



# Quantum Criticality and Black Holes

Talk online: [sachdev.physics.harvard.edu](http://sachdev.physics.harvard.edu)



Particle theorists

Sean Hartnoll, KITP

Christopher Herzog, Princeton

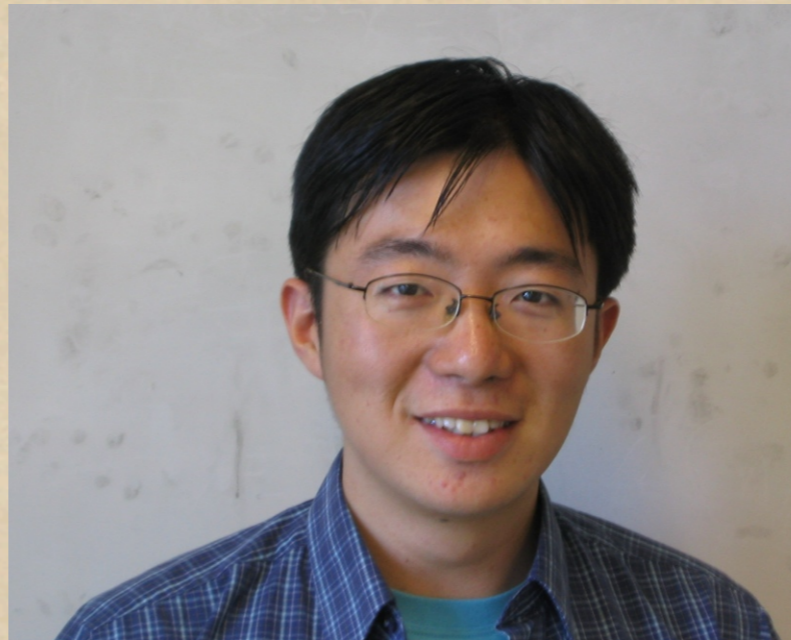
Pavel Kovtun, Victoria

Dam Son, Washington

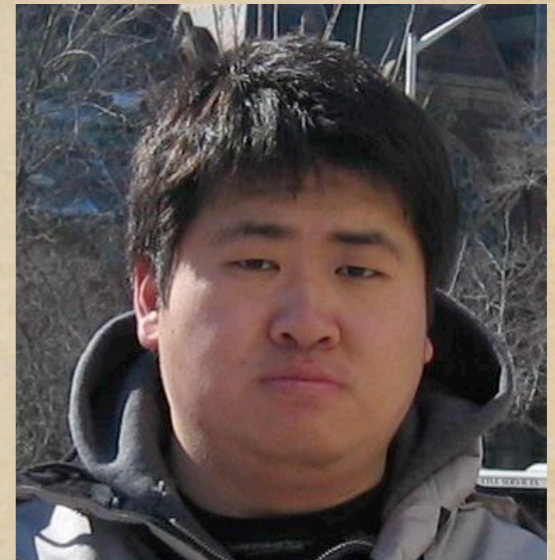
Condensed matter  
theorists



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

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

# Three foci of modern physics

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Hydrodynamics

Black holes

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Hydrodynamics

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

Black holes

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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

New insights and results from detour unifies disparate fields of physics

Black holes

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# Three foci of modern physics

Quantum phase transitions

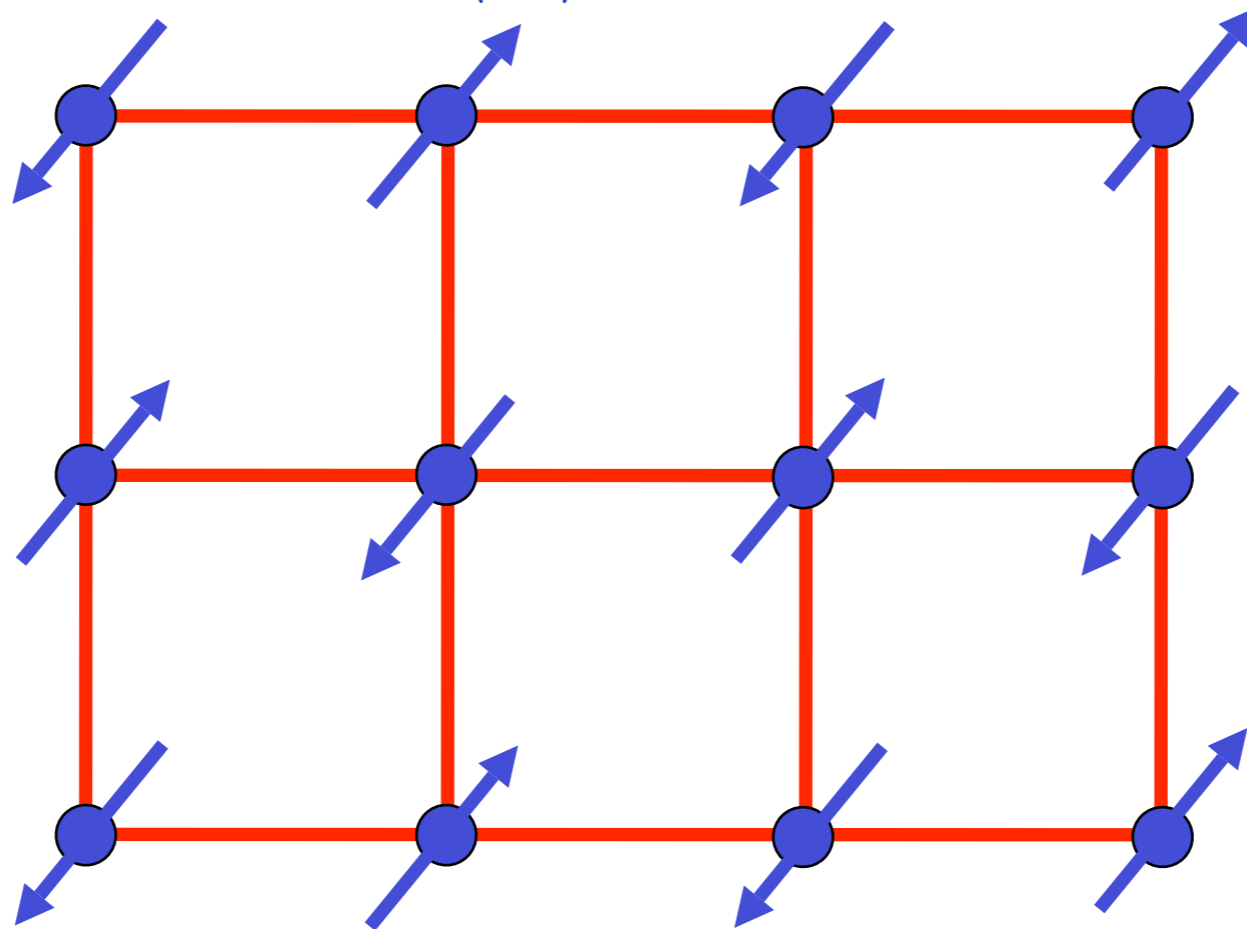
Many QPTs of correlated electrons in  $2+1$  dimensions are described by conformal field theories (CFTs)

Hydrodynamics

Black holes

# Square lattice antiferromagnet

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



Ground state has long-range Néel order

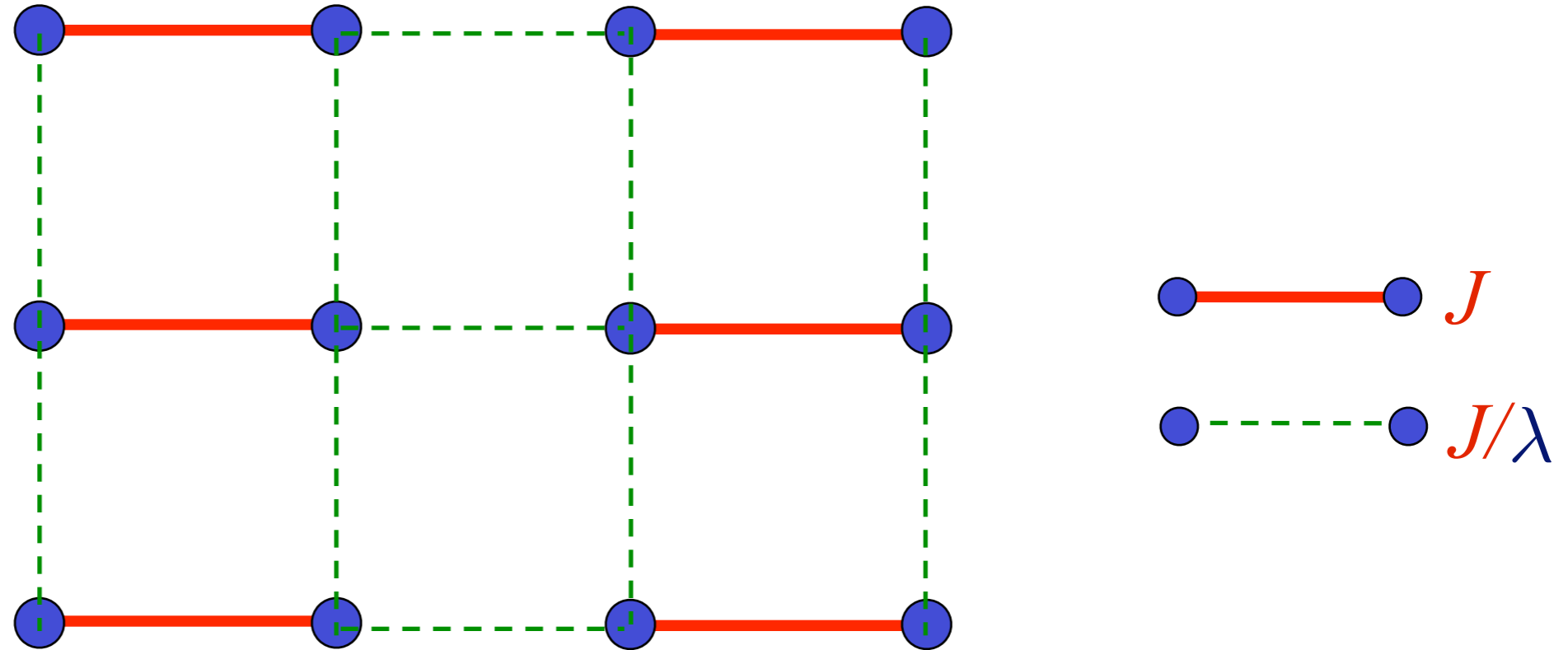
Order parameter is a single vector field  $\vec{\varphi} = \eta_i \vec{S}_i$

$\eta_i = \pm 1$  on two sublattices

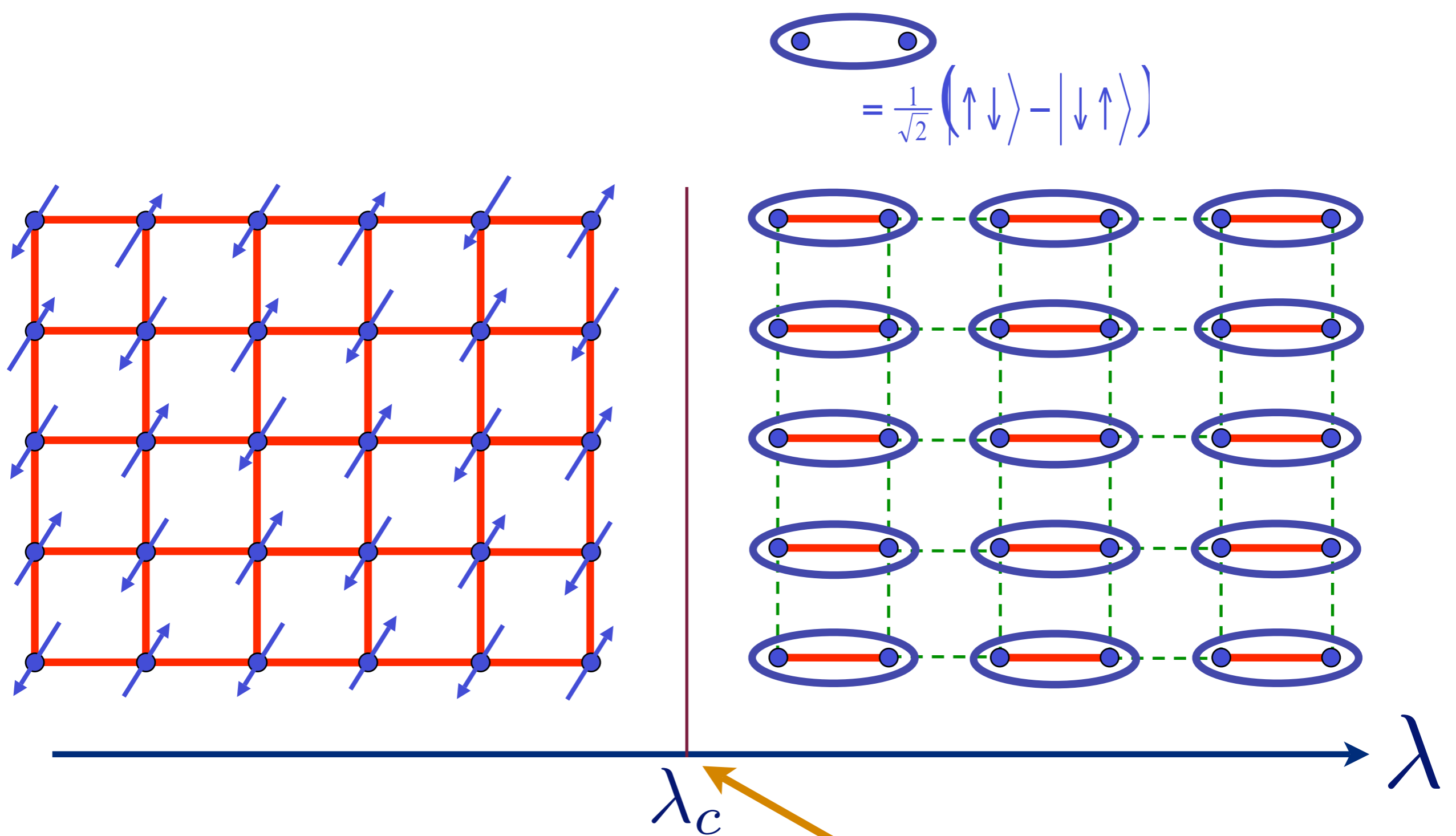
$\langle \vec{\varphi} \rangle \neq 0$  in Néel state.

# Square lattice antiferromagnet

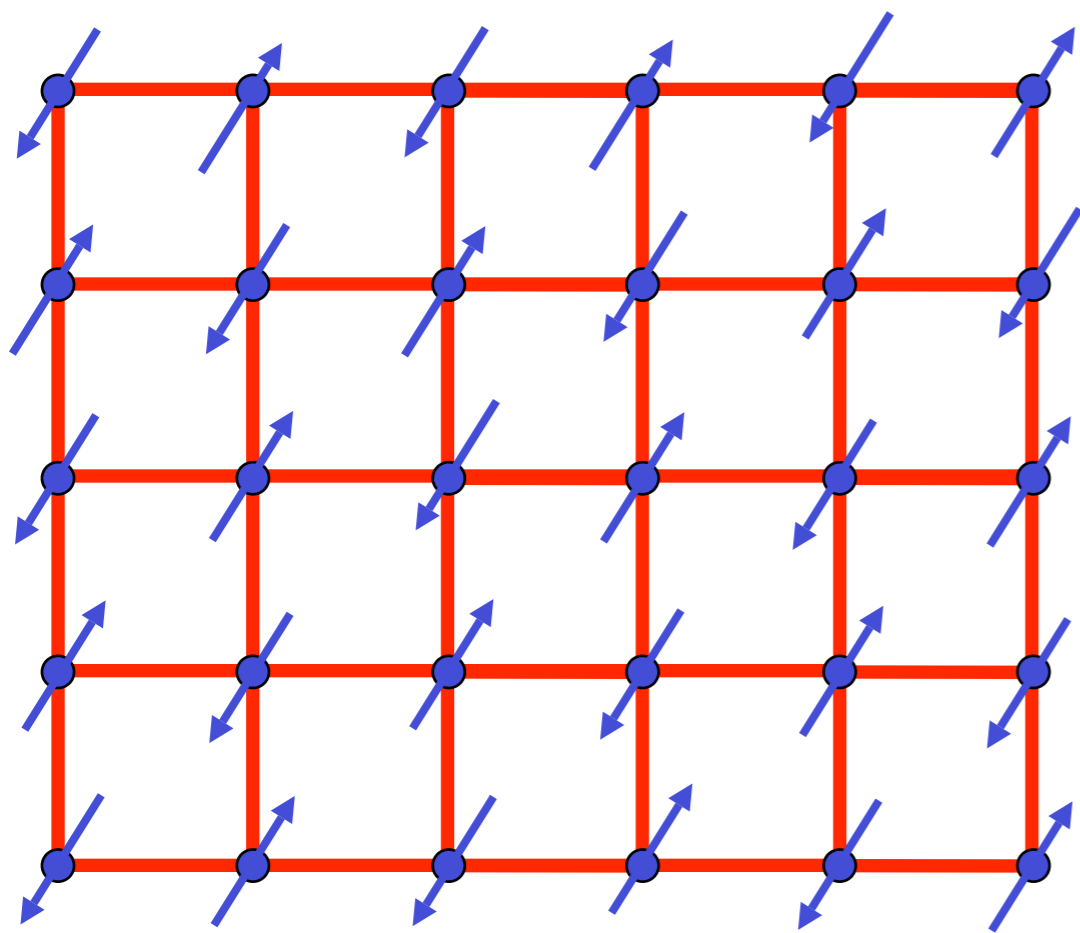
$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



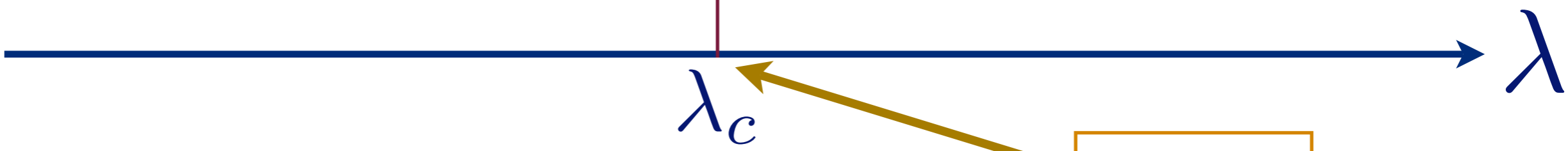
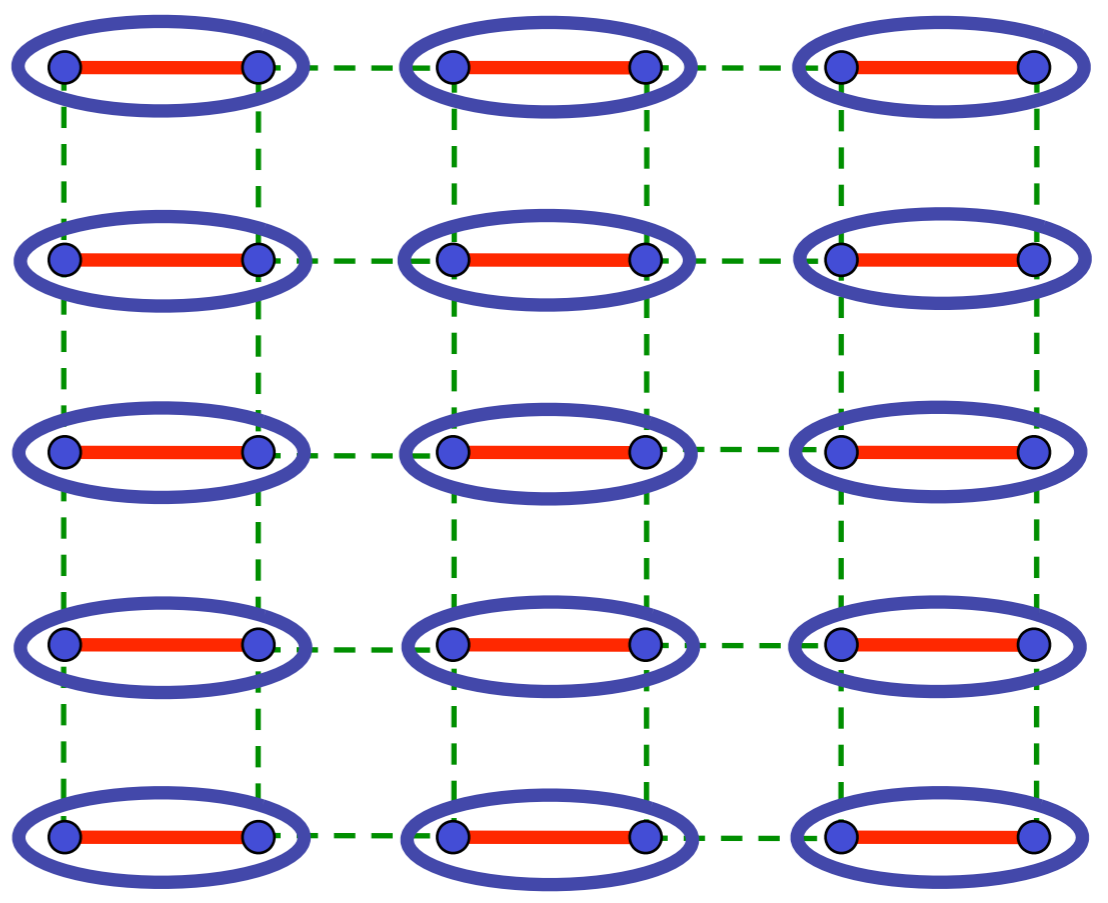
Weaken some bonds to induce spin entanglement in a new quantum phase



Quantum critical point with non-local entanglement in spin wavefunction



$$\begin{aligned}
 & \text{Diagram of two blue dots in a blue oval} \\
 & = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)
 \end{aligned}$$

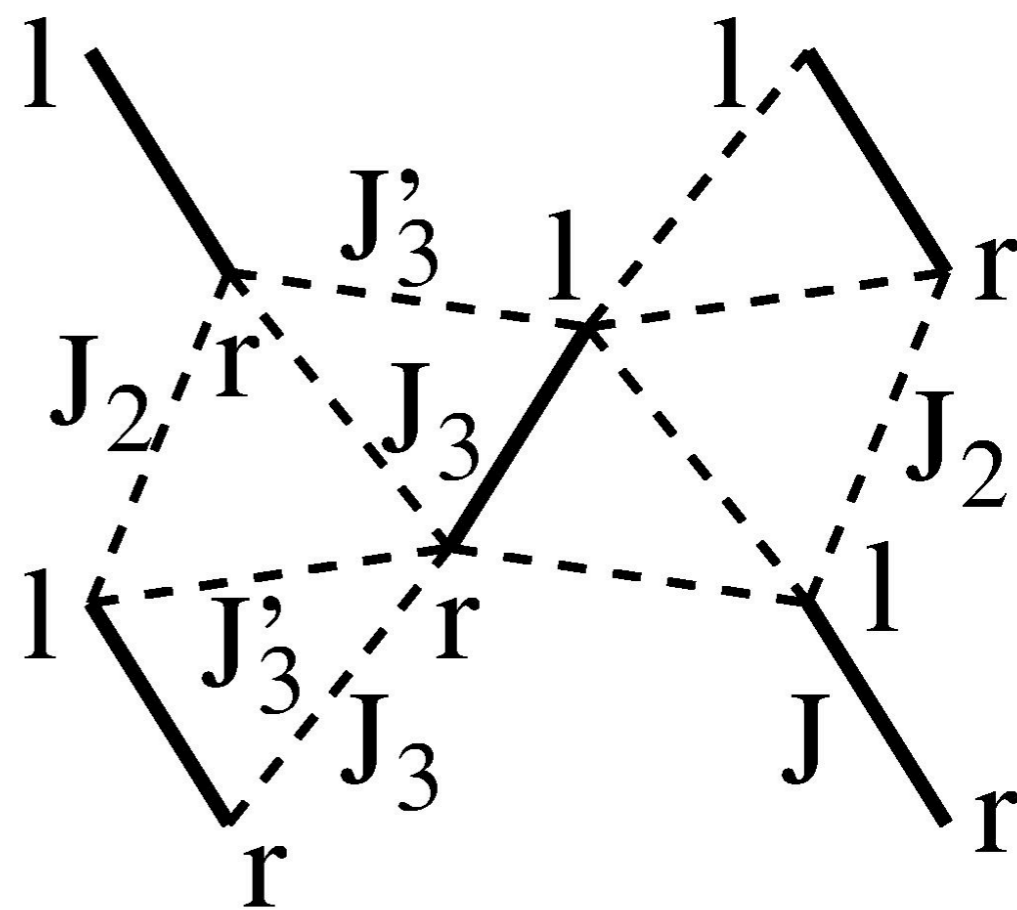
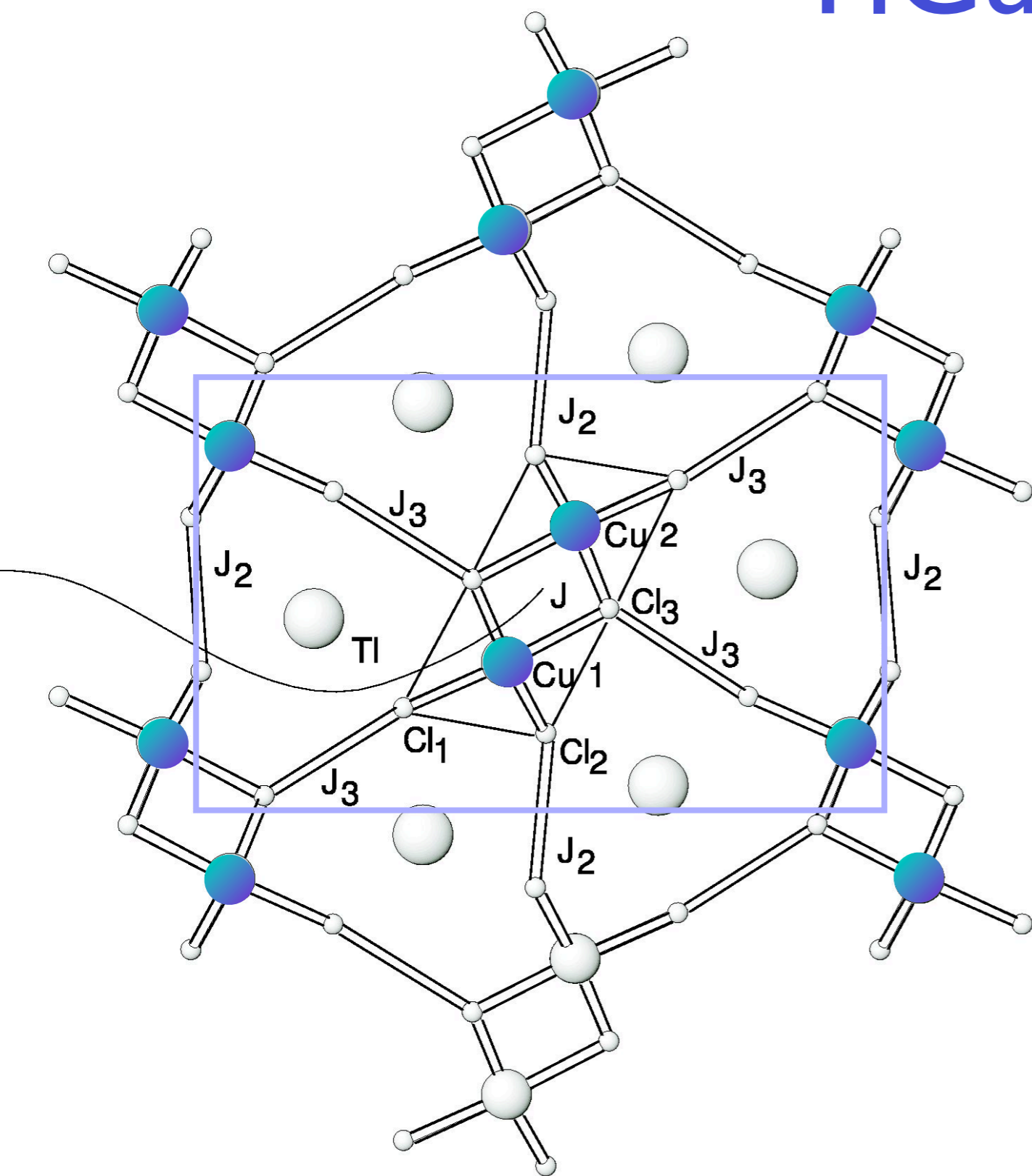


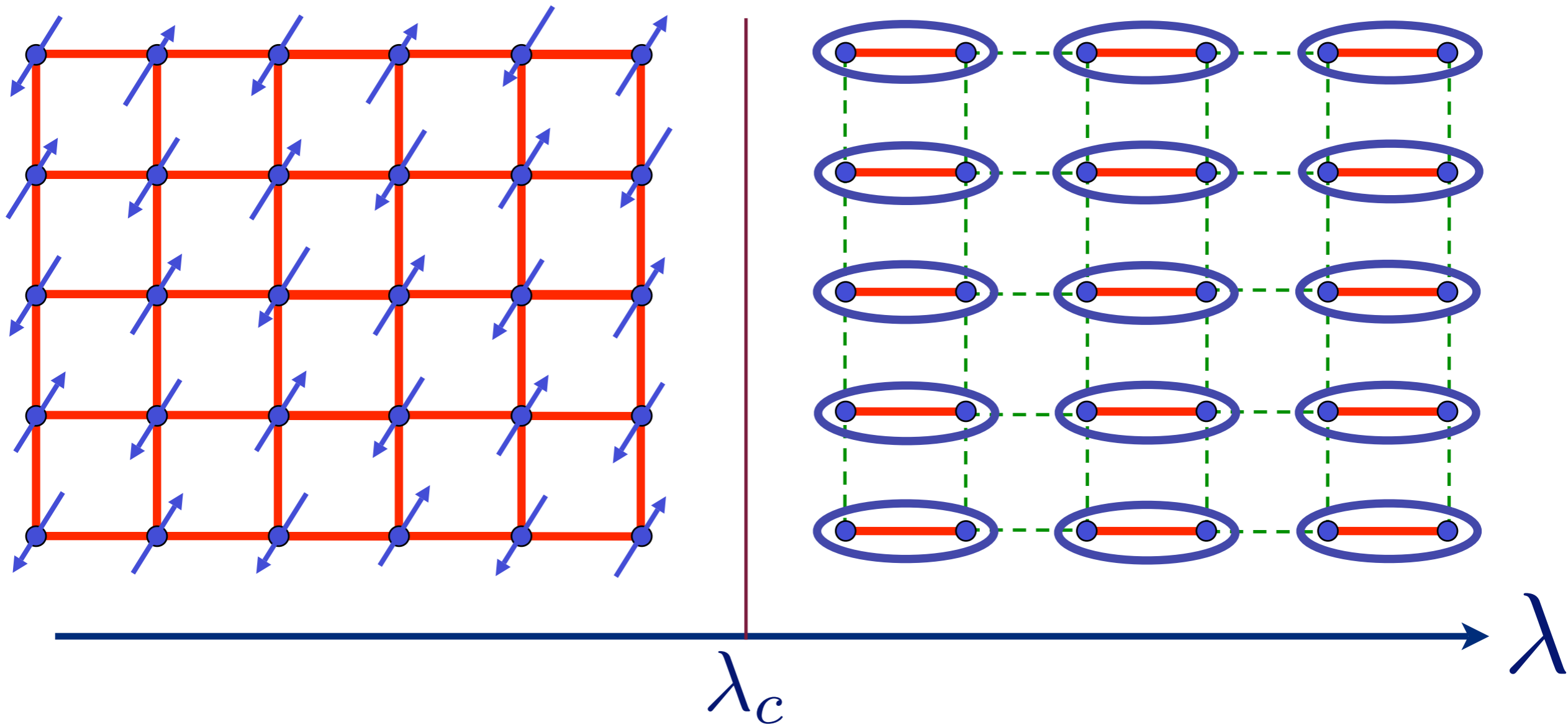
CFT3

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

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

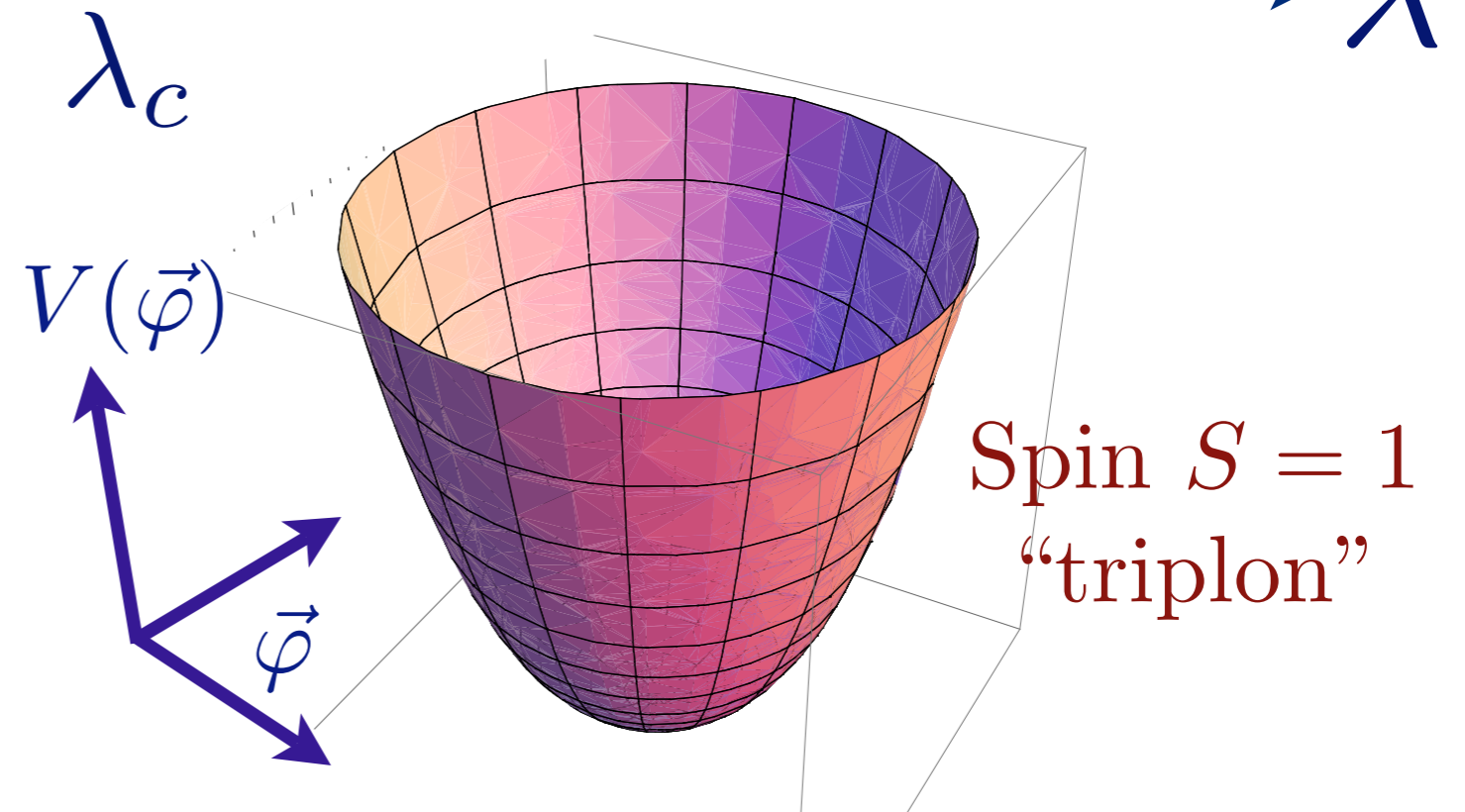
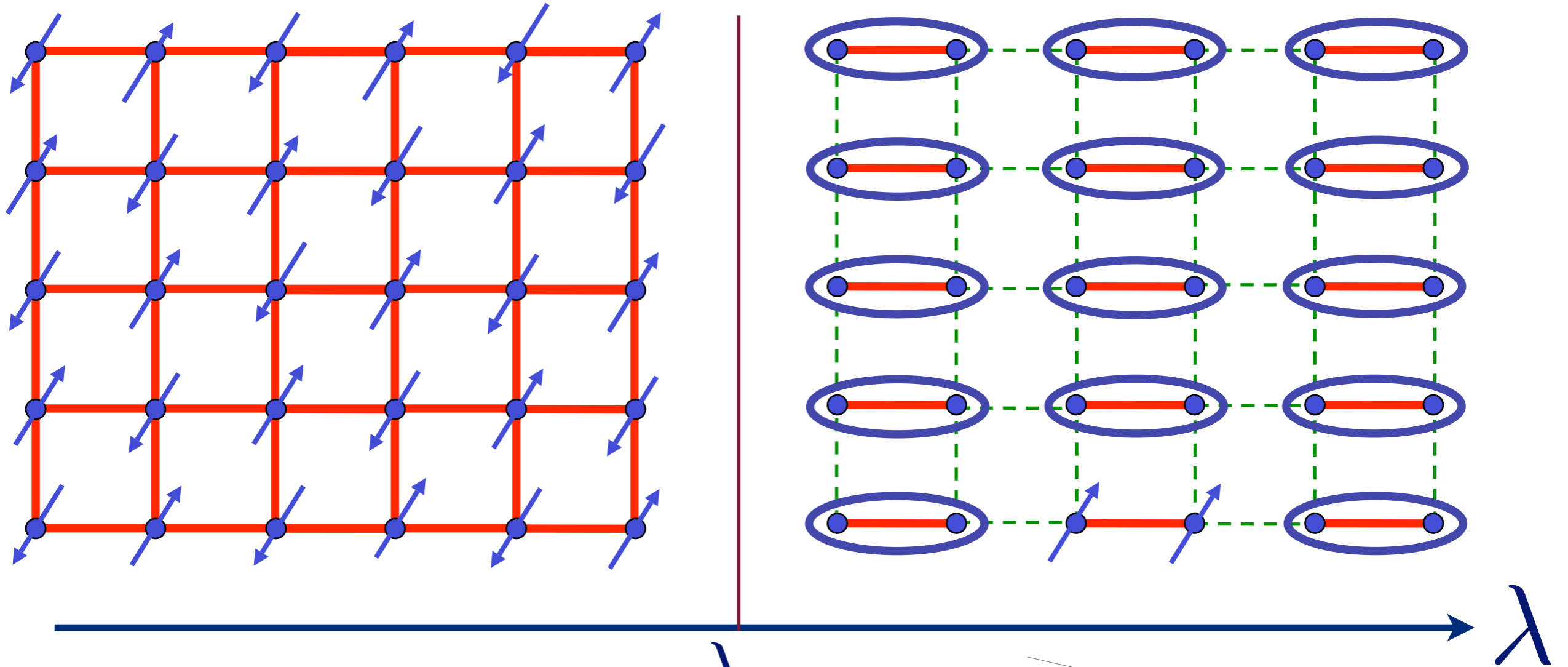
# TlCuCl<sub>3</sub>



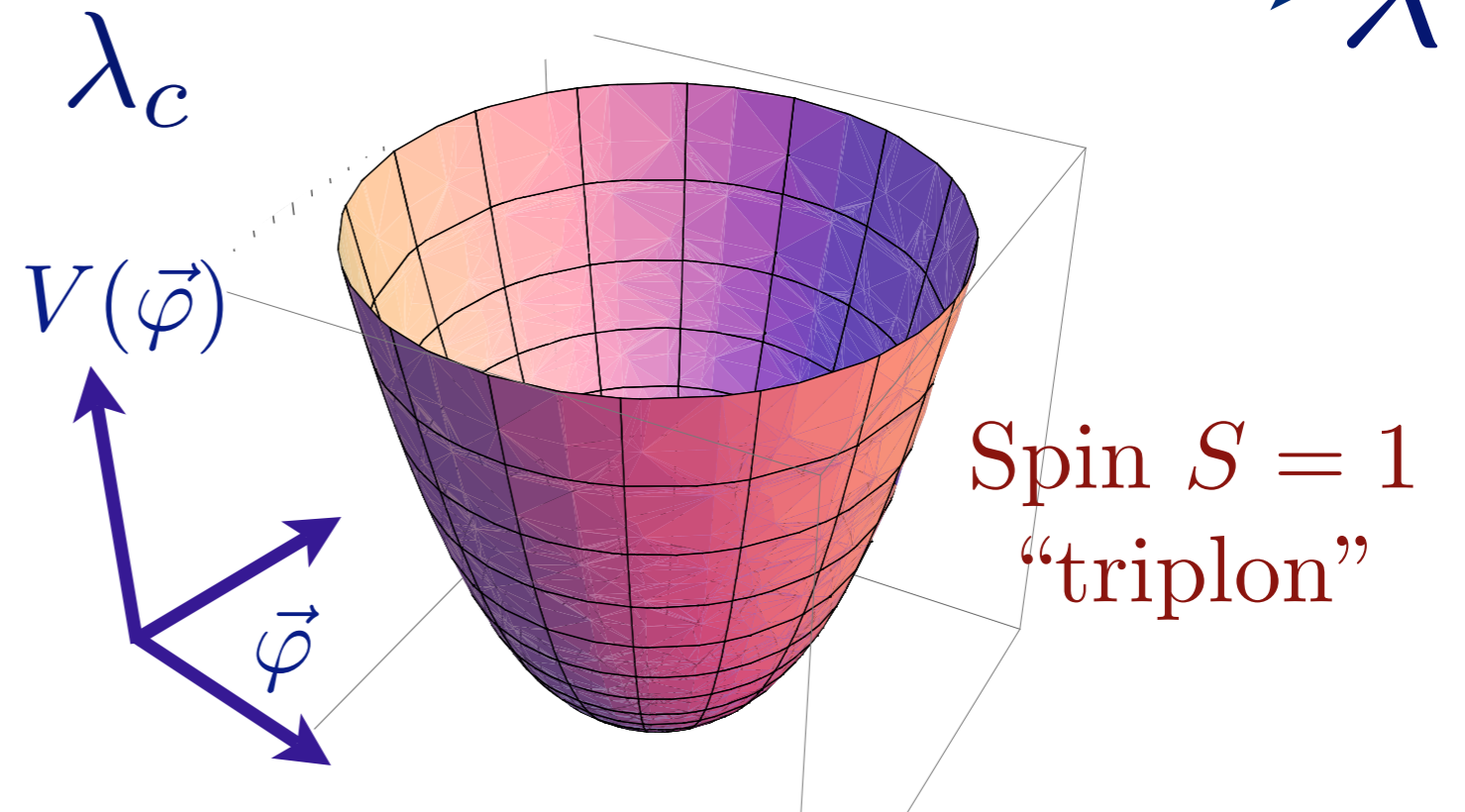
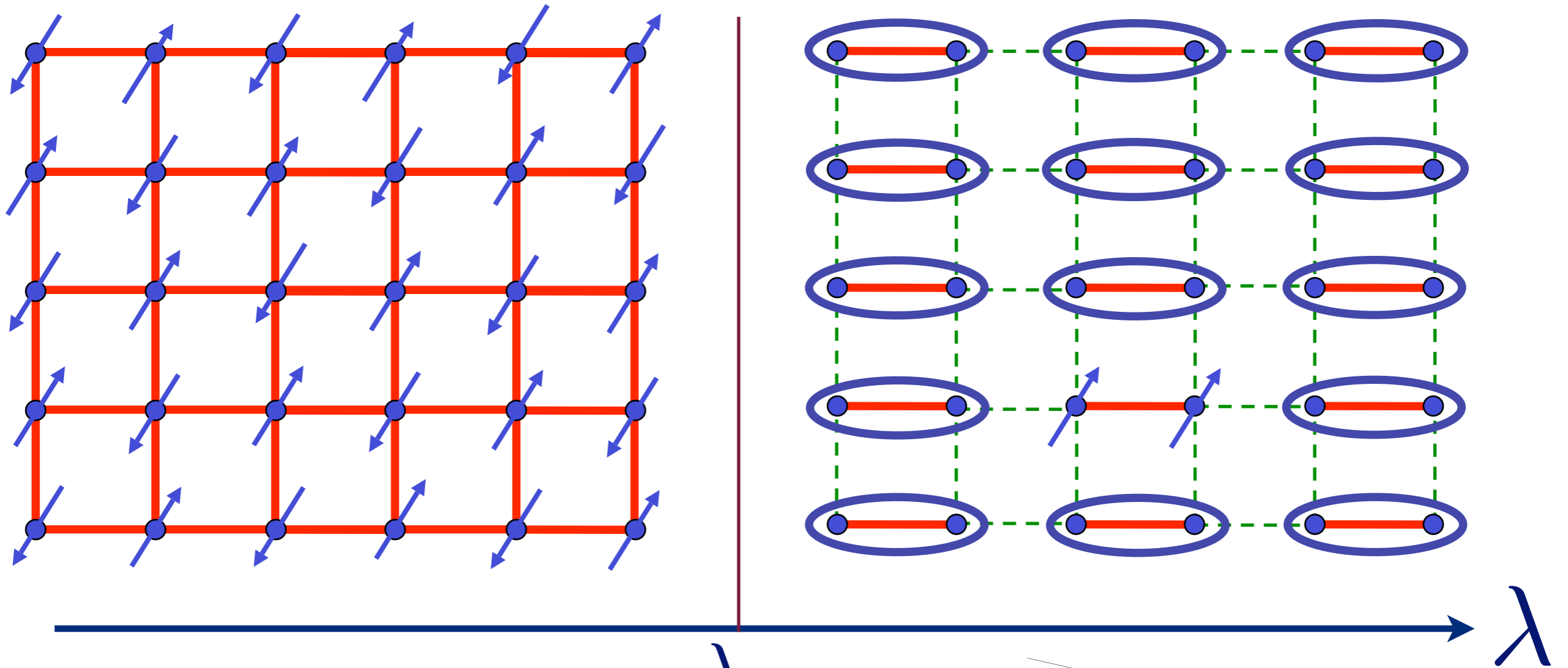


← Pressure in  $\text{TlCuCl}_3$

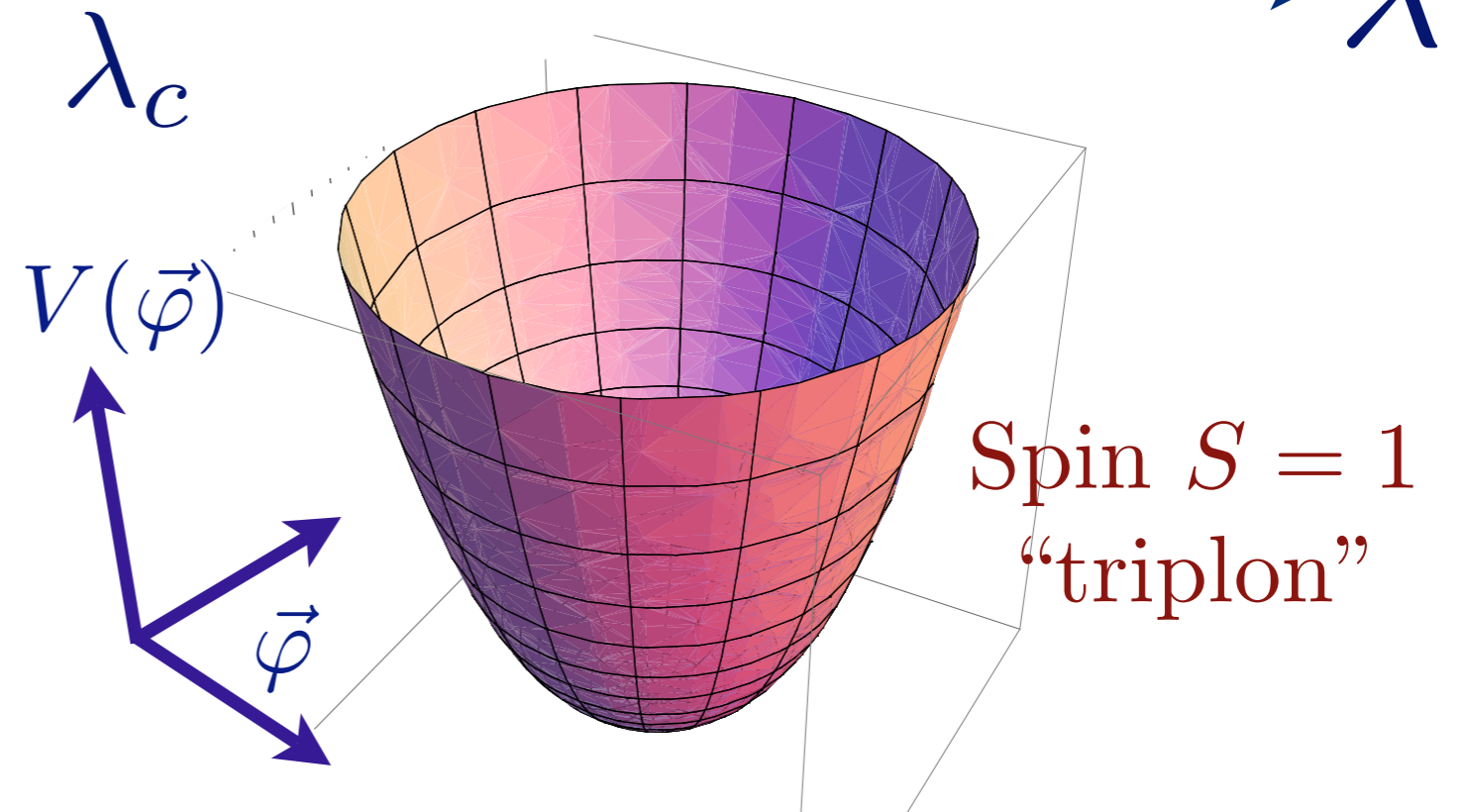
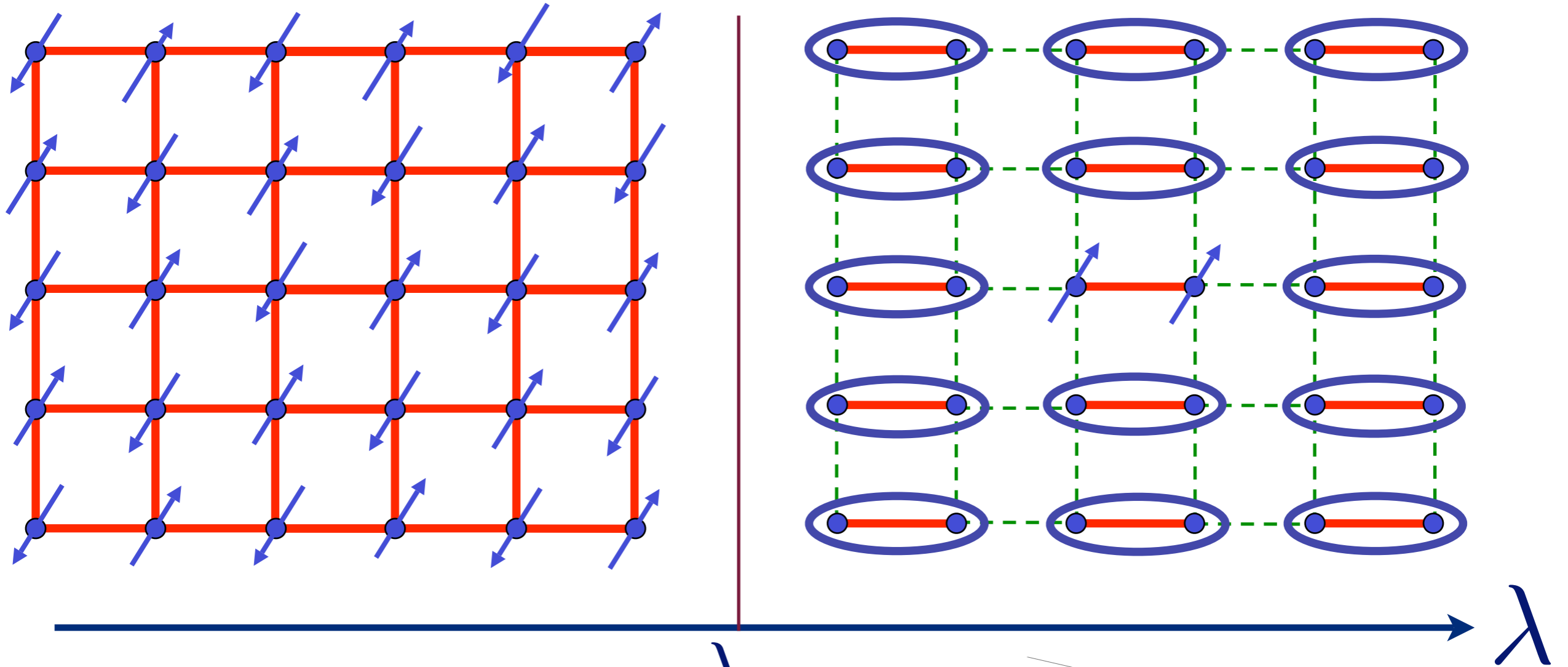
# Excitation spectrum in the paramagnetic phase



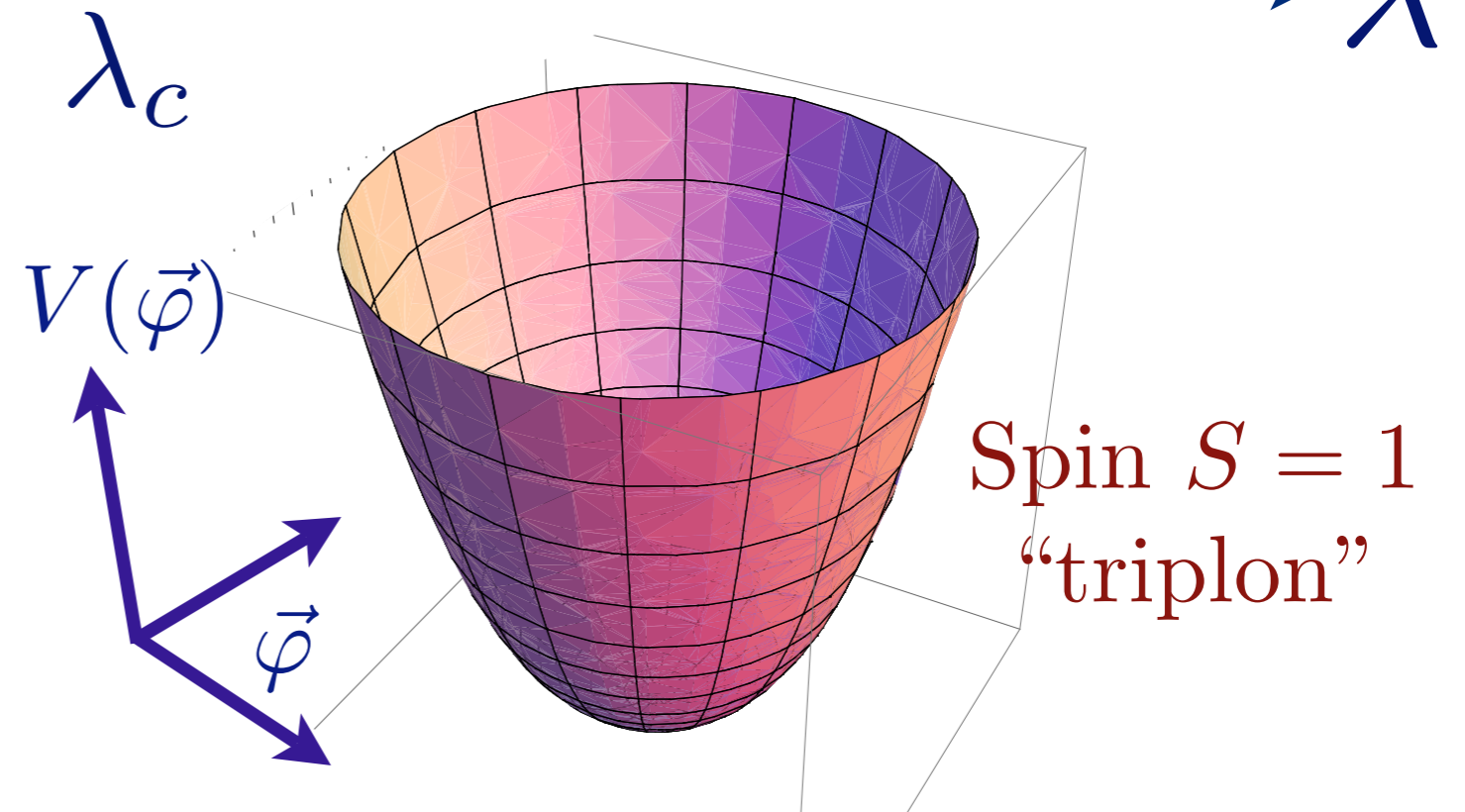
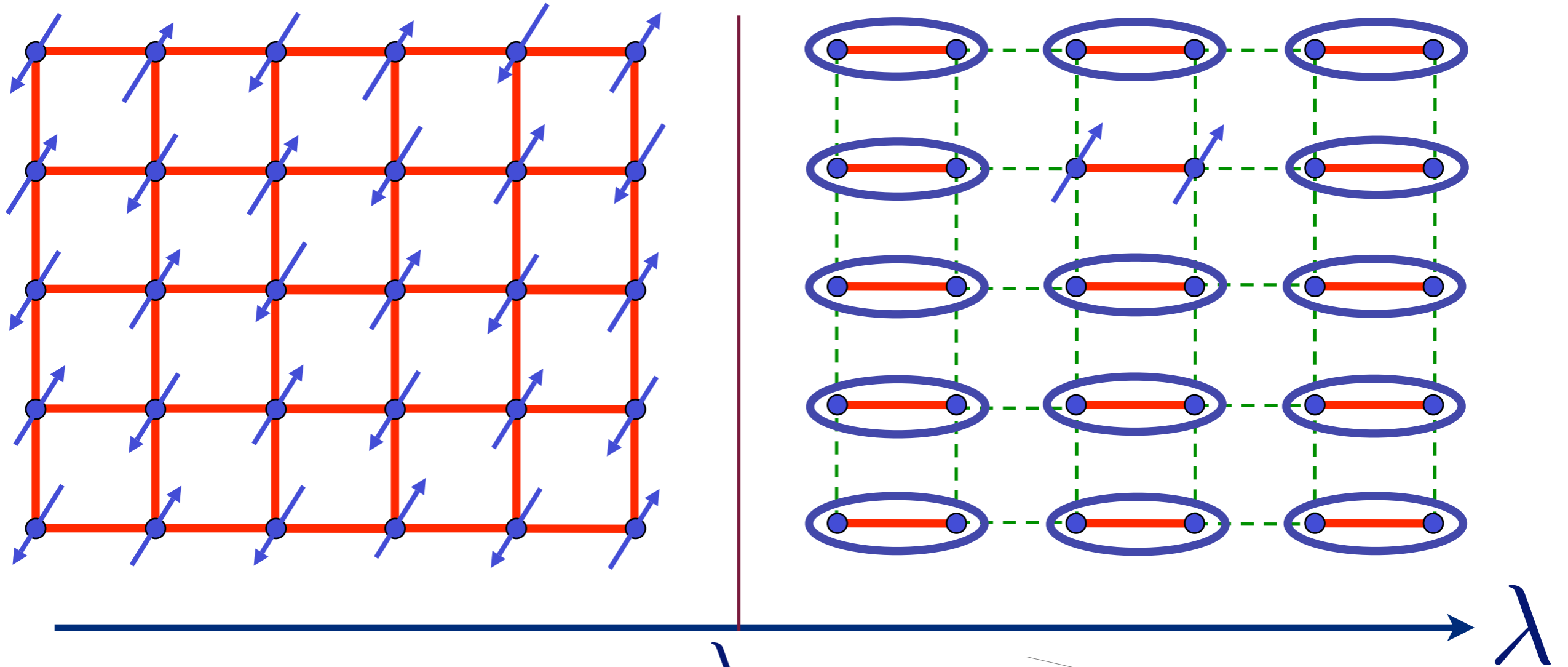
# Excitation spectrum in the paramagnetic phase



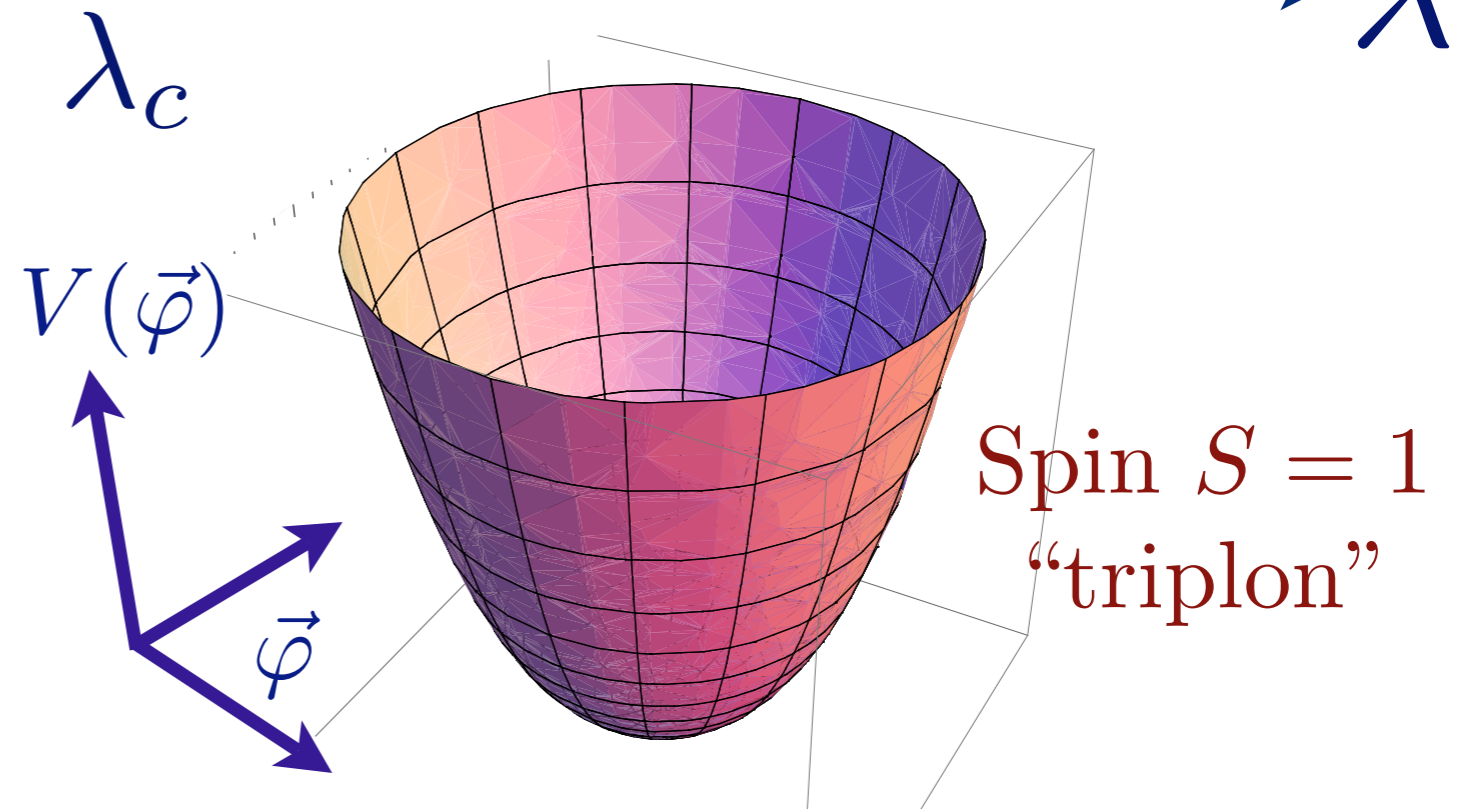
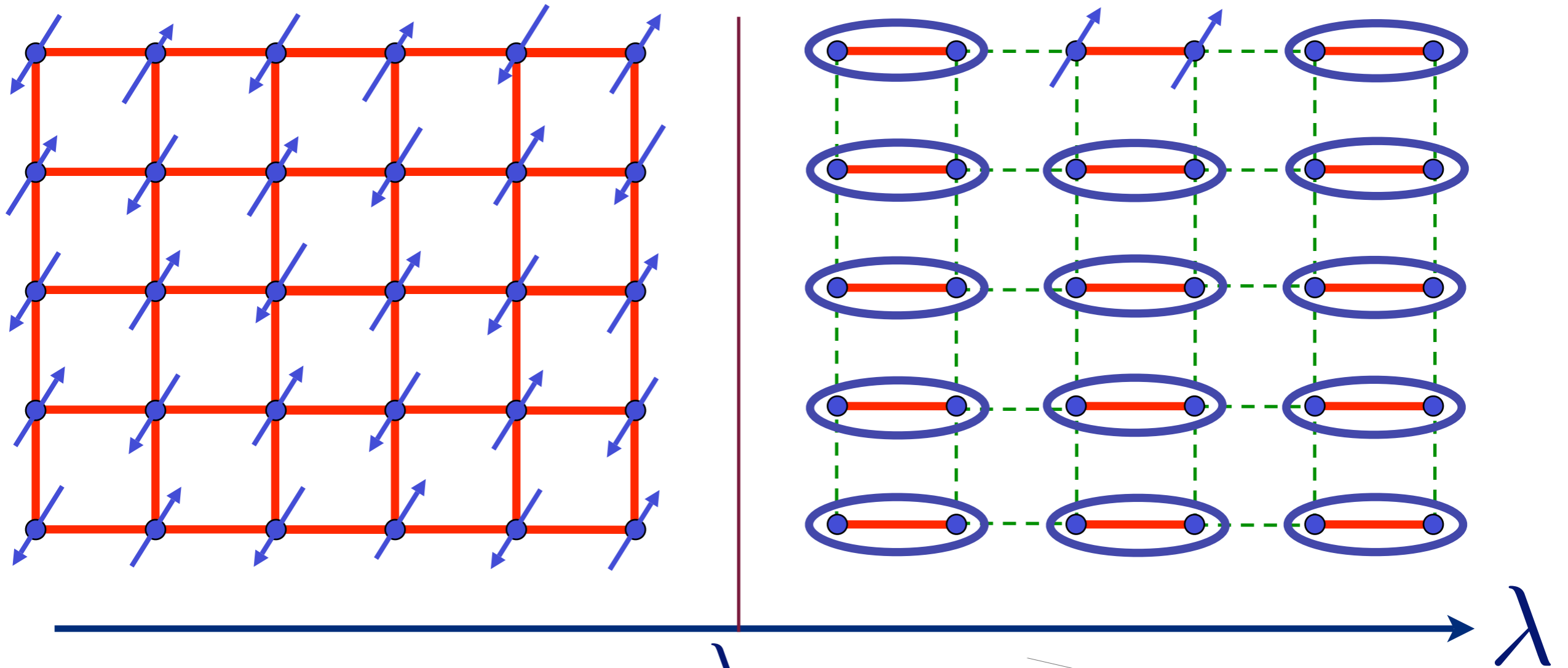
# Excitation spectrum in the paramagnetic phase



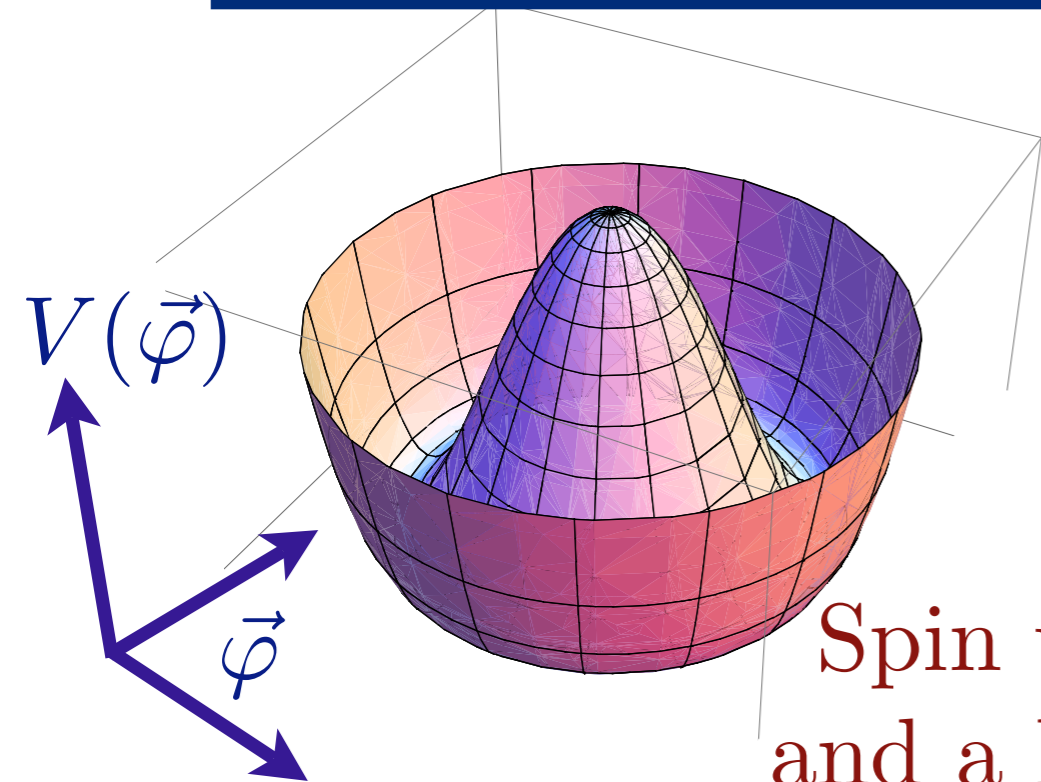
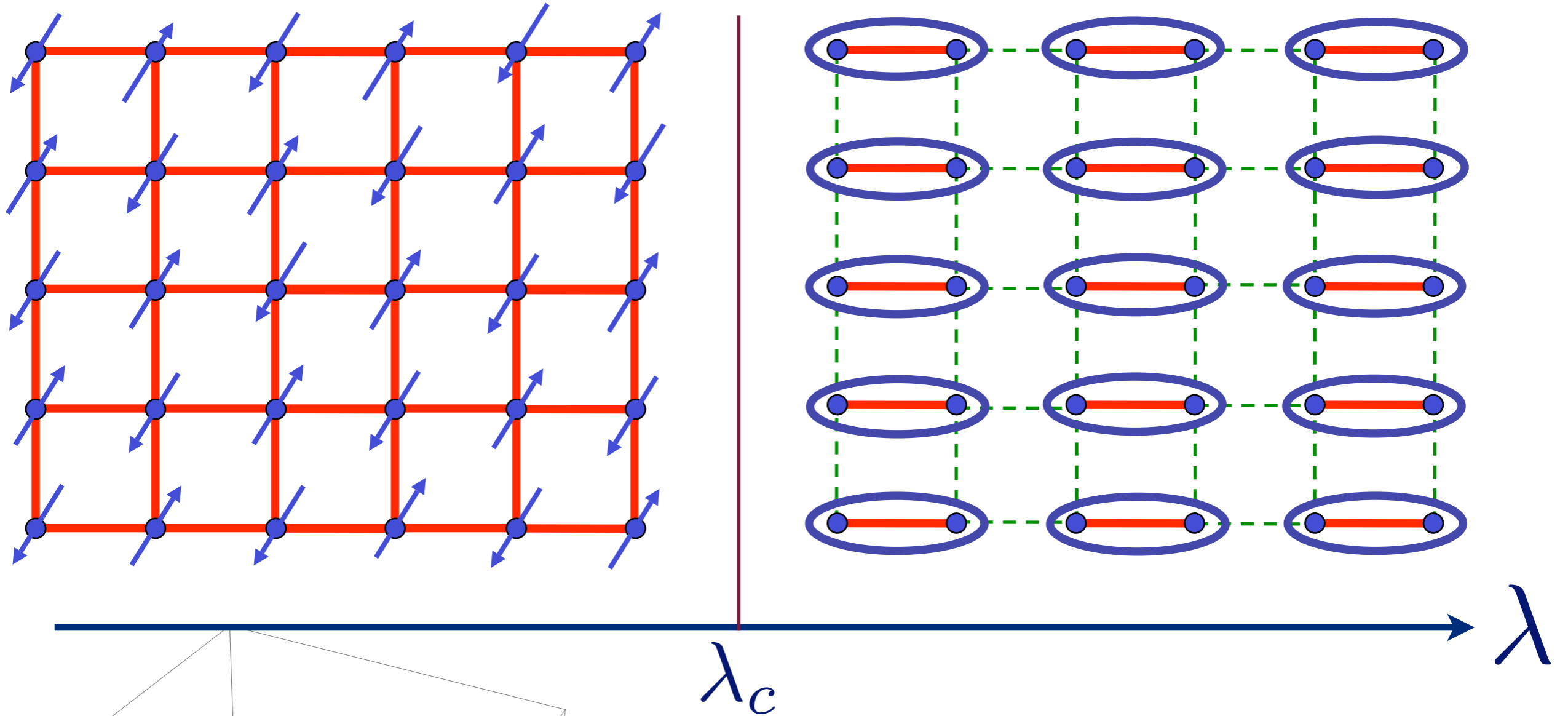
# Excitation spectrum in the paramagnetic phase



# Excitation spectrum in the paramagnetic phase

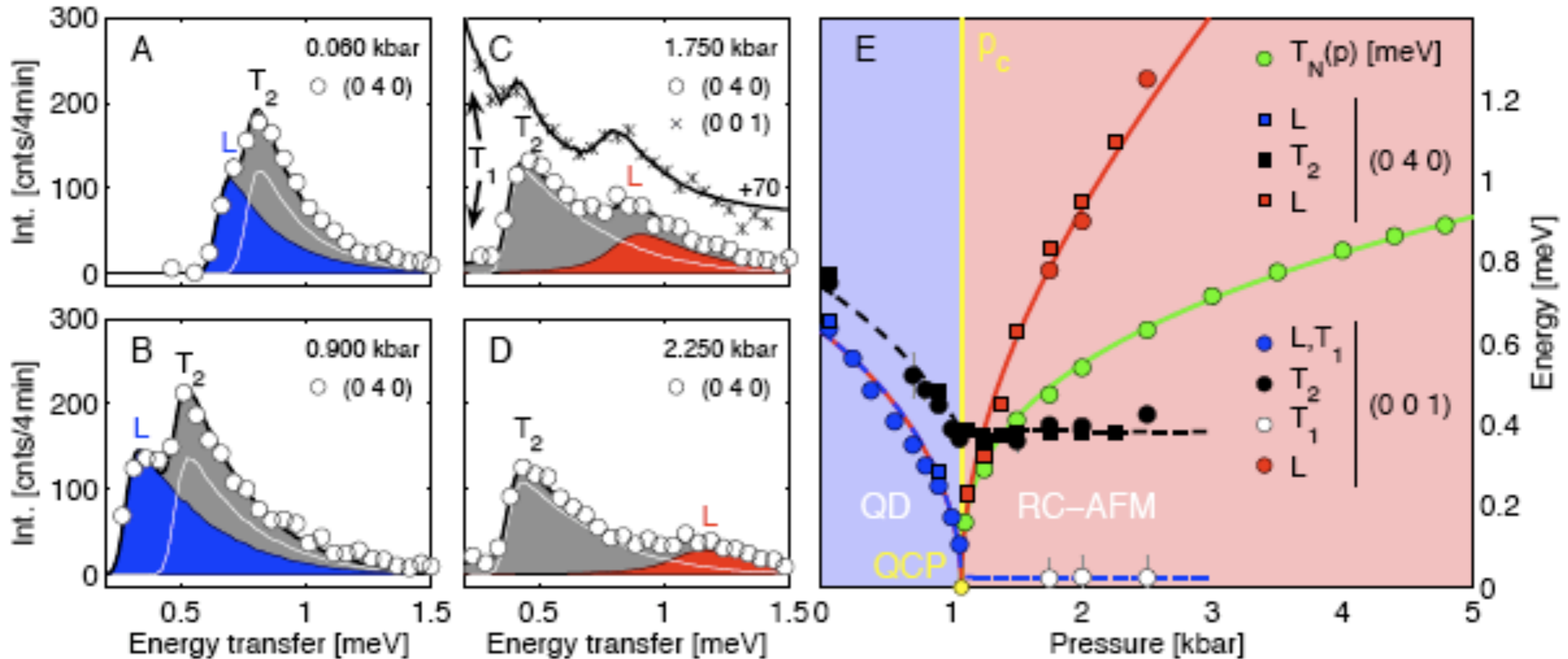


# Excitation spectrum in the Néel phase



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

# TiCuCl<sub>3</sub> with varying pressure

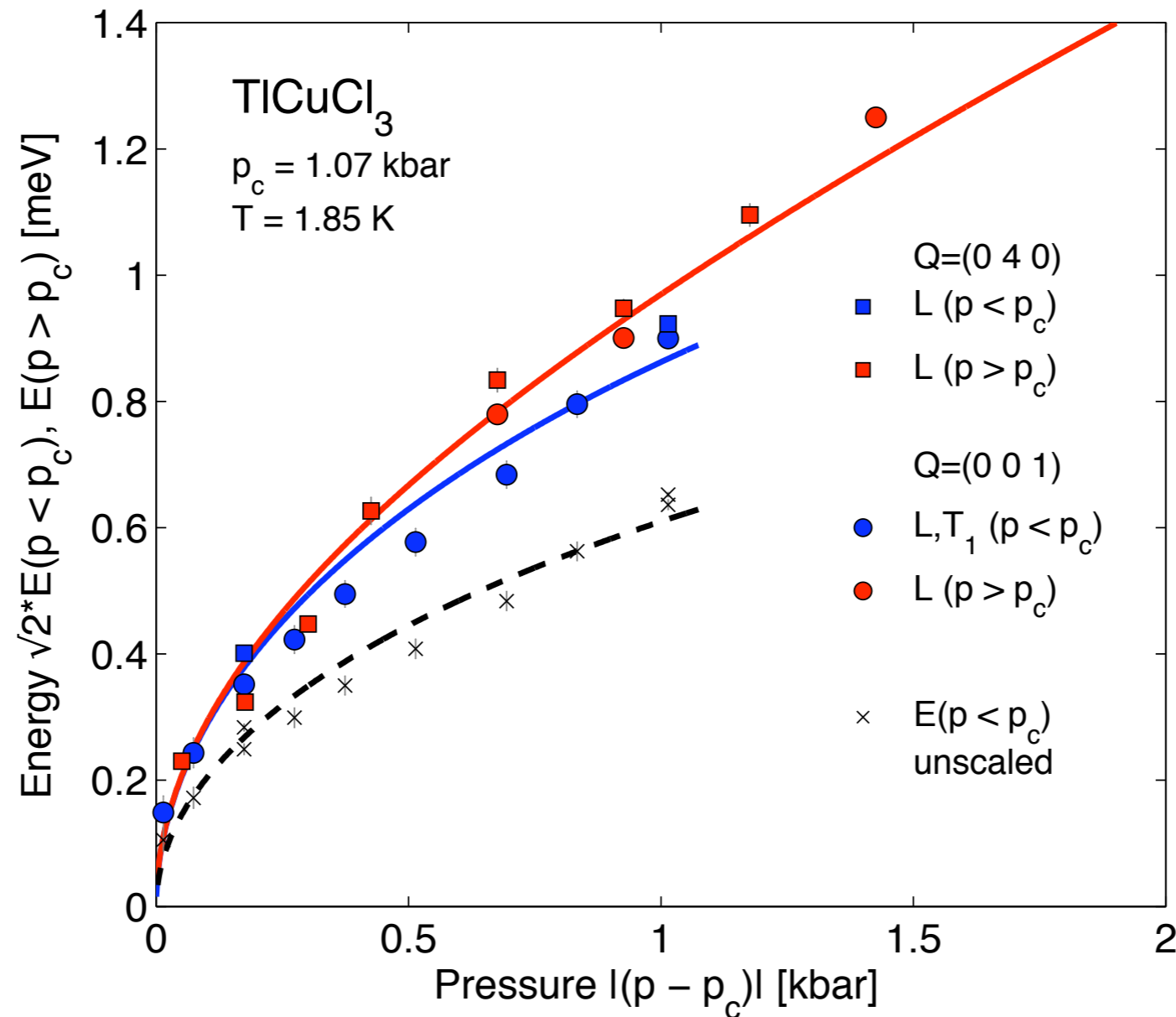


Observation of 3 → 2 low energy modes,  
emergence of new Higgs particle in the Néel phase,  
and vanishing of Néel temperature at the quantum critical point

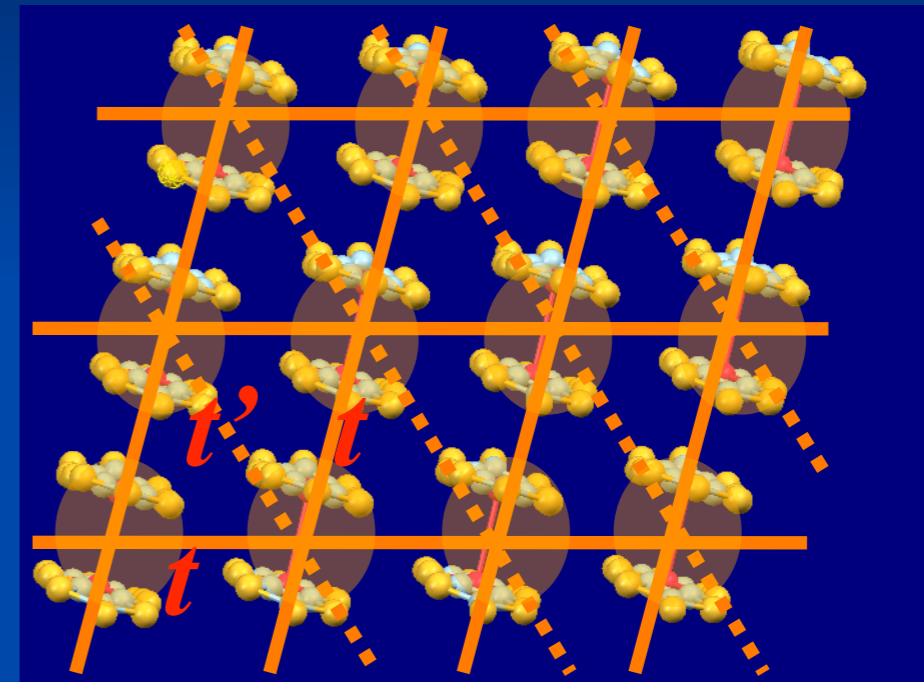
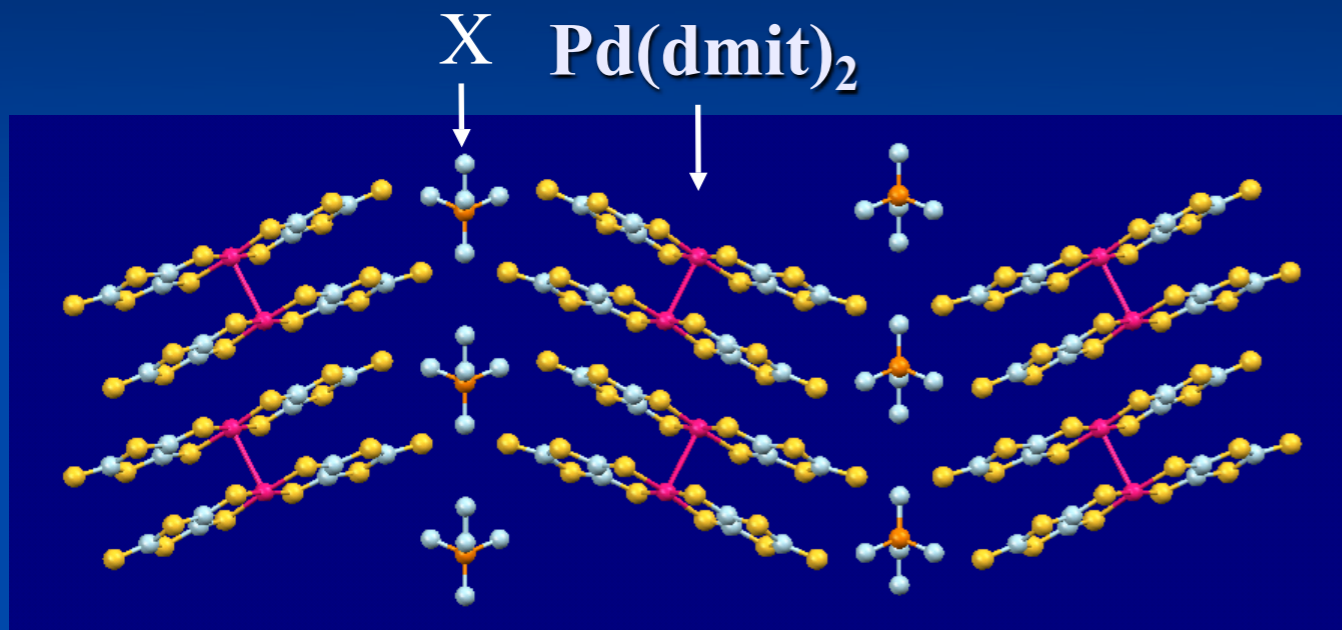
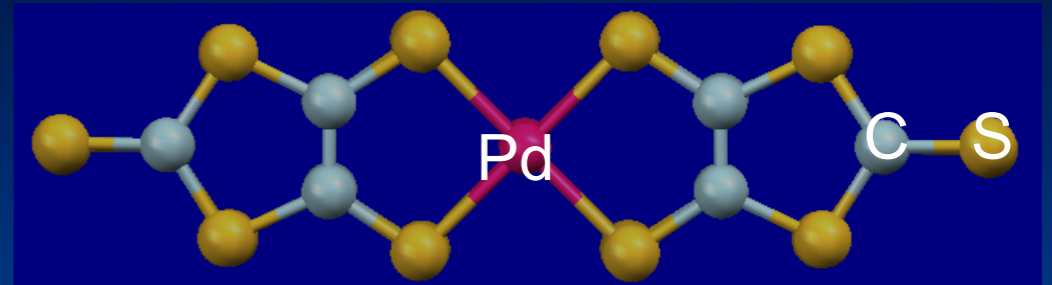
Christian Ruedg, Bruce Normand, Masashige Matsumoto, Albert Furrer,  
Desmond McMorro, Karl Kramer, Hans-Ulrich Gudel, Severian Gvasaliya,  
Hannu Mutka, and Martin Boehm, *Phys. Rev. Lett.* **100**, 205701 (2008)

# Prediction of quantum field theory

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



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)



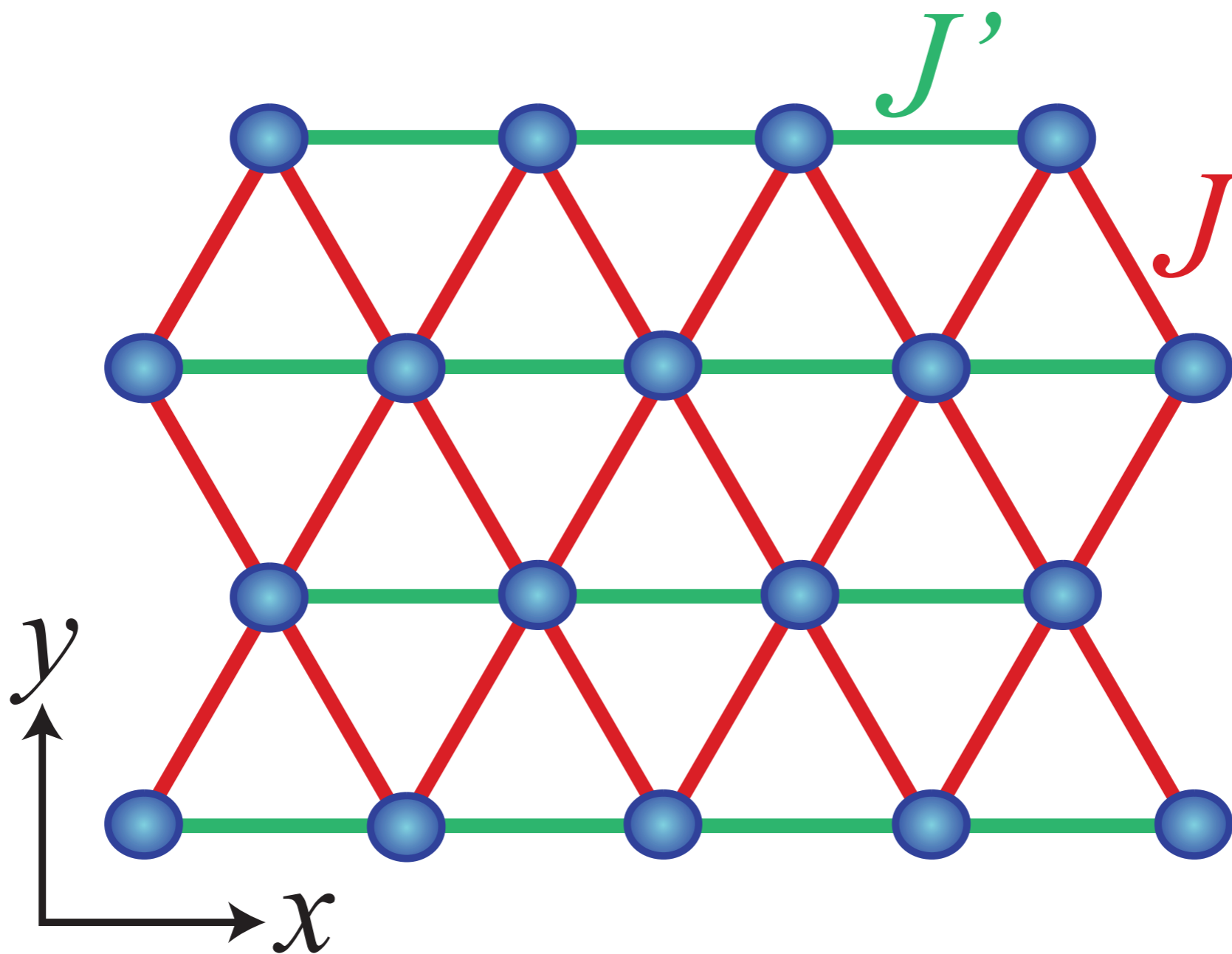
Half-filled band  $\rightarrow$  Mott insulator with spin  $S = 1/2$

Triangular lattice of  $[\text{Pd}(\text{dmit})_2]_2$

$\rightarrow$  frustrated quantum spin system

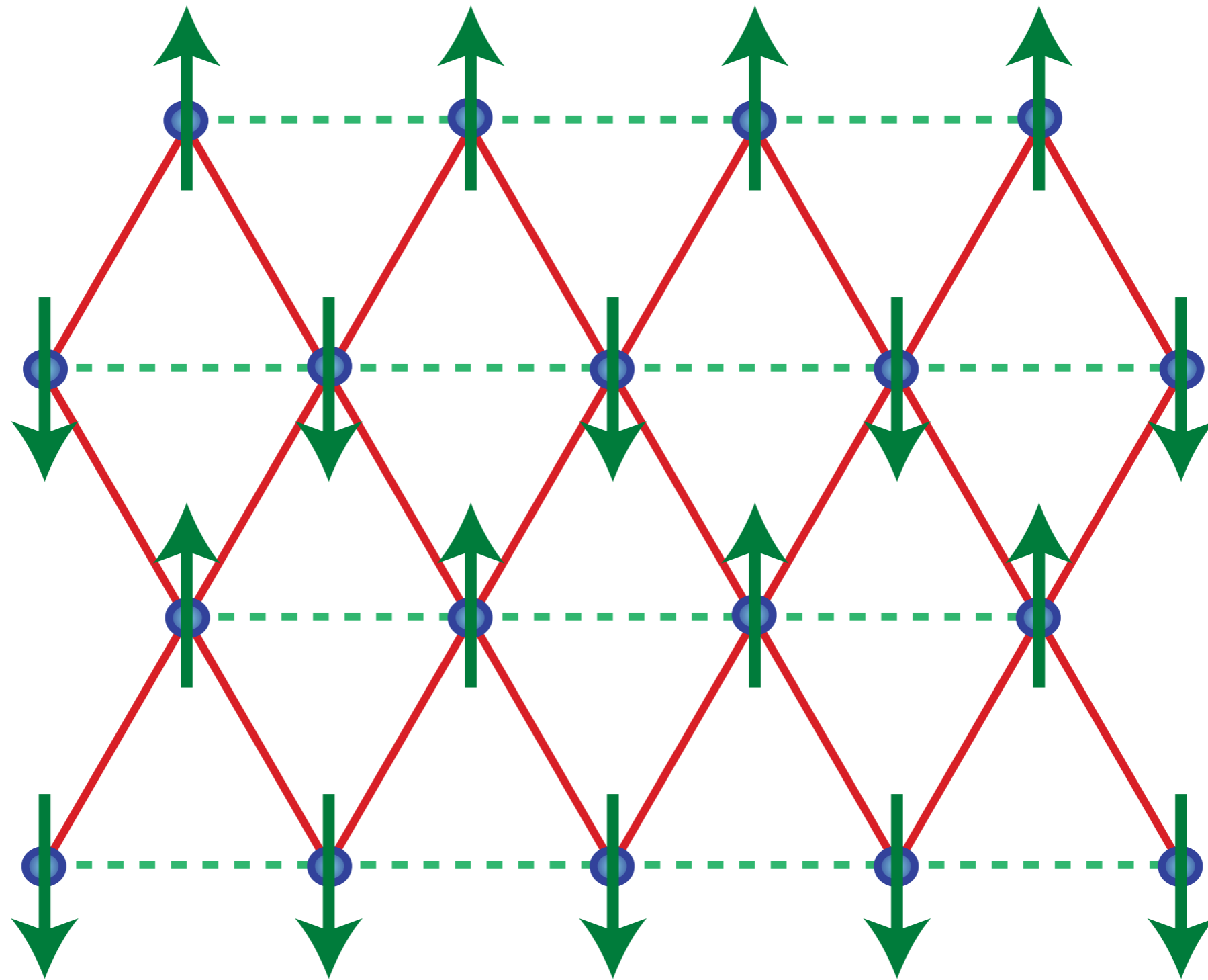
$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j + \dots$$

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



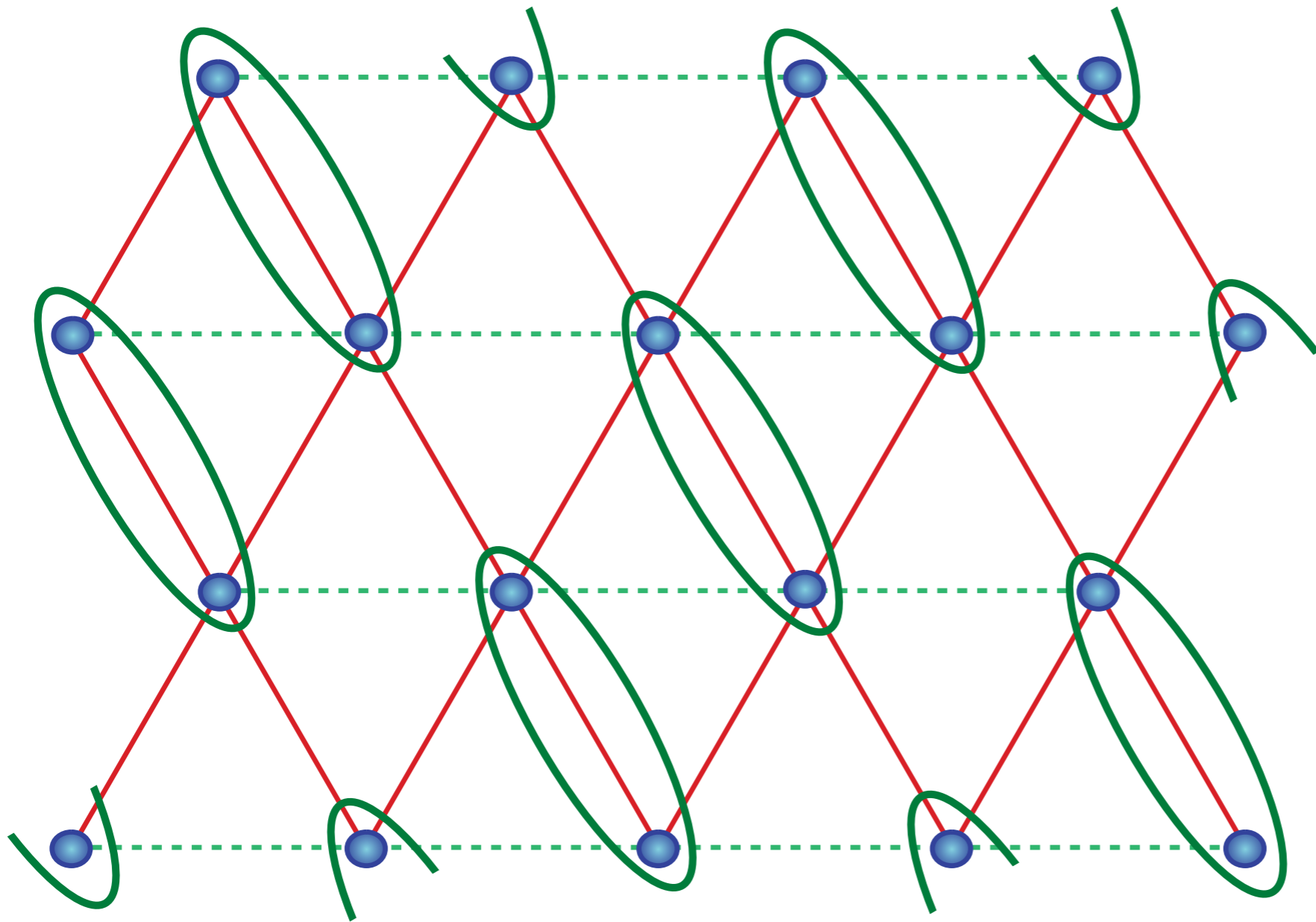
# Anisotropic triangular lattice antiferromagnet

Broken spin rotation symmetry



Neel ground state for small  $J'/J$

# Anisotropic triangular lattice antiferromagnet

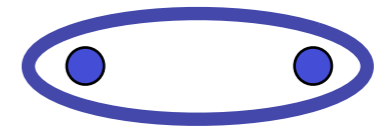
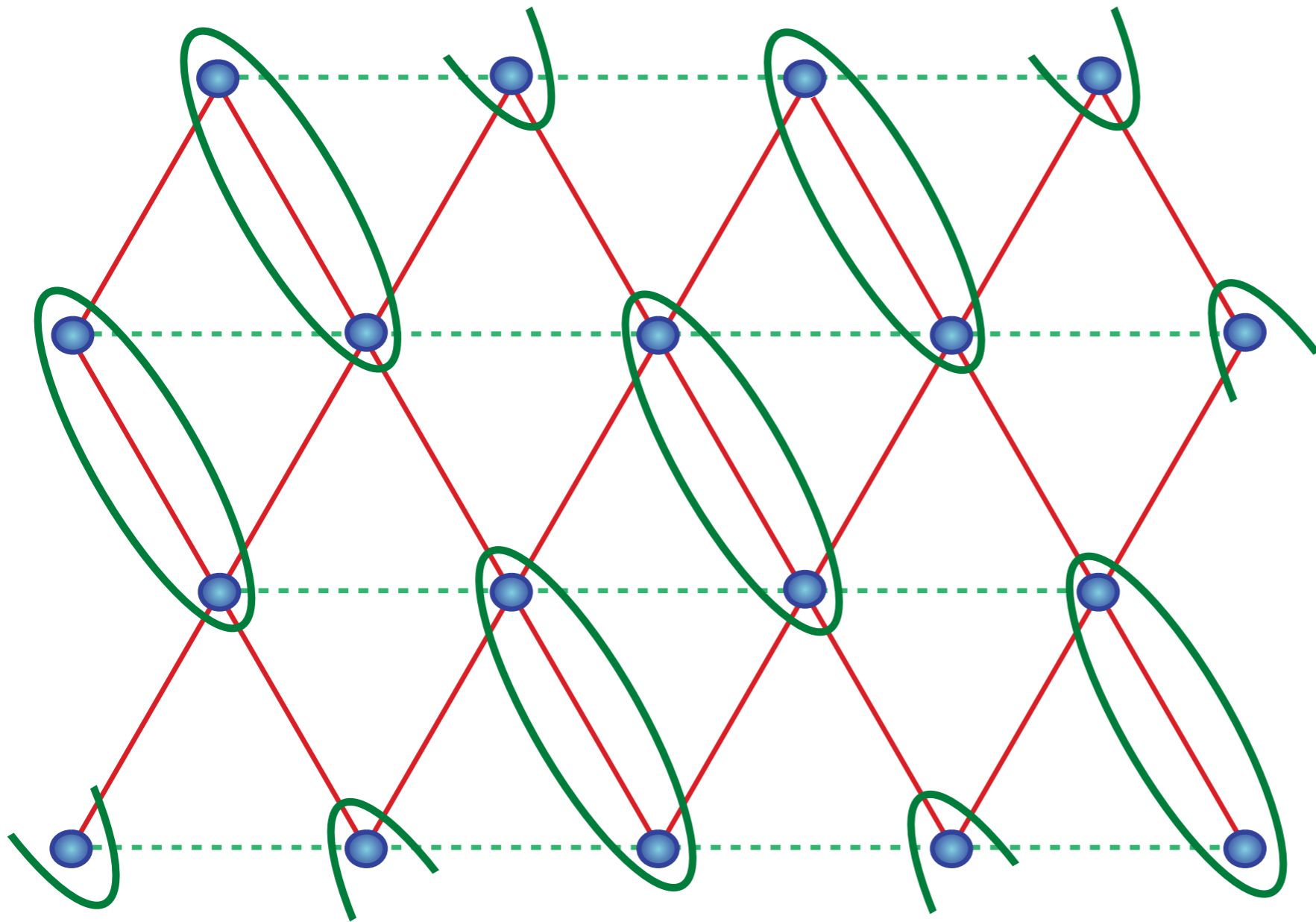


$$\begin{array}{l} \text{Diagram of two spheres in an oval} \\ = \frac{(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)}{\sqrt{2}} \end{array}$$

Possible ground state for intermediate  $J'/J$

# Anisotropic triangular lattice antiferromagnet

Broken lattice space group symmetry



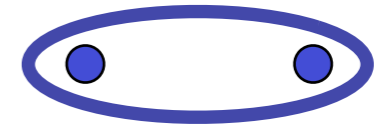
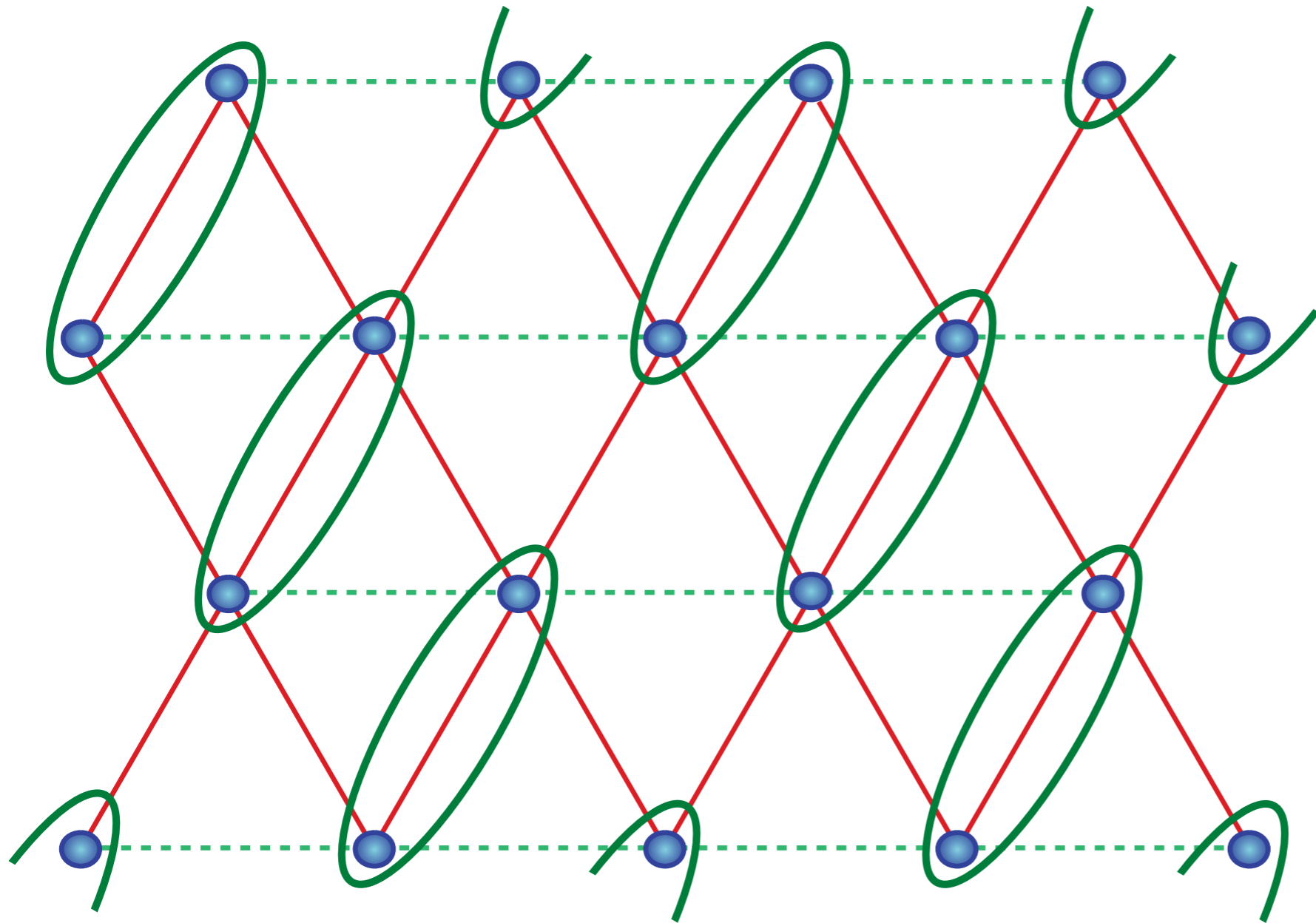
$$= \frac{(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)}{\sqrt{2}}$$

## Valence bond solid (VBS)

Possible ground state for intermediate  $J'/J$

# Anisotropic triangular lattice antiferromagnet

Broken lattice space group symmetry



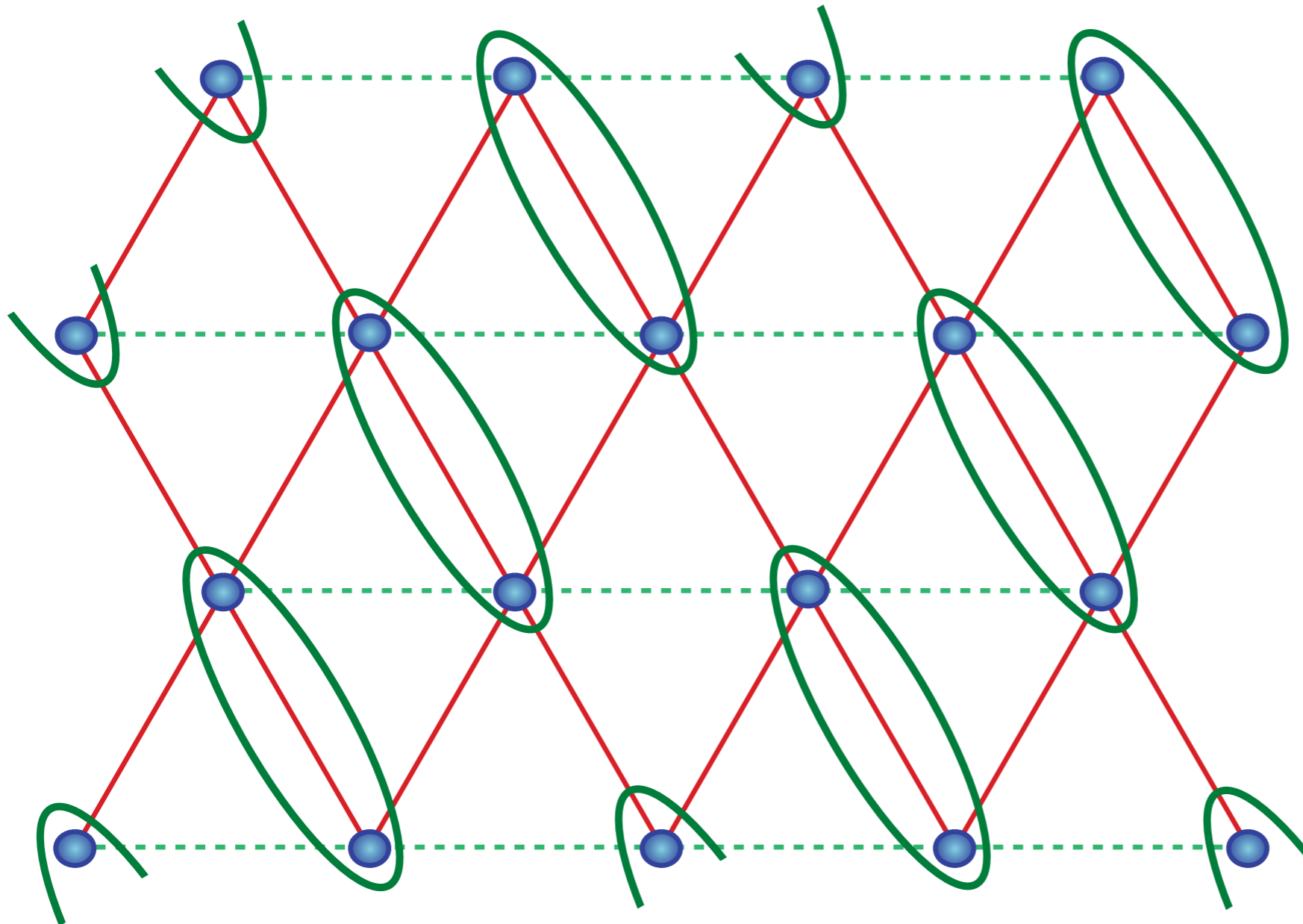
$$= \frac{(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)}{\sqrt{2}}$$

## Valence bond solid (VBS)

Possible ground state for intermediate  $J'/J$

# Anisotropic triangular lattice antiferromagnet

Broken lattice space group symmetry



$$\begin{array}{c} \text{Diagram of two atoms in a dimer} \\ = \frac{(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)}{\sqrt{2}} \end{array}$$

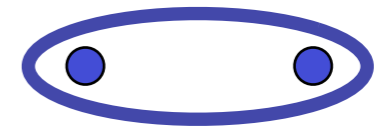
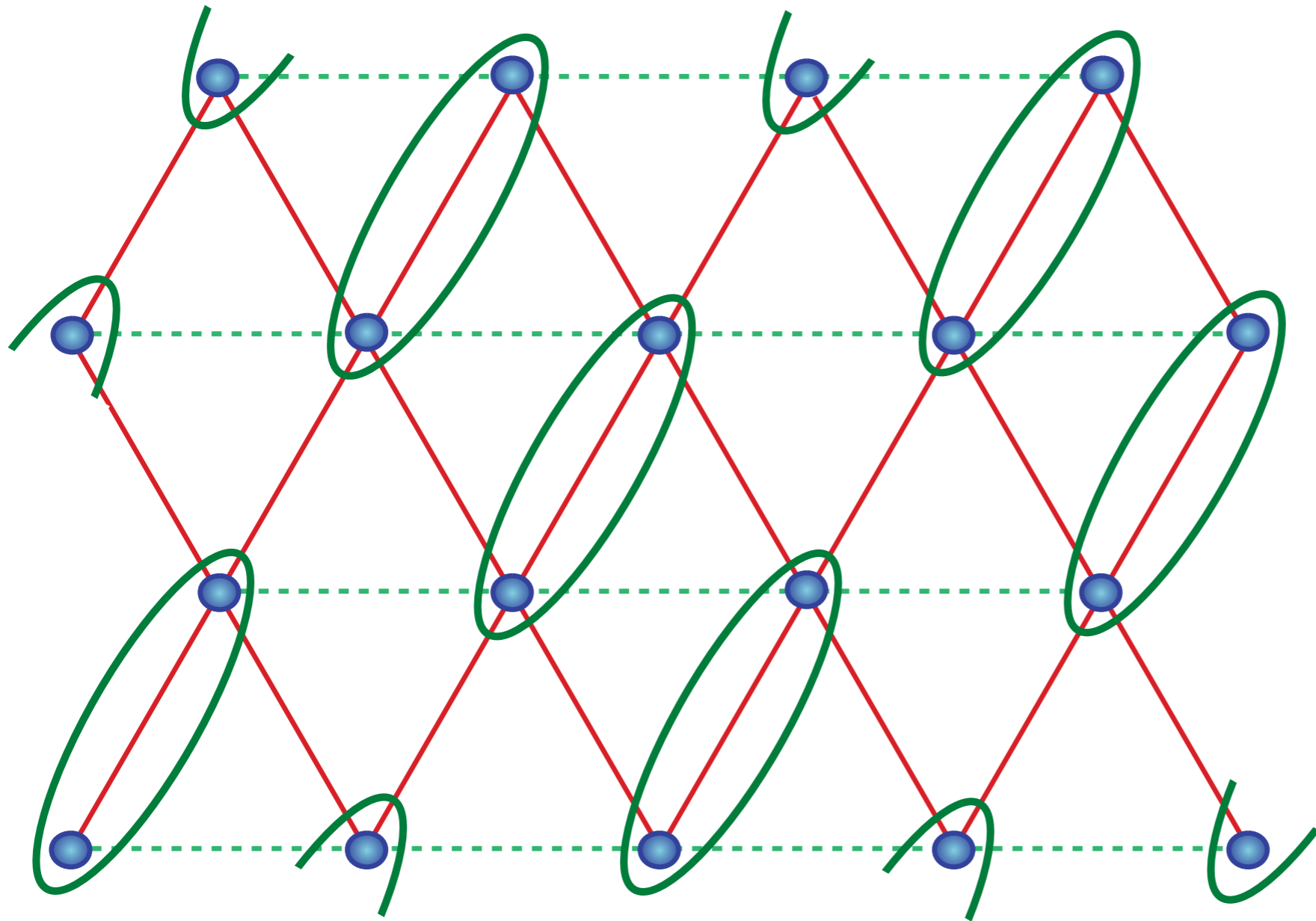


## Valence bond solid (VBS)

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# Anisotropic triangular lattice antiferromagnet

Broken lattice space group symmetry



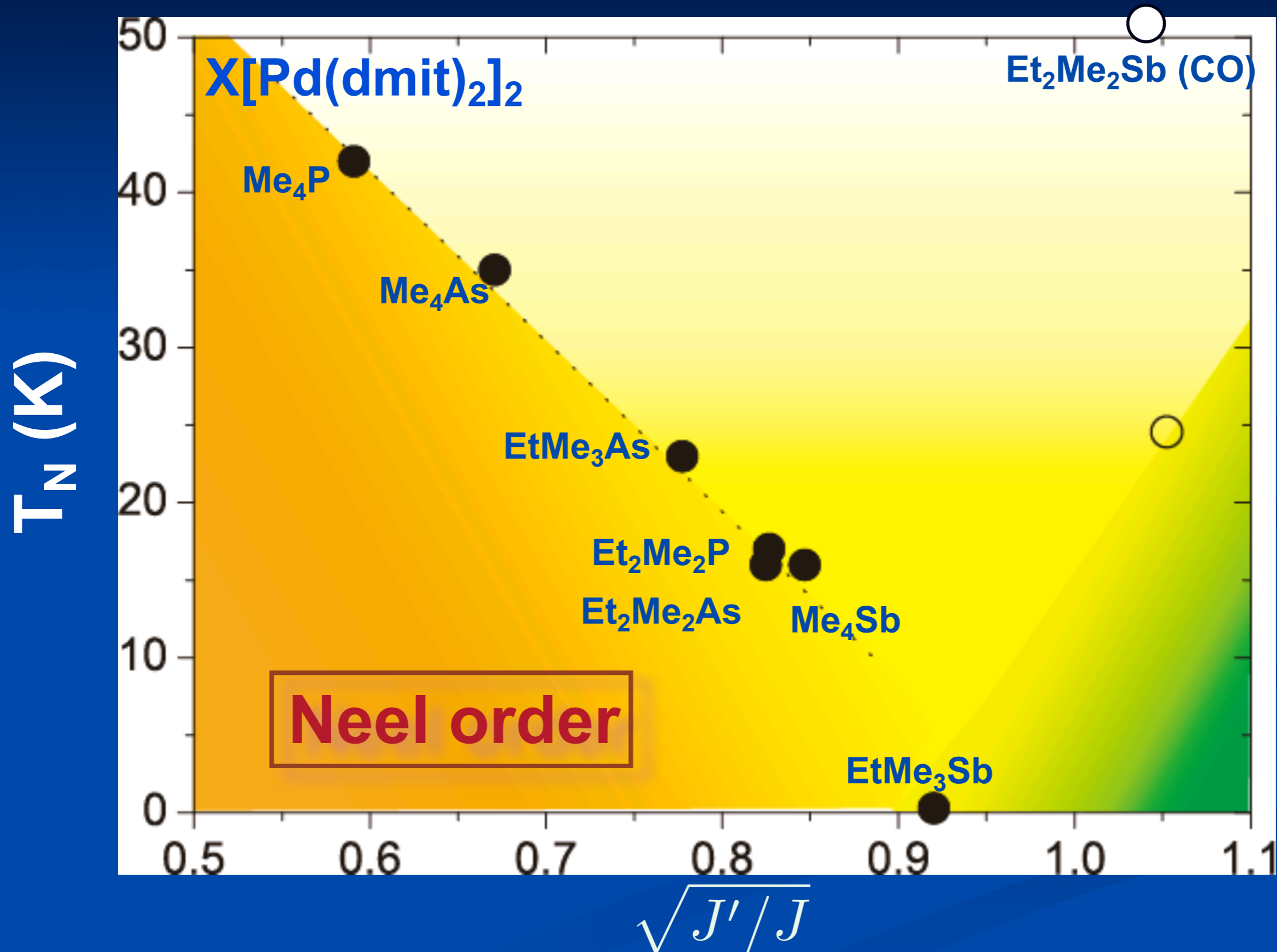
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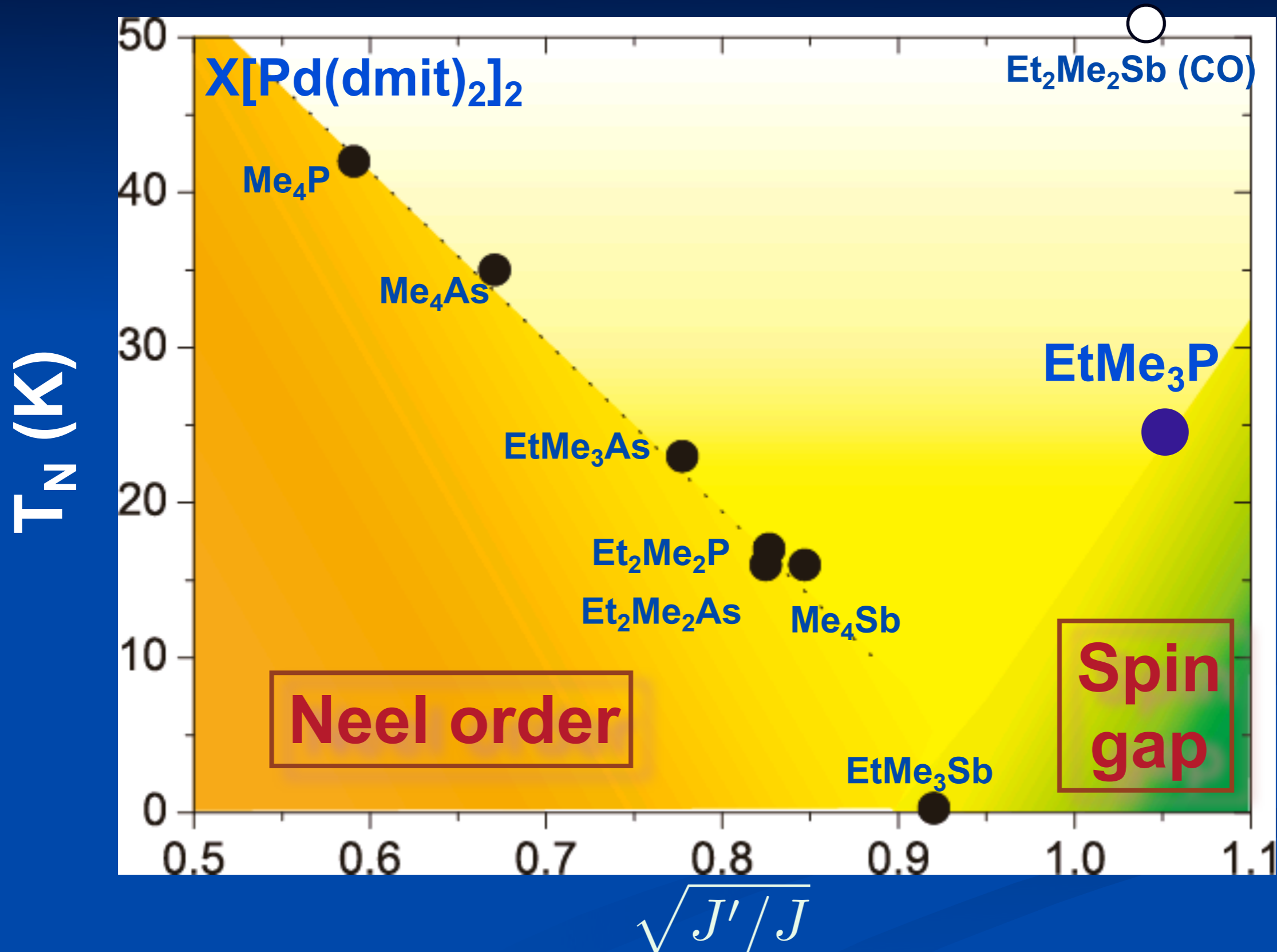
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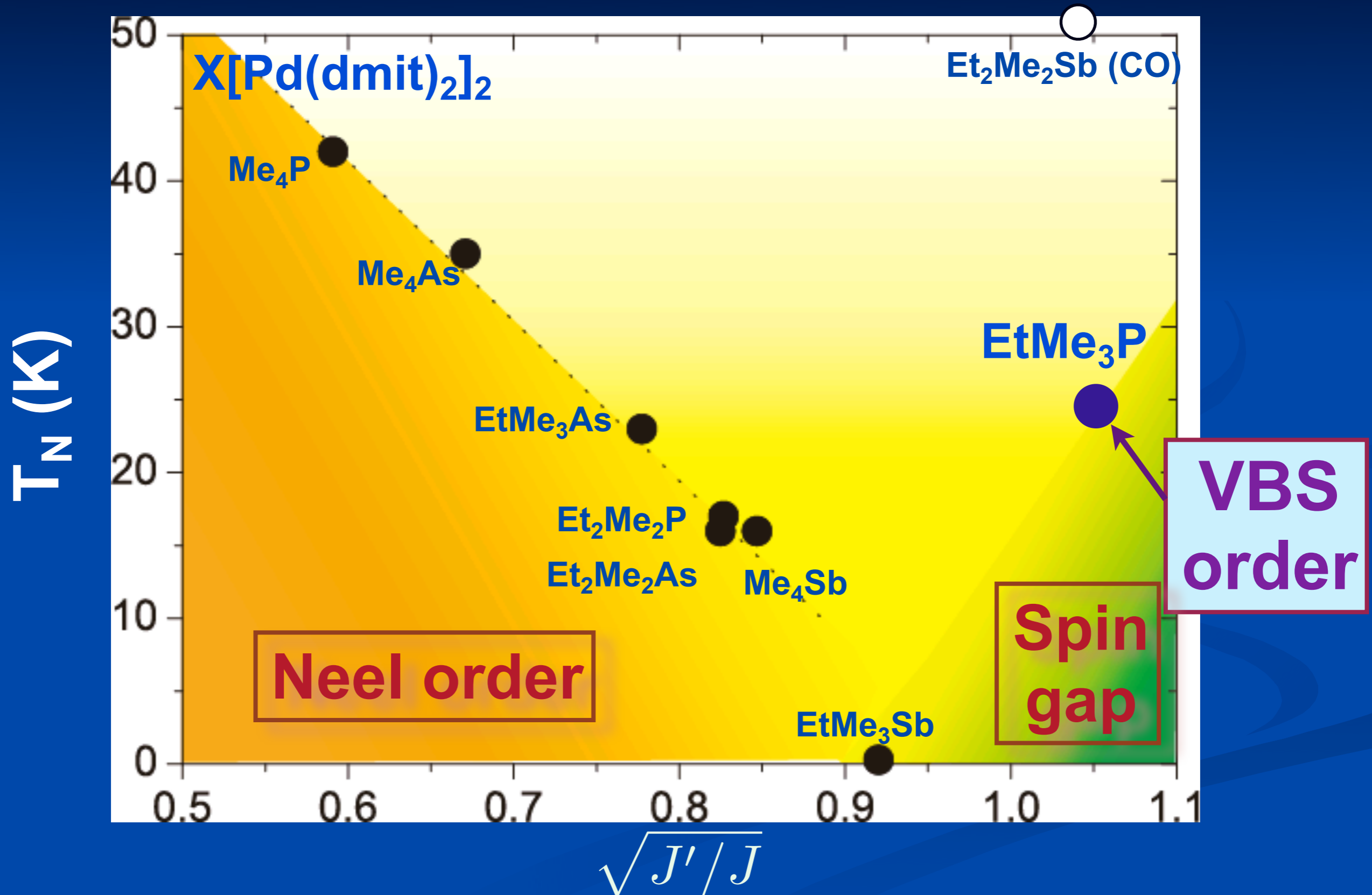
# Magnetic Criticality



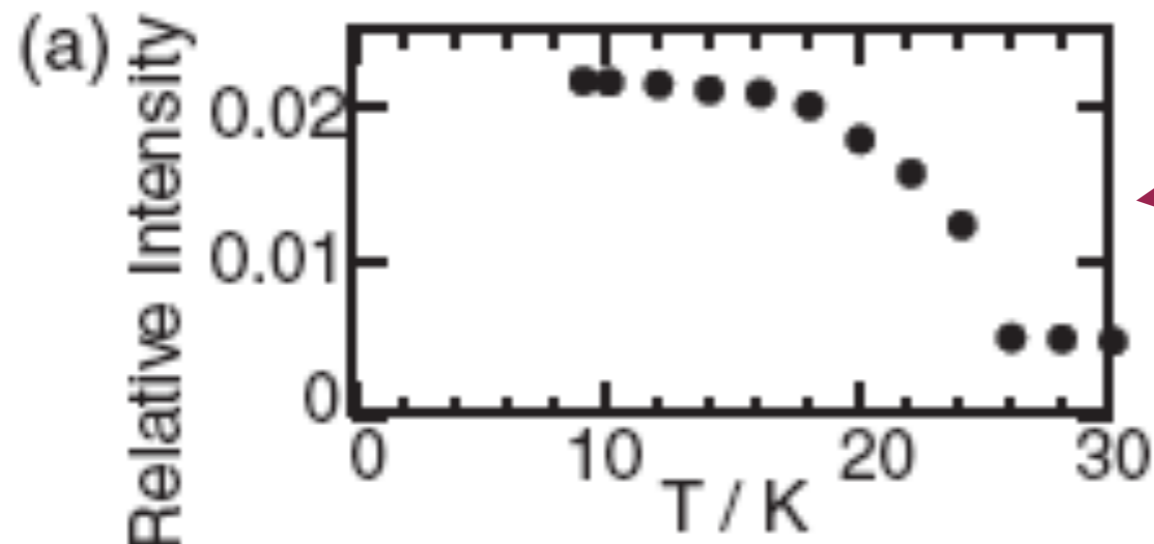
# Magnetic Criticality



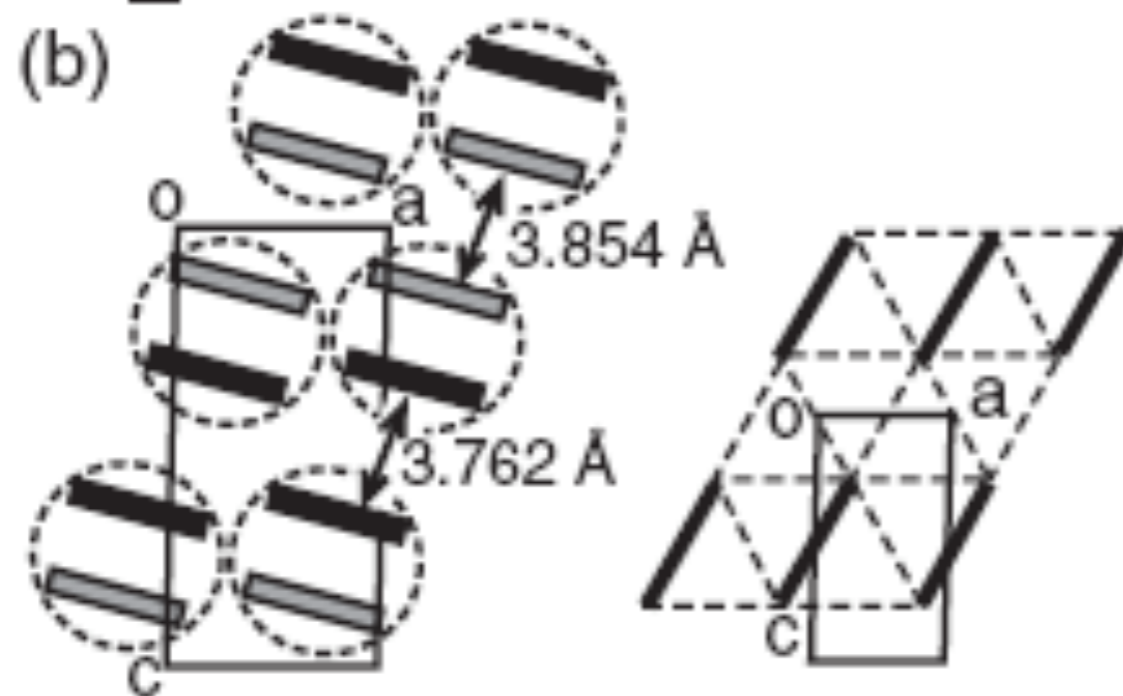
# Magnetic Criticality



# Observation of a valence bond solid (VBS) in $\text{ETMe}_3\text{P}[\text{Pd}(\text{dmit})_2]_2$



X-ray scattering

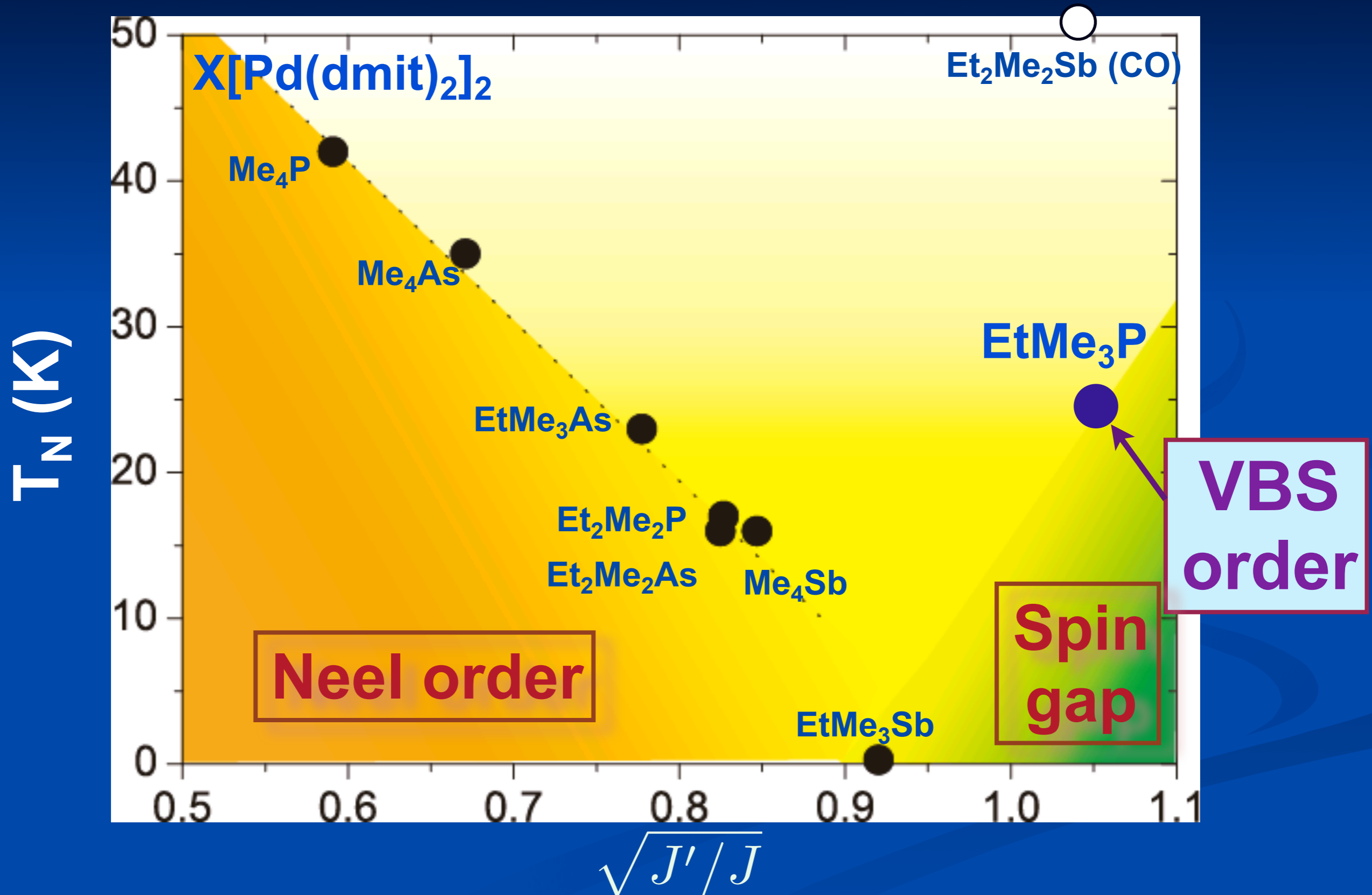


Spin gap  $\sim 40$  K  
 $J \sim 250$  K

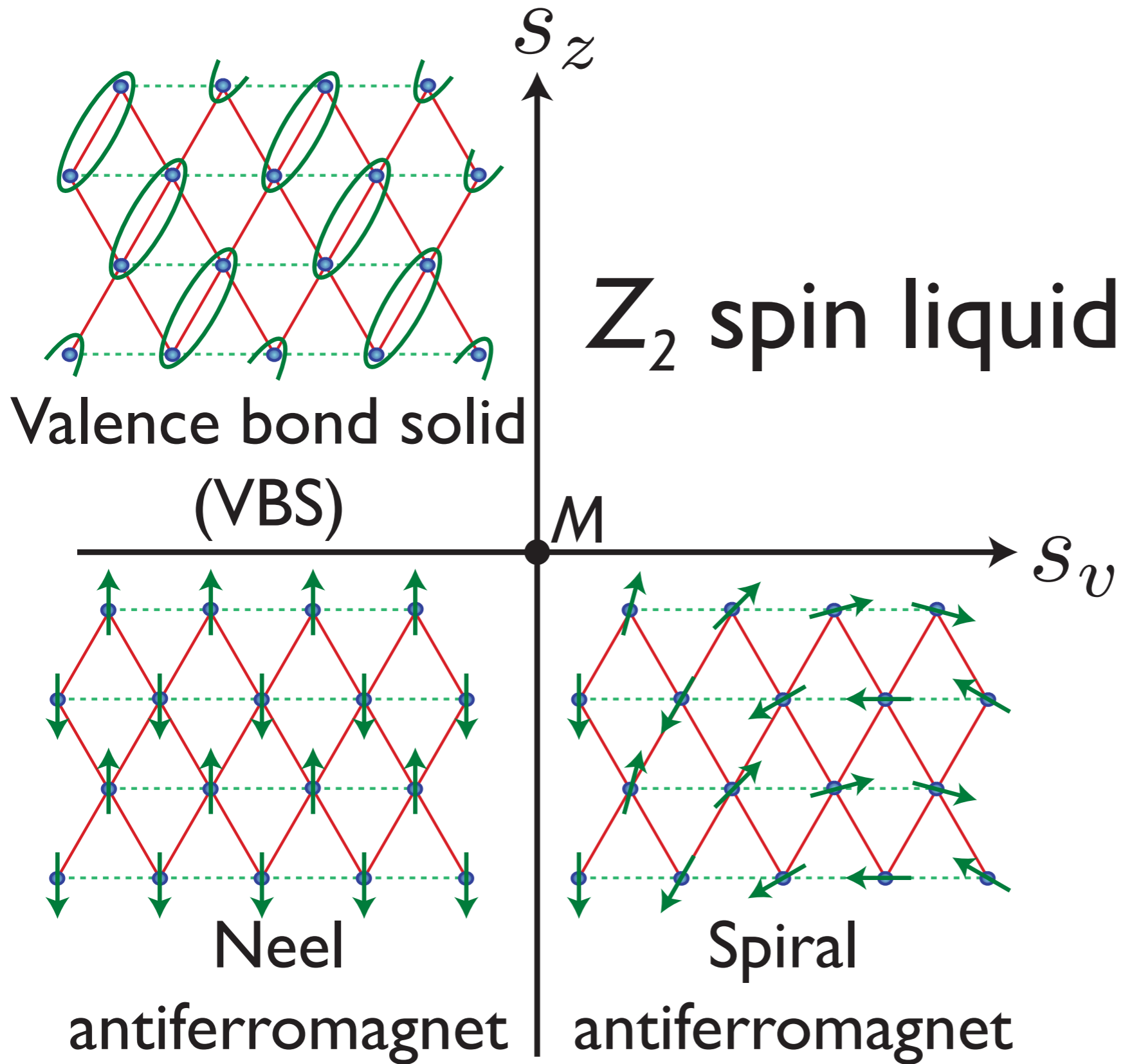
M. Tamura, A. Nakao and R. Kato, *J. Phys. Soc. Japan* **75**, 093701 (2006)

Y. Shimizu, H. Akimoto, H. Tsujii, A. Tajima, and R. Kato, *Phys. Rev. Lett.* **99**, 256403 (2007)

# Magnetic Criticality



# Theoretical global phase diagram

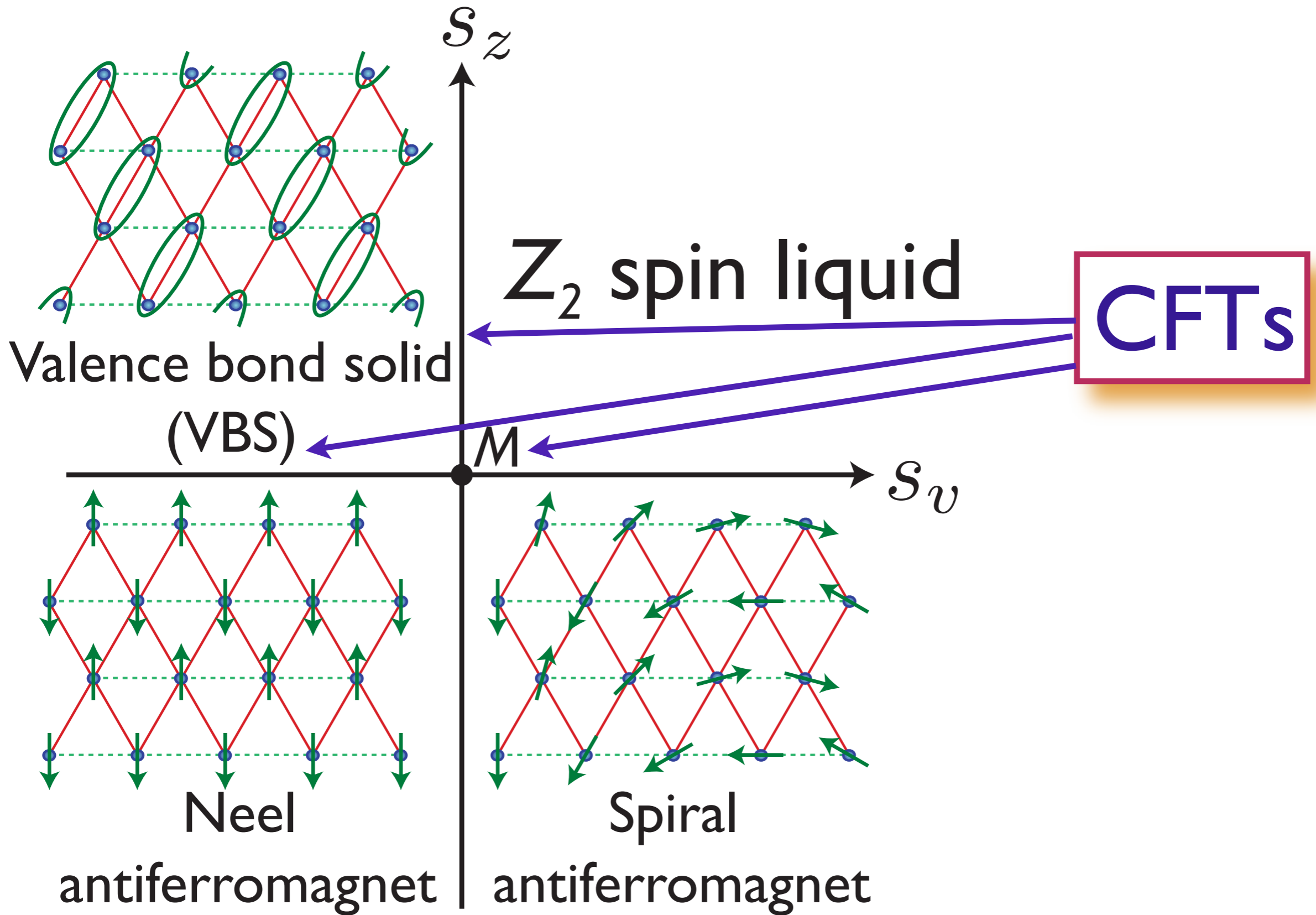


N. Read and S. Sachdev, *Phys. Rev. Lett.* **66**, 1773 (1991)

T. Senthil, A. Vishwanath, L. Balents, S. Sachdev and M.P.A. Fisher, *Science* **303**, 1490 (2004).

Cenke Xu and S. Sachdev, arXiv:0811.1220

# Theoretical global phase diagram



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# Theoretical global phase diagram

CFTs described by a doubled U(1) Chern Simons theory of spinons  $z_\alpha$  and visons  $v_a$ . (Structure similar to the supersymmetric ABJM theory of the M2 brane)

CFTs

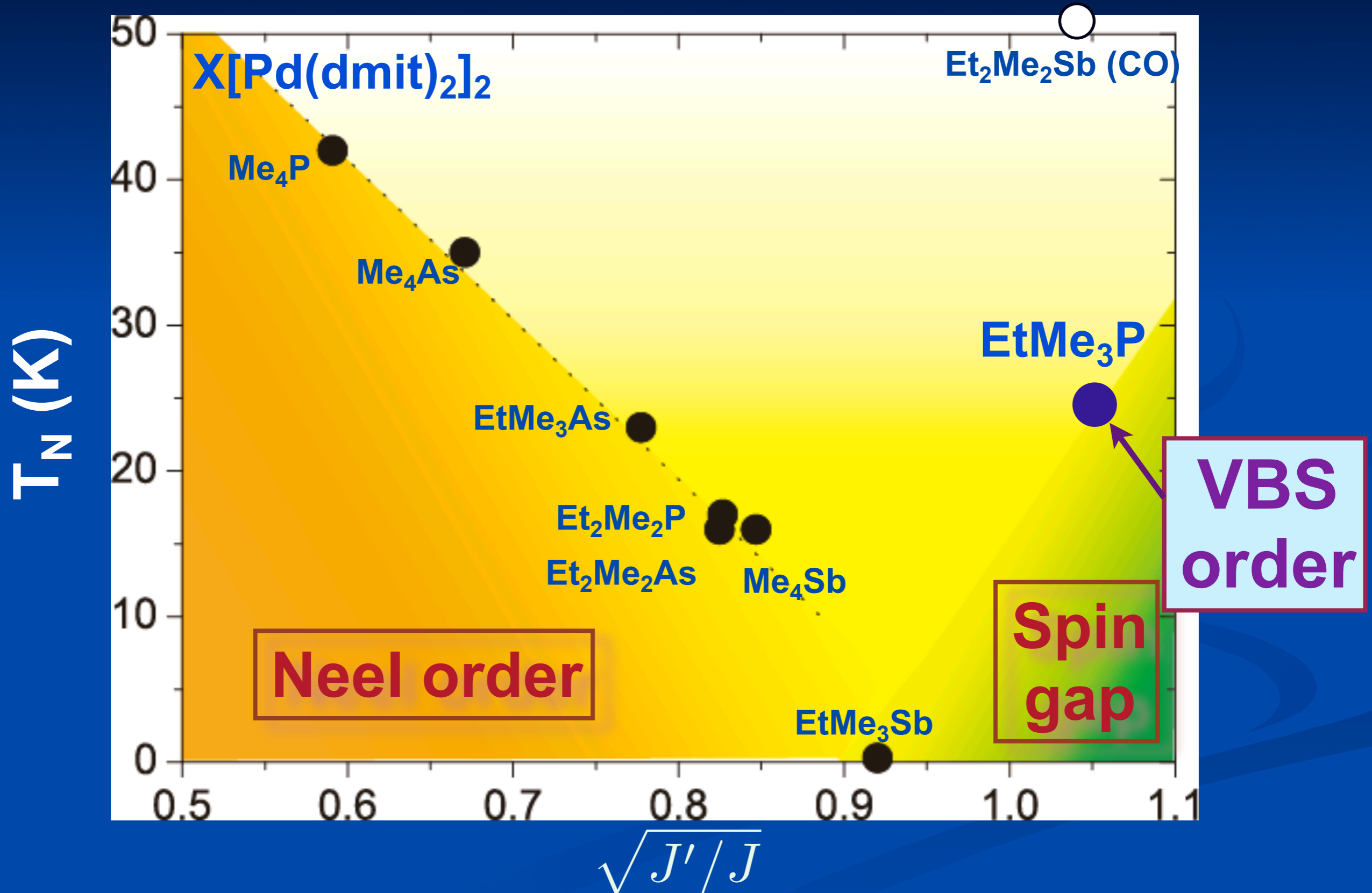
$$\begin{aligned}\mathcal{L} &= \sum_{\alpha=1}^2 \left\{ |(\partial_\mu - ia_\mu)z_\alpha|^2 + s_z |z_\alpha|^2 \right\} \\ &+ \sum_{a=1}^{N_v} \left\{ |(\partial_\mu - ib_\mu)v_a|^2 + s_v |v_a|^2 \right\} \\ &+ \frac{i}{\pi} \epsilon_{\mu\nu\lambda} a_\mu \partial_\nu b_\lambda + \dots\end{aligned}$$

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

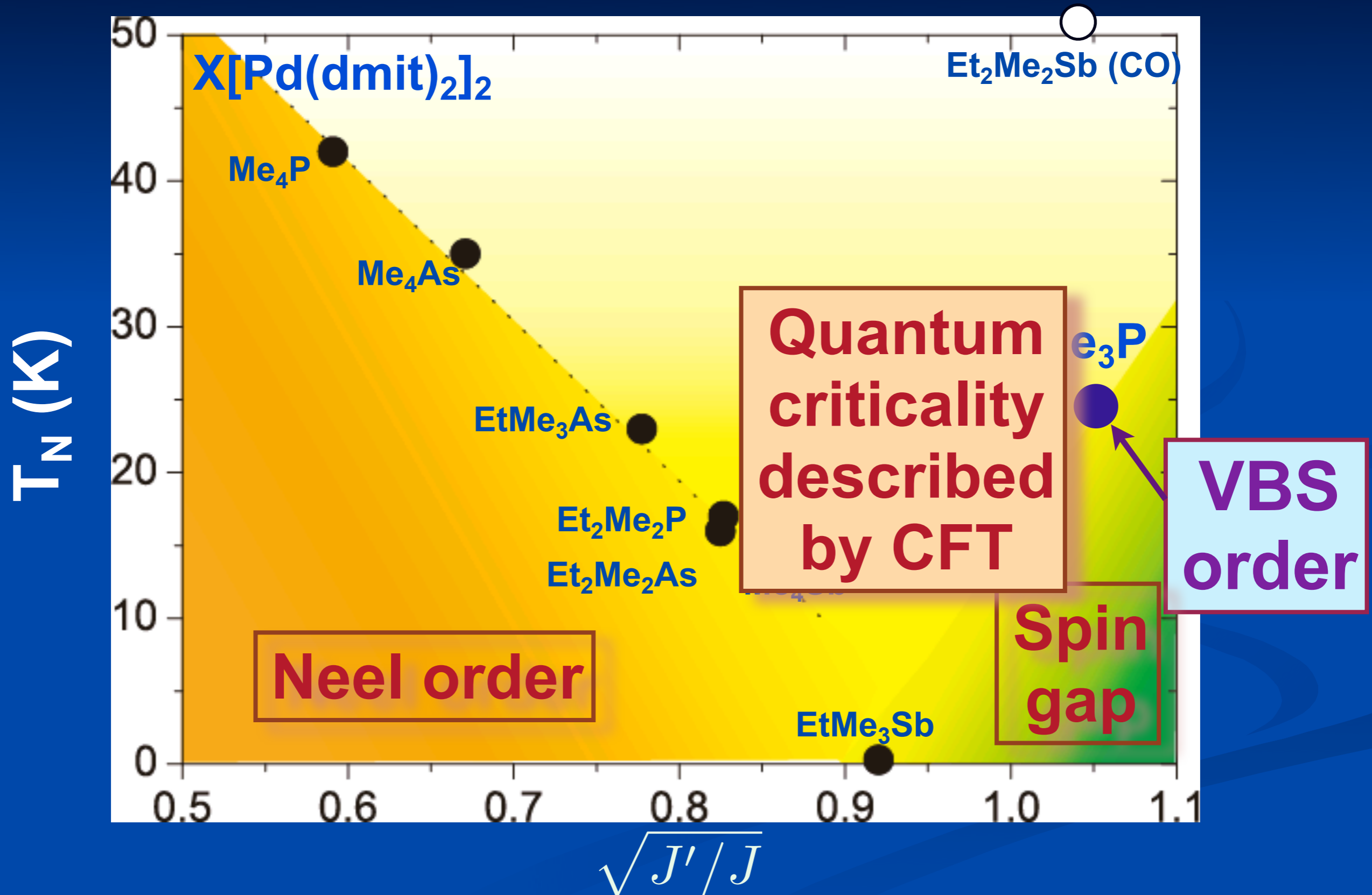
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# Magnetic Criticality



# Magnetic Criticality



# Three foci of modern physics

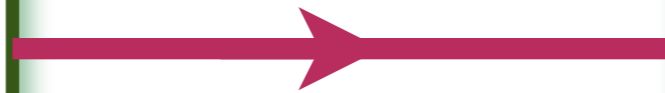
Quantum phase  
transitions

Hydrodynamics

Black holes

# Three foci of modern physics

Quantum phase  
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Hydrodynamics

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

Black holes

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Quantum phase  
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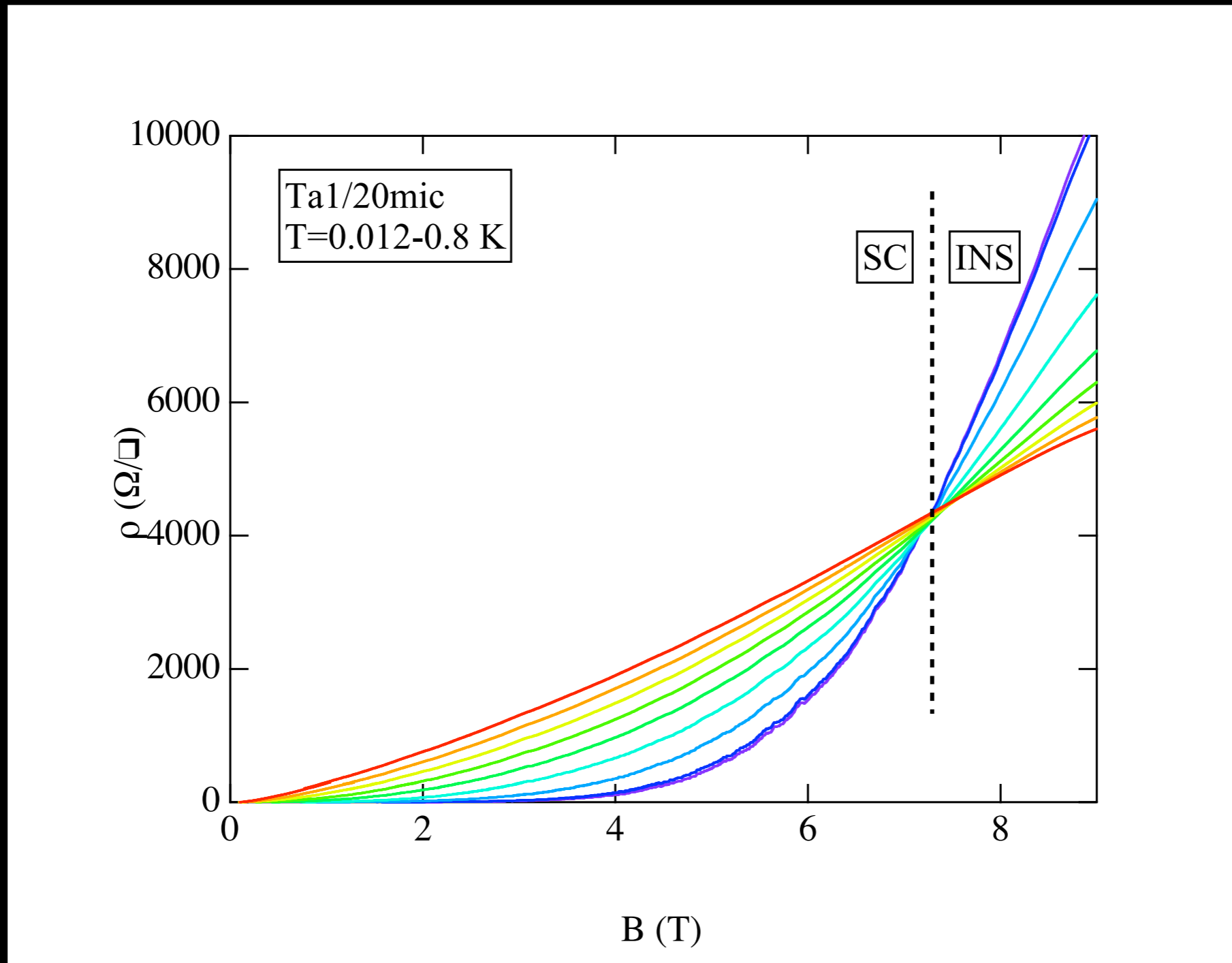
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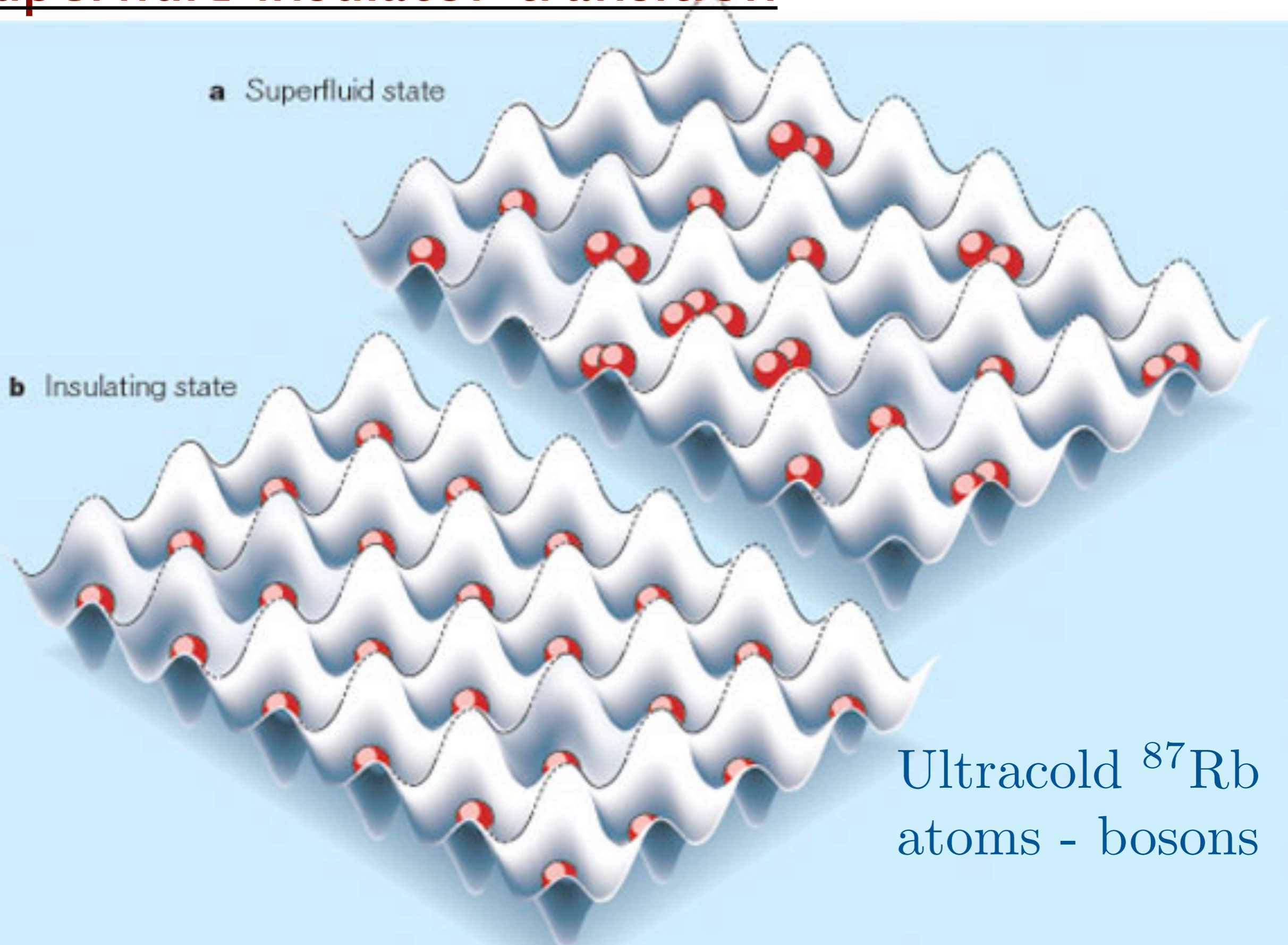
# Superfluid-insulator transition

## Indium Oxide films

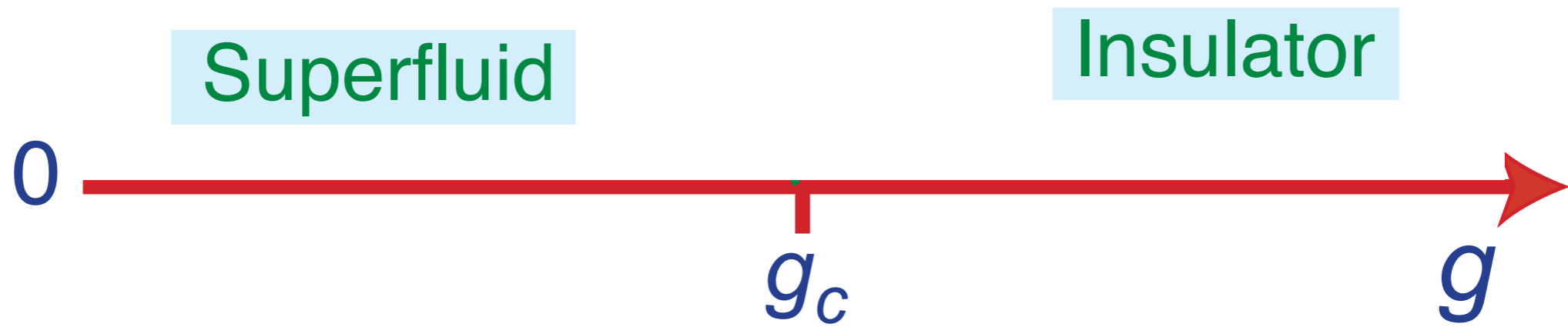


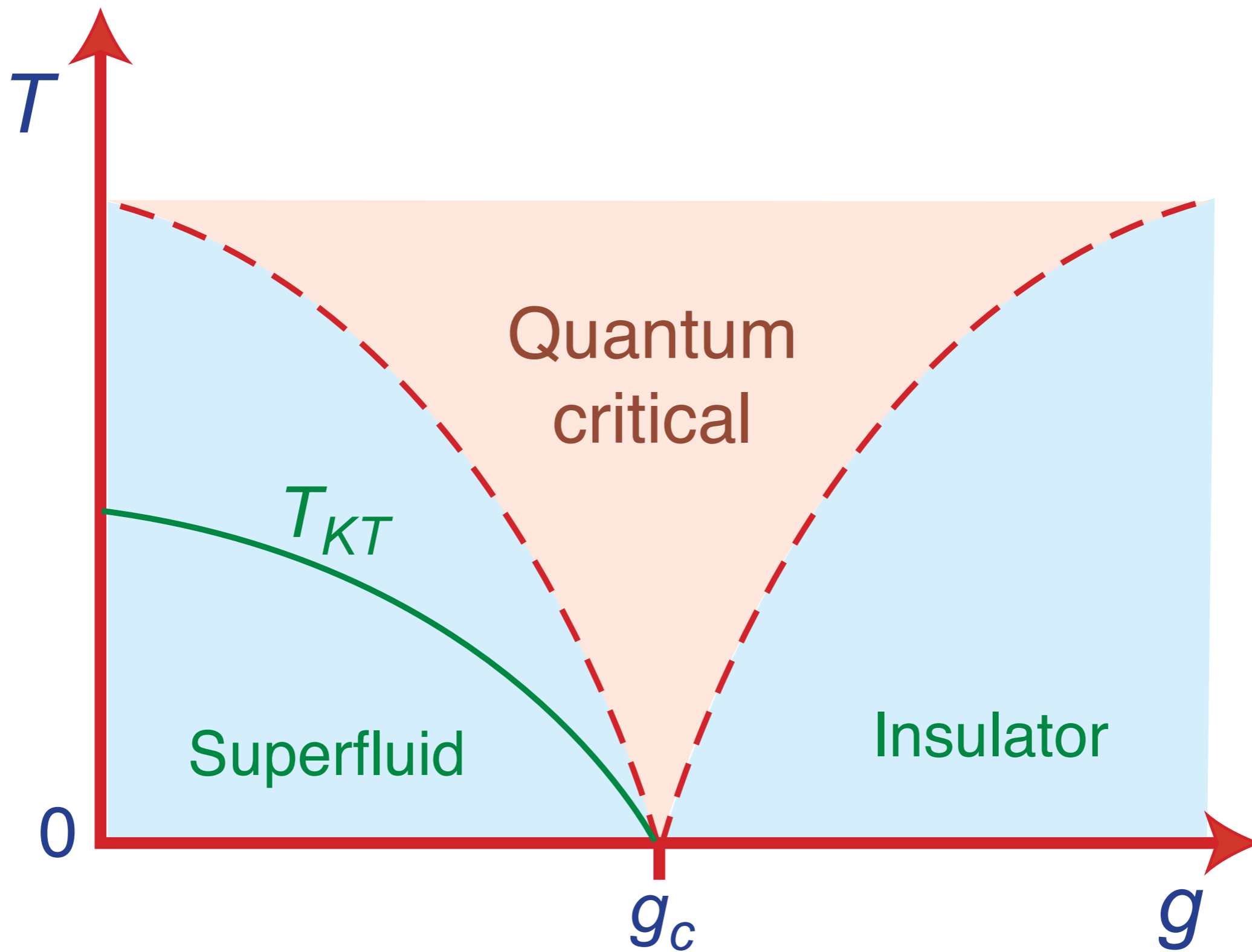
G. Sambandamurthy, A. Johansson, E. Peled, D. Shahar, P. G. Bjornsson, and K.A. Moler, *Europhys. Lett.* **75**, 611 (2006).

# Superfluid-insulator transition



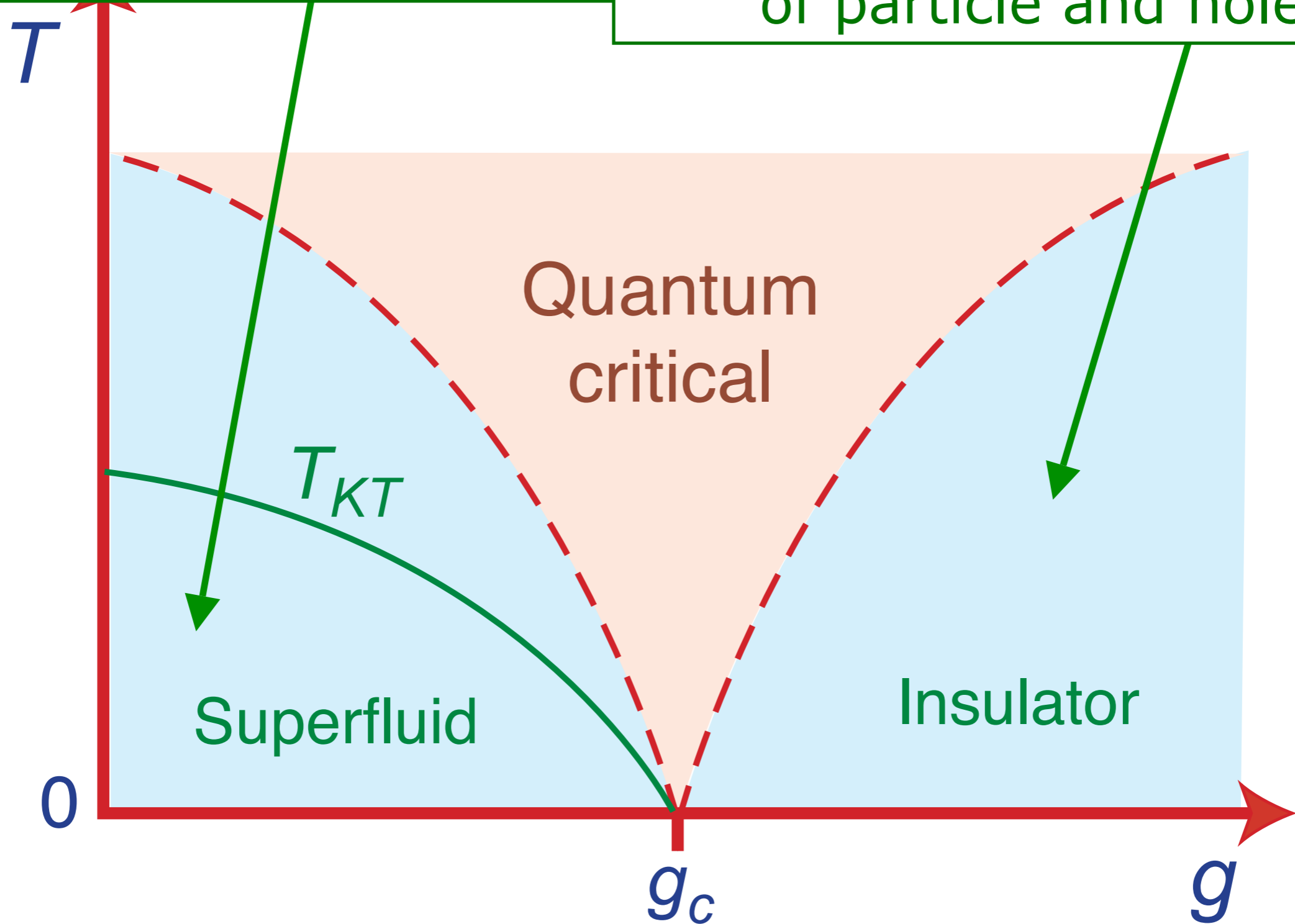
Ultracold  $^{87}\text{Rb}$   
atoms - bosons

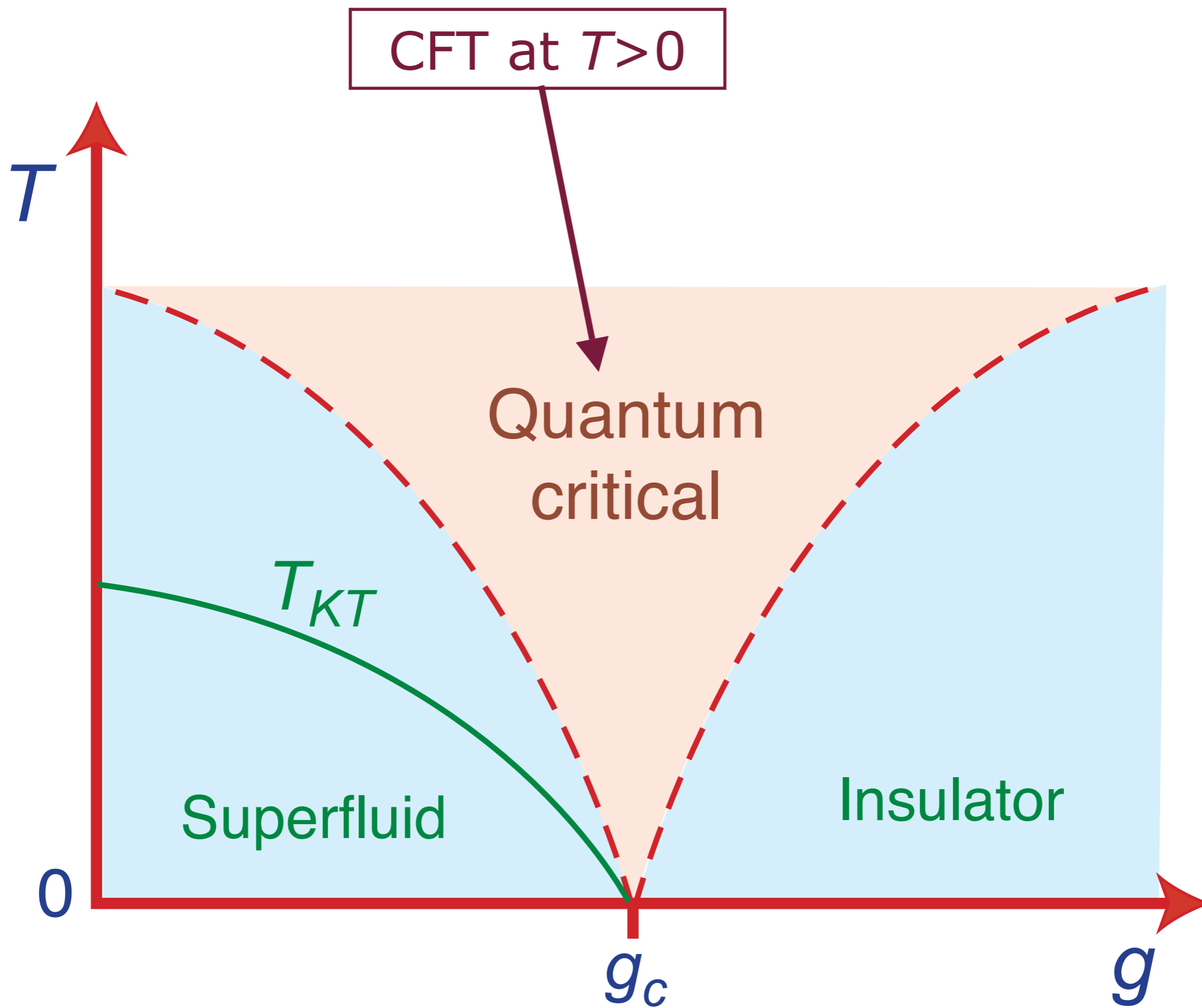




Classical vortices and wave oscillations of the condensate

Dilute Boltzmann/Landau gas of particle and holes





# Quantum critical transport

Quantum “*perfect fluid*”  
with shortest possible  
relaxation time,  $\tau_R$

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

# Quantum critical transport

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

## Electrical conductivity

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

# Quantum critical transport

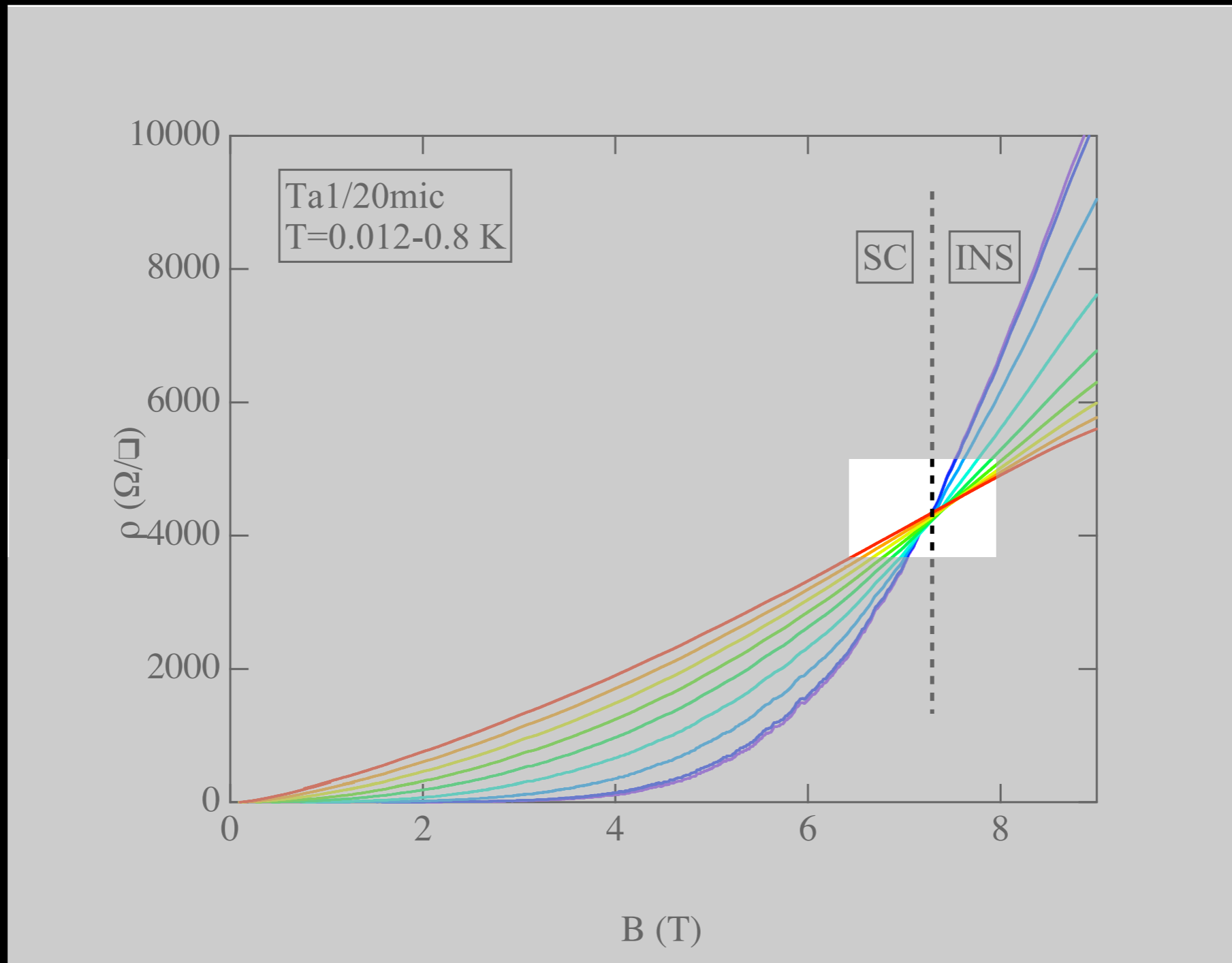
Transport co-efficients not determined  
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universal constants of nature

## Momentum transport

$$\frac{\eta}{s} \equiv \frac{\text{viscosity}}{\text{entropy density}}$$
$$= \frac{\hbar}{k_B} \times [\text{Universal constant } \mathcal{O}(1) ]$$

# Superfluid-insulator transition

## Indium Oxide films



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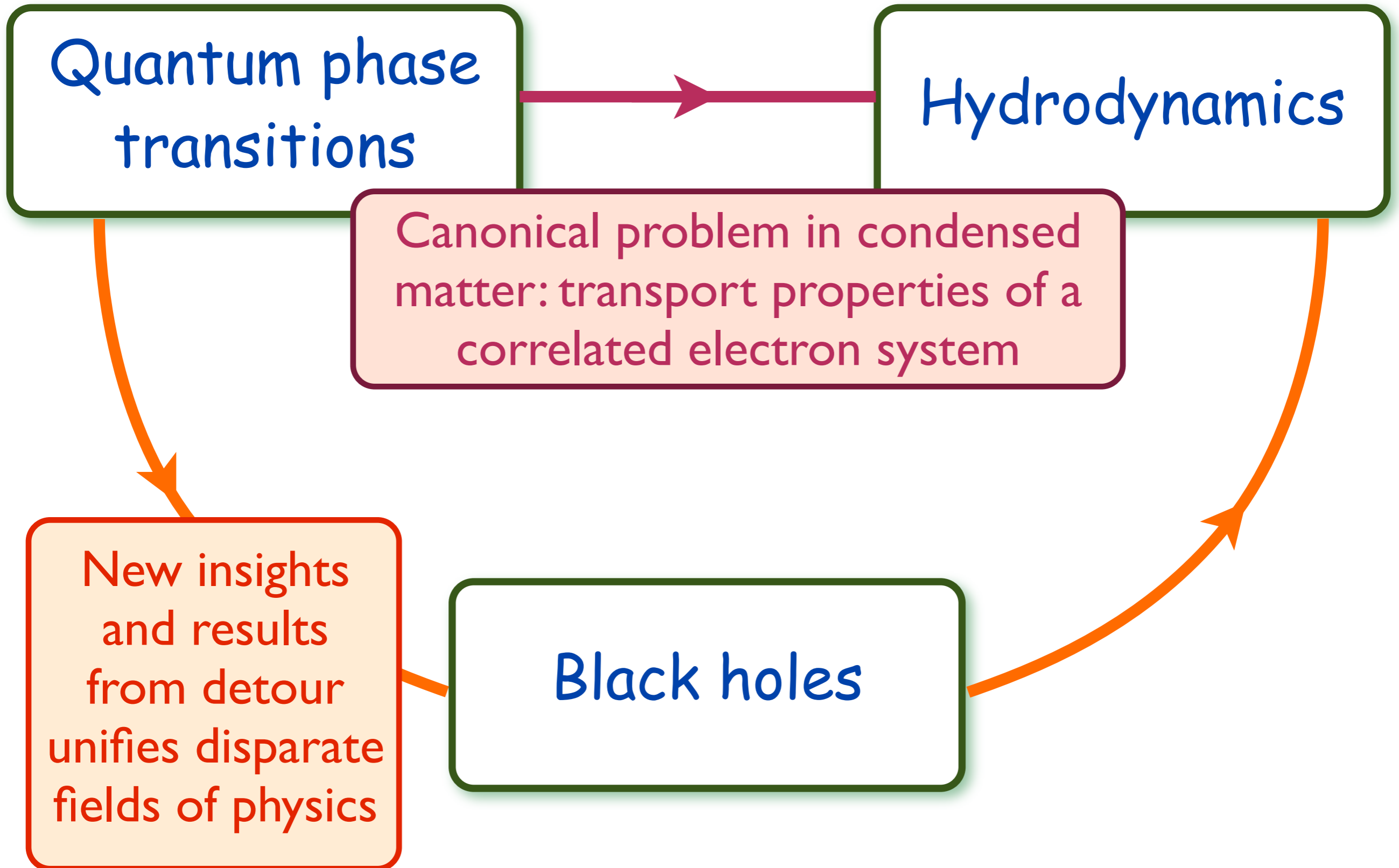
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Canonical problem in condensed matter: transport properties of a correlated electron system

New insights and results from detour unifies disparate fields of physics

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# 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

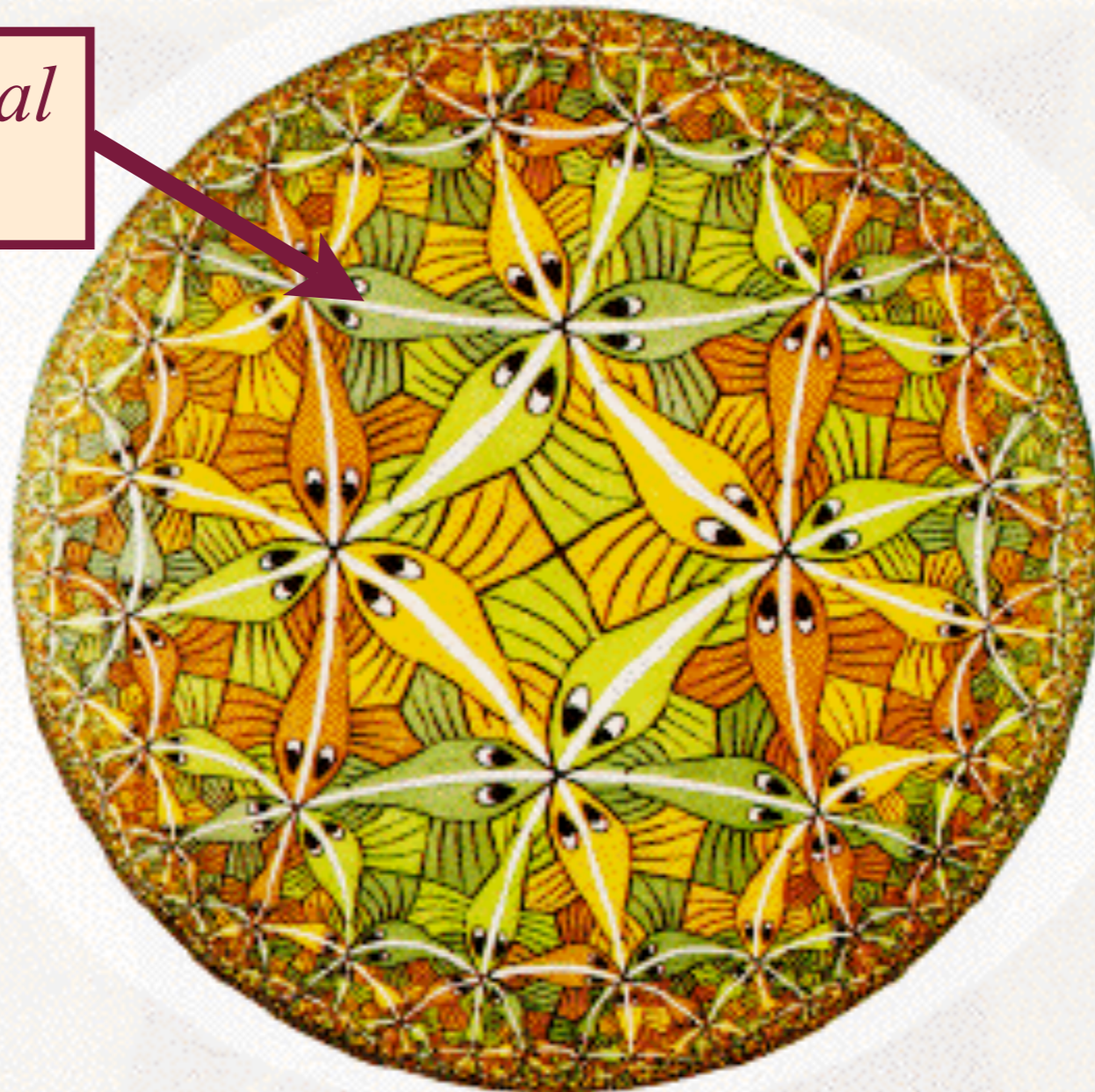
Bekenstein and Hawking discovered astonishing connections between the Einstein theory of black holes and the laws of thermodynamics

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

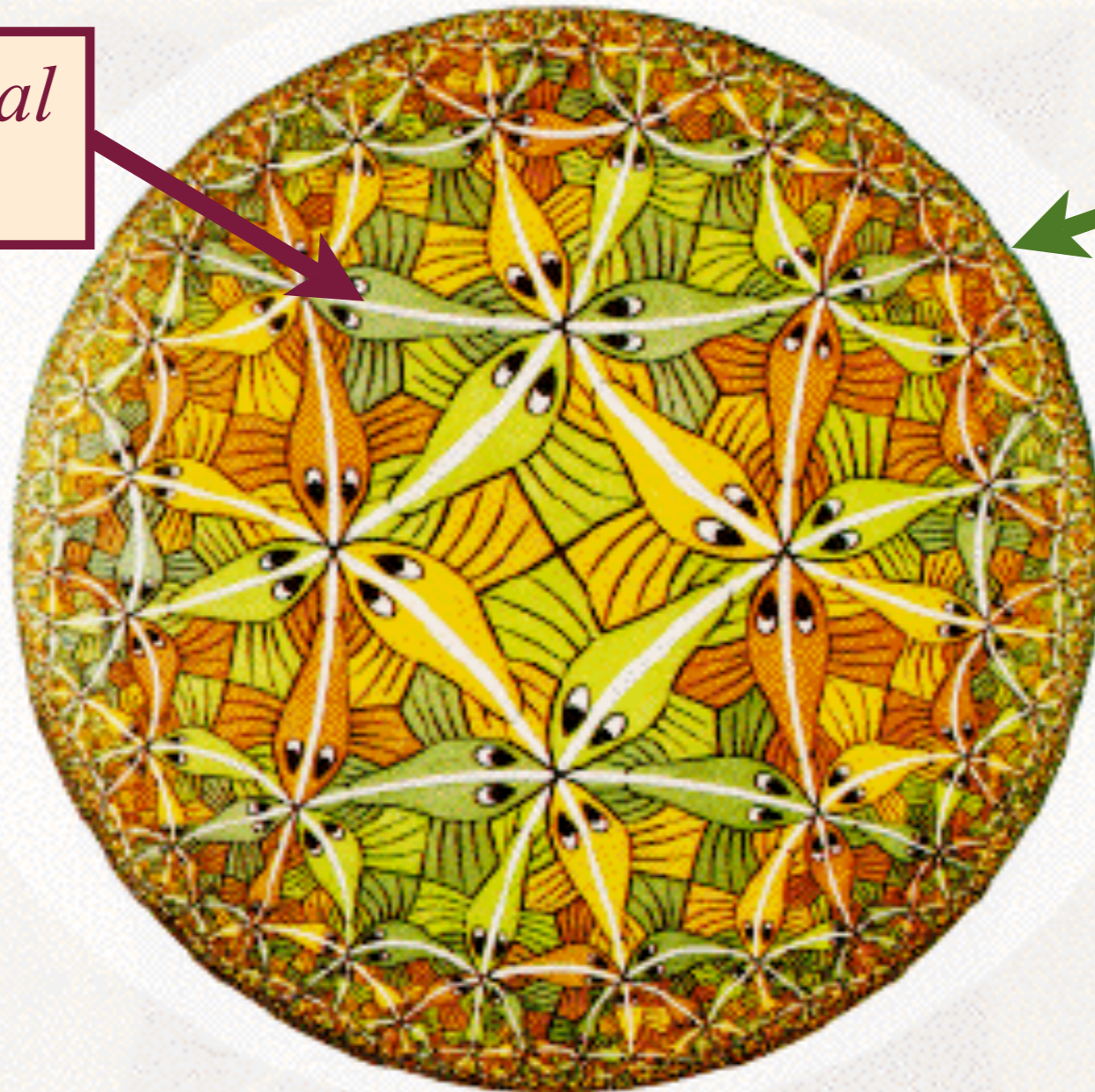
*3+1 dimensional  
AdS space*



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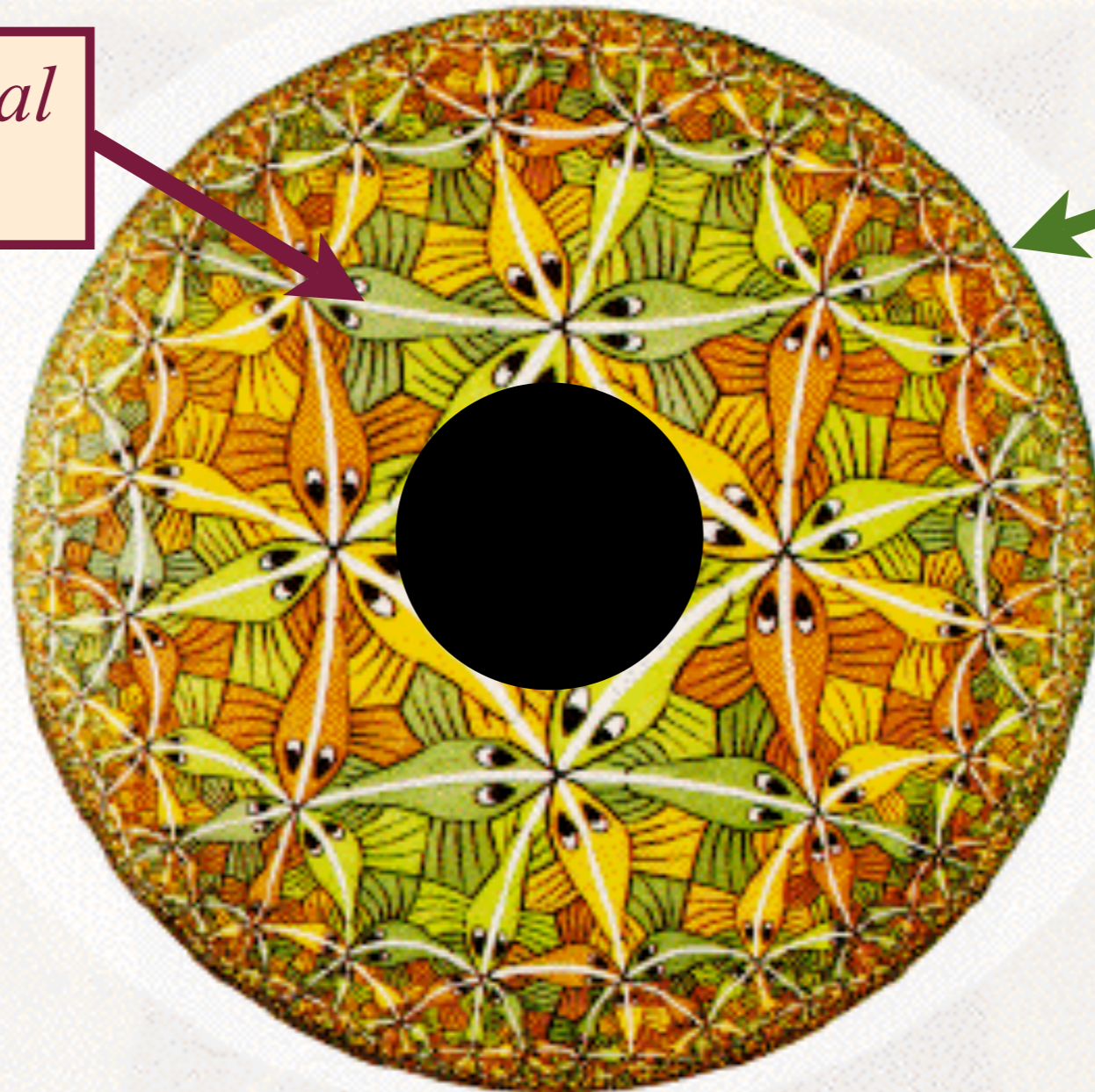
A 2+1  
dimensional  
system at its  
quantum  
critical point

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Quantum  
criticality in  
2+1  
dimensions



Black hole  
temperature  
=  
temperature  
of quantum  
criticality

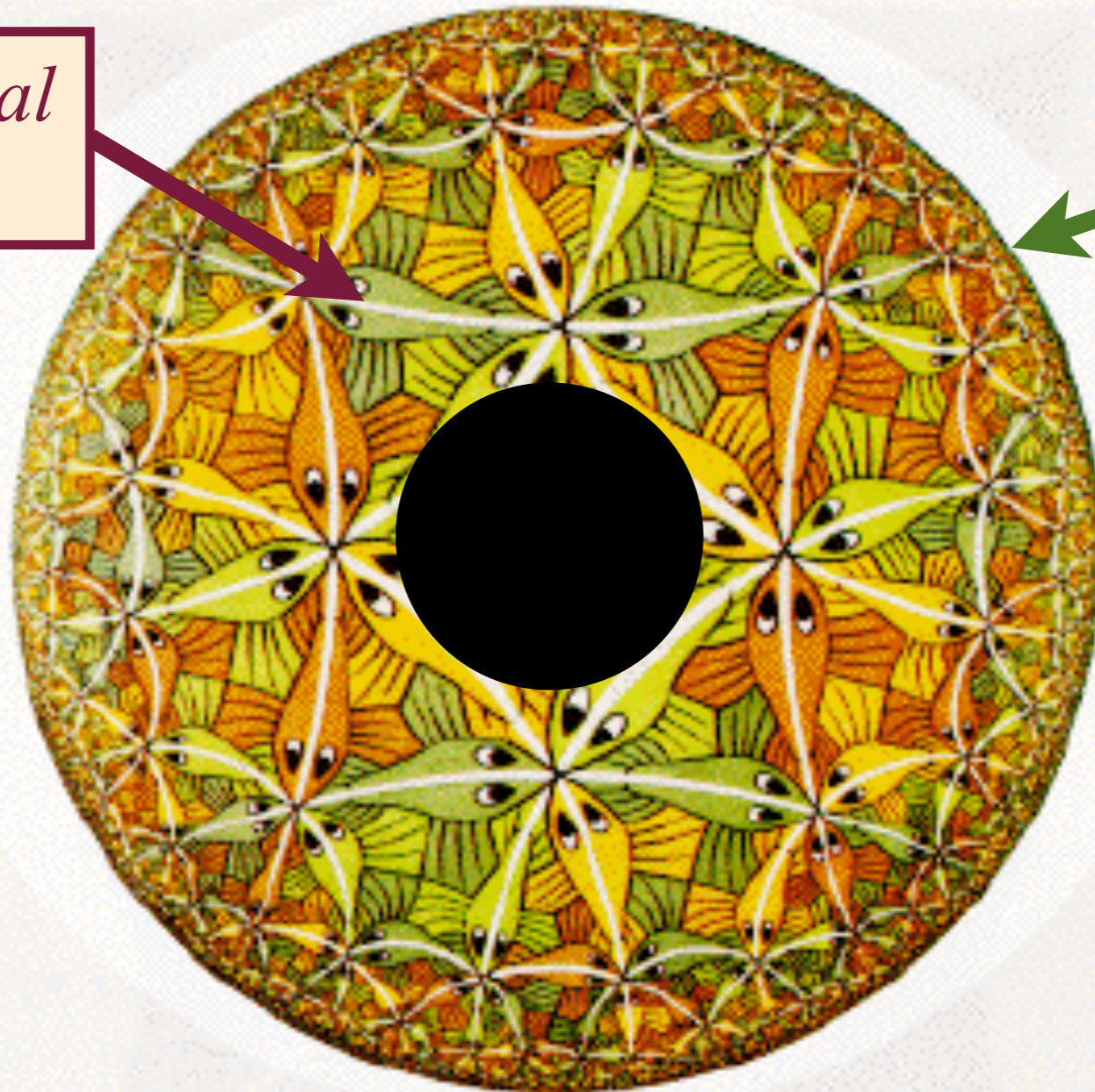
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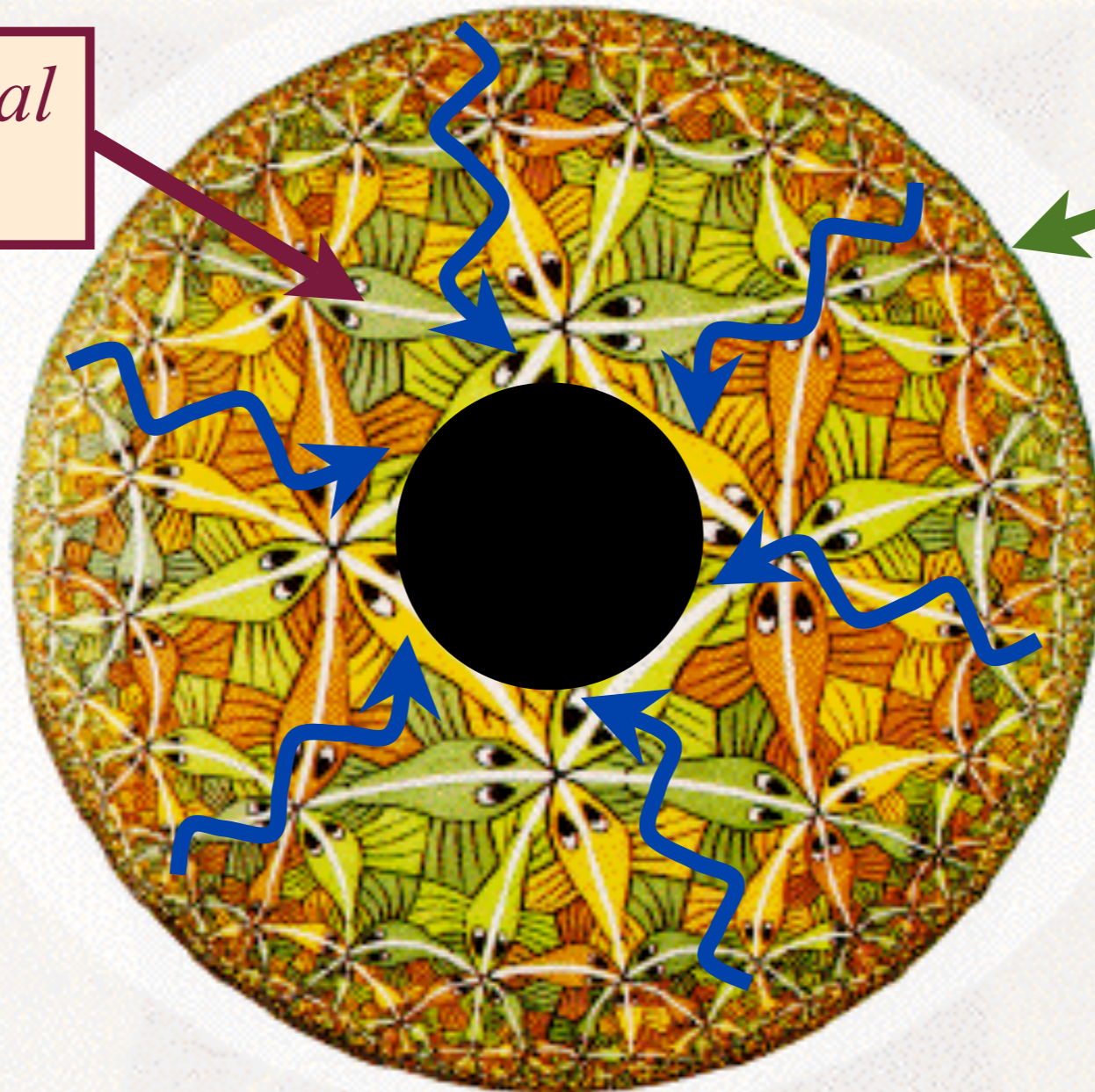
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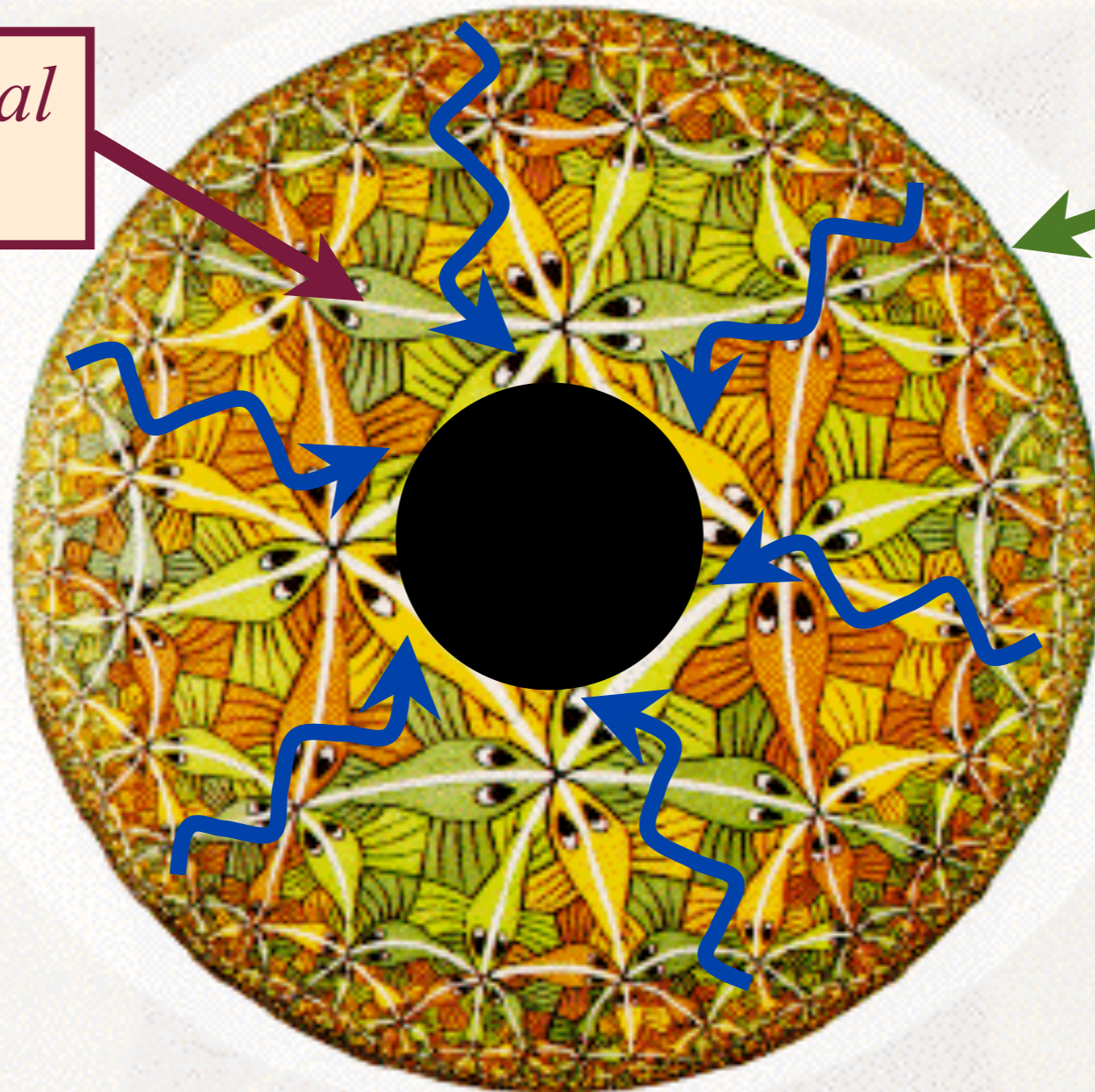
Quantum  
critical  
dynamics =  
waves in  
curved  
space



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*3+1 dimensional  
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Quantum  
criticality in  
2+1  
dimensions

Friction of  
quantum  
criticality =  
waves  
falling into  
black hole

# Three foci of modern physics

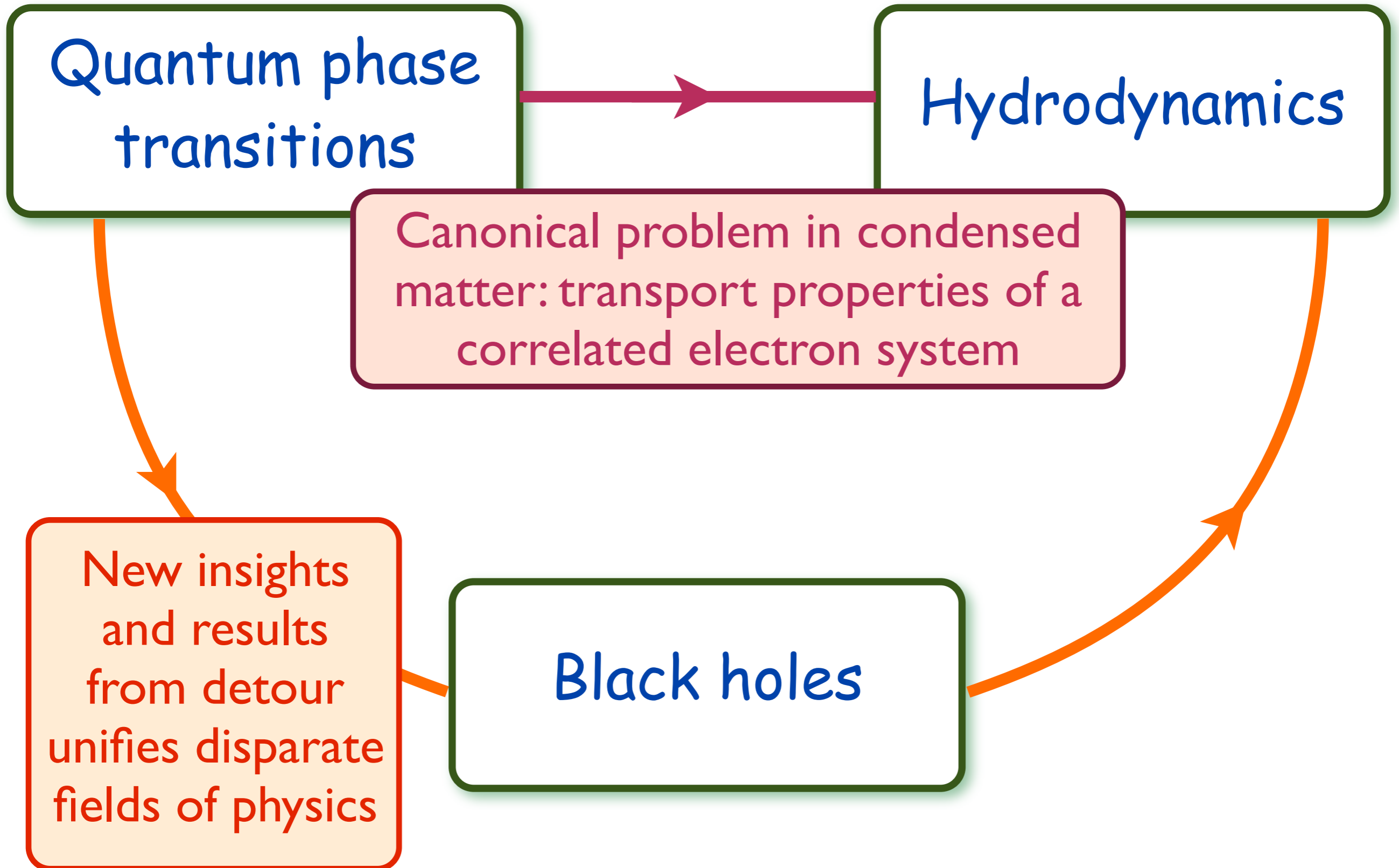
Quantum phase transitions

Hydrodynamics

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

New insights and results from detour unifies disparate fields of physics

Black holes



# Three foci of modern physics

①

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Hydrodynamics

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# Hydrodynamics of quantum critical systems

- I. Use quantum field theory + quantum transport equations + classical hydrodynamics  
*Uses physical model but strong-coupling makes explicit solution difficult*

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①

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②

# Hydrodynamics of quantum critical systems

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*Uses physical model but strong-coupling makes explicit solution difficult*

2. Solve Einstein-Maxwell equations in the background of a black hole in AdS space  
*Yields hydrodynamic relations which apply to general classes of quantum critical systems.  
First exact numerical results for transport co-efficients (for supersymmetric systems).*

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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

*Non-relativistic AdS/CFT*

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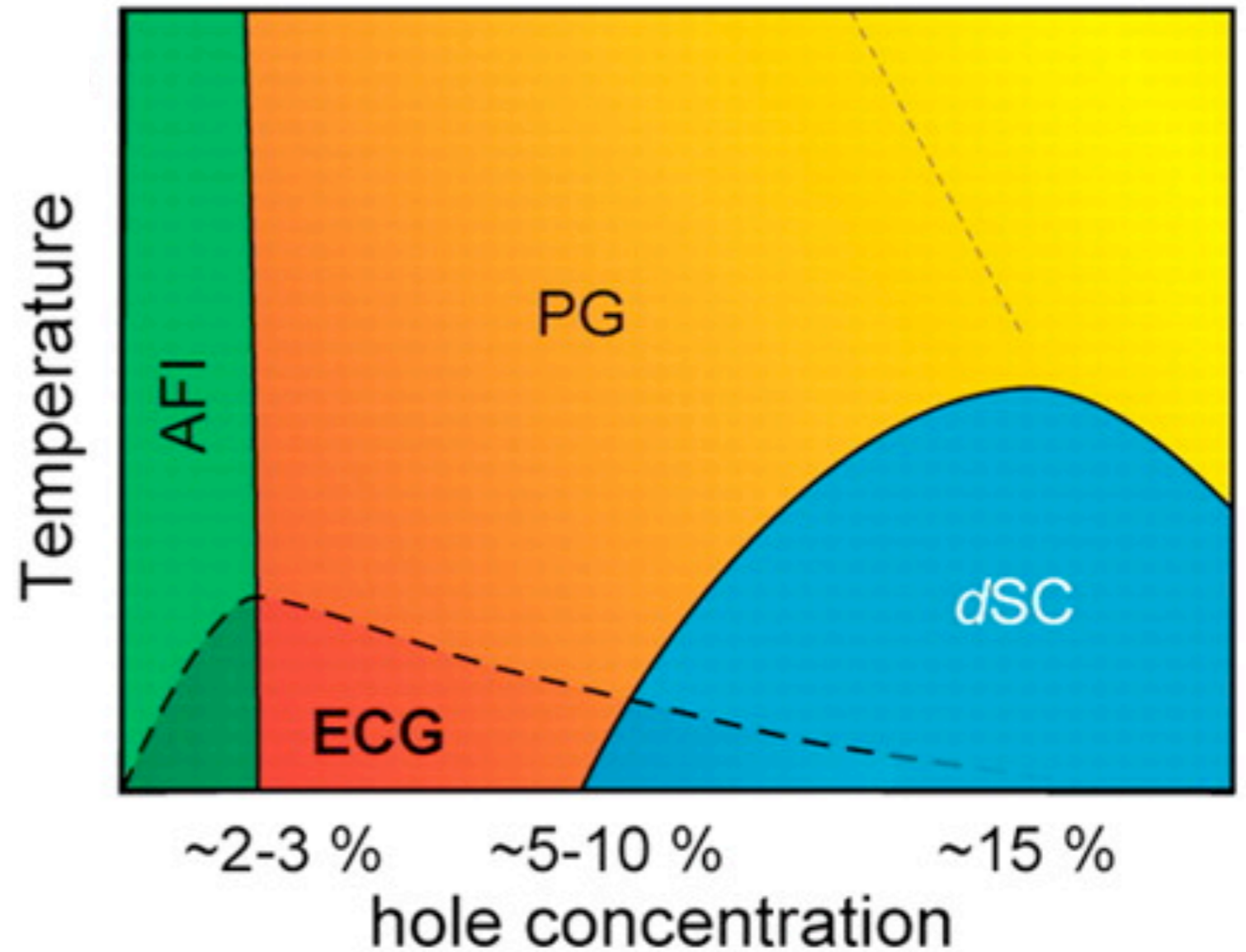
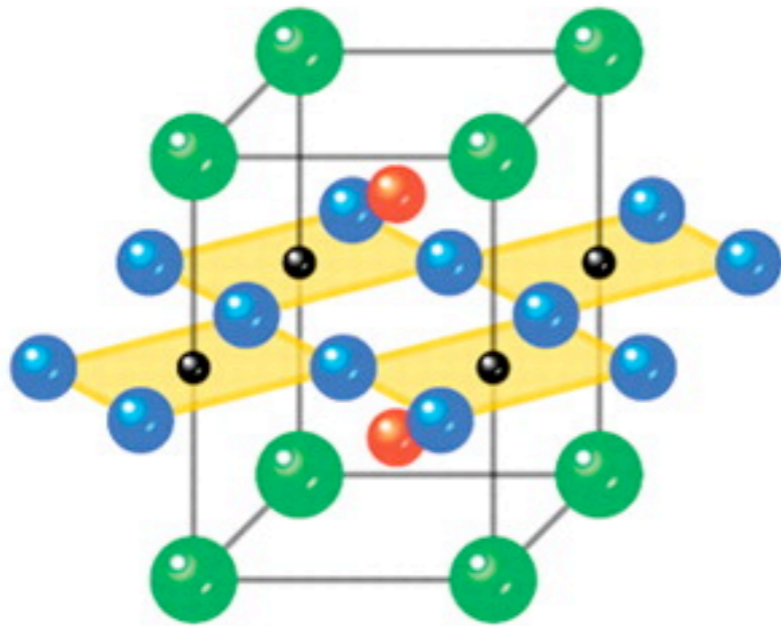
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# *The cuprate superconductors*

Na-CCOC

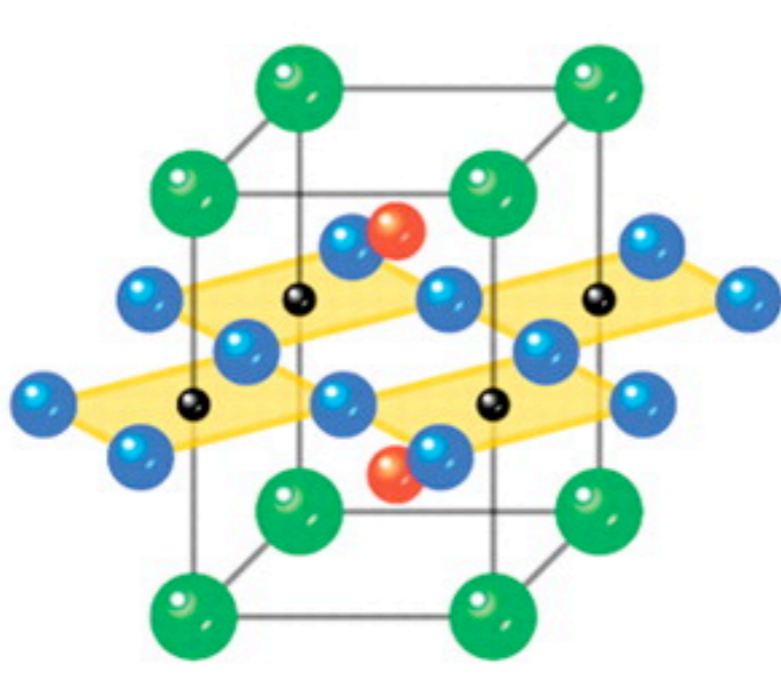
- Cu
- Ca/Na
- O
- Cl



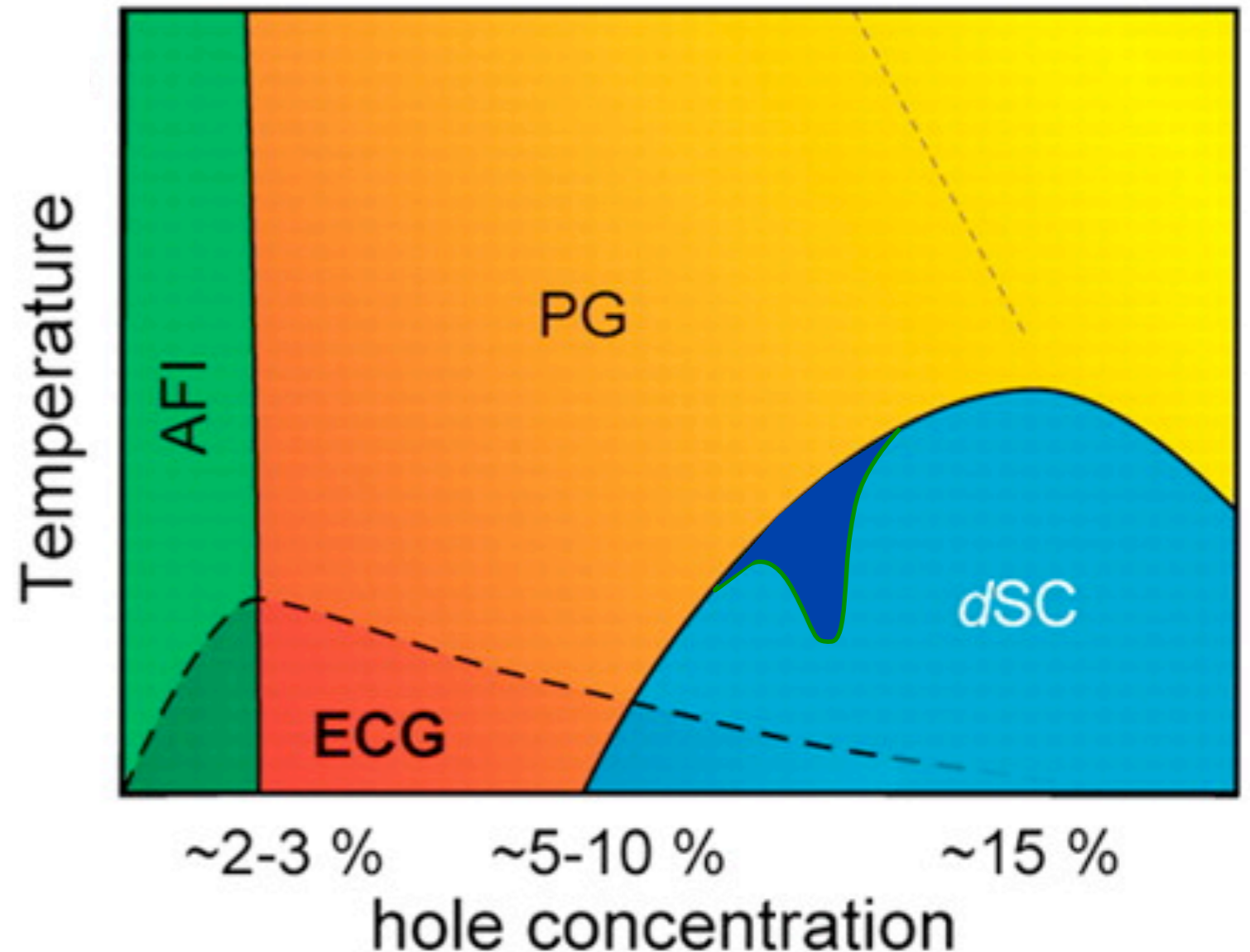
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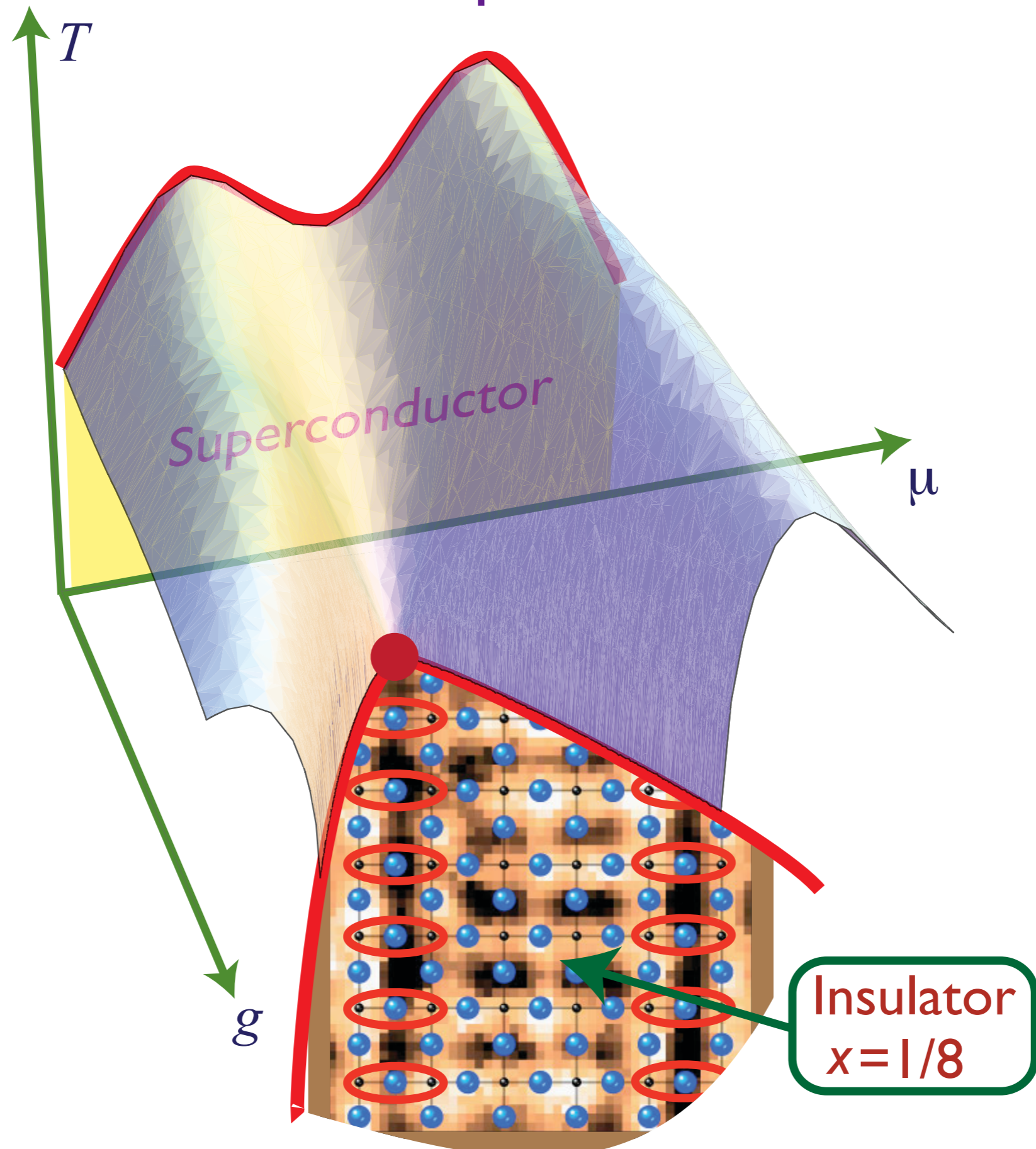
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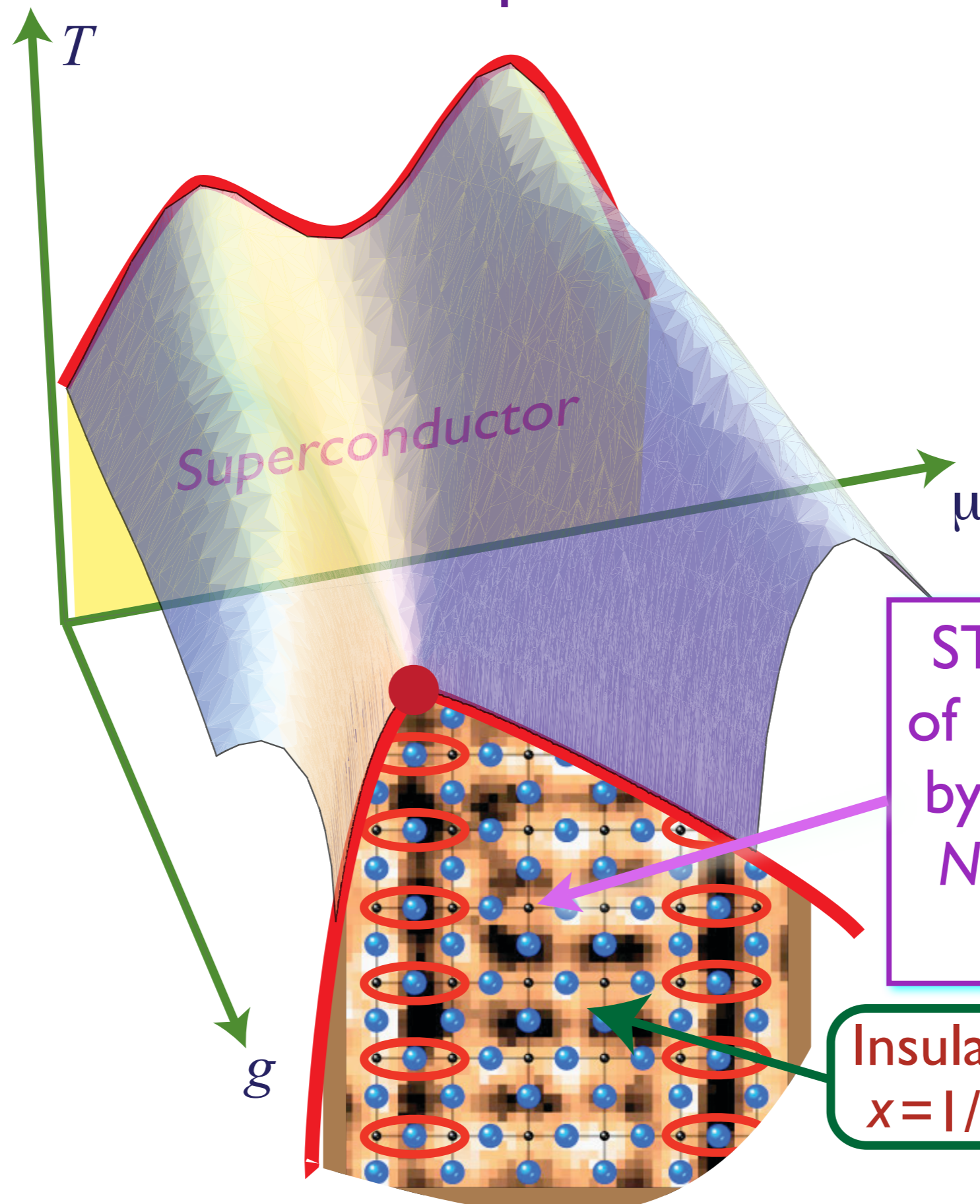
Proximity to an insulator at 12.5% hole concentration



# Cuprates



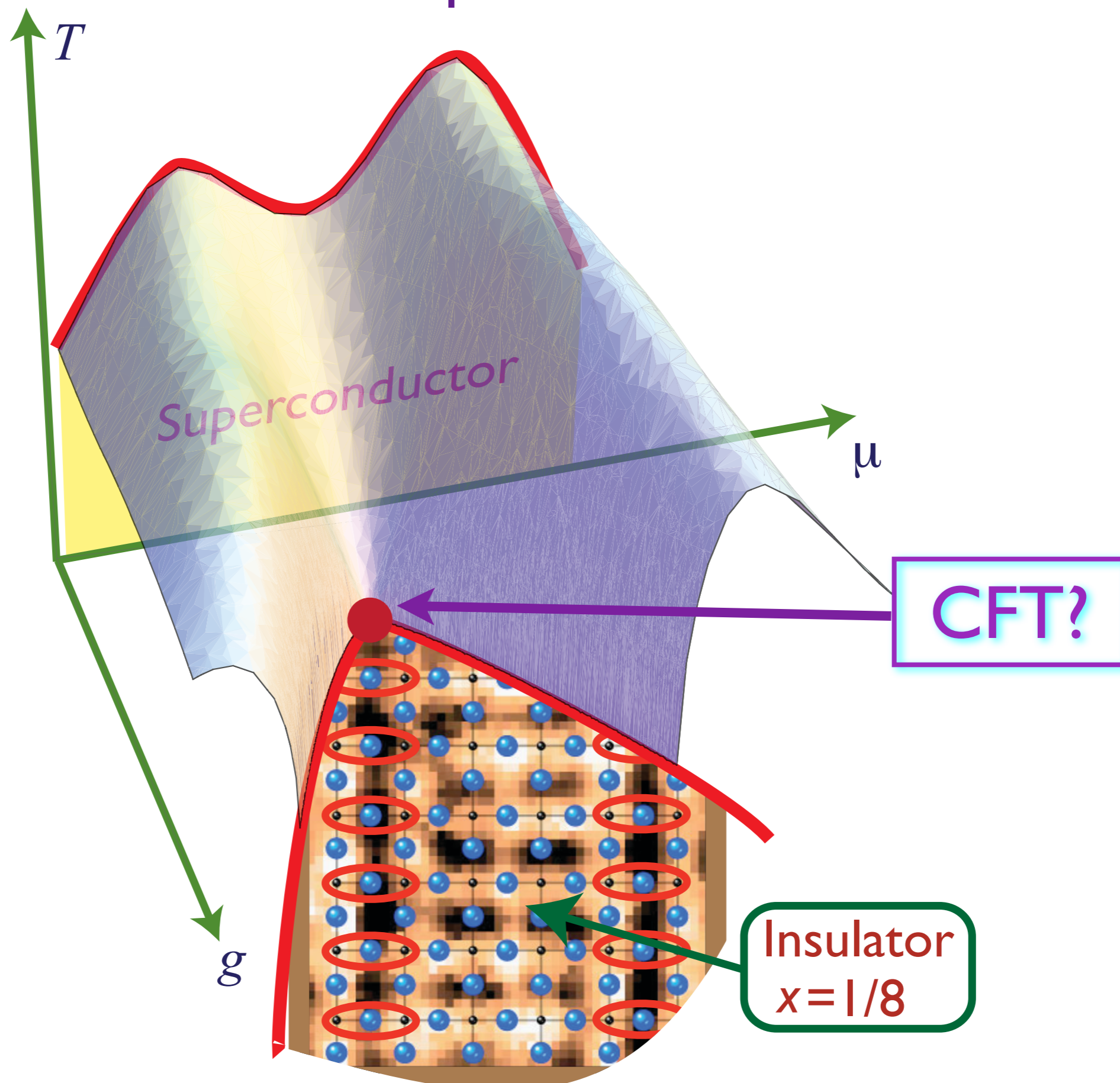
# Cuprates



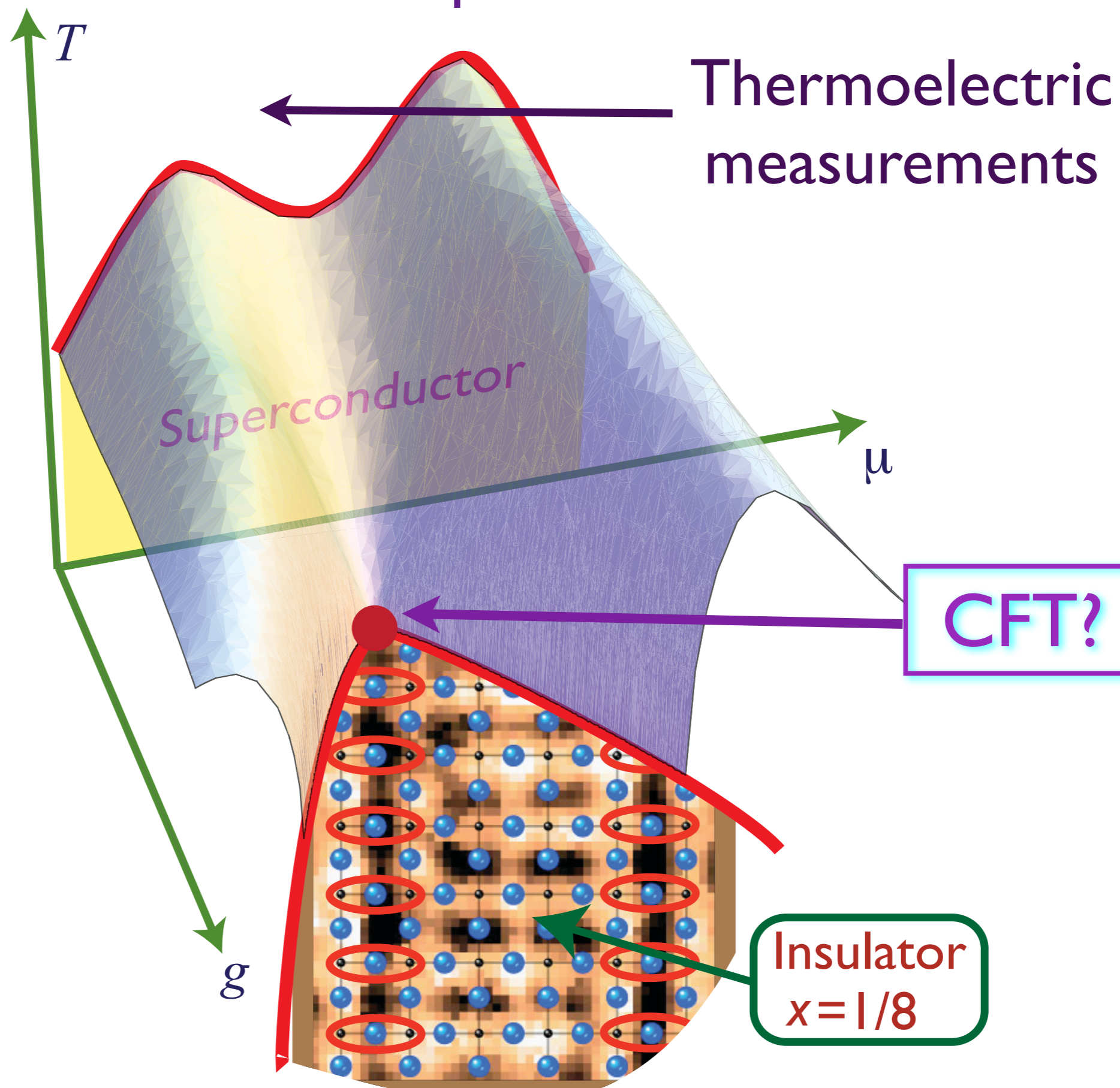
STM observations  
of VBS modulations  
by Y. Kohsaka *et al.*,  
*Nature* **454**, 1072  
(2008)

Insulator  
 $x = 1/8$

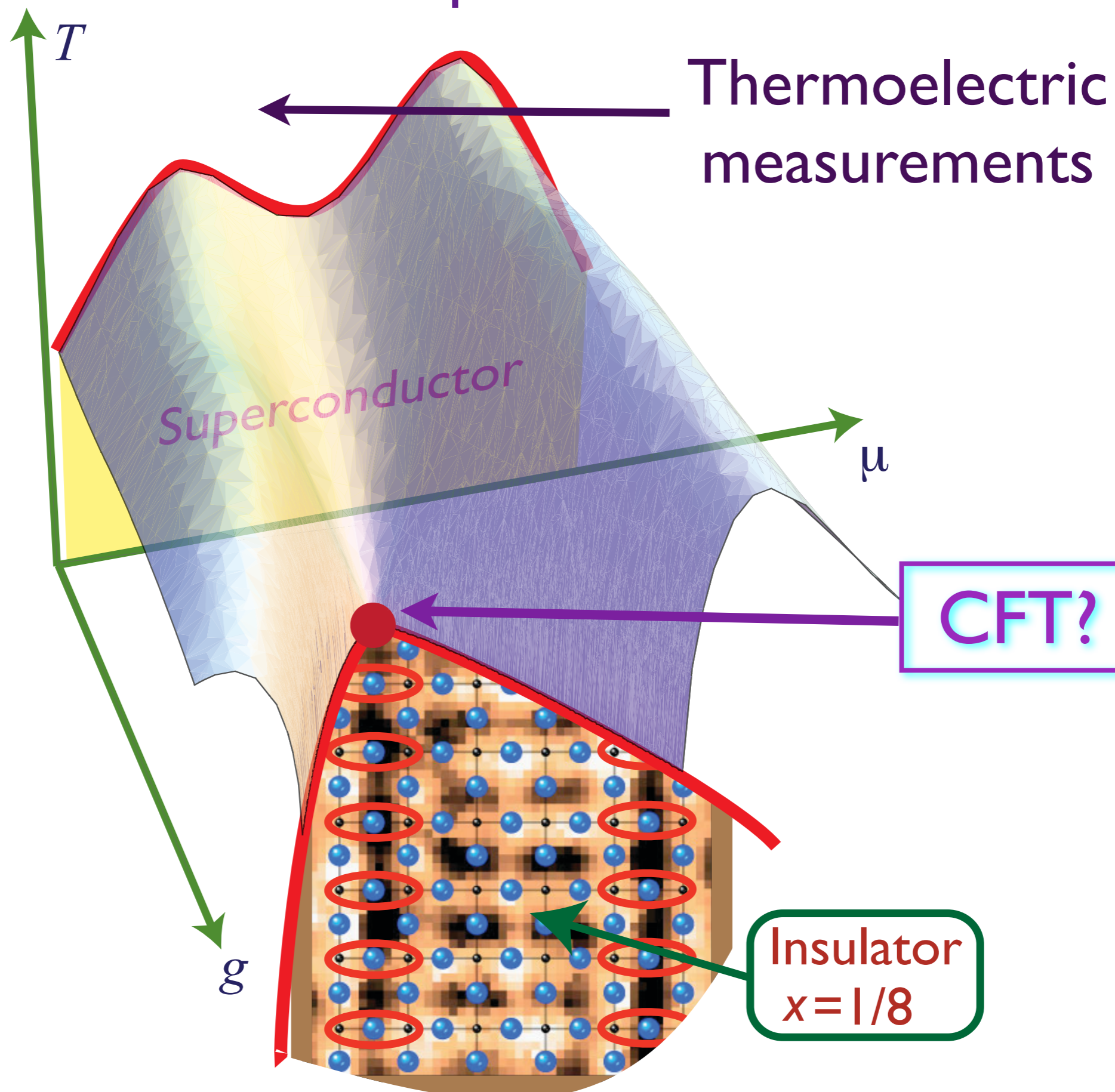
# Cuprates



# Cuprates



# 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,  $\rho$  = charge density away from density of CFT,  $\varepsilon$  = energy density,  $P$  = pressure,  $v$  = velocity of “light” in CFT, and  $\sigma_Q e^2/h$  is the universal conductivity of the CFT.

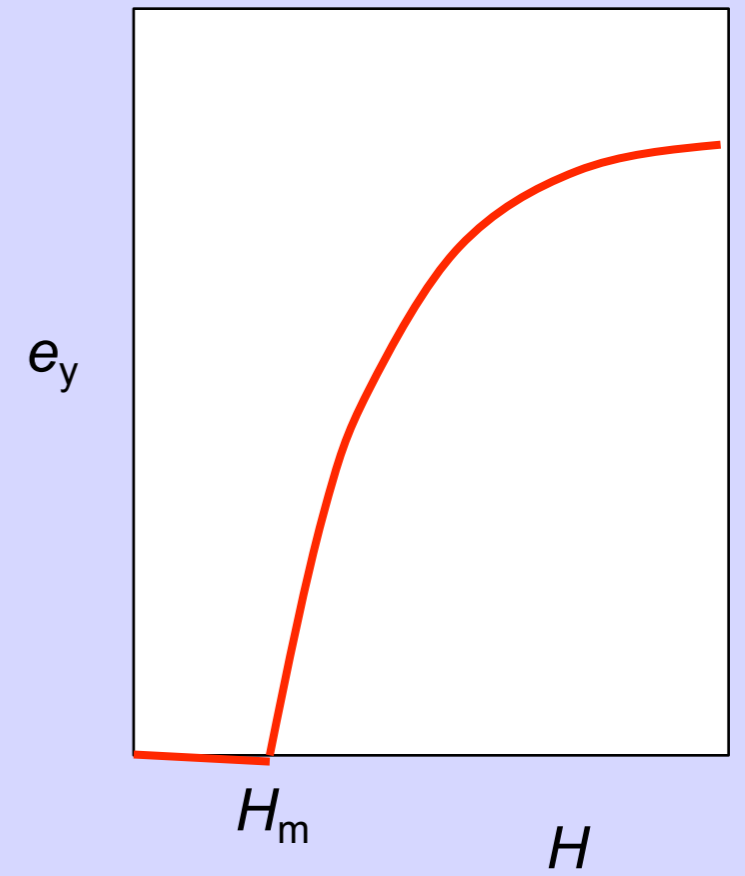
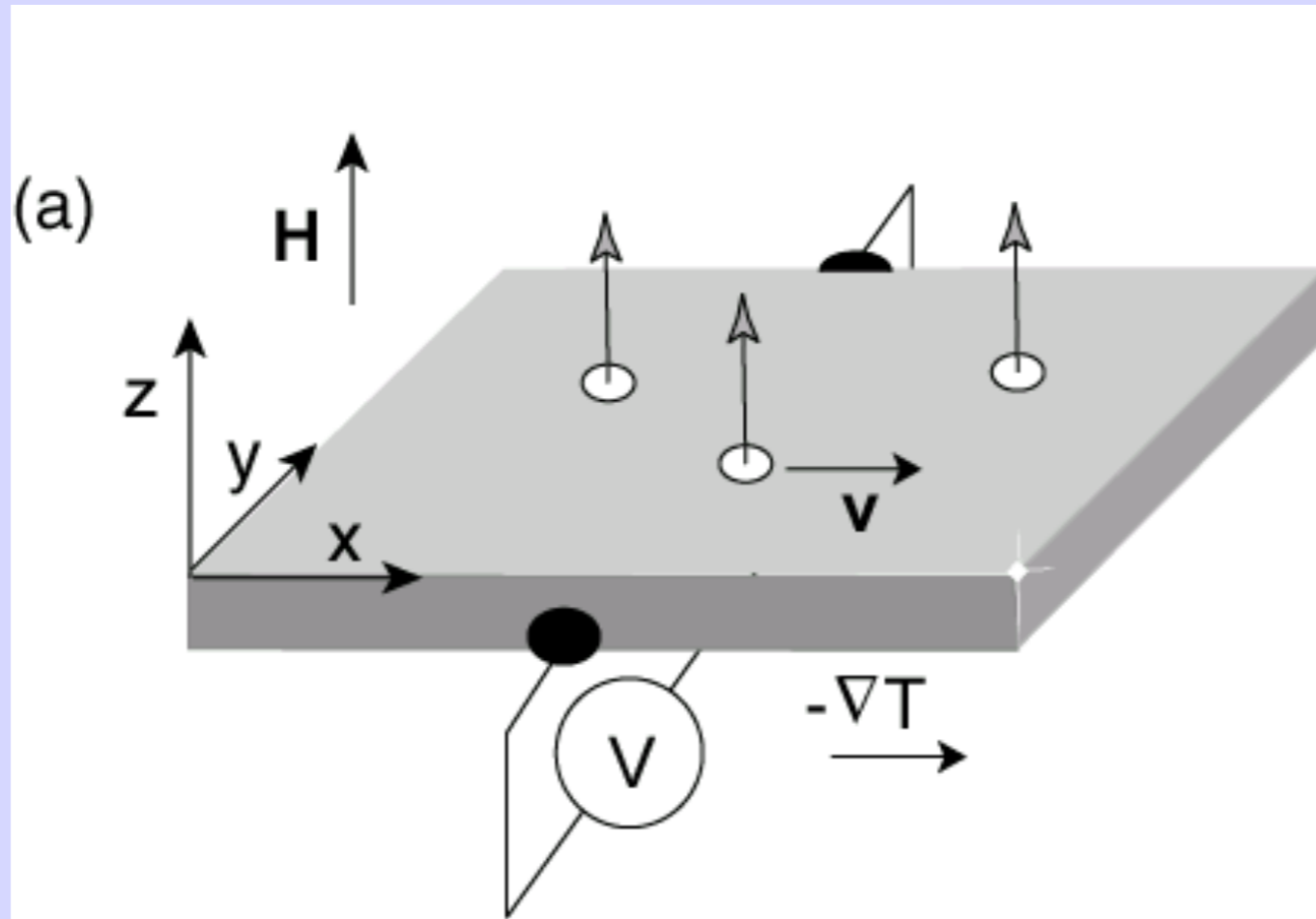
“Wiedemann-Franz”-like relation for thermal conductivity,  $\kappa$  at  $B = 0$

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

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

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

# Nernst experiment



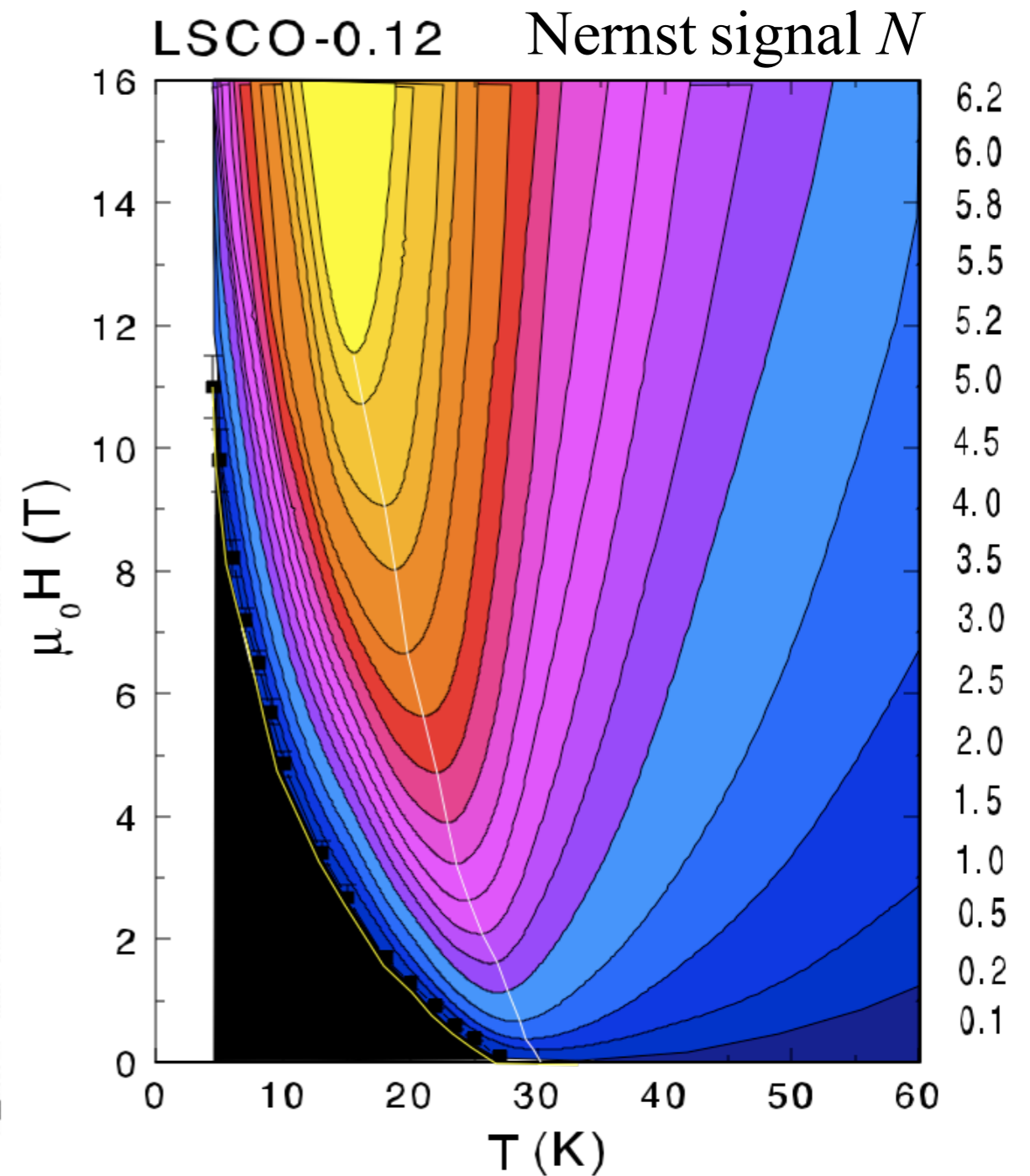
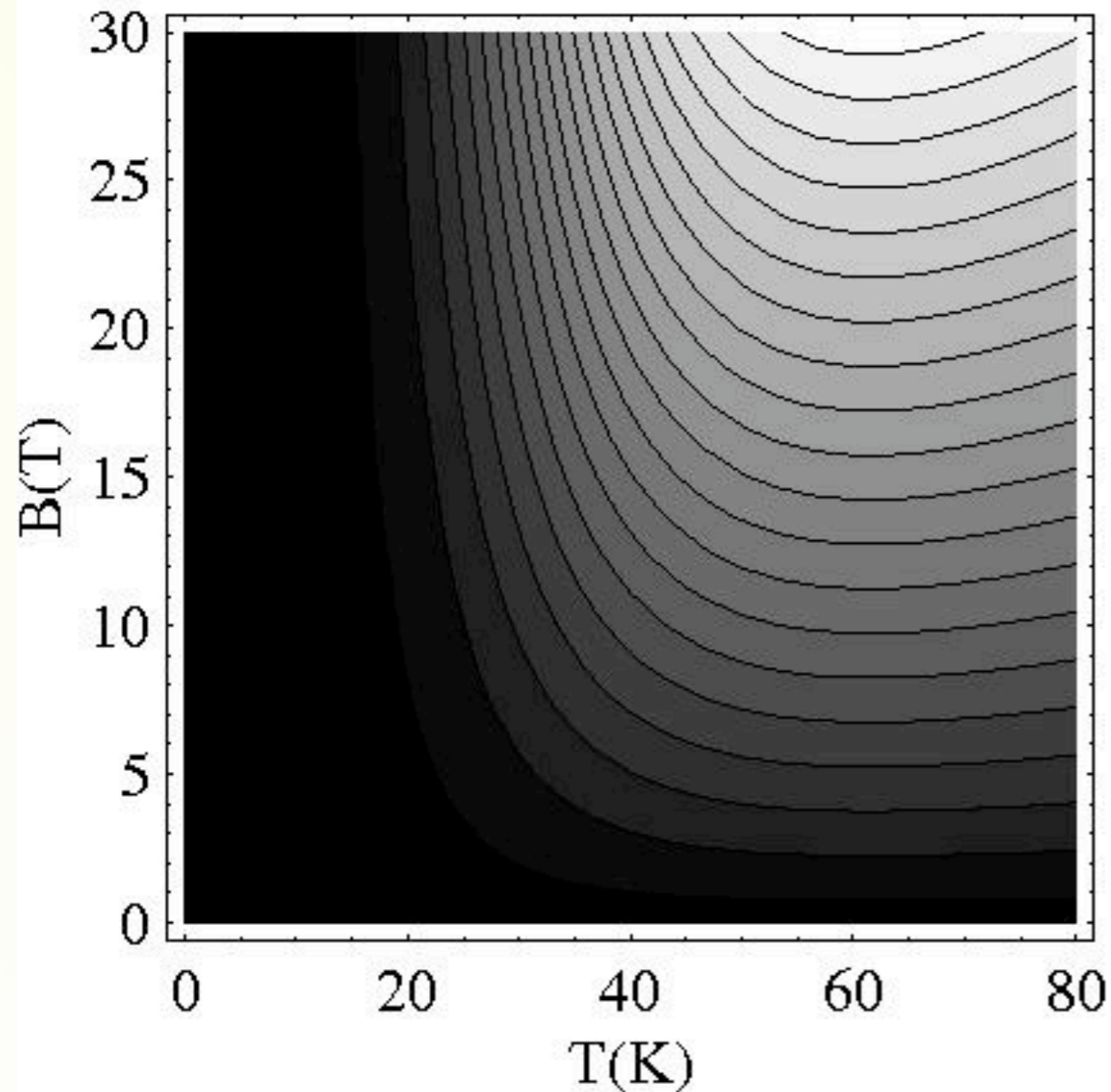
Nernst signal (transverse thermoelectric response)

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

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

# LSCO Experiments

Theory for  $N$



Y. Wang, L. Li, and N. P. Ong, *Phys. Rev. B* **73**, 024510 (2006).

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

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

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Similar results apply to electronic transport in graphene, where 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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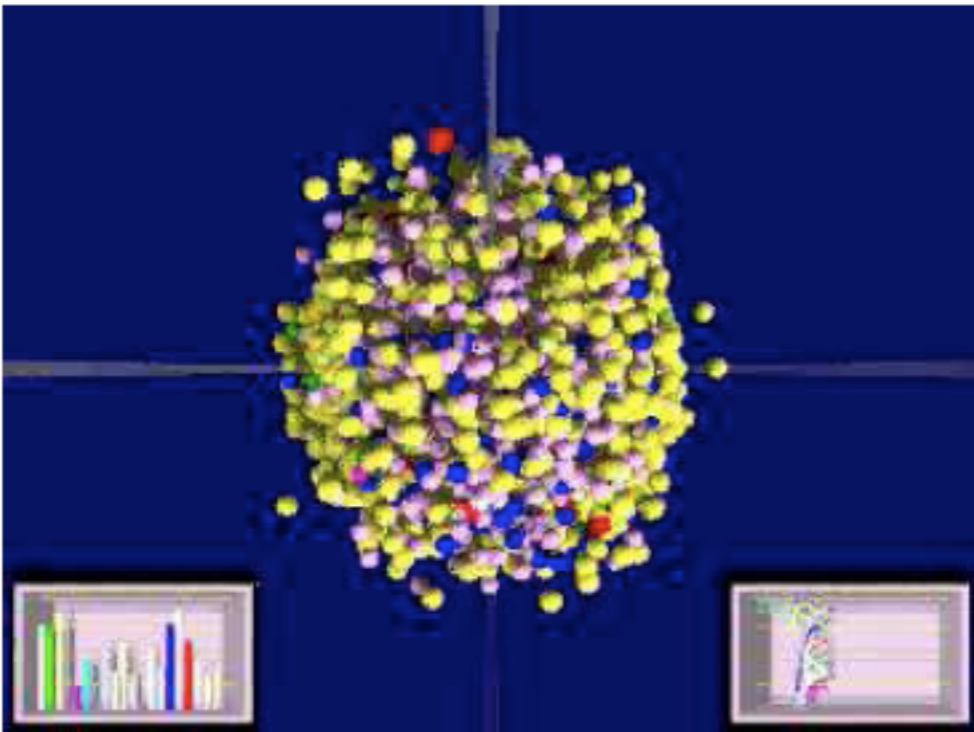
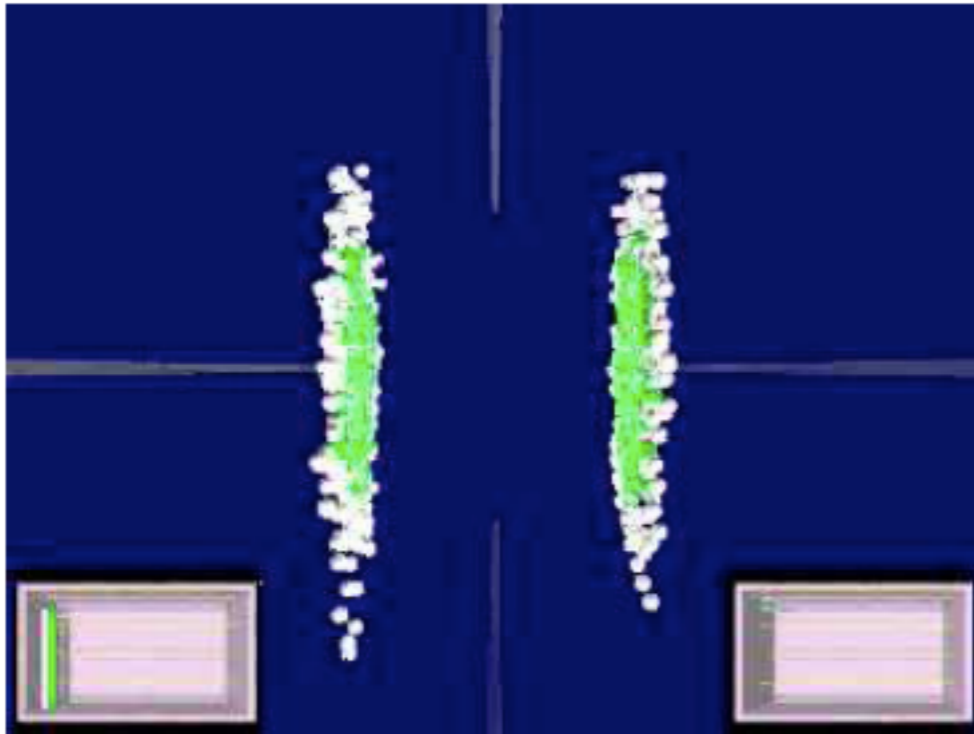
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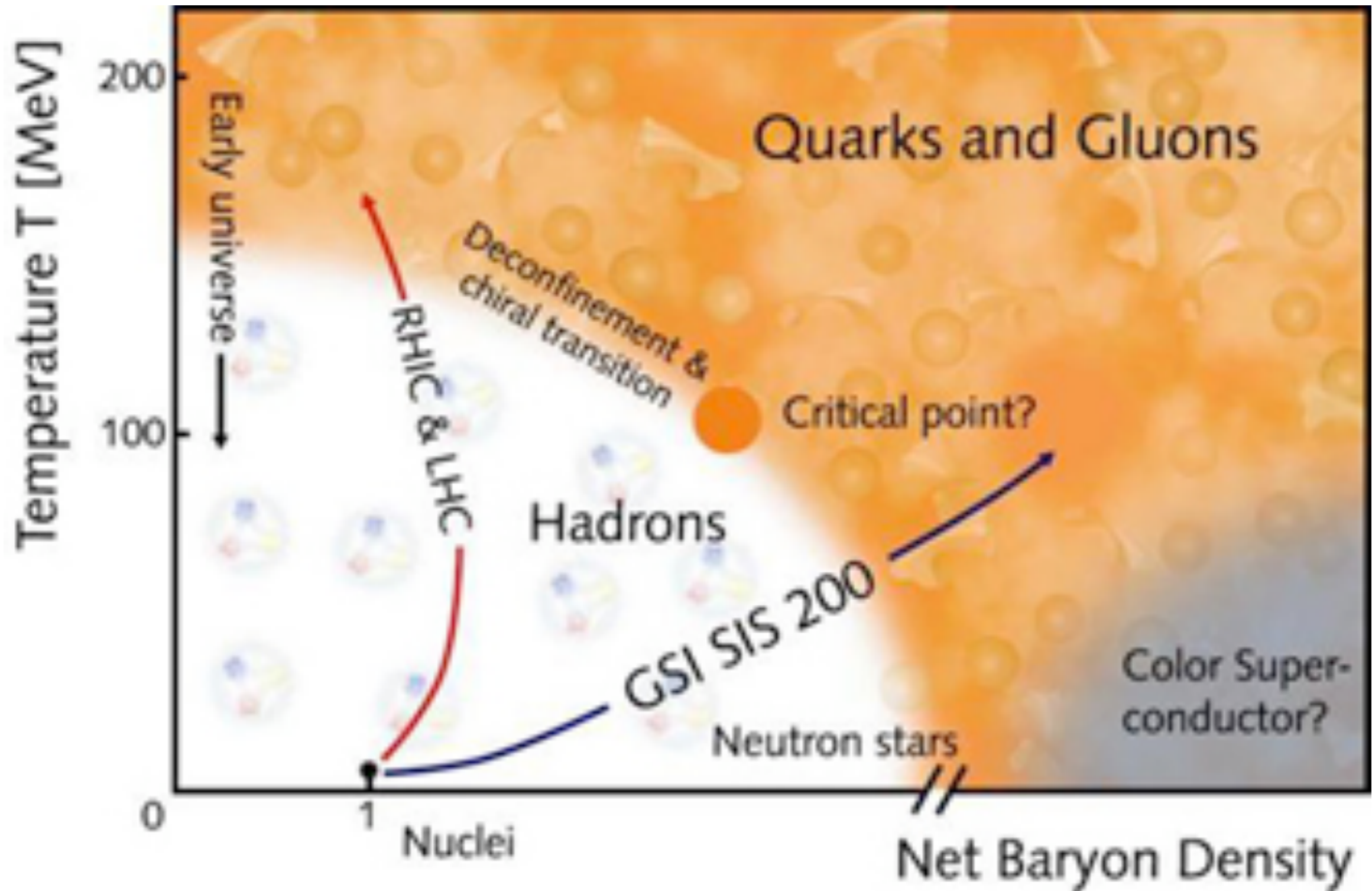
*Non-relativistic AdS/CFT*

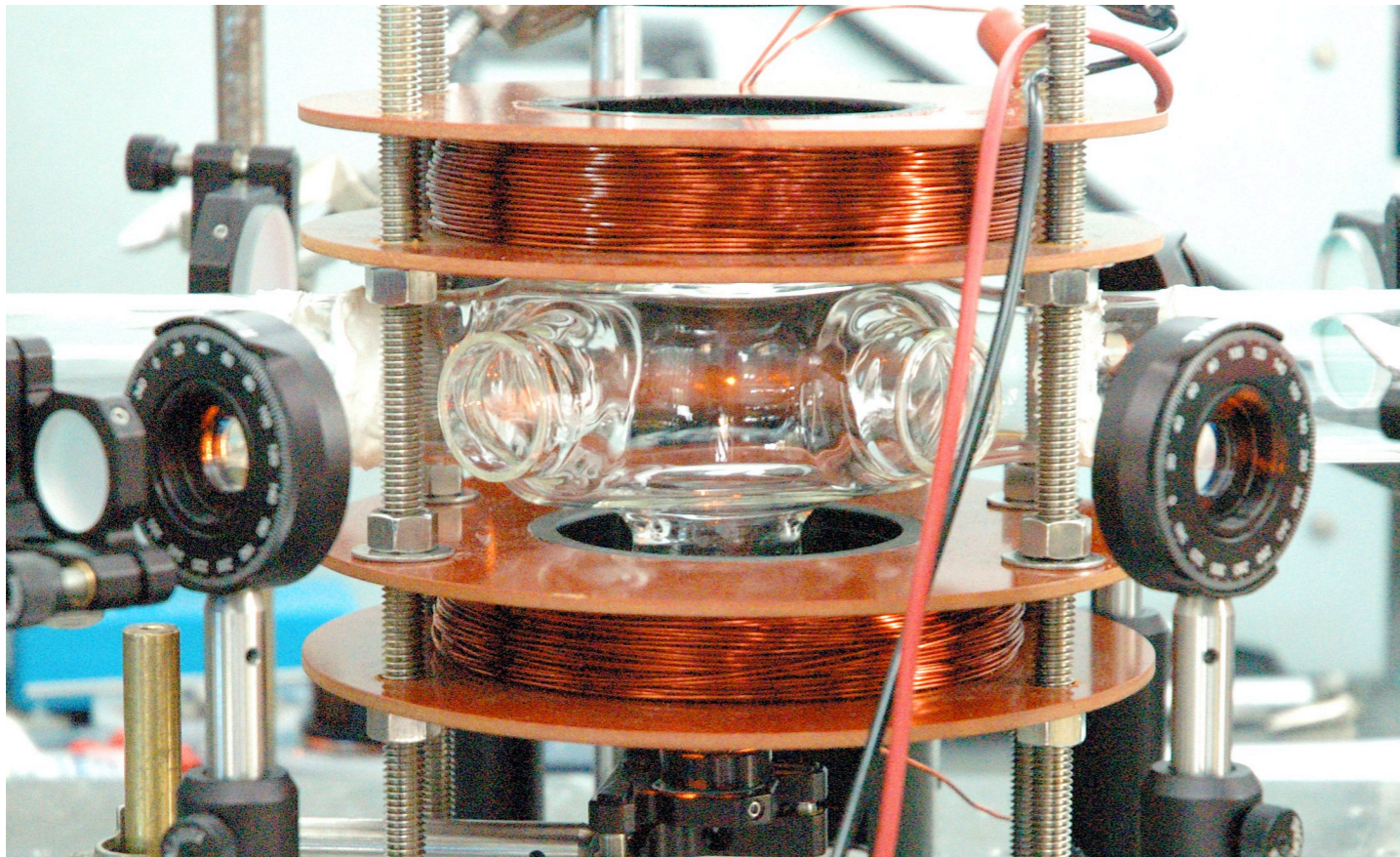
# Au+Au collisions at RHIC



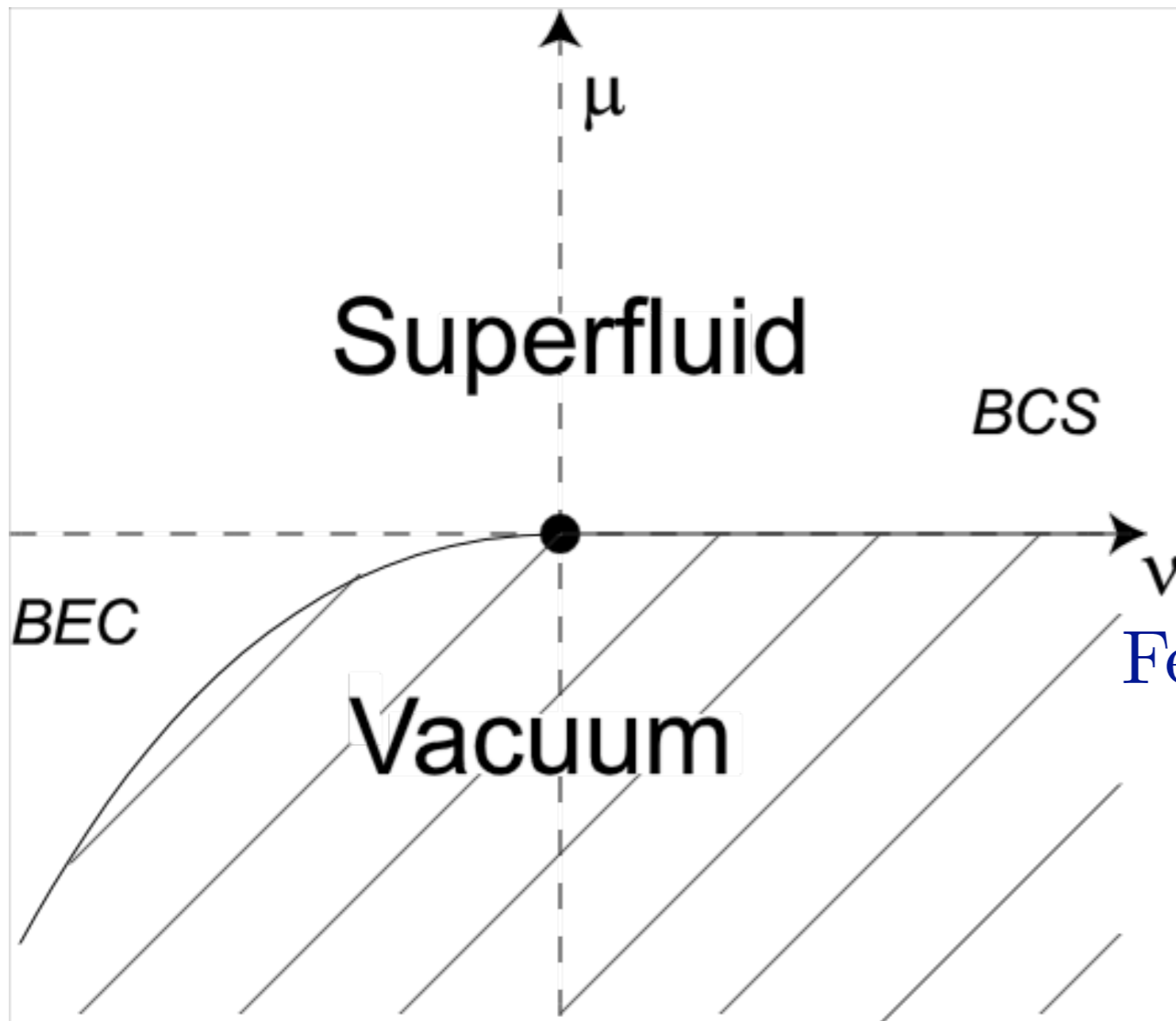
Quark-gluon plasma can be described as “quantum critical QCD”

# Phases of nuclear matter

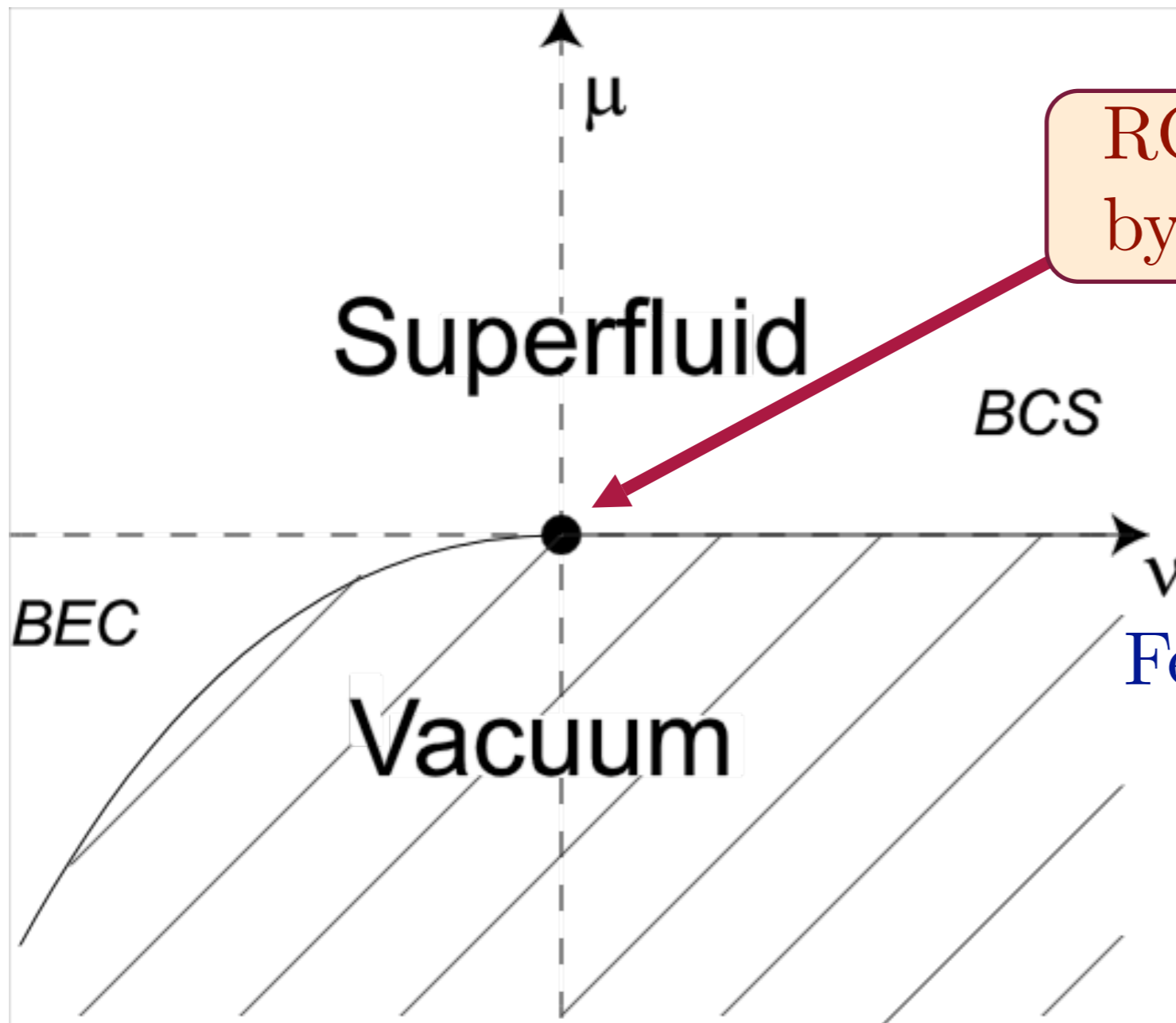




$S=1/2$  Fermi gas  
at a Feshbach  
resonance

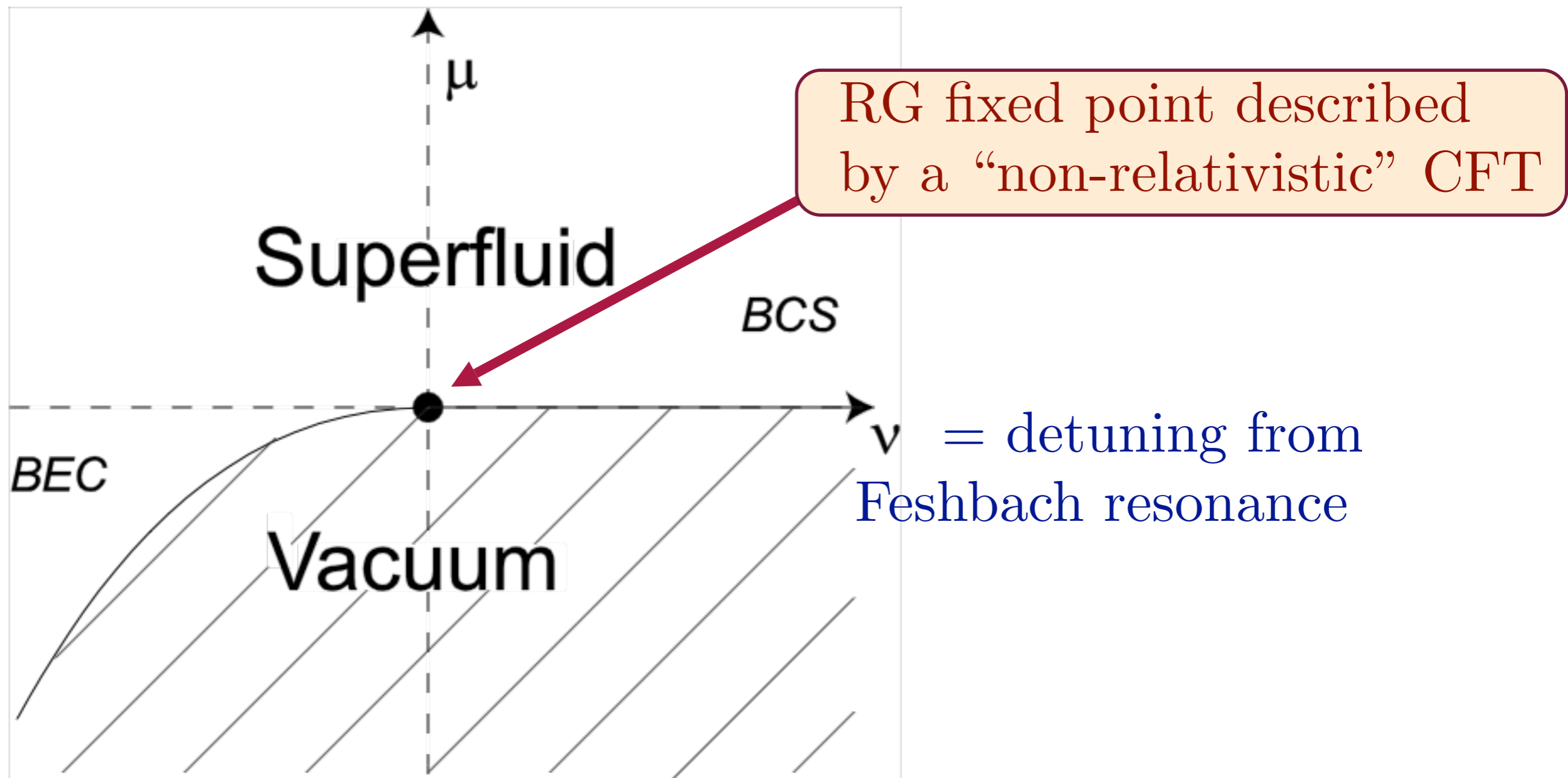


$\nu$  = detuning from  
Feshbach resonance



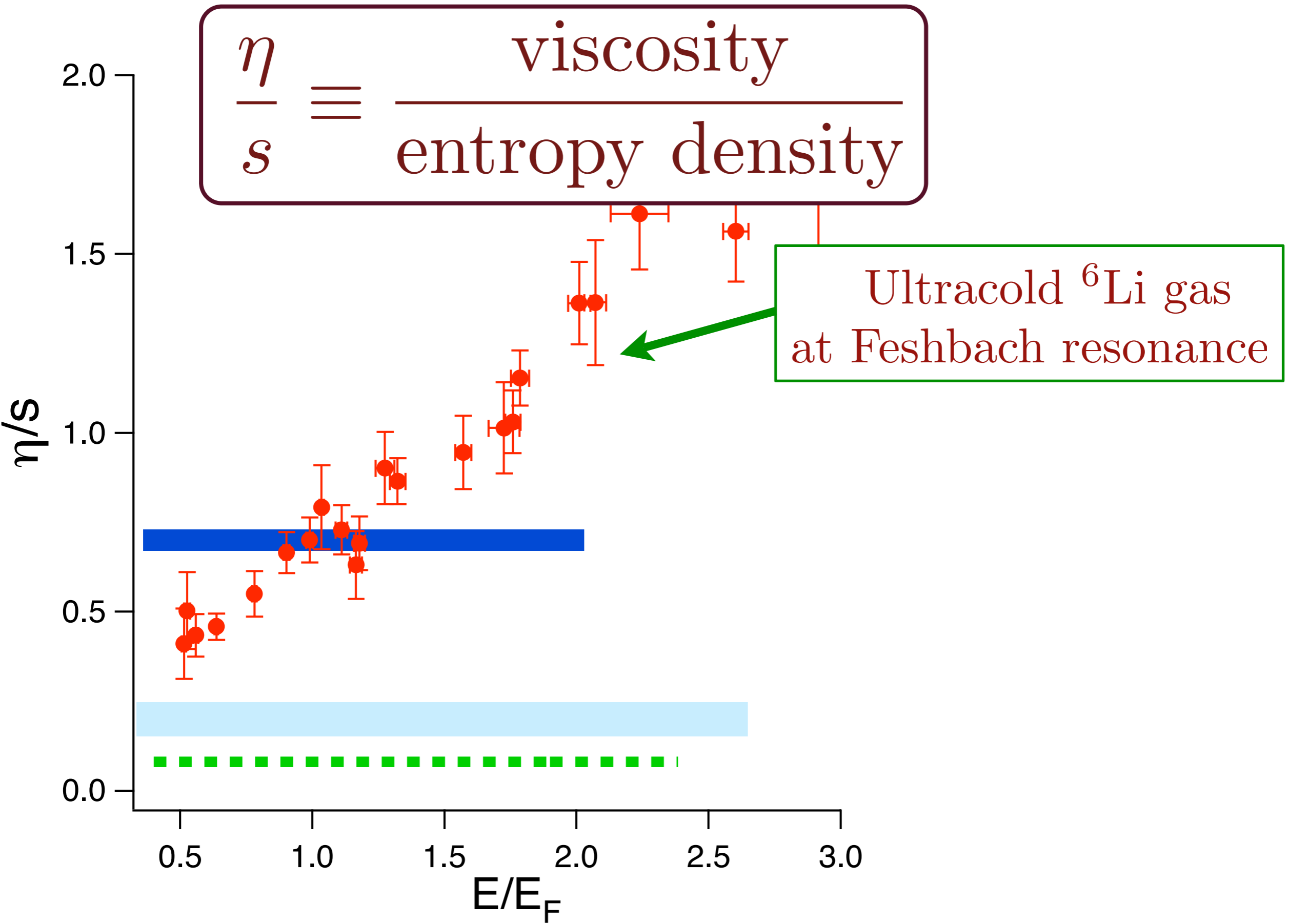
RG fixed point described by a “non-relativistic” CFT

$\nu$  = detuning from Feshbach resonance



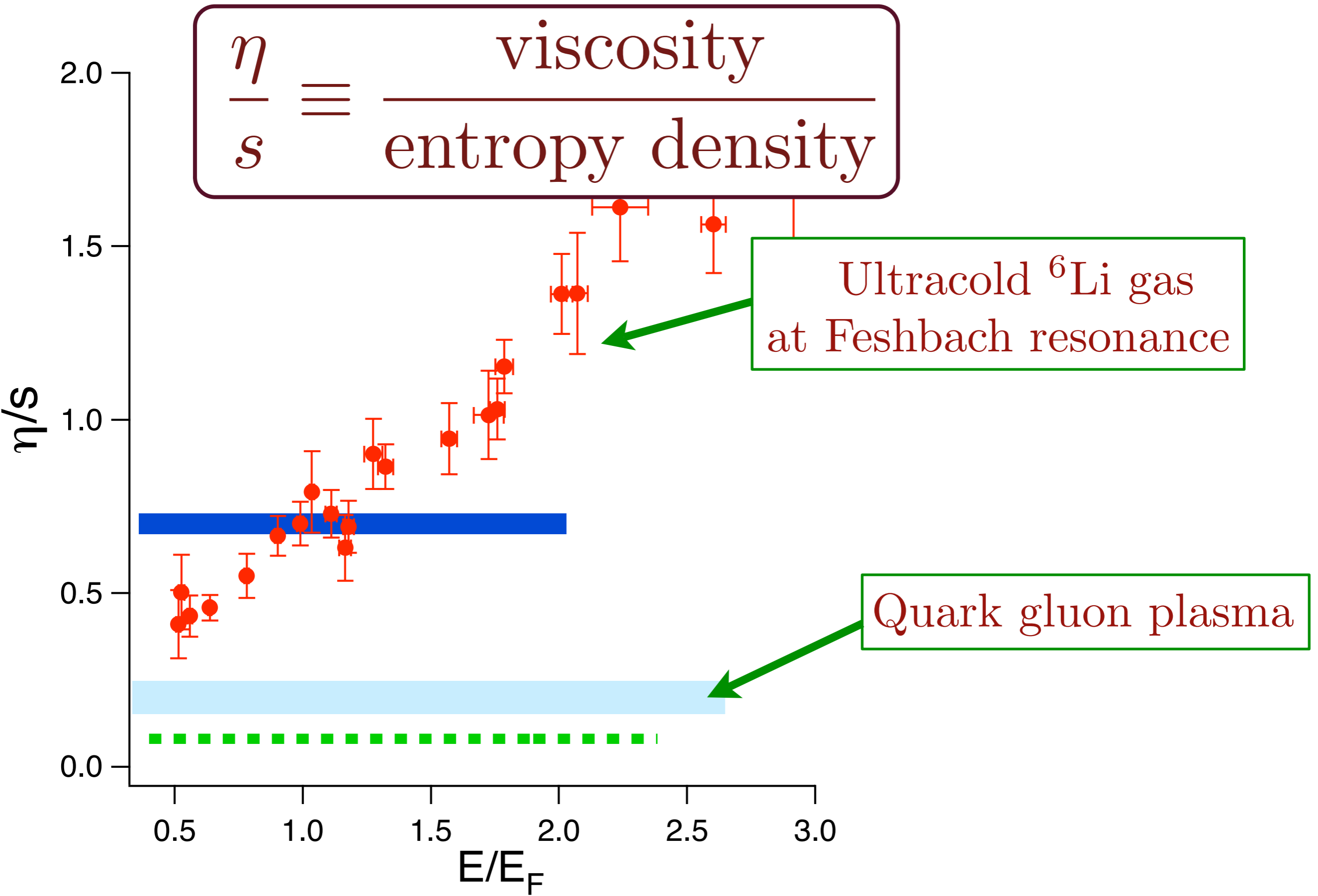
CFT is dual to quantum gravity models on AdS space. Explicit solutions of such gravity models with supersymmetry have been obtained

P. Nikolic and S. Sachdev, *Phys. Rev. A* **75**, 033608 (2007); D. T. Son, arXiv:0804.3972; K. Balasubramanian 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.



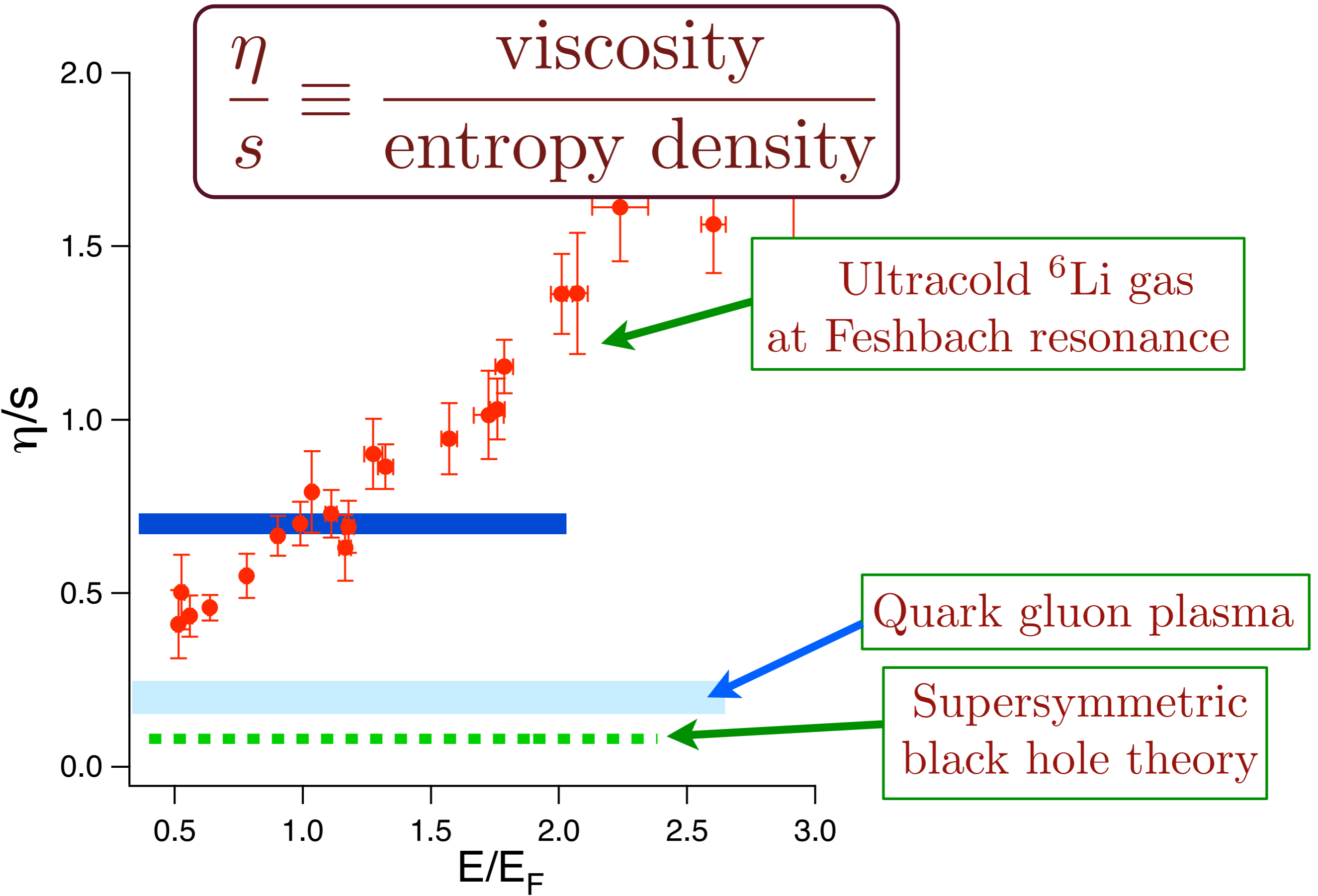
T. Schafer, *Phys. Rev.A* **76**, 063618 (2007).

A. Turlapov, J. Kinast, B. Clancy, Le Luo, J. Joseph, J. E. Thomas, *J. Low Temp. Physics* **150**, 567 (2008)



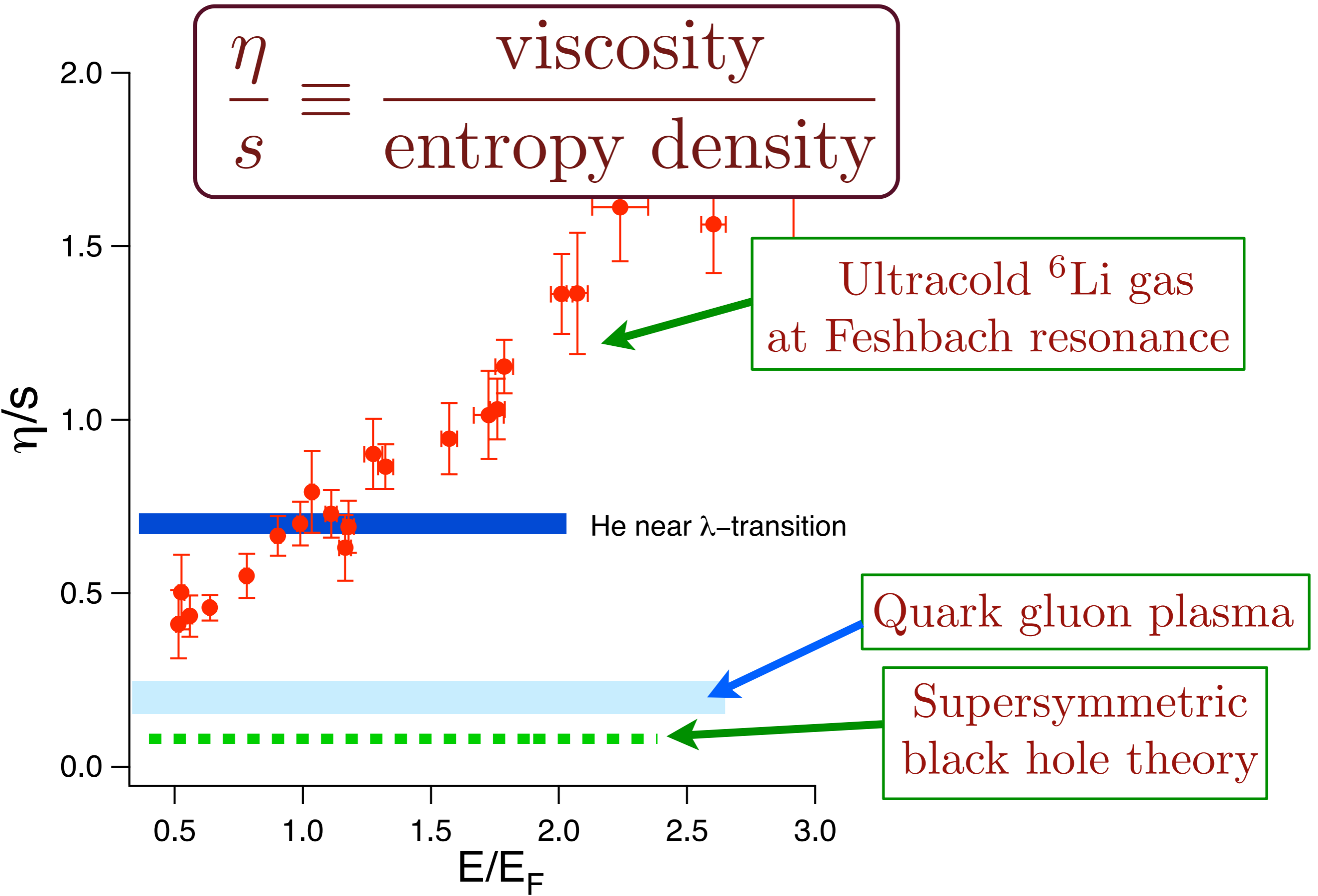
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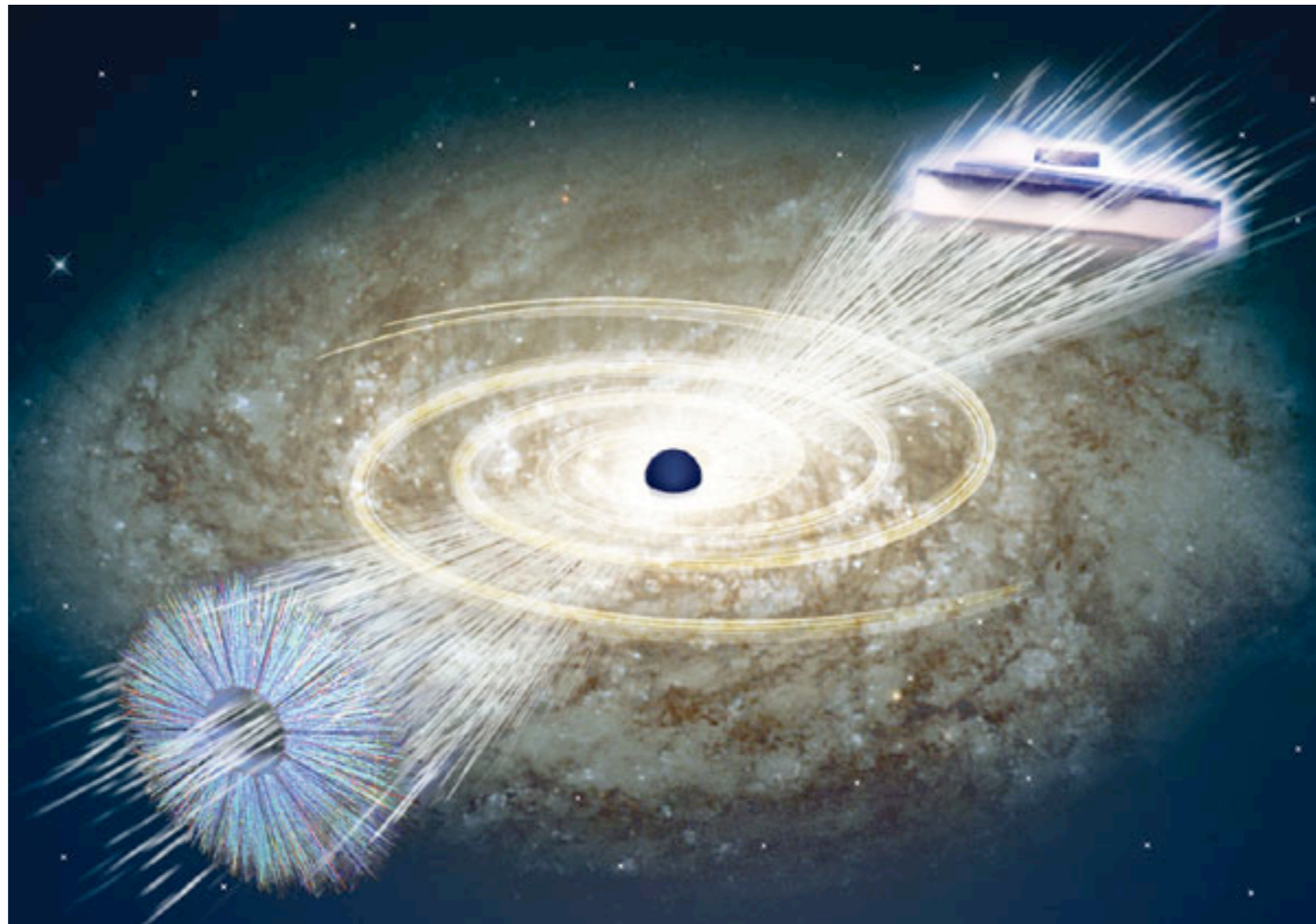
A. Turlapov, J. Kinast, B. Clancy, Le Luo, J. Joseph, J. E. Thomas, *J. Low Temp. Physics* **150**, 567 (2008)

# 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.