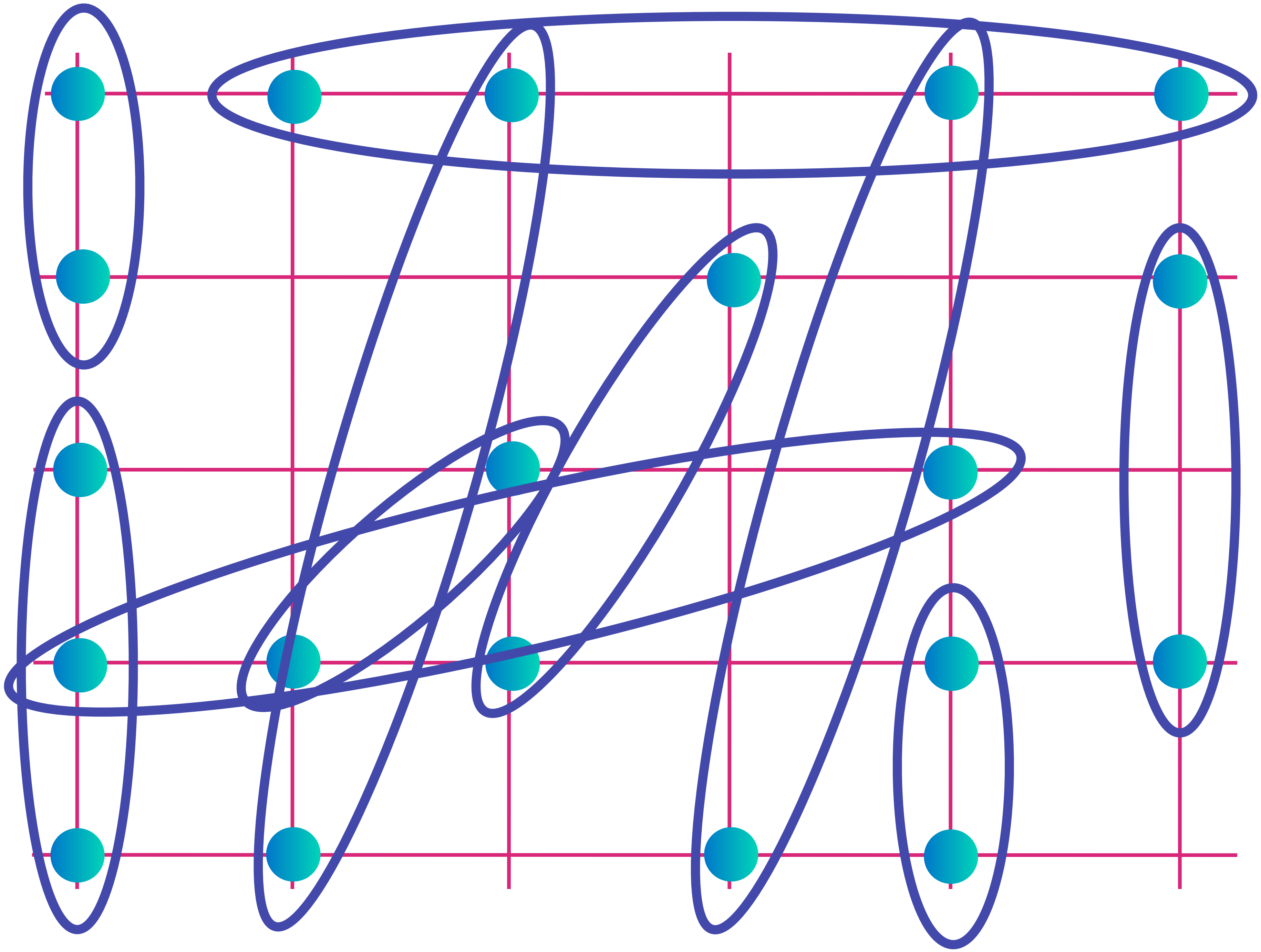
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

This describes both a strange metal and a black hole!



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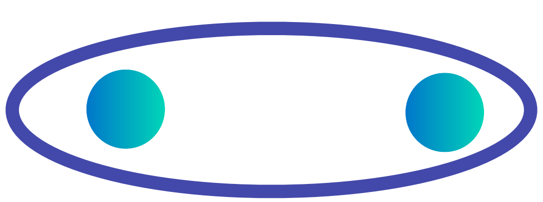


$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

A strange metal: lattice of SYK islands

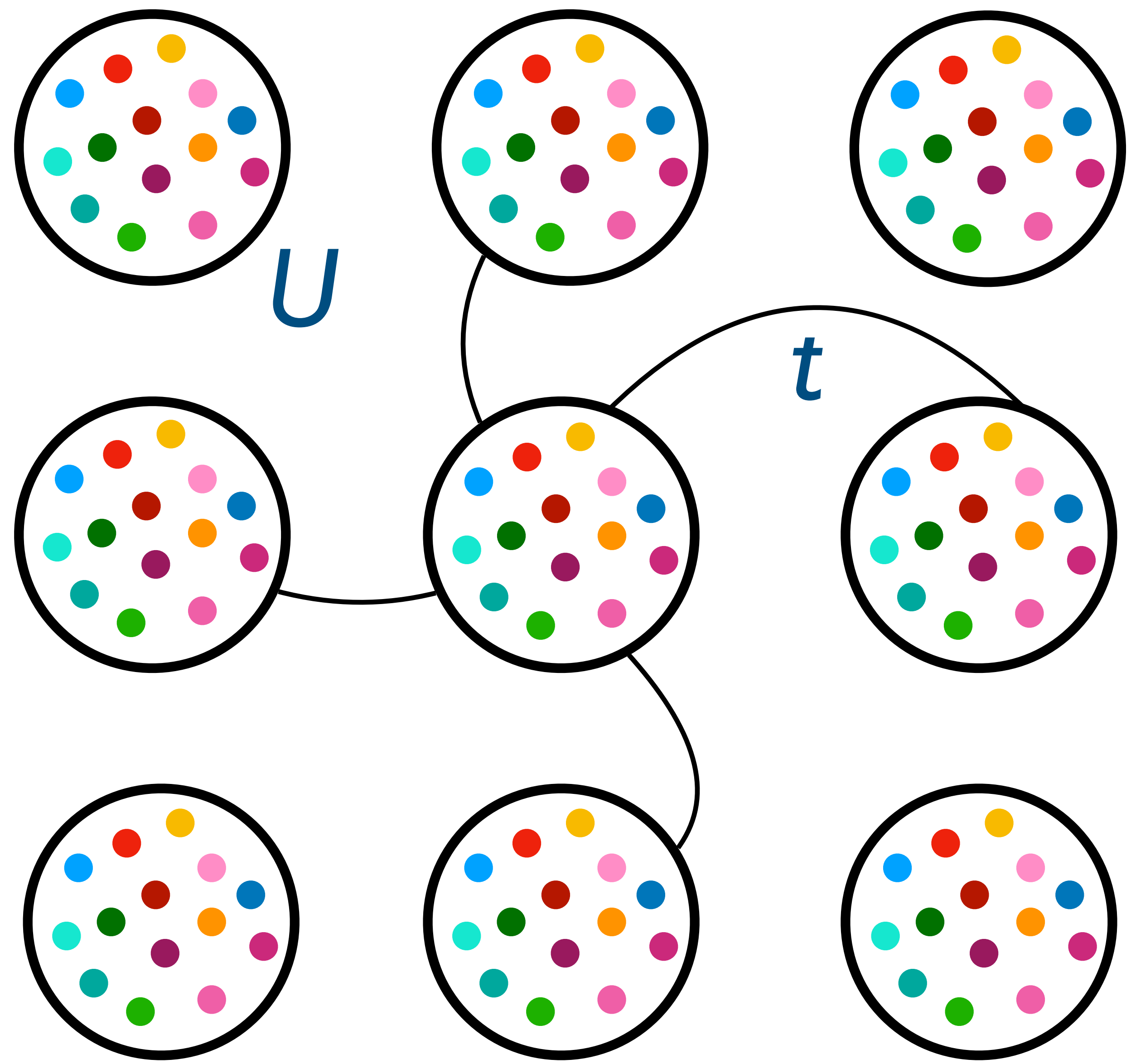
Entanglement amplitude within each island $= U$.

Amplitude to hop between islands $= t$.

Model yields

$$\rho \sim \frac{1}{\tau} \sim T$$

for $t^2/U \lesssim T \lesssim U$

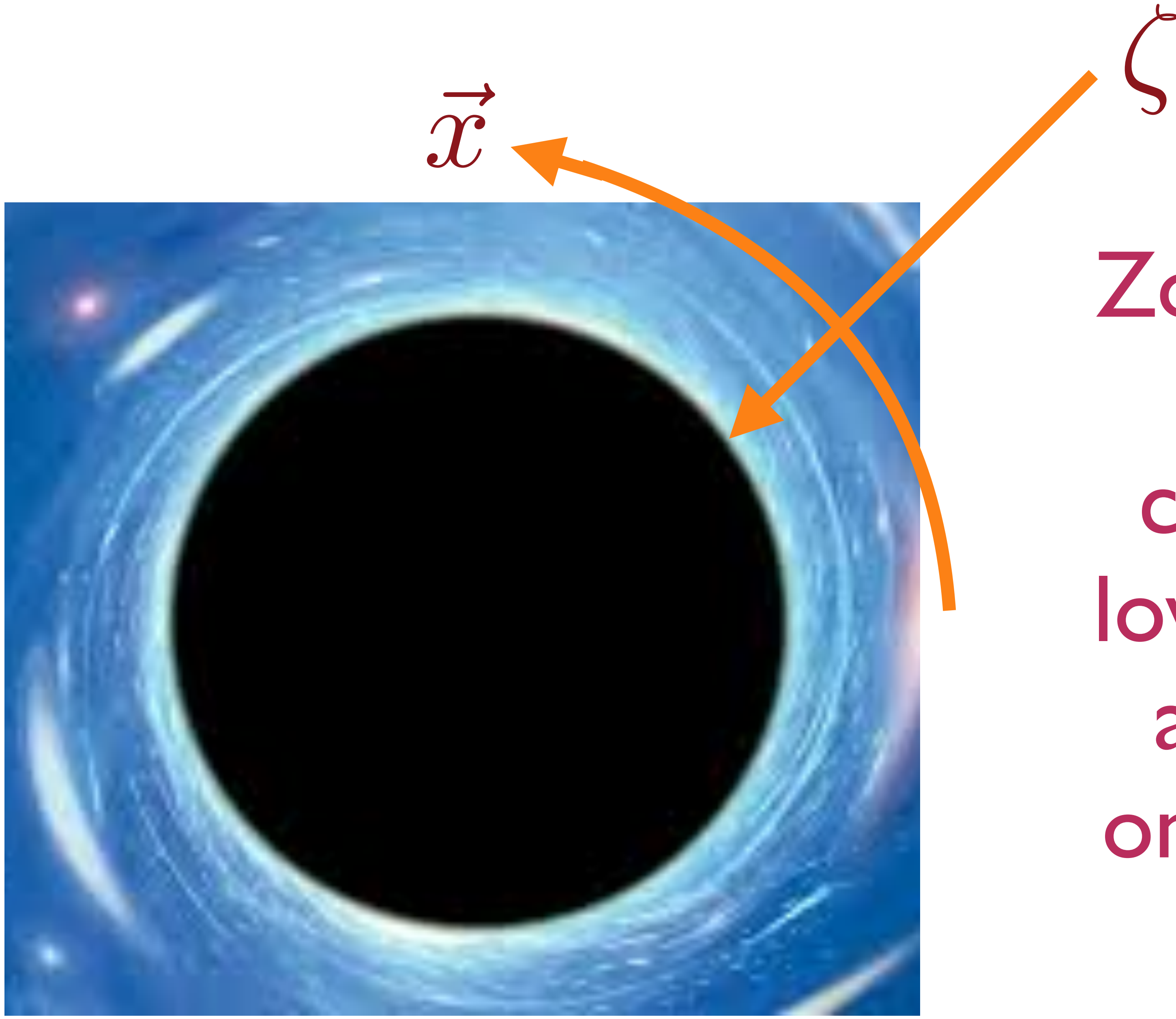


Xue-Yang Song, Chao-Ming Jian, and L. Balents, PRL **119**, 216601 (2017); Pengfei Zhang, PRB **96**, 205138 (2017); Debanjan Chowdhury, Yochai Werman, Erez Berg, T. Senthil, PRX **8**, 031024 (2018); Aavishkar A. Patel, John McGreevy, Daniel P. Arovas, Subir Sachdev, PRX **8**, 021049 (2018)

See also Antoine Georges and Olivier Parcollet PRB **59**, 5341 (1999)

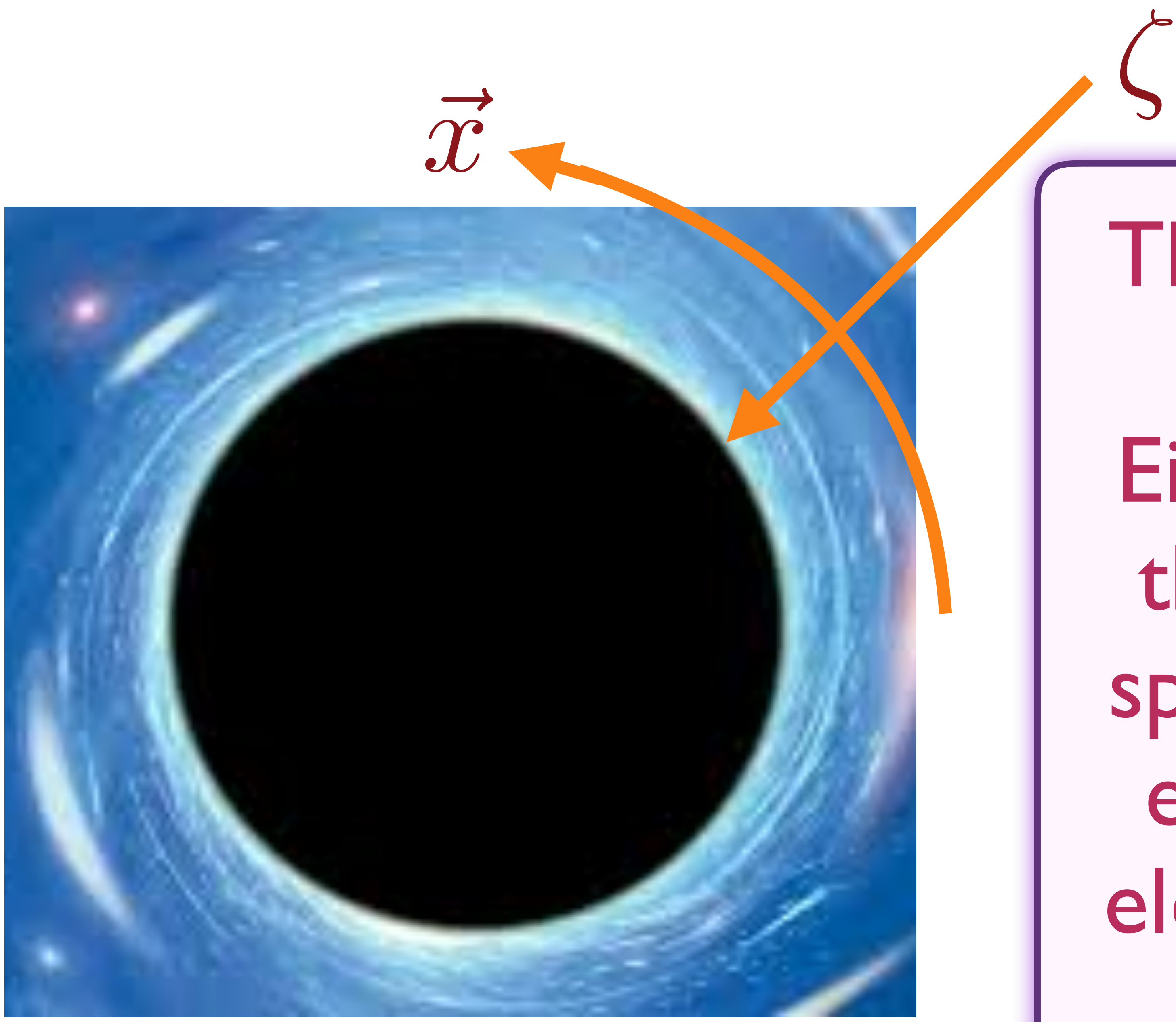
Maxwell's electromagnetism and Einstein's general relativity allow black hole solutions with a net charge

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



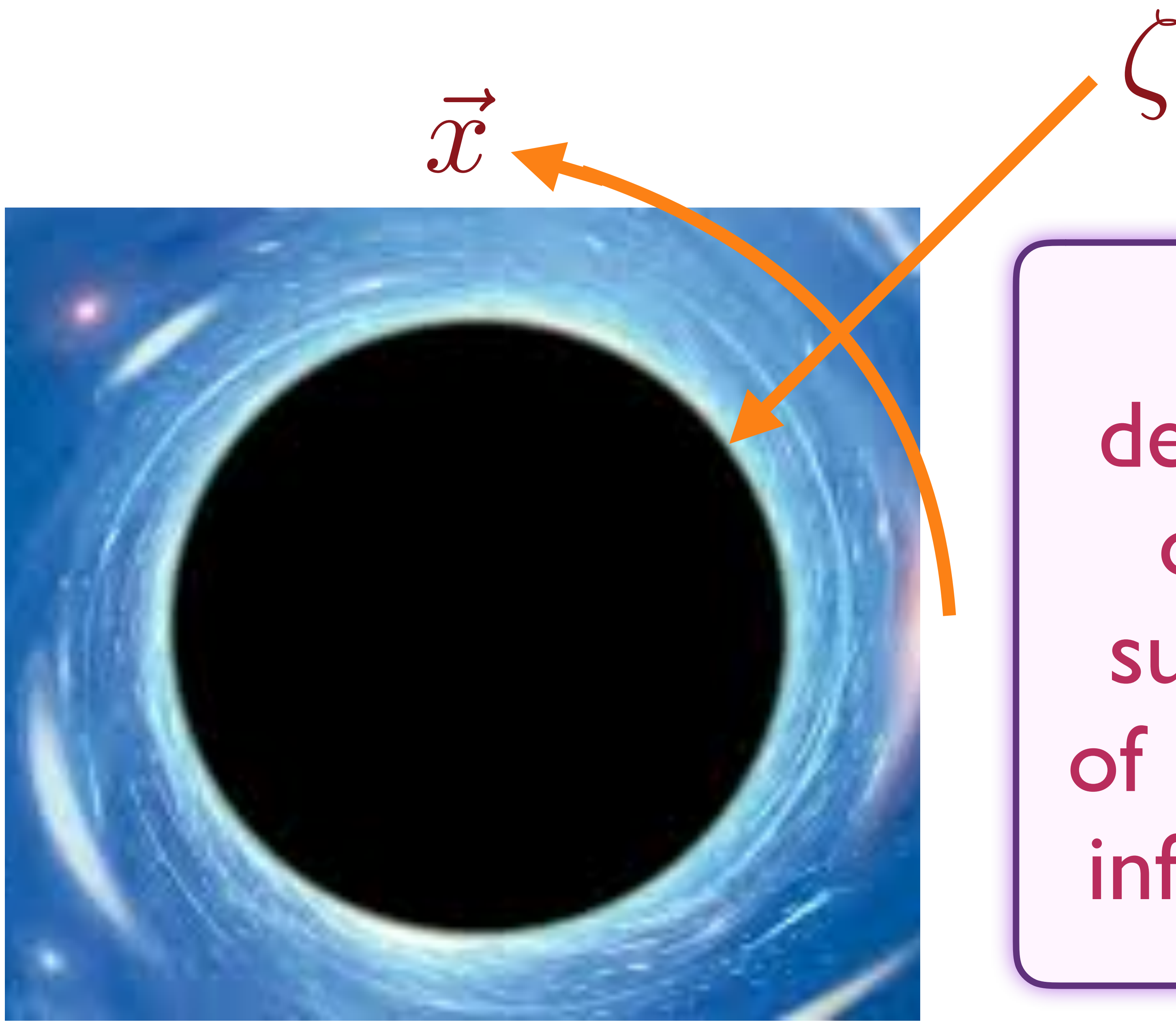
Zooming into the near-horizon region of a charged black hole at low temperature, yields a quantum theory in one space (ζ) and one time dimension

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



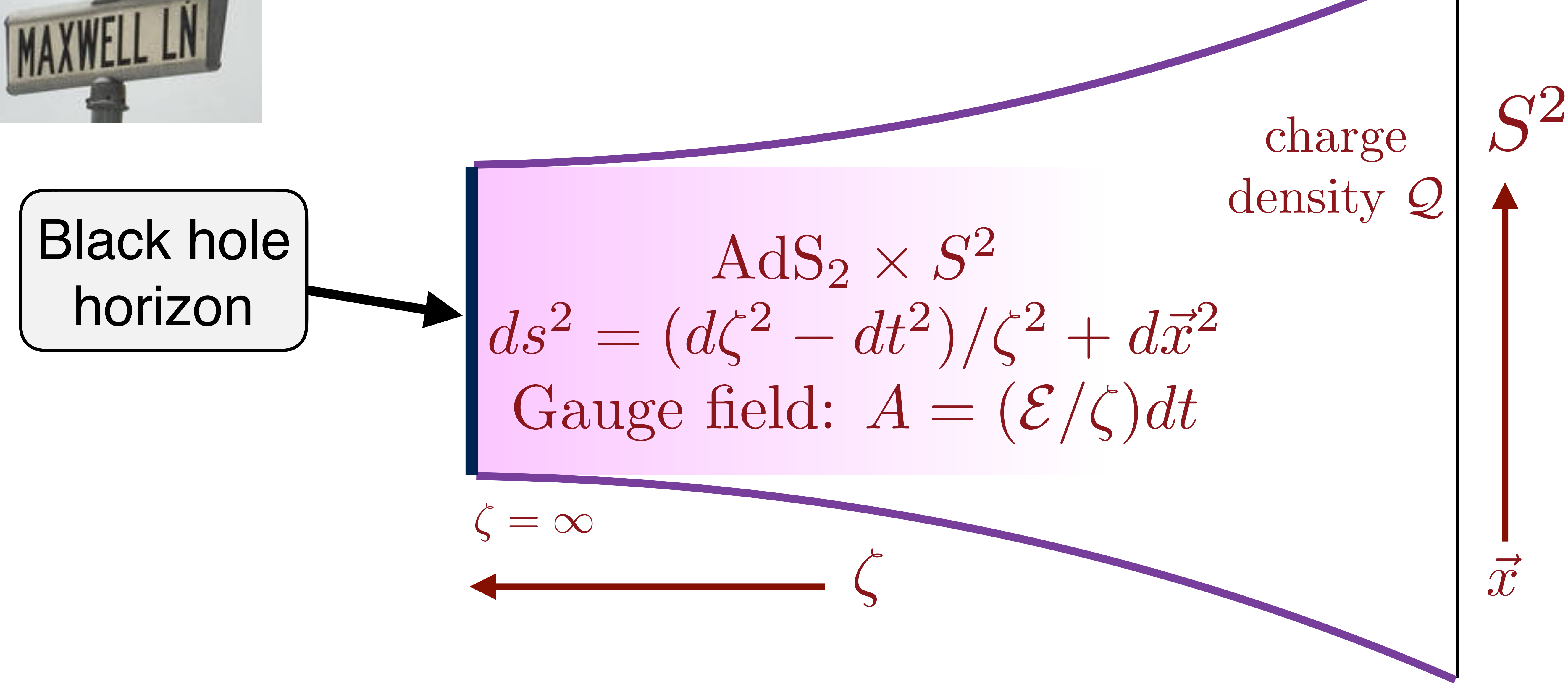
The quantum versions of Maxwell's and Einstein's equations in this two-dimensional spacetime are also the equations describing electron entanglement in the SYK model

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



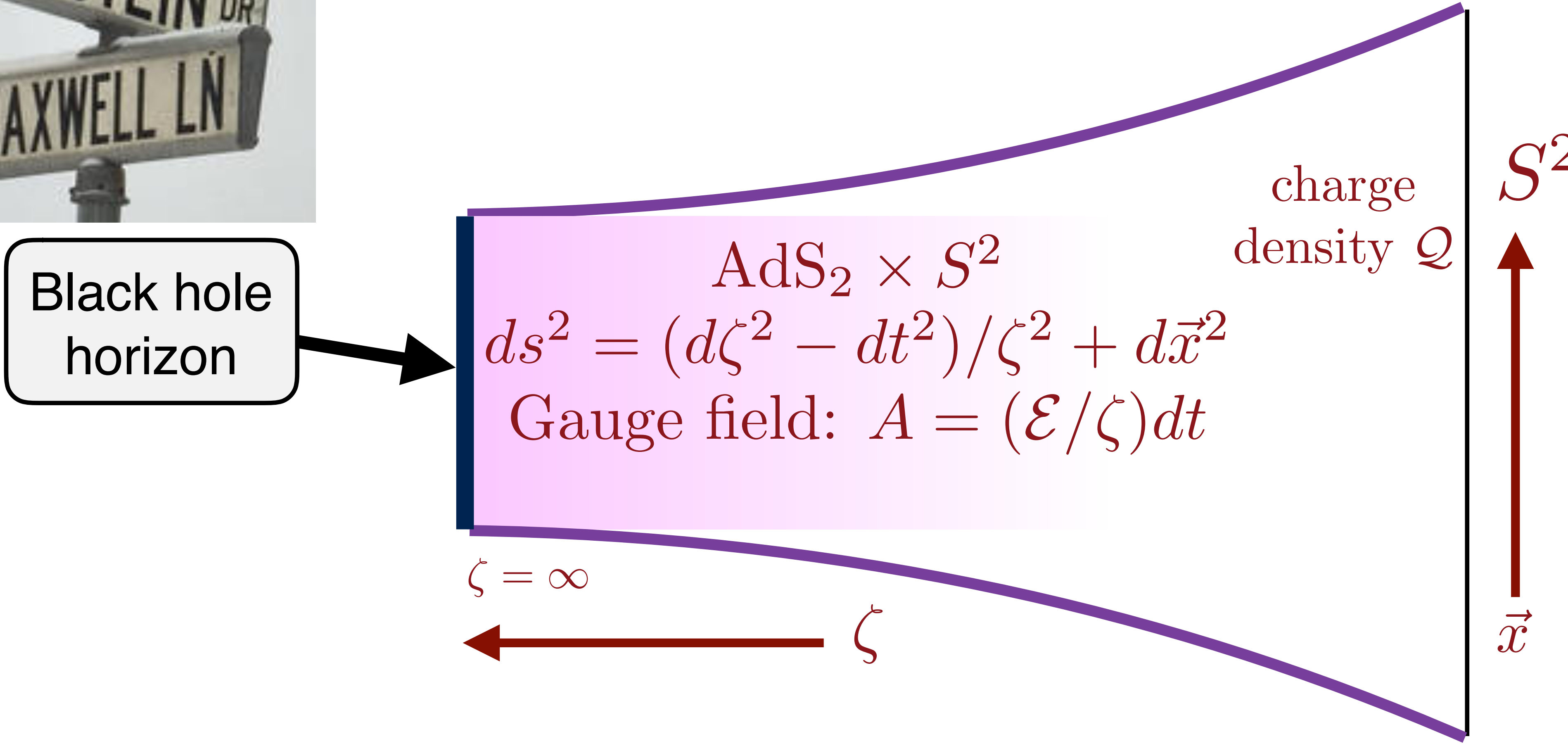
This has led to a deeper understanding of entanglement in superconductors and of Hawking's black hole information "paradox"

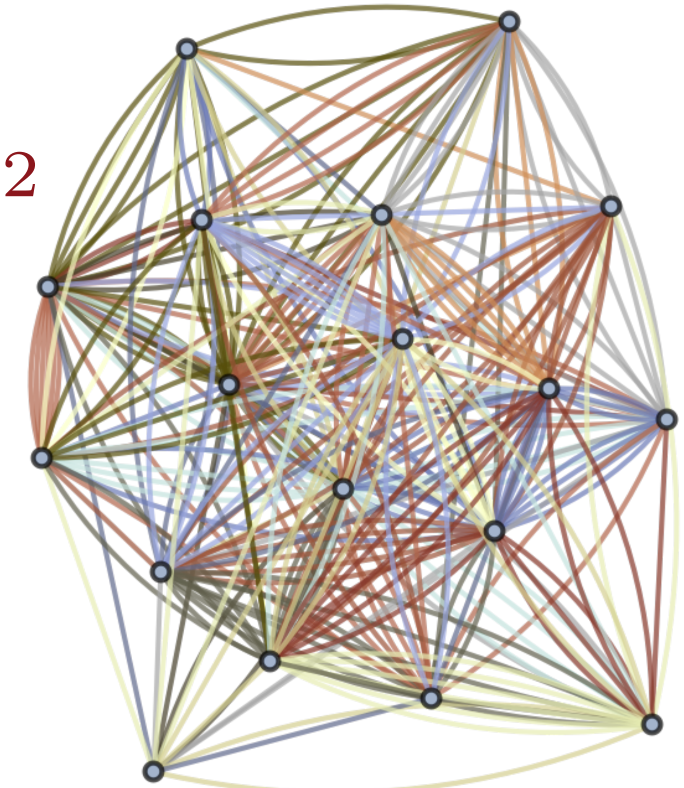
SYK model and charged black holes



The near-horizon region of a charged black hole has the geometry of (1+1)-dimensional anti-de Sitter spacetime. By holography, this should map to a zero-dimensional quantum system: this turns out to be the SYK model

SYK model and charged black holes



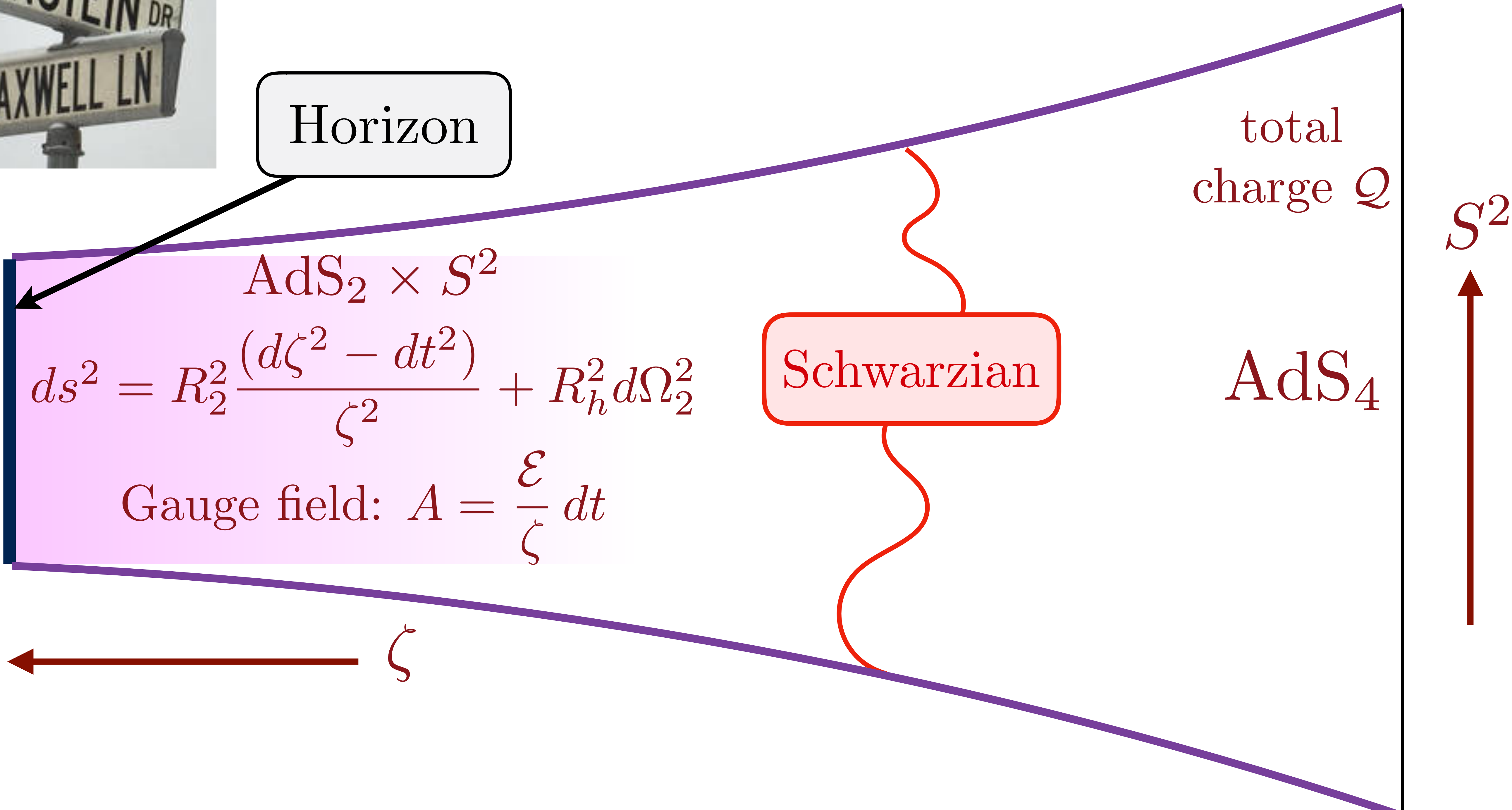


Bekenstein-Hawking entropy of AdS_2 horizon at $T = 0 \Leftrightarrow N s_0$ entropy of SYK model.

$\frac{ds_0}{d\mathcal{Q}} = 2\pi\mathcal{E}$ can be obtained from the Einstein equations for the black hole, and the quantum theory of the SYK model, and $\mathcal{E}$ determines identical fermion spectral functions.

S. Sachdev, Phys. Rev. Lett. **105**, 151602 (2010); PRX **5,** 041025 (2015)

SYK model and charged black holes



Remarkably, the correspondence between charged black holes and the SYK model also holds for the leading fluctuations at higher temperatures: both are described by a 'Schwarzian' theory with emergent SL(2,R) and U(1) gauge symmetries. For the black hole, the Schwarzian describes the fluctuations of the boundary between AdS_2 and AdS_4.

Main result

S. Sachdev, Phys. Rev. Lett. **105**, 151602 (2010)

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R. Davison, Wenbo Fu, A. Georges, Yingfei Gu, K. Jensen, S. Sachdev,
Phys. Rev. B **95**, 155131 (2017)

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R.M. Soni, S.P. Trivedi, and V. Vishal, arXiv:1802.09547

P. Chaturvedi, Yingfei Gu, Wei Song, Boyang Yu, arXiv:1808.08062

U. Moitra, S. P. Trivedi, and V. Vishal, arXiv:1808.08239

S. Sachdev, arXiv:1902.04078

Main result

SYK model of fermions with random interactions of mean-square-value U, with total fermion number $\mathcal{Q}$, at temperatures $T \ll U$

Main result

SYK model of fermions with random interactions of mean-square-value U, with total fermion number $\mathcal{Q}$, at temperatures $T \ll U$

and

Charged black holes in 3+1 dimensions of radius R_h, with total charge $\mathcal{Q}$, at temperatures $T \ll 1/R_h$

are described by a common low energy quantum theory in $0 + 1$ dimensions

Main result

The common low T path integral is $\mathcal{Z} = \int \mathcal{D}f\, \mathcal{D}\phi\, e^{-I}$. This can be exactly evaluated, and the action is

$$I = -s_0 + \int_0^{1/T} d\tau \left\{ \frac{K}{2} \left(\frac{\partial \phi}{\partial \tau} + i(2\pi\mathcal{E}T)\frac{\partial f}{\partial \tau} \right)^2 - \frac{\gamma}{4\pi^2} \mathrm{Sch}[\tan(\pi T f(\tau)), \tau] \right\},$$

where $f(\tau)$ is a monotonic reparameterization of the temporal circle with

$f(\tau + 1/T) = f(\tau) + 1/T$,

ϕ is a phase conjugate to the charge density with

$\phi(\tau + 1/T) = \phi(\tau) + 2\pi n$, n integer,

$\mathrm{Sch}[g[\tau], \tau]$ is the Schwarzian derivative of $g(\tau)$.

The couplings are related to the entropy $S(T, \mathcal{Q})$ and the chemical potential μ via

$$S(T \to 0, \mathcal{Q}) = s_0 + \gamma T, \quad K = \left(\frac{d\mathcal{Q}}{d\mu}\right)_{T \to 0}, \quad 2\pi\mathcal{E} = \frac{ds_0}{d\mathcal{Q}}$$

Quantum entanglement

Black holes

Metals (ordinary and strange) and superconductors

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