Spin liquids on the triangular lattice

ICFCM, Sendai, Japan, Jan 11-14, 2011

Talk online: sachdev.physics.harvard.edu

PHYSICS

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Outline

1. Classification of spin liquids

   Quantum-disordering magnetic order vs. projected Fermi sea

2. Quantum-disordering magnetic order

   Application to κ*-*$(ET)_2Cu_2(CN)_3$

3. Fermi surfaces of spinful Majorana fermions

   Candidate for $EtMe_3Sb[Pd(dmit)_2]_2$ *?*

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   Candidate for EtMe$_3$Sb[Pd(dmit)$_2$]$_2$?

Fractionalization of the electron spin and charge

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A) Quantum "disordering" magnetic order

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = \begin{pmatrix} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{pmatrix} \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

Fractionalization of the electron spin and charge

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neutral bosonic spinons which transform to a rotating reference from along the local antiferromagnetic order

Fractionalization of the electron spin and charge

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spinless charge -*e* fermions

Fractionalization of the electron spin and charge

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$\mathrm{SU(2)}_{\mathrm{spin}}$

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$\mathrm{U(1)_{charge}}$

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$U \times U^{-1}$

Theory has $\mathrm{SU(2)_s}$ gauge invariance

S. Sachdev, M. A. Metlitski, Y. Qi, and S. Sachdev *Phys. Rev. B* **80**, 155129 (2009)

Fractionalization of the electron spin and charge

B) Projected Fermi sea

X.-G. Wen, P.A. Lee,
O. Motrunich, M. P.A. Fisher

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow^\dagger \end{pmatrix} = \begin{pmatrix} b_1^* & b_2^* \\ -b_2 & b_1 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2^\dagger \end{pmatrix}$$

Fractionalization of the electron spin and charge

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charge e spinless bosons (or "rotors") whose fluctuations project onto the single electron states on each site

Fractionalization of the electron spin and charge

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neutral fermionic spinons

Fractionalization of the electron spin and charge

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$\mathrm{SU}(2)_{\mathrm{pseudospin}} \supset \mathrm{U}(1)_{\mathrm{charge}}$

Fractionalization of the electron spin and charge

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On the triangular lattice, this leads to a
U(1) spin liquid with a Fermi surface of spinons
which has been proposed to apply to $EtMe_3Sb[Pd(dmit)_2]_2$.

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On the triangular lattice, this leads to a
U(1) spin liquid with a Fermi surface of spinons
which has been proposed to apply to $\mathrm{EtMe_3Sb[Pd(dmit)_2]_2}$.

This spin liquid has a thermal Hall response
which is not observed.

Complete fractionalization: separate excitations carrying spin, charge, and Fermi statistics

Cenke Xu and S. Sachdev, *Phys. Rev. Lett.* **105**, 057201 (2010)

Complete fractionalization: separate excitations carrying spin, charge, and Fermi statistics

Decompose electron operator into real fermions, χ:

$$c_\uparrow = \chi_1 + i\chi_2 \quad ; \quad c_\downarrow = \chi_3 + i\chi_4$$

Introduce a 4-component Majorana fermion ζ_i, $i = 1 \ldots 4$ and a SO(4) matrix $\mathcal{R}$, and decompose:

$$\chi = \quad \mathcal{R} \quad \zeta$$

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$$\mathrm{SO}(4) \cong \mathrm{SU}(2)_{\mathrm{pseudospin}} \times \mathrm{SU}(2)_{\mathrm{spin}}$$

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$O \times O^T$

$\mathrm{SO}(4)_{\mathrm{gauge}} \cong \mathrm{SU}(2)_{\mathrm{p;gauge}} \times \mathrm{SU}(2)_{\mathrm{s;gauge}}$

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By breaking $SO(4)_{\text{gauge}}$ with different Higgs fields, we can reproduce essentially all earlier theories of spin liquids. We also find many new spin liquid phases, some with Majorana fermion excitations which carry neither spin nor charge

Cenke Xu and S. Sachdev, *Phys. Rev. Lett.* **105**, 057201 (2010)

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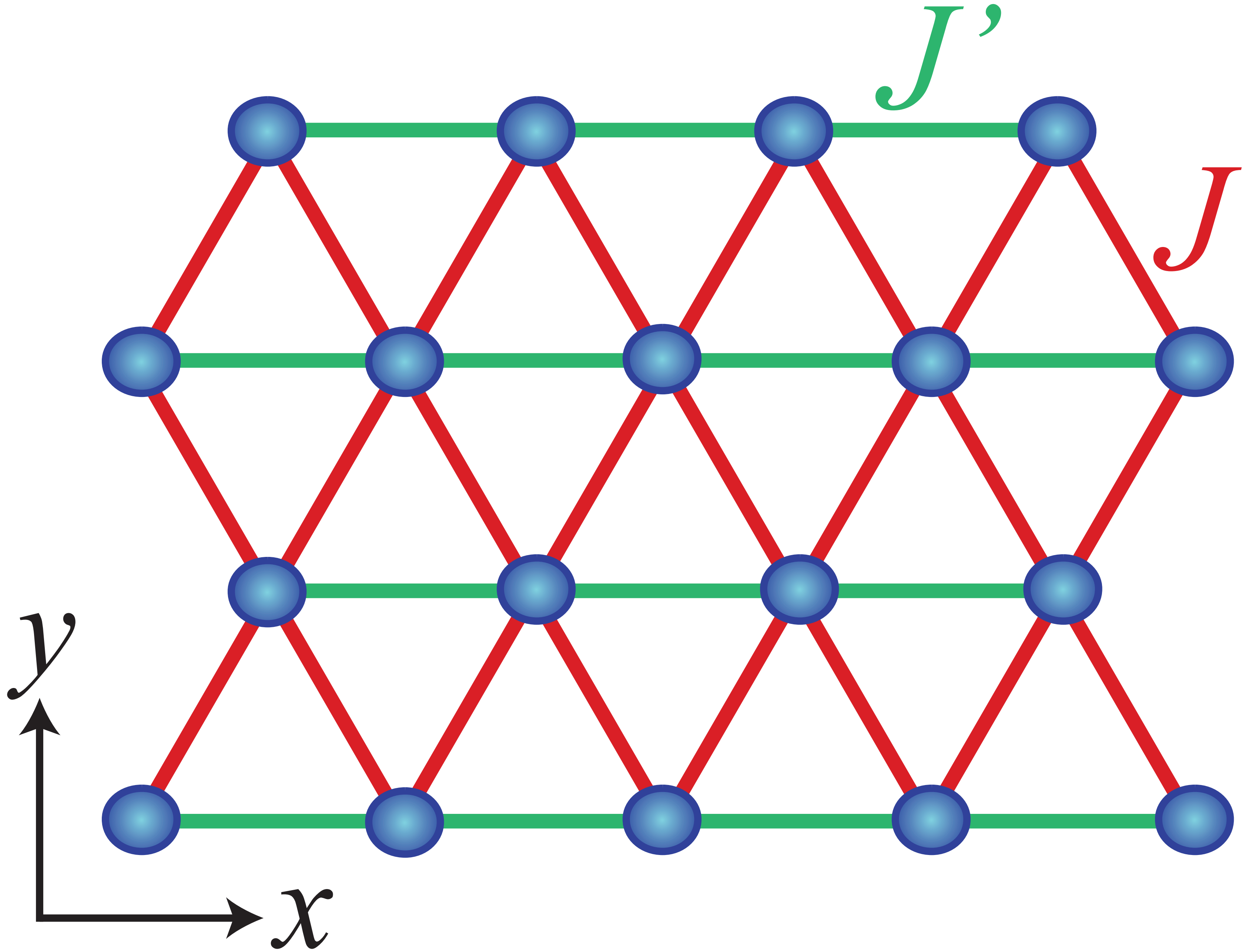
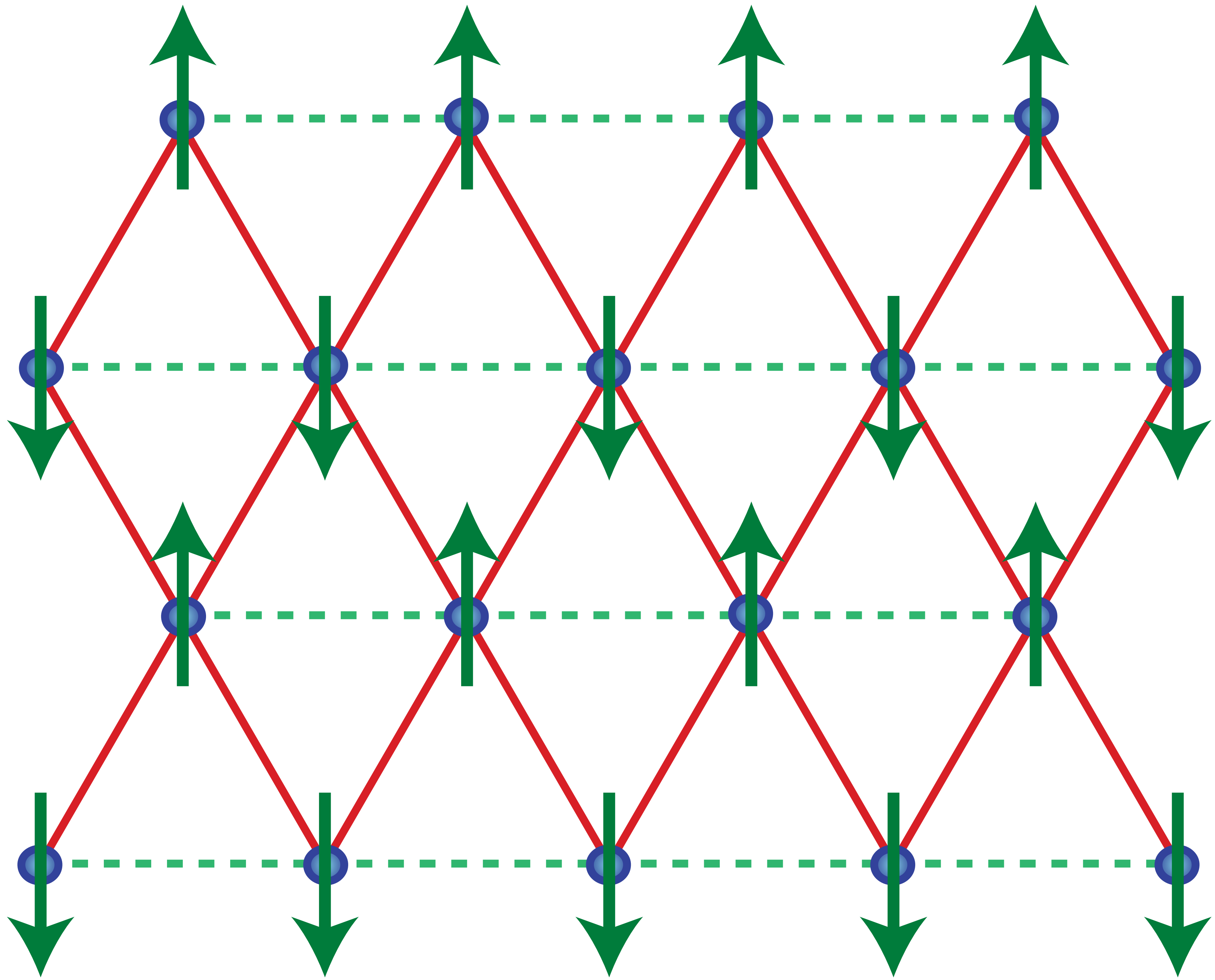
$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j + \ldots$$

$\vec{S}_i \Rightarrow$ spin operator with $S = 1/2$



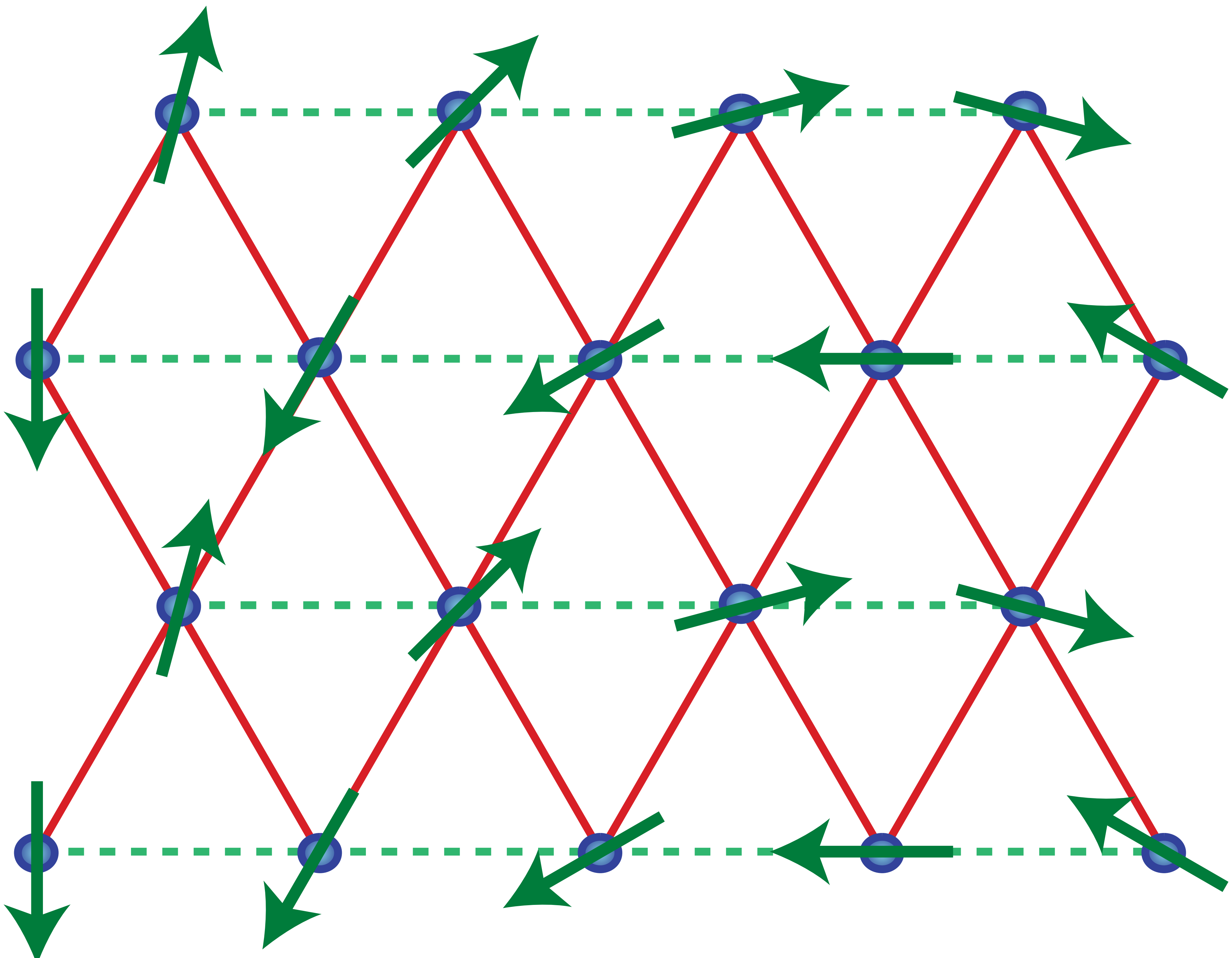
Anisotropic triangular lattice antiferromagnet



Classical ground state for small J'/J

Found in κ-$(ET)_2Cu[N(CN)_2]Cl$

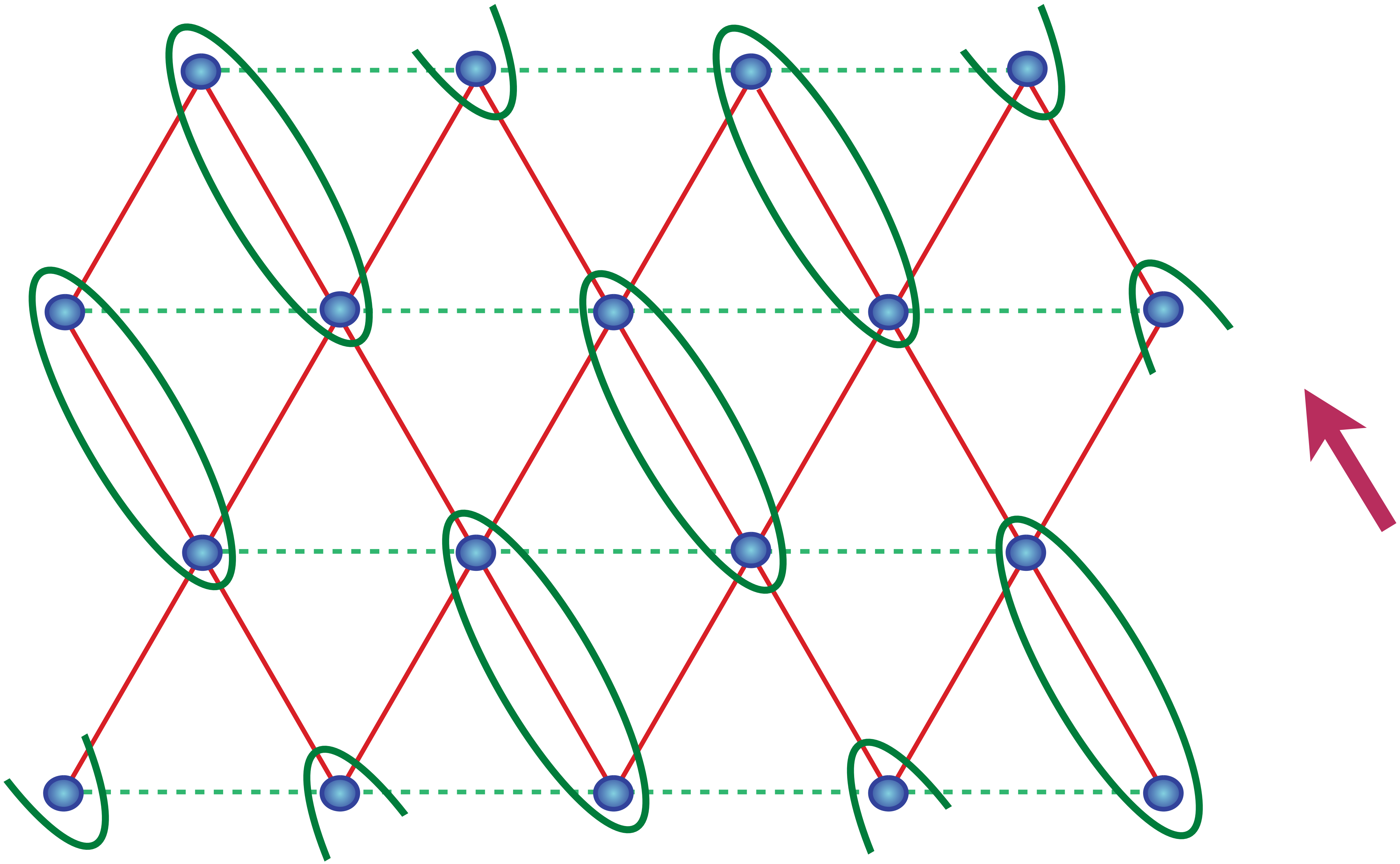
Anisotropic triangular lattice antiferromagnet



Classical ground state for large J'/J

Found in Cs_2CuCl_4

Anisotropic triangular lattice antiferromagnet



Valence bond solid

N. Read and S. Sachdev, *Phys. Rev. Lett*. **62**, 1694 (1989)

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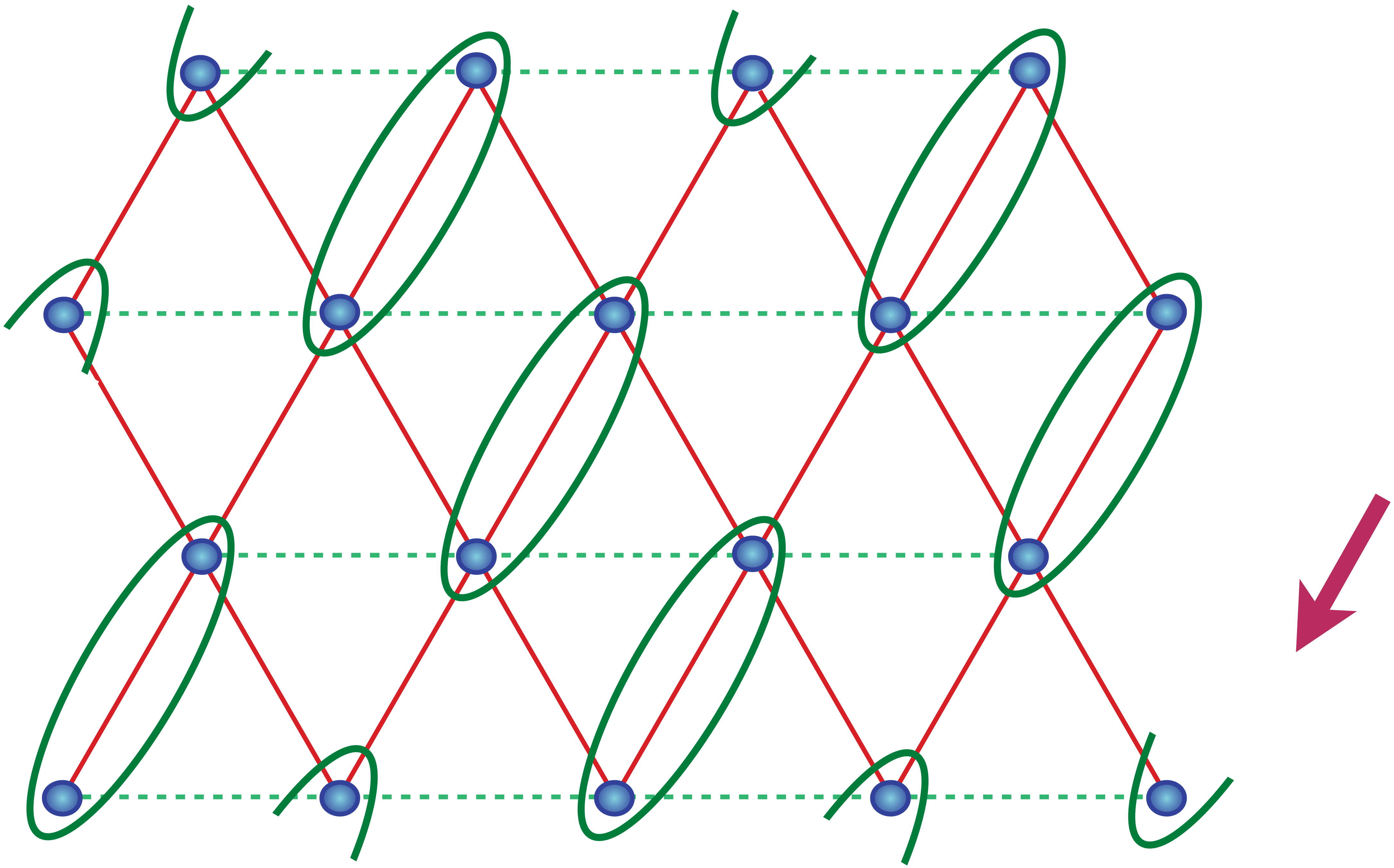

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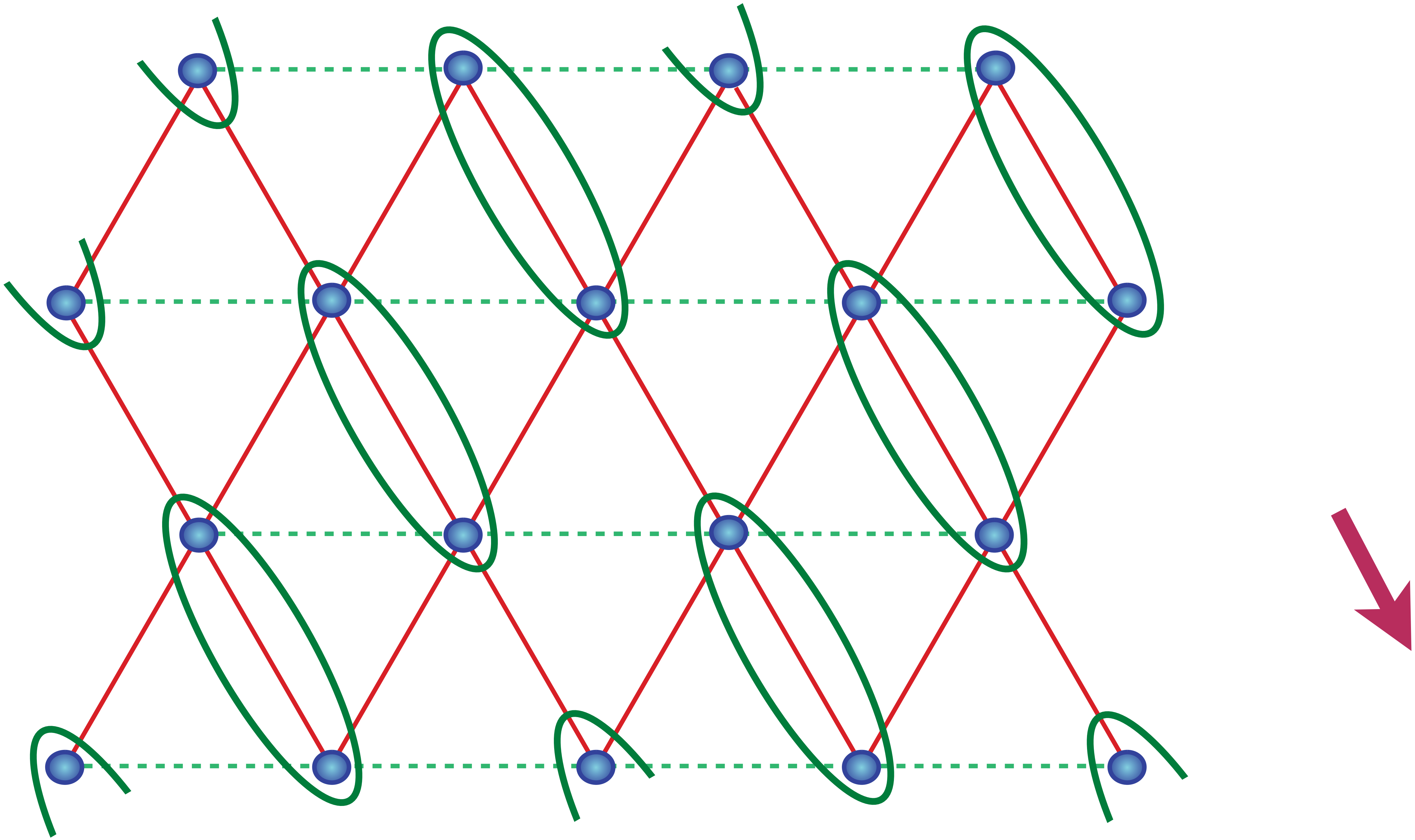

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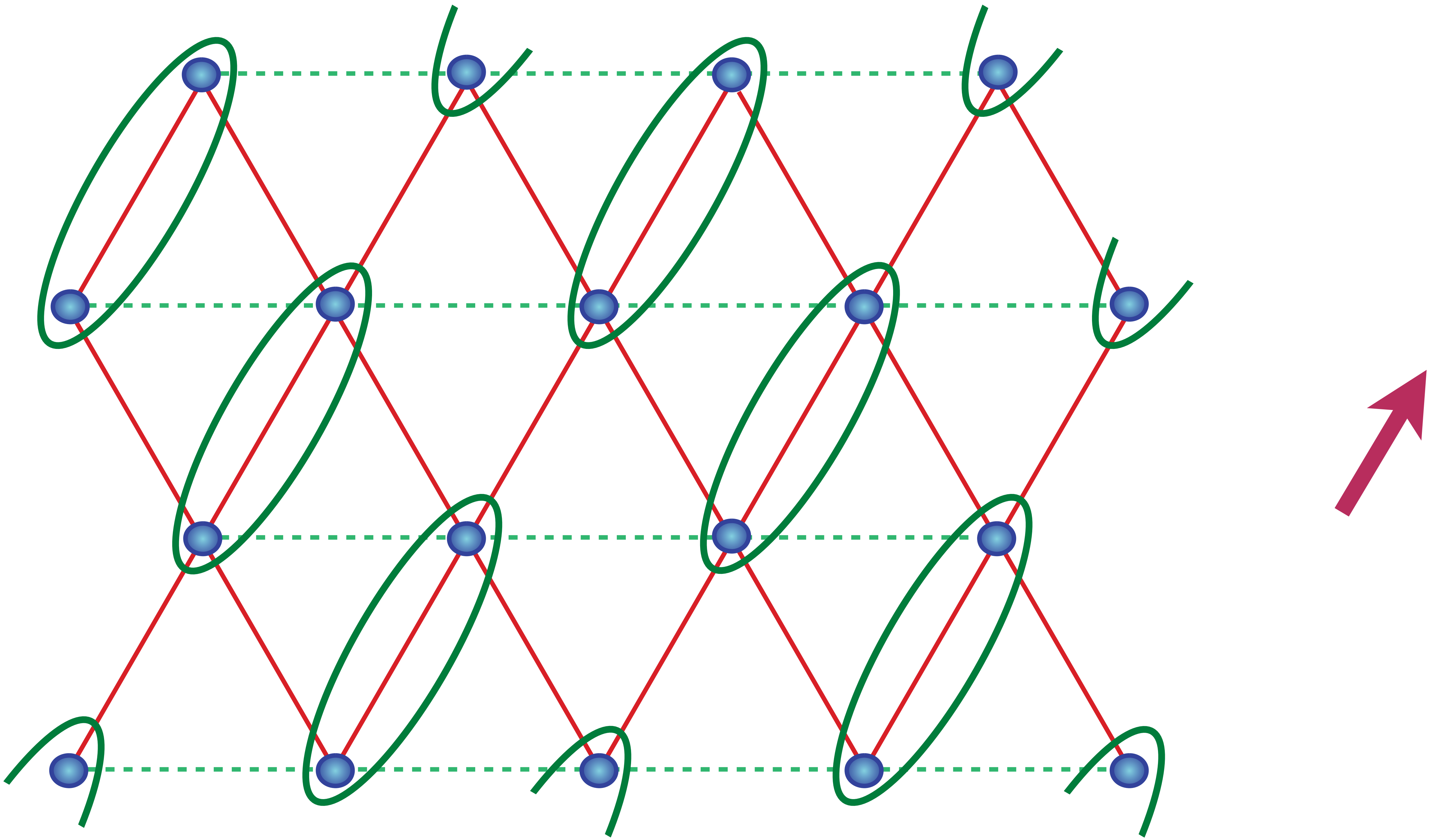

Valence bond solid

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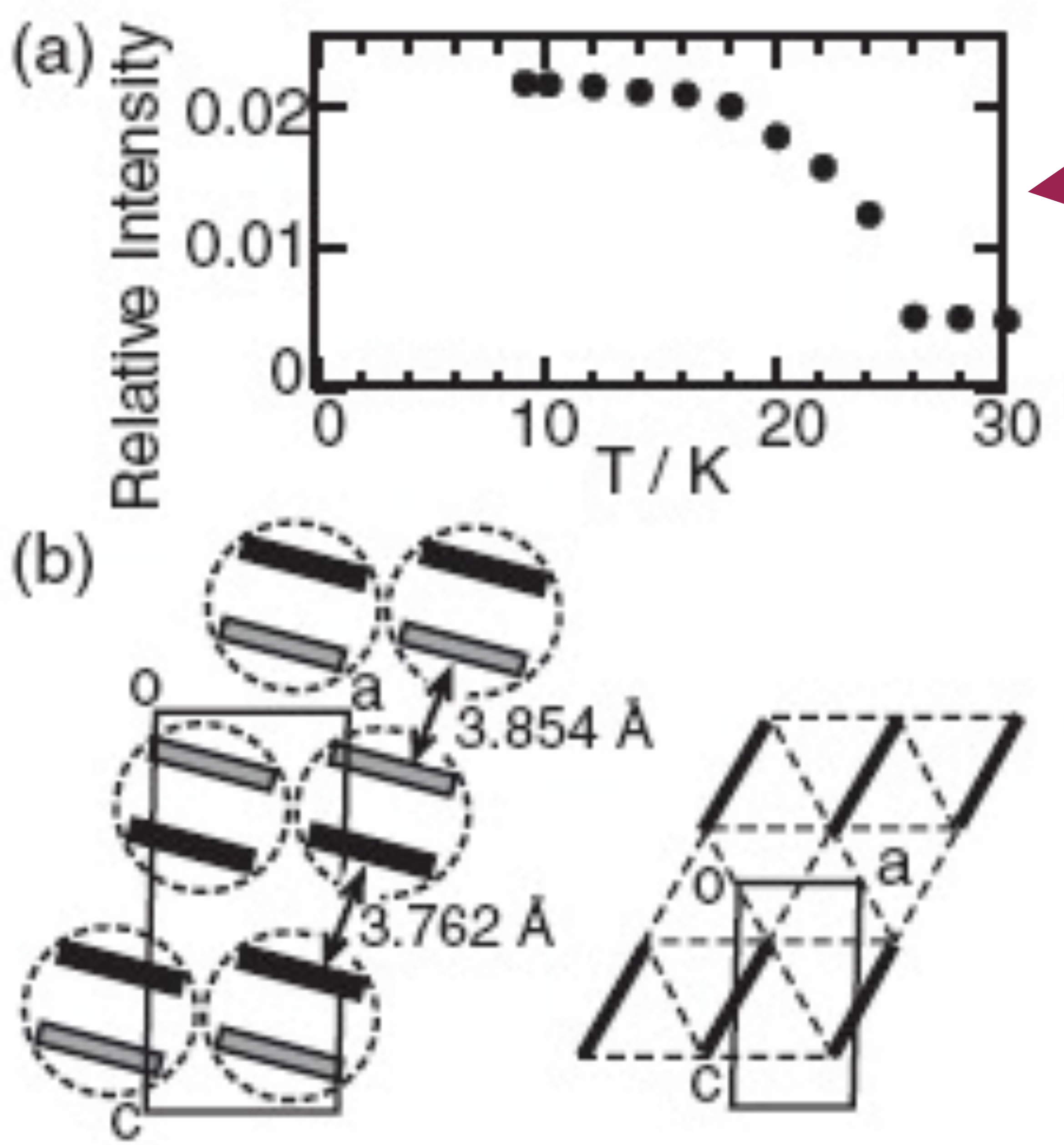
Observation of a valence bond solid (VBS) in $ETMe_3P[Pd(dmit)_2]_2$



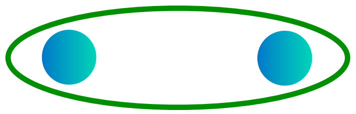
X-ray scattering

Spin gap ~ 40 K
J ~ 250 K

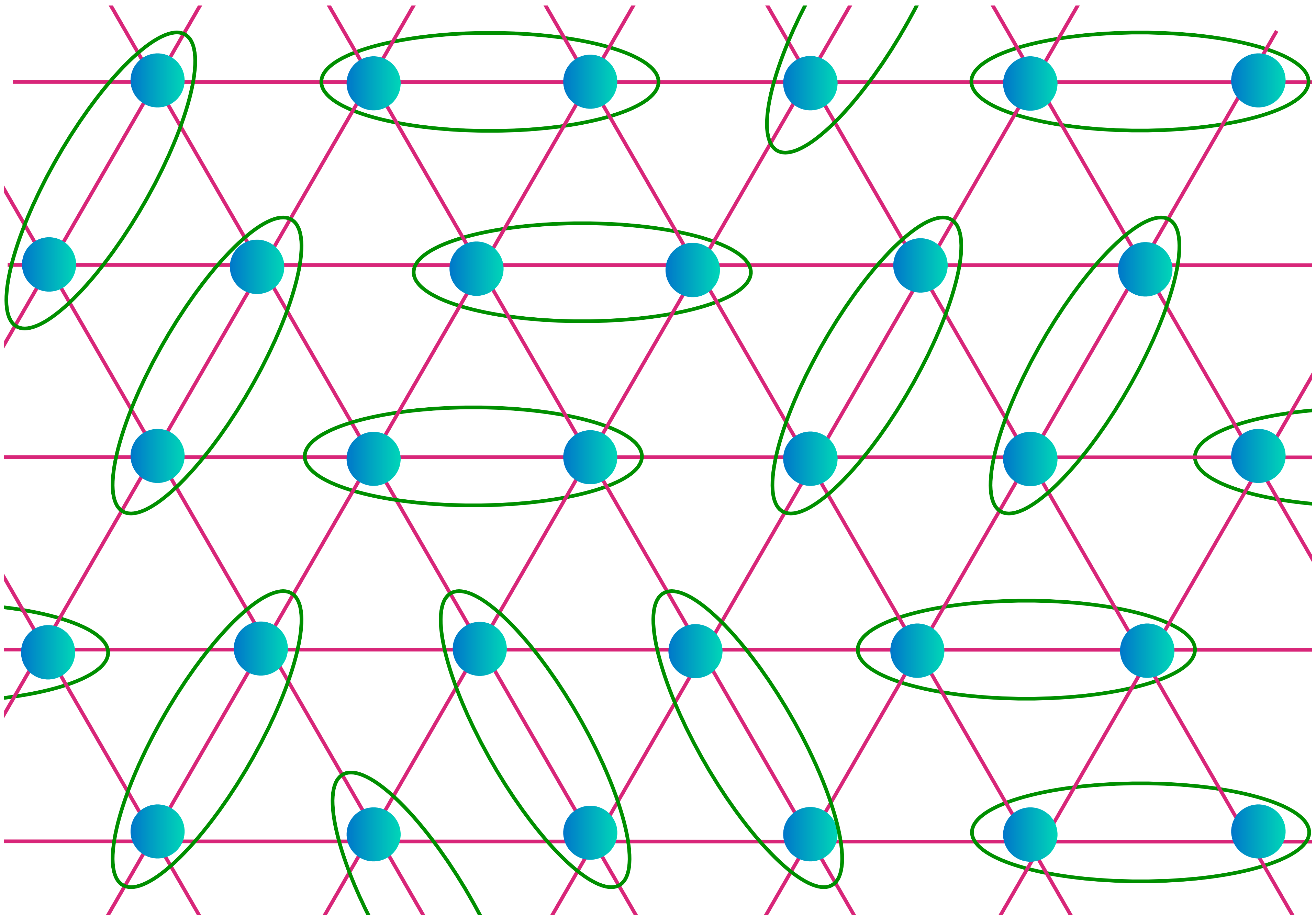
M. Tamura, A. Nakao and R. Kato, *J. Phys. Soc. Japan* **75**, 093701 (2006)
Y. Shimizu, H. Akimoto, H. Tsujii, A. Tajima, and R. Kato, *Phys. Rev. Lett.* **99**, 256403 (2007)

Triangular lattice antiferromagnet

Spin liquid obtained in a generalized spin model with S=1/2 per unit cell



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



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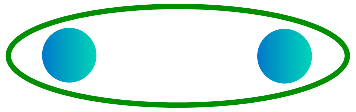

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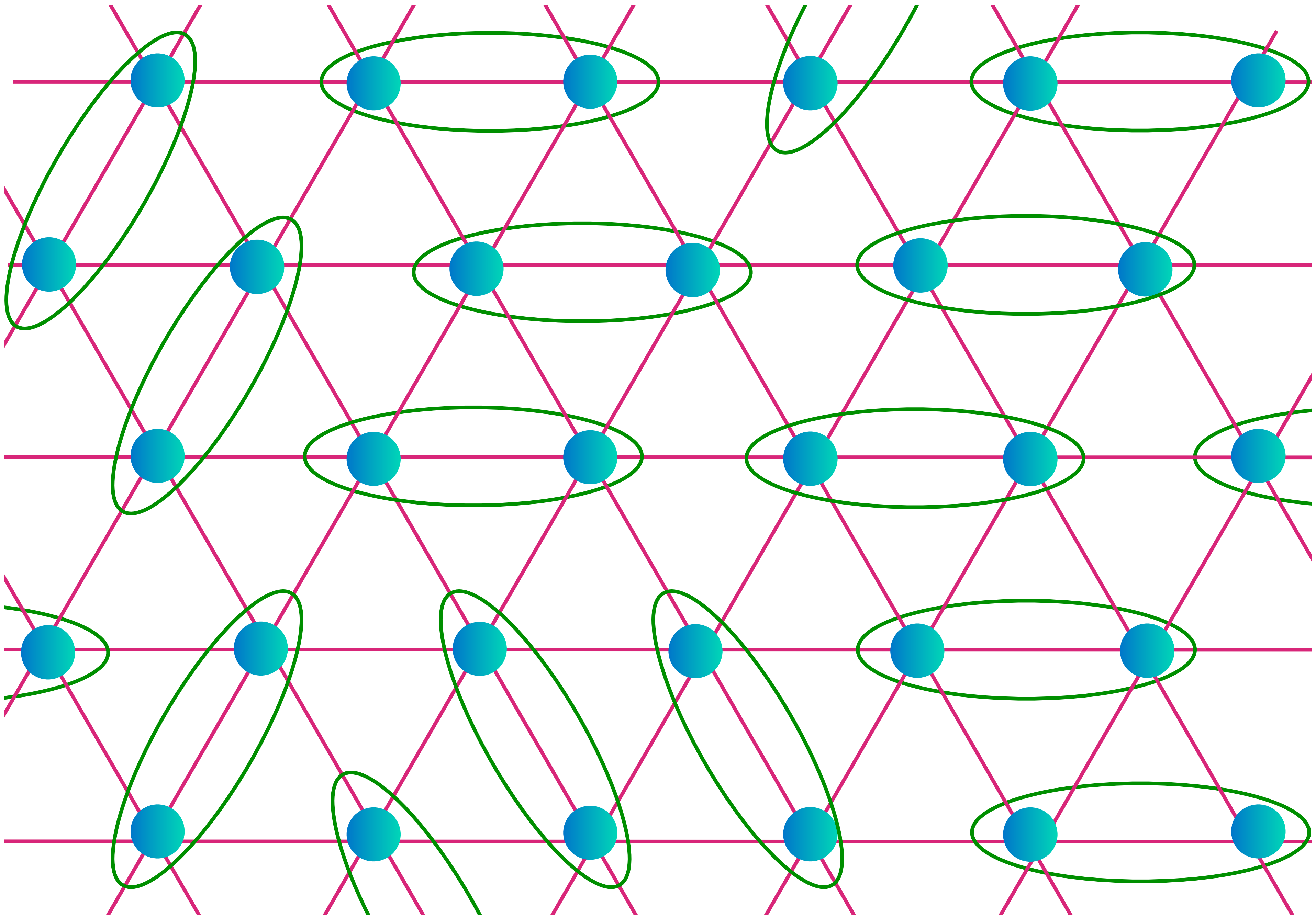

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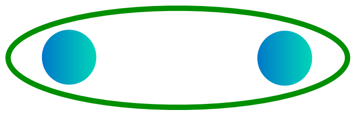

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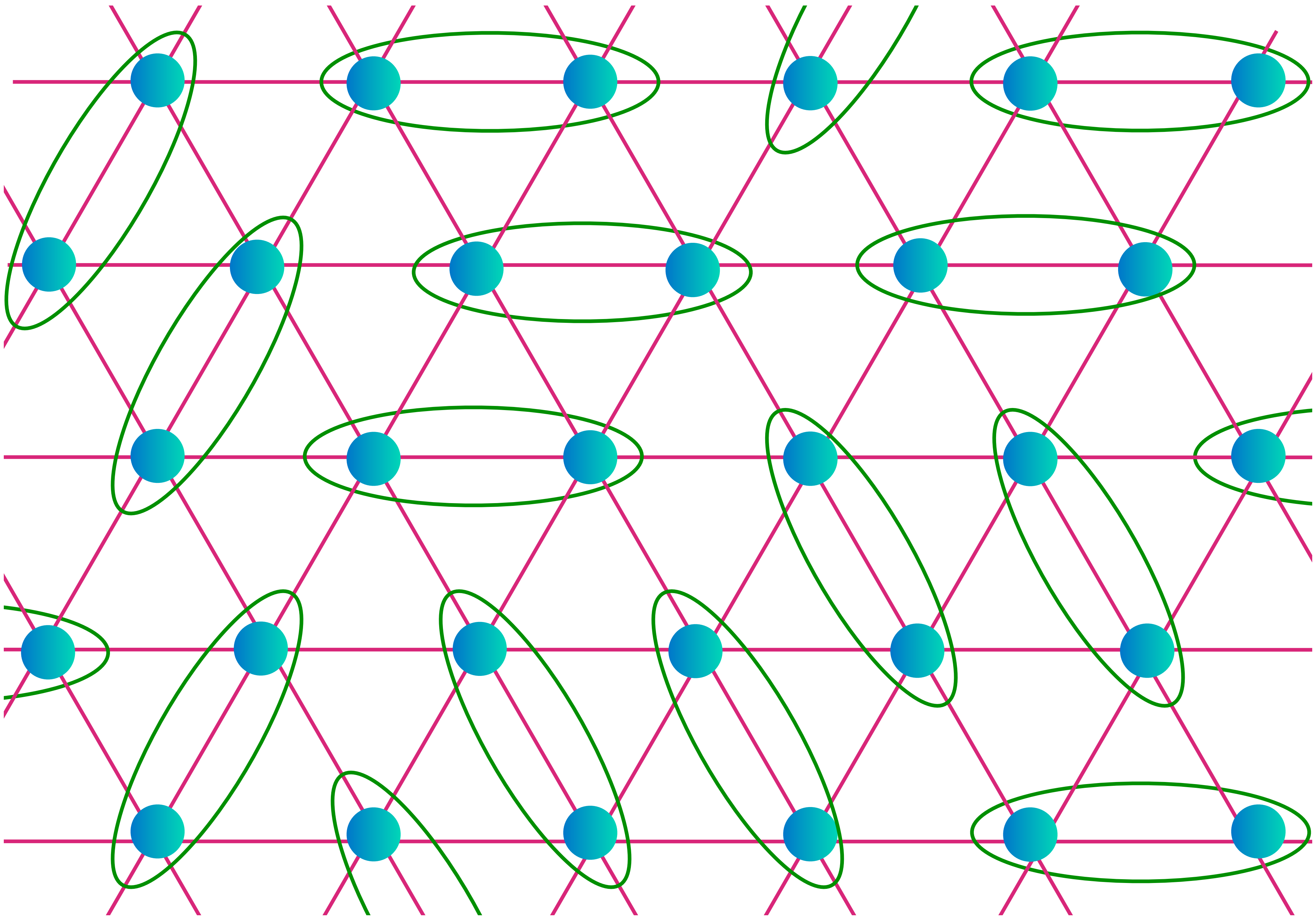

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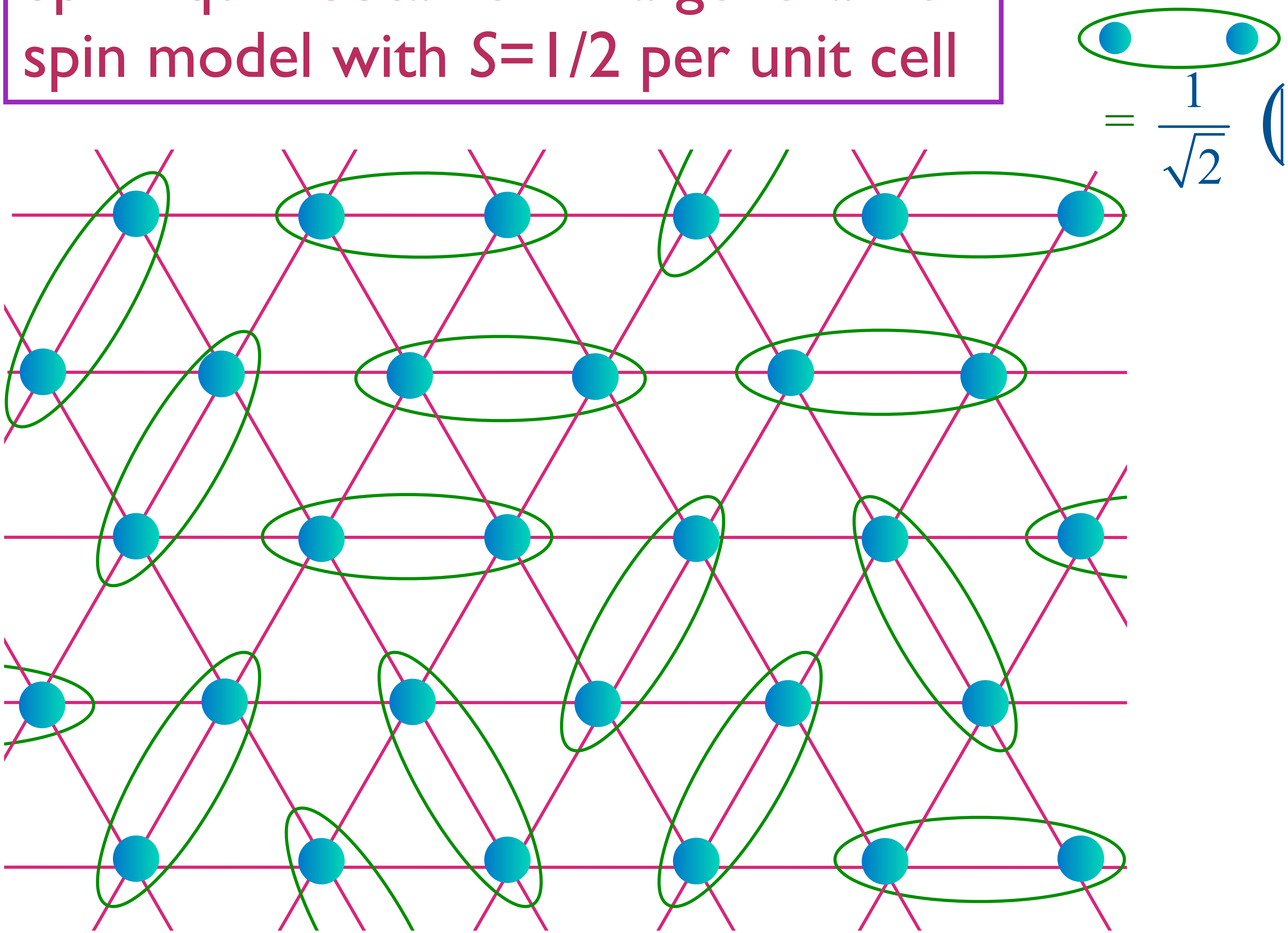

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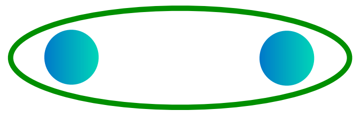

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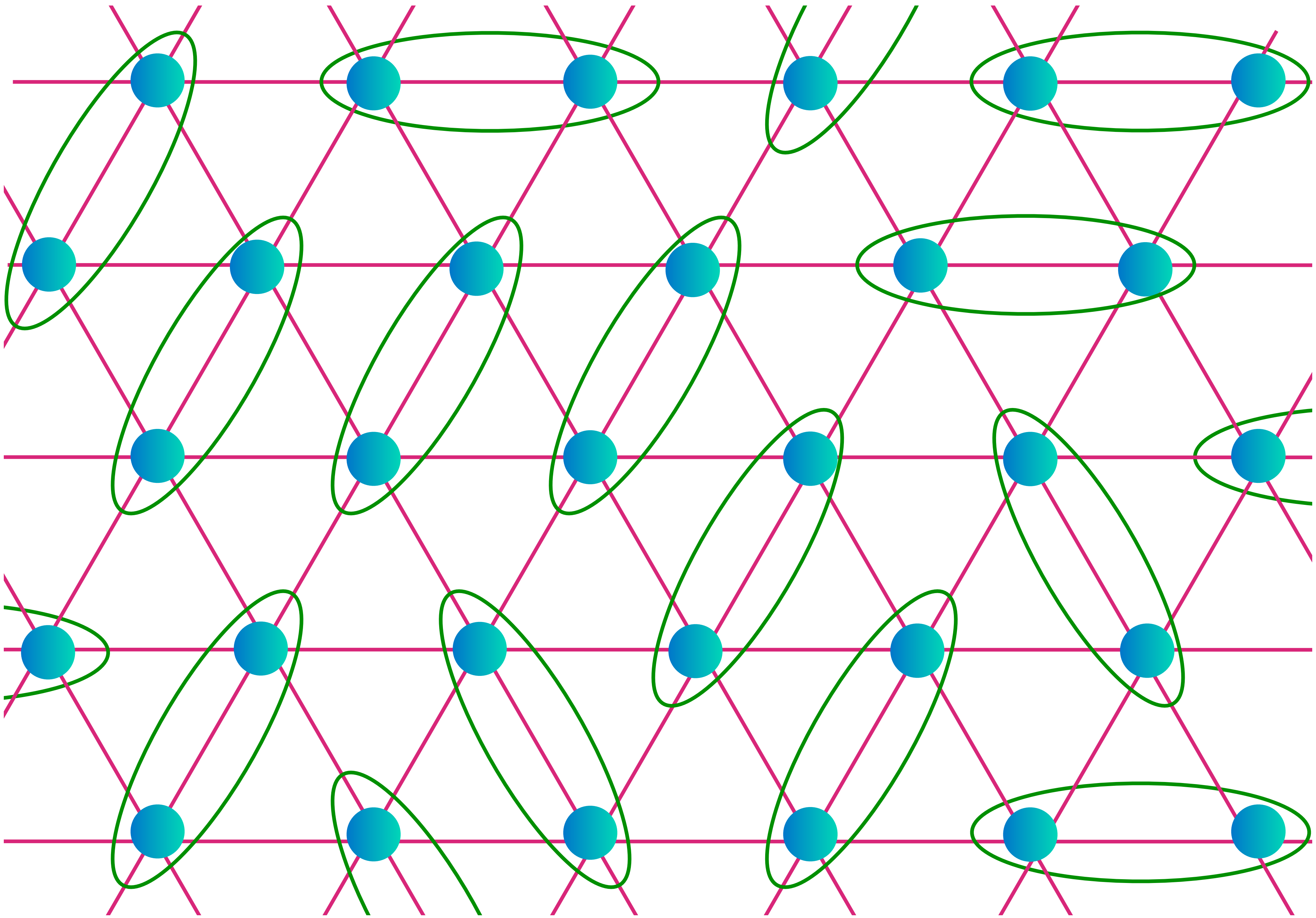

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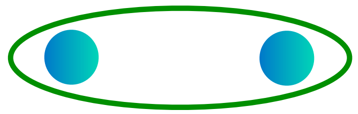

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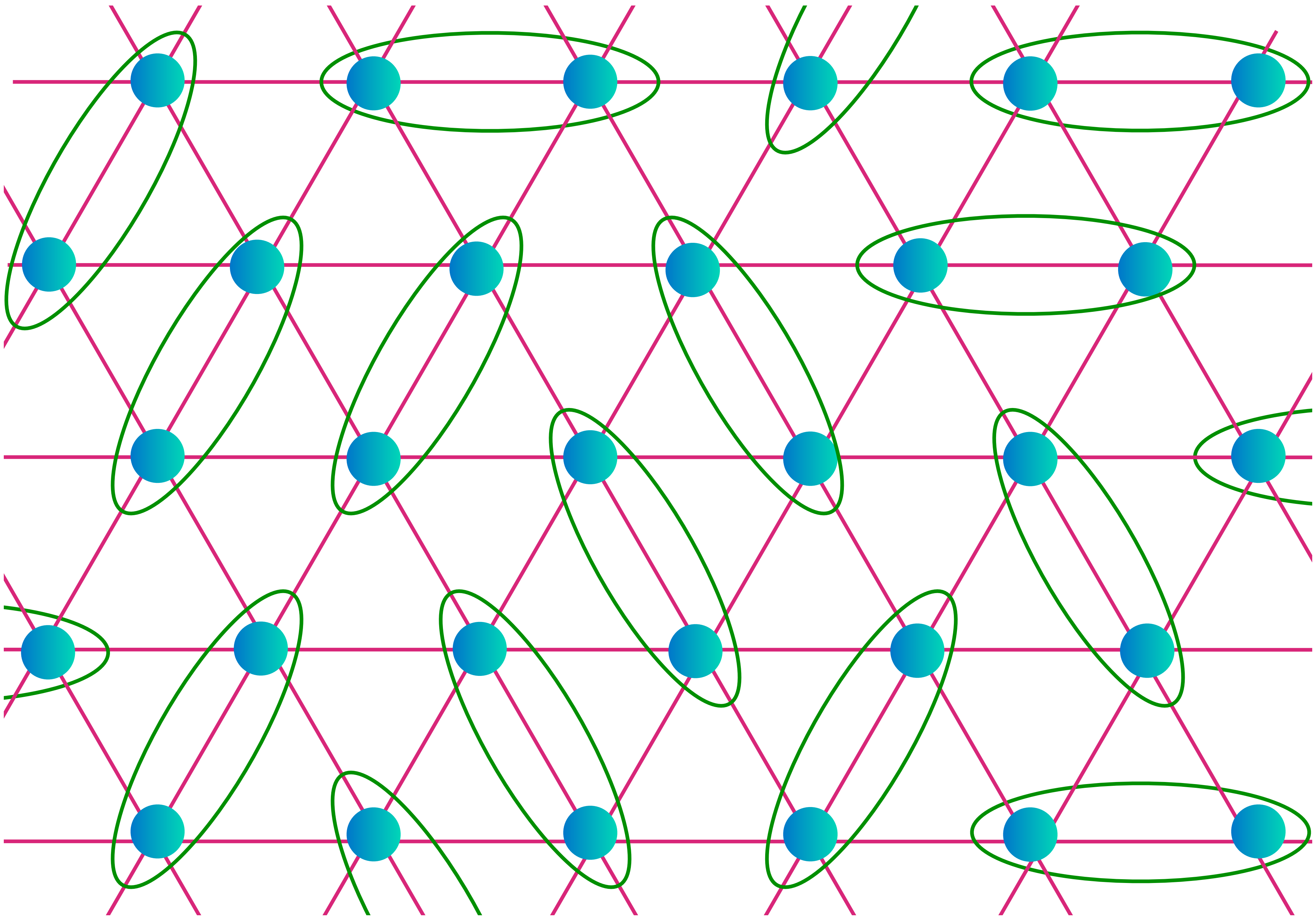

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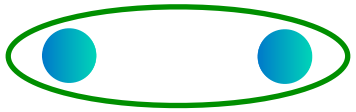
Excitations of the Z_2 Spin liquid



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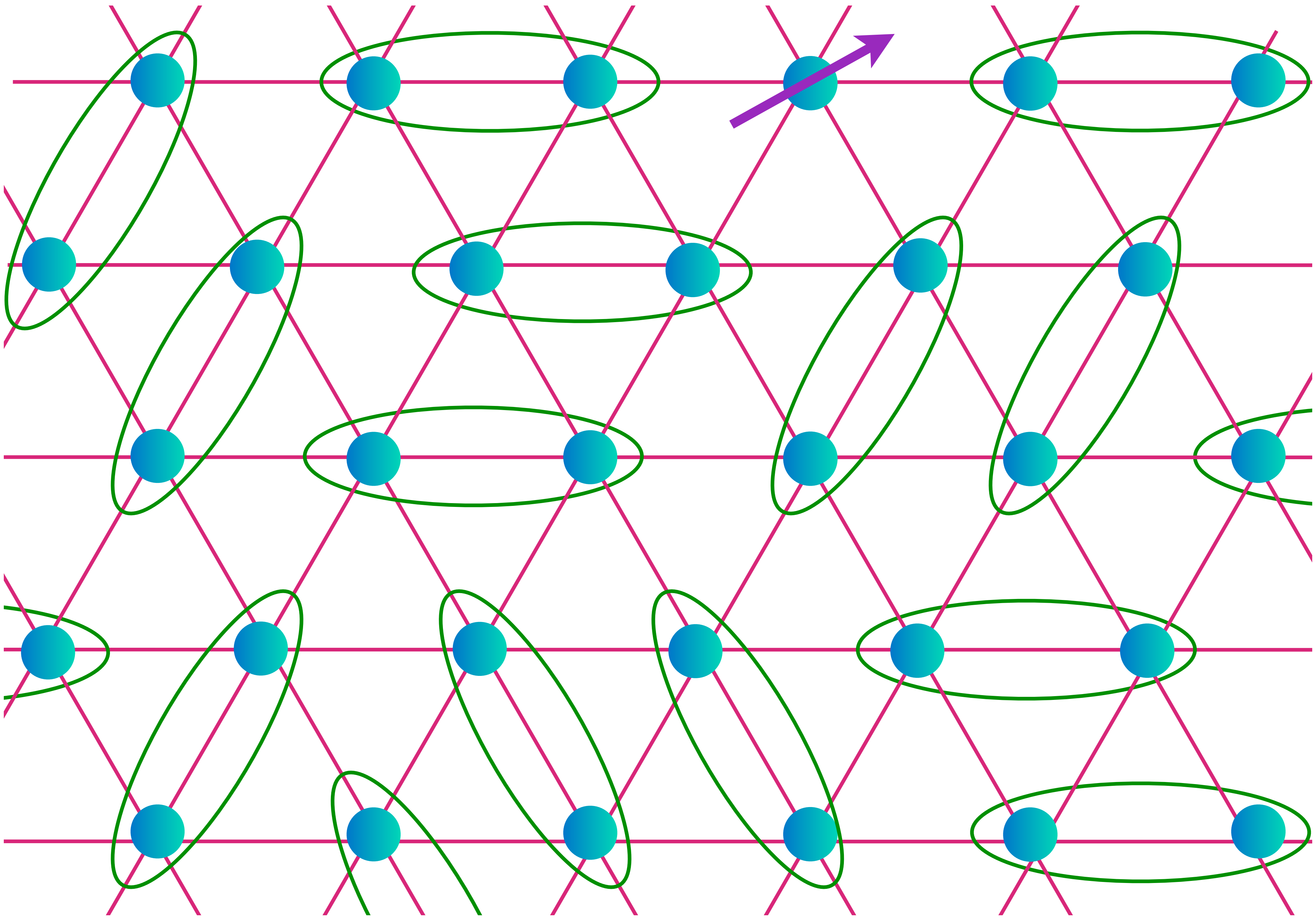
A spinon



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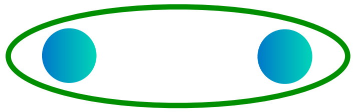

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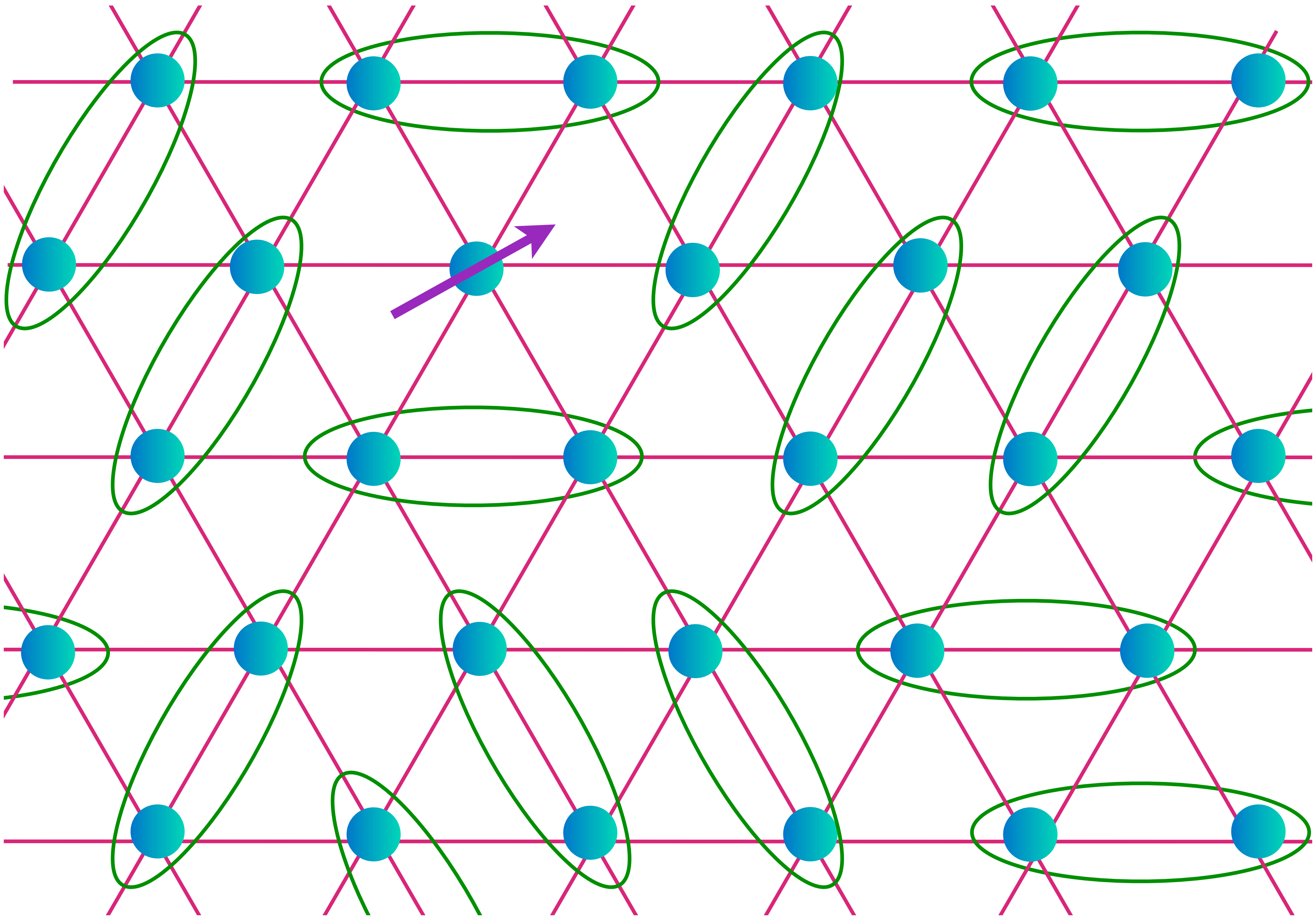

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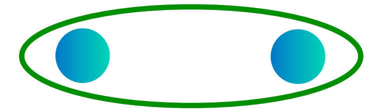

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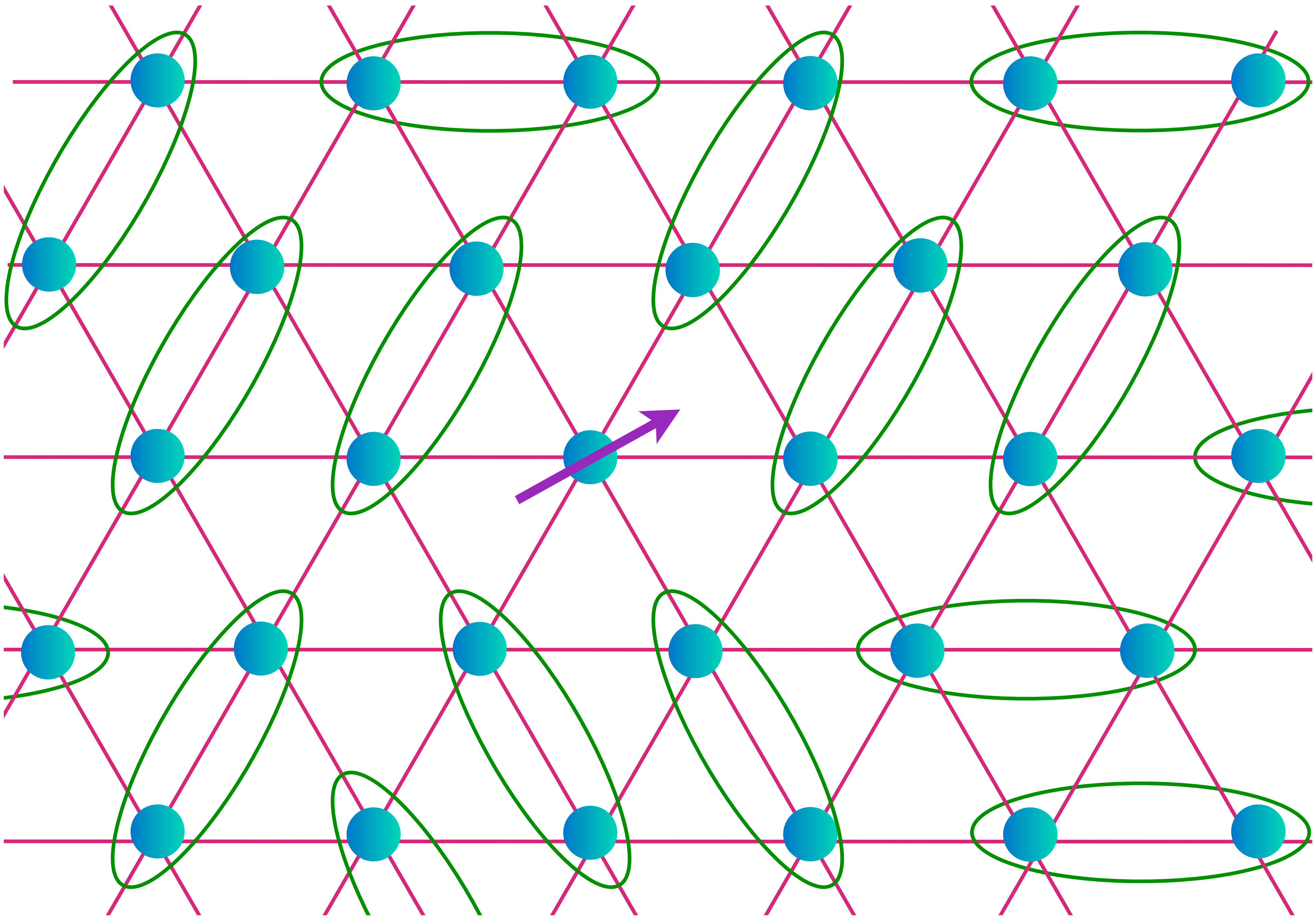

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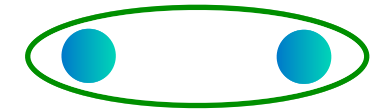

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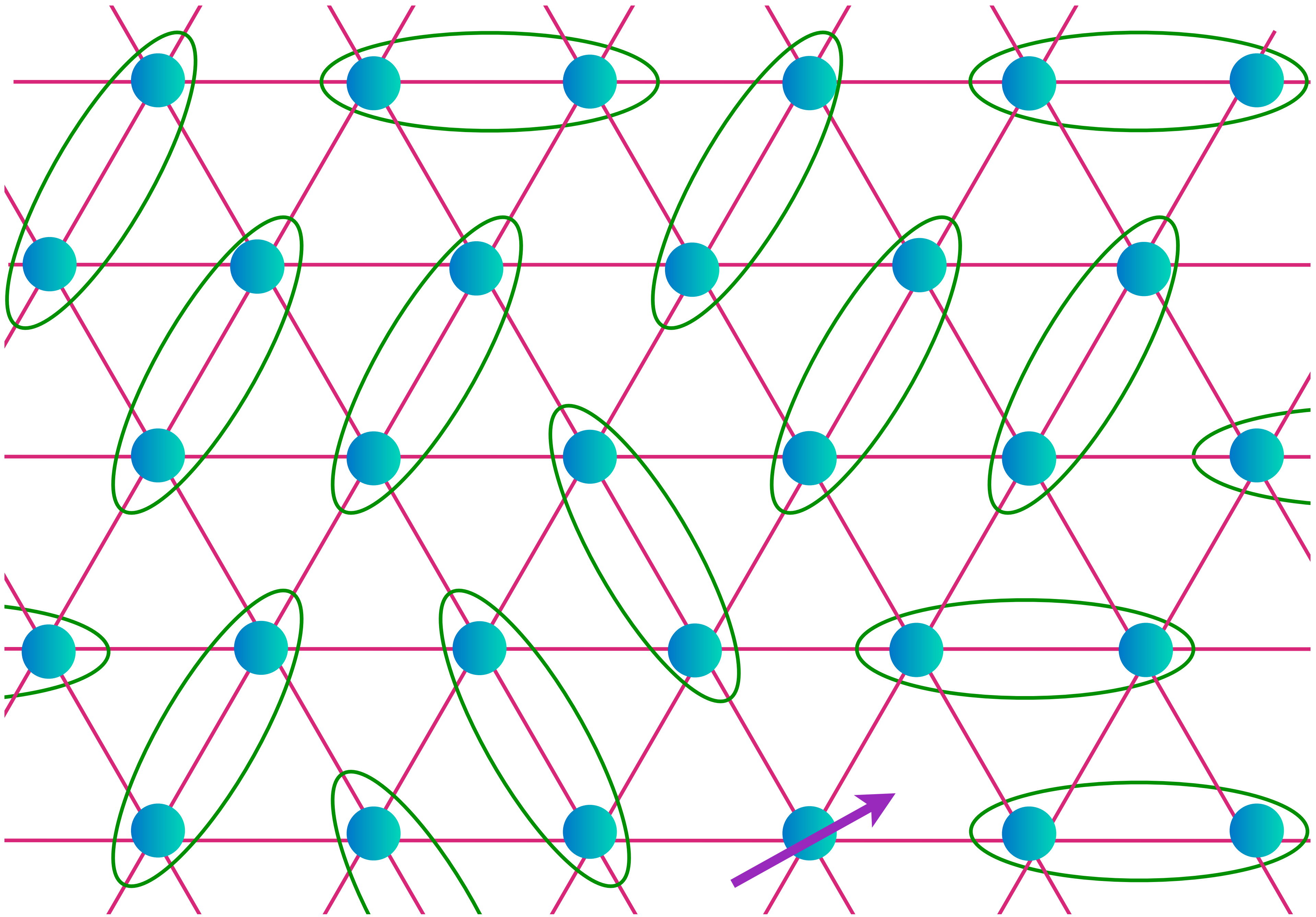

Excitations of the Z_2 Spin liquid

A vison

- A characteristic property of a Z_2 spin liquid is the presence of a spinon pair condensate
- A vison is an Abrikosov vortex in the pair condensate of spinons
- Visons are are the **dark matter** of spin liquids: they likely carry most of the energy, but are very hard to detect because they do not carry charge or spin.

N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)

Excitations of the Z_2 Spin liquid

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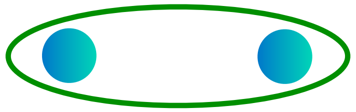

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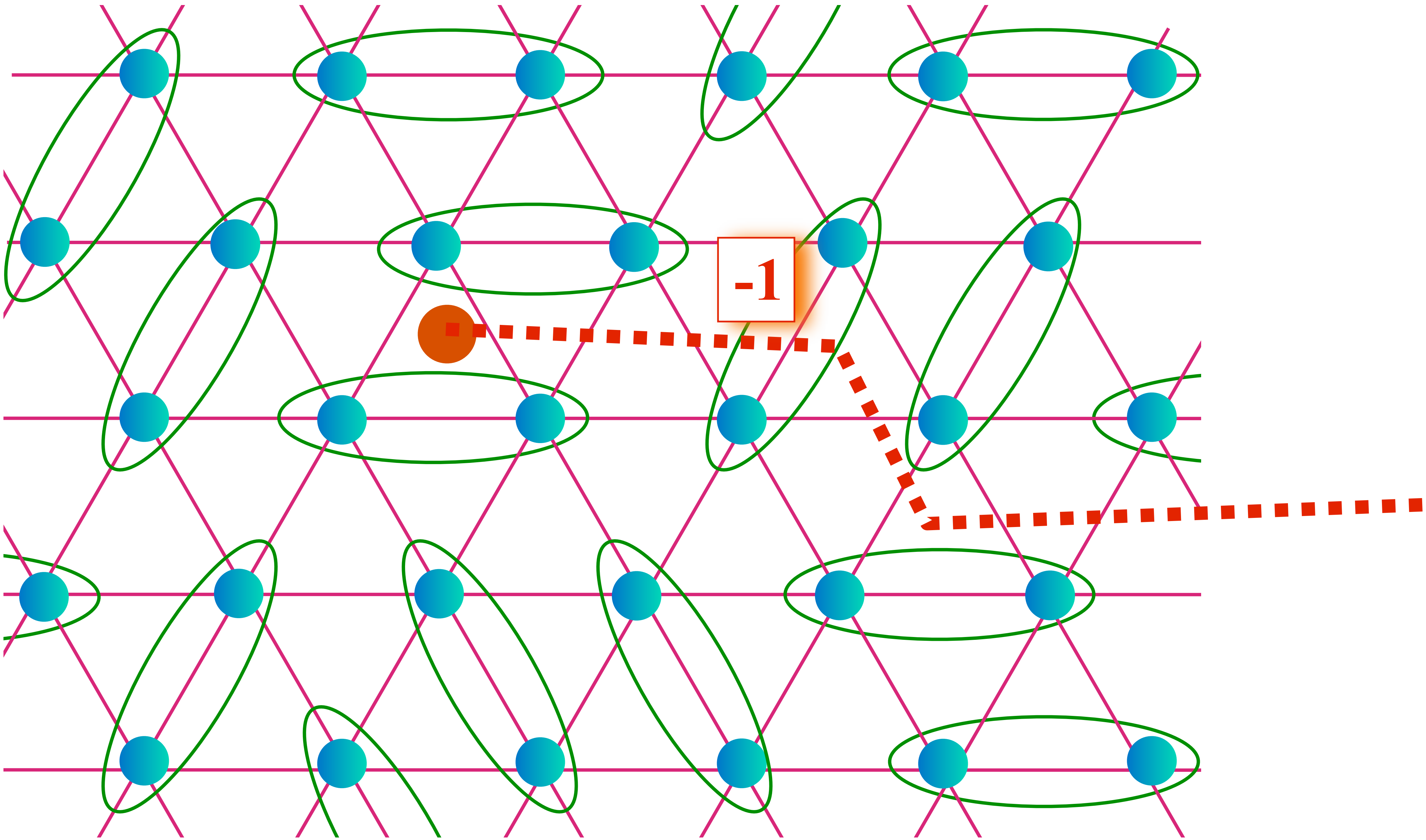

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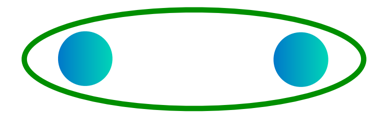

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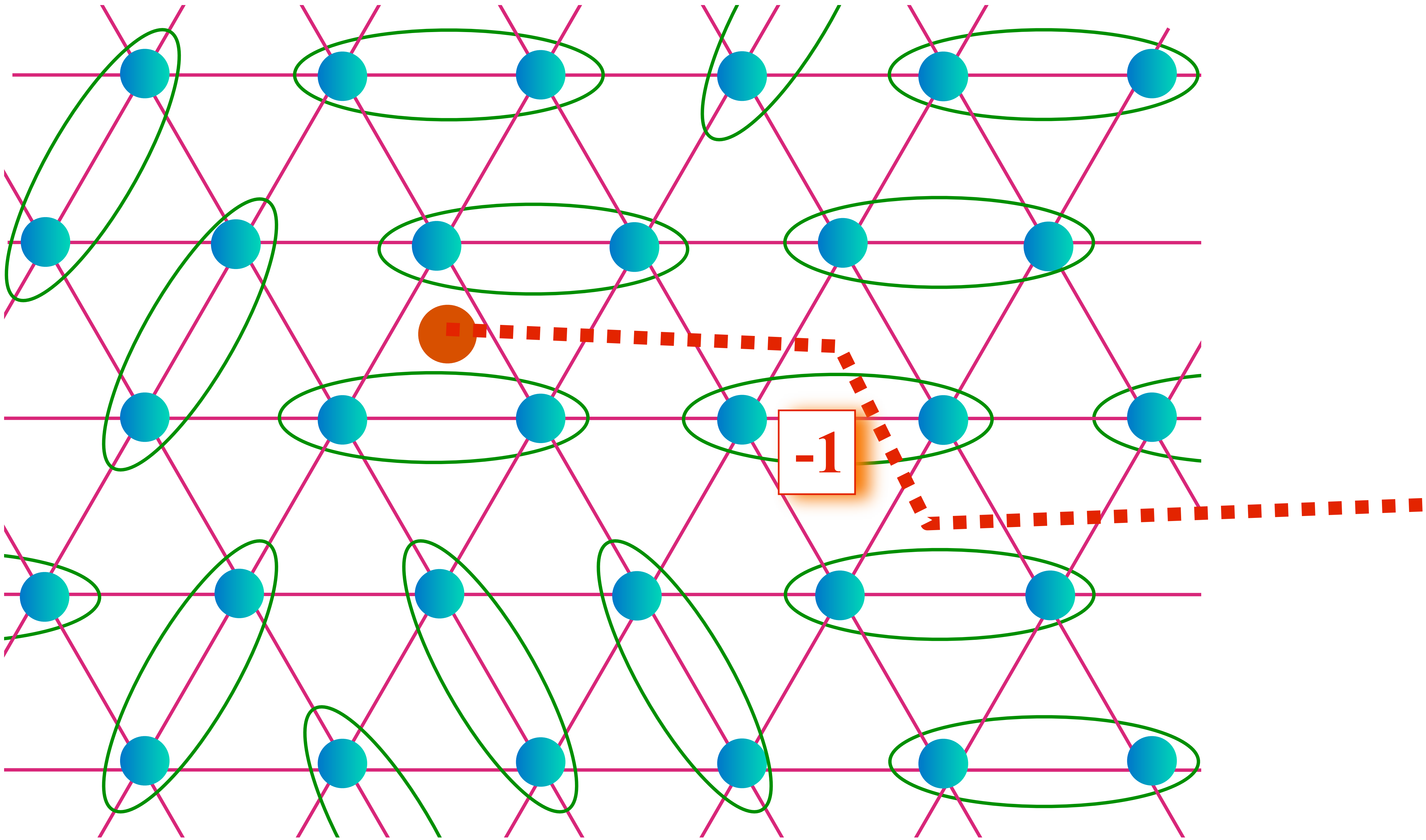

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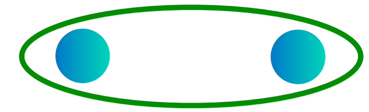

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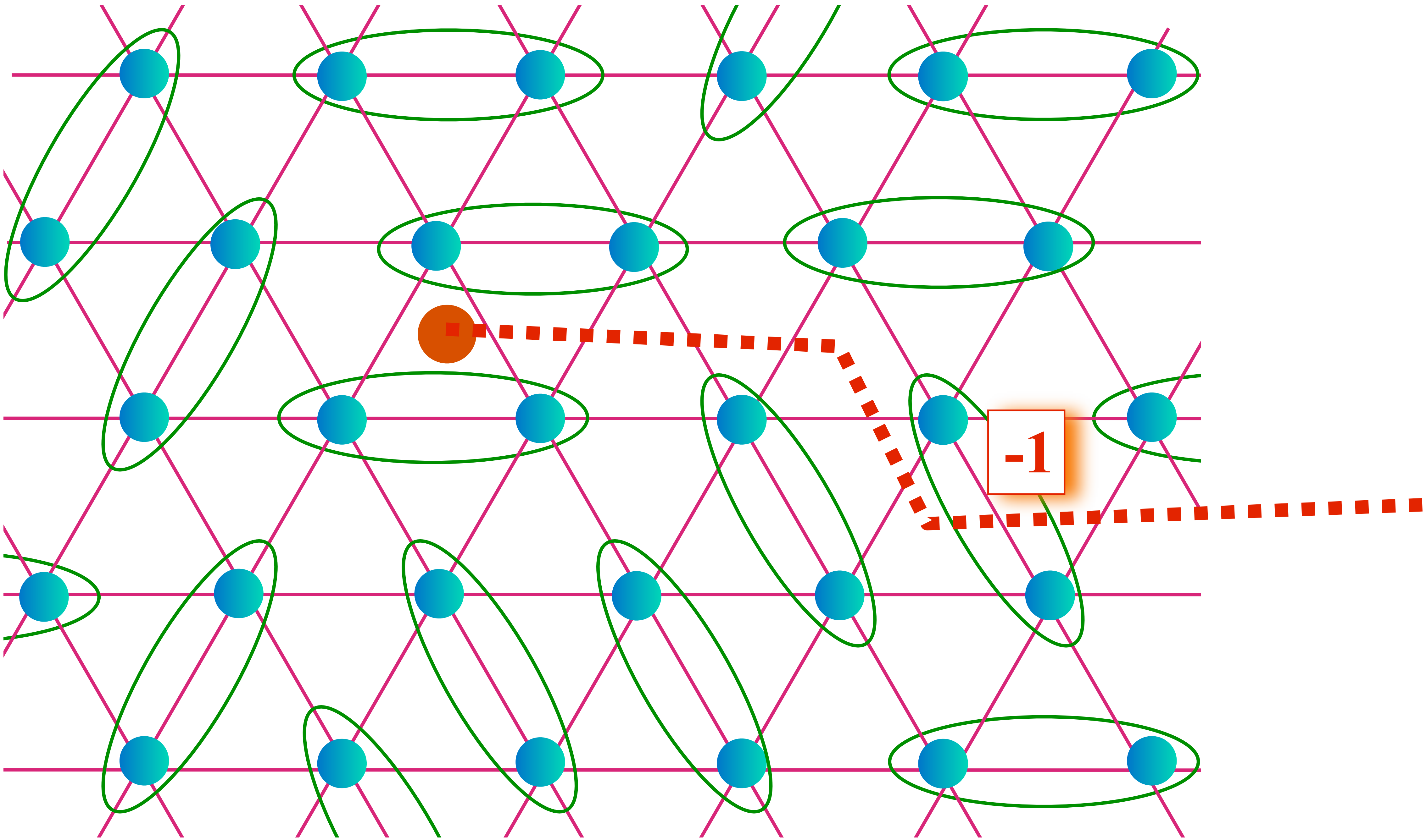

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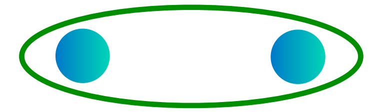
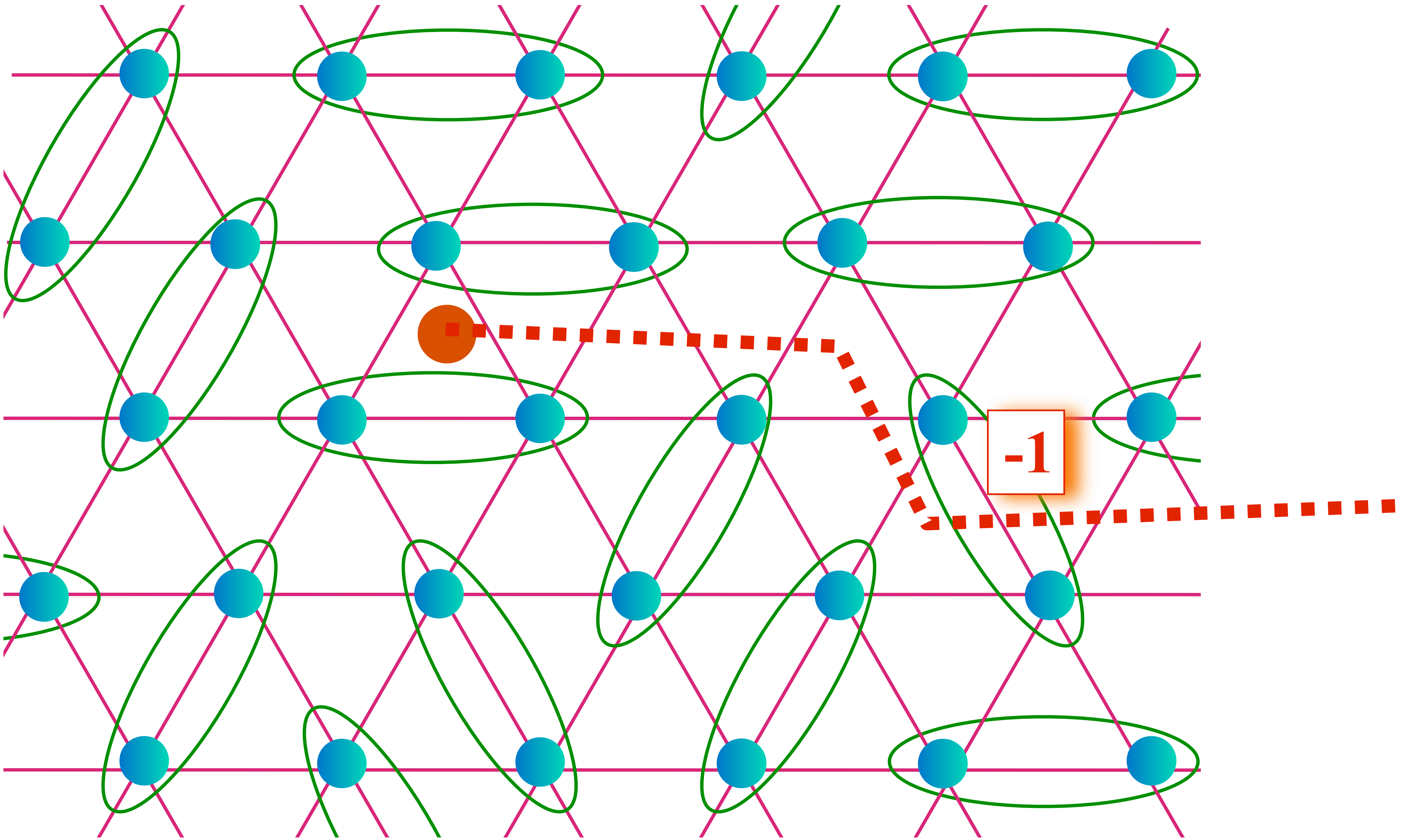
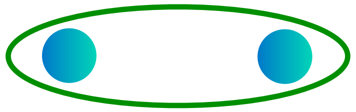


A vison



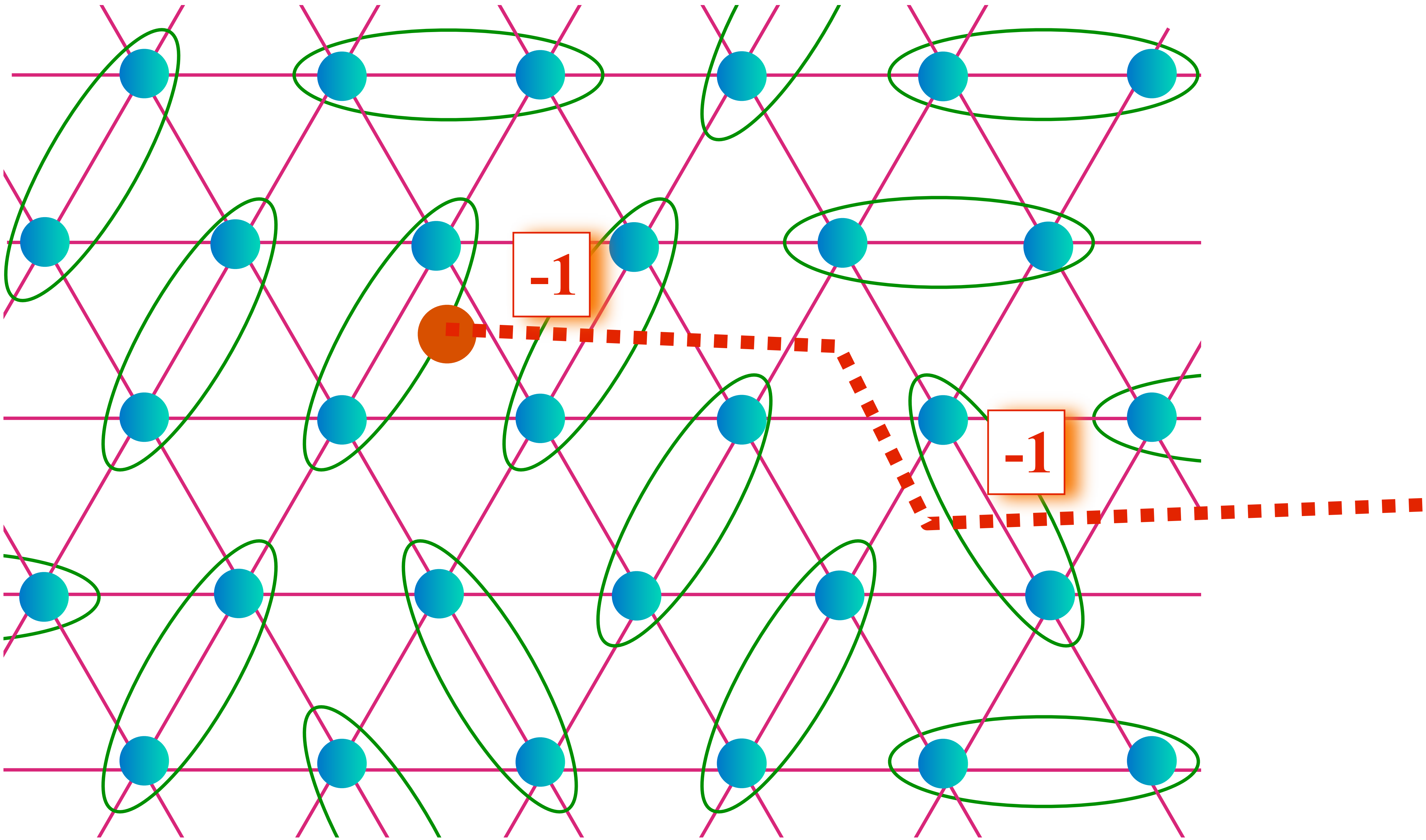
N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)

Excitations of the Z_2 Spin liquid



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

A vison



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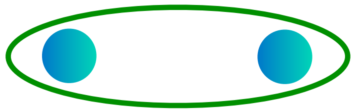

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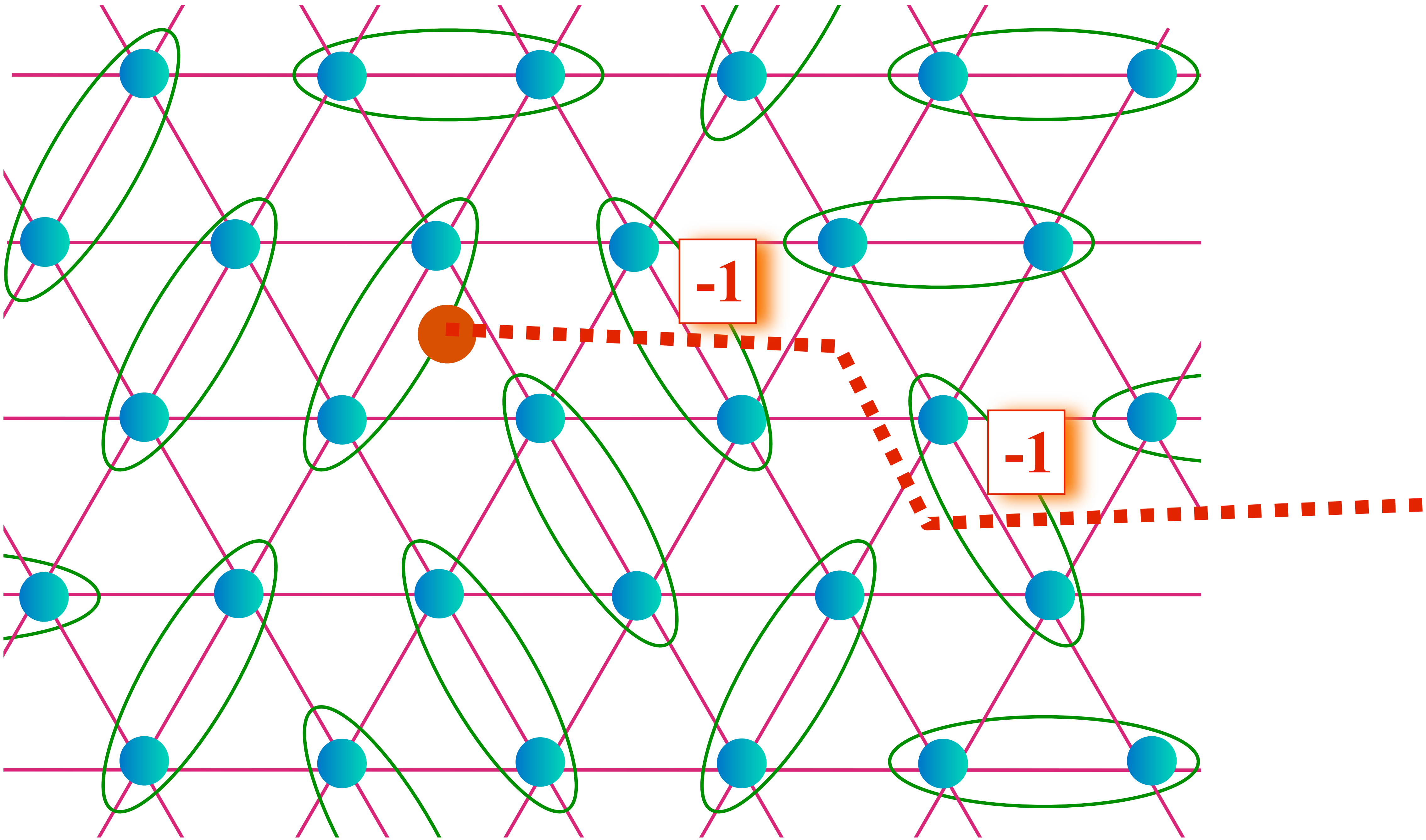

N. Read and S. Sachdev, *Phys. Rev. Lett.* **66**, 1773 (1991)

Mutual Chern-Simons Theory

Express theory in terms of the physical excitations of the Z_2 spin liquid: the spinons, z_α, and the visons. After accounting for Berry phase effects, the visons can be described by complex fields v_a, which transforms non-trivially under the square lattice space group operations.

The spinons and visons have mutual semionic statistics, and this leads to the mutual CS theory at $k = 2$:

$$
\begin{aligned}
\mathcal{L} &= \sum_{\alpha=1}^{2} \left\{ |(\partial_\mu - i a_\mu) z_\alpha|^2 + s_z |z_\alpha|^2 \right\} \\
&+ \sum_{a=1}^{N_v} \left\{ |(\partial_\mu - i b_\mu) v_a|^2 + s_v |v_a|^2 \right\} \\
&+ \frac{ik}{2\pi} \epsilon_{\mu\nu\lambda} a_\mu \partial_\nu b_\lambda + \cdots
\end{aligned}
$$

Cenke Xu and S. Sachdev,
Phys. Rev. B **79**, 064405 (2009)

Phase diagram of frustrated antiferromagnets

N. Read and S. Sachdev
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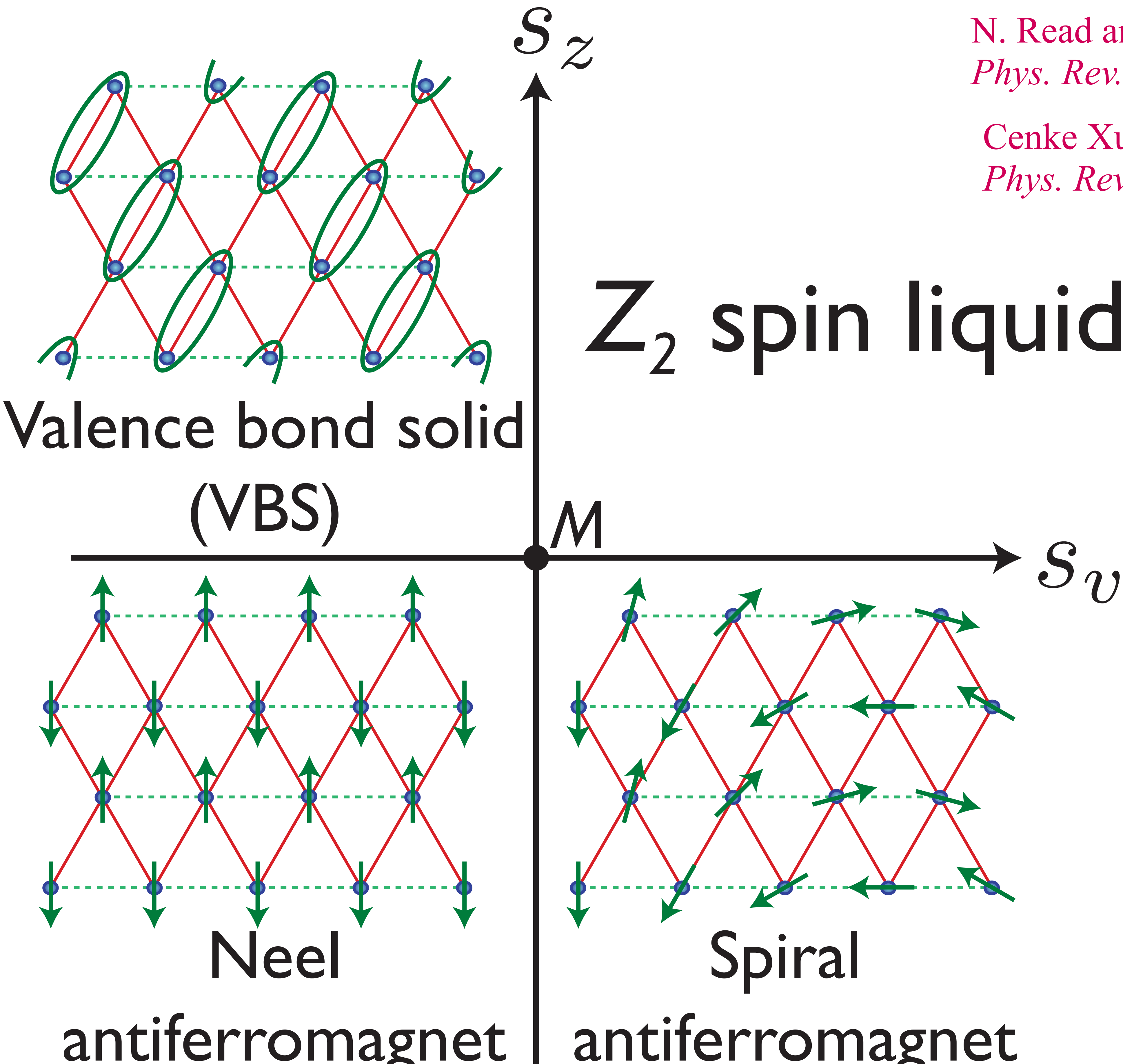

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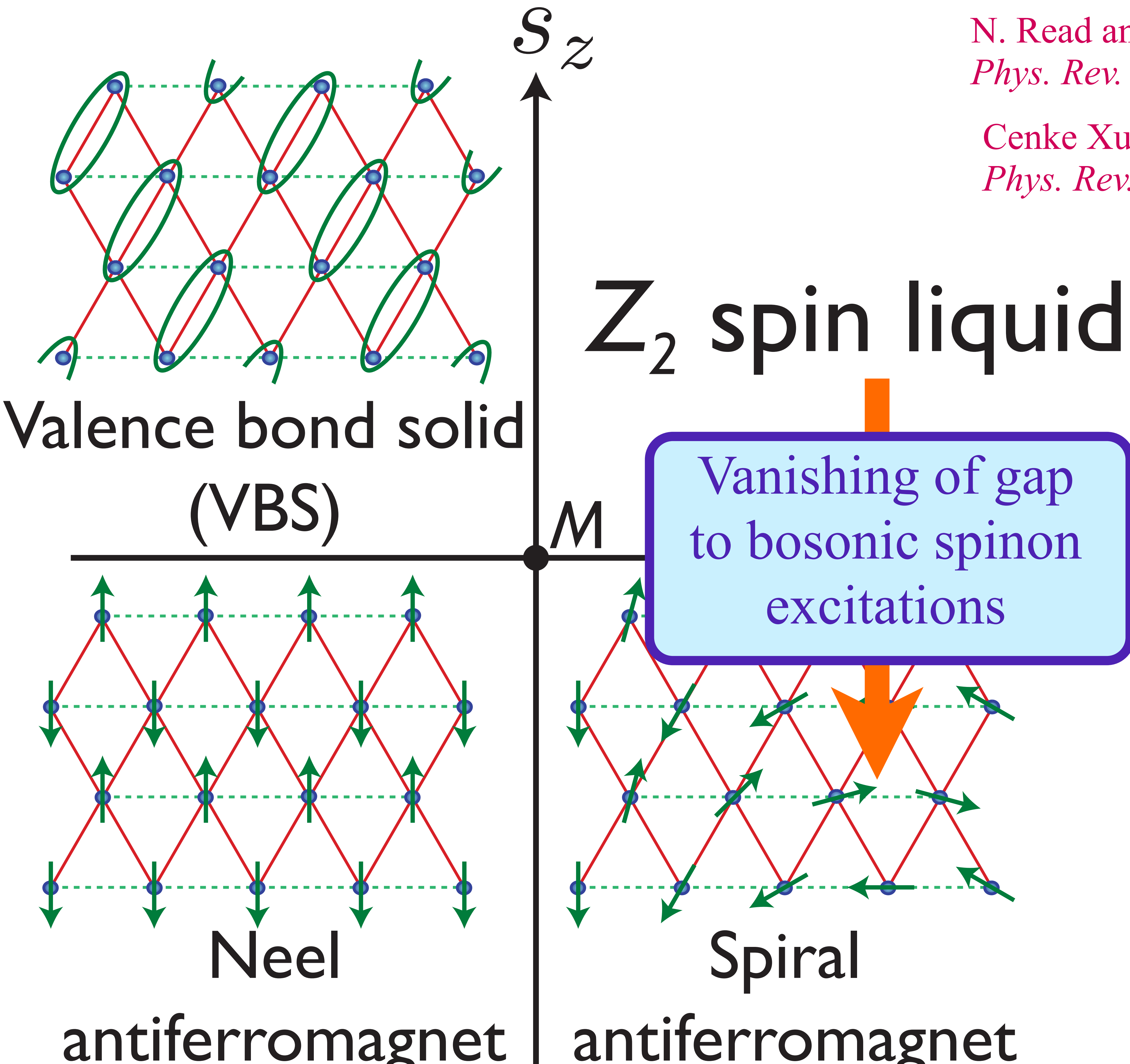

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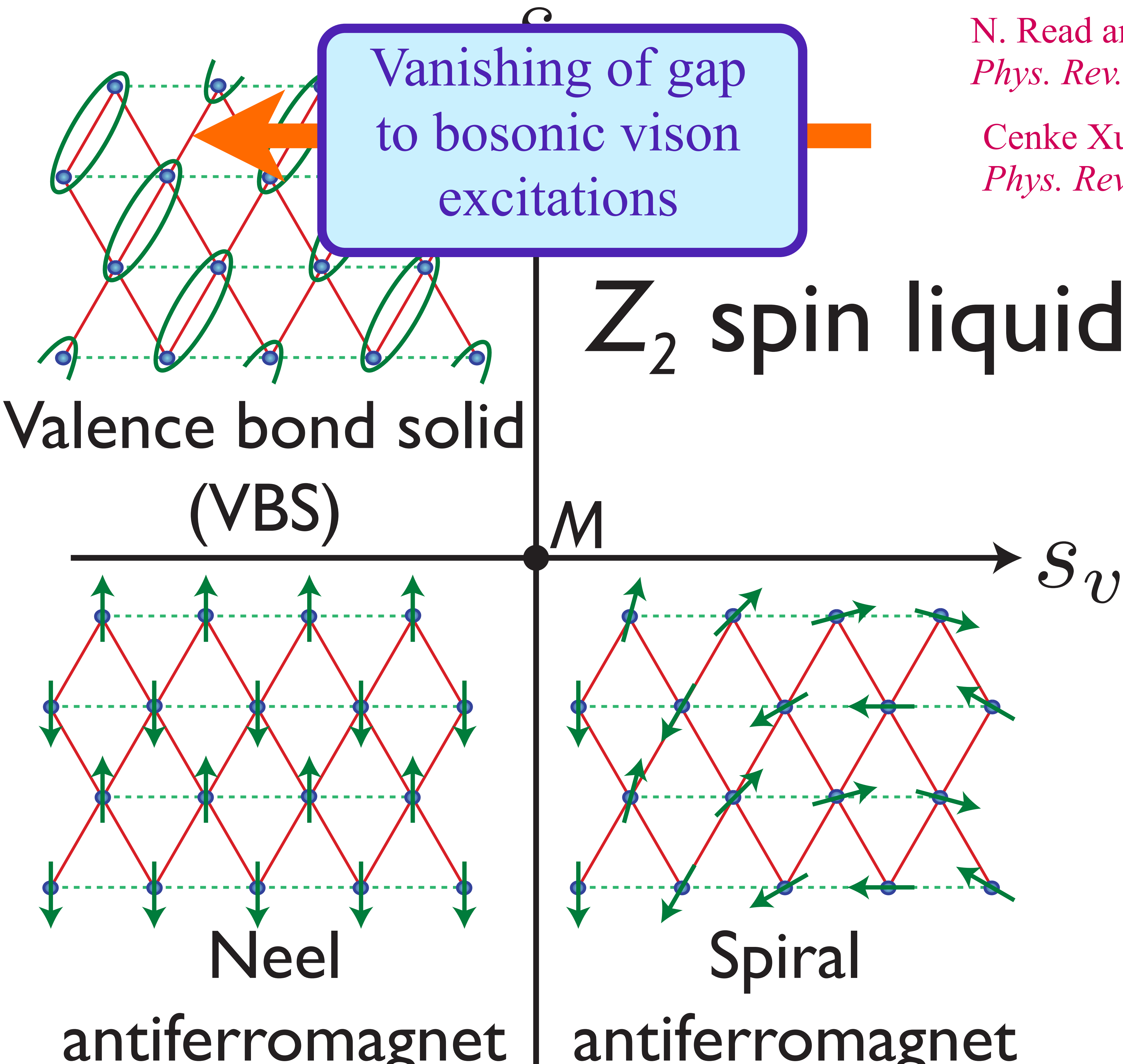

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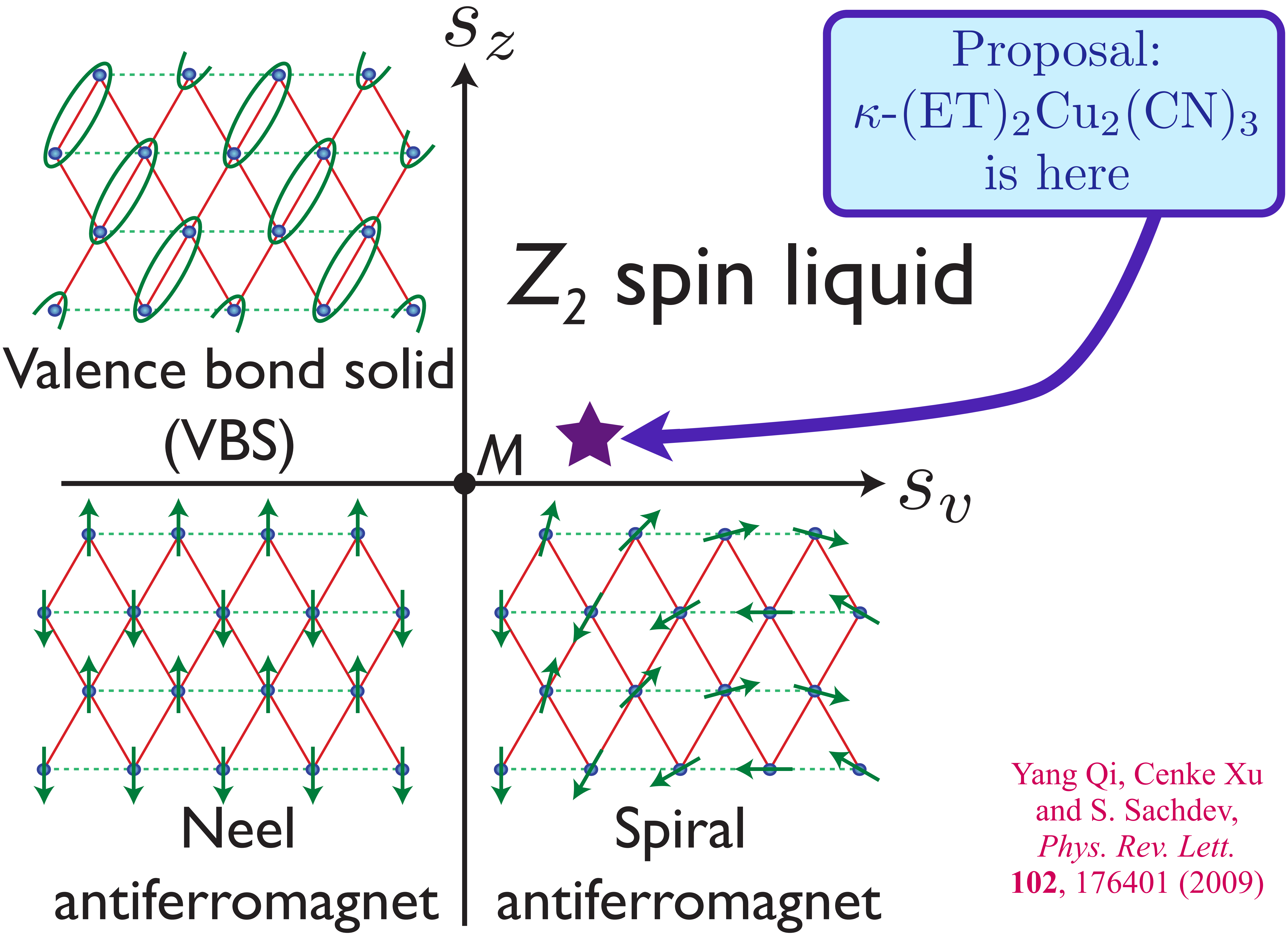


Yang Qi, Cenke Xu and S. Sachdev, *Phys. Rev. Lett.* **102**, 176401 (2009)

Proposal: κ-$(ET)_2Cu_2(CN)_3$ is a Z_2 spin liquid near a quantum phase transition to magnetic order

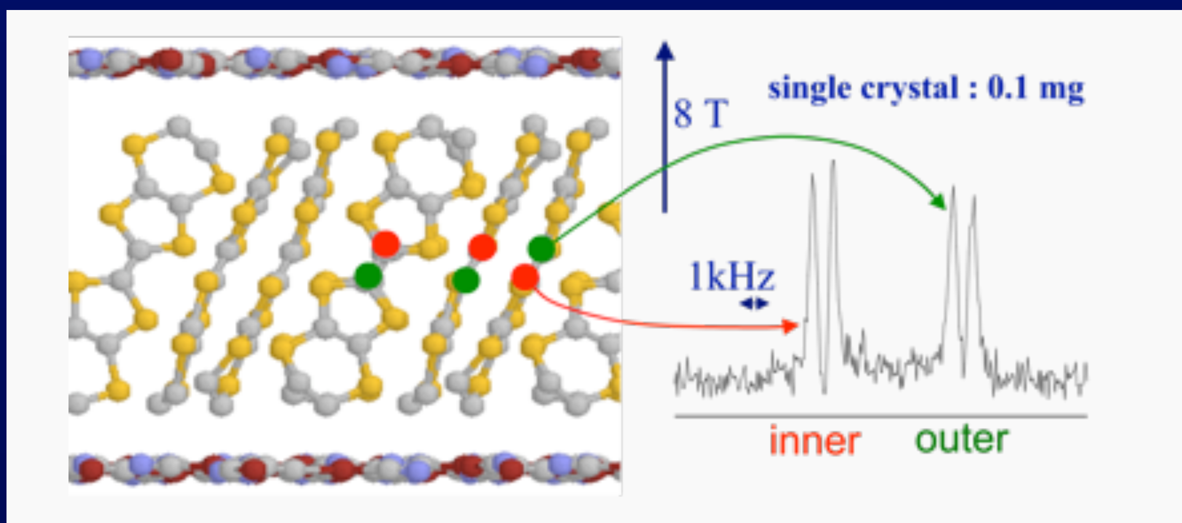
- Originally motivated by NMR relation. The quantum critical point has O(4) symmetry and has $1/T_1 \sim T^\eta$ with $\eta = 1.374(12)$.

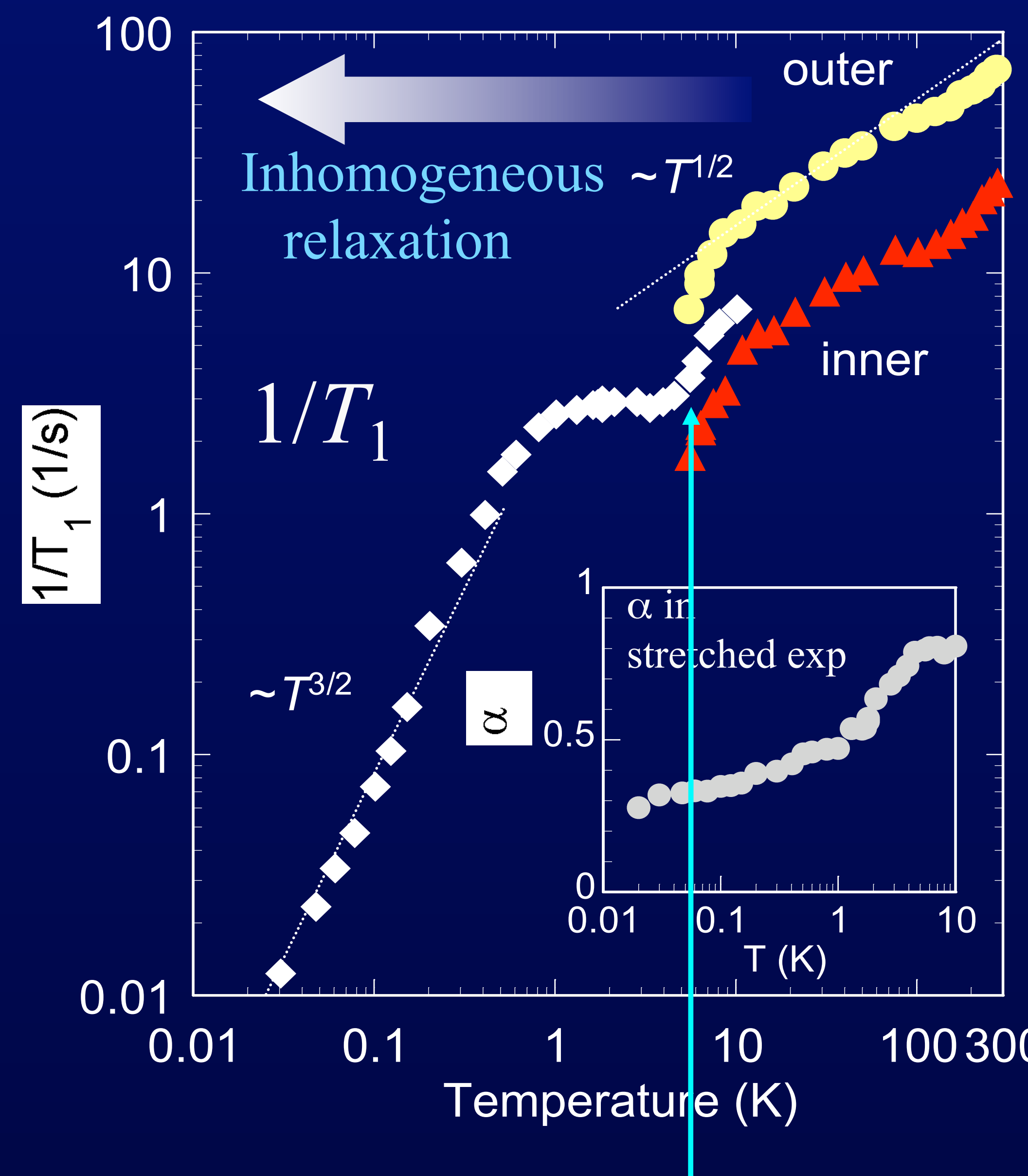
Yang Qi, Cenke Xu and S. Sachdev, *Phys. Rev. Lett.* **102**, 176401 (2009)

Spin excitation in κ-$(ET)_2Cu_2(CN)_3$

^{13}C NMR relaxation rate

Shimizu *et al.*, PRB 70 (2006) 060510





$1/T_1$ ~ power law of T

Low-lying spin excitation at low-T

Anomaly at 5-6 K

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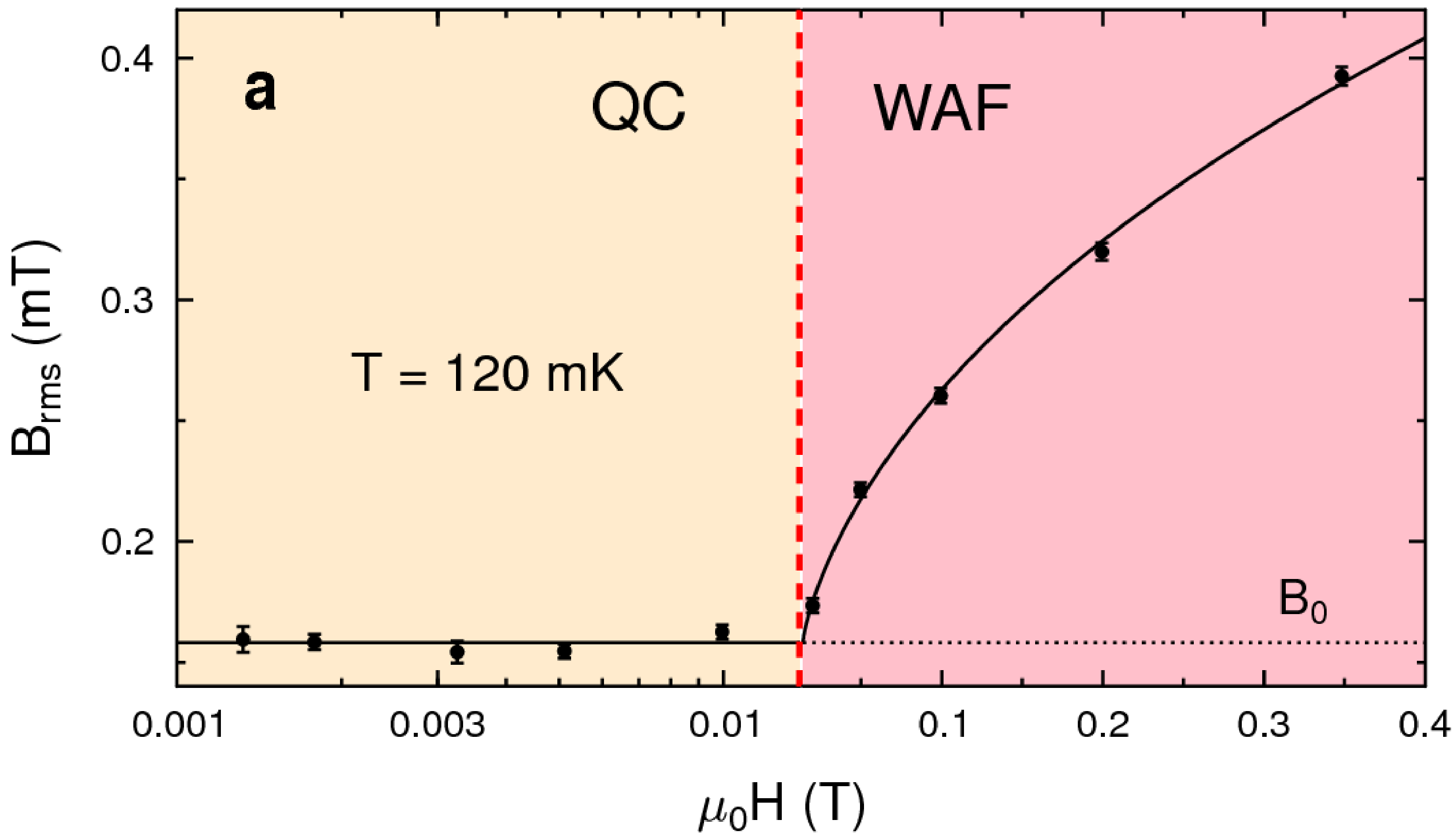
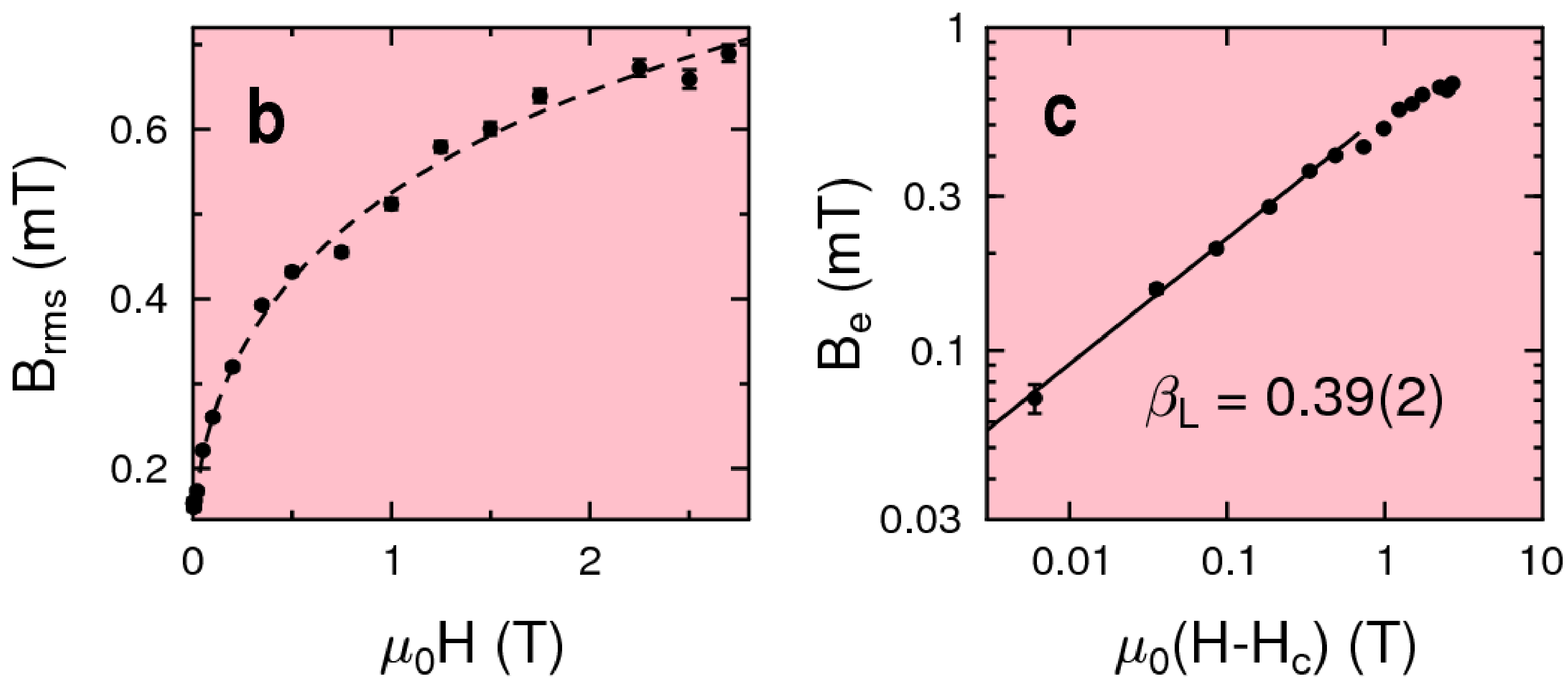
Field-induced QPT from μSR Line Width

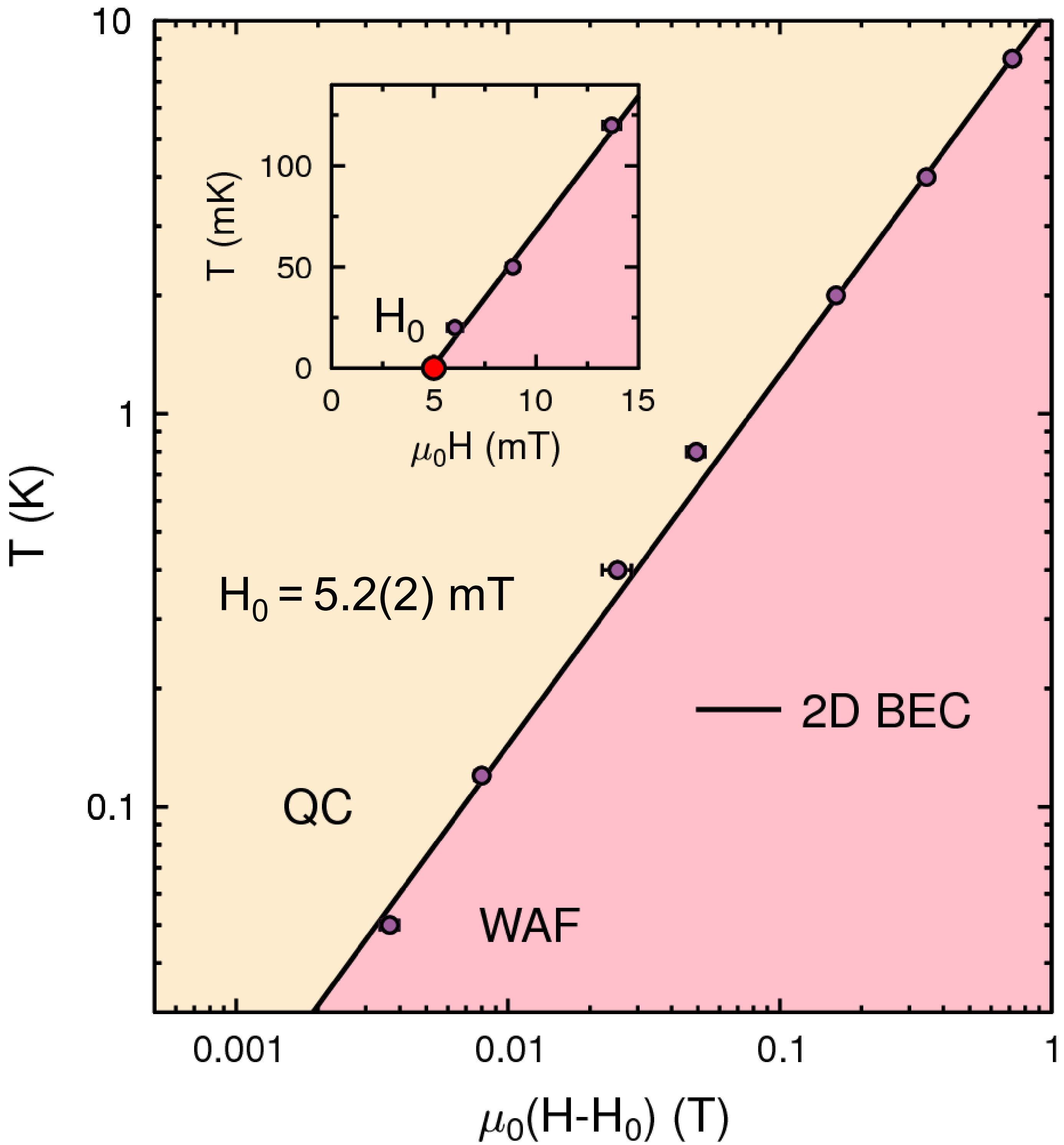


Consistent with high field ^{13}C NMR broadening of Shimizu et al
PRB 73,140407 (2006)



F. Pratt *et al.*
(ISIS, UK)
preprint

Measured Phase Boundary of the QPT



2D BEC:

$$T_c \propto \mu \frac{\ln(t_{\parallel}/\mu)}{\ln\ln(t_{\parallel}/\mu)}$$

$$\mu \propto H - H_0$$

F. Pratt *et al.* (ISIS, UK) preprint

Tiny H_0 implies that spin gap per spin1/2 is $\Delta_z \sim 3.5$ mK !

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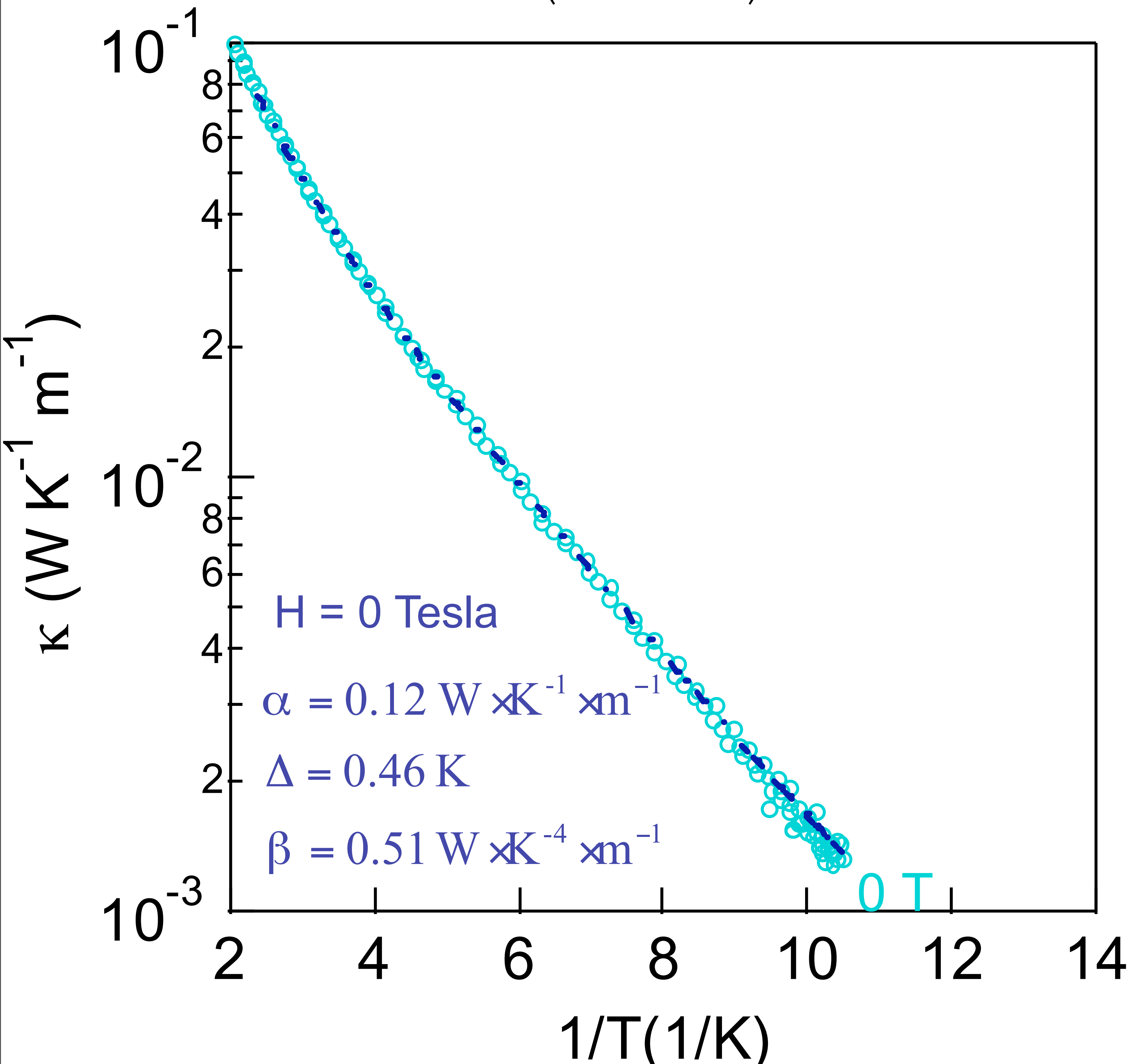
Thermal conductivity of κ-$(ET)_2Cu_2(CN)_3$

$$\kappa = \alpha \exp\left(-\Delta/_{k_B T}\right) + \beta T^3$$



- Arrhenius behavior for T < Δ !

- Tiny gap
  - ➢ Δ = 0.46 K ~ *J*/500

M. Yamashita *et al.*, *Nature Physics* **5**, 44 (2009)

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Outline

1. Classification of spin liquids

   Quantum-disordering magnetic order vs. projected Fermi sea

2. Quantum-disordering magnetic order

   Application to κ*-(ET)$_2$Cu$_2$(CN)$_3$*

3. Fermi surfaces of spinful Majorana fermions

   Candidate for EtMe$_3$Sb[Pd(dmit)$_2$]$_2$?

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Shastry-Kitaev Majorana representation

On each site, we introduce neutral Majorana fermions γ_{i0}, γ_{ix}, γ_{iy}, γ_{iz} which obey

$$\gamma_{i\alpha}\gamma_{j\beta} + \gamma_{j\beta}\gamma_{i\alpha} = 2\delta_{ij}\delta_{\alpha\beta}$$

We write the $S = 1/2$ spin operators as

$$\begin{aligned} S_{jx} &= \frac{i}{2}\gamma_{jy}\gamma_{jz} \\ S_{jy} &= \frac{i}{2}\gamma_{jz}\gamma_{jx} \\ S_{jz} &= \frac{i}{2}\gamma_{jx}\gamma_{jy} \end{aligned}$$

along with the constraint

$$\gamma_{j0}\gamma_{jx}\gamma_{jy}\gamma_{jz} = 1 \quad \text{for all } j$$

SU(2)-invariant spin liquids with neutral, spinful Majorana excitations

- Postulate an SU(2)-invariant effective Hamiltonian for physical $S = 1$ excitations created by Majorana fermions γ_{ix}, γ_{iy}, γ_{iz}.

Rudro Biswas, Liang Fu, Chris Laumann, and S. Sachdev, to appear

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- Ensure there is a Projective Symmetry Group (PSG) under which physical observables have the full translational symmetry of the triangular lattice.

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- Examine stability of the effective Hamiltonian to gauge fluctuations.

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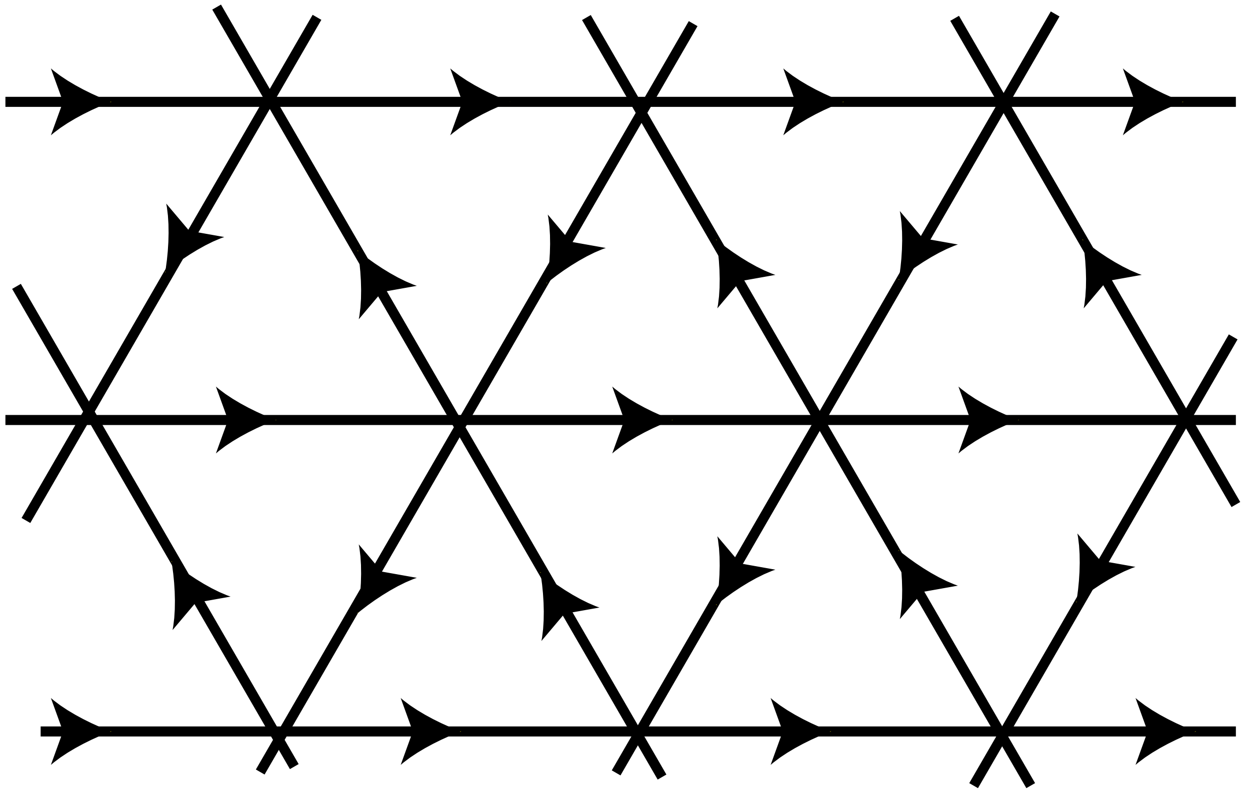
Majorana fermions on the triangular lattice

$$H = -i \sum_{\alpha=x,y,z} \sum_{i<j} t_{ij} \gamma_{i\alpha} \gamma_{j\alpha}$$

where t_{ij} is an anti-symmetric matrix with the following symmetry



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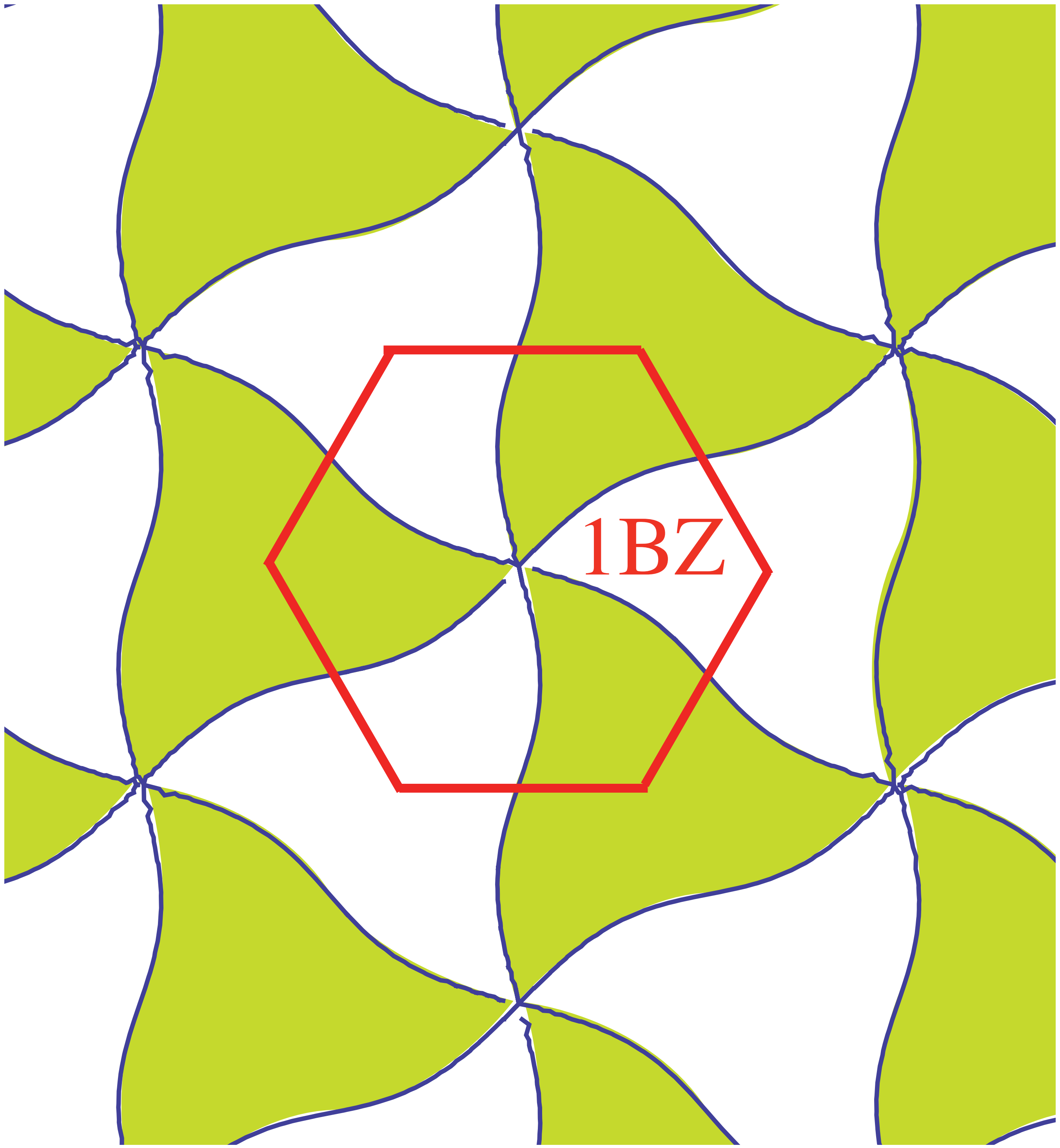
Fermi surfaces

The Majorana fermions generically have Fermi surfaces with the structure shown. 6 Fermi surface lines intersect at $\mathbf{k} = 0$, and the excitation energy $\sim k^3$ as $\mathbf{k} \to 0$.



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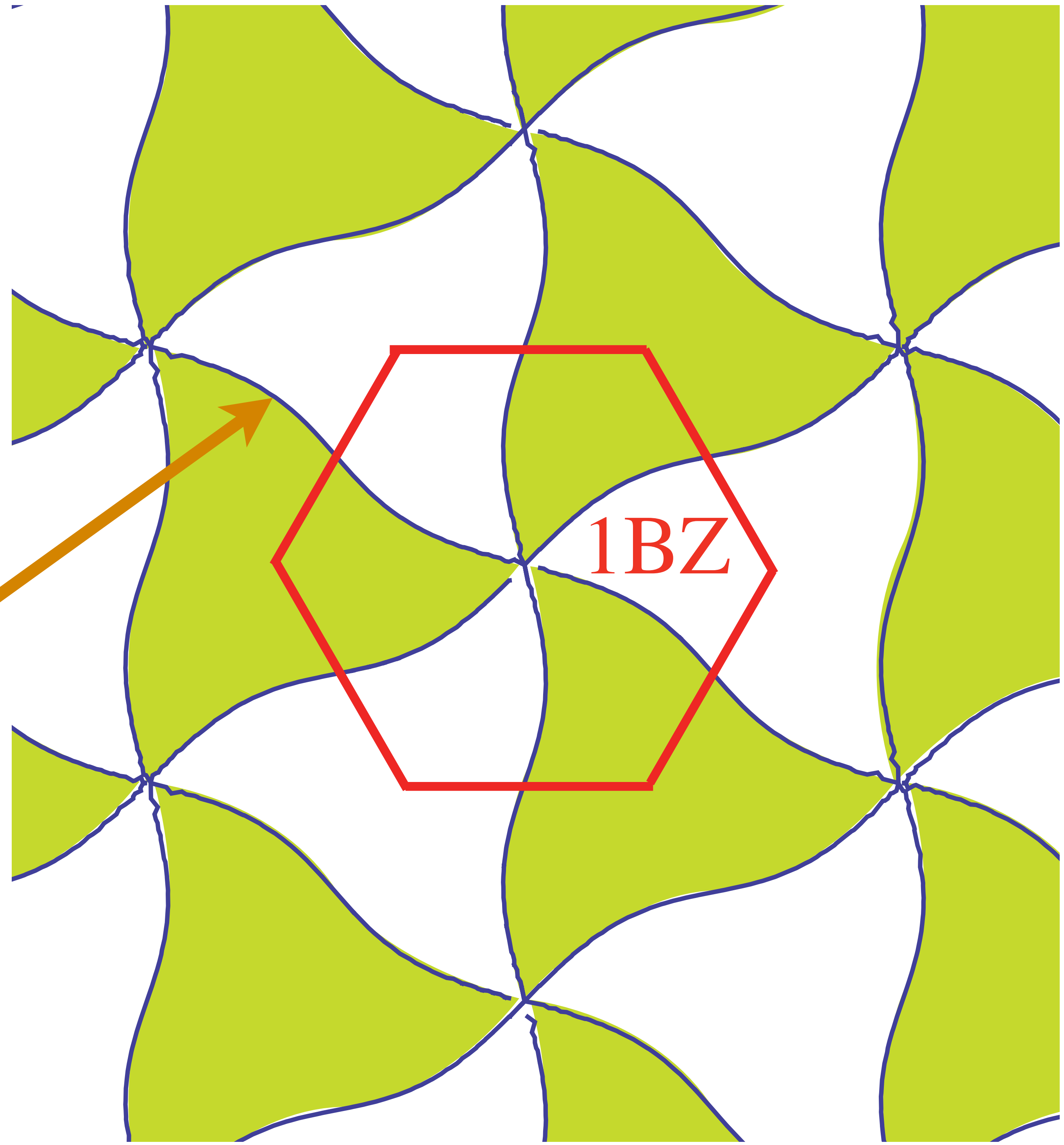
Excitation $\sim k - k_F$



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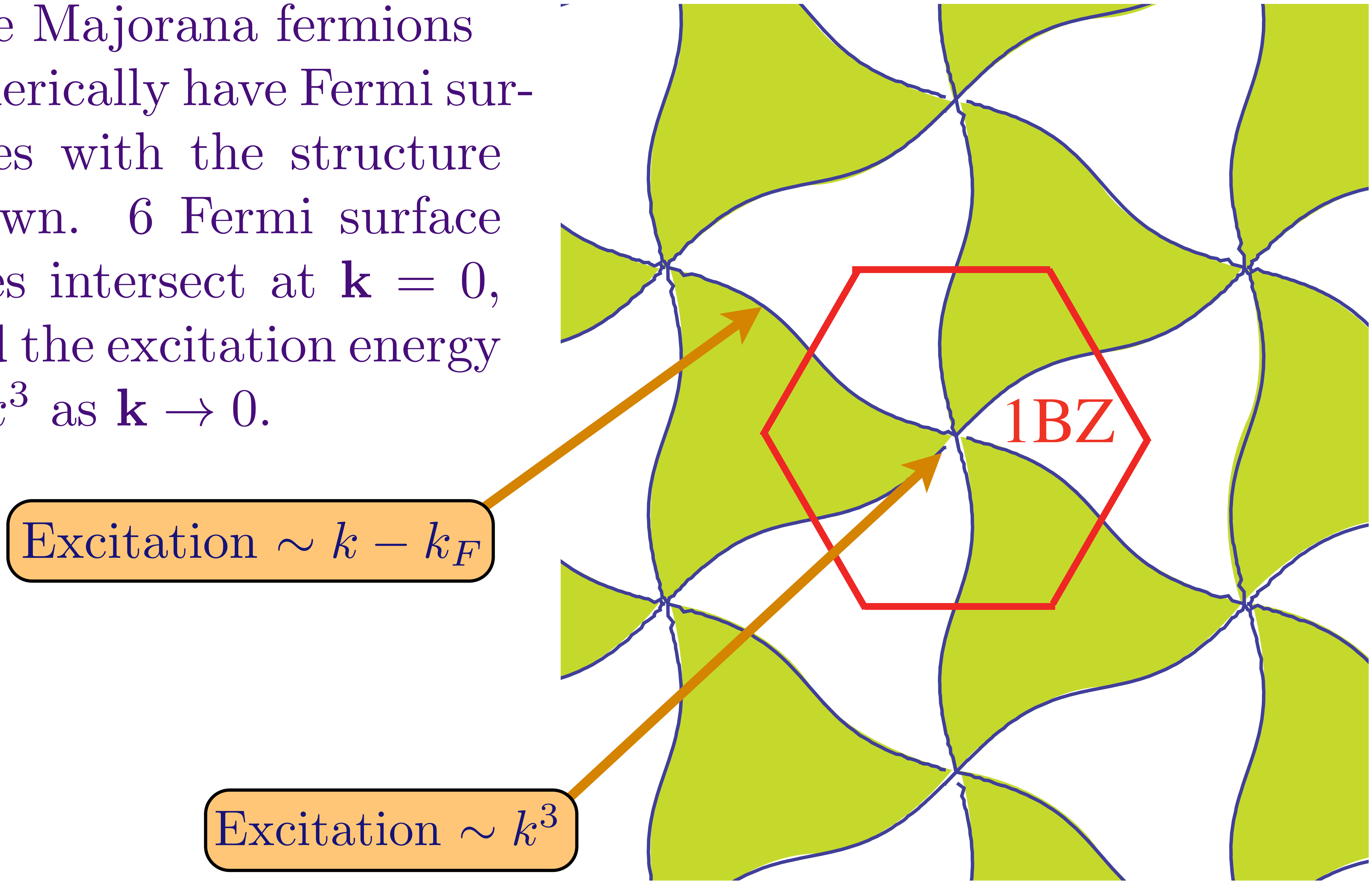

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- There is no thermal Hall transport.

Rudro Biswas, Liang Fu, Chris Laumann, and S. Sachdev, to appear

Conclusions

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- Proposed novel spin liquid with Fermi surfaces of spinful Majorana fermions