A simple model of many-particle entanglement: how it describes black holes and superconductors

KAIST, Korea
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Talk online: sachdev.physics.harvard.edu

PHYSICS
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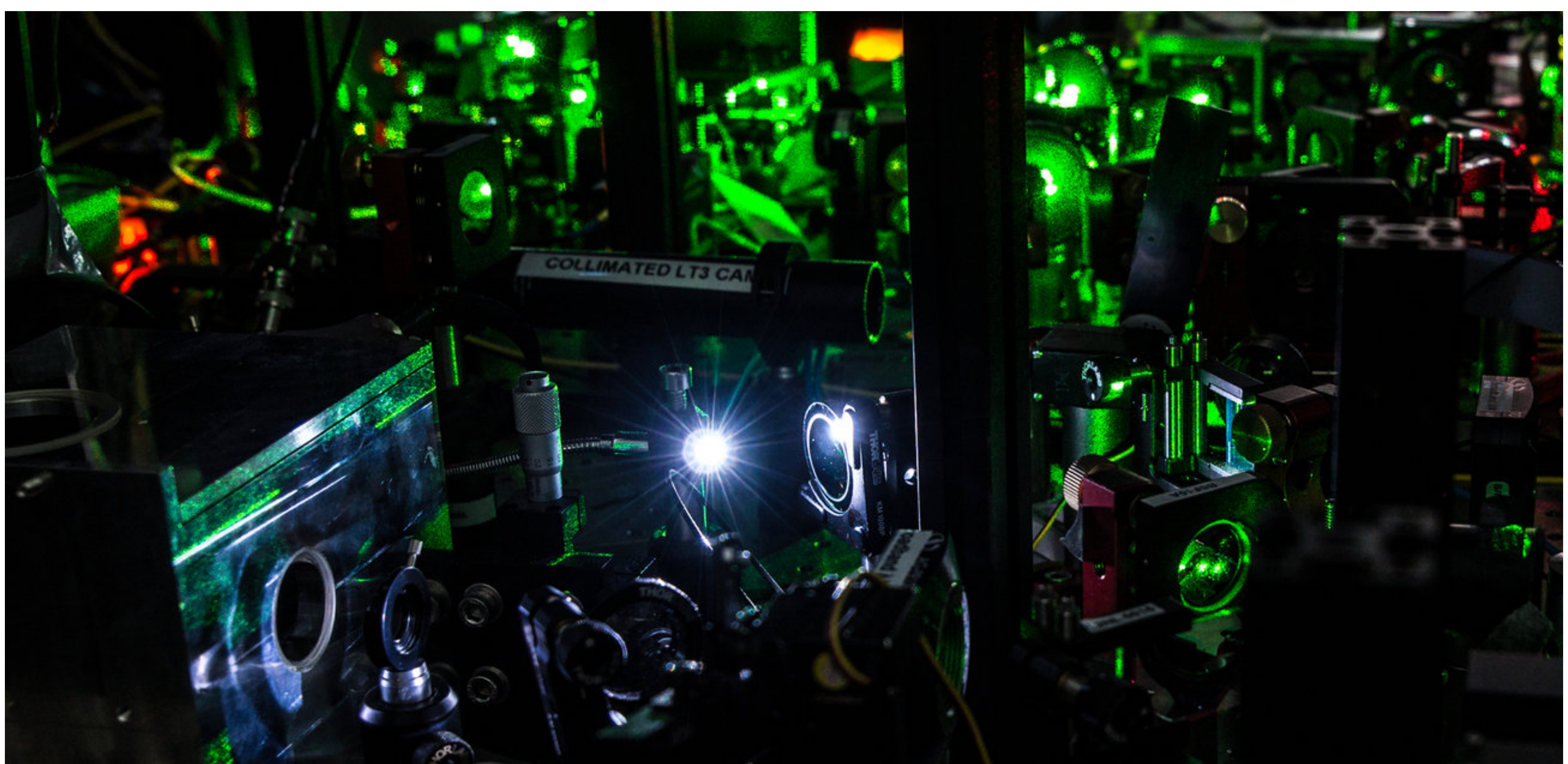
The New York Times

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.

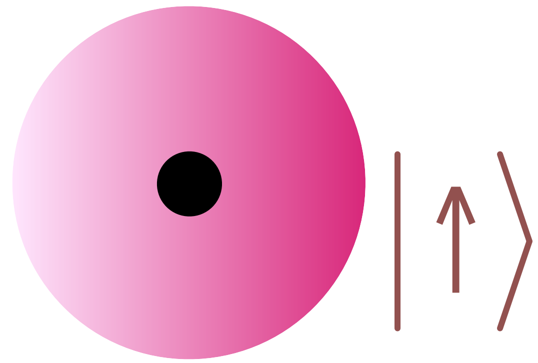


Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.

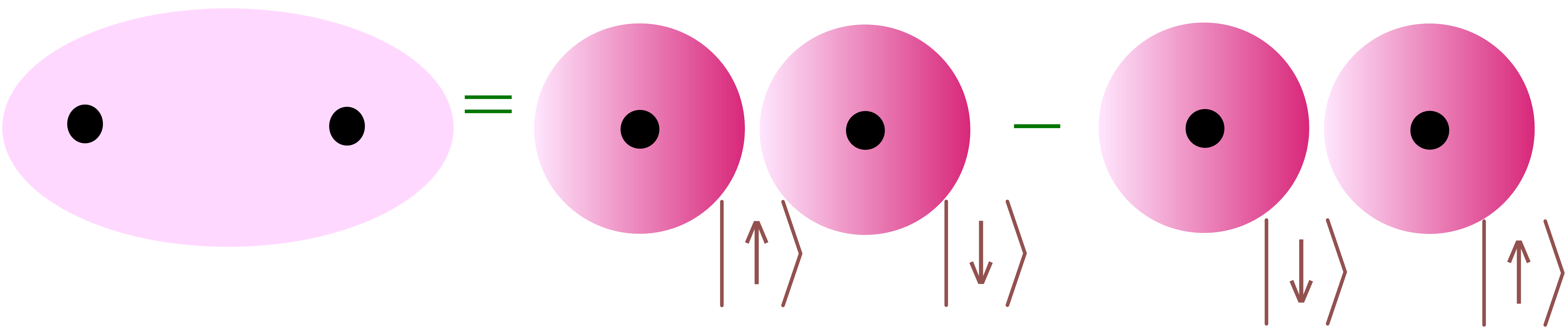
Quantum entanglement

Quantum Entanglement: quantum superposition with more than one particle

Hydrogen atom:

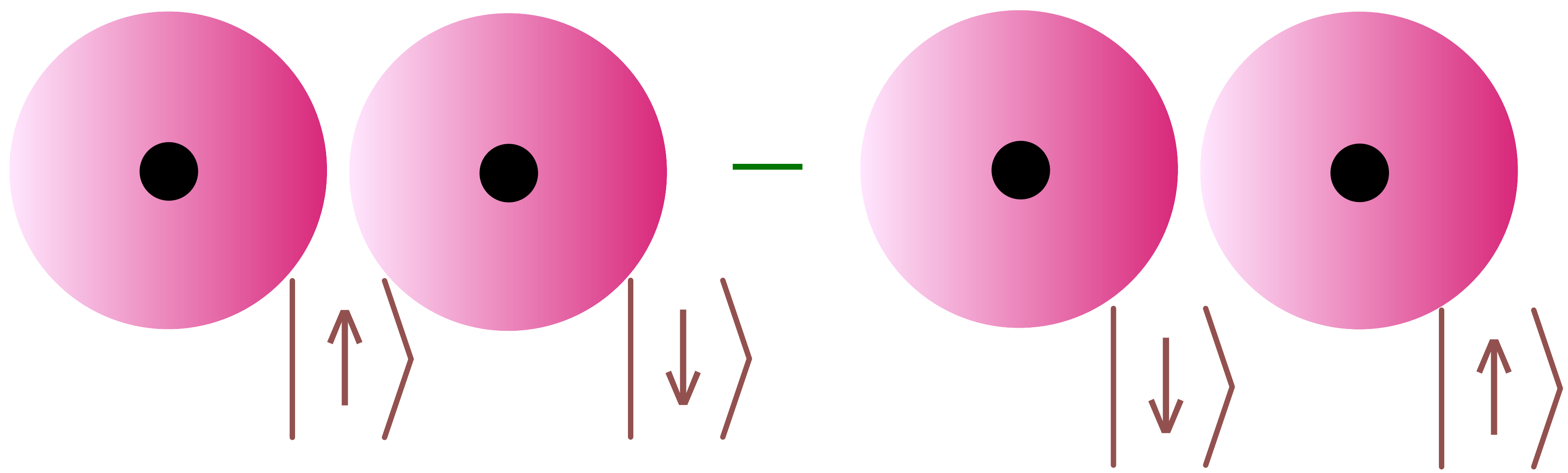


Hydrogen molecule:



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

Quantum Entanglement: quantum superposition with more than one particle



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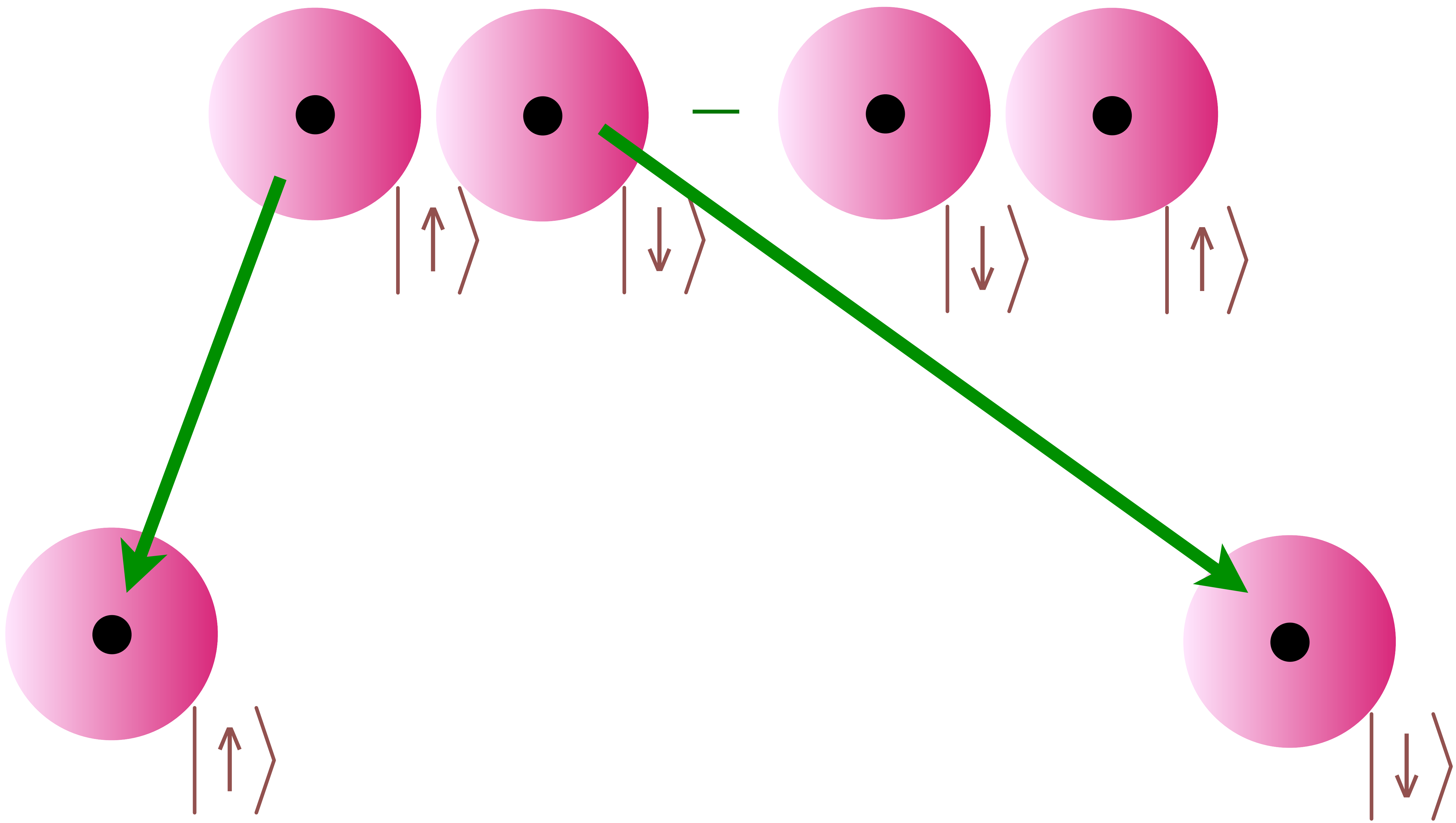

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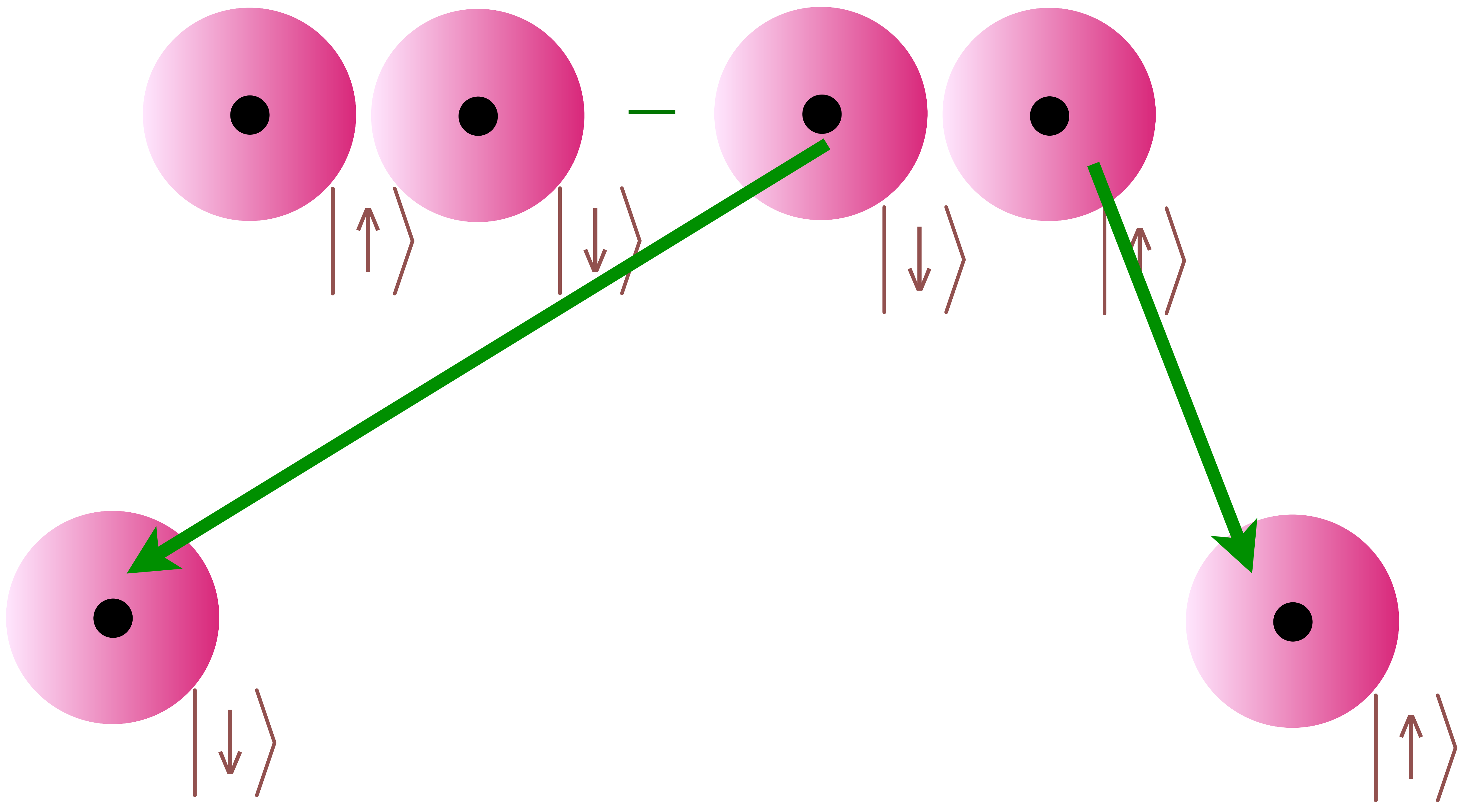

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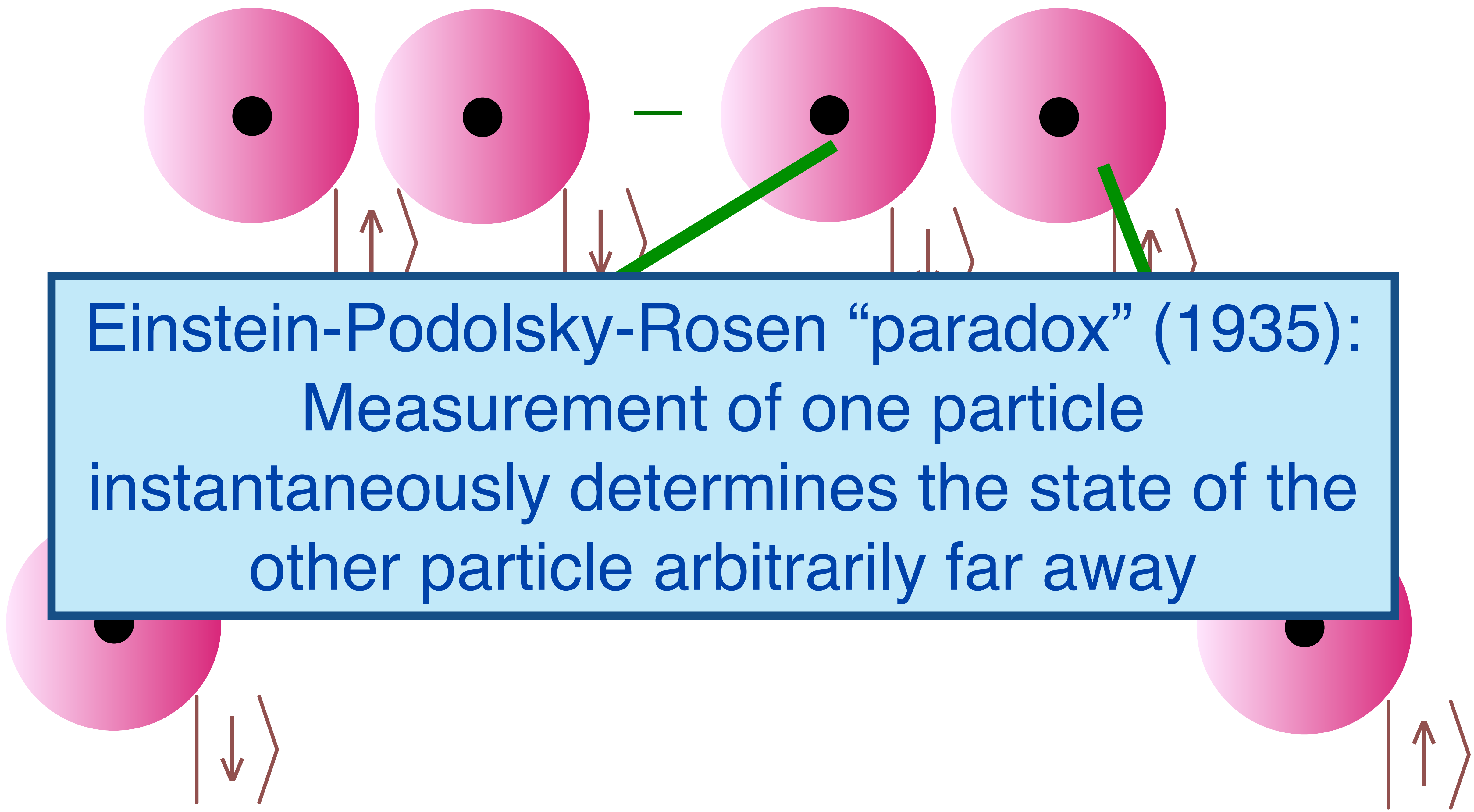


Einstein-Podolsky-Rosen "paradox" (1935):
Measurement of one particle instantaneously determines the state of the other particle arbitrarily far away

Quantum entanglement

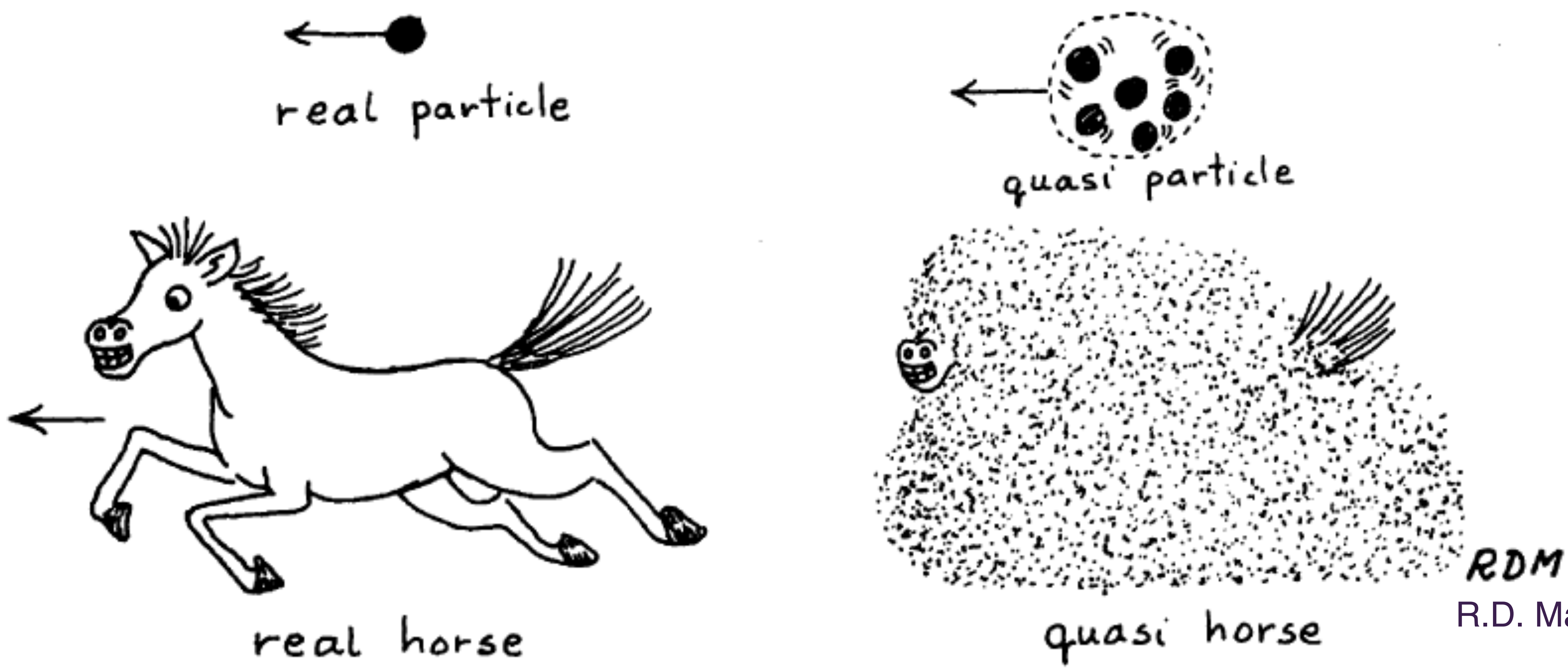
Quantum entanglement

A simple many-particle (SYK) model

Ordinary metals

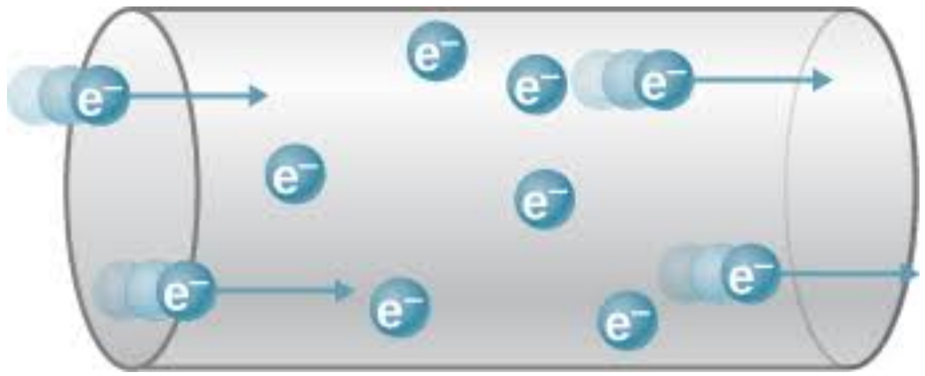
Ordinary metals are shiny, and they conduct heat and electricity efficiently. Each atom donates electrons which are delocalized throughout the entire crystal

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. The existence of quasiparticles implies limited many-particle entanglement



R.D. Mattuck

Current flow with quasiparticles

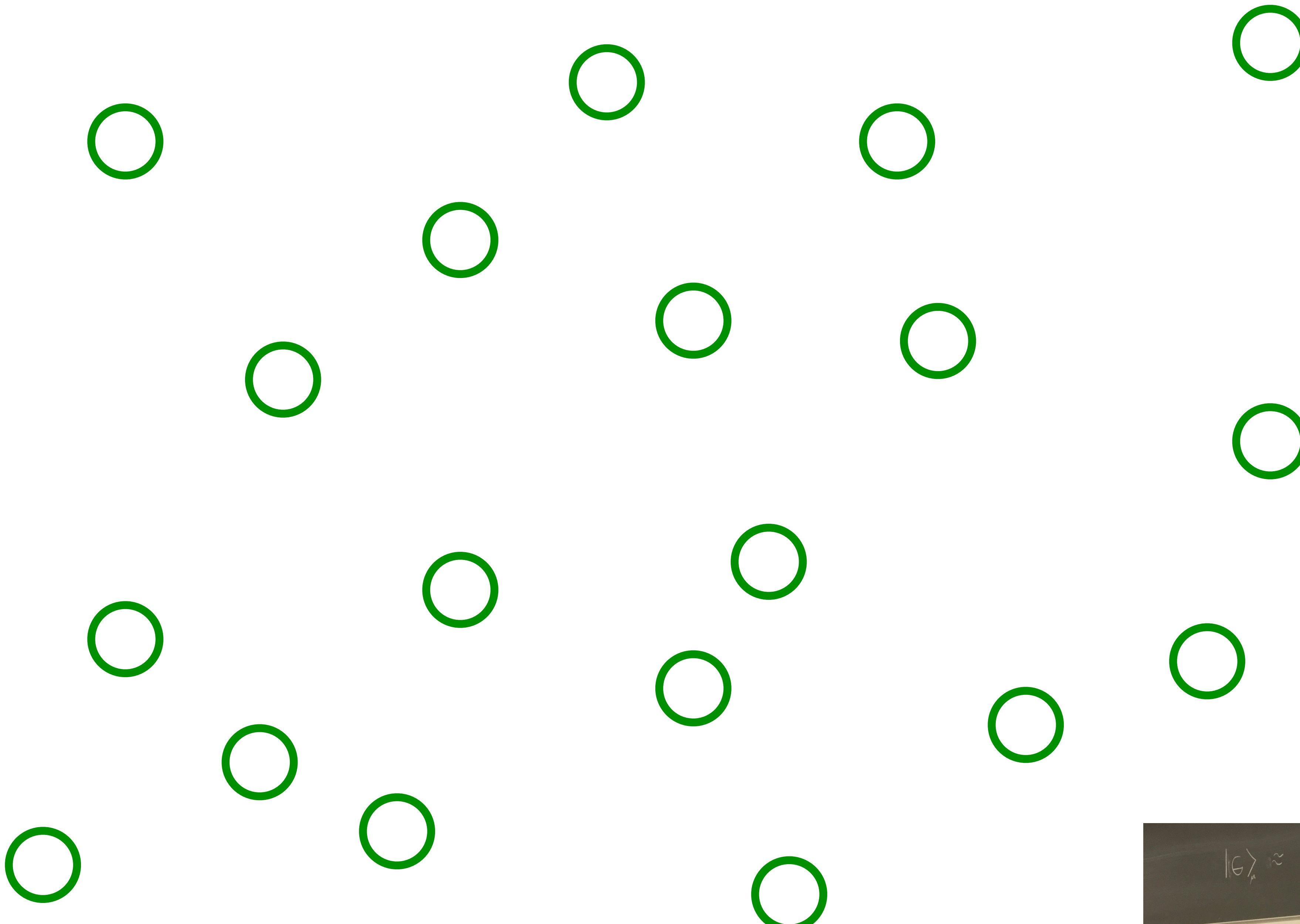


Flowing quasiparticles scatter off each other in a typical scattering time τ

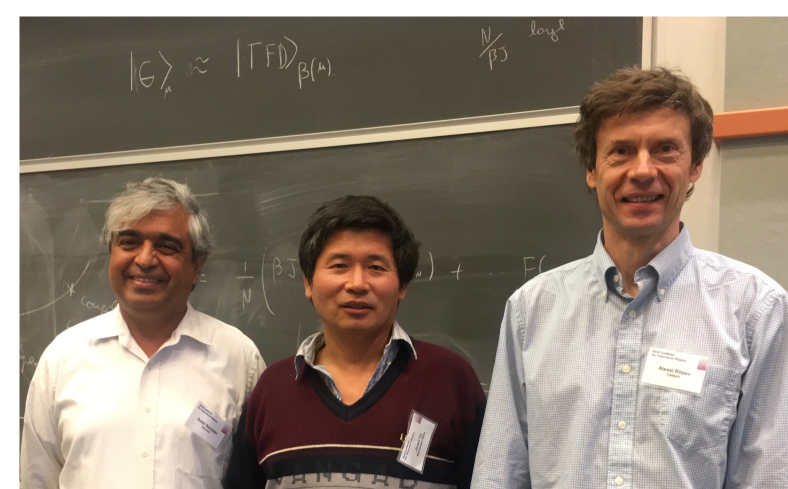
This time is much longer than a limiting 'Planckian time' $\dfrac{\hbar}{k_B T}$.

The long scattering time implies that quasiparticles are well-defined.

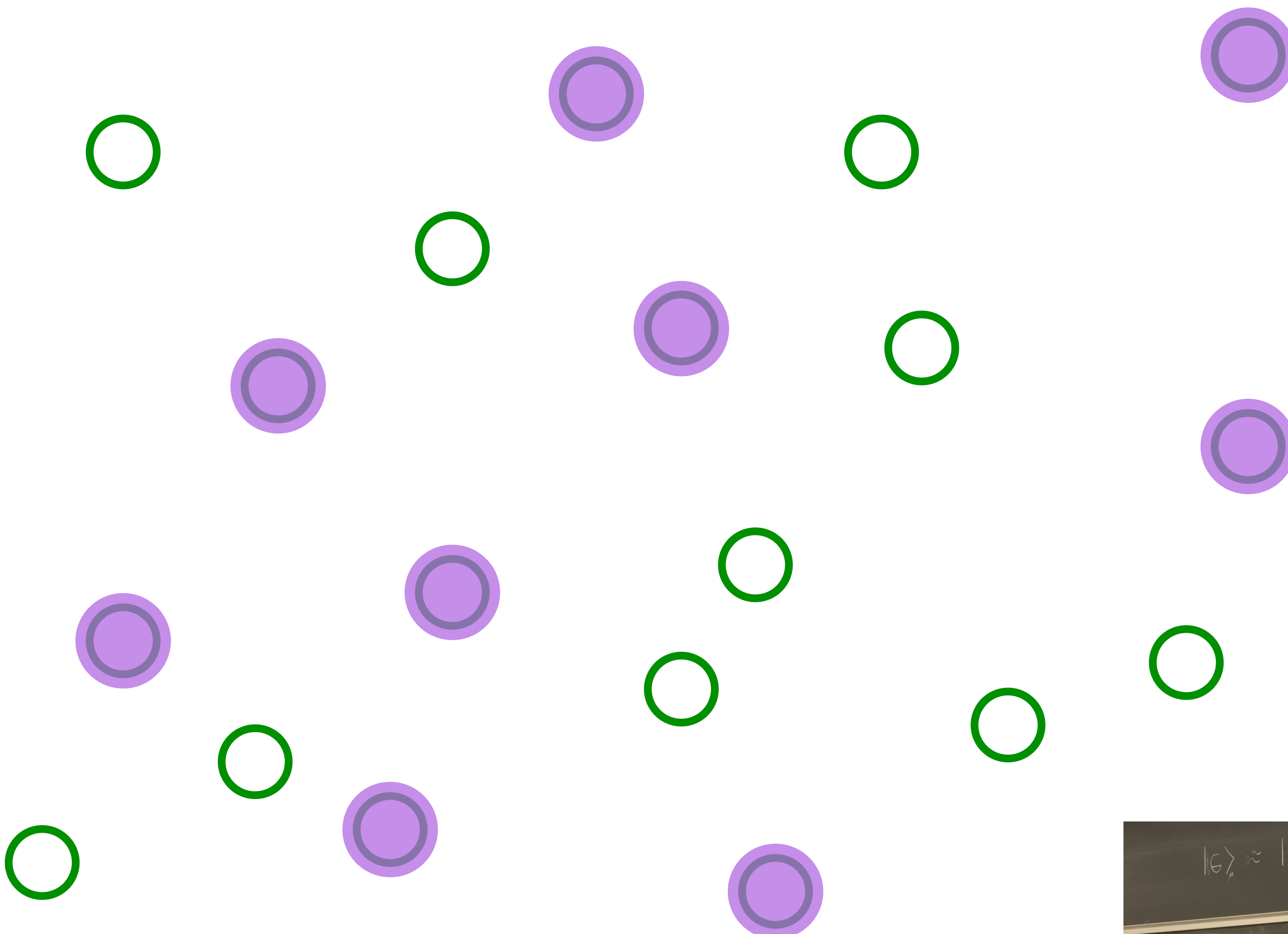
The Sachdev-Ye-Kitaev (SYK) model



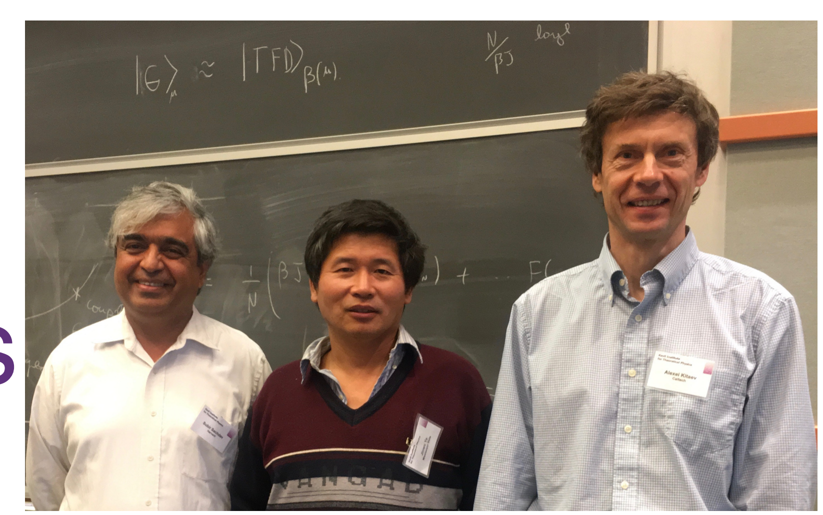
Pick a set of random positions



The SYK model



Place electrons randomly on some sites



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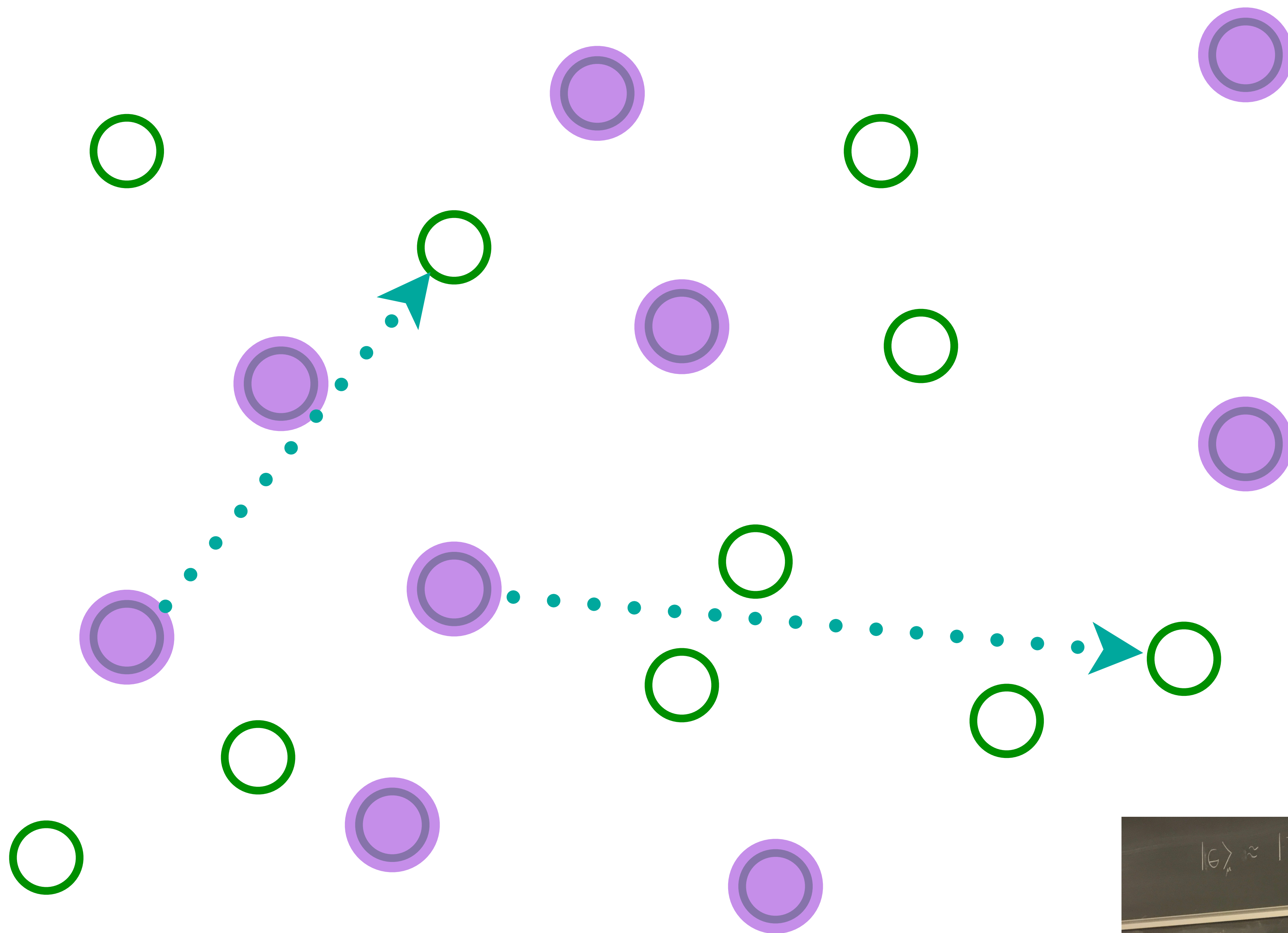

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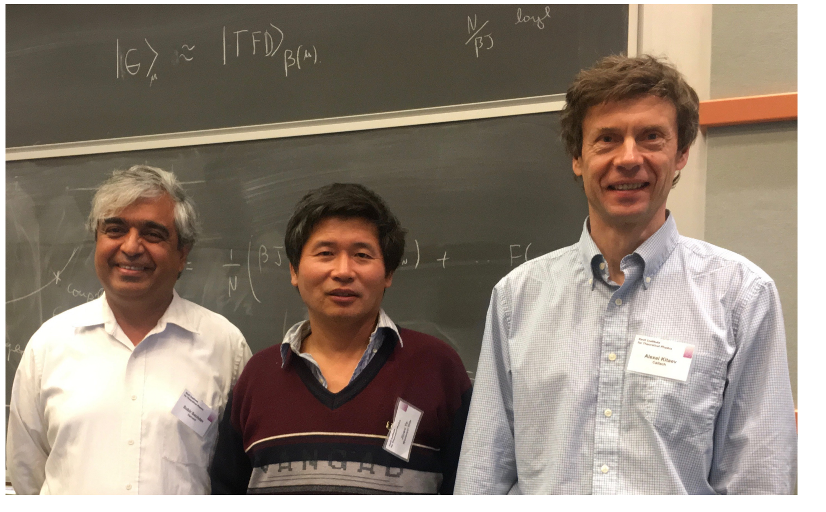

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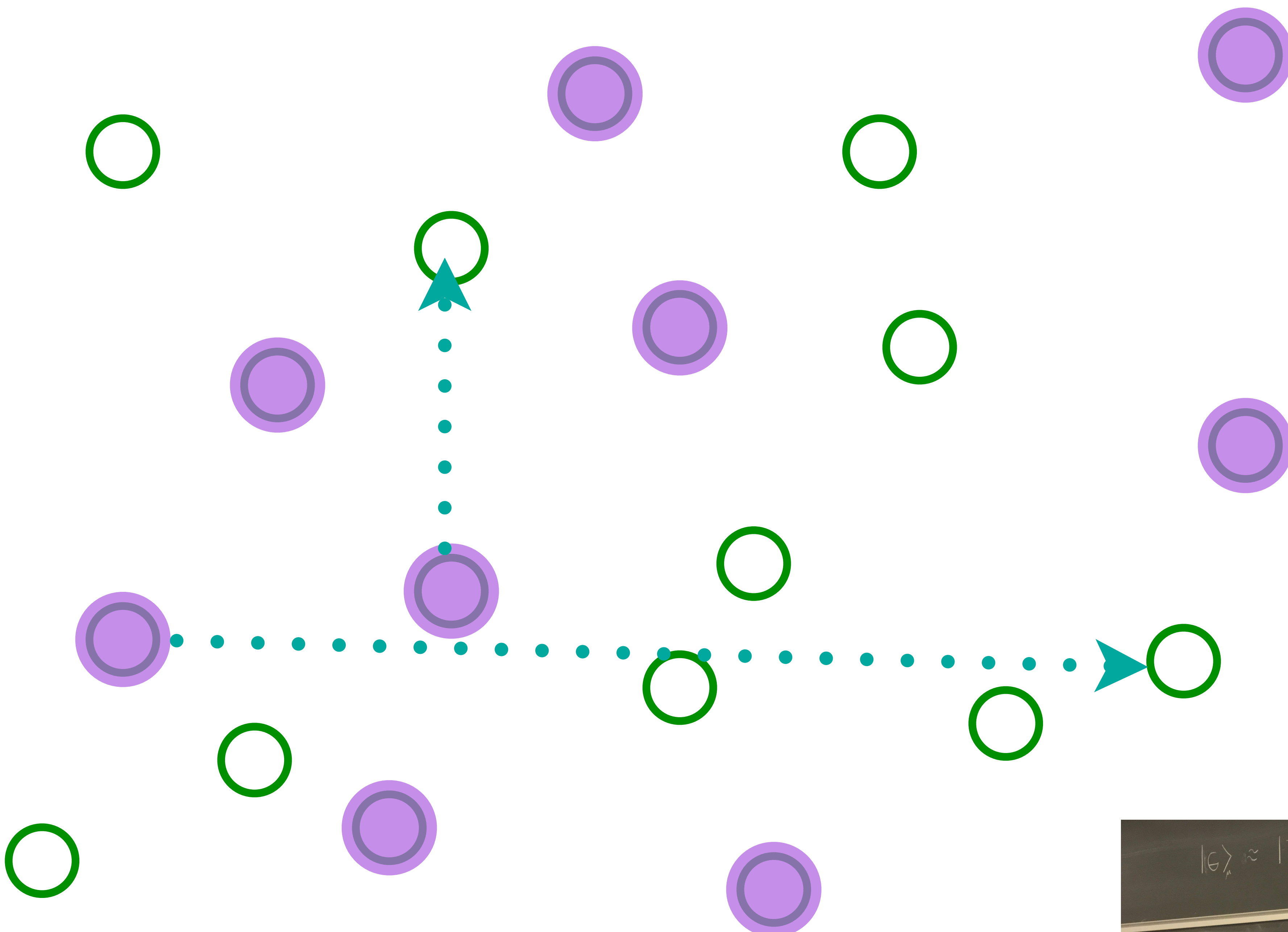

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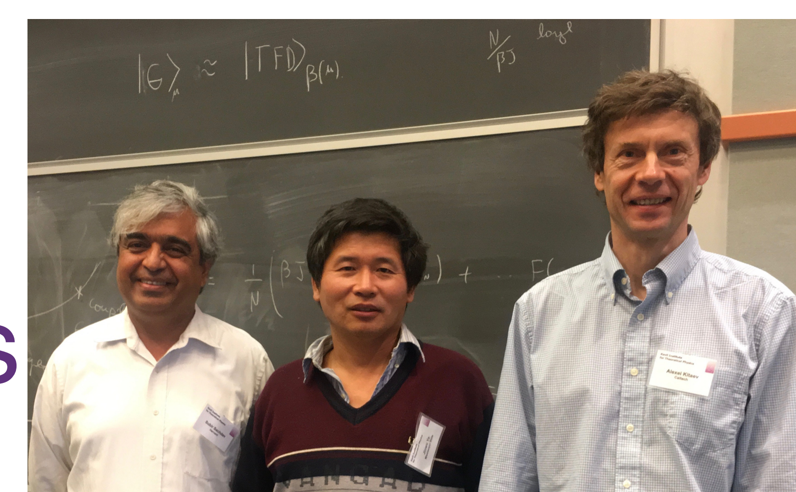

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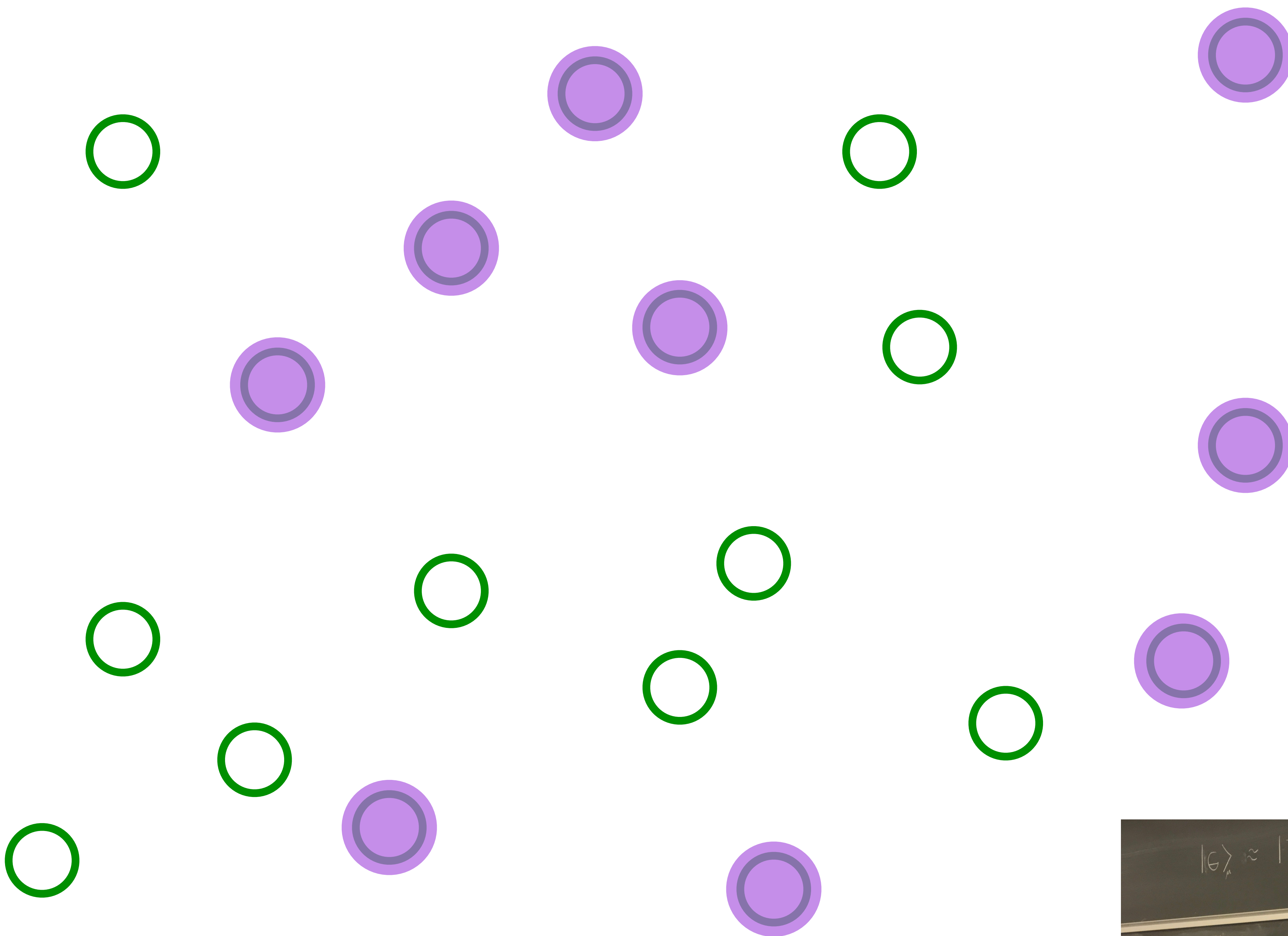
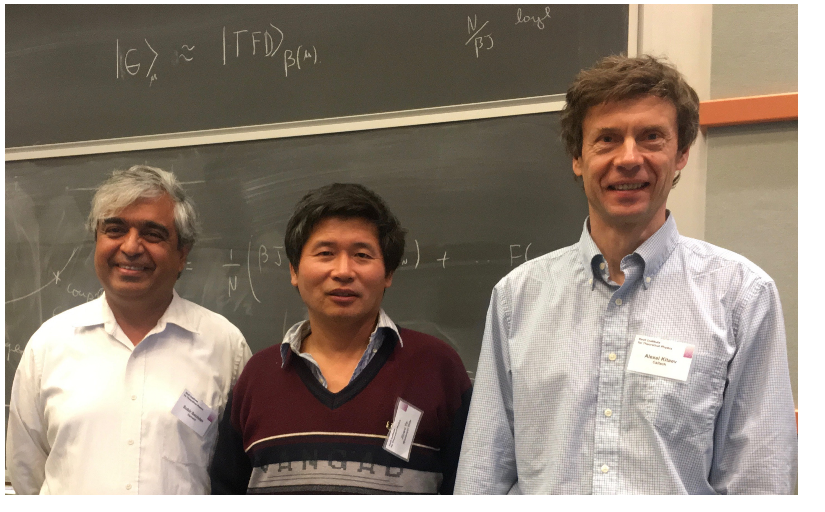


Entangle electrons pairwise randomly



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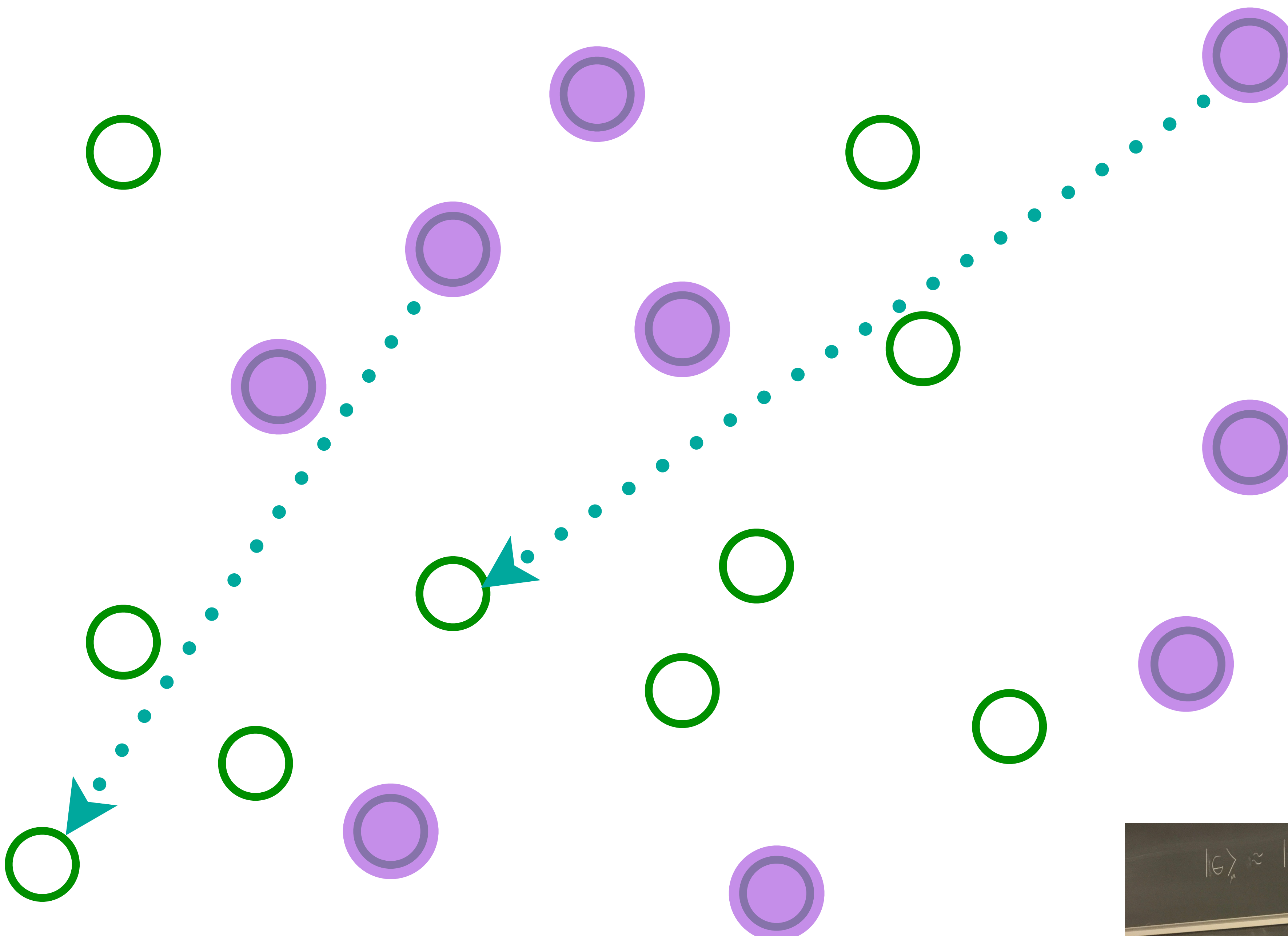

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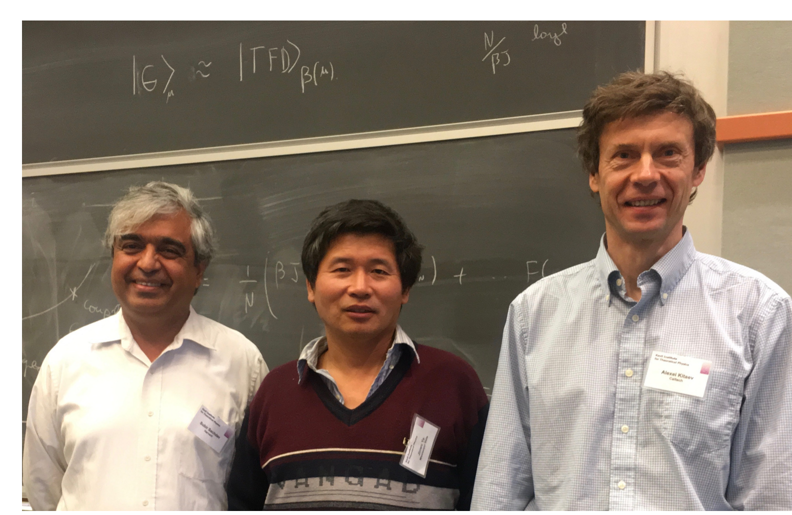

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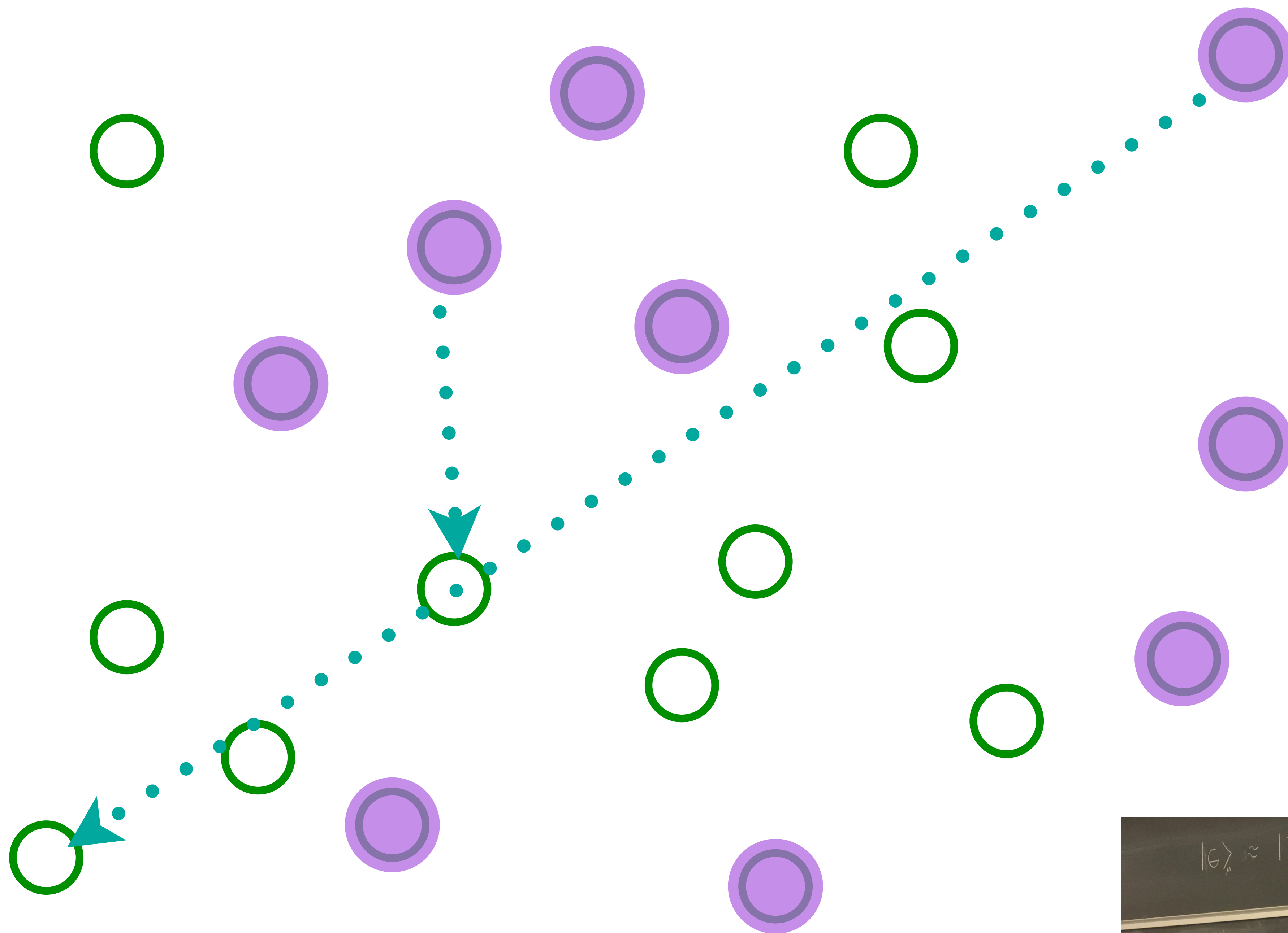

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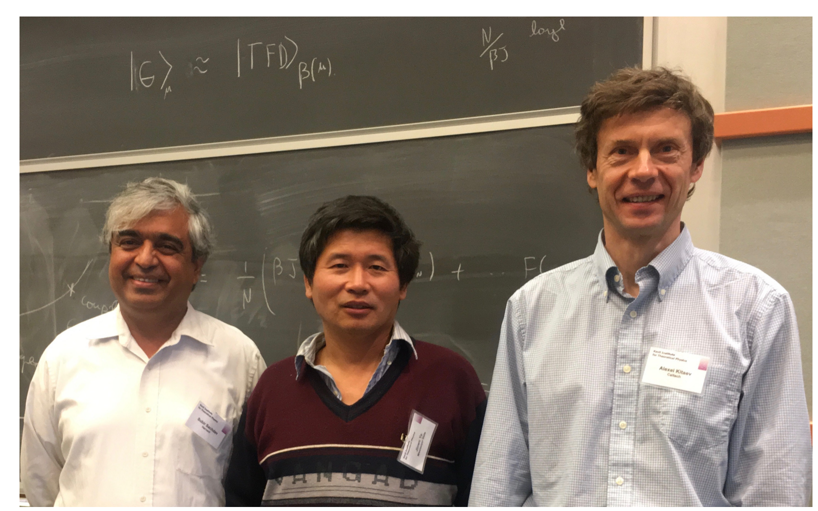

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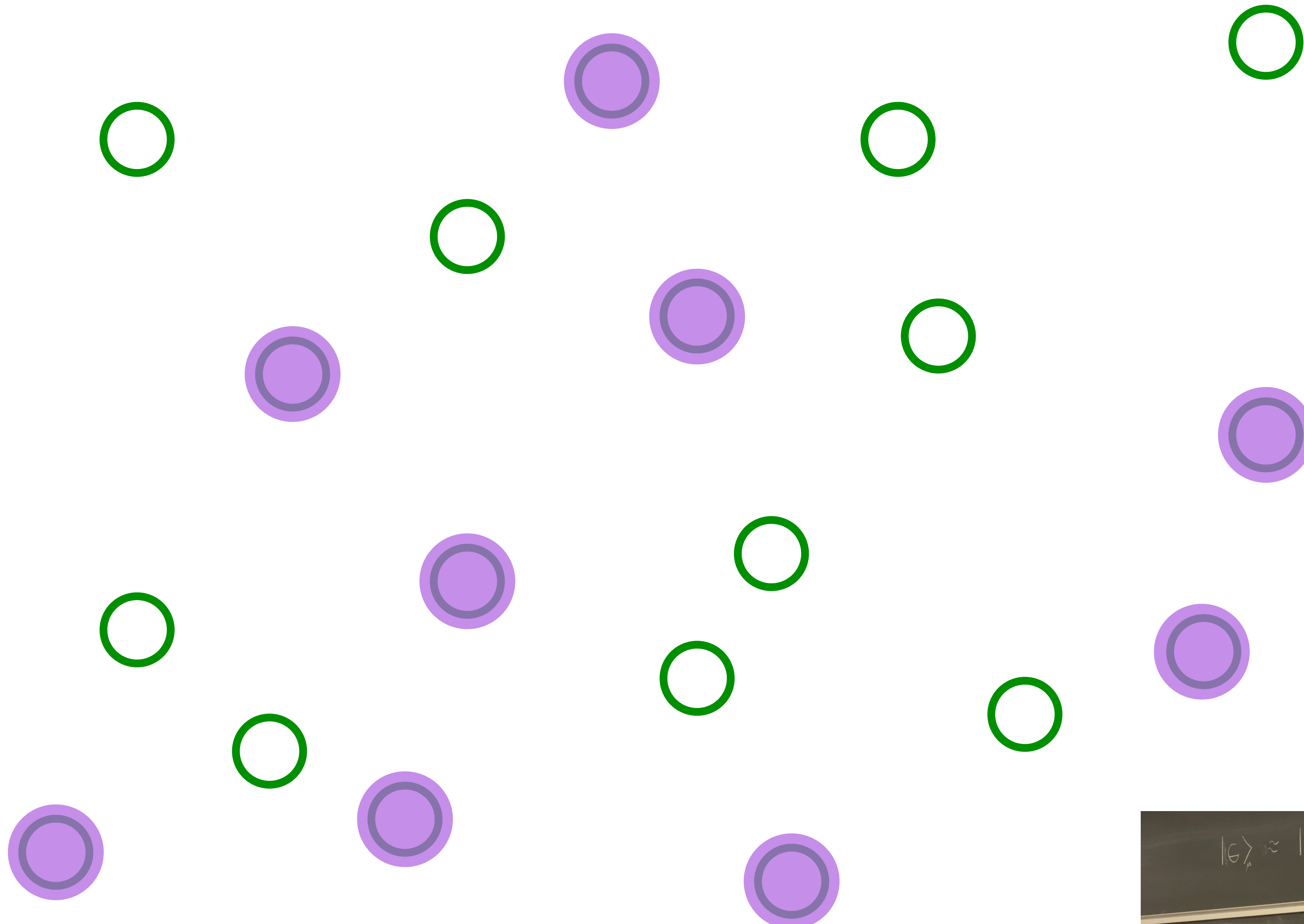

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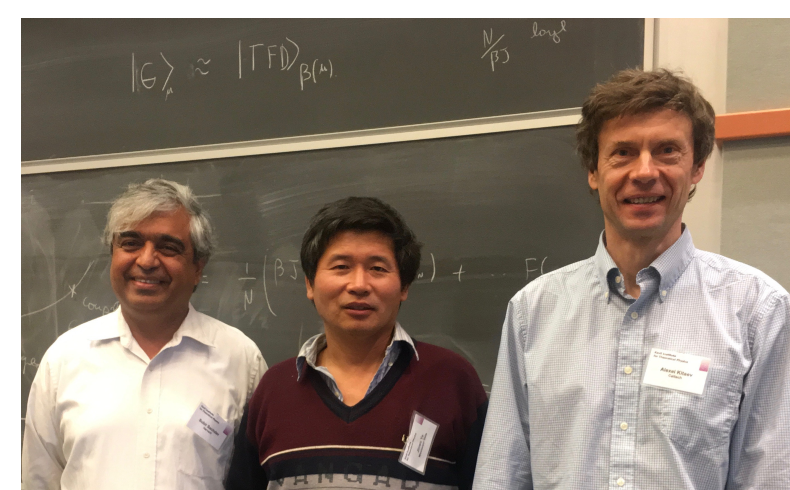

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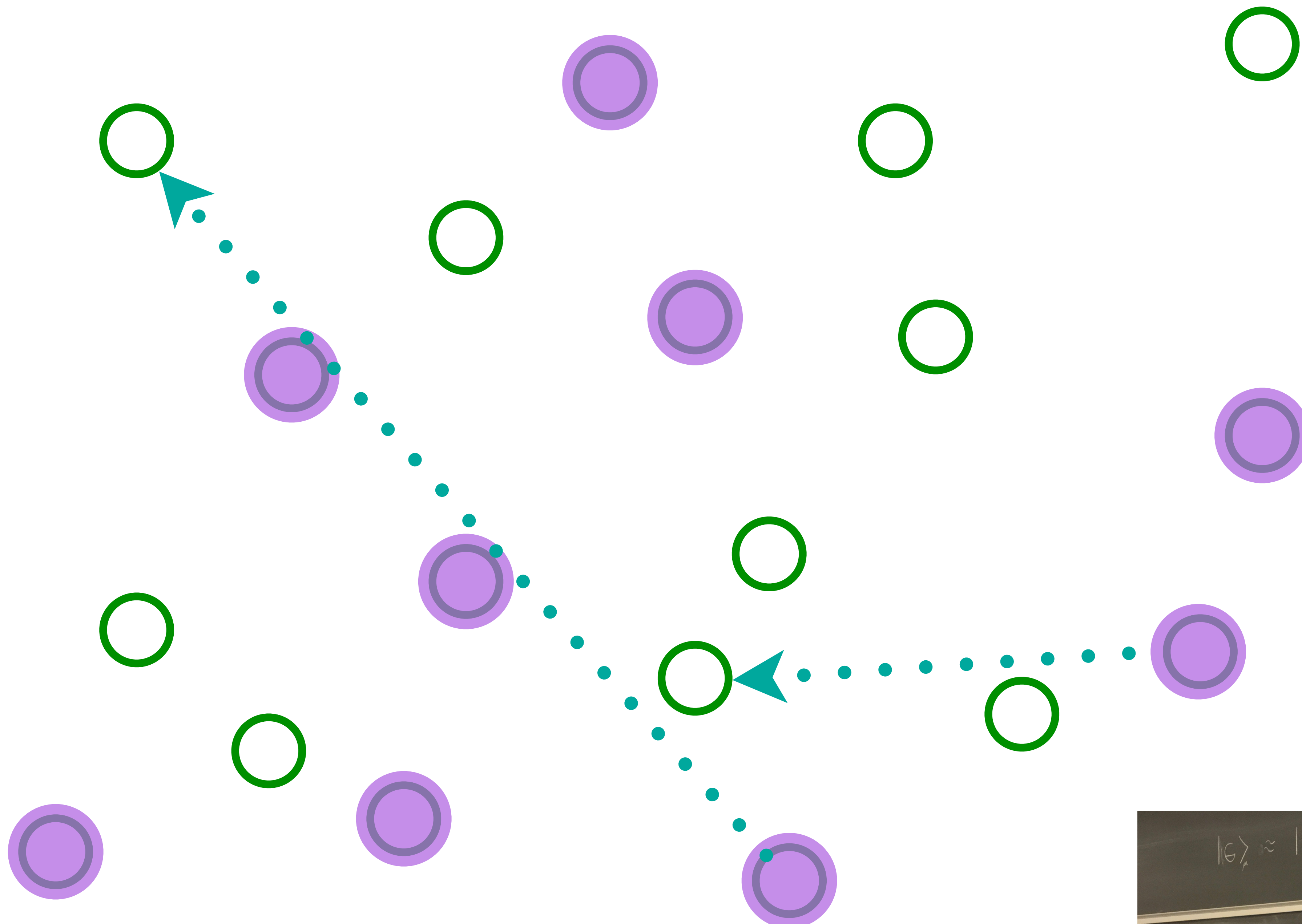

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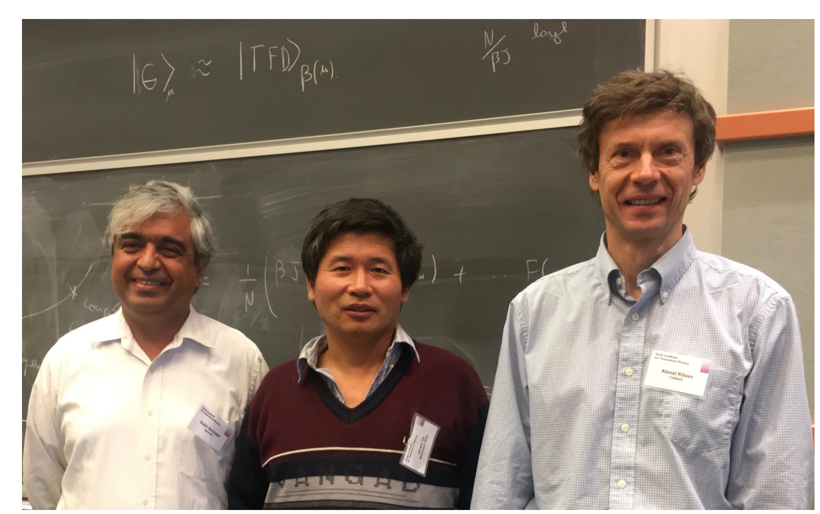

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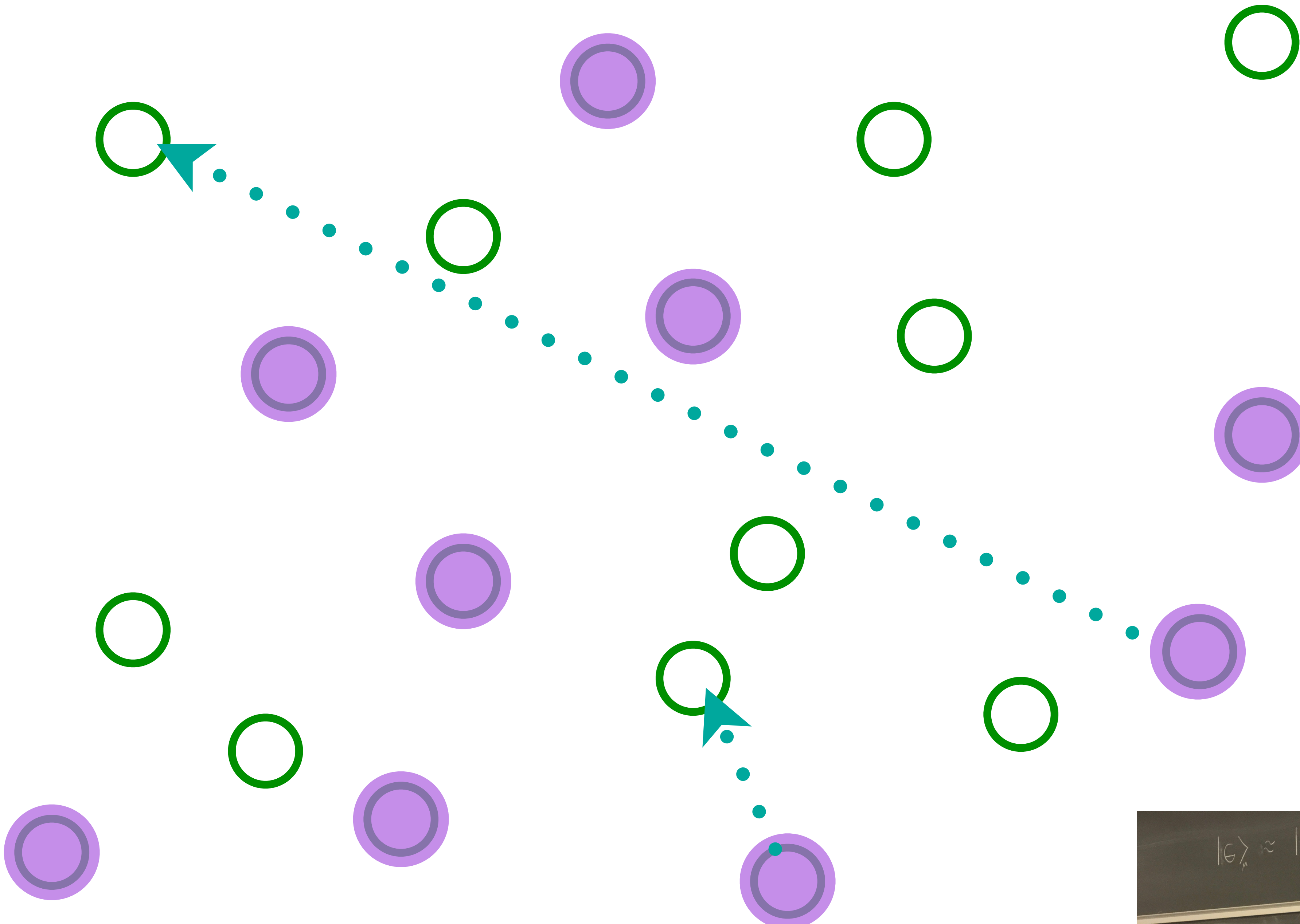

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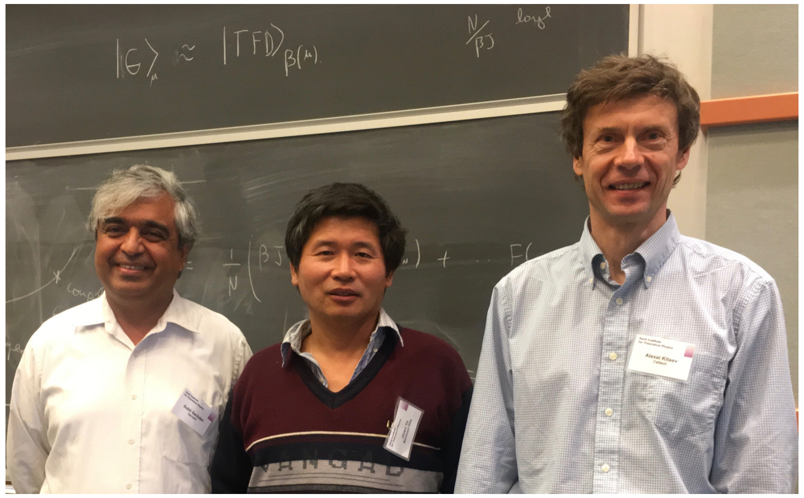

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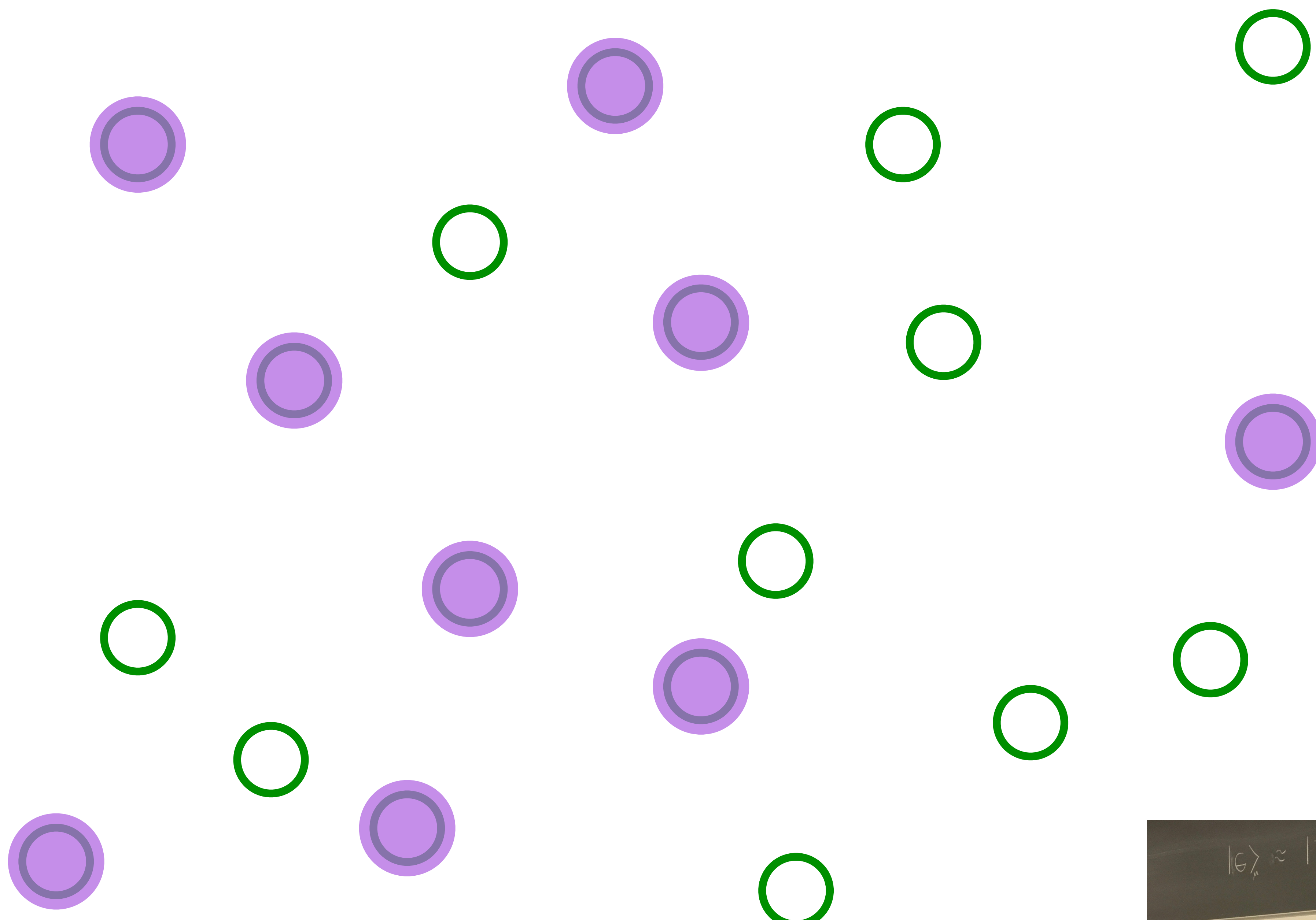

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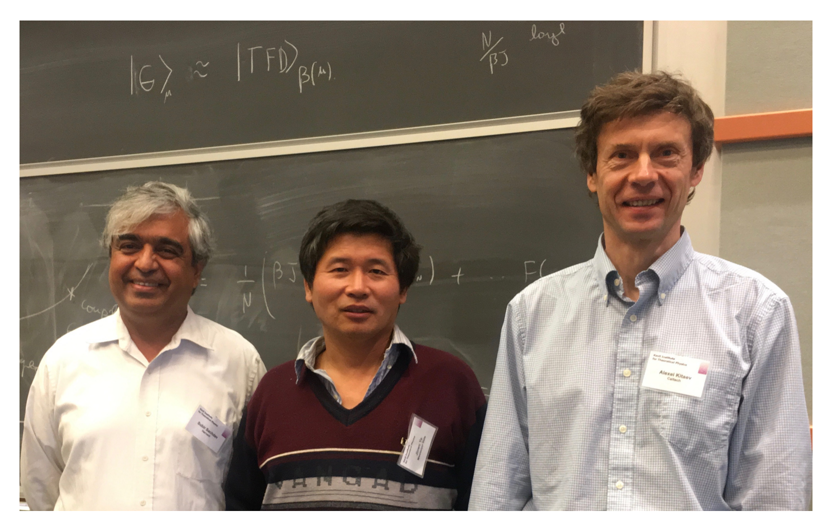

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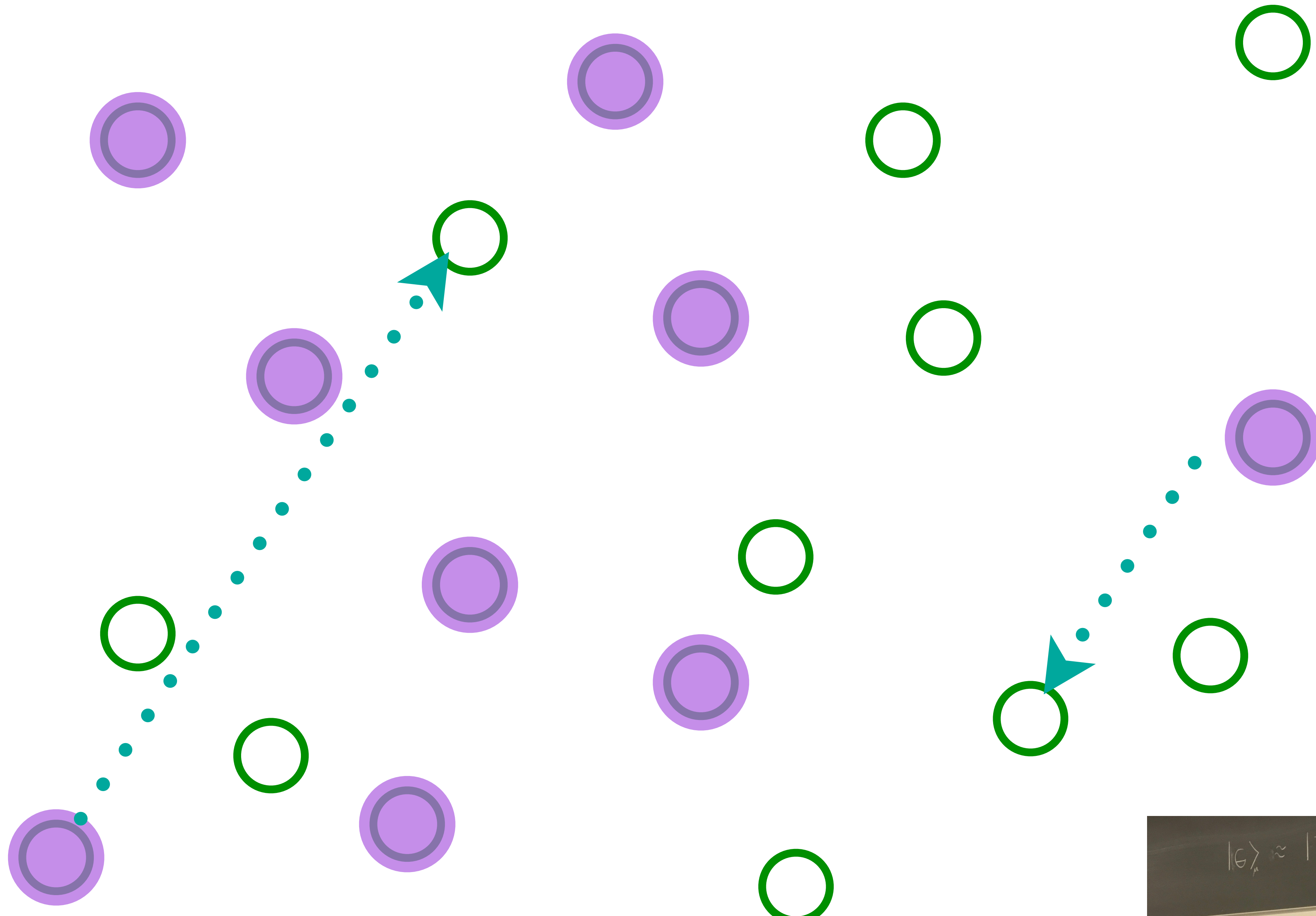

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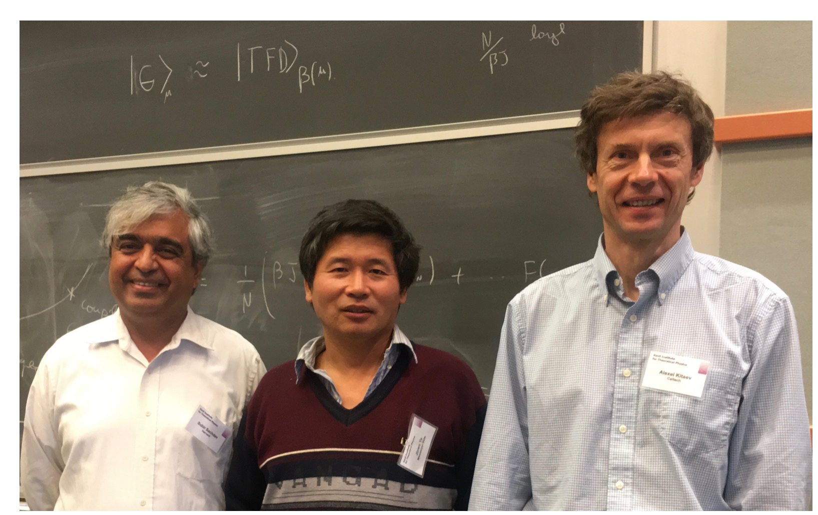

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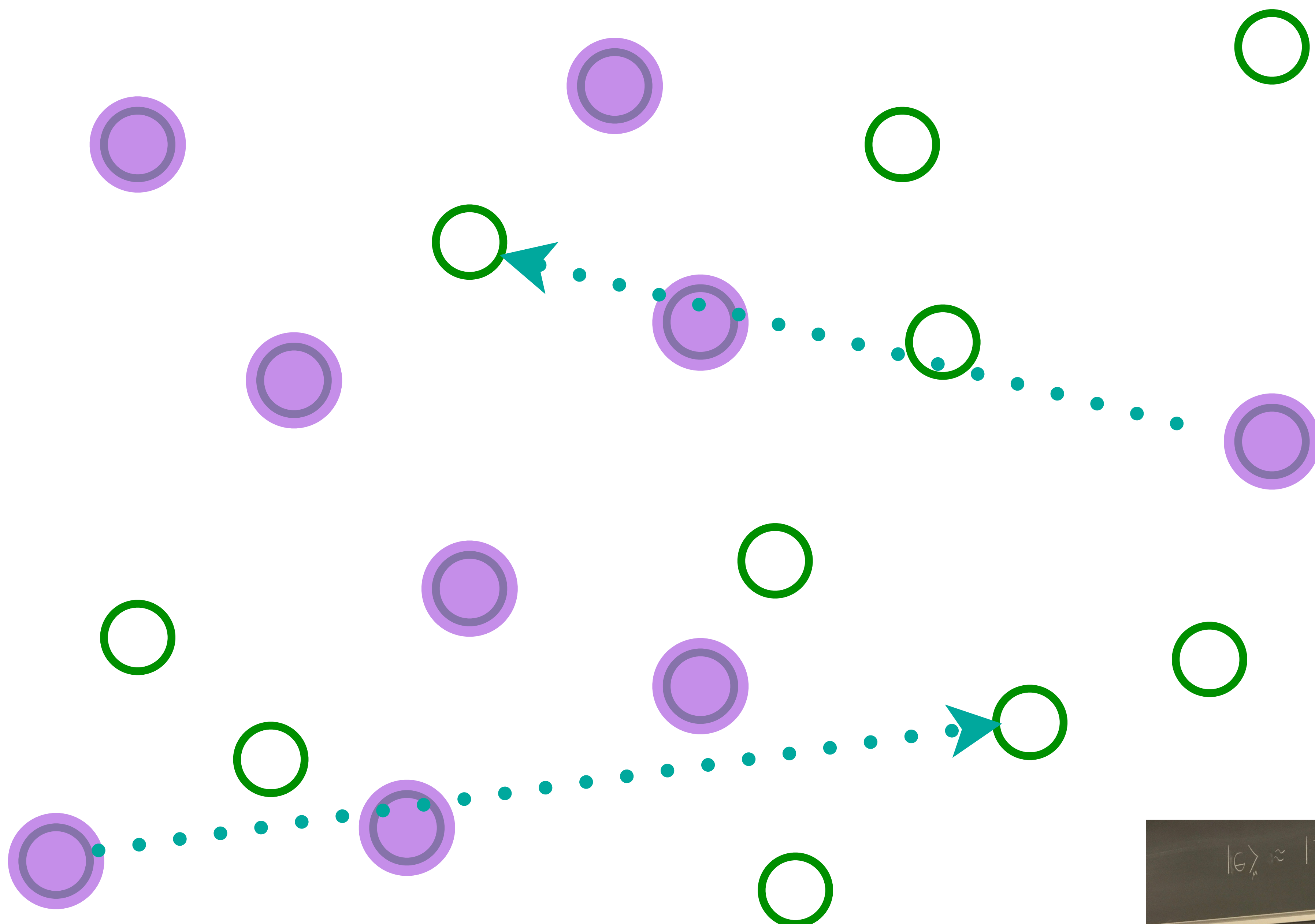

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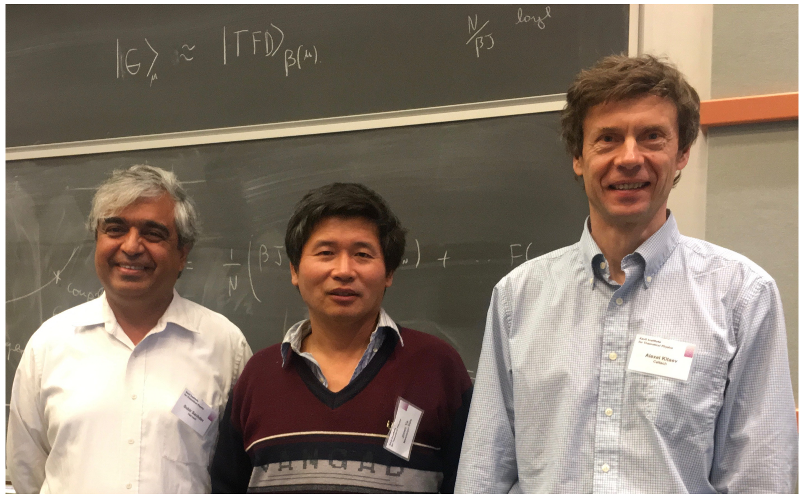

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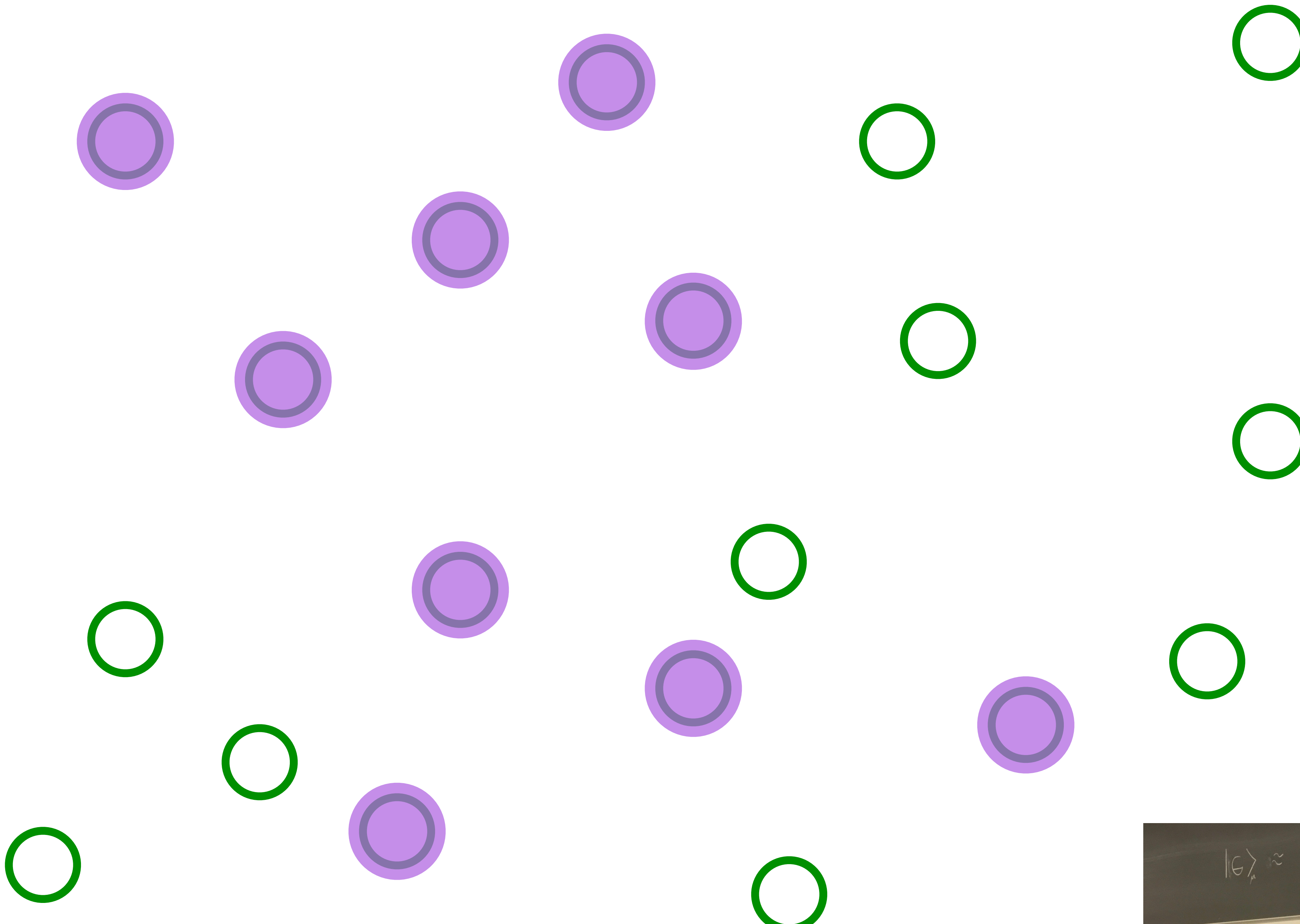

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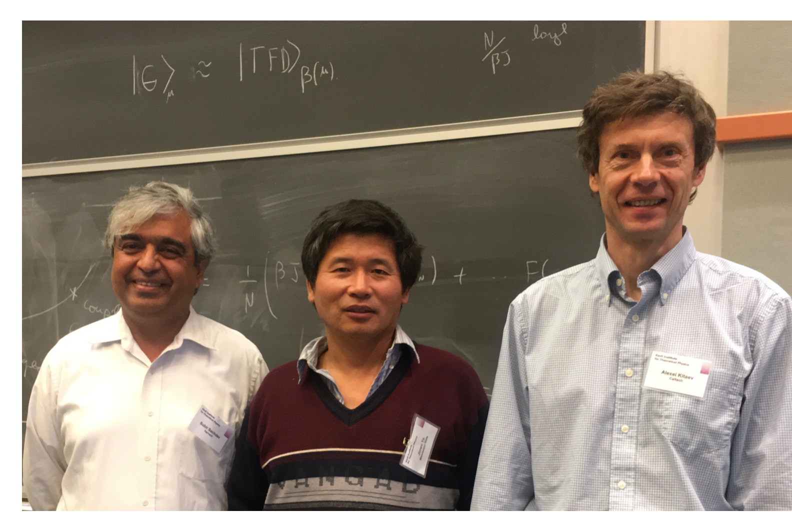

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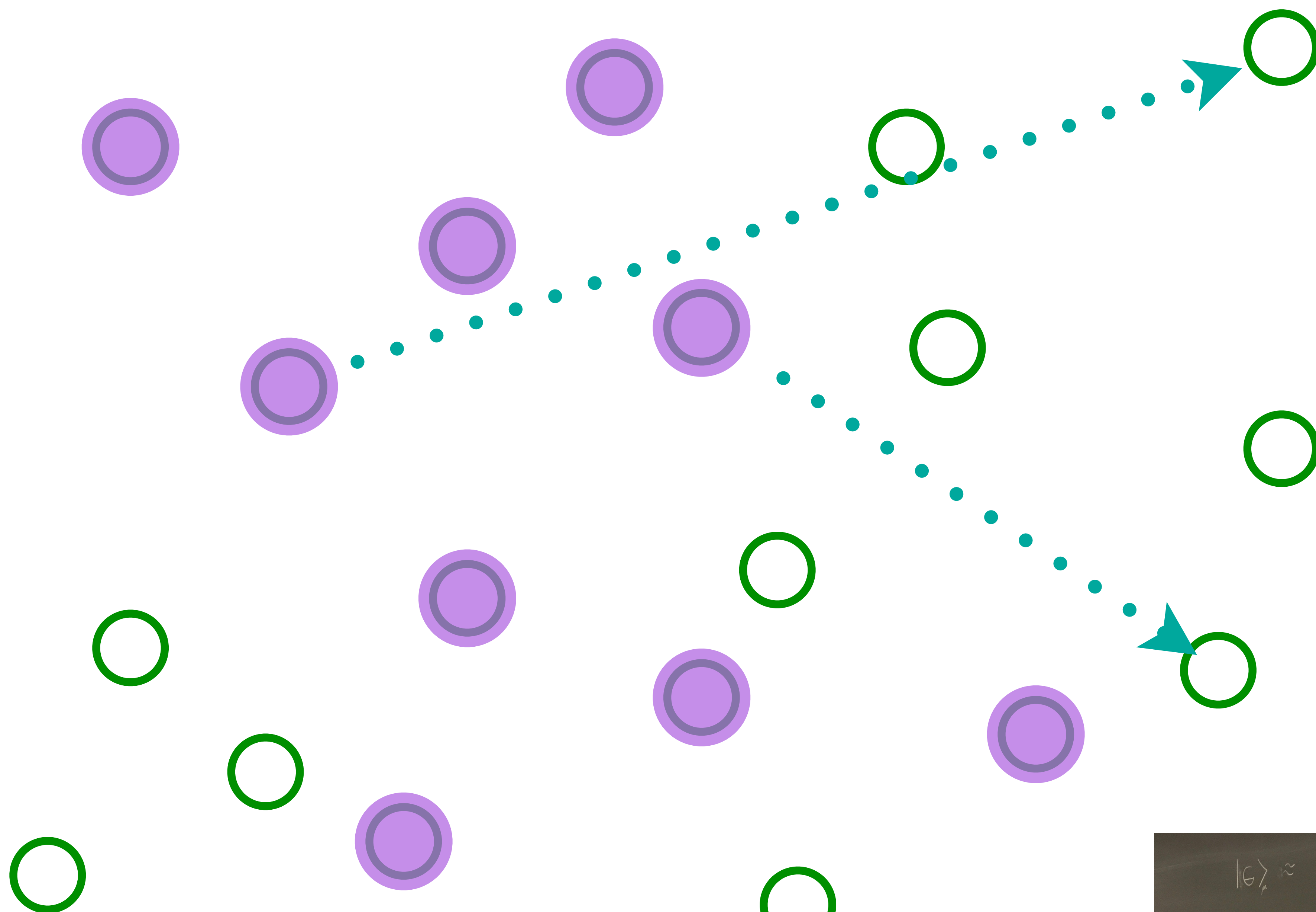

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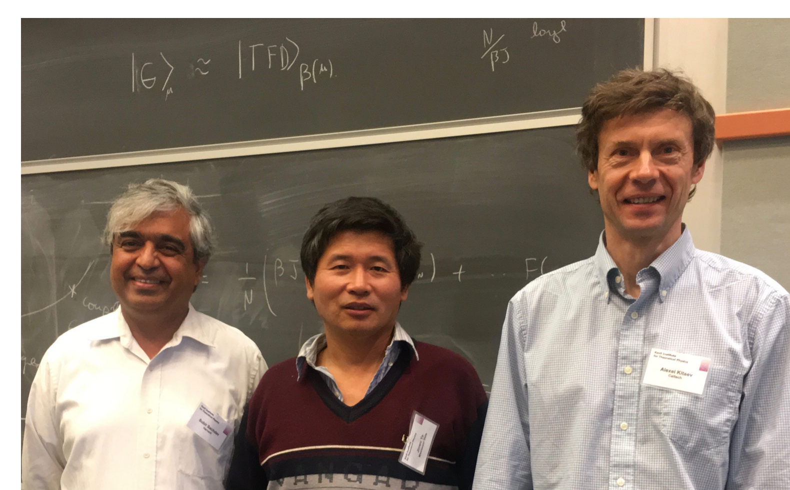

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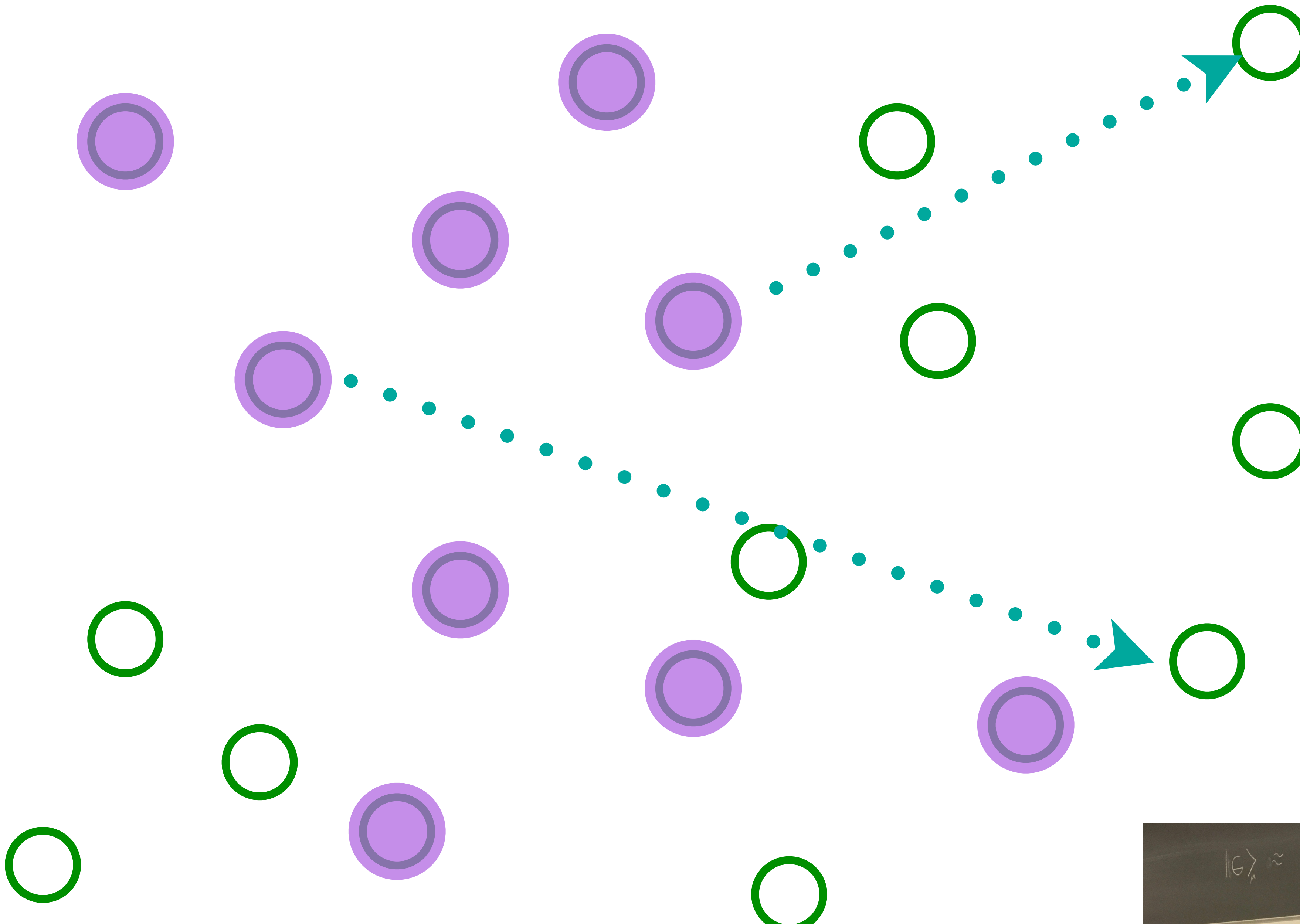

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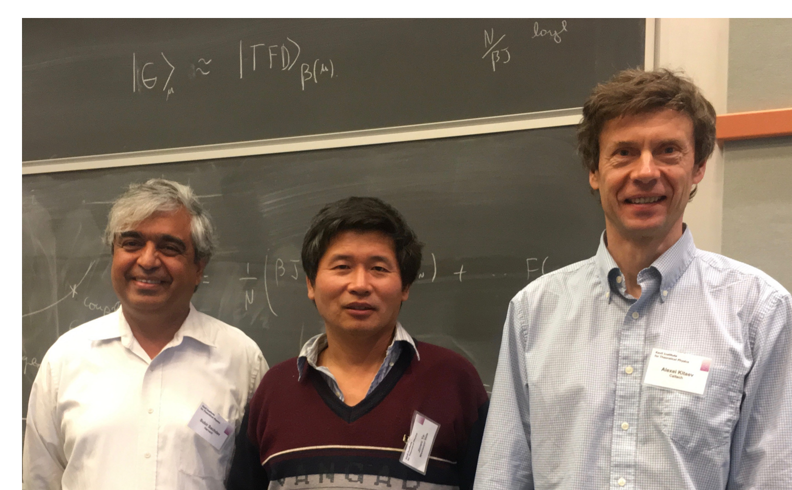

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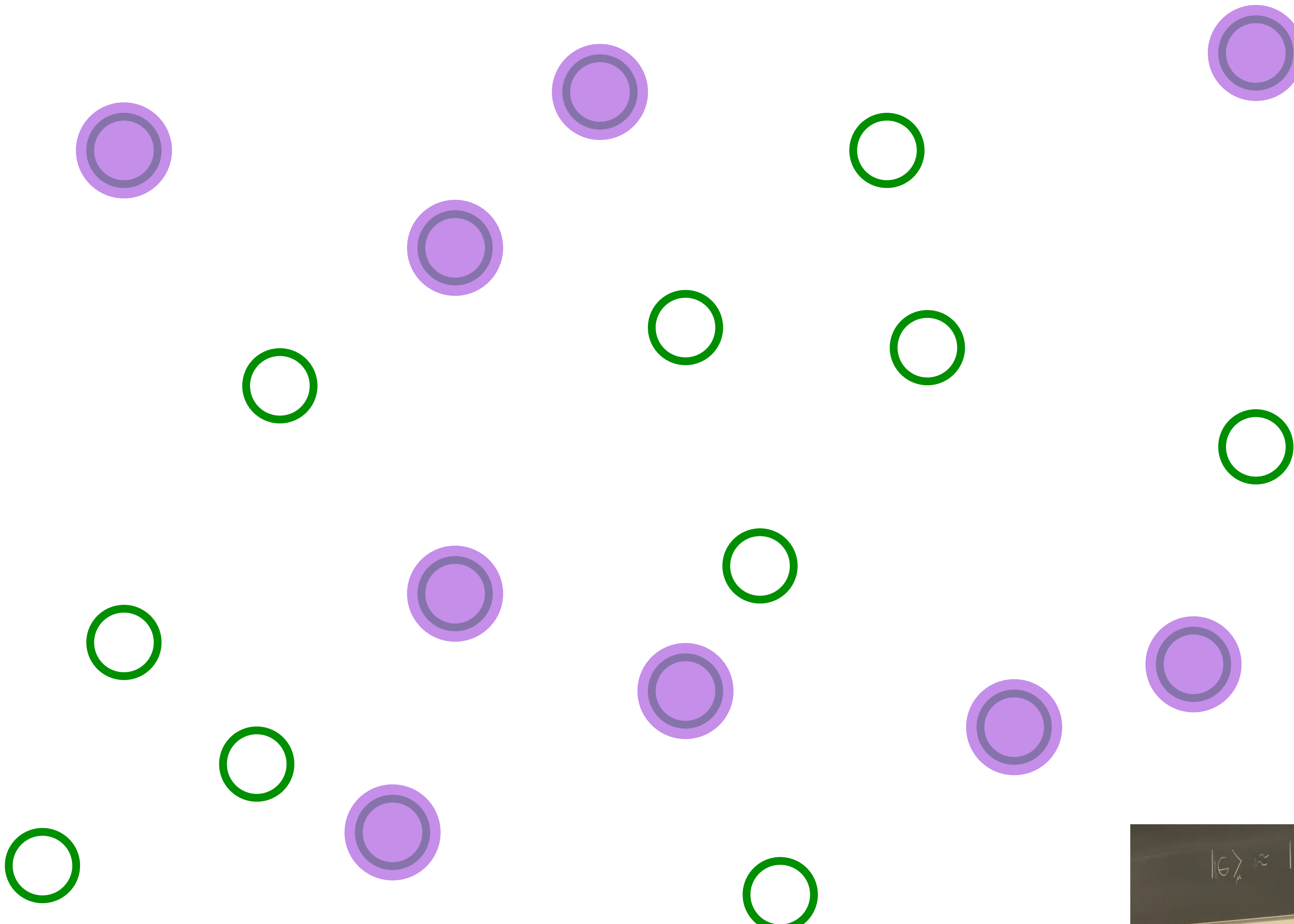

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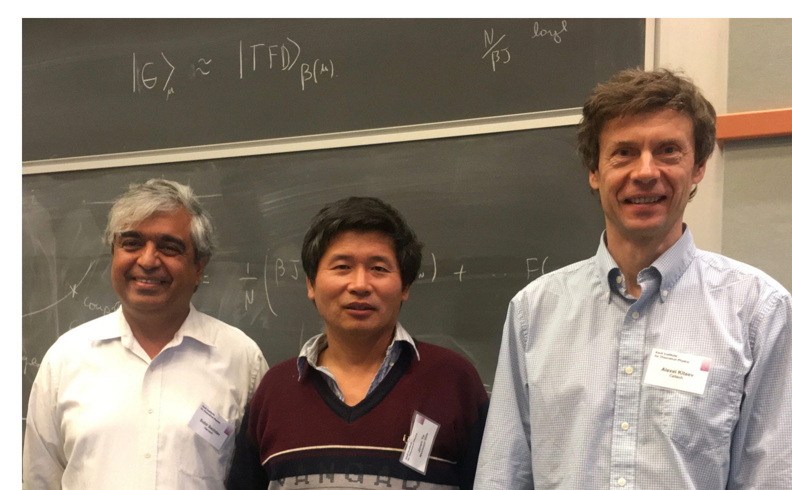

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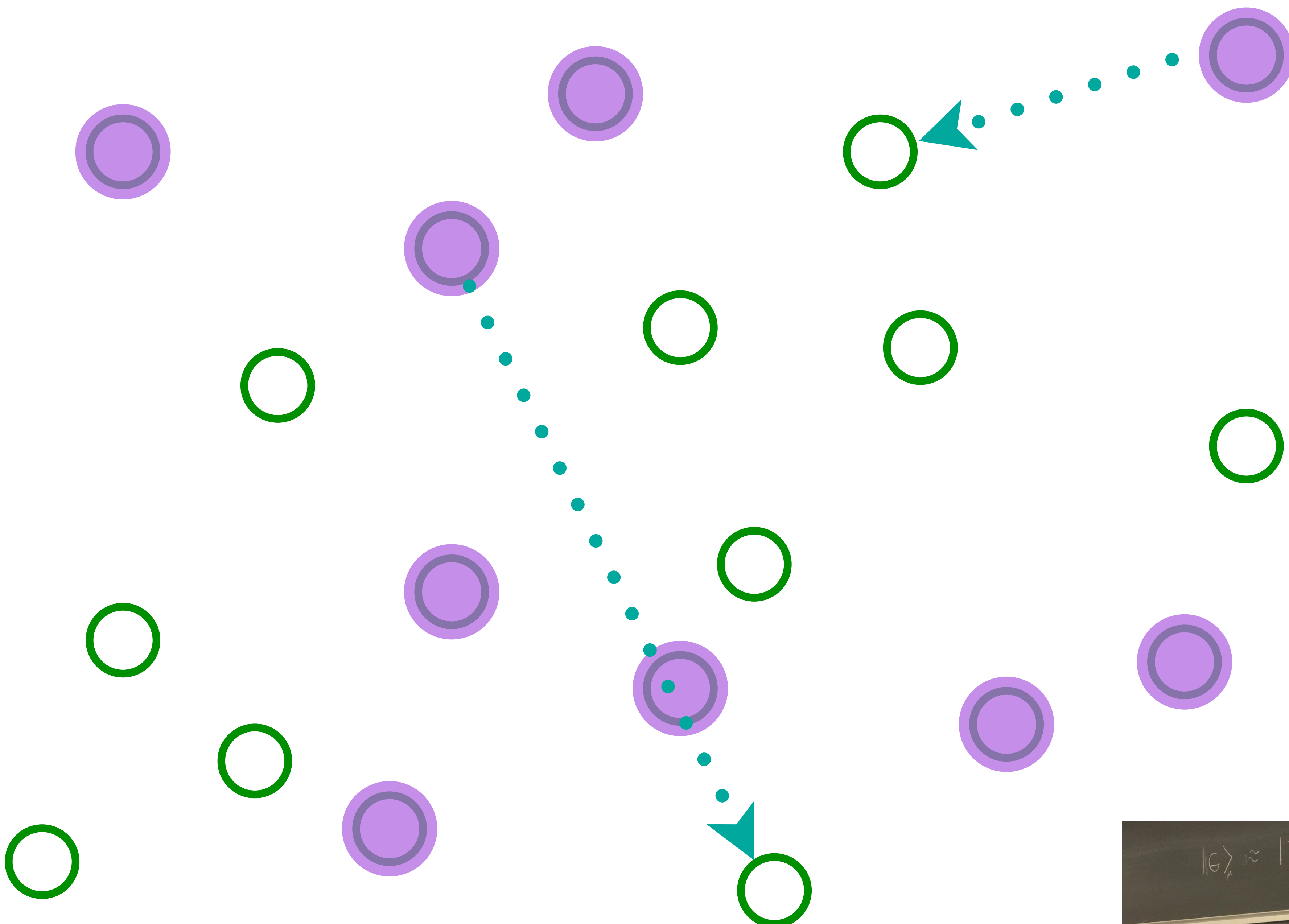

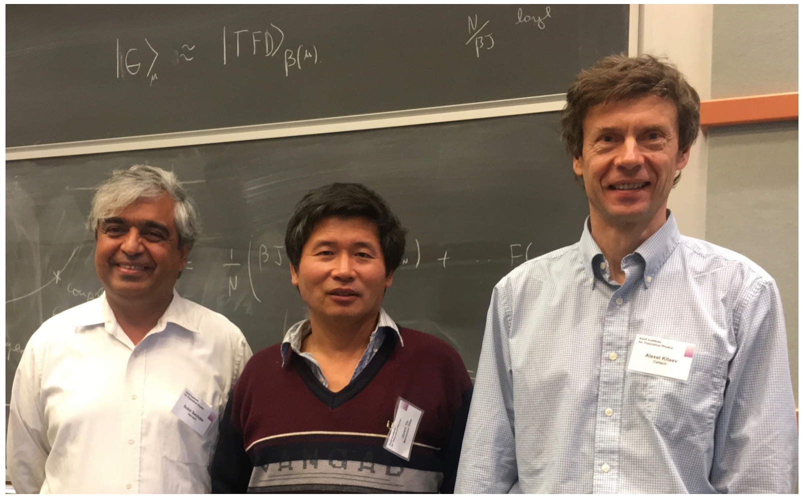

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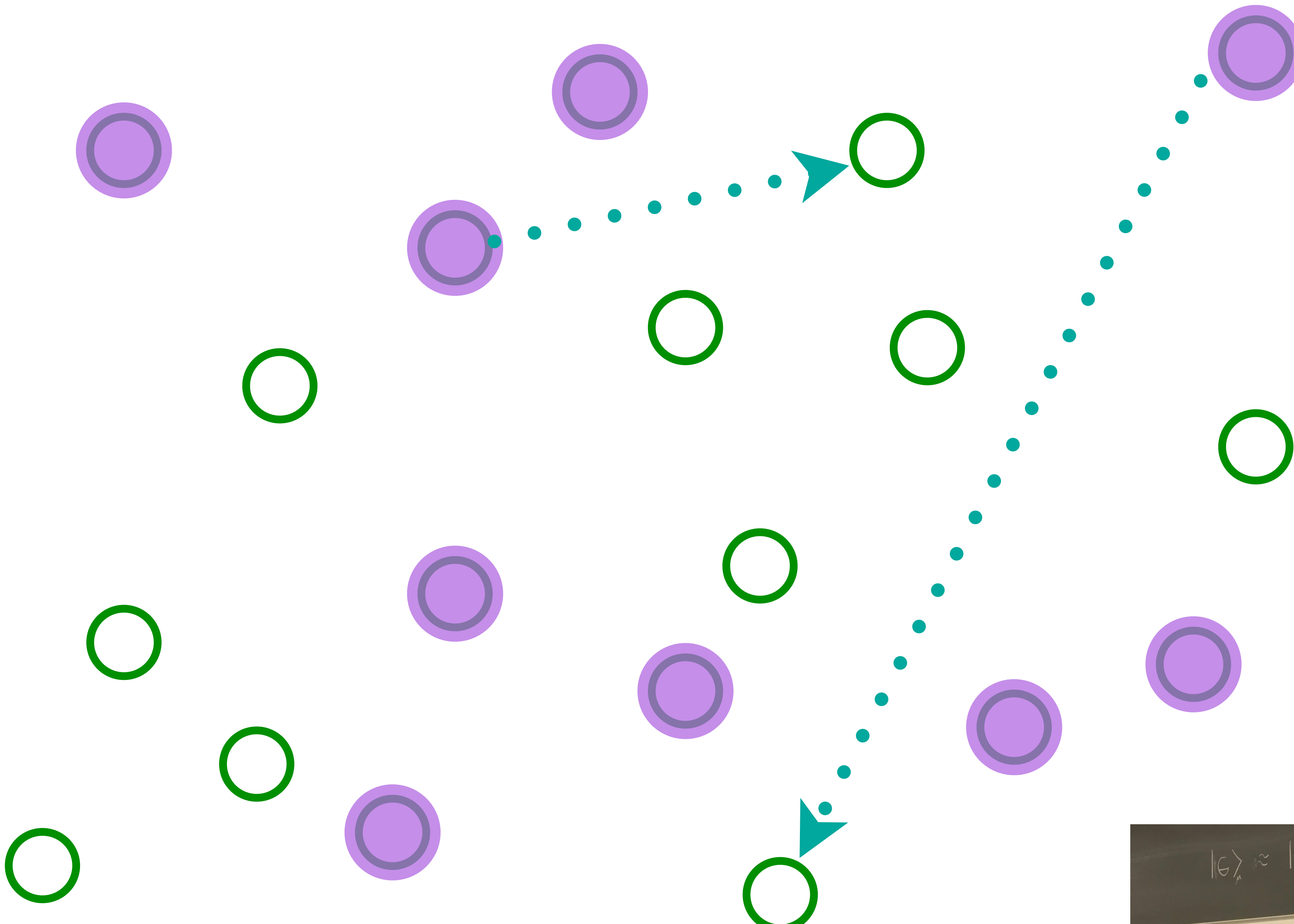

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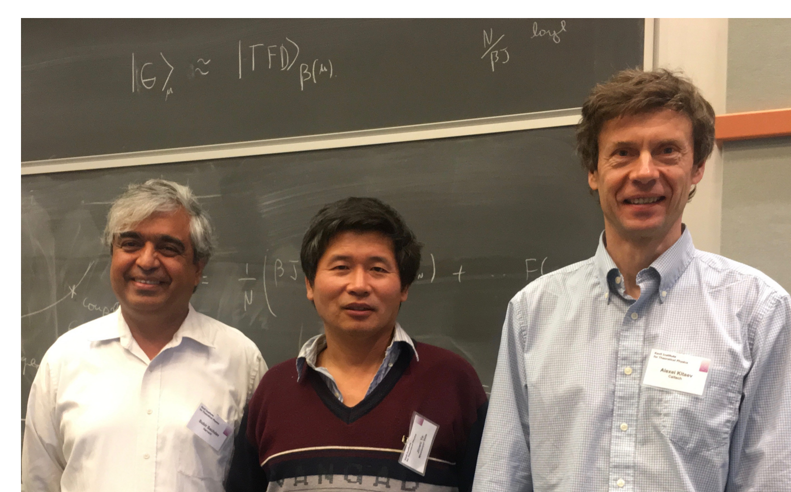

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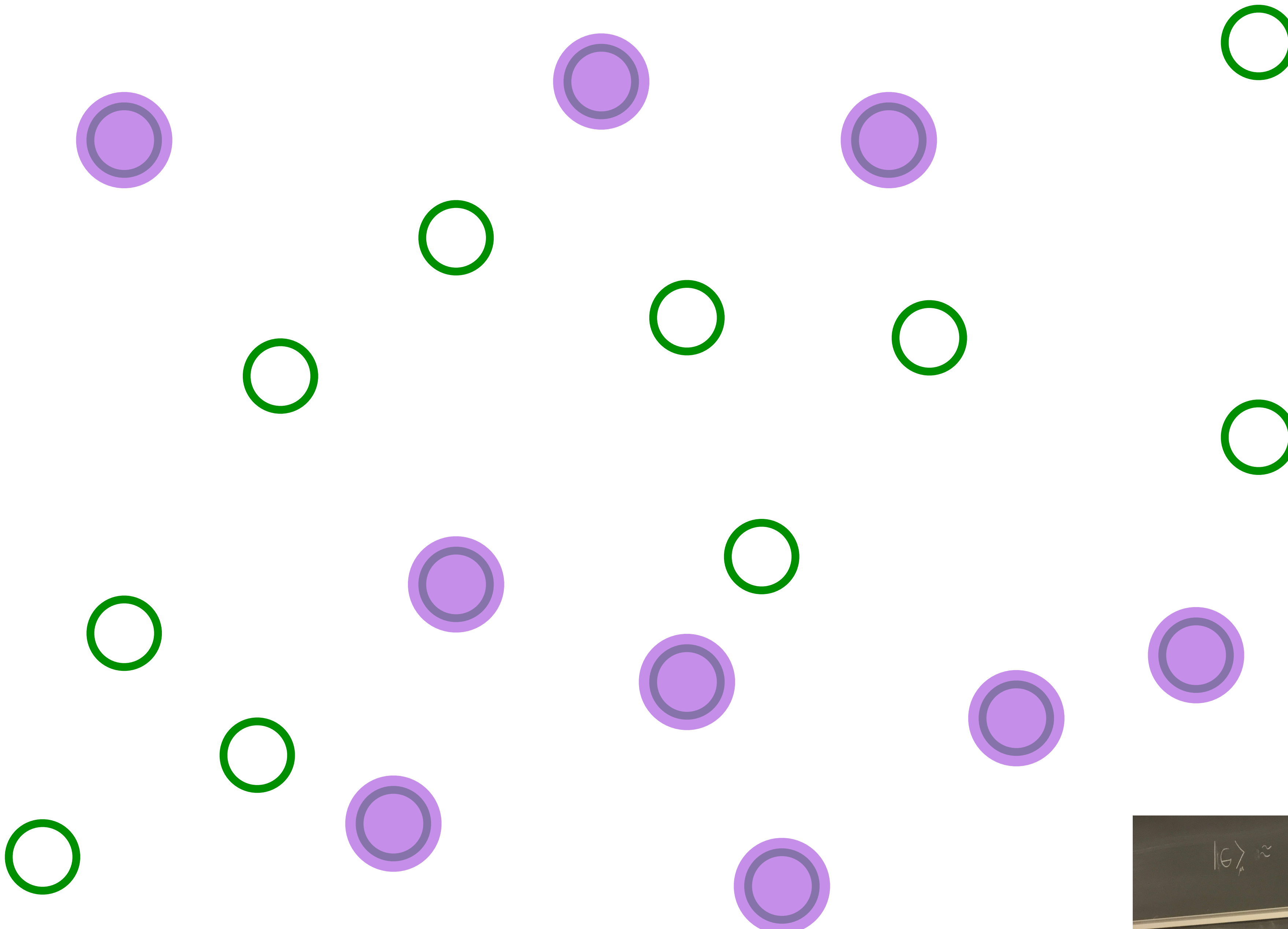

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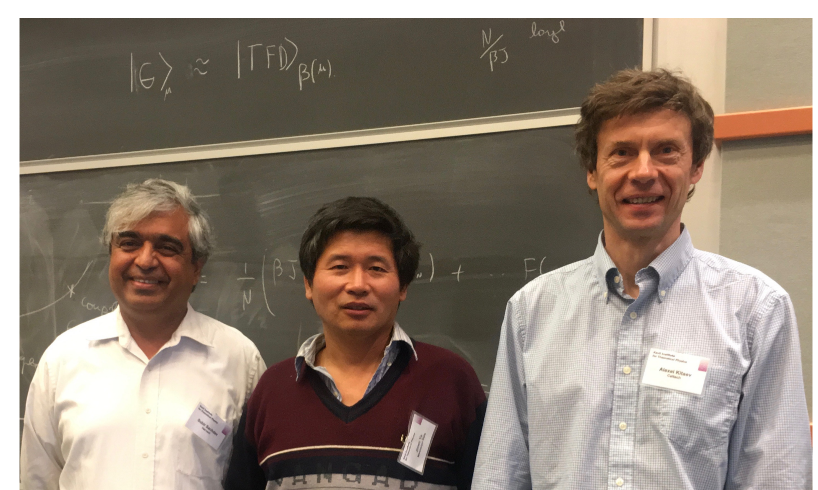


The SYK model

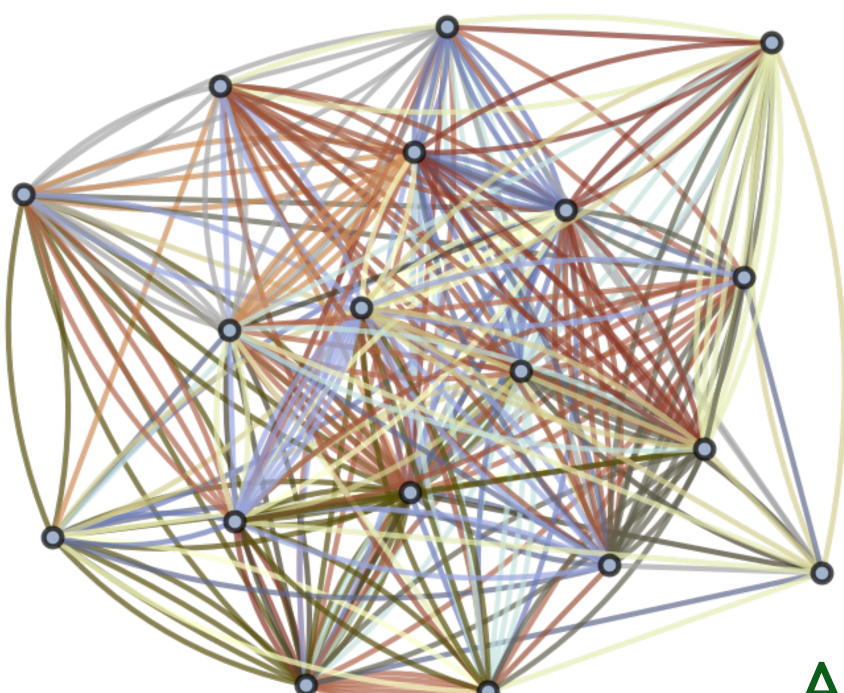
(See also: the "2-Body Random Ensemble" in nuclear physics; did not obtain the large N limit;
T.A. Brody, J. Flores, J.B. French, P.A. Mello, A. Pandey, and S.S.M. Wong, Rev. Mod. Phys. **53**, 385 (1981))

$$\mathcal{H} = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} U_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell - \mu \sum_i c_i^\dagger c_i$$

$$c_i c_j + c_j c_i = 0 \quad , \quad c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$$\mathcal{Q} = \frac{1}{N} \sum_i c_i^\dagger c_i$$

$U_{ij;k\ell}$ are independent random variables with $\overline{U_{ij;k\ell}} = 0$ and $\overline{|U_{ij;k\ell}|^2} = U^2$
$N \to \infty$ yields critical strange metal.



S. Sachdev and J. Ye, PRL **70**, 3339 (1993)
A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

Complex multi-particle entanglement in the SYK model leads to a state without 'quasiparticle' excitations; *i.e.* multiple excitations cannot be built by composing an elementary set of 'quasiparticle' excitations.

Complex multi-particle entanglement in the SYK model leads to a state without 'quasiparticle' excitations; *i.e.* multiple excitations cannot be built by composing an elementary set of 'quasiparticle' excitations.

Many-body chaos and thermal equilibration in the shortest possible Planckian time $\sim \dfrac{\hbar}{k_B T}$.

Main result I

Low temperature thermodynamics: for $k_B T \ll U$

$$\begin{aligned} \mathcal{Z} &= \operatorname{Tr} \exp\left(-\frac{\mathcal{H}}{k_B T}\right) \\ &= \exp\left(N \frac{S_0}{k_B}\right) \int \mathcal{D} f(\tau) \exp\left(-\frac{1}{\hbar} \mathcal{S}_{\text{2D}-\text{gravity}} \left[f(\tau) \right] \right) \end{aligned}$$

S. Sachdev, Phys. Rev. Lett. **105**, 151602 (2010)
A. Kitaev (2015)
J. Maldacena and D. Stanford, Phys. Rev. D **94,** 106002 (2016)

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S_0 is the $T \to 0$ entropy of the SYK model.
This entropy is a consequence of the exponentially large number of ways of entangling many particles.

A. Georges, O. Parcollet, and S. Sachdev, PRB **63**, 134406 (2001)

$S(T) = S_0 + \ldots$ will map on to the Bekenstein-Hawking entropy of black holes

S. Sachdev, Phys. Rev. Lett. **105**, 151602 (2010)
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- Feynman path integral over $f(\tau)$, the reparameterization of the time of the SYK model.

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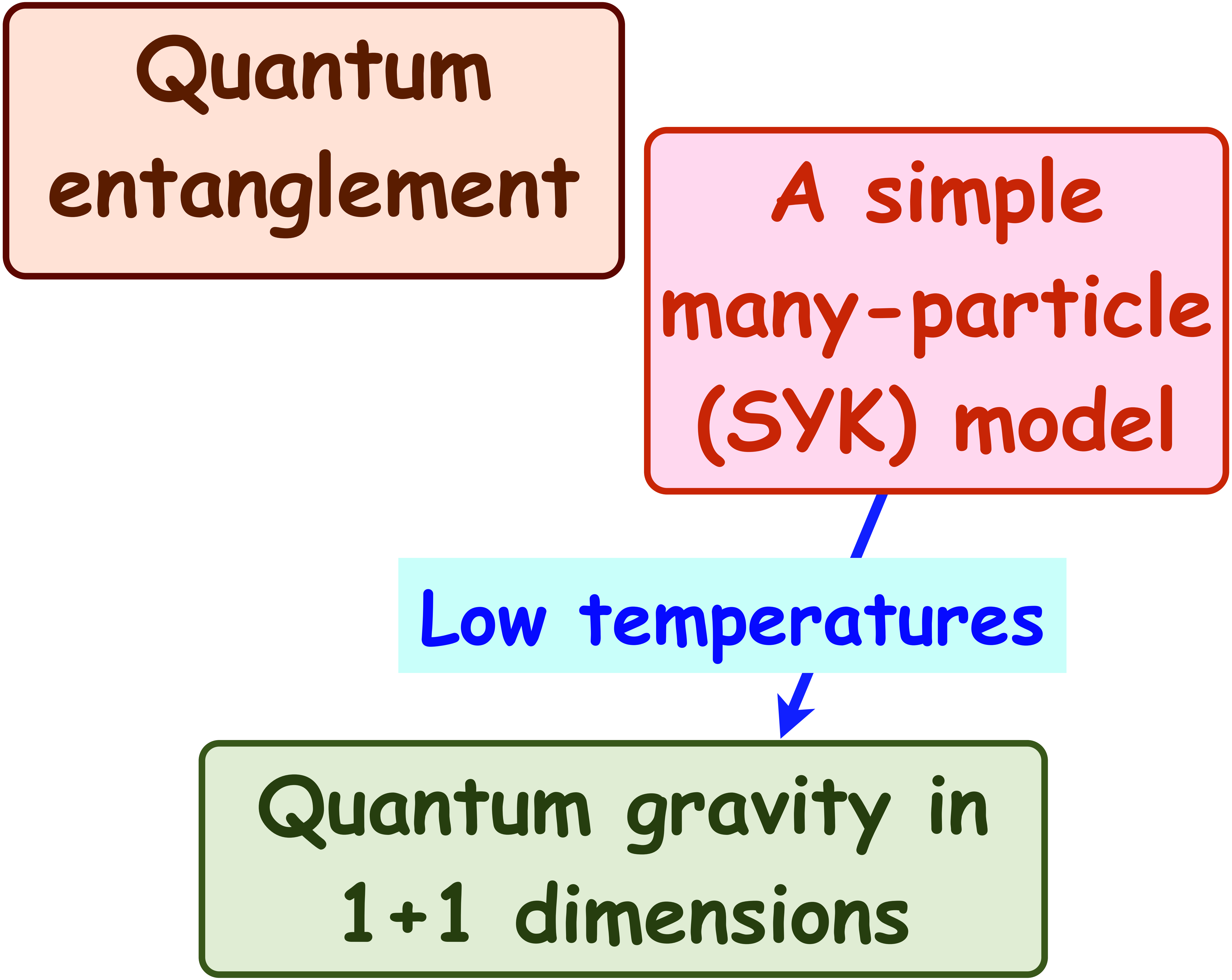
- Feynman path integral over $f(\tau)$, the reparameterization of the time of the SYK model.

- $f(\tau)$ is also the fluctuation of the boundary of a theory of 2D-gravity in 1+1 spacetime dimensions: a 'boundary graviton':
  the SYK model is a 'hologram' of quantum gravity.

S. Sachdev, Phys. Rev. Lett. **105**, 151602 (2010)
A. Kitaev (2015)
J. Maldacena and D. Stanford, Phys. Rev. D **94,** 106002 (2016)


Quantum entanglement
A simple many-particle (SYK) model
Low temperatures
Quantum gravity in 1+1 dimensions

Quantum entanglement

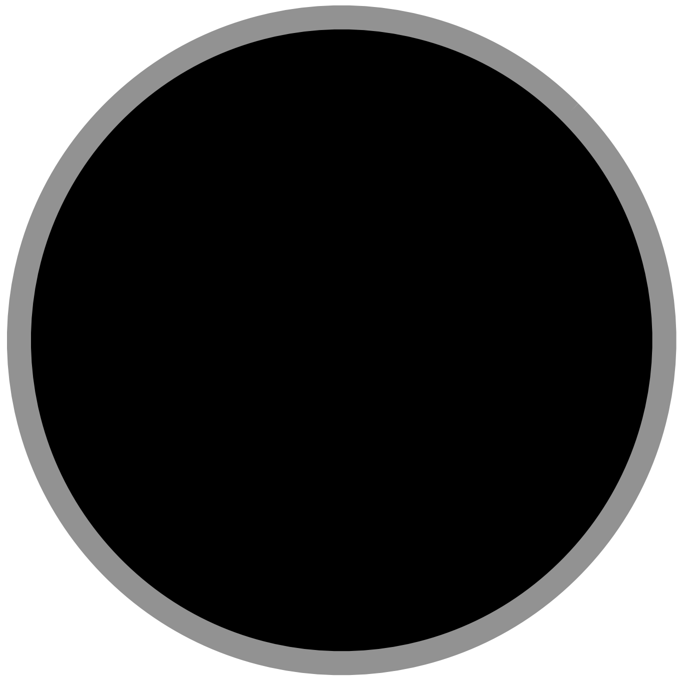
Black holes

A simple many-particle (SYK) model

Black Holes

Objects so dense that light is gravitationally bound to them.

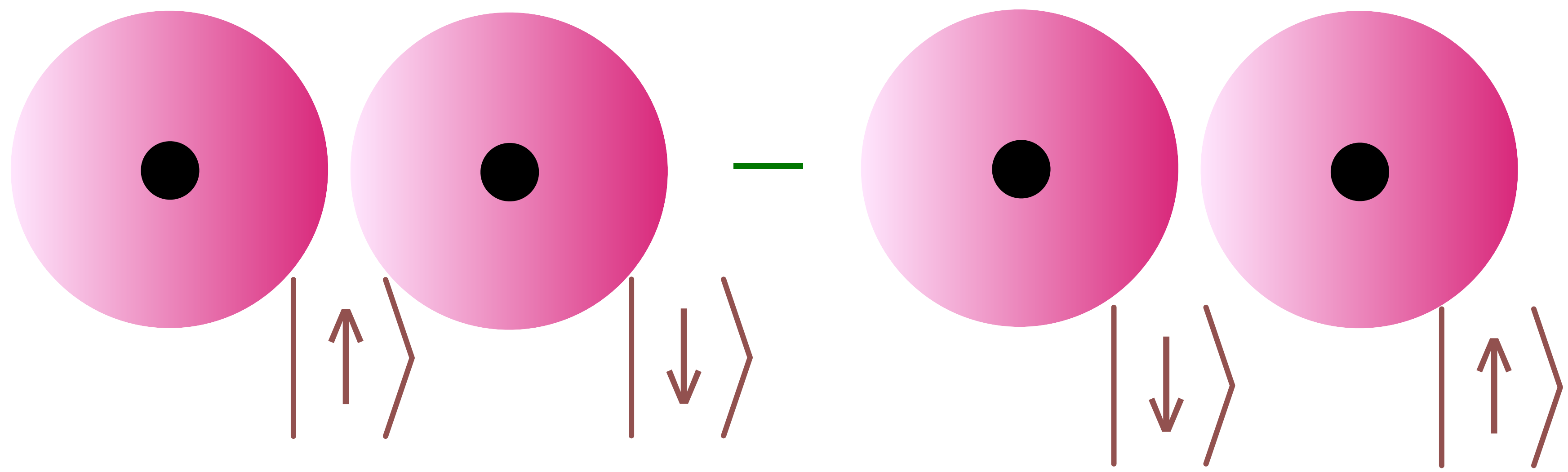
In Einstein's theory, the region inside the black hole **horizon** is disconnected from the rest of the universe.



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

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

Quantum Entanglement across a black hole horizon



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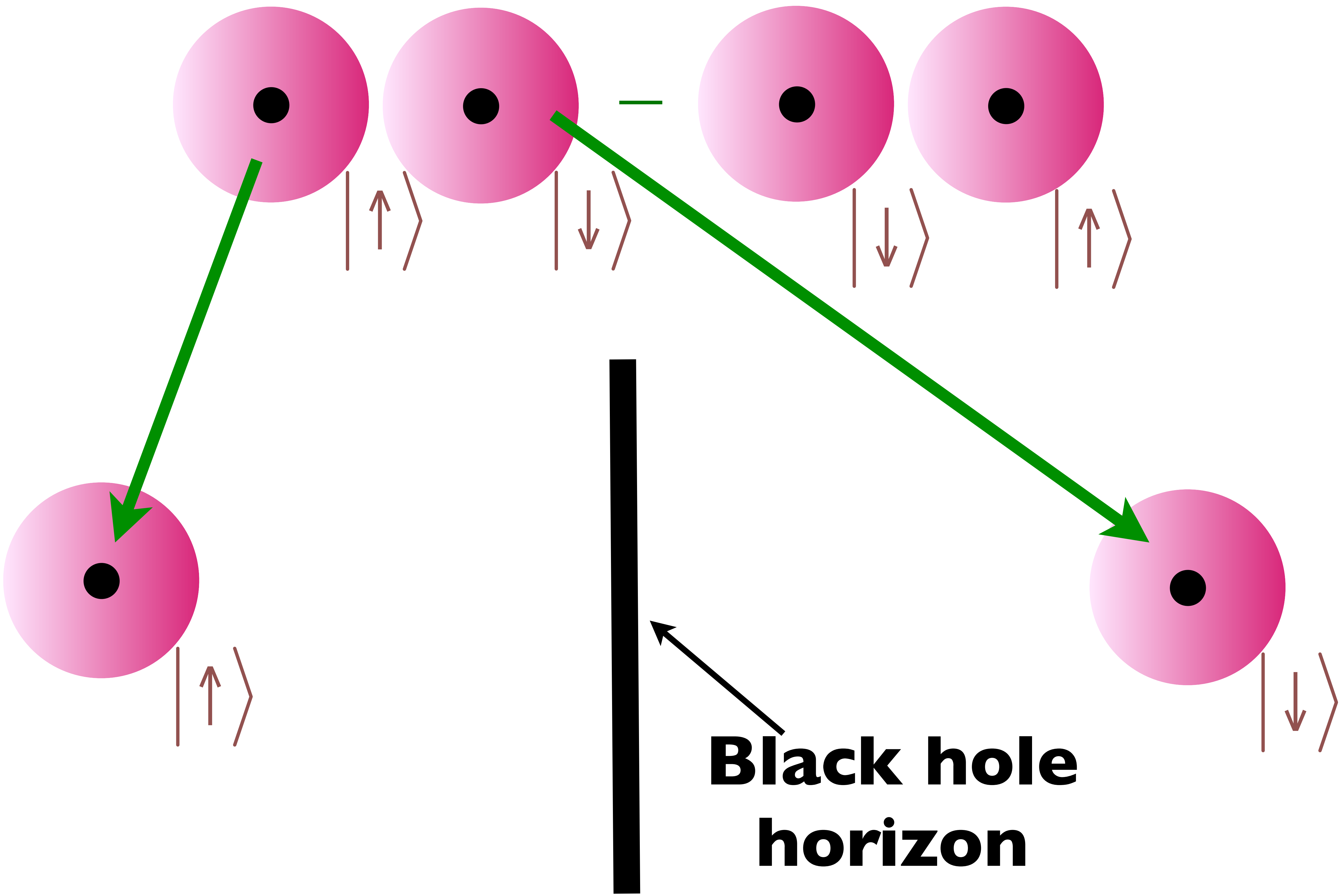

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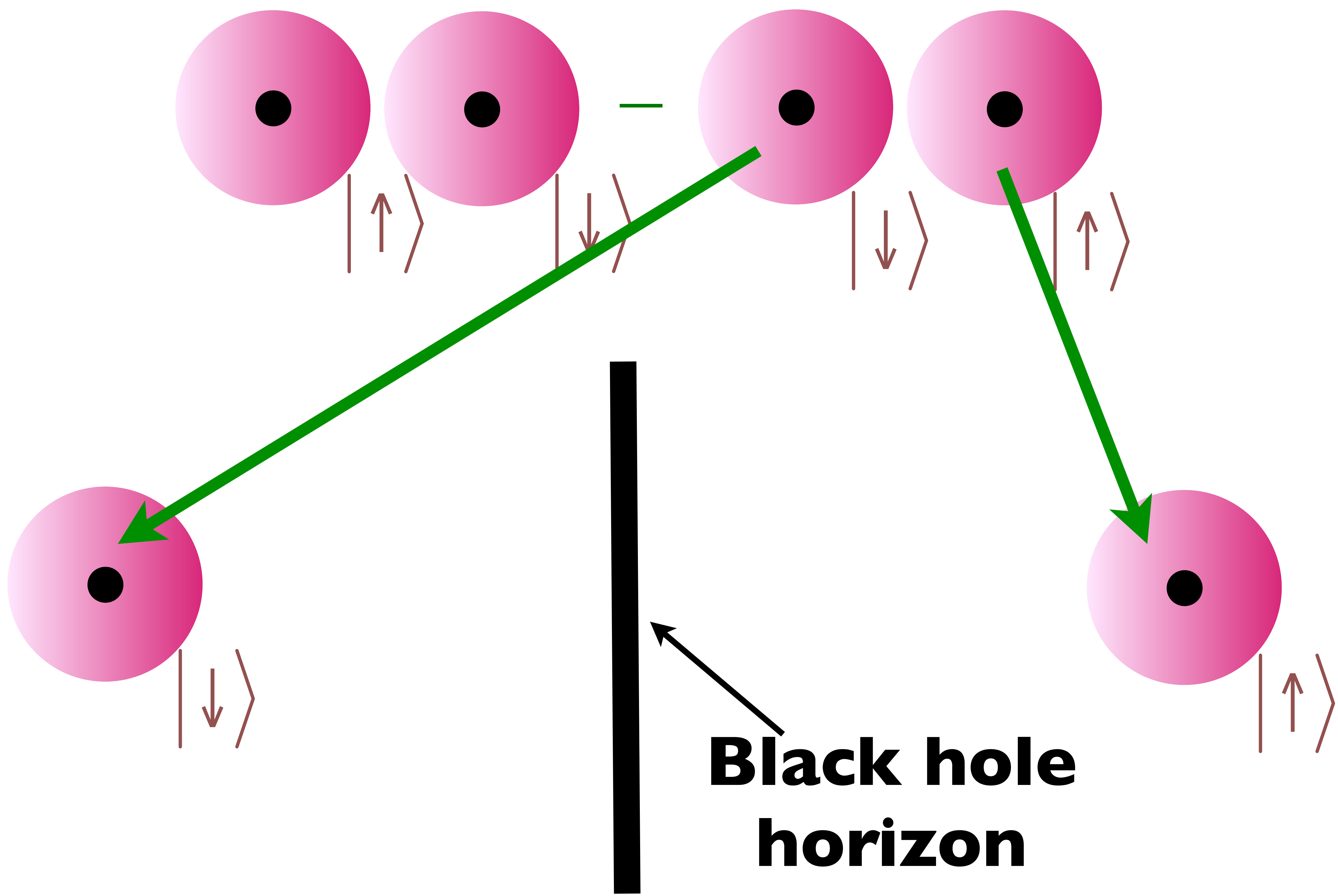
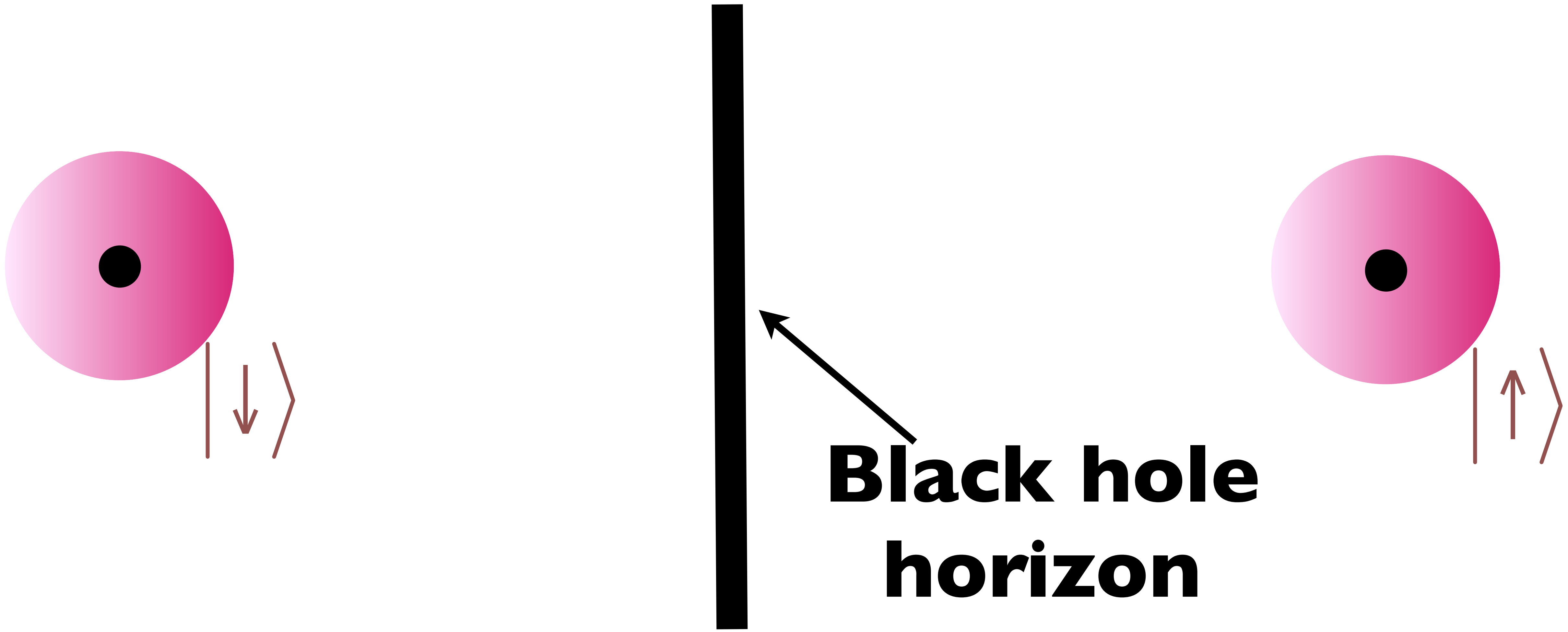


Quantum Entanglement across a black hole horizon

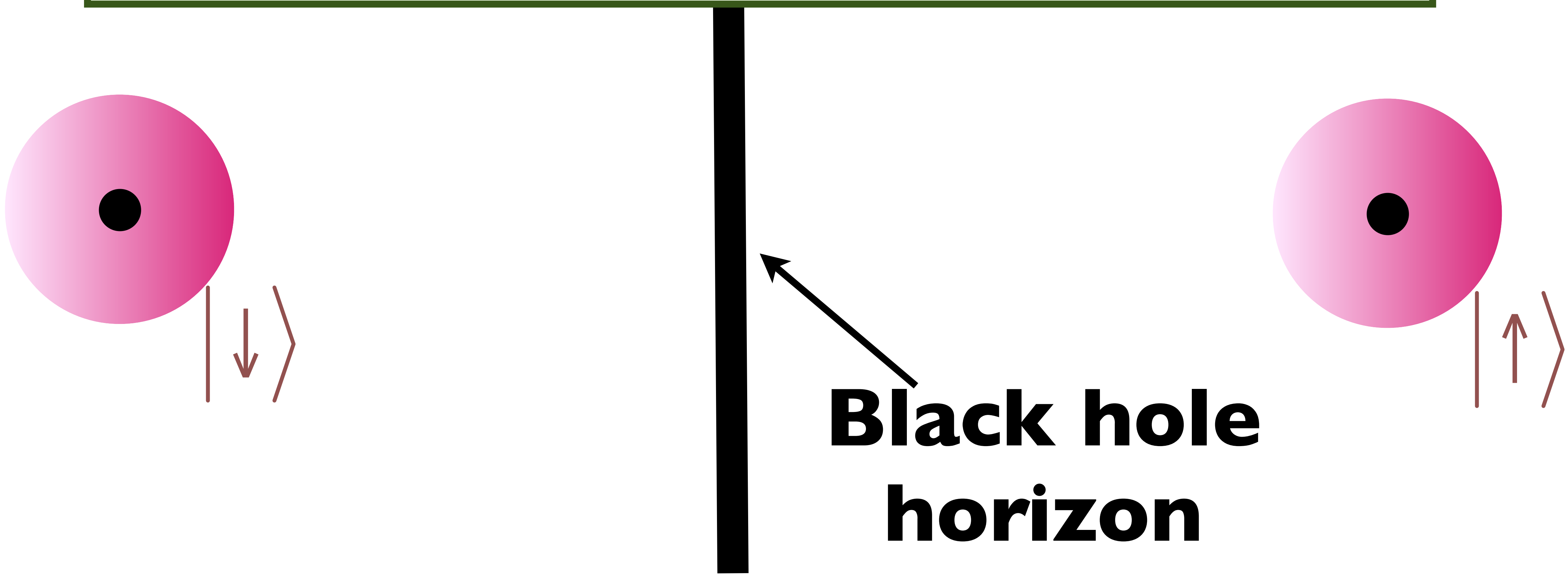
There is quantum entanglement between the inside and outside of a black hole



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, S_{BH} is proportional to their surface area.

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S.W. Hawking, Nature **248**, 30 (1974)

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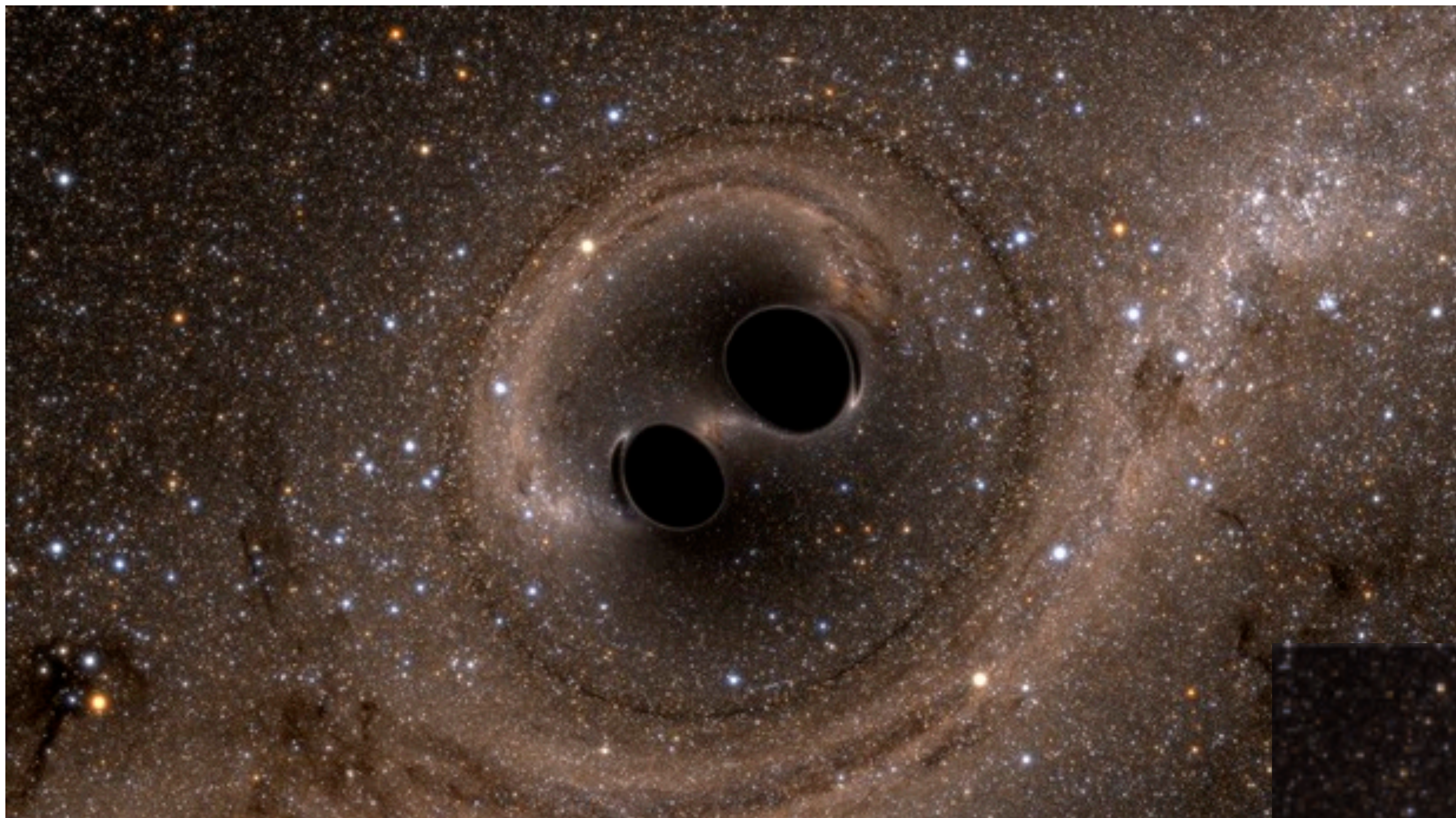
All many-body quantum systems (without quantum gravity) have an entropy proportional to their volume.

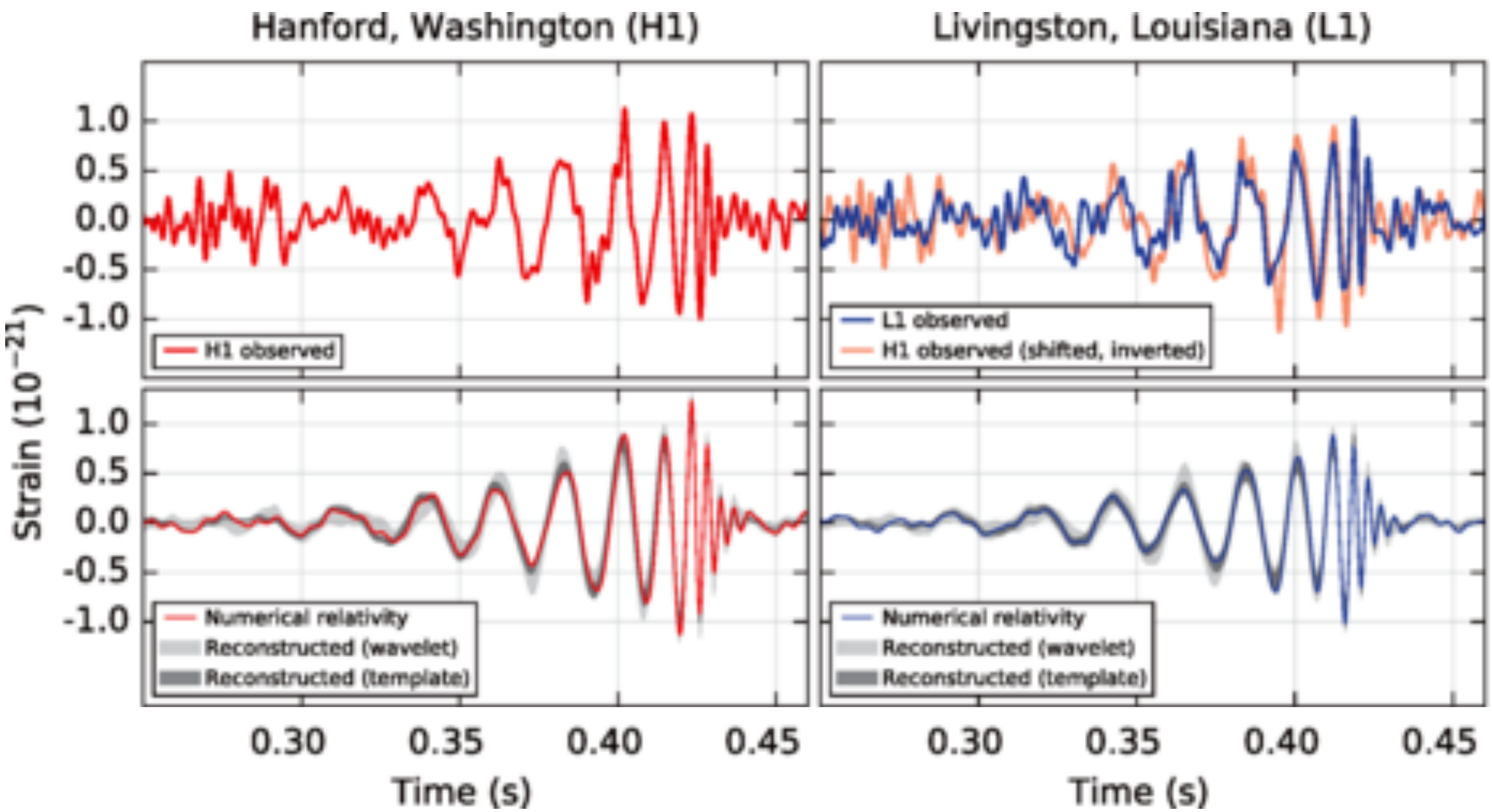
Holography: Black holes have an entropy proportional to their surface area, and so they can be represented as a `hologram' by a quantum many-body system in one lower dimension.

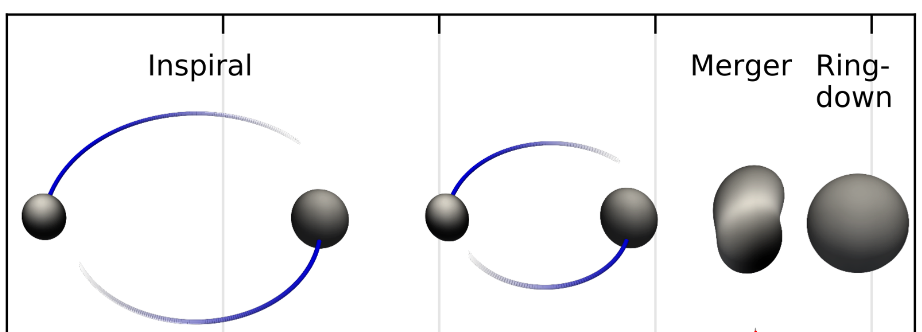
Susskind, Maldacena…..

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 !

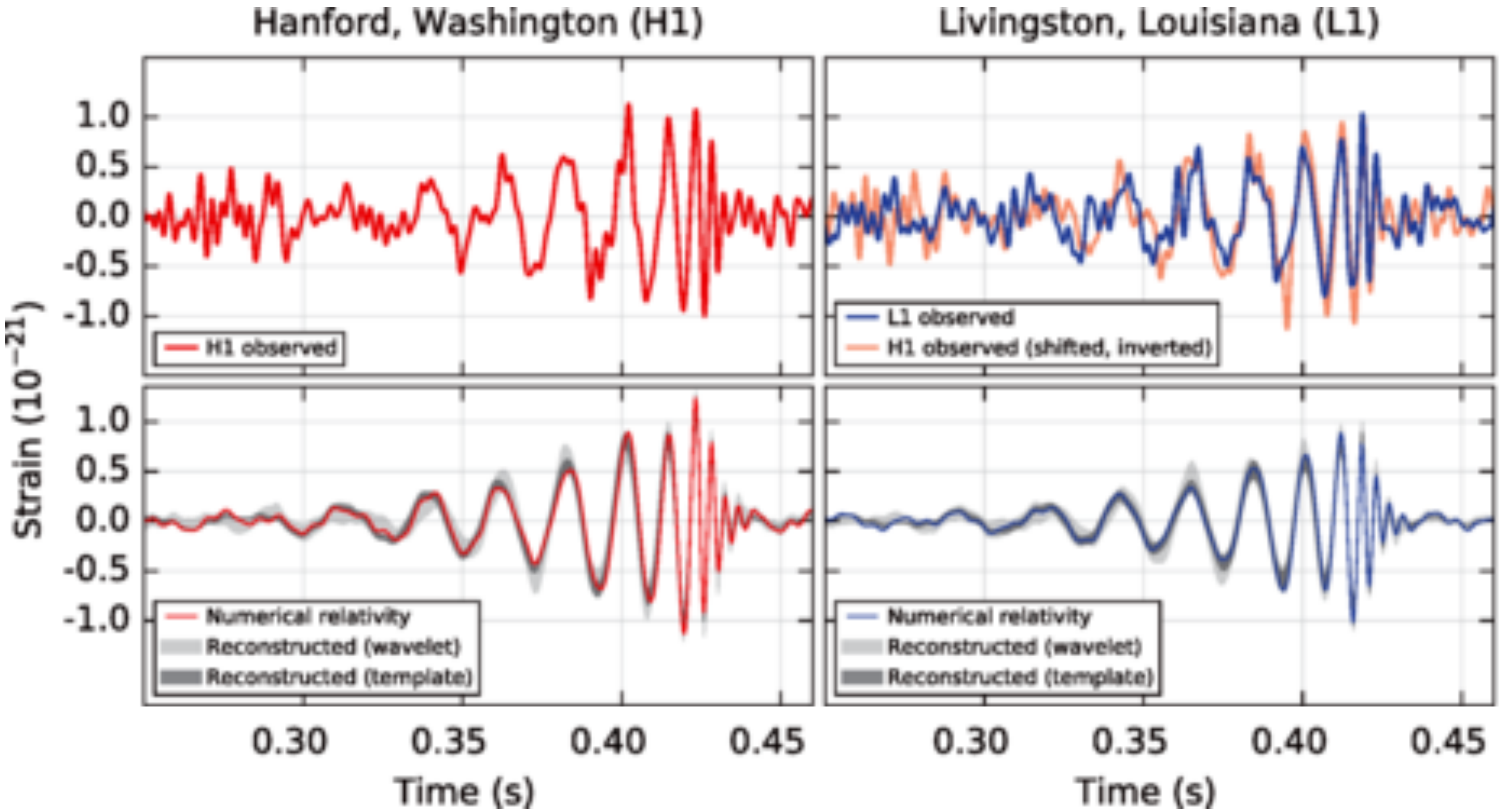


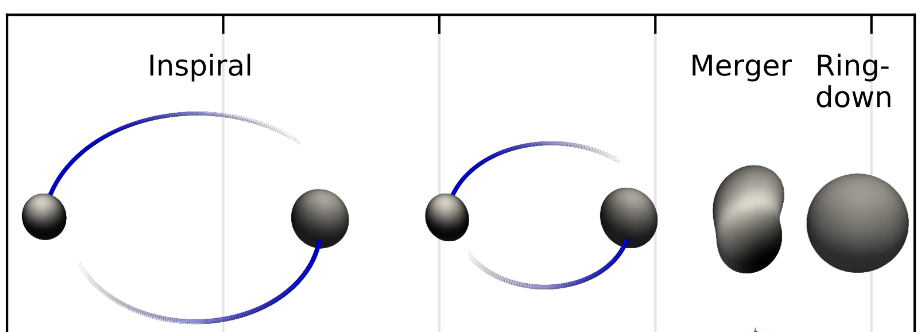


LIGO
September 14, 2015

- 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

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





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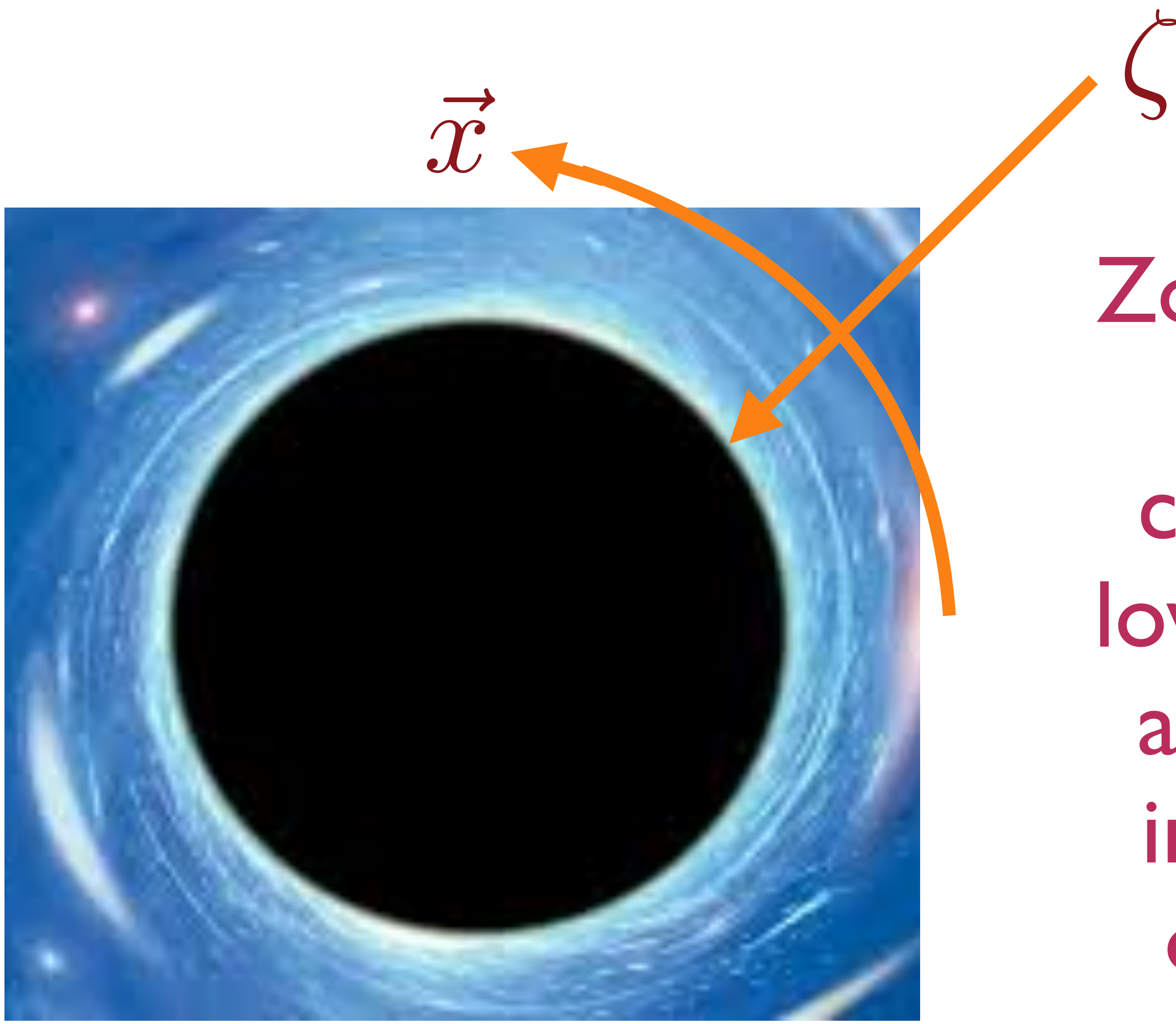
Quantum Black holes

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

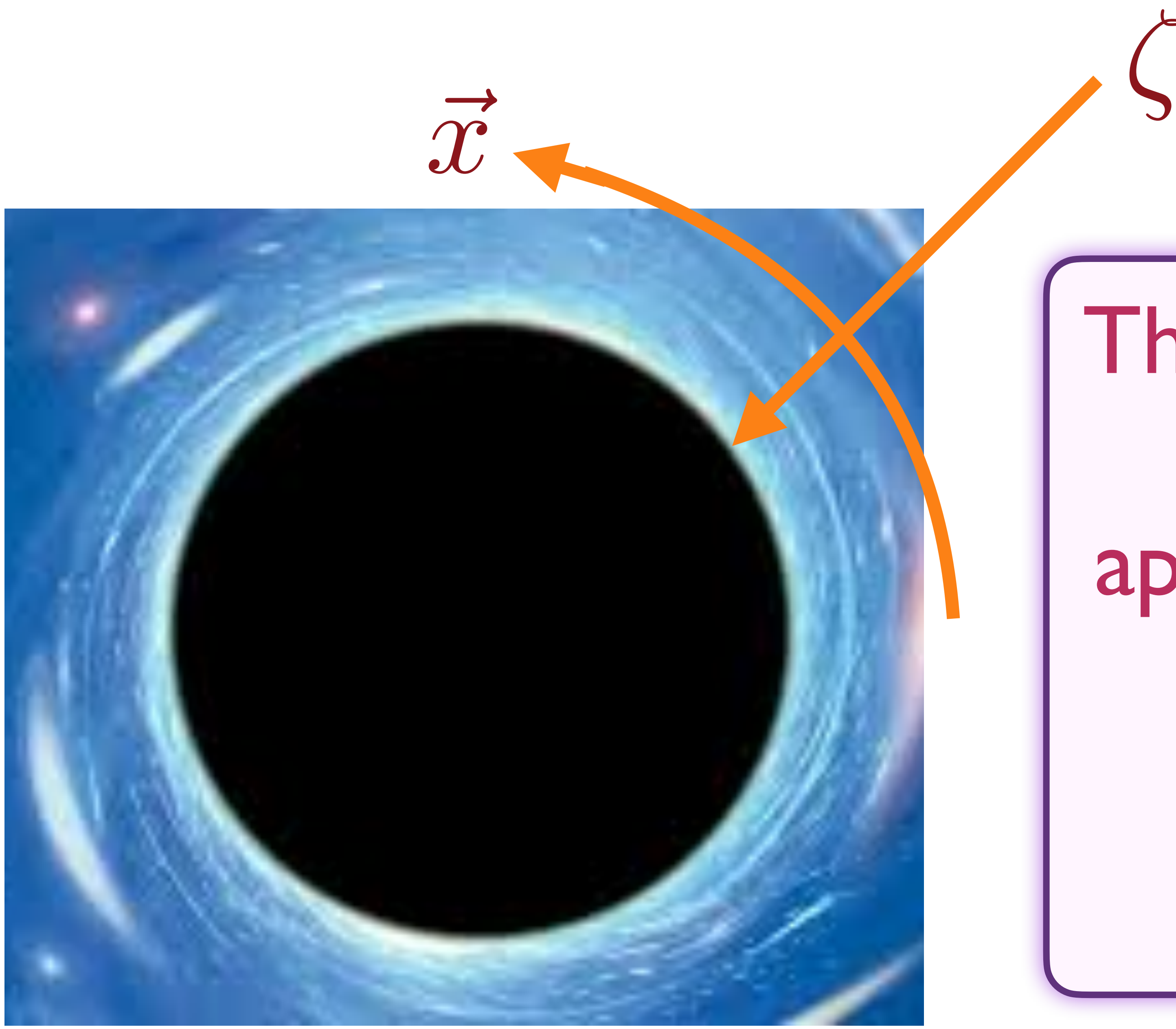
Maxwell's electromagnetism and Einstein's general relativity allow black hole solutions with a net charge

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



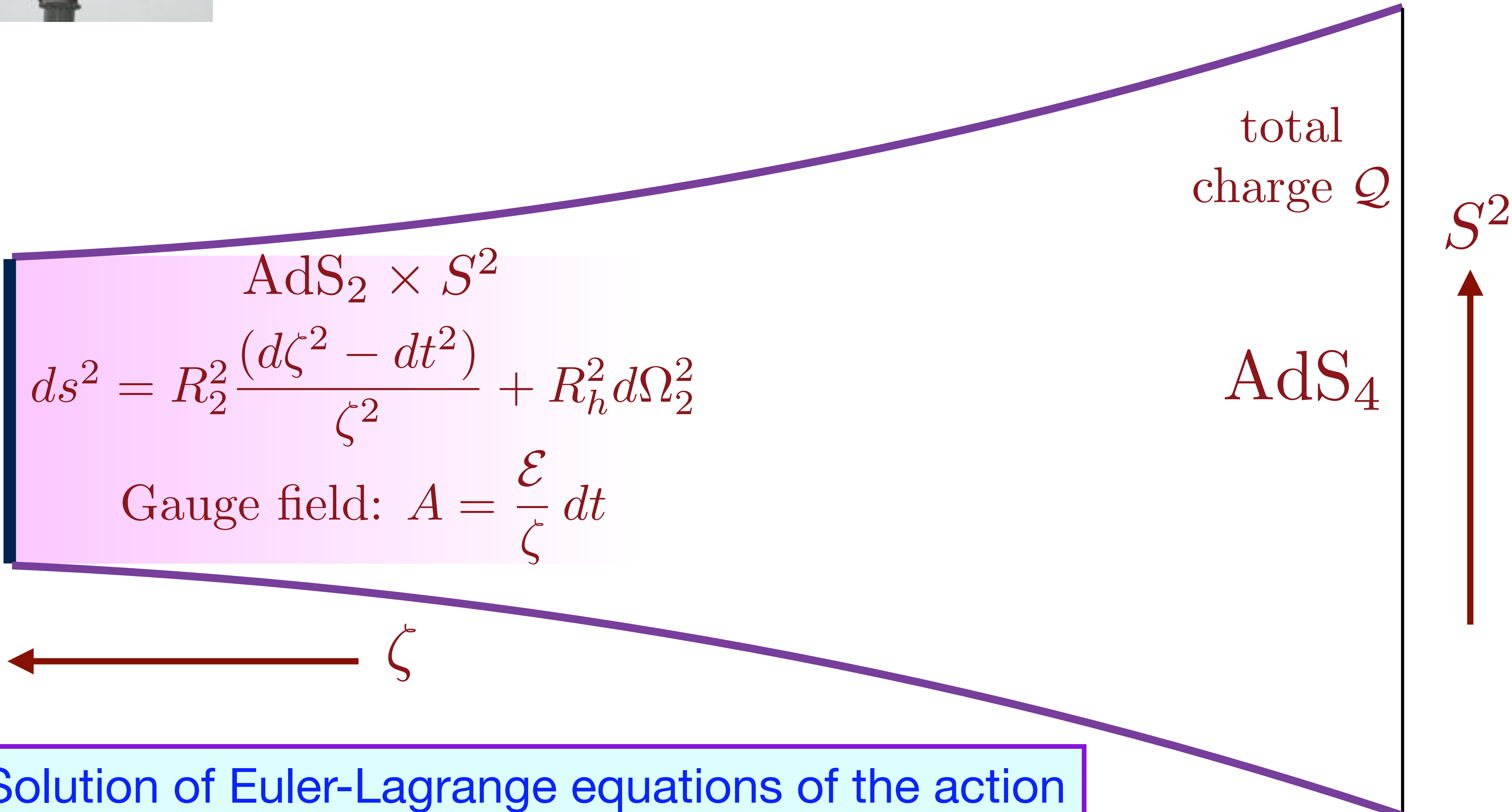
Zooming into the near-horizon region of a charged black hole at low temperature, yields a gravitational theory in one space (ζ) and one time dimension

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



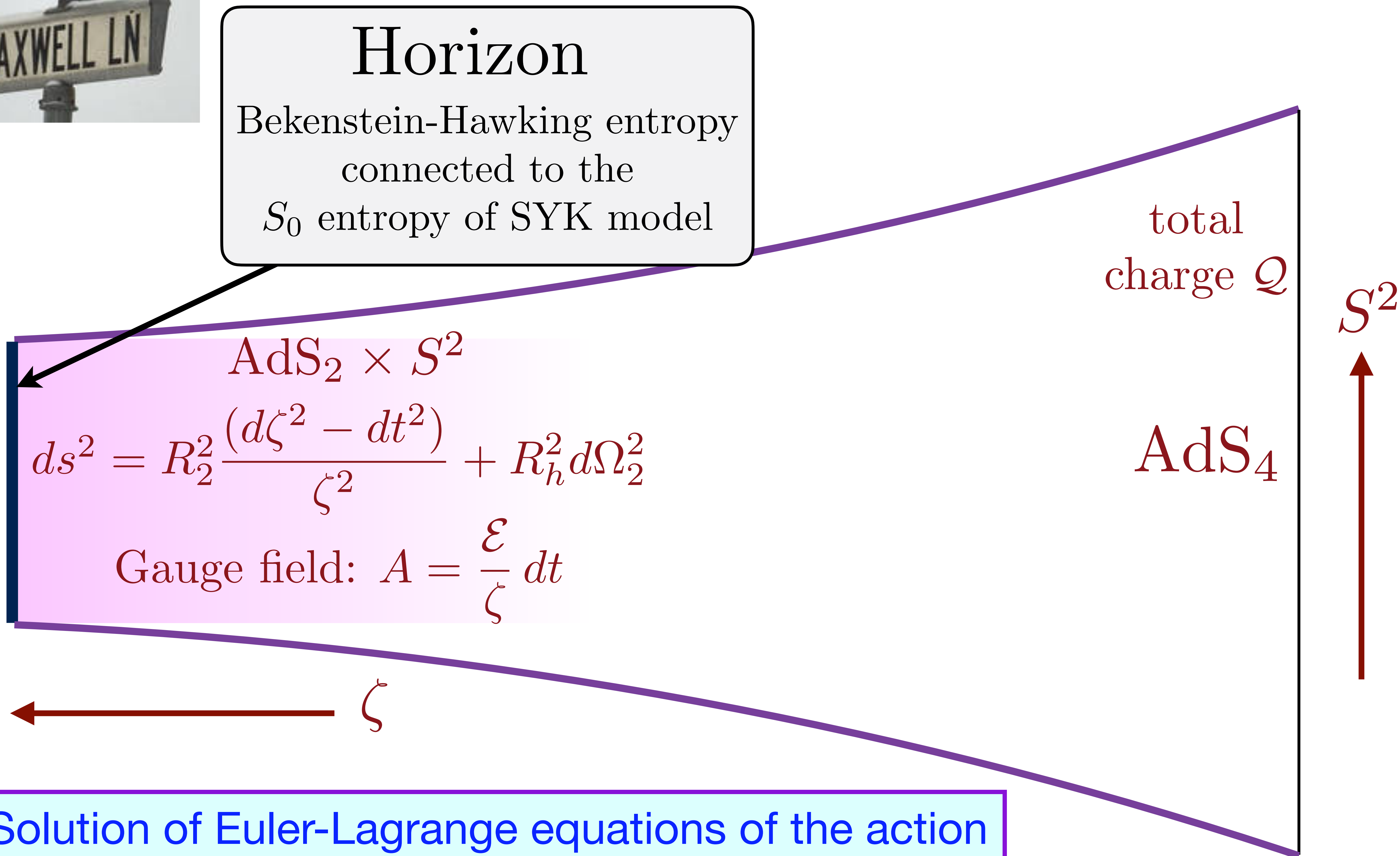
This 2D-gravity theory is precisely that appearing in the low T limit of the Sachdev-Ye-Kitaev (SYK) models

SYK model and charged black holes



Solution of Euler-Lagrange equations of the action of Einstein gravity and Maxwell electromagnetism

SYK model and charged black holes



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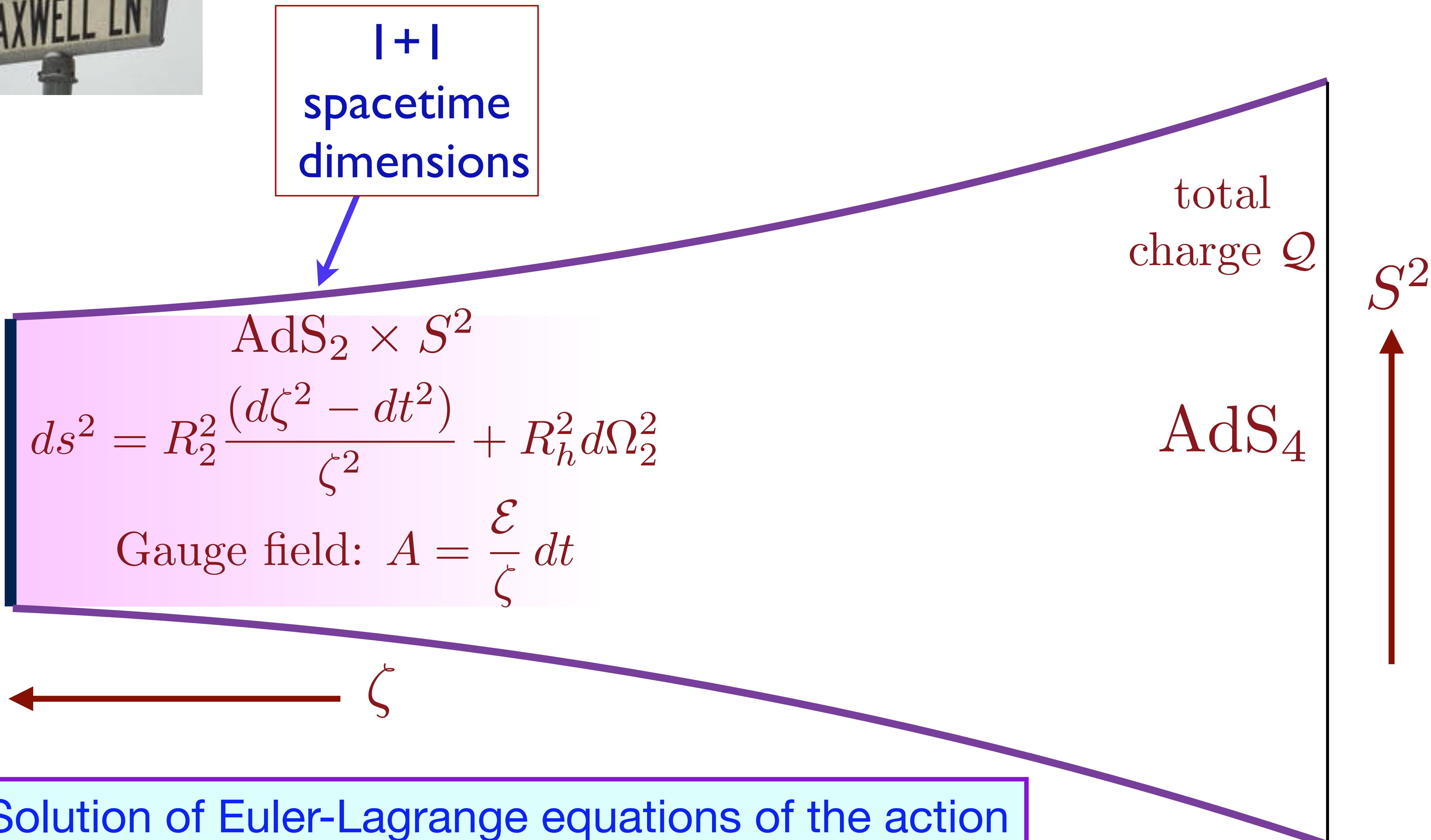

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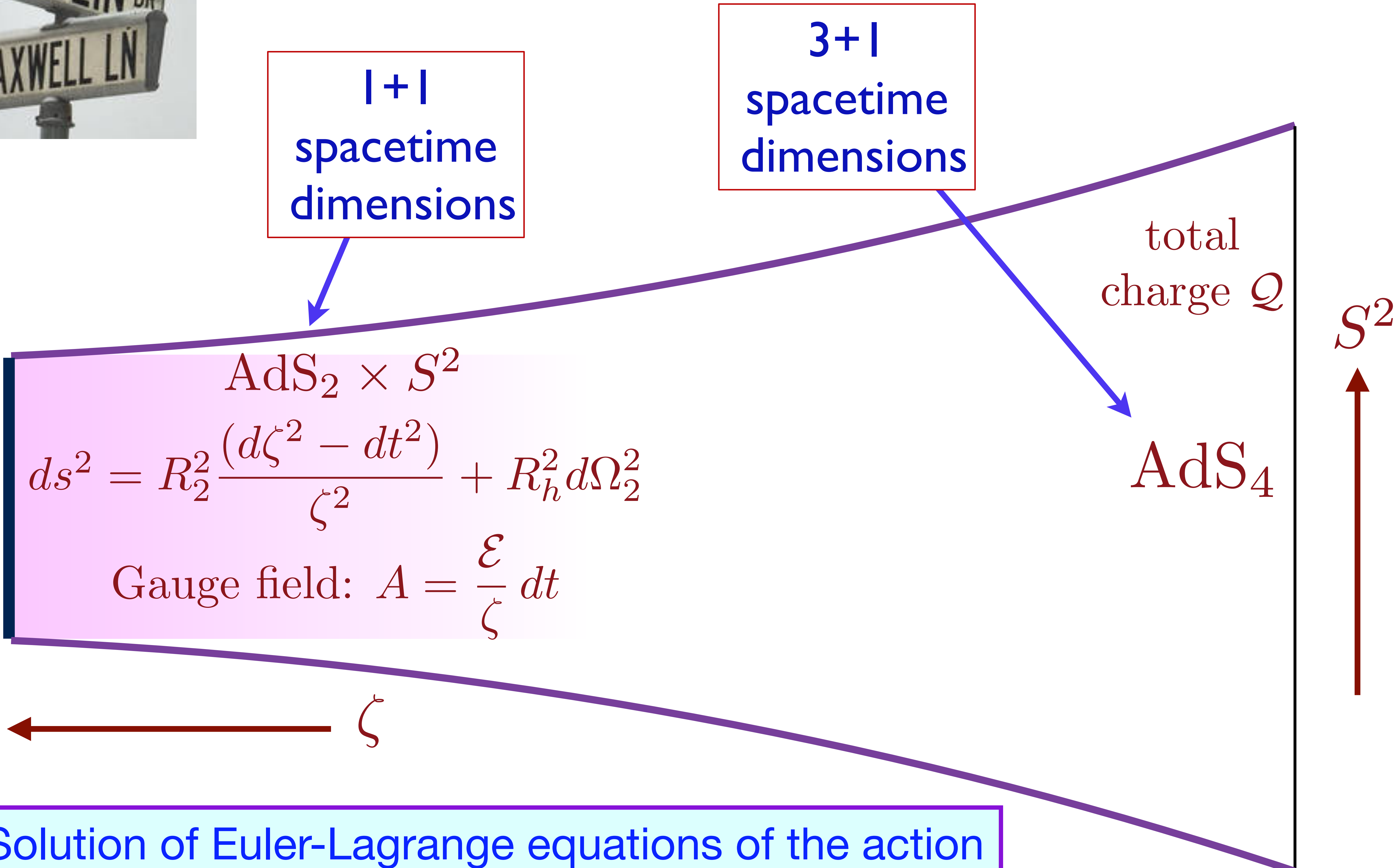

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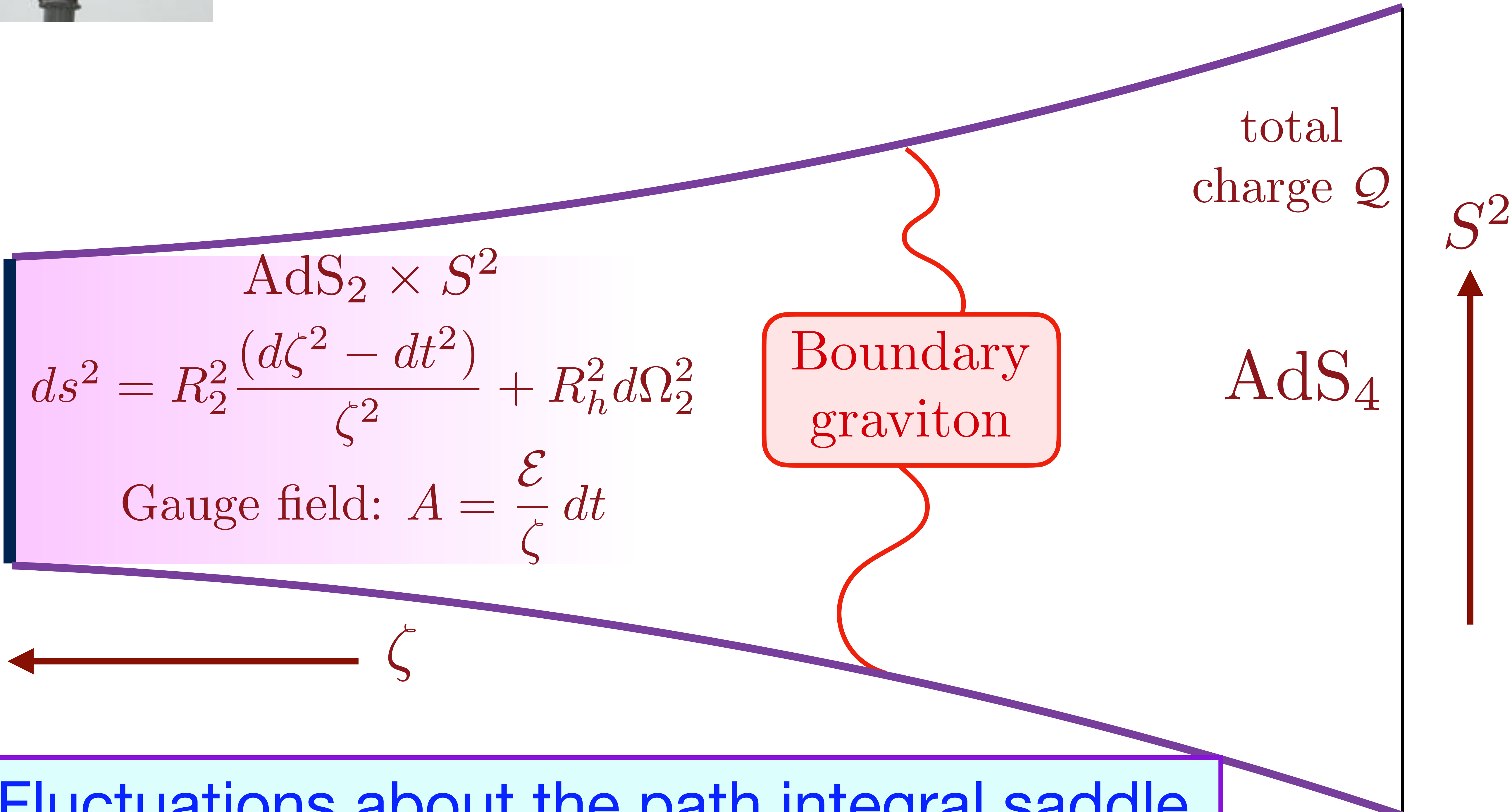


Fluctuations about the path integral saddle of quantum gravity AND SYK model

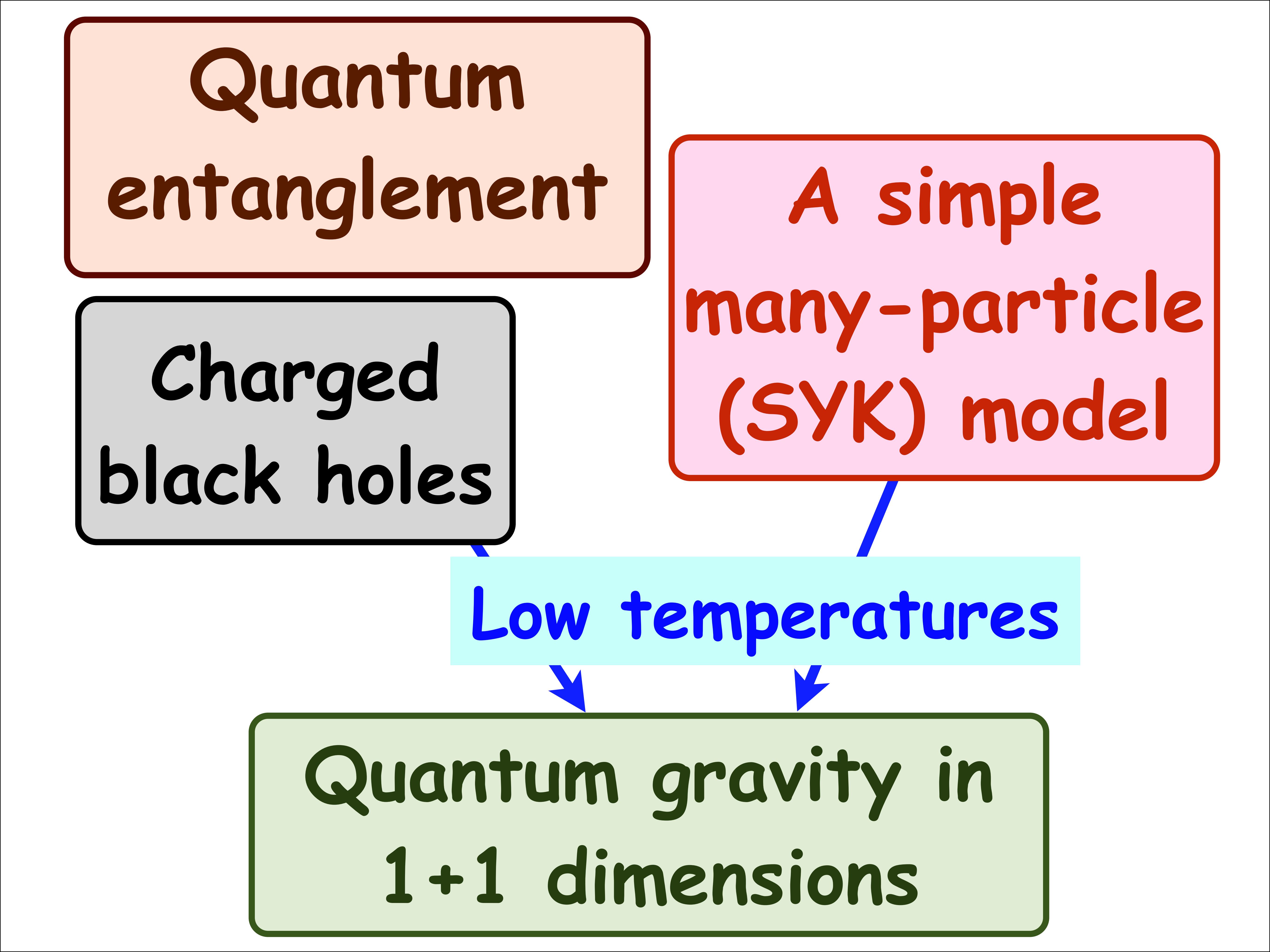
Quantum entanglement

A simple many-particle (SYK) model

Charged black holes

Low temperatures

Quantum gravity in 1+1 dimensions


Quantum entanglement
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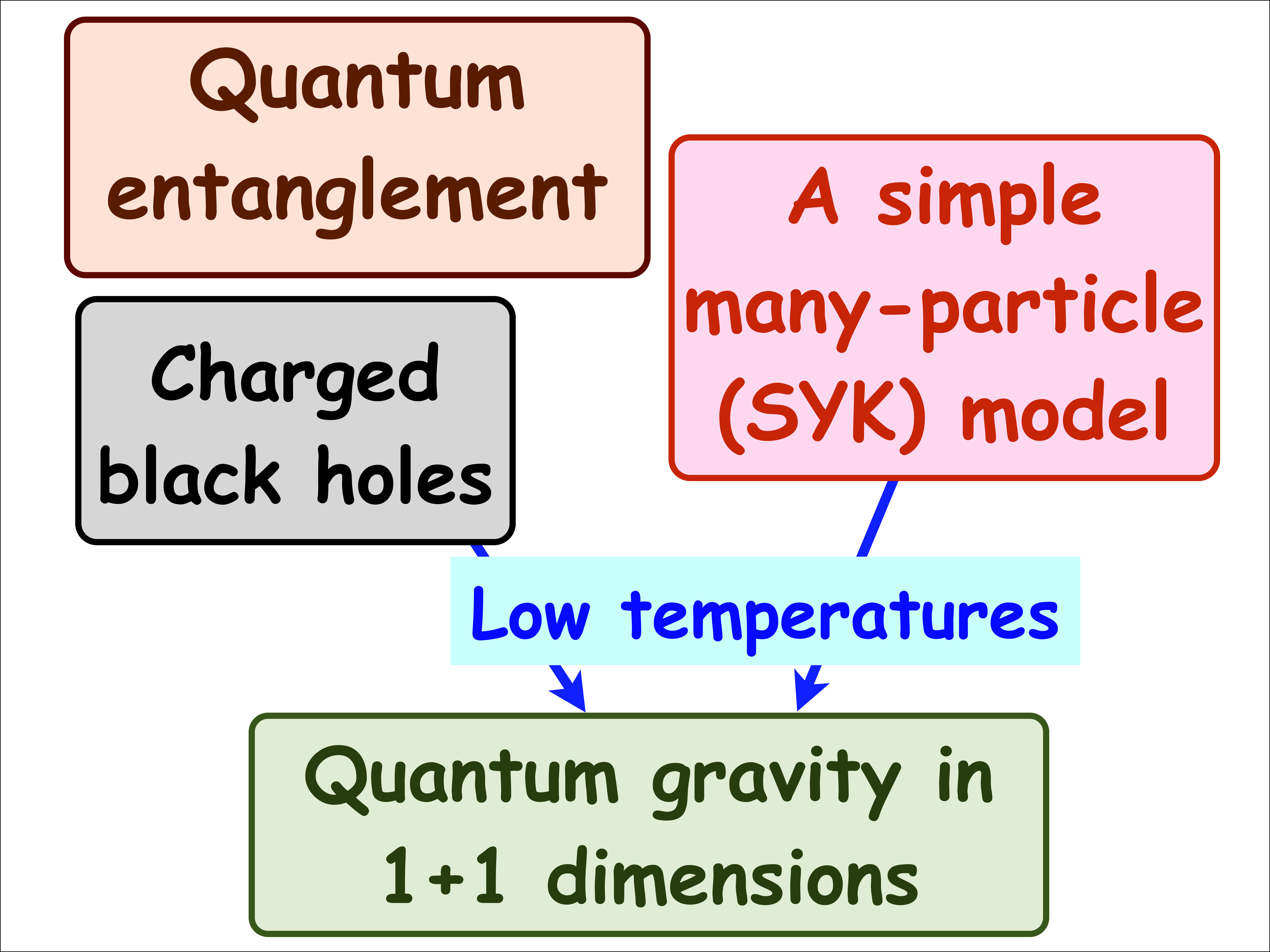
Complex multi-particle entanglement leads to quantum systems without quasiparticle excitations.

Many-body chaos and thermal equilibration in the shortest possible

$$\text{Planckian time} \sim \frac{\hbar}{k_B T}.$$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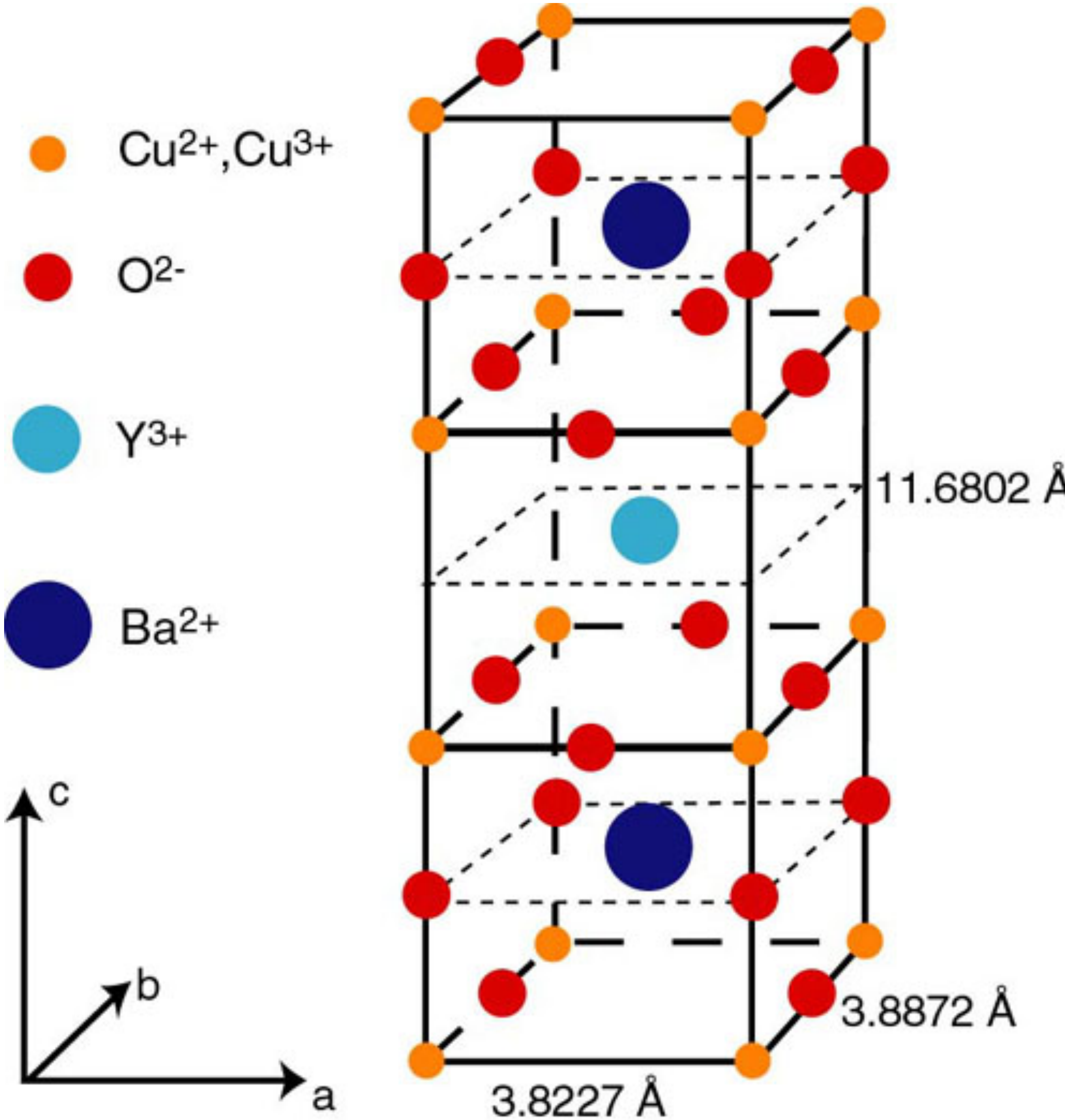
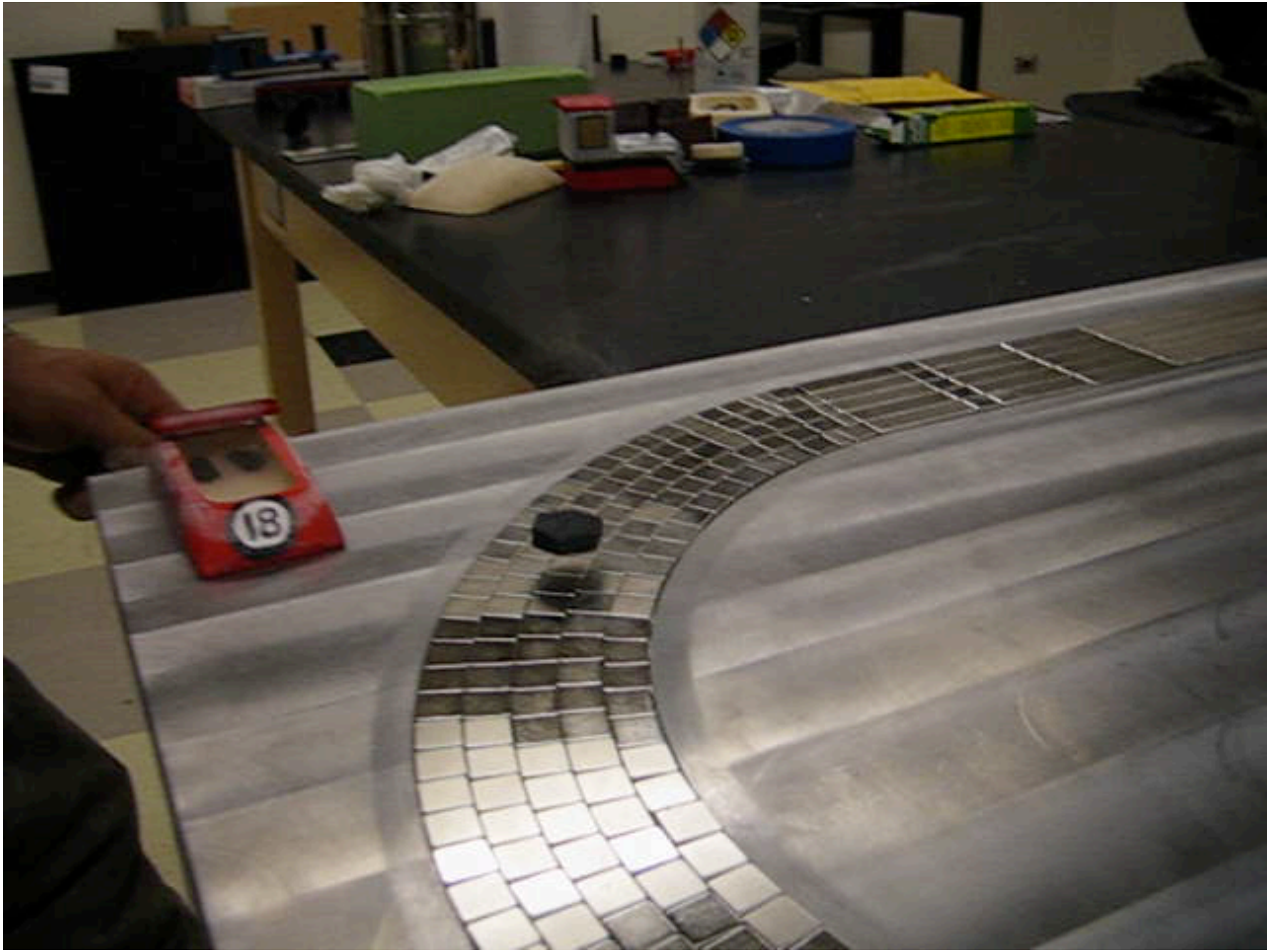
Copper-based superconductors

High temperature superconductors



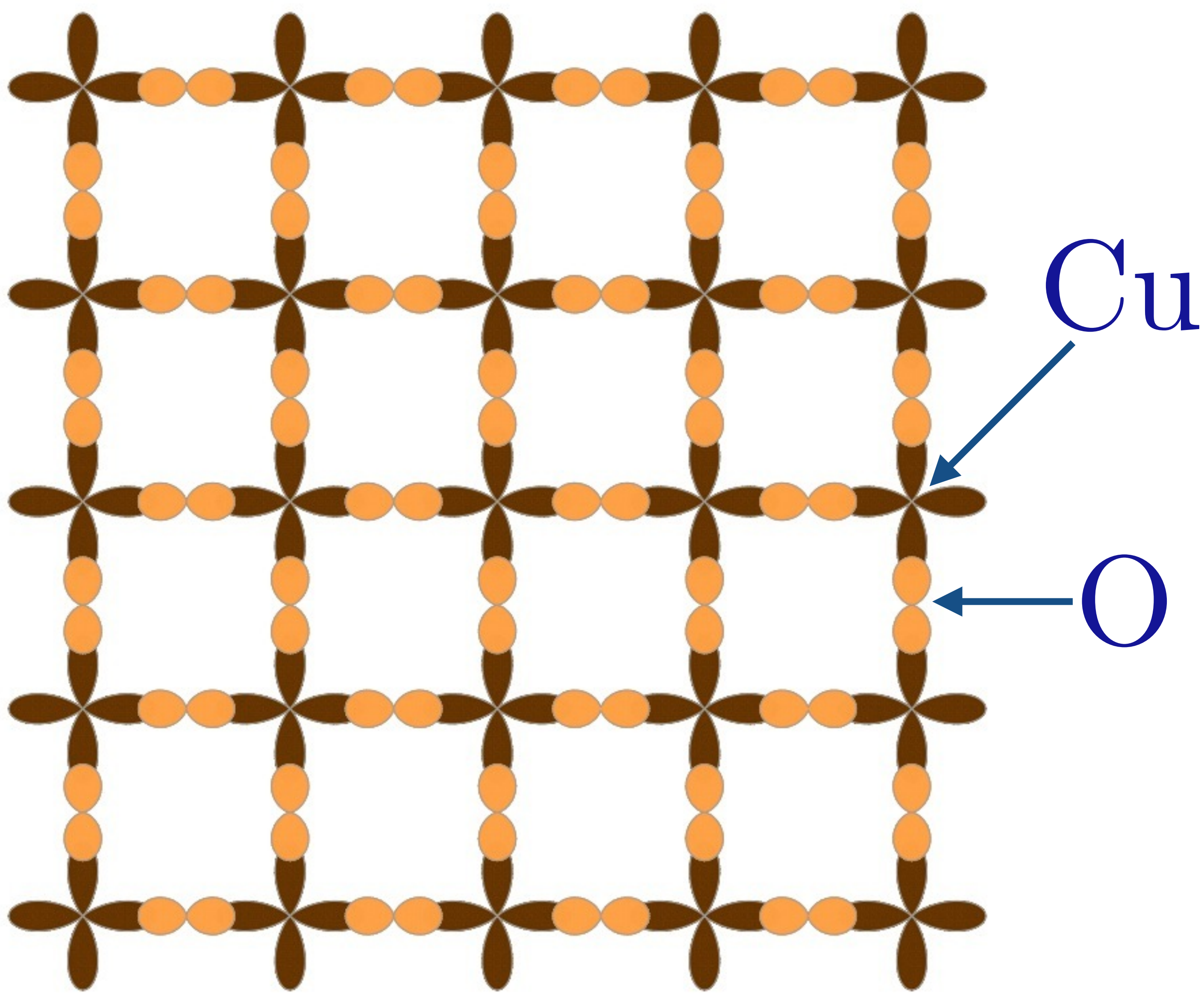
$YBa_2Cu_3O_{6+x}$



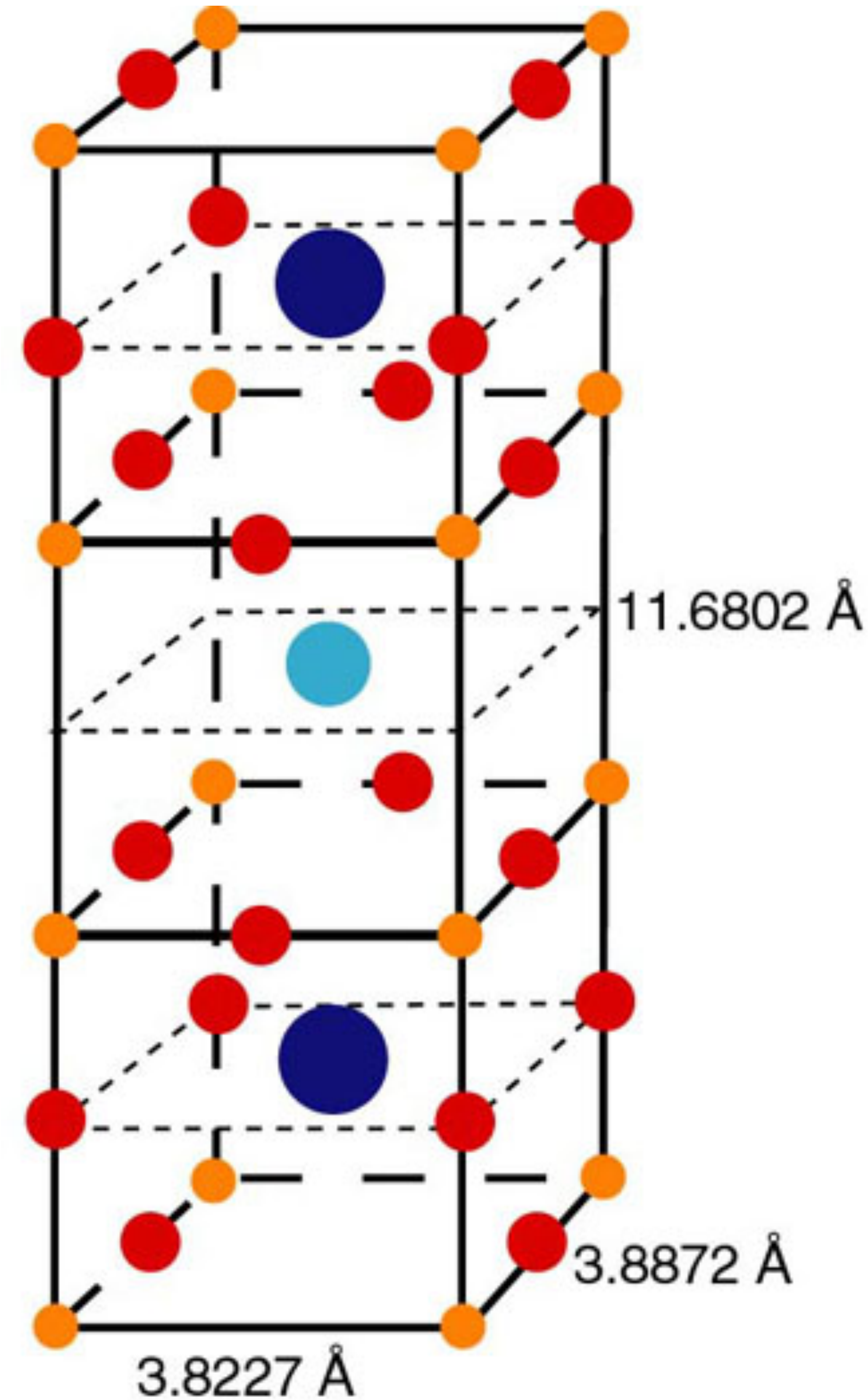
Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

High temperature superconductors



CuO_2 plane



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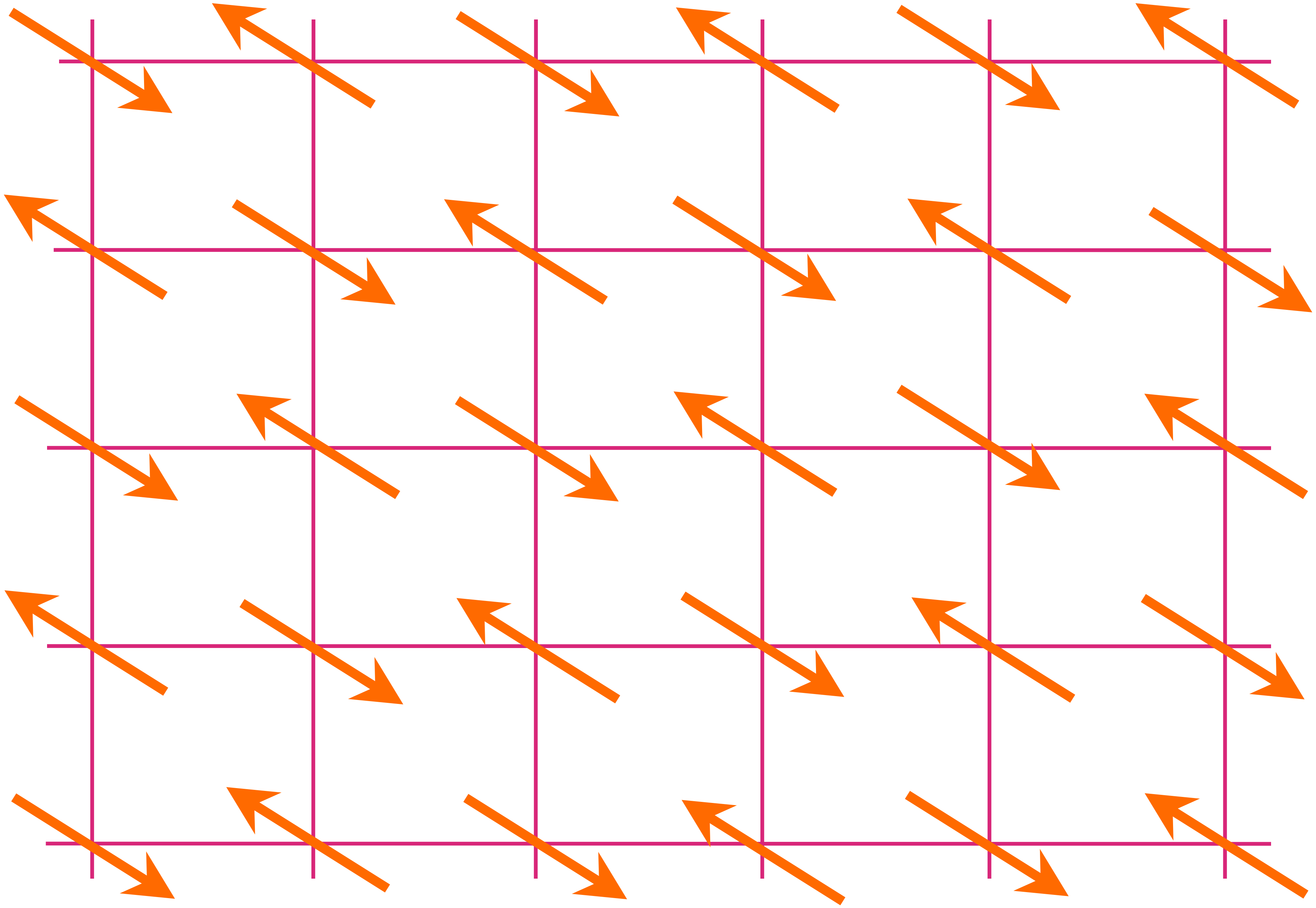
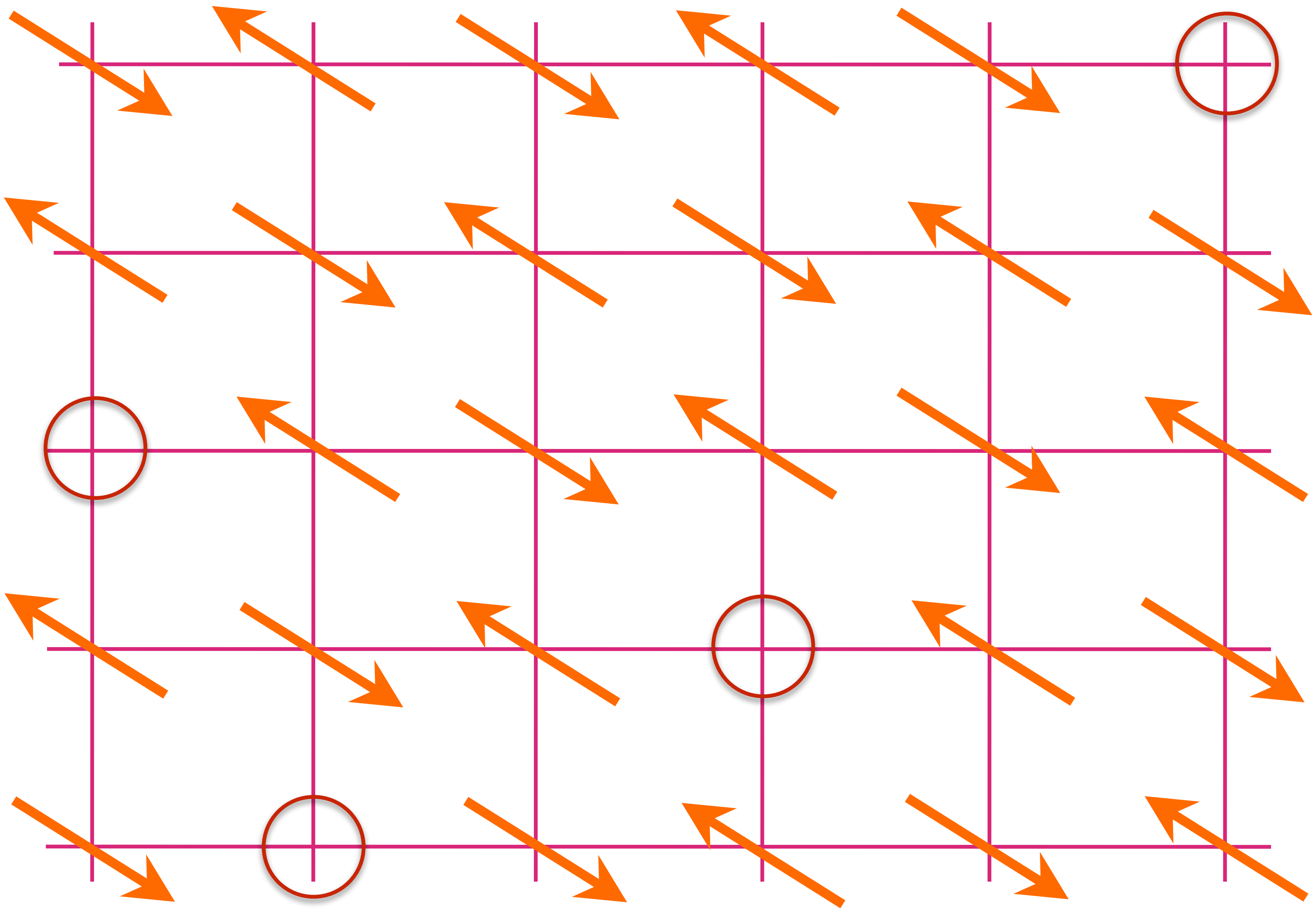
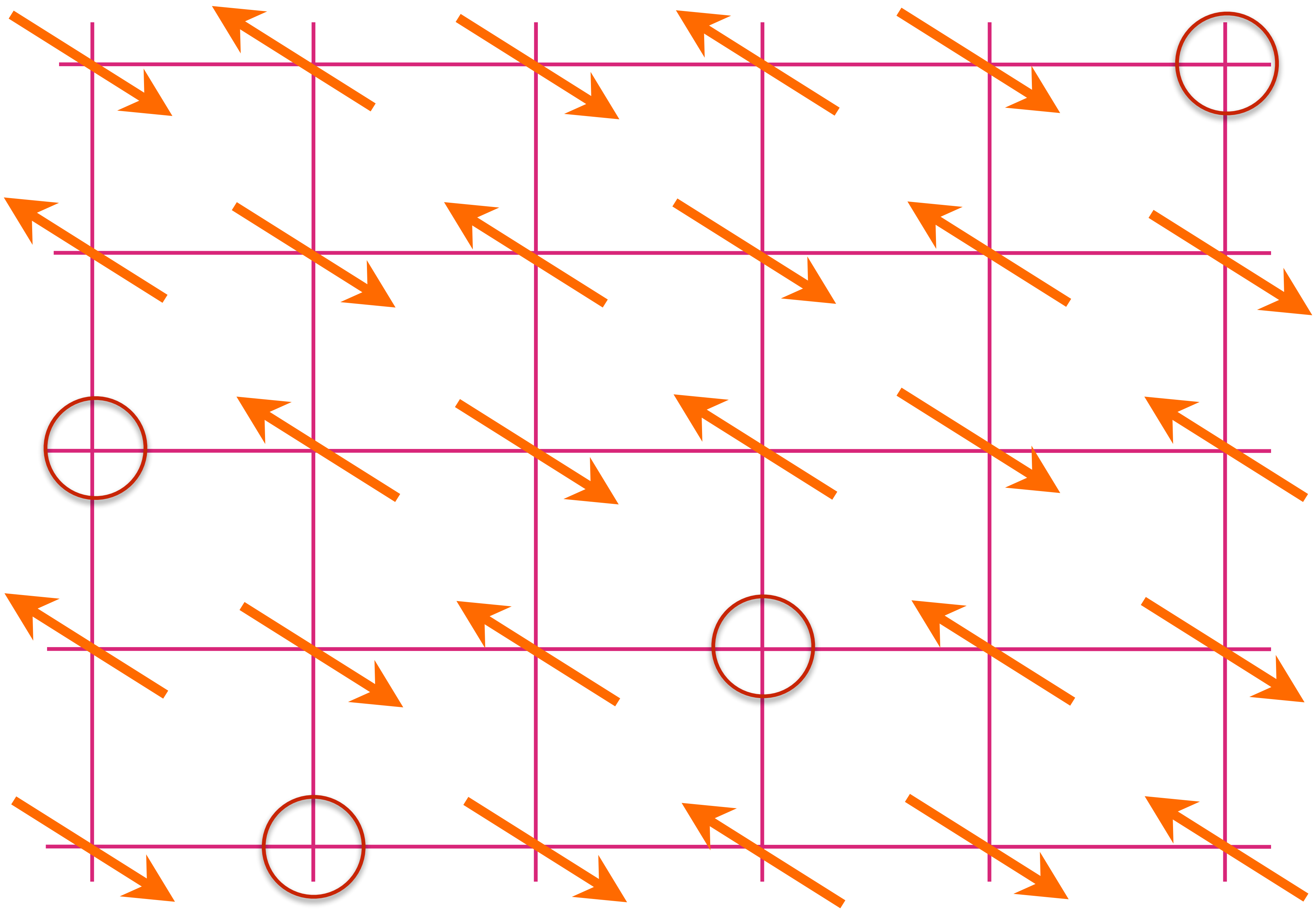
Insulating antiferromagnet



Antiferromagnet doped with hole density p



Real-space view



p mobile holes in a background of fluctuating spins

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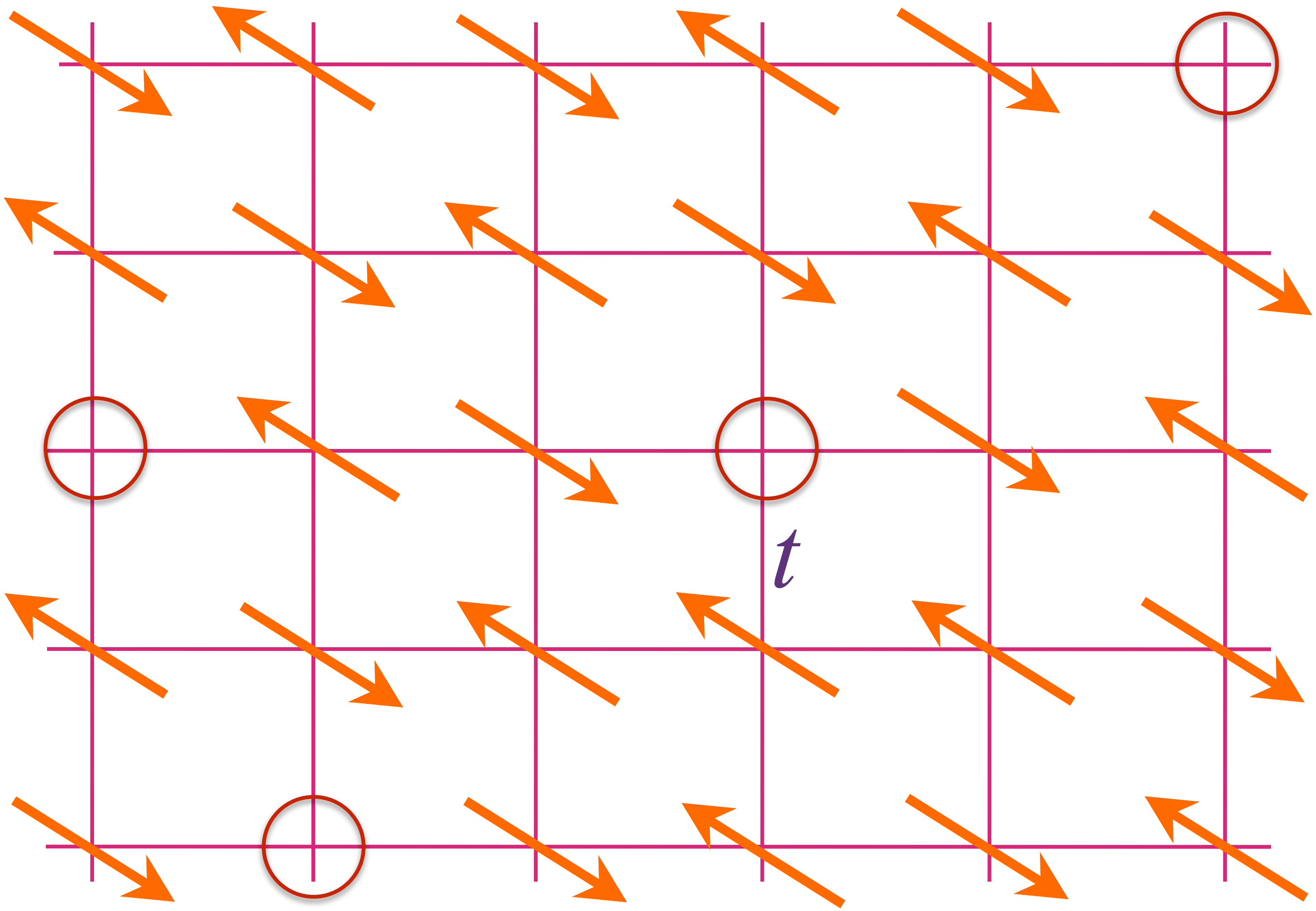

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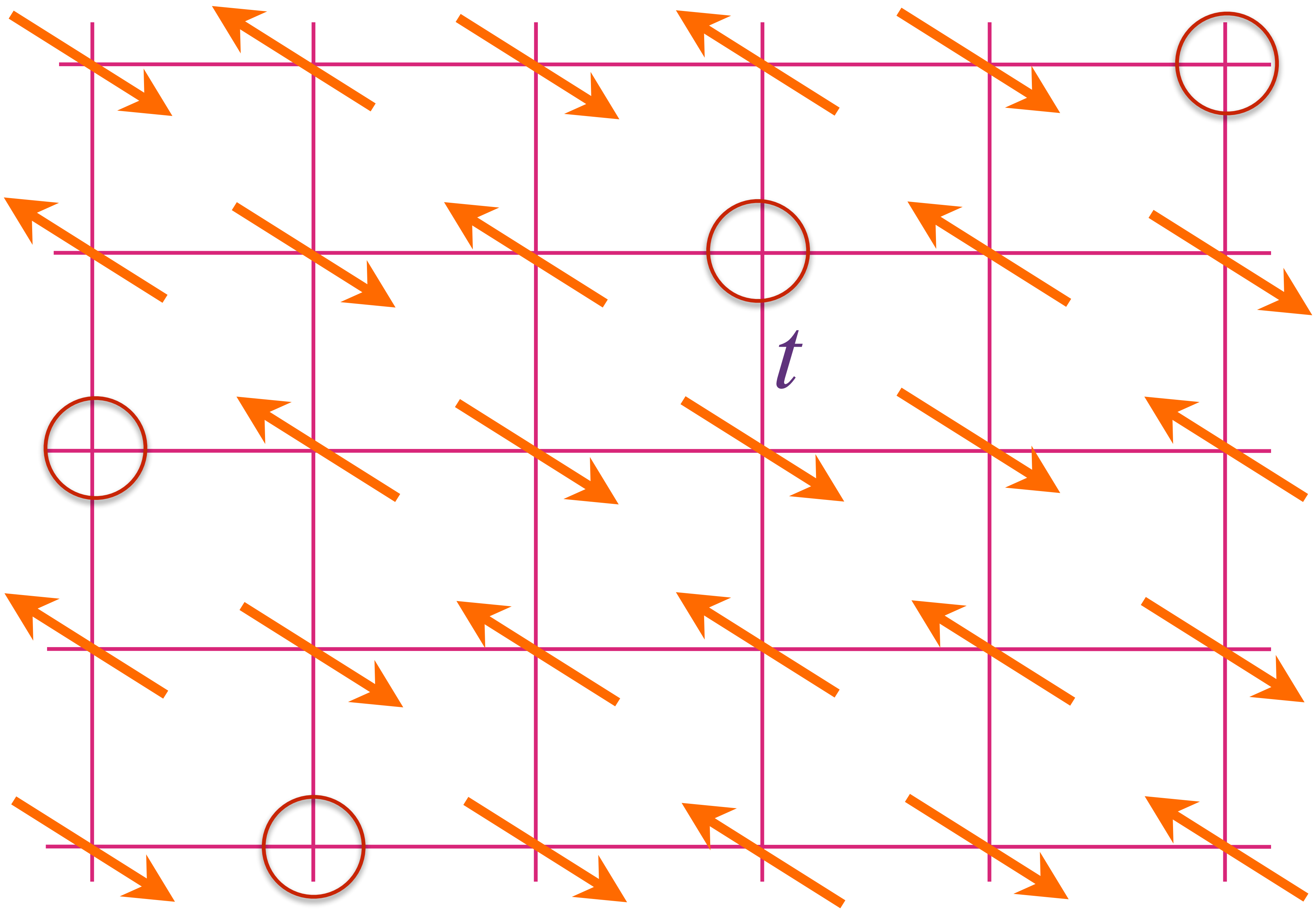

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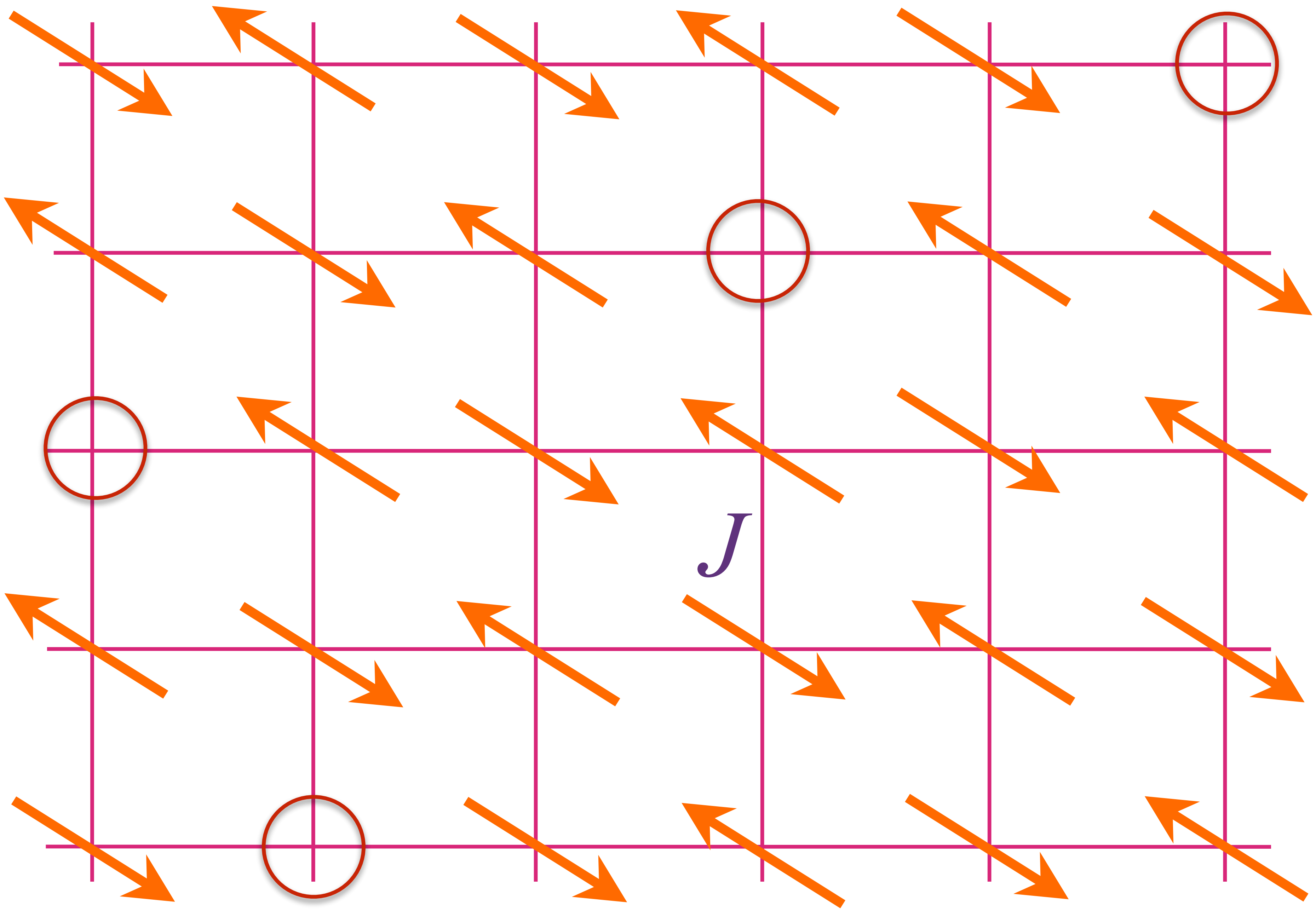

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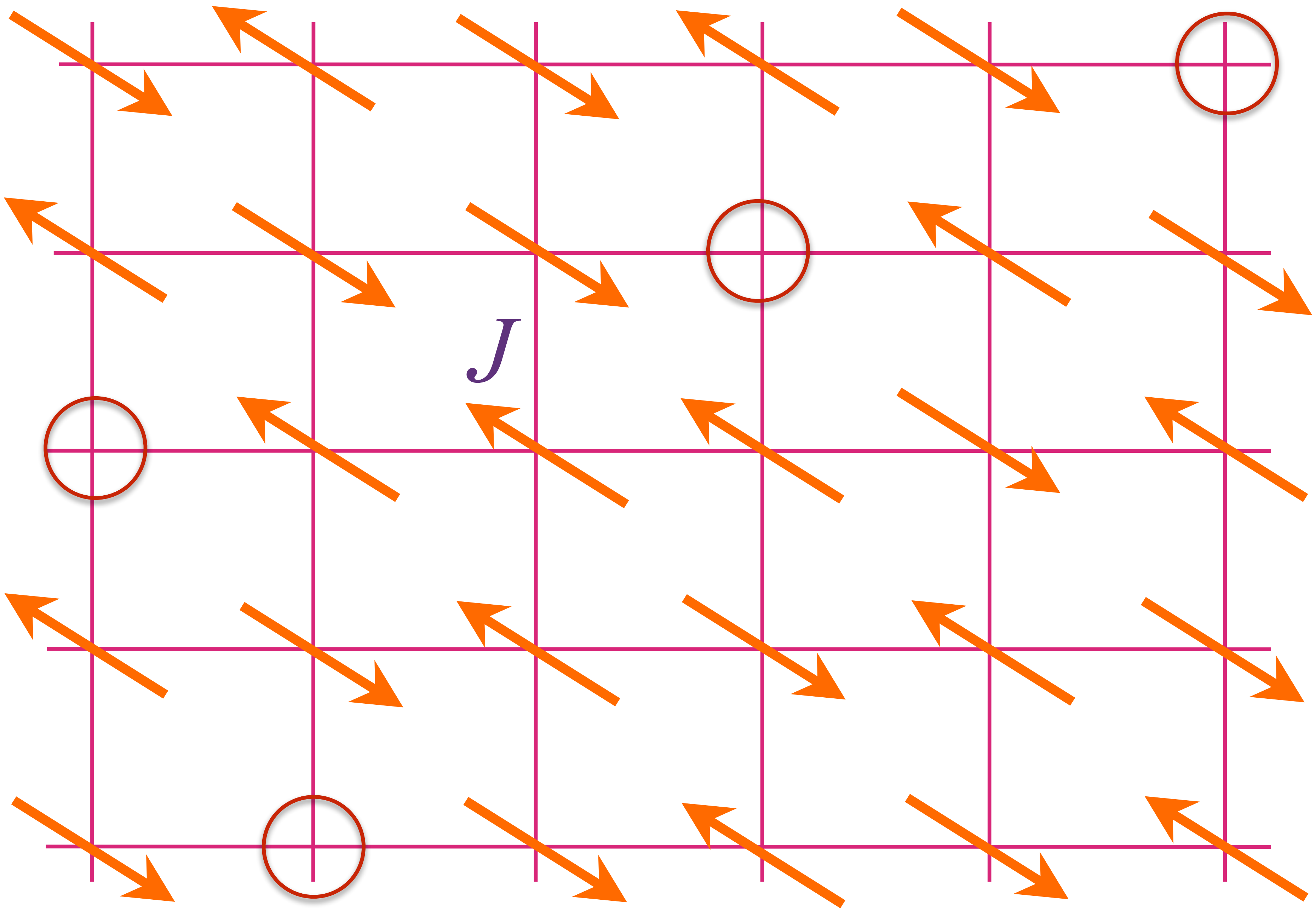

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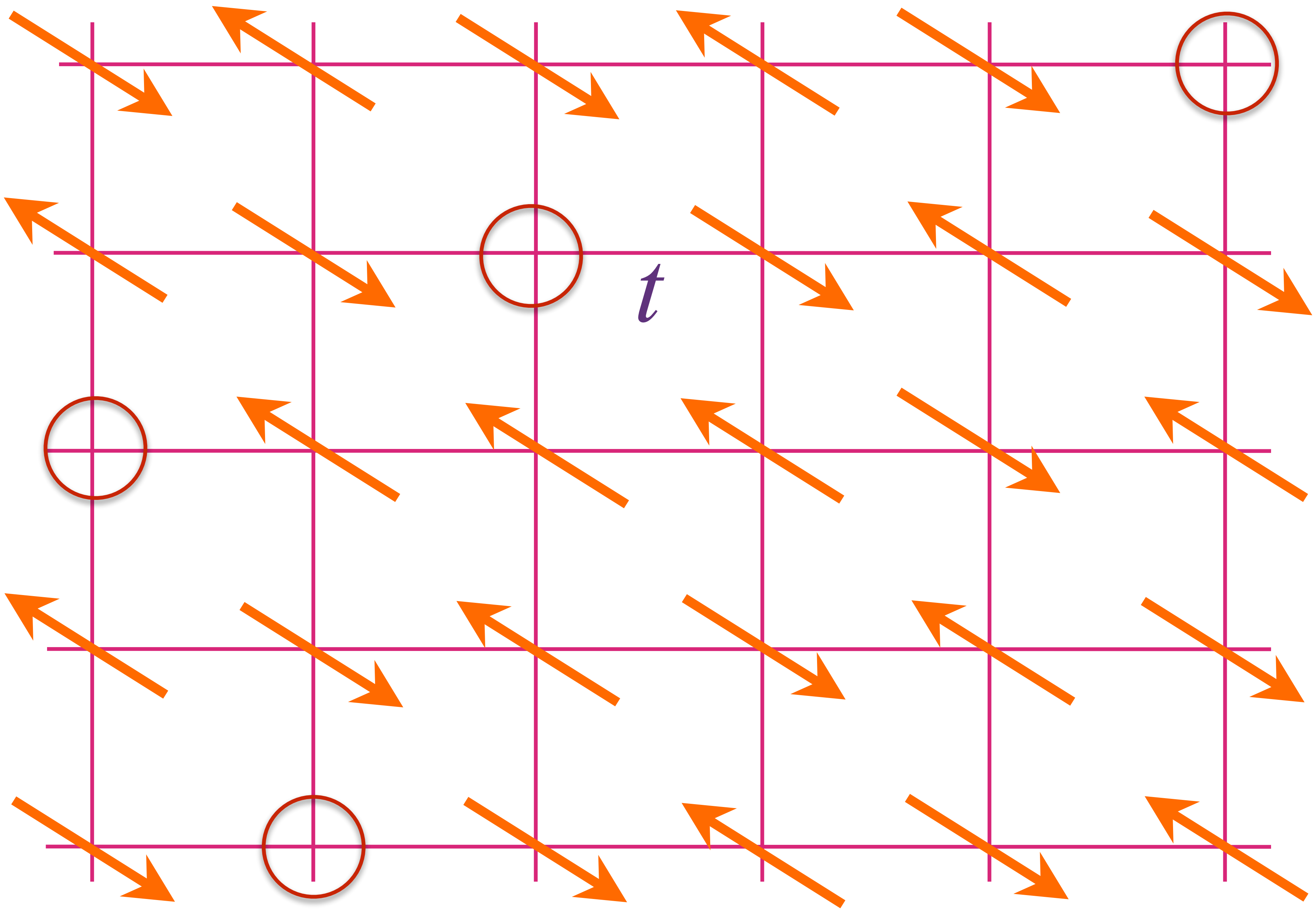

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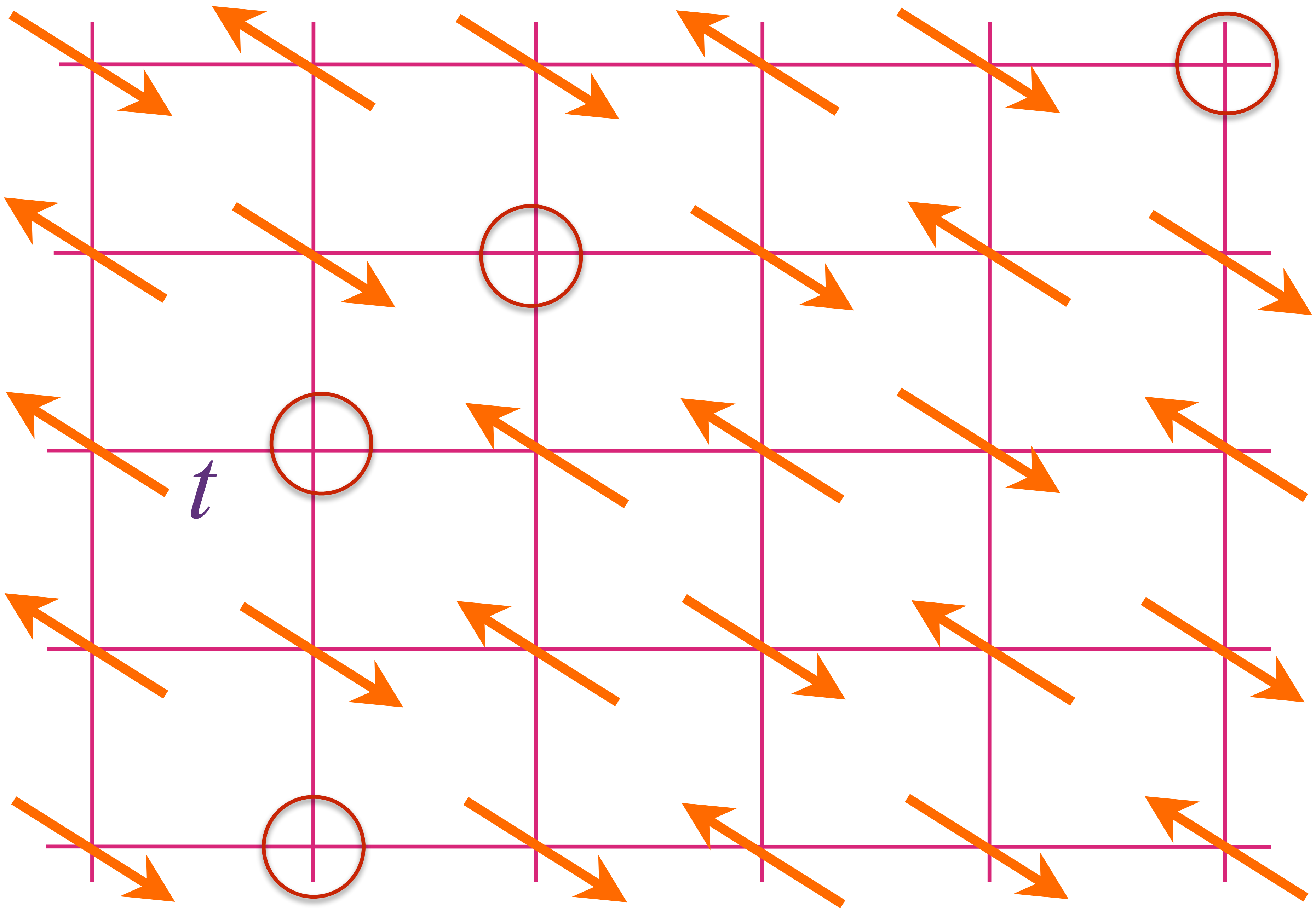

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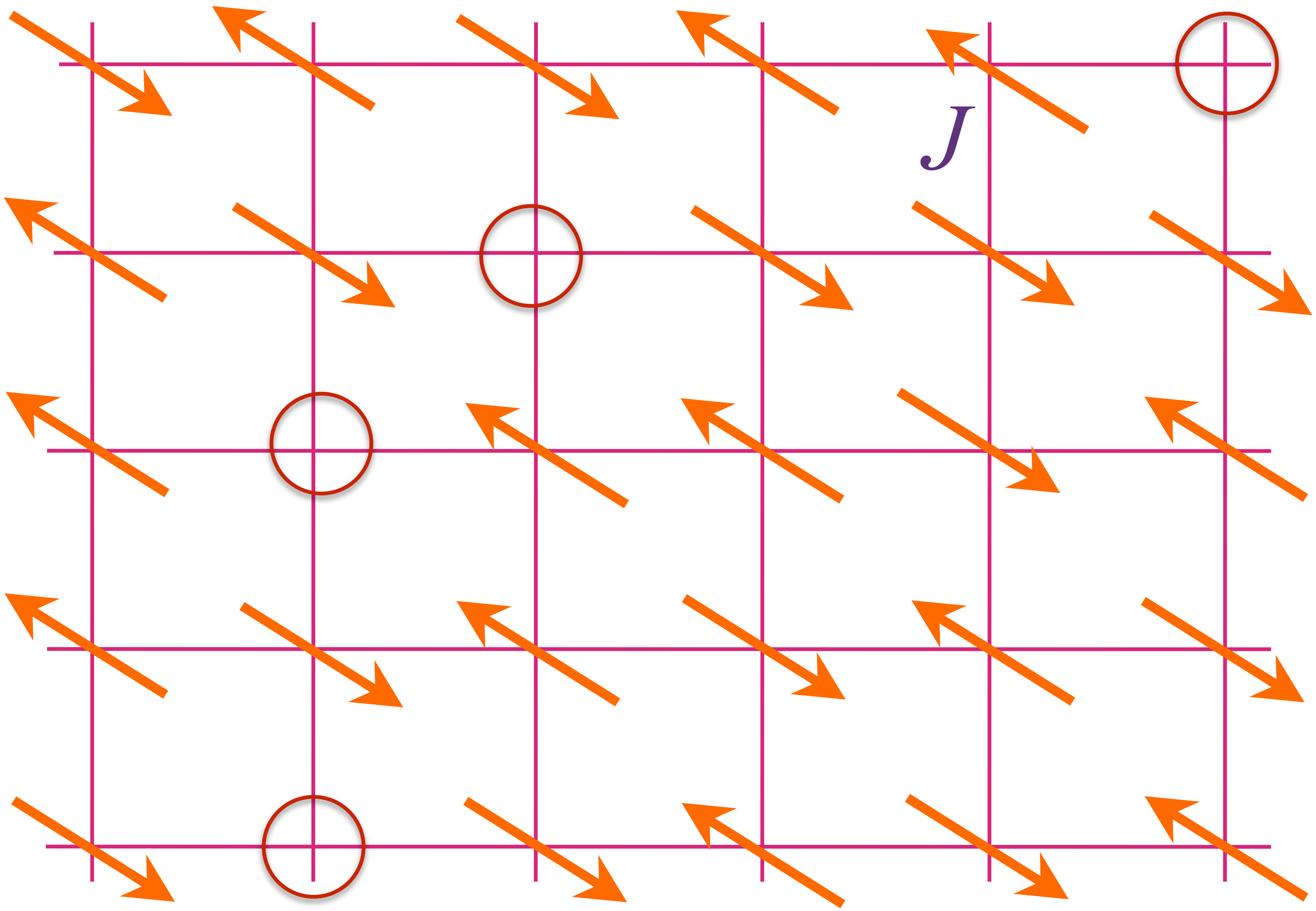

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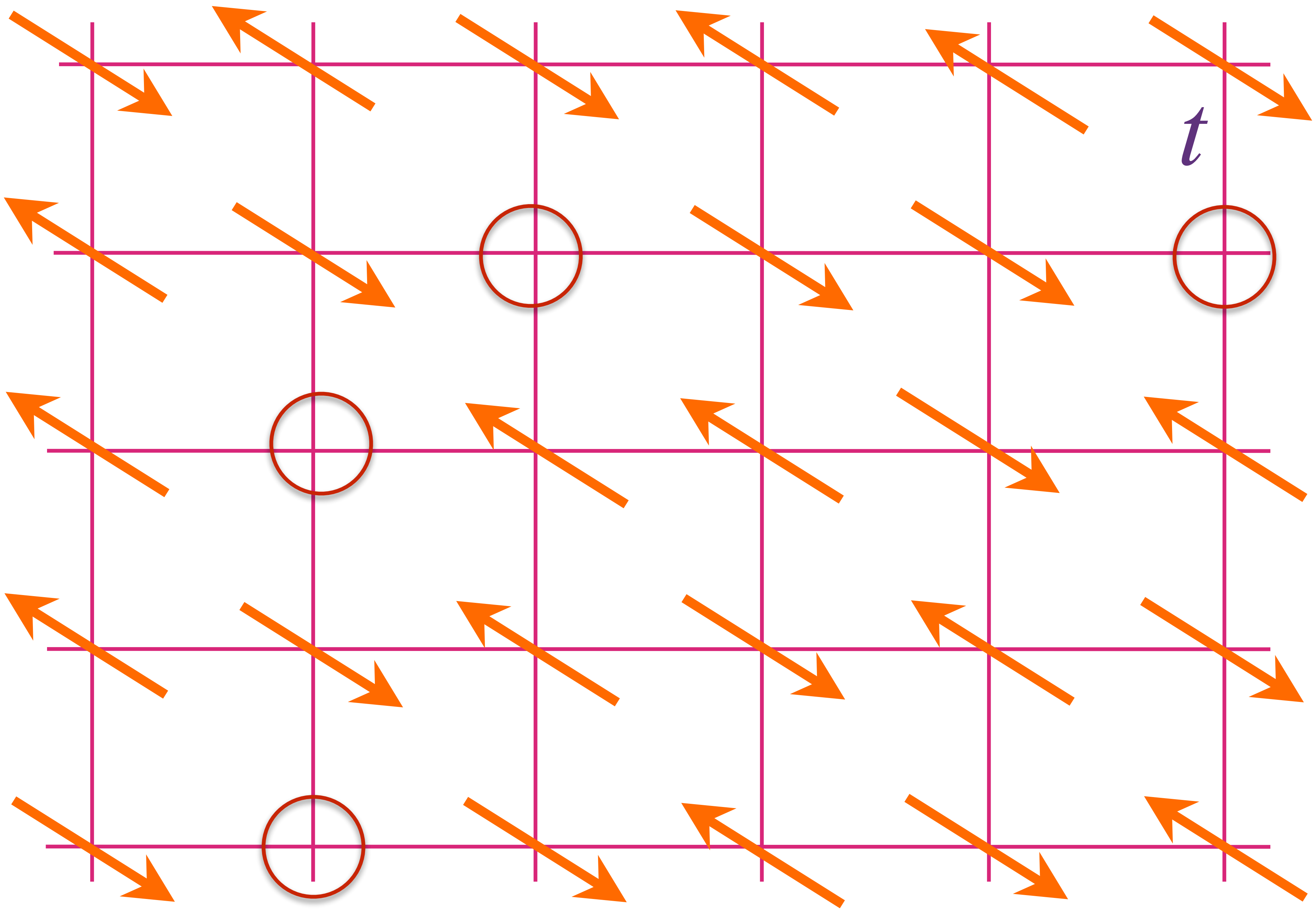

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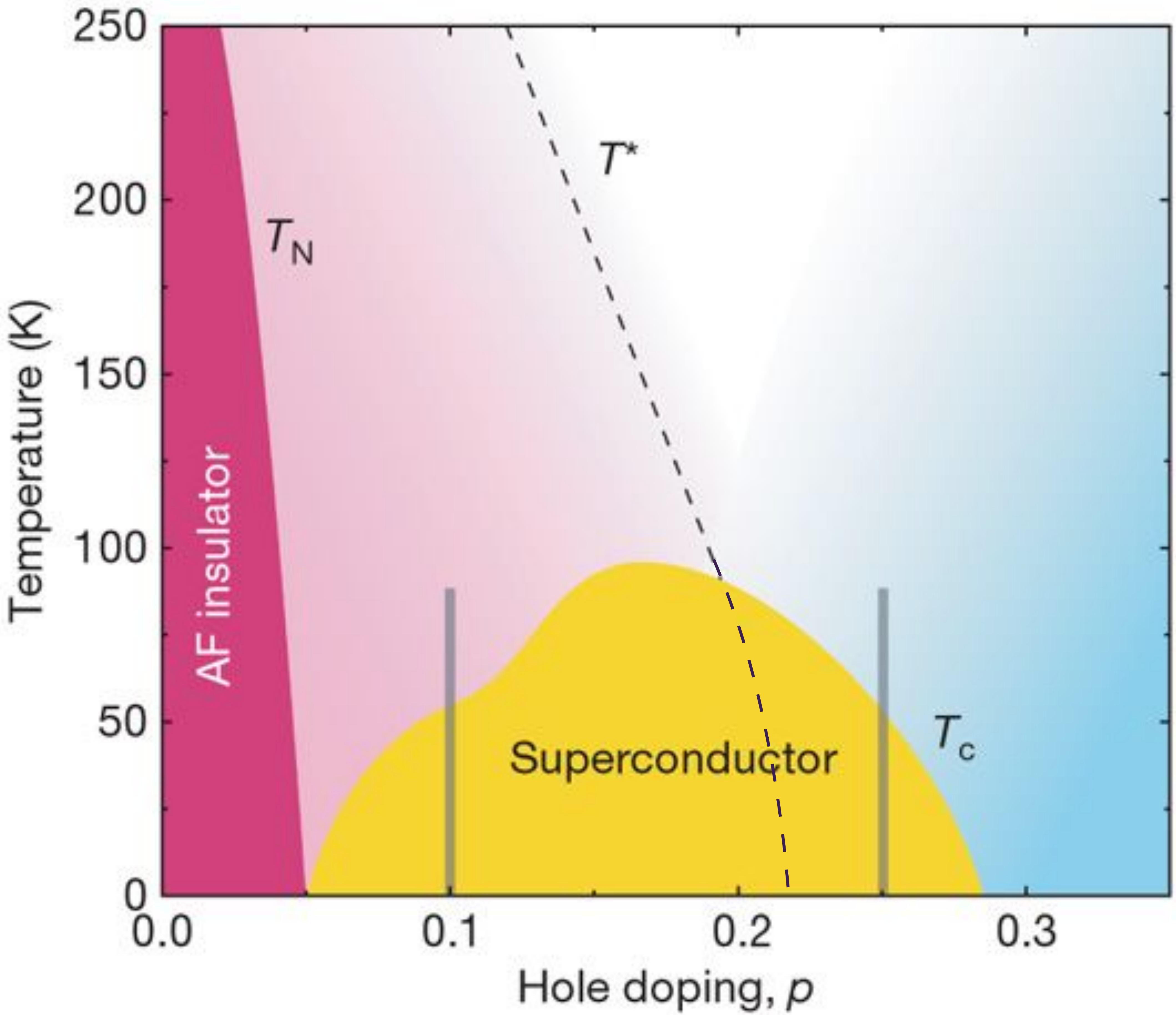
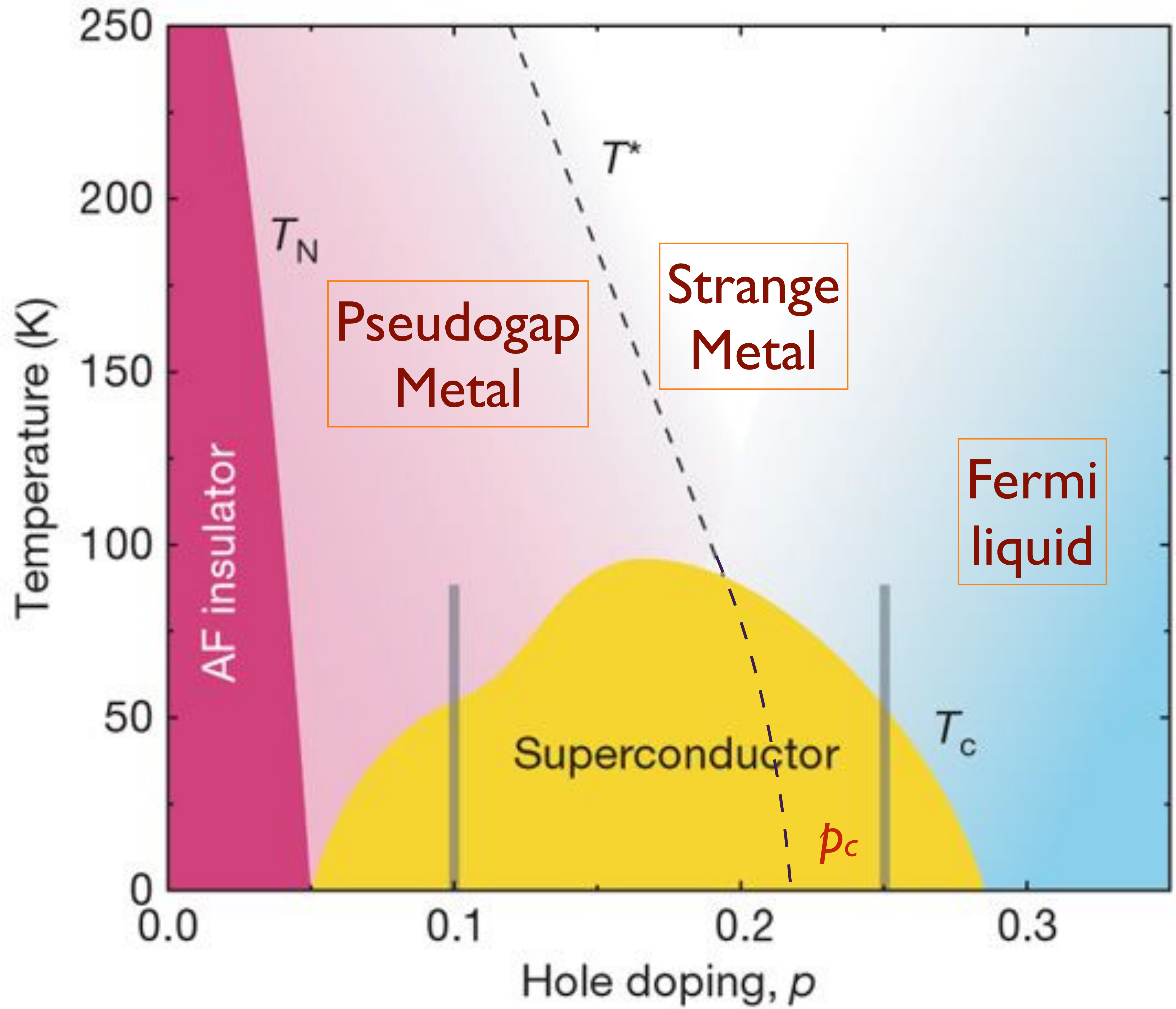


250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T*
Superconductor
T_c



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Strange Metal
Fermi liquid
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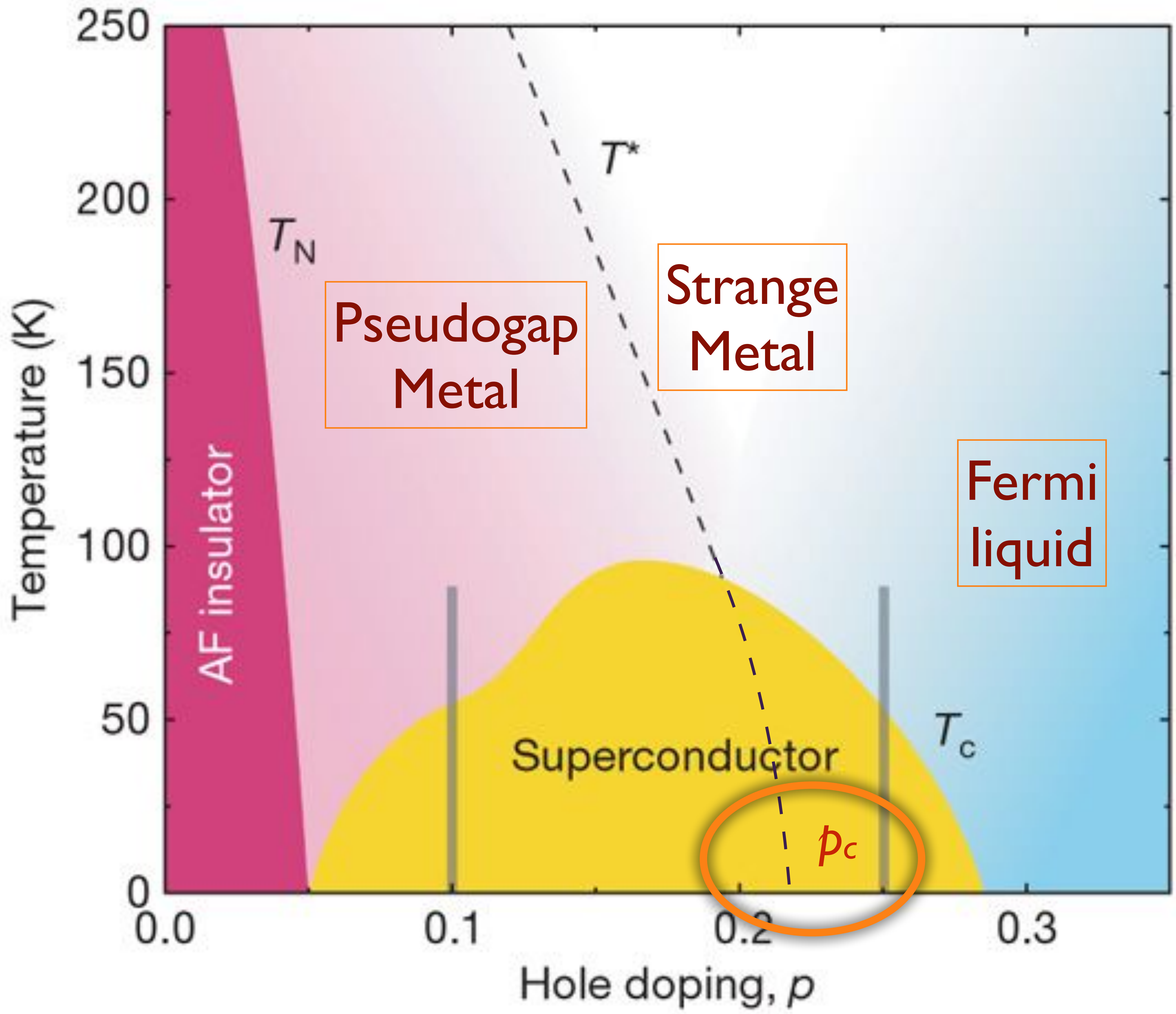
p_c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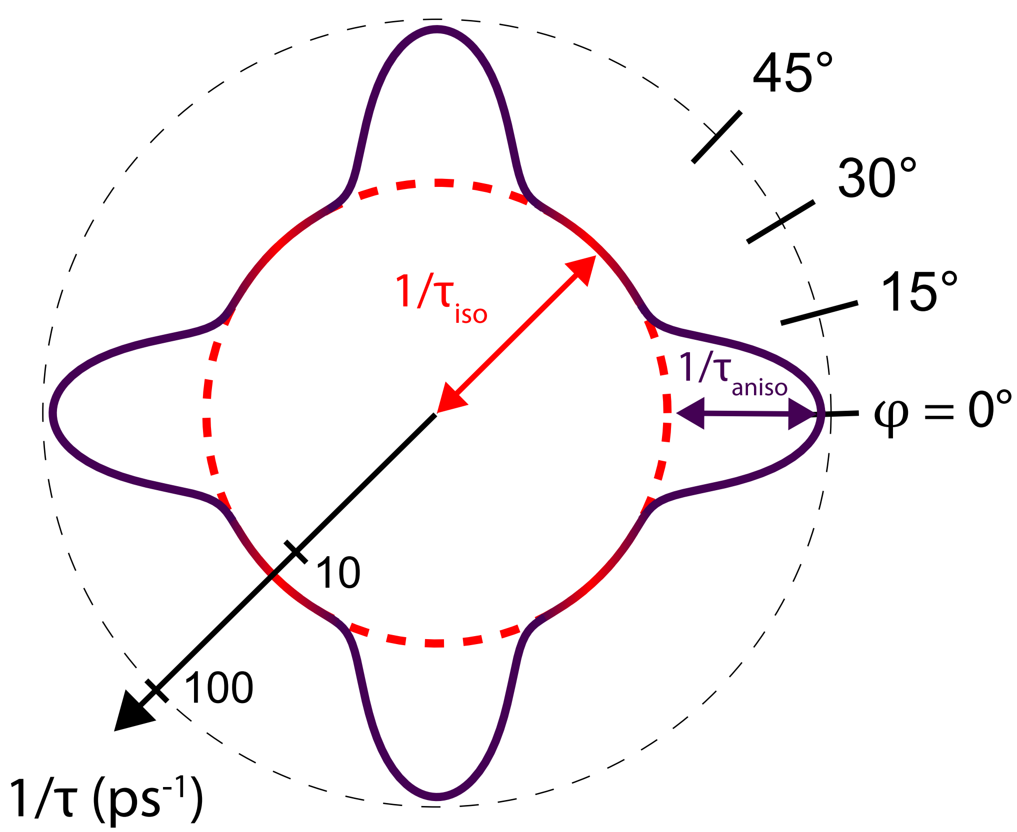
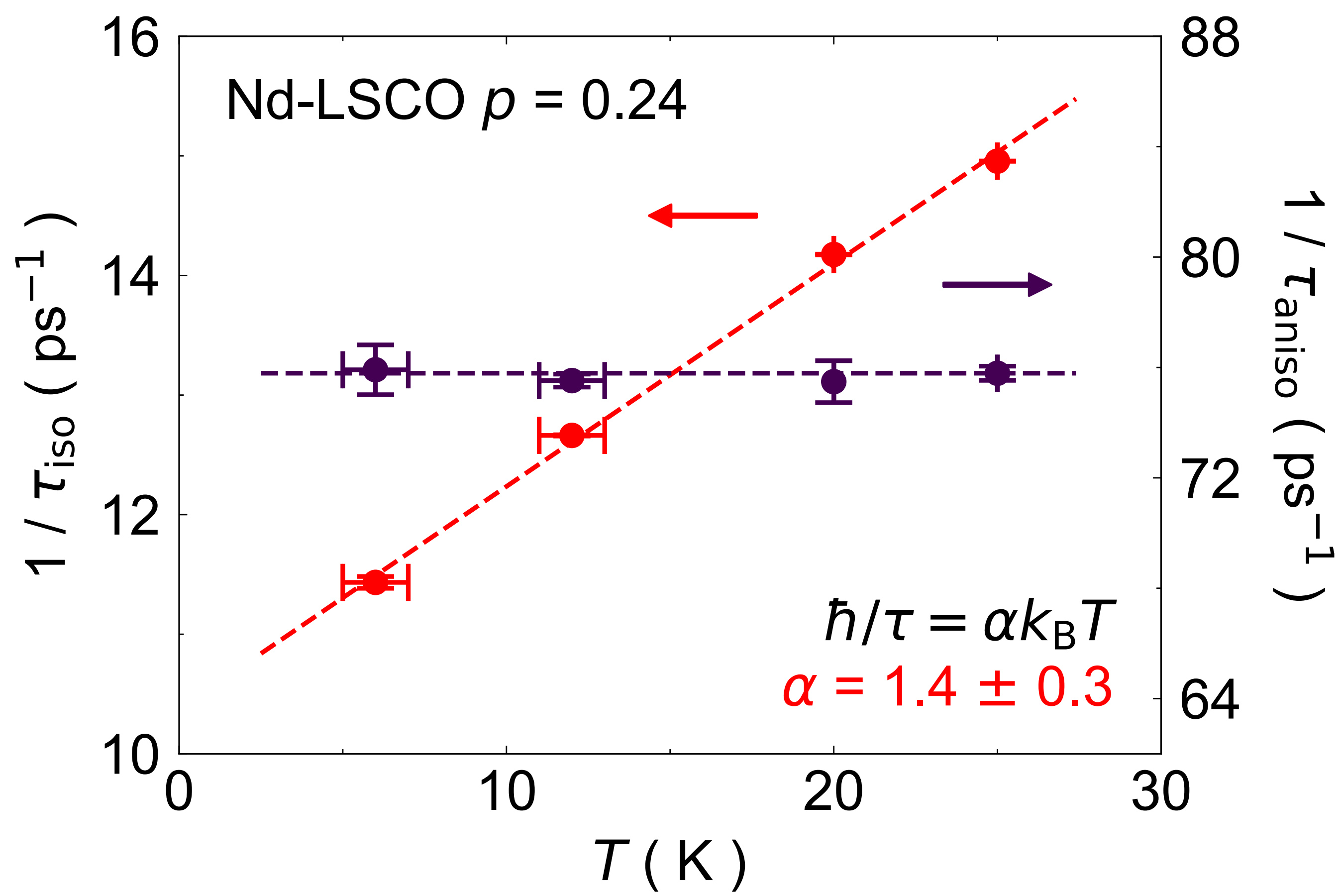
Measurement of the Planckian Scattering Rate

G. Grissonnanche, Y. Fang, A. Legros, S. Verret, F. Laliberté, C. Collignon, J. Zhou, D. Graf, P. Goddard, L. Taillefer, B. J. Ramshaw, arXiv:2011.13054

Angle-dependent magnetoresistance in Nd-LSCO near $p = p_c \approx 0.23$.





$$\frac{1}{\tau} = \frac{1}{\tau_{\text{aniso}}(\vec{k})} + \frac{\alpha}{\hbar} k_B T$$

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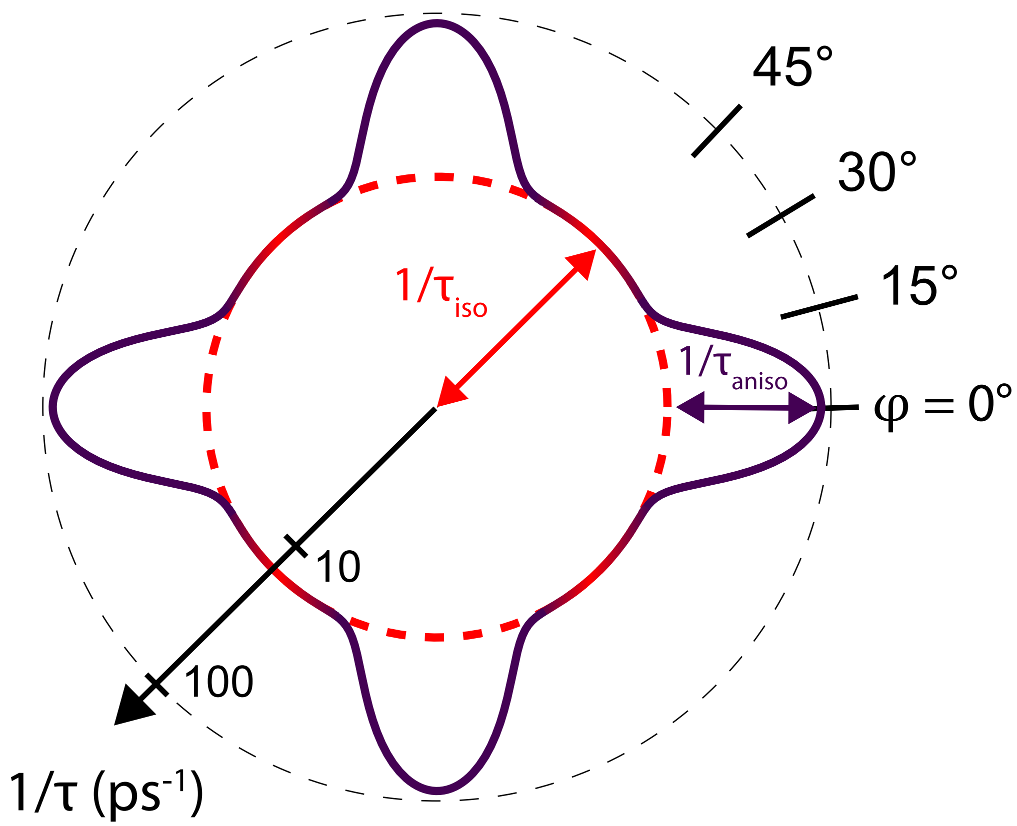

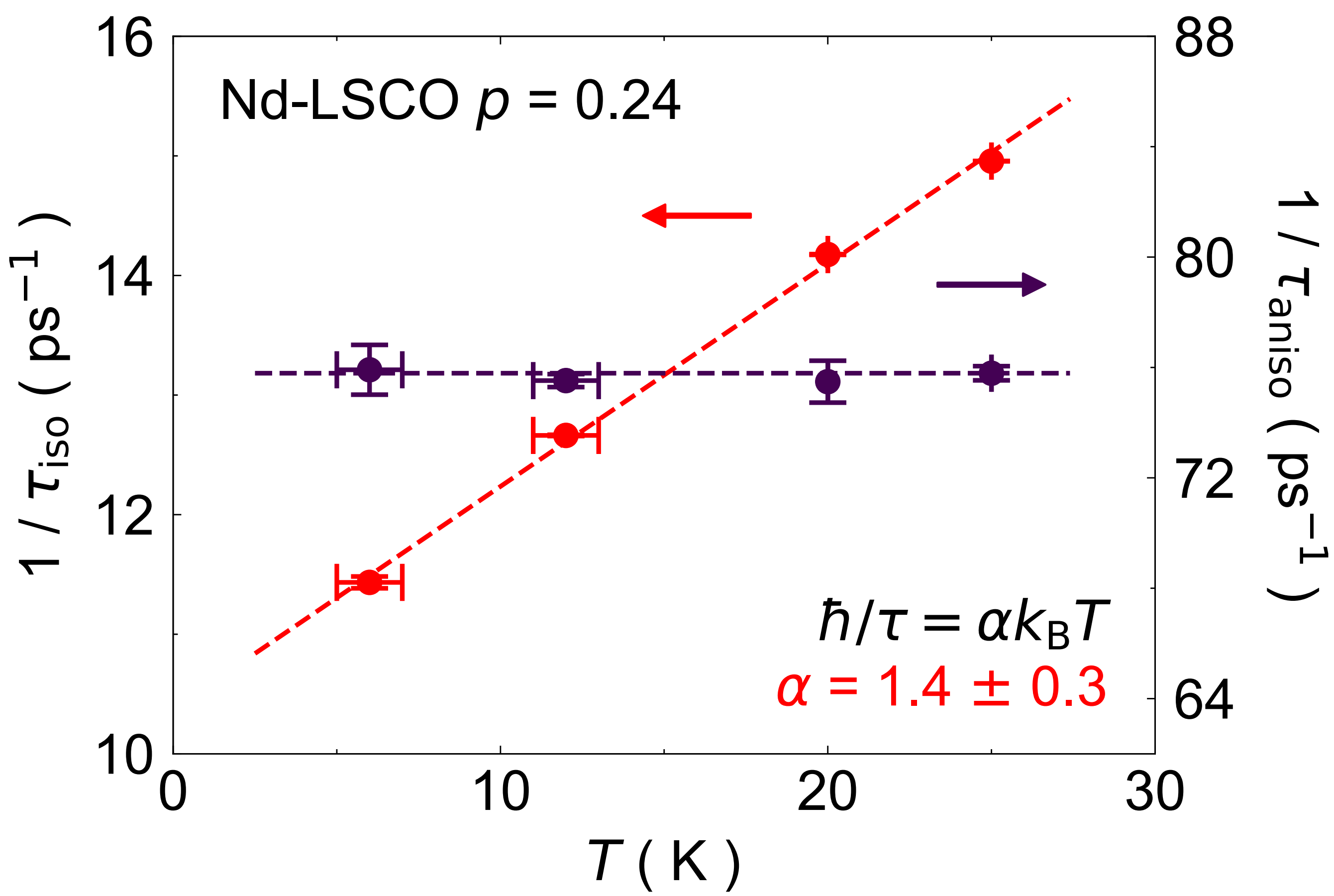

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Henry Shackleton

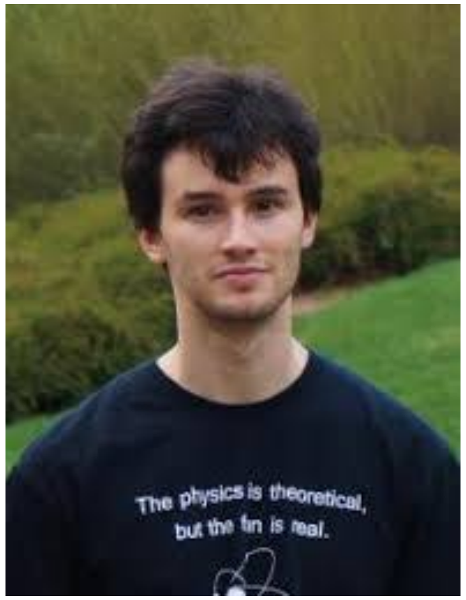
Alexander Wietek

Antoine Georges

arXiv:2012.06589

Maria Tikhanovskaya

Haoyu Guo



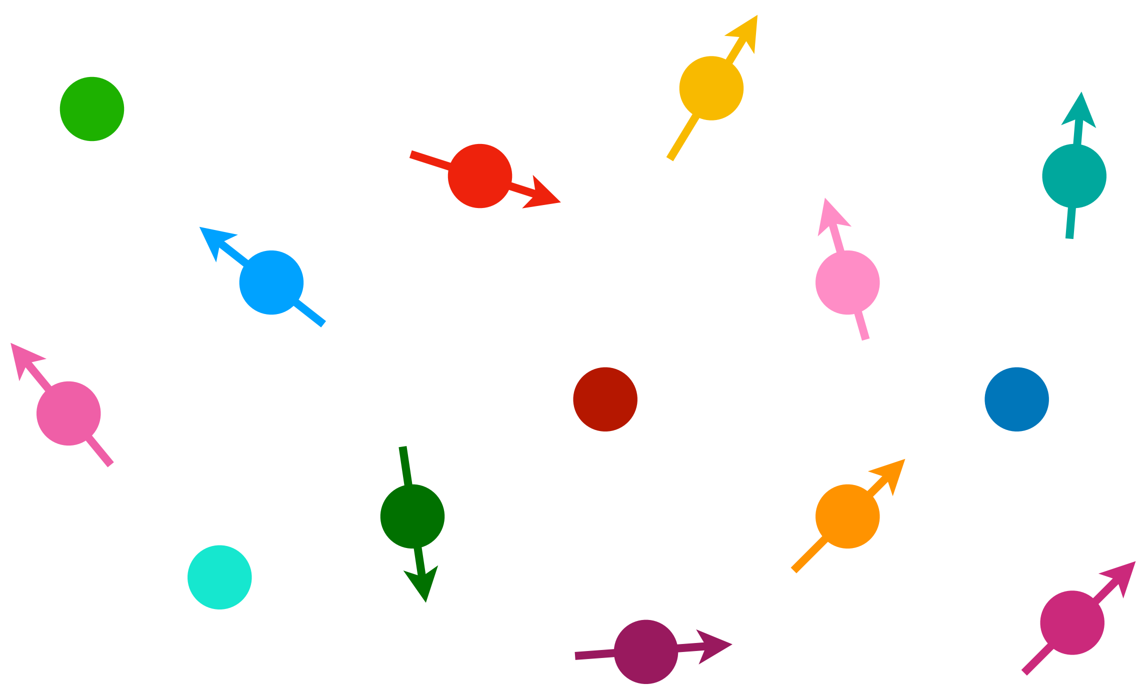
Grigory Tarnopolsky

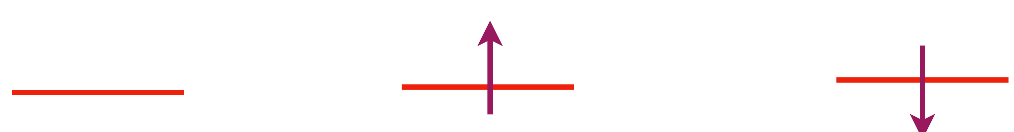
arXiv:2010.09742
arXiv:2012.14449

Random *t-J* model

$$H = -\frac{1}{\sqrt{N}} \sum_{i,j=1}^{N} t_{ij}\, c_{i\alpha}^{\dagger} c_{j\alpha} + \frac{1}{\sqrt{N}} \sum_{i<j=1}^{N} J_{ij}\, \vec{S}_i \cdot \vec{S}_j$$

We consider the hole-doped case, with no double occupancy.





$|0\rangle$ $\quad c_{\uparrow}^{\dagger}|0\rangle$ $\quad c_{\downarrow}^{\dagger}|0\rangle$

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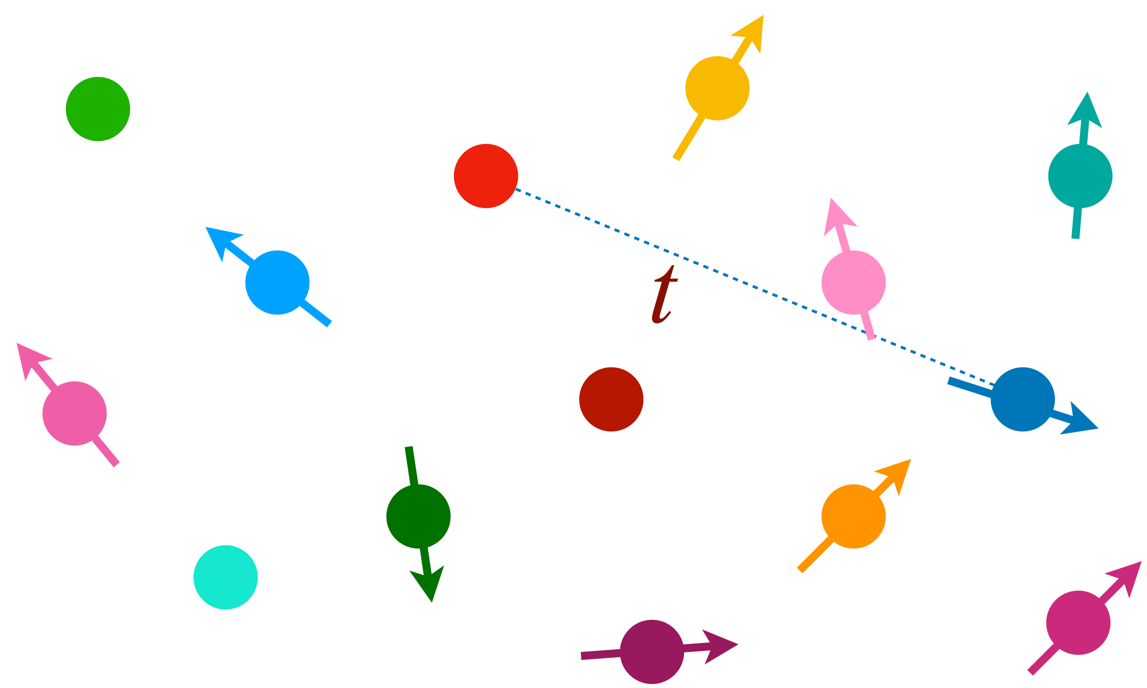

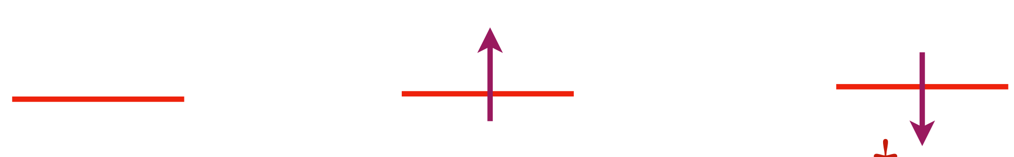

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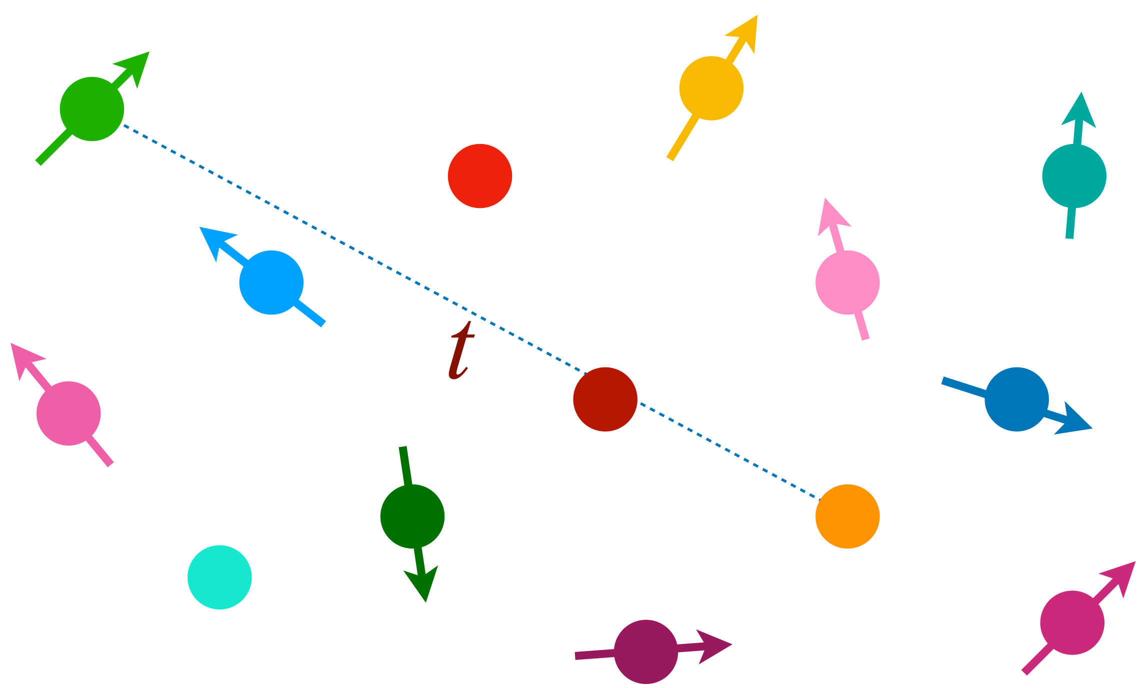

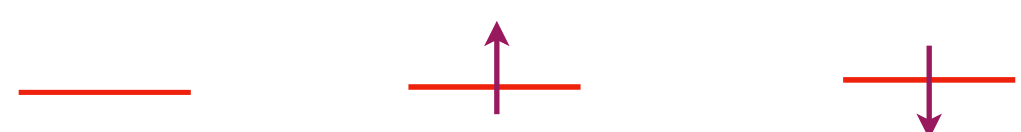

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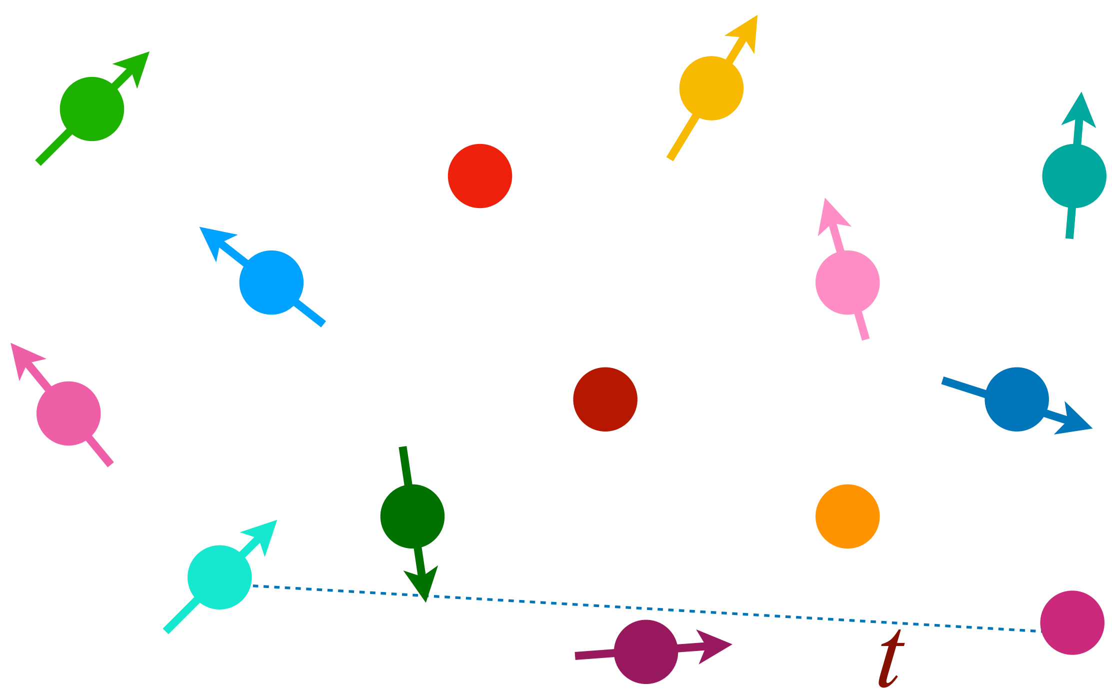

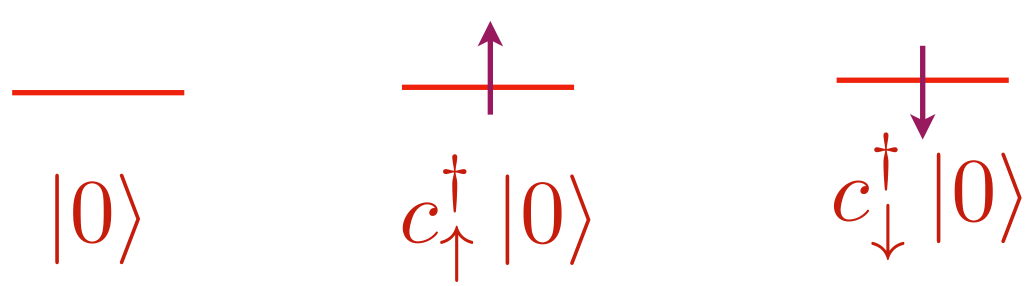

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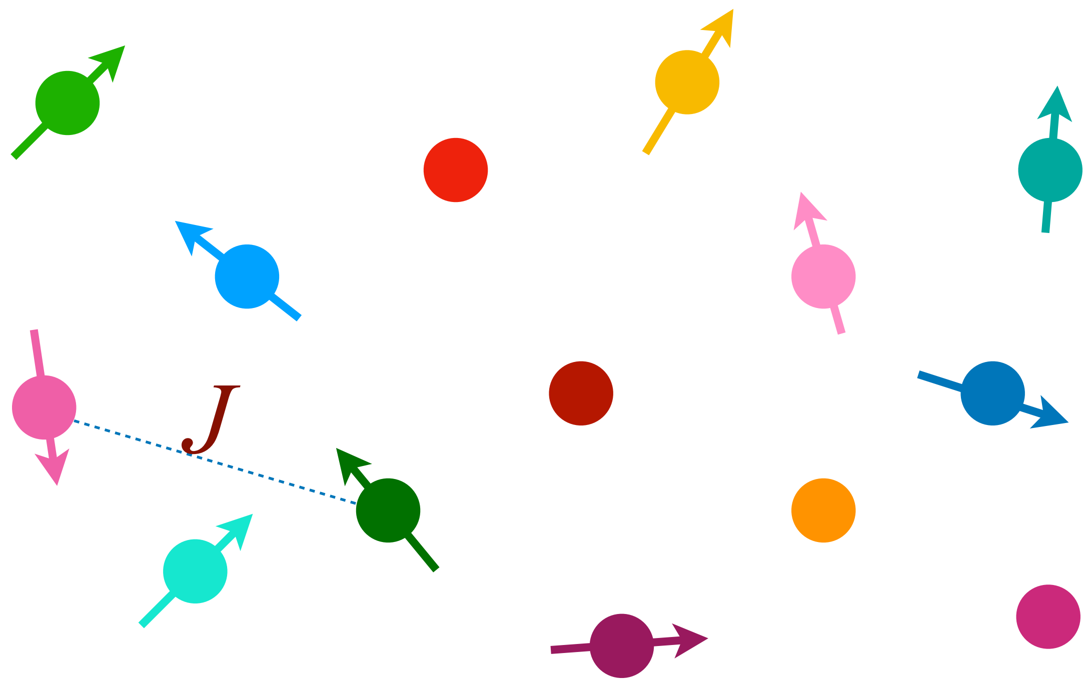

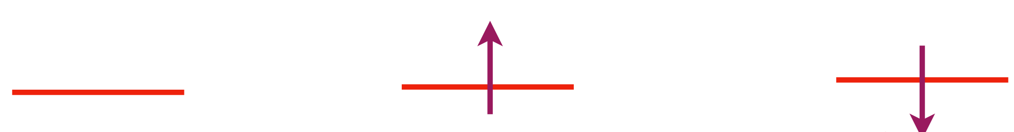

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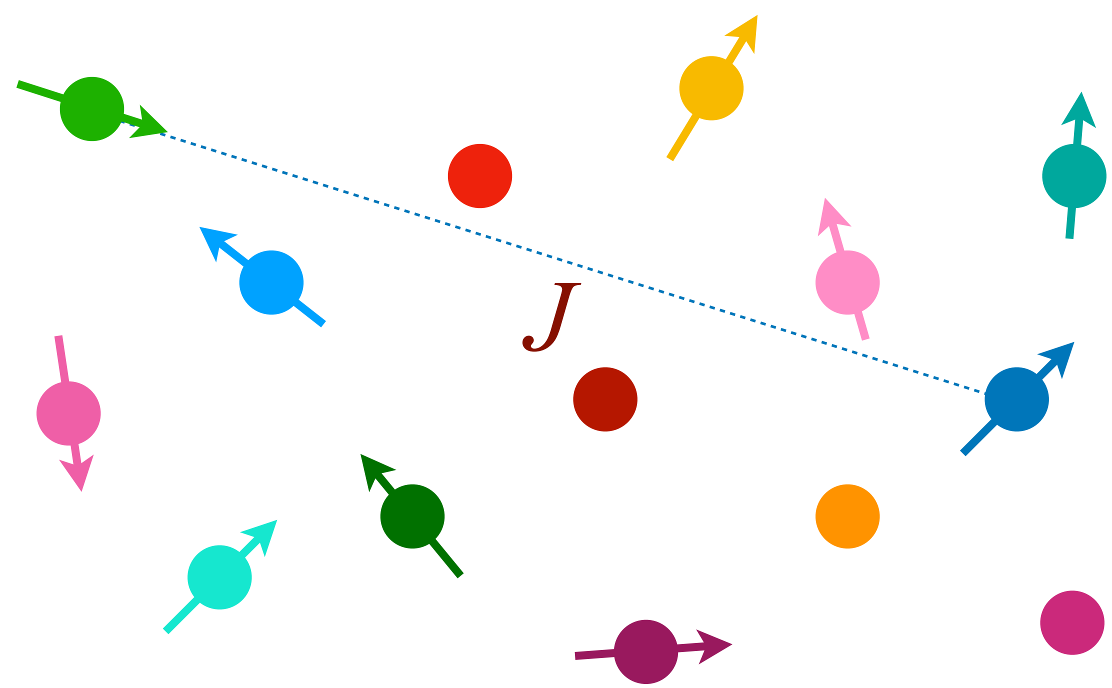

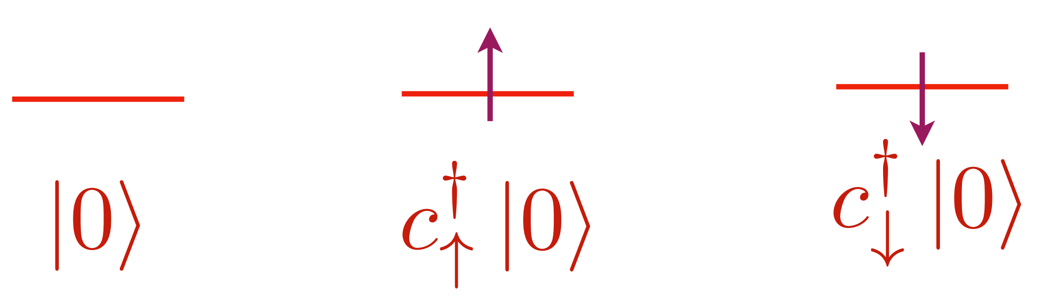

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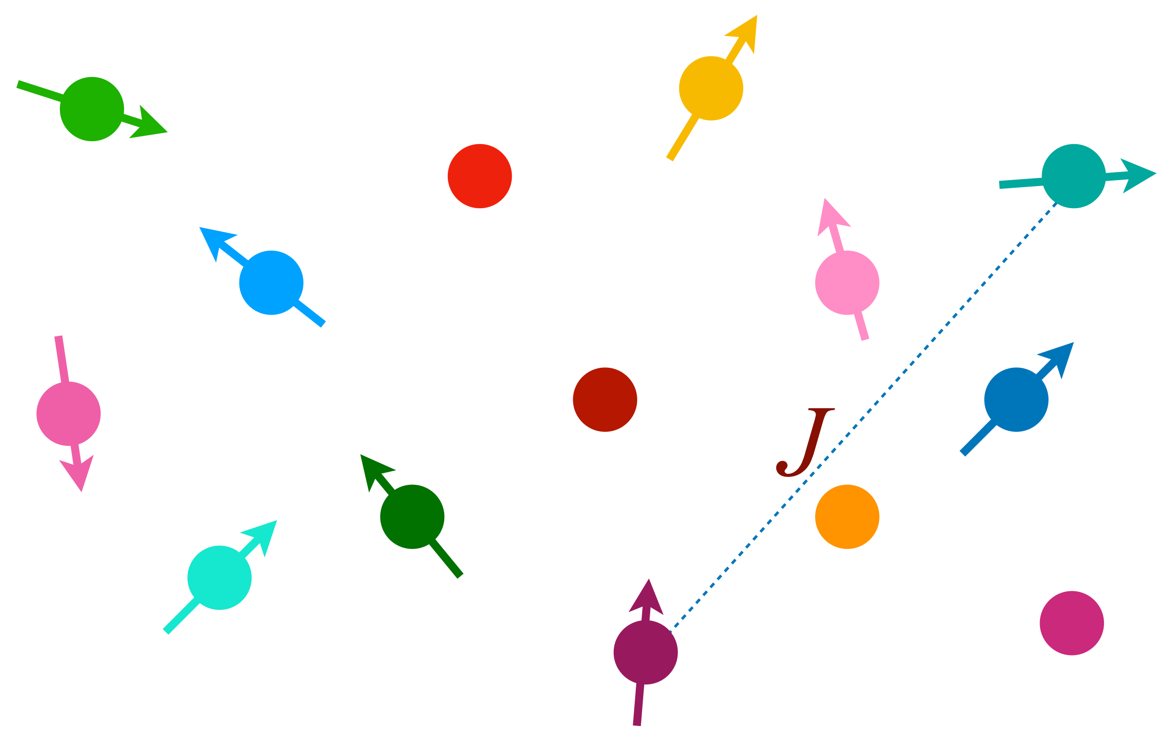
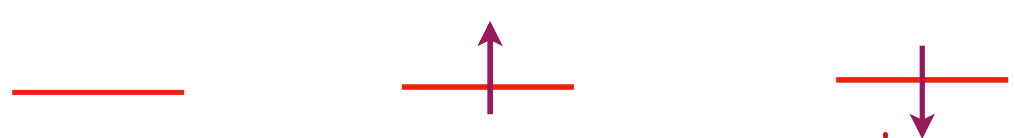
$$H = -\frac{1}{\sqrt{N}} \sum_{i,j=1}^{N} t_{ij}\, c_{i\alpha}^{\dagger} c_{j\alpha} + \frac{1}{\sqrt{N}} \sum_{i<j=1}^{N} J_{ij}\, \vec{S}_i \cdot \vec{S}_j$$

We consider the hole-doped case, with no double occupancy.

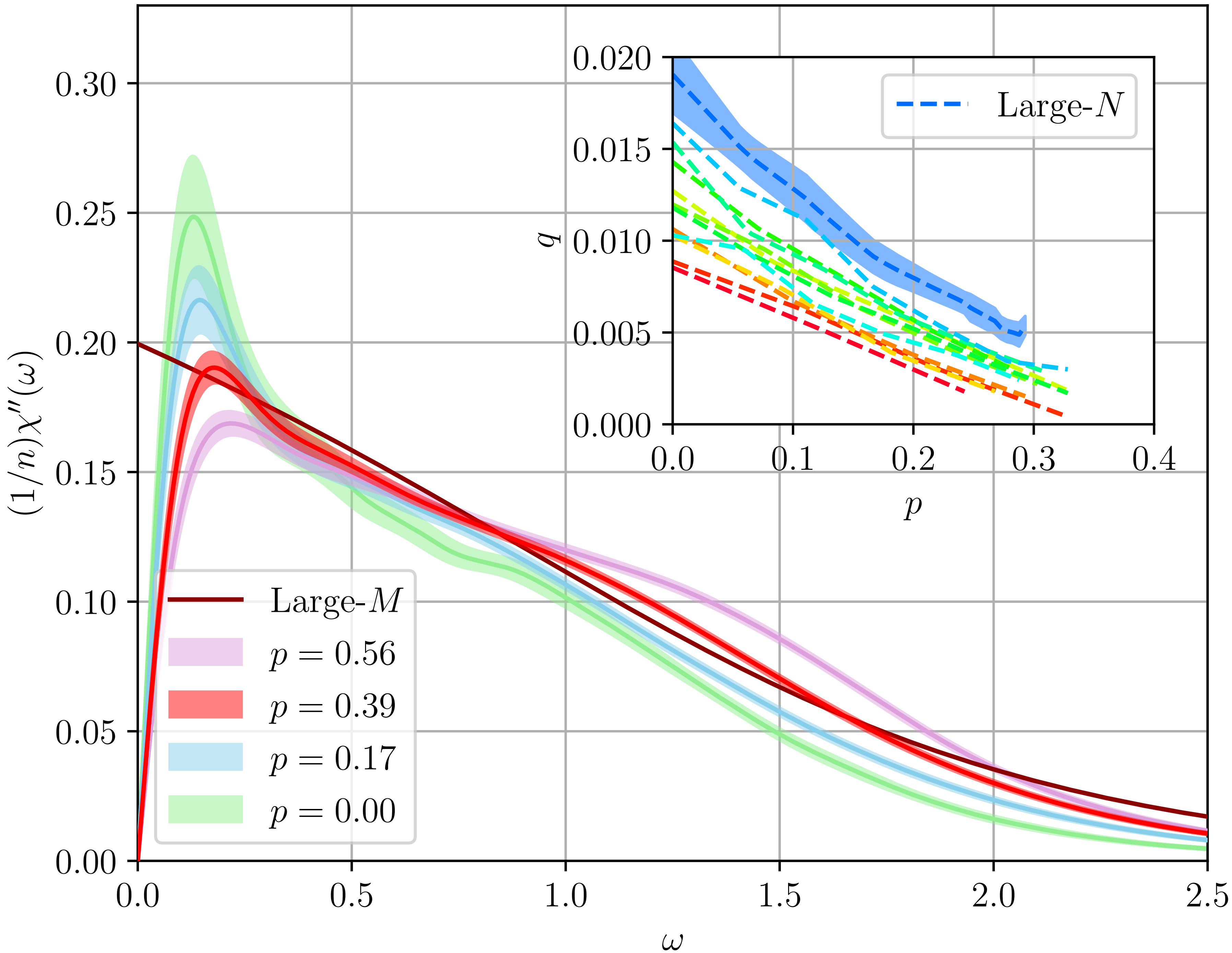




$|0\rangle$ $\qquad c_{\uparrow}^{\dagger}\,|0\rangle$ $\qquad c_{\downarrow}^{\dagger}\,|0\rangle$

Dynamic spin susceptibility

$$\chi''(\omega) = \sum_n |\langle 0| S_{+i} |n\rangle|^2 \, \delta(\hbar\omega - E_n + E_0), \text{ (at } T = 0)$$



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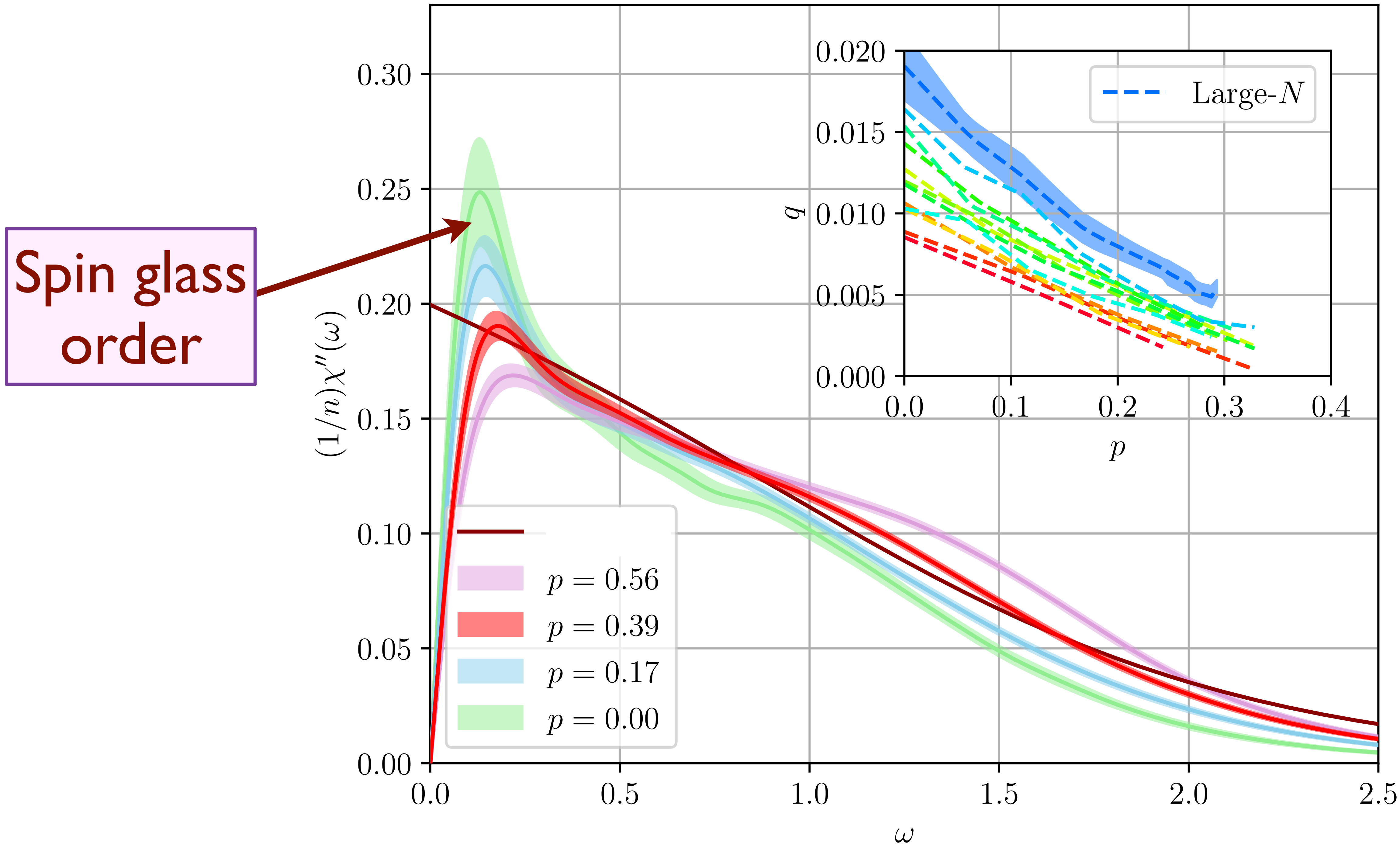

Spin glass order q non-zero for $p < p_c \approx 0.4$

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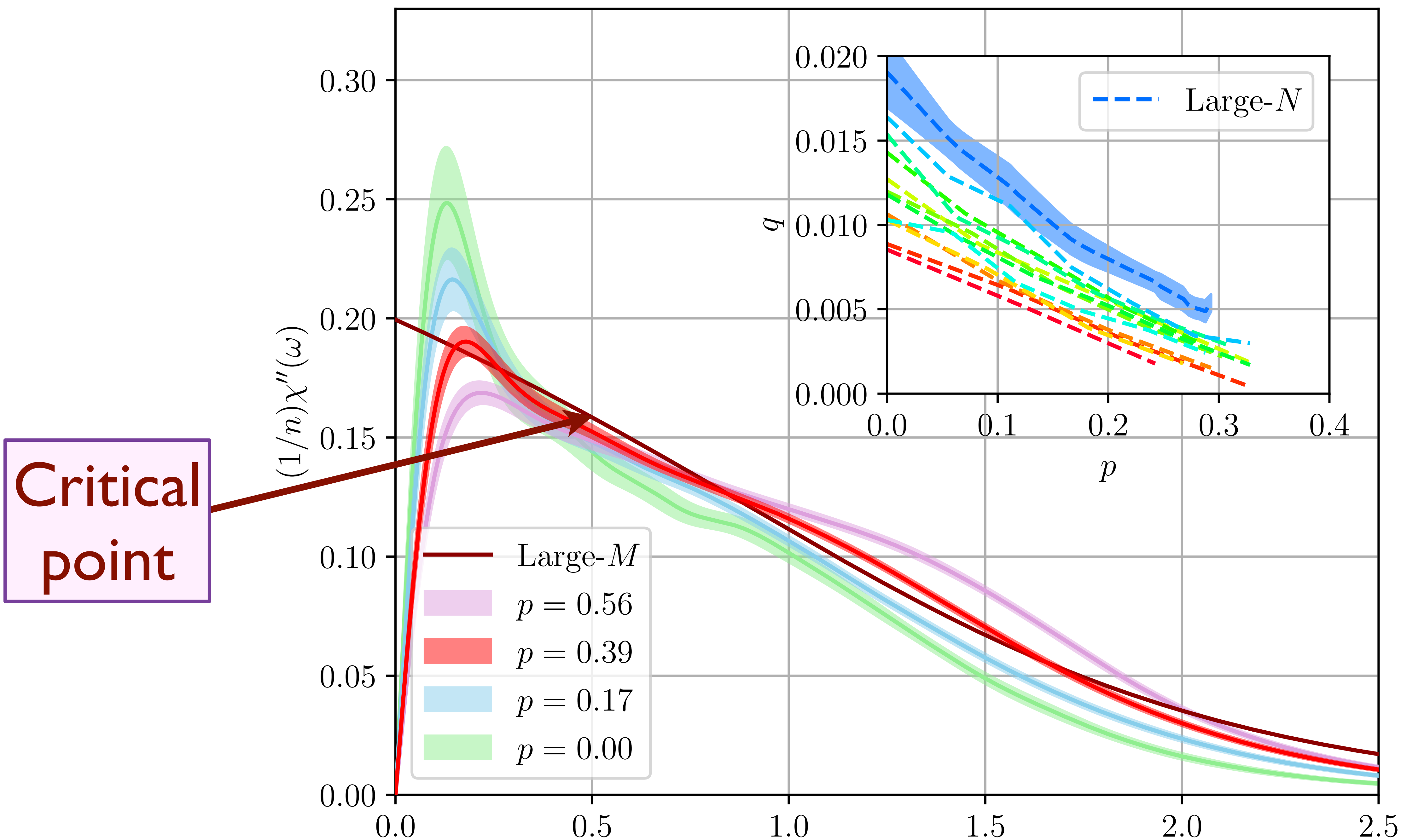


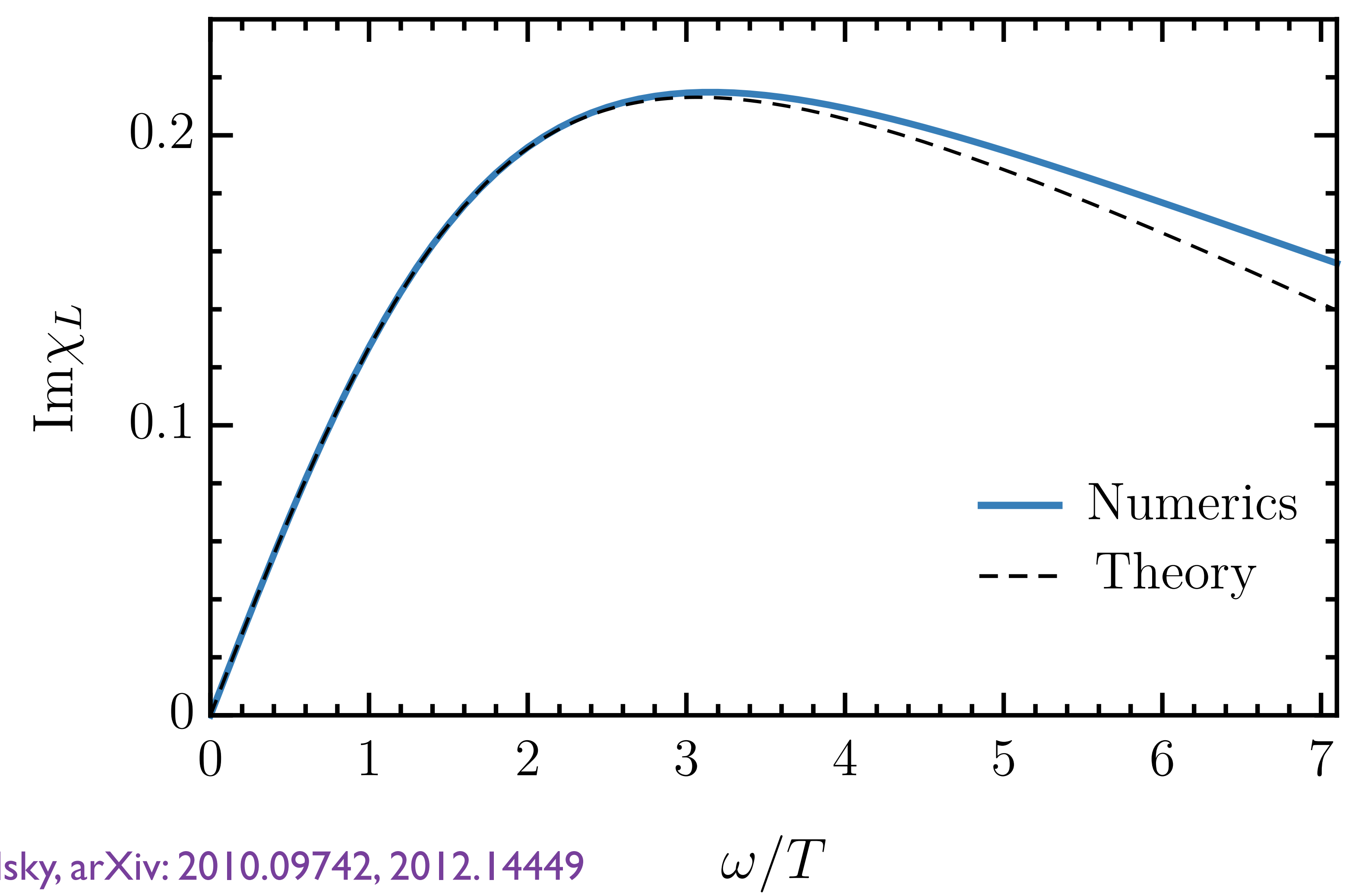
Critical spin susceptibility matches the SYK model!

$$\chi''(\omega) \sim \text{sgn}(\omega)\left[1 - \mathcal{C}\gamma|\omega| + \ldots\right]$$

Consequences of 2D-gravity for the SYK model

$$\chi''(\omega) = \sum_n |\langle 0| S_{+i} |n\rangle|^2 \, \delta(\hbar\omega - E_n + E_0), \text{ (at } T = 0)$$

$$\chi''(\omega) \sim \tanh\left(\frac{\hbar\omega}{2k_B T}\right)\left[1 - \mathcal{C}\gamma\,\omega \tanh\left(\frac{\hbar\omega}{2k_B T}\right) - \ldots\right]$$



Maria Tikhanovskaya, Haoyu Guo, S. Sachdev, G. Tarnopolsky, arXiv: 2010.09742, 2012.14449

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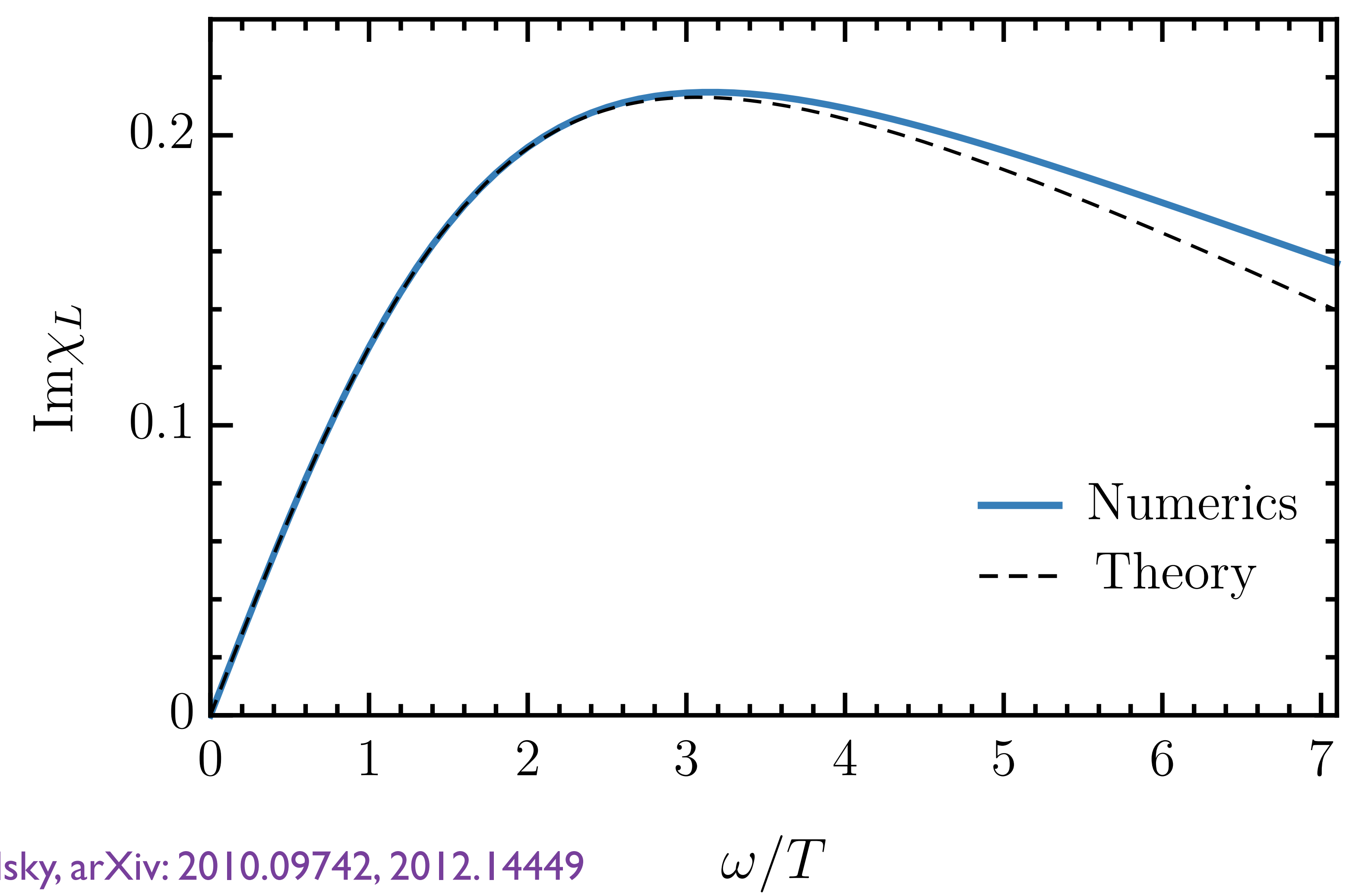
Conformally (SL(2,R)) invariant result with characteristic dissipative time $\sim \hbar/(k_B T)$

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



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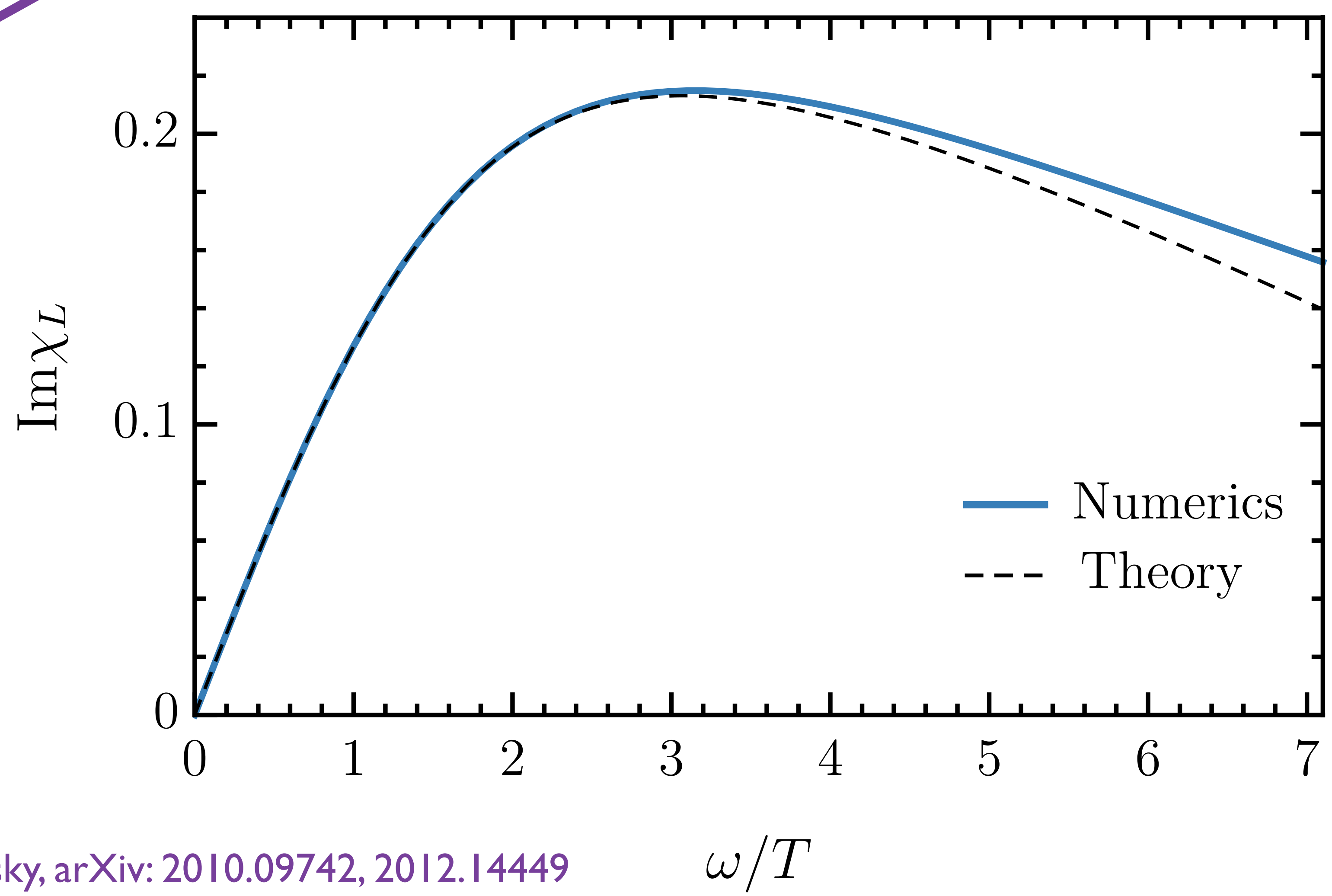
Correction from the boundary graviton



Maria Tikhanovskaya, Haoyu Guo, S. Sachdev, G. Tarnopolsky, arXiv: 2010.09742, 2012.14449

The random t-J model has

- Spin glass order for $p < p_c$.
- Fermi liquid with *"large Fermi surface"* for $p > p_c$
- Maxima in entropy, specific heat, and entanglement entropy near $p = p_c$
- SYK-Planckian criticality near p_c.
- *Boundary graviton* correction in critical spin susceptibility!

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- *Boundary graviton* correction in critical spin susceptibility!
- SYK criticality can be understood in a model in which the electron fractionalizes into spinons and holons: then both the t and J terms map onto 4-particle SYK terms.

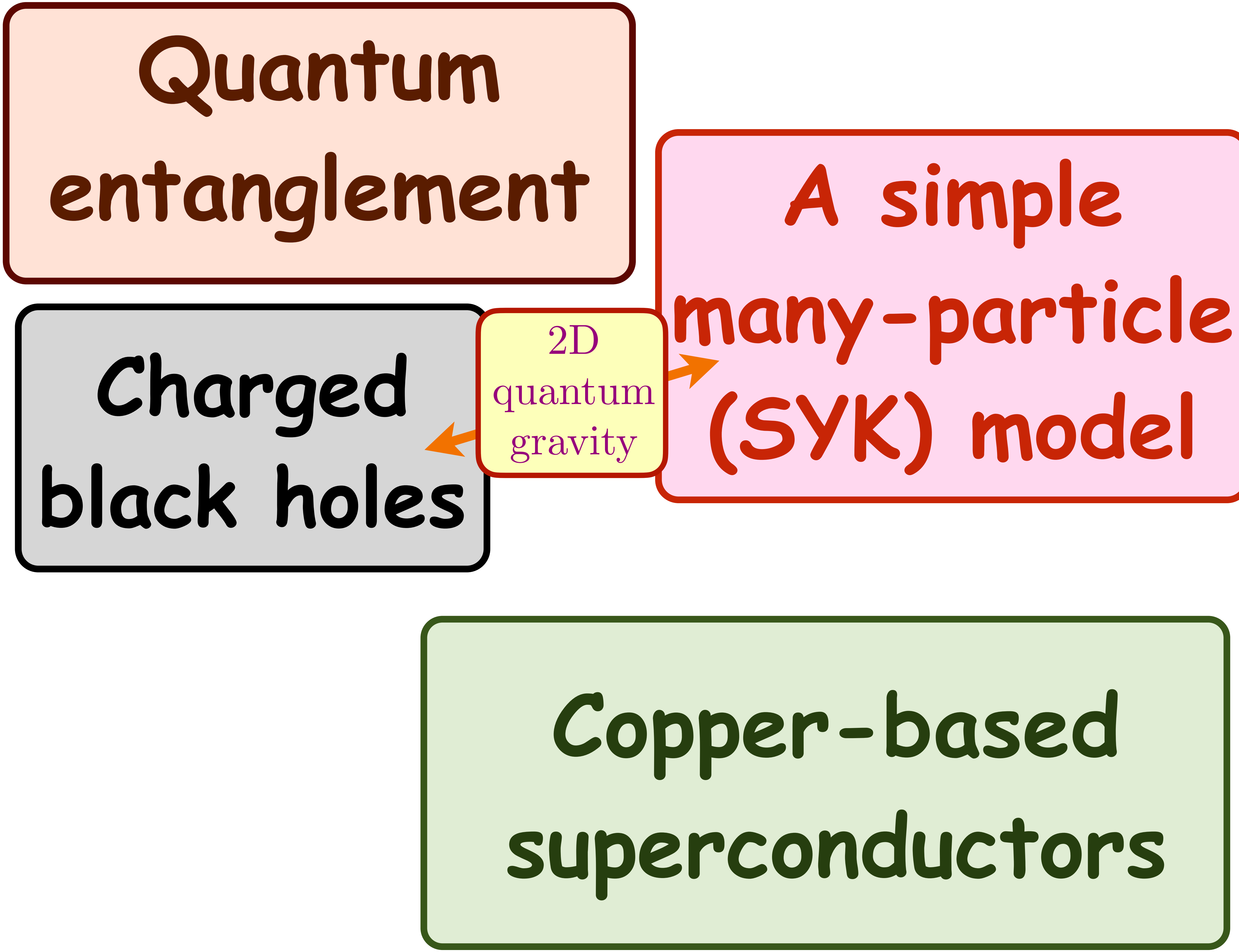
D. G. Joshi, Chenyuan Li, G. Tarnopolsky, A. Georges, and S. Sachdev, PRX **10**, 021033 (2020)

Quantum entanglement

A simple many-particle (SYK) model

Charged black holes

Copper-based superconductors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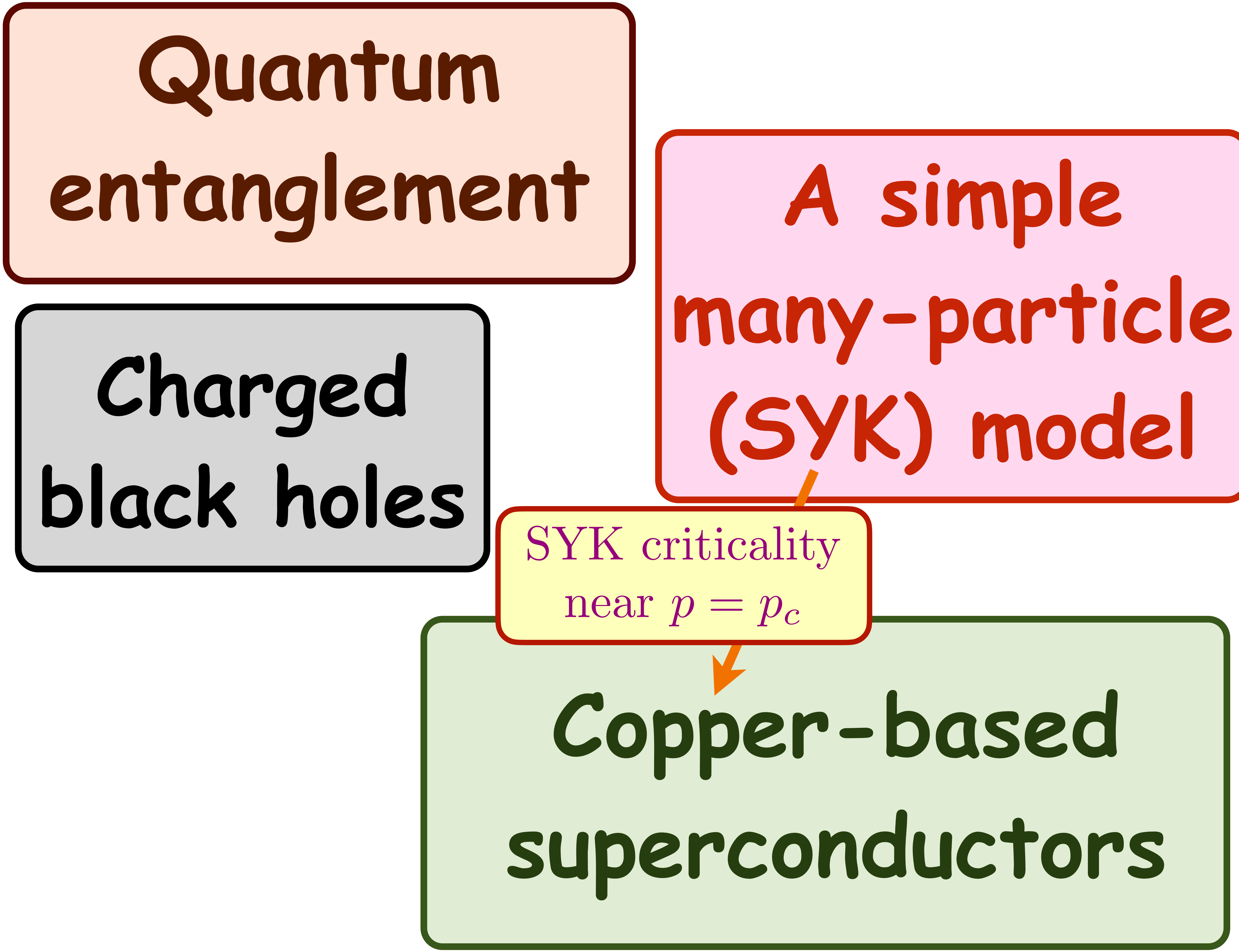
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Complex multi-particle entanglement leads to quantum systems without quasiparticle excitations.

Many-body chaos and thermal equilibration in the shortest possible Planckian time $\sim \dfrac{\hbar}{k_B T}$.