Quantum phases of matter with Rydberg atoms

Interacting Topological Matter:
Atomic, Molecular, and Optical Systems
Kavli Institute for Theoretical Physics
University of California, Santa Barbara
July 6, 2021

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
HARVARD

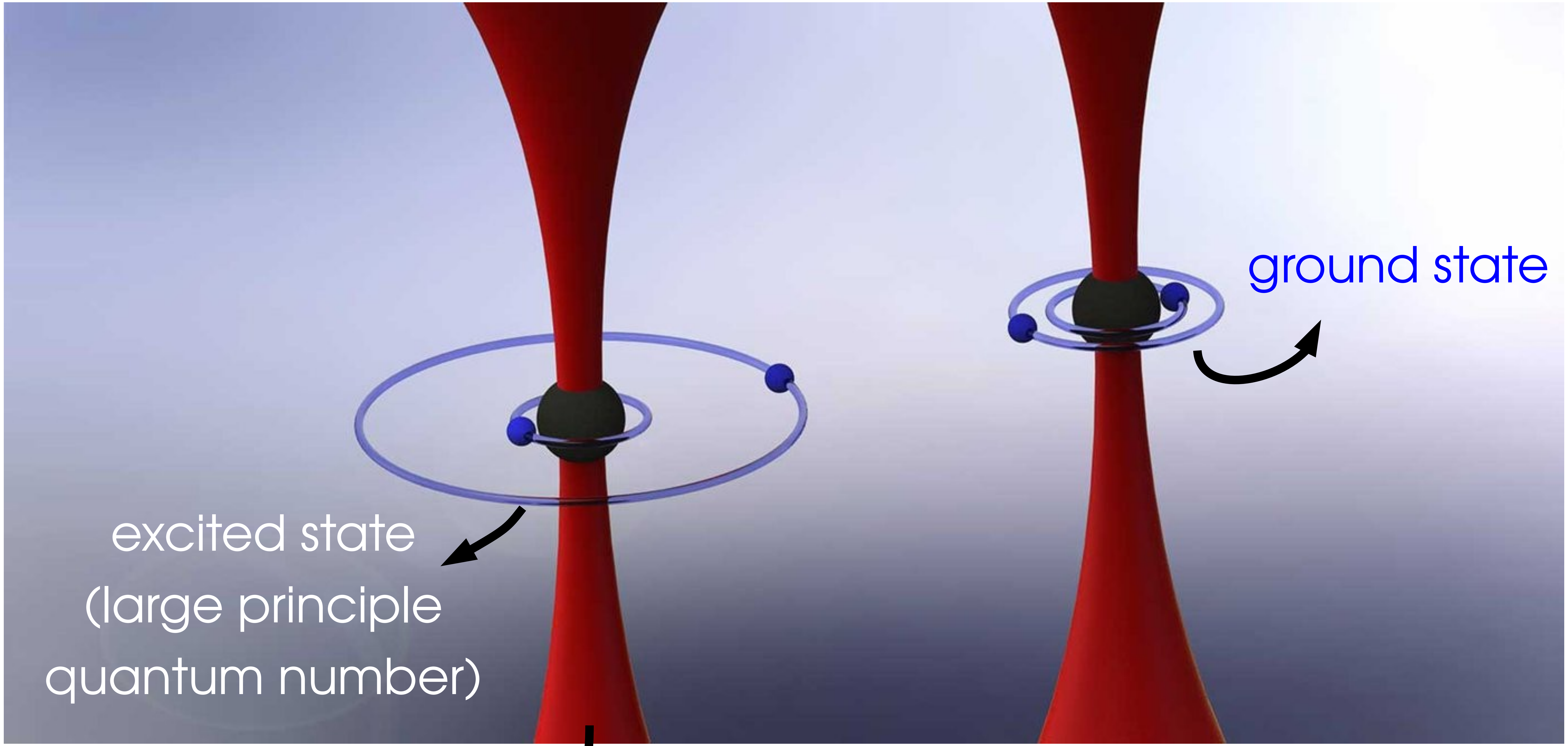
Rhine Samajdar

Seth Whitsitt

Wen Wei Ho

Hannes Pichler

Mikhail Lukin



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

optical tweezer (traps atom)

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

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

1. Rydberg chains

   The Z_3 chiral clock transition

2. Square lattice

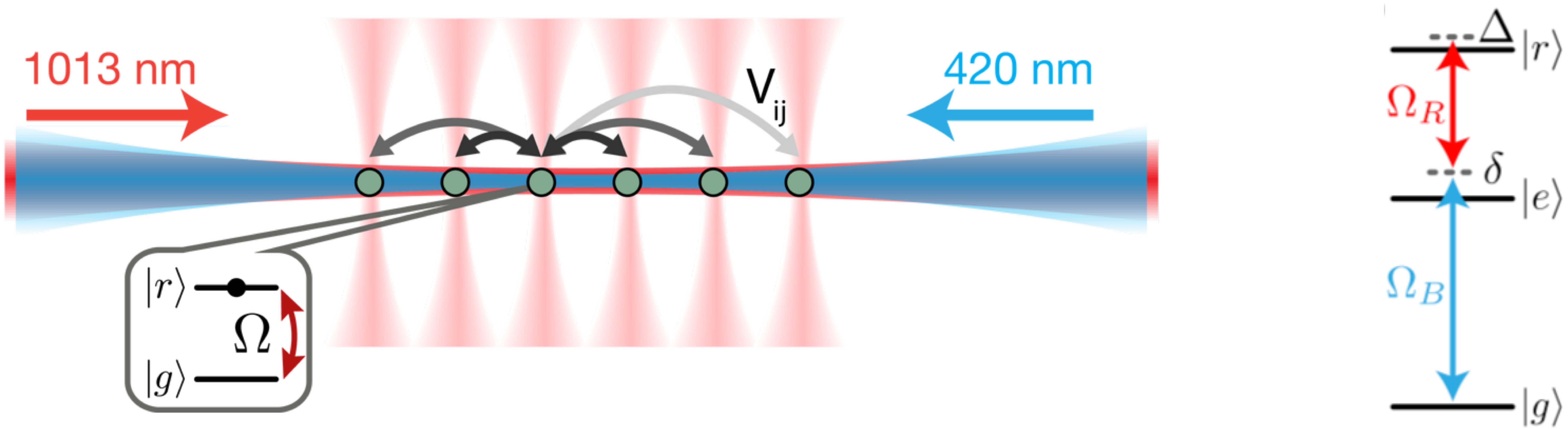
   Quantum Ising criticality in 2+1 dimensions

3. Kagome symmetry lattices

   Probing topological spin liquids

4. Theory of odd and even Z_2 spin liquids

QPTs in a Rydberg quantum simulator



$$H_{\text{Ryd}} = \sum_{i=1}^{N} \frac{\Omega}{2} \Big(|g\rangle\langle r| + |r\rangle\langle g| \Big)_i - \Delta \sum_{i=1}^{N} |r\rangle\langle r|_i + \sum_{i<j} V_{|i-j|} \Big(|r\rangle\langle r|_i \otimes |r\rangle\langle r|_j \Big)$$

$$V_{|i-j|} \sim \frac{1}{|r_i - r_j|^6}$$

Bernien et. al., Nature **551**, 579, (2017)
Keesling et. al., arXiv:1809.05540

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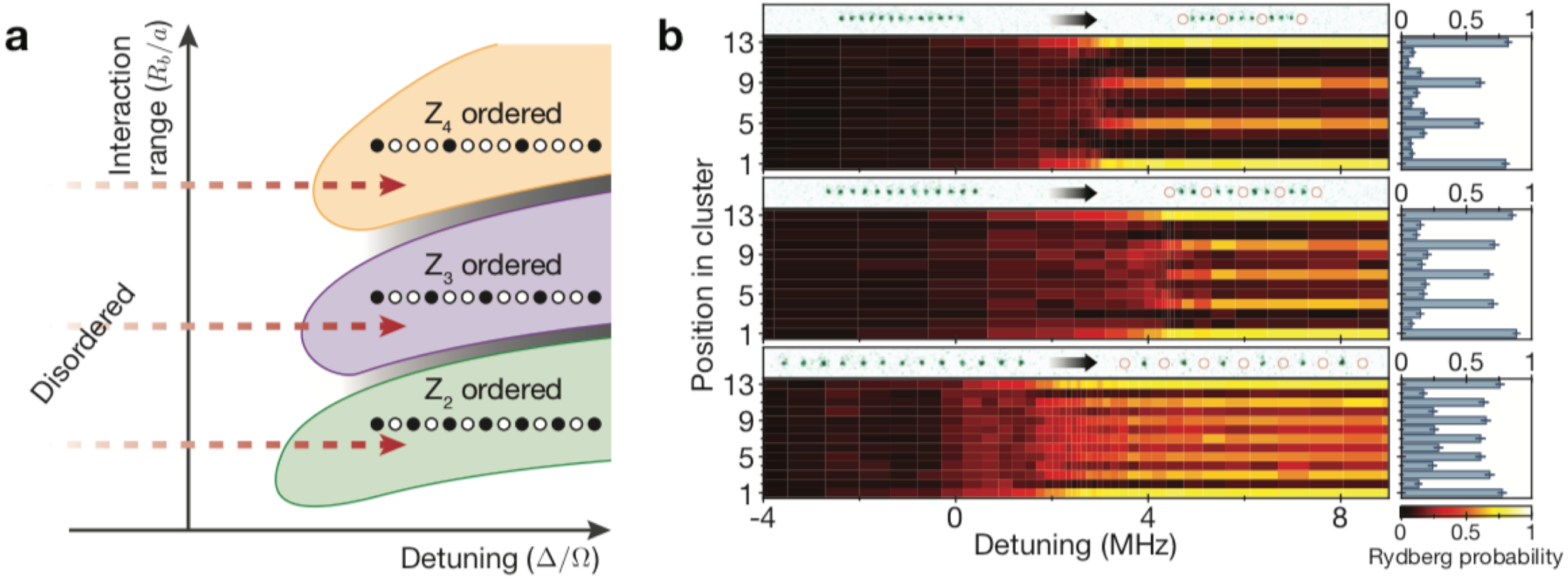

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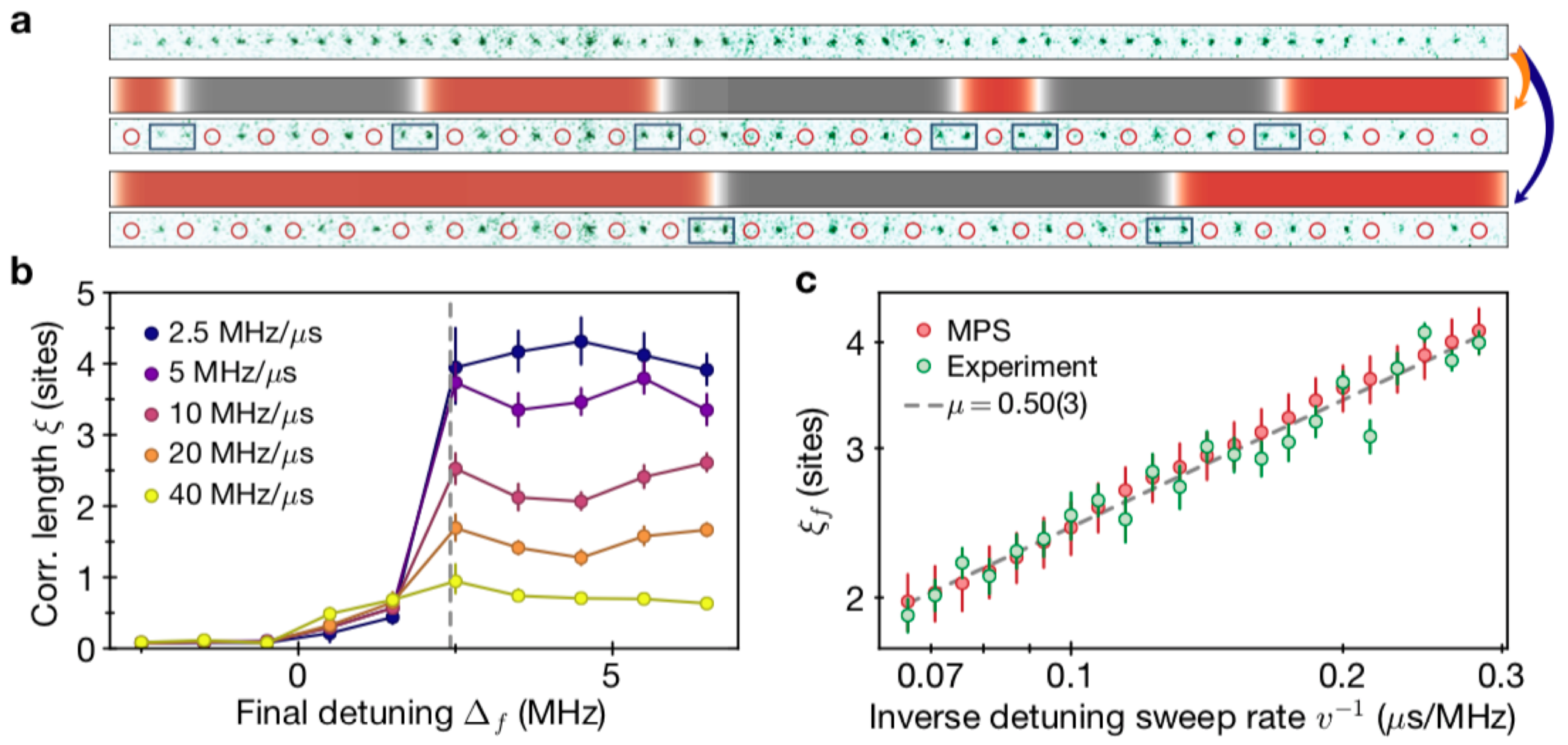
Keesling et. al. Nature **568**, 207 (2019)

QPTs in a Rydberg quantum simulator

Universal critical dynamics: quantum Kibble-Zurek mechanism



Tune through transition at rate v:

$$\Delta(t) = \Delta_c + vt$$

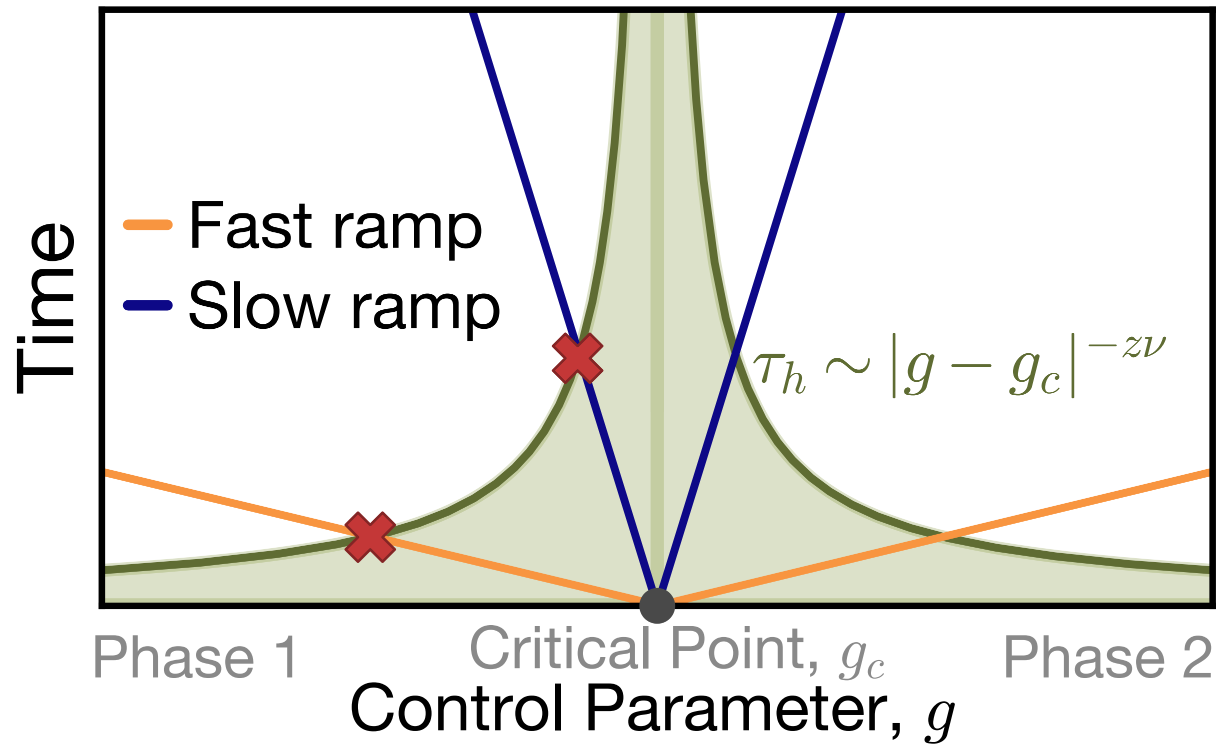
Correlation length saturates!

$$\xi \sim v^{-\nu/(1+\nu z)}$$

Experimental probe of critical exponents

Quantum Kibble-Zurek mechanism and critical dynamics on a programmable Rydberg simulator

Alexander Keesling, Ahmed Omran, Harry Levine, Hannes Bernien, Hannes Pichler, Soonwon Choi, Rhine Samajdar, Sylvain Schwartz, Pietro Silvi, Subir Sachdev, Peter Zoller, Manuel Endres, Markus Greiner, Vladan Vuletic, and Mikhail D. Lukin, *Nature* **568**, 207 (2019)



Competing density-wave orders in a one-dimensional hard-boson model

PHYSICAL REVIEW B **69**, 075106 (2004) P. Fendley, K. Sengupta, S. Sachdev

$$n_j \equiv b_j^\dagger b_j$$

$$\mathcal{H} = \sum_j \left[\frac{\Omega}{2} \left(b_j + b_j^\dagger \right) - \Delta n_j \right] + \sum_{i<j} V_{|i-j|} n_i n_j$$

$$V_1 = \infty, \quad V_2 = V, \quad V_{i>2} = 0$$

The $V = 0$ case is the 'PXP' model, originally introduced in
S. Sachdev, K. Sengupta, and S.M. Girvin, PRB **66**, 075128 (2002)

These models were motivated by 'tilted lattices' of bosonic atoms,
and the $\mathbb{Z}_2$ quantum transition was observed in
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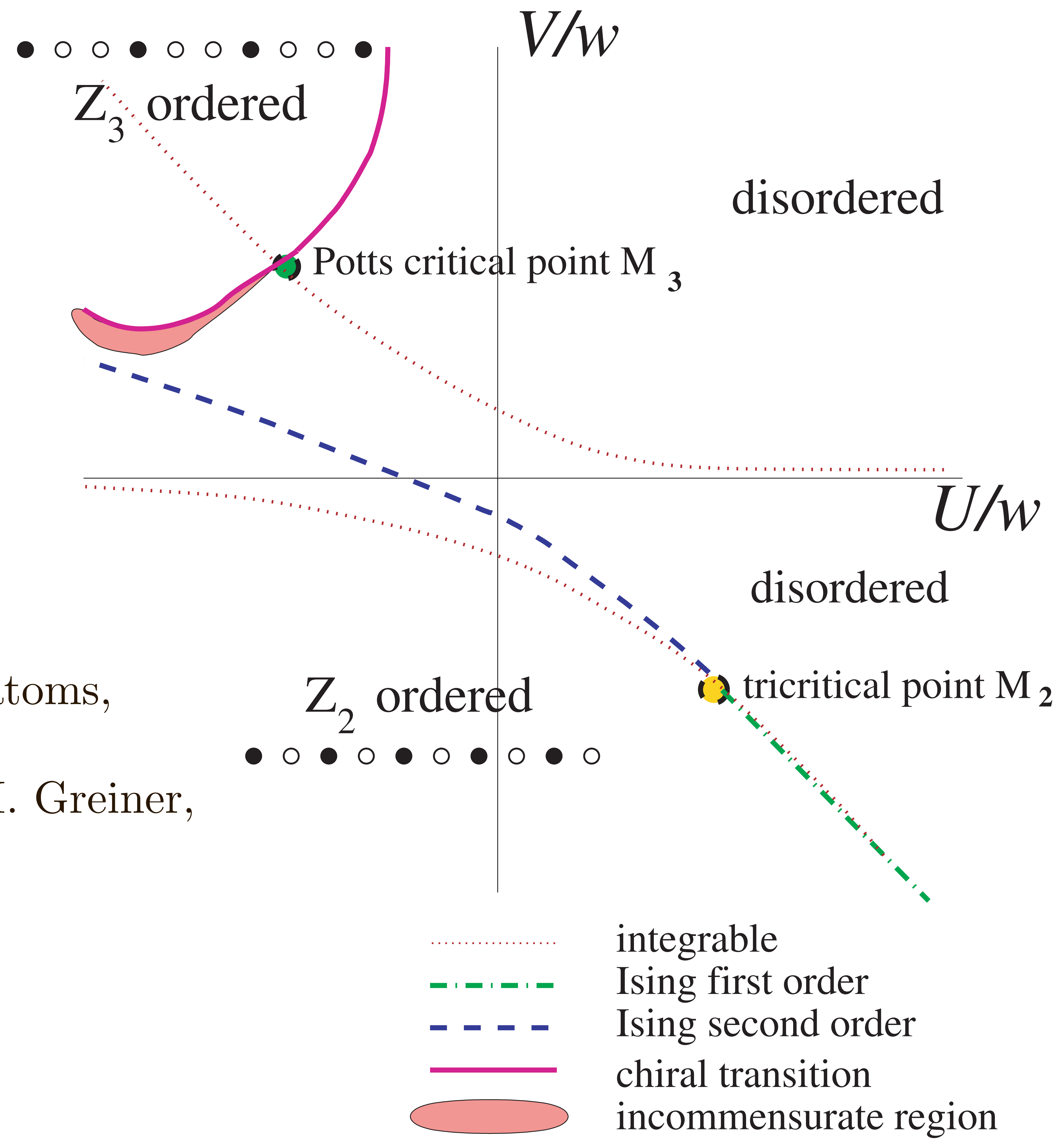

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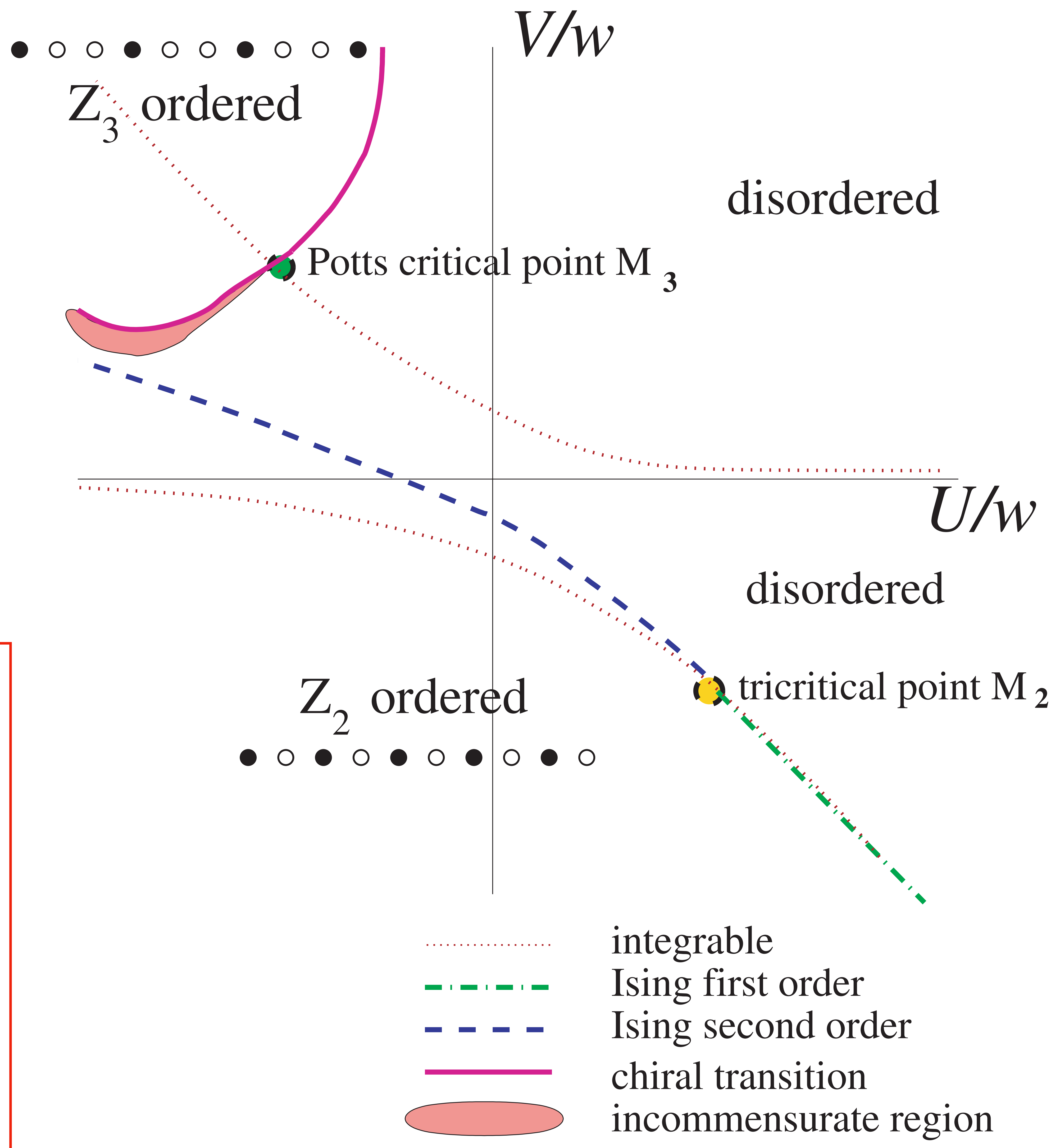

Nature of Z_3 ordering transition

Direct:

Ostlund, PRB **24**, 398 (1981).
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Selke and Yeomans, Z. Phys. B **46**, 311 (1982).
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Haldane, Bak, Bohr, PRB **28**, 2743 (1983).
Schulz, PRB **28**, 2746 (1983)
Von Gehlen and Rittenberg, Nucl. Phys. B, 473 (1984)

Floating Phase versus Chiral Transition in a 1D Hard-Boson Model

PHYSICAL REVIEW LETTERS **122,** 017205 (2019) N. Chepiga and F. Mila

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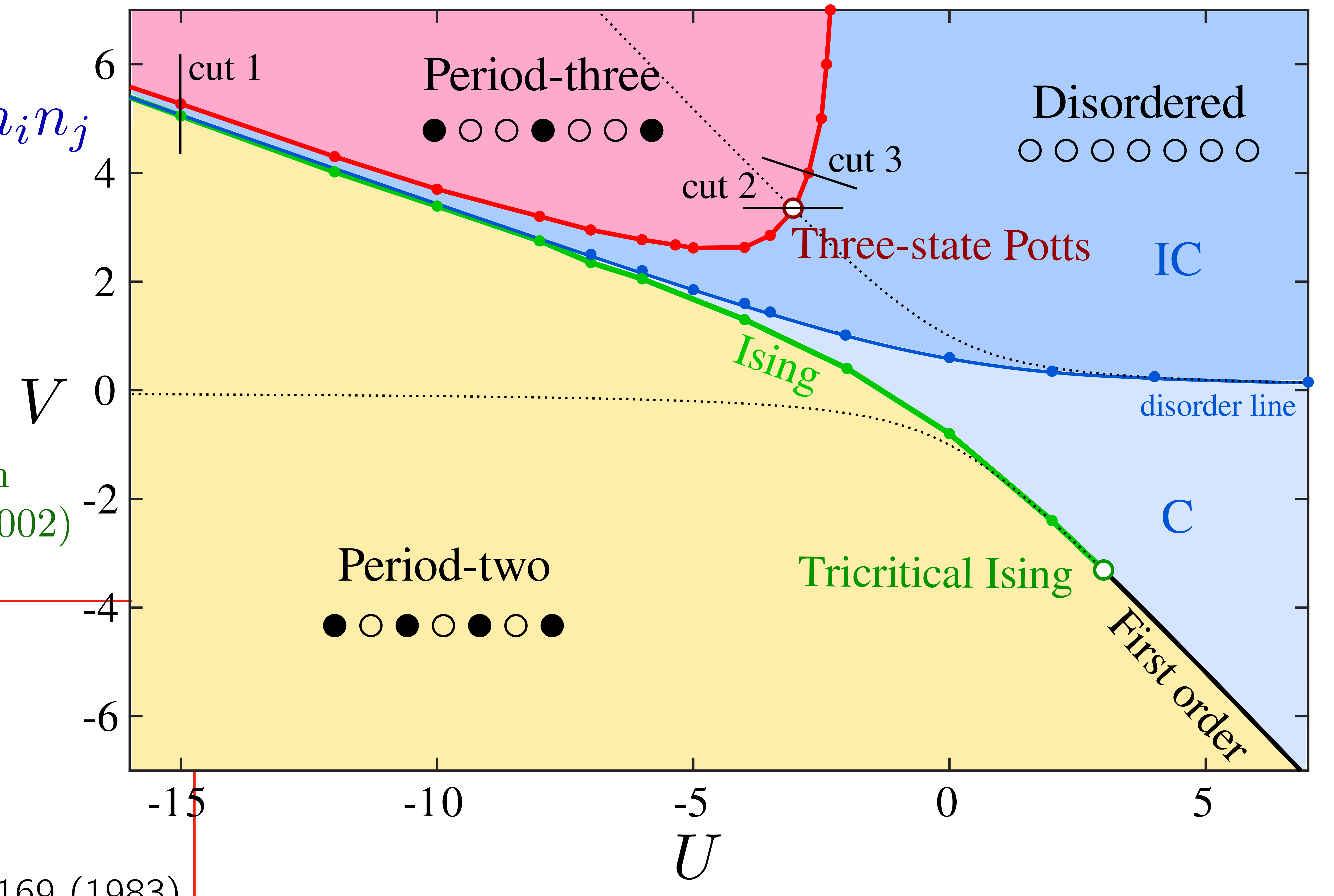

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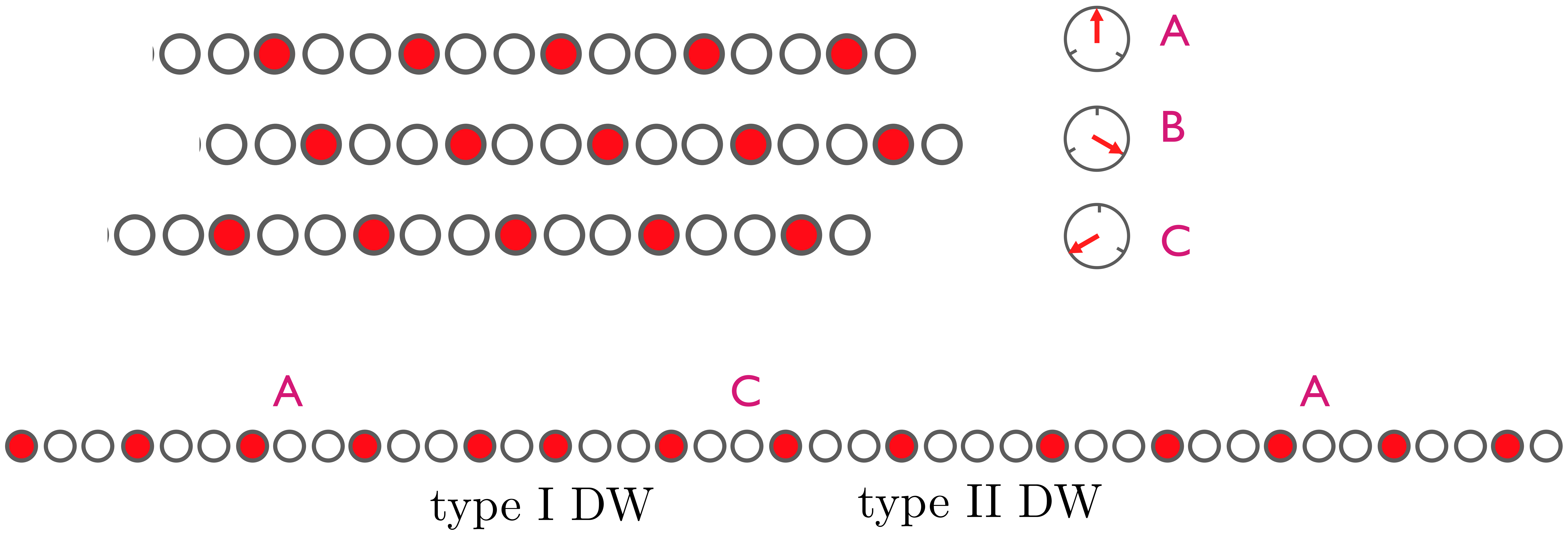
Quantum field theory for the chiral clock transition in one spatial dimension

PHYSICAL REVIEW B **98**, 205118 (2018)

S. Whitsitt, R. Samajdar, and S. Sachdev



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What is the critical field theory? First try: write the most general theory for order parameter with appropriate symmetries.

$$\Phi \to e^{2\pi i/N}\,\Phi \qquad\qquad \Phi(x,\tau) \to \Phi^*(-x,\tau)$$

$$\mathcal{S}_\Phi = \int dx\, d\tau [|\partial_\tau \Phi|^2 + |\partial_x \Phi|^2 + i\alpha_x \Phi^* \partial_x \Phi$$

$$+ s_\Phi |\Phi|^2 + u|\Phi|^4 + \lambda(\Phi^N + (\Phi^*)^N)].$$

In perturbation theory, the field condenses at nonzero momentum.

$$\mathcal{S}_\Phi = \int \frac{d\omega\, dk}{(2\pi)^2}\, \Phi^* \left[\omega^2 + k^2 - \alpha_x k + s\right] \Phi + \cdots$$

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In perturbation theory, the field condenses at nonzero momentum.

Can only describe transition to incommensurate phase.

$$\langle \Phi(x)\Phi(0)\rangle \sim e^{ik_0 x}$$

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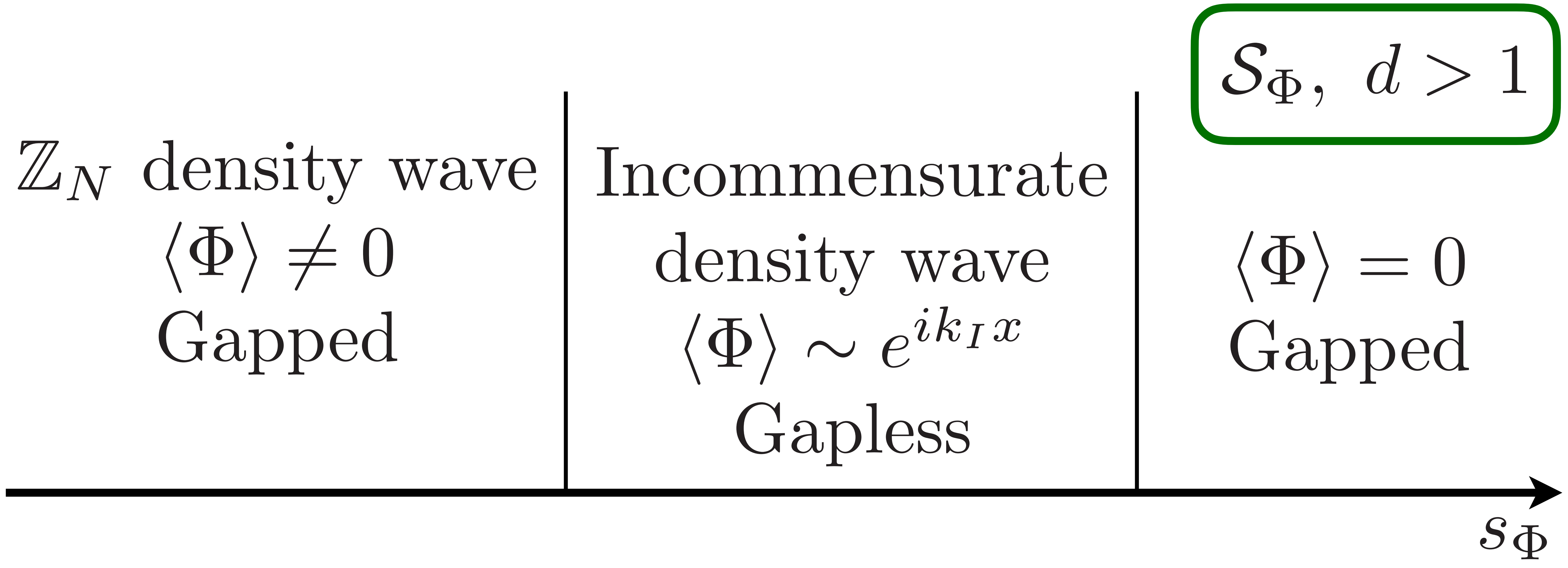

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Field theory for $\mathbb{Z}_N$ density wave ordering

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field theory for Bose condensation in the presence of a background N boson condensate

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field theory for Bose condensation in the presence of a background N boson condensate

Note: this is not a Wick rotation—
there is a crucial difference in the factor of i !!

Quantum field theory for the chiral clock transition in one spatial dimension

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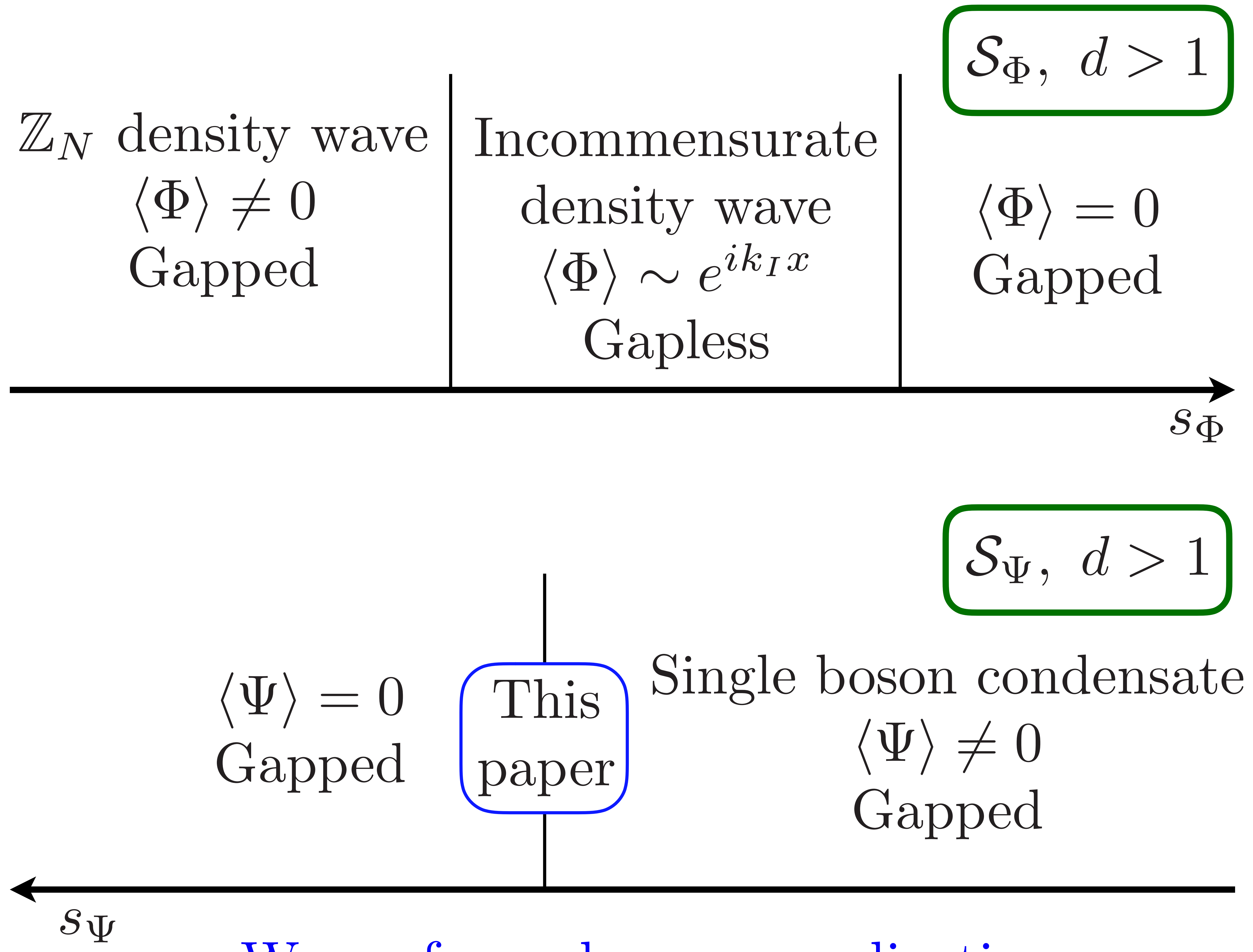

We performed a renormalization group analysis for the Bose gas transition in a expansion in $2-d$, with $4-N$ chosen to be order $2-d$. This led a strongly-coupled critical point with $z \neq 1$.

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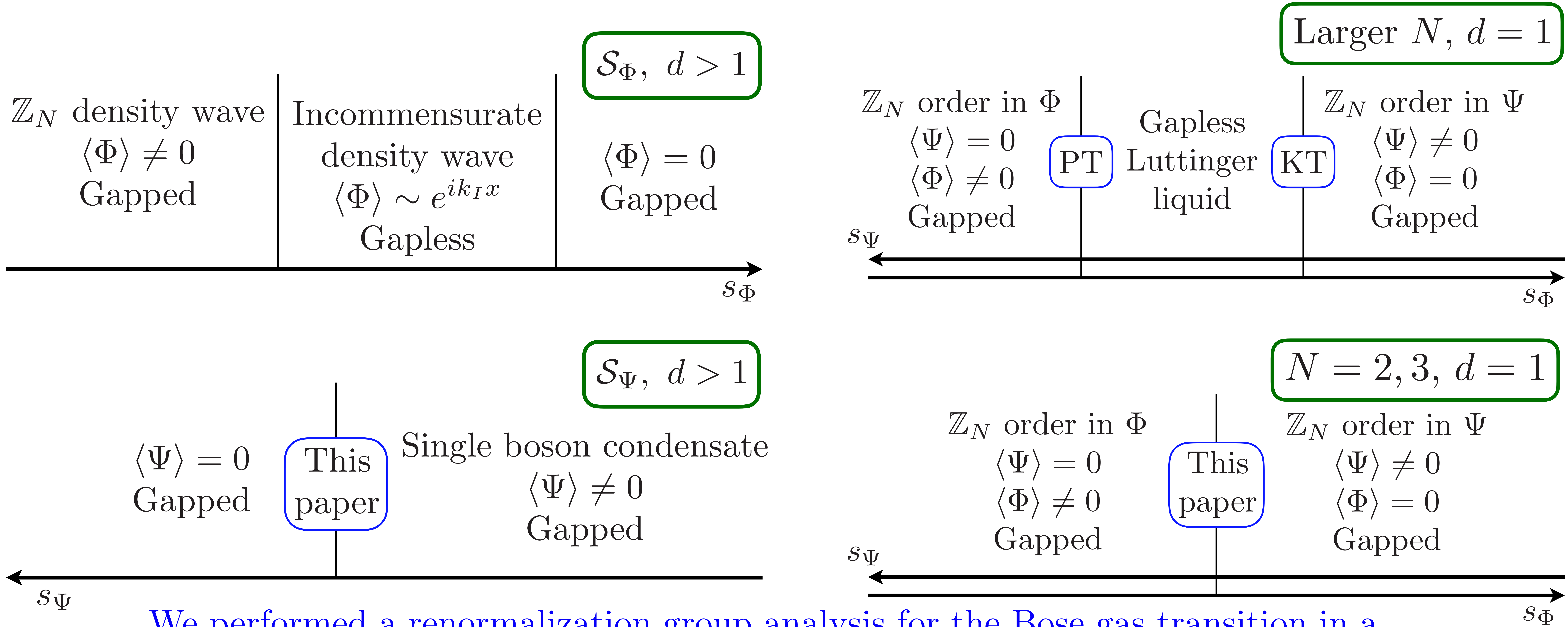

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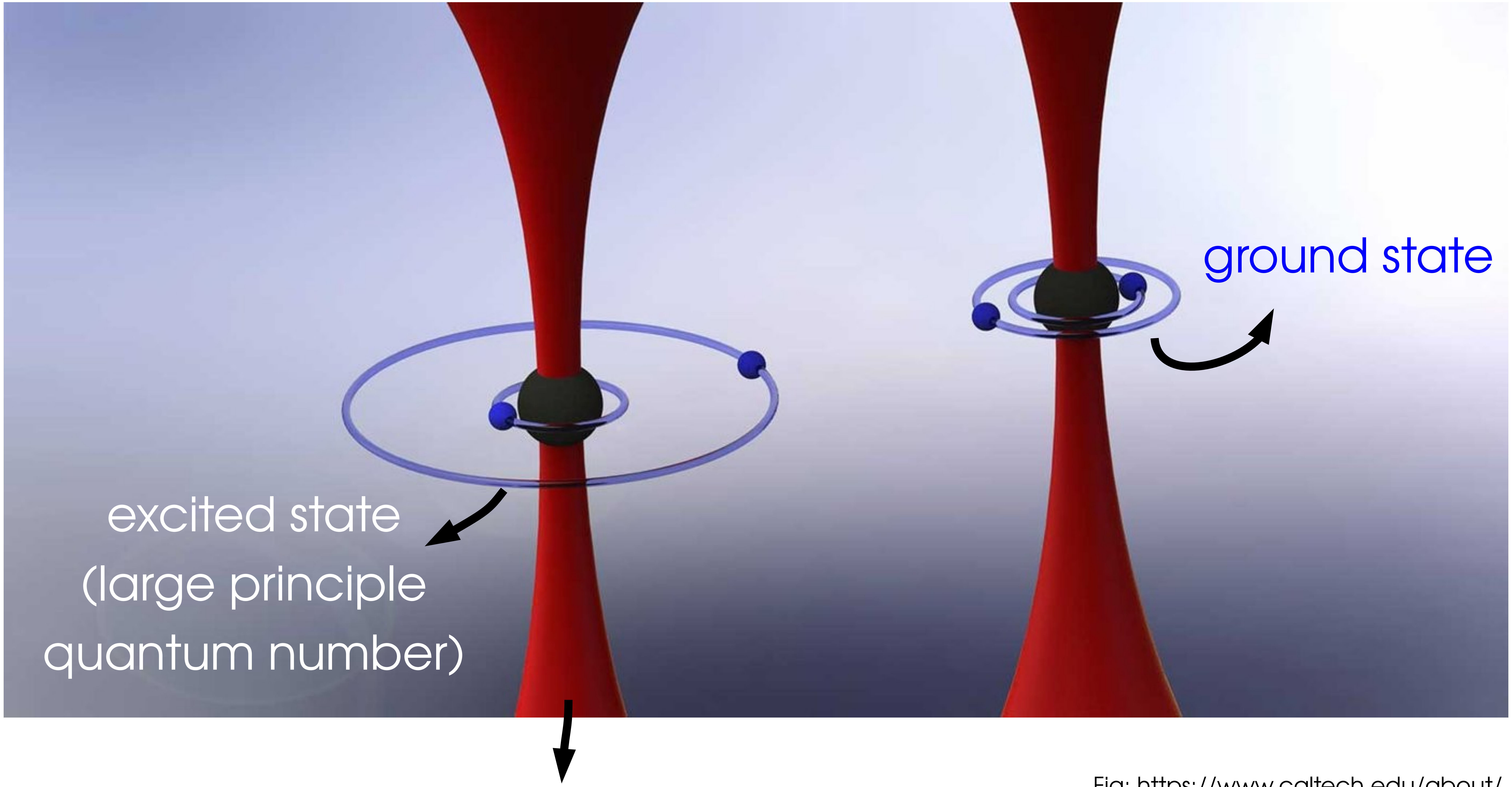

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Fig: https://www.caltech.edu/about/news/quantum-innovations-achieved-using-alkaline-earth-atoms

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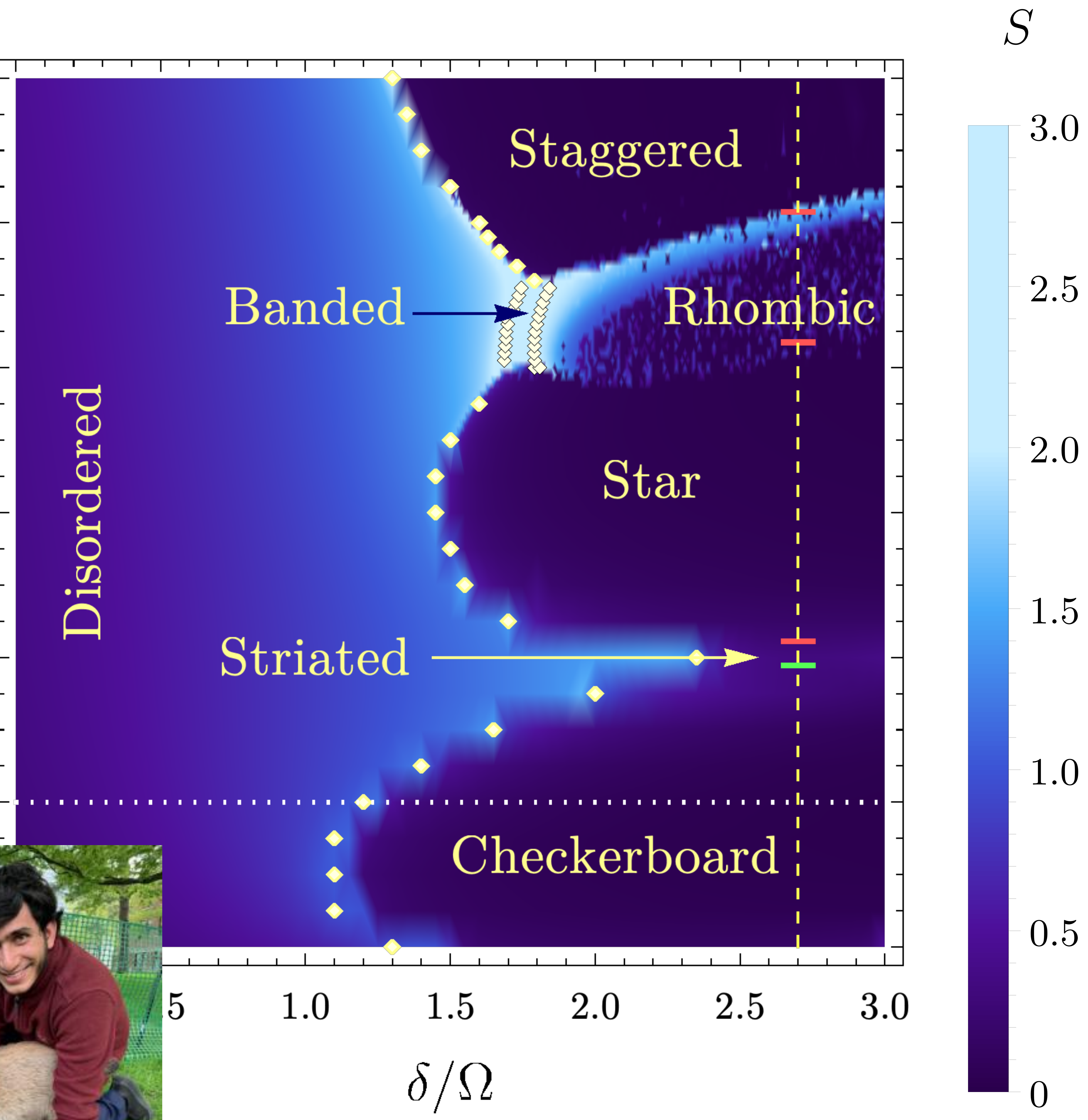
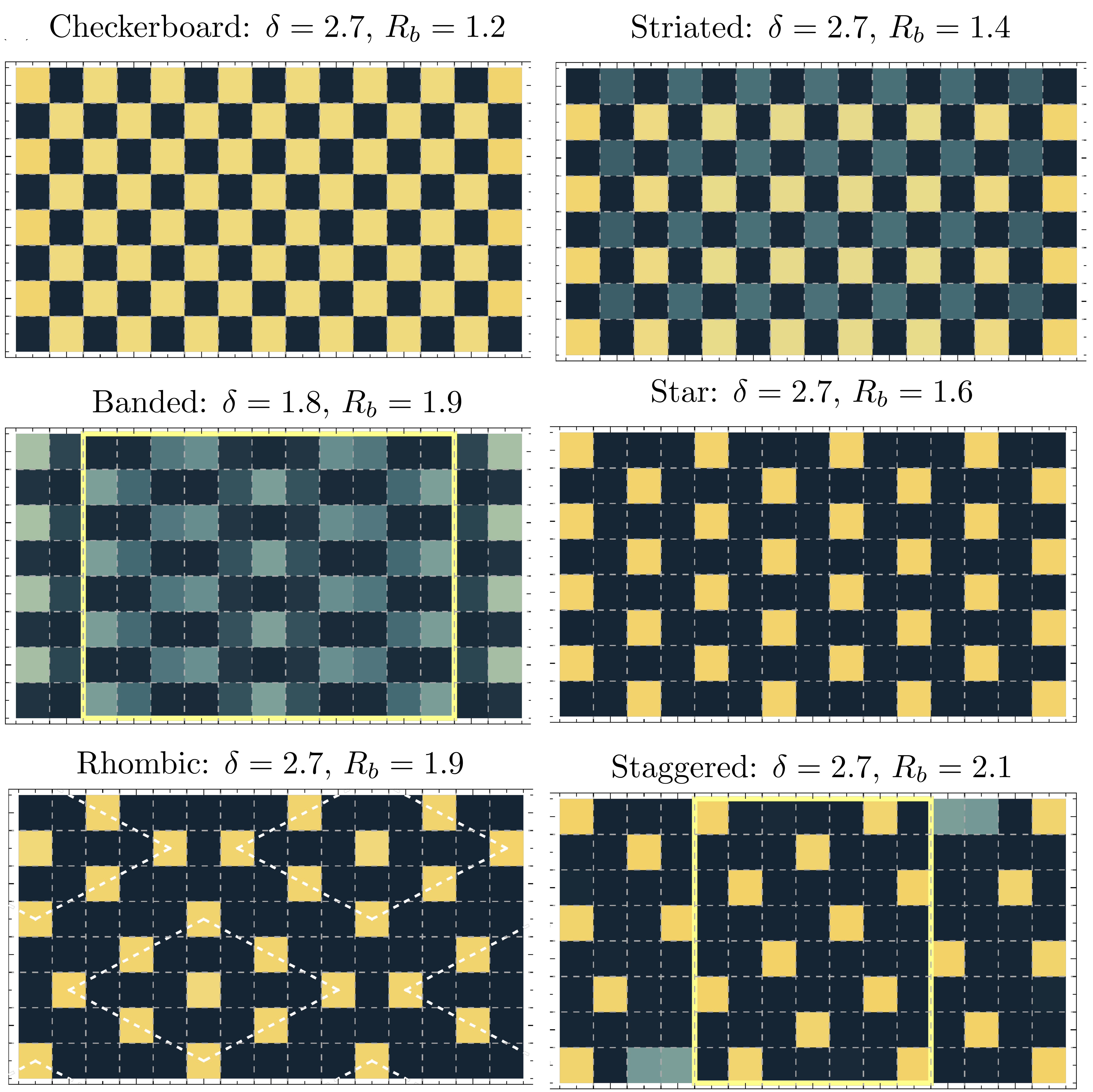


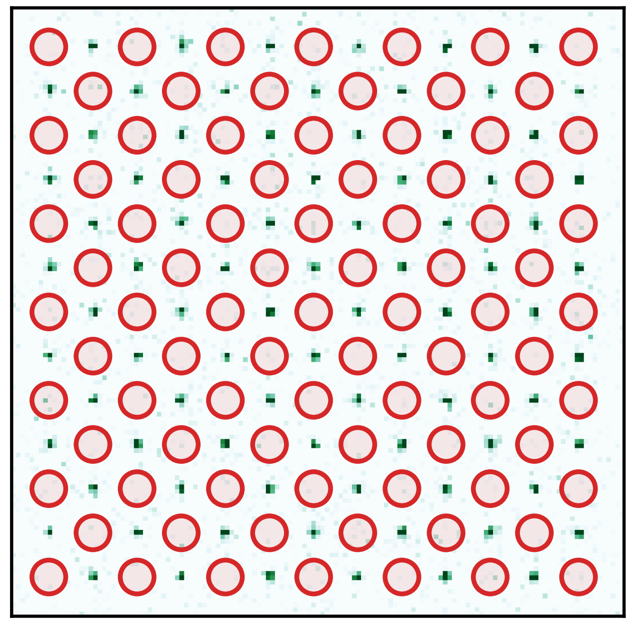


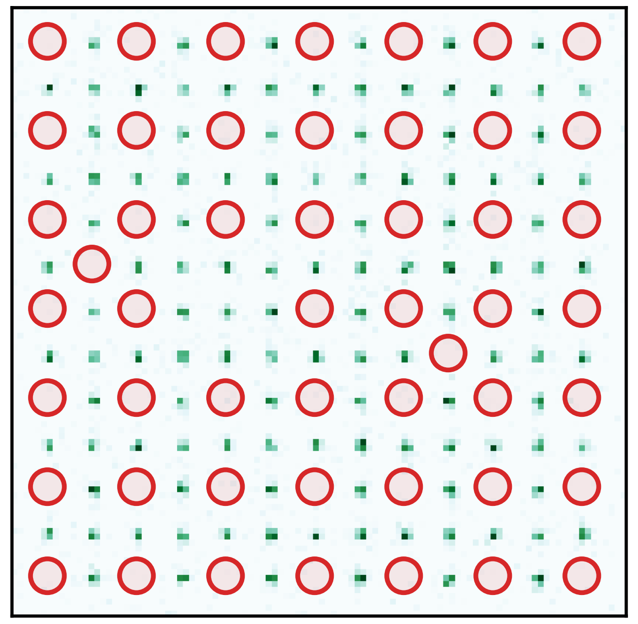
R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, S. Sachdev, PRL **124**, 103601 (2020)

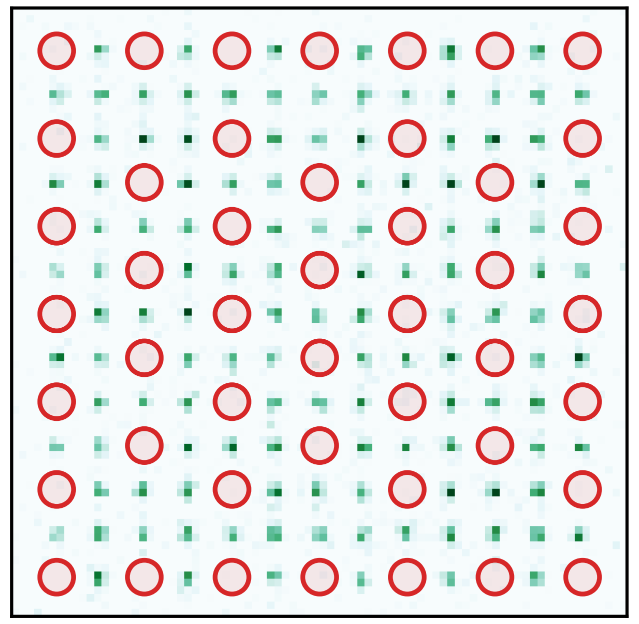
Rydberg atoms on the square lattice: experiment

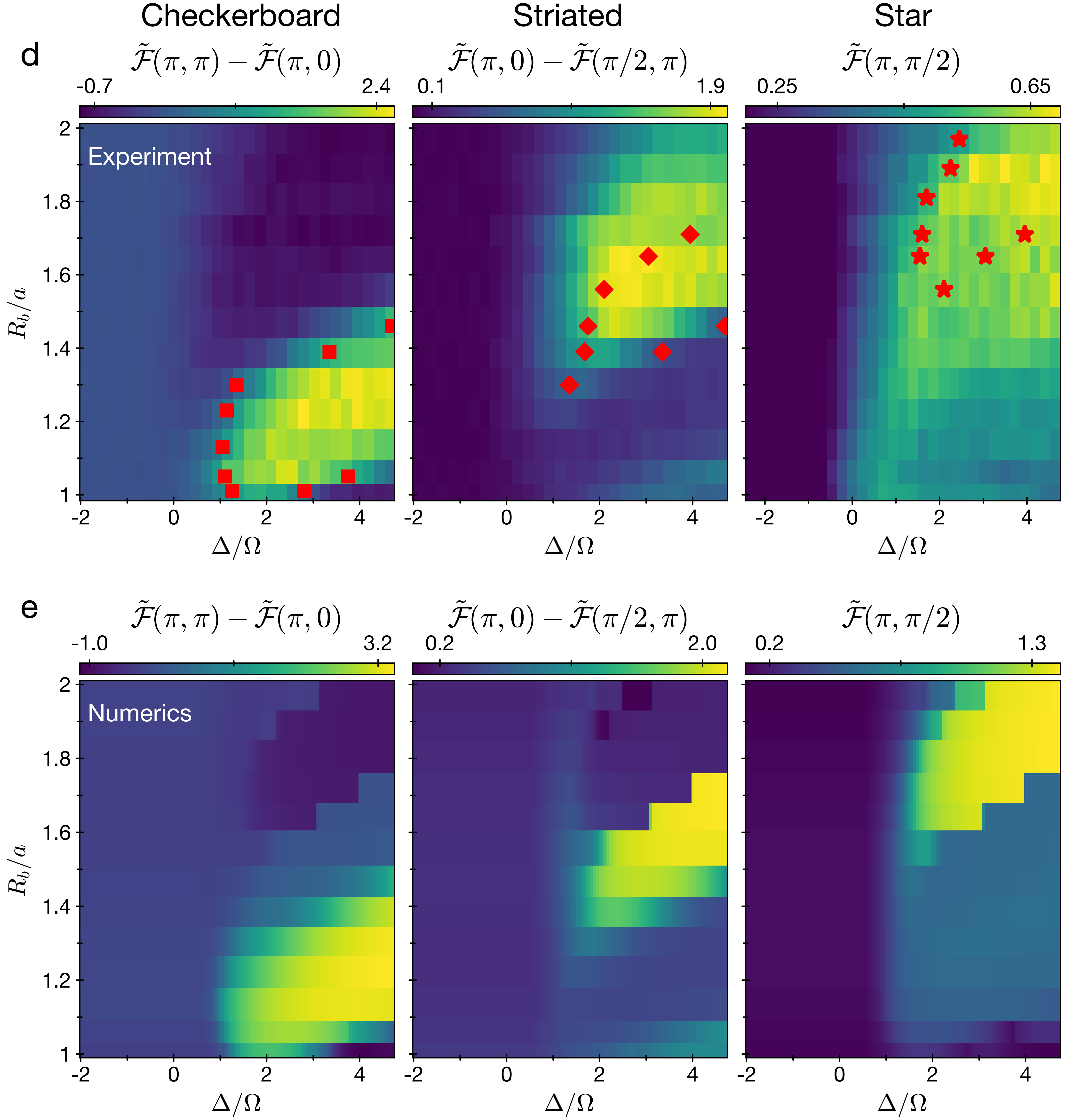
$$\tilde{\xi} = \xi (s/s_0)^{\mu}$$

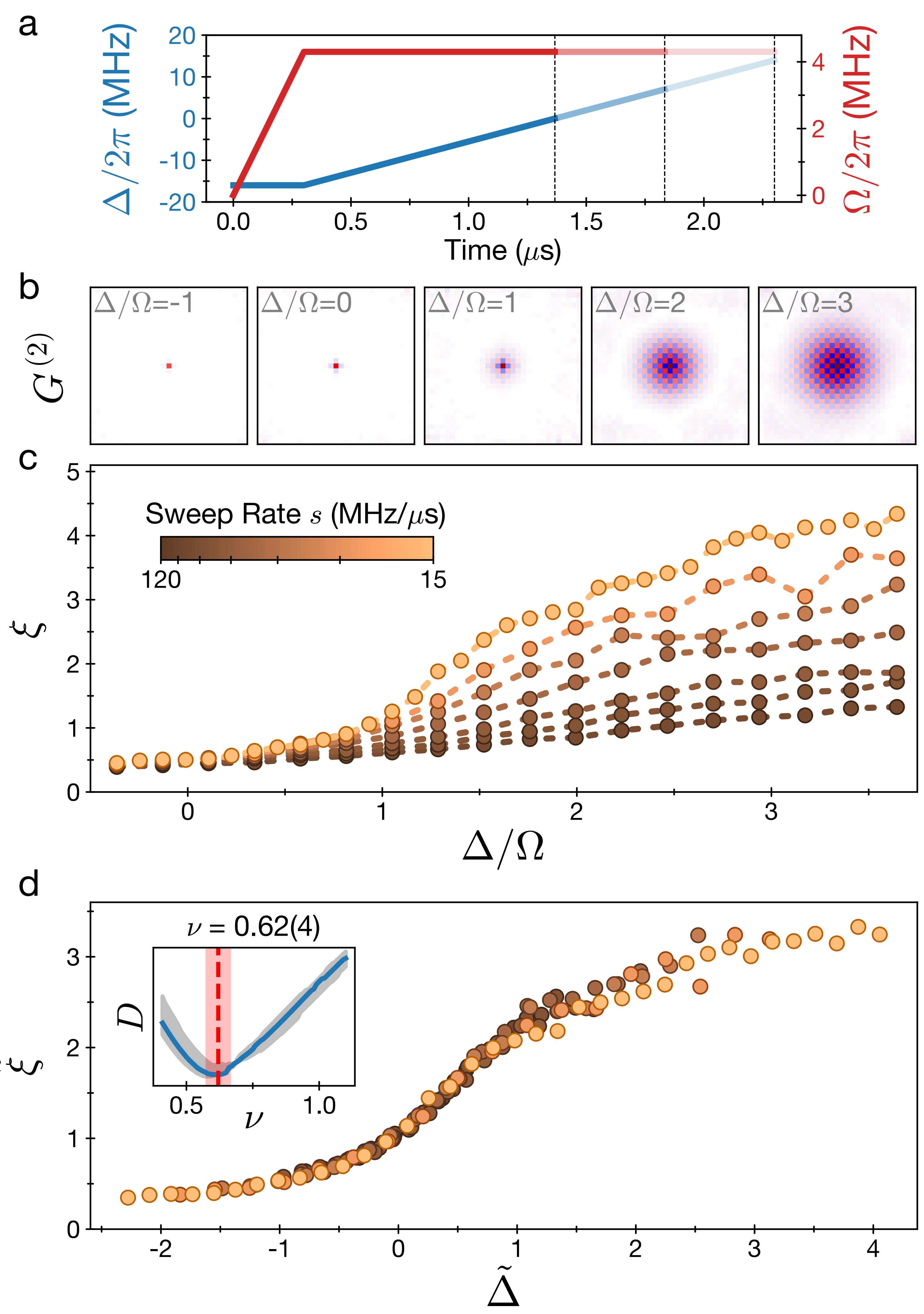
$$\tilde{\Delta} = (\Delta - \Delta_c)(s/s_0)^{\kappa}$$











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 to appear, arXiv:2012.12281; Pascal Scholl et al. arXiv:2012.12268

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

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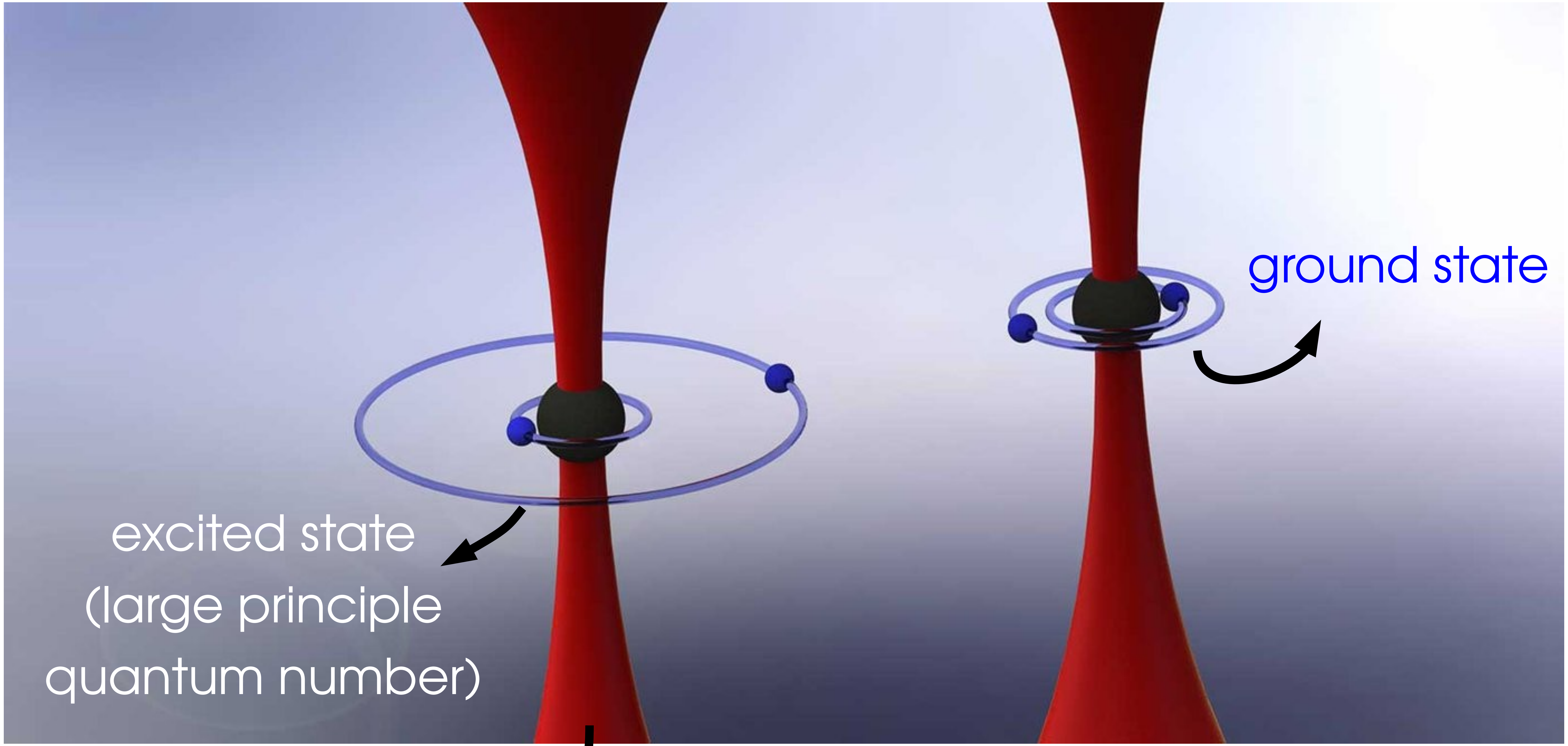

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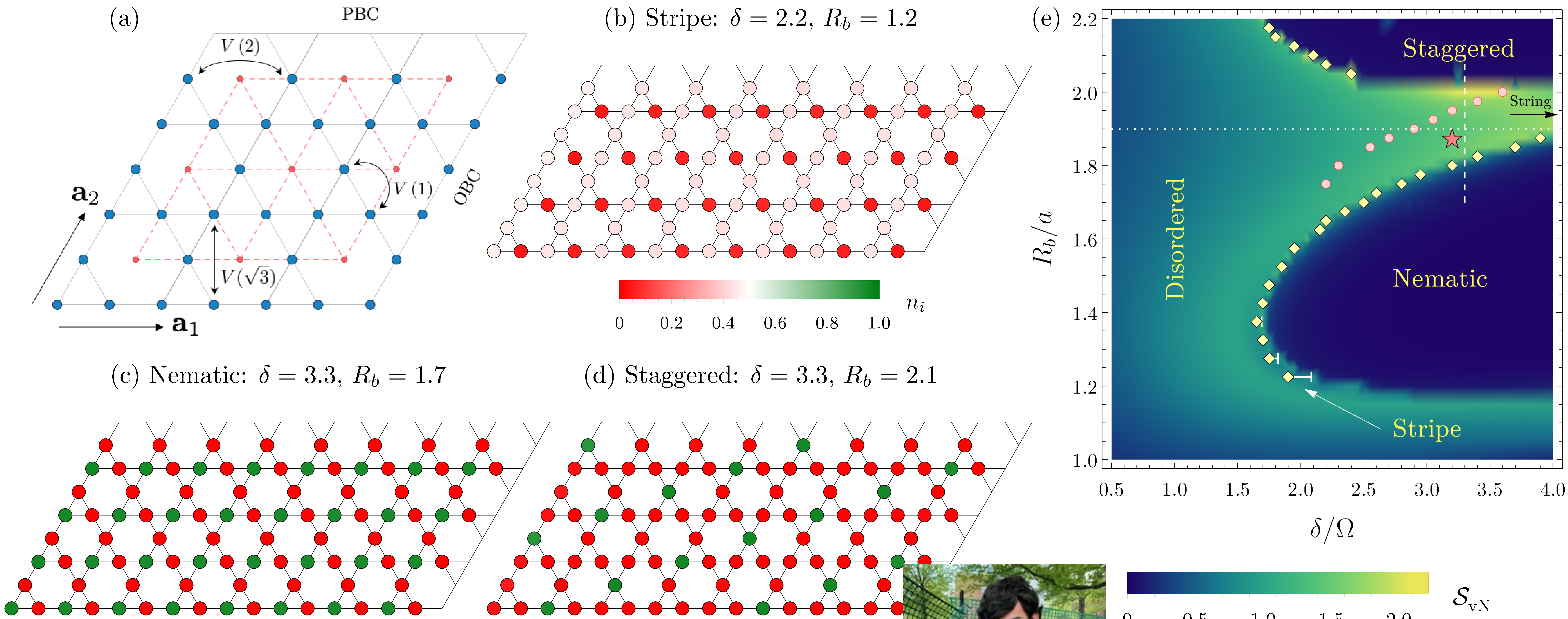

R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, and S. Sachdev, PNAS **118**, e2015785118 (2021)

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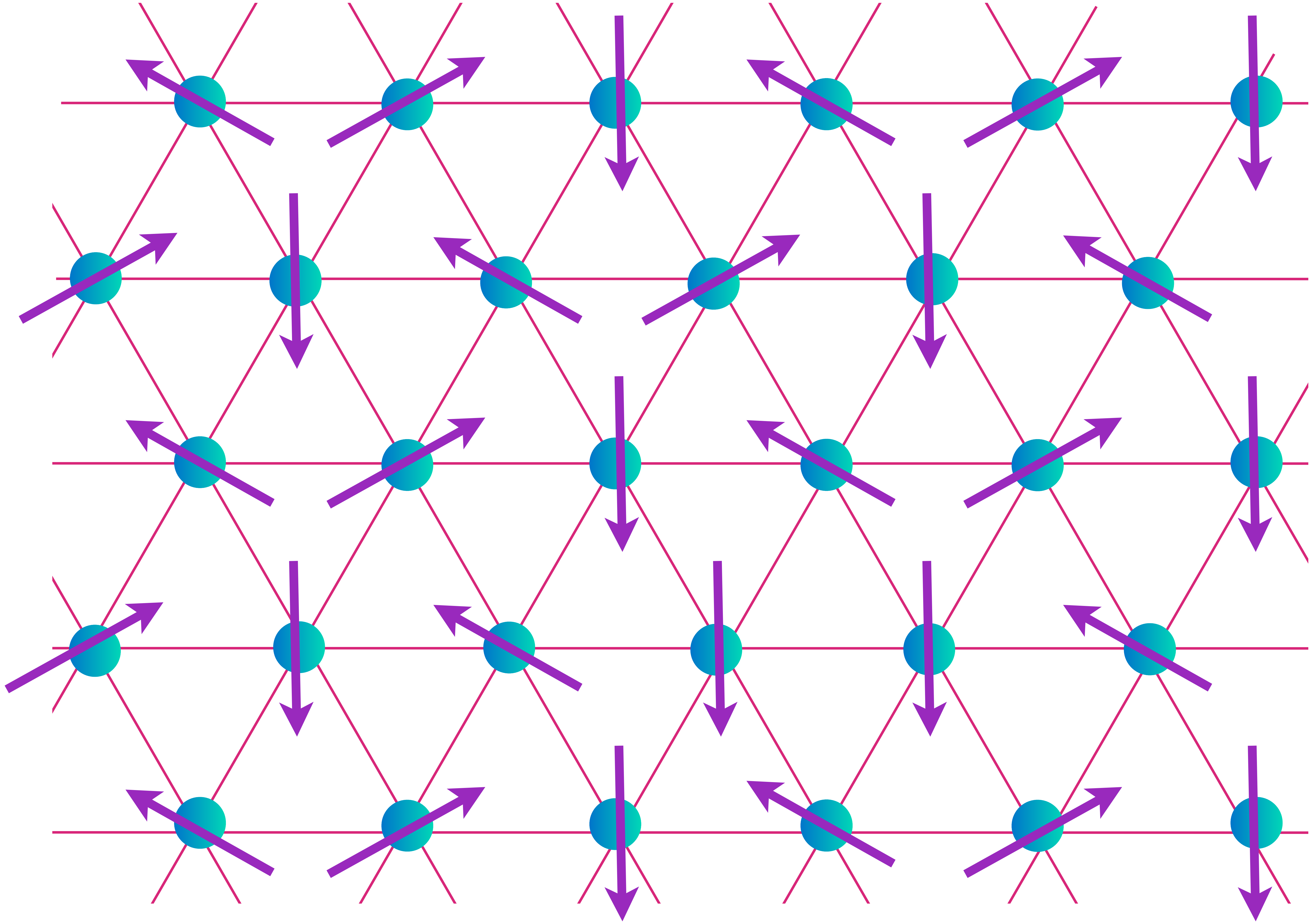
Mott insulator: Triangular lattice antiferromagnet

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



Nearest-neighbor model has non-collinear Neel order

Mapping of bosons and spins

Boson B	Spin $\vec{S}$
$B^\dagger B \leq 1$	$\vec{S}^2 = 3/4$
States $\|0\rangle$, $B^\dagger\|0\rangle$	States $\|\uparrow\rangle$ $\|\downarrow\rangle$
Operators	Operators
$B^\dagger$ ⟷	$S_+ = S_x + iS_y$
B ⟷	$S_- = S_x - iS_y$
$B^\dagger B - \frac{1}{2}$ ⟷	S_z

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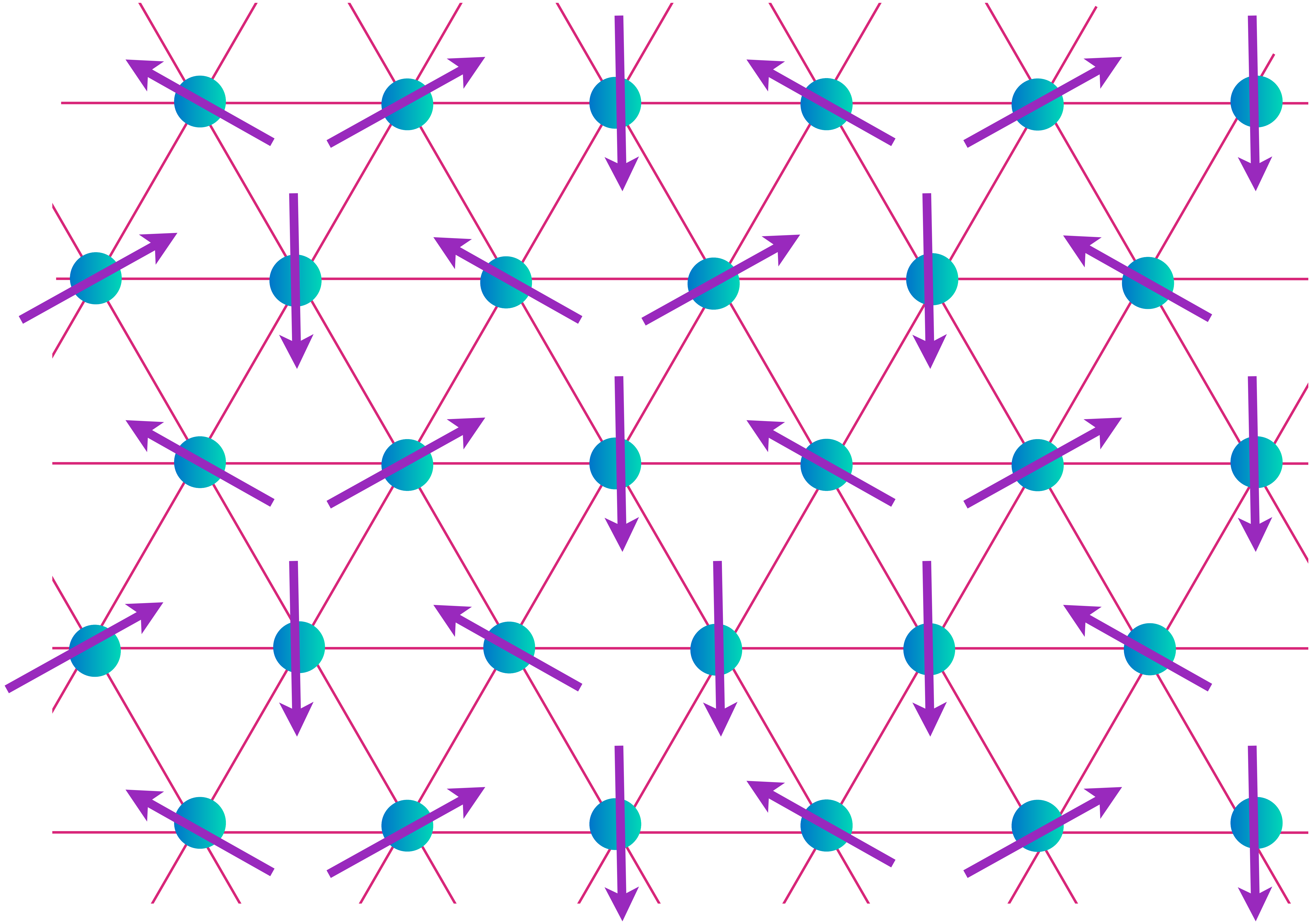

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Spin liquid for bosons at half-filling,
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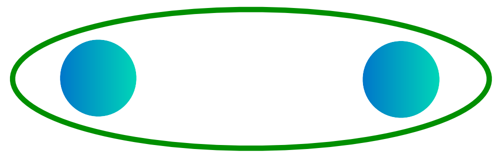
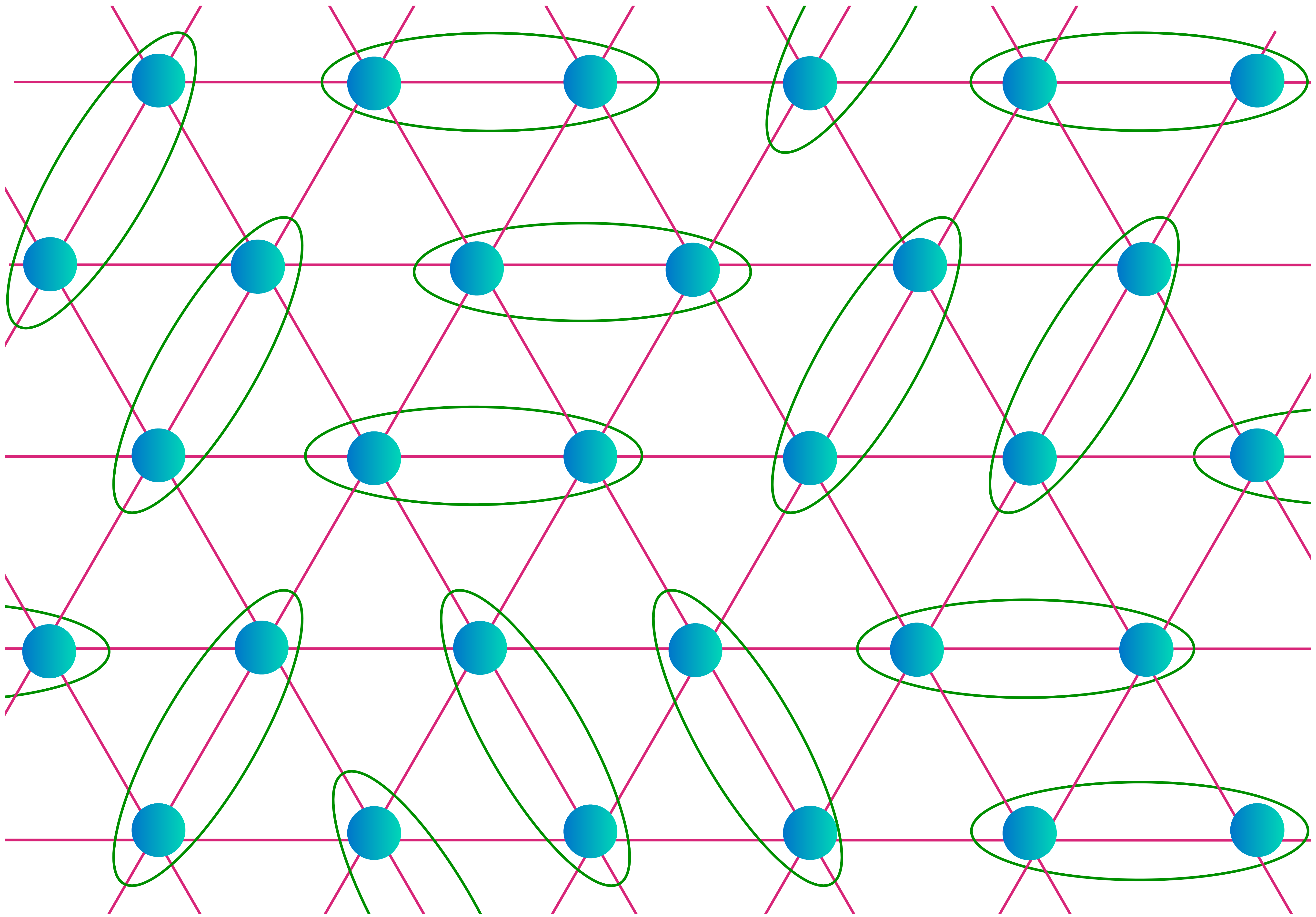


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$



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

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

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

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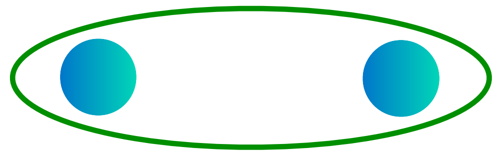

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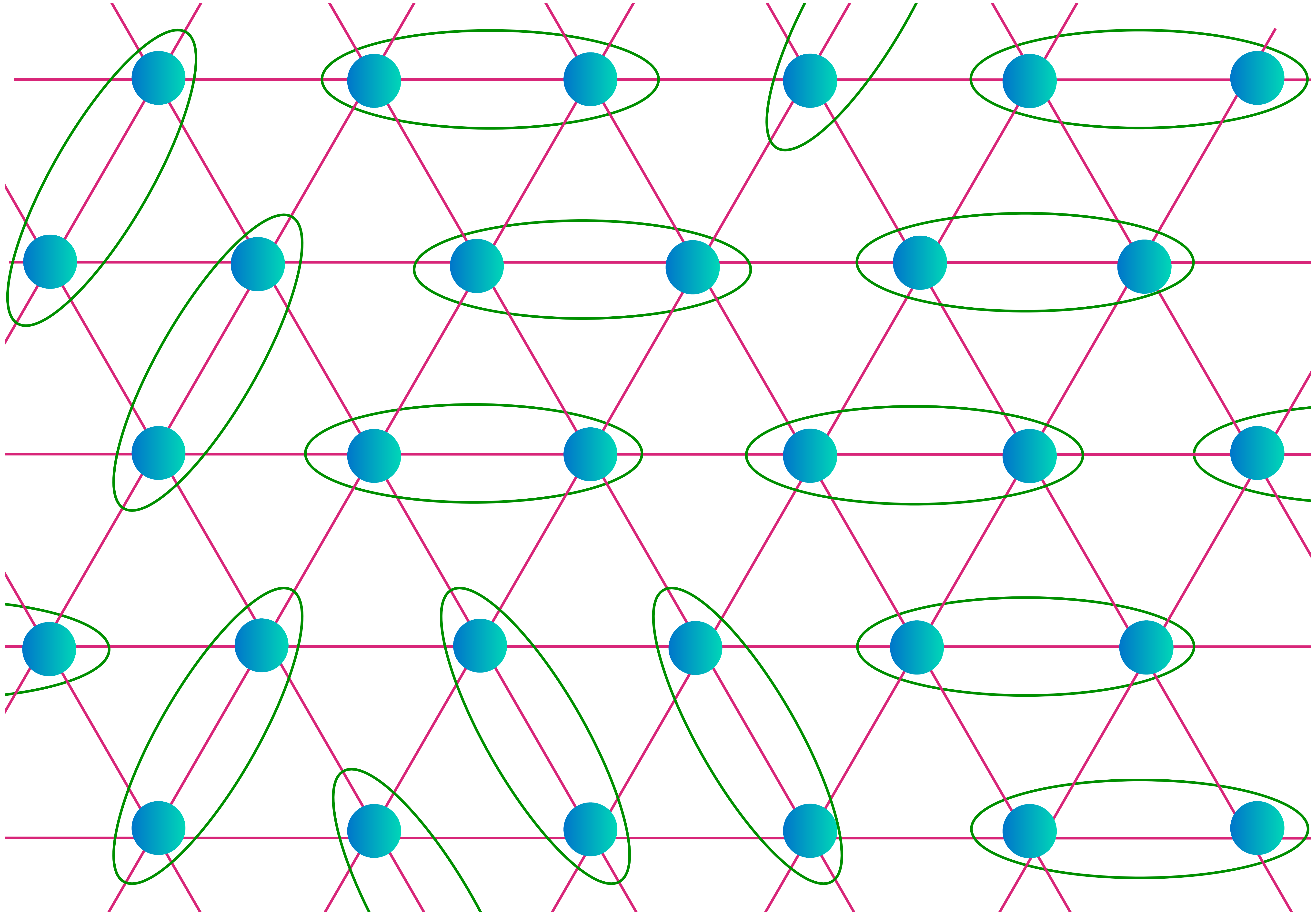

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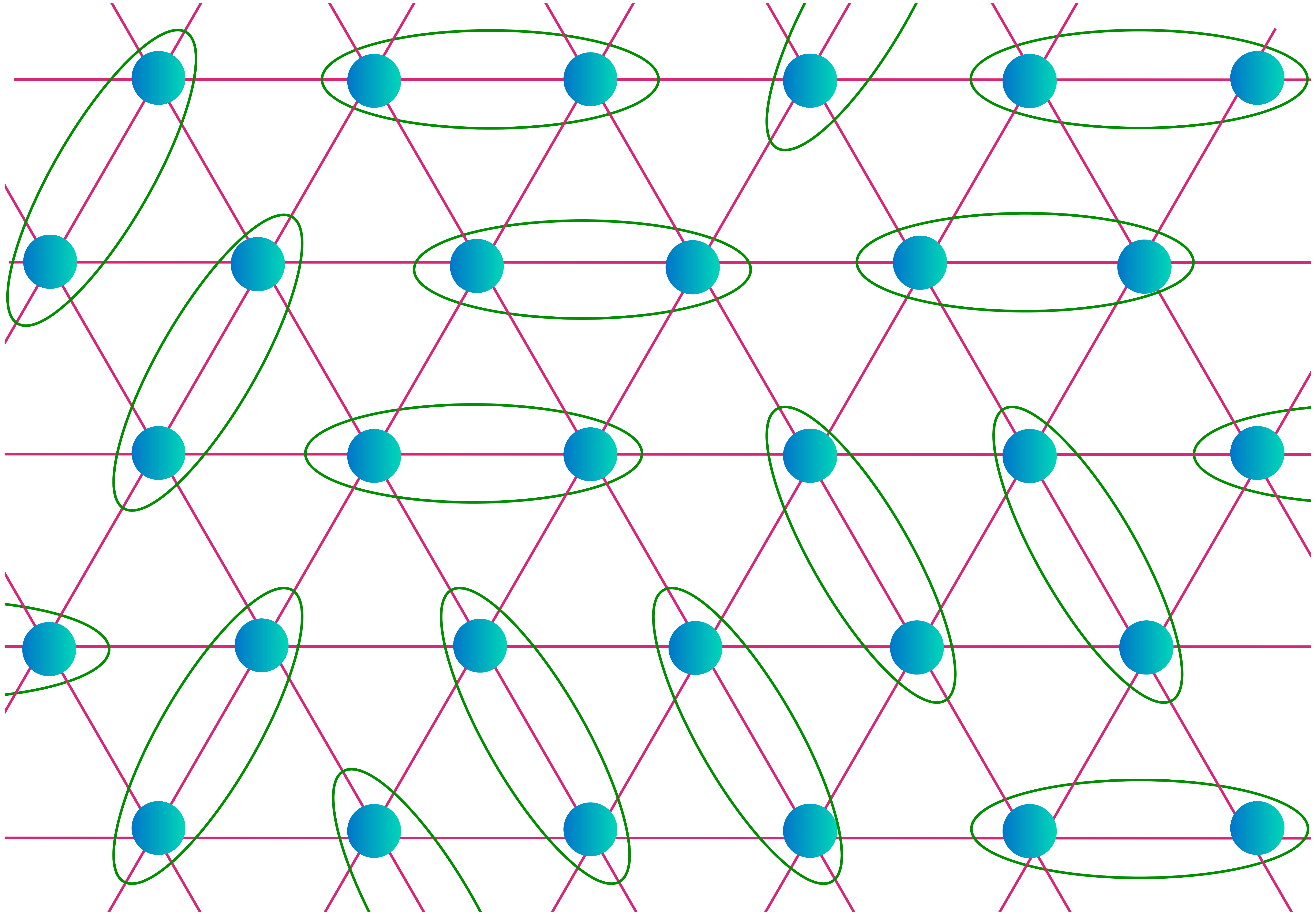
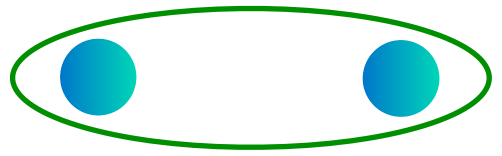
Mott insulator: Triangular lattice antiferromagnet

Spin liquid for bosons at half-filling, or a spin model with S=1/2 per unit cell





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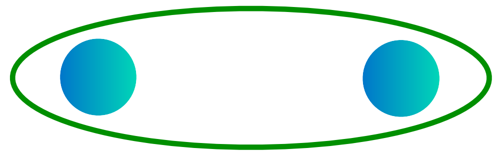

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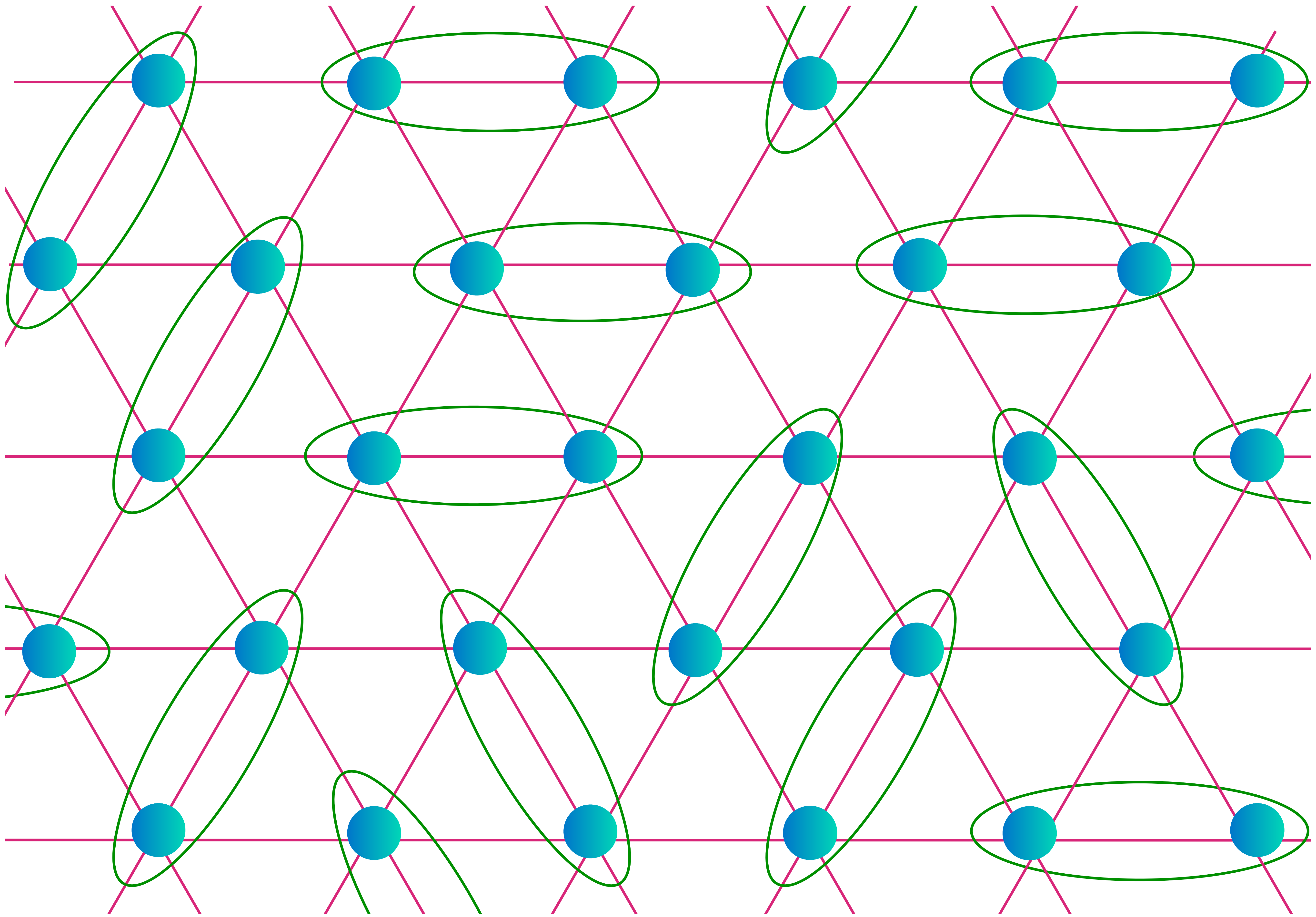

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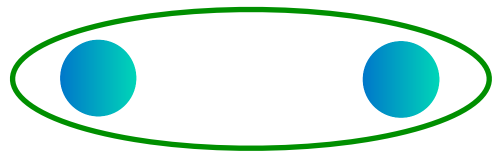

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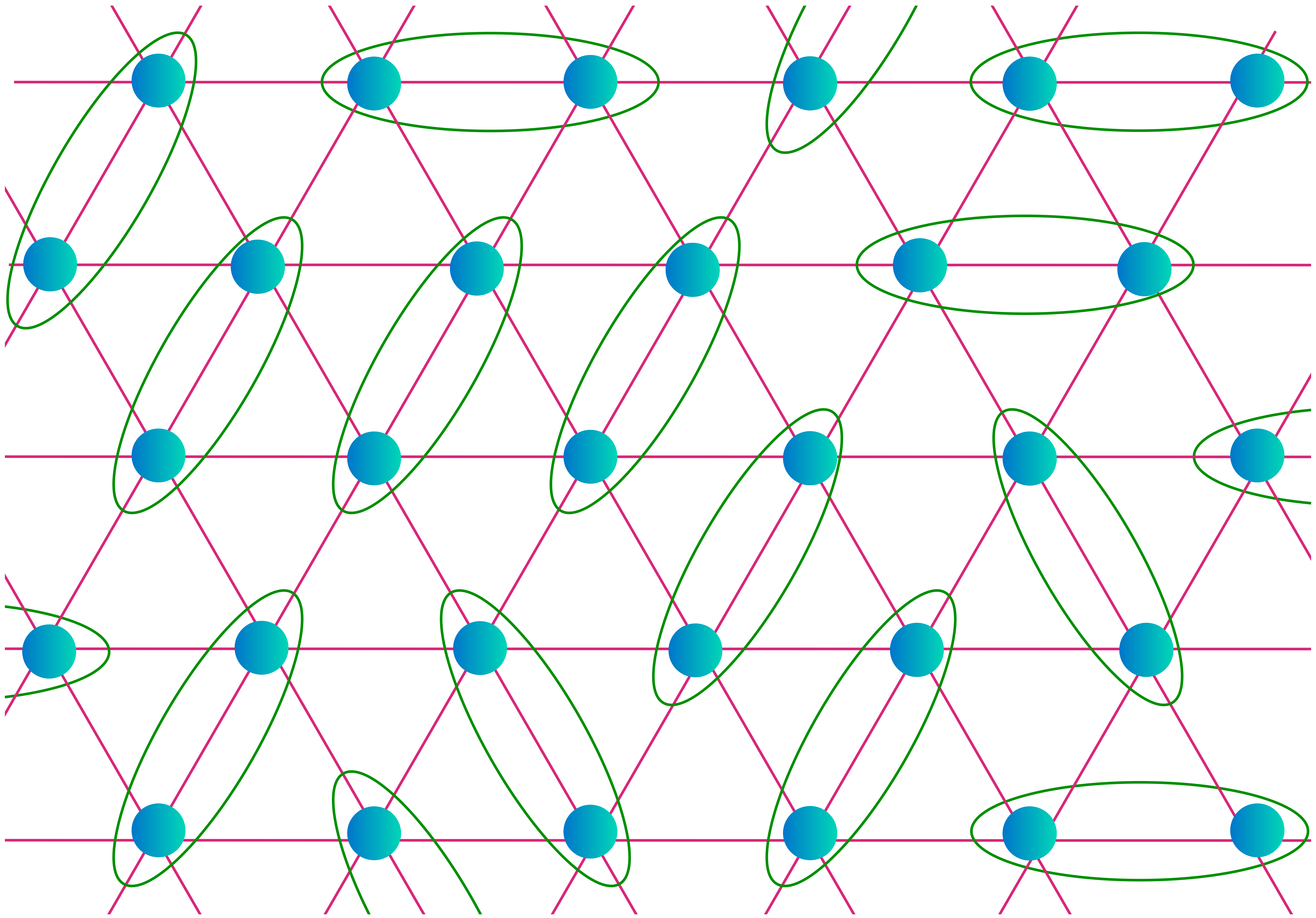

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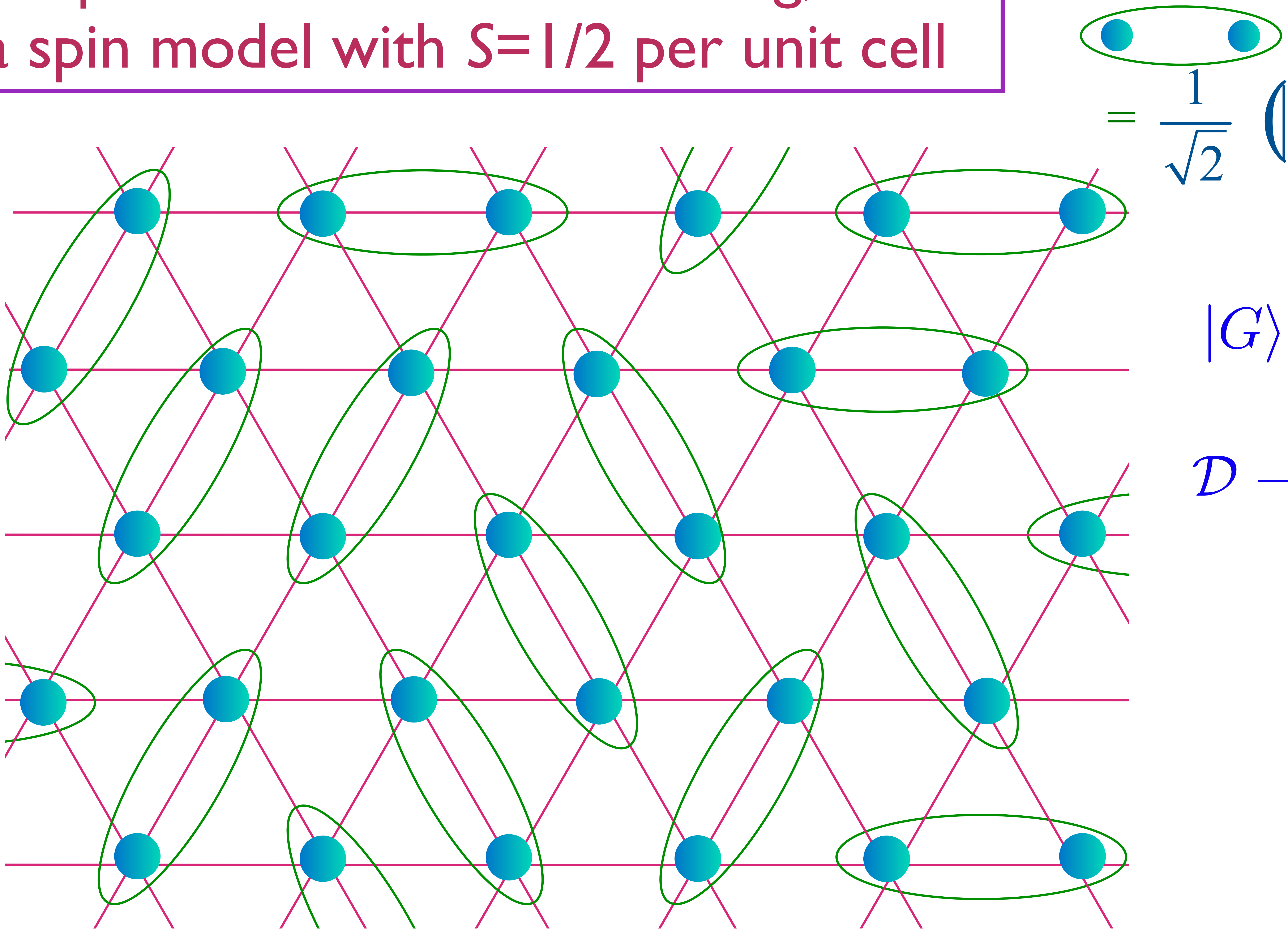

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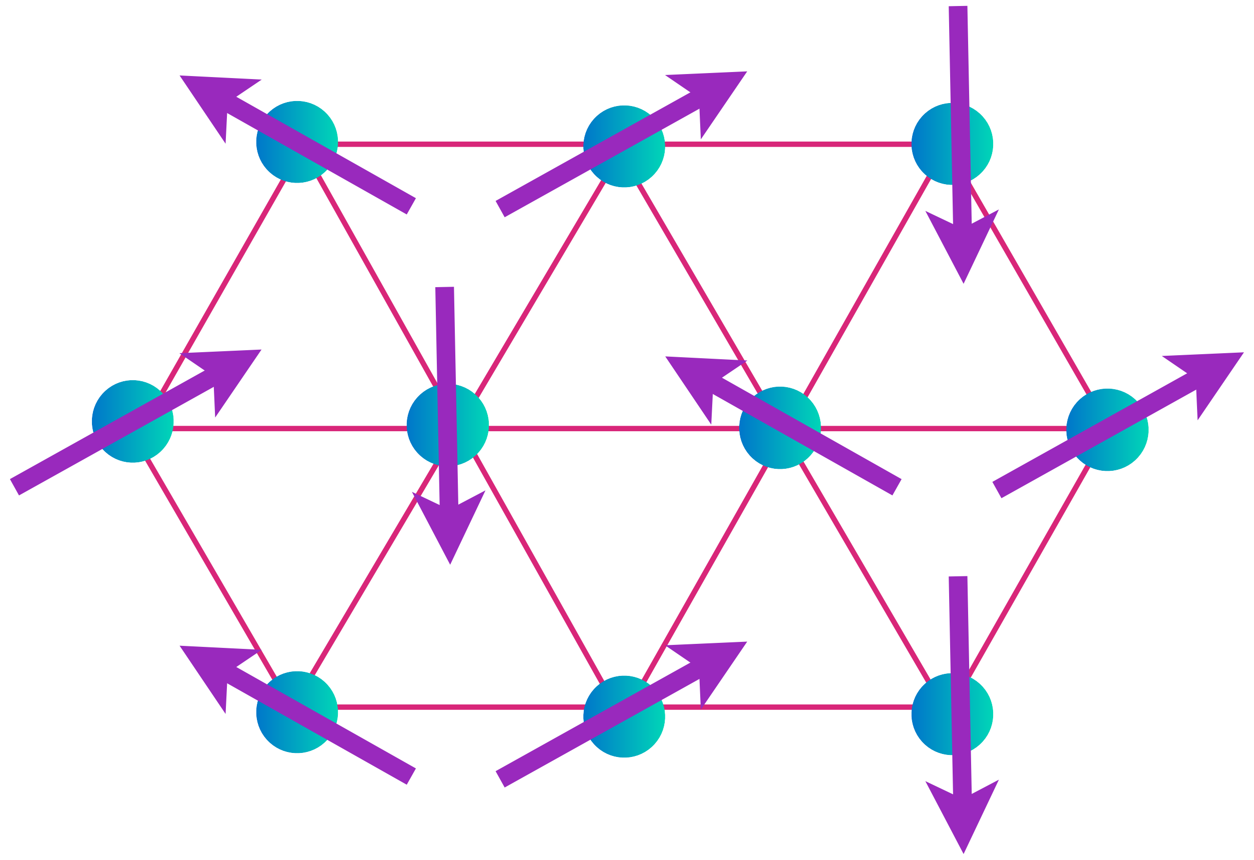


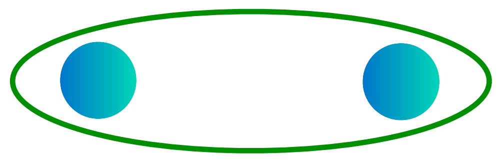
Z_2 spin liquid
with neutral $S = 1/2$ spinons
and **vison** excitations

non-collinear Néel state

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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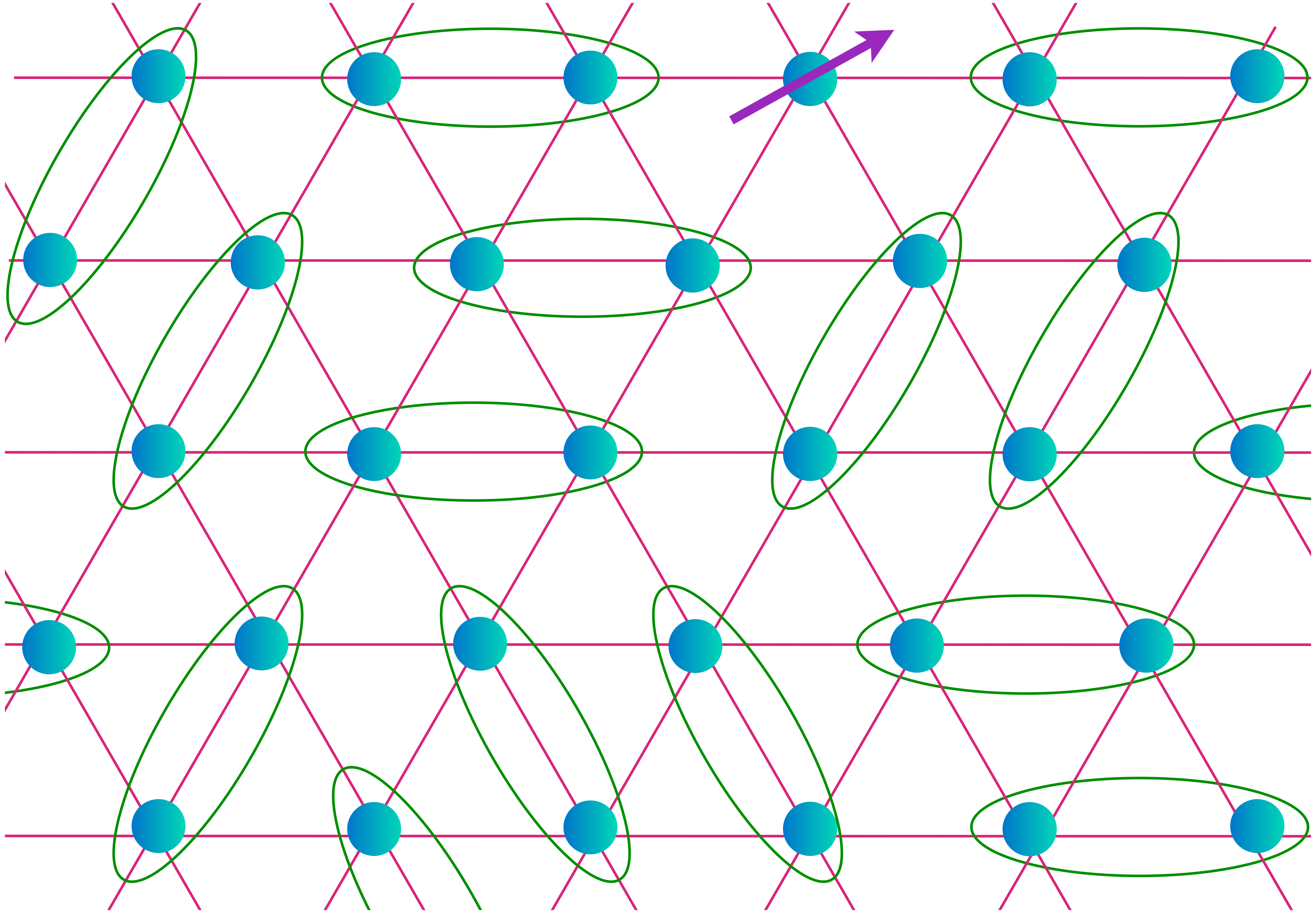
Spinon: $S_z = 1/2$

e (boson) or ϵ (fermion) particle



Excitations of the Z_2 Spin liquid

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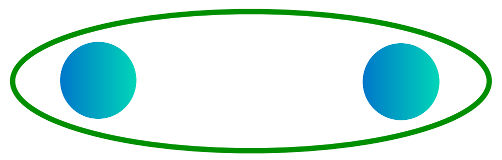

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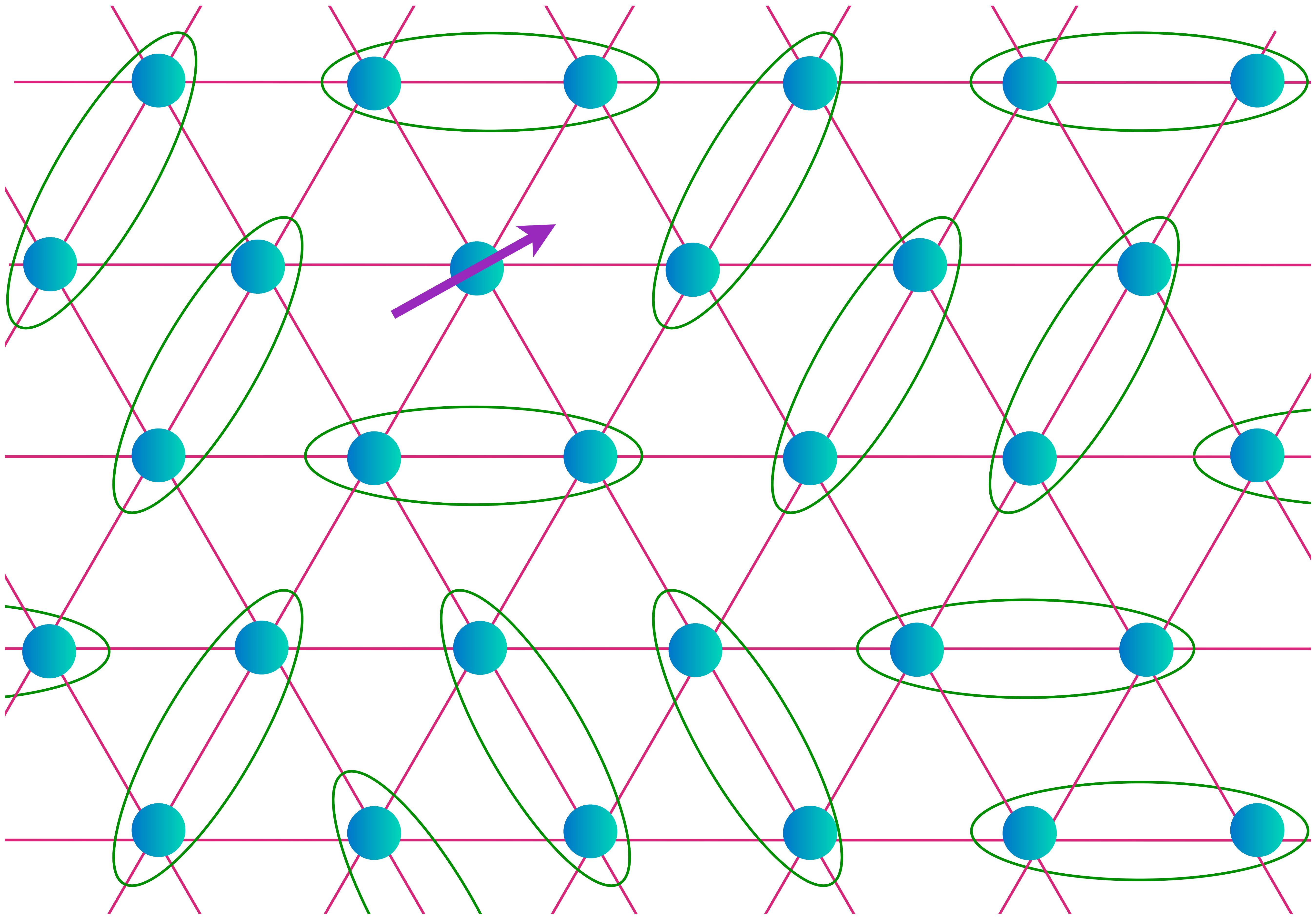

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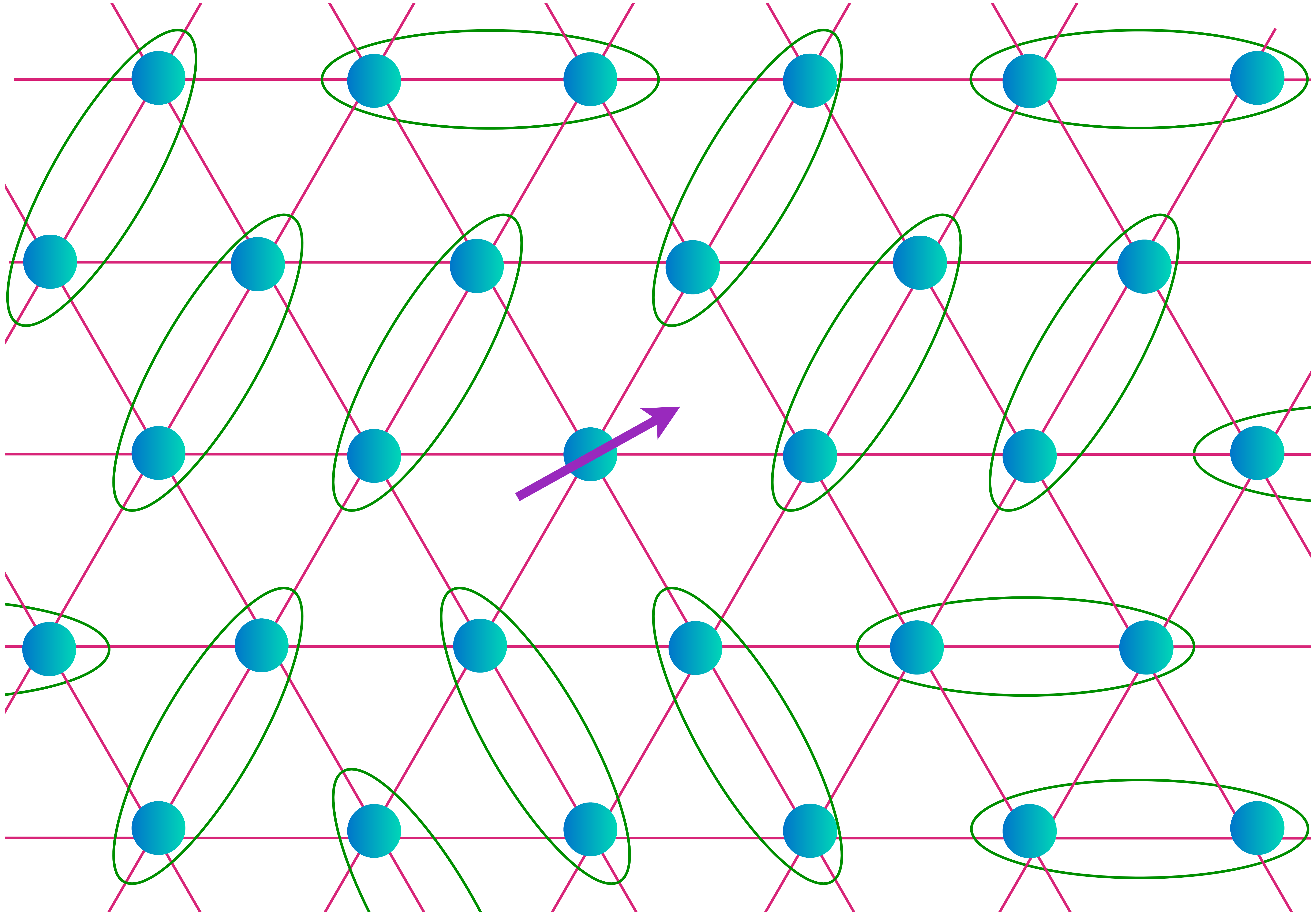

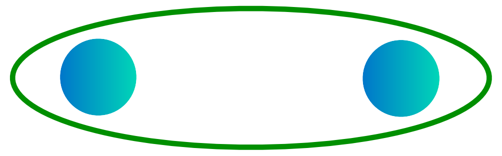

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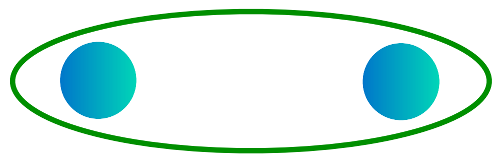

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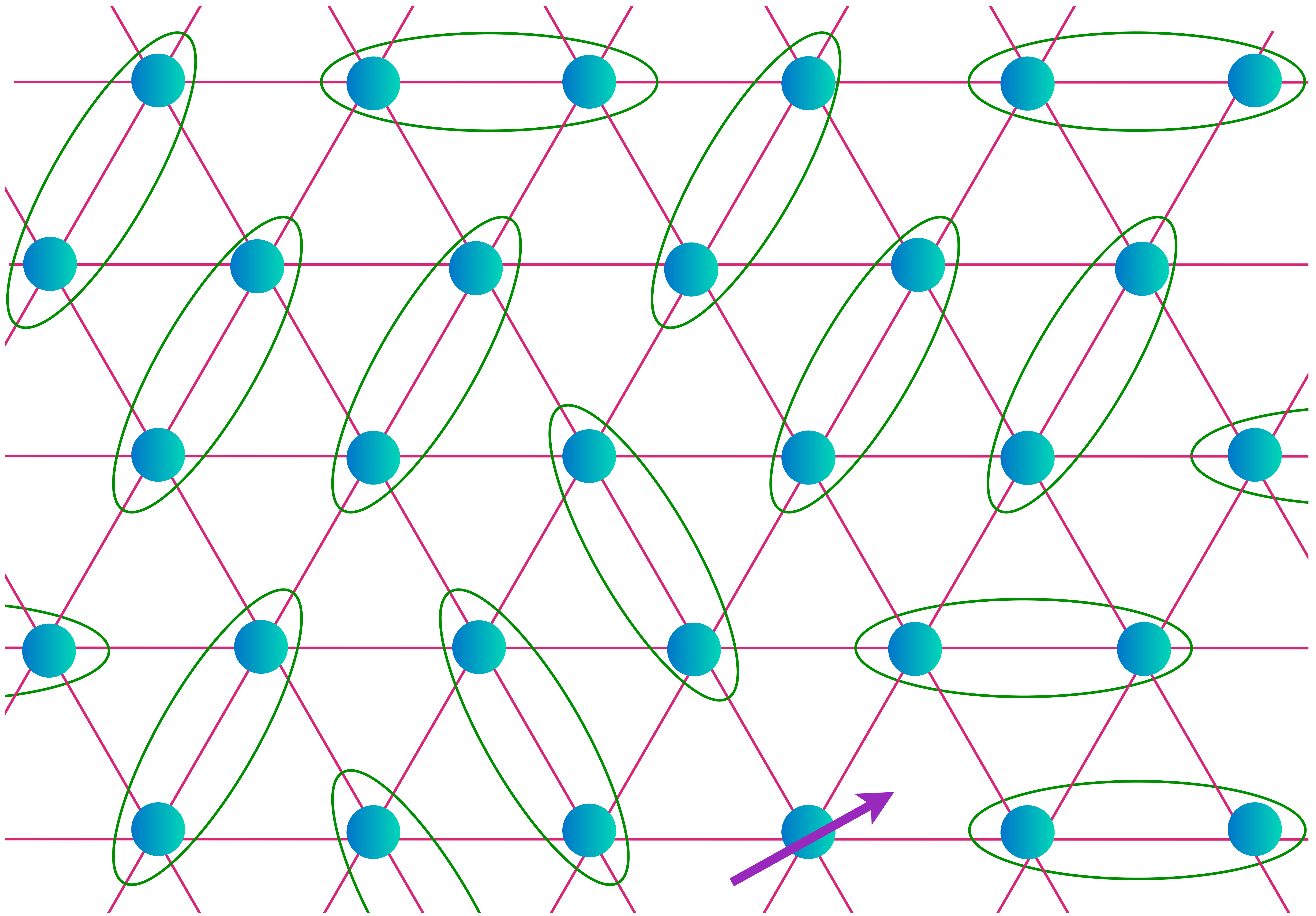

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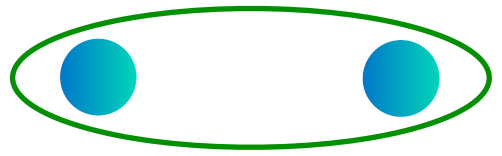

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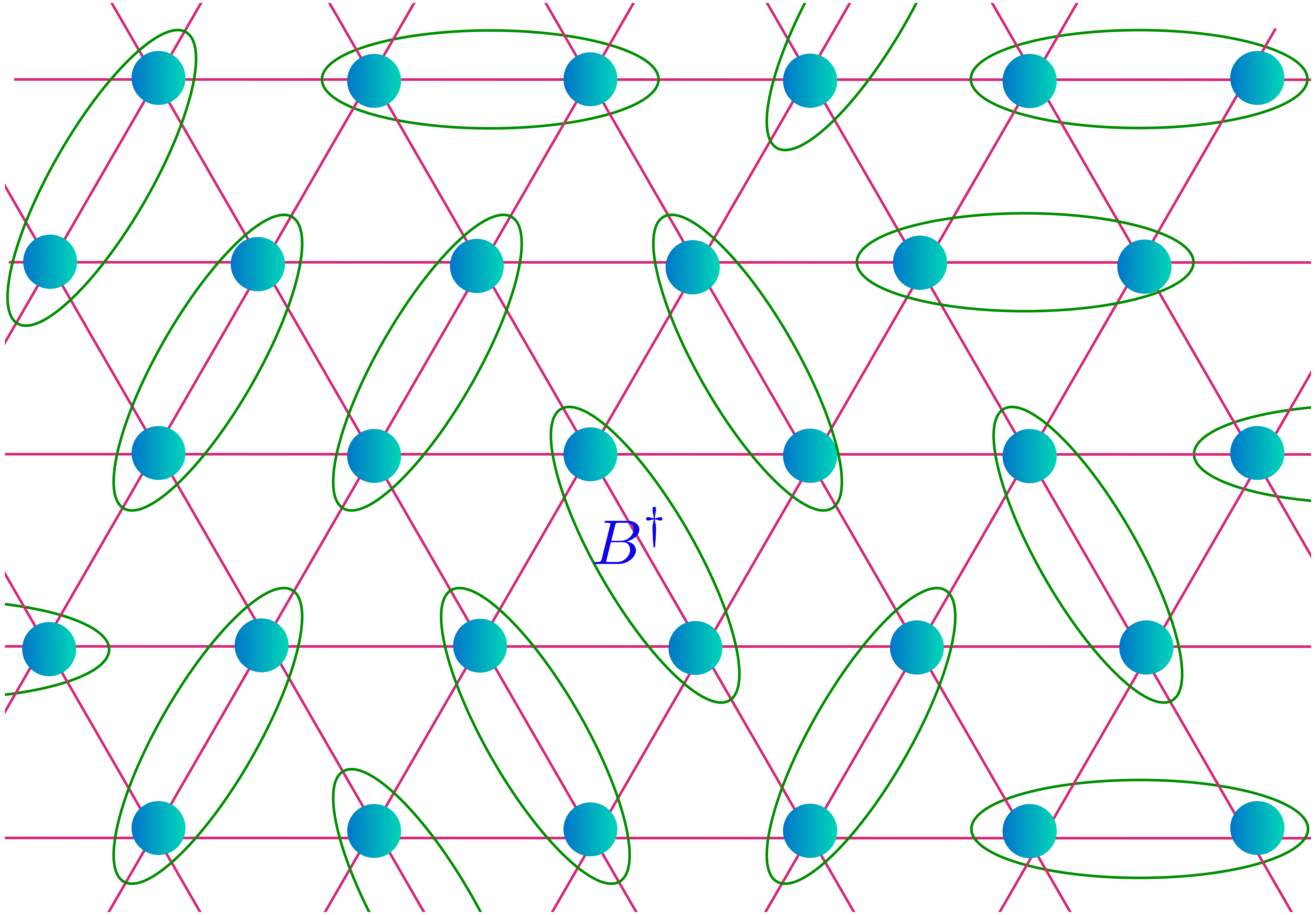
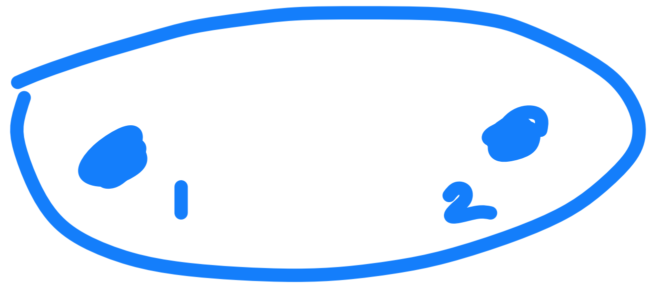


$B_2^\dagger$



$$= \frac{1}{\sqrt{2}} |\uparrow\rangle_1 |\uparrow\rangle_2$$

Excitations of the Z_2 Spin liquid

Spinon: $S_z = 1/2$

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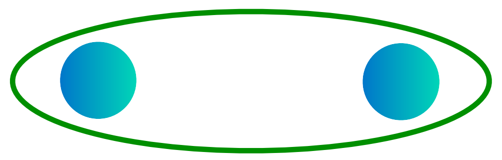
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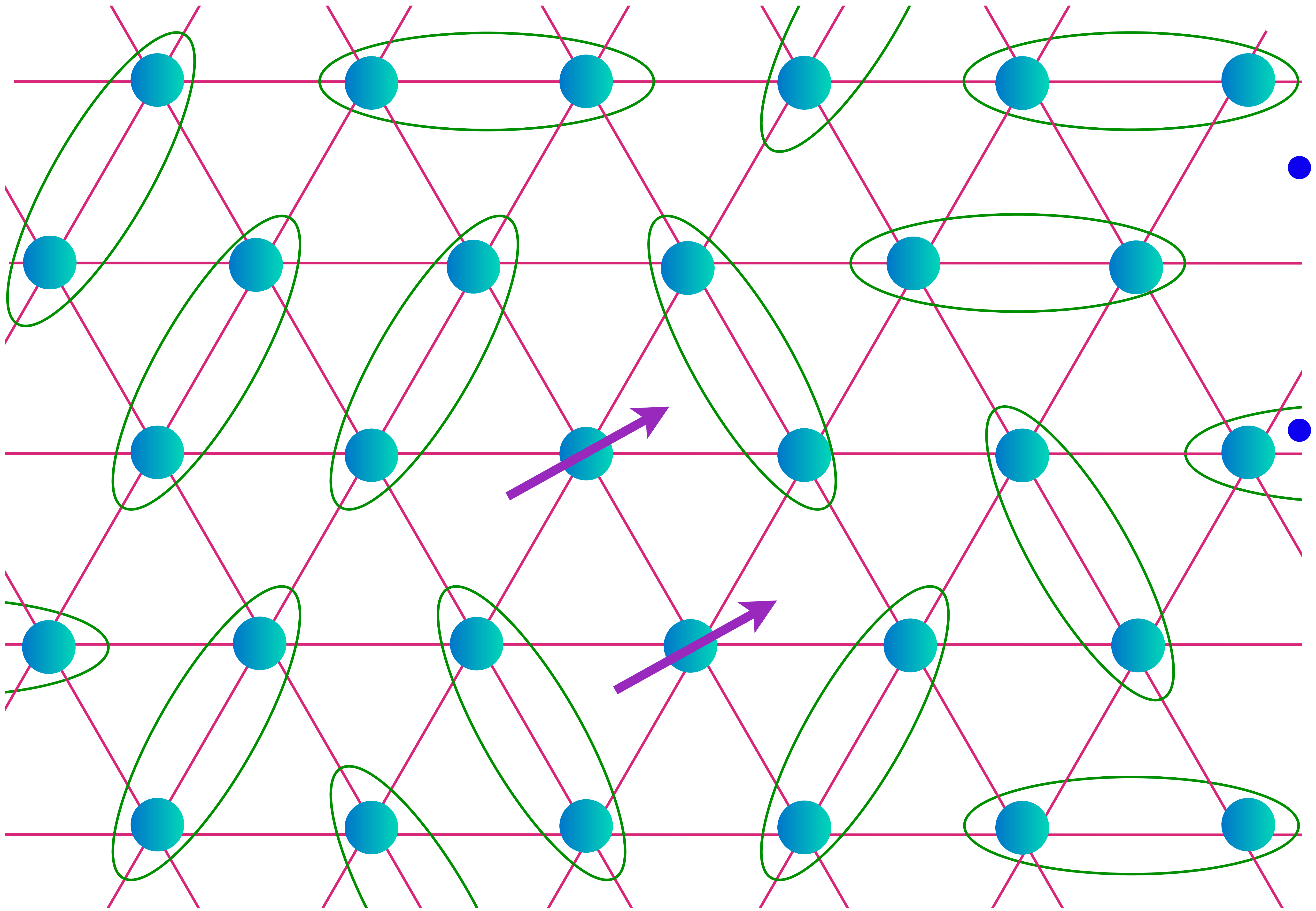

- Spinons can only be created in pairs by a local operator ($e.g.$ $B^\dagger$)
- A single spinon carries boson number $B^\dagger B = 1/2$: fractionalization!

Excitations of the Z_2 Spin liquid

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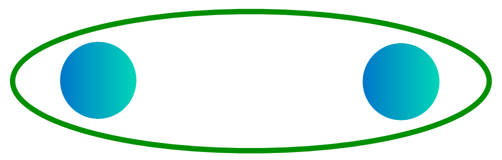

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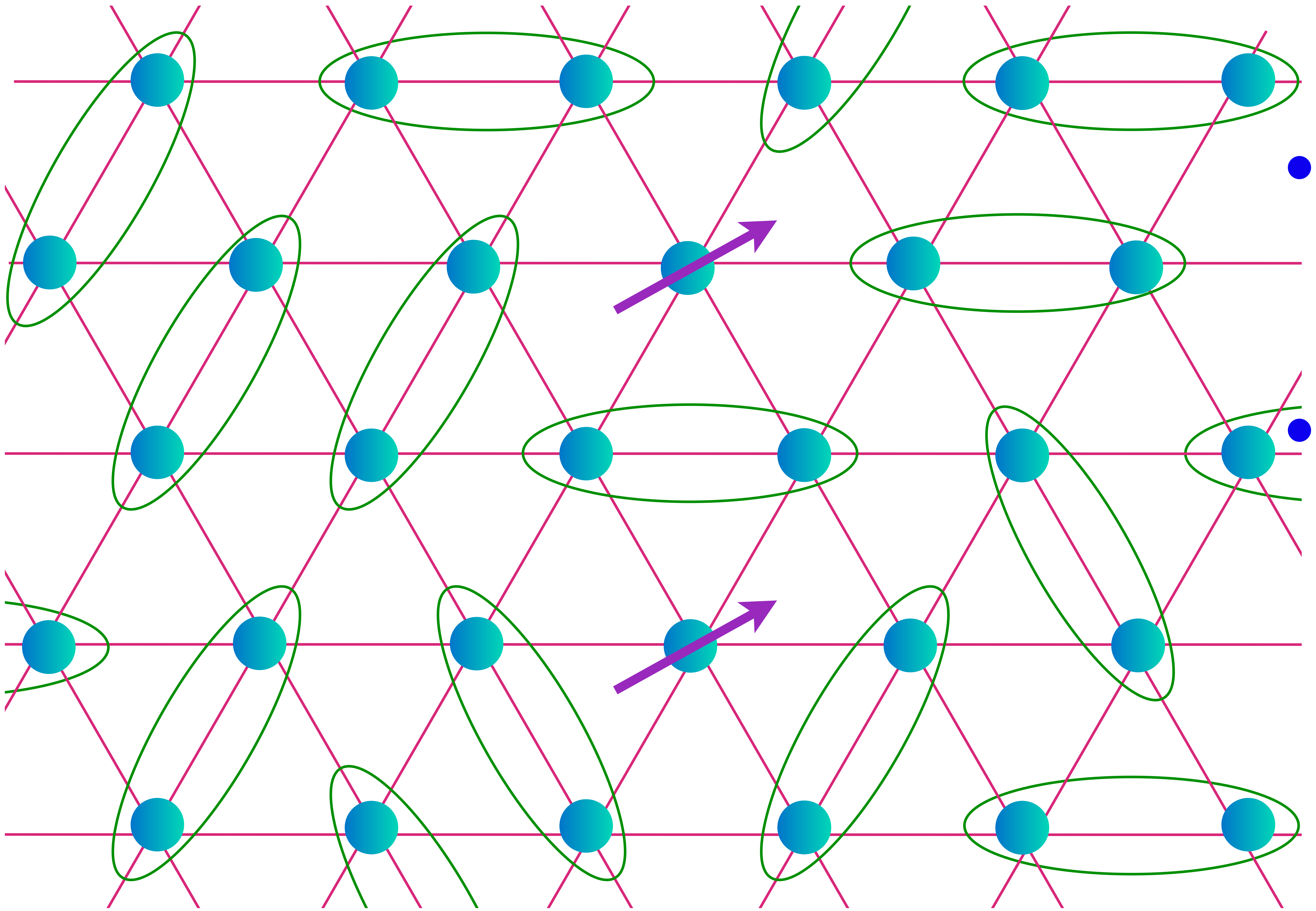

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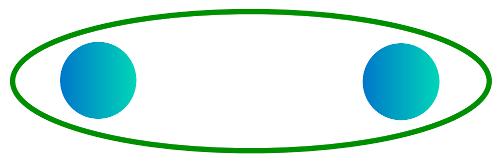

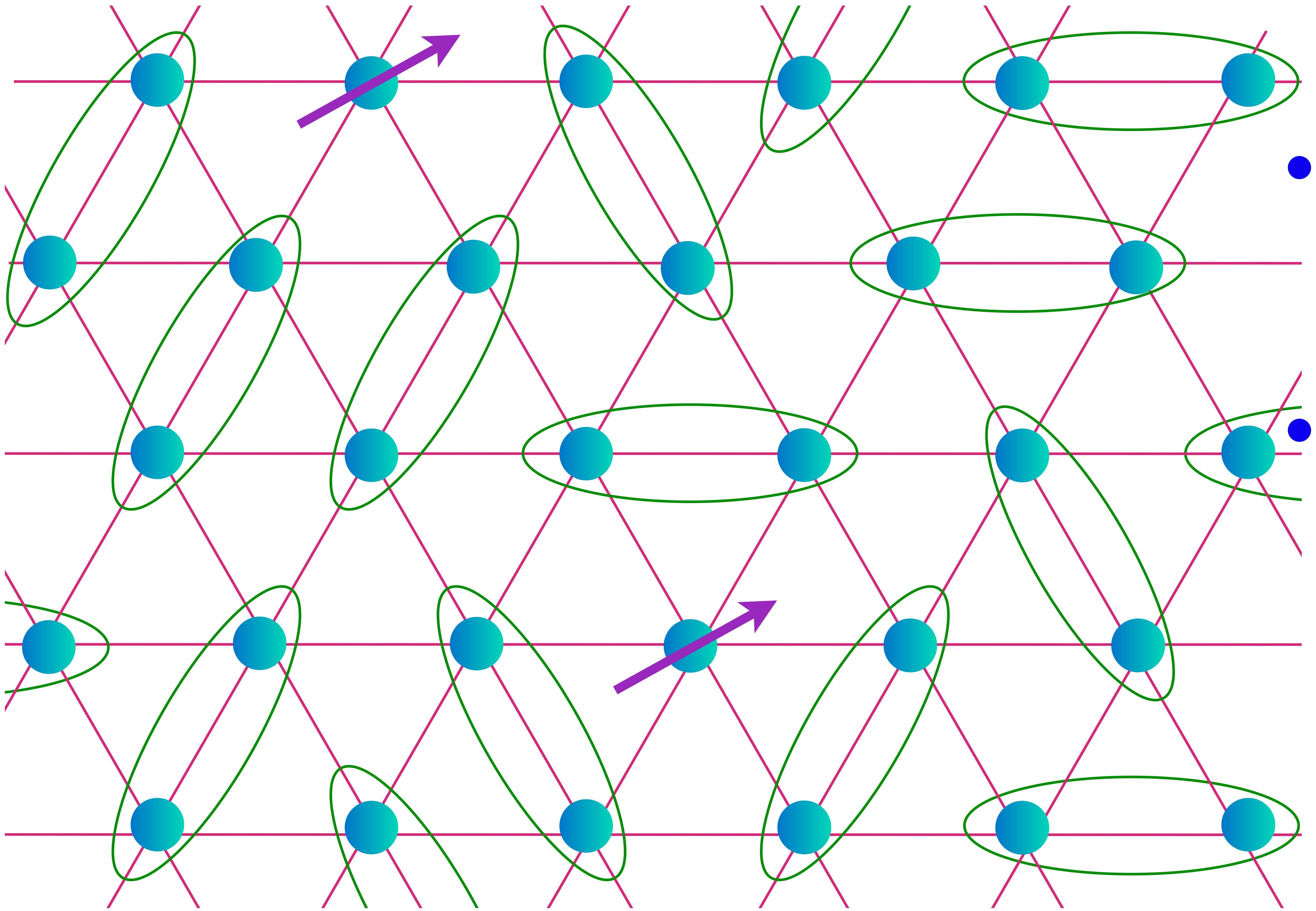

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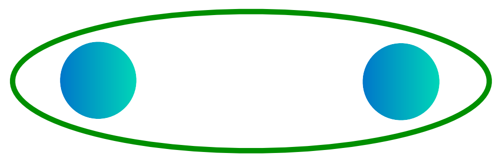

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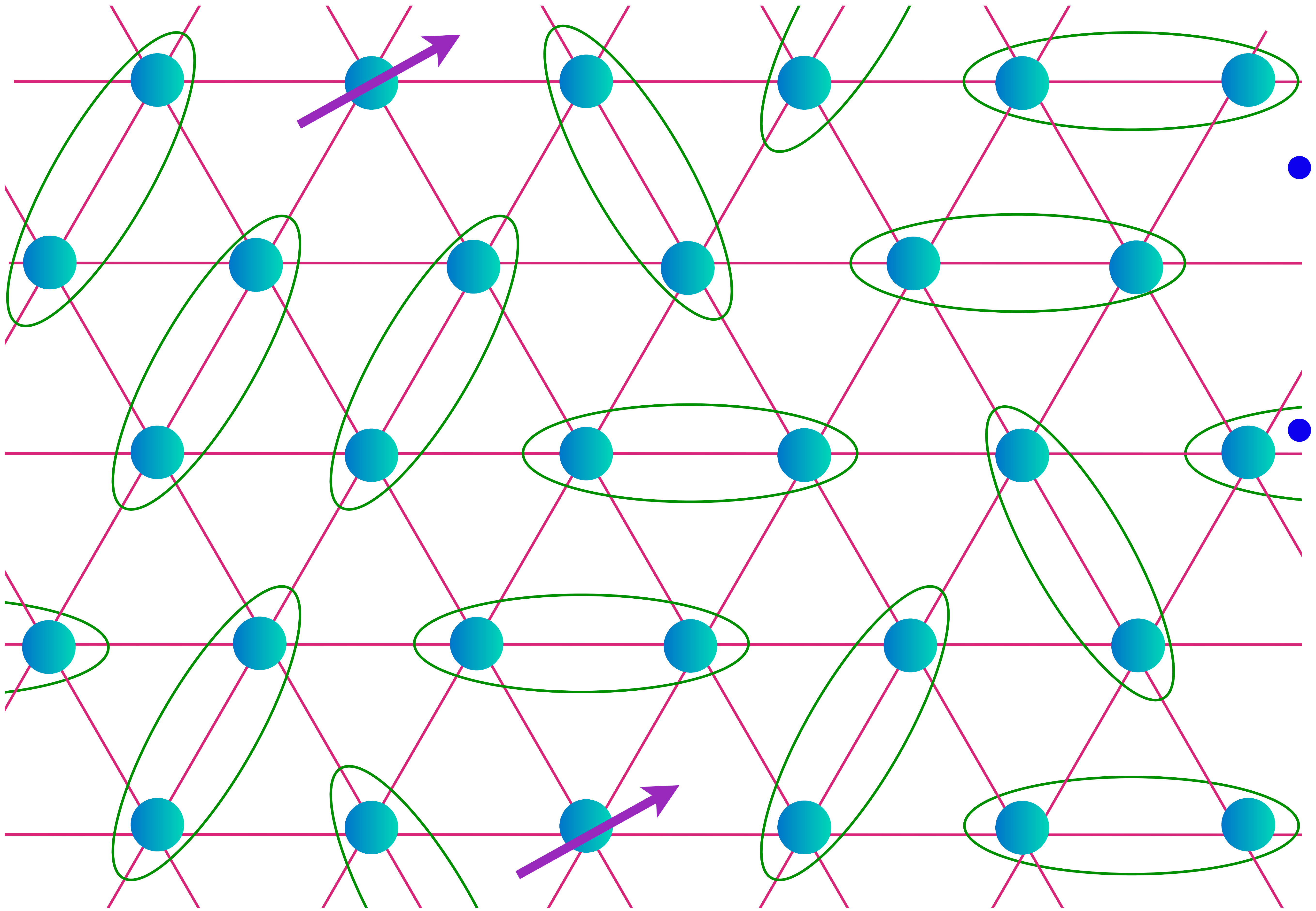

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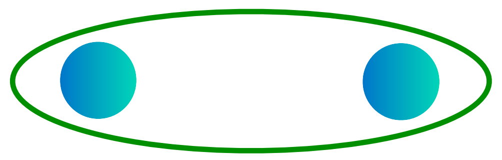
Excitations of the Z_2 Spin liquid

A vison

m (boson) particle



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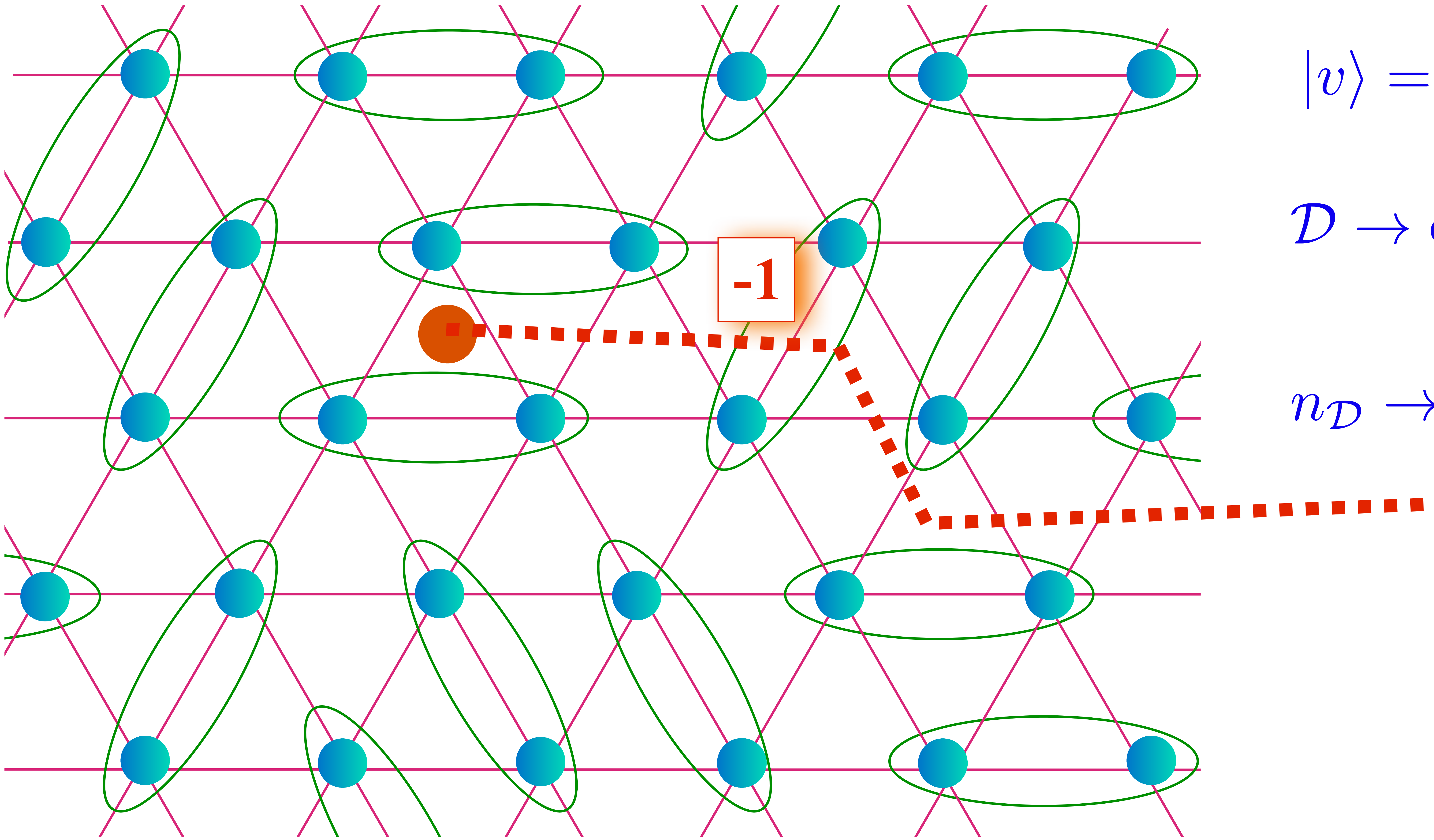

$$|v\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} (-1)^{n_{\mathcal{D}}} |\mathcal{D}\rangle$$

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

$n_{\mathcal{D}} \to$ number of dimers crossing red line

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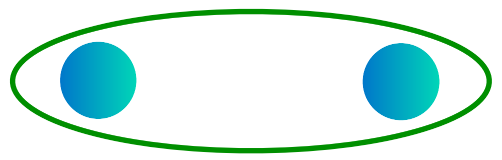

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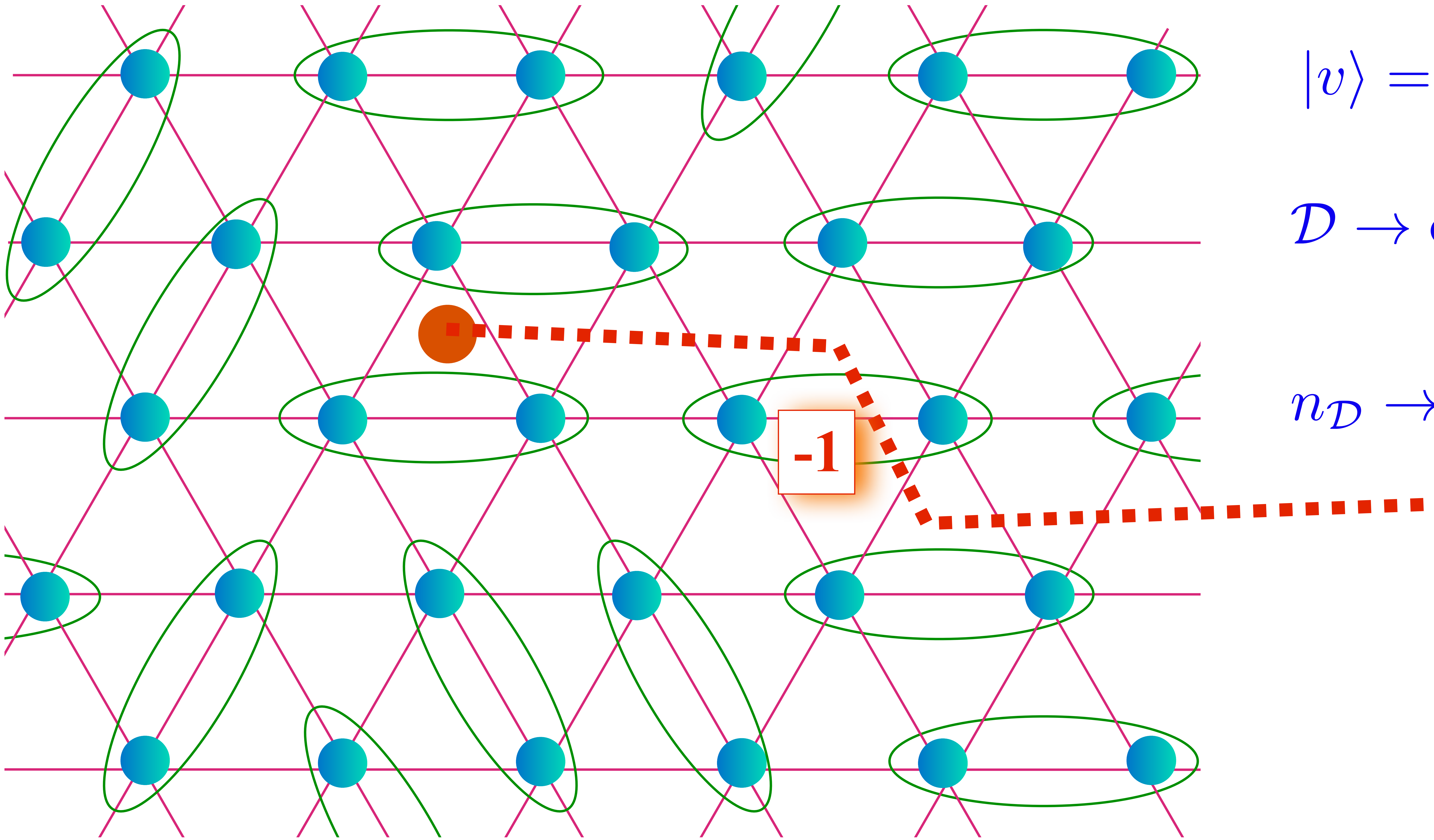

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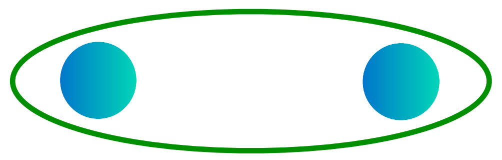

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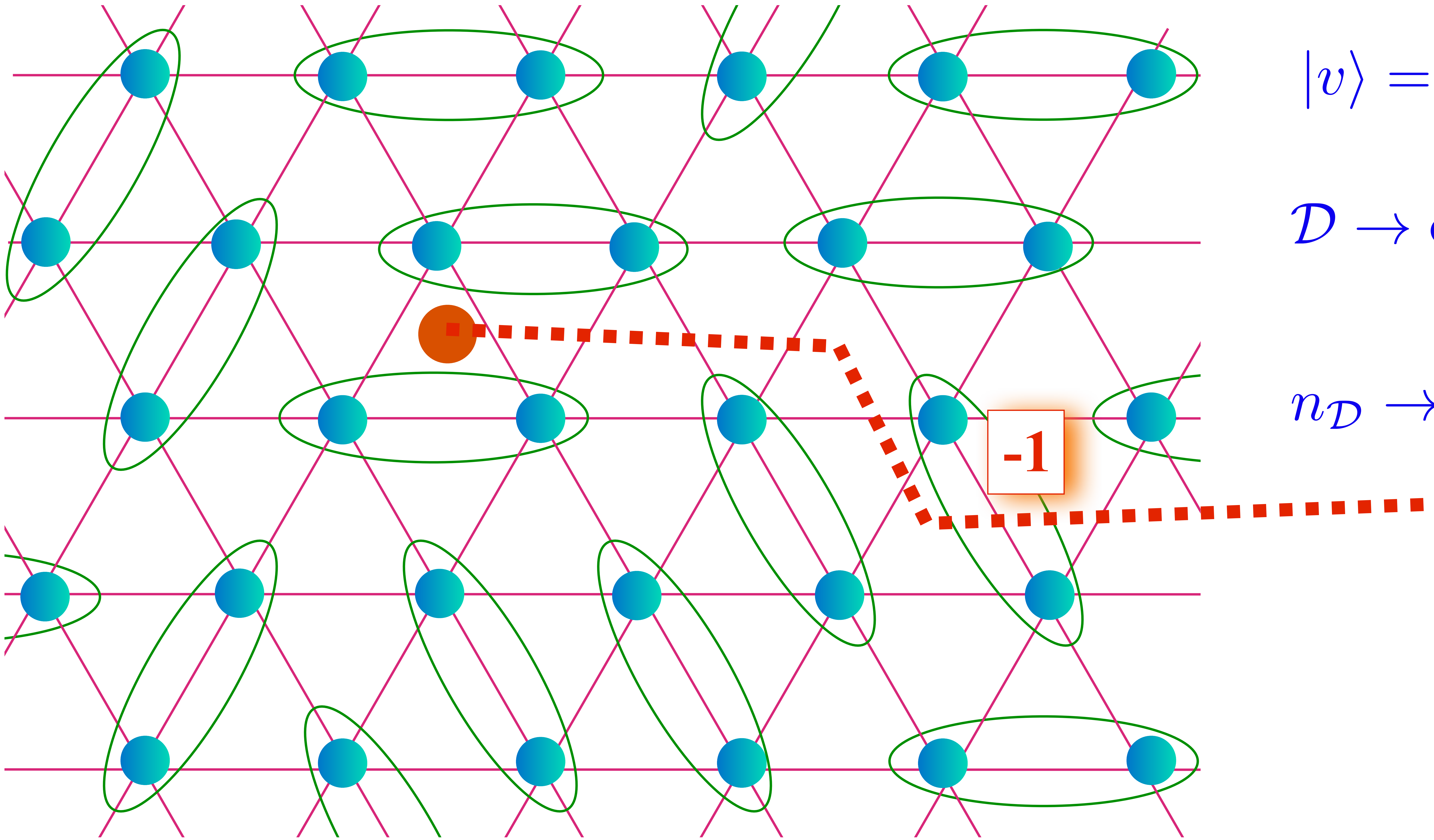

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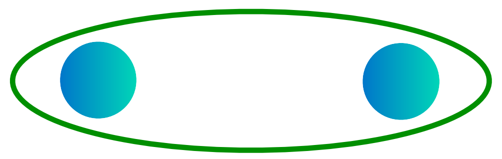

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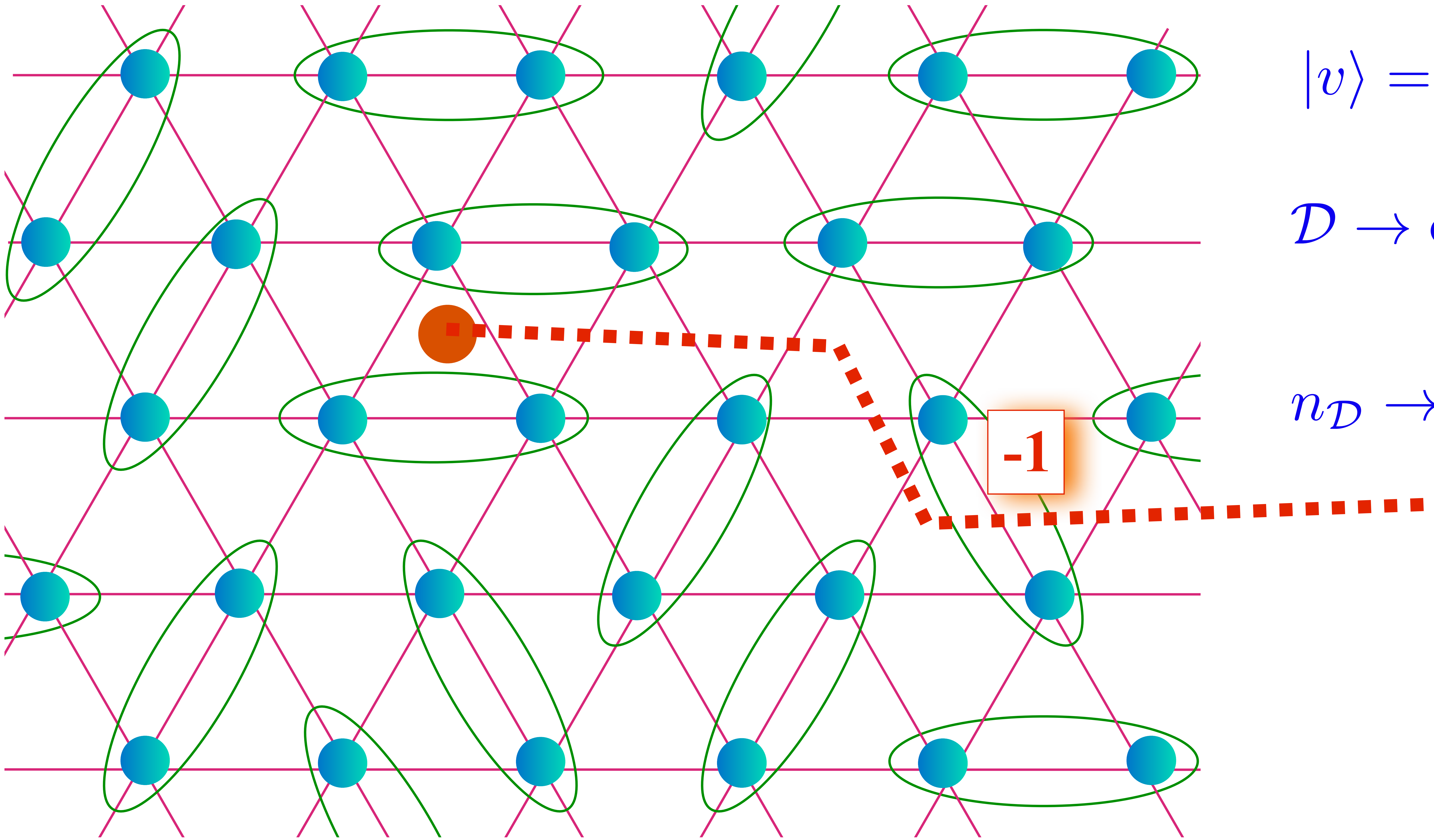

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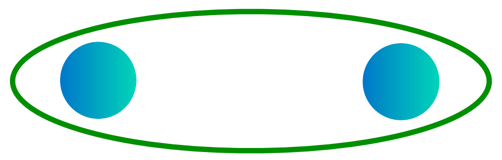

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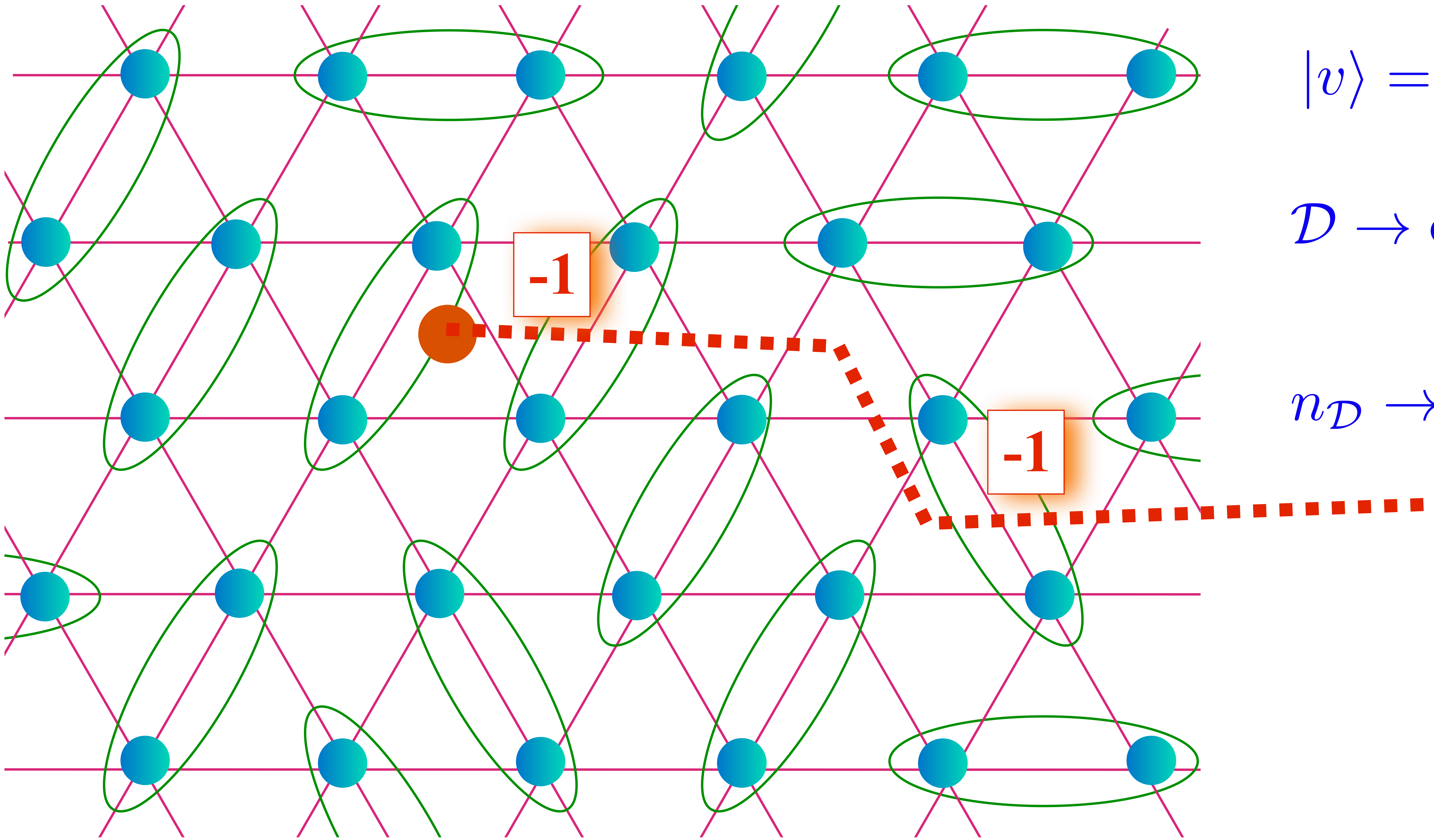

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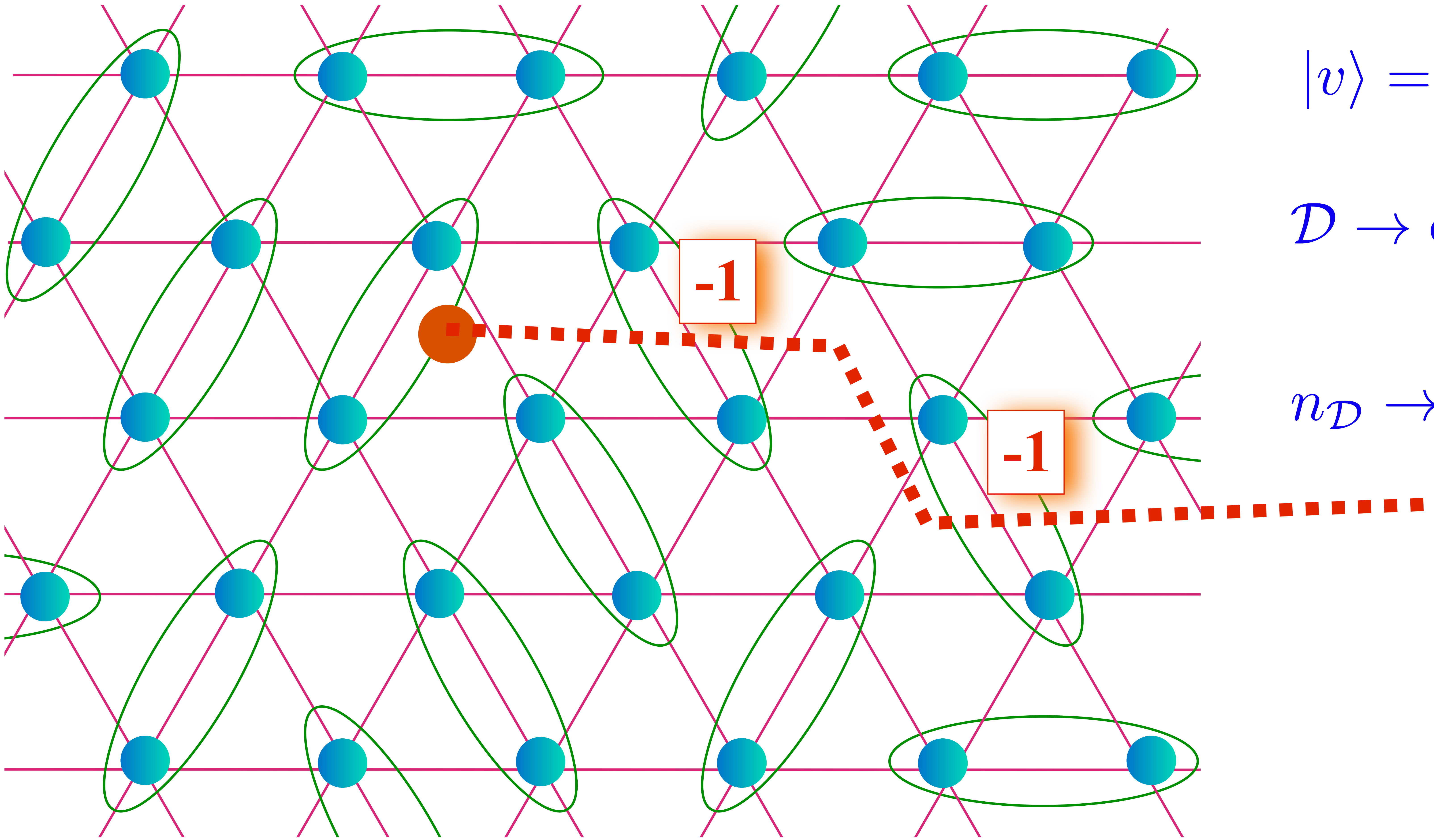

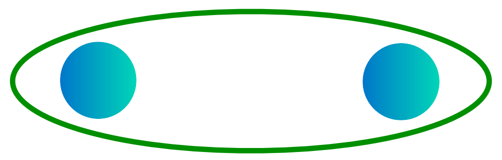

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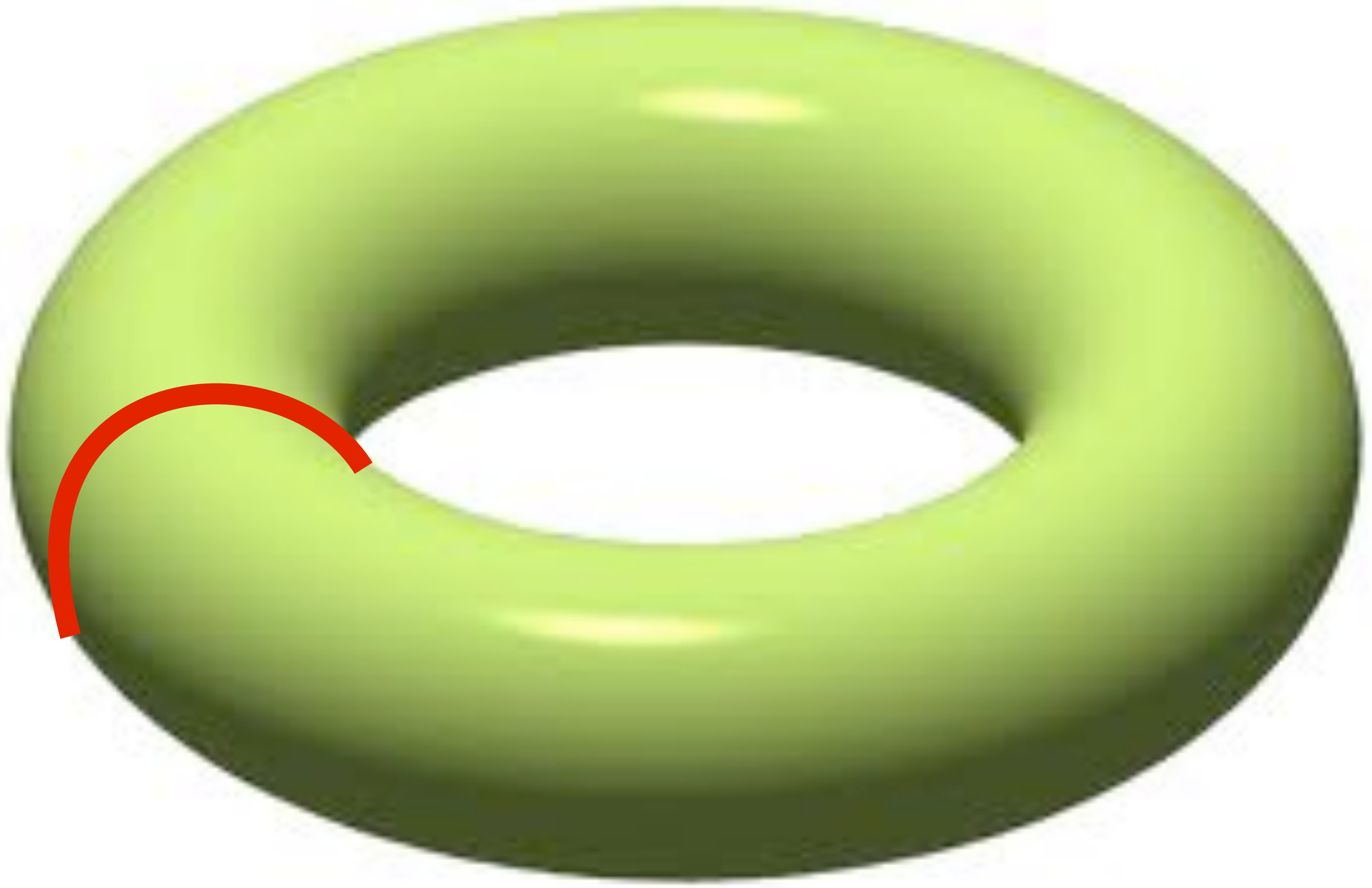
Excitations of the Z_2 Spin liquid

- 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 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:

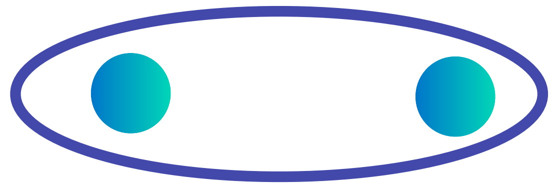
Ground state degeneracy on the torus



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



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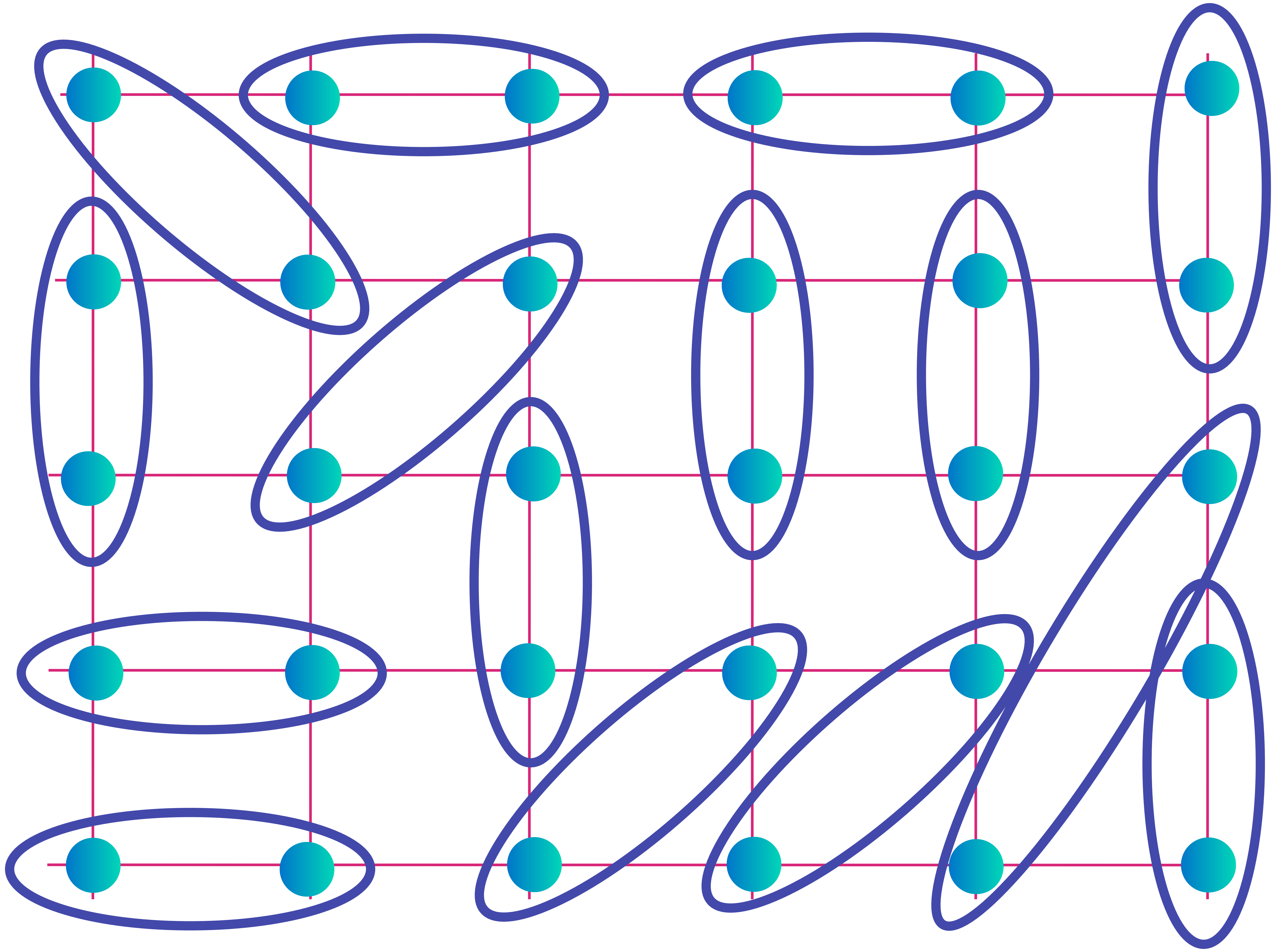

Place insulator on a torus:

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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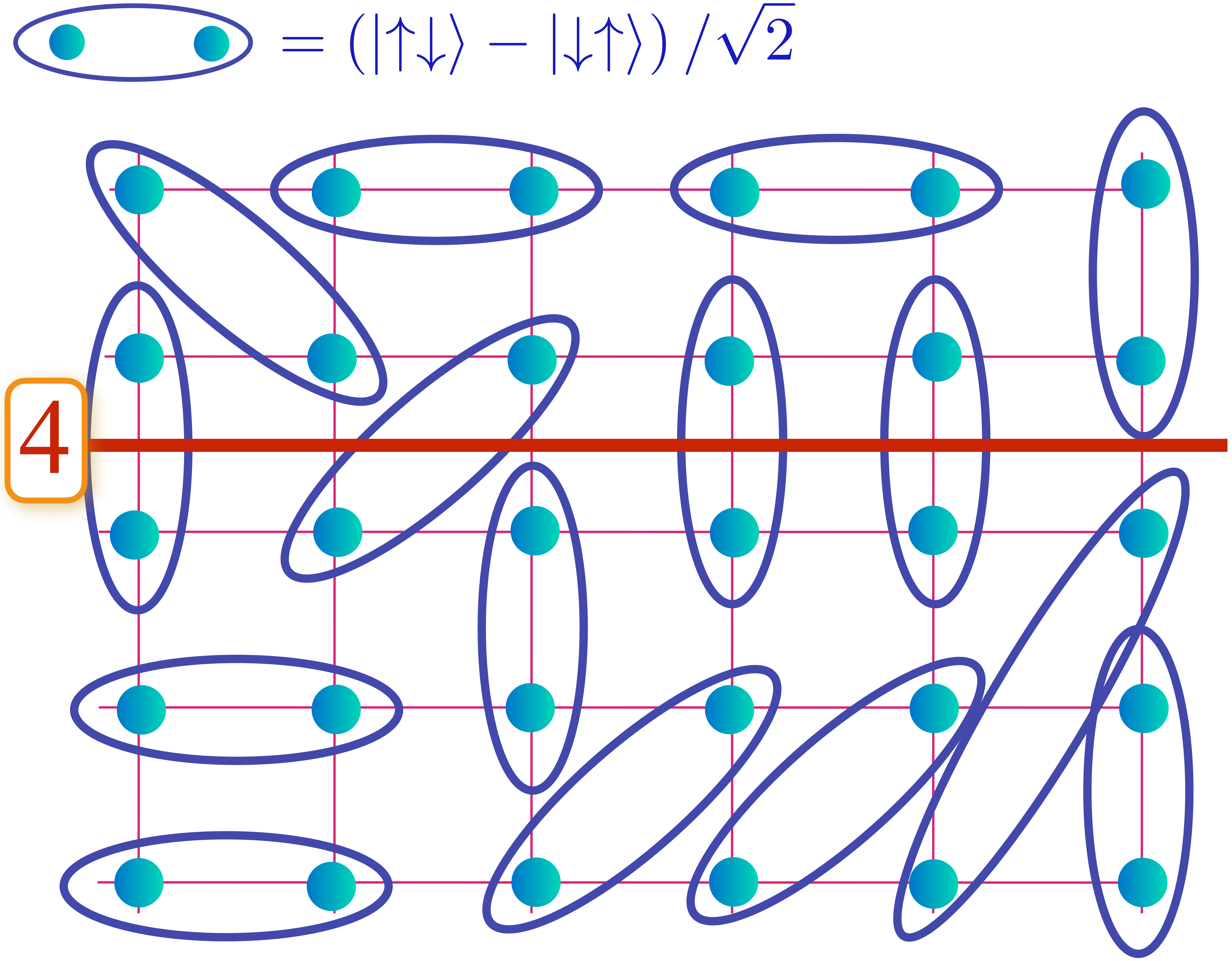

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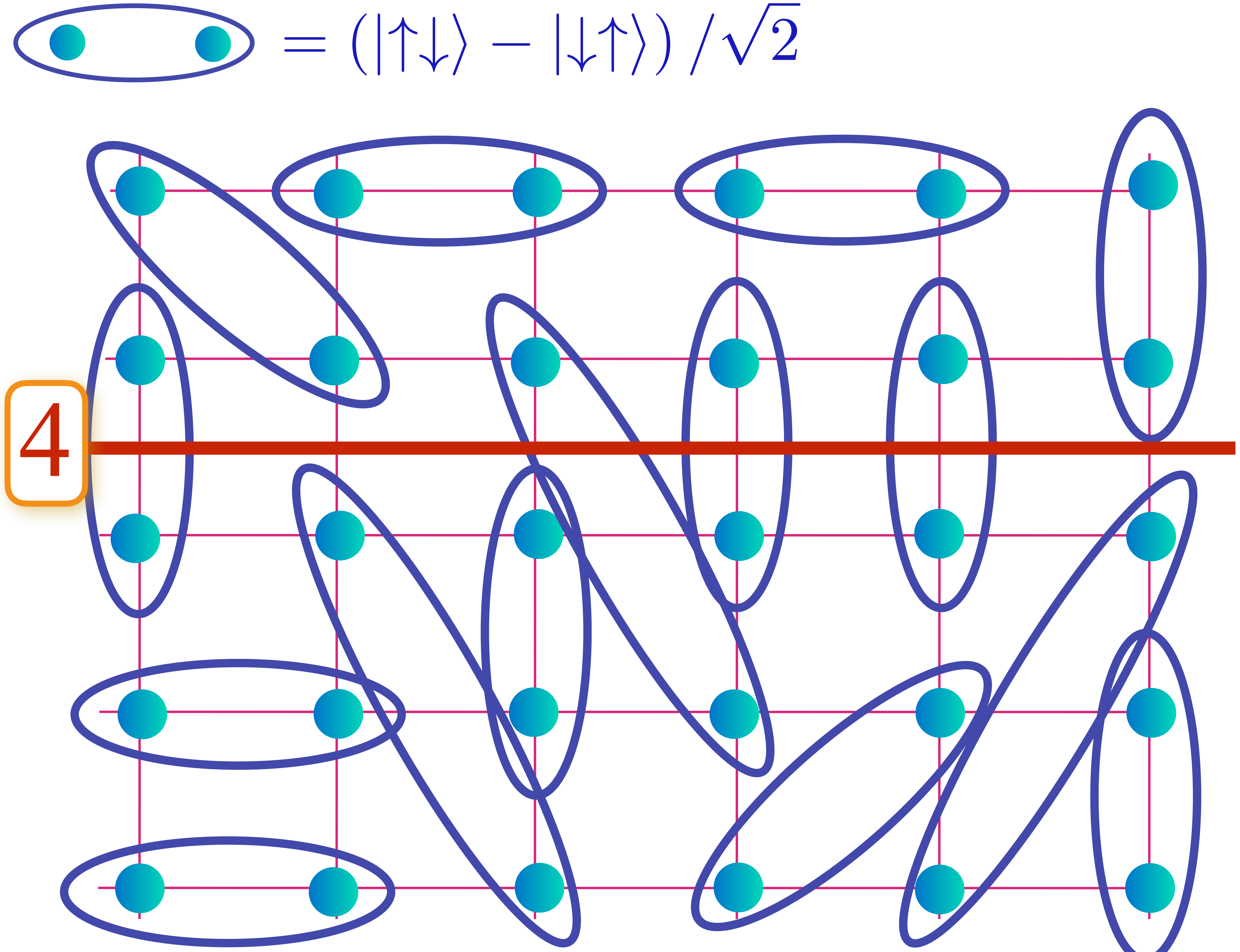

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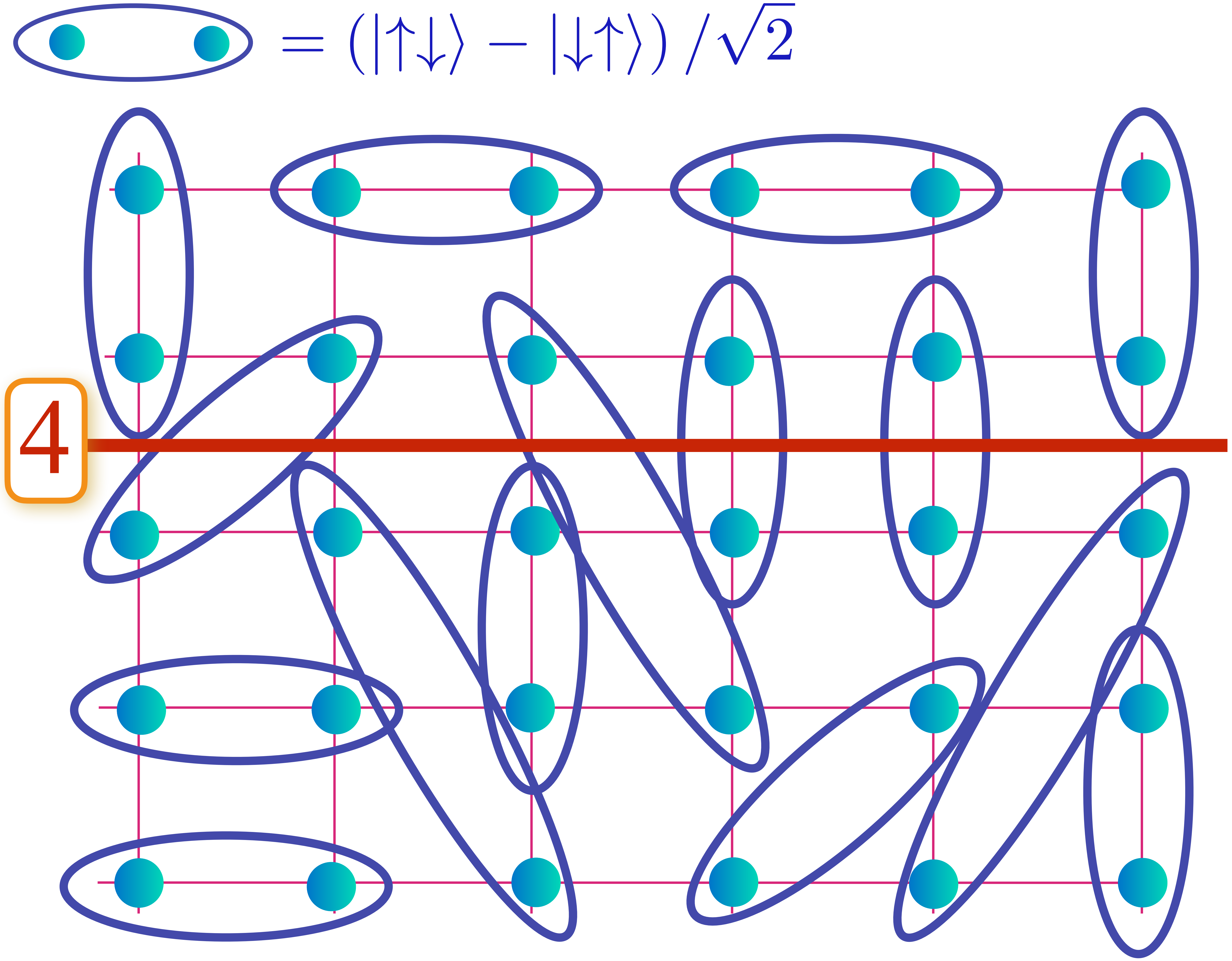

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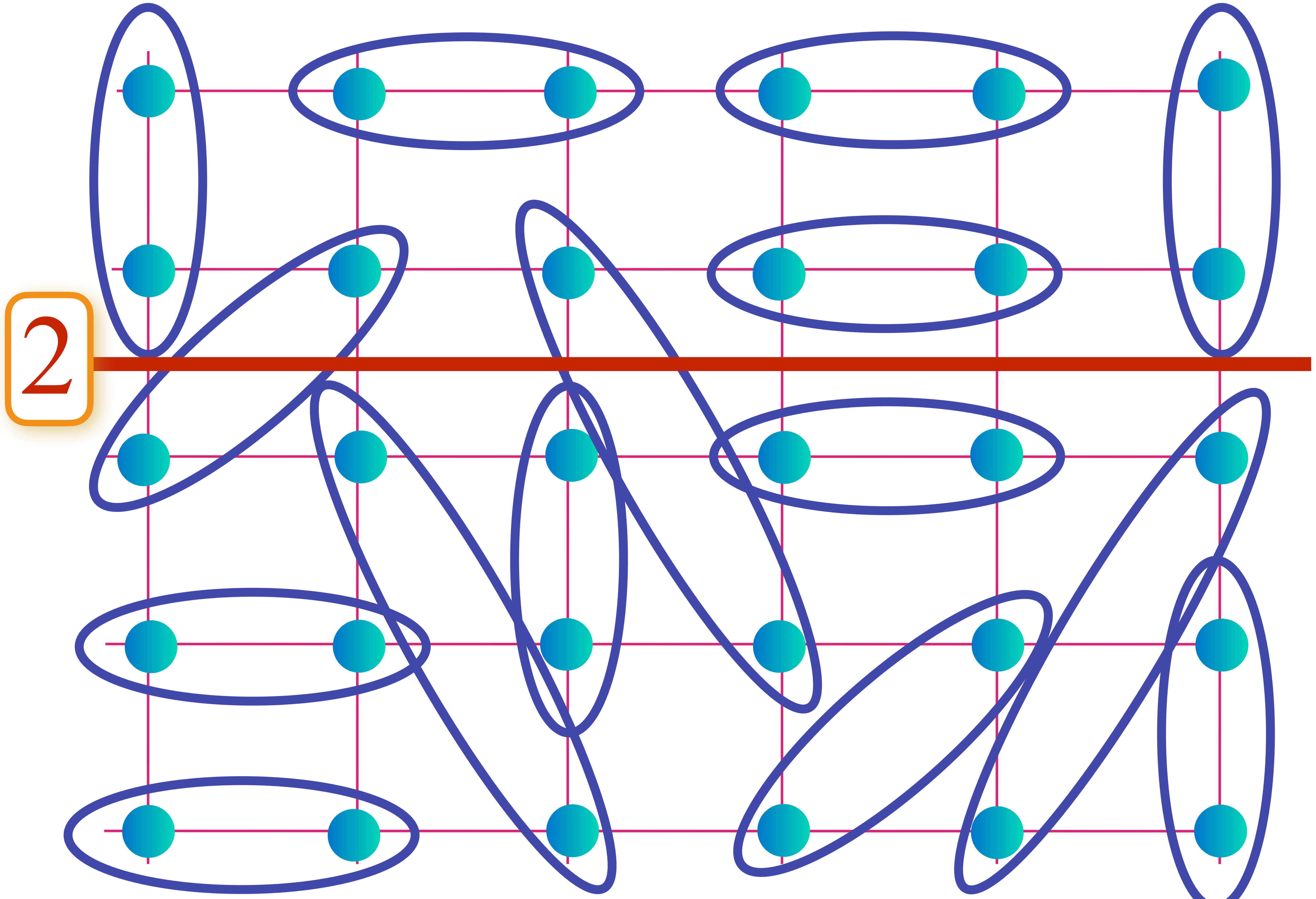
$$\text{(dimer)} = \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$



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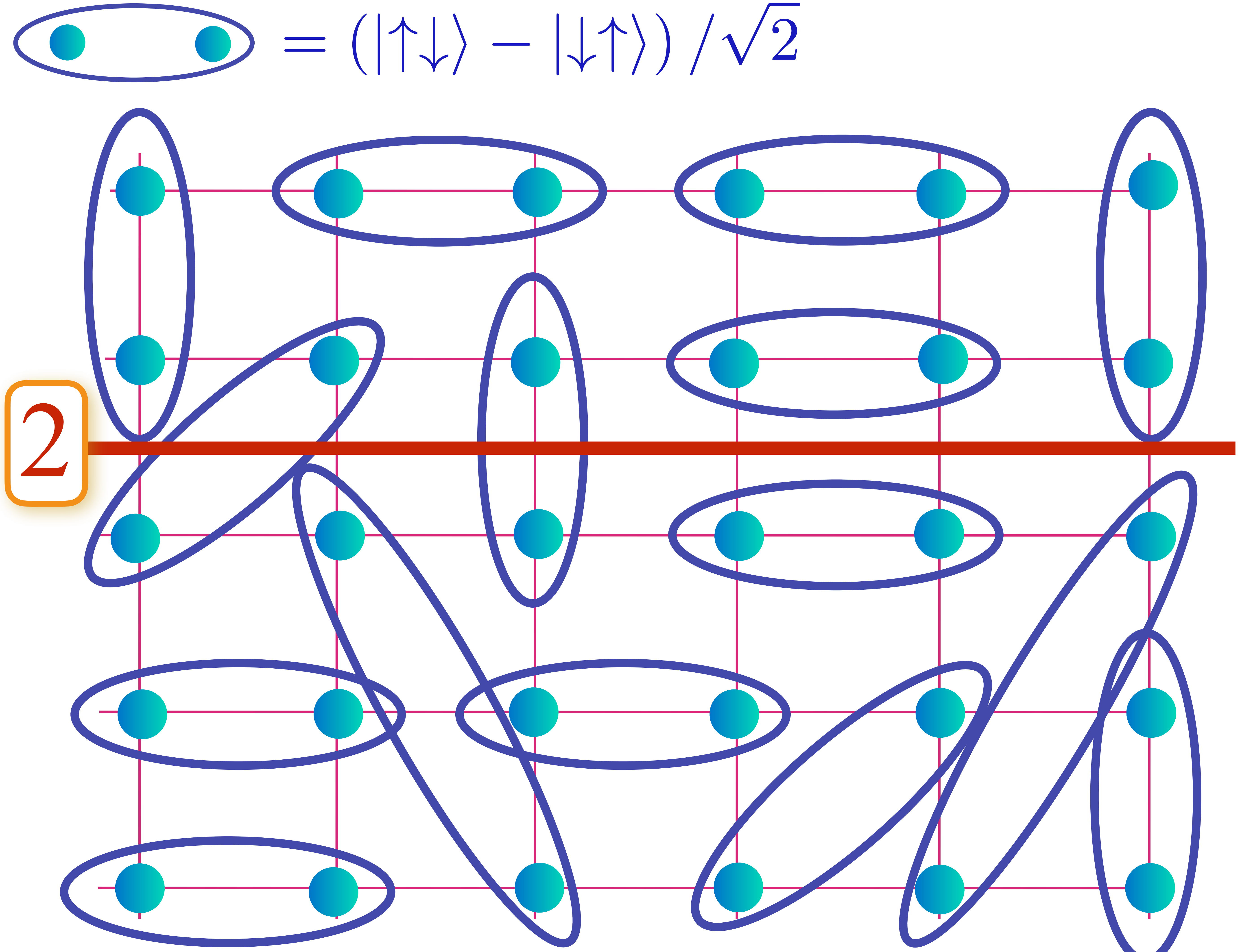

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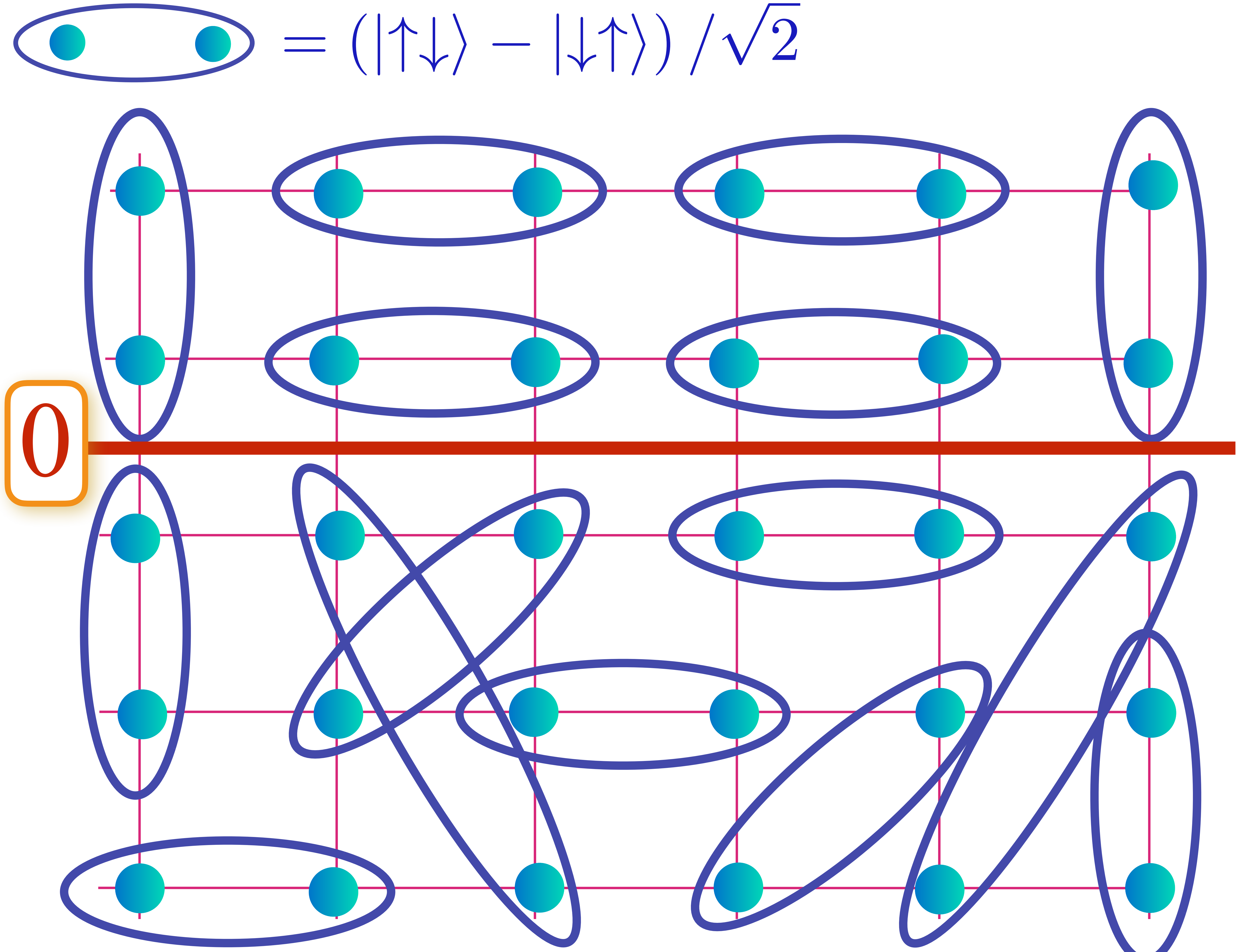
Ground state degeneracy on the torus



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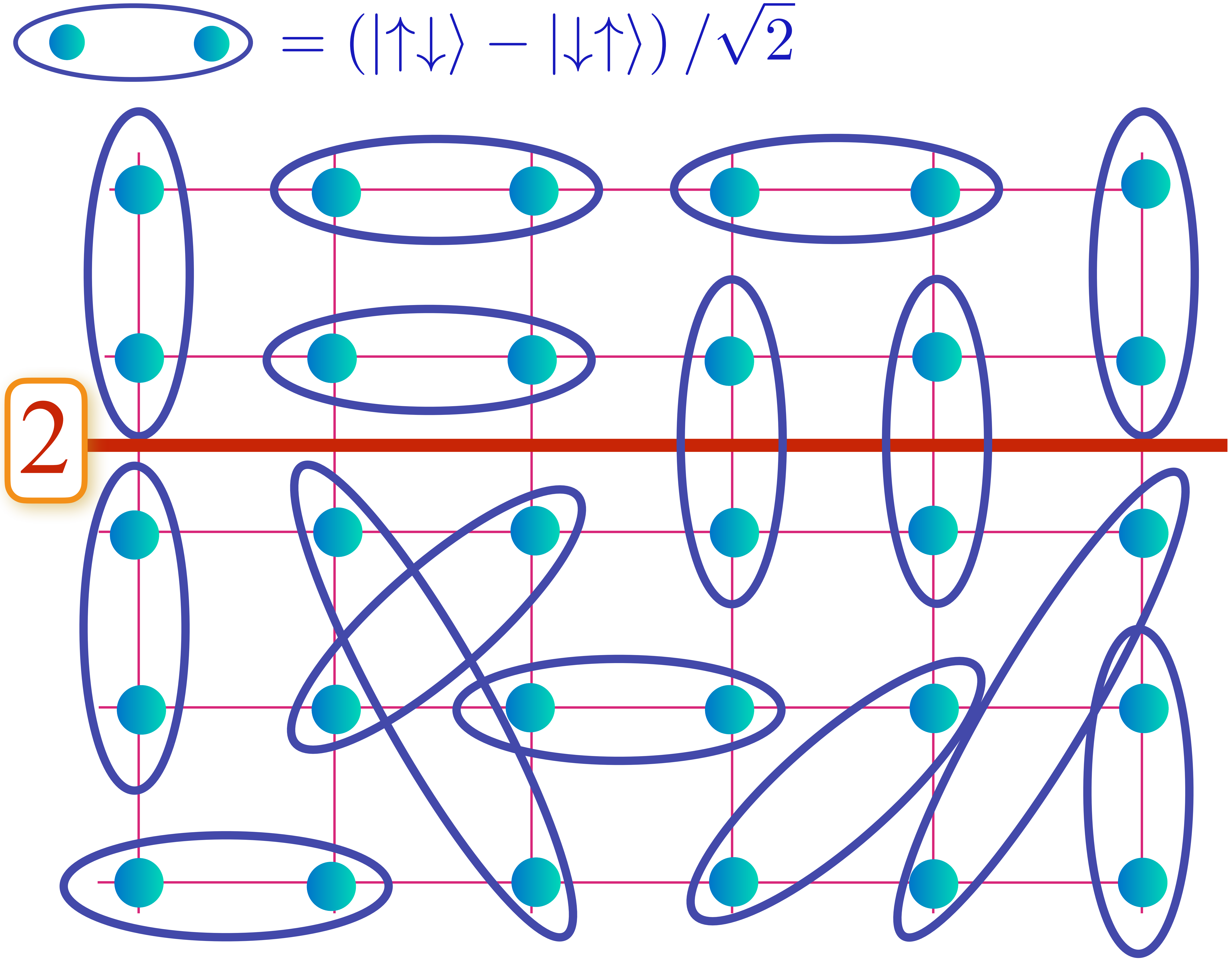

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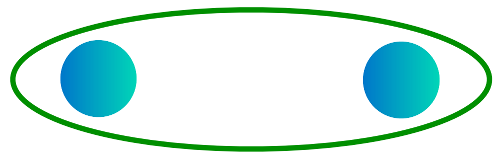
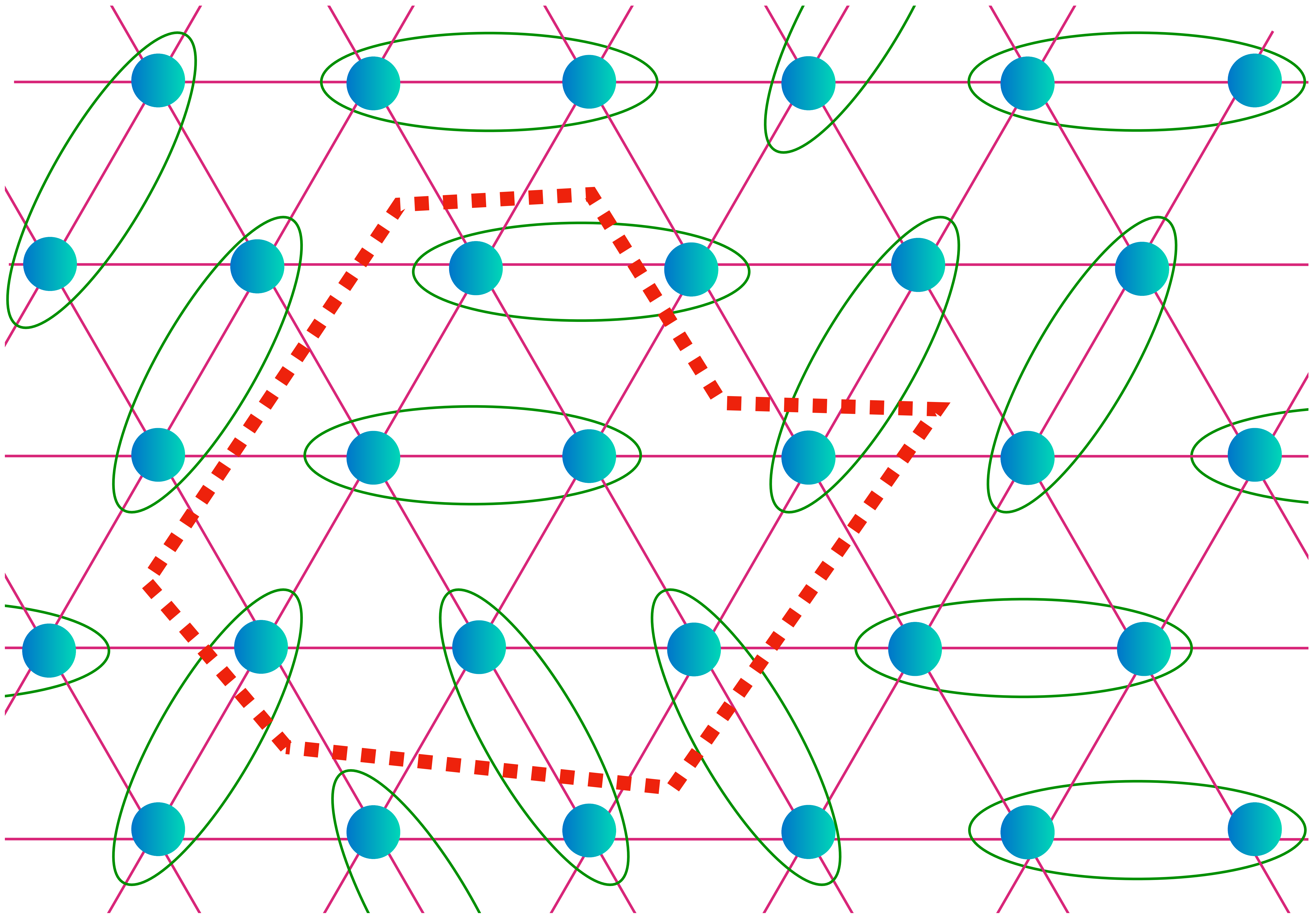
Topological Z operator of the Z_2 Spin liquid



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

5



$Z = (-1)^{n_{\mathcal{D}}}$

= parity of sites enclosed by red line

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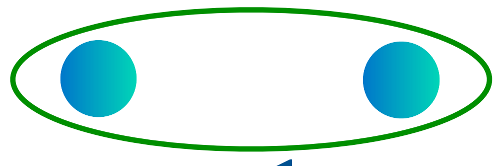

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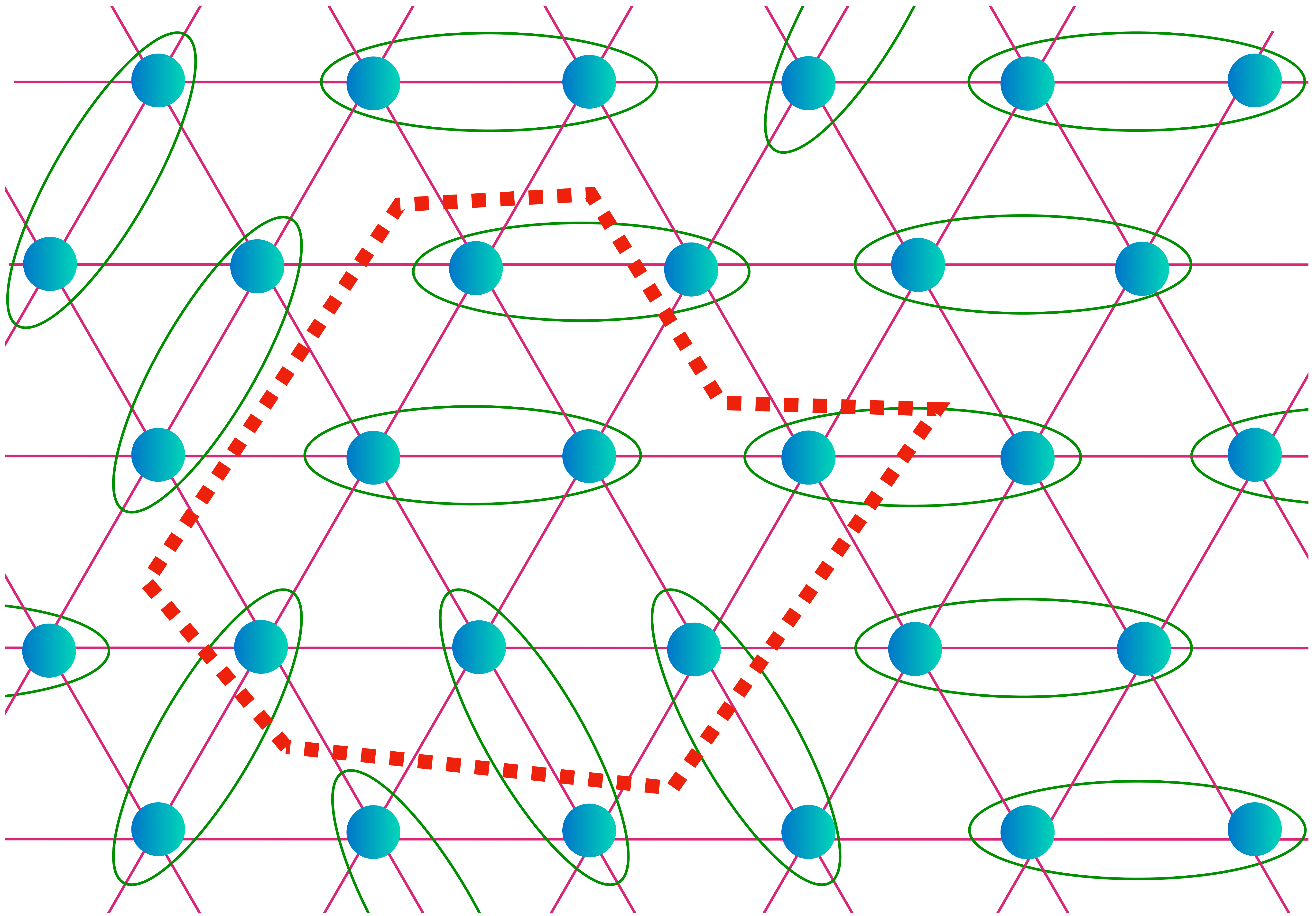

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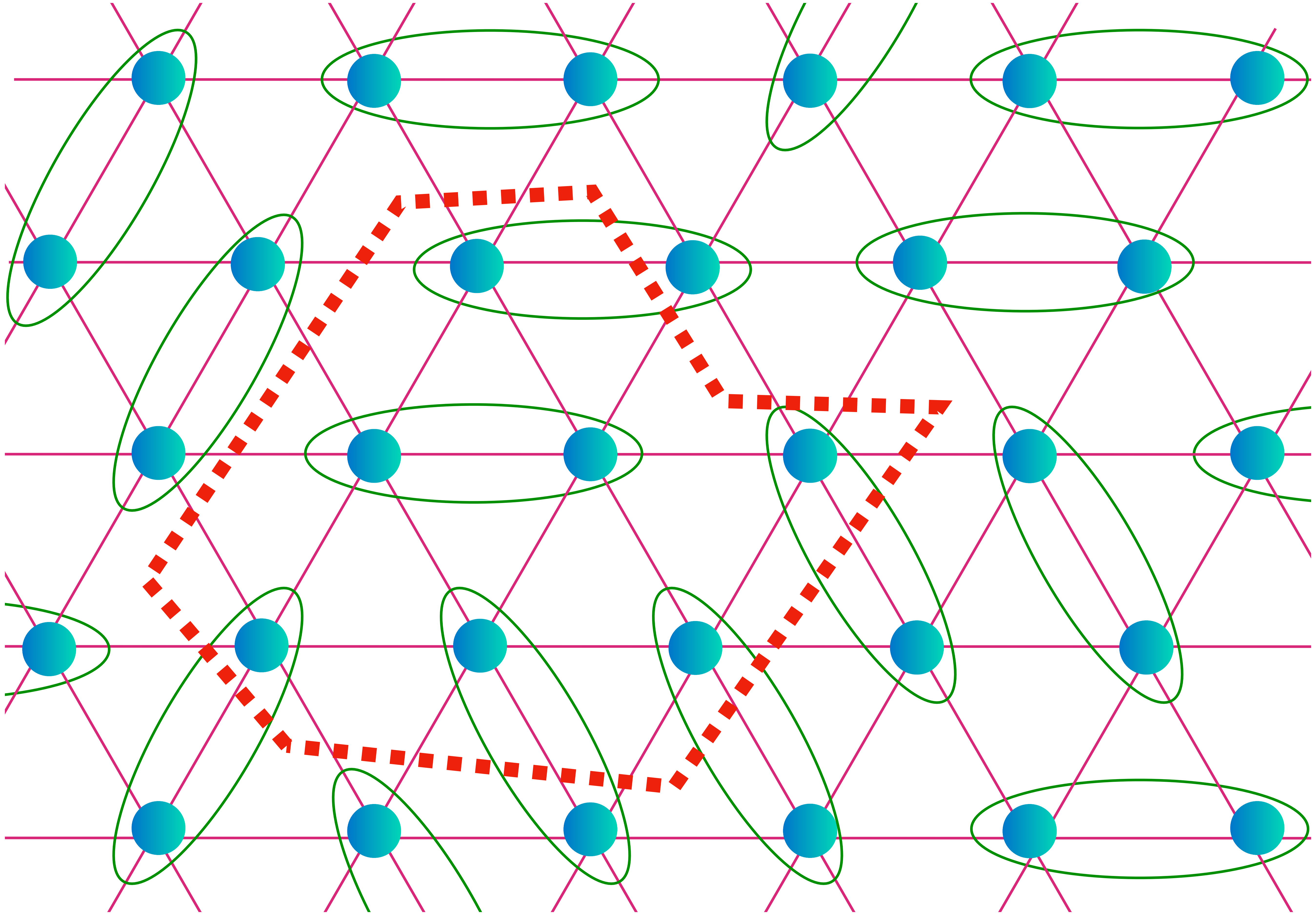

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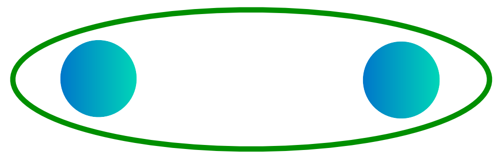

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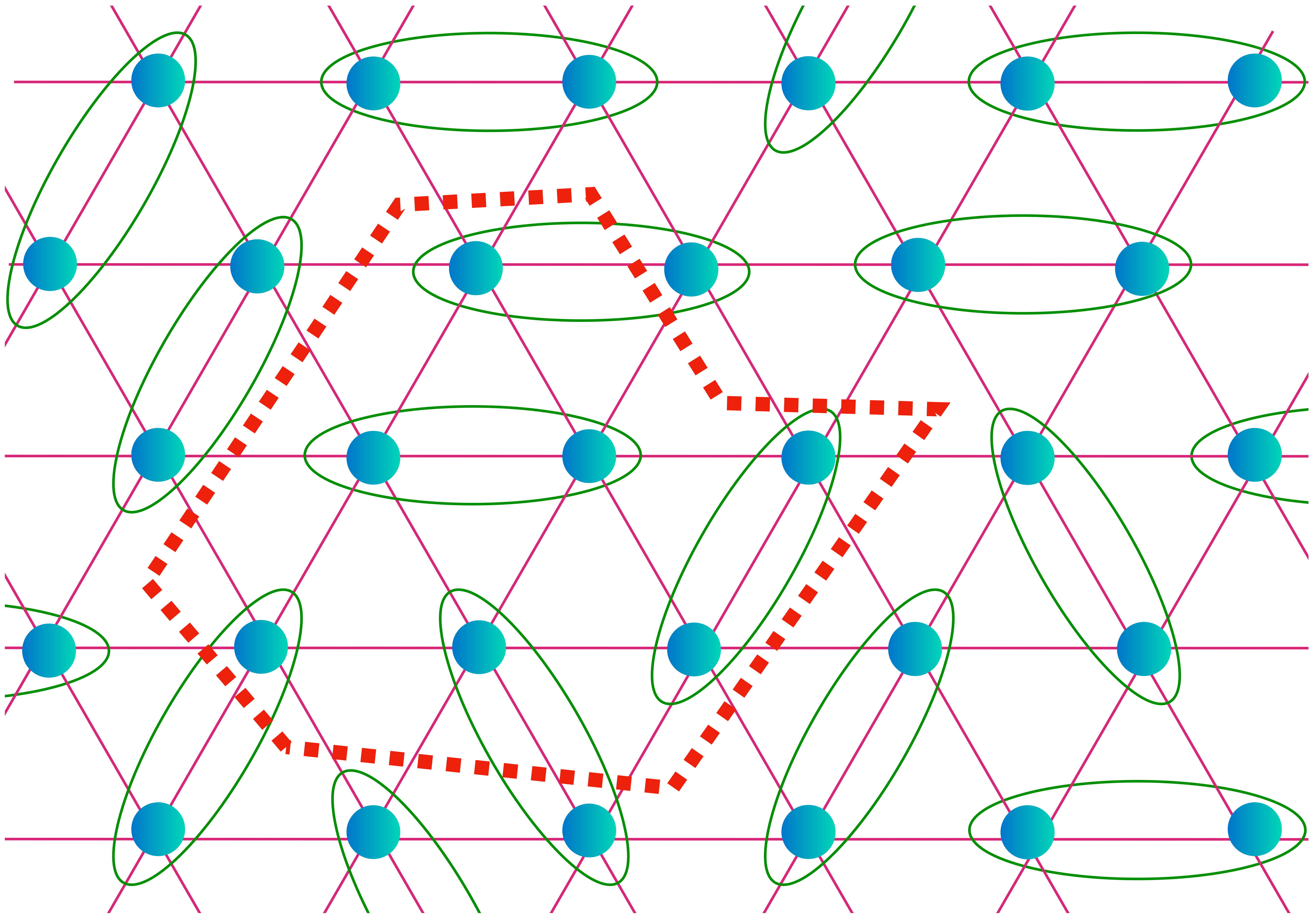

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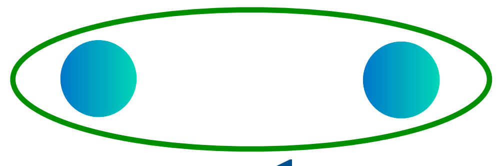

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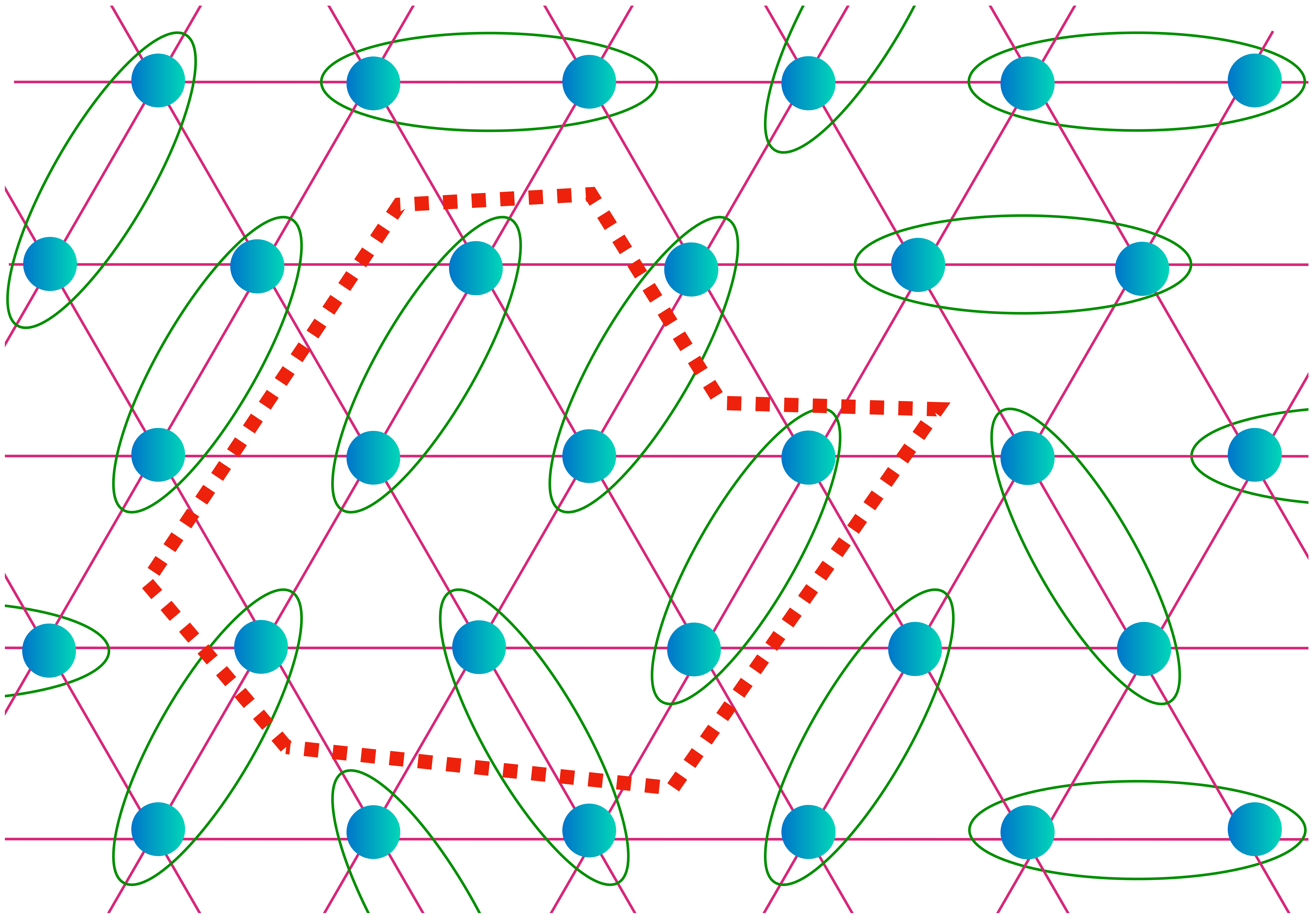

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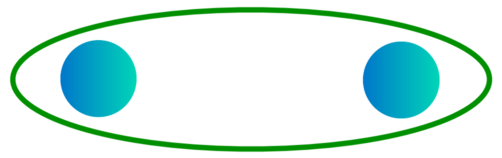

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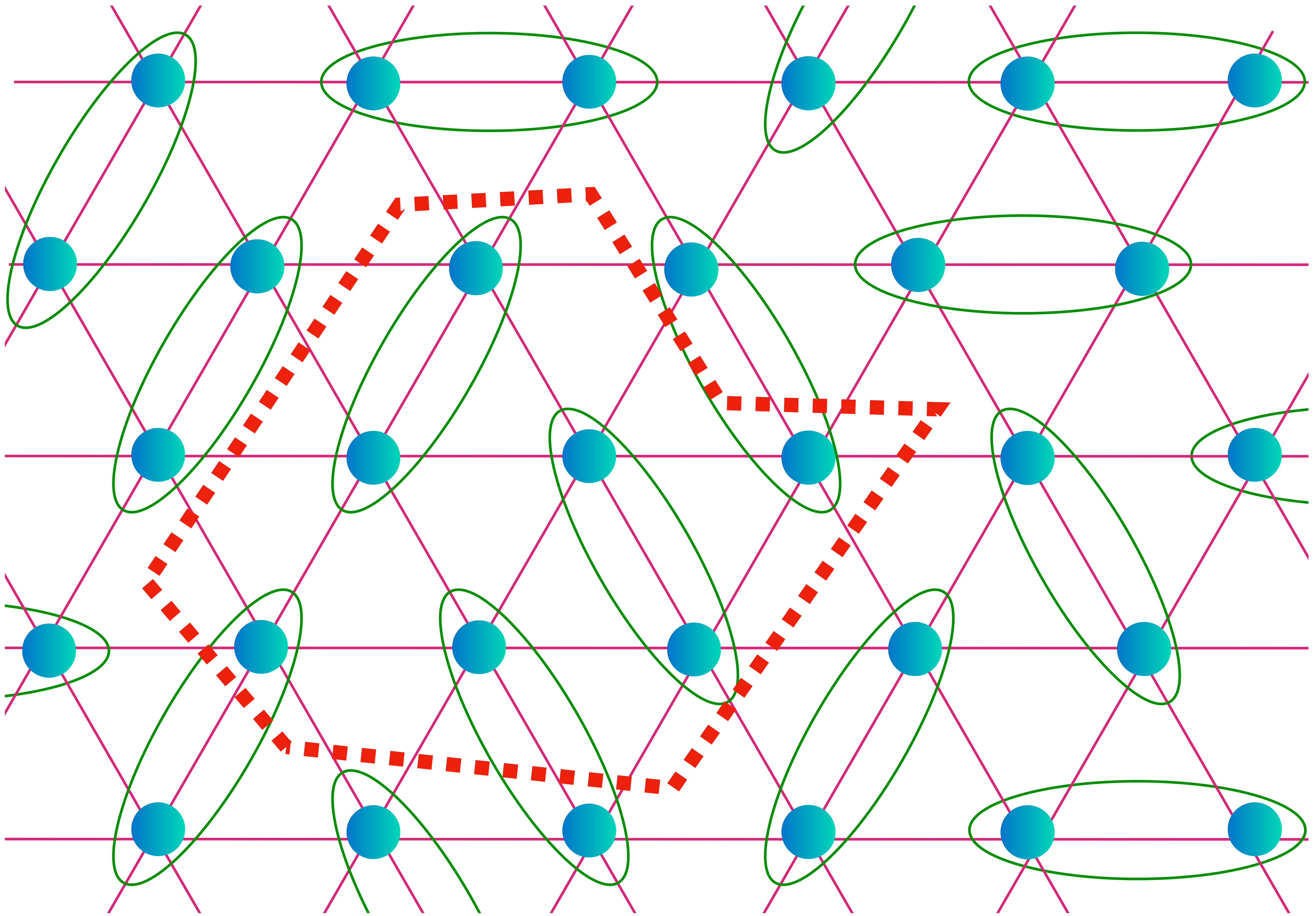

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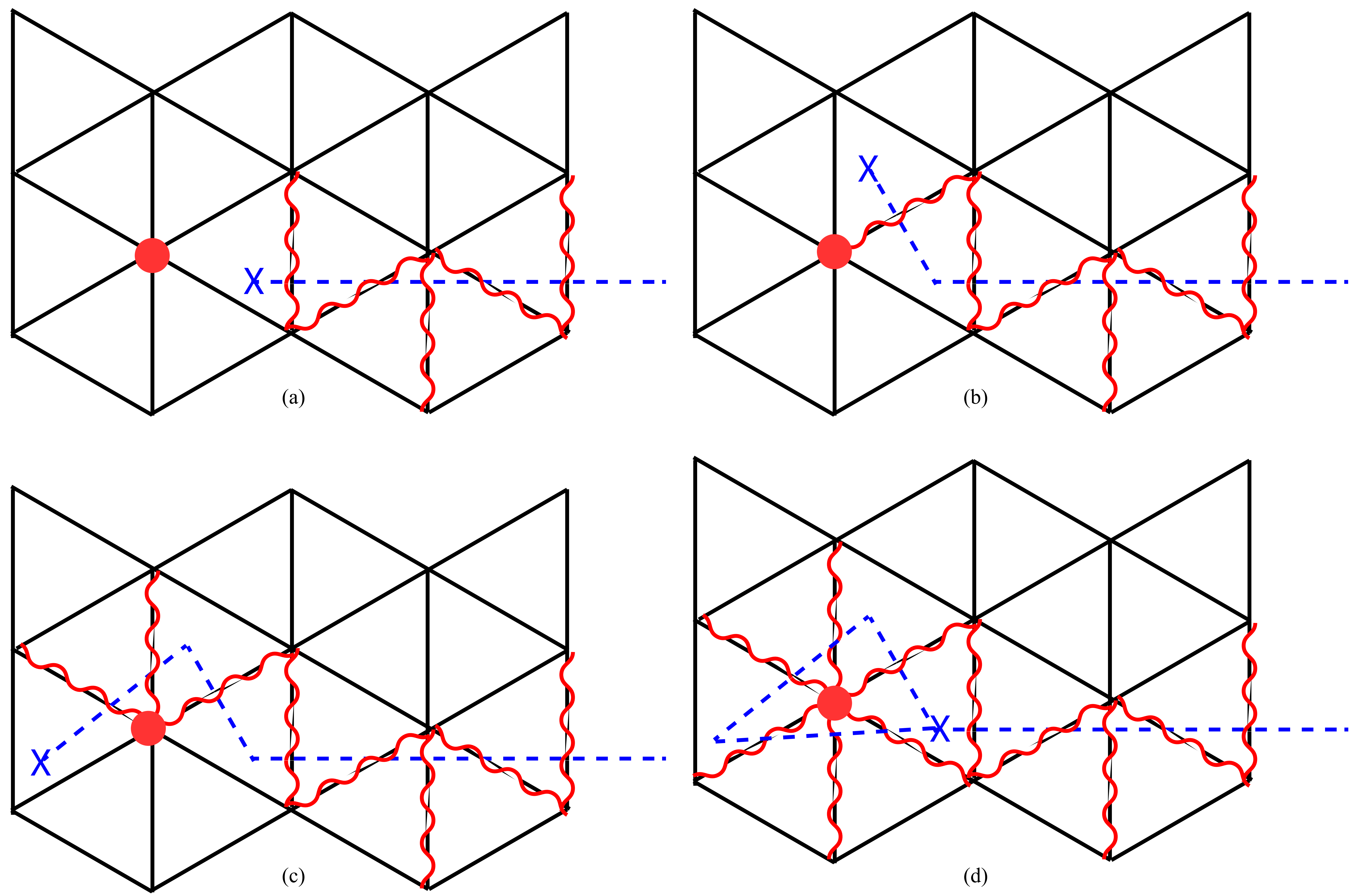
Simplest example with time-reversal symmetry: "Z_2 spin liquid" or "toric code"

- Anyons: $\mathbb{1}$, e, m, ϵ. The e, m, ϵ anyons cannot be created from the ground state ($\mathbb{1}$) by any local operator.
- The e and ϵ are spinons, the m is the 'vison'.
- Self statistics: e and m are bosons, while ϵ is a fermion.
- Mutual statistics: Any pair of e, m, ϵ are mutual semions *i.e.* one anyon picks up a (-1) upon encircling any other type of anyon.
- Fusion rules: $e \times m = \epsilon$, $e \times \epsilon = m$, $m \times \epsilon = e$, $e \times e = \epsilon \times \epsilon = m \times m = \mathbb{1}$.
- 4-fold ground state degeneracy on a torus.
- Emergent, deconfined $\mathbb{Z}_2$ gauge field.
- No protected edge states in general, but could appear with special symmetries.
- Topological entanglement entropy $= \ln 2$.

The $\mathbb{Z}_2$ spin liquid was obtained in N. Read and S. Sachdev, Phys. Rev. Lett. **66**, 1773 (1991) and X.-G. Wen, Phys. Rev. B **44**, 2664 (1991). A. Kitaev, arXiv:quant-ph/9707021 described the toric code.

Odd and even Z_2 spin liquids

Berry phase of vison motion



To return to the initial state, we need a gauge transformation factor of -1 for each dimer ending on the red circle: this yields a factor $e^{i\pi S}$, because there are $2S$ dimers on each site.

R. A. Jalabert and S. Sachdev, PRB **44**, 686 (1991); S. Sachdev and M Vojta, J. Phys. Soc. Jpn. Suppl. B **69**, (2000); T. Senthil and M.P.A. Fisher, PRB **62**, 7850 (2000).

Odd and even Z_2 spin liquids

- The spinons carry spin $S_z = 1/2$ boson number $B^\dagger B = 1/2$.
- $\mathbb{Z}_2$ spin liquids of bosons (more generally, in systems with a global U(1) symmetry) must obey contraints associated with a ''tHooft anomaly' which is determined by the boson filling n.
  - On a square lattice, the single vison state exhibit 'translational symmetry fractionalization' with
$$T_x T_y = T_y T_x e^{2\pi i n},$$
    with n integer or half-integer.
  - For antiferromagnets of spin S, the translational symmetry fractionalization is
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  - For antiferromagnets of spin S, the translational symmetry fractionalization is
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- More generally, any $\mathbb{Z}_2$ spin liquid, even without a conserved U(1), can exhibit *symmetry fractionalization* , with $T_x T_y = T_y T_x$ for an even $\mathbb{Z}_2$ spin liquid, and $T_x T_y = -T_y T_x$ for an odd $\mathbb{Z}_2$ spin liquid on the square lattice (generalizes to other lattices)

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1. Rydberg chains

   The Z_3 chiral clock transition

2. Square lattice

   Quantum Ising criticality in 2+1 dimensions

3. Kagome symmetry lattices

   Probing topological spin liquids

4. Theory of odd and even Z_2 spin liquids

Rydberg atoms on site-kagome lattice: theory

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

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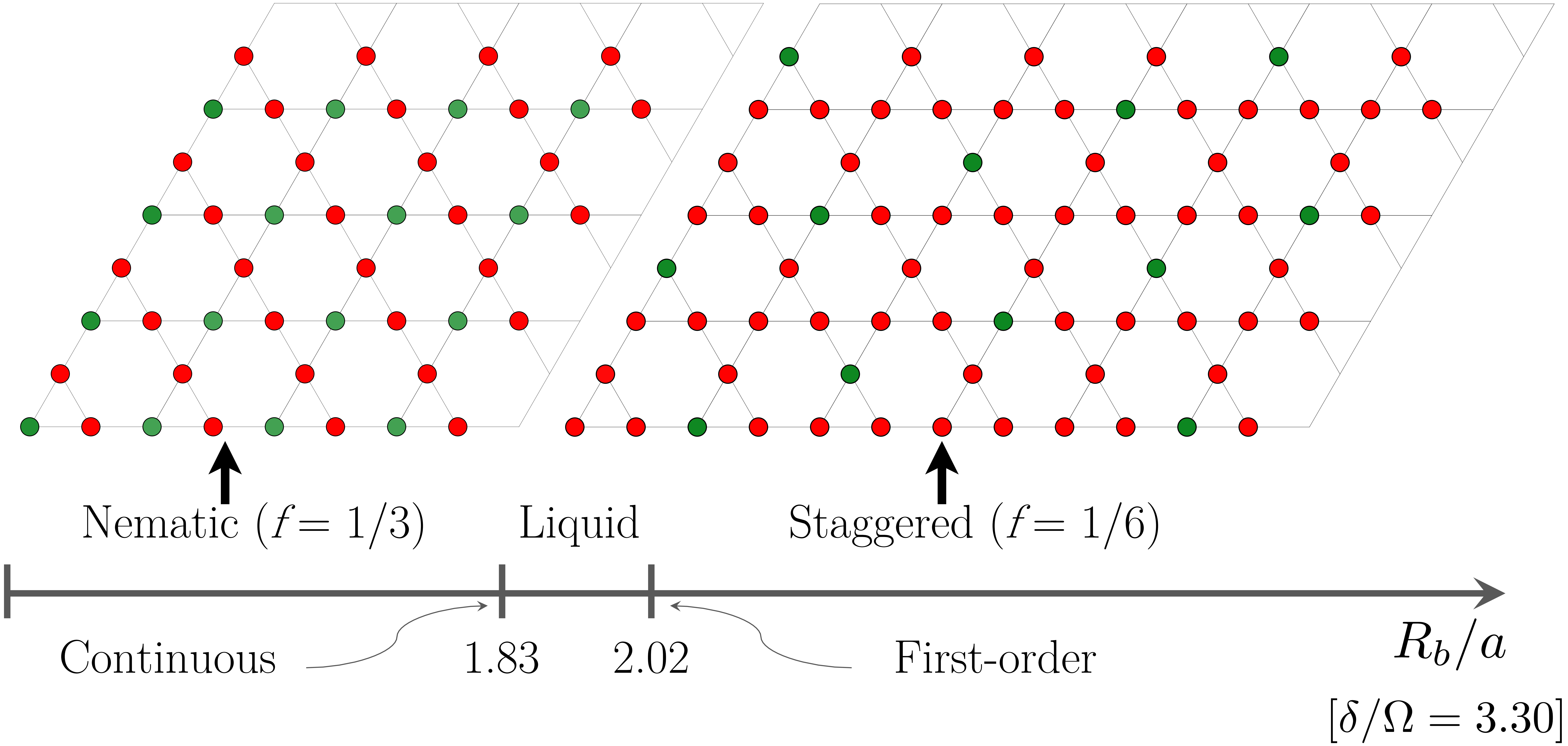

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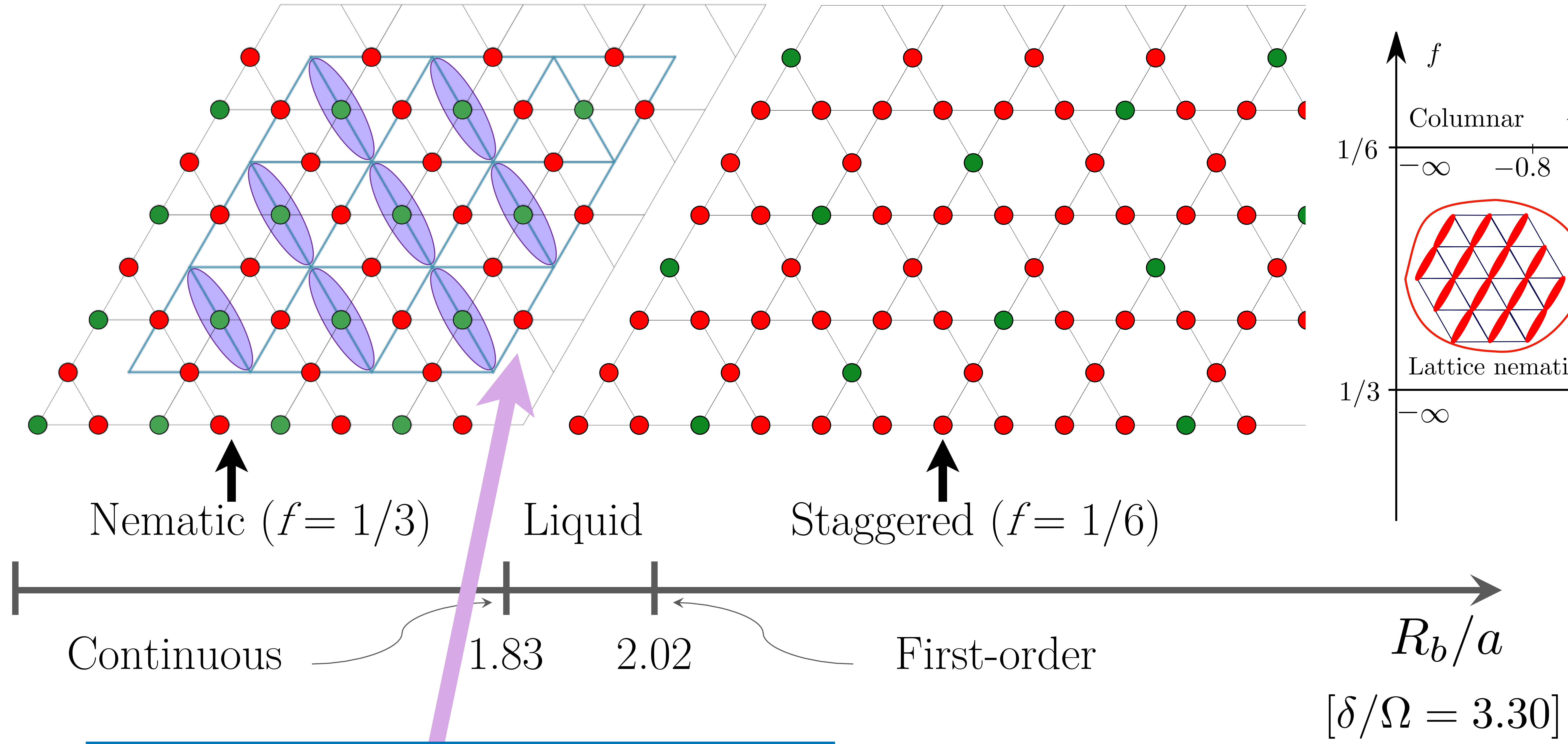

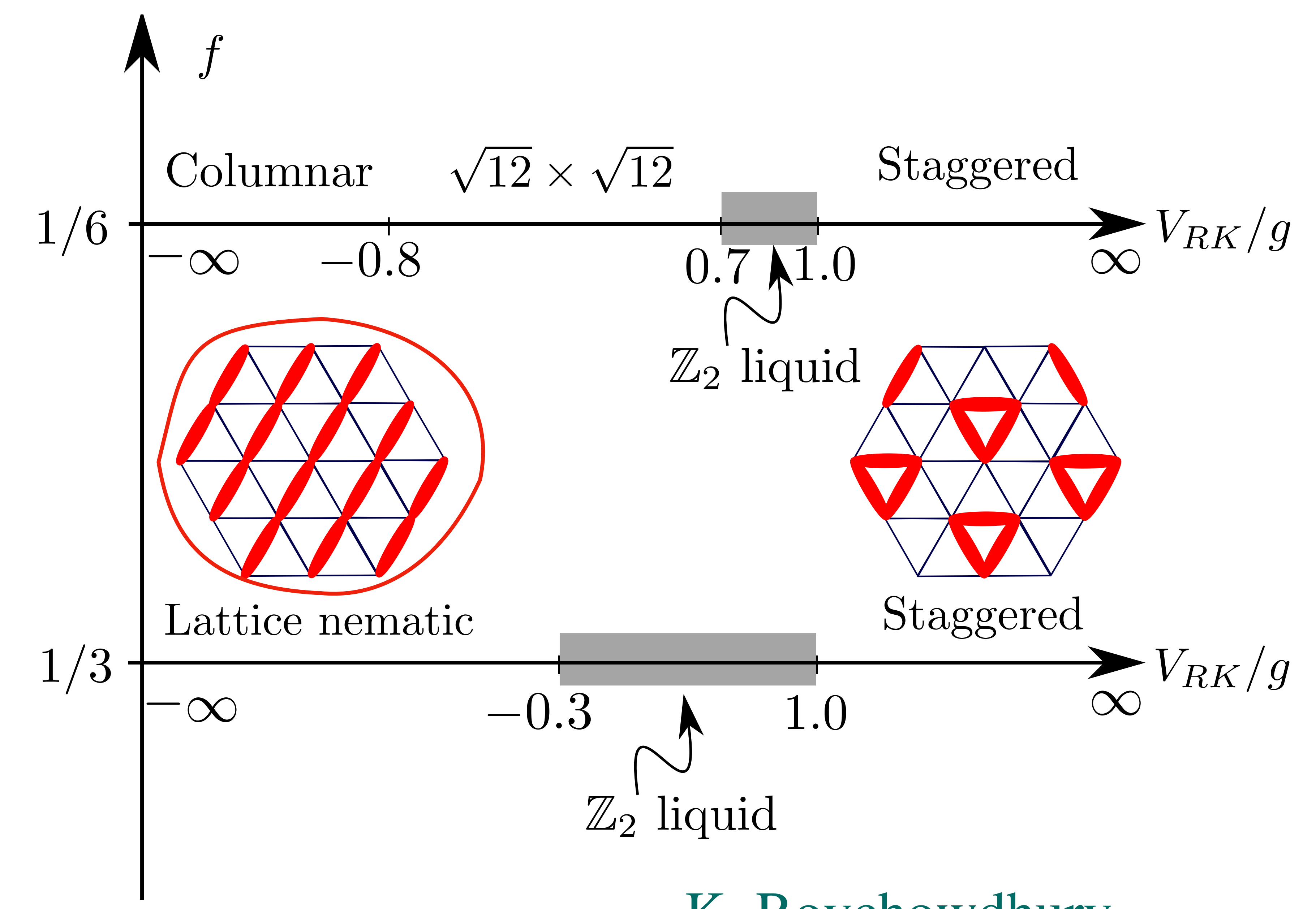

K. Roychowdhury, S. Bhattacharjee, F. Pollmann, *Phys. Rev. B* **92**, 075141 (2015).

Solid phase of the *even* quantum dimer model on the triangular lattice

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

'Hard boson' of Fendley, Sengupta, Sachdev
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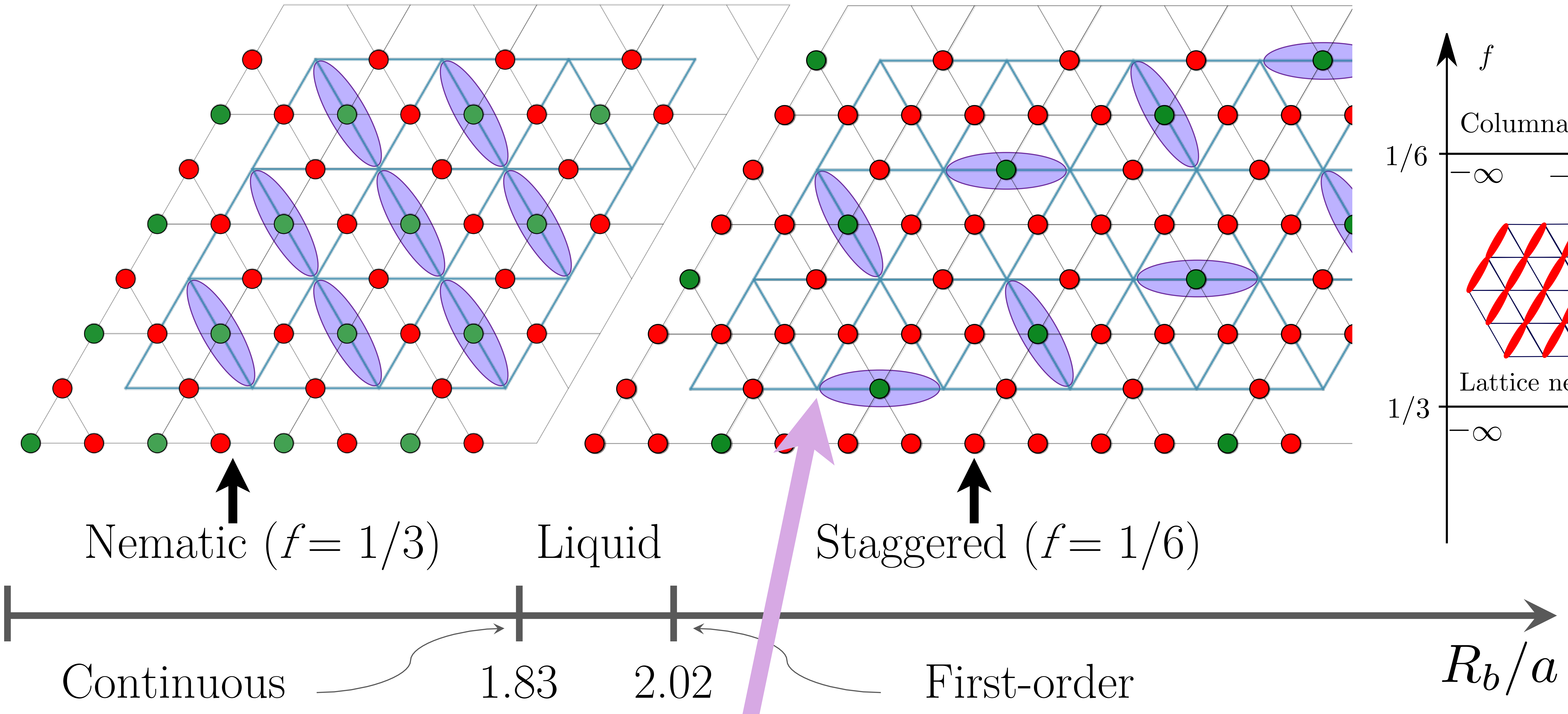

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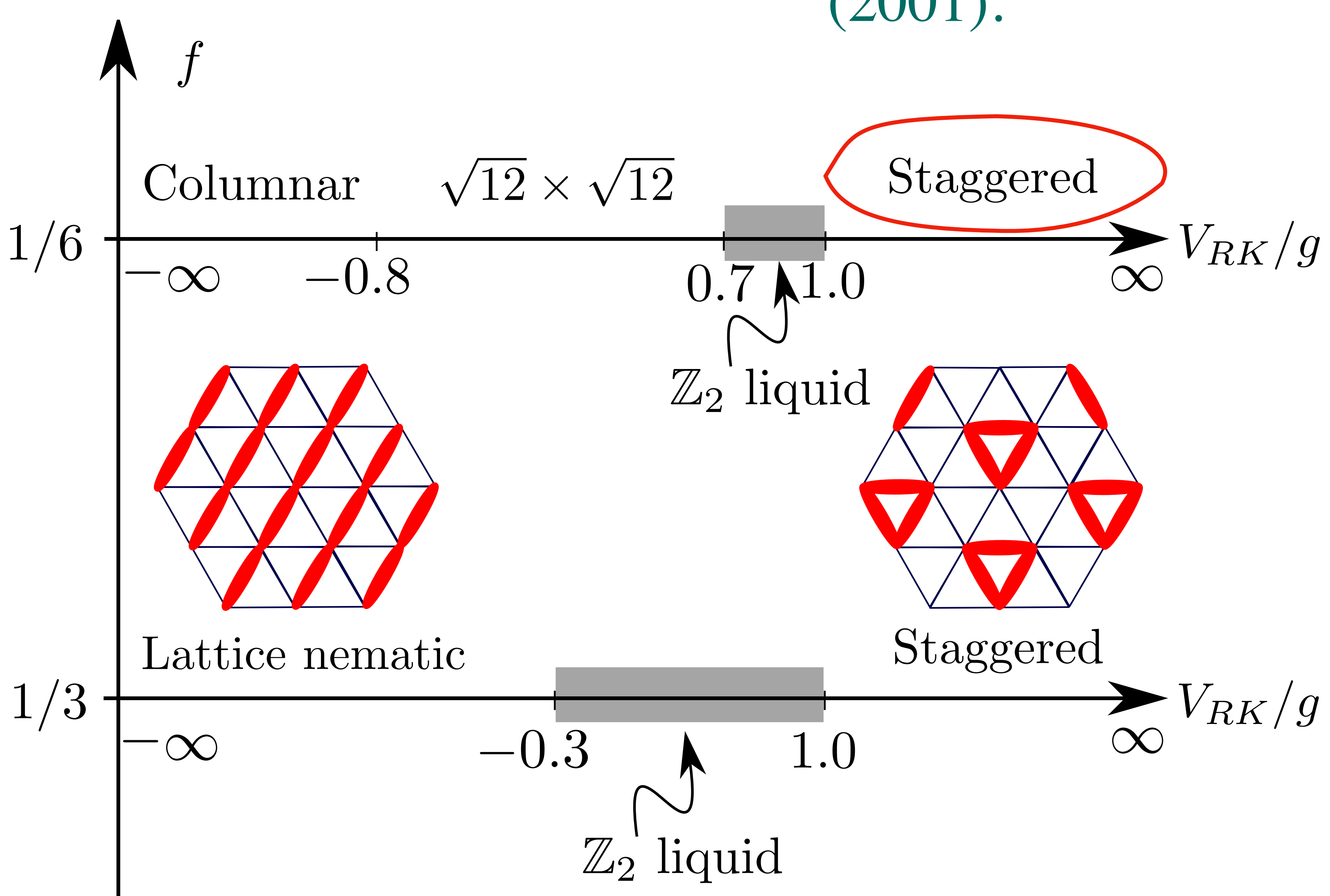

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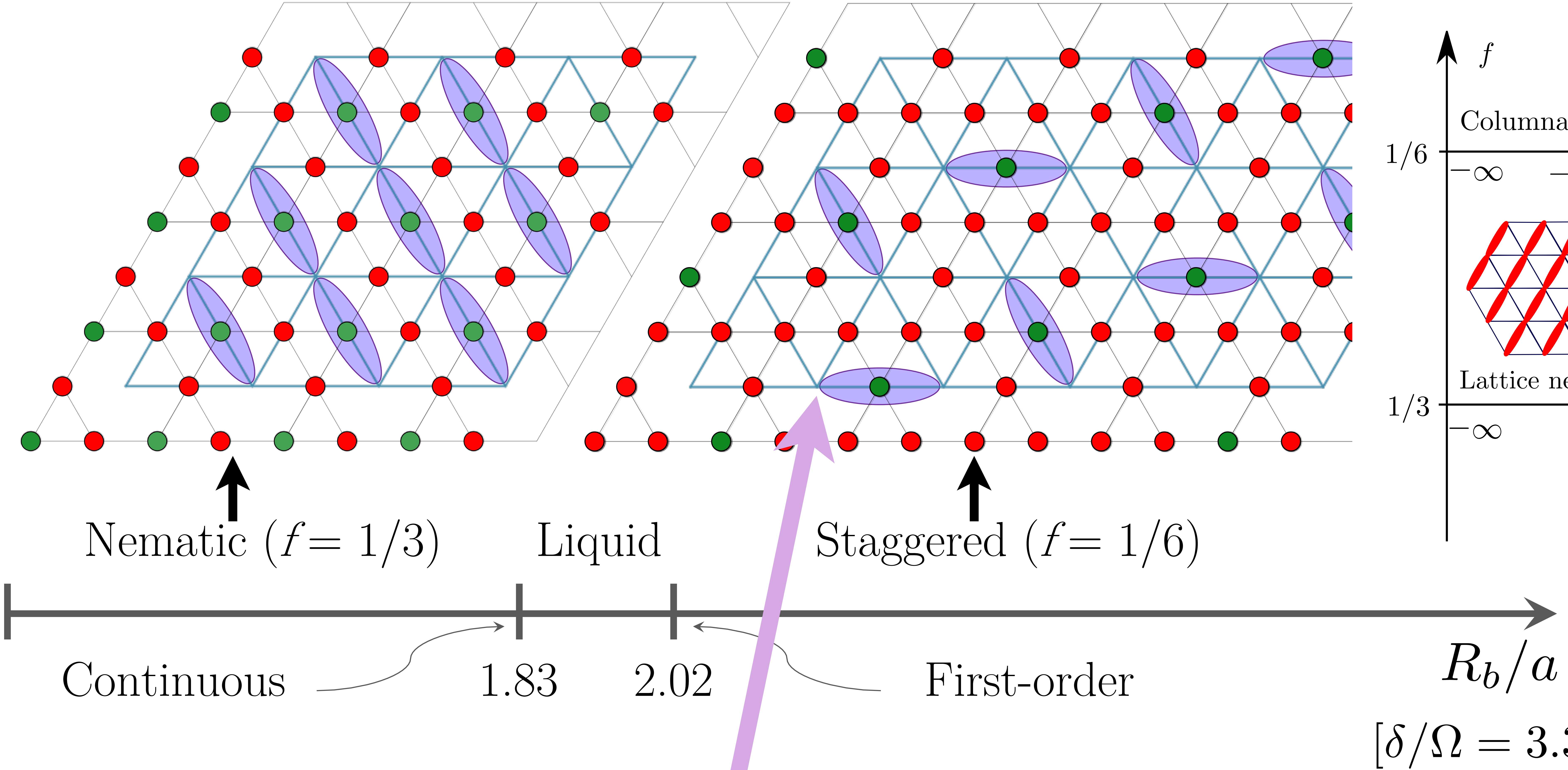

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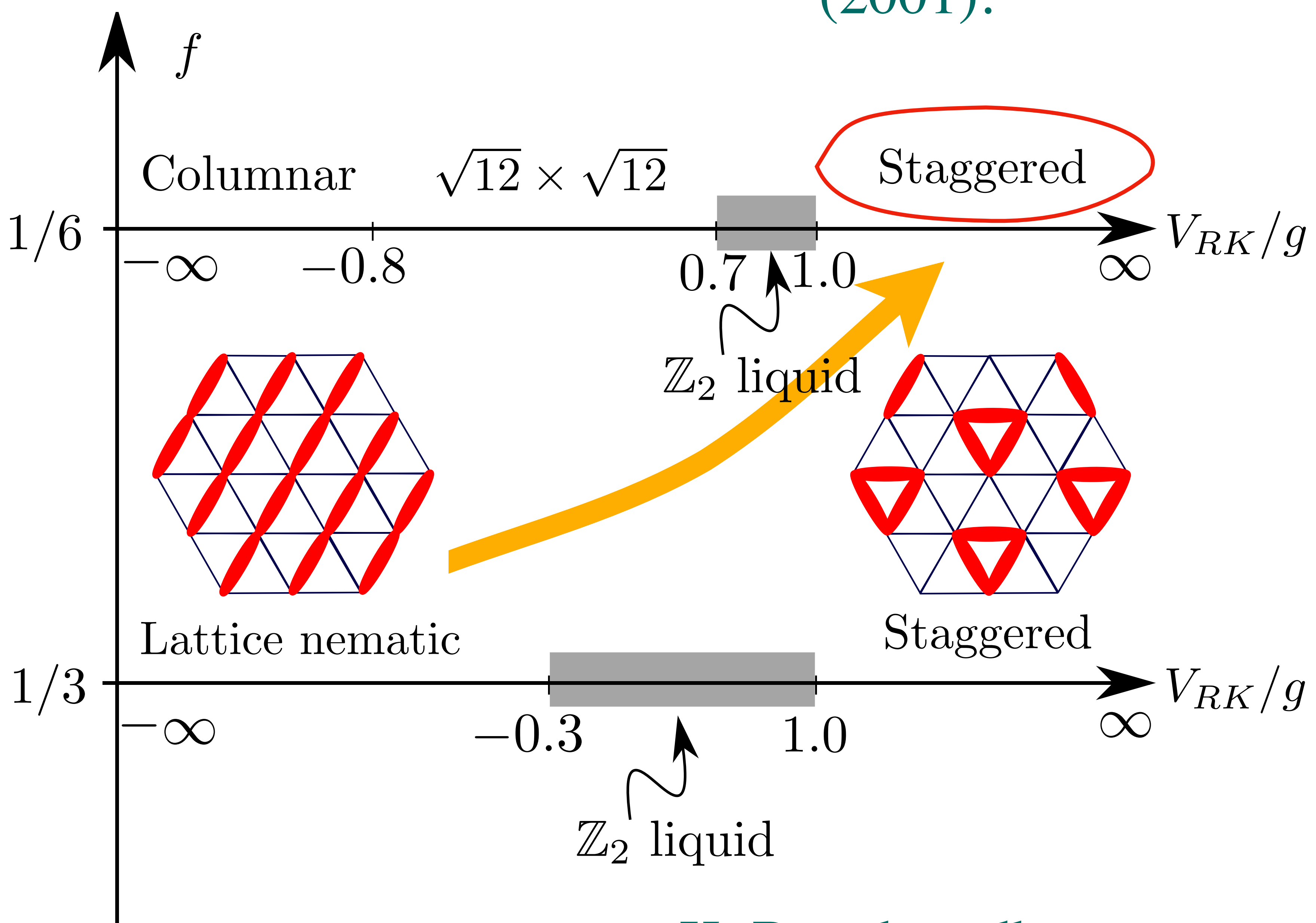

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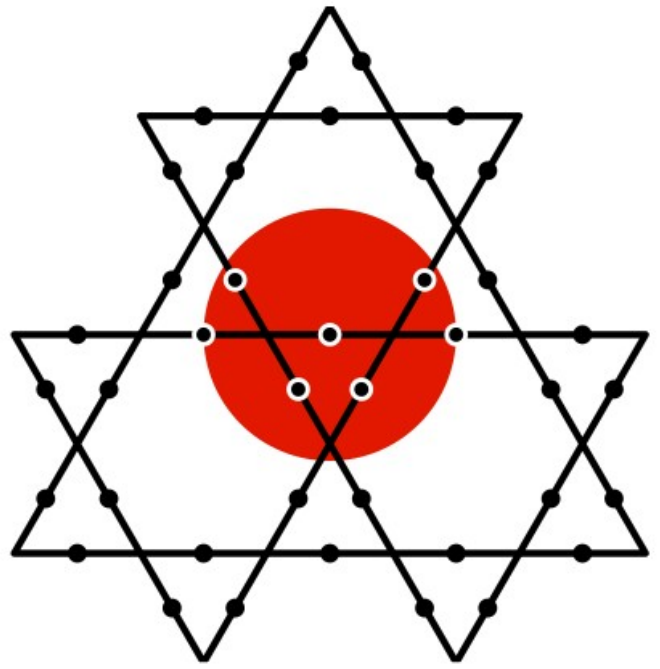

we put the model on an infinitely-long cylinder

→ use density matrix renormalization group (DMRG)

(White '92, Stoudenmire '13, Hauschild '18)

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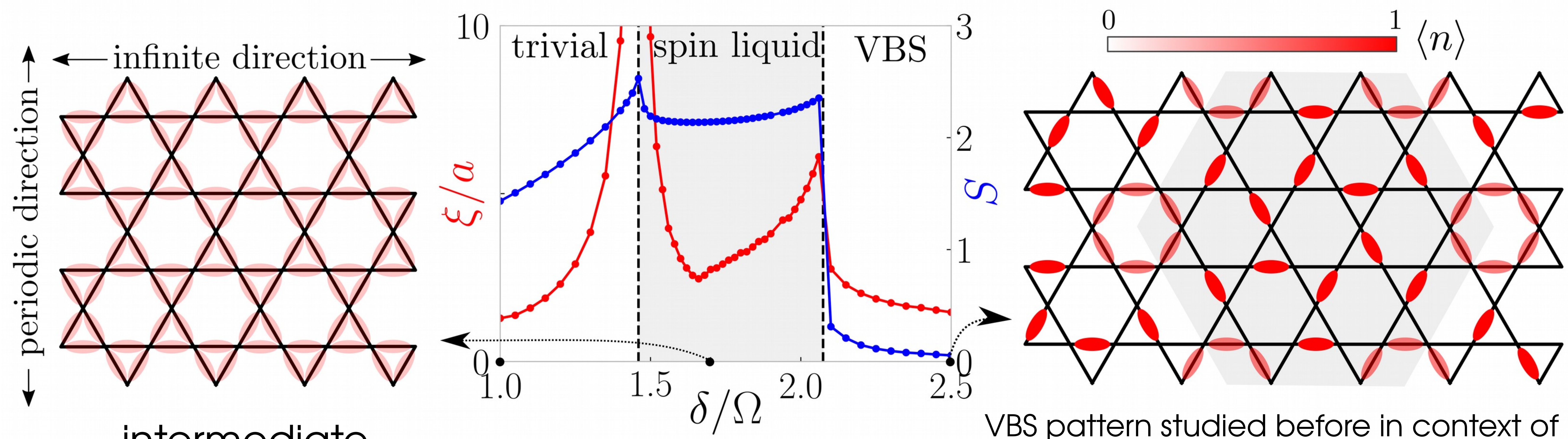

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VBS pattern studied before in context of Heisenberg model on kagome lattice (Nikolic and Senthil, Singh and Huse, ...)

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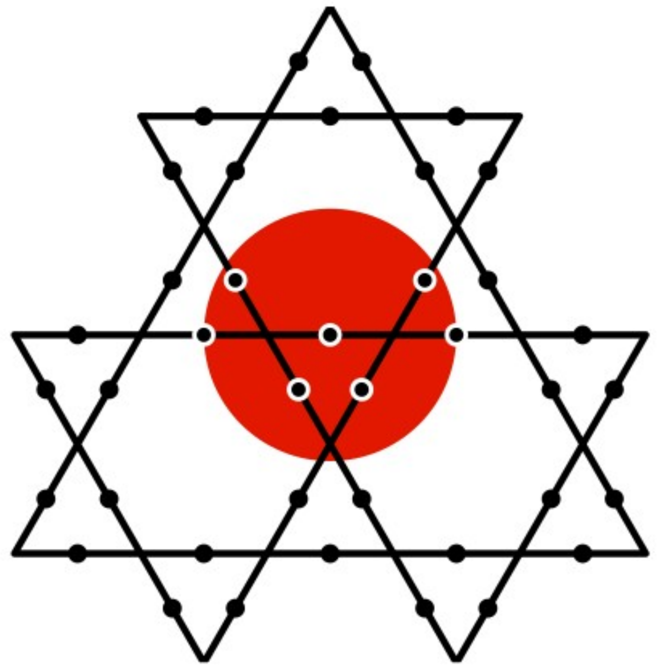

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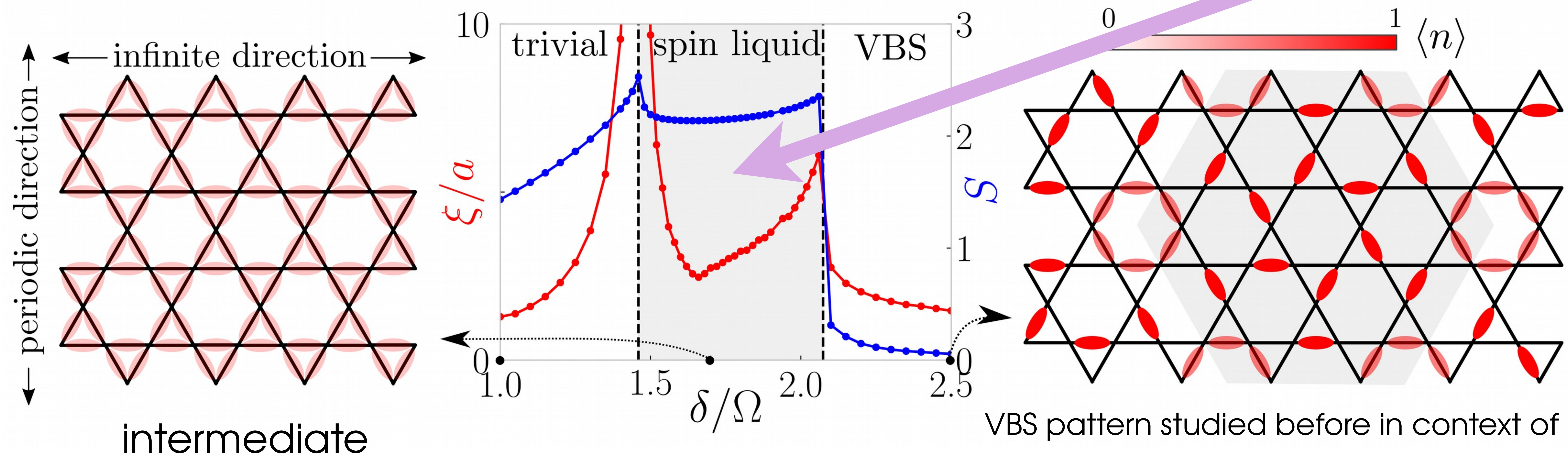

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G. Semeghini, H. Levine, A. Keesling, S. Ebadi, T. T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletic, M. D. Lukin, arXiv:2104.04119

Rydberg atoms
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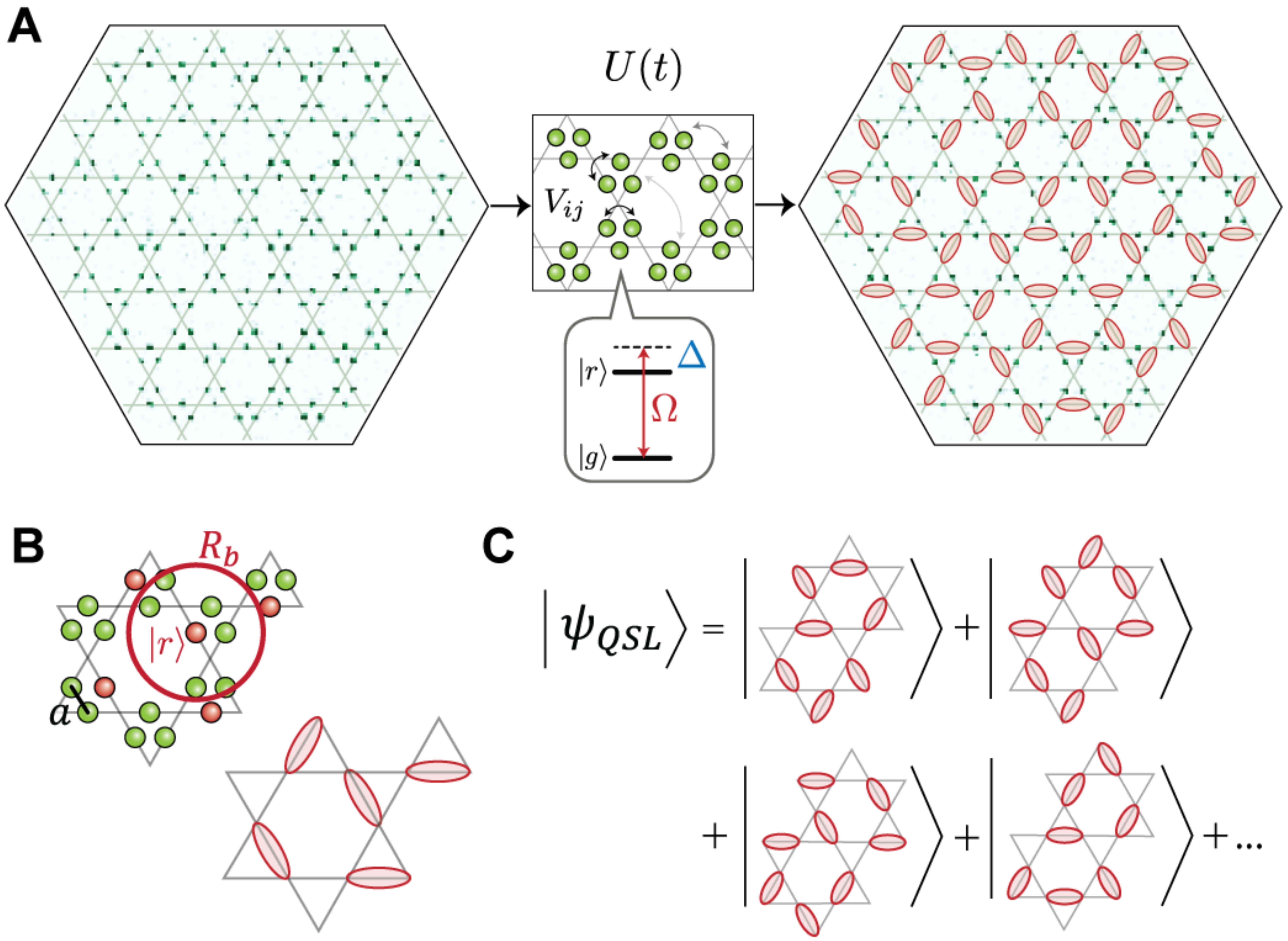

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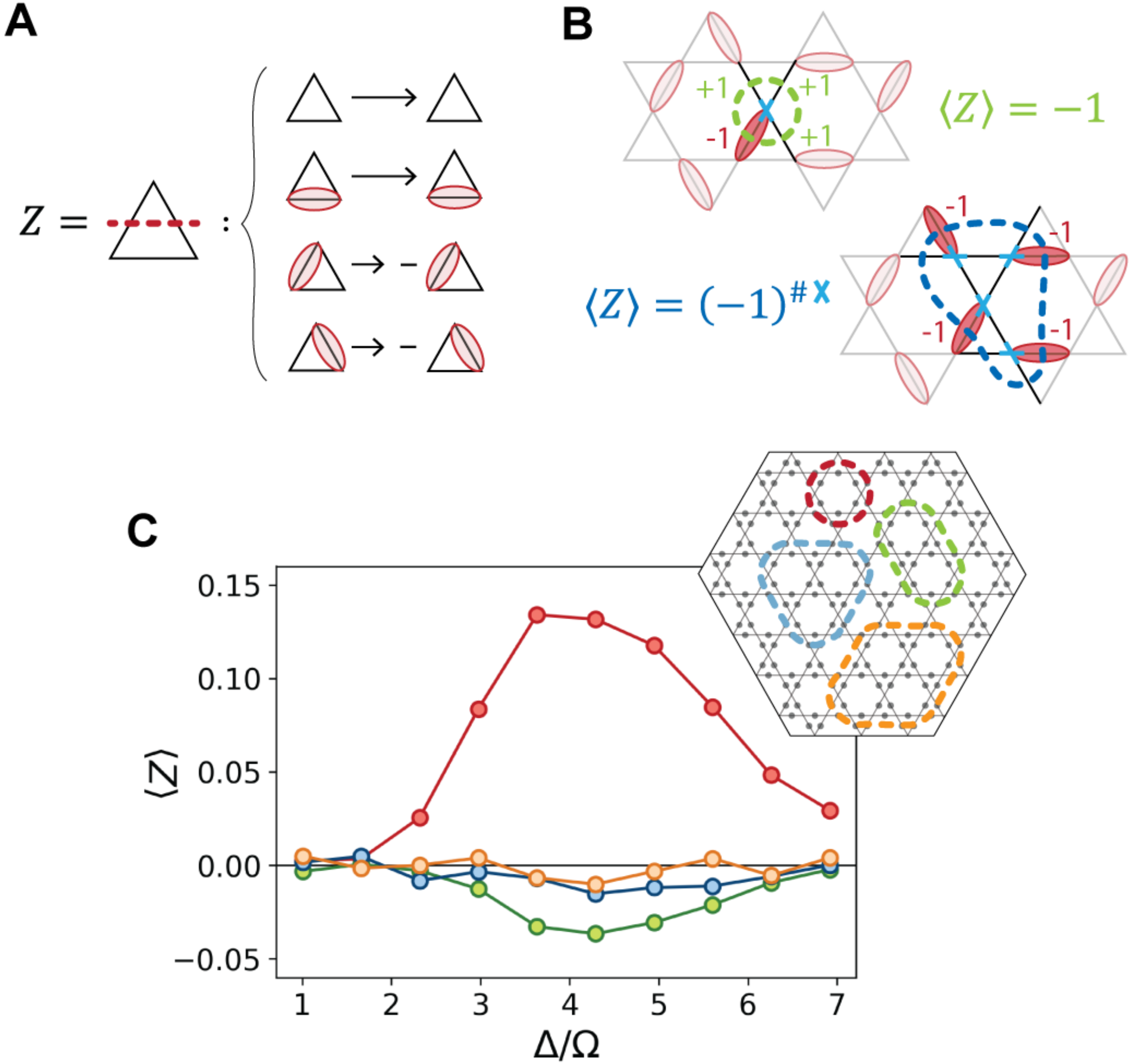
Measurement of the topological Z operator



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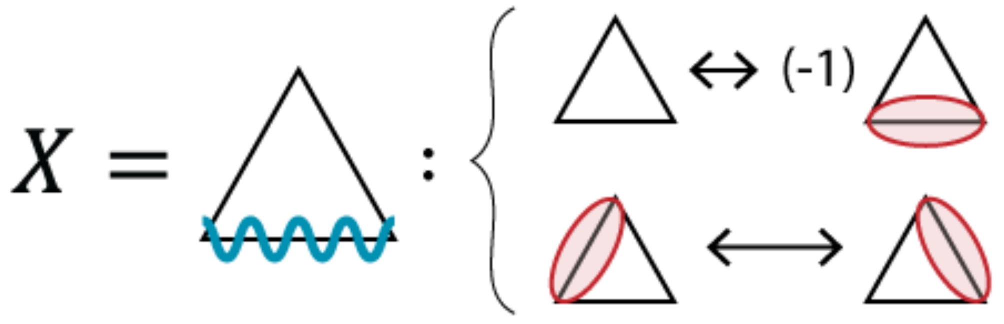
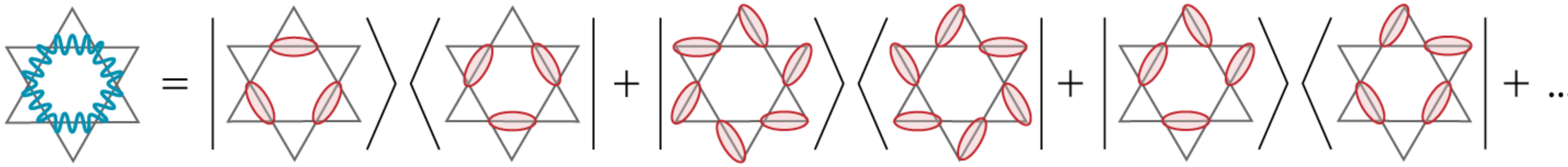
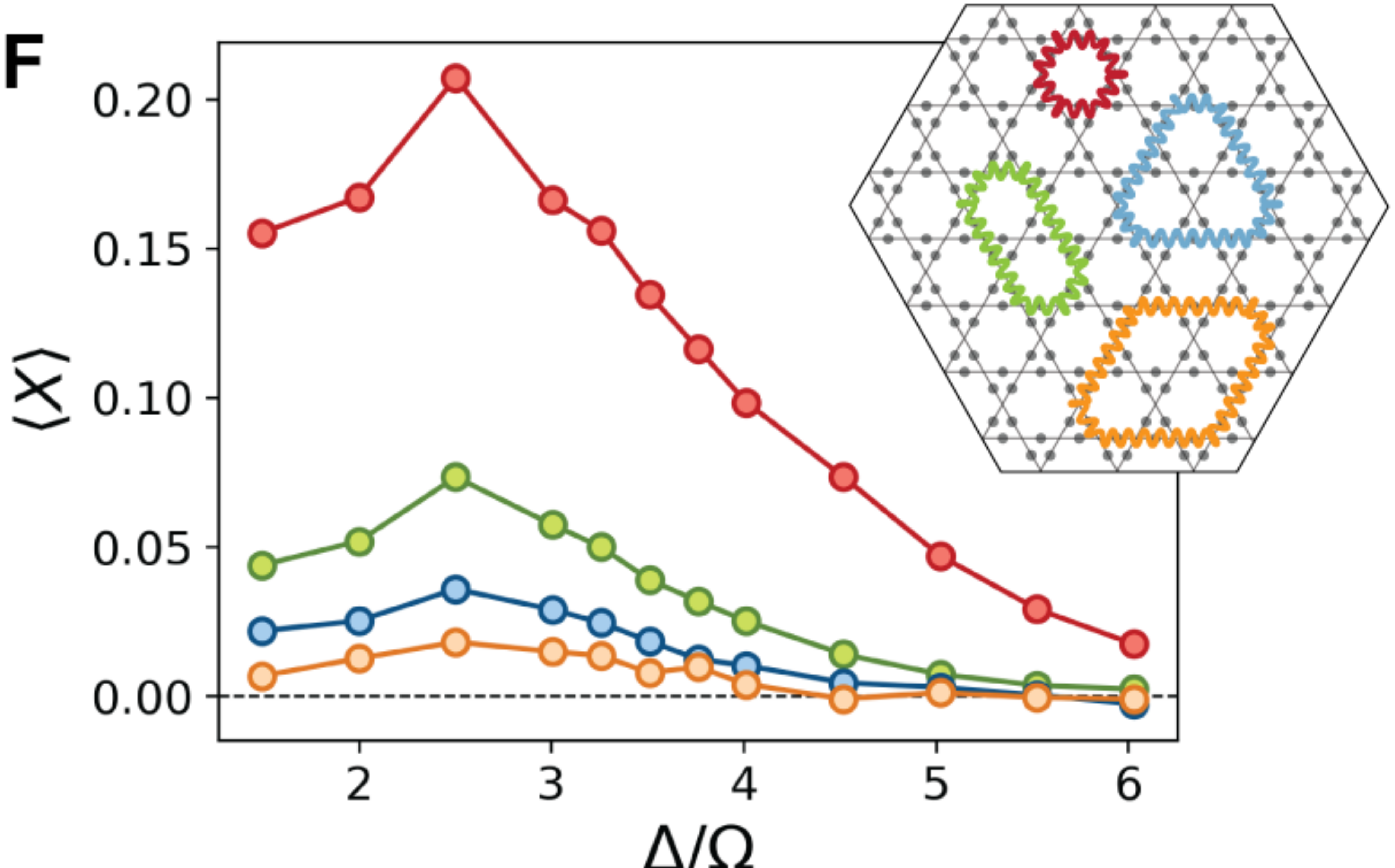




Can also define a topological X operator which resonates between different dimer configurations of the kagome dimer model.

$$XZ = (-1)^{\text{number of intersections}}\, ZX$$

N. Schuch, D. Poilblanc, J.I. Cirac,
D. Perez-Garcia, PRB **86**, 115108 (2012).
R. Verresen, M. D. Lukin,
A. Vishwanath, arXiv: 2011.12310



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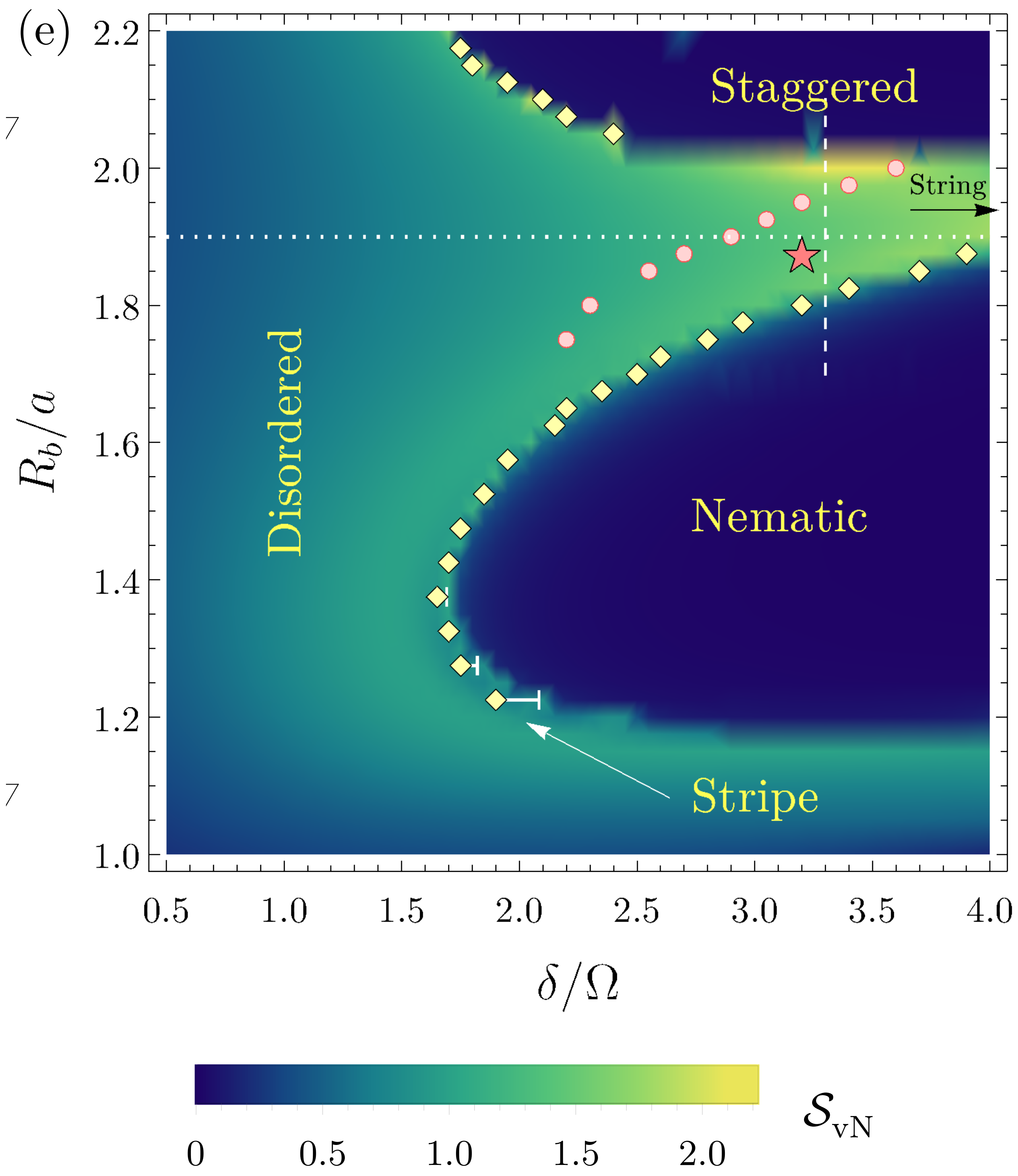

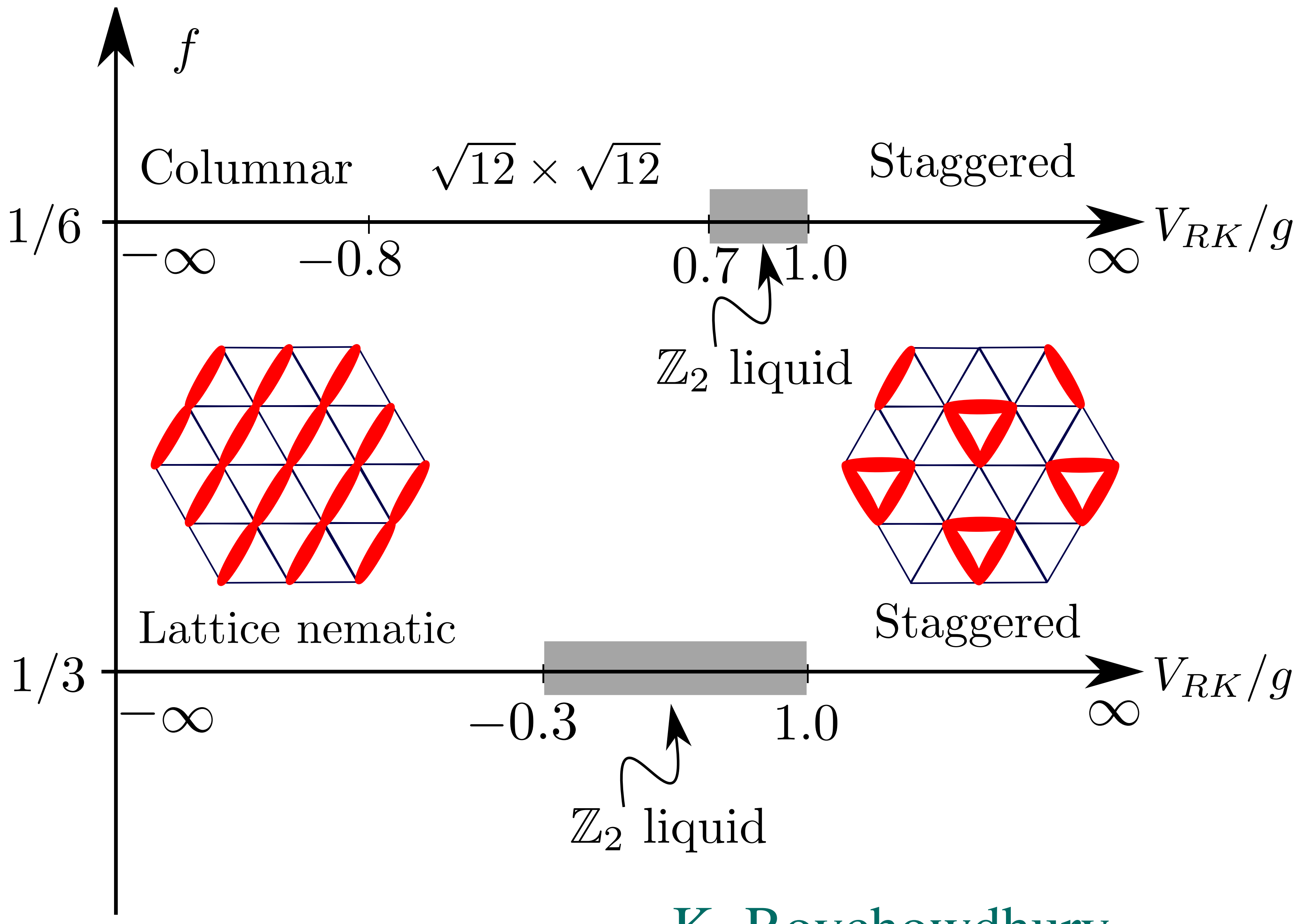

K. Roychowdhury, S. Bhattacharjee, F. Pollmann, *Phys. Rev. B* **92**, 075141 (2015).

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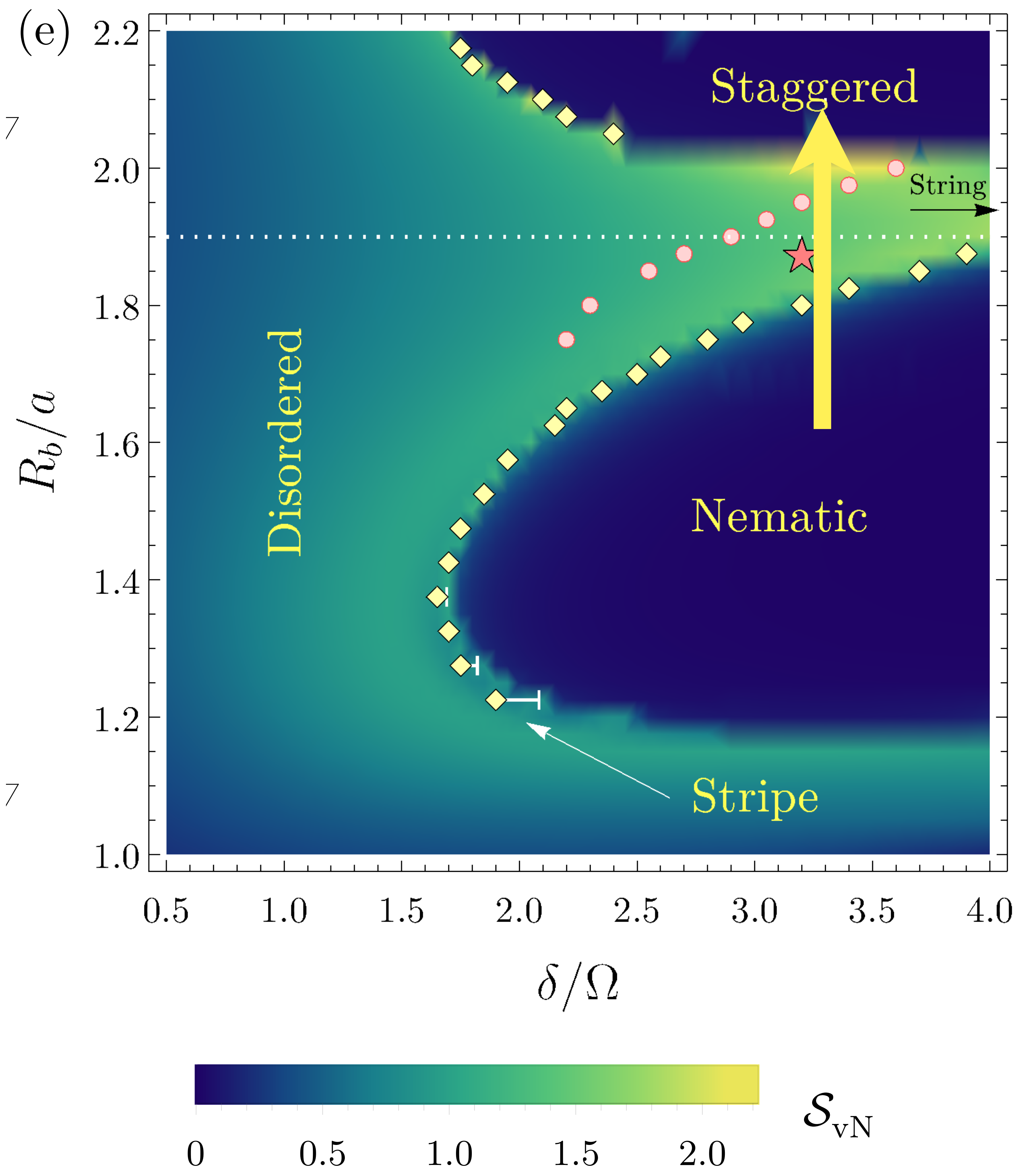

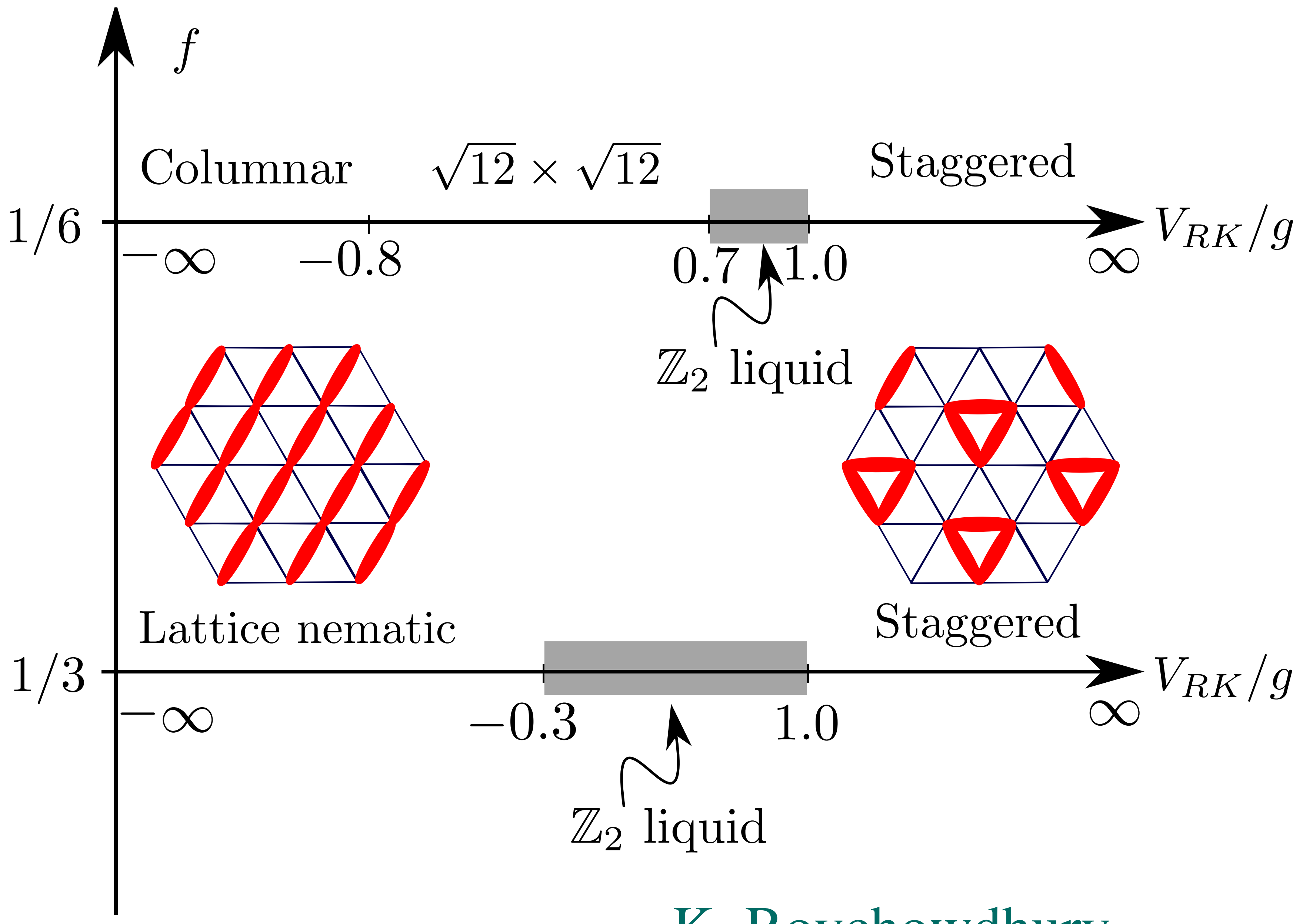

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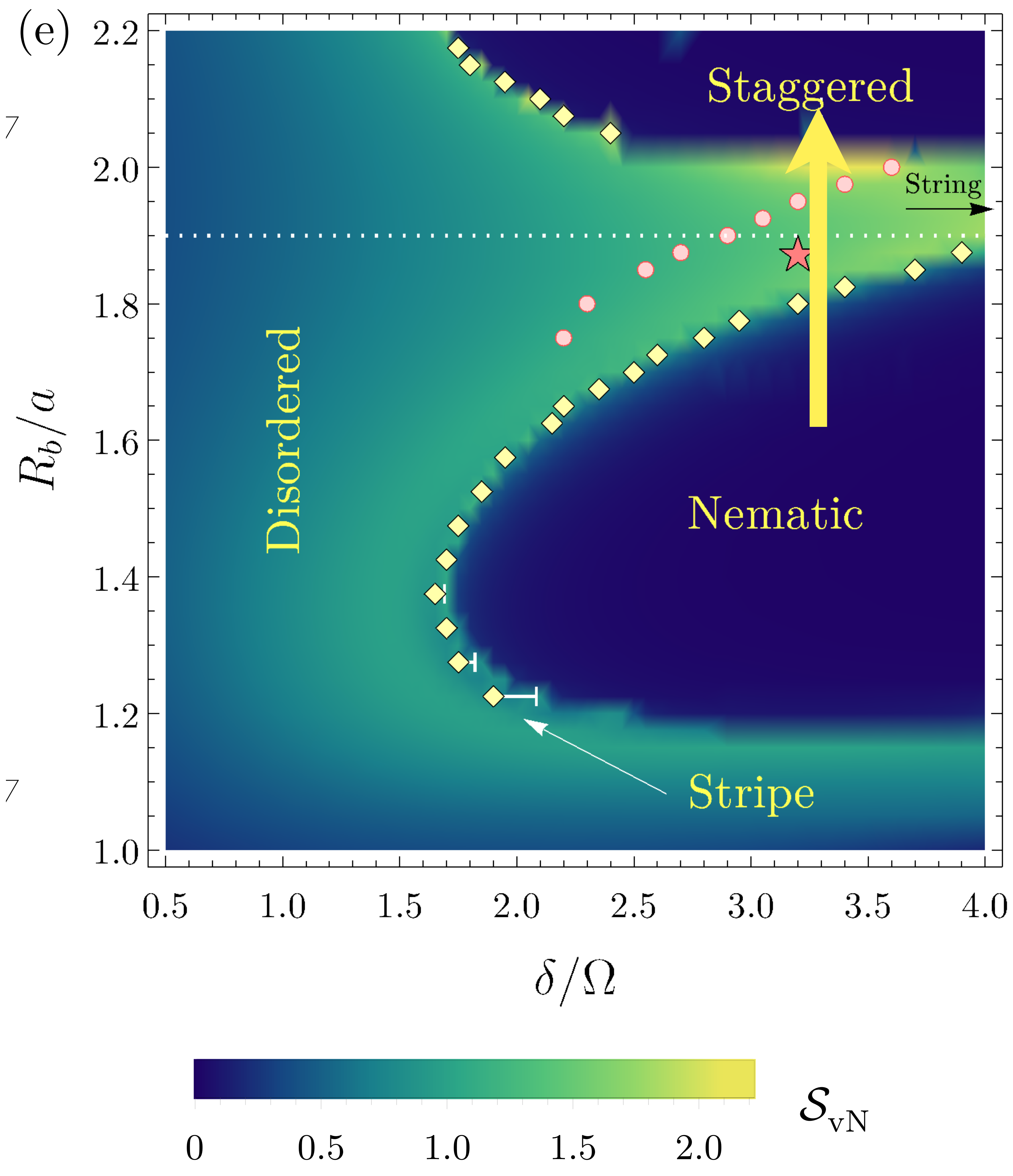

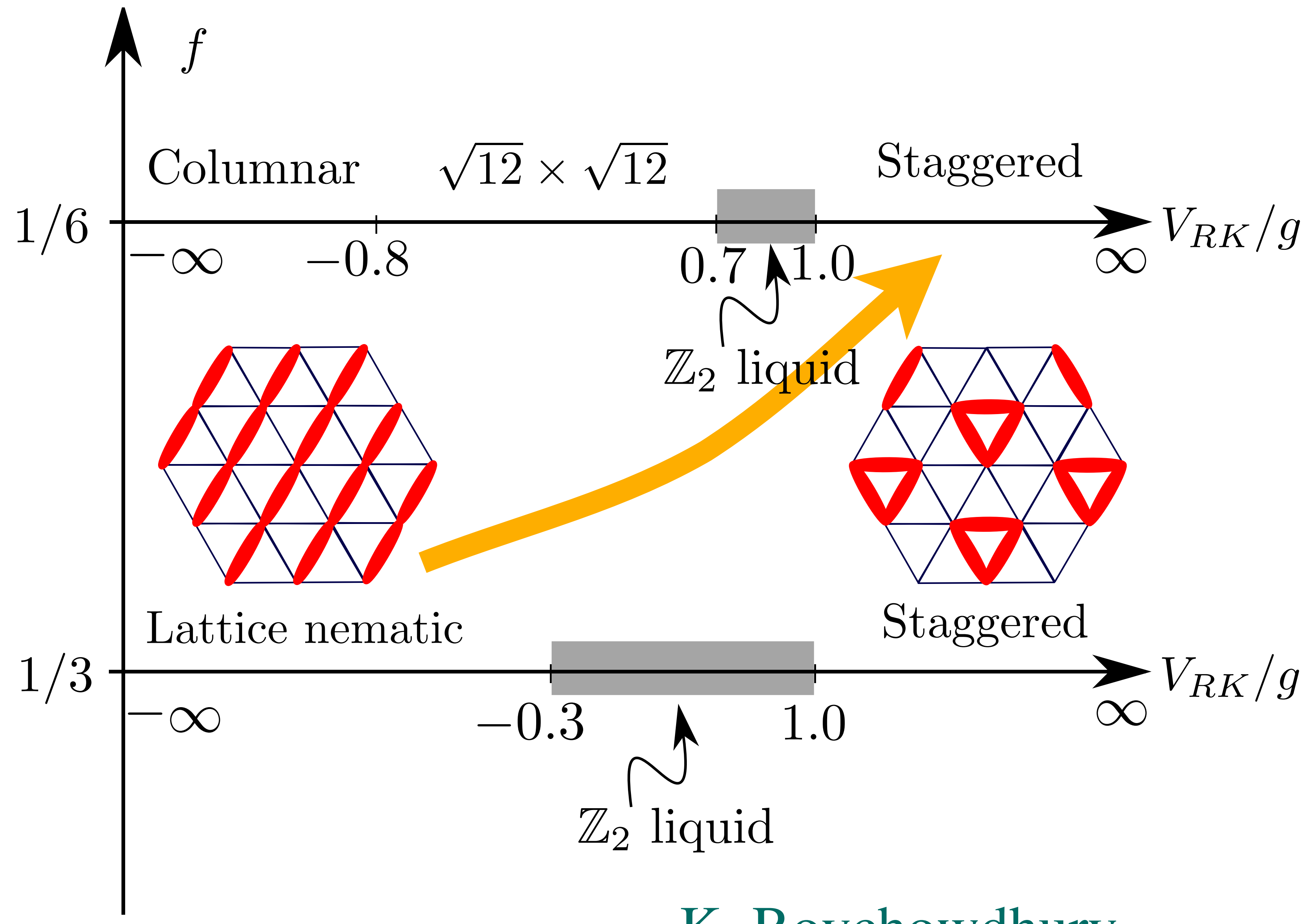

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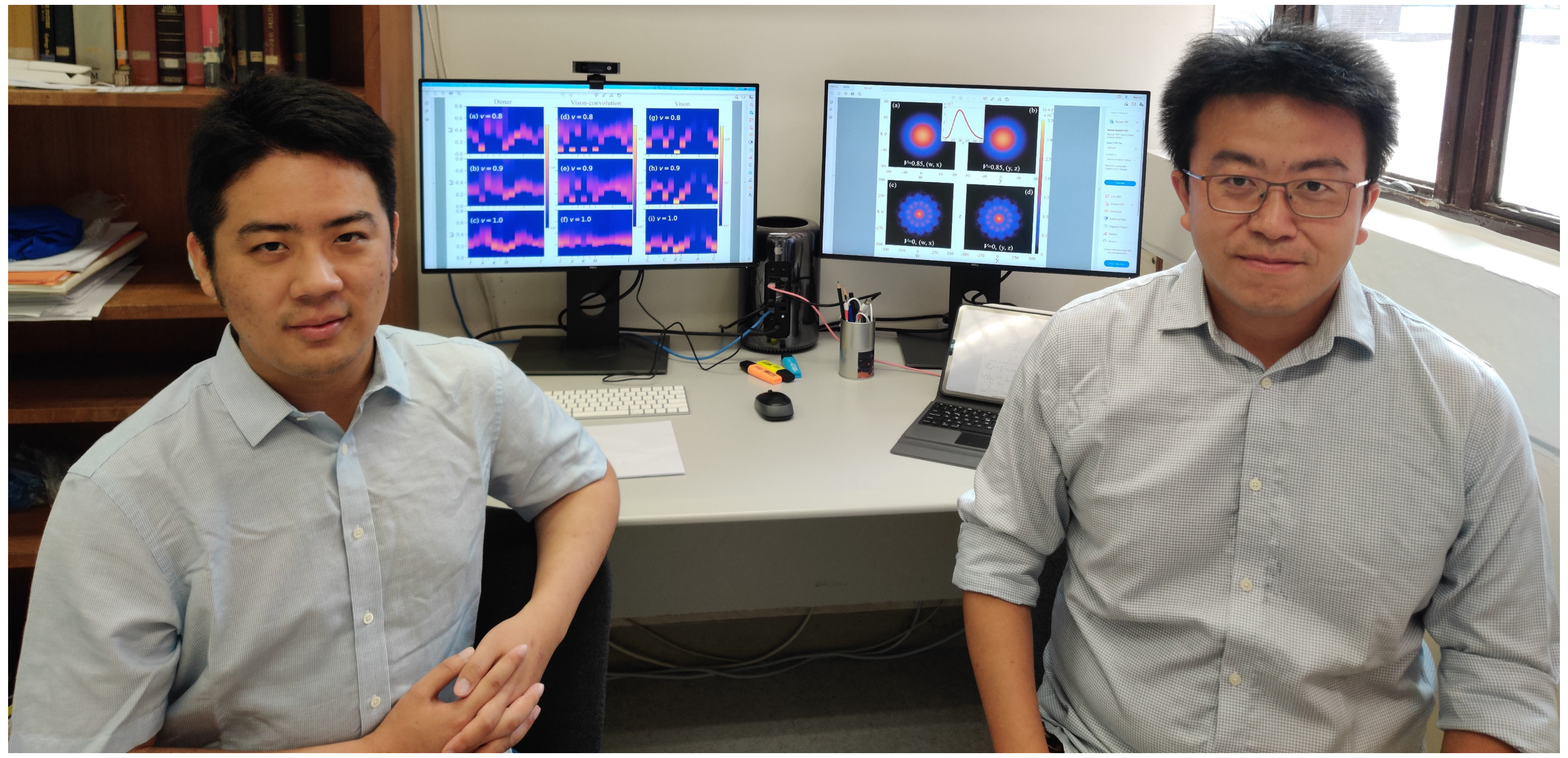
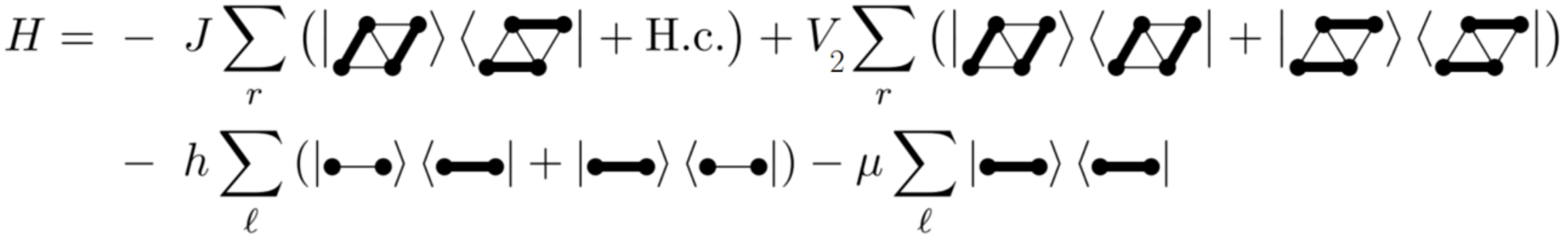
Work in progress:
Zheng Yan
Zi Yang Meng
Rhine Samajdar





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Work in progress:
Zheng Yan
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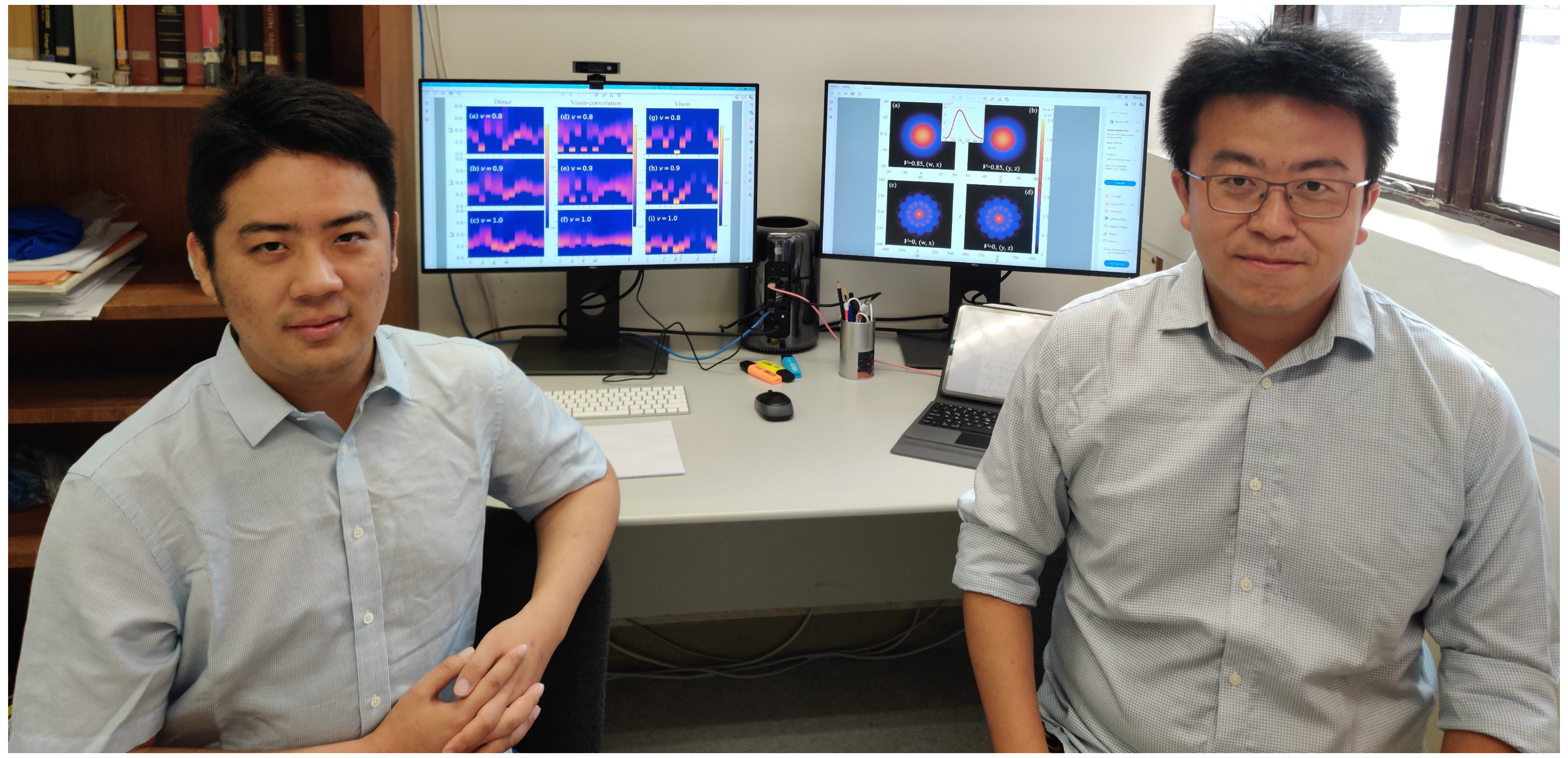
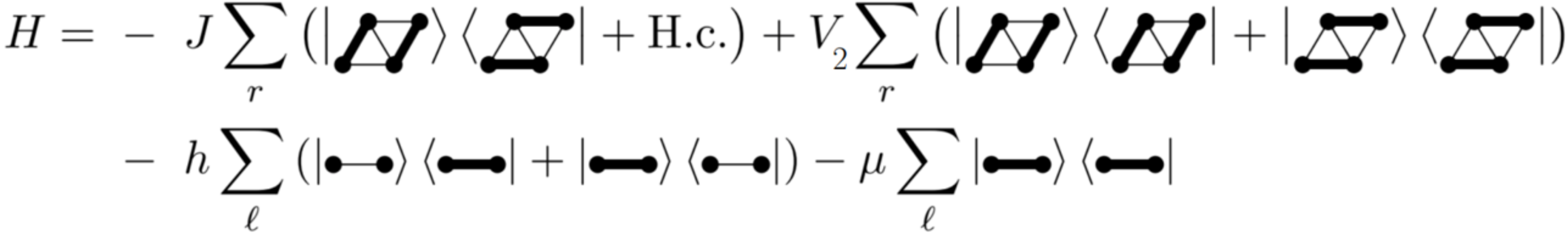
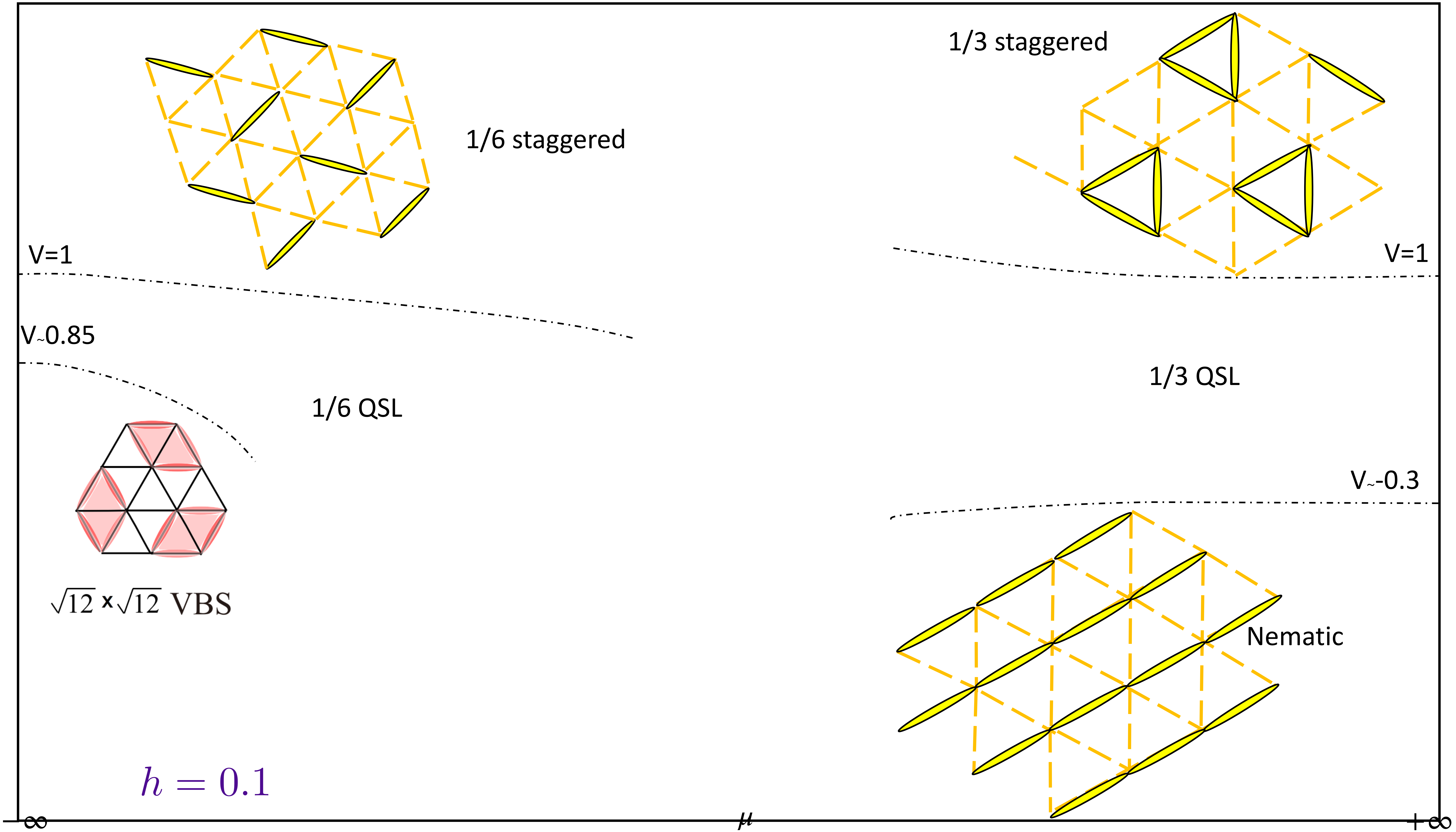


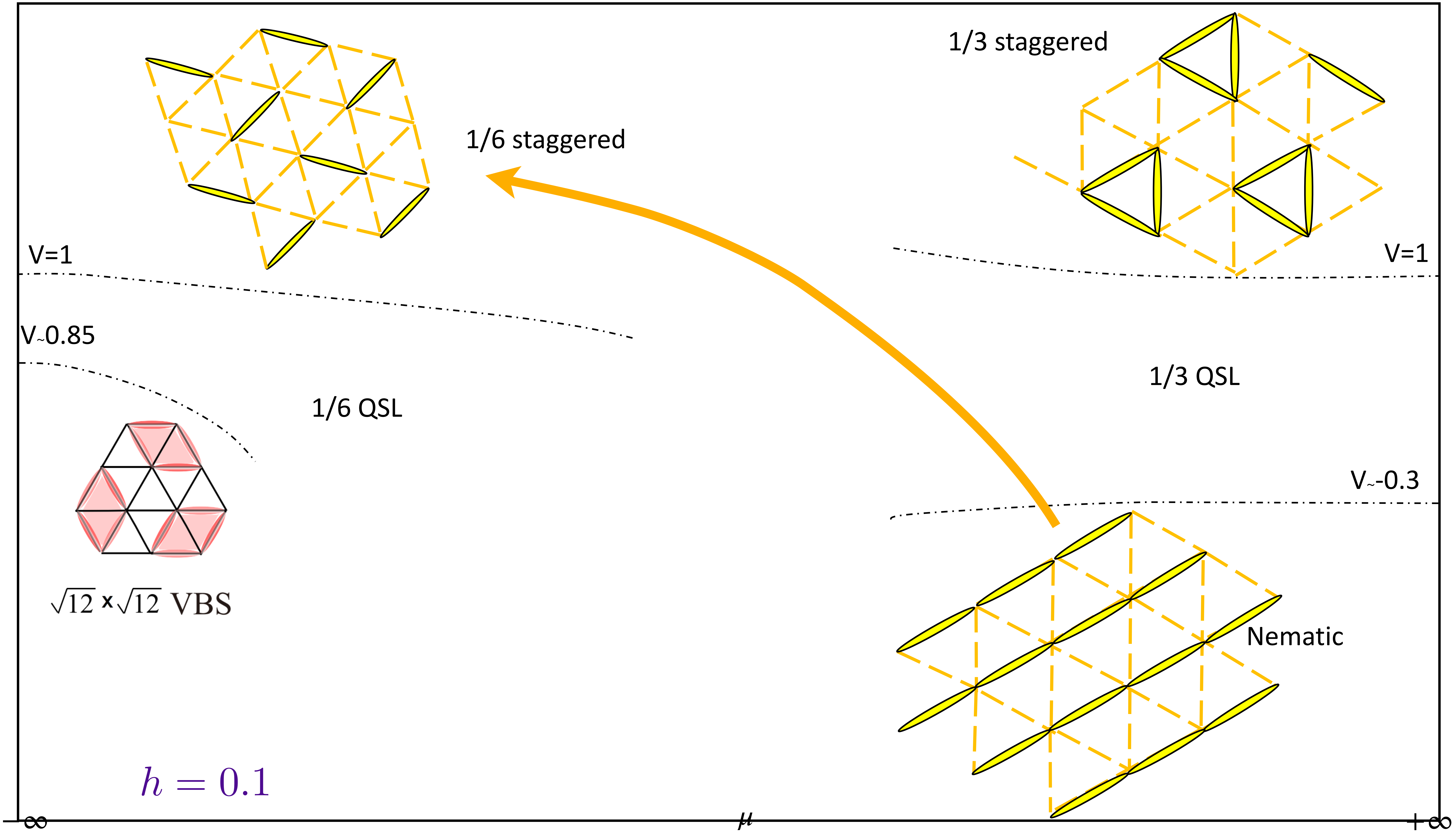
Related to Ising gauge theory (σ_{ij}) with matter fields (τ_i):

$$H = -K \prod_{\square} \sigma^z_{ij} - g \sum_{\langle ij \rangle} \sigma^x_{ij} - J \sum_{\langle ij \rangle} \tau^z_i \sigma^z_{ij} \tau^z_j - h \sum_i \tau^x_i$$





1/6 staggered
1/3 staggered
V=1
V=1
V~0.85
1/6 QSL
1/3 QSL
V~-0.3
$\sqrt{12}$ x $\sqrt{12}$ VBS
Nematic
$h = 0.1$
$-\infty$
μ
$+\infty$



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1. Rydberg chains

   The Z_3 chiral clock transition

2. Square lattice

   Quantum Ising criticality in 2+1 dimensions

3. Kagome symmetry lattices

   Probing topological spin liquids