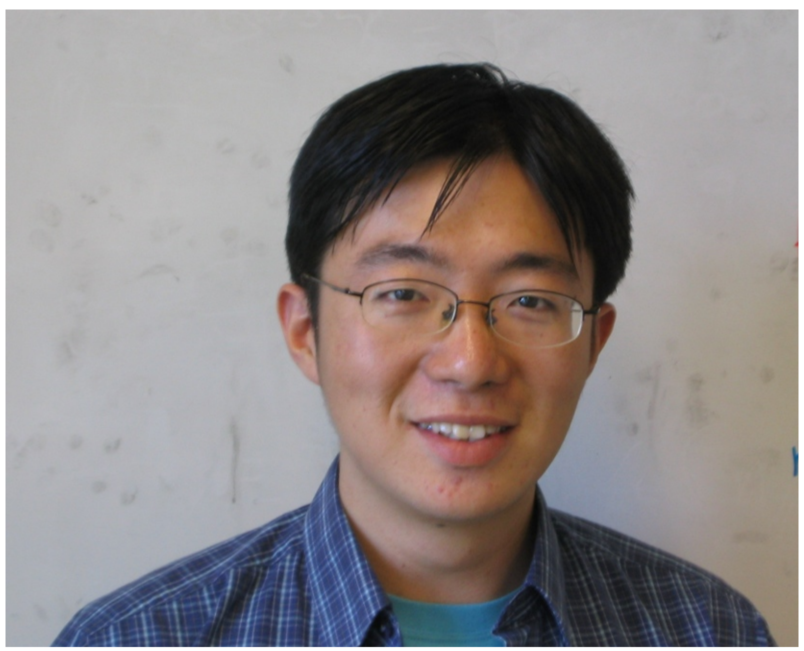
Global phase diagrams of two-dimensional quantum antiferromagnets



Cenke Xu

Yang Qi

Subir Sachdev

Harvard University

Outline

1. Review of experiments

   Phases of the S=1/2 antiferromagnet on the anisotropic triangular lattice

2. The Z_2 spin liquid and its excitations

   Spinons and visons

3. Field theory for spinons and visons

   Berry phases and the doubled Chern-Simons theory

4. Is κ-(ET)$_2$Cu$_2$(CN)$_3$ a Z_2 spin liquid ?

   Thermal conductivity of κ-(ET)$_2$Cu$_2$(CN)$_3$

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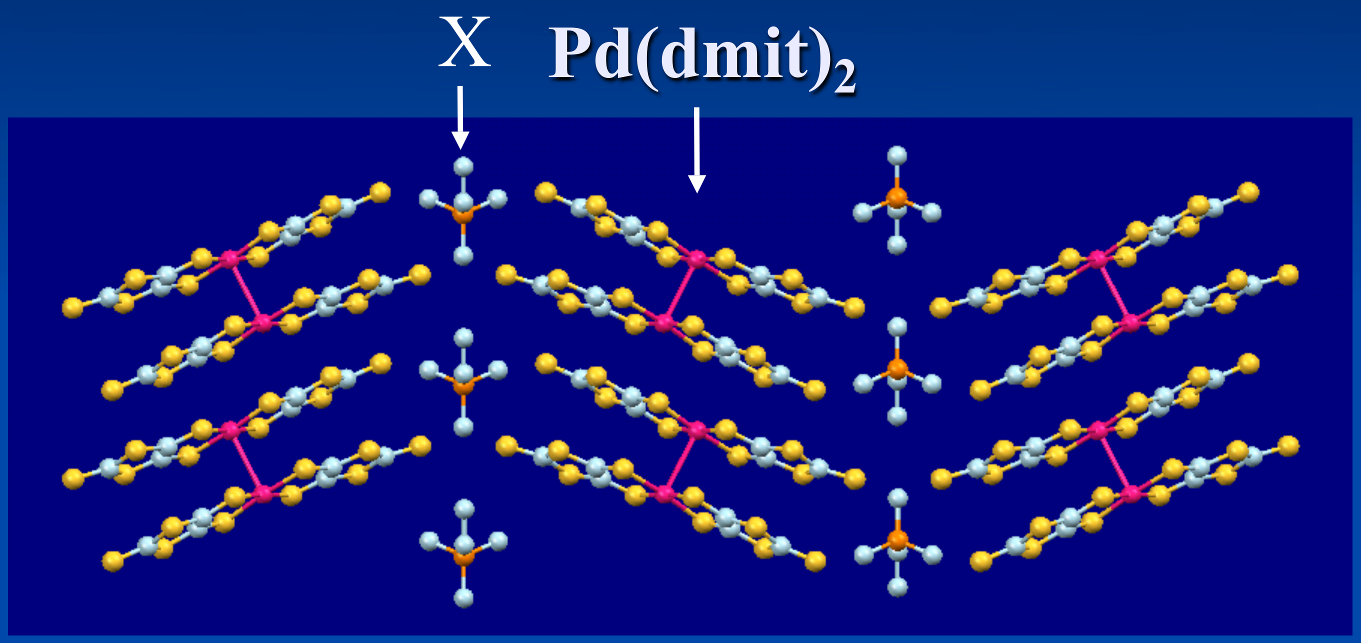
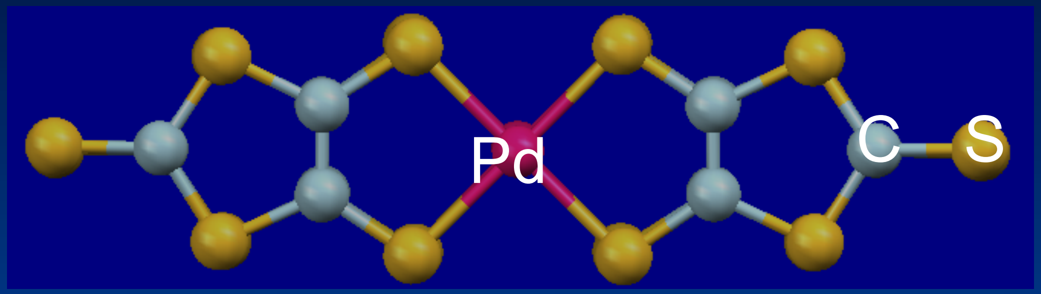
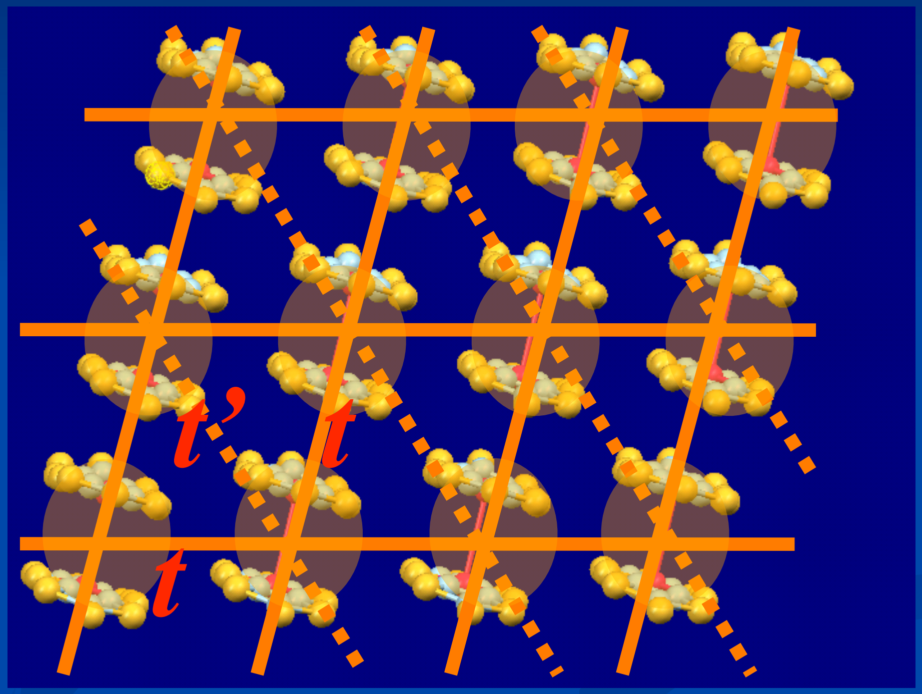
   Thermal conductivity of κ-$(ET)_2Cu_2(CN)_3$

X[Pd(dmit)$_2$]$_2$





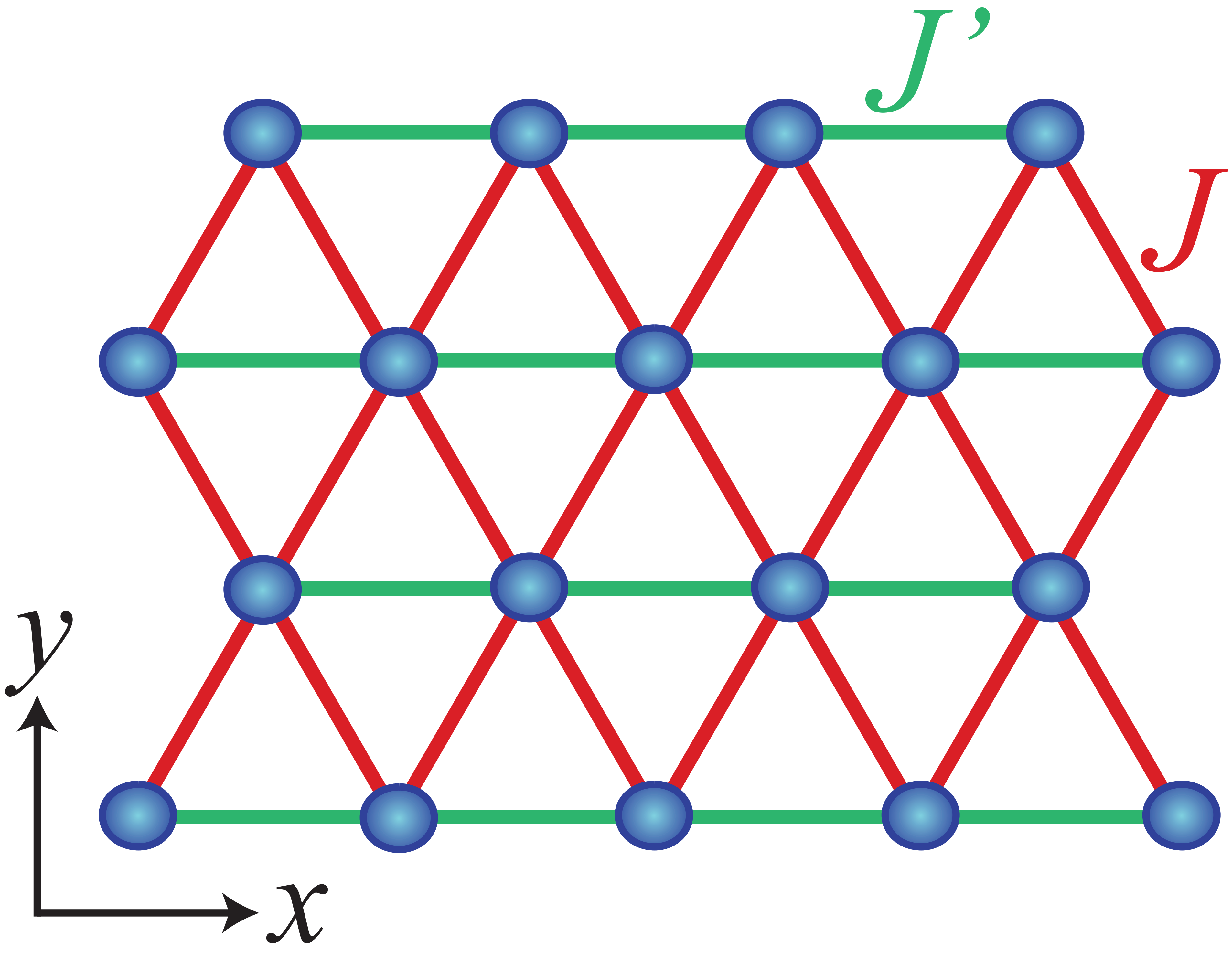


Half-filled band → Mott insulator with spin S = 1/2

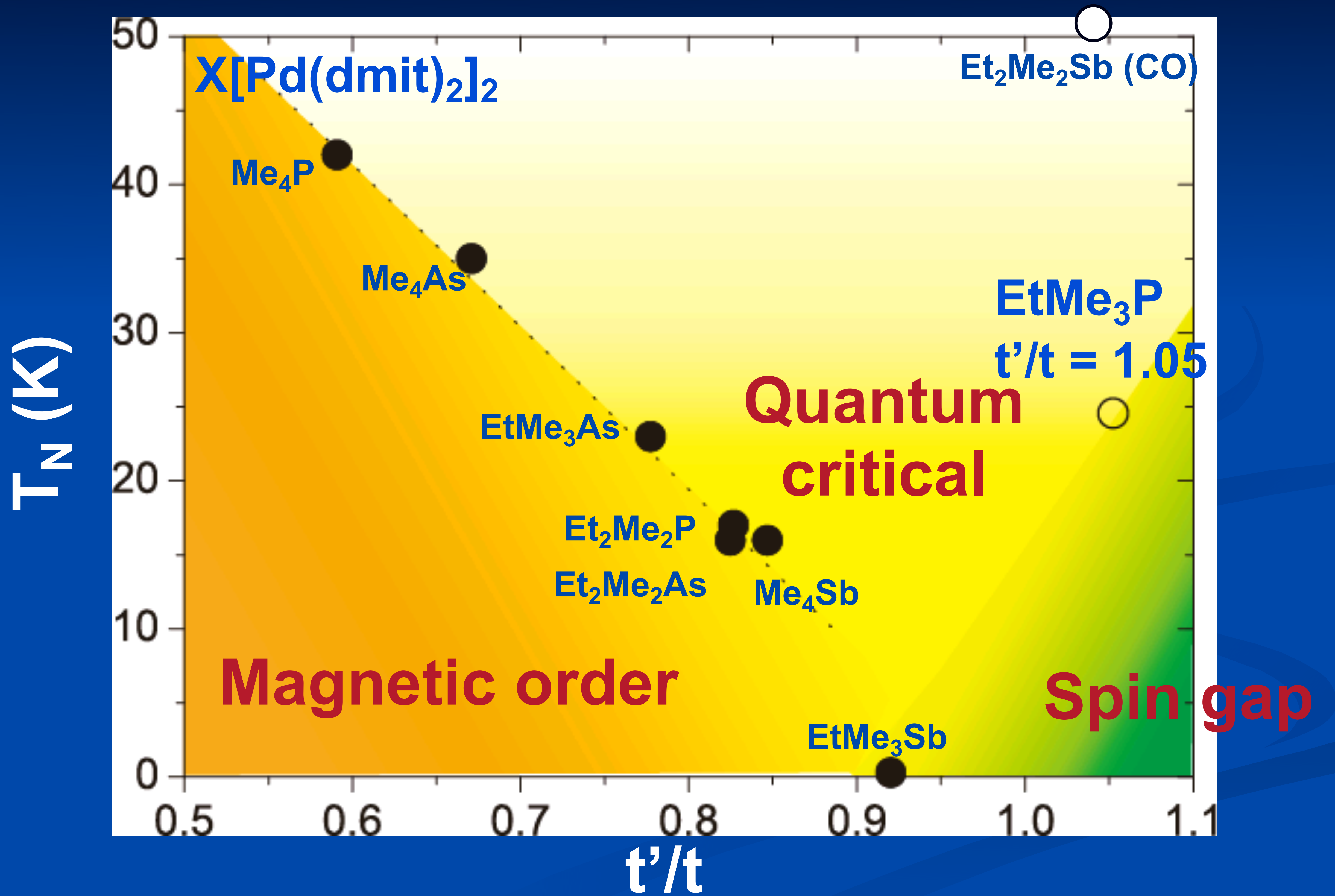
Triangular lattice of [Pd(dmit)$_2$]$_2$

→ frustrated quantum spin system

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

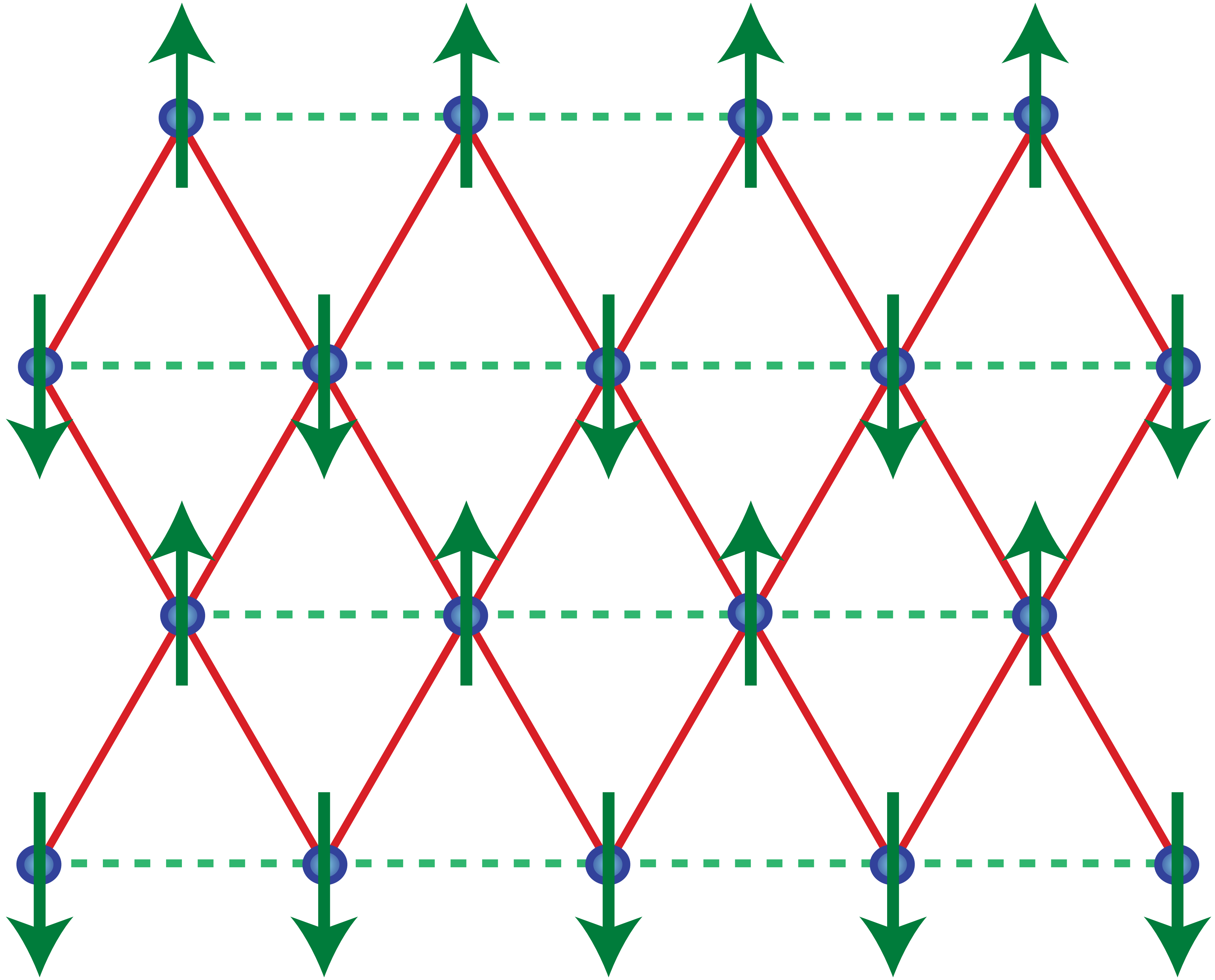


Magnetic Criticality



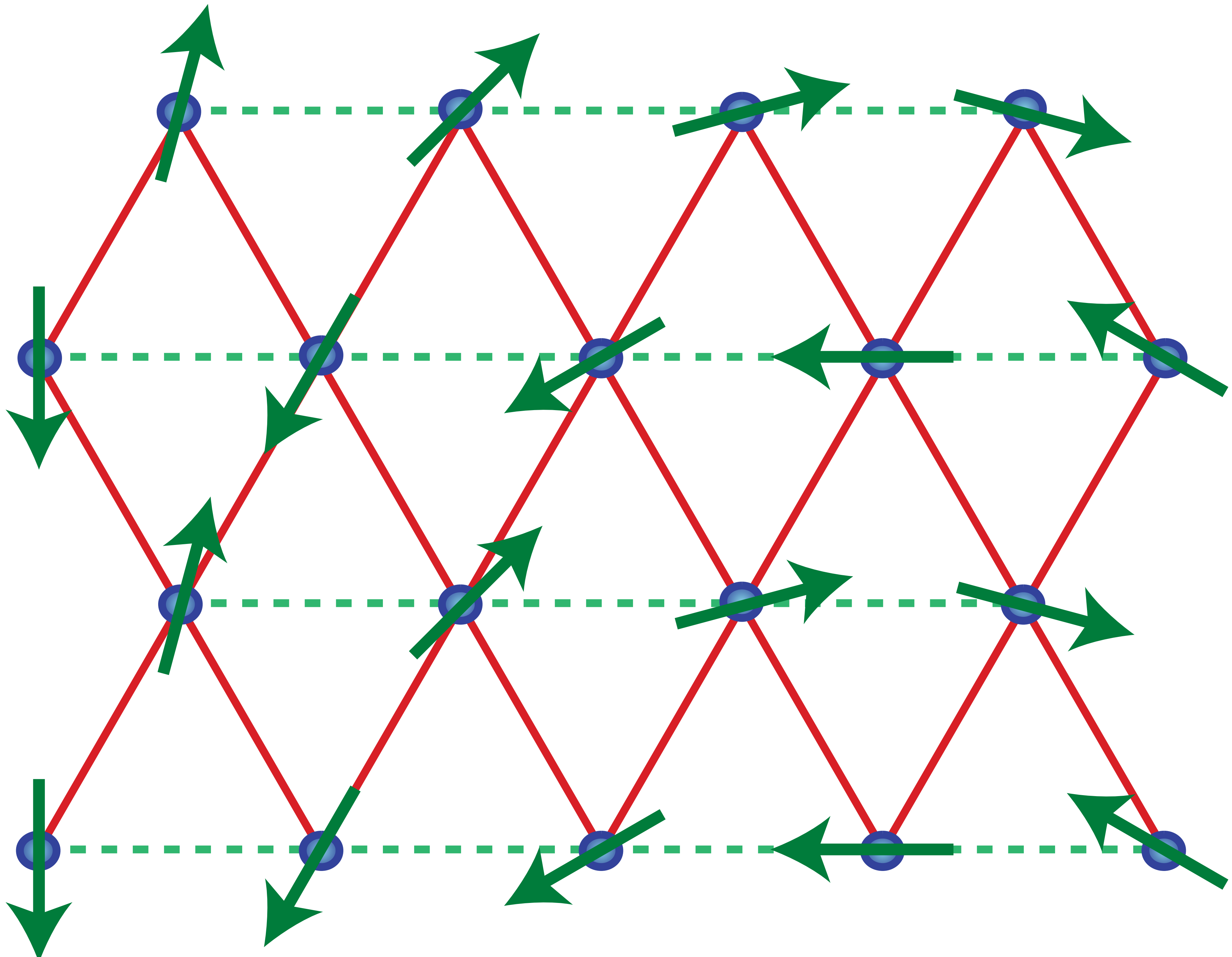
Y. Shimizu, H. Akimoto, H. Tsujii, A. Tajima, and R. Kato, *J. Phys.: Condens. Matter* **19**, 145240 (2007)

Anisotropic triangular lattice antiferromagnet



Classical ground state for small J'/J

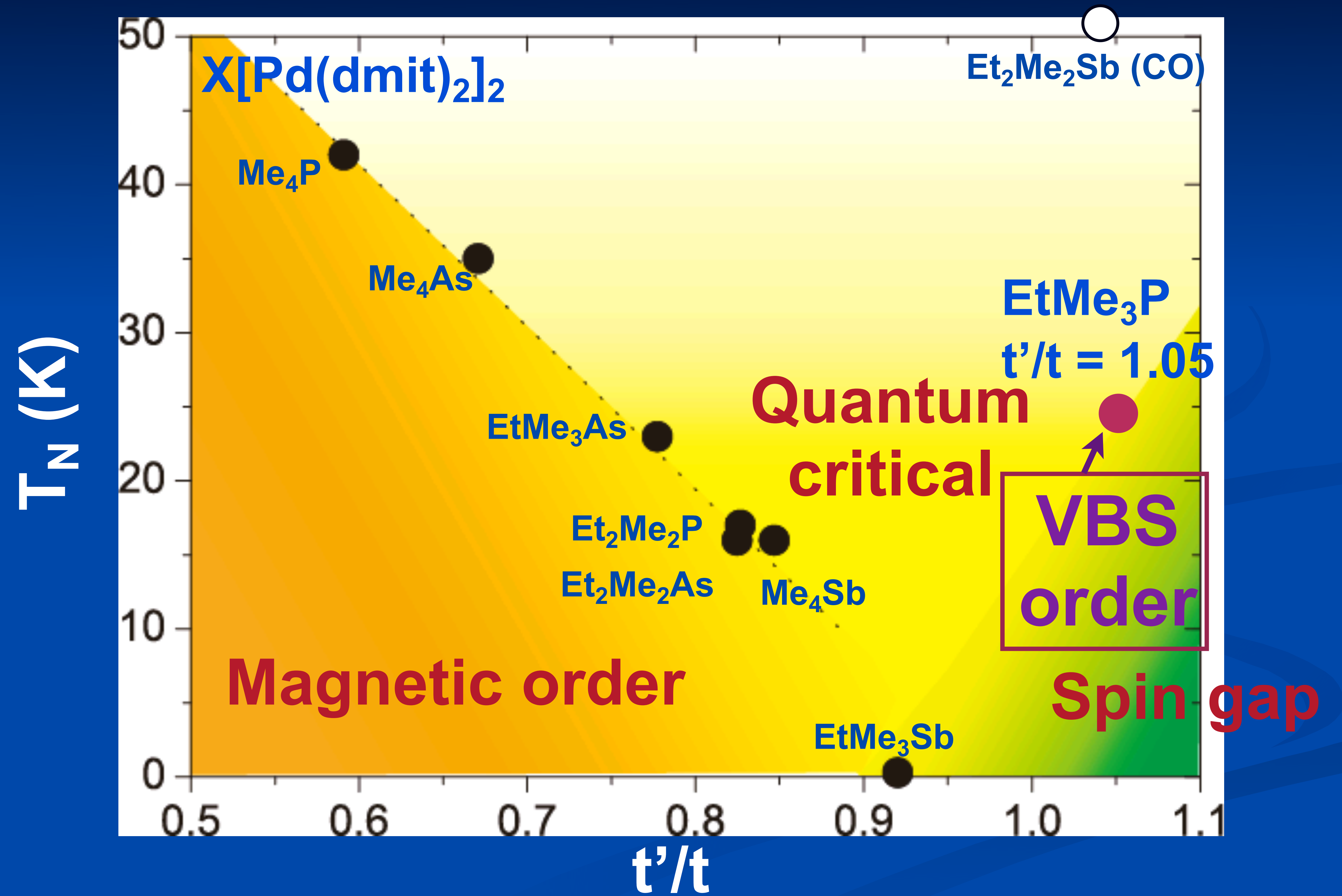
Anisotropic triangular lattice antiferromagnet



Classical ground state for large J'/J

Found in Cs_2CuCl_4

Magnetic Criticality



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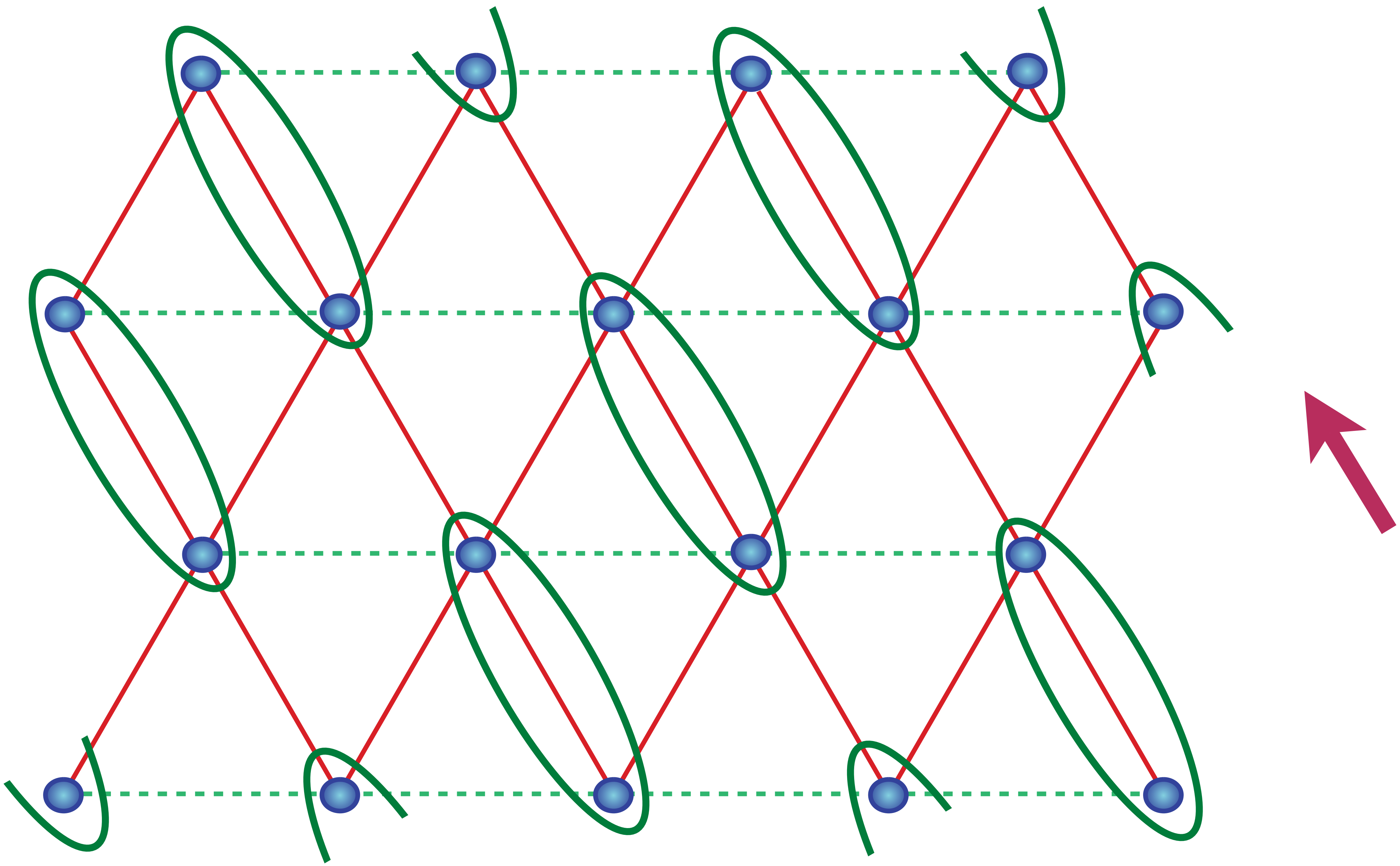
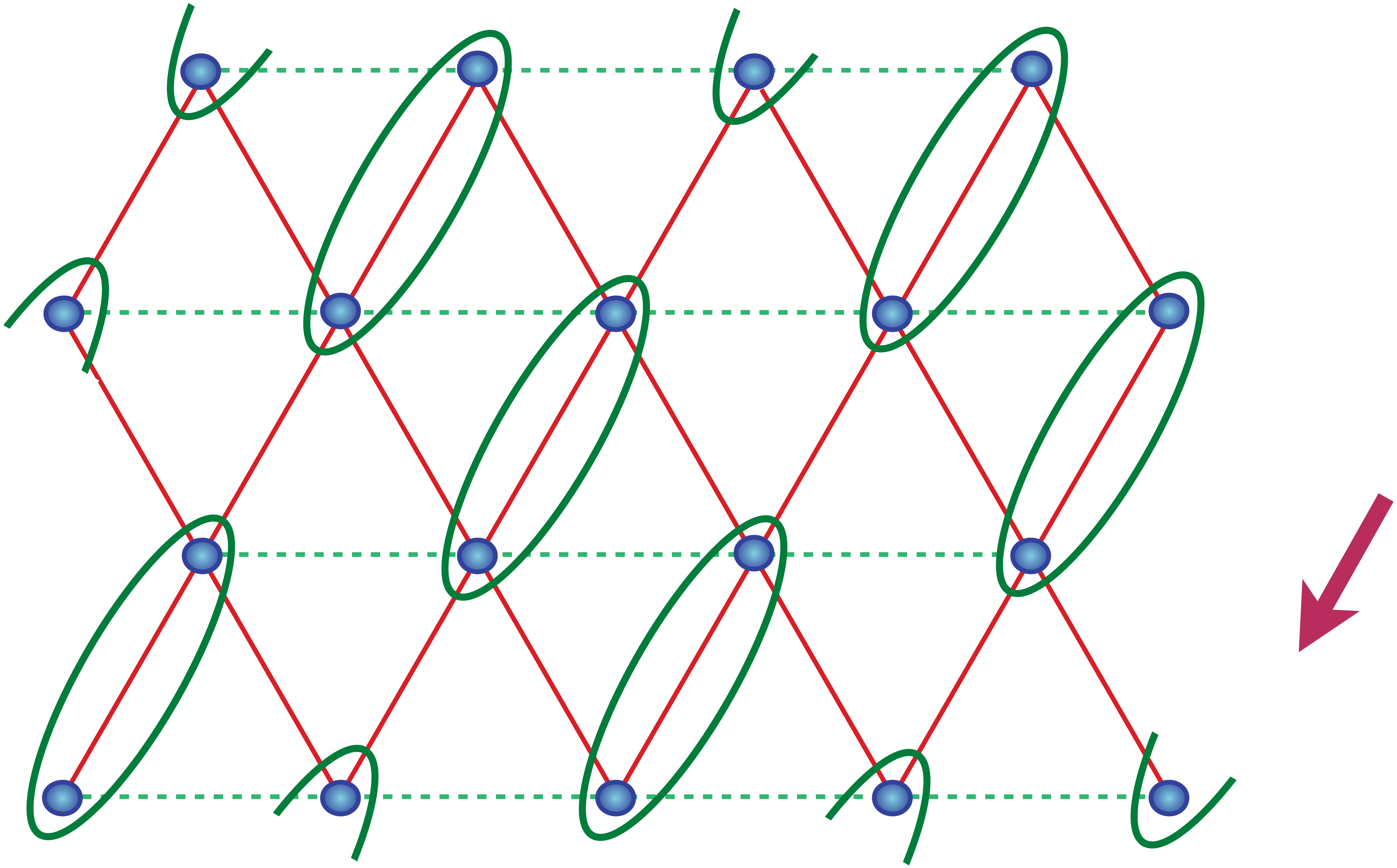


Valence bond solid

Anisotropic triangular lattice antiferromagnet



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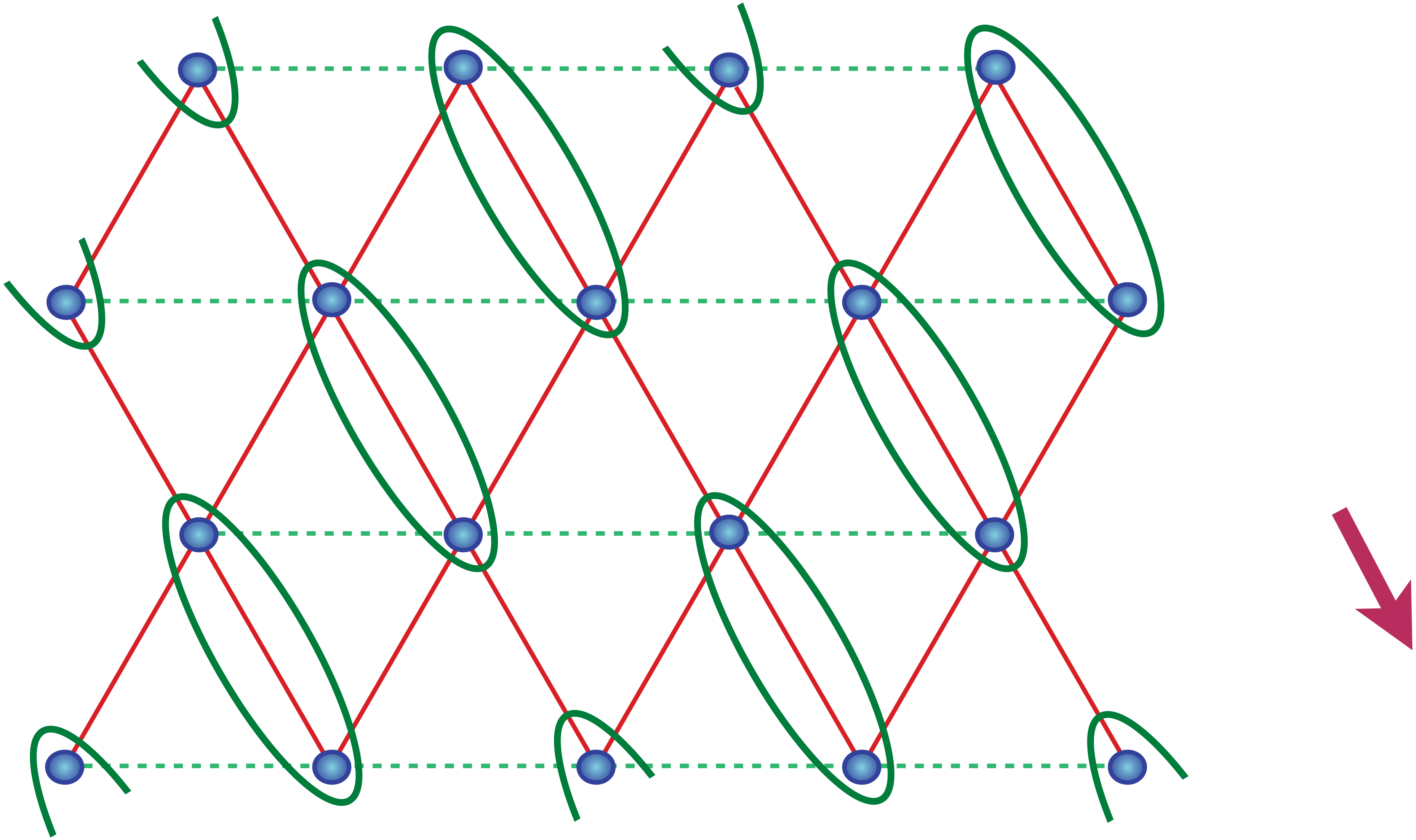

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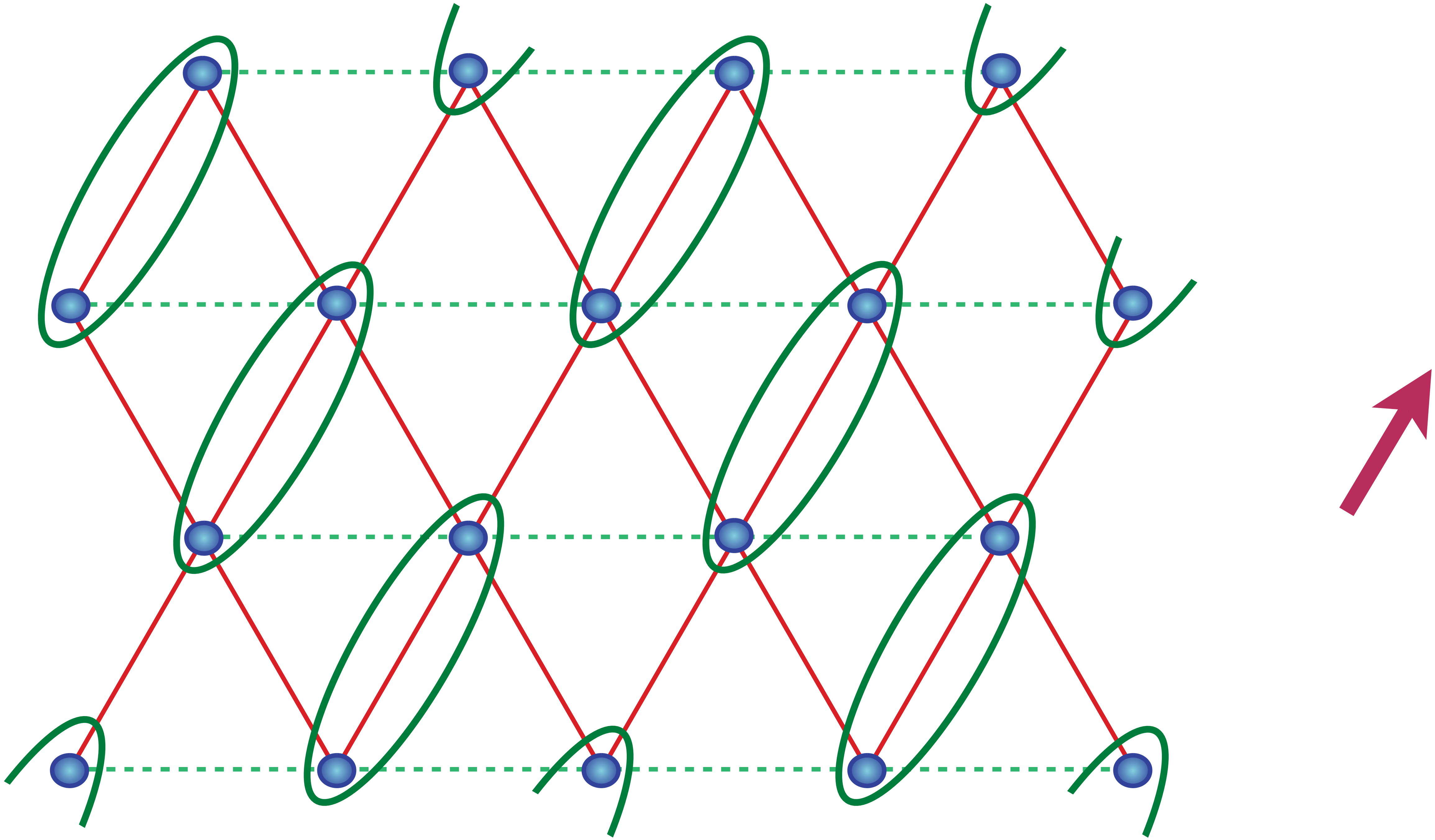
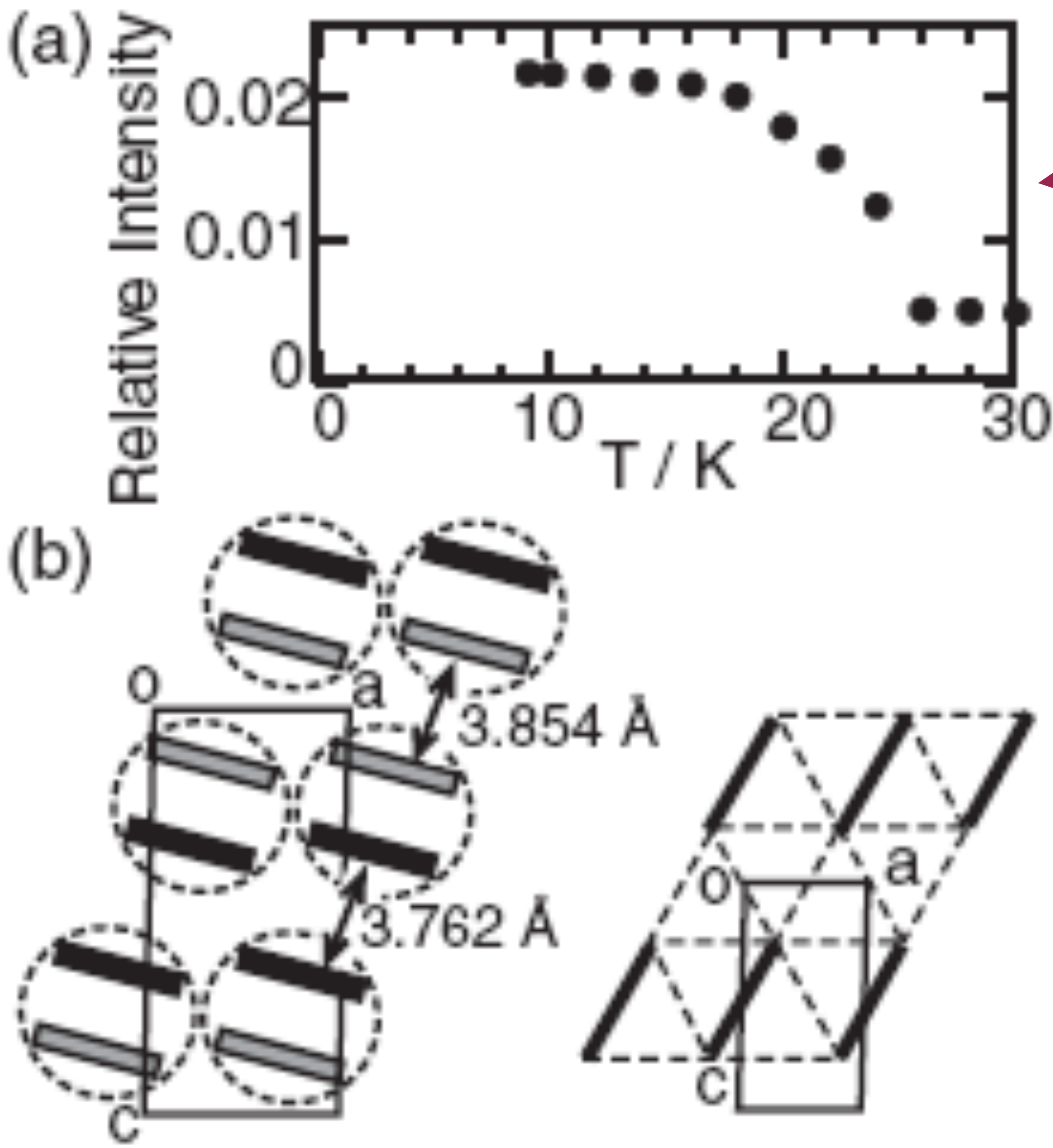


Valence bond solid

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)

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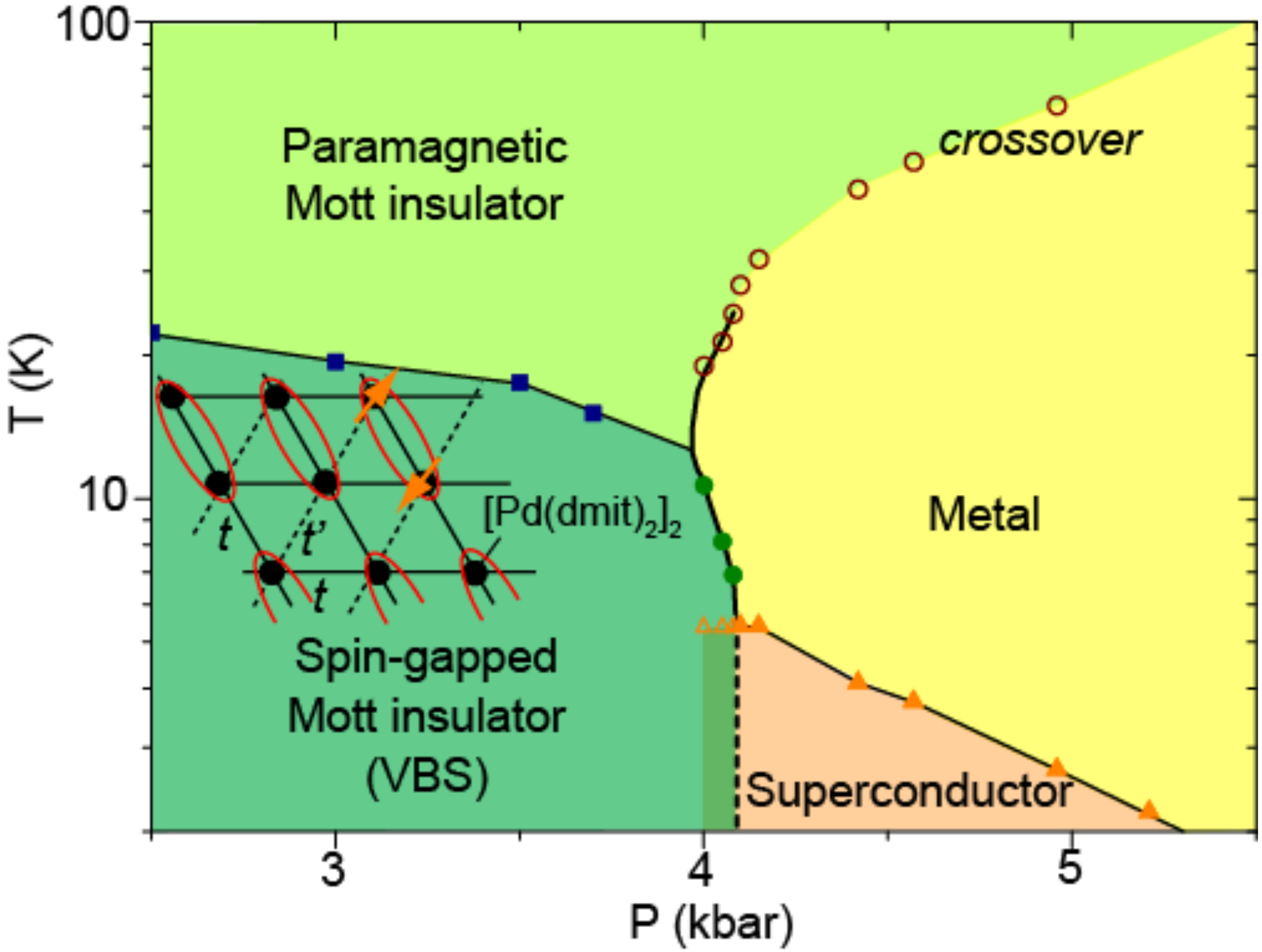

Pressure-temperature phase diagram

M. Tamura, A. Nakao and R. Kato, *J. Phys. Soc. Japan* **75**, 093701 (2006)
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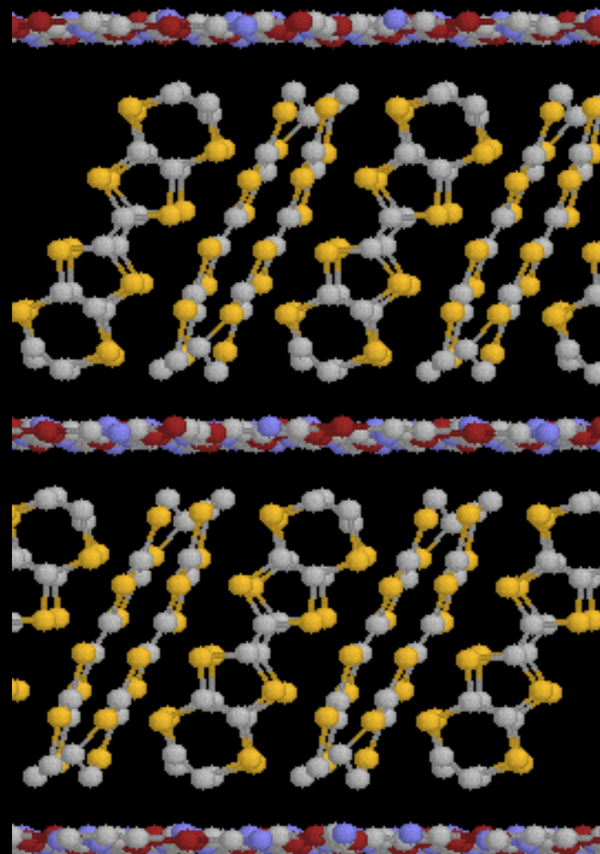
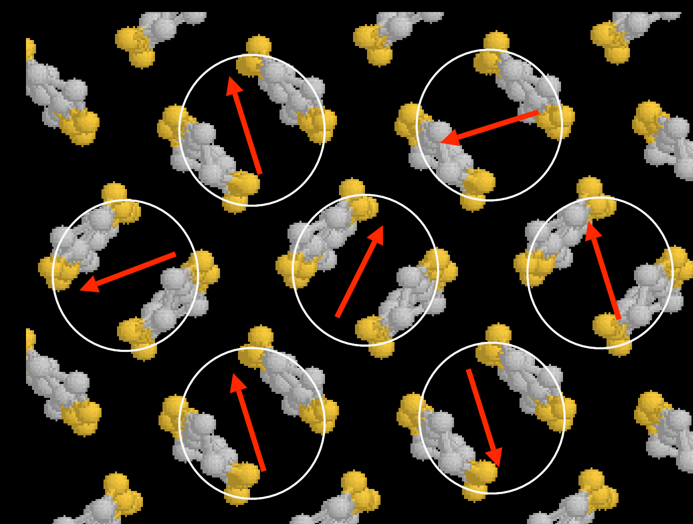
Q2D organics κ-$(ET)_2X$; spin-1/2 on triangular lattice

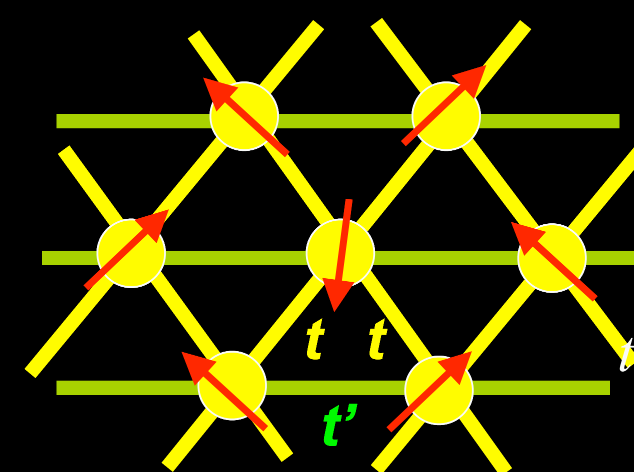
ET layer

X layer





Kino & Fukuyama dimer model

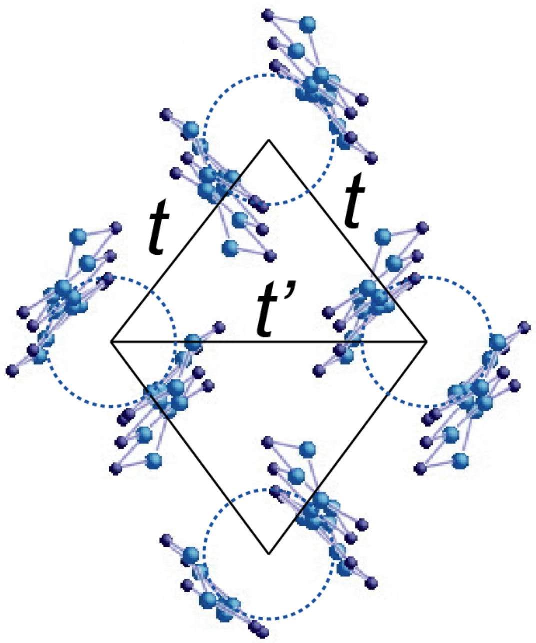


$t'/t = 0.5 \sim 1.1$

Triangular lattice
Half-filled band

X^-	Ground State	t'/t
$Cu_2(CN)_3$	Mott insulator	1.06
$Cu[N(CN)_2]Cl$	Mott insulator	0.75
$Cu[N(CN)_2]Br$	SC	0.68
$Cu(NCS)_2$	SC	0.84

κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$

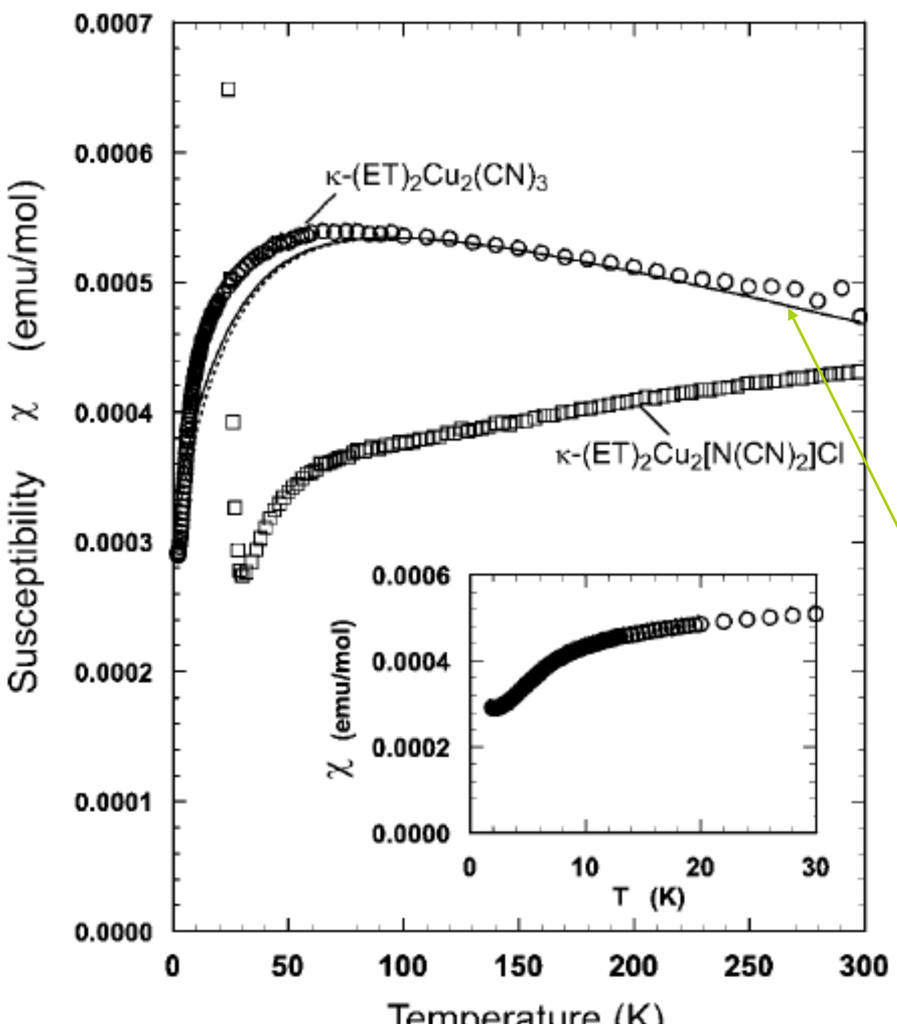


•face-to-face pairs of BEDT-TTF molecules form dimers by strong coupling.

•Dimers locate on a vertex of triangular lattice and ratio of the transfer integral is ~1.

$$t'/t = 1.06, \; U/t = 8.2$$

•Charge +1 for each ET dimer; Half-filling Mott insulator.



•Cu$_2$[N(CN)$_2$]Cl (t'/t = 0.75, U/t = 7.8)
Néel order at T_N=27 K

•Cu$_2$(CN)$_3$ (t'/t = 1.06. U/t = 8.2)
No sign of magnetic order down to 1.9 K.

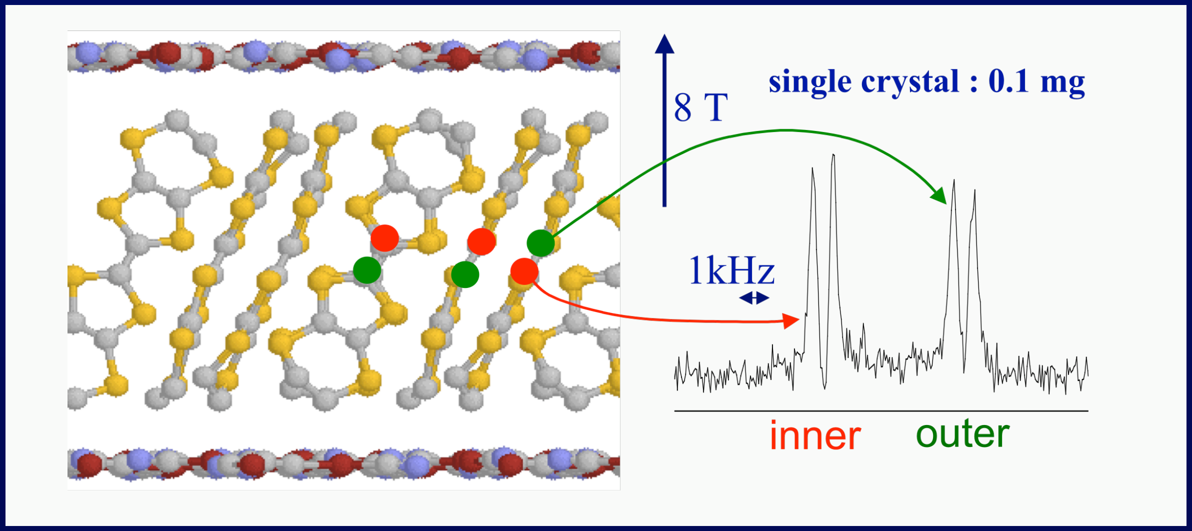
Heisenberg High-T Expansion
(PRL, **71** 1629 (1993))
J ~ 250 K

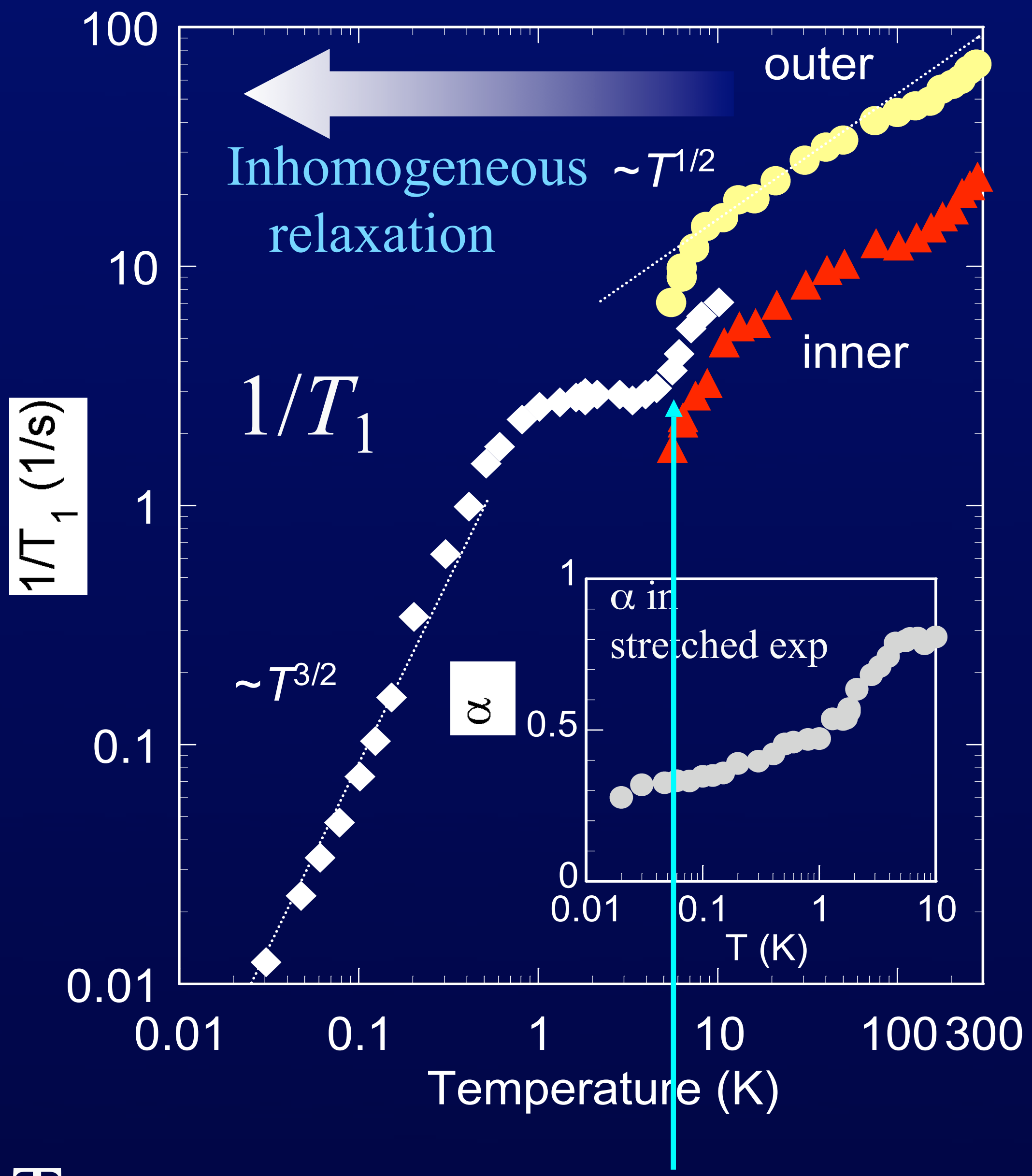
Y. Shimizu etal, PRL **91**, 107001 (2003)

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

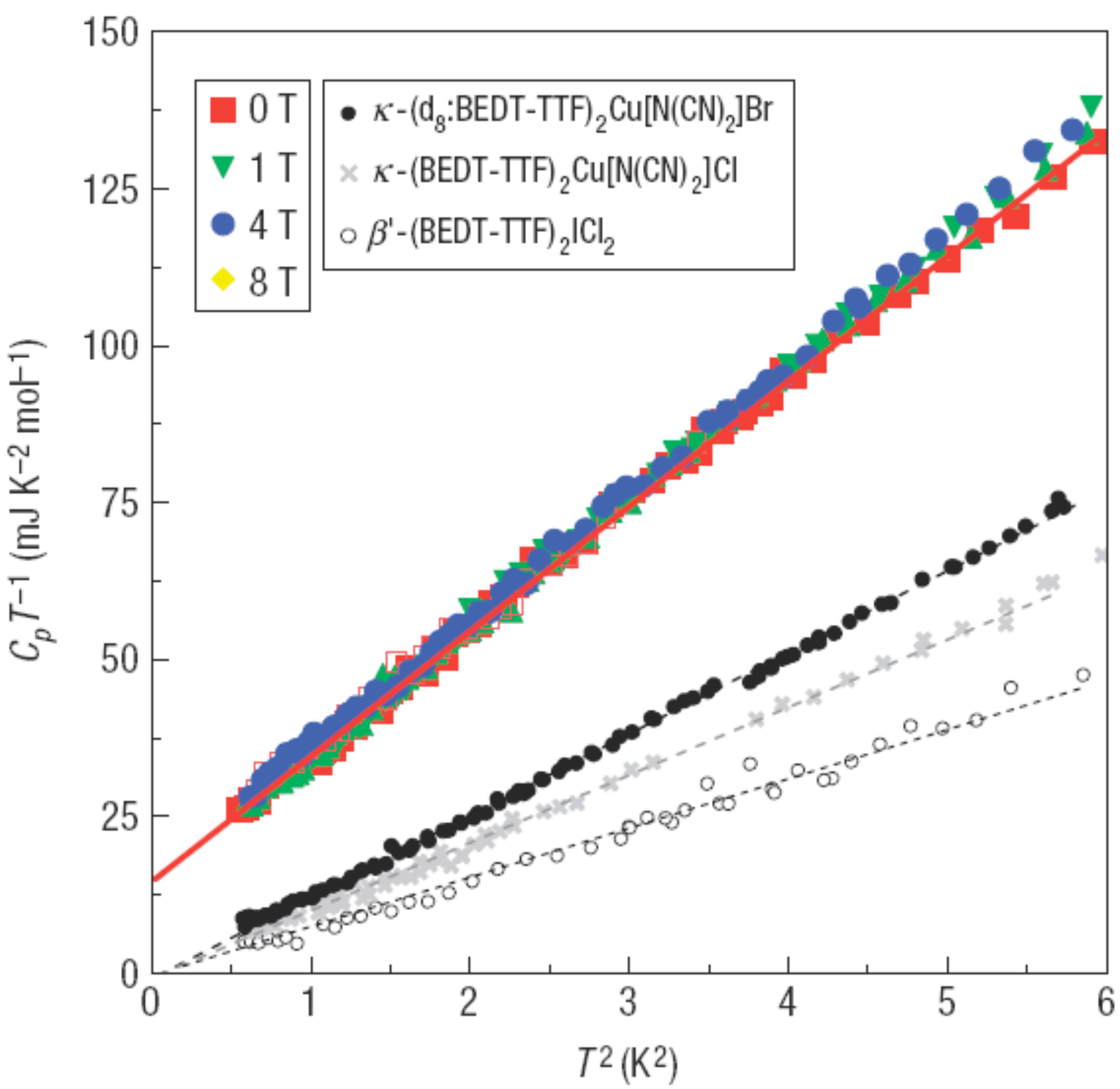
Heat capacity measurements

Thermodynamic properties of a spin-1/2 spin-liquid state in a κ-type organic salt

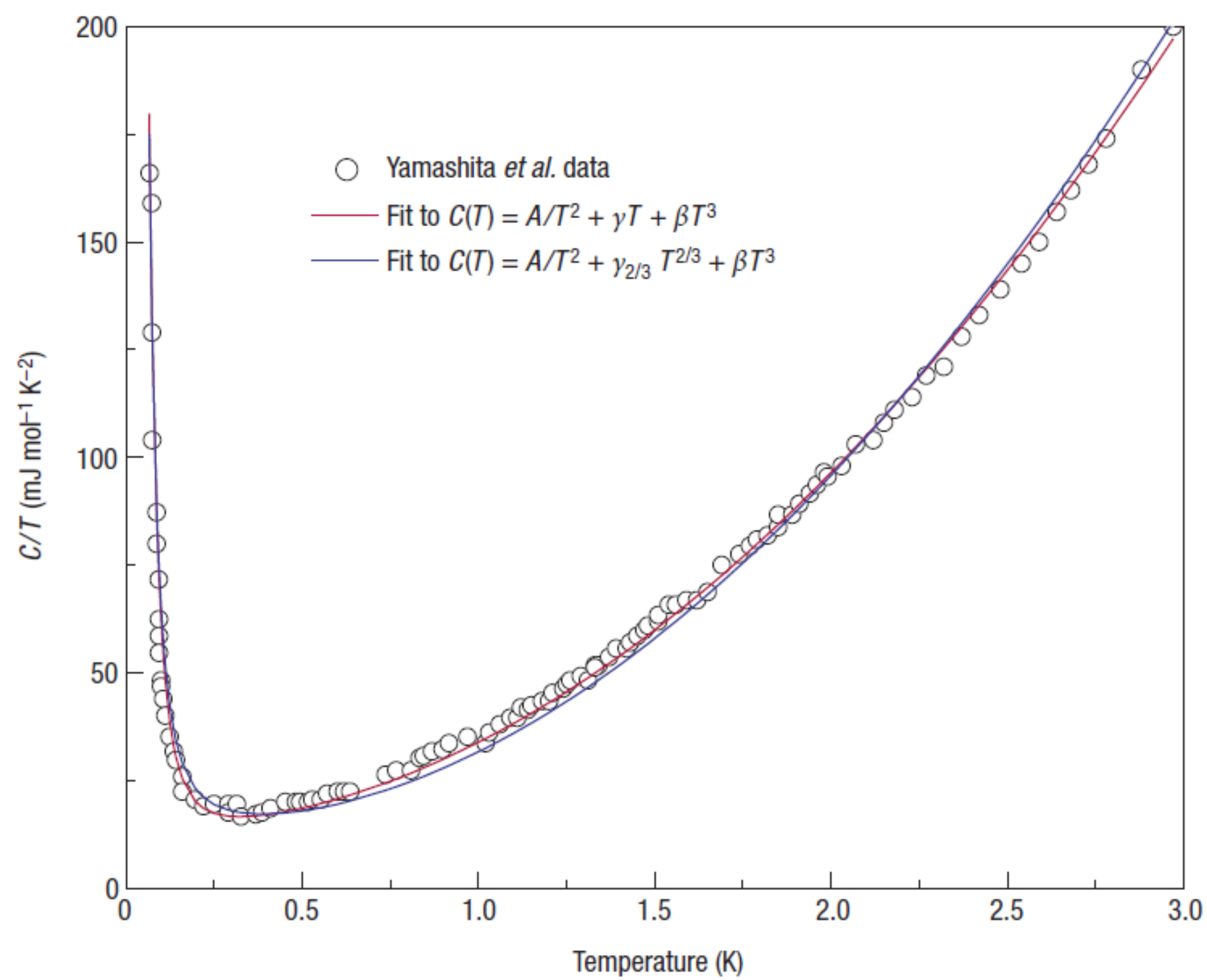
SATOSHI YAMASHITA[1], YASUHIRO NAKAZAWA[1,2*], MASAHARU OGUNI[3], YUGO OSHIMA[2,4], HIROYUKI NOJIRI[2,4], YASUHIRO SHIMIZU[5], KAZUYA MIYAGAWA[2,6] AND KAZUSHI KANODA[2,6]

$$\gamma = 15 \,\mathrm{mJ}/\mathrm{K^2 mol}$$

Evidence for Gapless spinon?



S. Yamashita, et al., Nature Physics **4**, 459 - 462 (2008)



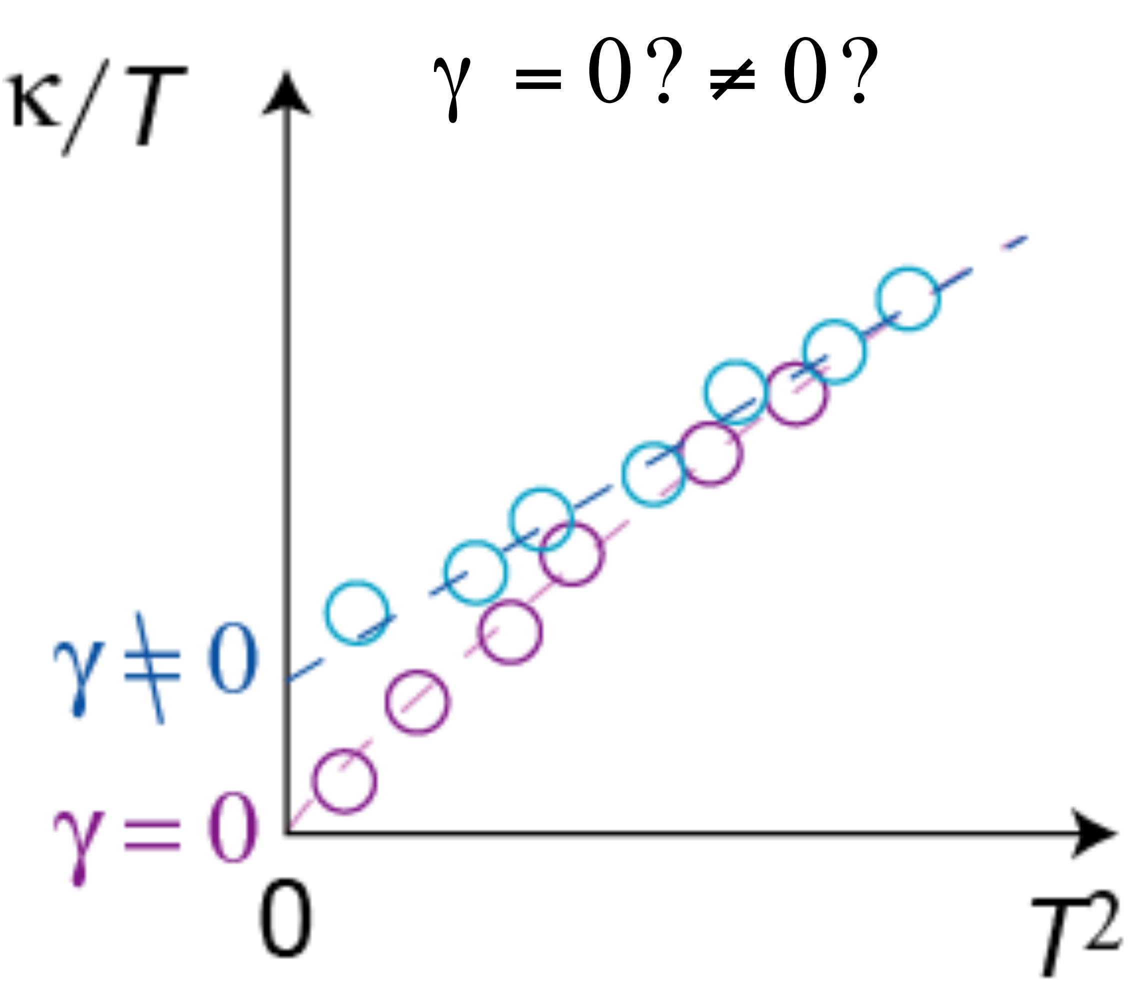
A. P. Ramirez, Nature Physics **4**, 442 (2008)

Thermal-Transport Measurements

Only itinerant excitations carrying entropy can be measured without localized ones

- no impurity contamination
  - $1/T_1$, χ measurement ← free spins
  - Heat capacity ← Schottky contamination

Best probe to reveal the low-lying excitation at low temperatures.



$$\frac{\kappa}{T} \approx \frac{1}{T}\left(C \times v \times l\right) \propto \gamma + \beta T^2$$

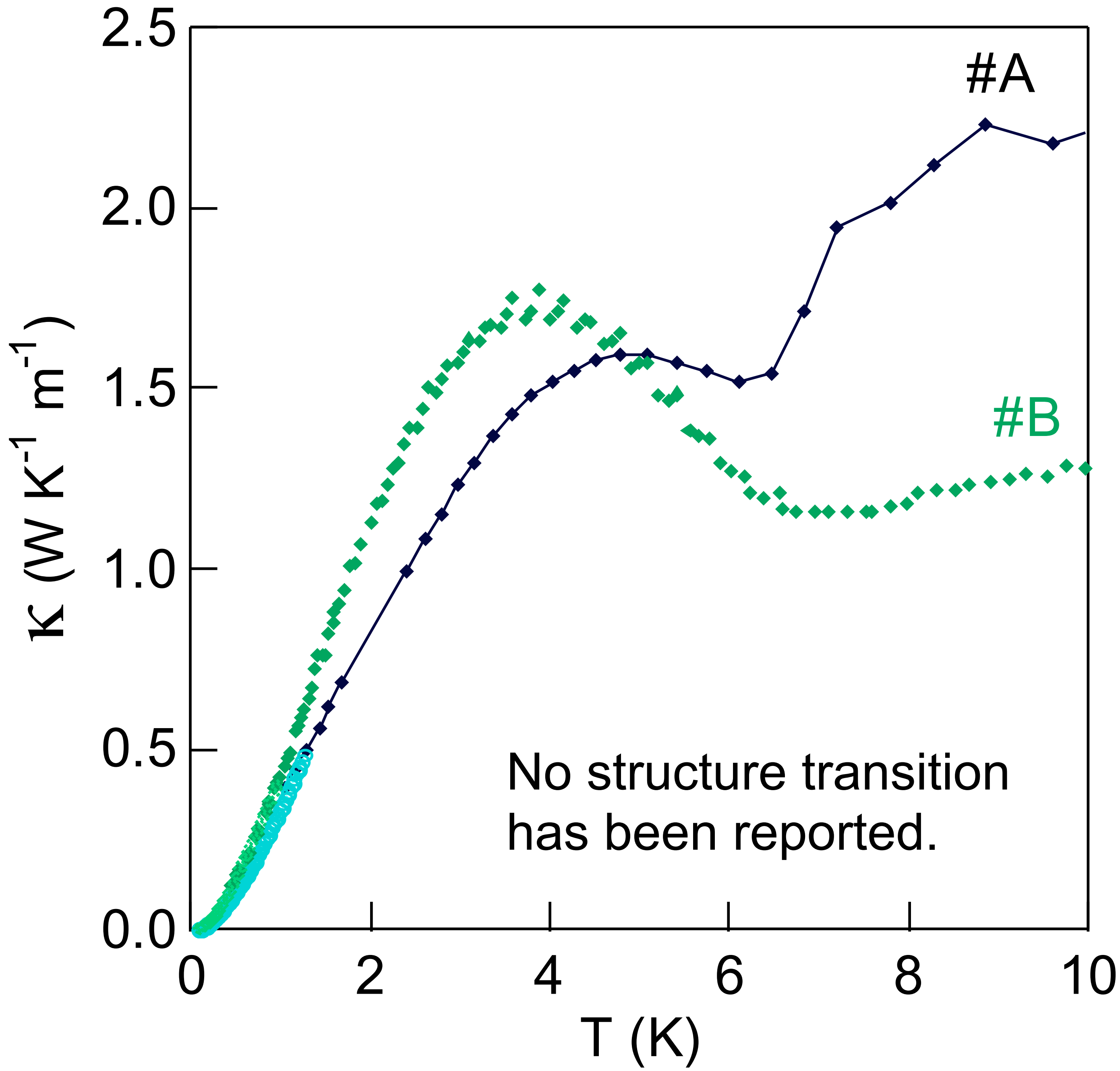
$C \propto \gamma T + \beta T^3$
γ : Gapless spin liquid (Spinon)
β : Phonon

•What is the low-lying excitation of the quantum spin liquid found in κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$.
•Gapped or Gapless spin liquid? Spinon with a Fermi surface?

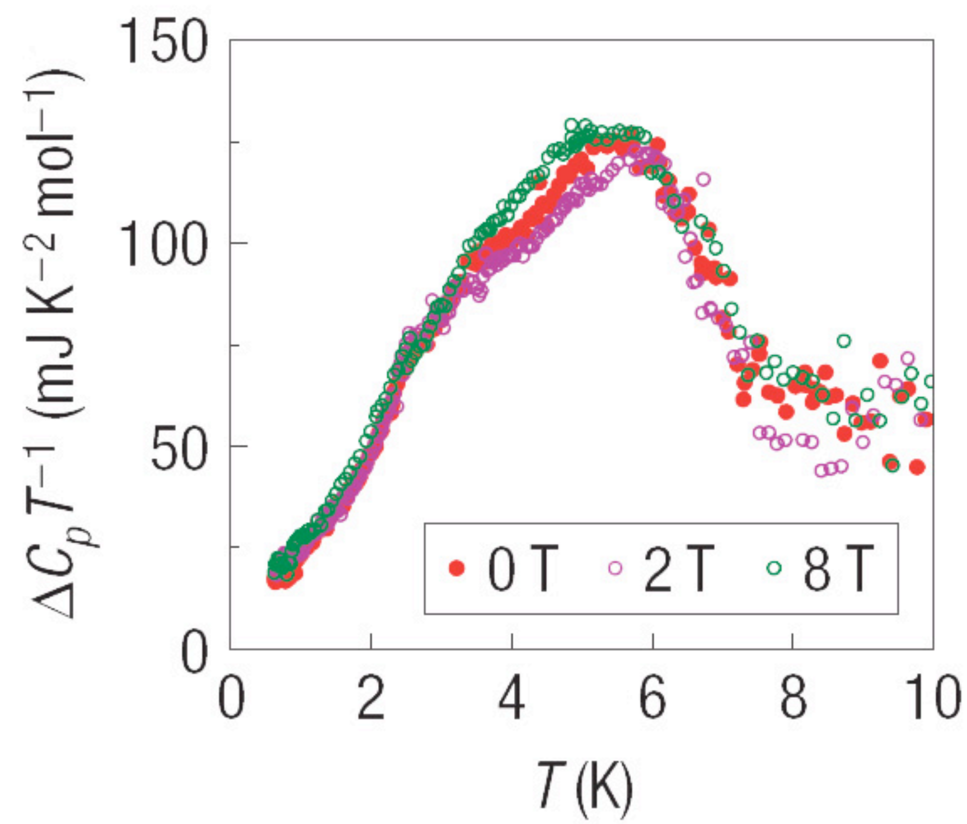
M. Yamashita *et al.*, Nature Physics online, doi:10.1038/nphys1134

Thermal Conductivity below 10K

κ vs. *T* below 10 K



Difference of heat capacity between X = $Cu_2(CN)_3$ and $Cu(NCS)_2$ (superconductor).



S. Yamashita, et al., Nature Physics **4**, 459 - 462 (2008)

Similar to

- $1/T_1$ by ^{1}H NMR
- Heat capacity

- Magnetic contribution to κ
- Phase transition or crossover?
  - Chiral order transition?
  - Instability of spinon Fermi surface?

M. Yamashita *et al.*, Nature Physics online, doi:10.1038/nphys1134

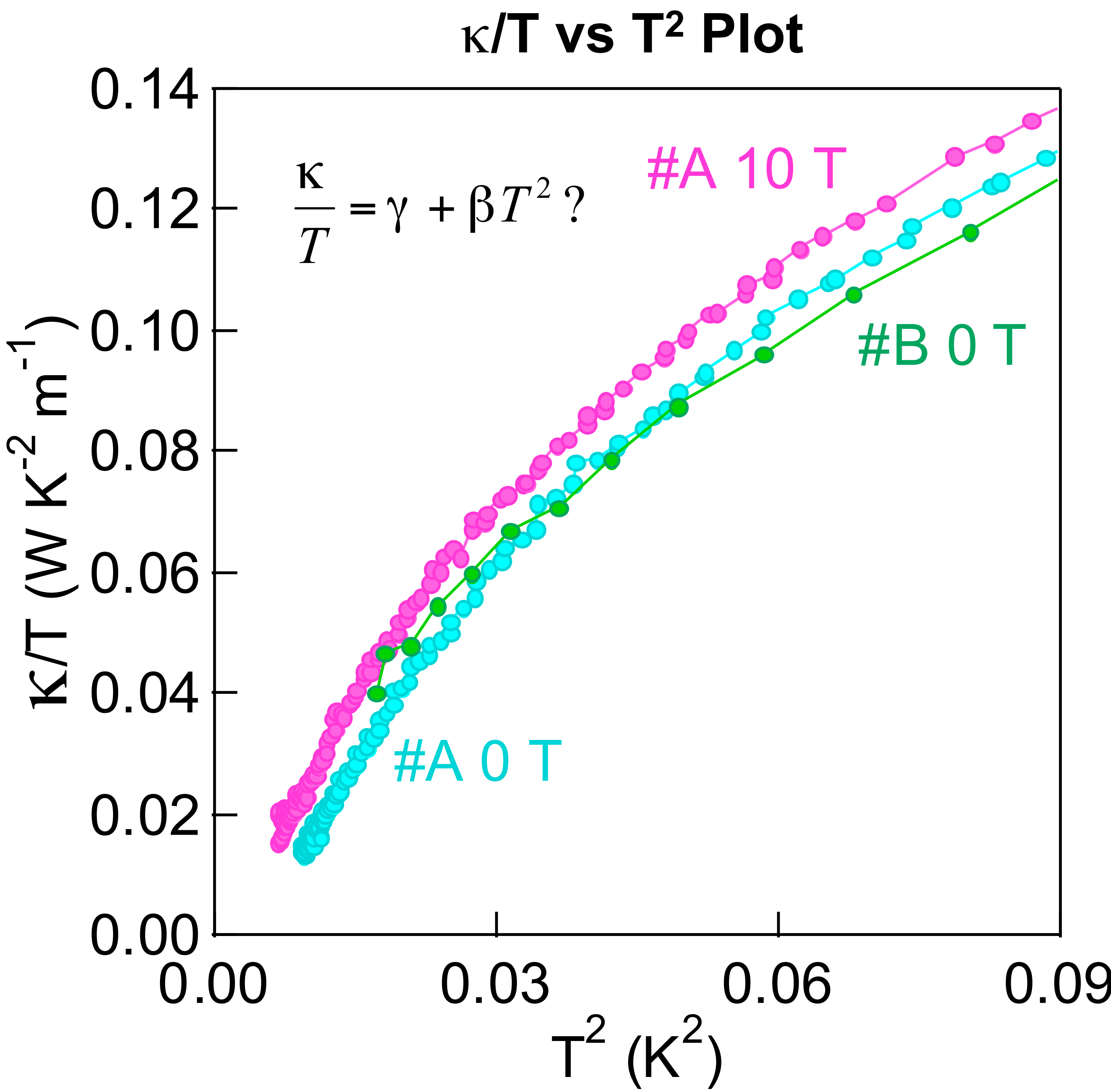
Thermal Conductivity below 300 mK

- Convex, non-T^3 dependence in κ
- Magnetic fields enhance κ

$$\kappa = \kappa_{phonon} + \kappa_{mag}$$

$(\kappa_{phonon} \propto T^3$ in low T)

Substantial portion of κ_{mag} in κ



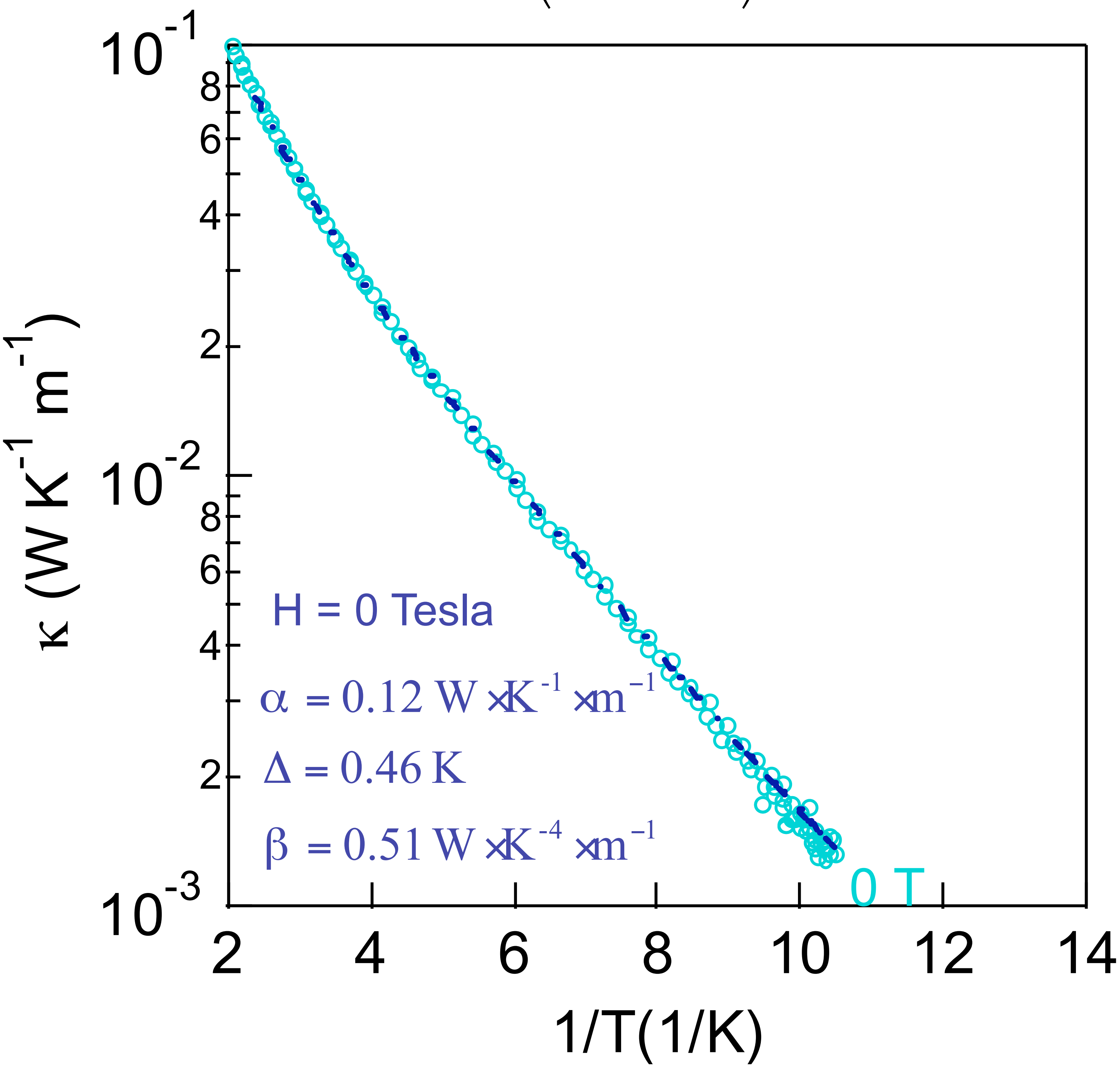
$\gamma = 0$

Note: phonon contribution has no effect on this conclusion.

M. Yamashita *et al.*, Nature Physics online, doi:10.1038/nphys1134

Arrhenius plot

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



- Arrhenius behavior for T < Δ !
- Tiny gap
  - Δ = 0.46 K ~ *J*/500

M. Yamashita *et al.*, Nature Physics online, doi:10.1038/nphys1134

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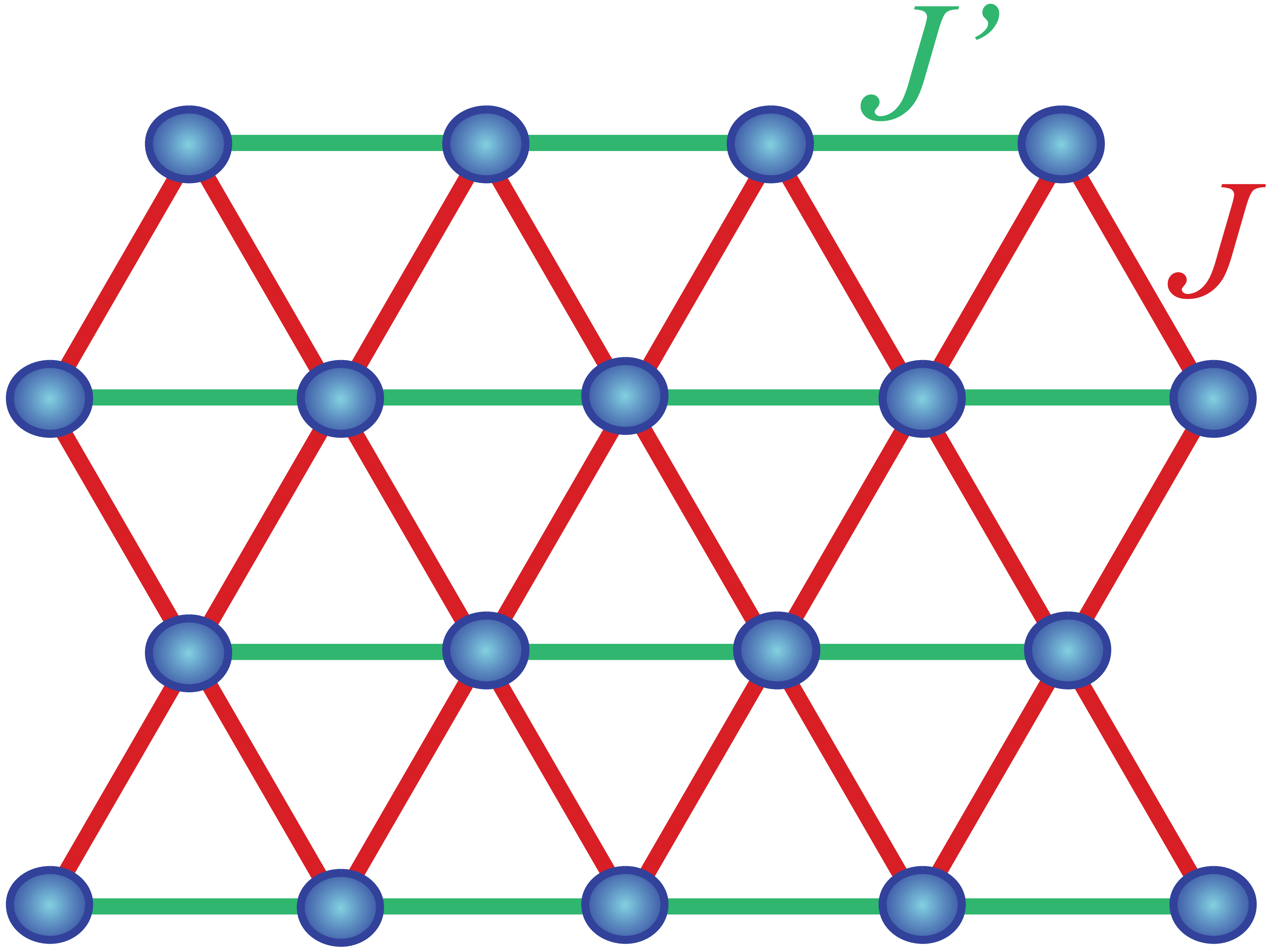
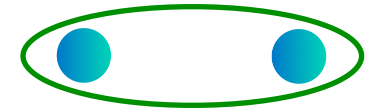
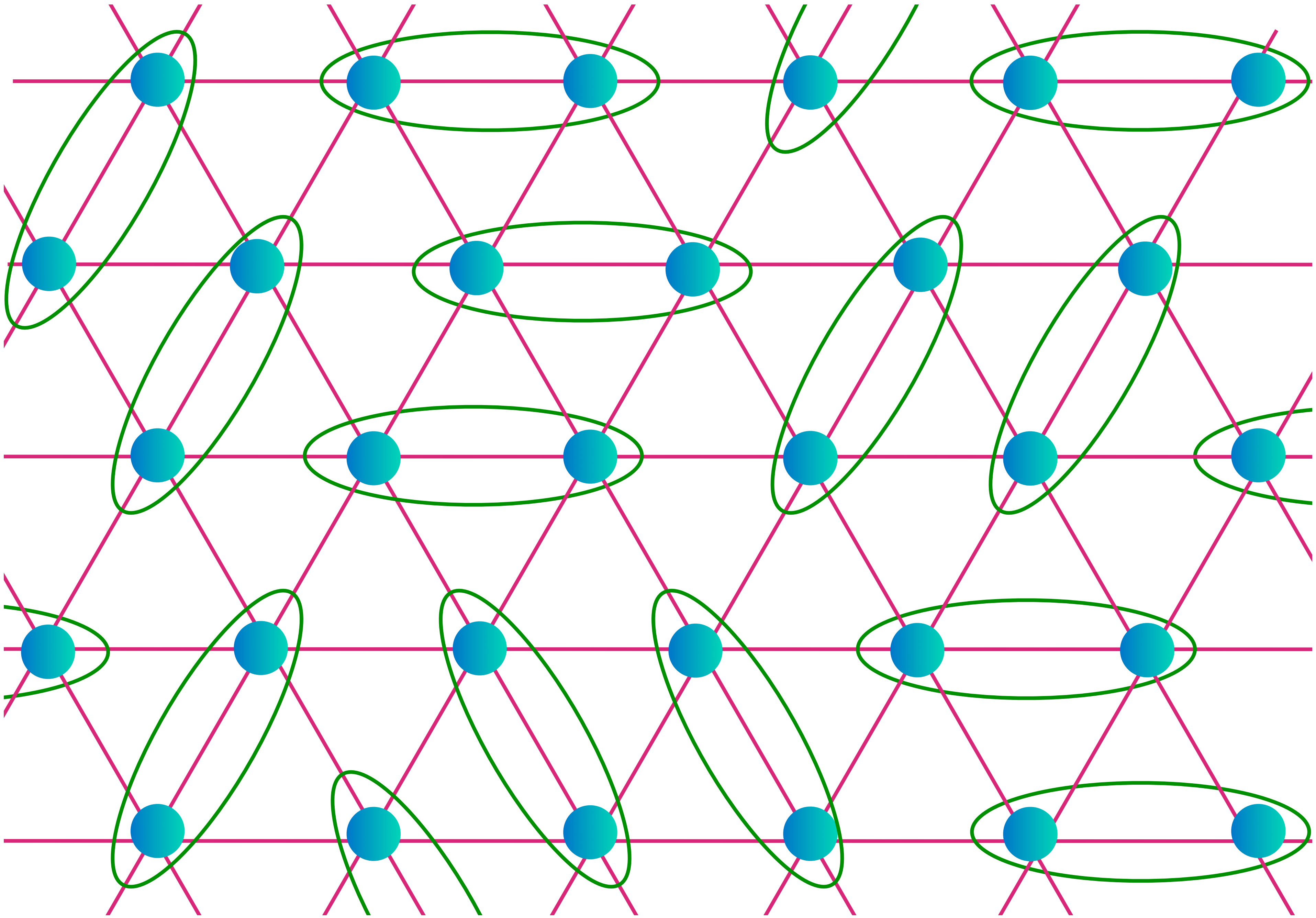


Triangular lattice antiferromagnet

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



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



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

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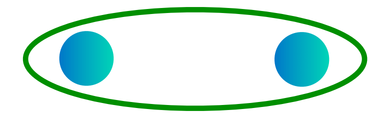

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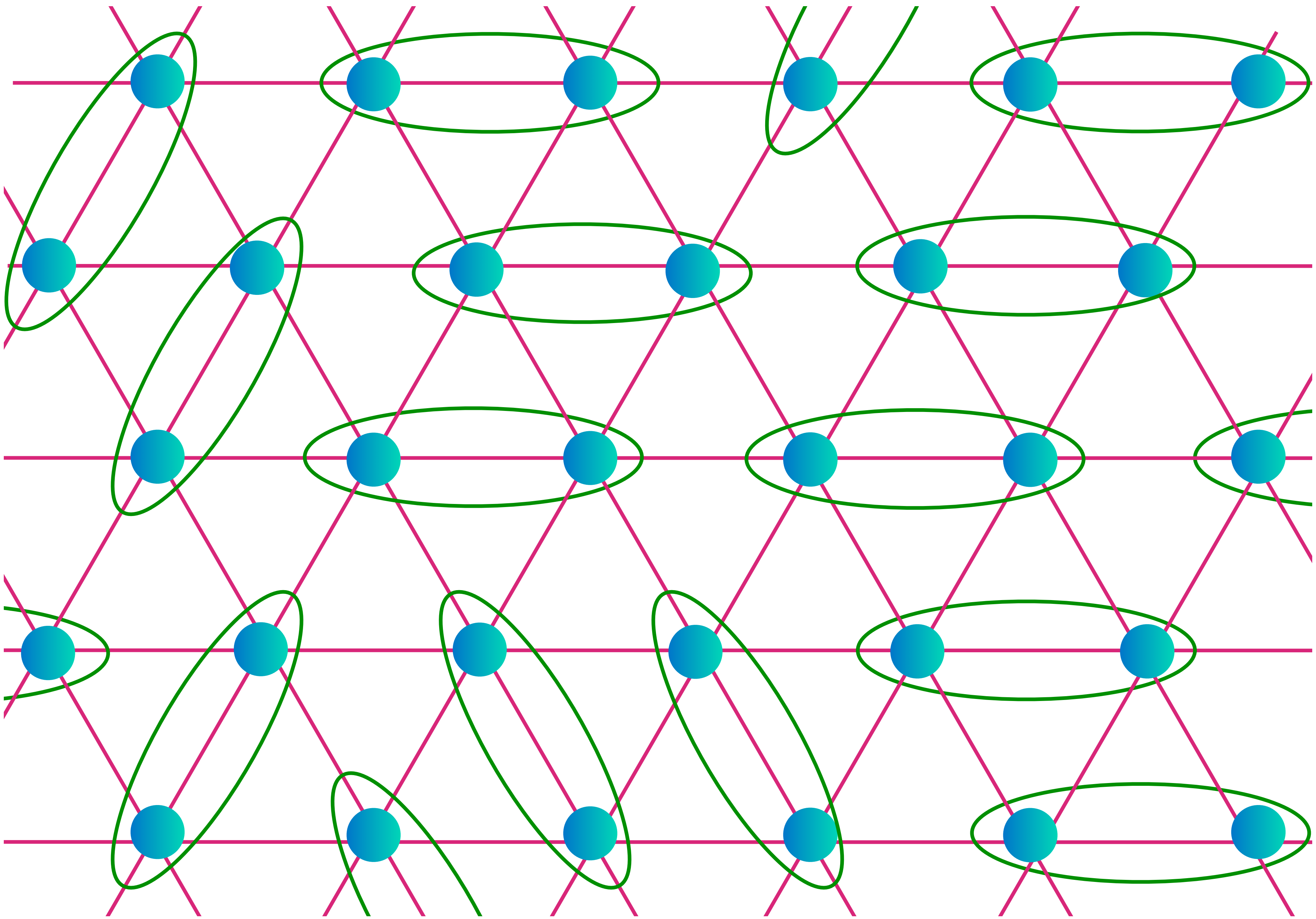

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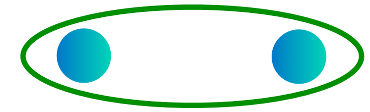

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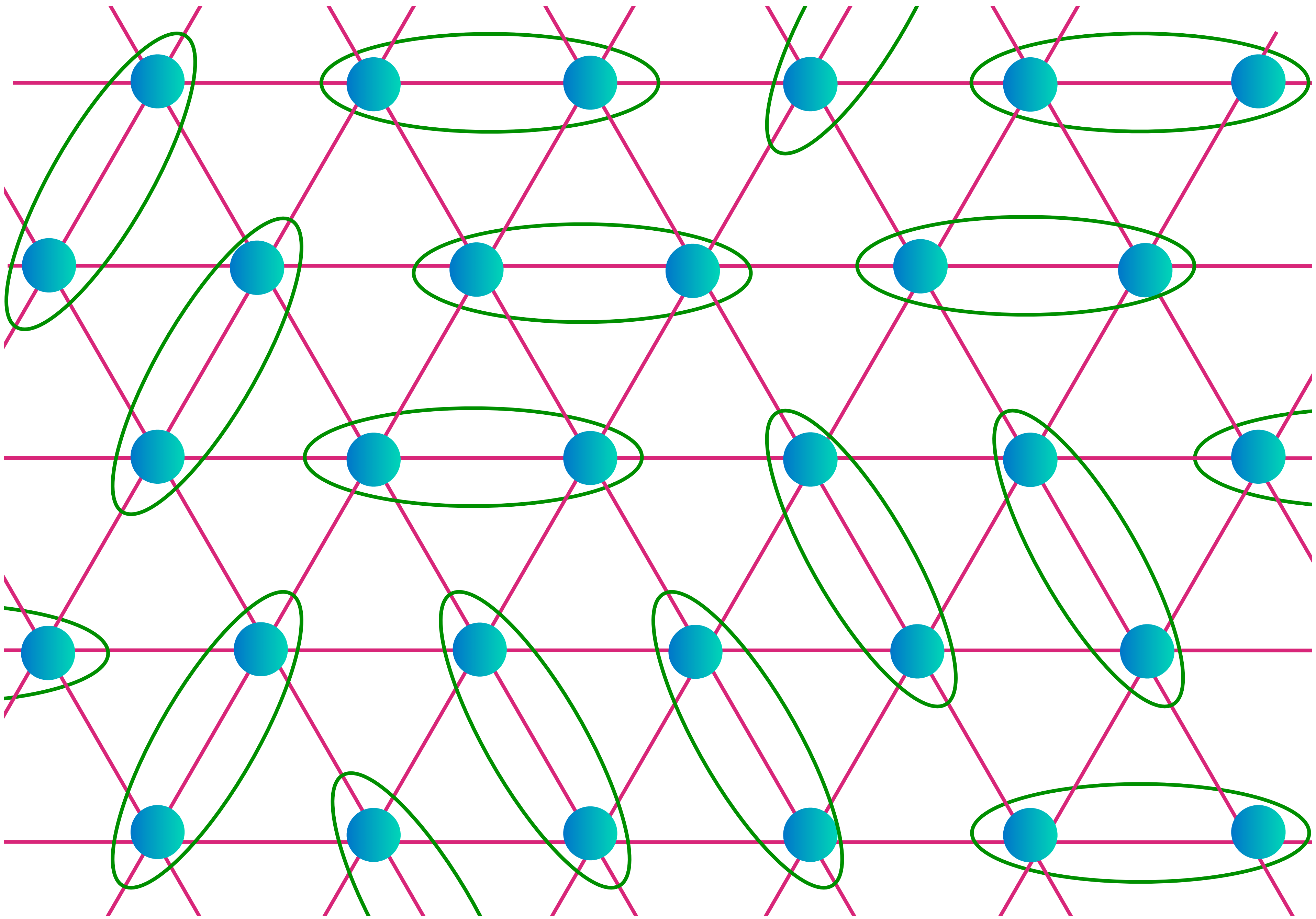

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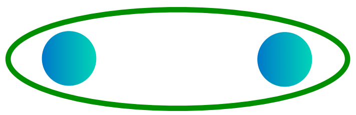

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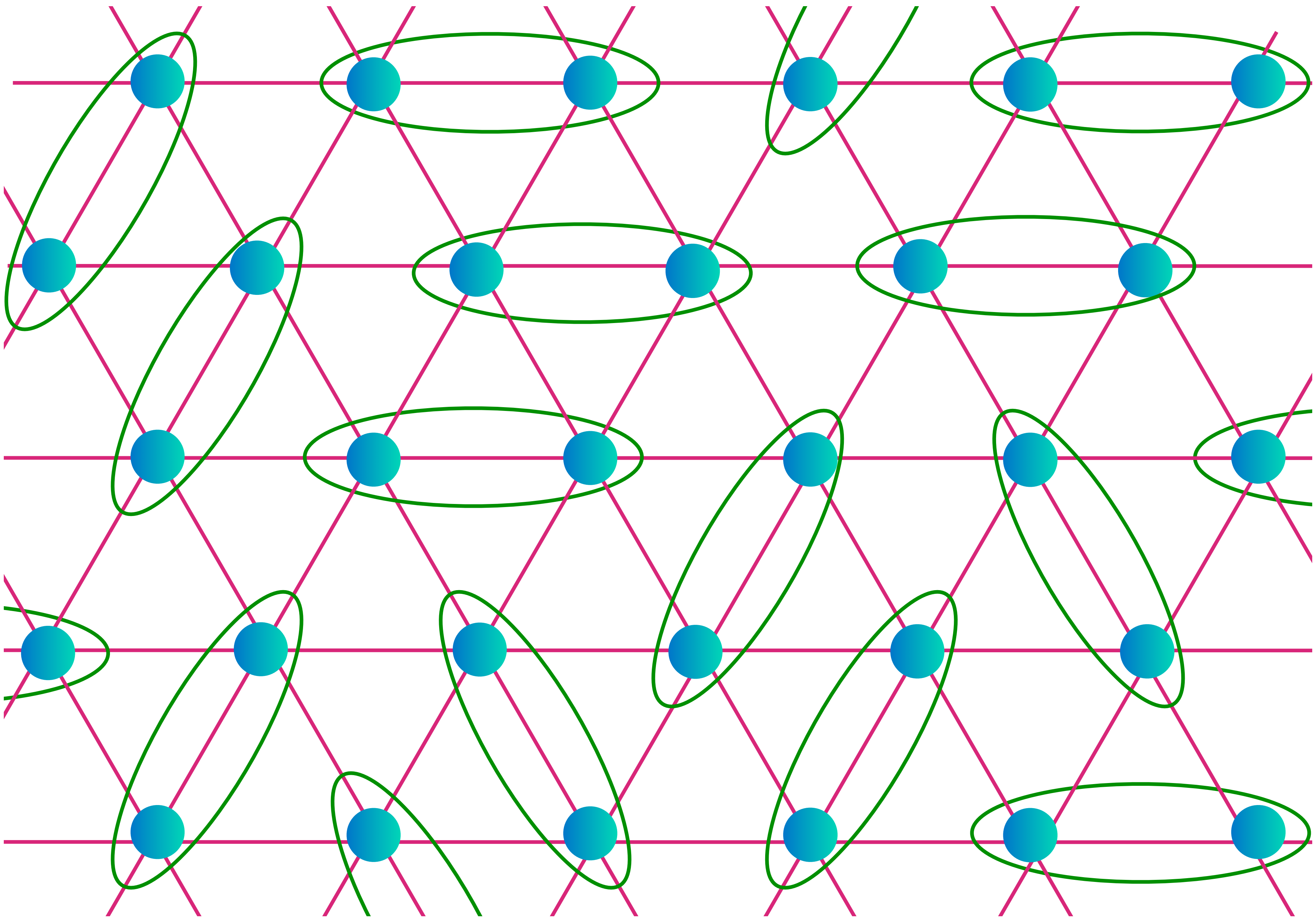

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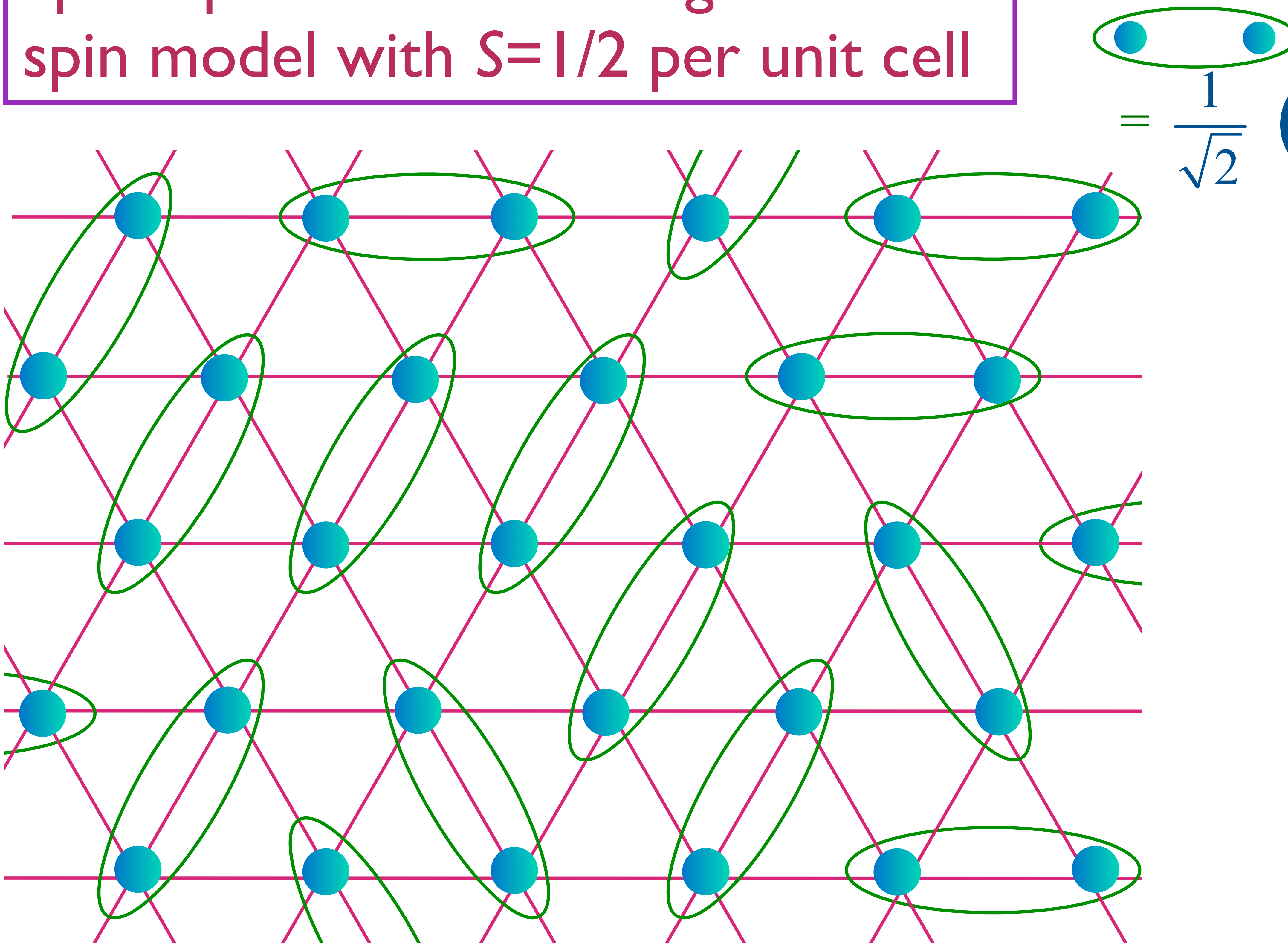

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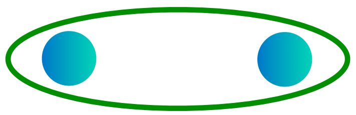

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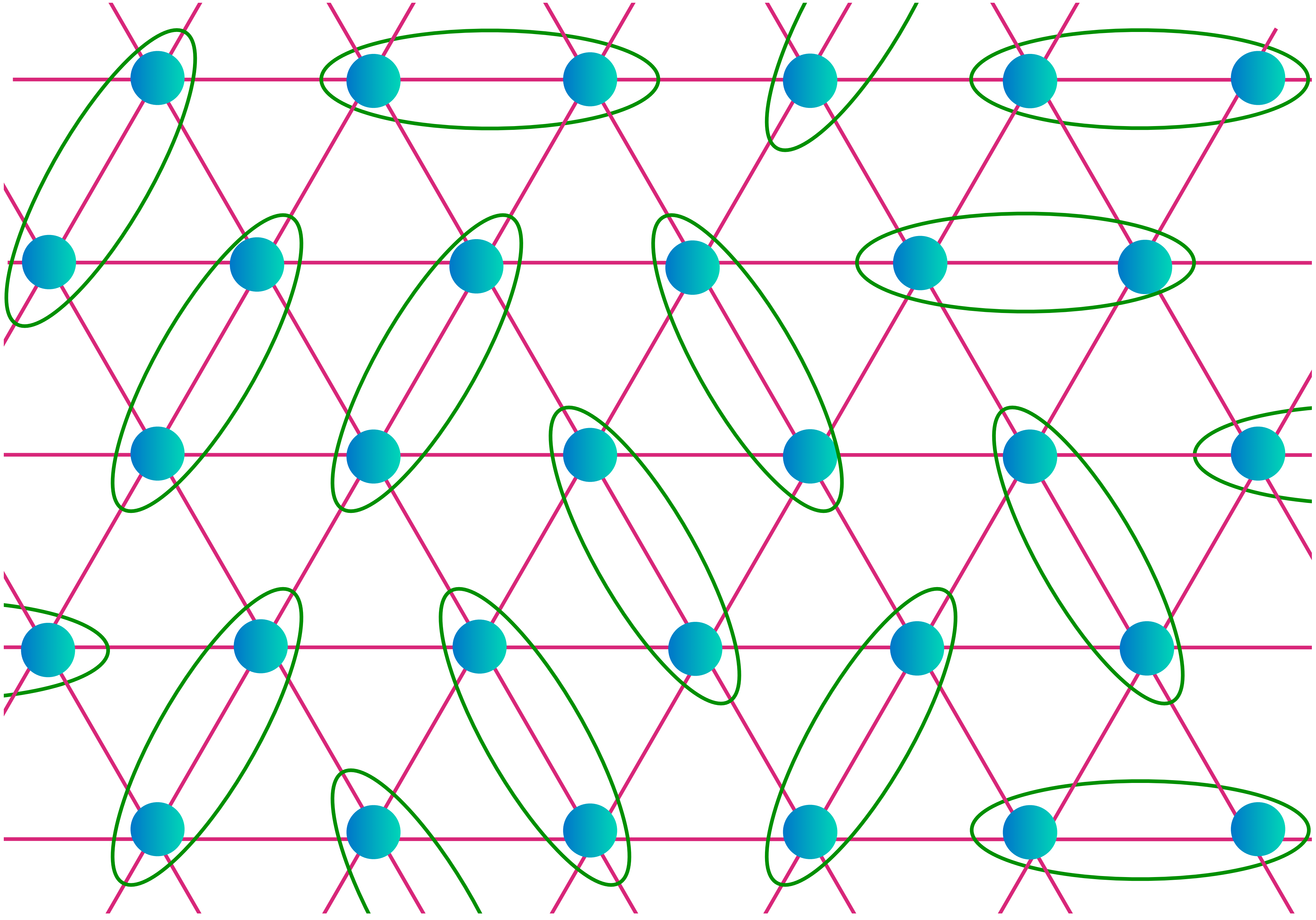

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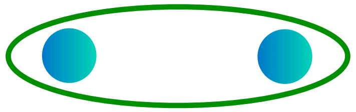
Excitations of the Z_2 Spin liquid

A spinon



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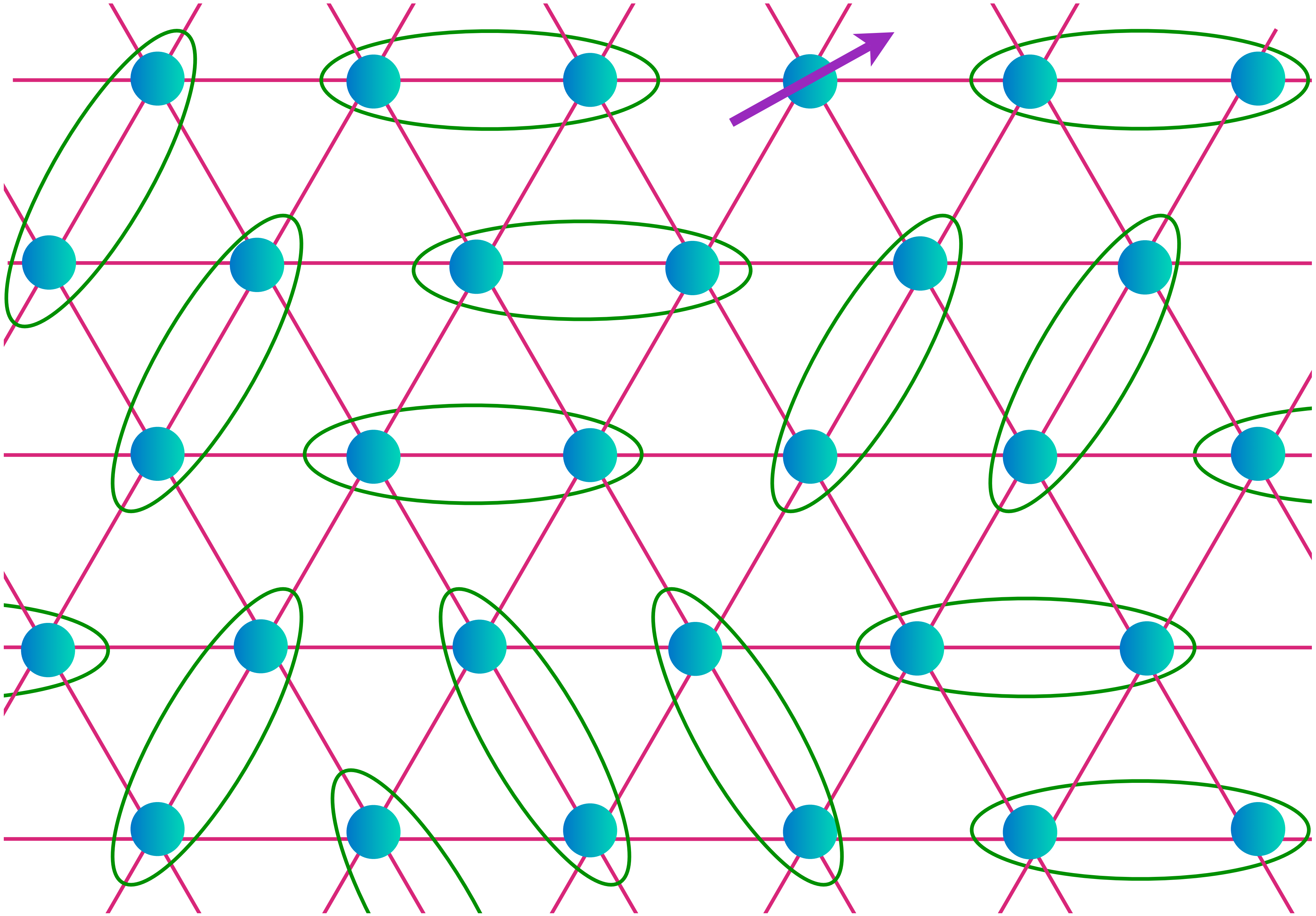

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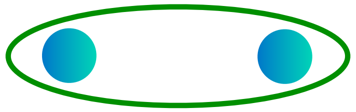

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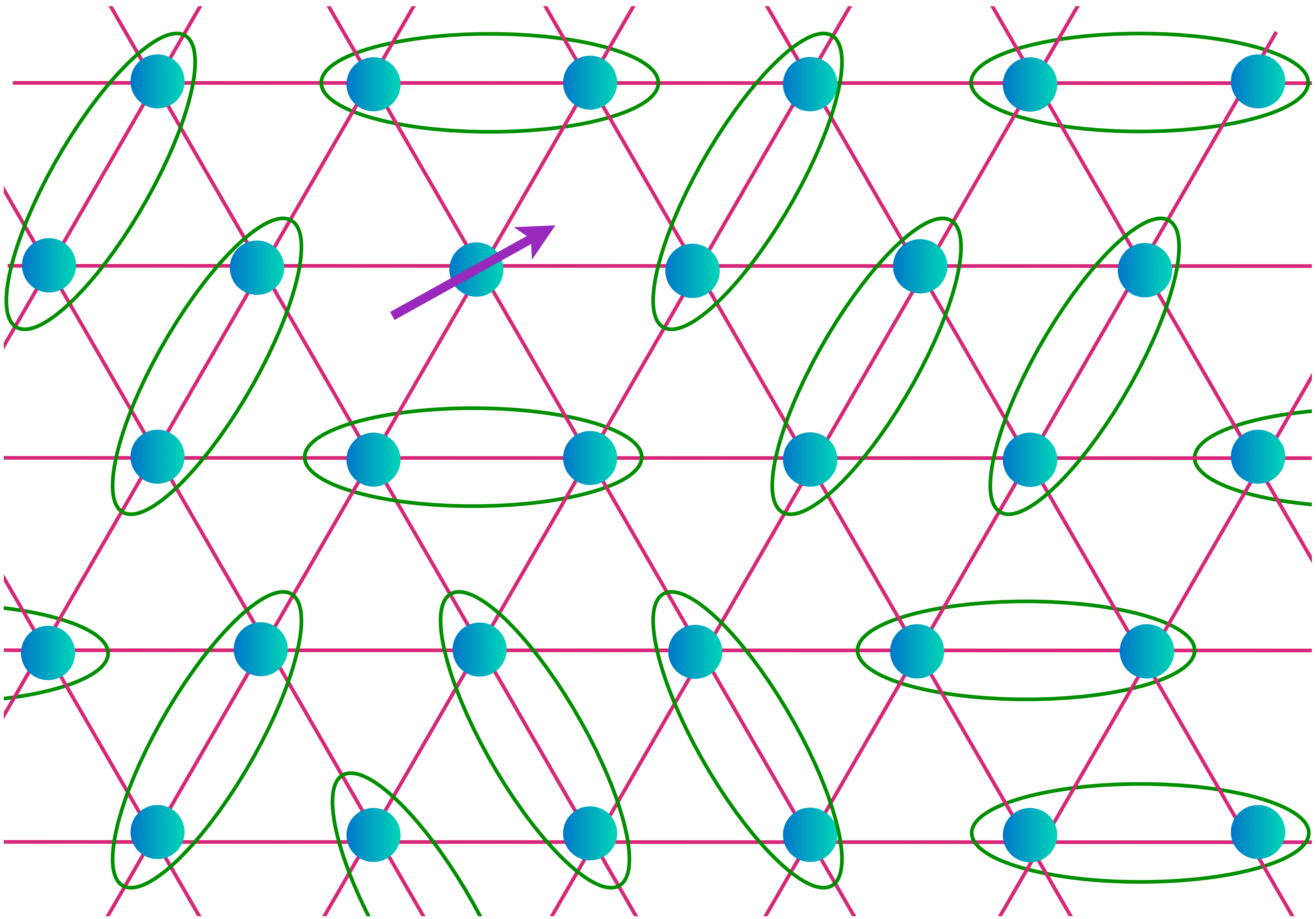

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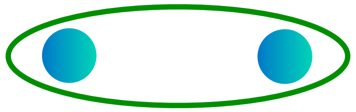

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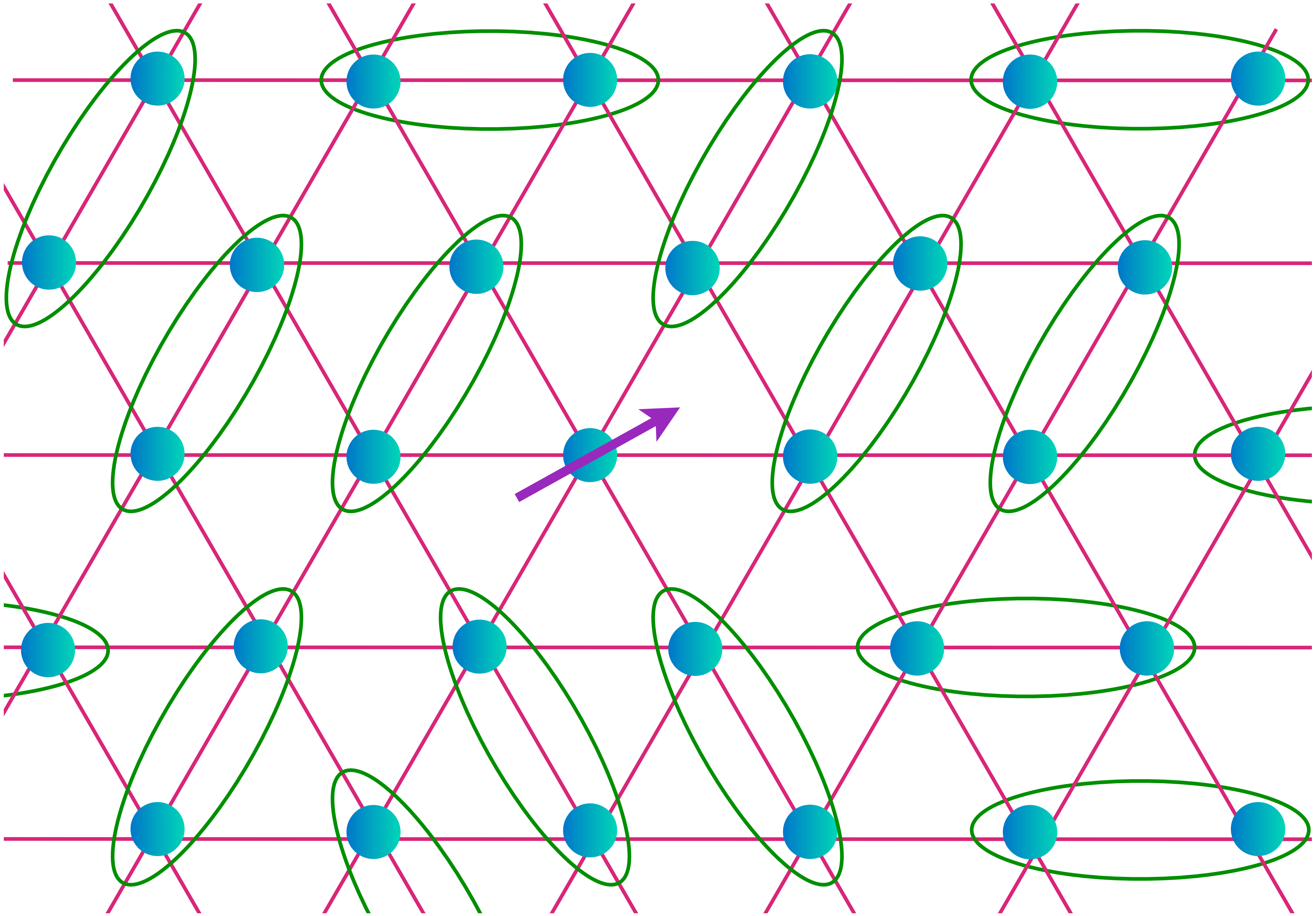

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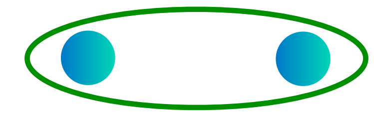
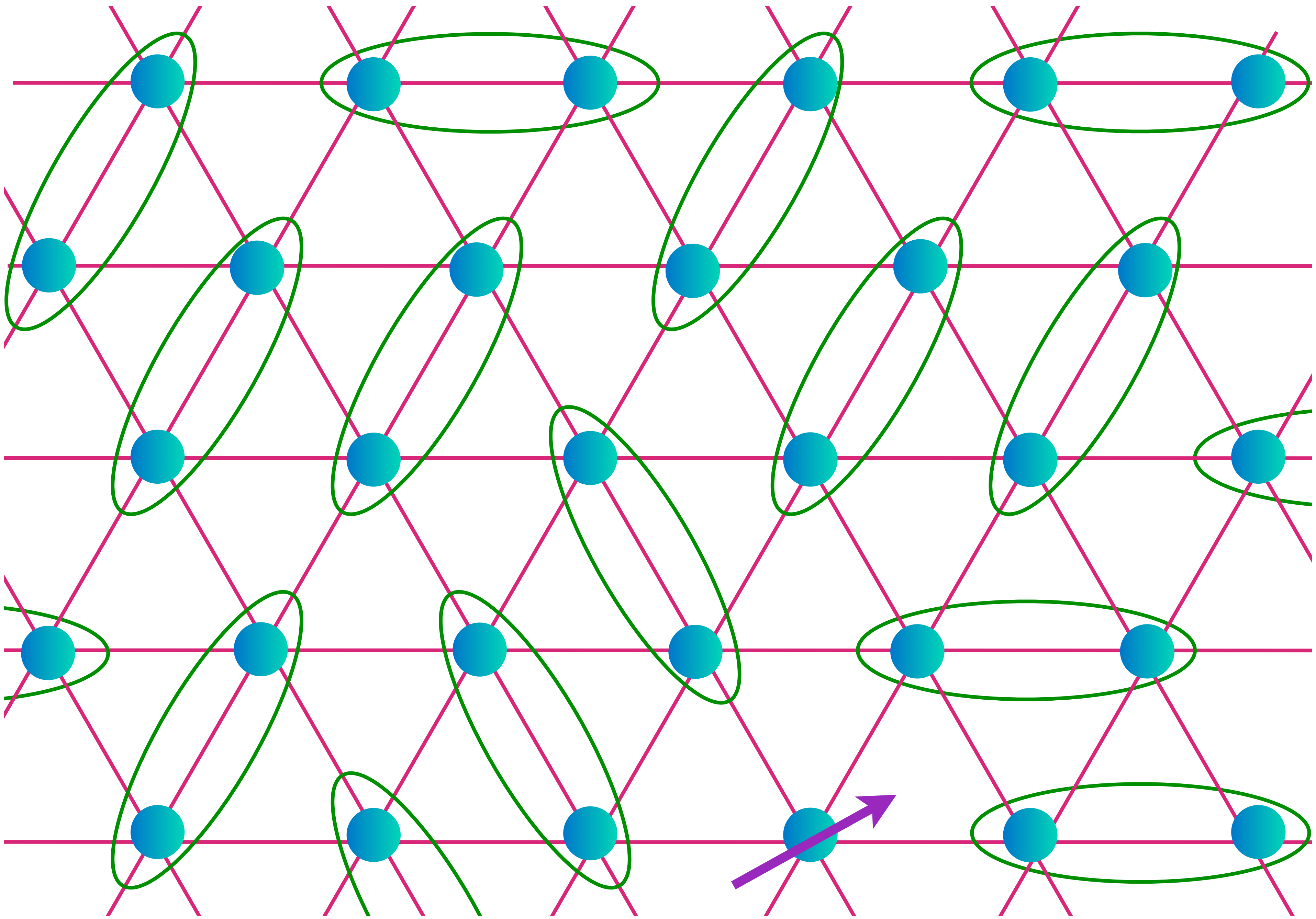


$$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

A spinon



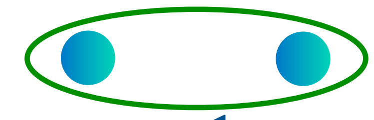
Excitations of the Z_2 Spin liquid

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.

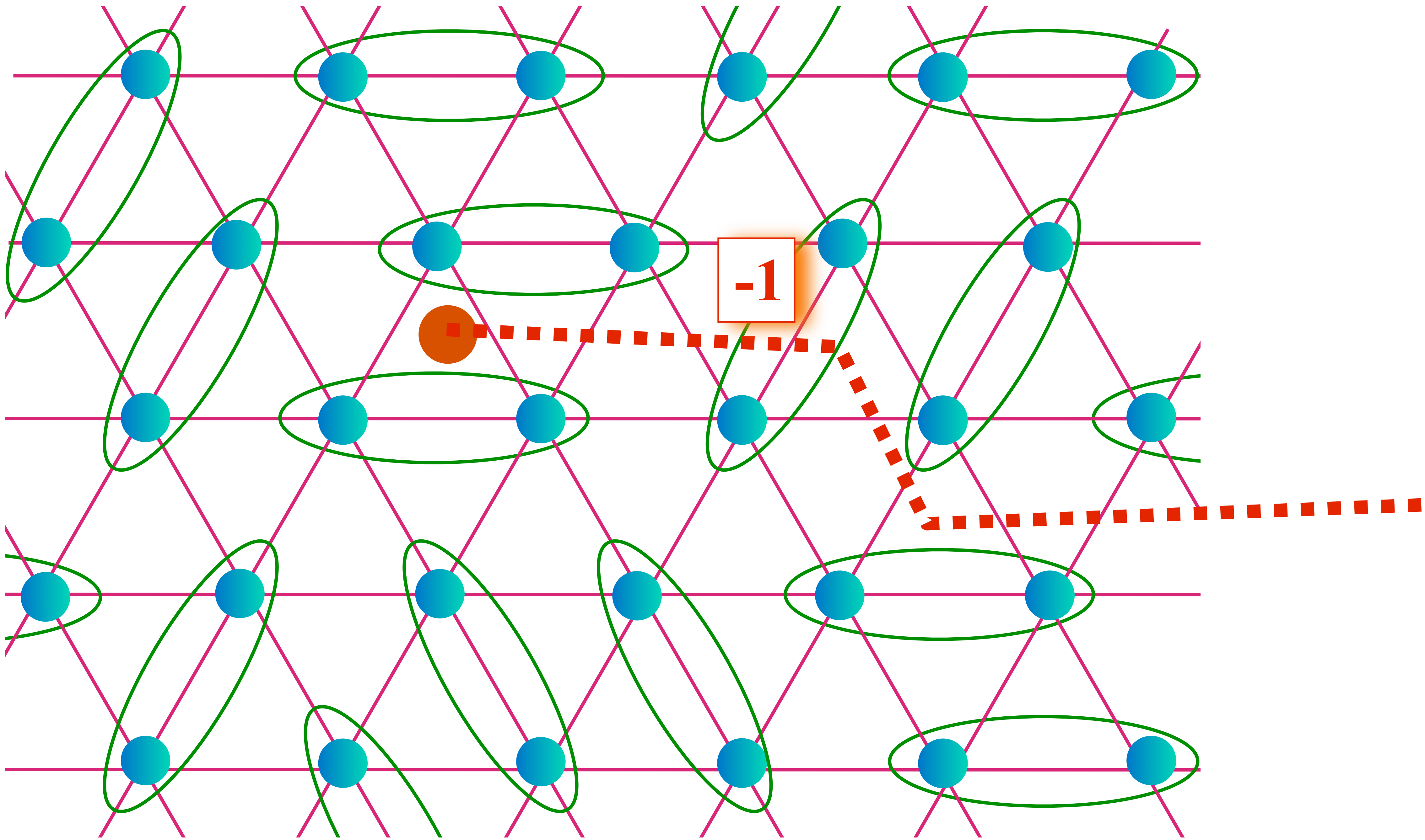
N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)

Excitations of the Z_2 Spin liquid



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

A vison



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

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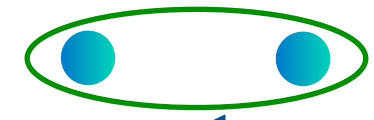
A vison



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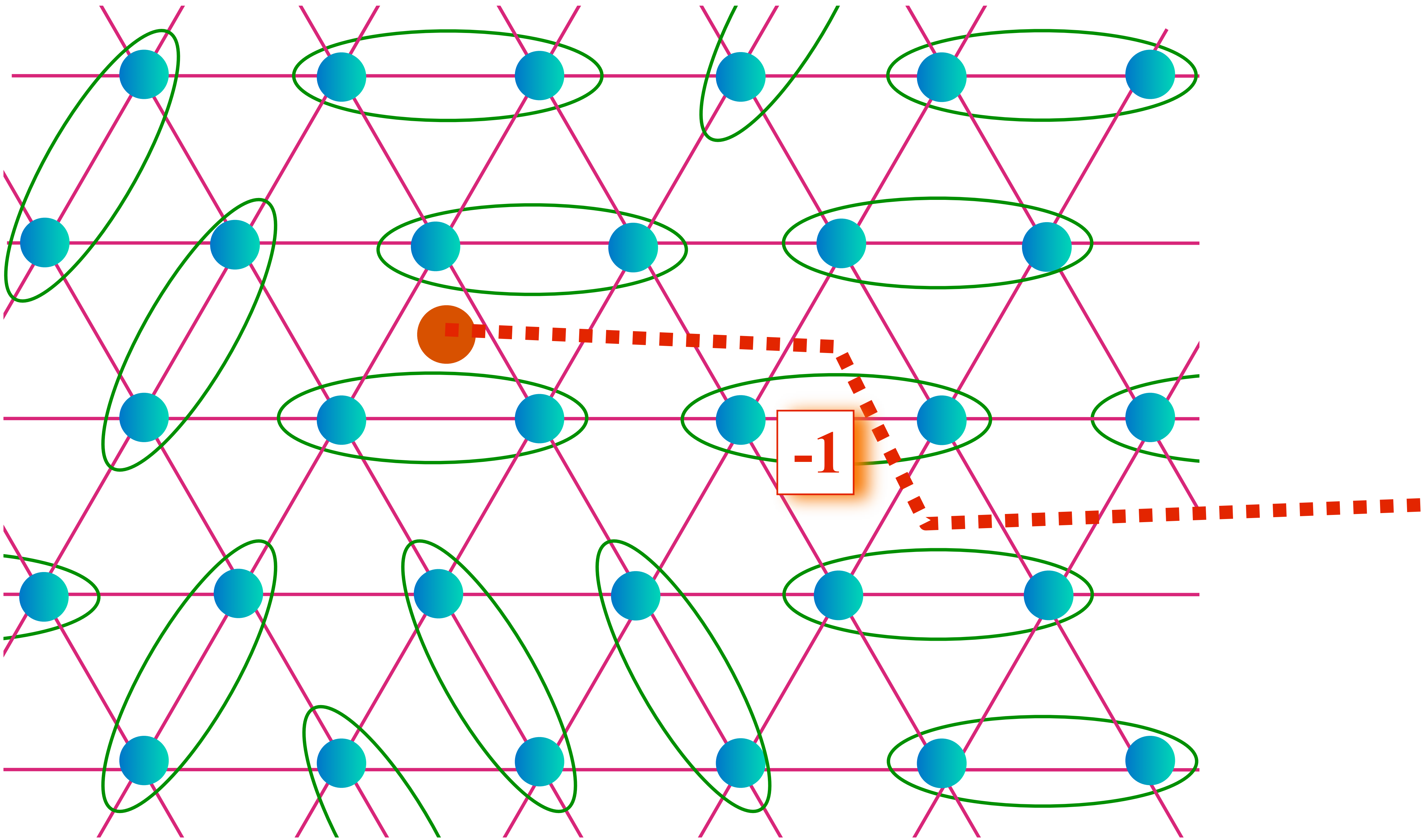
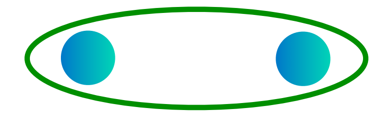


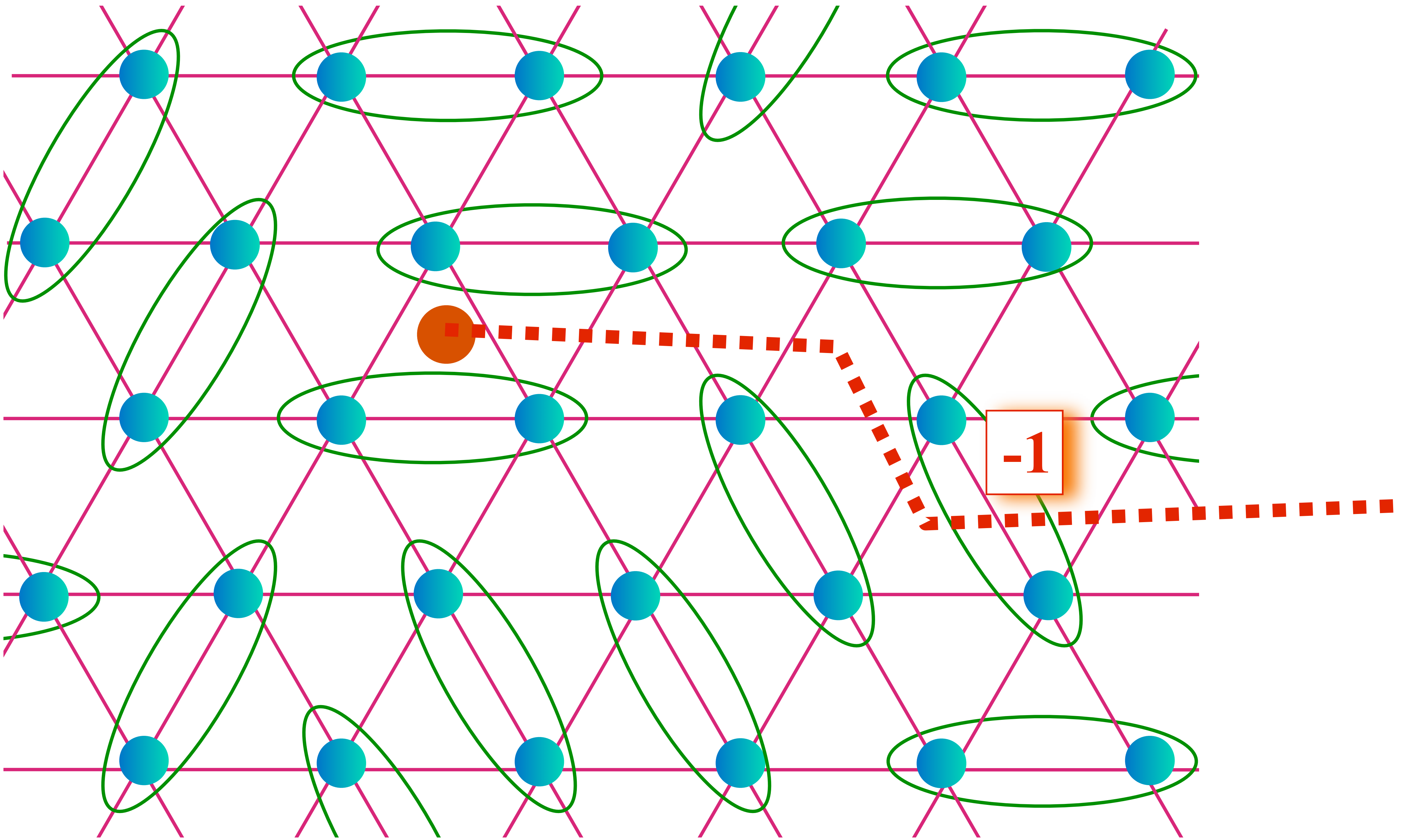
N. Read and S. Sachdev, *Phys. Rev. Lett.* **66**, 1773 (1991)

Excitations of the Z_2 Spin liquid



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

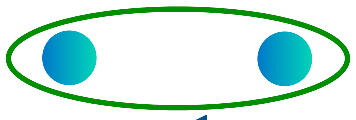
A vison



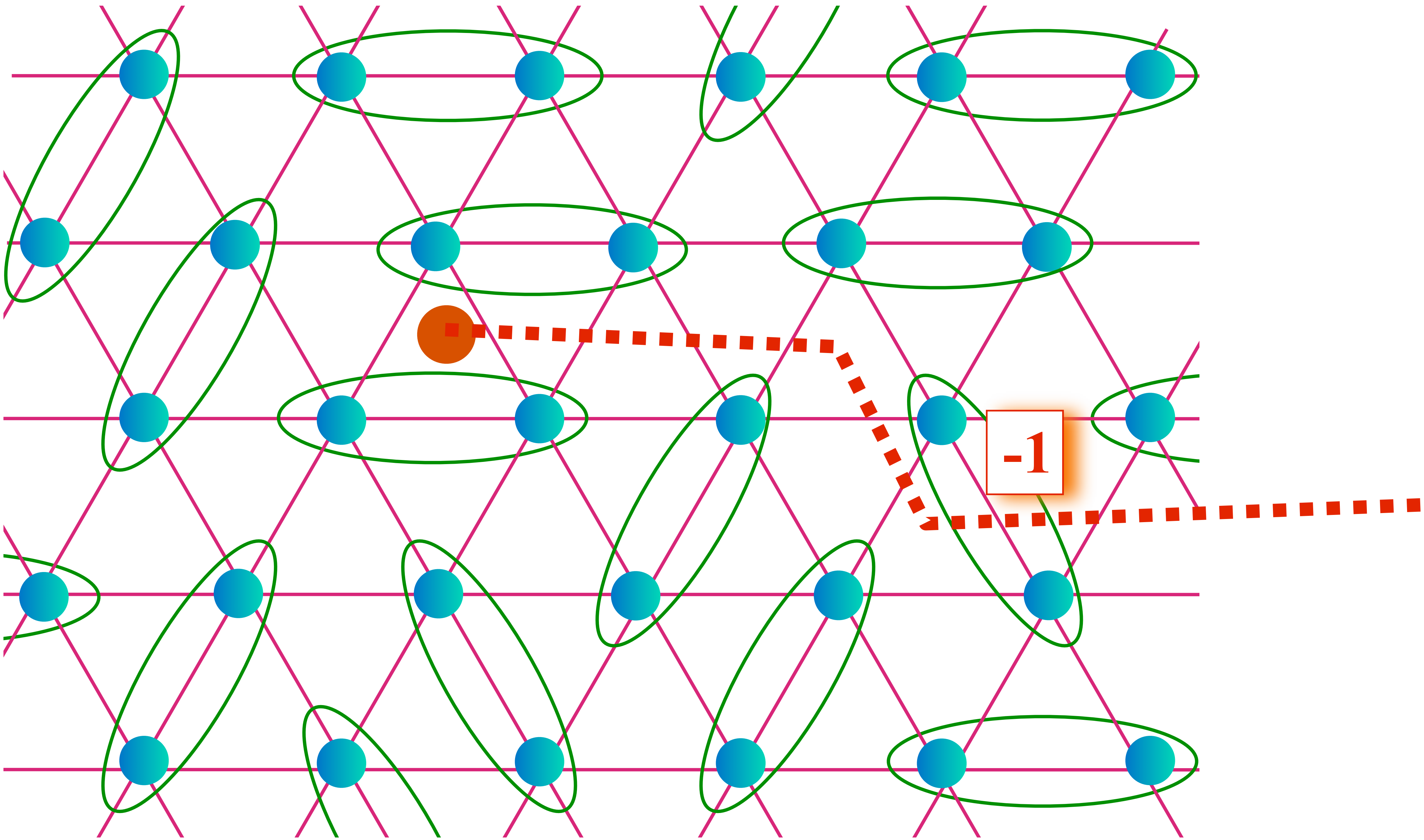
N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)

Excitations of the Z_2 Spin liquid

A vison



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



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

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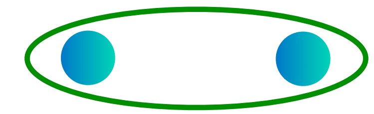

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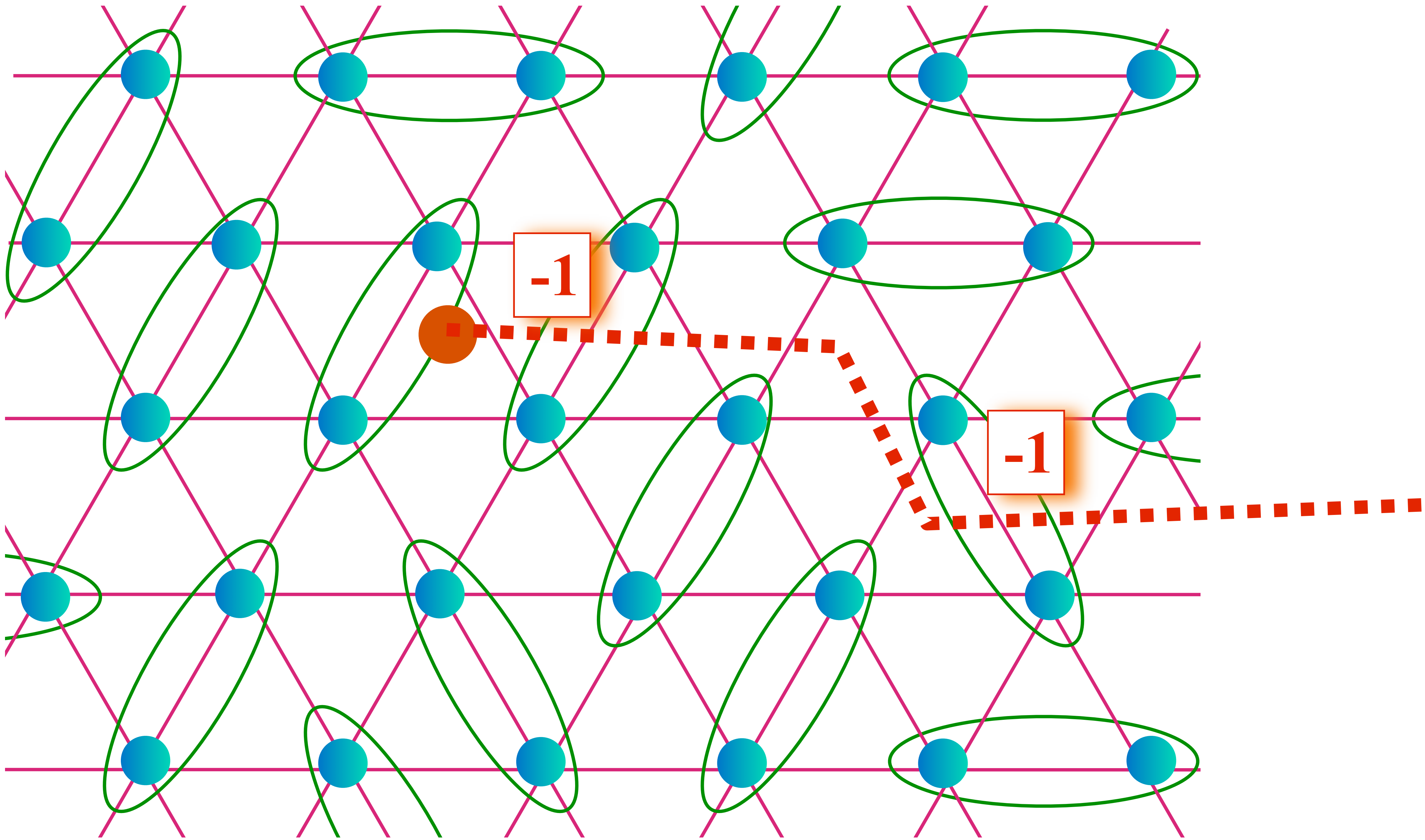

N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)

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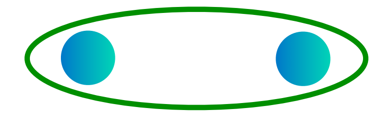
A vison



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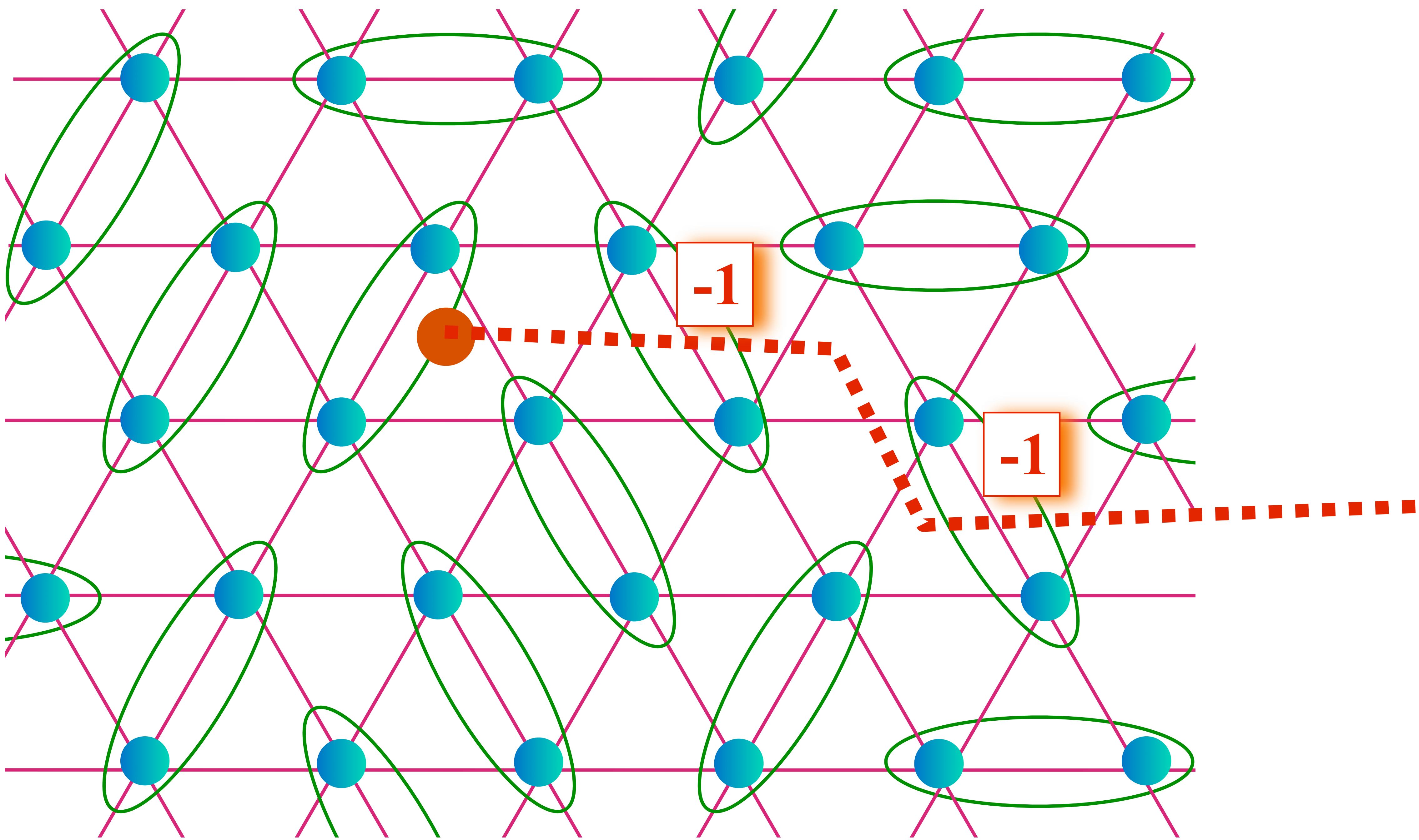

N. Read and S. Sachdev, *Phys. Rev. Lett*. **66**, 1773 (1991)

Outline

1. Review of experiments

   Phases of the S=1/2 antiferromagnet on the anisotropic triangular lattice

2. The Z_2 spin liquid and its excitations

   Spinons and visons

3. Field theory for spinons and visons

   Berry phases and the doubled Chern-Simons theory

4. Is κ-$(ET)_2Cu_2(CN)_3$ a Z_2 spin liquid ?

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

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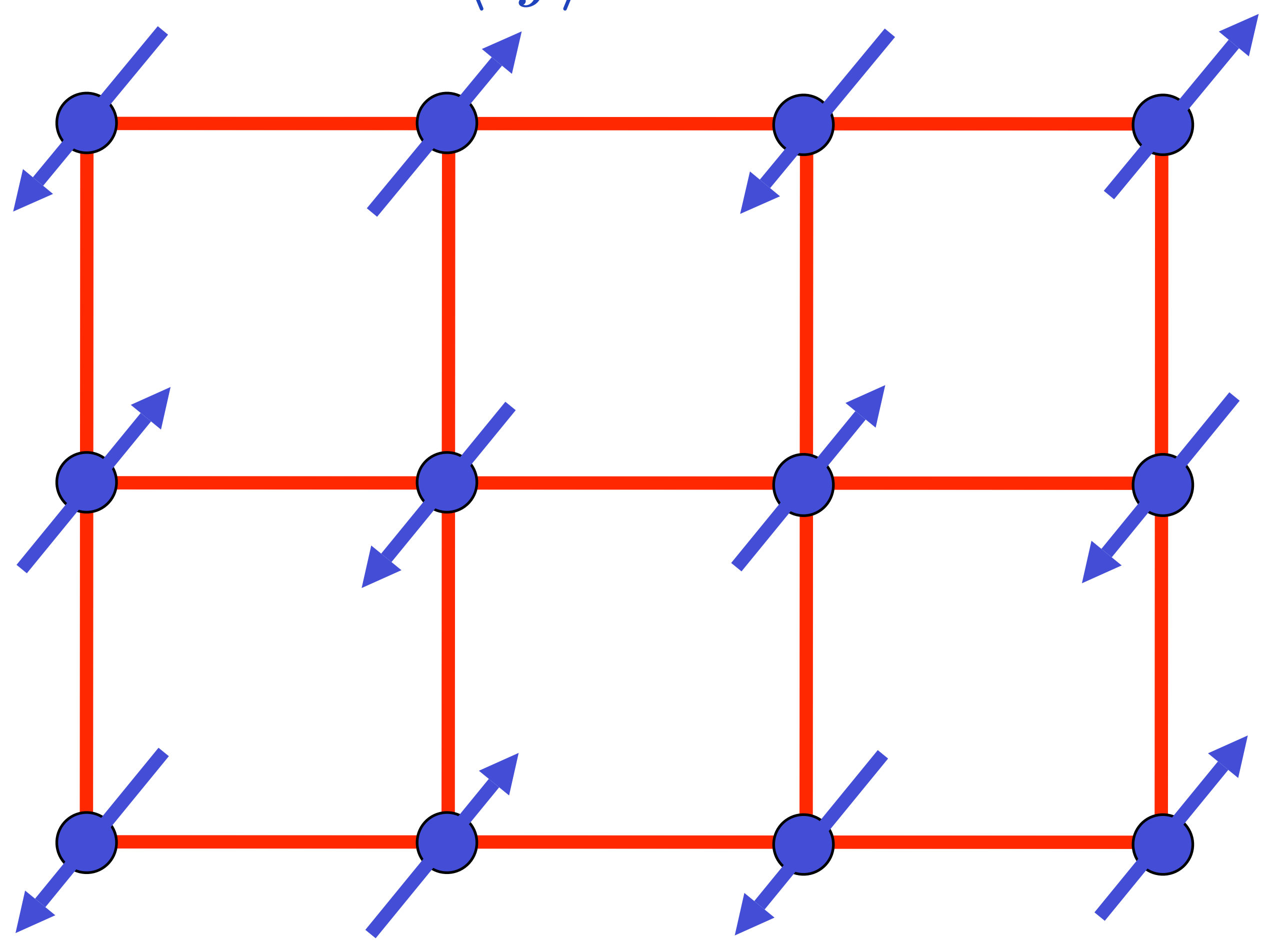
Square lattice antiferromagnet

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



Ground state has long-range Néel order

Order parameter is a single vector field $\vec{\varphi} = \eta_i \vec{S}_i$

$\eta_i = \pm 1$ on two sublattices

$\langle \vec{\varphi} \rangle \neq 0$ in Néel state.

Theory for loss of Neel order

Write the spin operator in terms of
Schwinger bosons (spinons) $z_{i\alpha}$, $\alpha = \uparrow, \downarrow$:

$$\vec{S}_i = z_{i\alpha}^\dagger \vec{\sigma}_{\alpha\beta} z_{i\beta}$$

where $\vec{\sigma}$ are Pauli matrices, and the bosons obey the local constraint

$$\sum_\alpha z_{i\alpha}^\dagger z_{i\alpha} = 2S$$

Effective theory for spinons must be invariant under the U(1) gauge transformation

$$z_{i\alpha} \rightarrow e^{i\theta} z_{i\alpha}$$

Perturbation theory

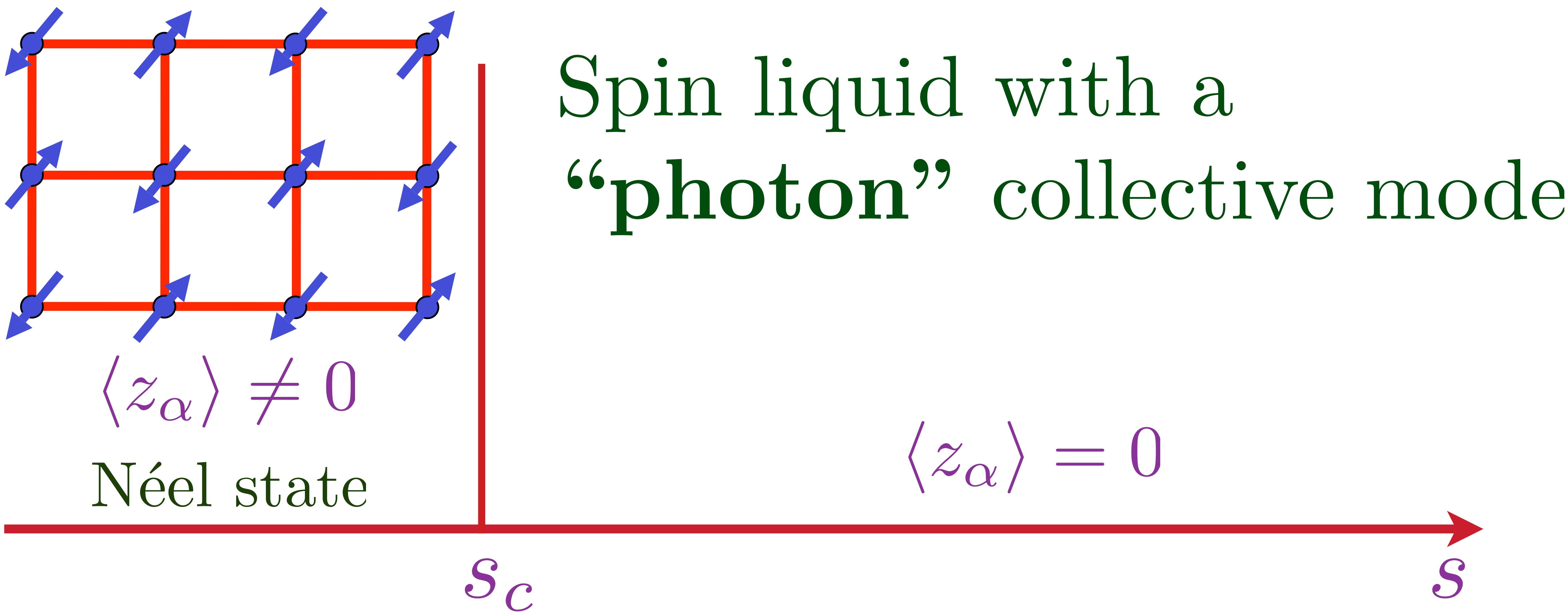
Low energy spinon theory for "quantum disordering" the Néel state is the CP^1 model

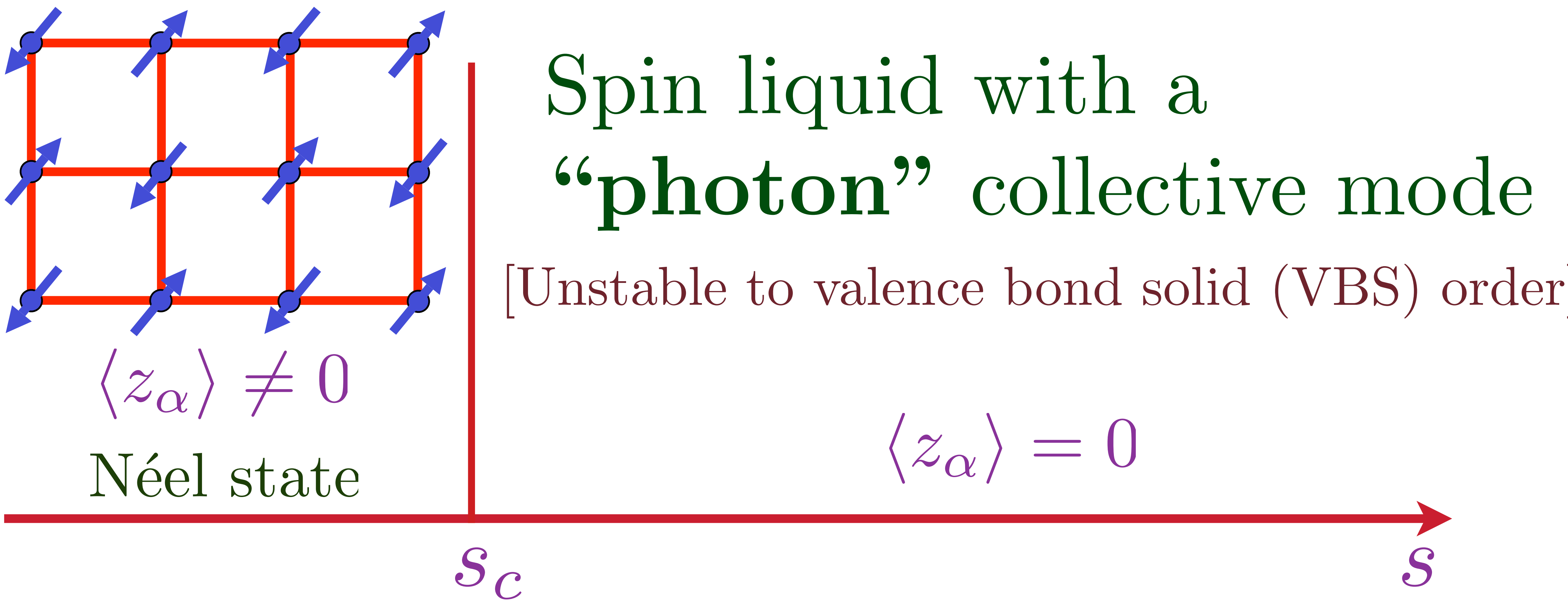
$$\mathcal{S}_z = \int d^2x d\tau \Big[c^2 \left|(\nabla_x - iA_x) z_\alpha\right|^2 + \left|(\partial_\tau - iA_\tau) z_\alpha\right|^2 + s\left|z_\alpha\right|^2 + u\left(\left|z_\alpha\right|^2\right)^2 + \frac{1}{4e^2}(\epsilon_{\mu\nu\lambda}\partial_\nu A_\lambda)^2 \Big]$$

where A_μ is an emergent U(1) gauge field (the **"photon"**) which describes low-lying spin-singlet excitations.

Phases:

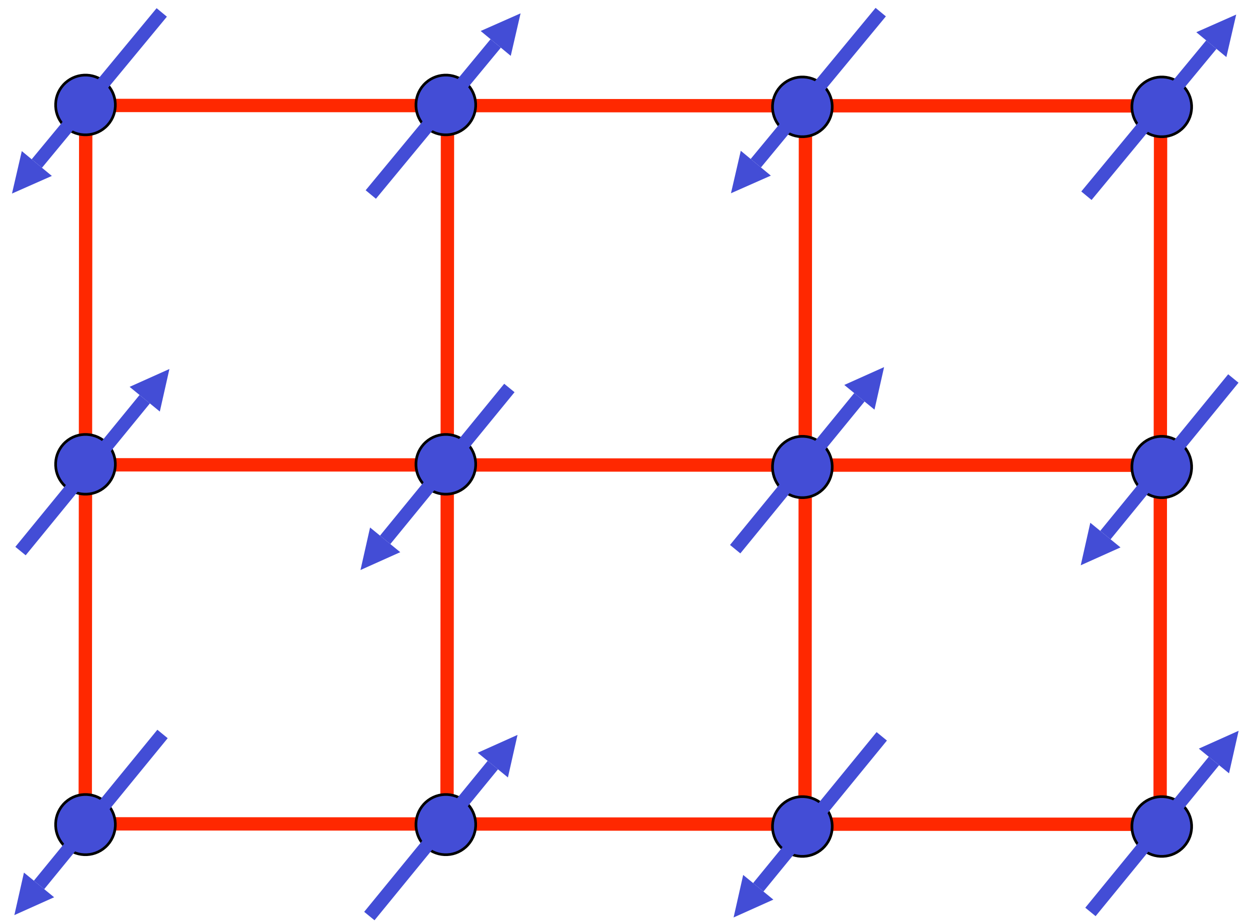
$\langle z_\alpha \rangle \neq 0$	$\Rightarrow$	Néel (Higgs) state
$\langle z_\alpha \rangle = 0$	$\Rightarrow$	Spin liquid (Coulomb) state


Spin liquid with a
“**photon**” collective mode
$\langle z_\alpha \rangle \neq 0$
Néel state
$\langle z_\alpha \rangle = 0$
s_c
s



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

From the square to the triangular lattice

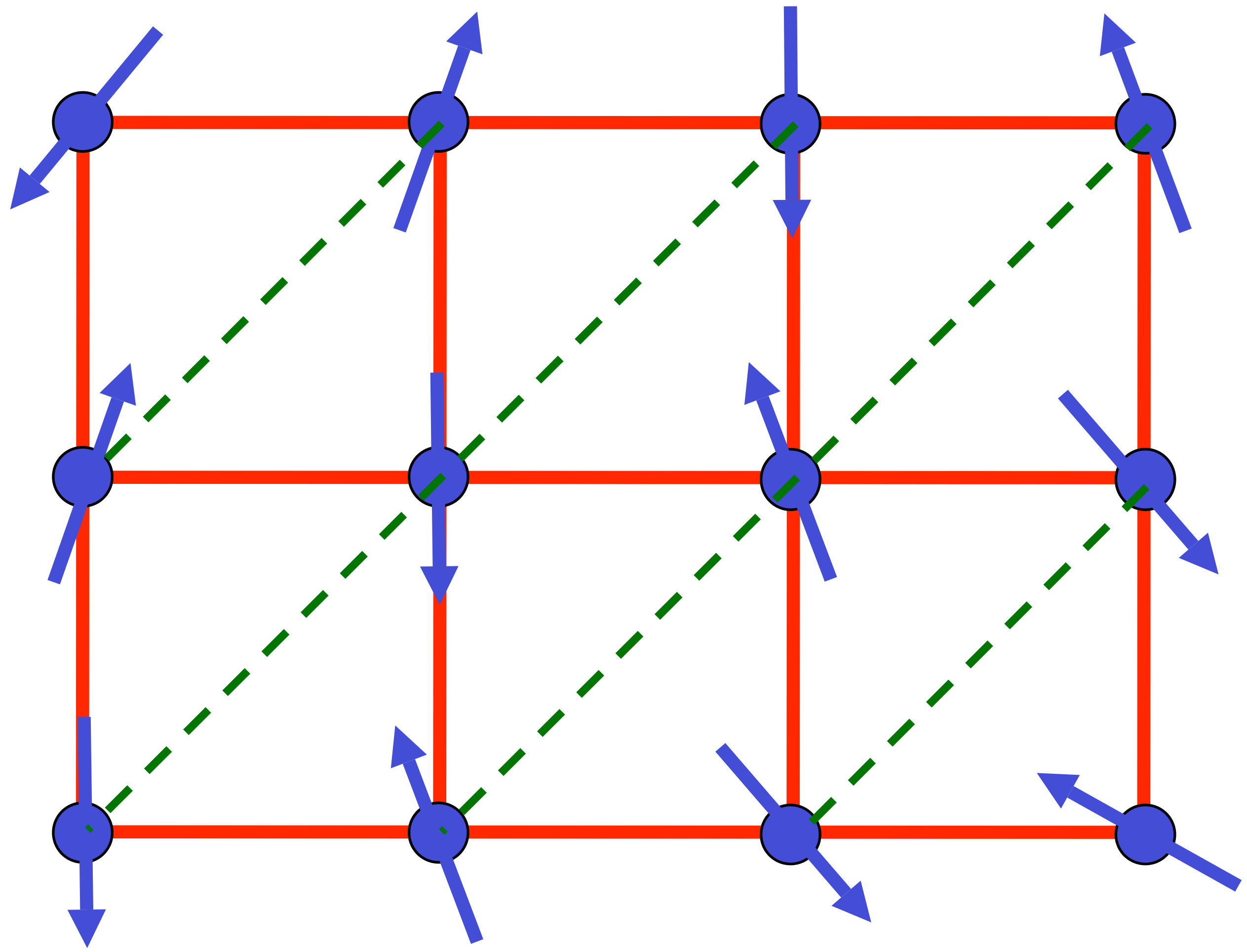


A spin density wave with

$$\langle \vec{S}_i \rangle \propto (\cos(\mathbf{K} \cdot \mathbf{r}_i, \sin(\mathbf{K} \cdot \mathbf{r}_i))$$

and $\mathbf{K} = (\pi, \pi)$.

From the square to the triangular lattice



A spin density wave with

$$\langle \vec{S}_i \rangle \propto (\cos(\mathbf{K} \cdot \mathbf{r}_i, \sin(\mathbf{K} \cdot \mathbf{r}_i))$$

and $\mathbf{K} = (\pi + \Phi, \pi + \Phi)$.

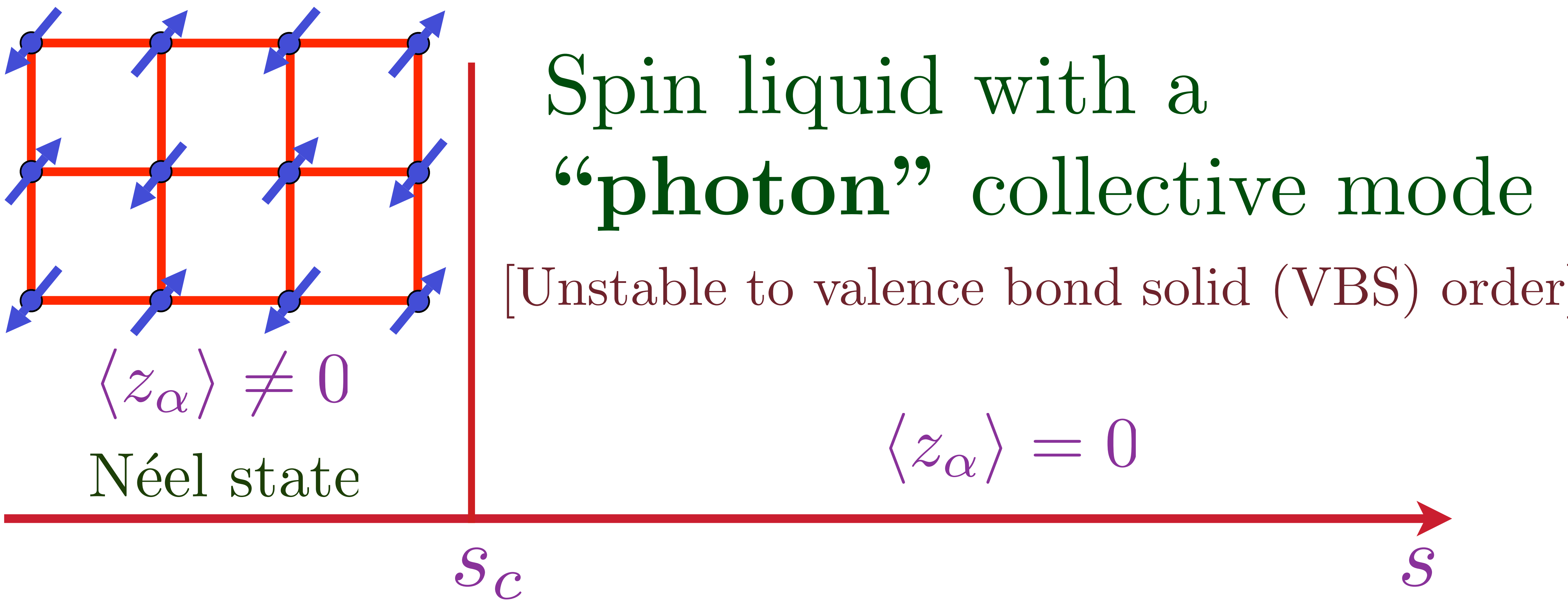
Interpretation of non-collinearity Φ

Its physical interpretation becomes clear from the allowed coupling to the spinons:

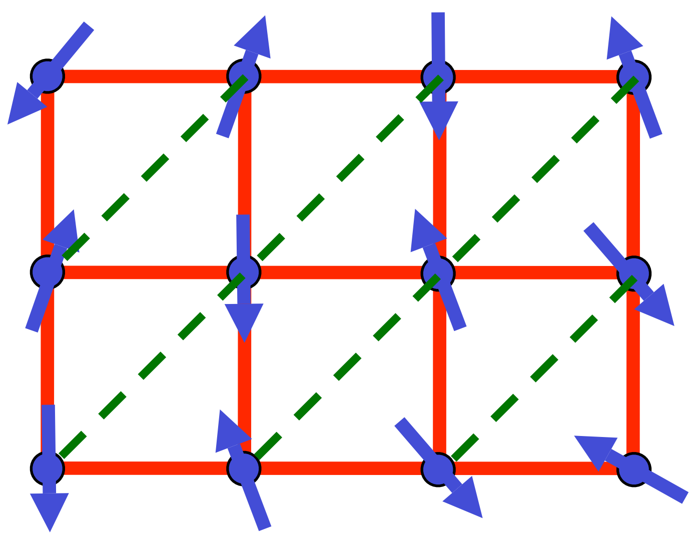
$$\mathcal{S}_{z,\Phi} = \int d^2 r d\tau \left[\lambda \Phi^* \epsilon_{\alpha\beta} z_\alpha \partial_x z_\beta + \text{c.c.}\right]$$

Φ is a spinon pair field

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



Spin liquid with a
"photon" collective mode
[Unstable to valence bond solid (VBS) order]
$\langle z_\alpha \rangle \neq 0$
Néel state
$\langle z_\alpha \rangle = 0$
s_c
s



Z_2 spin liquid with a **vison** excitation

$\langle z_\alpha \rangle \neq 0 \; , \; \langle \Phi \rangle \neq 0$

non-collinear Néel state

$\langle z_\alpha \rangle = 0 \; , \; \langle \Phi \rangle \neq 0$

s_c

s

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

What is a vison ?

A vison is an Abrikosov vortex in the spinon pair field Φ.

In the Z_2 spin liquid, the vison is $S = 0$ quasiparticle with a finite energy gap

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

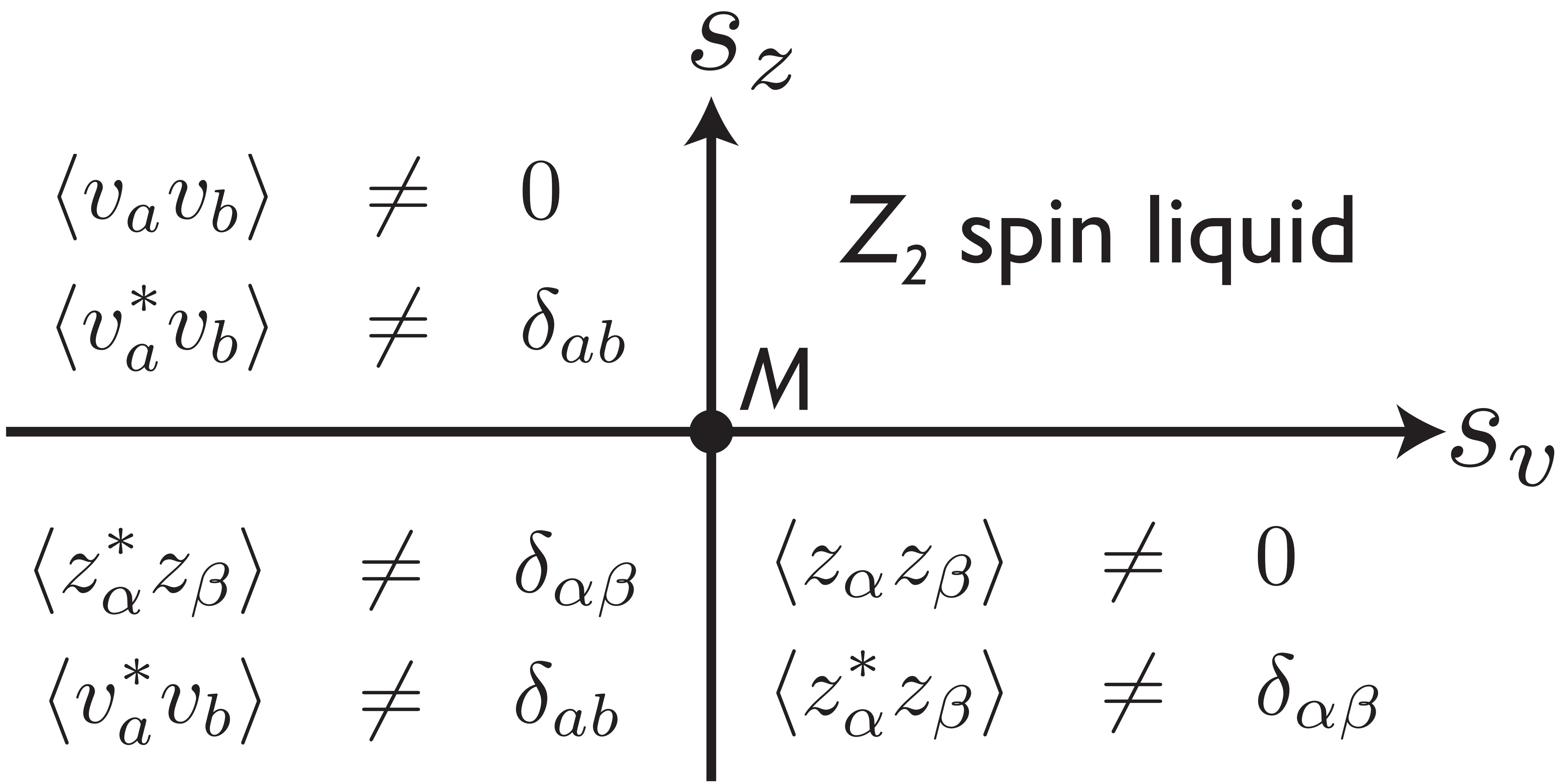
Mutual Chern-Simons Theory

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.

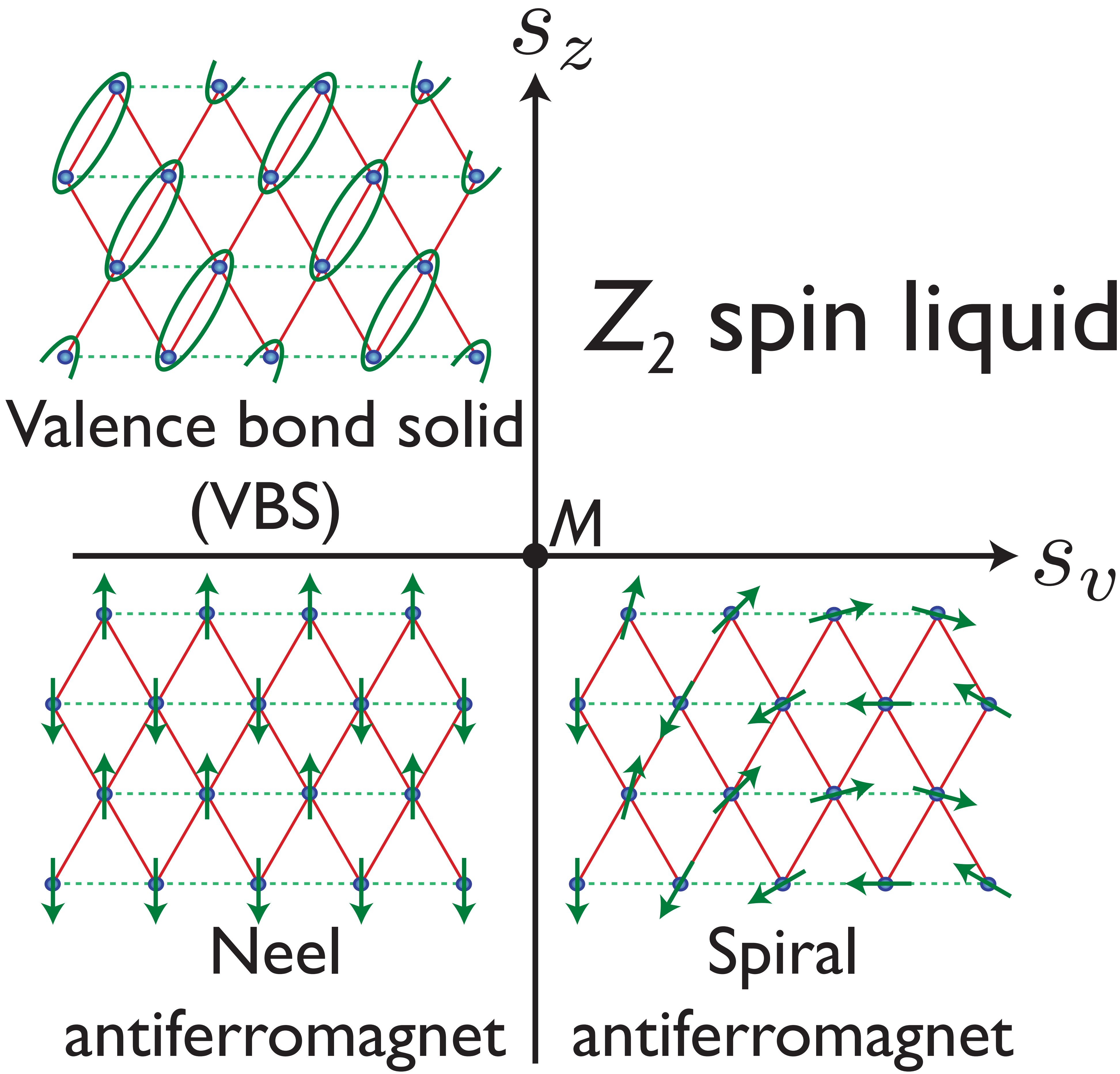
The spinons and visons have mutual semionic statistics, and this leads to the mutual CS theory at $k = 2$:

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

Cenke Xu and S. Sachdev, arXiv:0811.1220



Cenke Xu and S. Sachdev, arXiv:0811.1220



Cenke Xu and S. Sachdev, arXiv:0811.1220

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How do we reconcile power-law *T* dependence in $1/T_1$ with activated thermal conductivity ?

How do we reconcile power-law T dependence in $1/T_1$ with activated thermal conductivity ?

I. Thermal conductivity is dominated by vison transport

The thermal conductivity (per layer) of N_v species of slowly moving visons of mass m_v, above an energy gap Δ_v, scattering off impurities of density n_{imp} is

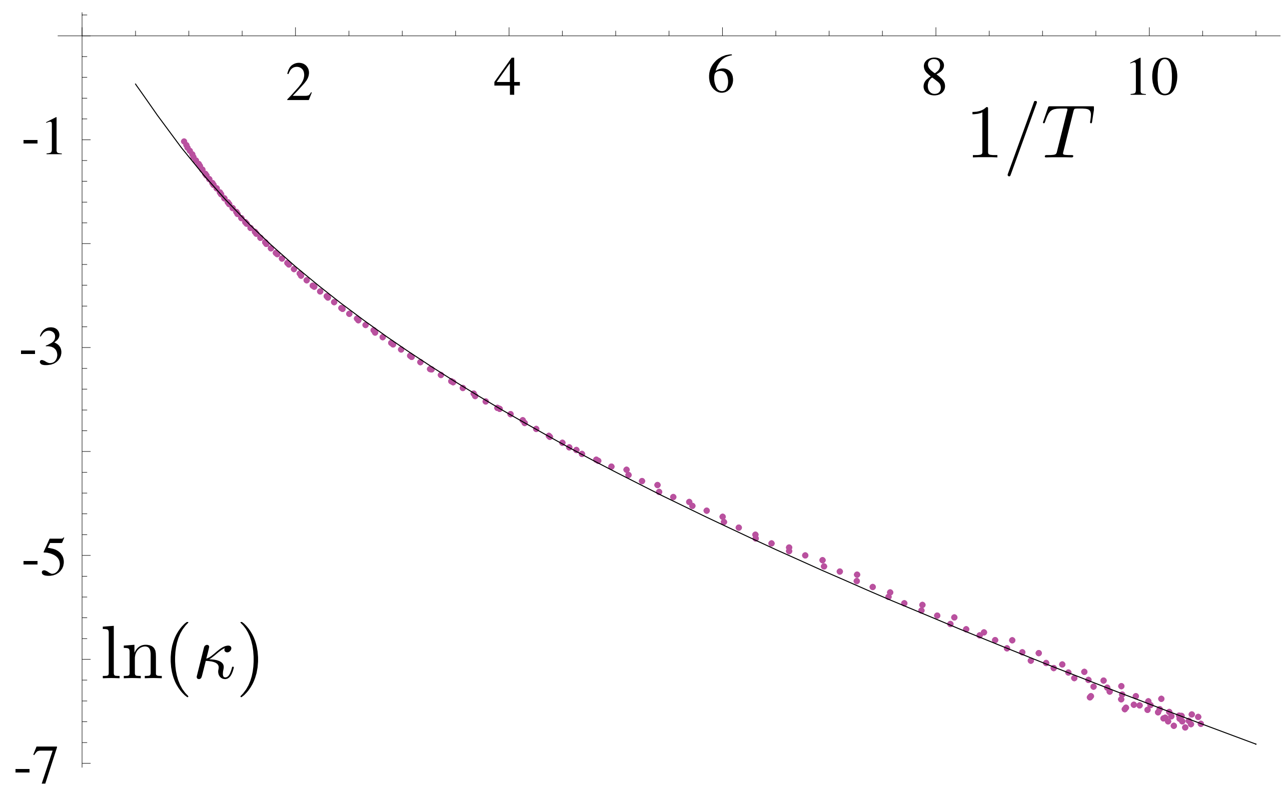
$$\kappa_v = \frac{N_v m_v k_B^3 T^2 \ln^2(T_v/T) e^{-\Delta_v/(k_B T)}}{4\pi \hbar^3 n_{\text{imp}}}.$$

where T_v is of order the vison bandwidth.

Yang Qi, Cenke Xu and S. Sachdev, arXiv:0809:0694

How do we reconcile power-law T dependence in $1/T_1$ with activated thermal conductivity ?

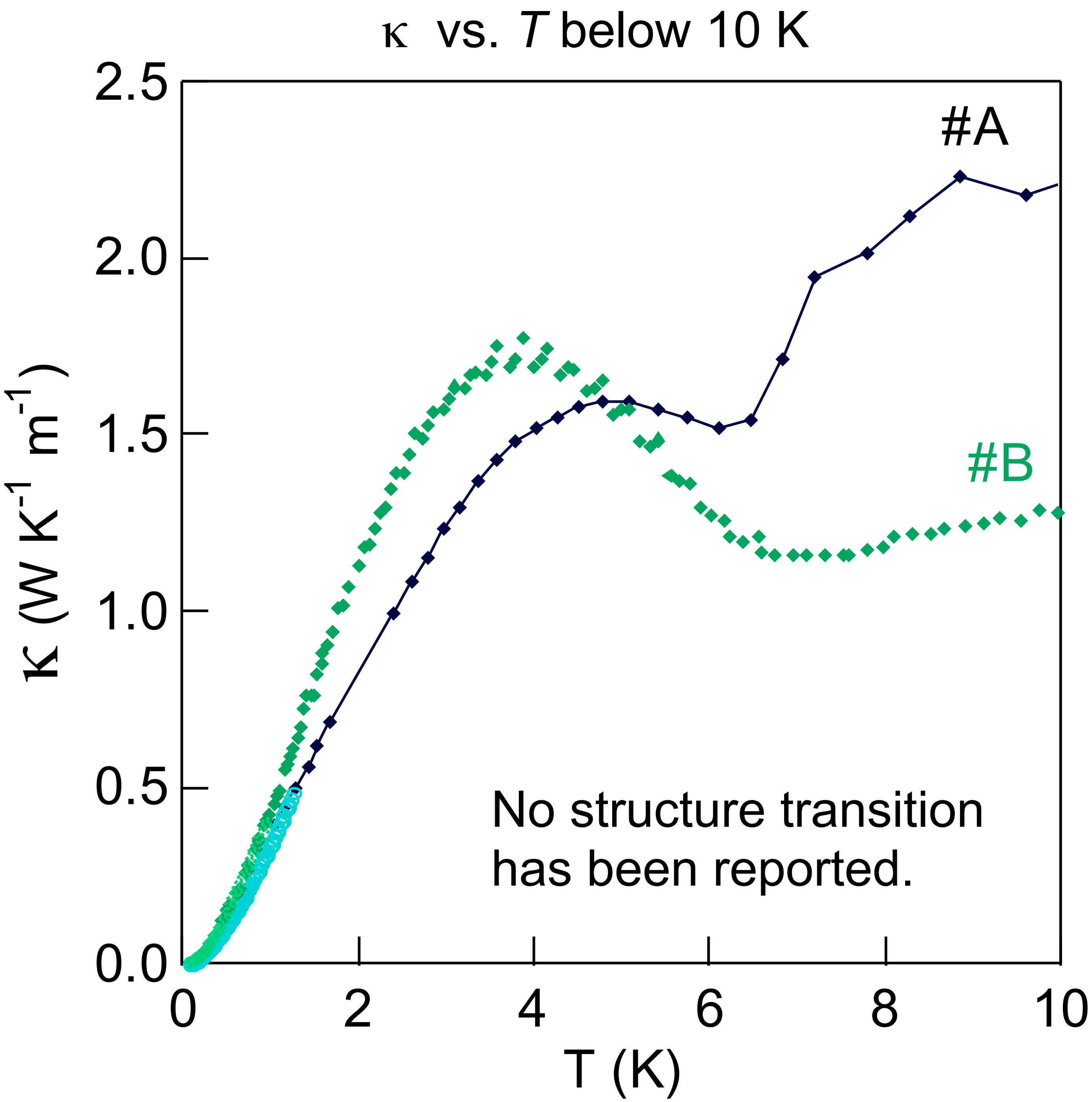
I. Thermal conductivity is dominated by vison transport



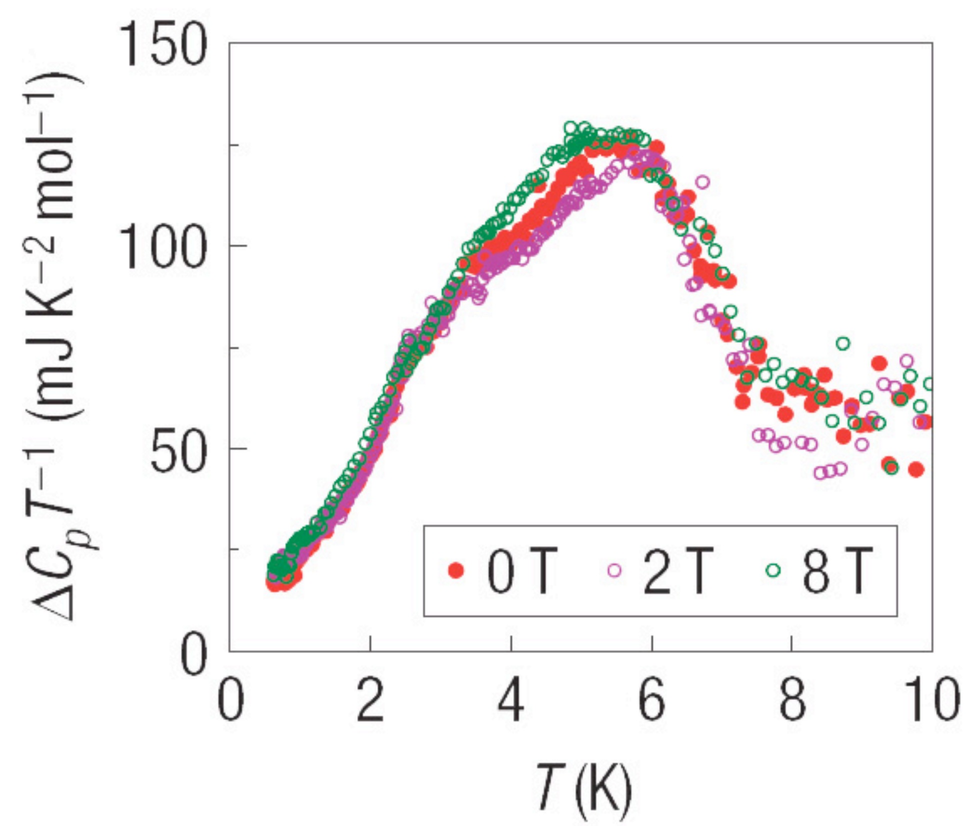
Best fit to data yields, $\Delta_v \approx 0.24$ K and $T_v \approx 8$ K.

Yang Qi, Cenke Xu and S. Sachdev, arXiv:0809:0694

Thermal Conductivity below 10K



Difference of heat capacity between X = $Cu_2(CN)_3$ and $Cu(NCS)_2$ (superconductor).



S. Yamashita, et al., Nature Physics **4**, 459 - 462 (2008)

Similar to

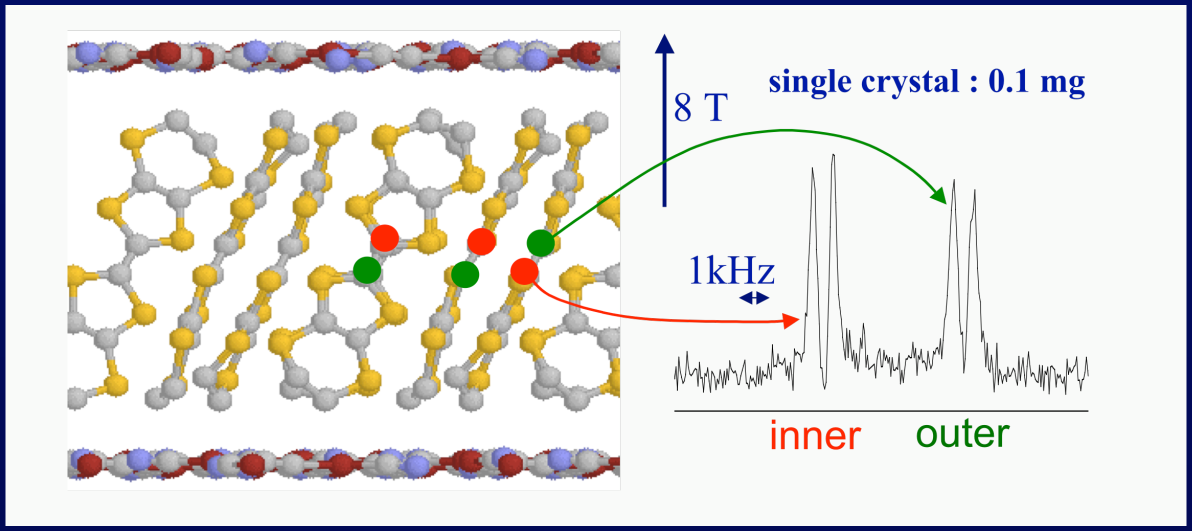
- $1/T_1$ by ^1H NMR
- Heat capacity

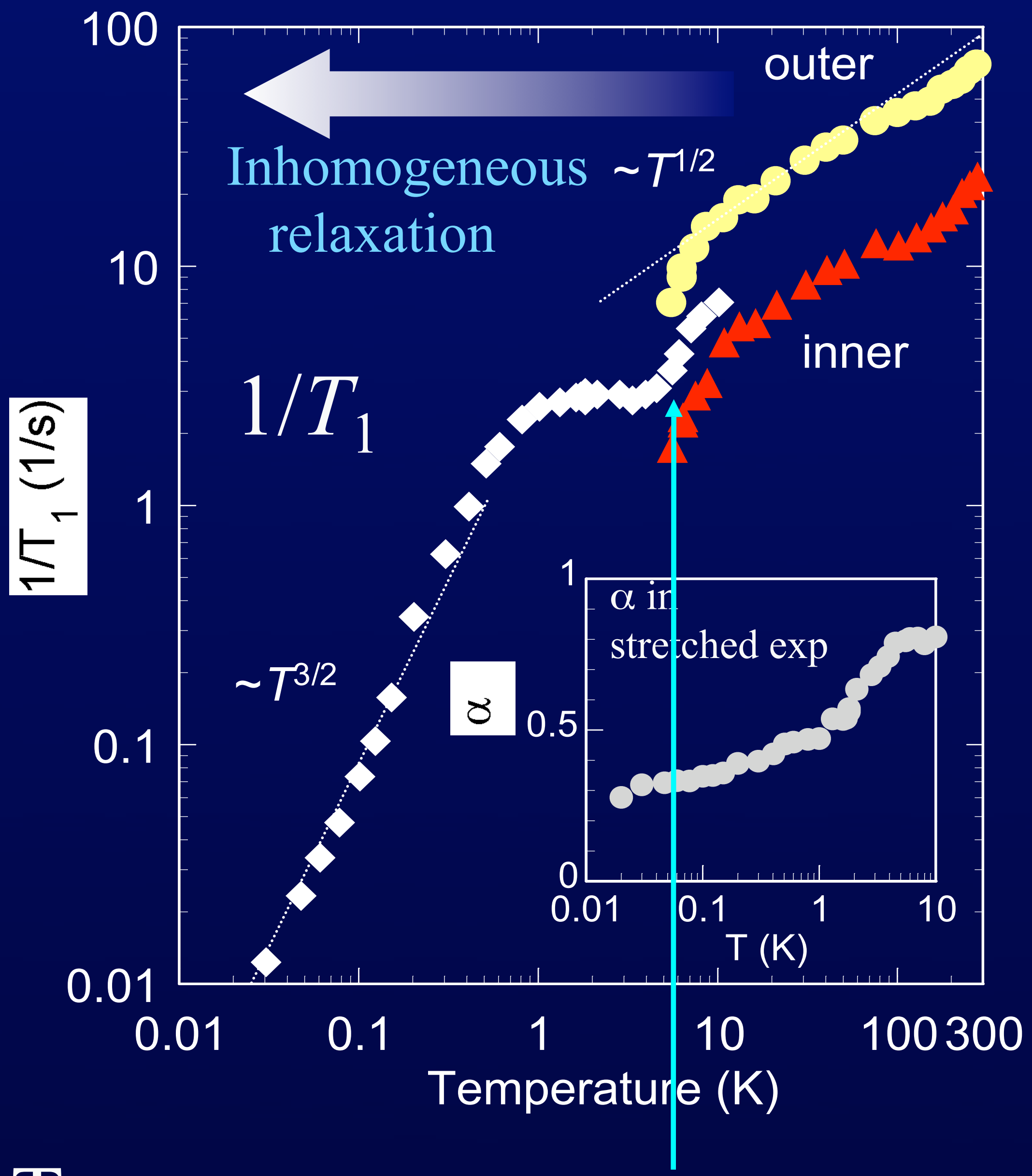
- Magnetic contribution to κ
- Phase transition or crossover?
  - Chiral order transition?
  - Instability of spinon Fermi surface?

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

How do we reconcile power-law T dependence in $1/T_1$ with activated thermal conductivity ?

II. NMR relaxation is caused by spinons close to the quantum critical point between the non-collinear Néel state and the Z_2 spin liquid

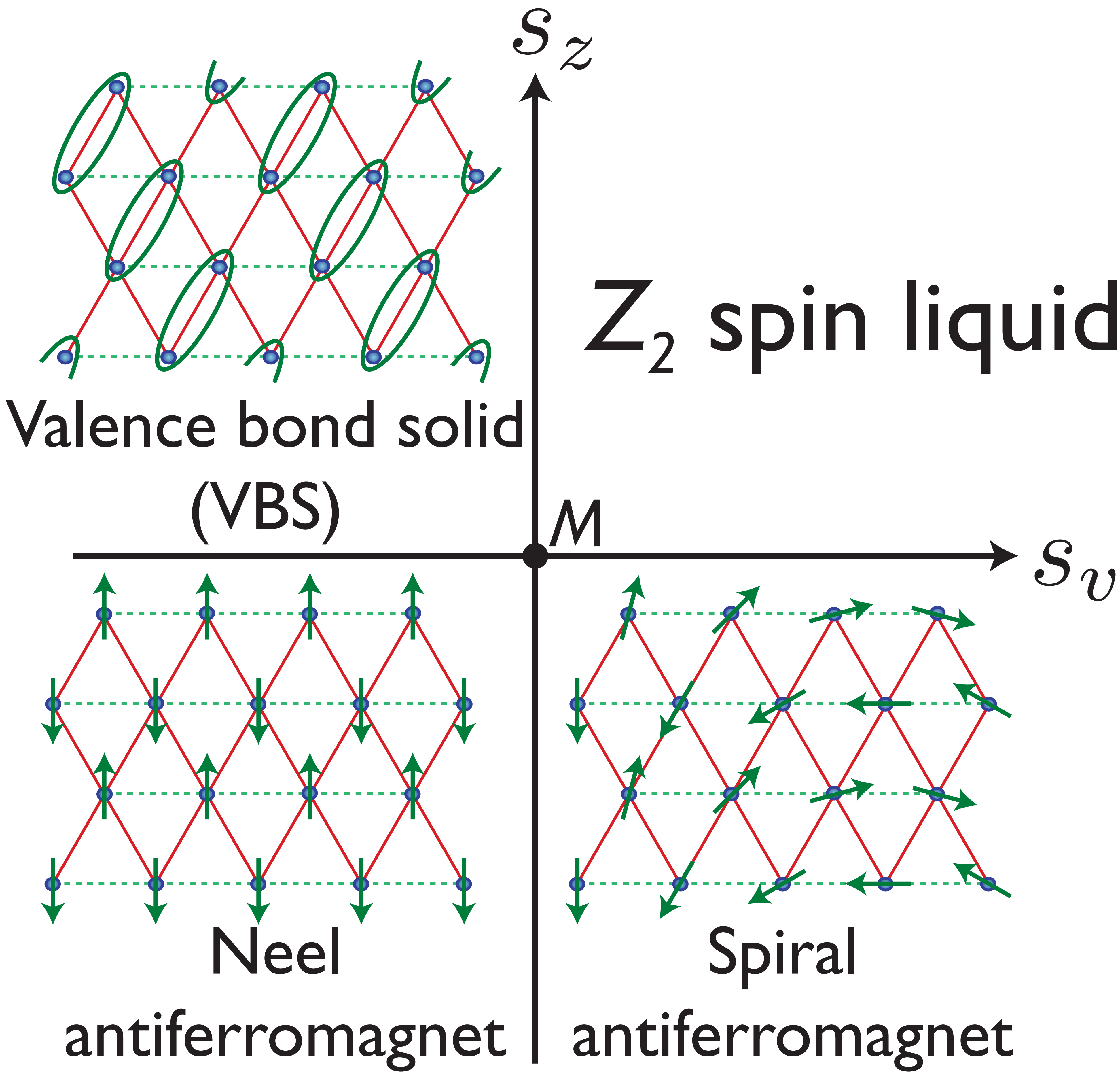
The quantum-critical region of magnetic ordering on the triangular lattice is described by the O(4) model and has

$$\frac{1}{T_1} \sim T^{\bar{\eta}}$$

where $\bar{\eta} = 1.374(12)$. This compares well with the observed $1/T_1 \approx T^{3/2}$ behavior.

(Note that the singlet gap is associated with a spinon-pair excitations, which is distinct from the vison gap, Δ_v.)

Yang Qi, Cenke Xu and S. Sachdev, arXiv:0809:0694



Cenke Xu and S. Sachdev, arXiv:0811.1220

How do we reconcile power-law *T* dependence in *1/T₁* with activated thermal conductivity ?

II. NMR relaxation is caused by spinons close to the quantum critical point between the non-collinear Néel state and the Z_2 spin liquid

At higher $T > \Delta_v$, the NMR will be controlled by the spinon-vison multicritical point, described by the mutual Chern-Simons theory. This multicritical point has

$$\frac{1}{T_1} \sim T^{\eta_{\rm cs}}$$

We do not know the value $\eta_{\rm cs}$ accurately, but the $1/N$ expansion (and physical arguments) show that $\eta_{\rm cs} < \overline{\eta}$.

Cenke Xu and S. Sachdev, arXiv:0811.1220

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

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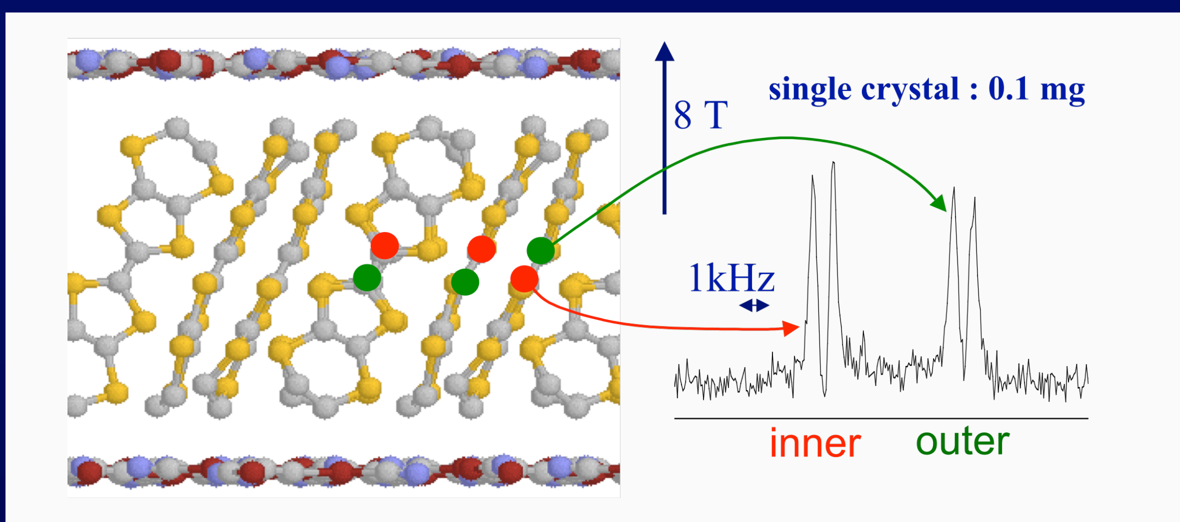

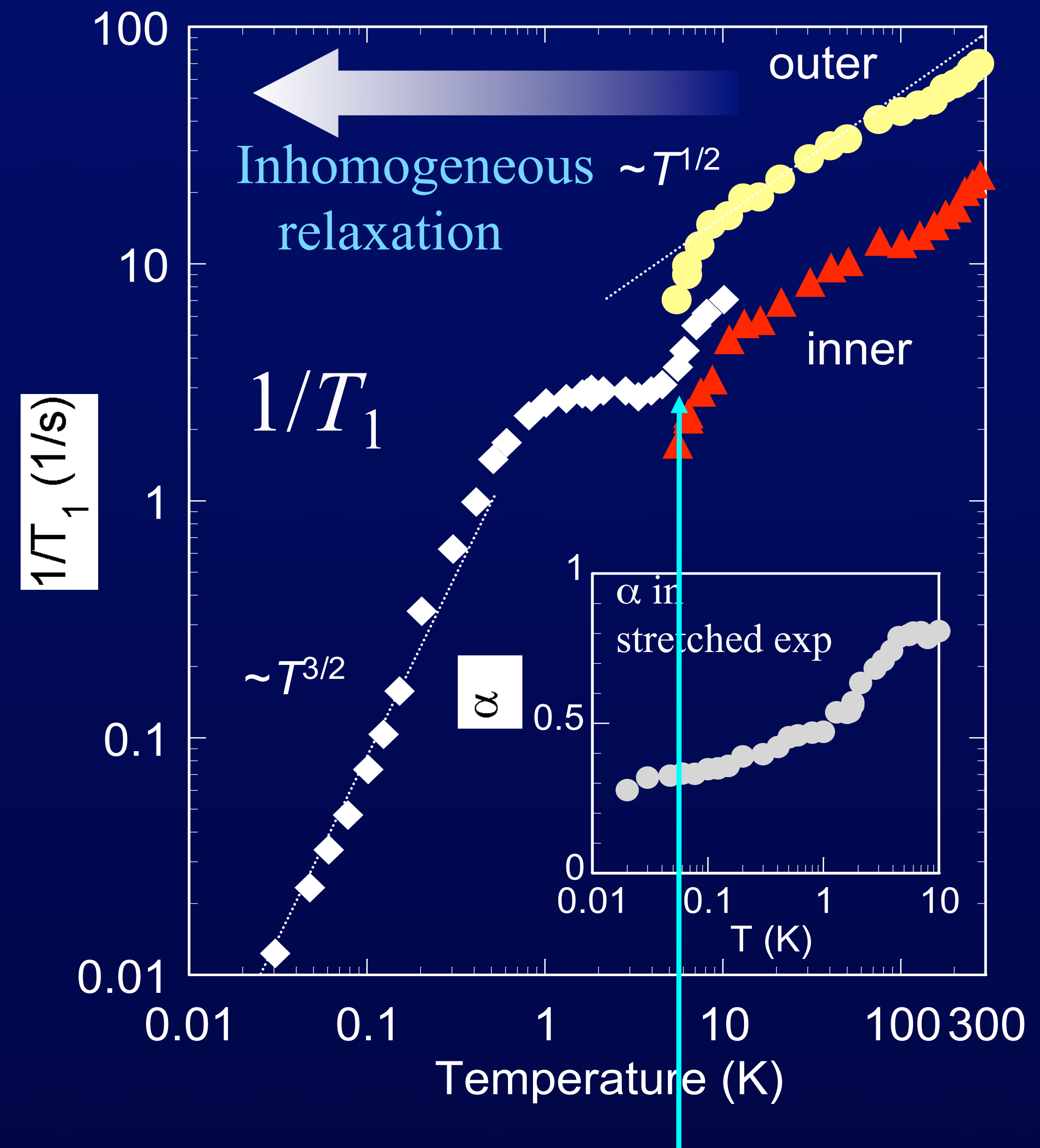

$1/T_1$ ~ power law of T

Low-lying spin excitation at low-T

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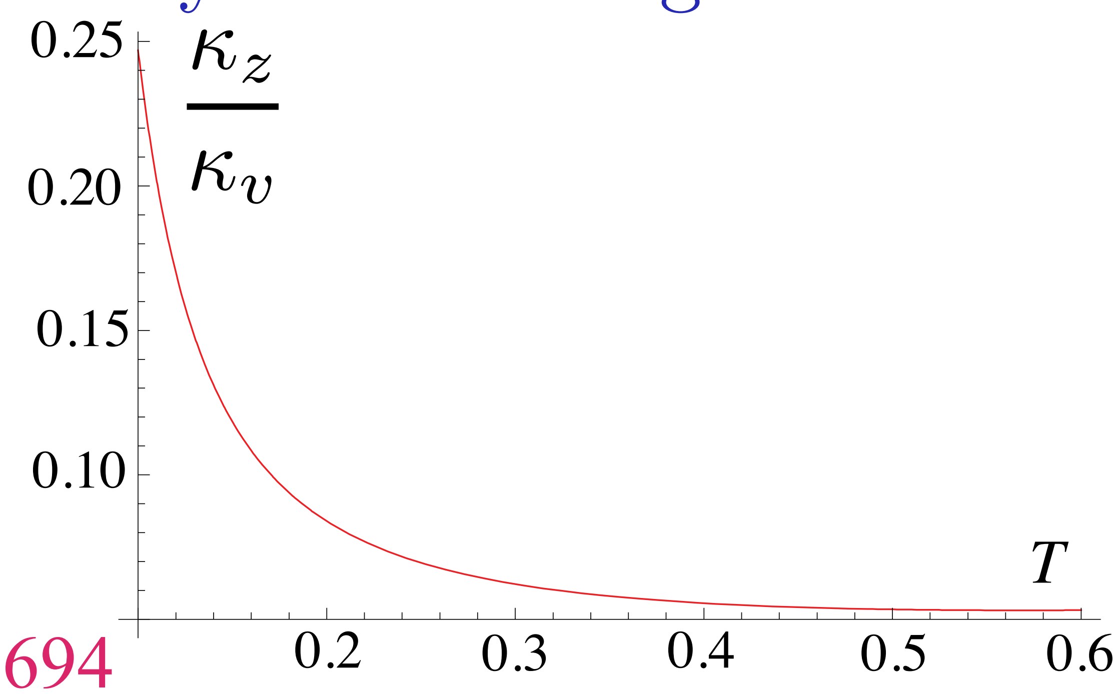
III. The thermal conductivity of the visons is larger than the thermal conductivity of spinons

We compute the spinon thermal conductivity (κ_z) by the methods of quantum-critical hydrodynamics (developed recently using the AdS/CFT correspondence). Because the spinon bandwidth ($T_z \sim J \sim 250$ K) is much larger than the vison mass/bandwidth ($T_v \sim 8$ K), the vison thermal conductivity is much larger over the T range of the experiments.



Yang Qi, Cenke Xu and S. Sachdev, arXiv:0809:0694

Conclusions

- Global phase diagram obtained by condensing vison and spin excitations of the simplest Z_2 spin liquid

- Possible explanation for NMR and thermal conductivity measurements on κ-$(ET)_2Cu_2(CN)_3$