Quantum Criticality and Black Holes

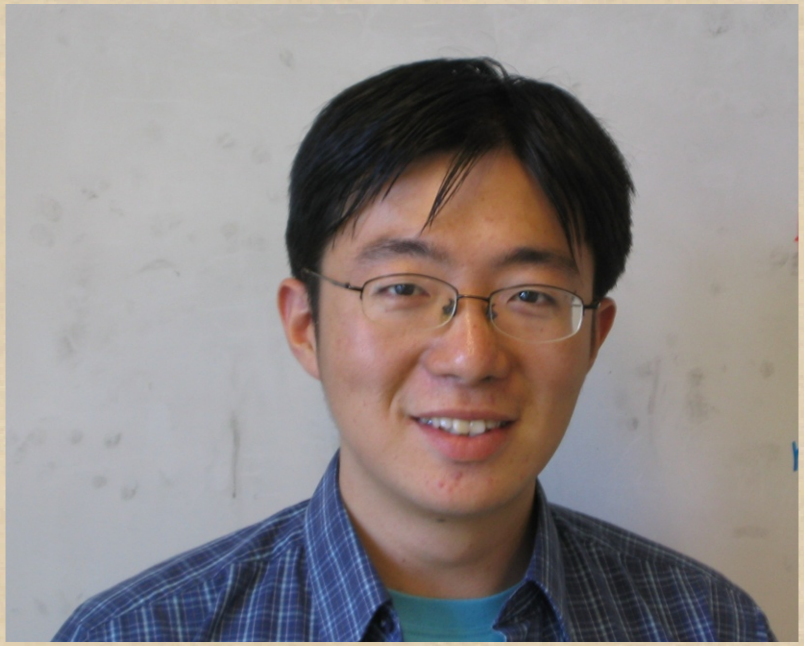
Talk online: sachdev.physics.harvard.edu

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

Three foci of modern physics

Quantum phase transitions

Three foci of modern physics

Quantum phase transitions

Many QPTs of correlated electrons in 2+1 dimensions are described by conformal field theories (CFTs)

Three foci of modern physics

Quantum phase transitions

Black holes

Three foci of modern physics

Quantum phase transitions

Black holes

Bekenstein and Hawking originated the quantum theory, which has found fruition in string theory

Three foci of modern physics

Quantum phase transitions

Hydrodynamics

Black holes

Three foci of modern physics

Quantum phase transitions

Hydrodynamics

Universal description of fluids based upon conservation laws and positivity of entropy production

Black holes

Three foci of modern physics

Quantum phase transitions

Hydrodynamics

Black holes

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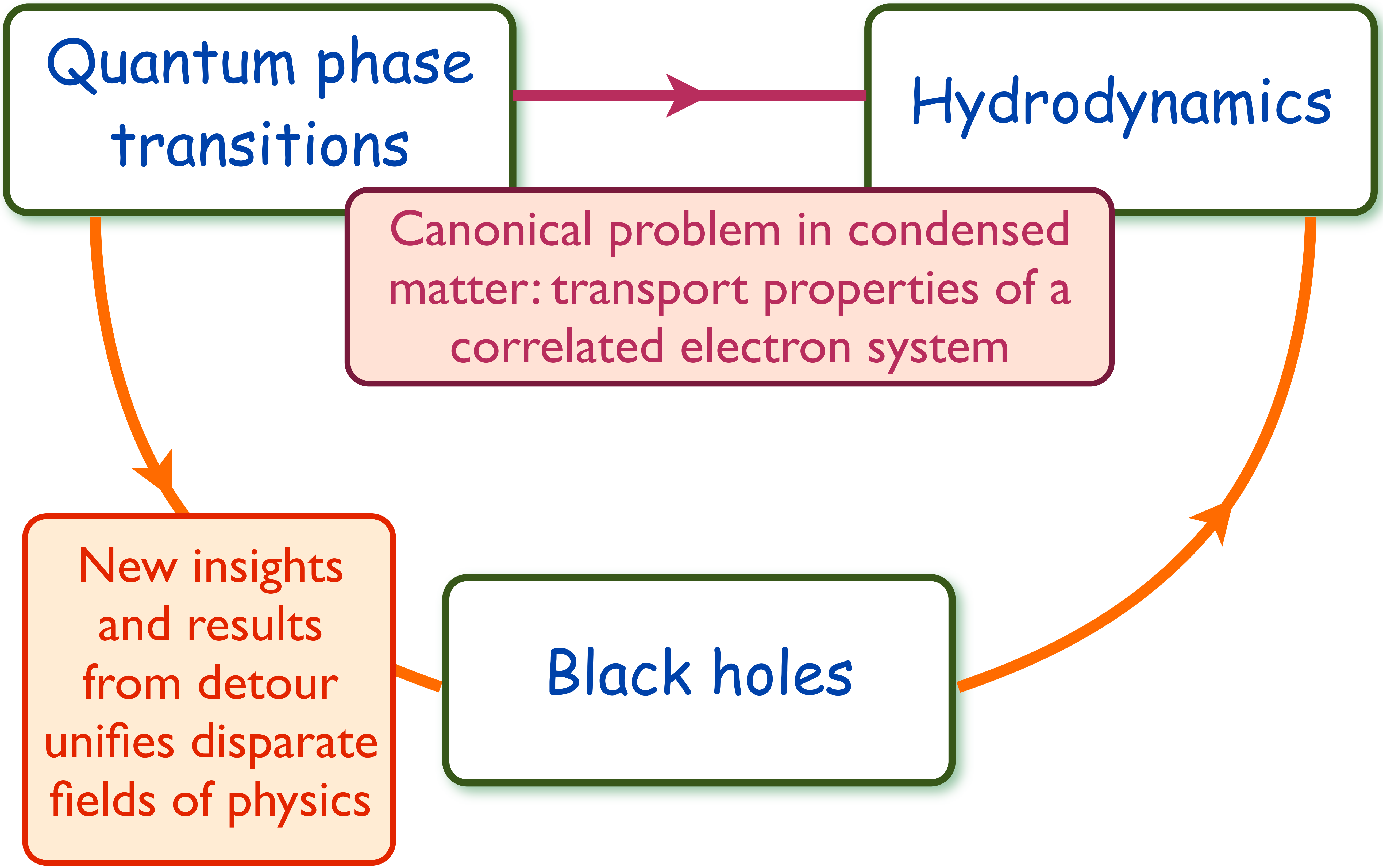
Quantum phase transitions

Hydrodynamics

Canonical problem in condensed matter: transport properties of a correlated electron system

Black holes

Three foci of modern physics



Three foci of modern physics

Quantum phase transitions

Hydrodynamics

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Quantum phase transitions

Many QPTs of correlated electrons in 2+1 dimensions are described by conformal field theories (CFTs)

Hydrodynamics

Black holes

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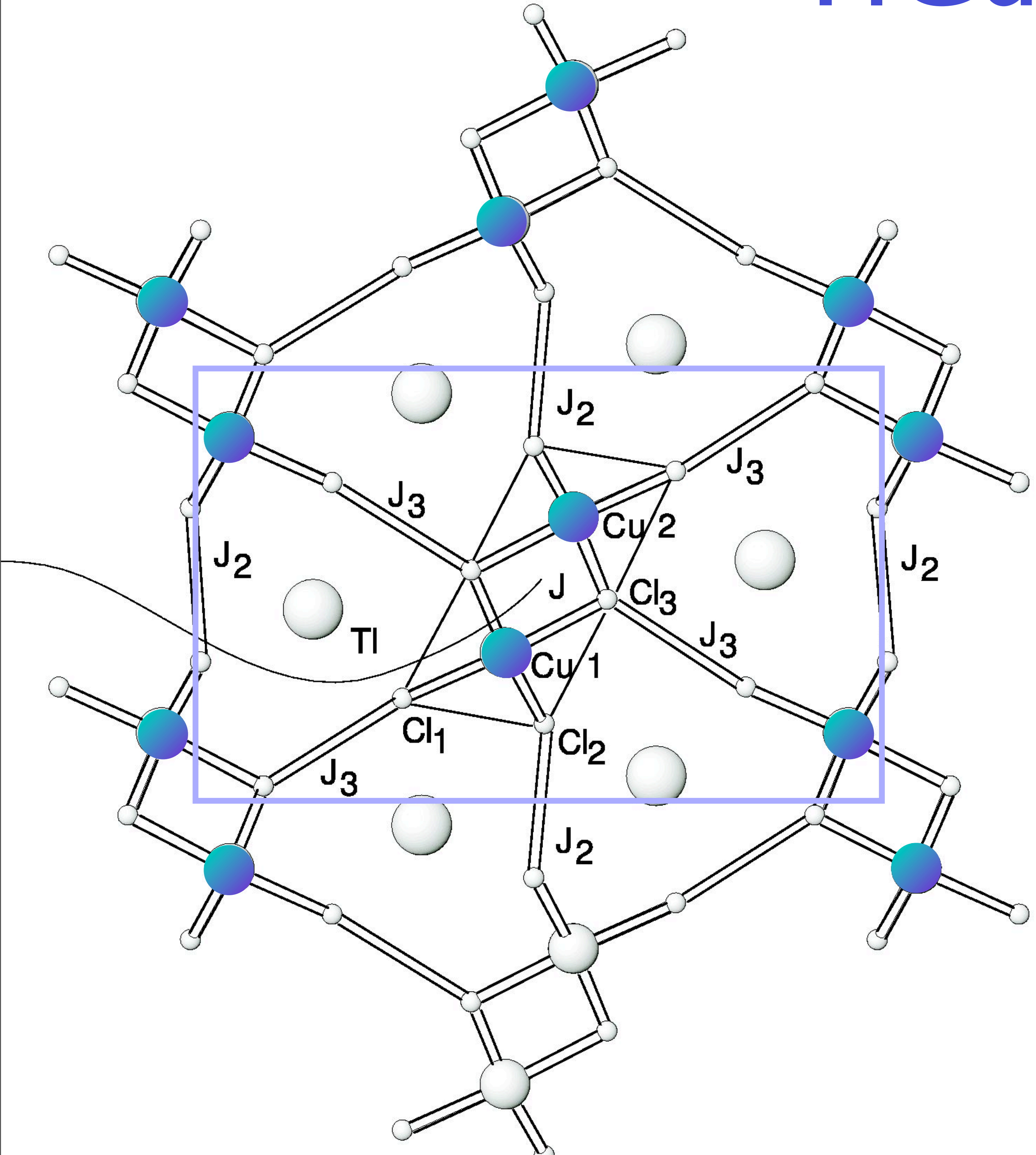
Quantum phase transitions

Many QPTs of correlated electrons in 2+1 dimensions are described by conformal field theories (CFTs)

Hydrodynamics

Black holes

$TlCuCl_3$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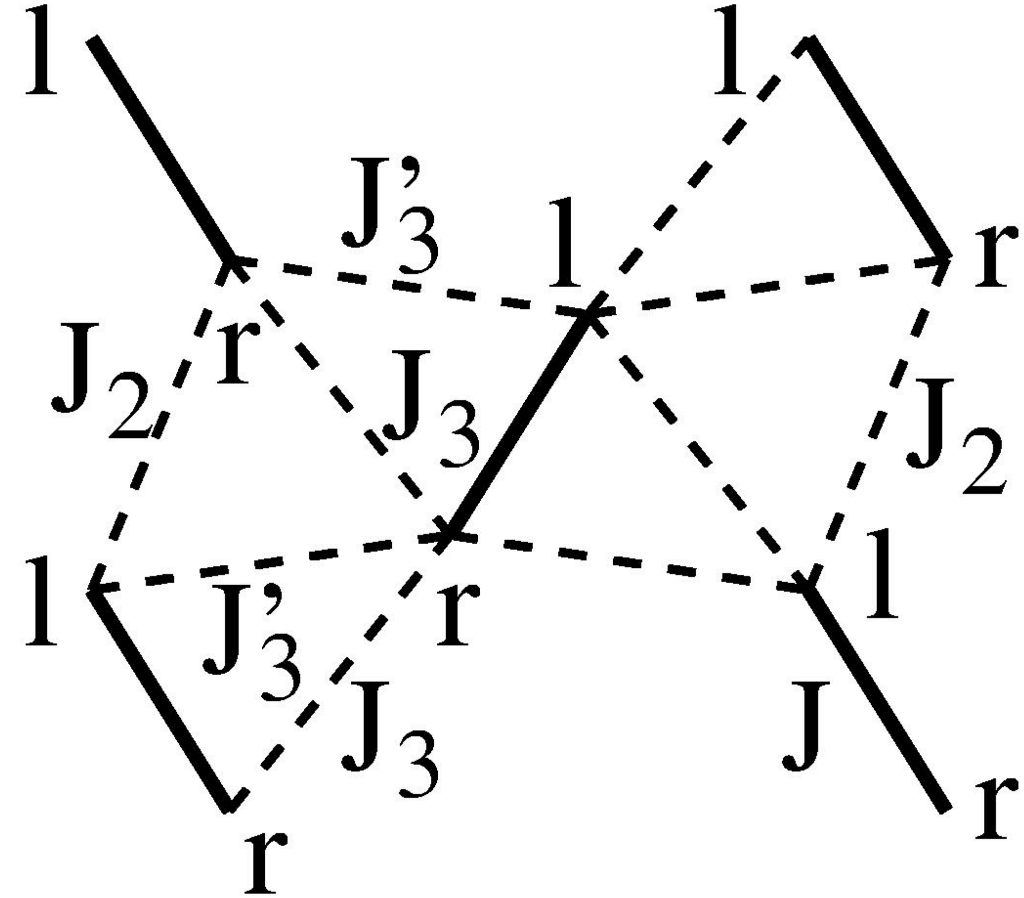
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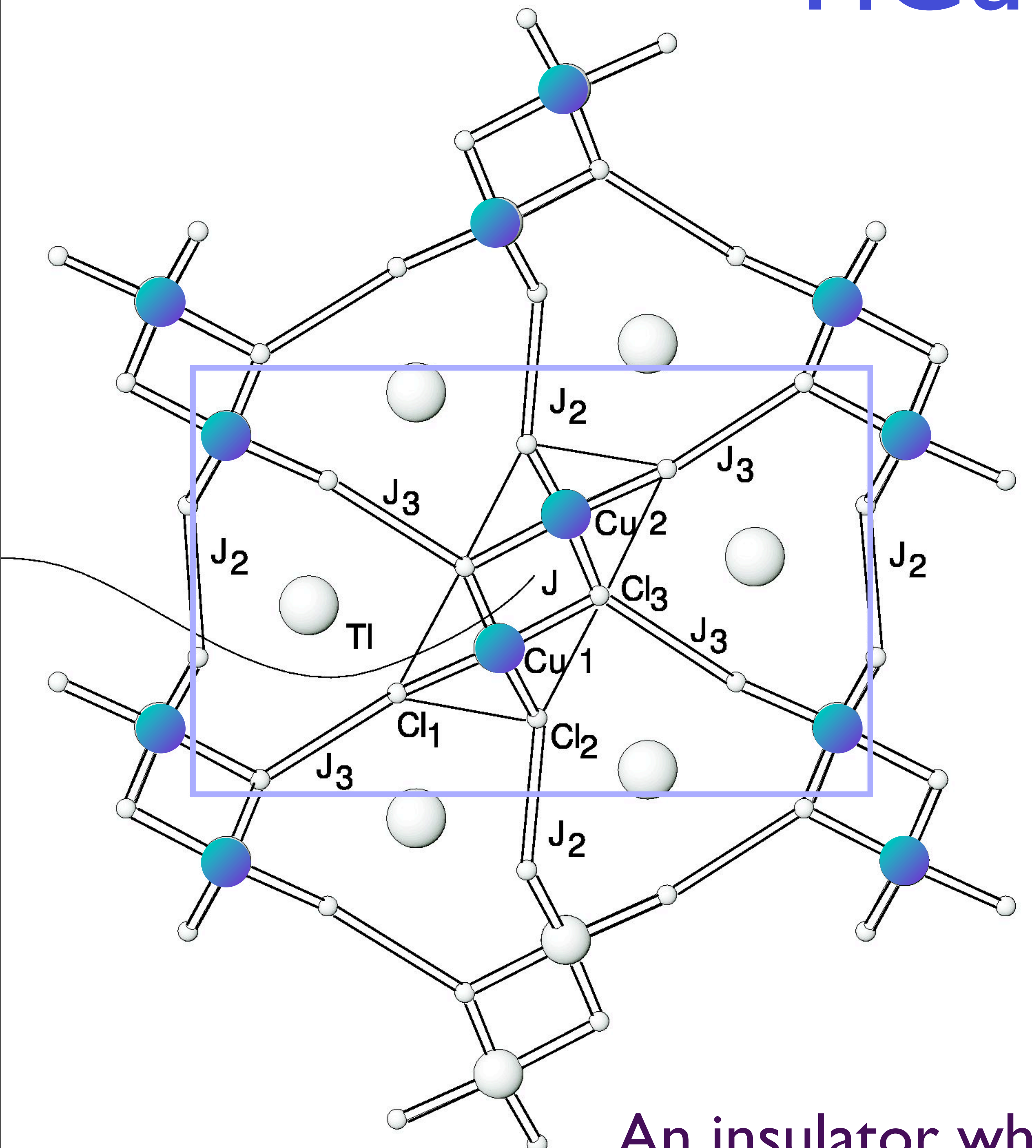
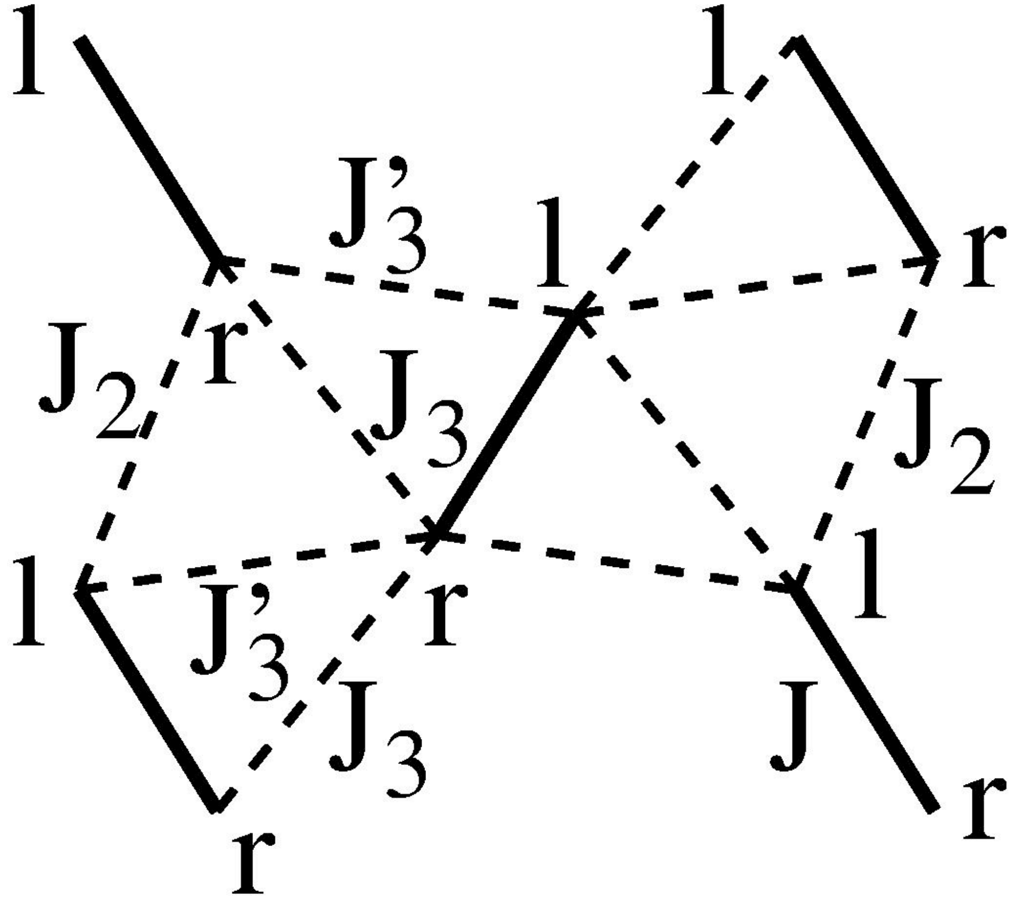
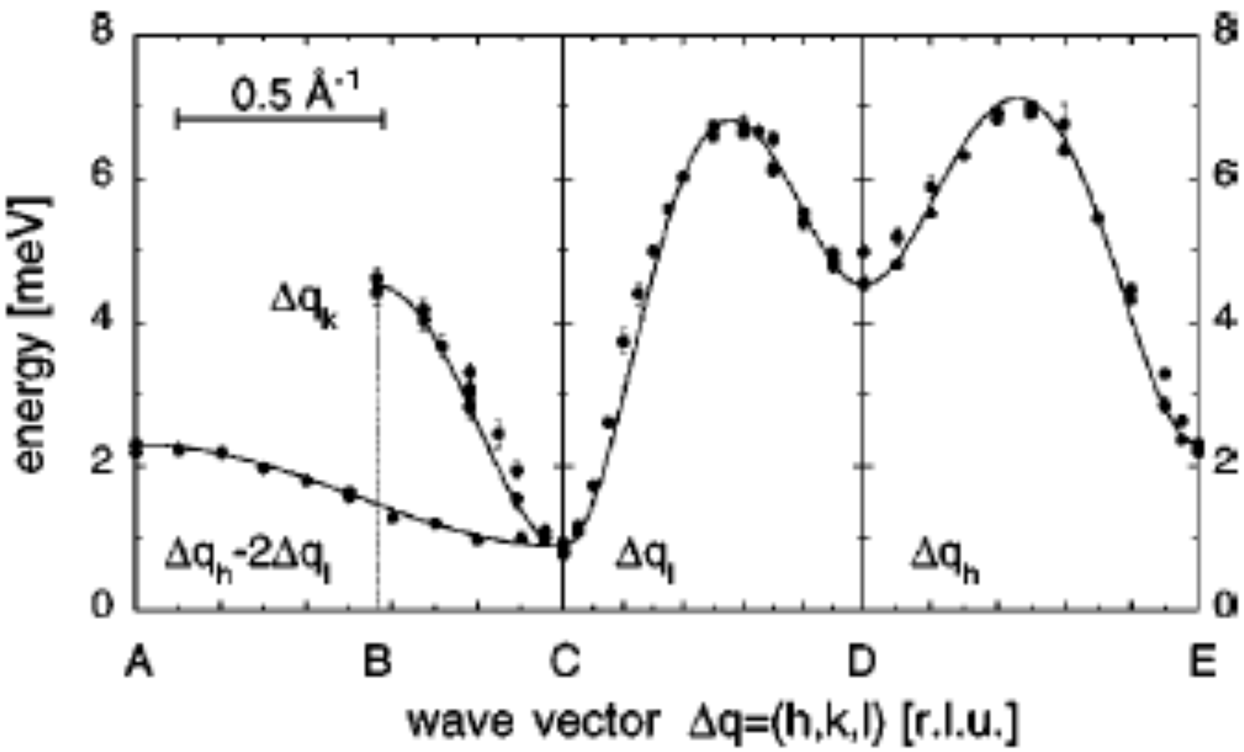
$TlCuCl_3$





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

$TlCuCl_3$ at ambient pressure



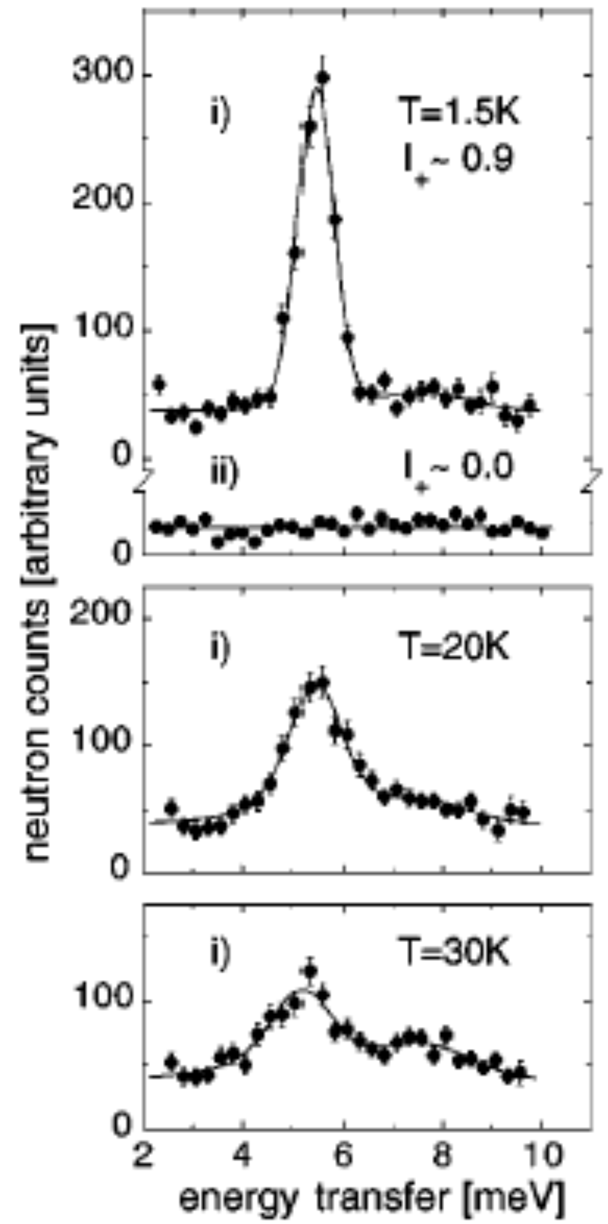
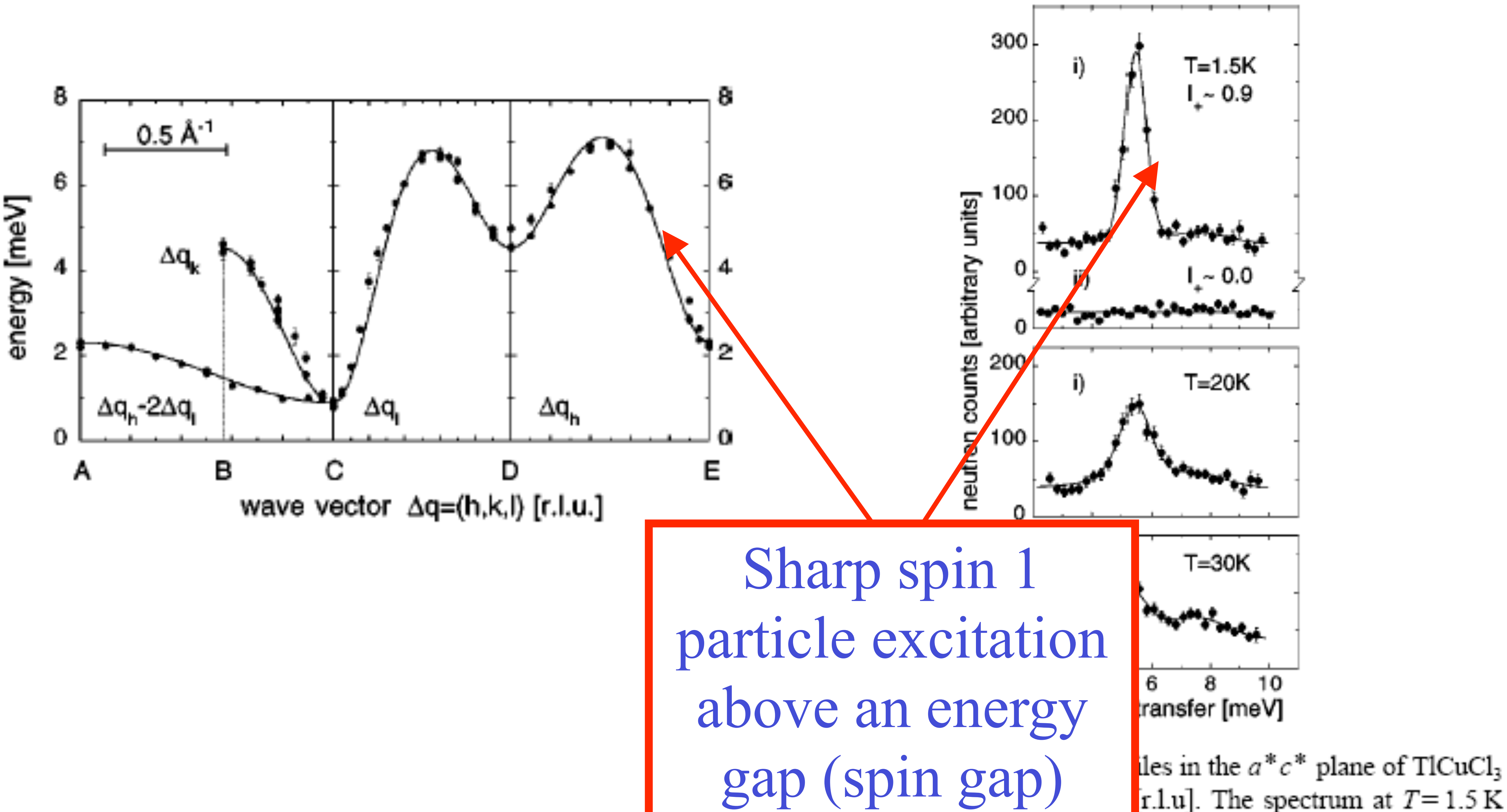


FIG. 1. Measured neutron profiles in the a^*c^* plane of $TlCuCl_3$ for $i=(1.35,0,0)$, $ii=(0,0,3.15)$ [r.l.u]. The spectrum at $T=1.5$ K

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

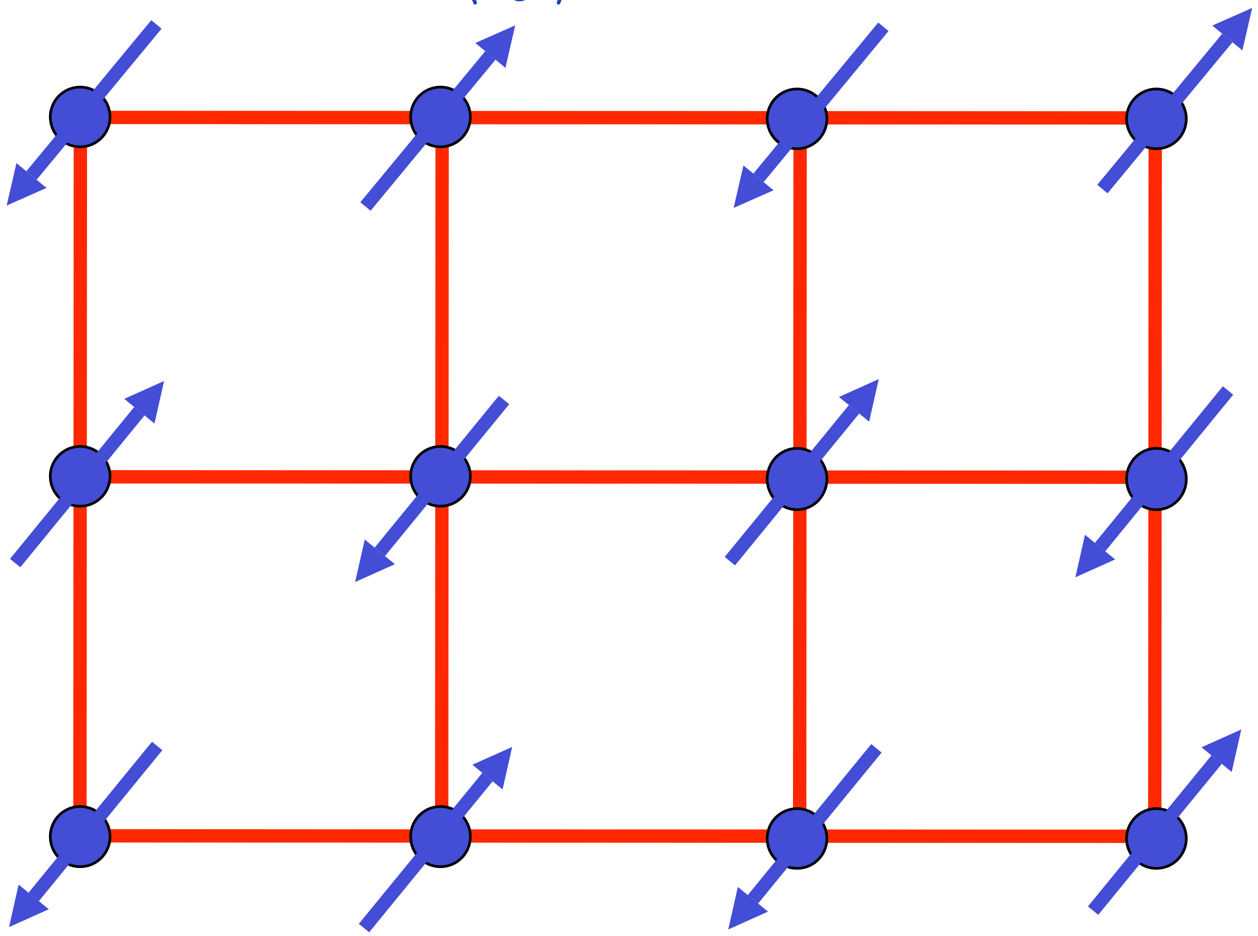


Sharp spin 1 particle excitation above an energy gap (spin gap)

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

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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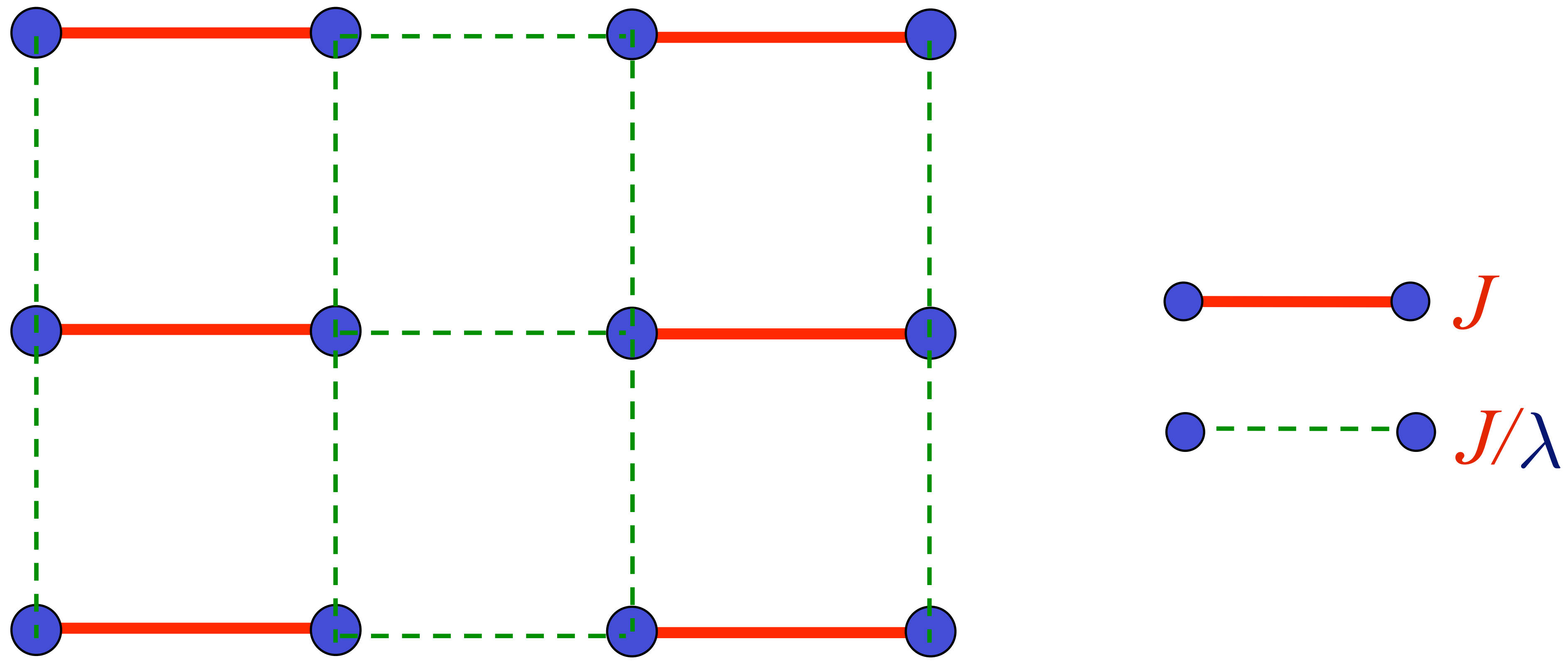
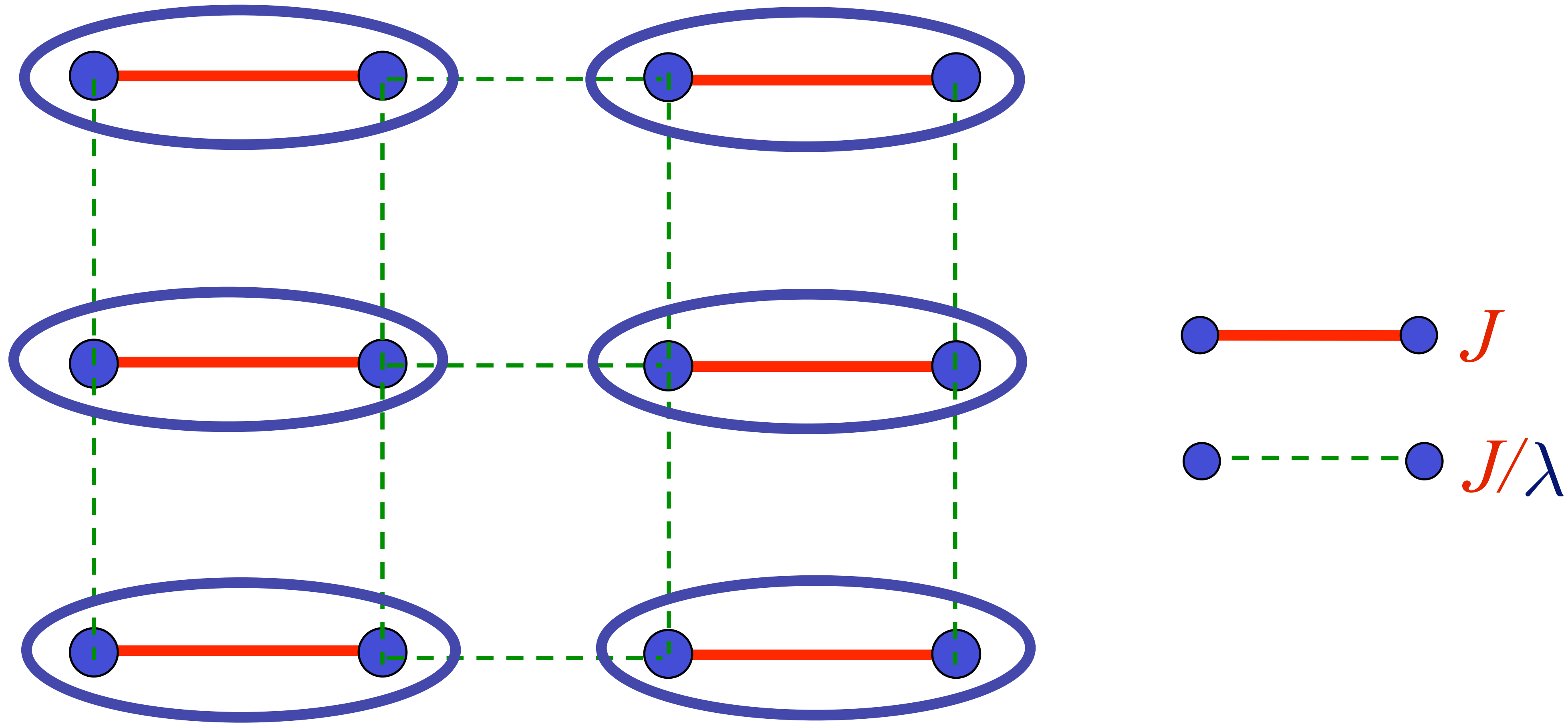


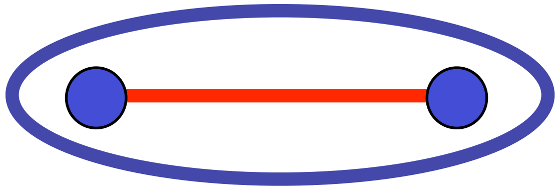
Weaken some bonds to induce spin entanglement in a new quantum phase

Square lattice antiferromagnet

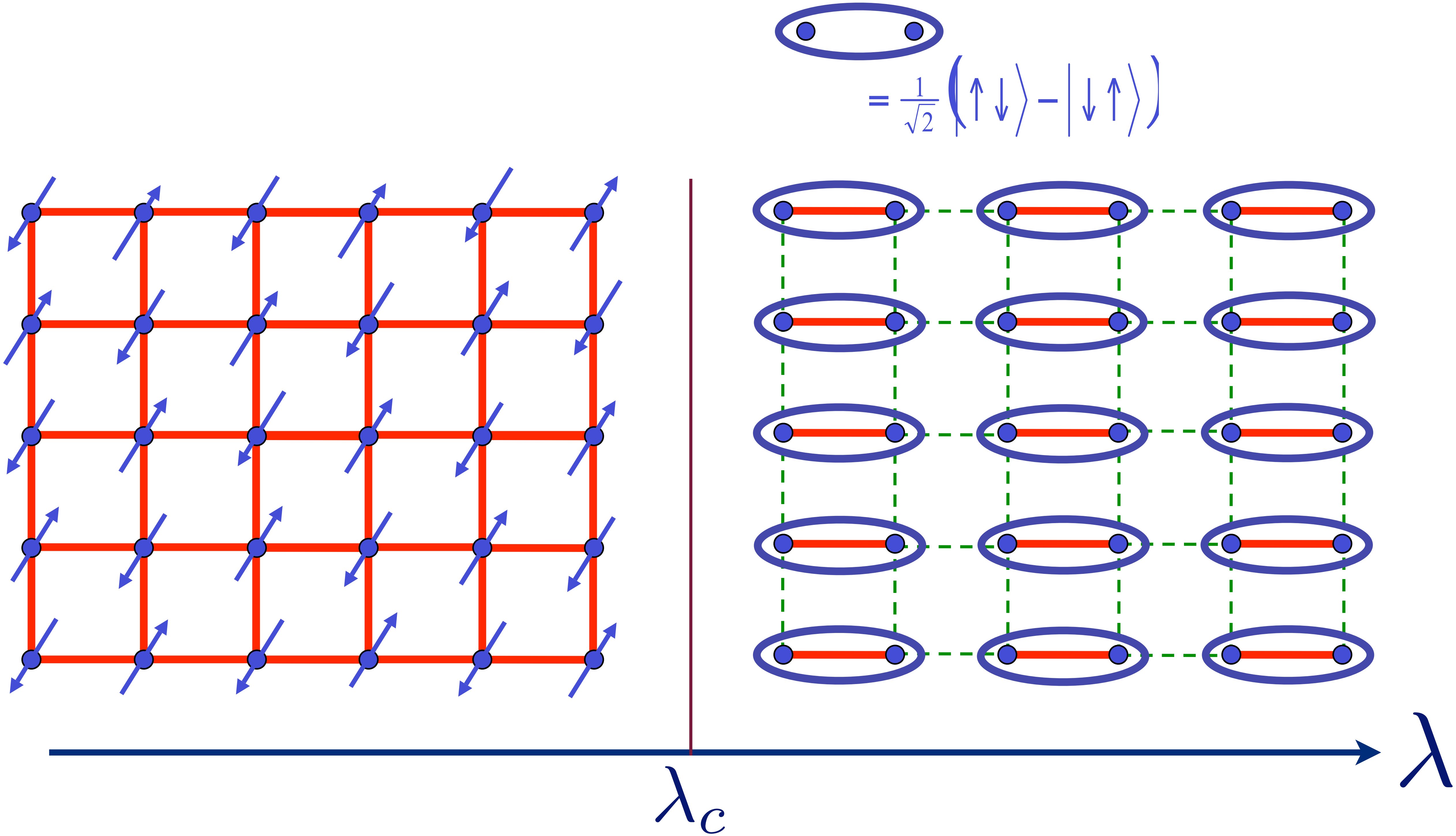
$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



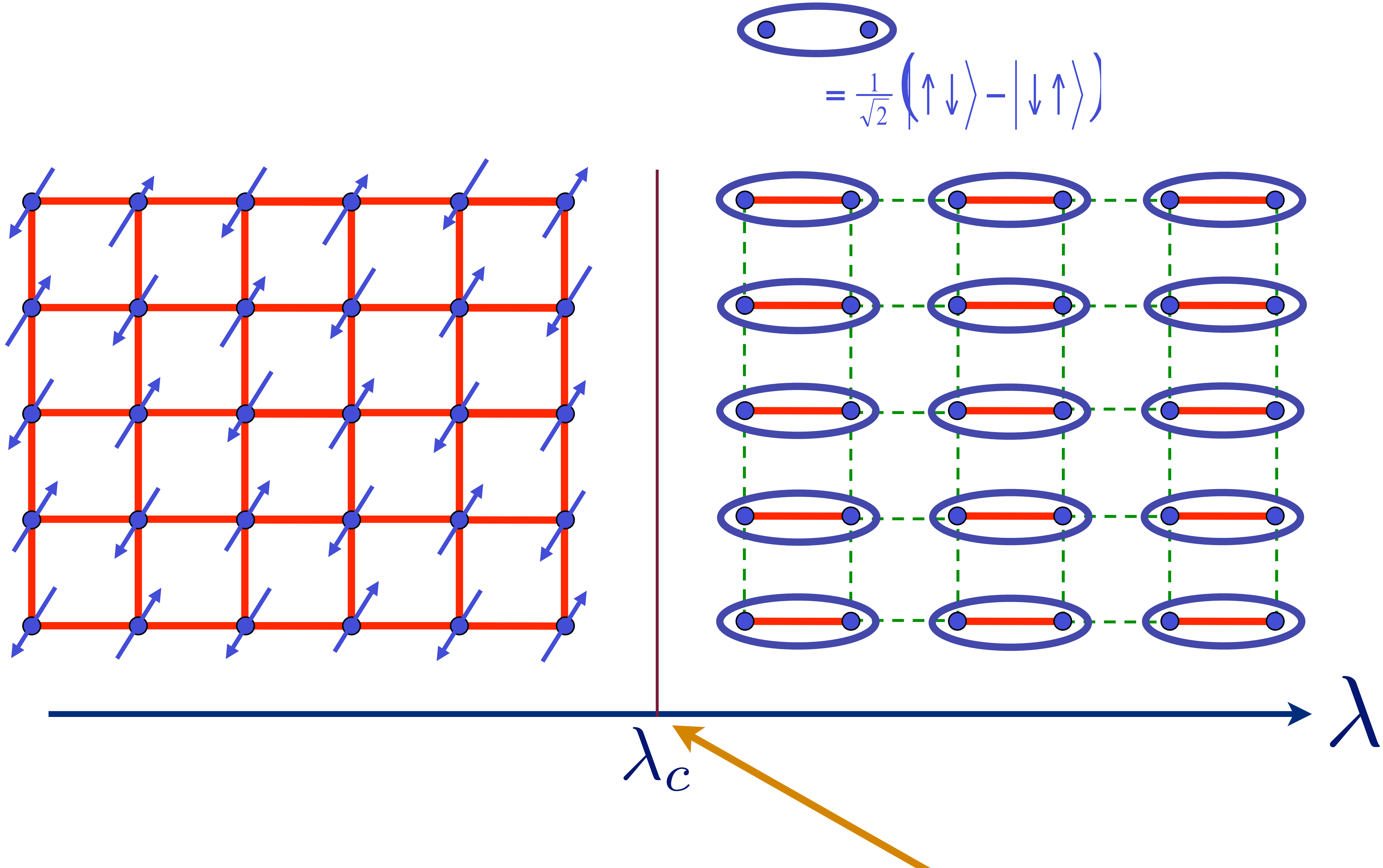
Ground state is a "quantum paramagnet" with spins locked in valence bond singlets



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

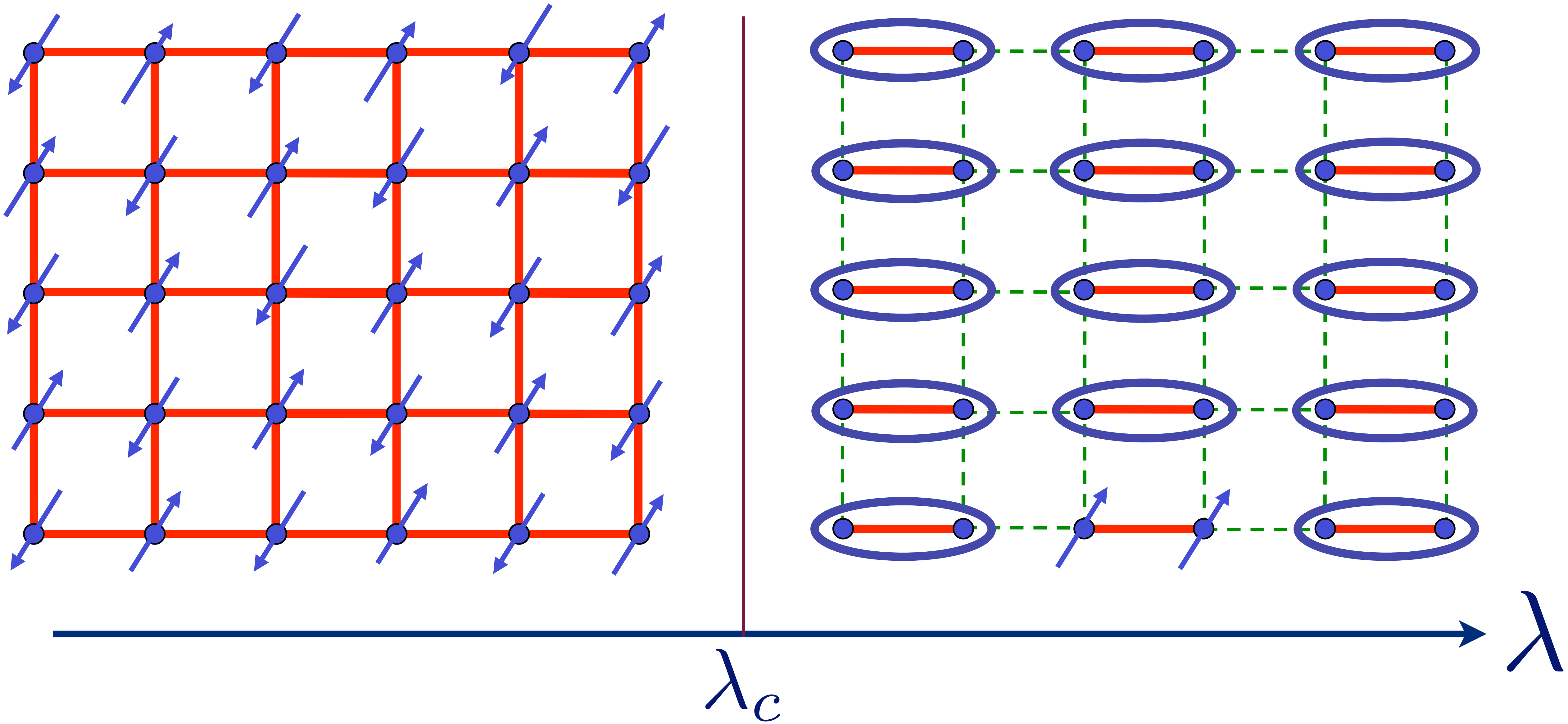


Pressure in $TlCuCl_3$

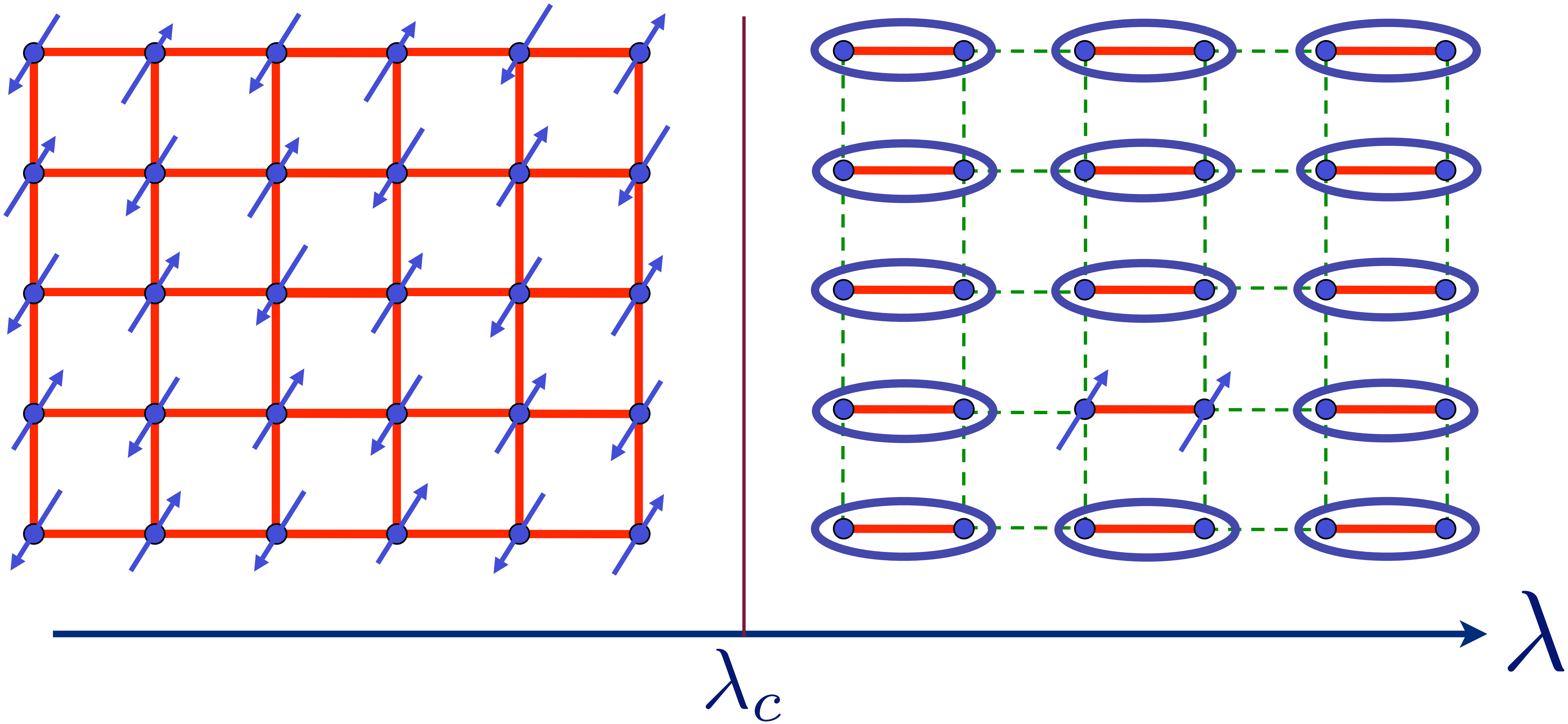


Quantum critical point with non-local entanglement in spin wavefunction

Excitation spectrum in the paramagnetic phase



Excitation spectrum in the paramagnetic phase



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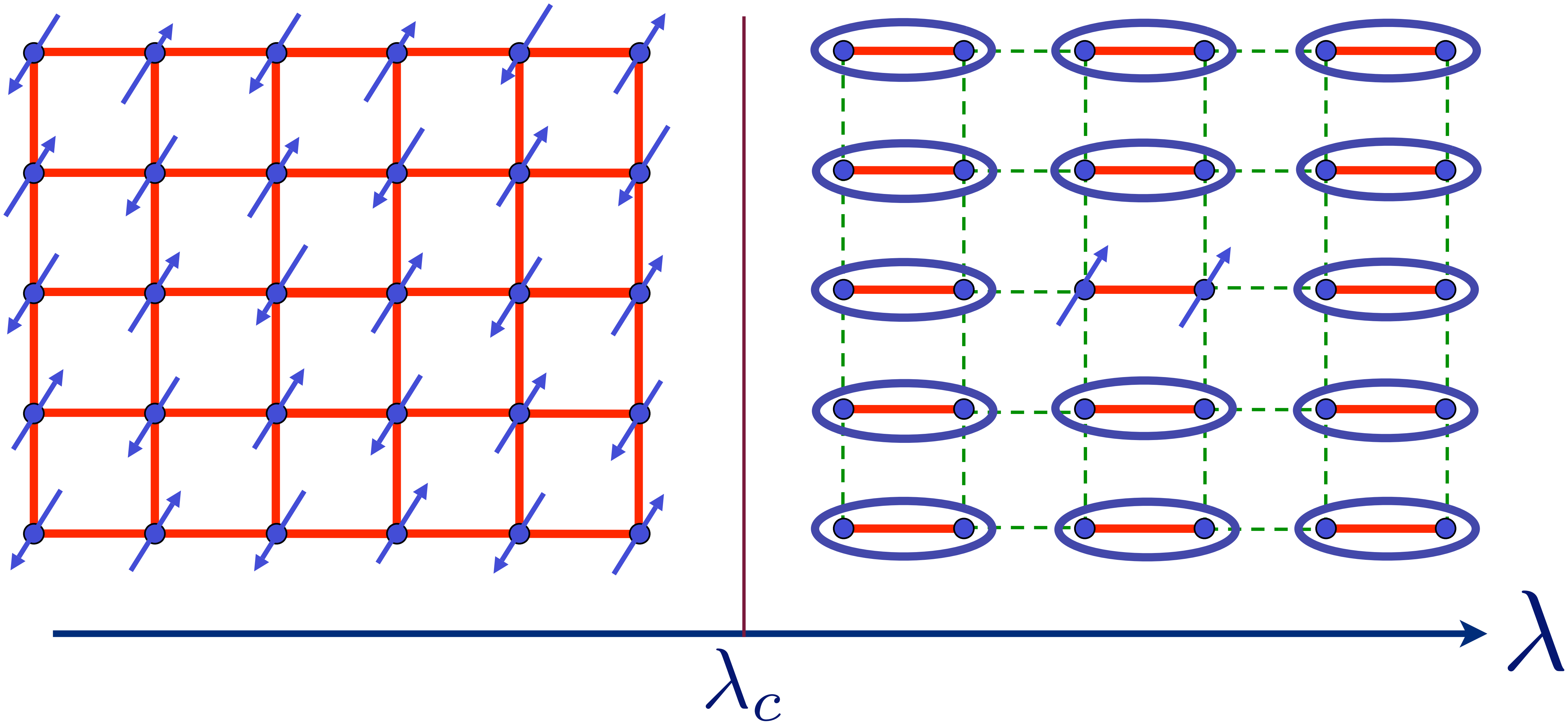
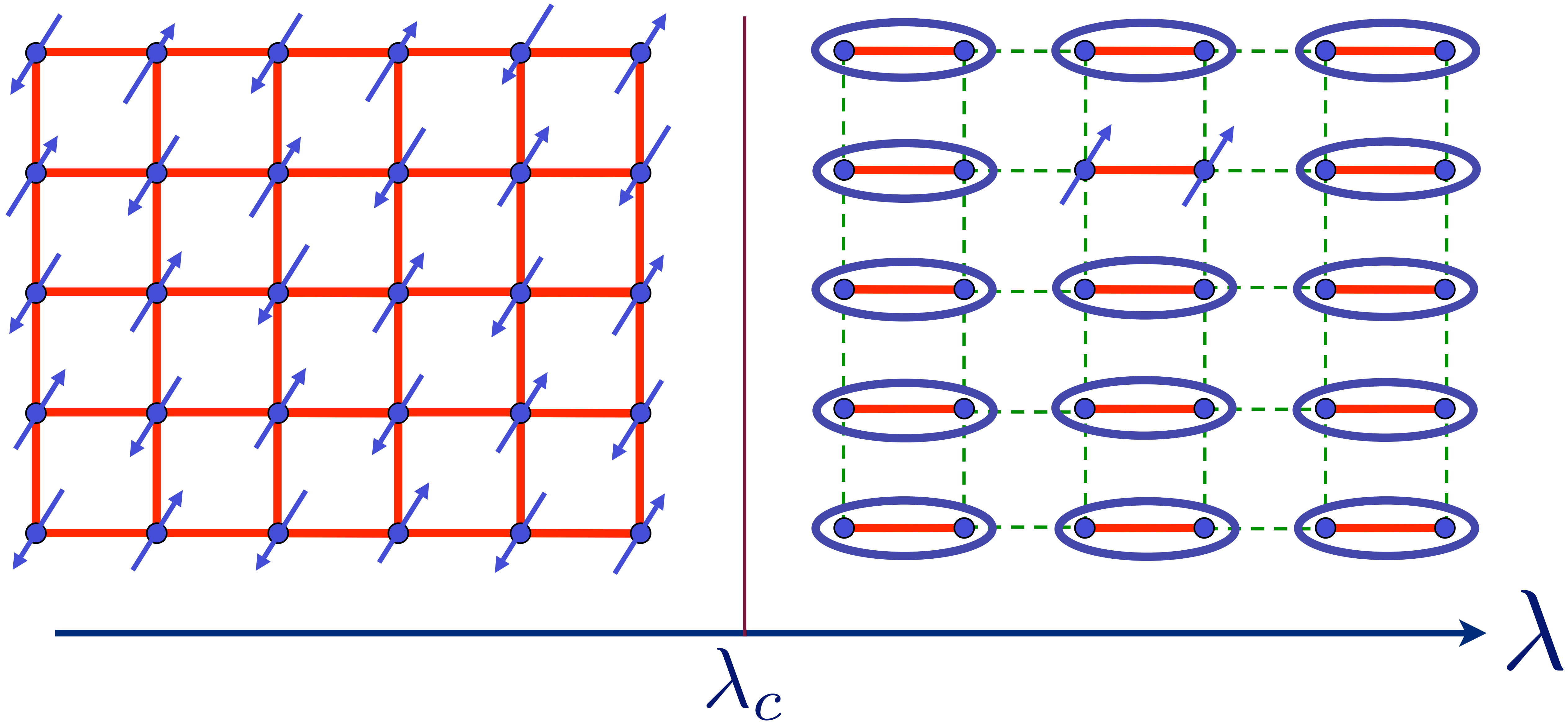
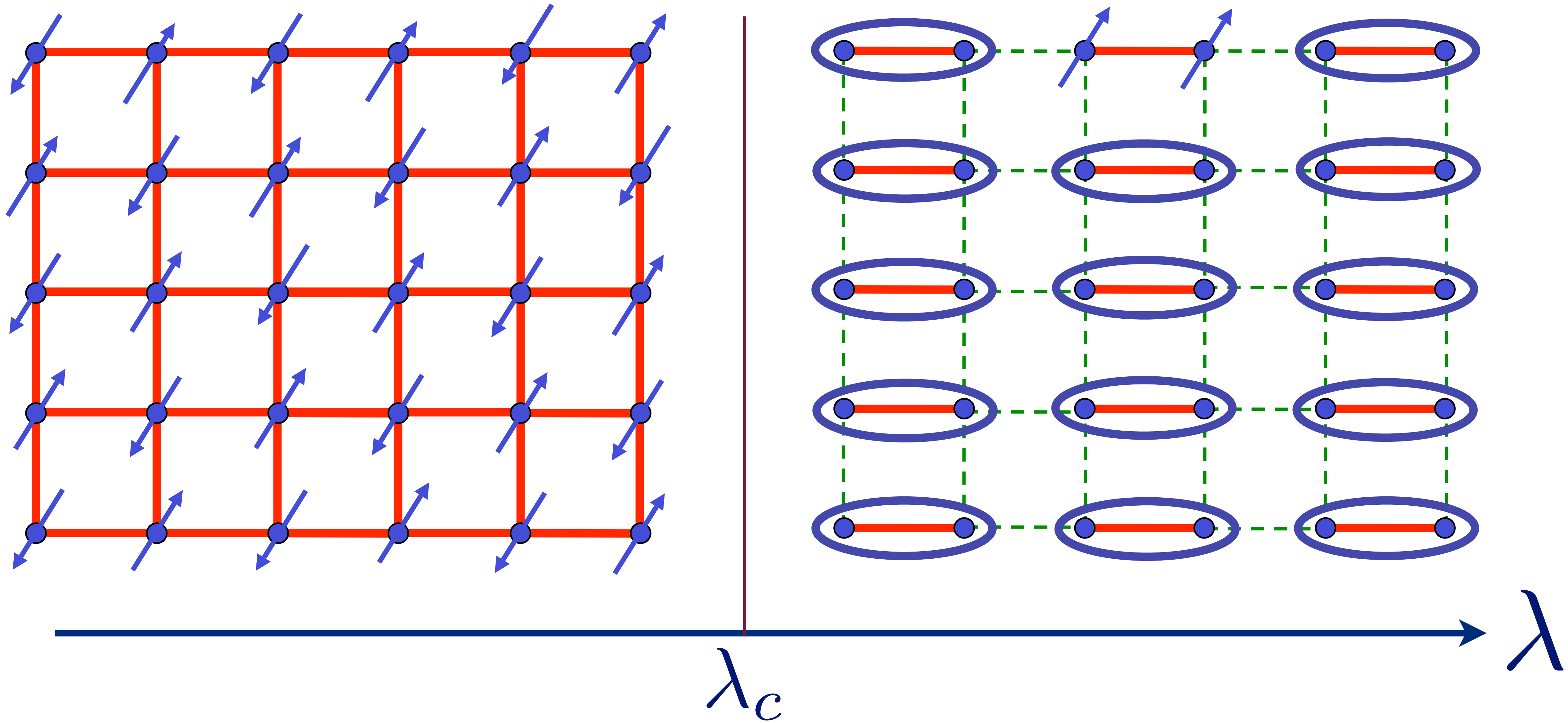


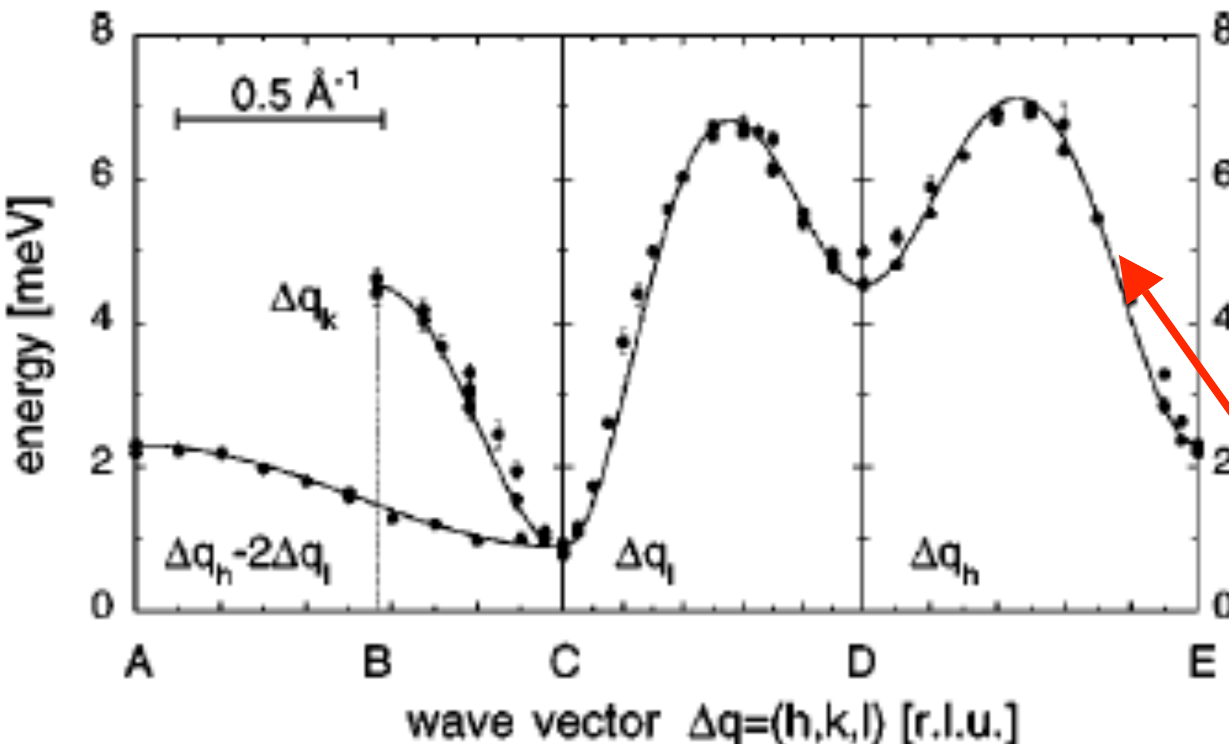
Excitation spectrum in the paramagnetic phase

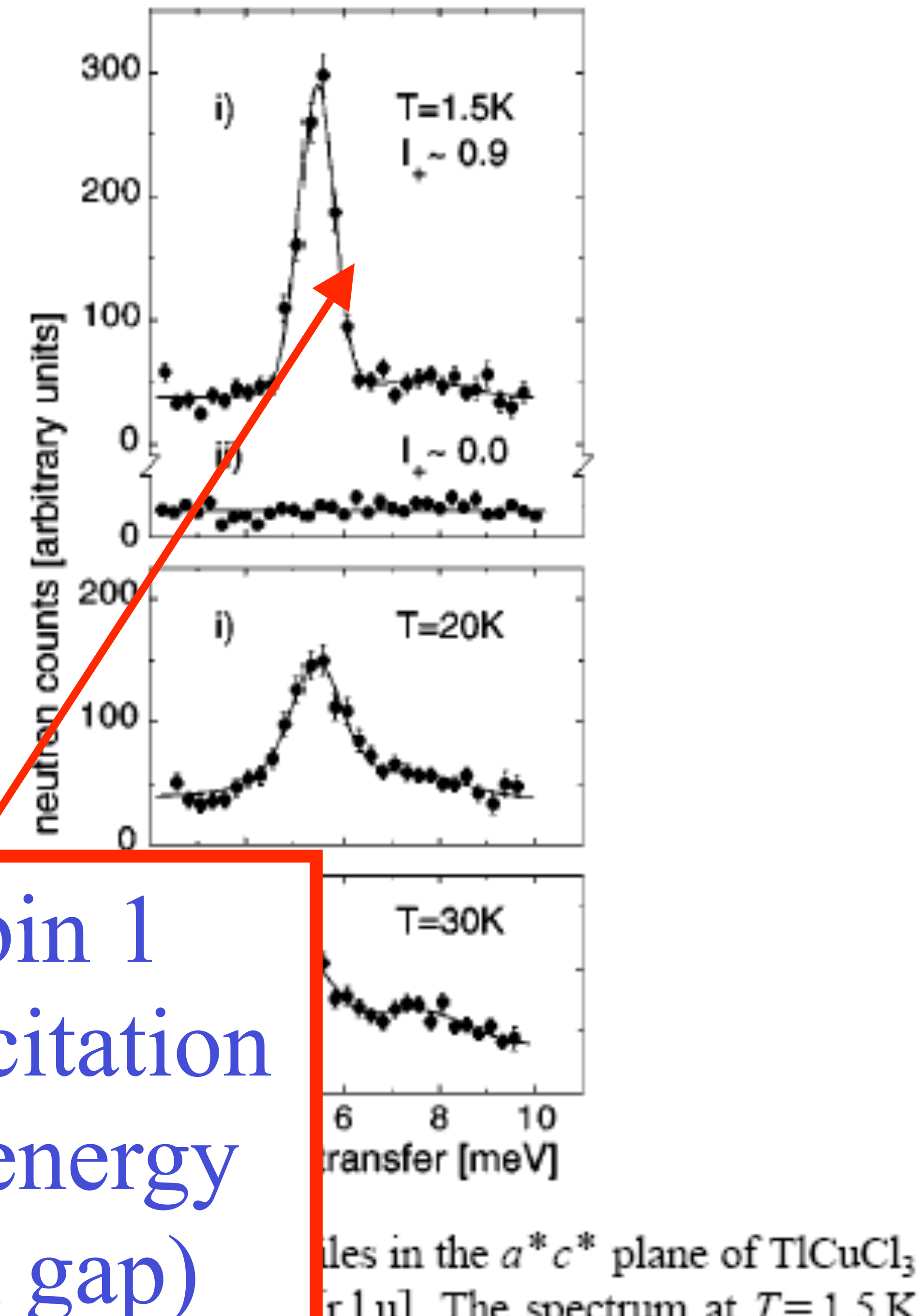


Excitation spectrum in the paramagnetic phase



$TlCuCl_3$ at ambient pressure





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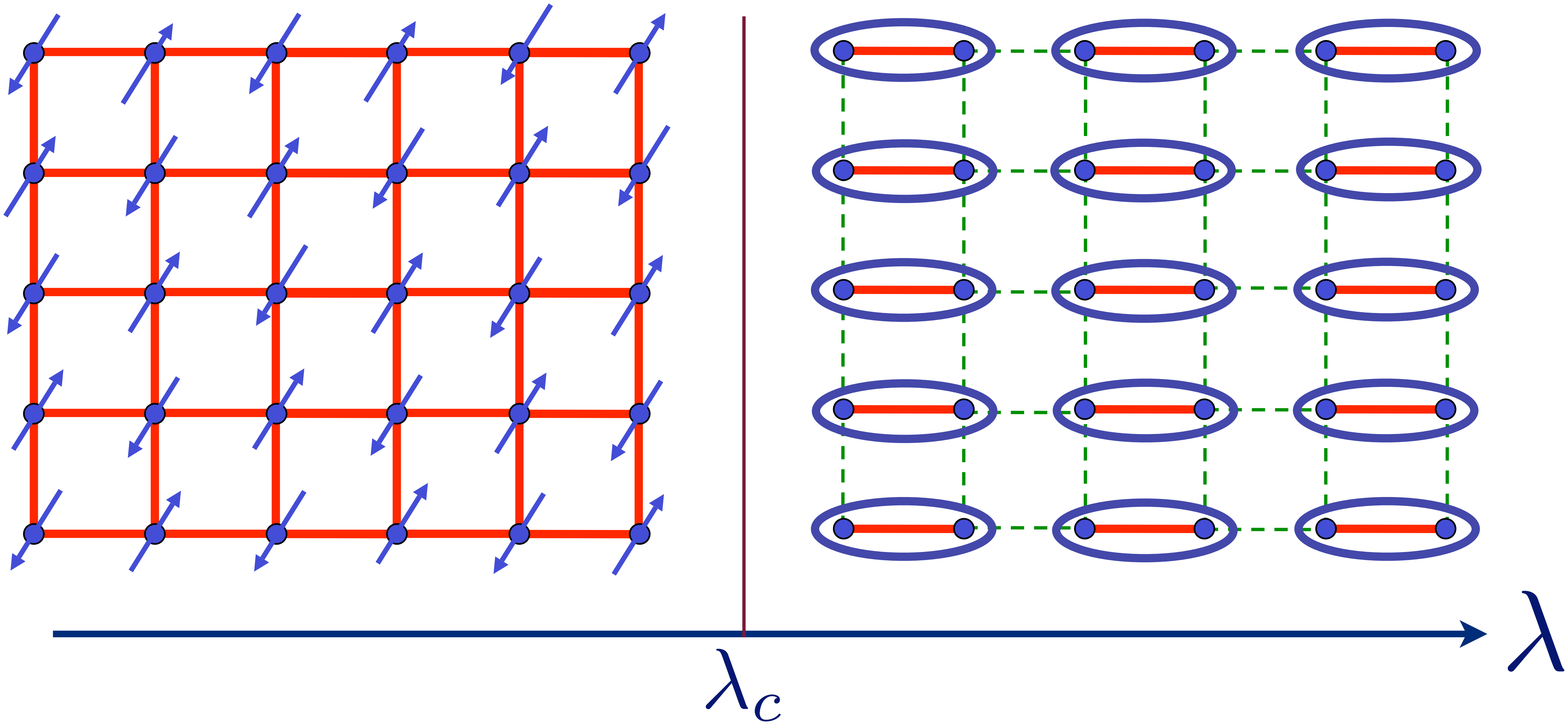
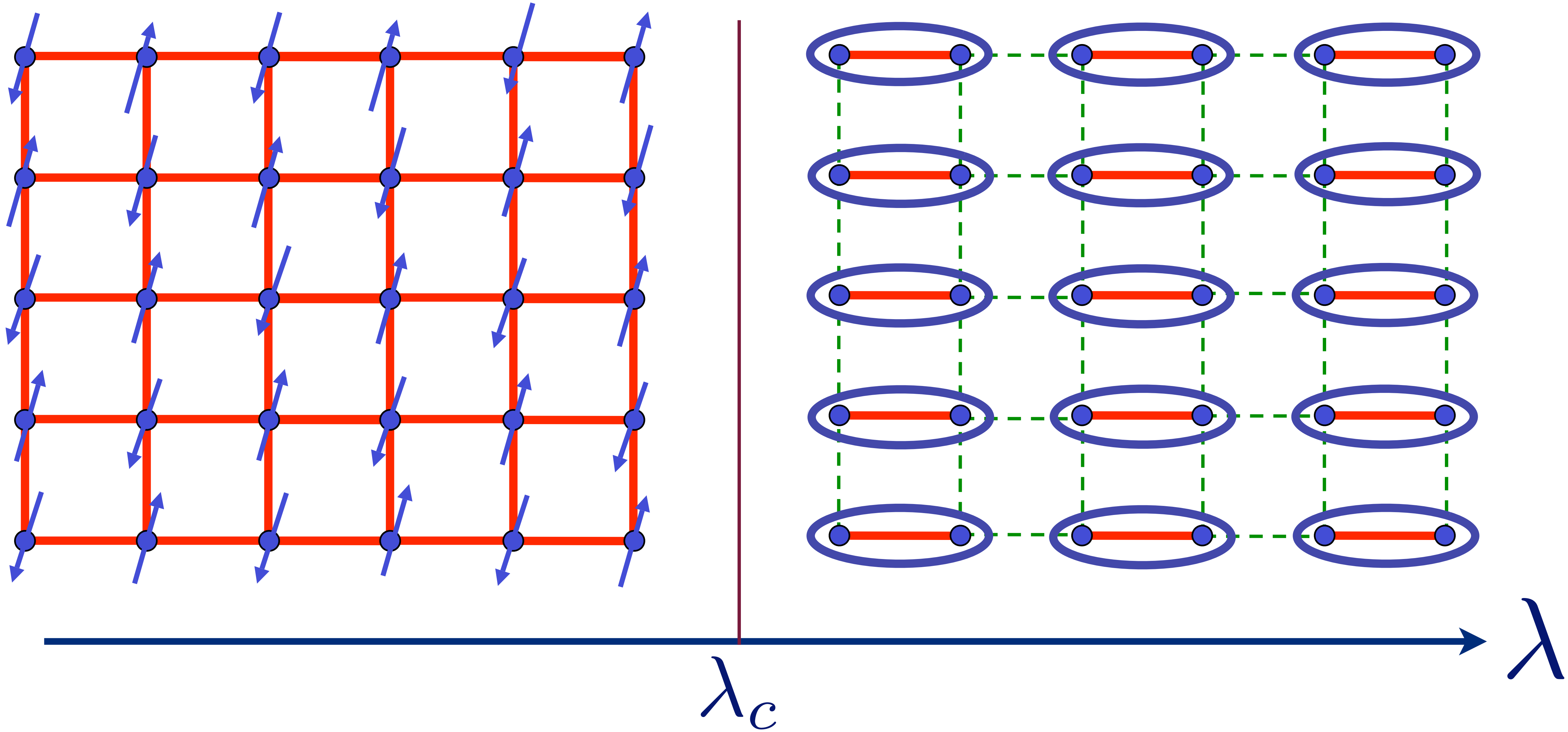
Excitation spectrum in the Néel phase

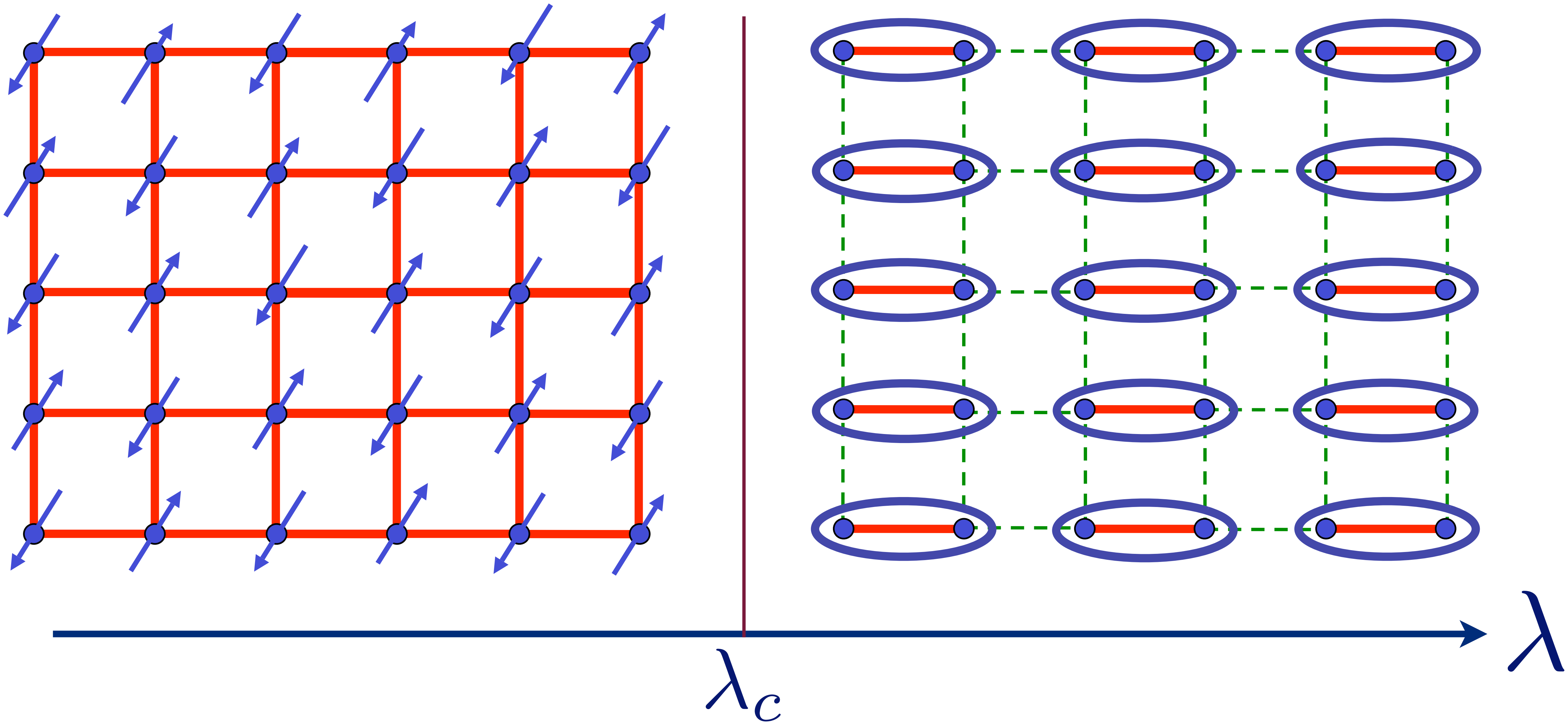


Excitation spectrum in the Néel phase



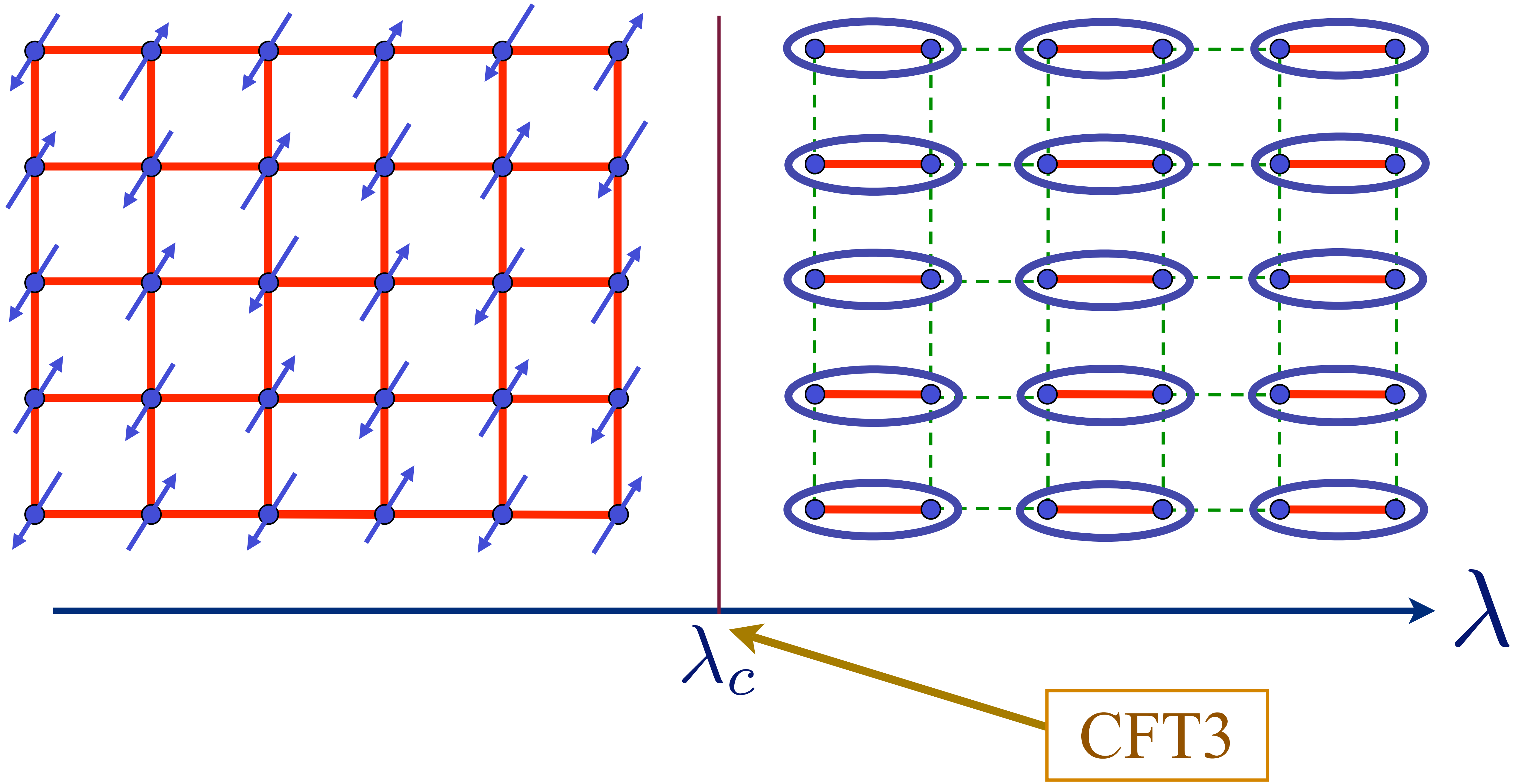
Spin waves

Excitation spectrum in the Néel phase



Spin waves

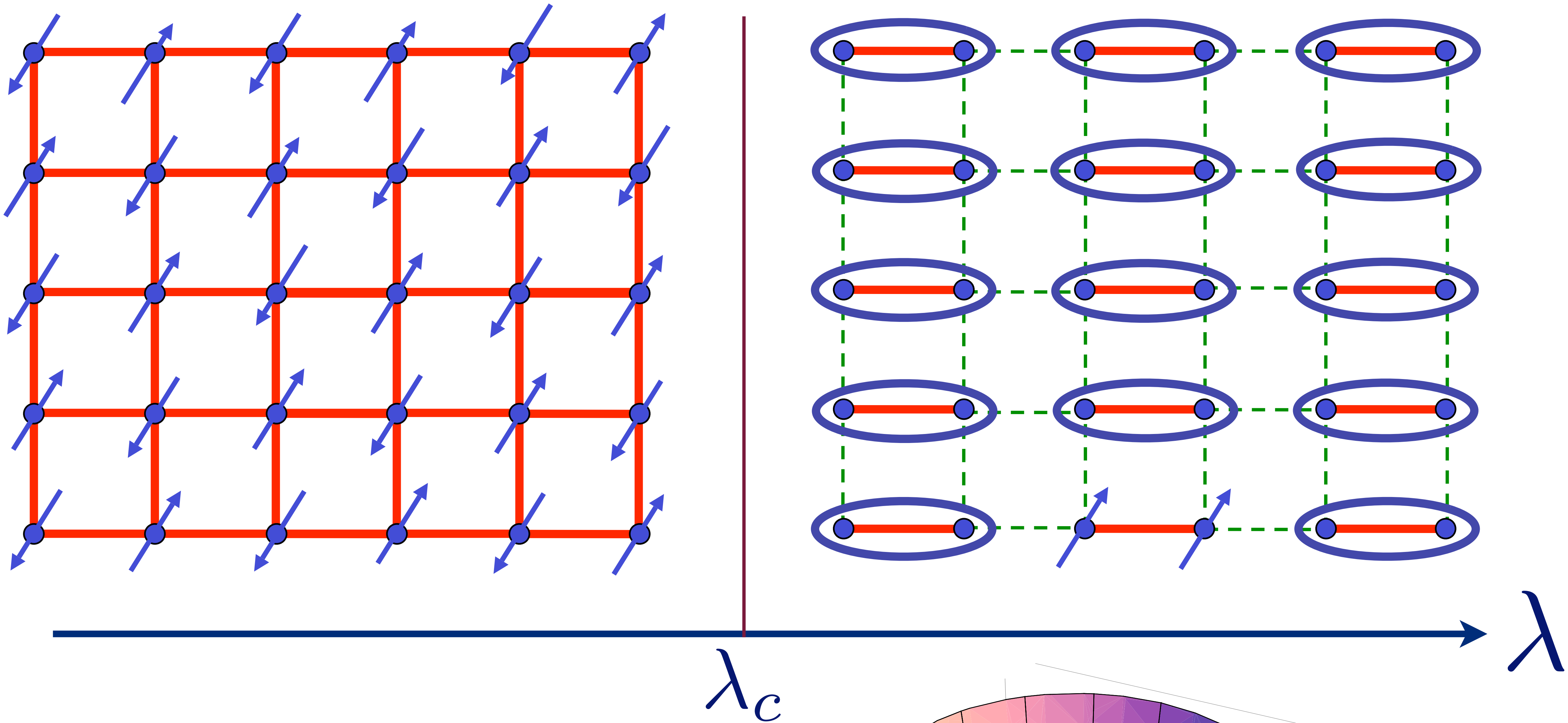
Description using Landau-Ginzburg field theory



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

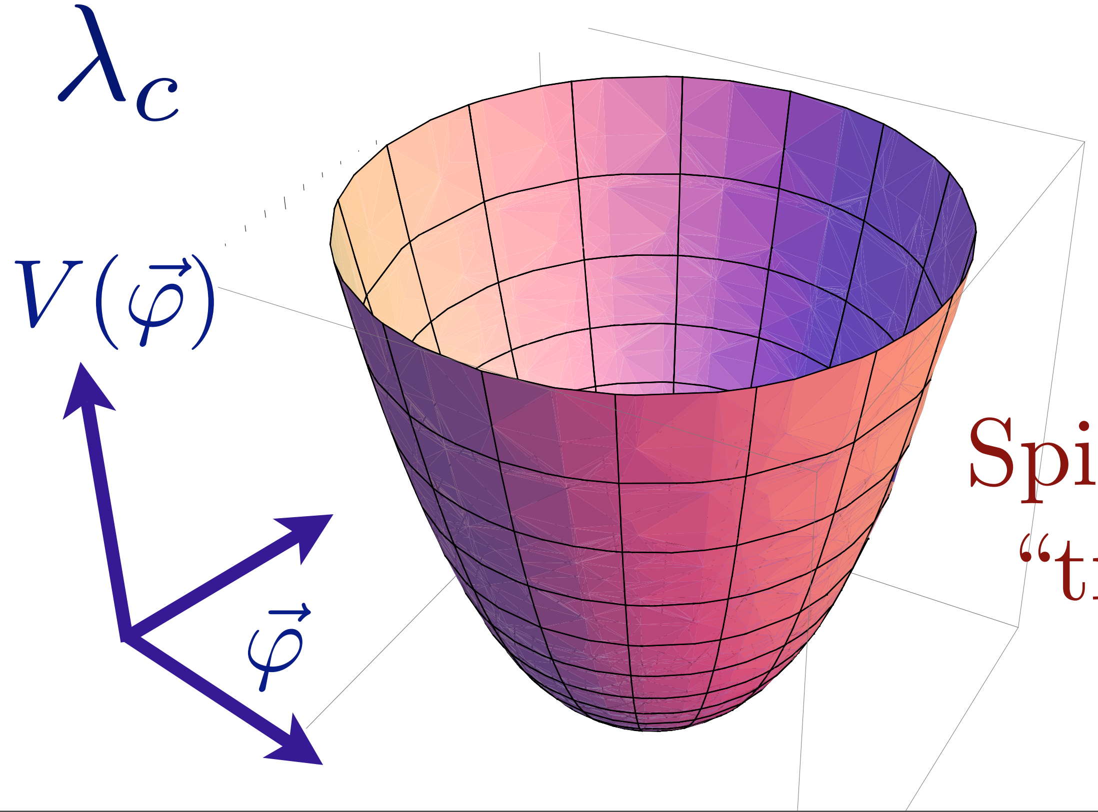
$$\mathcal{S} = \int d^2 r d\tau \left[(\partial_\tau \varphi)^2 + c^2 (\nabla_r \vec{\varphi})^2 + (\lambda - \lambda_c) \vec{\varphi}^2 + u \left(\vec{\varphi}^2 \right)^2 \right]$$

Excitation spectrum in the paramagnetic phase



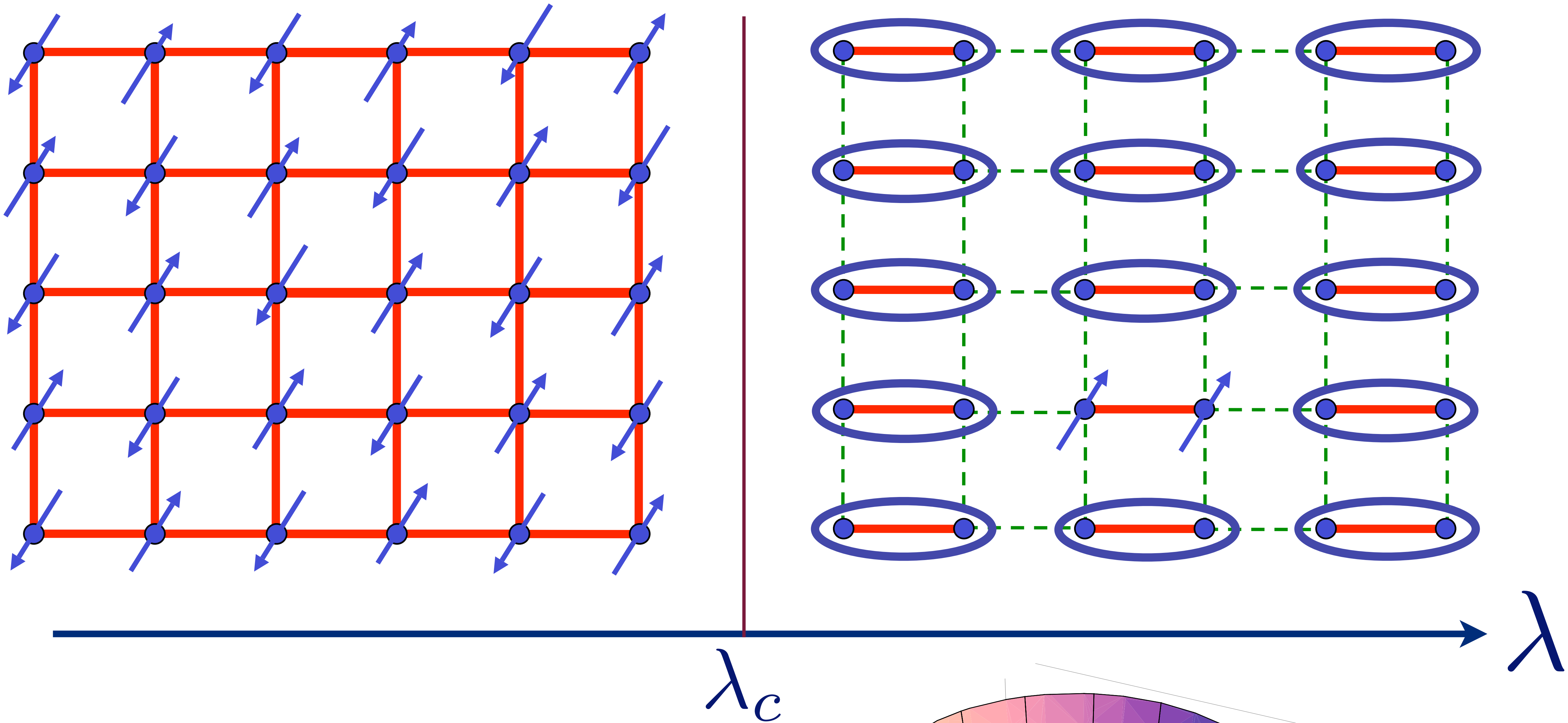
$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$

$$\lambda > \lambda_c$$



Spin $S = 1$
"triplon"

Excitation spectrum in the paramagnetic phase



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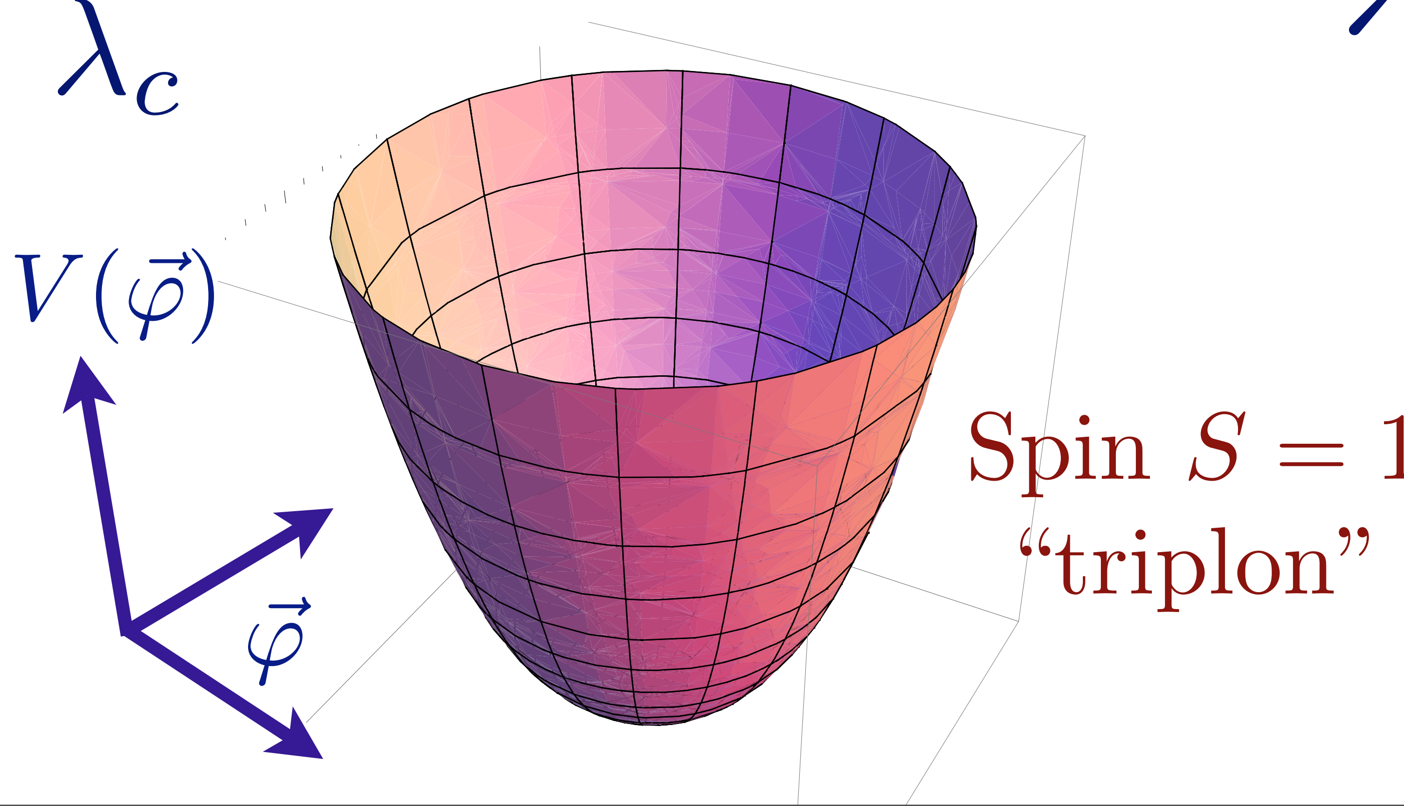
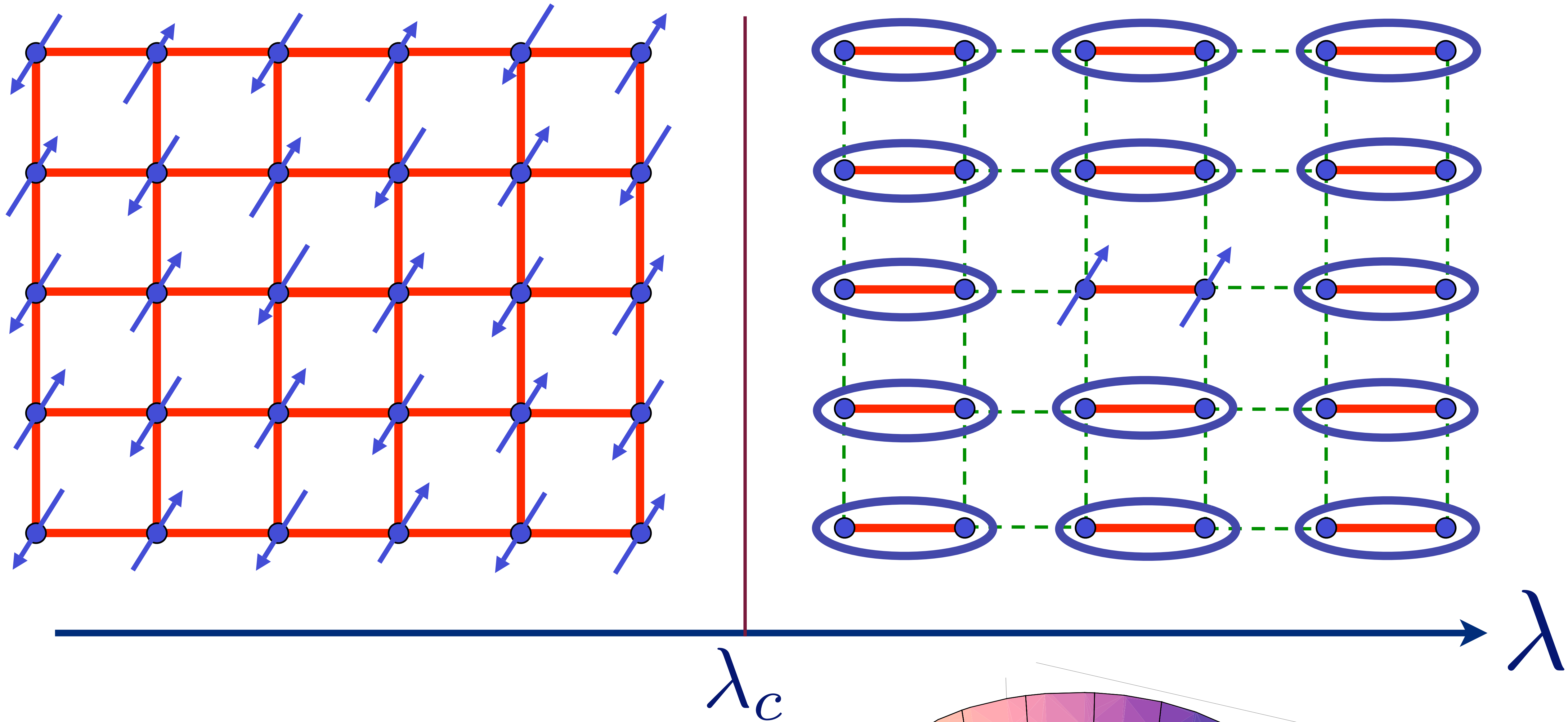


Excitation spectrum in the paramagnetic phase



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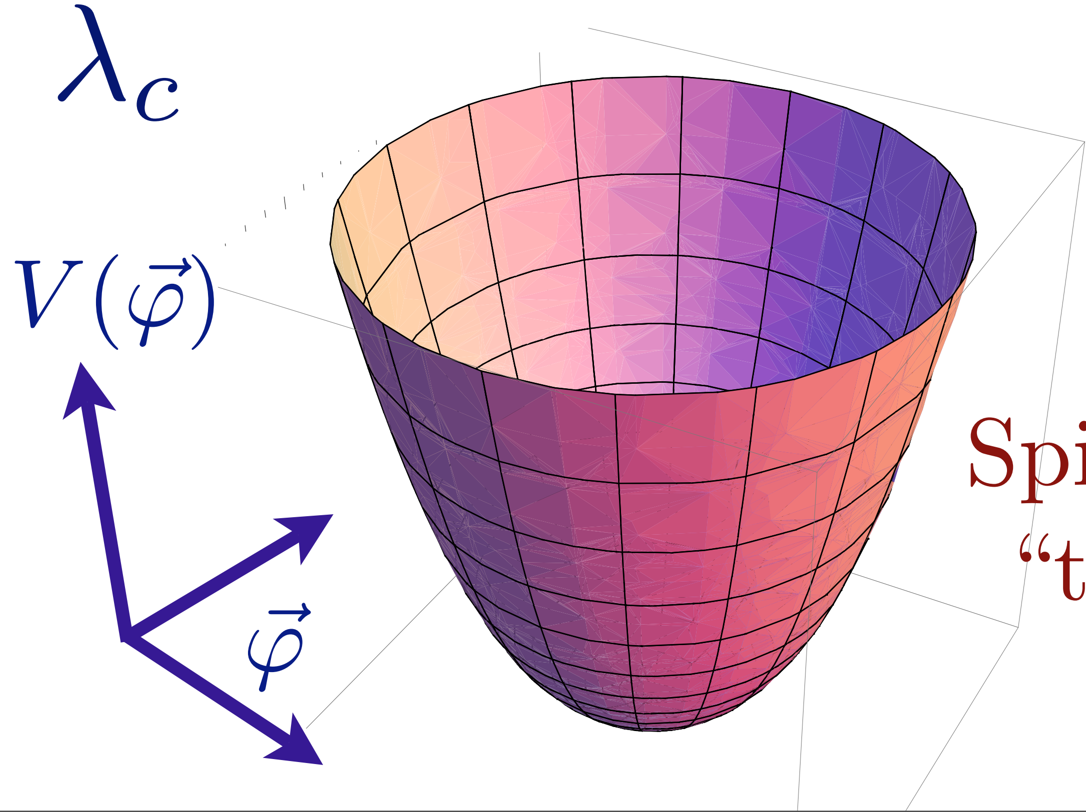

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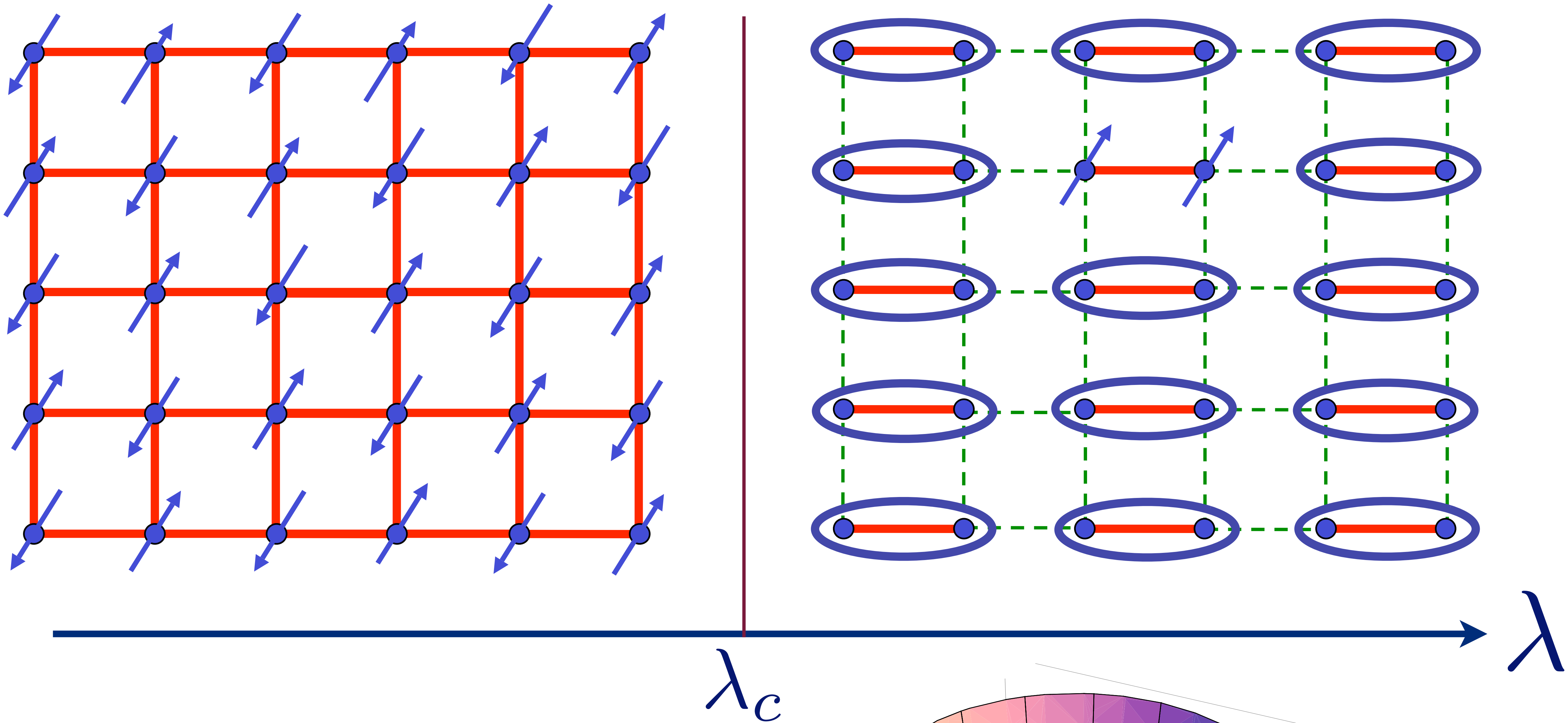

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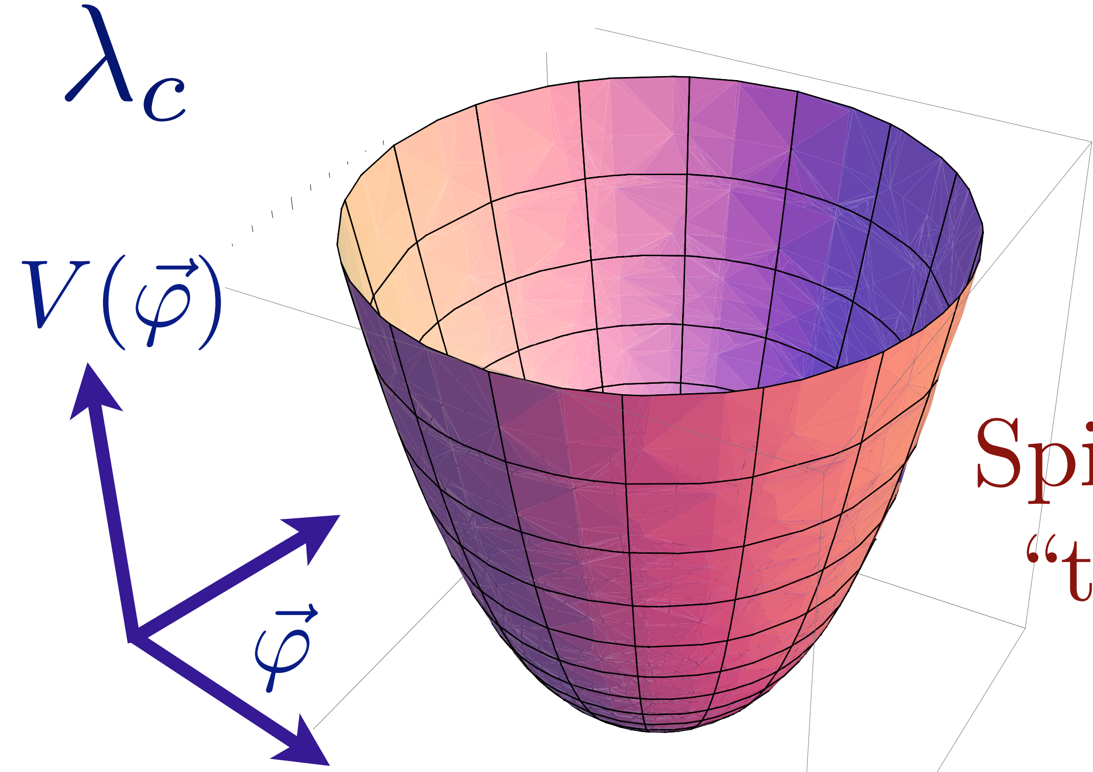

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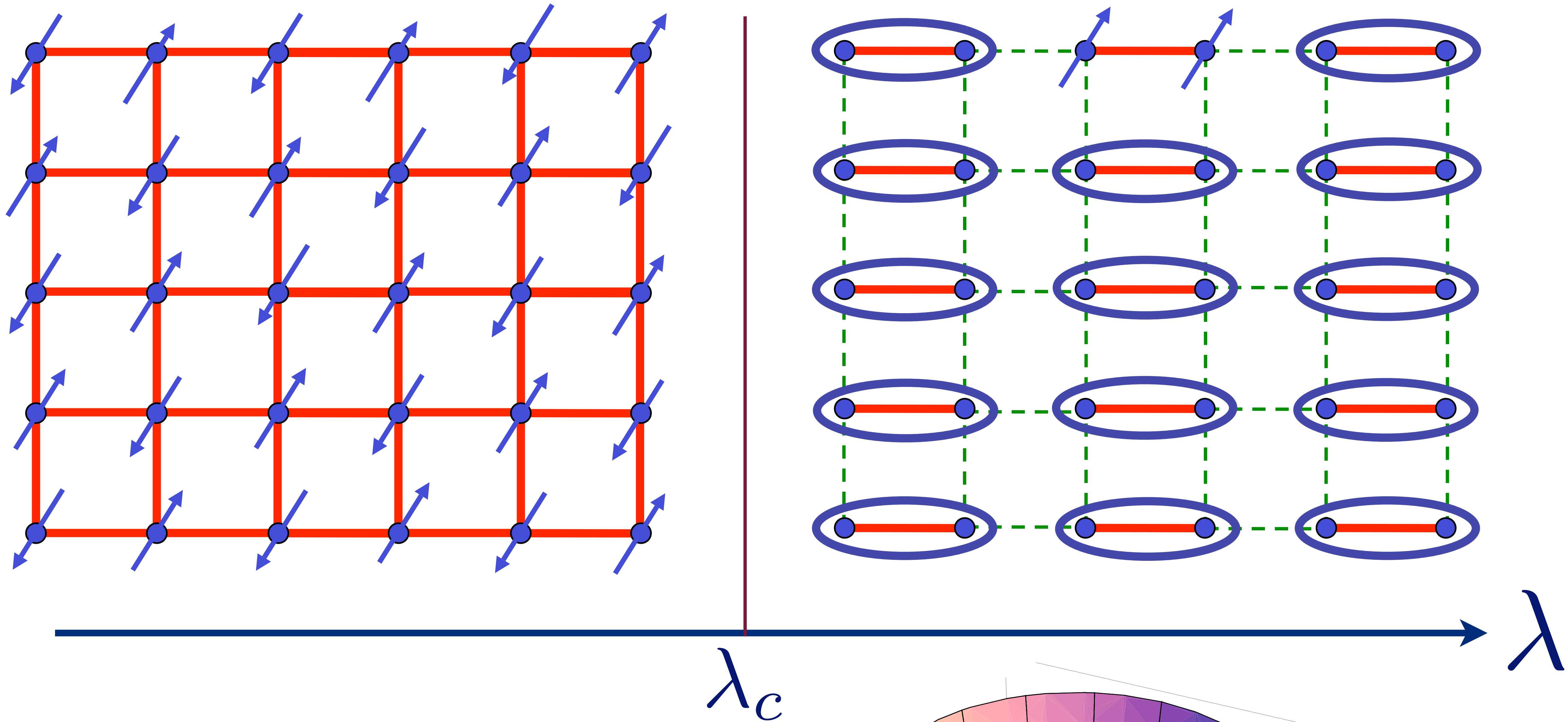

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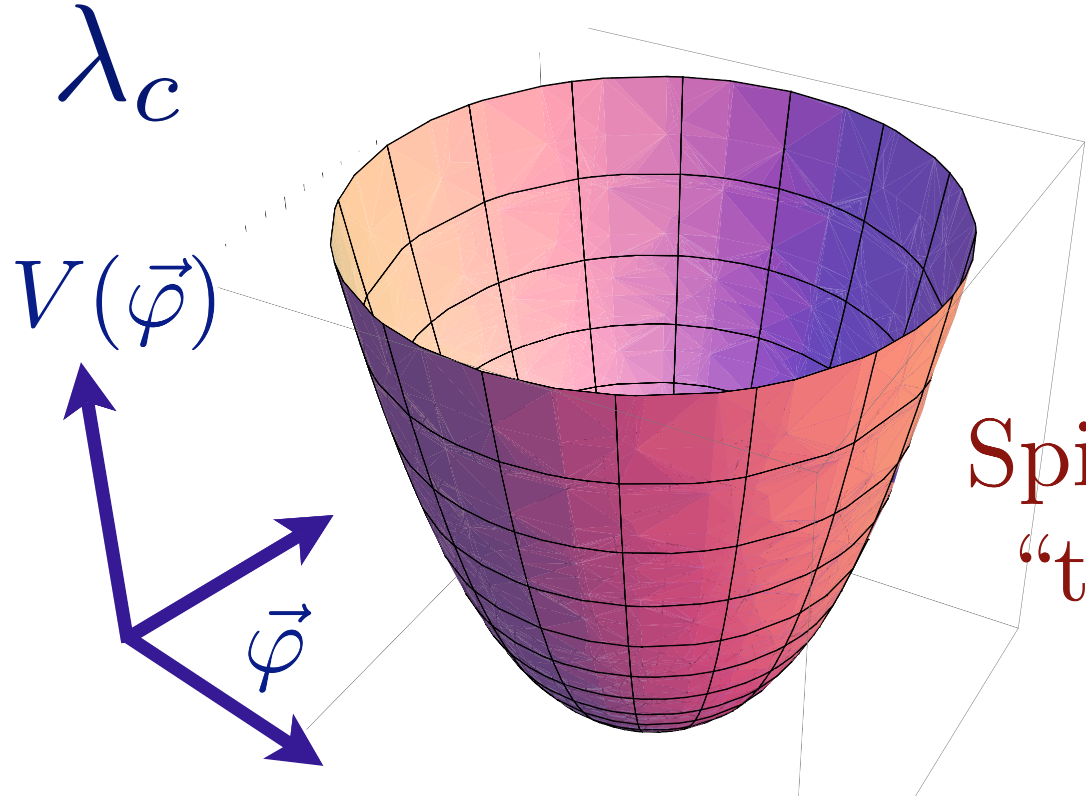
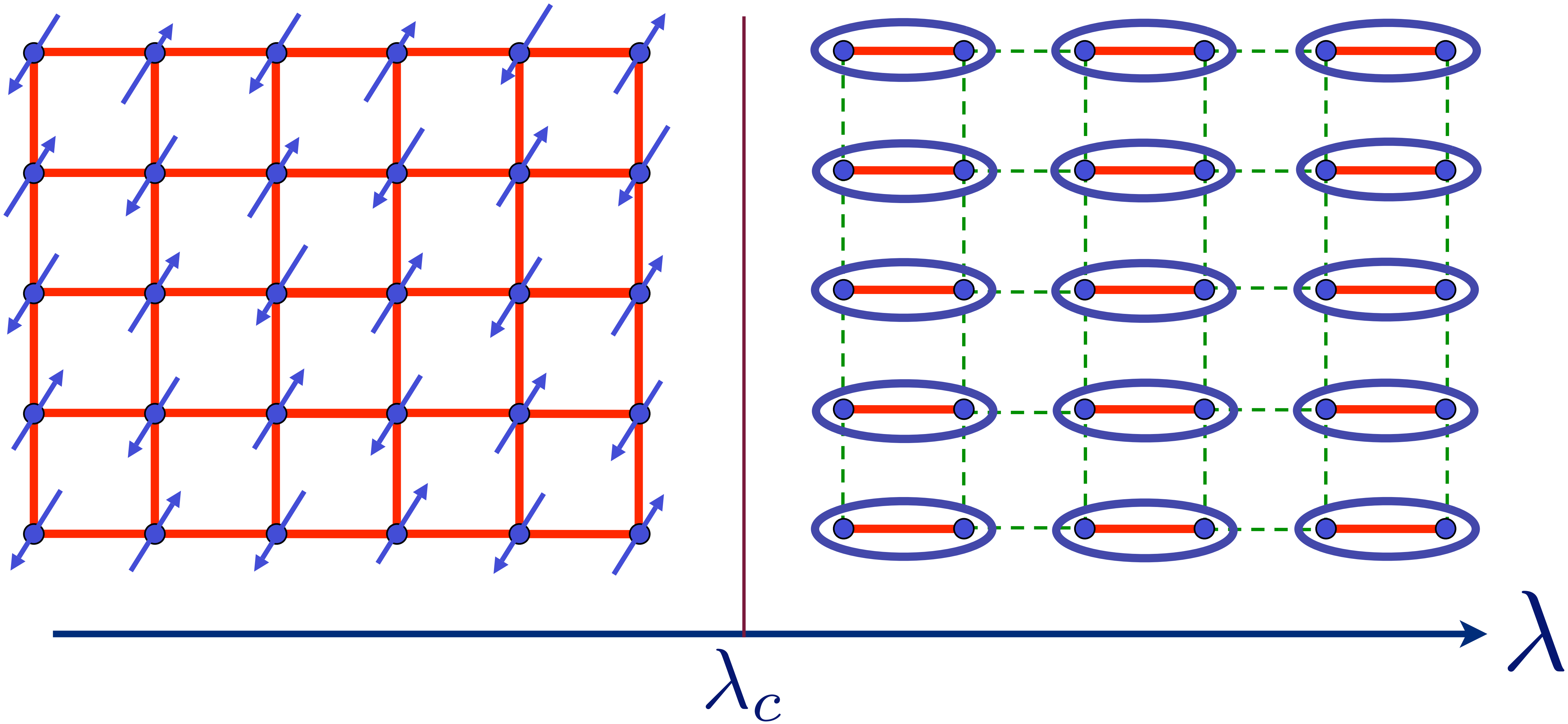
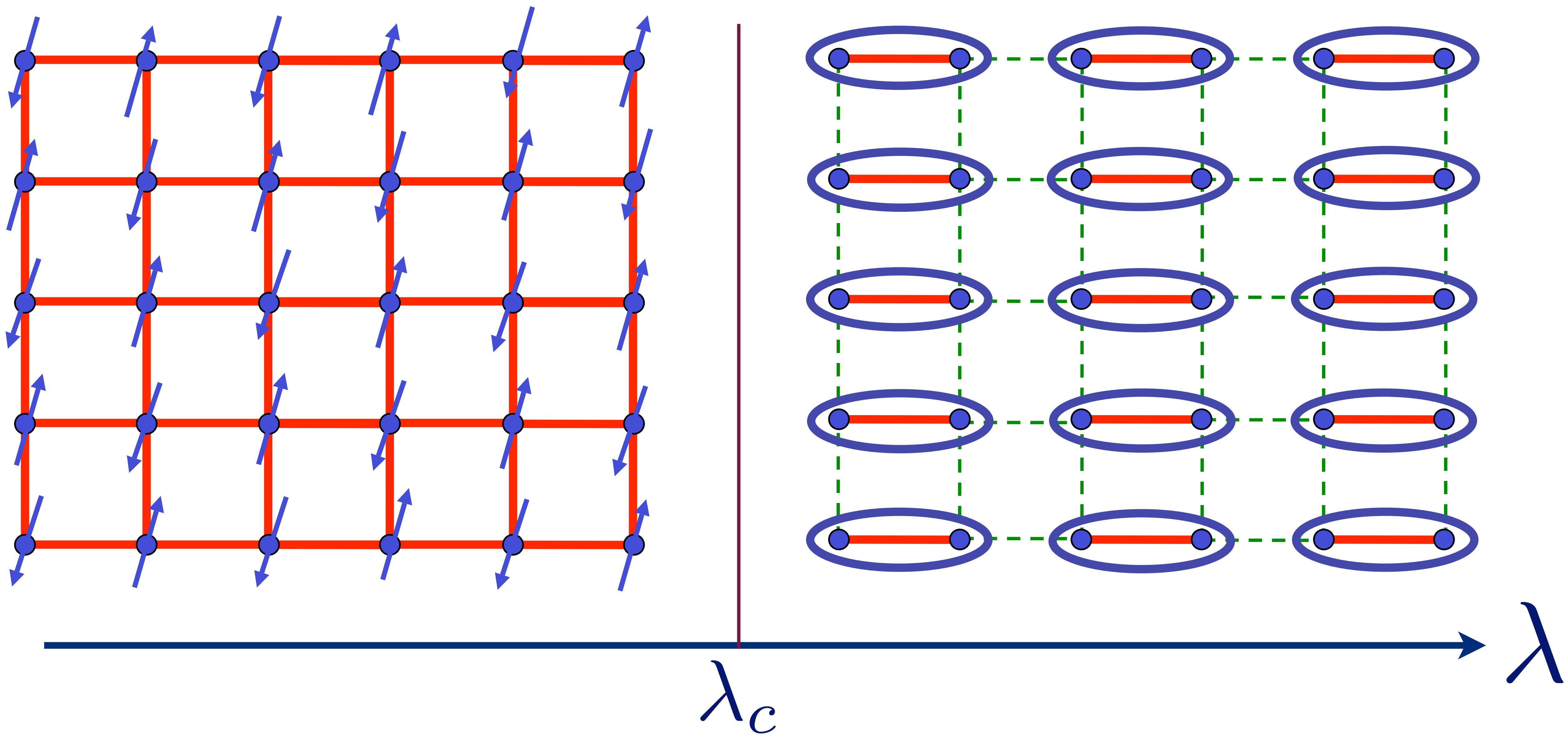


Spin $S = 1$
"triplon"

Excitation spectrum in the Néel phase

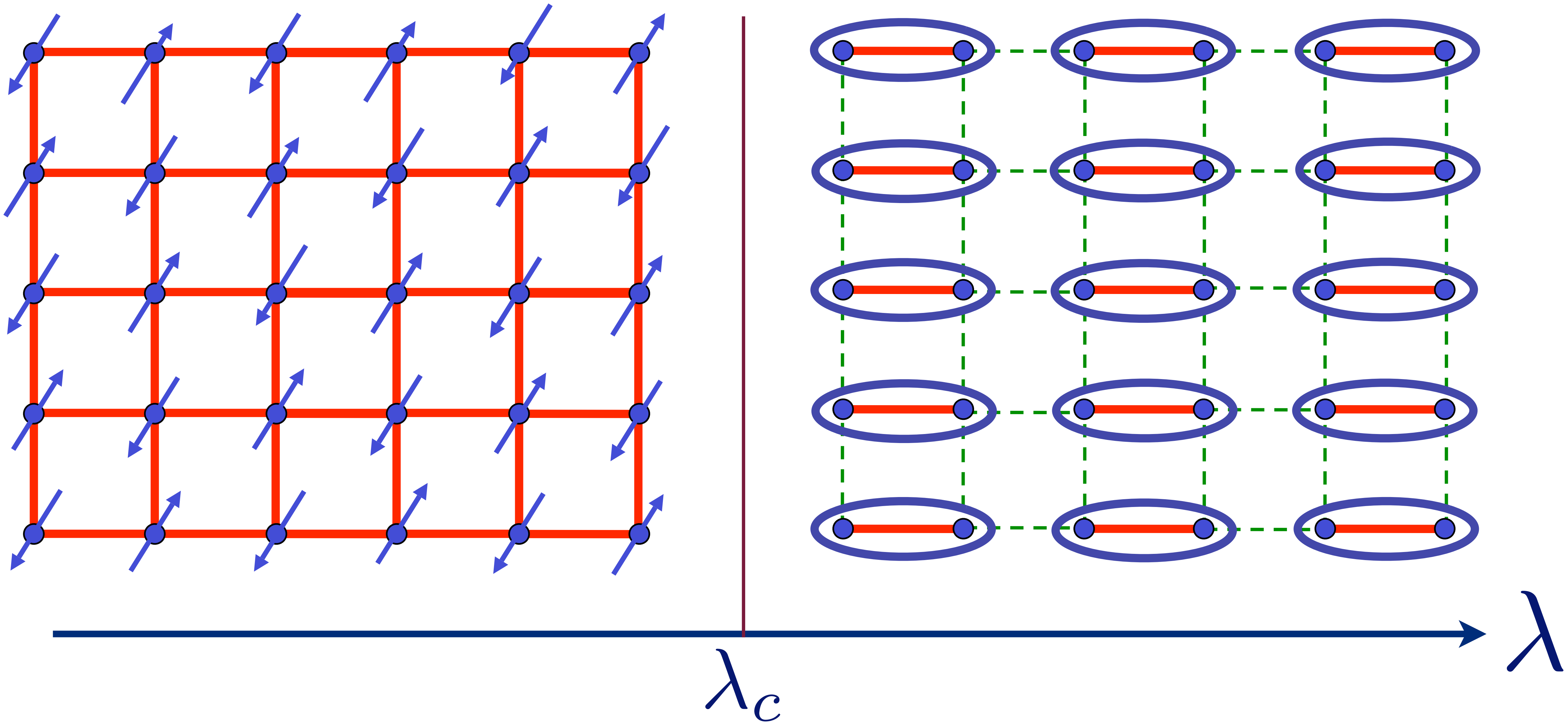


Excitation spectrum in the Néel phase



Spin waves

Excitation spectrum in the Néel phase



Spin waves

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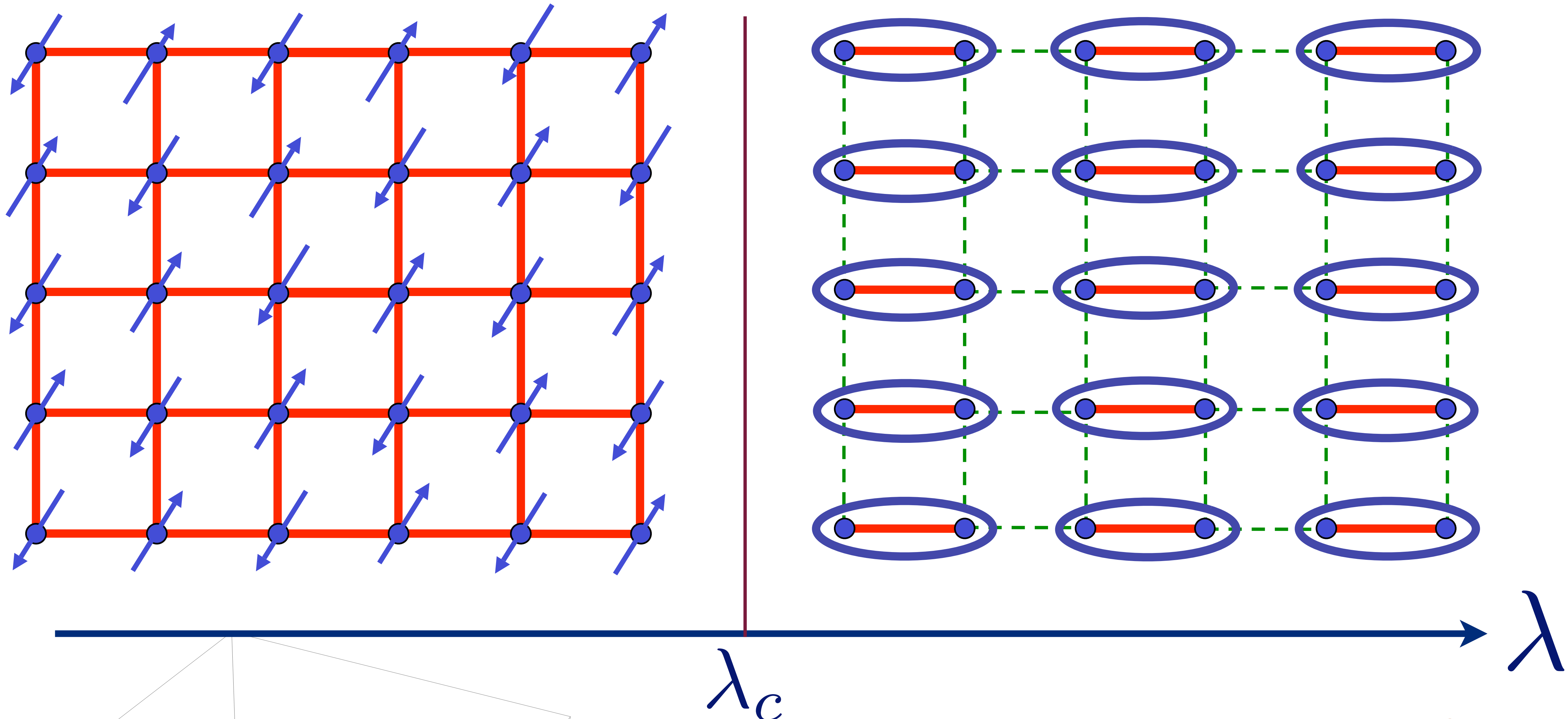

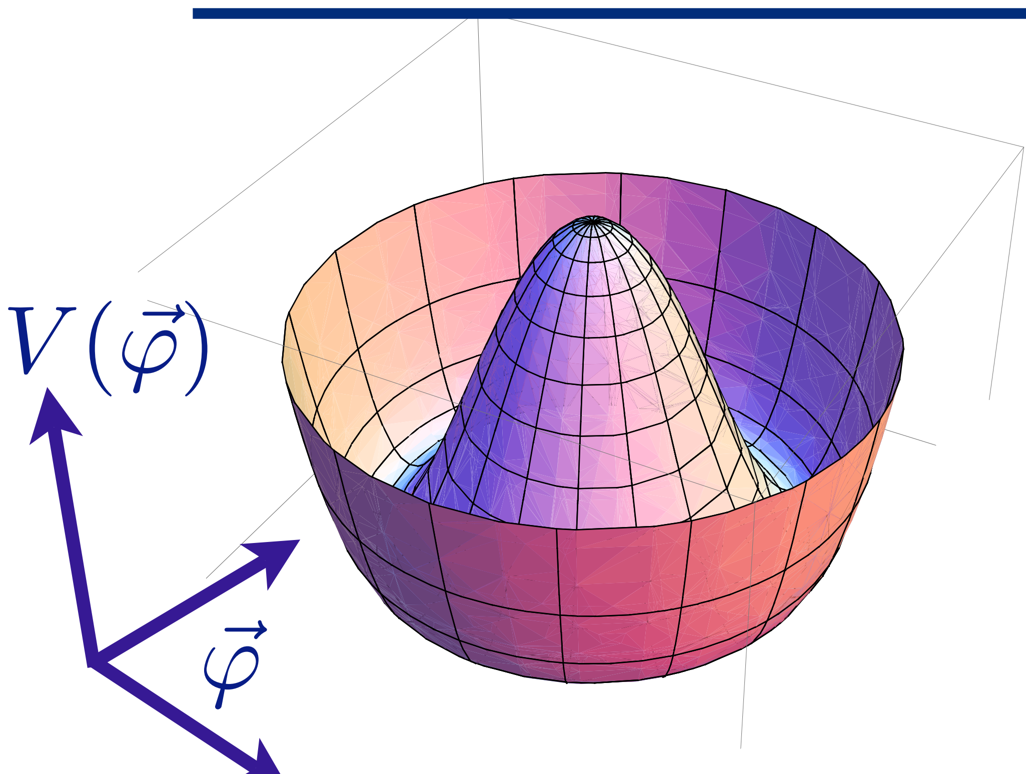

$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$

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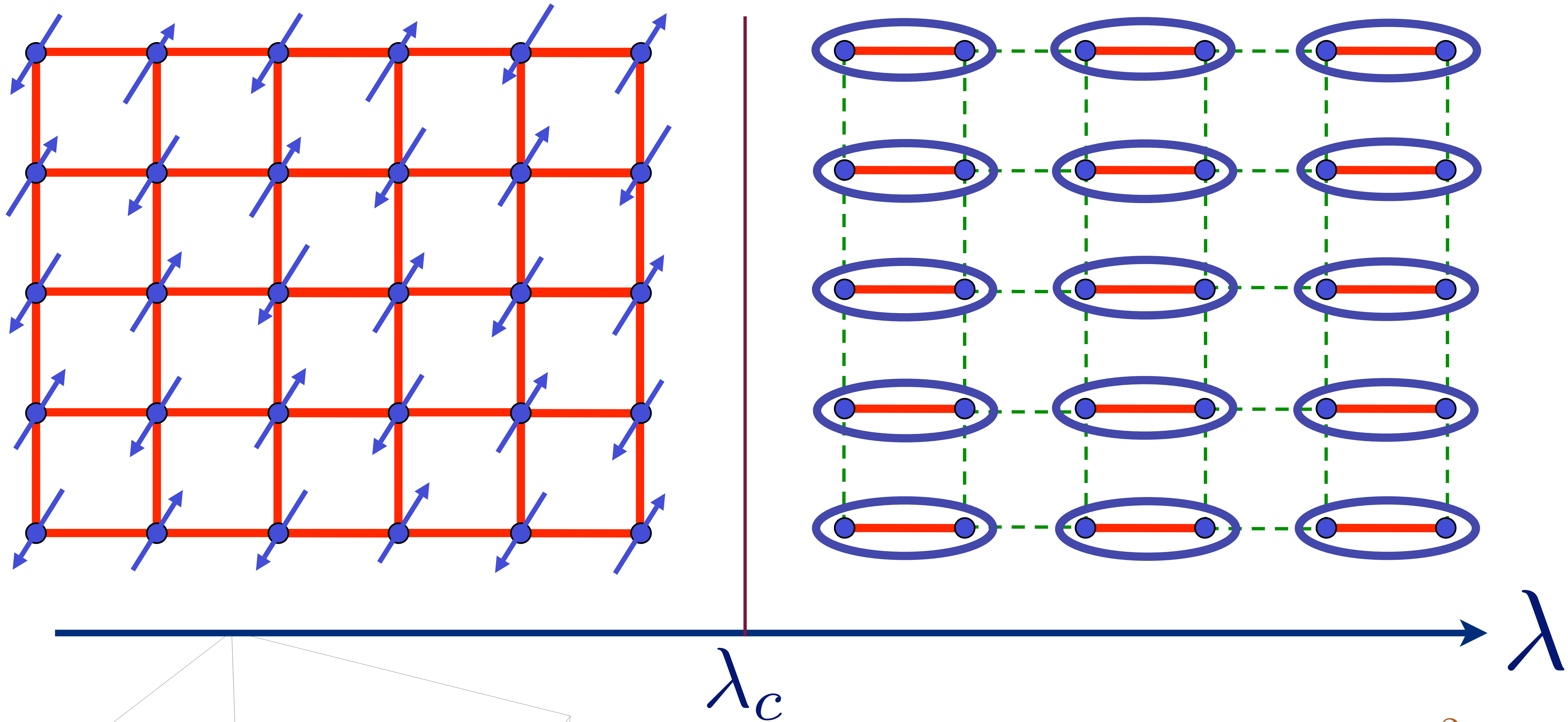
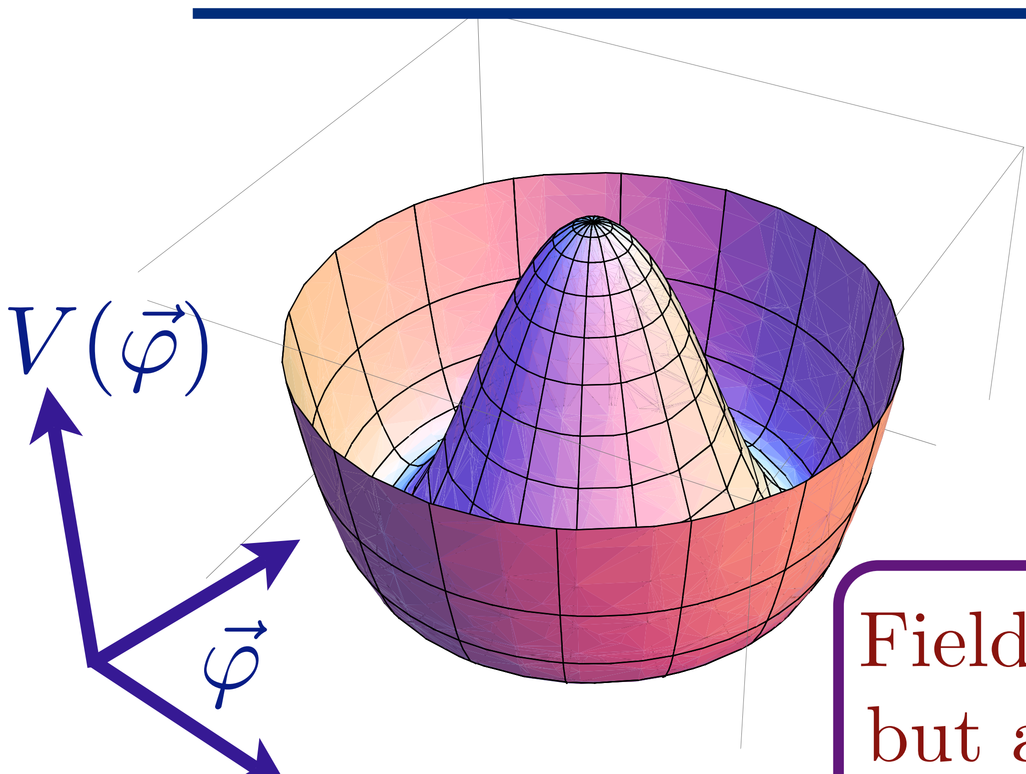
Excitation spectrum in the Néel phase



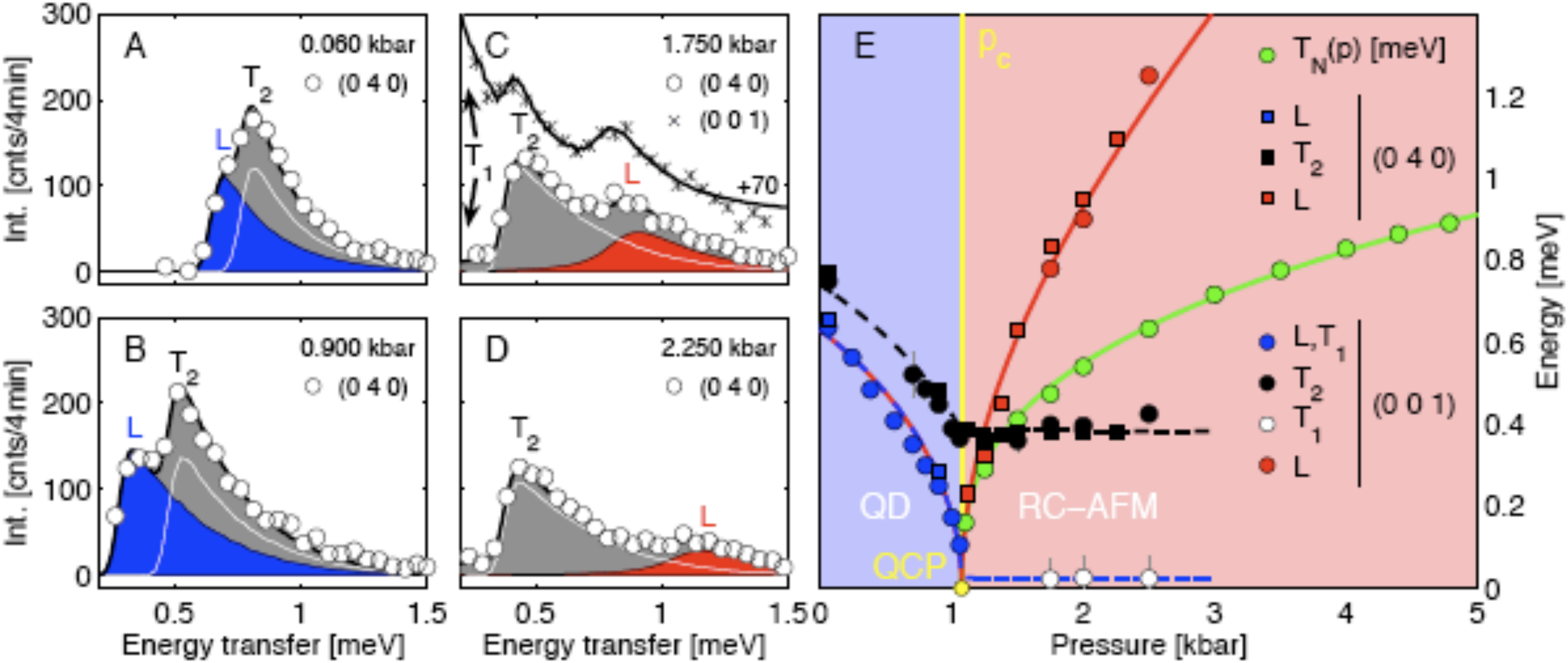


$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$

$$\lambda < \lambda_c$$

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

$TlCuCl_3$ with varying pressure



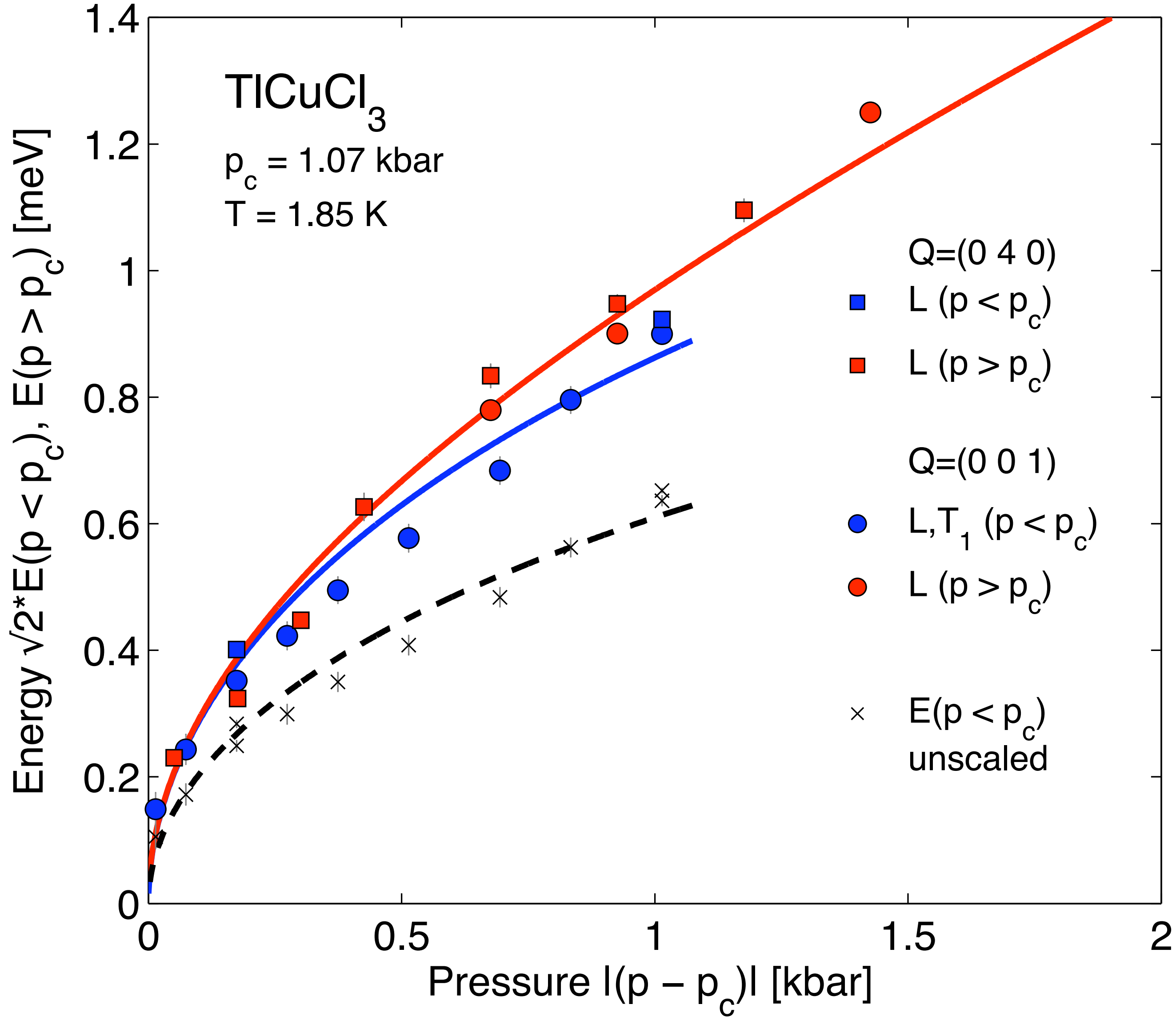
Observation of 3 → 2 low energy modes,
emergence of new Higgs particle in the Néel phase,
and vanishing of Néel temperature at the quantum critical point

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

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

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



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Three foci of modern physics

Quantum phase transitions

Hydrodynamics

Black holes

Three foci of modern physics

Quantum phase transitions

Hydrodynamics

Canonical problem in condensed matter: transport properties of a correlated electron system

Black holes

Three foci of modern physics

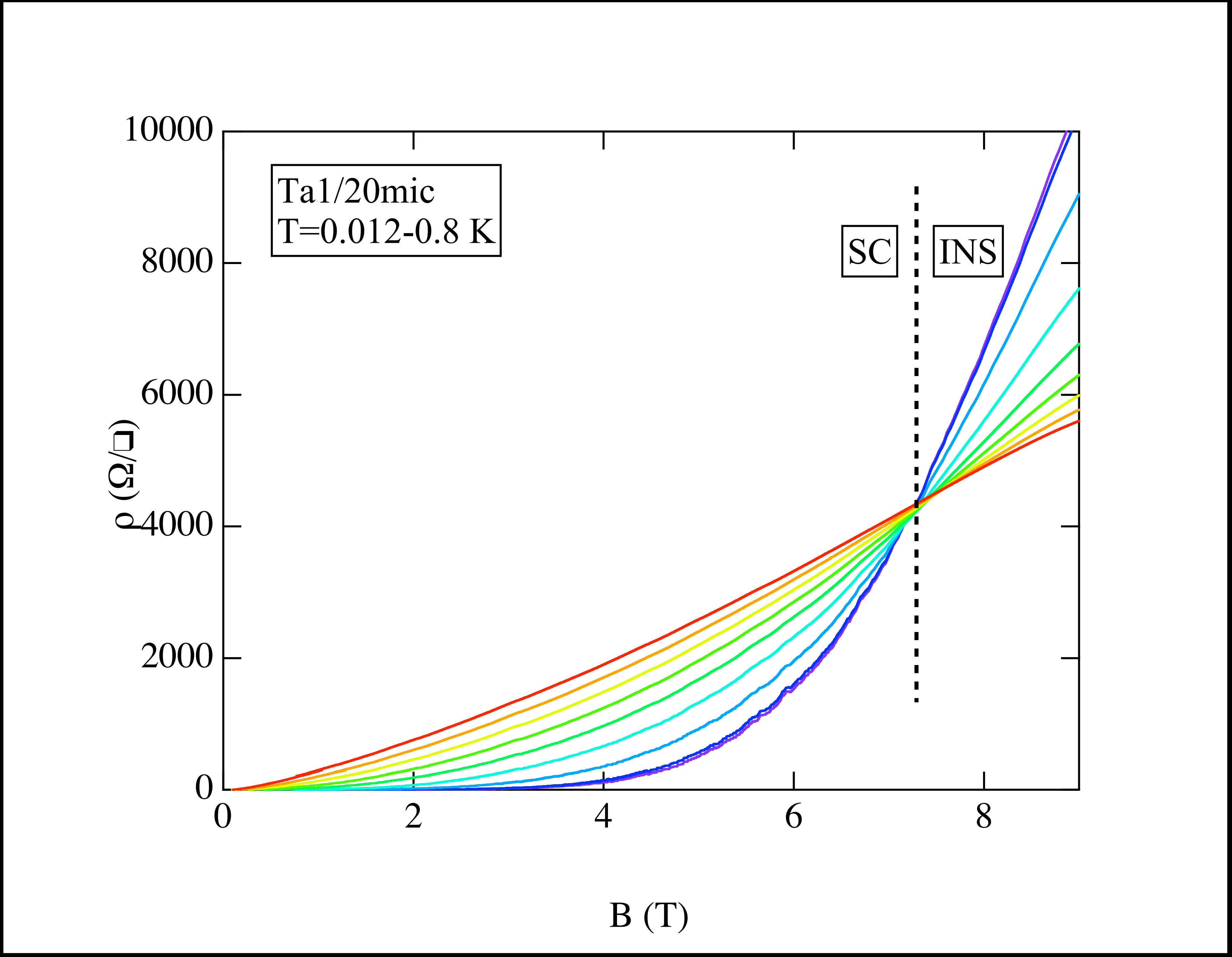
Quantum phase transitions → Hydrodynamics

Canonical problem in condensed matter: transport properties of a correlated electron system

Black holes

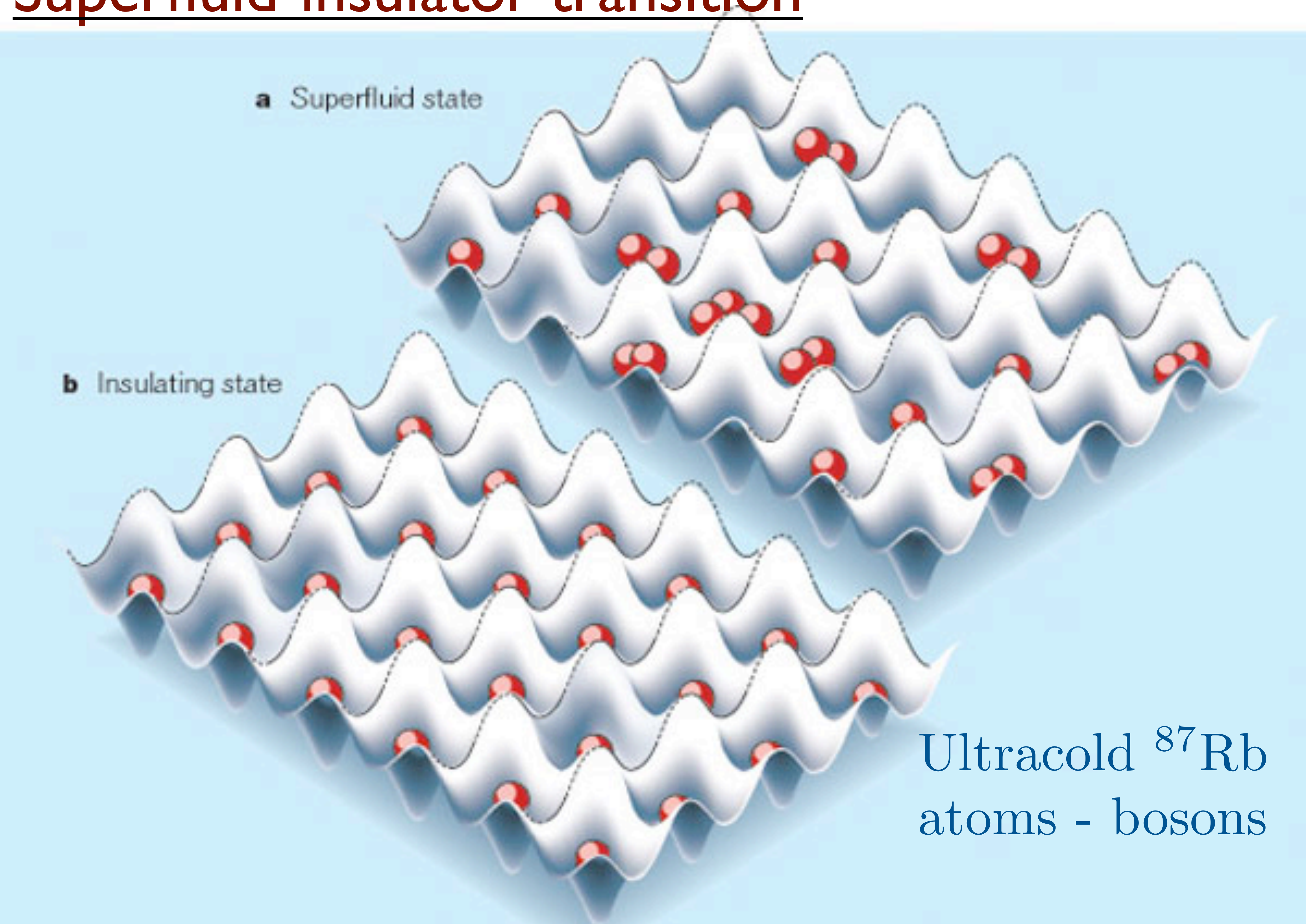
Superfluid-insulator transition

Indium Oxide films



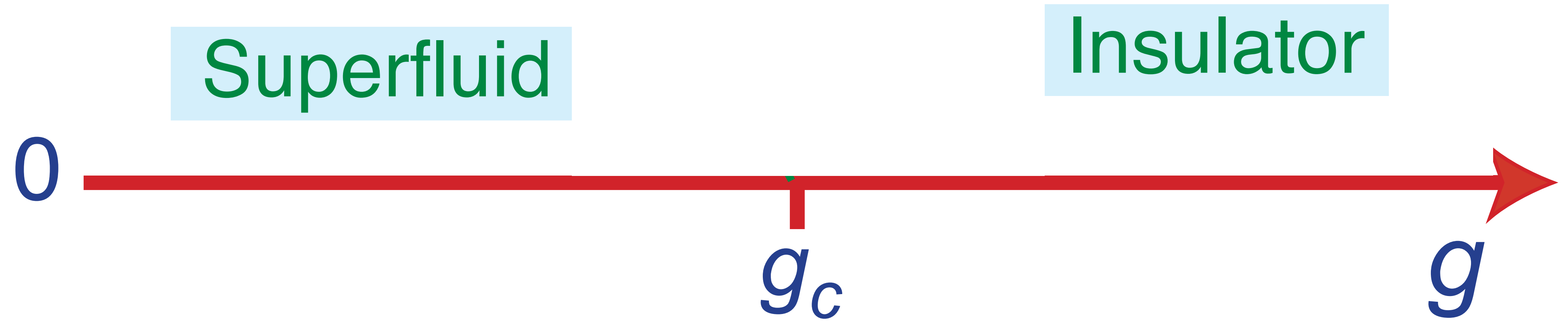
G. Sambandamurthy, A. Johansson, E. Peled, D. Shahar, P. G. Bjornsson, and K. A. Moler, *Europhys. Lett.* **75**, 611 (2006).

Superfluid-insulator transition

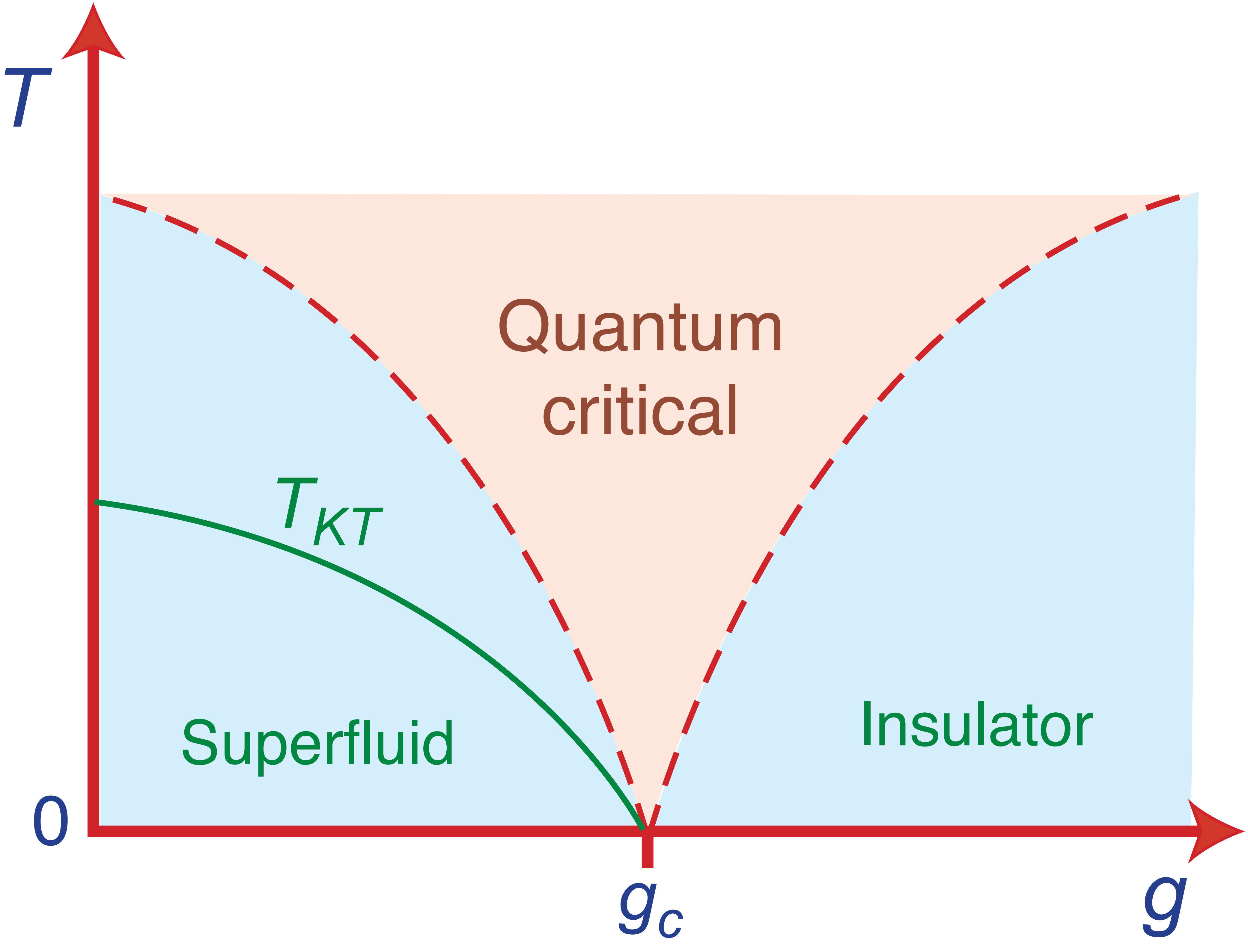


Ultracold ^{87}Rb atoms - bosons

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



Superfluid
Insulator
0
g_c
g


T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
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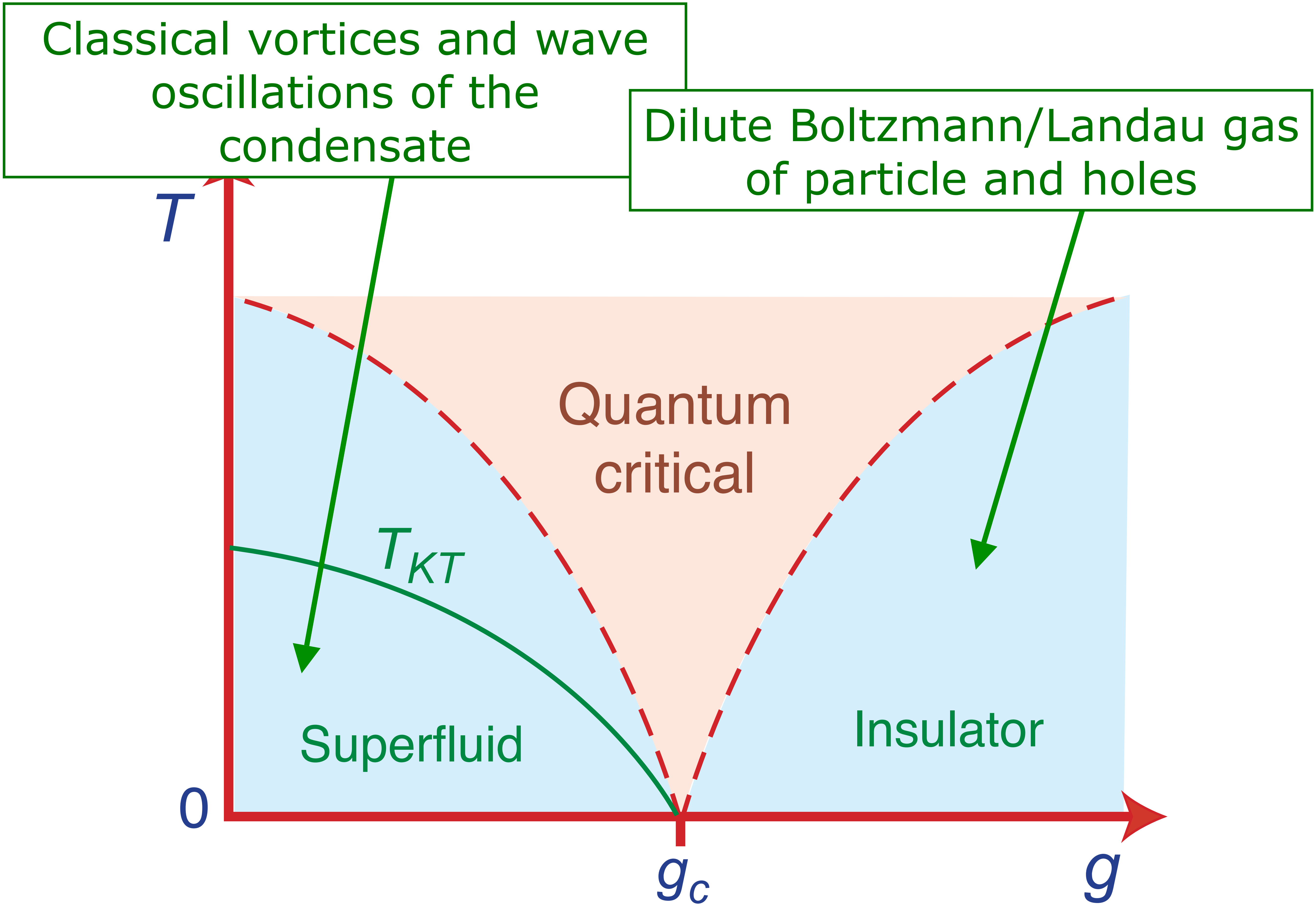
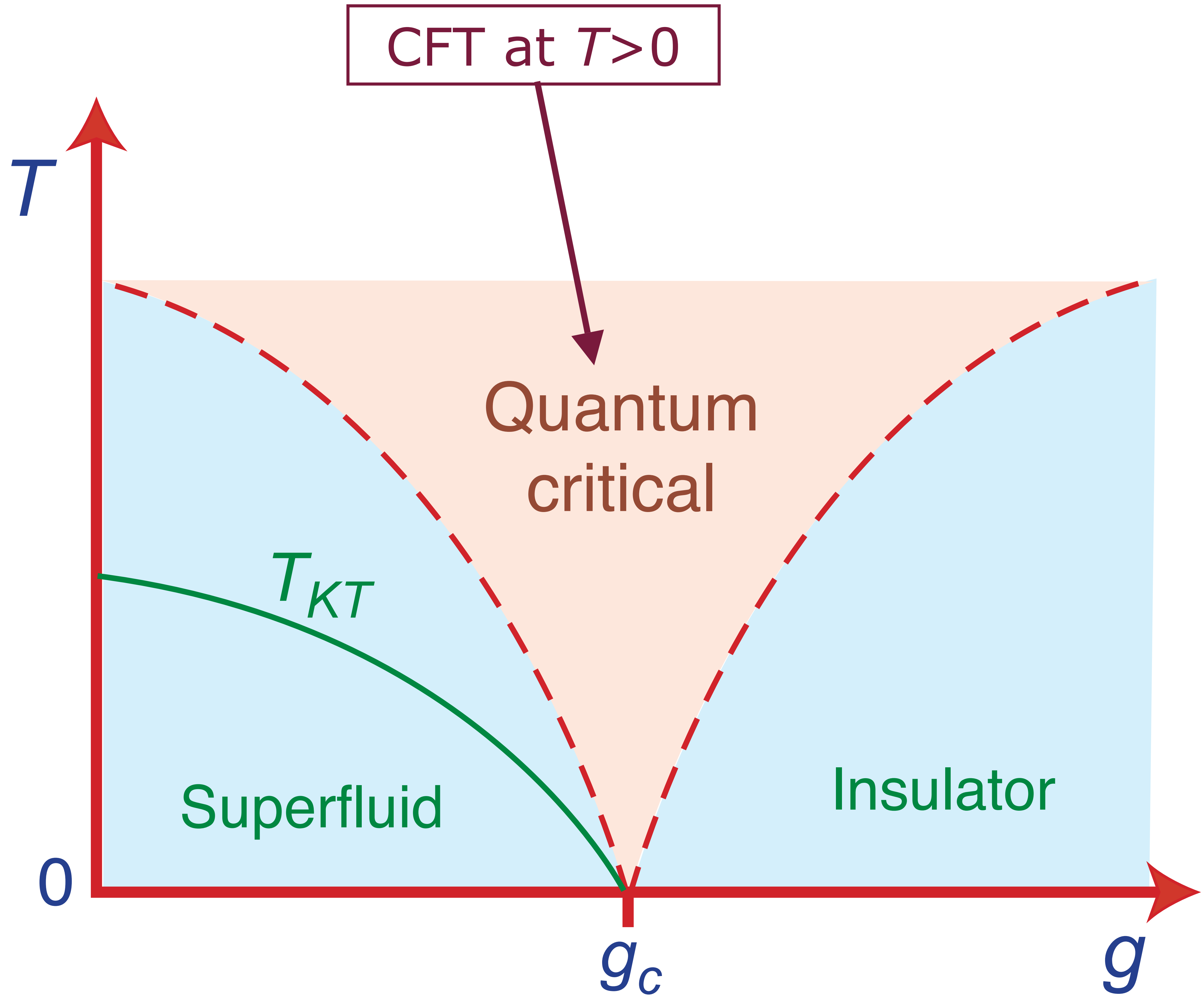

Classical vortices and wave oscillations of the condensate
Dilute Boltzmann/Landau gas of particle and holes
T
Quantum critical
T_{KT}
Superfluid
Insulator
0
g_c
g



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

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).

Quantum critical transport

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

Momentum transport

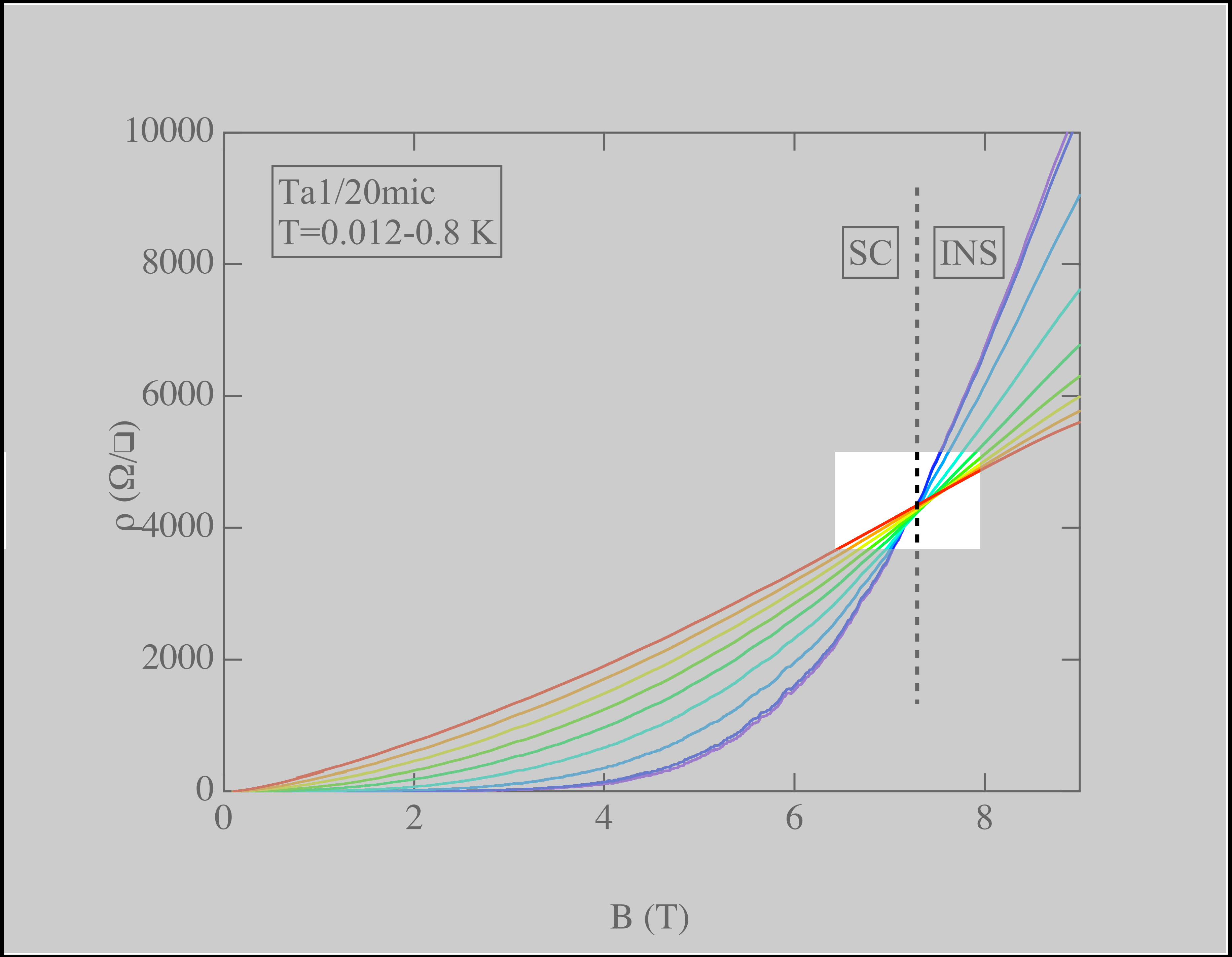
$$\frac{\eta}{s} \equiv \frac{\text{viscosity}}{\text{entropy density}}$$

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

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

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).

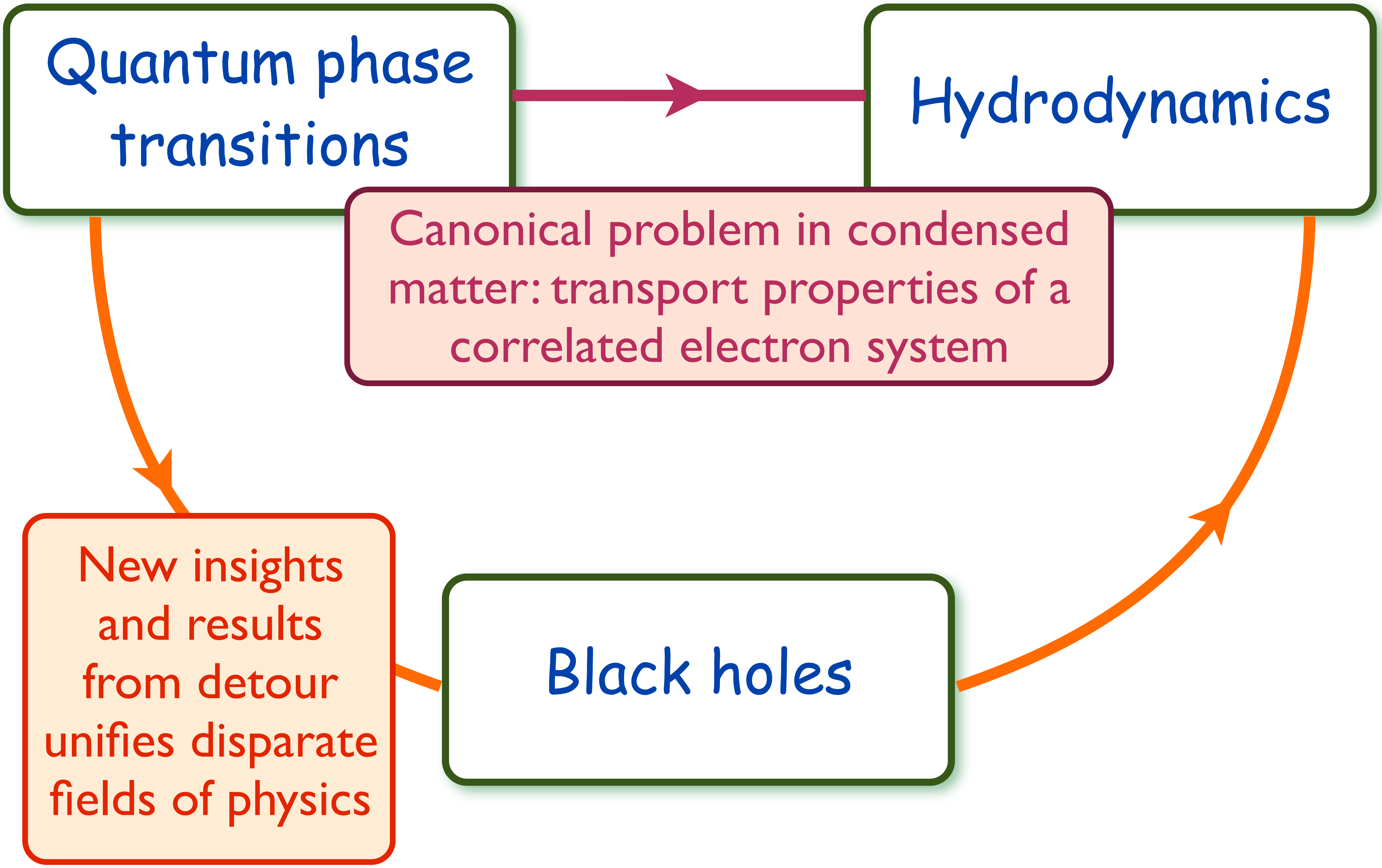
Three foci of modern physics

Quantum phase transitions

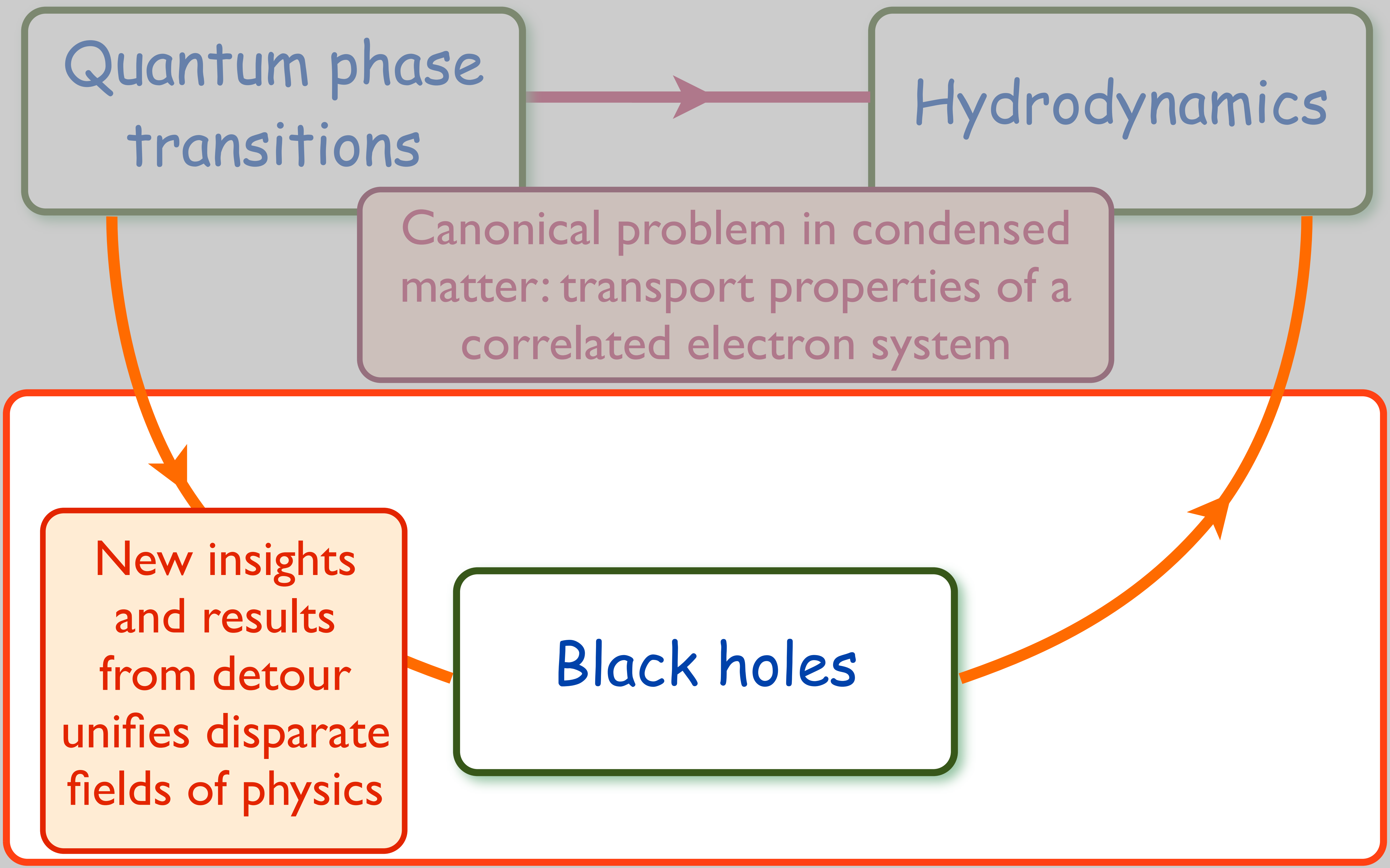
Hydrodynamics

Black holes

Three foci of modern physics



Three foci of modern physics



Black Holes

Objects so massive that light is gravitationally bound to them.

Black Holes

Objects so massive that light is gravitationally bound to them.

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 $S = \frac{k_B A}{4\ell_P^2}$

where A is the area of the horizon, and

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

The Second Law: $dA \geq 0$

Black Hole Thermodynamics

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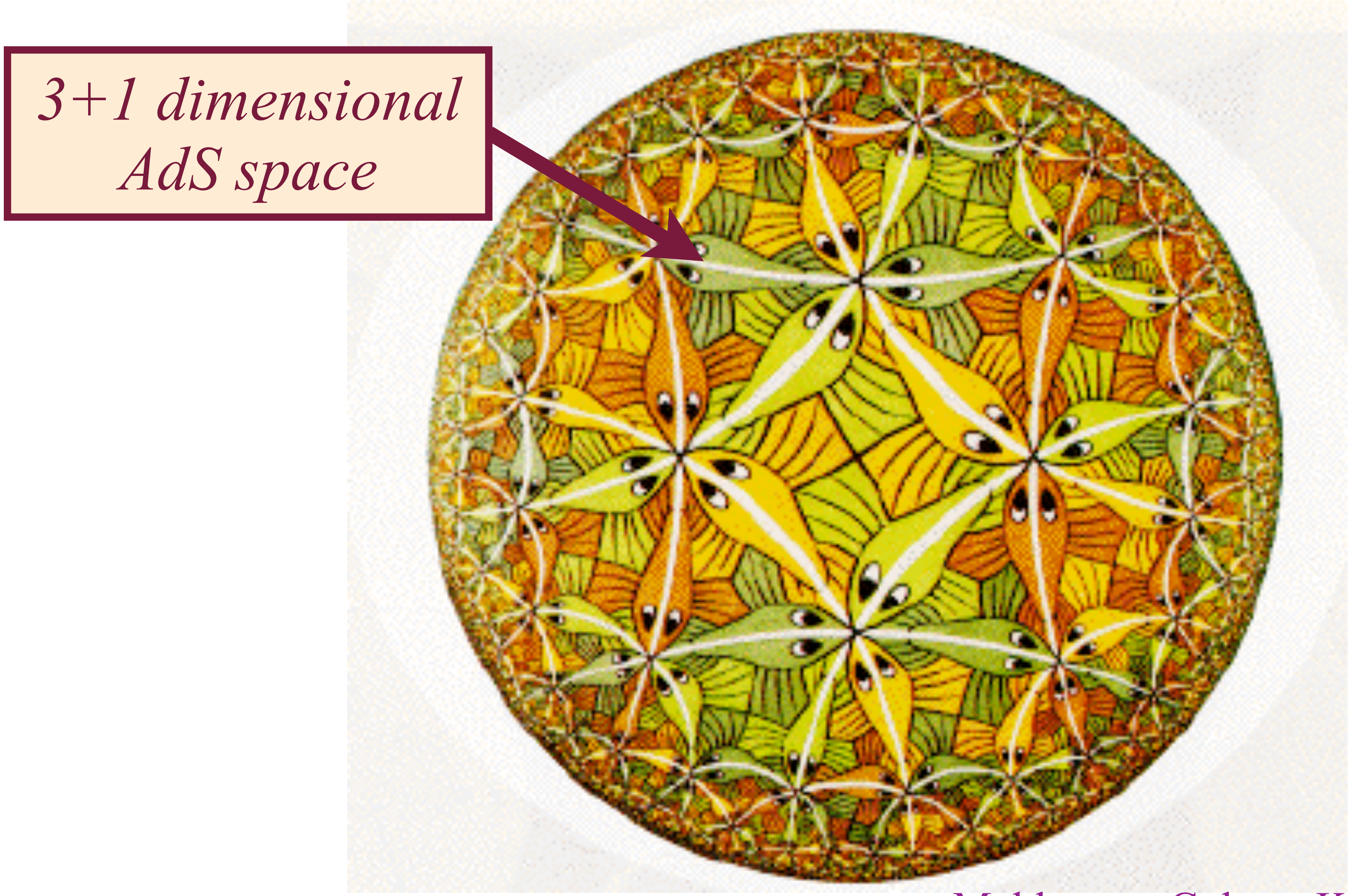
$$\text{Horizon temperature: } 4\pi k_B T = \frac{\hbar^2}{2M\ell_P^2}$$

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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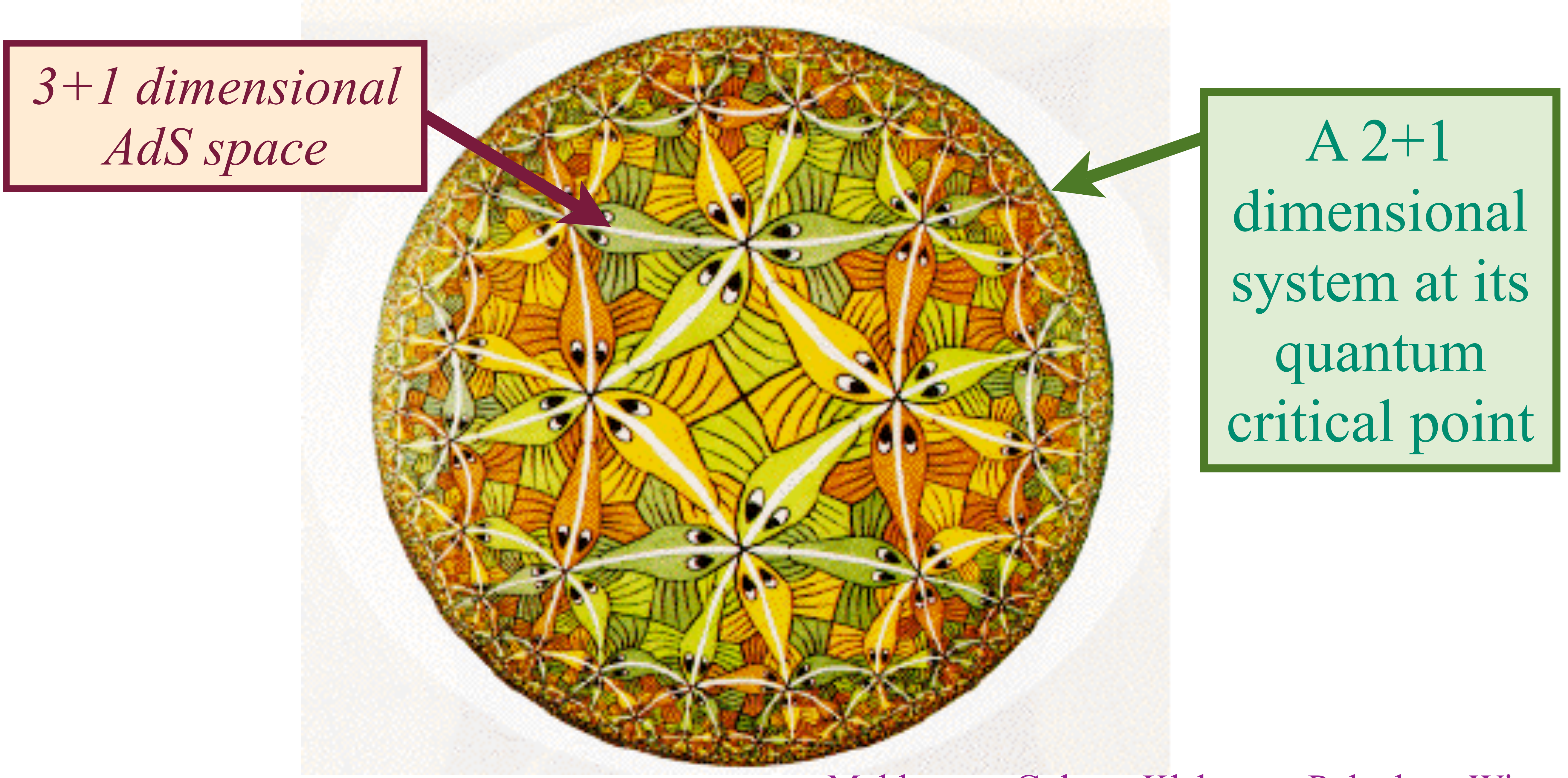

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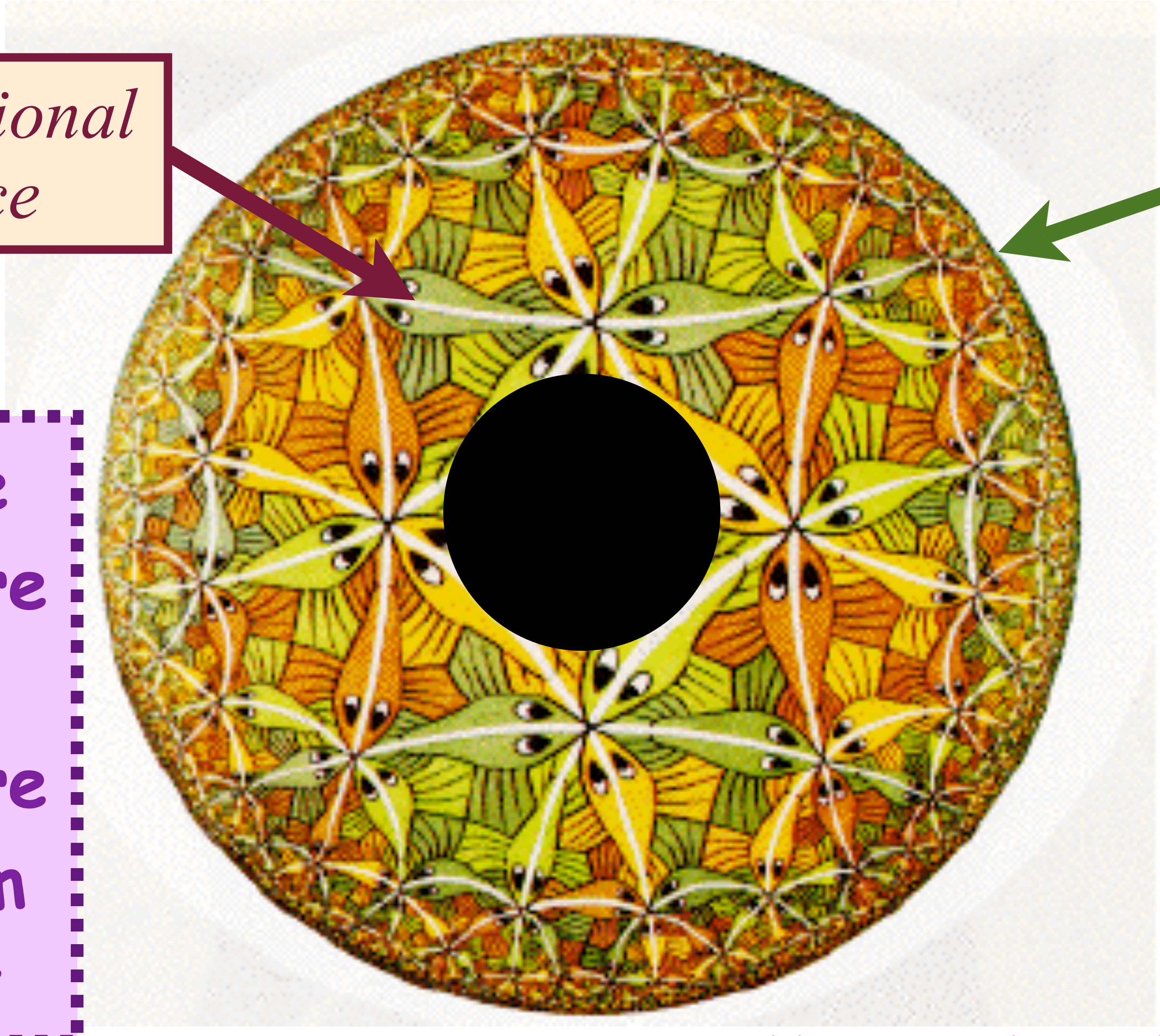
3+1 dimensional AdS space



Quantum criticality in 2+1 dimensions

Black hole temperature = temperature of quantum criticality

Maldacena, Gubser, Klebanov, Polyakov, Witten

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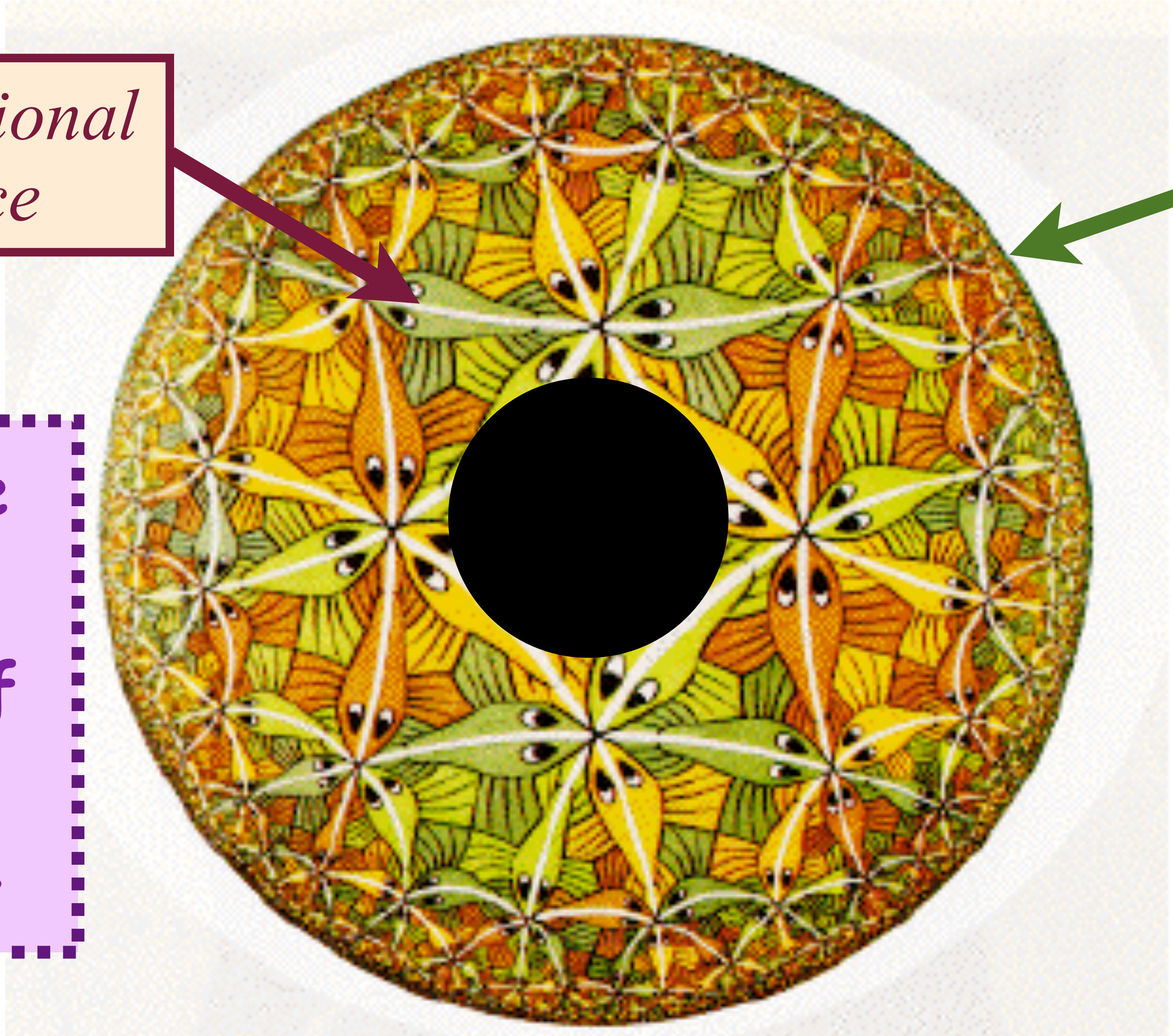

Black hole entropy = entropy of quantum criticality

Strominger, Vafa

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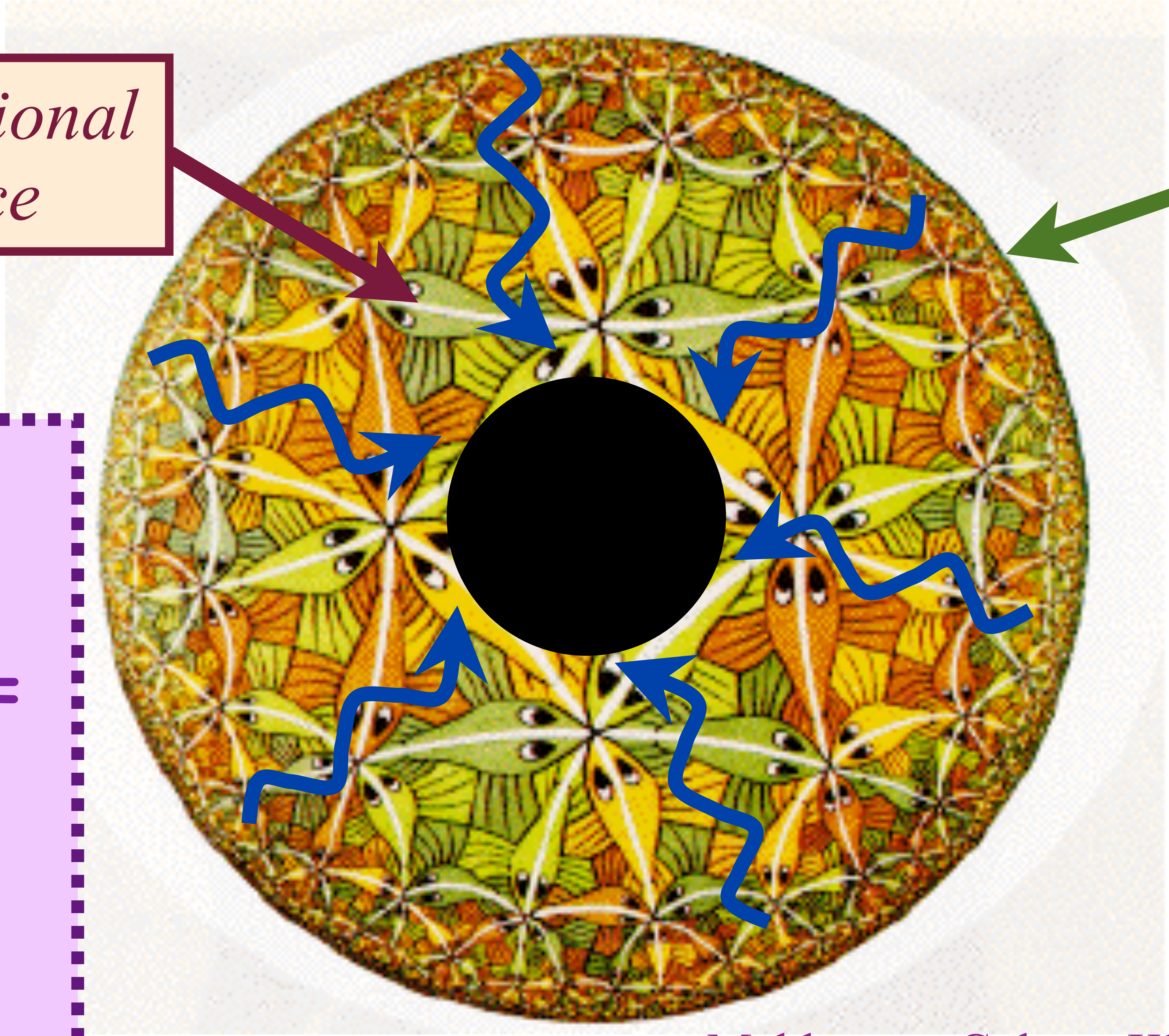

3+1 dimensional AdS space

Quantum criticality in 2+1 dimensions

Quantum critical dynamics = waves in curved space

Maldacena, Gubser, Klebanov, Polyakov, Witten

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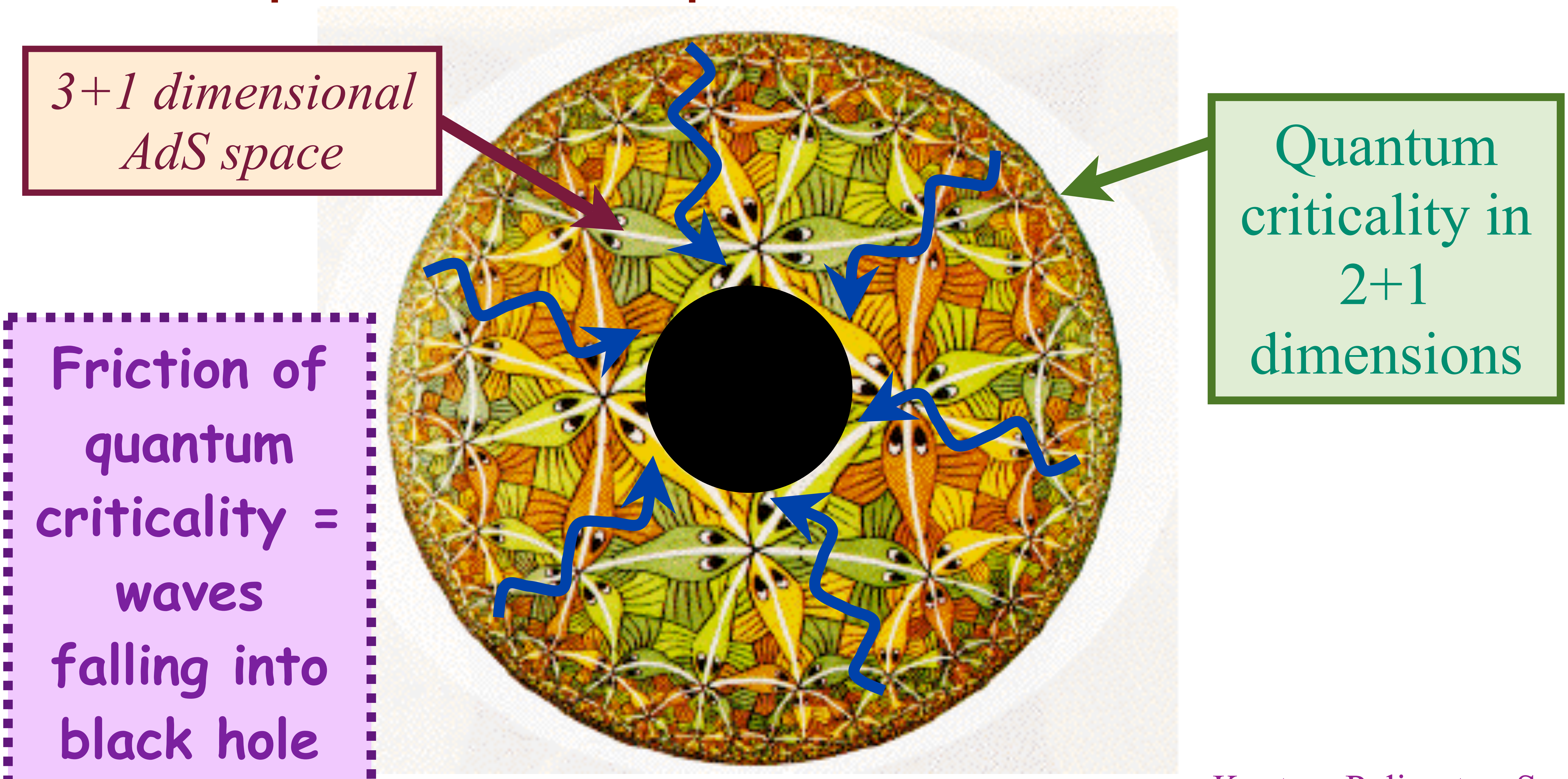
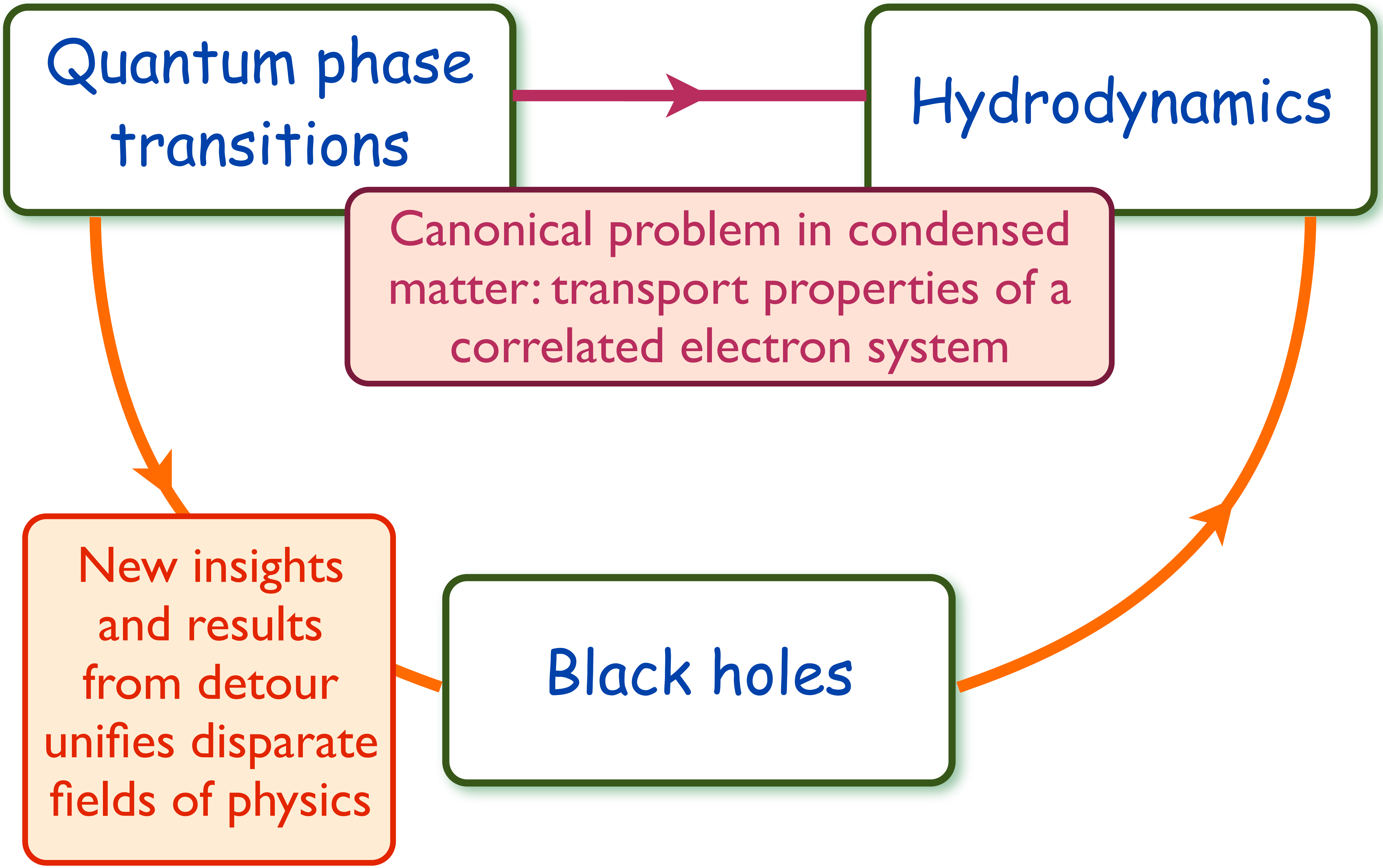


Kovtun, Policastro, Son

Three foci of modern physics



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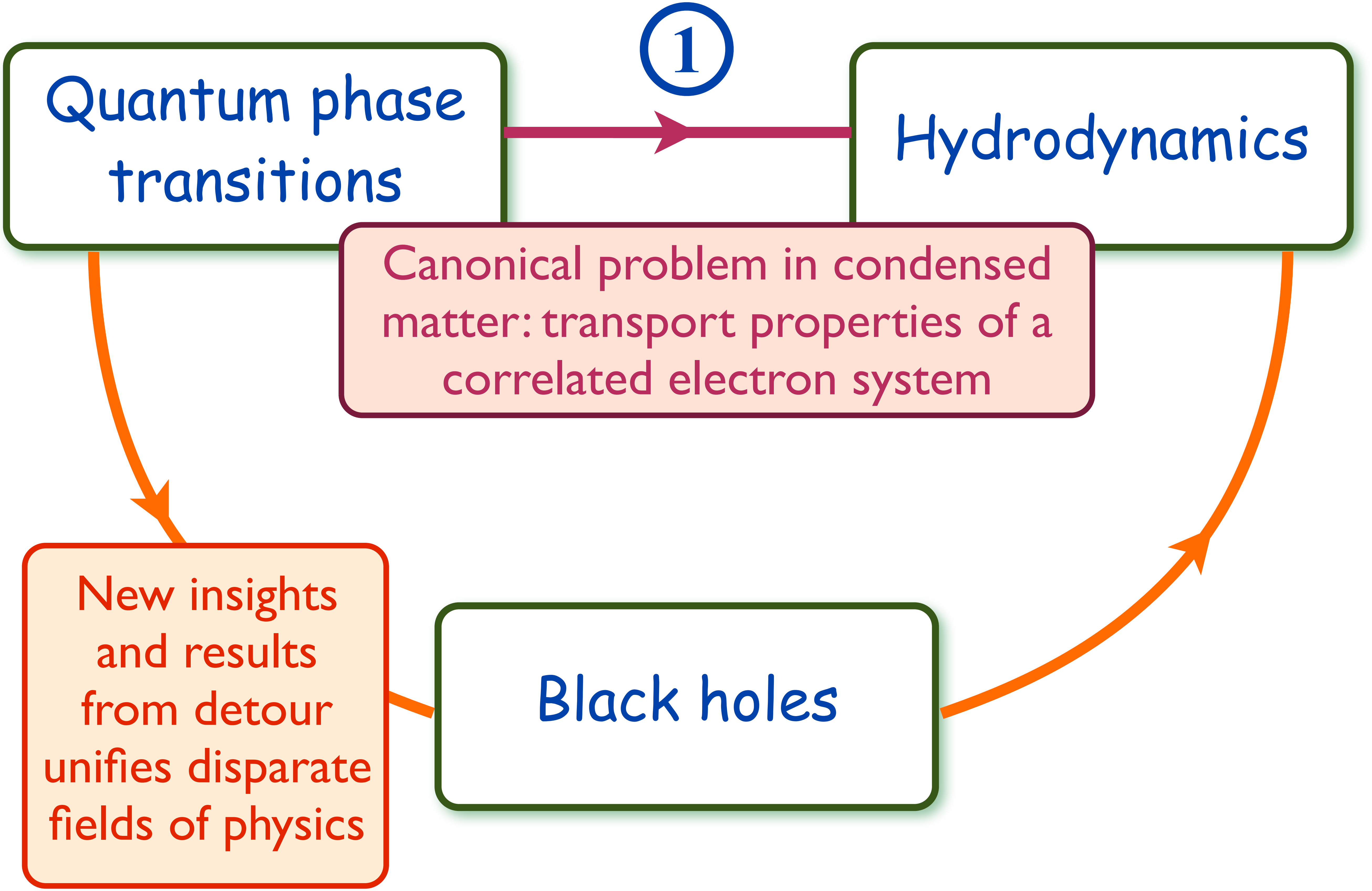
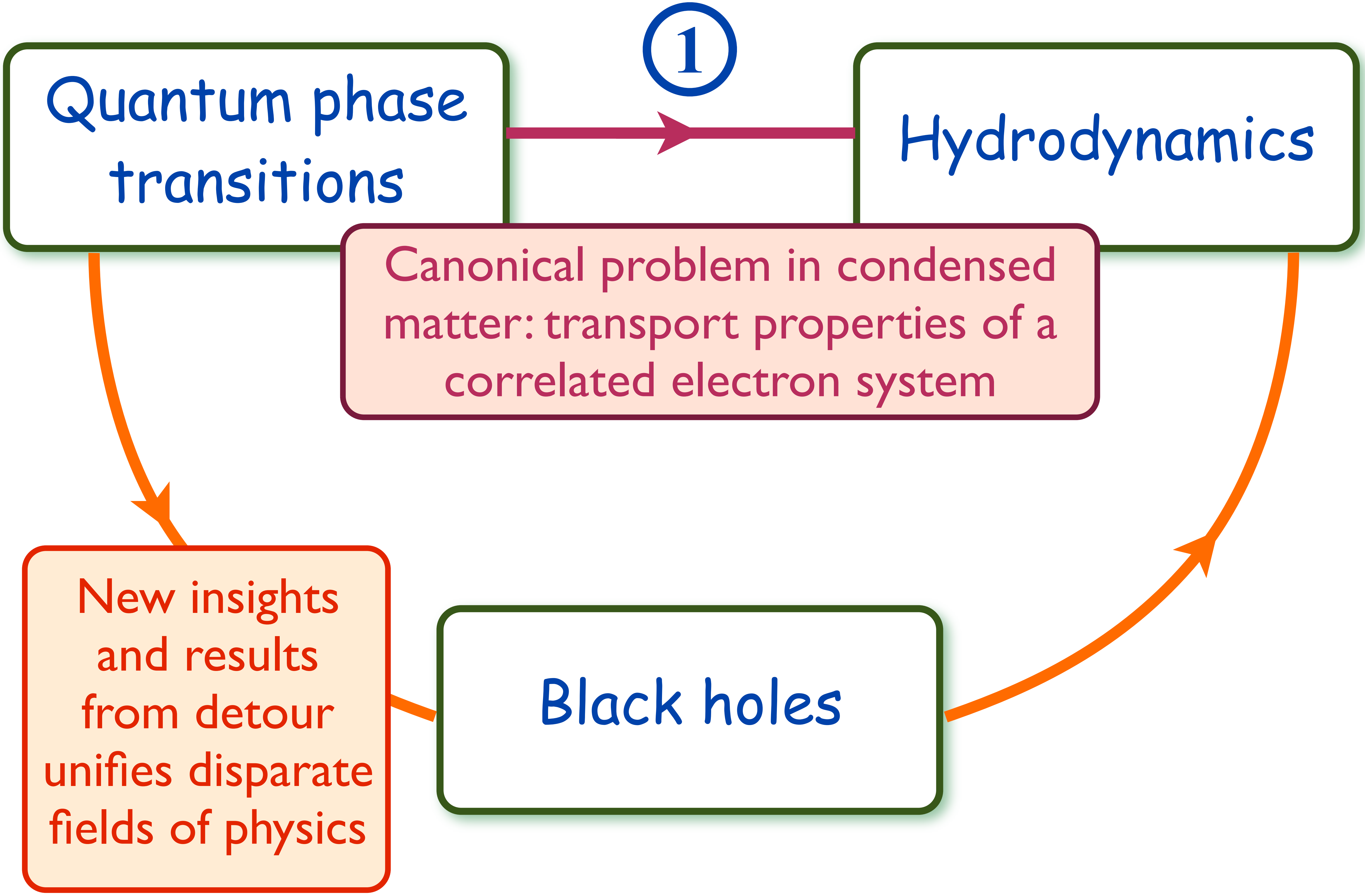


Hydrodynamics of quantum critical systems

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

   Uses physical model but strong-coupling makes explicit solution difficult

Three foci of modern physics



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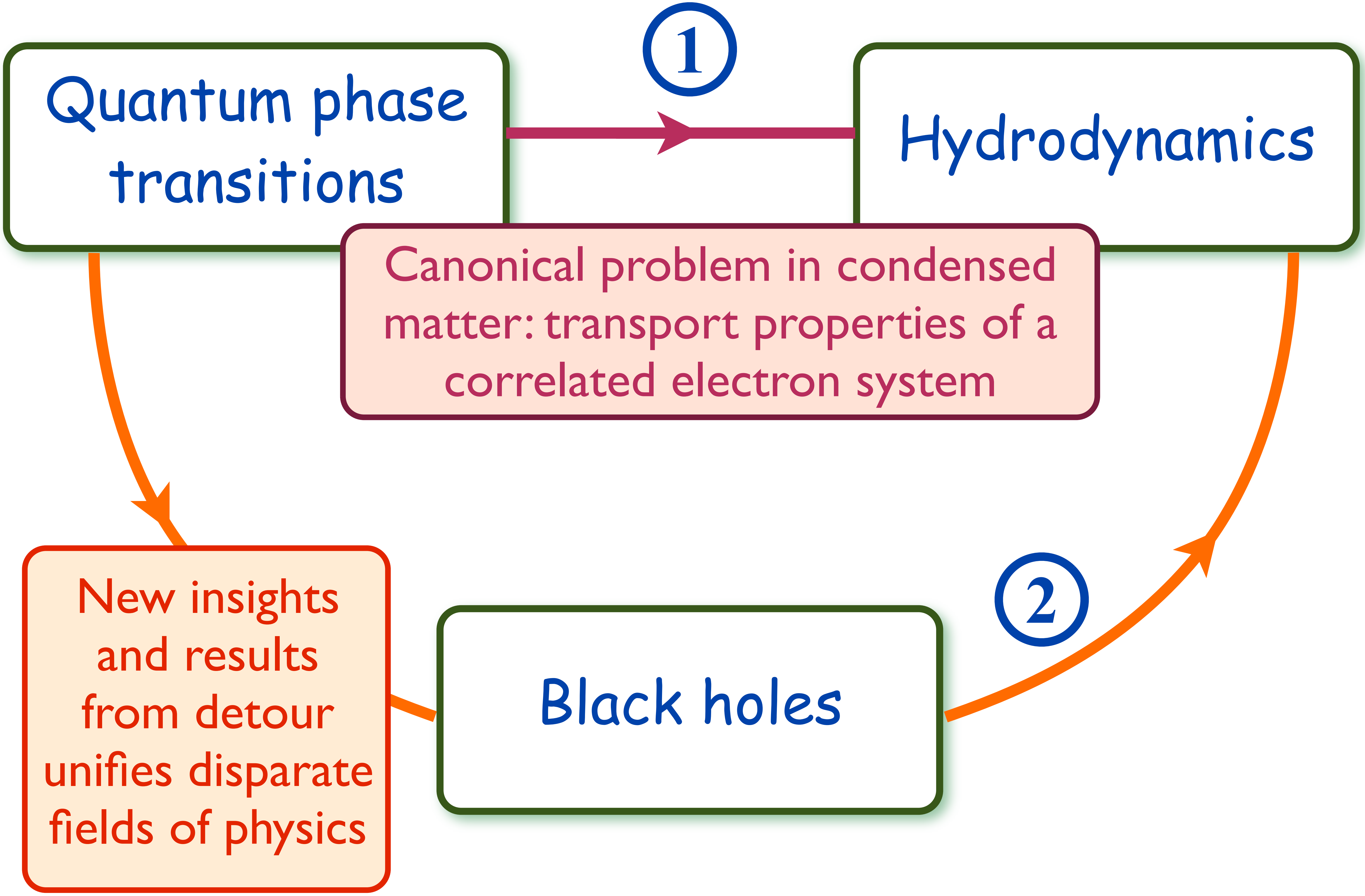

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Find perfect agreement between 1. and 2.
In some cases, results were obtained by 2. earlier !!

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

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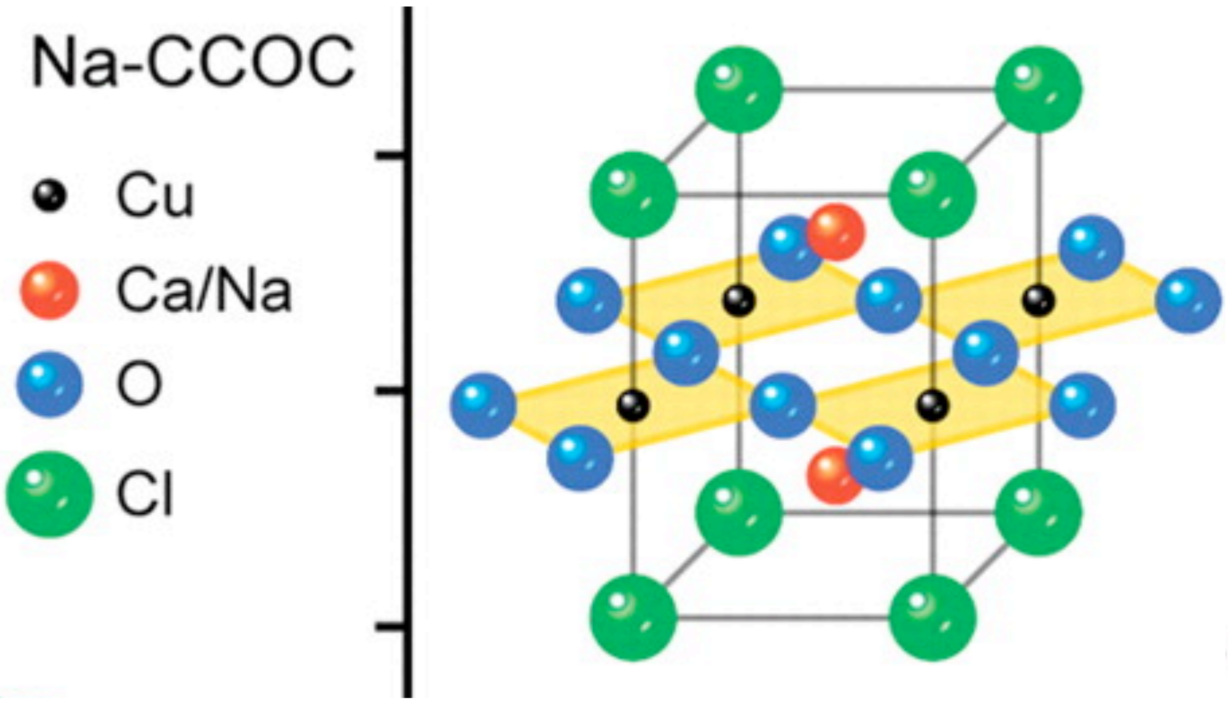
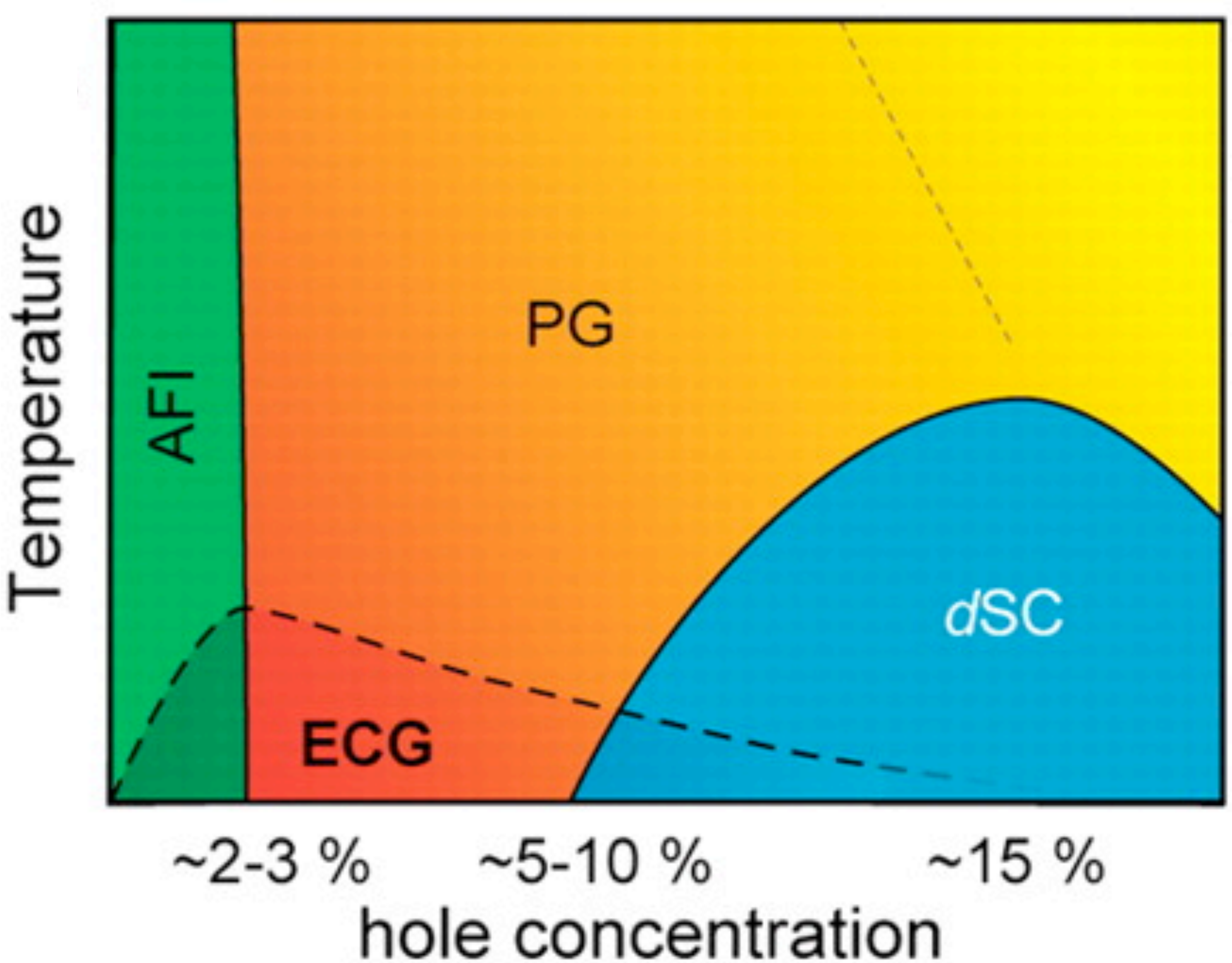
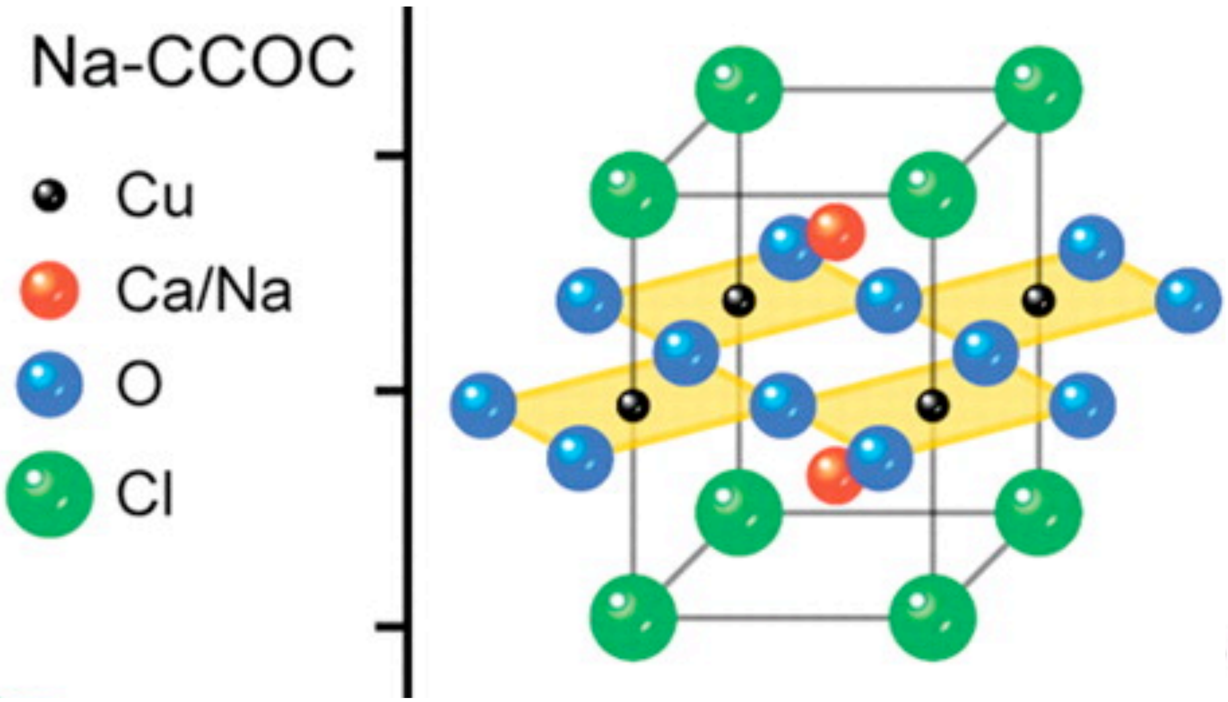
The cuprate superconductors

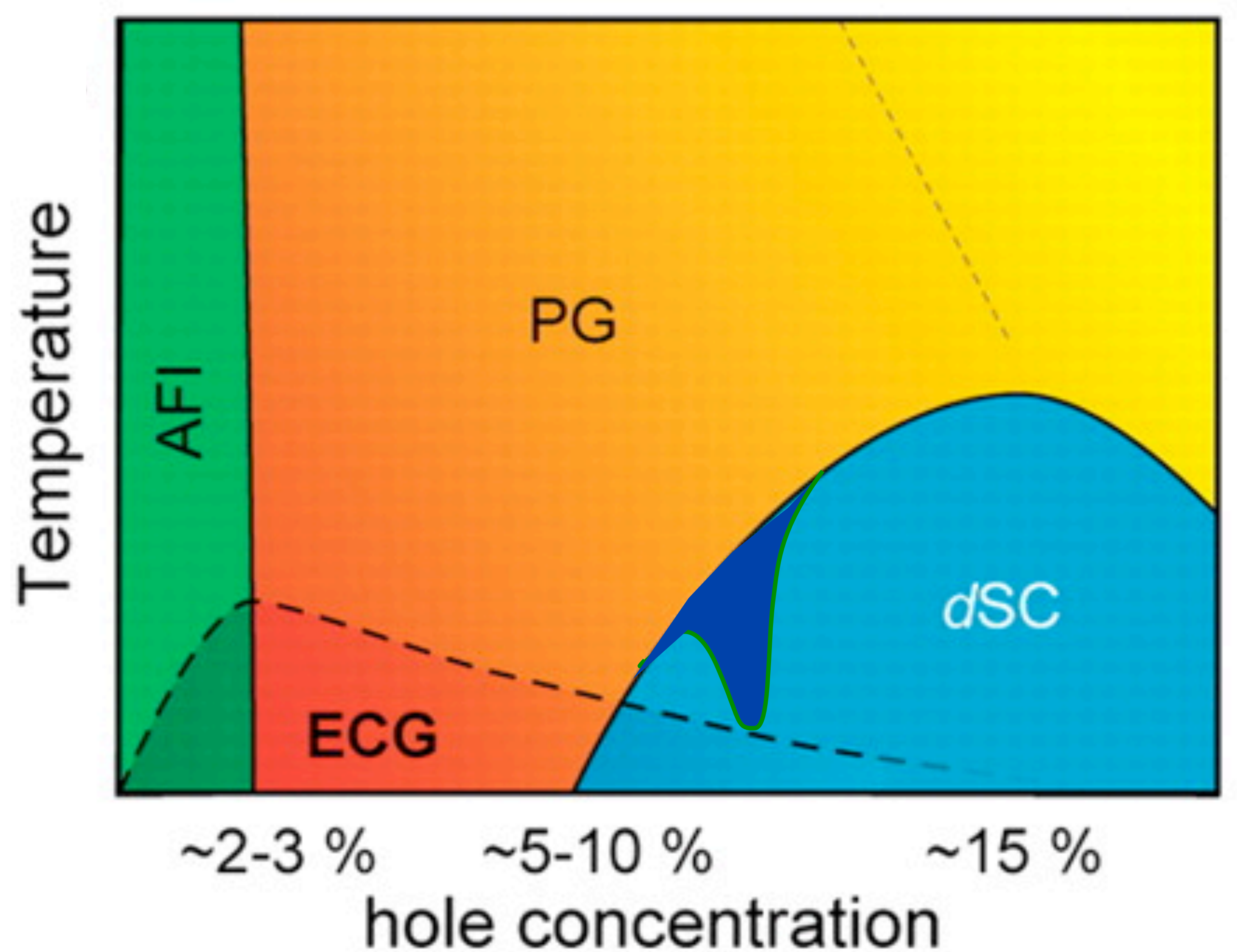




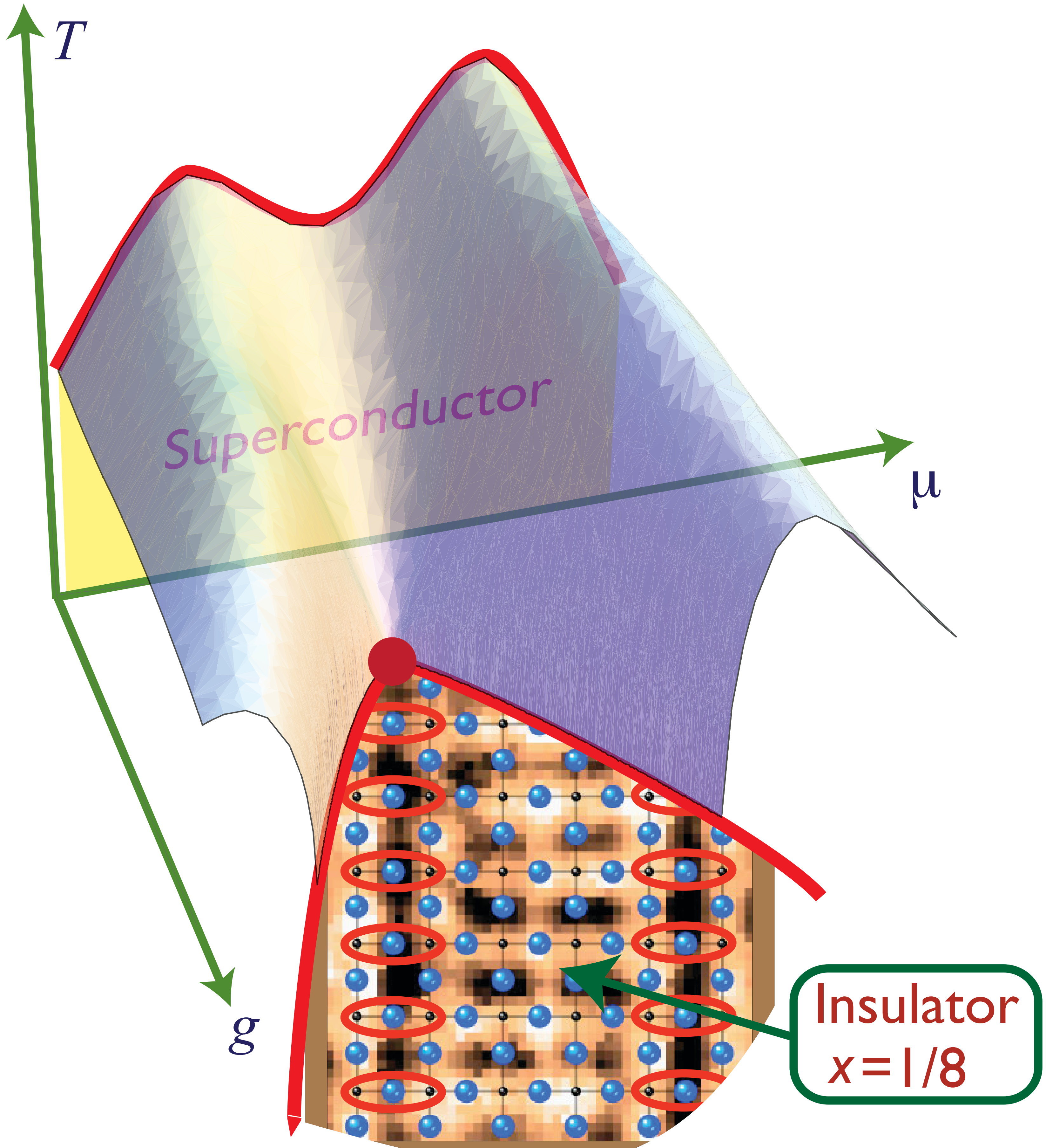
The cuprate superconductors



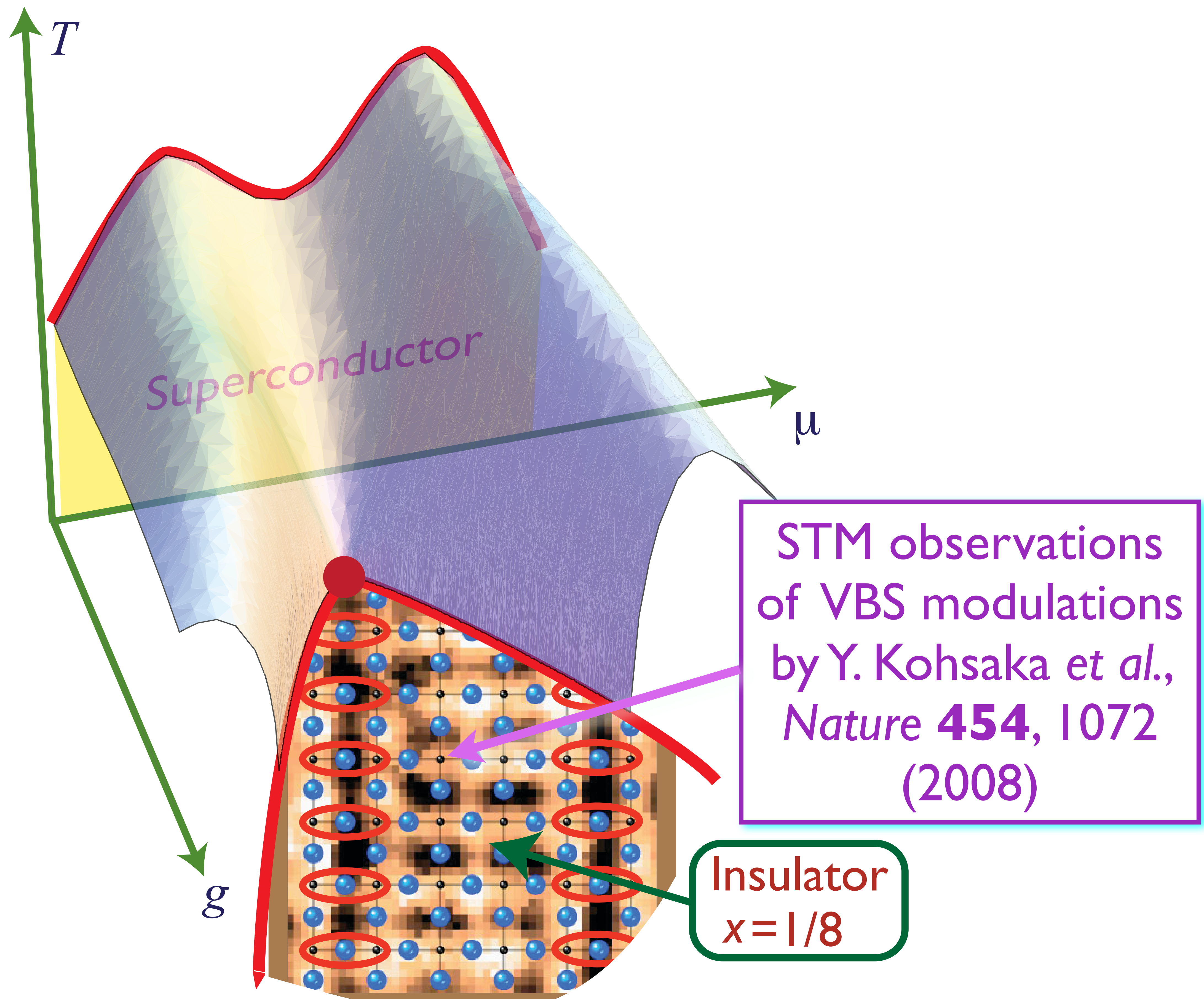
Proximity to an insulator at 12.5% hole concentration in the "underdoped" regime



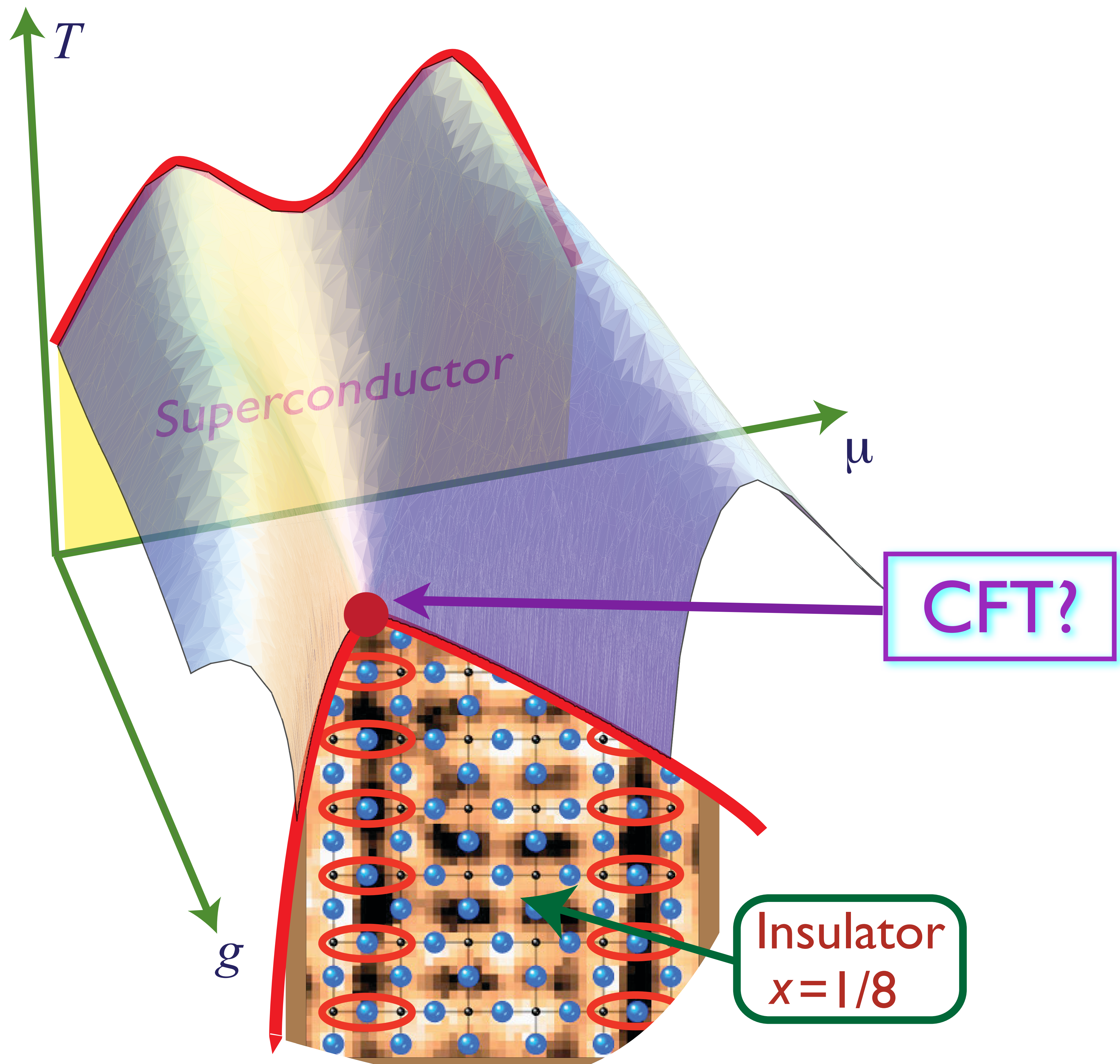
Underdoped Cuprates



Underdoped Cuprates



Underdoped Cuprates



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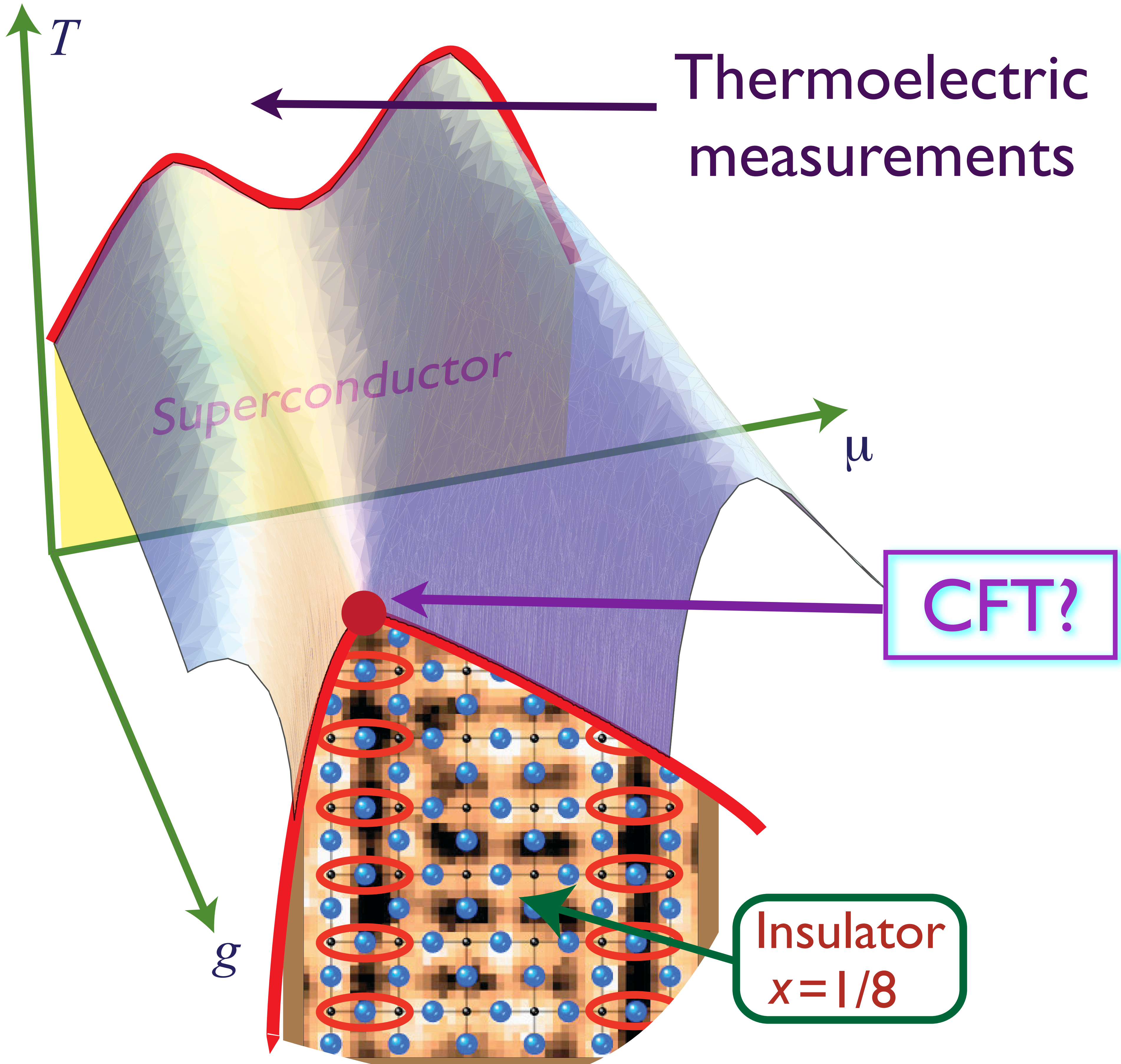
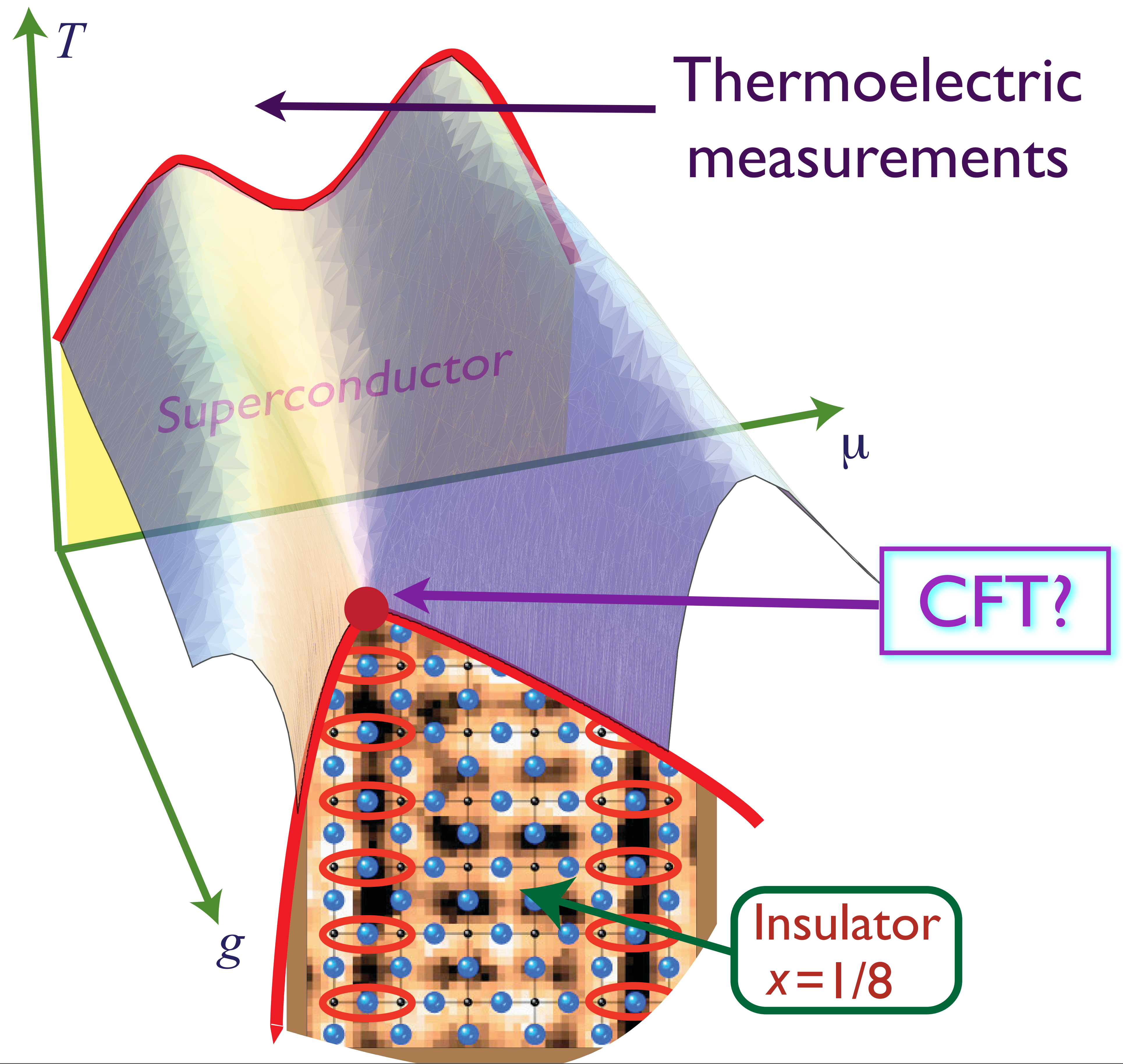


Underdoped Cuprates



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 $B = 0$

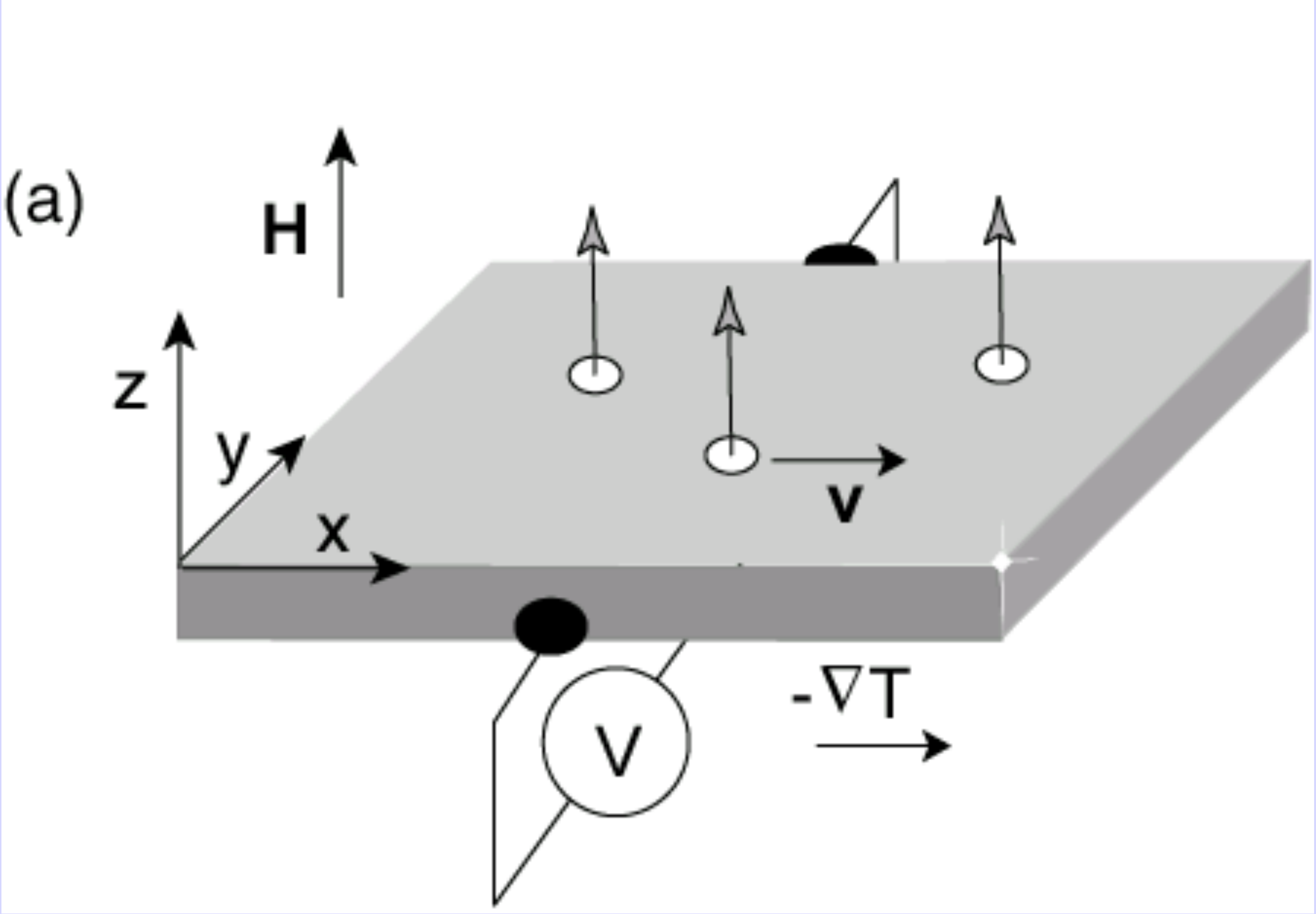
$$\kappa = \sigma_Q \left(\frac{k_B^2 T}{e^{*2}} \right) \left(\frac{\varepsilon + P}{k_B T \rho} \right)^2 .$$

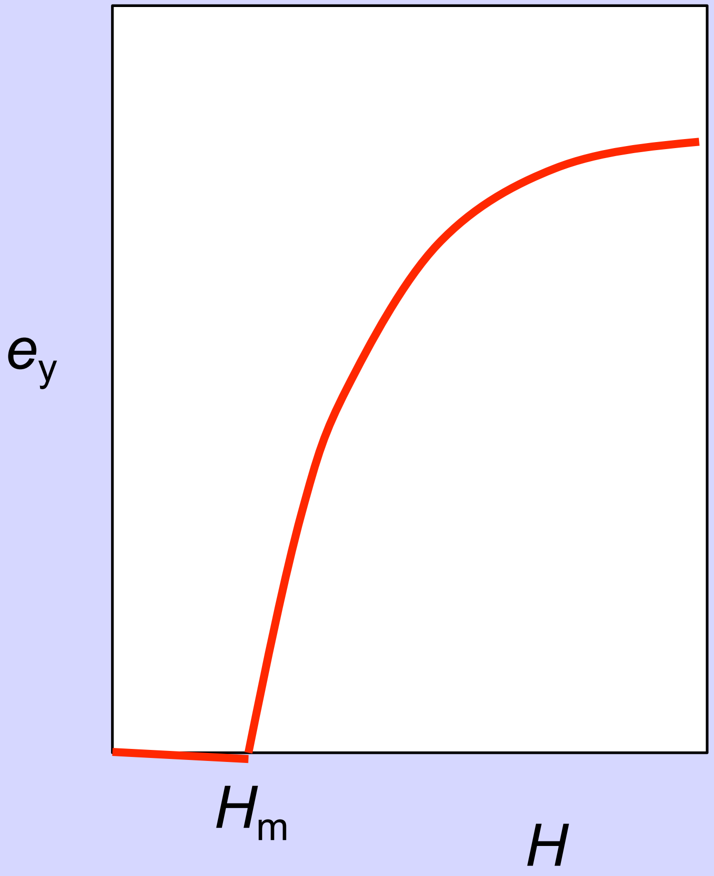
At $B \neq 0$ and $\rho = 0$ we have a "Wiedemann-Franz" relation for "vortices"

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

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

Nernst experiment





Nernst signal (transverse thermoelectric response)

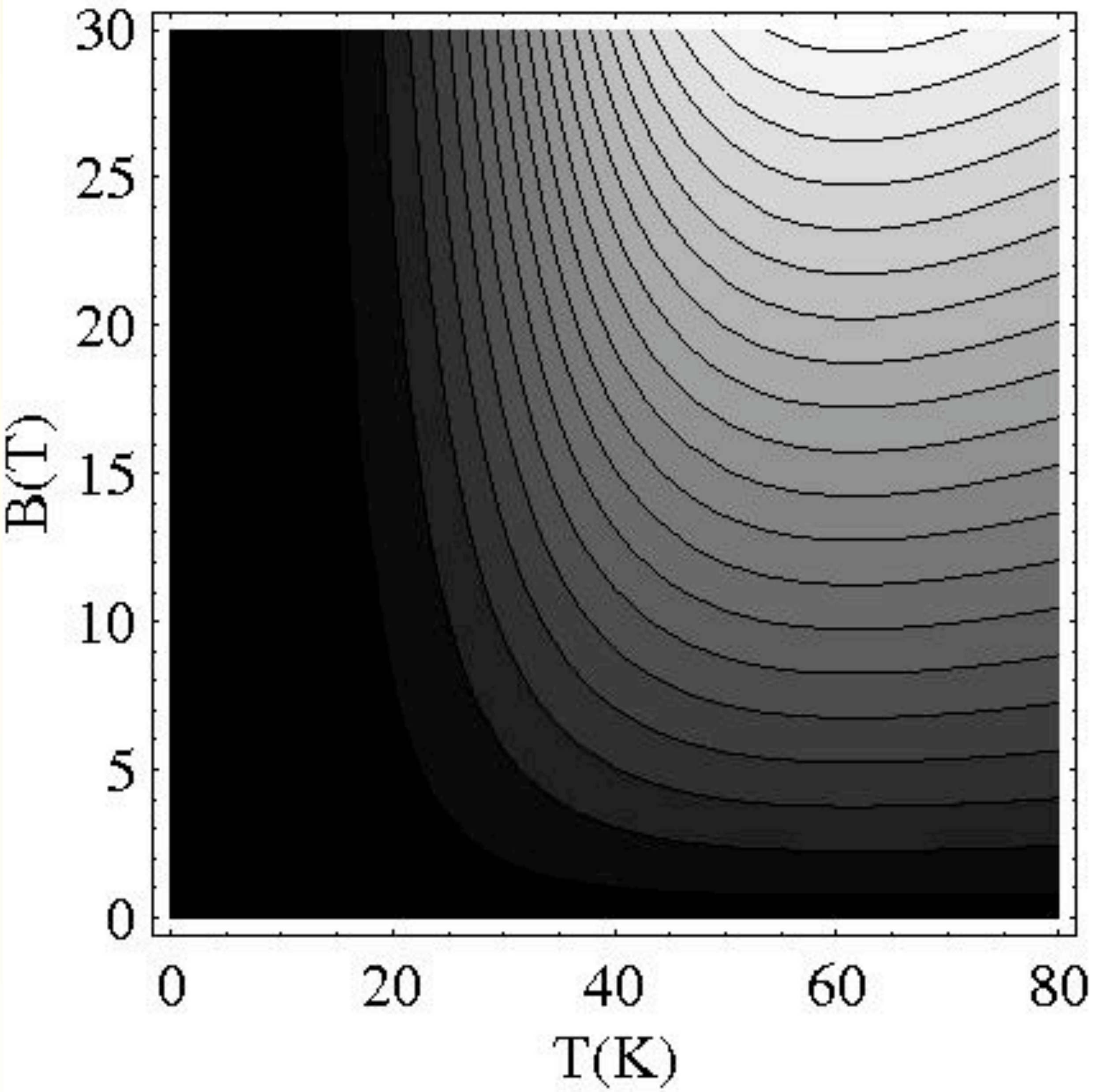
$$e_N = \left(\frac{k_B}{e^*}\right)\left(\frac{\varepsilon + P}{k_B T \rho}\right)\left[\frac{\omega_c/\tau_{\rm imp}}{(\omega_c^2/\gamma + 1/\tau_{\rm imp})^2 + \omega_c^2}\right]$$

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

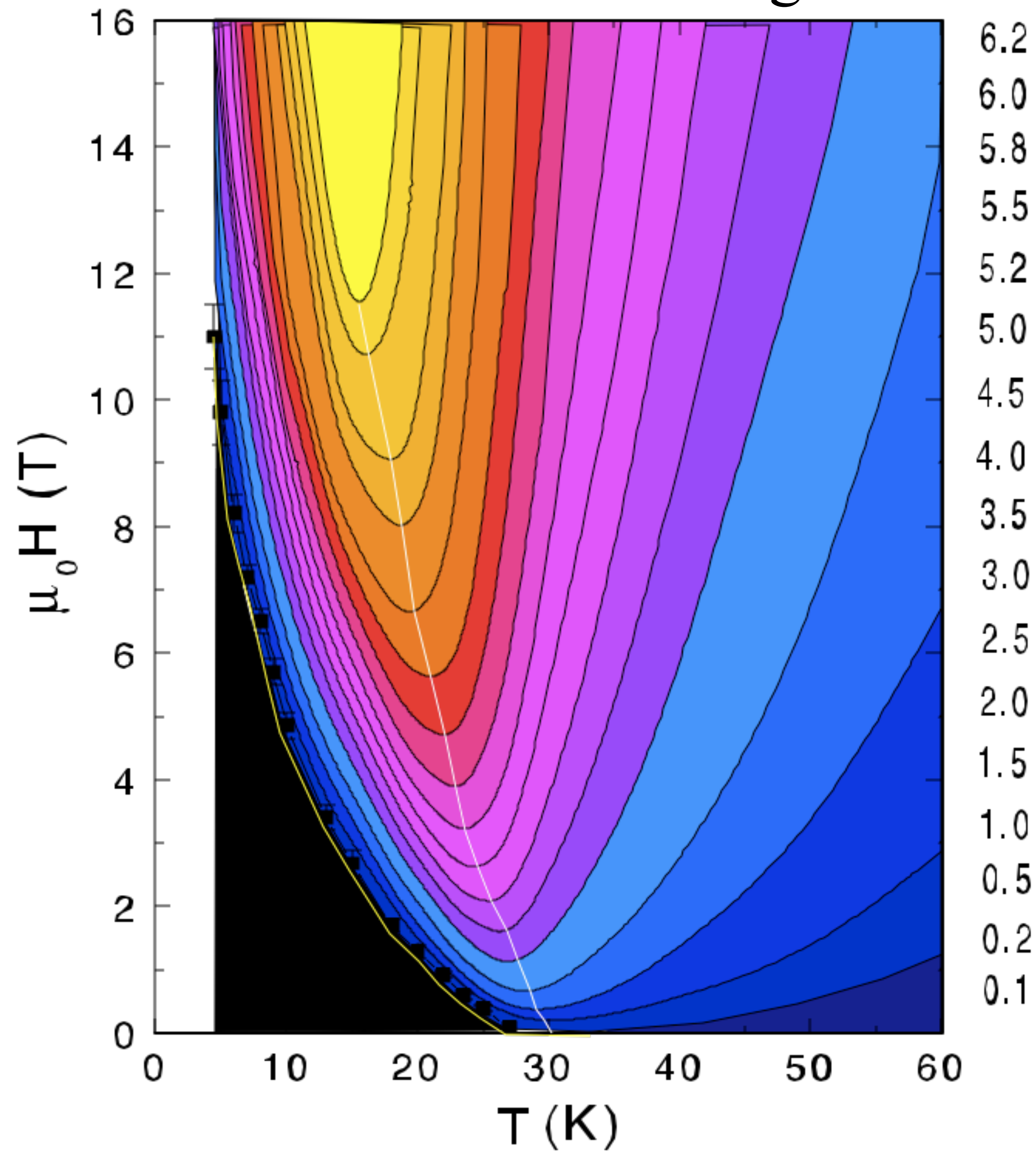
S.A. Hartnoll, P.K. Kovtun, M. Müller, and S. Sachdev, *Phys. Rev.* B **76** 144502 (2007)

LSCO Experiments

Theory for N



LSCO-0.12 Nernst signal 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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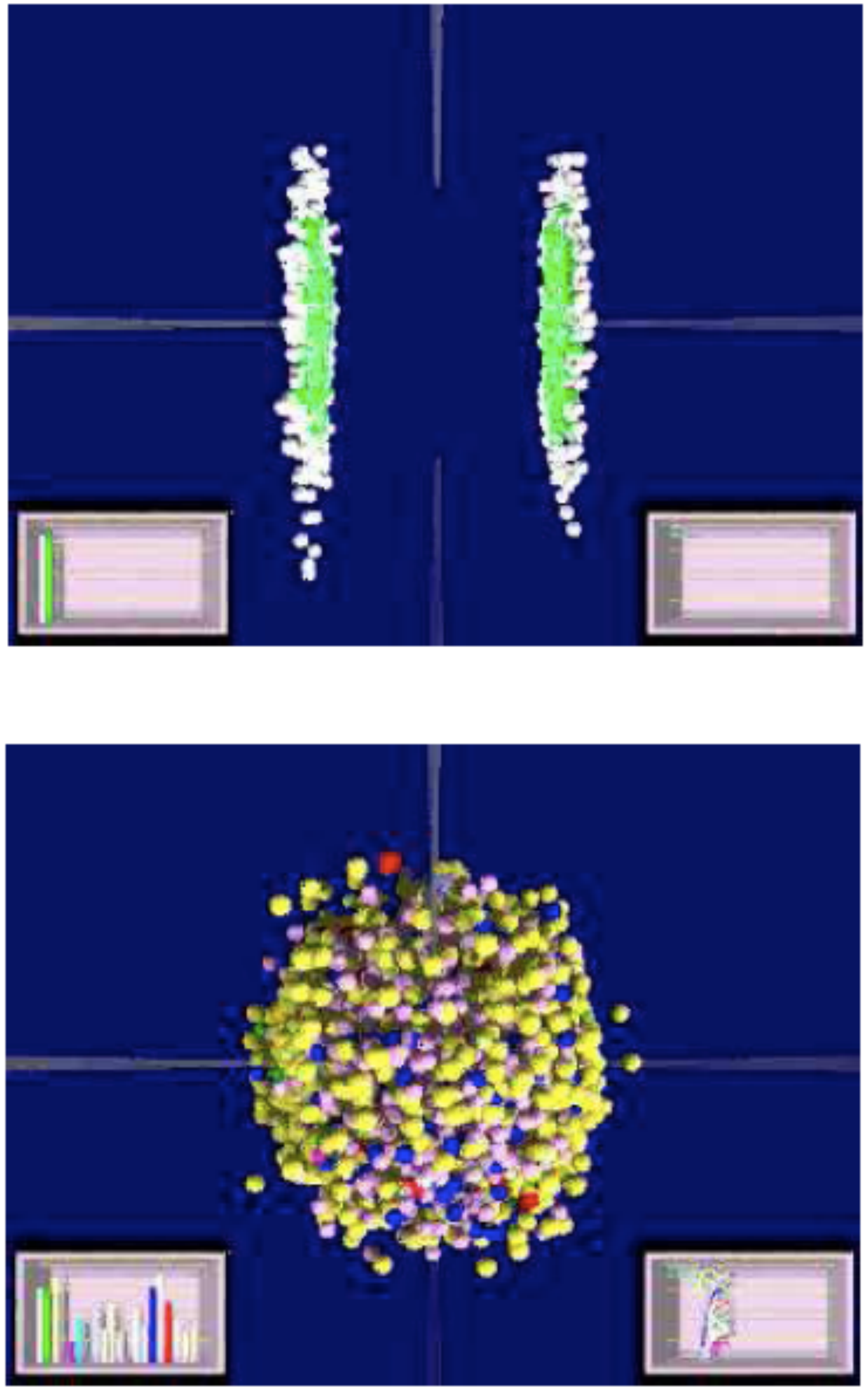
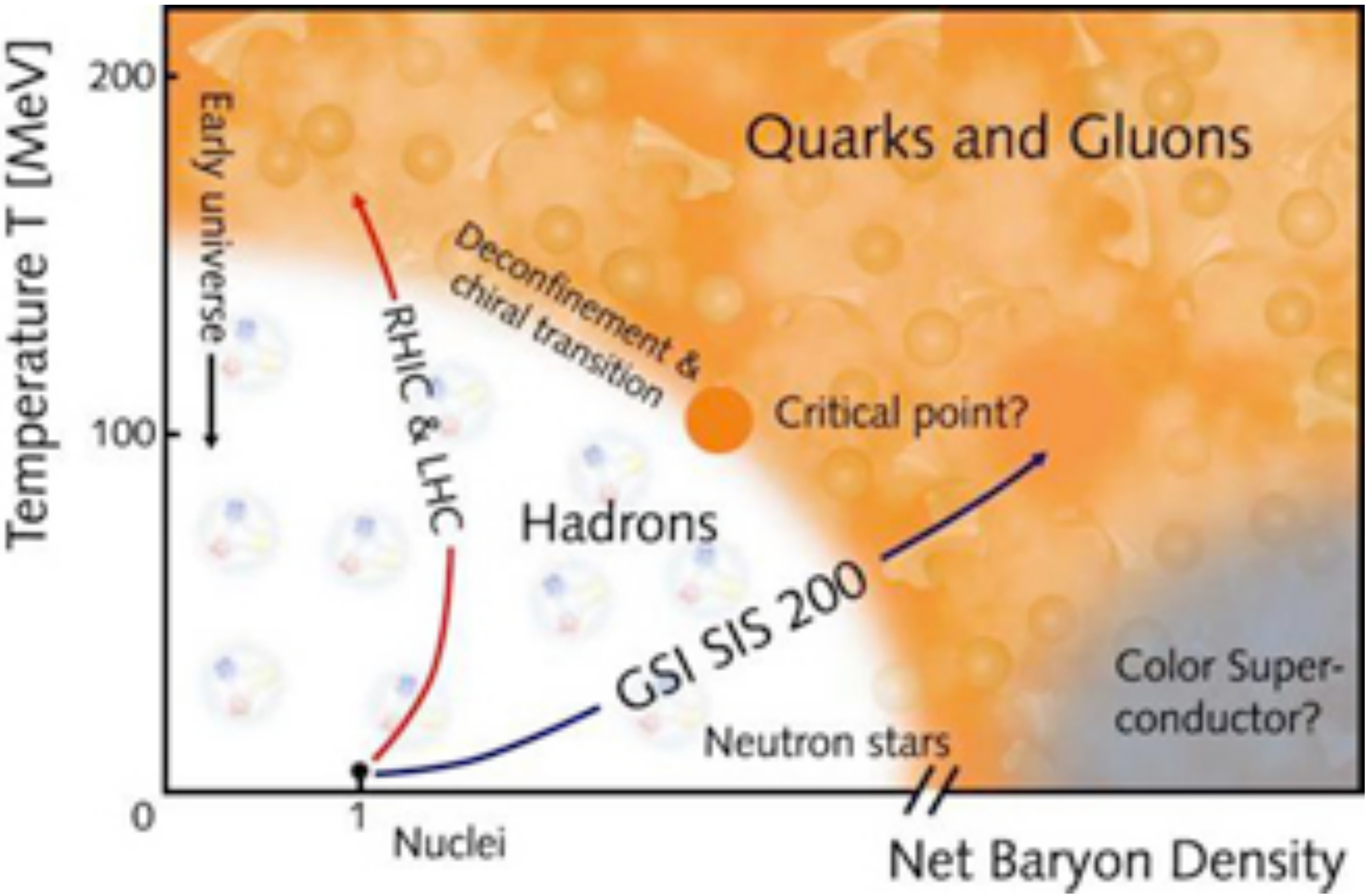
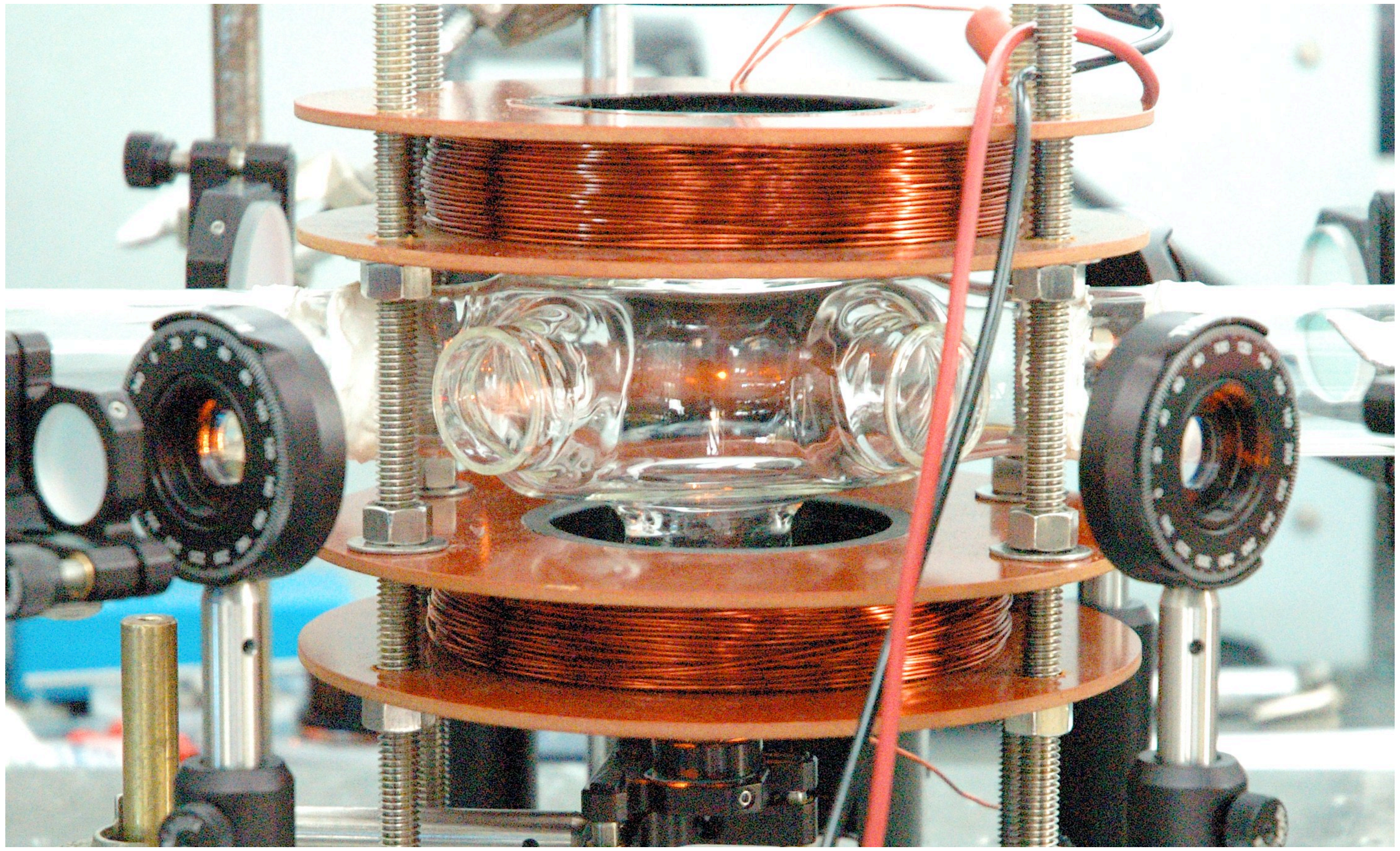
Au+Au collisions at RHIC



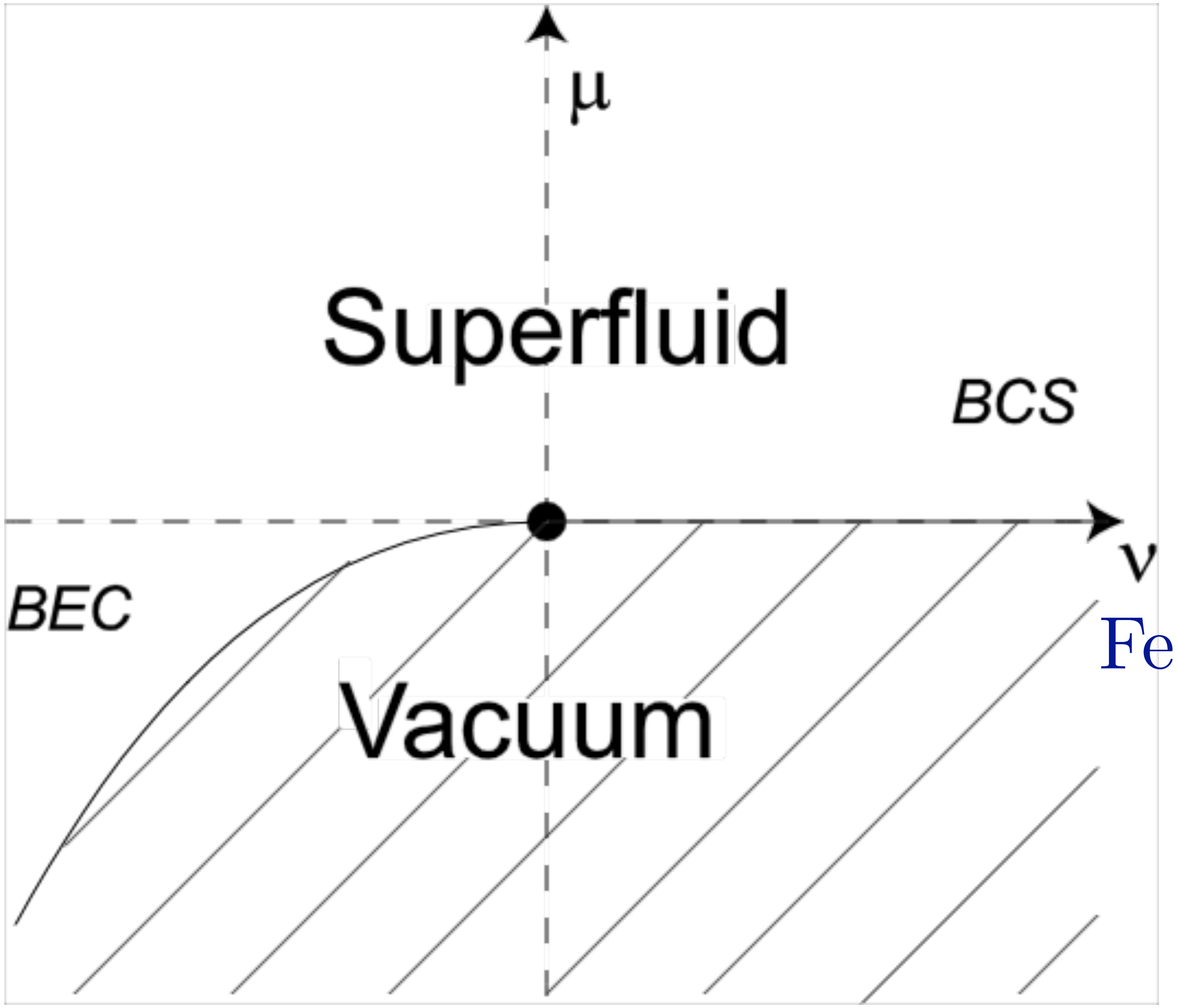
Quark-gluon plasma can be described as "quantum critical QCD"

Phases of nuclear matter

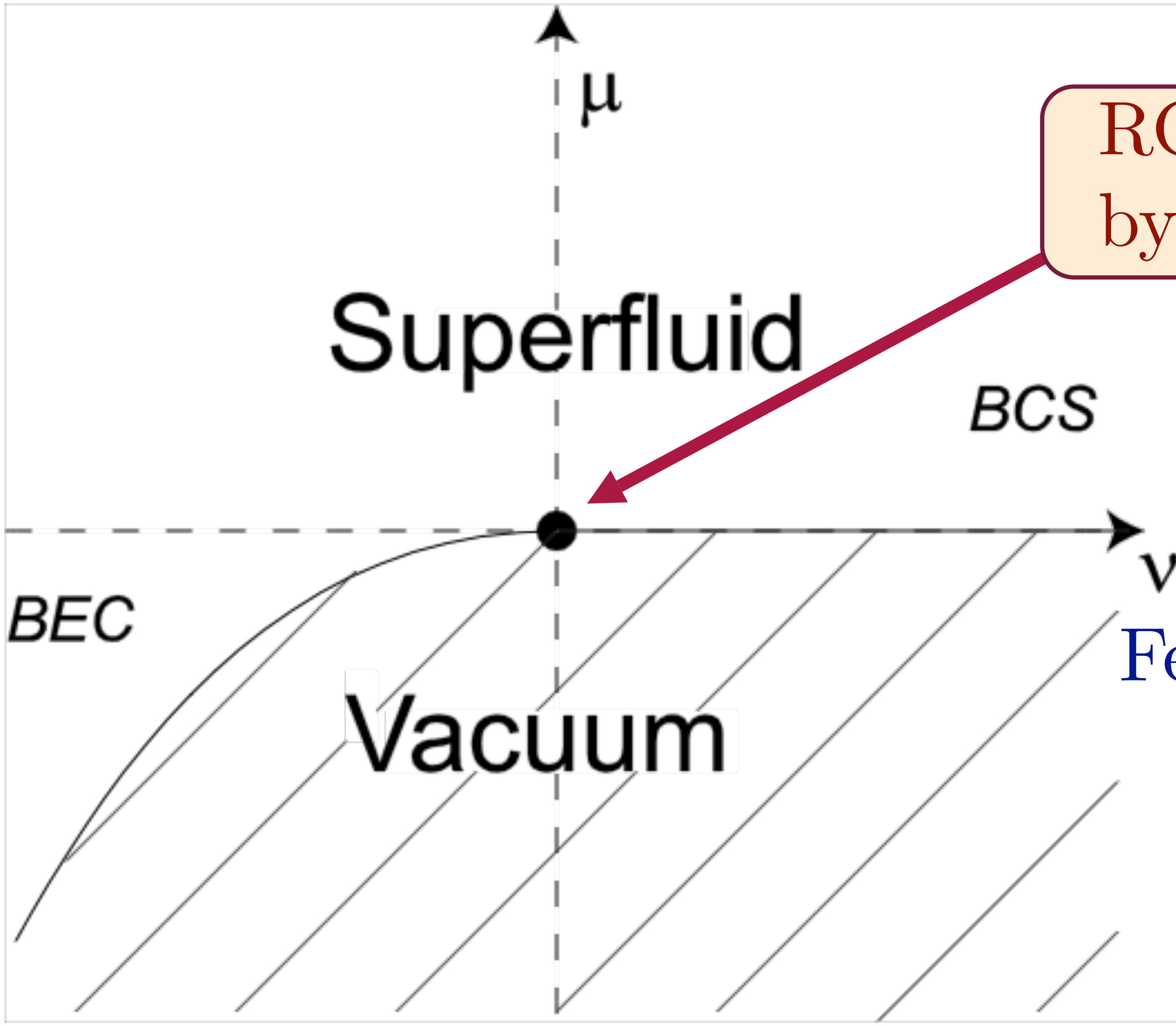




S=1/2 Fermi gas
at a Feshbach
resonance



= detuning from Feshbach resonance



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

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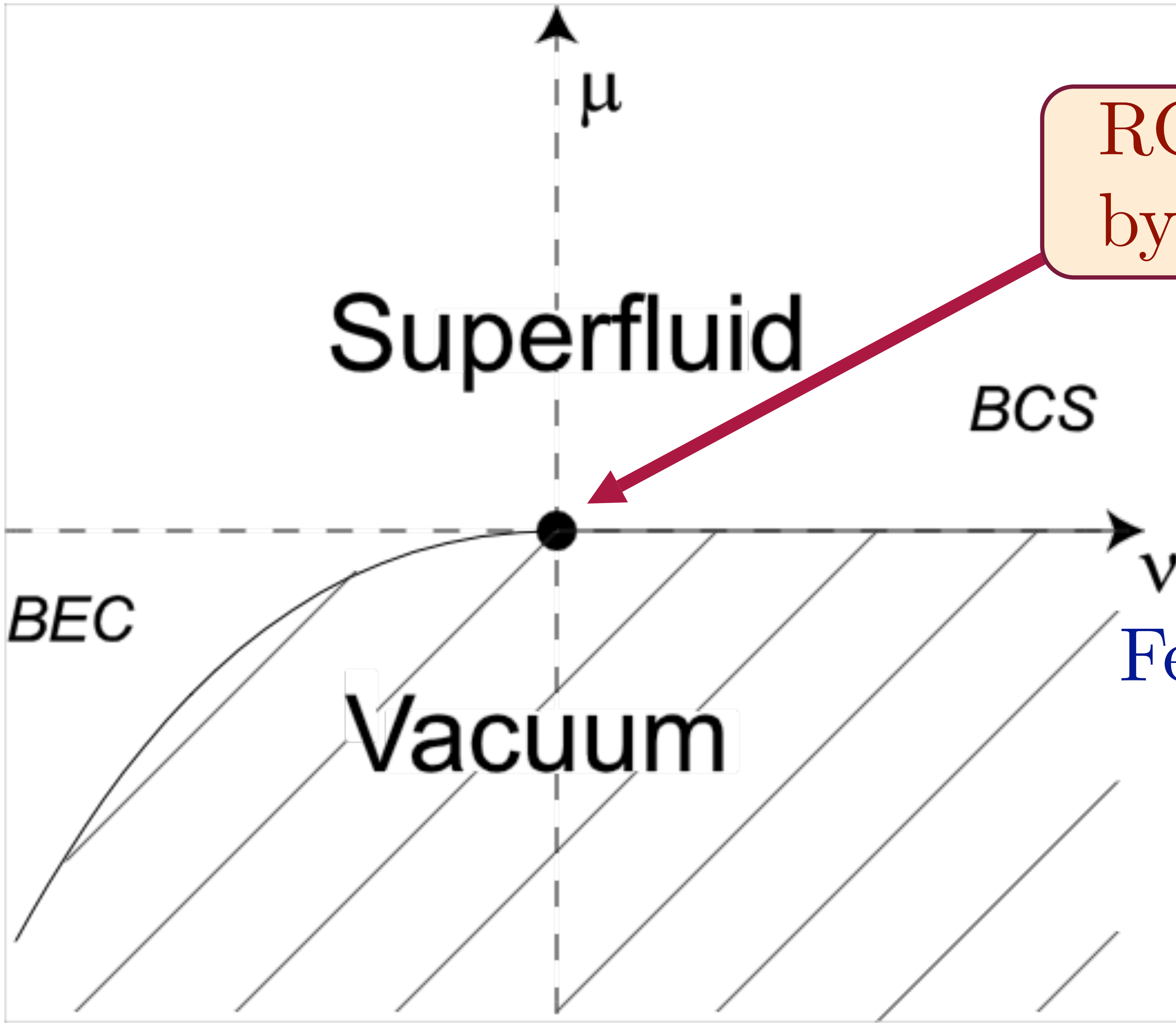

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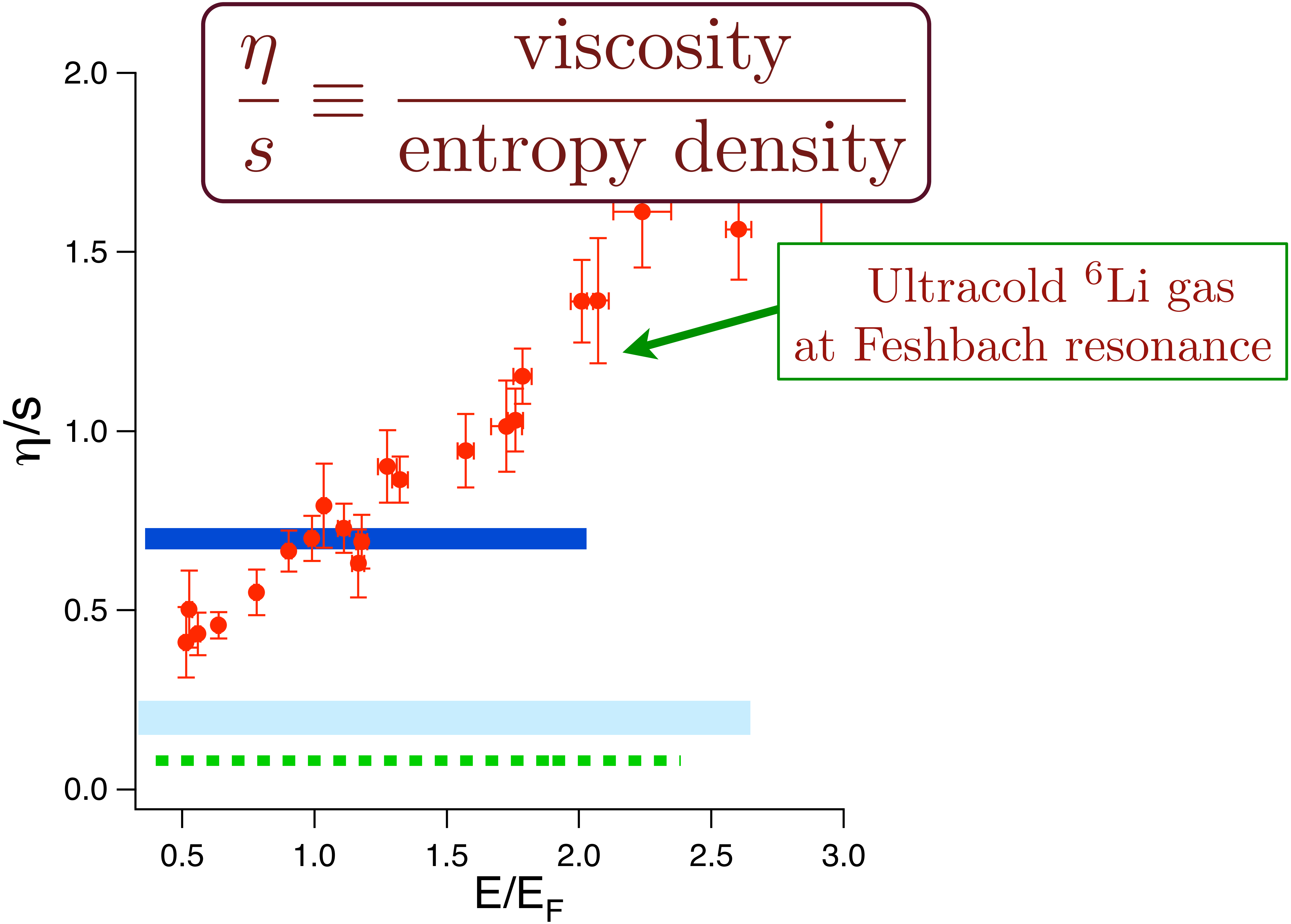
CFT is dual to quantum gravity models on AdS space. Explicit solutions of such gravity models with supersymmetry have been obtained

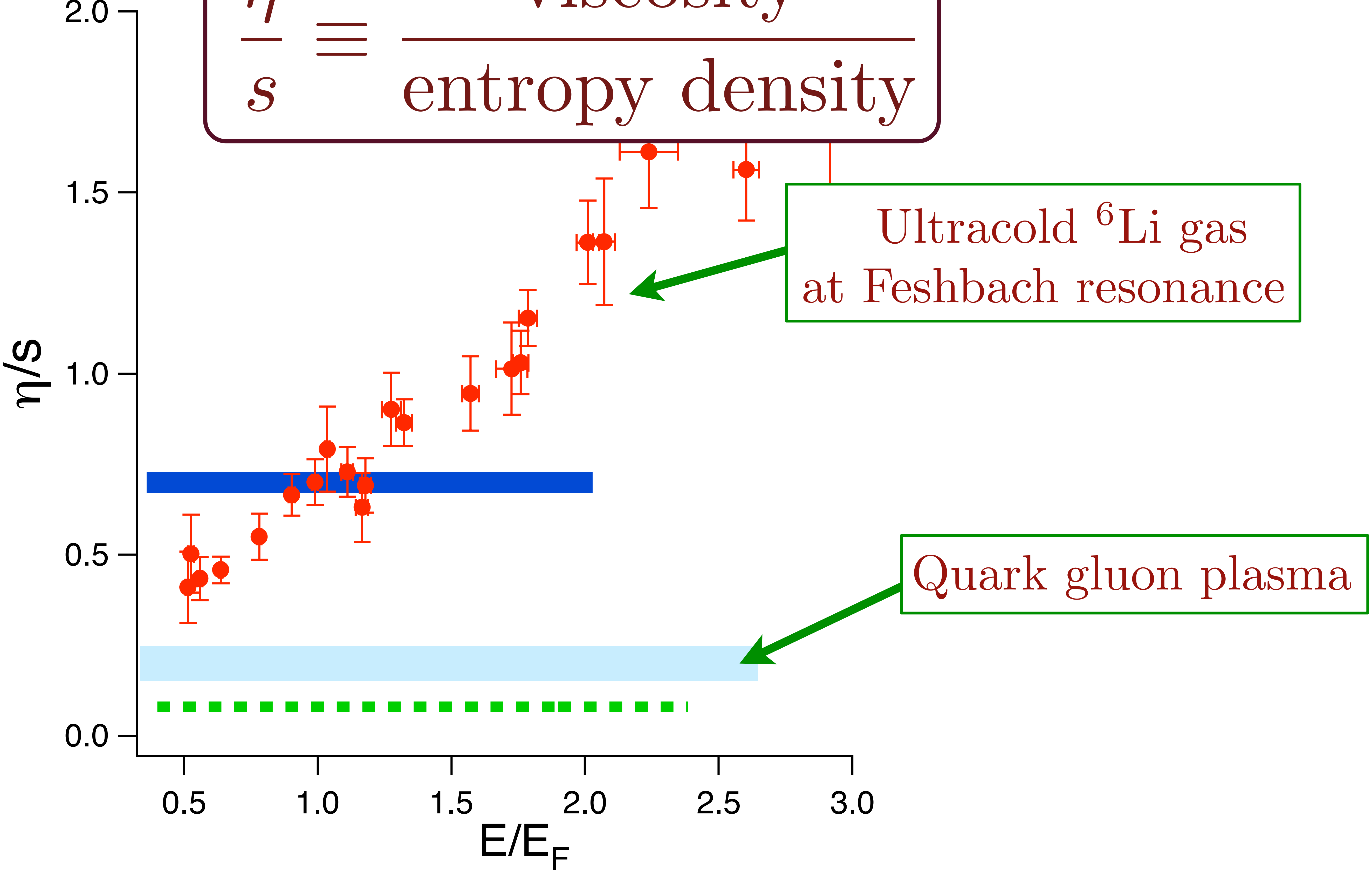
P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007); D. T. Son, arXiv:0804.3972; K. Balasubramaniam and J. McGreevy, arXiv:0804.4053; W. D. Goldberger, arXiv:0806.2867; J. L. F. Barbón and C. A. Fuertes, arXiv:0806.3244; J. Maldacena, D. Martelli, and Y. Tachikawa, arXiv:0807.1100; A. Adams,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



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)

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



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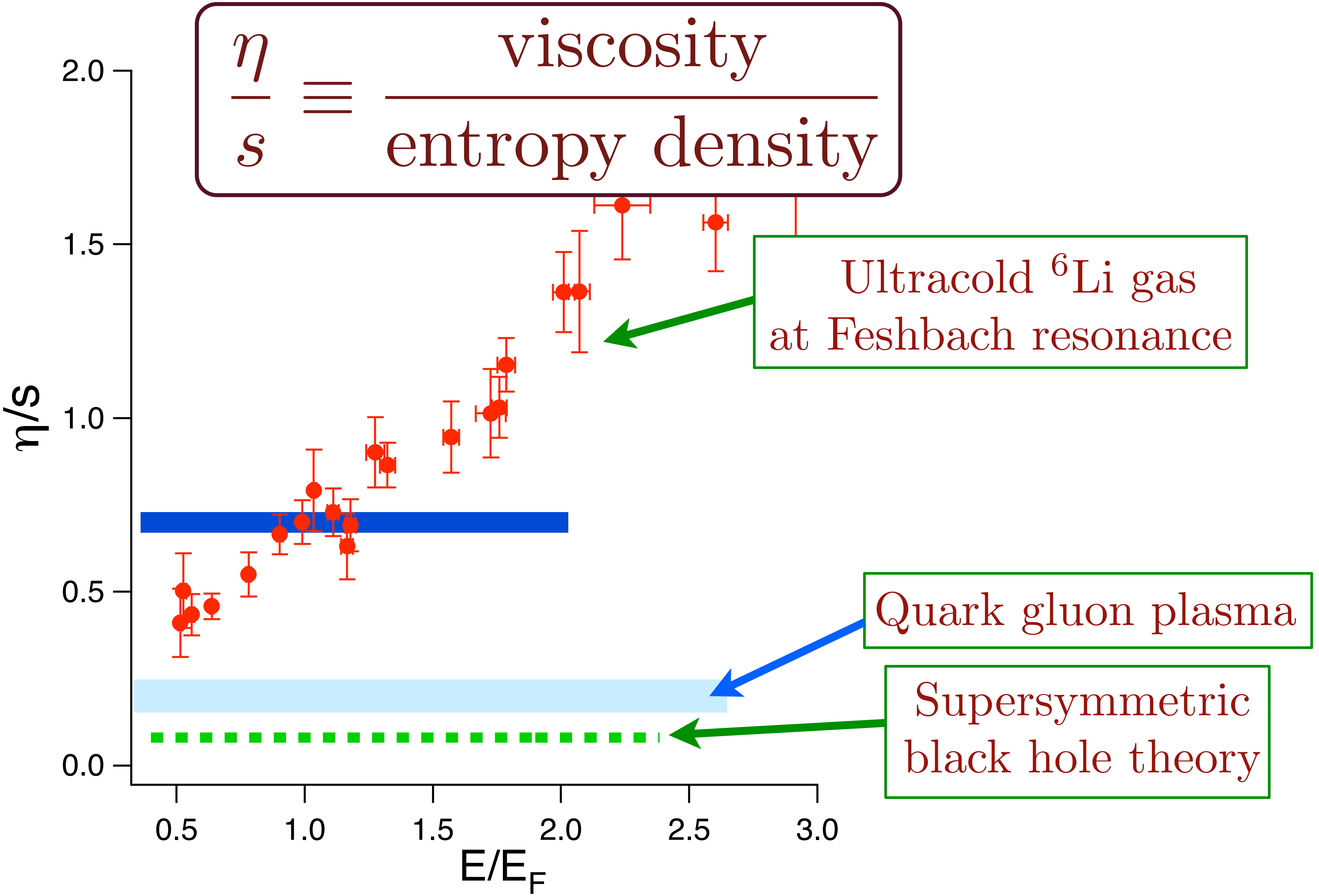

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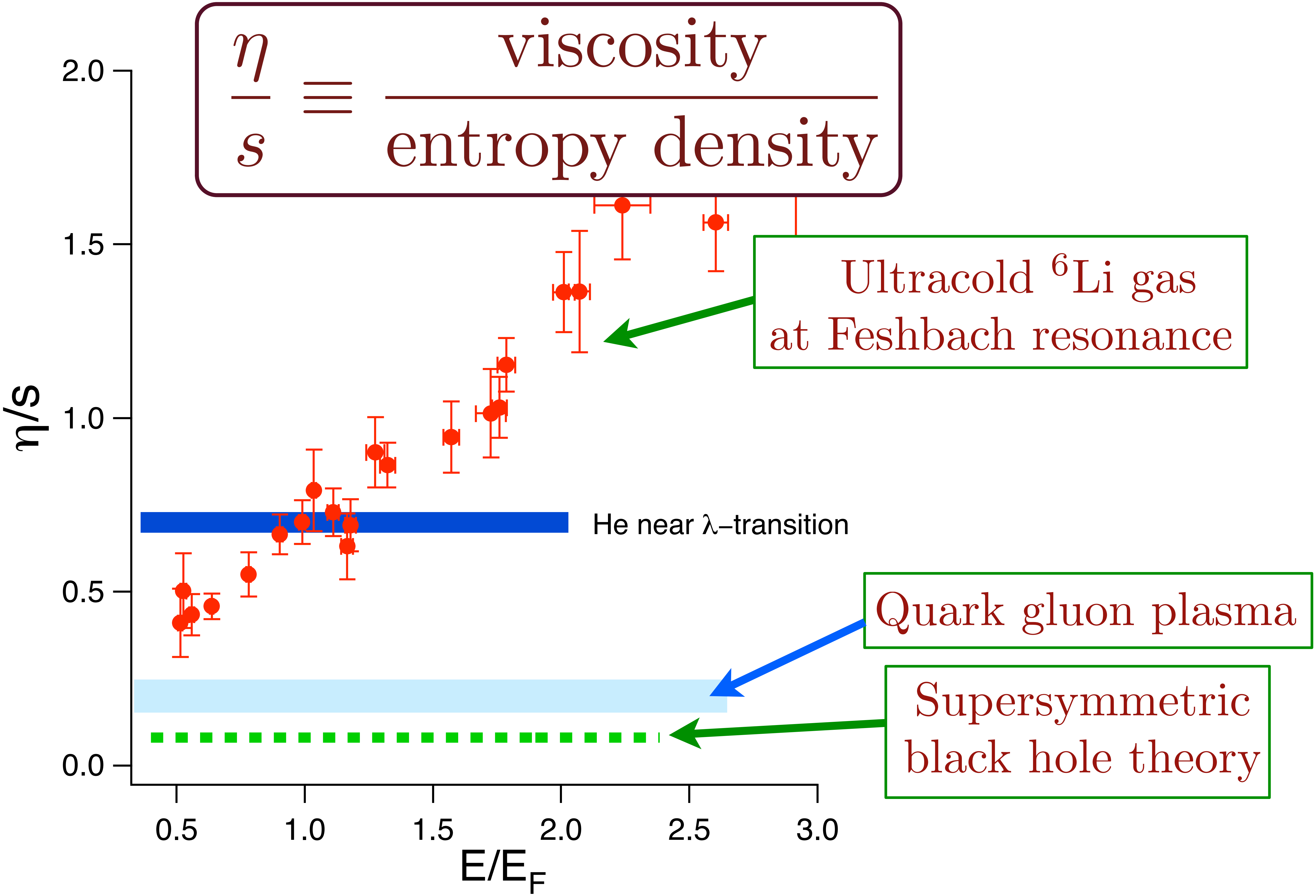

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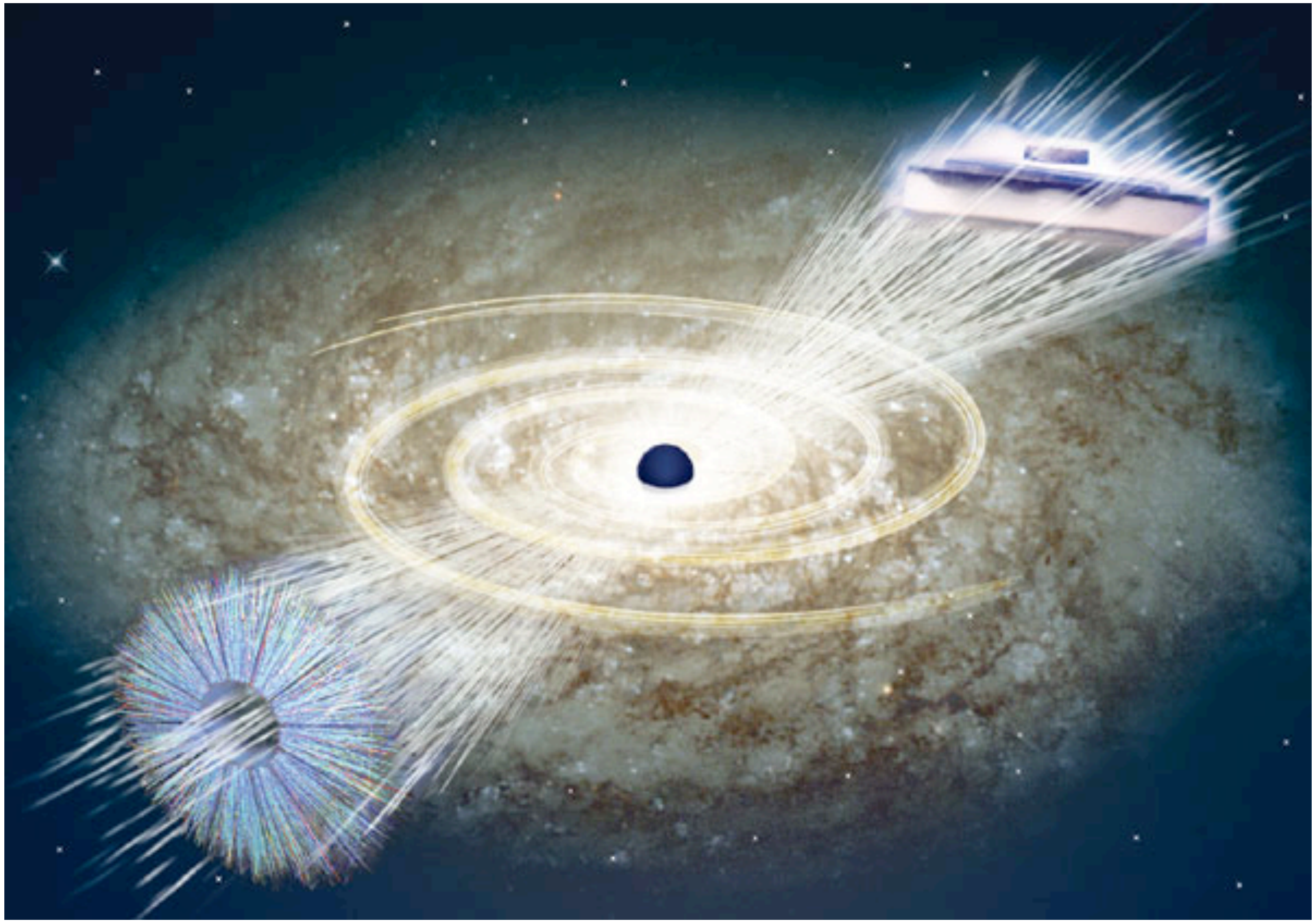
THEORETICAL PHYSICS

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.