The quantum phases of matter

Physics Training and Talent Search
Infosys Science Foundation
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Talk online: sachdev.physics.harvard.edu

INSTITUTE FOR ADVANCED STUDY

PHYSICS
HARVARD

1. “Conventional” phases of matter

   Metals, insulators, superconductors

2. Emergent gauge fields and topology

   Spin liquids with Rydberg atoms

3. Strange metals

   SYK model and emergent gravity

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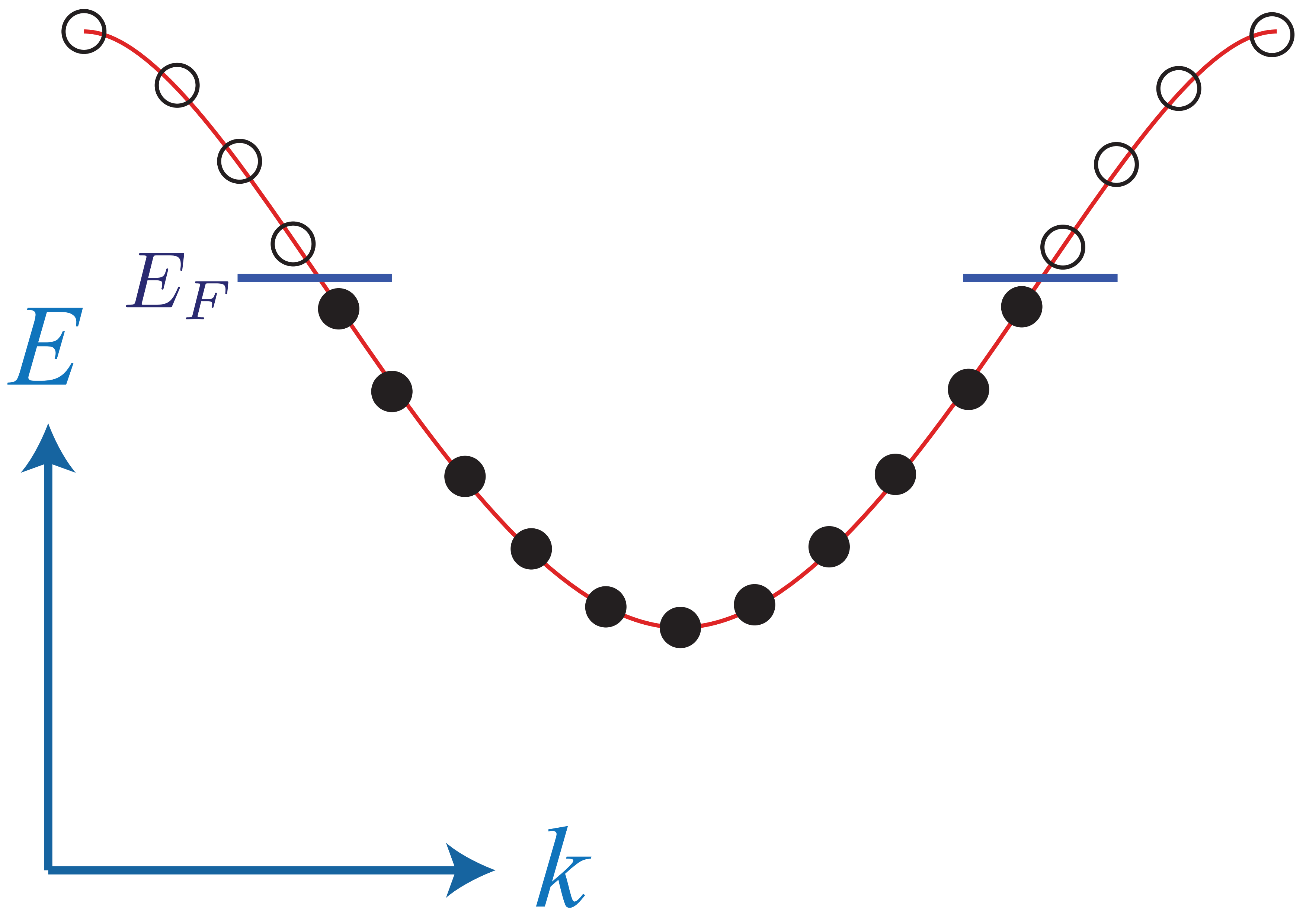
Ordinary metals

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

Foundations of quantum many body theory:

1. Ground states <u>connected</u> adiabatically to independent electron states

<u>Metals</u>

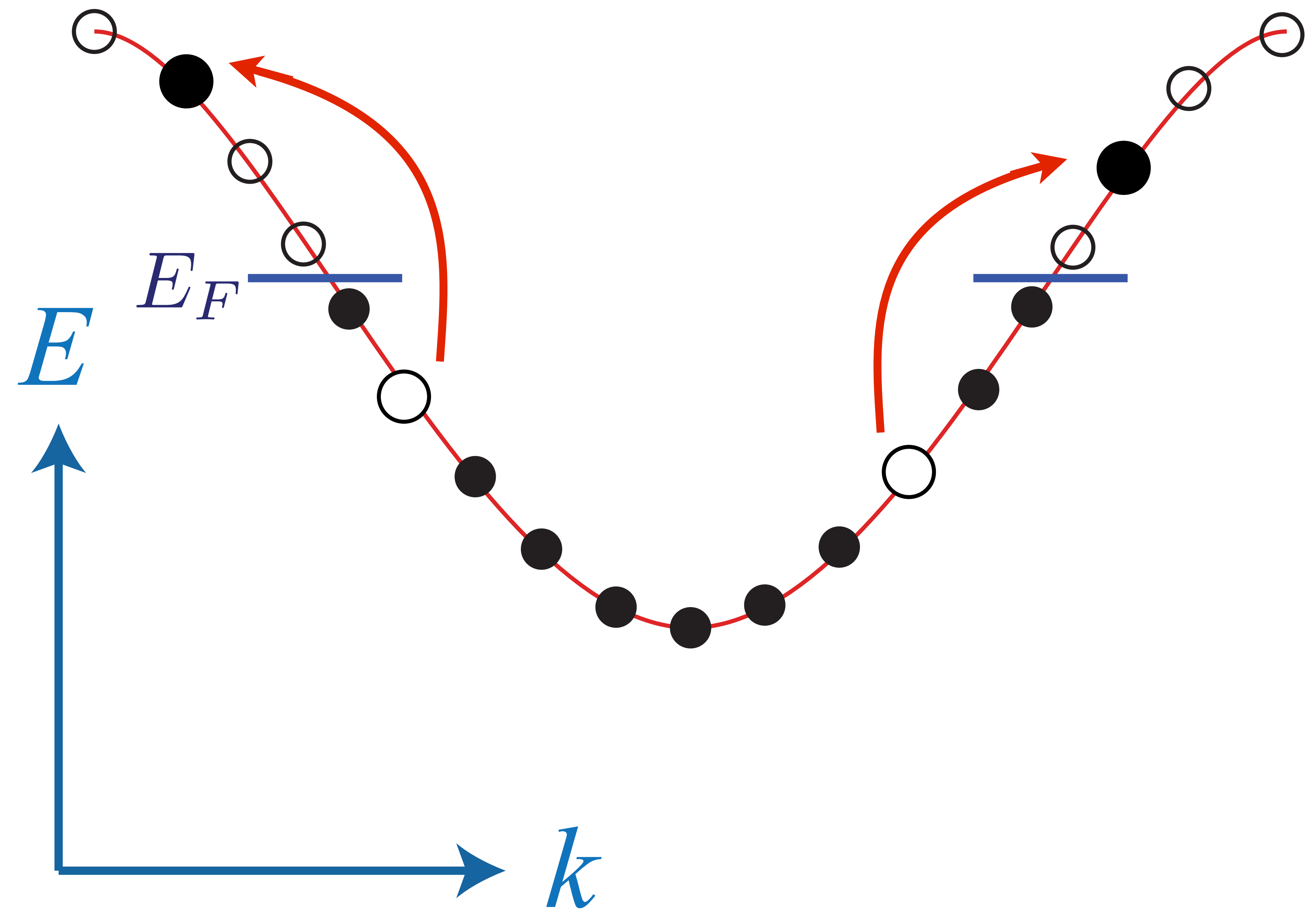


Foundations of quantum many body theory:

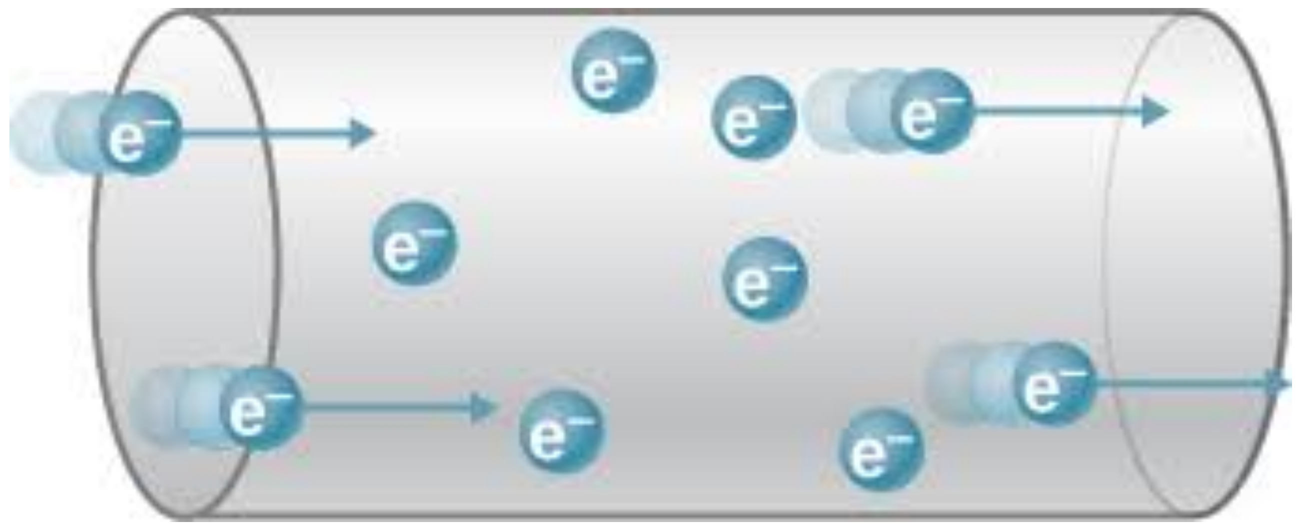
1. Ground states connected adiabatically to independent electron states

2. Boltzmann-Landau theory of quasiparticles

Metals



Current flow with quasiparticles

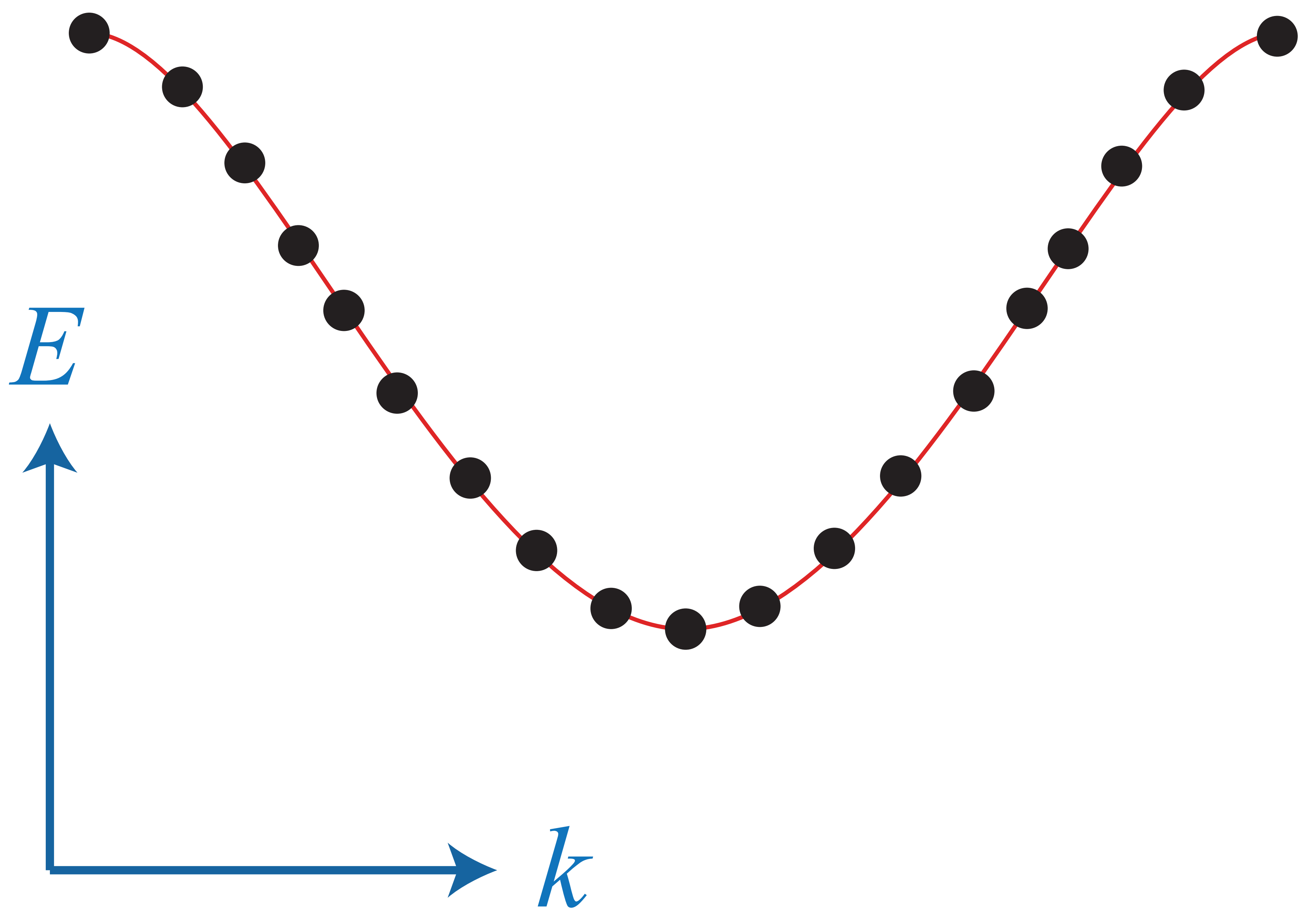


Flowing quasiparticles scatter off each other in a typical scattering time τ

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

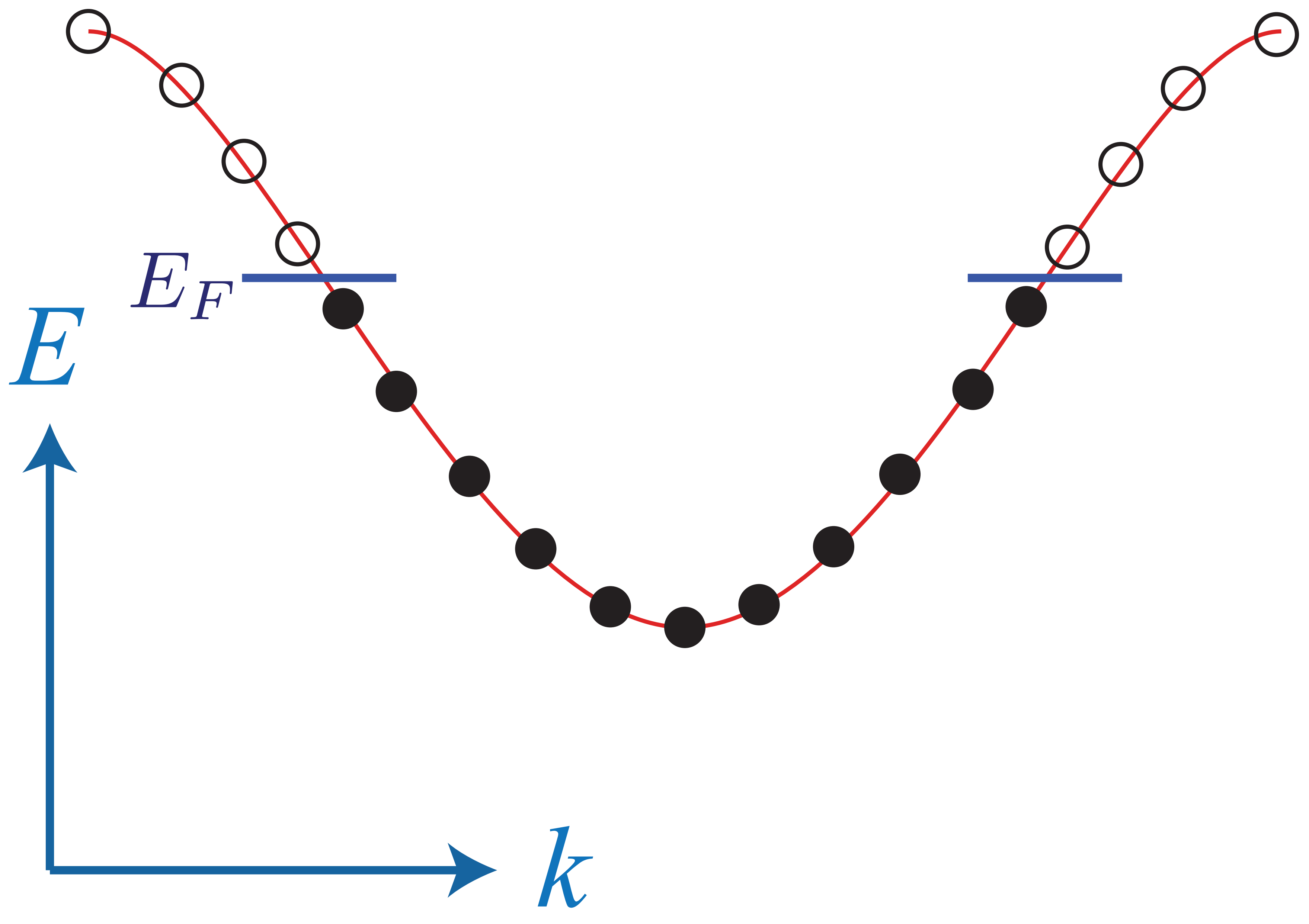
The long scattering time implies that quasiparticles are well-defined.

Band insulators

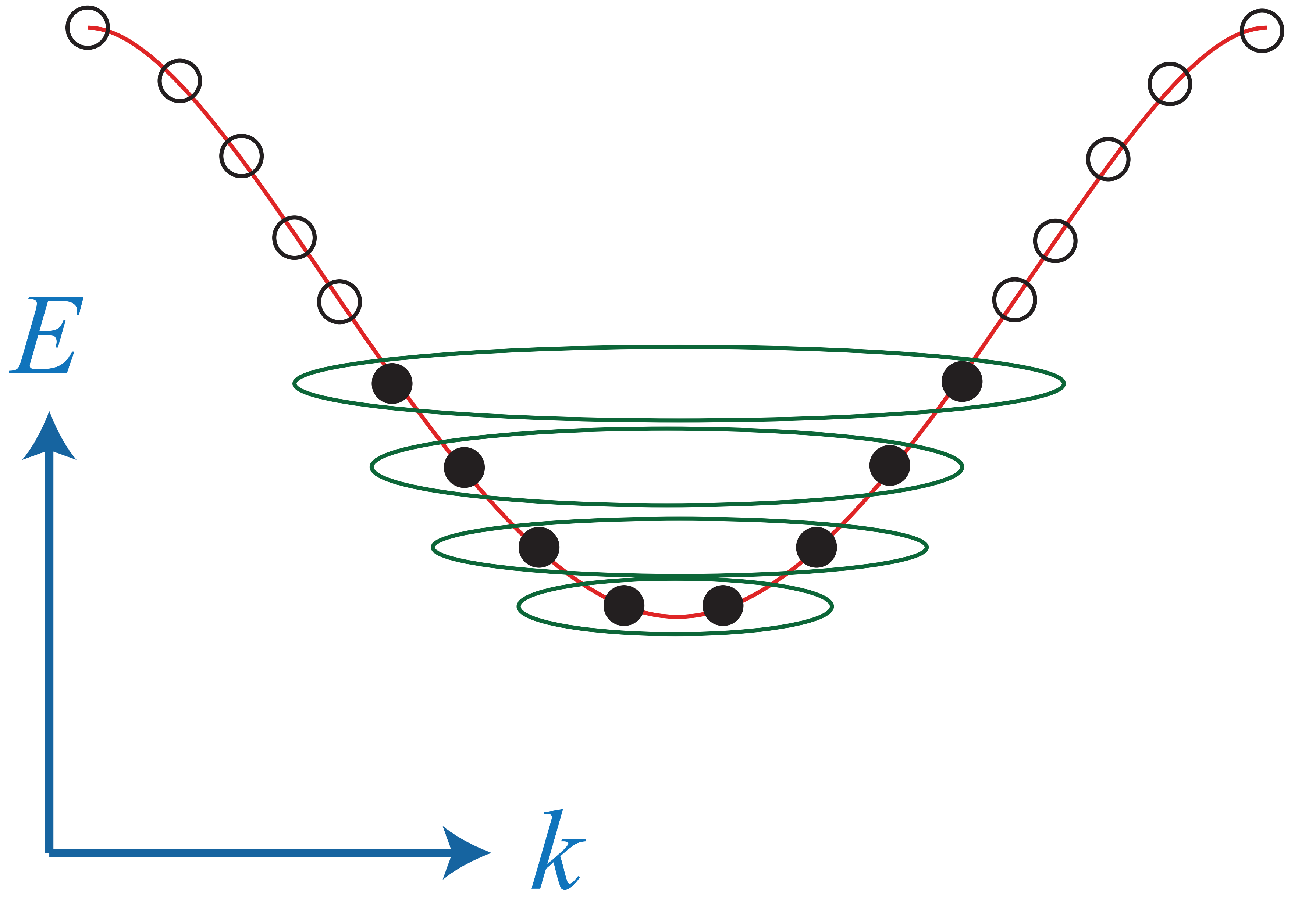


An even number of electrons per unit cell

Metals

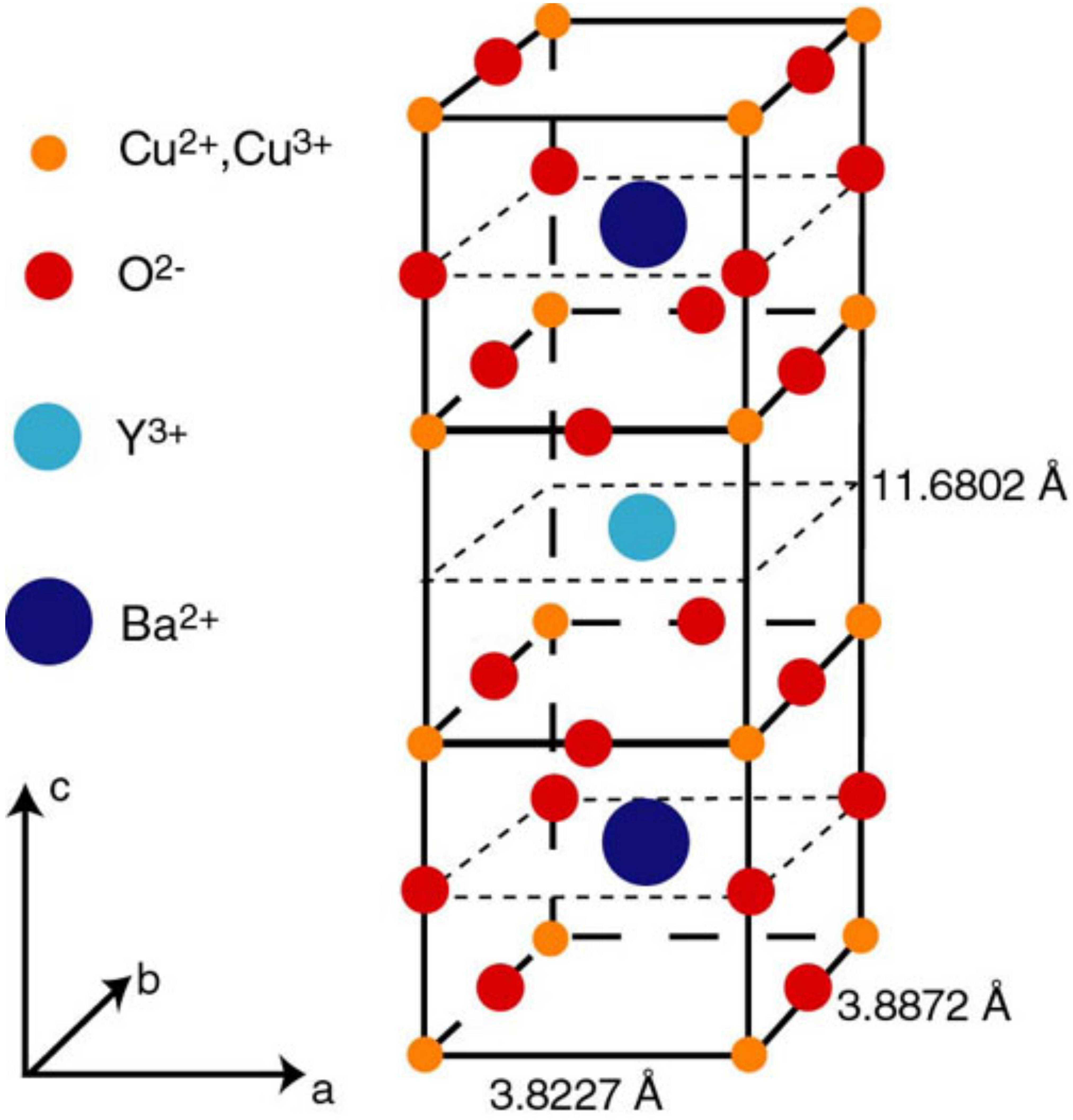


Superconductor

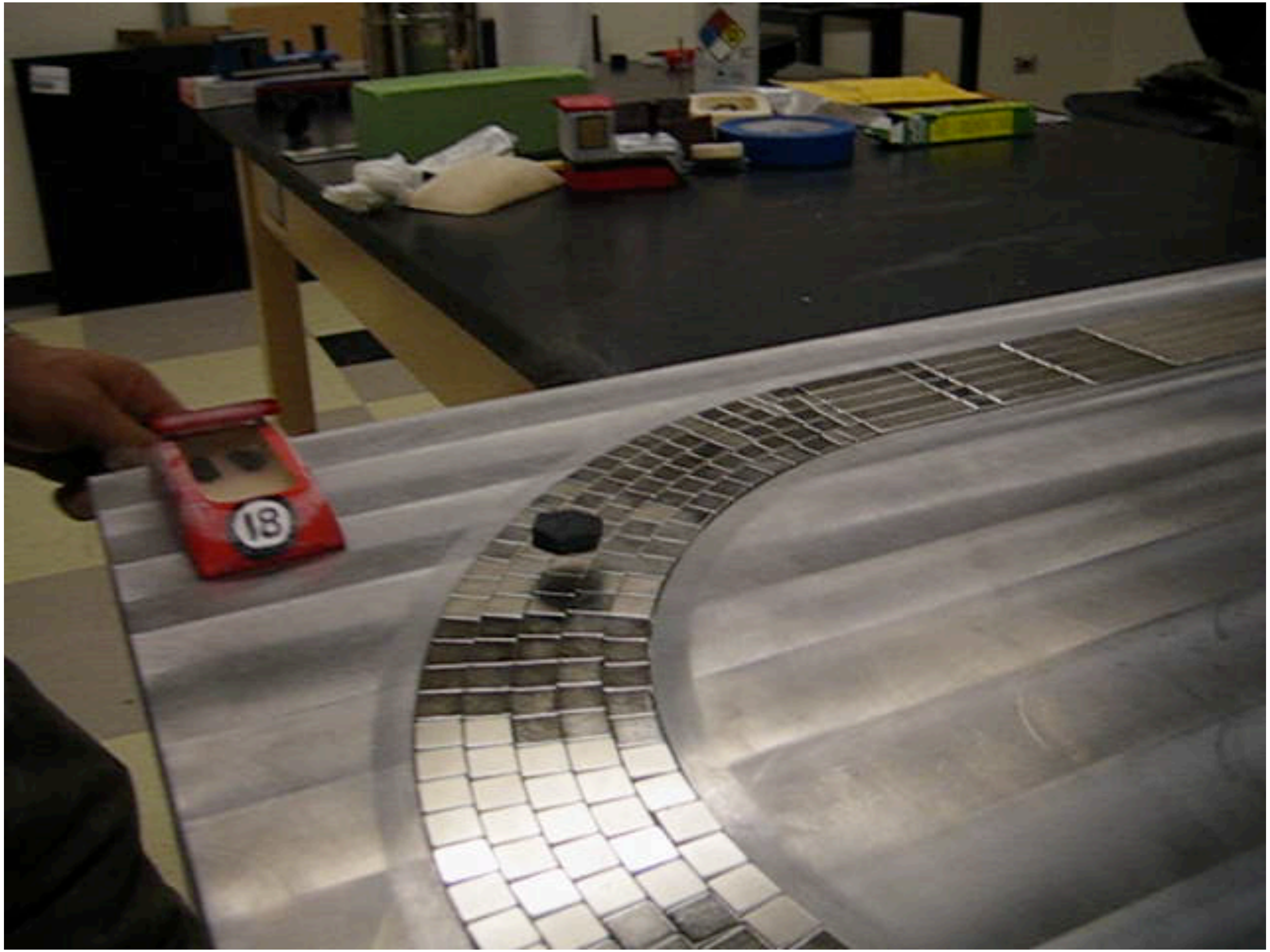


Electrons pair, and the pairs undergo Bose-Einstein condensation

High temperature superconductors



$$YBa_2Cu_3O_{6+x}$$



Nd-Fe-B magnets, YBaCuO superconductor

Julian Hetel and Nandini Trivedi, Ohio State University

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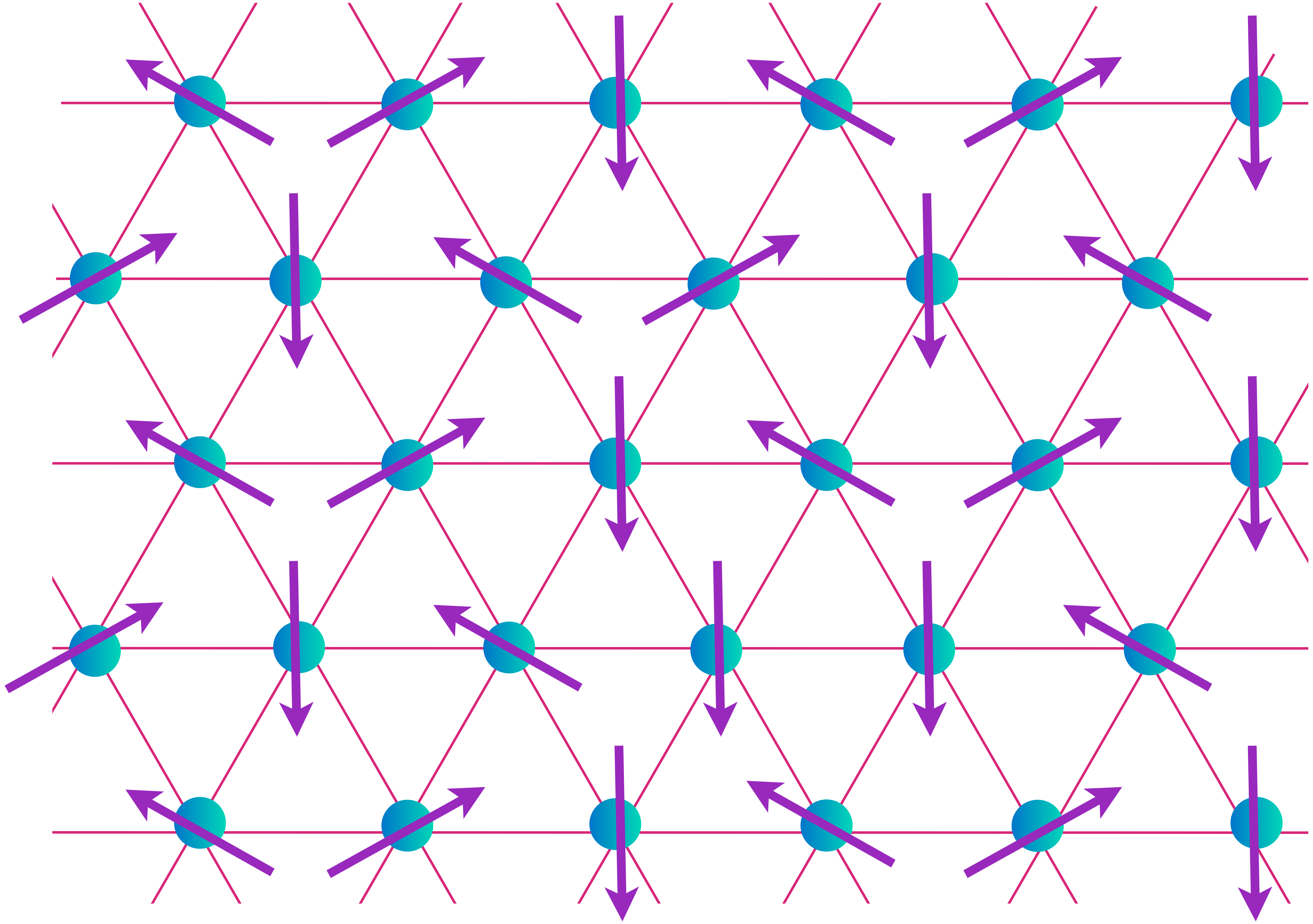
Mott insulator: Triangular lattice antiferromagnet

$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$



Nearest-neighbor model has non-collinear Neel order

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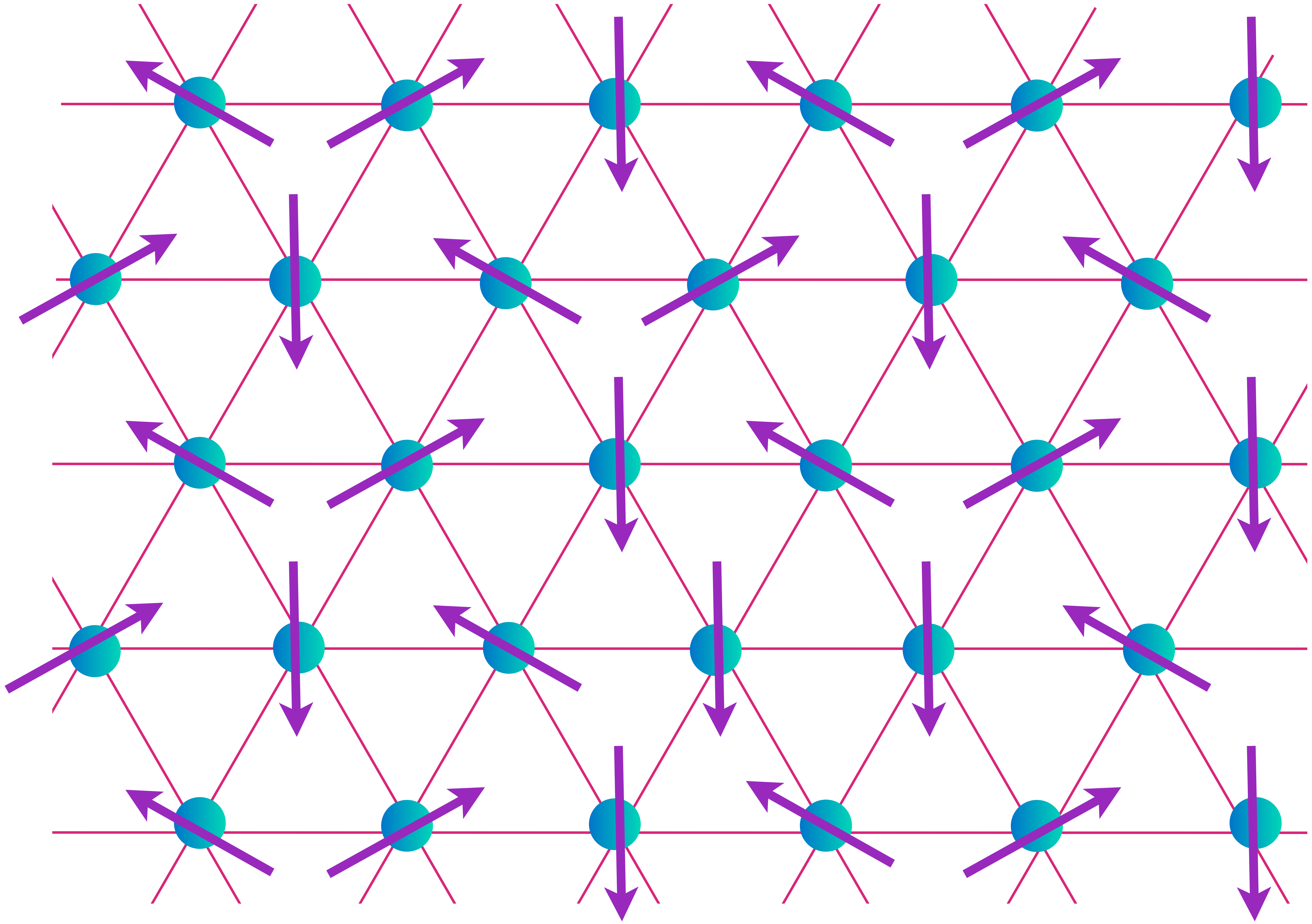

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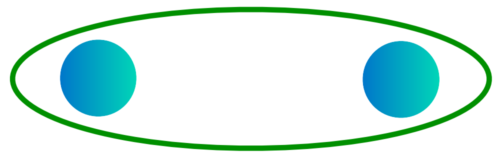

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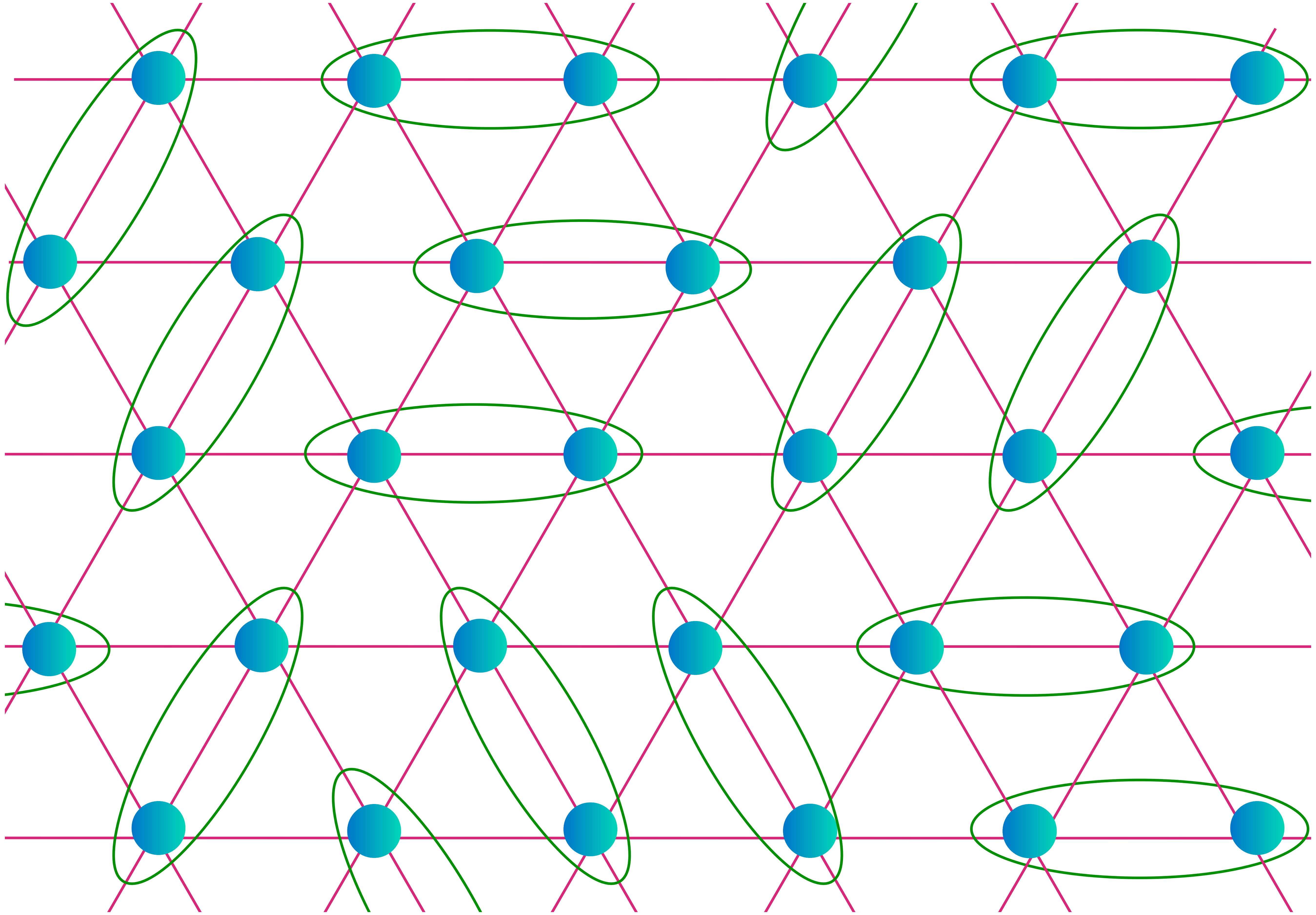

$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} \, |\mathcal{D}\rangle$$

$\mathcal{D} \rightarrow$ dimer covering of lattice

P. Fazekas and P. W. Anderson, *Philos. Mag.* **30**, 23 (1974).

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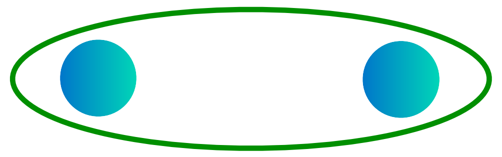

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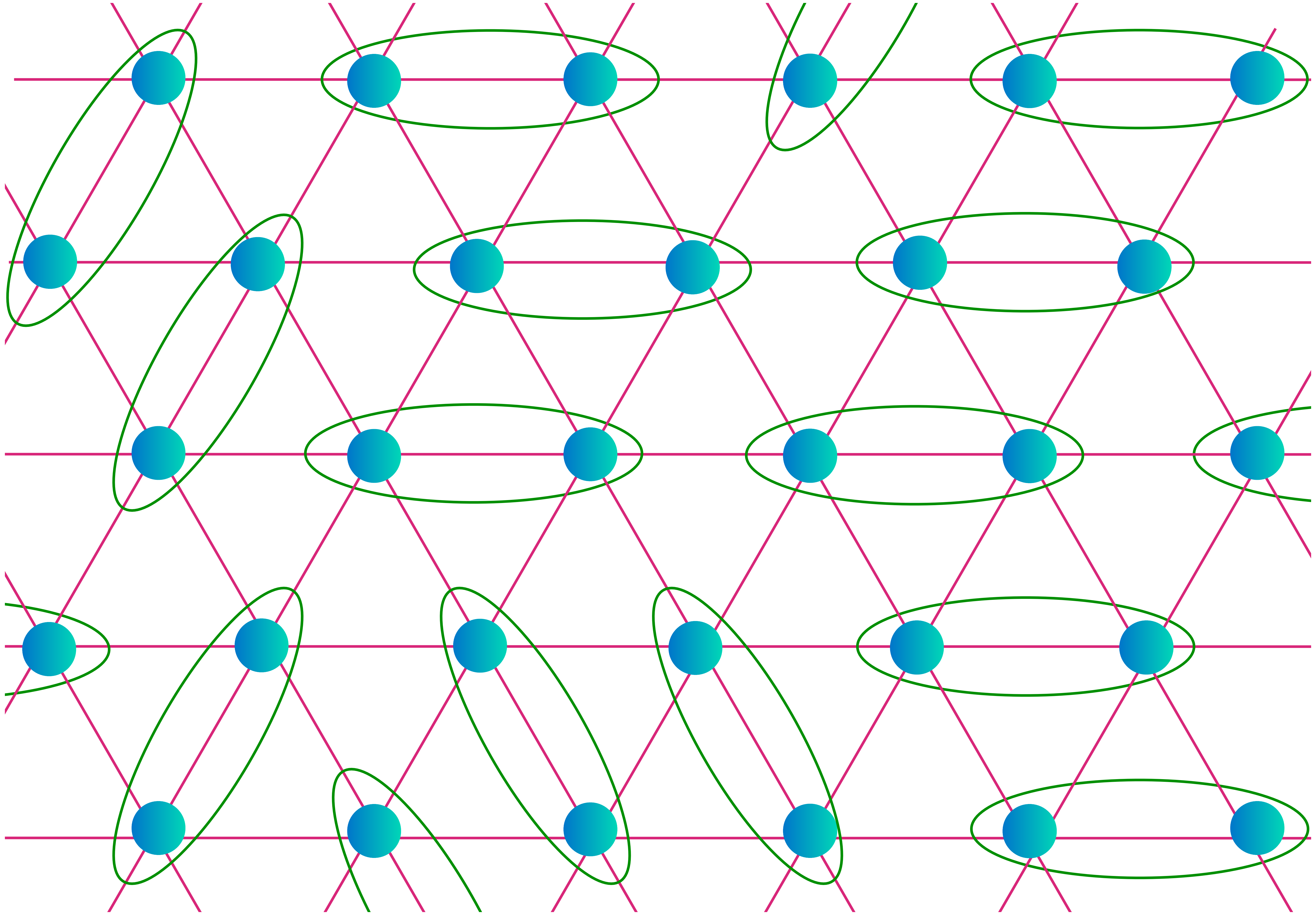

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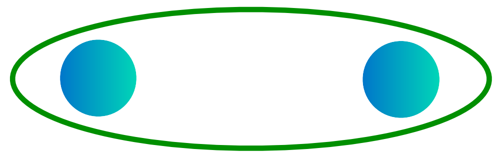

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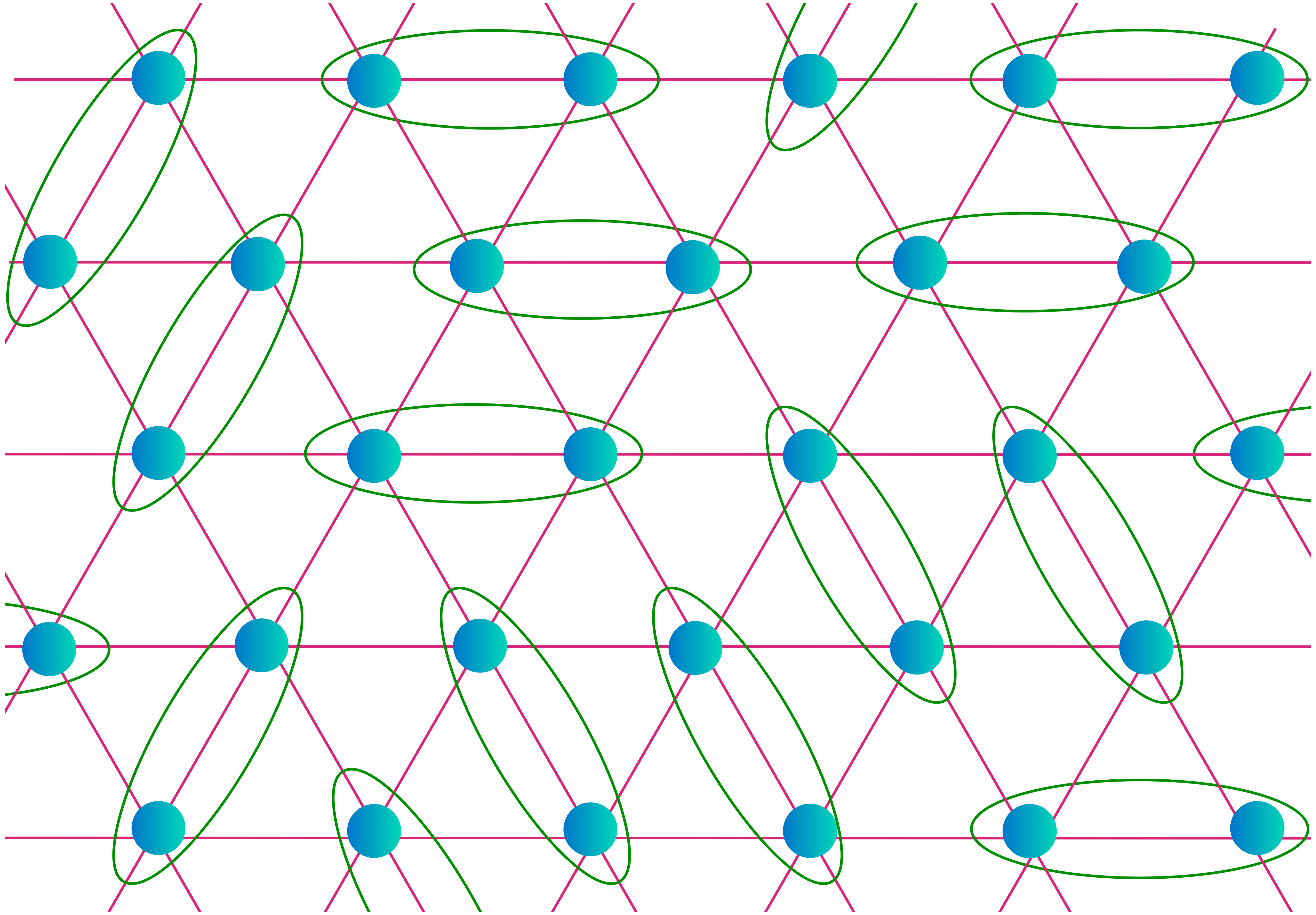

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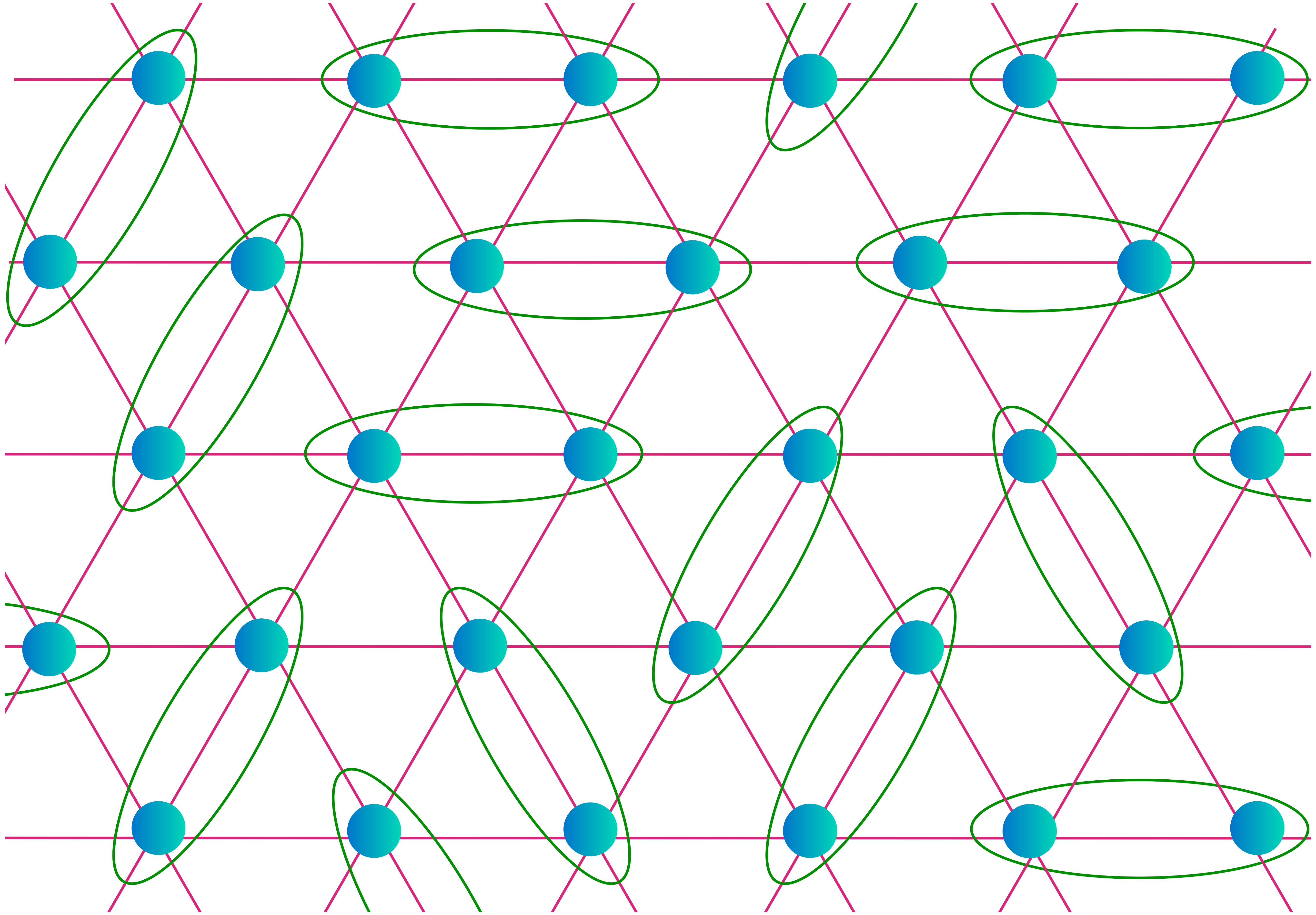

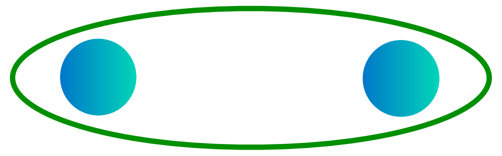

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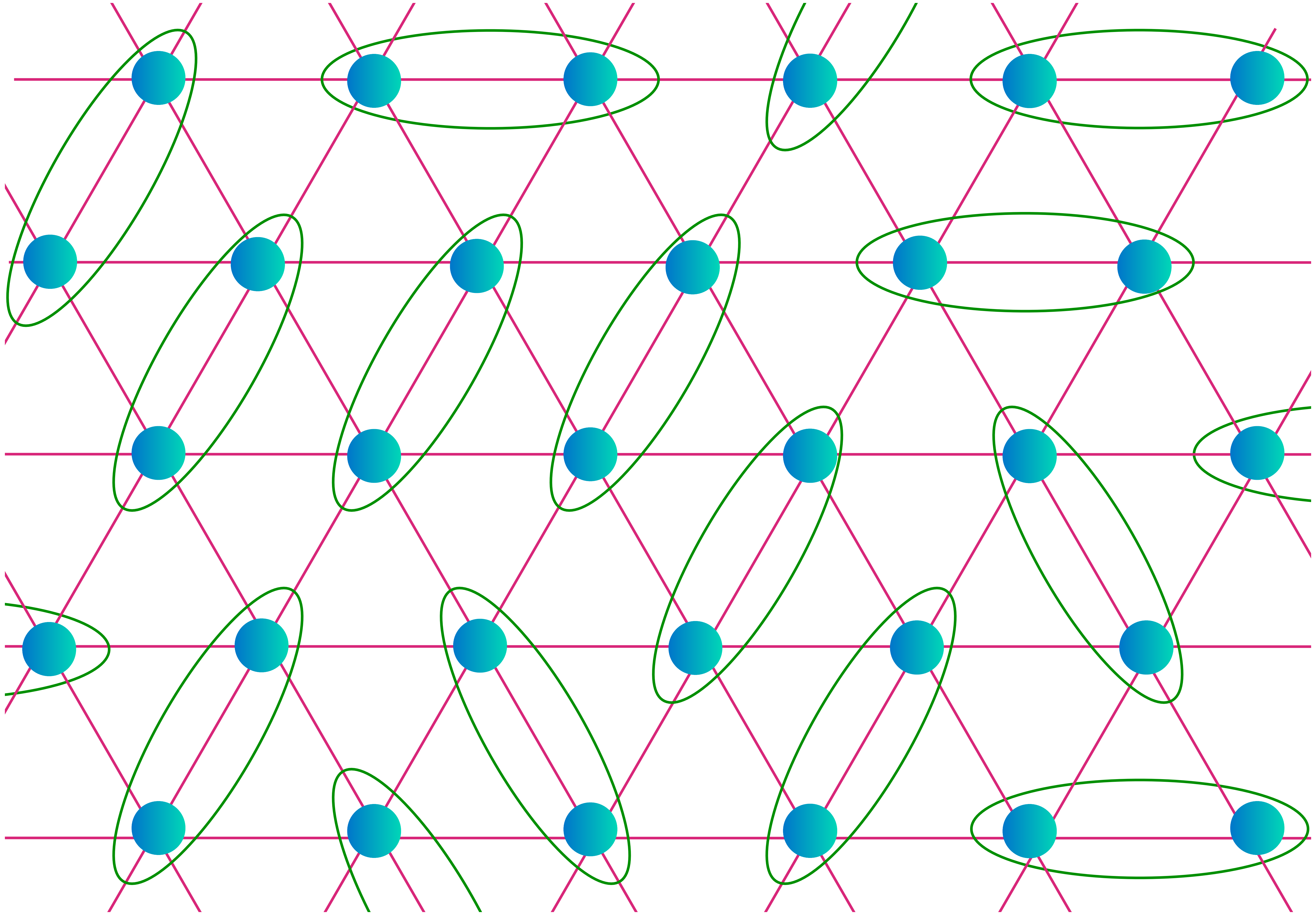

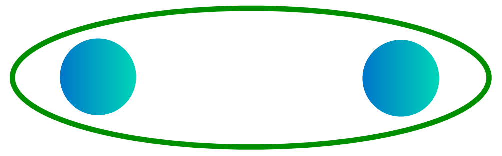

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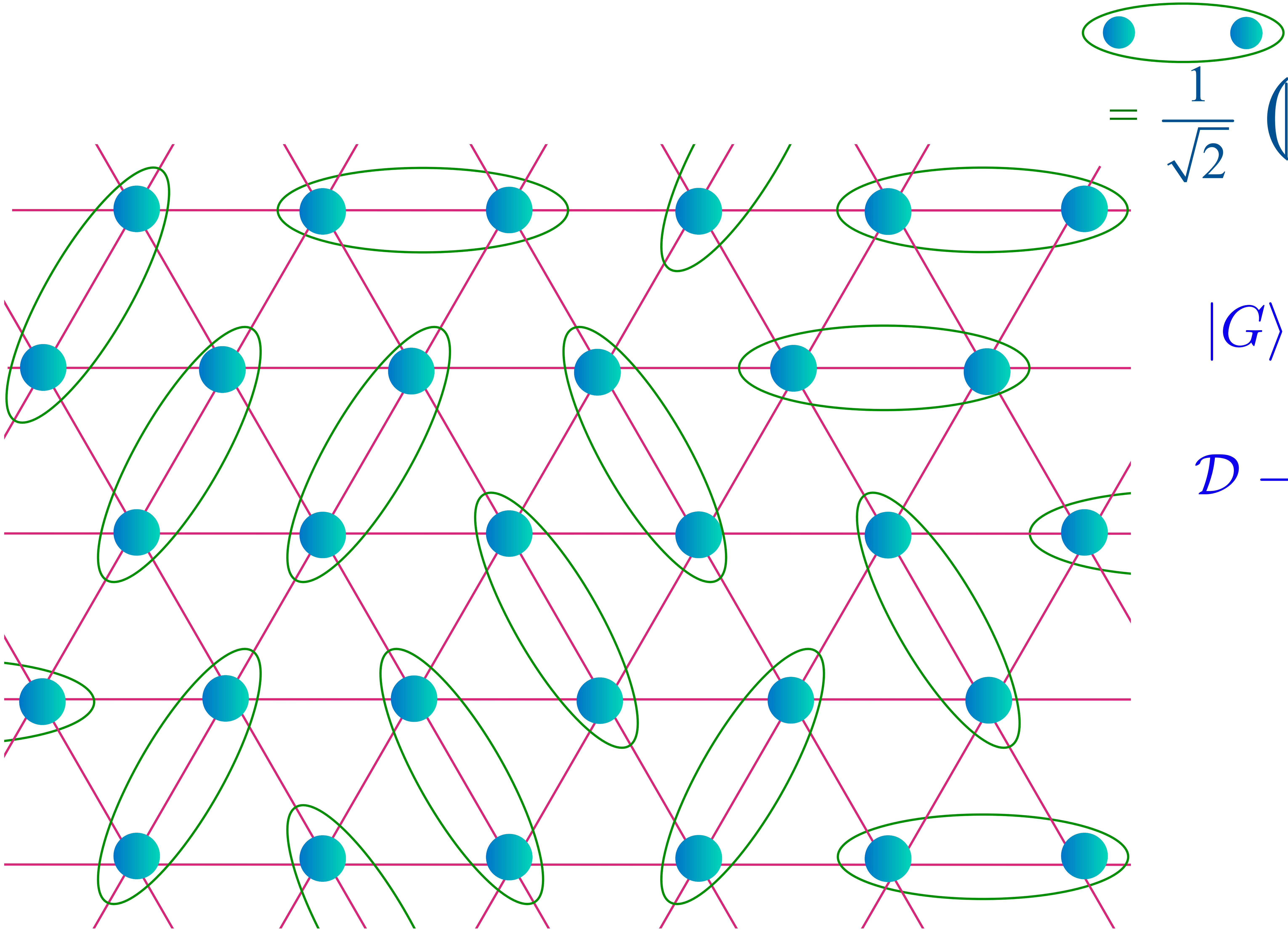

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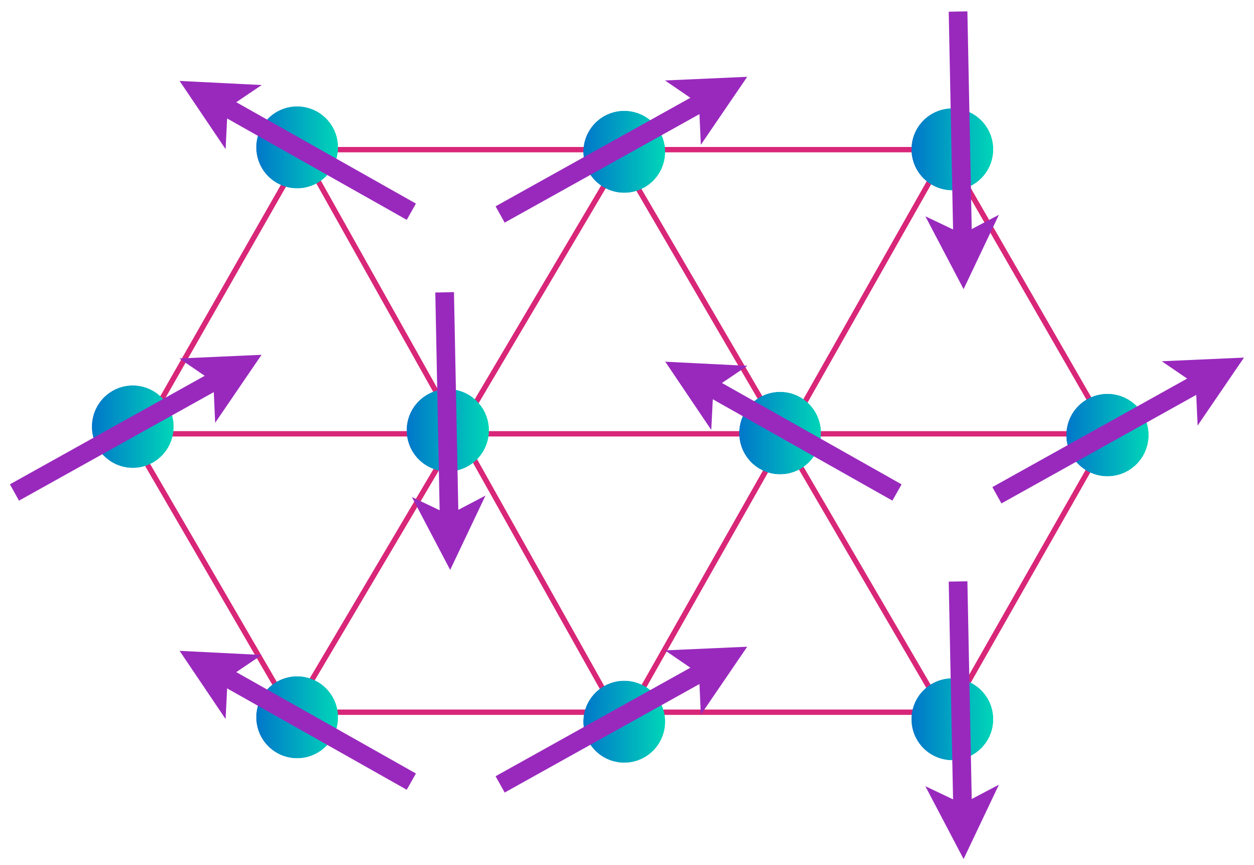


non-collinear Néel state

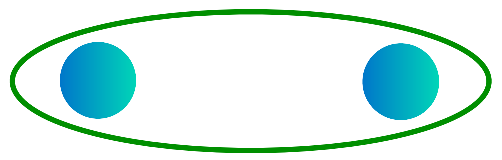
Z_2 spin liquid
with neutral $S = 1/2$ spinons
and **vison** excitations

s_c

s

N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)
X.-G. Wen, *Phys. Rev. B* **44**, 2664 (1991)

Excitations of the Z_2 Spin liquid



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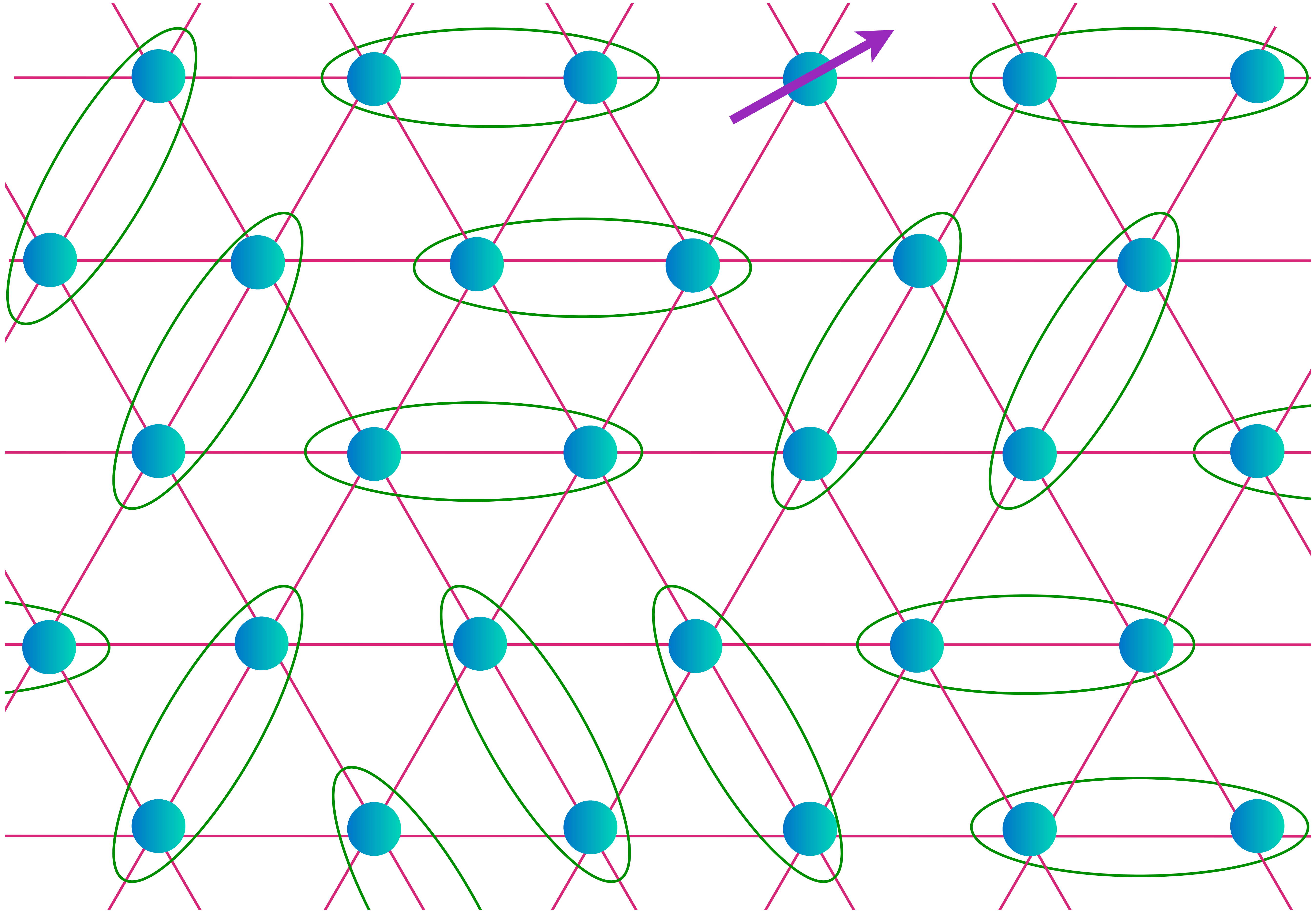
Spinon: $S_z = 1/2$

e (boson) or ϵ (fermion) particle



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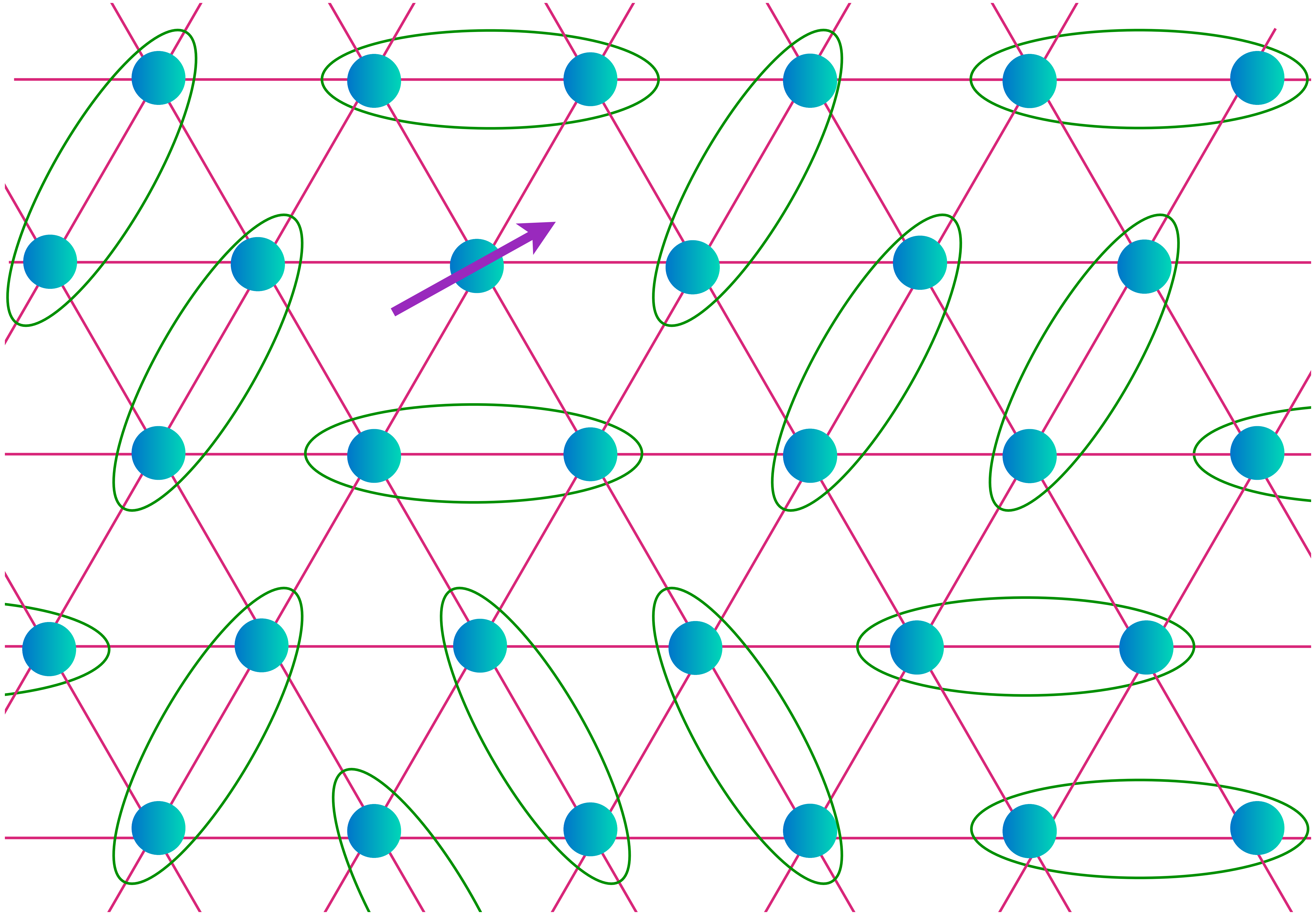

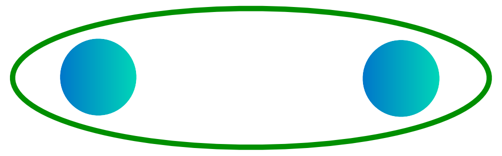

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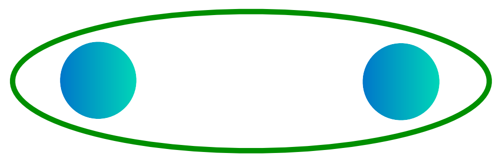

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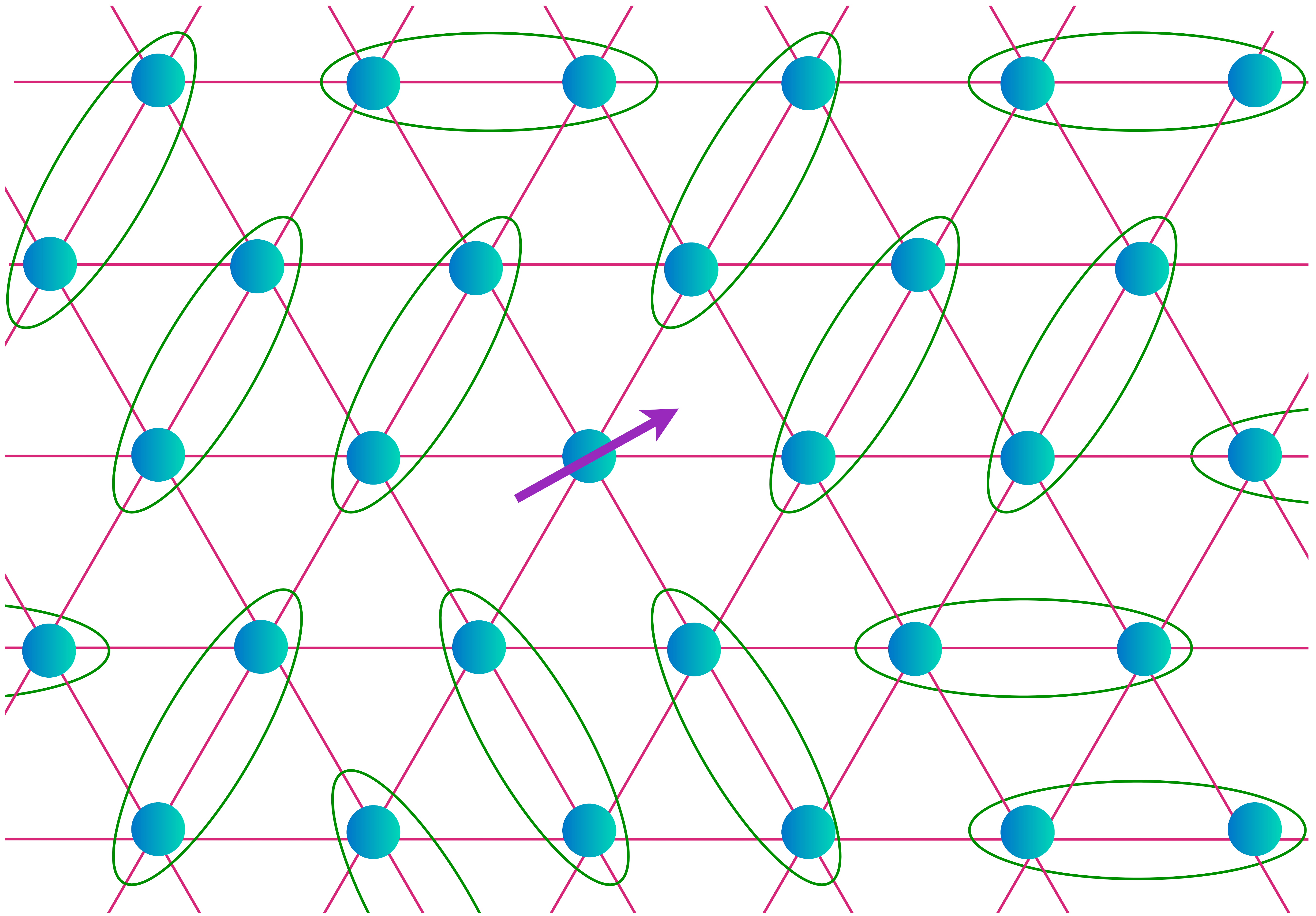

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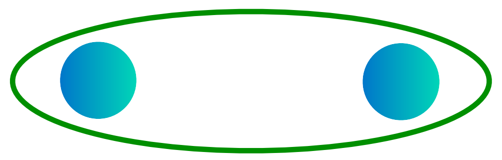

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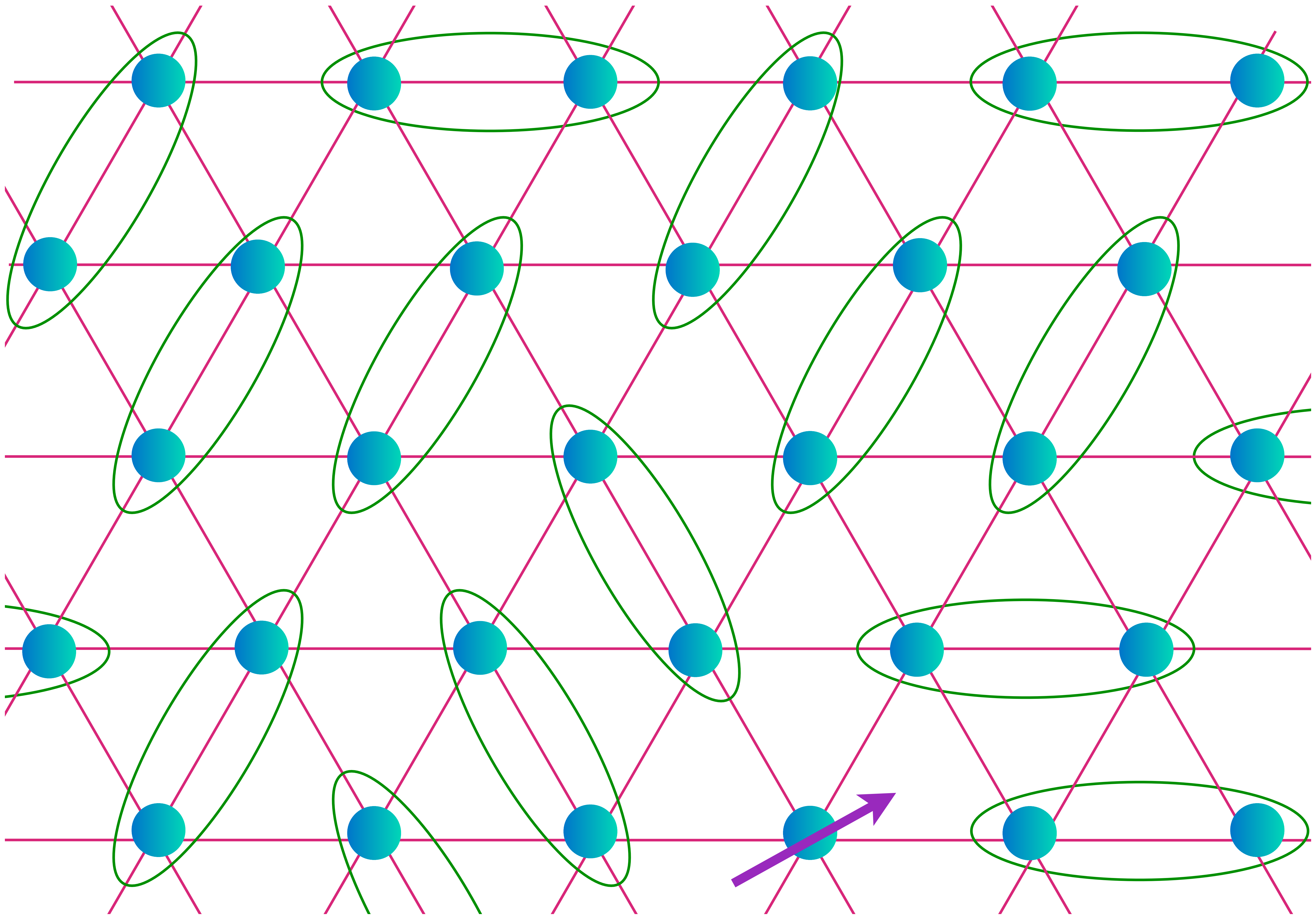

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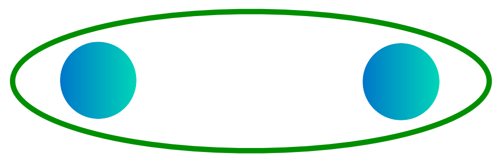

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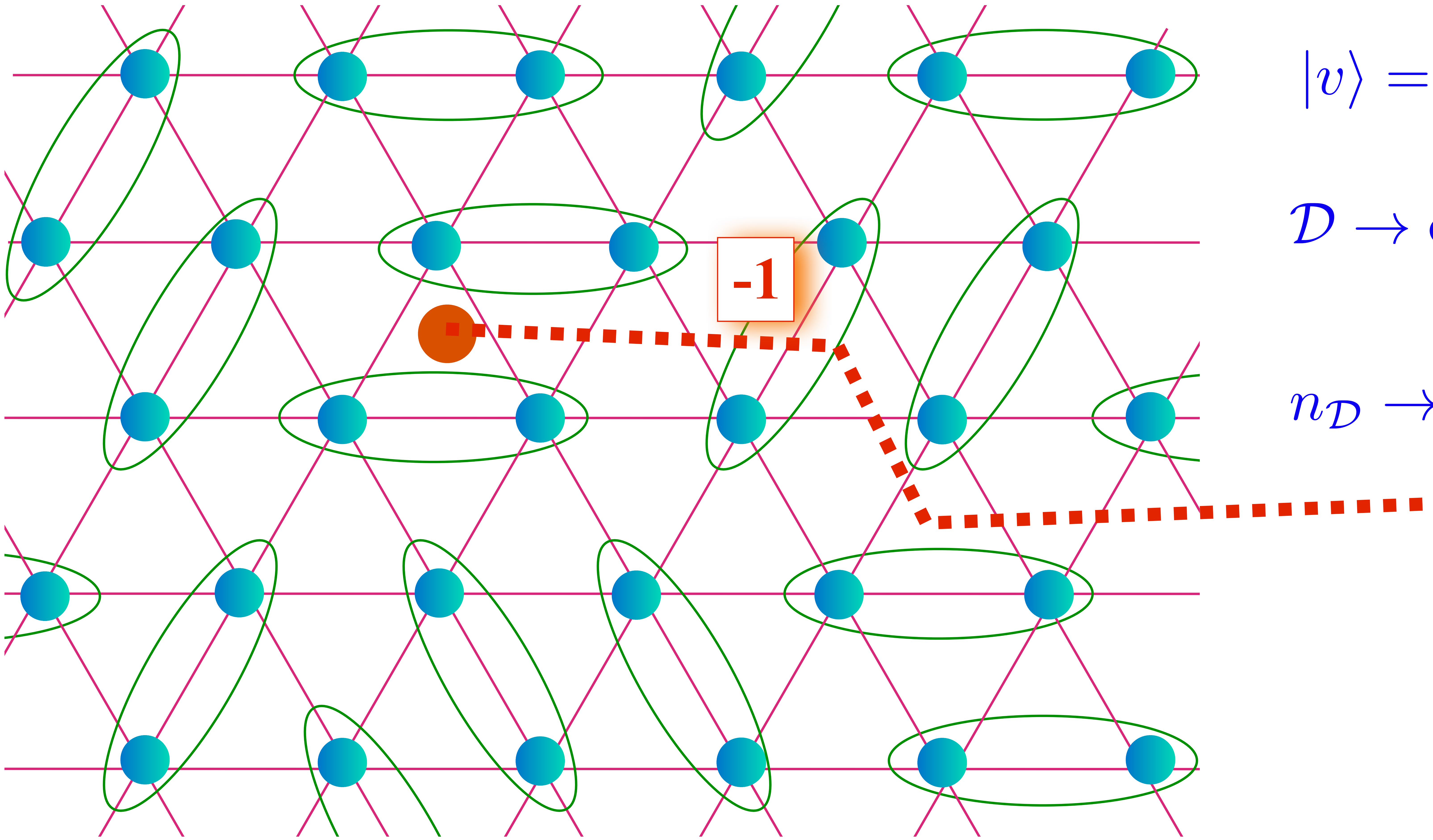
A vison

m (boson) particle



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Excitations of the Z_2 Spin liquid

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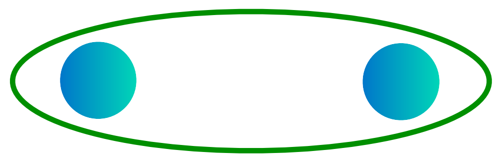

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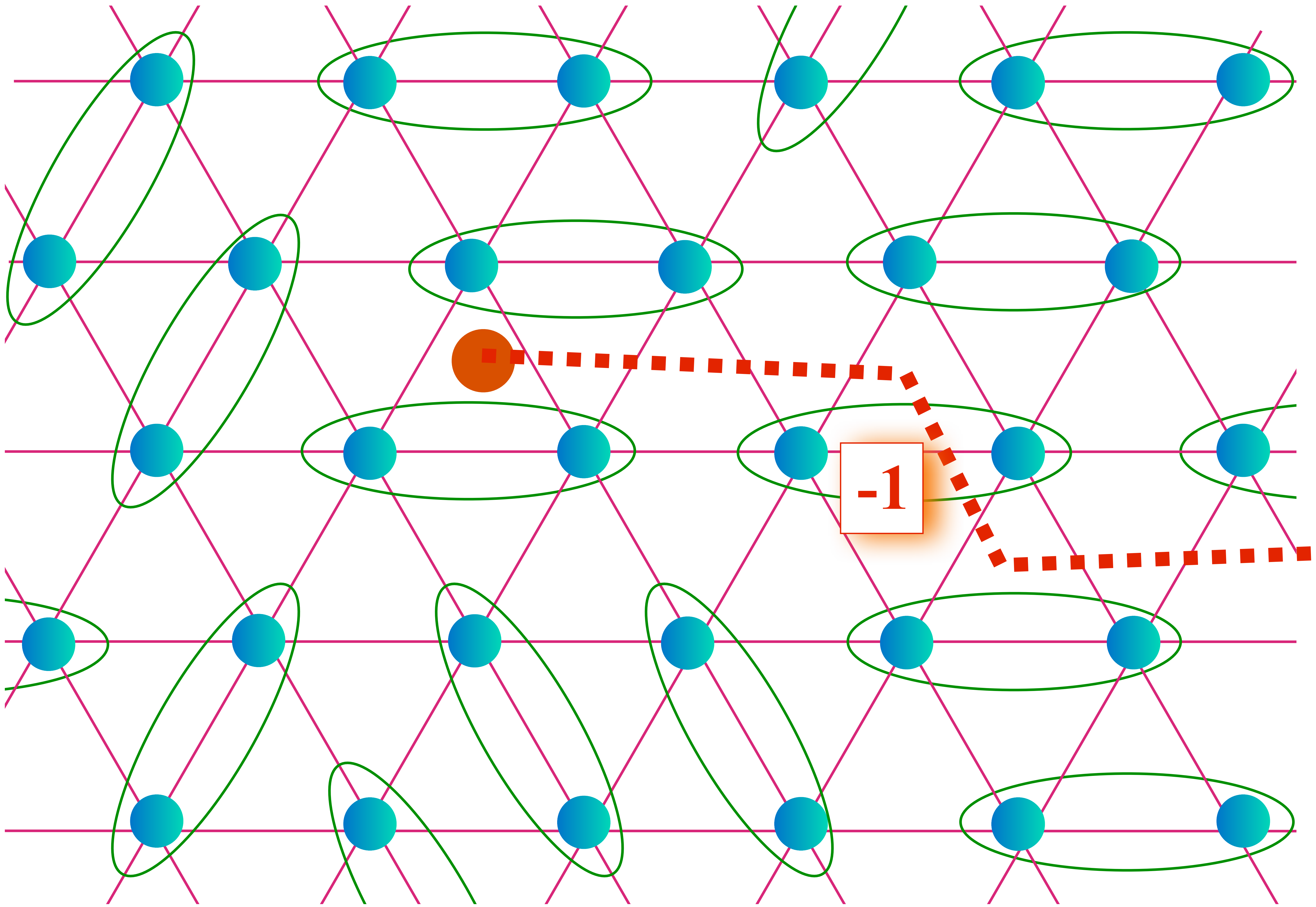

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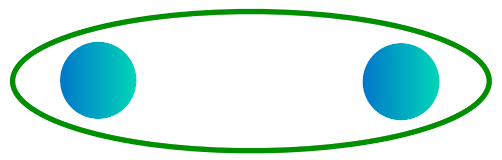

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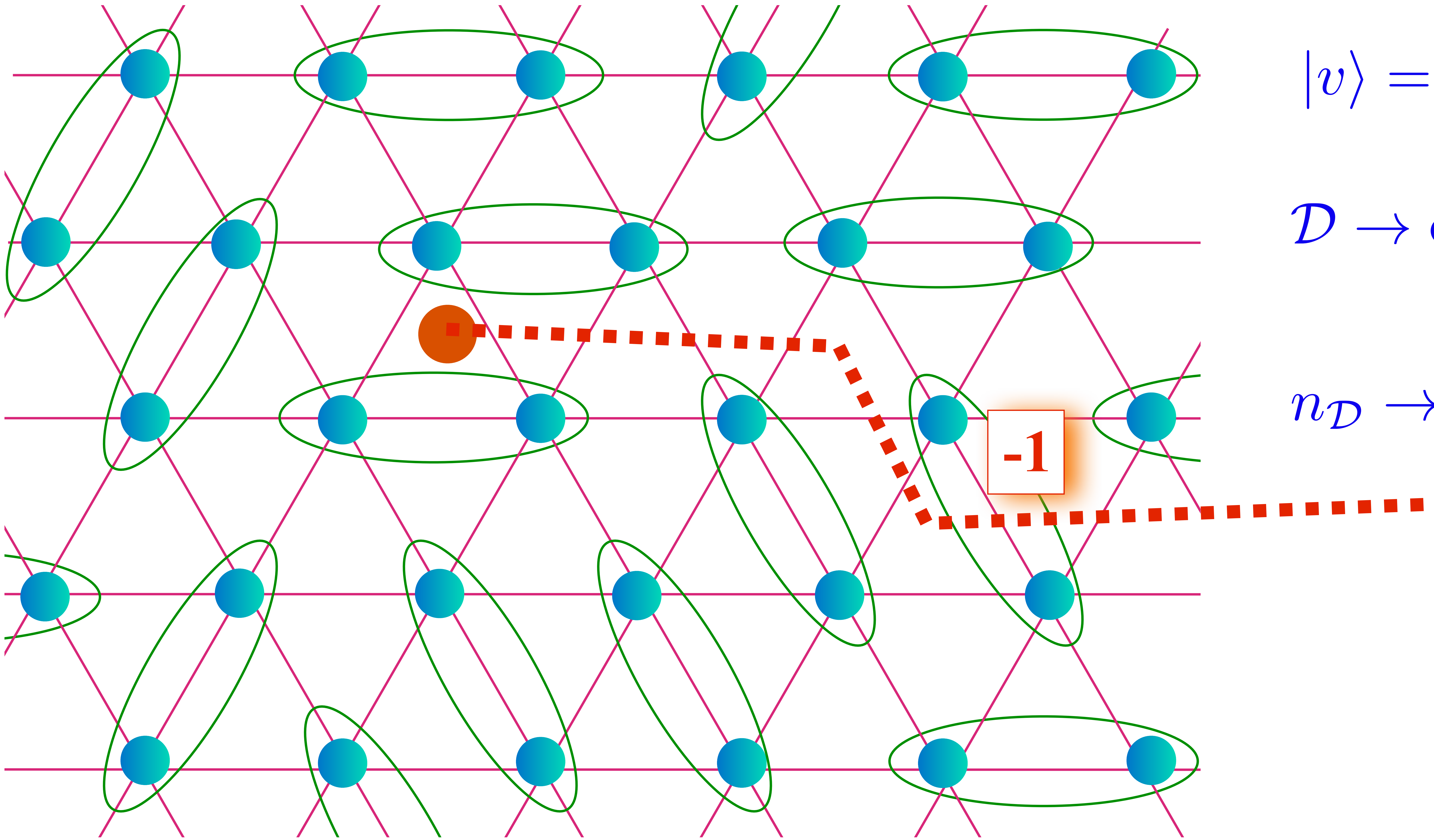

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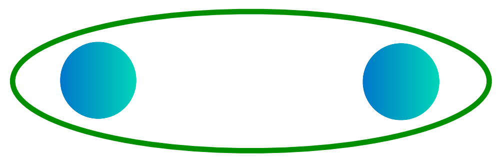

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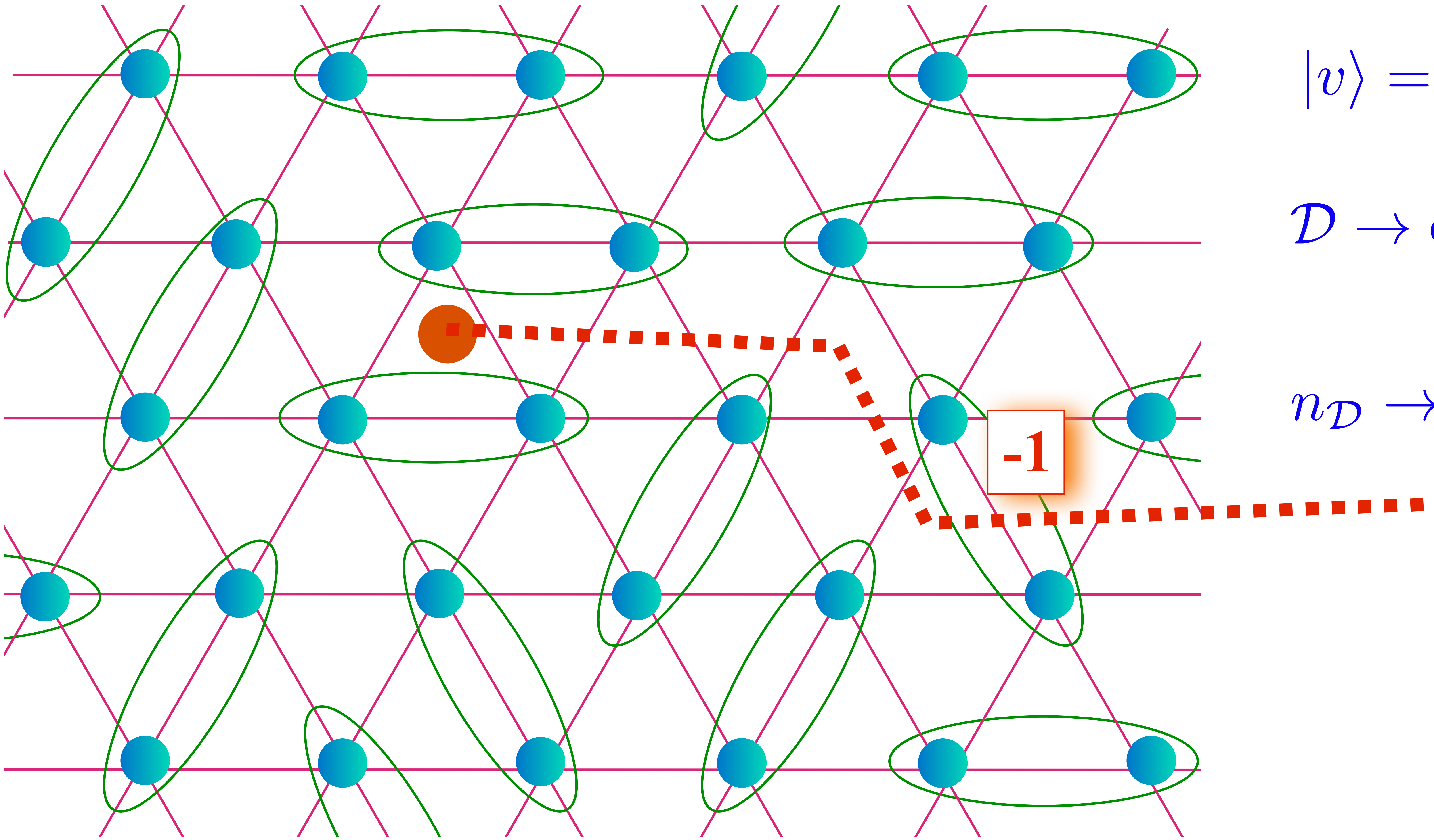

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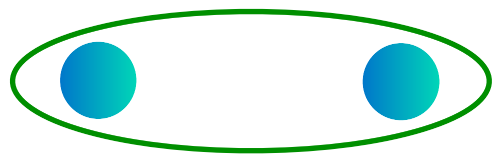

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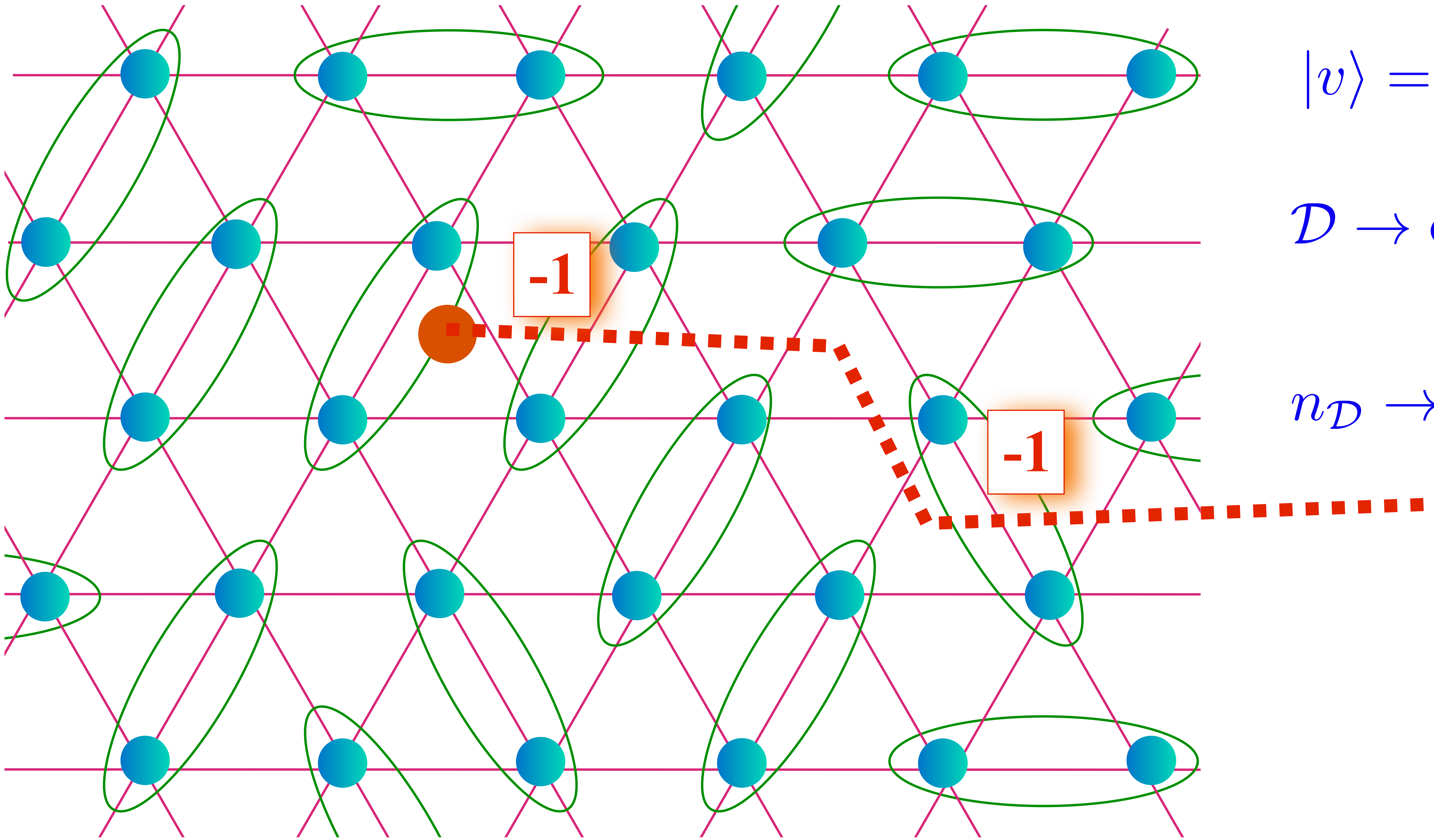

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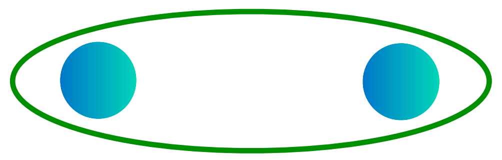
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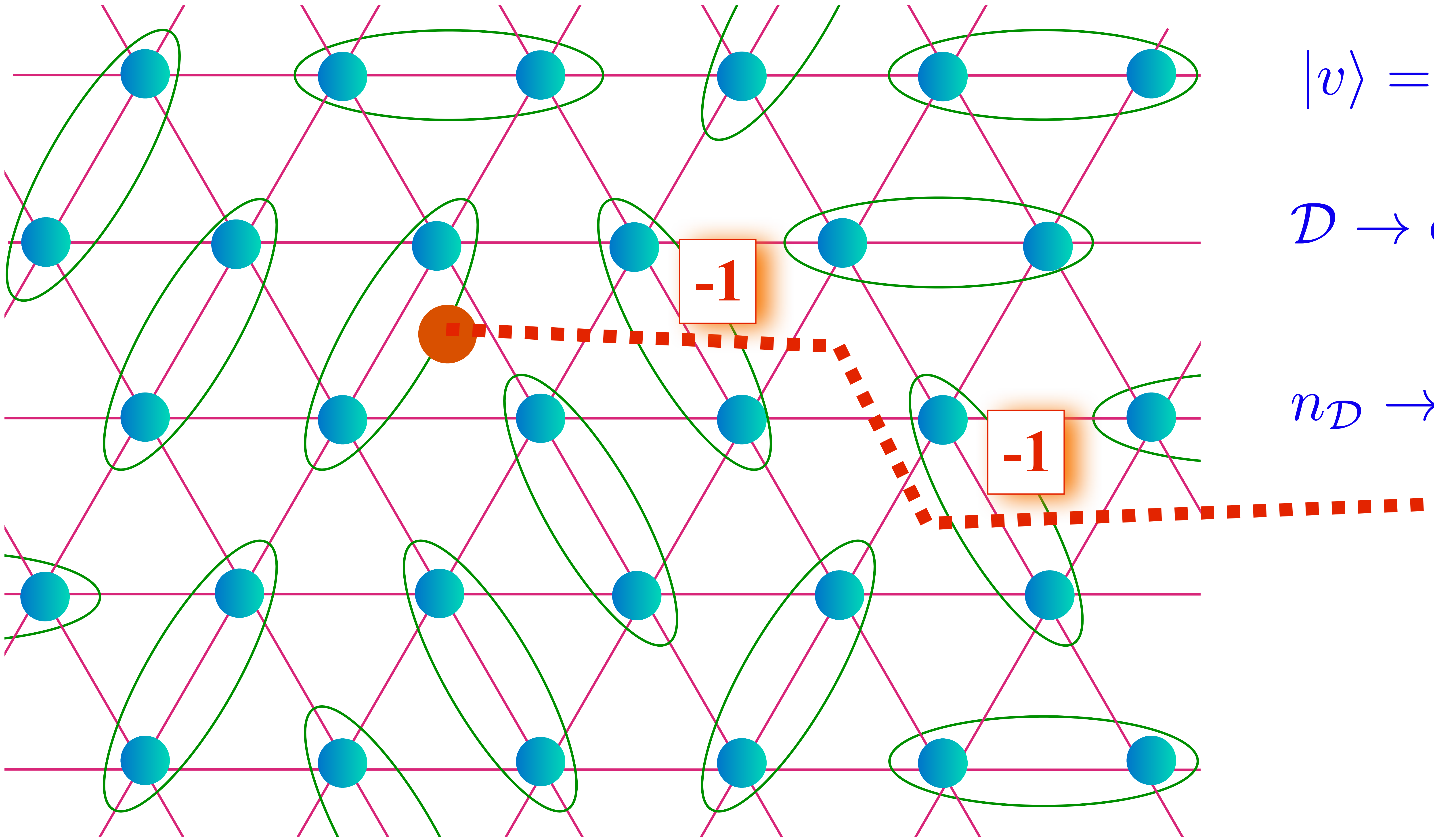

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Excitations of the Z_2 Spin liquid

- A spinon adiabatically transported around a vison picks up a phase factor of -1: spinons and visons are mutual semions.

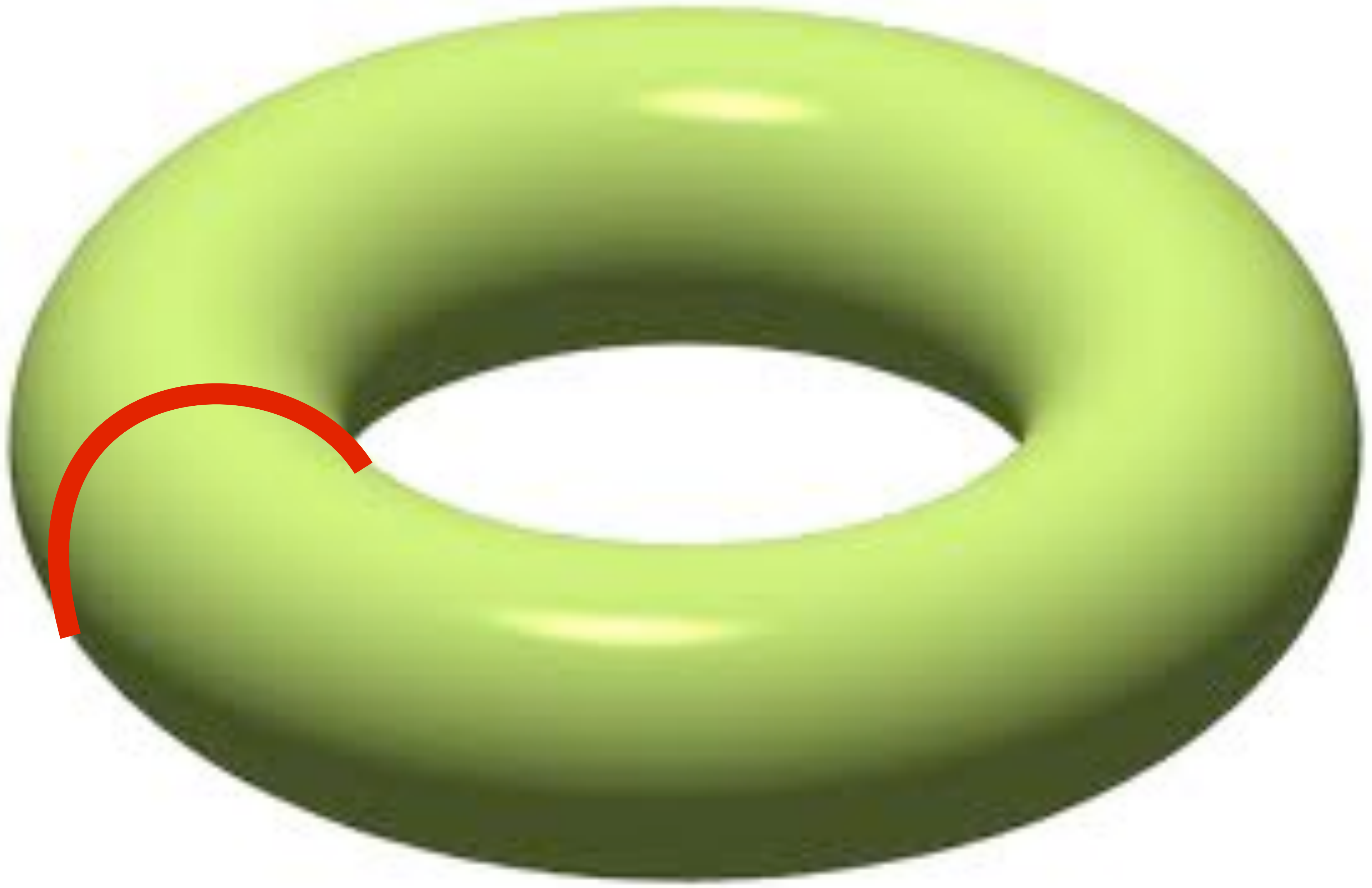
- A bound state of a spinon and a vison picks up a phase factor of -1 when exchanged with another bound state of a spinon and a vison:

  - The ϵ spinon (fermion) is a bound state of the e spinon (boson) and a vison ($\epsilon = e \times m$).
  - The e spinon (boson) is a bound state of the ϵ spinon (fermion) and a vison ($e = \epsilon \times m$).

Ground state degeneracy on the torus

Place insulator on a torus:

Ground state degeneracy on the torus

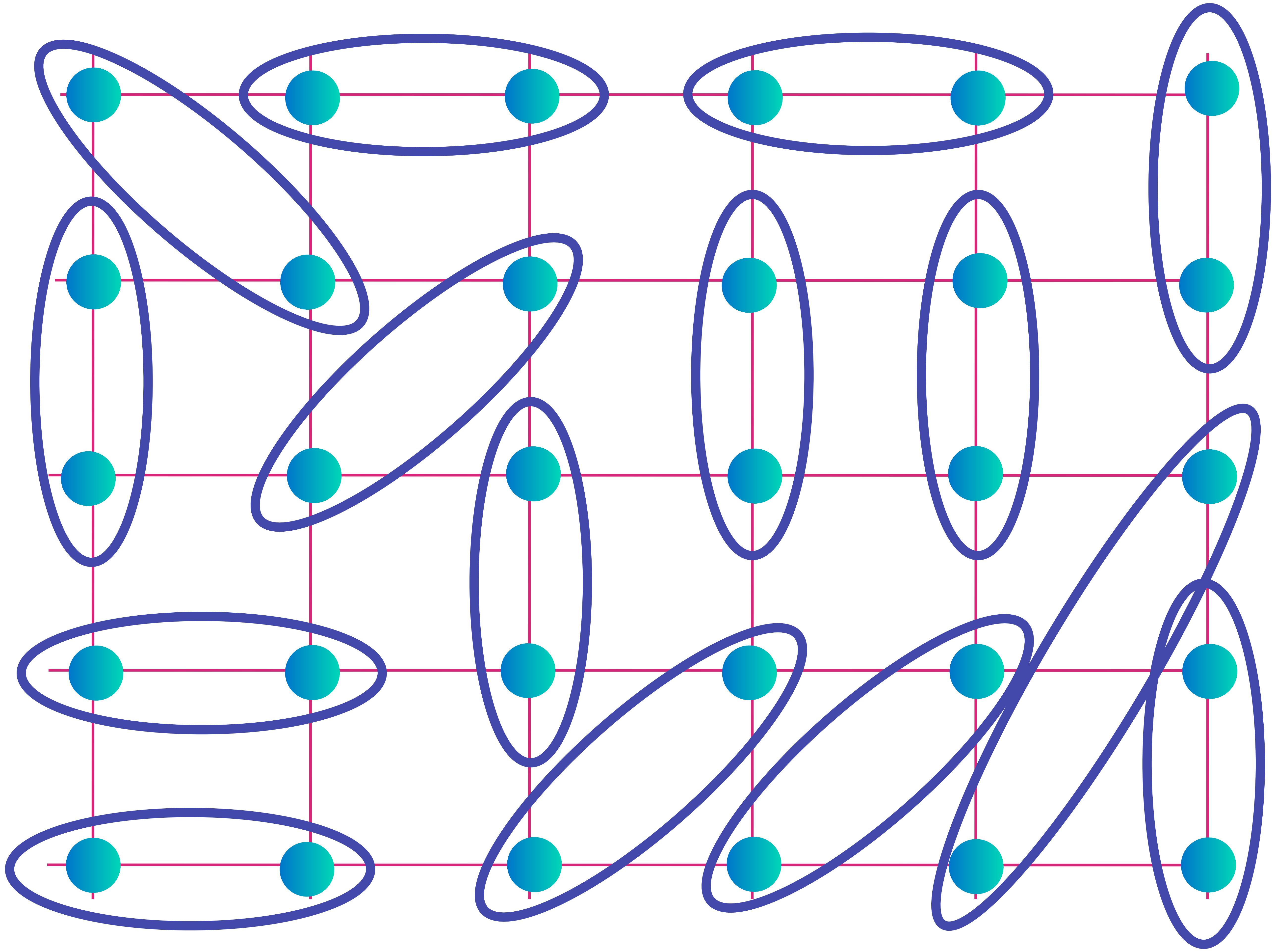


Place insulator on a torus:

Obtain a degenerate orthogonal state by modifying the wavefunction on a “branch-cut” encircling the torus.

Ground state degeneracy on the torus

$$\bullet\!\!-\!\!\bullet = \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$



Place insulator on a torus:

Number of dimers crossing "branch-cut" is conserved modulo 2: there are nearly degenerate states with odd and even dimer-cuts

D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

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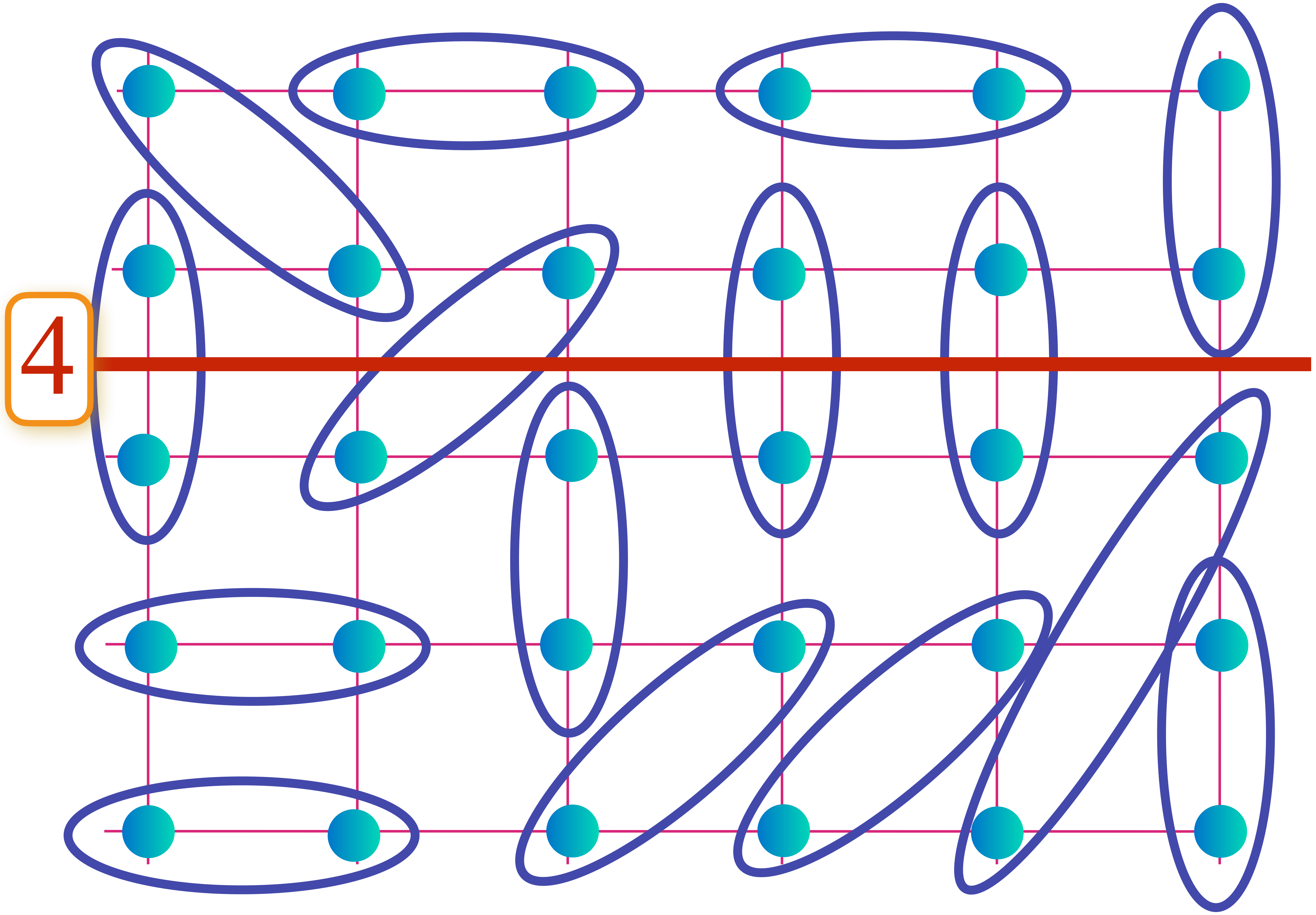

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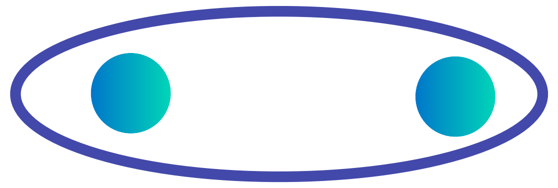

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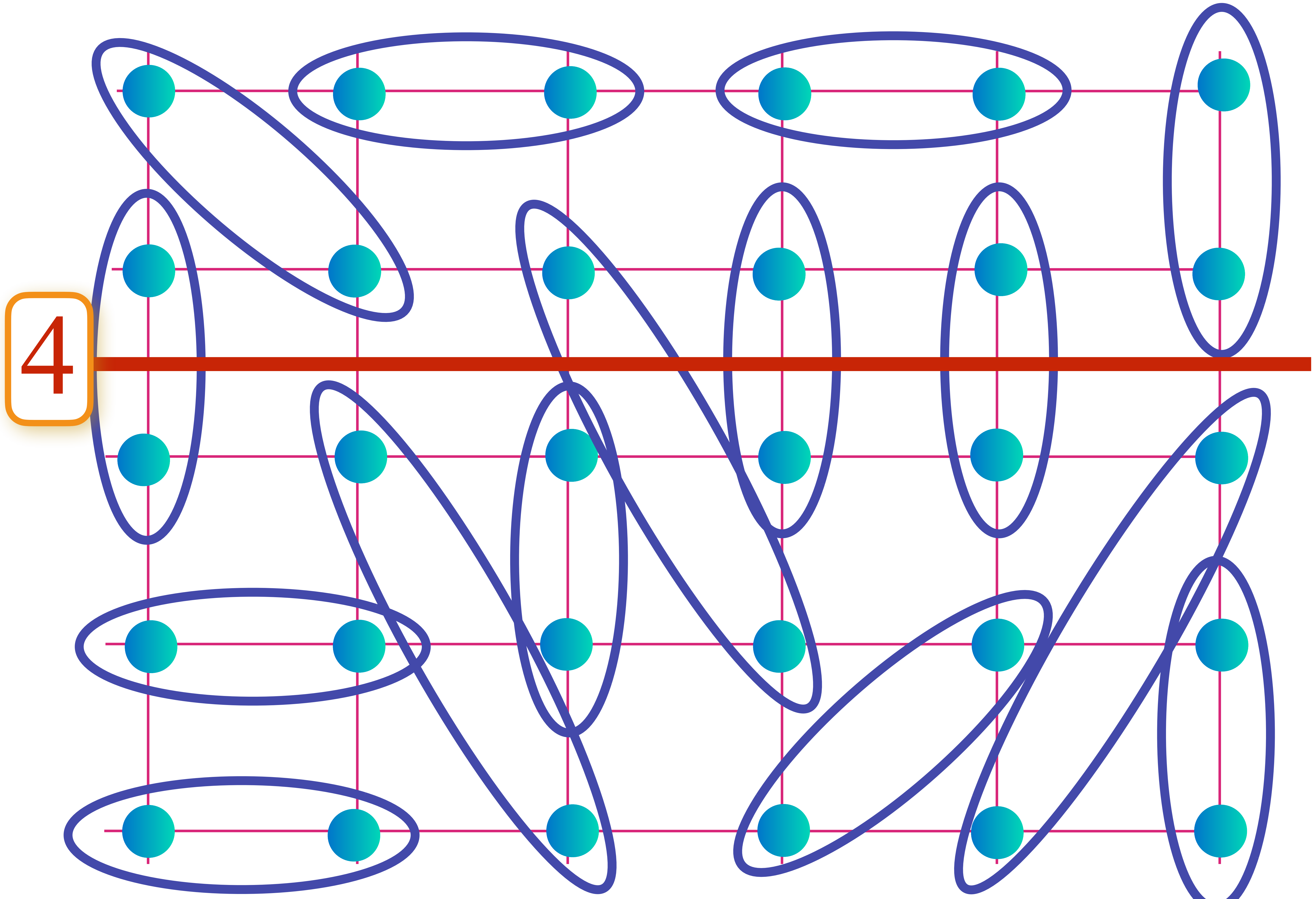

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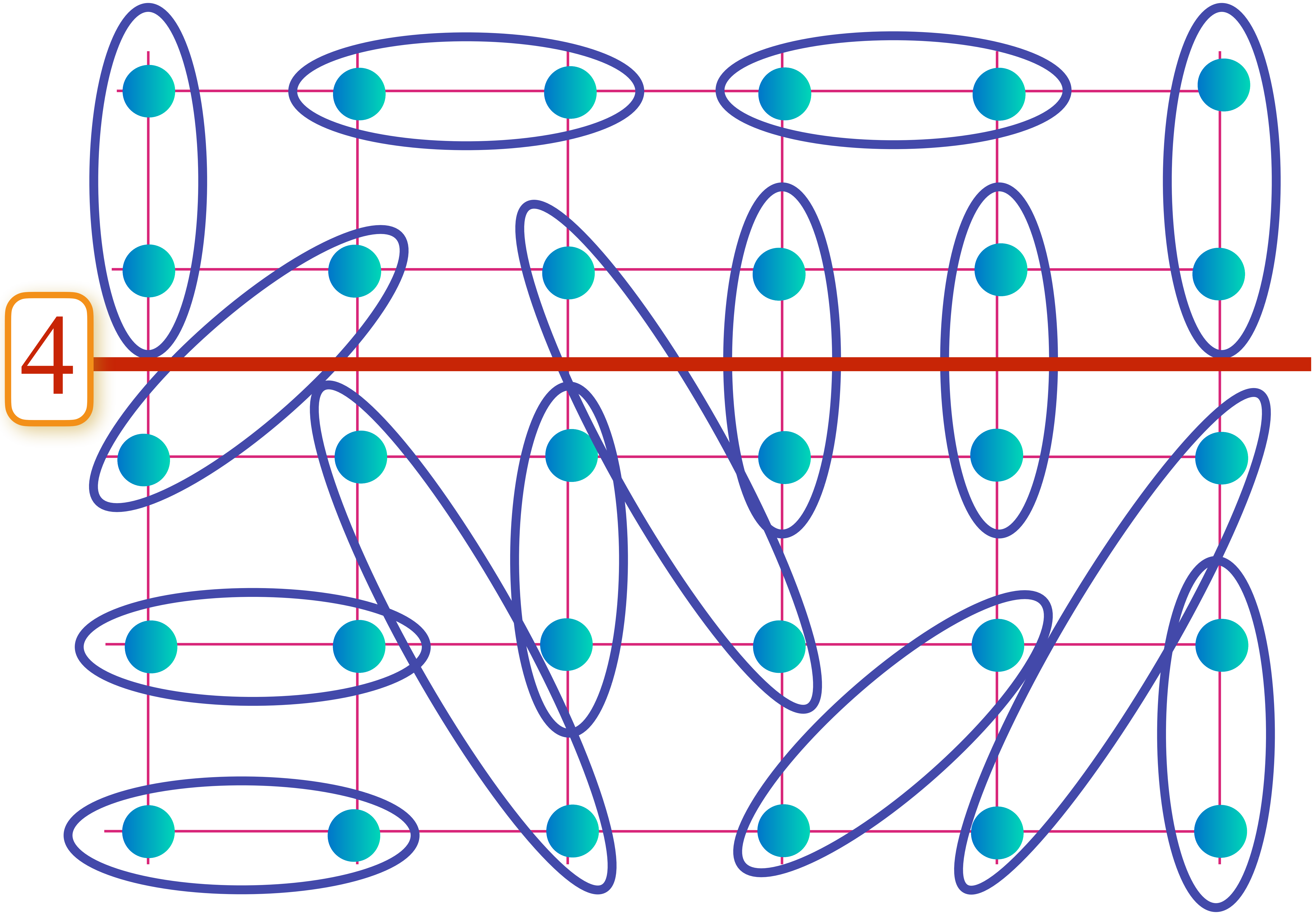

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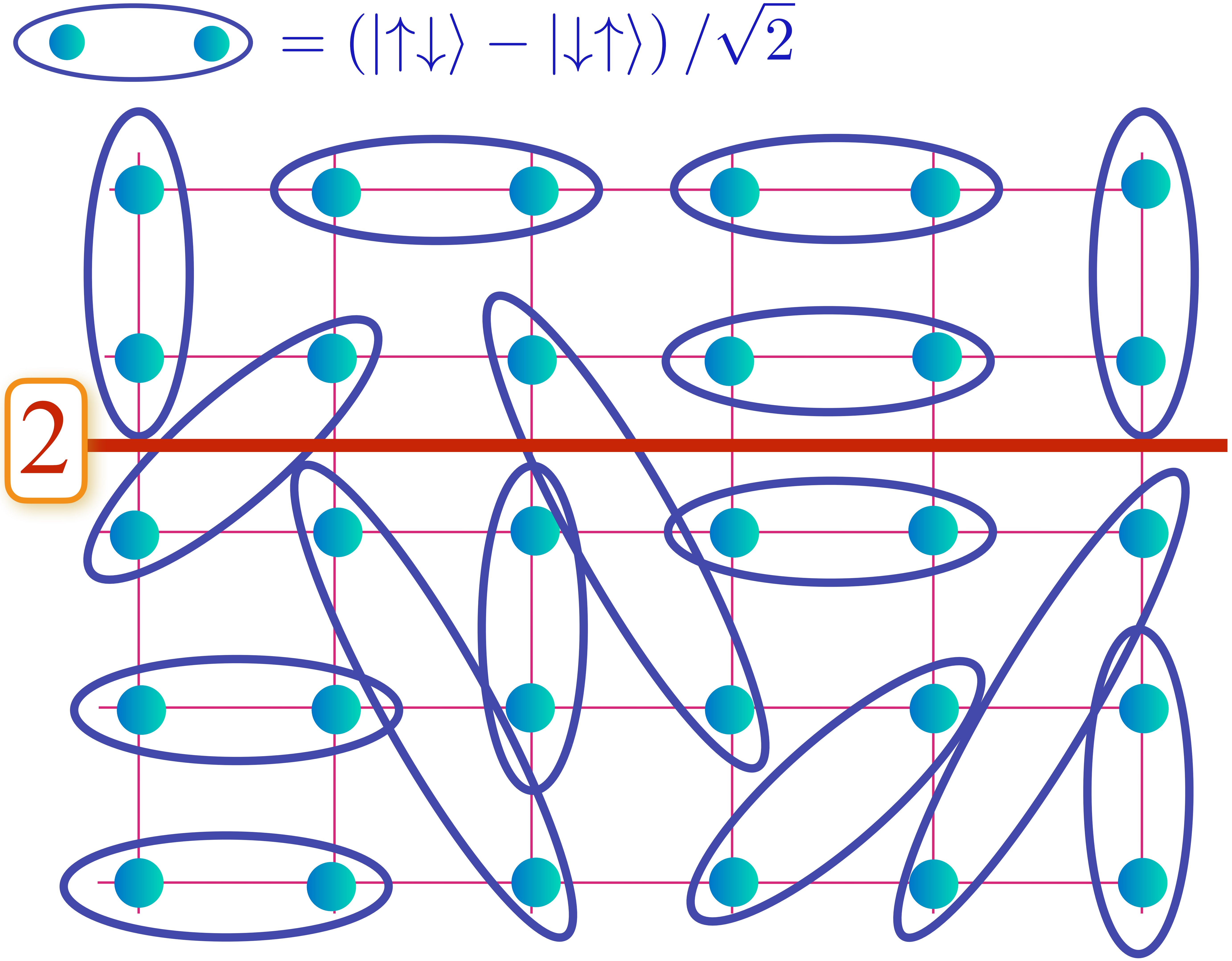
D.J. Thouless, PRB **36**, 7187 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, Europhys. Lett. **6**, 353 (1988)

Ground state degeneracy on the torus

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



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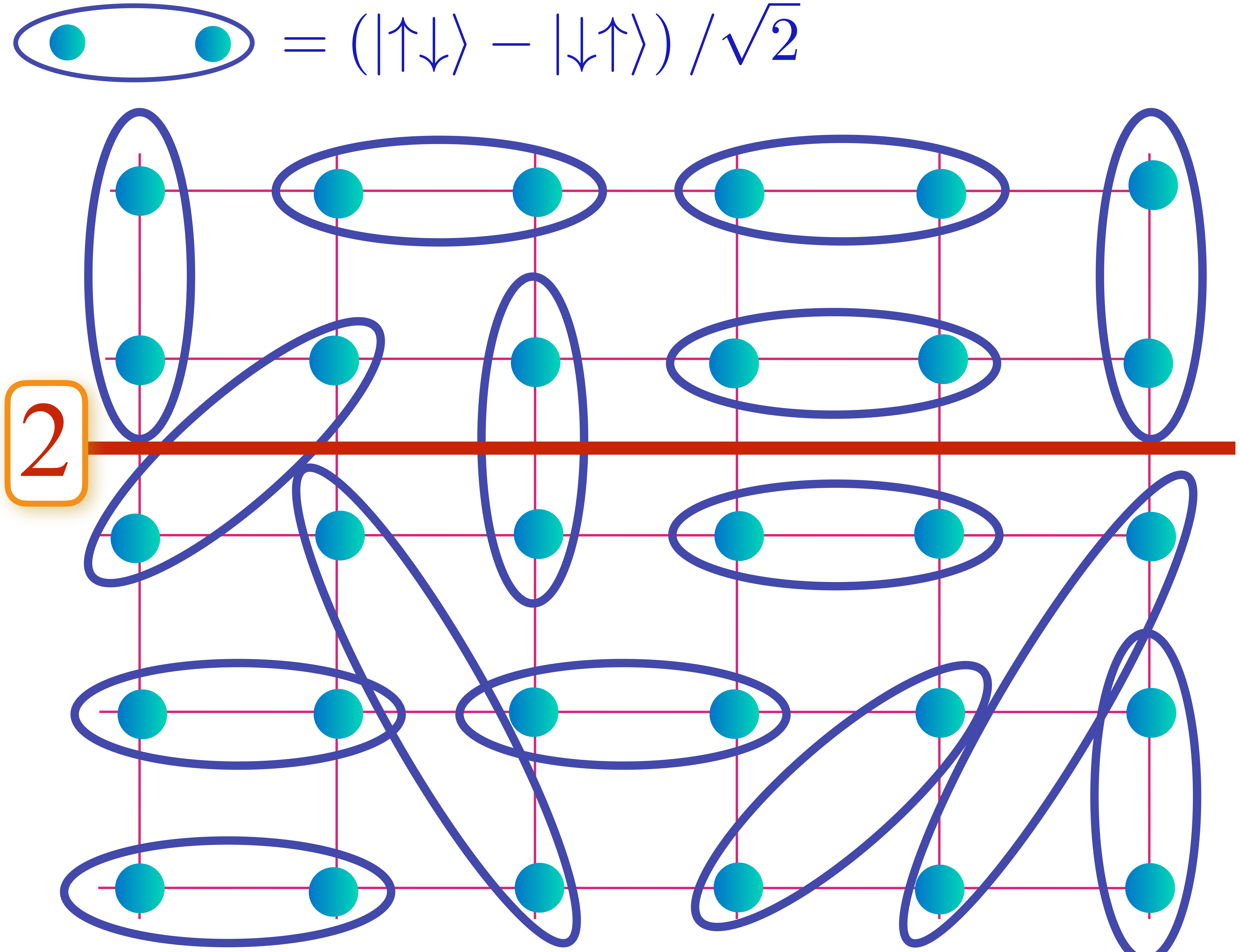

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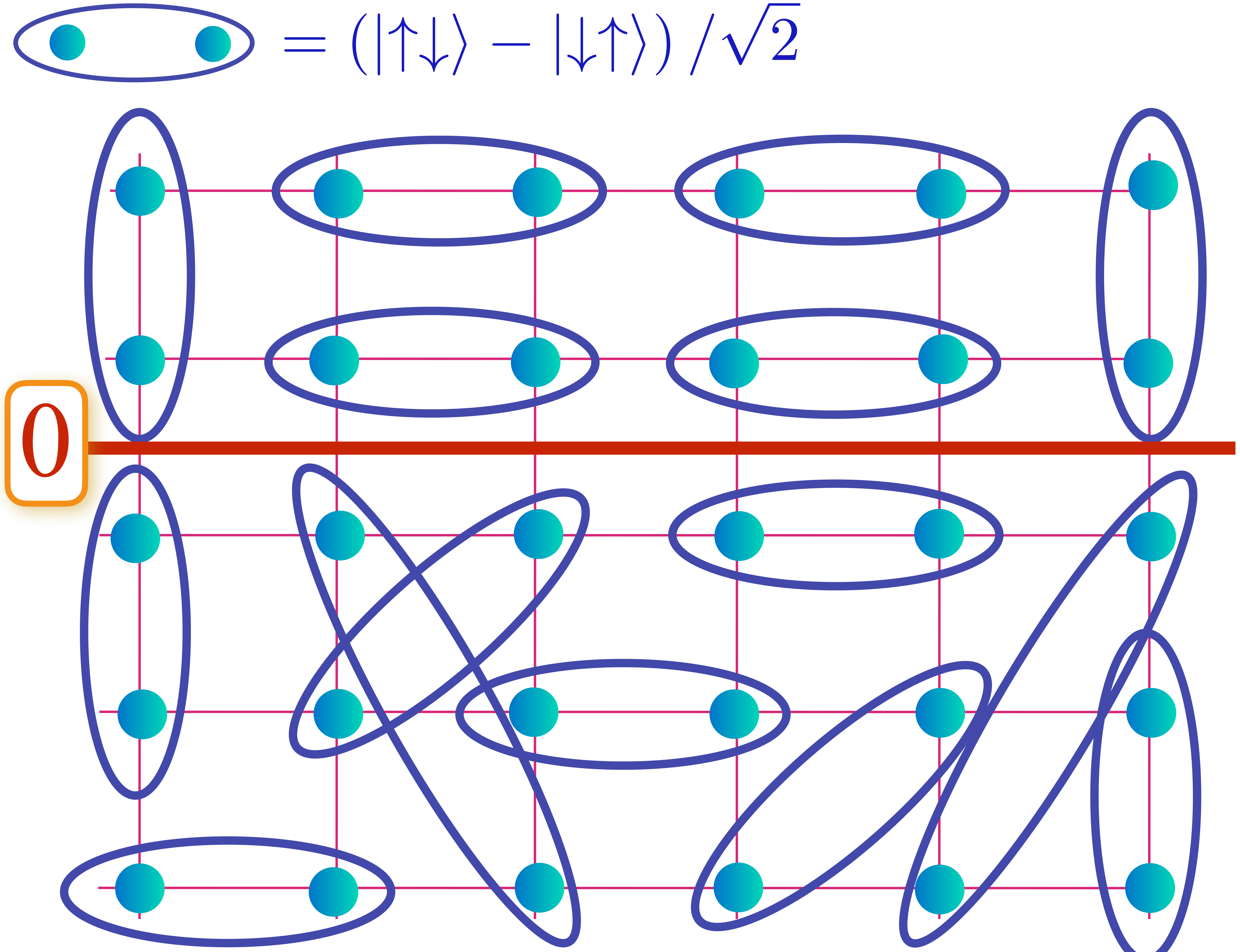

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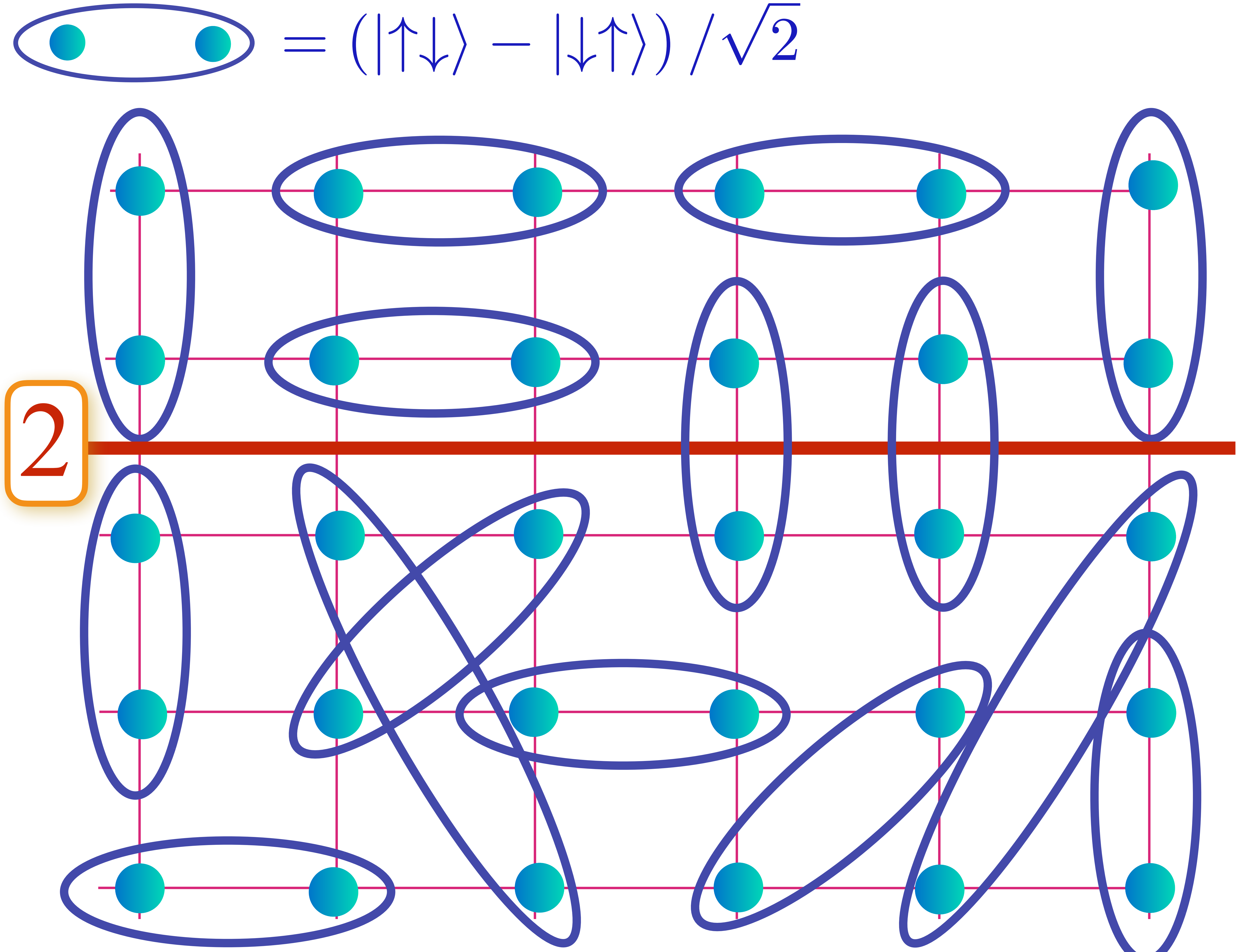

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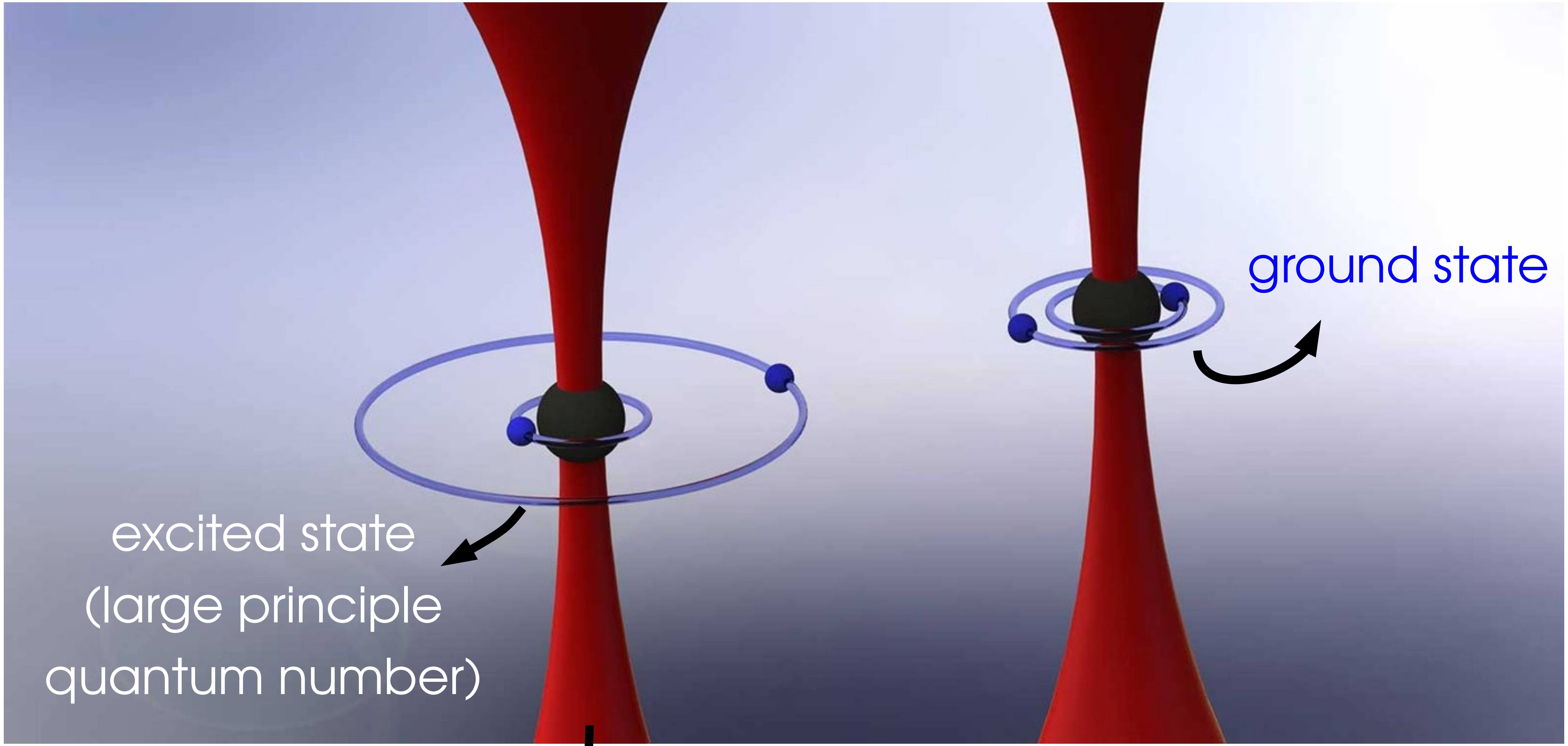
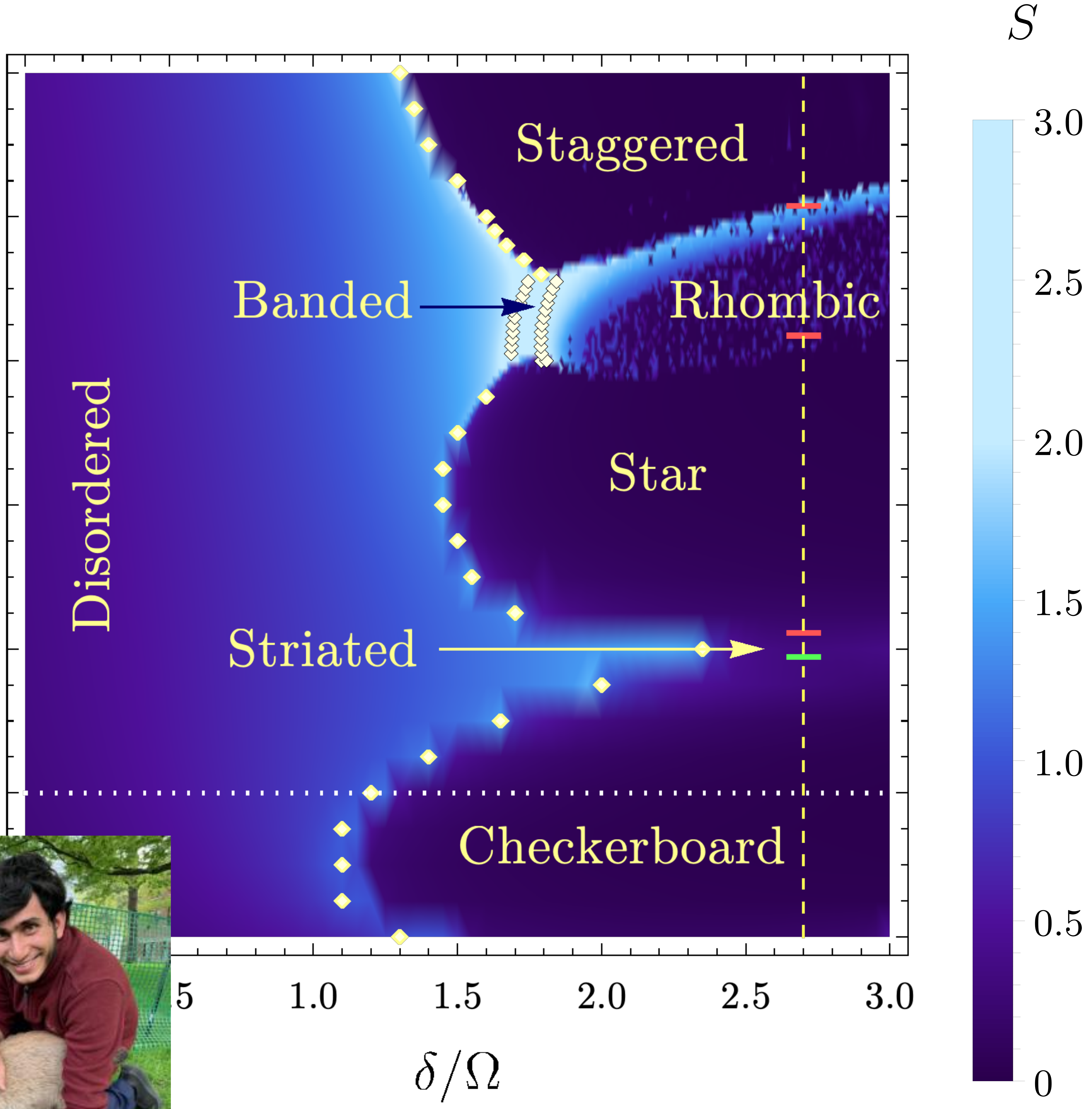


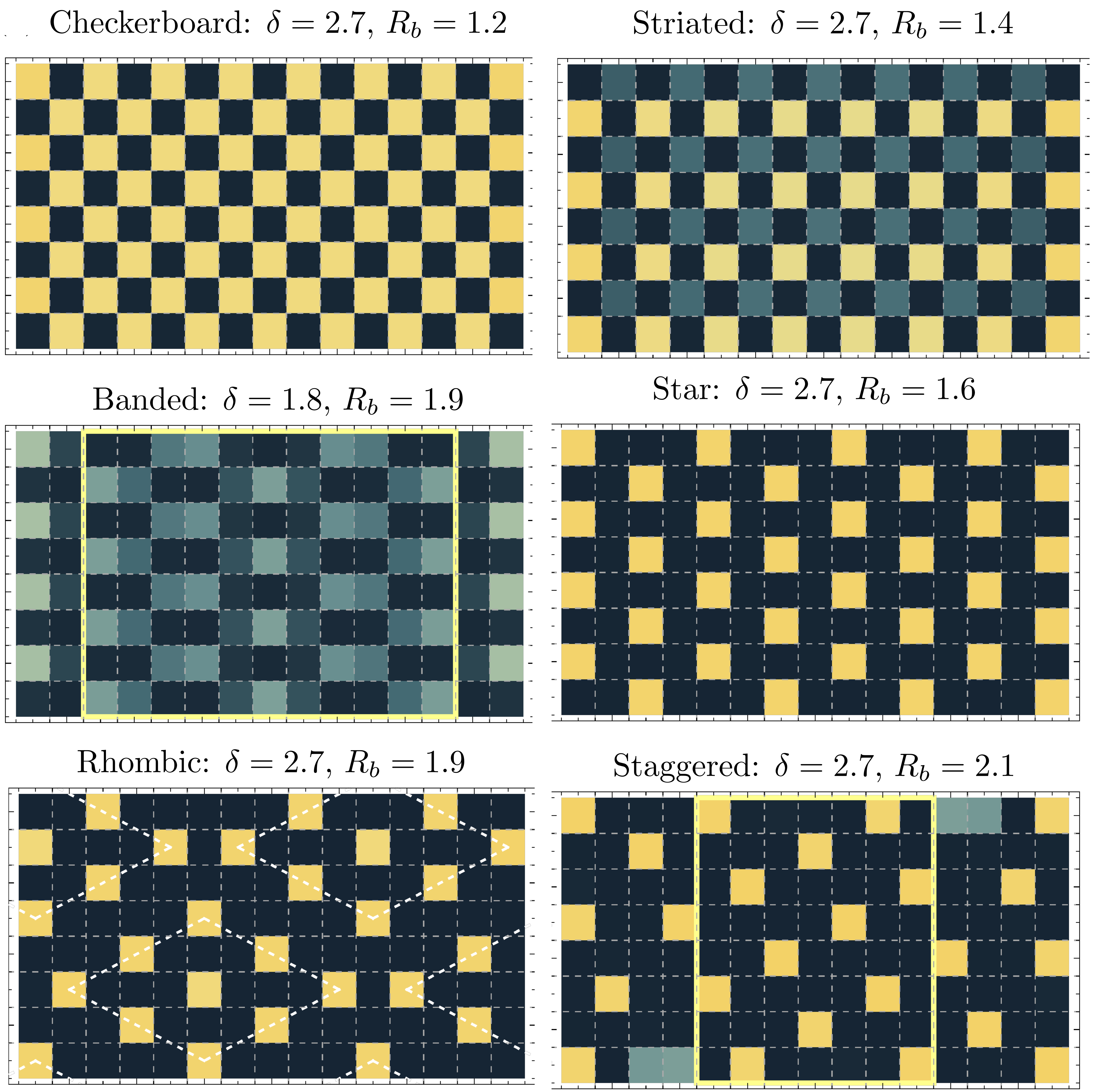
$$V_{|i-j|} \sim |i-j|^{-6}$$

Fig: https://www.caltech.edu/about/news/quantum-innovations-achieved-using-alkaline-earth-atoms

$$H_{\mathrm{Ryd}} = \sum_i \left[\frac{\Omega}{2} \left(|g\rangle\langle r| + |r\rangle\langle g| \right)_i - \Delta |r\rangle\langle r| \right] + \sum_{(i,j)} V_{|i-j|} \Big(|r\rangle\langle r|_i \otimes |r\rangle\langle r|_j \Big)$$

Rydberg atoms on the square lattice: theory



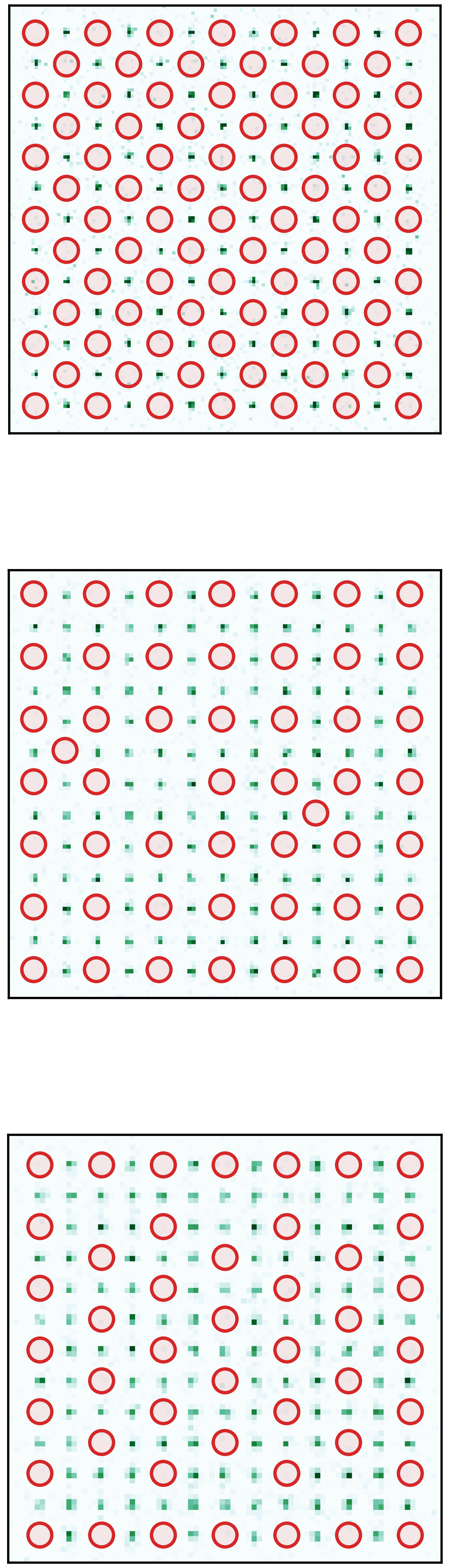


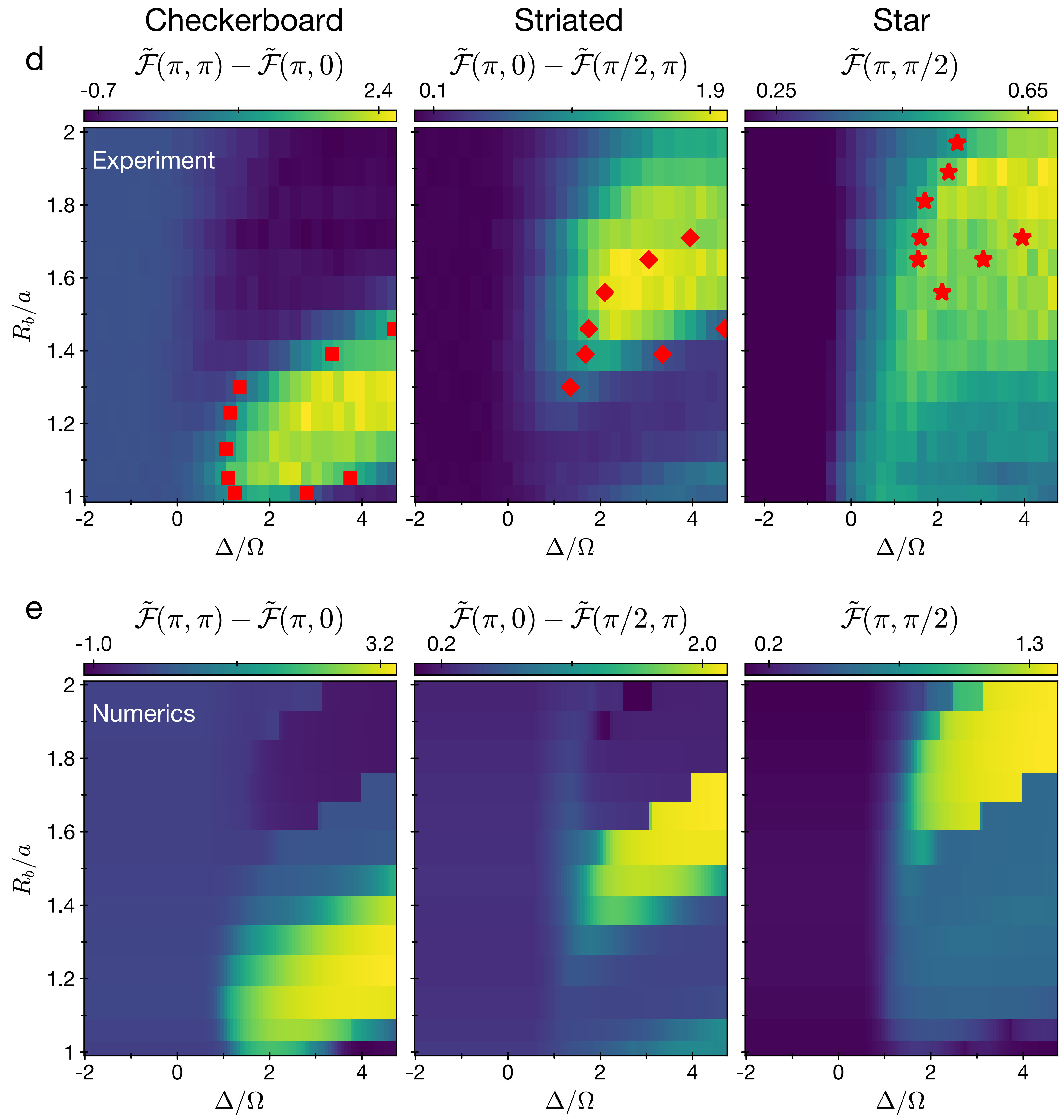
R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PRL **124**, 103601 (2020)

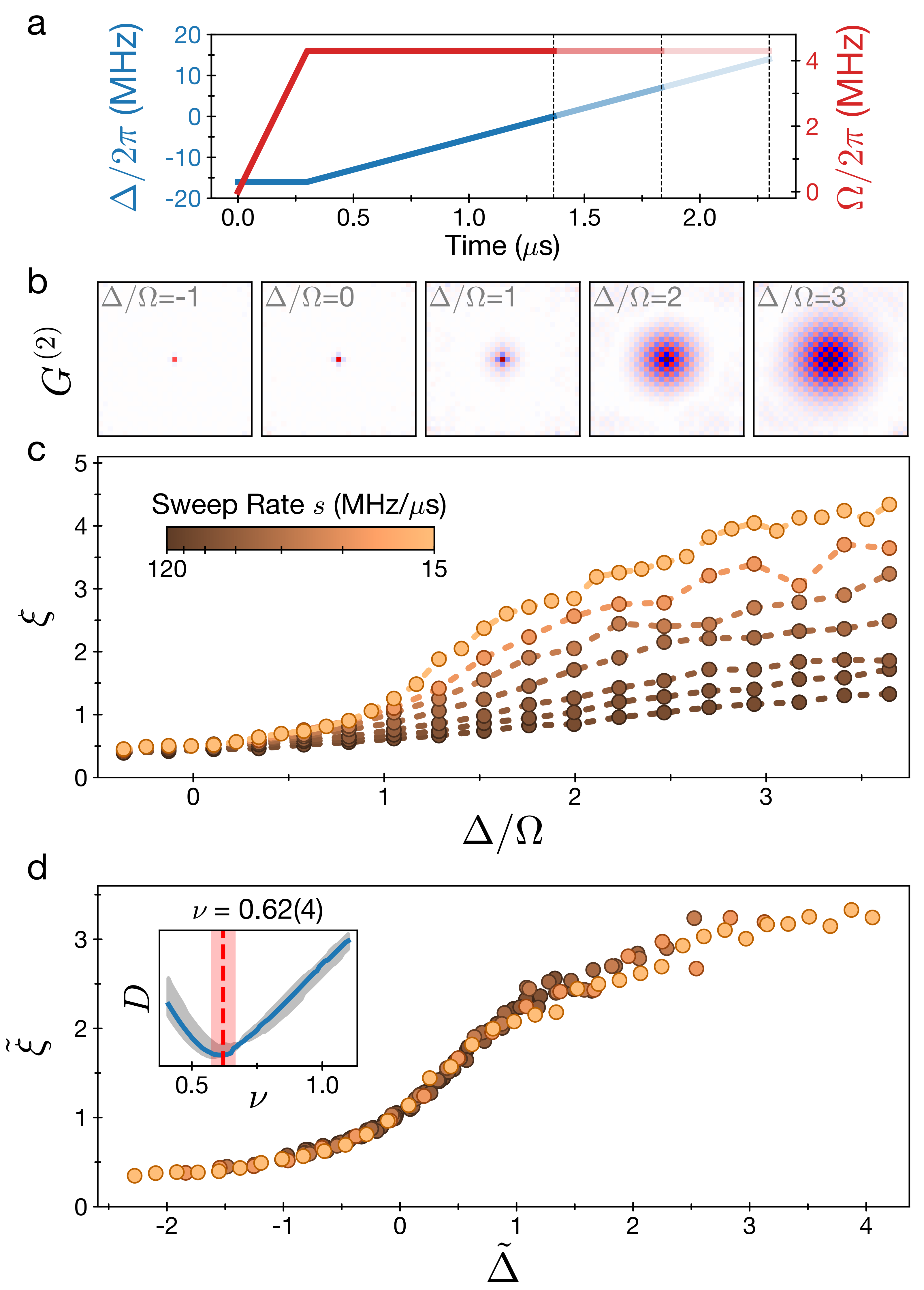
Rydberg atoms on the square lattice: experiment

$$\tilde{\xi} = \xi (s/s_0)^{\mu}$$

$$\tilde{\Delta} = (\Delta - \Delta_c)(s/s_0)^{\kappa}$$



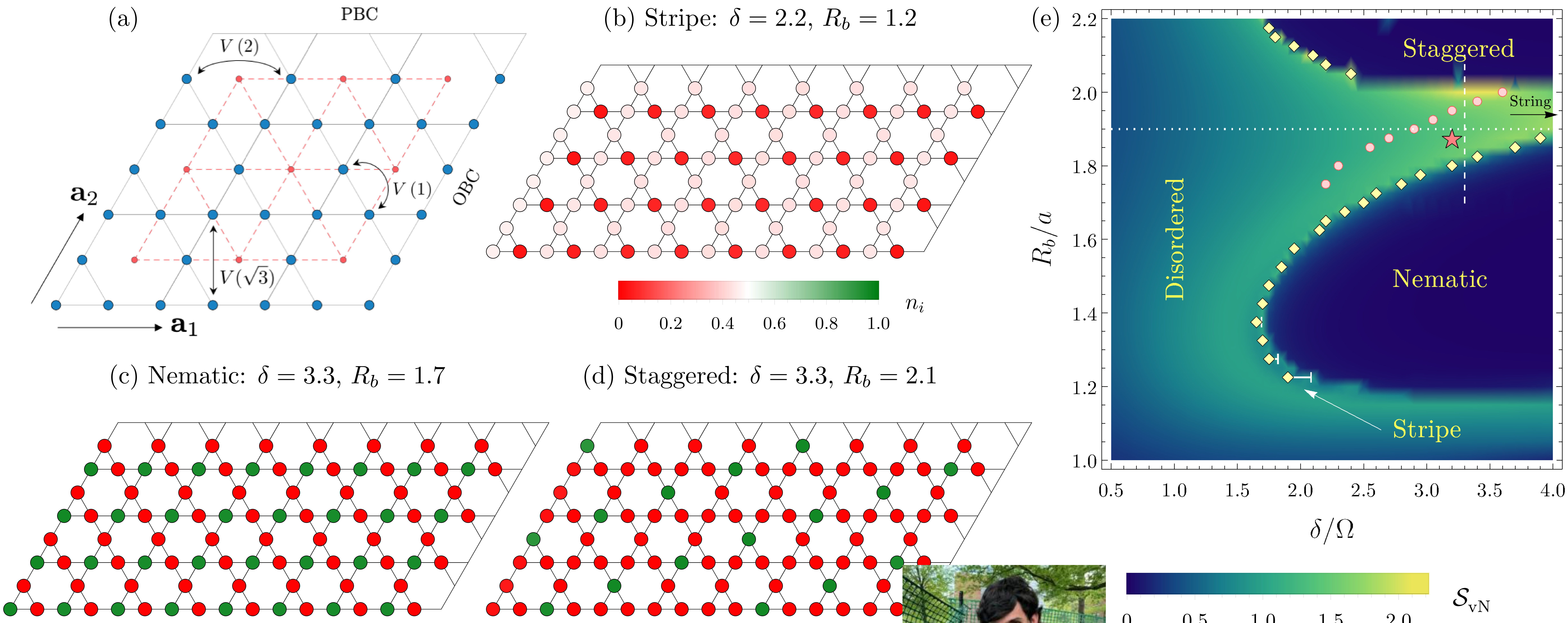




Quantum Phases of Matter on a 256-Atom Programmable Quantum Simulator, Sepehr Ebadi, Tout T. Wang, Harry Levine, Alexander Keesling, Giulia Semeghini, Ahmed Omran, Dolev Bluvstein, Rhine Samajdar, Hannes Pichler, Wen Wei Ho, Soonwon Choi, Subir Sachdev, Markus Greiner, Vladan Vuletic, and Mikhail D. Lukin, Nature **595**, 227 (2021); Pascal Scholl et al. arXiv:2012.12268

First observation of Ising quantum phase transition in 2+1 dimensions

Rydberg atoms on site-kagome lattice: theory



R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, and S. Sachdev, PNAS **118**, e2015785118 (2021)

Rydberg atoms on site-kagome lattice: theory

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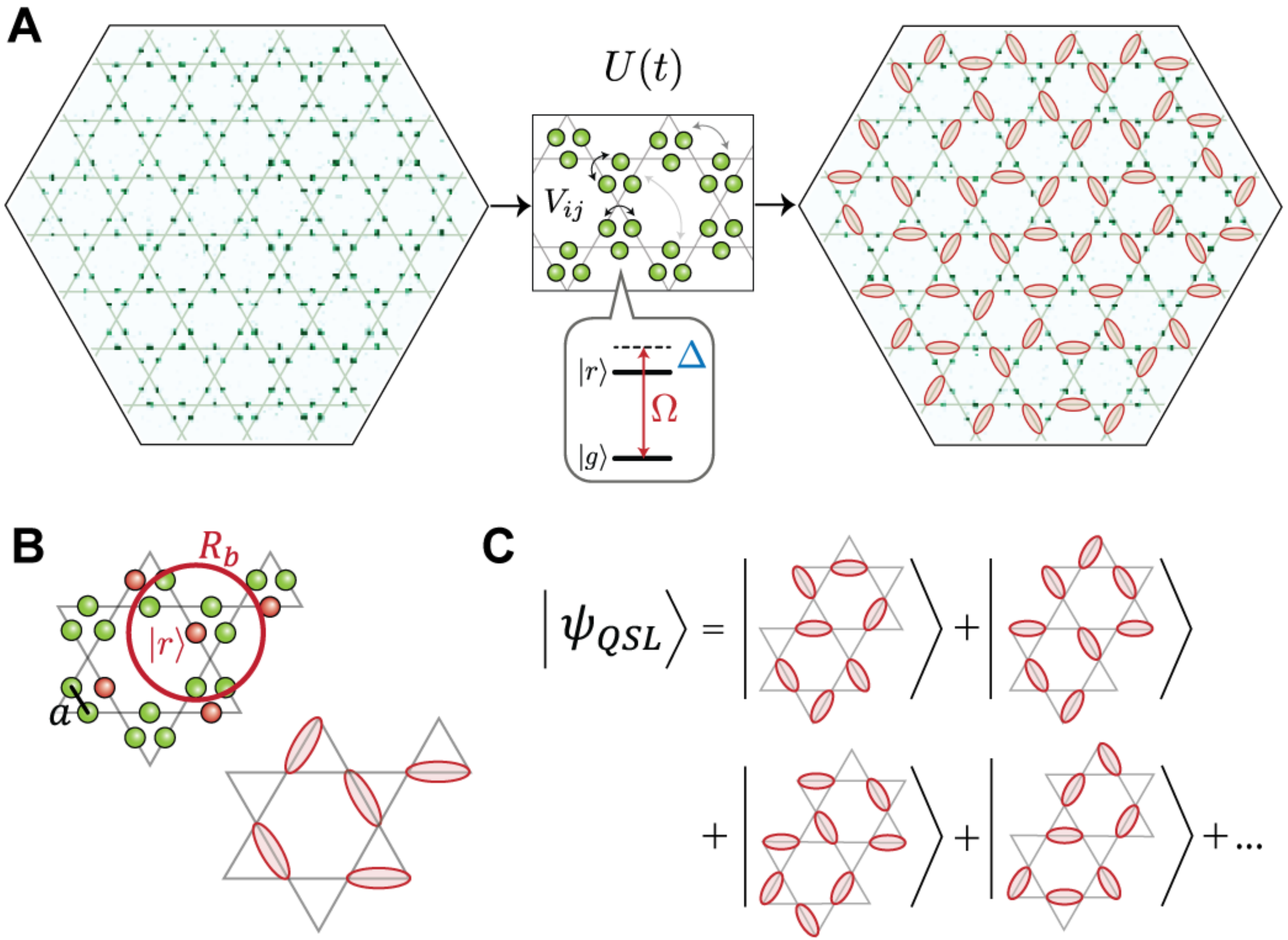
Probing Topological Spin Liquids on a Programmable Quantum Simulator

G. Semeghini, H. Levine, A. Keesling, S. Ebadi, T. T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletic, M. D. Lukin, arXiv:2104.04119

Rydberg atoms
on the
link-kagome lattice:
experiment



1. “Conventional” phases of matter

Metals, insulators, superconductors

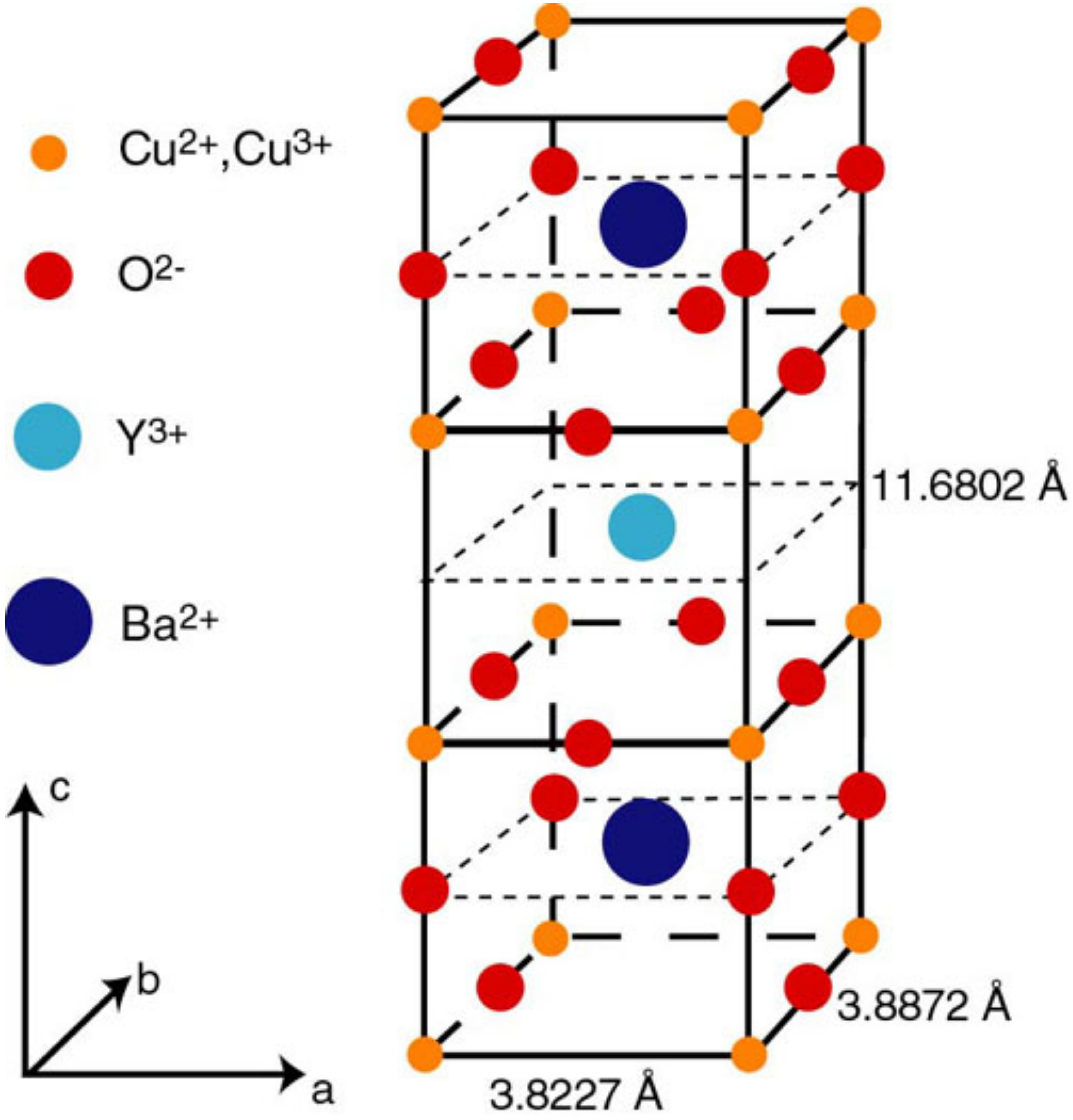
2. Emergent gauge fields and topology

Spin liquids with Rydberg atoms

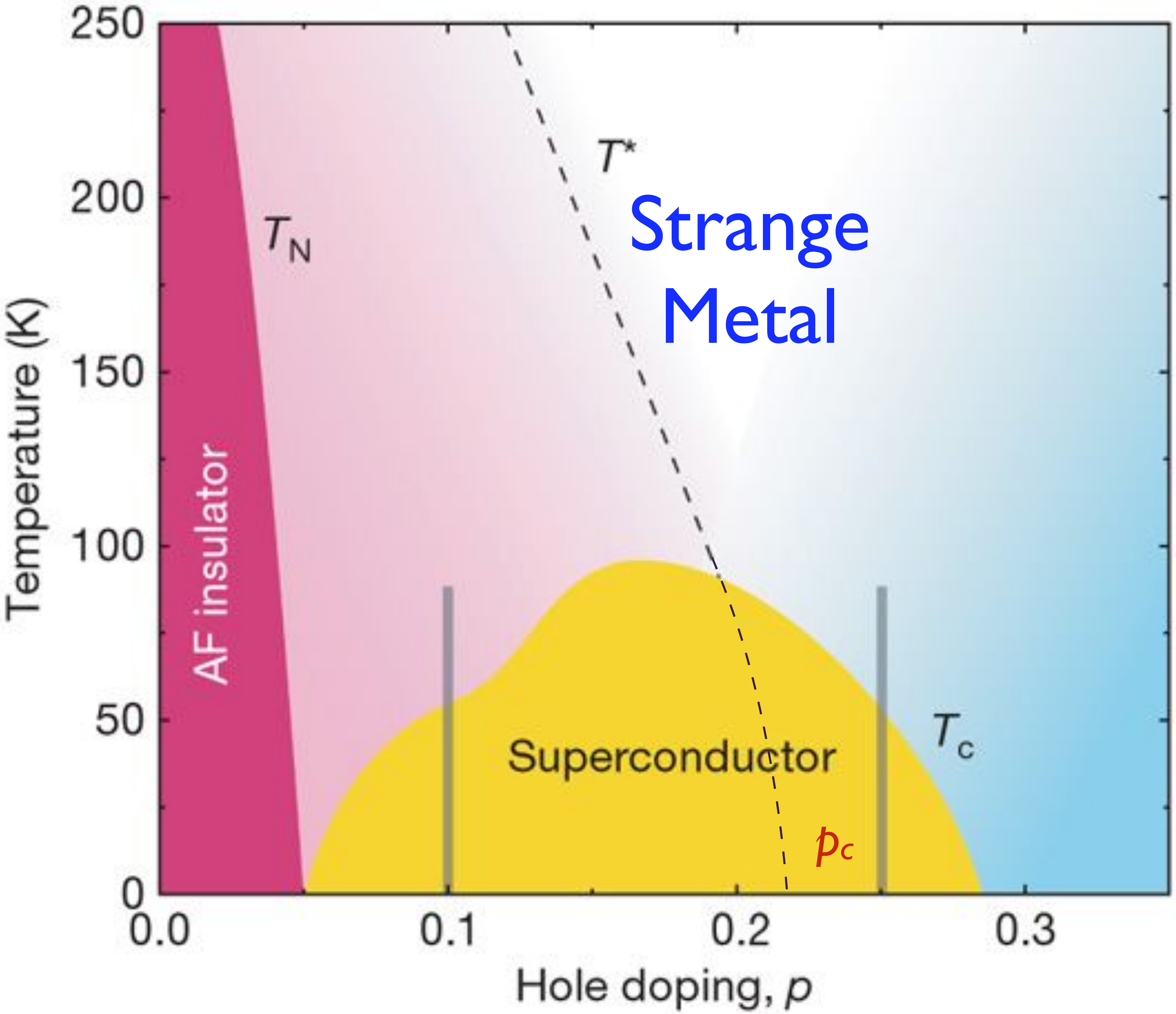
3. Strange metals

SYK model and emergent gravity

High temperature superconductors



$YBa_2Cu_3O_{6+x}$



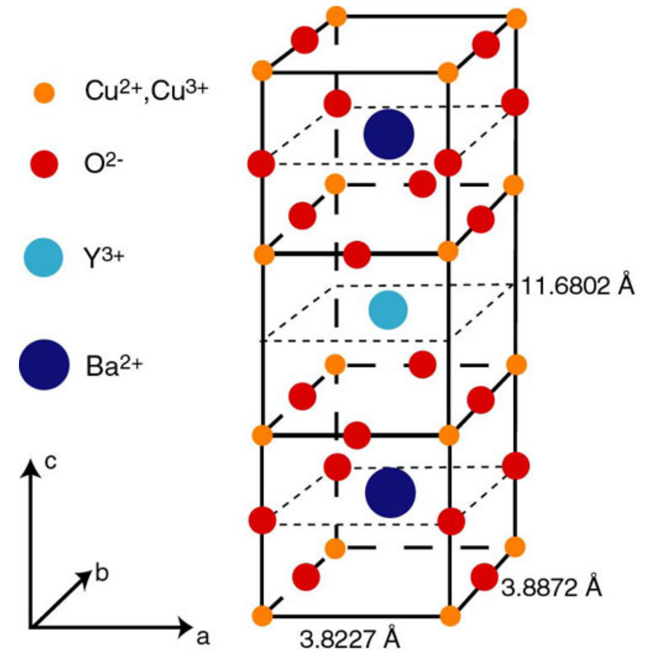
250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Strange
Metal
Superconductor
T_c
p_c

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

Electron scattering time τ in 7 different strange metals

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



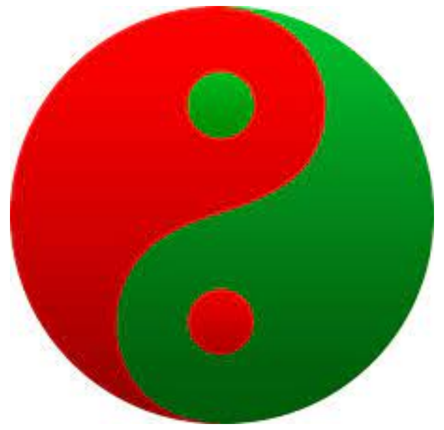
Current flow without quasiparticles

The Sachdev-Ye-Kitaev (SYK) model

The SYK model has a scale-invariant entanglement structure: i.e. electrons are entangled at all distance and time scales

In one set of variables, it describes certain ***strange metals***

Sachdev, Ye (1993)

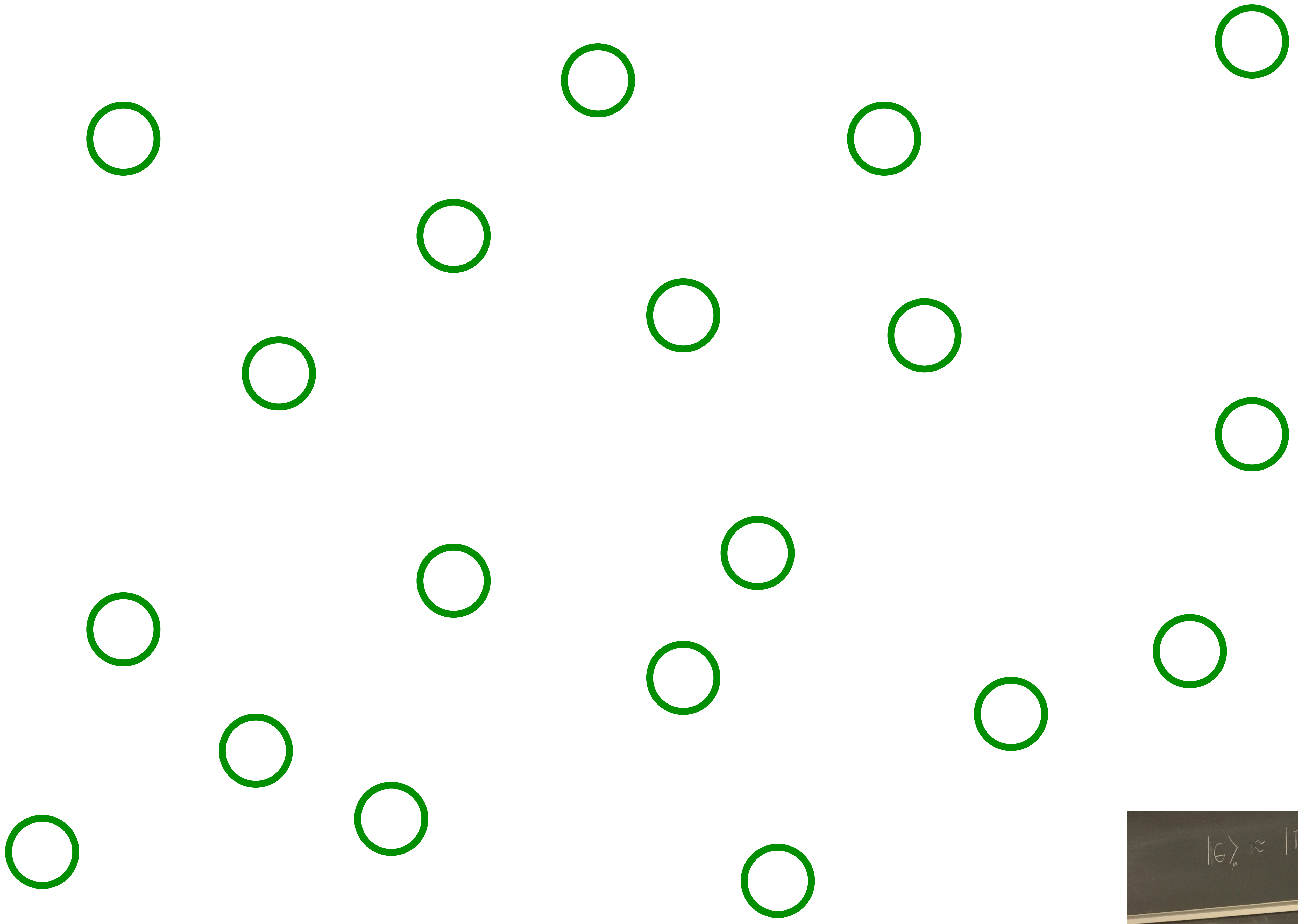


In a *dual* set of variables it describes certain ***black holes***

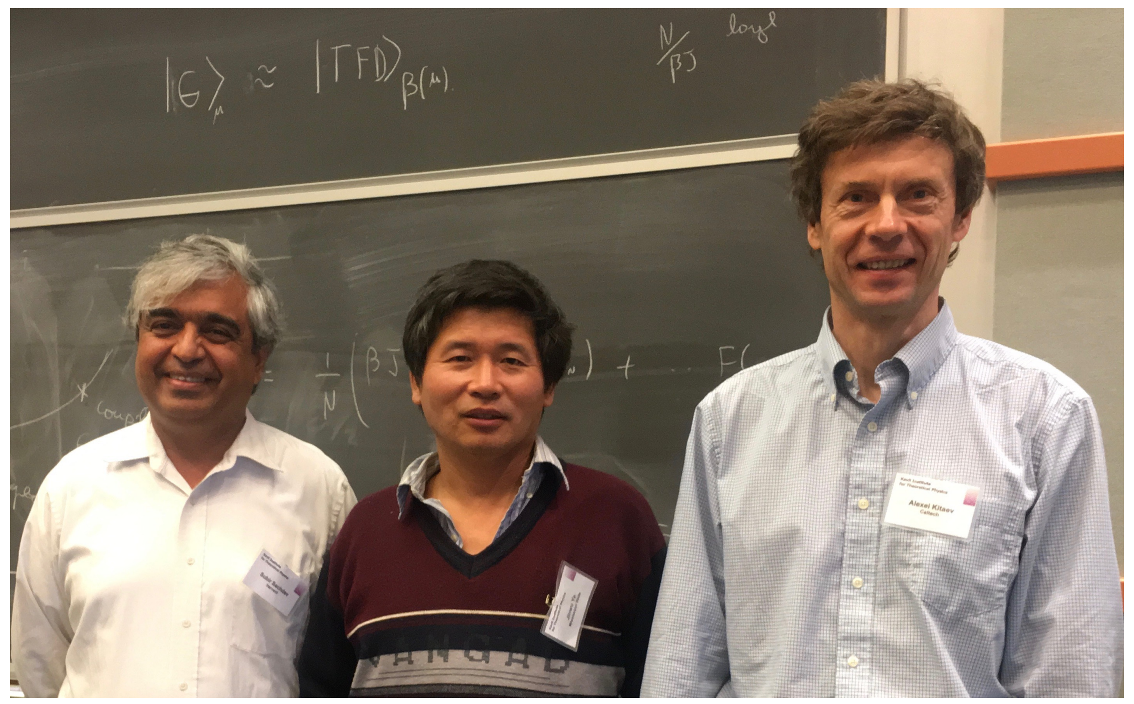
Sachdev (2010), Kitaev (2015), Maldacena Stanford (2015)

The Sachdev-Ye-Kitaev (SYK) model

Sachdev, Ye (1993); Kitaev (2015)

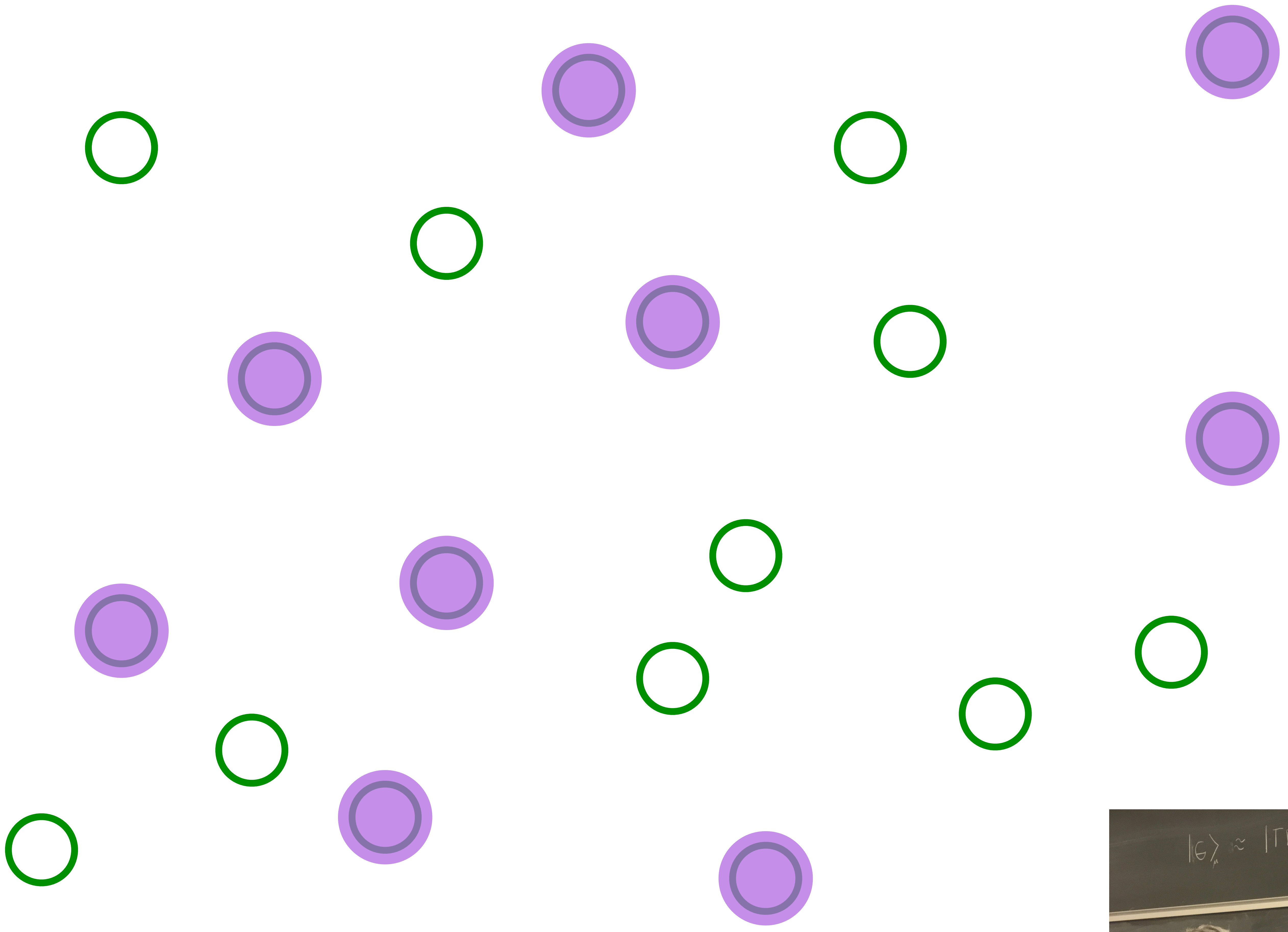


Pick a set of random positions

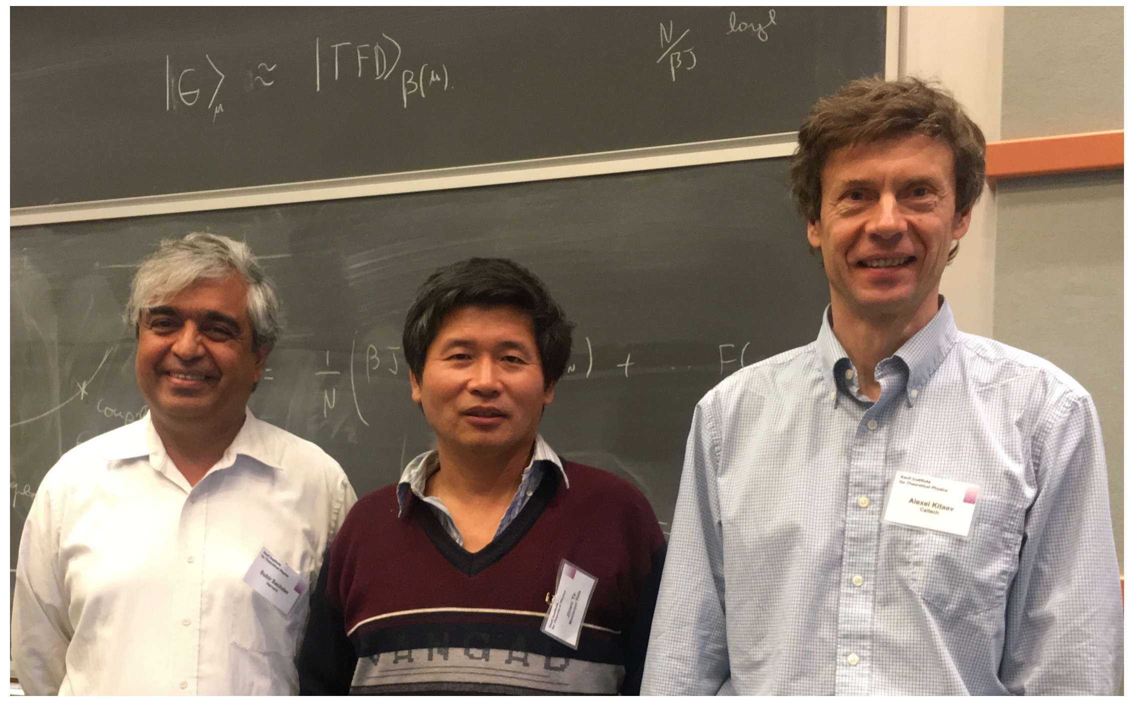


The SYK model

Sachdev, Ye (1993); Kitaev (2015)



Place electrons randomly on some sites



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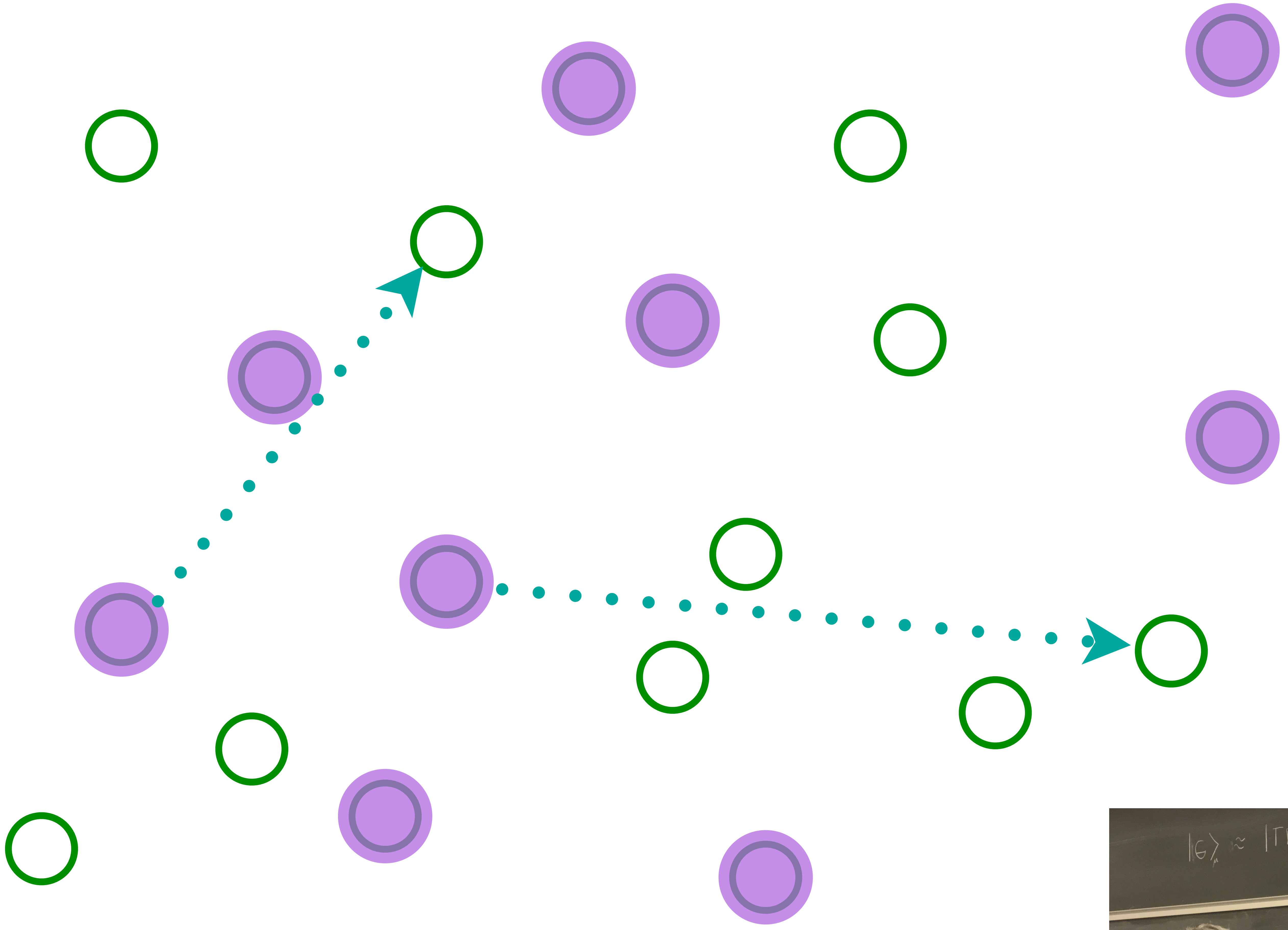

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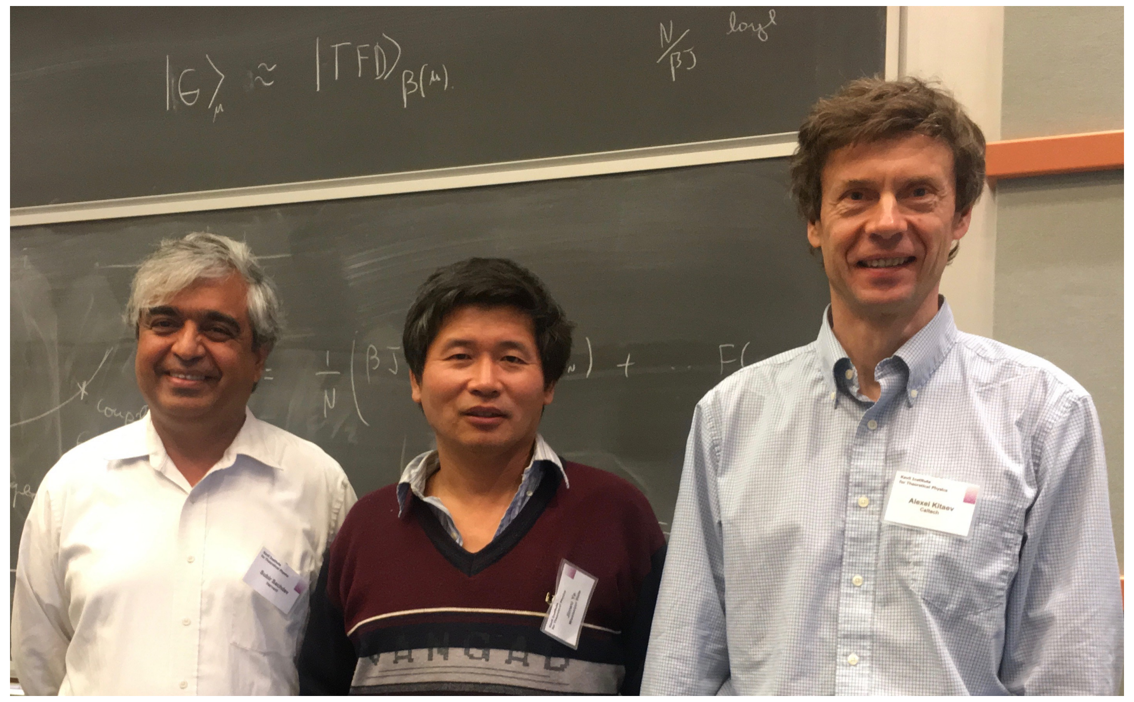

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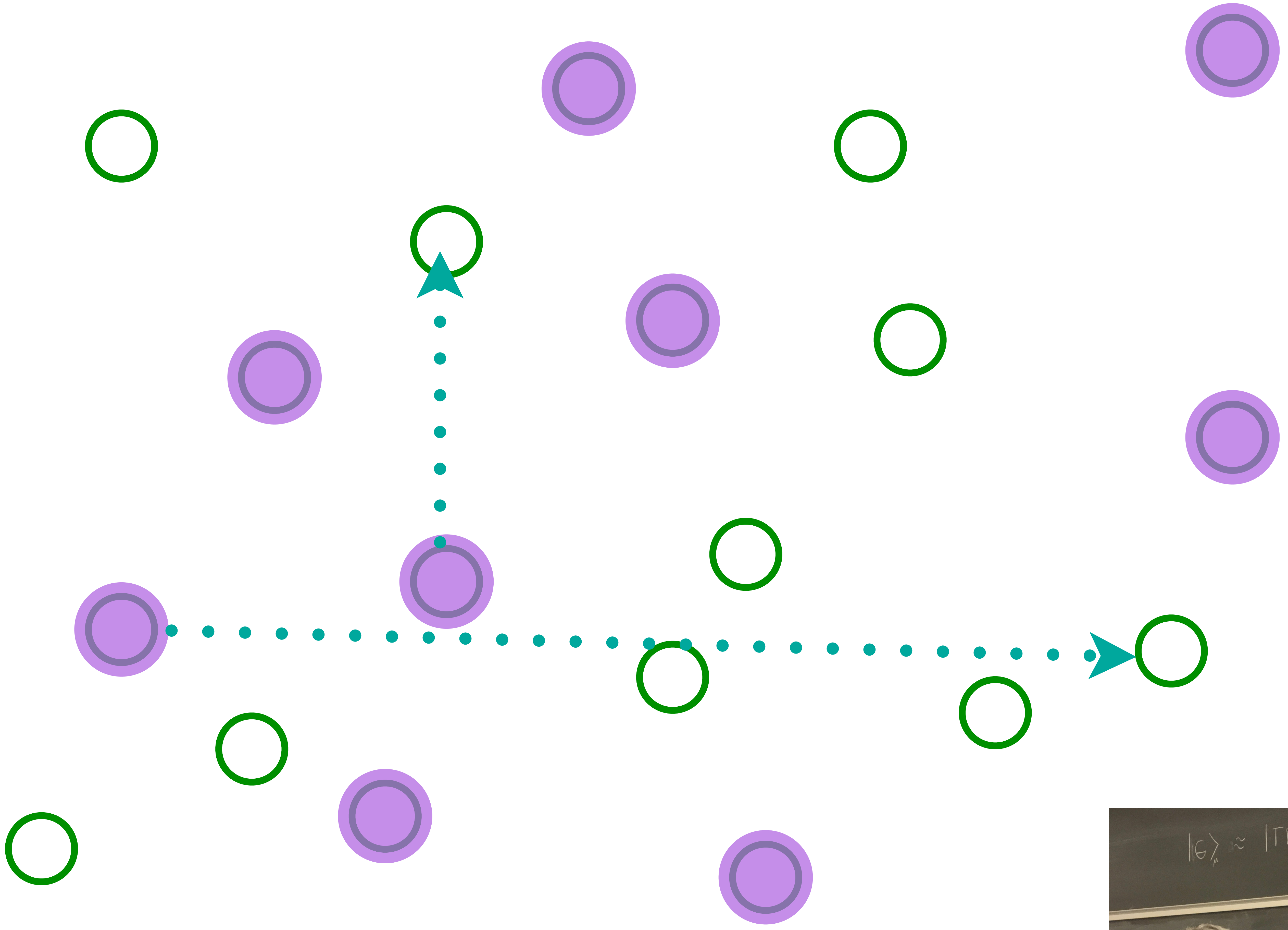

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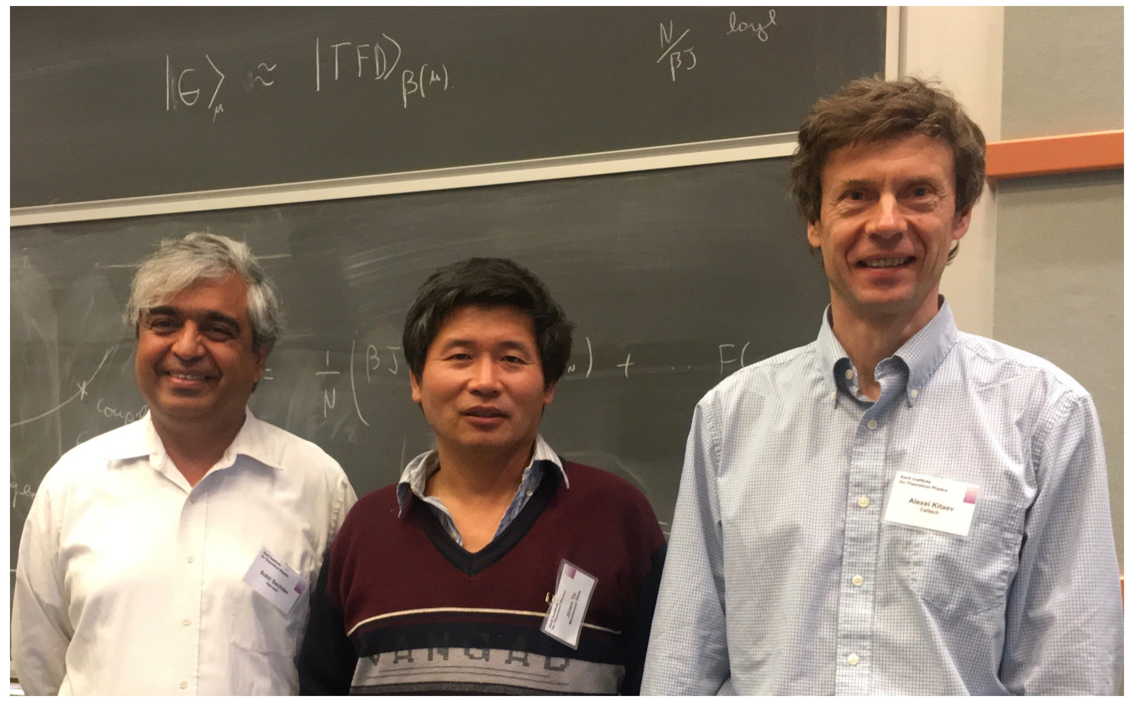

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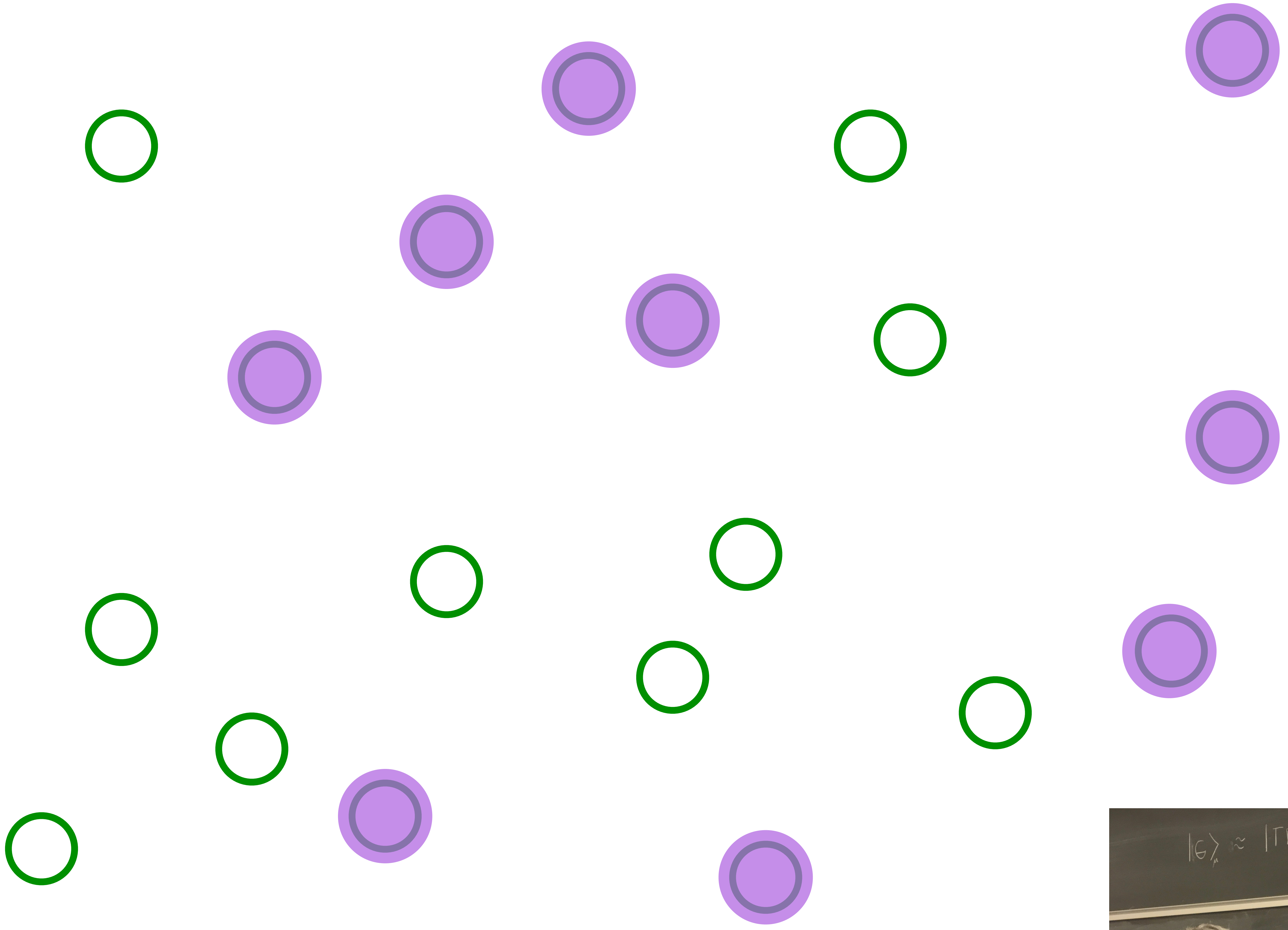
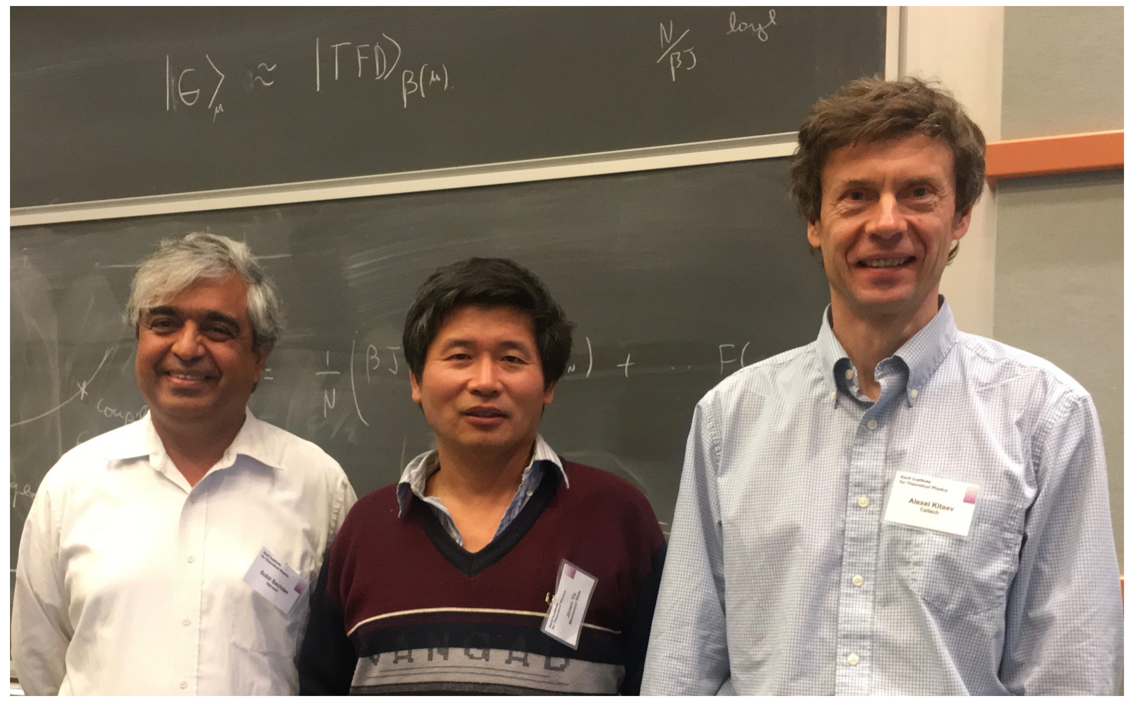


Entangle electrons pairwise randomly



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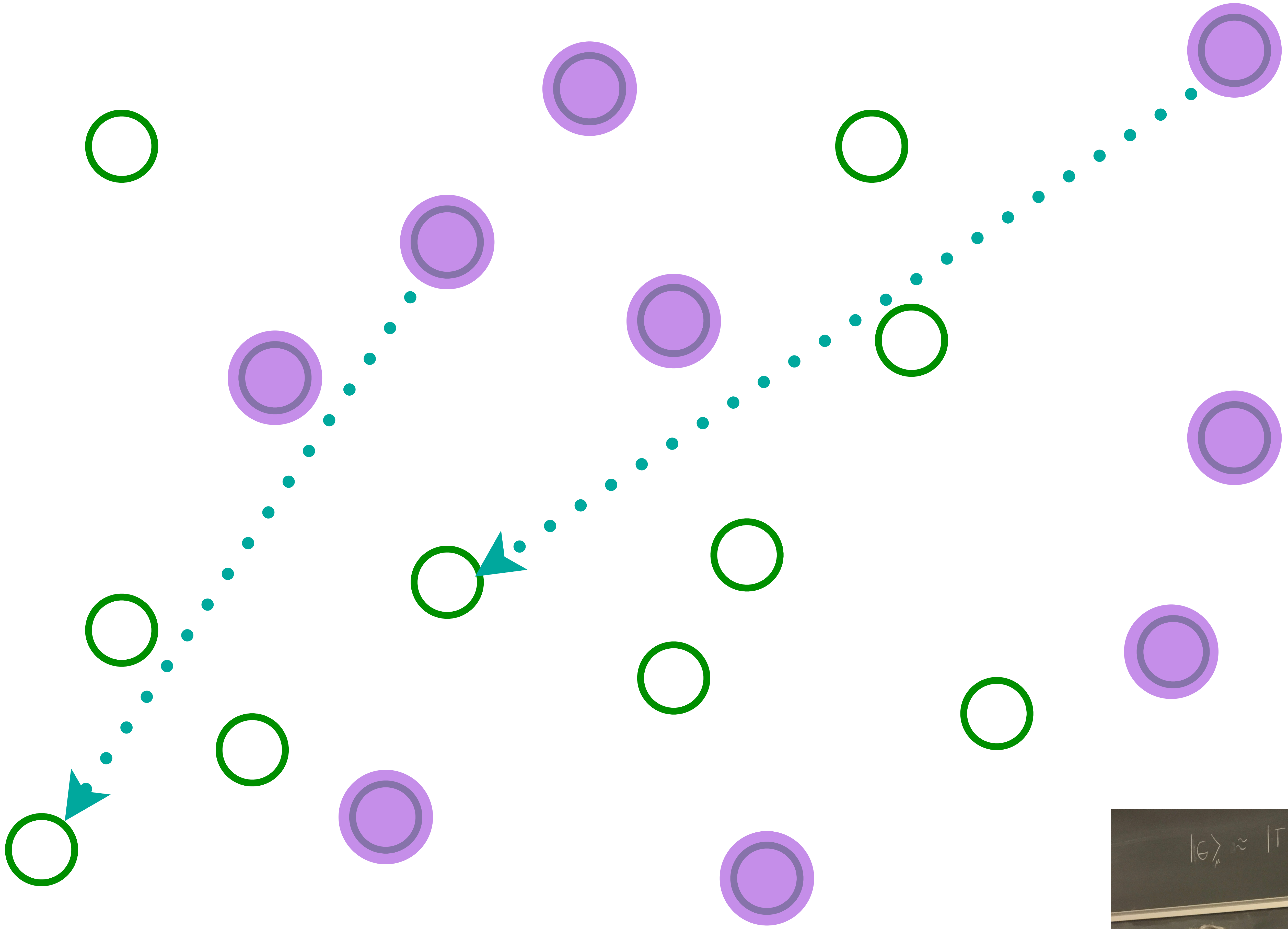

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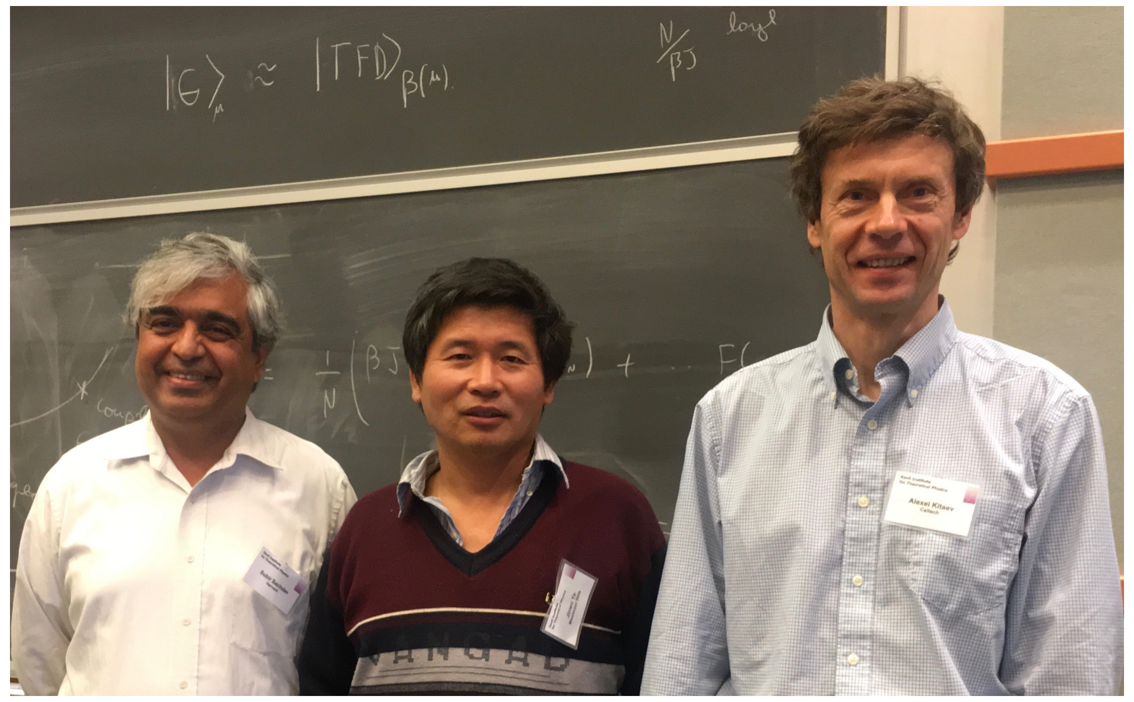

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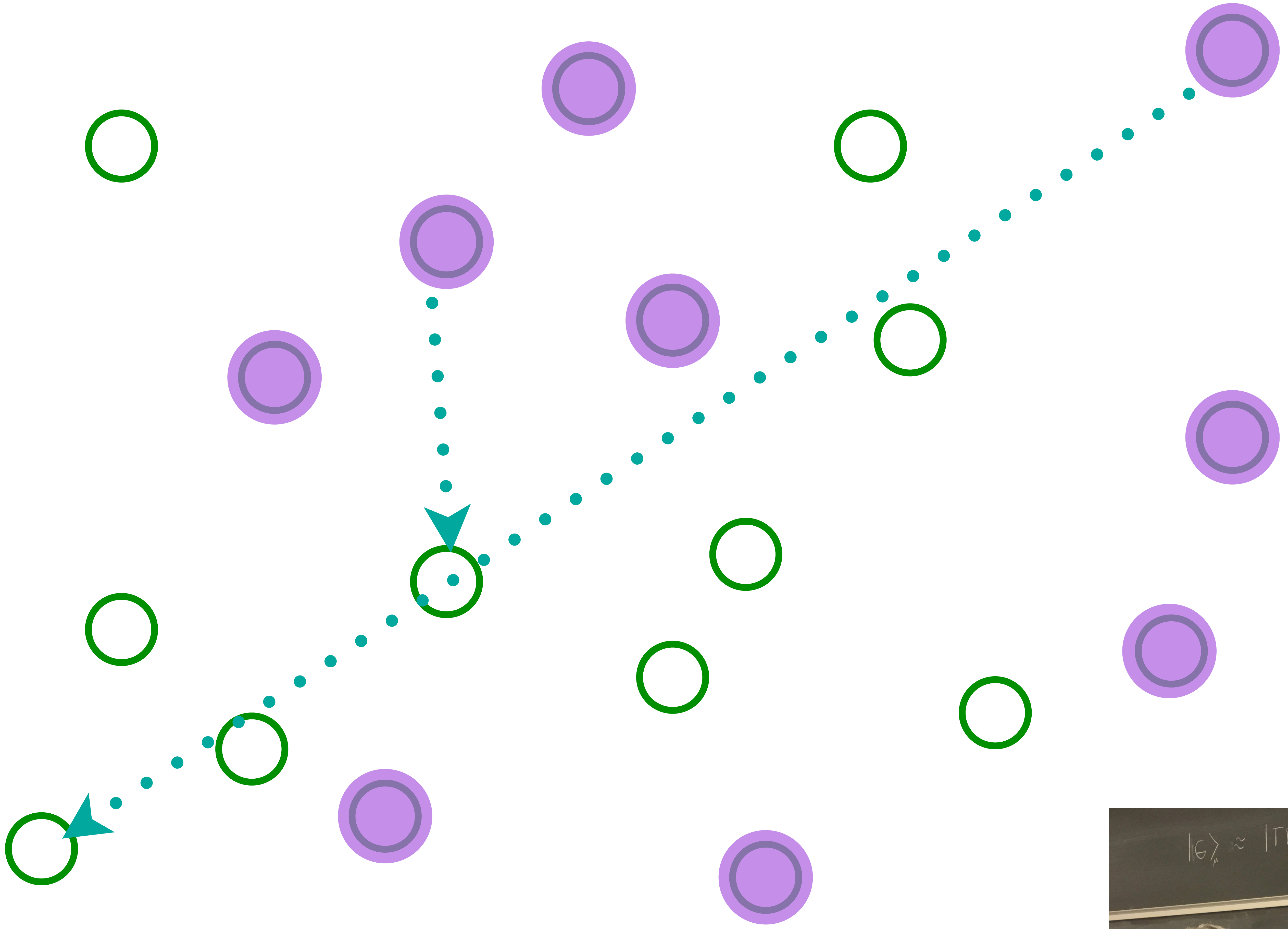

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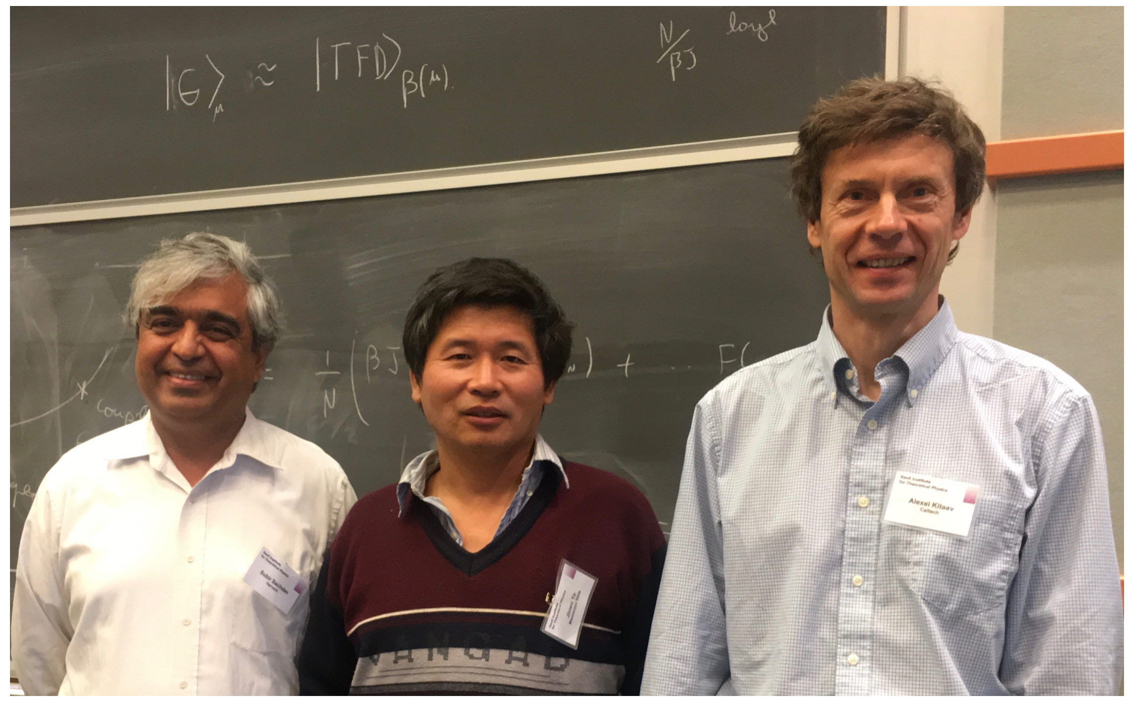

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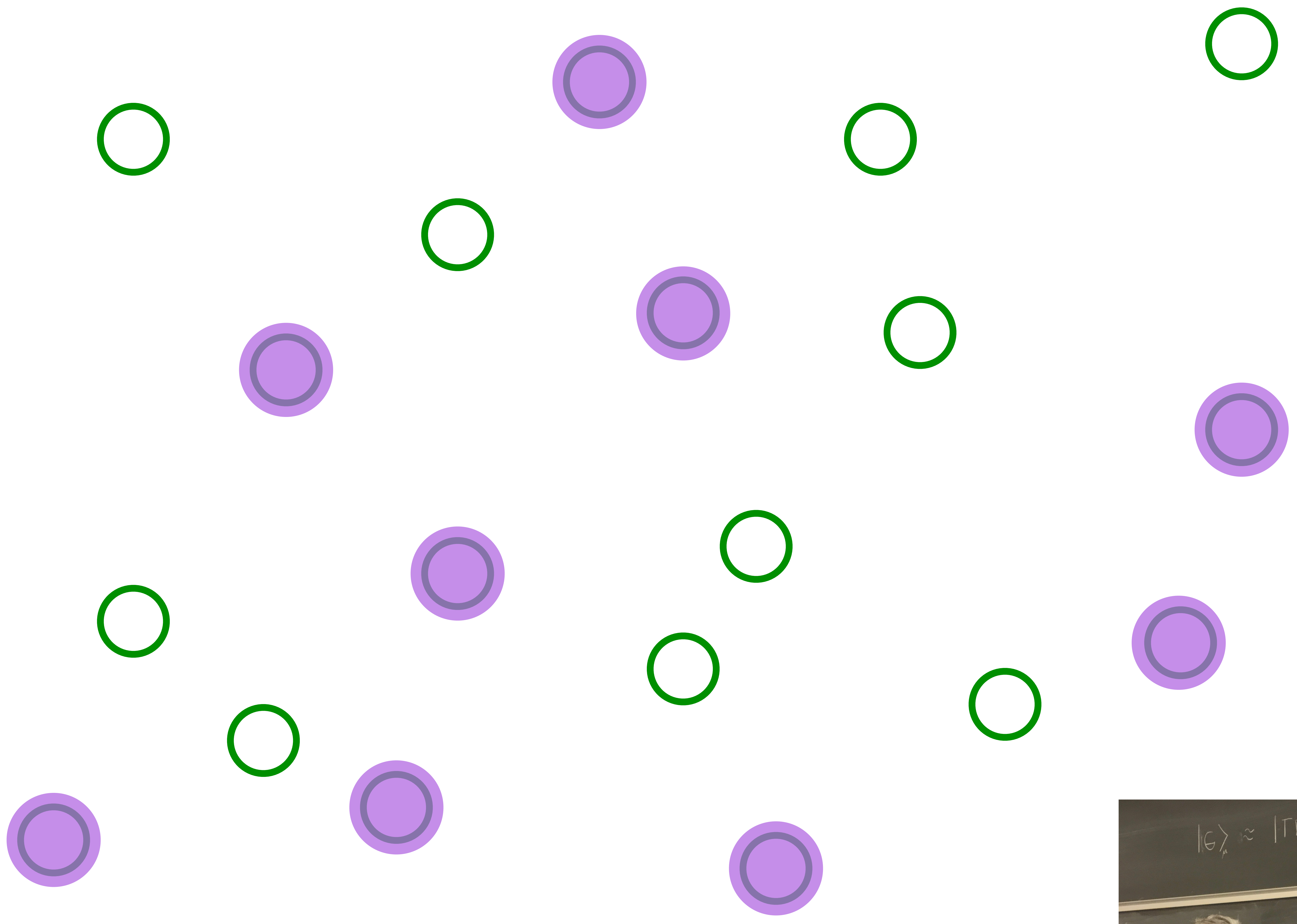

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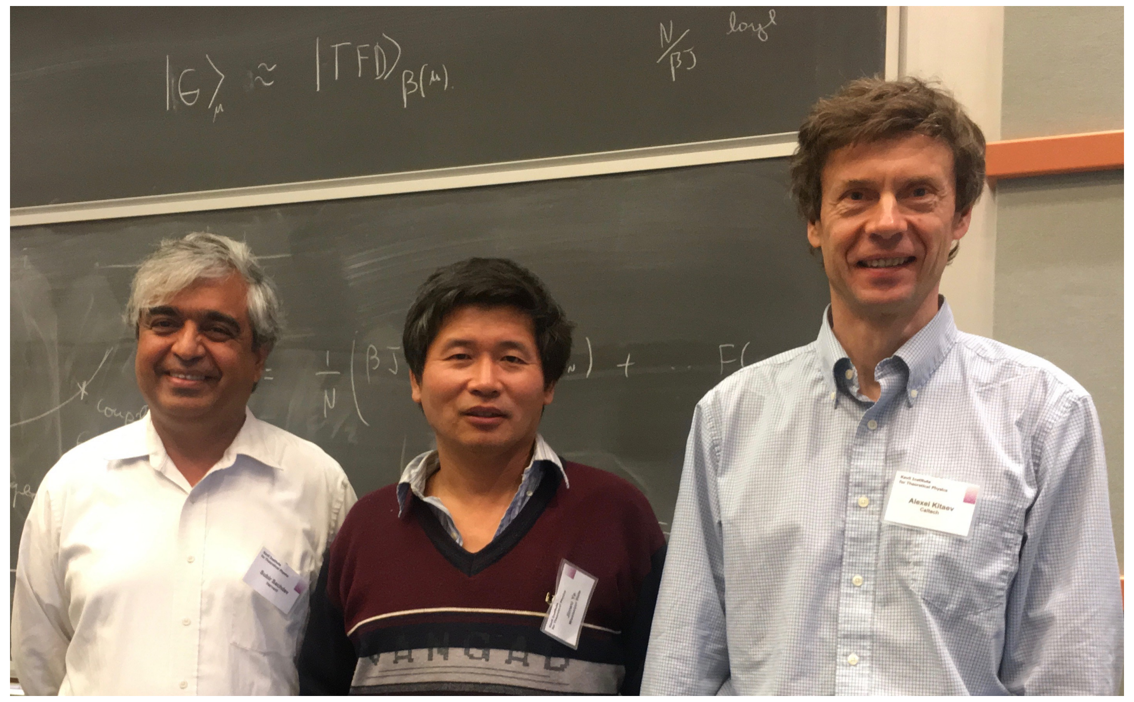

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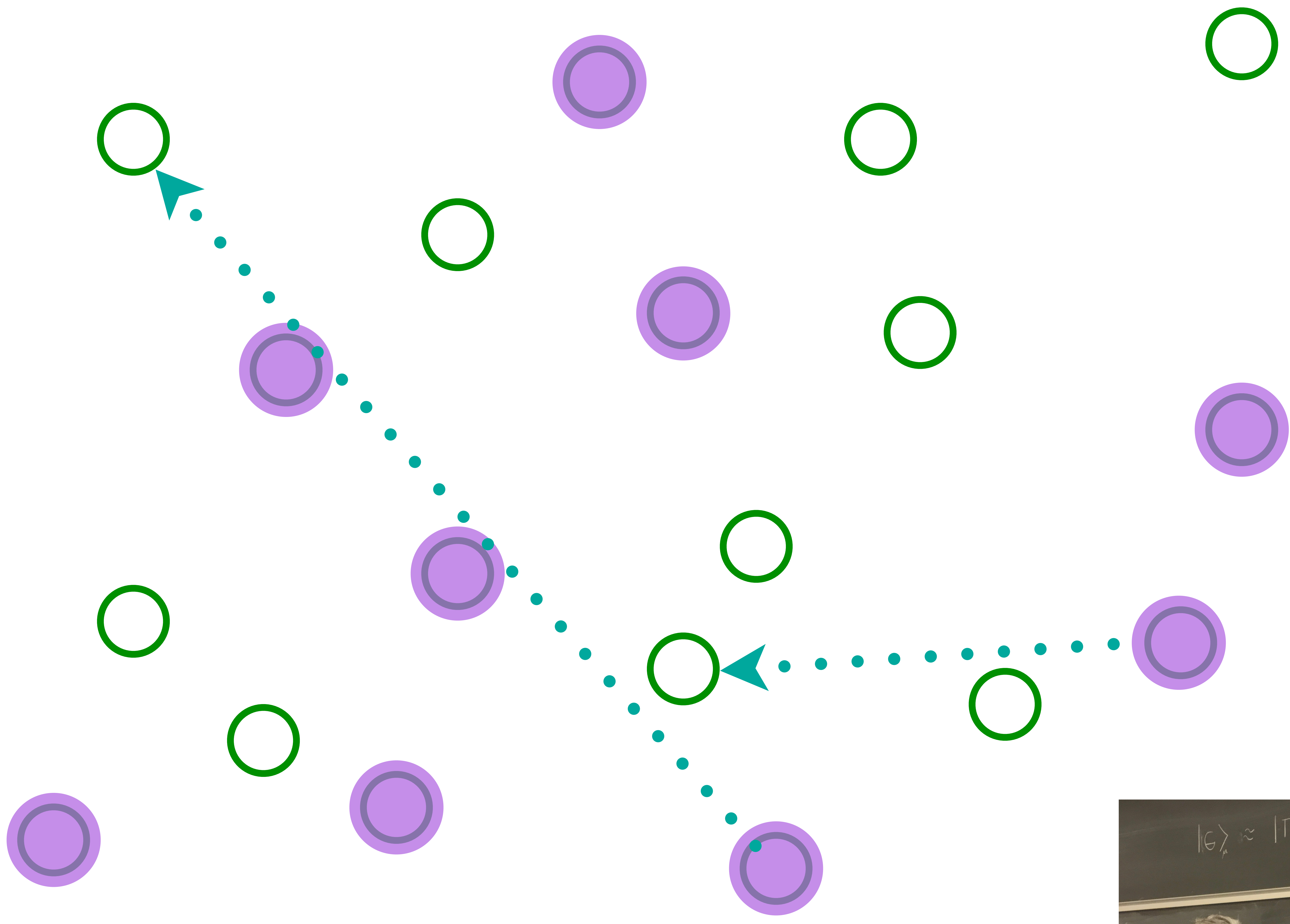

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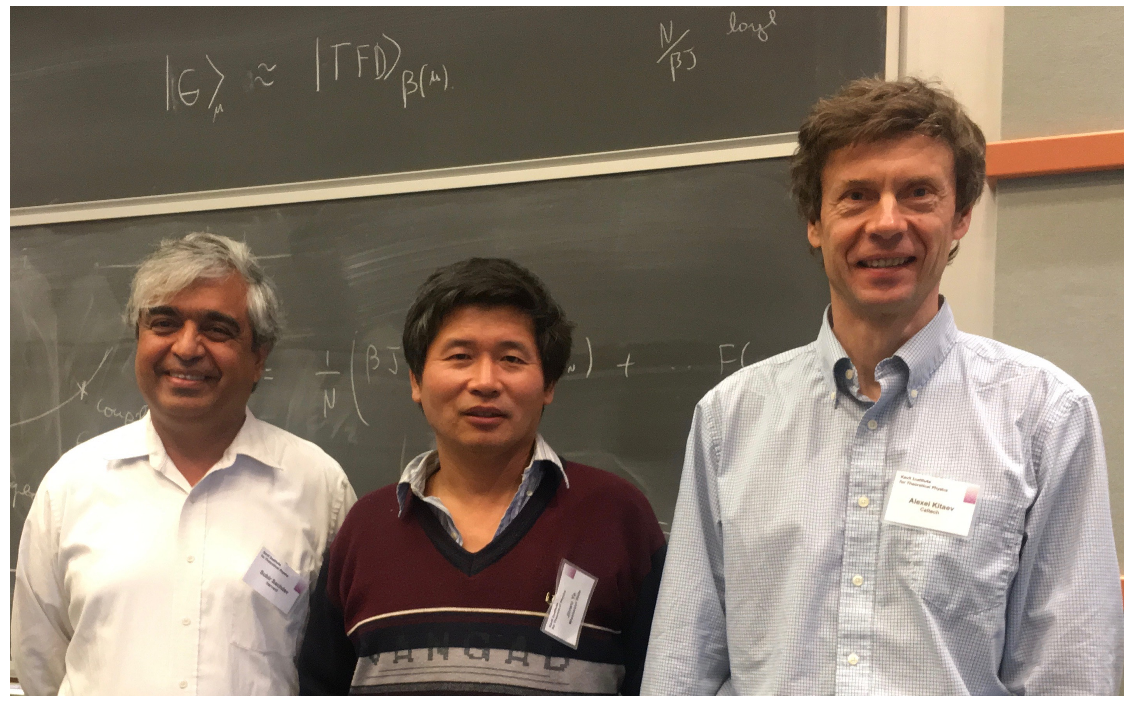

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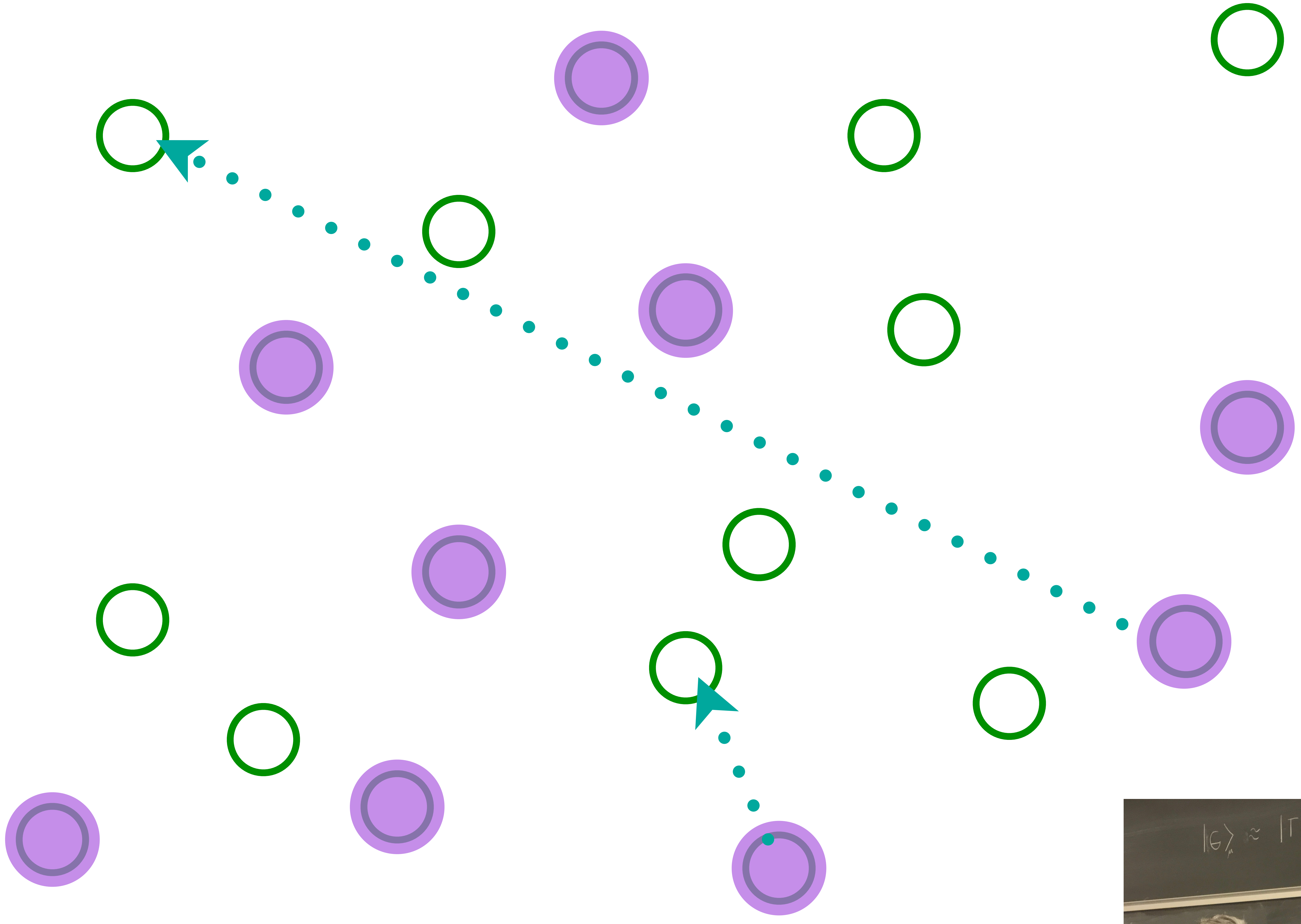

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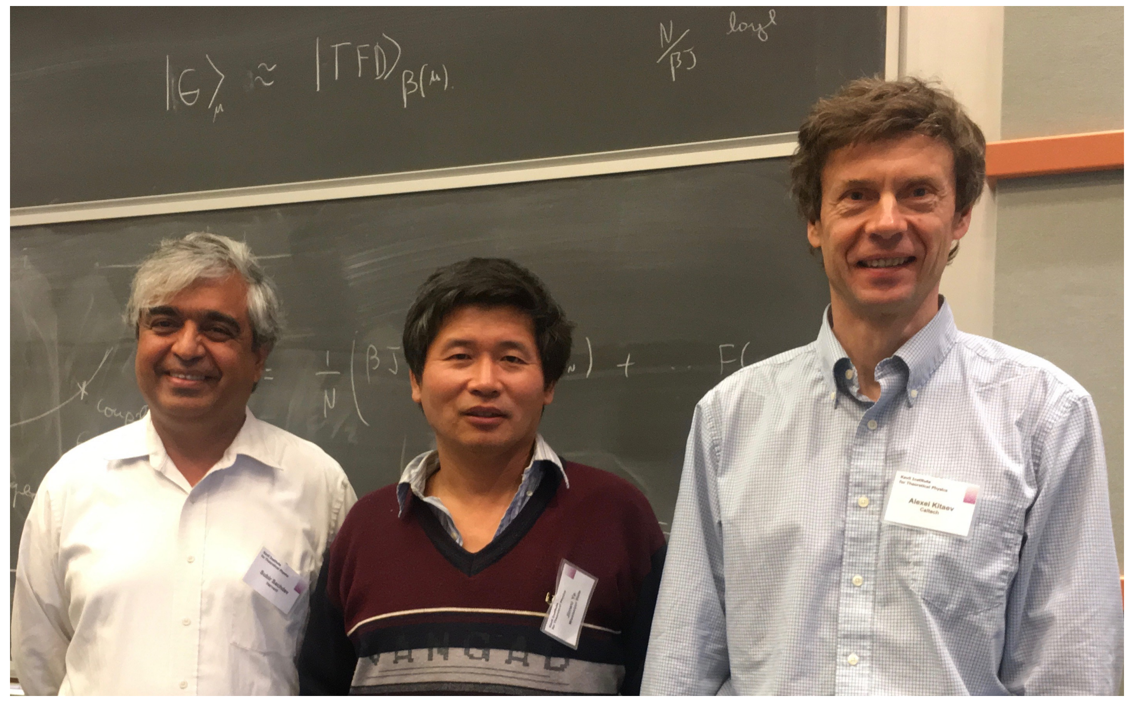

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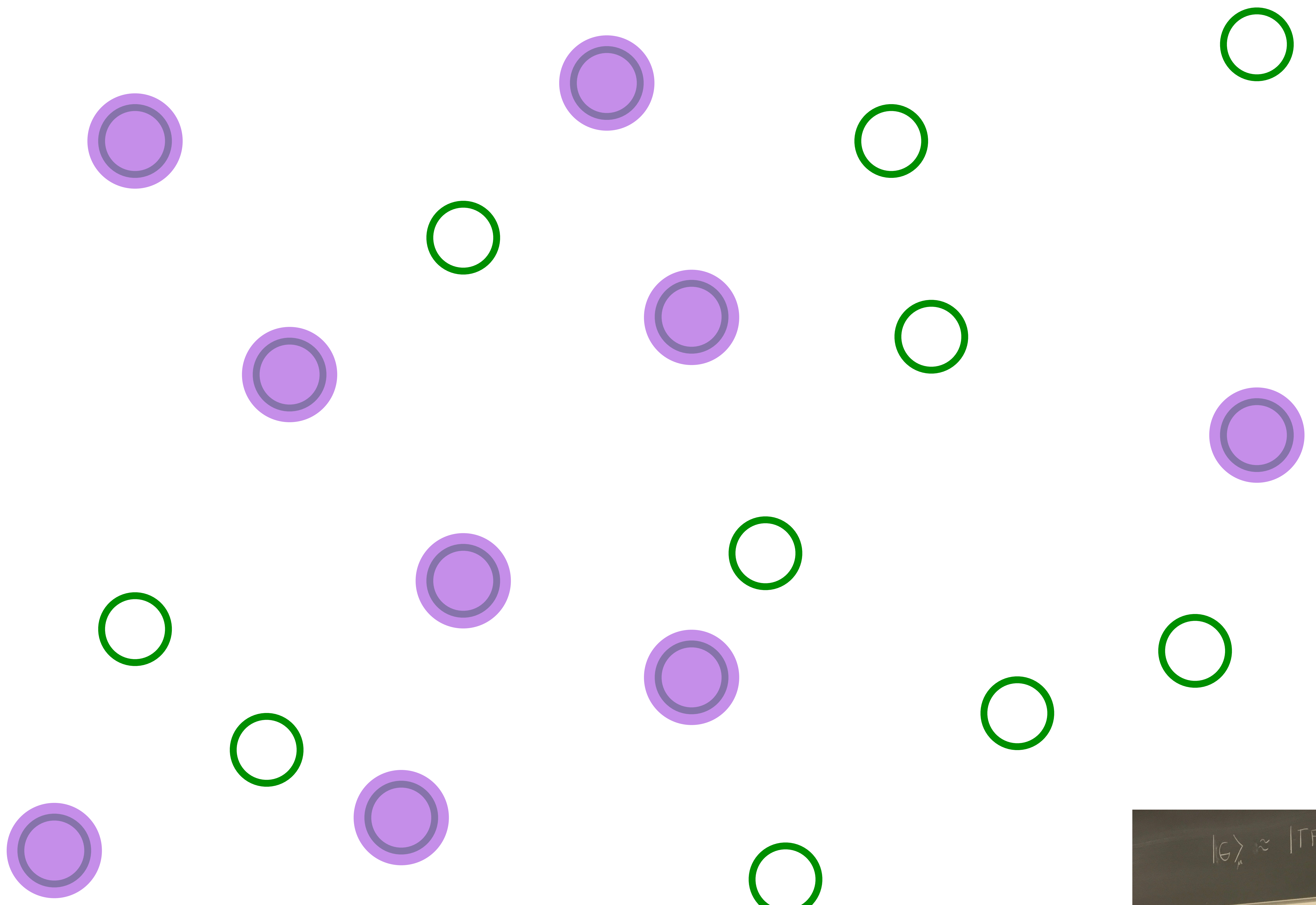

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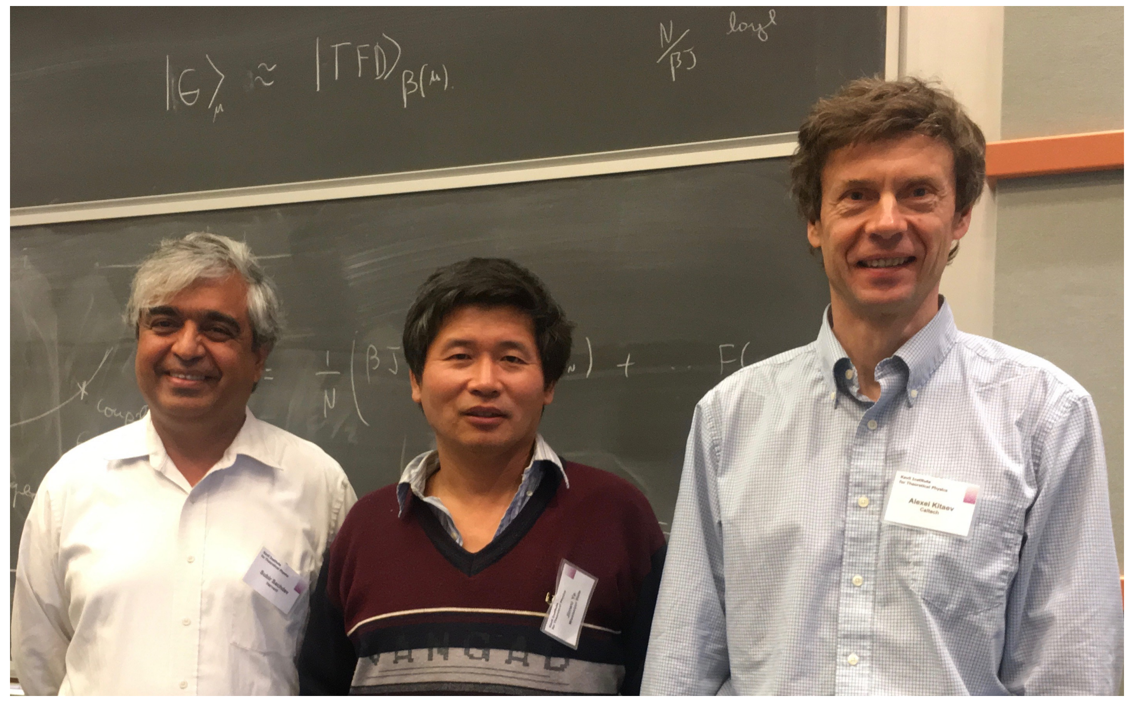

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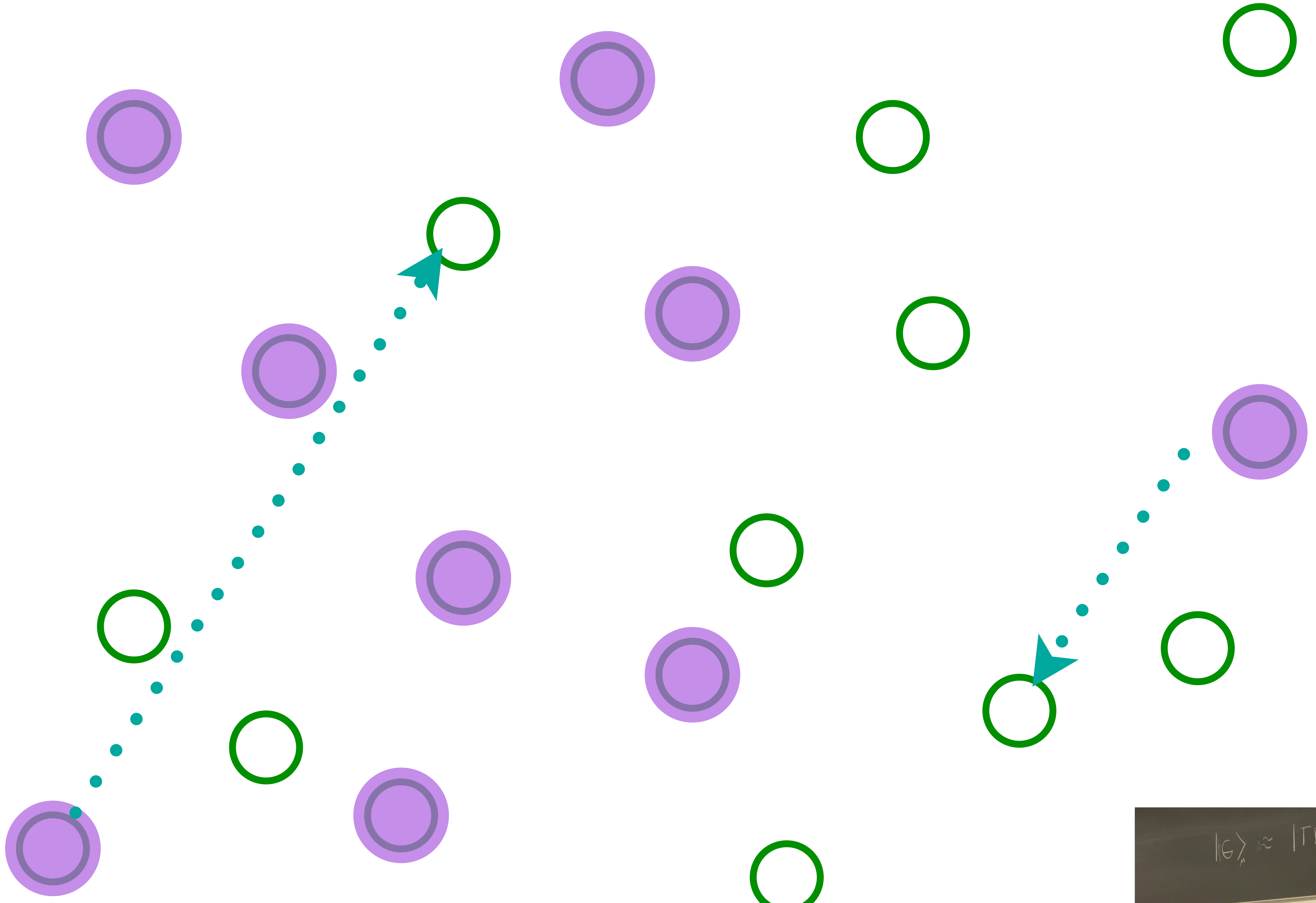

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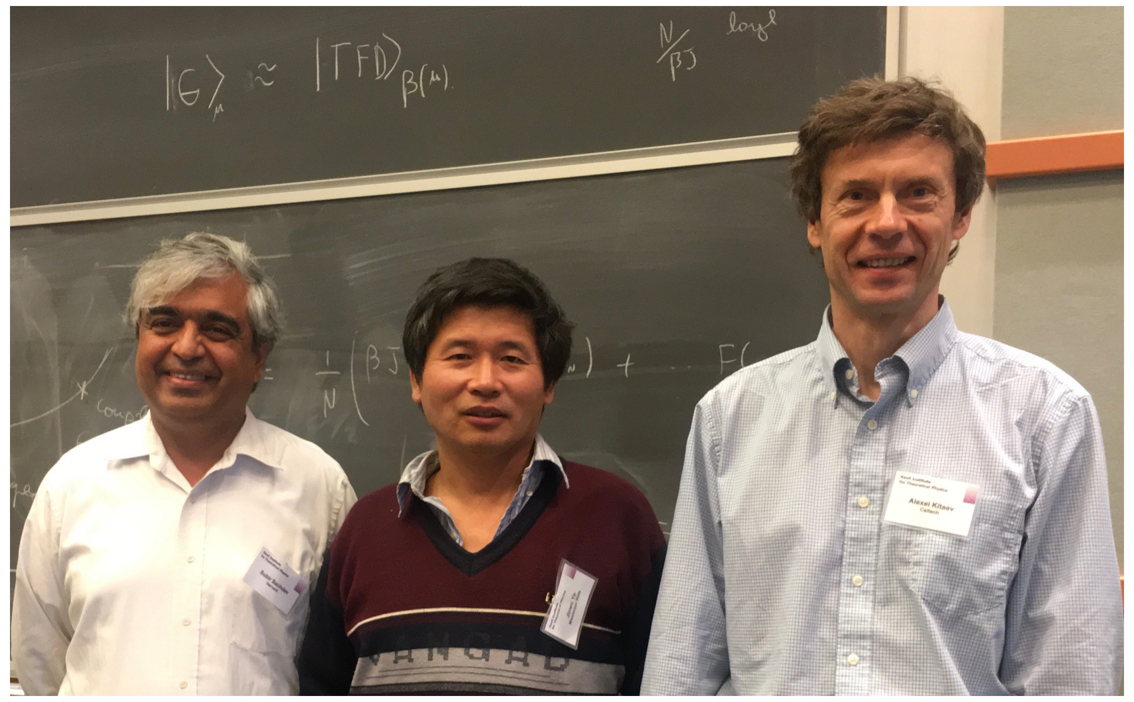

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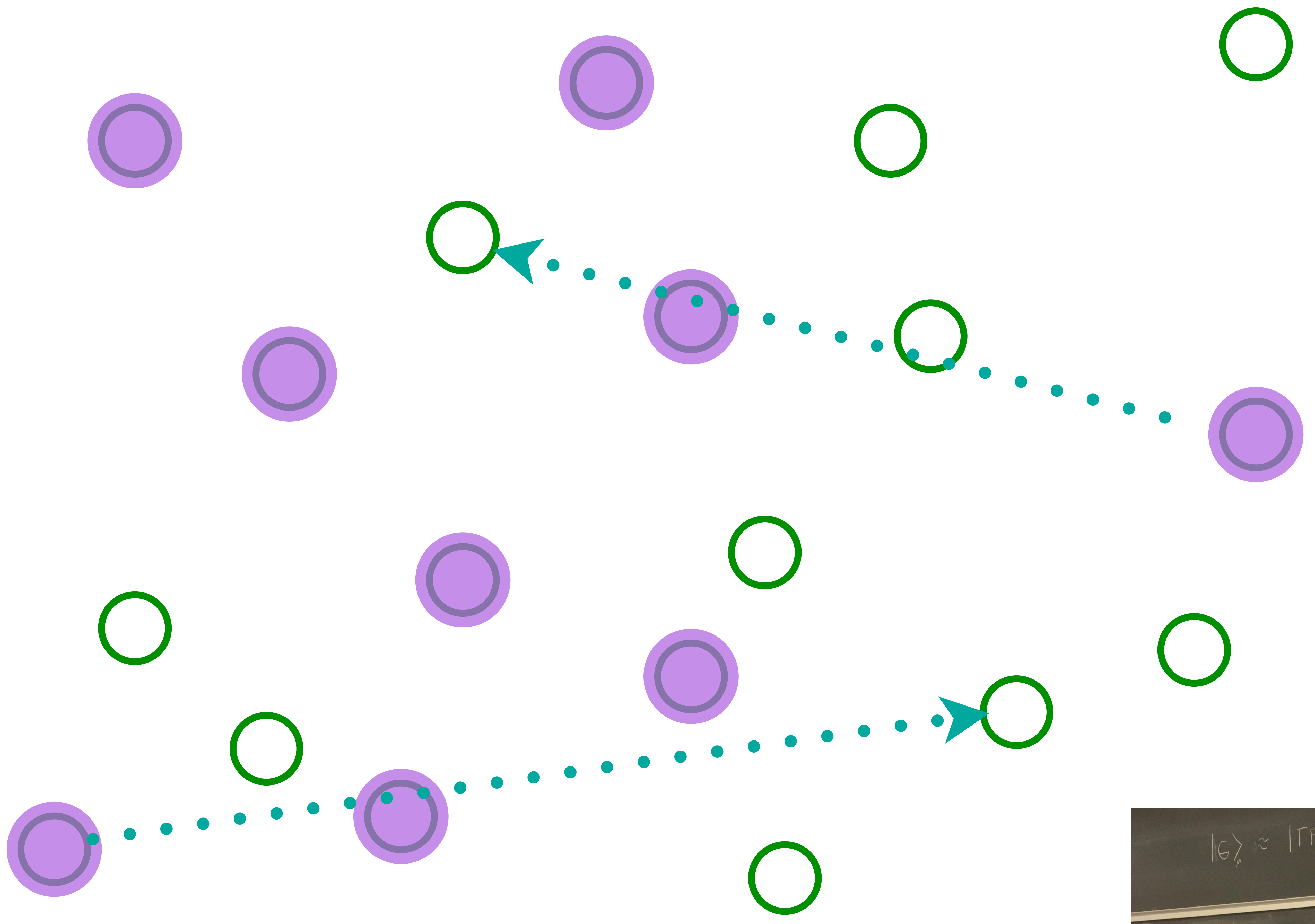

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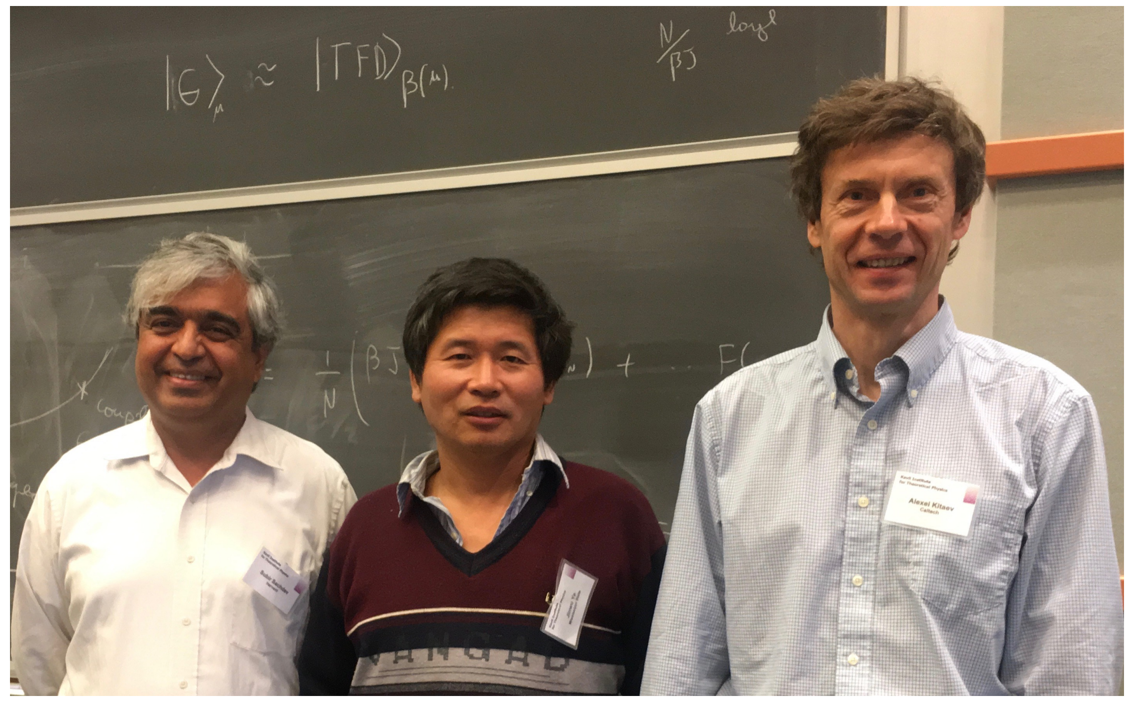

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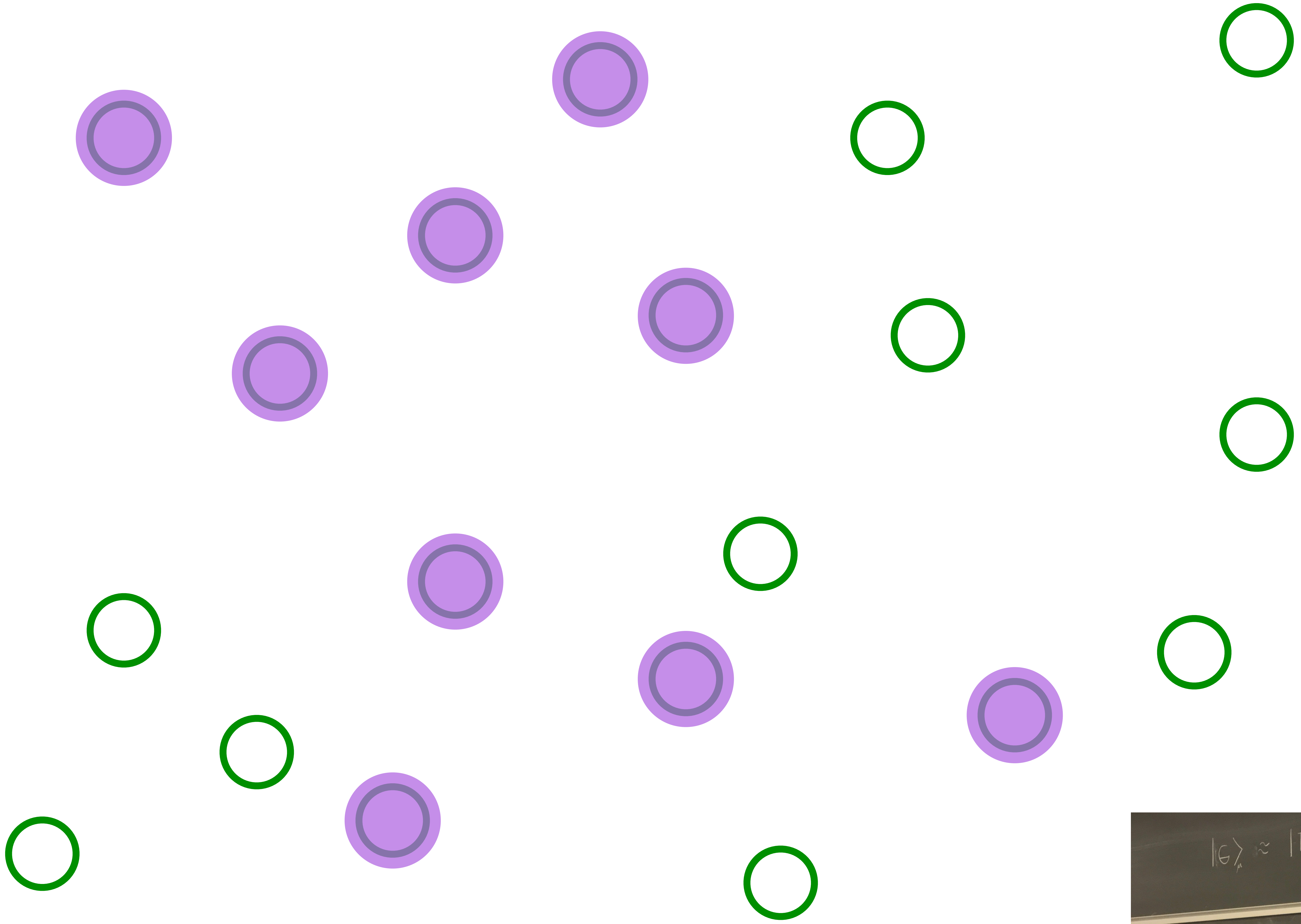

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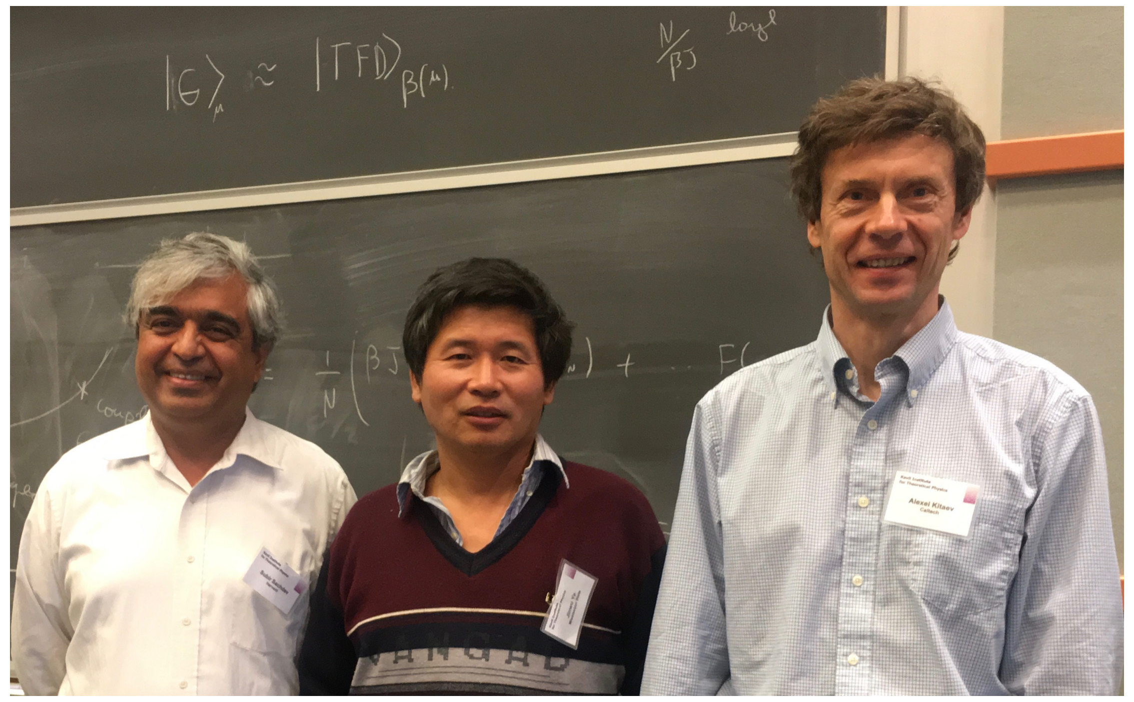

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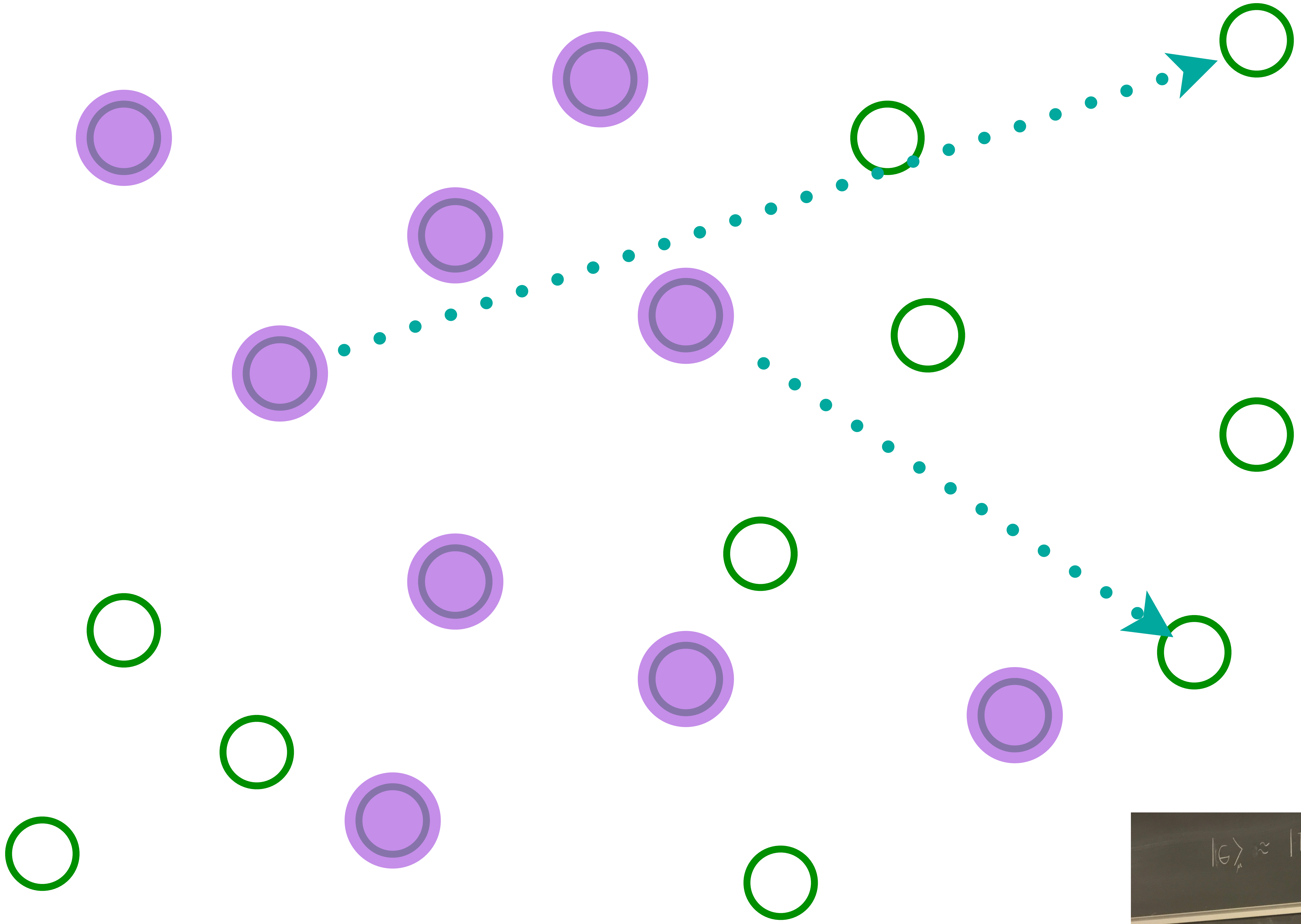

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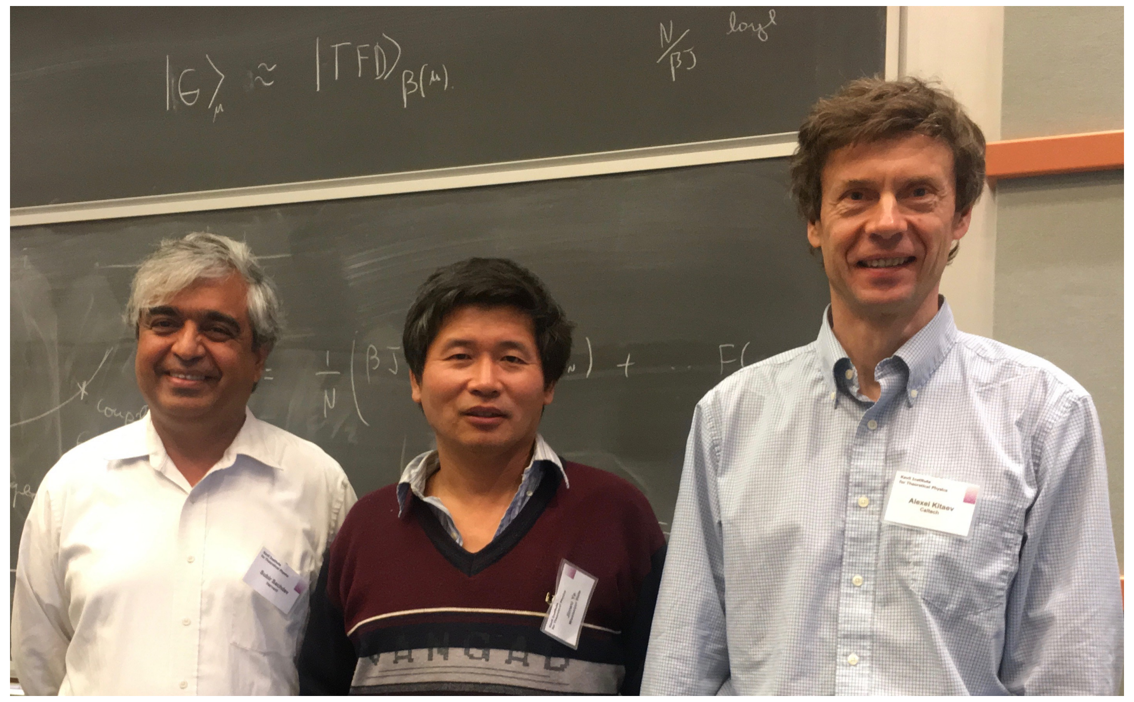

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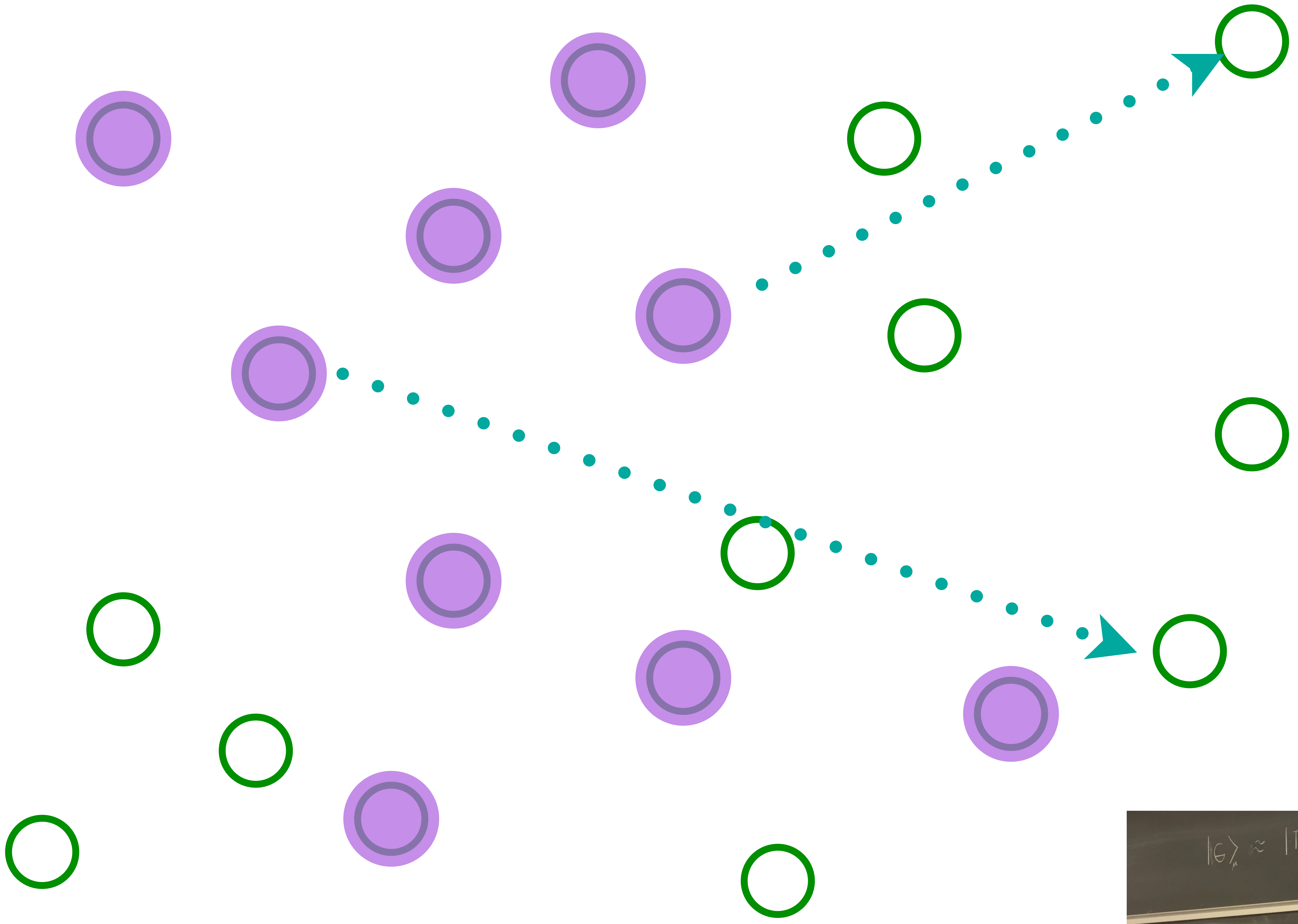

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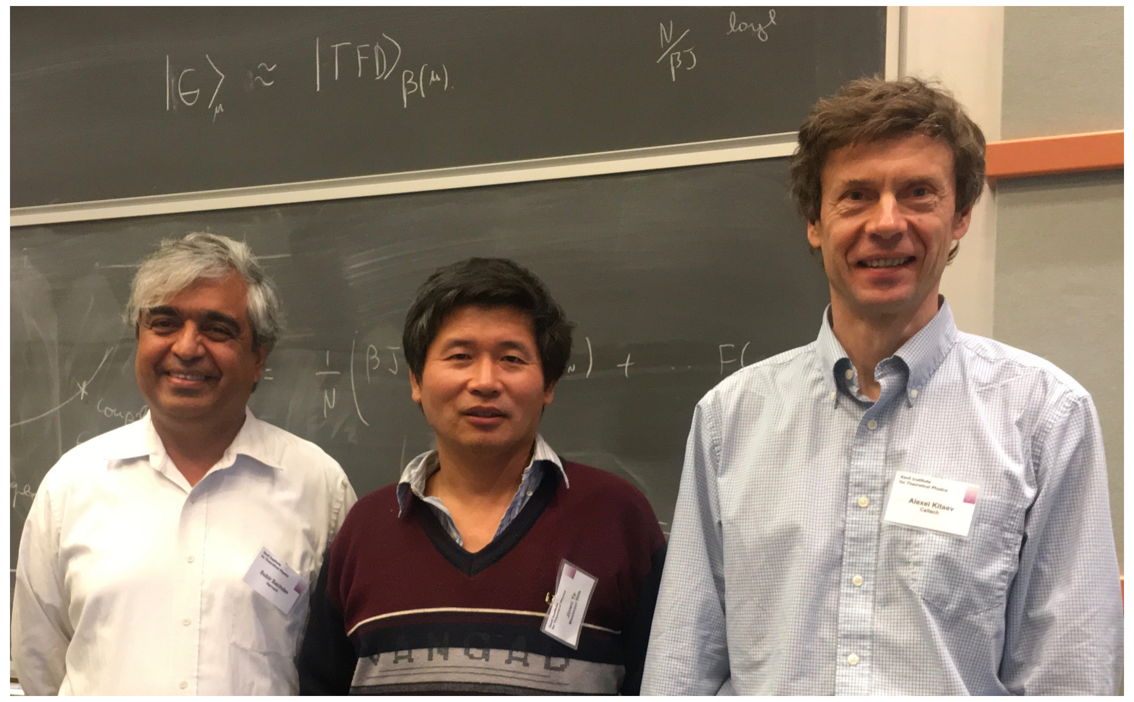

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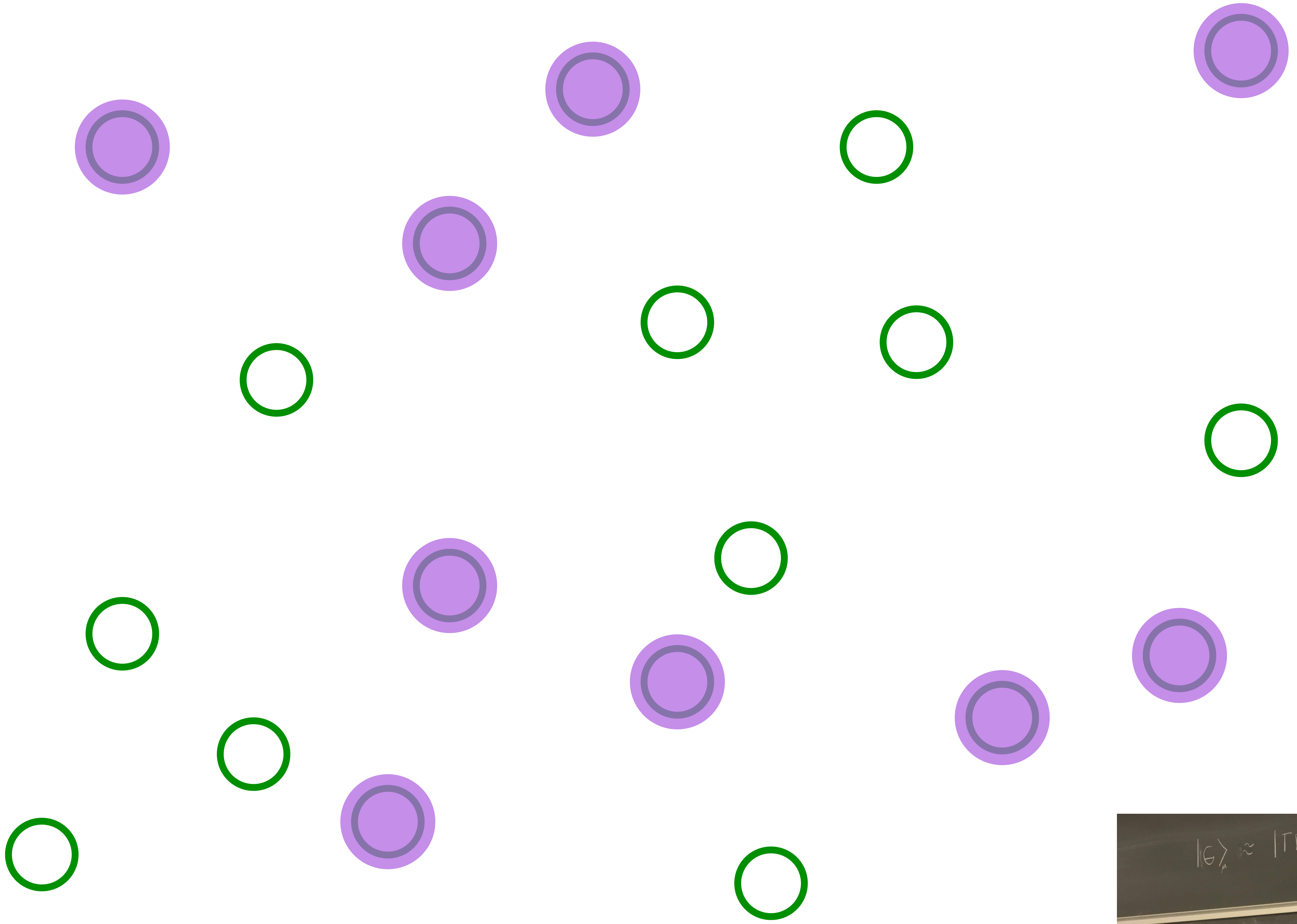

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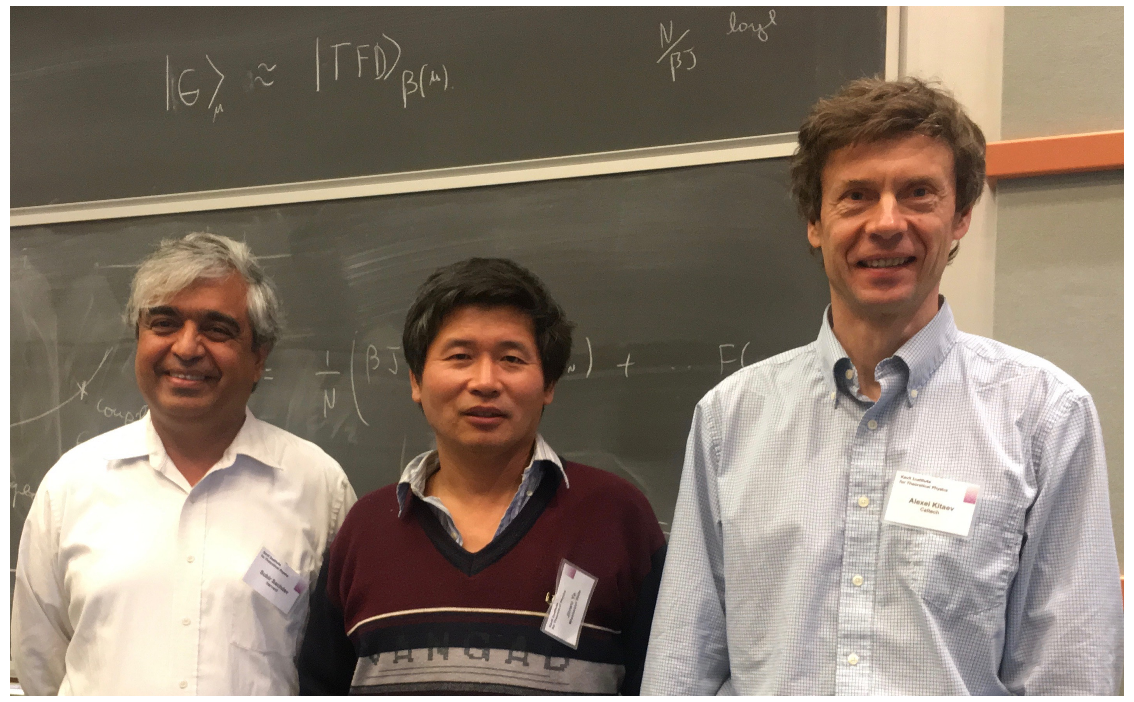

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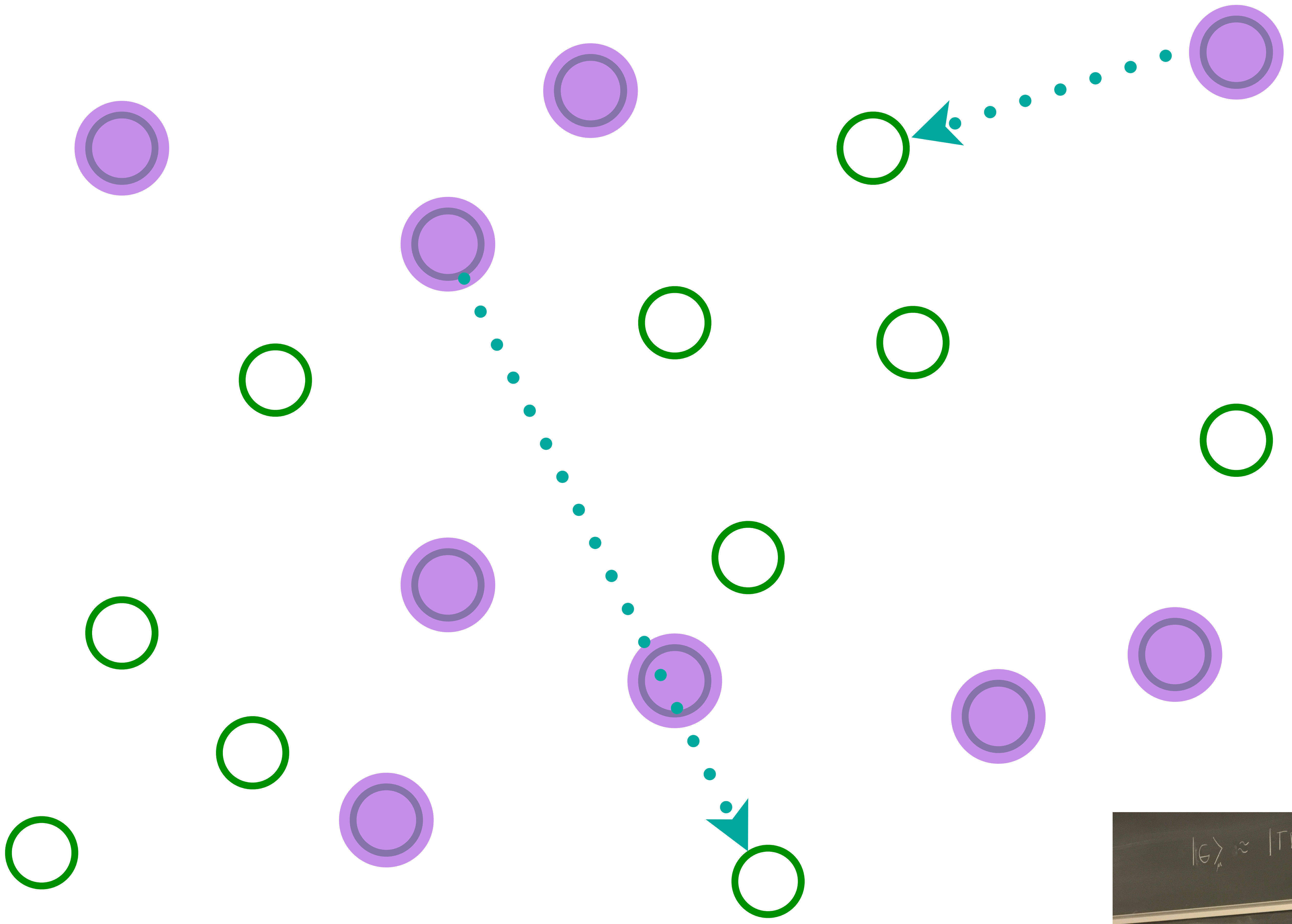

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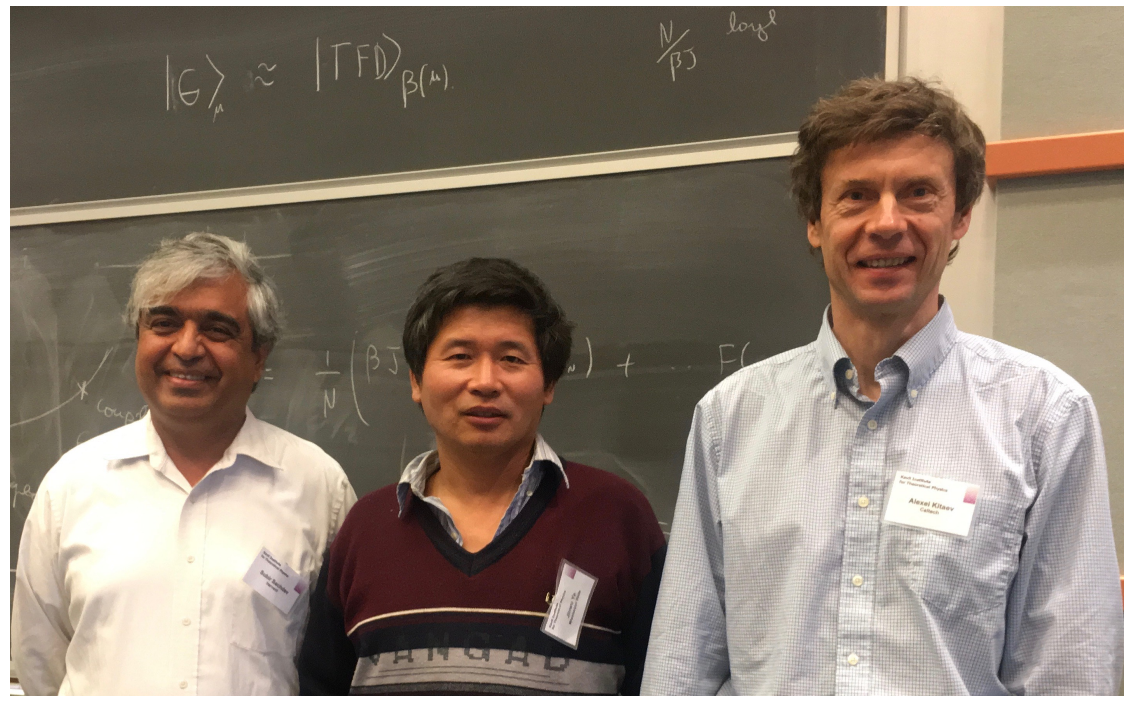

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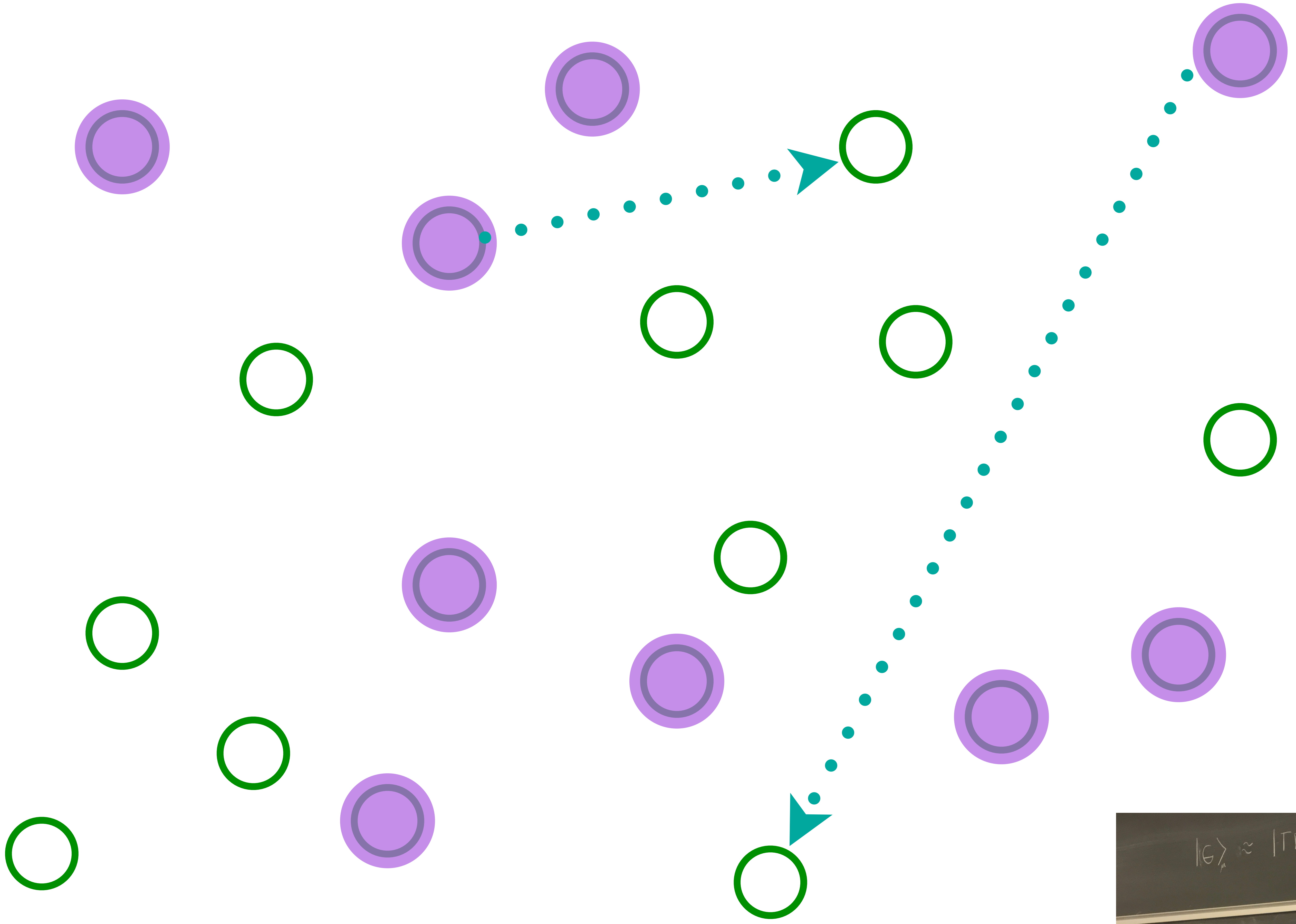
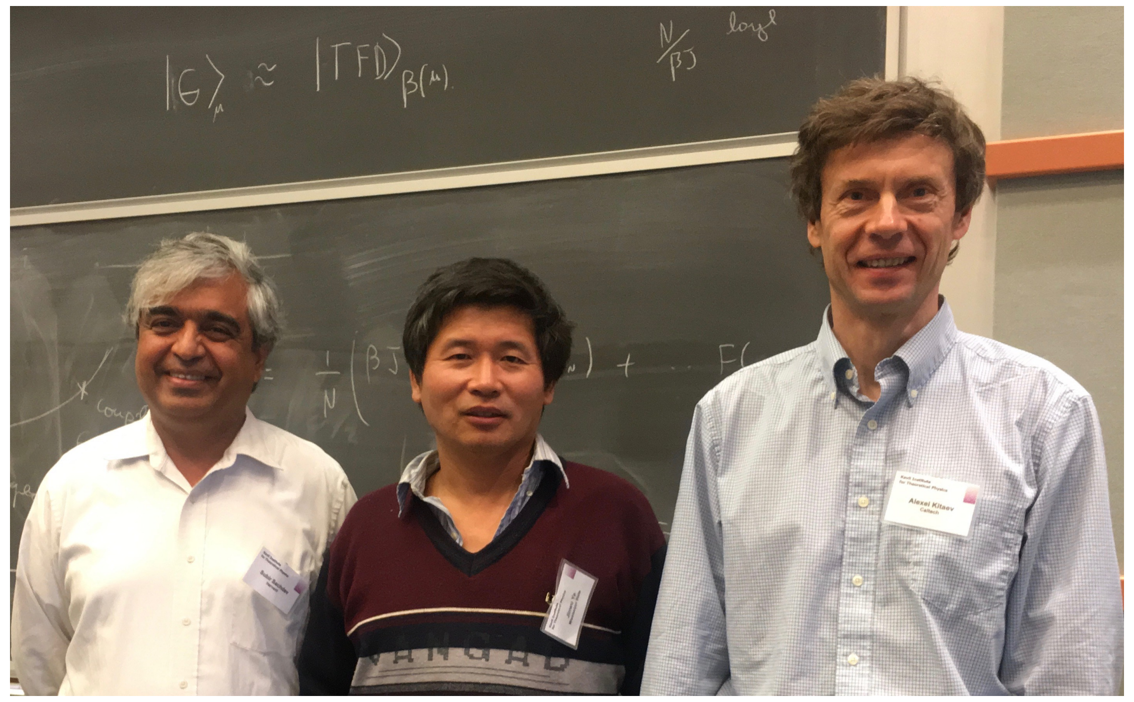
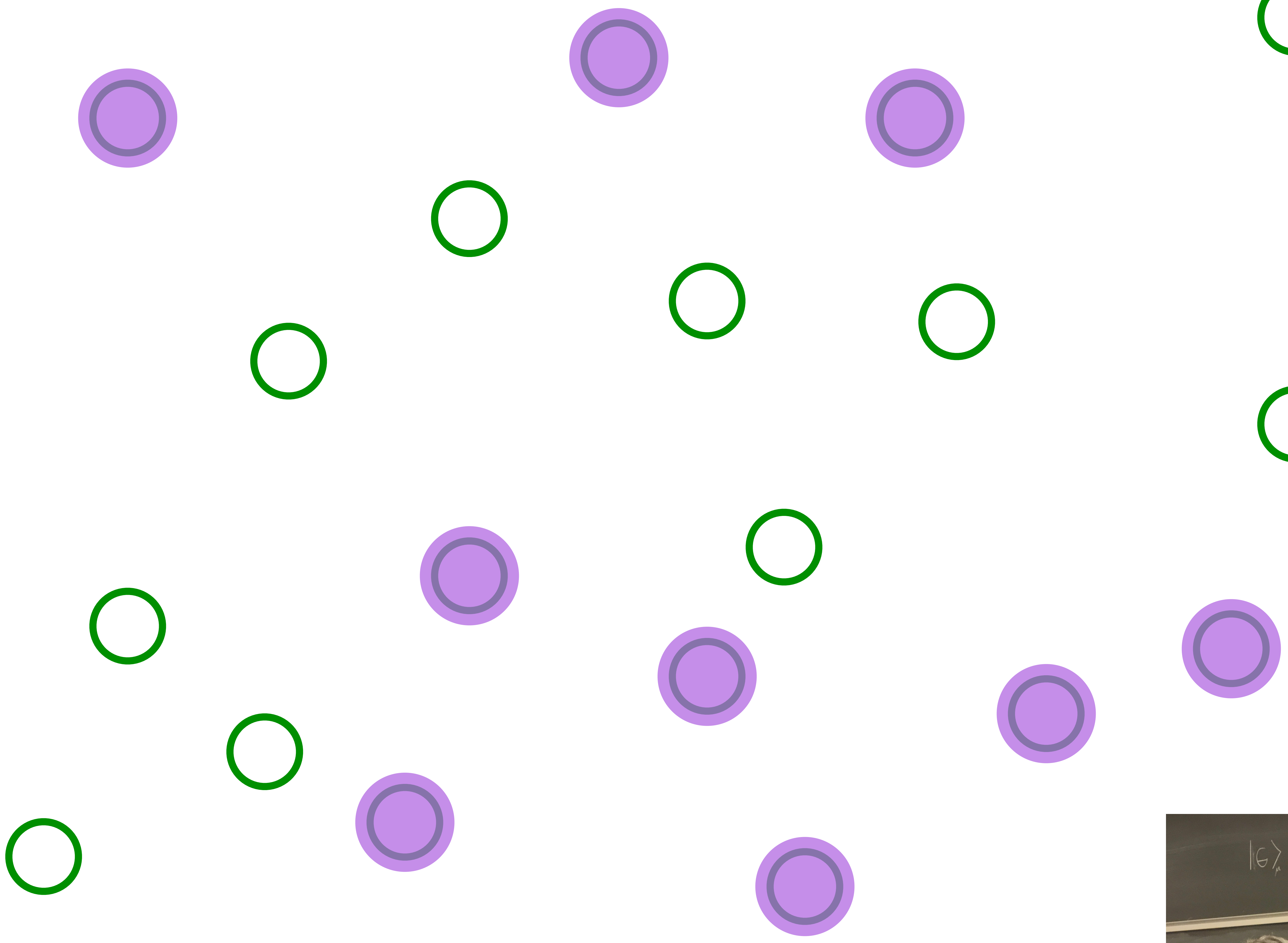


Entangle electrons pairwise randomly



The SYK model

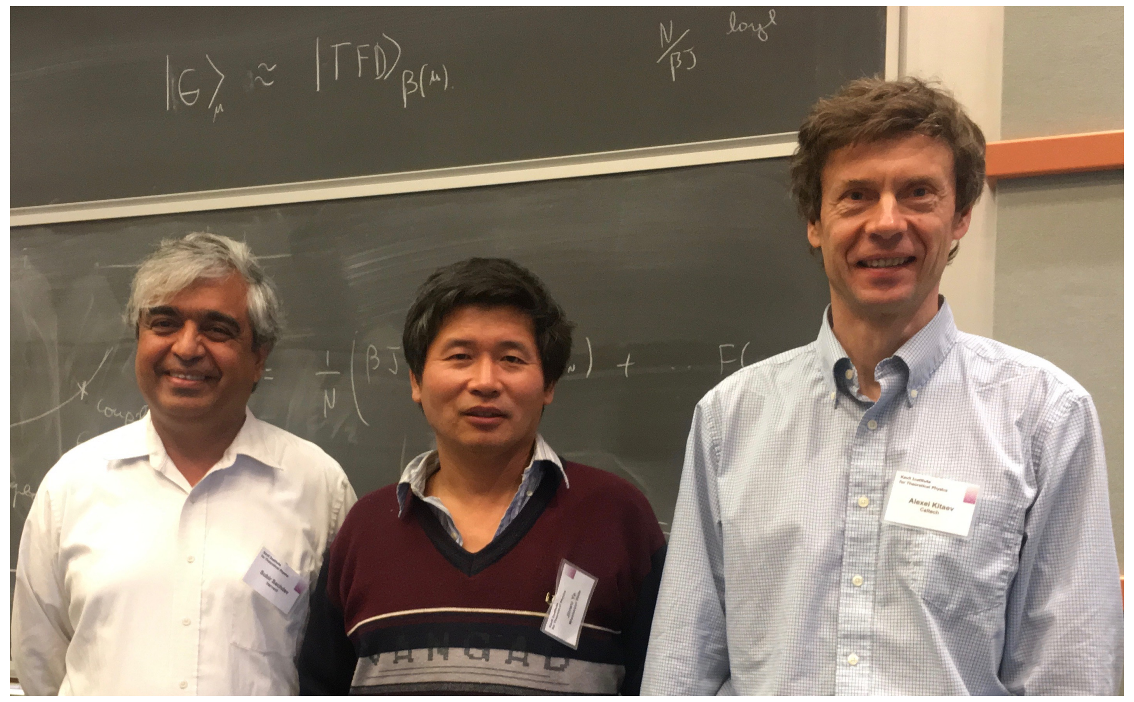
Sachdev, Ye (1993); Kitaev (2015)



Electron scattering time τ in the SYK model

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

Entangle electrons pairwise randomly

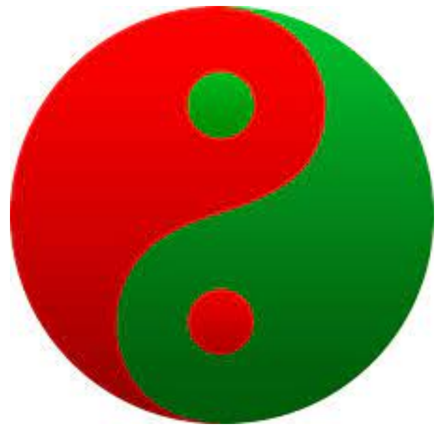


The Sachdev-Ye-Kitaev (SYK) model

The SYK model has a scale-invariant entanglement structure: i.e. electrons are entangled at all distance and time scales

In one set of variables, it describes certain ***strange metals***

Sachdev, Ye (1993)



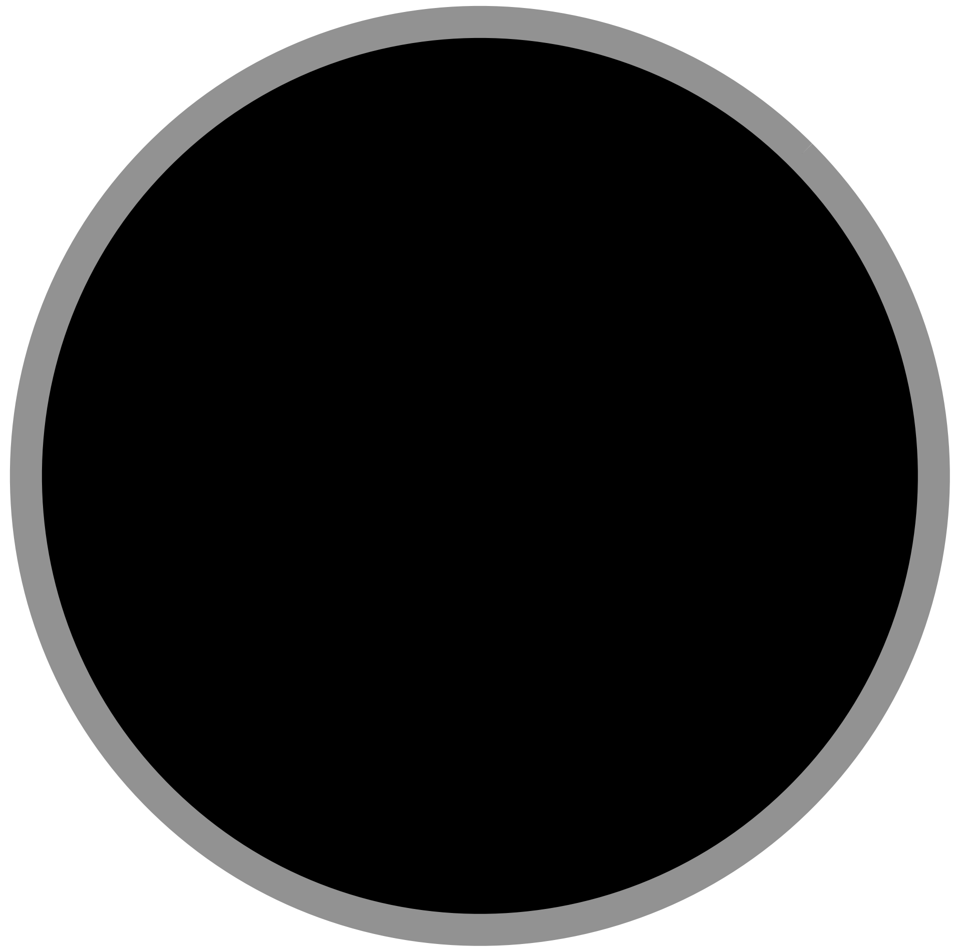
In a *dual* set of variables it describes certain ***black holes***

Sachdev (2010), Kitaev (2015), Maldacena Stanford (2015)

Black Holes

Objects so dense that light is gravitationally bound to them.

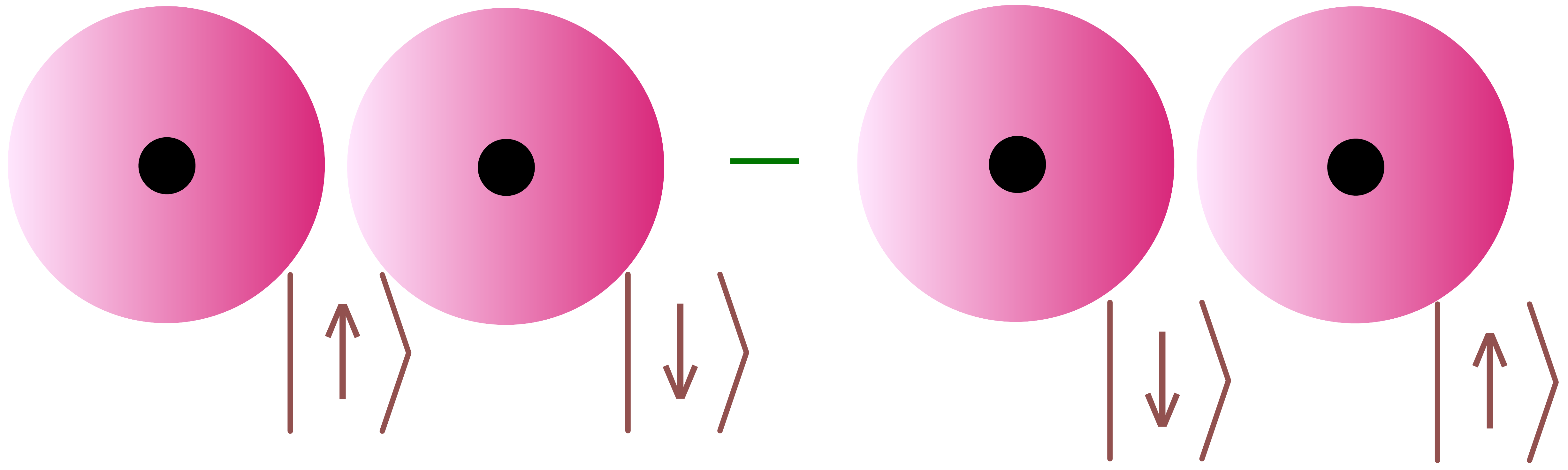
Horizon radius $R = \dfrac{2GM}{c^2}$



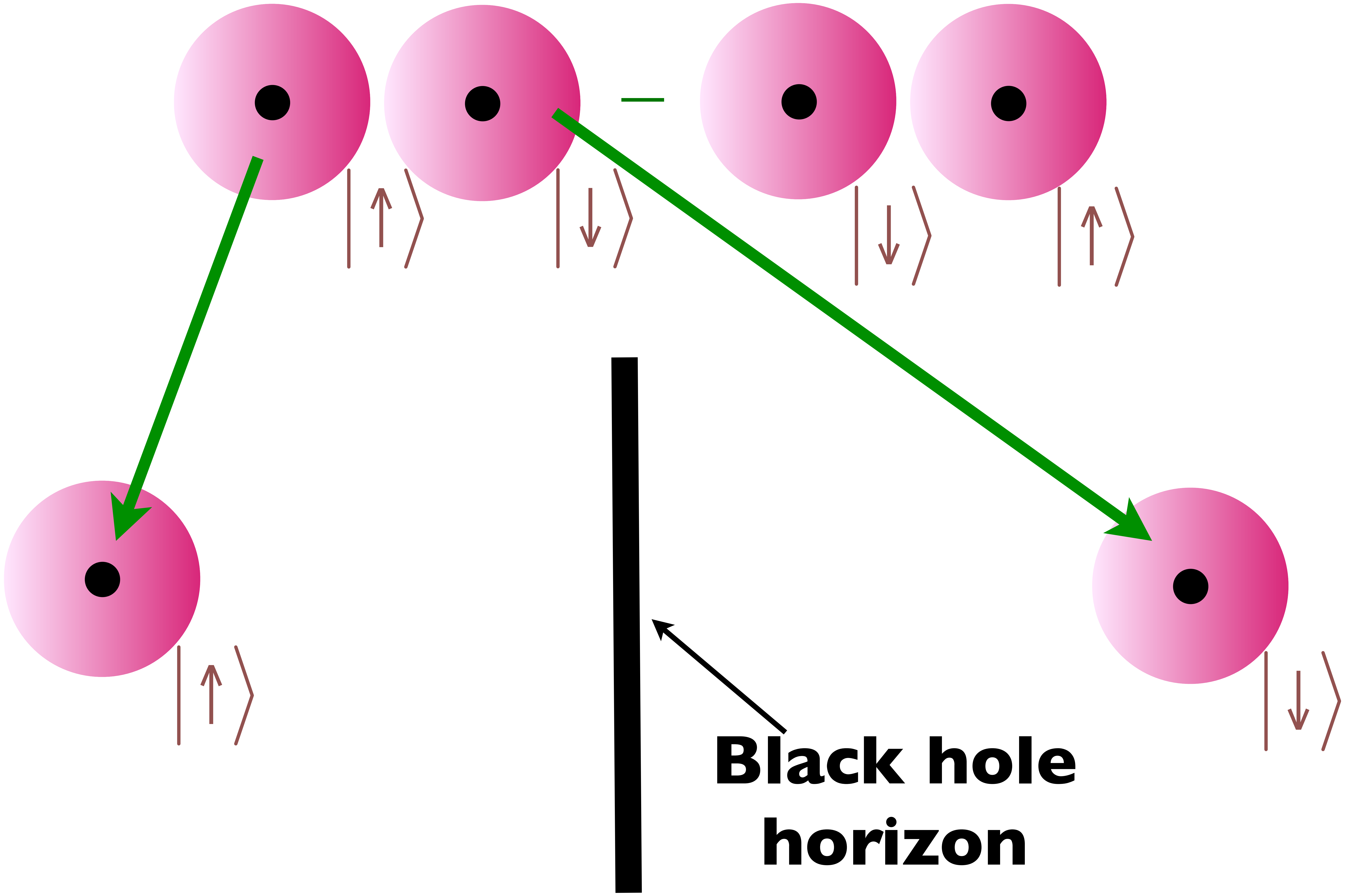
G Newton's constant, c velocity of light, M mass of black hole

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

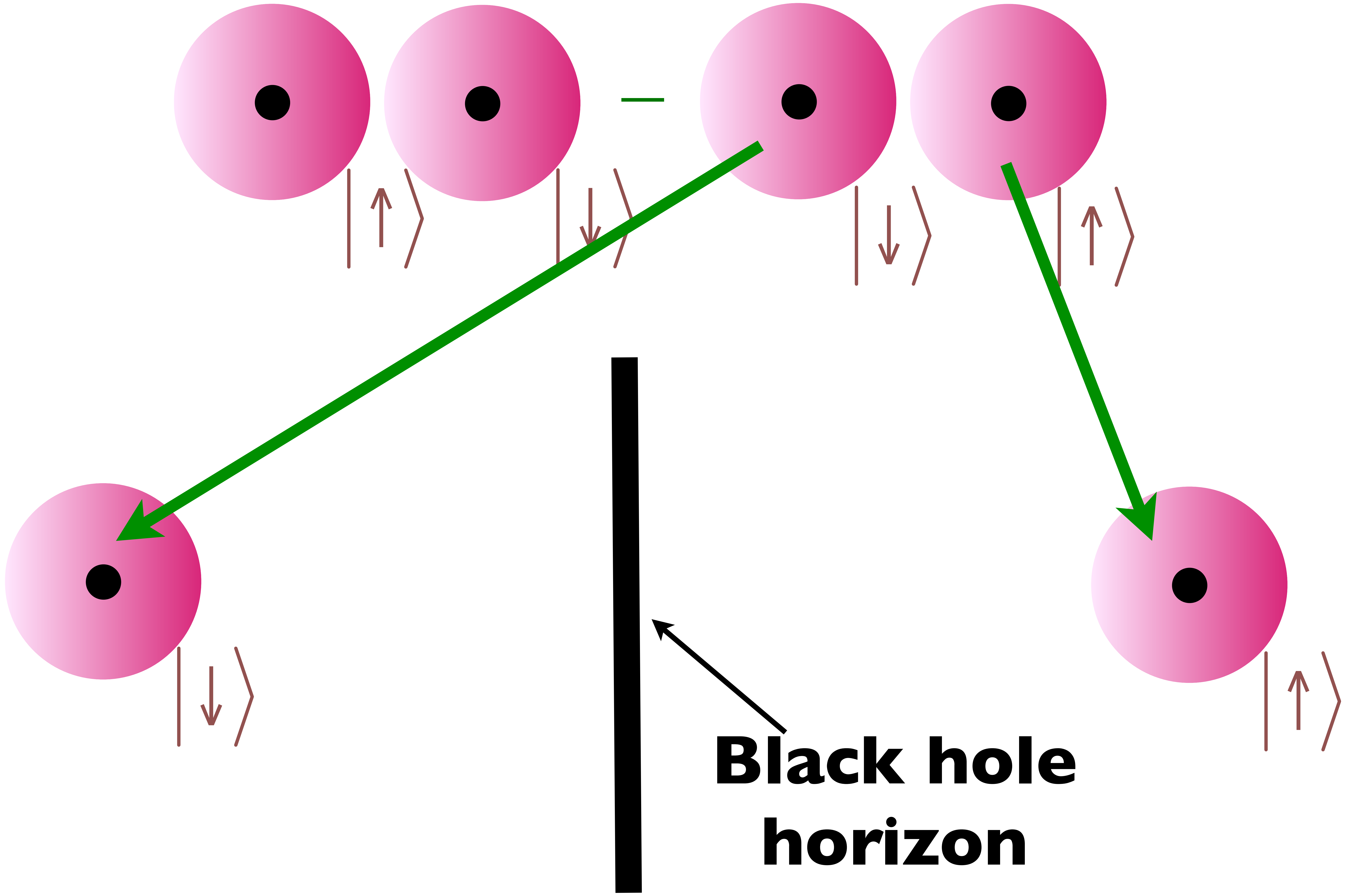
Quantum Entanglement across a black hole horizon



Quantum Entanglement across a black hole horizon

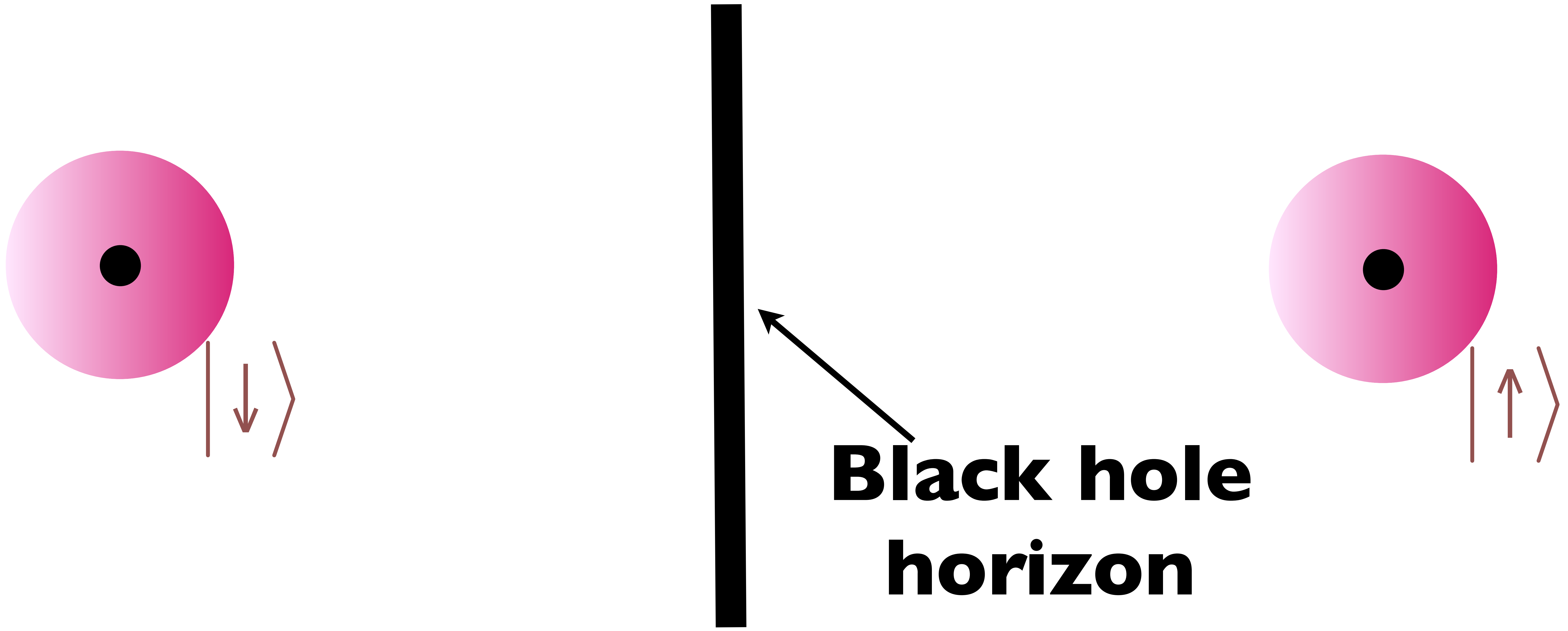


Quantum Entanglement across a black hole horizon



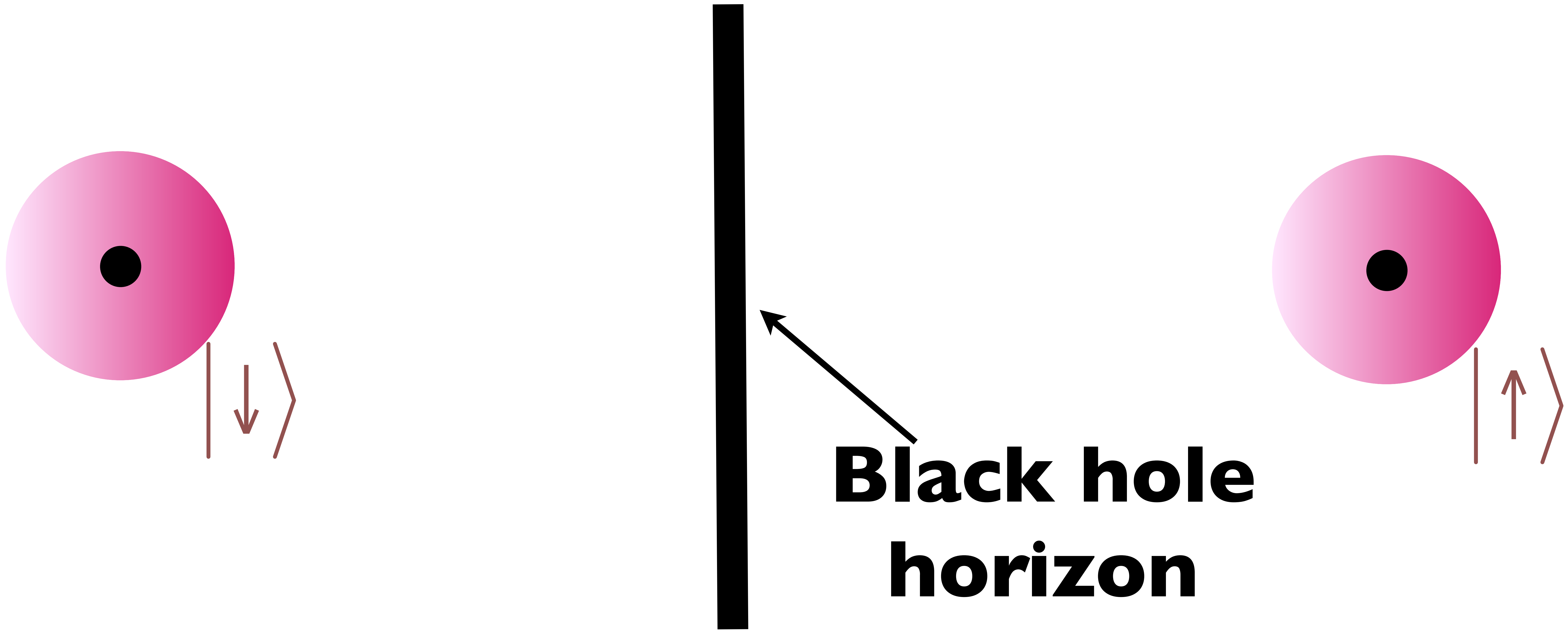
Quantum Entanglement across a black hole horizon

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



Quantum Entanglement across a black hole horizon

Hawking (1975) used other arguments to show that black hole horizons have a temperature
(The entanglement reasoning: to an outside observer, the state of the electron inside the black hole cannot be known, and so the outside electron is in a random state.)



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

Black holes are represented as a `*hologram*' by a quantum many-body system in one lower dimension.

Duality: a `*change of variables*' between the many-particle configurations and the metric of spacetime

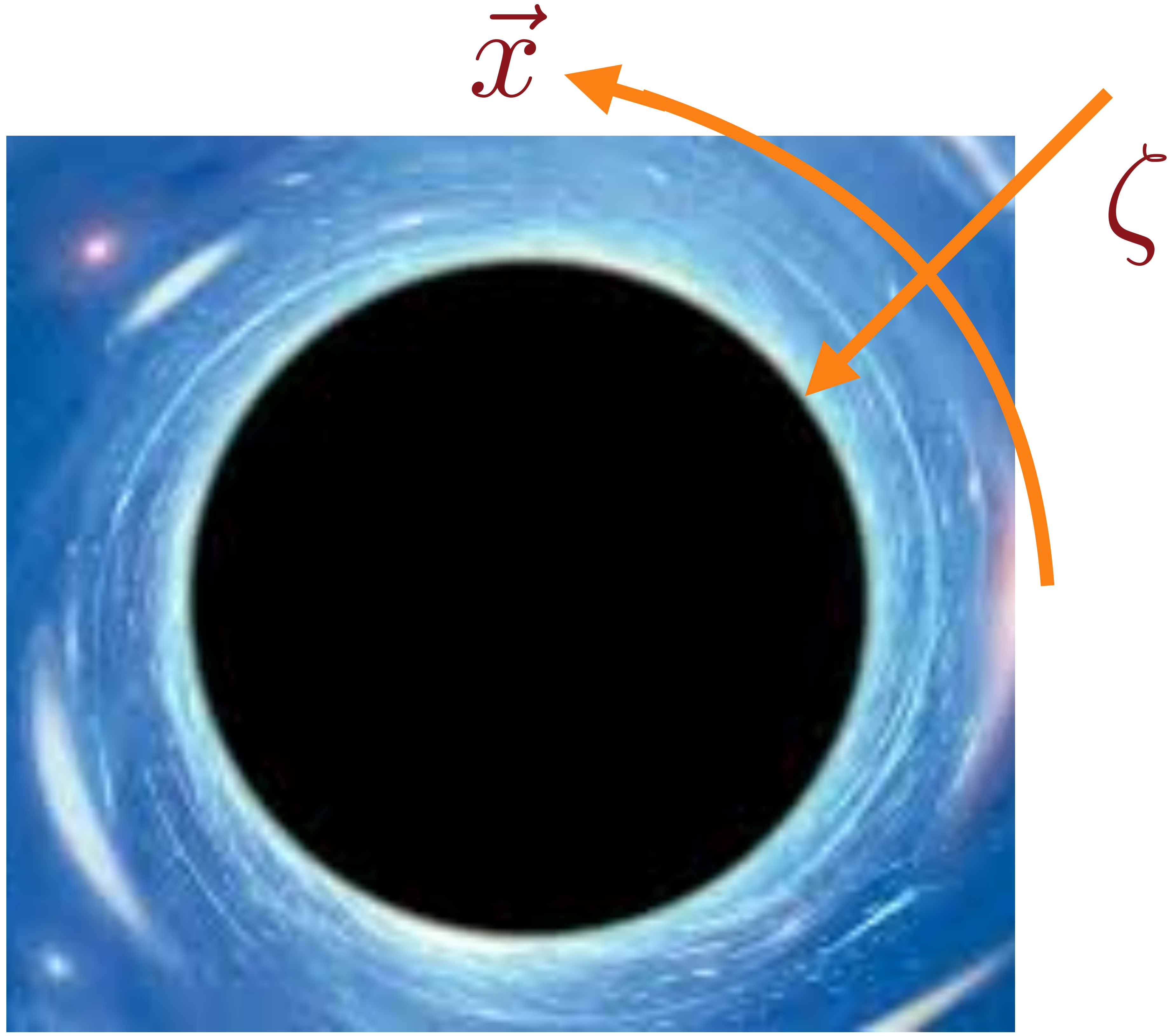
Susskind, Maldacena…..

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

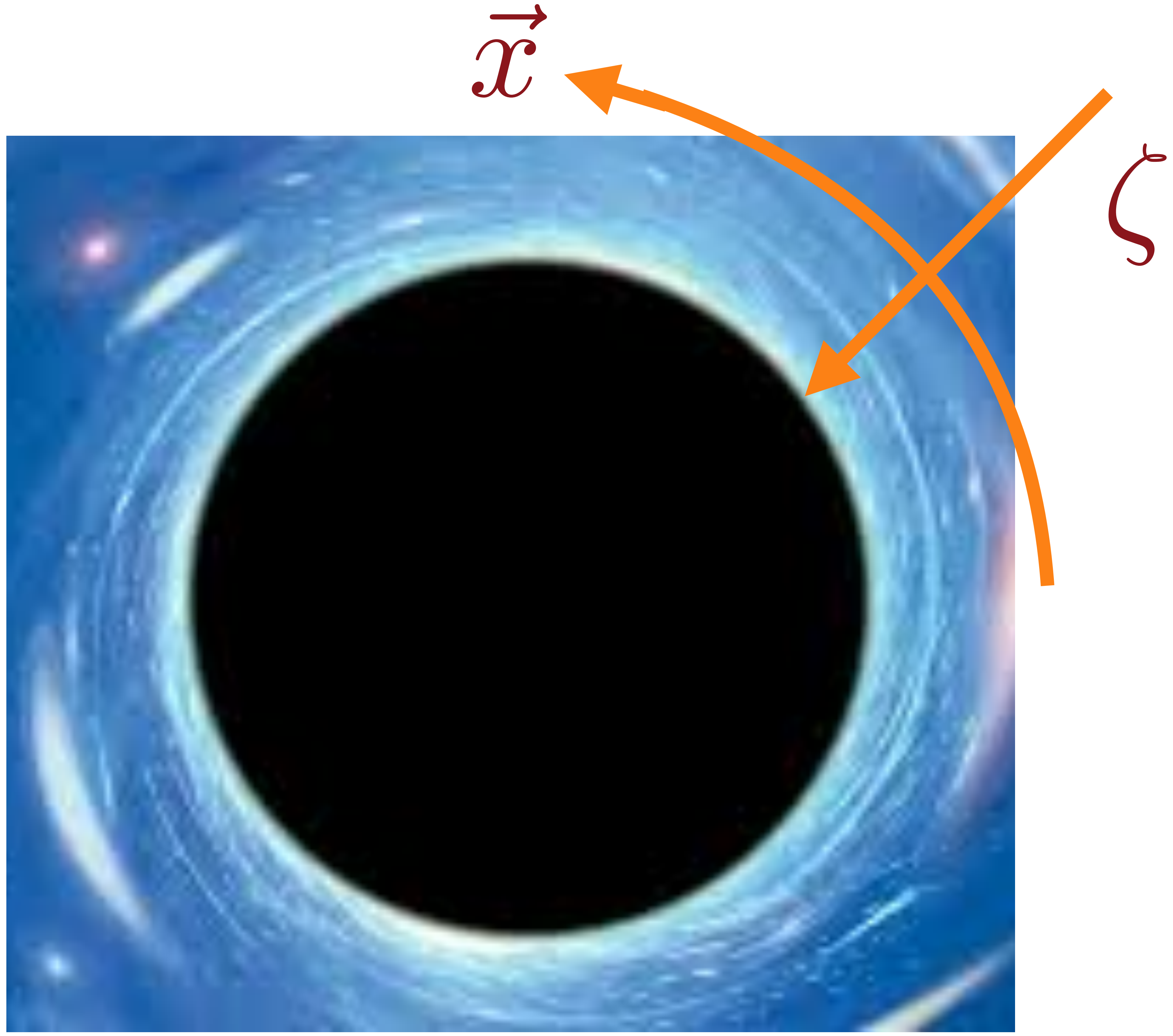
The hologram of a black hole
in d dimensions
is a quantum many-particle system
in $(d-1)$ dimensions
which relaxes to thermal equilibrium
in a Planckian time $\sim \hbar/(k_B T)$

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



The near-horizon geometry of a charged black hole is one-dimensional (ζ)

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



The hologram of the 1+1 dimensional gravity near the horizon of a charged black hole is the 0+1 dimensional SYK model

Sachdev (2010); Kitaev (2015); Sachdev (2015); Maldacena, Stanford, Yang (2016) ; Moitra, Trivedi, Vishal (2018) ; Gaikwad, Joshi, Mandal, Wadia (2018); Iliesiu, Turaci (2020)

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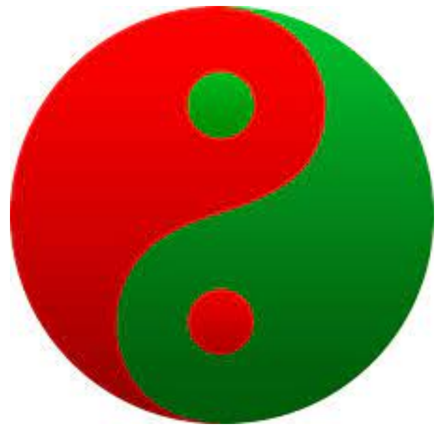

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1. "Conventional" phases of matter

   Metals, insulators, superconductors

2. Emergent gauge fields and topology

   Spin liquids with Rydberg atoms

3. Strange metals

   SYK model and emergent gravity