Quantum criticality, the cuprate superconductors, and the AdS/CFT correspondence

Niels Bohr lecture, Copenhagen, May 5, 2010

Talk online: sachdev.physics.harvard.edu

PHYSICS

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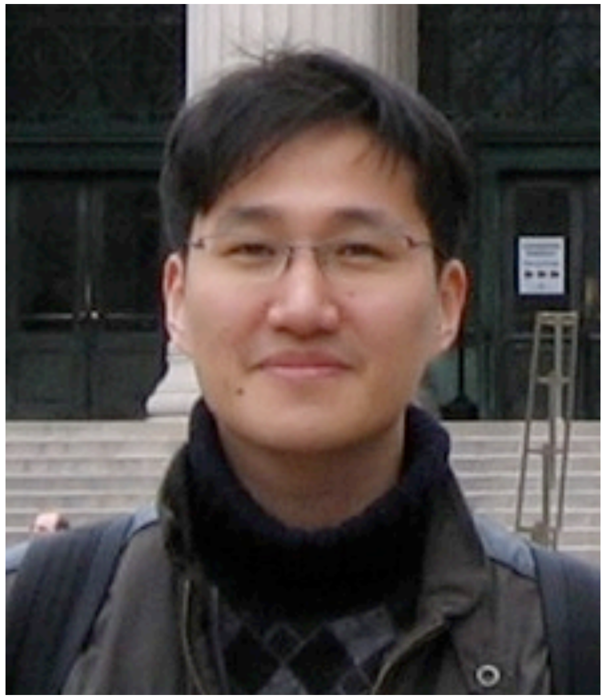

Max Metlitski, Harvard

Eun Gook Moon, Harvard

arXiv:1001.1153

Phys. Rev. B **80**, 035117 (2009)

PHYSICS HARVARD

Outline

1. Coupled dimer antiferromagnets
   Introduction to quantum criticality

2. Theory of Ising-nematic ordering in the cuprate metals
   Strongly-coupled field theory

3. The AdS/CFT correspondence
   Phases of quantum matter at strong coupling

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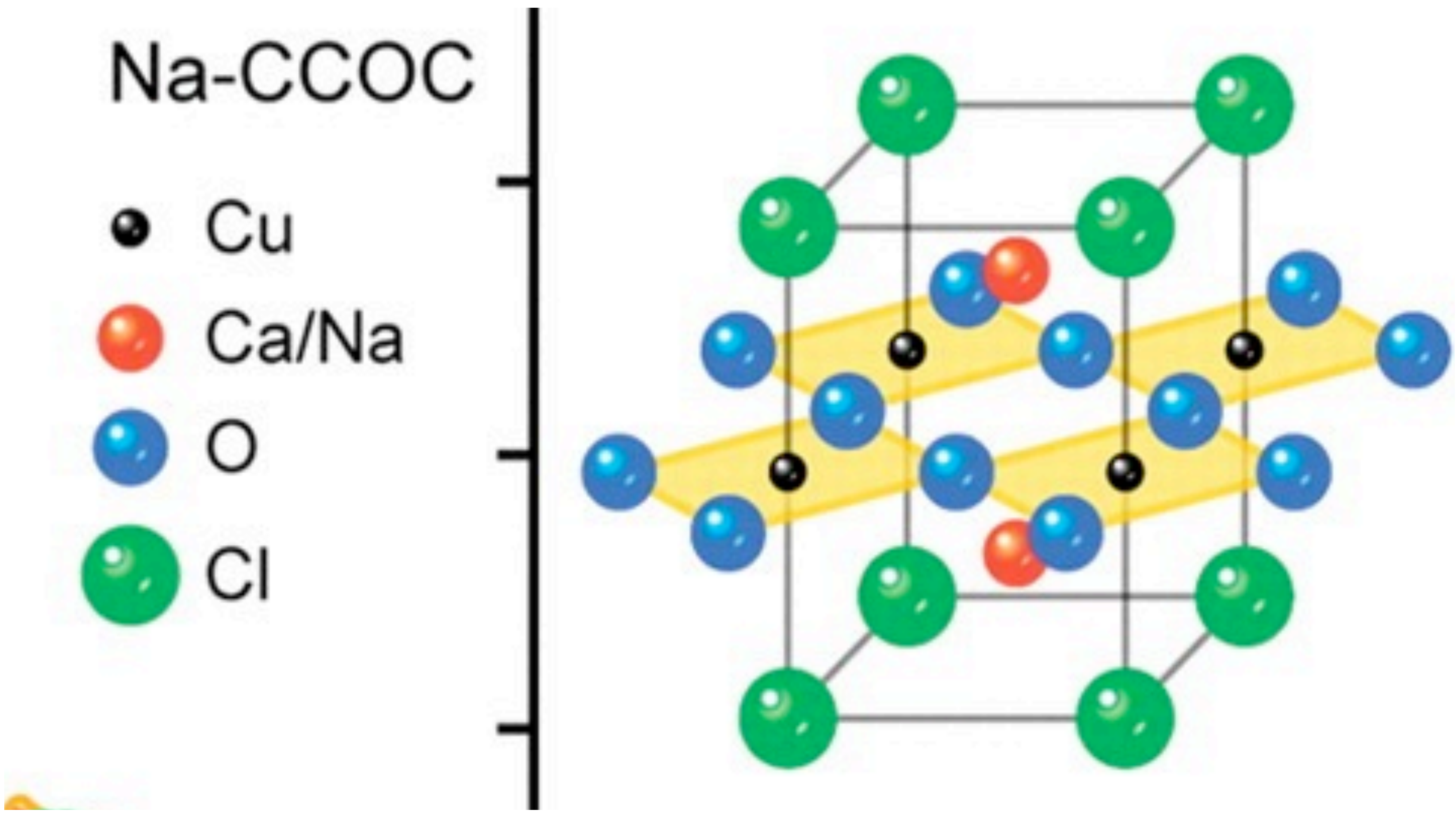
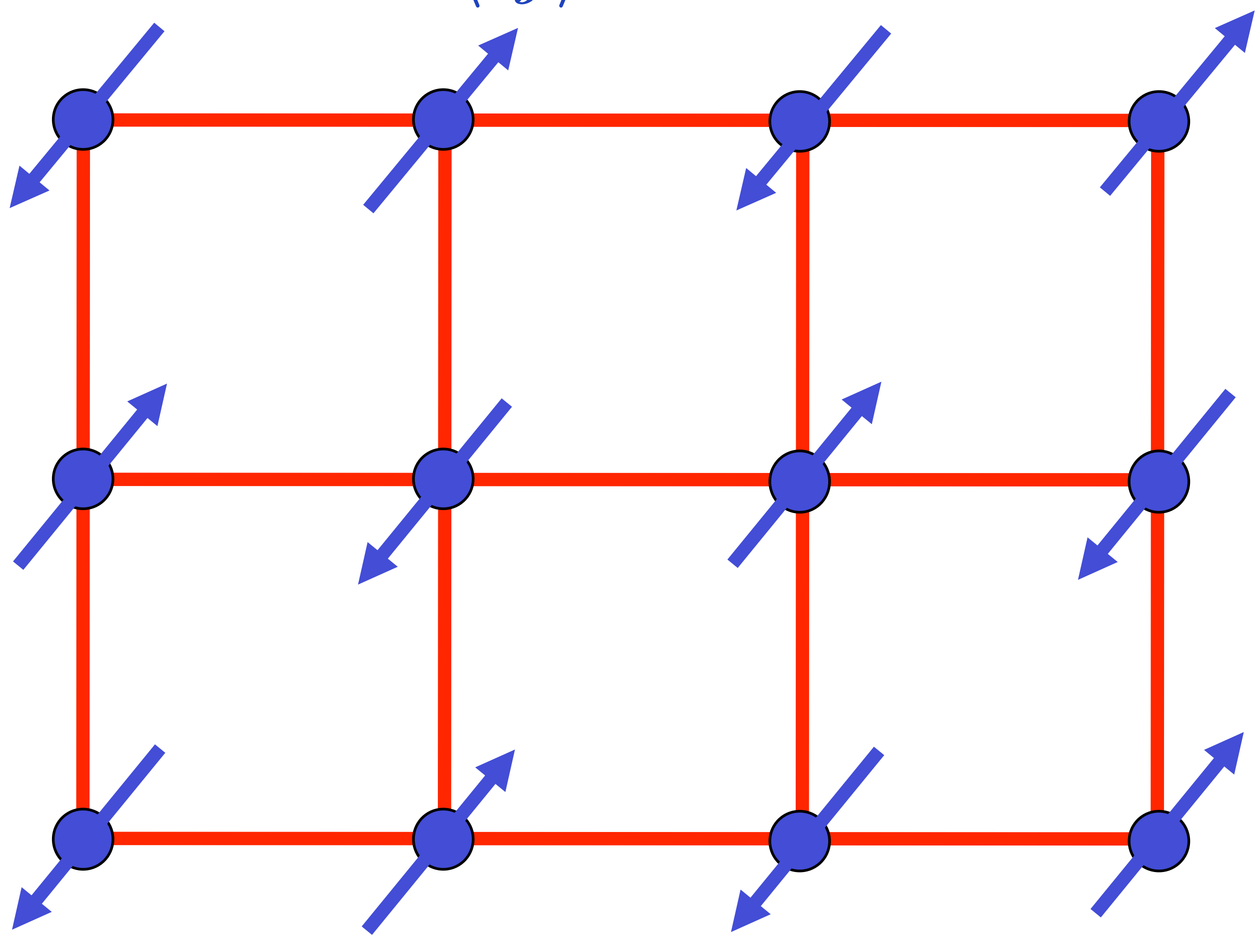
The cuprate superconductors



Square lattice antiferromagnet

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



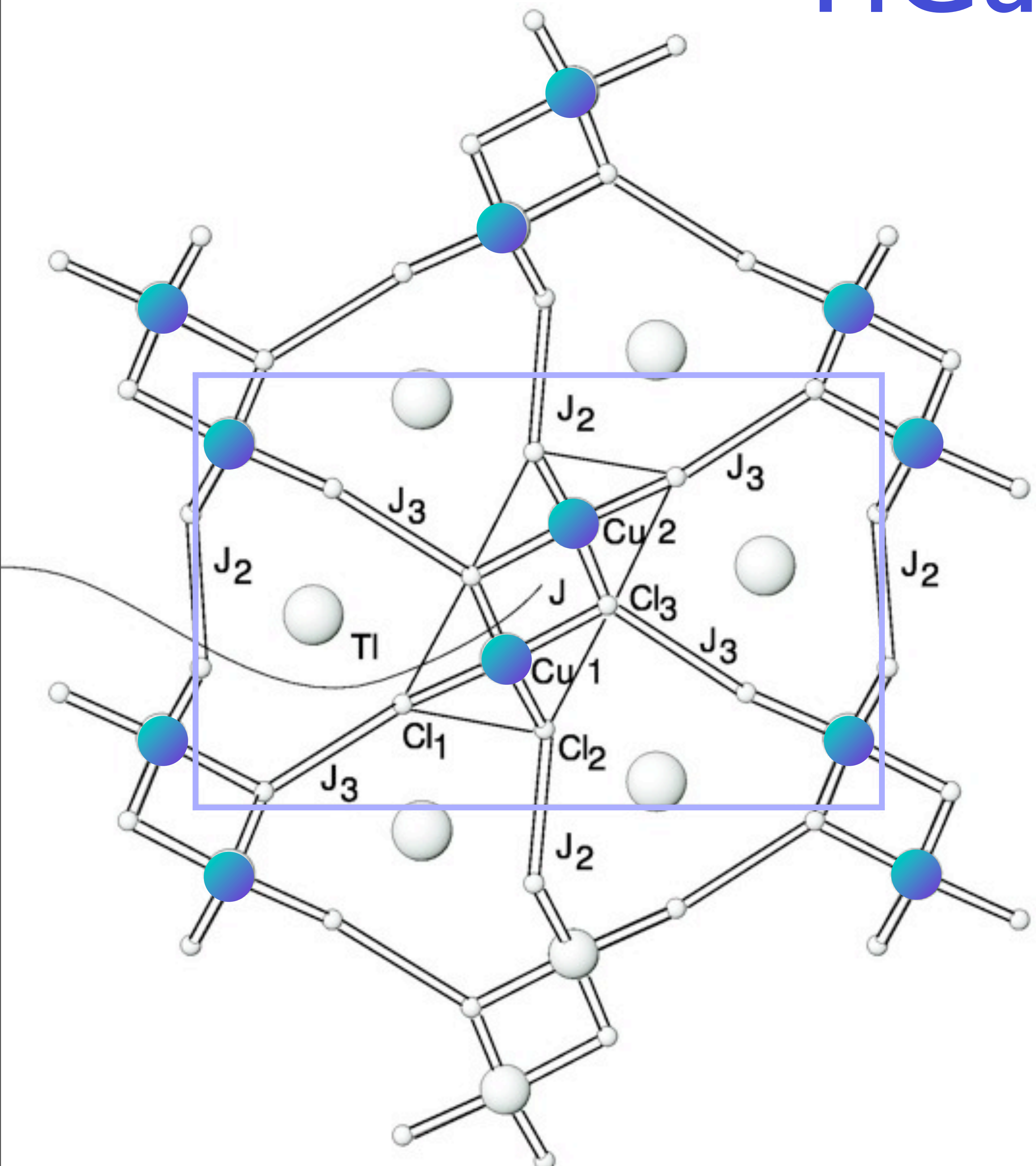
Ground state has long-range Néel order

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.

$TlCuCl_3$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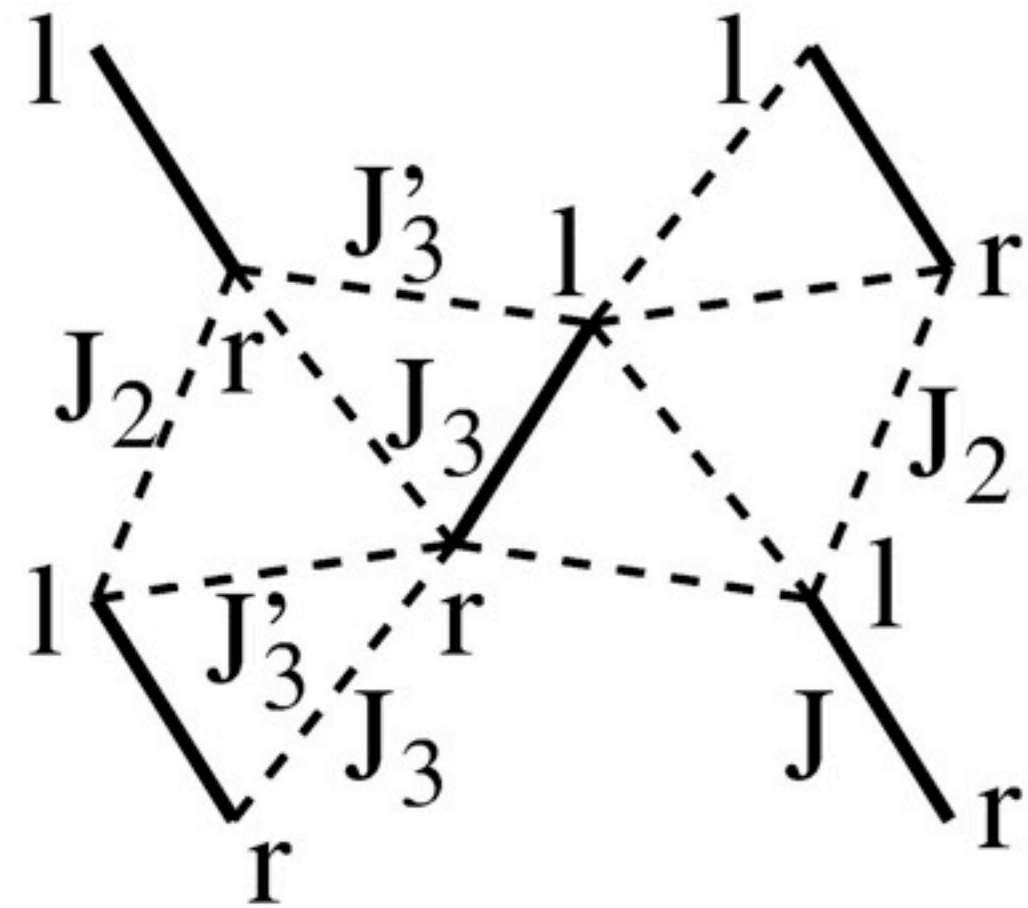
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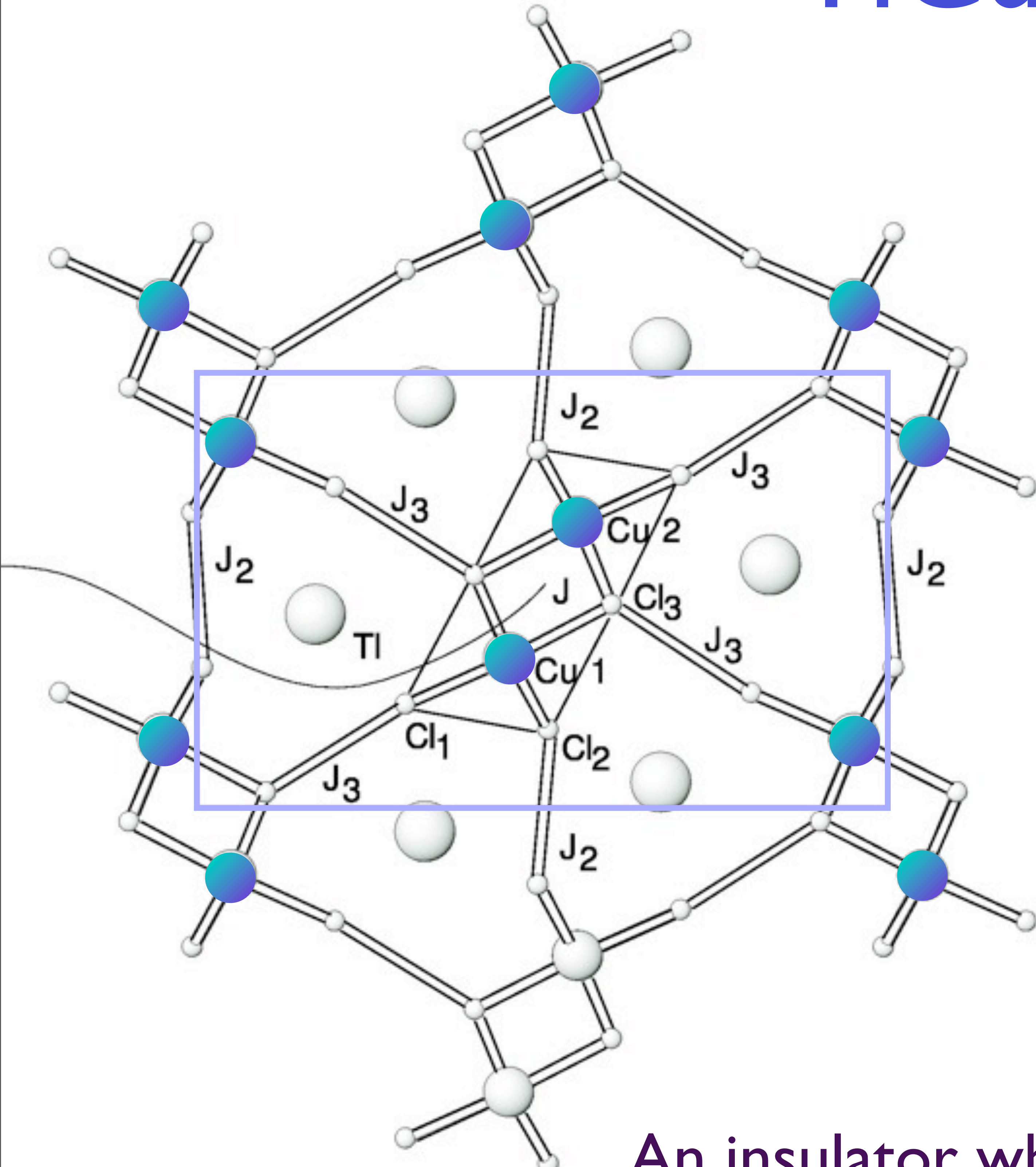
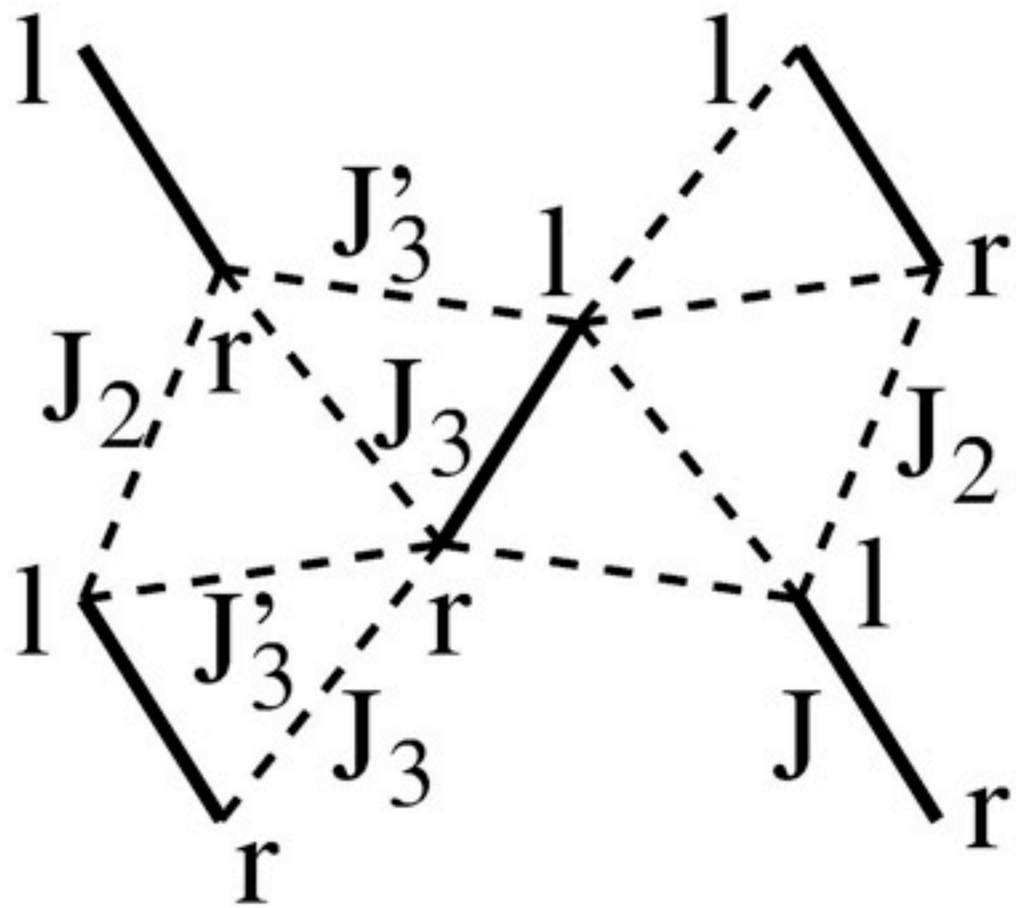
$TlCuCl_3$





An insulator whose spin susceptibility vanishes exponentially as the temperature T tends to zero.

Square lattice antiferromagnet

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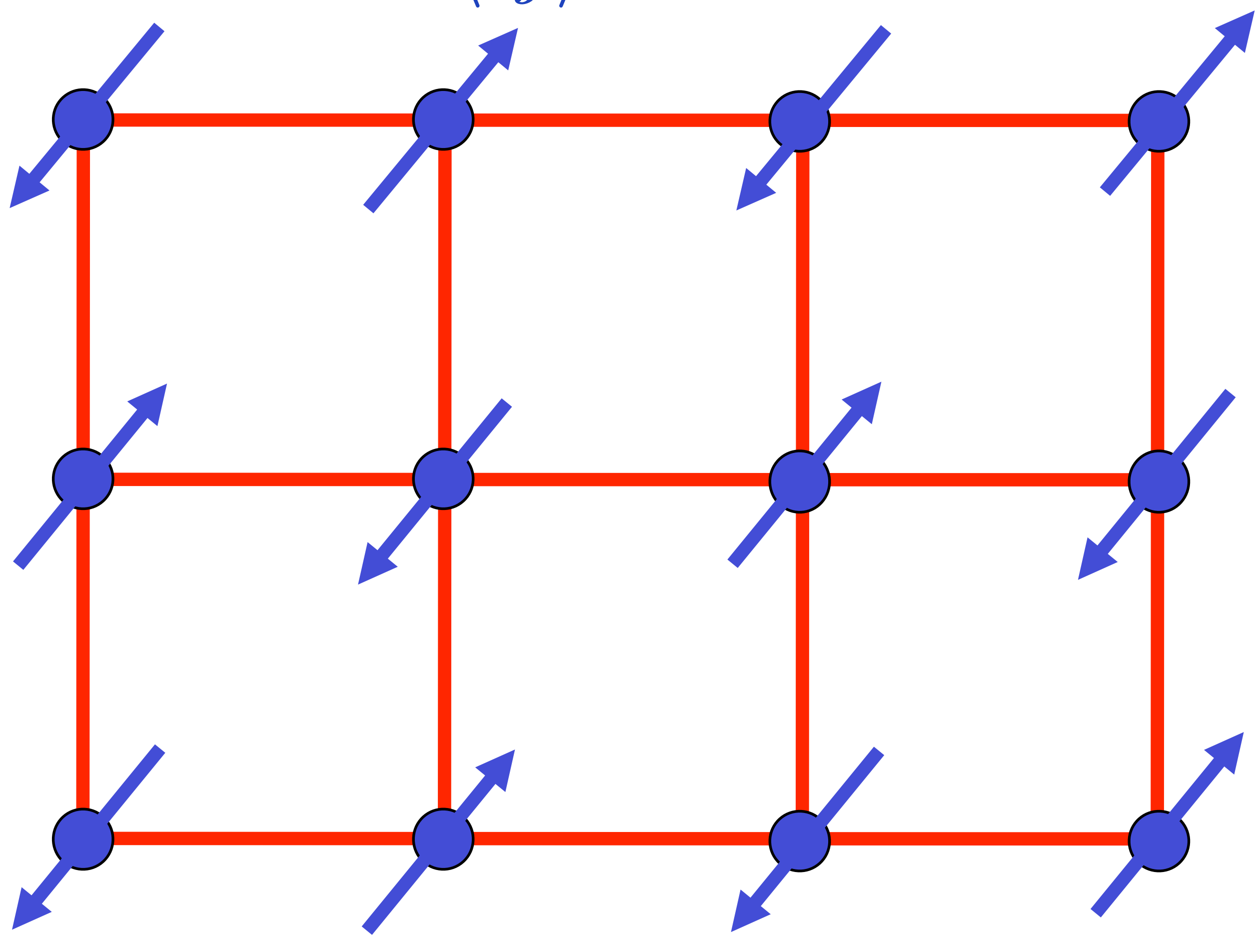

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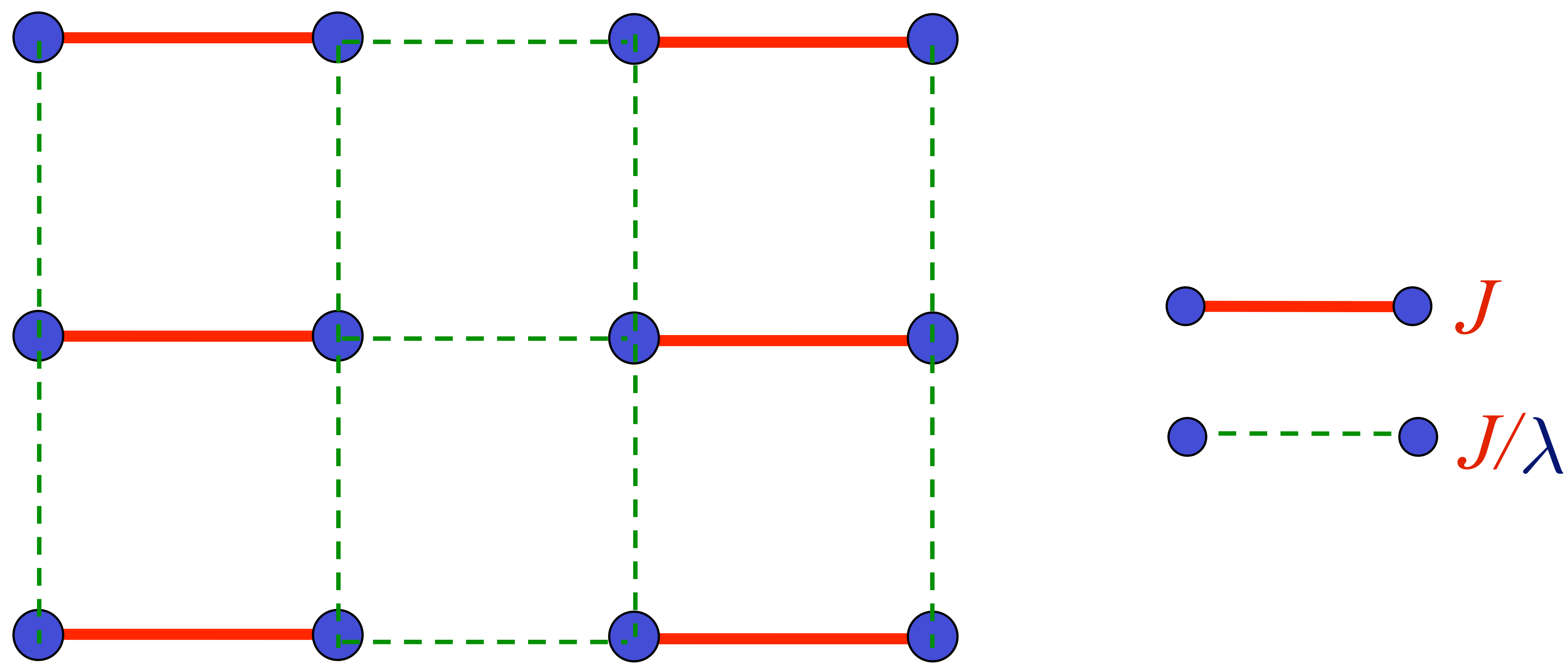
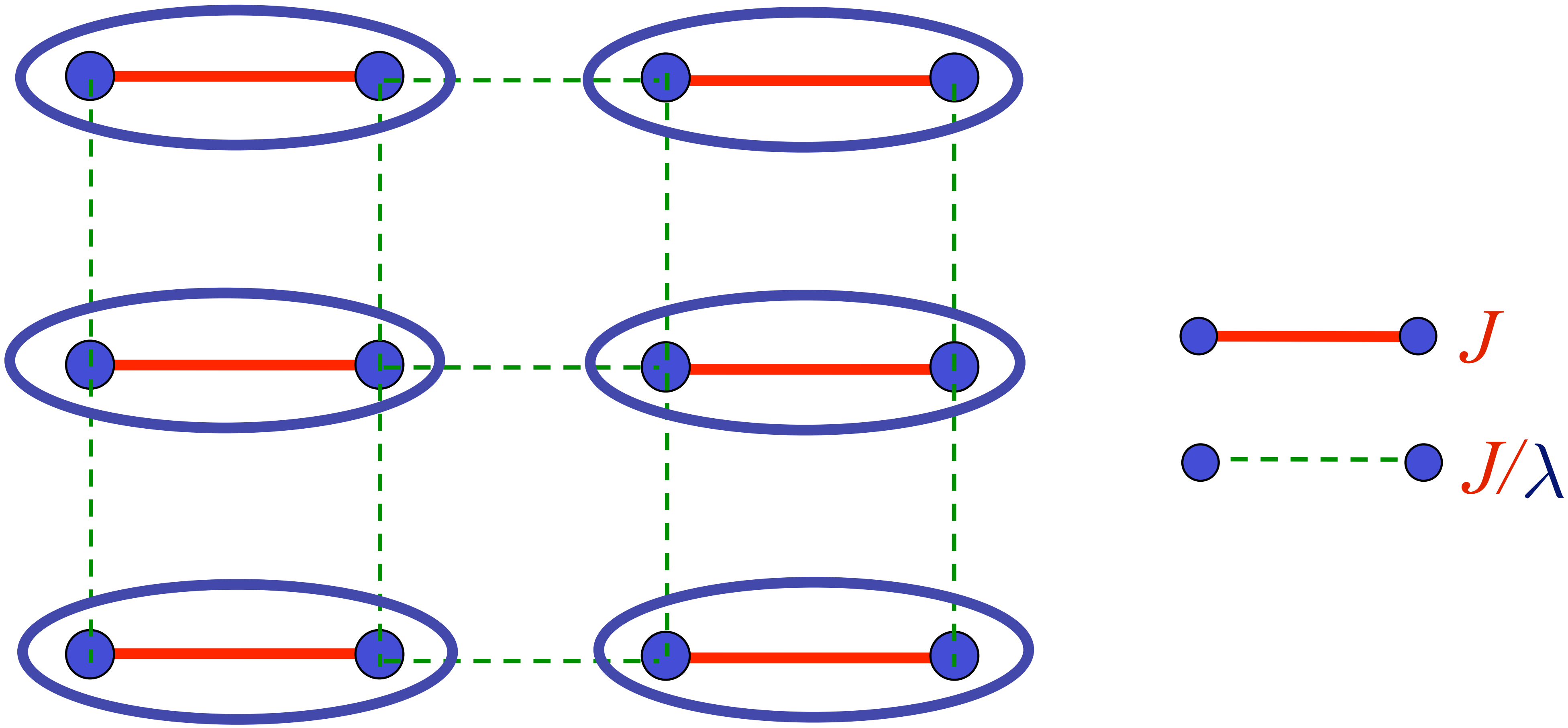


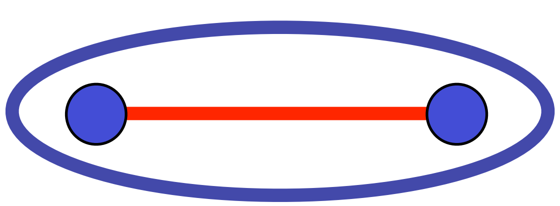
Weaken some bonds to induce spin entanglement in a new quantum phase

Square lattice antiferromagnet

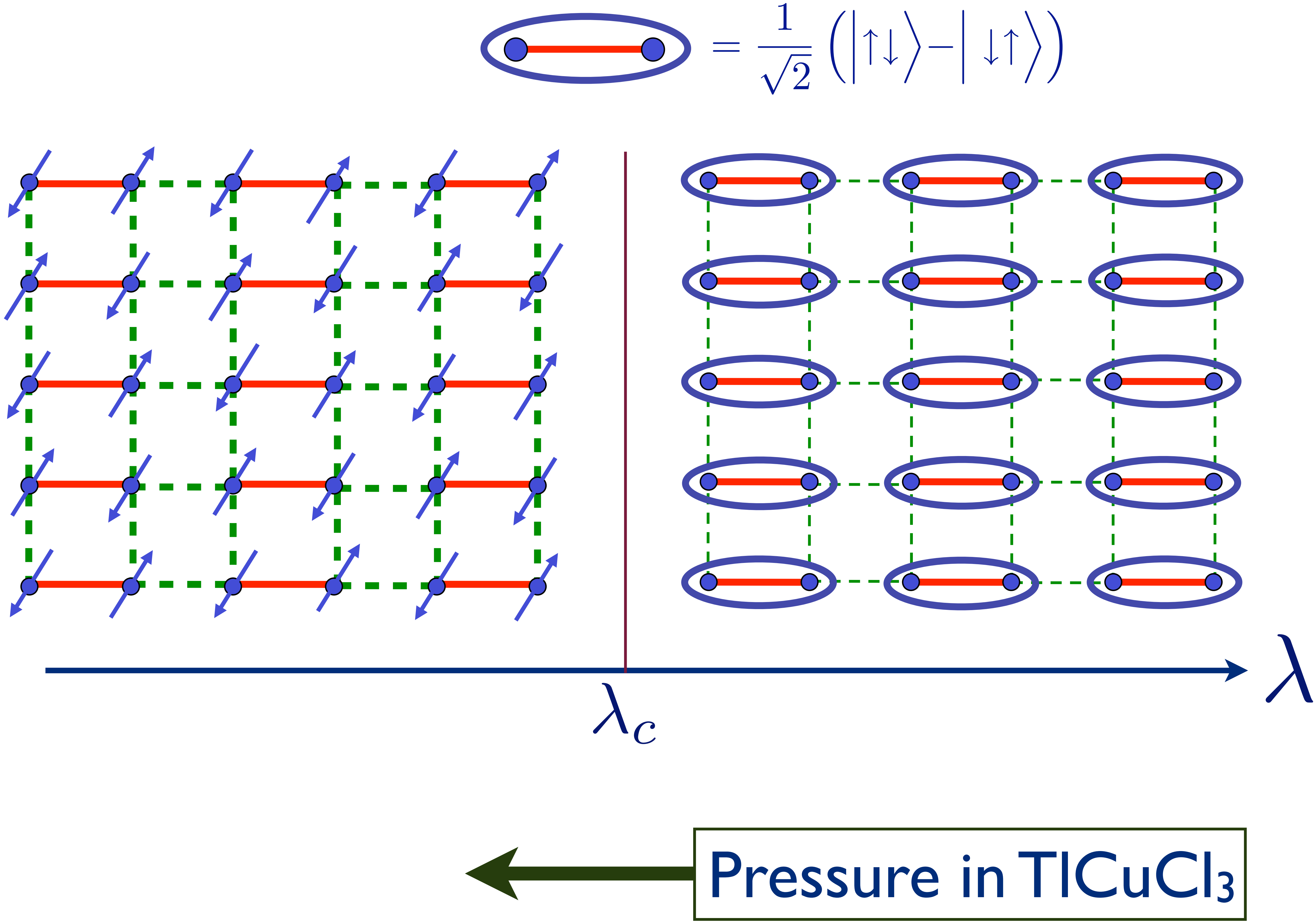
$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



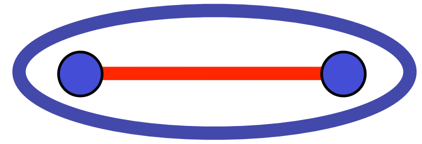
Ground state is a "quantum paramagnet" with spins locked in valence bond singlets



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



Wednesday, May 5, 2010



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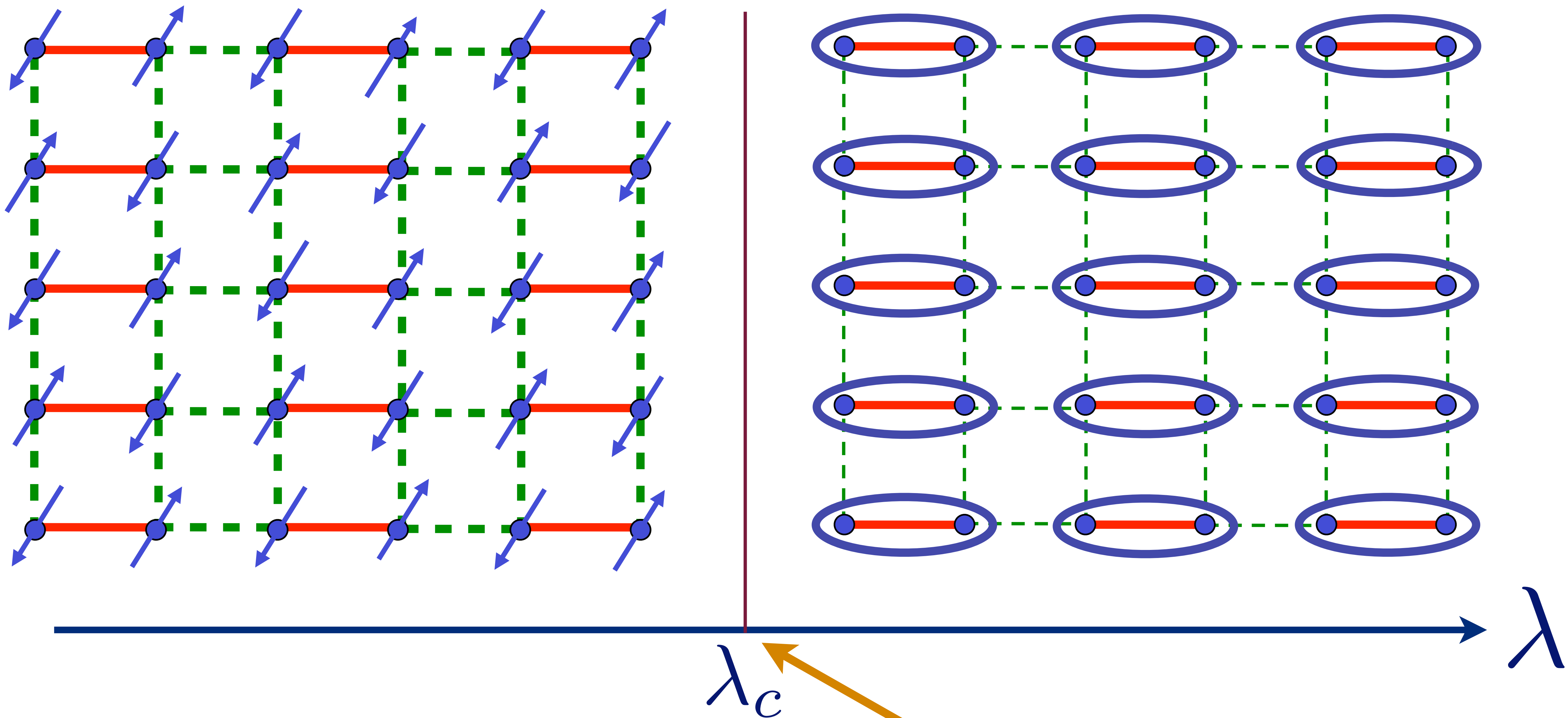
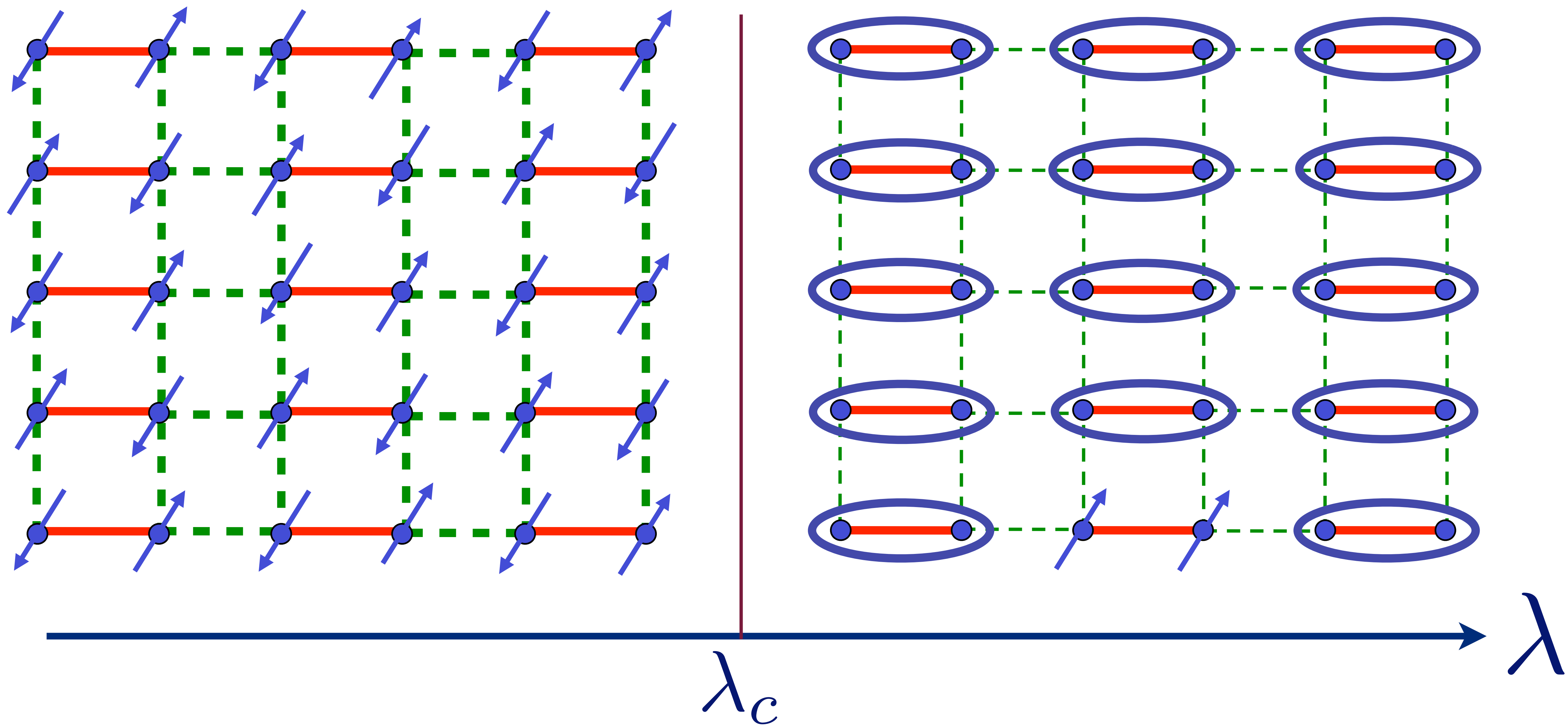


Quantum critical point with non-local entanglement in spin wavefunction

Excitation spectrum in the paramagnetic phase



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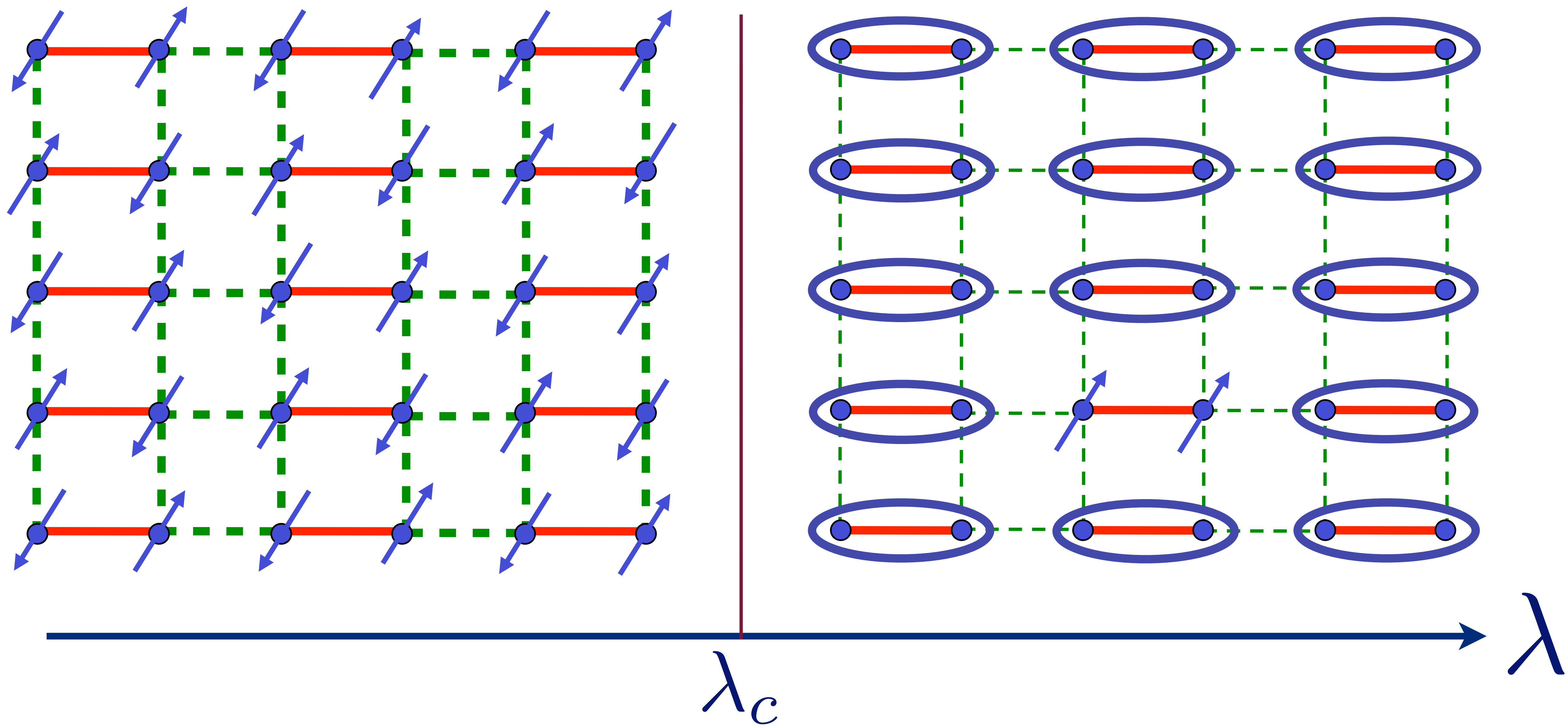

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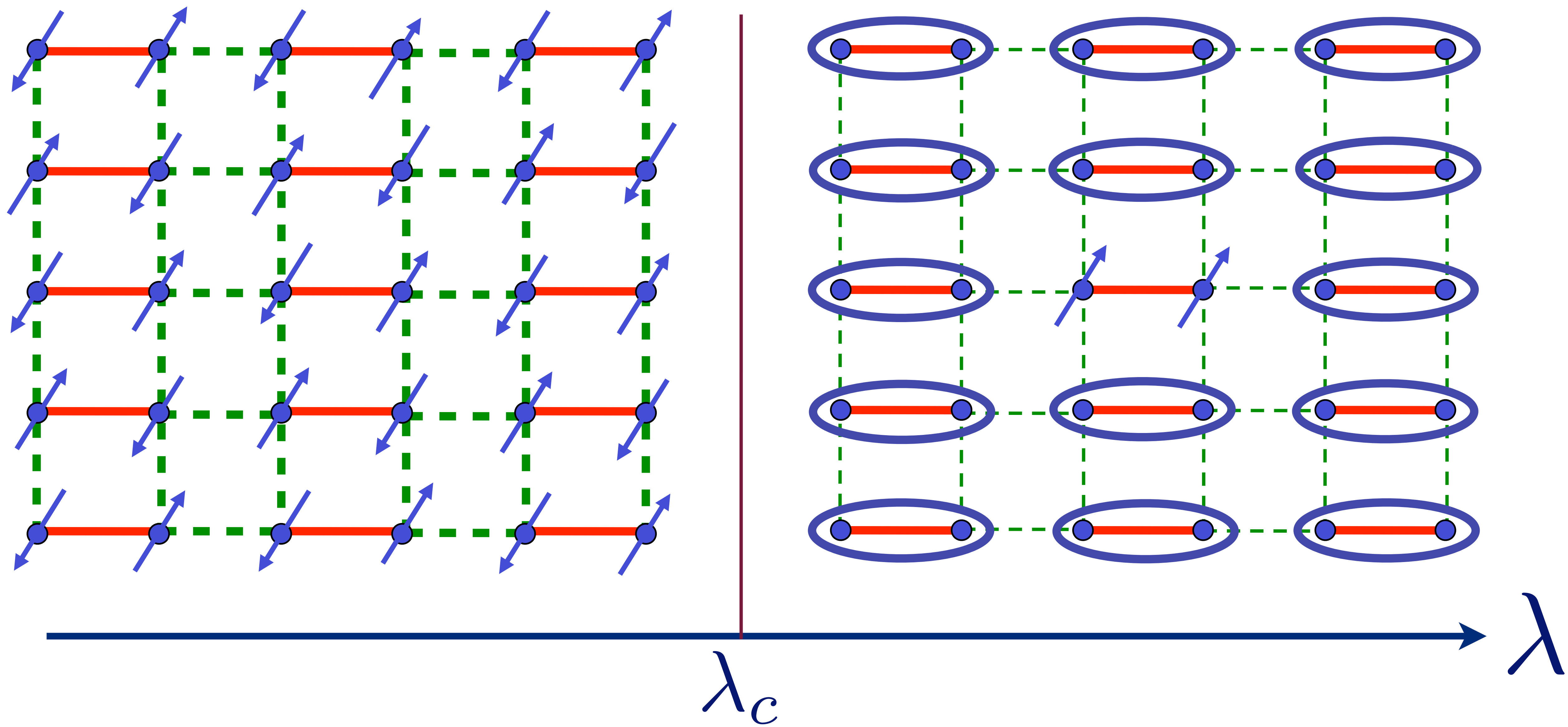

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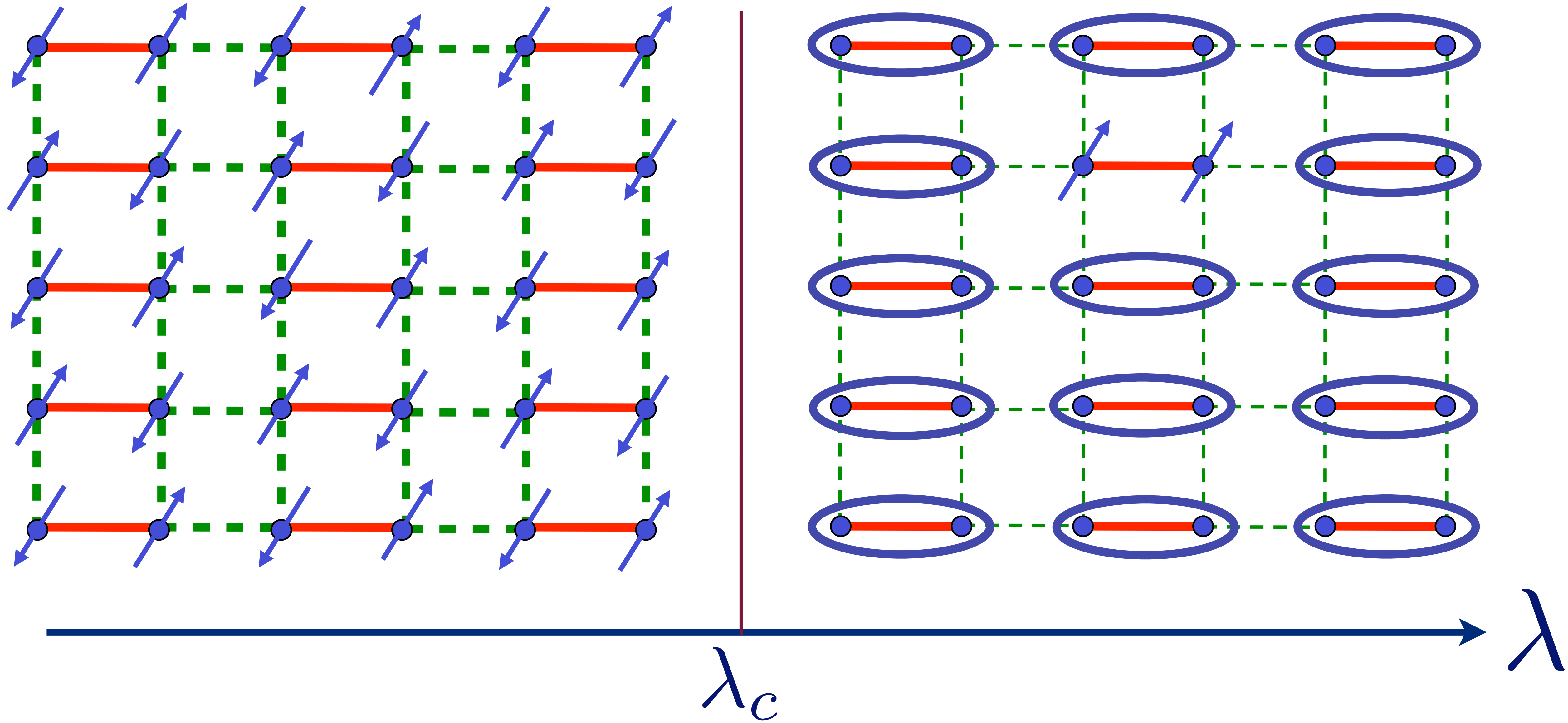

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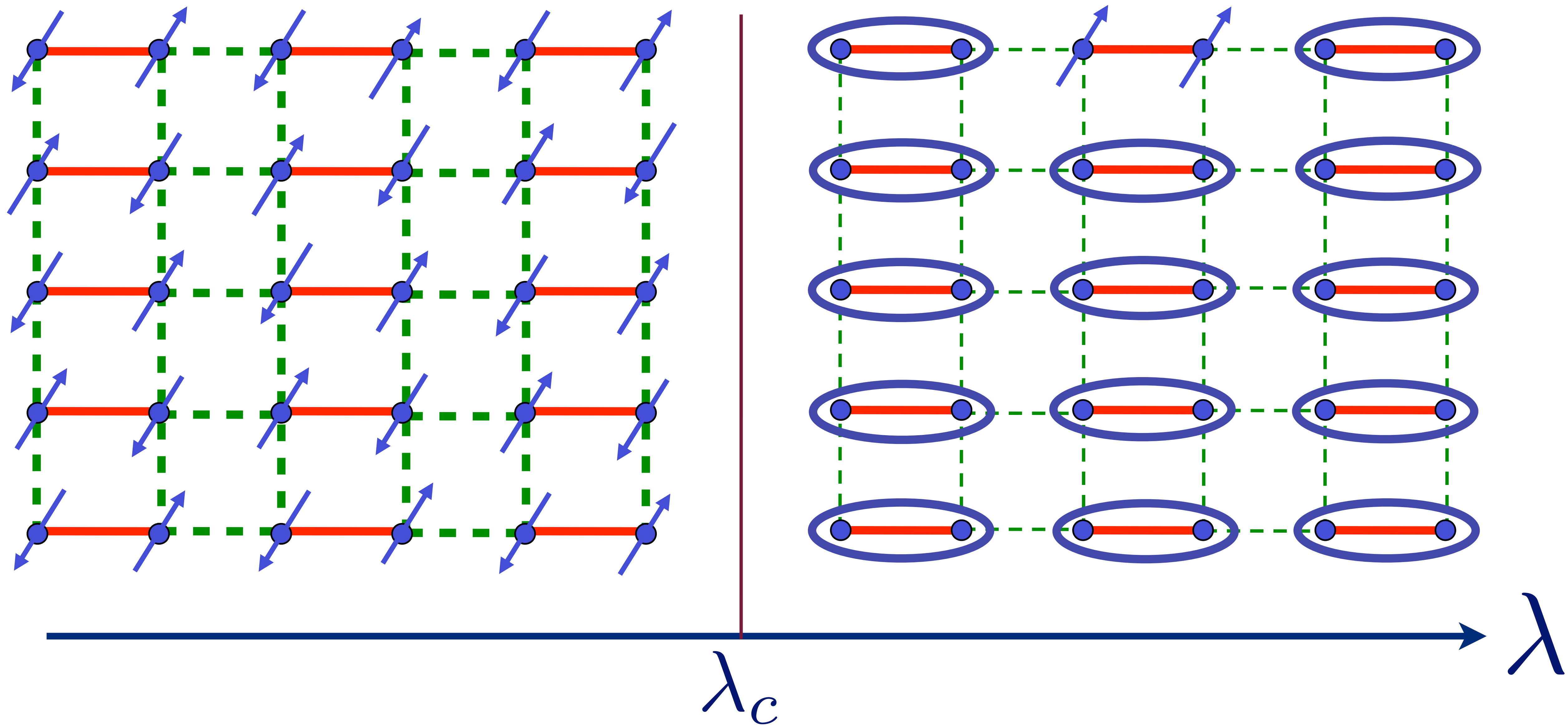
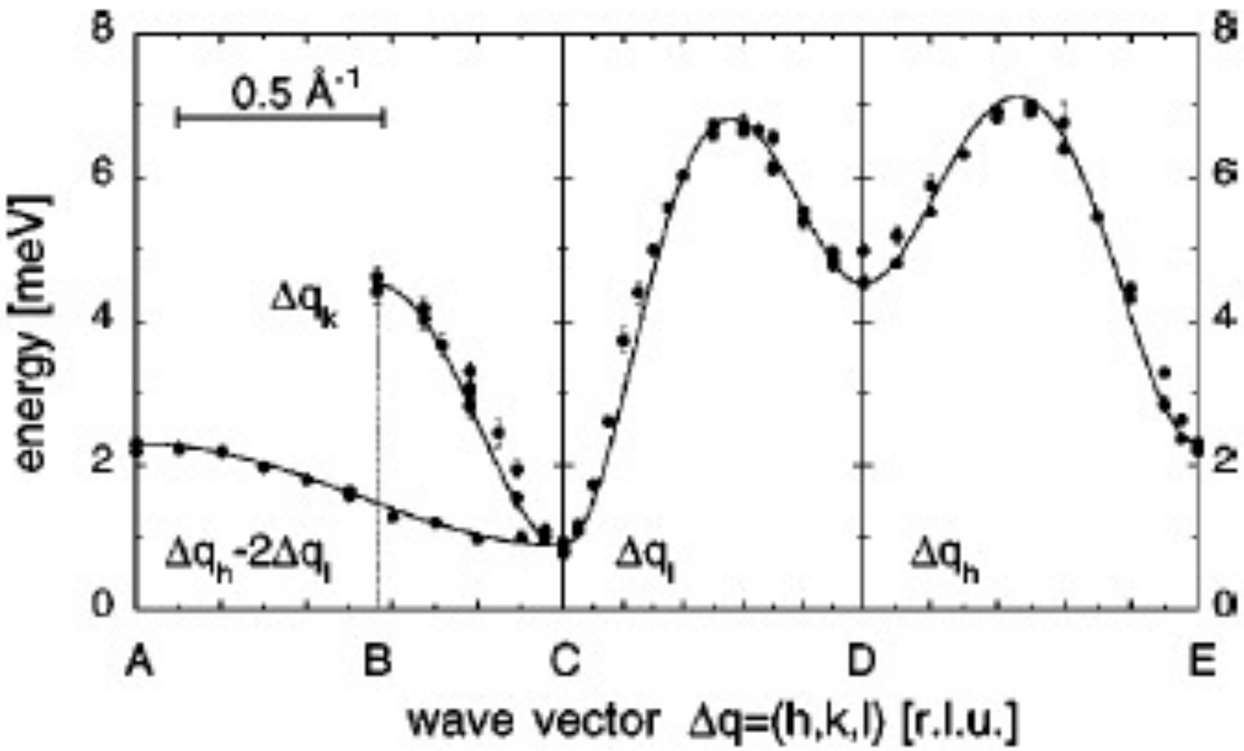


$TlCuCl_3$ at ambient pressure



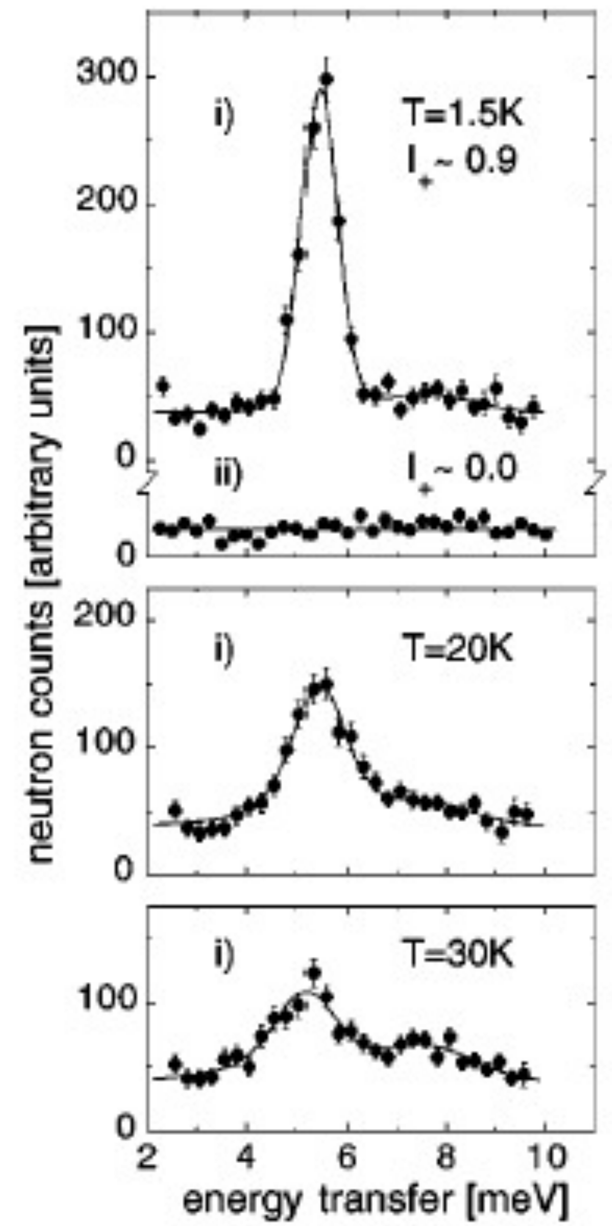


FIG. 1. Measured neutron profiles in the a^*c^* plane of $TlCuCl_3$ for $i=(1.35,0,0)$, $ii=(0,0,3.15)$ [r.l.u]. The spectrum at $T=1.5$ K

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

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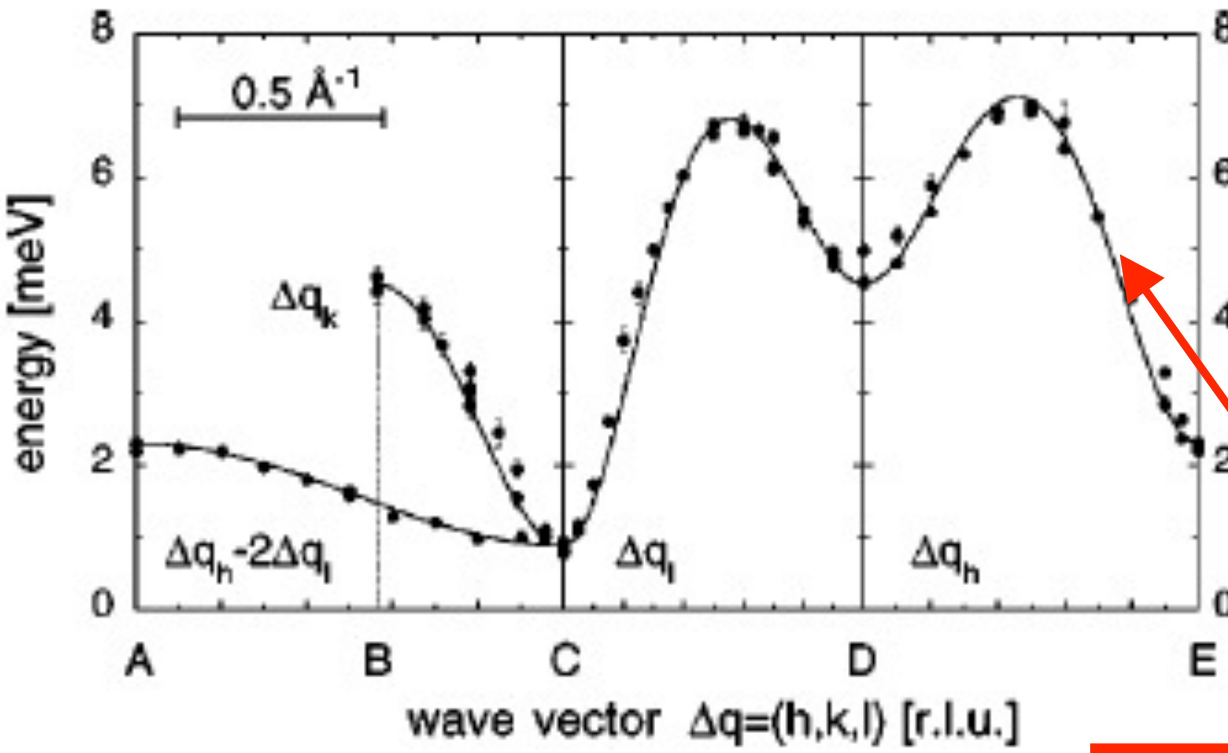
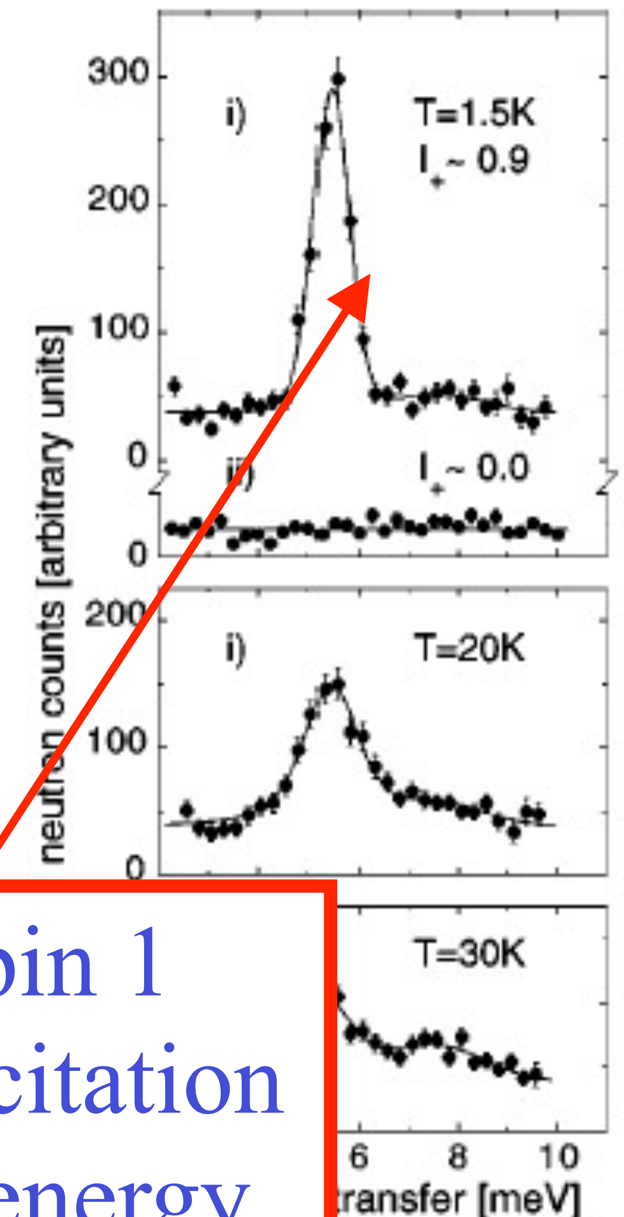


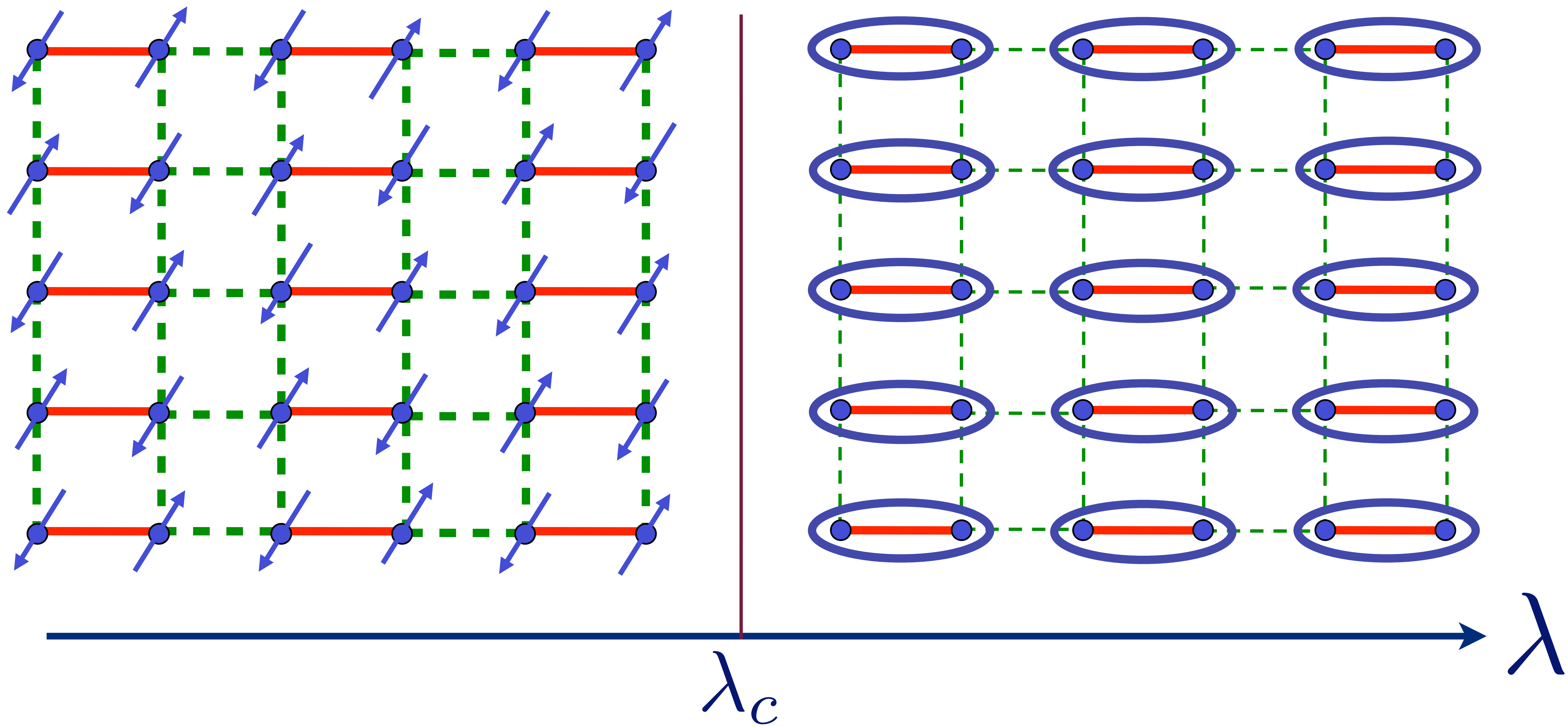


Sharp spin 1 particle excitation above an energy gap (spin gap)

...les in the a^*c^* plane of $TlCuCl_3$ ... [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



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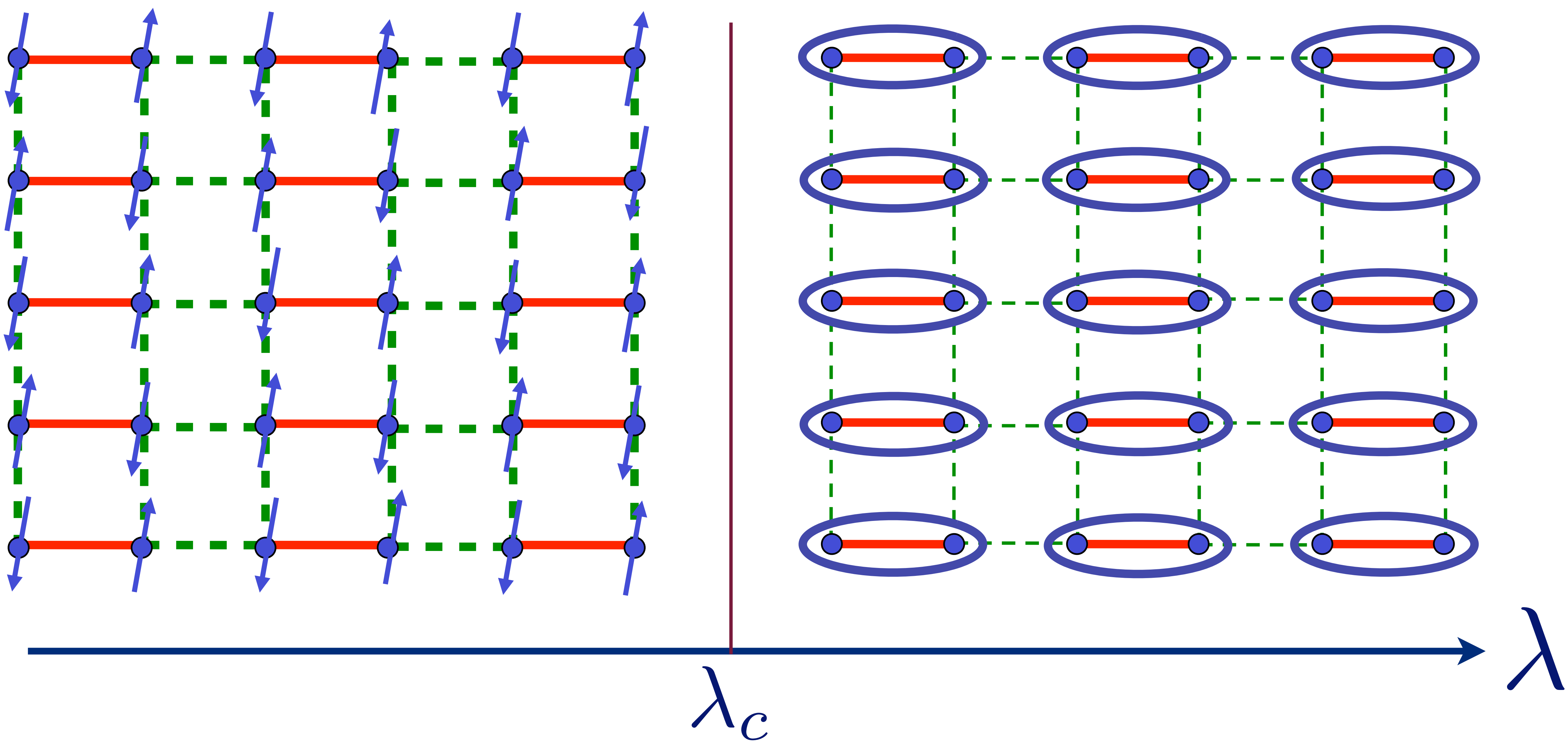
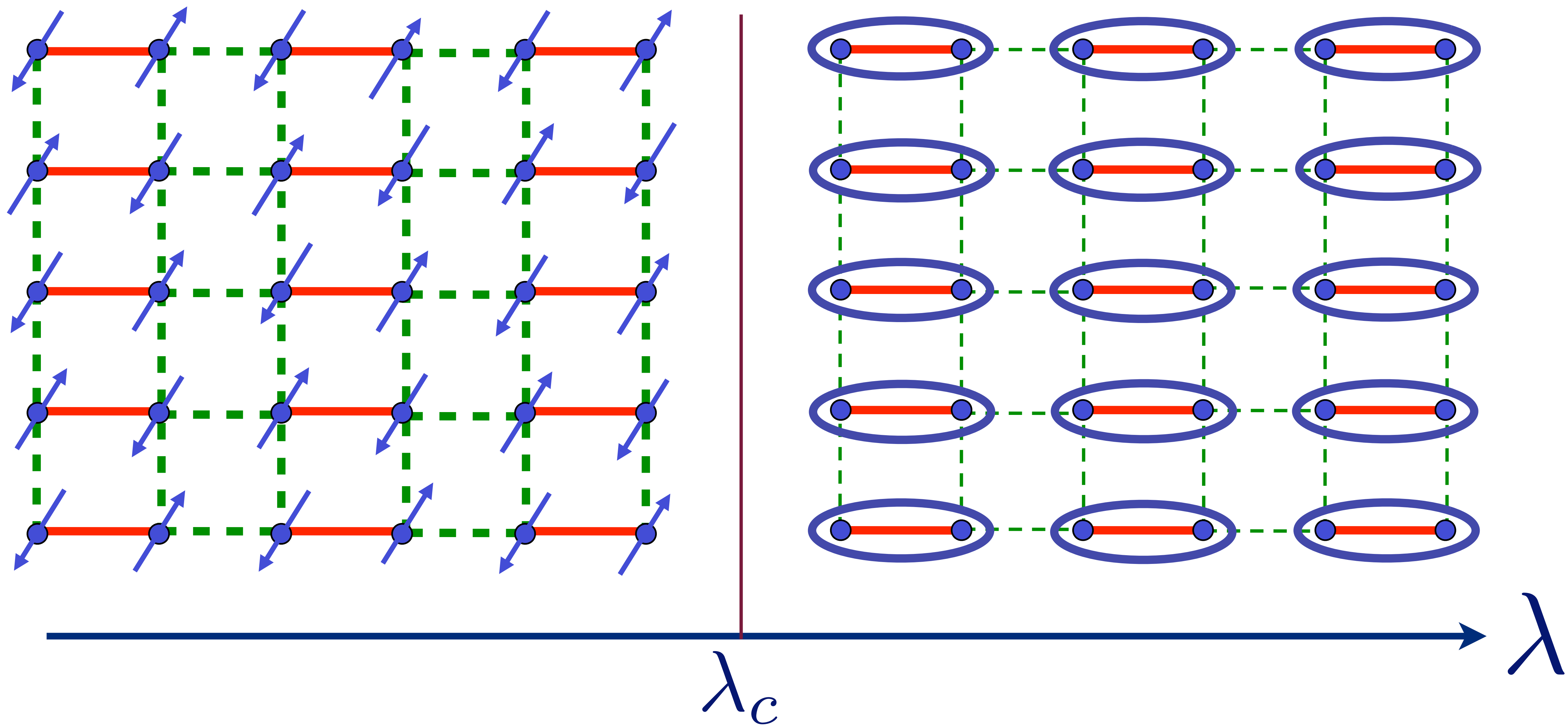


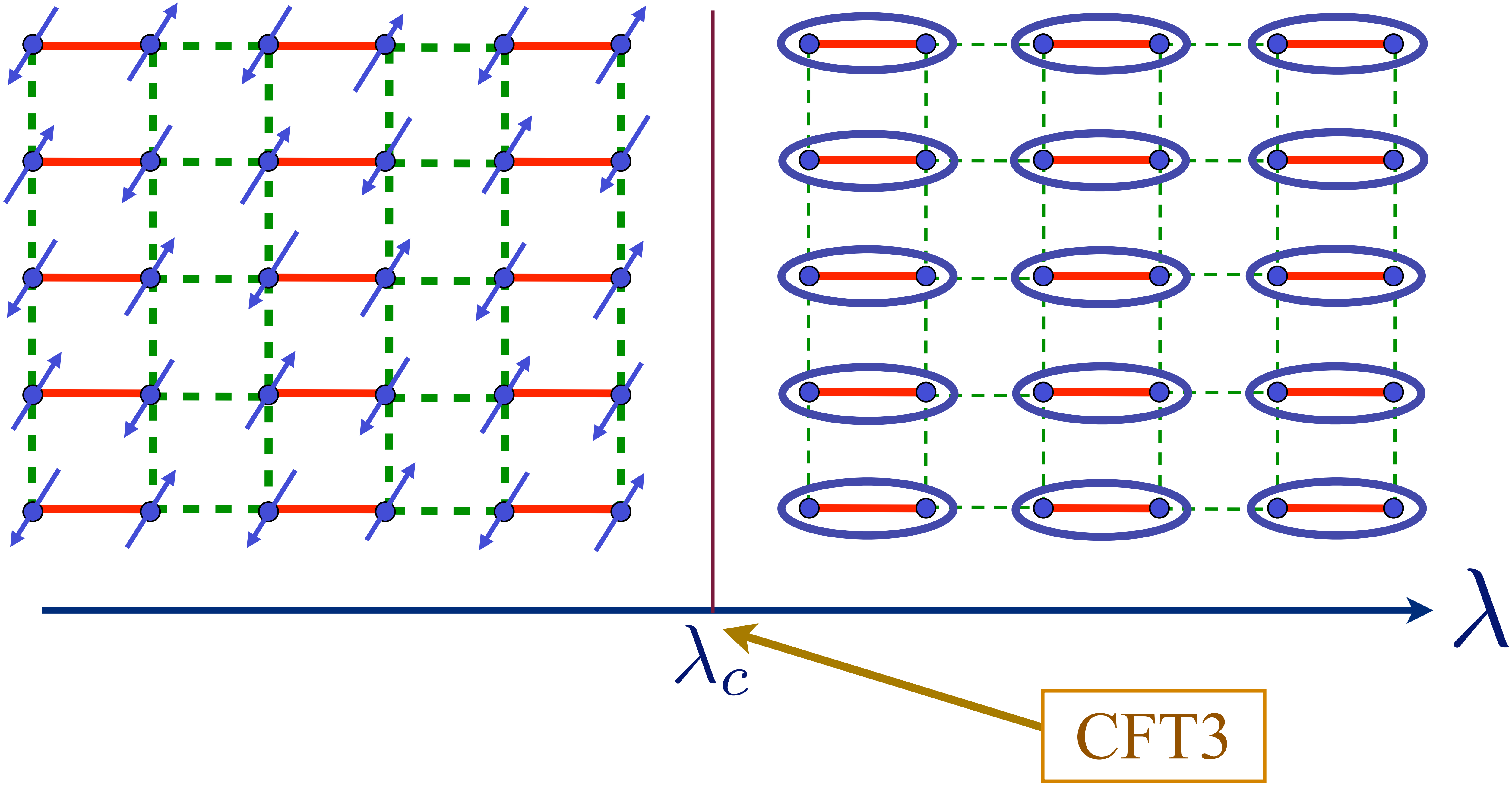
Spin waves

Excitation spectrum in the Néel phase



Spin waves

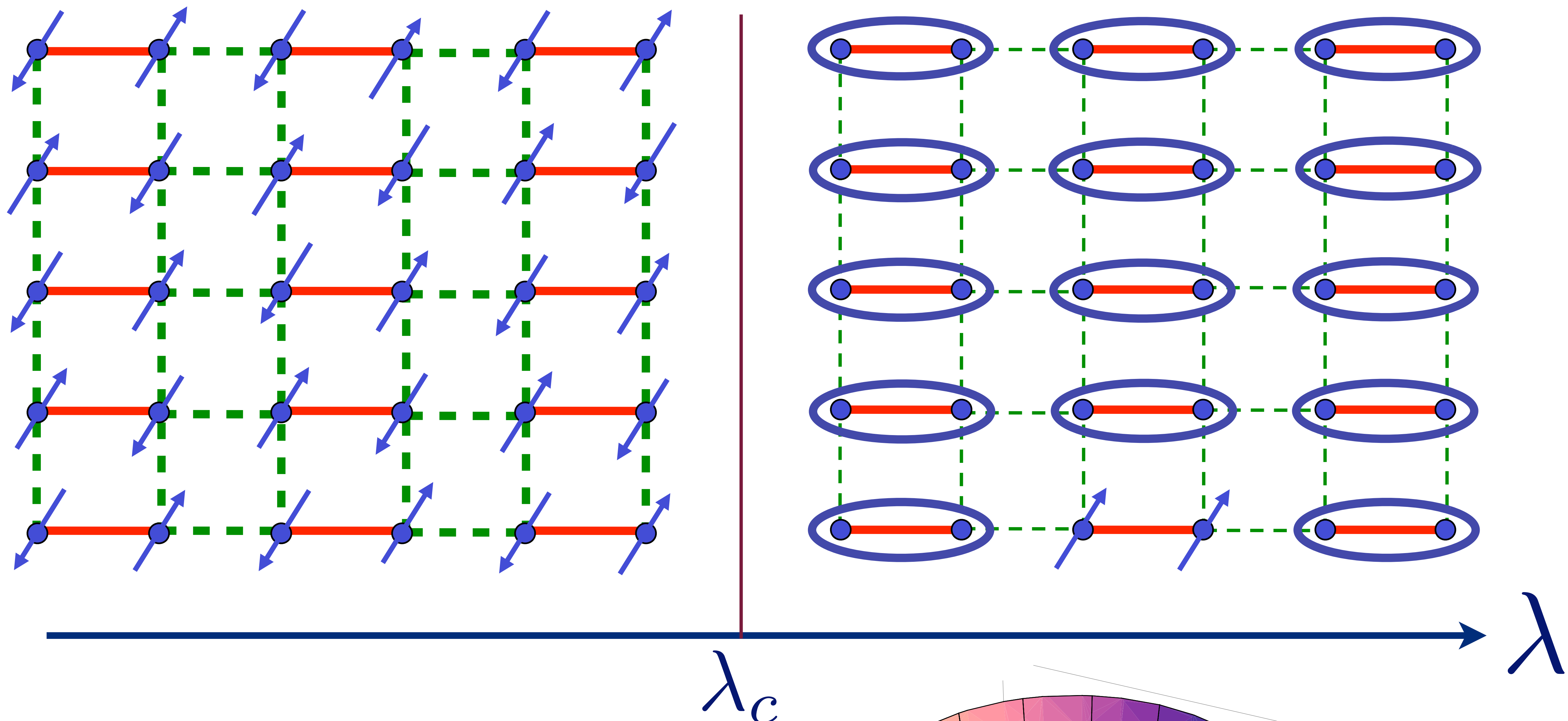
Description using Landau-Ginzburg field theory



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

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

Excitation spectrum in the paramagnetic phase



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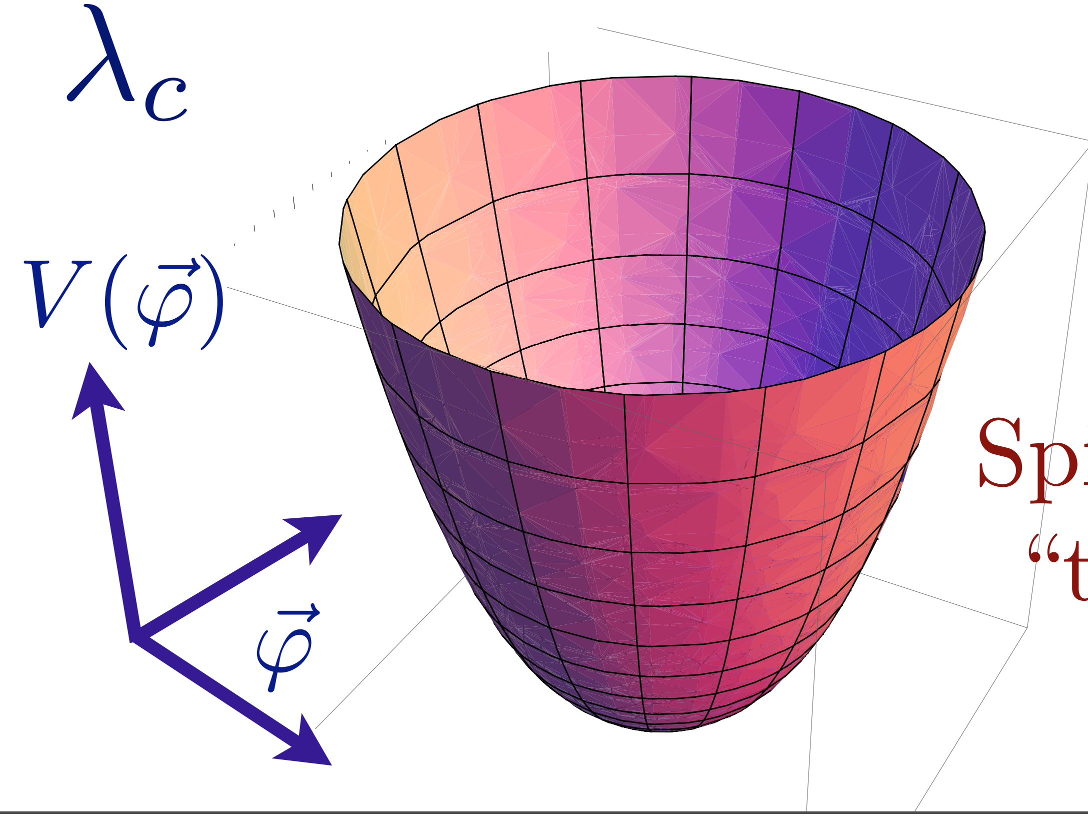
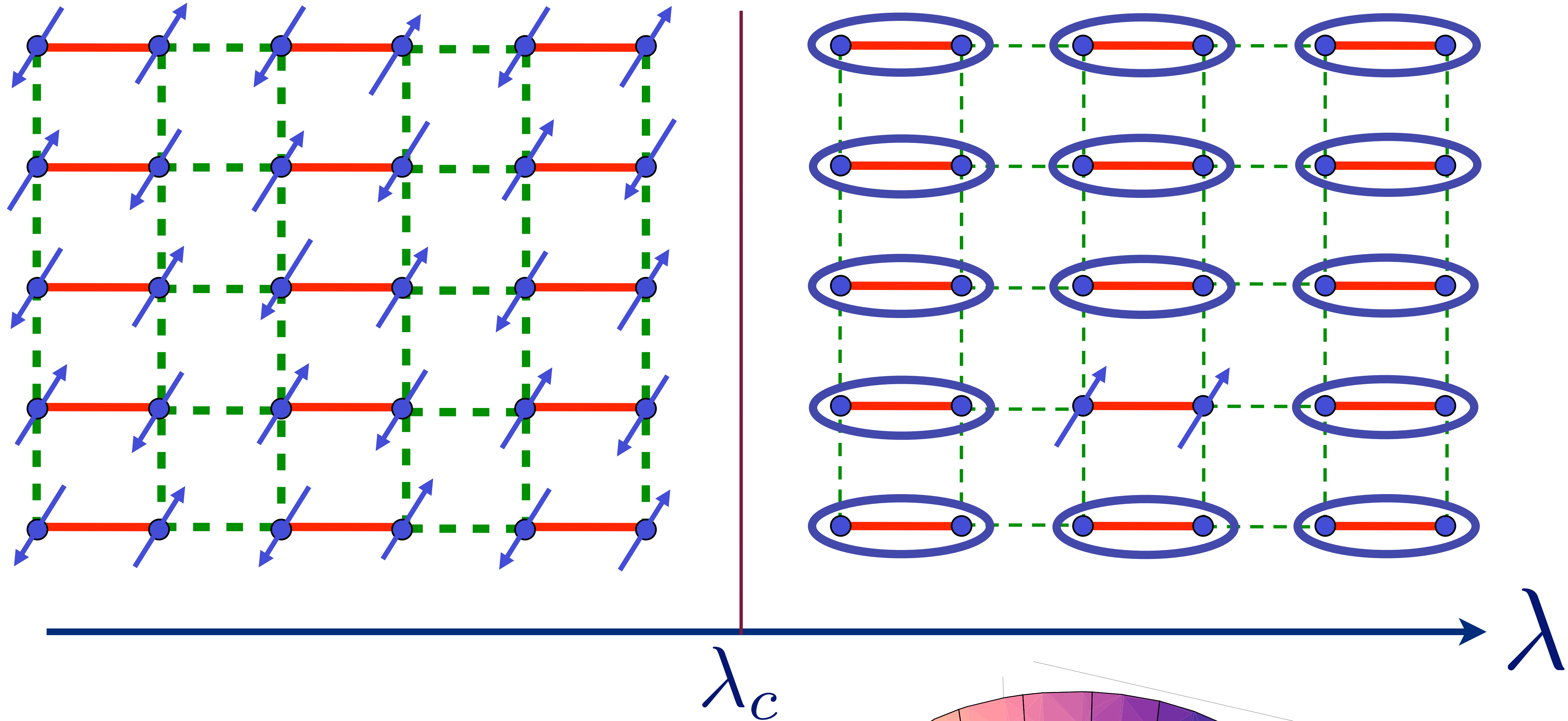
$$\lambda > \lambda_c$$



Spin $S = 1$
"triplon"

Excitation spectrum in the paramagnetic phase



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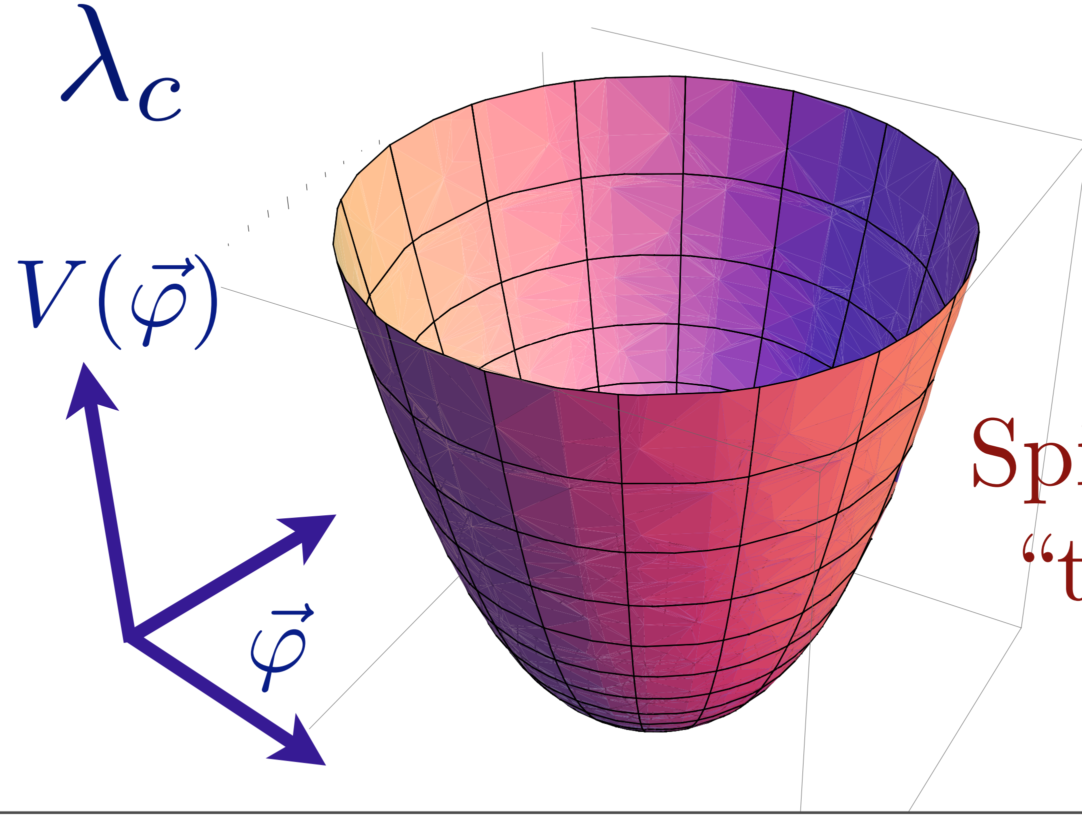

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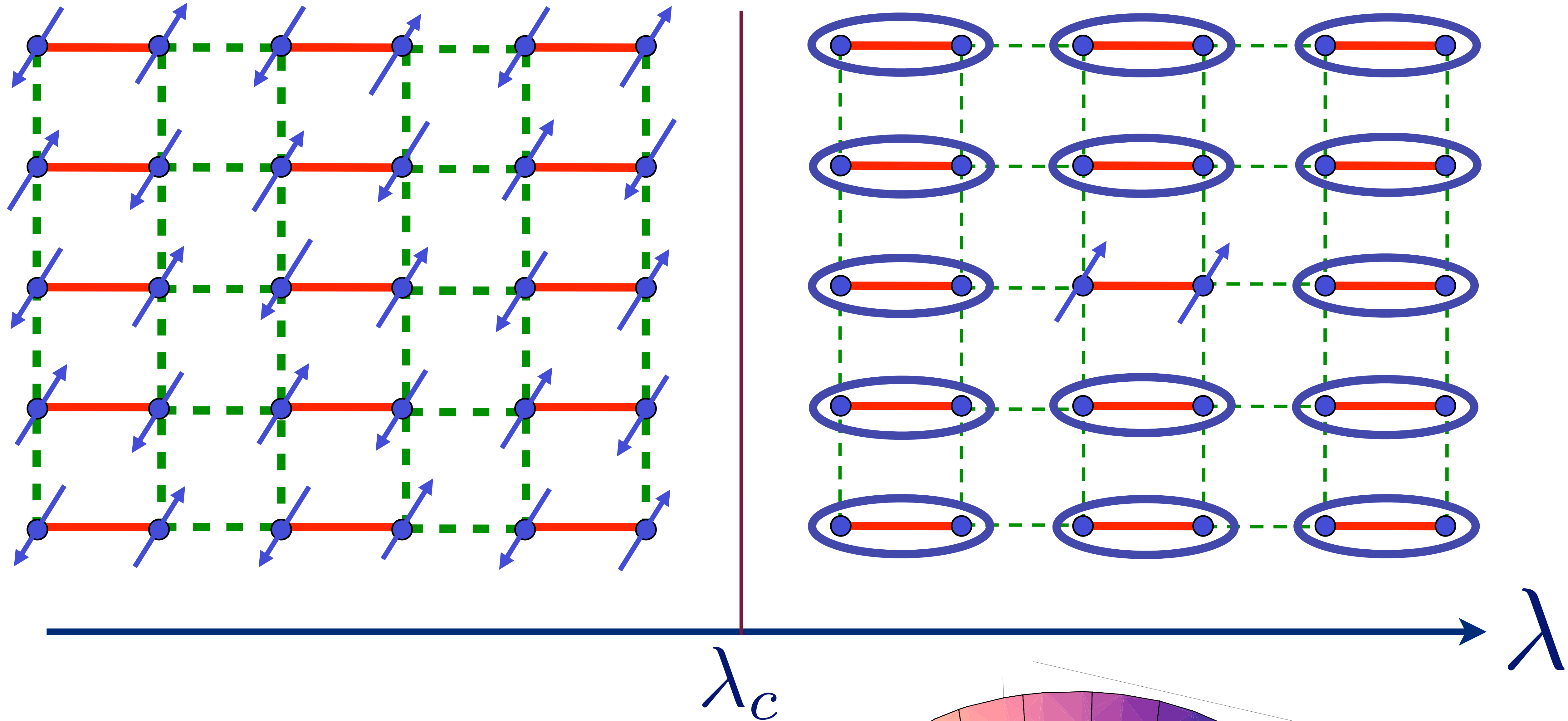

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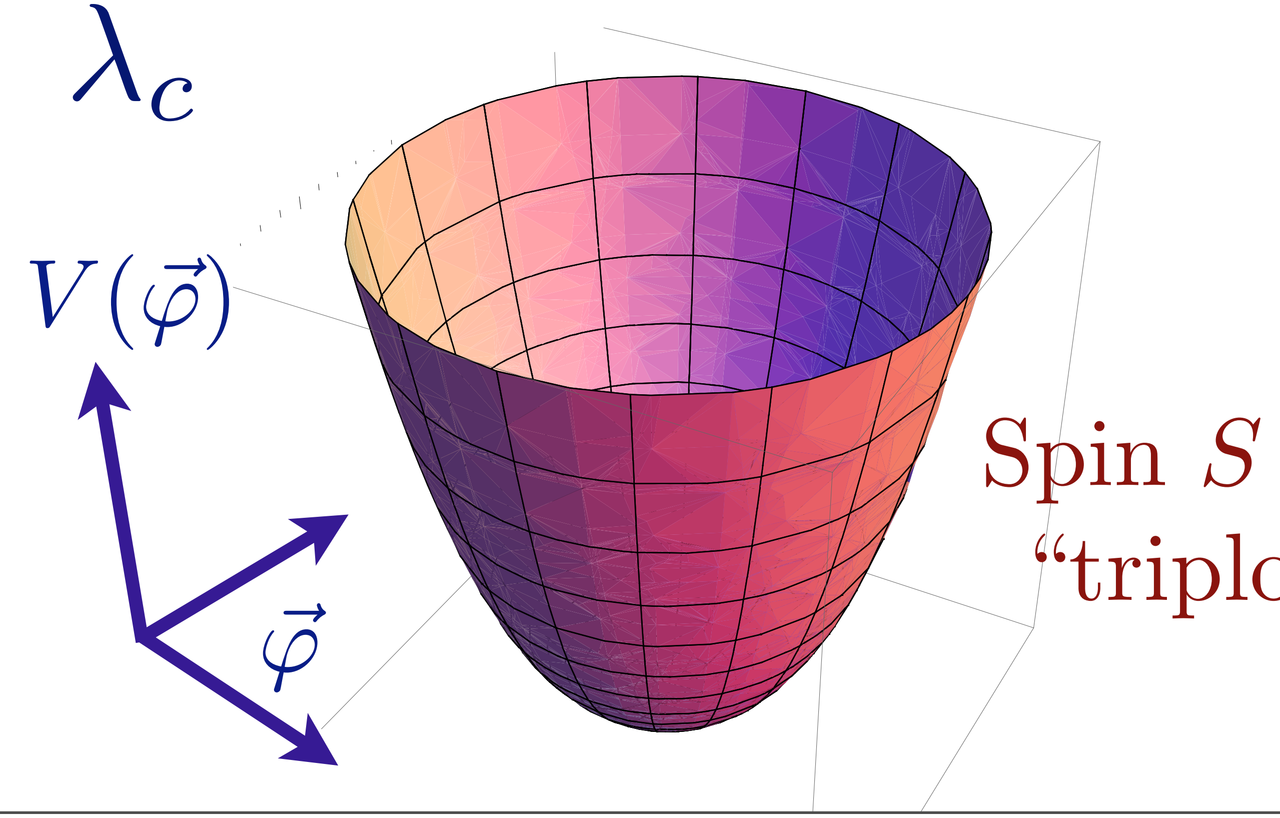

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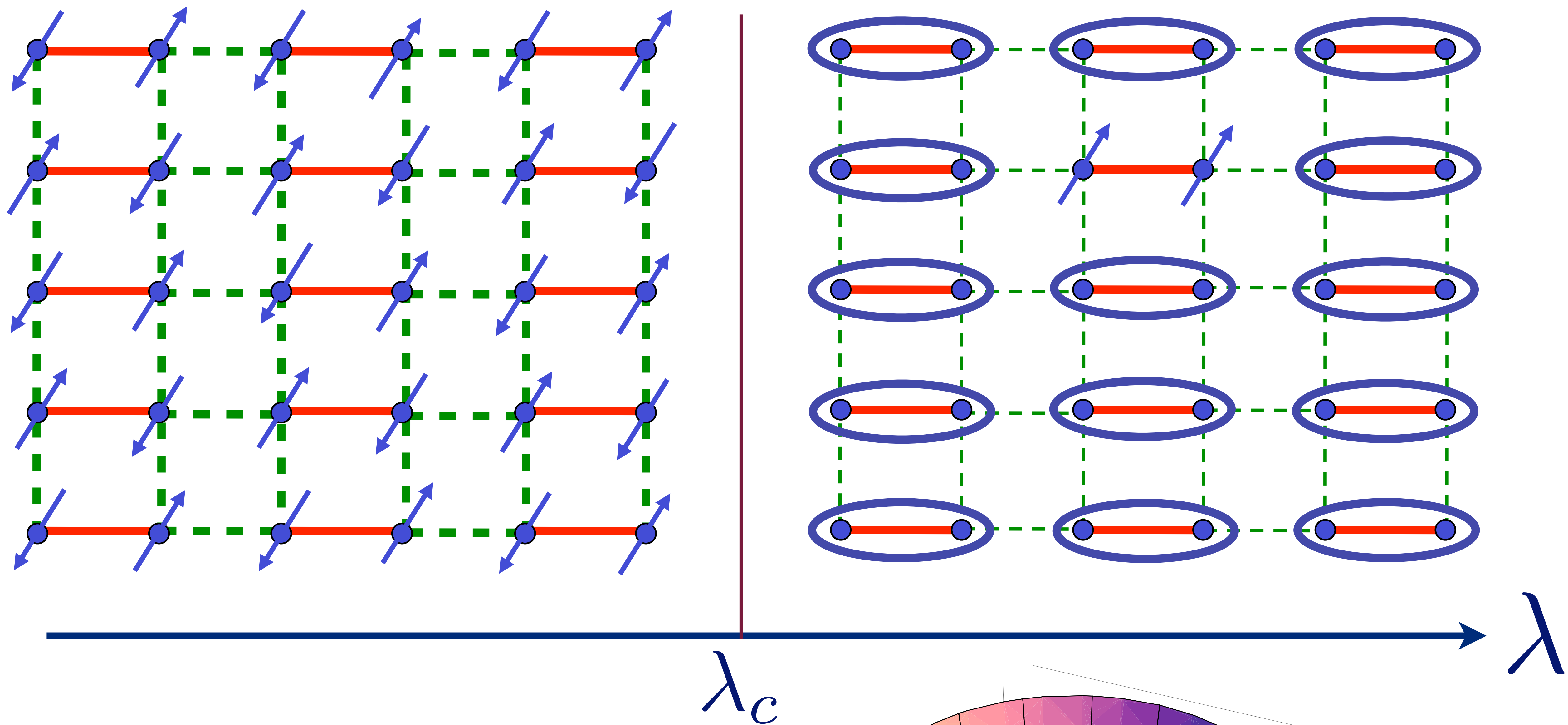

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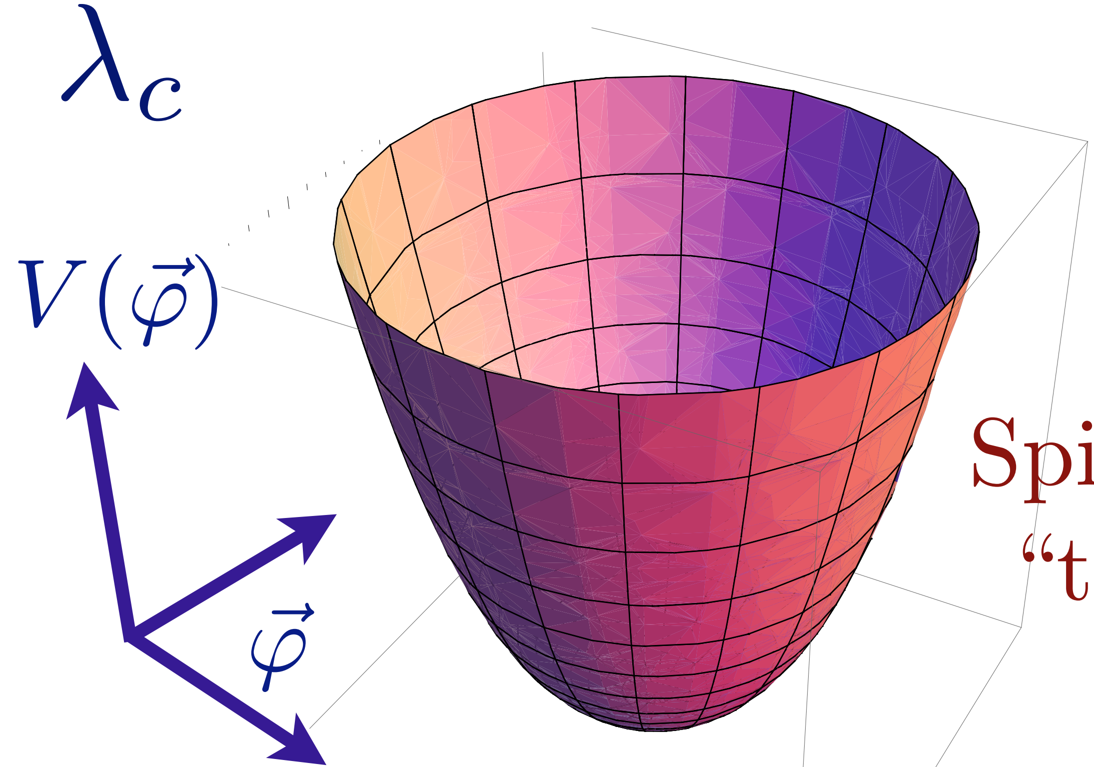

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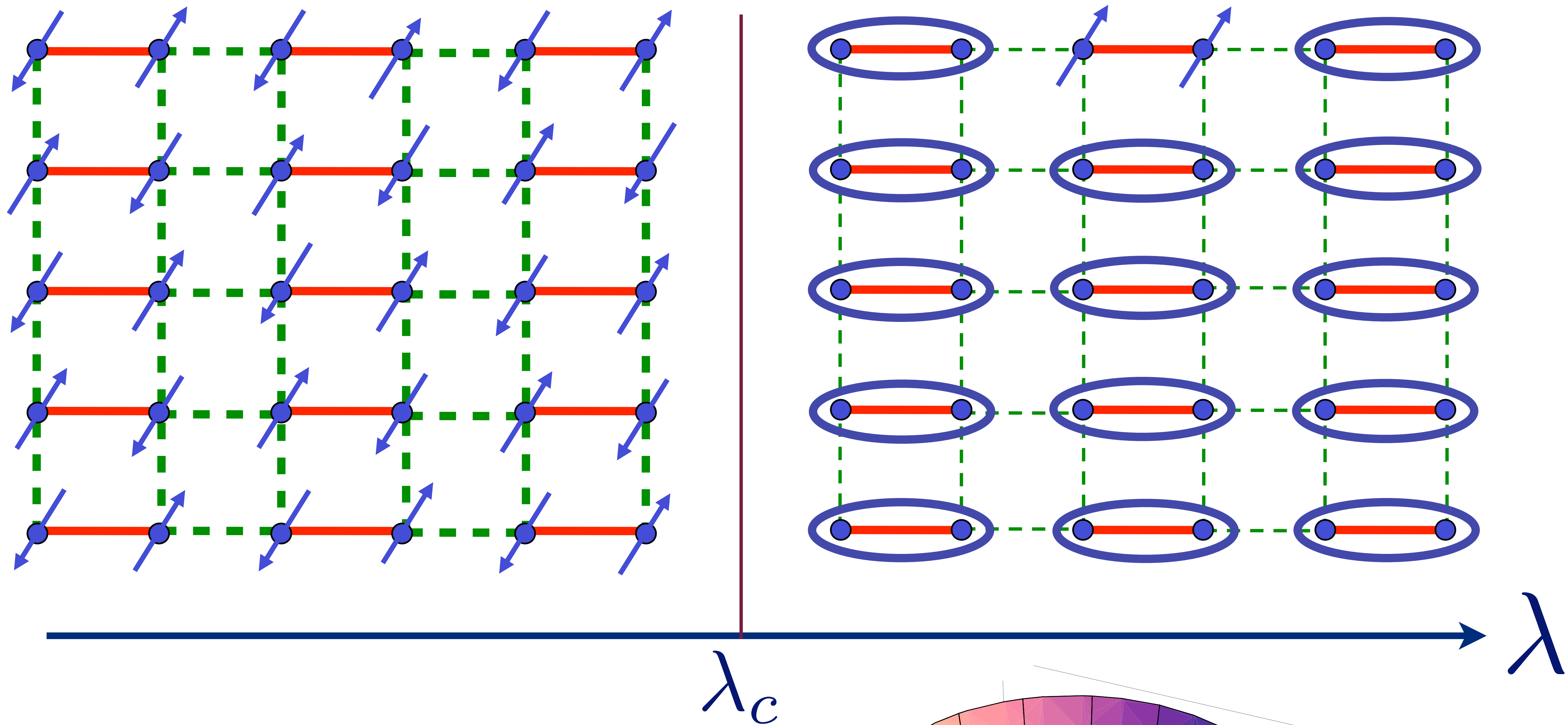

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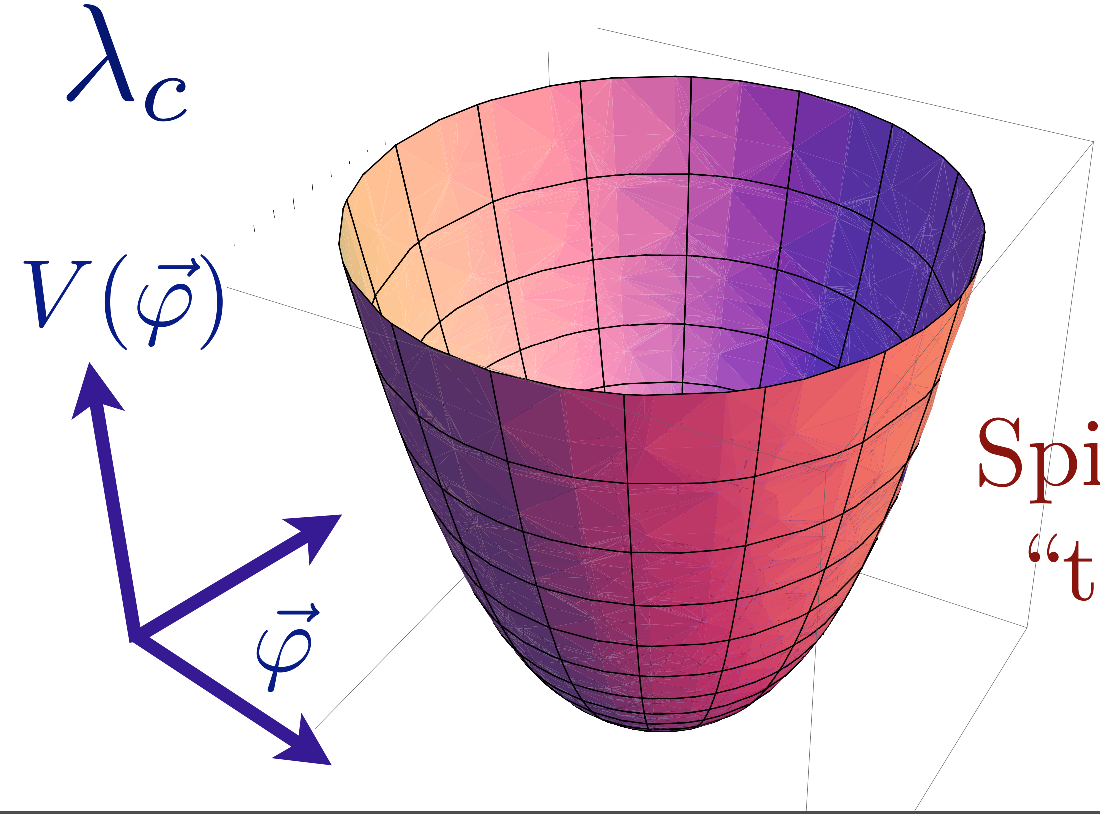

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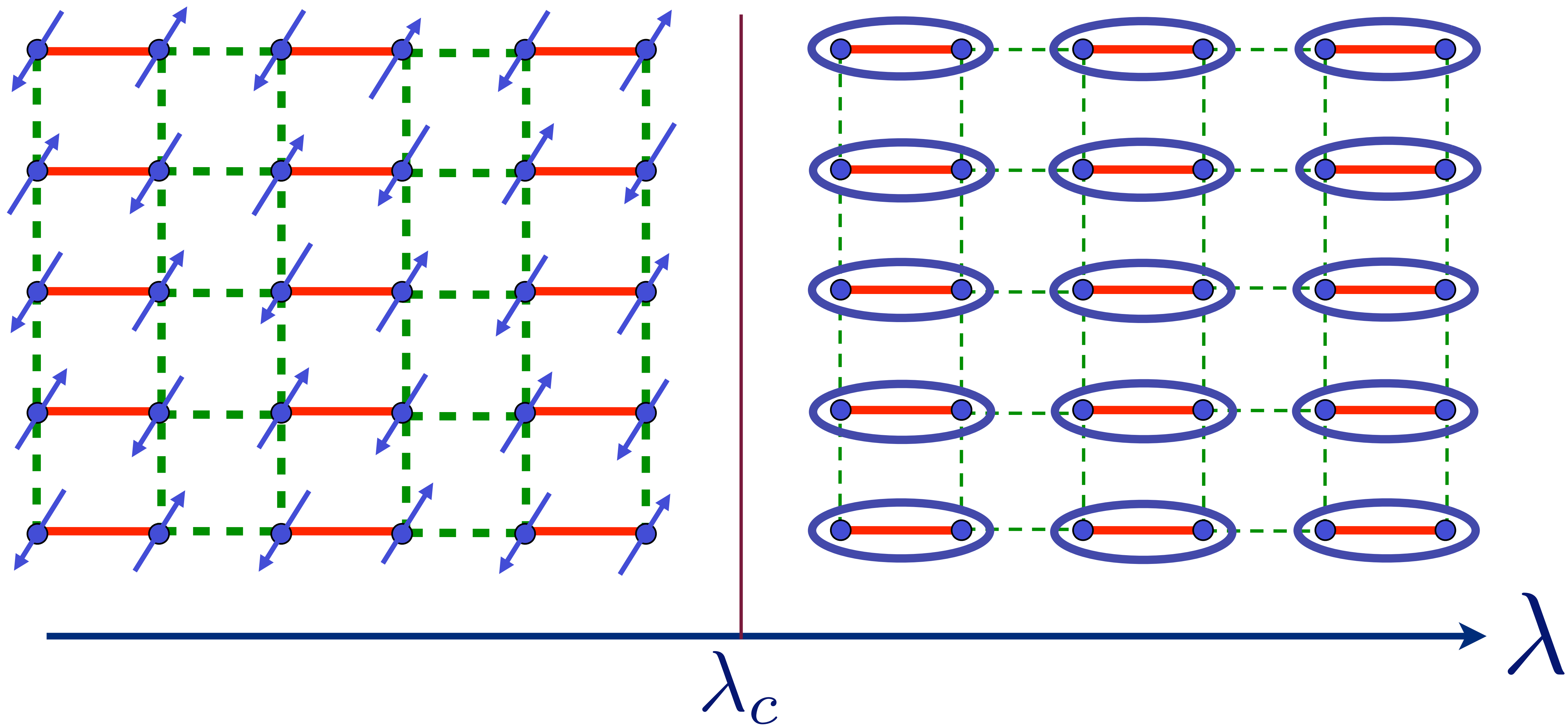
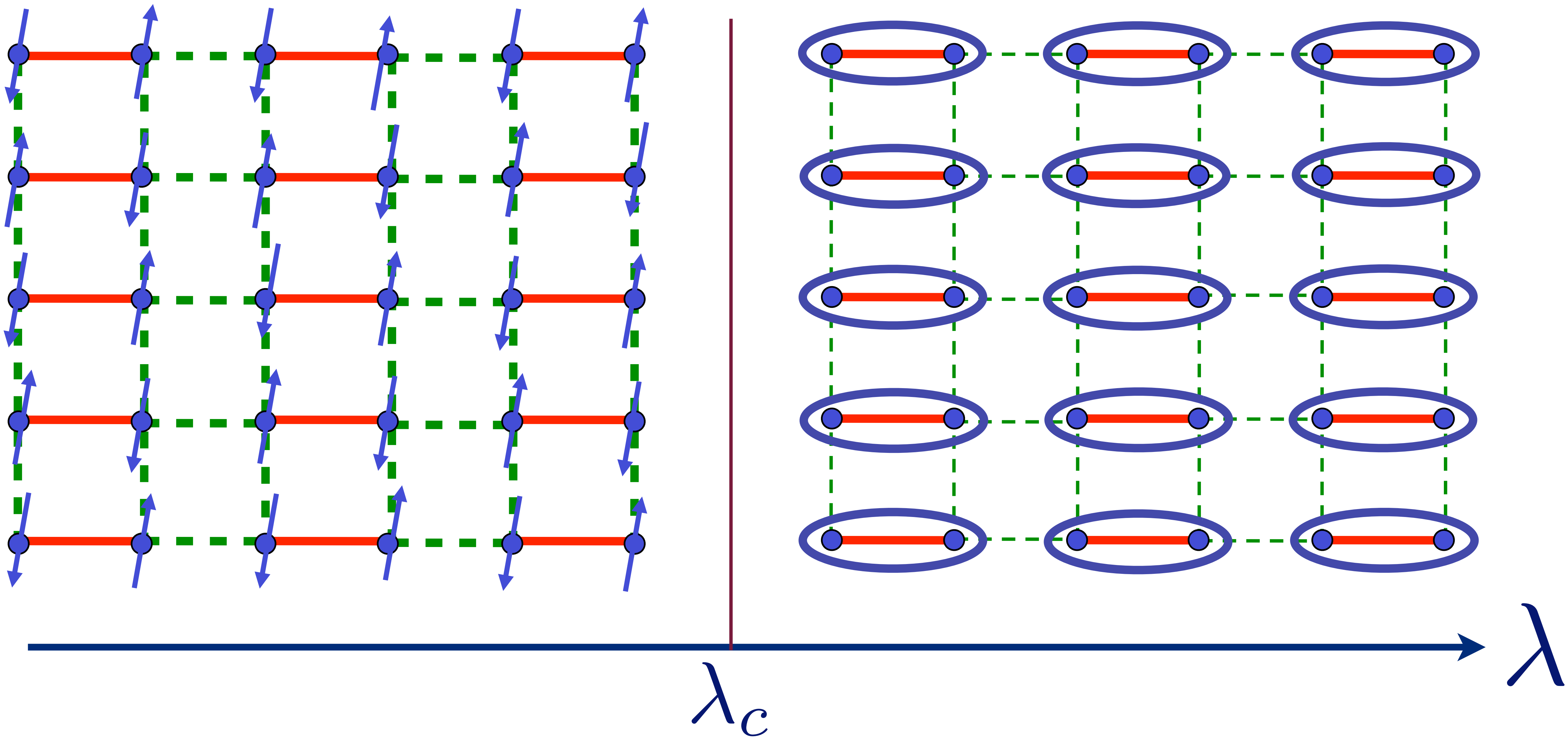
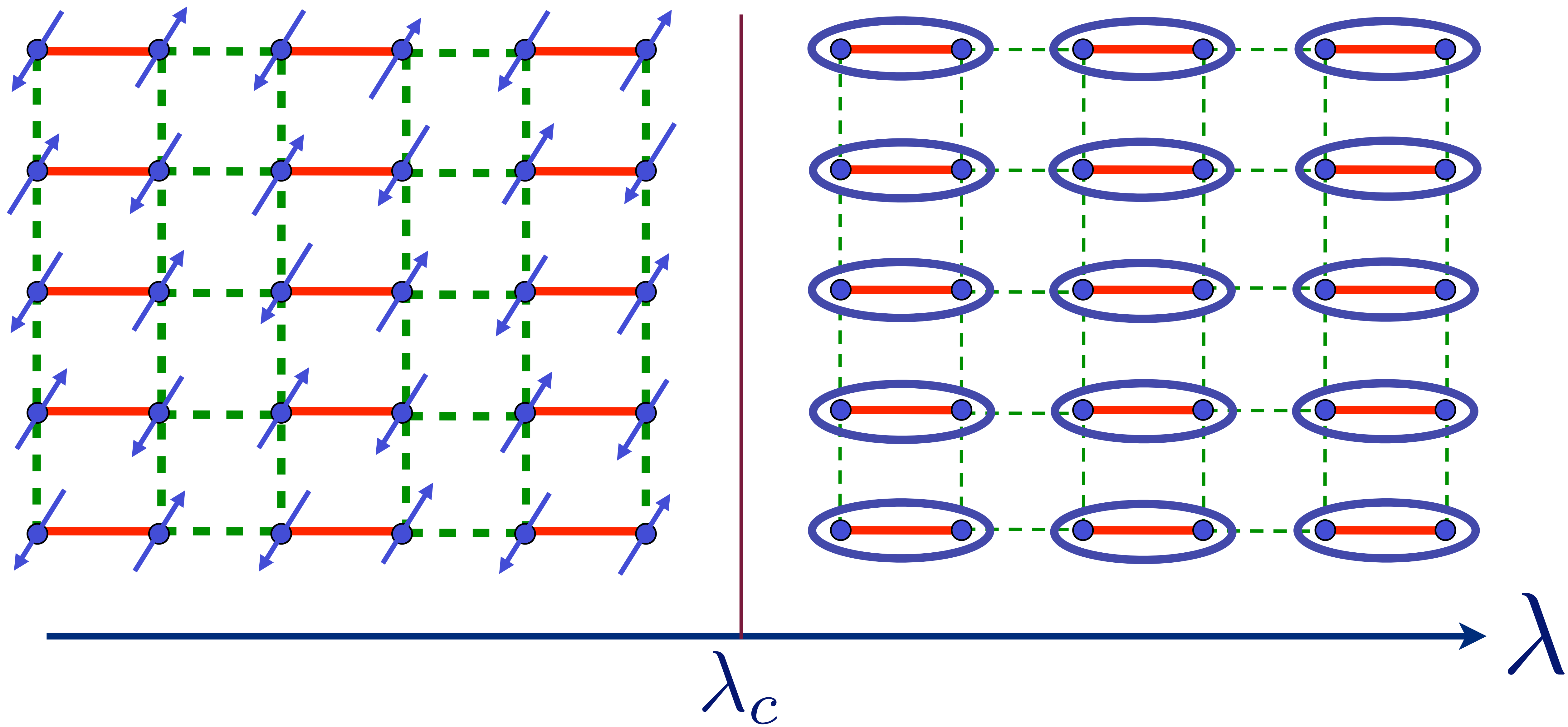


Excitation spectrum in the Néel phase



Spin waves

Excitation spectrum in the Néel phase



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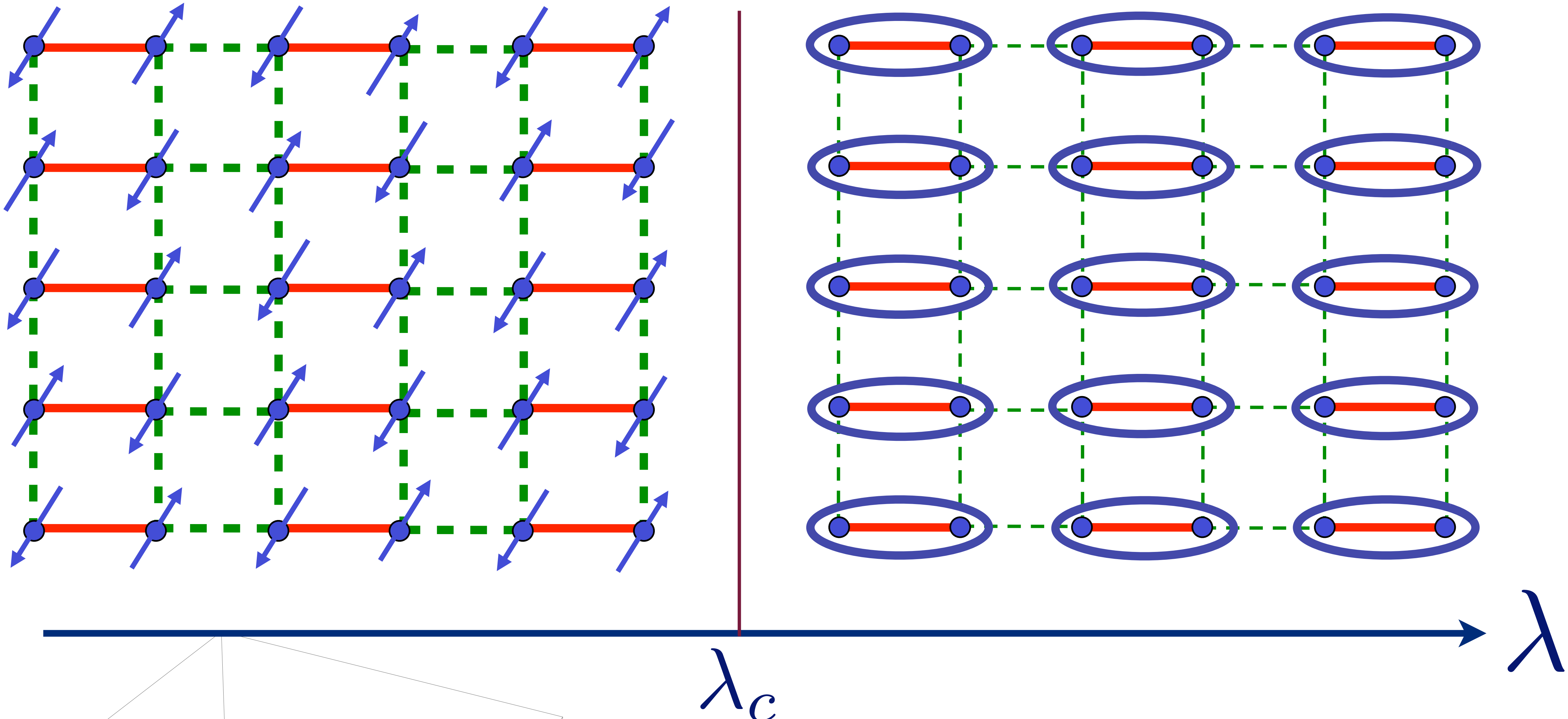

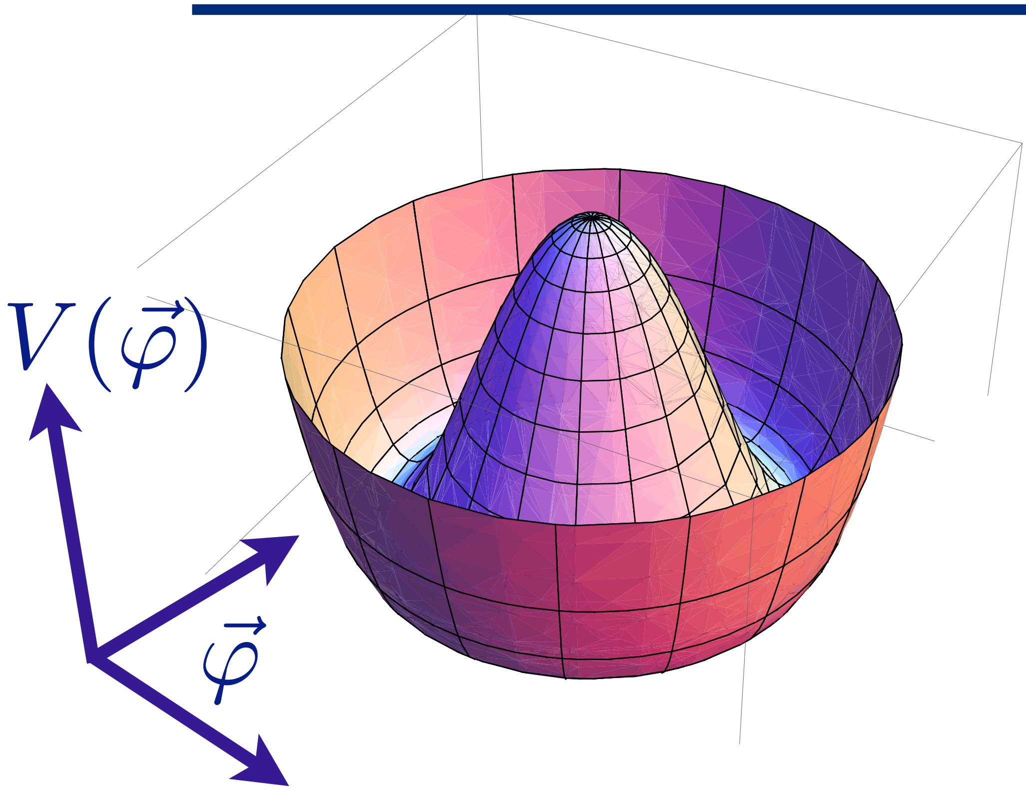

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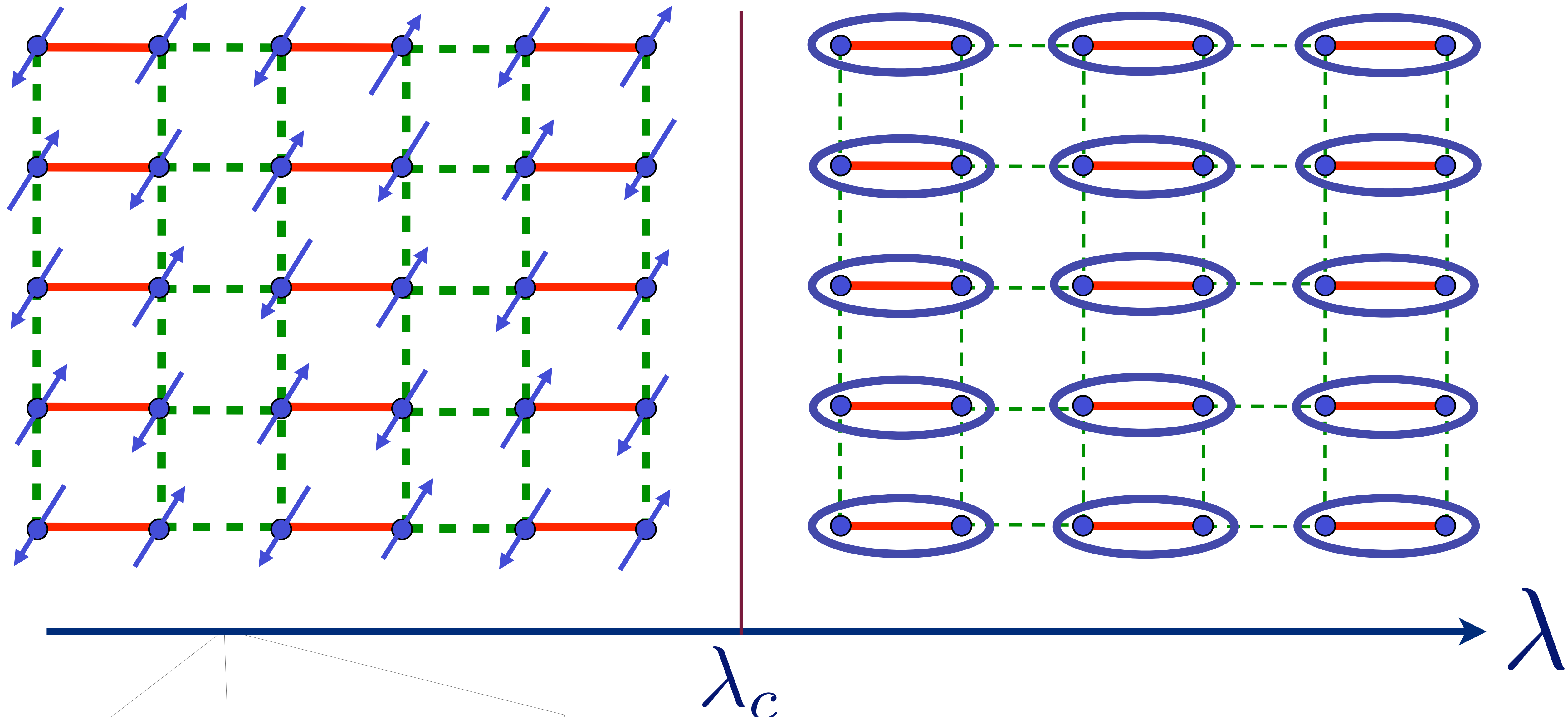

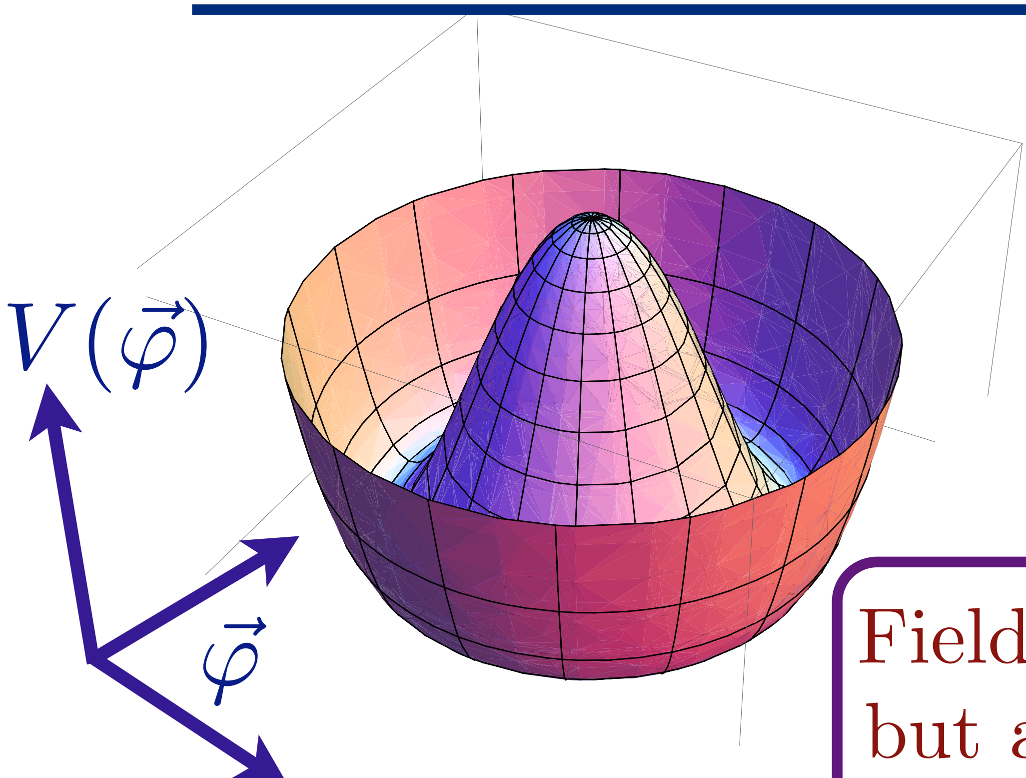

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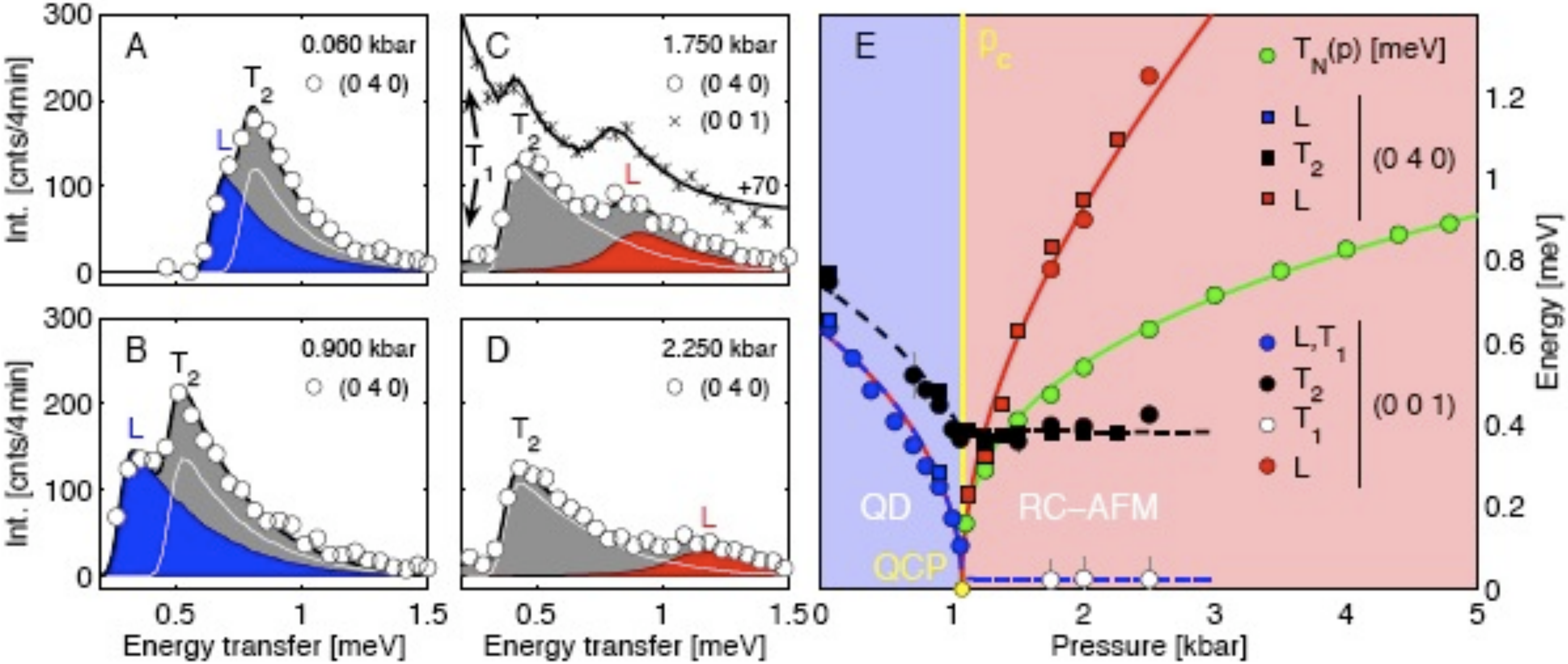
Field theory yields spin waves ("Goldstone" modes)
but also an additional longitudinal "Higgs" particle

$TlCuCl_3$ with varying pressure



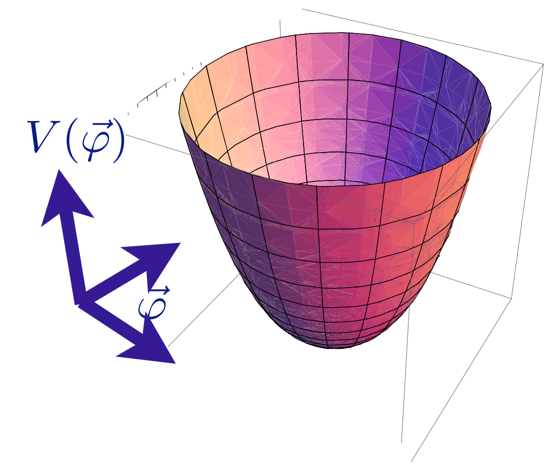
Observation of 3 → 2 low energy modes,
emergence of new Higgs particle in the Néel phase,
and vanishing of Néel temperature at the quantum critical point

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

Potential for $\vec{\varphi}$ fluctuations: $V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$

Paramagnetic phase, $\lambda > \lambda_c$



Expand about $\vec{\varphi} = 0$:

$$V(\vec{\varphi}) \approx (\lambda - \lambda_c)\vec{\varphi}^2$$

Yields 3 particles with energy gap $\sim \sqrt{(\lambda - \lambda_c)}$

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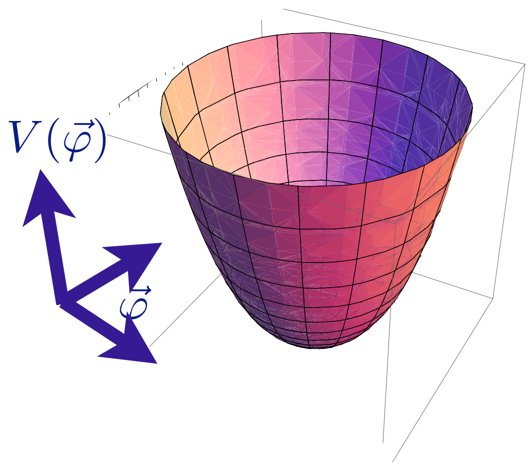

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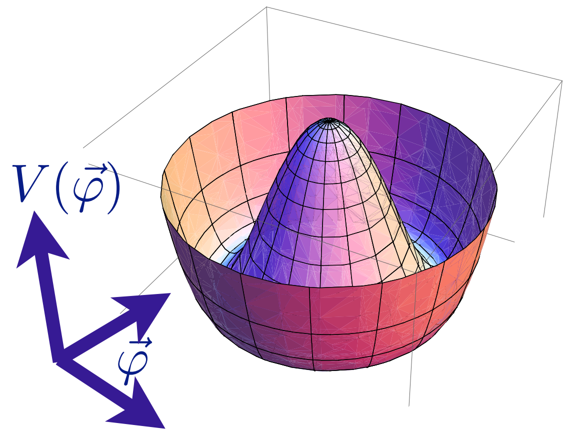
Néel phase, $\lambda < \lambda_c$



Expand $\vec{\varphi} = \left(0, 0, \sqrt{(\lambda_c - \lambda)/(2u)}\right) + \vec{\varphi}_1$:

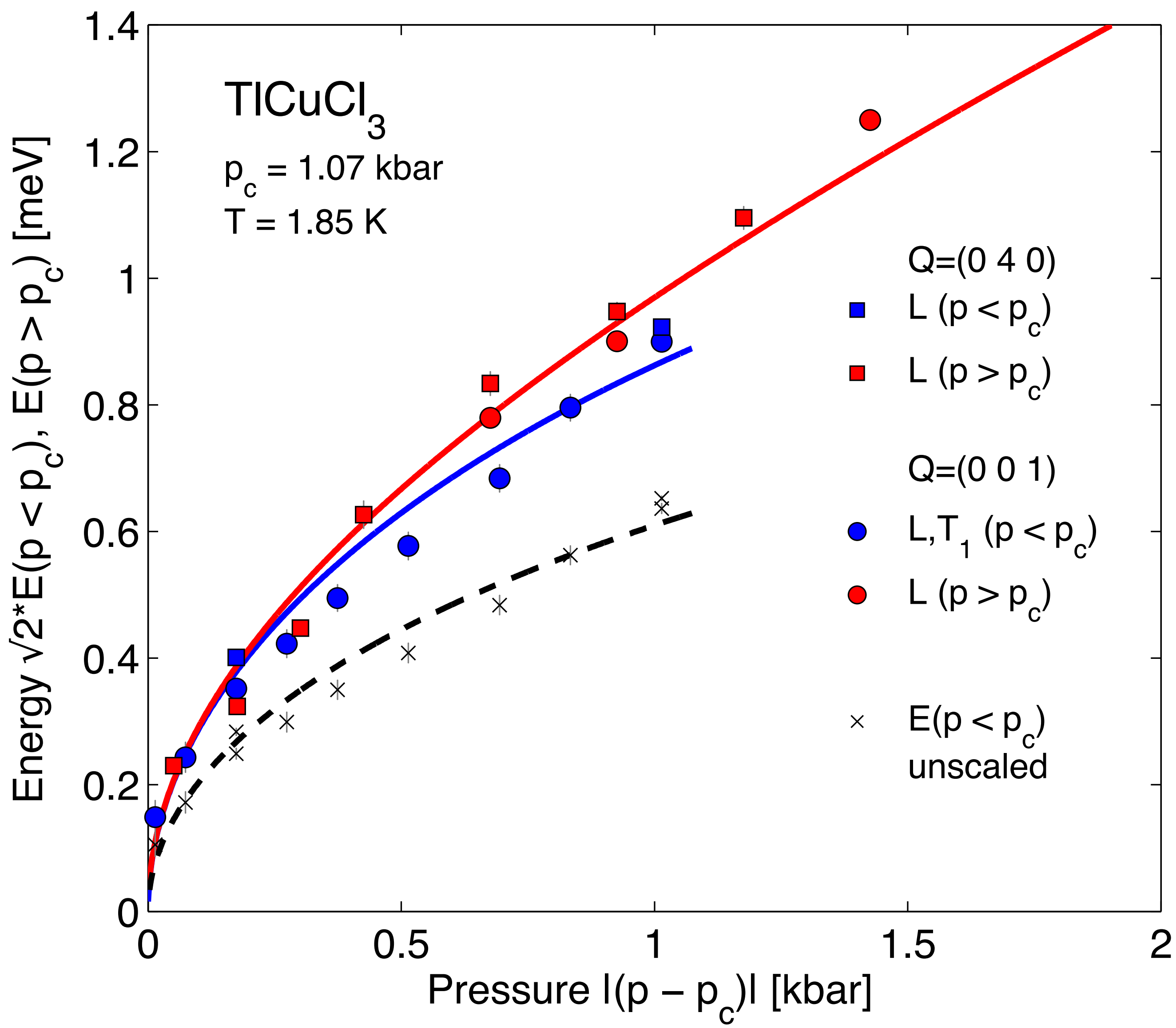
$$V(\vec{\varphi}) \approx 2(\lambda_c - \lambda)\varphi_{1z}^2$$

Yields 2 gapless spin waves and one Higgs particle with energy gap $\sim \sqrt{2(\lambda_c - \lambda)}$

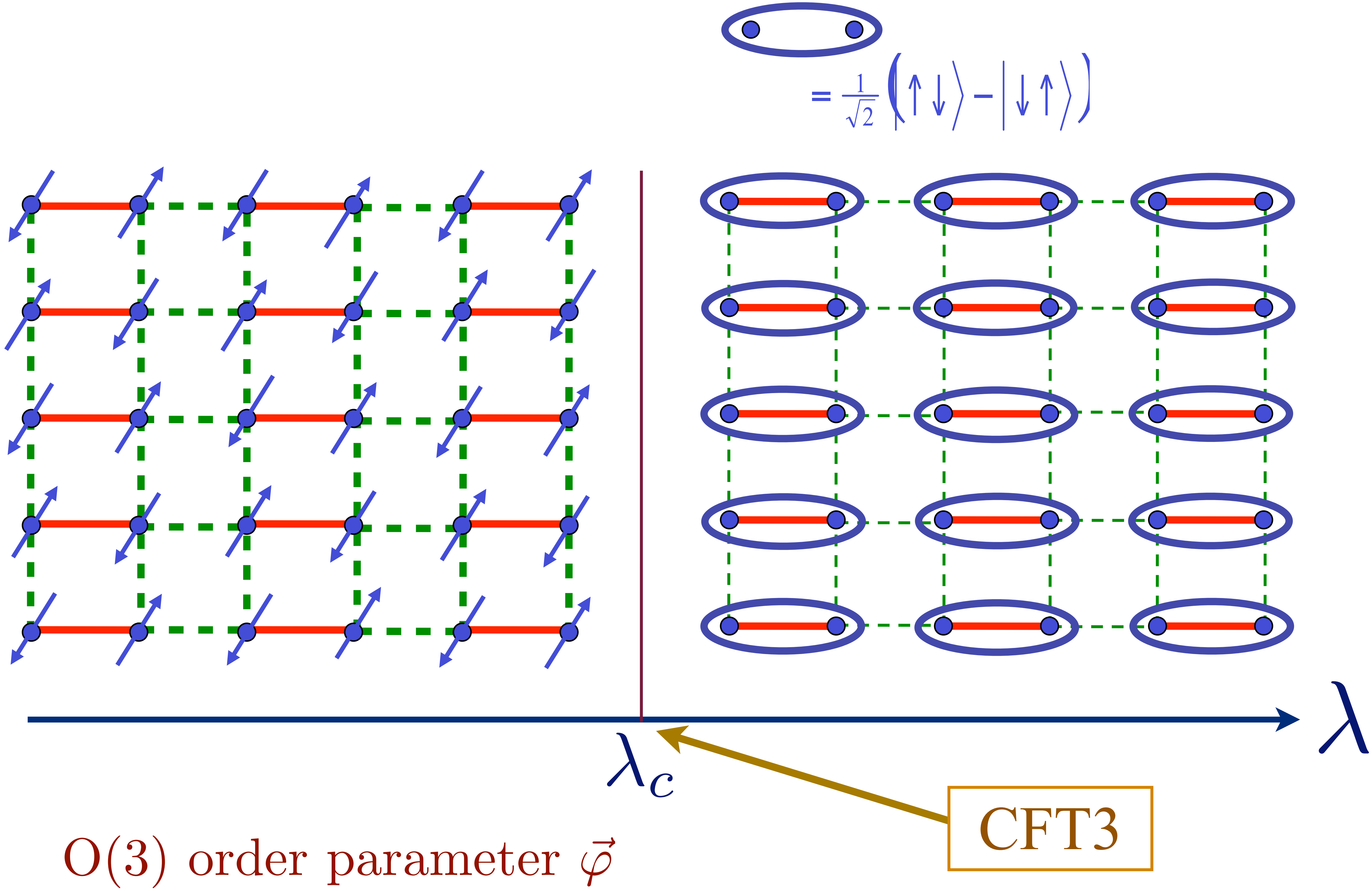
Prediction of quantum field theory

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

$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$



S. Sachdev, arXiv:0901.4103



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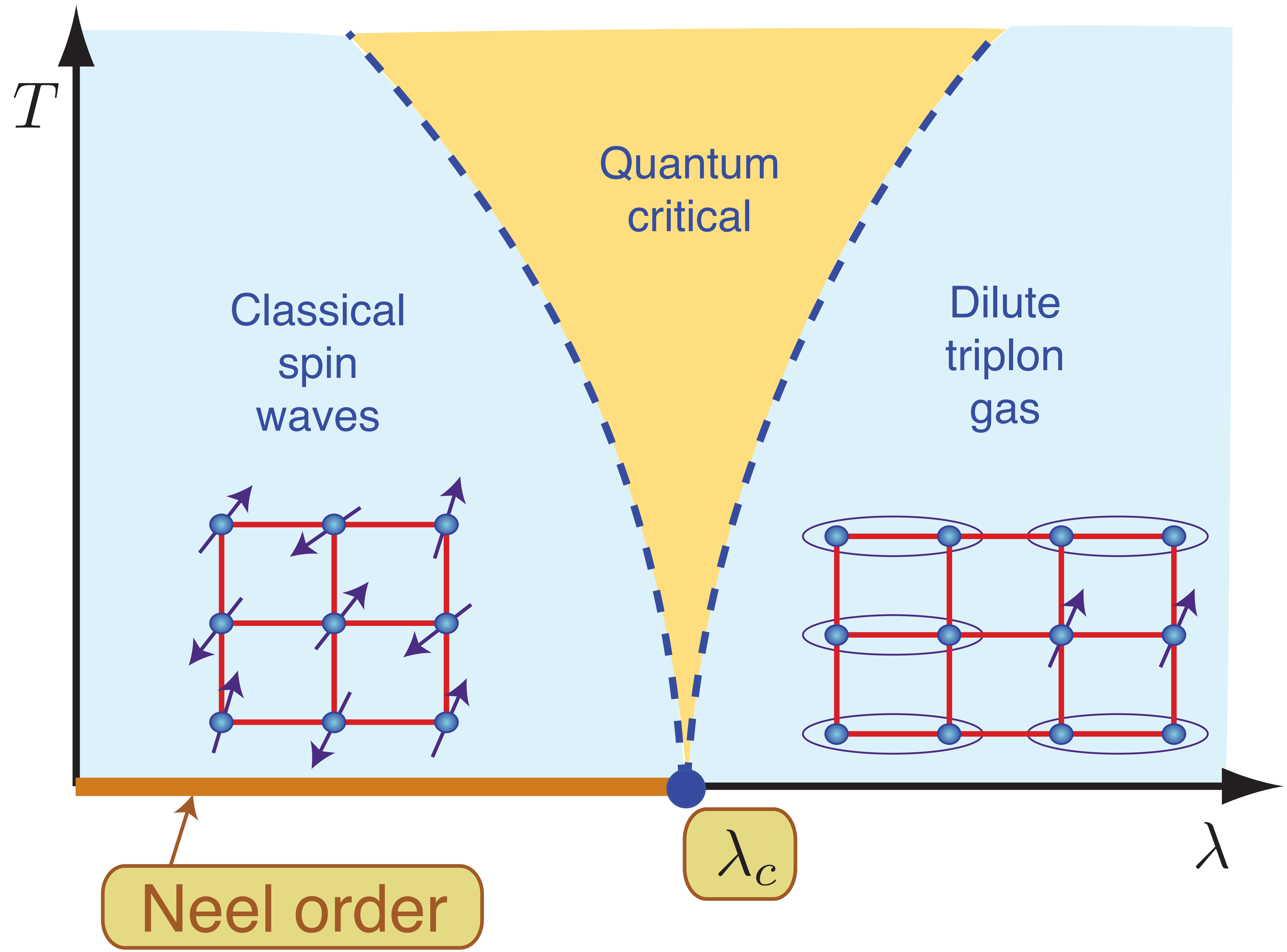
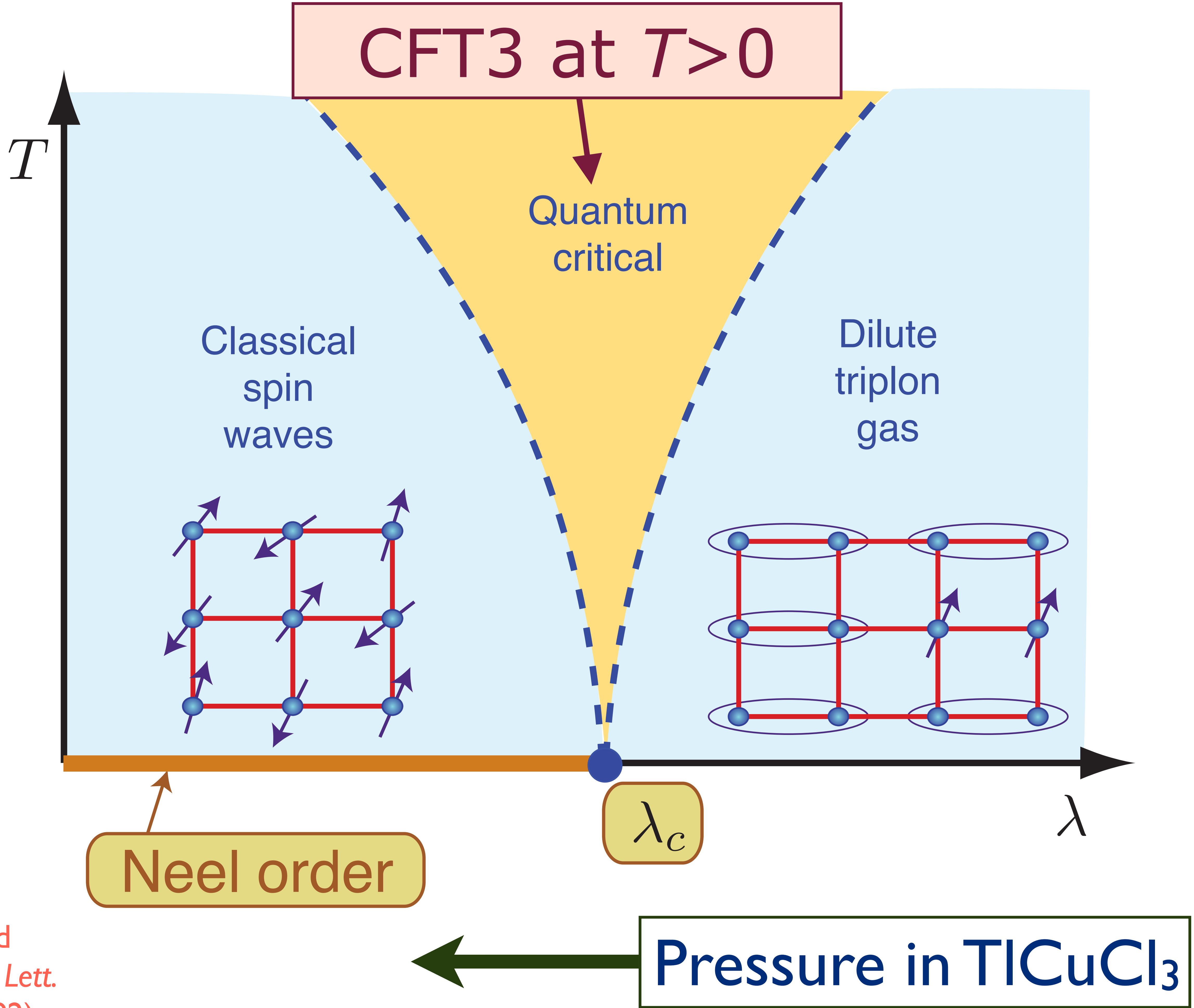


Pressure in $TlCuCl_3$

S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).



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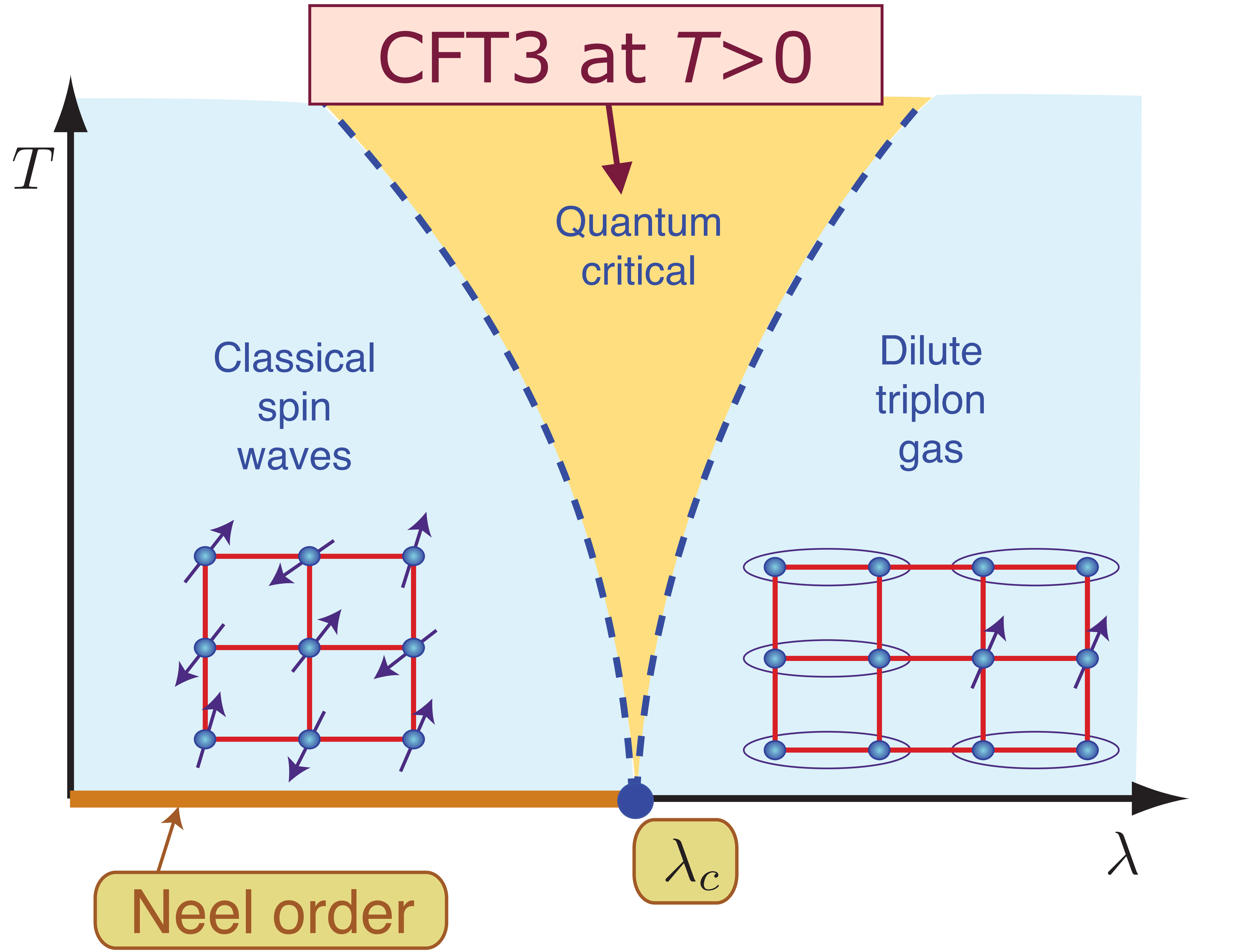
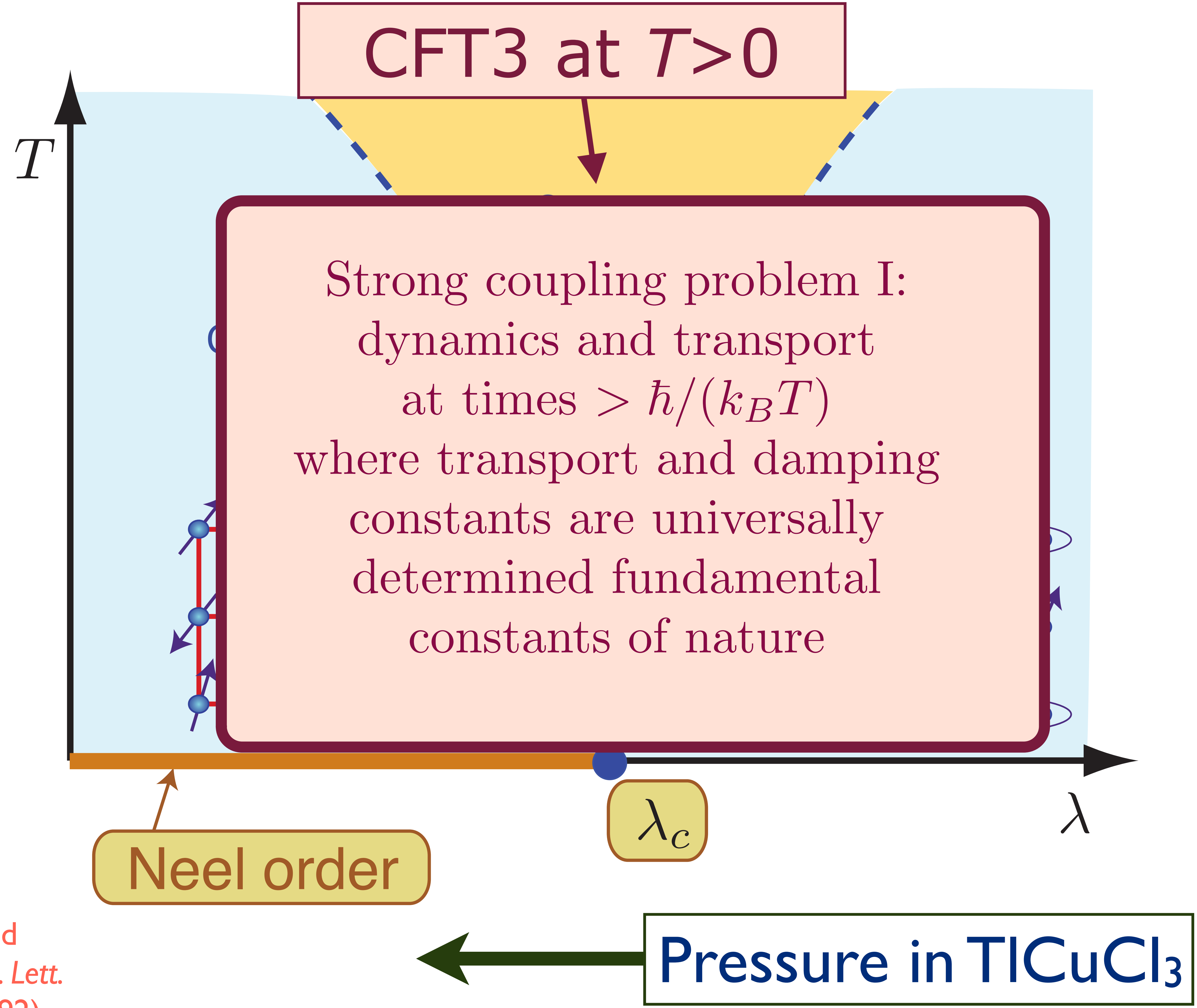


S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).



Strong coupling problem I:
dynamics and transport
at times $> \hbar/(k_B T)$
where transport and damping
constants are universally
determined fundamental
constants of nature

S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).

Outline

1. Coupled dimer antiferromagnets
   Introduction to quantum criticality

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   Strongly-coupled field theory

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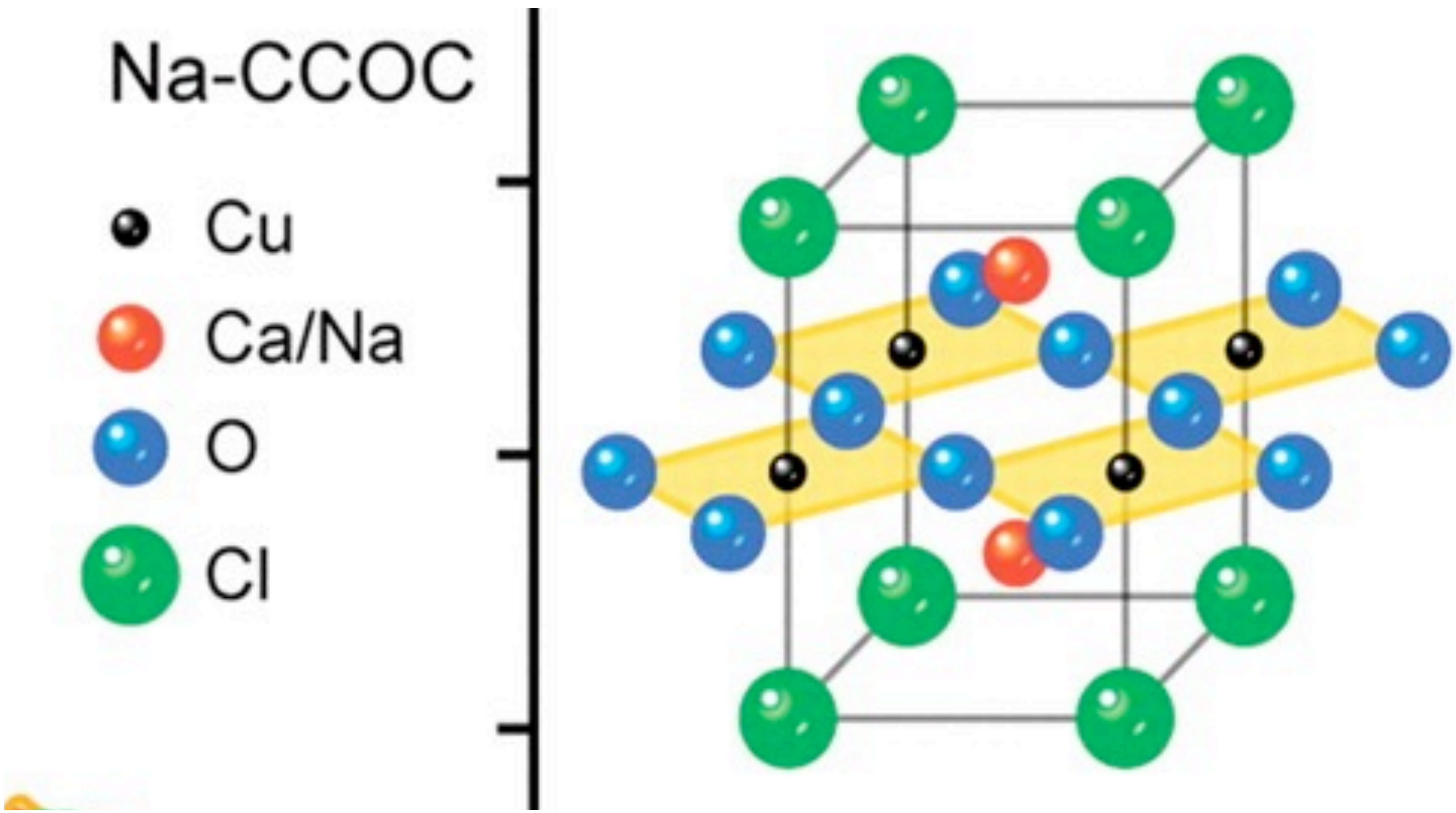
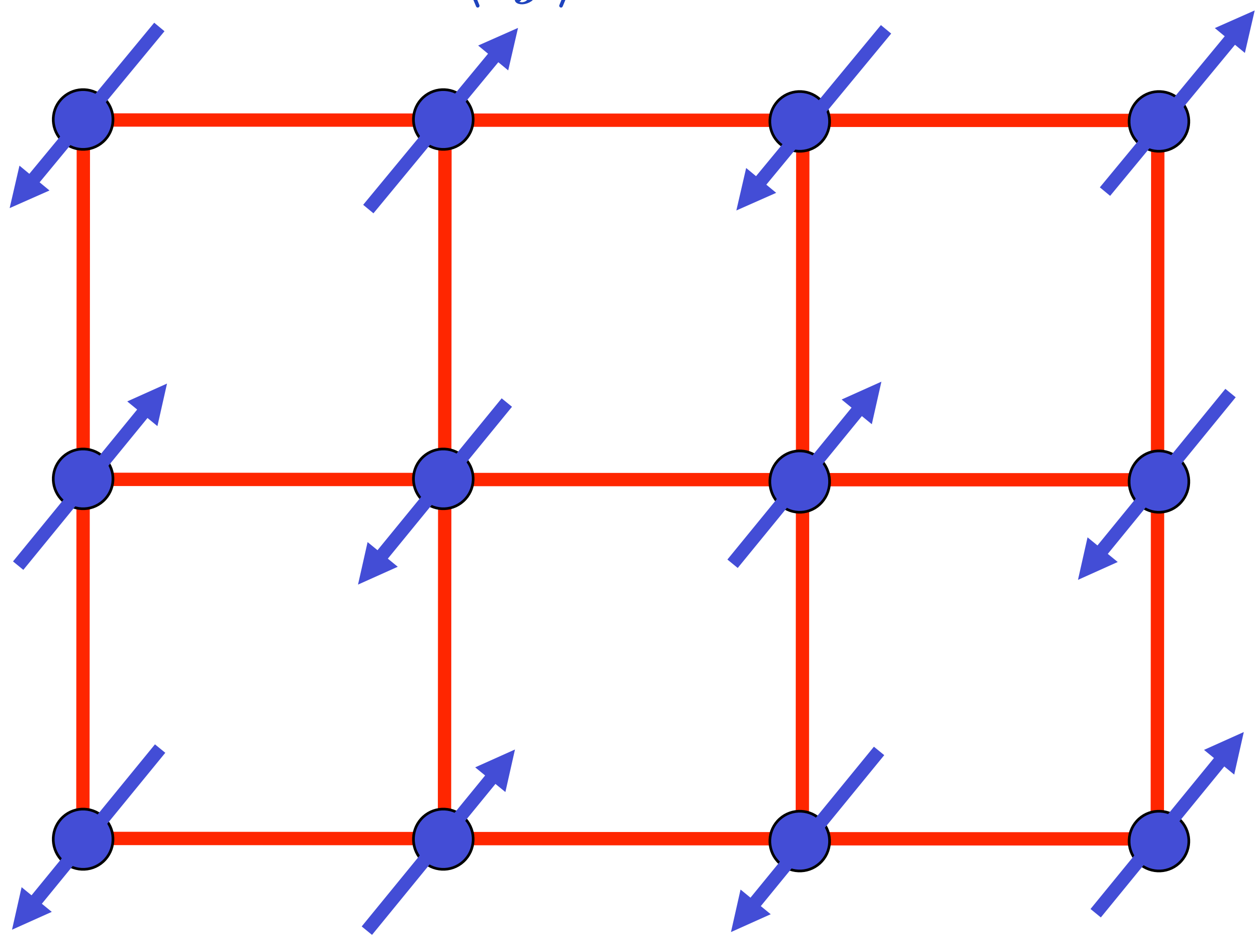
The cuprate superconductors



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.

Doped square lattice antiferromagnet

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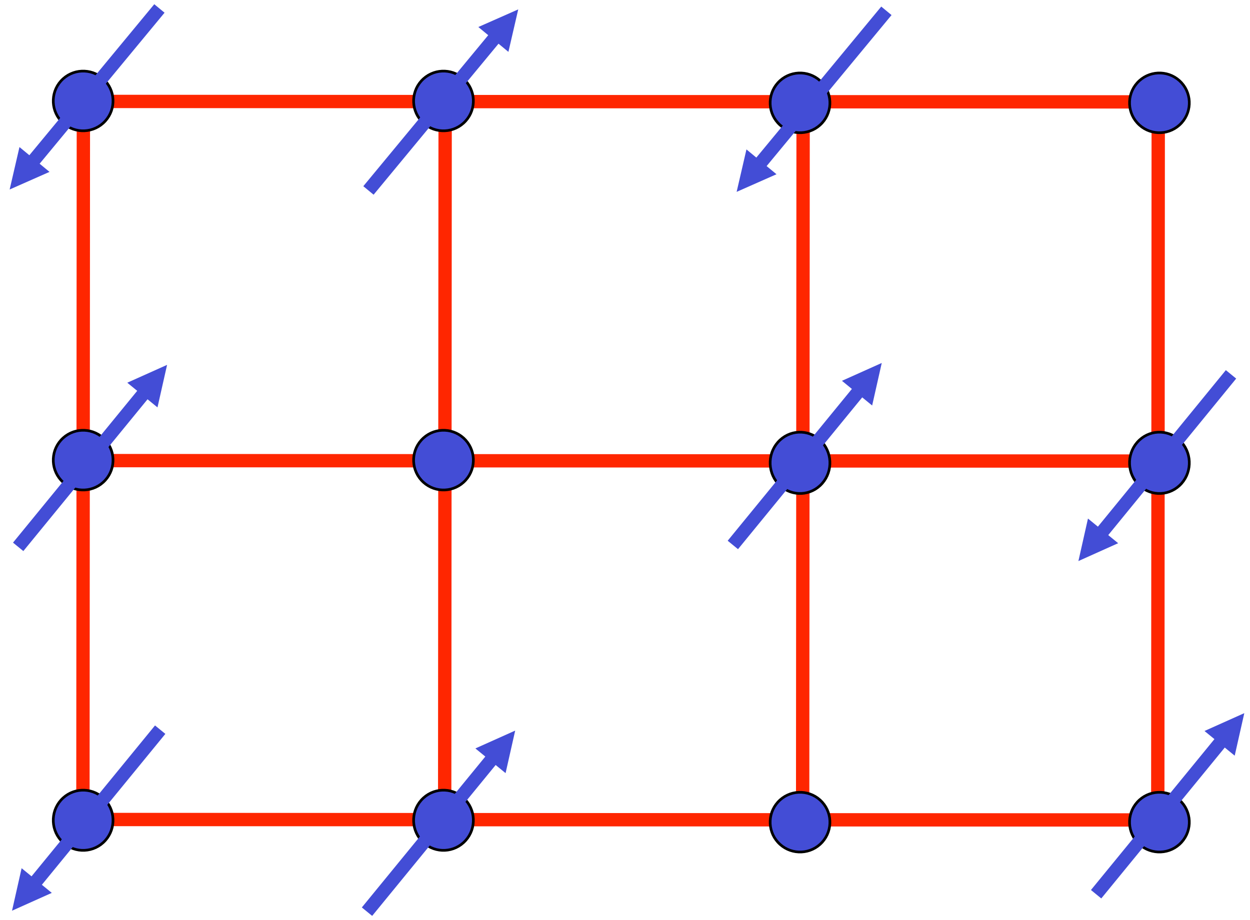

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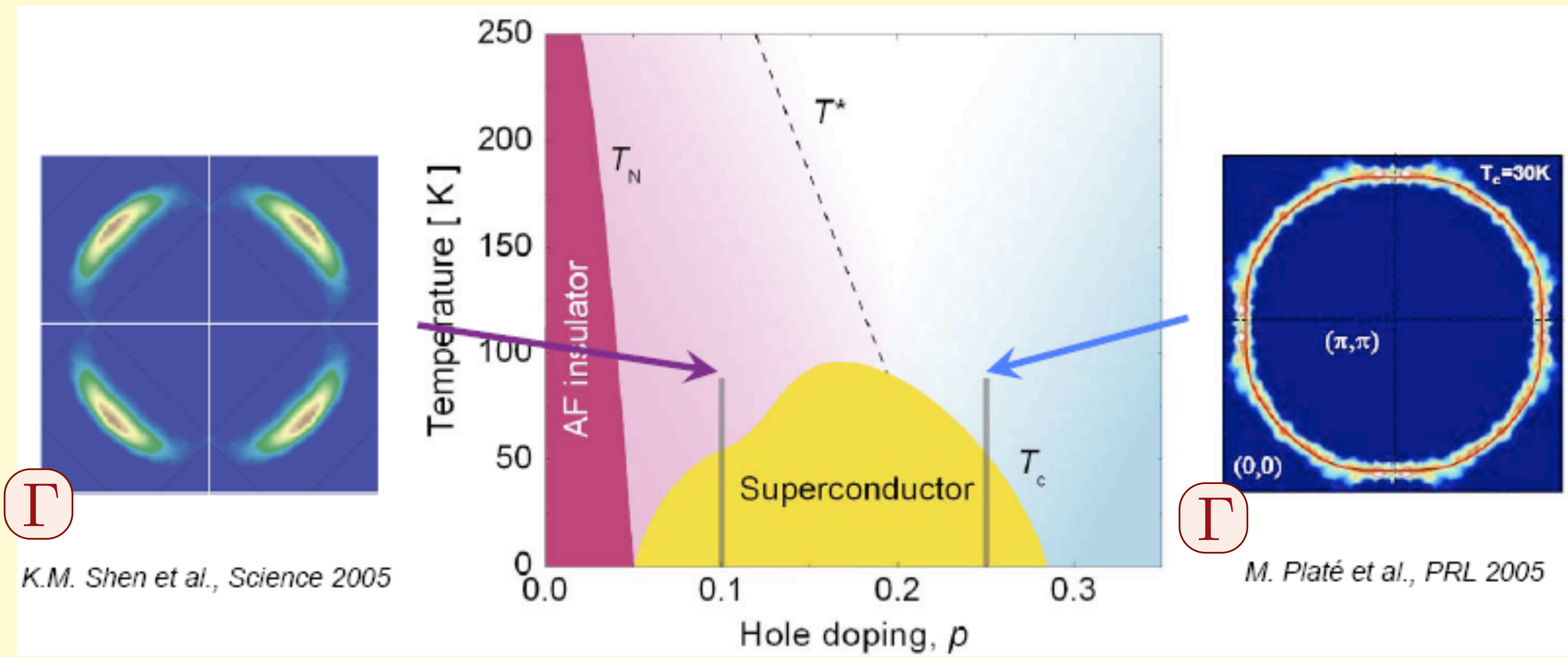
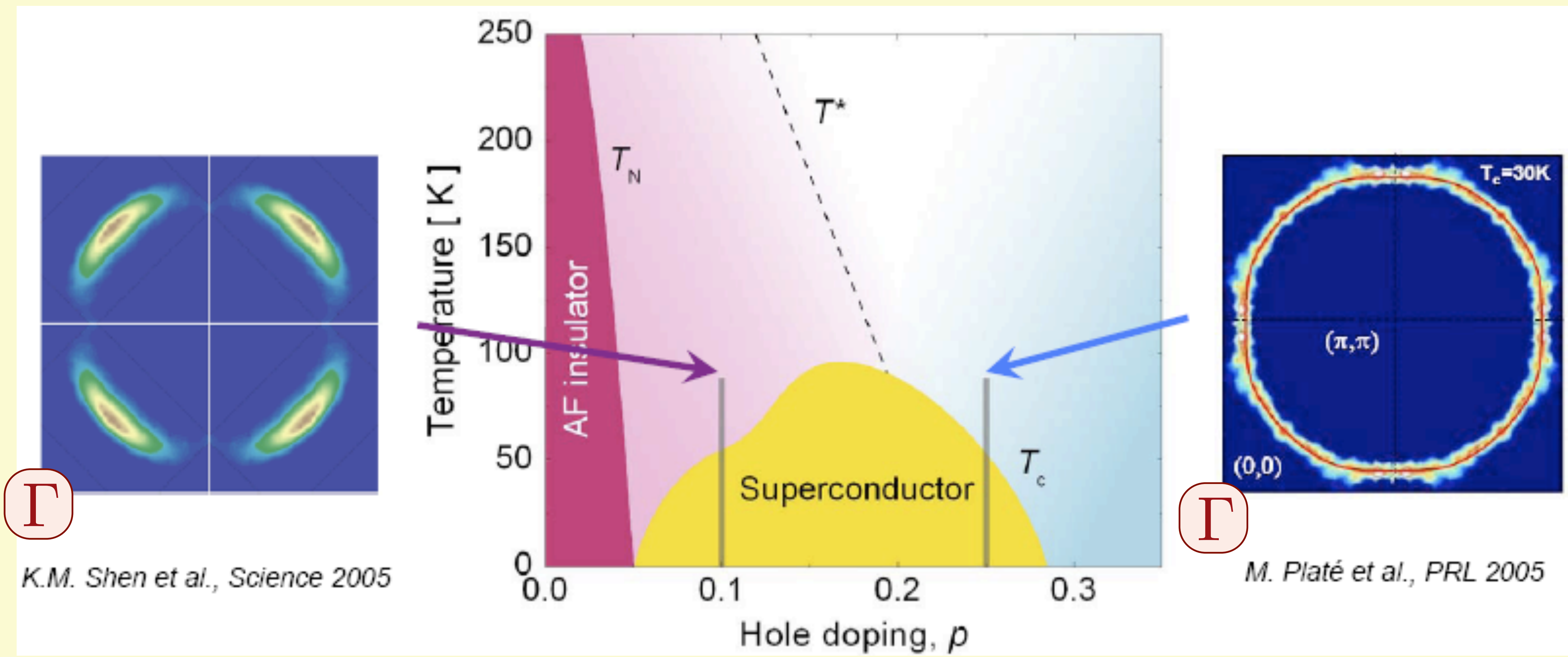
Central ingredients in cuprate phase diagram: antiferromagnetism, superconductivity, and change in Fermi surface



Smaller hole Fermi-pockets

Large hole Fermi surface

Central ingredients in cuprate phase diagram: antiferromagnetism, superconductivity, and change in Fermi surface



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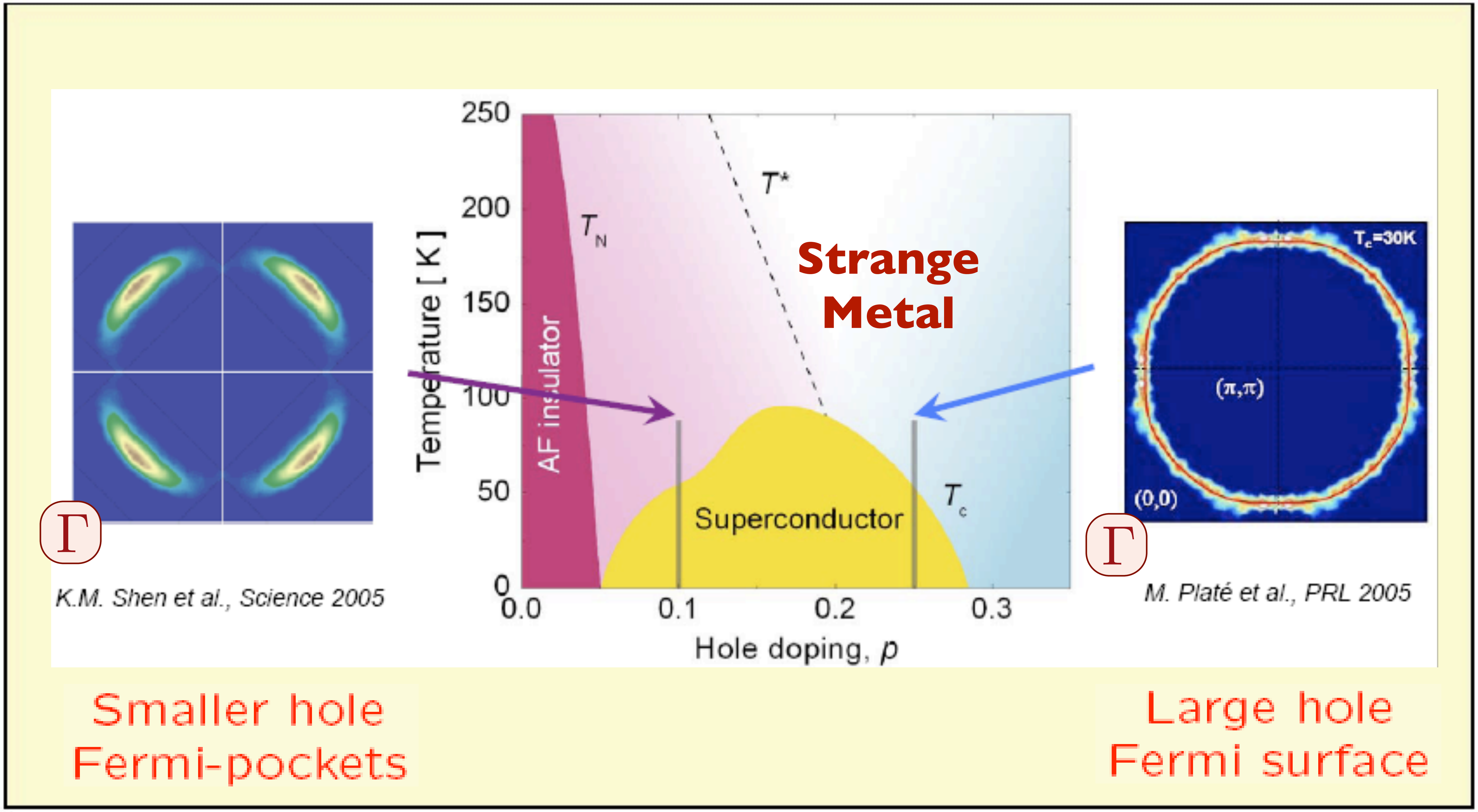
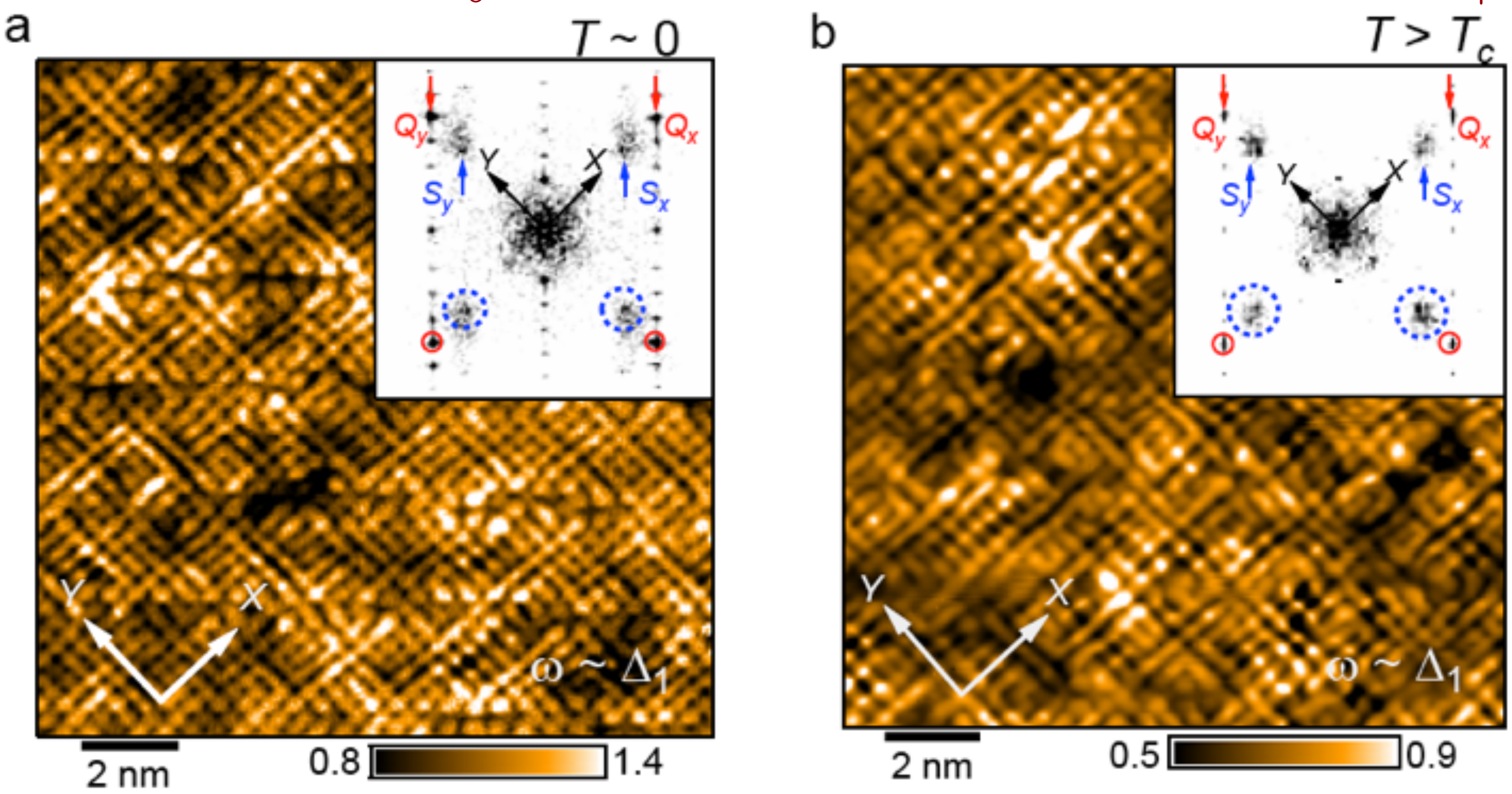


STM measurements of $Z(r)$, the energy asymmetry in density of states in $Bi_2Sr_2CaCu_2O_{8+\delta}$.



M. J. Lawler, K. Fujita, Jhinhwan Lee, A. R. Schmidt, Y. Kohsaka, Chung Koo Kim, H. Eisaki, S. Uchida, J. C. Davis, J. P. Sethna, and Eun-Ah Kim, preprint

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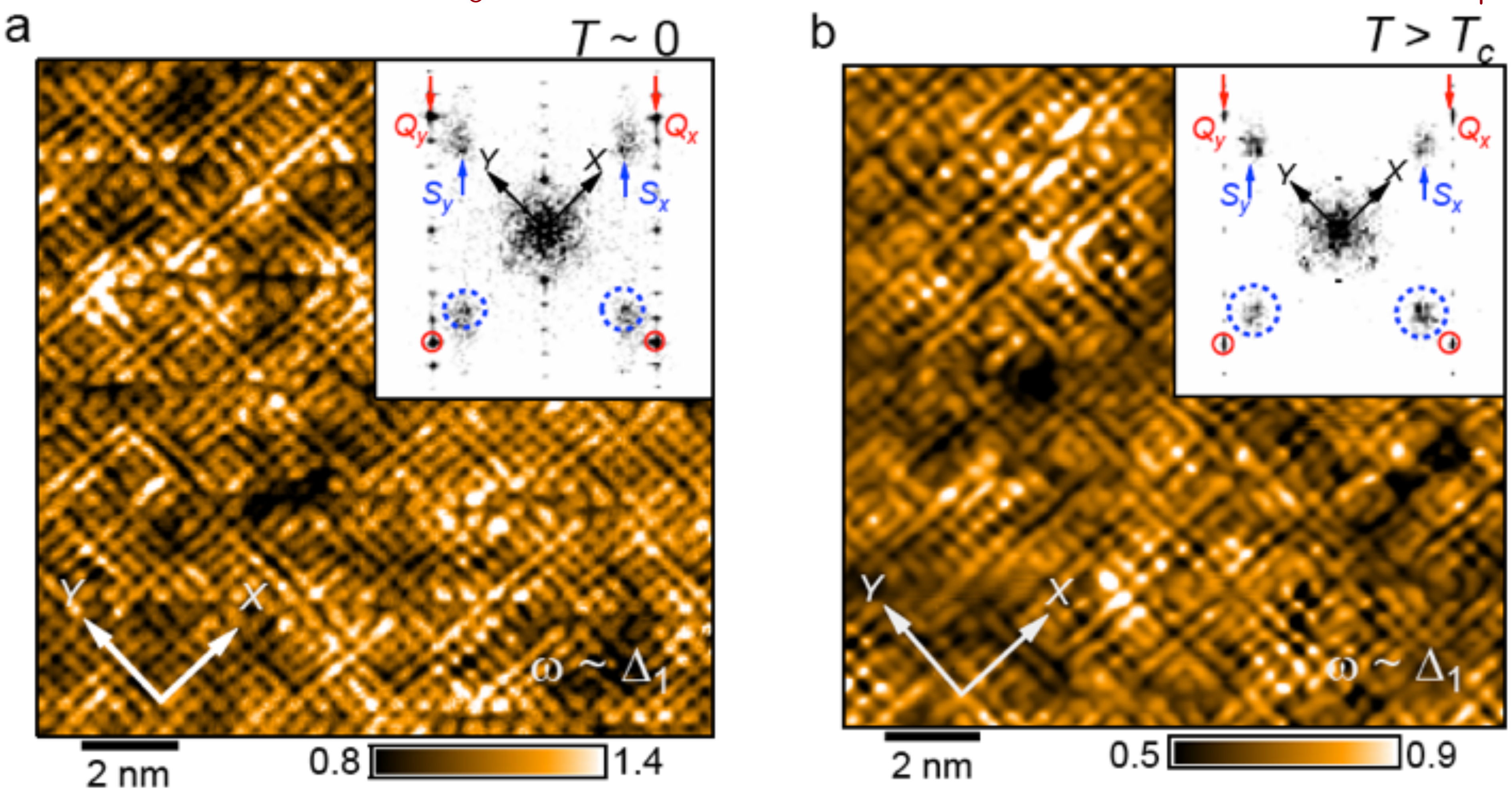

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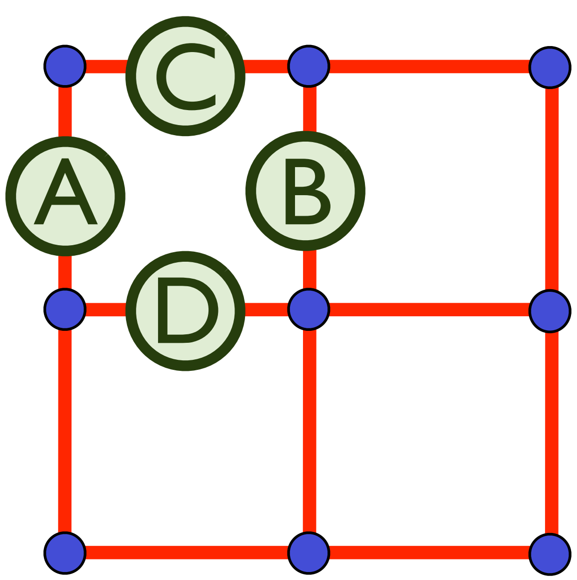

$$O_N = Z_A + Z_B - Z_C - Z_D$$

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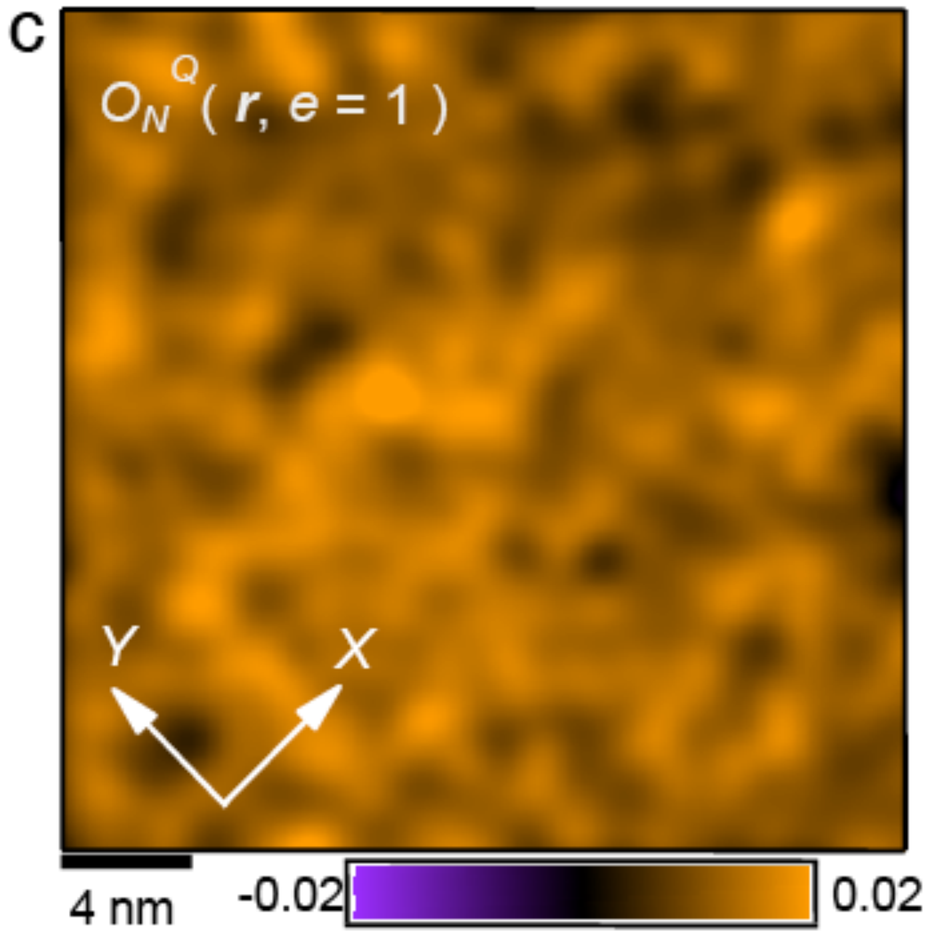

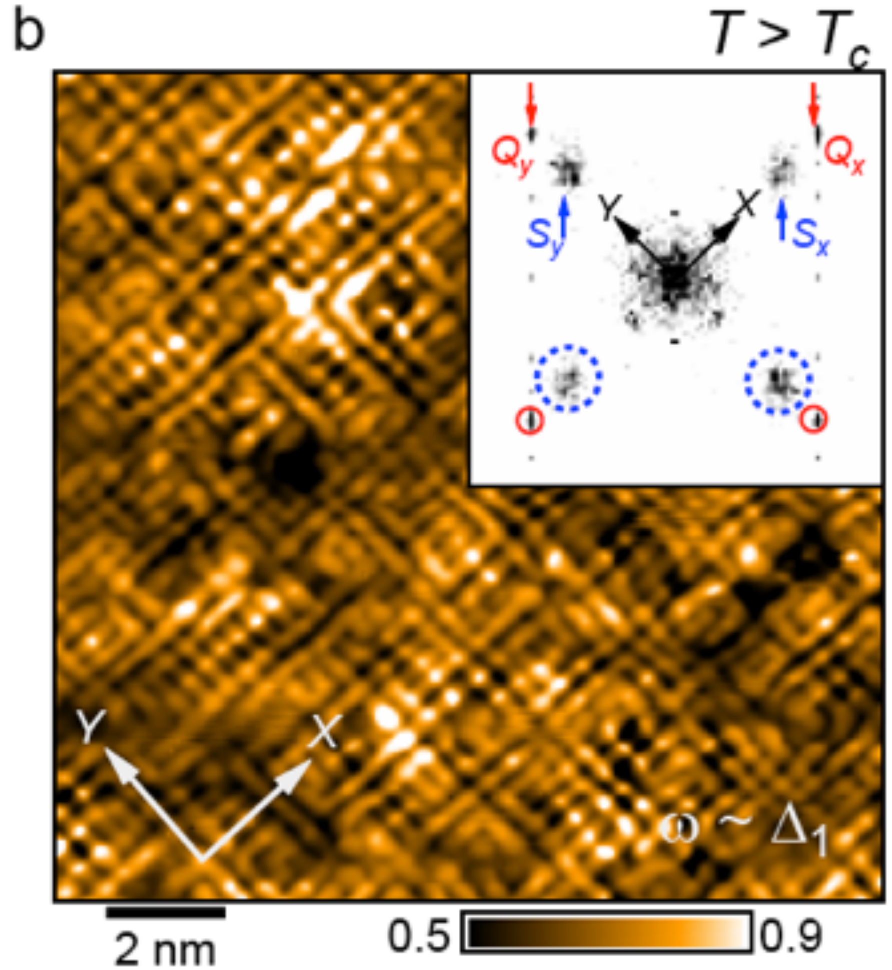

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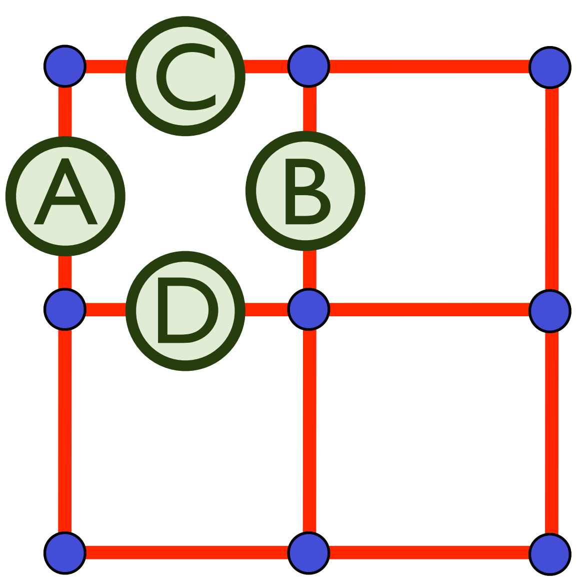
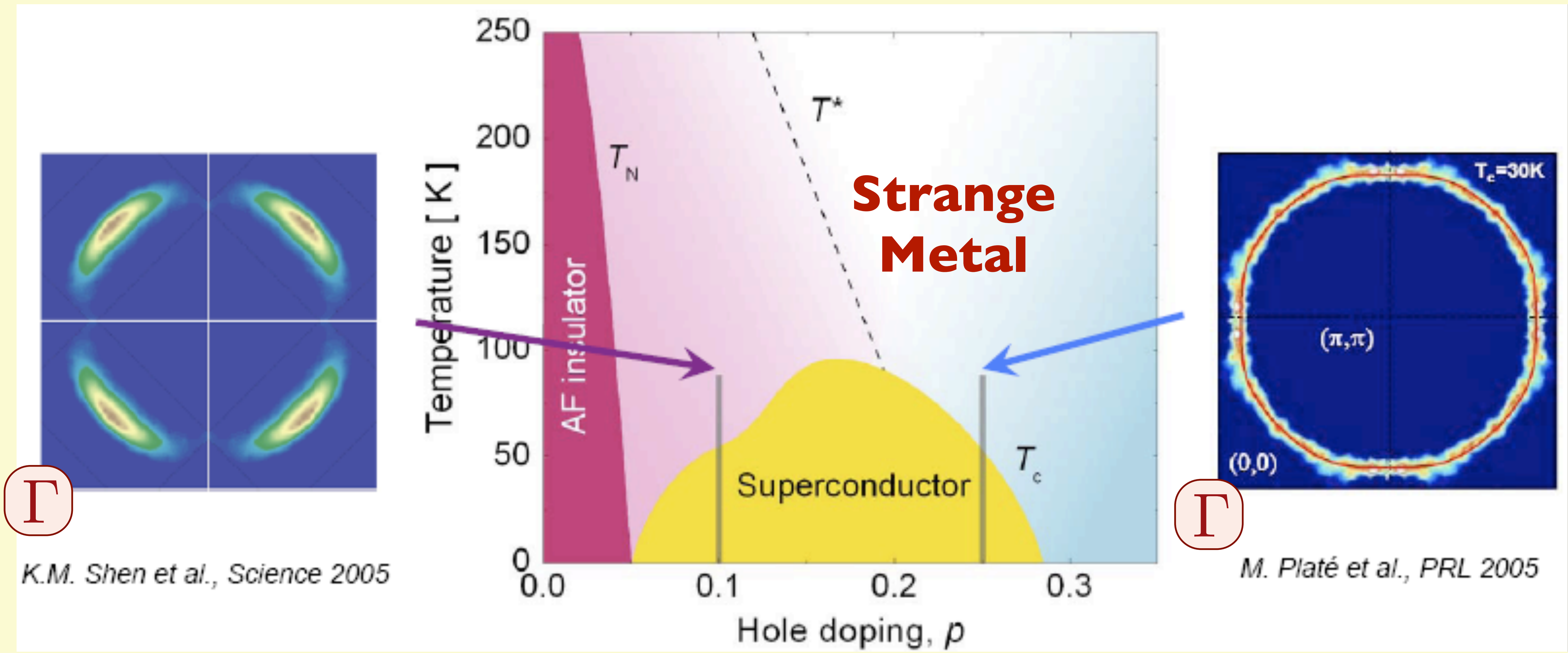


$$O_N = Z_A + Z_B - Z_C - Z_D$$

Strong anisotropy of electronic states between *x* and *y* directions: Electronic "Ising-nematic" order

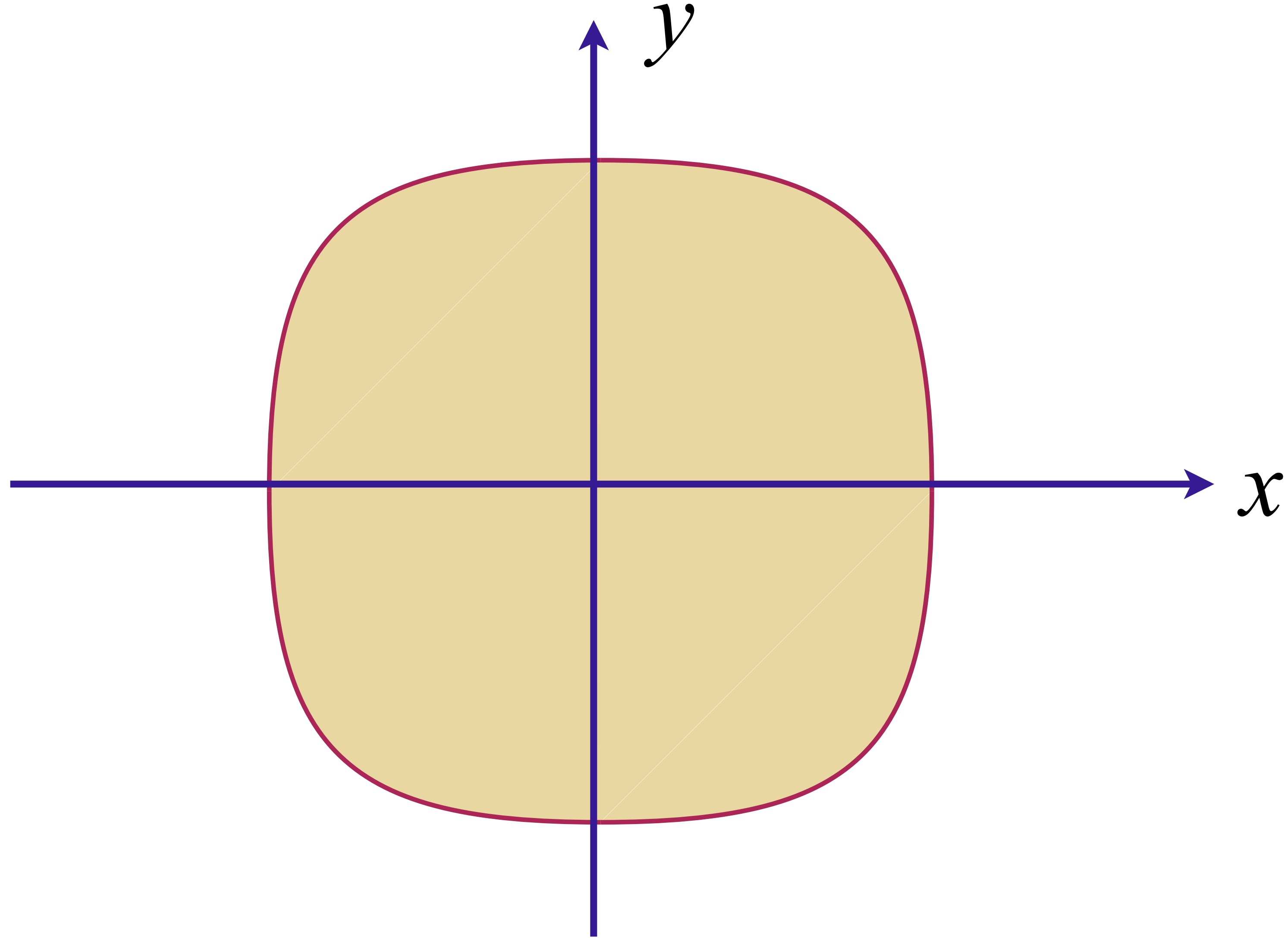
Central ingredients in cuprate phase diagram: antiferromagnetism, superconductivity, and change in Fermi surface



Smaller hole Fermi-pockets

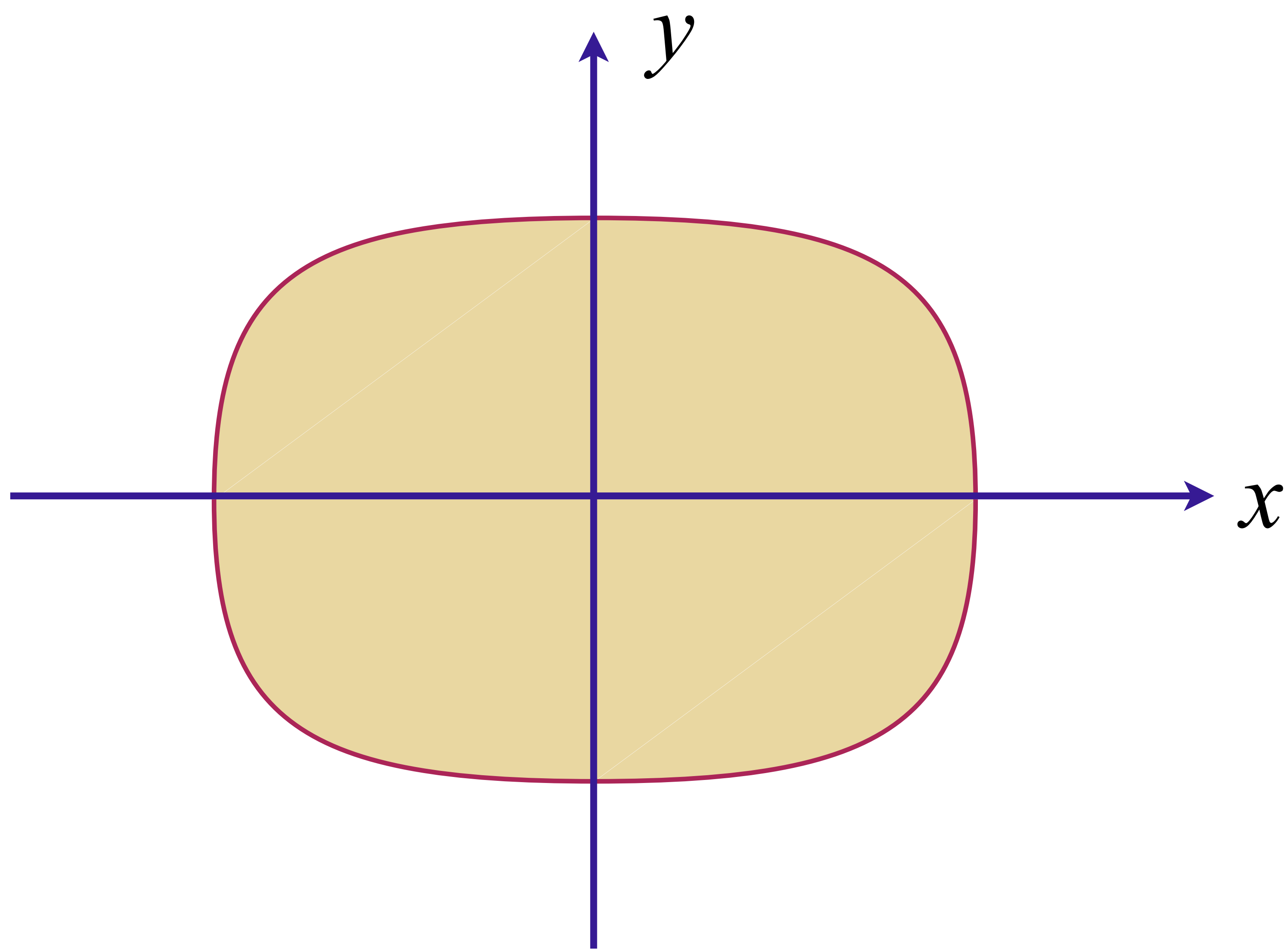
Large hole Fermi surface

Quantum criticality of Ising-nematic ordering



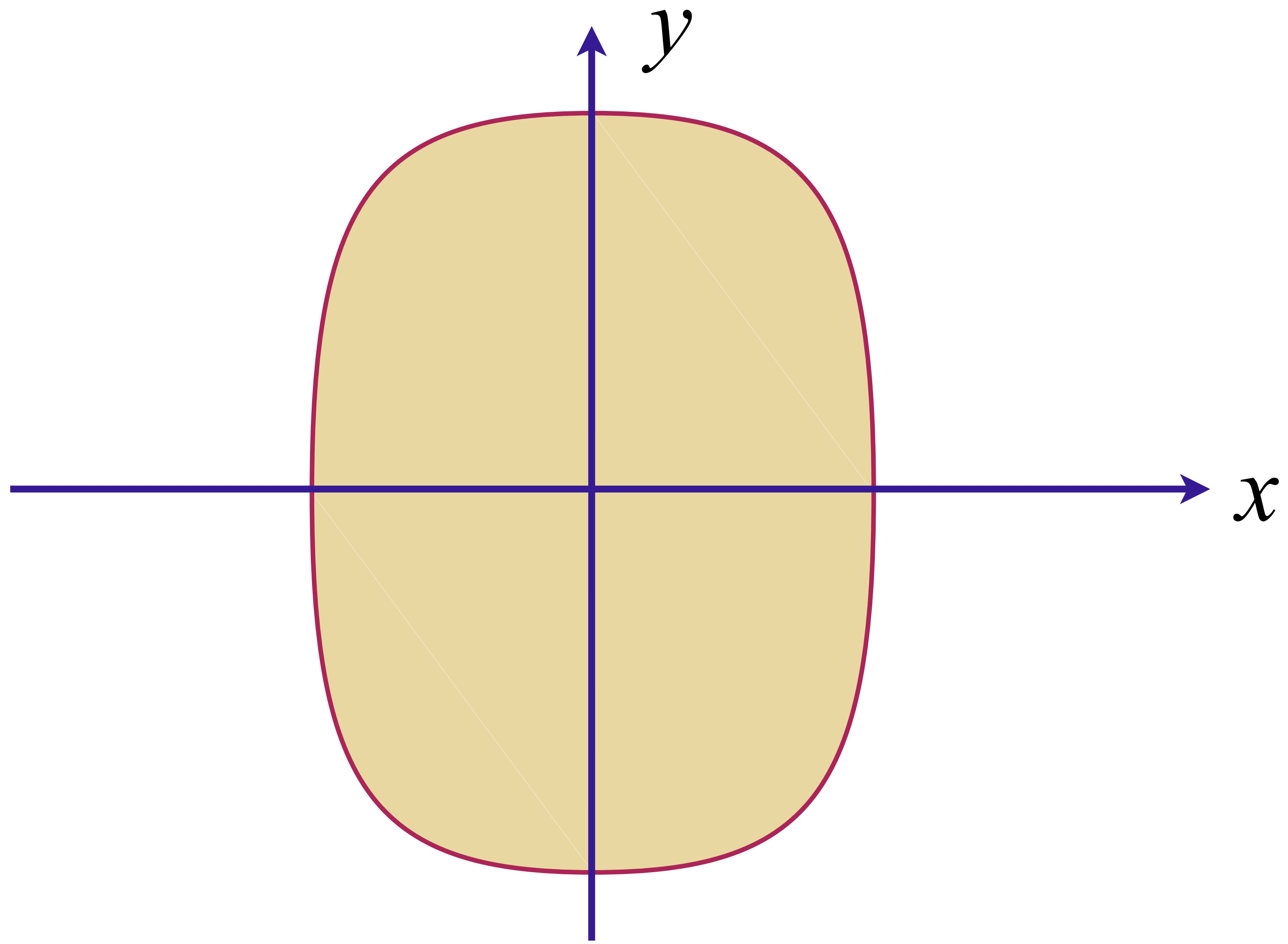
Fermi surface with full square lattice symmetry

Quantum criticality of Ising-nematic ordering



Spontaneous elongation along x direction:

Quantum criticality of Ising-nematic ordering



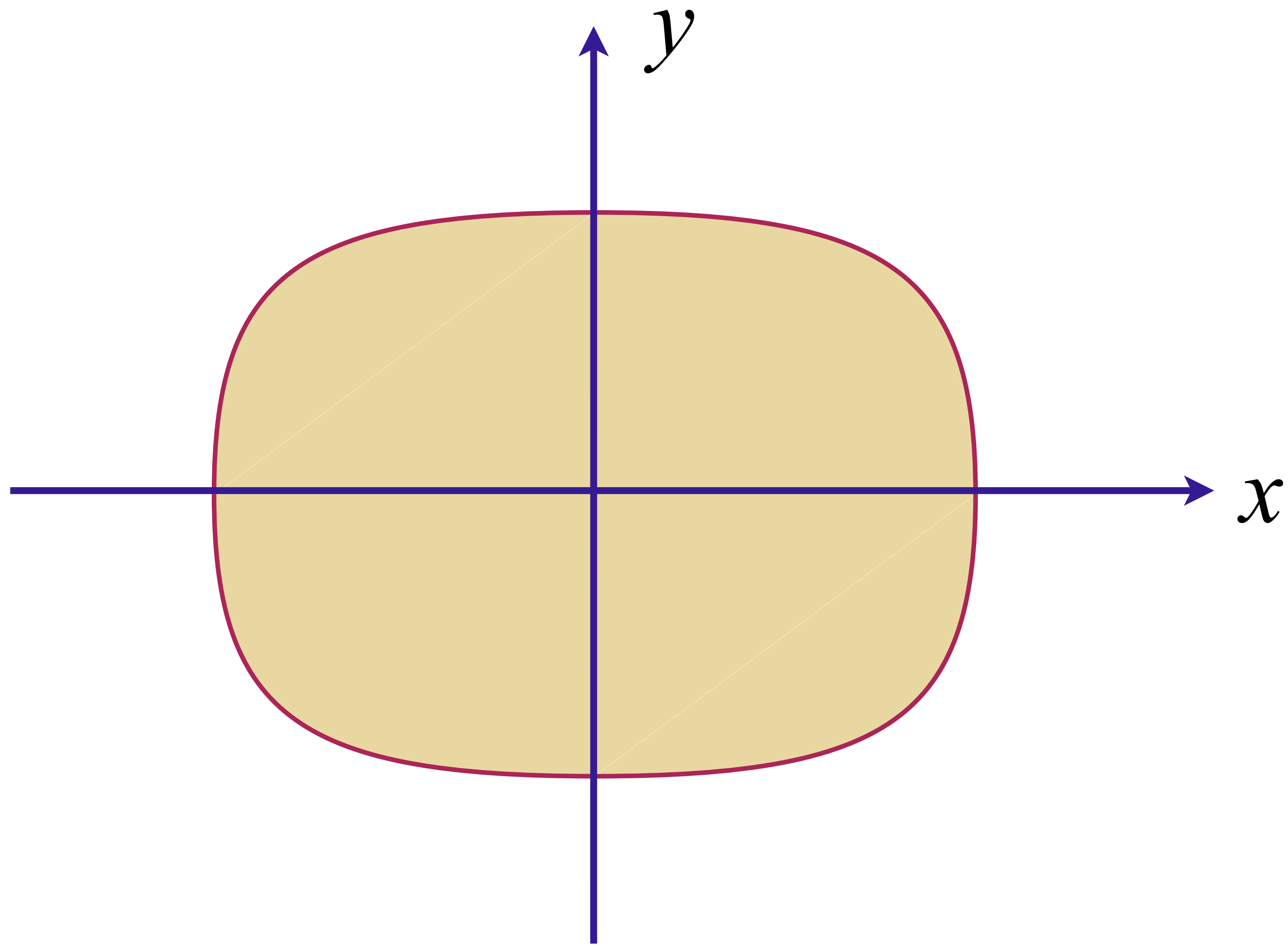
Spontaneous elongation along y direction:

Ising-nematic order parameter

$$\phi \sim \int d^2k \left(\cos k_x - \cos k_y\right) c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$

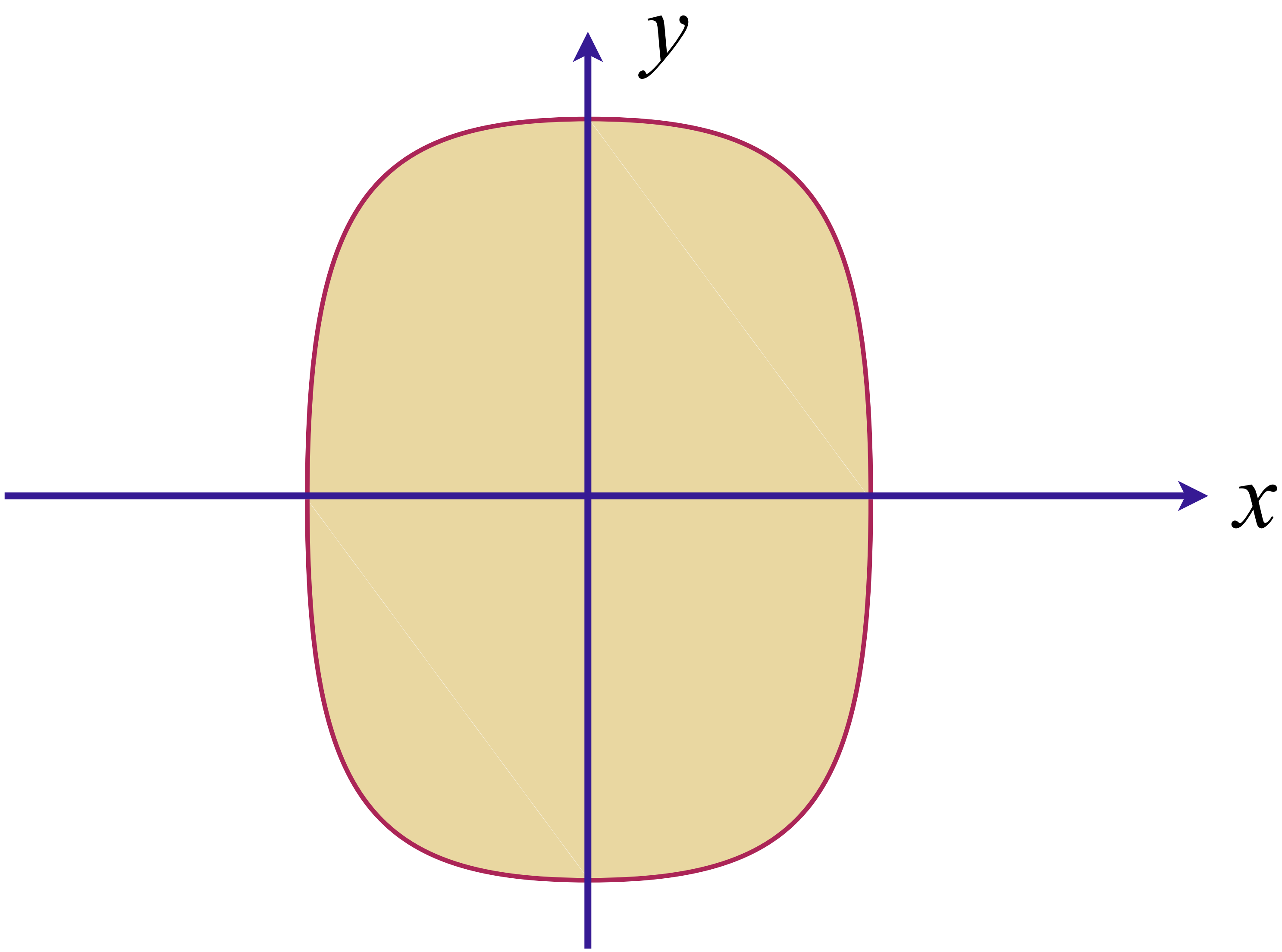
Measures spontaneous breaking of square lattice point-group symmetry of underlying Hamiltonian

Quantum criticality of Ising-nematic ordering



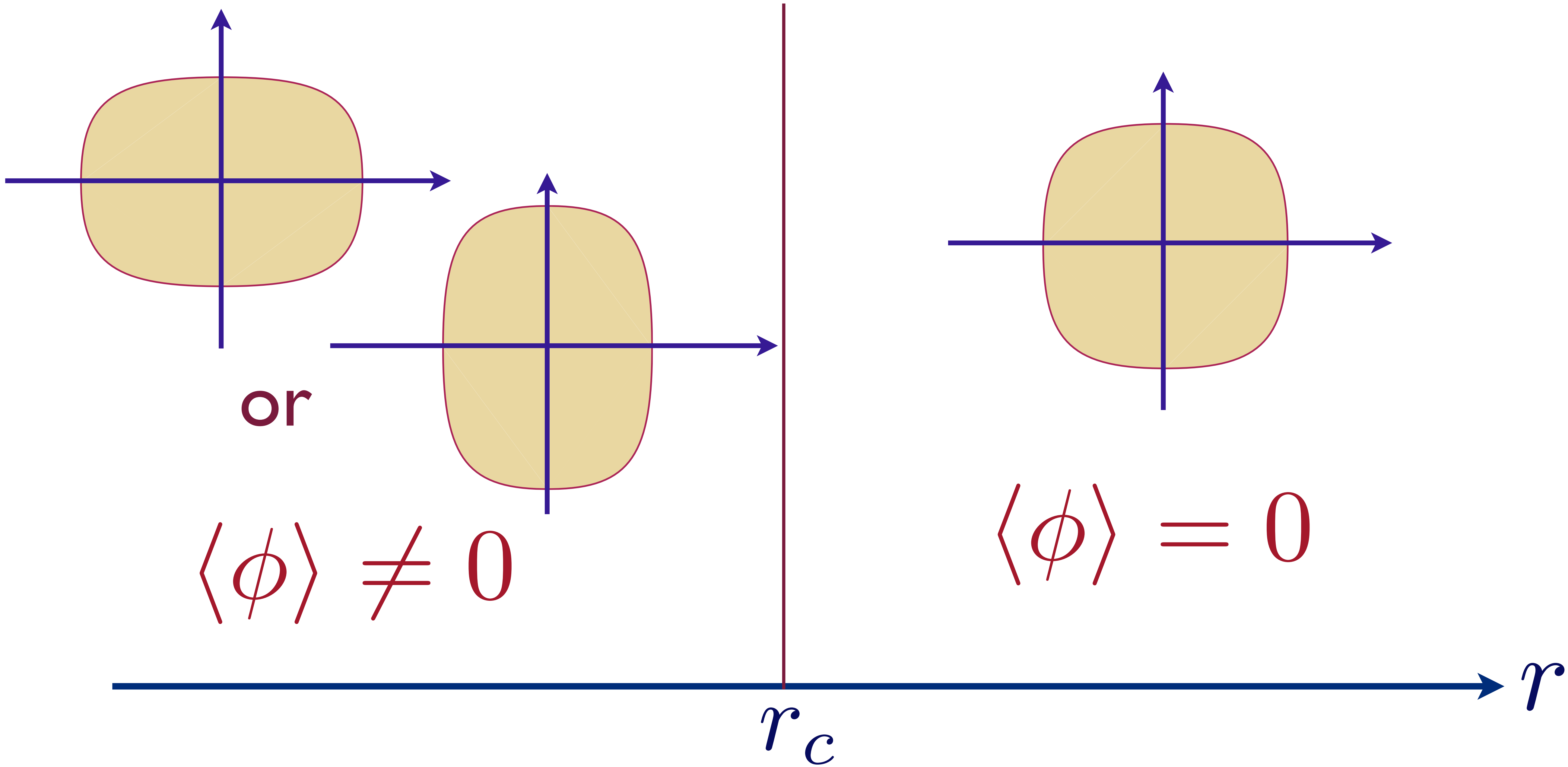
Spontaneous elongation along x direction:
Ising order parameter $\phi > 0$.

Quantum criticality of Ising-nematic ordering



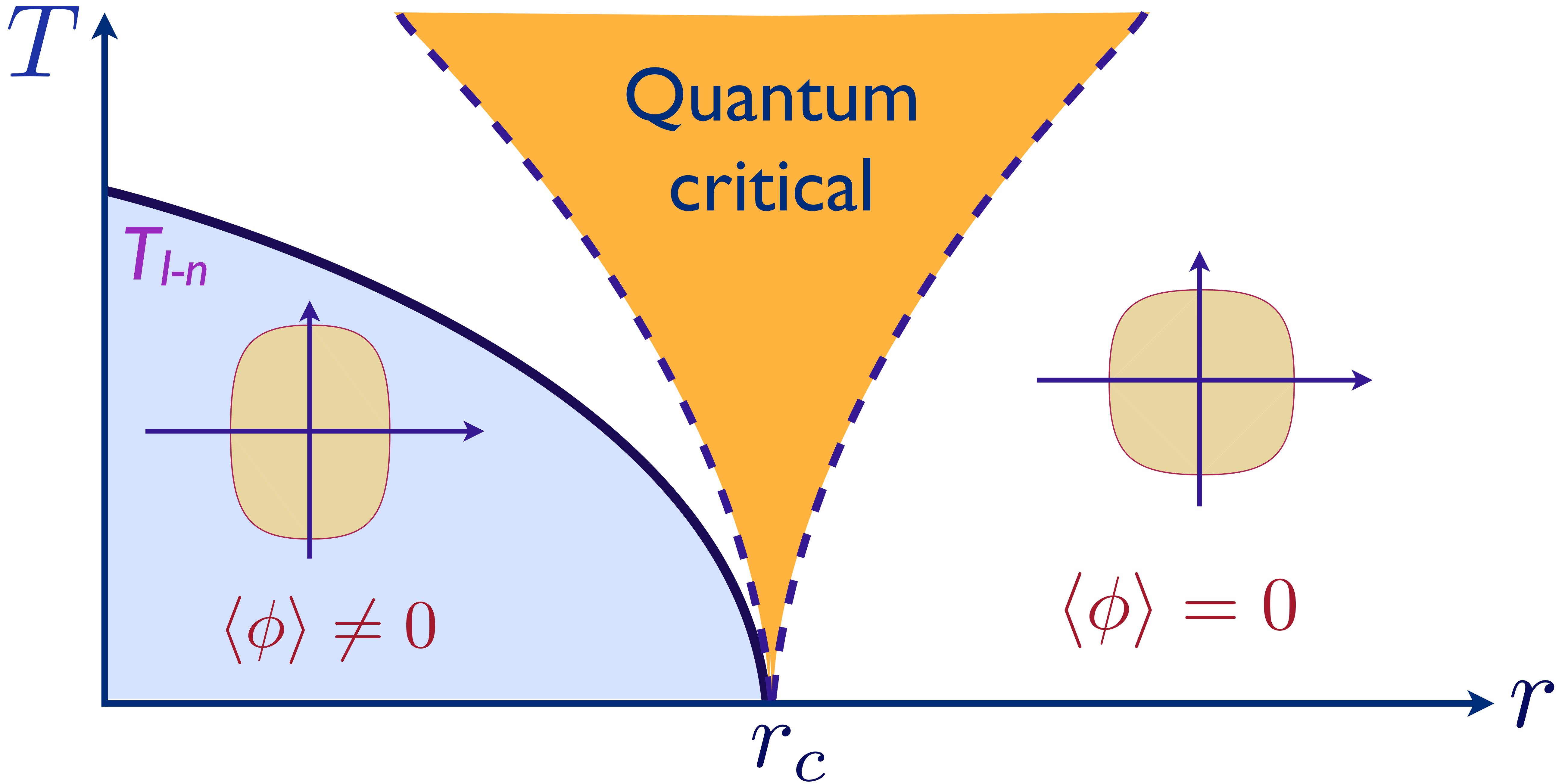
Spontaneous elongation along y direction:
Ising order parameter $\phi < 0$.

Quantum criticality of Ising-nematic ordering



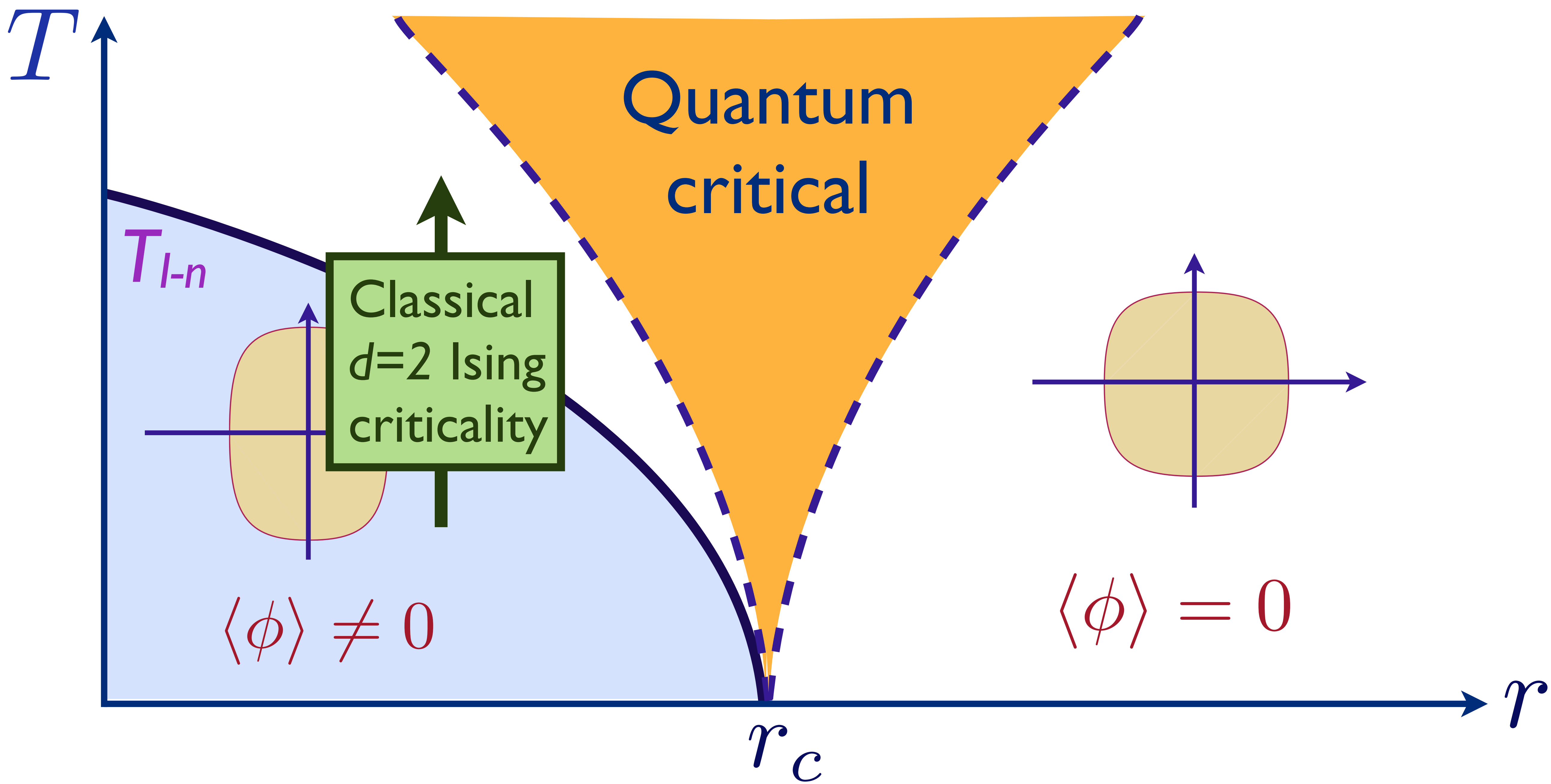
Pomeranchuk instability as a function of coupling r

Quantum criticality of Ising-nematic ordering



Phase diagram as a function of T and r

Quantum criticality of Ising-nematic ordering



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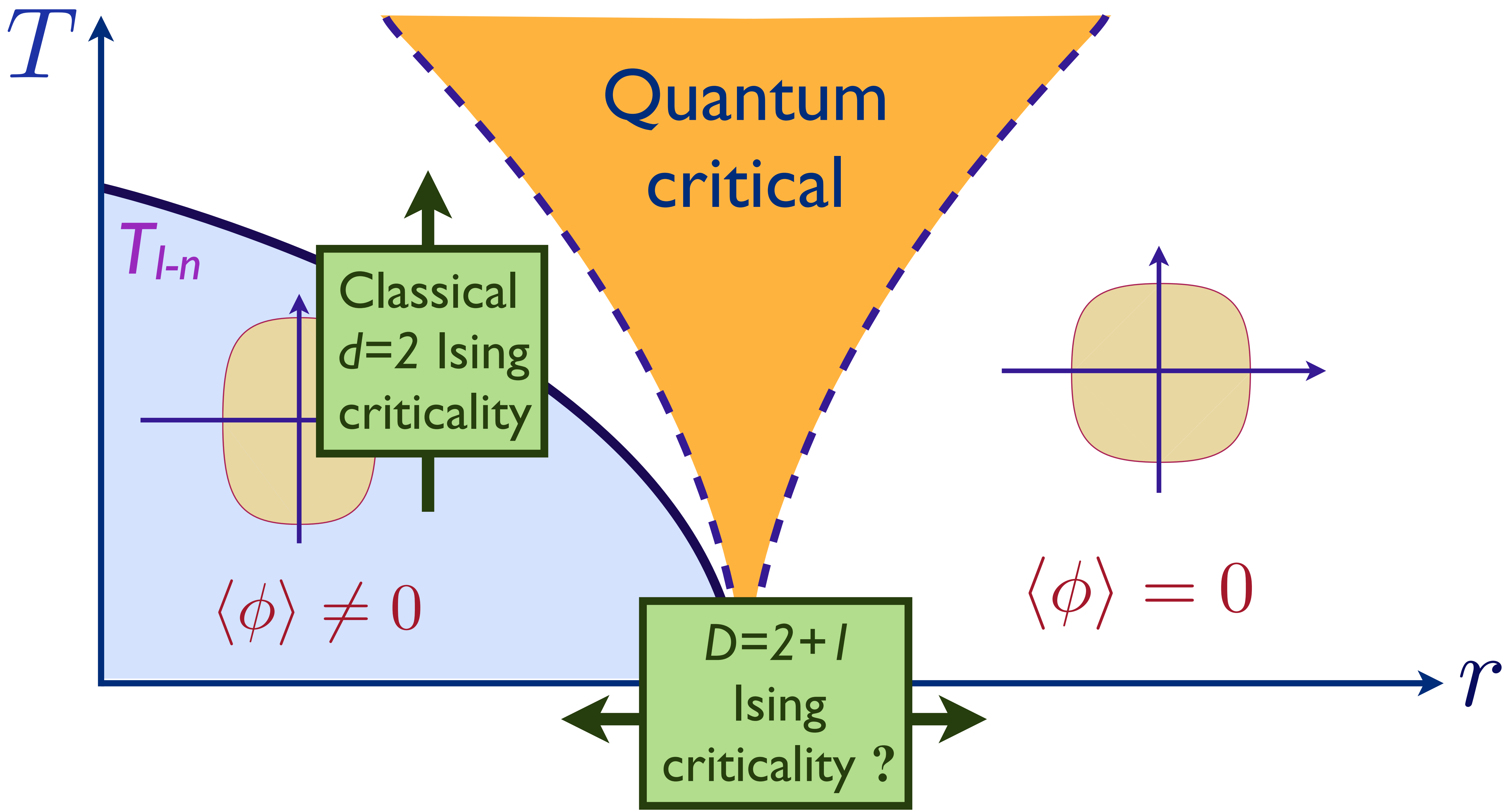

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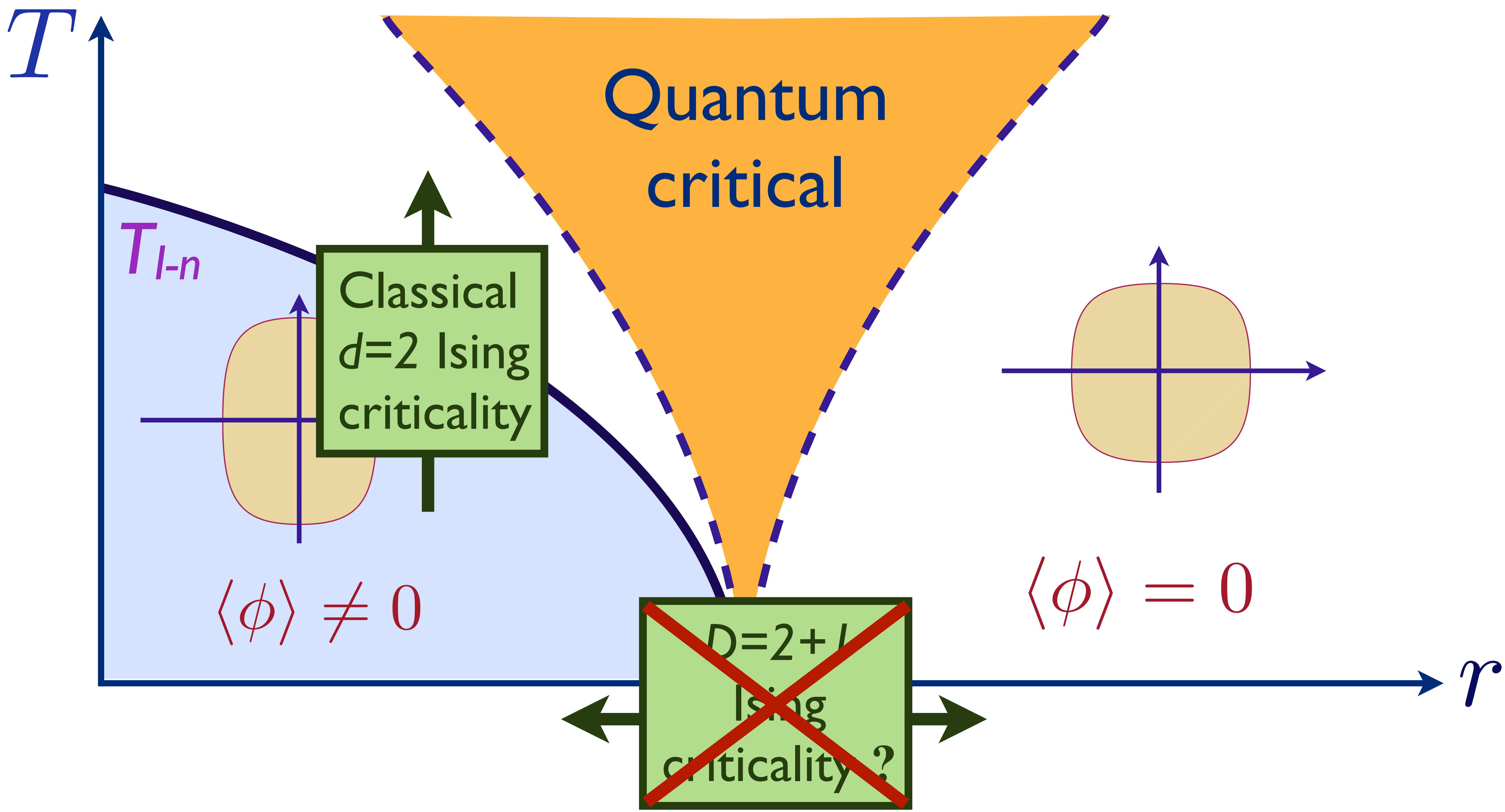
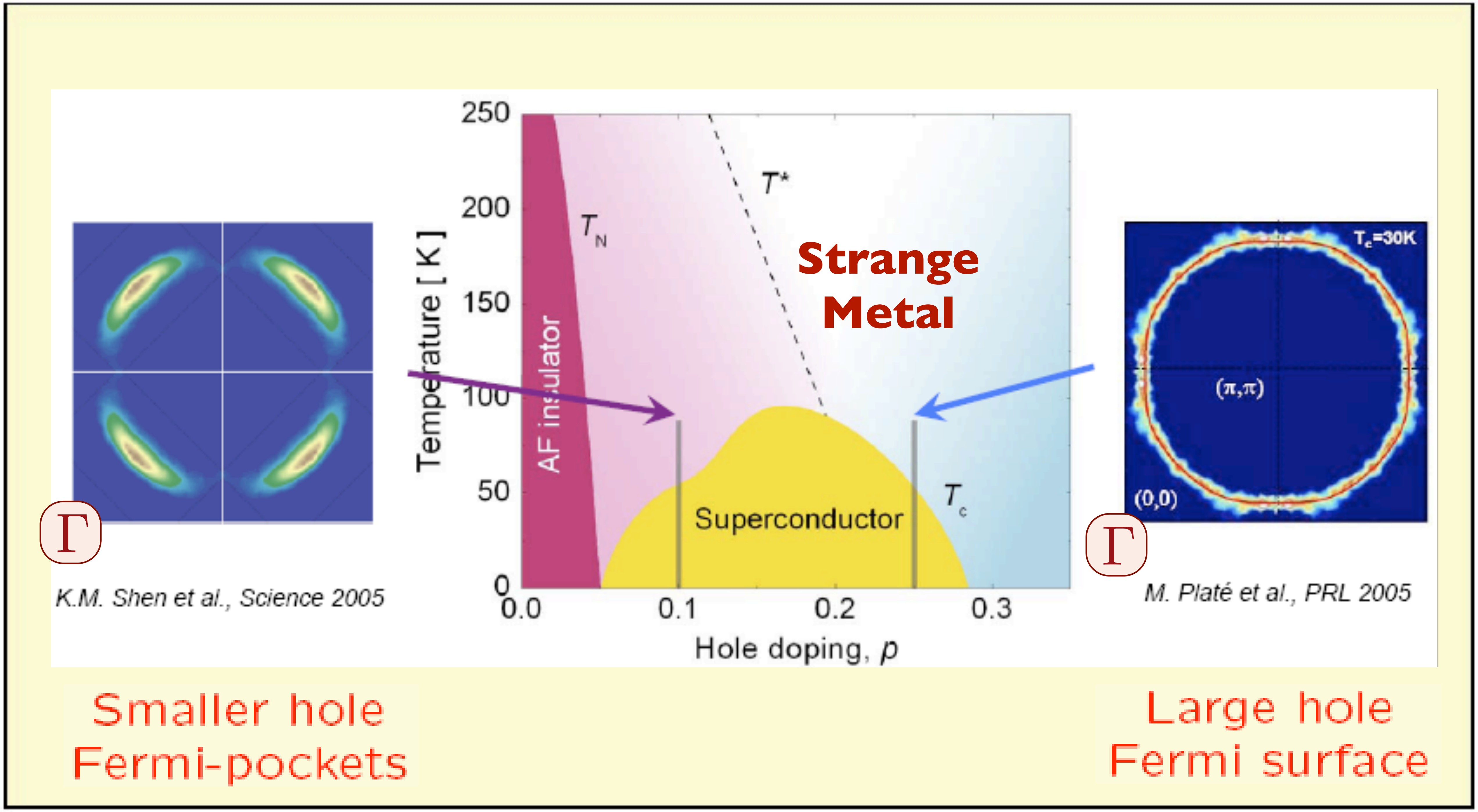


Phase diagram as a function of T and r

Central ingredients in cuprate phase diagram: antiferromagnetism, superconductivity, and change in Fermi surface



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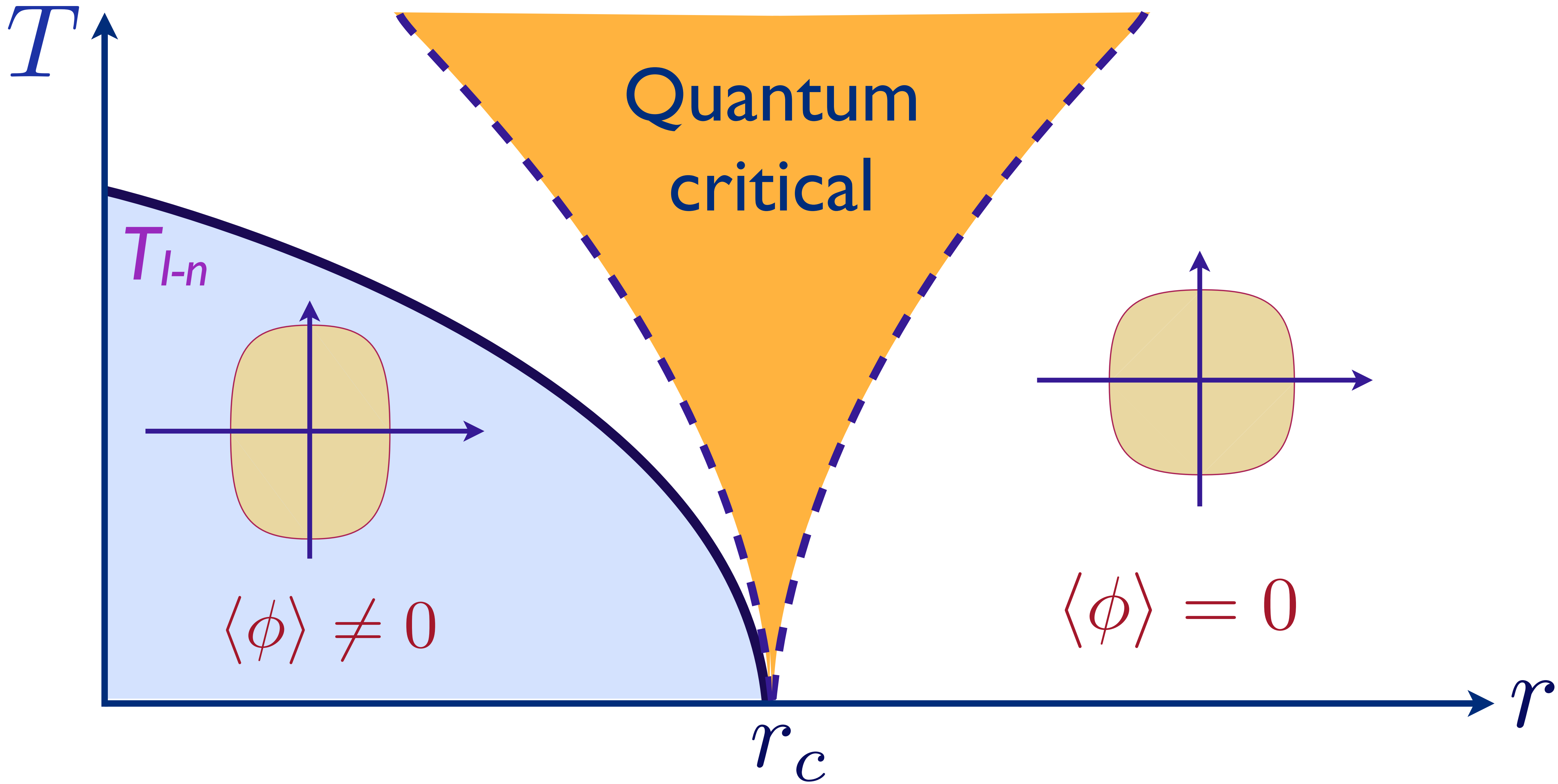

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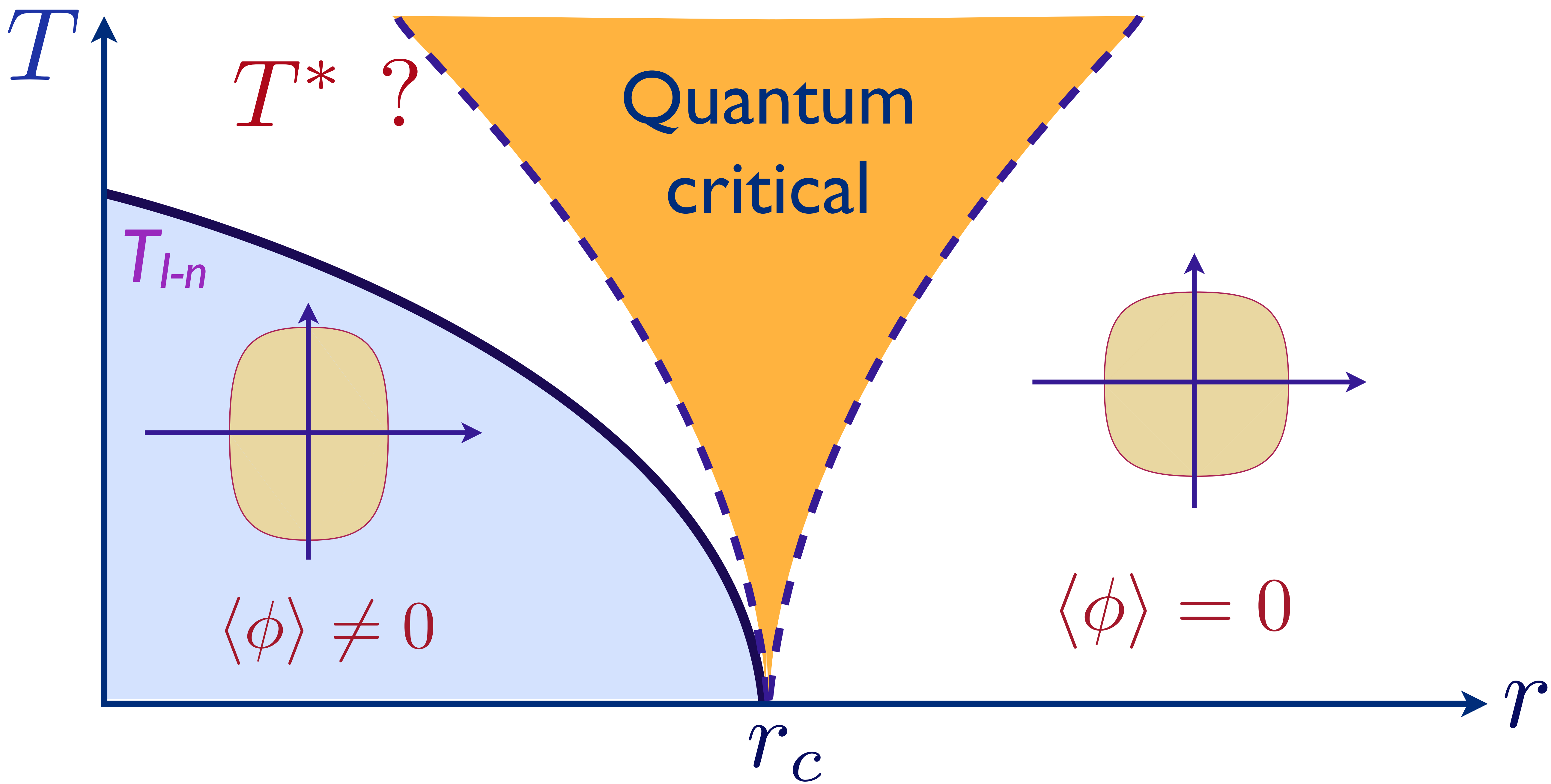

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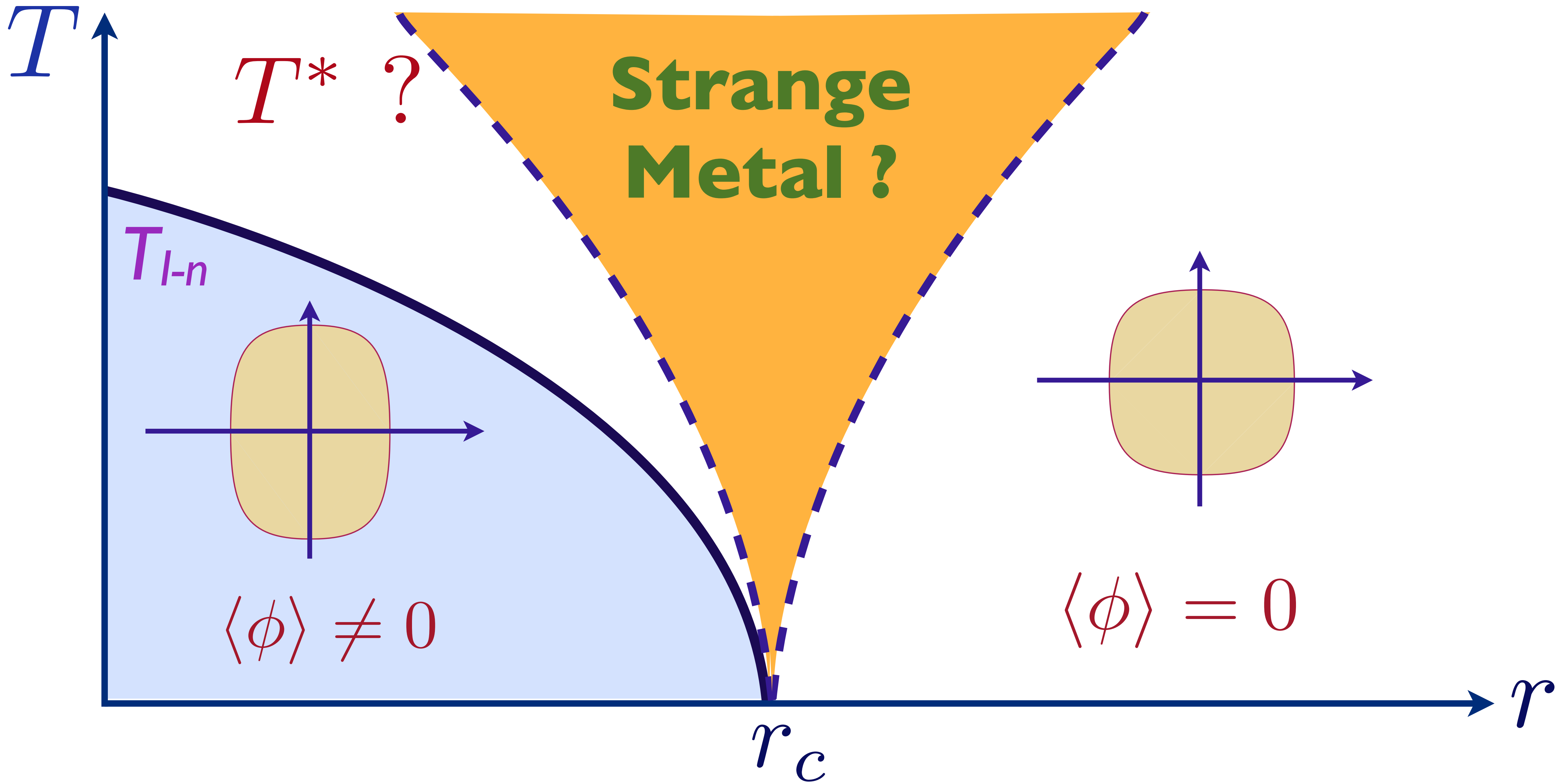
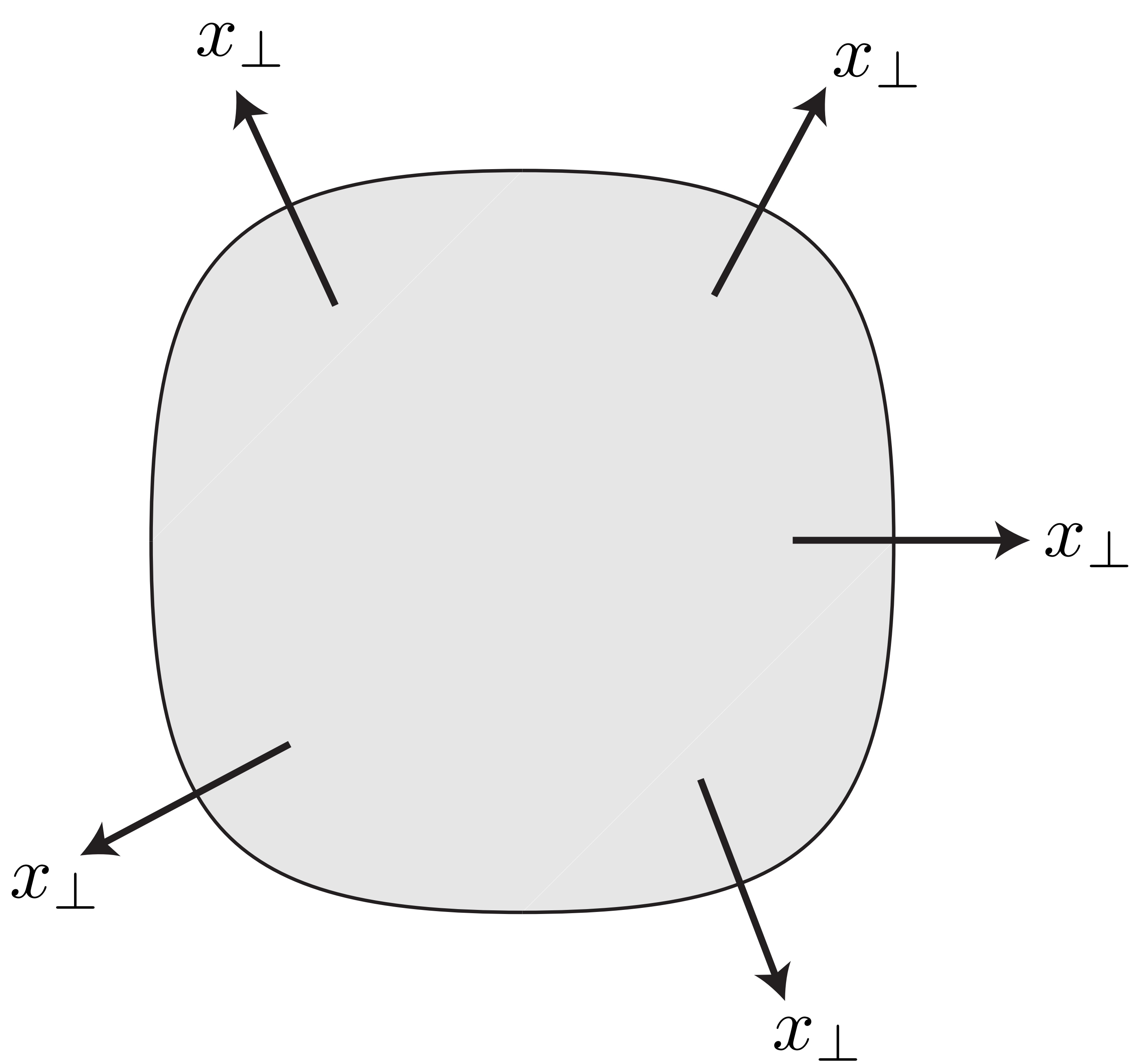


Phase diagram as a function of T and r

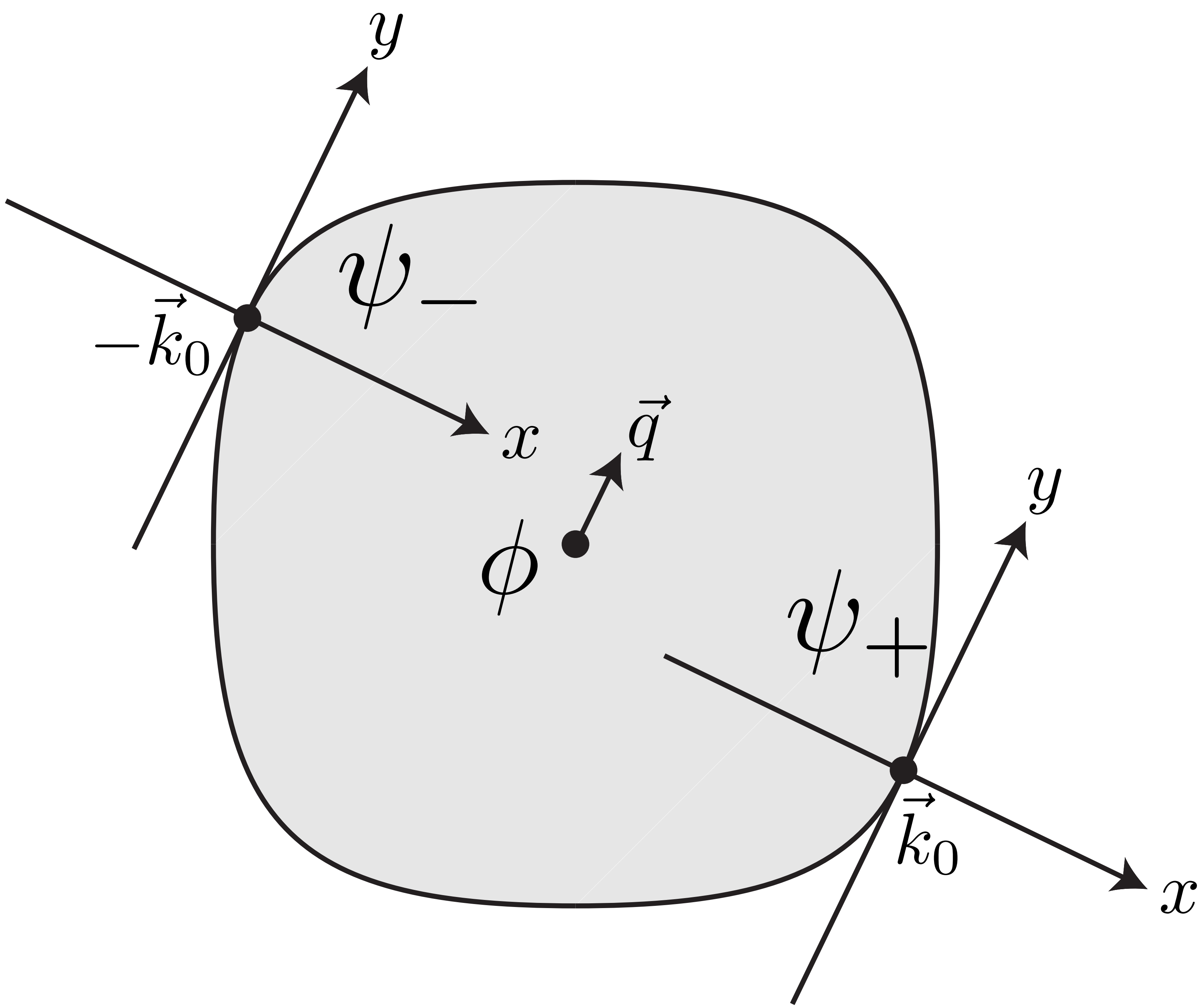
Fermi liquid theory



$$\mathcal{S}_{\rm FL} = \int d\Omega_{\hat{n}} \int dx_\perp \psi^\dagger_{\hat{n}a}(x_\perp) \left(\frac{\partial}{\partial \tau} - i v_F(\hat{n}) \frac{\partial}{\partial x_\perp} \right) \psi_{\hat{n}a}(x_\perp)$$

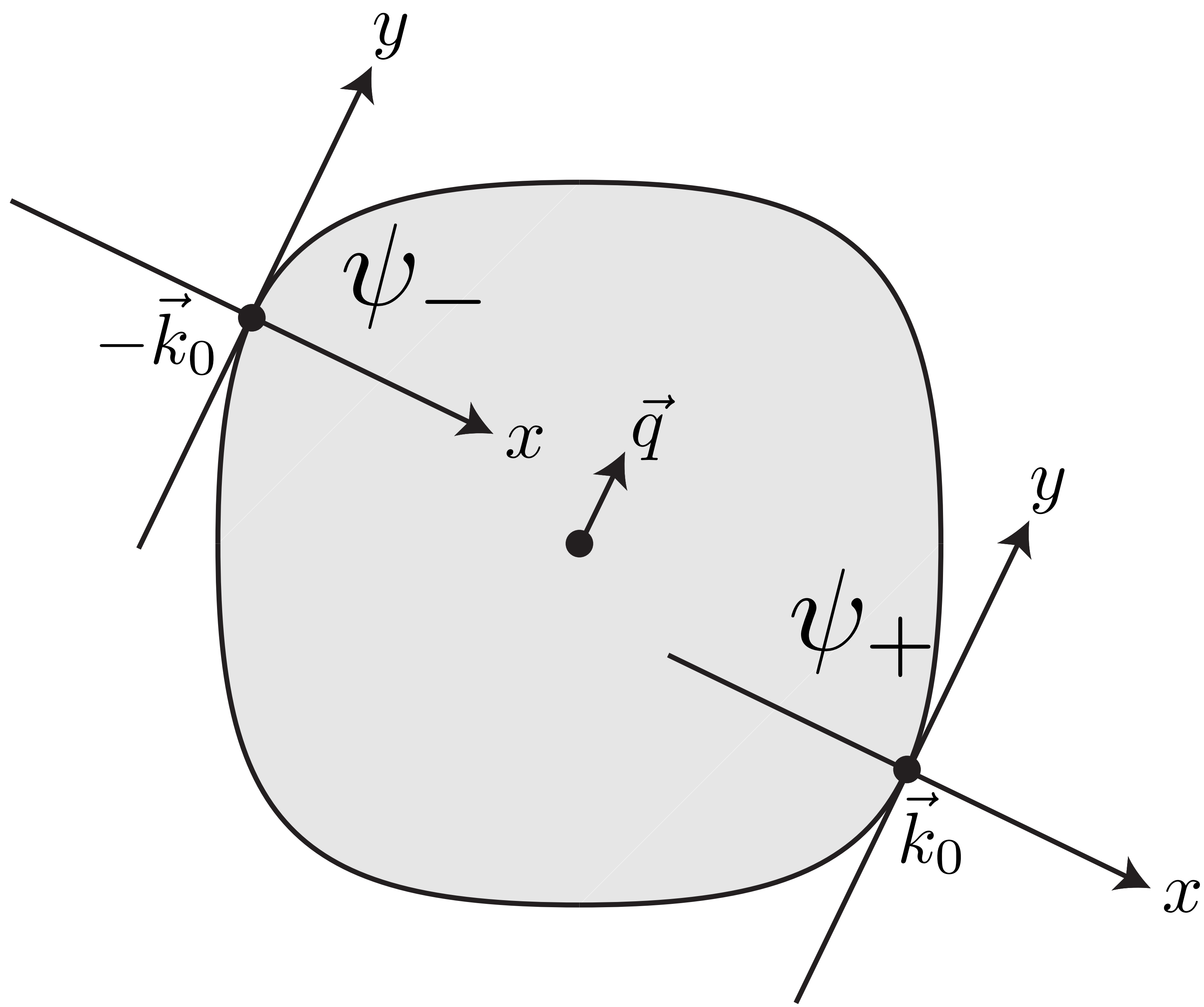
Infinite number of 1+1 dimensional chiral fermions

Non-Fermi liquid quantum critical point



- Critical point is described by an *infinite* set of 2+1 dimensional field theories, one for each direction $\hat{q}$.

Non-Fermi liquid quantum critical point



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Non-Fermi liquid quantum critical point

y

Strong coupling problem II:
Infinite number of 2+1
dimensional field theories
at Ising-nematic
quantum critical point

- Critical point is described by an *infinite* set of 2+1 dimensional field theories, one for each direction $\hat{q}$.

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   Introduction to quantum criticality

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Field theories in D spacetime dimensions are characterized by couplings g which obey the renormalization group equation

$$u\frac{dg}{du} = \beta(g)$$

where u is the energy scale. The RG equation is *local* in energy scale, *i.e.* the RHS does not depend upon u.

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where u is the energy scale. The RG equation is *local* in energy scale, *i.e.* the RHS does not depend upon u.

Key idea: $\Rightarrow$ Implement u as an extra dimension, and map to a local theory in $D+1$ dimensions.

At the RG fixed point, $\beta(g) = 0$, the D dimensional field theory is invariant under the scale transformation

$$x^\mu \to x^\mu / b \quad , \quad u \to b\, u$$

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This is an invariance of the *metric* of the theory in $D+1$ dimensions. The unique solution is

$$ds^2 = \left(\frac{u}{L}\right)^2 dx^\mu dx_\mu + L^2 \frac{du^2}{u^2}.$$

Or, using the length scale $z = L^2/u$

$$ds^2 = L^2 \frac{dx^\mu dx_\mu + dz^2}{z^2}.$$

This is the space AdS_{D+1}, and L is the AdS radius.

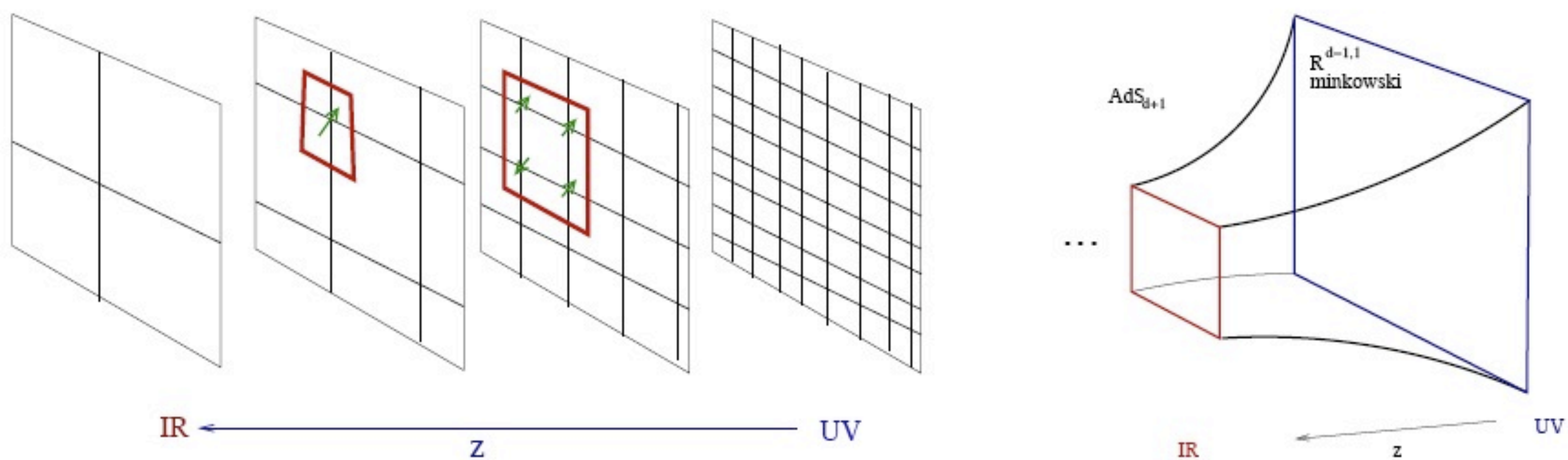
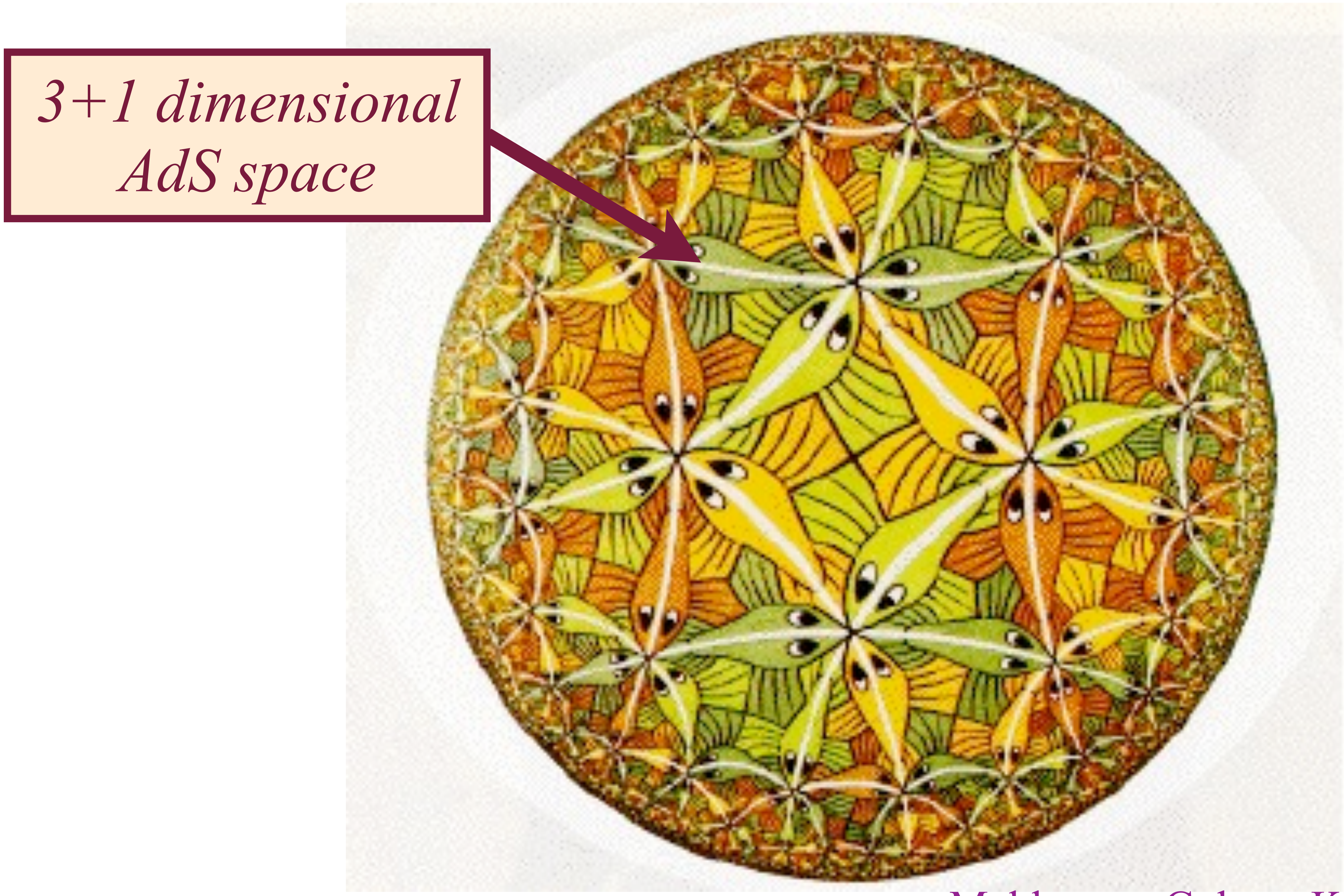


Figure 1: The extra ('radial') dimension of the bulk is the resolution scale of the field theory. The left figure indicates a series of block spin transformations labelled by a parameter z. The right figure is a cartoon of AdS space, which organizes the field theory information in the same way. In this sense, the bulk picture is a hologram: excitations with different wavelengths get put in different places in the bulk image.

J. McGreevy, arXiv0909.0518

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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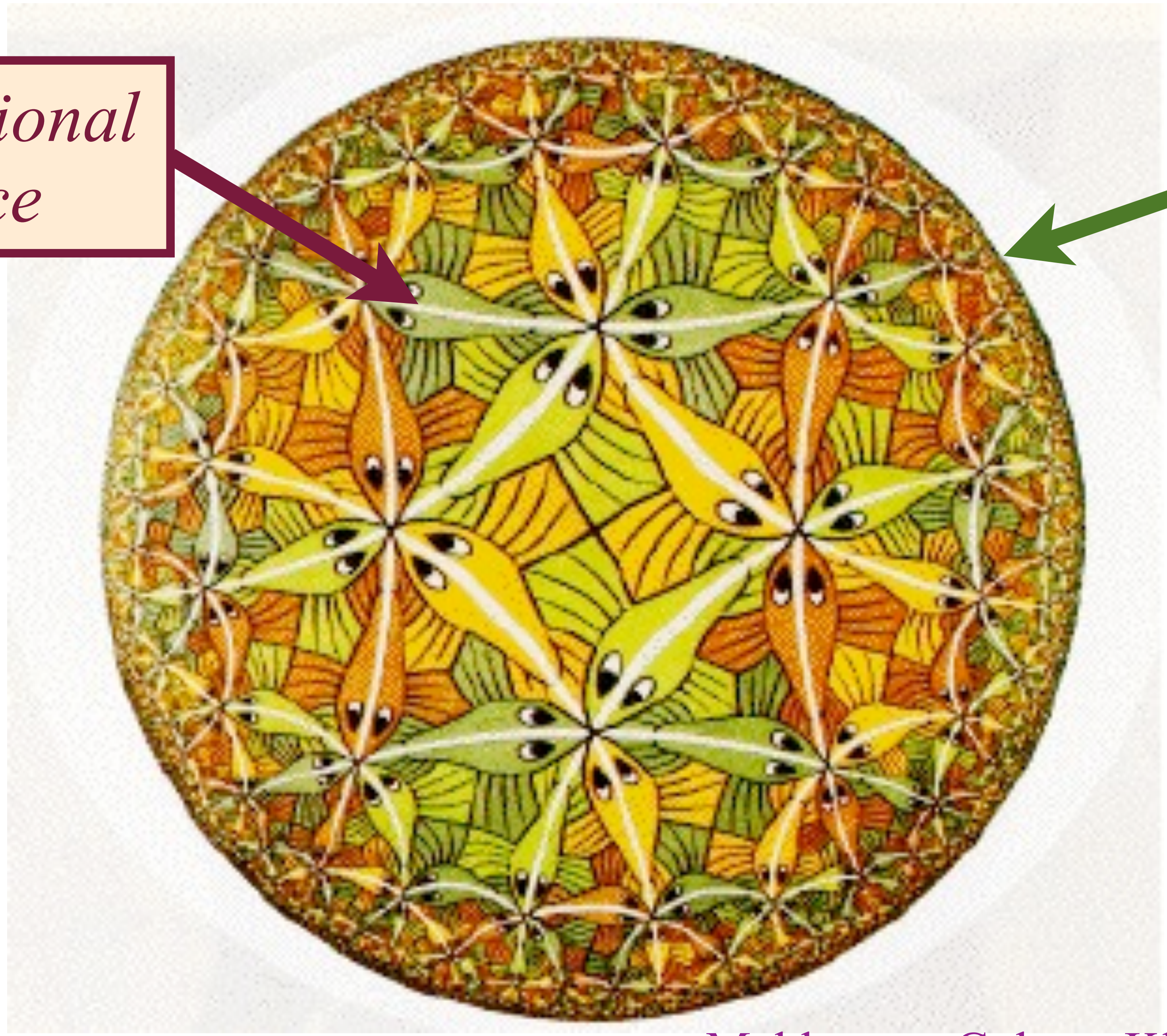
3+1 dimensional AdS space



A 2+1 dimensional system at its quantum critical point

Maldacena, Gubser, Klebanov, Polyakov, Witten

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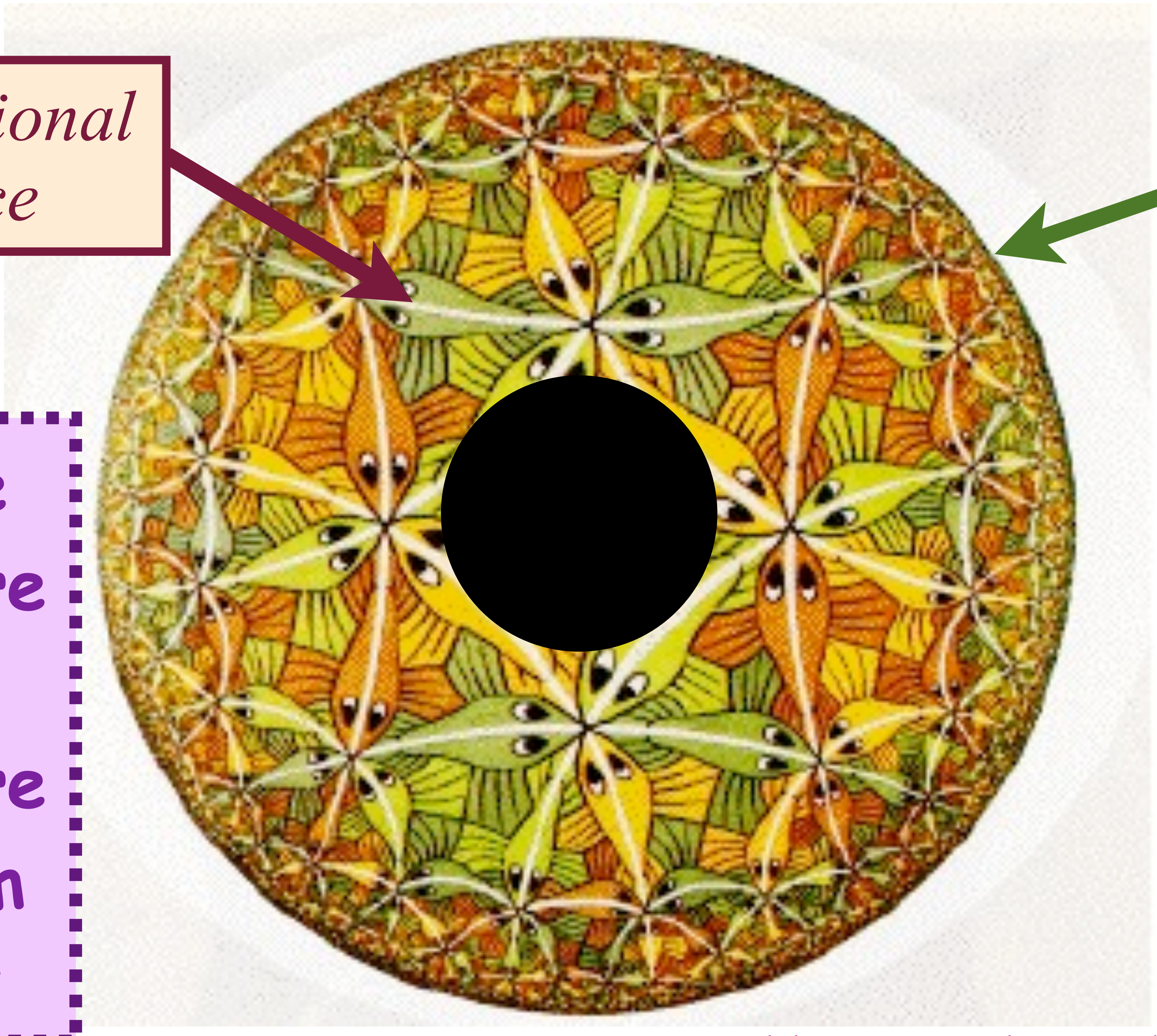

Quantum criticality in 2+1 dimensions

Black hole temperature = temperature of quantum criticality

Maldacena, Gubser, Klebanov, Polyakov, Witten

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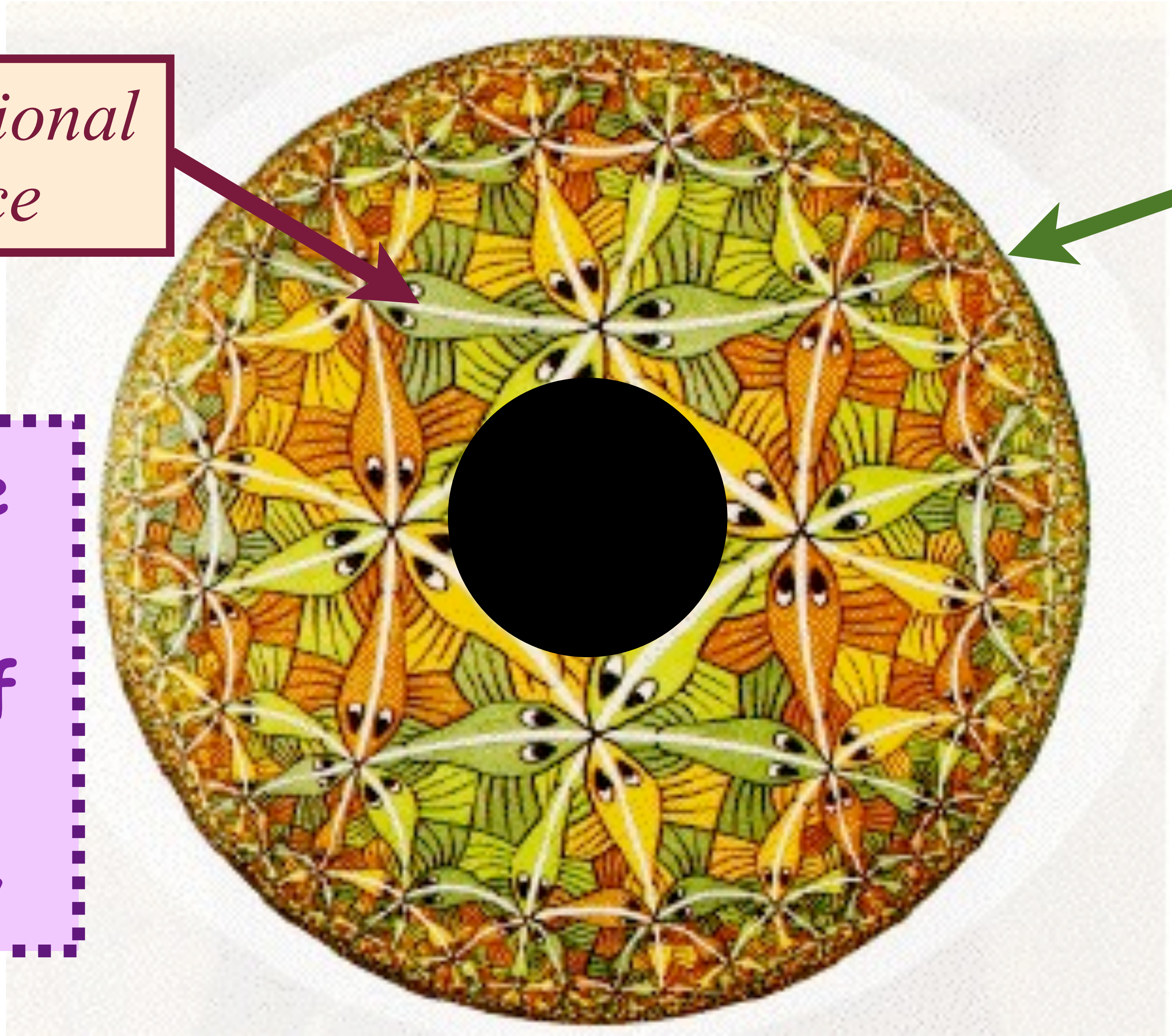

3+1 dimensional AdS space

Quantum criticality in 2+1 dimensions

Black hole entropy = entropy of quantum criticality

Strominger, Vafa

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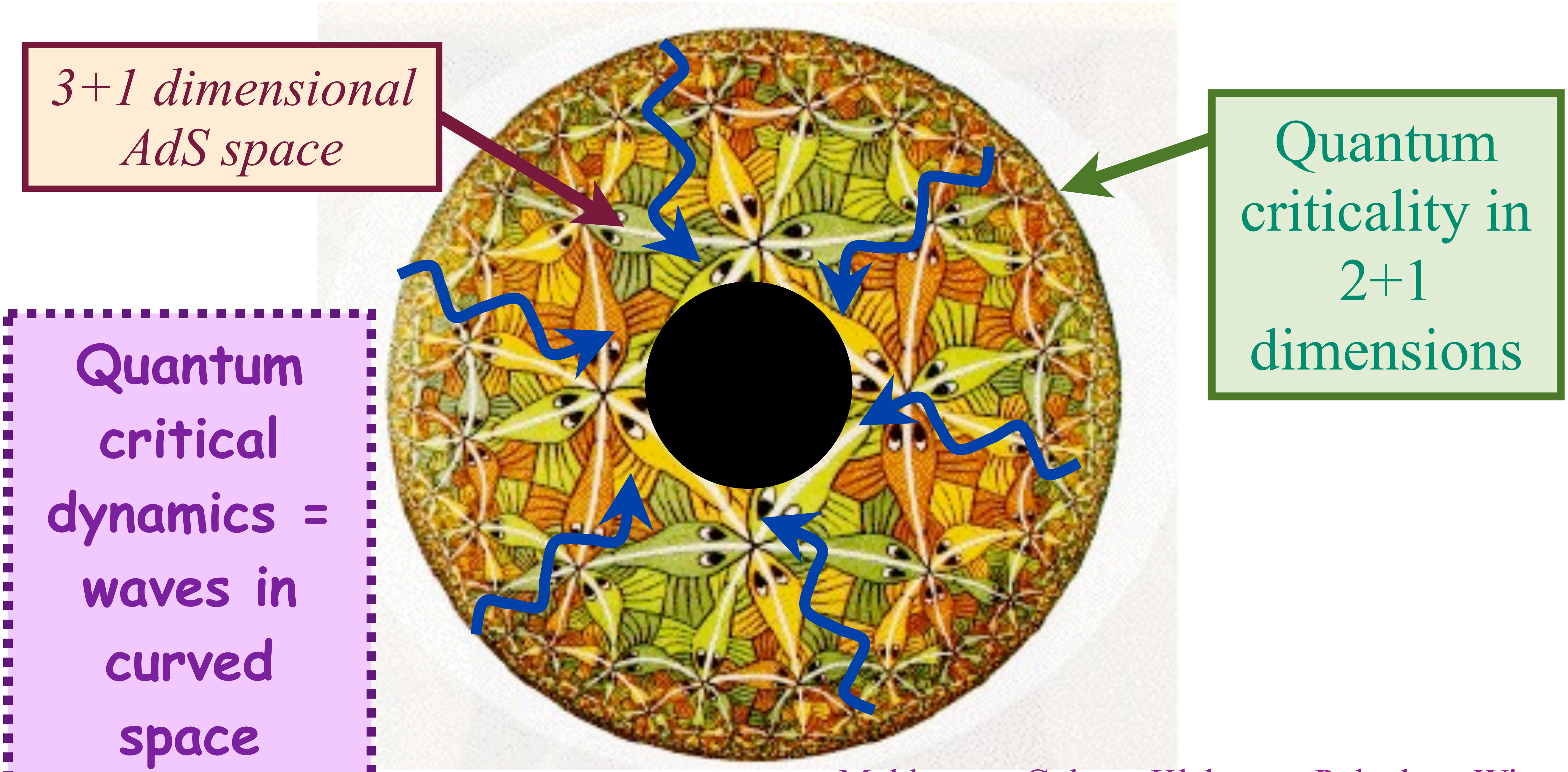

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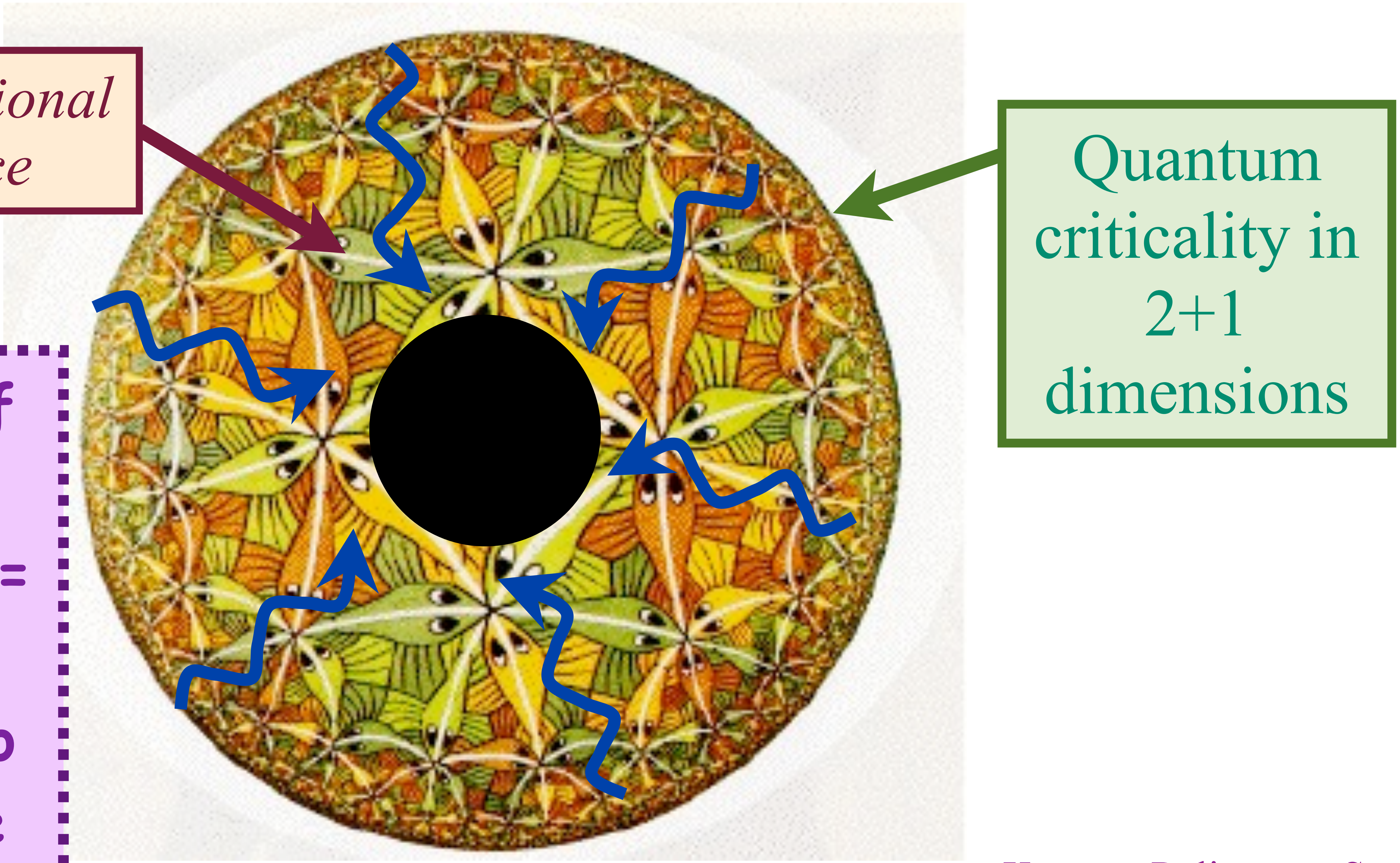

Friction of quantum criticality = waves falling into black hole

Kovtun, Policastro, Son

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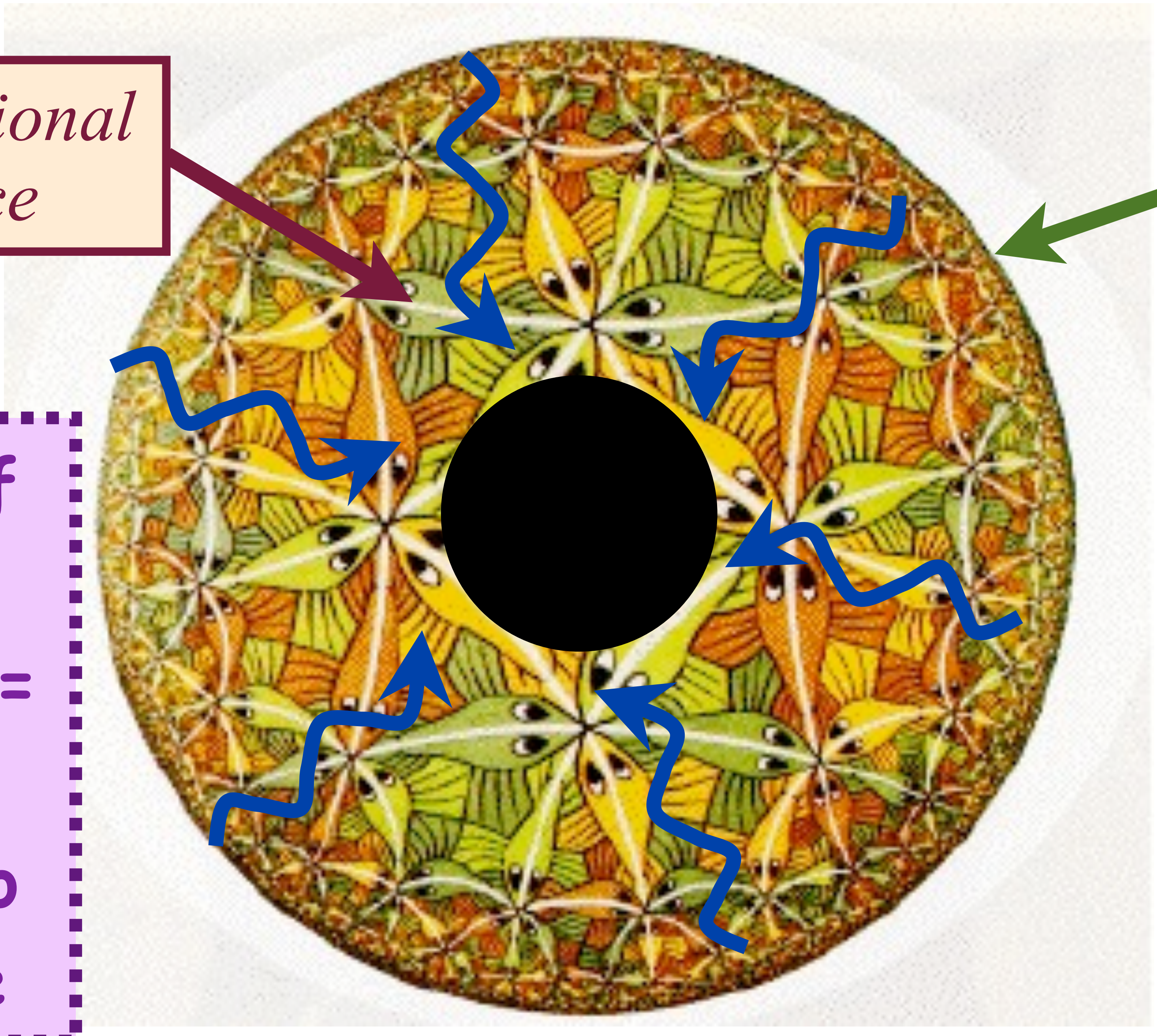

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AdS/CFT correspondence

The quantum theory of a black hole in a 3+1-

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Strong coupling problem I: General solution of magneto-thermo-electric transport in quantum critical region.

C. P. Herzog, P. Kovtun. S. Sachdev, and D. T. Son, *Phys. Rev.* D **75**, 085020 (2007).
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, *Phys. Rev.* B **76**, 144502 (2007).

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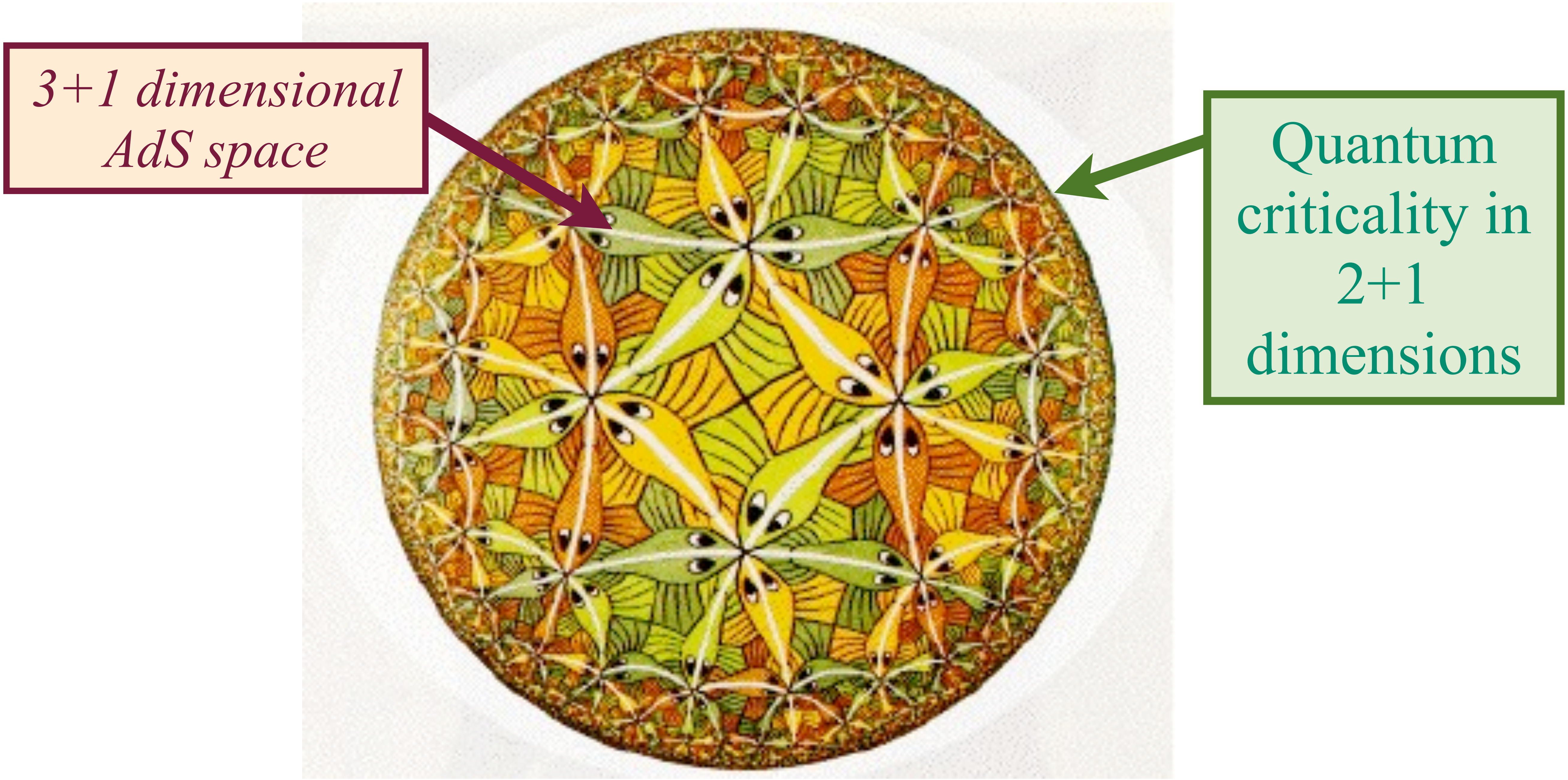
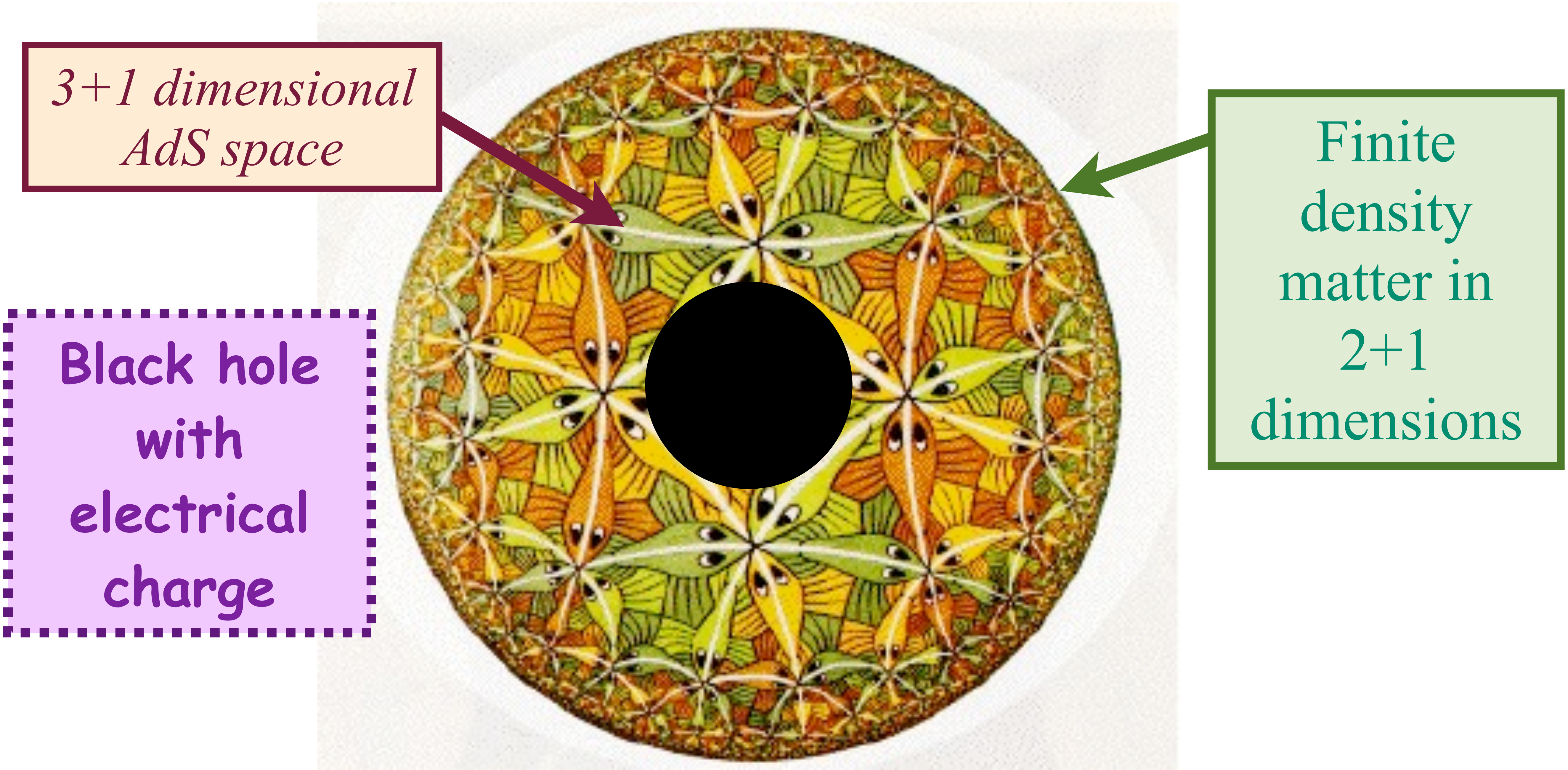
Wednesday, May 5, 2010

AdS/CFT correspondence



AdS/CFT correspondence

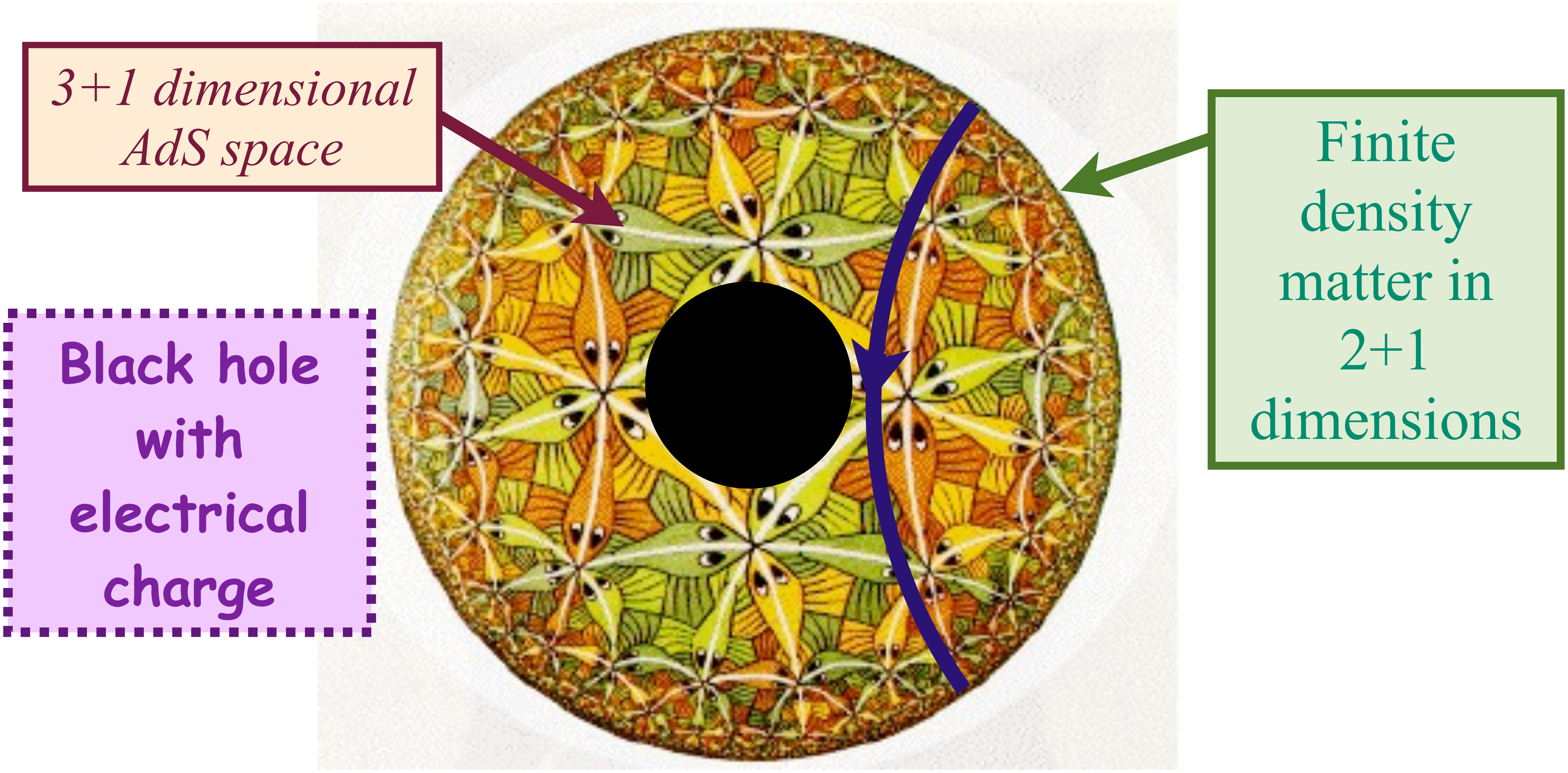
Move away from the quantum critical point to a system of matter at non-zero density: equivalent to adding an electrical charge to the black hole.



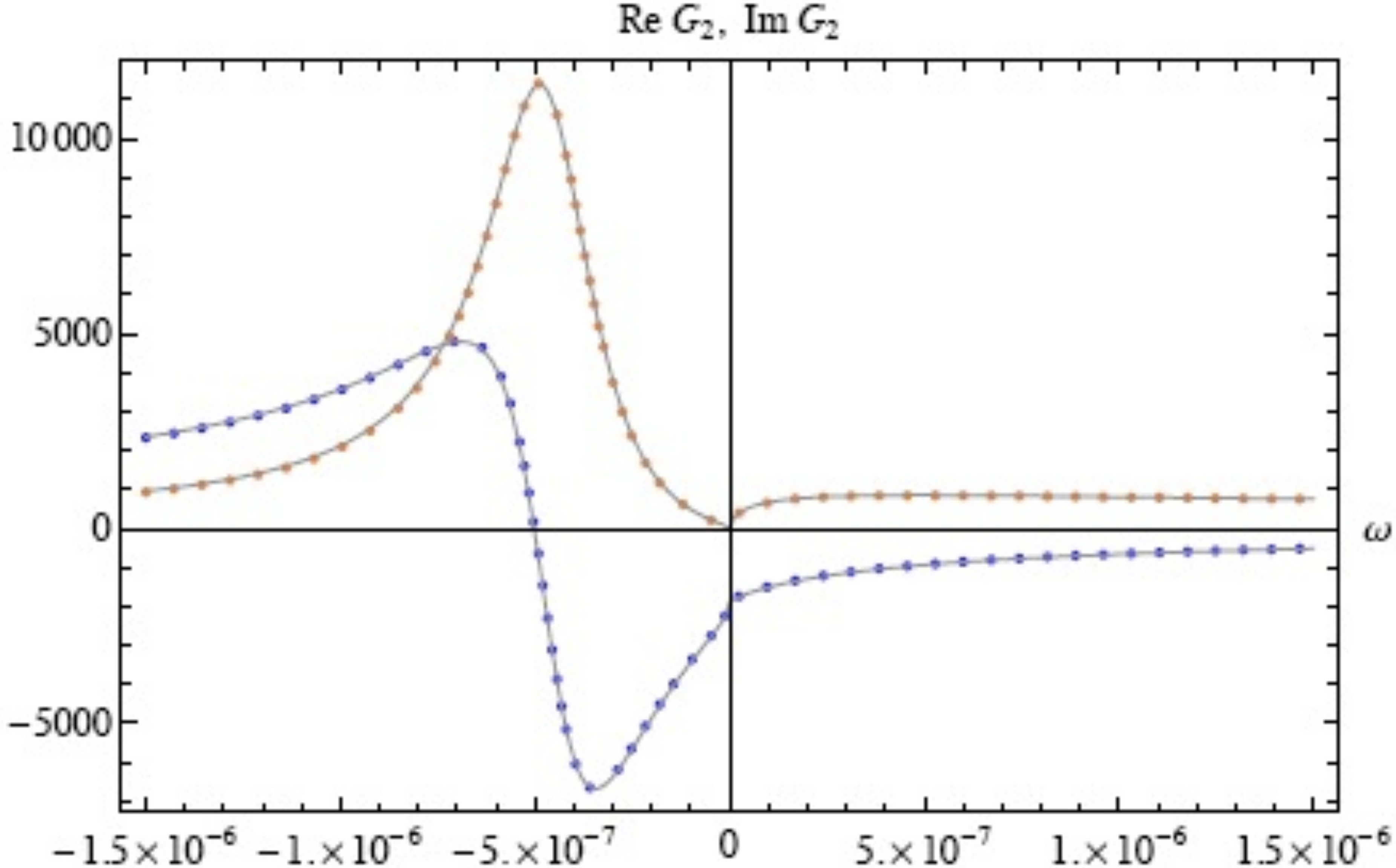
AdS/CFT correspondence

Examine the free energy and Green's function of a probe particle

T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694
F. Denef, S. Hartnoll, and S. Sachdev, arXiv:0908.1788



Green's function of a fermion

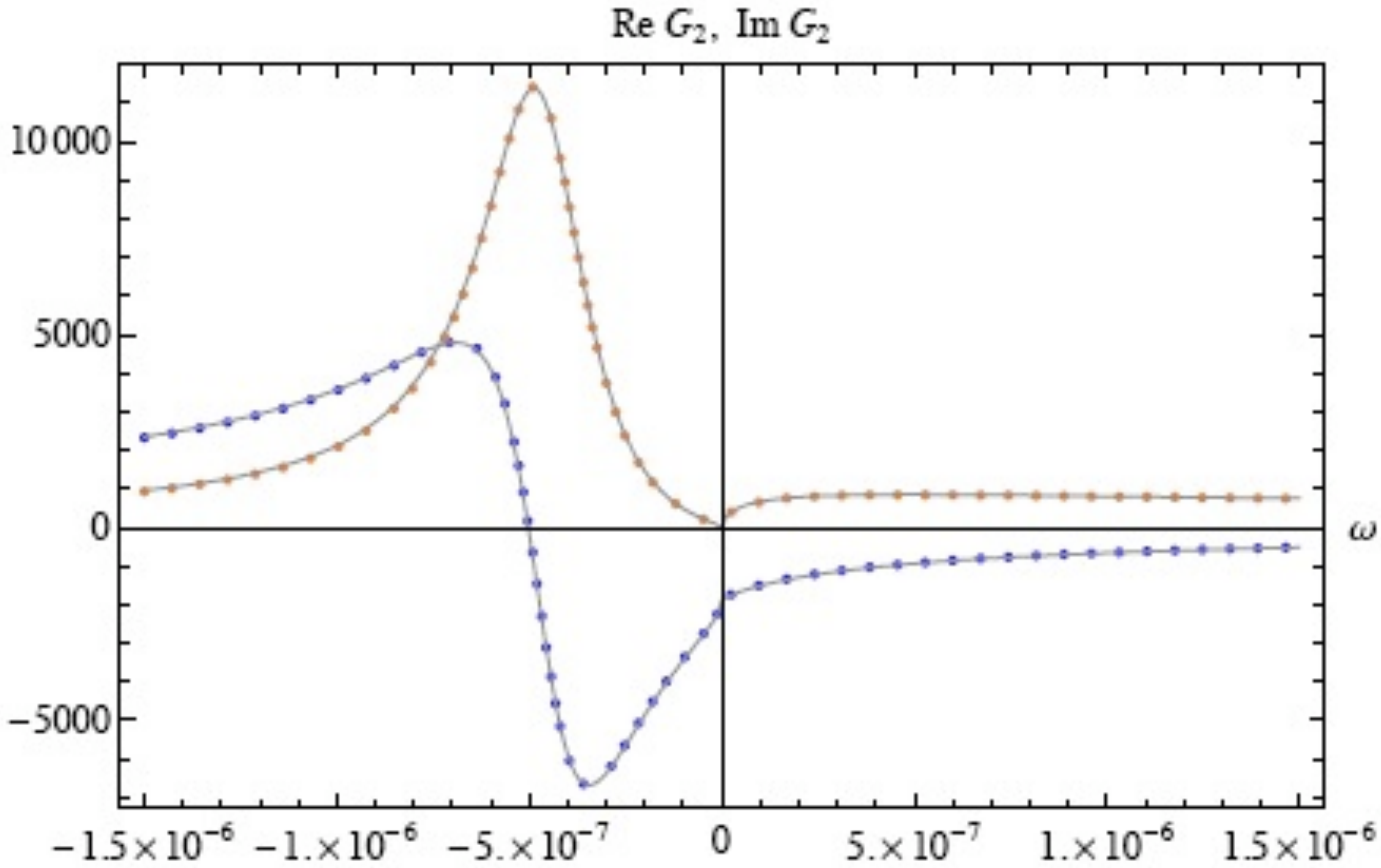


T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694

$$G(k,\omega) \approx \frac{1}{\omega - v_F(k-k_F) - i\omega^{\theta(k)}}$$

See also S.-S. Lee, *Phys. Rev. D* **79**, 086006 (2009);
M. Cubrovic, J. Zaanen, and K. Schalm, *Science* **325**, 439 (2009);
F. Denef, S. A. Hartnoll, and S. Sachdev, *Phys. Rev. D* **80**, 126016 (2009)

Green's function of a fermion

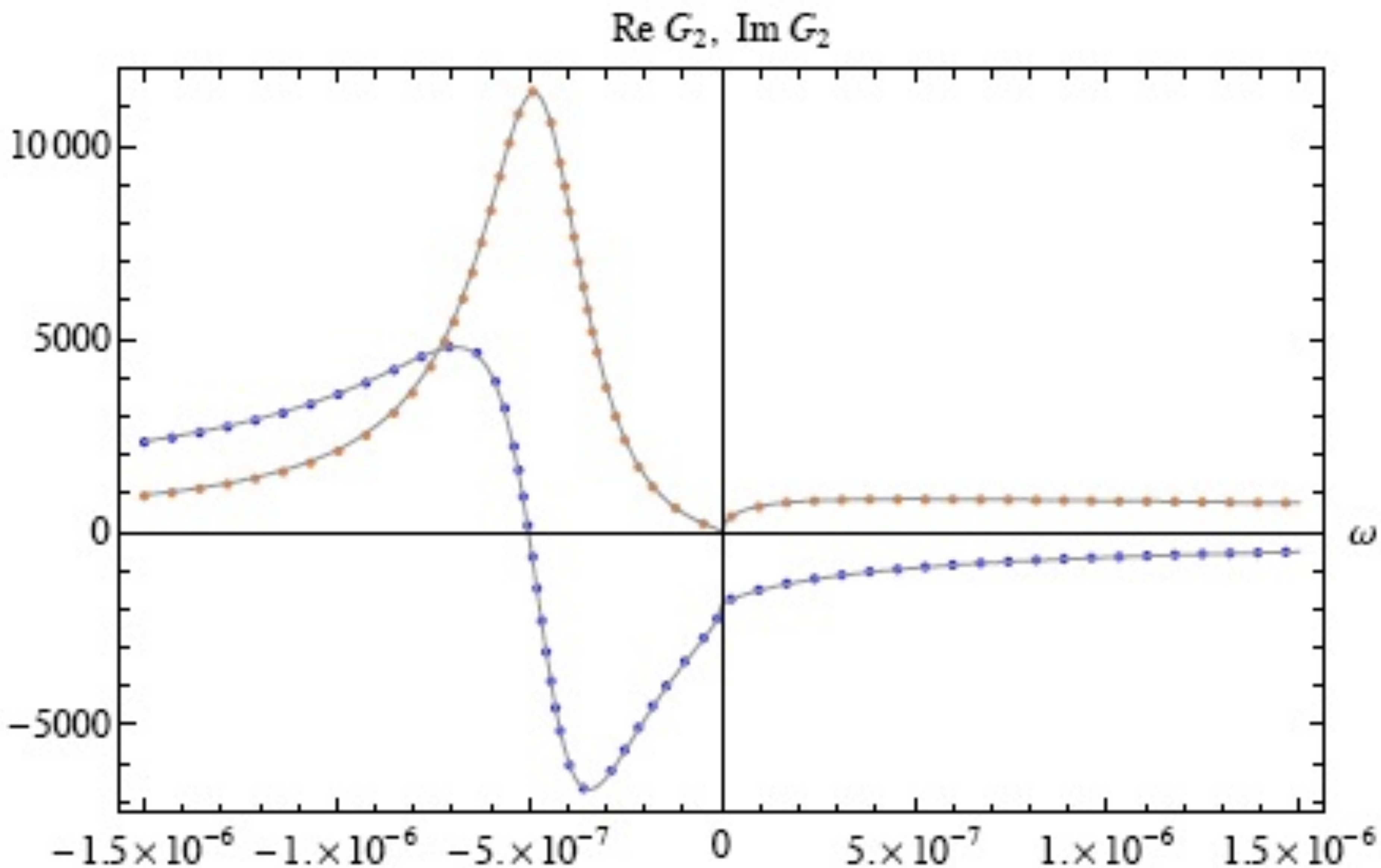


T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694

$$G(k,\omega) \approx \frac{1}{\omega - v_F(k-k_F) - i\omega^{\theta(k)}}$$

Similar to our theory of the singular Fermi surface near the Ising-nematic quantum critical point

Green's function of a fermion



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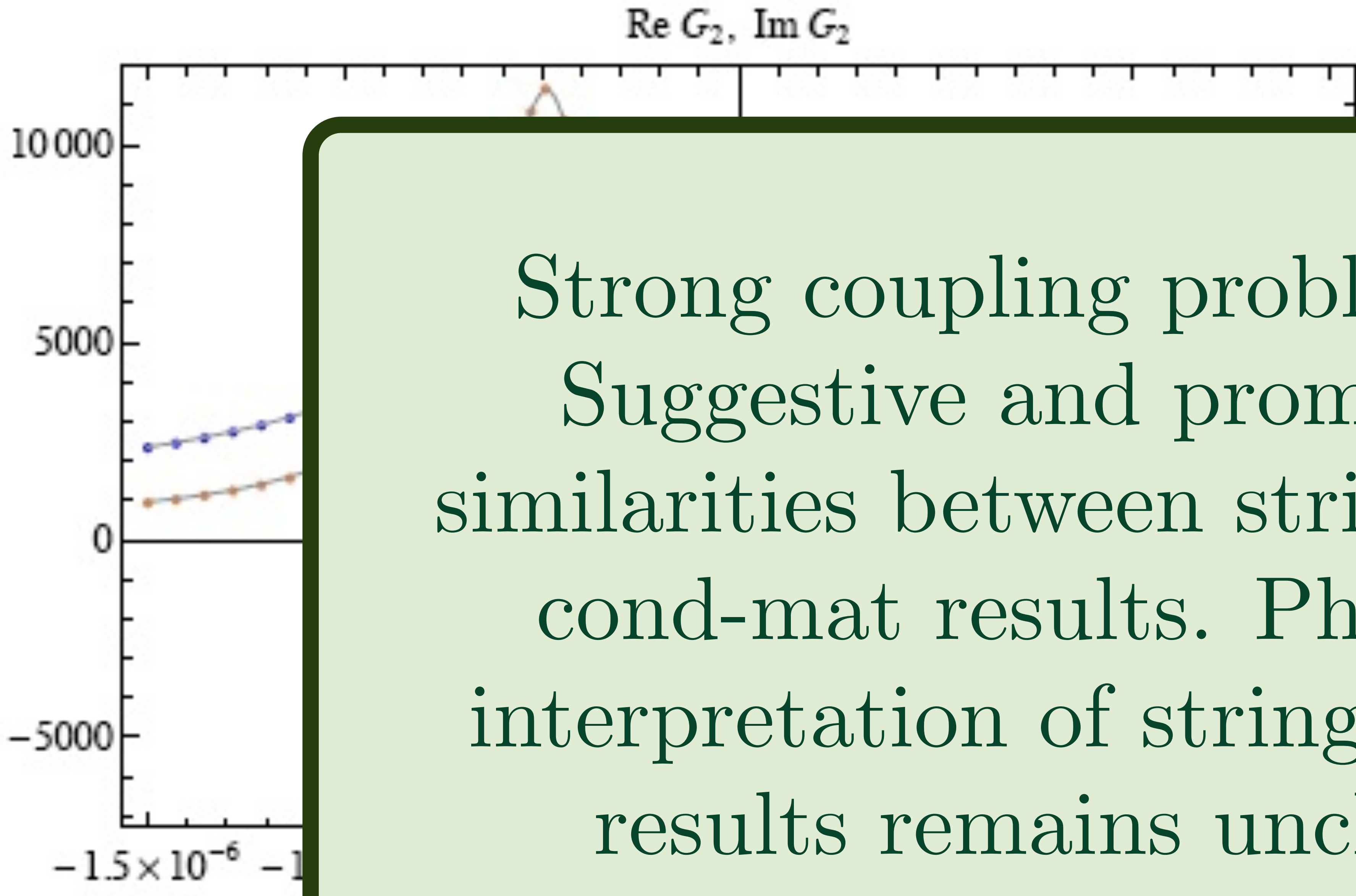

Strong coupling problem II: Suggestive and promising similarities between stringy and cond-mat results. Physical interpretation of string theory results remains unclear.

H. Liu,
y, and
n,
.2694

$$G(k,\omega) \sim \frac{\cdots}{\omega - v_F(k-k_F) - i\omega^{\theta(k)}}$$

Similar to our theory of the singular Fermi surface near the Ising-nematic quantum critical point

Conclusions

Theories for the onset of Ising-nematic order (and spin density wave order) in metals are *strongly* coupled in two dimensions

Conclusions

The AdS/CFT offers promise in providing a new understanding of strongly interacting quantum matter at non-zero density