Quantum matter without quasiparticles

M.I.T.
March 13, 2014

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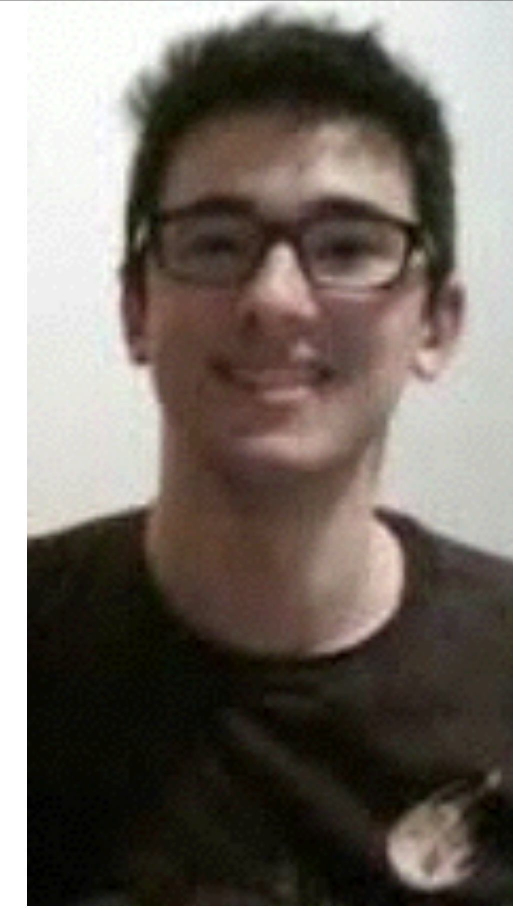

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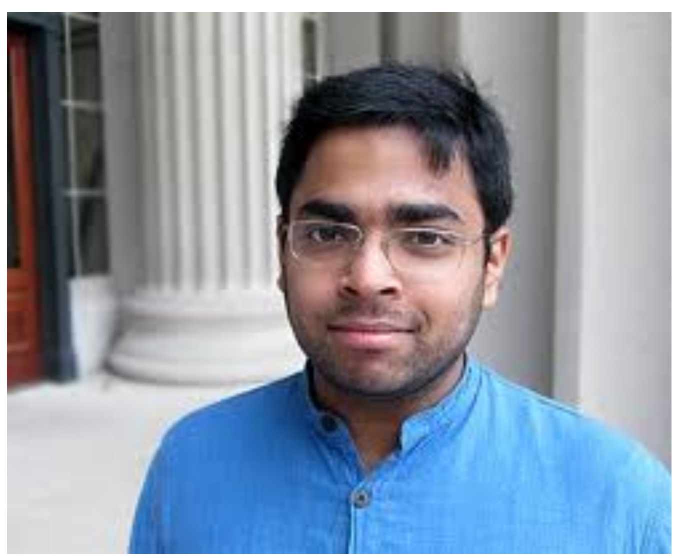

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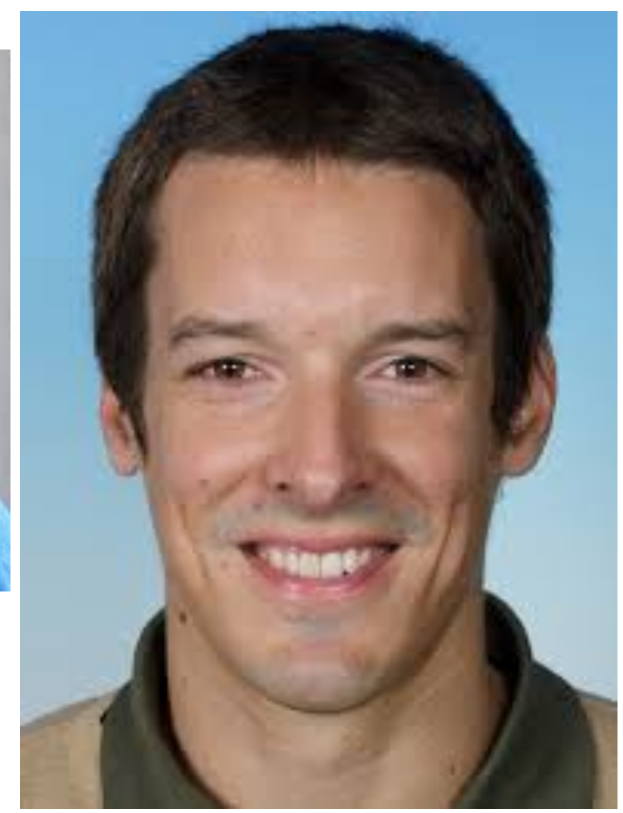

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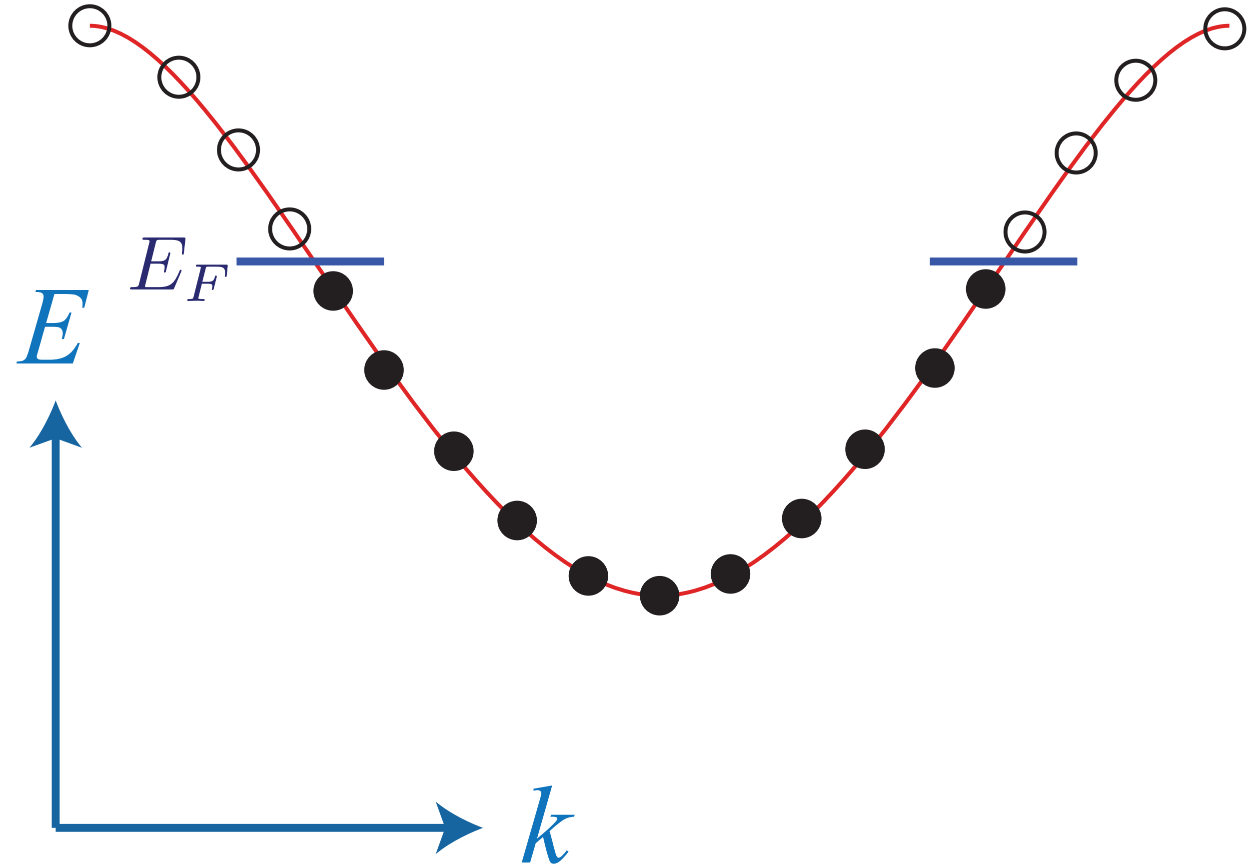
Foundations of quantum many body theory:

1. Ground states connected adiabatically to independent electron states

Metals



Foundations of quantum many body theory:

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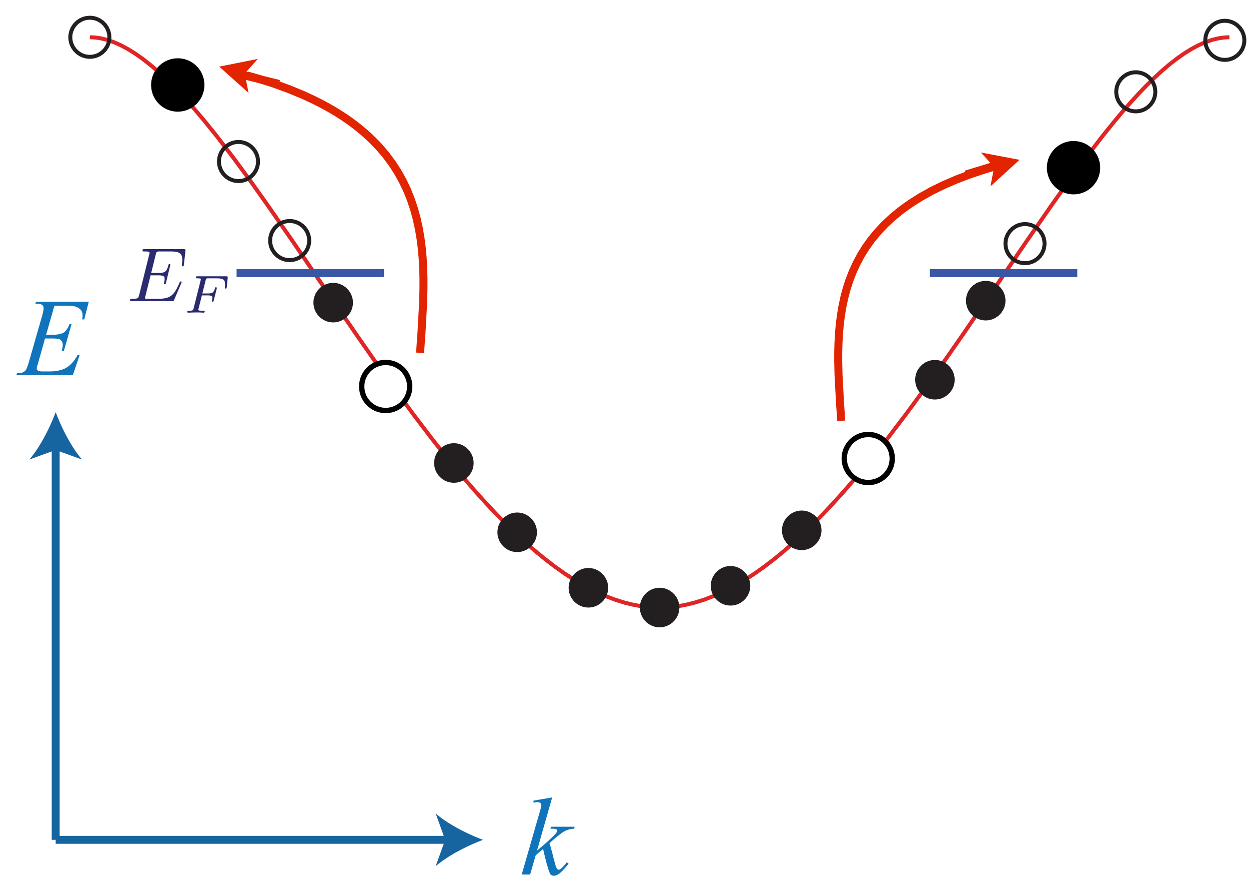
2. Boltzmann-Landau theory of quasiparticles

Metals



Modern phases of quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. Boltzmann-Landau theory of quasiparticles

Famous examples:

The fractional quantum Hall effect of electrons in two dimensions (e.g. in graphene) in the presence of a strong magnetic field. The ground state is described by Laughlin's wavefunction, and the excitations are *quasiparticles* which carry fractional charge.

Modern phases of quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement

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Famous examples:

Electrons in one dimensional wires form the Luttinger liquid. The quanta of density oscillations ("phonons") are a *quasiparticle* basis of the low-energy Hilbert space. Similar comments apply to magnetic insulators in one dimension.

Modern phases of quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. No quasiparticles

Modern phases of quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. No quasiparticles

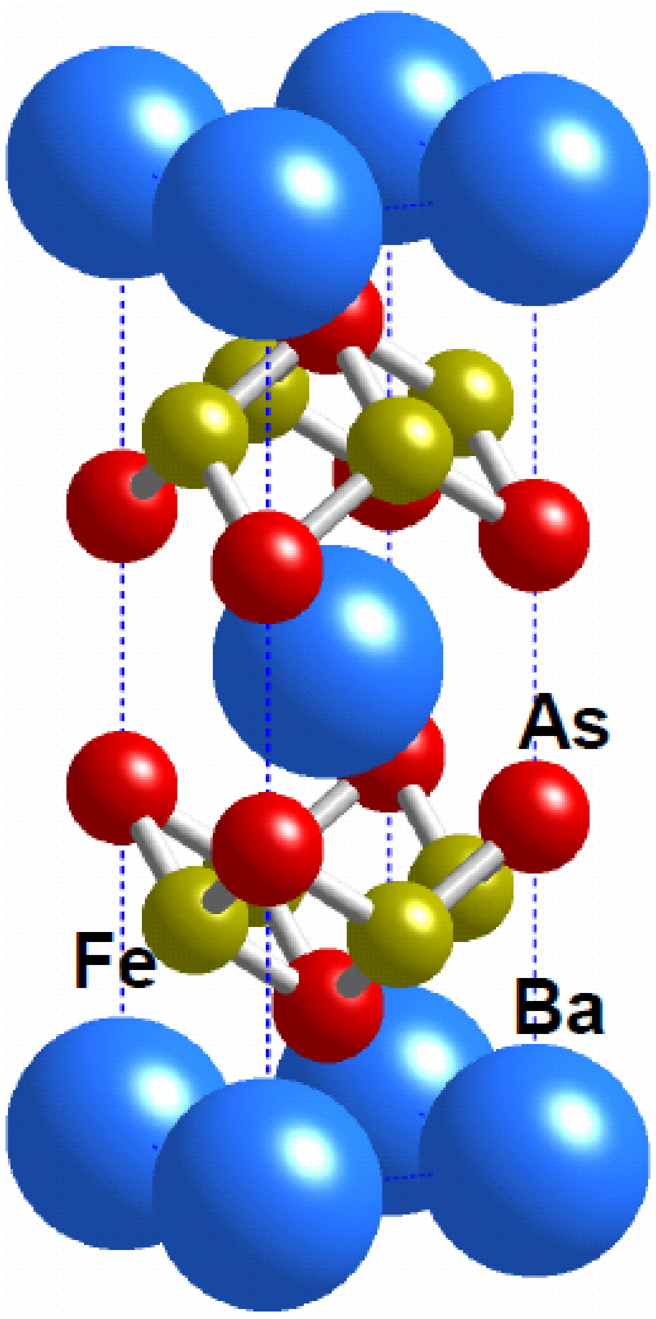
Only 2 examples:

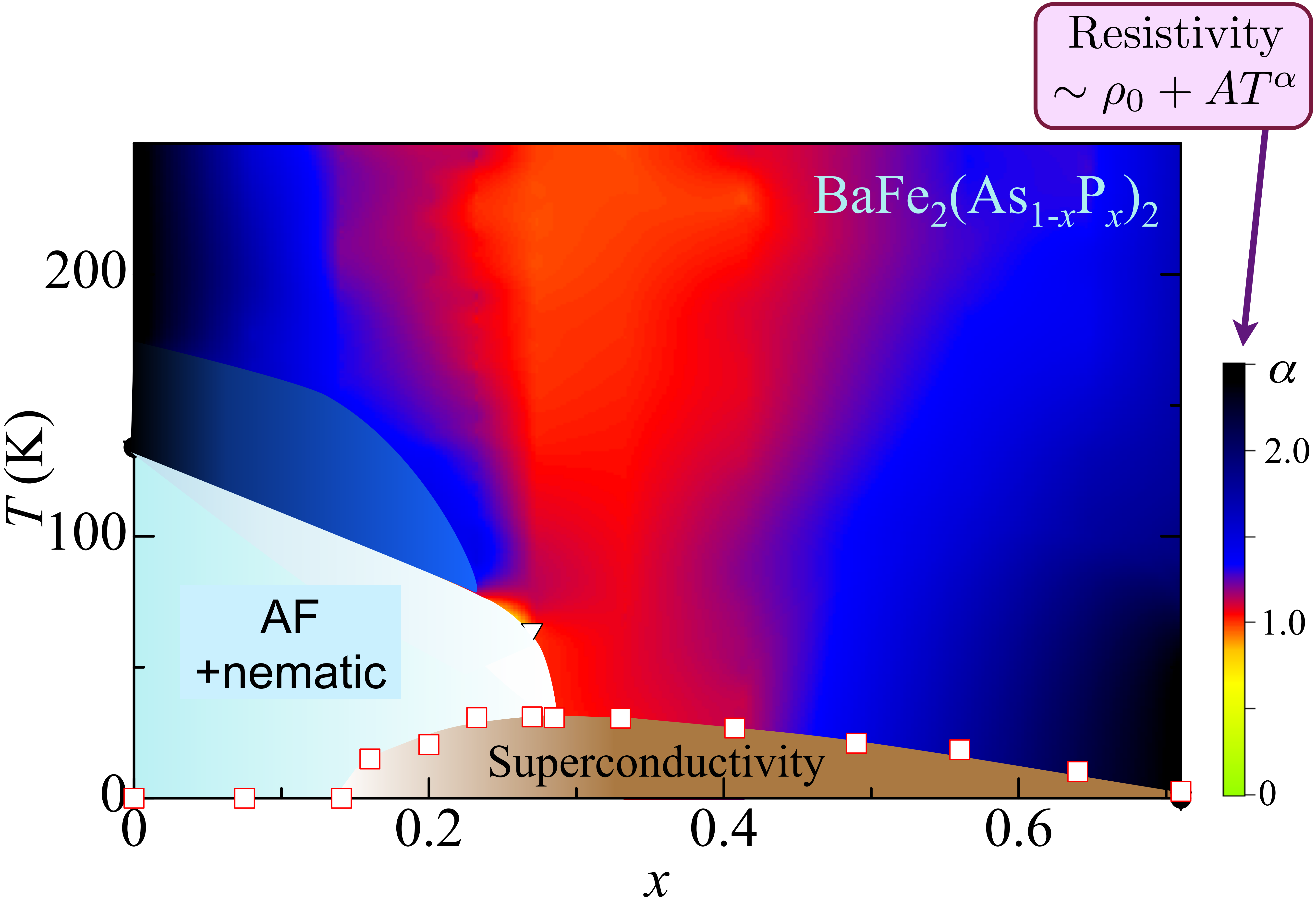
1. Conformal field theories in spatial dimension $d > 1$

2. Quantum critical metals in dimension $d=2$

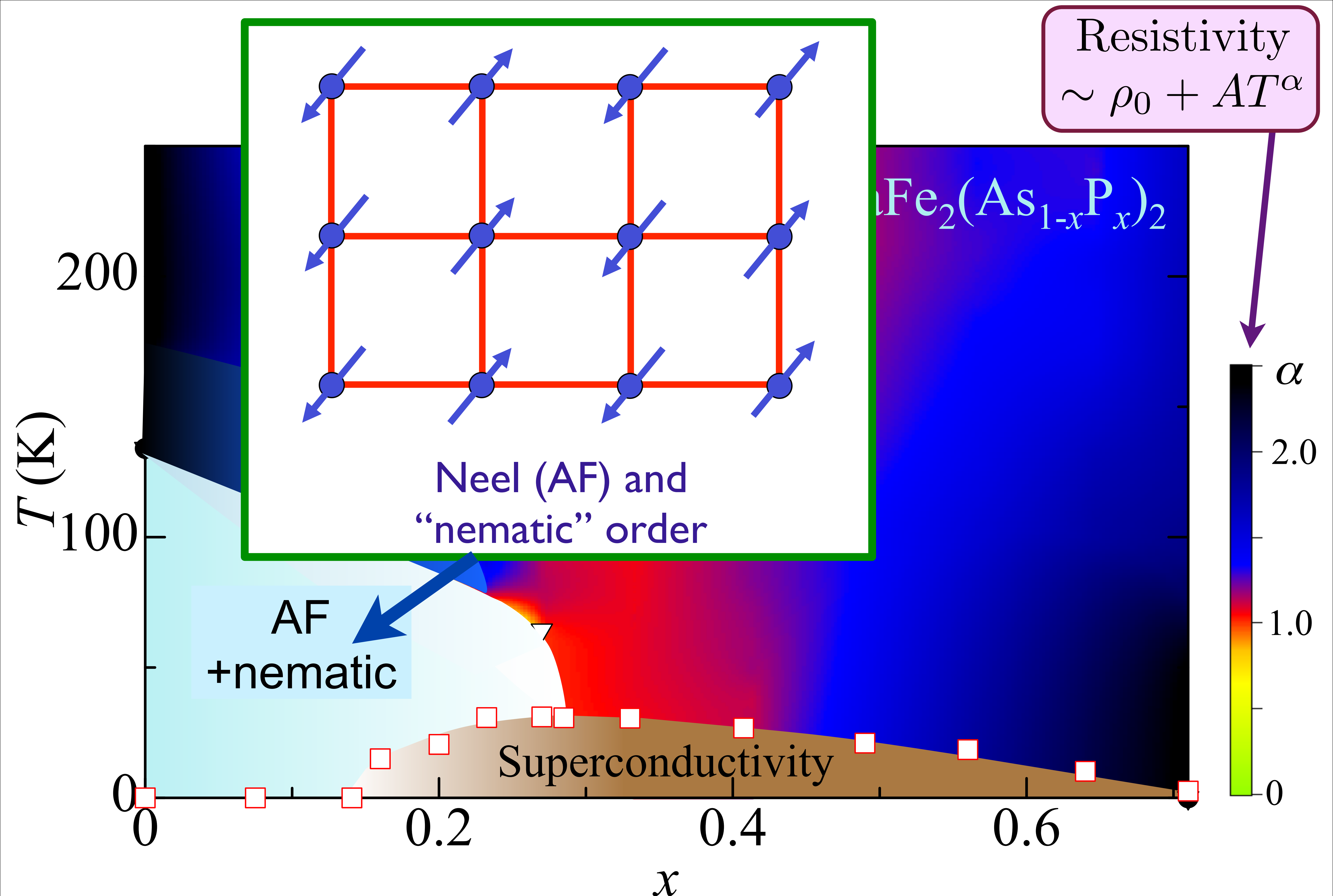
Iron pnictides:

a new class of high temperature superconductors





S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)



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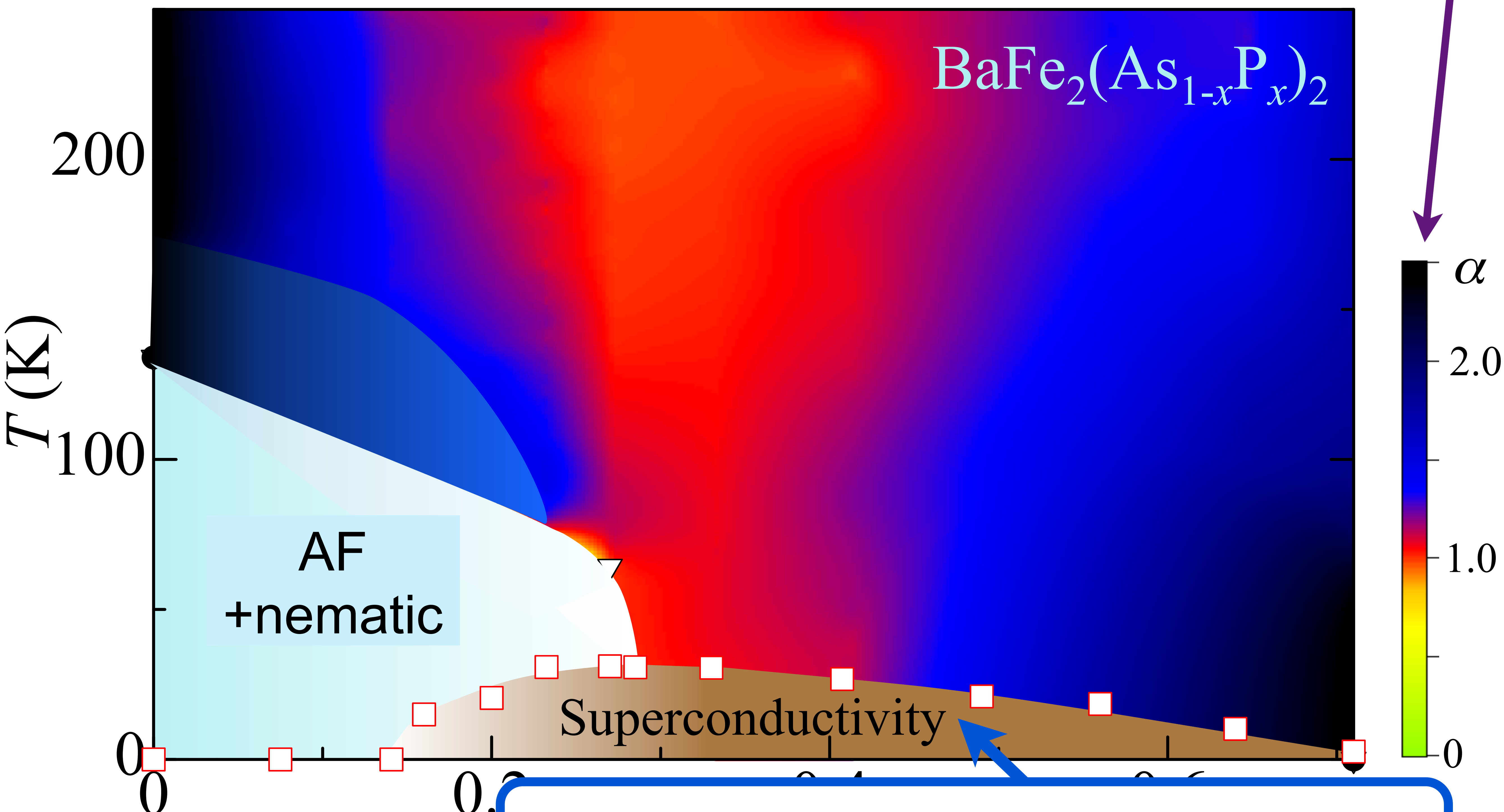
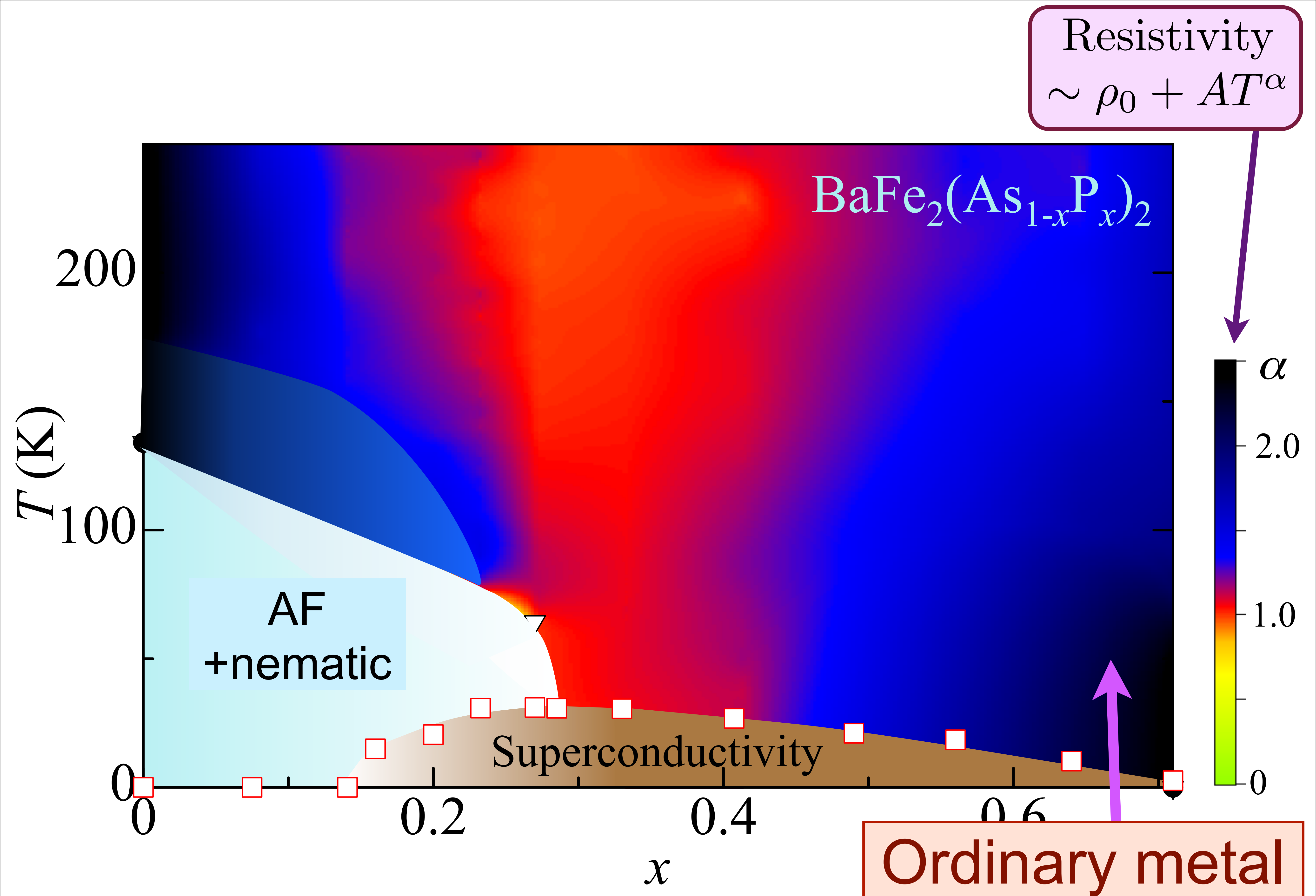
Resistivity $\sim \rho_0 + AT^{\alpha}$



Superconductor
Bose condensate of pairs of electrons

S. Kasahara, T. Shiba
H. Ike



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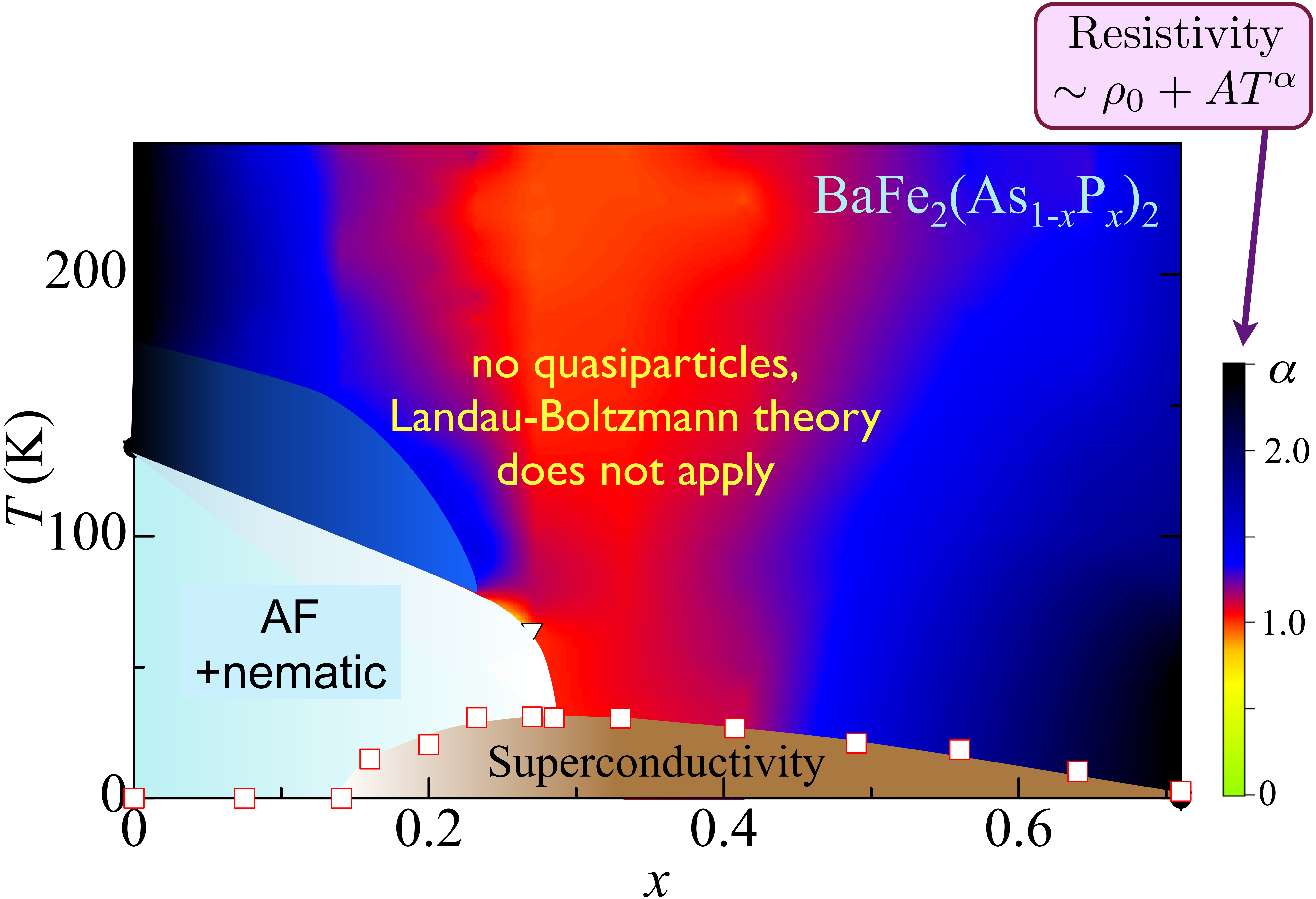

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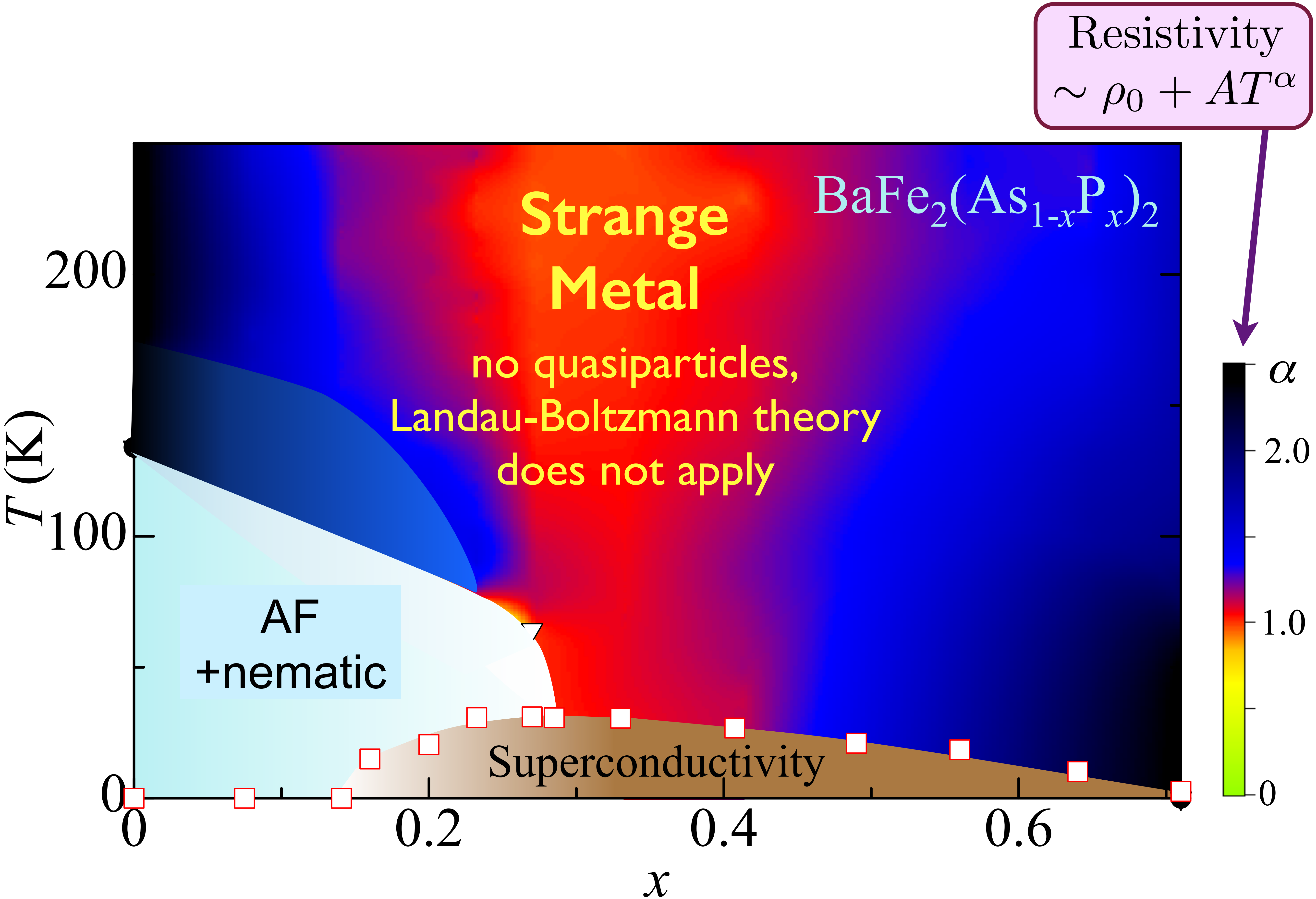

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Outline

1. The simplest model without quasiparticles

    Superfluid-insulator transition

    of ultracold bosonic atoms in an optical lattice

    (Conformal field theories in 2+1 dimensions)

2. Strange metals in the high T_c superconductors

    Non-quasiparticle transport at the

    Ising-nematic quantum critical point

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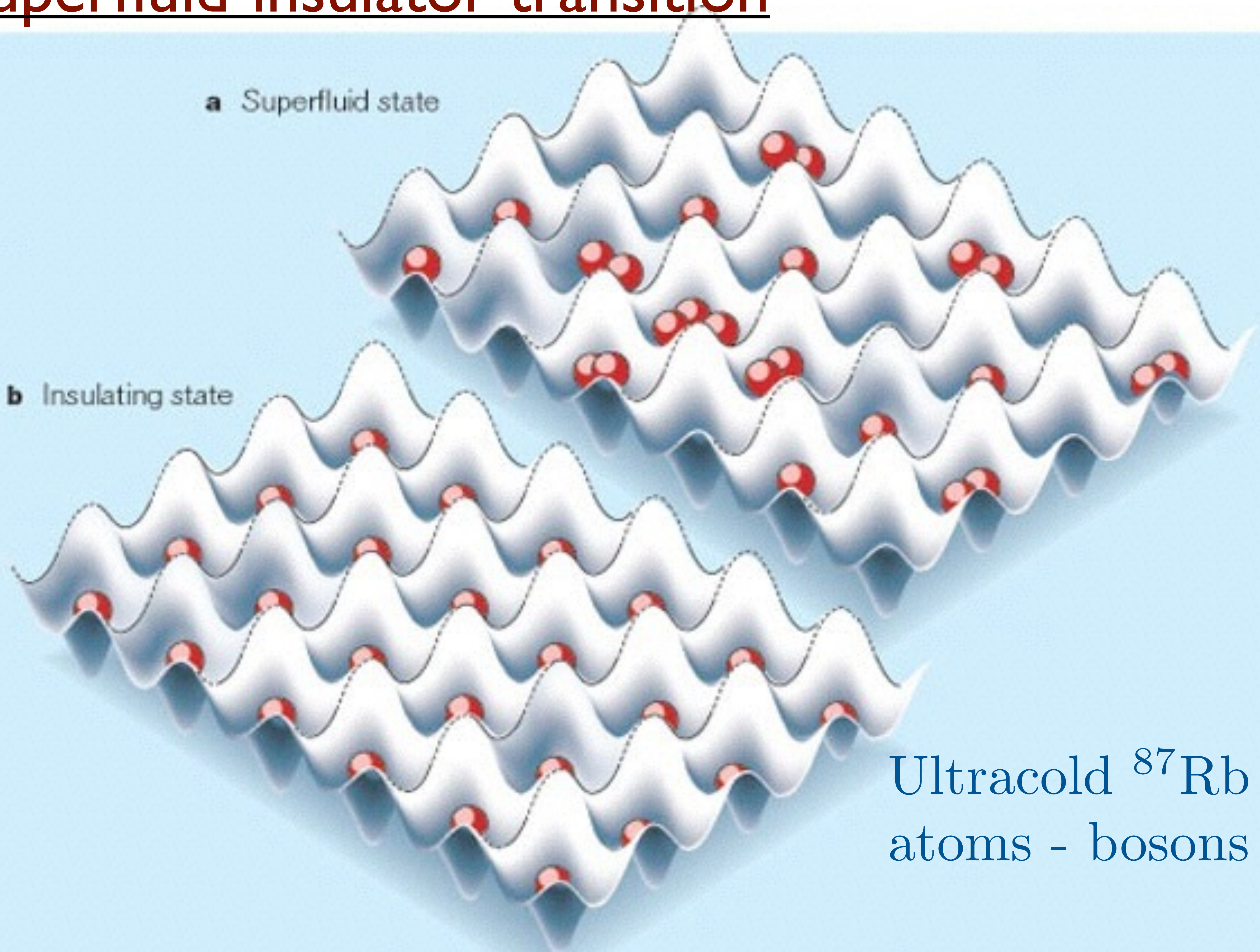
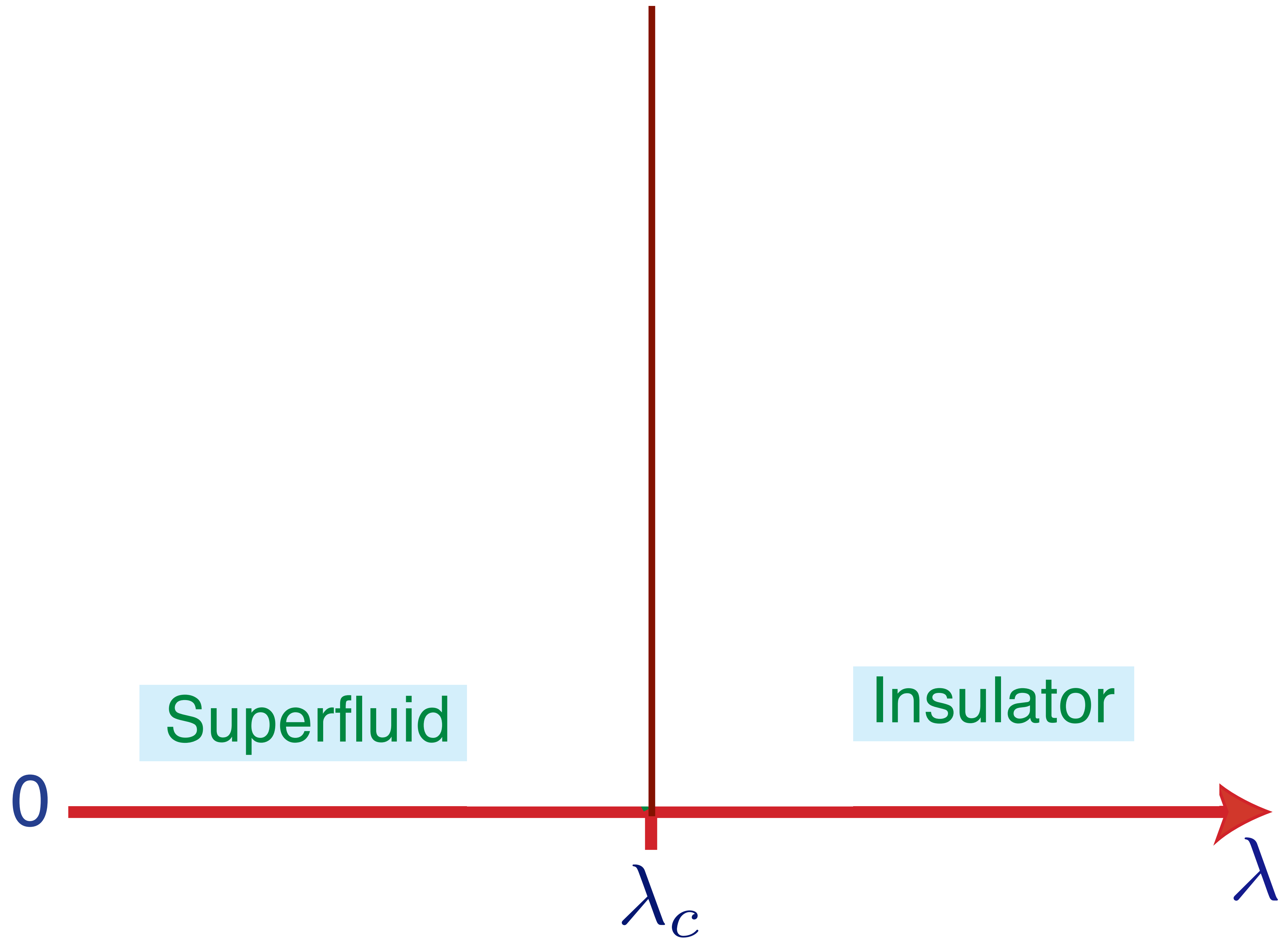
Superfluid-insulator transition



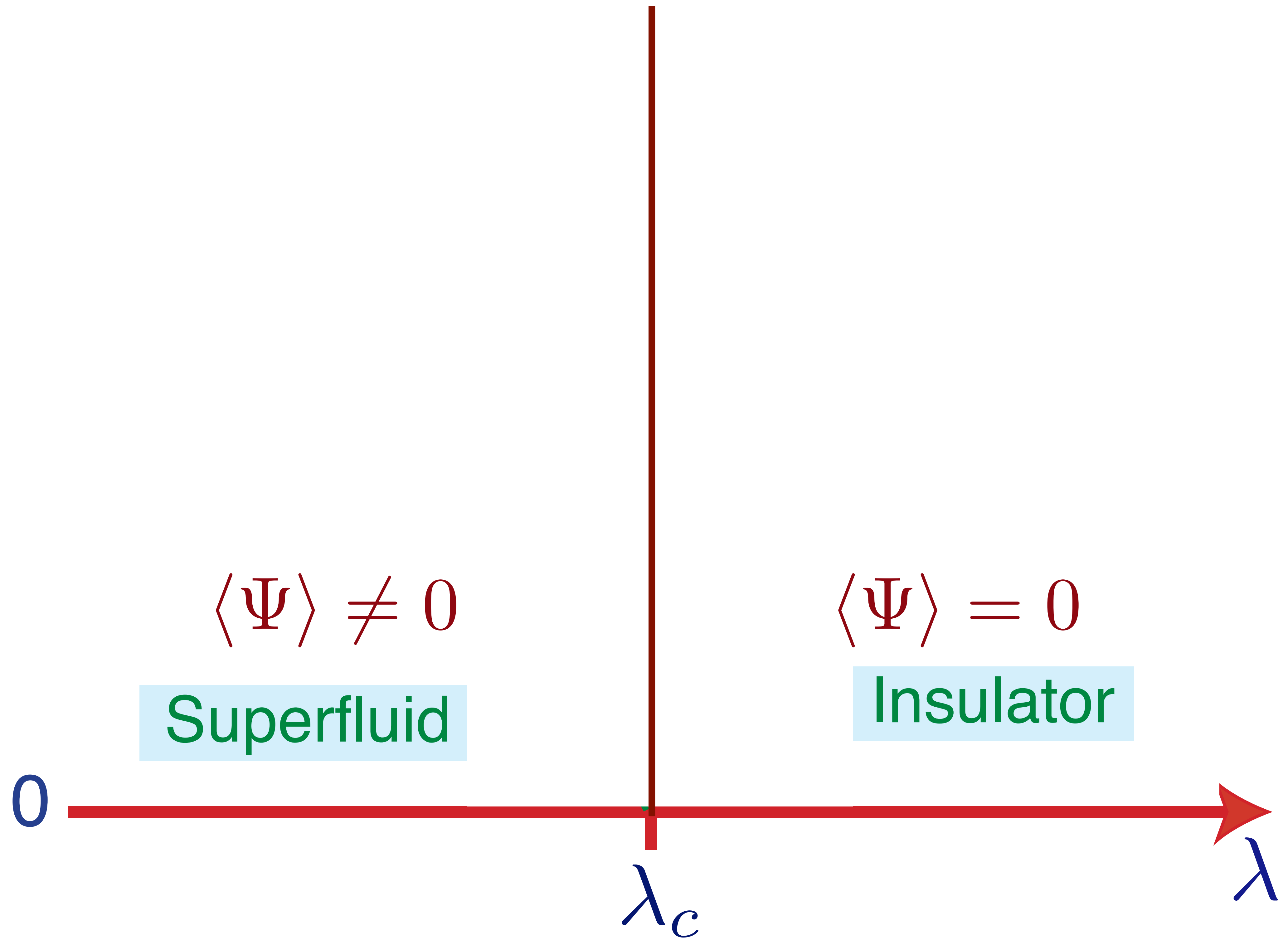
Ultracold ^{87}Rb atoms - bosons

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



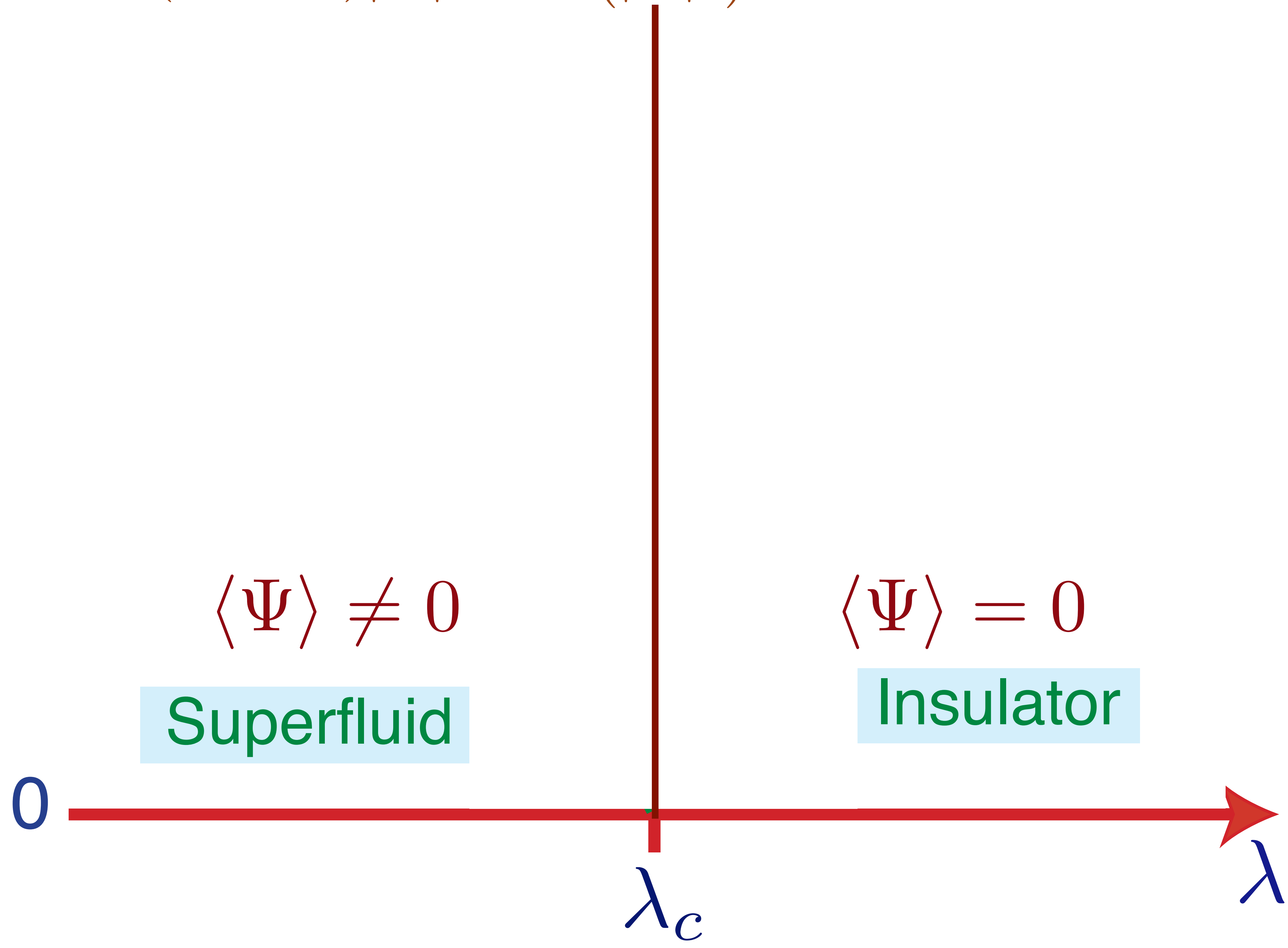
Superfluid
Insulator
0
λ_c
λ

$\Psi \rightarrow$ a complex field representing the Bose-Einstein condensate of the superfluid



$$\mathcal{S} = \int d^2r dt \left[|\partial_t \Psi|^2 - c^2 |\nabla_r \Psi|^2 - V(\Psi) \right]$$

$$V(\Psi) = (\lambda - \lambda_c)|\Psi|^2 + u \left(|\Psi|^2 \right)^2$$



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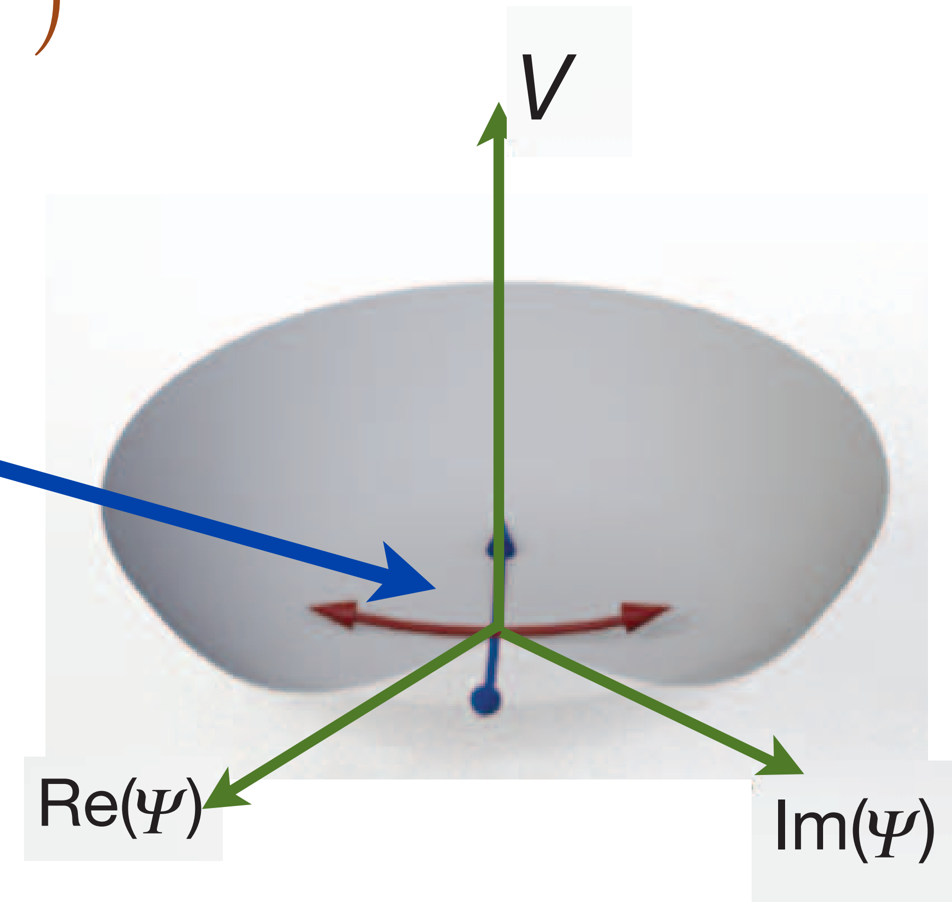
Particles and holes correspond to the 2 normal modes in the oscillation of Ψ about $\Psi = 0$.



$\langle \Psi \rangle \neq 0$

Superfluid

$\langle \Psi \rangle = 0$

Insulator

0

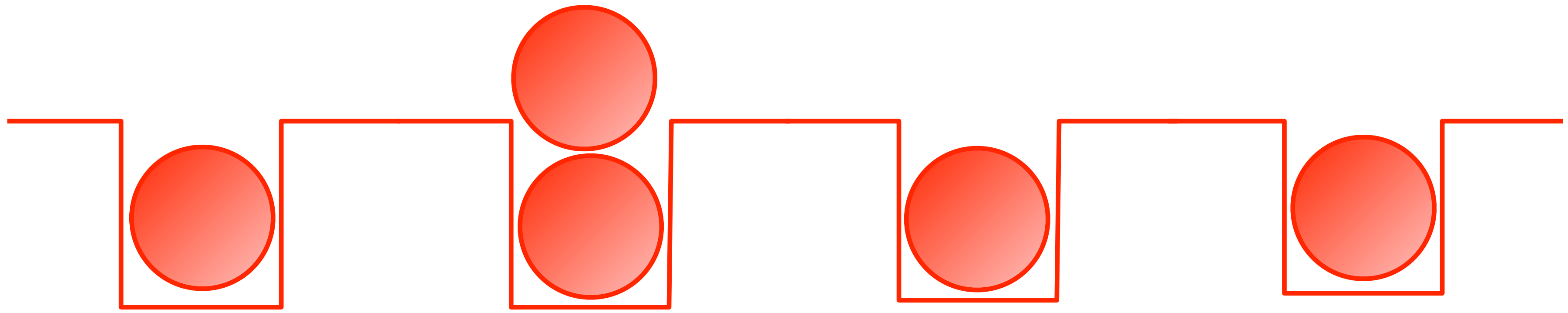
λ_c

λ

Insulator (the vacuum)
at large repulsion between bosons

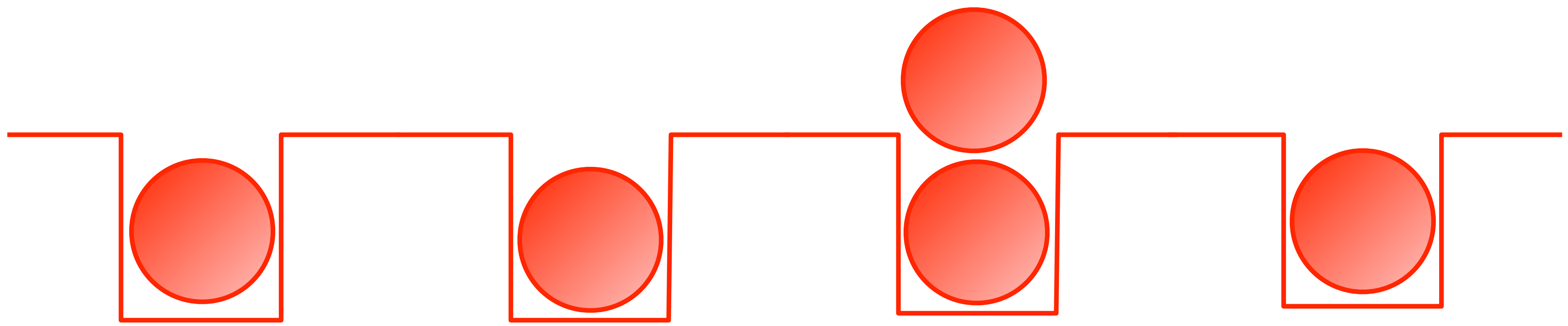
$$|\text{Ground state}\rangle = \prod_i b_i^\dagger |0\rangle$$

Excitations of the insulator:



Particles $\sim \psi^\dagger$

Excitations of the insulator:



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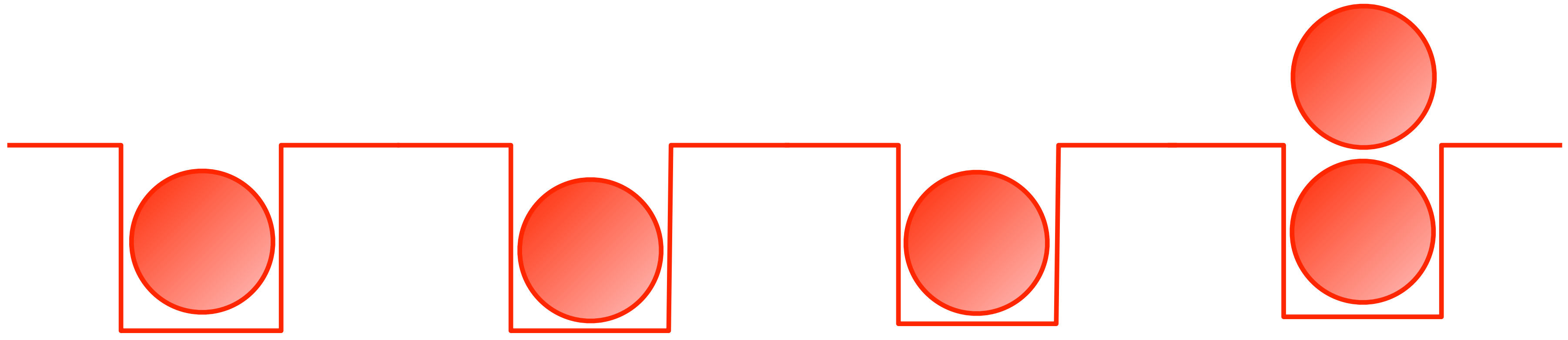
Excitations of the insulator:



Particles $\sim \psi^{\dagger}$

Excitations of the insulator:

Holes ~ ψ

Excitations of the insulator:

Holes $\sim \psi$

Excitations of the insulator:

Holes $\sim \psi$

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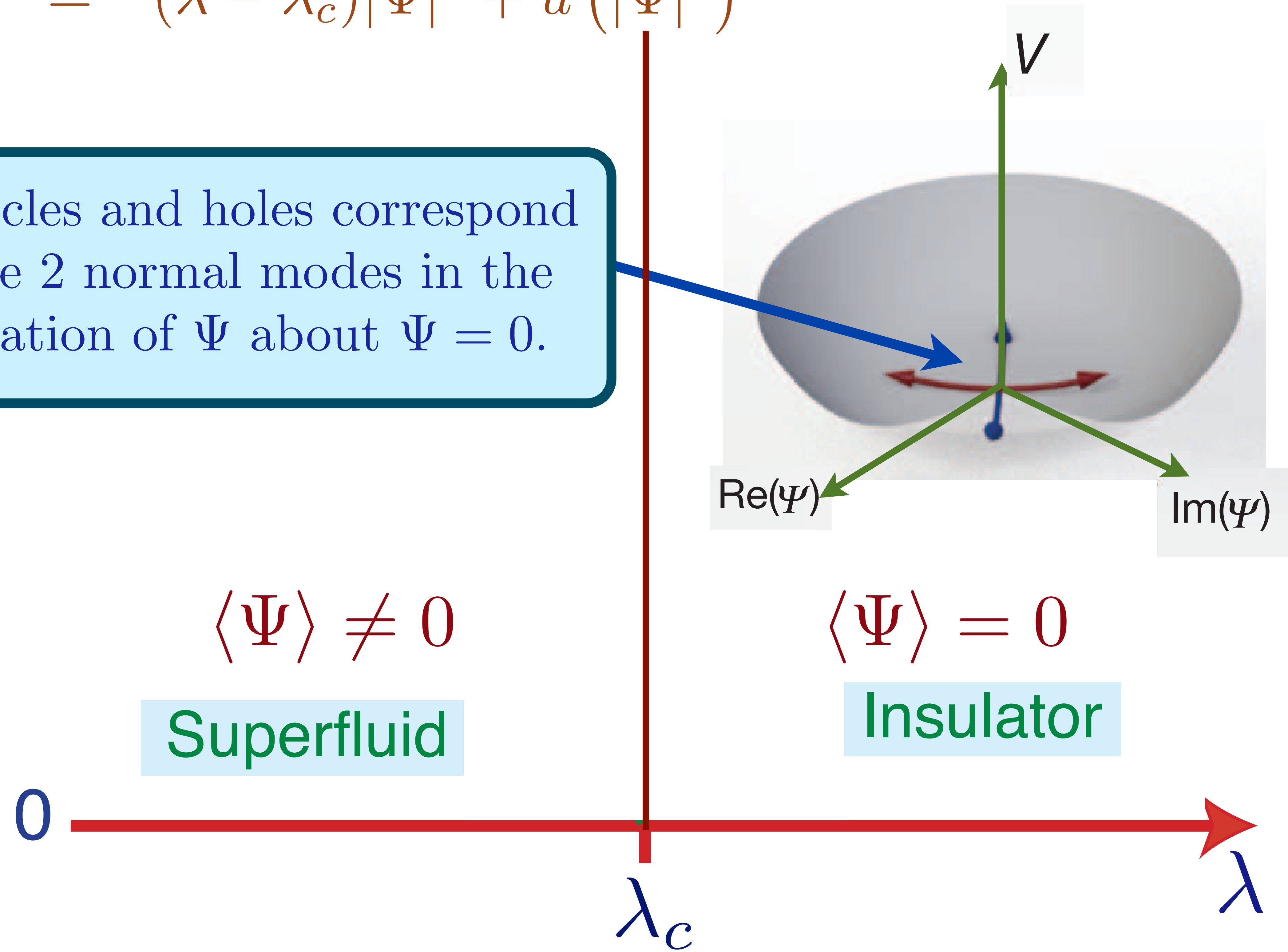

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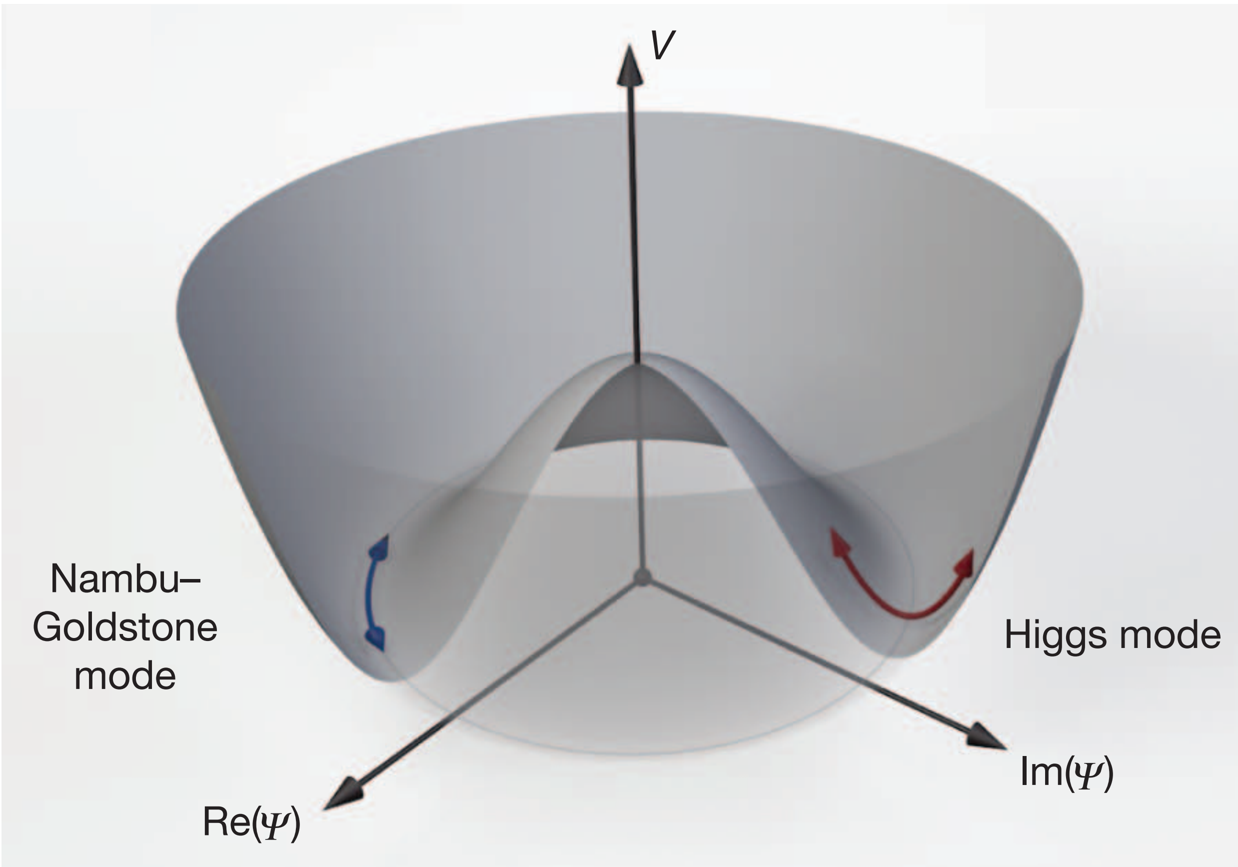


$\langle \Psi \rangle \neq 0$

Superfluid

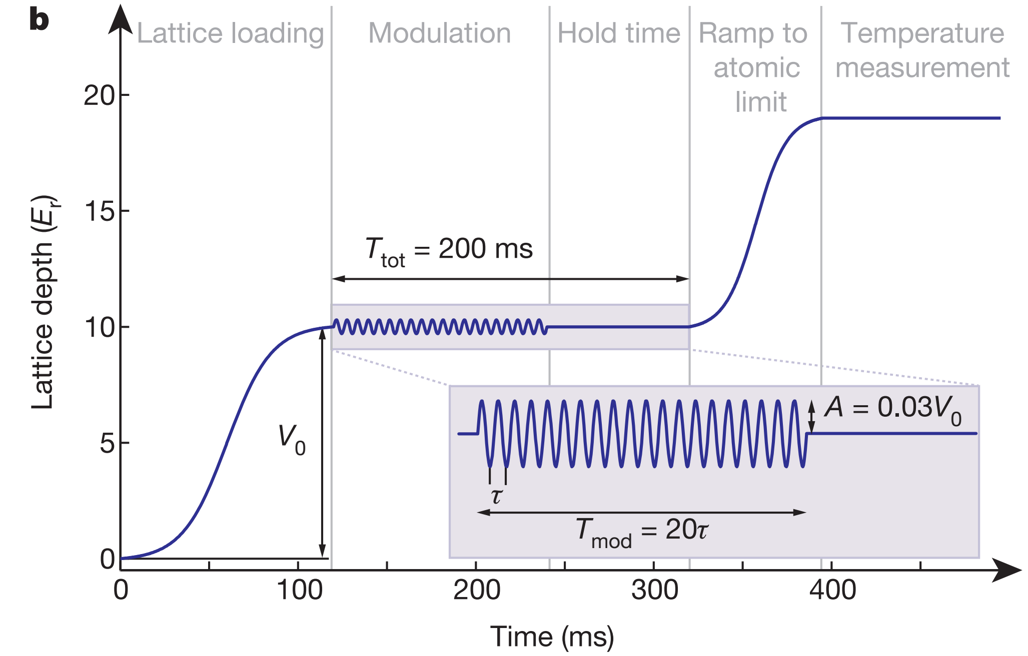
$\langle \Psi \rangle = 0$

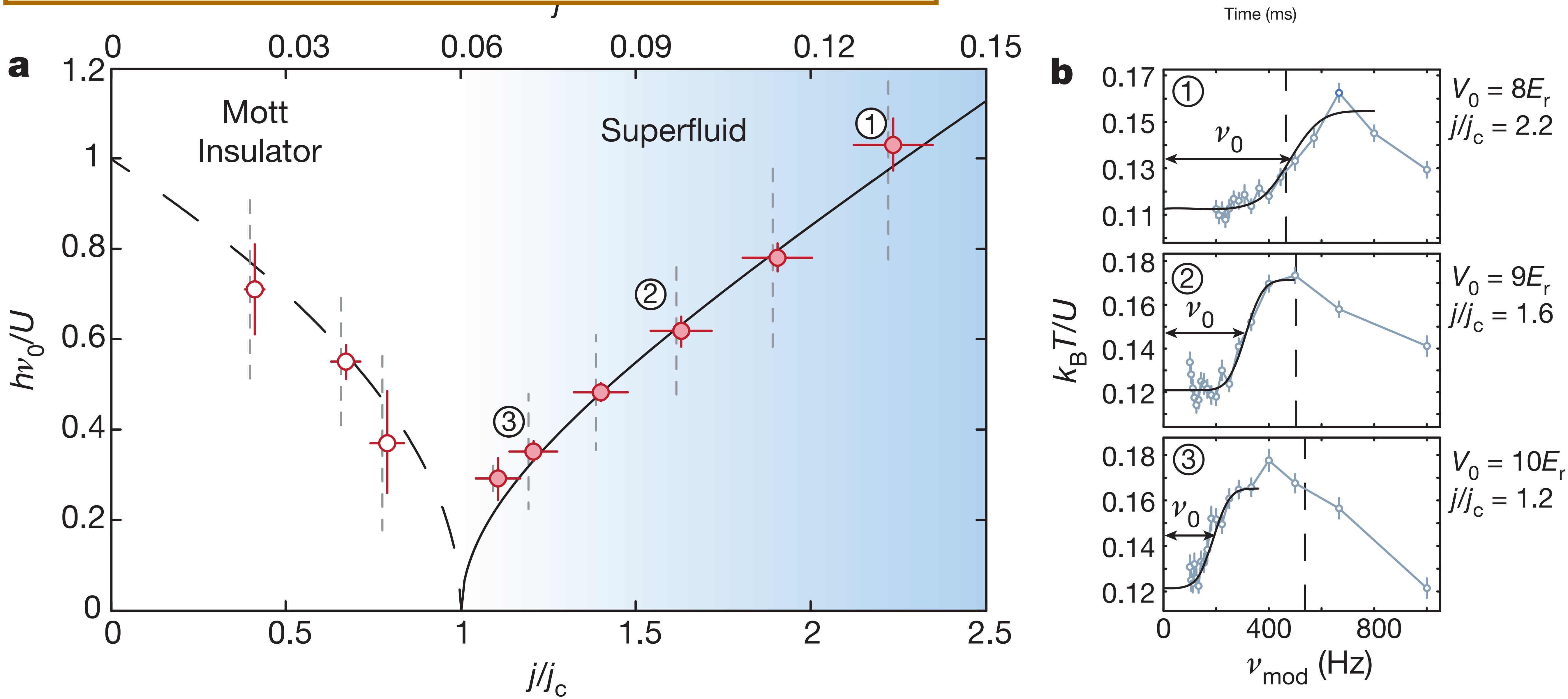
Insulator

0 λ_c λ

Observation of Higgs quasi-normal mode across the superfluid-insulator transition of ultracold atoms in a 2-dimensional optical lattice:

Response to modulation of lattice depth scales as expected from the LHP pole





Manuel Endres, Takeshi Fukuhara, David Pekker, Marc Cheneau, Peter Schaub, Christian Gross, Eugene Demler, Stefan Kuhr, and Immanuel Bloch, *Nature* **487**, 454 (2012).

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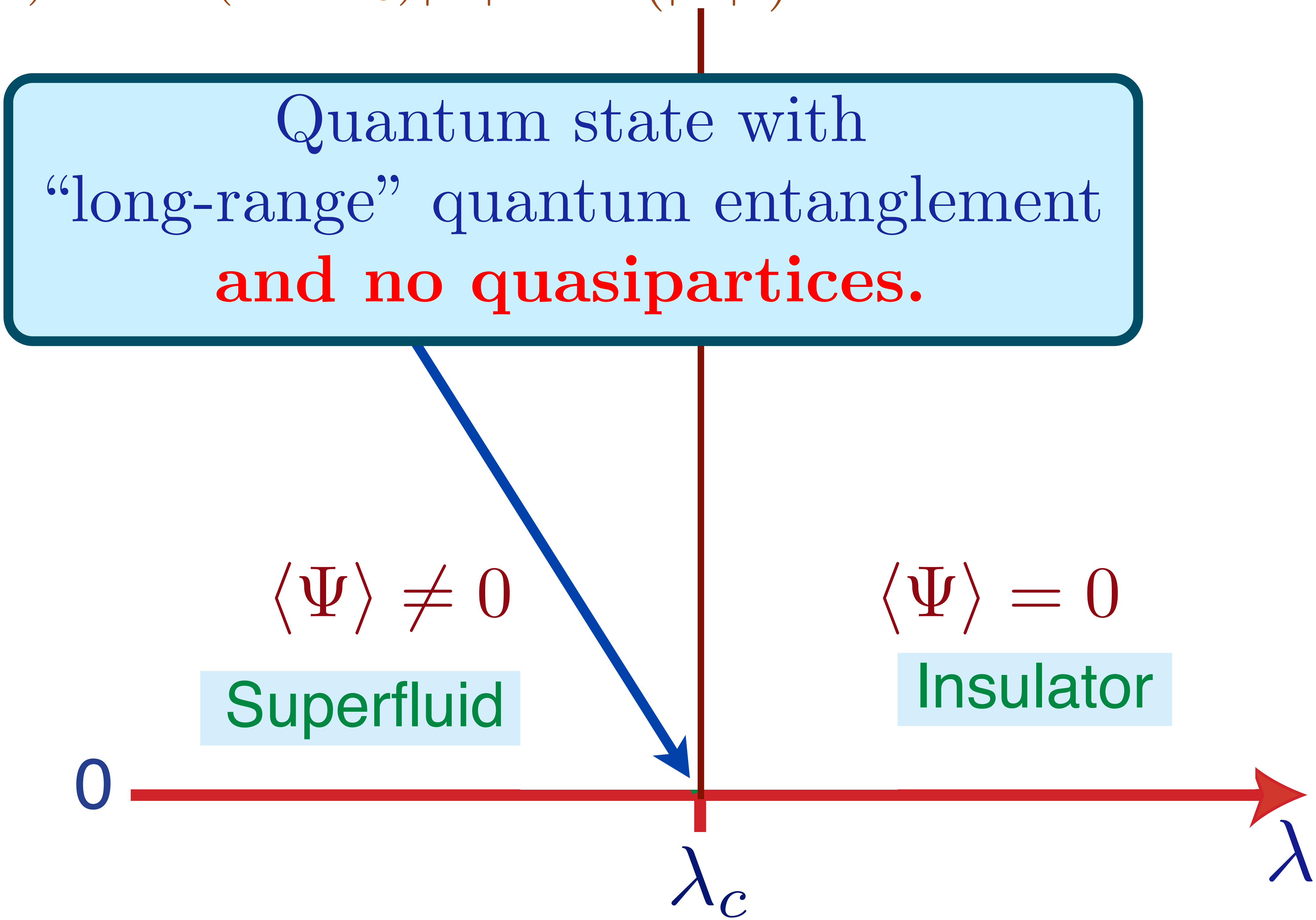

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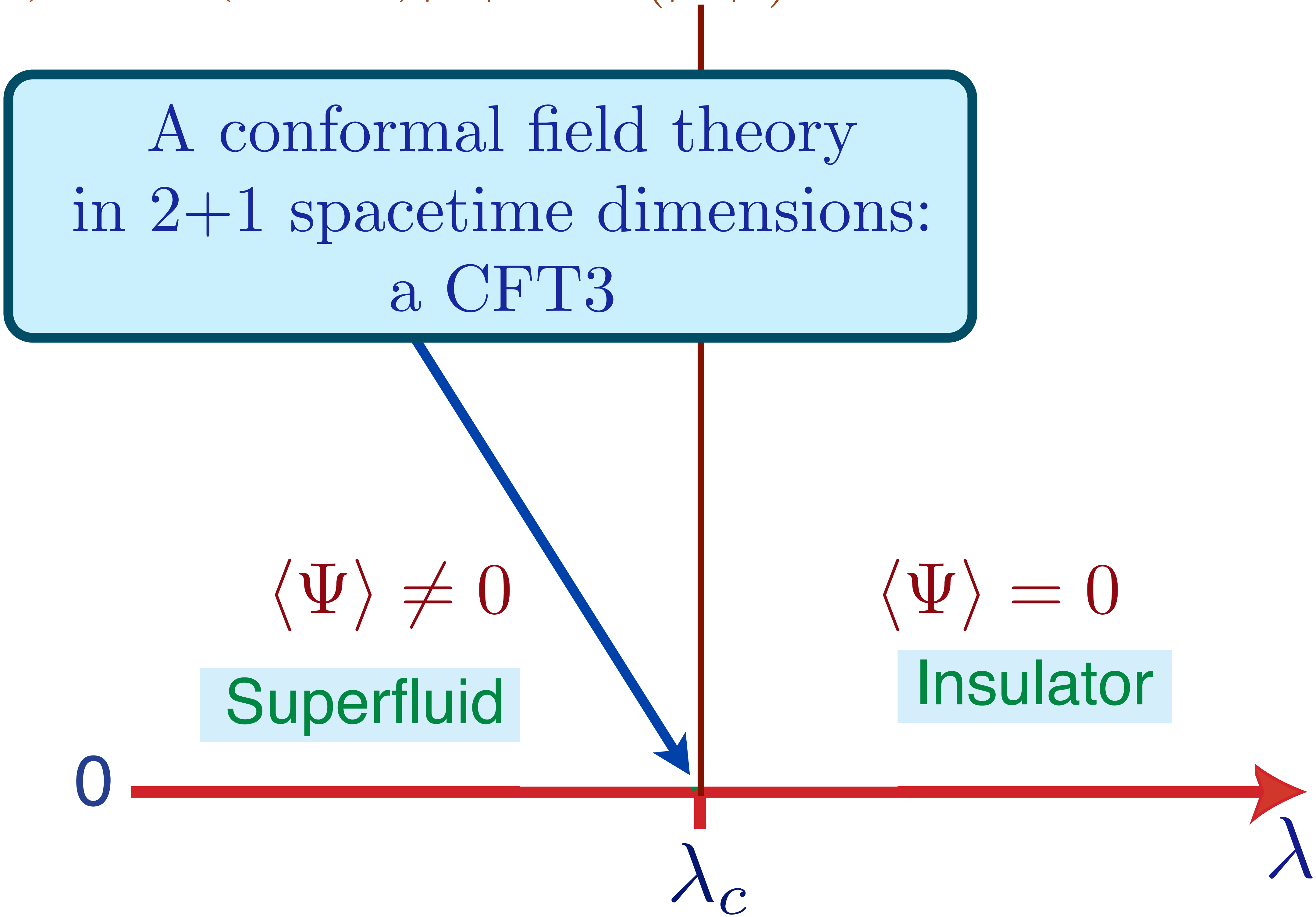
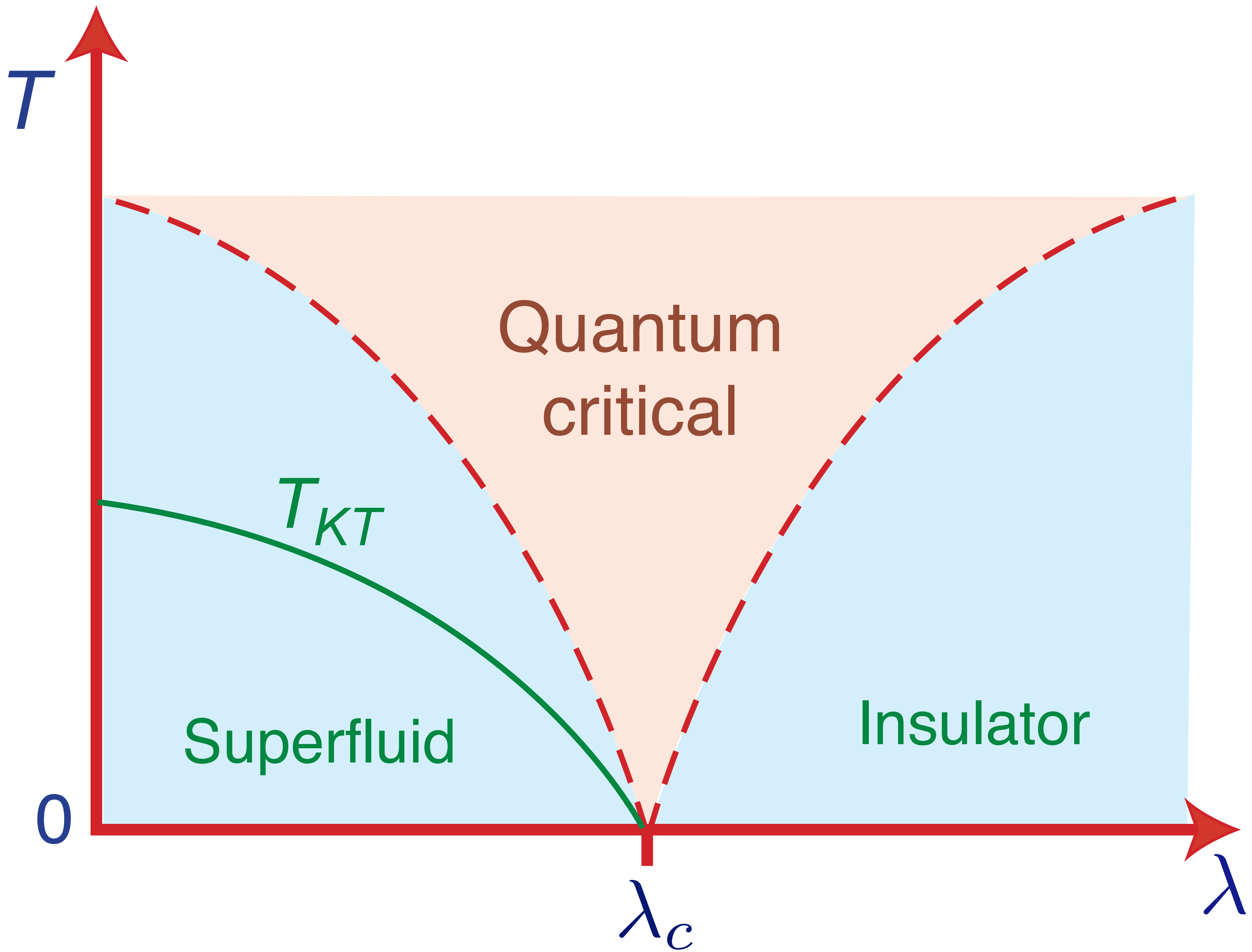
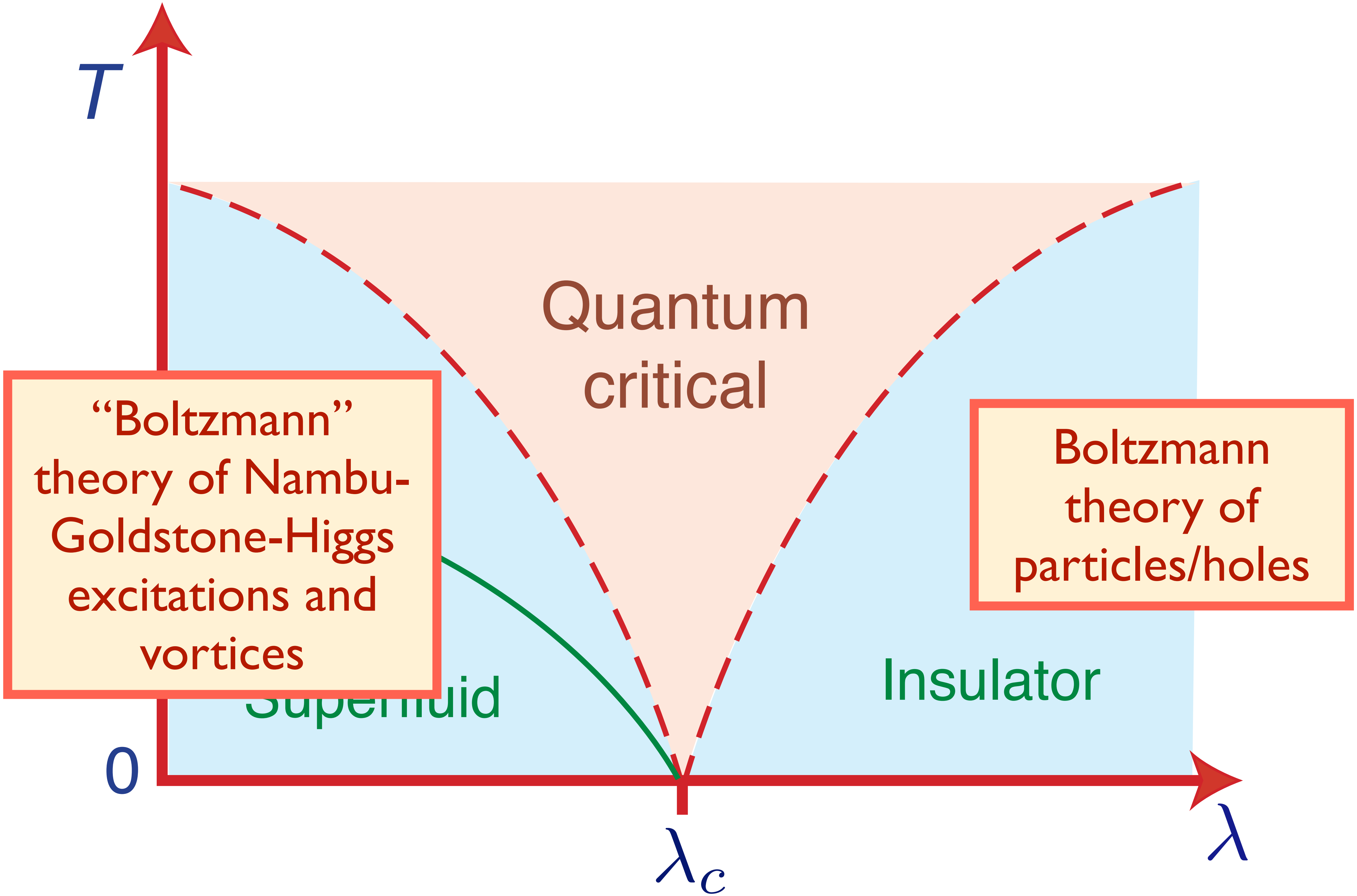
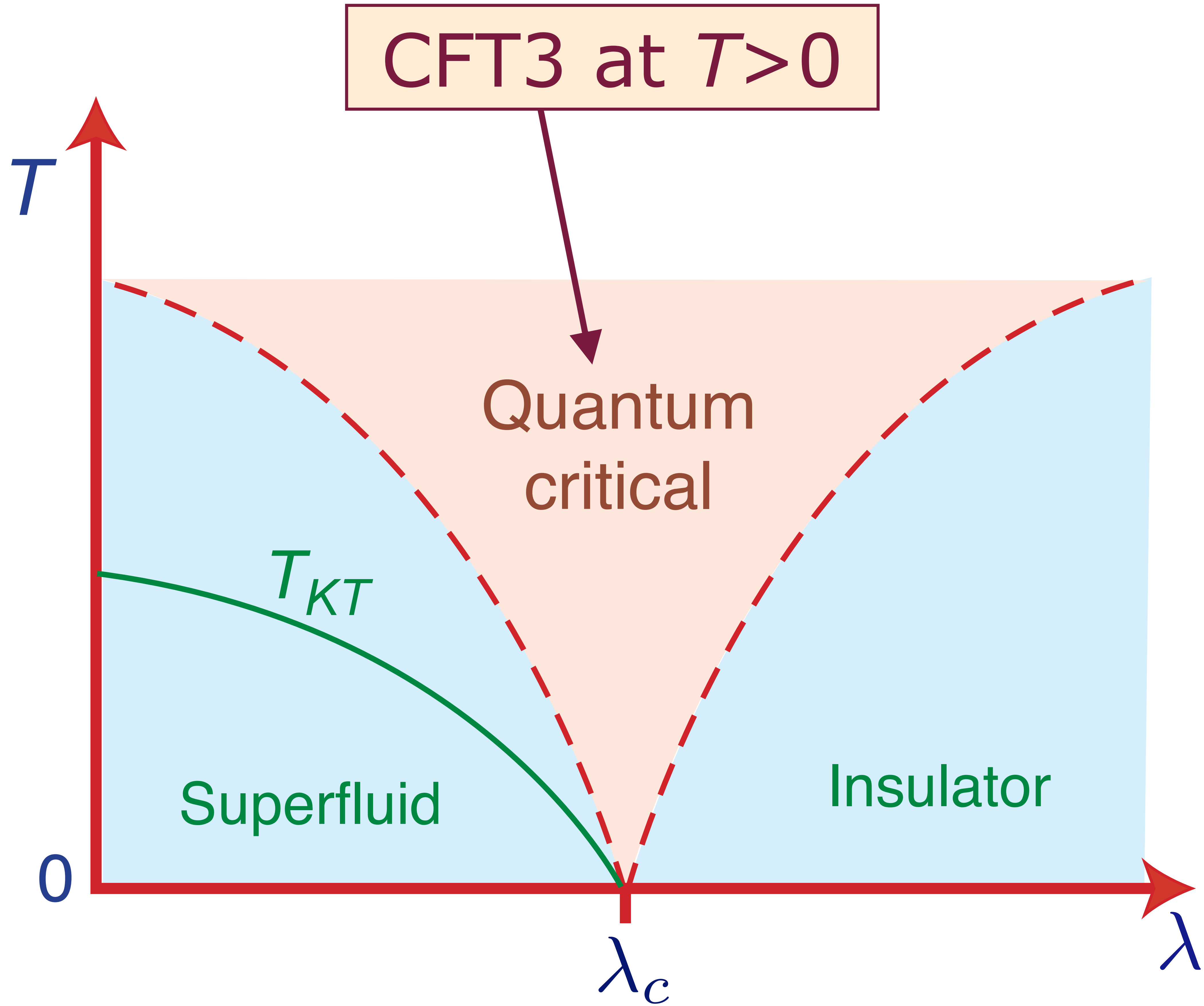




T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
λ


T
Quantum
critical
“Boltzmann”
theory of Nambu-
Goldstone-Higgs
excitations and
vortices
Boltzmann
theory of
particles/holes
Superfluid
Insulator
0
λ_c
λ


CFT3 at T>0
T
Quantum
critical
T_KT
Superfluid
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0
λ_c
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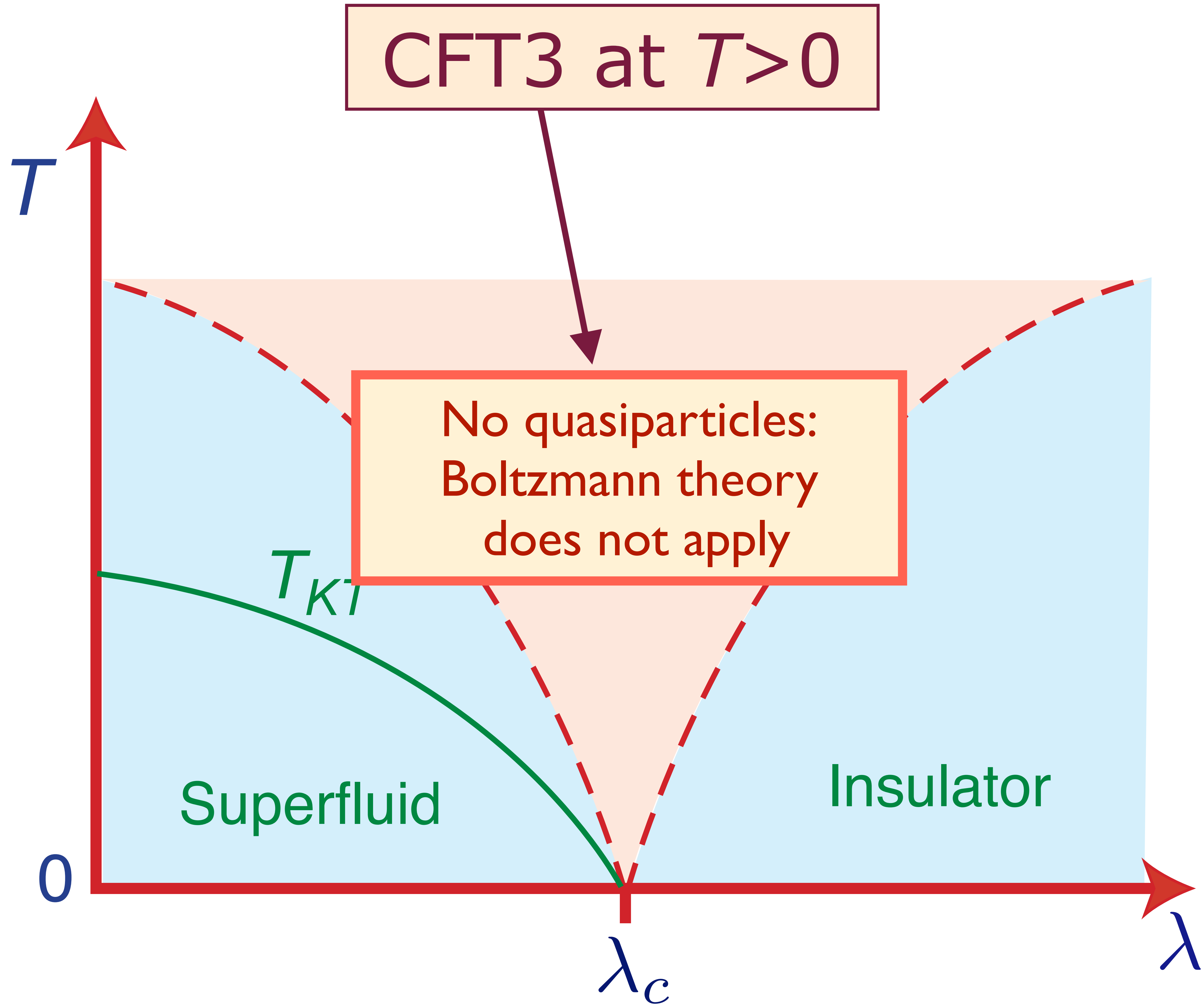

CFT3 at $T>0$
T
No quasiparticles:
Boltzmann theory
does not apply
T_{KT}
Superfluid
Insulator
0
λ_c
λ

Traditional CMT

- Identify quasiparticles and their dispersions

- Compute scattering matrix elements of quasiparticles (or of collective modes)

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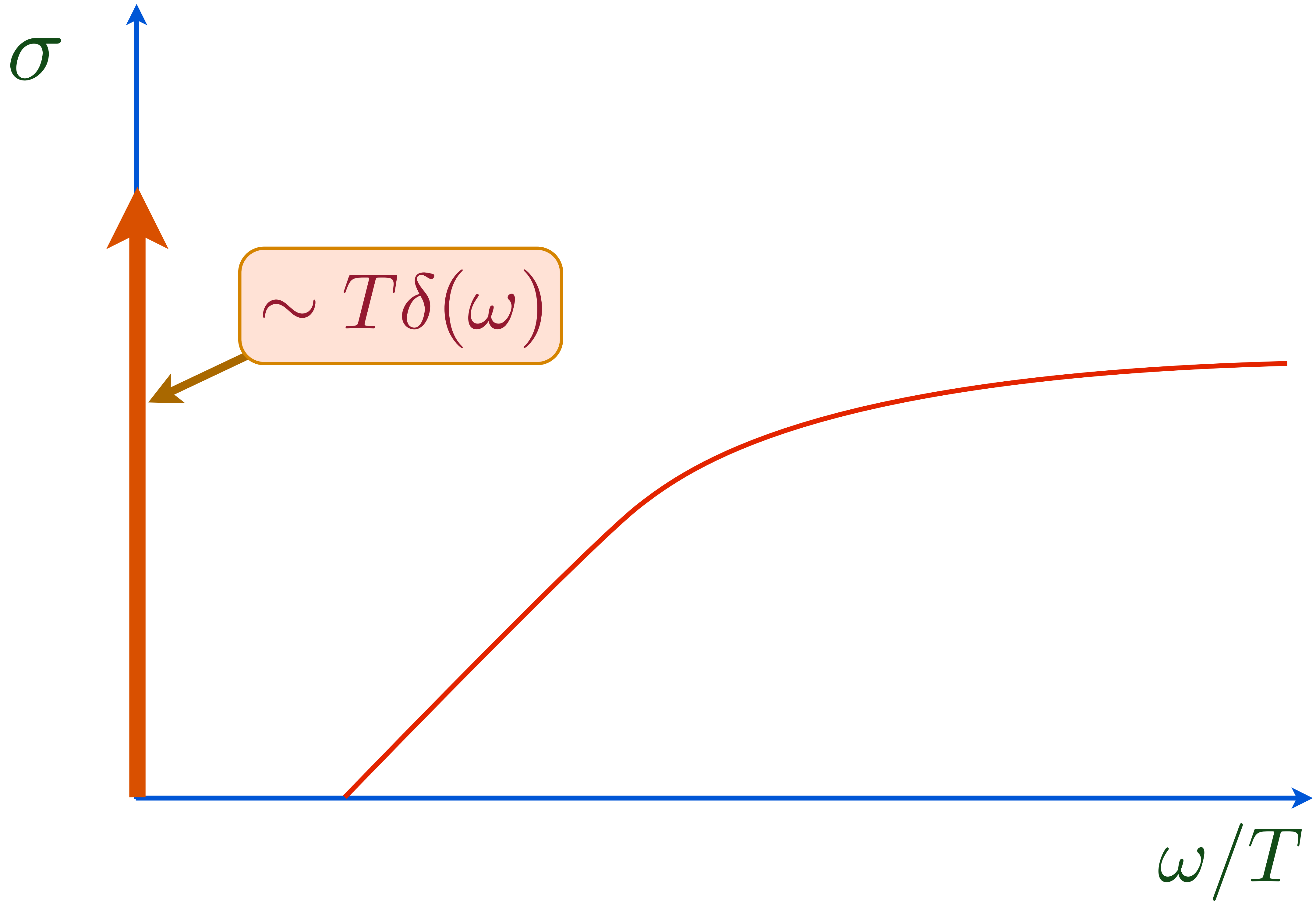
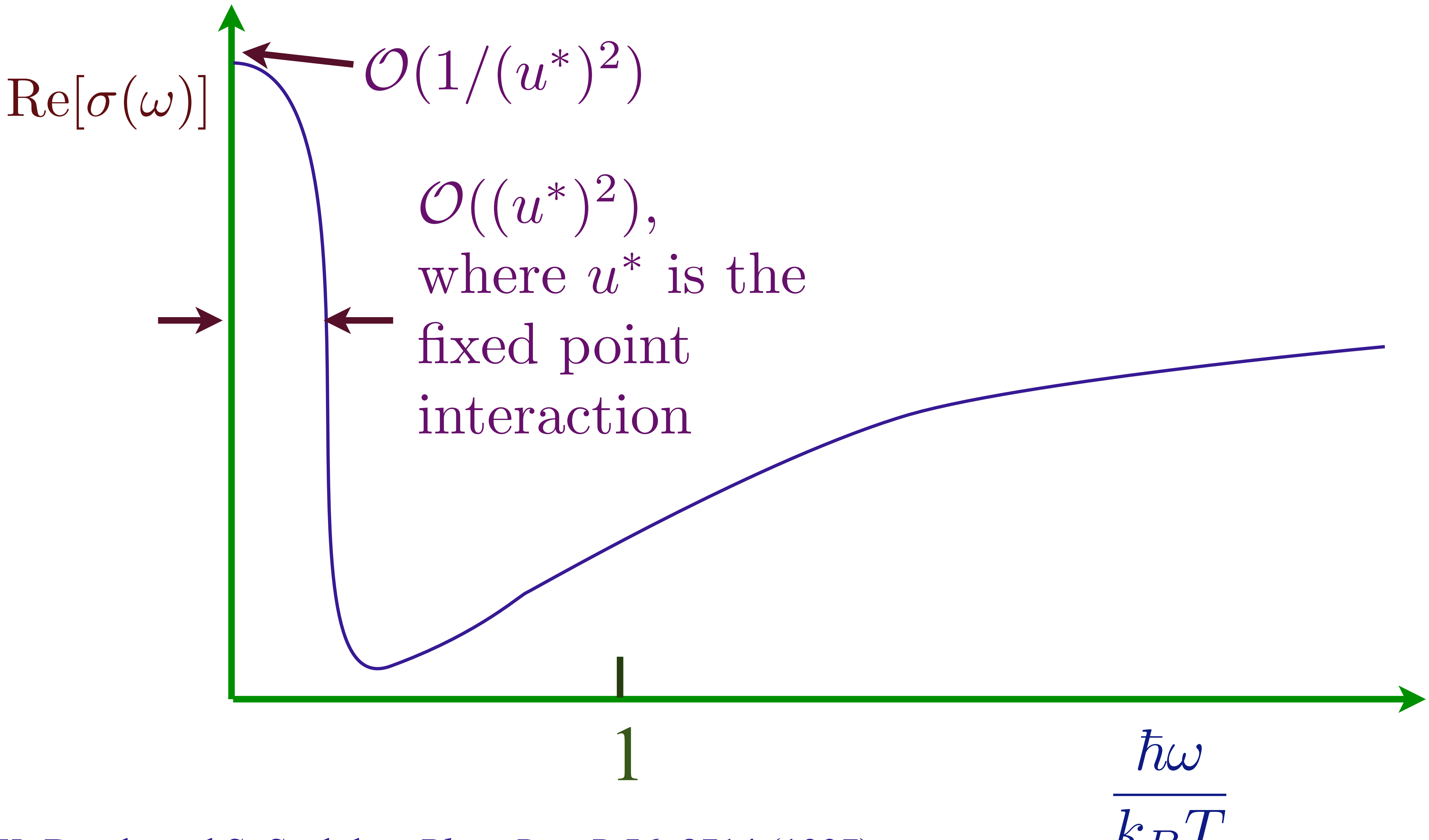
- Deduce dissipative and dynamic properties at non-zero temperatures

Quasiparticle view of quantum criticality (Boltzmann equation): Electrical transport for a free CFT3



Quasiparticle view of quantum criticality (Boltzmann equation): Electrical transport for a (weakly) interacting CFT3



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

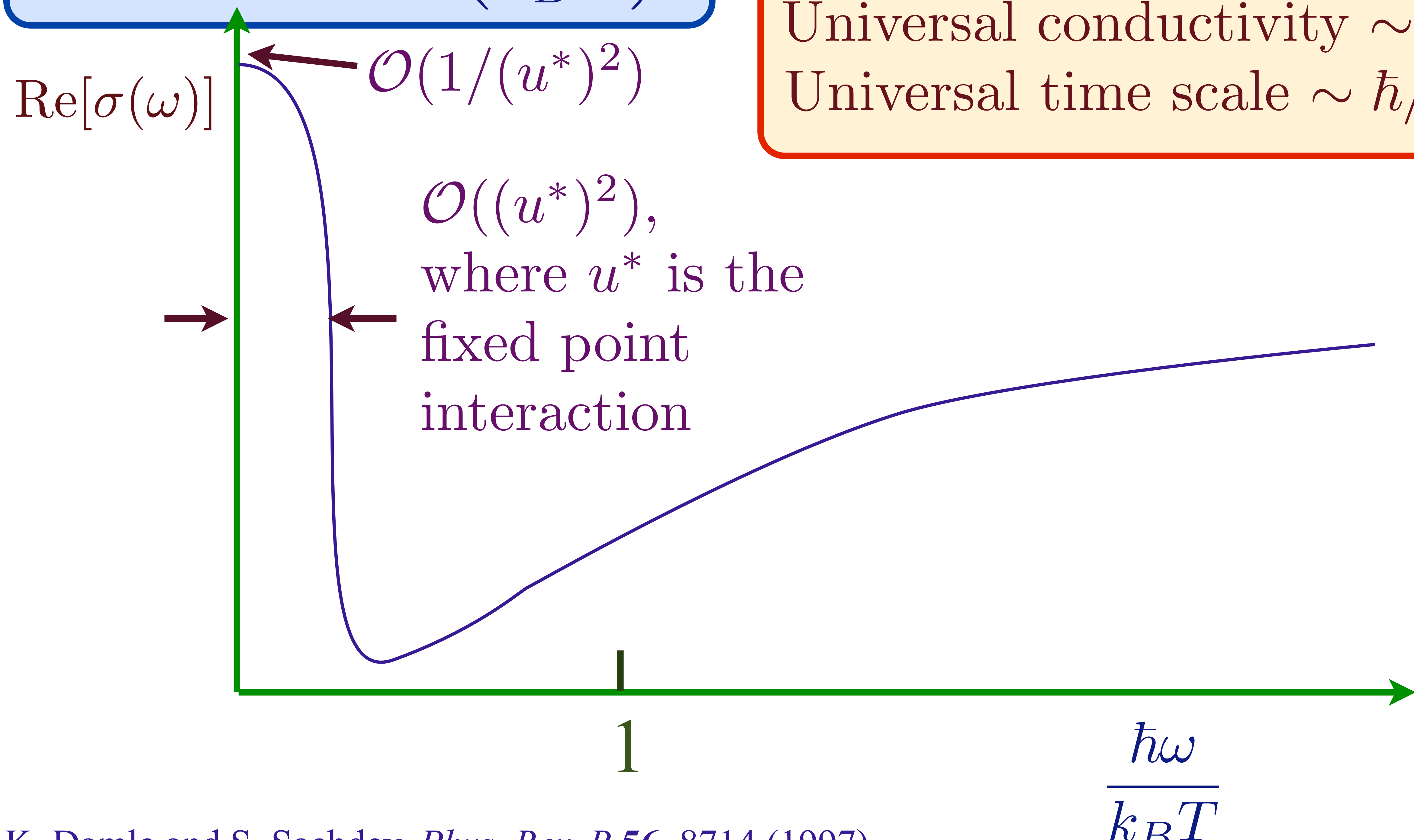
Quasiparticle view of quantum criticality (Boltzmann equation): Electrical transport for a (weakly) interacting CFT3

$$\sigma(\omega, T) = \frac{e^2}{h} \Sigma\left(\frac{\hbar\omega}{k_B T}\right) \; ;$$

$\Sigma \rightarrow$ a universal function

Universal conductivity $\sim e^2/h$

Universal time scale $\sim \hbar/k_B T$



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Dynamics without quasiparticles

- Start with strongly interacting CFT without particle- or wave-like excitations
- Compute scaling dimensions and OPE co-efficients of operators of the CFT

Basic characteristics of CFTs

Ordinary quantum field theories are characterized by their particle spectrum, and the S-matrices describing interactions between the particles. The analog of these concepts for CFTs are the *primary operators* $O_a(x)$ and their *operator product expansions* (OPEs). Each primary operator is associated with a scaling dimension Δ_a, defined by the ($T = 0$) expectation value (for the simplest case of scalar operators):

$$\langle O_a(x) O_b(0) \rangle = \frac{\delta_{ab}}{|x|^{2\Delta_a}}$$

Basic characteristics of CFTs

The OPE describes what happens when two operators come together at a single spacetime point (considering scalar operators only)

$$\lim_{x' \to x} \langle O_a(x') O_b(x) O_c(0) \rangle = \frac{f_{abc}}{|x|^{\Delta_a + \Delta_b + \Delta_c}}$$

The values of $\{\Delta_a, f_{abc}\}$ determine (in principle) all observable properties of the CFT, as constrained by a complex set of conformal Ward identities.

For the Wilson-Fisher CFT3, systematic methods exist to compute (in principle) all the $\{\Delta_a, f_{abc}\}$, and we will assume this data is *known*. This knowledge will be taken as an *input* to the computation of the finite T dynamics

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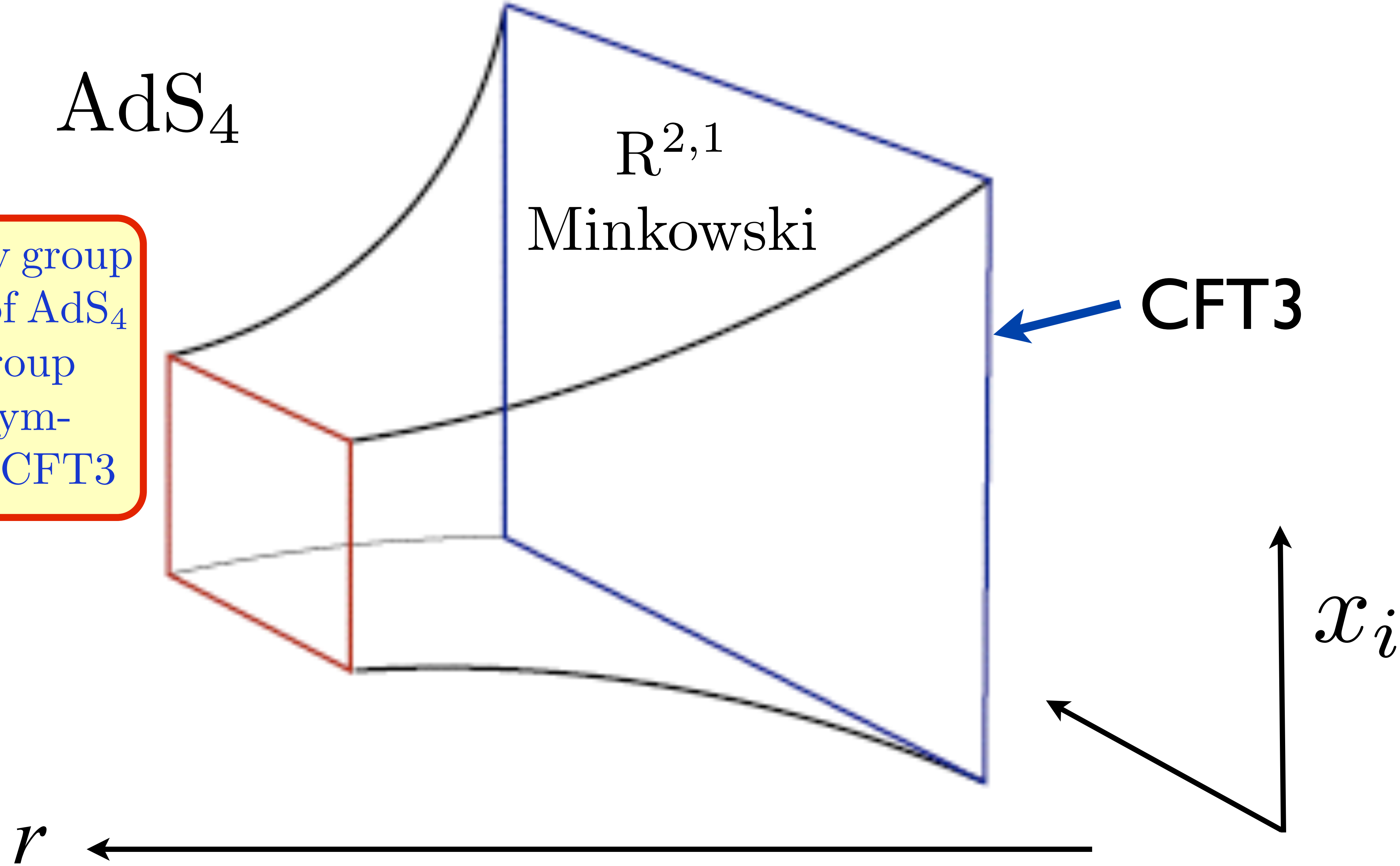
- Relate OPE co-efficients to couplings of an effective gravitational theory on AdS

AdS/CFT correspondence at zero temperature

The symmetry group of isometries of AdS_4 maps to the group of conformal symmetries of the CFT3



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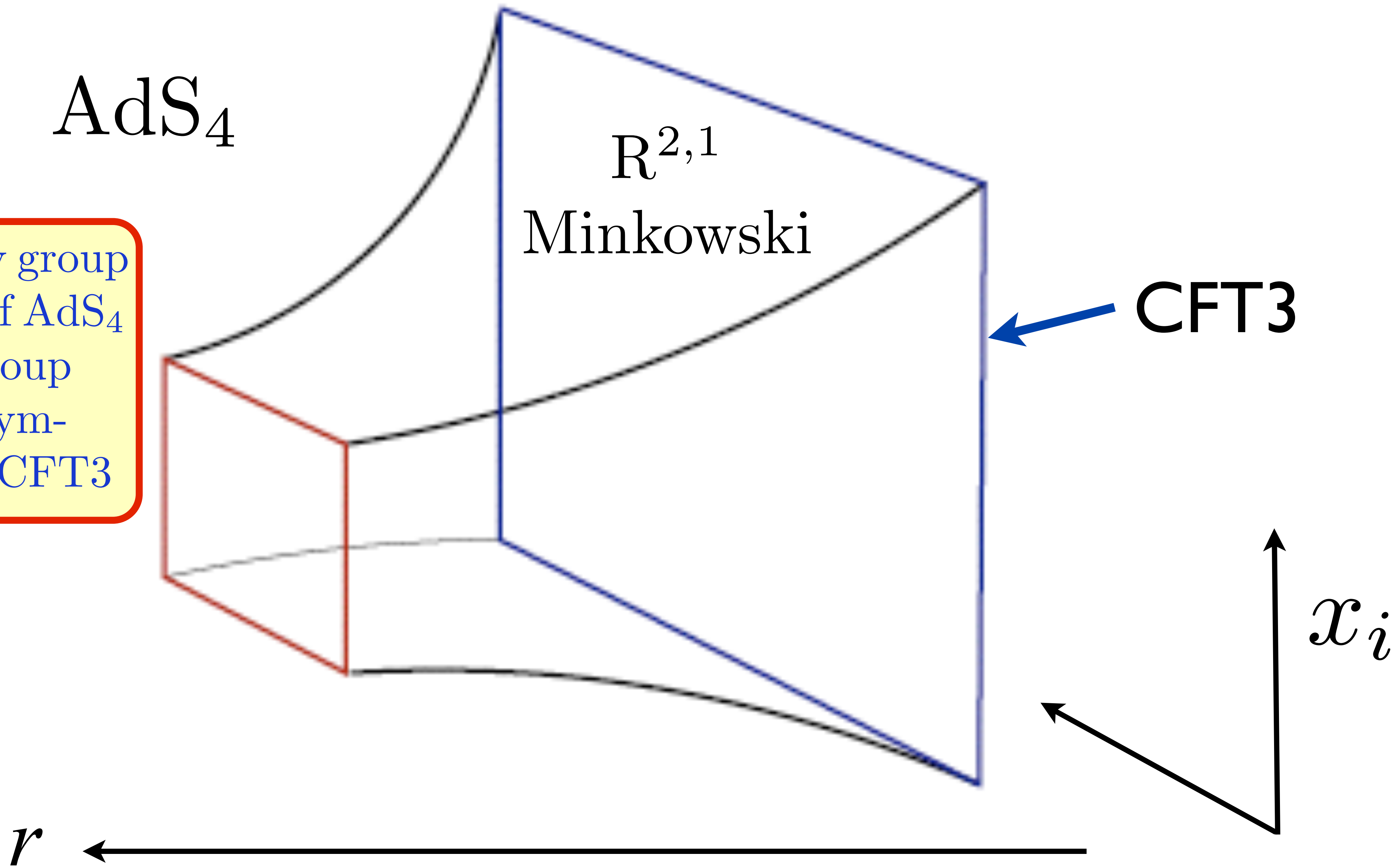

The symmetry group of isometries of AdS_4 maps to the group of conformal symmetries of the CFT3

A classical gravitational theory on AdS_4 encodes the CFT3 data of $\{\Delta_a, f_{abc}\}$, and allows computation of CFT3 correlators consistent with all conformal Ward identities

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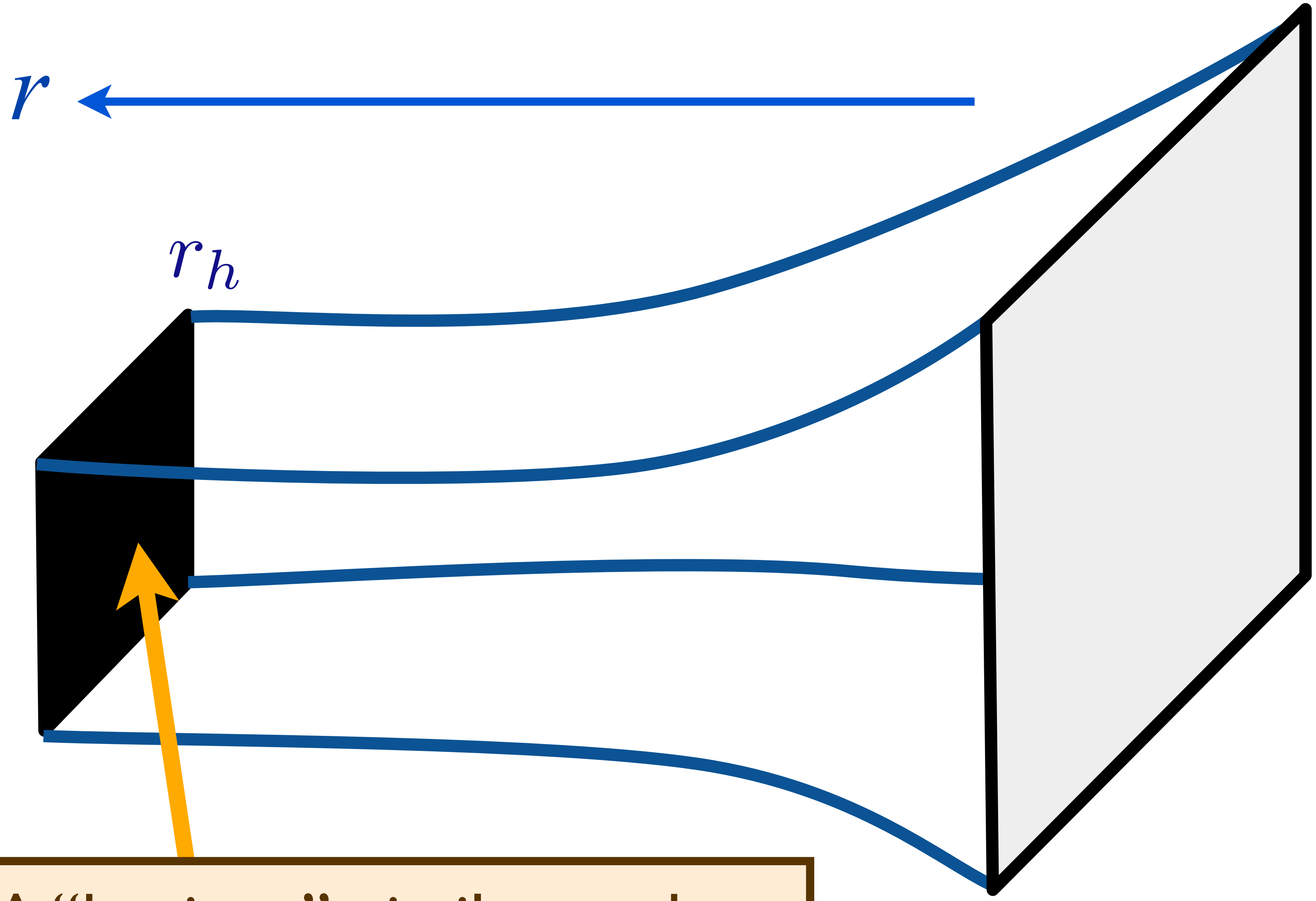
- Non-zero *T* dynamics of CFT maps to dynamics of a "horizon" in (Einstein's) gravitational theory

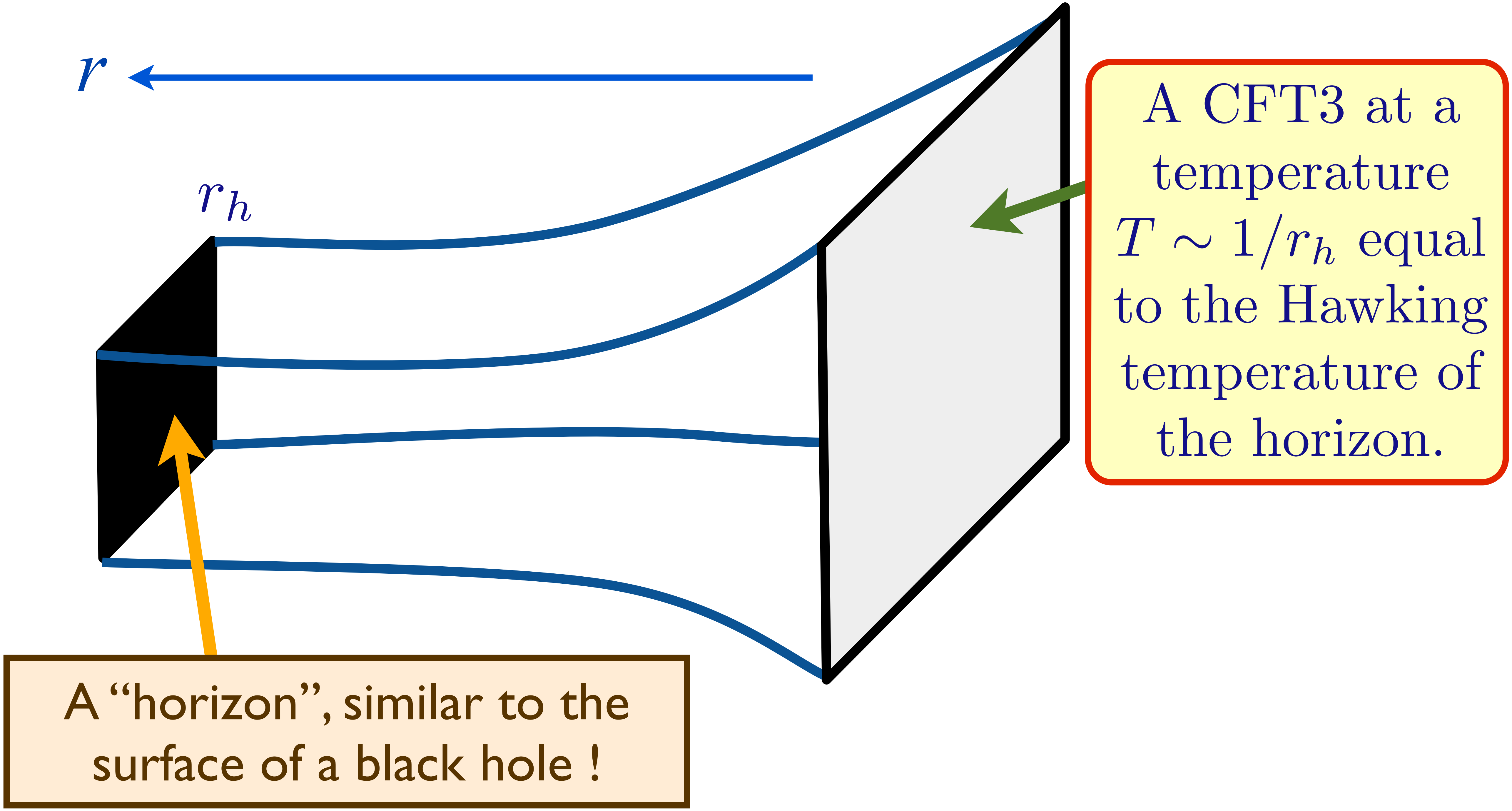
Gauge-gravity duality at non-zero temperatures



A "horizon", similar to the surface of a black hole !

There is a family of solutions of Einstein's equations which are AdS_4 as $r \to 0$, but which have horizons at $r = r_h$.

Gauge-gravity duality at non-zero temperatures



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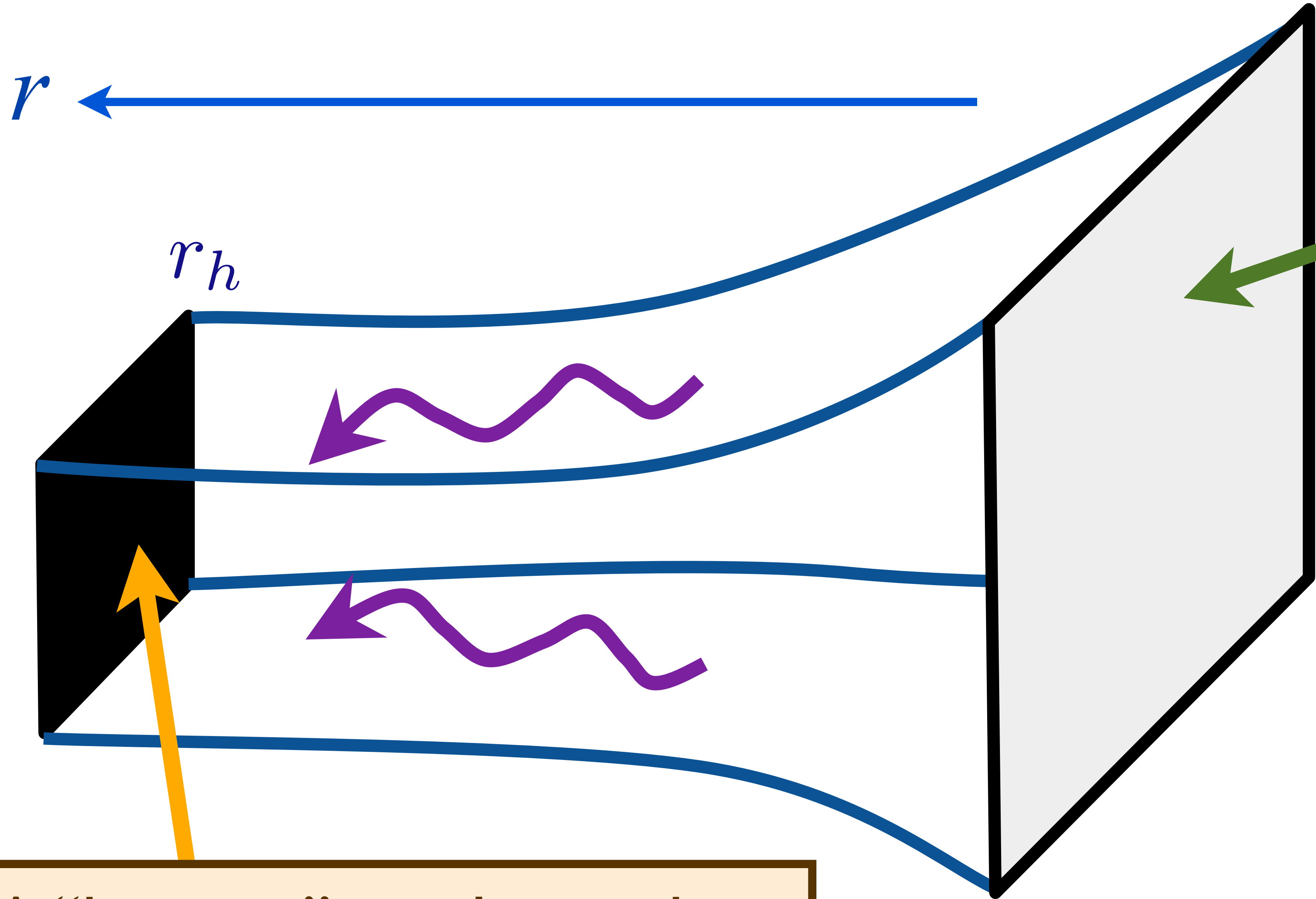


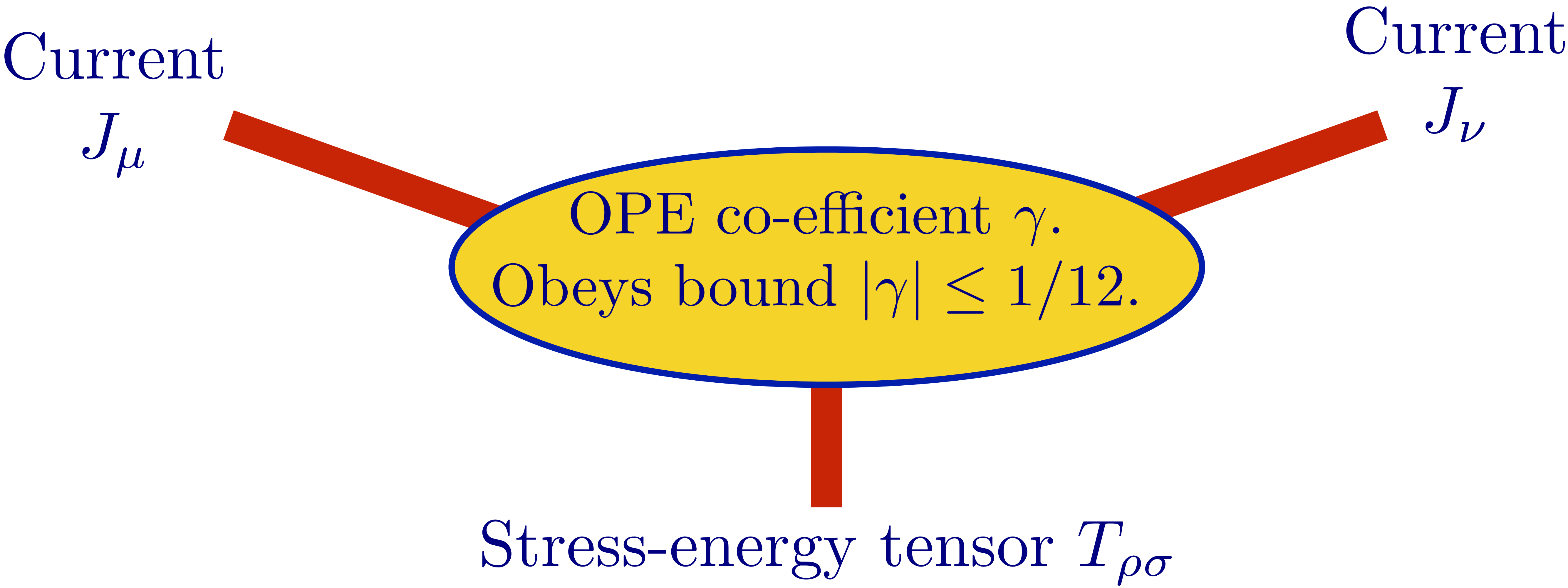
A CFT3 at a temperature $T \sim 1/r_h$ equal to the Hawking temperature of the horizon.

A "horizon", similar to the surface of a black hole !

Dissipation and friction in the CFT3 = waves falling past the horizon

Traditional CMT	Dynamics without quasiparticles
Identify quasiparticles and their dispersions	Start with strongly interacting CFT without particle- or wave-like excitations
Compute scattering matrix elements of quasiparticles (or of collective modes)	Compute scaling dimensions and OPE co-efficients of operators of the CFT
These parameters are input into a quantum Boltzmann equation	Relate OPE co-efficients to couplings of an effective gravitational theory on AdS
Deduce dissipative and dynamic properties at non-zero temperatures	Non-zero *T* dynamics of CFT maps to dynamics of a "horizon" in (Einstein's) gravitational theory

Physical picture of electrical transport in a CFT3



Conductivity at $T > 0$ determined by "scattering" of current by thermal stress-energy tensor.

R. C. Myers, S. Sachdev, and A. Singh, *Physical Review D* **83**, 066017 (2011)
D. Chowdhury, S. Raju, S. Sachdev, A. Singh, and P. Strack, *Physical Review B* **87**, 085138 (2013).

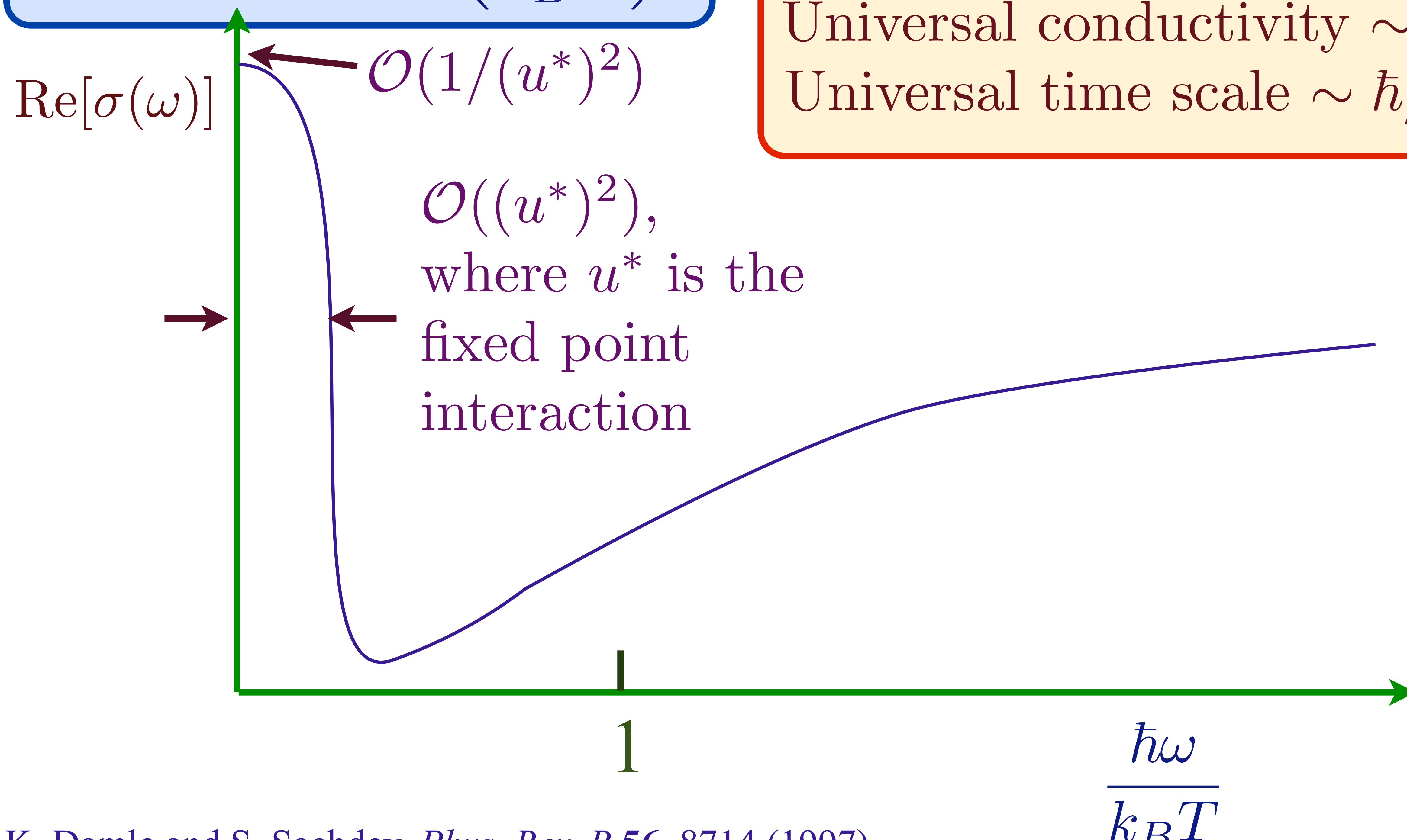
Quasiparticle view of quantum criticality (Boltzmann equation): Electrical transport for a (weakly) interacting CFT3

$$\sigma(\omega, T) = \frac{e^2}{h}\Sigma\left(\frac{\hbar\omega}{k_B T}\right) \quad ;$$

$\Sigma \rightarrow$ a universal function

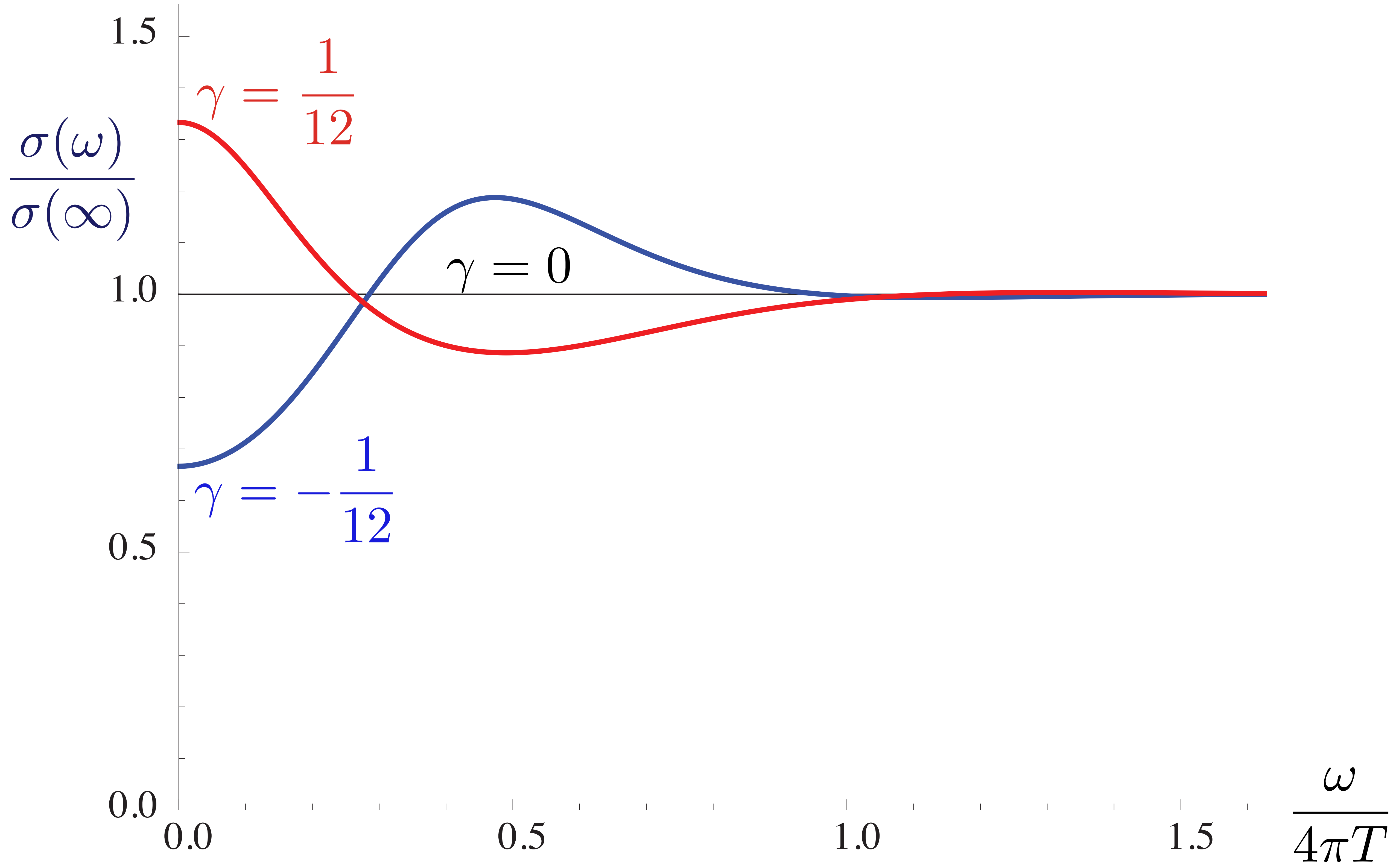
Universal conductivity $\sim e^2/h$

Universal time scale $\sim \hbar/k_B T$



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

AdS$_4$ theory of quantum criticality



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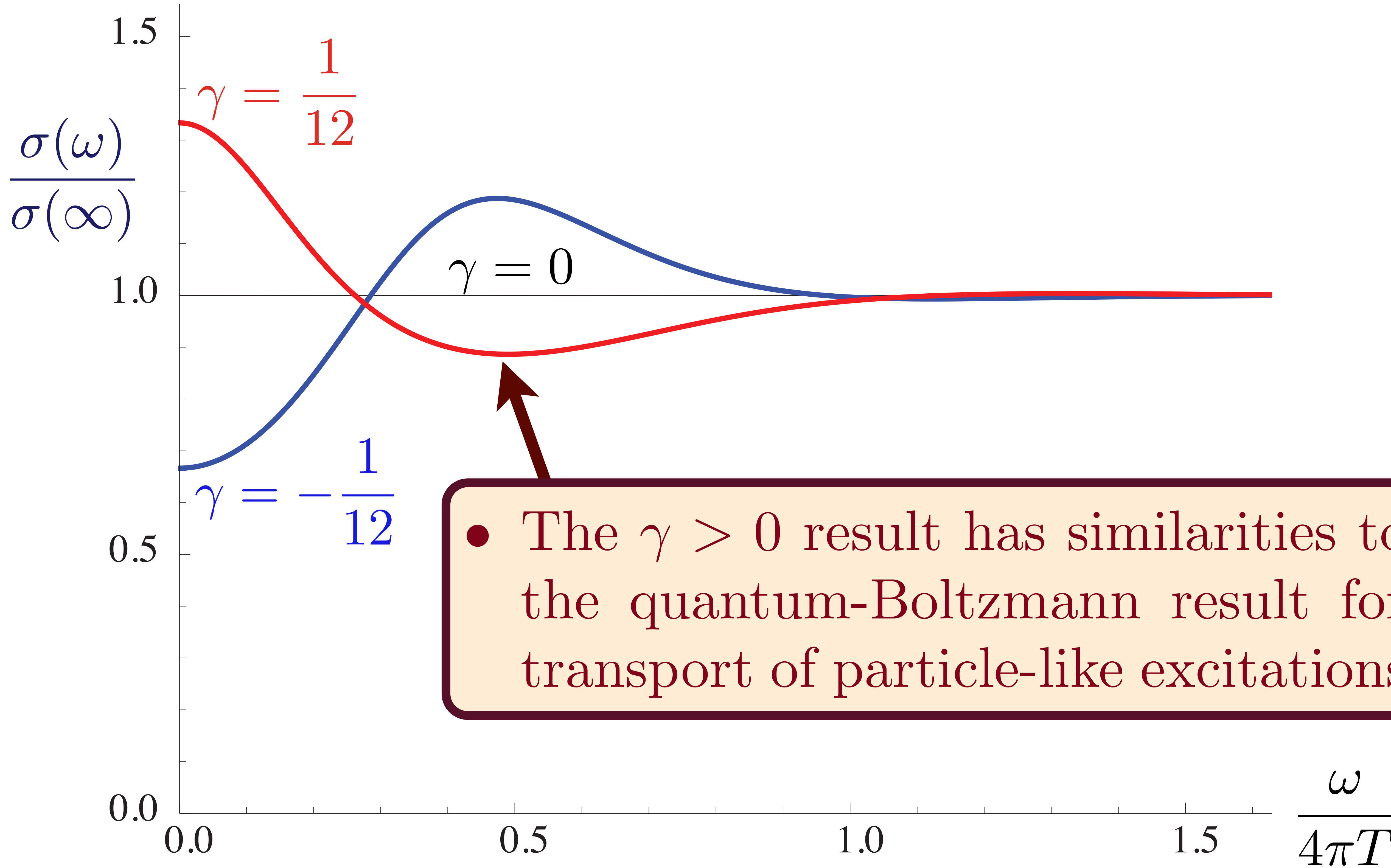

- The $\gamma > 0$ result has similarities to the quantum-Boltzmann result for transport of particle-like excitations

R. C. Myers, S. Sachdev, and A. Singh, *Physical Review D* **83**, 066017 (2011)

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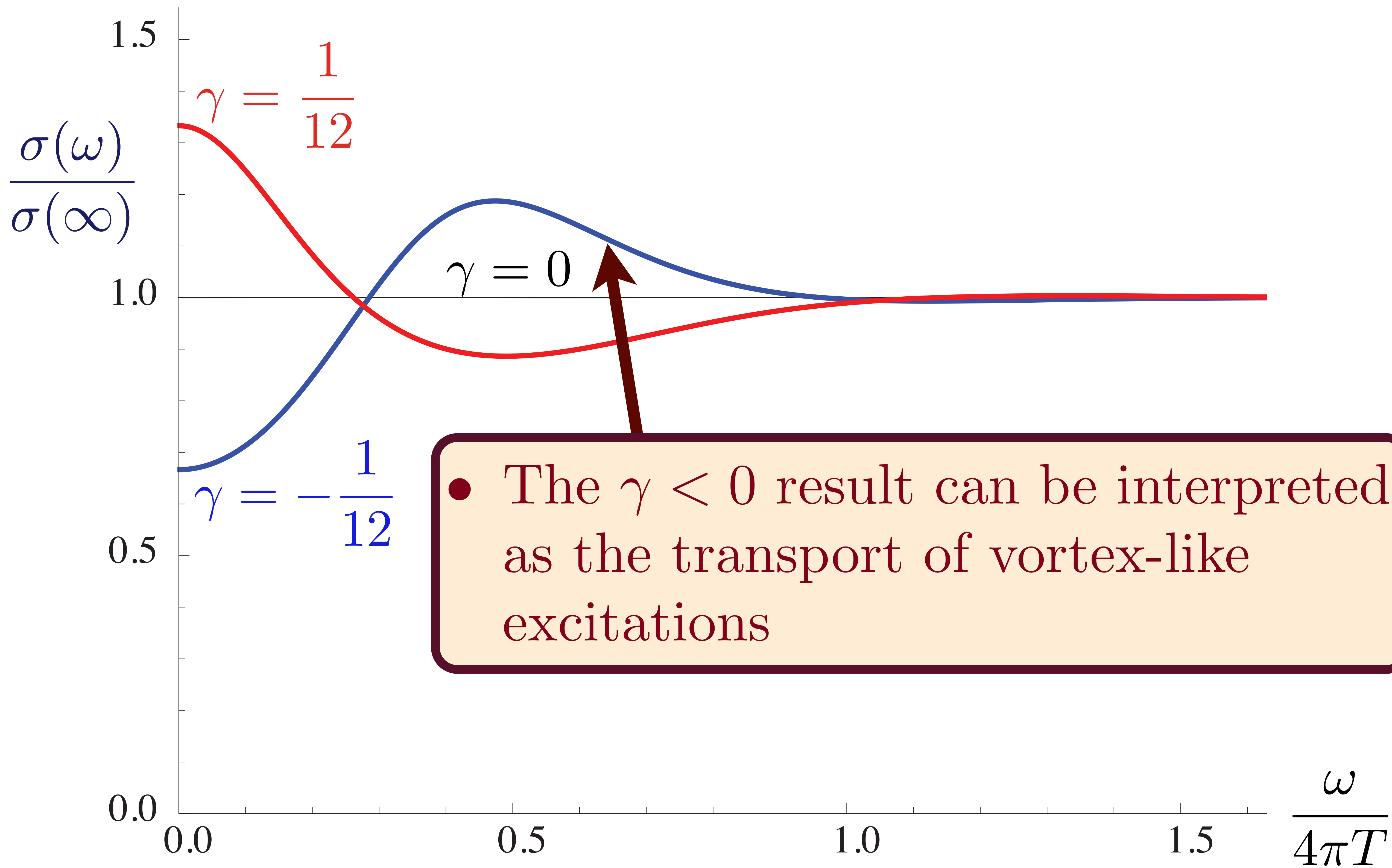
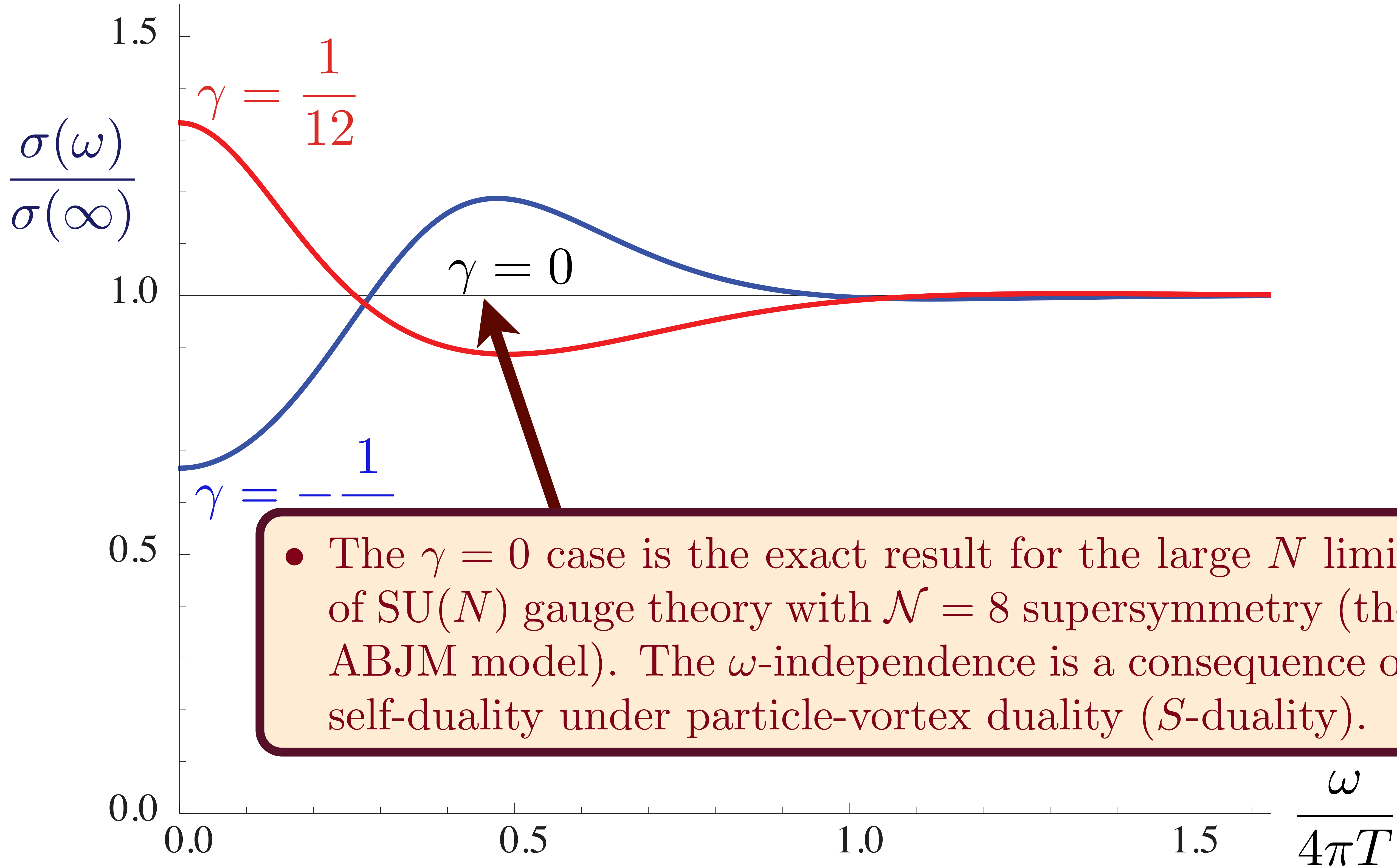


- The $\gamma < 0$ result can be interpreted as the transport of vortex-like excitations

R. C. Myers, S. Sachdev, and A. Singh, *Physical Review D* **83**, 066017 (2011)

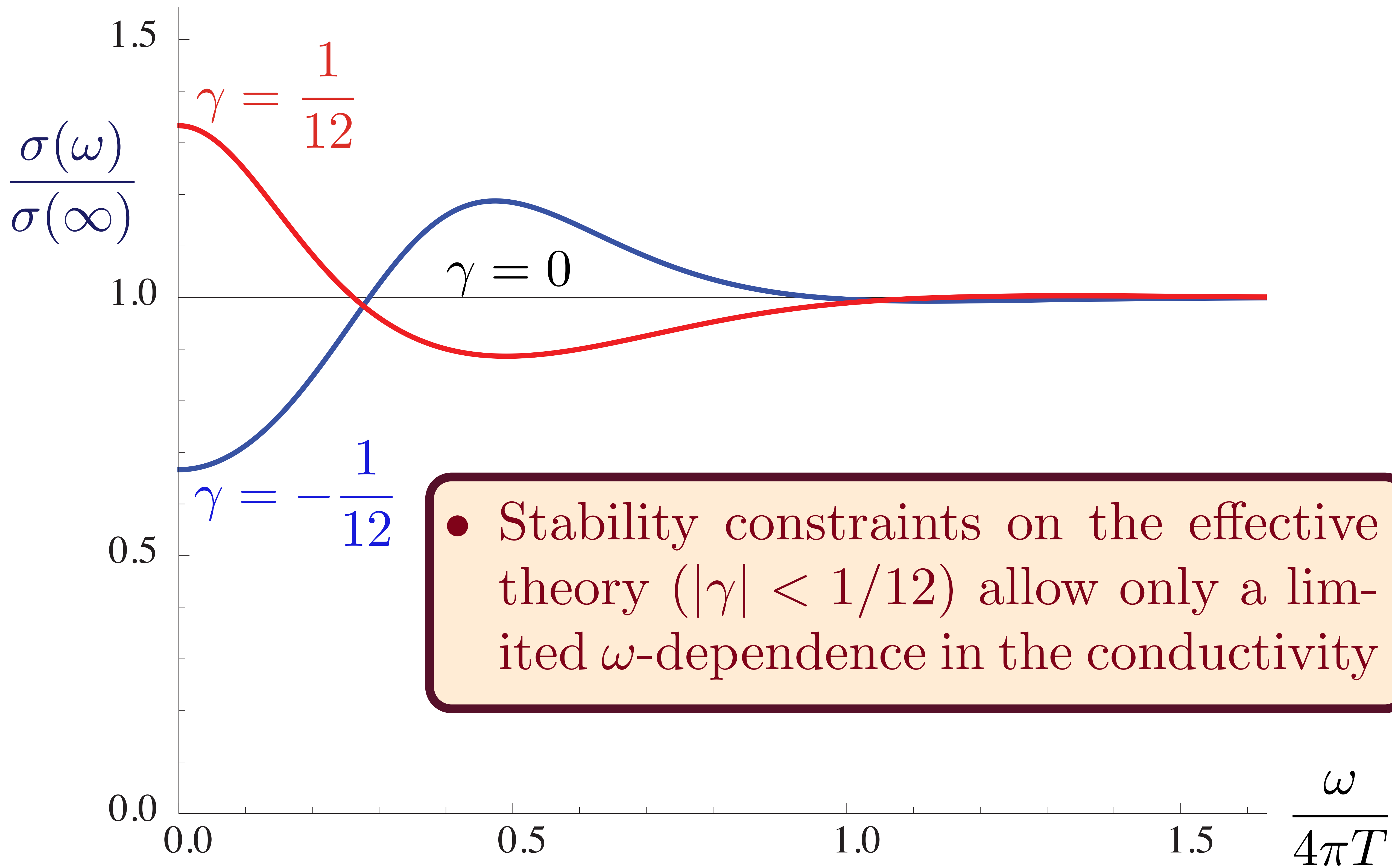
AdS_4 theory of quantum criticality



- The $\gamma = 0$ case is the exact result for the large N limit of SU(N) gauge theory with $\mathcal{N} = 8$ supersymmetry (the ABJM model). The ω-independence is a consequence of self-duality under particle-vortex duality (S-duality).

R. C. Myers, S. Sachdev, and A. Singh, *Physical Review D* **83**, 066017 (2011)

AdS$_4$ theory of quantum criticality



- Stability constraints on the effective theory ($|\gamma| < 1/12$) allow only a limited ω-dependence in the conductivity

R. C. Myers, S. Sachdev, and A. Singh, *Physical Review D* **83**, 066017 (2011)

Search or Articl

The dynamics of quantum criticality via Quantum Monte Carlo and holography

William Witczak-Krempa, Erik Sorensen, Subir Sachdev

(Submitted on 11 Sep 2013 (v1), last revised 29 Nov 2013 (this version, v2))

Understanding the real time dynamics of quantum systems without quasiparticles constitutes an important yet challenging problem. We study the superfluid-insulator quantum-critical point of bosons on a two-dimensional lattice, a system whose excitations cannot be described in a quasiparticle basis. We present detailed quantum Monte Carlo results for two separate lattice realizations: their low-frequency conductivities are found to have the same universal dependence on imaginary frequency and temperature. We then use the structure of the real time dynamics of conformal field theories described by the holographic gauge/gravity duality to make progress on the difficult problem of analytically continuing the Monte Carlo data to real time. Our method yields quantitative and experimentally testable results on the frequency-dependent conductivity near the quantum critical point, and on the spectrum of quasinormal modes in the vicinity of the superfluid-insulator quantum phase transition. Extensions to other observables and universality classes are discussed.

Search or

Condensed Matter > Strongly Correlated Electrons

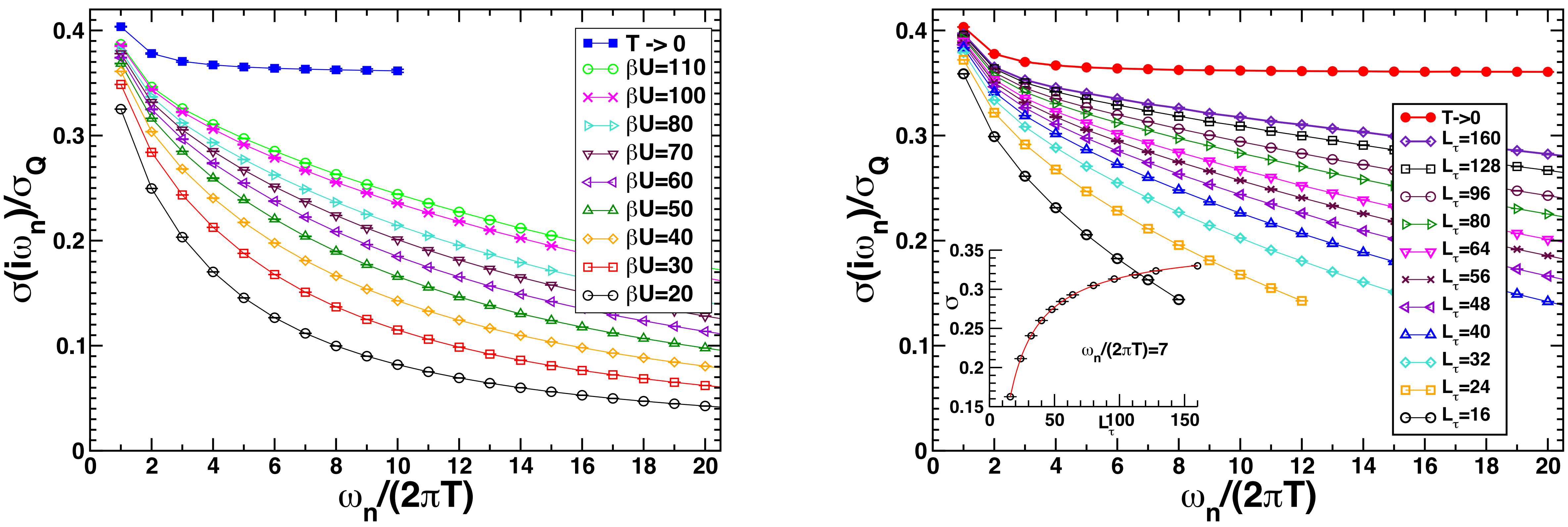
Universal Conductivity in a Two-dimensional Superfluid-to-Insulator Quantum Critical System

Kun Chen, Longxiang Liu, Youjin Deng, Lode Pollet, Nikolay Prokof'ev

(Submitted on 22 Sep 2013)

We compute the universal conductivity of the (2+1)-dimensional XY universality class, which is realized for a superfluid-to-Mott insulator quantum phase transition at constant density. Based on large-scale Monte Carlo simulations of the classical (2+1)-dimensional J-current model and the two-dimensional Bose-Hubbard model, we can precisely determine the conductivity on the quantum critical plateau, $\sigma(\infty) = 0.359(4)\sigma_Q$ with σ_Q the conductivity quantum. The universal conductivity is the schoolbook example of where the AdS/CFT correspondence from string theory can be tested and made to use. The shape of our $\sigma(i\omega_n) - \sigma(\infty)$ function in the Matsubara representation is accurate enough for a conclusive comparison and establishes the particle-like nature of charge transport. We find that the holographic gauge/gravity duality theory for transport properties can be made compatible with the data if temperature of the horizon of the black brane is different from the temperature of the conformal field theory. The requirements for measuring the universal conductivity in a cold gas experiment are also determined by our calculation.

Quantum Monte Carlo for lattice bosons



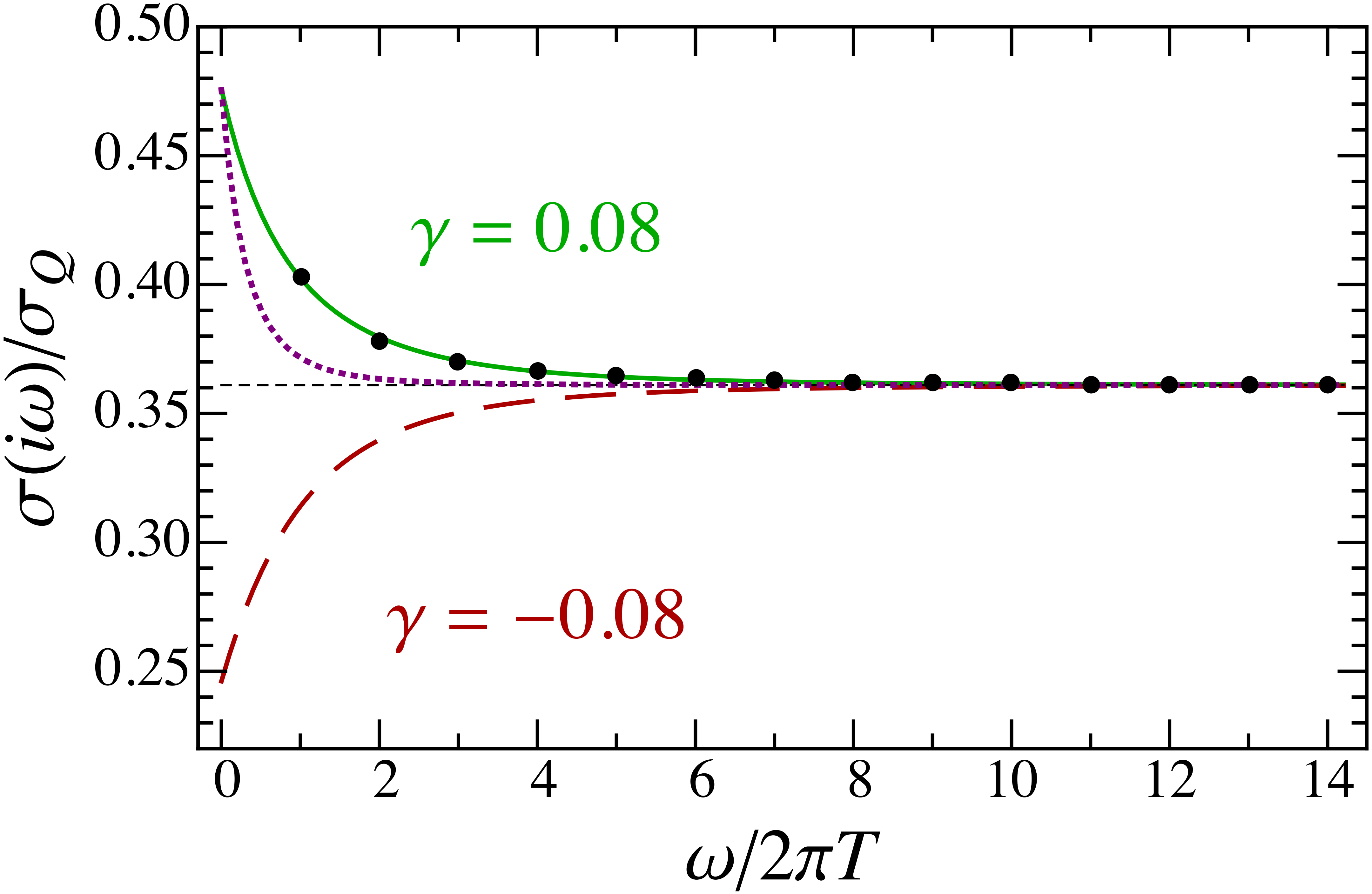
(a) (b)

FIG. 2. **Quantum Monte Carlo data** (a) Finite-temperature conductivity for a range of βU in the $L \to \infty$ limit for the quantum rotor model at $(t/U)_c$. The solid blue squares indicate the final $T \to 0$ extrapolated data. (b) Finite-temperature conductivity in the $L \to \infty$ limit for a range of L_τ for the Villain model at the QCP. The solid red circles indicate the final $T \to 0$ extrapolated data. The inset illustrates the extrapolation to $T = 0$ for $\omega_n/(2\pi T) = 7$. The error bars are statistical for both a) and b).

W. Witczak-Krempa, E. Sorensen, and S. Sachdev, arXiv:1309.2941

See also K. Chen, L. Liu, Y. Deng, L. Pollet, and N. Prokof'ev, arXiv:1309.5635

AdS_4 theory of quantum criticality

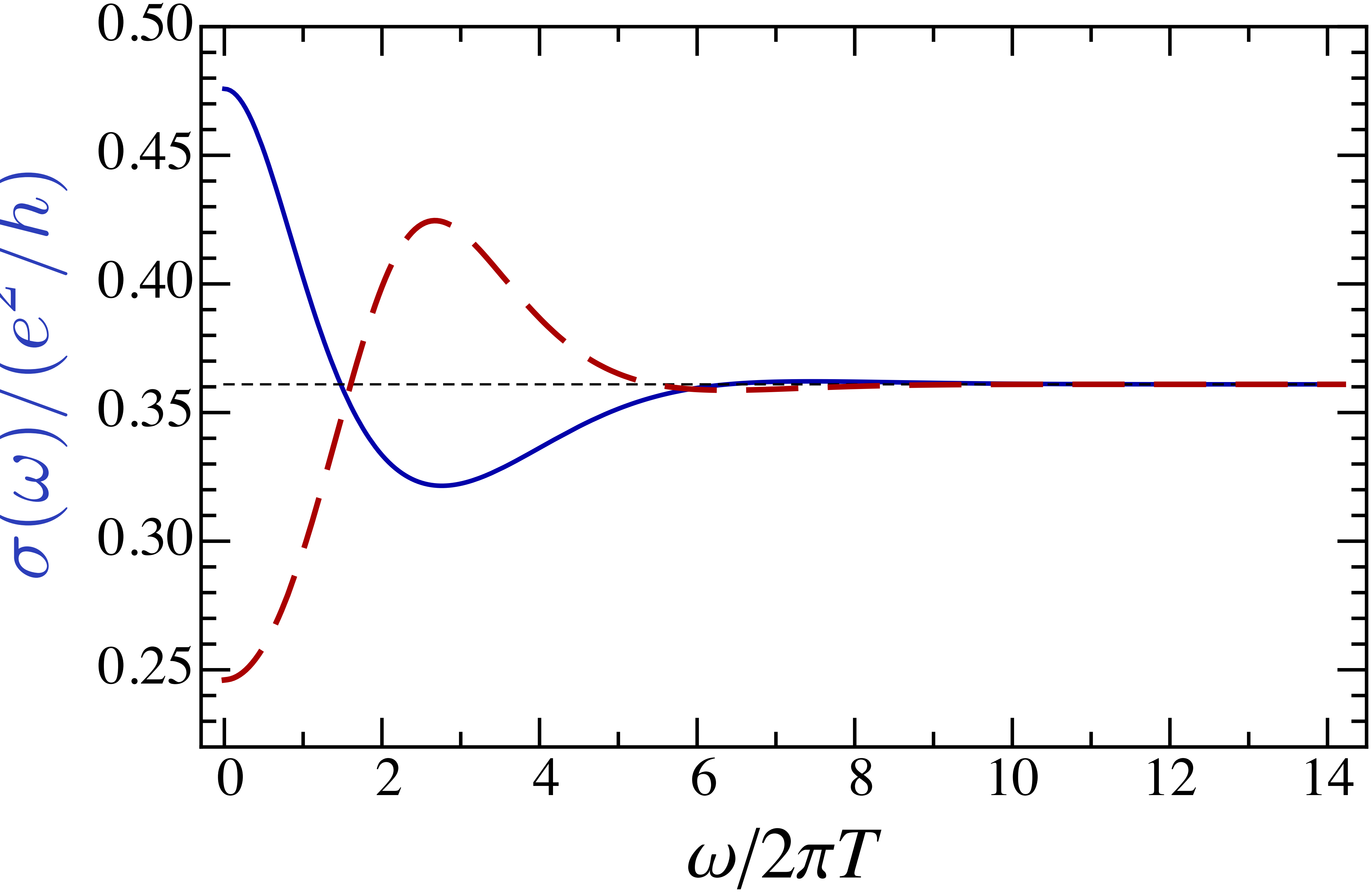


Good agreement between high precision Monte Carlo for imaginary frequencies, and holographic theory after rescaling effective T and taking $\sigma_Q = 1/g_M^2$.

W. Witczak-Krempa, E. Sorensen, and S. Sachdev, arXiv:1309.2941

See also K. Chen, L. Liu, Y. Deng, L. Pollet, and N. Prokof'ev, arXiv:1309.5635

AdS_4 theory of quantum criticality



Predictions of holographic theory,
after analytic continuation to real frequencies

W. Witczak-Krempa, E. Sorensen, and S. Sachdev, arXiv:1309.2941

See also K. Chen, L. Liu, Y. Deng, L. Pollet, and N. Prokof'ev, arXiv:1309.5635

Outline

1. The simplest model without quasiparticles

Superfluid-insulator transition

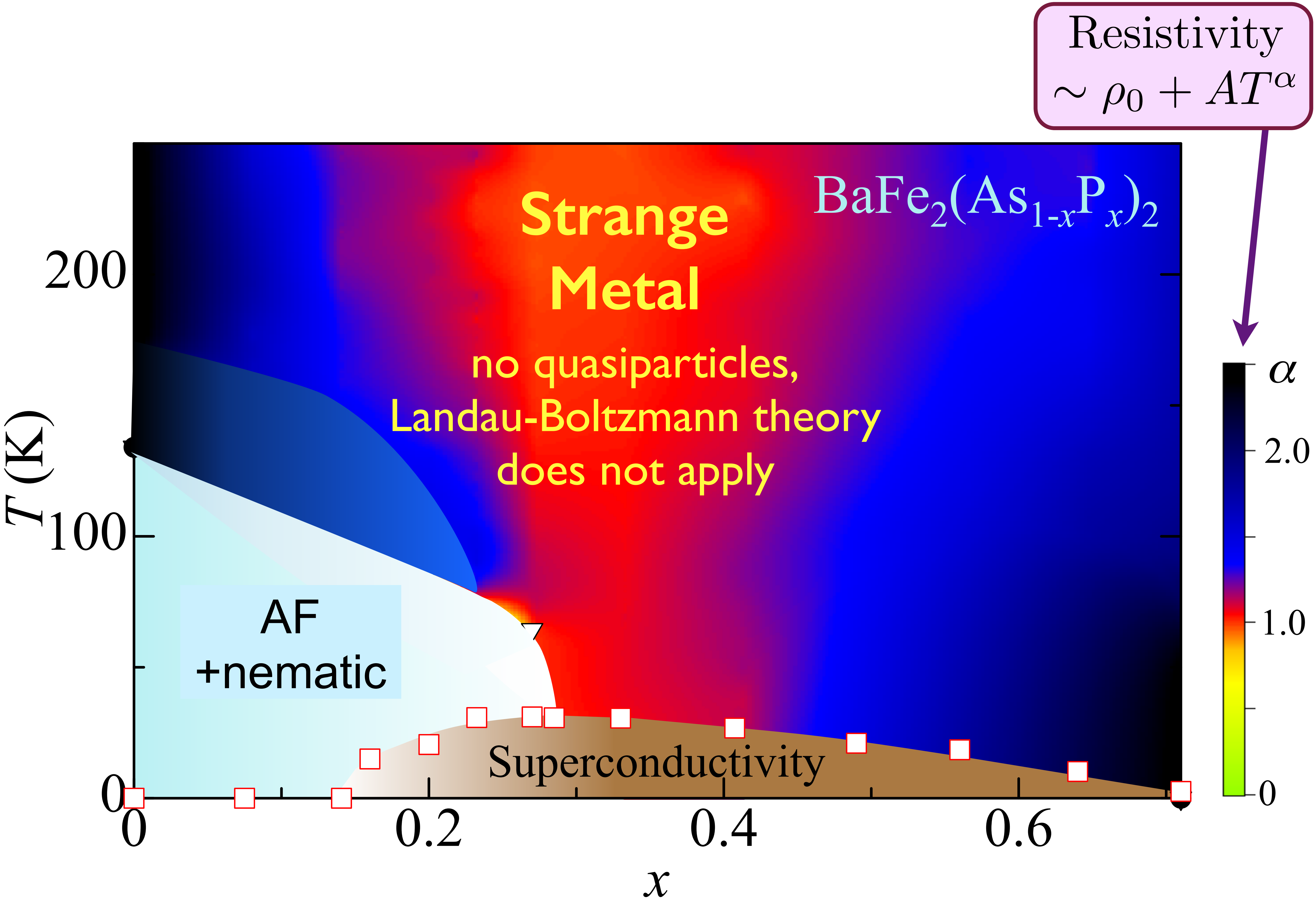
of ultracold bosonic atoms in an optical lattice

(Conformal field theories in 2+1 dimensions)

2. Strange metals in the high T_c superconductors

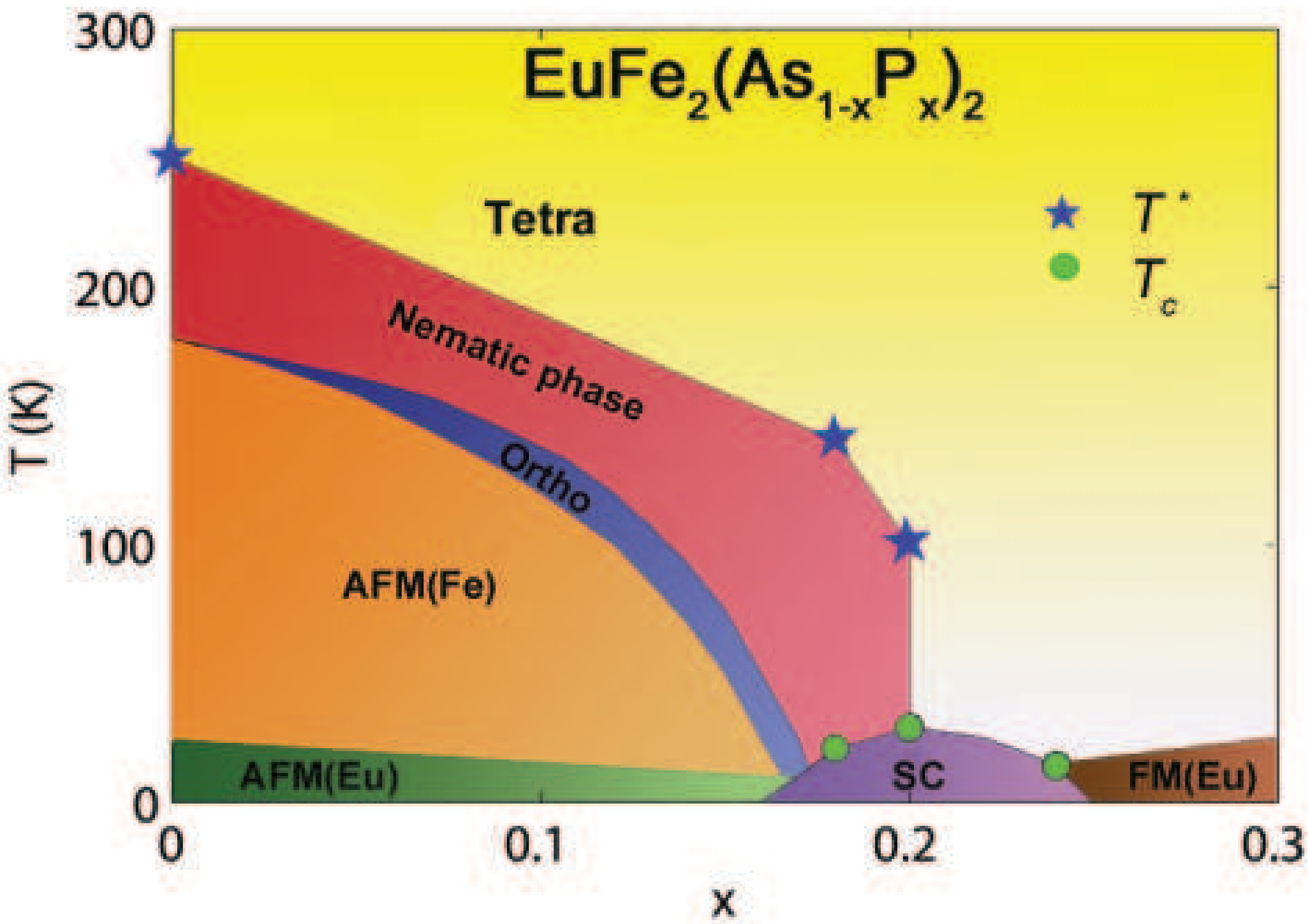
Non-quasiparticle transport at the

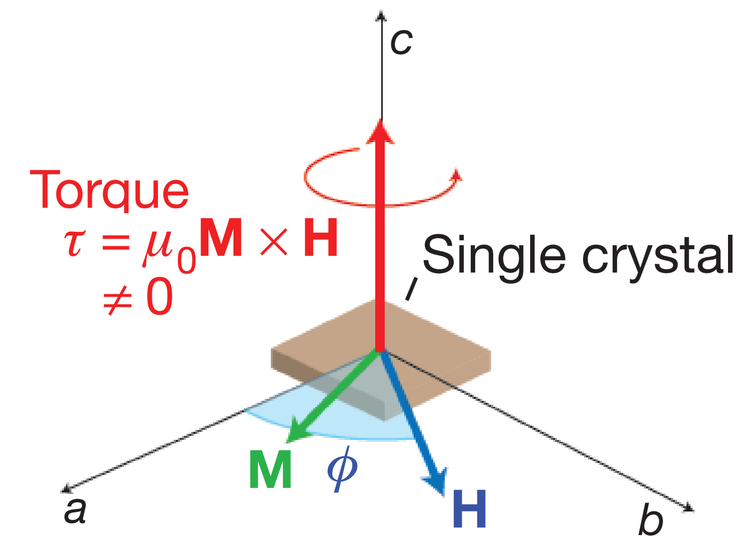
Ising-nematic quantum critical point



S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)

Xiaofeng Xu, W. H. Jiao, N. Zhou, Y. K. Li, B. Chen, C. Cao, Jianhui Dai, A. F. Bangura, and Guanghan Cao, arXiv:1402.4124





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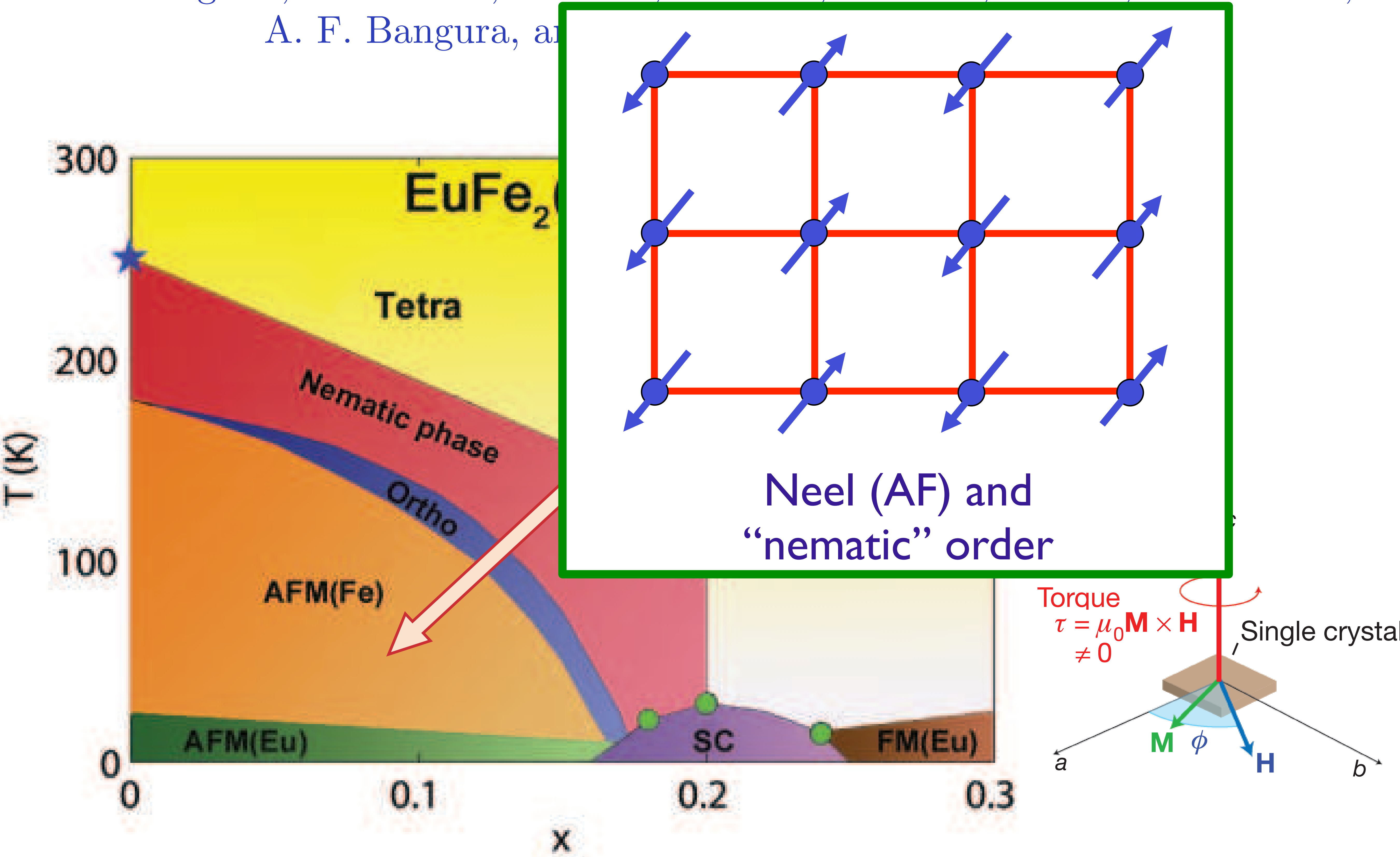

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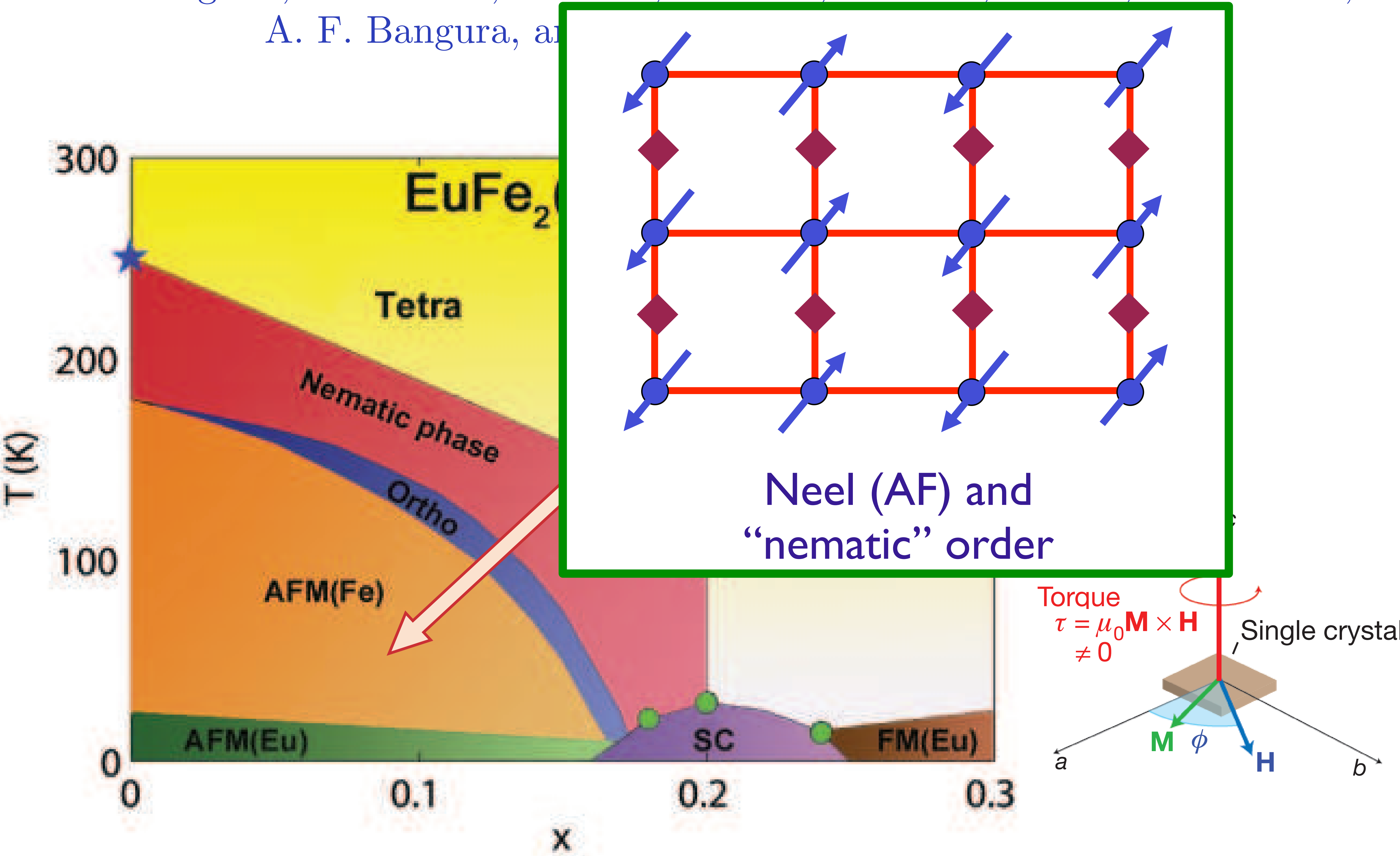

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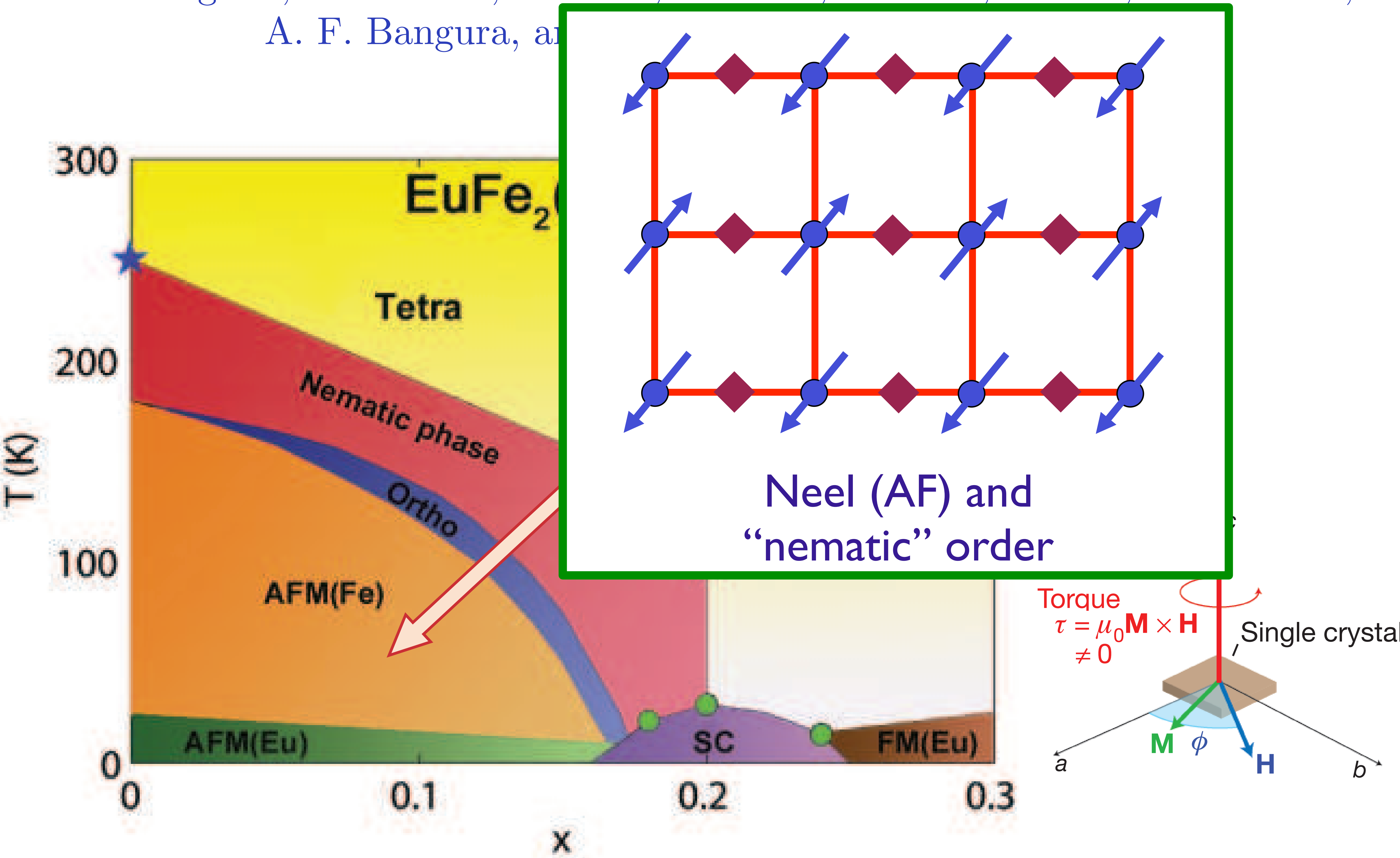

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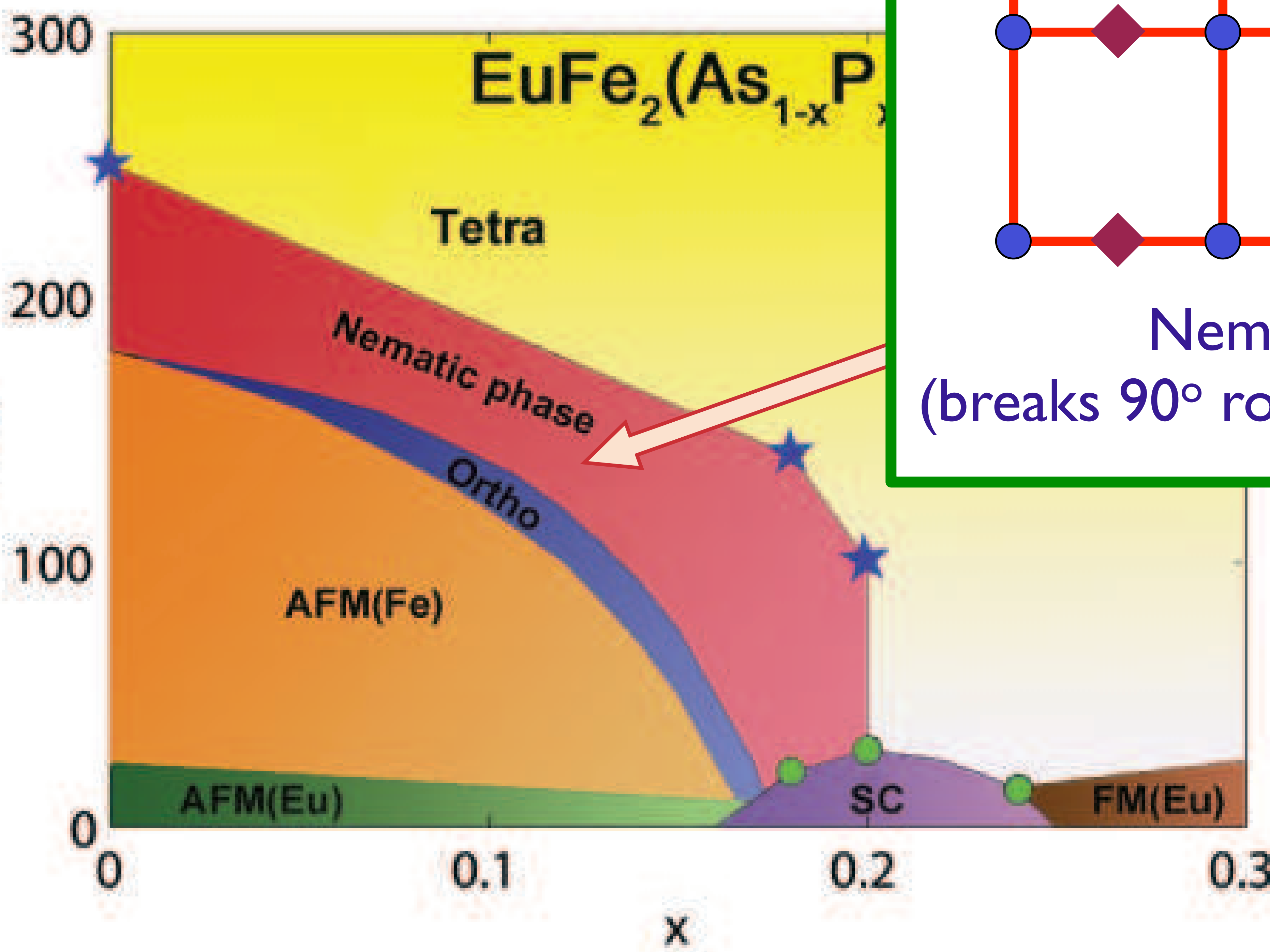
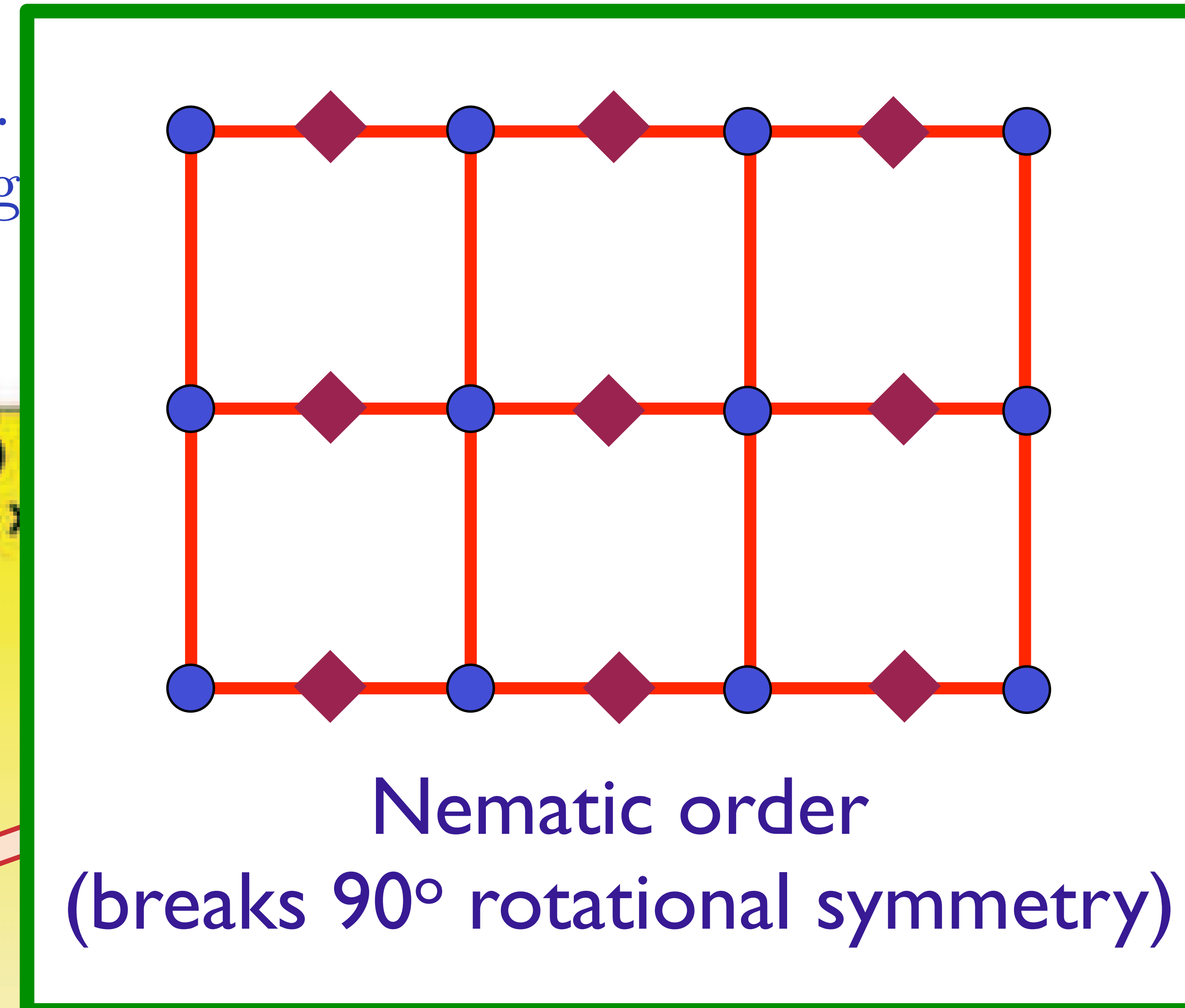
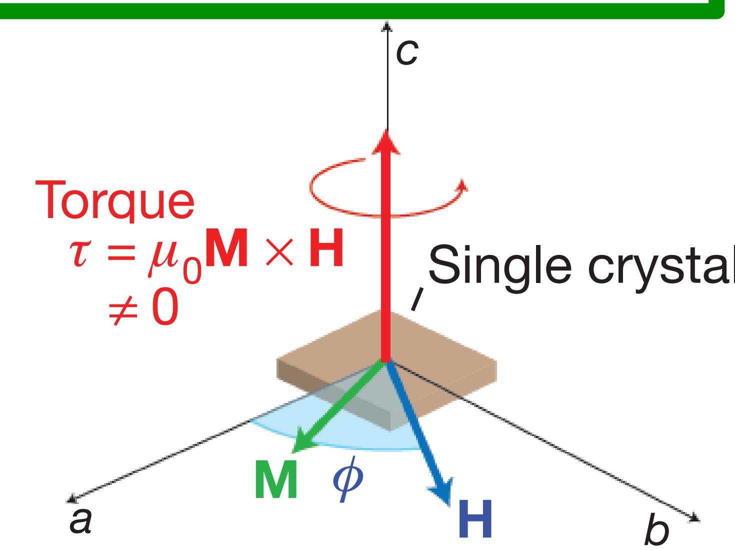
A. F. Bangura, and Guang







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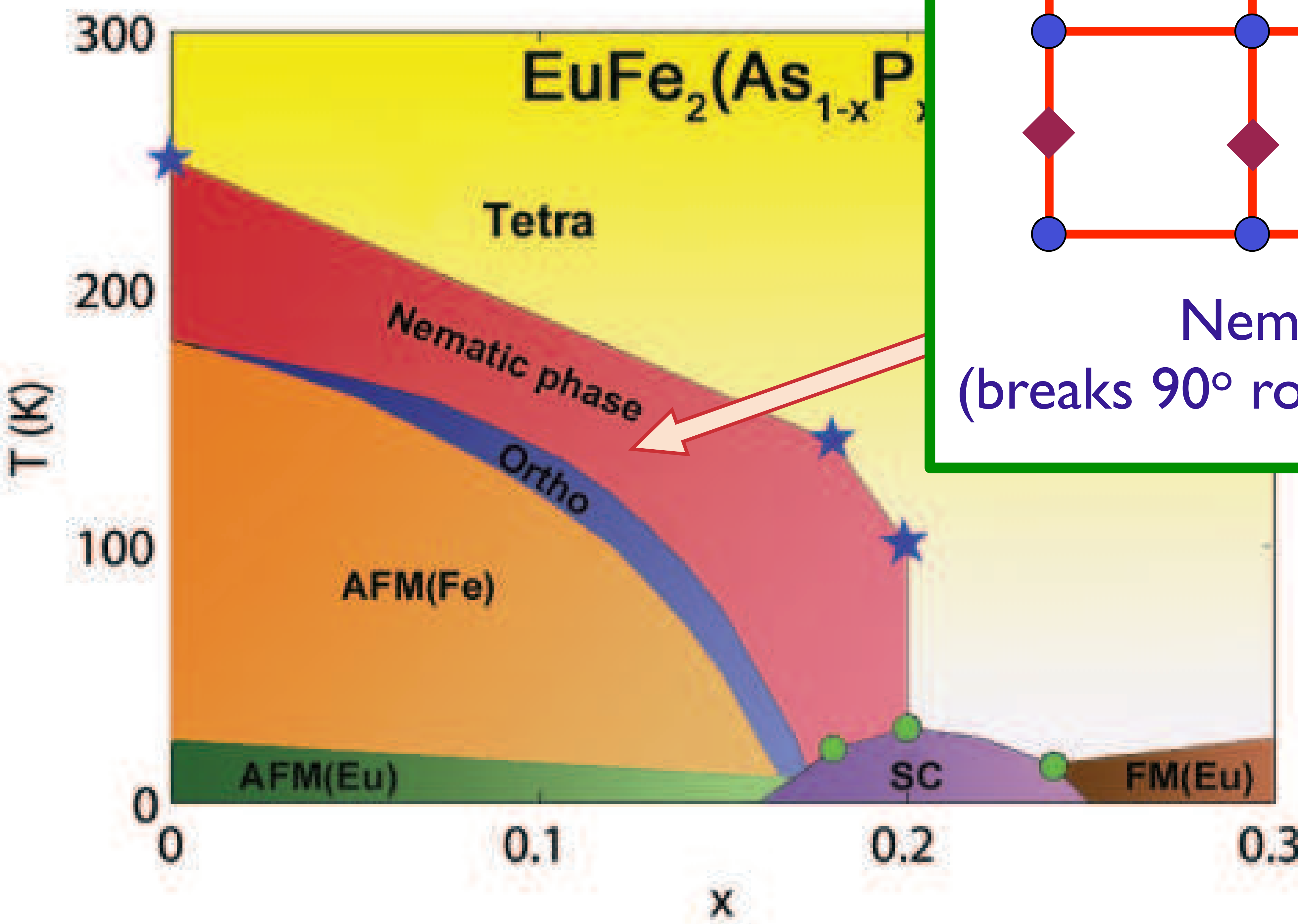
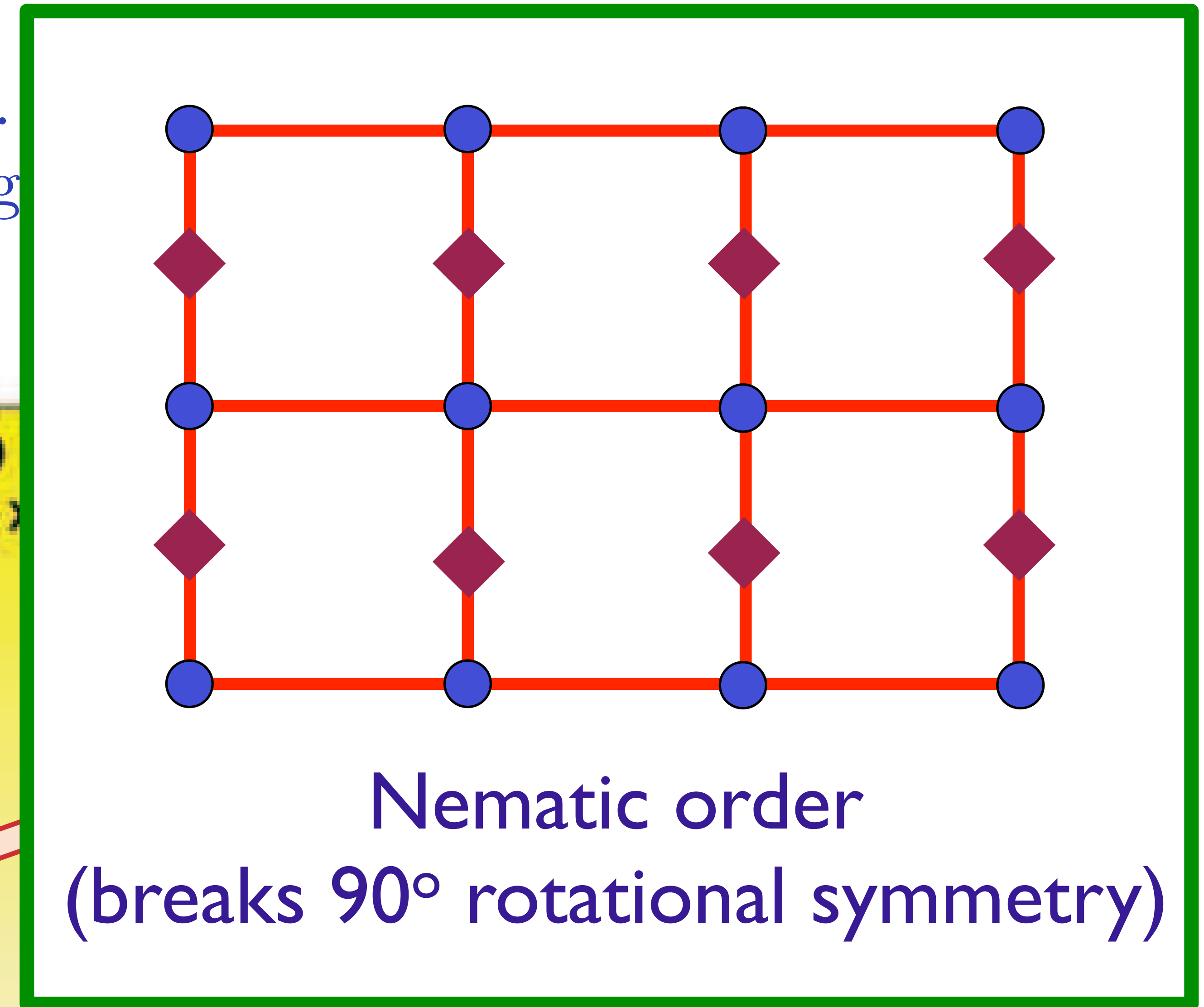
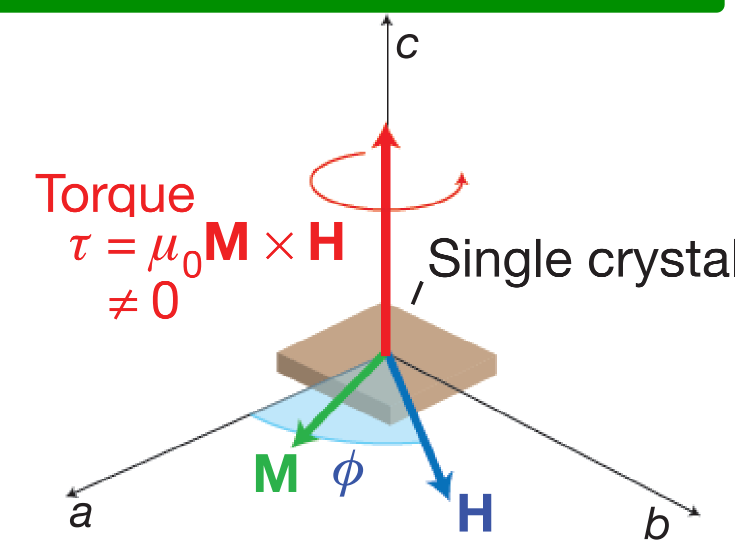
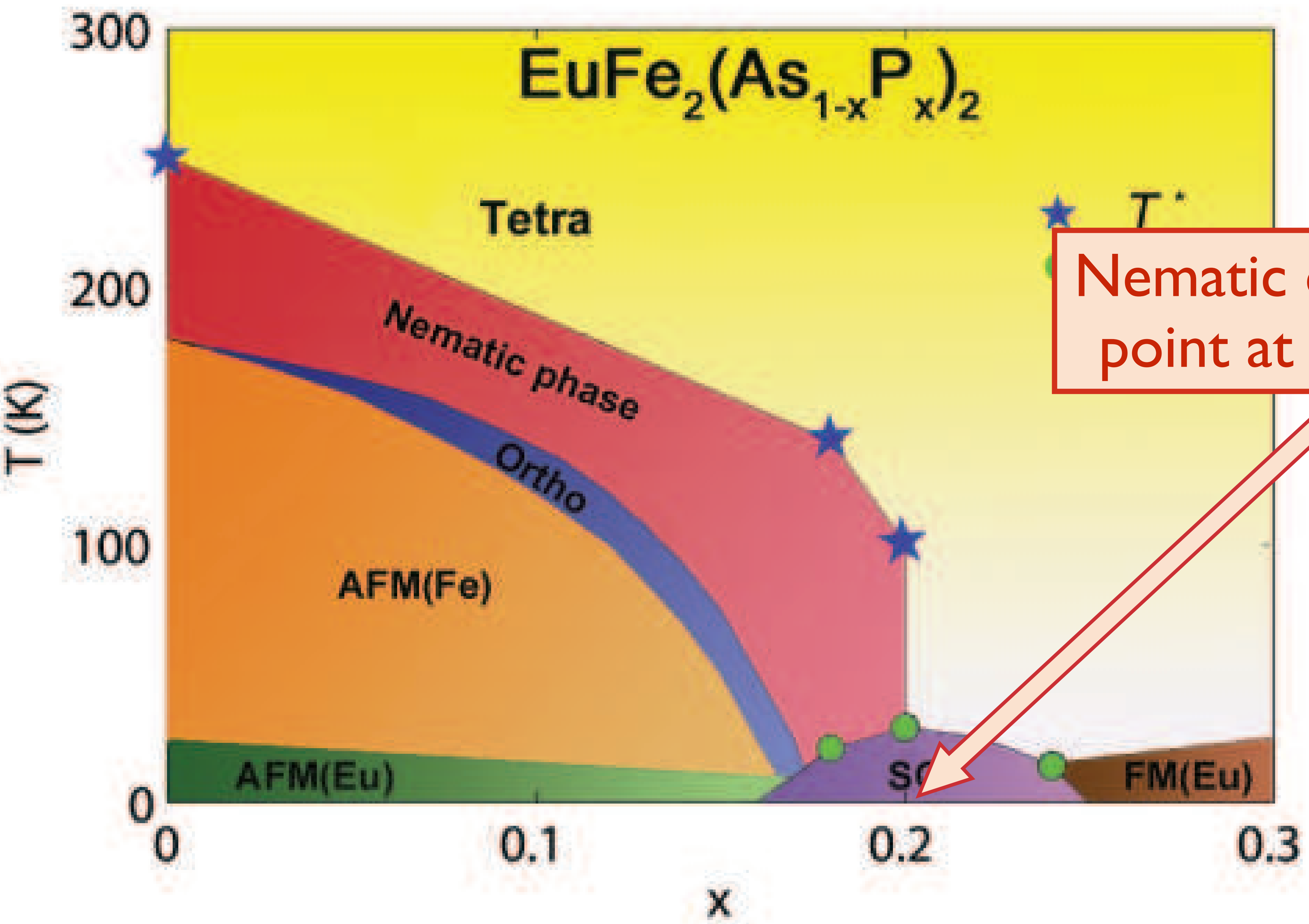
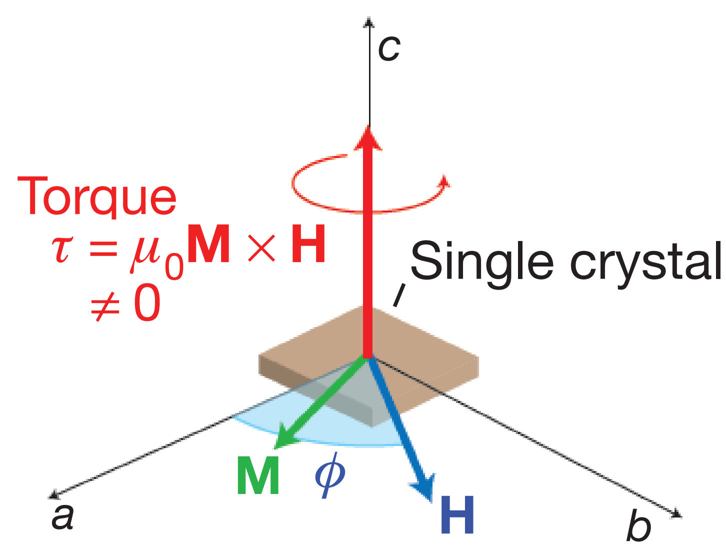




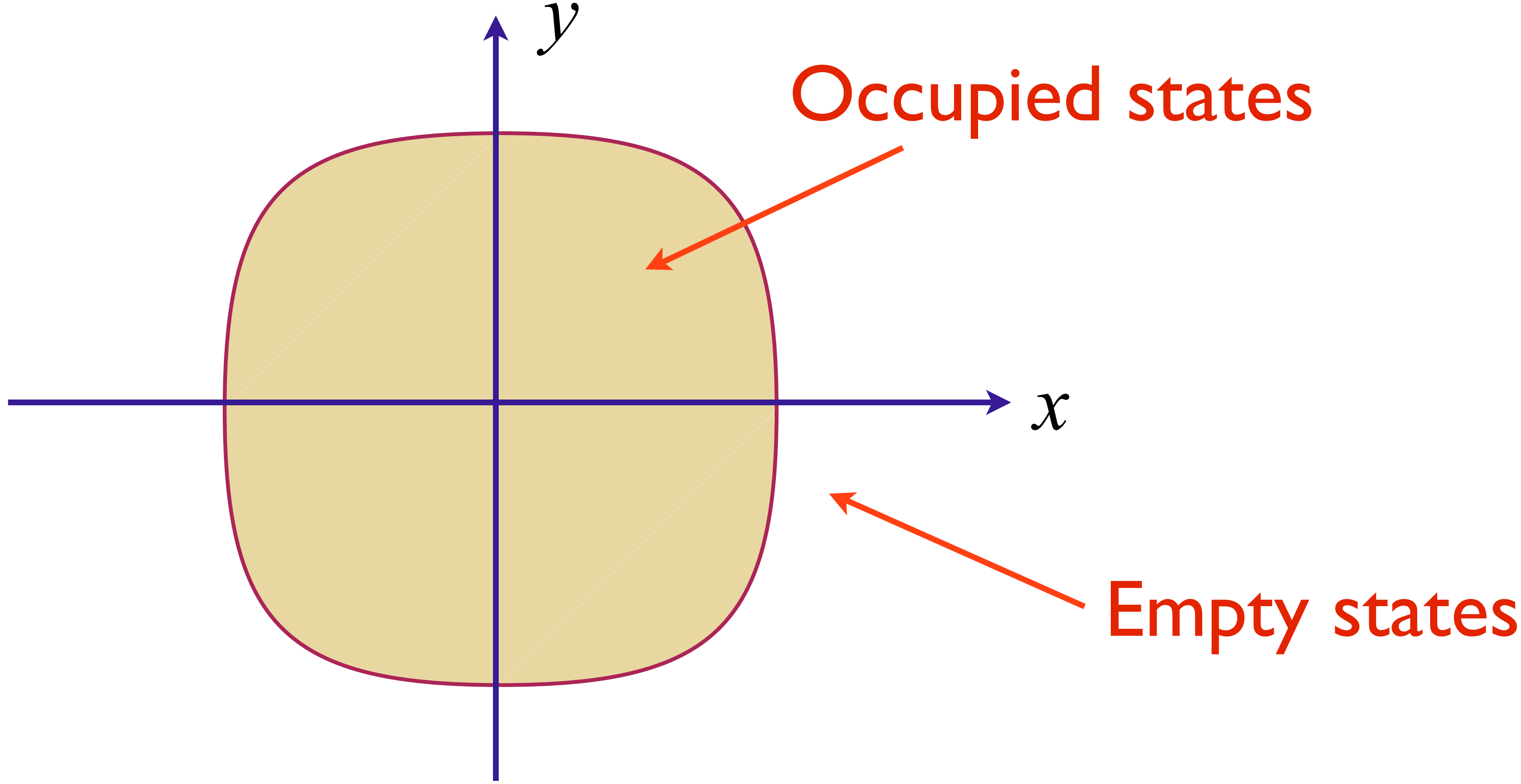


Xiaofeng Xu, W. H. Jiao, N. Zhou, Y. K. Li, B. Chen, C. Cao, Jianhui Dai, A. F. Bangura, and Guanghan Cao, arXiv:1402.4124



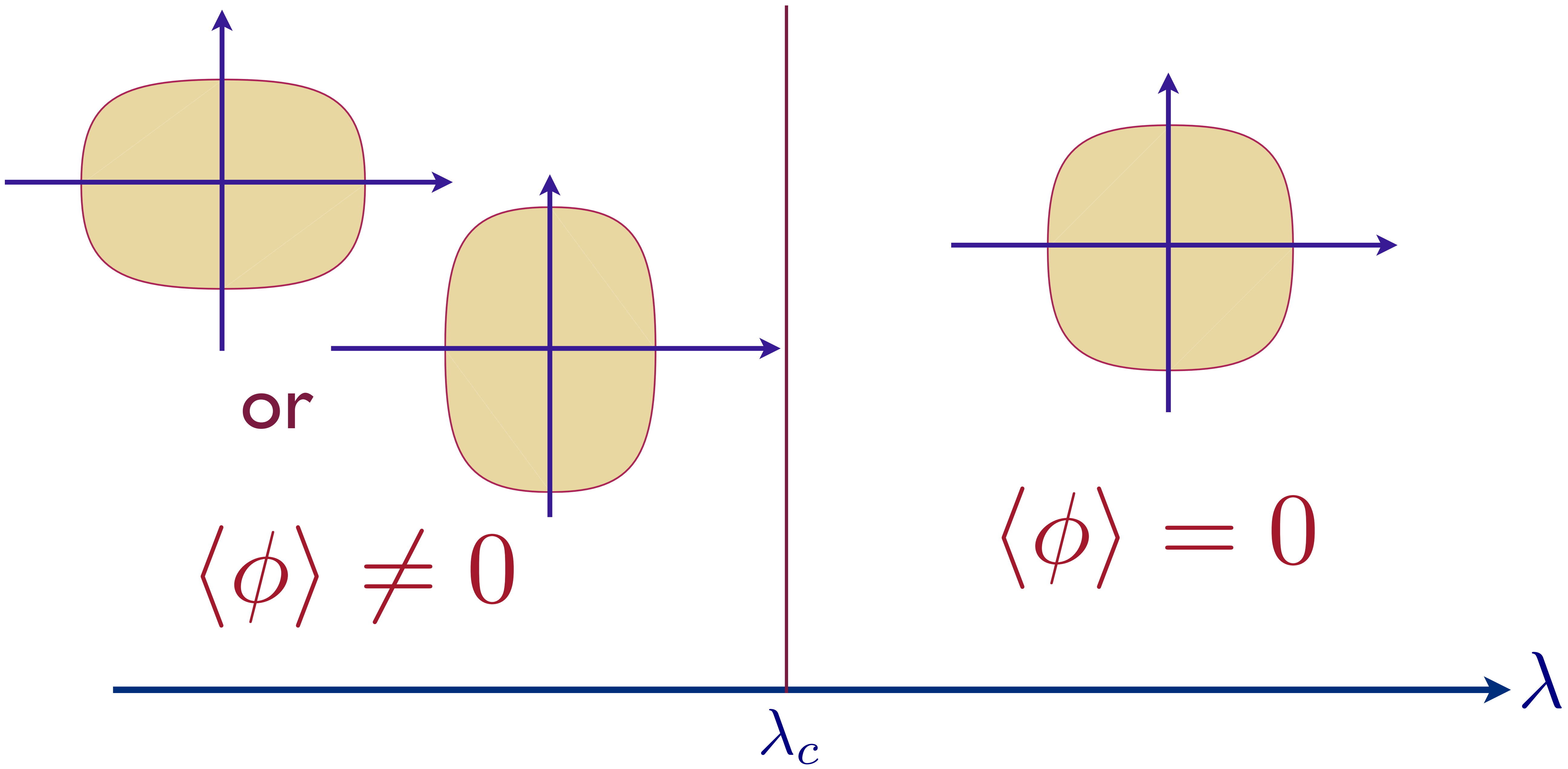


Quantum criticality of Ising-nematic ordering in a metal



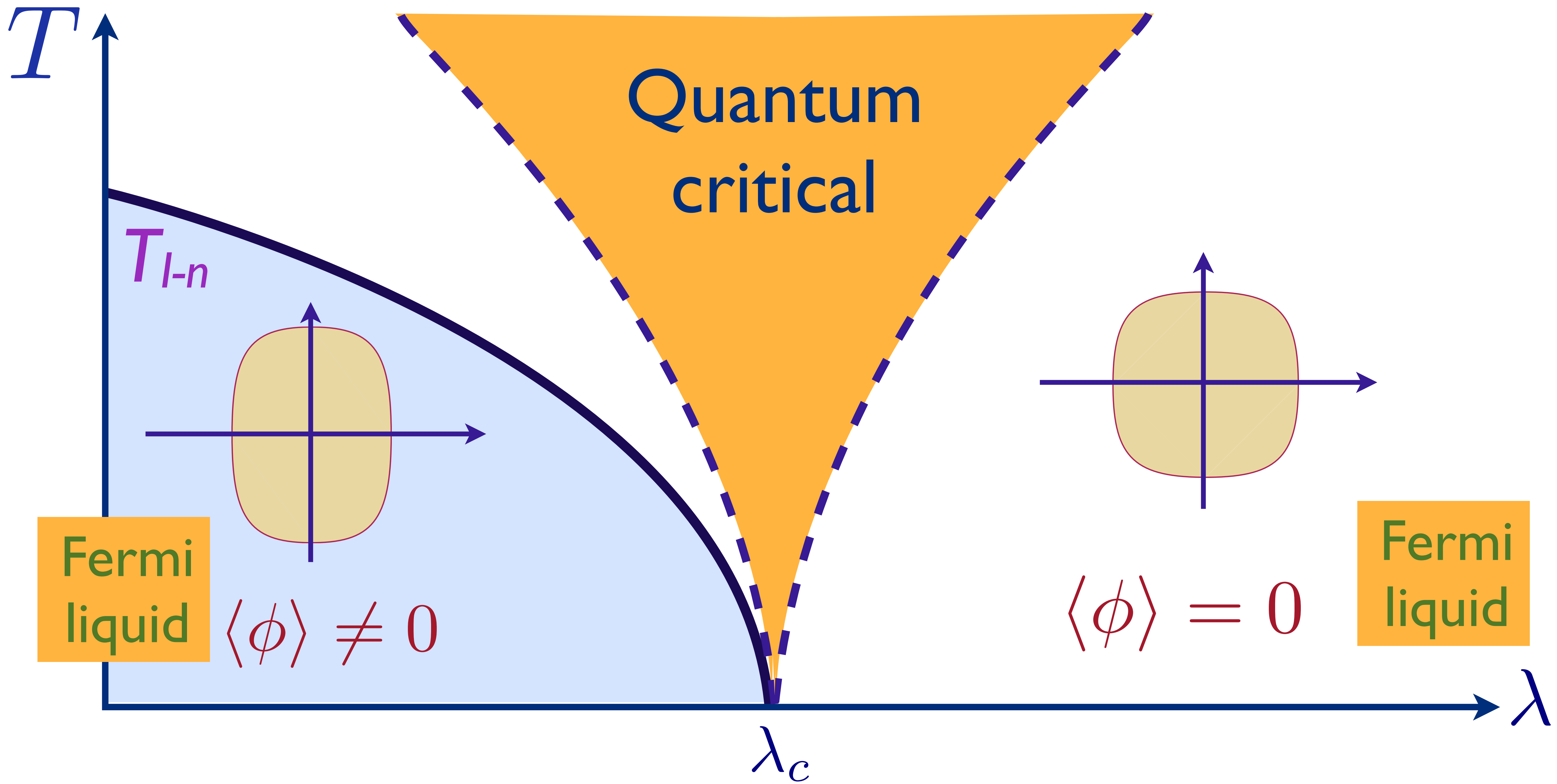
A metal with a Fermi surface
with full square lattice symmetry

Quantum criticality of Ising-nematic ordering in a metal



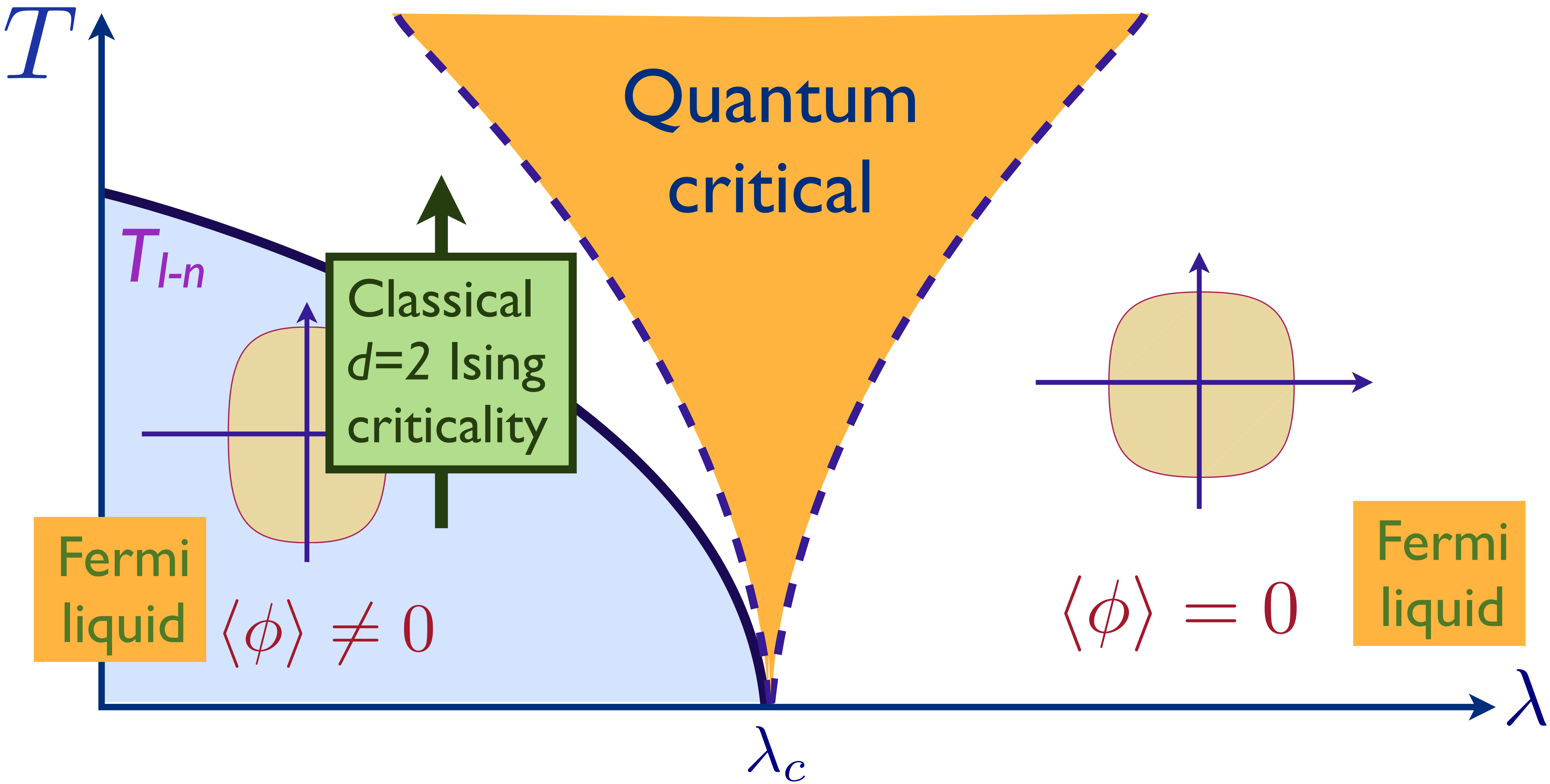
Pomeranchuk instability as a function of coupling λ

Quantum criticality of Ising-nematic ordering in a metal



Phase diagram as a function of T and λ

Quantum criticality of Ising-nematic ordering in a metal



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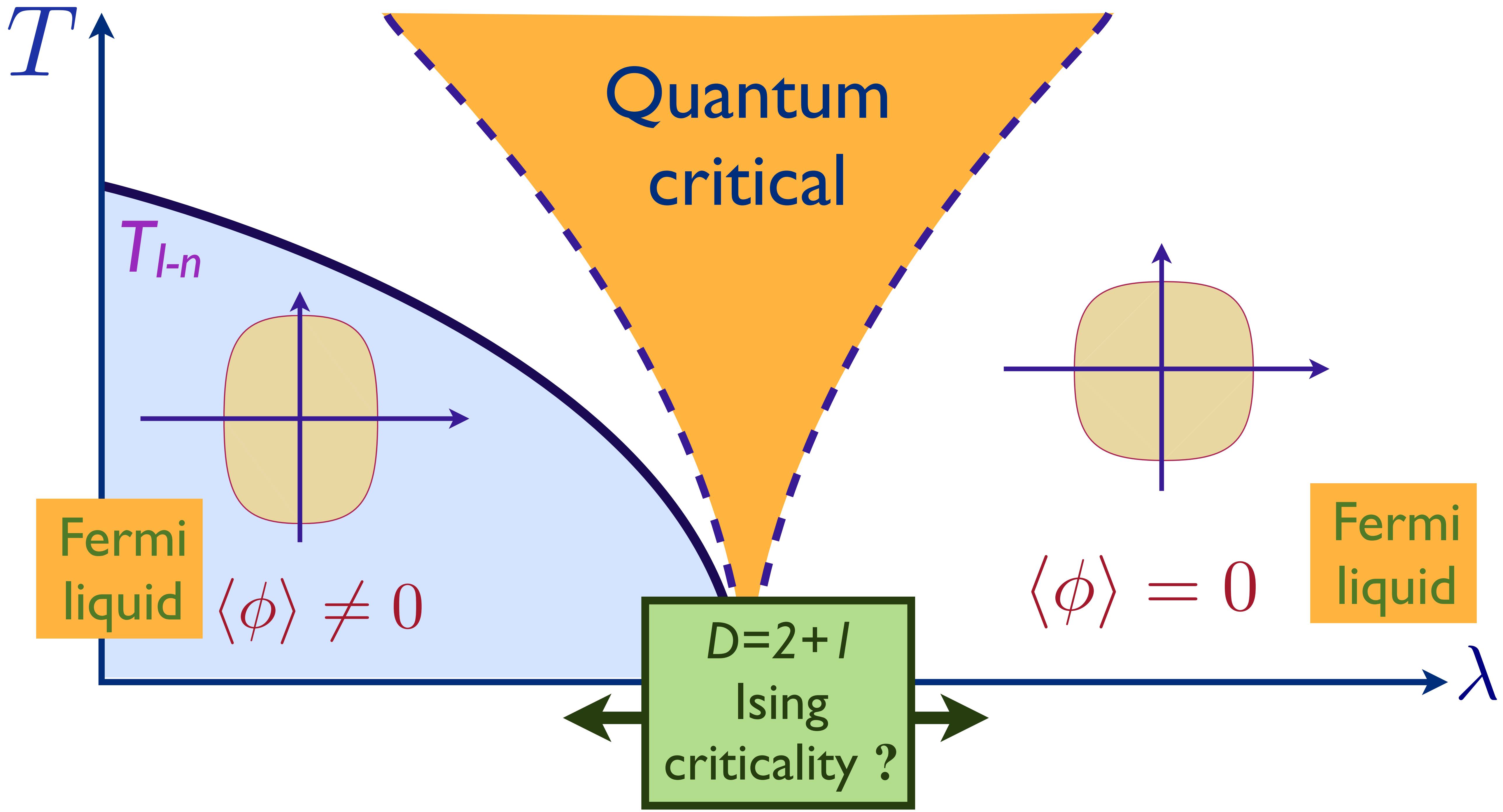

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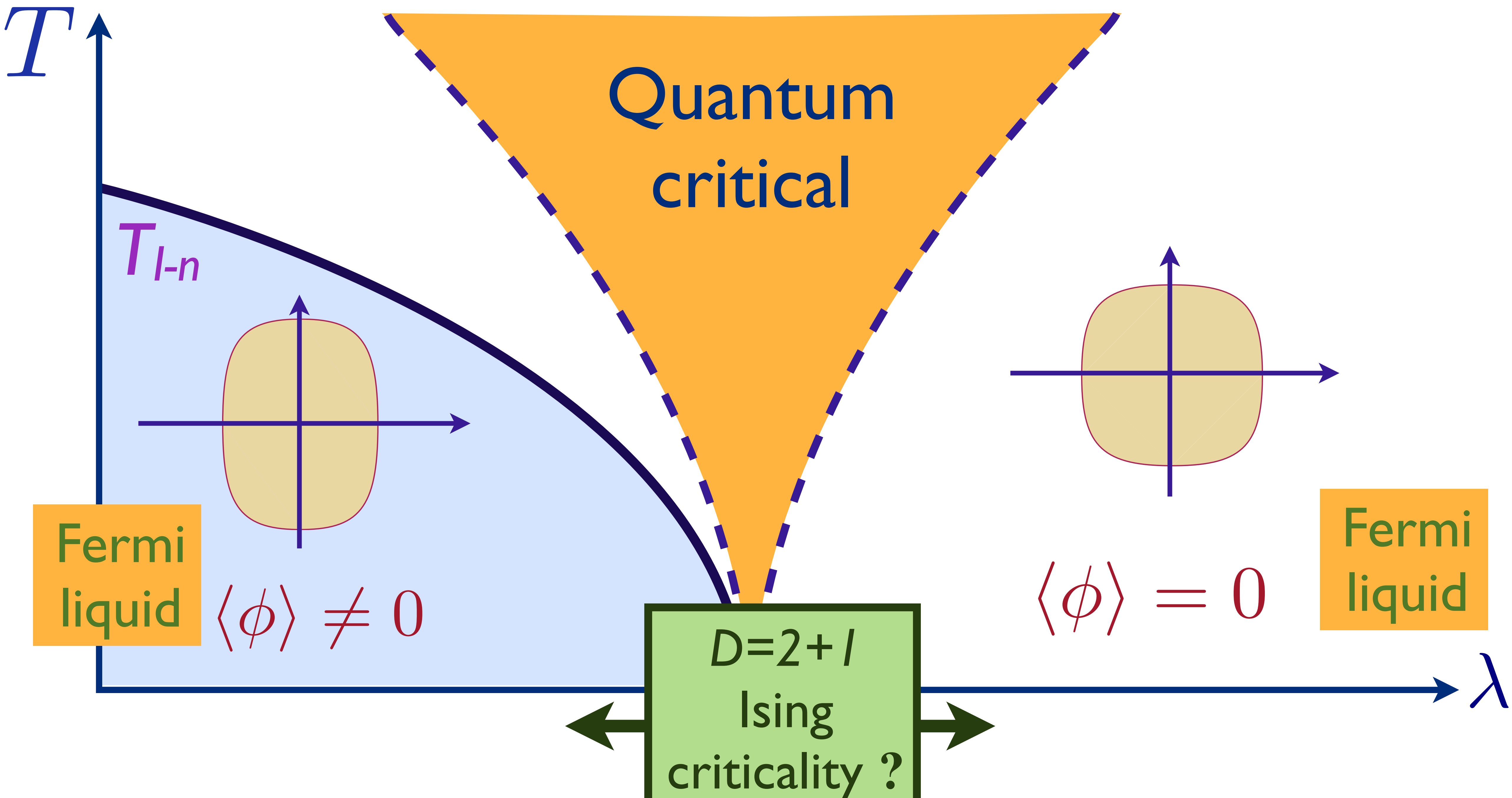

Only at higher energies; at the lowest energy bosonic ϕ fluctuations are strongly coupled to fermionic excitations near Fermi surface.

Phase diagram as a function of T and λ

Quantum criticality of Ising-nematic ordering in a metal

Boltzmann view of electrical transport:

- Identify charge carriers: electrons near the Fermi surface. Compute the scattering rate of these charged excitations off the bosonic ϕ fluctuations.

Quantum criticality of Ising-nematic ordering in a metal

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- Analogous to electron-phonon scattering in metals, where we have "Bloch's law": a resistivity $\rho(T) \sim T^5$.

- "Bloch's law" for the Ising-nematic critical point yields $\rho(T) \sim T^{4/3}$.

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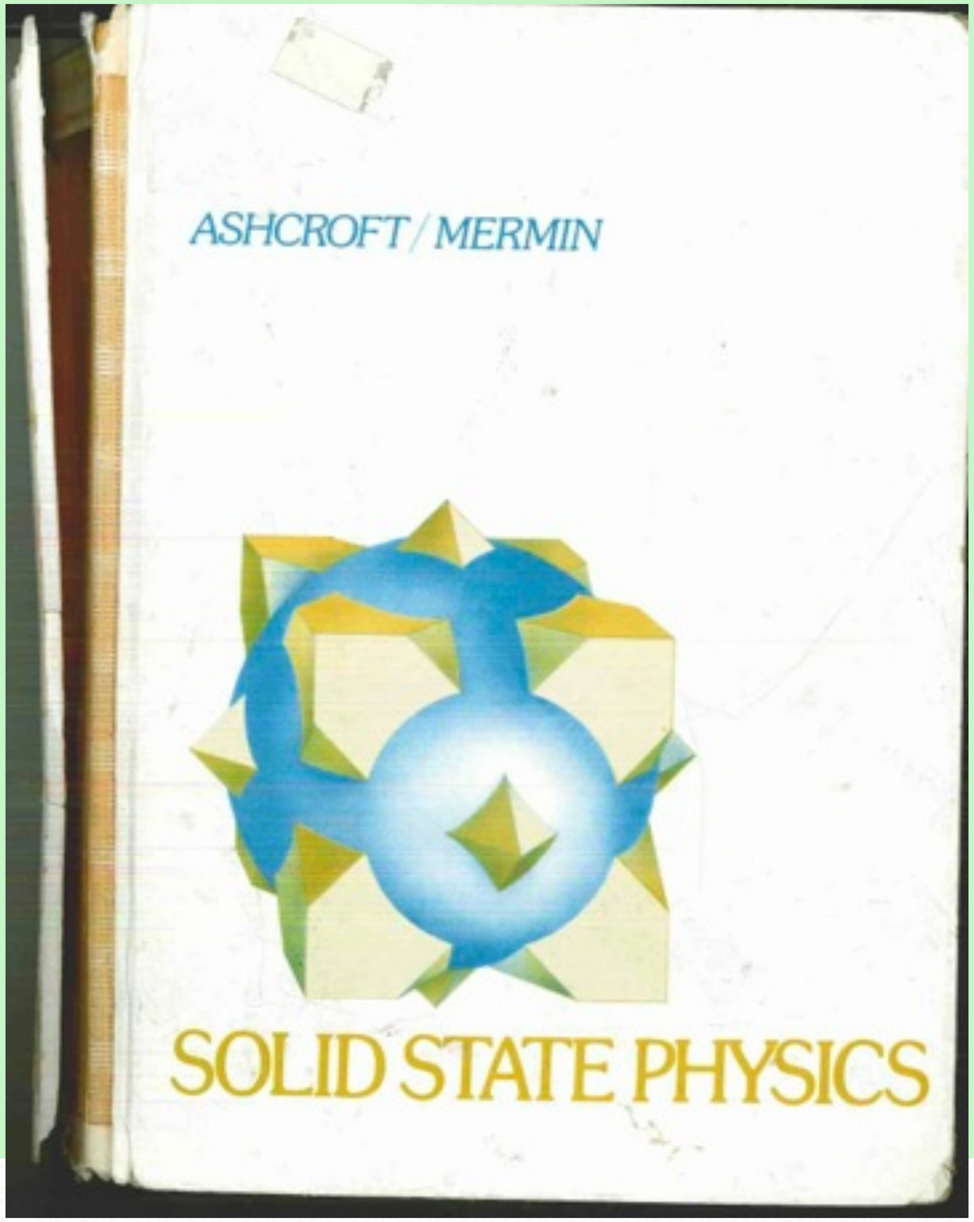

PHONON DRAG

Peierls[28] pointed out a way in which the low temperature resistivity might decline more rapidly than T^5.

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Quantum criticality of Ising-nematic ordering in a metal

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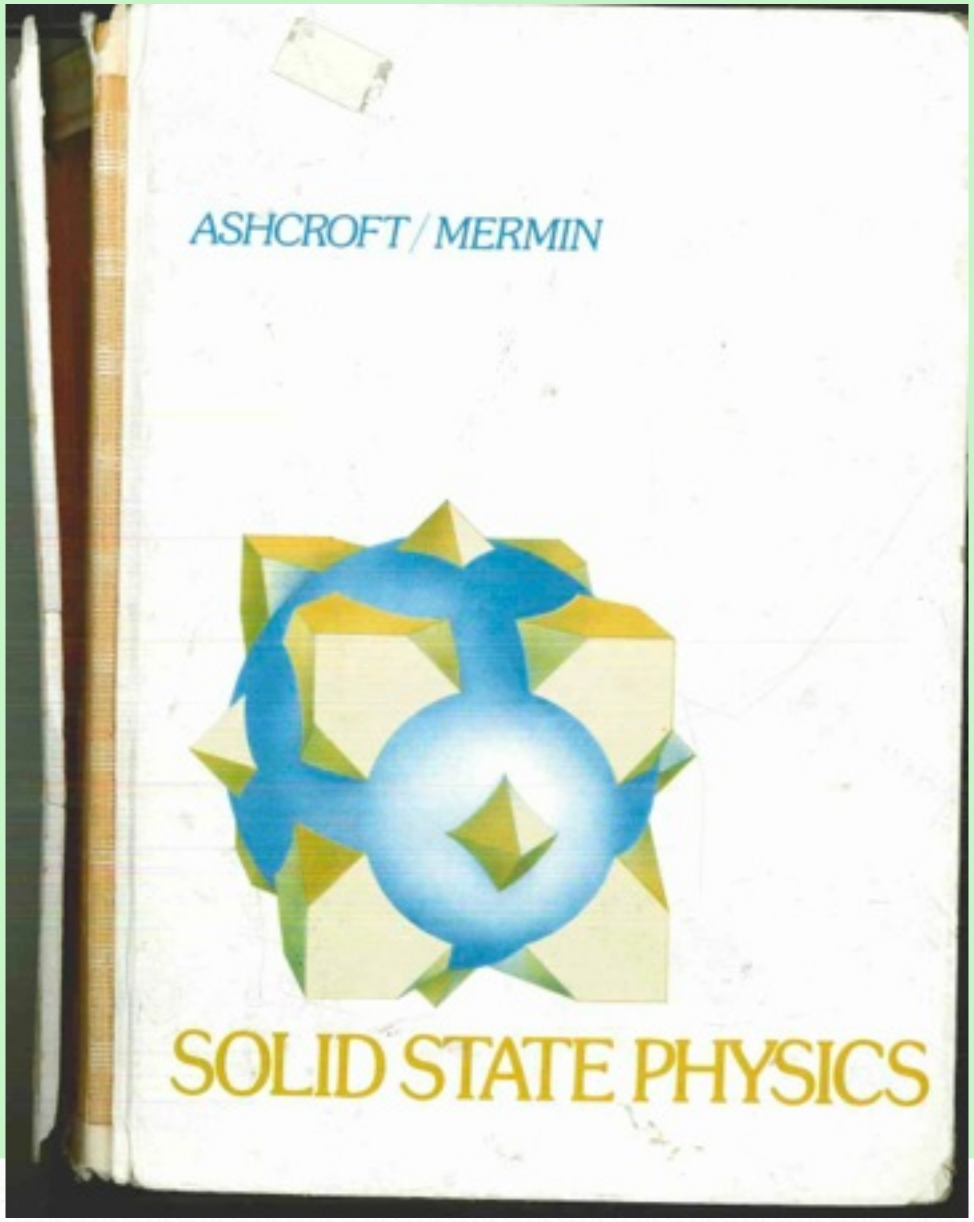

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Quantum criticality of Ising-nematic ordering in a metal

The "standard model":

$$\mathcal{S}_\phi = \int d^2r d\tau \left[(\partial_\tau \phi)^2 + c^2 (\nabla \phi)^2 + (\lambda - \lambda_c) \phi^2 + u \phi^4 \right]$$

$$\mathcal{S}_c = \sum_{\alpha=1}^{N_f} \sum_{\mathbf{k}} \int d\tau c^\dagger_{\mathbf{k}\alpha} \left(\partial_\tau + \varepsilon_{\mathbf{k}} \right) c_{\mathbf{k}\alpha}$$

$$\mathcal{S}_{\phi c} = -g \int d\tau \sum_{\alpha=1}^{N_f} \sum_{\mathbf{k},\mathbf{q}} \phi_{\mathbf{q}} \left(\cos k_x - \cos k_y \right) c^\dagger_{\mathbf{k}+\mathbf{q}/2,\alpha} c_{\mathbf{k}-\mathbf{q}/2,\alpha}$$

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Field theory of bosonic order parameter

Quantum criticality of Ising-nematic ordering in a metal

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Electrons with a Fermi surface: $\varepsilon_{\mathbf{k}} = -2t(\cos k_x + \cos k_y) - \mu \ldots$

$$\mathcal{S}_{\phi c} = -g \int d\tau \sum_{\alpha=1}^{N_f} \sum_{\mathbf{k},\mathbf{q}} \phi_{\mathbf{q}} \left(\cos k_x - \cos k_y \right) c_{\mathbf{k}+\mathbf{q}/2,\alpha}^\dagger c_{\mathbf{k}-\mathbf{q}/2,\alpha}$$

Quantum criticality of Ising-nematic ordering in a metal

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"Yukawa" coupling between bosons and fermions

Quantum criticality of Ising-nematic ordering in a metal

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$$\mathcal{S}_c = \sum_{\alpha=1}^{N_f} \int d^2 r d\tau c_\alpha^\dagger \left(\partial_\tau - \frac{\nabla^2}{2m} + \frac{\nabla^4}{2m'} + \ldots - \mu \right) c_\alpha$$

$$\mathcal{S}_{\phi c} = -g \int d^2 r d\tau \sum_{\alpha=1}^{N_f} \phi \left[c_\alpha^\dagger \left\{ (\partial_x^2 - \partial_y^2 + \ldots) c_\alpha \right\} + \left\{ (\partial_x^2 - \partial_y^2 + \ldots) c_\alpha^\dagger \right\} c_\alpha \right]$$

This continuum theory has a conserved momentum $\mathbf{P}$, and $\chi_{\mathbf{J},\mathbf{P}} \neq 0$, and so the resistivity $\rho(T) = 0$.

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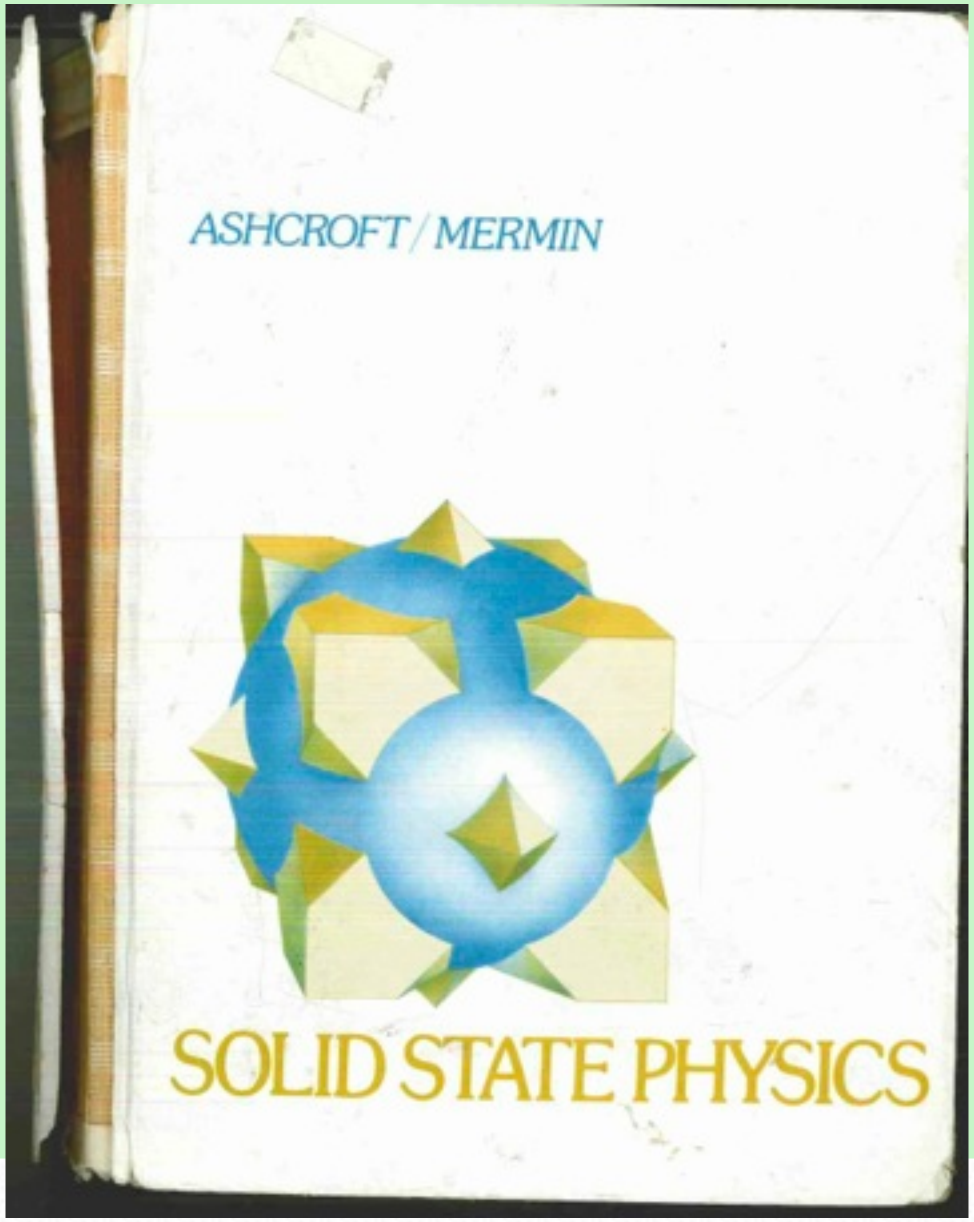

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- "Bloch's law" for the Ising-nematic critical point yields $\rho(T) \sim T^{4/3}$.
- However, Bloch's law ignores conservation of total momentum, or **phonon drag**.
- The field theory for the Ising-nematic critical point has strong electron$-\phi$ scattering, and no quasi-particle excitations. Nevertheless, because of the central importance of the analog of phonon drag, it has $\rho(T) = 0$.

Quantum criticality of Ising-nematic ordering in a metal

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- Focus on the interplay between J_μ and $T_{\mu\nu}$!

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The resistivity of this metal is *not* determined by the scattering rate of charged excitations near the Fermi surface, but by the dominant rate of momentum loss by *any* excitation, whether neutral or charged, or fermionic or bosonic

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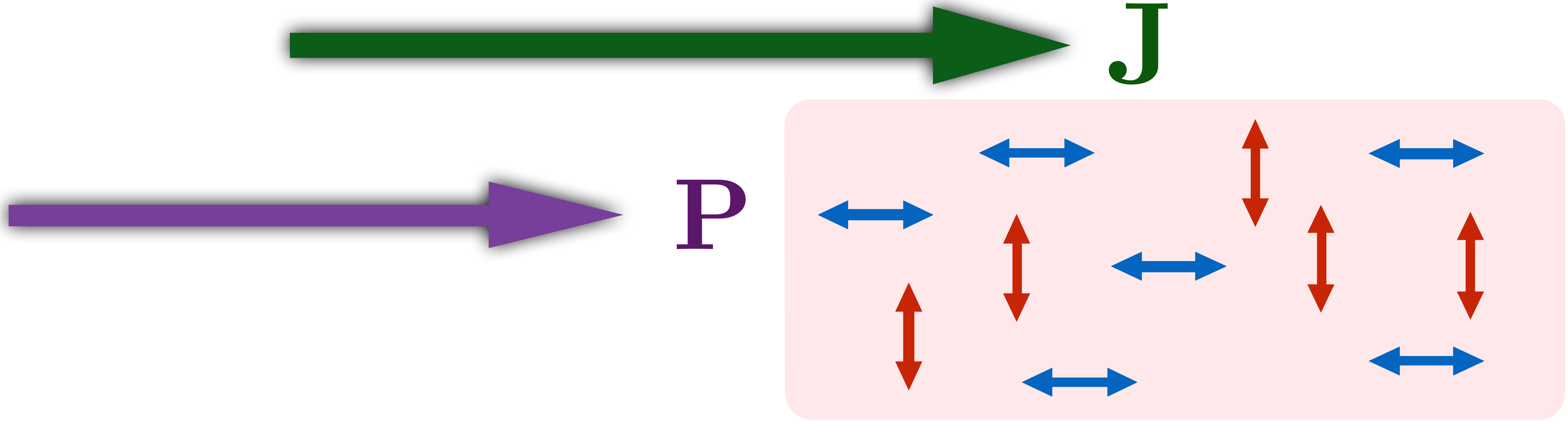
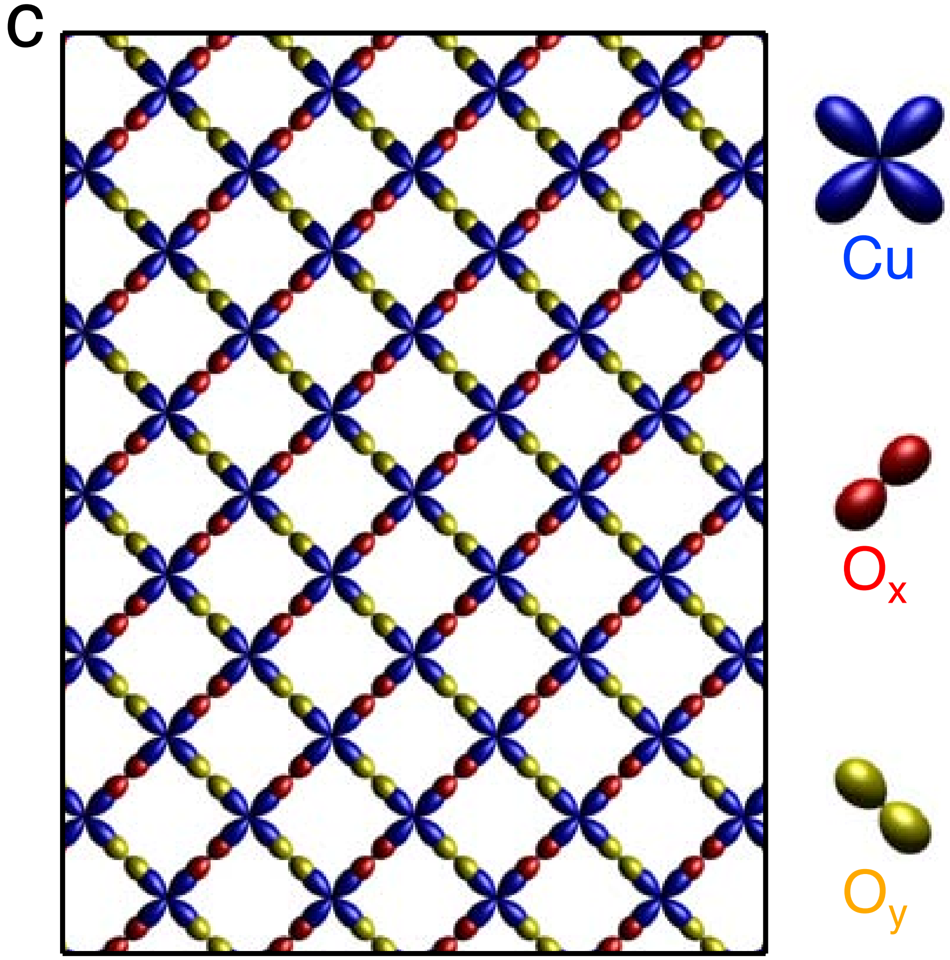


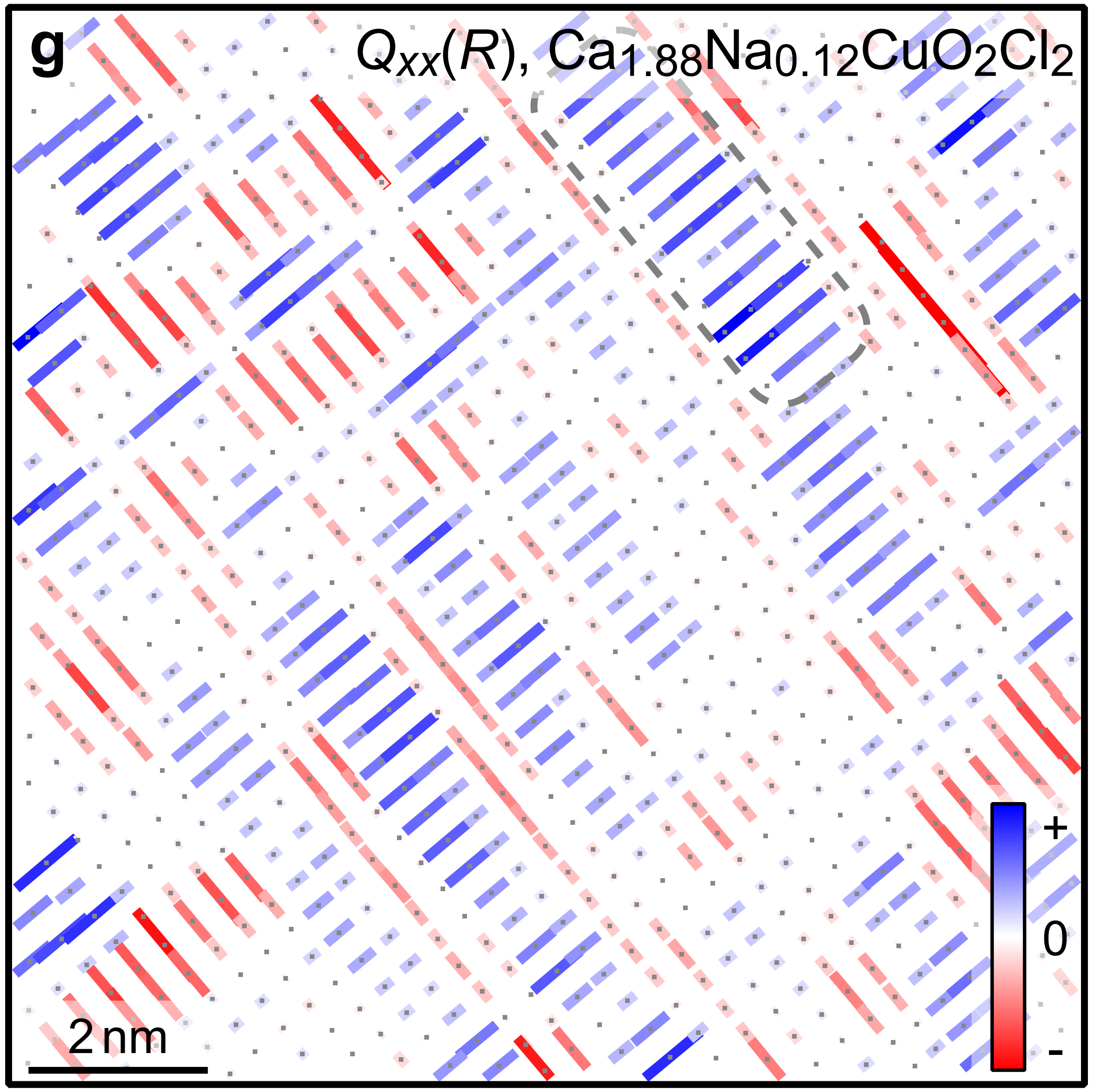
The dominant momentum loss occurs via the scattering of the neutral bosonic ϕ excitations off **random fields**

S. A. Hartnoll, R. Mahajan, M. Punk and S. Sachdev, arXiv:1401.7012.
A. Lucas, S. Sachdev, and K. Schalm, arXiv:1401.7933

Visualization of the emergence of the pseudogap state and the evolution to superconductivity in a lightly hole-doped Mott insulator

Y. Kohsaka, T. Hanaguri, M. Azuma, M. Takano, J. C. Davis, and H. Takagi
Nature Physics, **8**, 534 (2012).





Evidence for "nematic" order
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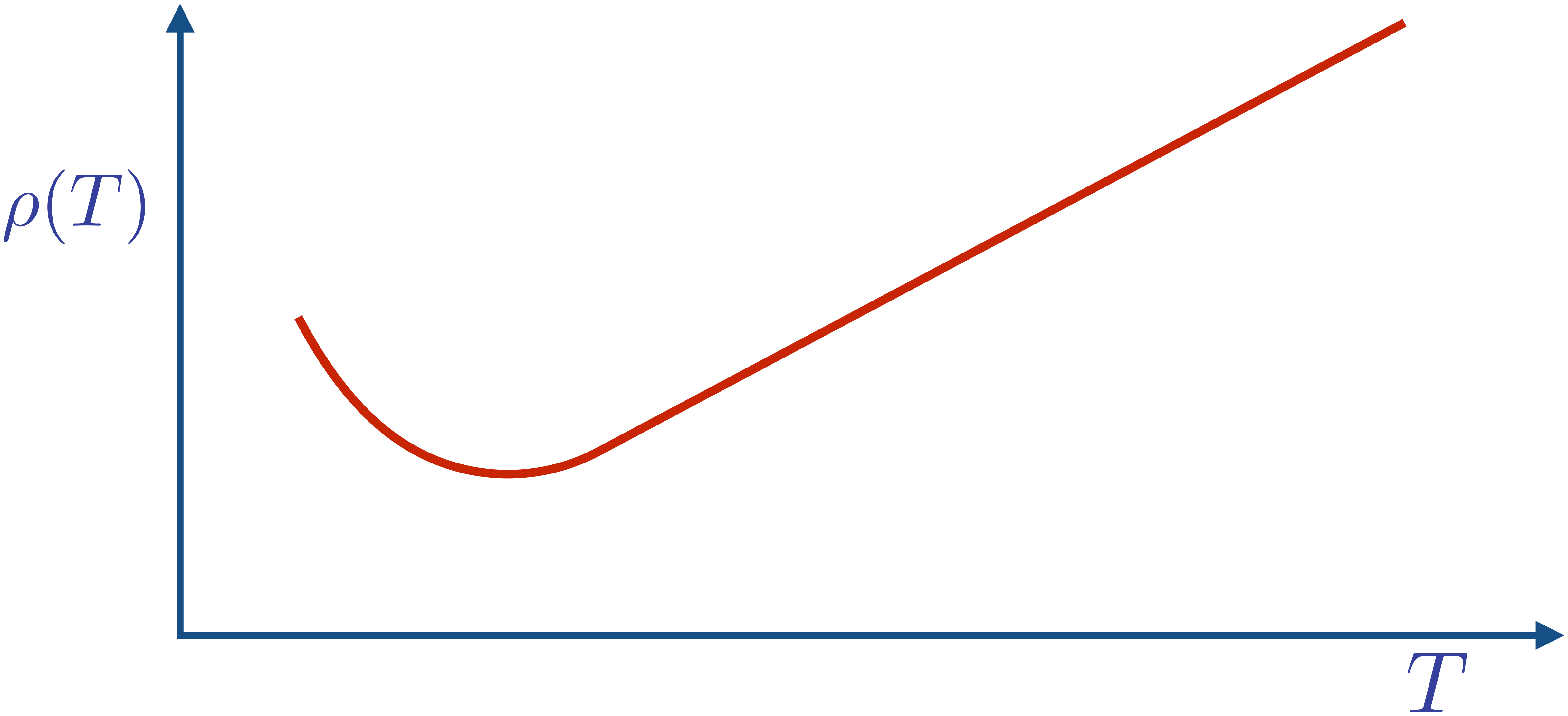

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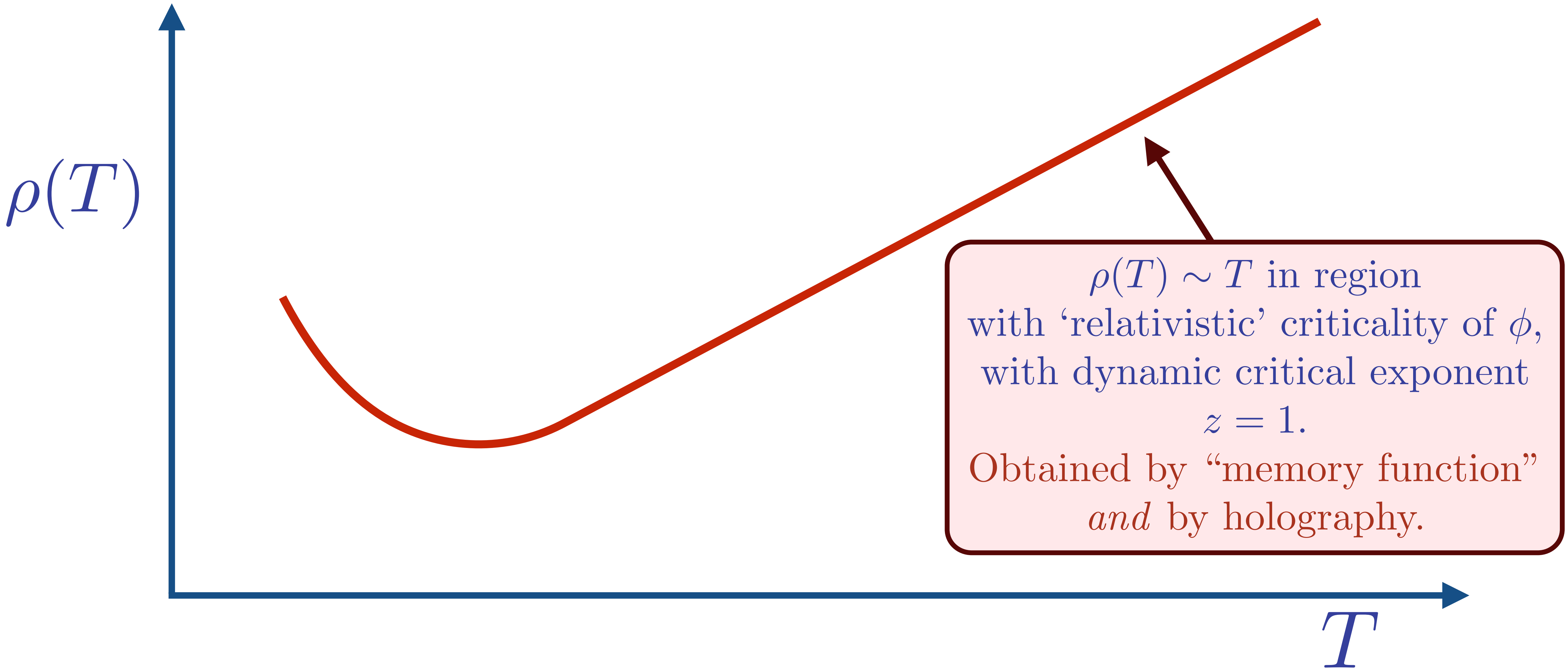

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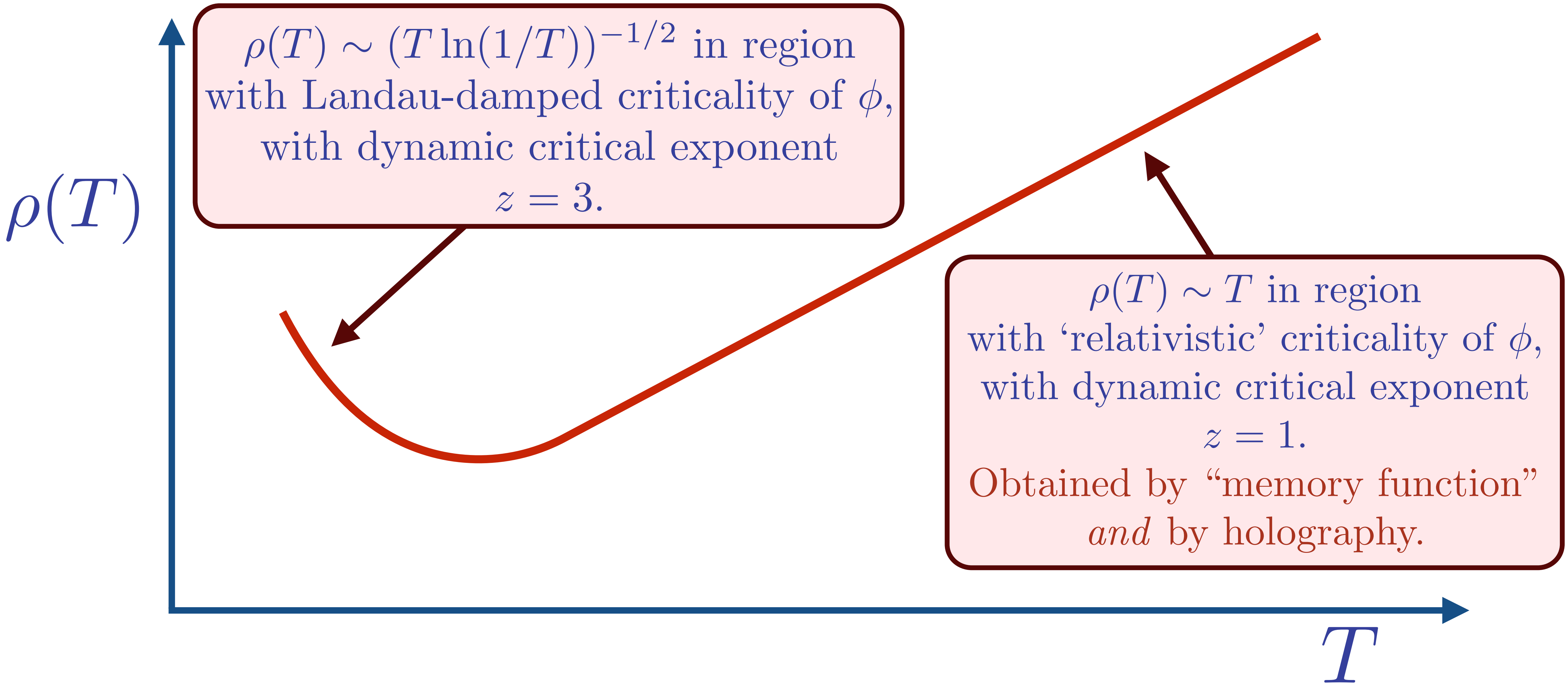

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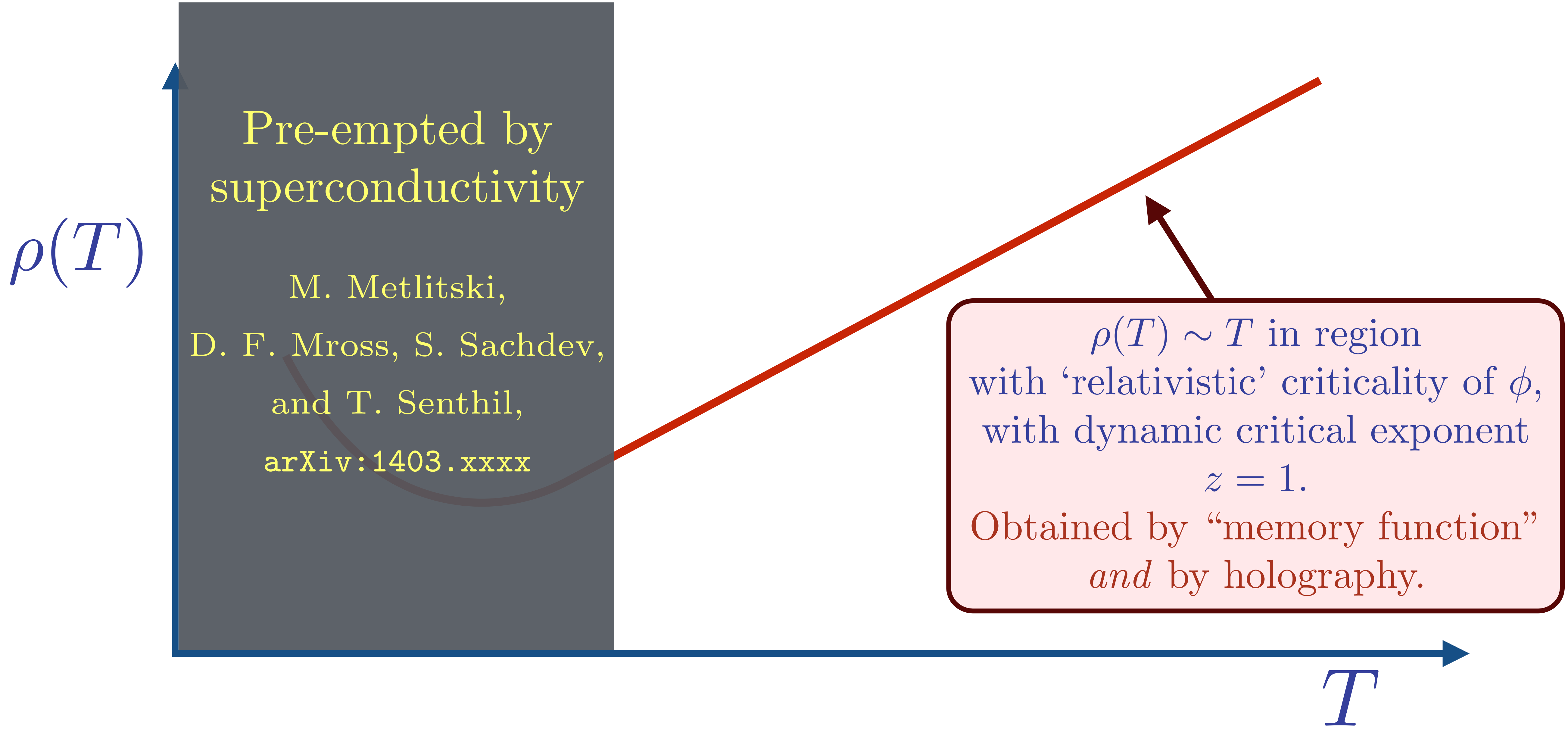

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- Exciting recent progress on the description of transport in metallic states without quasiparticles, via field theory and holography.