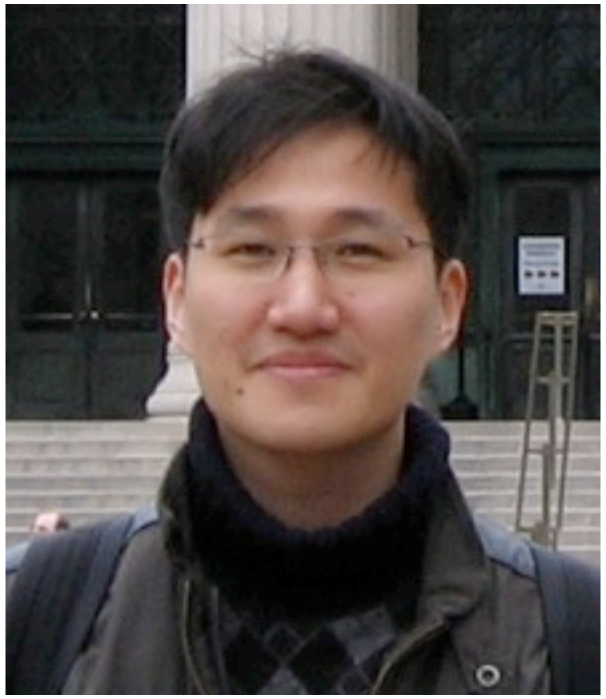
Quantum criticality, the cuprate superconductors, and the AdS/CFT correspondence

Talk online: sachdev.physics.harvard.edu

PHYSICS

VE RI TAS

HARVARD



Max Metlitski, Harvard

arXiv:1001.1153

Eun Gook Moon, Harvard

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

PHYSICS

VE RI TAS

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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 finite density quantum matter at strong coupling

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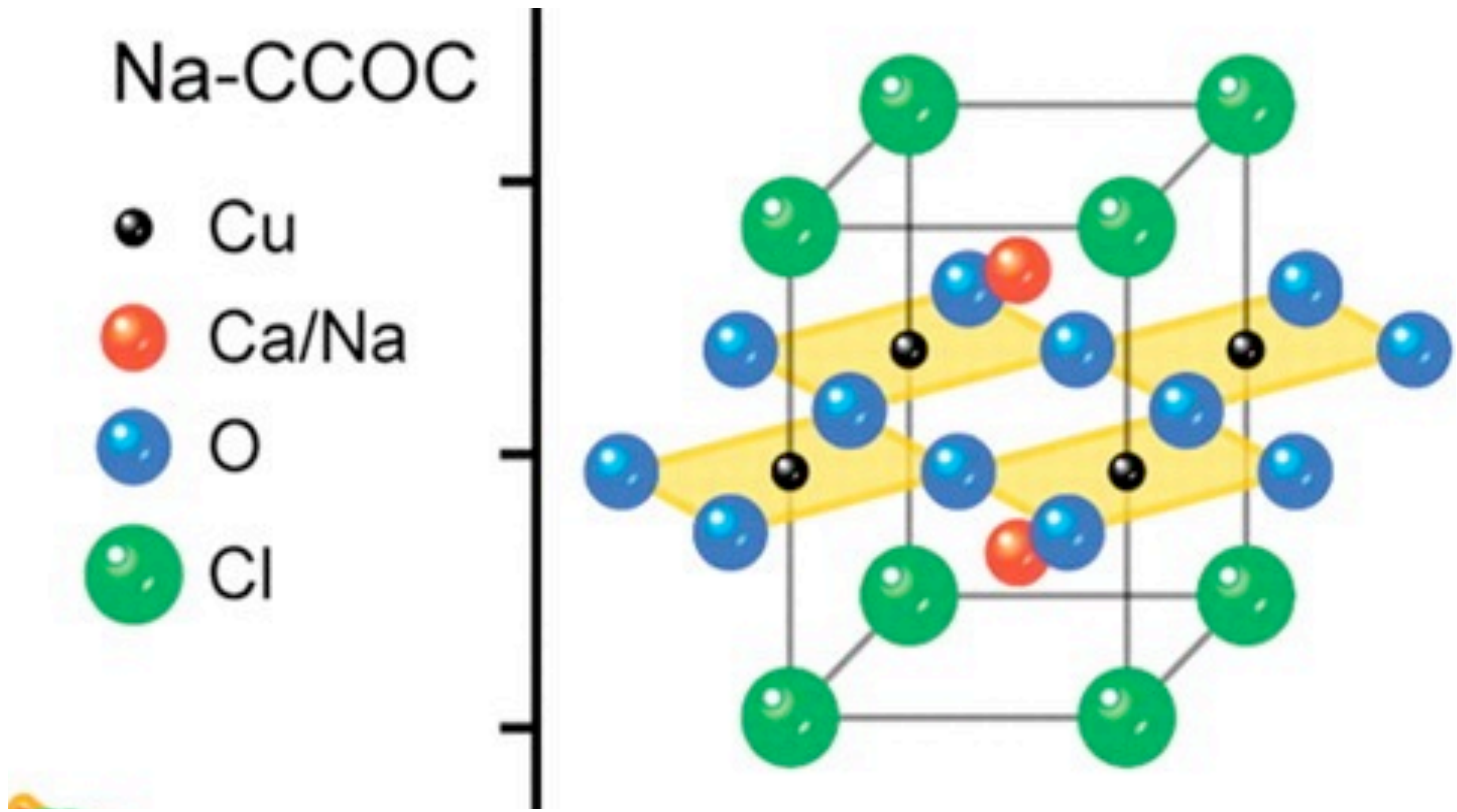
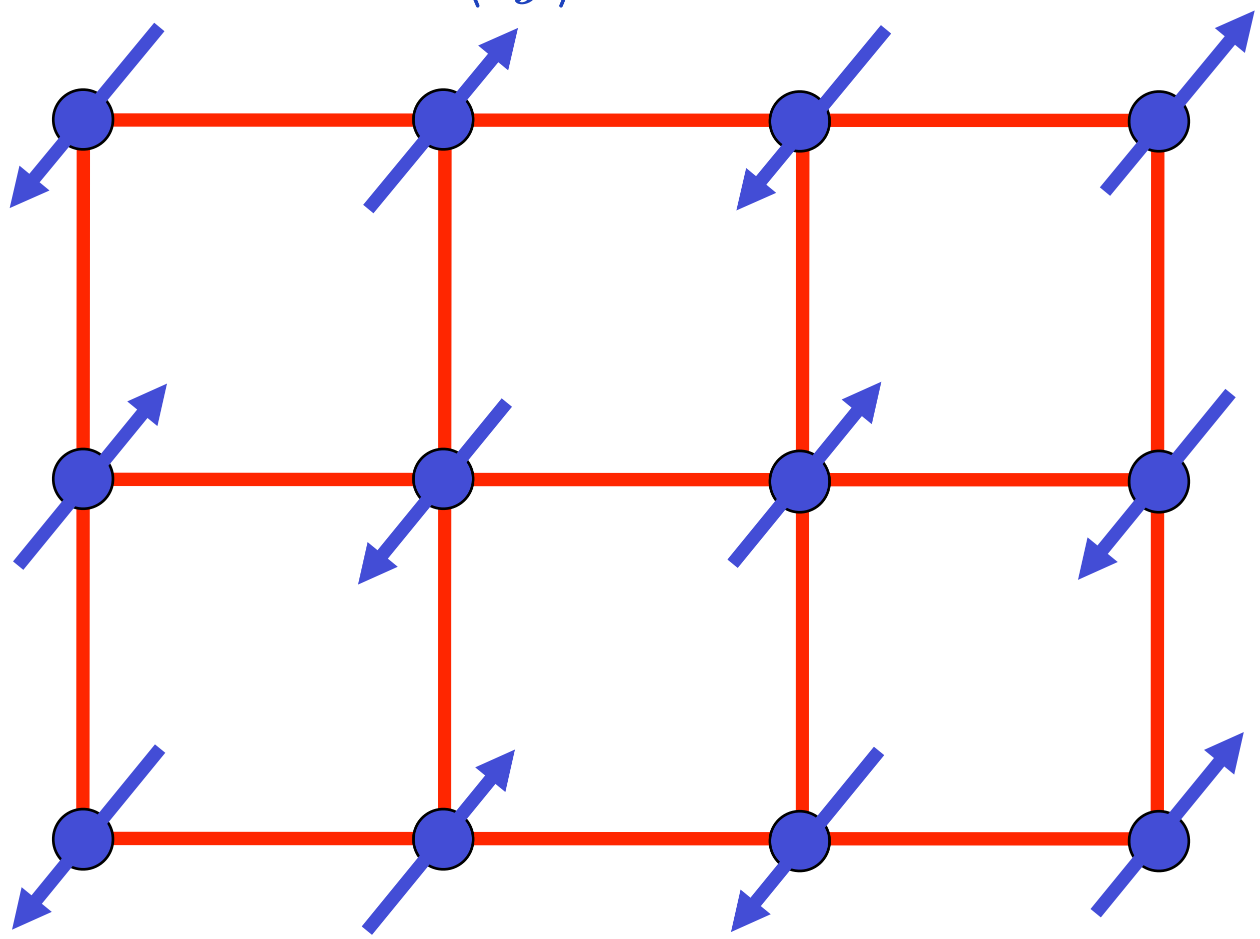
The cuprate superconductors



Square lattice antiferromagnet

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



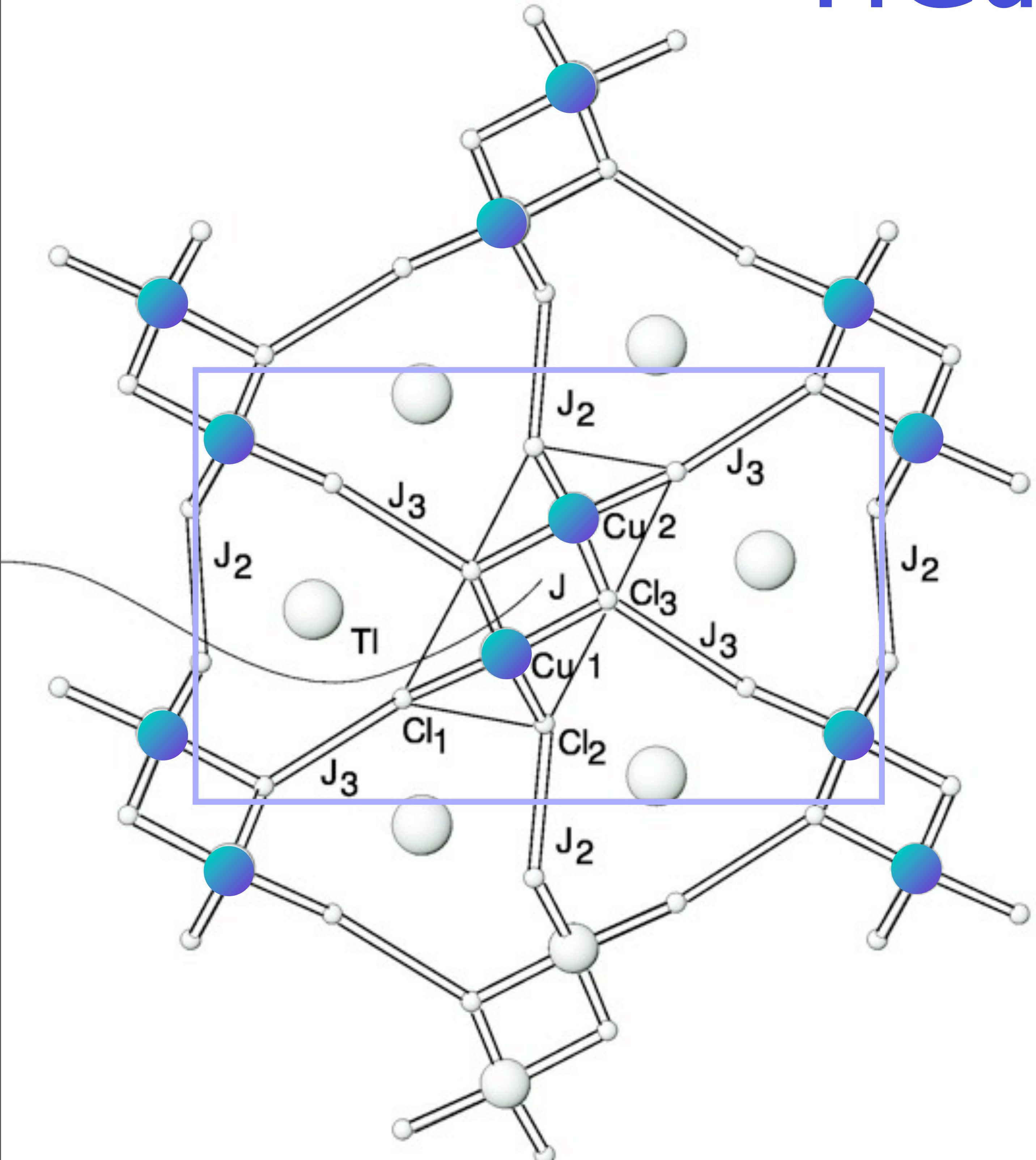
Ground state has long-range Néel order

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.

$TlCuCl_3$


J2
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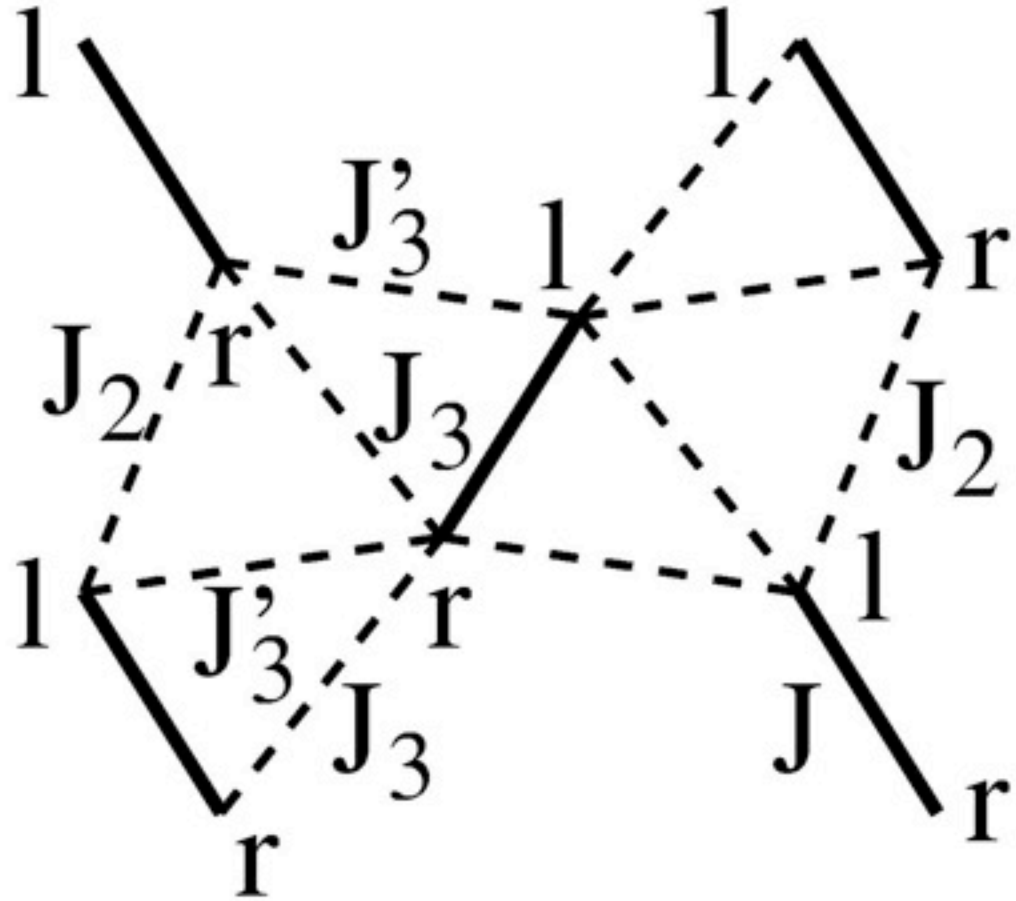
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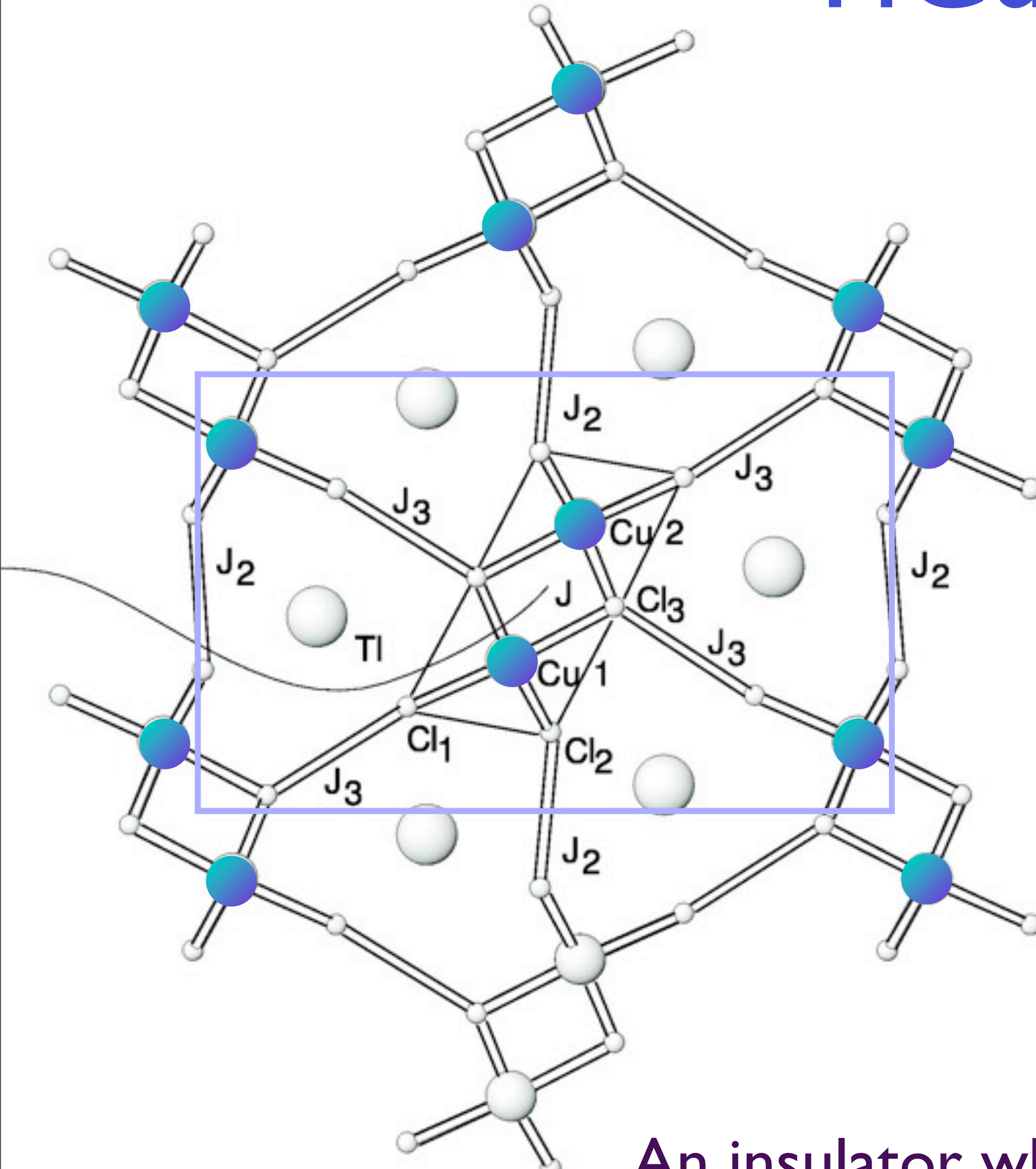
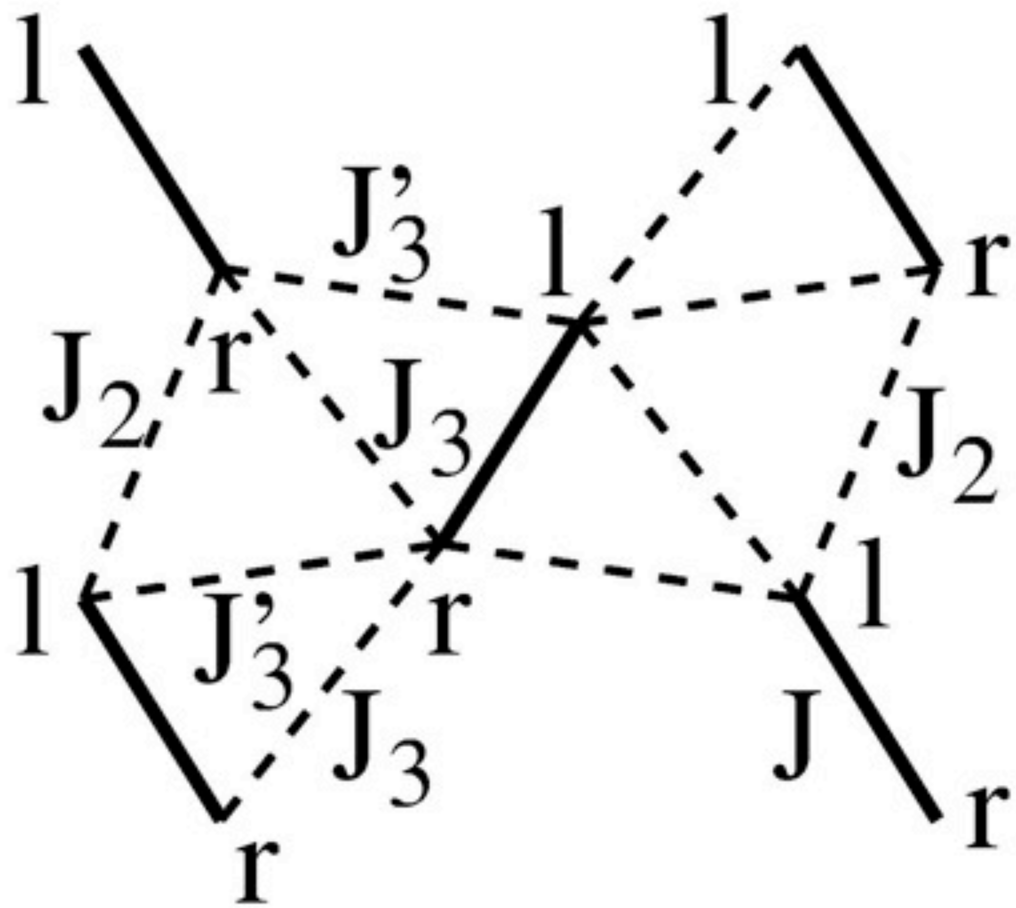
$TlCuCl_3$

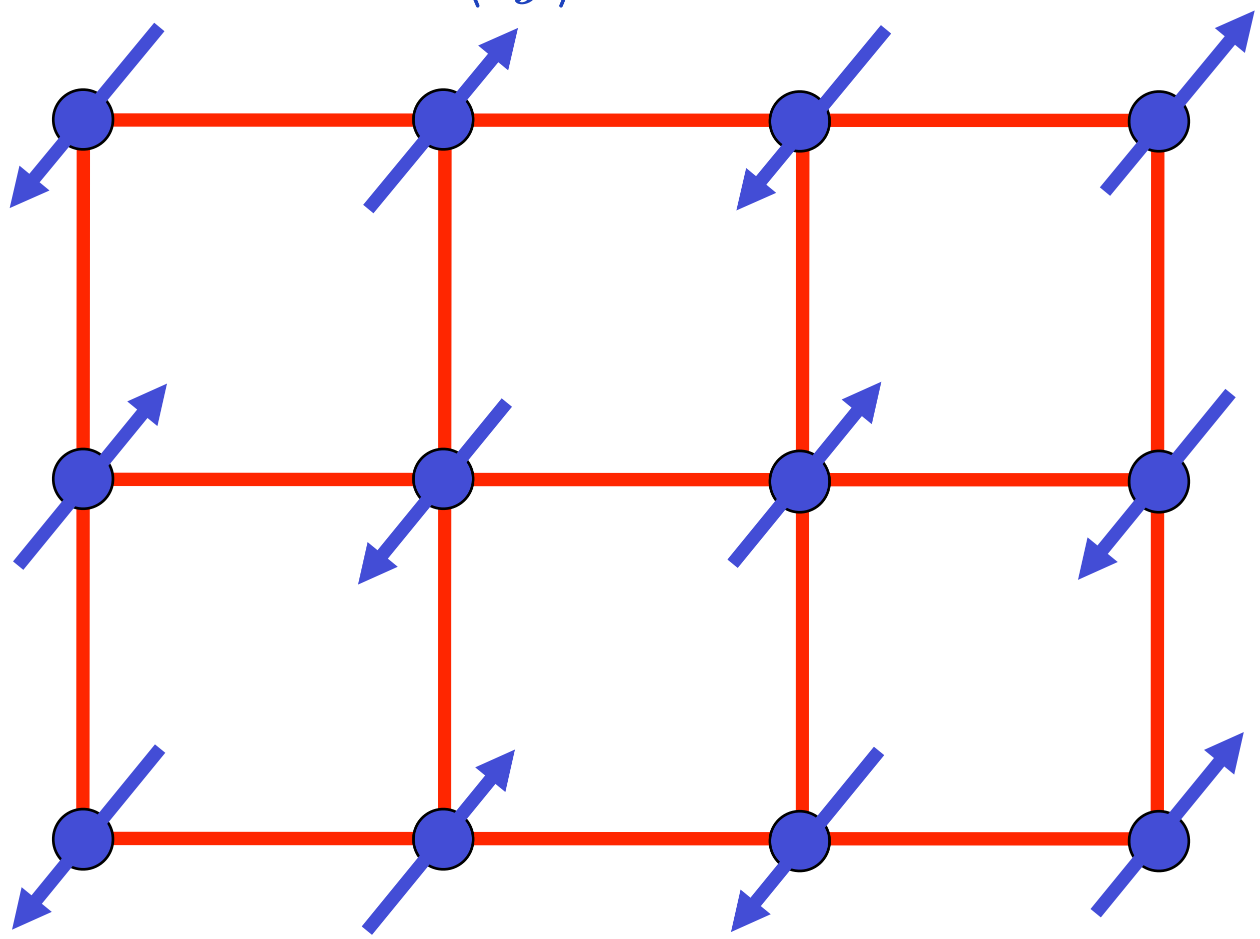




An insulator whose spin susceptibility vanishes exponentially as the temperature T tends to zero.

Square lattice antiferromagnet

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



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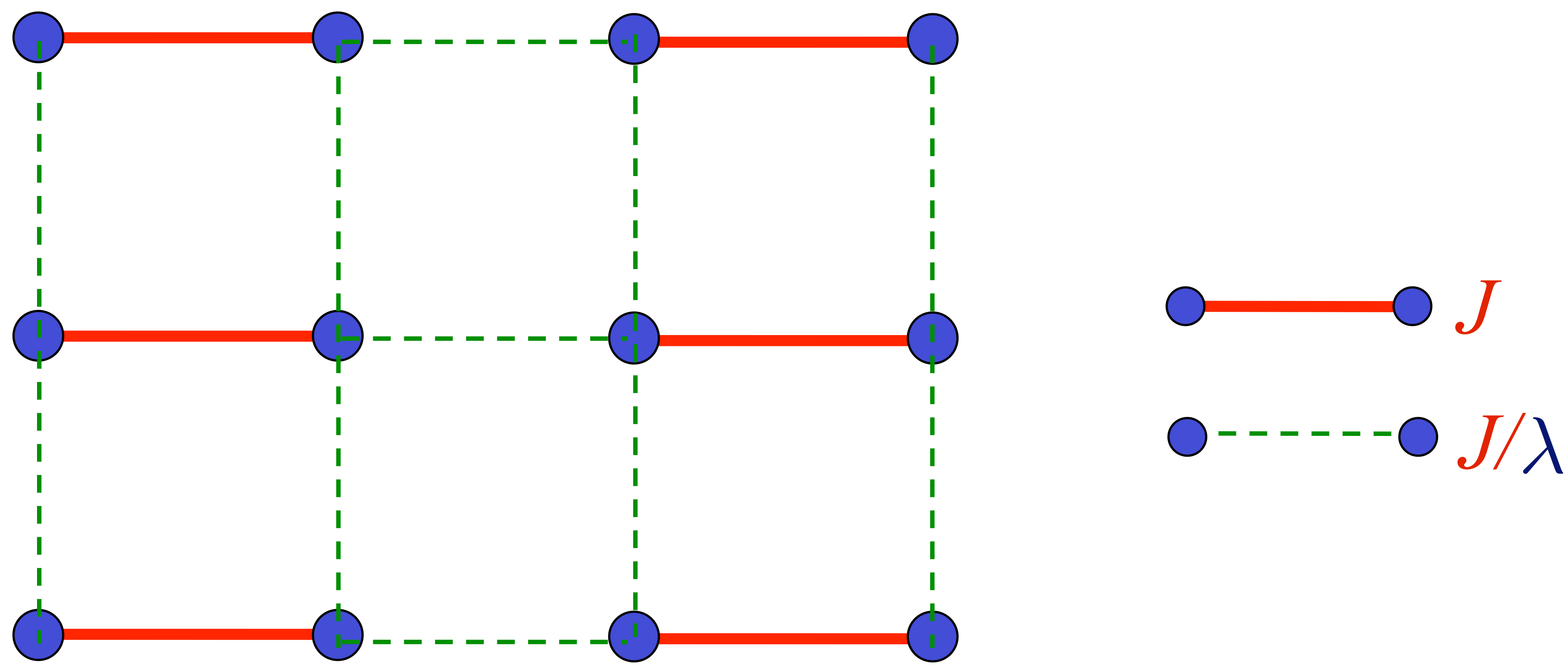
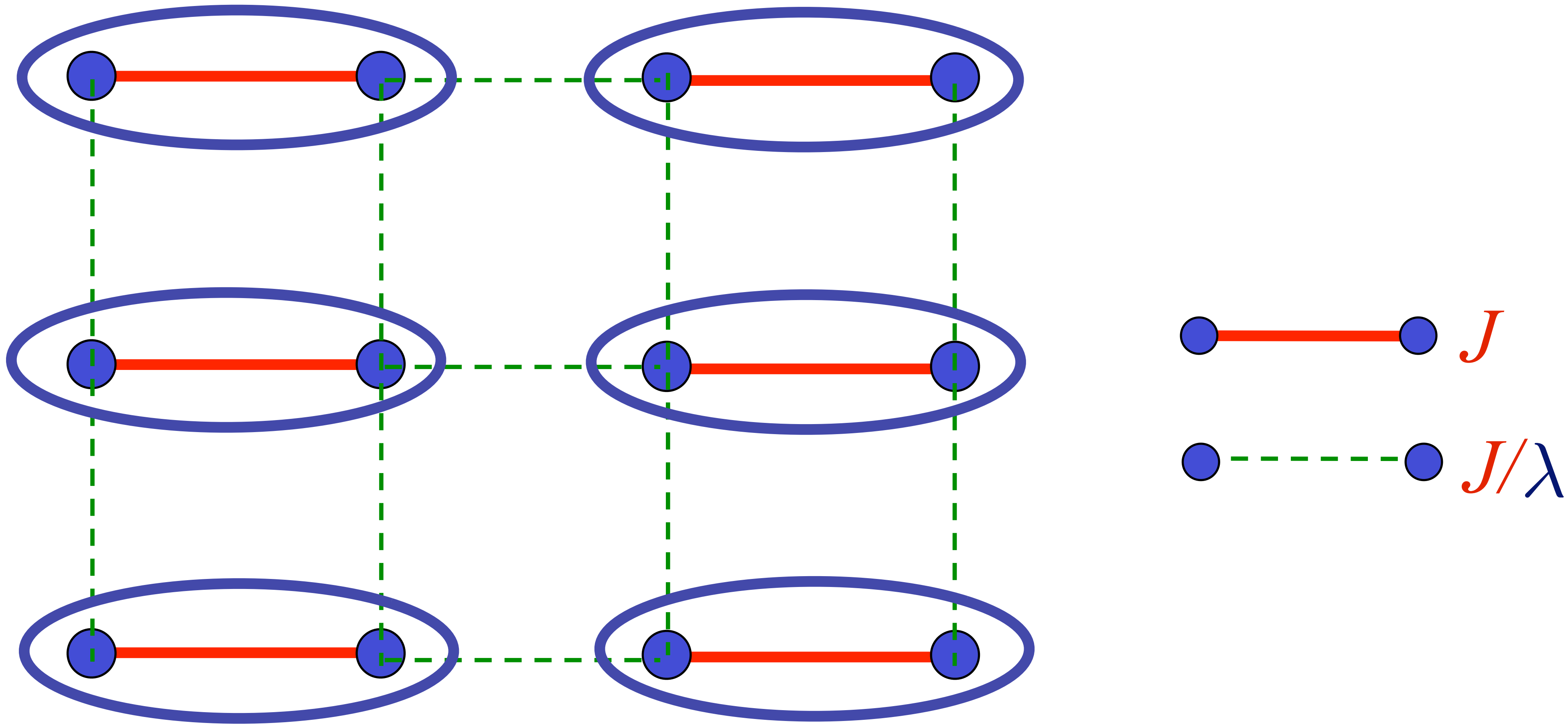


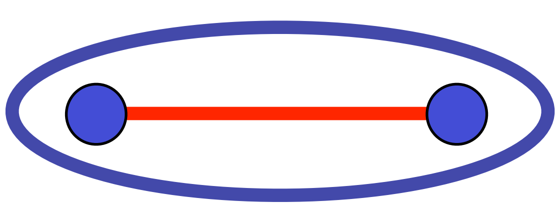
Weaken some bonds to induce spin entanglement in a new quantum phase

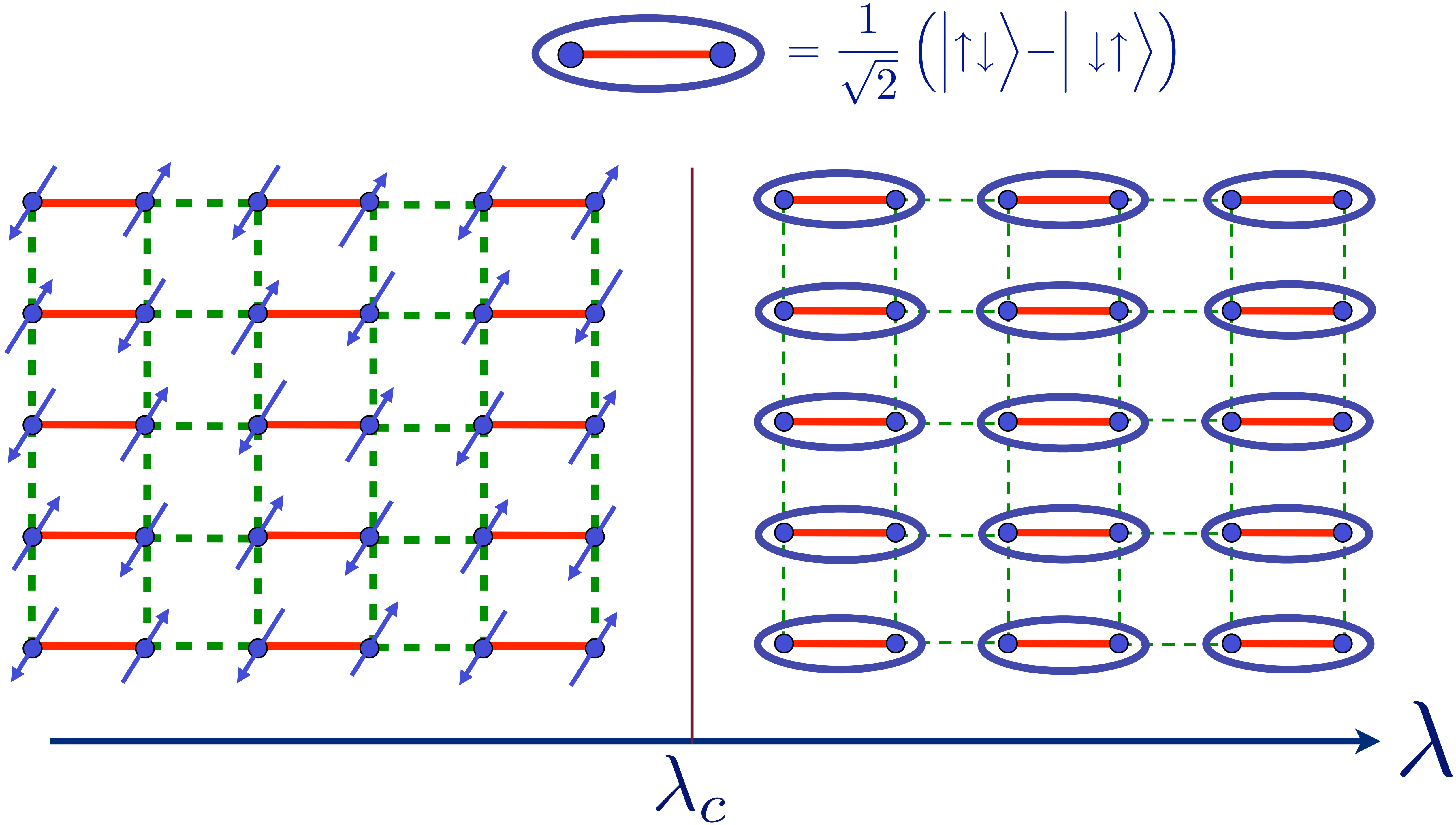
Square lattice antiferromagnet

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



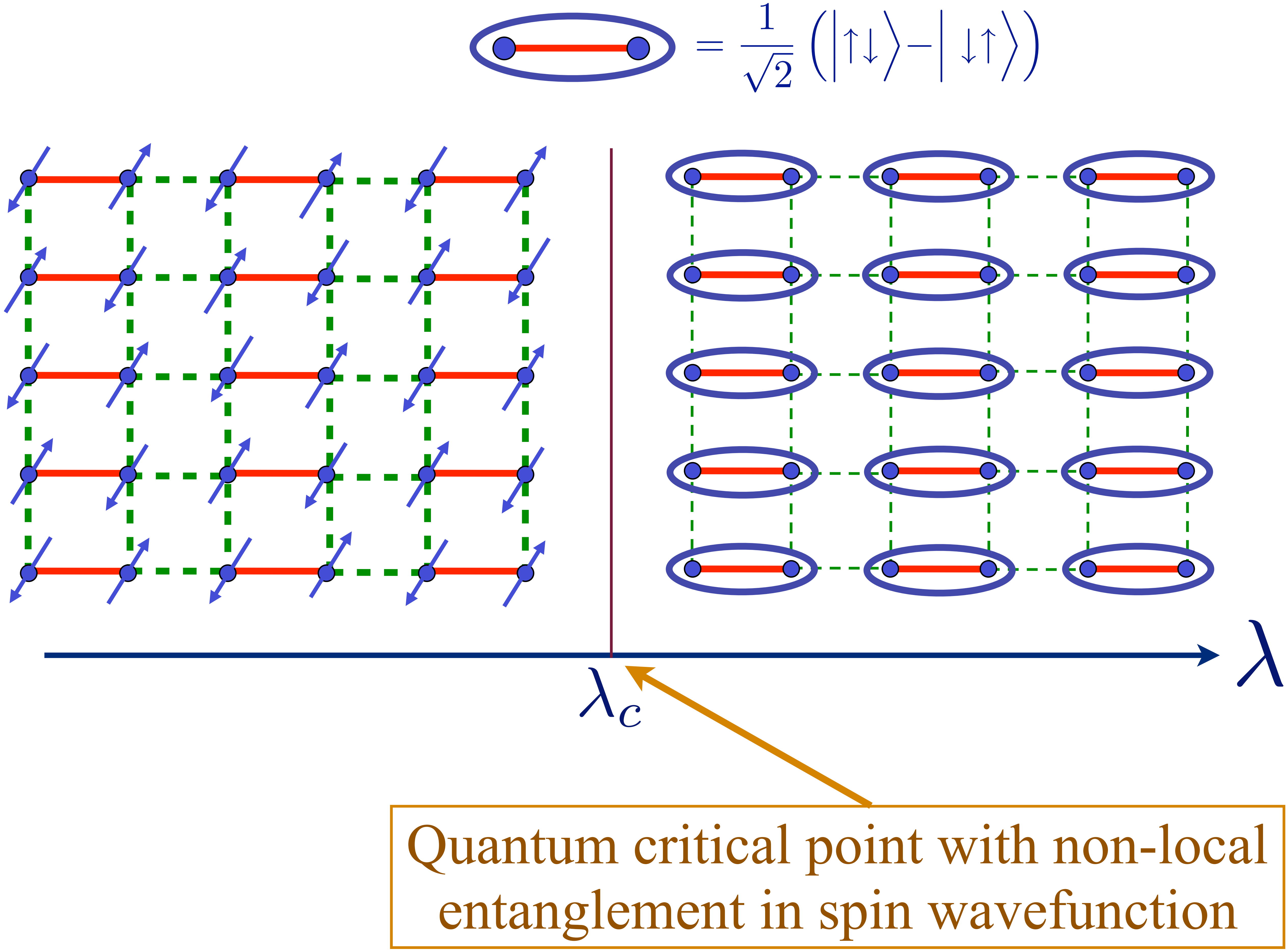
Ground state is a "quantum paramagnet" with spins locked in valence bond singlets

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



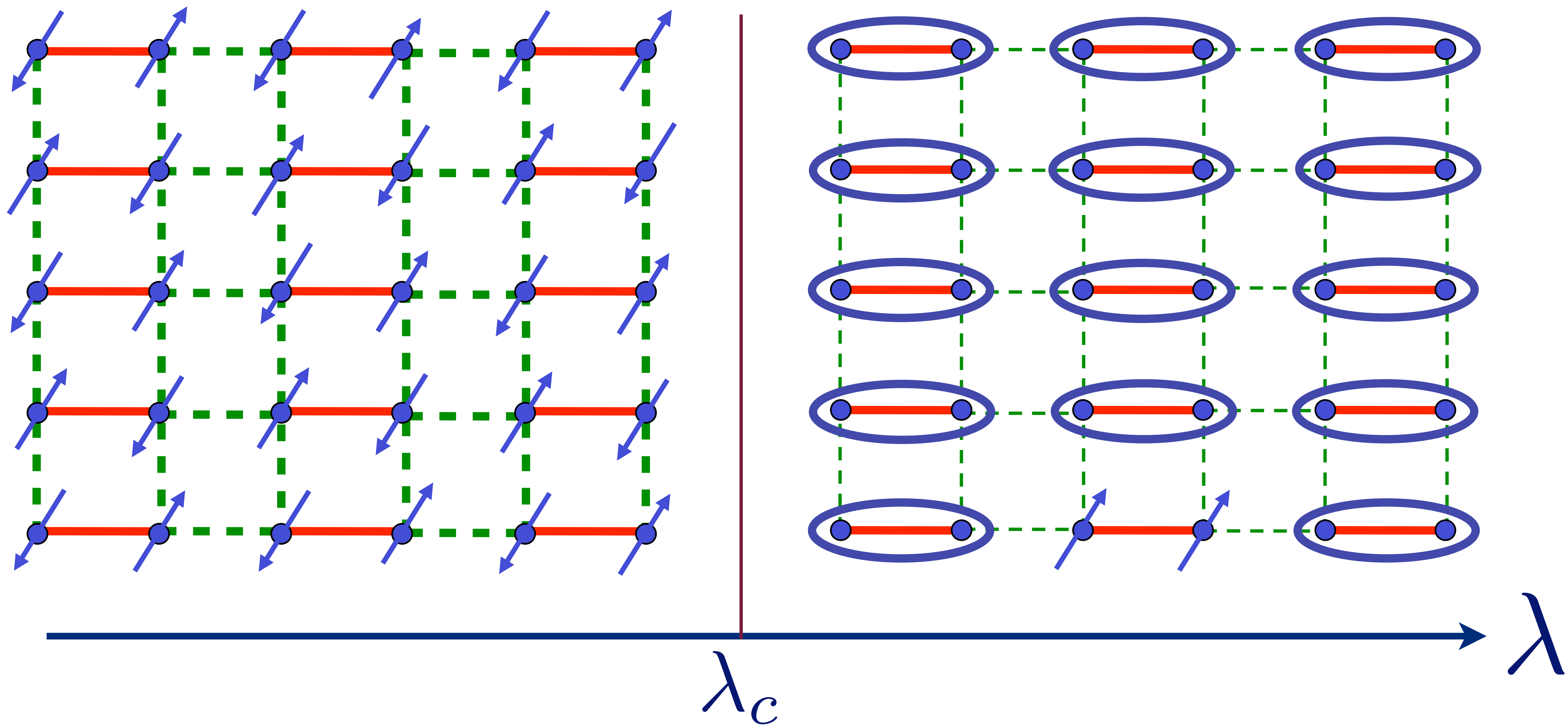
$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$
λ
λ_c

Pressure in $TlCuCl_3$



$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$
λ_c
λ
Quantum critical point with non-local entanglement in spin wavefunction

Excitation spectrum in the paramagnetic phase



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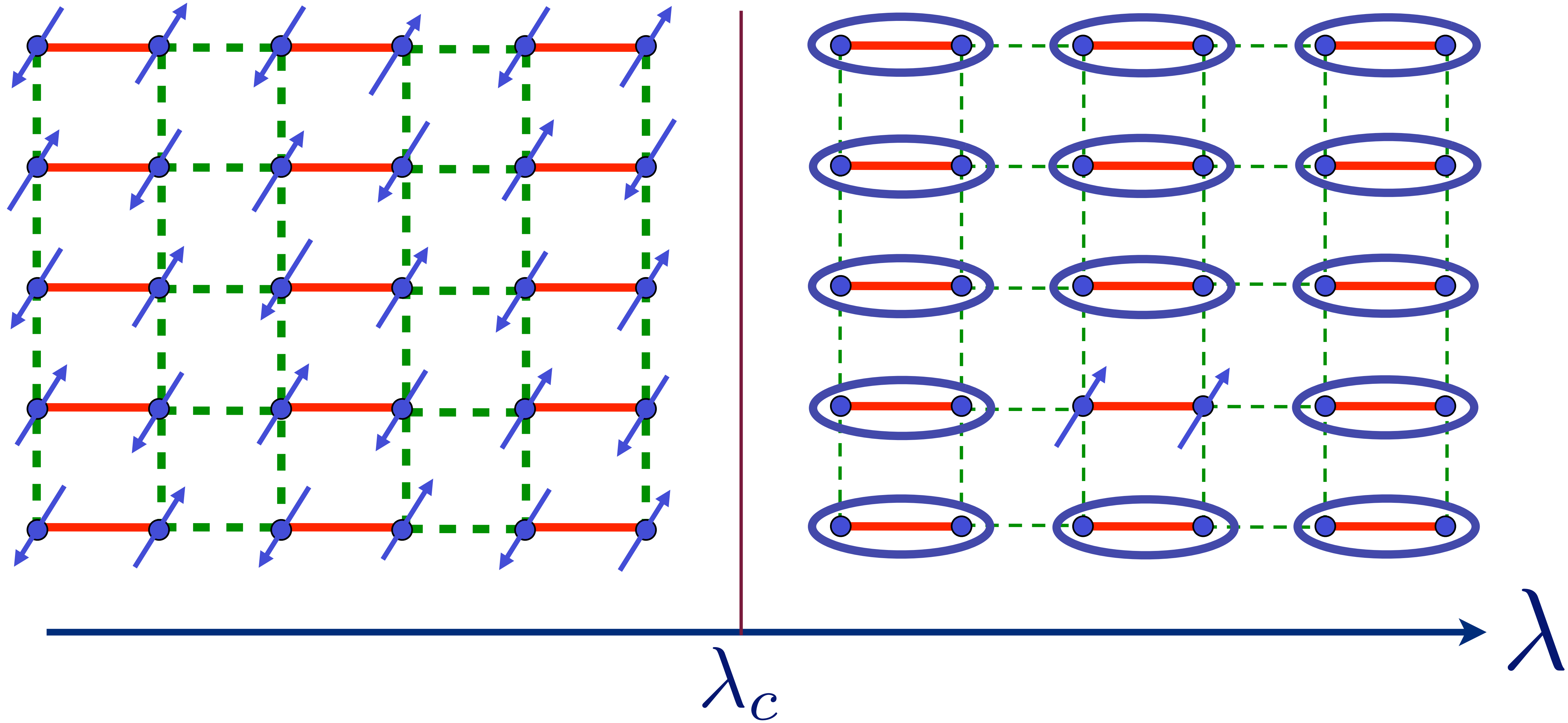

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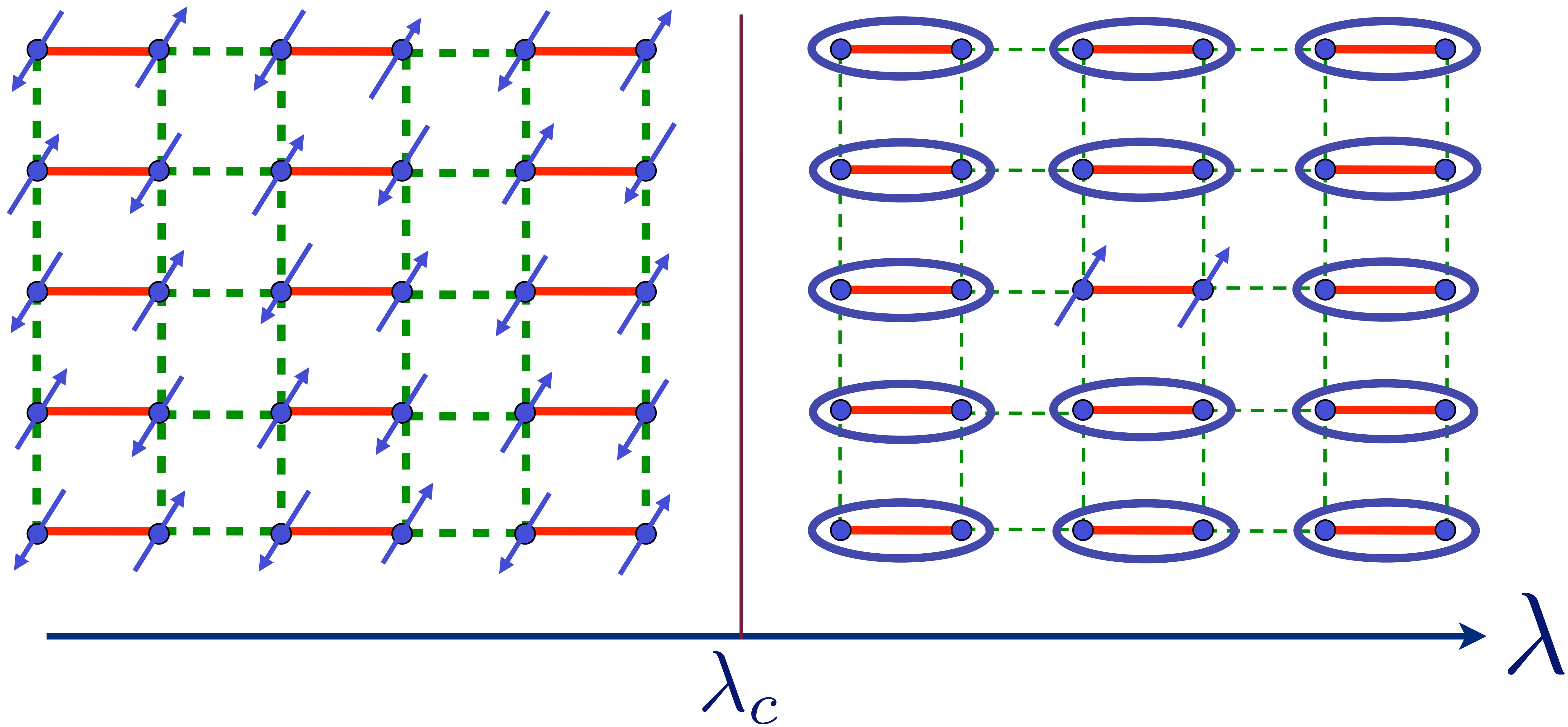
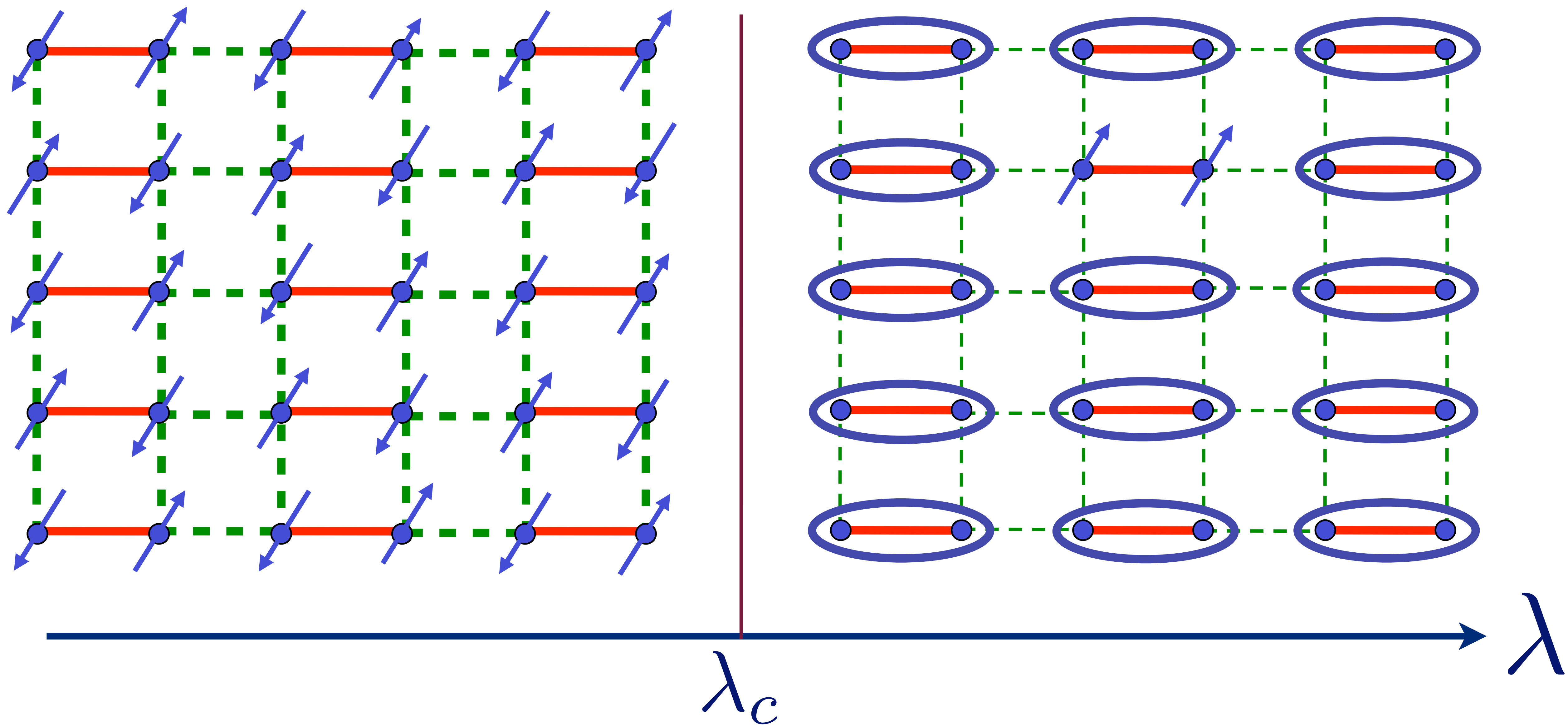


Excitation spectrum in the paramagnetic phase



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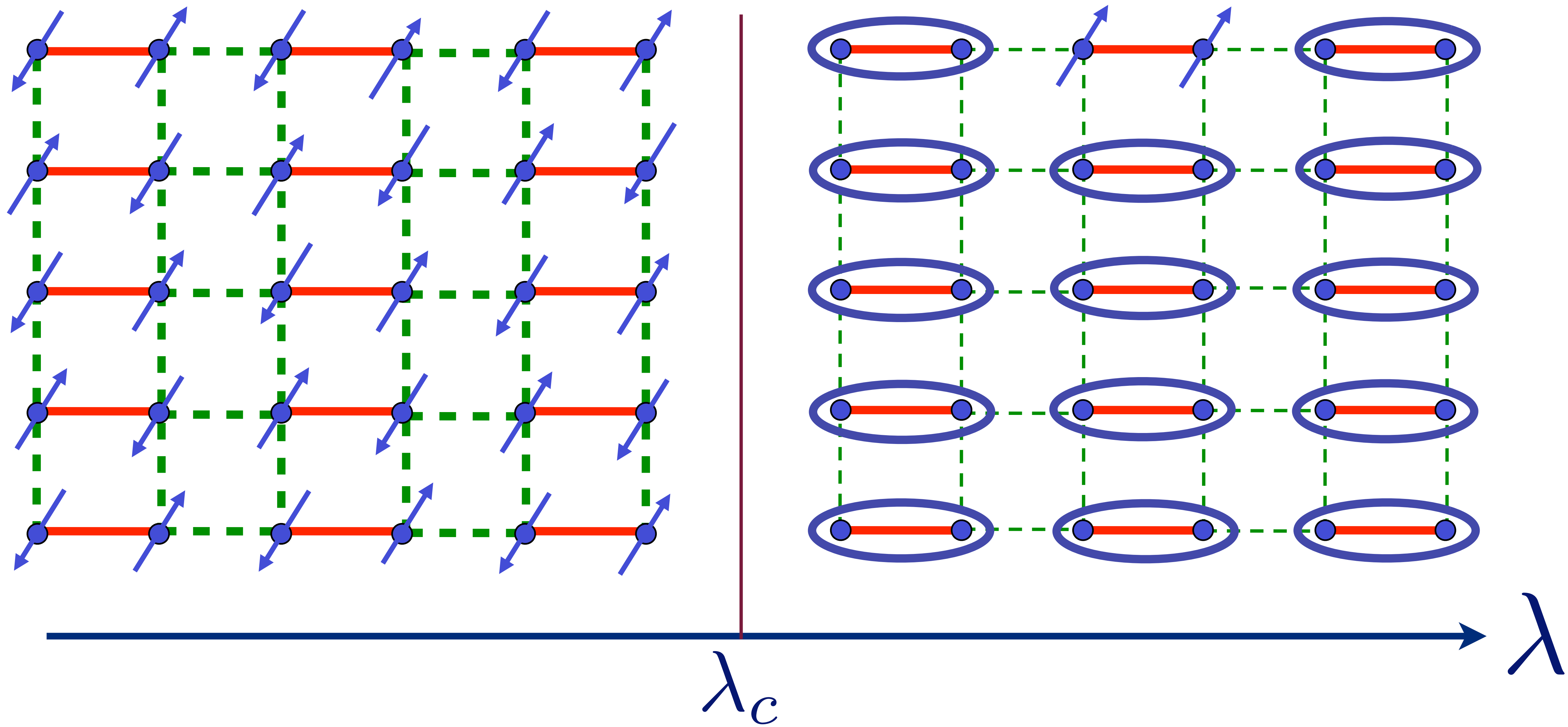
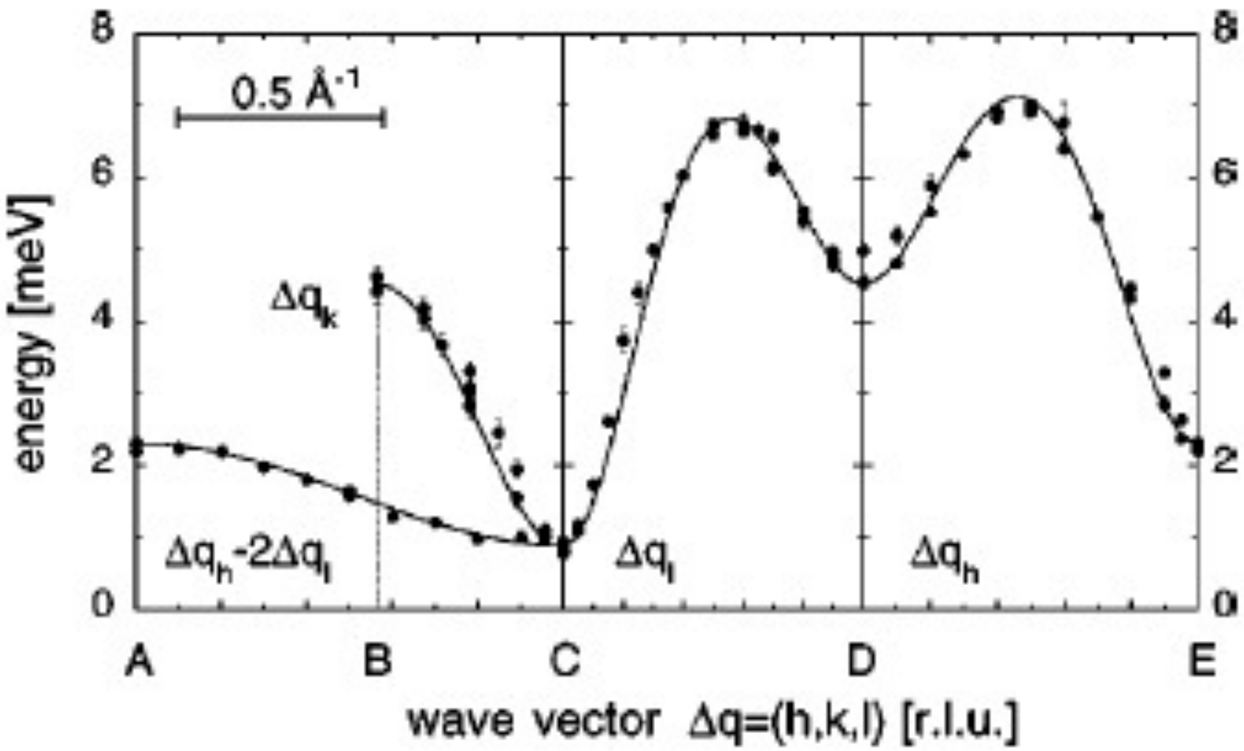


$TlCuCl_3$ at ambient pressure



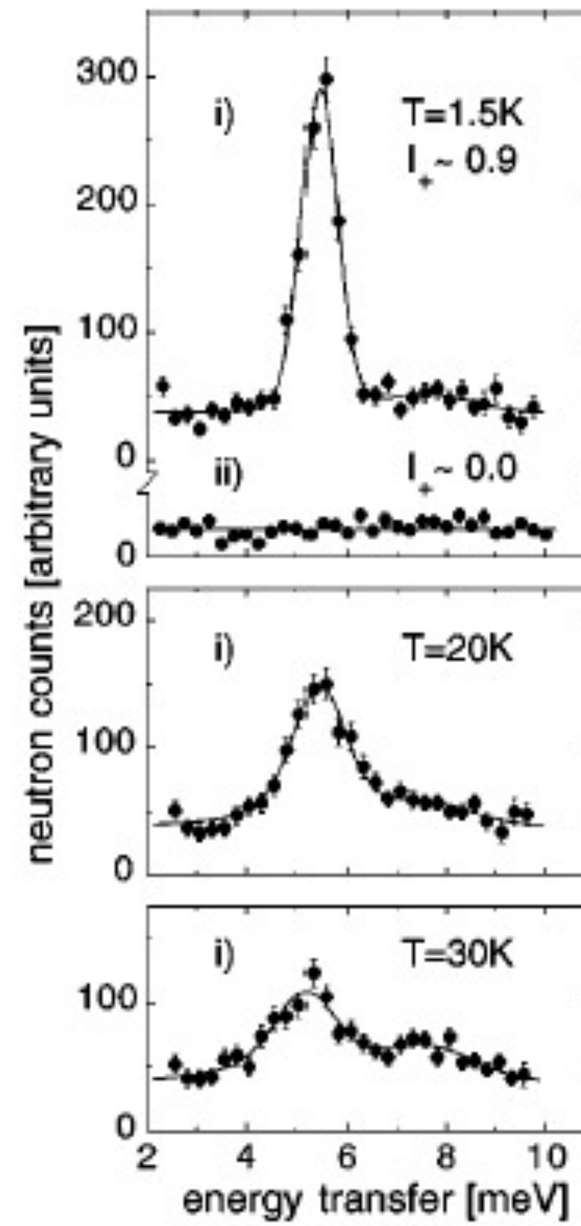
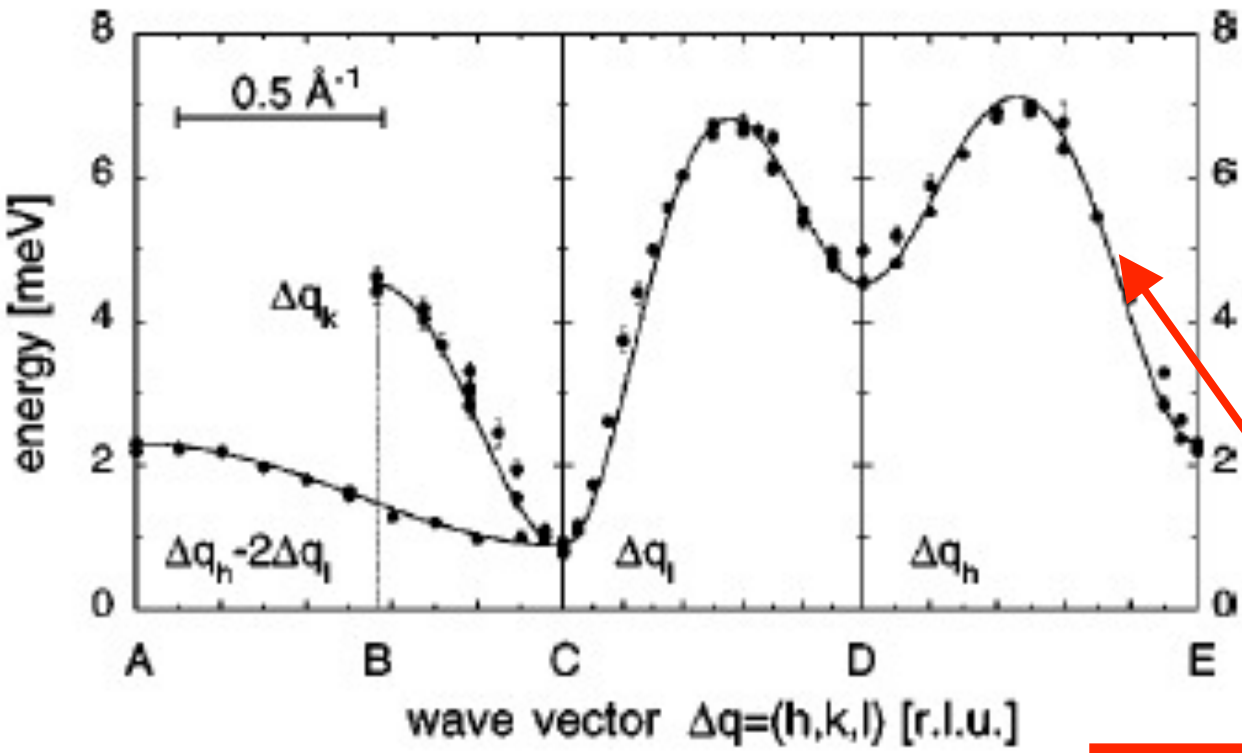
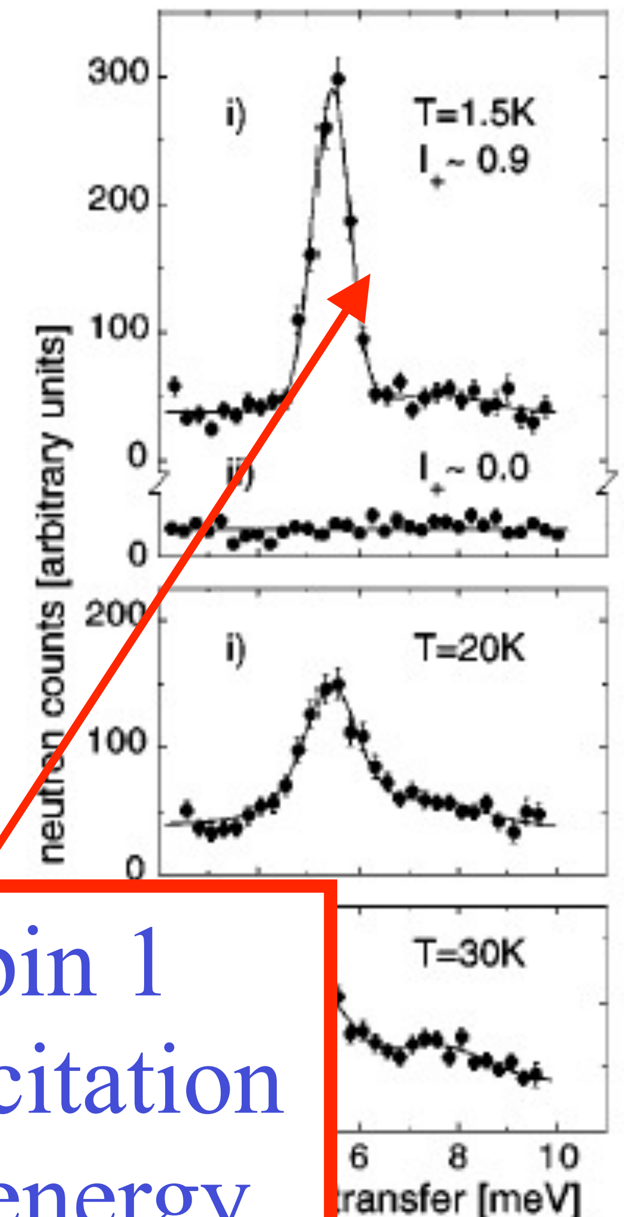


FIG. 1. Measured neutron profiles in the a^*c^* plane of $TlCuCl_3$ for $i=(1.35,0,0)$, $ii=(0,0,3.15)$ [r.l.u]. The spectrum at $T=1.5$ K

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

$TlCuCl_3$ at ambient pressure



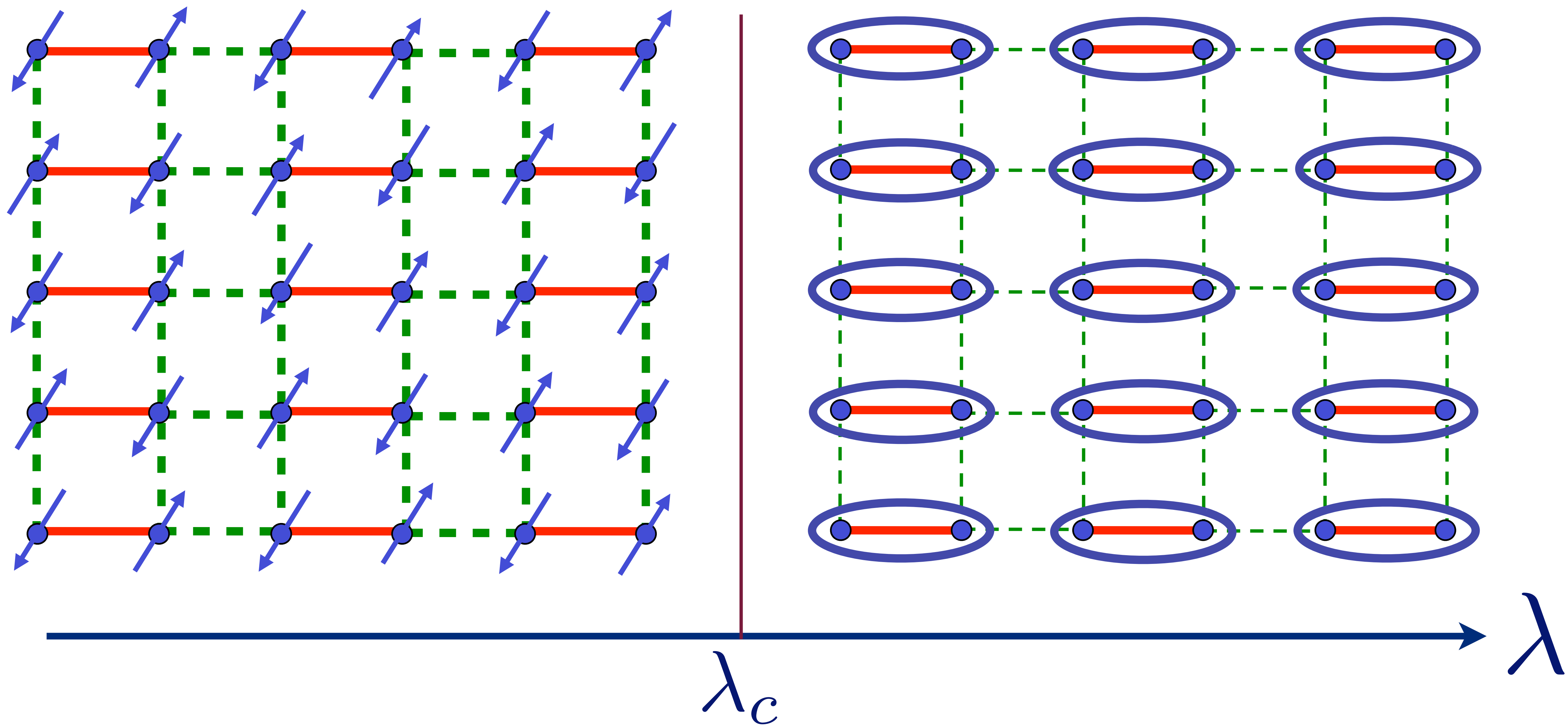


Sharp spin 1 particle excitation above an energy gap (spin gap)

...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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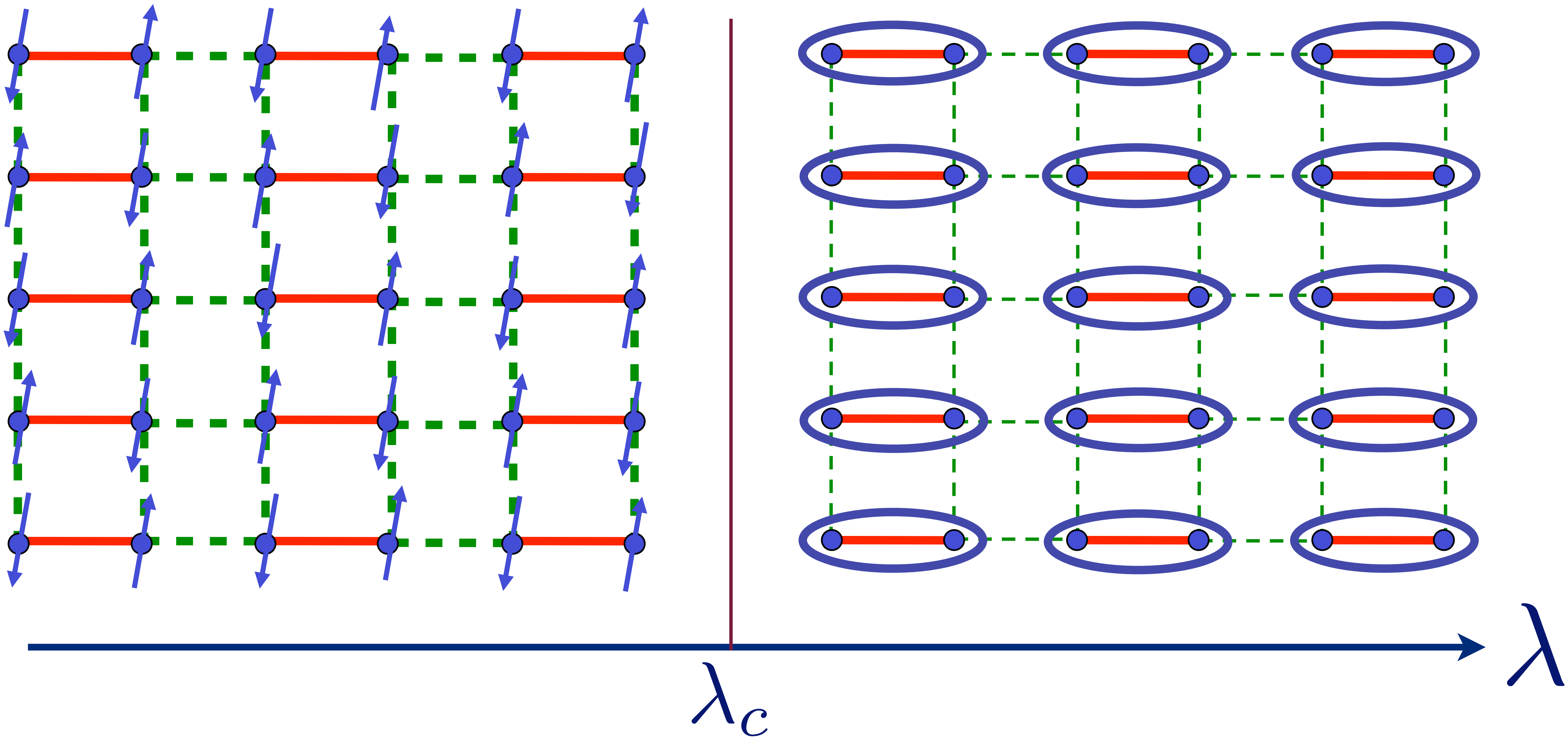
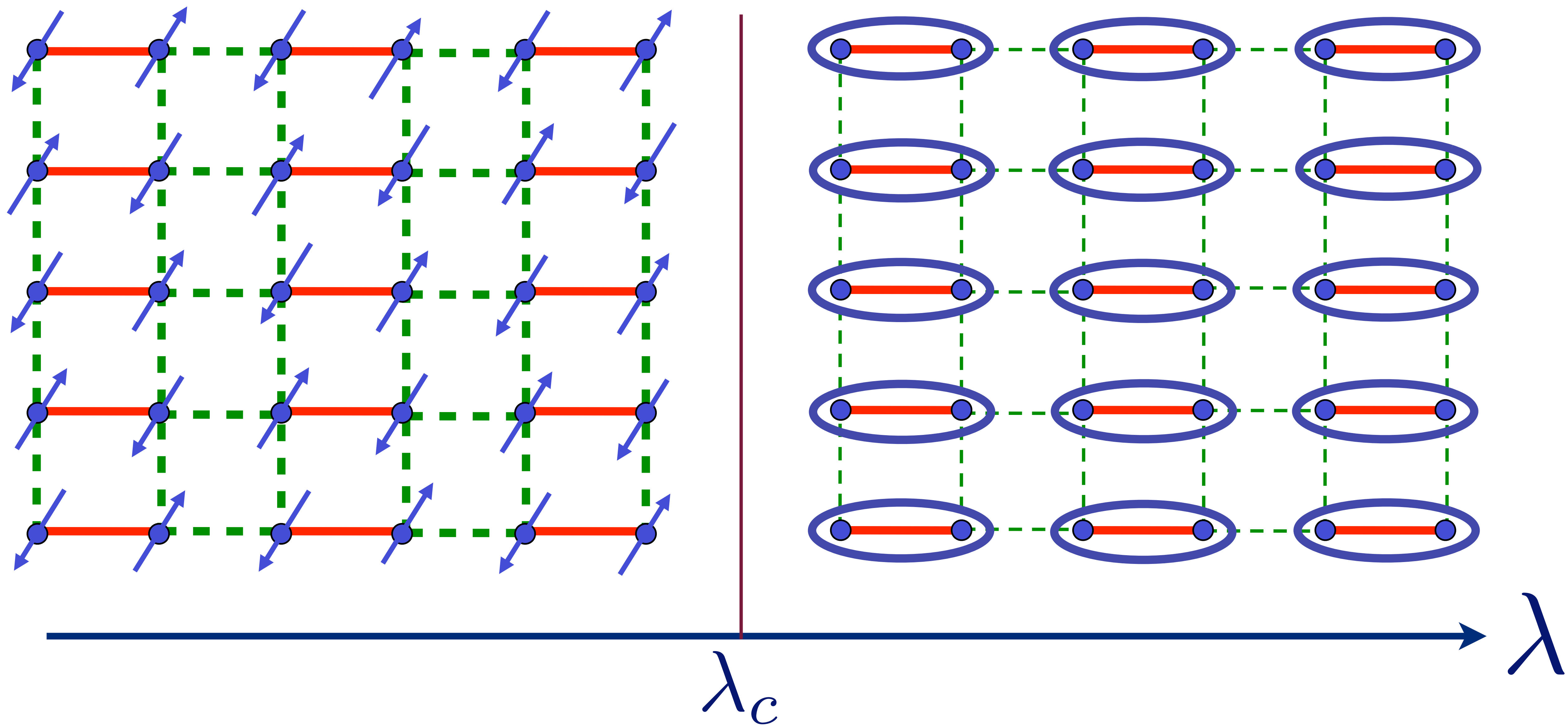


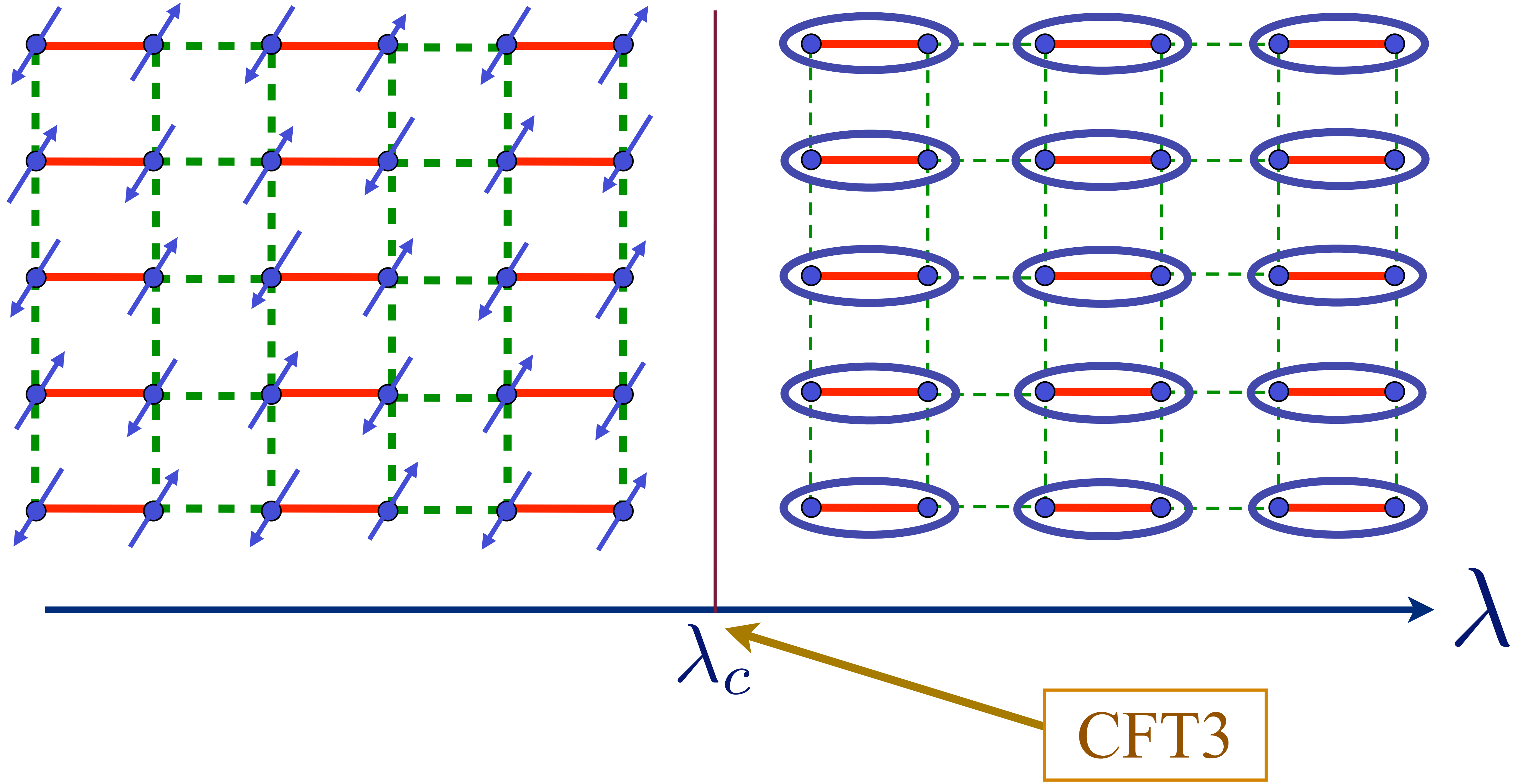
Spin waves

Excitation spectrum in the Néel phase



Spin waves

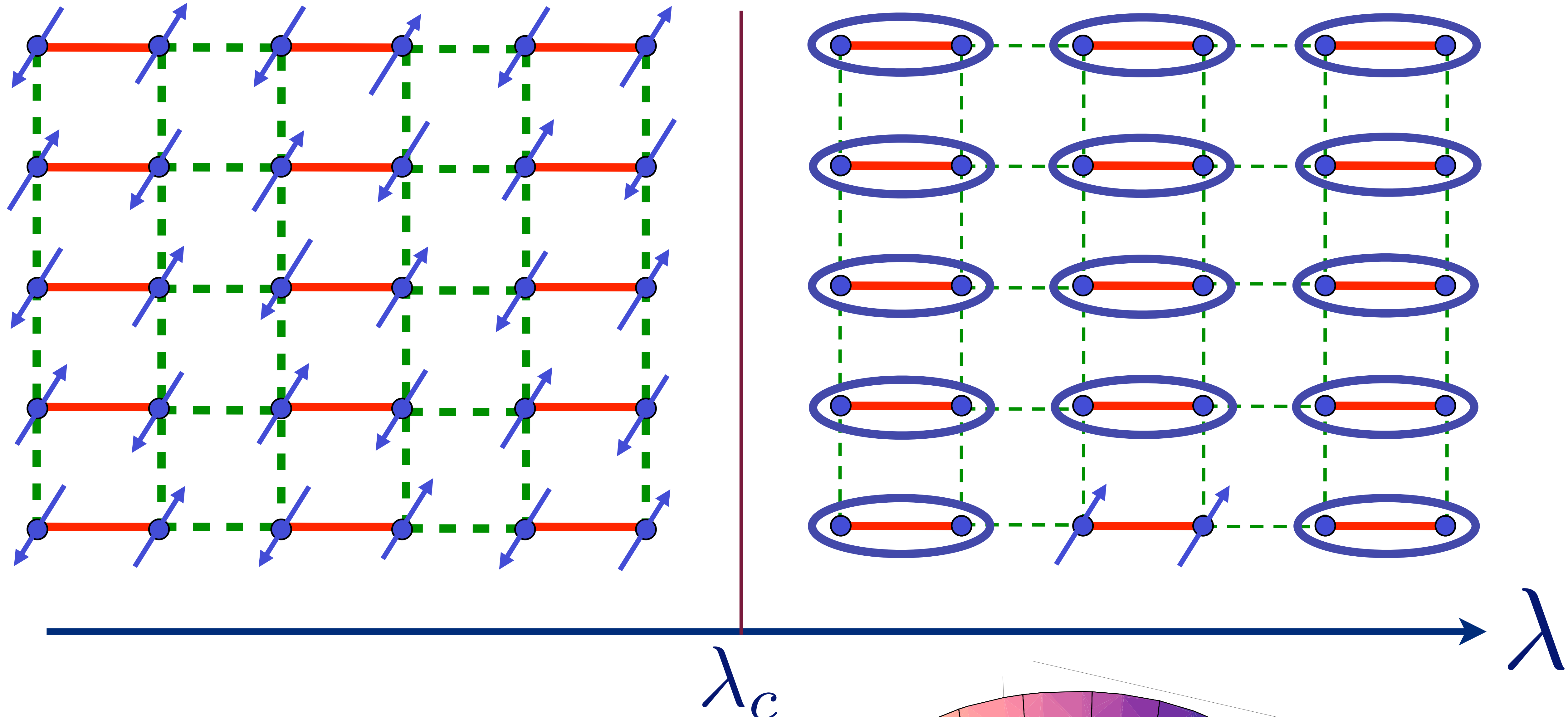
Description using Landau-Ginzburg field theory



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

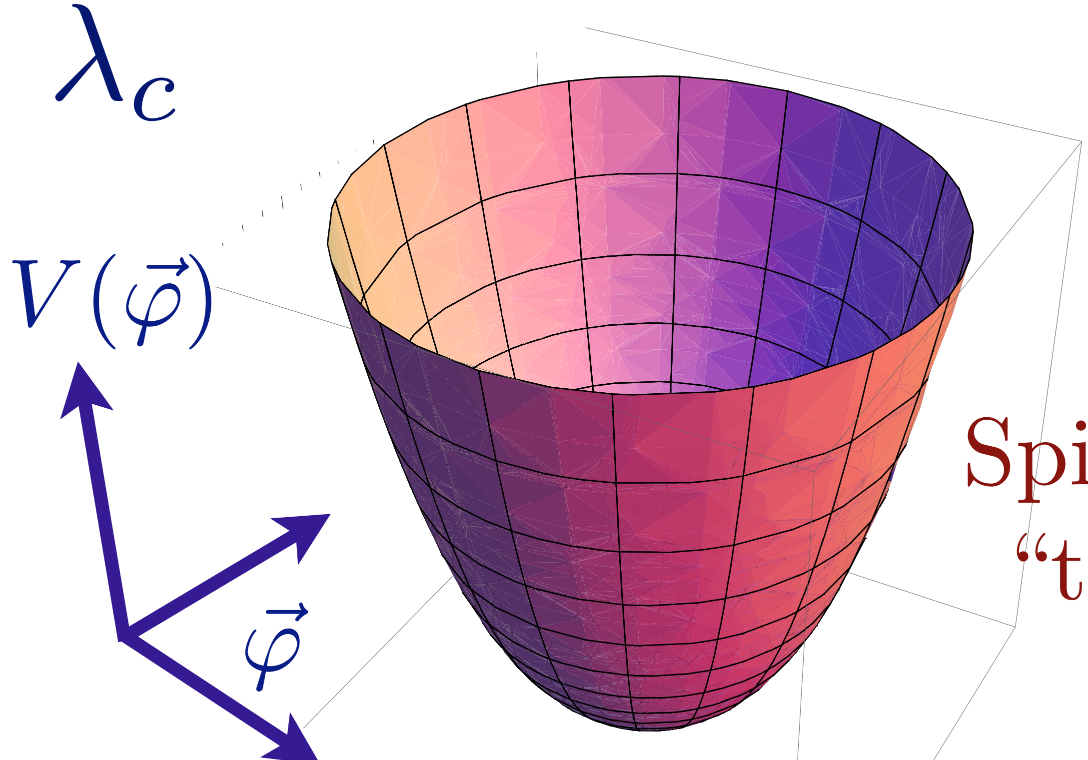
$$\mathcal{S} = \int d^2 r d\tau \left[(\partial_\tau \vec{\varphi})^2 + c^2 (\nabla_r \vec{\varphi})^2 + (\lambda - \lambda_c) \vec{\varphi}^2 + u \left(\vec{\varphi}^2 \right)^2 \right]$$

Excitation spectrum in the paramagnetic phase



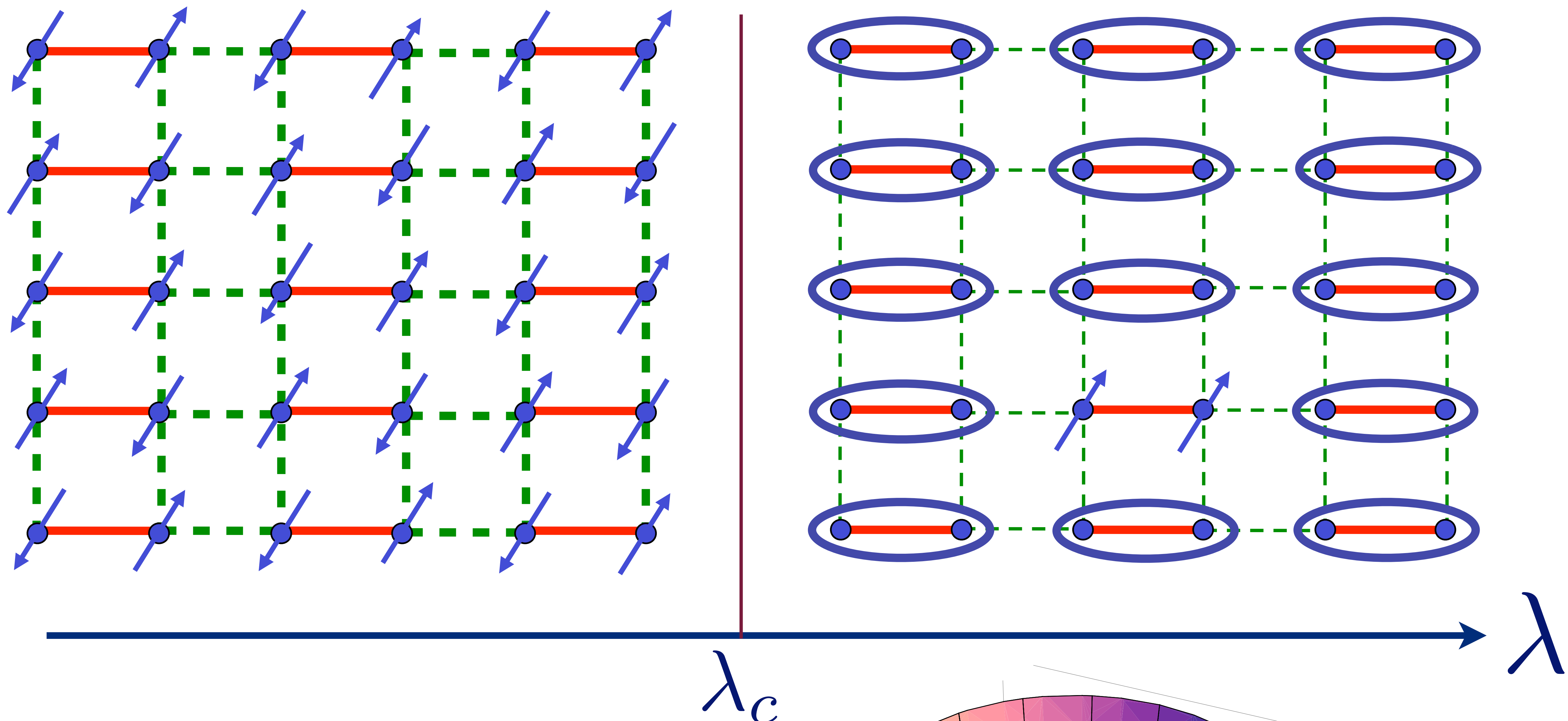
$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$

$$\lambda > \lambda_c$$



Spin $S = 1$
"triplon"

Excitation spectrum in the paramagnetic phase



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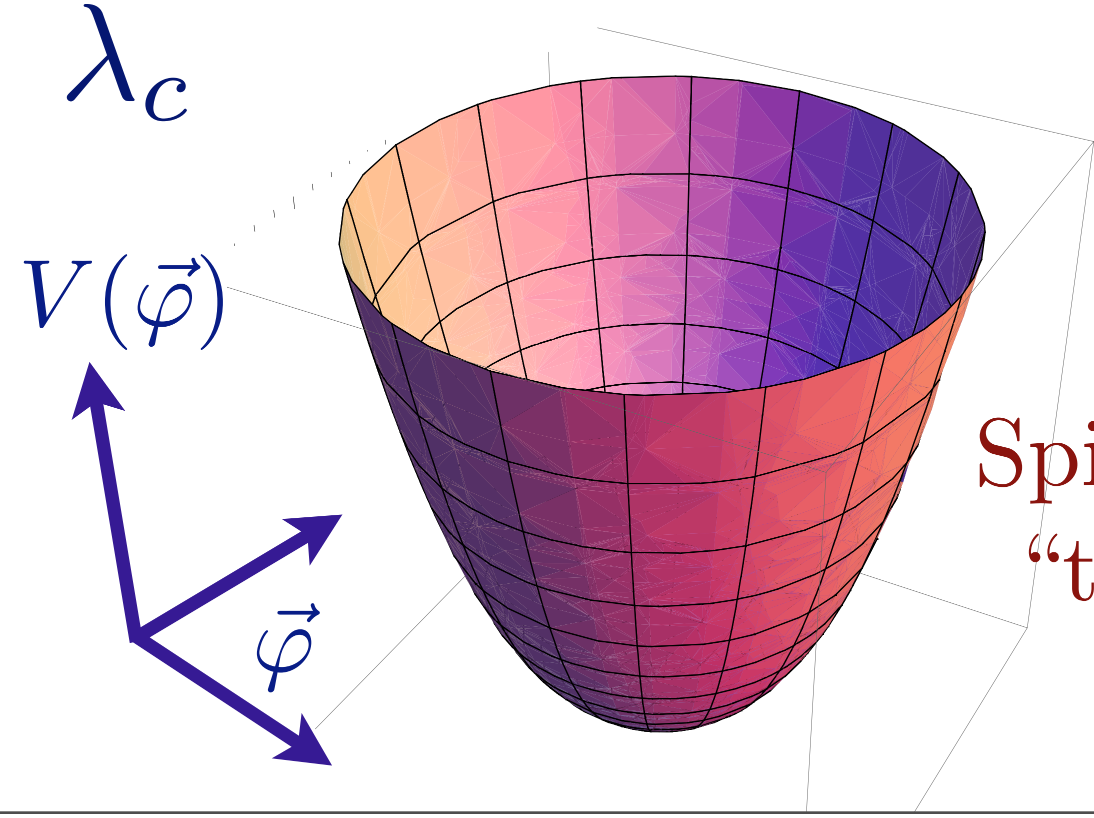

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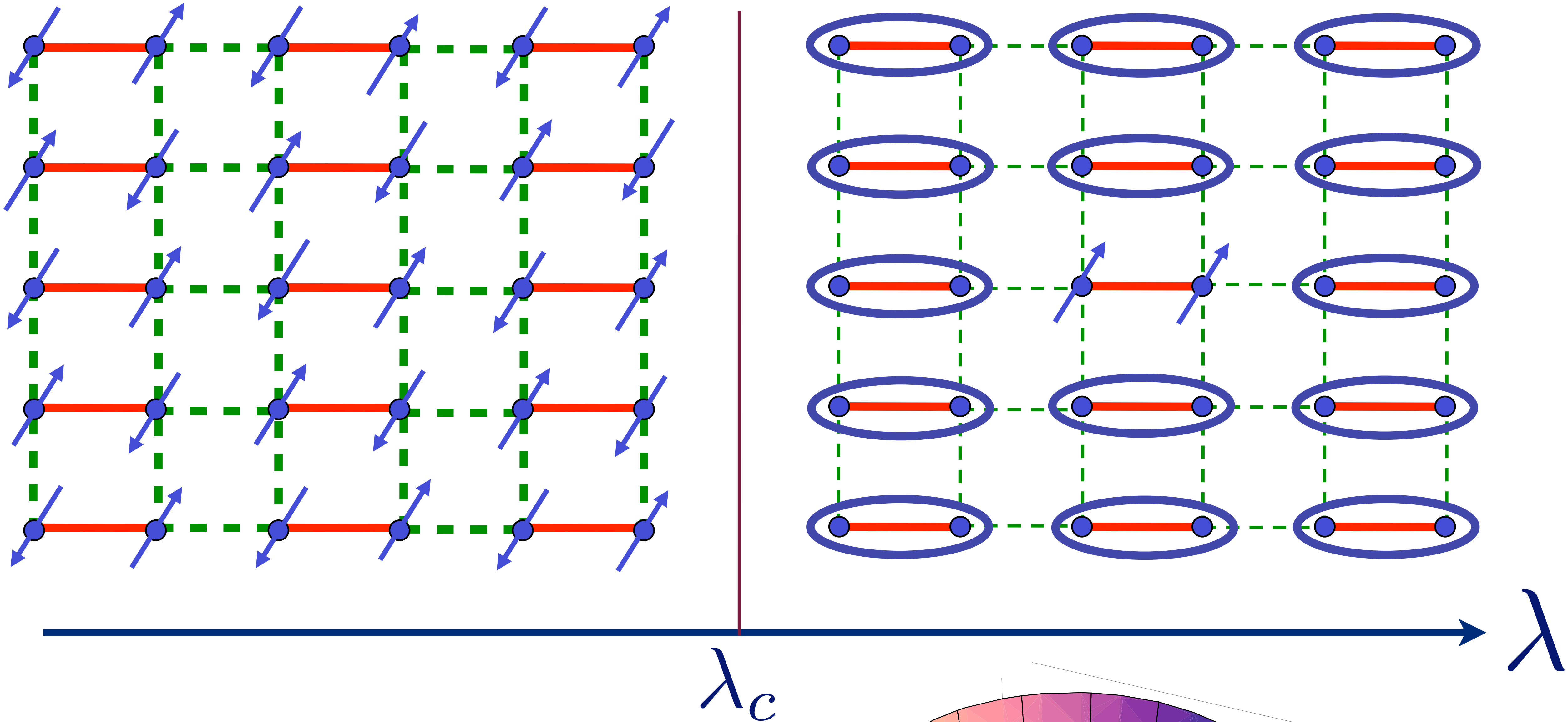

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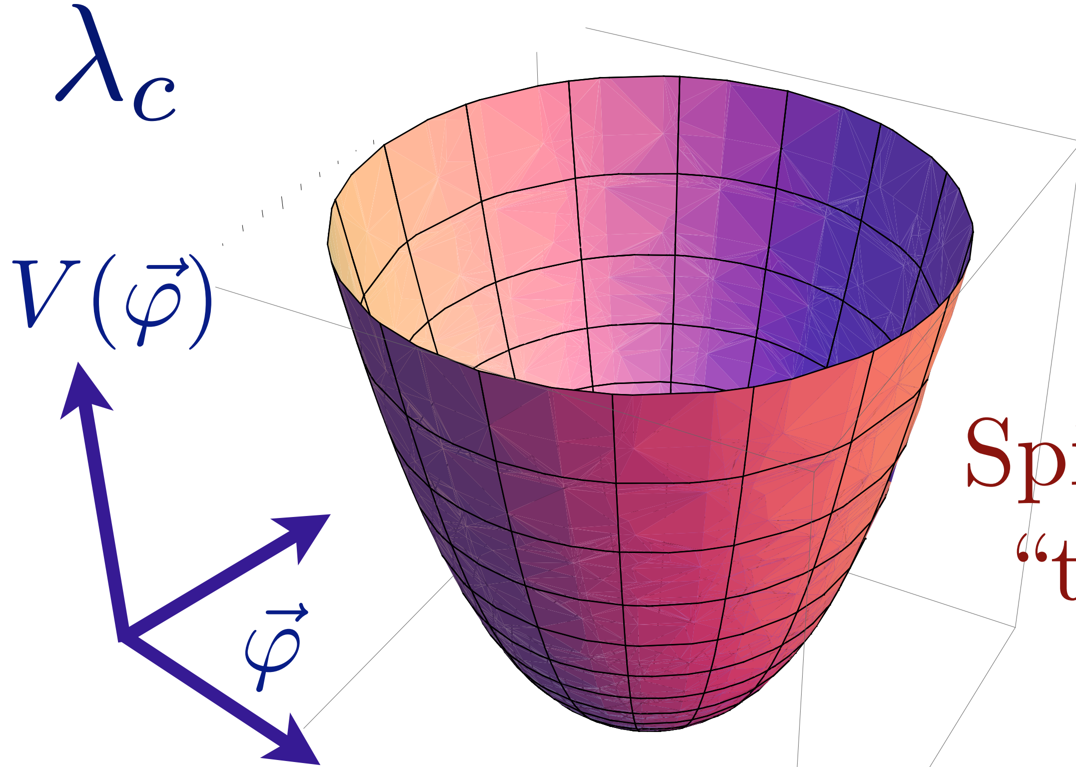

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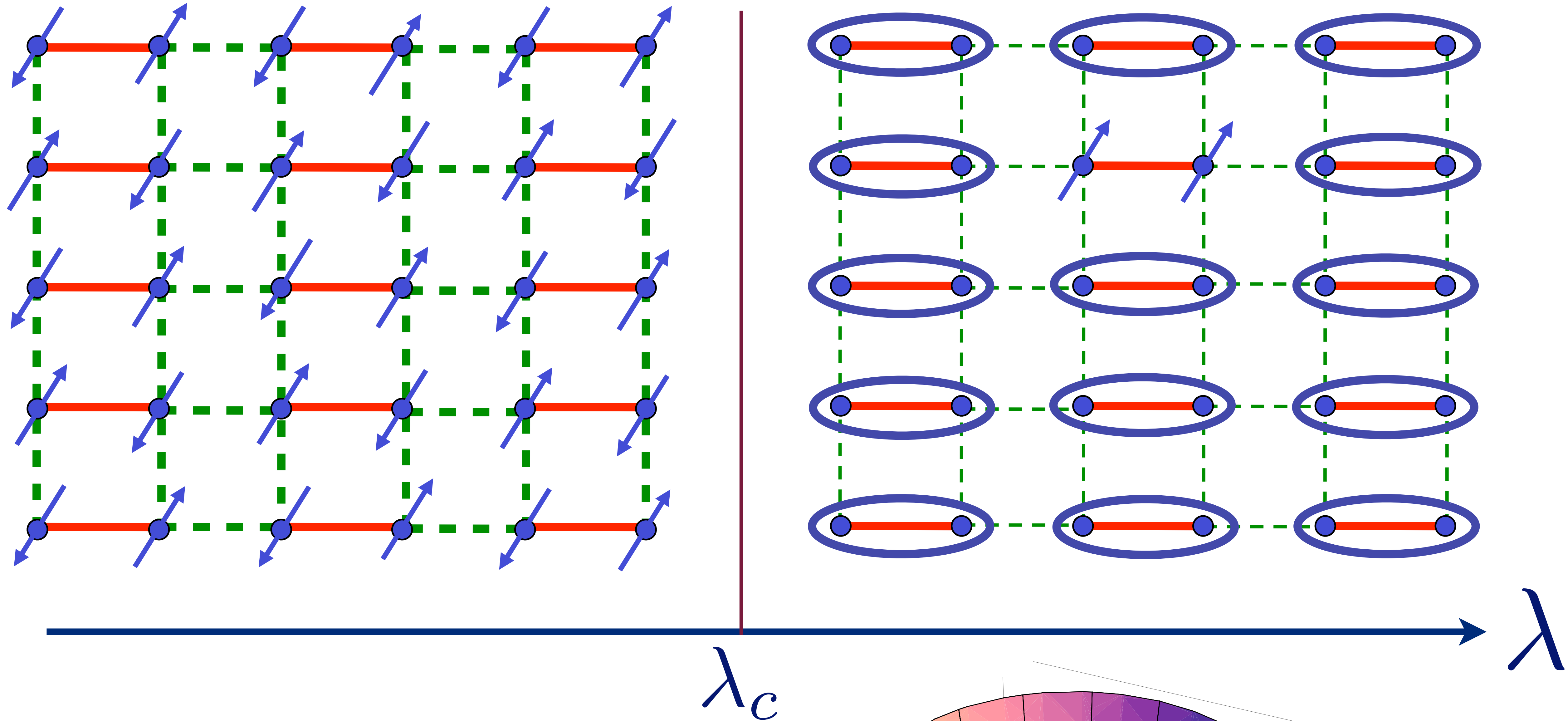

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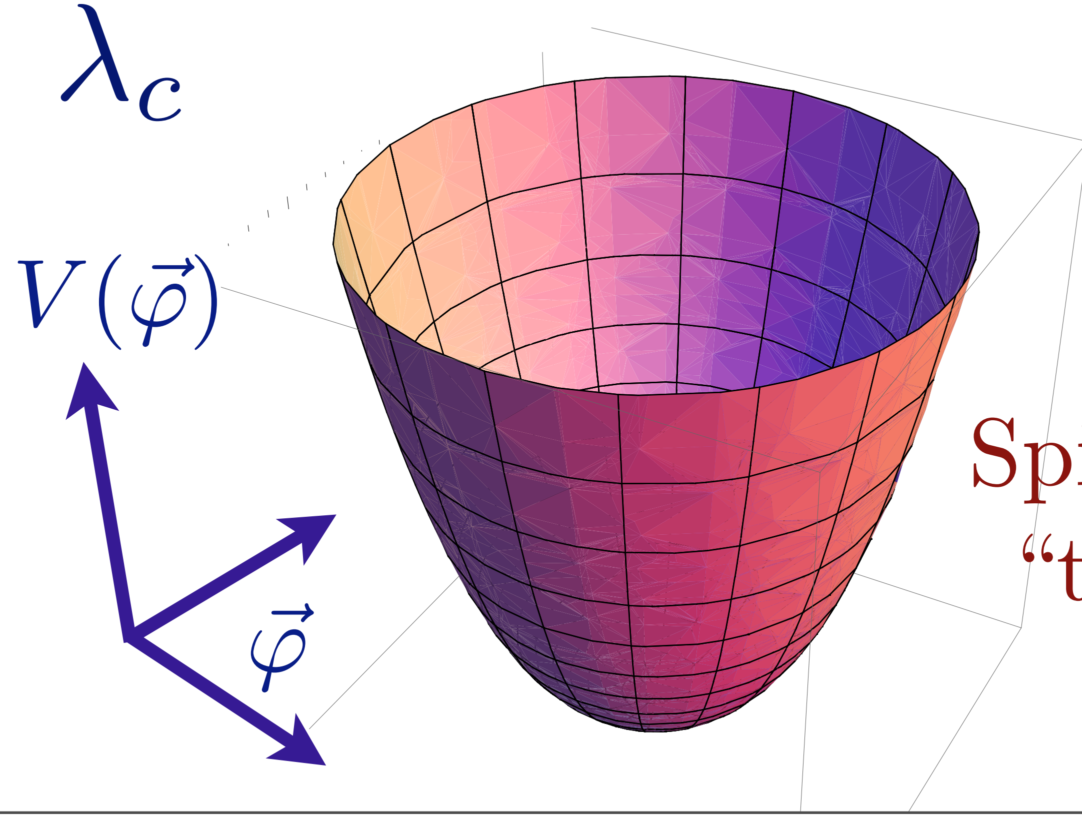

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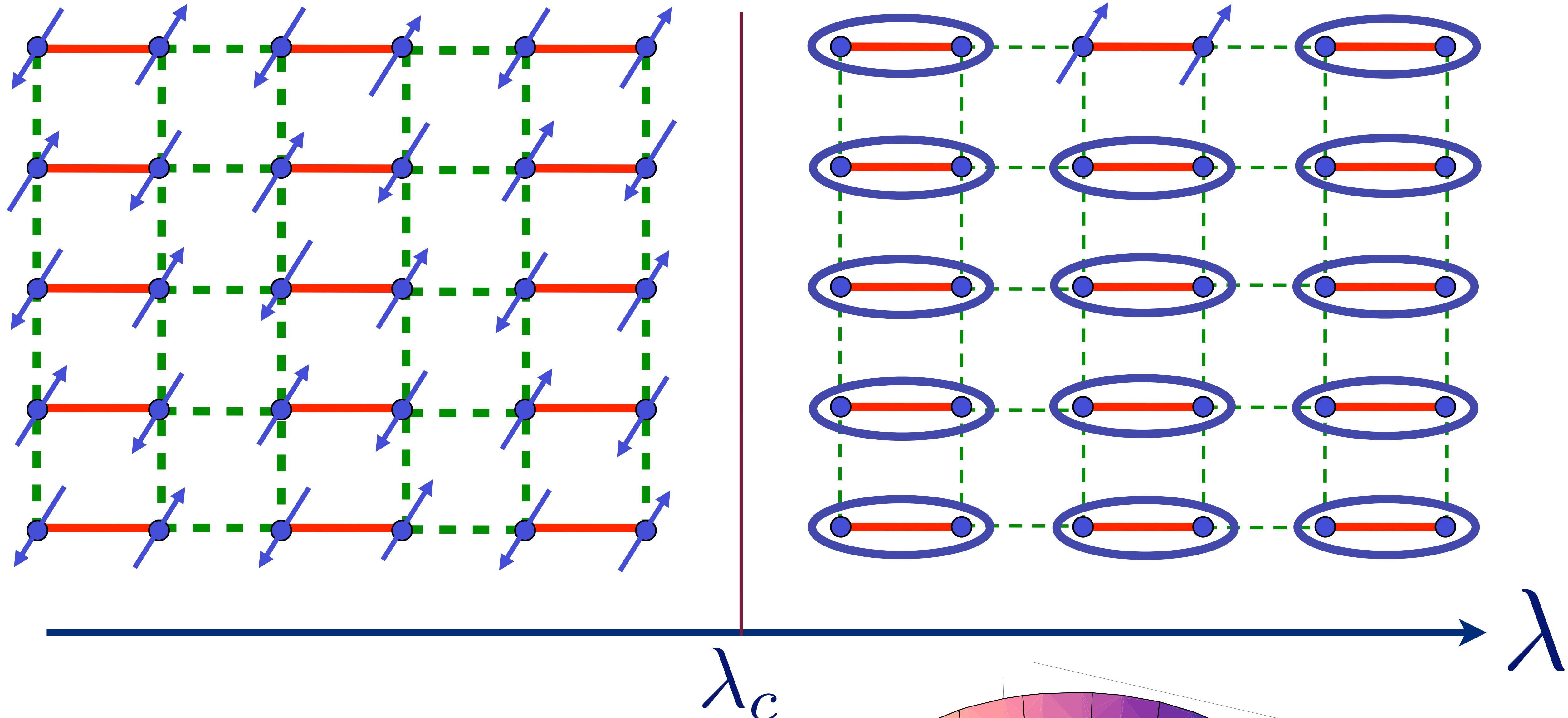

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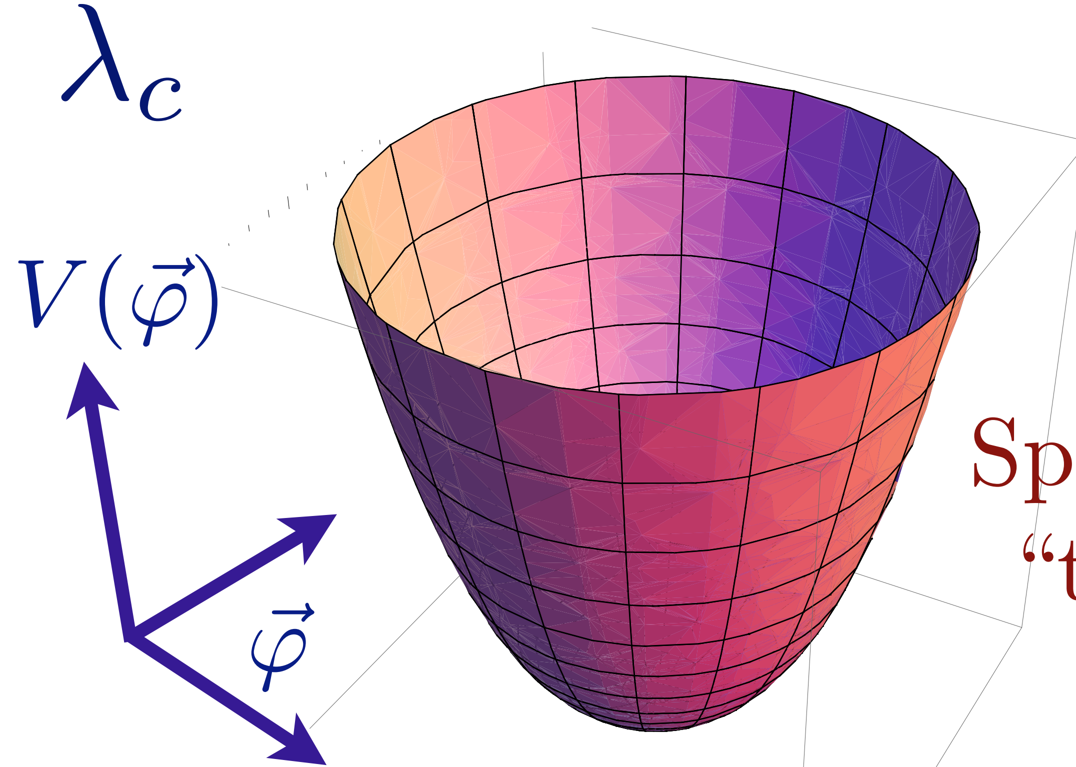

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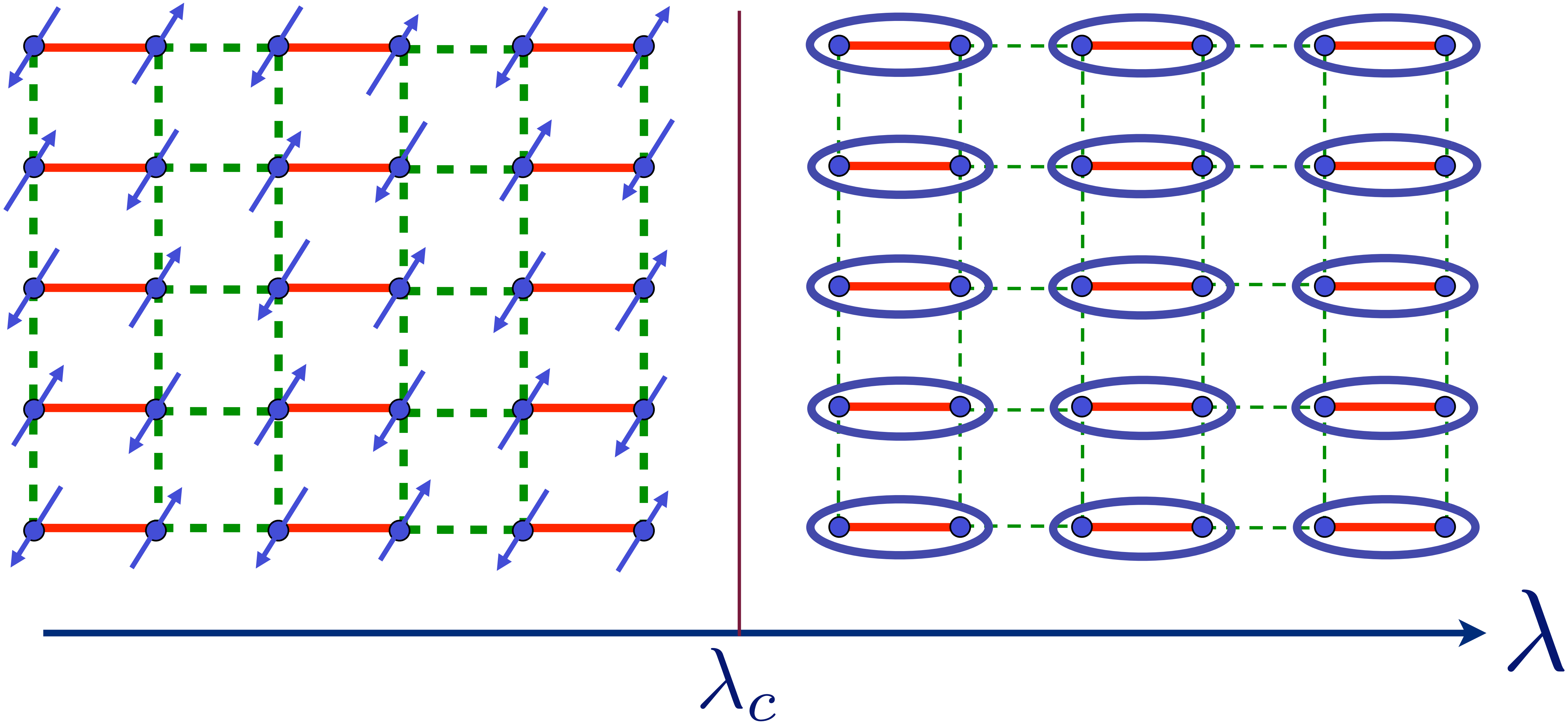
Excitation spectrum in the Néel phase



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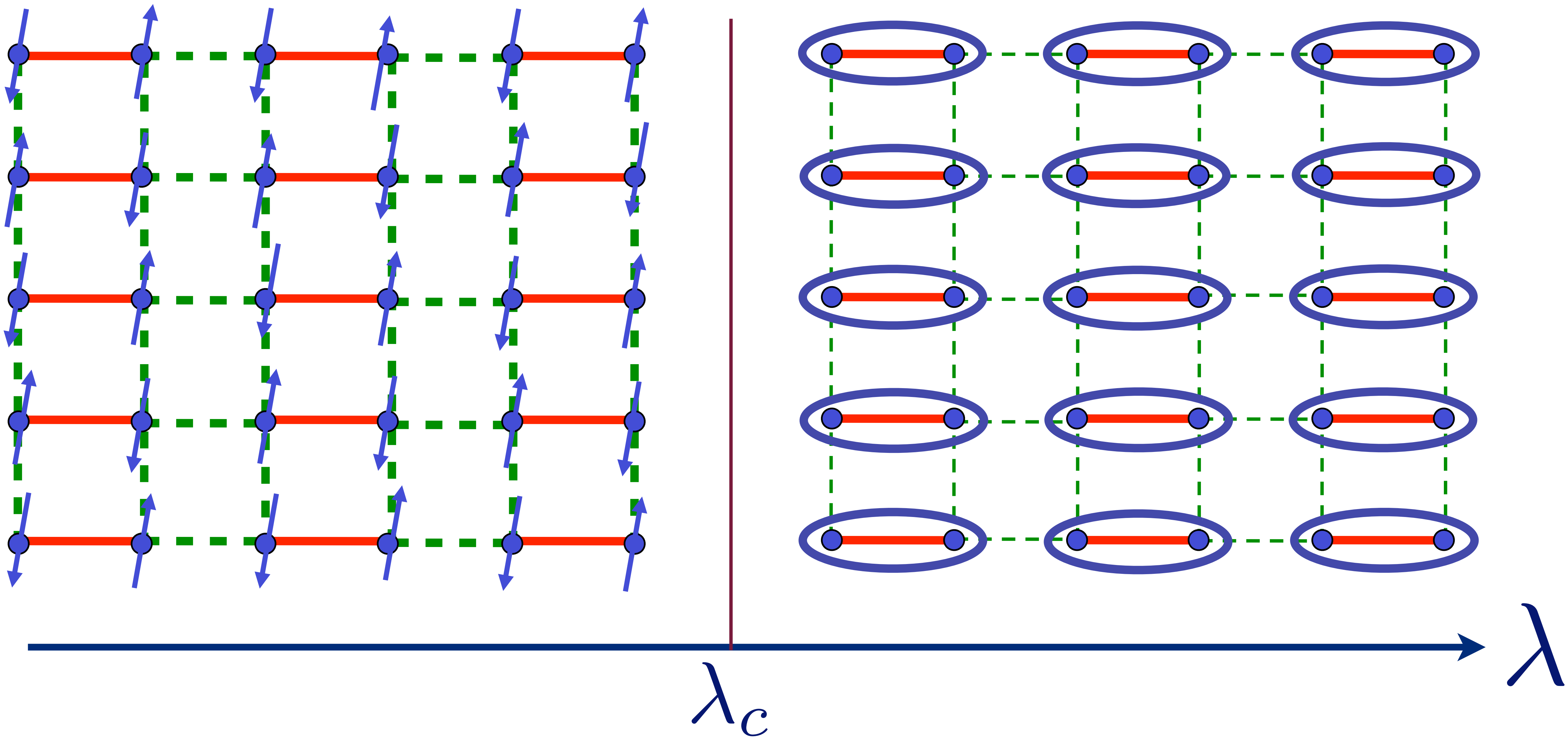

Spin waves

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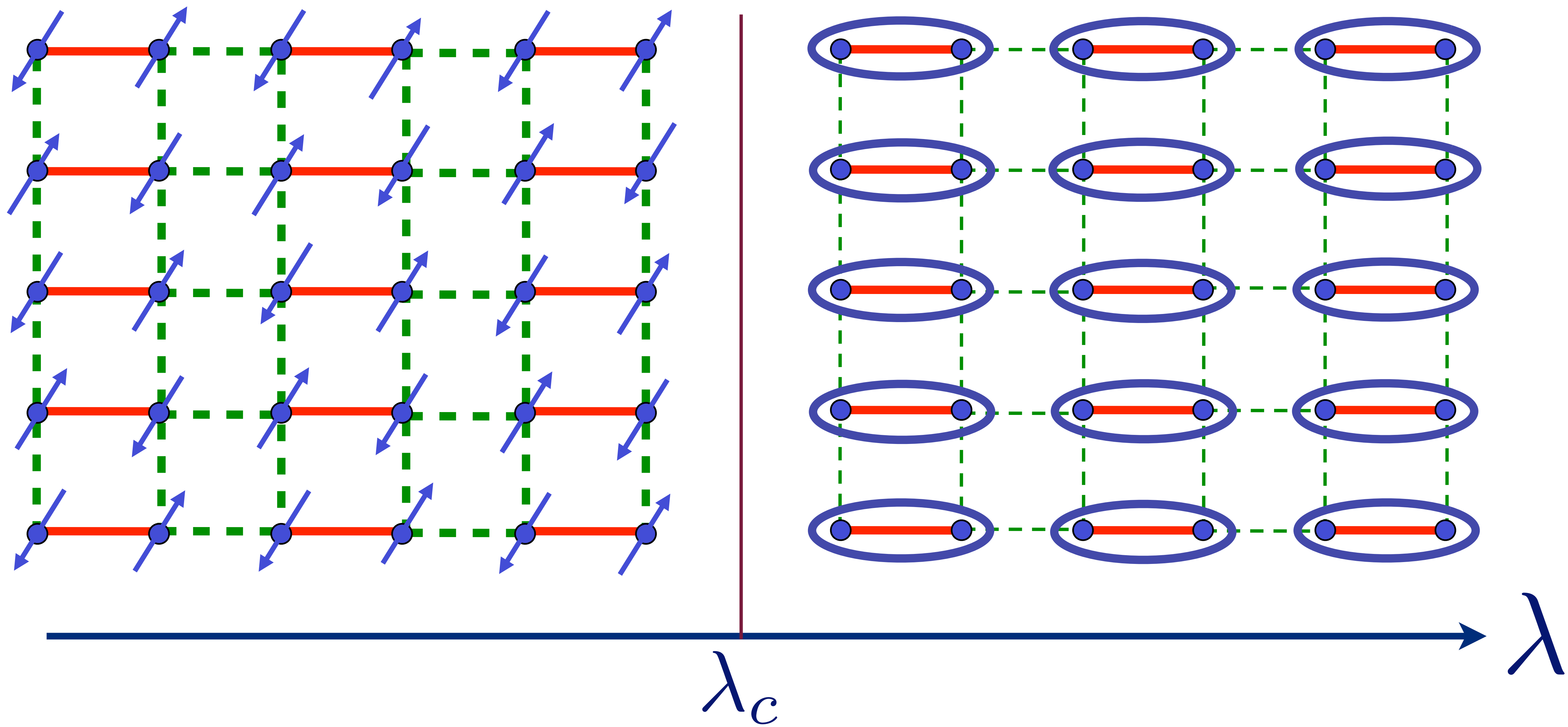

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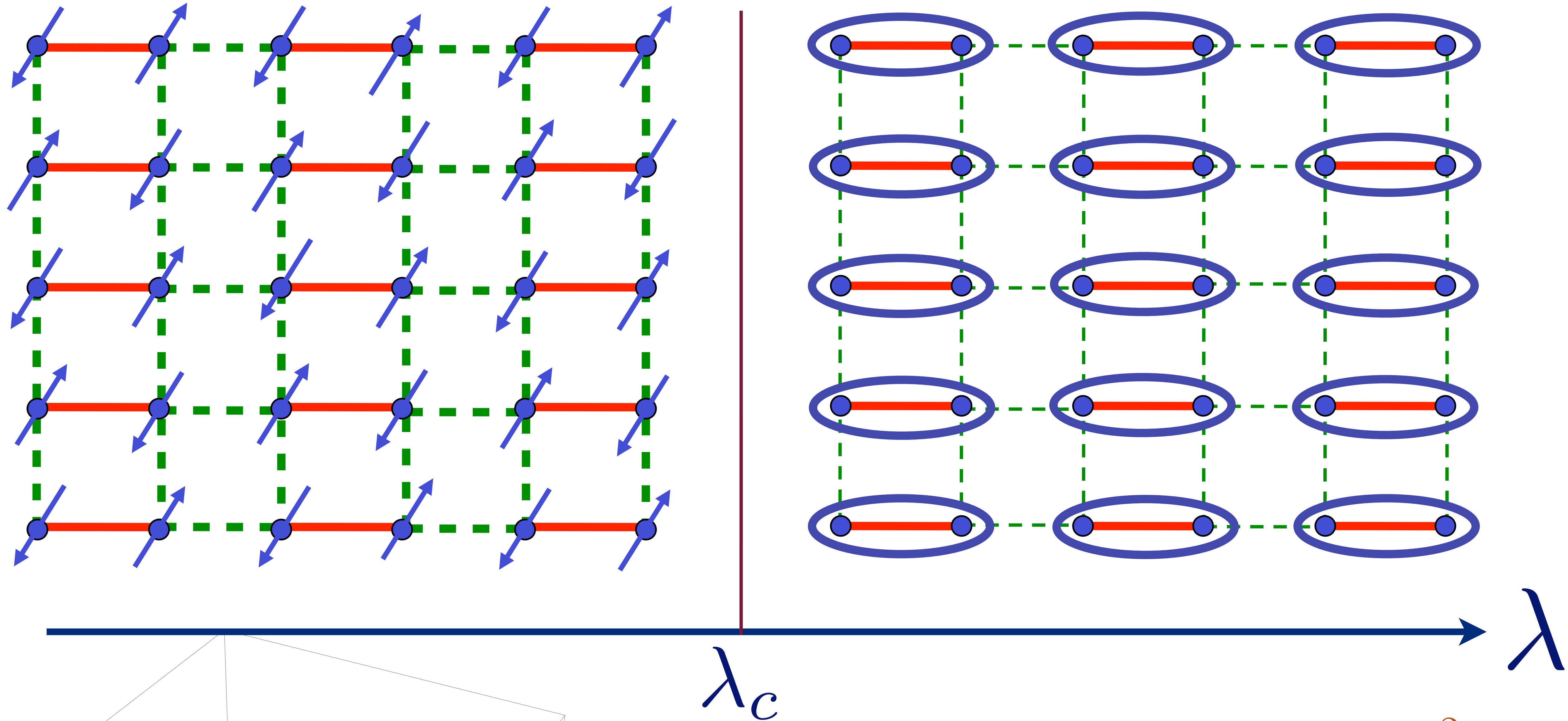

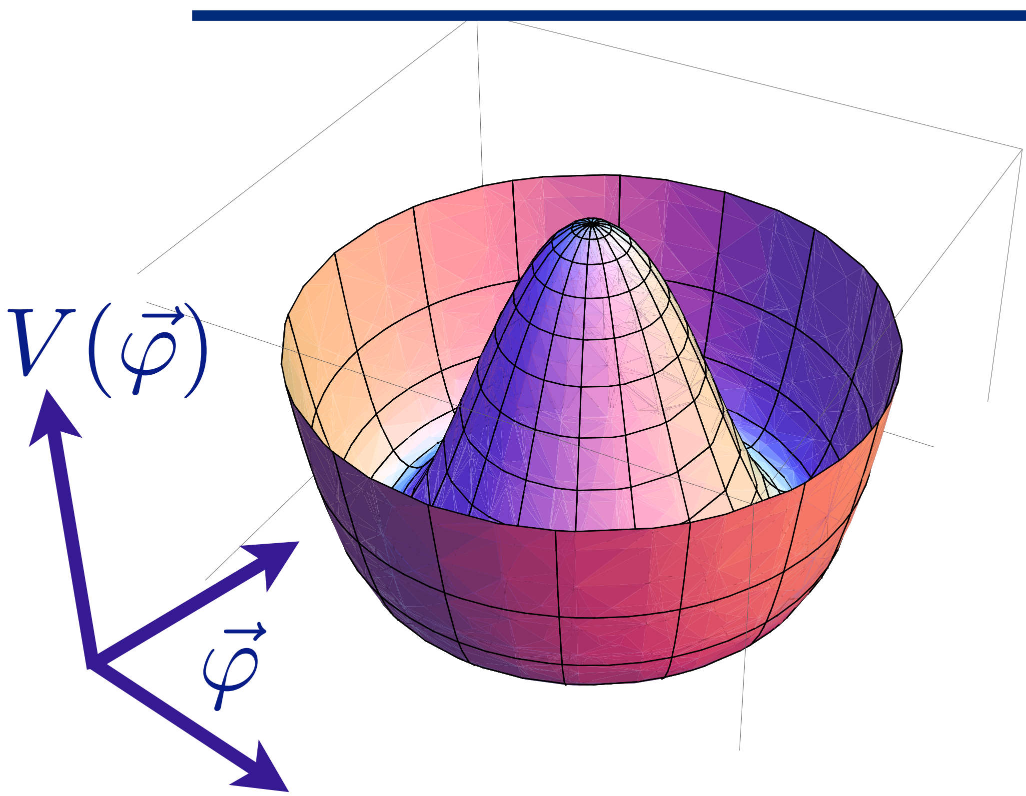

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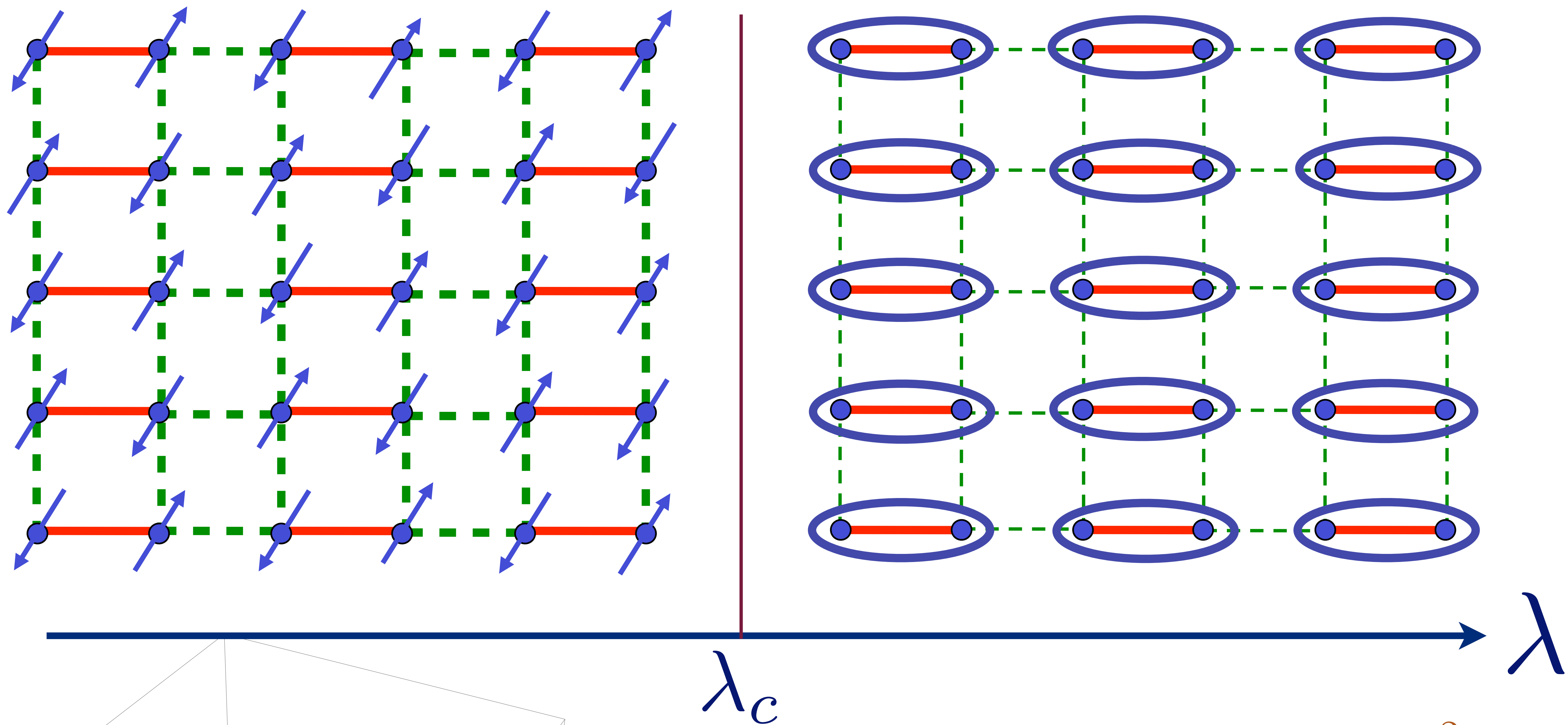

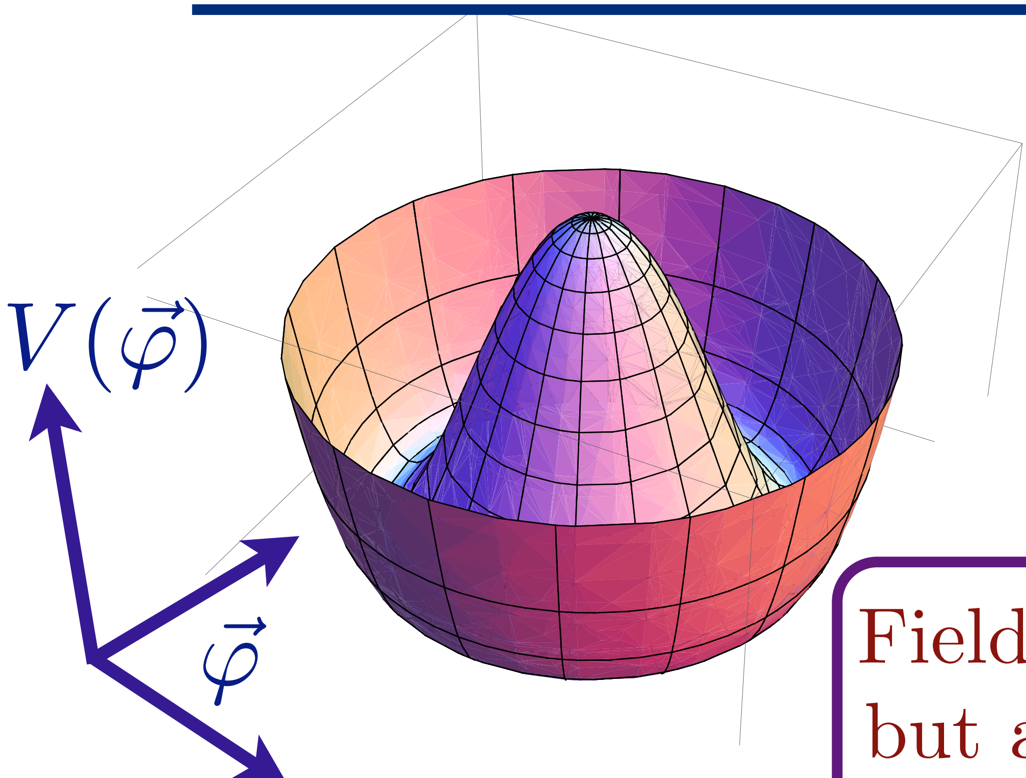

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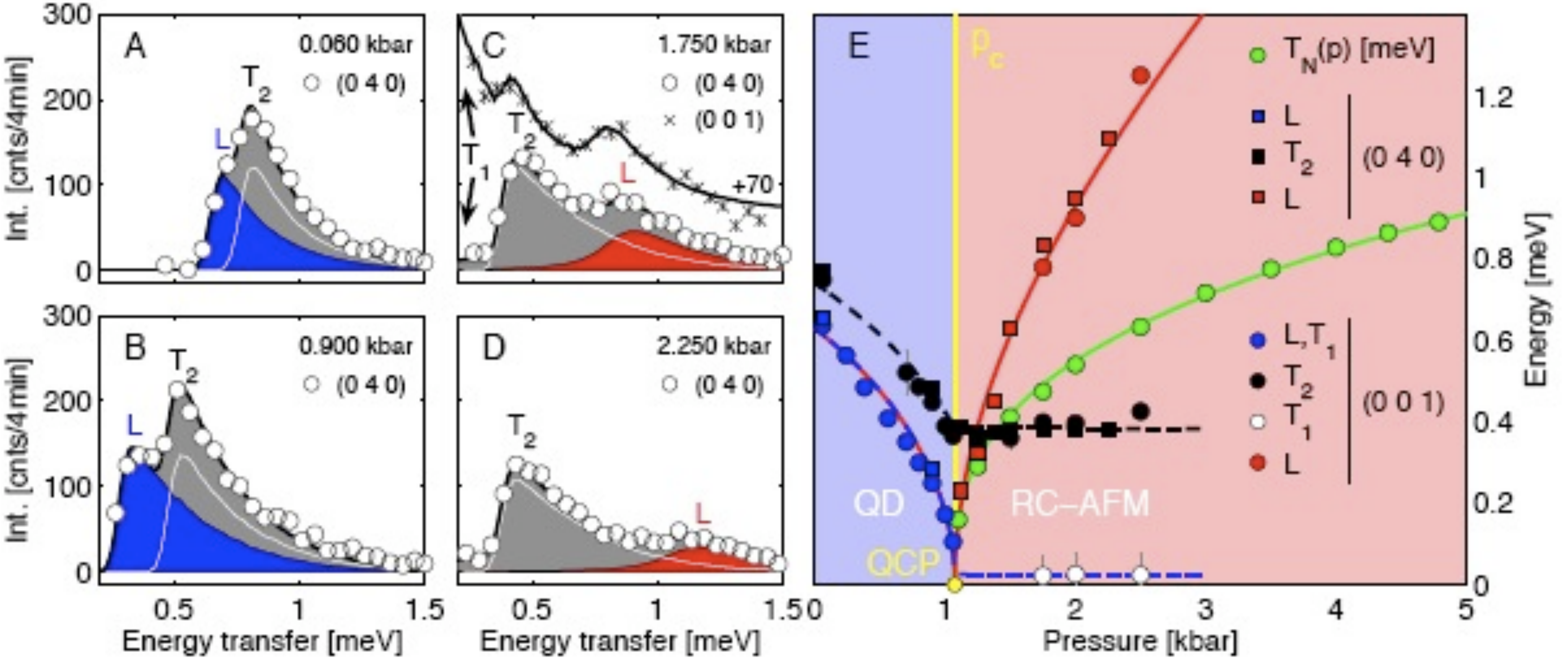
Field theory yields spin waves ("Goldstone" modes) but also an additional longitudinal "Higgs" particle

$TlCuCl_3$ 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

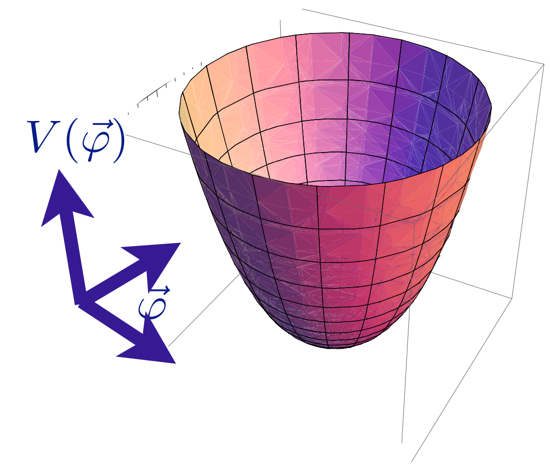
Christian Ruegg, Bruce Normand, Masashige Matsumoto, Albert Furrer, Desmond McMorrow, Karl Kramer, Hans-Ulrich Gudel, Severian Gvasaliya, Hannu Mutka, and Martin Boehm, *Phys. Rev. Lett.* **100**, 205701 (2008)

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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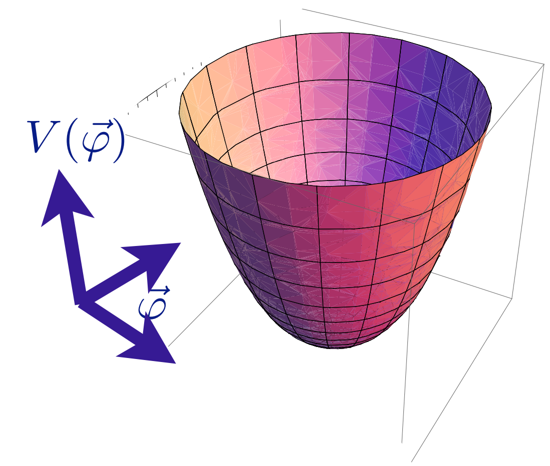

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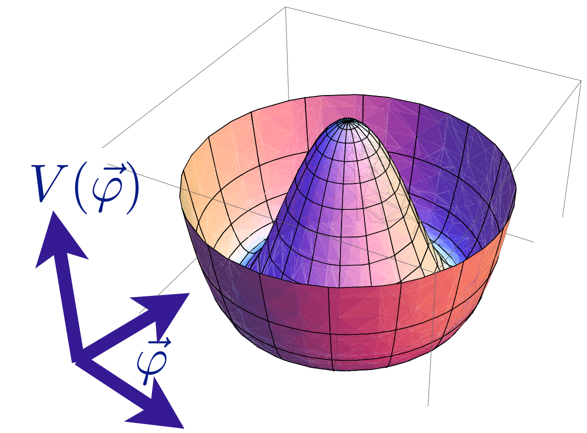
Néel phase, $\lambda < \lambda_c$



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

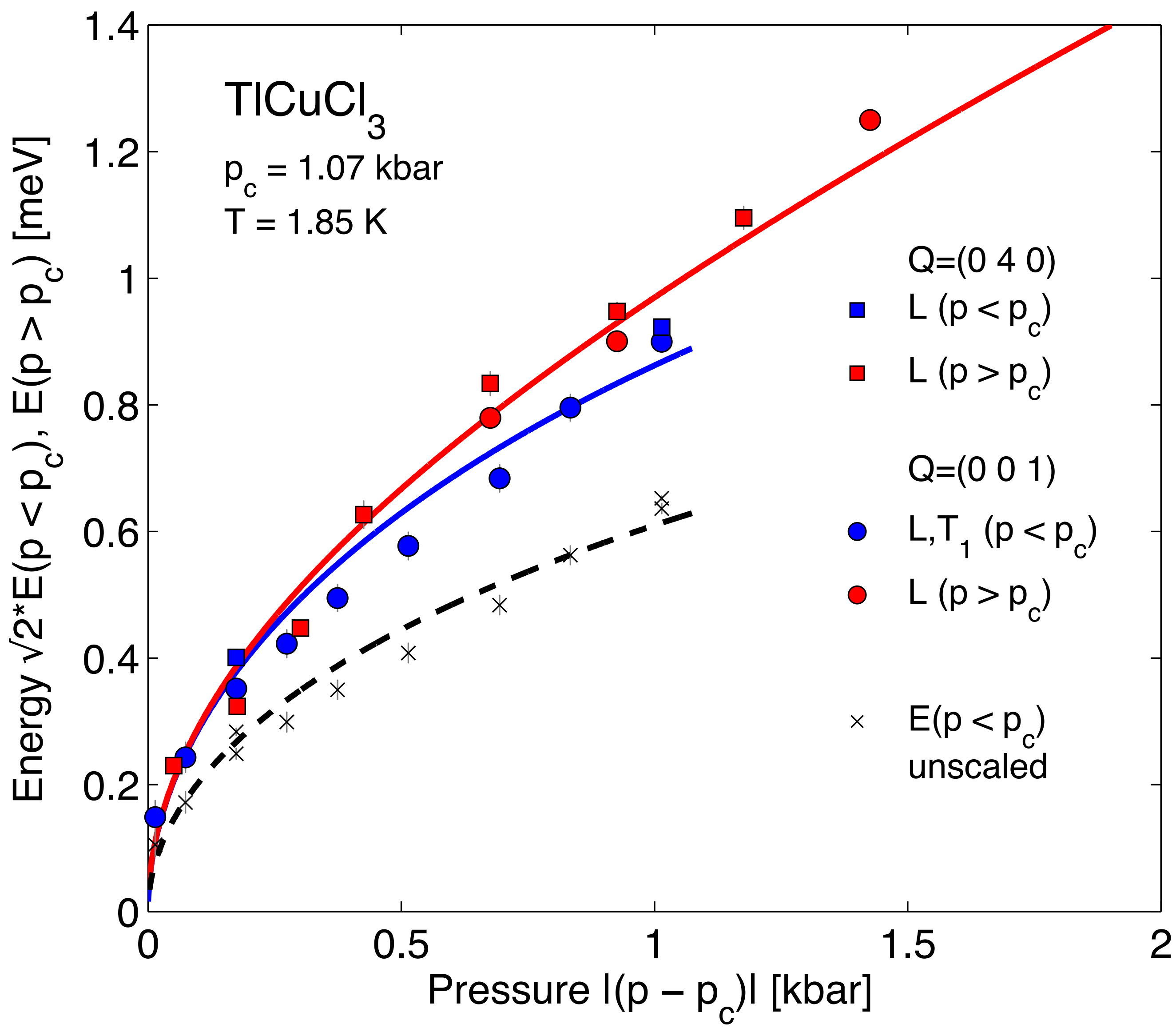
$$V(\vec{\varphi}) \approx 2(\lambda_c - \lambda)\varphi_{1z}^2$$

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

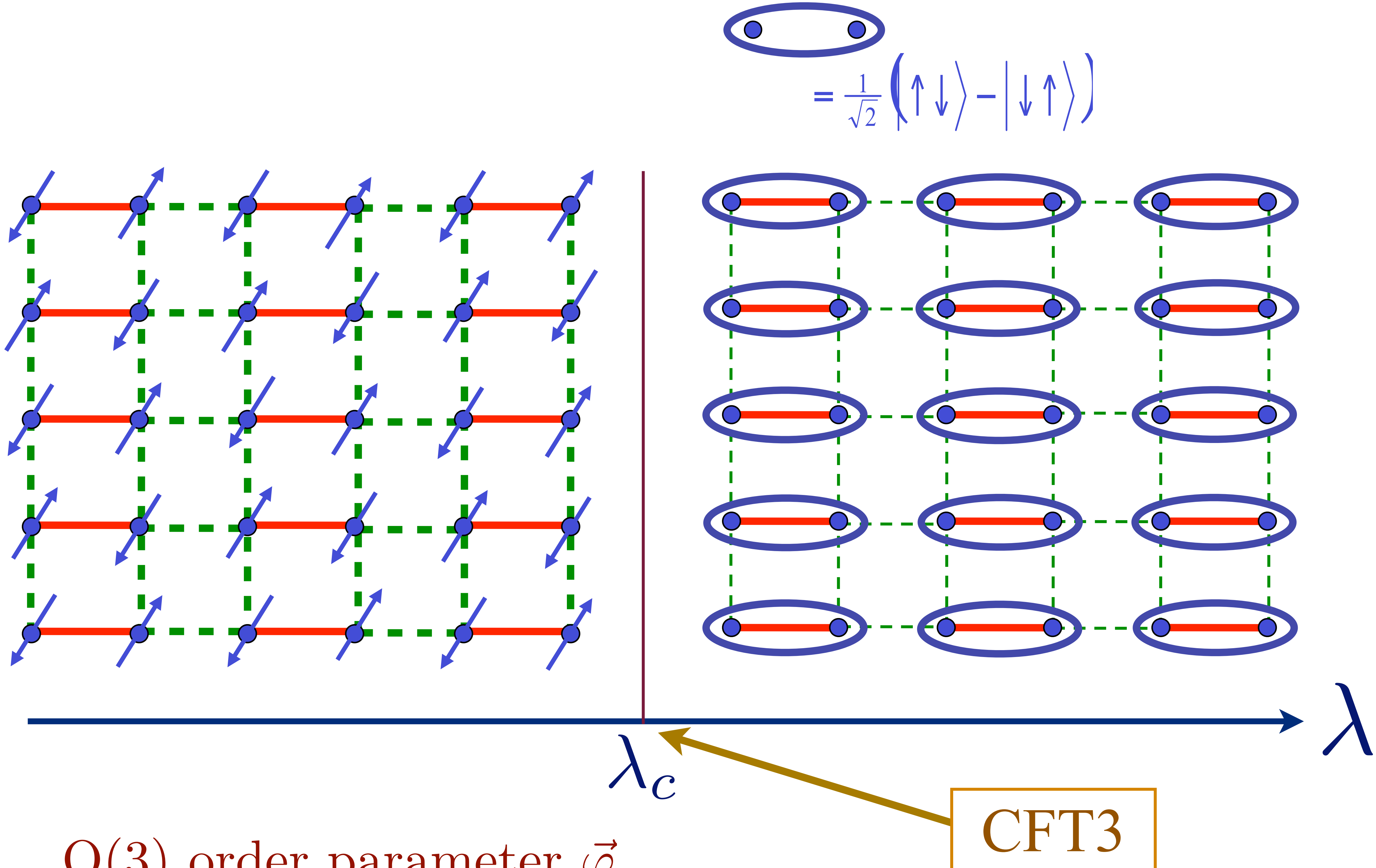
Prediction of quantum field theory

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

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



S. Sachdev, arXiv:0901.4103



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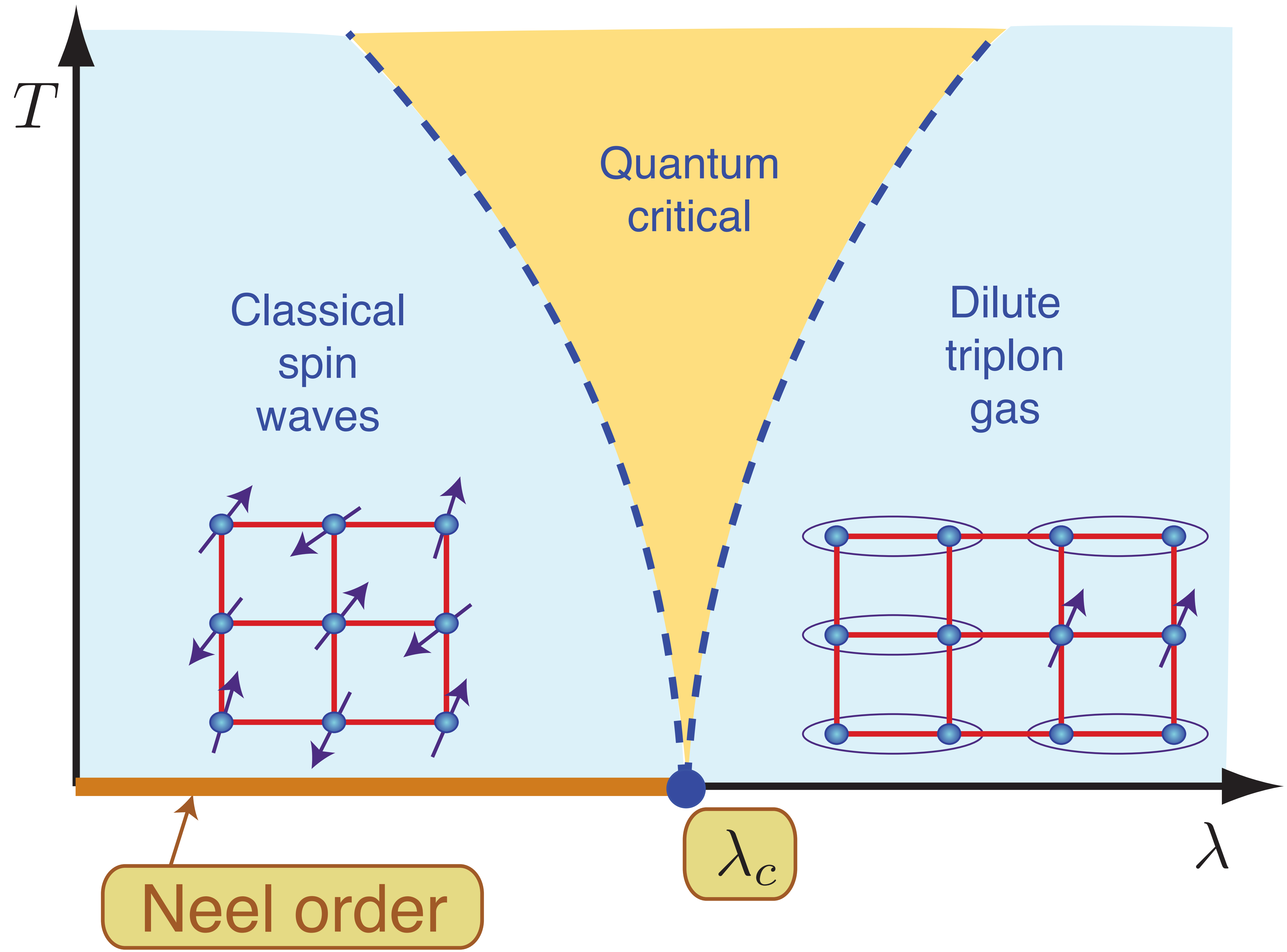
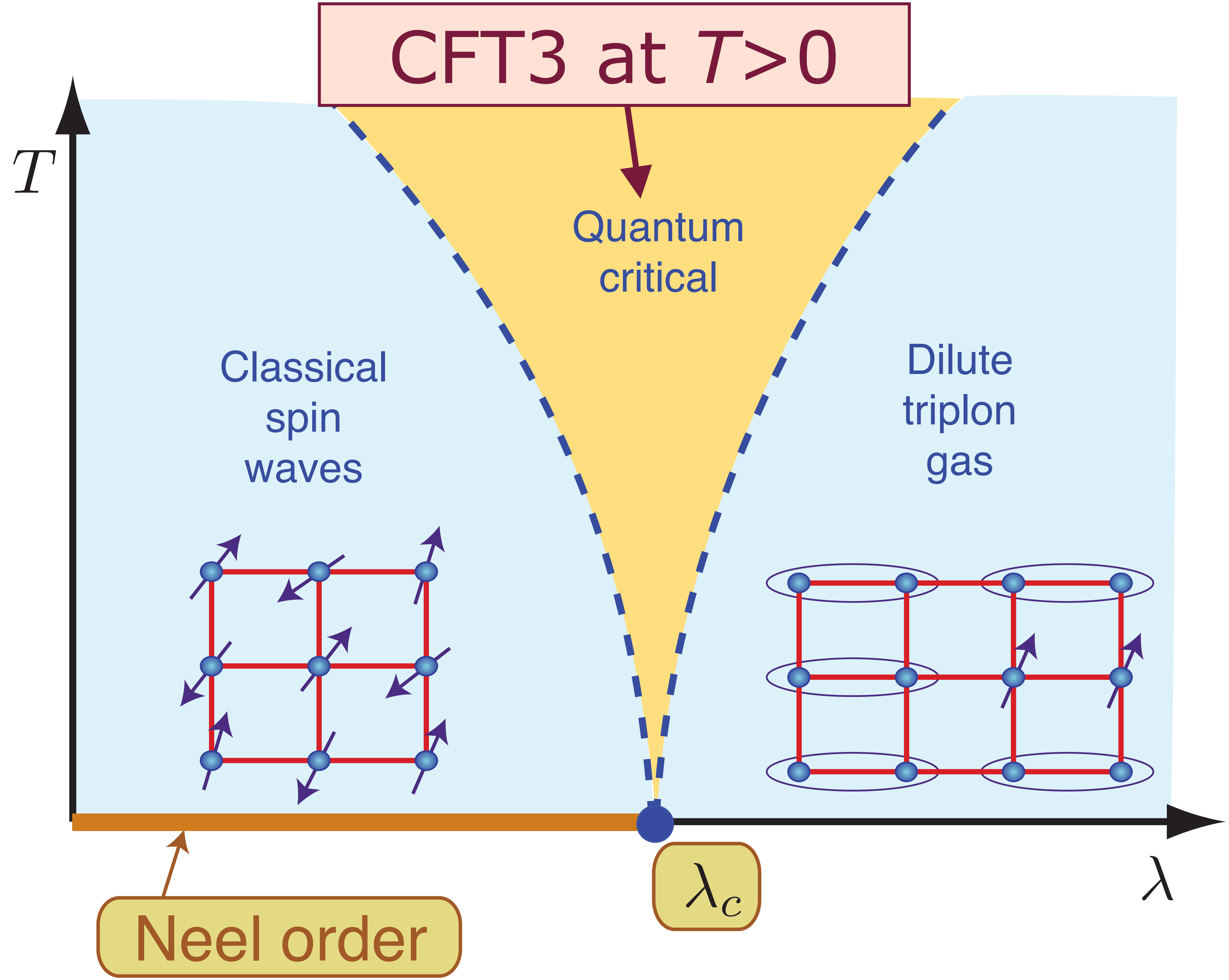


S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).

Pressure in $TlCuCl_3$



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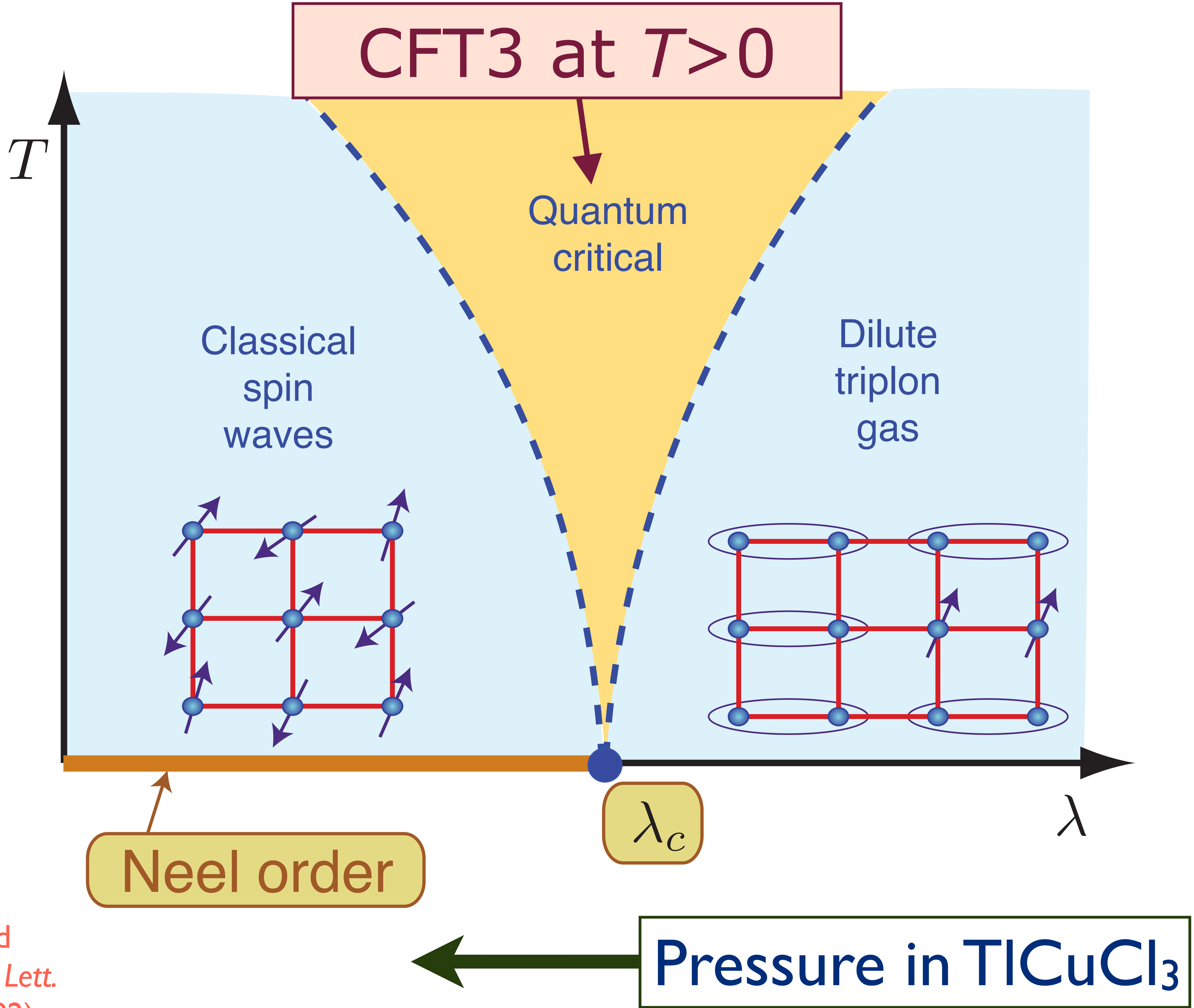

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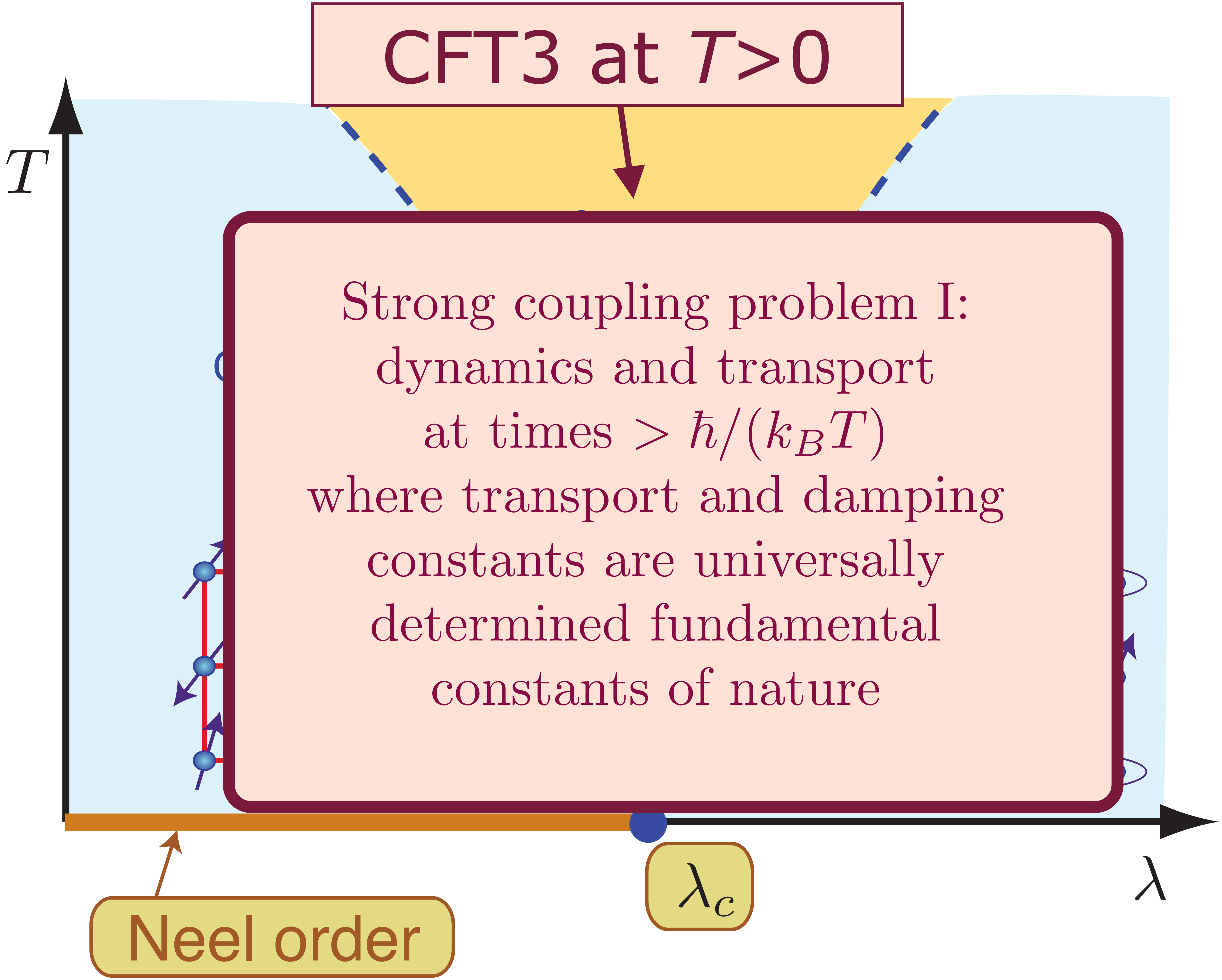

Strong coupling problem I:
dynamics and transport
at times $> \hbar/(k_B T)$
where transport and damping
constants are universally
determined fundamental
constants of nature

Pressure in $TlCuCl_3$

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

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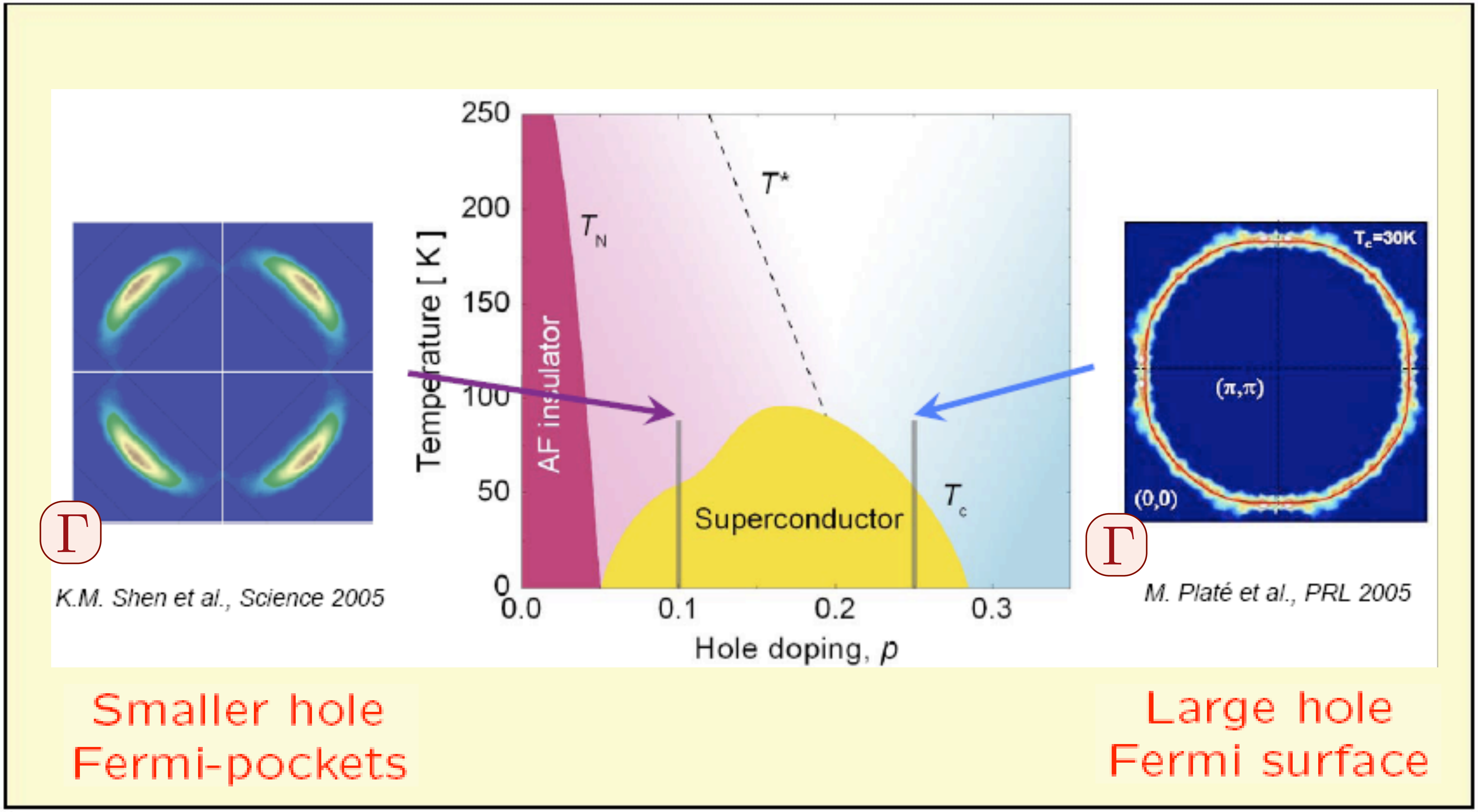
Central ingredients in cuprate phase diagram: antiferromagnetism, superconductivity, and change in Fermi surface



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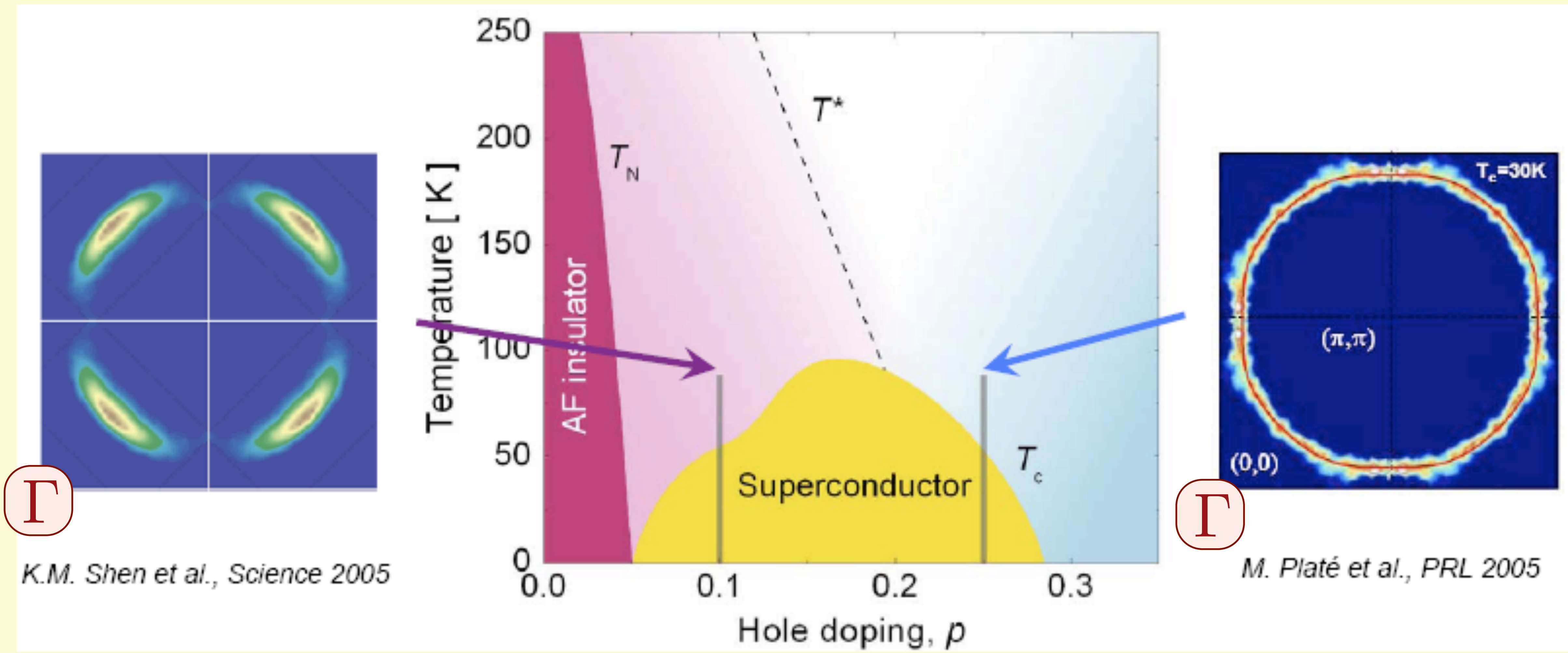
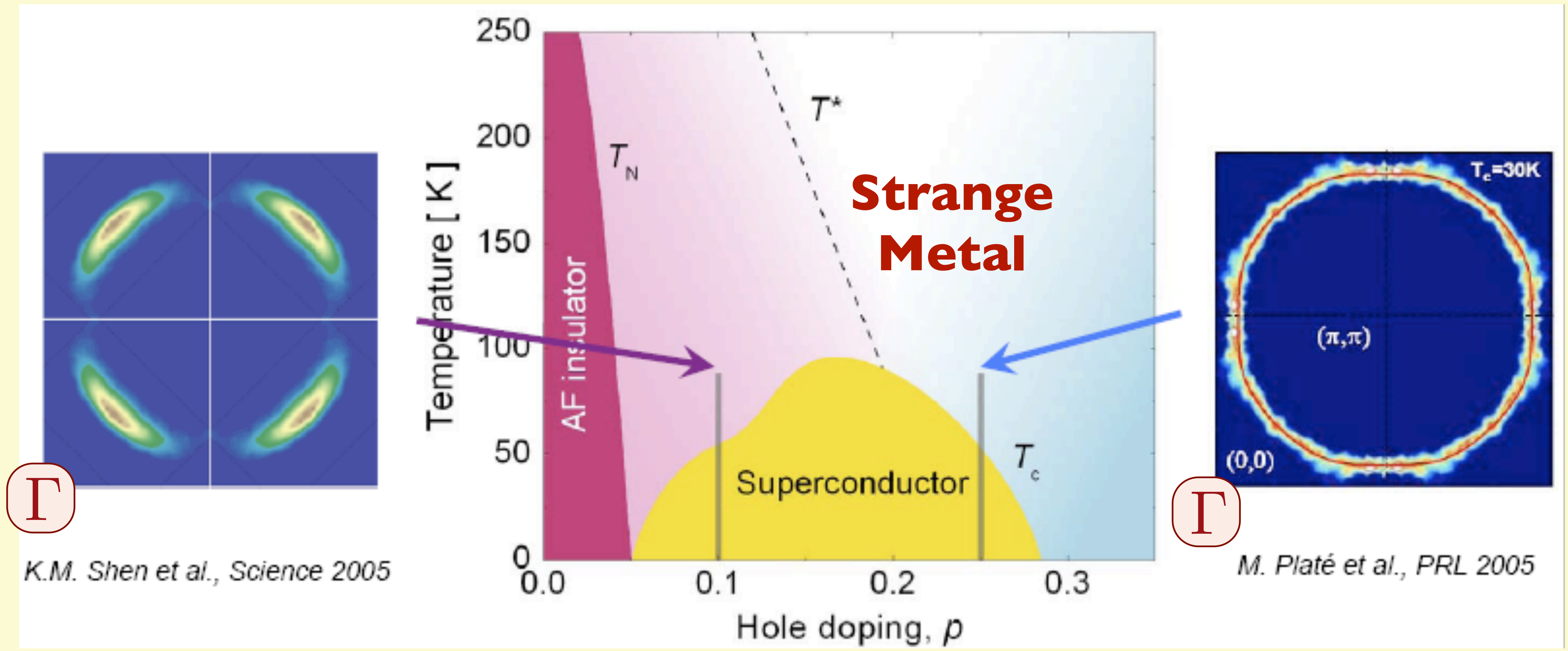


Smaller hole Fermi-pockets

Large hole Fermi surface

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



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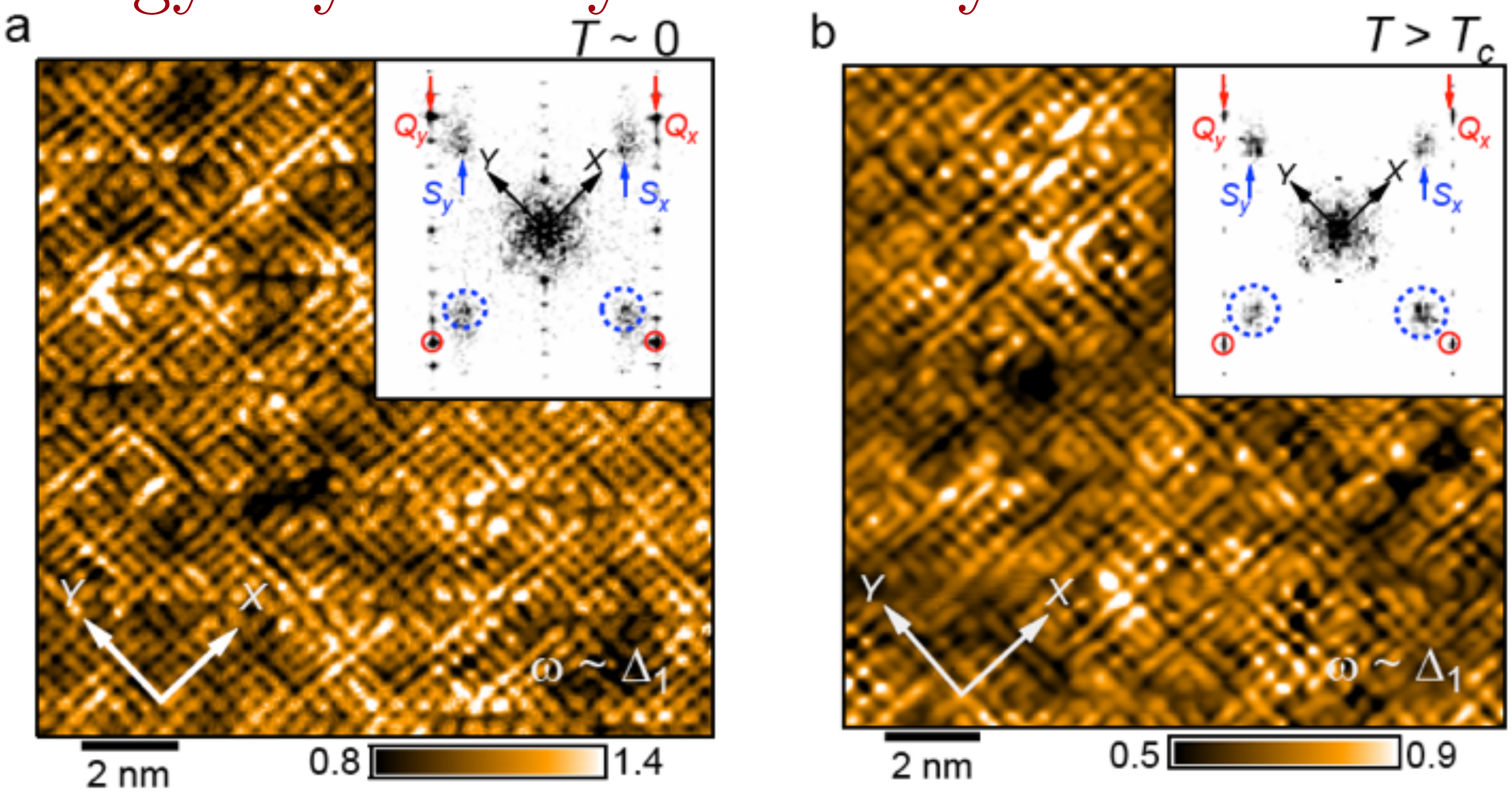
STM measurements of $Z(r)$, energy asymmetry in density of states



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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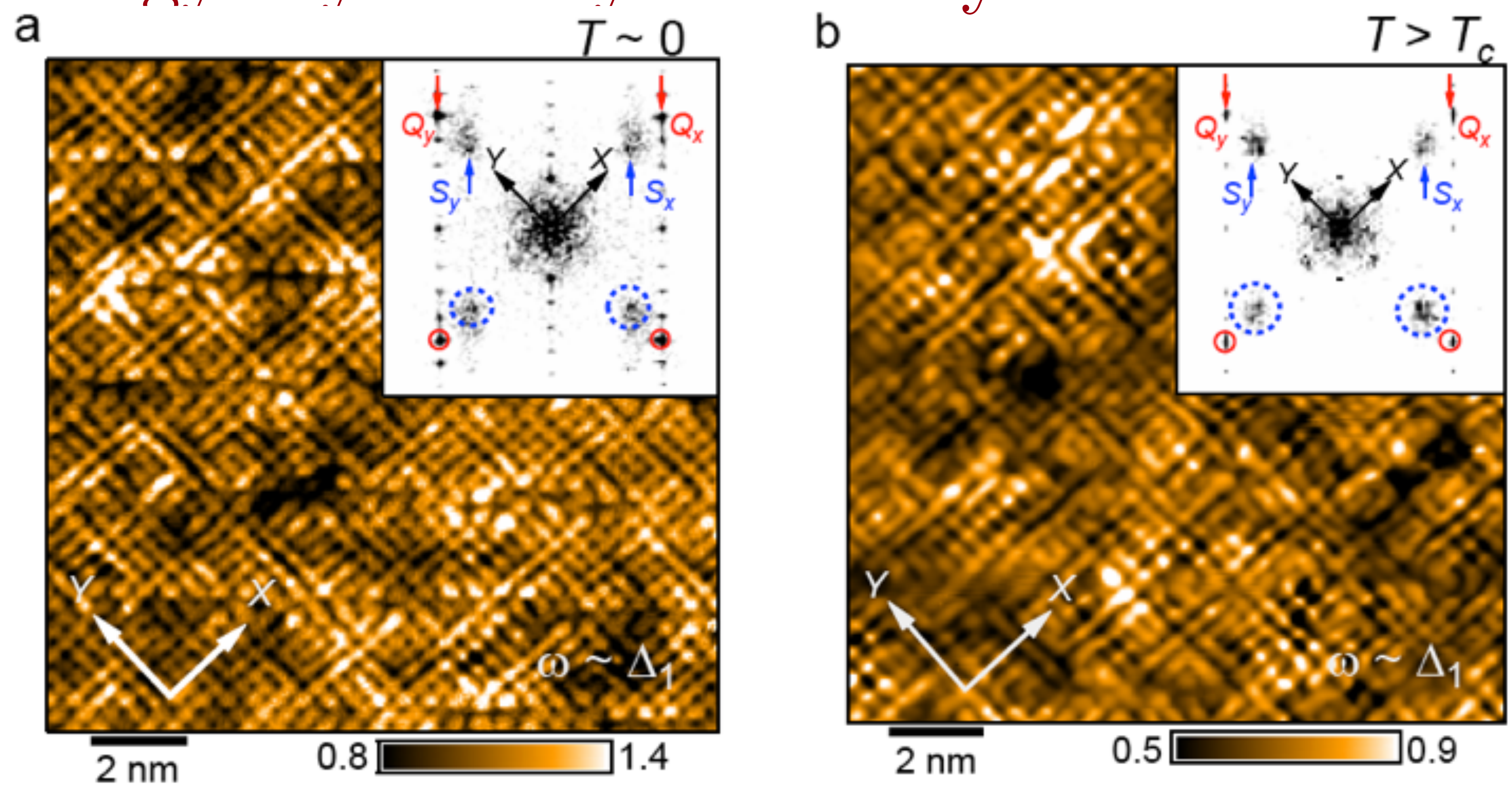

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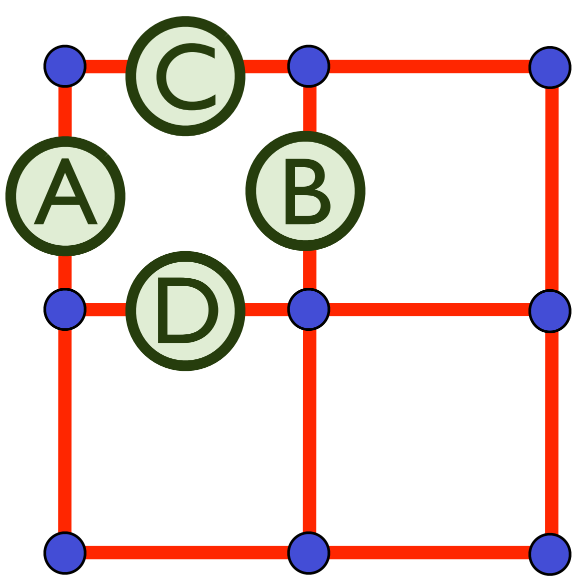
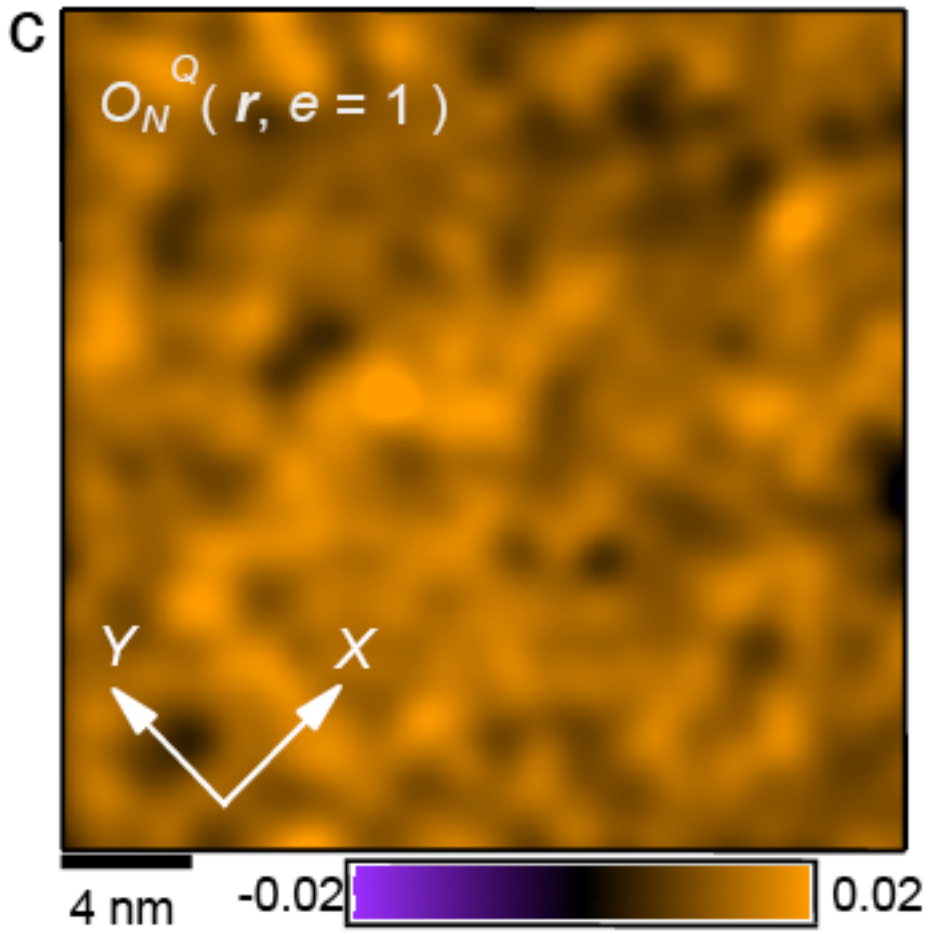
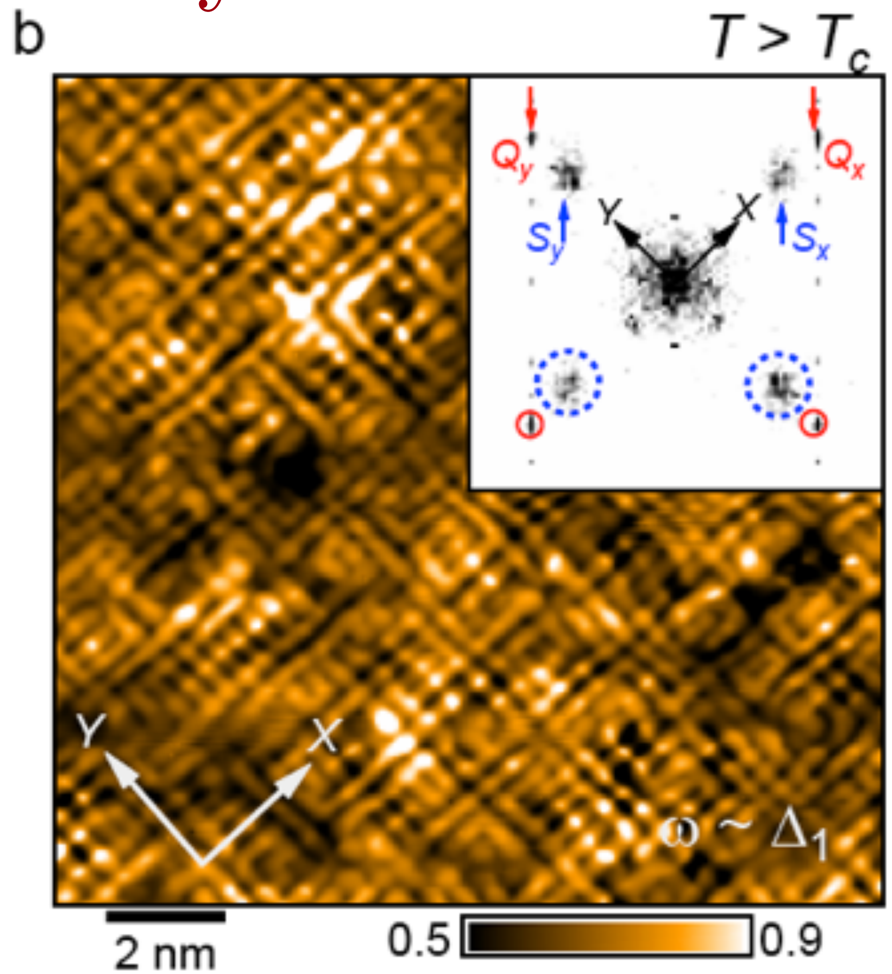


$$O_N = Z_A + Z_B - Z_C - Z_D$$

STM measurements of $Z(r)$, energy asymmetry in density of states





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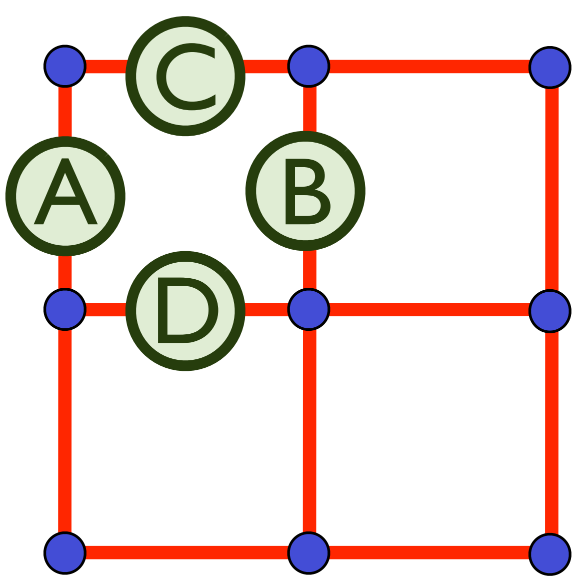
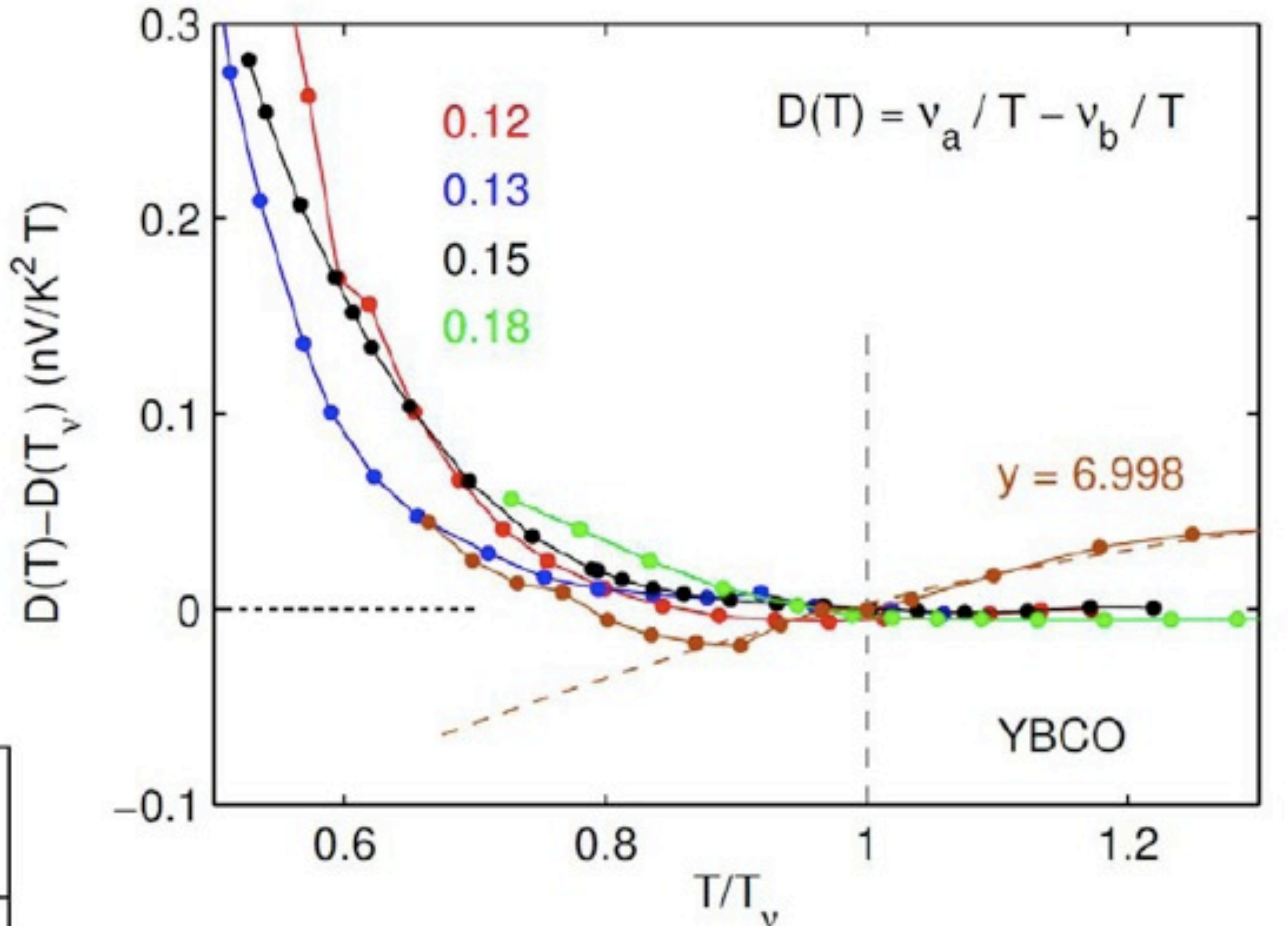


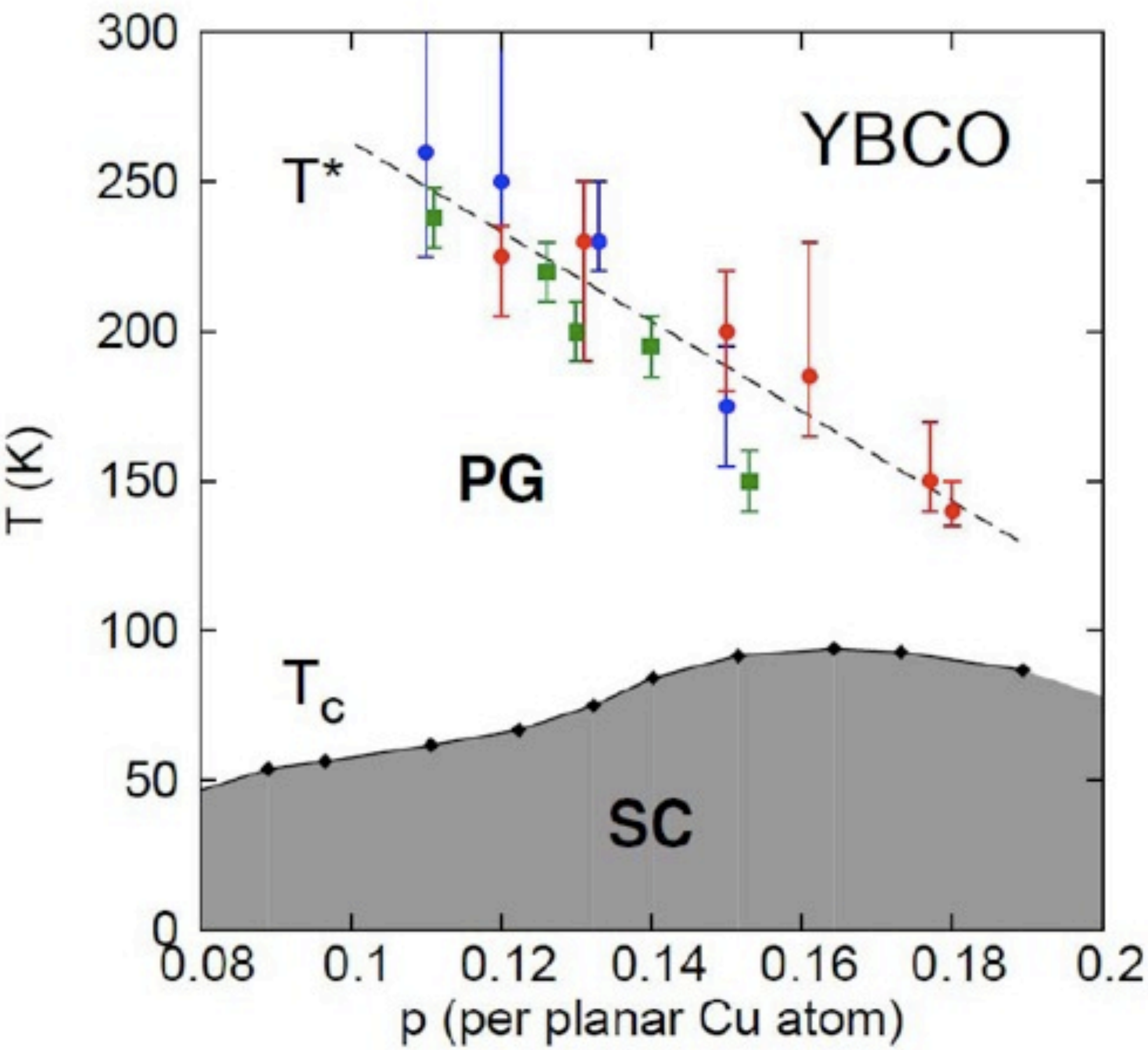
$$O_N = Z_A + Z_B - Z_C - Z_D$$

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

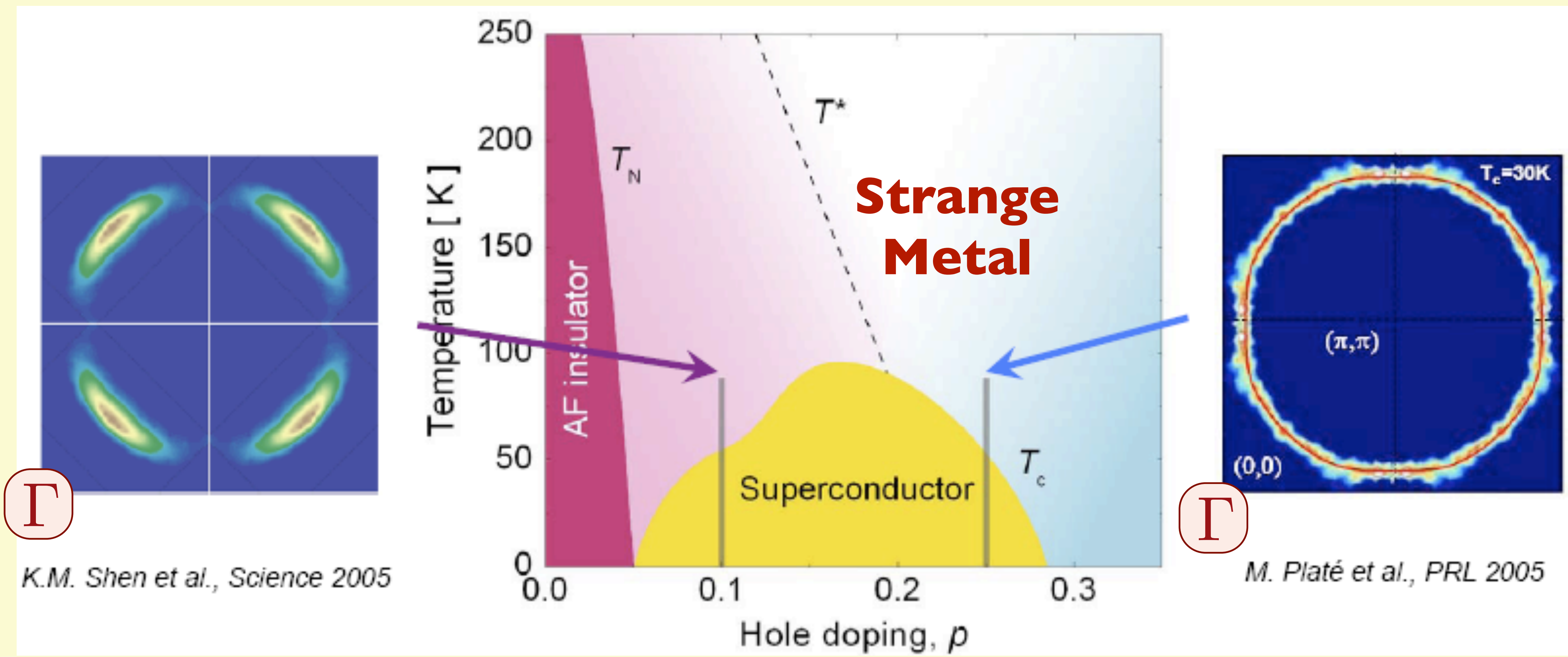
Broken rotational symmetry in the pseudogap phase of a high-Tc superconductor

R. Daou, J. Chang, David LeBoeuf, Olivier Cyr-Choiniere, Francis Laliberte, Nicolas Doiron-Leyraud, B. J. Ramshaw, Ruixing Liang, D.A. Bonn, W. N. Hardy, and Louis Taillefer
Nature, **463**, 519 (2010).





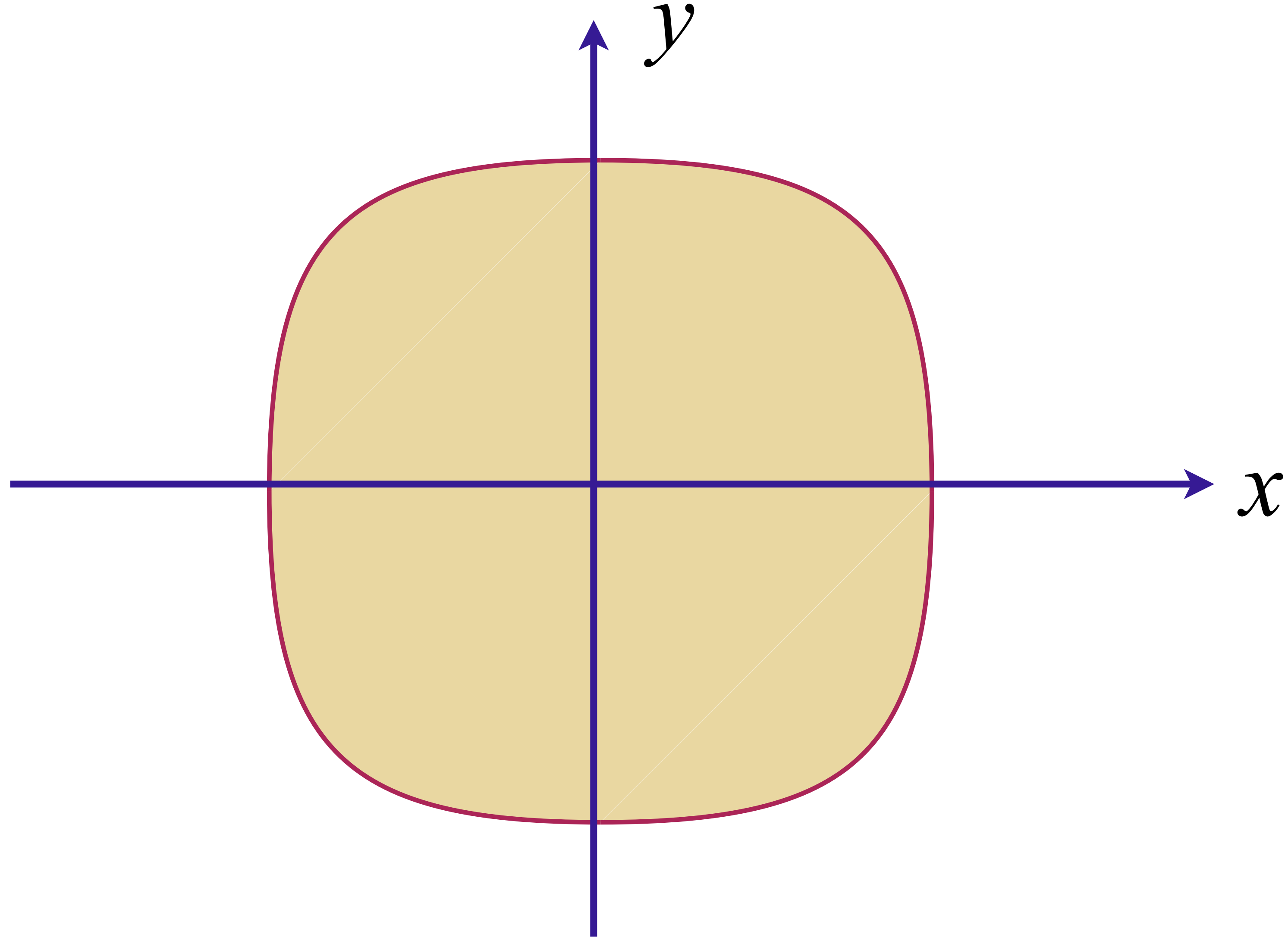
Central ingredients in cuprate phase diagram: antiferromagnetism, superconductivity, and change in Fermi surface



Smaller hole Fermi-pockets

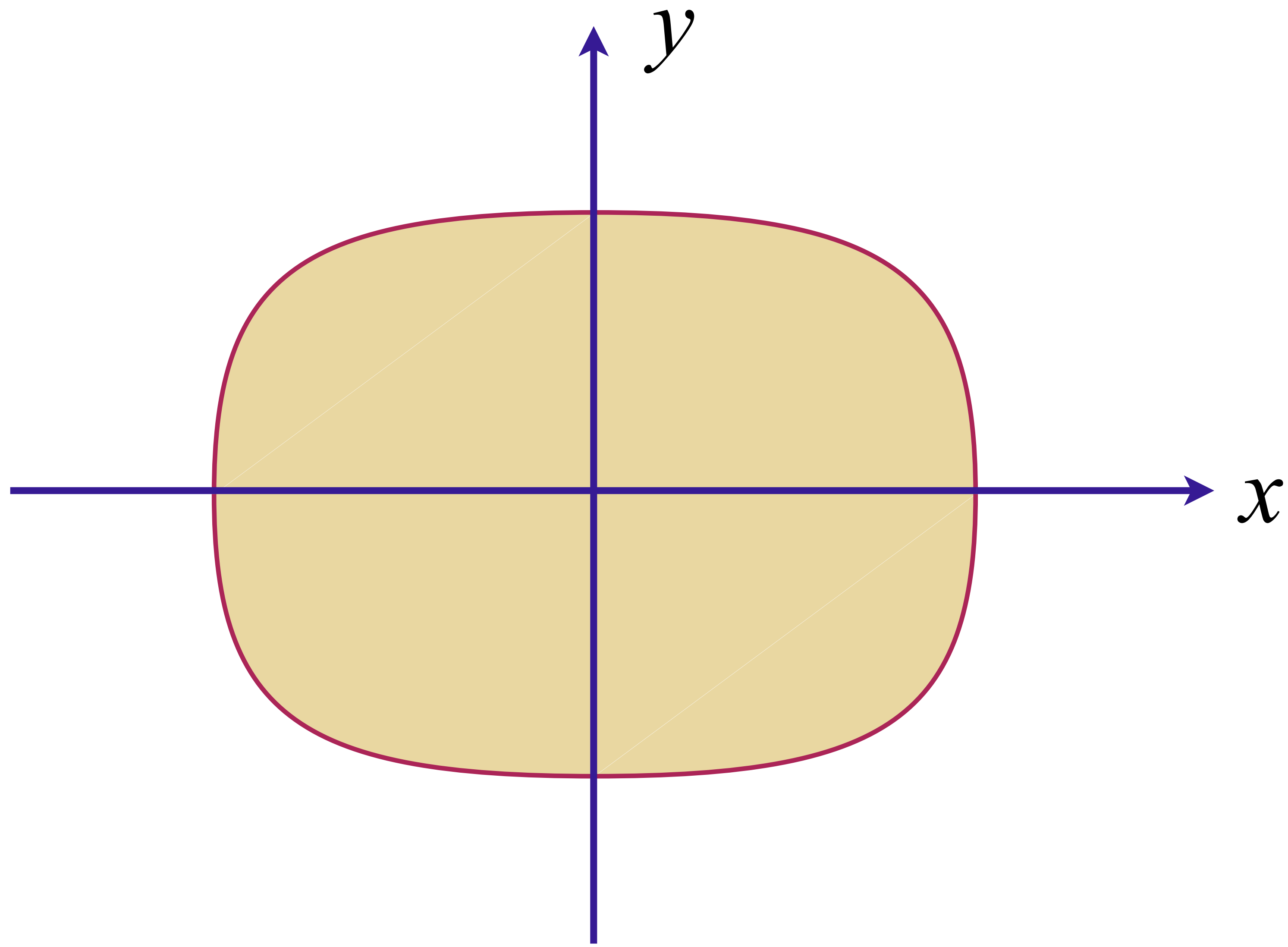
Large hole Fermi surface

Quantum criticality of Ising-nematic ordering



Fermi surface with full square lattice symmetry

Quantum criticality of Ising-nematic ordering



Spontaneous elongation along x direction:

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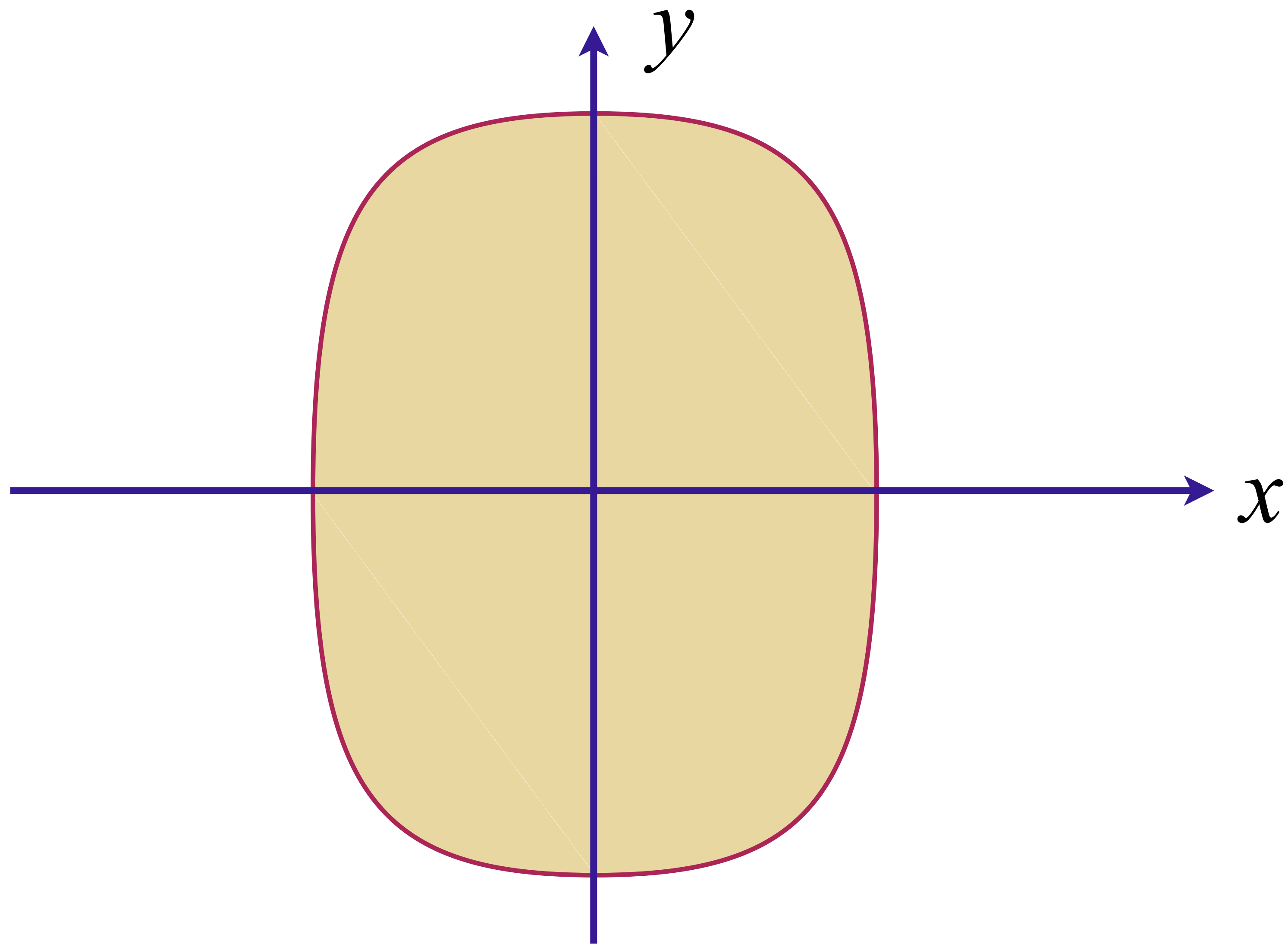


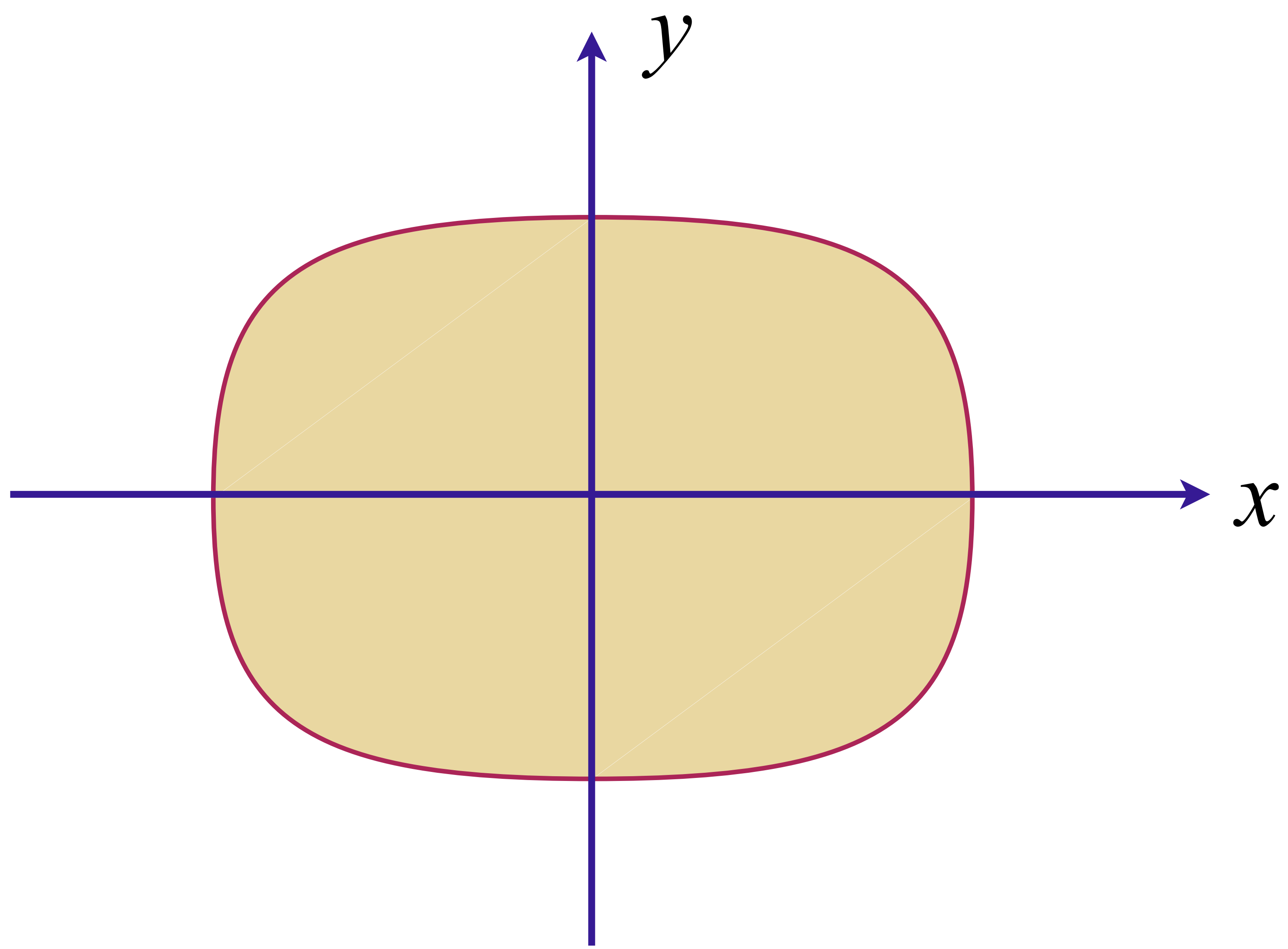
Spontaneous elongation along y direction:

Ising-nematic order parameter

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

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 $\phi > 0$.

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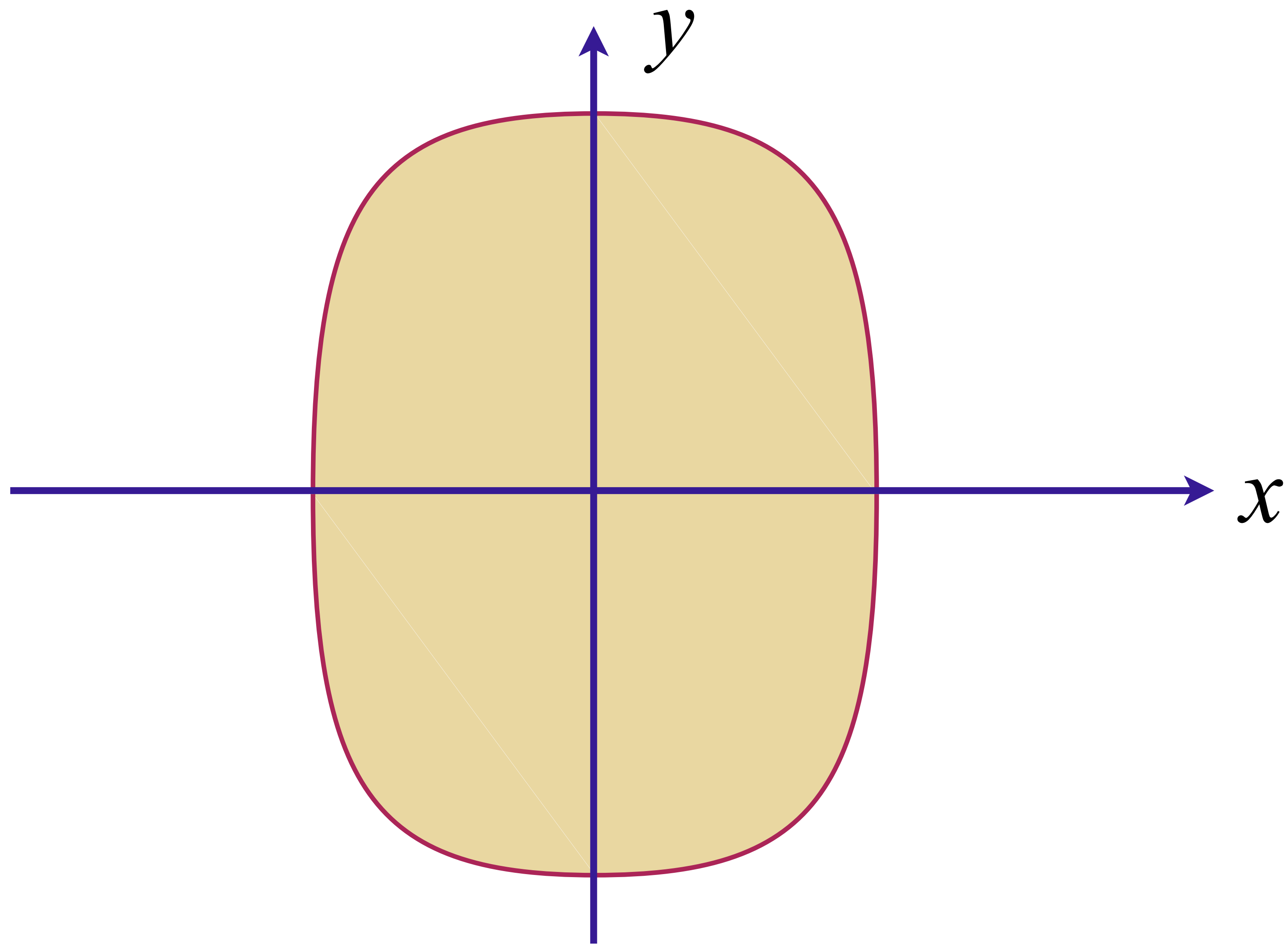

Spontaneous elongation along y direction:
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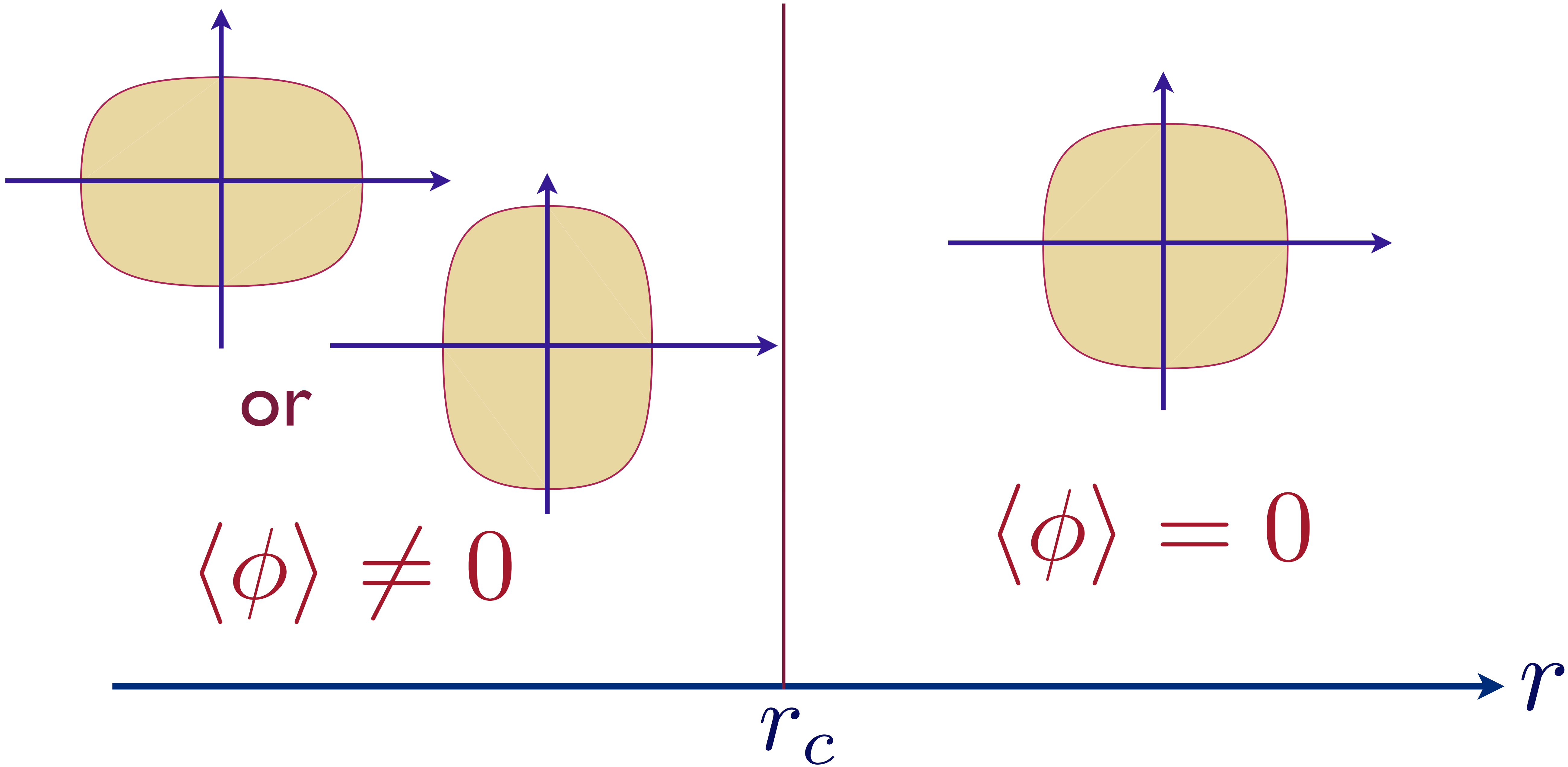
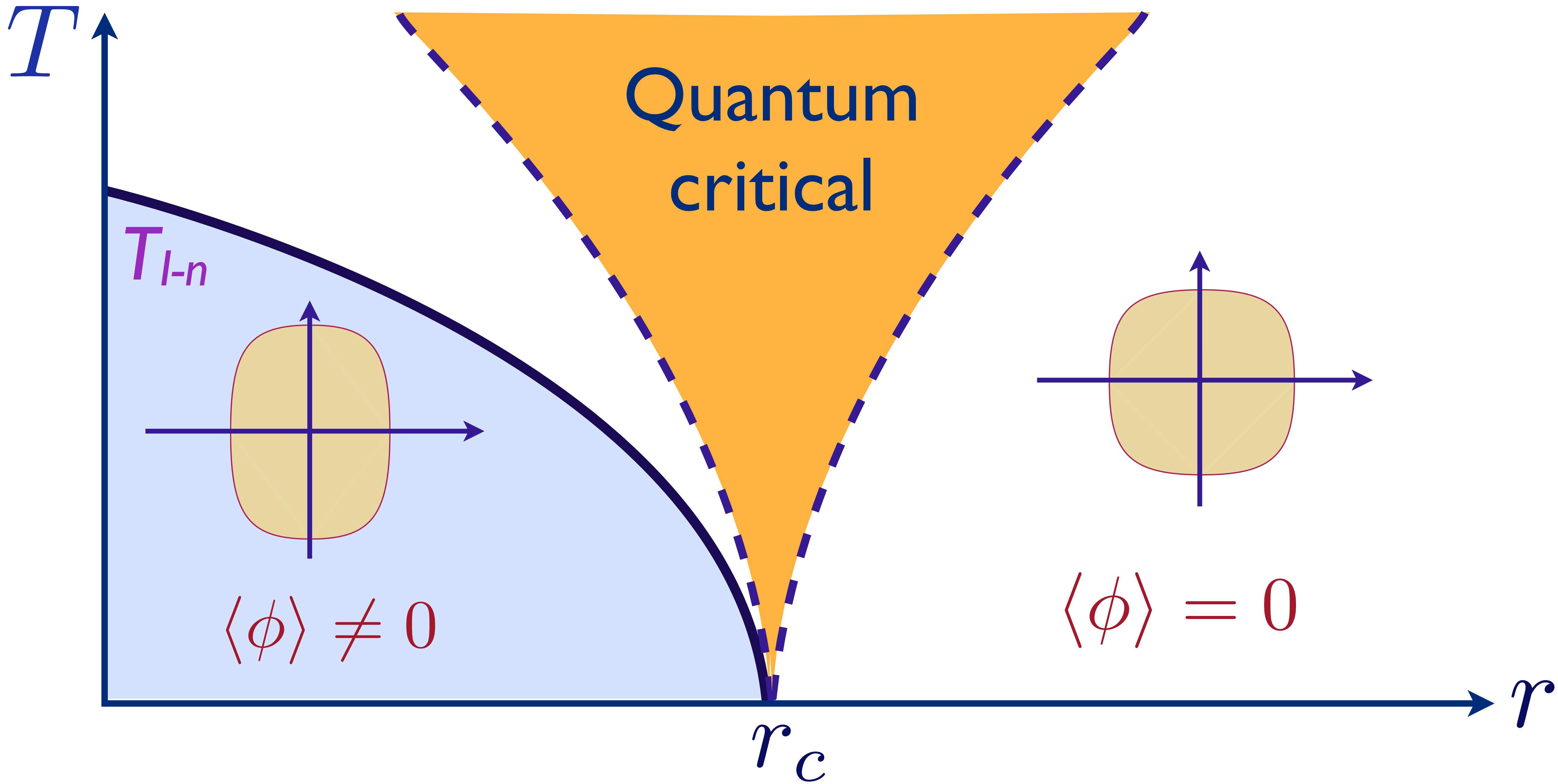


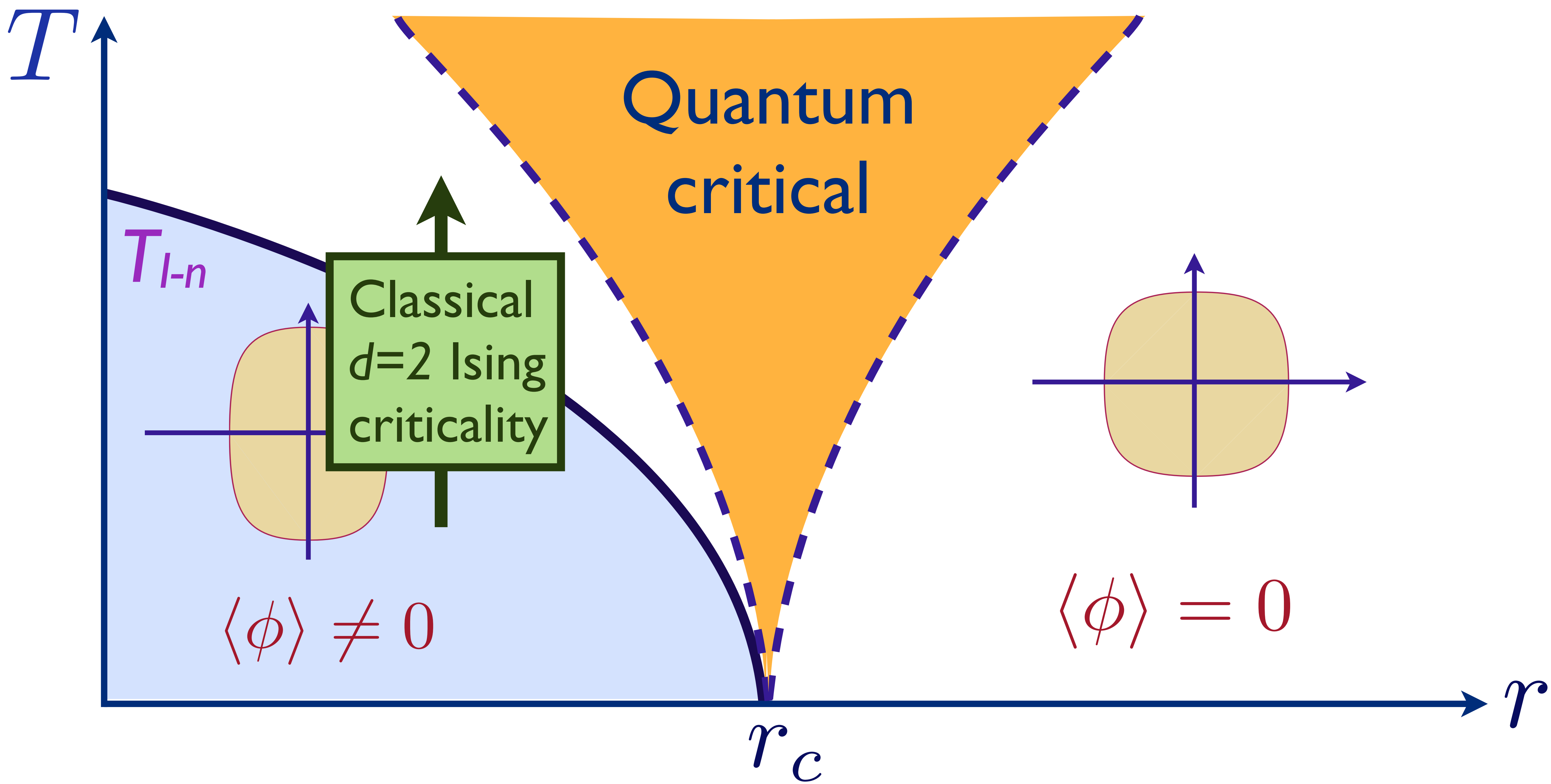
Pomeranchuk instability as a function of coupling r

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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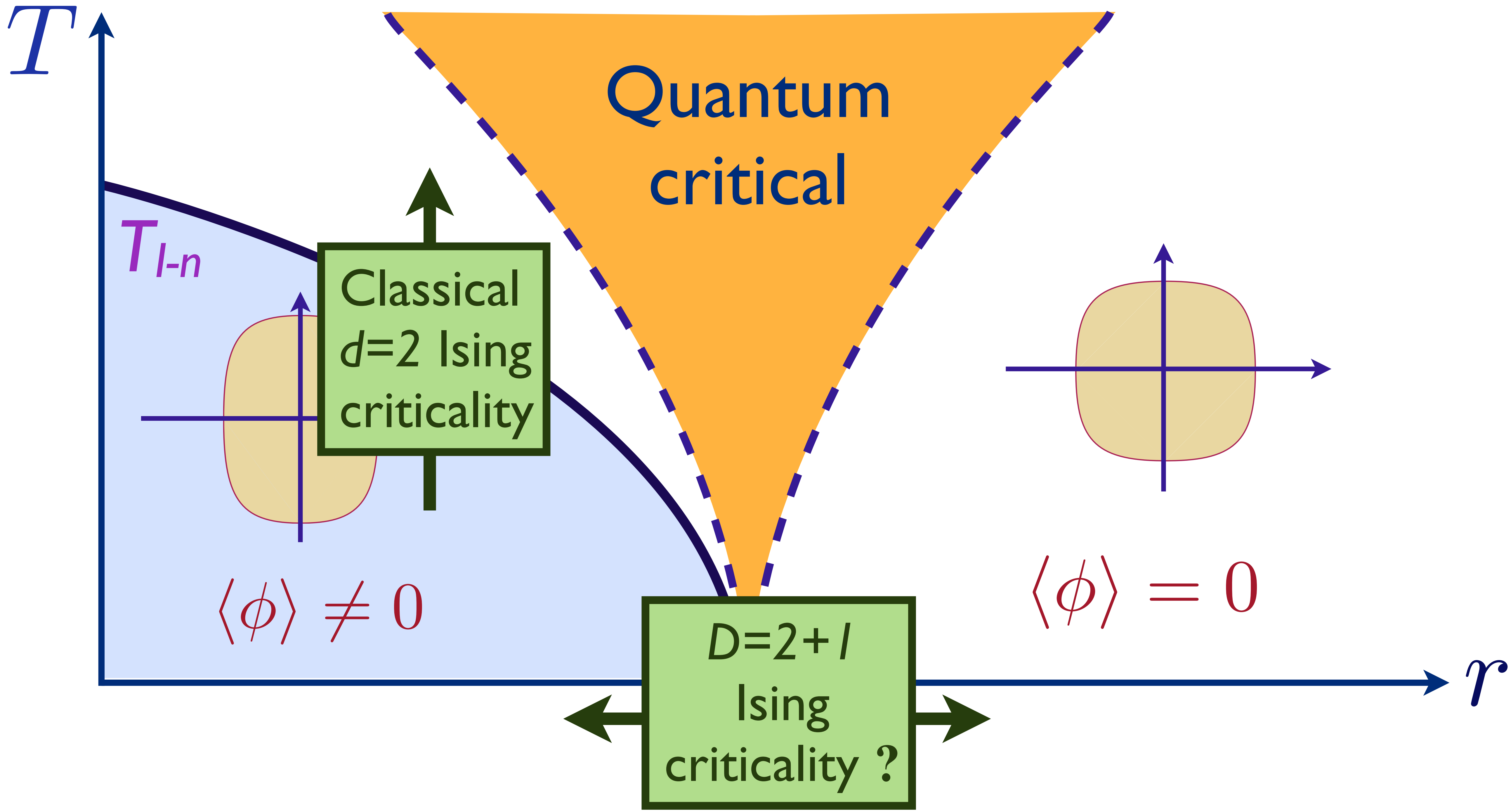

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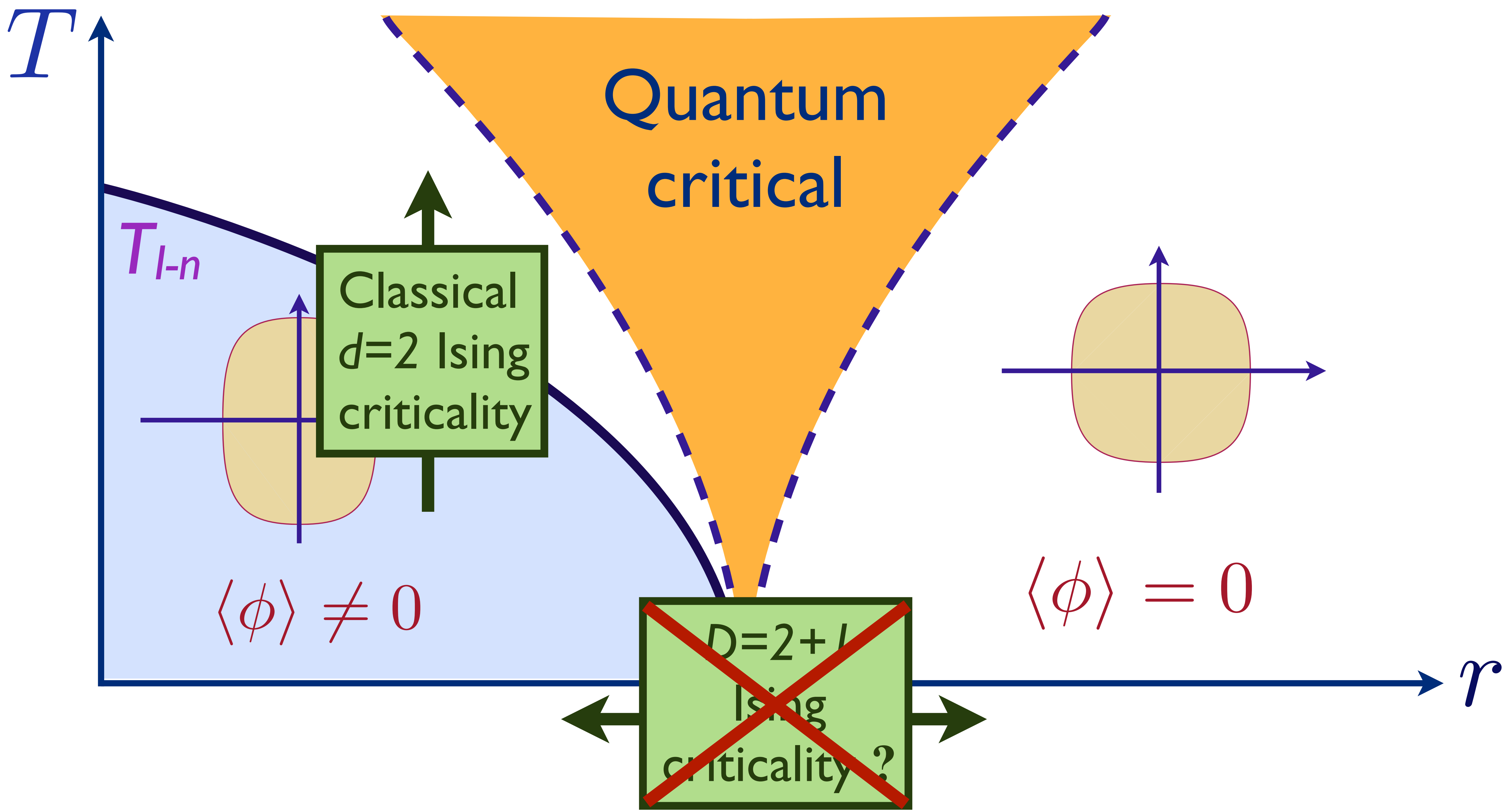

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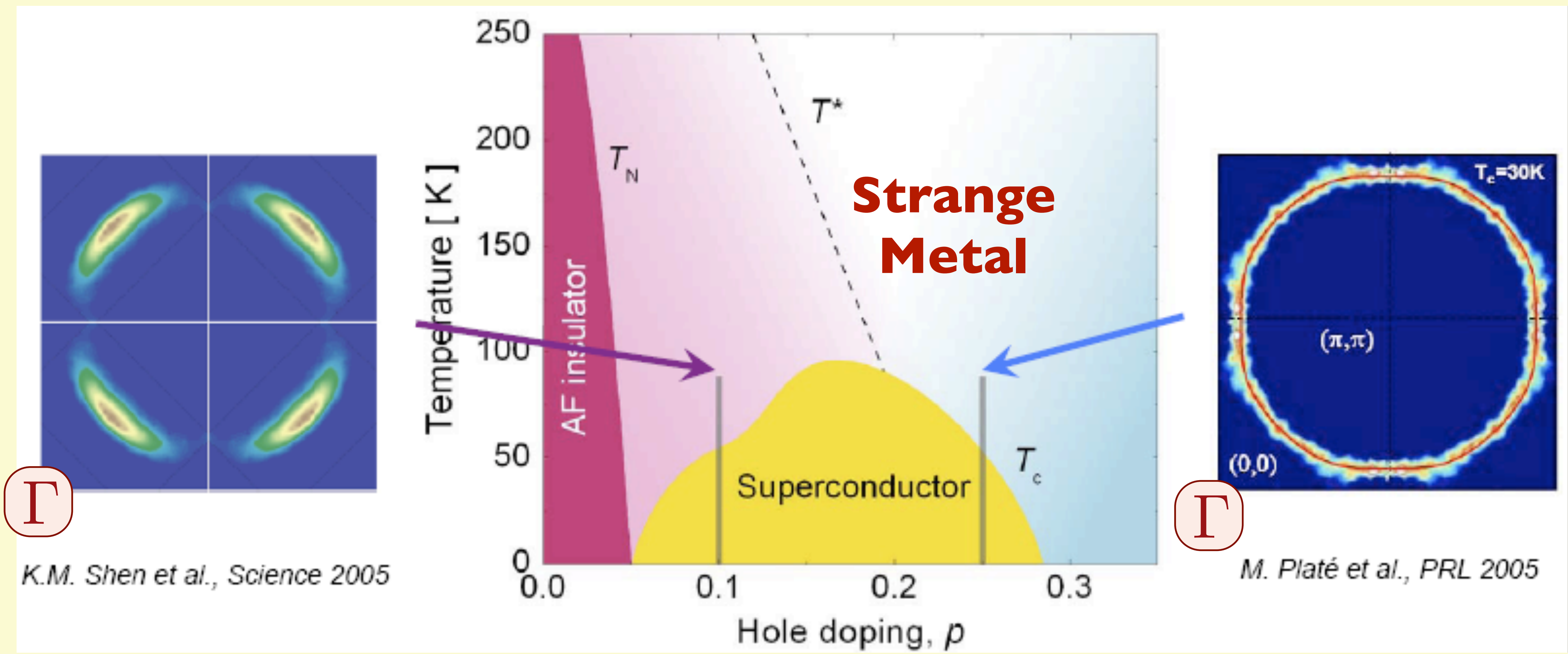

Smaller hole Fermi-pockets

Large hole Fermi surface

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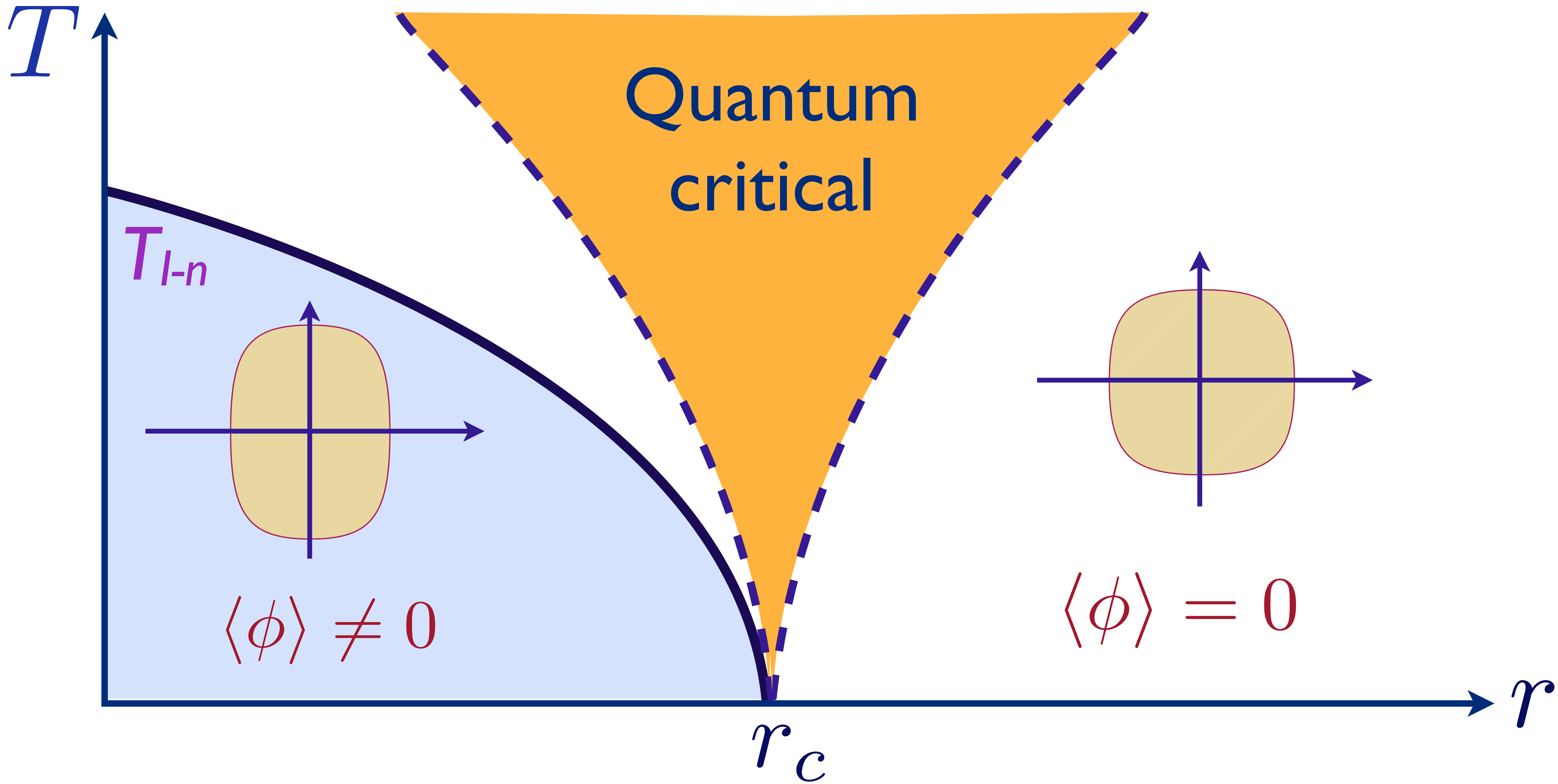

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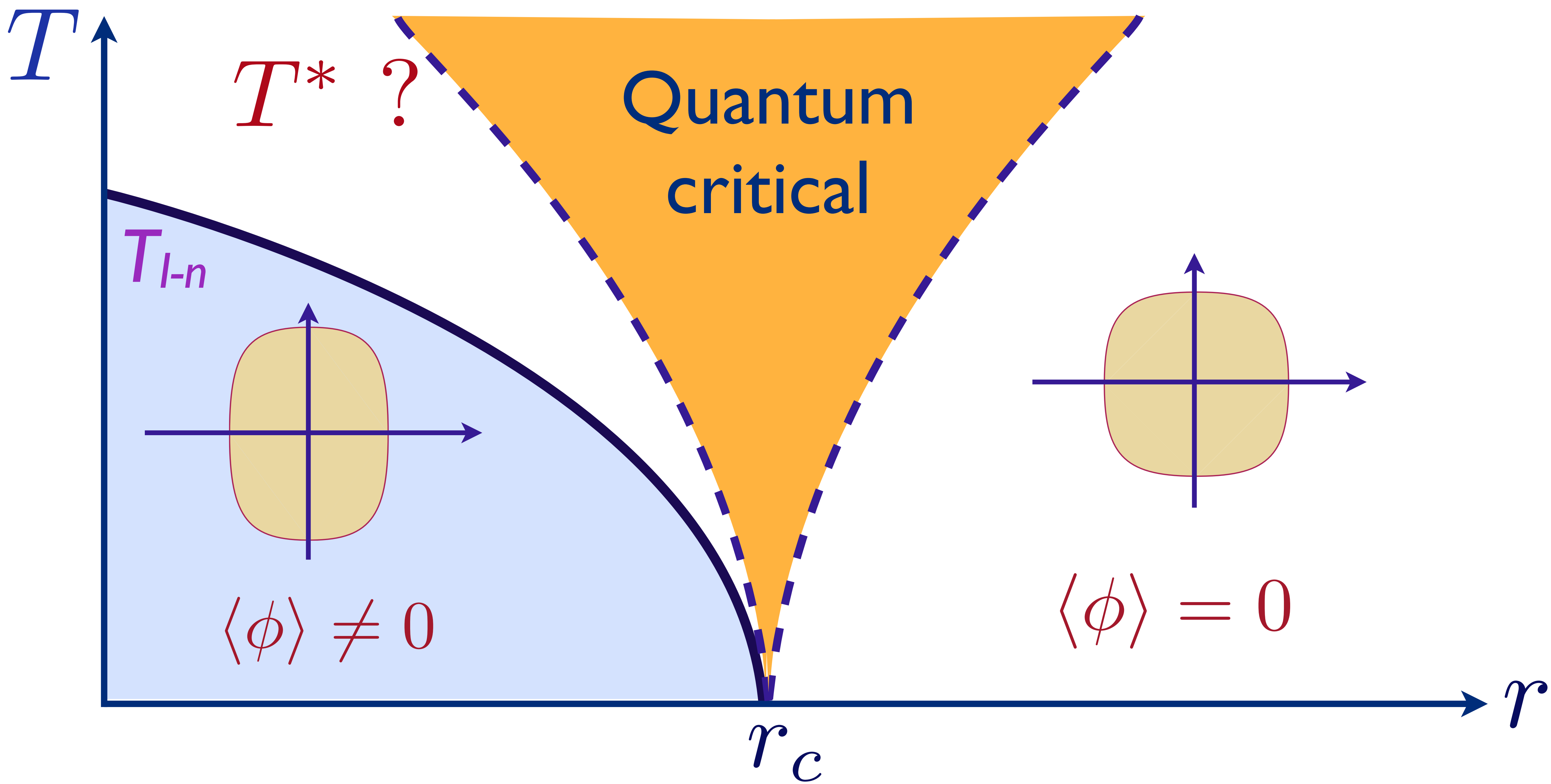

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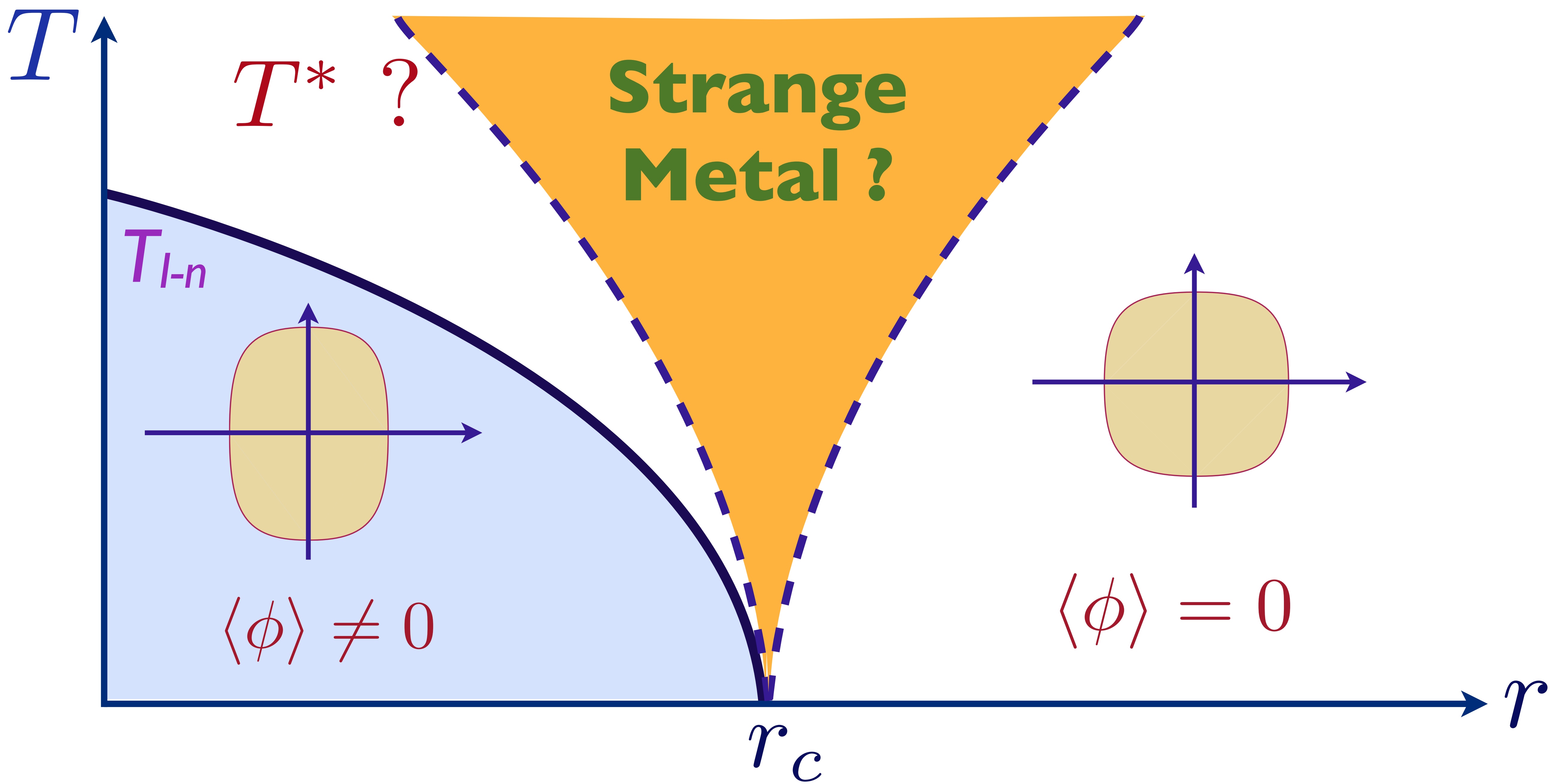

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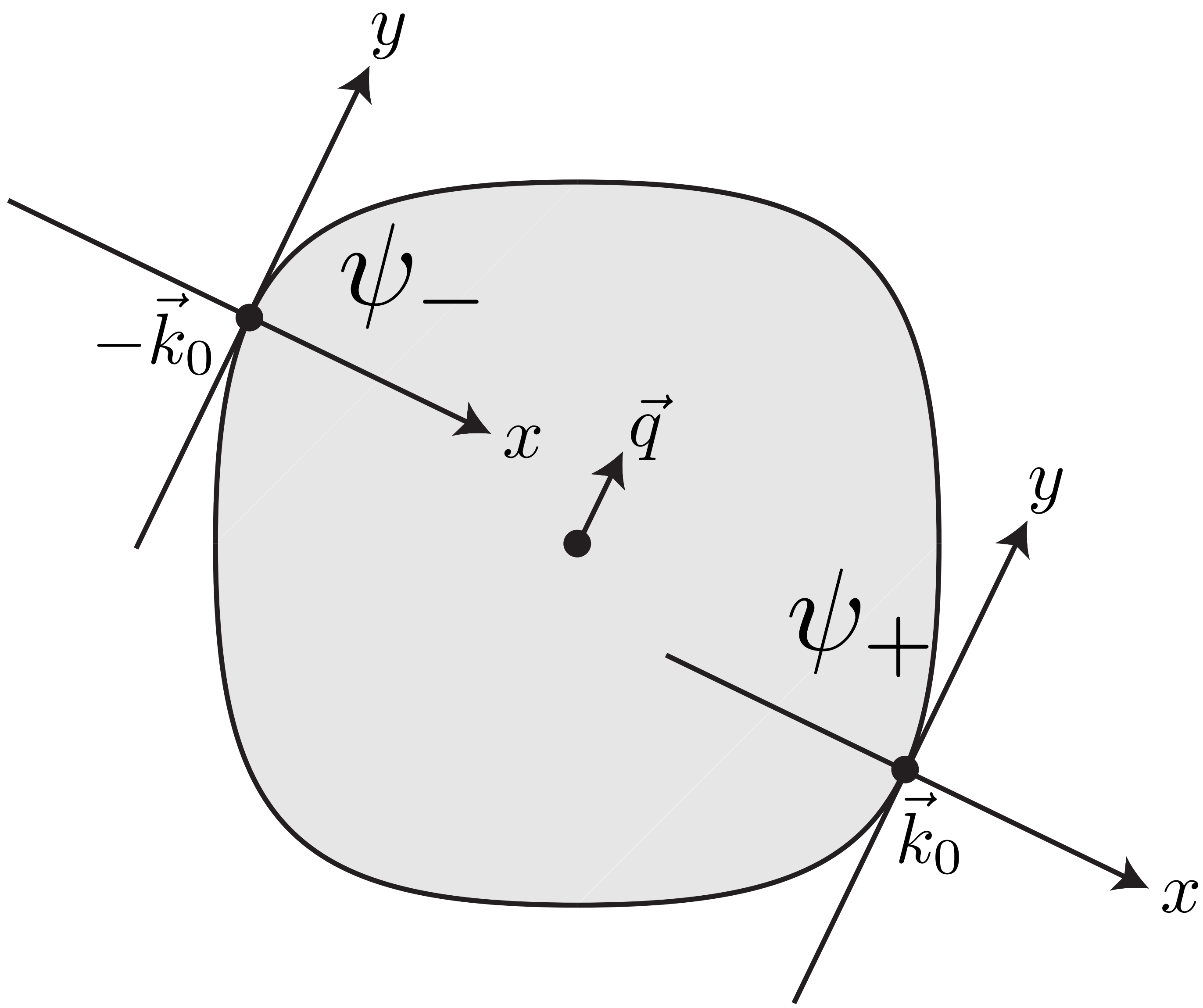
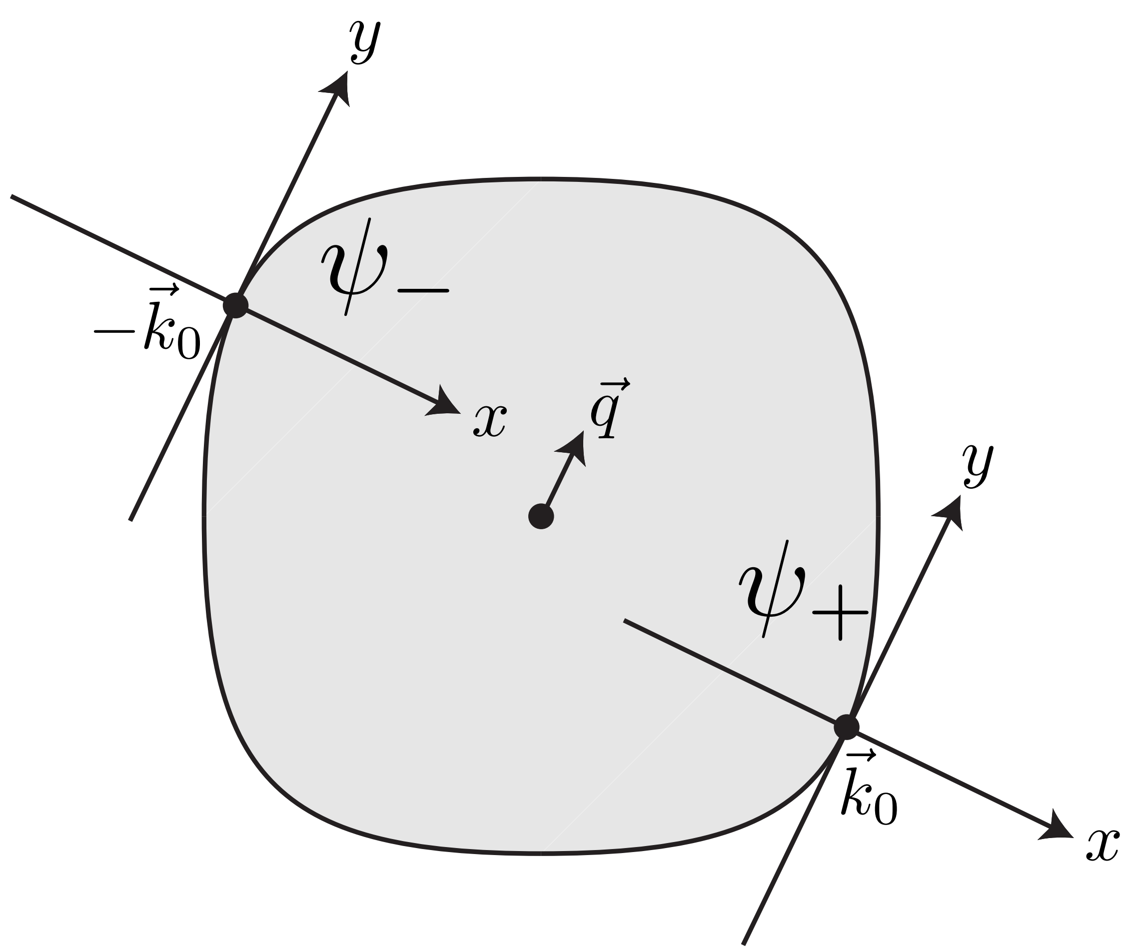


A ϕ fluctuation at wavevector $\vec{q}$ couples most efficiently to fermions near $\pm\vec{k}_0$.

Expand fermion kinetic energy at wavevectors about $\vec{k}_0$

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



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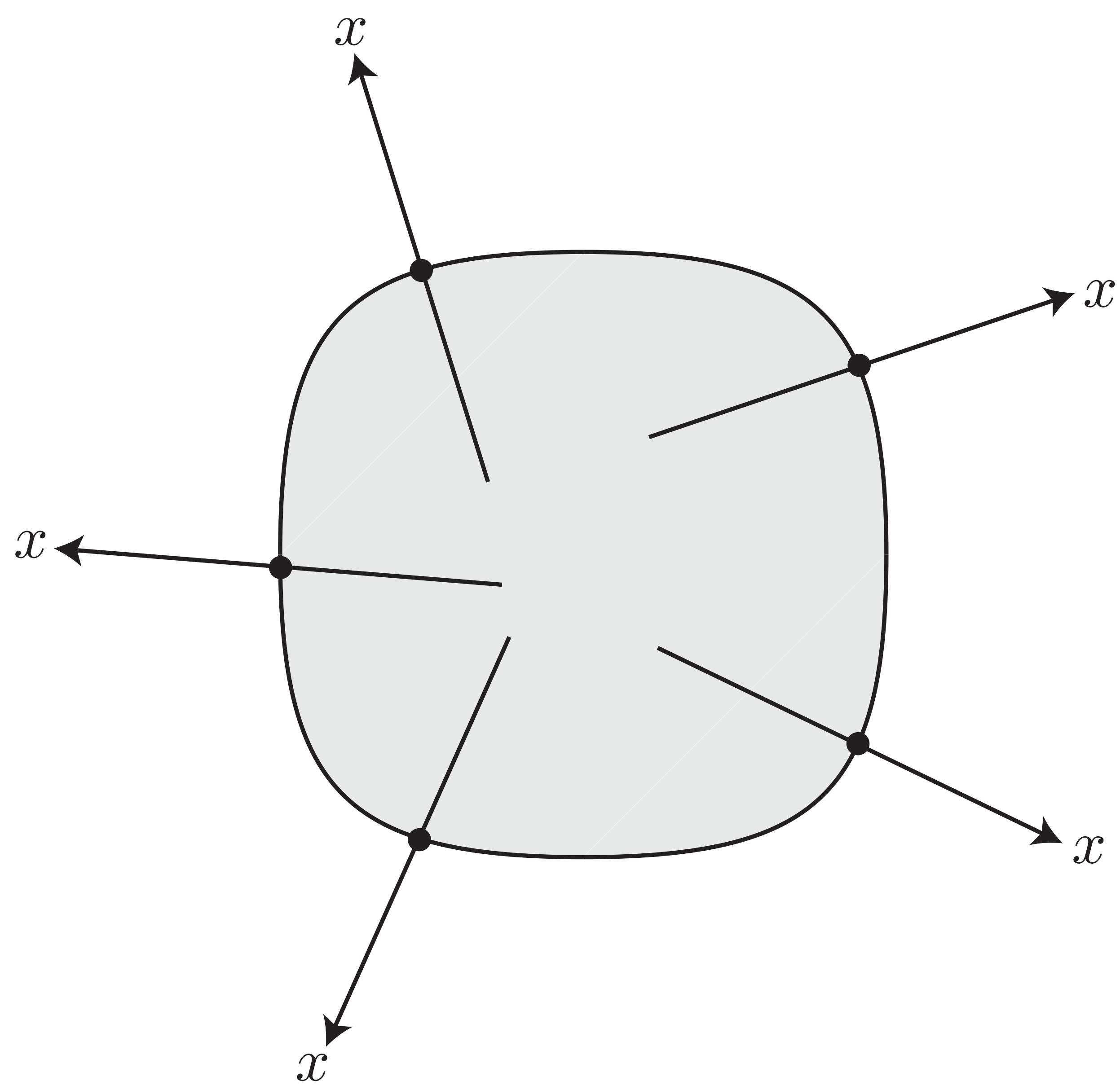
- Contrast with "Fermi surface bosonization" methods where there are an infinite set of 1+1 dimensional field theories, one for each direction $\hat{q}$.



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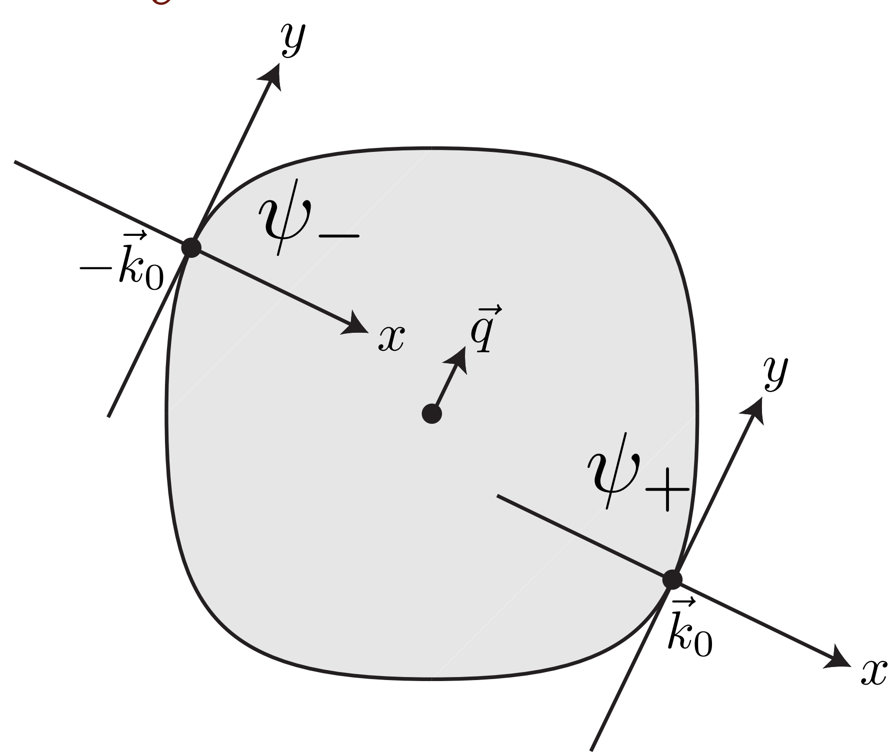
- Our approach leads to a redundant description of underlying degrees of freedom. A "Galilean symmetry" ensures consistency of redundant description.



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

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 finite density quantum matter at strong coupling

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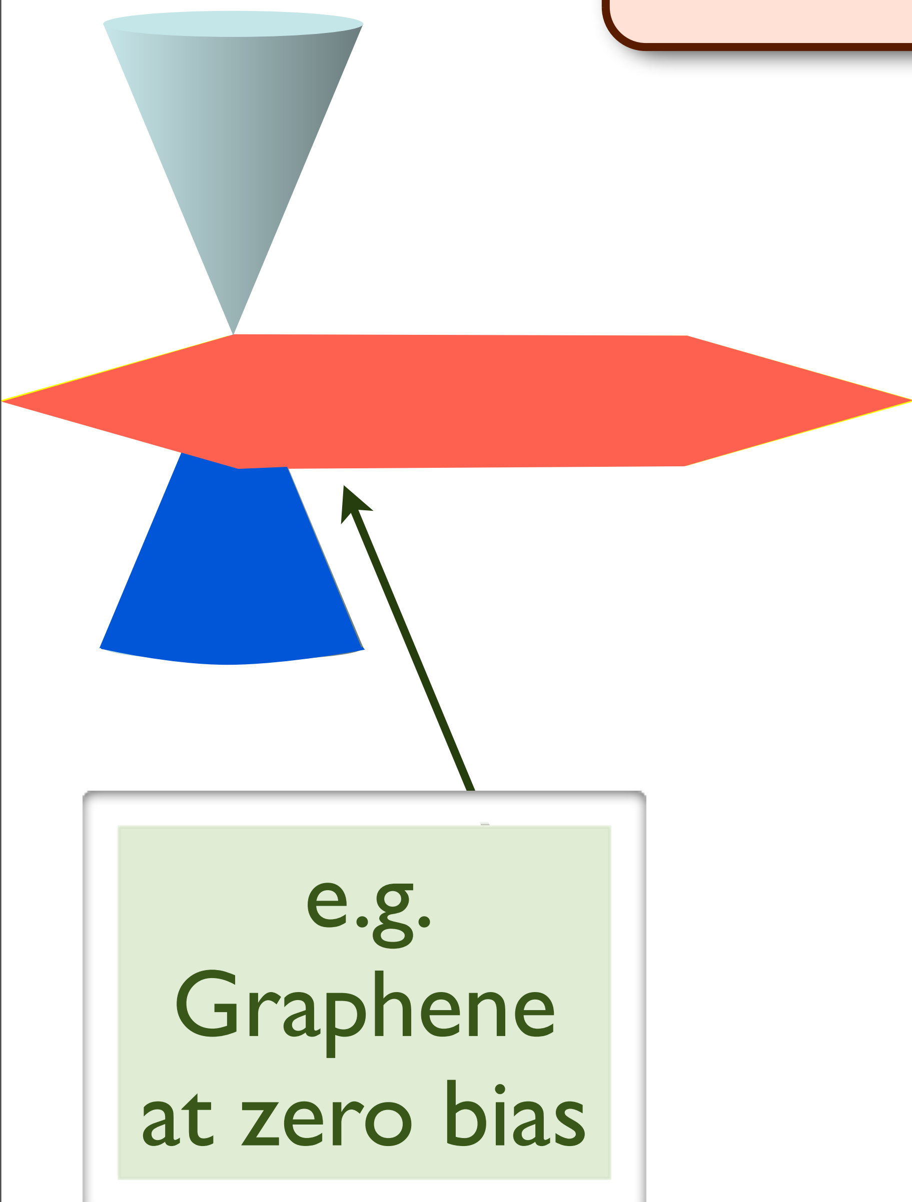
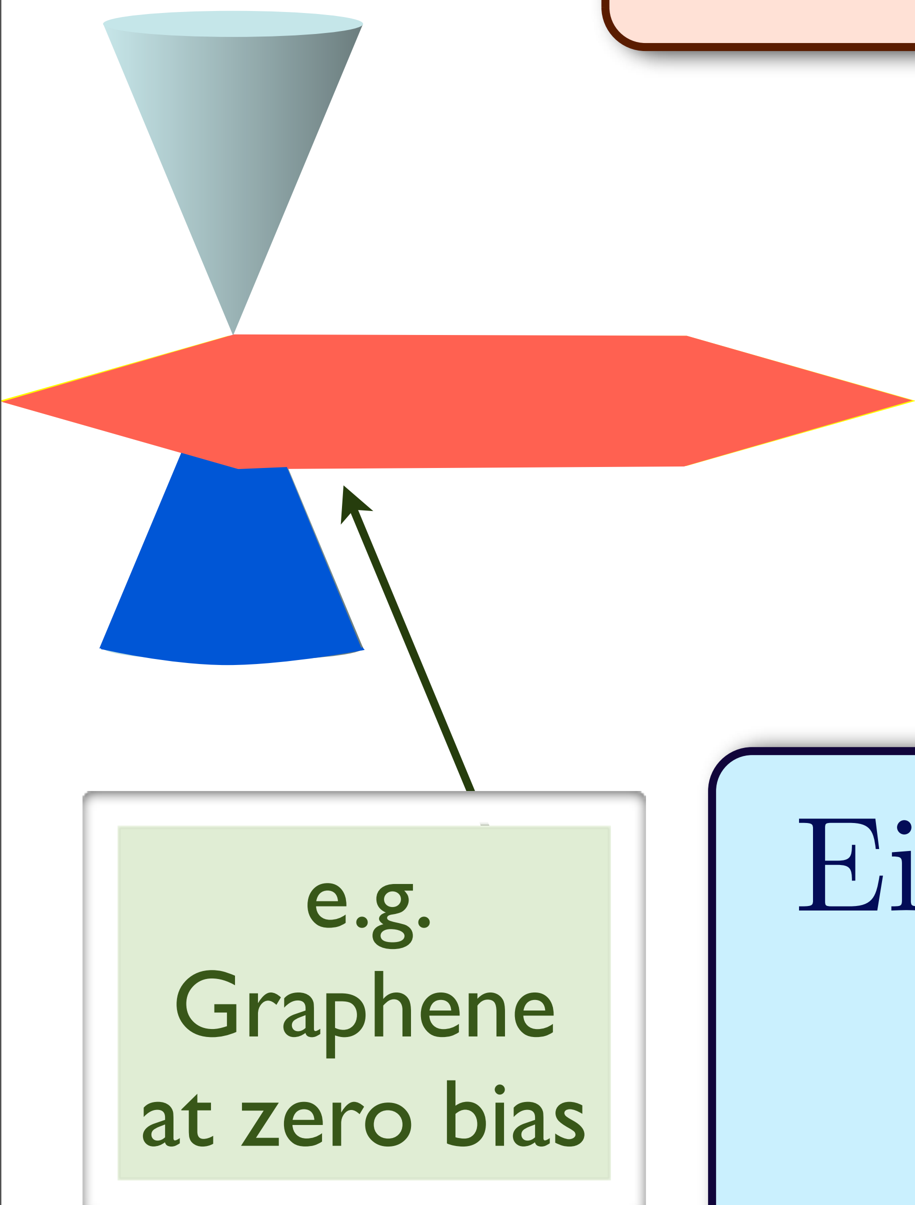
Conformal field theory in 2+1 dimensions at $T = 0$



$\Updownarrow$

Einstein gravity on AdS_4

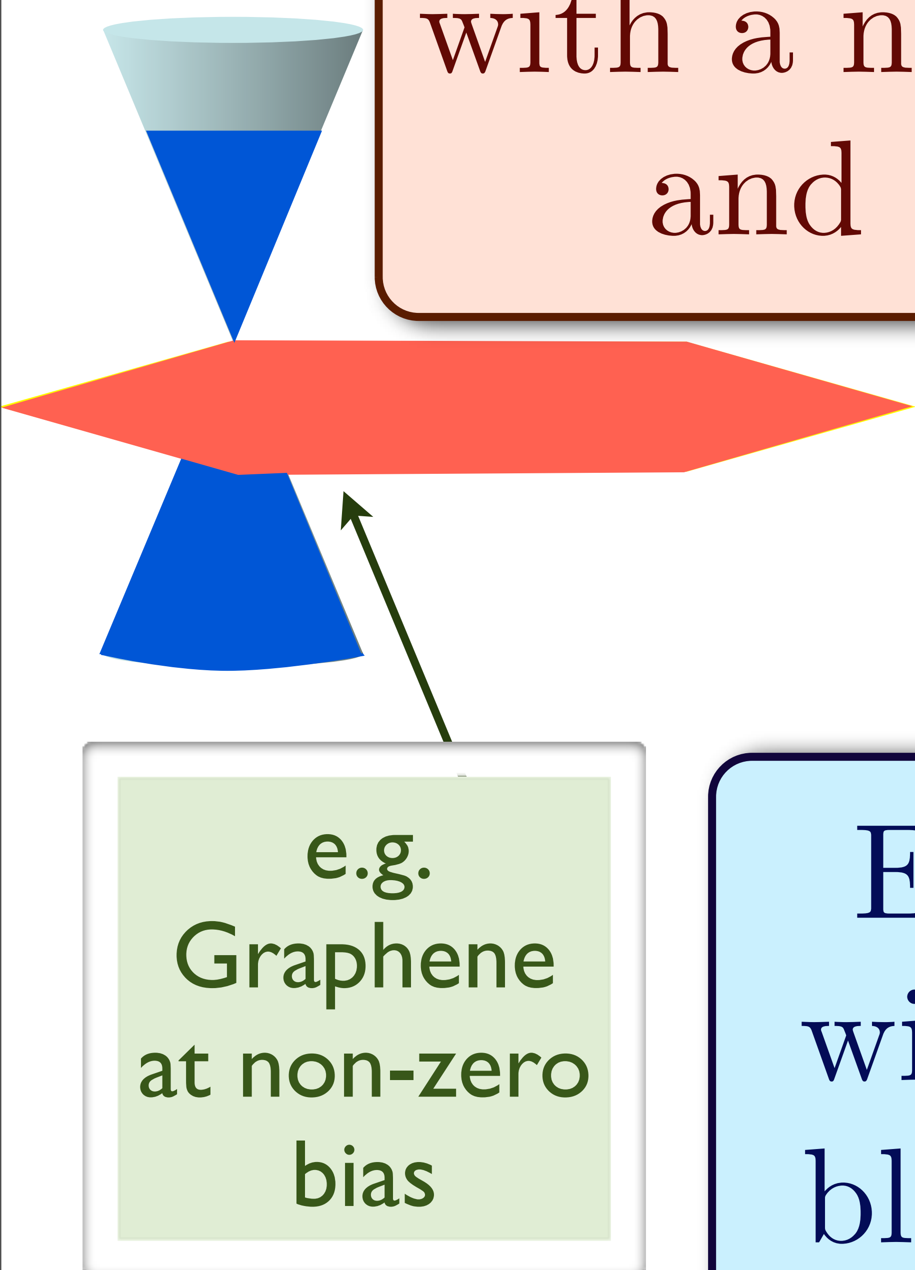
Conformal field theory
in 2+1 dimensions at $T > 0$



$\Updownarrow$

Einstein gravity on AdS_4
with a Schwarzschild
black hole

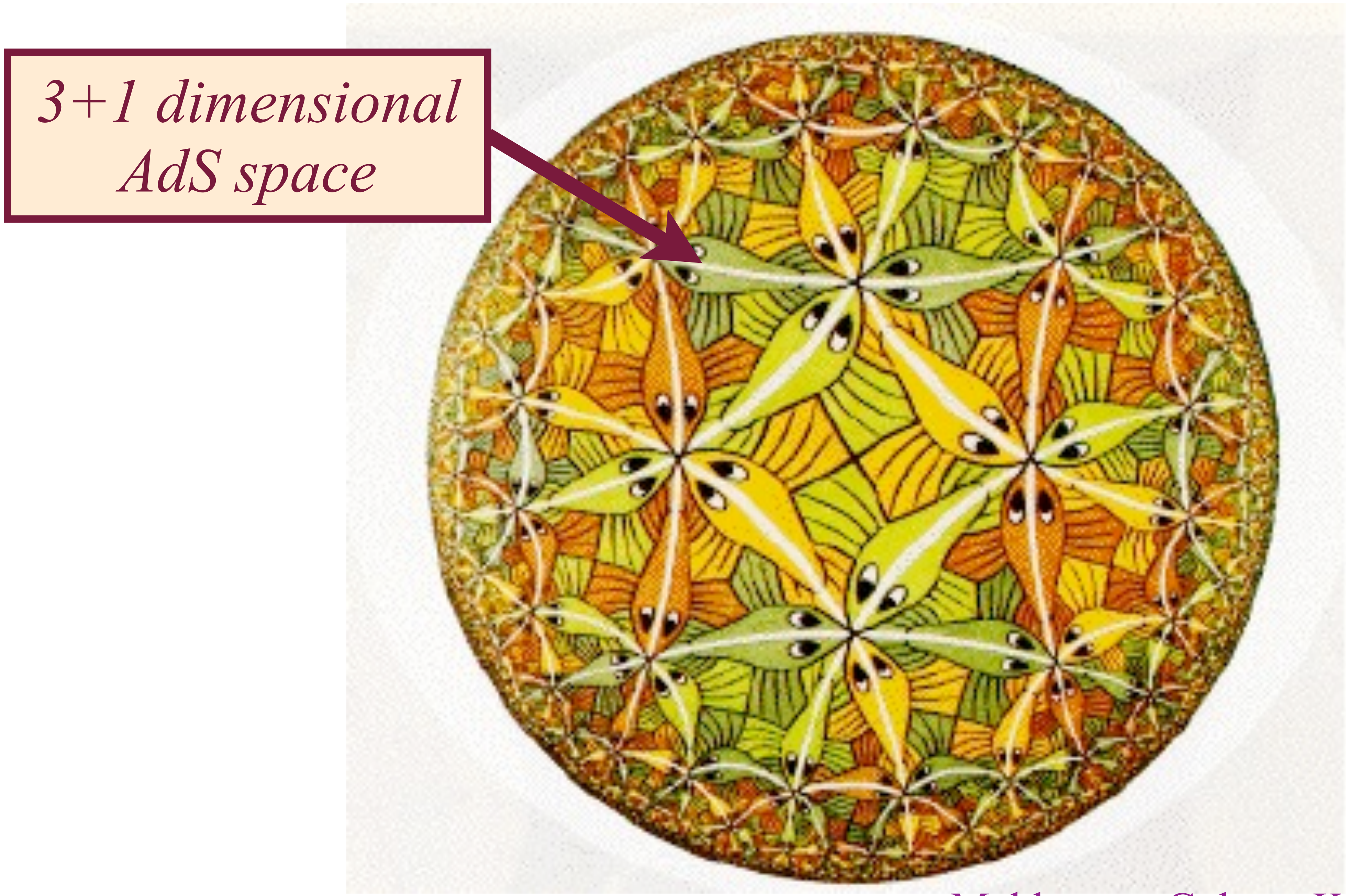
Conformal field theory
in 2+1 dimensions at $T > 0$,
with a non-zero chemical potential, μ
and applied magnetic field, B



Einstein gravity on AdS_4
with a Reissner-Nordstrom
black hole carrying electric
and magnetic charges

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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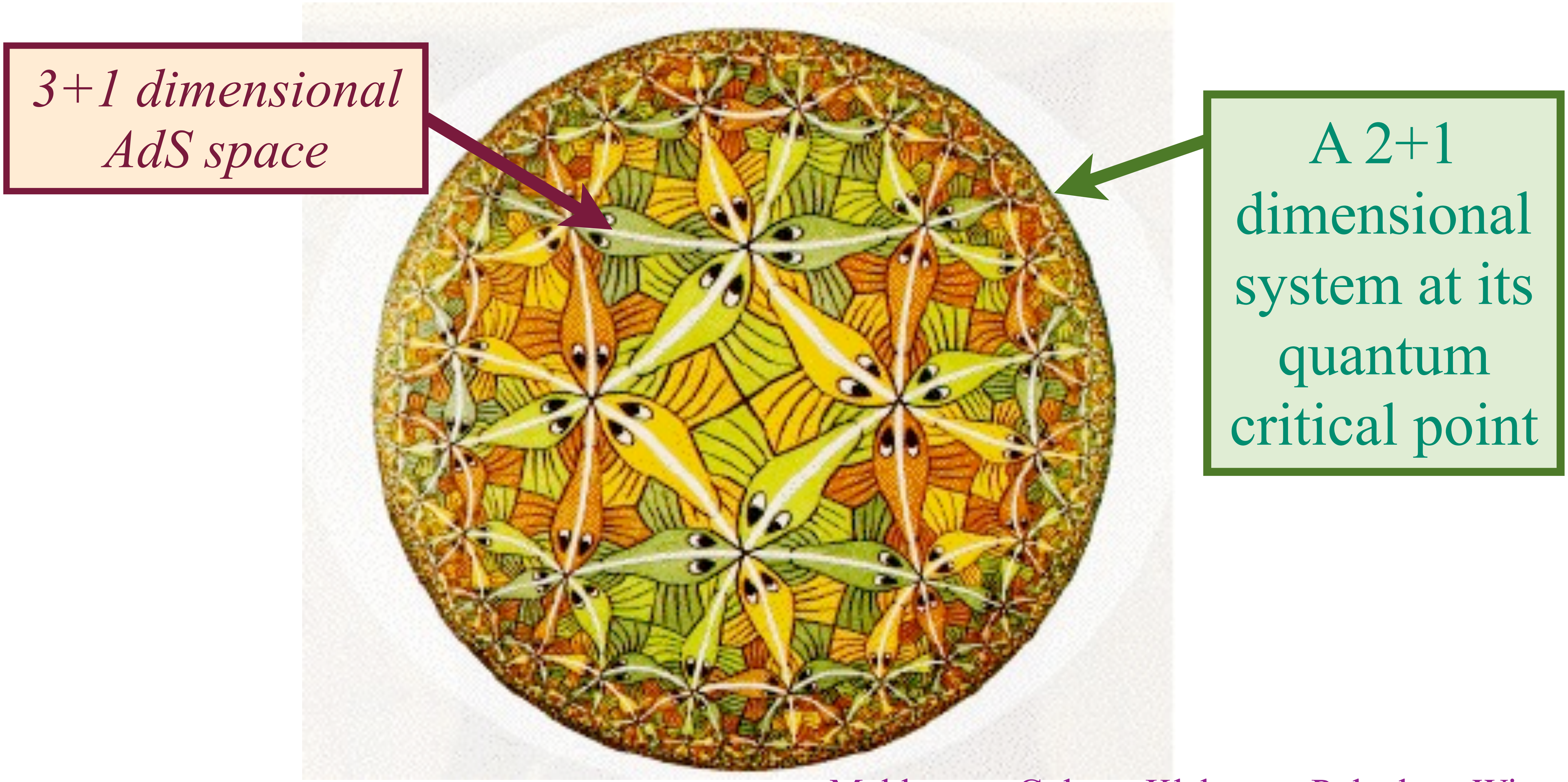

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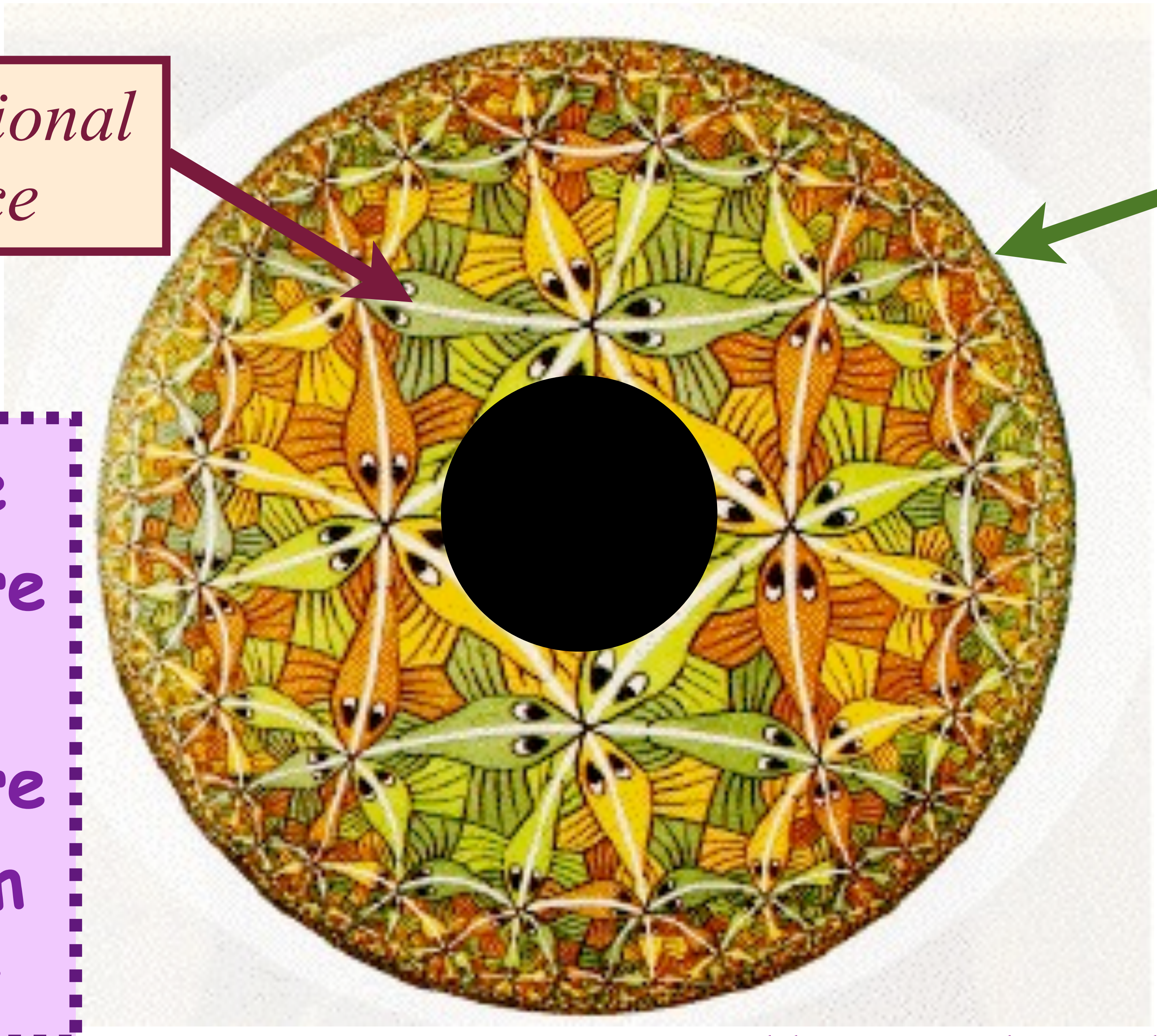
3+1 dimensional AdS space



Quantum criticality in 2+1 dimensions

Black hole temperature = temperature of quantum criticality

Maldacena, Gubser, Klebanov, Polyakov, Witten

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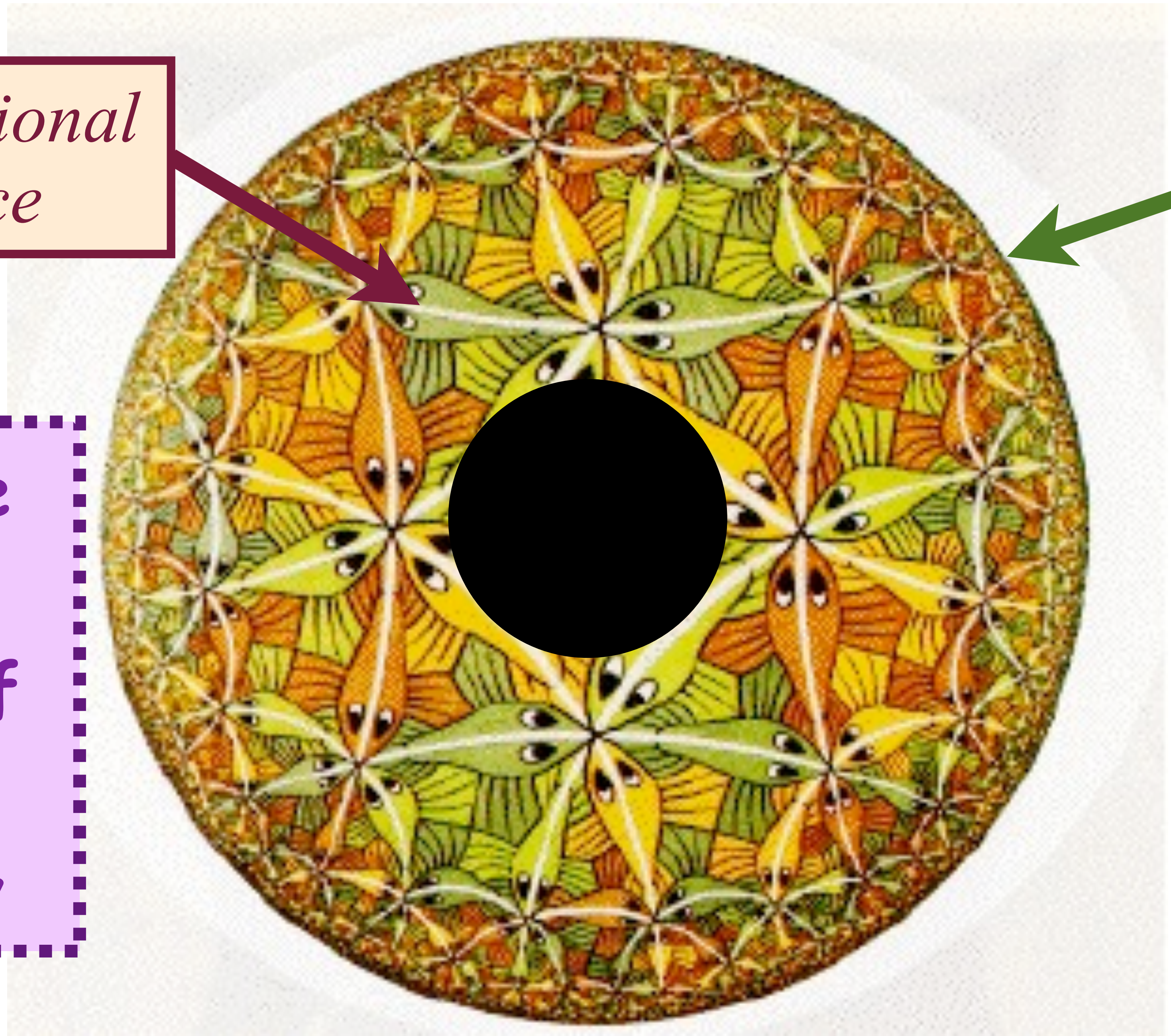

3+1 dimensional AdS space

Quantum criticality in 2+1 dimensions

Black hole entropy = entropy of quantum criticality

Strominger, Vafa

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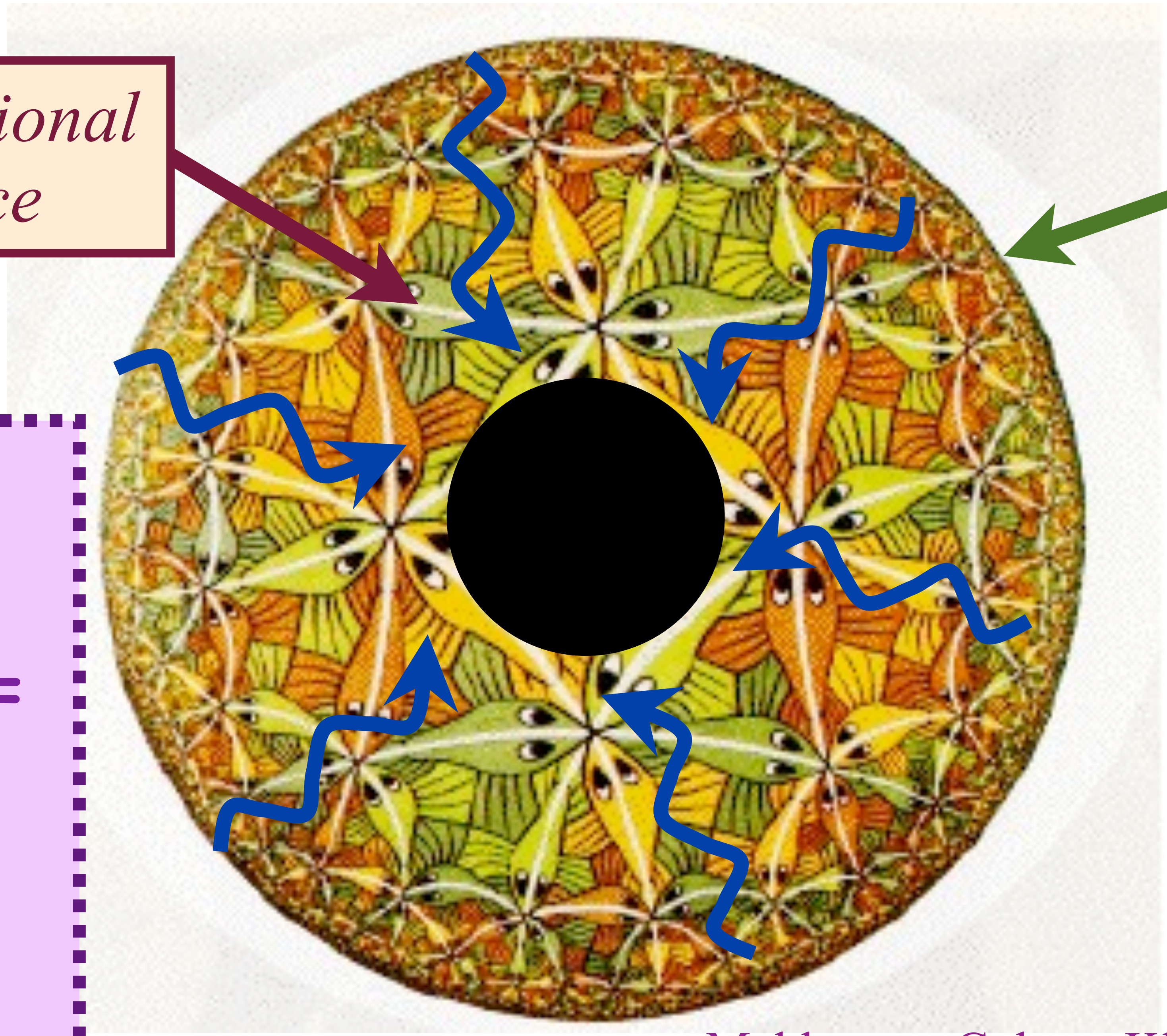
3+1 dimensional AdS space



Quantum criticality in 2+1 dimensions

Quantum critical dynamics = waves in curved space

Maldacena, Gubser, Klebanov, Polyakov, Witten

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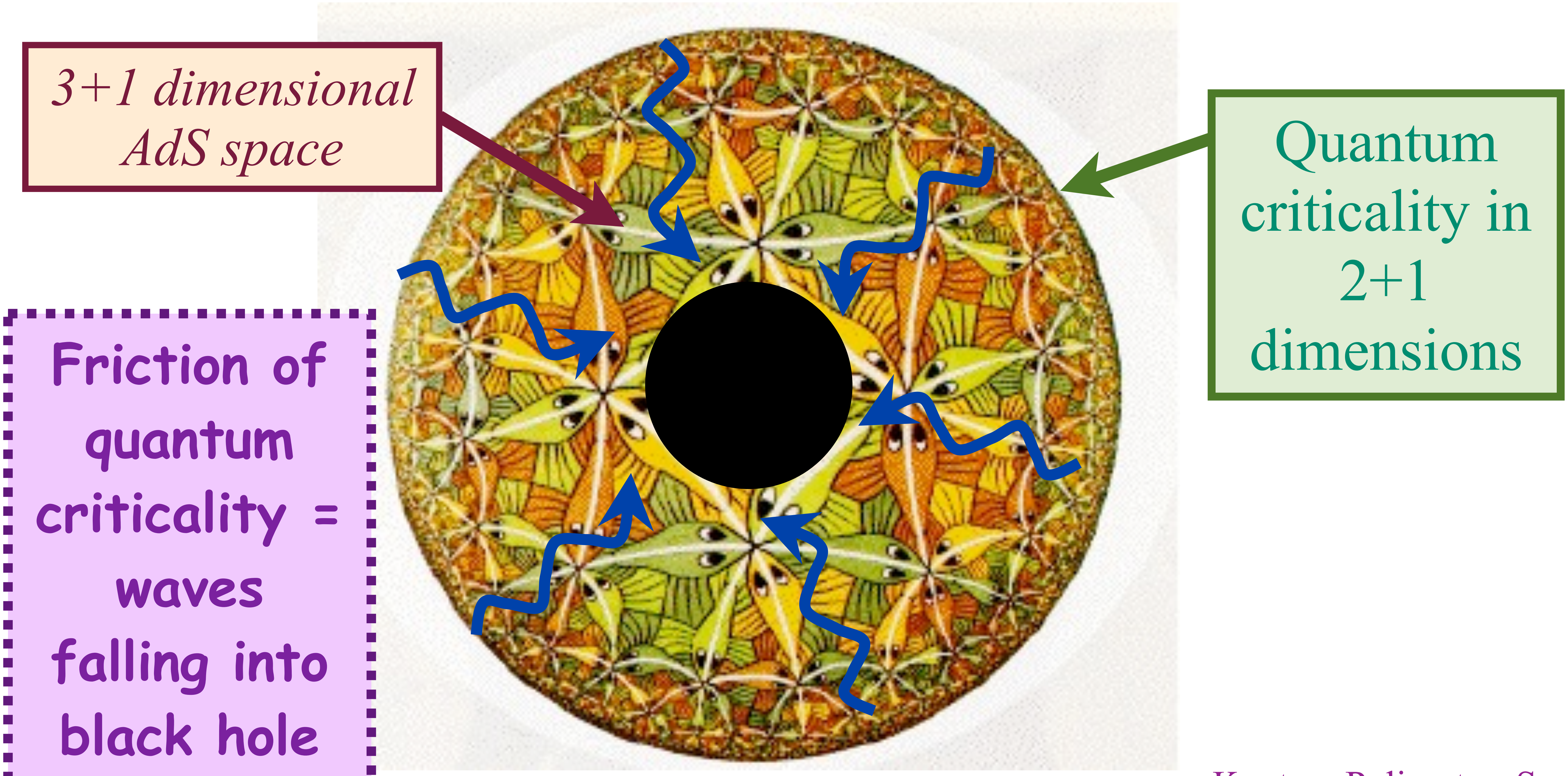

Kovtun, Policastro, Son

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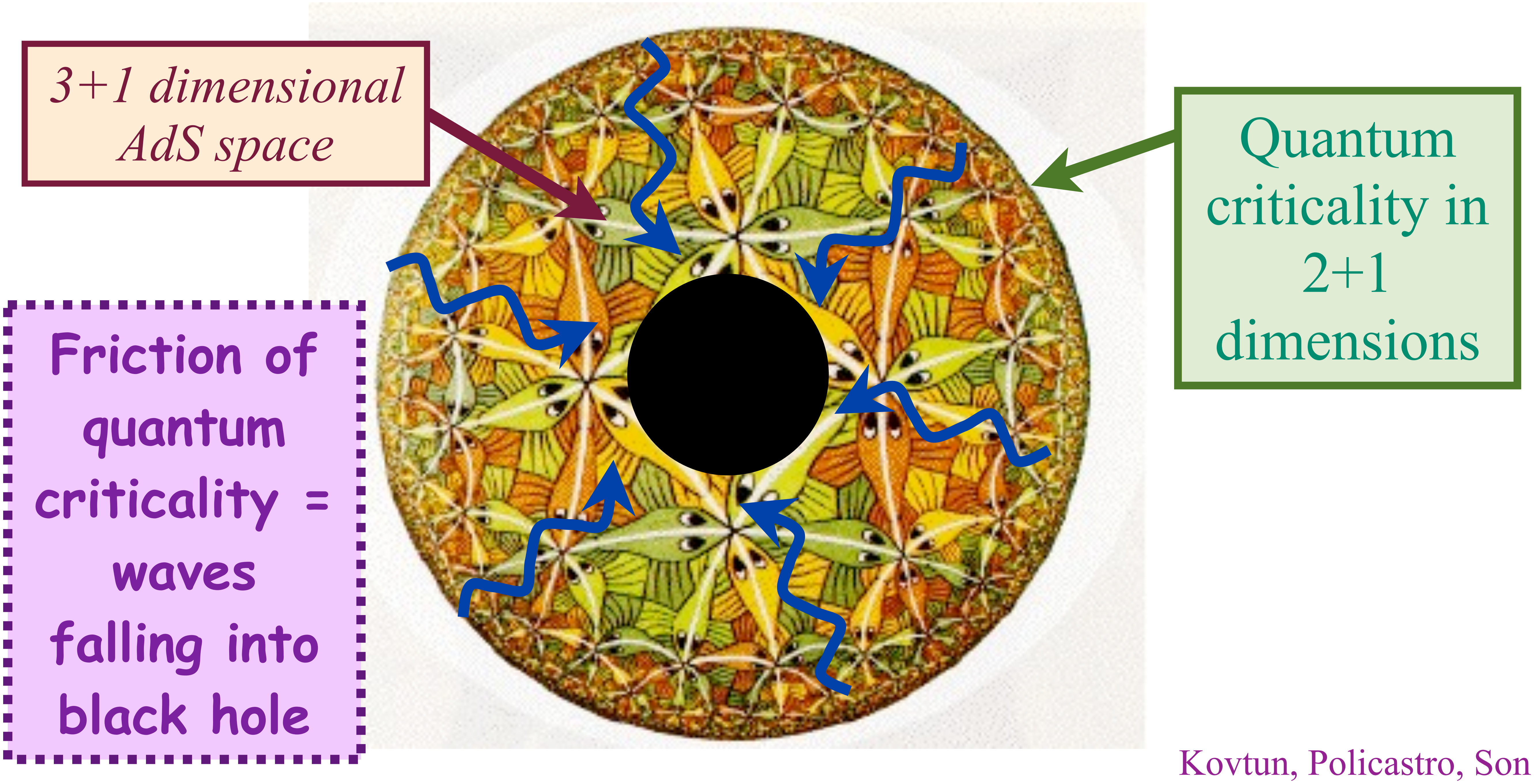

AdS/CFT correspondence

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).

Fricti
quan
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waves
falling into
black hole

Kovtun, Policastro, Son

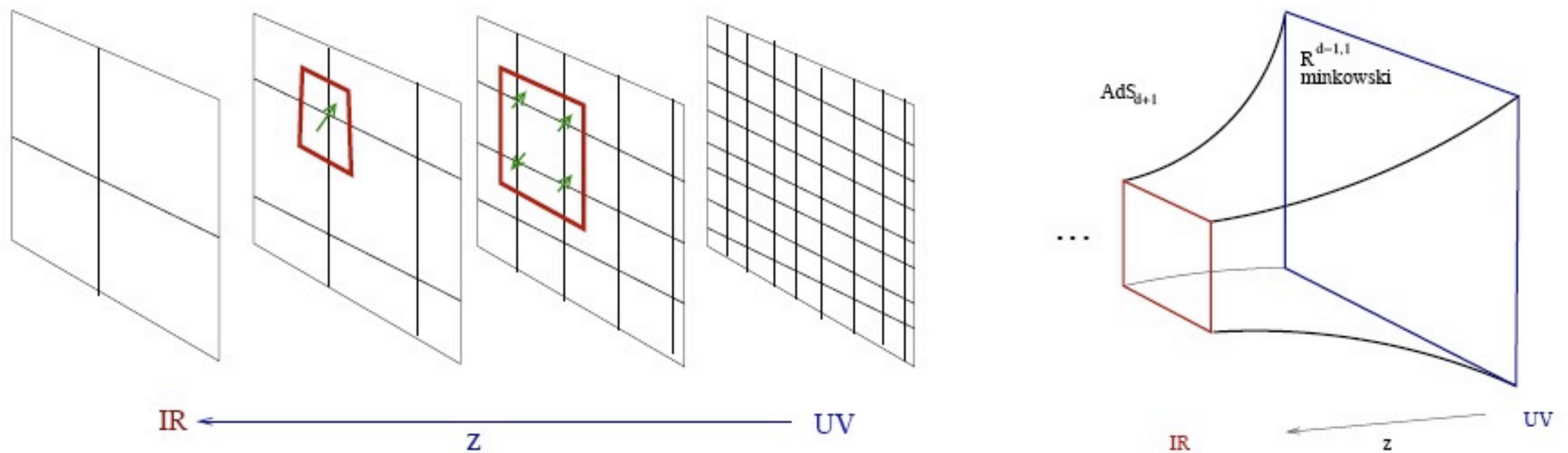
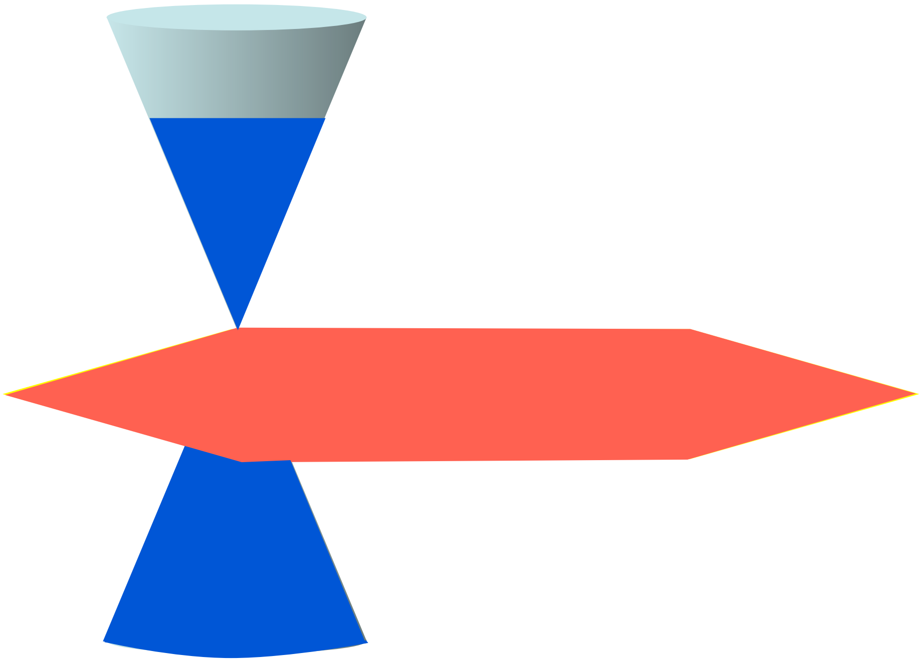
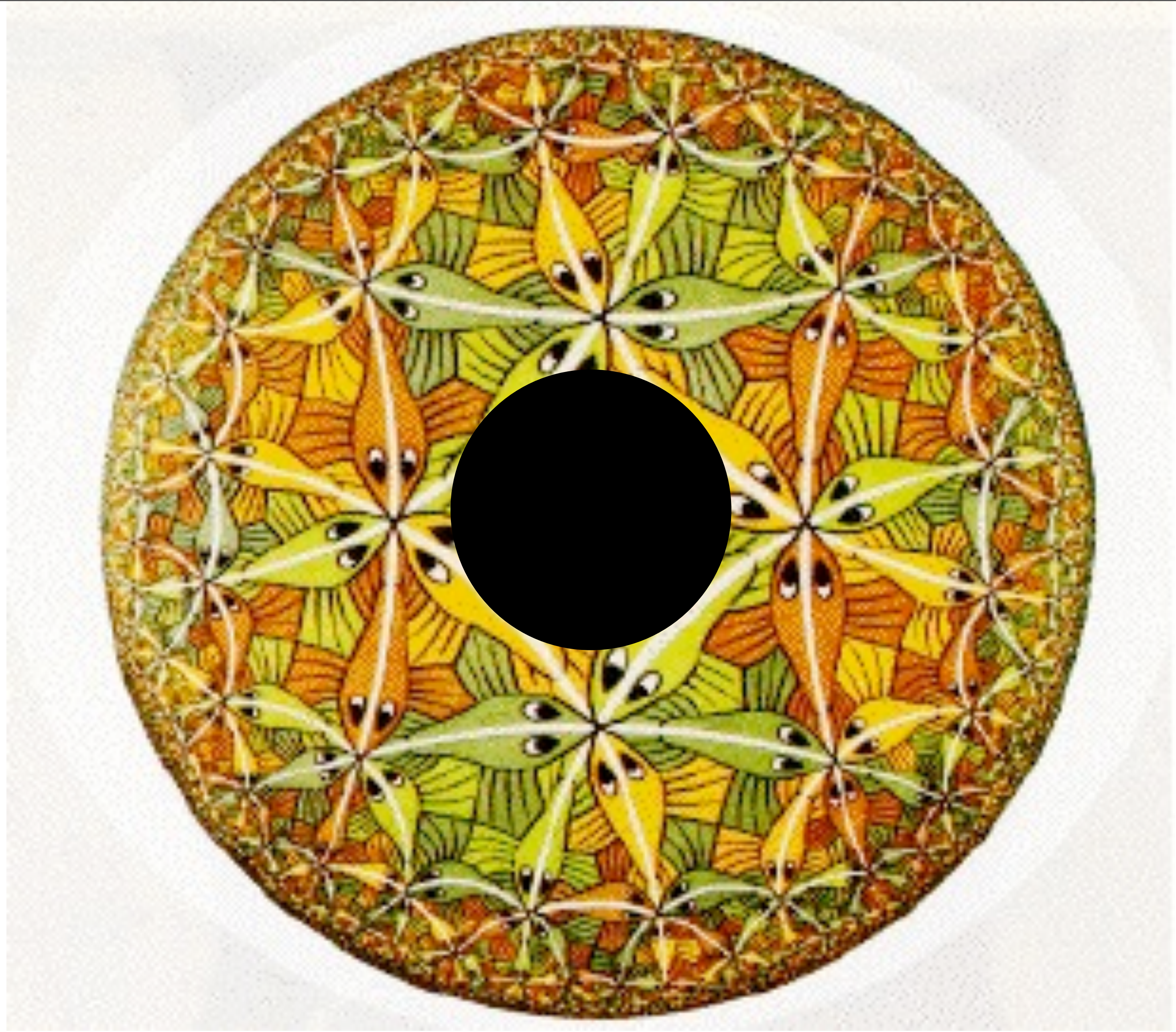
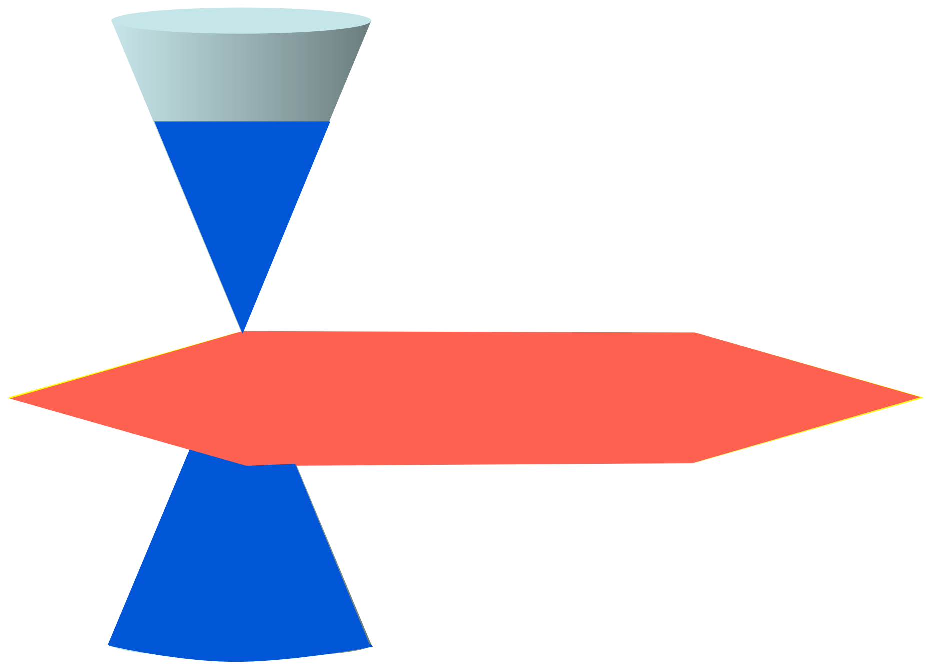


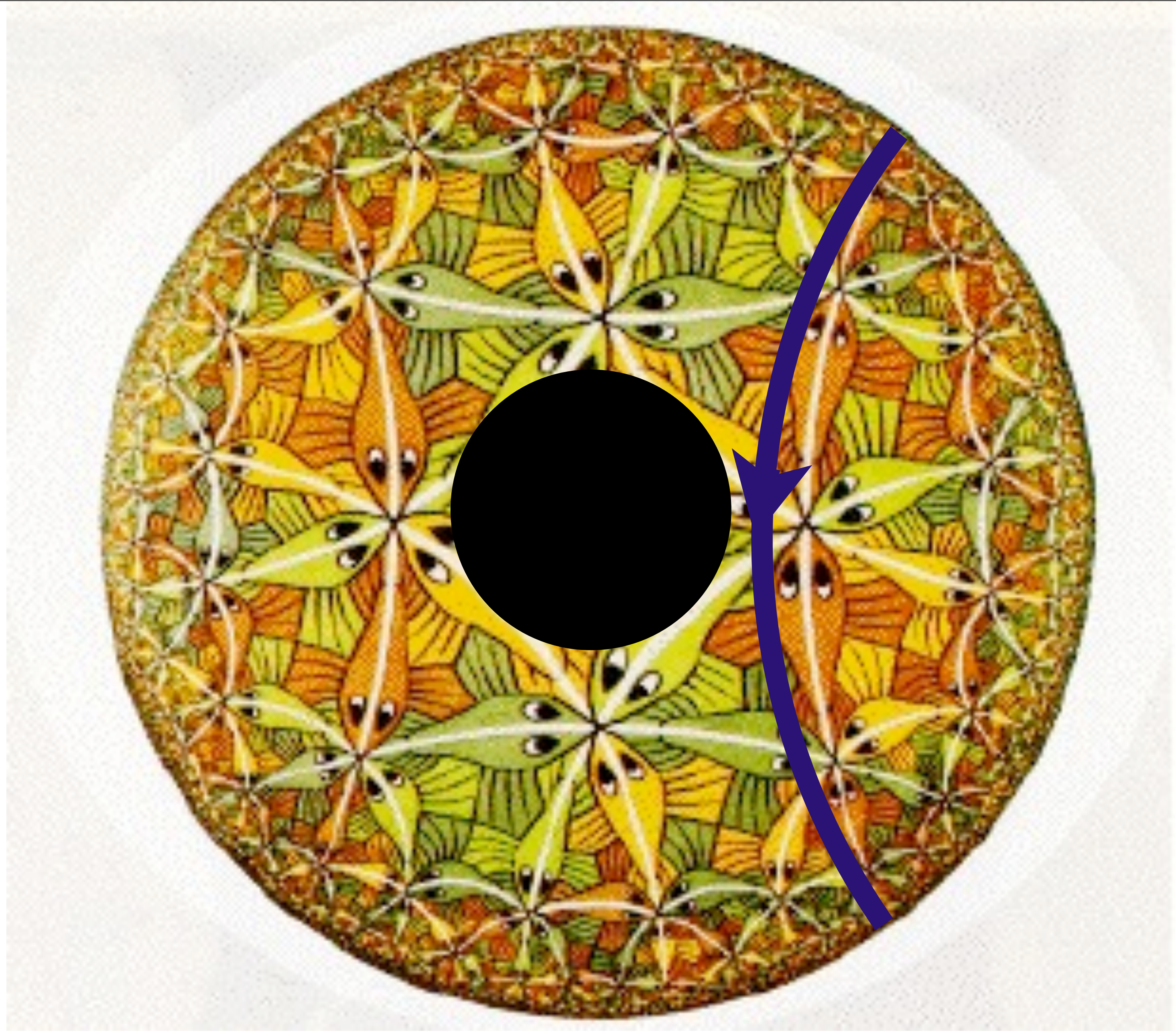
Figure 1: The extra ('radial') dimension of the bulk is the resolution scale of the field theory. The left figure indicates a series of block spin transformations labelled by a parameter z. The right figure is a cartoon of AdS space, which organizes the field theory information in the same way. In this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

J. McGreevy, arXiv0909.0518



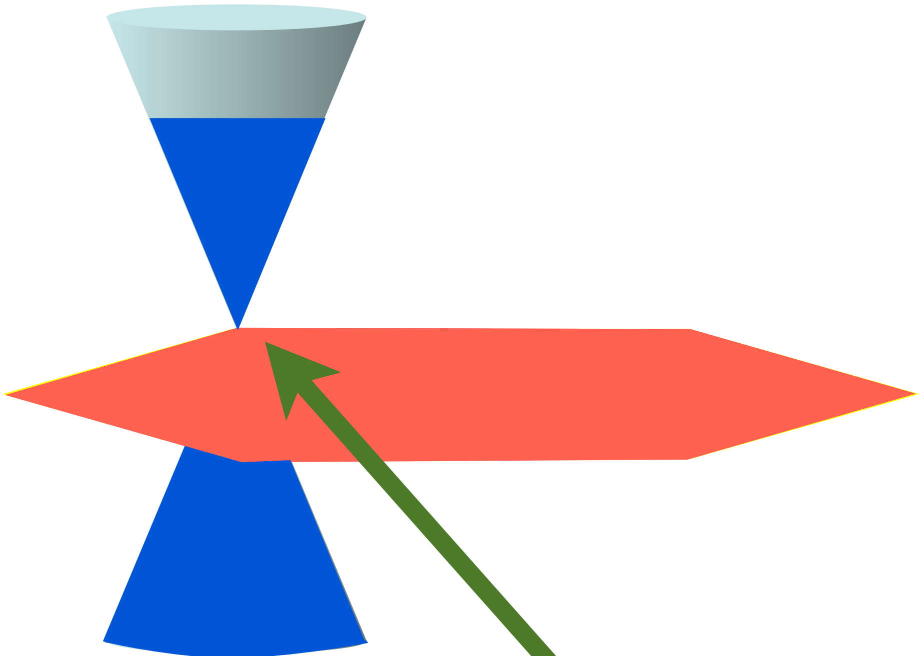


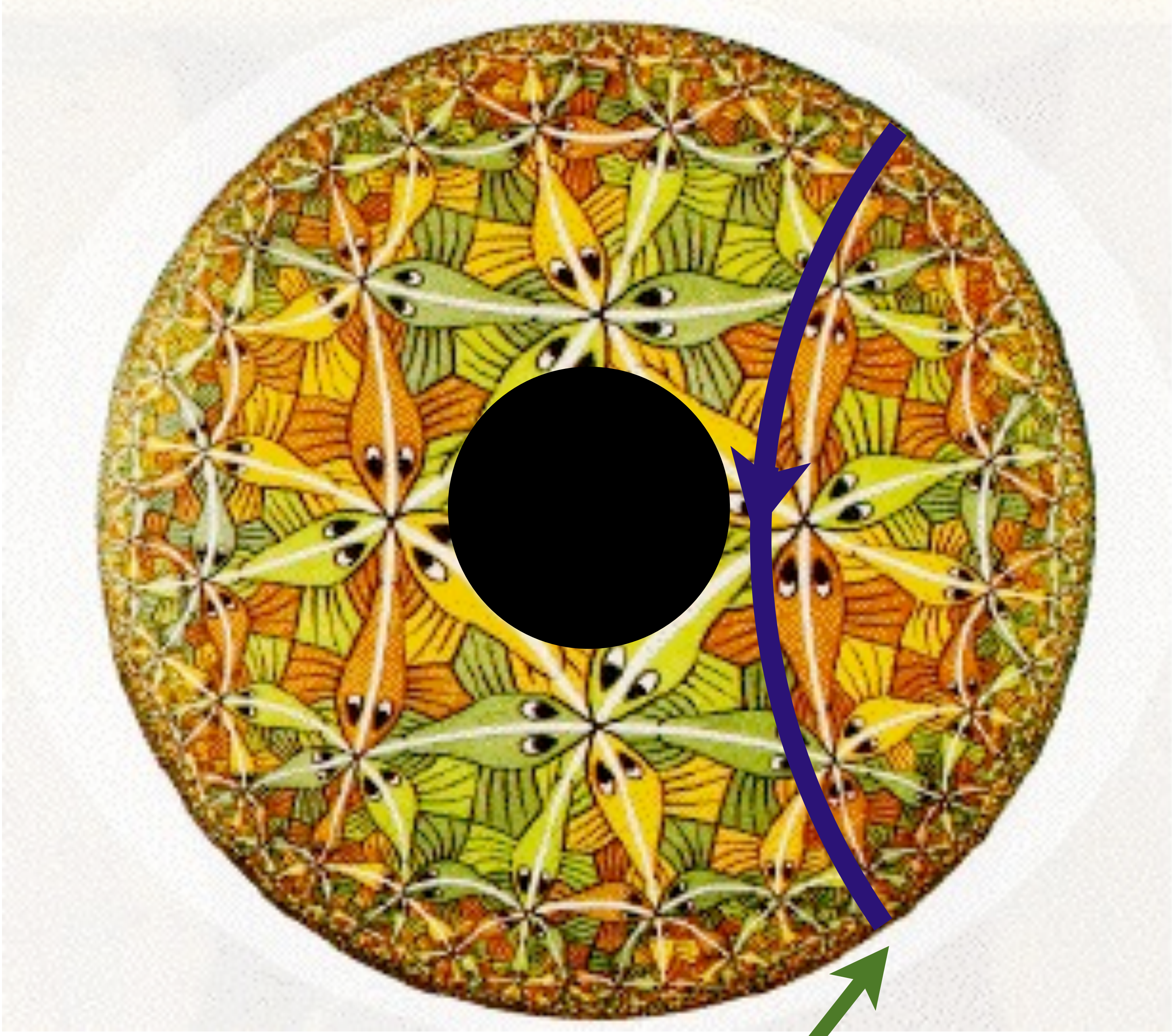




Examine free energy and Green's function of a probe particle

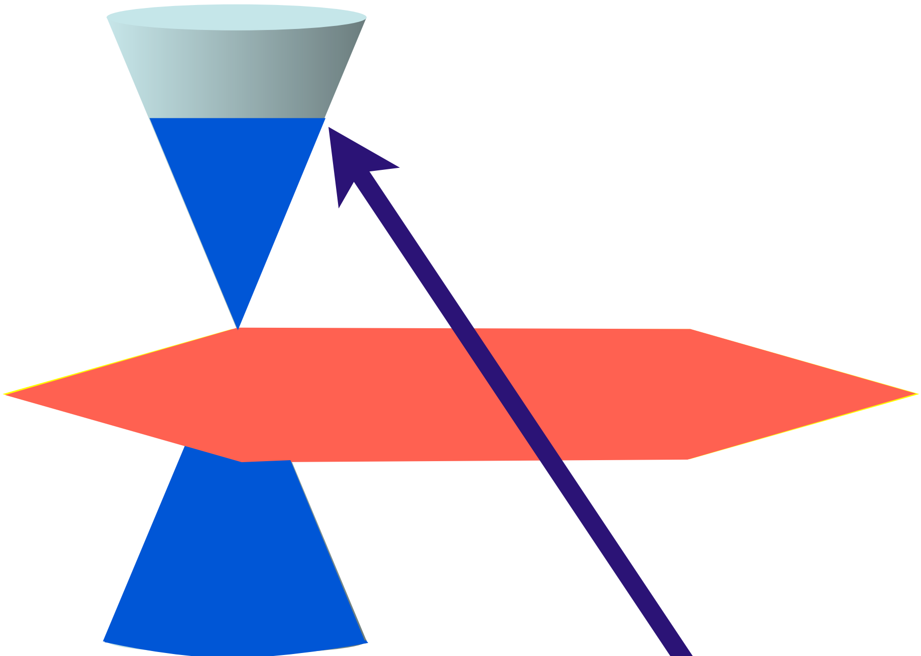
T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694
F. Denef, S. Hartnoll, and S. Sachdev, arXiv:0908.1788

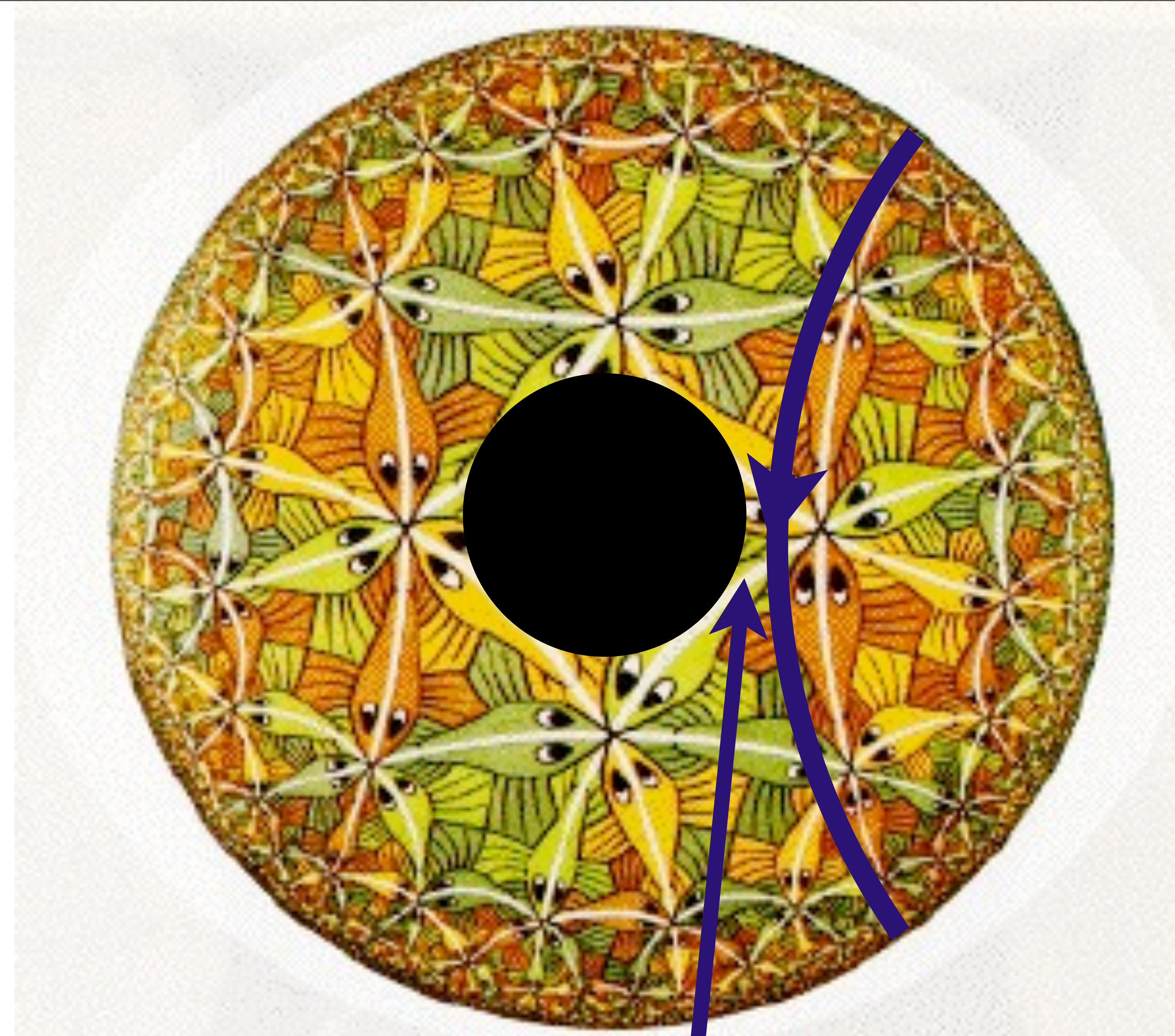




Short time behavior depends upon conformal AdS_4 geometry near boundary

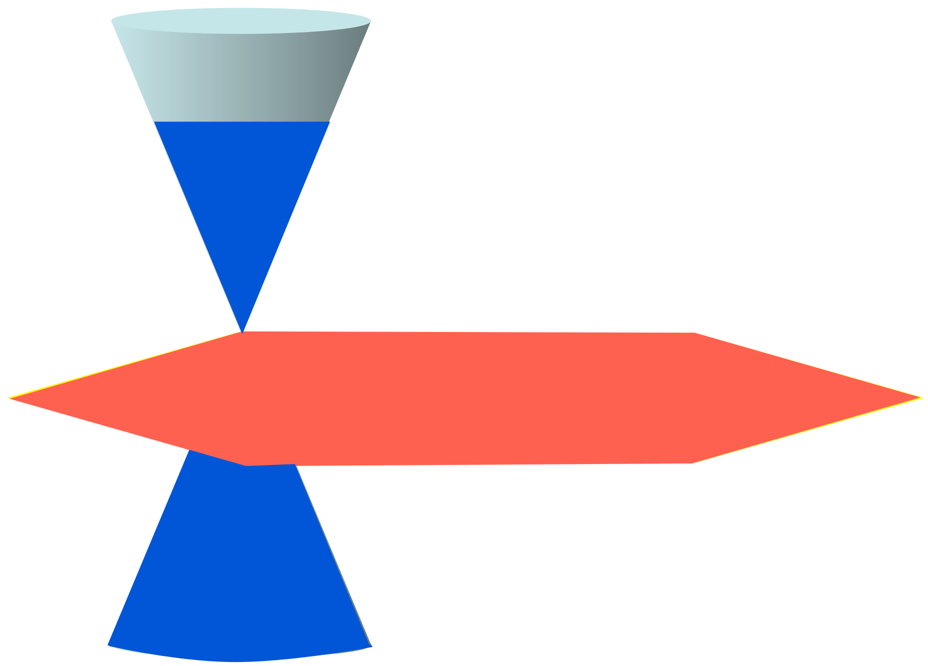
T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694
F. Denef, S. Hartnoll, and S. Sachdev, arXiv:0908.1788

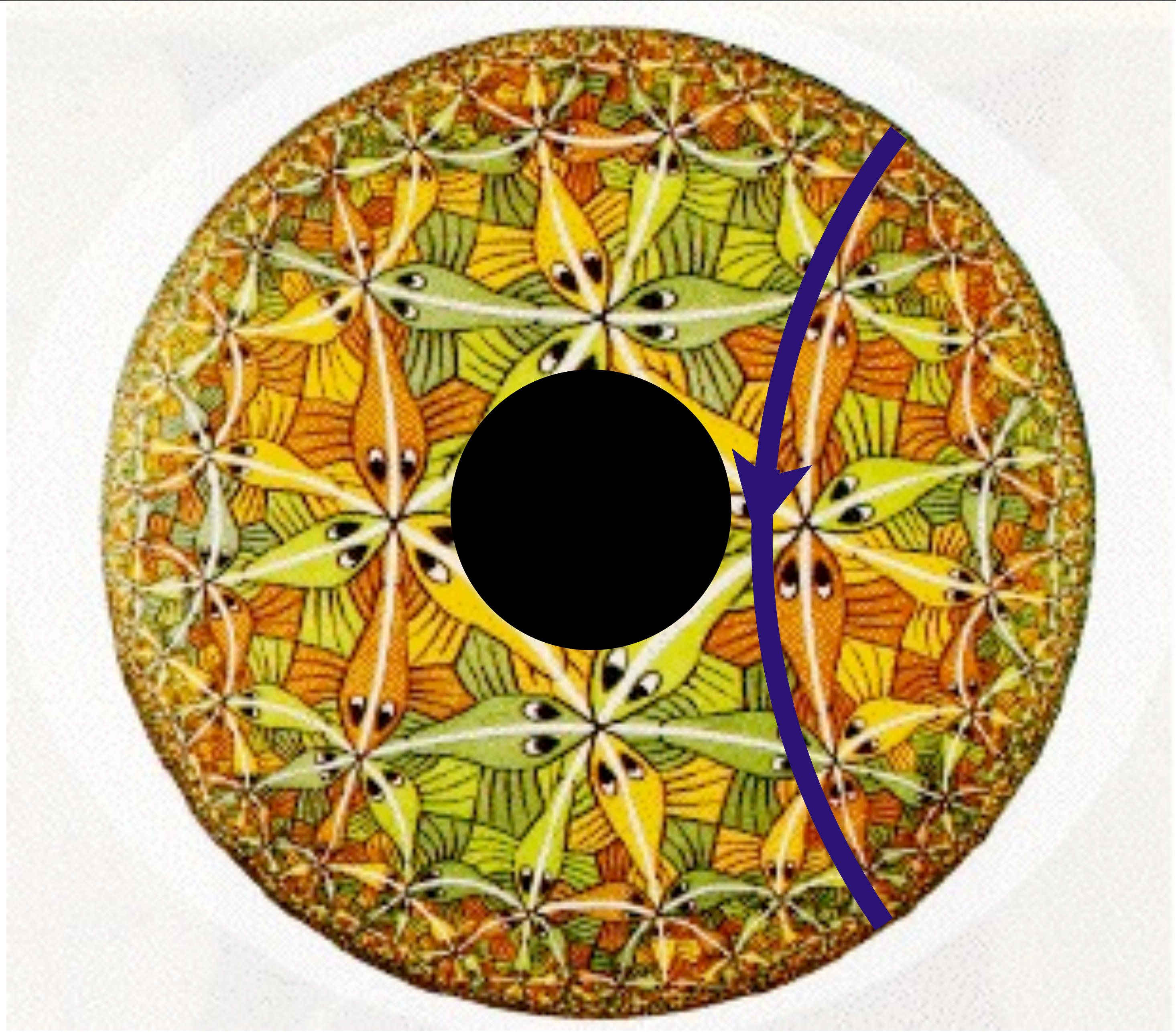




Long time behavior depends upon near-horizon geometry of black hole

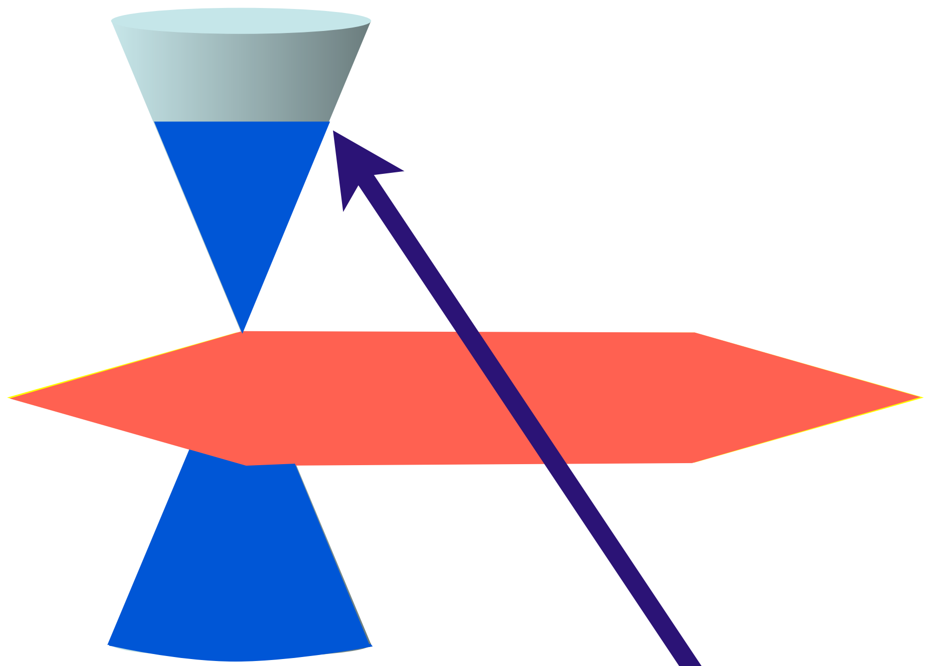
T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694
F. Denef, S. Hartnoll, and S. Sachdev, arXiv:0908.1788

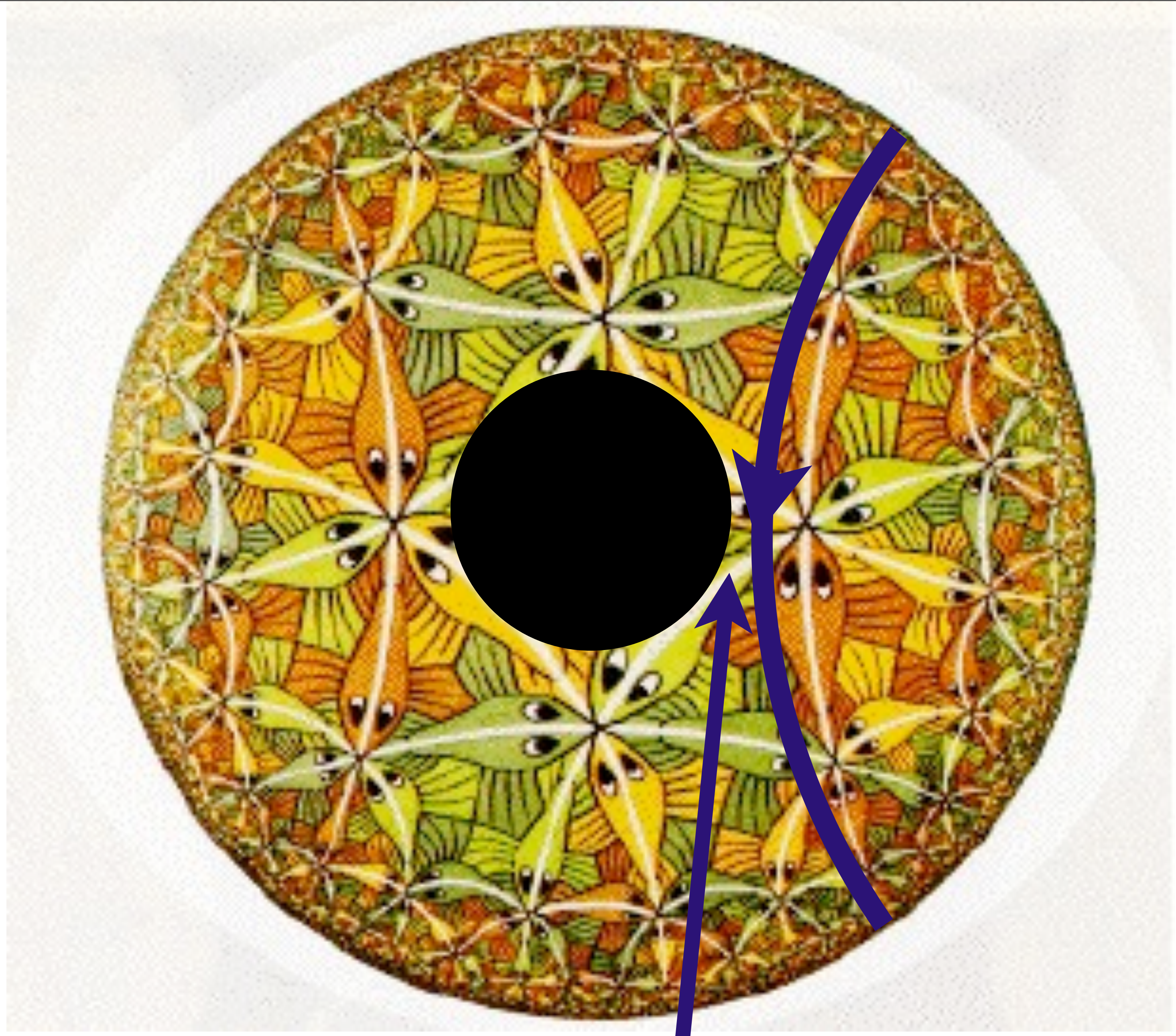




Radial direction of gravity theory is measure of energy scale in CFT

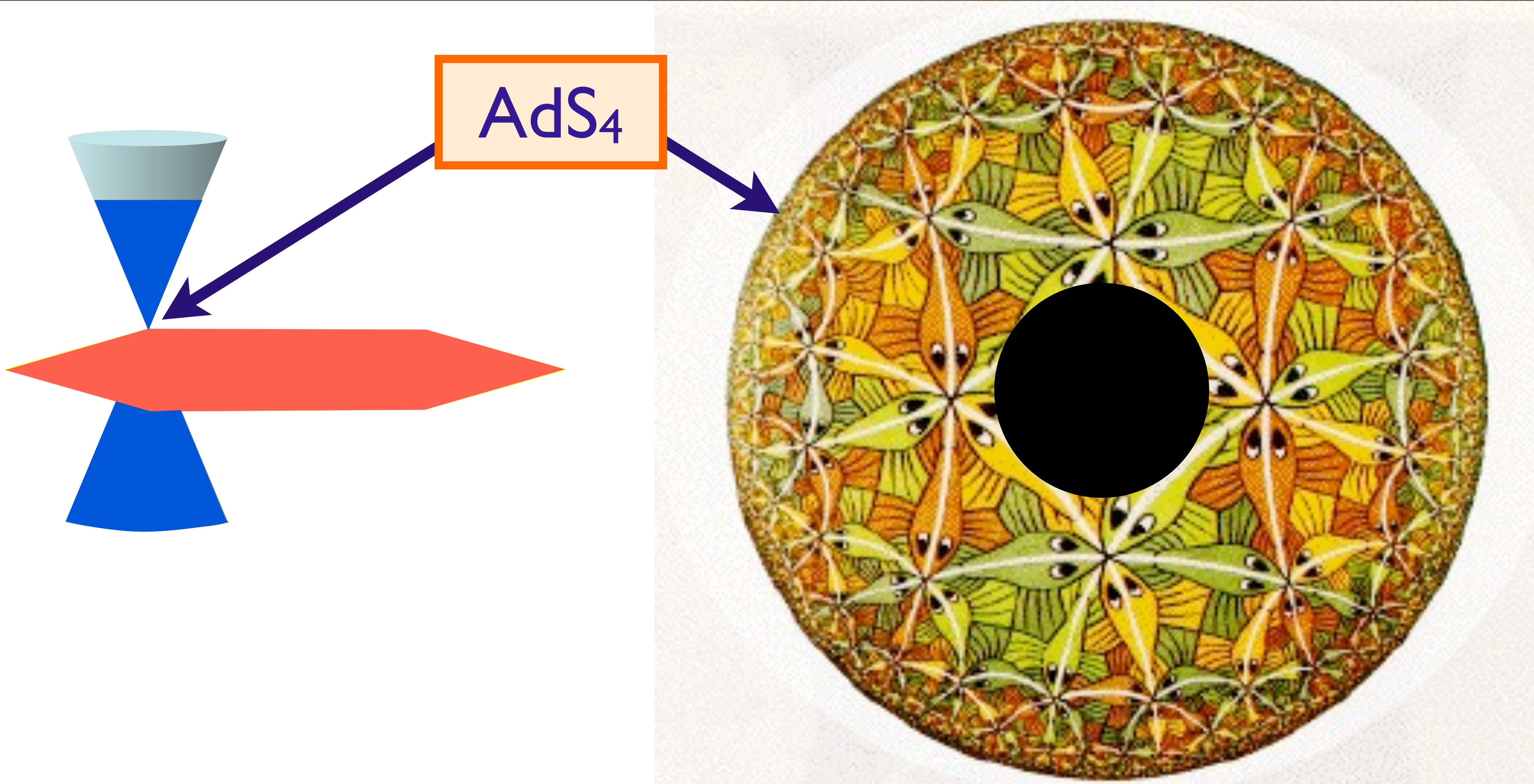
T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694
F. Denef, S. Hartnoll, and S. Sachdev, arXiv:0908.1788





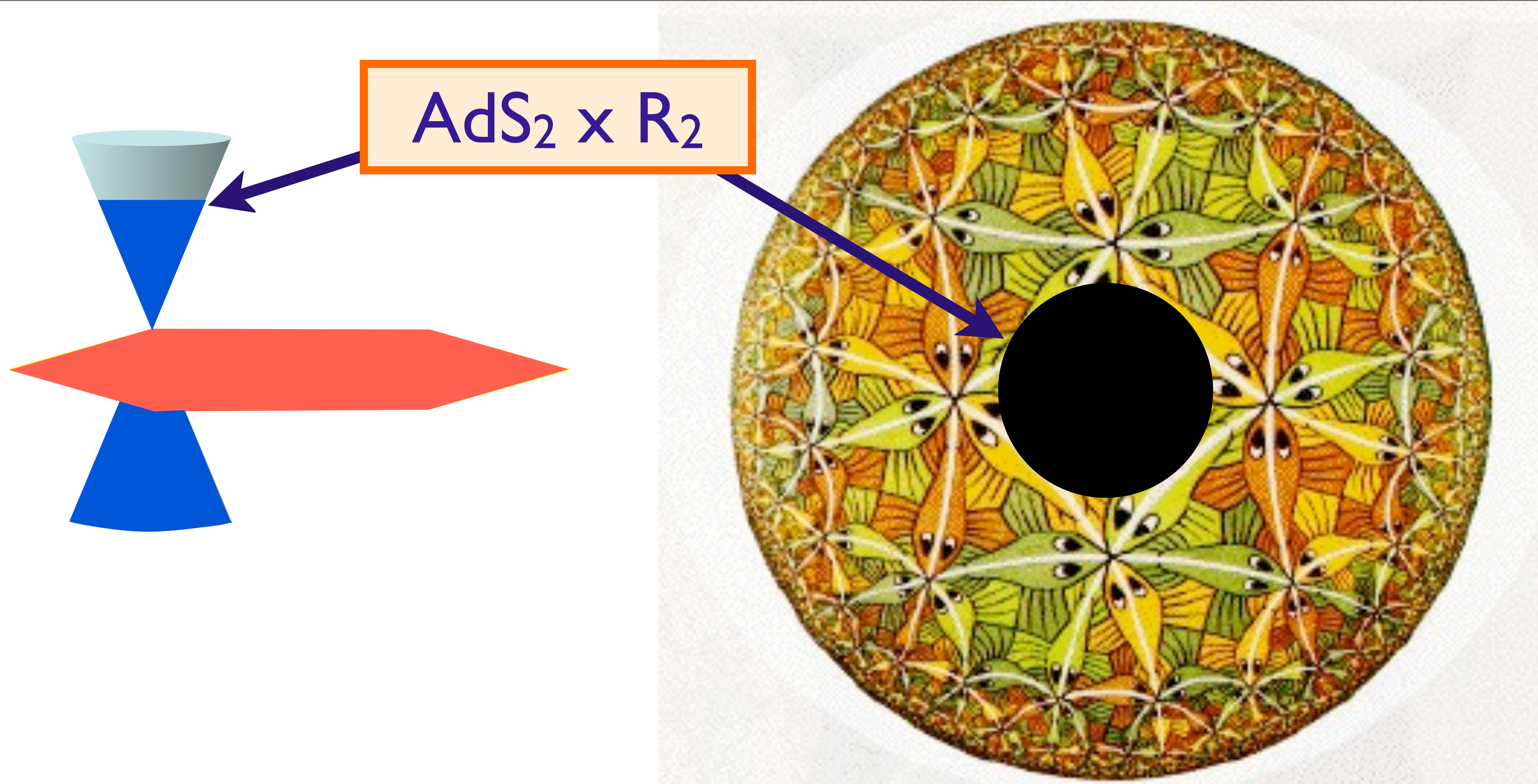
Infrared physics of Fermi surface is linked to the near horizon AdS_2 geometry of Reissner-Nordstrom black hole

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



Geometric interpretation of RG flow

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



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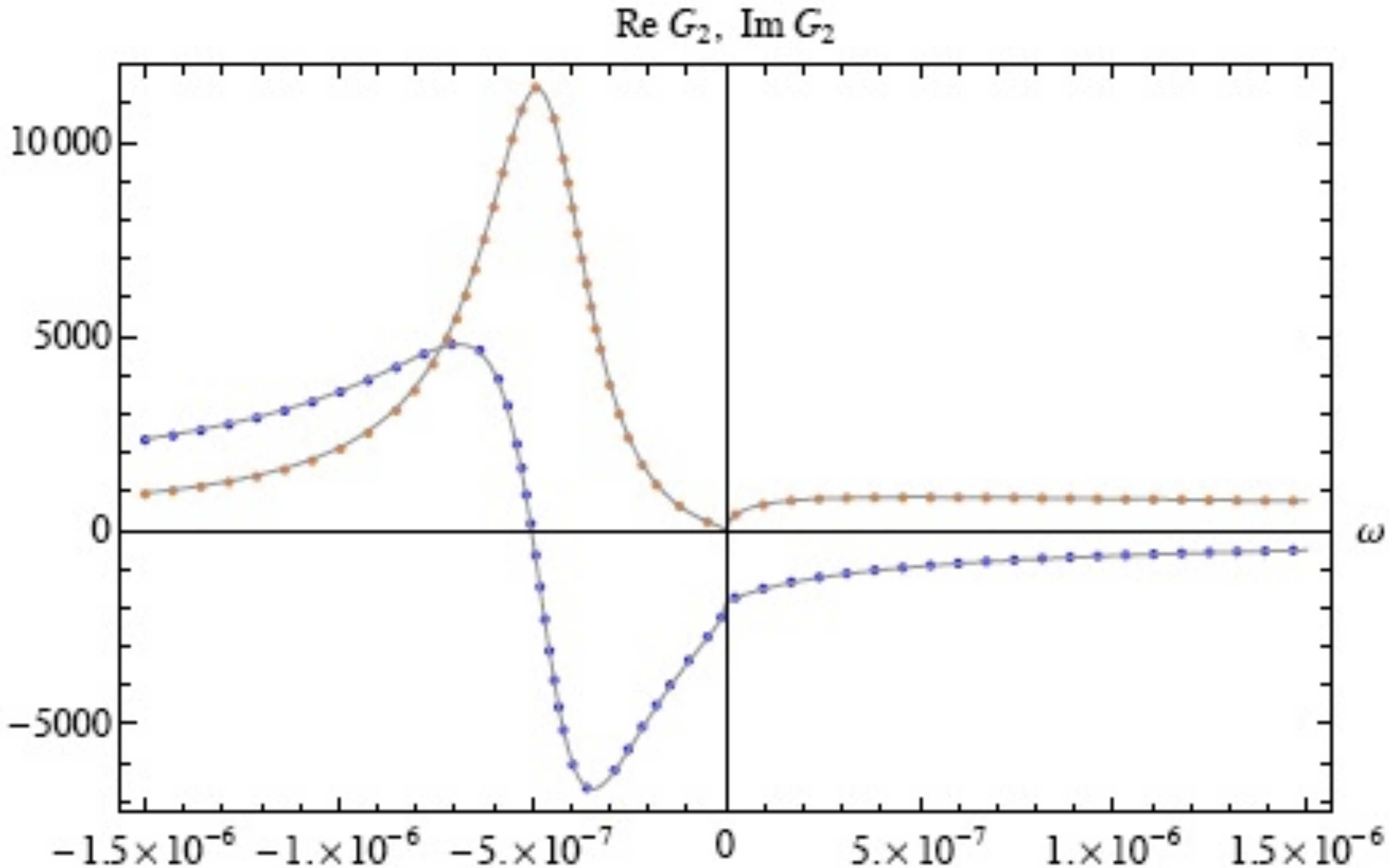
Green's function of a fermion

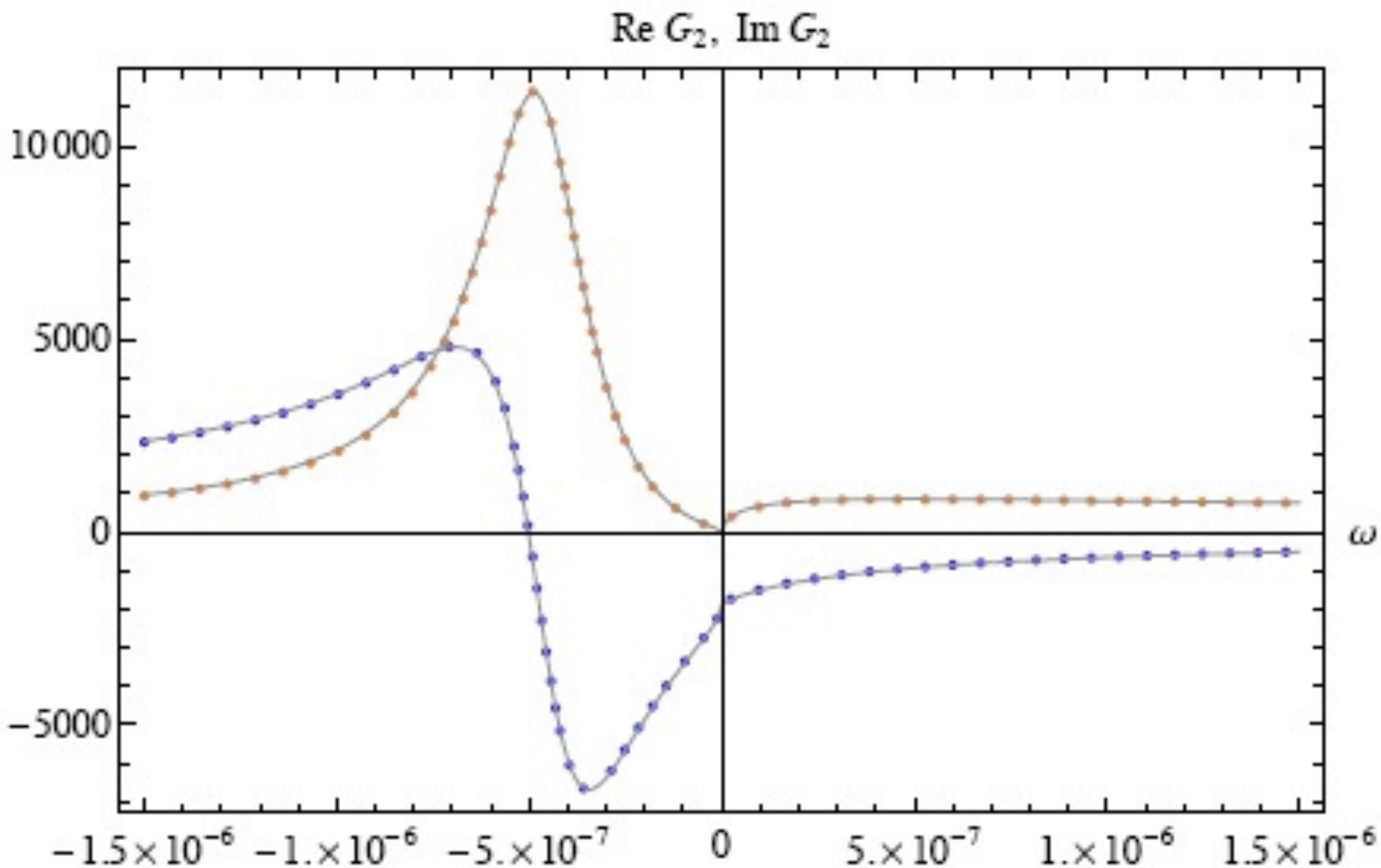


T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694

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

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

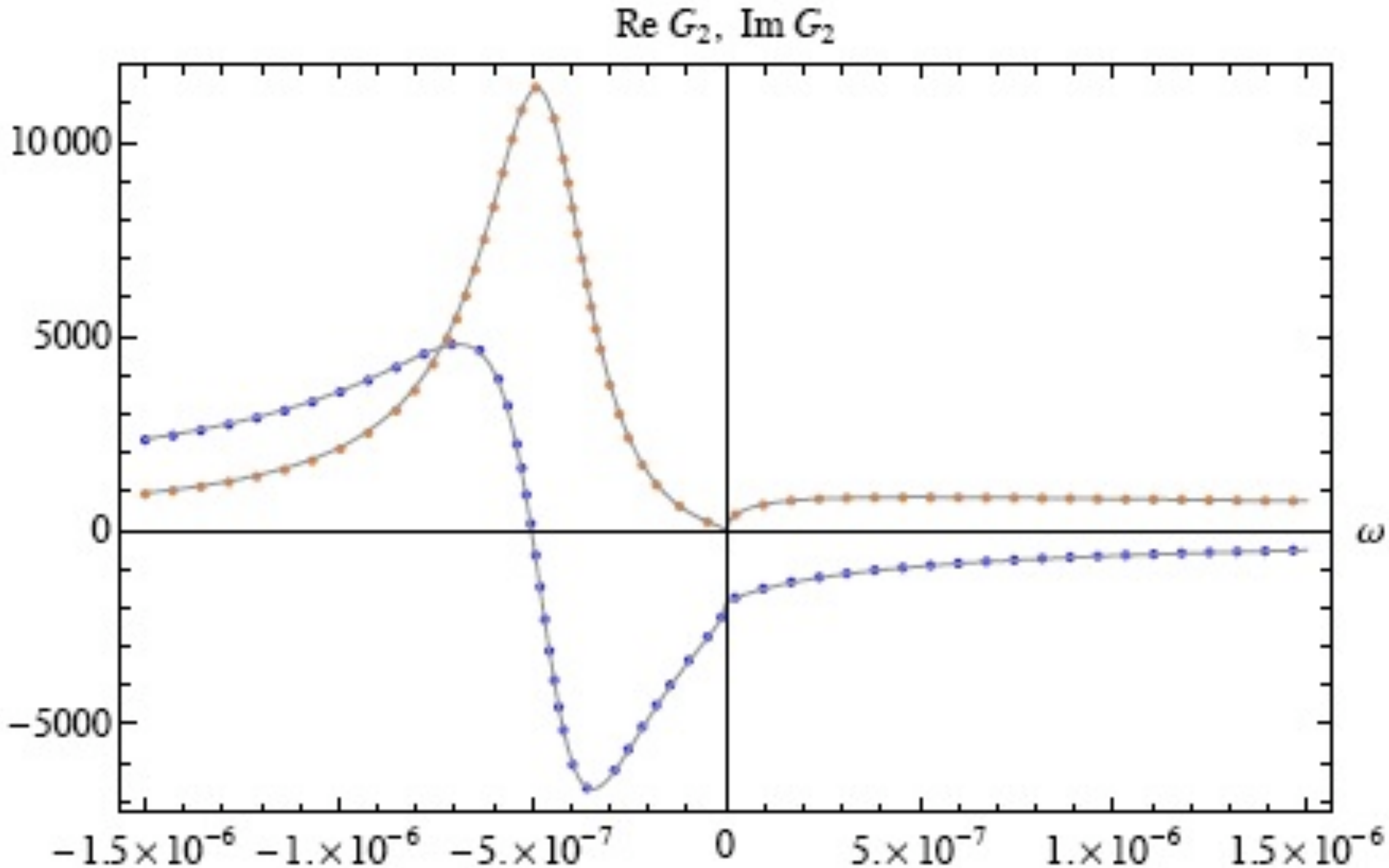


T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694

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

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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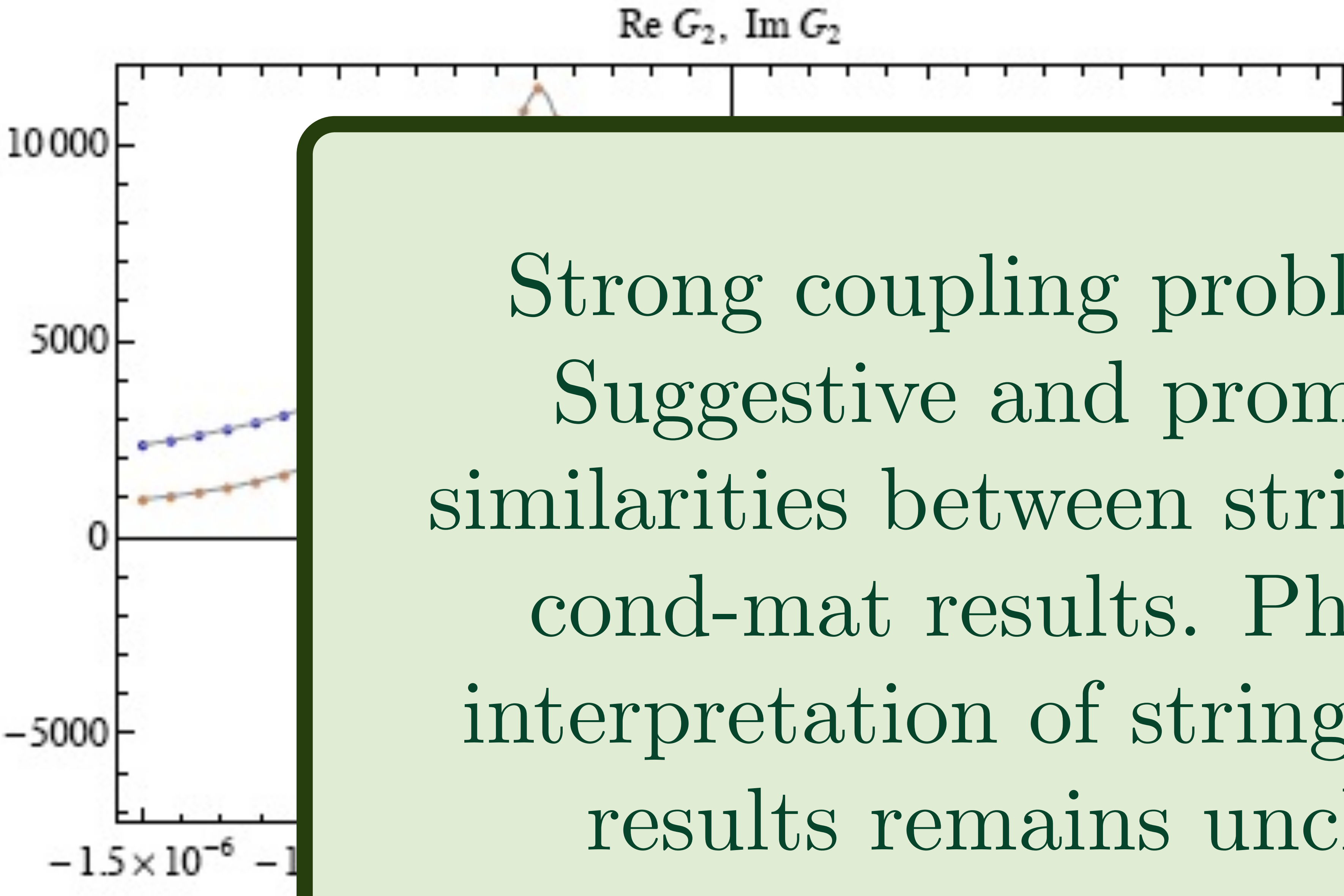

Strong coupling problem II: Suggestive and promising similarities between stringy and cond-mat results. Physical interpretation of string theory results remains unclear.

H. Liu,
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$$\frac{\quad}{\omega - v_F(k-k_F) - i\omega^{\theta(k)}}$$

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