AdS/CFT and condensed matter

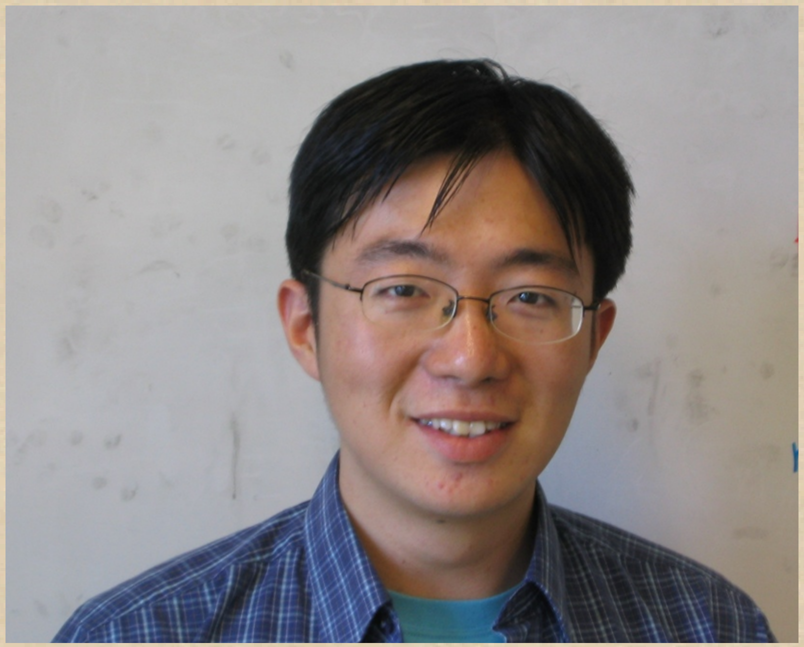
Talk online: sachdev.physics.harvard.edu

Particle theorists

Sean Hartnoll, KITP
Christopher Herzog, Princeton
Pavel Kovtun, Victoria
Dam Son, Washington

Condensed matter theorists

Markus Mueller
Geneva



Cenke Xu
Harvard

Yang Qi
Harvard

Outline

1. CFT3s in condensed matter physics

   (a) Coupled-dimer antiferromagnets

   (b) Triangular lattice antiferromagnets

   (c) The superfluid-insulator transition

2. Black holes and quantum criticality

3. Applications

   Nernst effect in the cuprate superconductors

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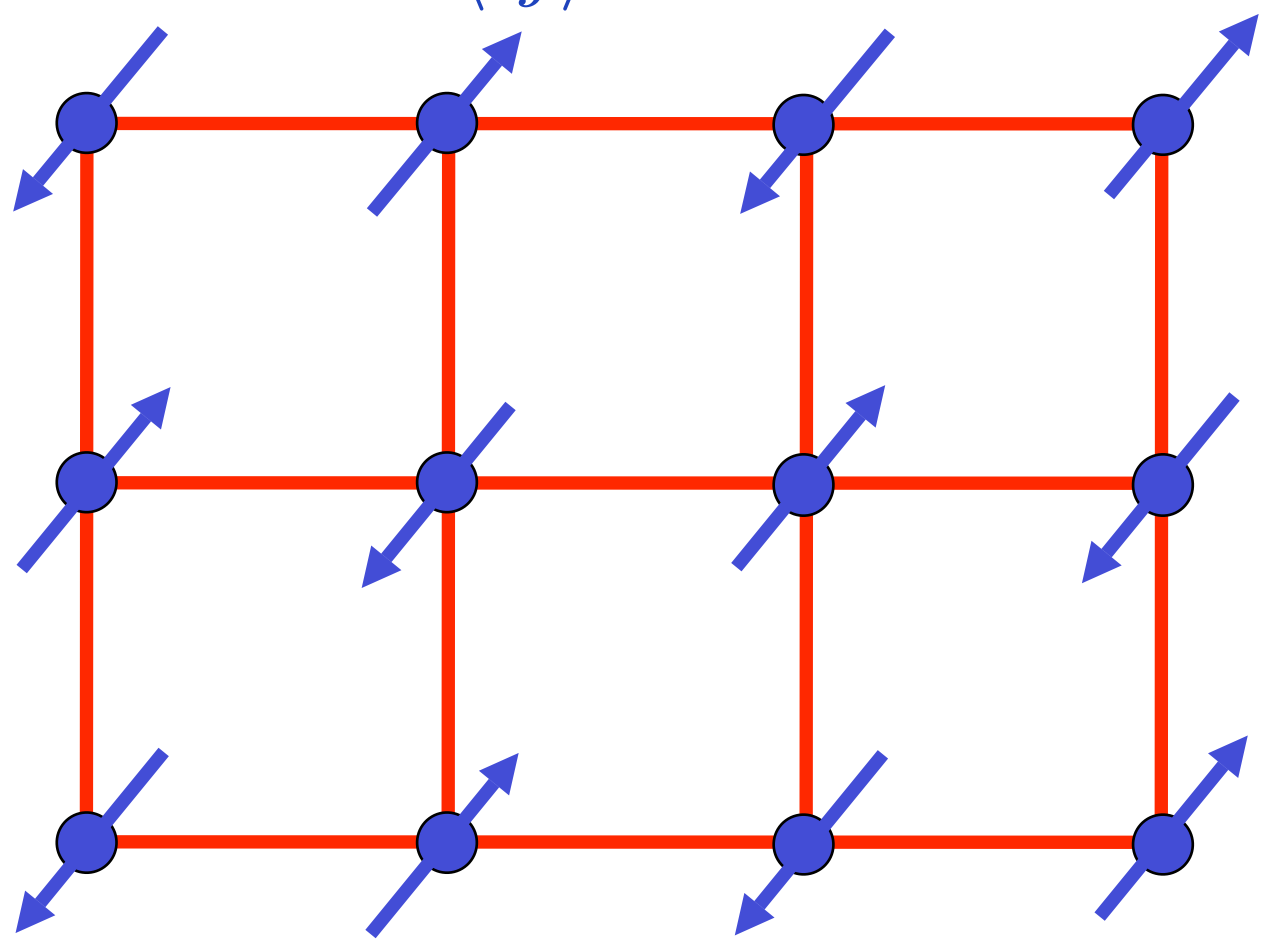
Square lattice antiferromagnet

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



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.

Square lattice antiferromagnet

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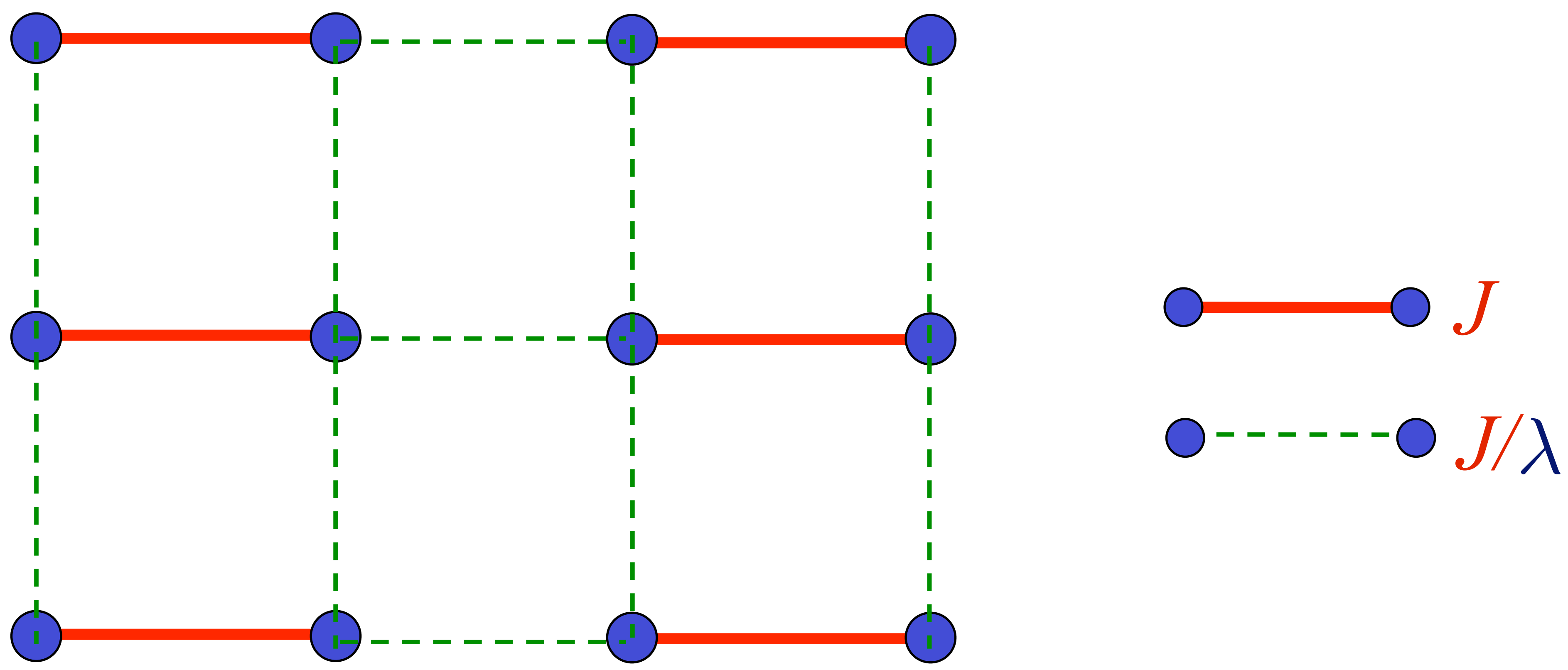
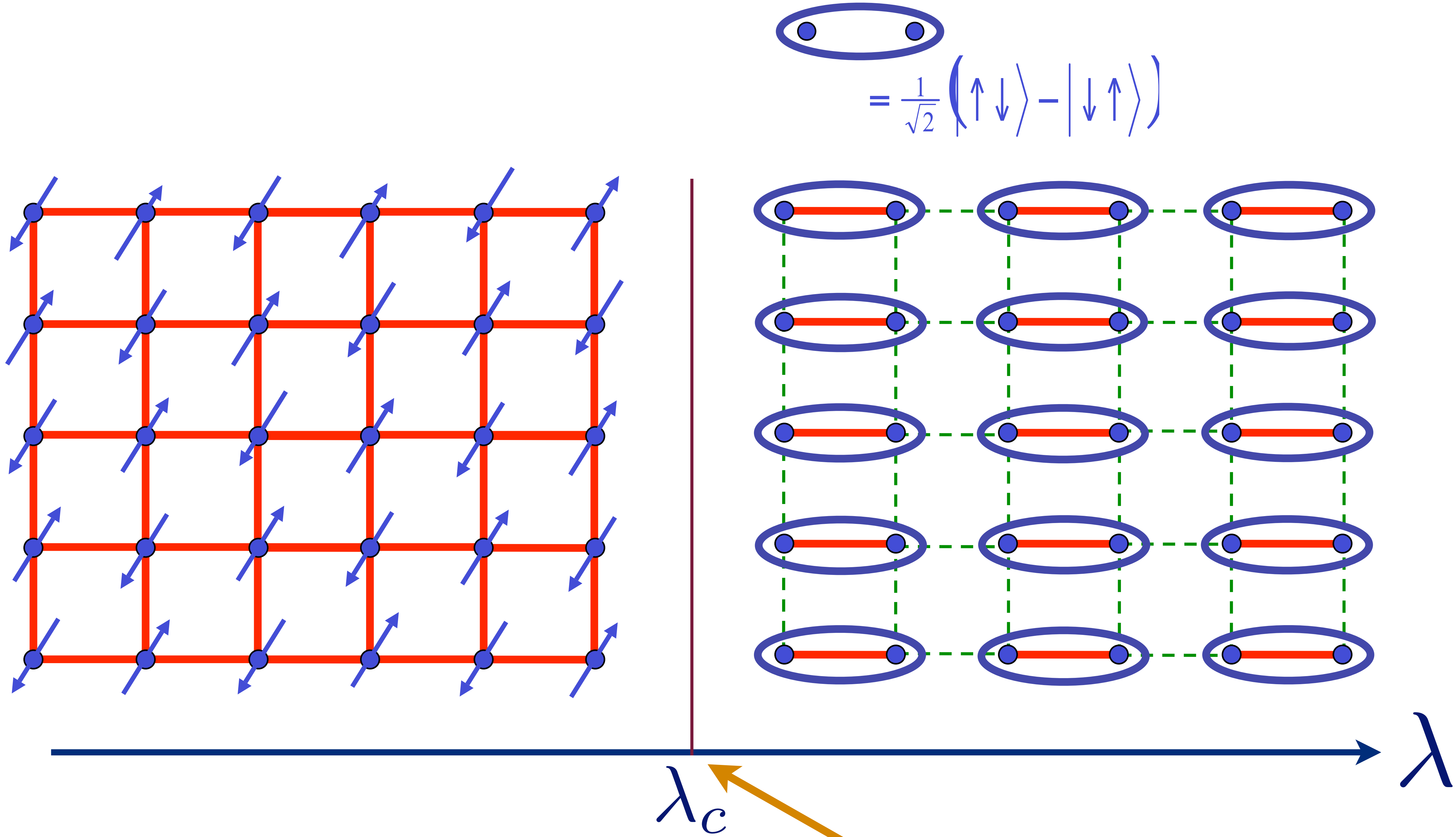
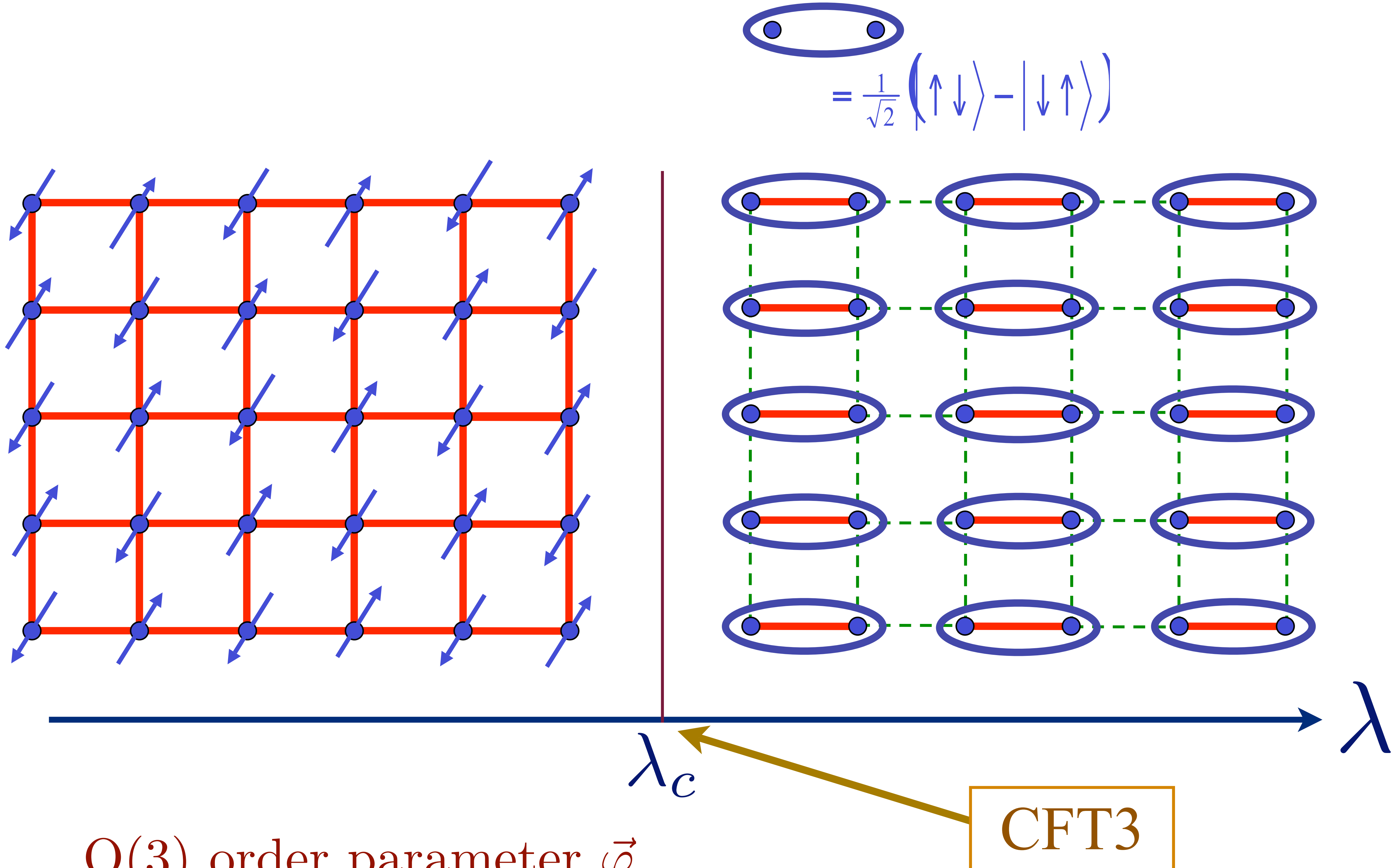


Weaken some bonds to induce spin entanglement in a new quantum phase



Quantum critical point with non-local entanglement in spin wavefunction

M. Matsumoto, C. Yasuda, S. Todo, and H. Takayama, *Phys. Rev.* B **65**, 014407 (2002).



O(3) order parameter $\vec{\varphi}$

$$\mathcal{S} = \int d^2 r d\tau \left[(\partial_\tau \vec{\varphi})^2 + c^2 (\nabla_r \vec{\varphi})^2 + (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2 \right]$$

Quantum Monte Carlo - critical exponents

Table IV: Fit results for the critical exponents ν, β/ν, and η. We summarize results including a variation of the critical point within its error bar. For the ladder model (top group of values) fit results and quality of fits are also given at the previous best estimate of α_c. The bottom group are results for the plaquette model. Numbers in [...] brackets denote the χ^2/d.o.f. For comparison relevant reference values for the 3D $O(3)$ universality class are given in the last line.

α_c	ν^a	β/ν^b	η^c
$1.9096-\sigma$	0.712(4) [1.8]	0.516(2) [0.5]	0.026(2) [0.2]
1.9096	0.711(4) [1.8]	0.518(2) [1.1]	0.029(5) [0.8]
$1.9096+\sigma$	0.710(4) [1.8]	0.519(3) [2.5]	0.032(7) [1.4]
1.9107^d	0.709(3) [1.7]	0.525(8) [15.3]	0.051(10) [12]
$1.8230-\sigma$	0.708(4) [0.99]	0.515(2) [0.84]	0.025(4) [0.15]
1.8230	0.706(4) [1.04]	0.516(2) [0.40]	0.028(3) [0.31]
$1.8230+\sigma$	0.706(4) [1.10]	0.517(2) [1.6]	0.031(5) [0.80]
Ref. 49	0.7112(5)	0.518(1)	0.0375(5)

$^a L > 12$.
$^b L > 16$.
$^c L > 20$.
^{d}Previous best estimate of Ref. 19.

S. Wenzel and W. Janke, arXiv:0808.1418
M. Troyer, M. Imada, and K. Ueda, *J. Phys. Soc. Japan* (1997)

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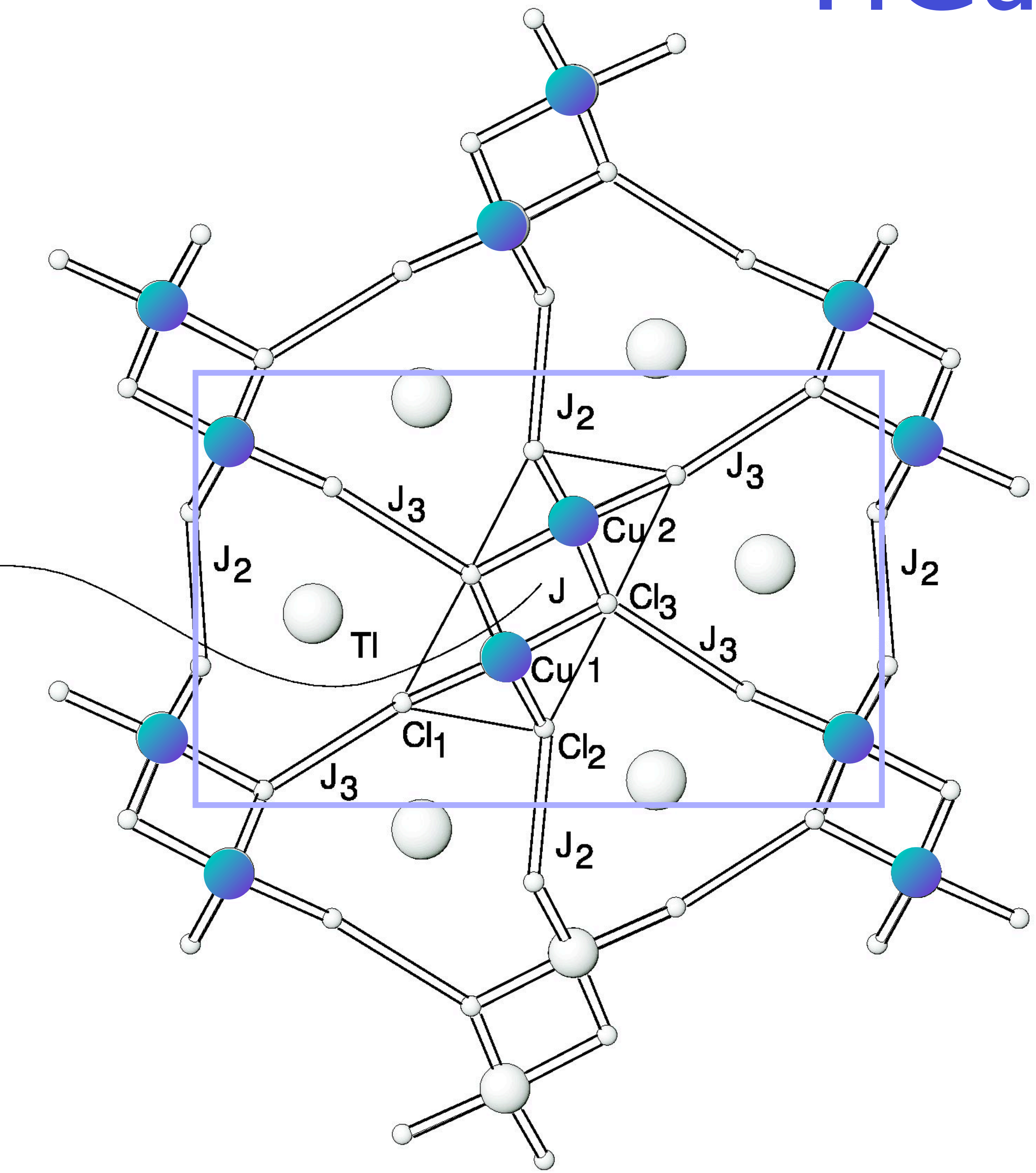
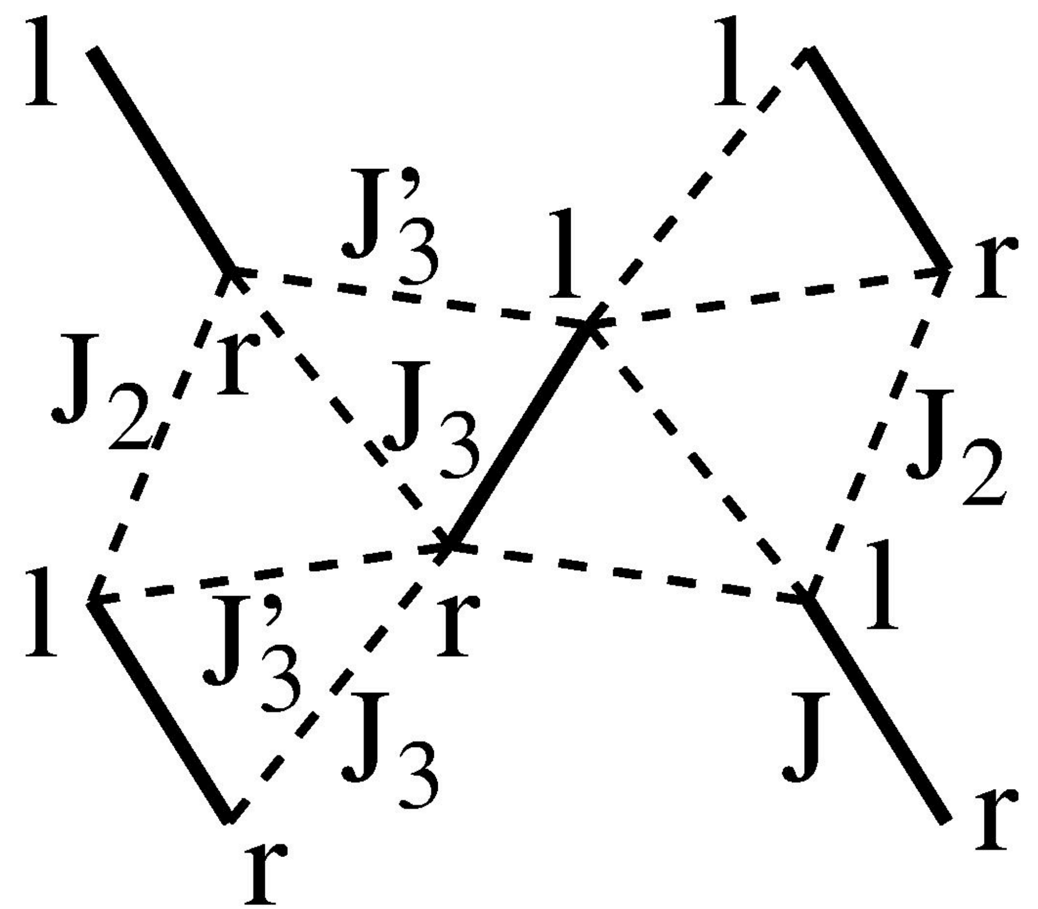
Field-theoretic RG of CFT3
E. Vicari *et al.*

S. Wenzel and W. Janke, arXiv:0808.1418
M. Troyer, M. Imada, and K. Ueda, *J. Phys. Soc. Japan* (1997)

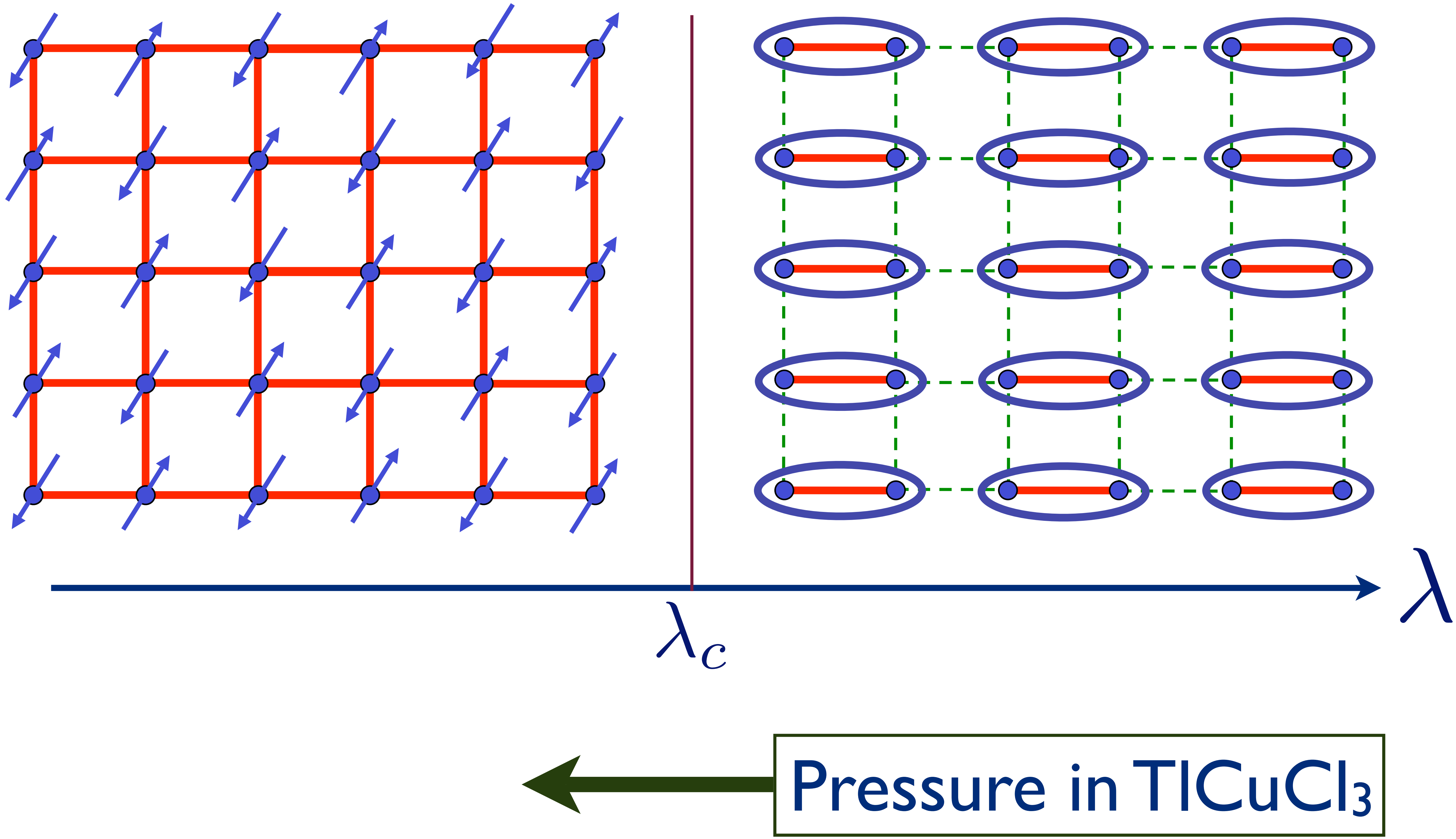
$TlCuCl_3$



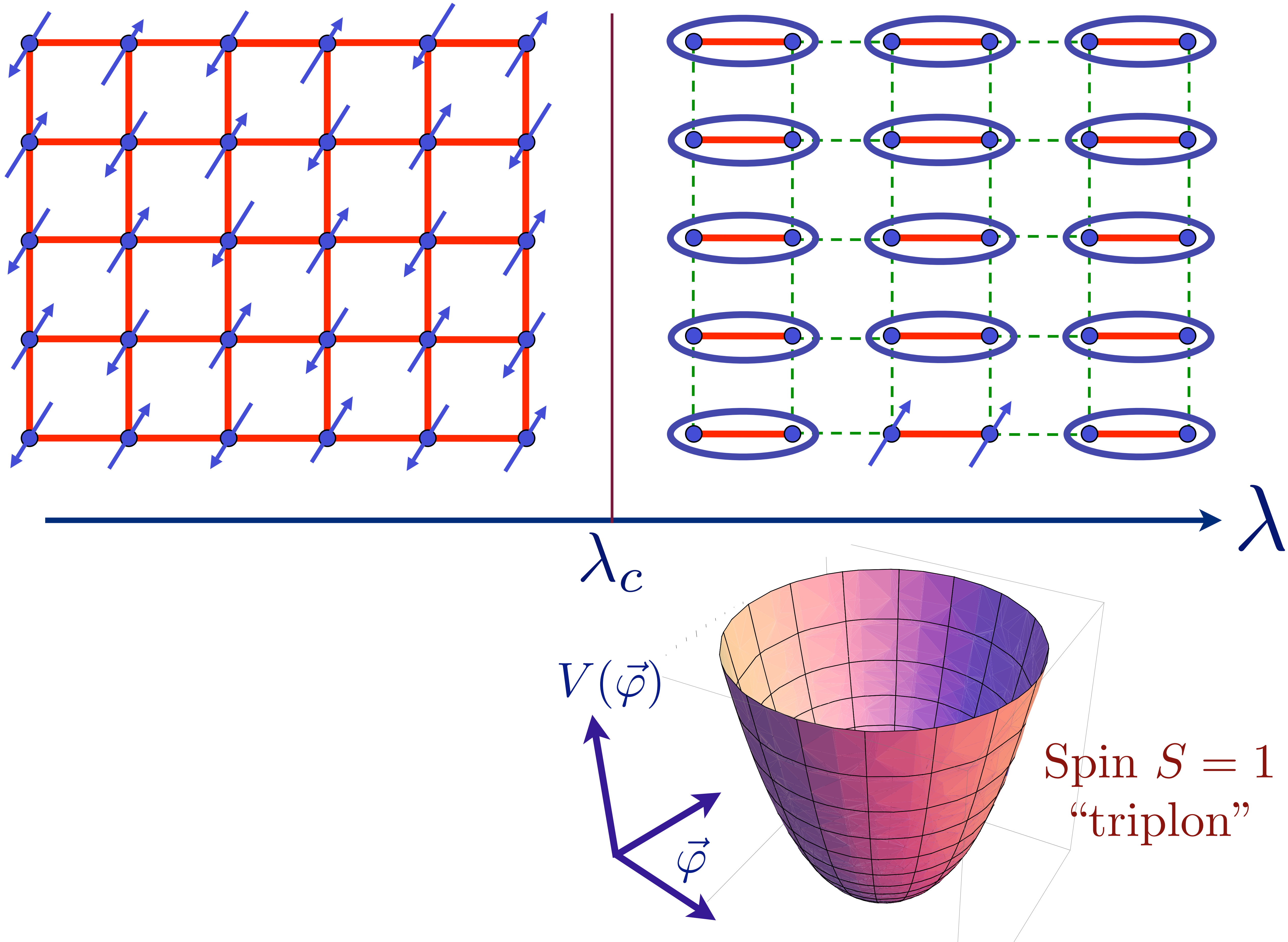
J2
J3
J3
Cu 2
J2
J2
J
Cl3
Tl
J3
Cu 1
Cl1
Cl2
J3
J2



l
l
J'3
l
r
r
J2
J3
J2
l
r
l
J'3
J3
J
r
r


λ
λ_c
Pressure in $TlCuCl_3$

Excitation spectrum in the paramagnetic phase



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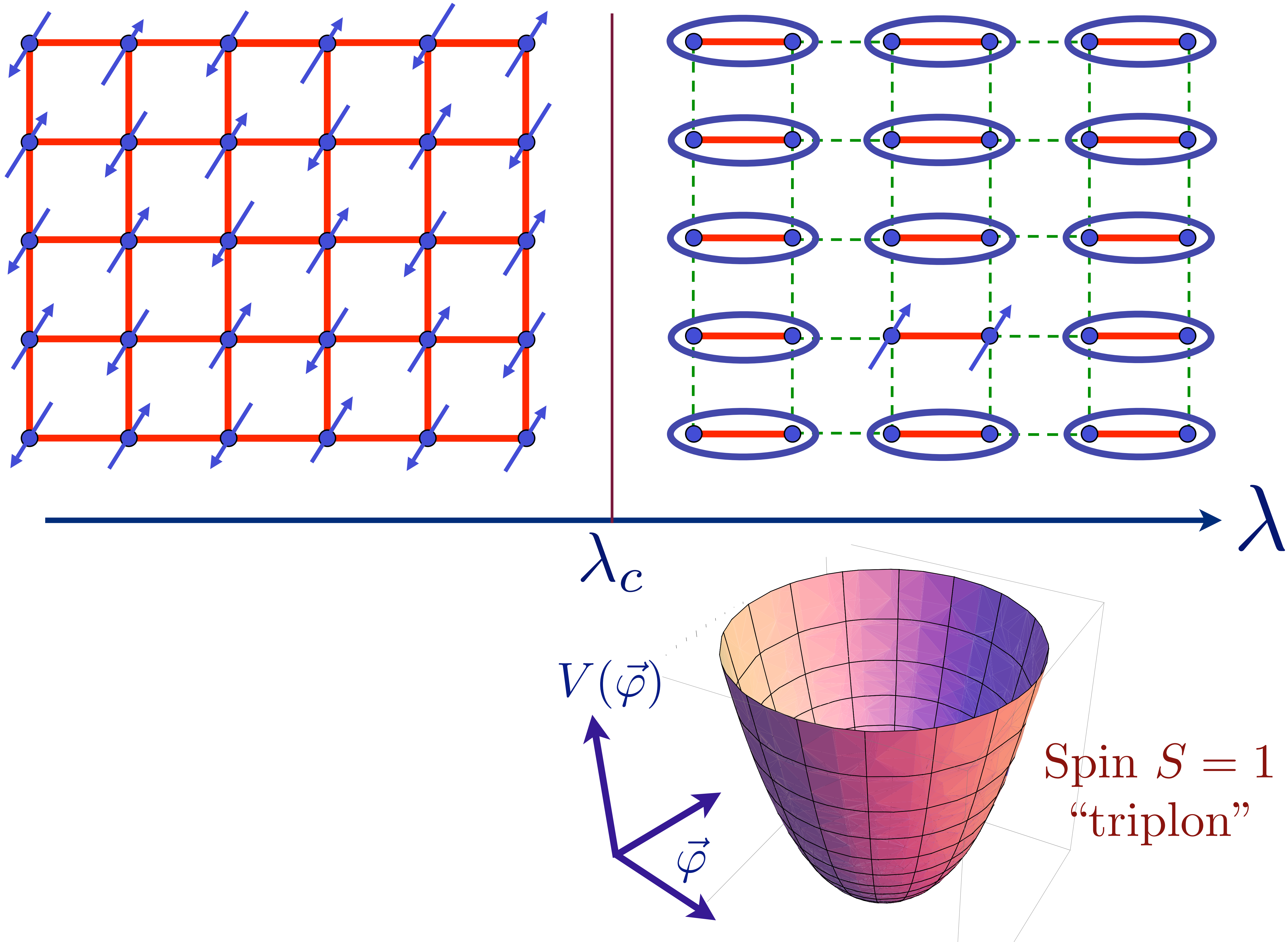
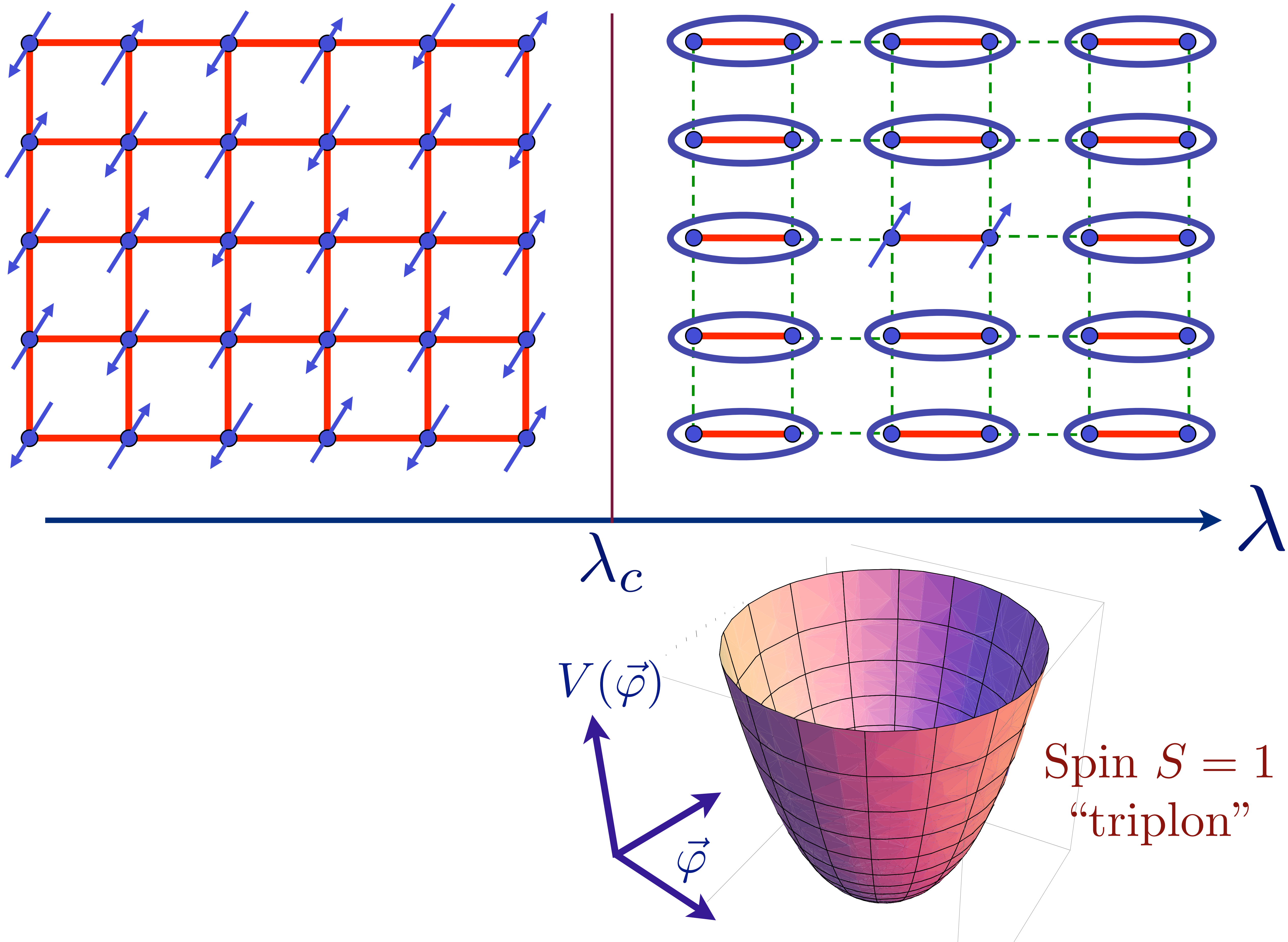


Excitation spectrum in the paramagnetic phase



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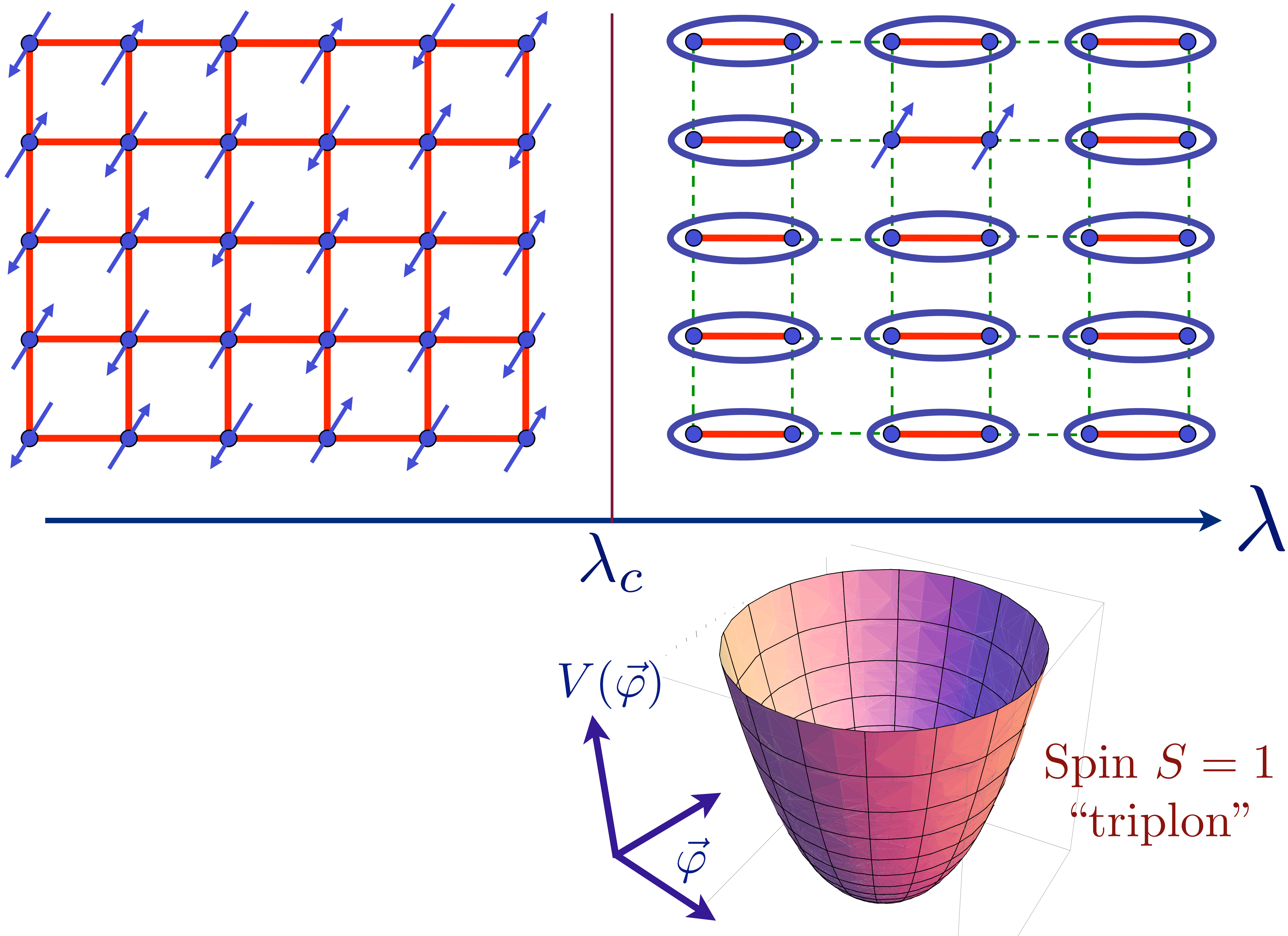
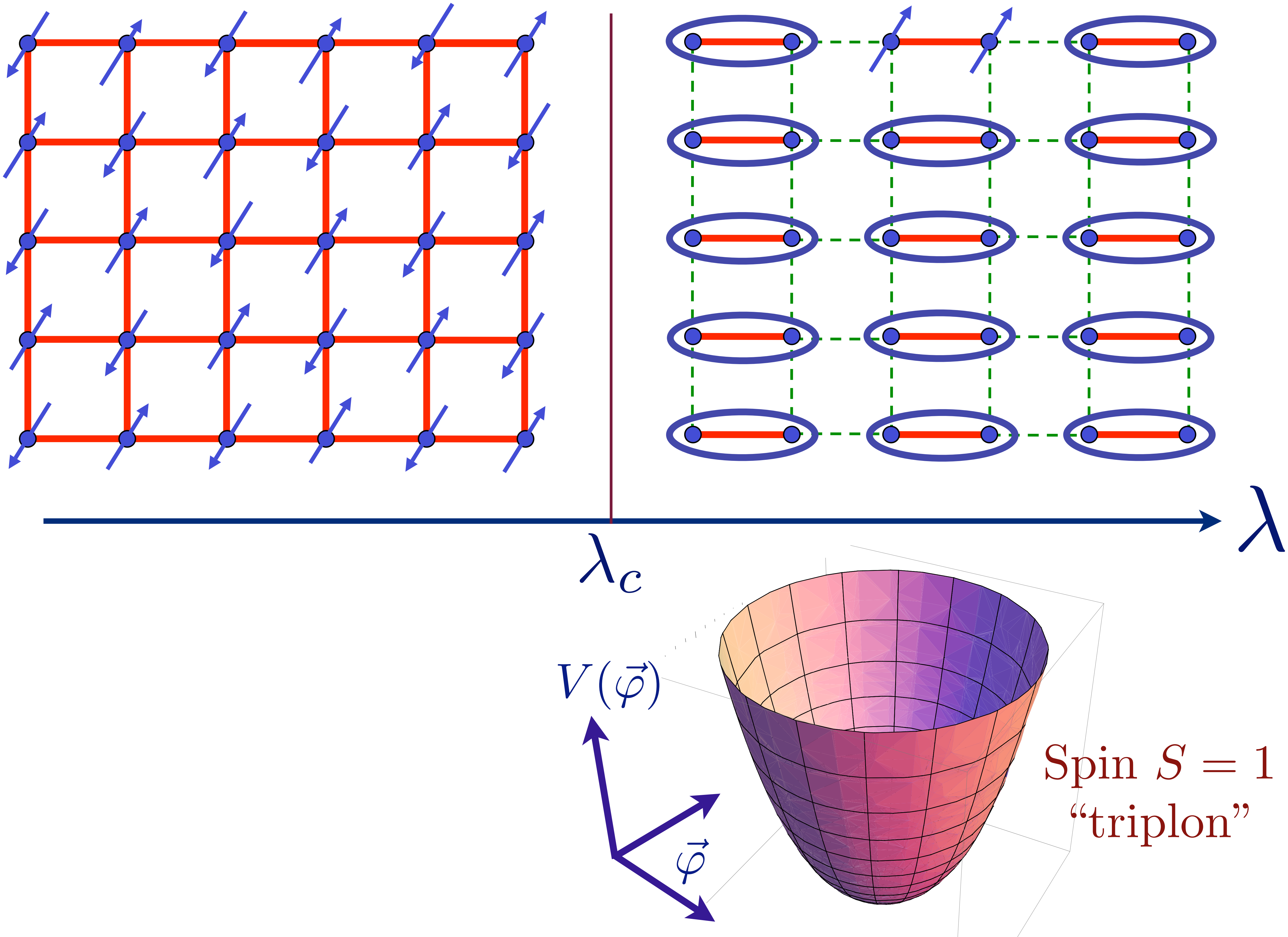
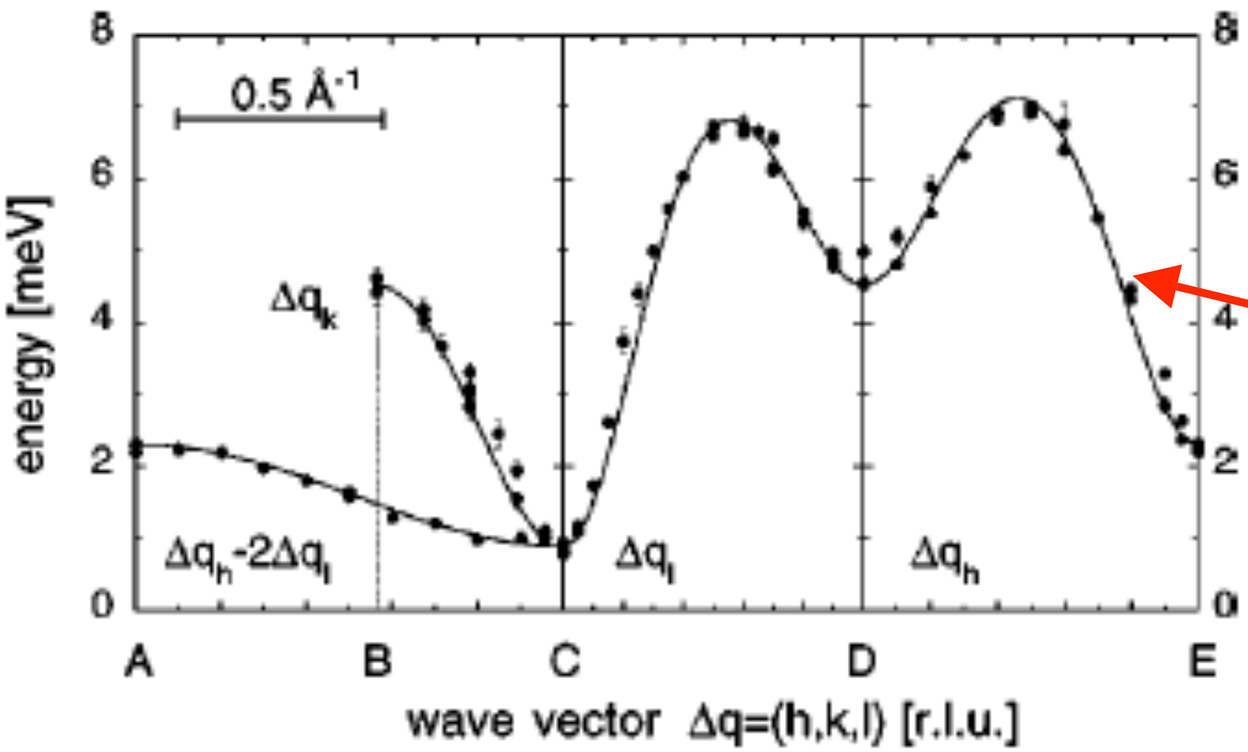


Excitation spectrum in the paramagnetic phase



$TlCuCl_3$ at ambient pressure



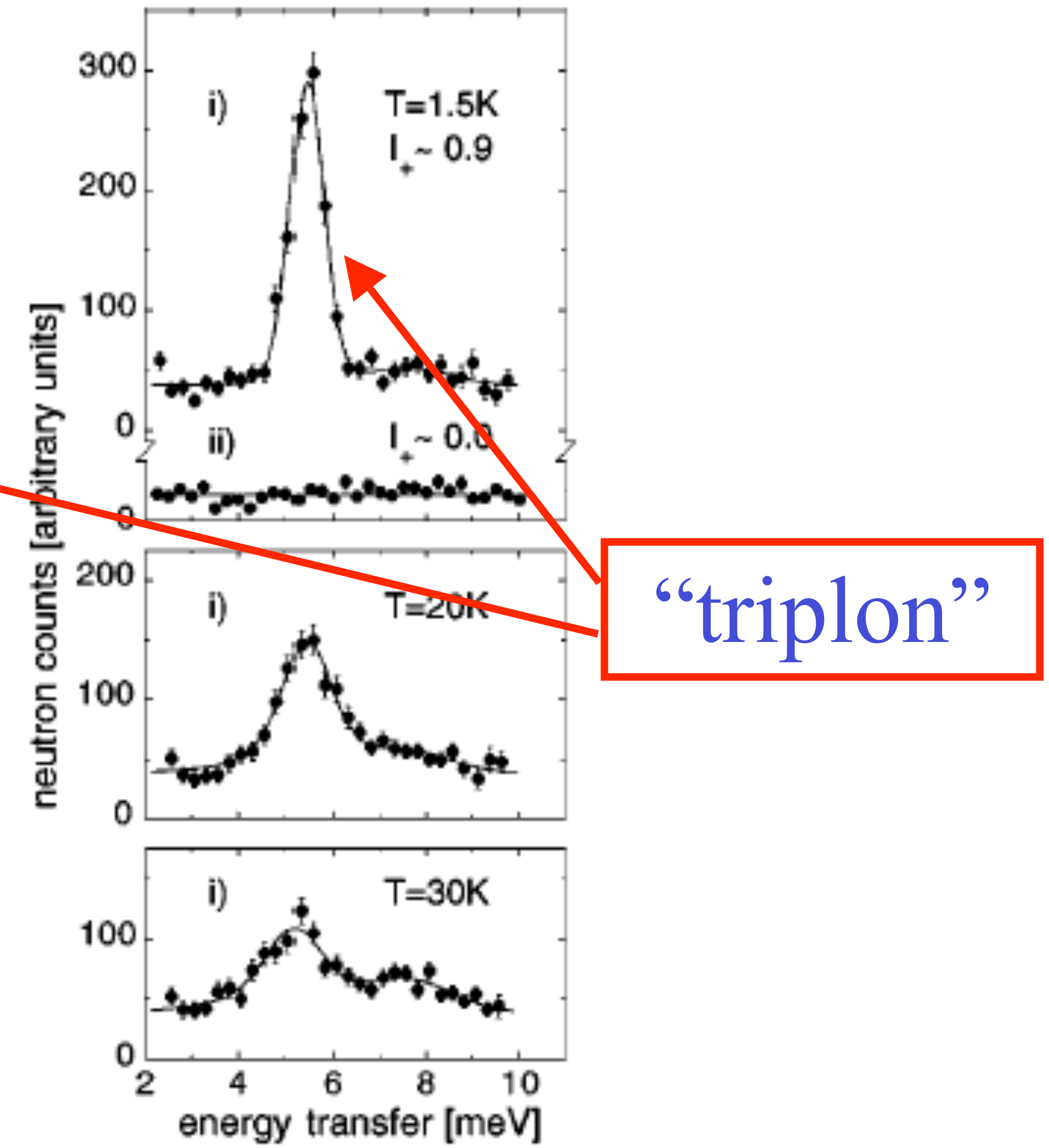
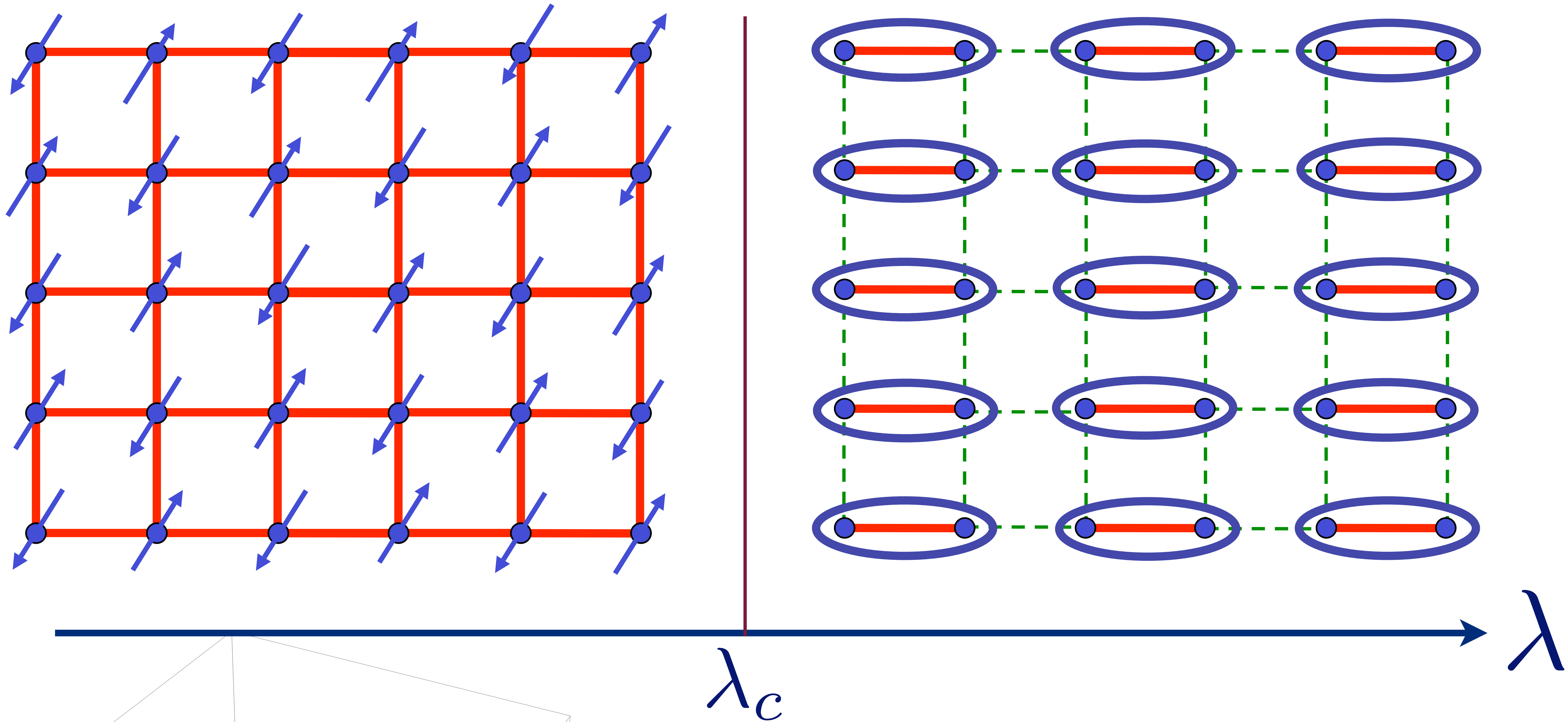
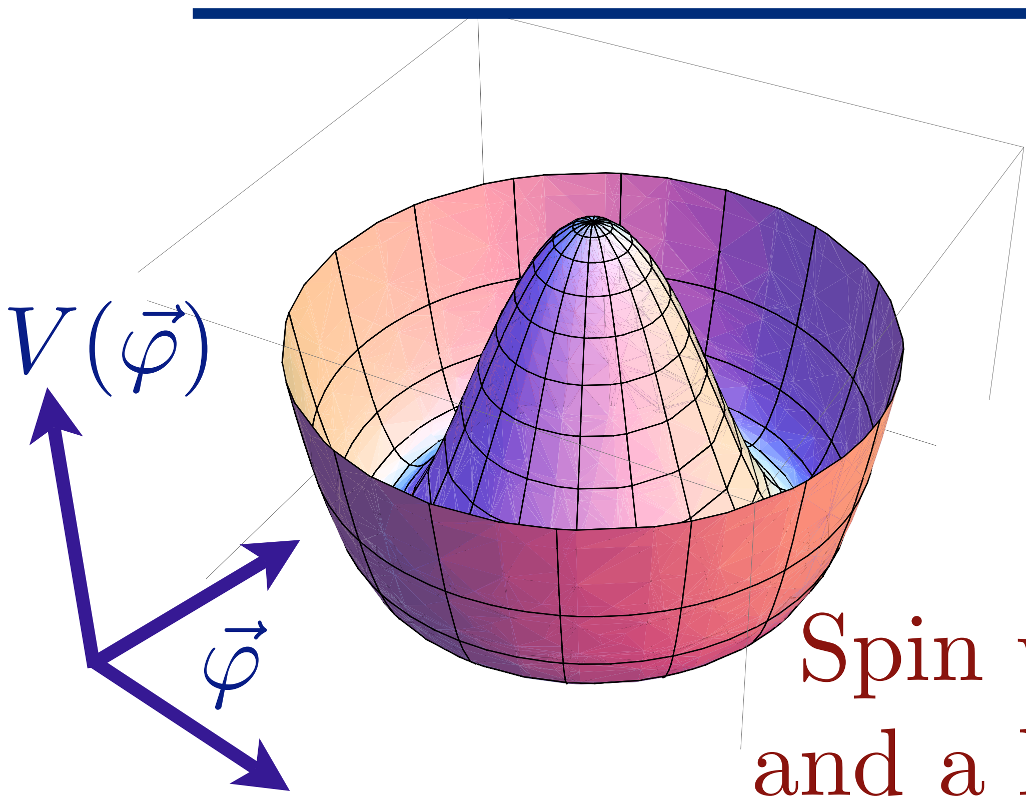


FIG. 1. Measured neutron profiles in the $a^* c^*$ plane of $TlCuCl_3$ for $i=(1.35,0,0)$, $ii=(0,0,3.15)$ [r.l.u]. The spectrum at $T=1.5$ K

N. Cavadini, G. Heigold, W. Henggeler, A. Furrer, H.-U. Güdel, K. Krämer and H. Mutka, *Phys. Rev.* B 63 172414 (2001).

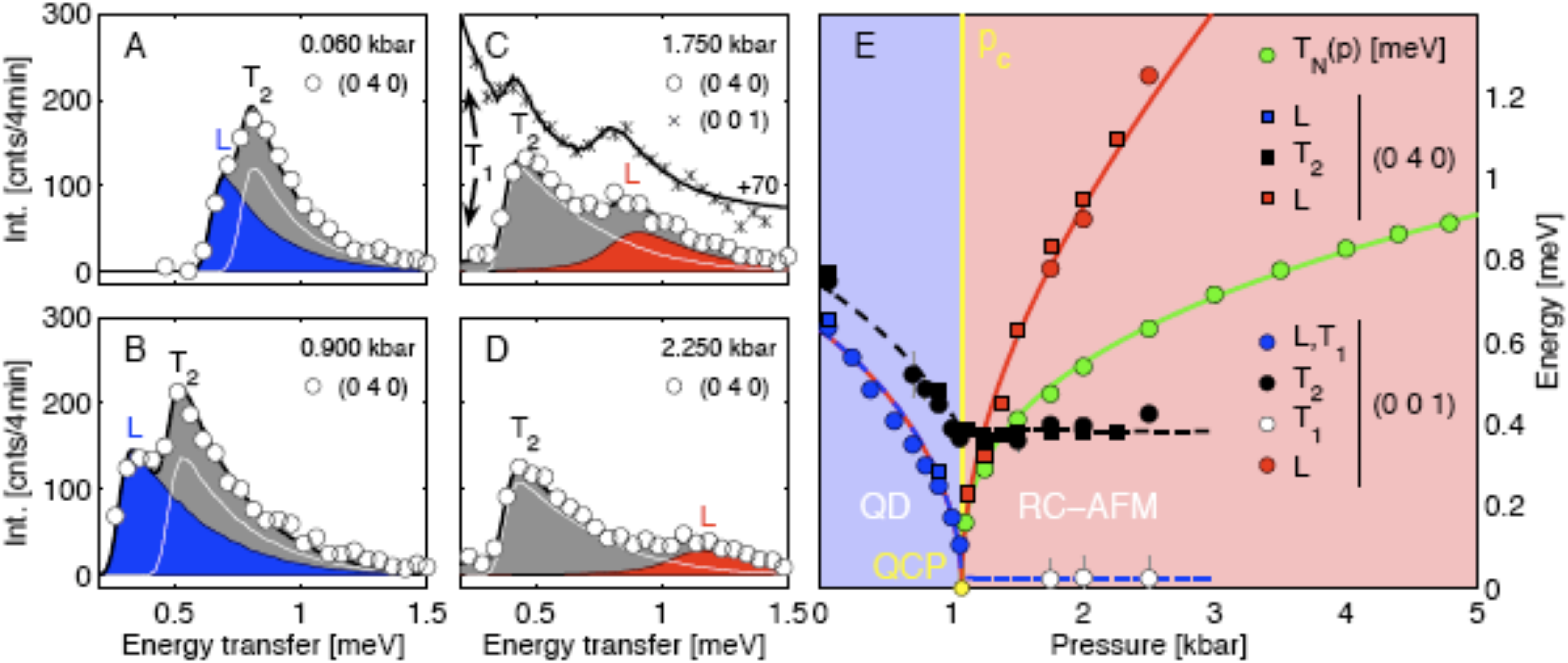
Excitation spectrum in the Néel phase





Spin waves (“Goldstone” modes)
and a longitudinal “Higgs” particle

$TlCuCl_3$ with varying pressure

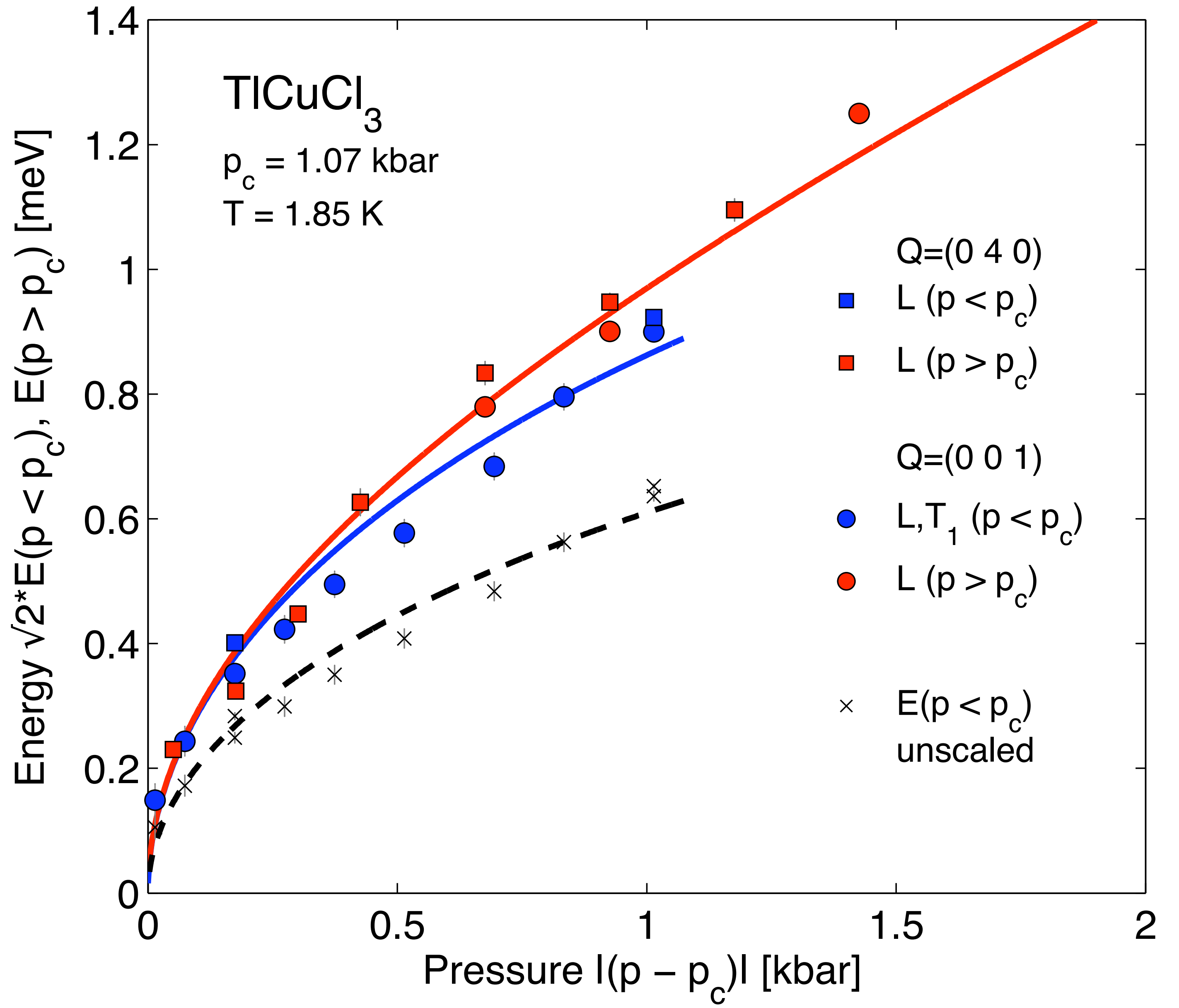


Observation of 3 → 2 low energy modes,
emergence of new Higgs particle in the Néel phase,
and vanishing of Néel temperature at the quantum critical point

Christian Ruegg, Bruce Normand, Masashige Matsumoto, Albert Furrer, Desmond McMorrow, Karl Kramer, Hans-Ulrich Gudel, Severian Gvasaliya, Hannu Mutka, and Martin Boehm, *Phys. Rev. Lett.* **100**, 205701 (2008)

Prediction of quantum field theory

$$\frac{\text{Energy of “Higgs” particle}}{\text{Energy of triplon}} = \sqrt{2}$$



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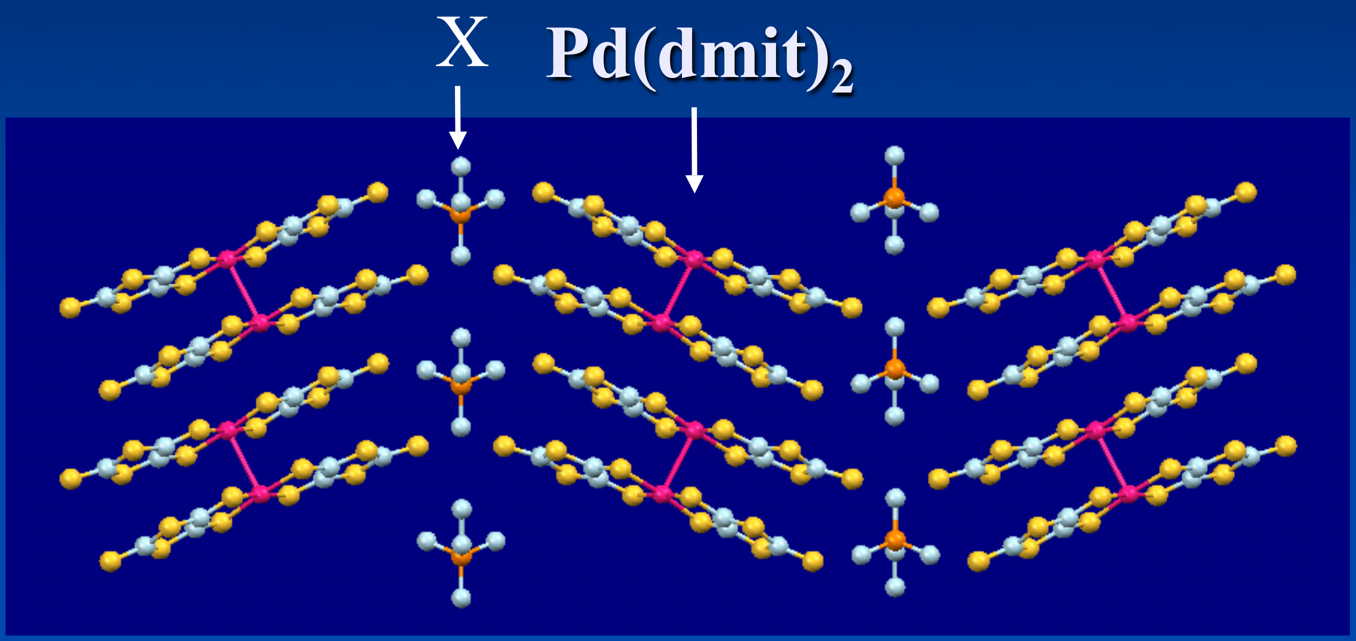
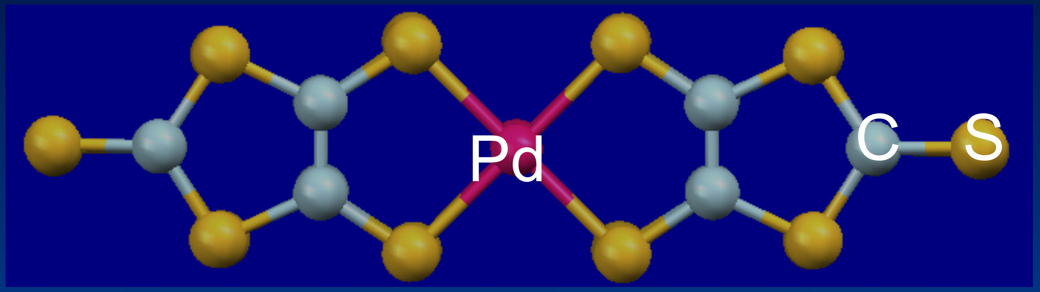
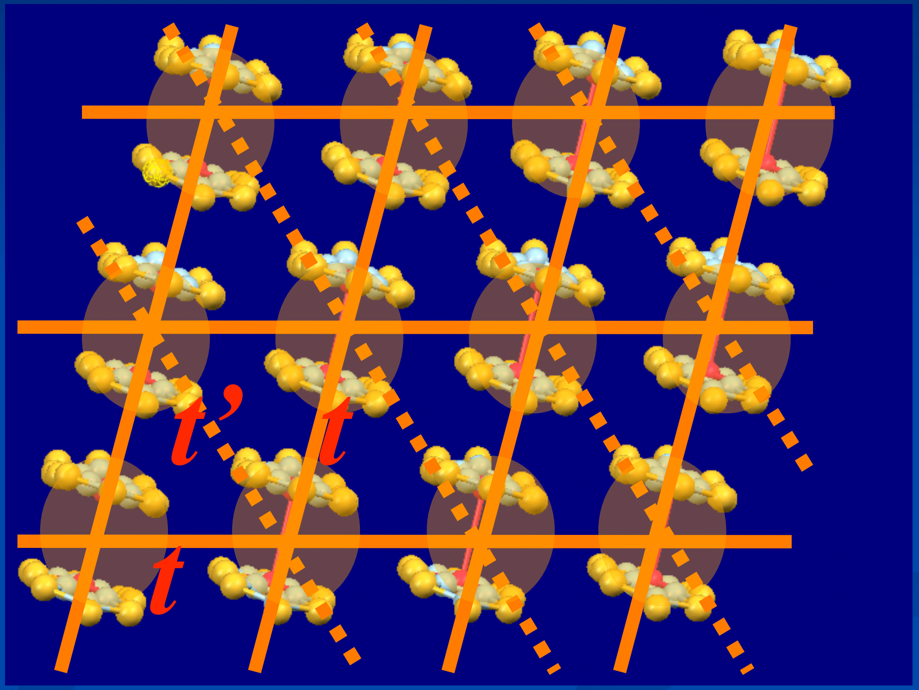
$X[Pd(dmit)_2]_2$







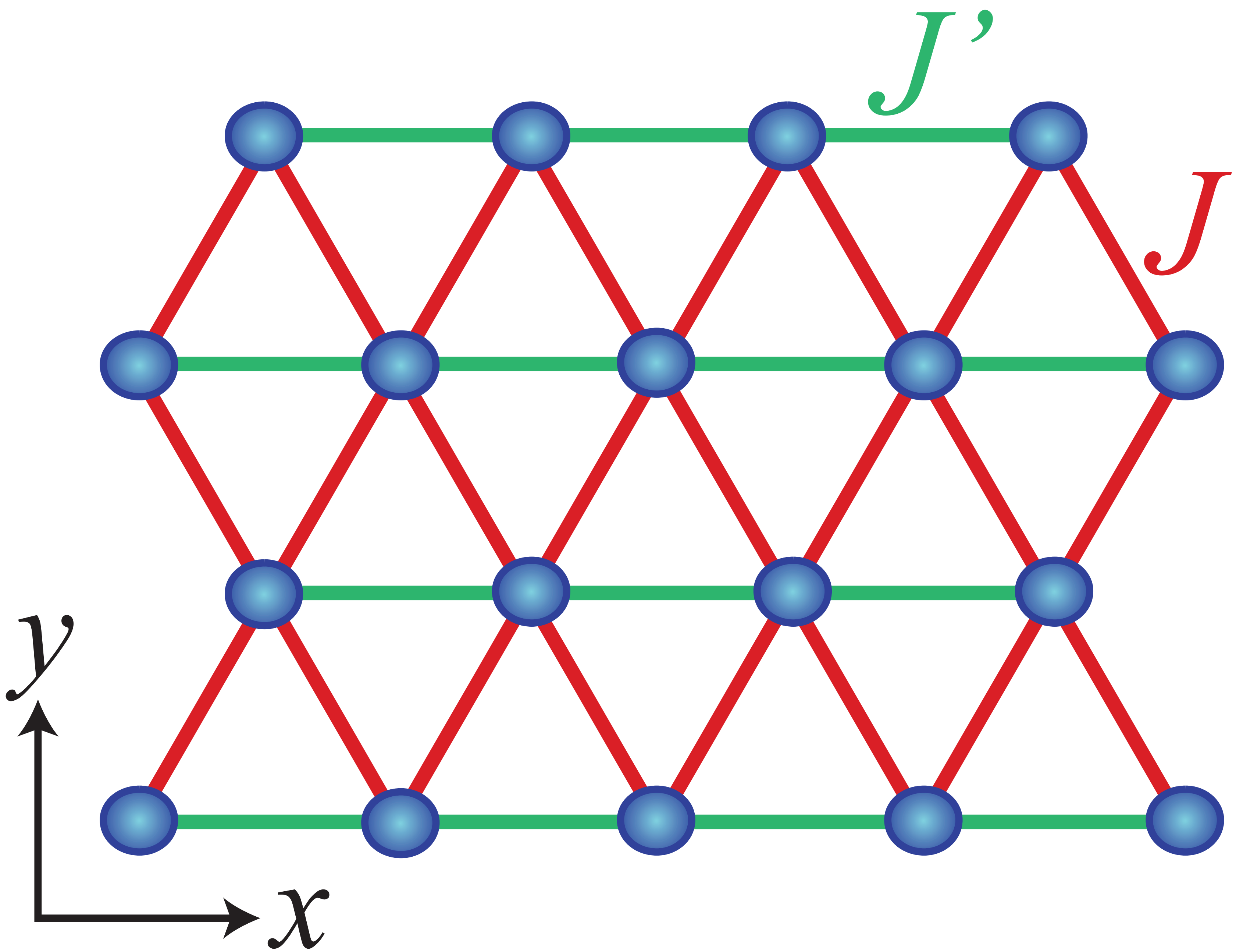
Half-filled band → Mott insulator with spin S = 1/2

Triangular lattice of $[Pd(dmit)_2]_2$
→ frustrated quantum spin system

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

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

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



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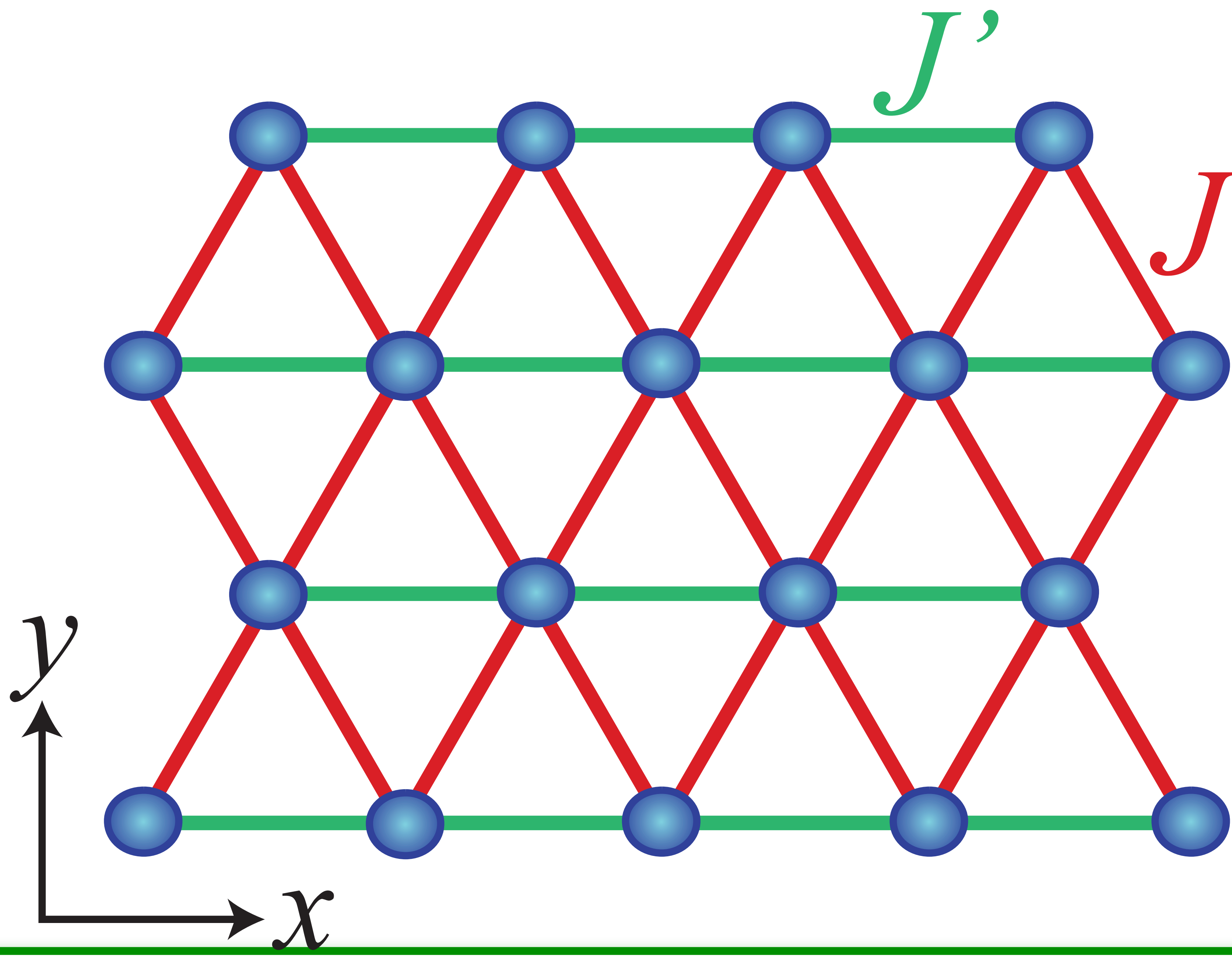
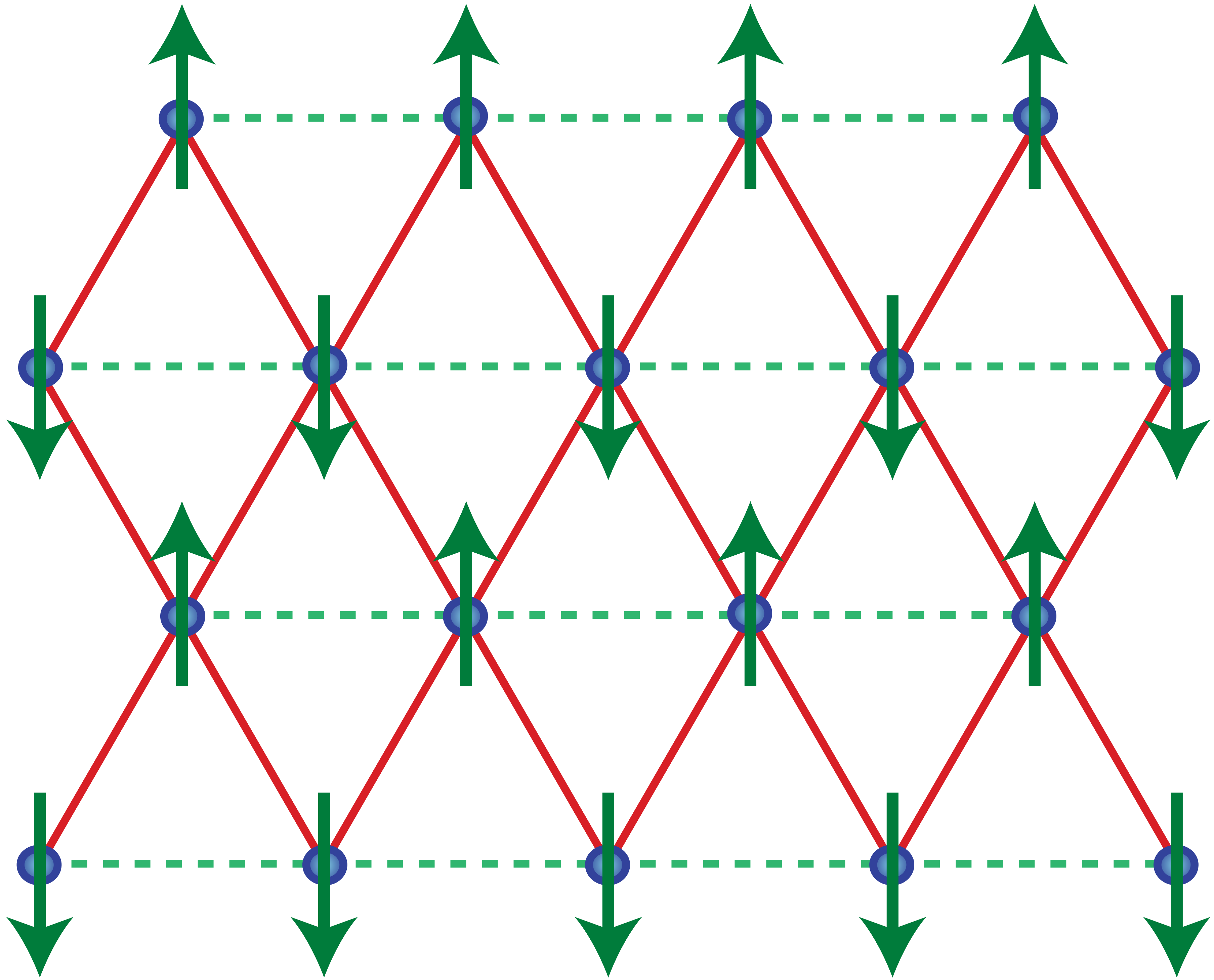


What is the ground state as a function of J'/J ?

Anisotropic triangular lattice antiferromagnet

Broken spin rotation symmetry



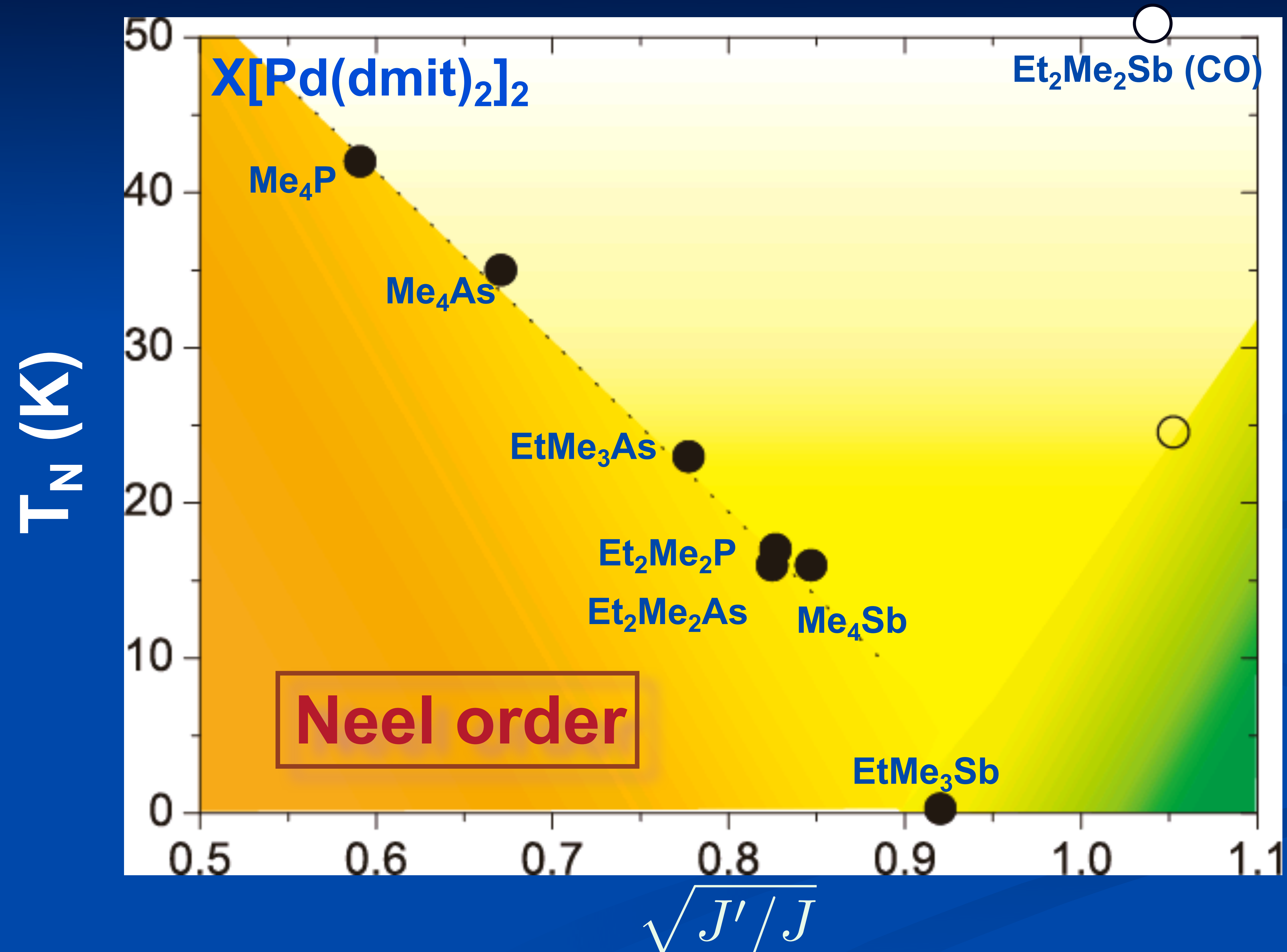
Neel ground state for small J'/J

Anisotropic triangular lattice antiferromagnet

Possible ground states as a function of J'/J

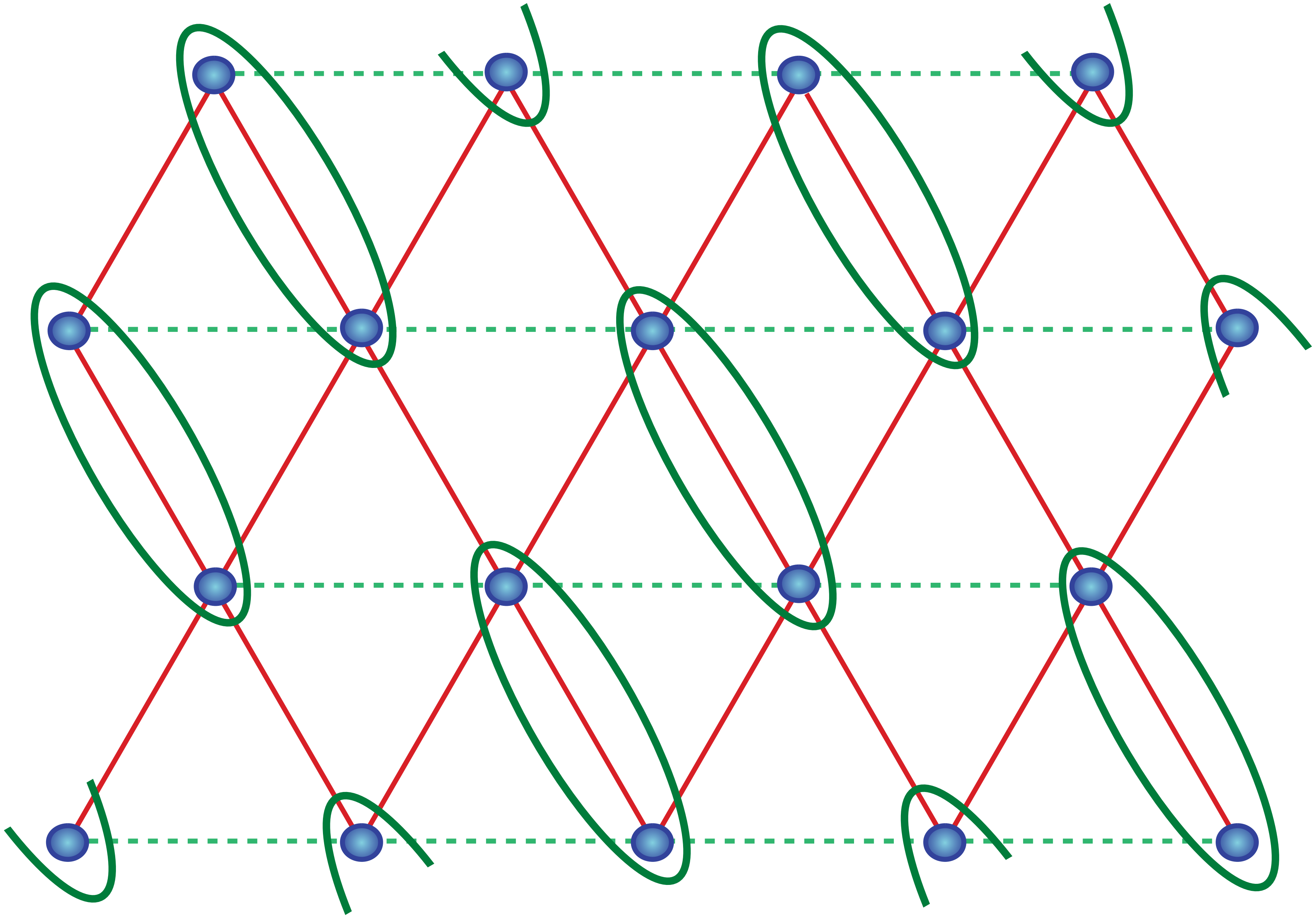
- Néel antiferromagnetic LRO

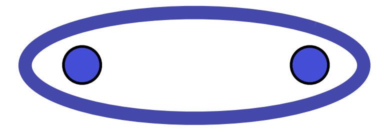
Magnetic Criticality



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

Anisotropic triangular lattice antiferromagnet





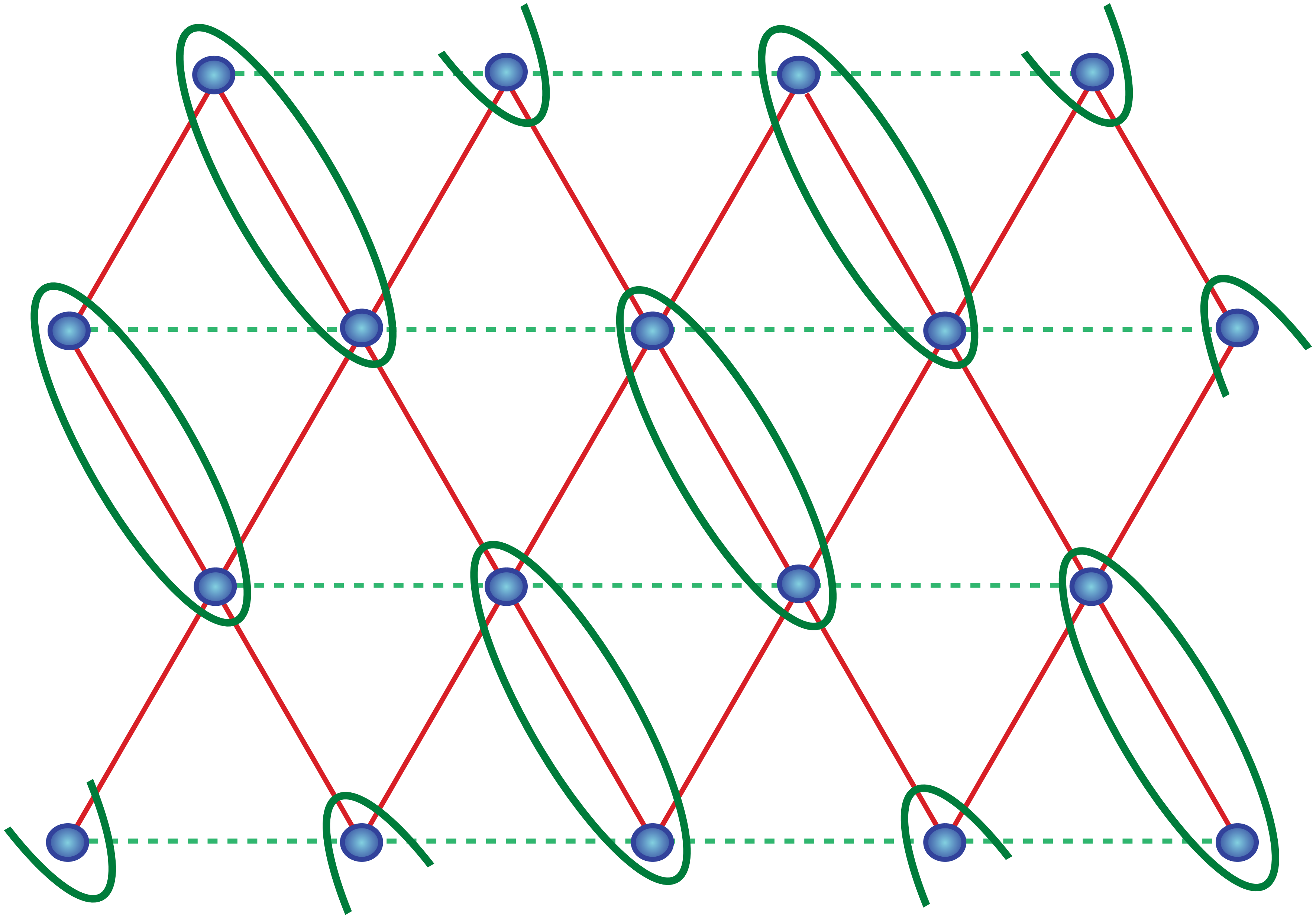
$$= \frac{(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)}{\sqrt{2}}$$

Possible ground state for intermediate J'/J

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

Anisotropic triangular lattice antiferromagnet

Broken lattice space group symmetry



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Valence bond solid (VBS)

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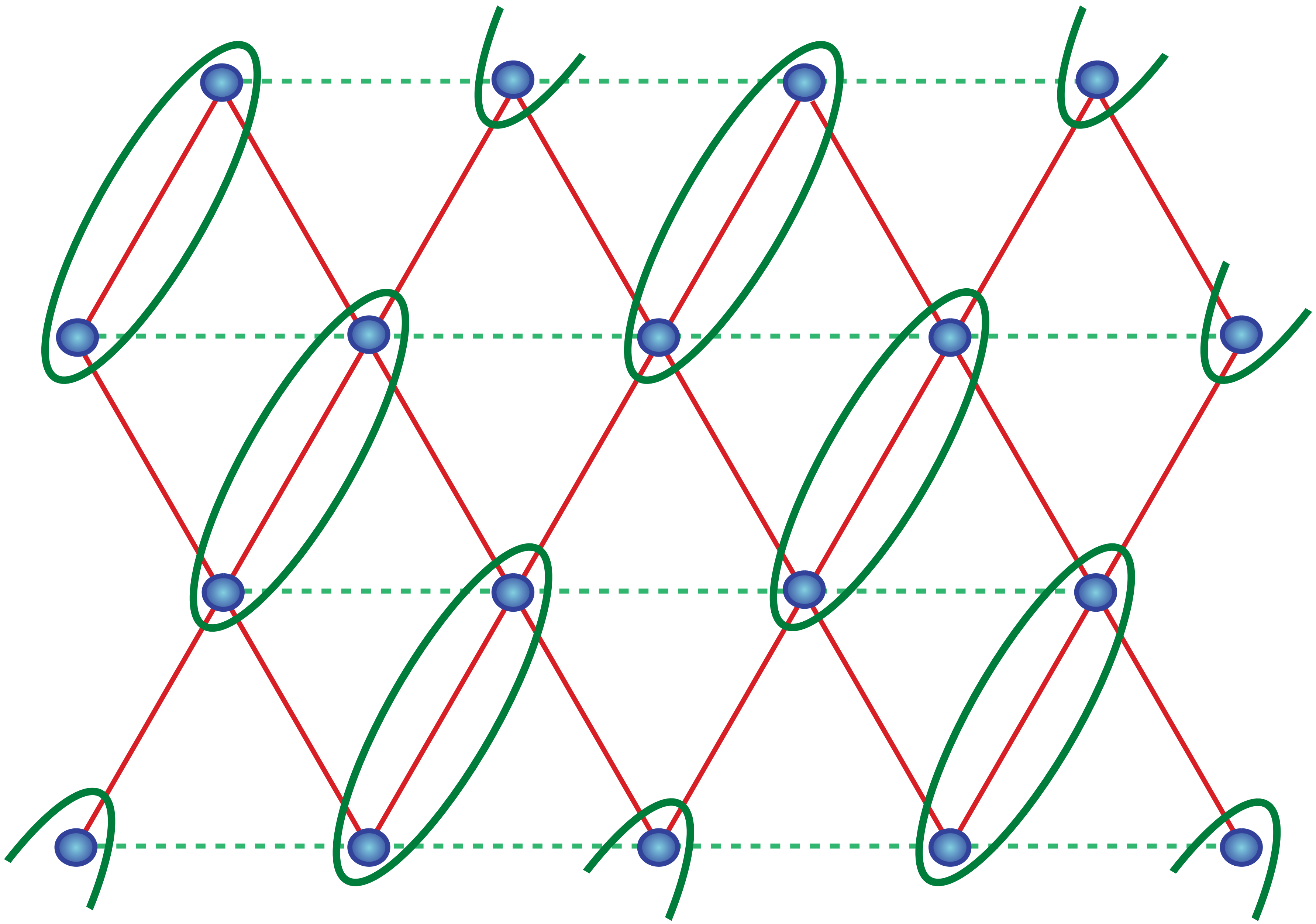

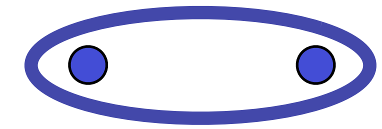

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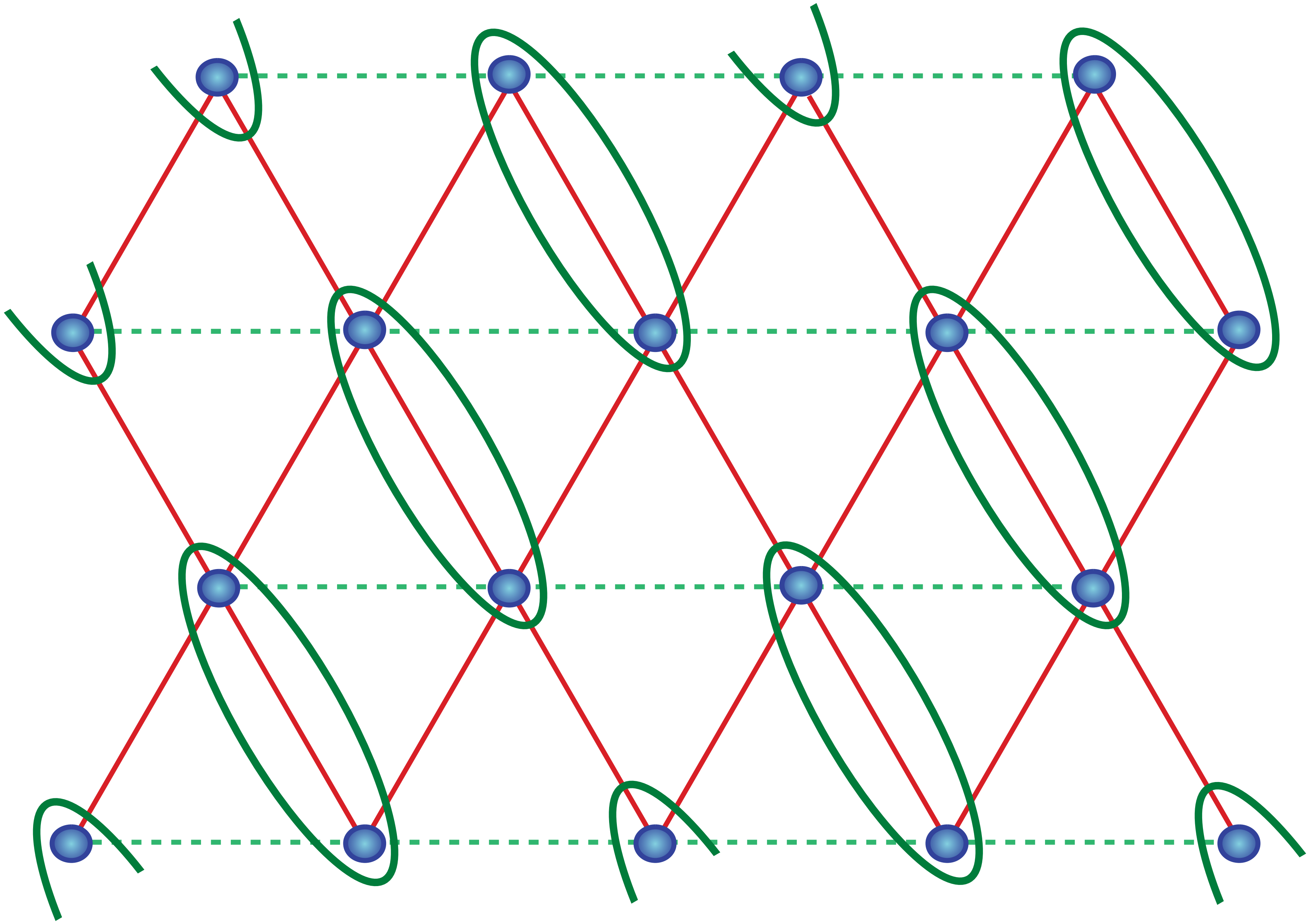

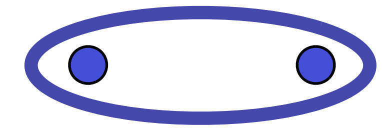

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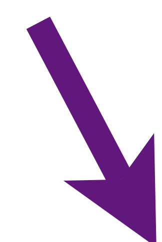

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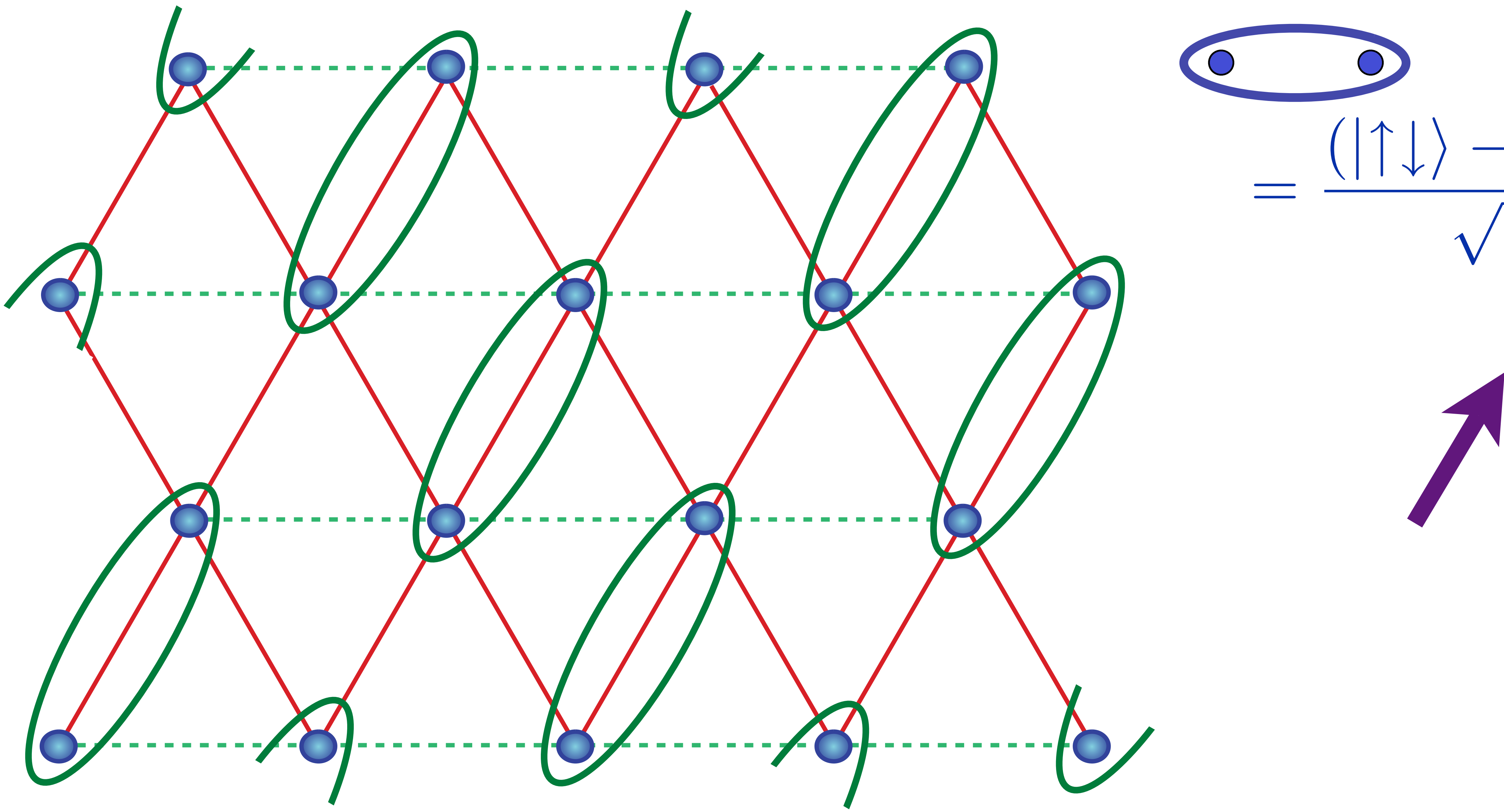

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Valence bond solid (VBS)

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

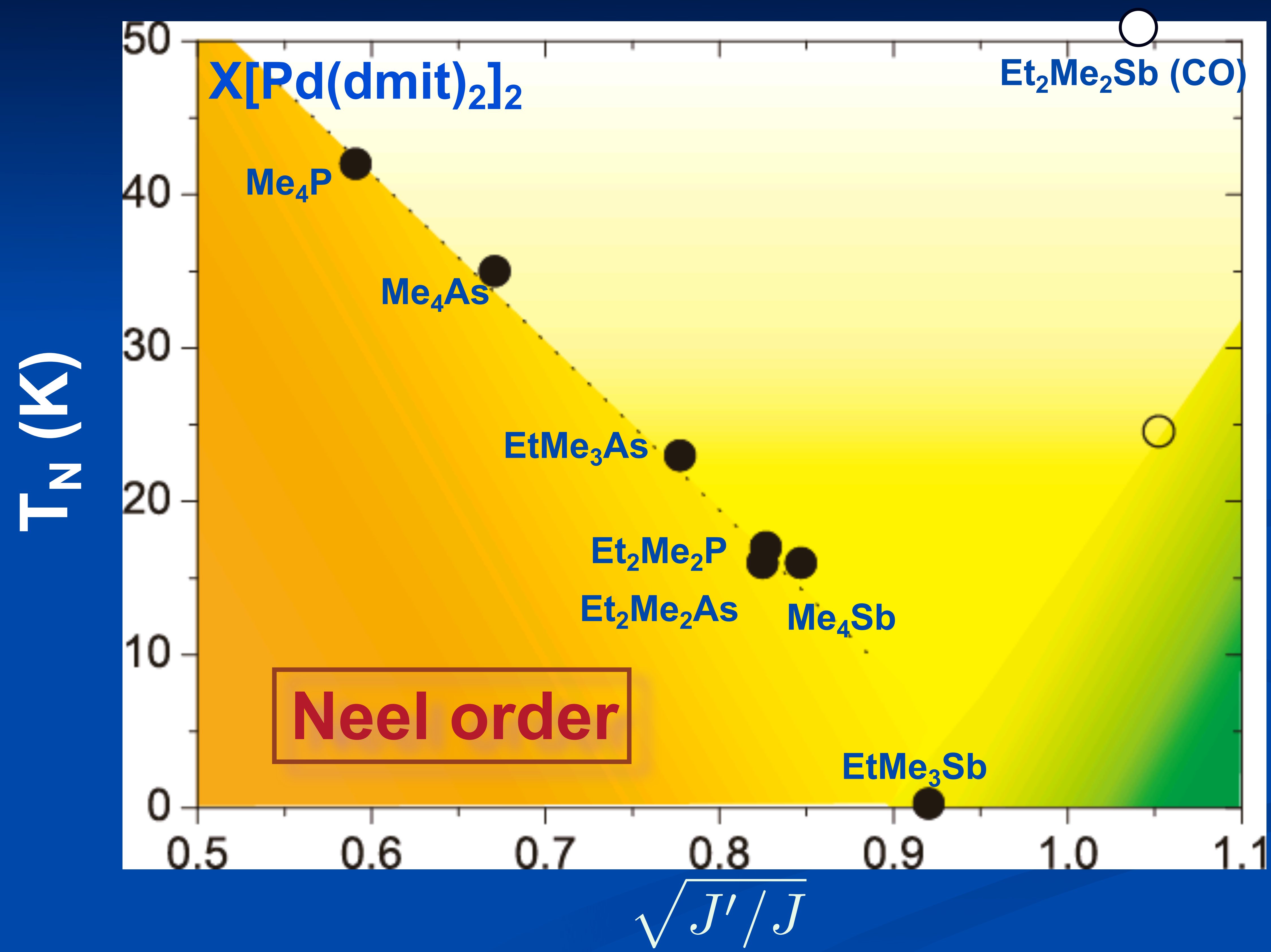
Anisotropic triangular lattice antiferromagnet

Possible ground states as a function of J'/J

- Néel antiferromagnetic LRO

- Valence bond solid

Magnetic Criticality



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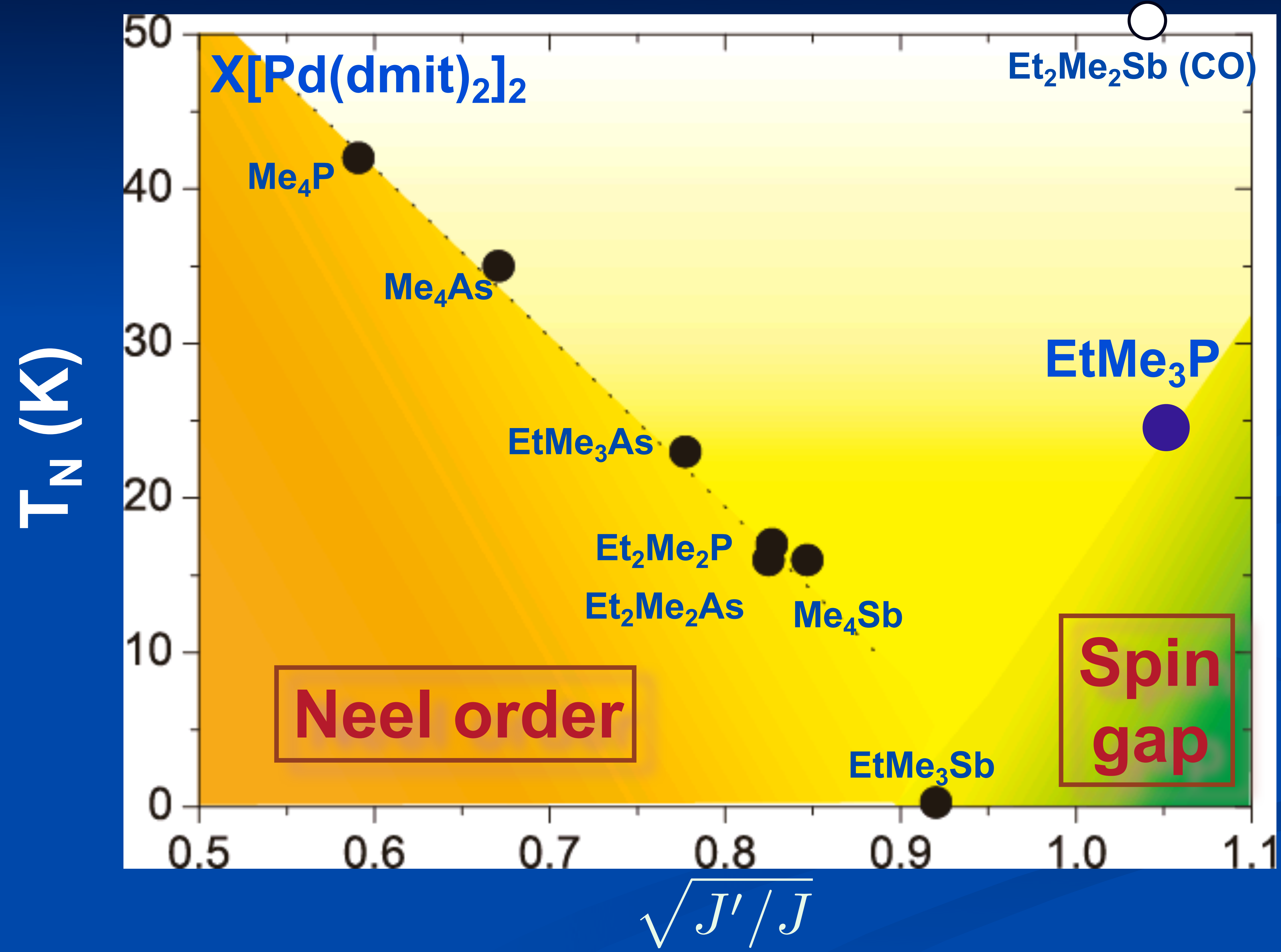
Magnetic Criticality



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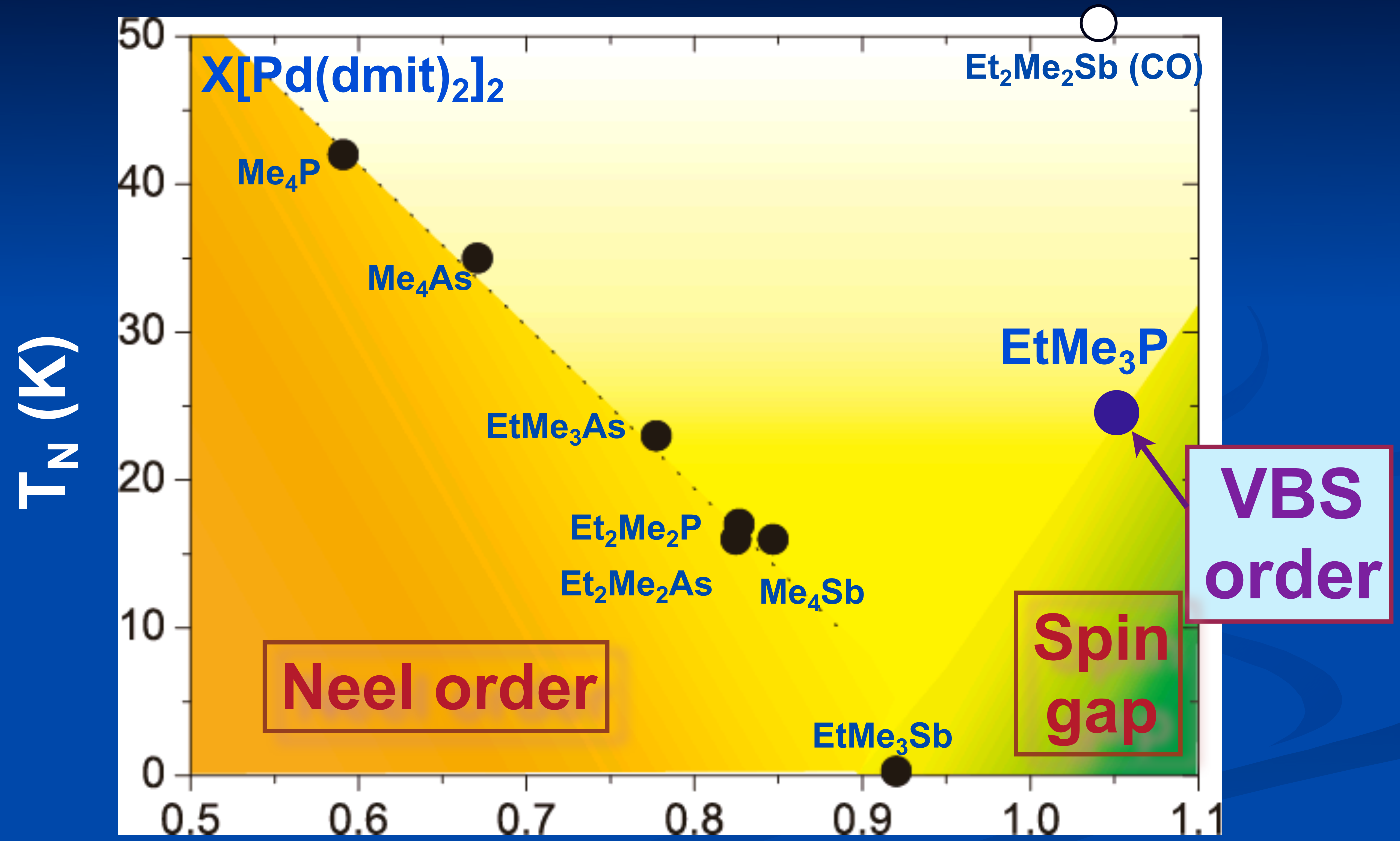
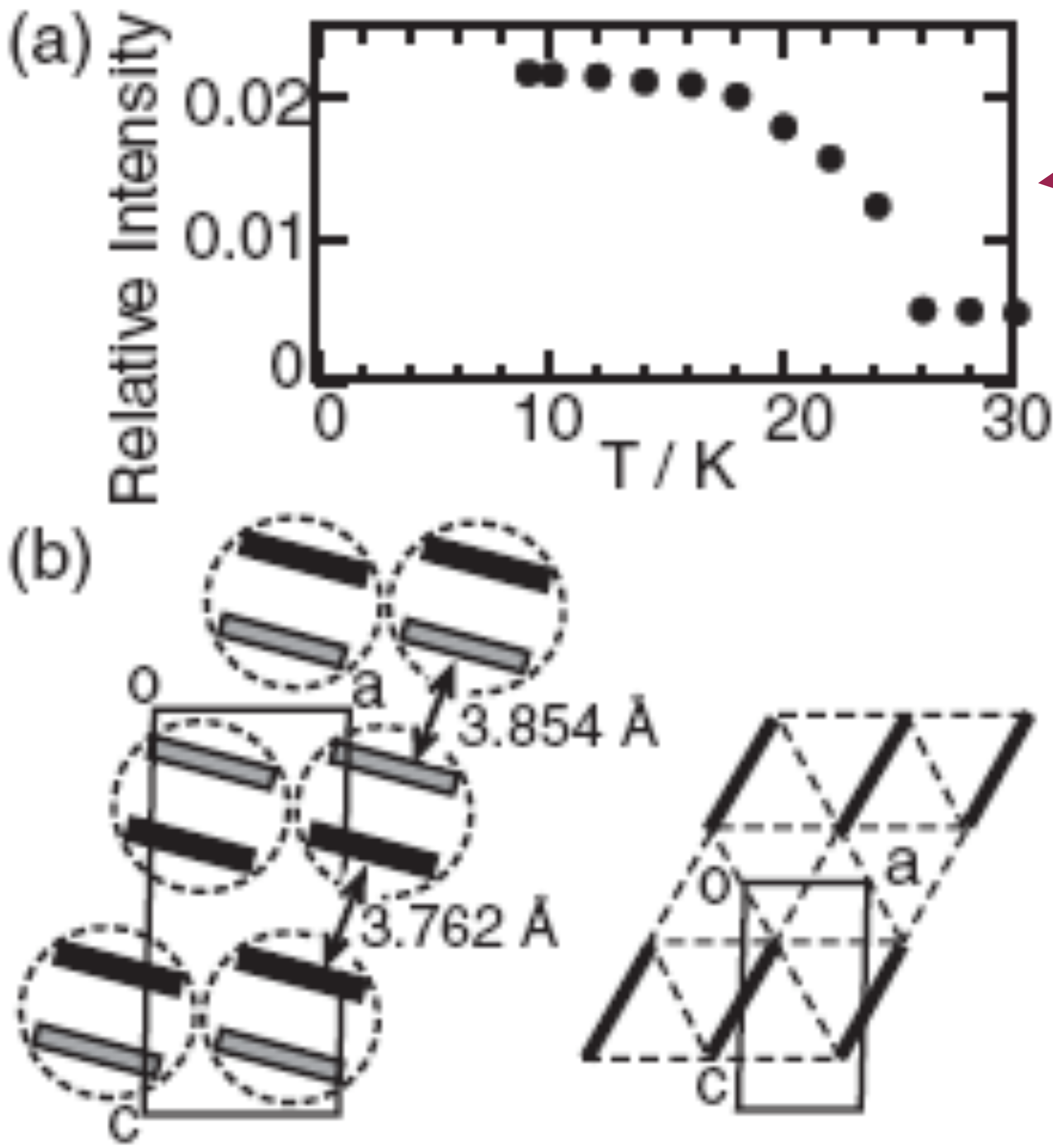
Magnetic Criticality



$$\sqrt{J'/J}$$

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

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

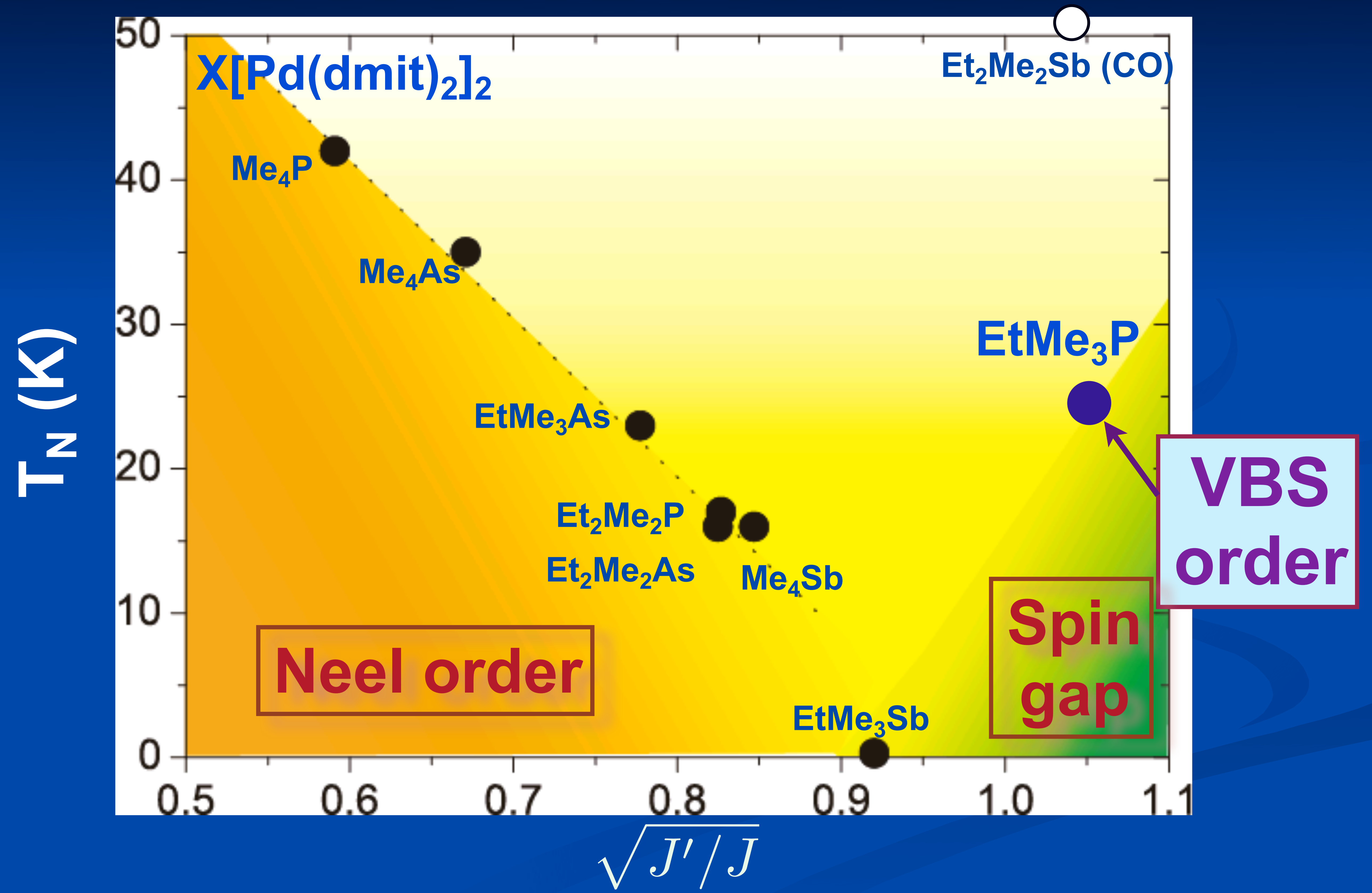


X-ray scattering

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)

Magnetic Criticality



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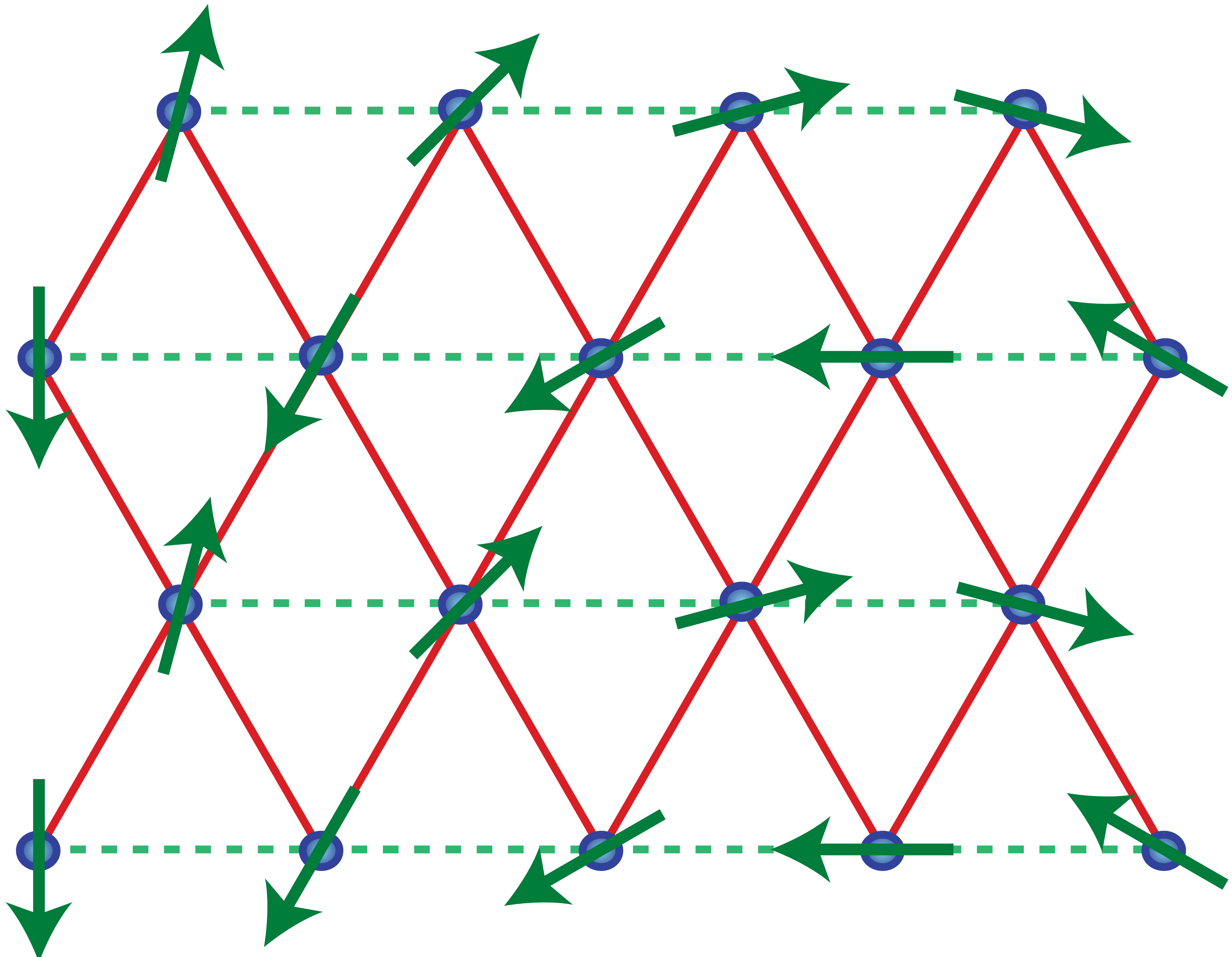
Anisotropic triangular lattice antiferromagnet

Possible ground states as a function of J'/J

- Néel antiferromagnetic LRO
- Valence bond solid

Anisotropic triangular lattice antiferromagnet



Classical ground state for large J'/J

Found in Cs_2CuCl_4

Anisotropic triangular lattice antiferromagnet

Possible ground states as a function of J'/J

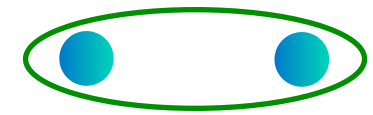
- Néel antiferromagnetic LRO
- Valence bond solid
- Spiral LRO

Possible ground states as a function of J'/J

- Néel antiferromagnetic LRO
- Valence bond solid
- Spiral LRO
- Z_2 spin liquid: preserves all symmetries of Hamiltonian

Triangular lattice antiferromagnet

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



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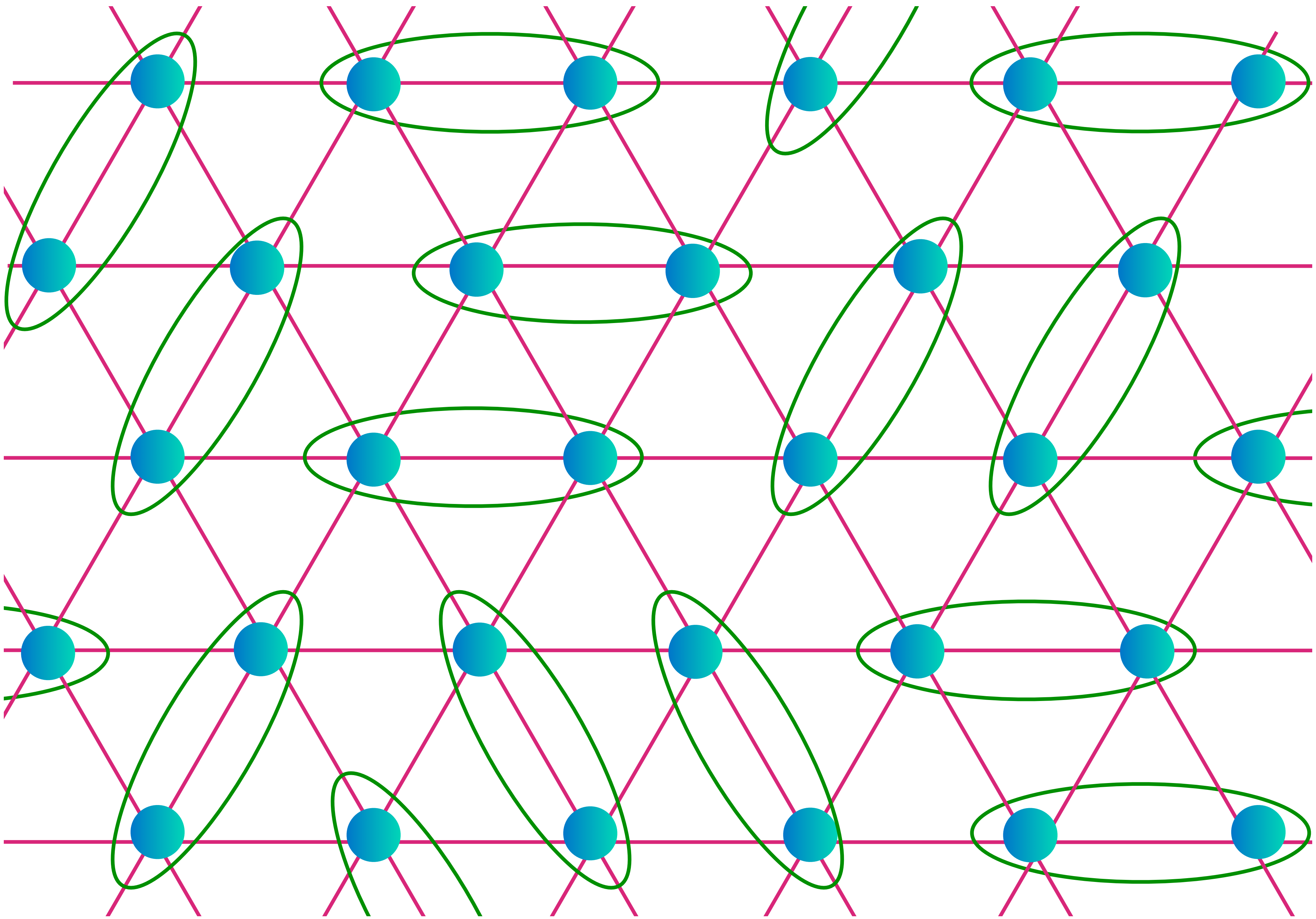

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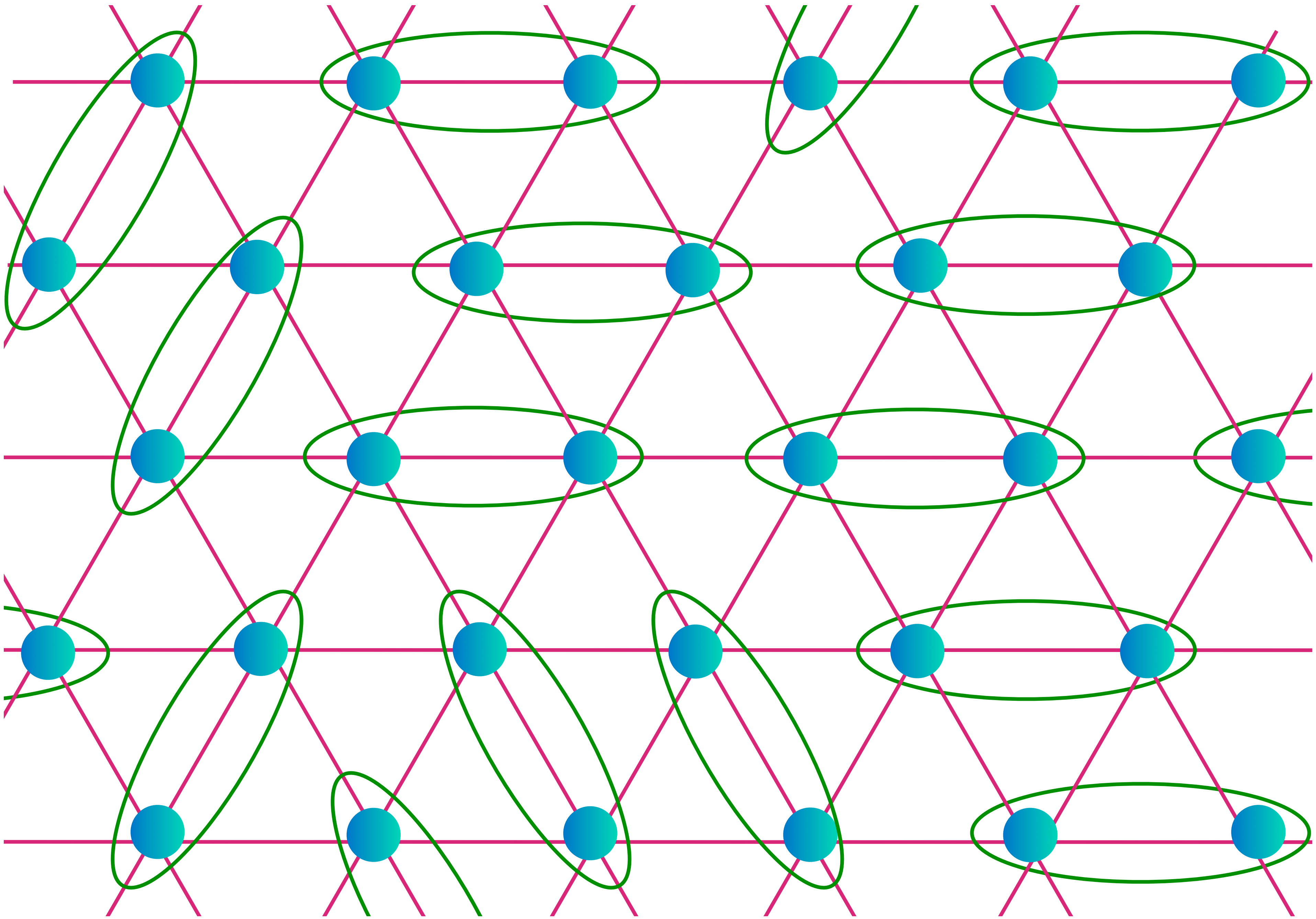

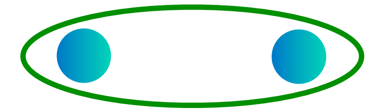

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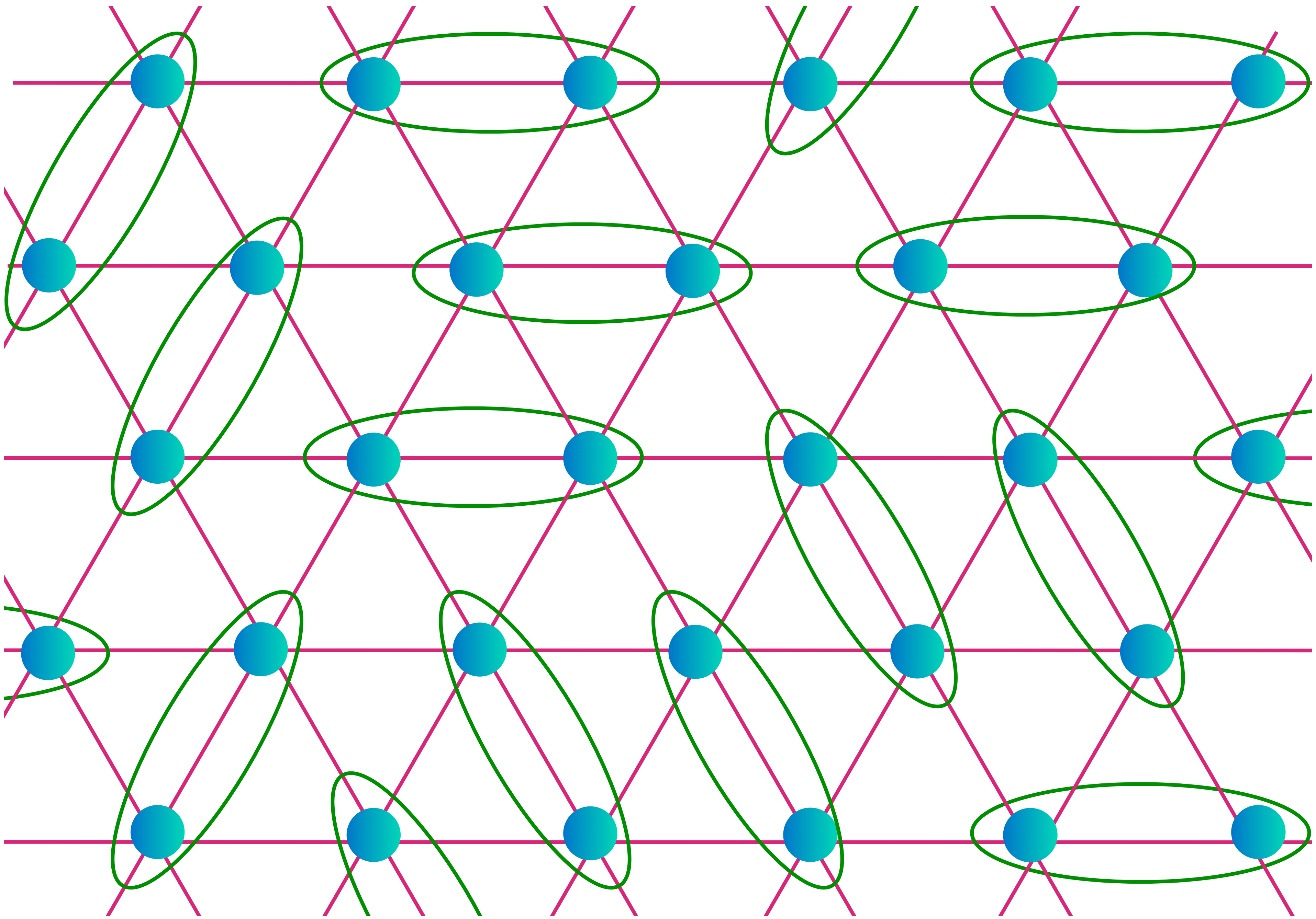

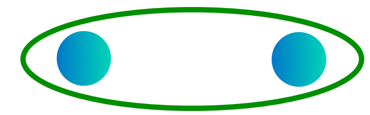

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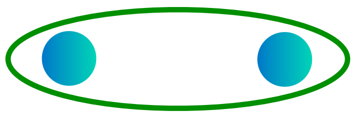

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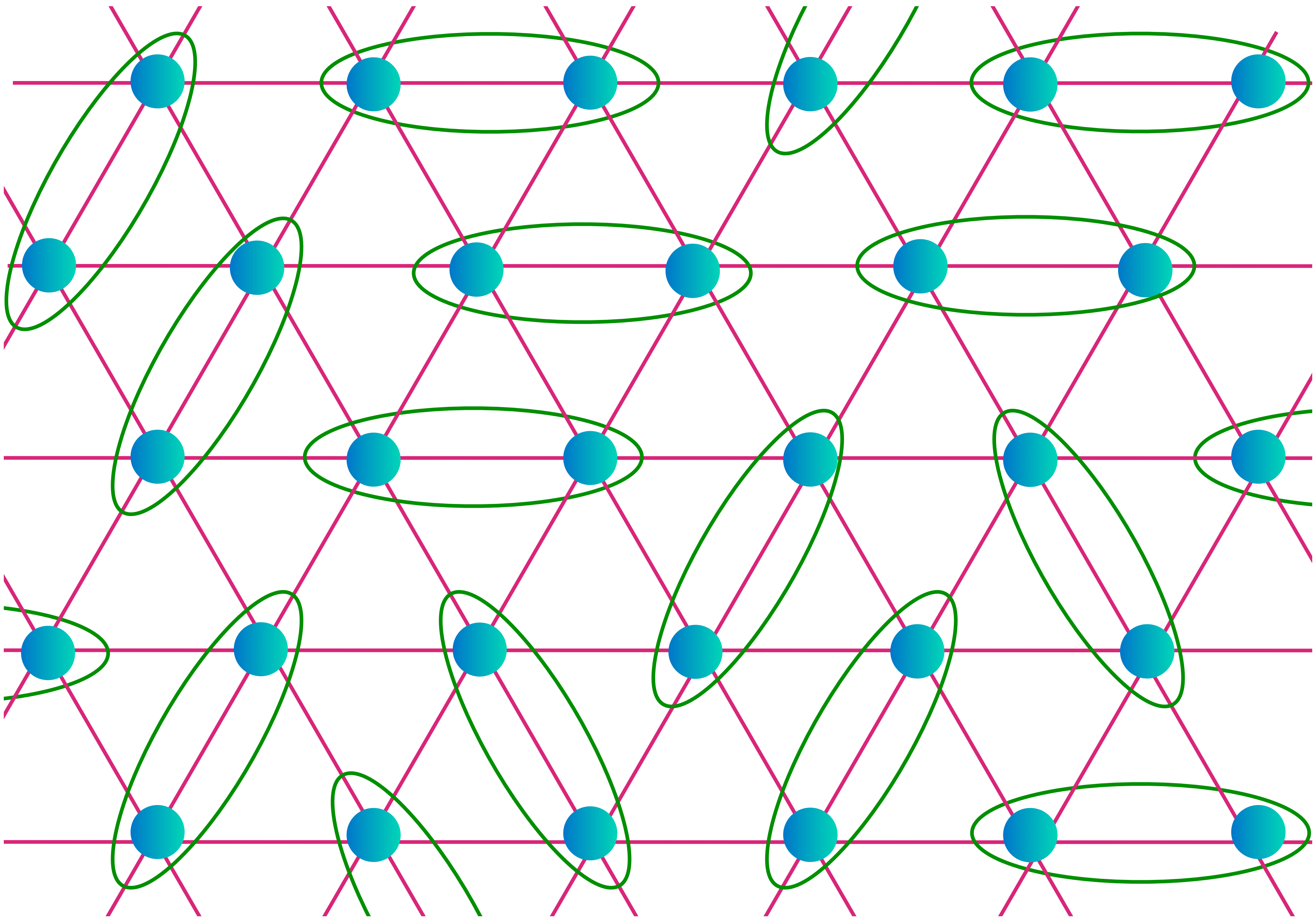

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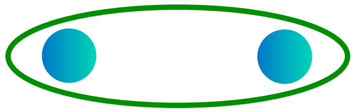

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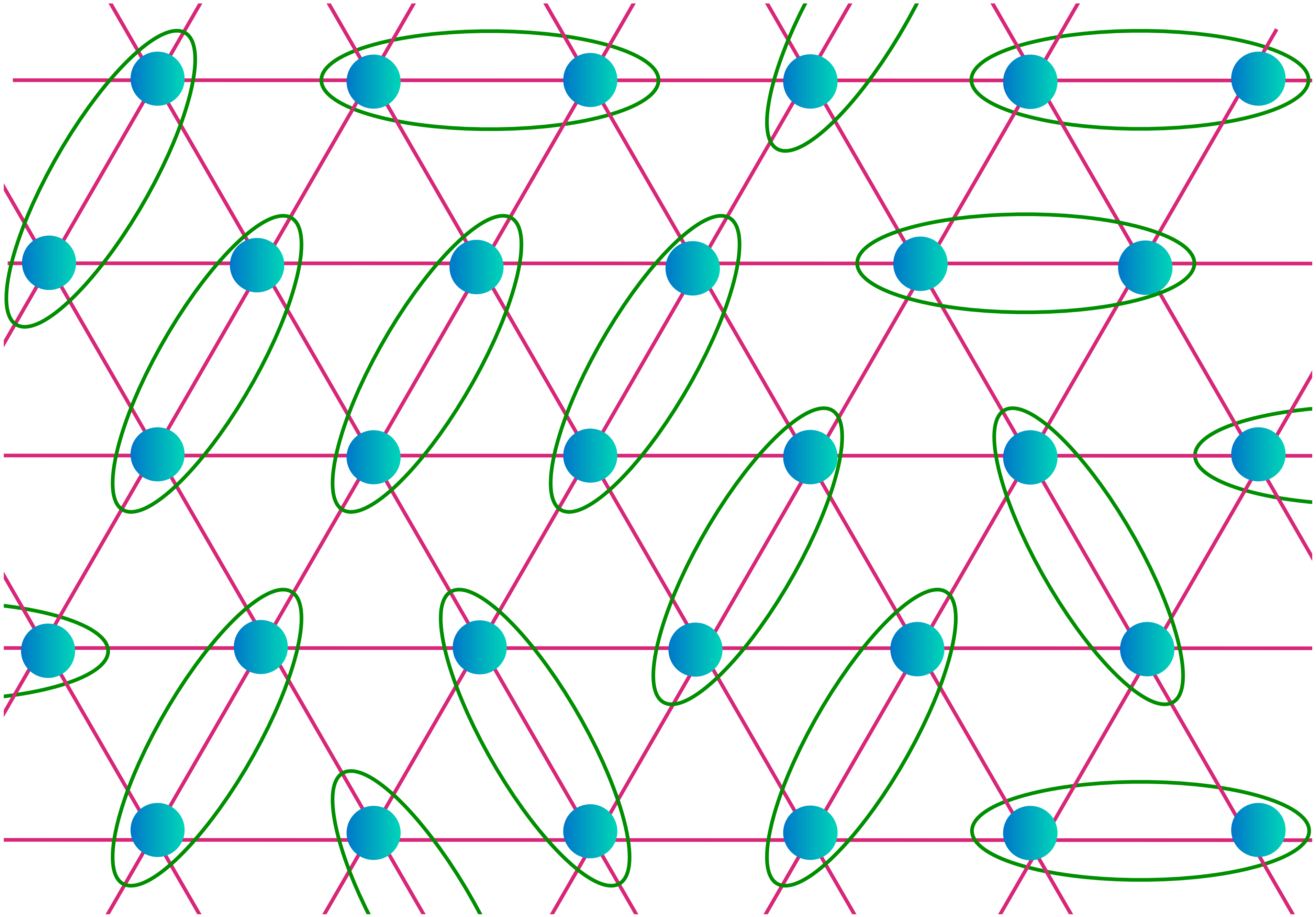

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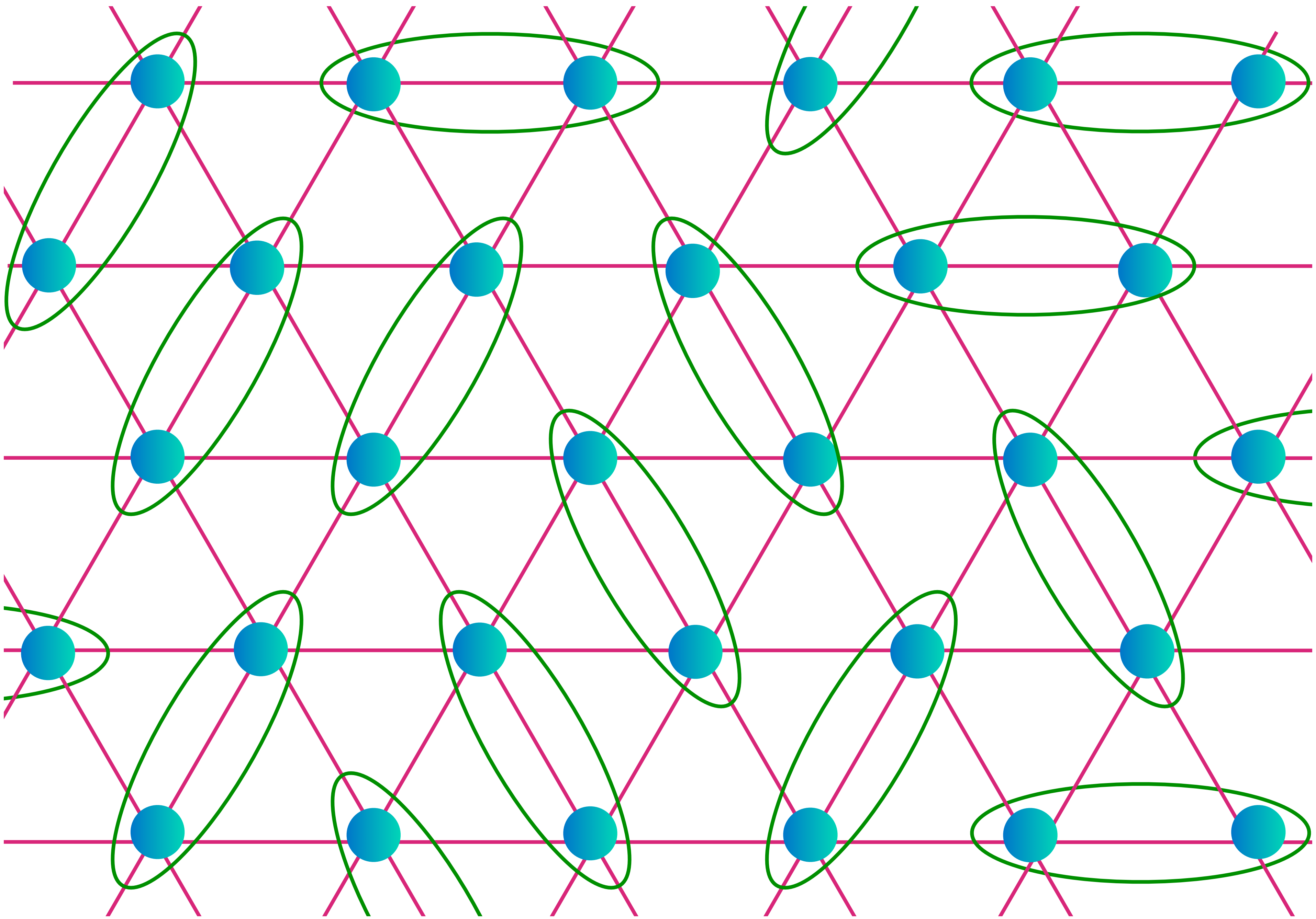

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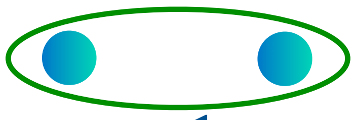

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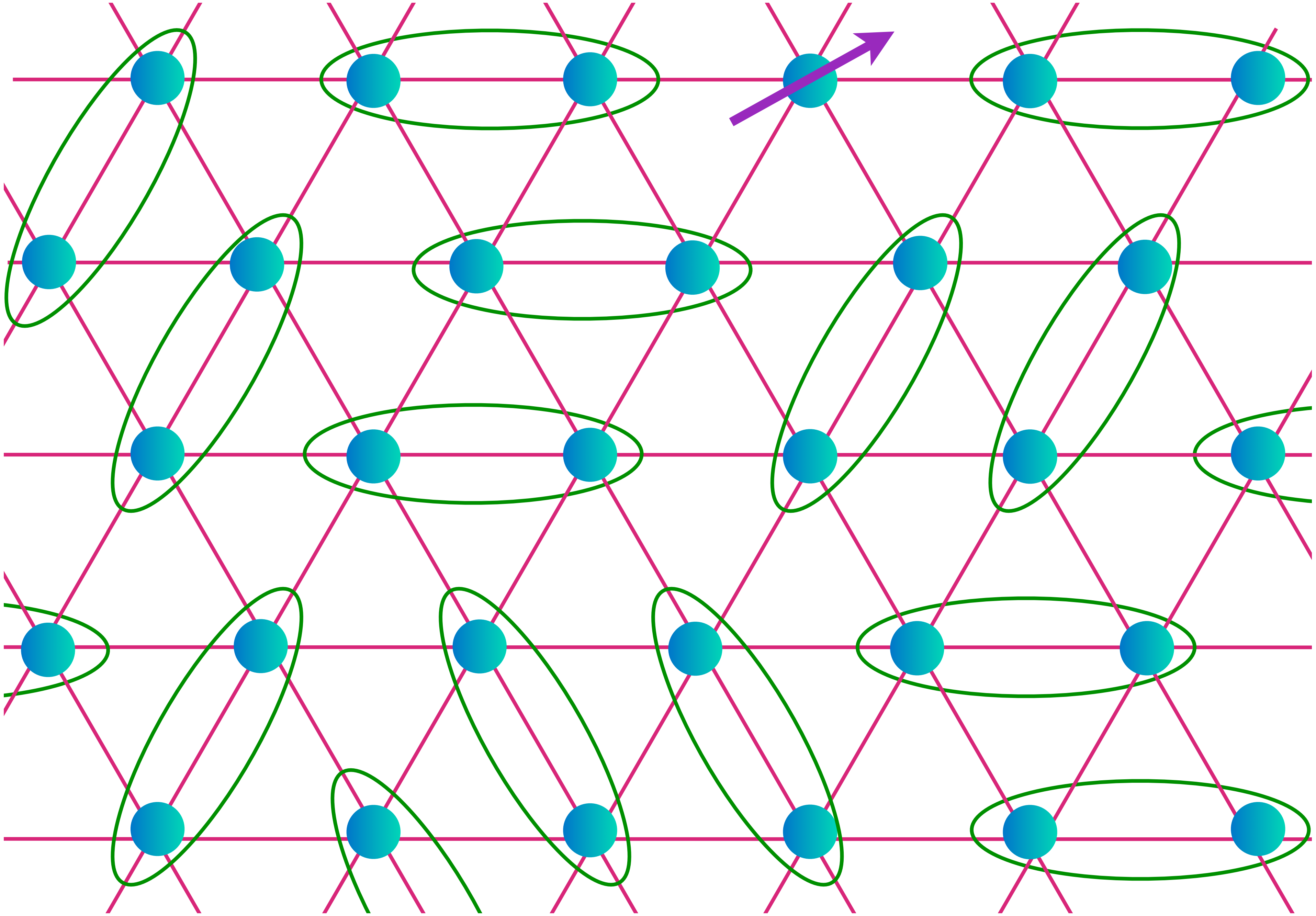

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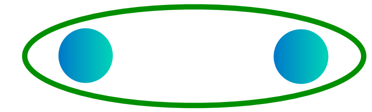

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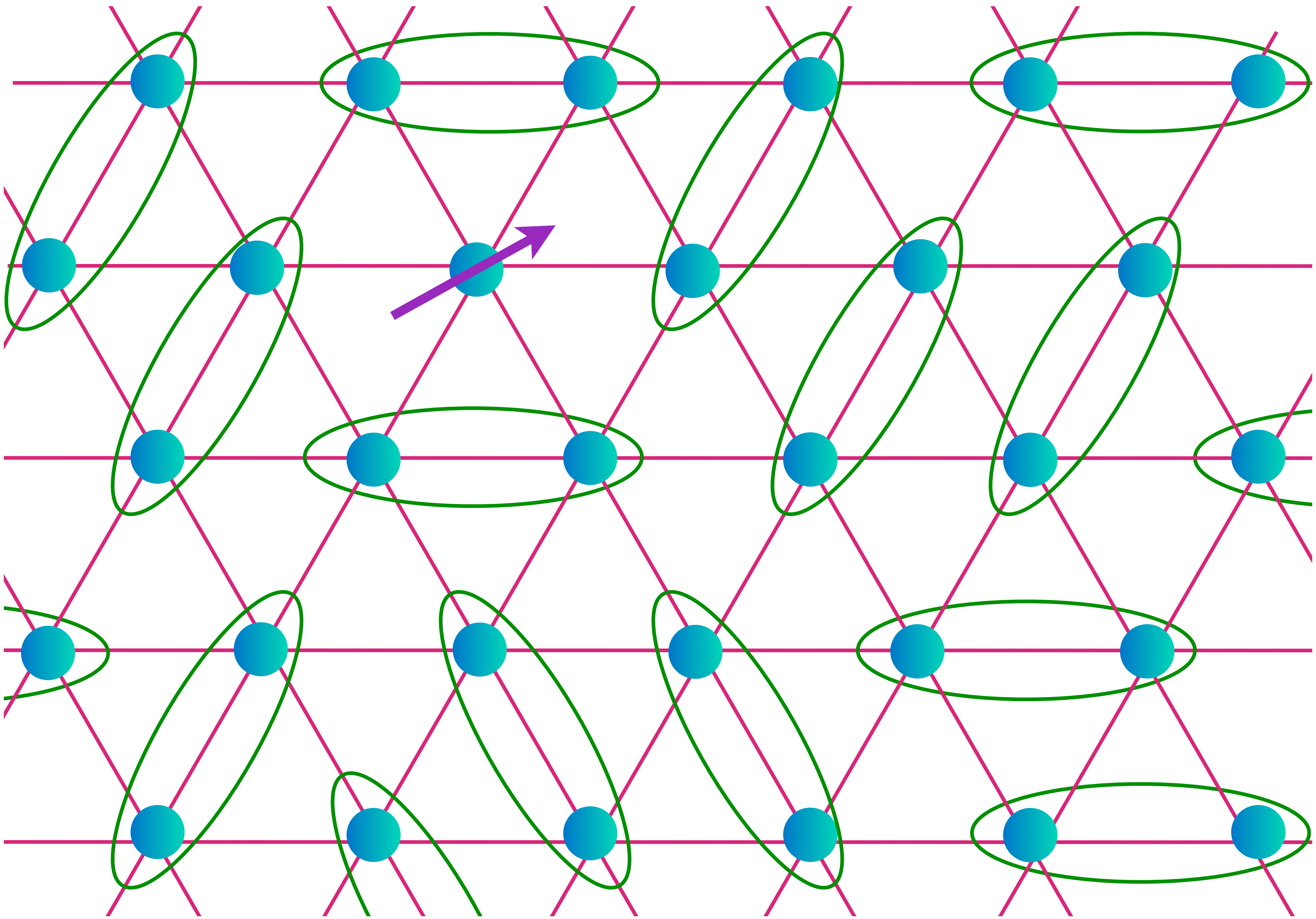

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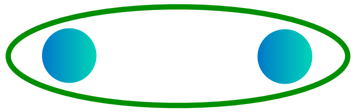

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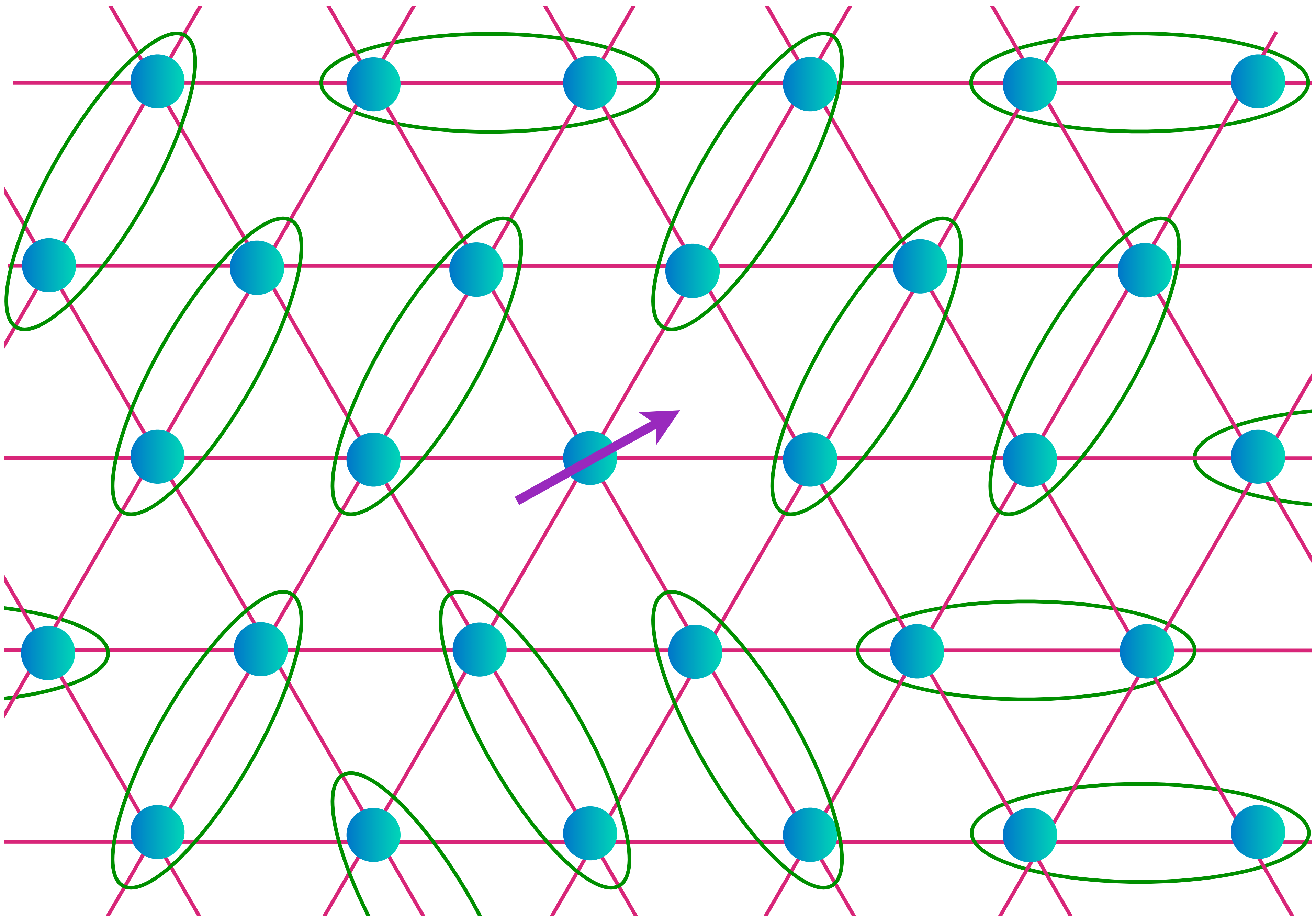

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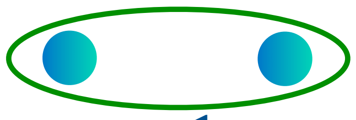

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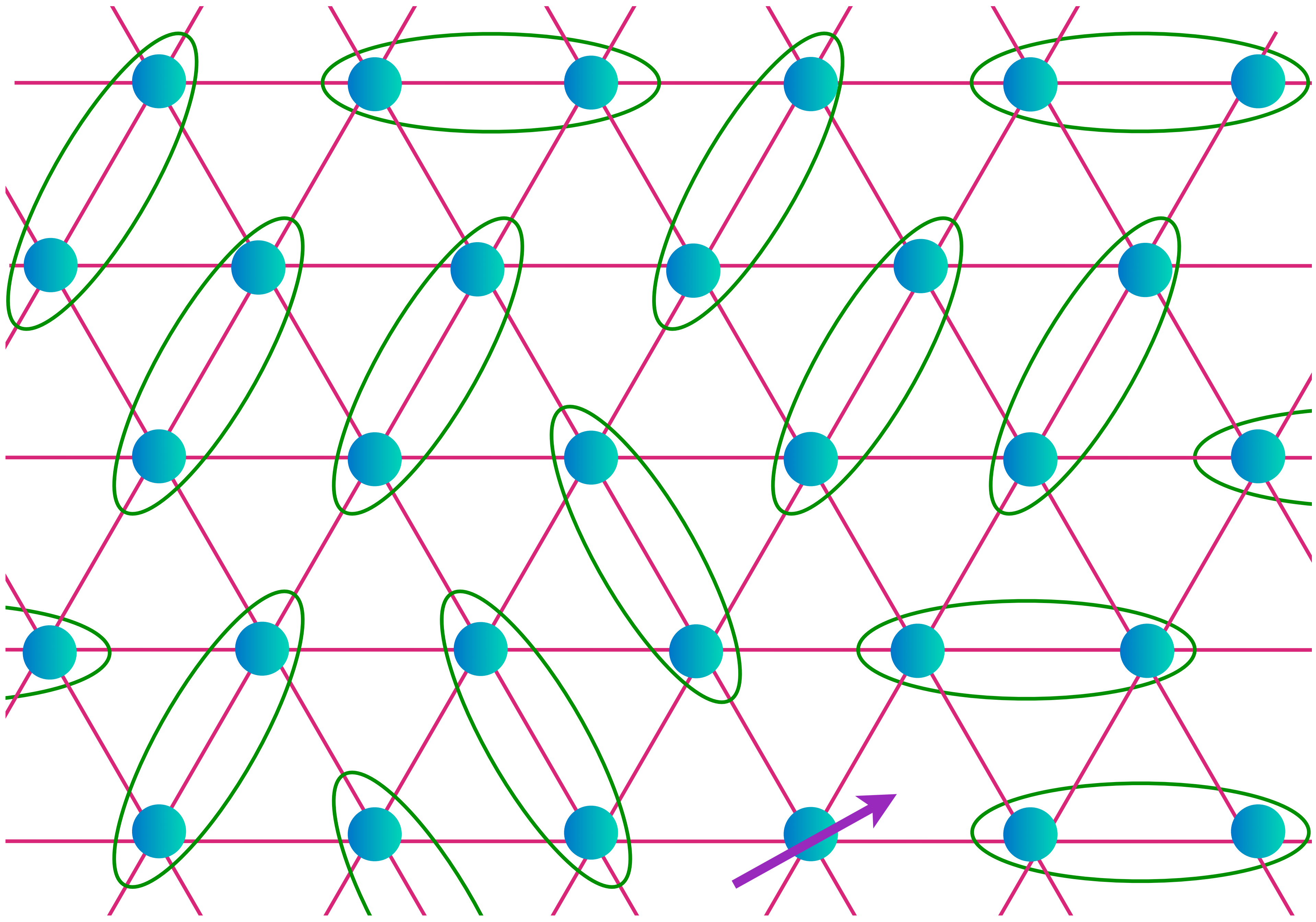

Excitations of the Z_2 Spin liquid

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The Néel order parameter, $\vec{\varphi}$ is a composite of the spinons:

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

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where $\vec{\sigma}$ are Pauli matrices

The theory for quantum phase transitions is expressed in terms of fluctuations of z_α, and *not* the order parameter $\vec{\varphi}$.

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

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

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)

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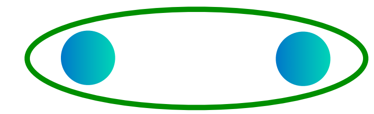

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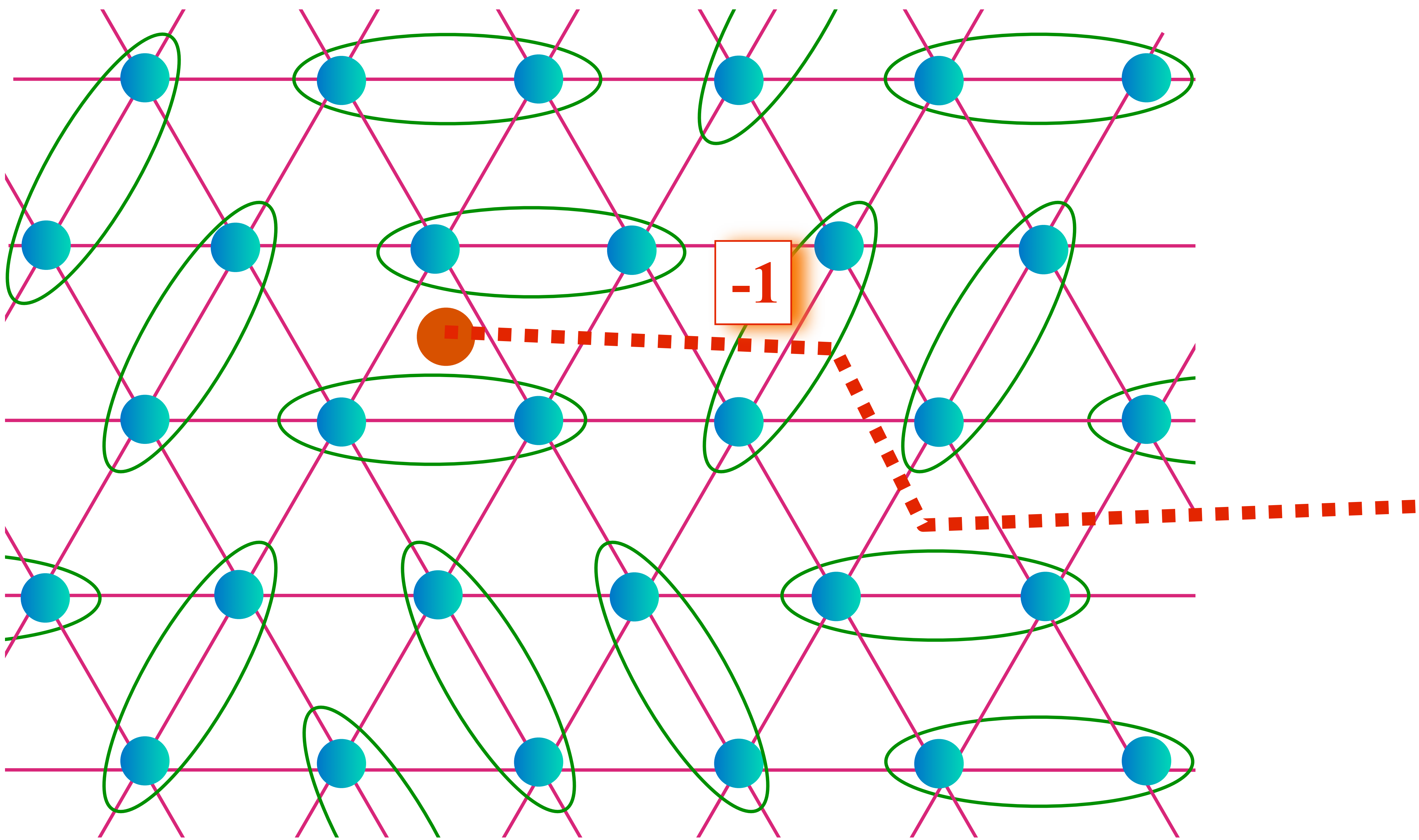

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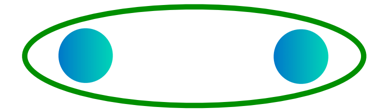

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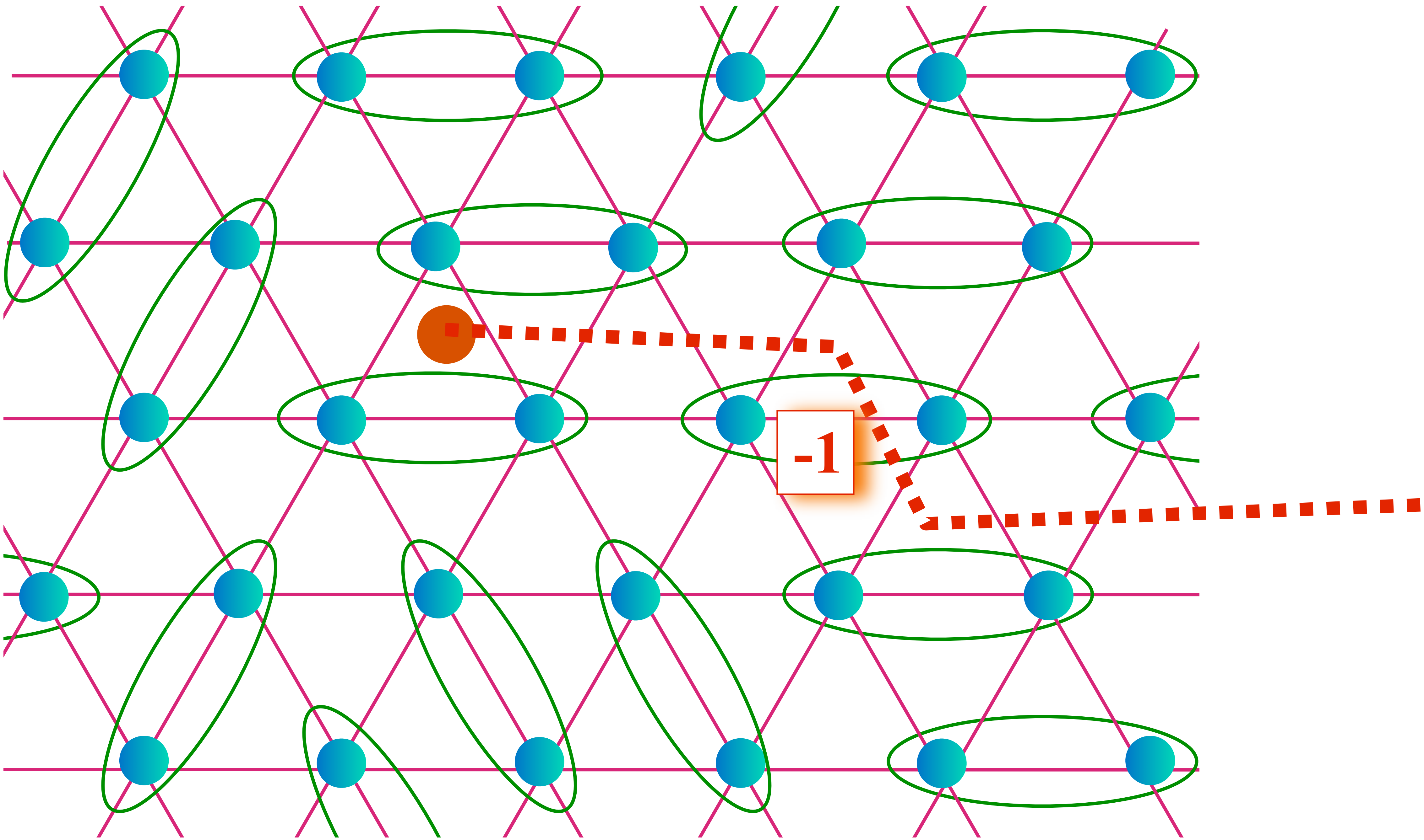

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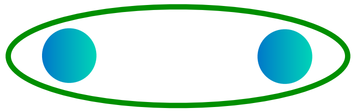

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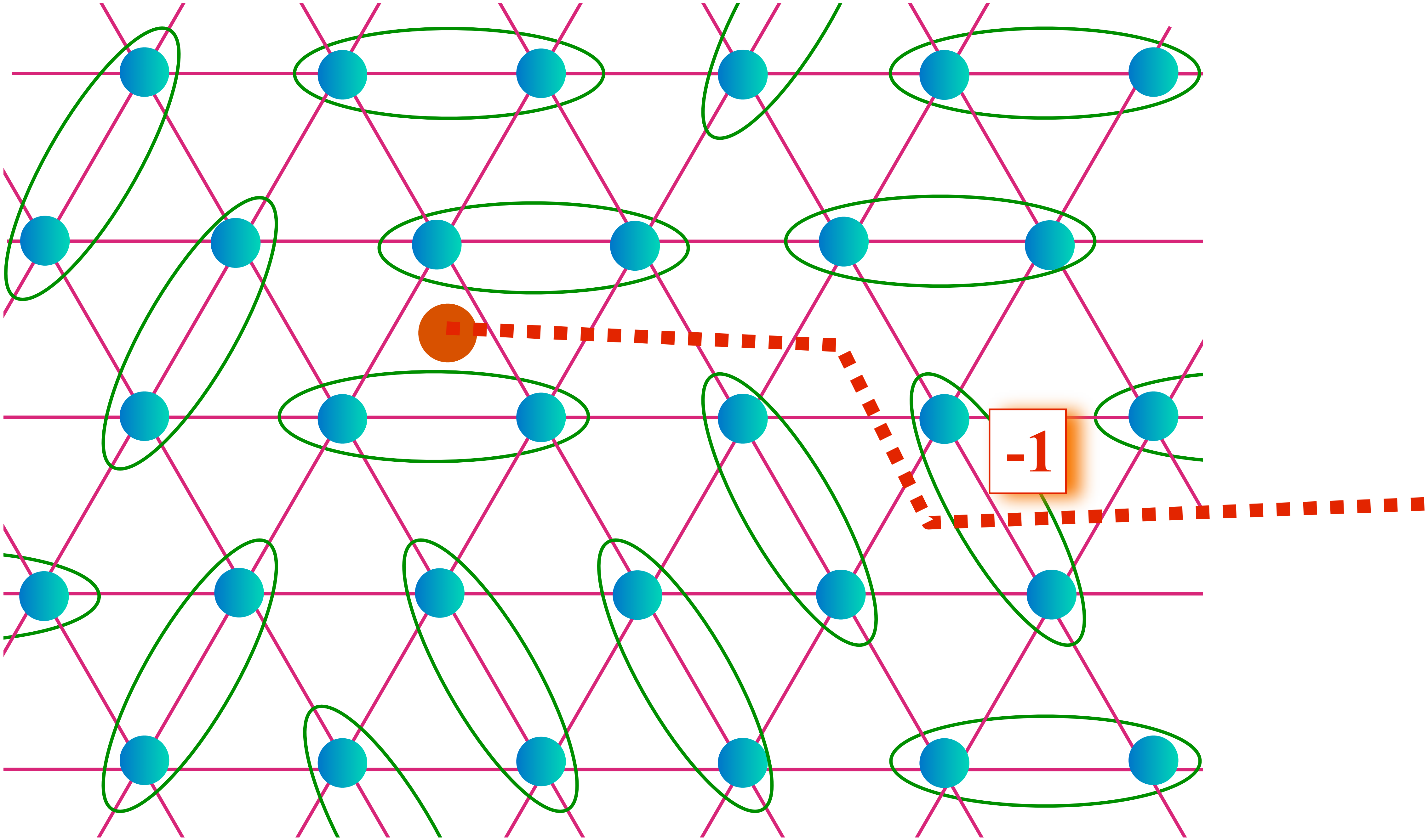

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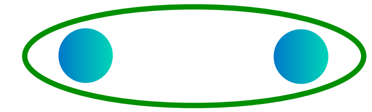

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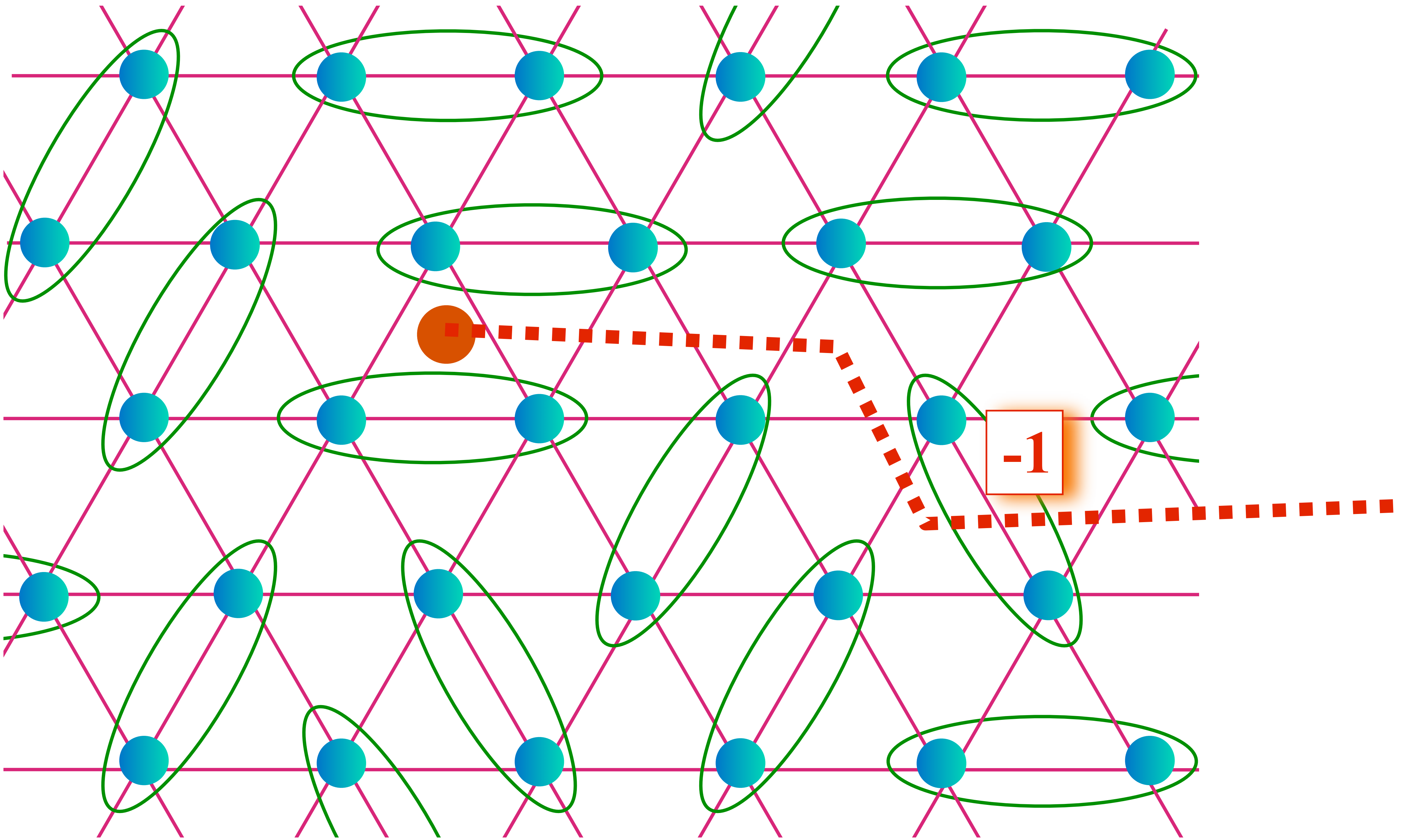

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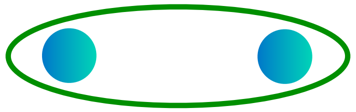

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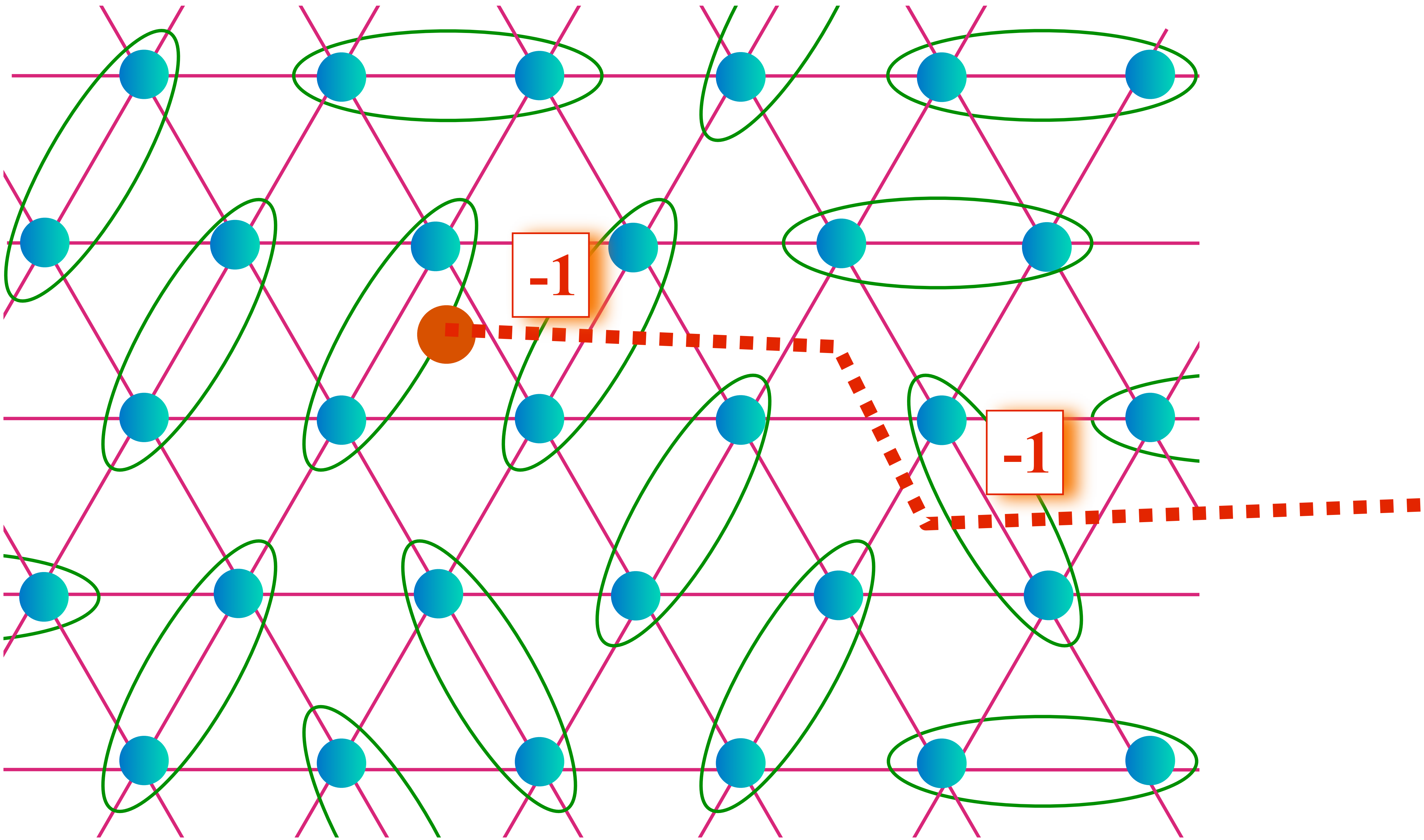

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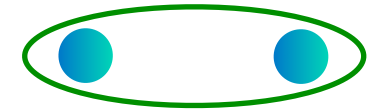

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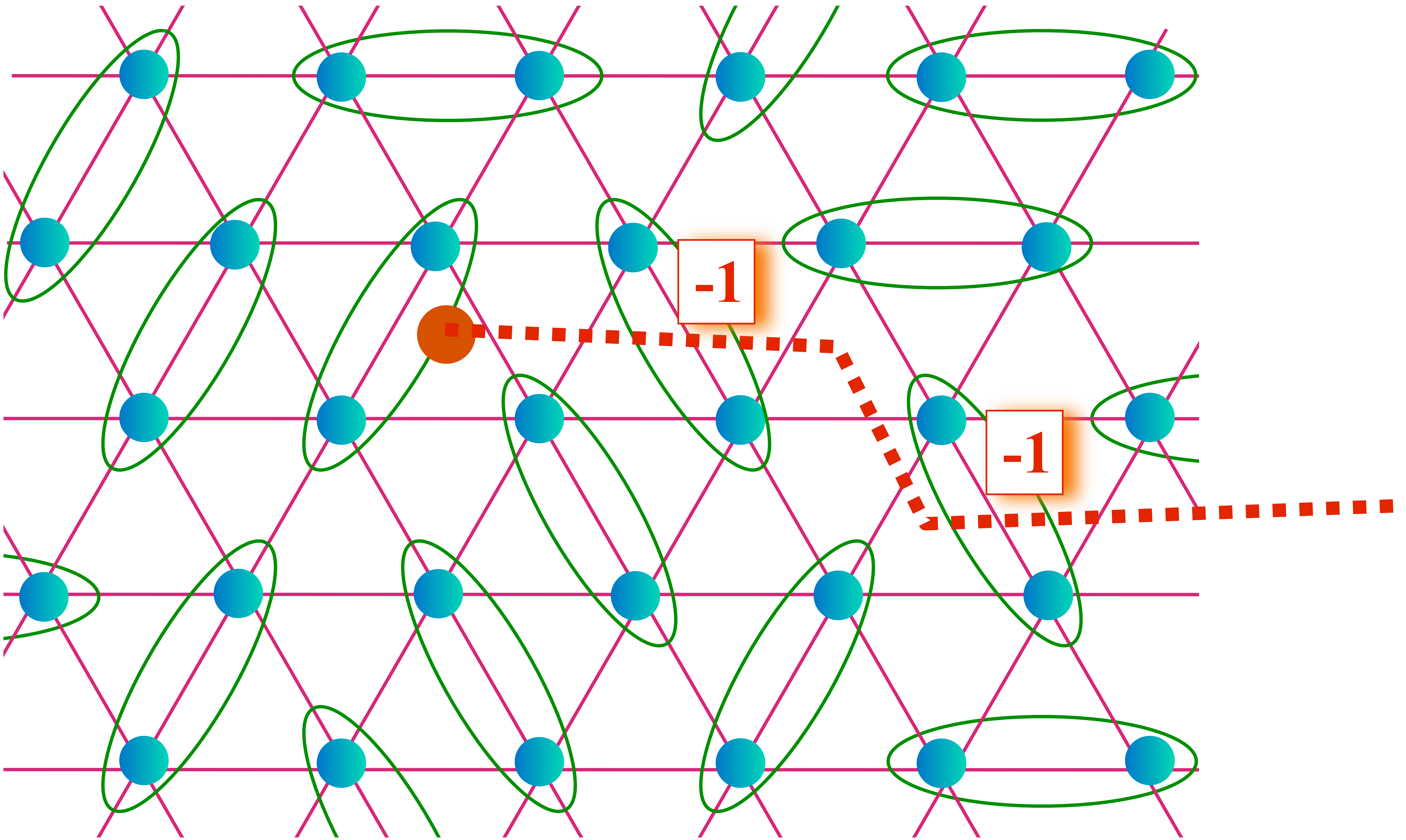

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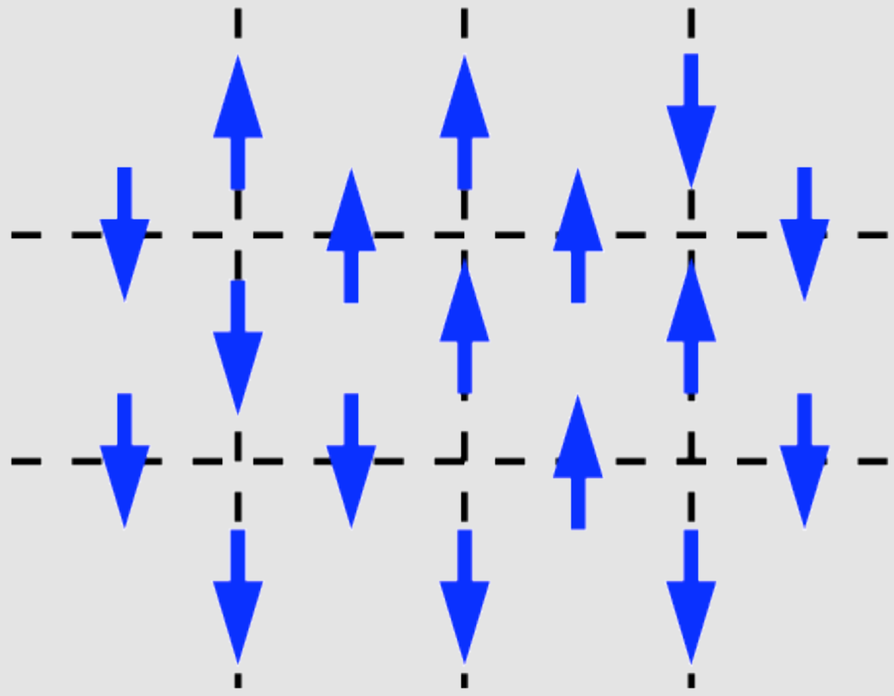
$$H = -J_1 \sum_i A_i - J_2 \sum_p F_p$$



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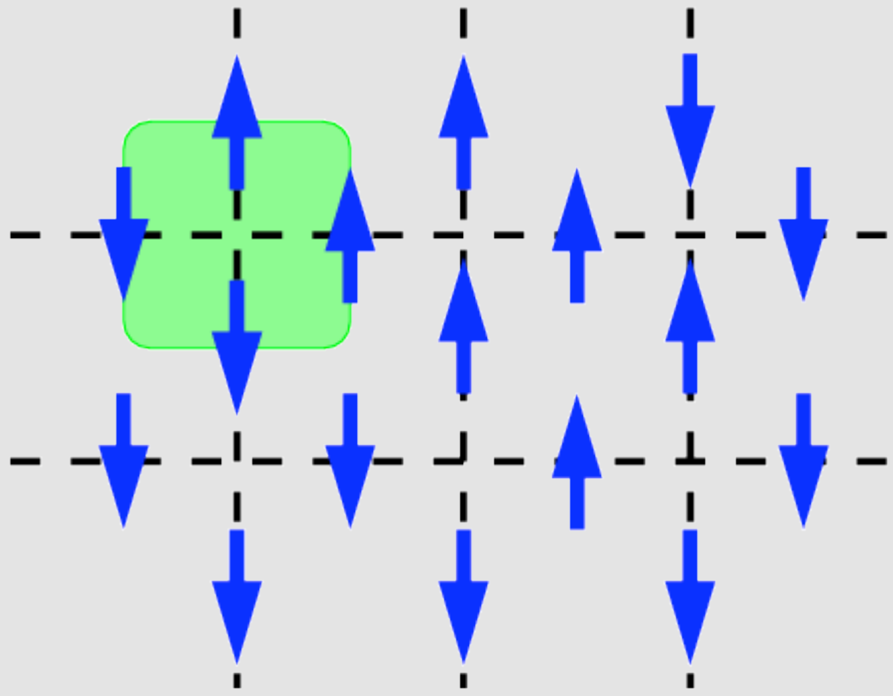

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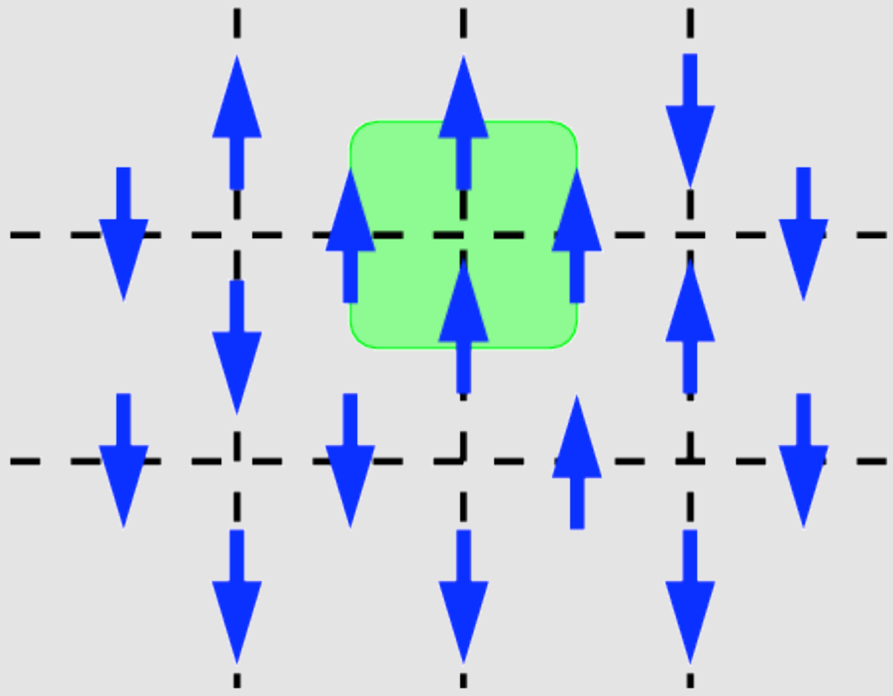

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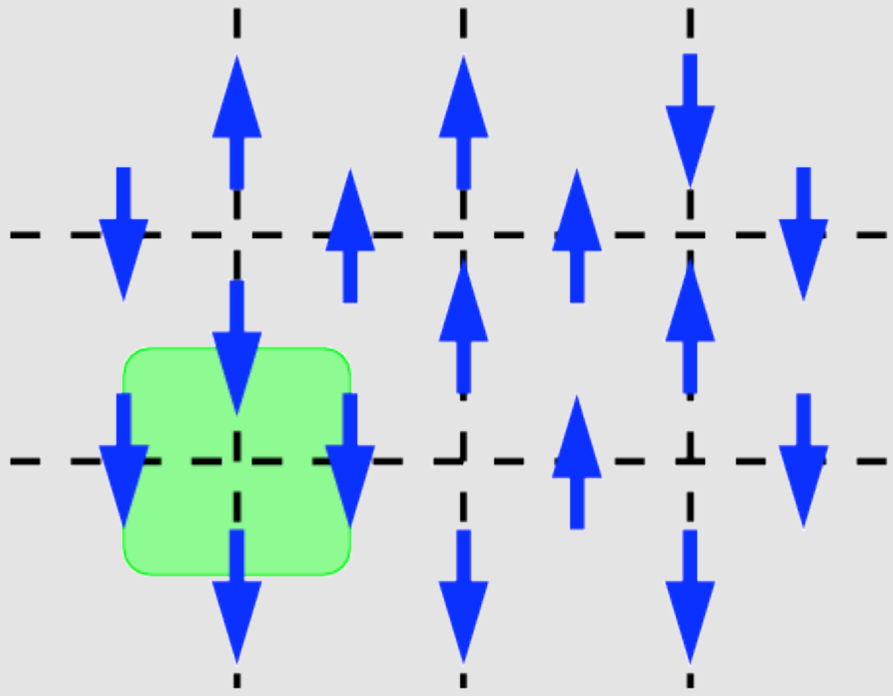

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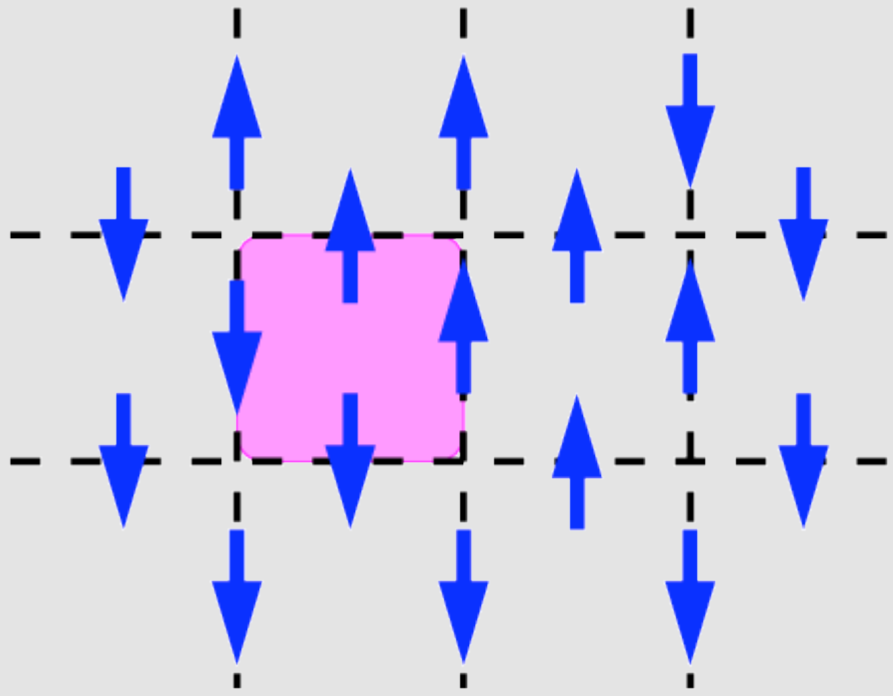

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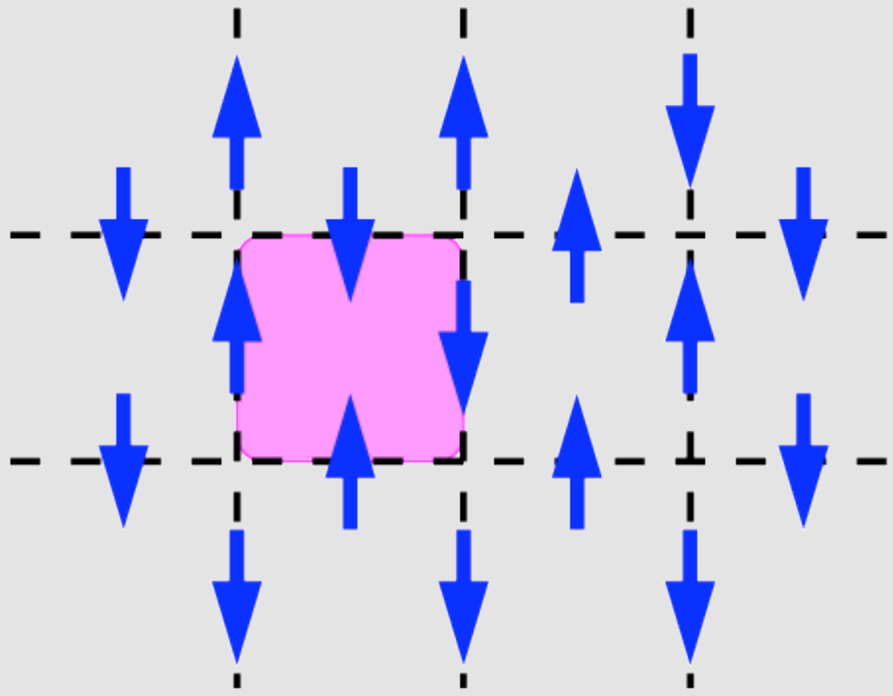

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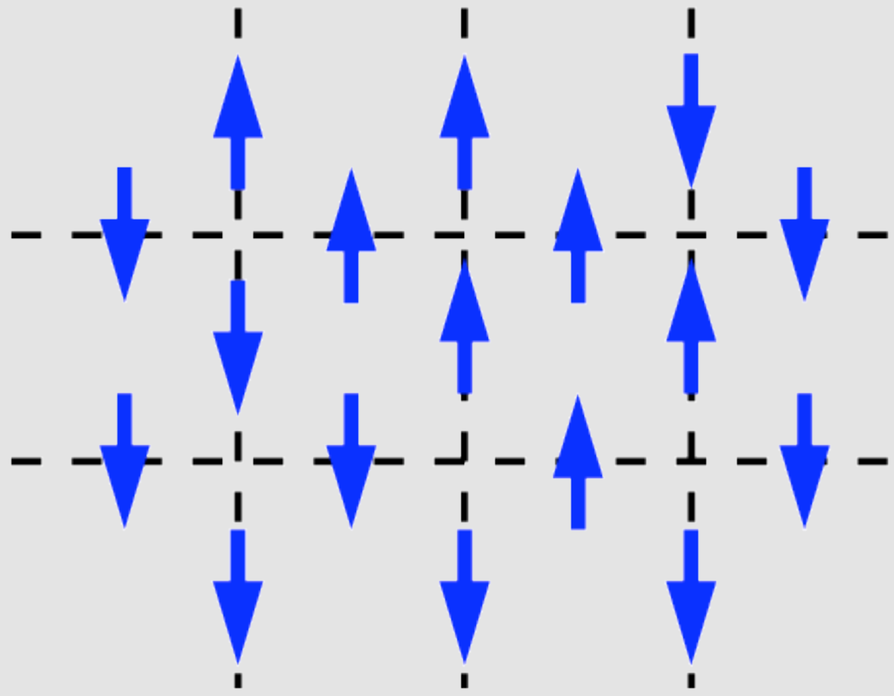

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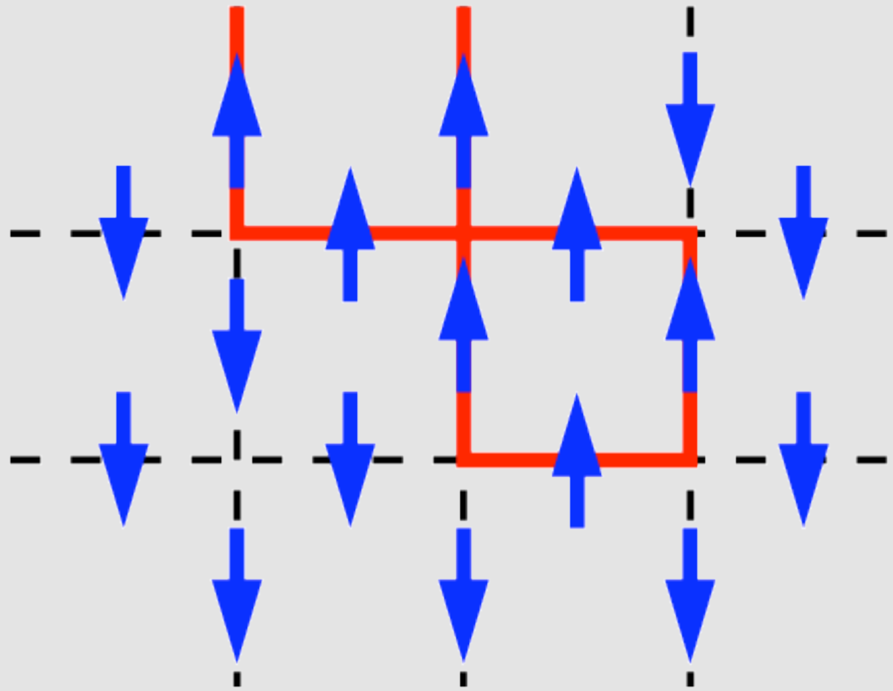

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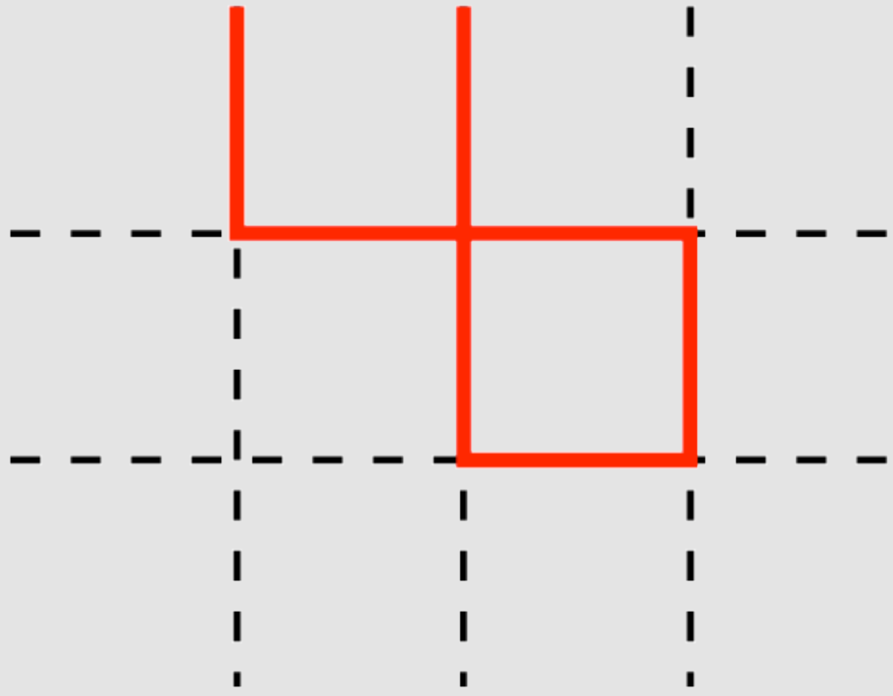

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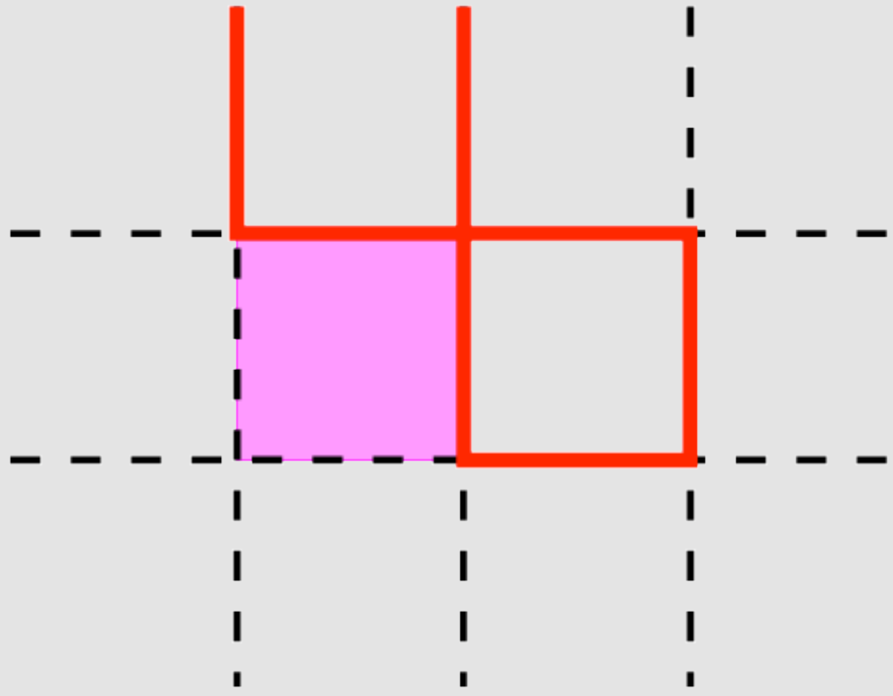

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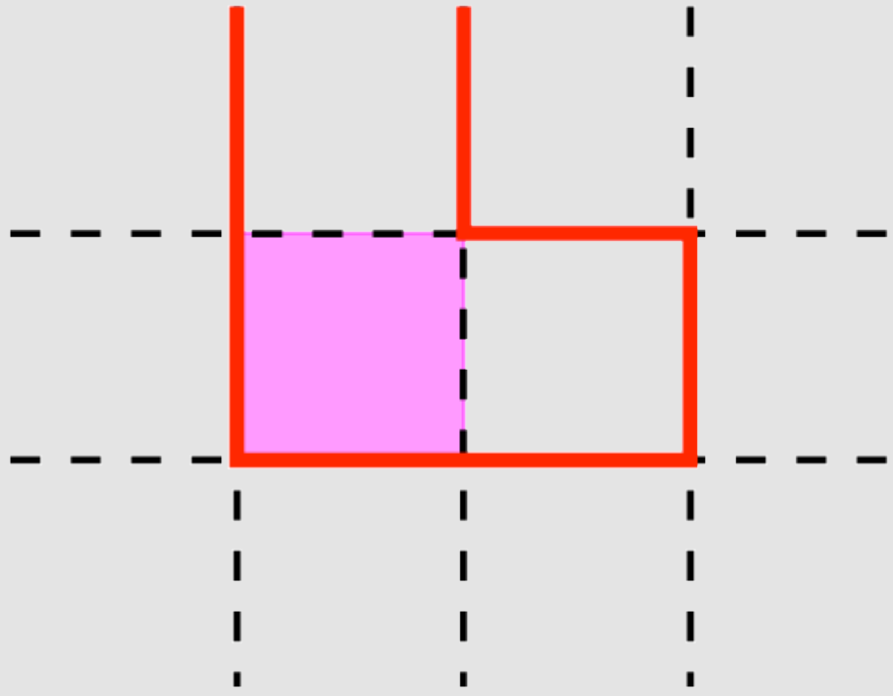

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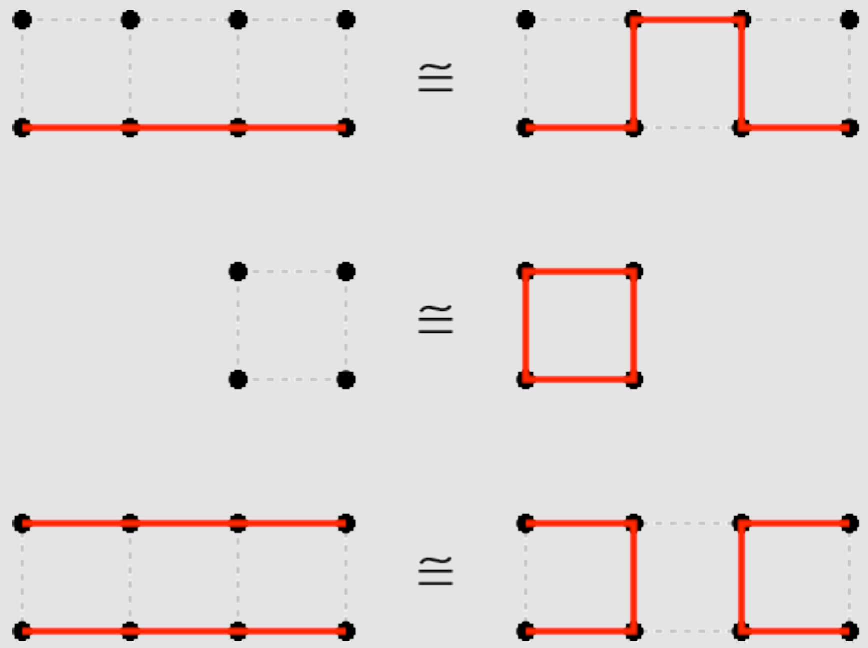
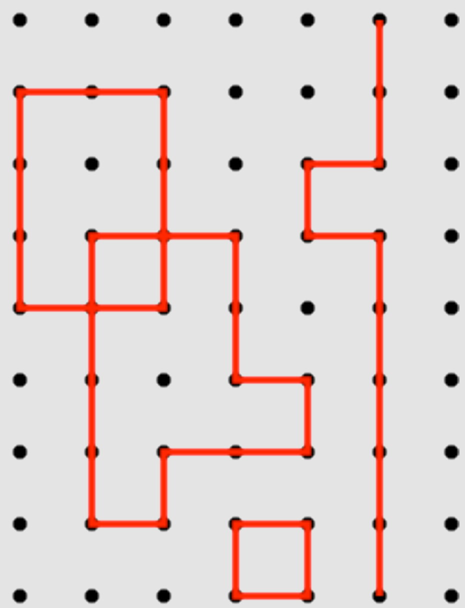
Properties of the Ground State

- Ground state: all A_i=1, F_p=1
- Pictorial representation: color each link with an up-spin.
- A_i=1 : closed loops.
- F_p=1 : every plaquette is an equal-amplitude superposition of inverse images.

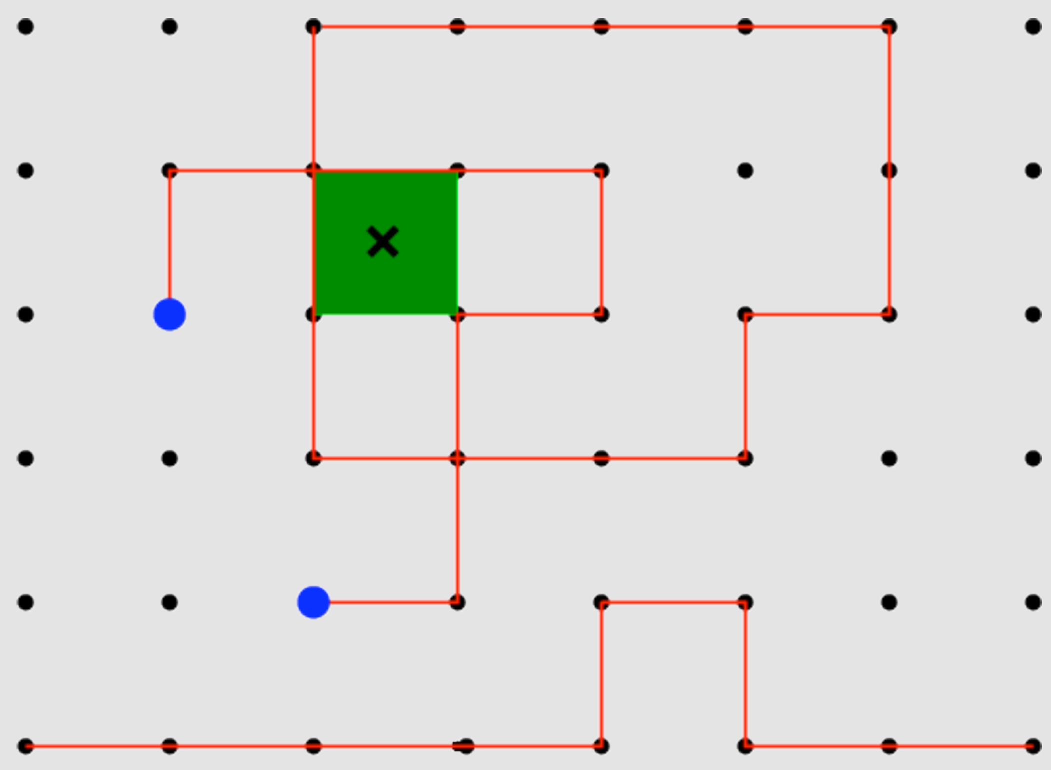




The GS wavefunction takes the same value on configurations connected by these operations. It does not depend on the geometry of the configurations, only on their topology.

Properties of Excitations

- "Electric" particle, or $A_i = -1$ – endpoint of a line
- "Magnetic particle", or *vortex*: $F_p = -1$ – a "flip" of this plaquette changes the sign of a given term in the superposition.
- Charges and vortices interact via topological Aharonov-Bohm interactions.



Properties of Excitations

- “Electric” particle, or $A_i = -1$ – endpoint of a line *(a “spinon”)*
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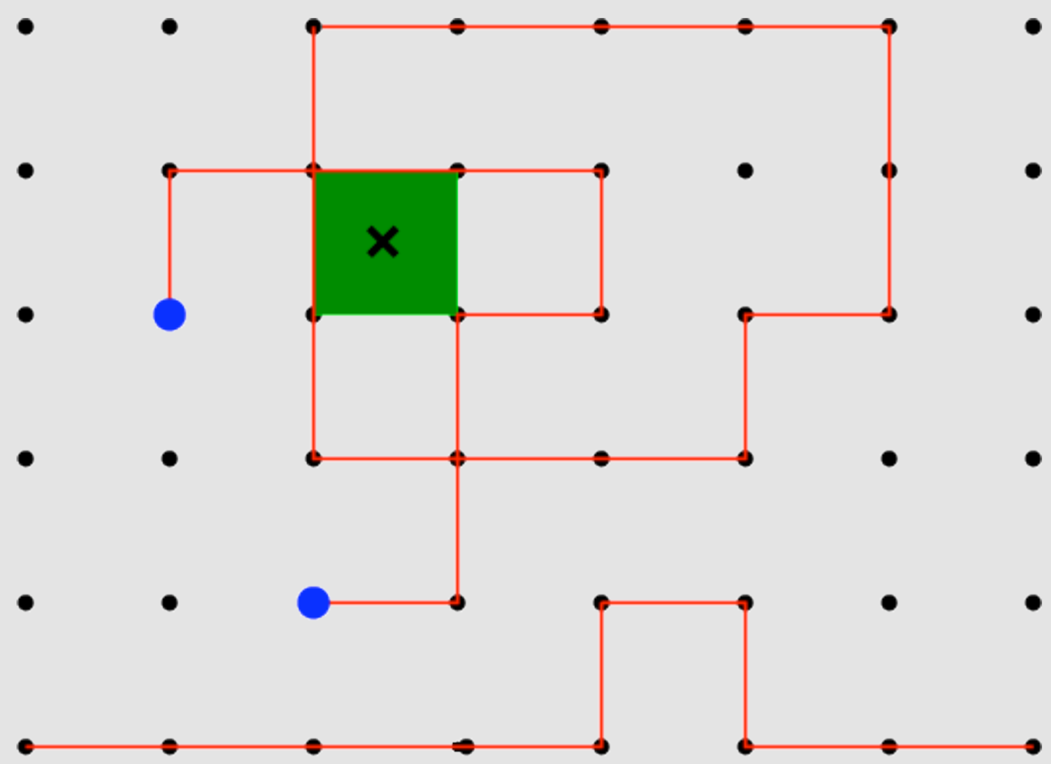

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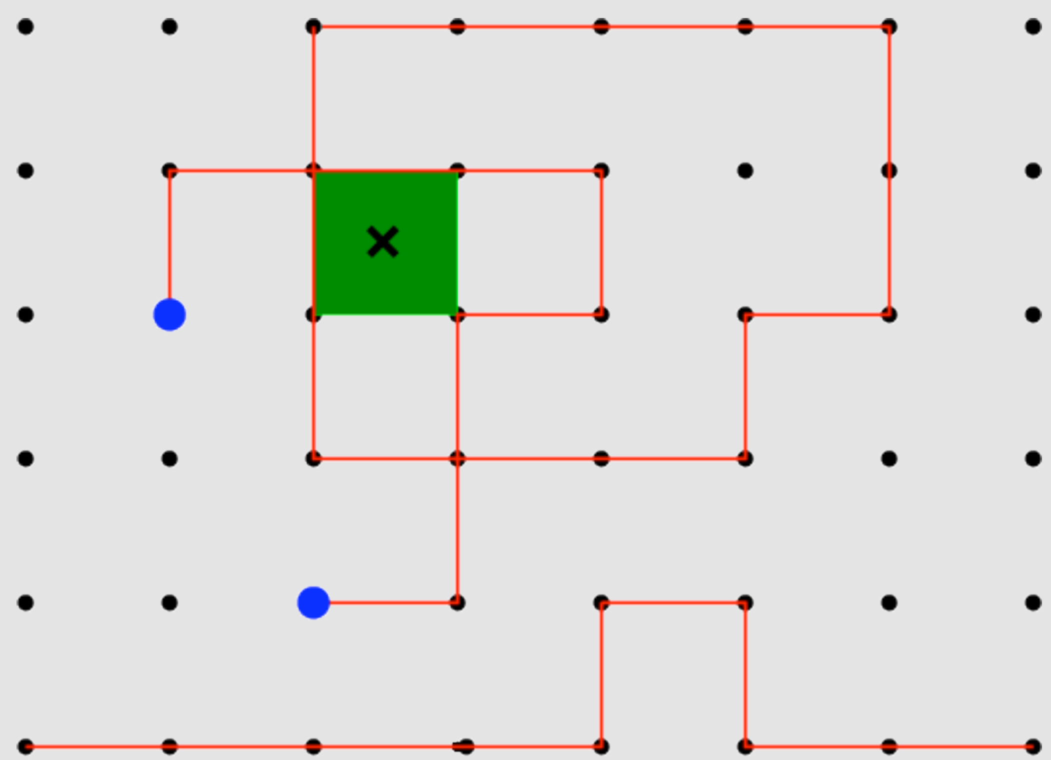

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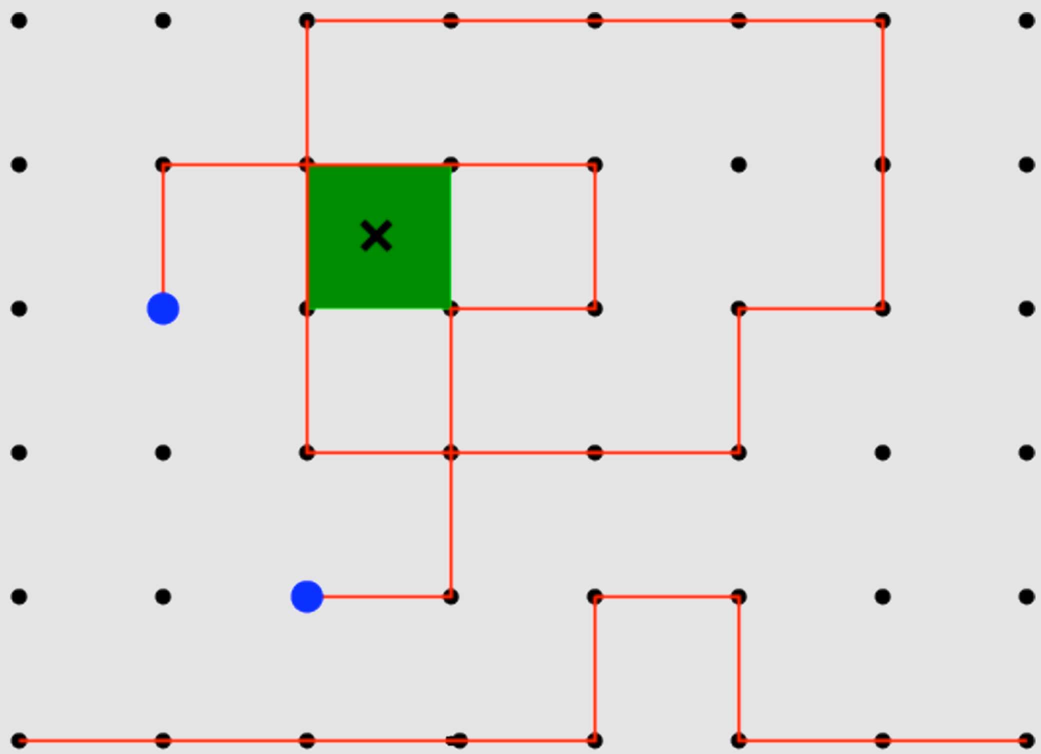


- *Spinons and visons are mutual semions*

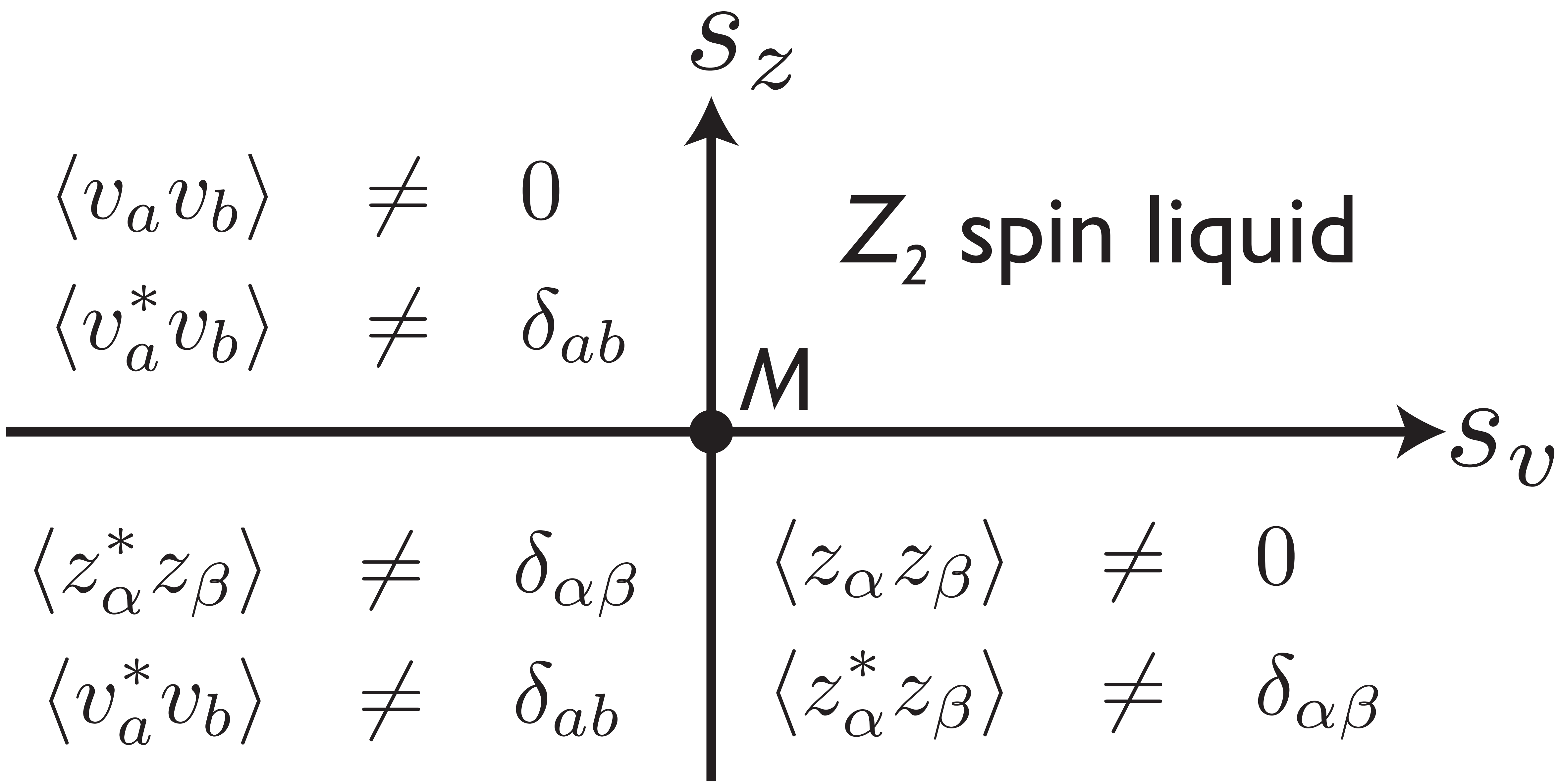
Mutual Chern-Simons Theory

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.

A related Berry phase is the phase of -1 acquired by a spinon encircling a vortex. This is implemented in the following "mutual Chern-Simons" theory at $k = 2$:

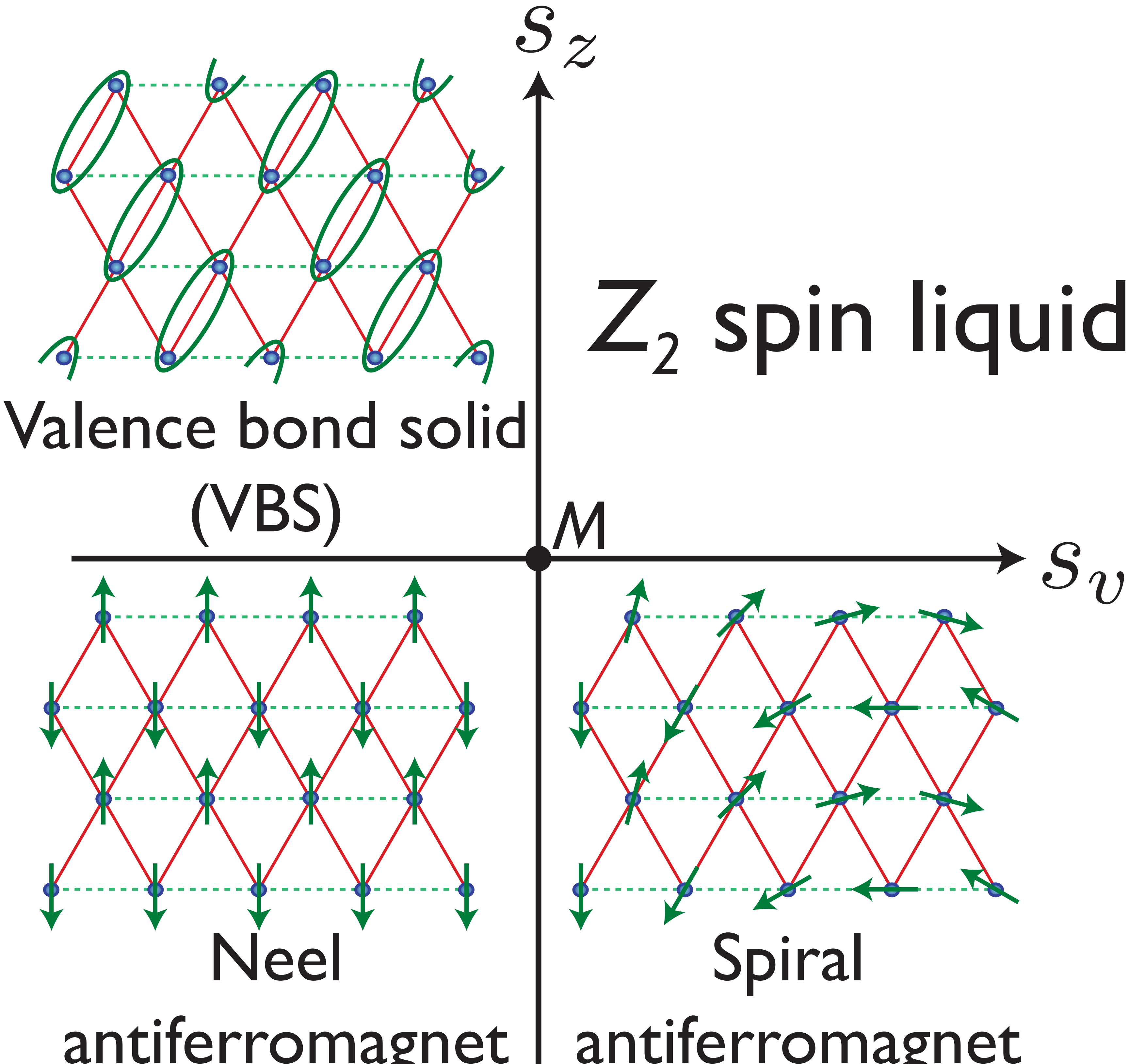
$$\begin{aligned}
\mathcal{L} &= \sum_{\alpha=1}^{2}\left\{|(\partial_\mu - i a_\mu) z_\alpha|^2 + s_z |z_\alpha|^2 + u_z(|z_\alpha|^2)^2\right\} \\
&+ \sum_{a=1}^{N_v}\left\{|(\partial_\mu - i b_\mu) v_a|^2 + s_v |v_a|^2 + u_v(|v_a|^2)^2\right\} \\
&+ \frac{ik}{2\pi}\epsilon_{\mu\nu\lambda} a_\mu \partial_\nu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

Cenke Xu and S. Sachdev, arXiv:0811.1220



Cenke Xu and S. Sachdev, arXiv:0811.1220

Theoretical global phase diagram



N. Read and S. Sachdev, *Phys. Rev. Lett.* **66**, 1773 (1991)
T. Senthil, A. Vishwanath, L. Balents, S. Sachdev and M.P.A. Fisher, *Science* **303**, 1490 (2004).
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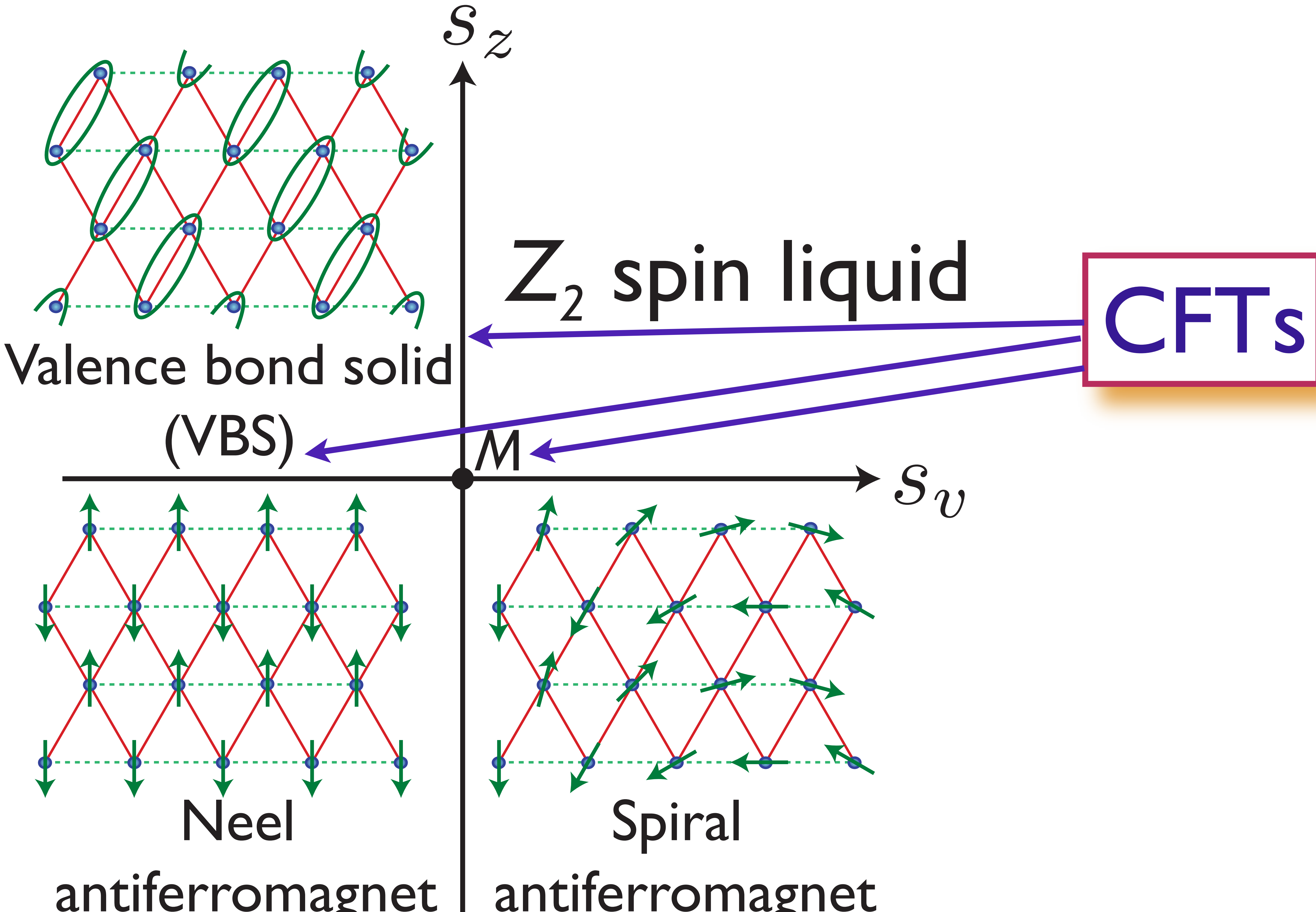

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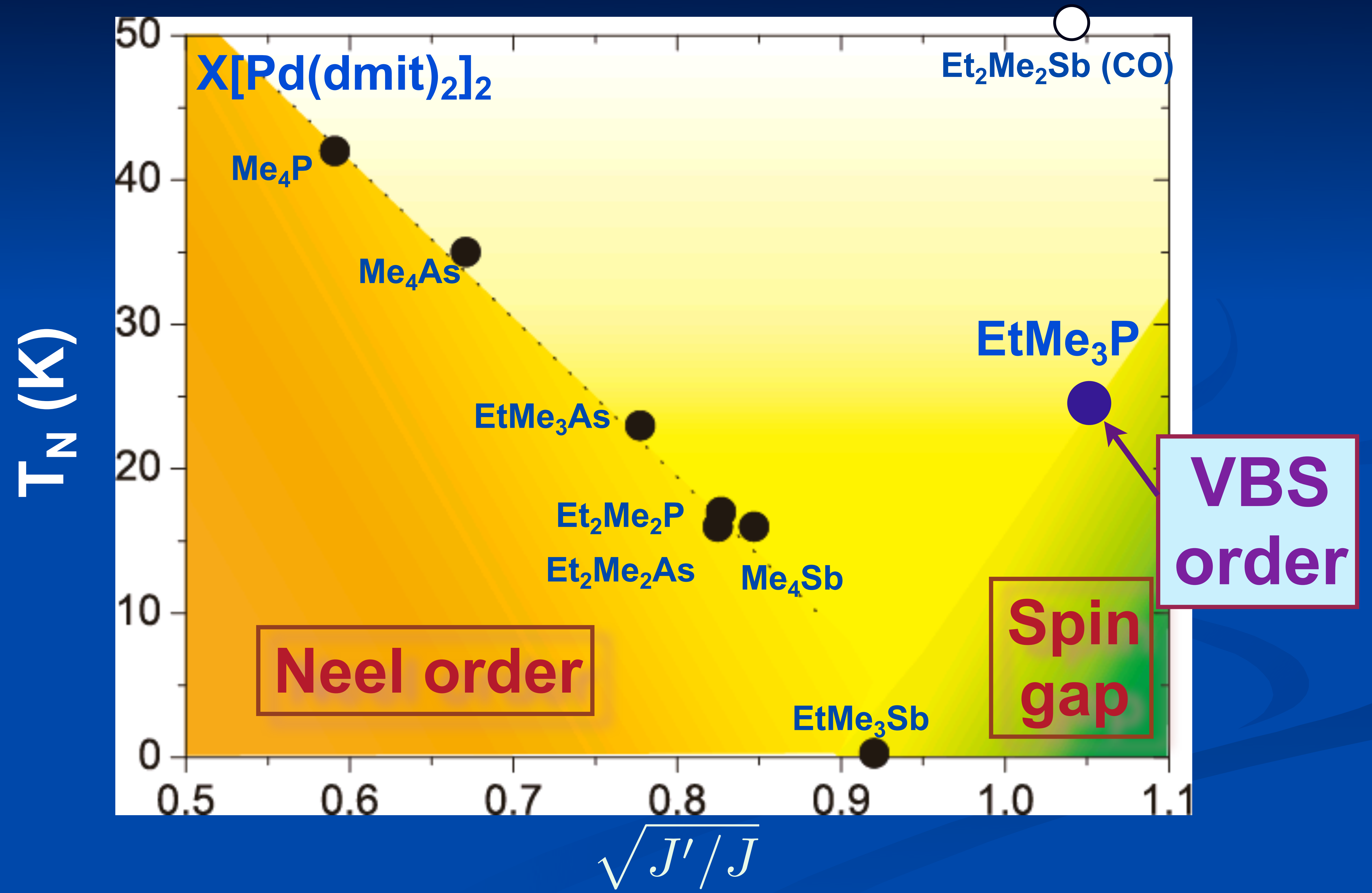
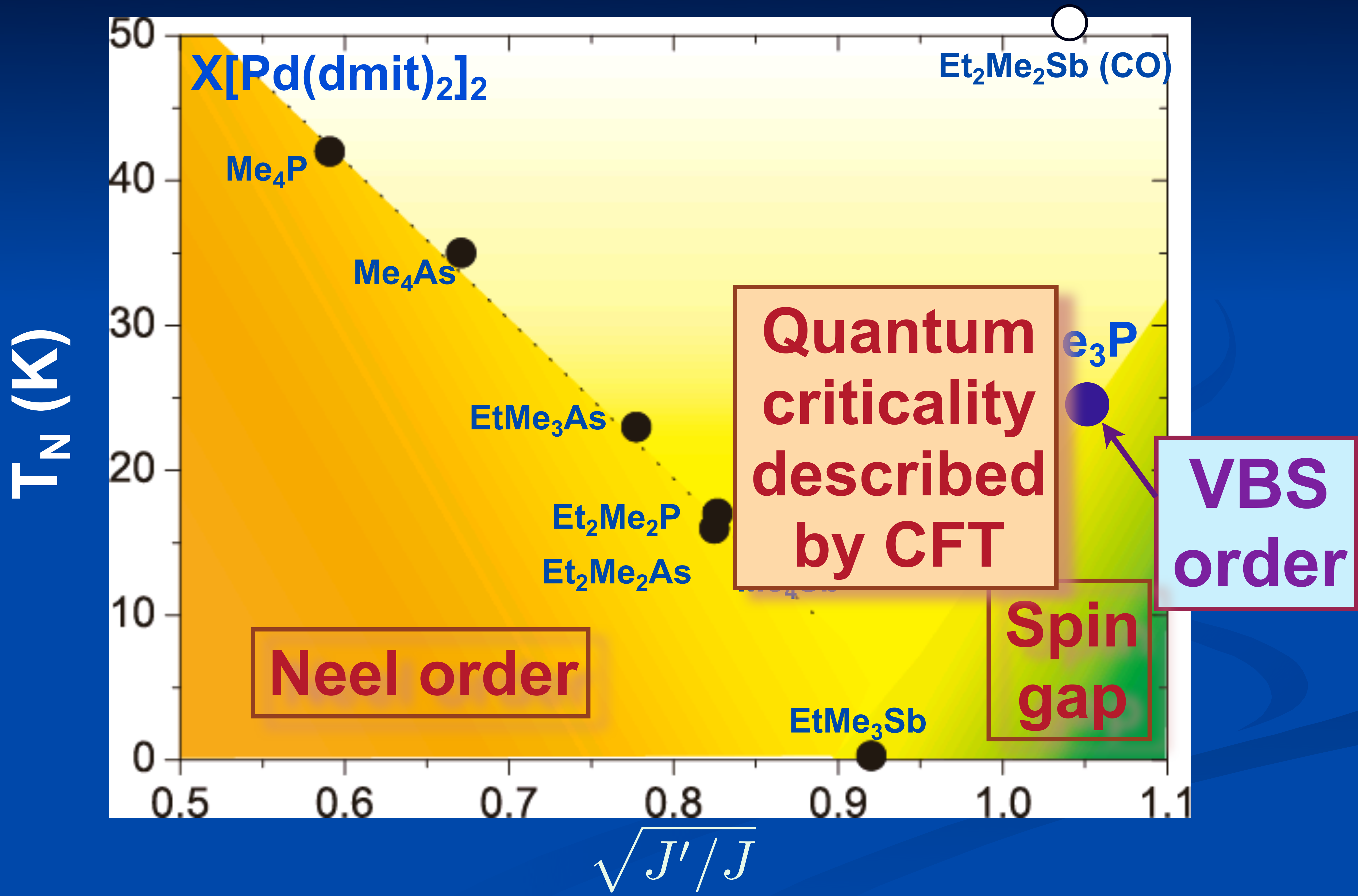
Cenke Xu and S. Sachdev, arXiv:0811.1220

Magnetic Criticality



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

Magnetic Criticality



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

From quantum antiferromagnets to string theory

A direct generalization of the CFT of the multicritical point M ($s_z = s_v = 0$) to $\mathcal{N} = 4$ supersymmetry and the U(N) gauge group was shown by O. Aharony, O. Bergman, D. L. Jafferis, J. Maldacena, JHEP **0810**, 091 (2008) to be dual to a theory of quantum gravity (M theory) on $\text{AdS}_4 \times \text{S}_7 / Z_k$.

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

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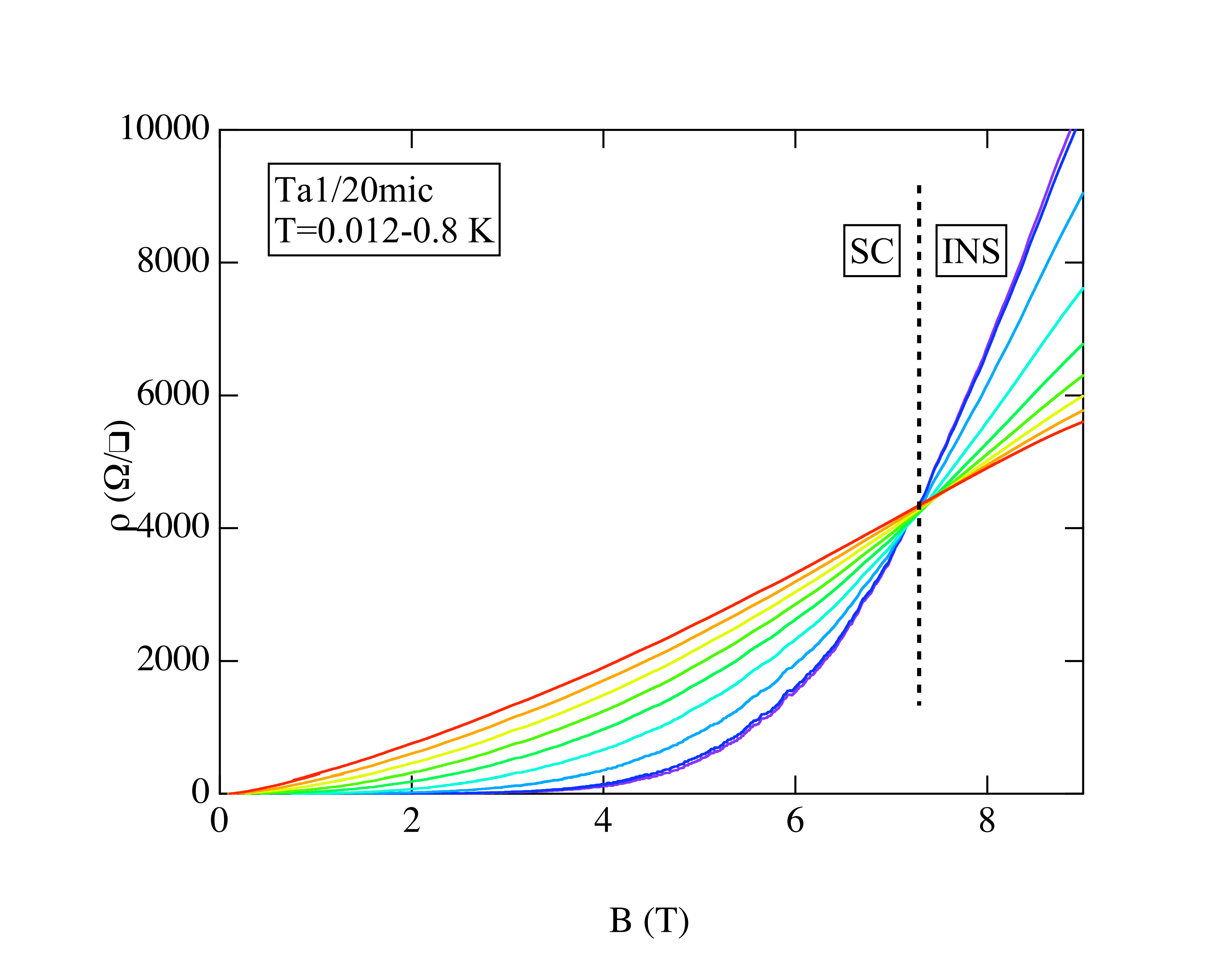
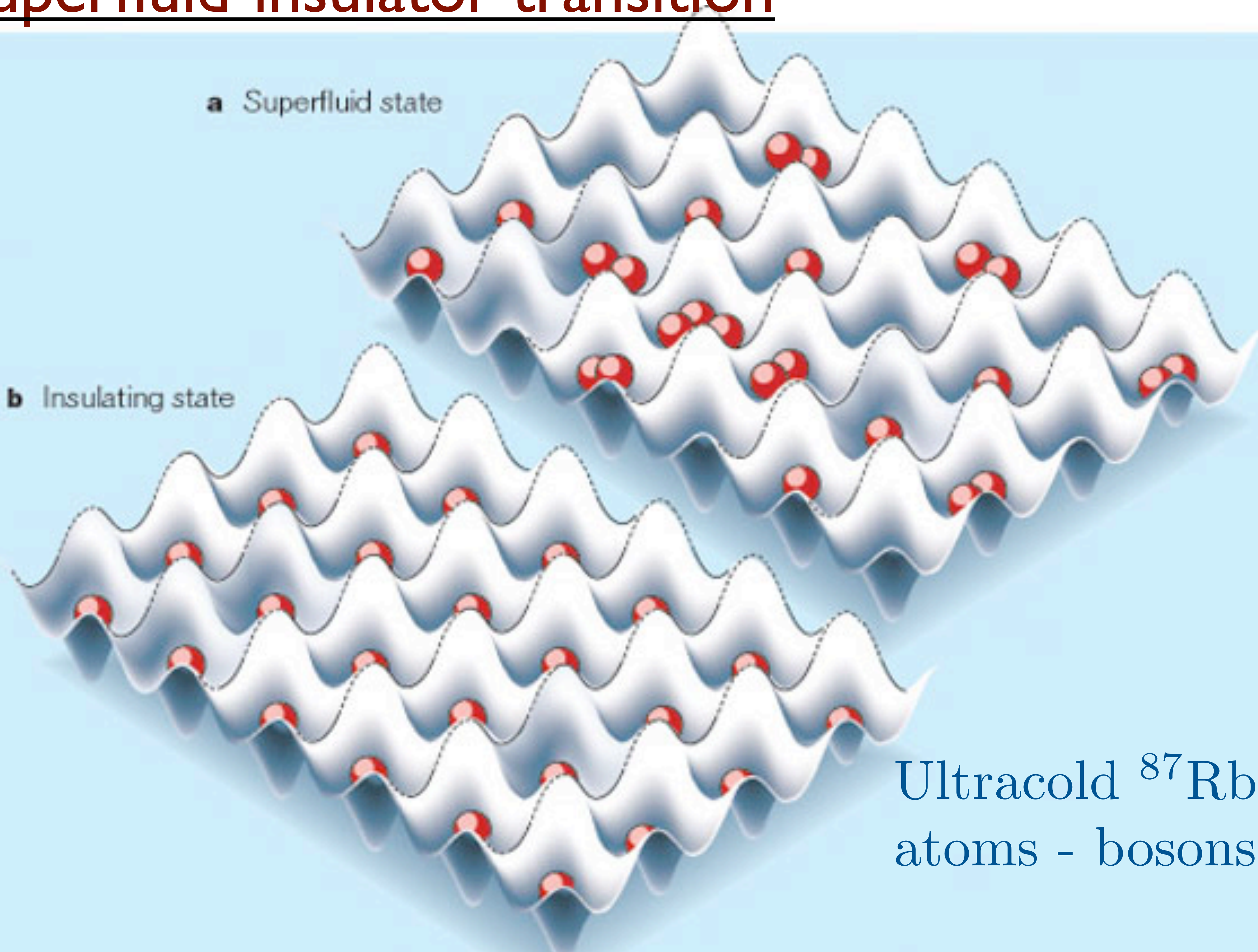
Superfluid-insulator transition

Indium Oxide films



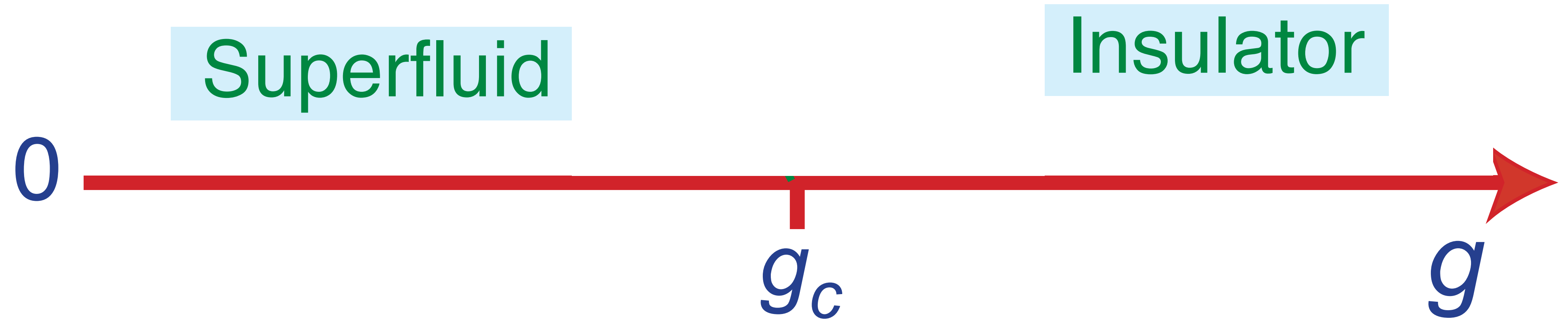
G. Sambandamurthy, A. Johansson, E. Peled, D. Shahar, P. G. Bjornsson, and K. A. Moler, *Europhys. Lett.* **75**, 611 (2006).

Superfluid-insulator transition



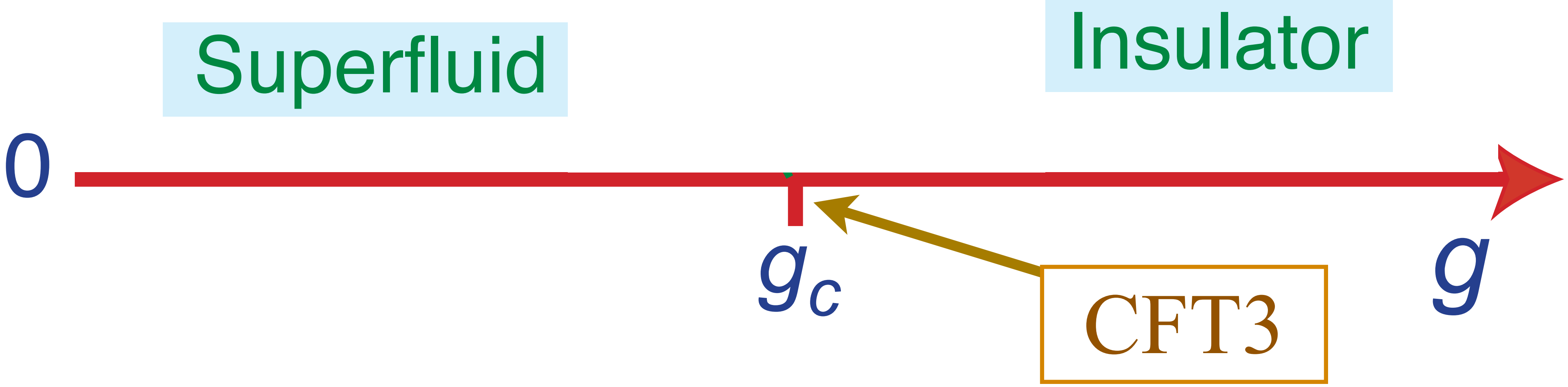
Ultracold ^{87}Rb atoms - bosons

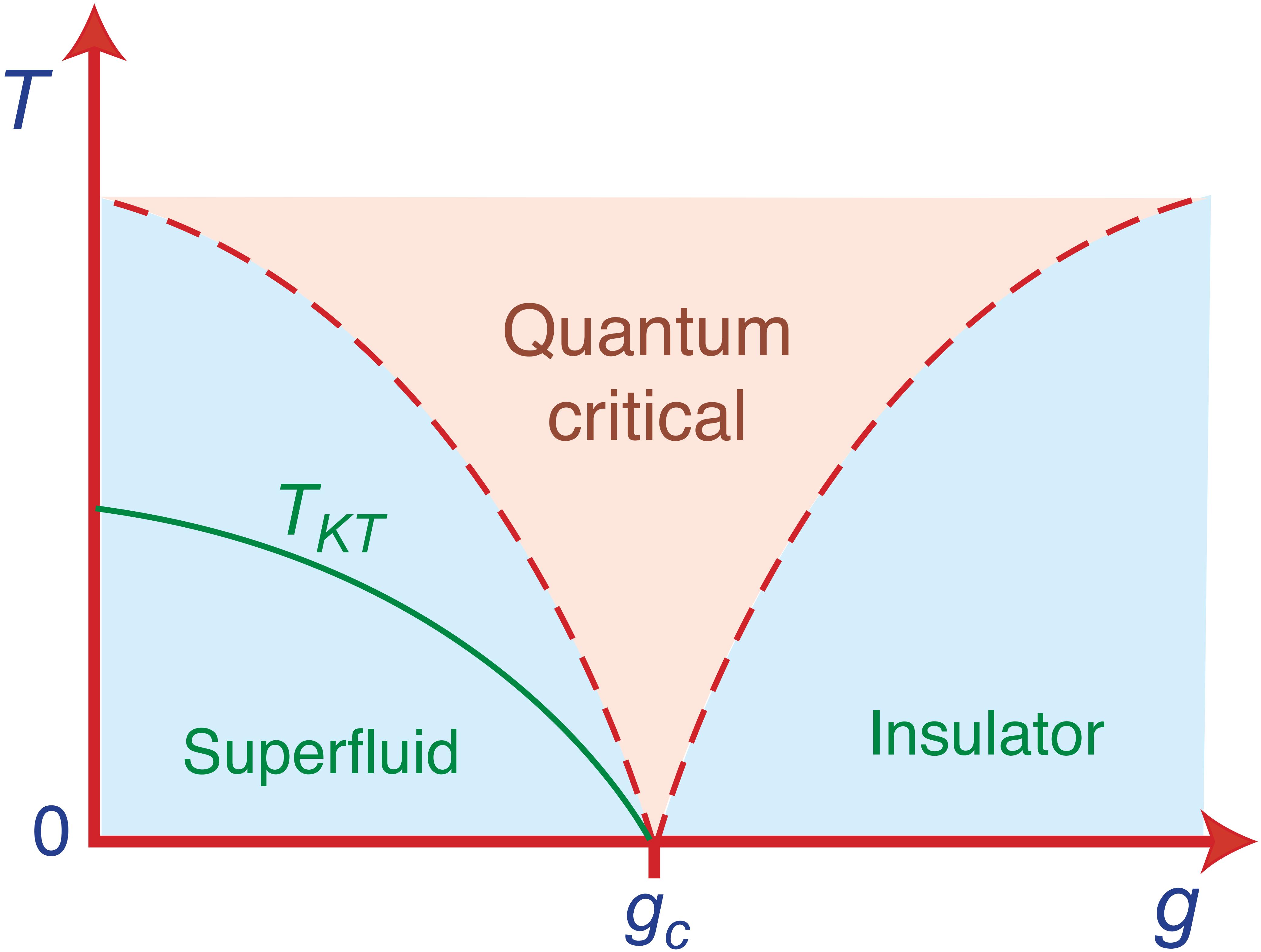
M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).


Superfluid
Insulator
0
g_c
g

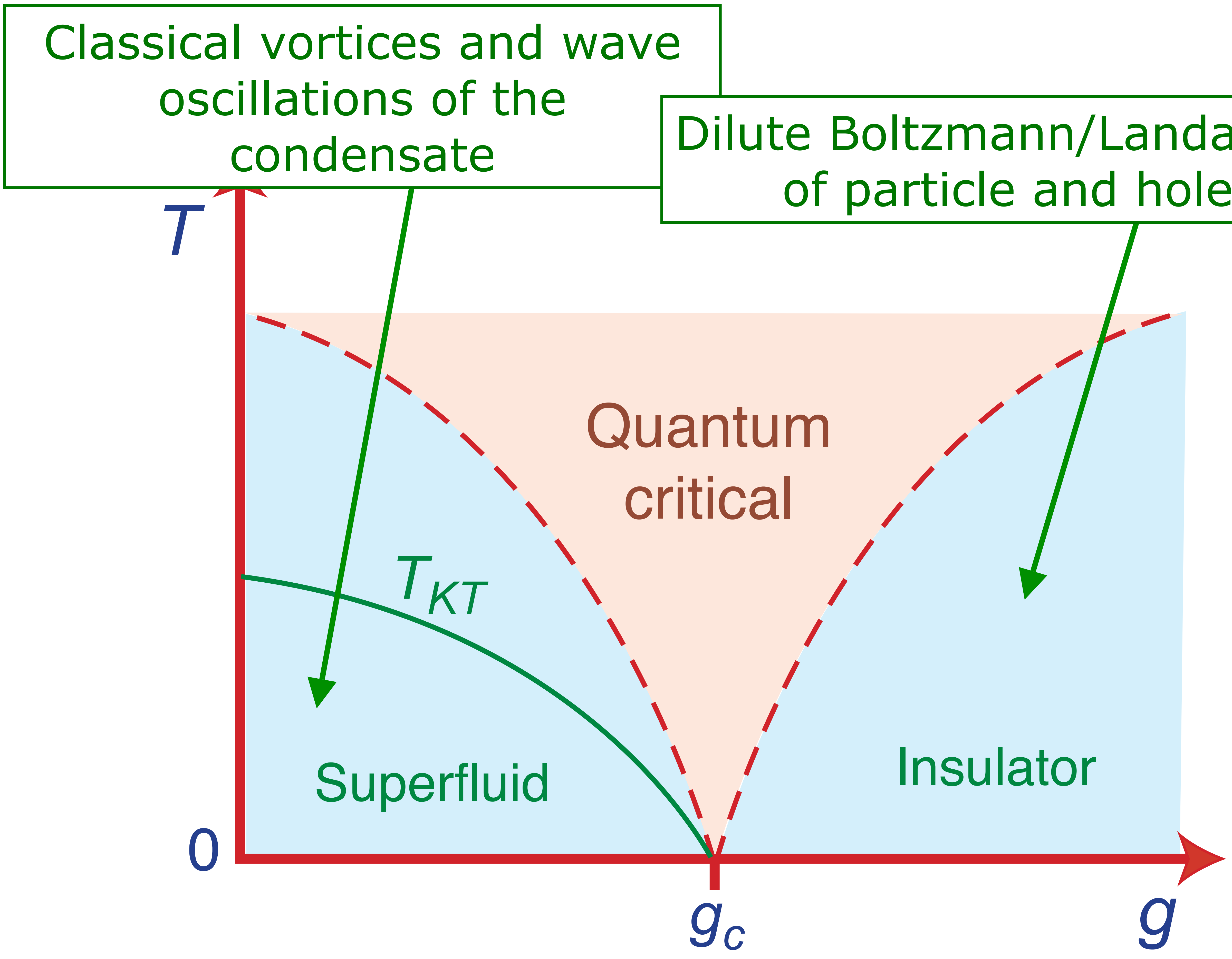
$$\mathcal{S} = \int d^2r d\tau \left[|\partial_\tau \psi|^2 + v^2 |\vec{\nabla}\psi|^2 + (g - g_c)|\psi|^2 + \frac{u}{2}|\psi|^4 \right]$$

$$\langle \psi \rangle \neq 0 \qquad\qquad \langle \psi \rangle = 0$$

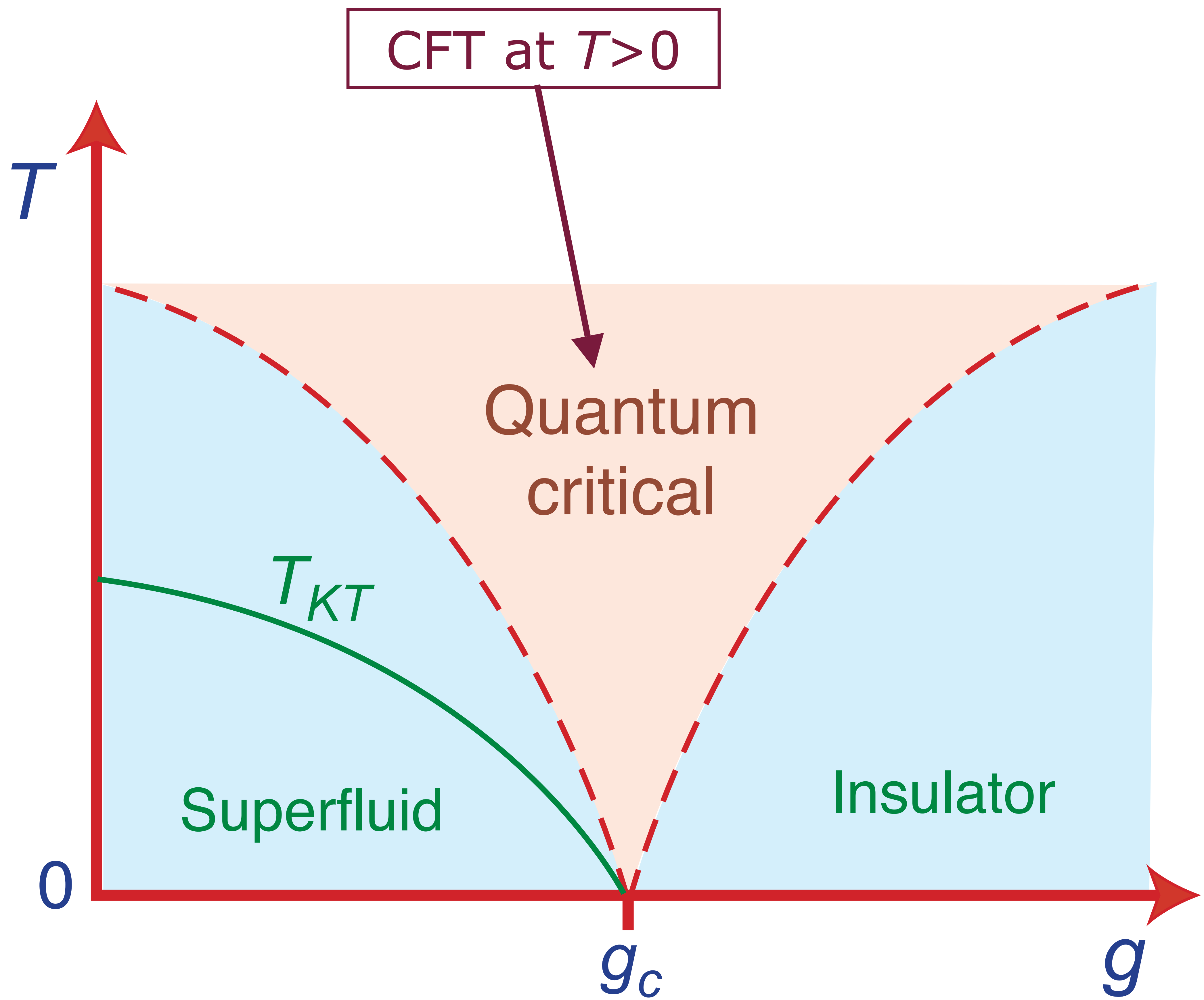




T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
g_c
g



Classical vortices and wave oscillations of the condensate
Dilute Boltzmann/Landau gas of particle and holes
T
Quantum critical
T_{KT}
Superfluid
Insulator
0
g_c
g


CFT at T>0
T
Quantum
critical
T_KT
Superfluid
Insulator
0
g_c
g

Density correlations in CFTs at $T > 0$

Two-point density correlator, $\chi(k,\omega)$

Kubo formula for conductivity $\sigma(\omega) = \lim_{k \to 0} \frac{-i\omega}{k^2} \chi(k,\omega)$

For *all* CFT3s, at $\hbar\omega \gg k_B T$

$$\chi(k,\omega) = \frac{4e^2}{h} K \frac{k^2}{\sqrt{v^2k^2 - \omega^2}} \quad ; \quad \sigma(\omega) = \frac{4e^2}{h} K$$

where K is a universal number characterizing the CFT3, and v is the velocity of "light".

Density correlations in CFTs at $T > 0$

Two-point density correlator, $\chi(k,\omega)$

Kubo formula for conductivity $\sigma(\omega) = \lim_{k\to 0} \frac{-i\omega}{k^2}\chi(k,\omega)$

However, for *all* CFT3s, at $\hbar\omega \ll k_B T$, we have the Einstein relation

$$\chi(k,\omega) = 4e^2\chi_c \frac{Dk^2}{Dk^2 - i\omega} \quad ; \quad \sigma(\omega) = 4e^2 D\chi_c = \frac{4e^2}{h}\Theta_1\Theta_2$$

where the **compressibility**, χ_c, and the **diffusion constant** D obey

$$\chi = \frac{k_B T}{(hv)^2}\Theta_1 \quad ; \quad D = \frac{hv^2}{k_B T}\Theta_2$$

with Θ_1 and Θ_2 universal numbers characteristic of the CFT3

K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

Density correlations in CFTs at $T > 0$

In CFT3s collisions are "phase" randomizing, and lead to relaxation to local thermodynamic equilibrium. So there is a crossover from collisionless behavior for $\hbar\omega \gg k_B T$, to hydrodynamic behavior for $\hbar\omega \ll k_B T$.

$$\sigma(\omega) = \begin{cases} \dfrac{4e^2}{h} K & , \quad \hbar\omega \gg k_B T \\ \dfrac{4e^2}{h} \Theta_1 \Theta_2 \equiv \sigma_Q & , \quad \hbar\omega \ll k_B T \end{cases}$$

and in general we expect $K \neq \Theta_1 \Theta_2$ (verified for Wilson-Fisher fixed point).

K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

Quantum critical transport

Quantum *"perfect fluid"*
with shortest possible
relaxation time, τ_R

$$\tau_R \gtrsim \frac{\hbar}{k_B T}$$

S. Sachdev, *Quantum Phase Transitions,* Cambridge (1999).

Quantum critical transport

Transport co-oefficients not determined by collision rate, but by universal constants of nature

Electrical conductivity

$$\sigma = \frac{e^2}{h} \times [\text{Universal constant } \mathcal{O}(1)\ ]$$

K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

Superfluid-insulator transition

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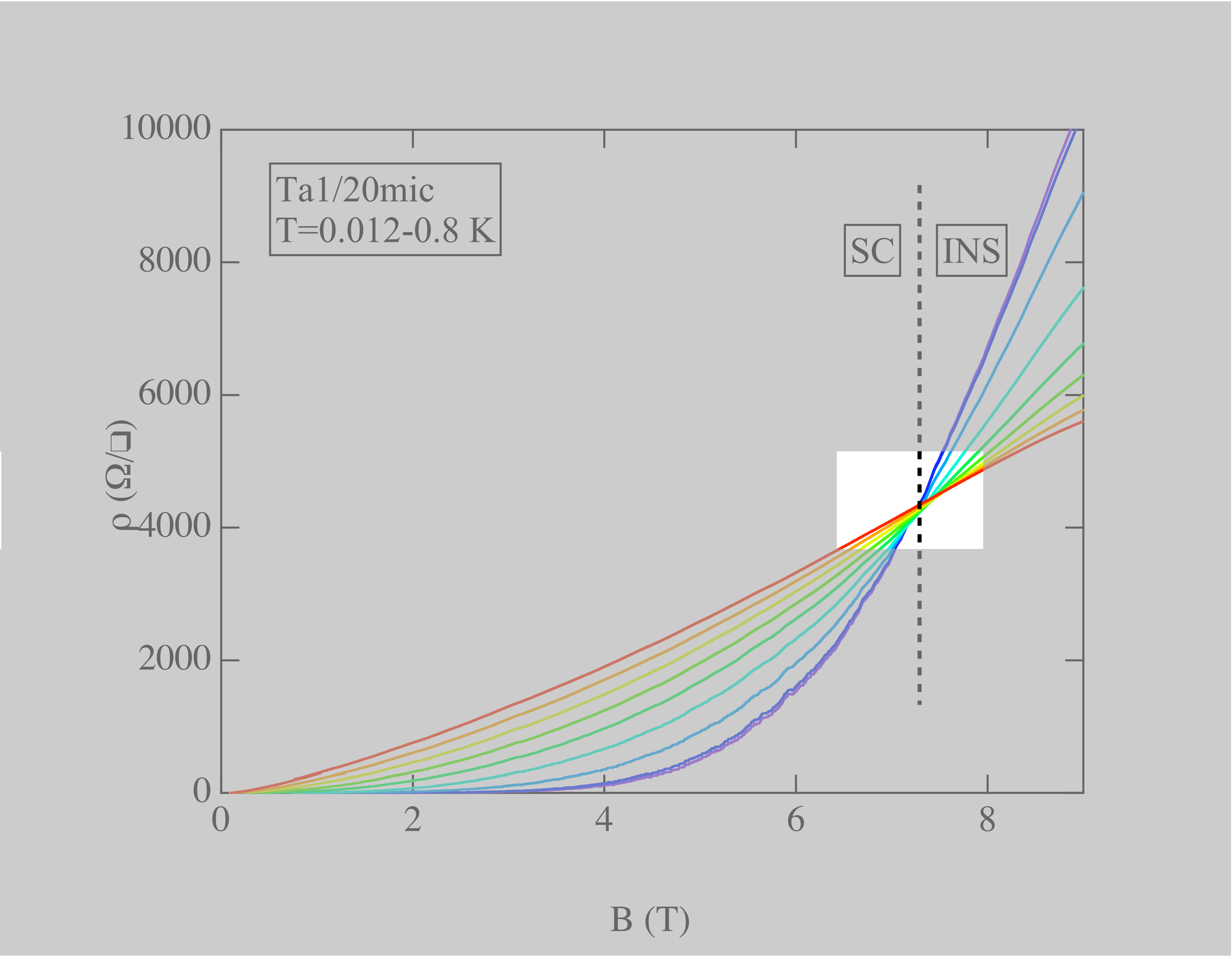

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Quantum critical transport

Transport co-oefficients not determined by collision rate, but by universal constants of nature

Momentum transport

$$\frac{\eta}{s} \equiv \frac{\text{viscosity}}{\text{entropy density}}$$

$$= \frac{\hbar}{k_B} \times [\text{Universal constant } \mathcal{O}(1)\ ]$$

P. Kovtun, D. T. Son, and A. Starinets, *Phys. Rev. Lett.* **94,** 11601 (2005)

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Black Holes

Objects so massive that light is gravitationally bound to them.

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The region inside the black hole horizon is causally disconnected from the rest of the universe.

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

Black Hole Thermodynamics

Bekenstein and Hawking discovered astonishing connections between the Einstein theory of black holes and the laws of thermodynamics

Entropy of a black hole $S = \dfrac{k_B A}{4\ell_P^2}$

where A is the area of the horizon, and

$\ell_P = \sqrt{\dfrac{G\hbar}{c^3}}$ is the Planck length.

The Second Law: $dA \geq 0$

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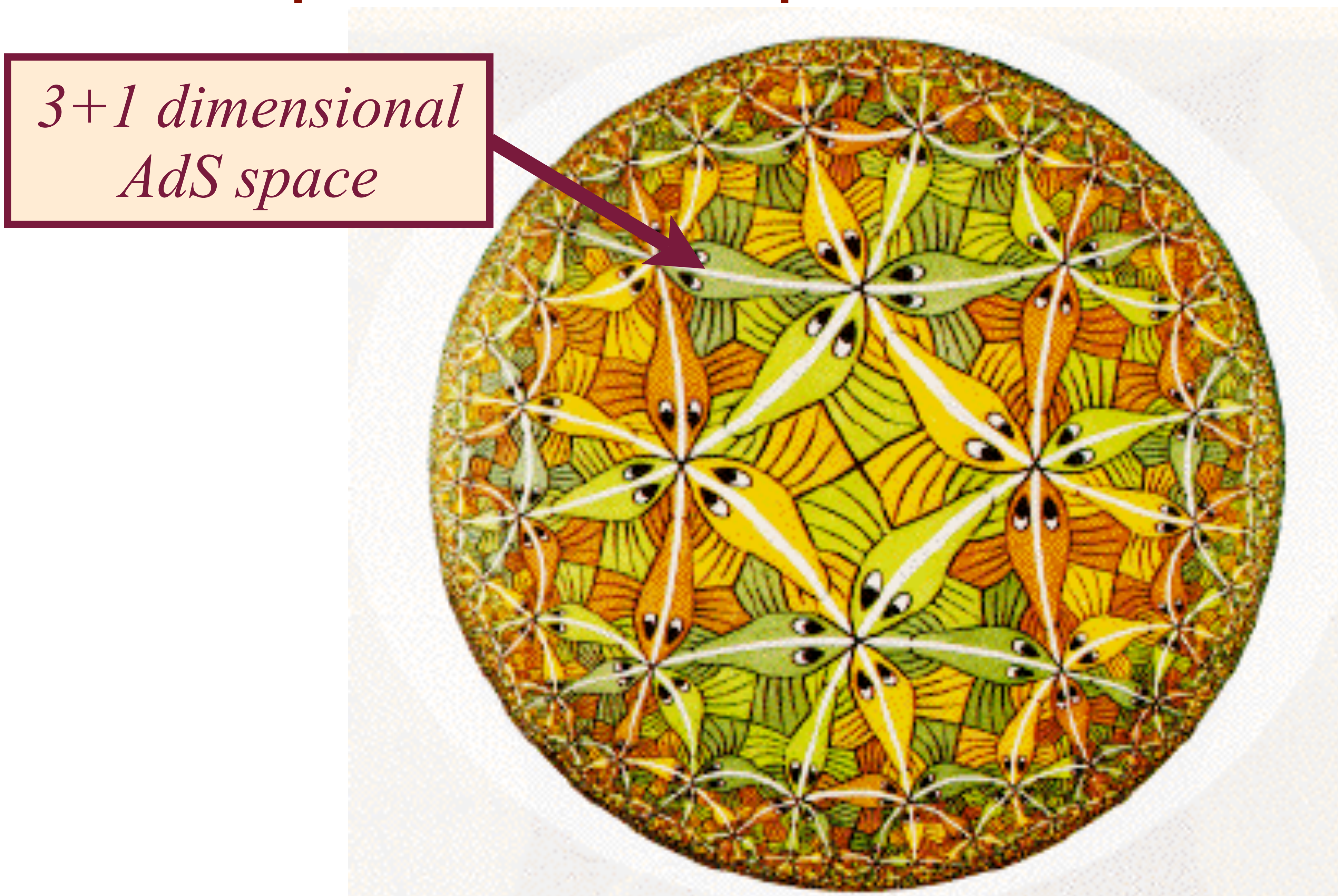
$$\text{Horizon temperature: } 4\pi k_B T = \frac{\hbar^2}{2M\ell_P^2}$$

AdS/CFT correspondence

The quantum theory of a black hole in a 3+1-dimensional negatively curved AdS universe is holographically represented by a CFT (the theory of a quantum critical point) in 2+1 dimensions



Maldacena, Gubser, Klebanov, Polyakov, Witten

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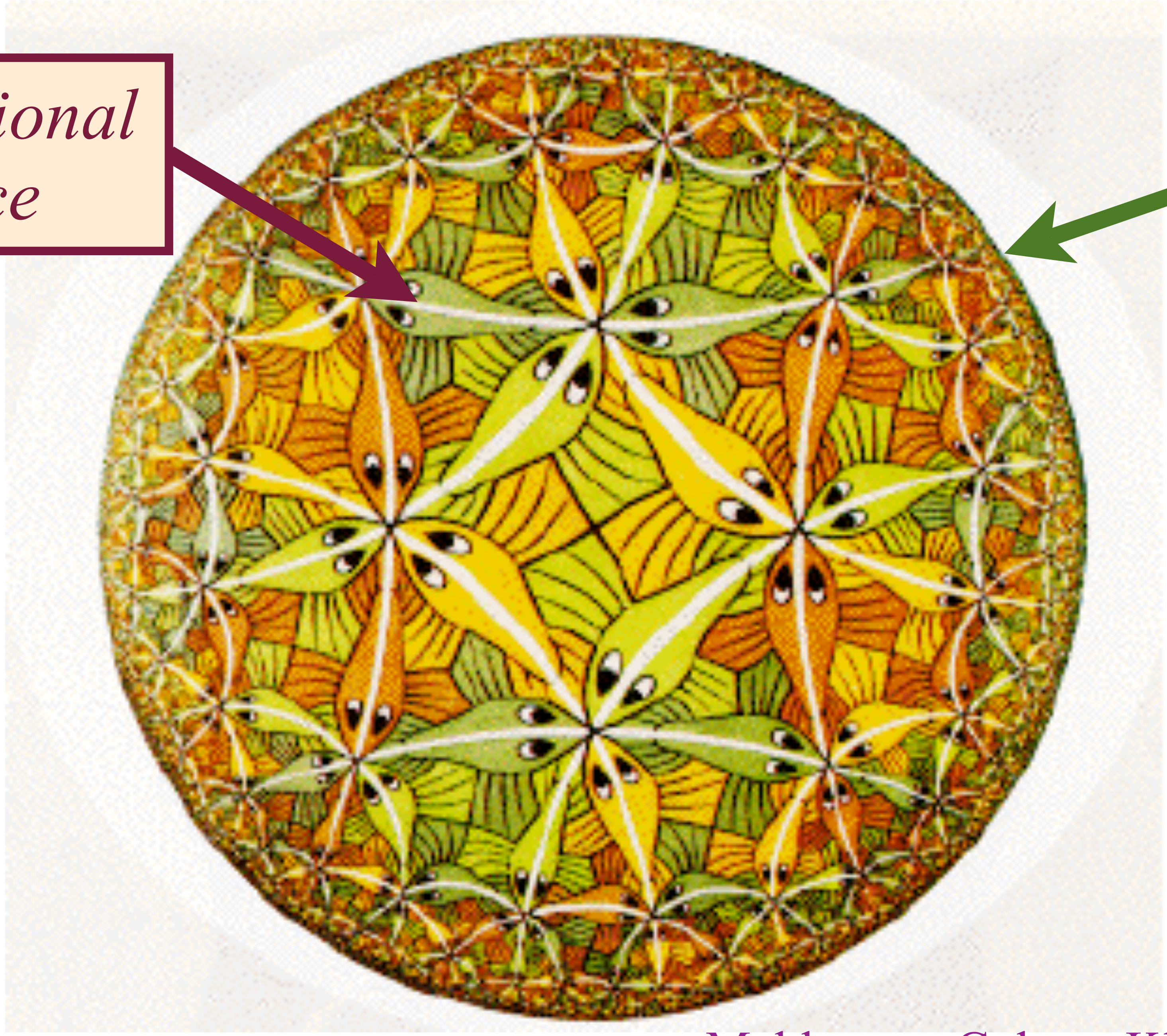

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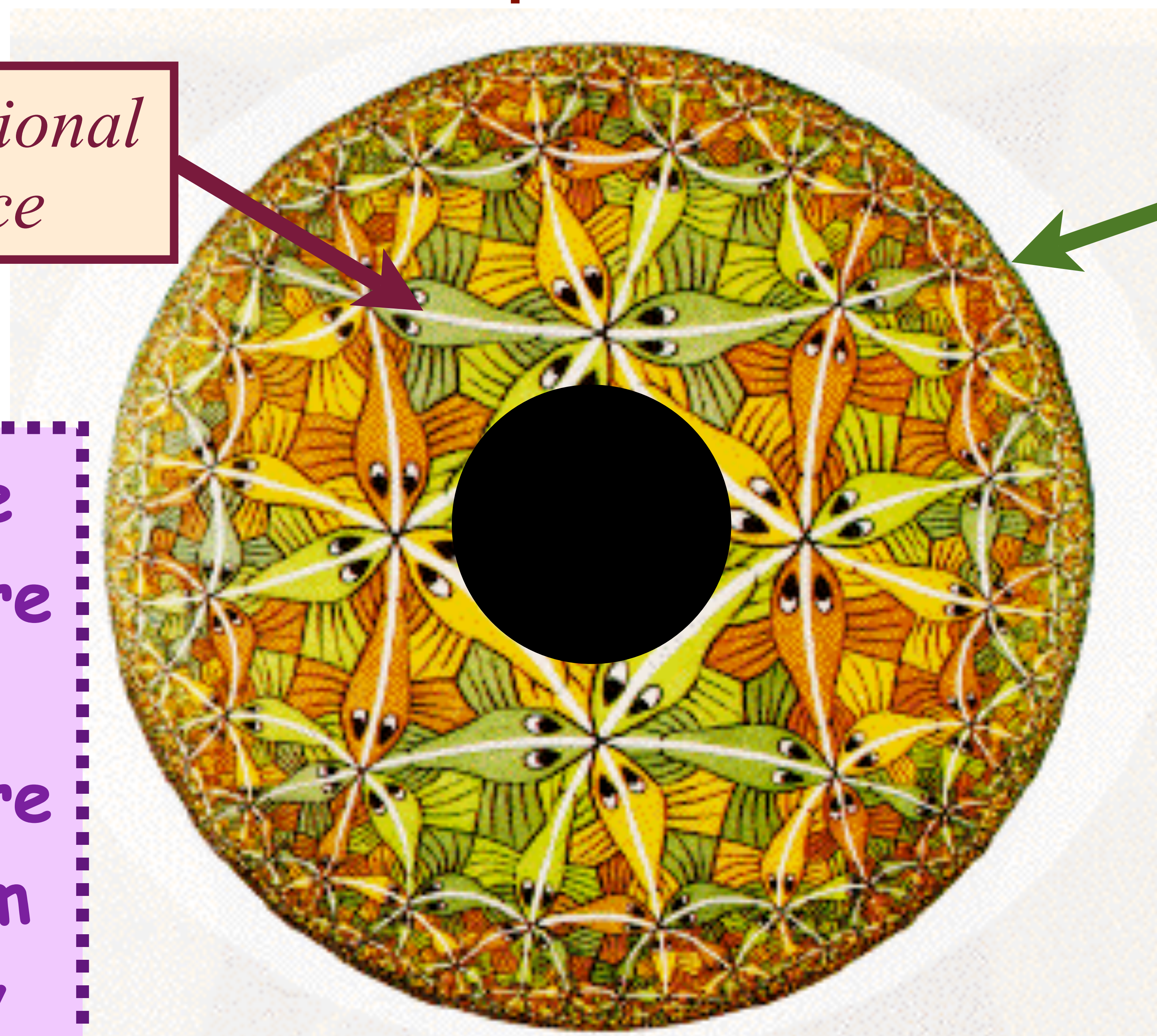
3+1 dimensional AdS space



Quantum criticality in 2+1 dimensions

Black hole temperature = temperature of quantum criticality

Maldacena, Gubser, Klebanov, Polyakov, Witten

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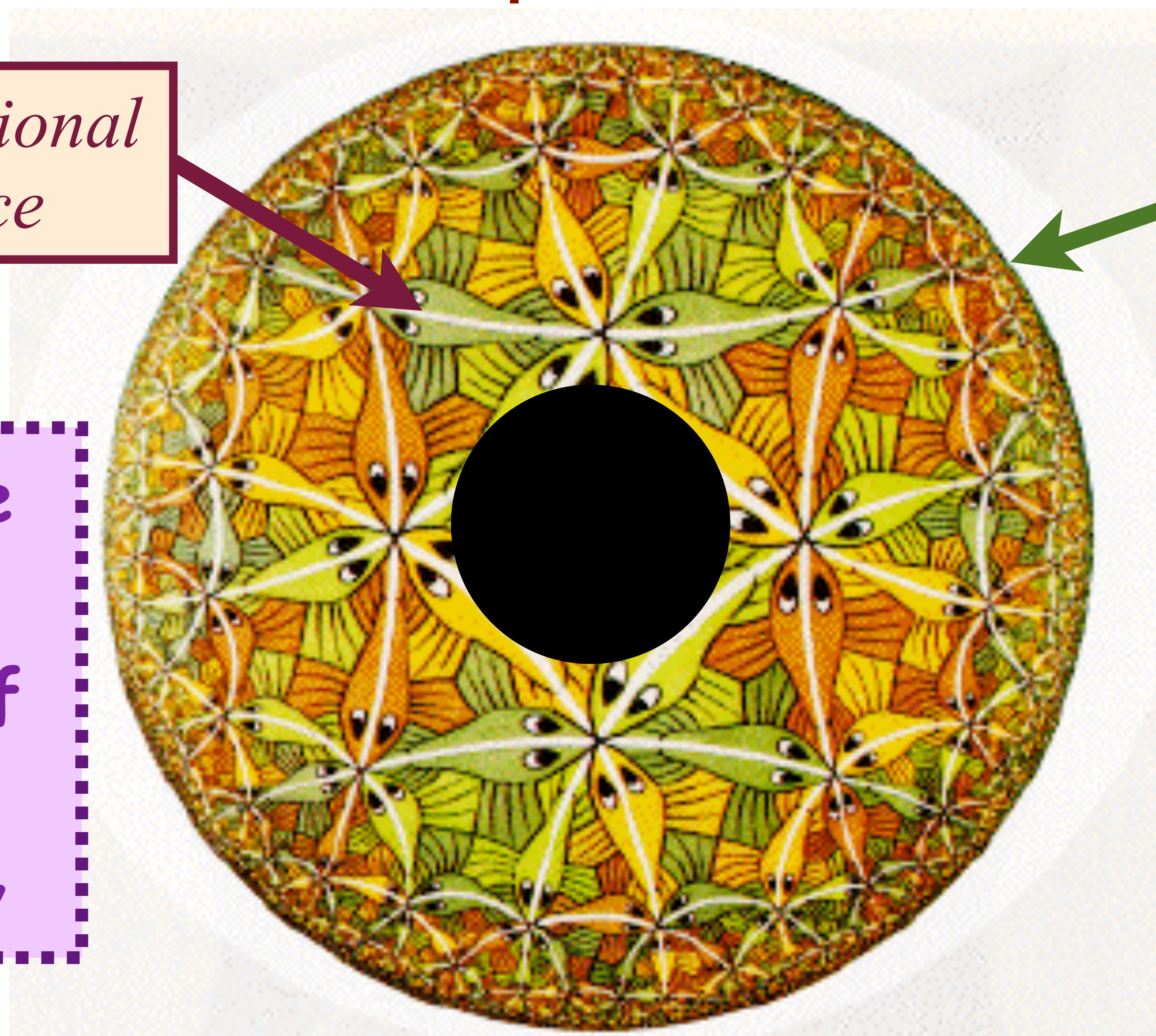

Strominger, Vafa

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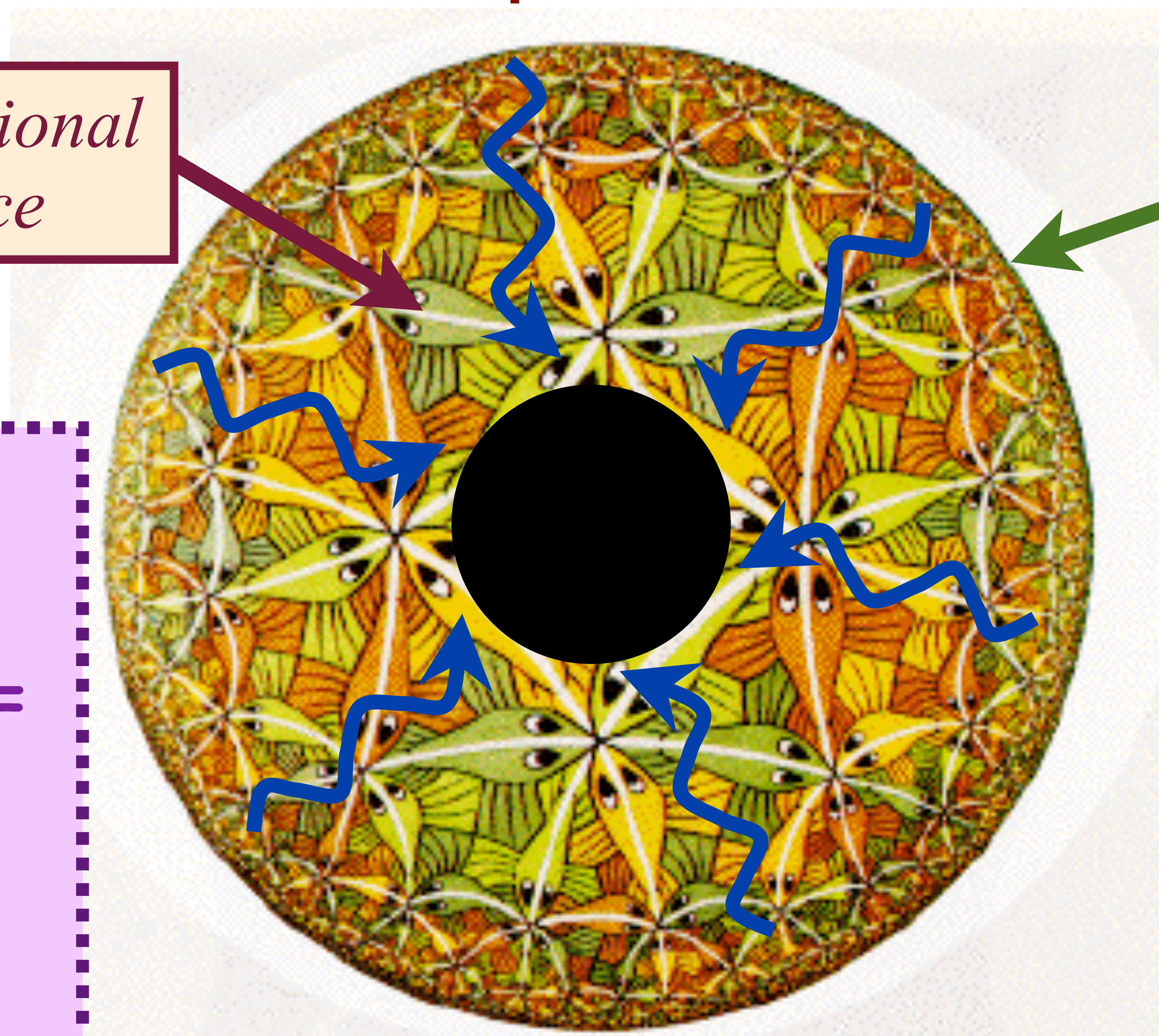

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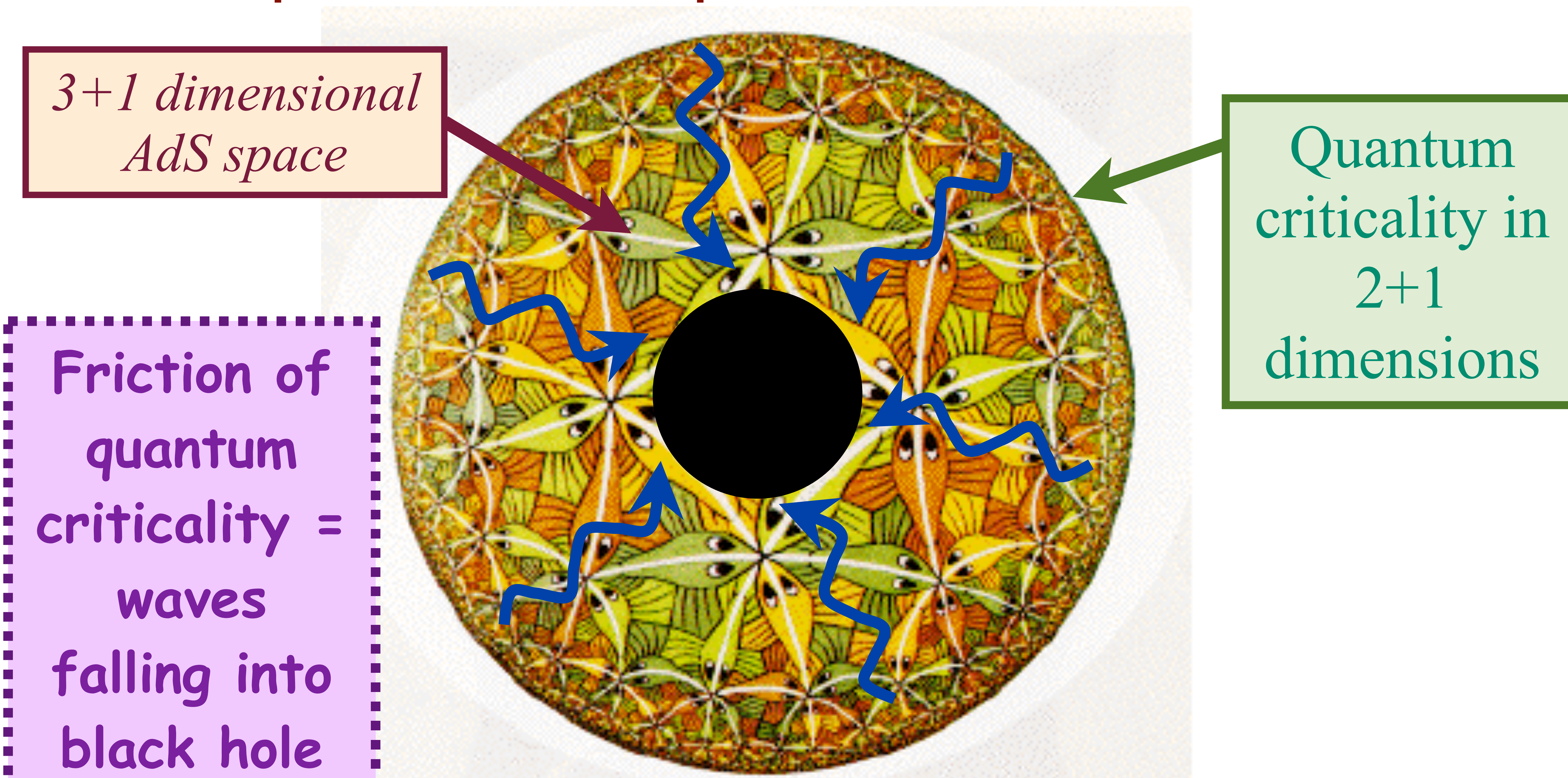

Kovtun, Policastro, Son

Hydrodynamics of quantum critical systems

1. Use quantum field theory + quantum transport equations + classical hydrodynamics

   Uses physical model but strong-coupling makes explicit solution difficult

2. Solve Einstein-Maxwell equations in the background of a black hole in AdS space

   Yields hydrodynamic relations which apply to general classes of quantum critical systems. First exact numerical results for transport co-efficients (for supersymmetric systems).

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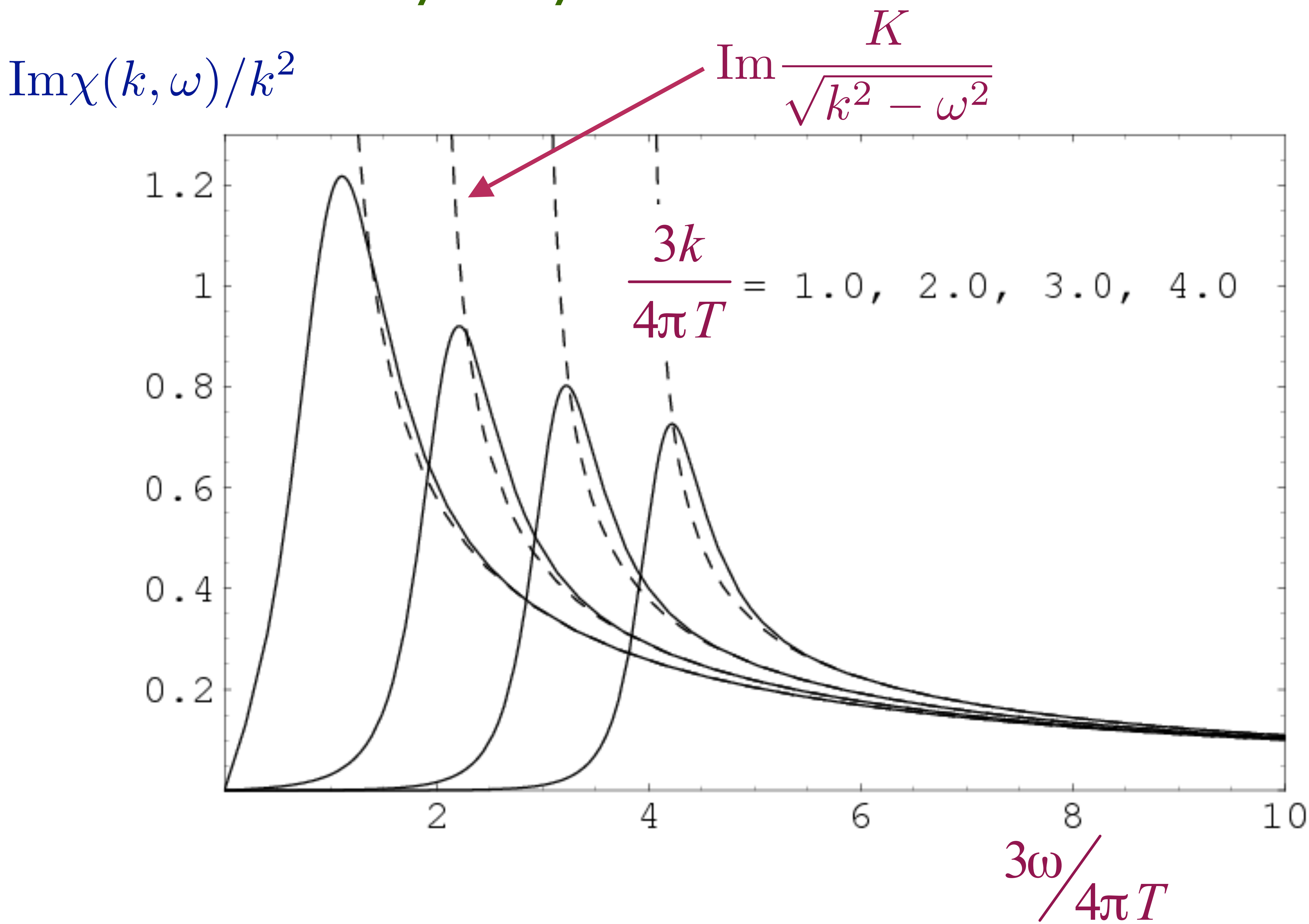
Collisionless to hydrodynamic crossover of SYM3



P. Kovtun, C. Herzog, S. Sachdev, and D.T. Son, Phys. Rev. D **75**, 085020 (2007)

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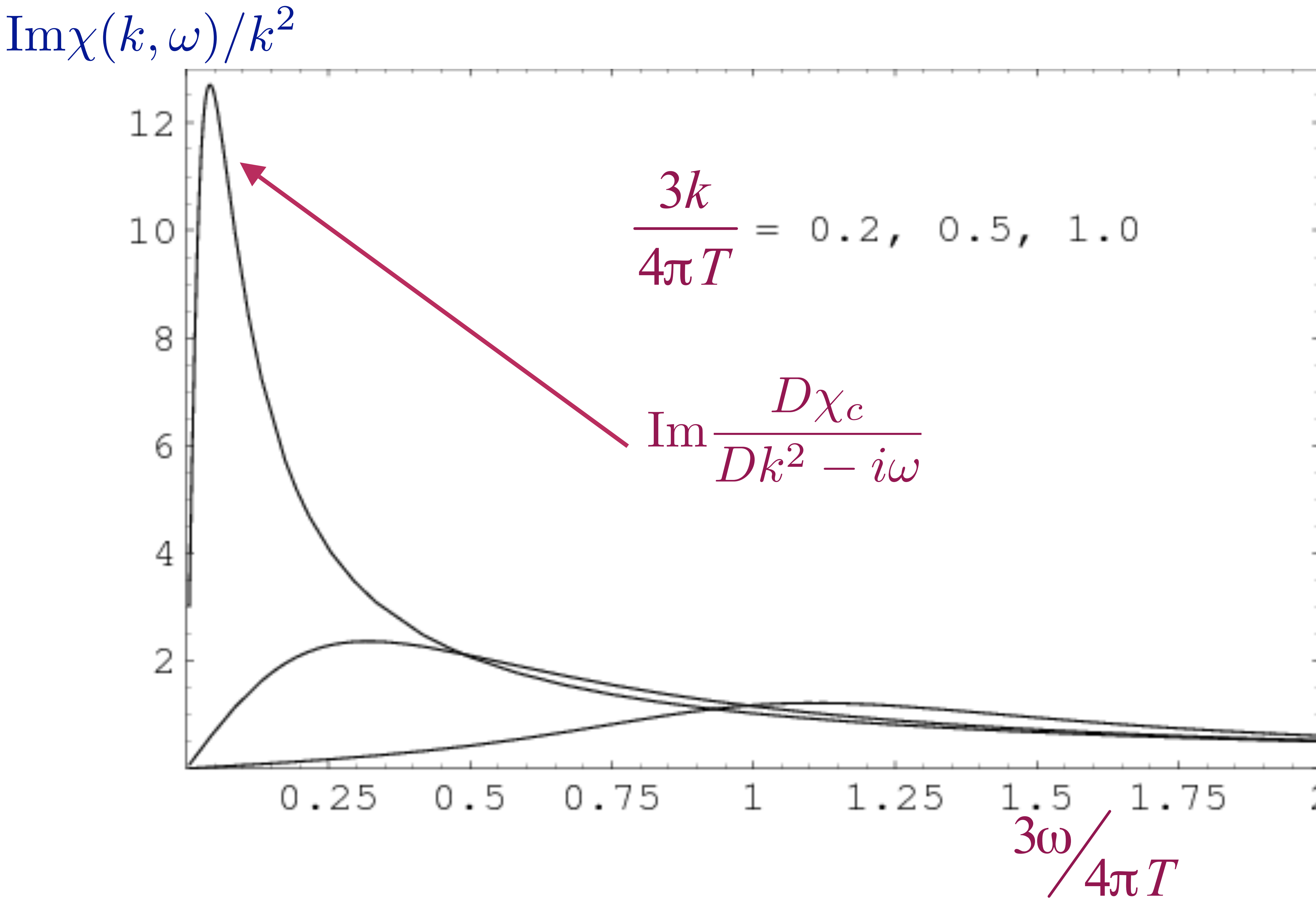

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Applications:

1. Magneto-thermo-electric transport near the superconductor-insulator transition and in graphene
   Hydrodynamic cyclotron resonance
   Nernst effect

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   Low viscosity fluid

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   Non-relativistic AdS/CFT

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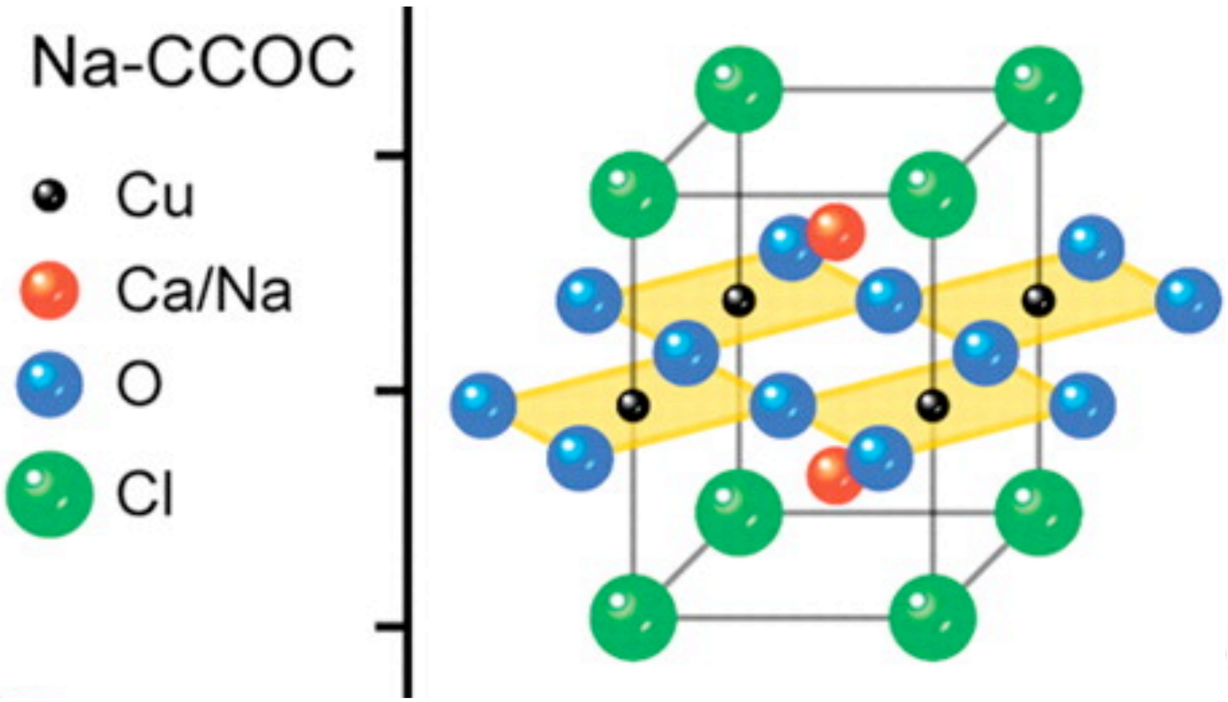
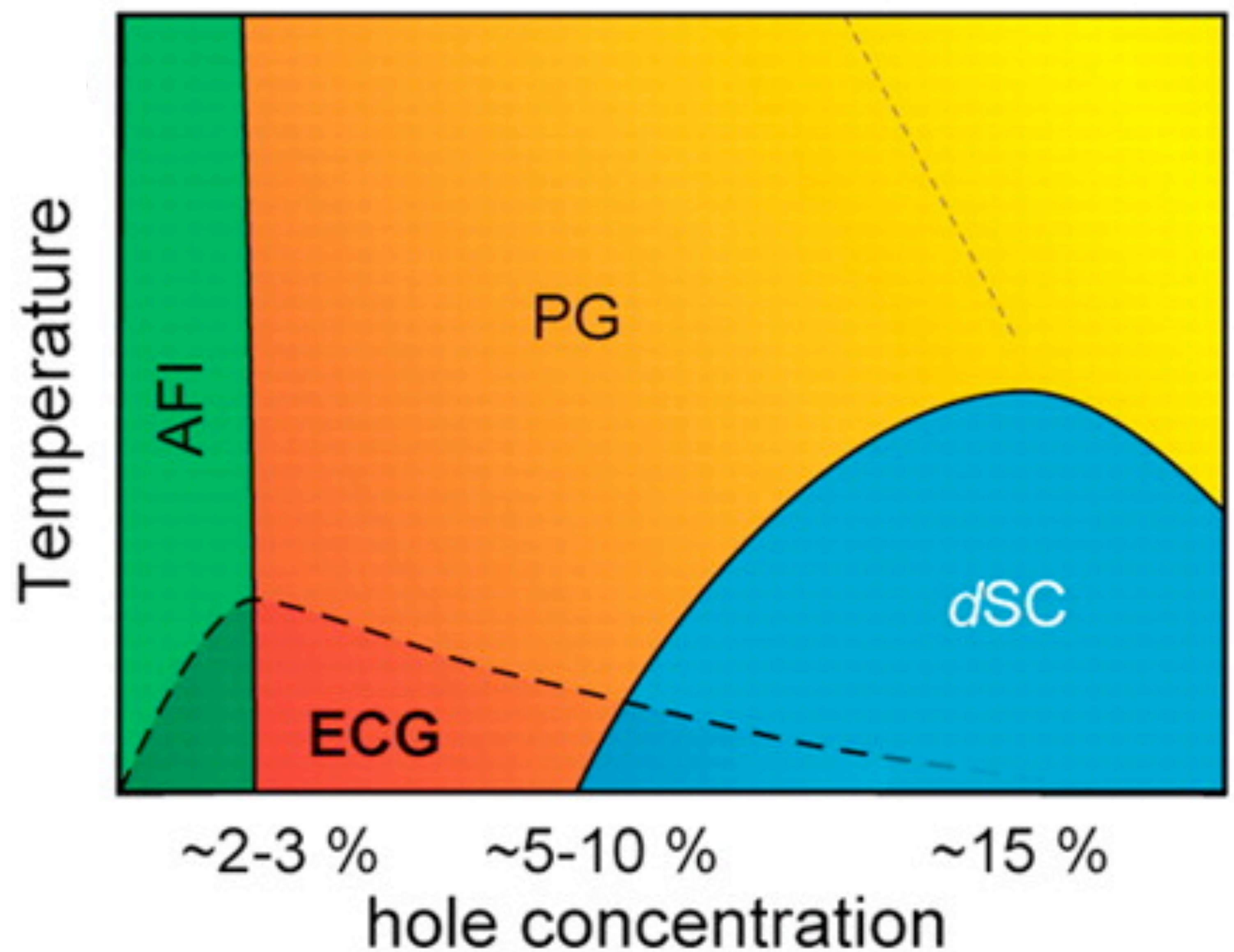
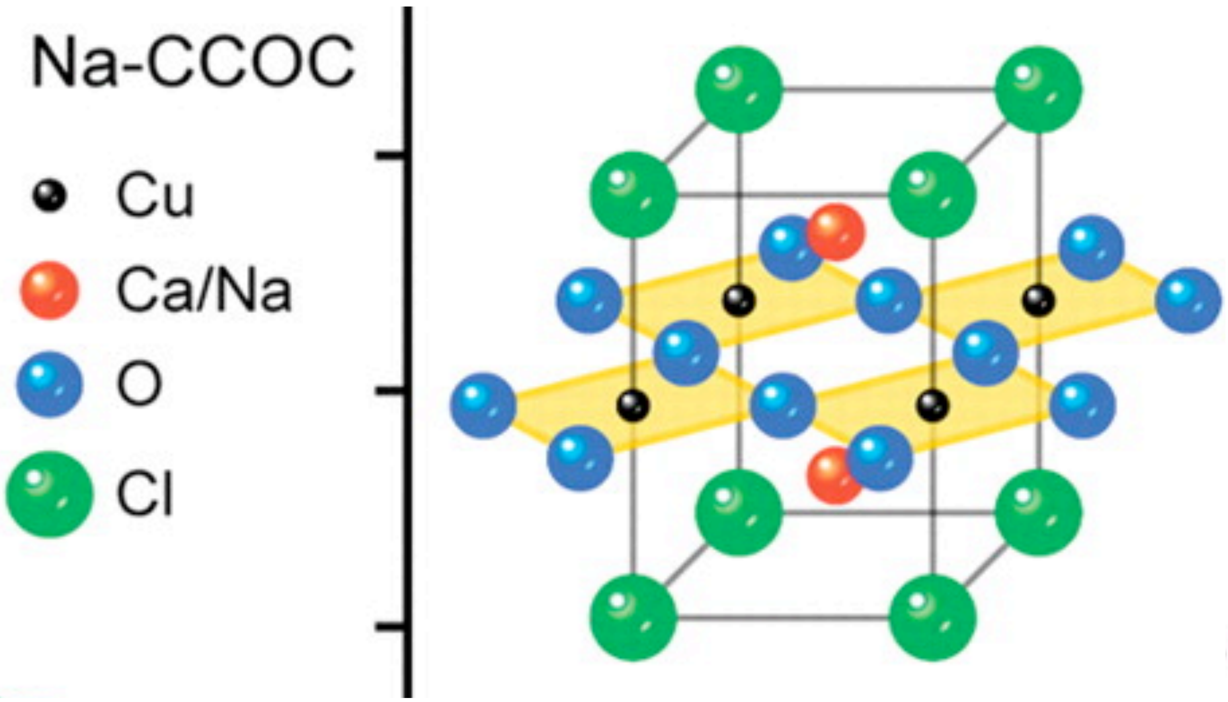
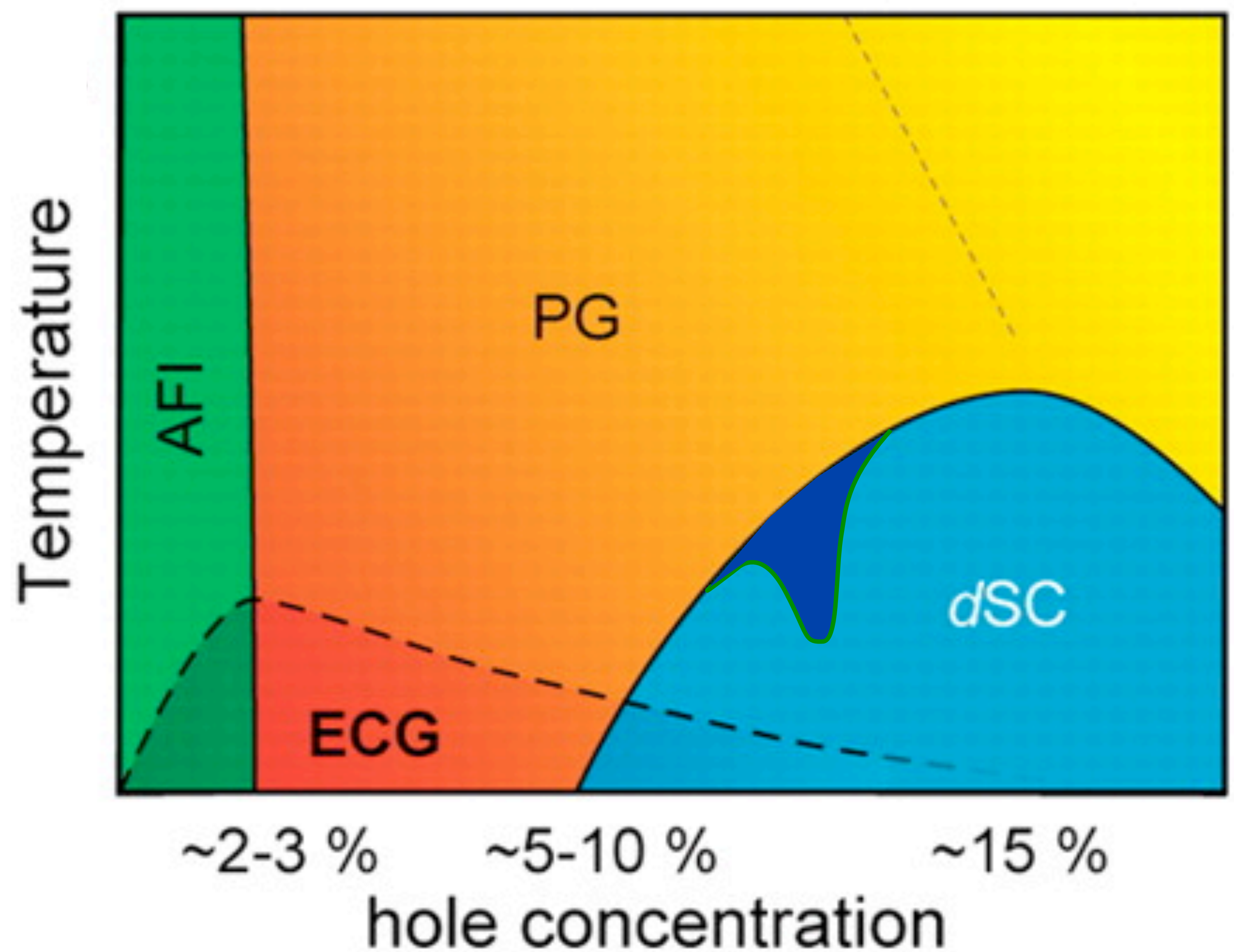
The cuprate superconductors





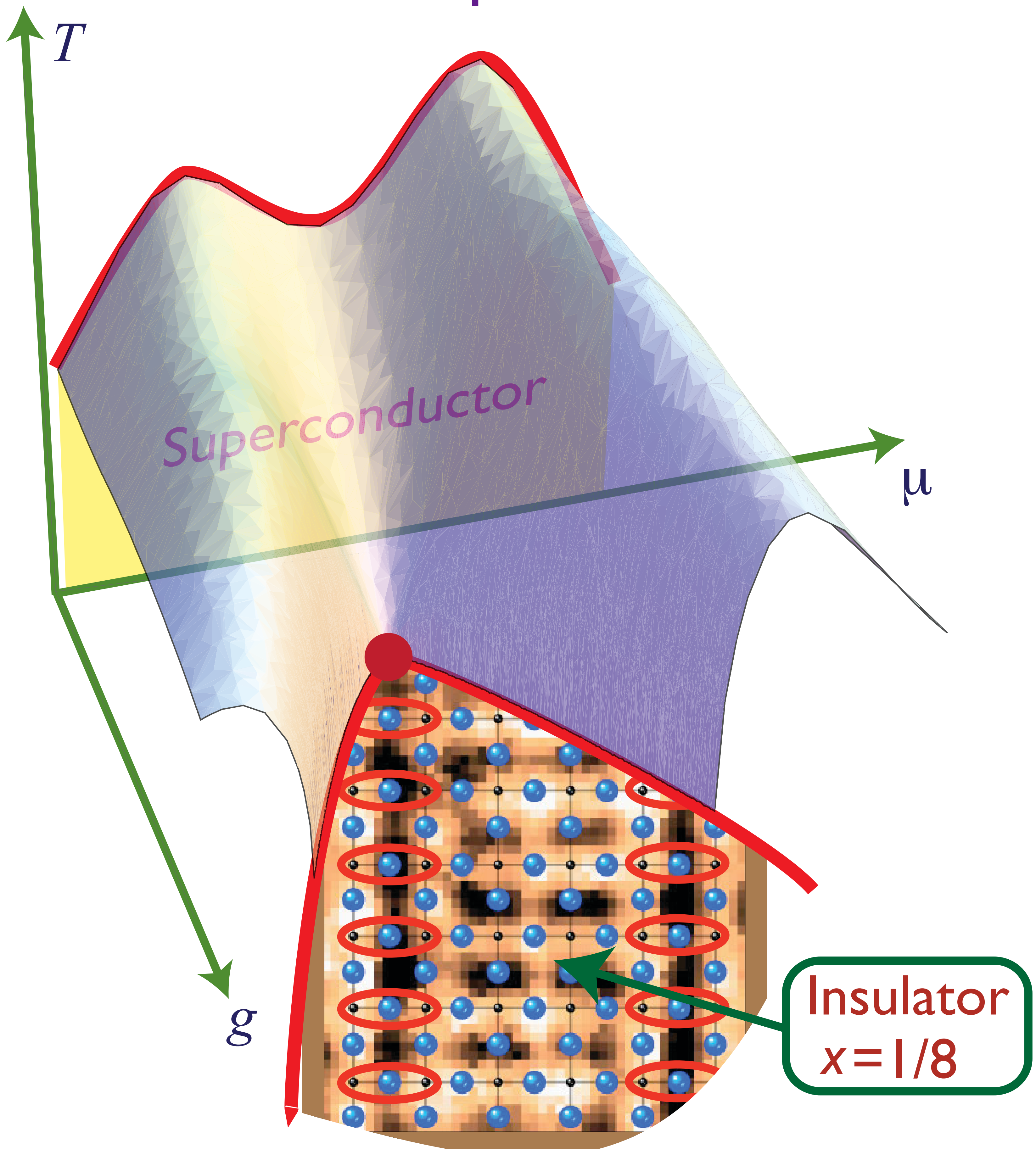
The cuprate superconductors



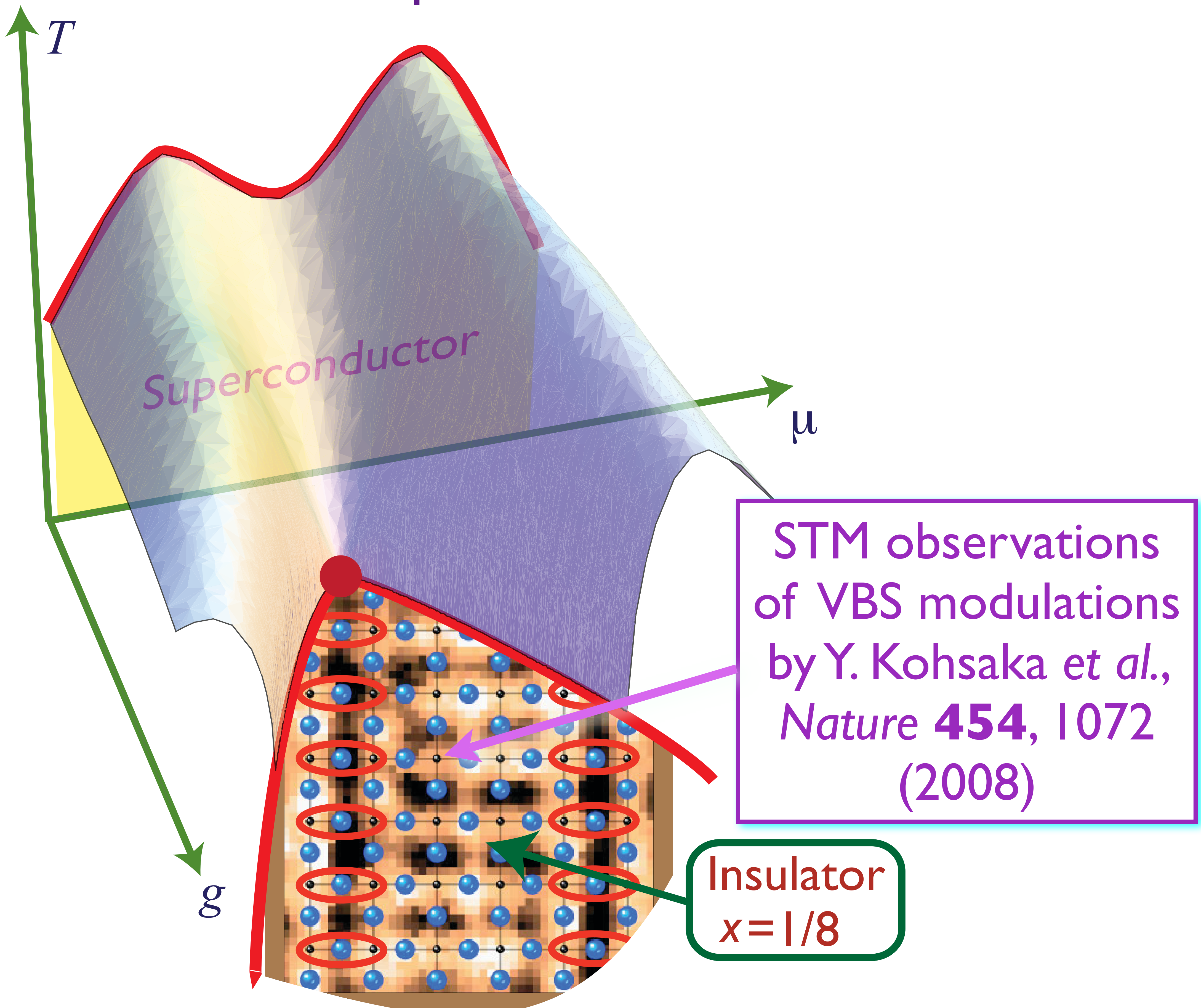


Proximity to an insulator at 12.5% hole concentration

Cuprates

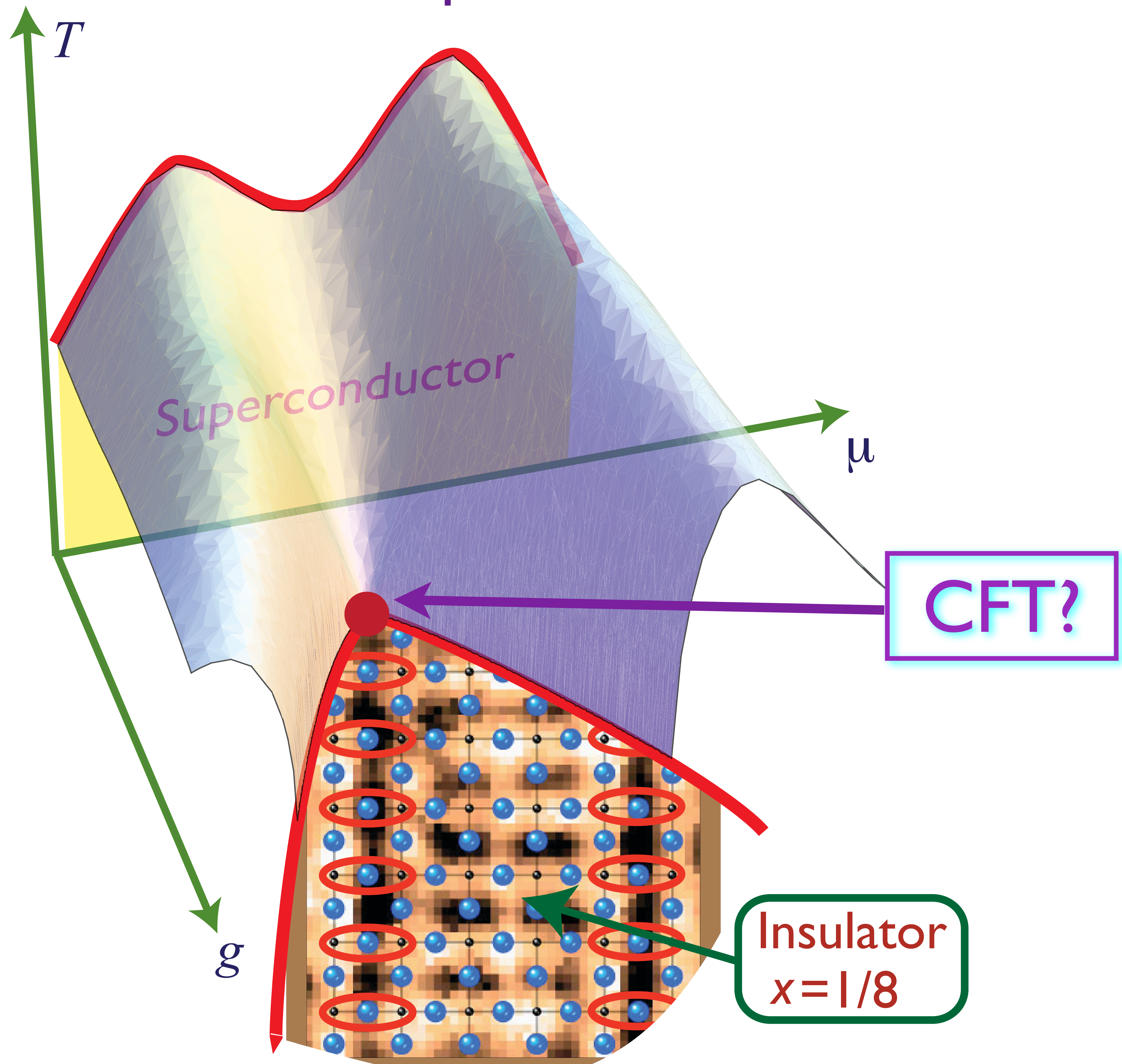


Cuprates

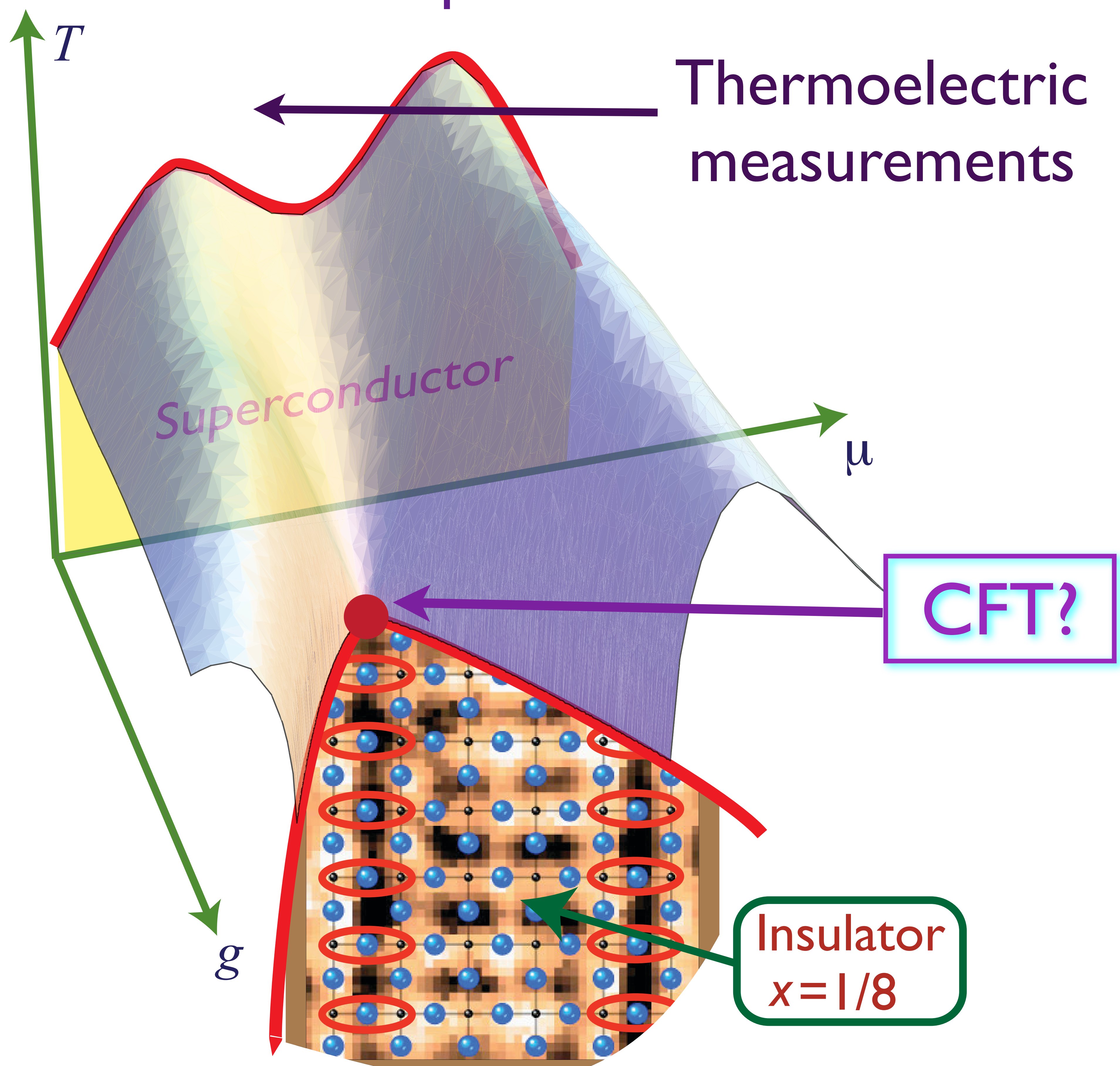


T
Superconductor
μ
g
STM observations of VBS modulations by Y. Kohsaka *et al.*, *Nature* **454**, 1072 (2008)
Insulator
x=1/8

Cuprates

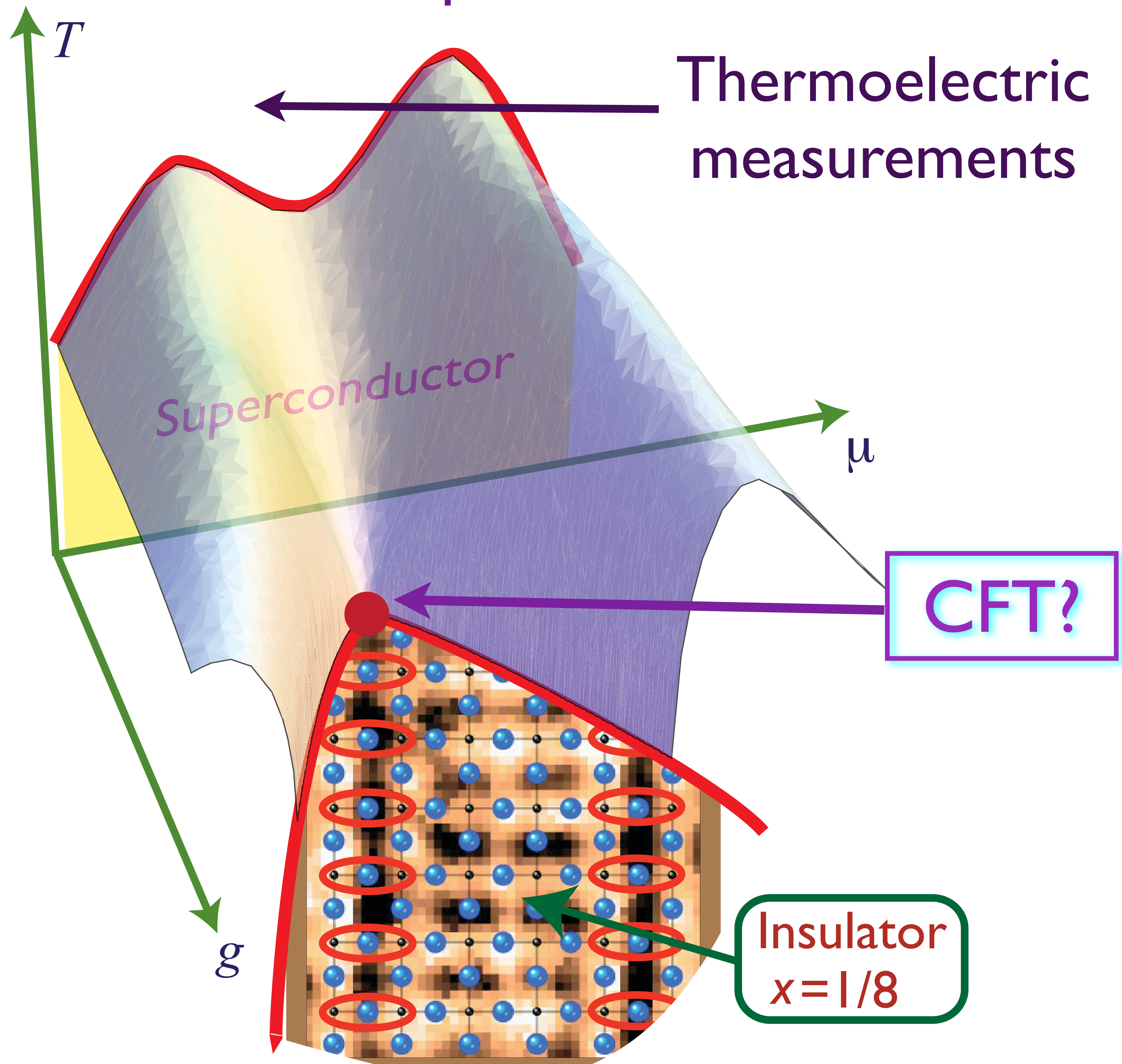


Cuprates



T
Thermoelectric measurements
Superconductor
μ
CFT?
g
Insulator
x=1/8

Cuprates


T
Thermoelectric measurements
Superconductor
μ
CFT?
g
Insulator
x=1/8

Hydrodynamic cyclotron resonance at a frequency

$$\omega_c = \frac{e^* B \rho v^2}{c(\varepsilon + P)}$$

and with width

$$\gamma = \sigma_Q \frac{B^2 v^2}{c^2(\varepsilon + P)}$$

where B = magnetic field, ρ = charge density away from density of CFT, ε = energy density, P = pressure, v = velocity of "light" in CFT, and $\sigma_Q e^2/h$ is the universal conductivity of the CFT.

S.A. Hartnoll, P.K. Kovtun, M. Müller, and S. Sachdev, *Phys. Rev.* B **76** 144502 (2007)

"Wiedemann-Franz"-like relation for thermal conductivity, κ at $B = 0$

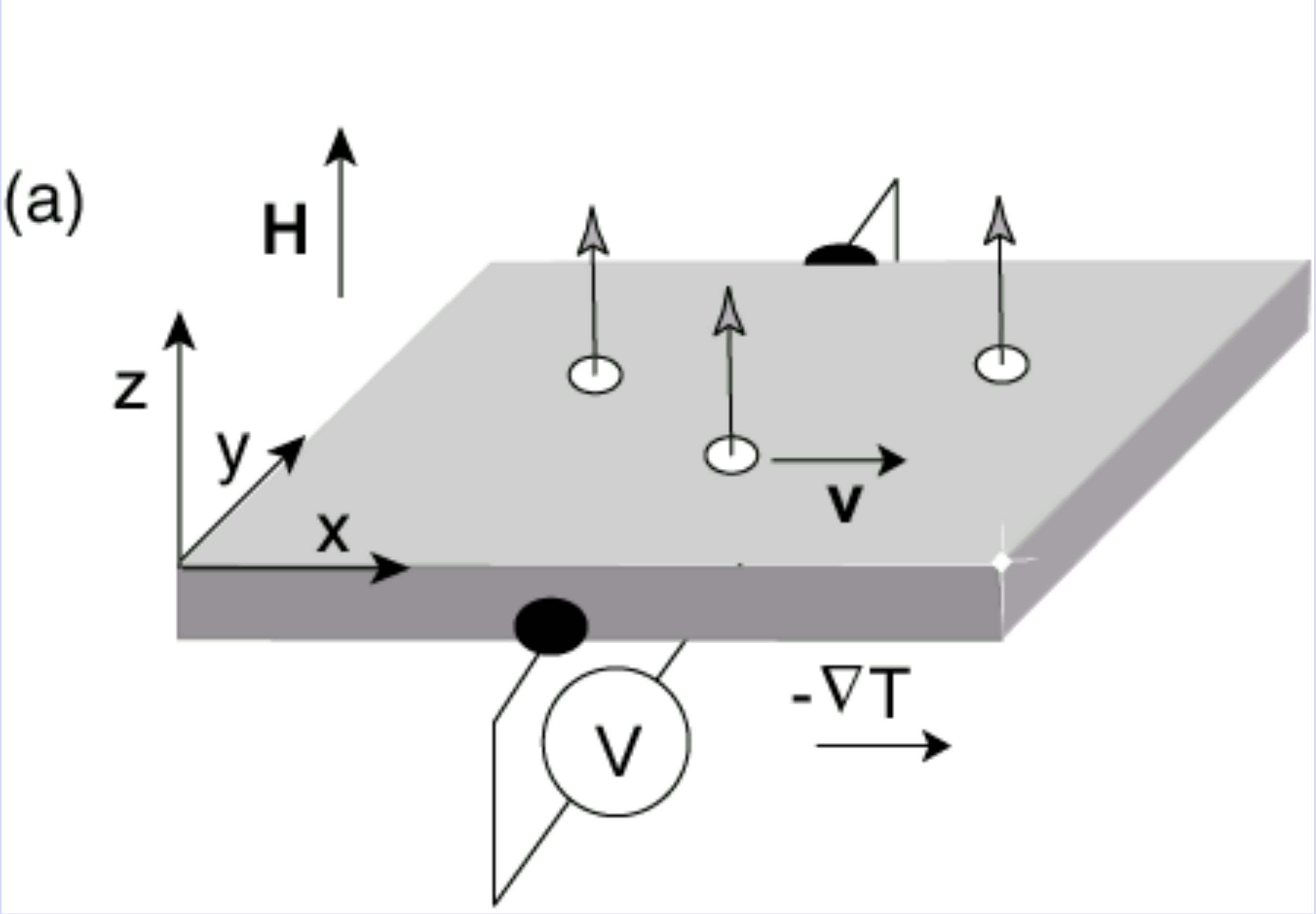
$$\kappa = \sigma_Q \left(\frac{k_B^2 T}{e^{*2}} \right) \left(\frac{\varepsilon + P}{k_B T \rho} \right)^2 .$$

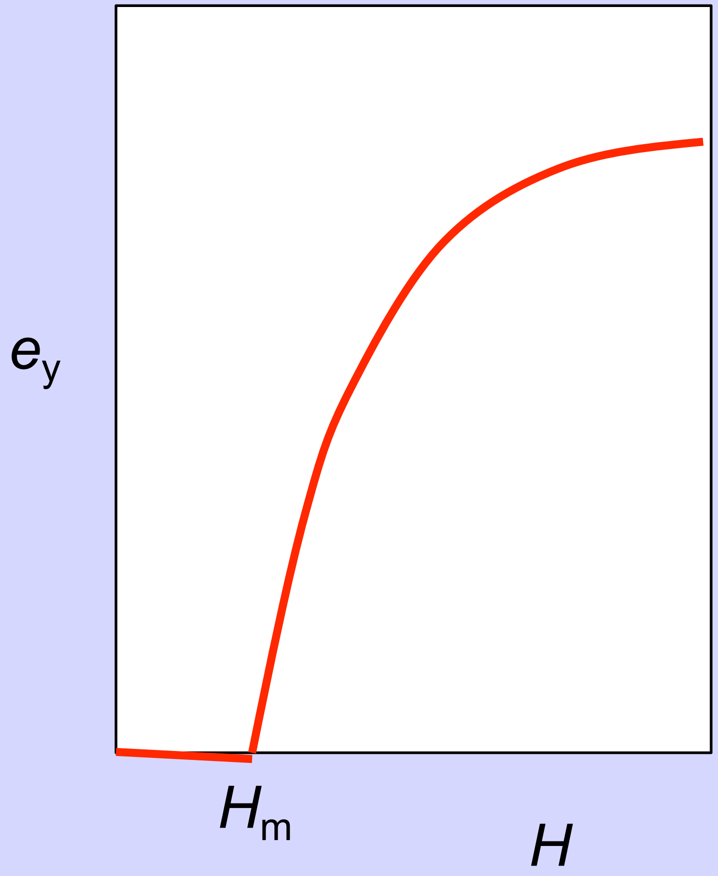
At $B \neq 0$ and $\rho = 0$ we have a "Wiedemann-Franz" relation for "vortices"

$$\kappa = \frac{1}{\sigma_Q} k_B^2 T \left(\frac{v(\varepsilon + P)}{k_B T B} \right)^2 .$$

S.A. Hartnoll, P.K. Kovtun, M. Müller, and S. Sachdev, *Phys. Rev.* B **76** 144502 (2007)

Nernst experiment





Nernst signal (transverse thermoelectric response)

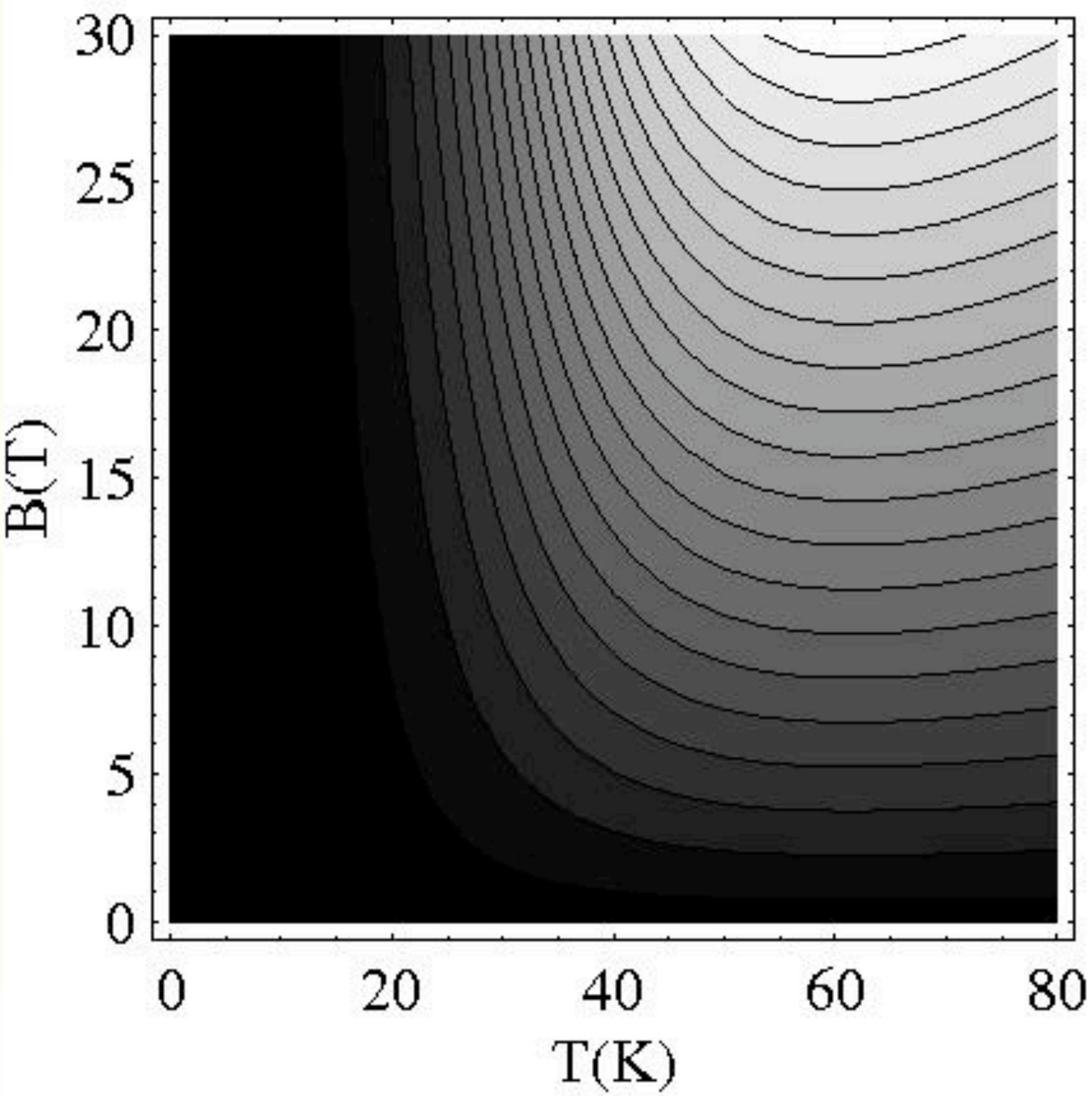
$$e_N = \left(\frac{k_B}{e^*}\right)\left(\frac{\varepsilon + P}{k_B T \rho}\right)\left[\frac{\omega_c/\tau_{\rm imp}}{(\omega_c^2/\gamma + 1/\tau_{\rm imp})^2 + \omega_c^2}\right]$$

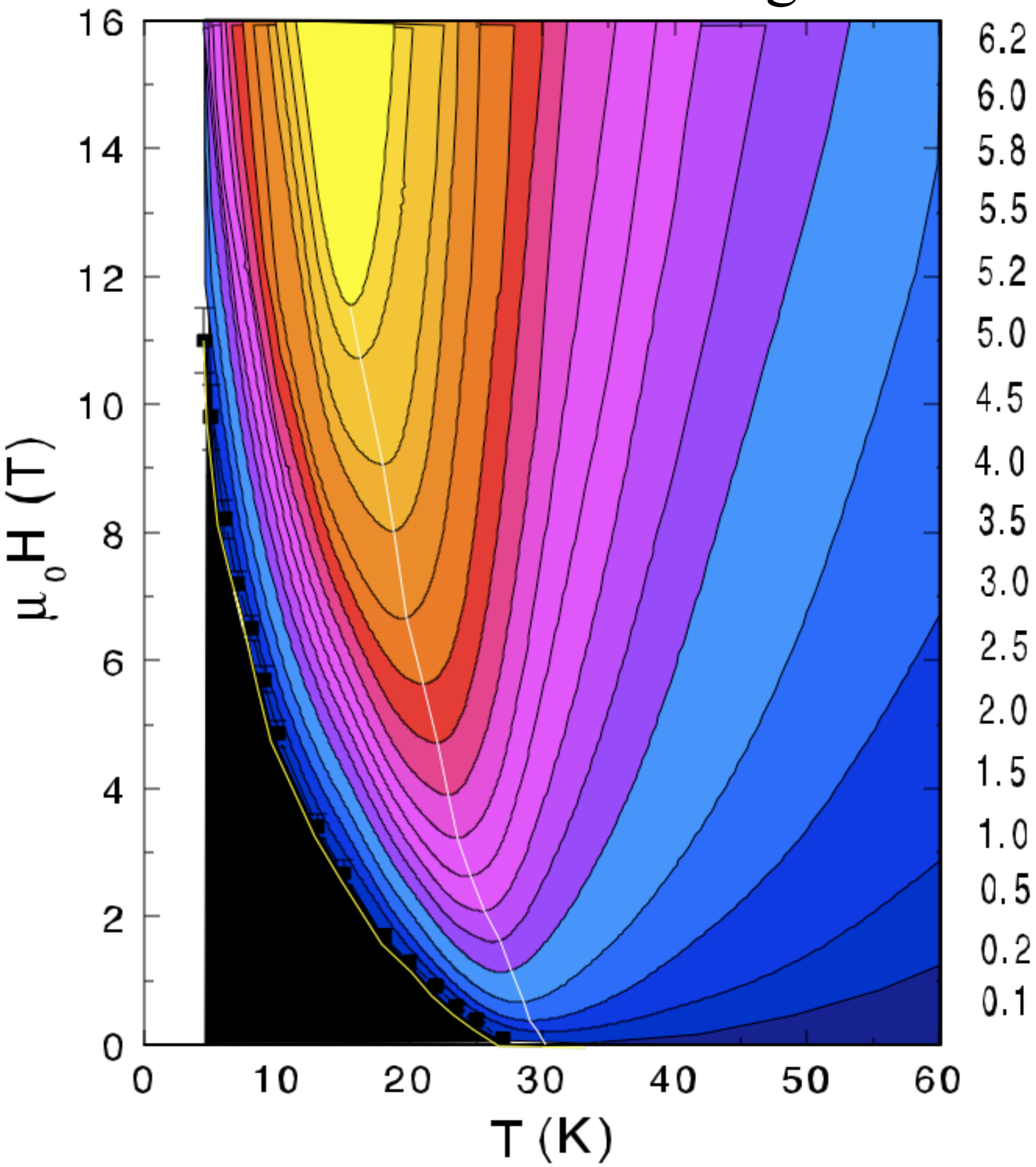
where $\tau_{\rm imp}$ is the momentum relaxation time due to impurities or umklapp scattering.

S.A. Hartnoll, P.K. Kovtun, M. Müller, and S. Sachdev, *Phys. Rev.* B **76** 144502 (2007)

LSCO Experiments

Theory for N





Y. Wang, L. Li, and N. P. Ong, *Phys. Rev.* B **73**, 024510 (2006).
S.A. Hartnoll, P.K. Kovtun, M. Müller, and S. Sachdev, *Phys. Rev.* B **76** 144502 (2007)

B and T dependencies are in semi-quantitative agreement with observations on cuprates, with reasonable values for only 2 adjustable parameters, $\tau_{\rm imp}$ and v.

B and T dependencies are in semi-quantitative agreement with observations on cuprates, with reasonable values for only 2 adjustable parameters, τ_{imp} and v.

Similar results apply to electronic transport in graphene, where the the relativistic Dirac spectrum of the electrons leads to analogies with the hydrodynamics of CFTs. We have made specific quantitative predictions for THz experiments on graphene at room temperature in the presence of a modest applied magnetic field.

Applications:

1. Magneto-thermo-electric transport near the superconductor-insulator transition and in graphene
   Hydrodynamic cyclotron resonance
   Nernst effect

2. Quark-gluon plasma
   Low viscosity fluid

3. Fermi gas at unitarity
   Non-relativistic AdS/CFT

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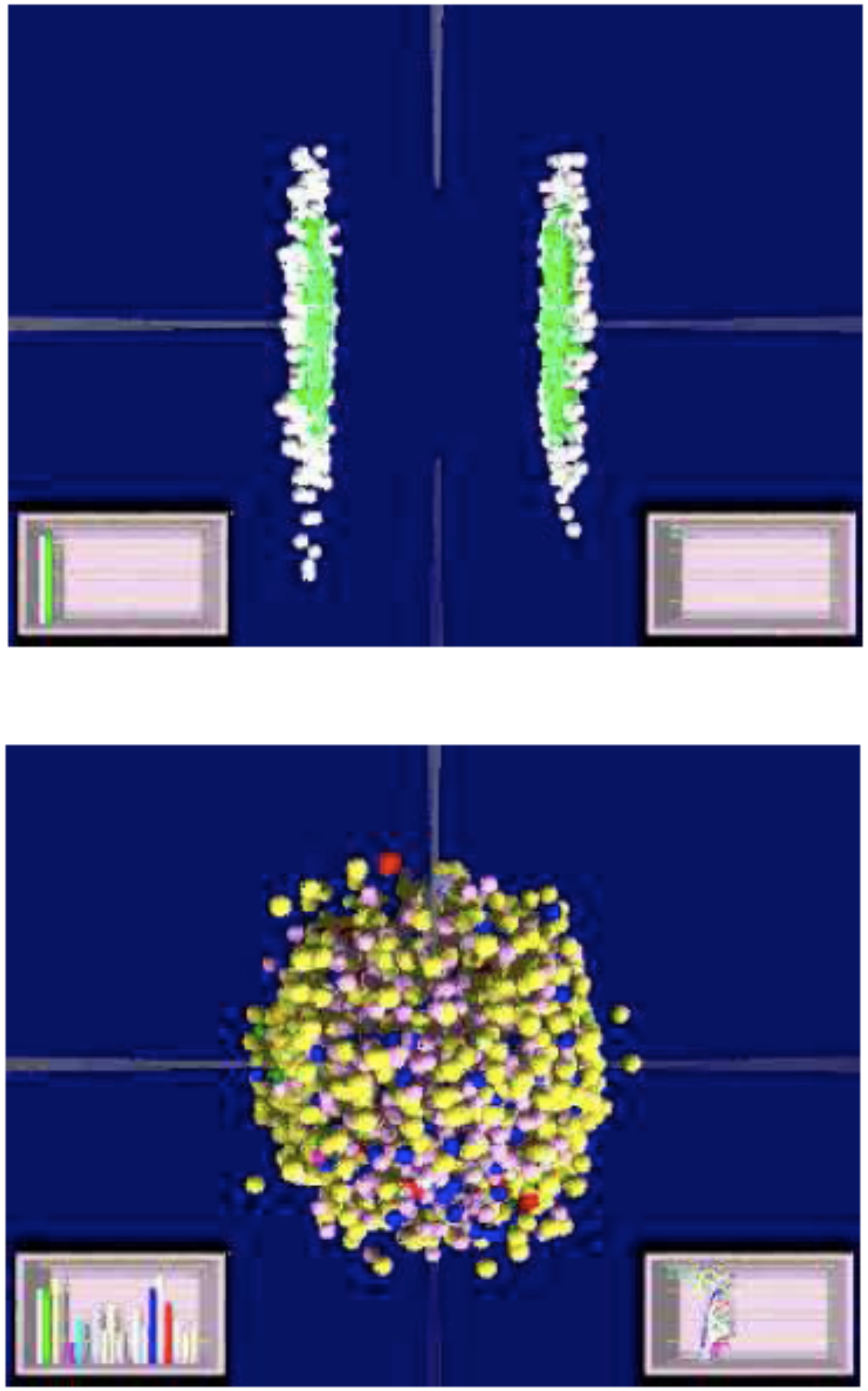
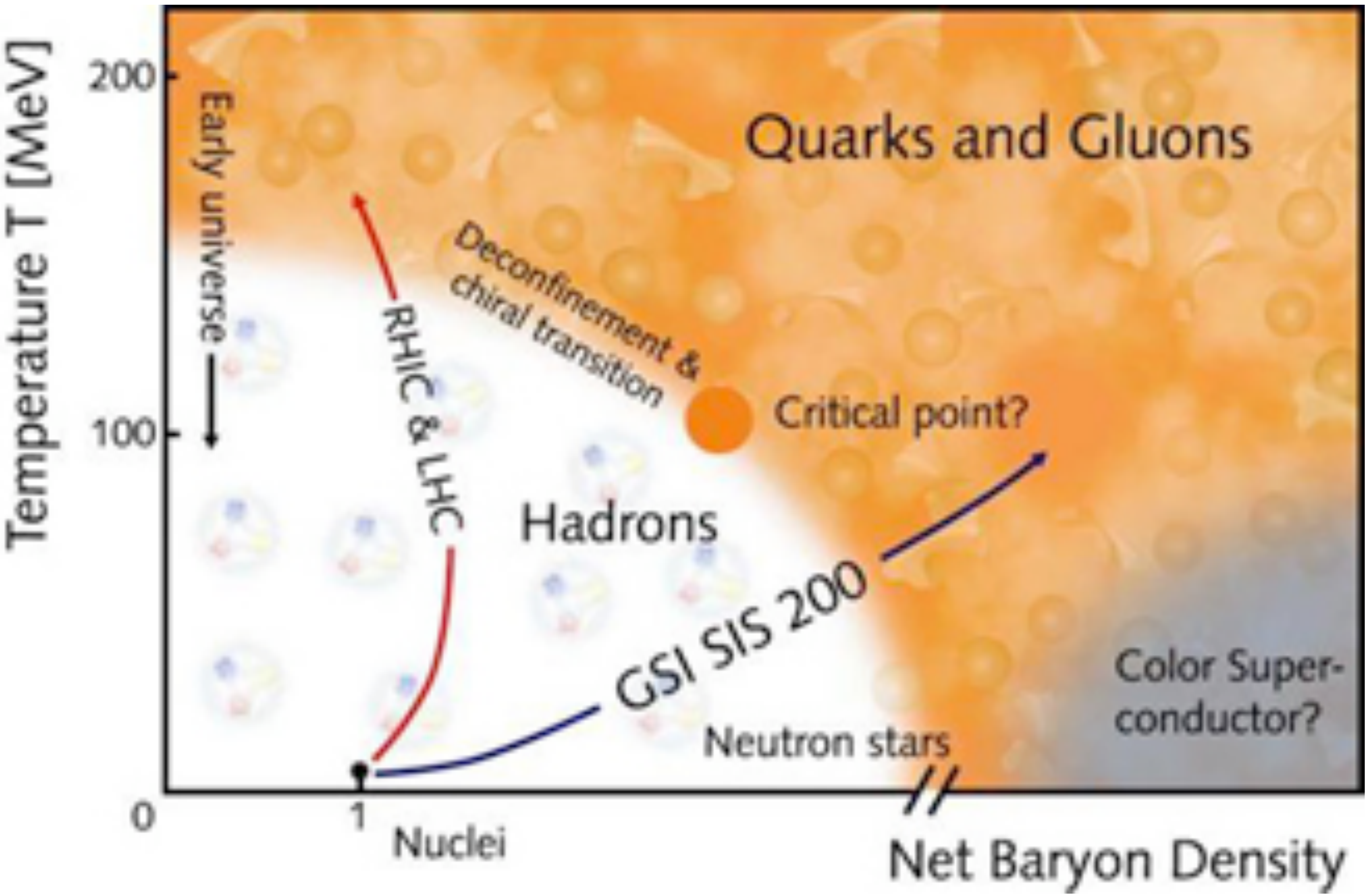
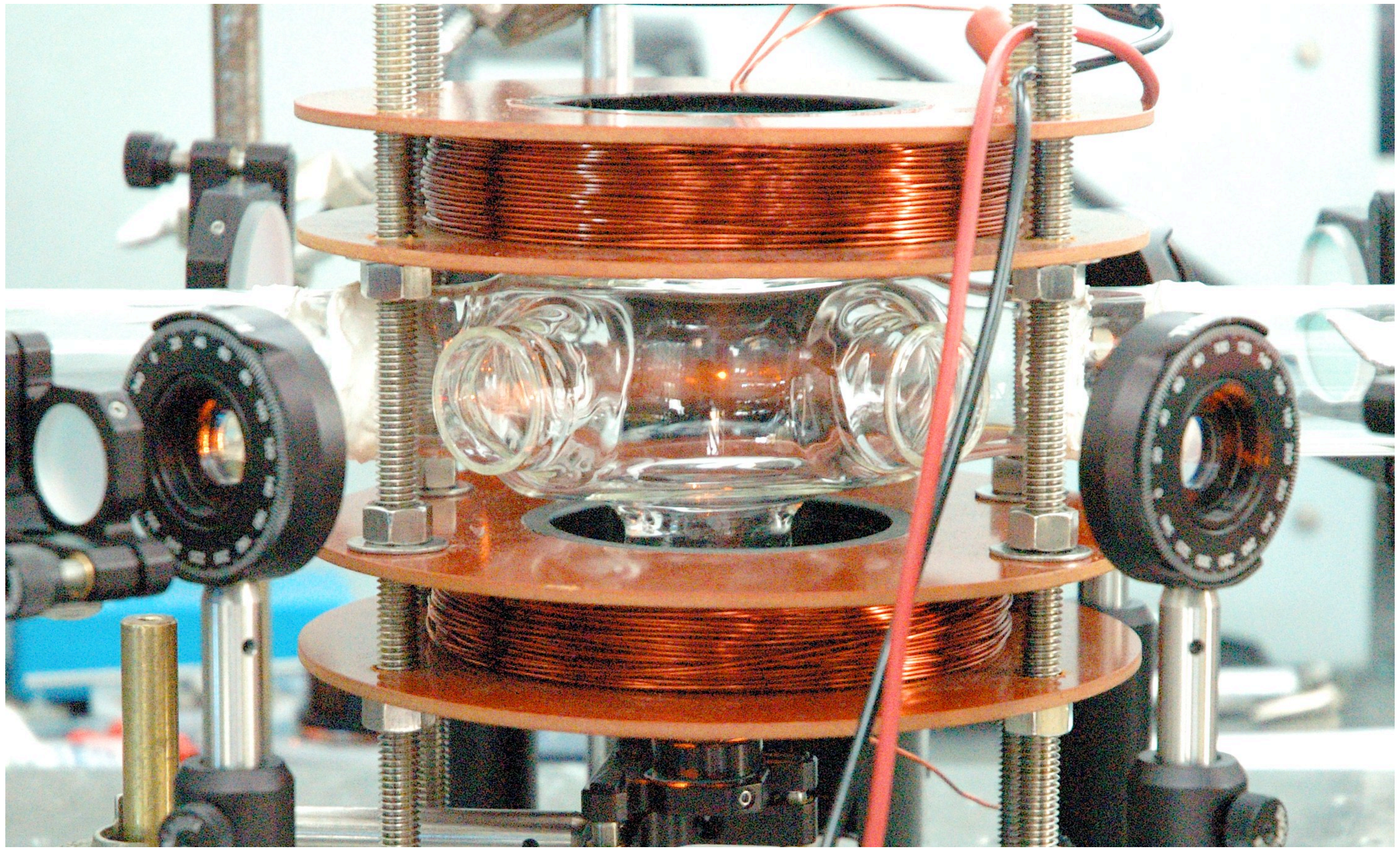
Au+Au collisions at RHIC



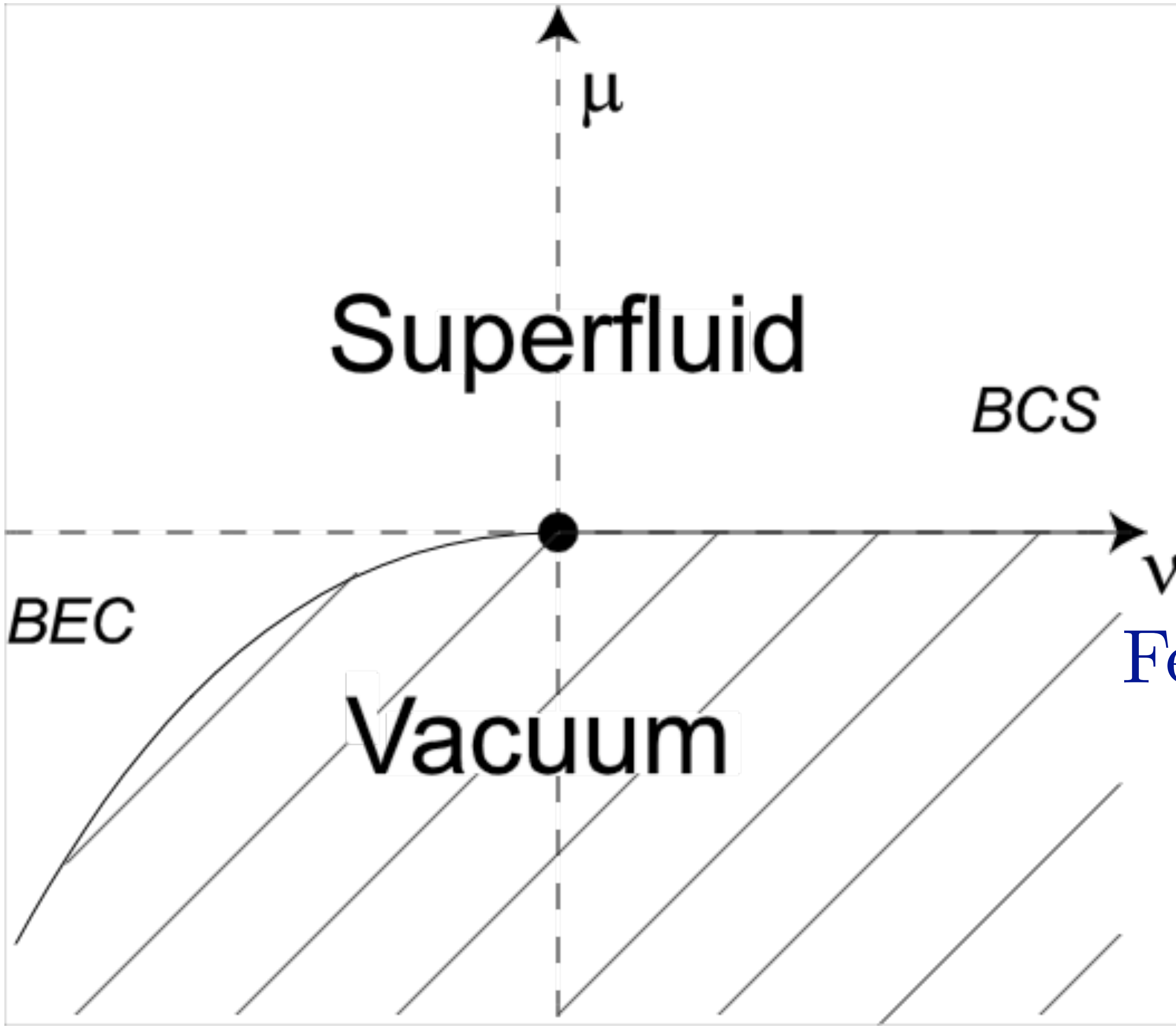
Quark-gluon plasma can be described as "quantum critical QCD"

Phases of nuclear matter

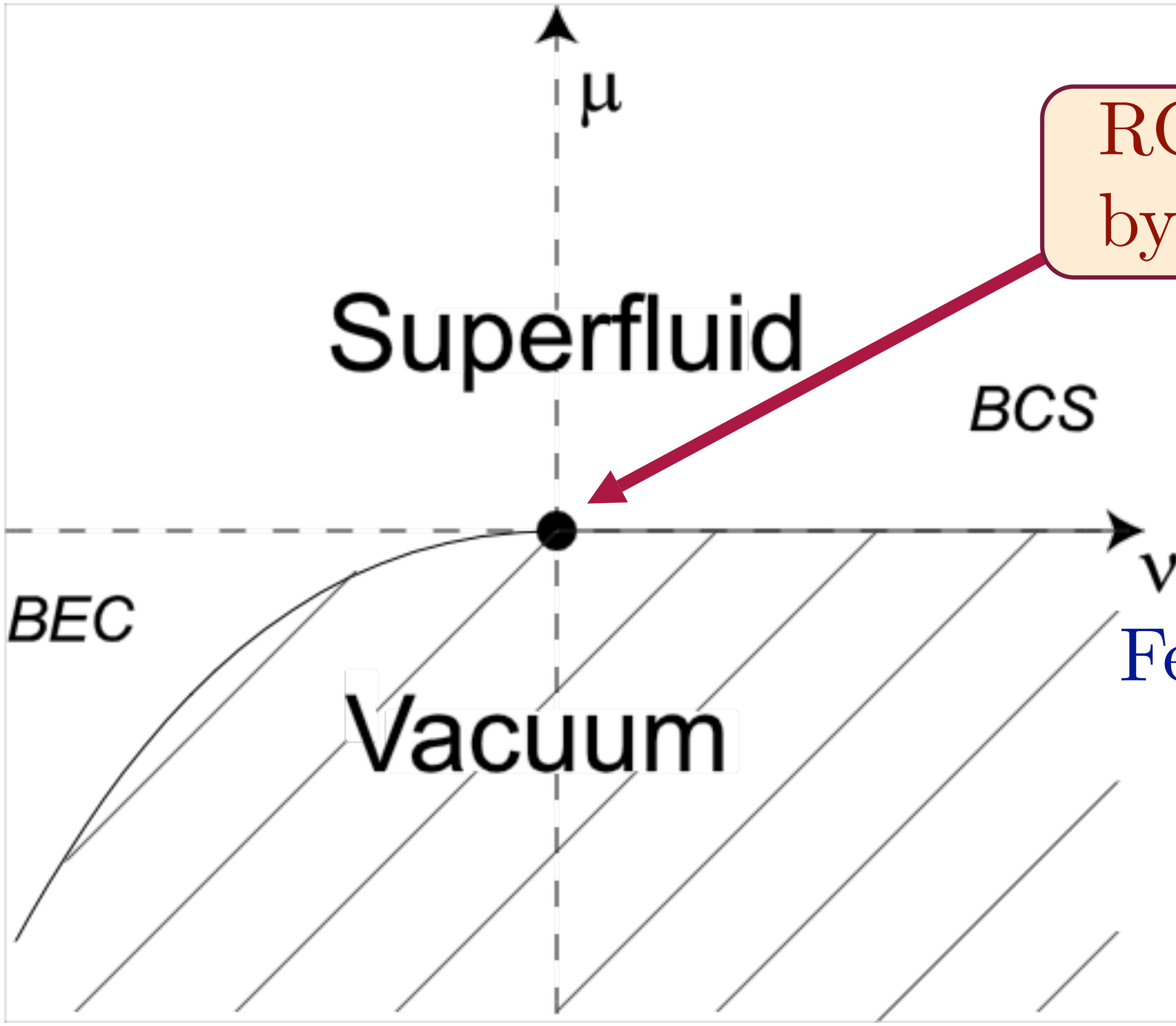




S=1/2 Fermi gas at a Feshbach resonance

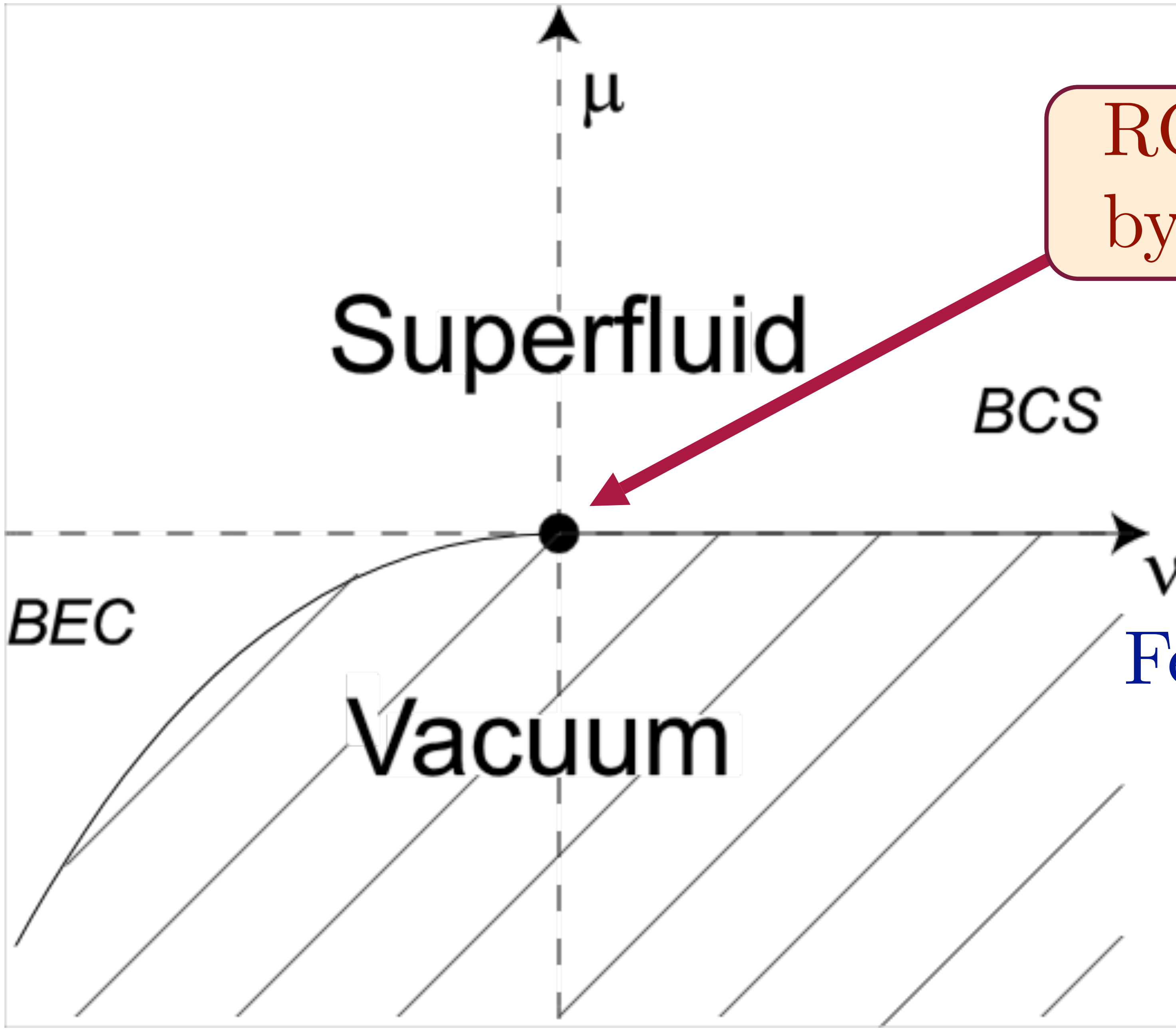


$= $ detuning from Feshbach resonance



RG fixed point described by a "non-relativistic" CFT

= detuning from Feshbach resonance



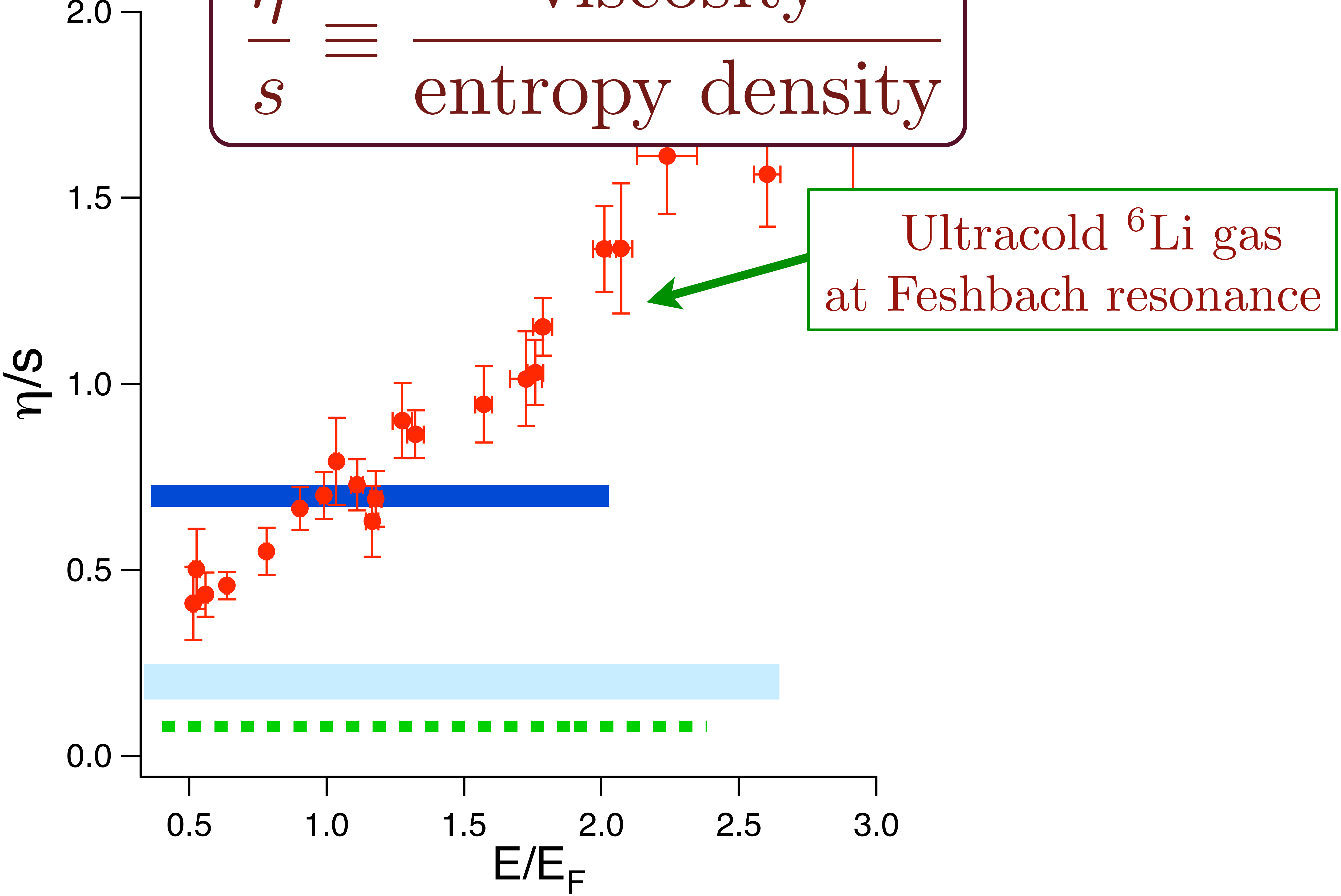
RG fixed point described by a "non-relativistic" CFT

ν = detuning from Feshbach resonance

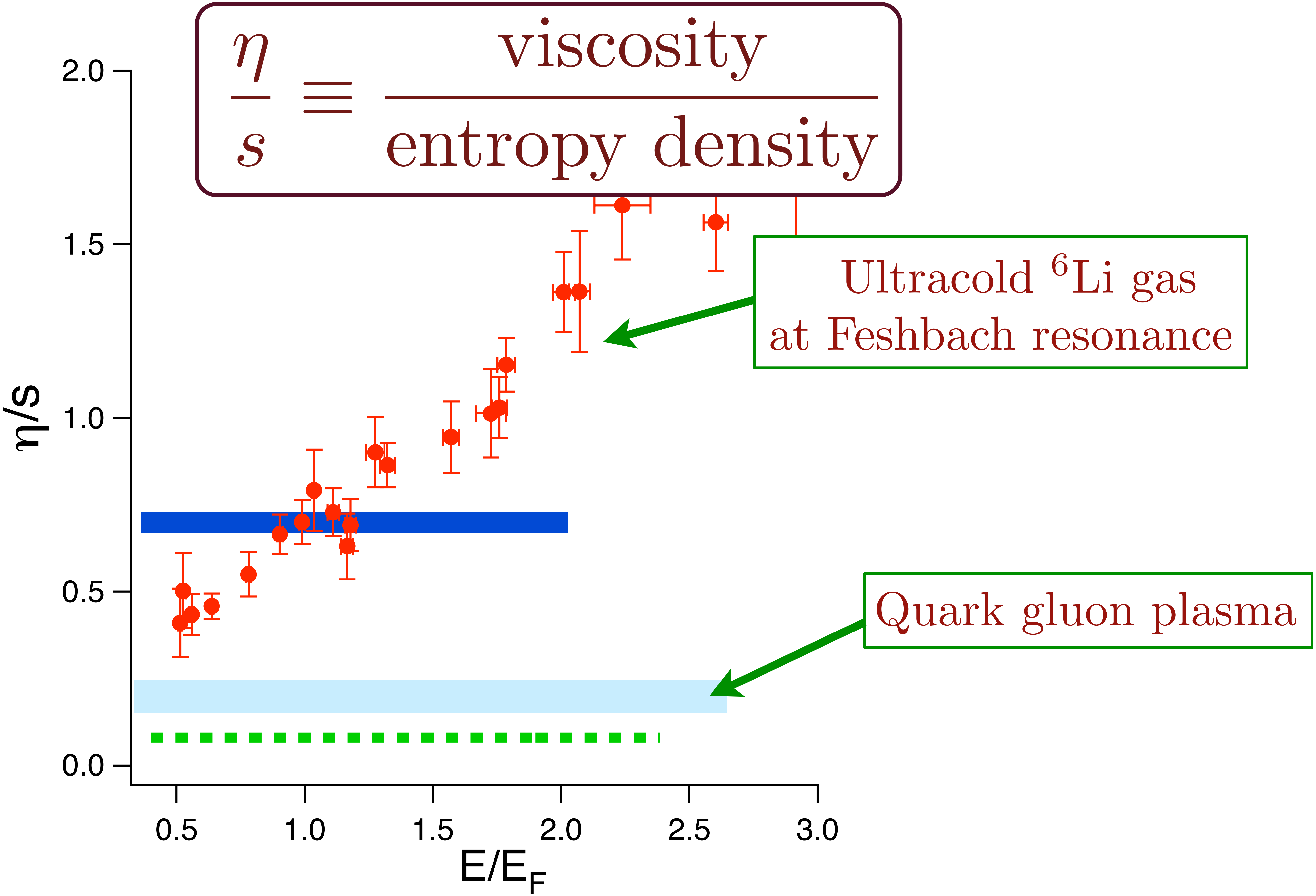
CFT is dual to quantum gravity models on AdS space. Explicit solutions of such gravity models with supersymmetry have been obtained

P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007); D. T. Son, arXiv:0804.3972; K. Balasubramaniam and J. McGreevy, arXiv:0804.4053; W. D. Goldberger, arXiv:0806.2867; J. L. F. Barbón and C. A. Fuertes, arXiv:0806.3244; J. Maldacena, D. Martelli, and Y. Tachikawa, arXiv:0807.1100; A. Adams, K. Balasubramanian, and J. McGreevy, arXiv:0807.1111.

$$\frac{\eta}{s} \equiv \frac{\text{viscosity}}{\text{entropy density}}$$



T. Schafer, *Phys. Rev. A* **76**, 063618 (2007).
A. Turlapov, J. Kinast, B. Clancy, Le Luo, J. Joseph, J. E. Thomas, *J. Low Temp. Physics* **150**, 567 (2008)



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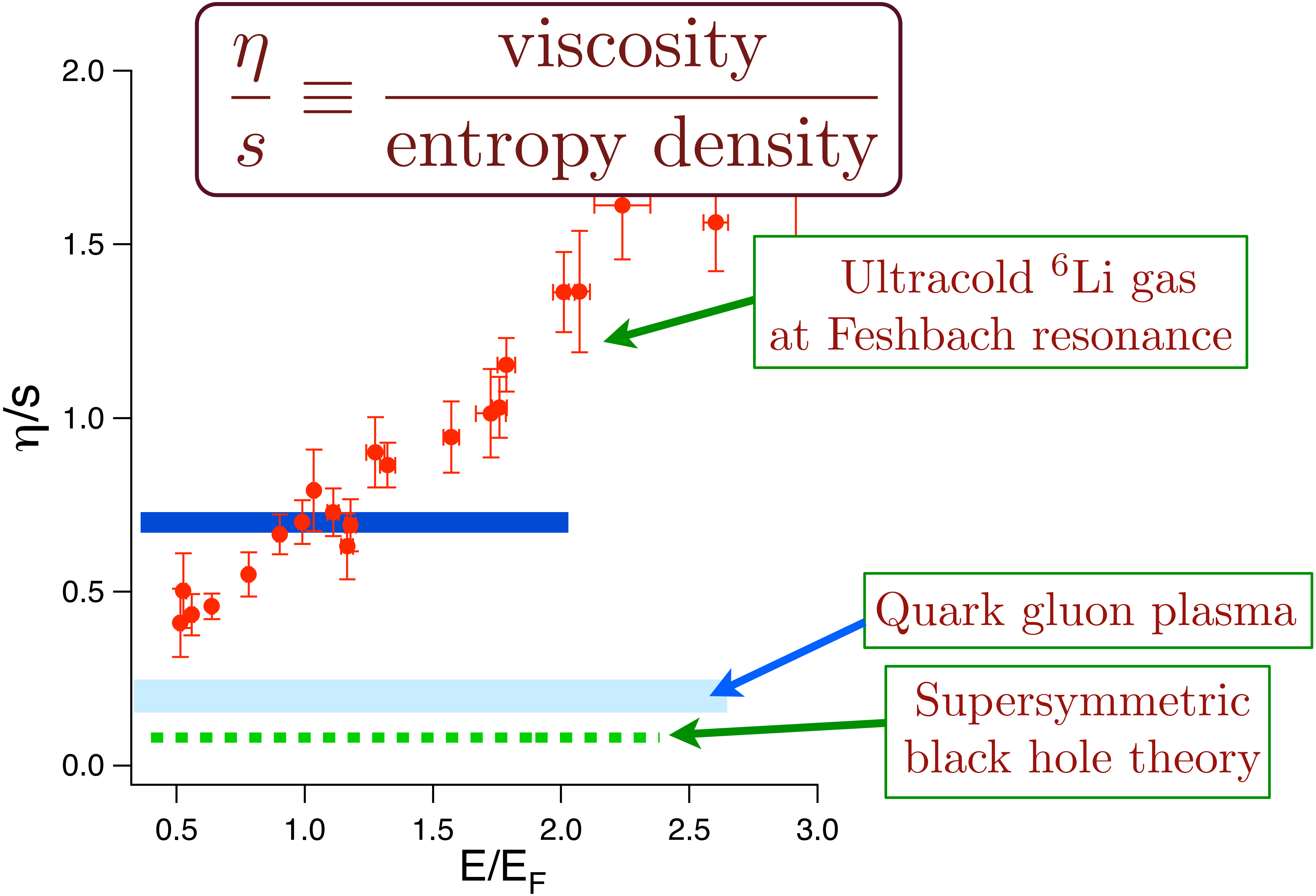

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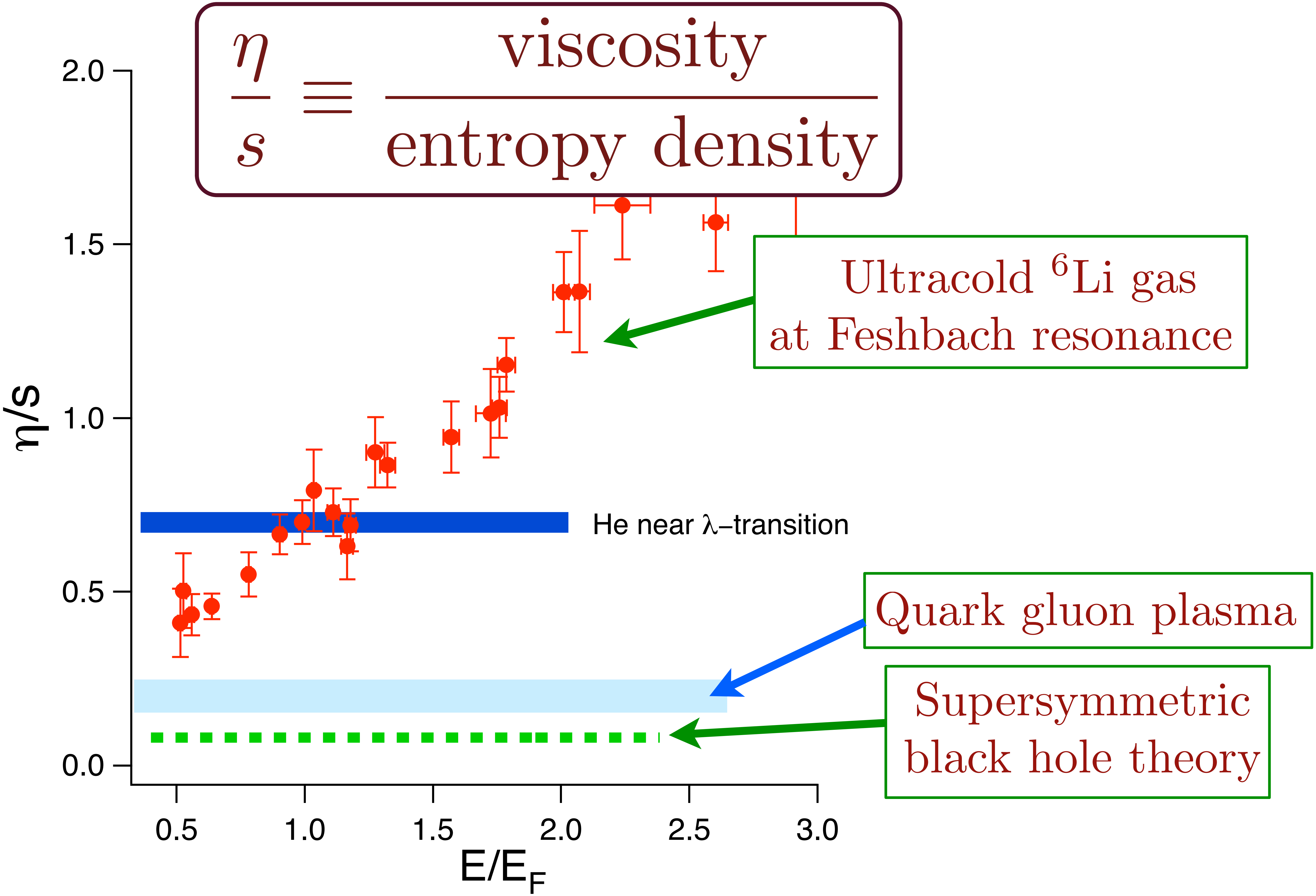

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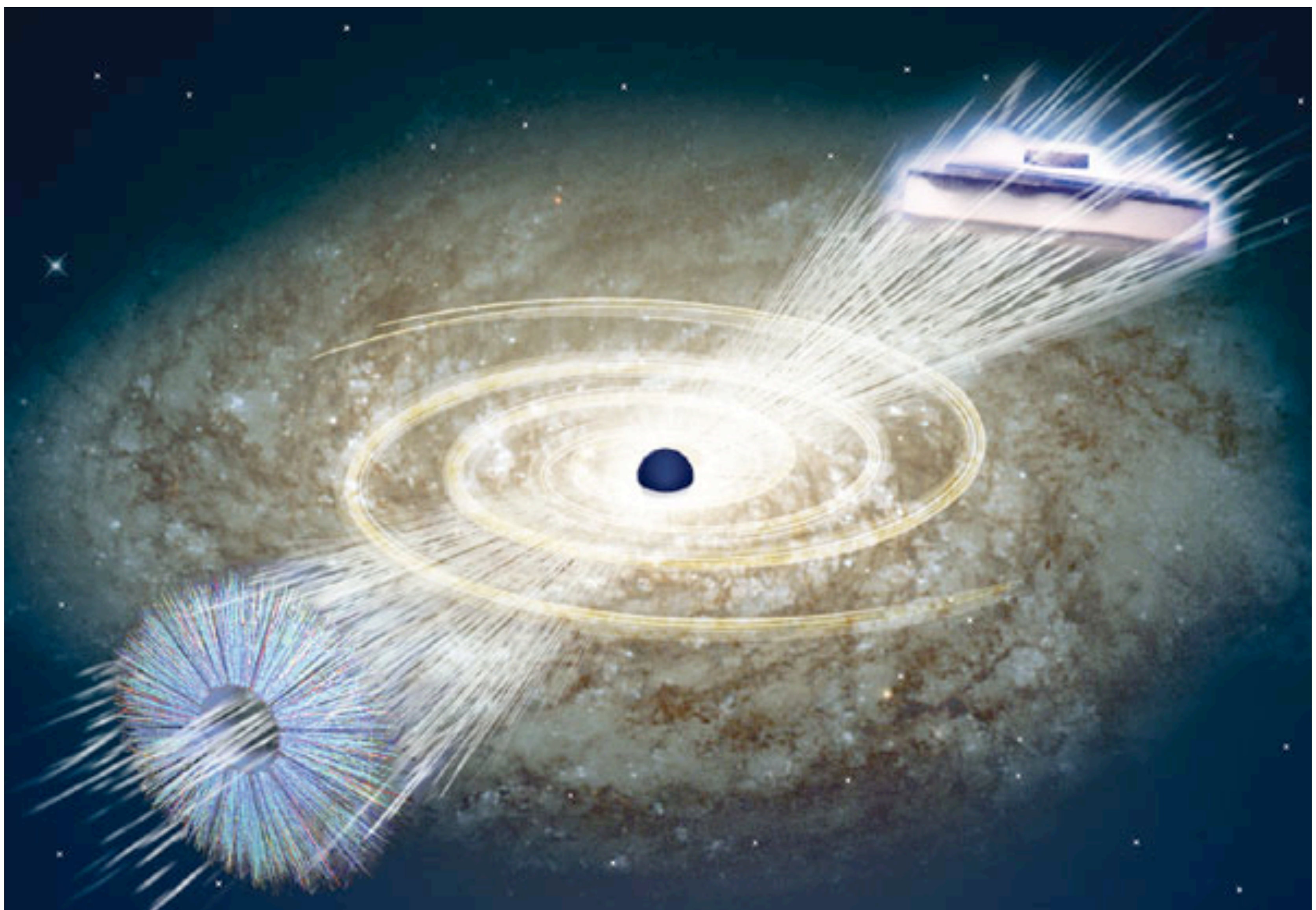
THEORETICAL PHYSICS

A black hole full of answers

Jan Zaanen

A facet of string theory, the currently favoured route to a 'theory of everything', might help to explain some properties of exotic matter phases — such as some peculiarities of high-temperature superconductors.

NATURE|Vol 448|30 August 2007



Conclusions

- Theory for transport near quantum phase transitions in superfluids and antiferromagnets
- Exact solutions via black hole mapping have yielded first exact results for transport co-efficients in interacting many-body systems, and were valuable in determining general structure of hydrodynamics.
- Theory of Nernst effect near the superfluid-insulator transition, and connection to cuprates.
- Quantum-critical magnetotransport in graphene.