Quantum mechanics without quasiparticles

New Directions in Theoretical Physics
Higgs Centre, University of Edinburgh
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Talk online: sachdev.physics.harvard.edu

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William Witczak-Krempa
Perimeter

Erik Sorensen
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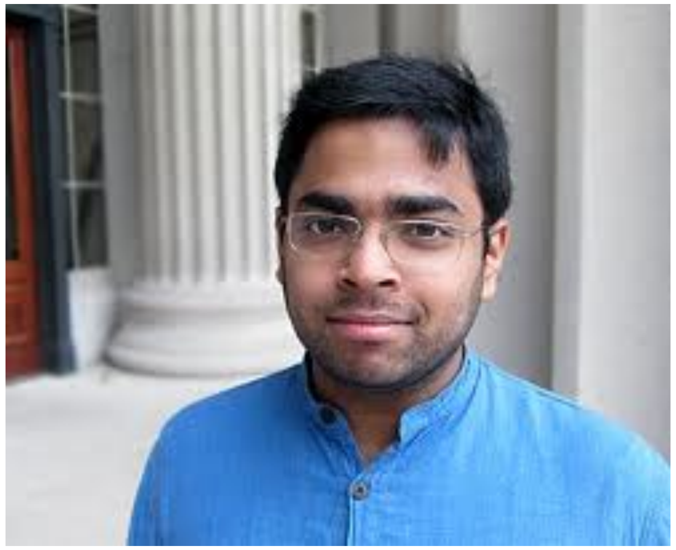


Raghu Mahajan
Stanford

Matthias Punk
Innsbruck

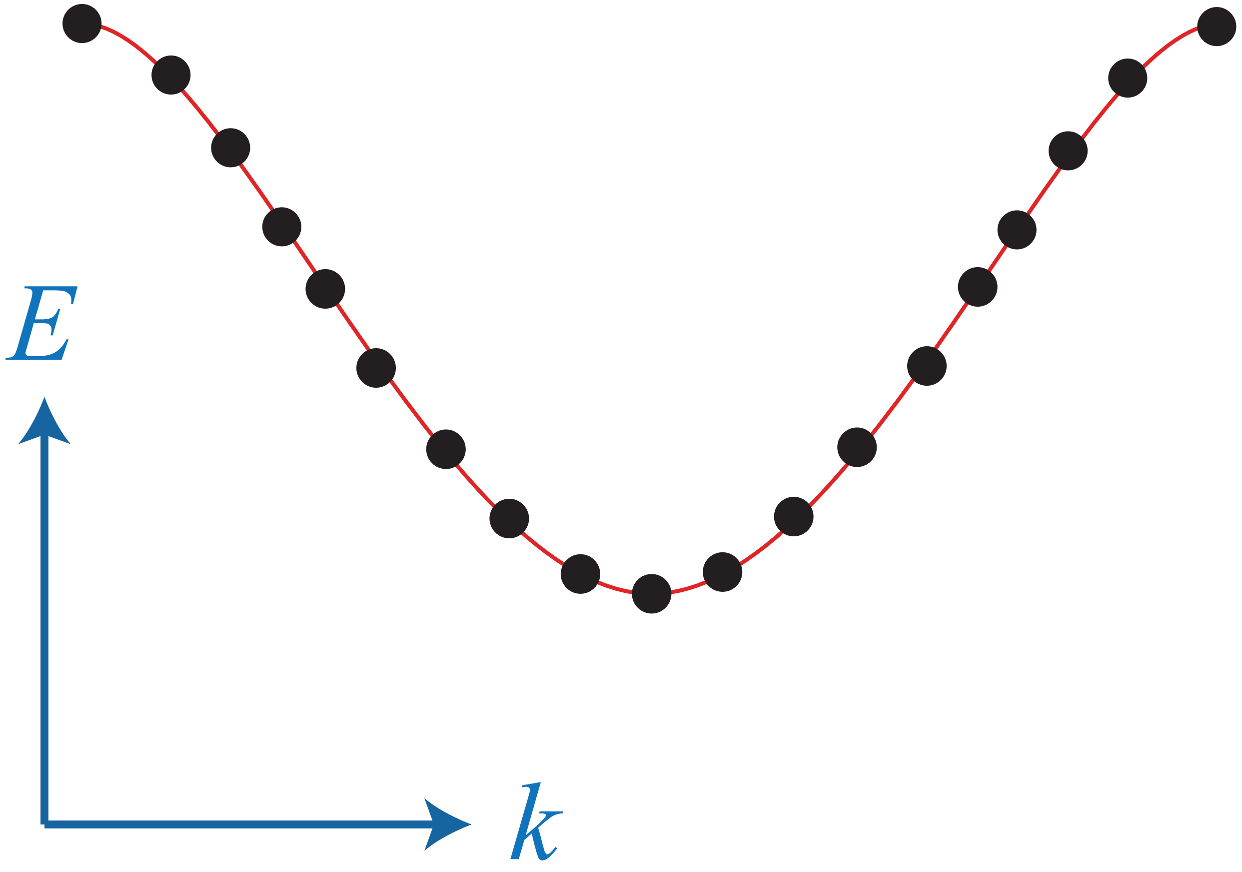
Sommerfeld-Bloch theory of metals, insulators, and superconductors:

many-electron quantum states are adiabatically connected to independent electron states

Sommerfeld-Bloch theory of metals, insulators, and superconductors:

many-electron quantum states are adiabatically connected to independent electron states

Band insulators

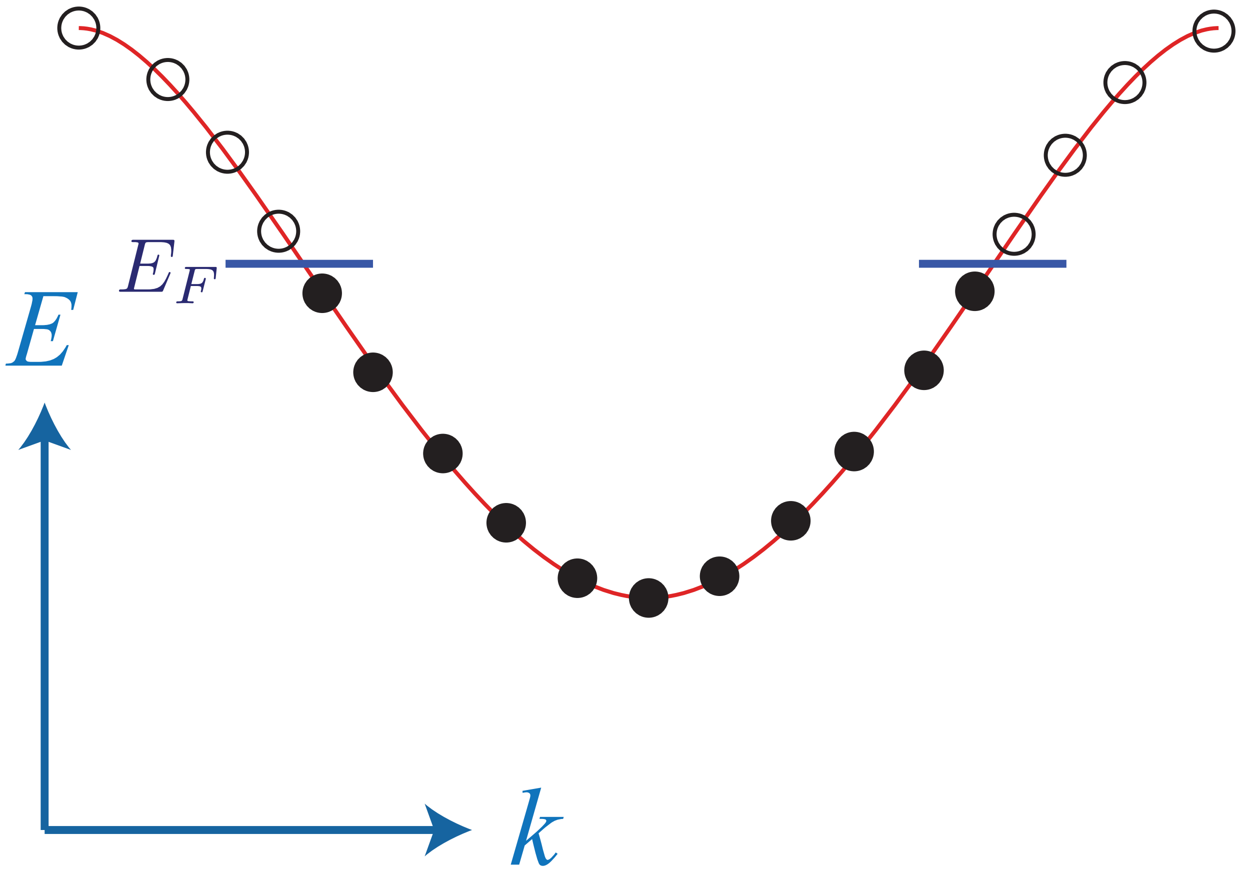


An even number of electrons per unit cell

Sommerfeld-Bloch theory of metals, insulators, and superconductors:

many-electron quantum states are adiabatically connected to independent electron states

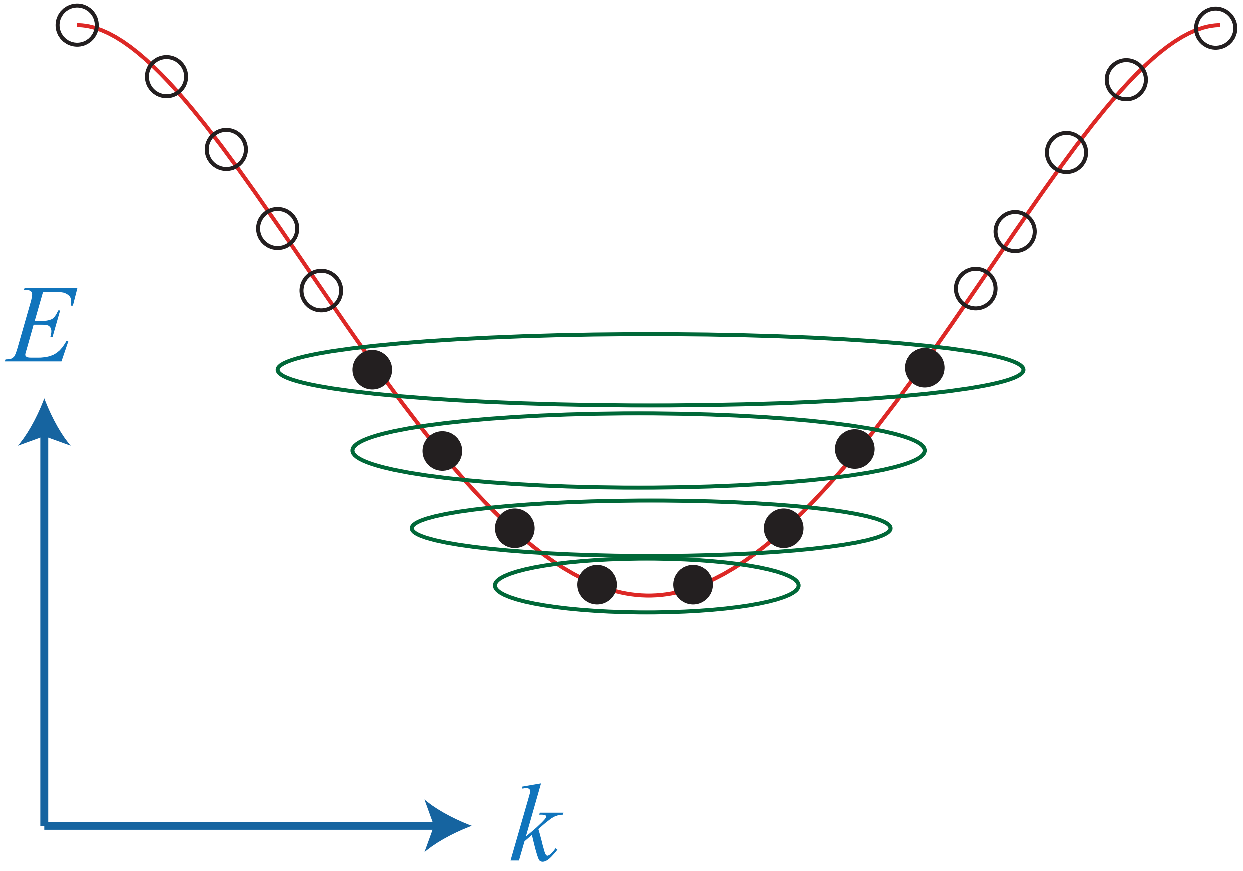
Metals



Sommerfeld-Bloch theory of metals, insulators, and superconductors:

many-electron quantum states are adiabatically connected to independent electron states

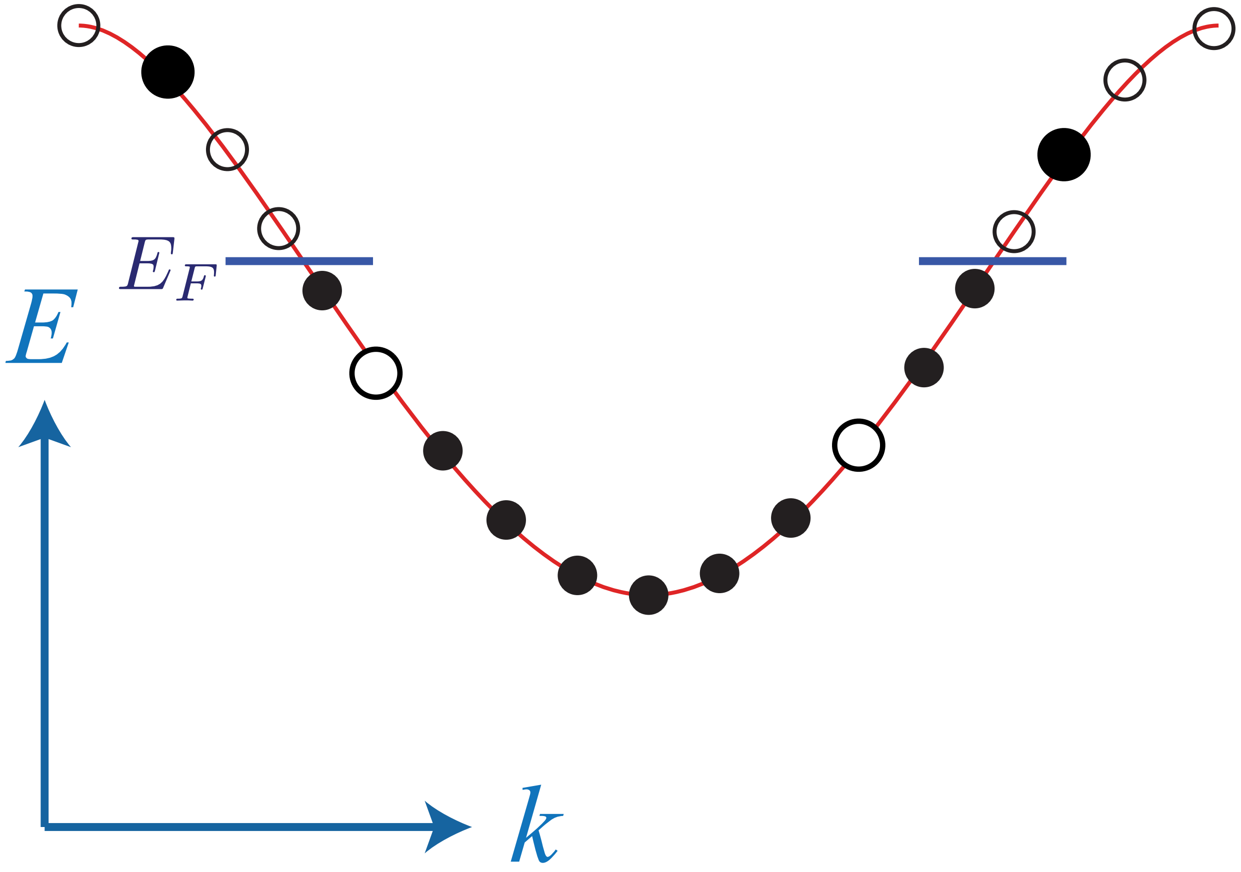
Superconductors



Boltzmann-Landau theory of dynamics of metals:

Long-lived ***quasiparticles*** (and ***quasiholes***) have weak interactions which can be described by a Boltzmann equation

Metals



Modern phases of quantum matter

Not adiabatically connected
to independent electron states:

many-particle
quantum entanglement,

Modern phases of quantum matter

Not adiabatically connected
to independent electron states:

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quantum entanglement,

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

Not adiabatically connected
to independent electron states:
many-particle
quantum entanglement,

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

Not adiabatically connected
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Modern phases of quantum matter

Not adiabatically connected
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many-particle
quantum entanglement,

Modern phases of quantum matter

Not adiabatically connected
to independent electron states:

many-particle
quantum entanglement,
and no quasiparticles

Outline

1. The simplest models without quasiparticles

   A. Superfluid-insulator transition

   of ultracold bosons in an optical lattice

   B. Conformal field theories in

   2+1 dimensions and

   the AdS/CFT correspondence

2. Metals without quasiparticles

   "Nematic" order in the high

   temperature superconductors

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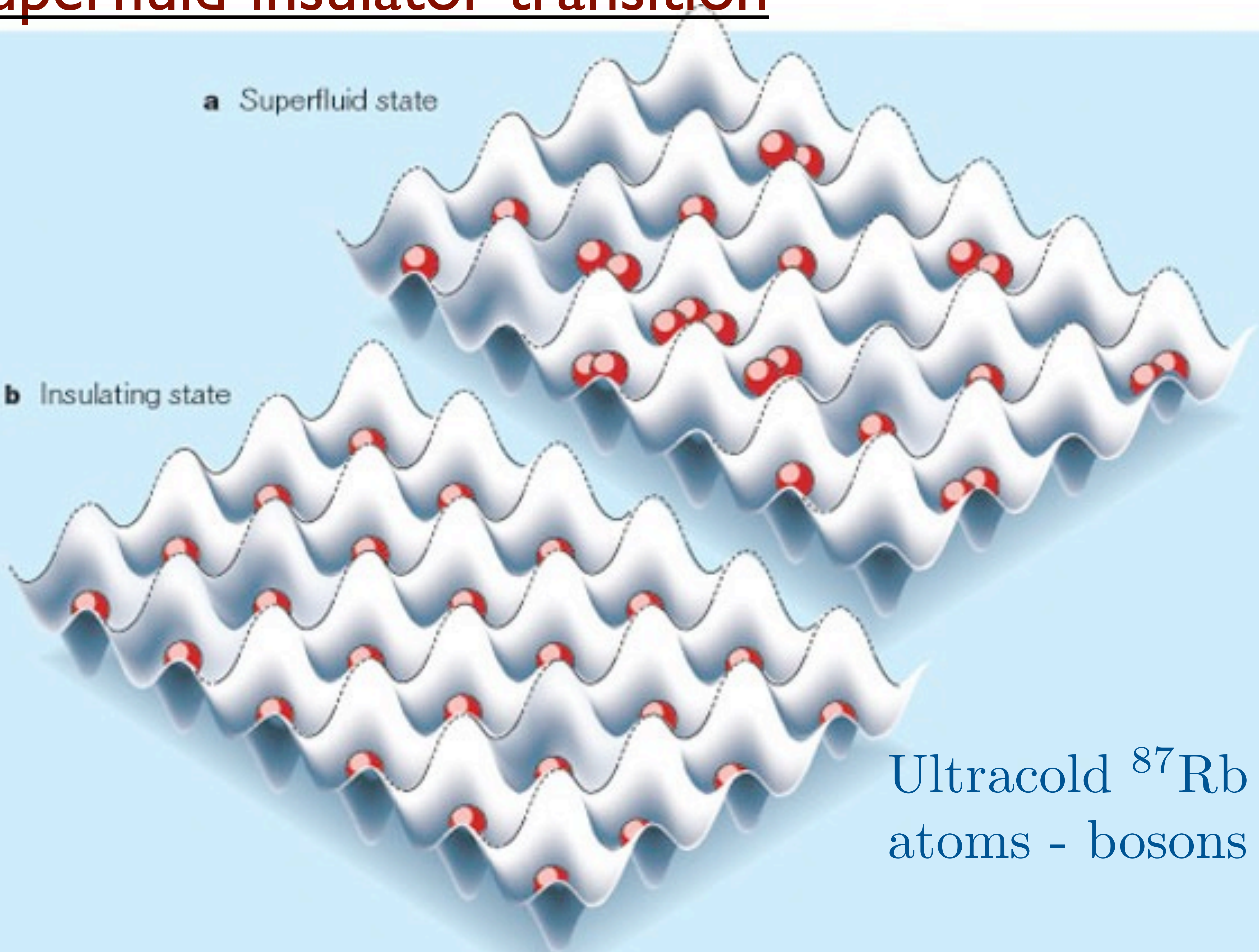
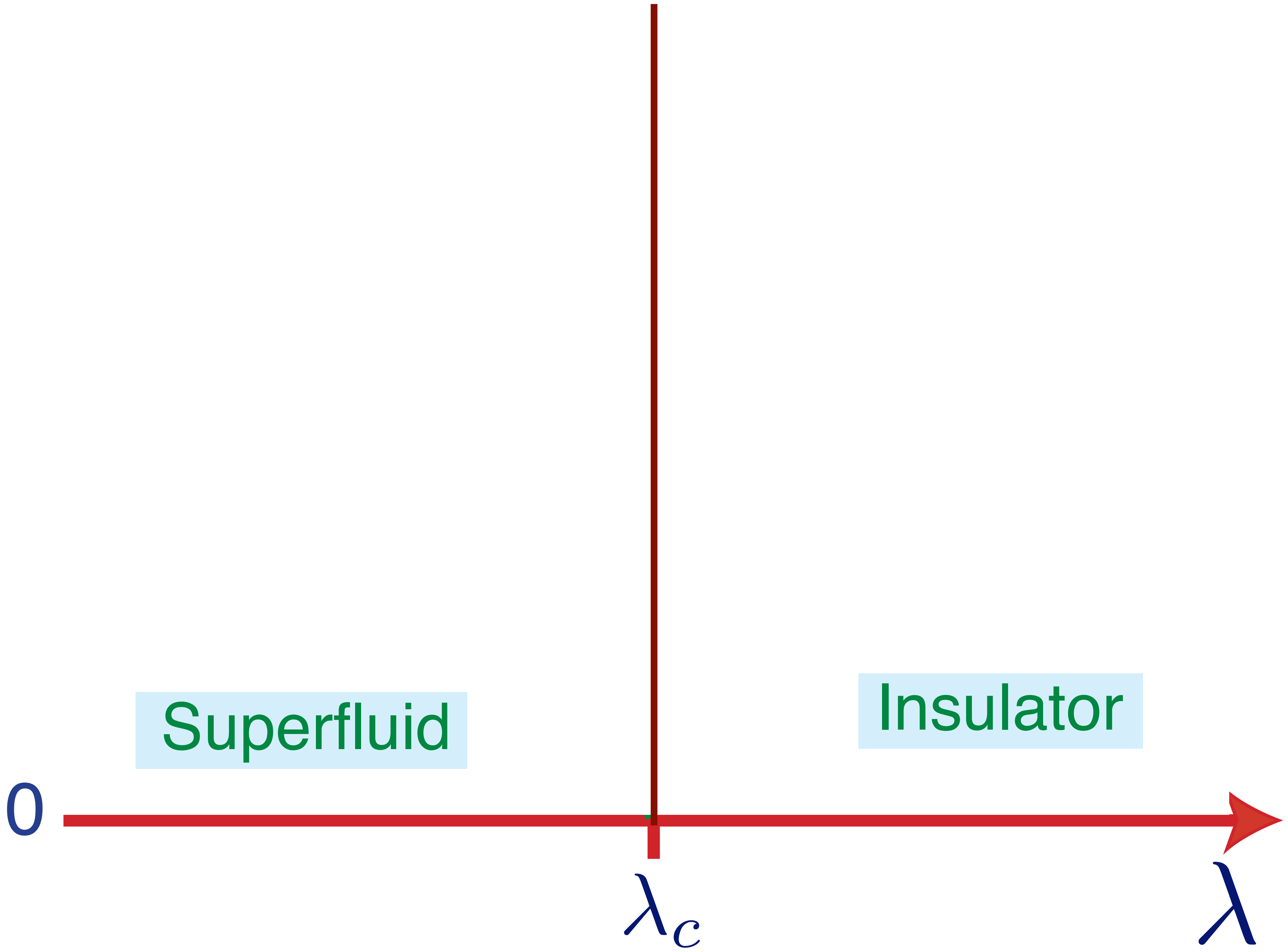
Superfluid-insulator transition

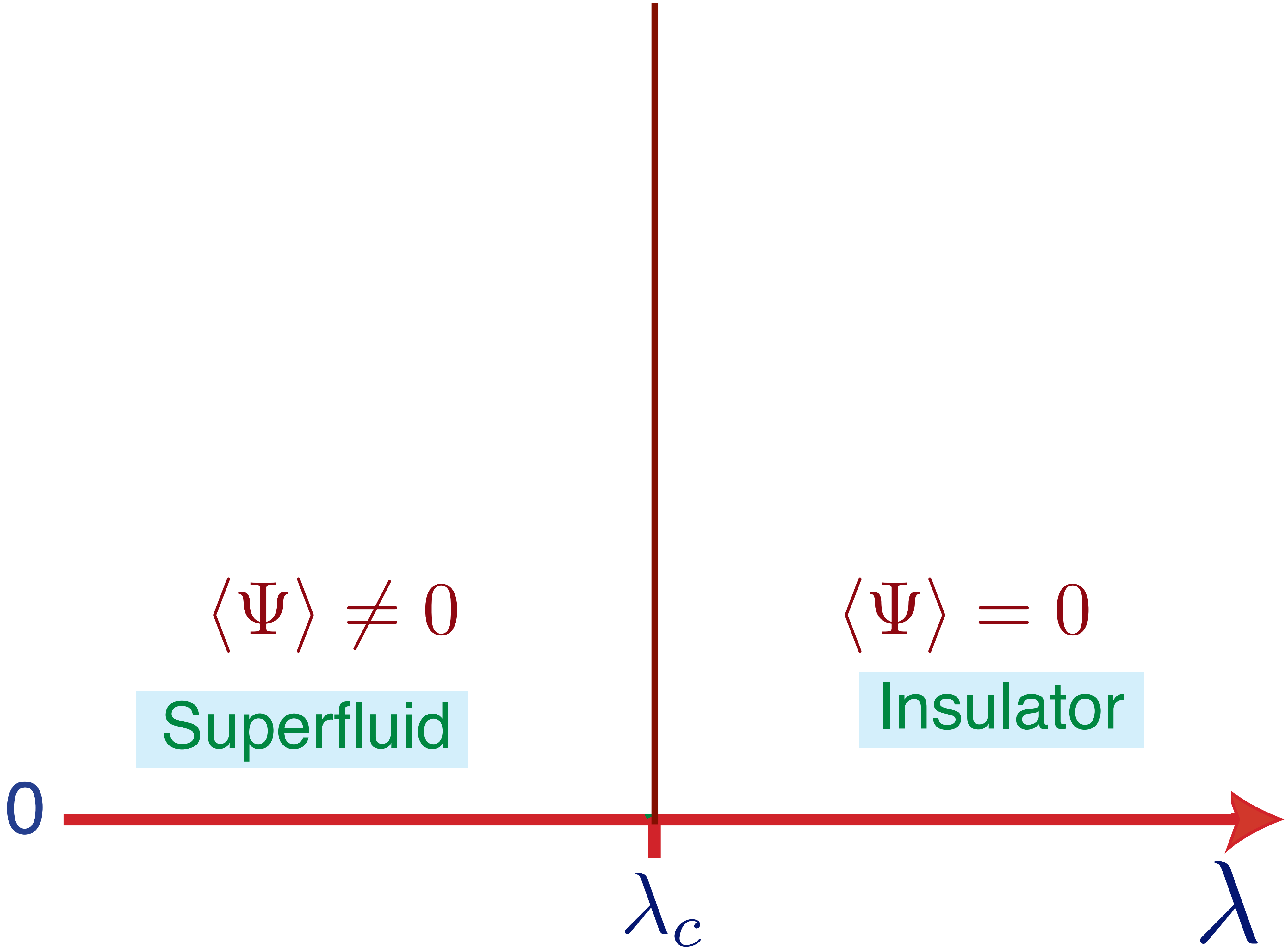


Ultracold ^{87}Rb atoms - bosons

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



$\langle \Psi \rangle \neq 0$

Superfluid

$\langle \Psi \rangle = 0$

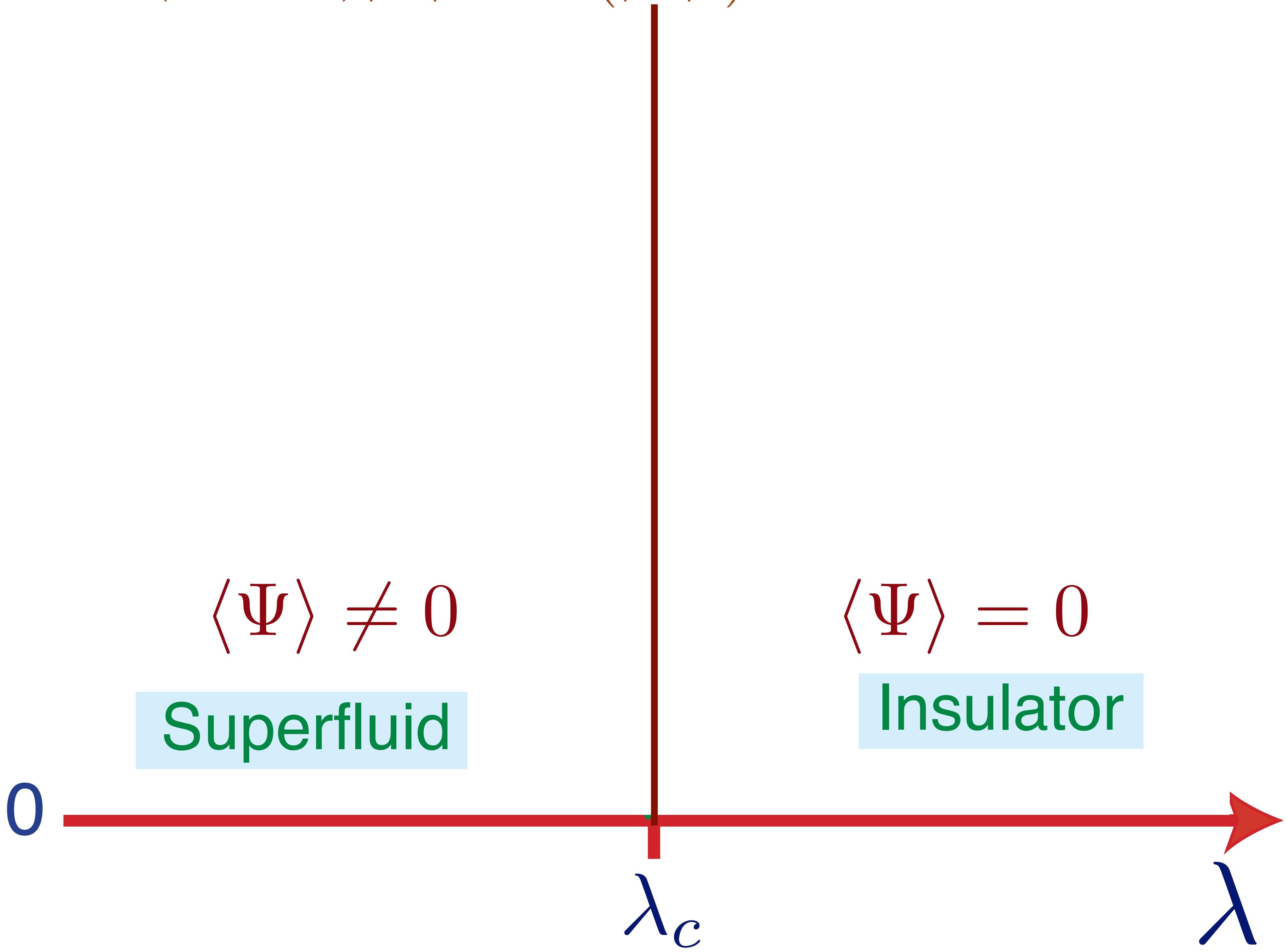
Insulator

0

λ_c

λ

$$
\begin{aligned}
\mathcal{S} &= \int d^2r dt \left[|\partial_t \Psi|^2 - c^2 |\nabla_r \Psi|^2 - V(\Psi) \right] \\
V(\Psi) &= (\lambda - \lambda_c)|\Psi|^2 + u \left(|\Psi|^2 \right)^2
\end{aligned}
$$



$\langle \Psi \rangle \neq 0$

Superfluid

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Insulator

0

λ_c

λ

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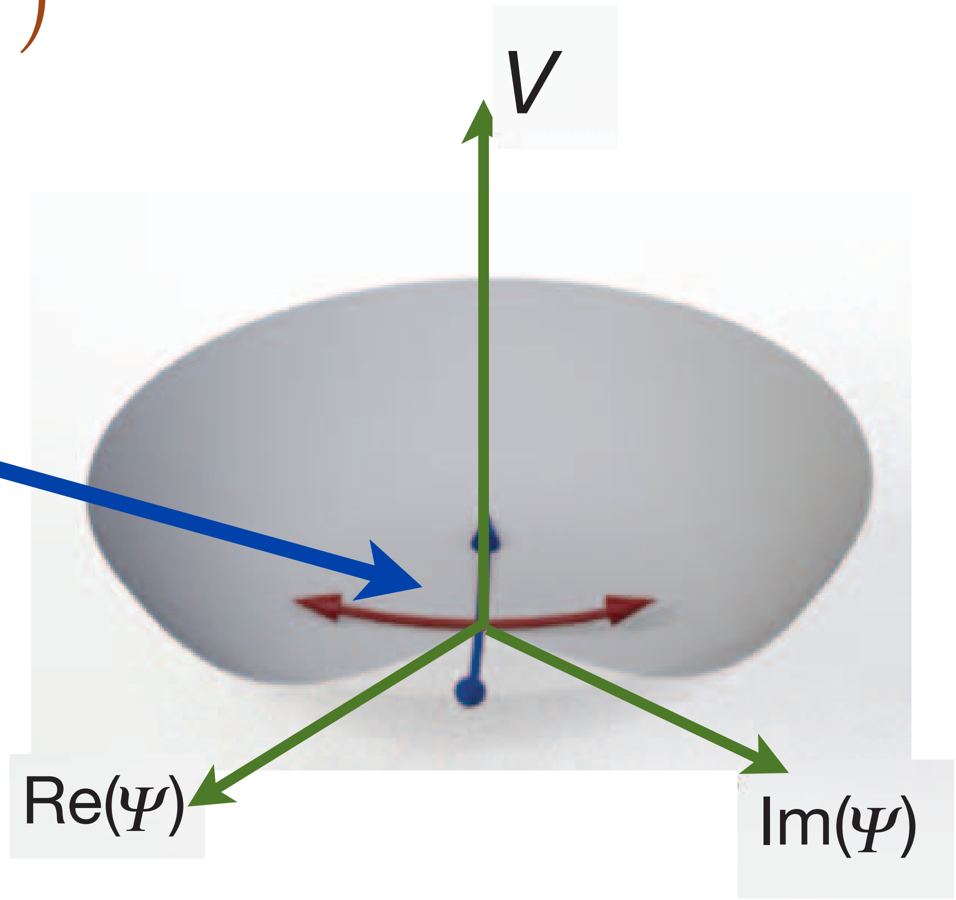
$$V(\Psi) = (\lambda - \lambda_c)|\Psi|^2 + u\left(|\Psi|^2\right)^2$$

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

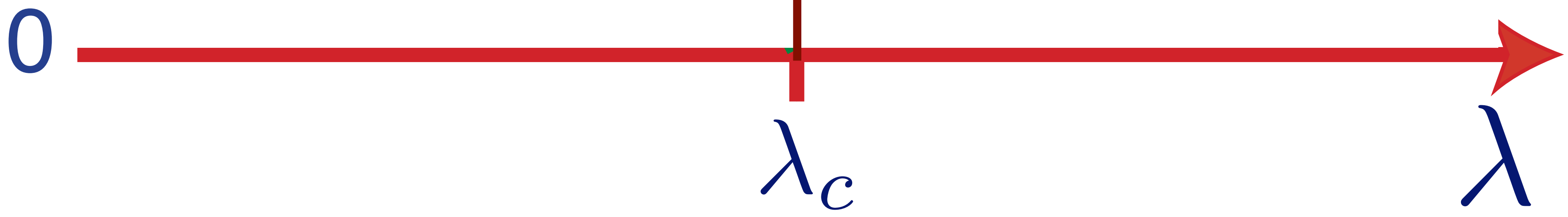


$\langle \Psi \rangle \neq 0$

Superfluid

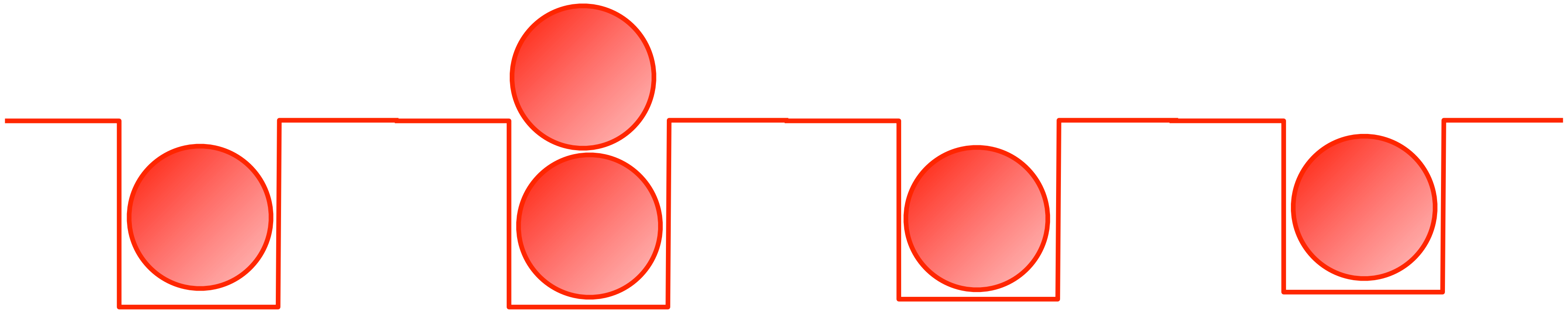
$\langle \Psi \rangle = 0$

Insulator



Insulator (the vacuum)
at large repulsion between bosons

Excitations of the insulator:



$\text{Particles} \sim \Psi^\dagger$

Excitations of the insulator:

$$\text{Holes} \sim \Psi$$

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

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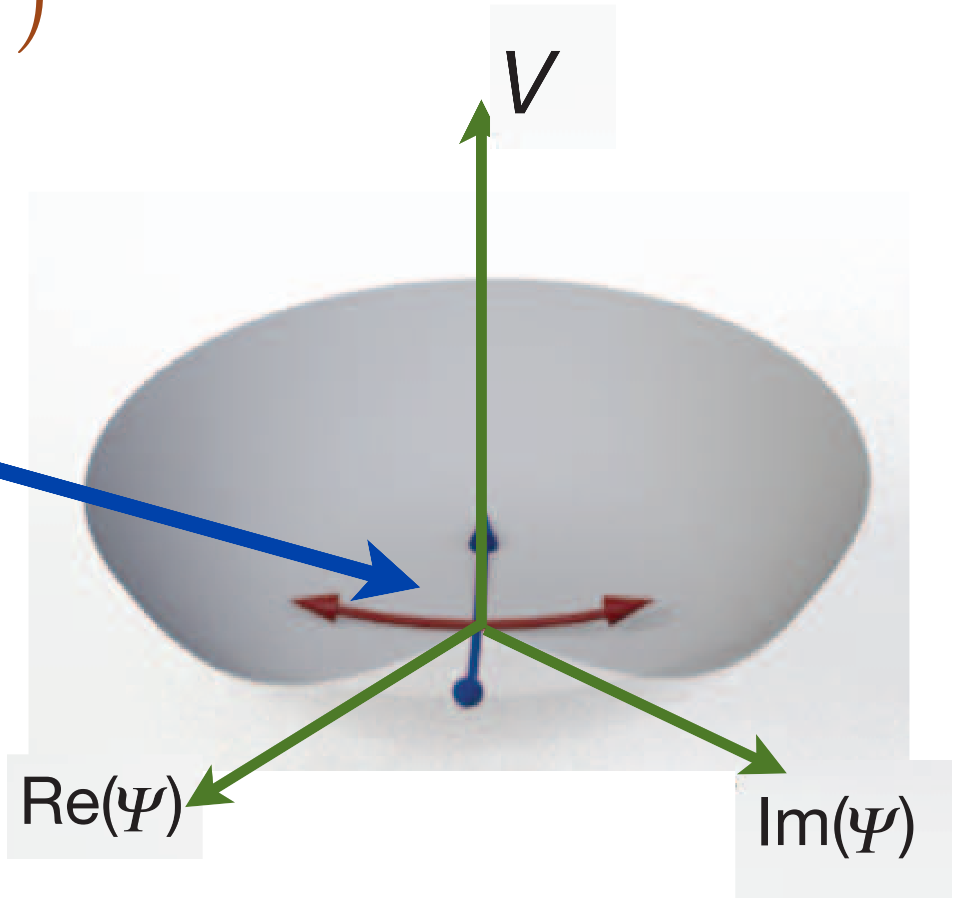
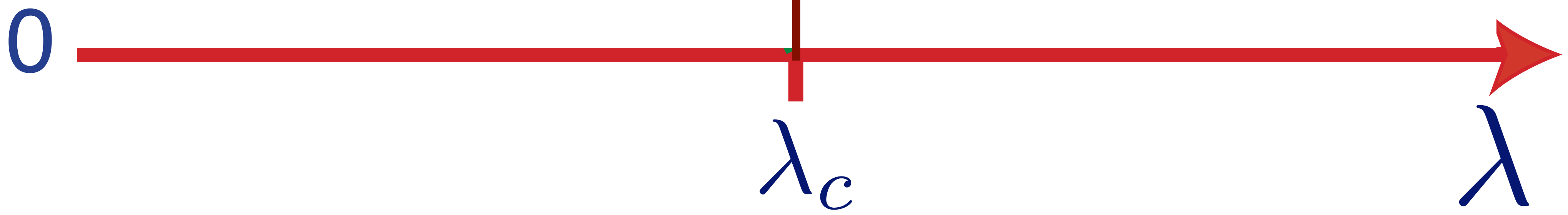


$\langle \Psi \rangle \neq 0$

Superfluid

$\langle \Psi \rangle = 0$

Insulator



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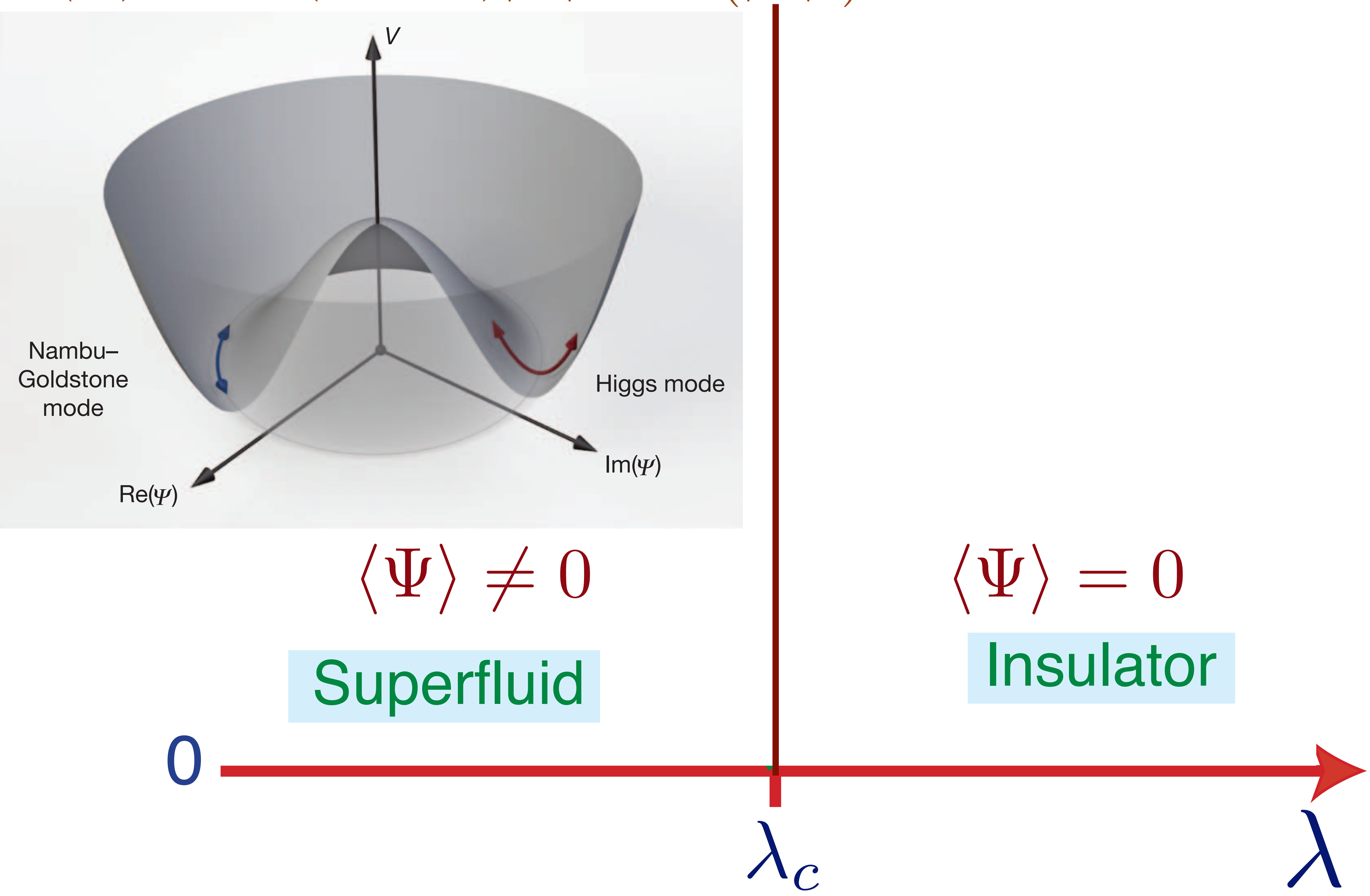


$$\langle \Psi \rangle \neq 0$$

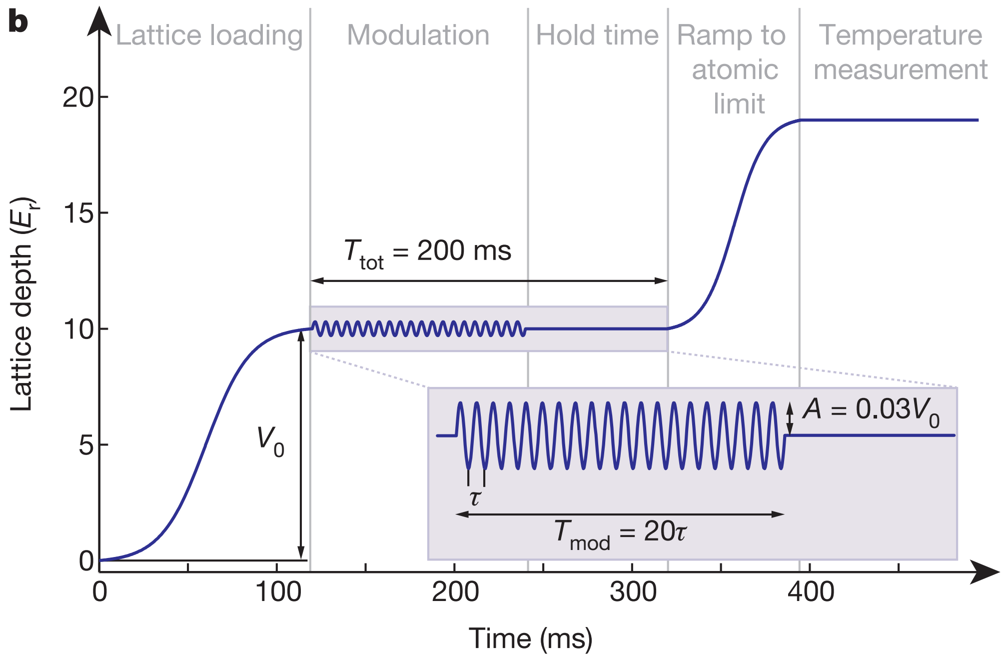
$$\langle \Psi \rangle = 0$$

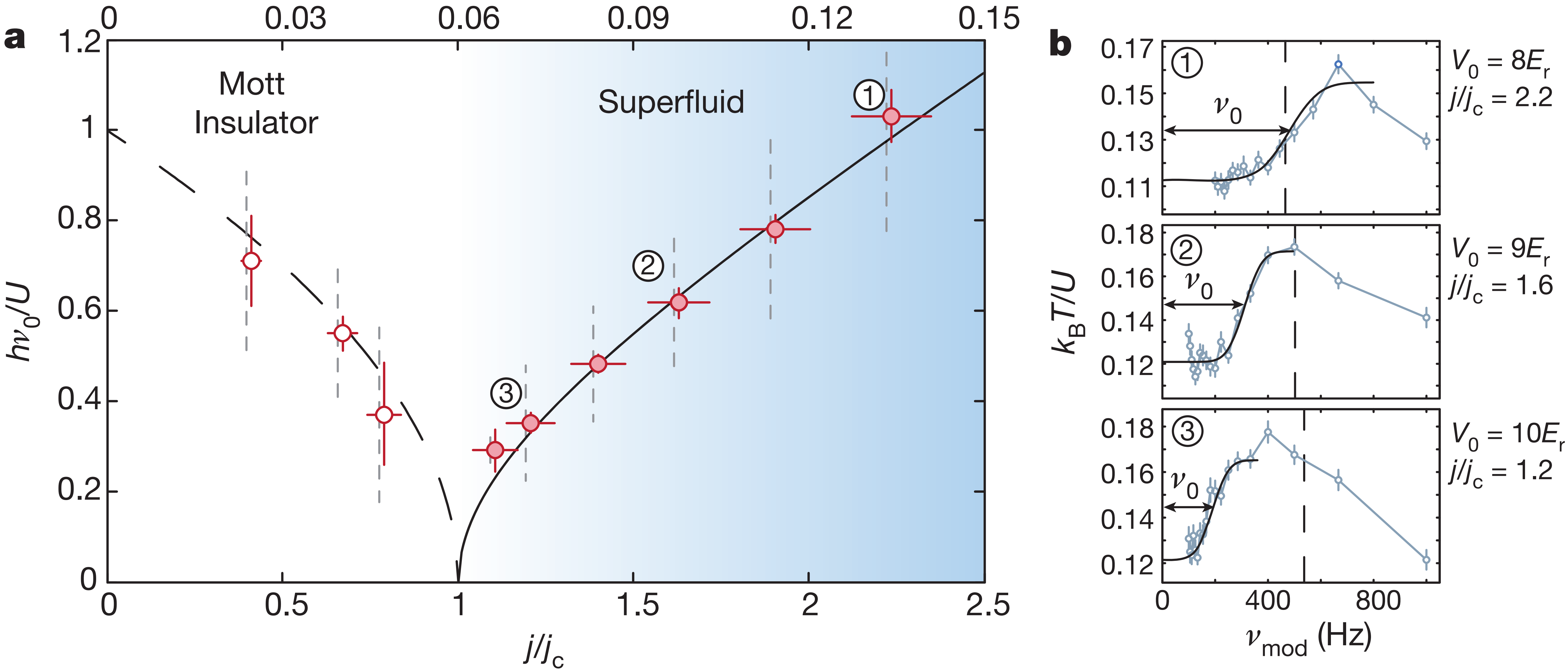
Superfluid

Insulator

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

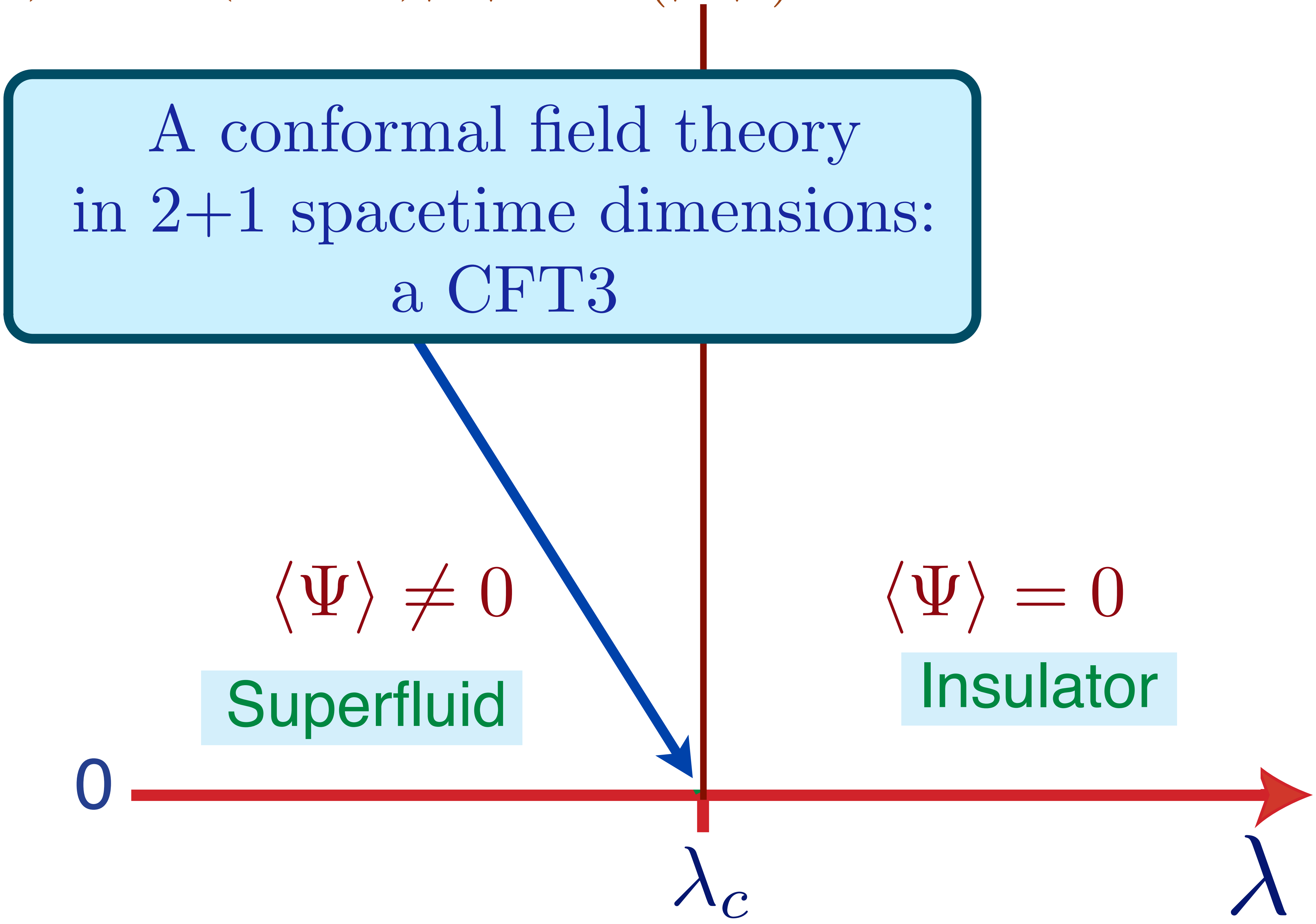




Manuel Endres, Takeshi Fukuhara, David Pekker, Marc Cheneau, Peter Schaub, Christian Gross, Eugene Demler, Stefan Kuhr, and Immanuel Bloch, *Nature* **487**, 454 (2012).

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

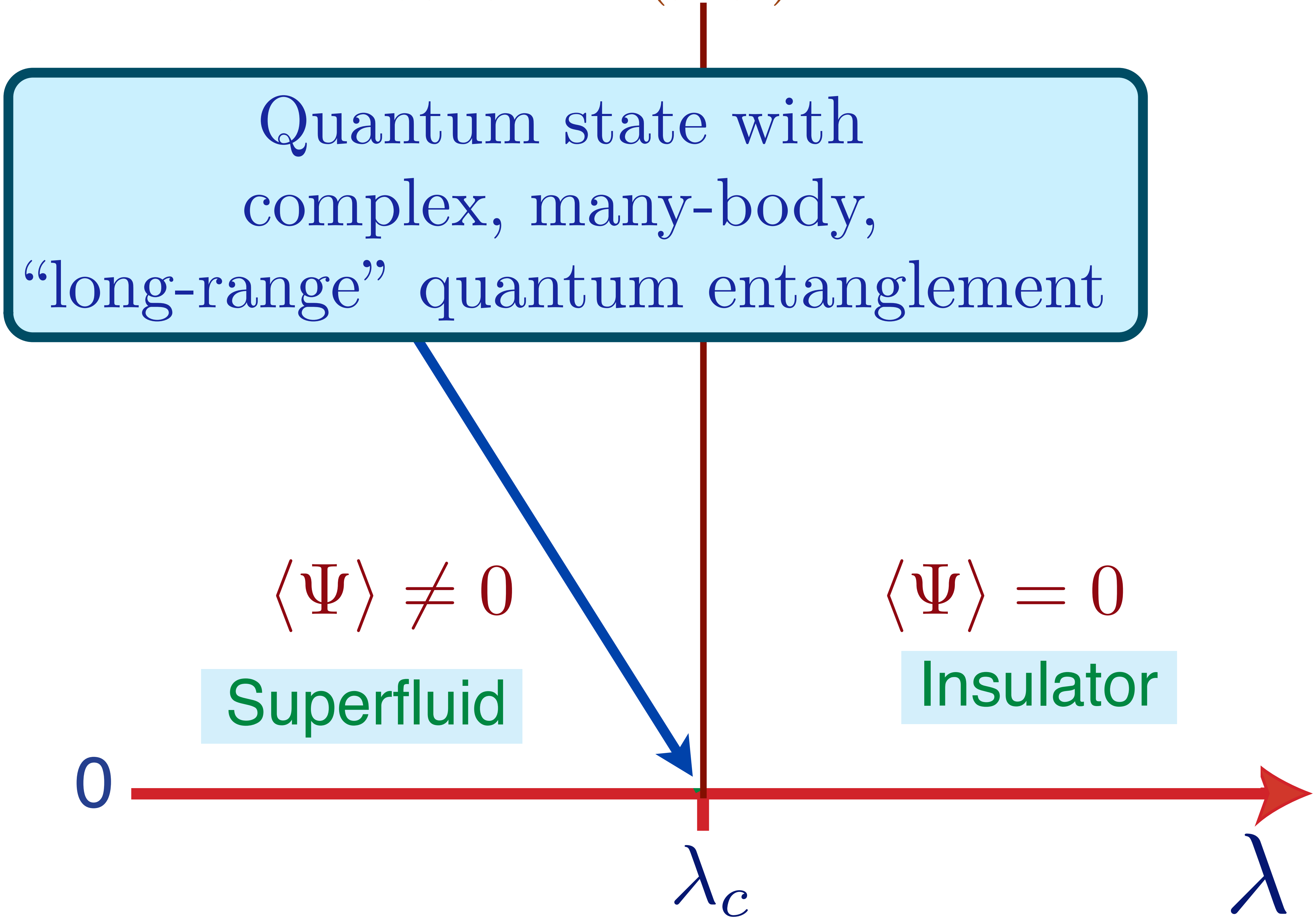
$$V(\Psi) = (\lambda - \lambda_c)|\Psi|^2 + u\left(|\Psi|^2\right)^2$$



A conformal field theory
in 2+1 spacetime dimensions:
a CFT3

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

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



Quantum state with
complex, many-body,
"long-range" quantum entanglement

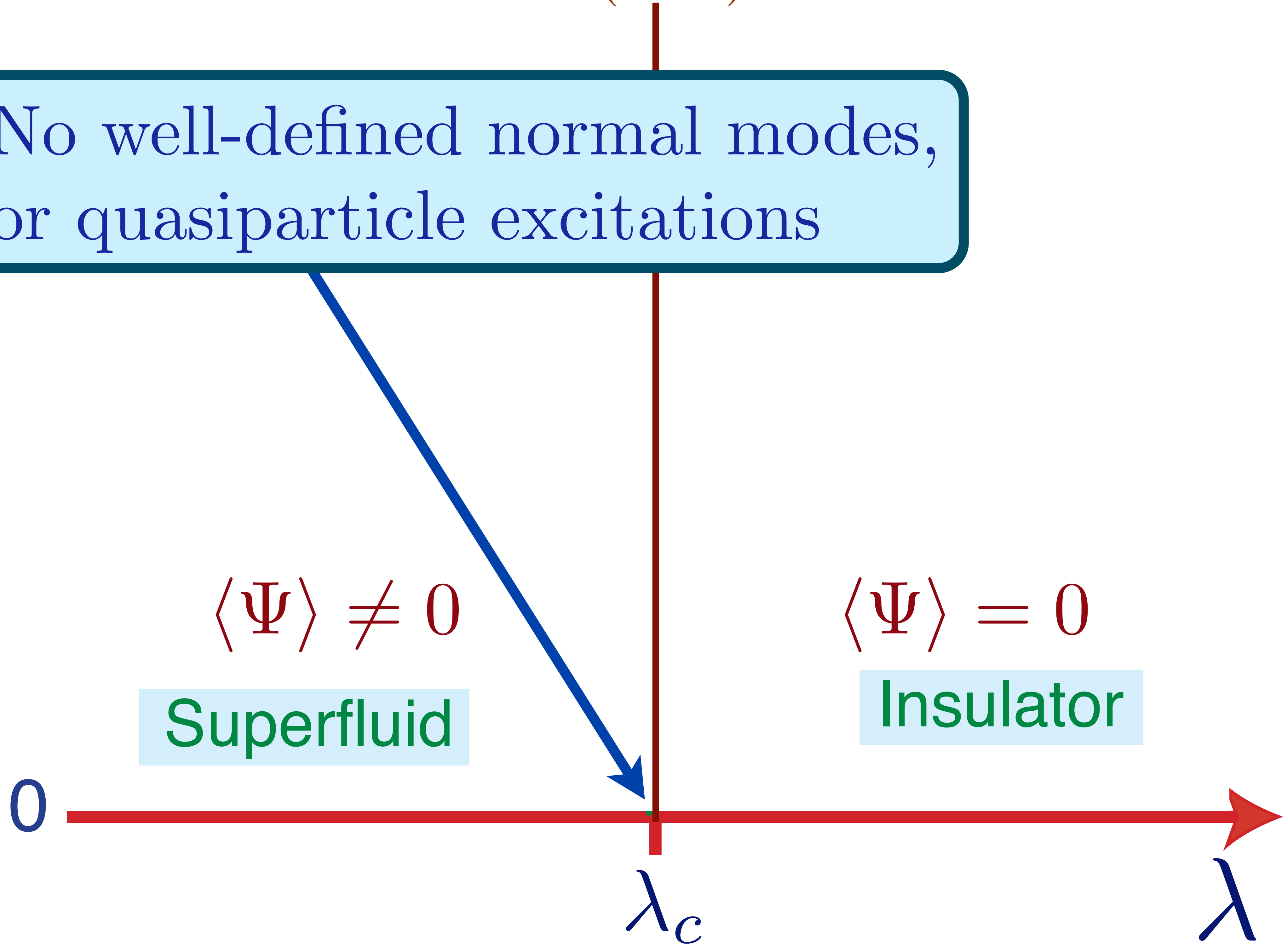
$\langle \Psi \rangle \neq 0$

Superfluid

$\langle \Psi \rangle = 0$

Insulator

$$\begin{aligned}\mathcal{S} &= \int d^2r\,dt\left[|\partial_t\Psi|^2 - c^2|\nabla_r\Psi|^2 - V(\Psi)\right] \\ V(\Psi) &= (\lambda-\lambda_c)|\Psi|^2 + u\left(|\Psi|^2\right)^2\end{aligned}$$



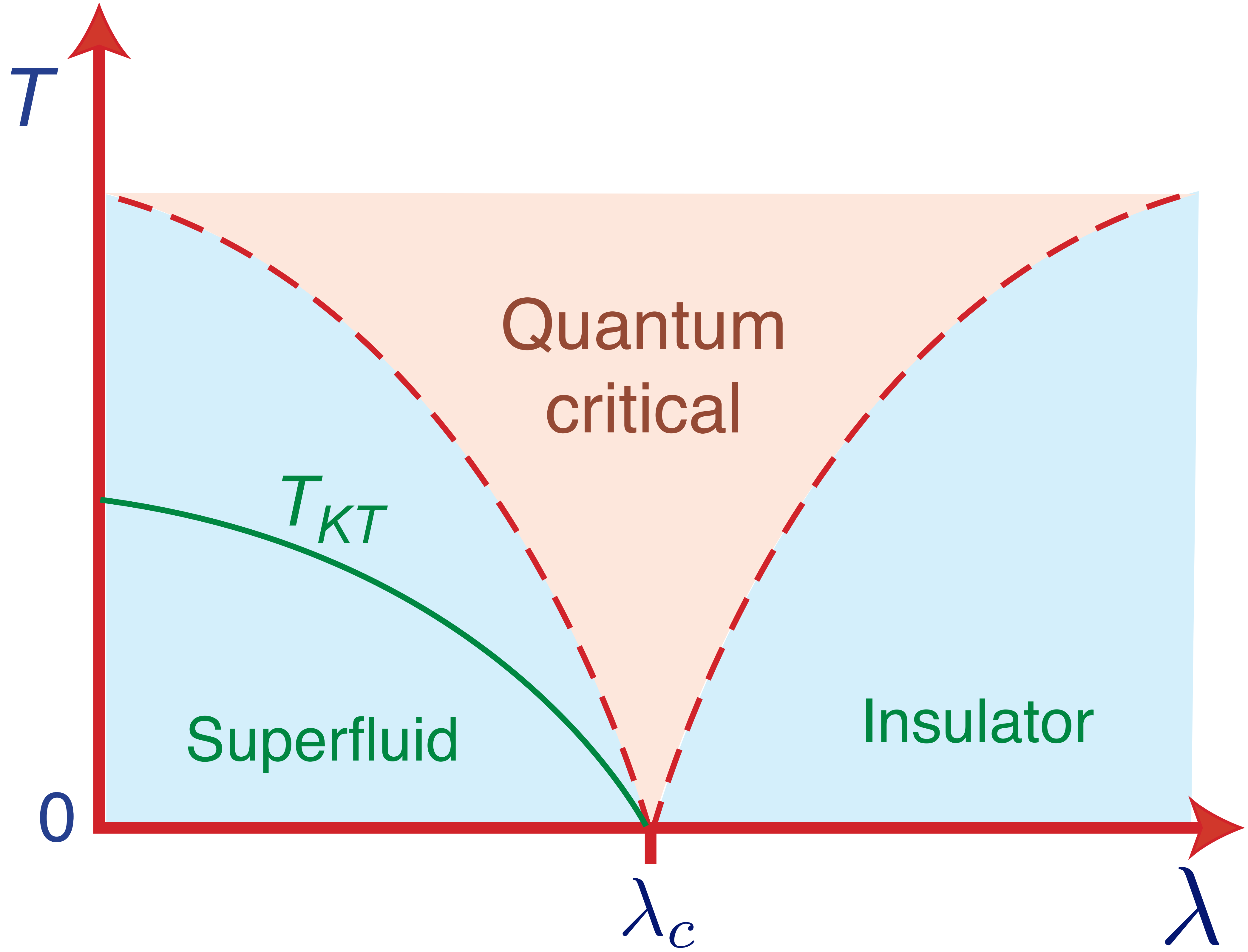
No well-defined normal modes, or quasiparticle excitations

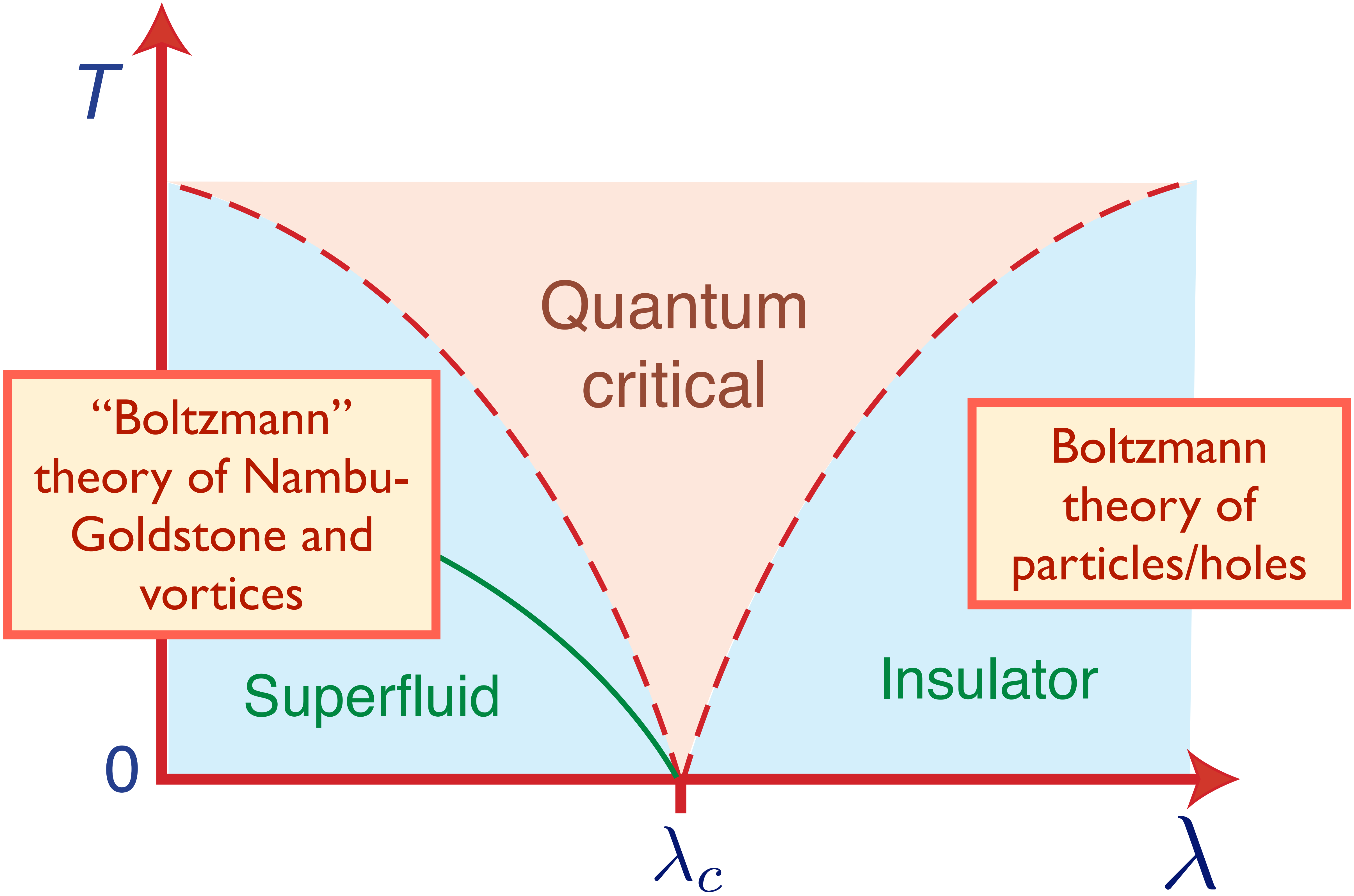
$\langle\Psi\rangle \neq 0$

Superfluid

$\langle\Psi\rangle = 0$

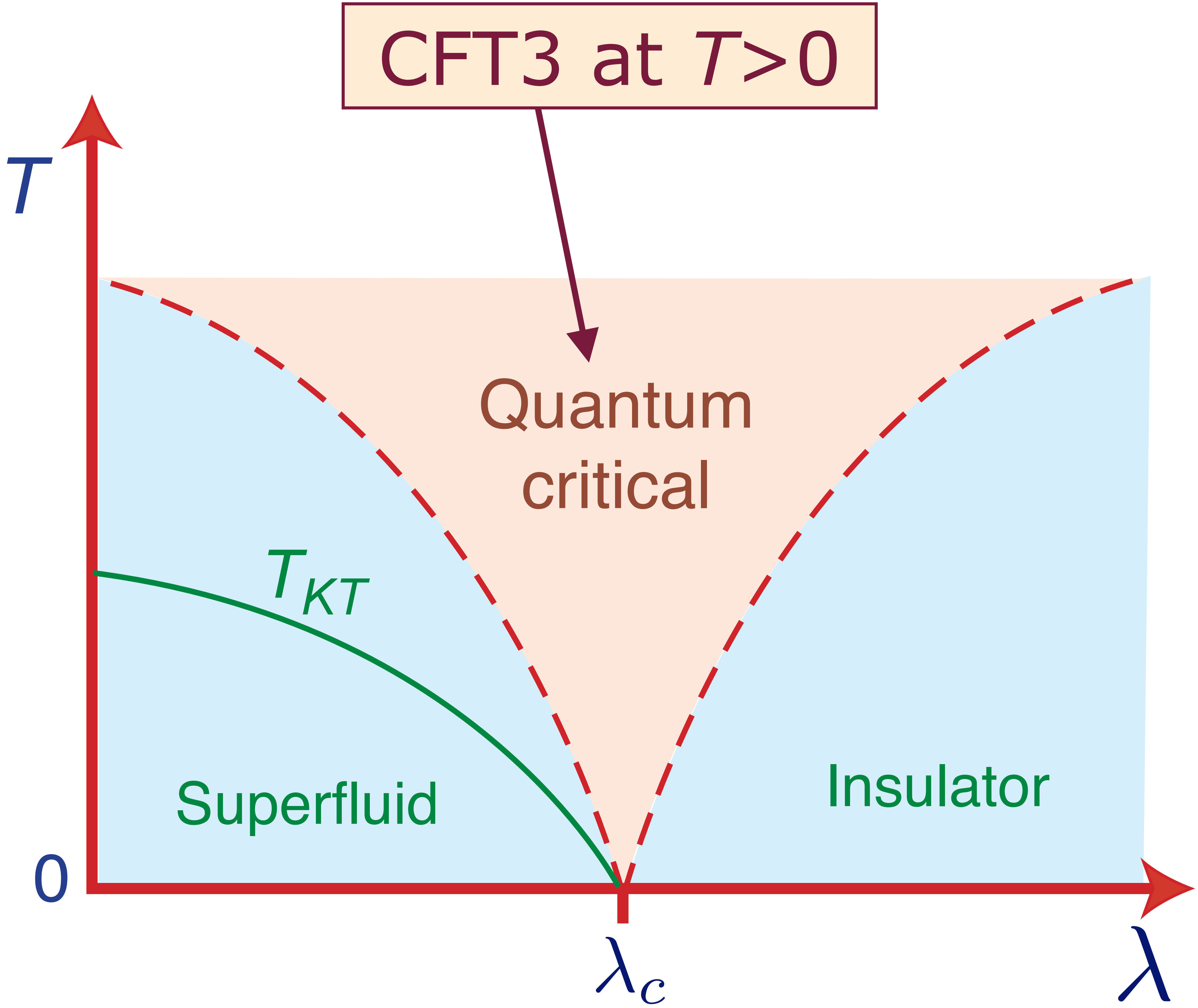
Insulator

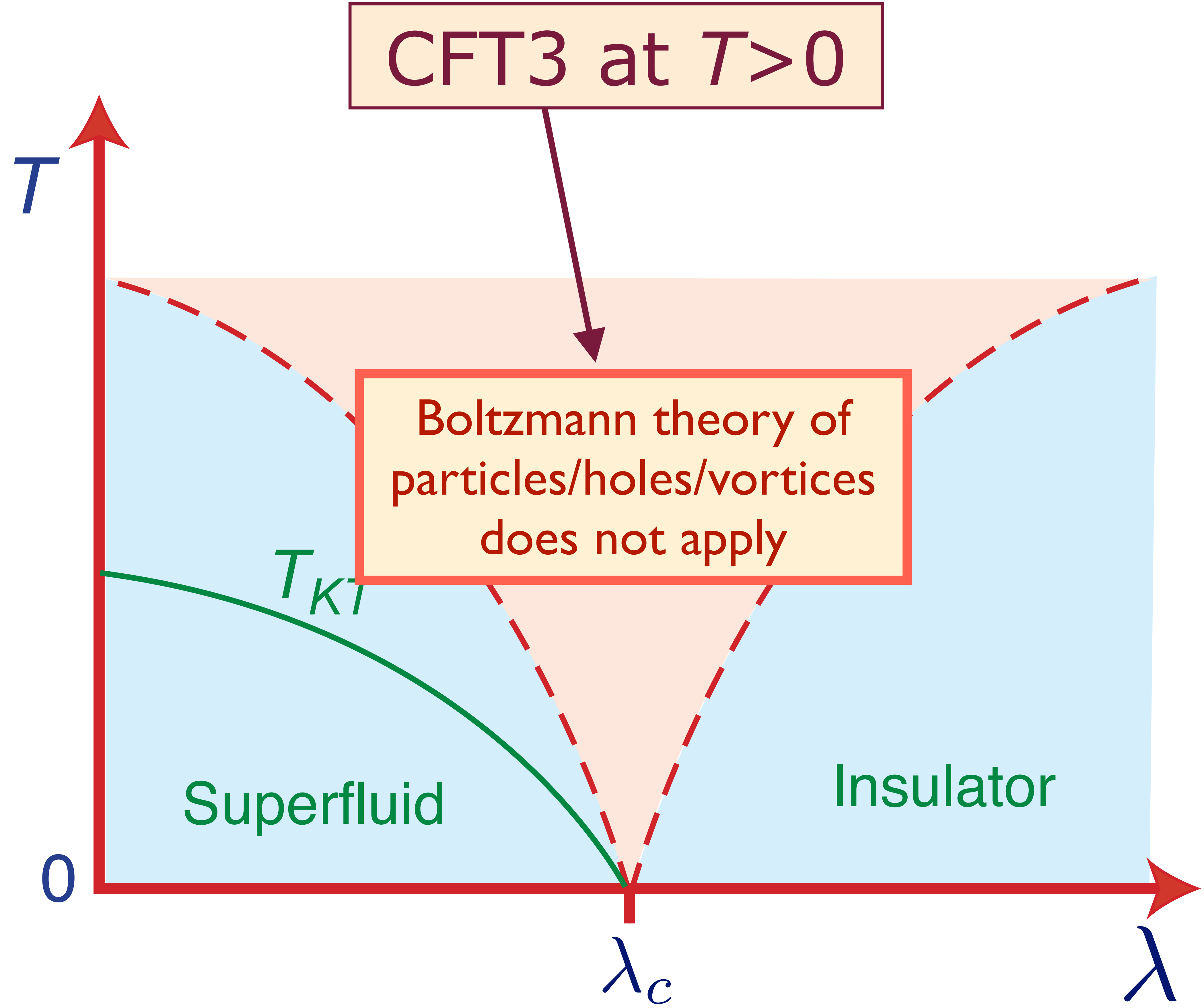

T
Quantum critical
T_{KT}
Superfluid
Insulator
0
λ_c
λ



“Boltzmann” theory of Nambu-Goldstone and vortices

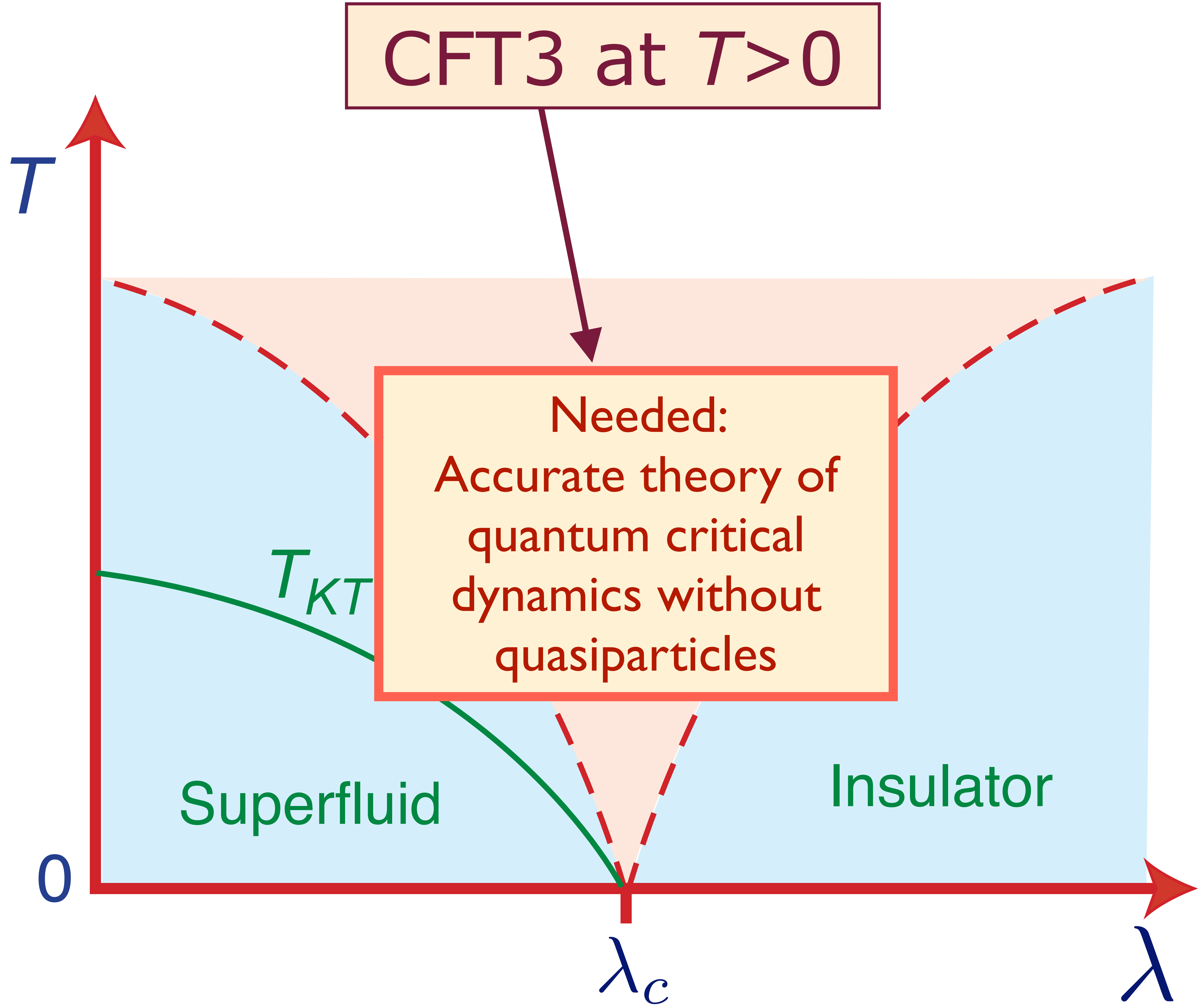
Boltzmann theory of particles/holes


CFT3 at $T>0$
T
Quantum critical
T_{KT}
Superfluid
Insulator
0
λ_c
λ



CFT3 at $T>0$

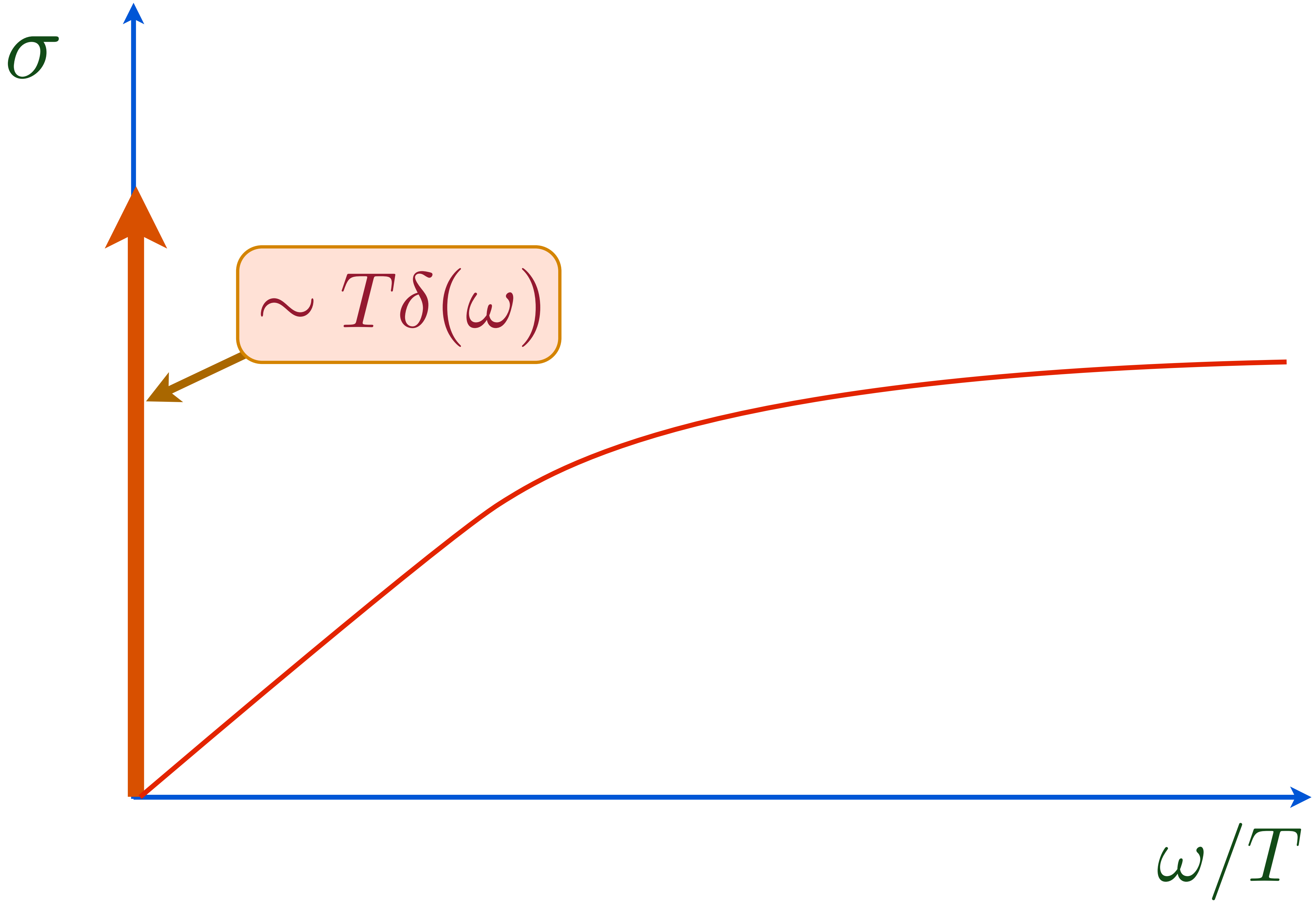
Boltzmann theory of particles/holes/vortices does not apply



CFT3 at $T>0$

Needed:
Accurate theory of quantum critical dynamics without quasiparticles

Electrical transport in a free quasiparticle CFT3 for *T* > *0*

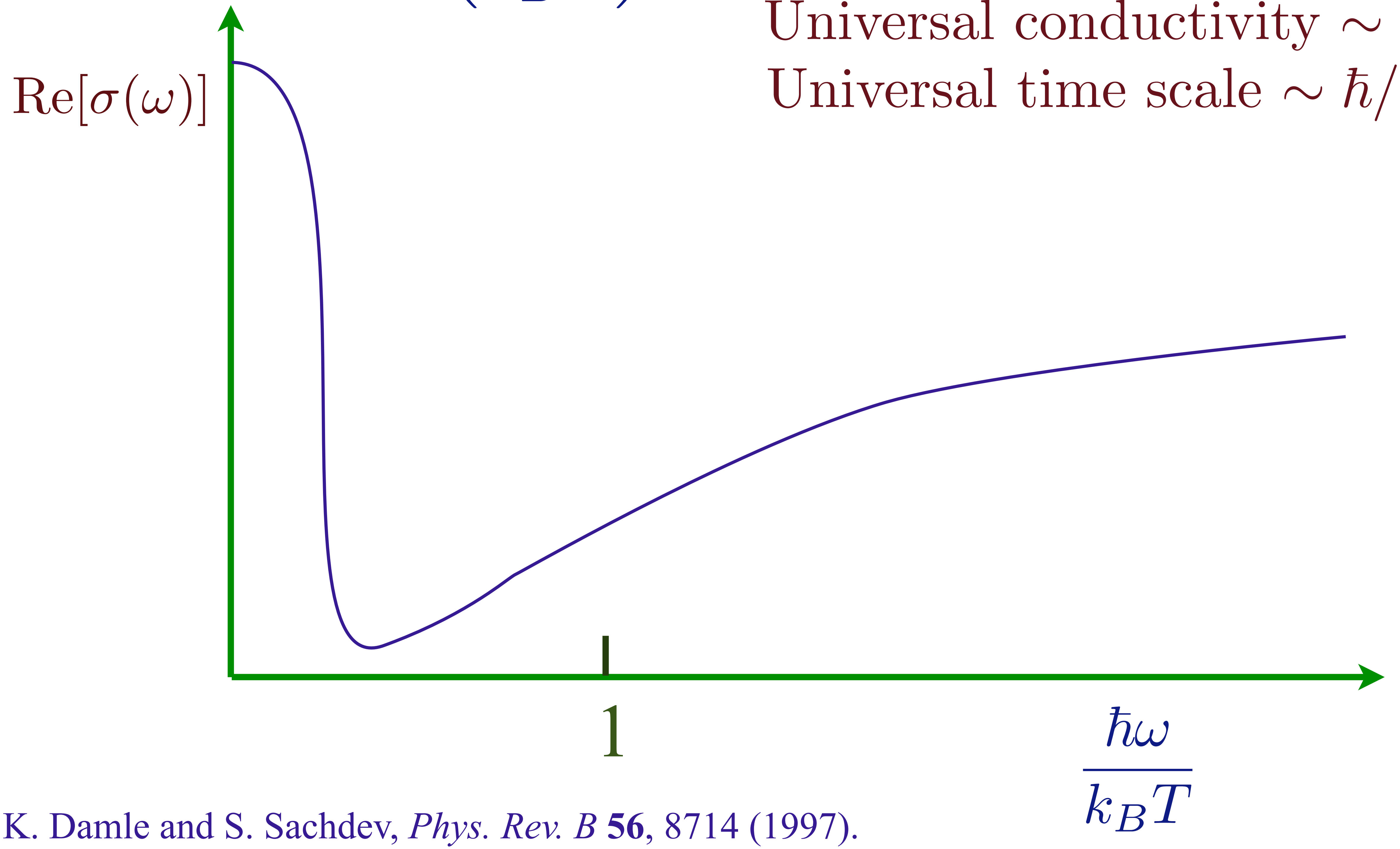


Quasiparticle view of quantum criticality: Electrical transport for a (weakly) interacting CFT3

$$\sigma(\omega, T) = \frac{e^2}{h}\Sigma\left(\frac{\hbar\omega}{k_B T}\right) \quad ; \qquad \Sigma \to \text{a universal function}$$

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).

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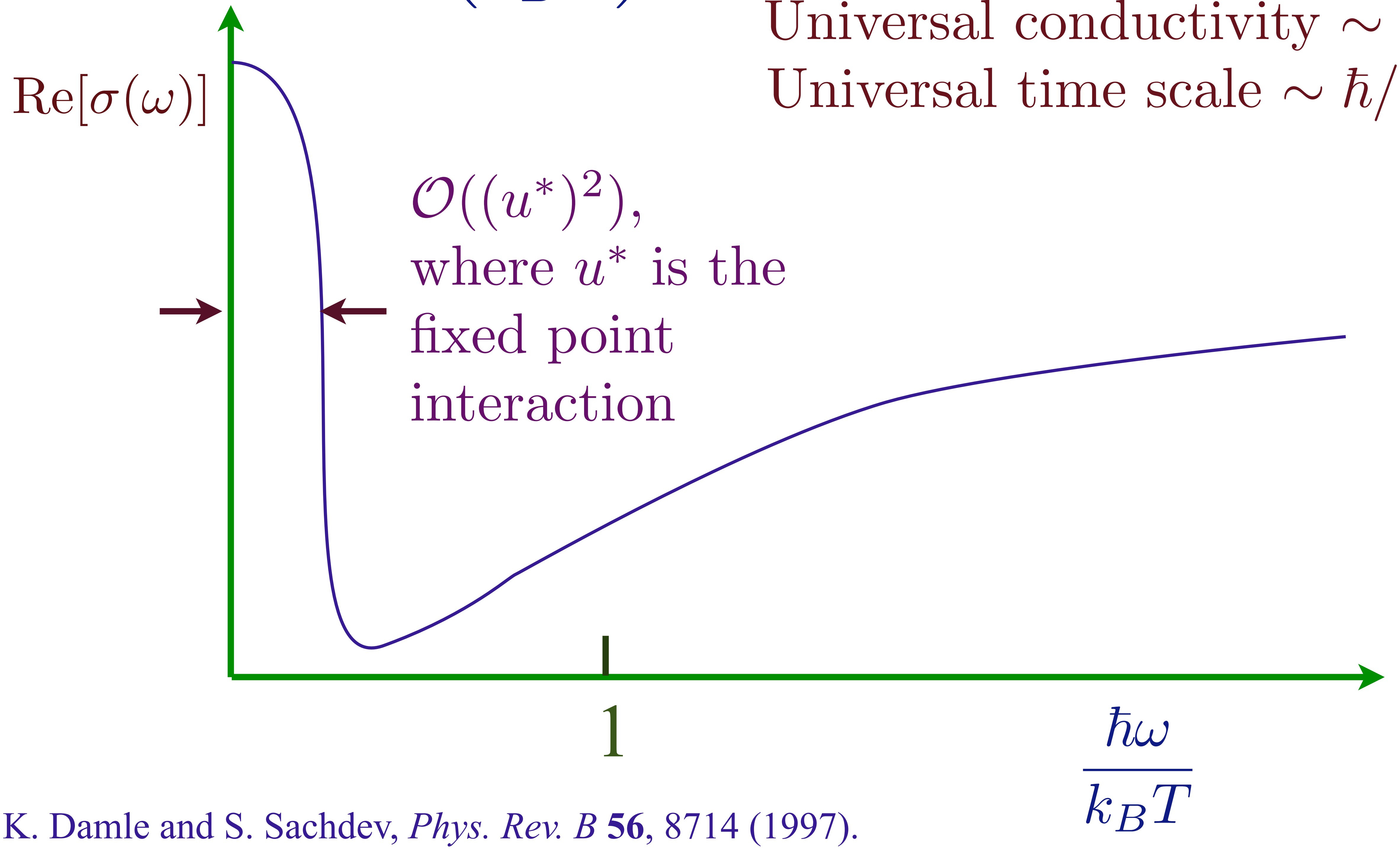

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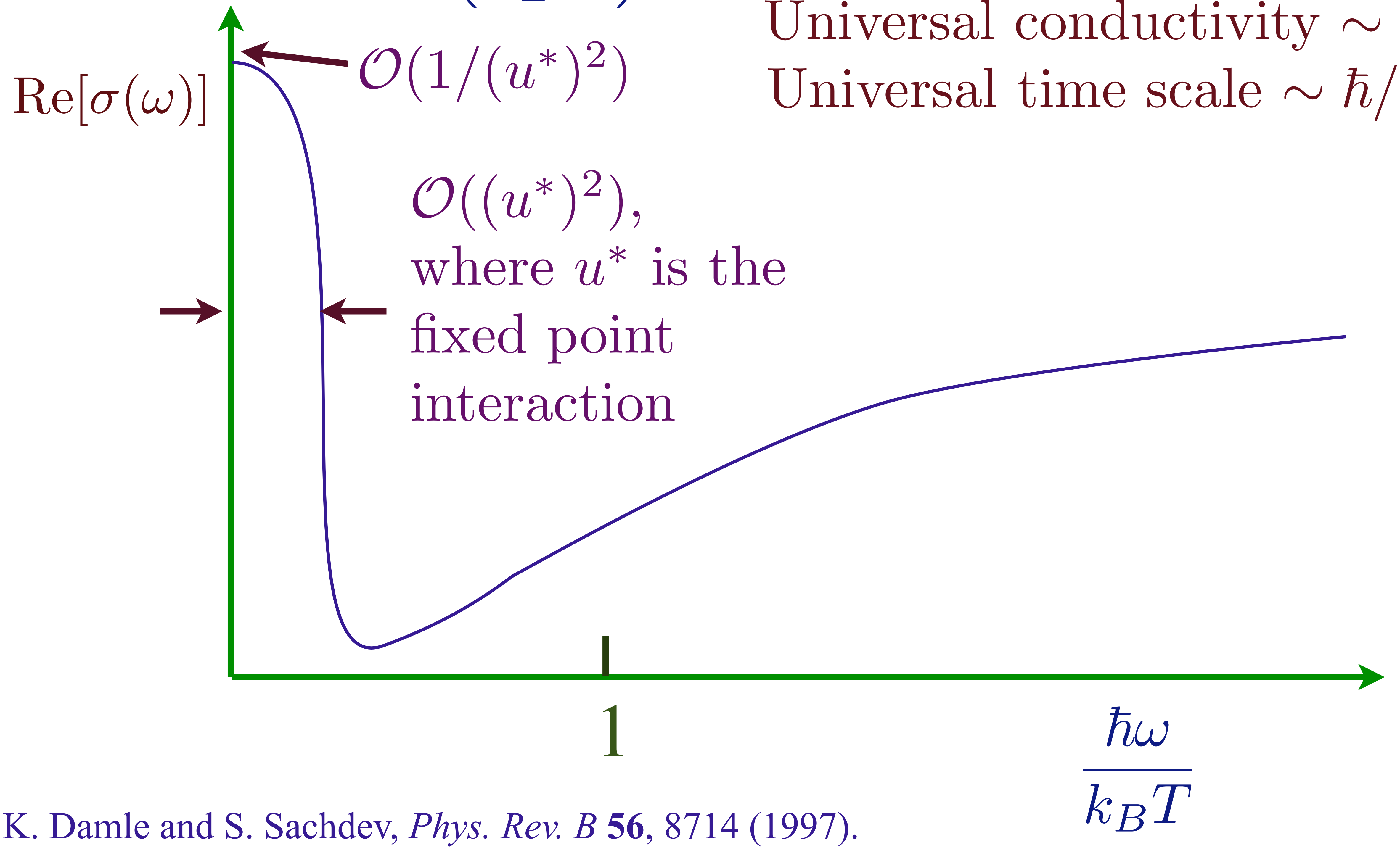

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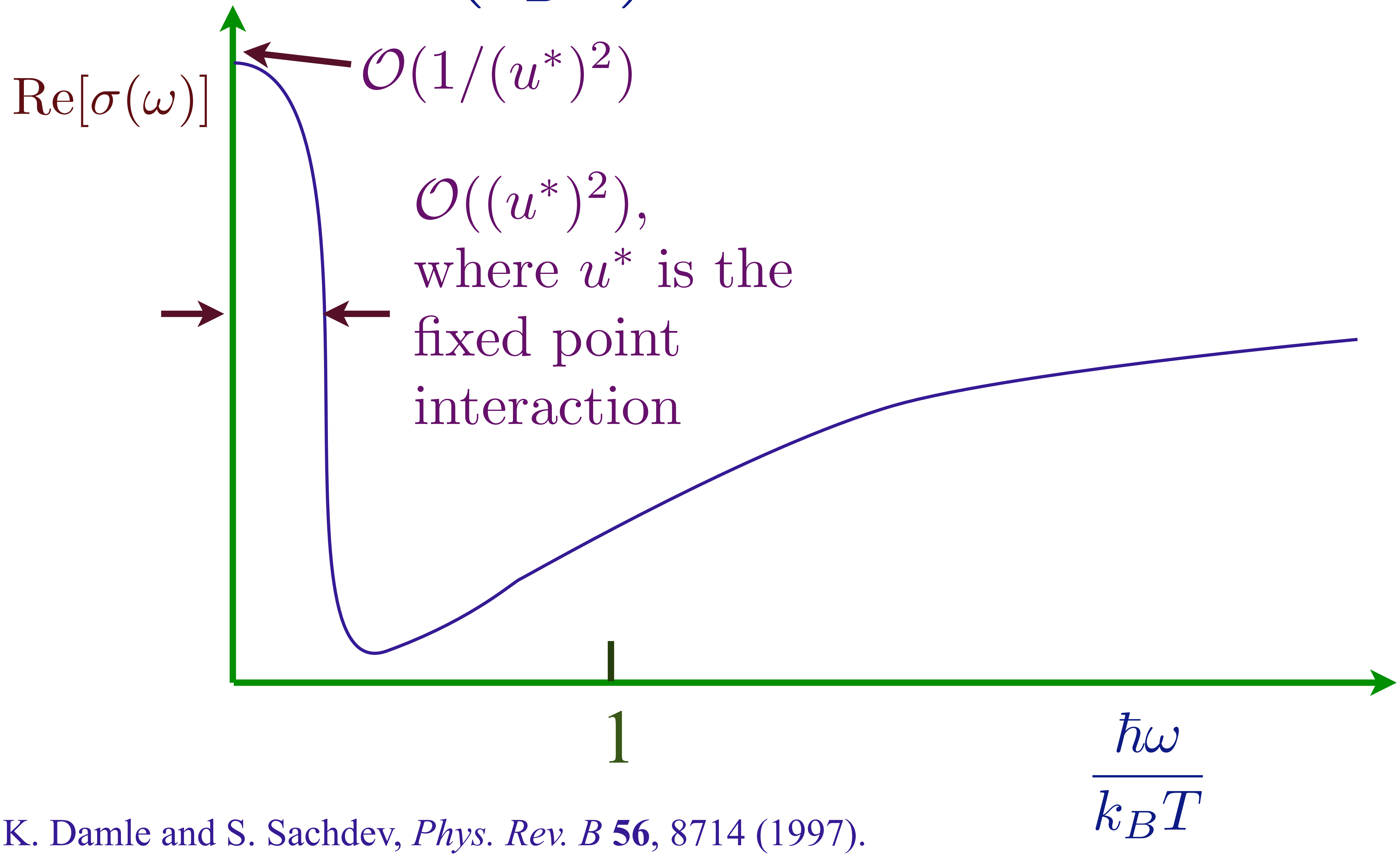

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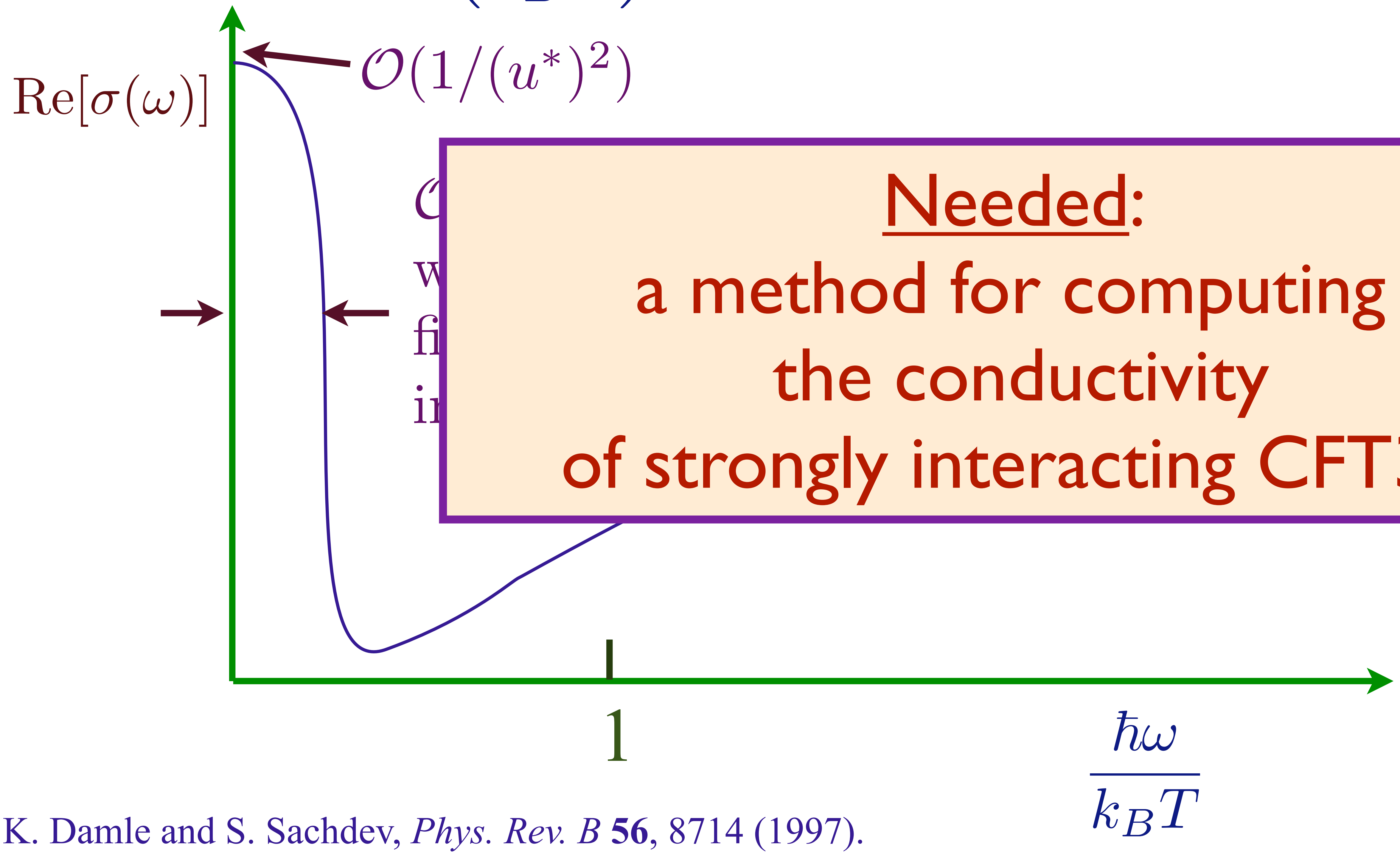
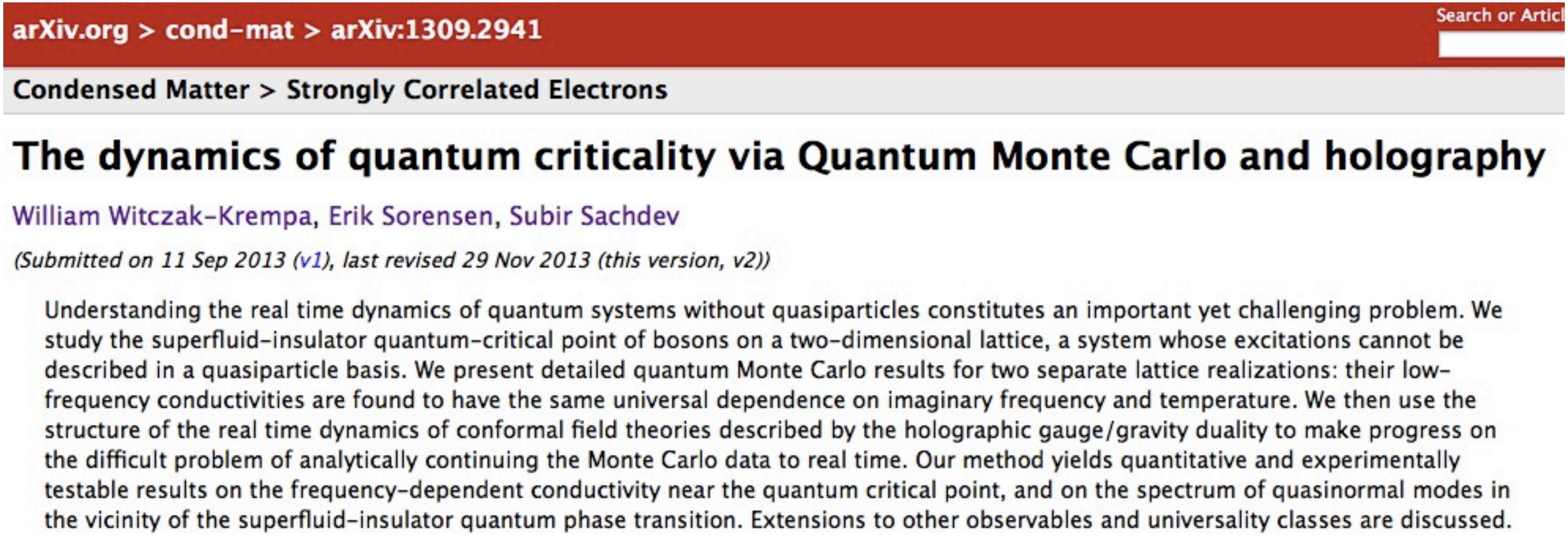


<u>Needed</u>:
a method for computing
the conductivity
of strongly interacting CFT3s

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



arXiv.org > cond-mat > arXiv:1309.2941

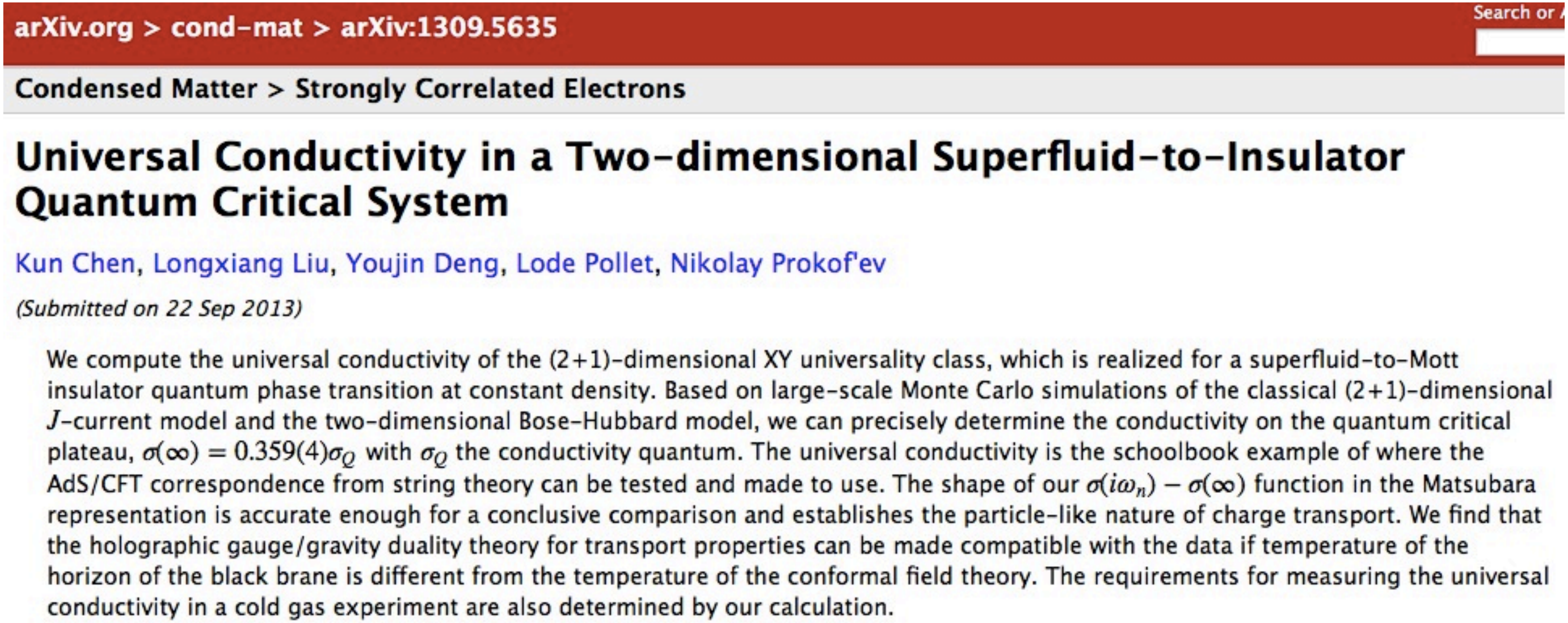
Condensed Matter > Strongly Correlated Electrons

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.



arXiv.org > cond-mat > arXiv:1309.5635

Condensed Matter > Strongly Correlated Electrons

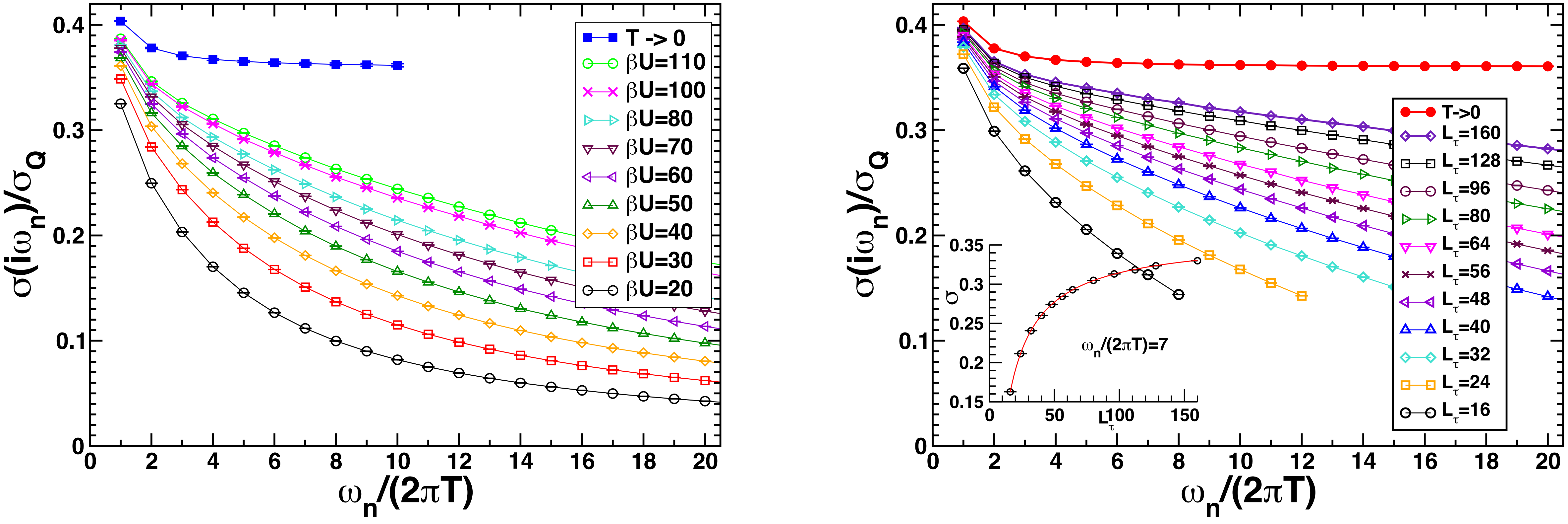
Universal Conductivity in a Two-dimensional Superfluid-to-Insulator Quantum Critical System

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)

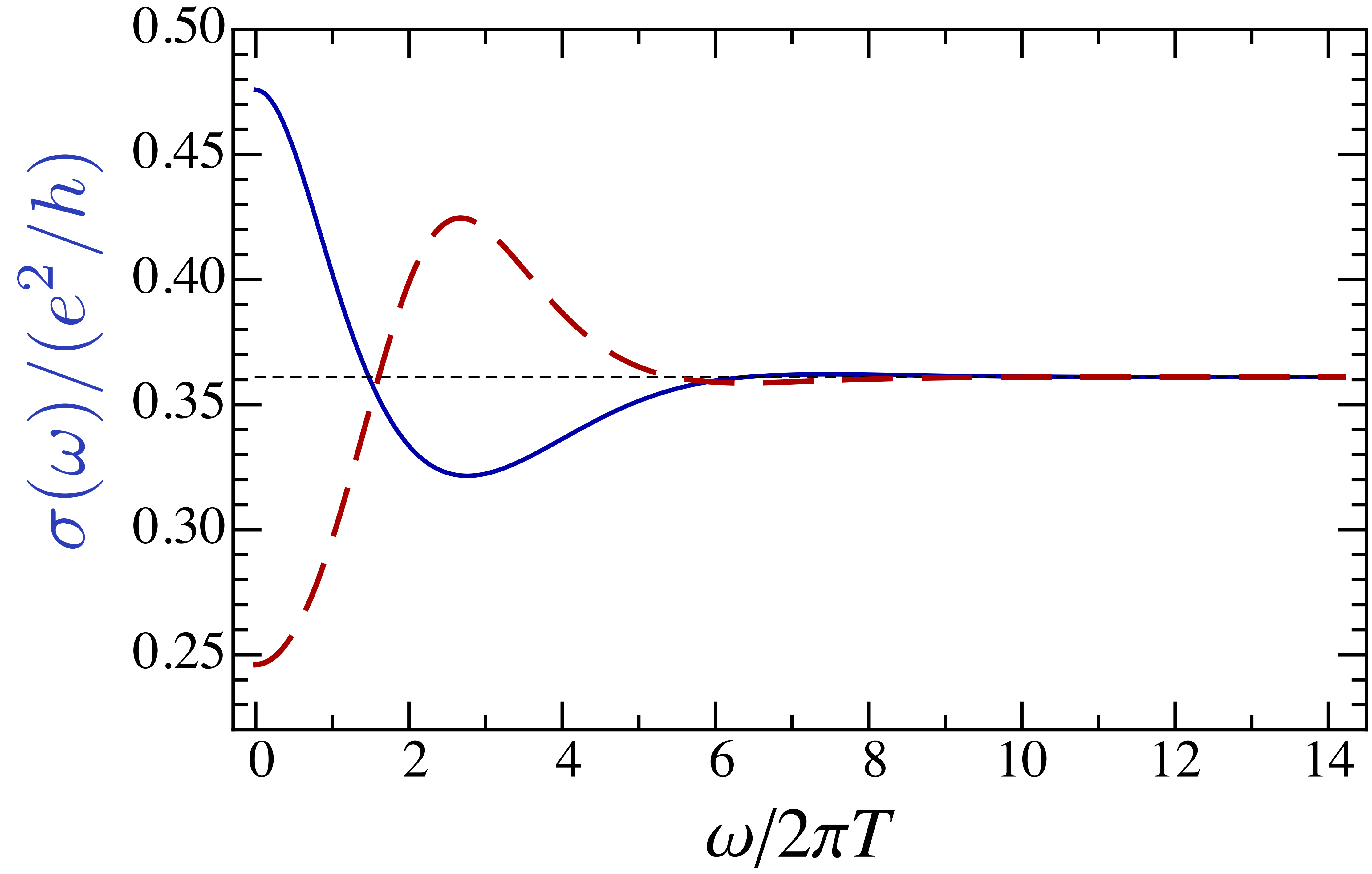
(b)

FIG. 2. **Quantum Monte Carlo data** (a) Finite-temperature conductivity for a range of βU in the $L \rightarrow \infty$ limit for the quantum rotor model at $(t/U)_c$. The solid blue squares indicate the final $T \rightarrow 0$ extrapolated data. (b) Finite-temperature conductivity in the $L \rightarrow \infty$ limit for a range of L_τ for the Villain model at the QCP. The solid red circles indicate the final $T \rightarrow 0$ 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

Quantum Monte Carlo for lattice bosons



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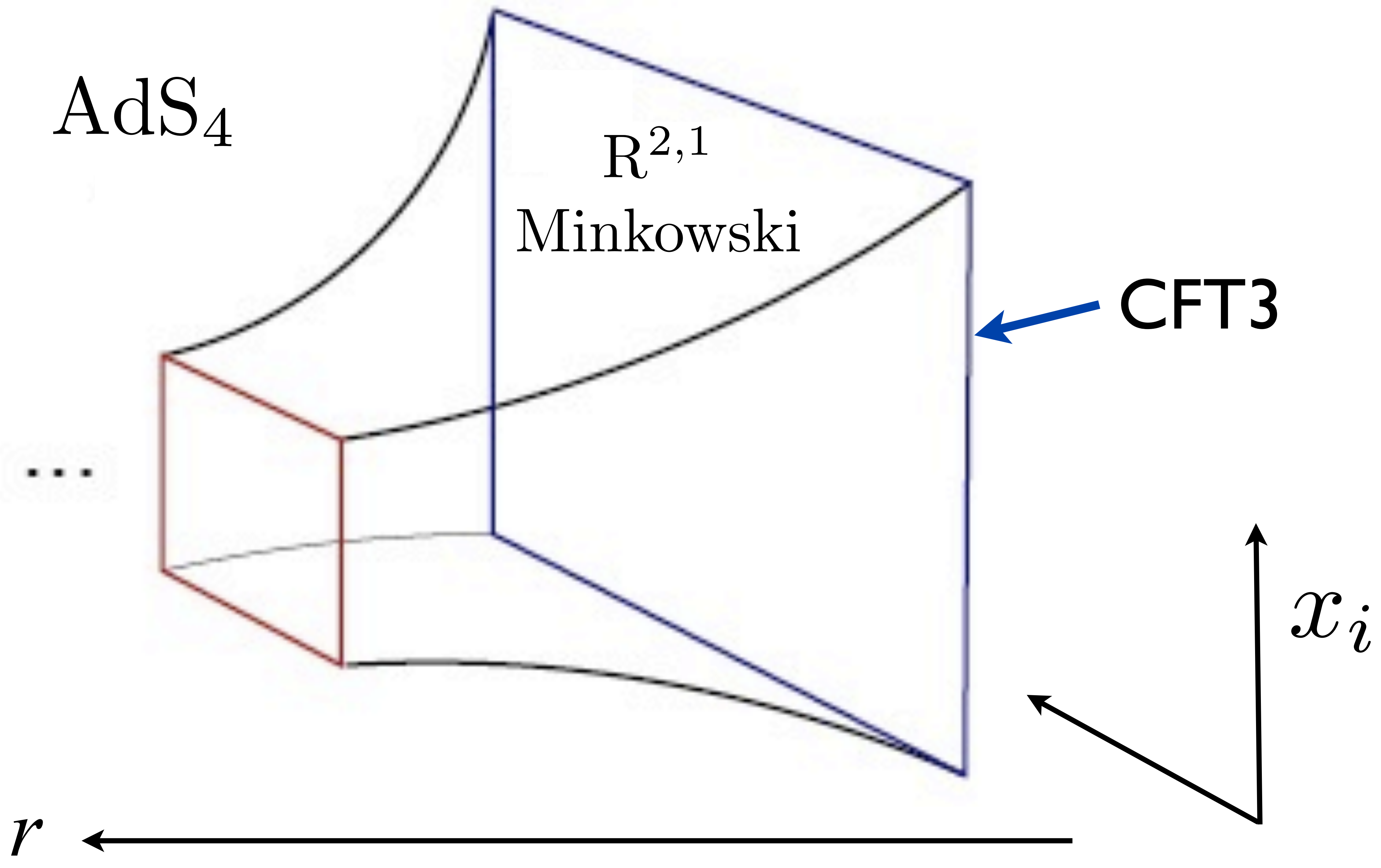
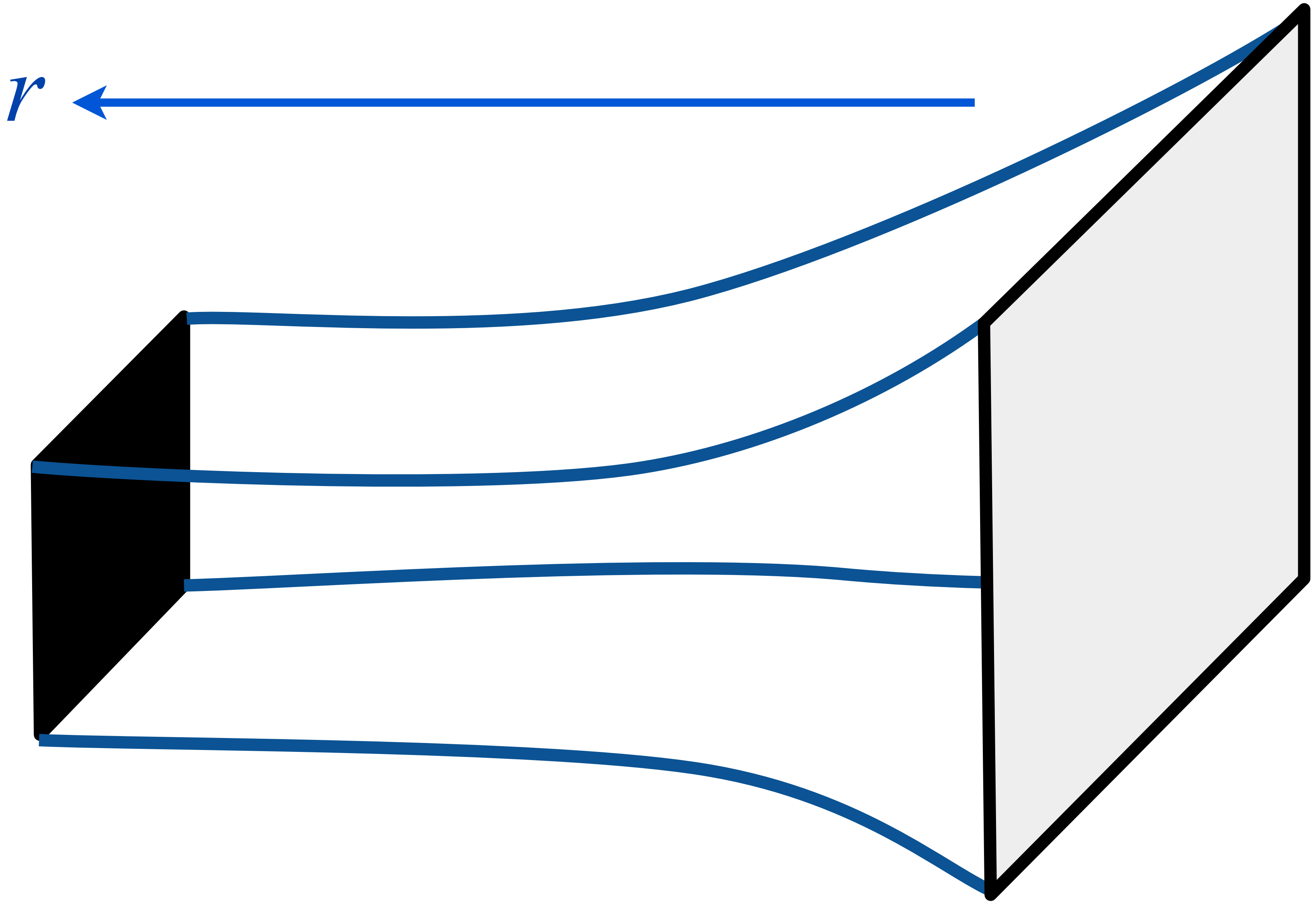
AdS/CFT correspondence



This emergent spacetime is a solution of Einstein gravity with a negative cosmological constant

$$\mathcal{S}_E = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}\left(R+\frac{6}{L^2}\right)\right]$$

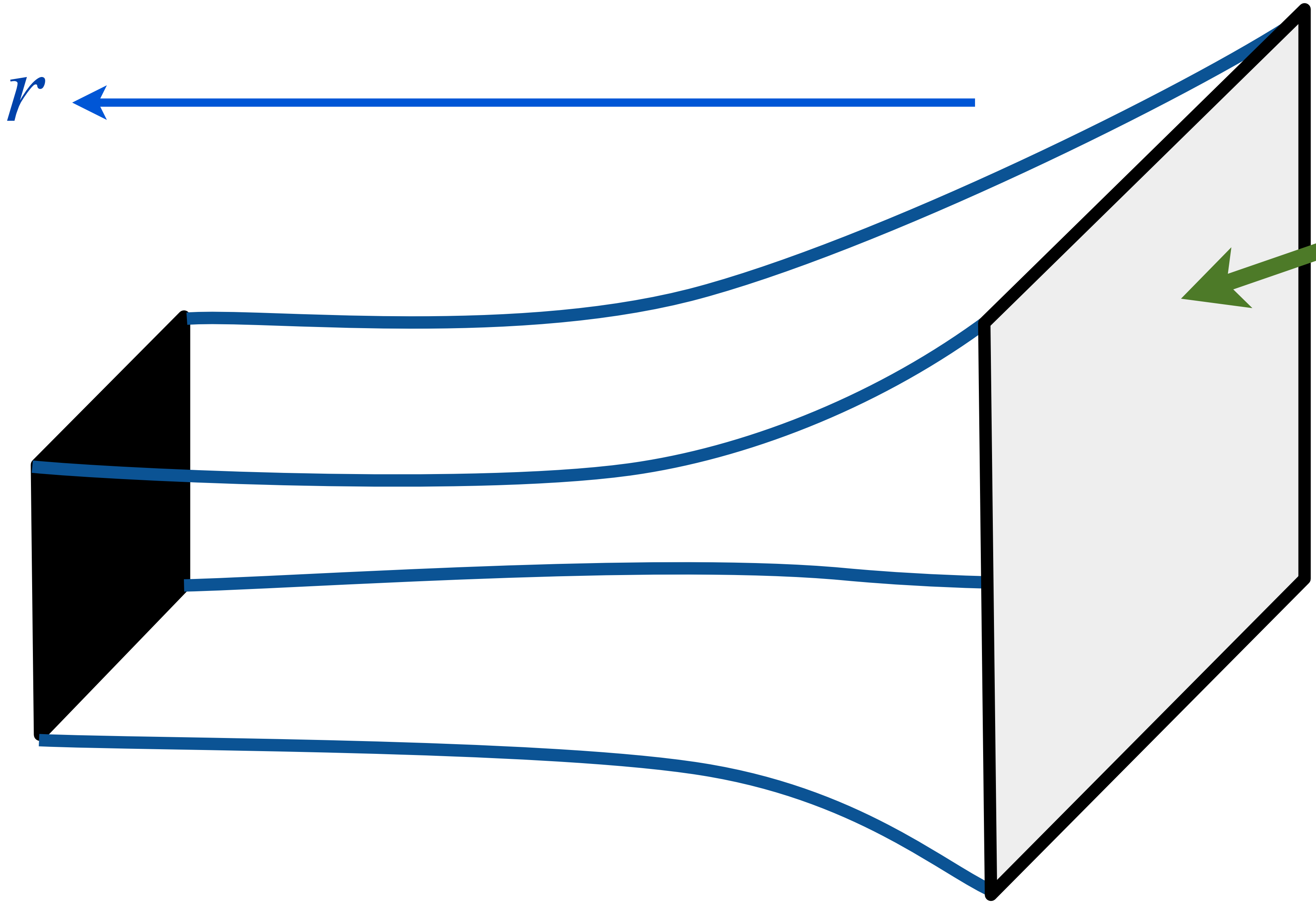
Gauge-gravity duality at non-zero temperatures



There is a family of solutions of Einstein gravity which describe non-zero temperatures

$$\mathcal{S}_E = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}\left(R + \frac{6}{L^2}\right)\right]$$

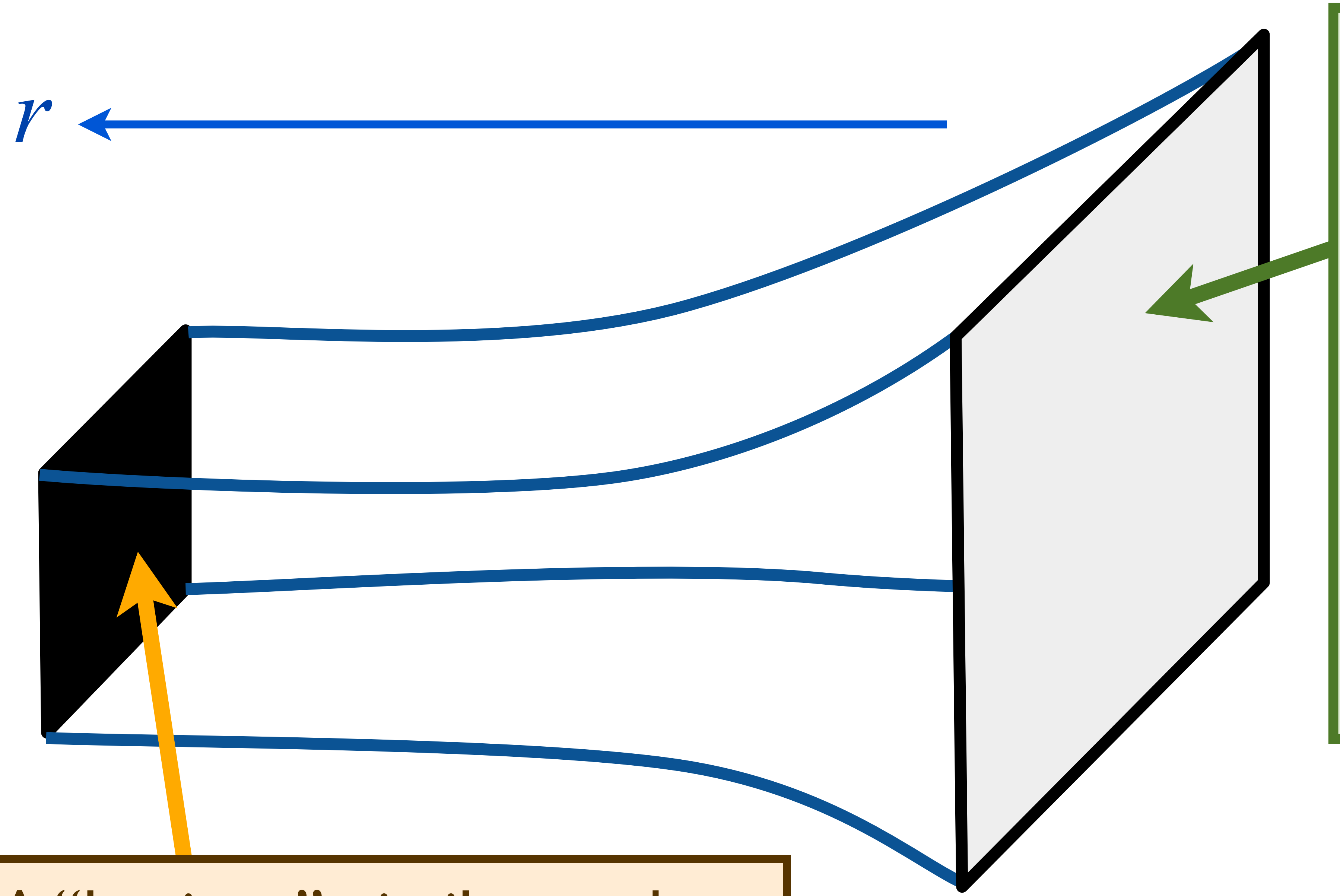
Gauge-gravity duality at non-zero temperatures



A 2+1 dimensional system at $T > 0$ with couplings at its quantum critical point

$$\mathcal{S}_E = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} \left(R + \frac{6}{L^2} \right) \right]$$

Gauge-gravity duality at non-zero temperatures



A 2+1 dimensional system at $T > 0$ with couplings at its quantum critical point

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

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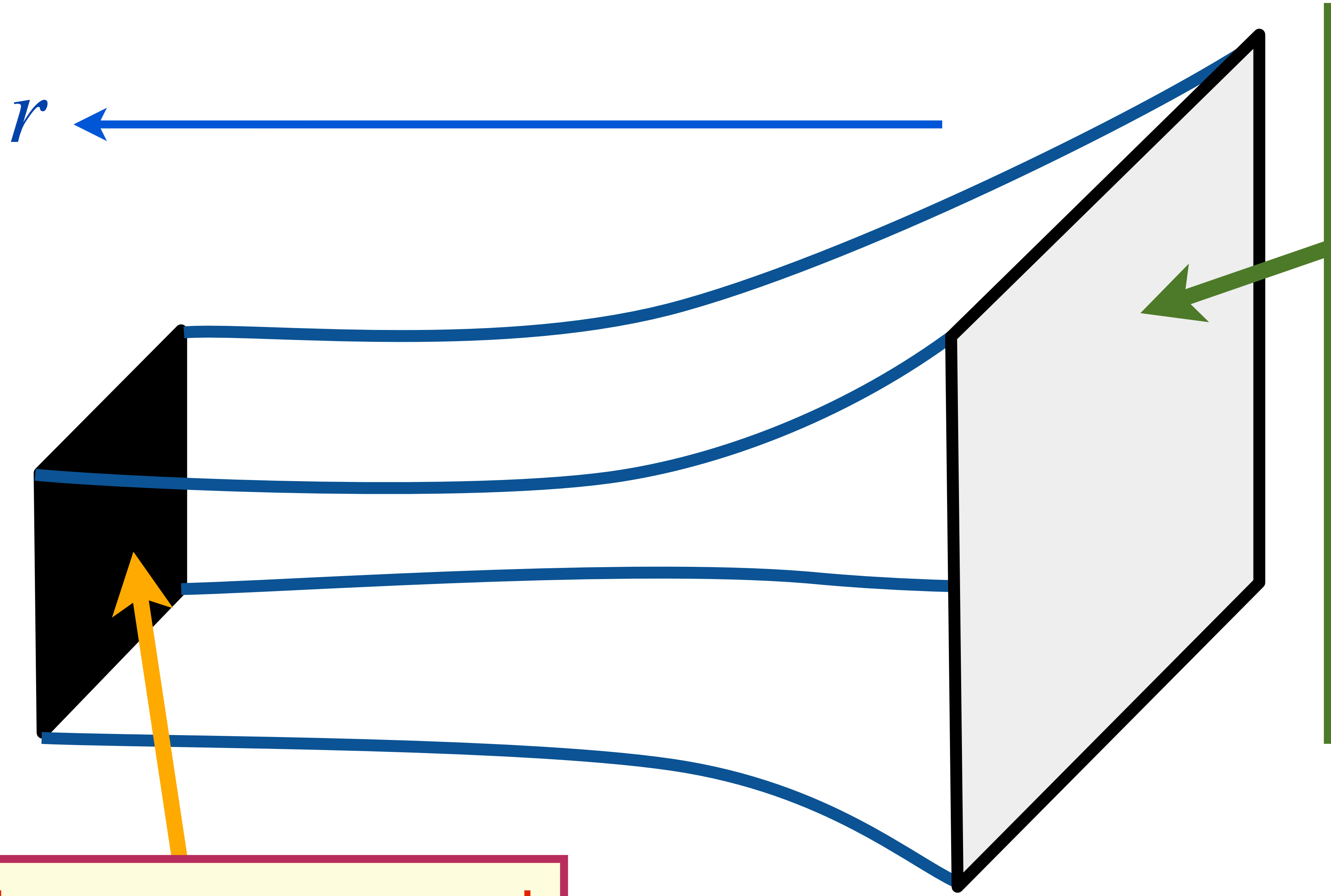
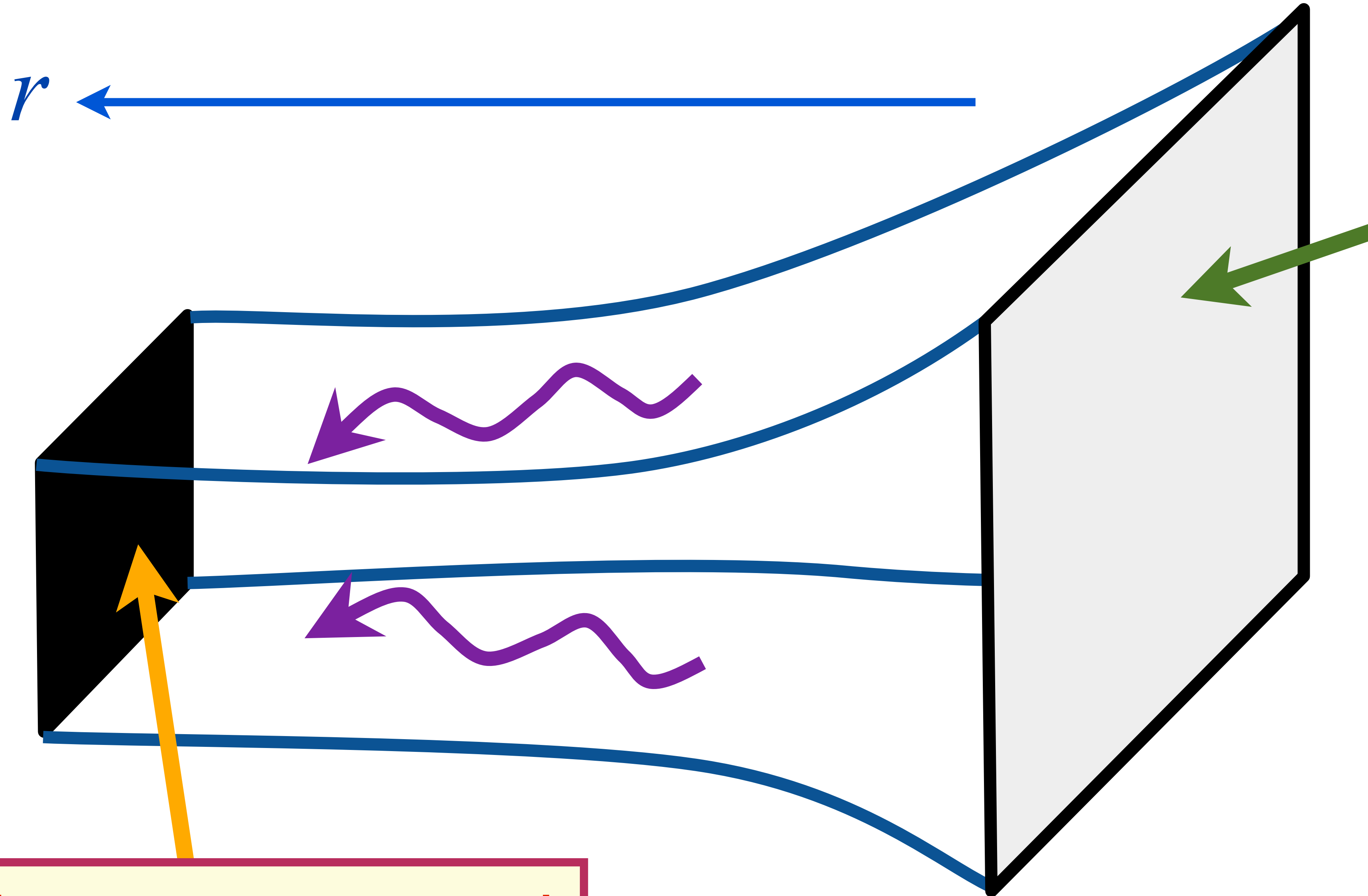


A 2+1 dimensional system at $T > 0$ with couplings at its quantum critical point

The temperature and entropy of the horizon equal those of the quantum critical point

Gauge-gravity duality at non-zero temperatures

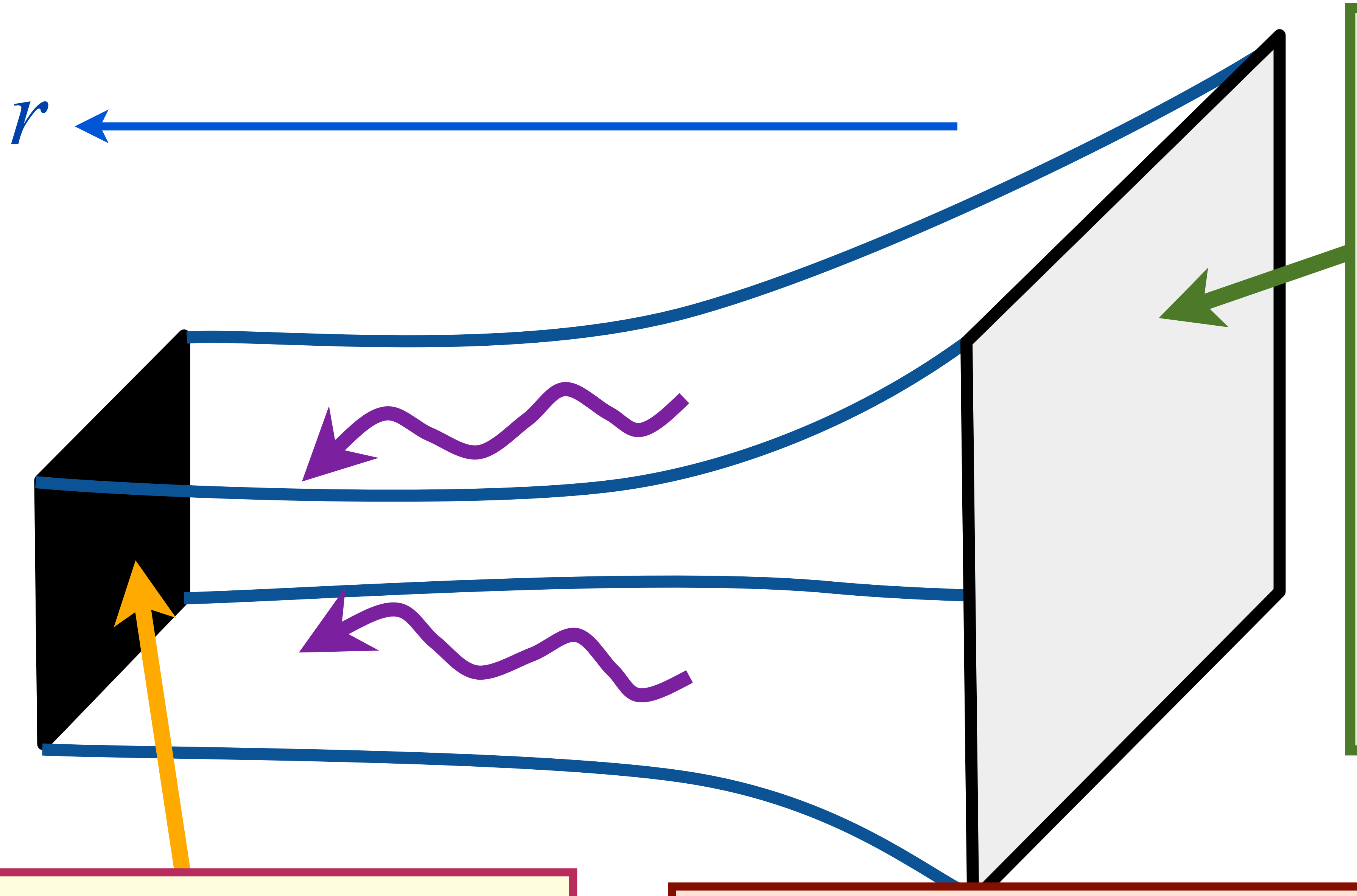


A 2+1 dimensional system at $T > 0$ with couplings at its quantum critical point

The temperature and entropy of the horizon equal those of the quantum critical point

Quasi-normal modes of quantum criticality = waves falling into black hole

Gauge-gravity duality at non-zero temperatures



A 2+1 dimensional system at $T > 0$ with couplings at its quantum critical point

The temperature and entropy of the horizon equal those of the quantum critical point

Characteristic damping time of quasi-normal modes: $(k_B/\hbar)\times$ Hawking temperature

Traditional CMT

- Identify quasiparticles and their dispersions

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

- These parameters are input into a quantum Boltzmann equation

- Deduce dissipative and dynamic properties at non-zero temperatures

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- Solve Einsten-Maxwell equations. Dynamics of quasi-normal modes of black branes.

AdS₄ theory of quantum criticality

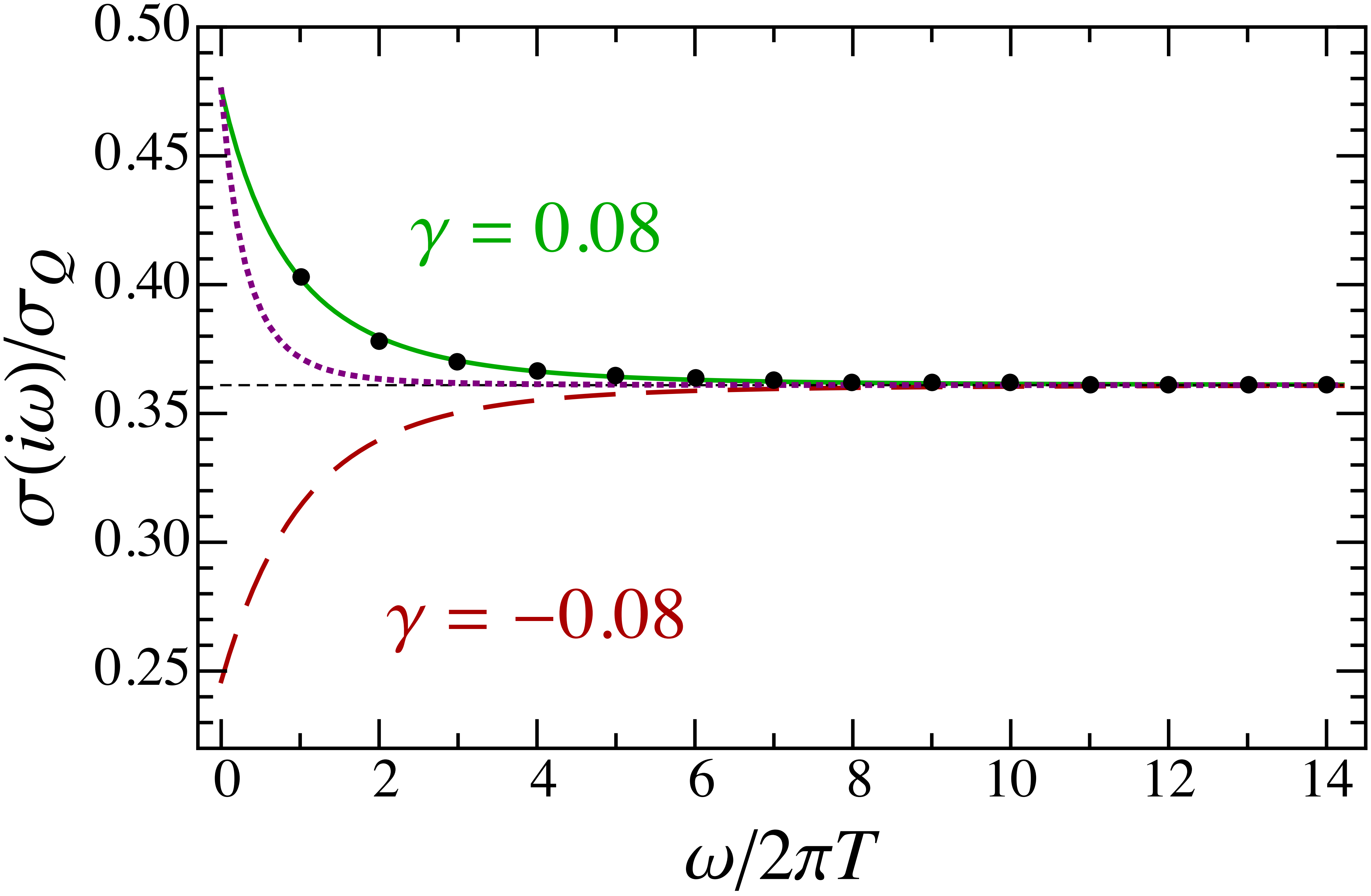
Most general effective holographic theory for linear charge transport with 4 spatial derivatives:

$$\mathcal{S}_{\text{bulk}} = \frac{1}{g_M^2}\int d^4x\,\sqrt{g}\left[\frac{1}{4}F_{ab}F^{ab} + \gamma L^2 C_{abcd}F^{ab}F^{cd}\right] + \int d^4x\sqrt{g}\left[-\frac{1}{2\kappa^2}\left(R + \frac{6}{L^2}\right)\right],$$

This action is characterized by 3 dimensionless parameters, which can be linked to data of the CFT (OPE coefficients): 2-point correlators of the conserved current J_μ and the stress energy tensor $T_{\mu\nu}$, and a 3-point T, J, J correlator. Constraints from both the CFT and the gravitational theory bound $|\gamma| \leq 1/12 = 0.0833$..

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

AdS$_4$ theory of quantum criticality

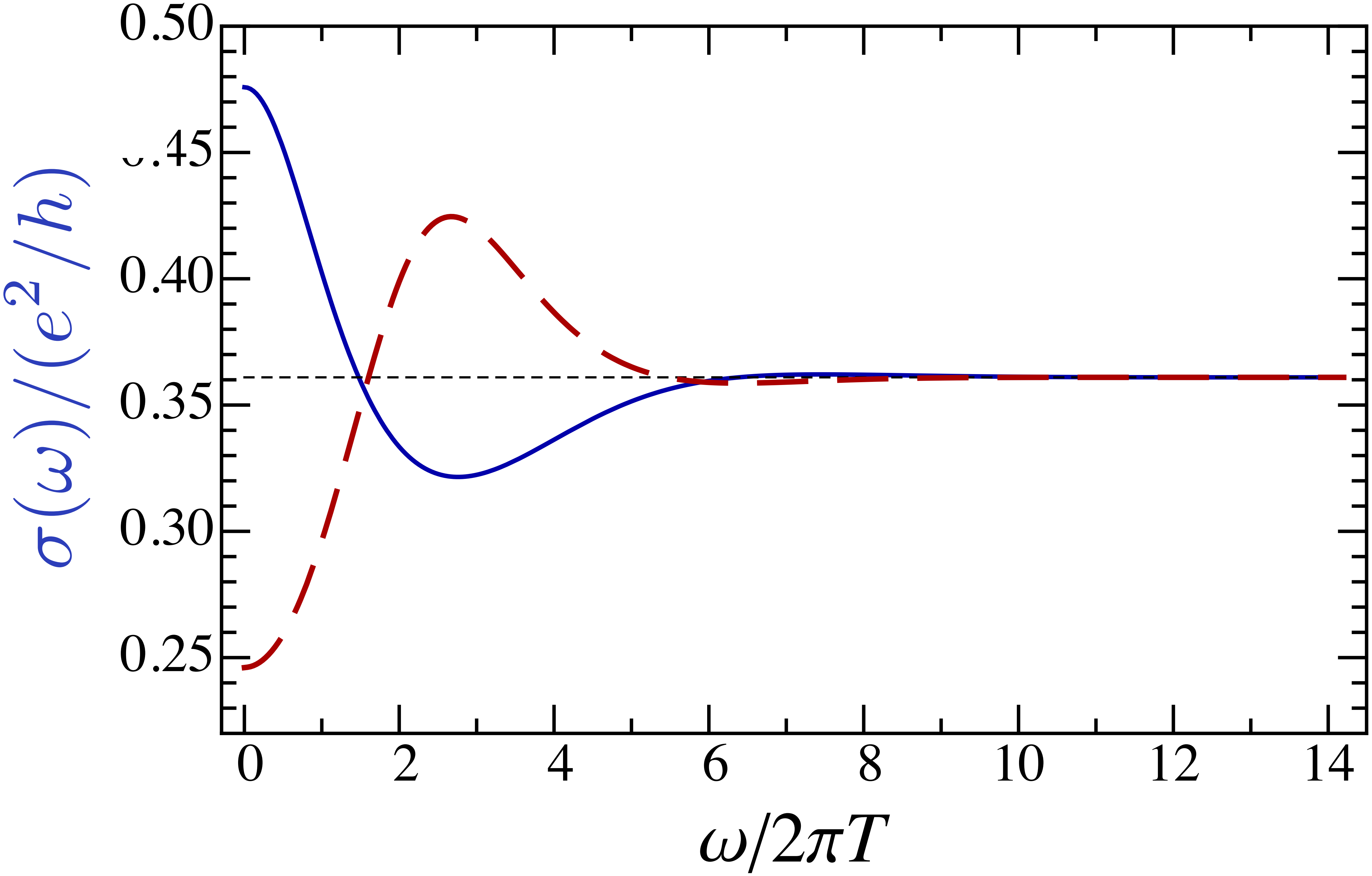


Good agreement between high precision Monte Carlo for imaginary frequencies, and holographic theory after rescaling effective T and taking $\sigma_Q = 1/g_M^2$.

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 models without quasiparticles

   A. Superfluid-insulator transition

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   B. Conformal field theories in

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2. Metals without quasiparticles

   "Nematic" order in the high

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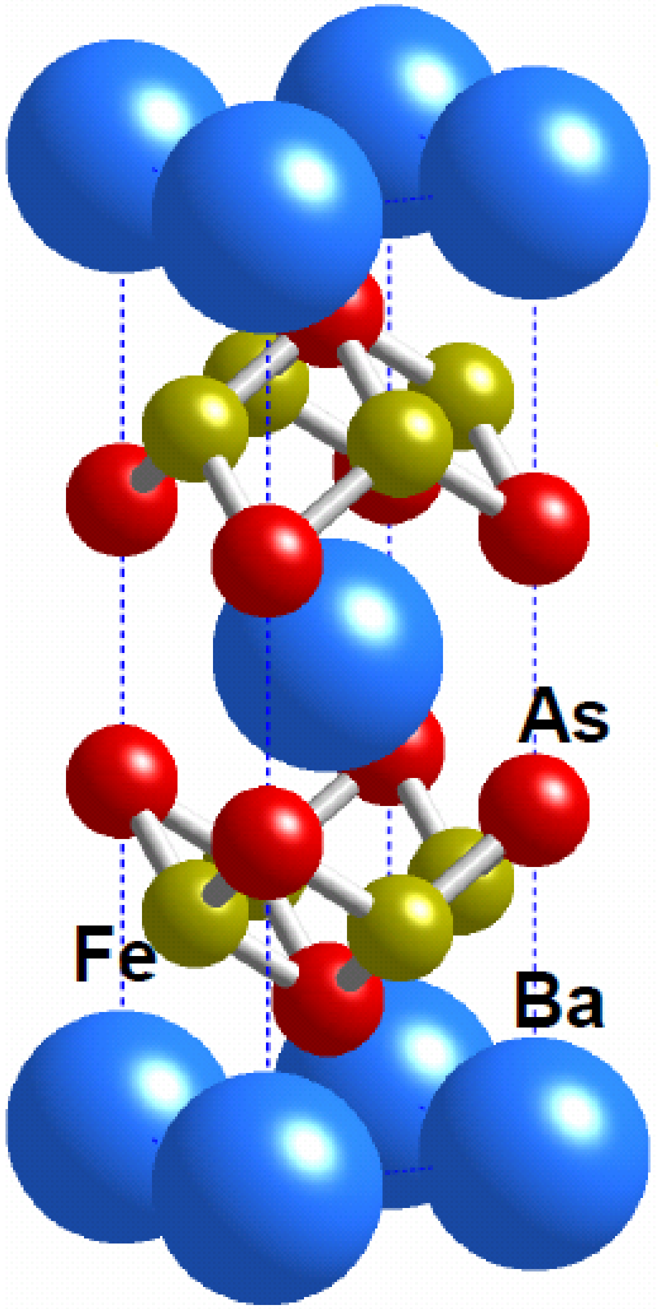
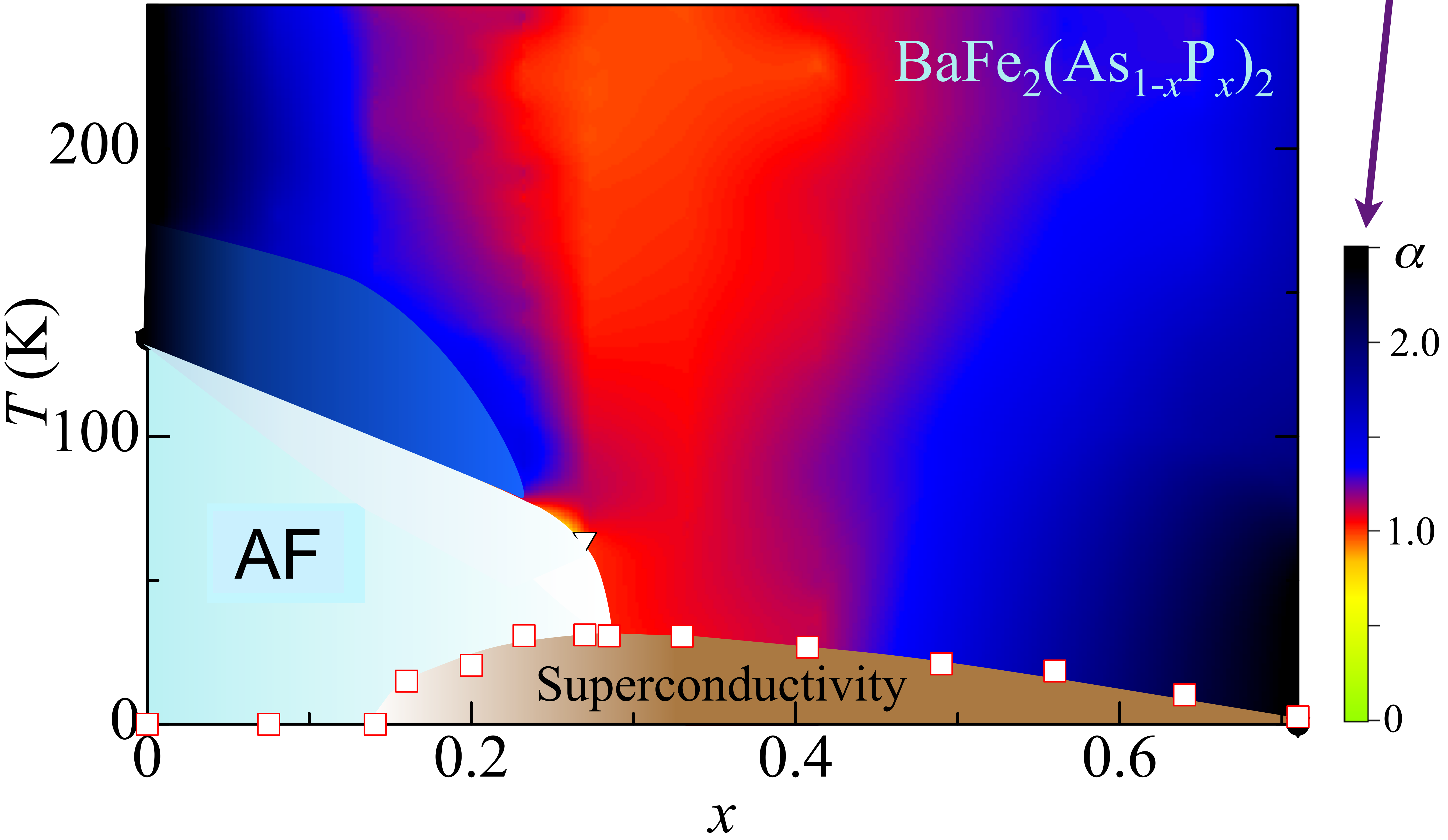
Iron pnictides:

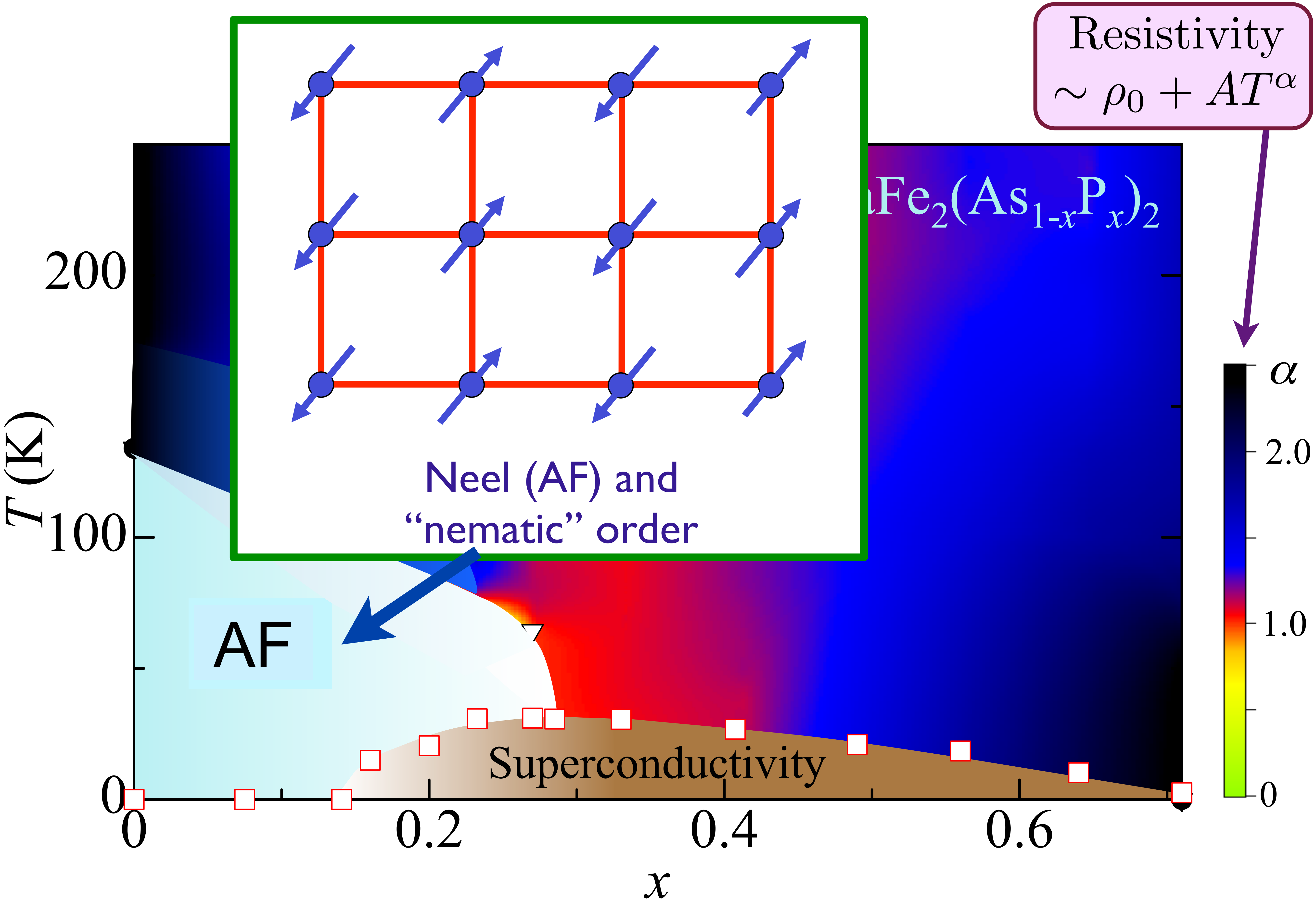
a new class of high temperature superconductors



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



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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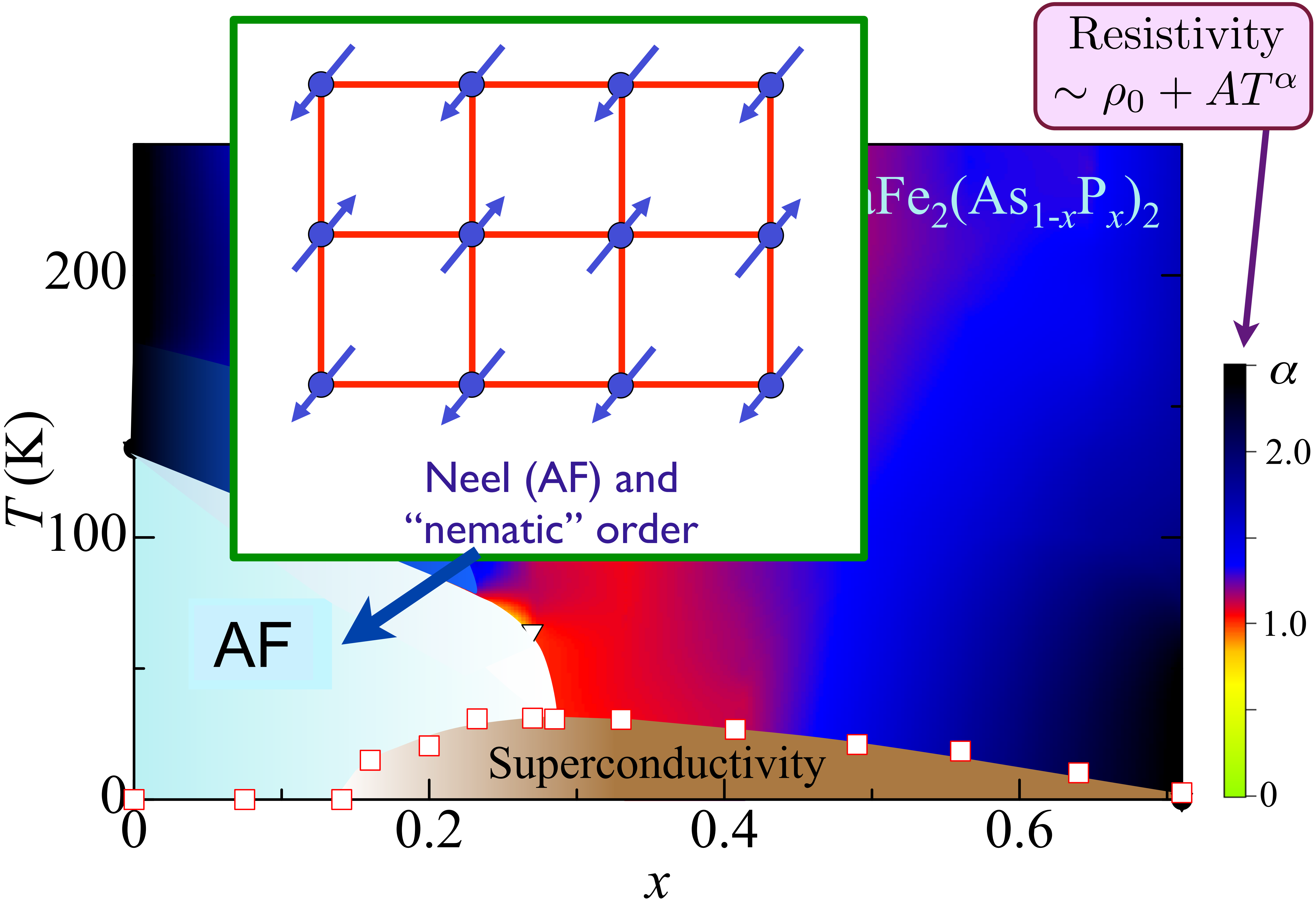

Neel (AF) and
“nematic” order

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

S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido,
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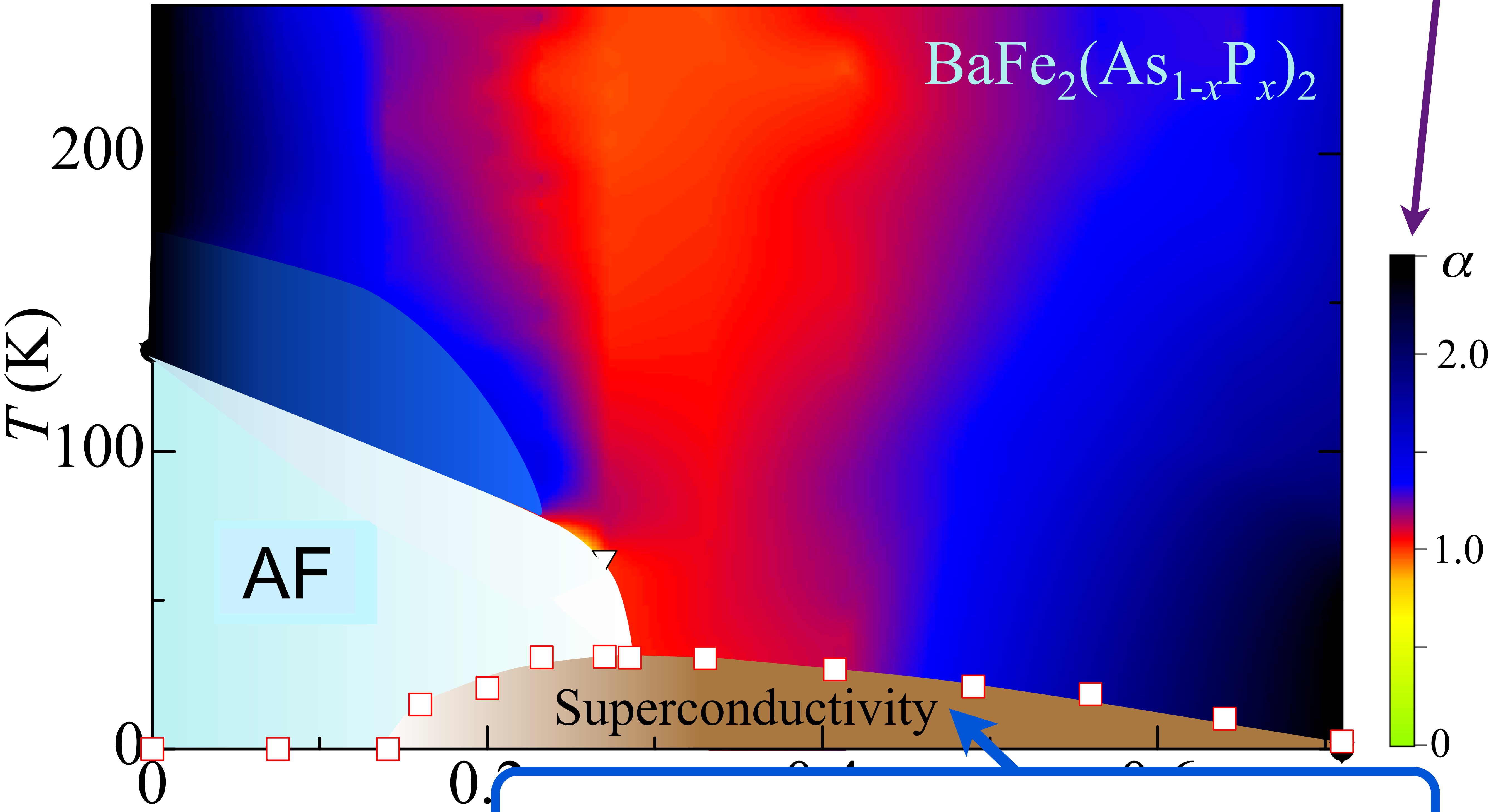
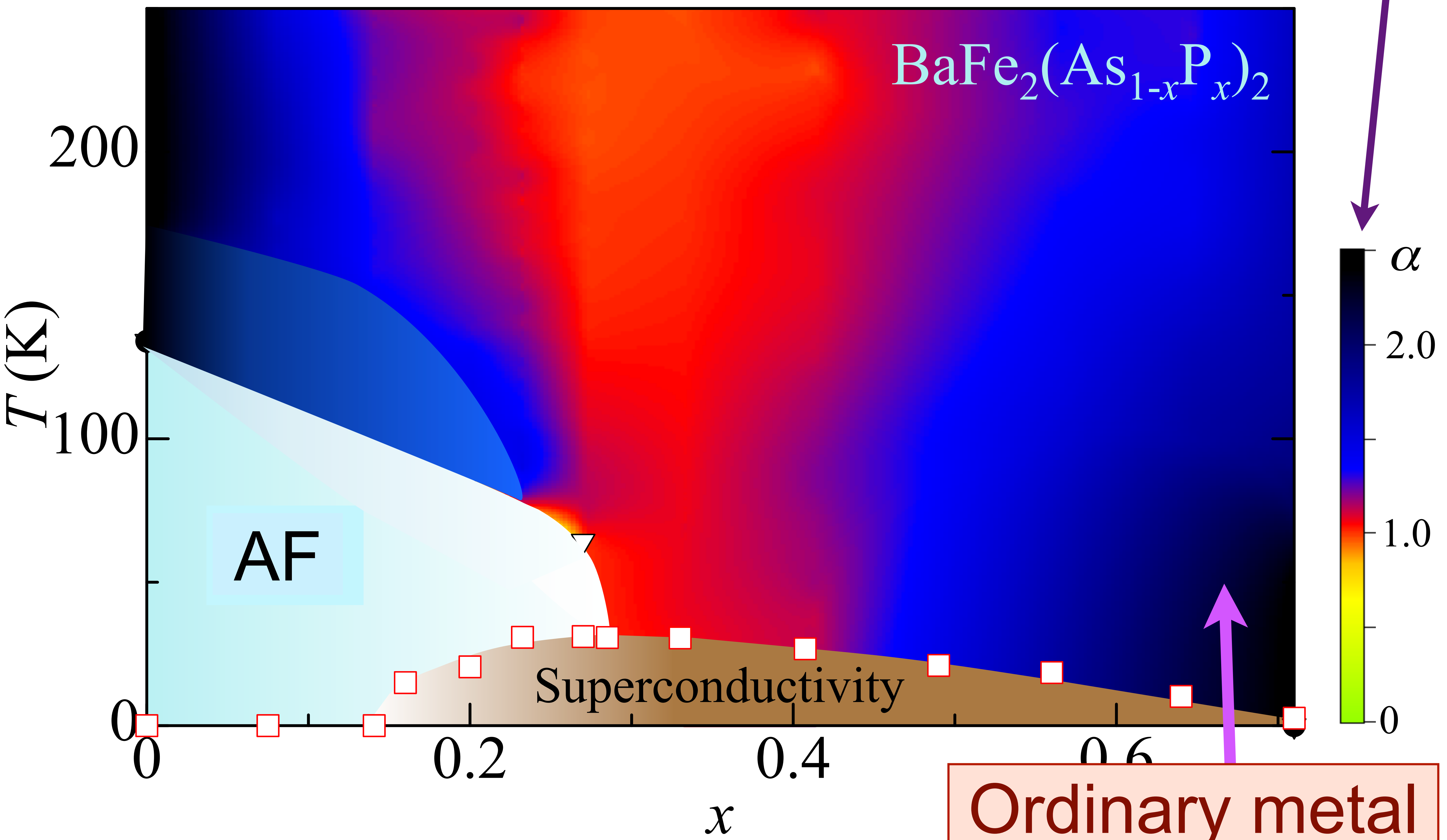


Superconductor
Bose condensate of pairs of electrons

S. Kasahara, T. Shiba
H. Ike

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



Ordinary metal
(Fermi liquid)

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

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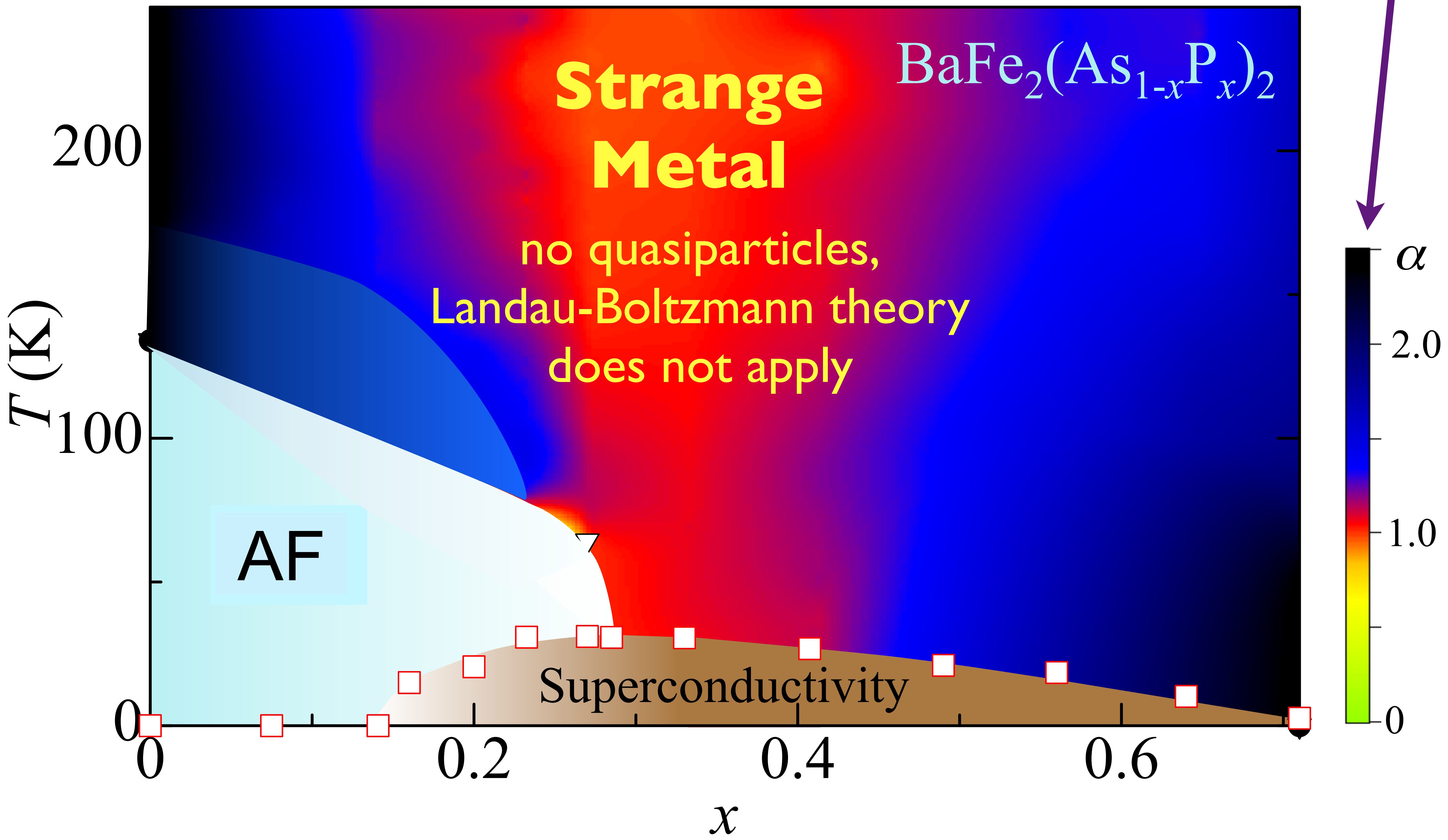

Strange Metal

no quasiparticles, Landau-Boltzmann theory does not apply

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,
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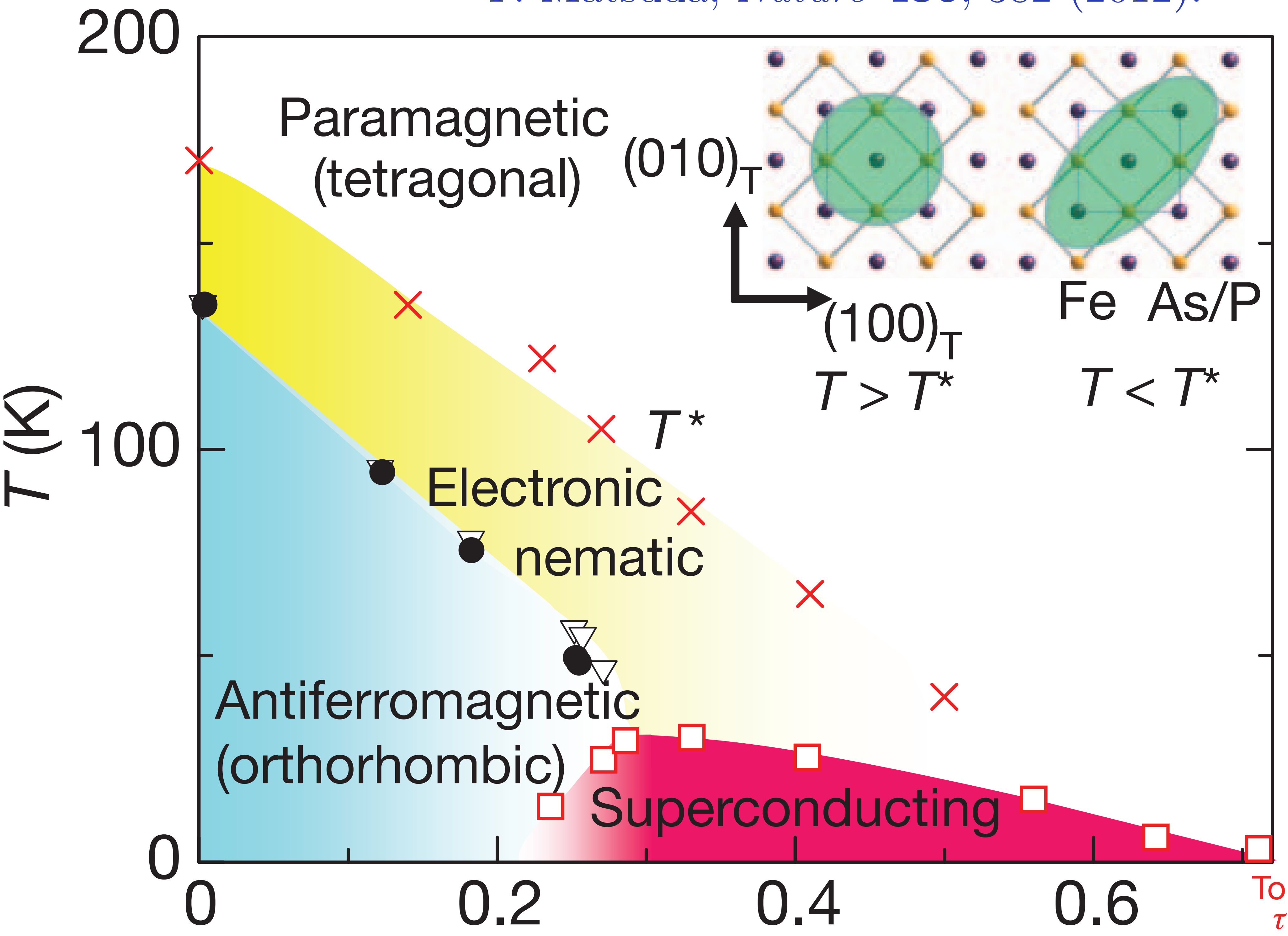
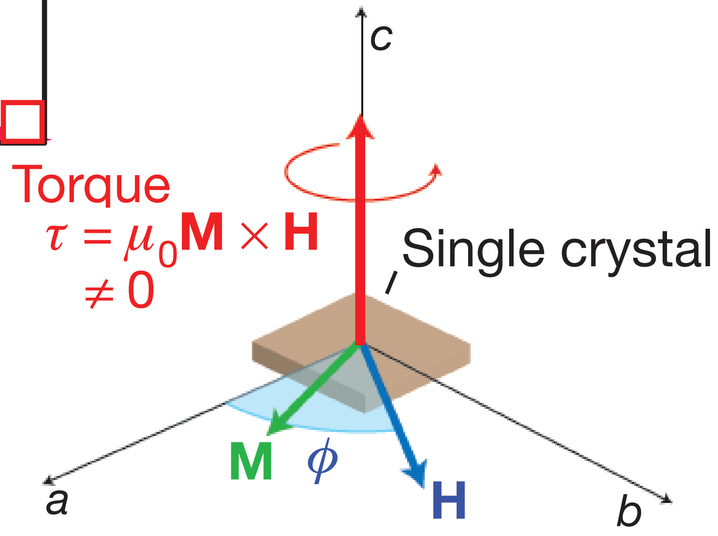
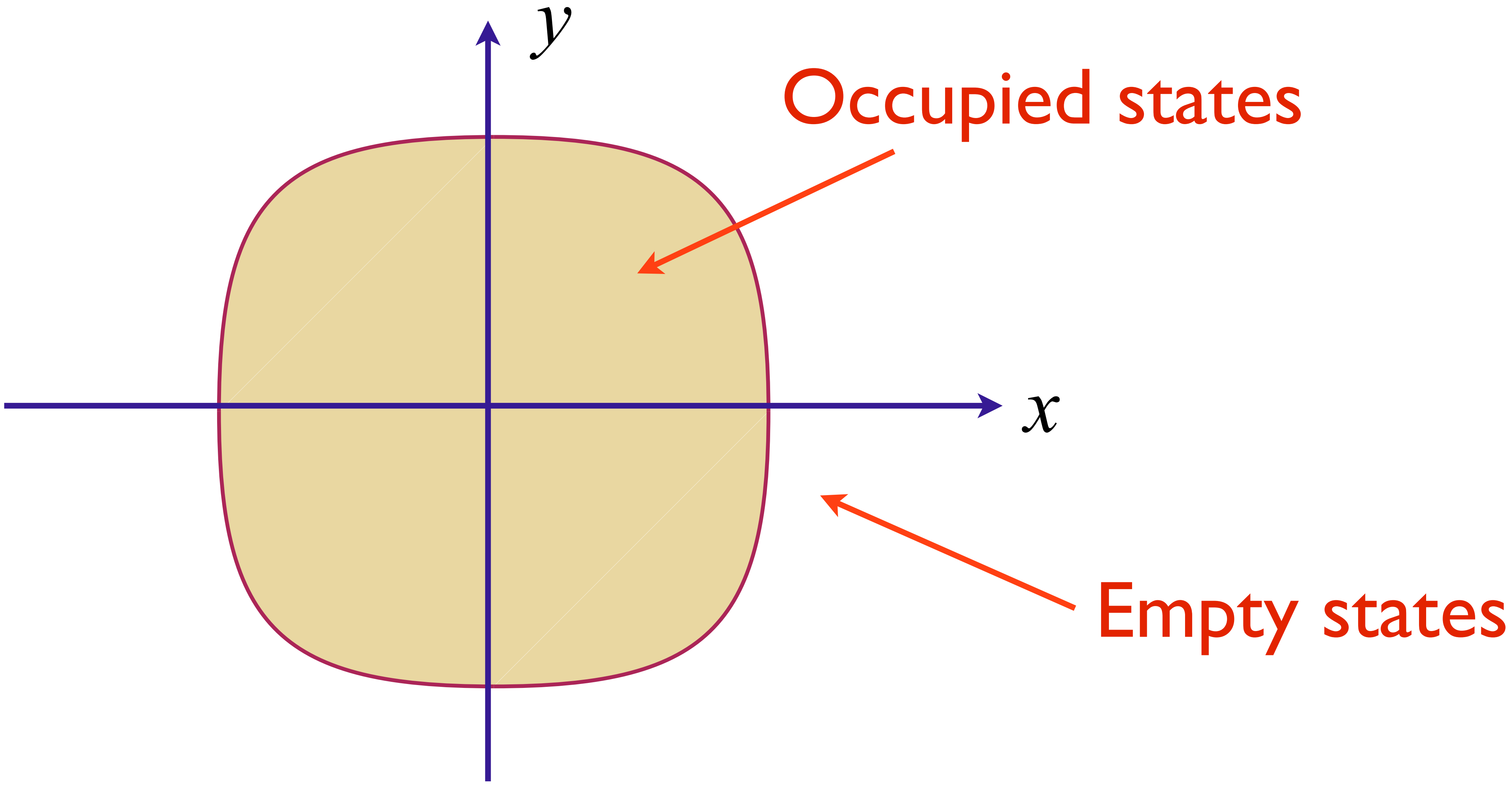
S. Kasahara, H.J. Shi, K. Hashimoto, S. Tonegawa, Y. Mizukami, T. Shibauchi, K. Sugimoto, T. Fukuda, T. Terashima, A.H. Nevidomskyy, and Y. Matsuda, *Nature* **486**, 382 (2012).



$BaFe_2(As_{1-x}P_x)_2$

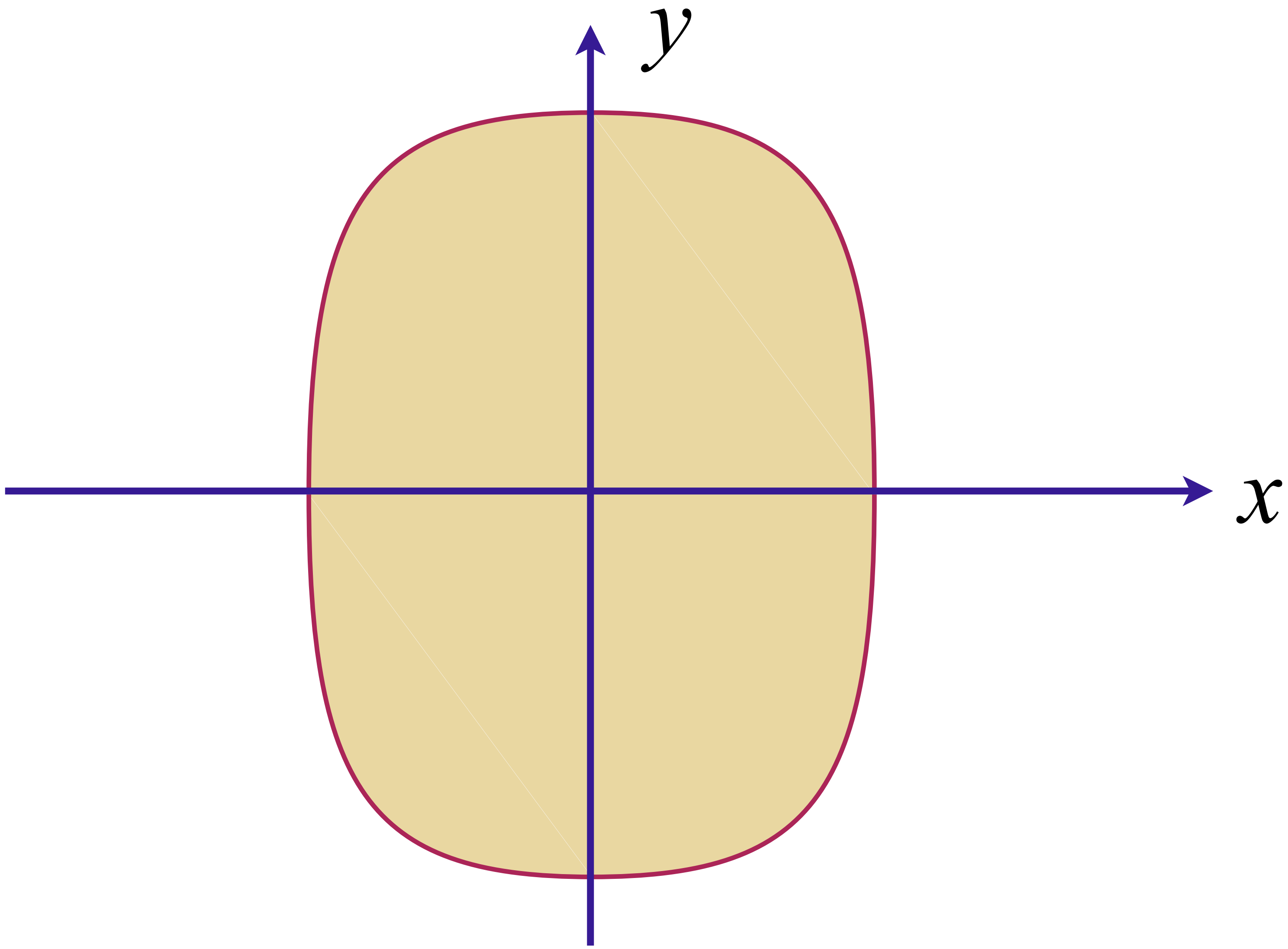


Quantum criticality of Ising-nematic ordering in a metal



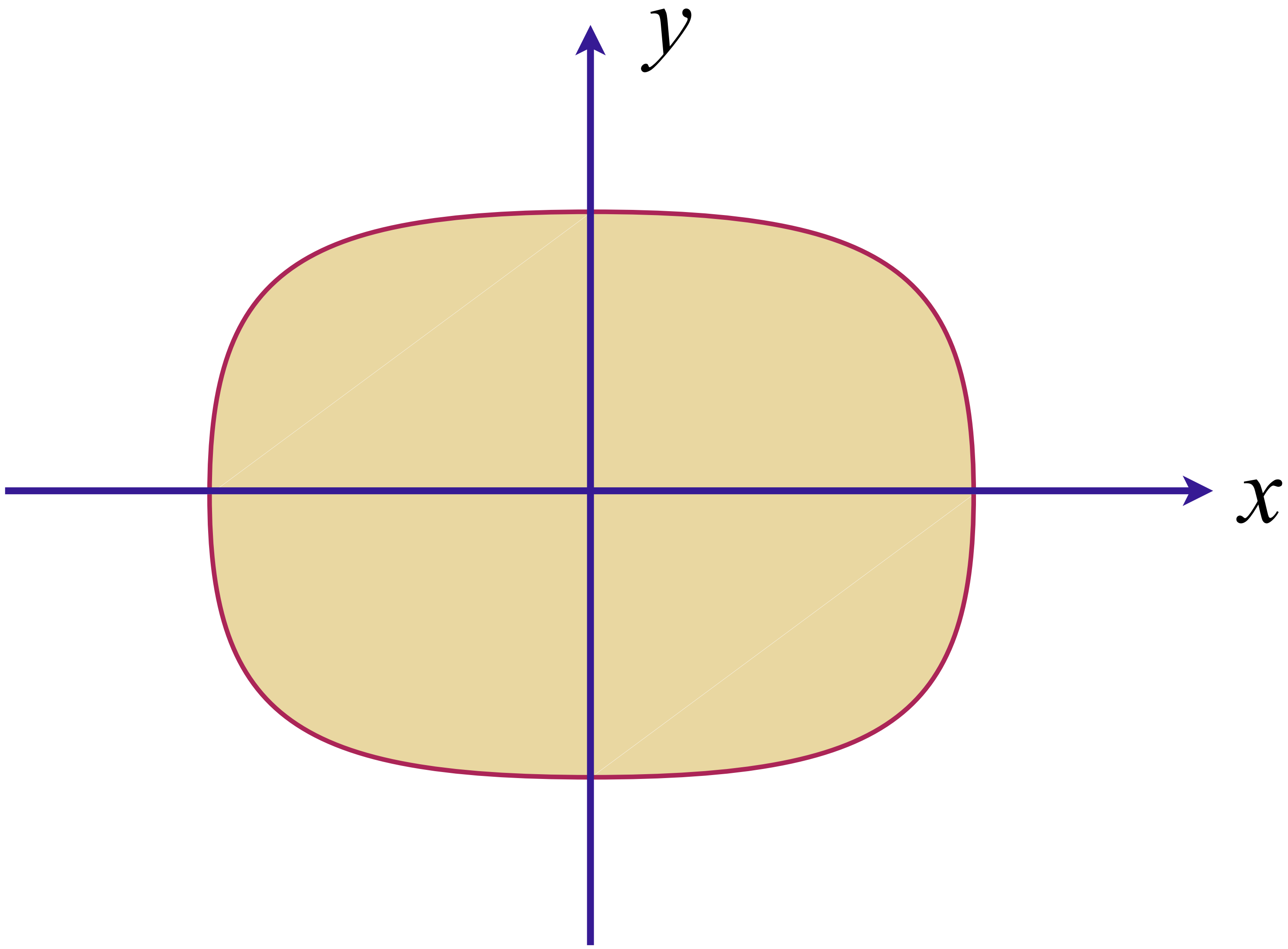
A metal with a Fermi surface
with full square lattice symmetry

Quantum criticality of Ising-nematic ordering in a metal



Spontaneous elongation along y direction:

Quantum criticality of Ising-nematic ordering in a metal



Spontaneous elongation along x direction:

Ising-nematic order parameter

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

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

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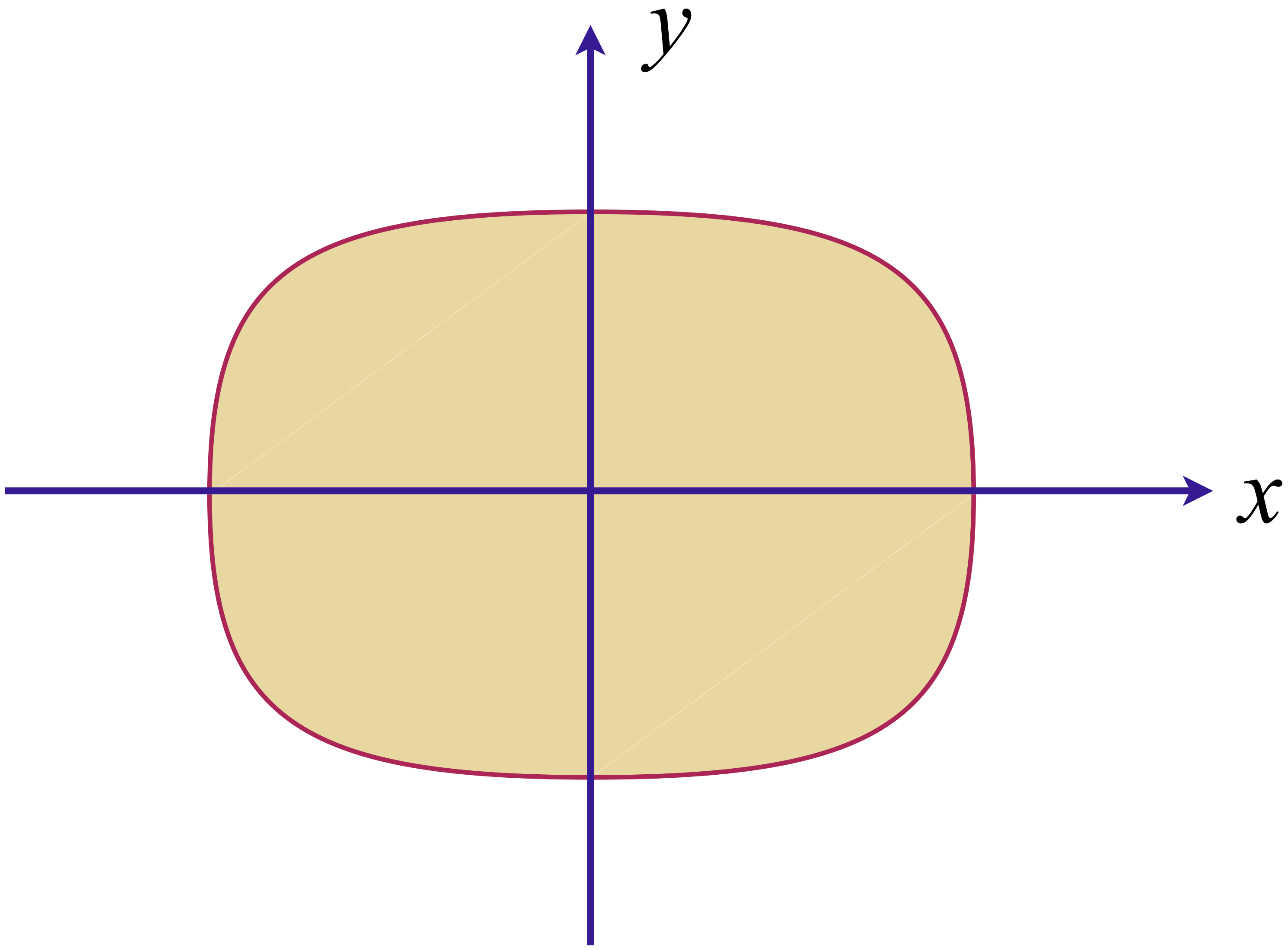

Spontaneous elongation along x direction:
Ising order parameter $\phi > 0$.

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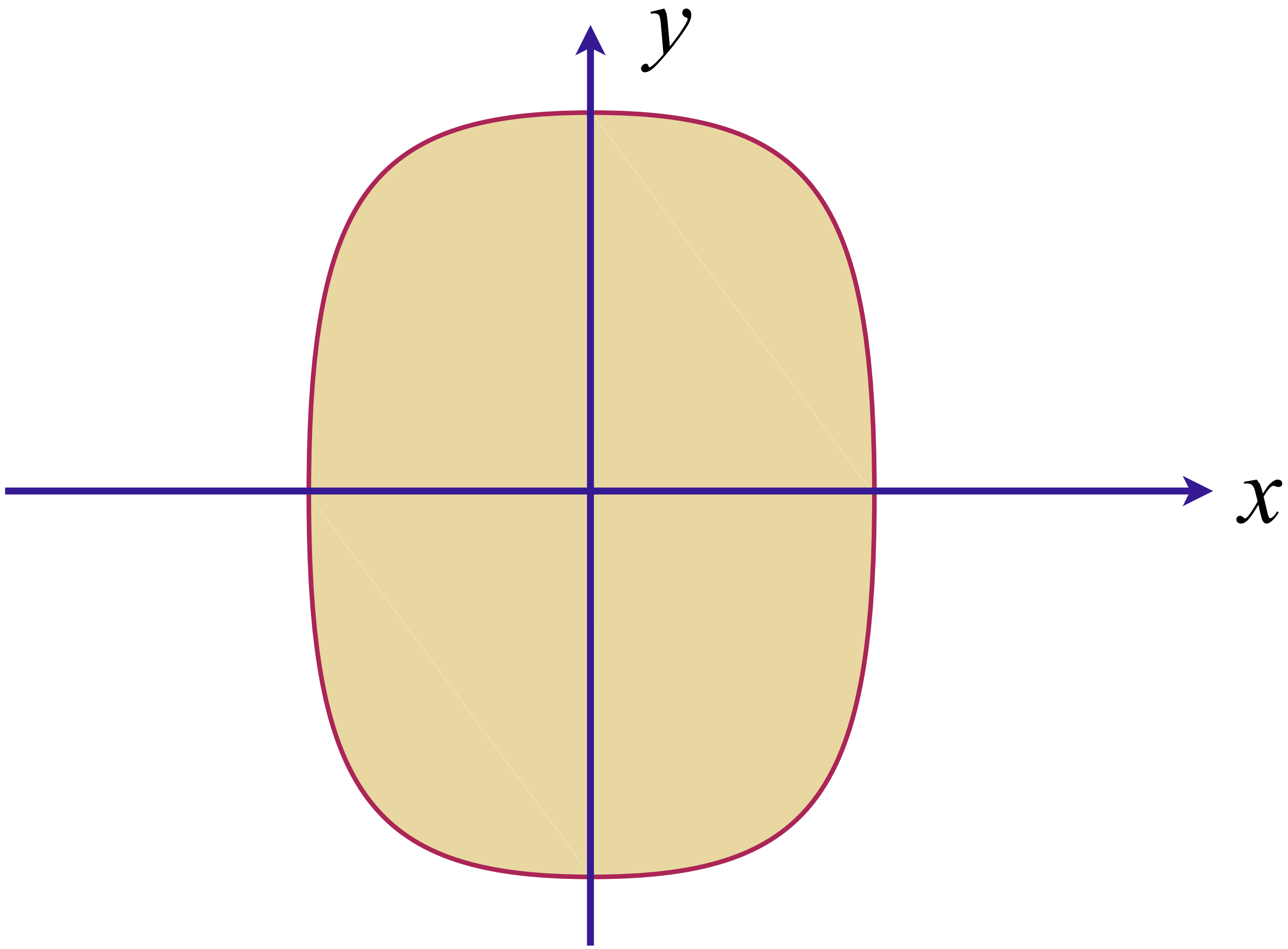

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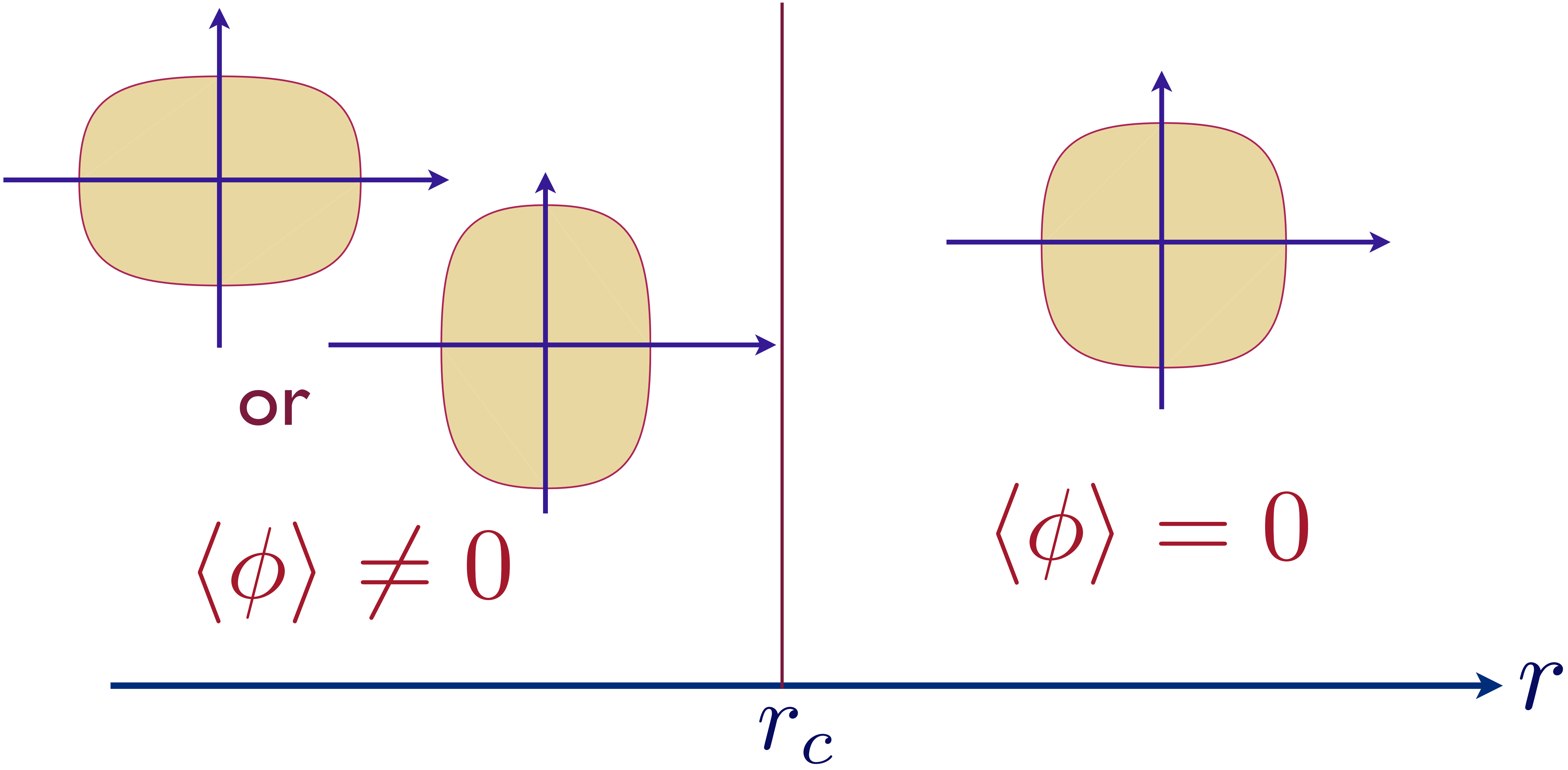


or

$\langle \phi \rangle \neq 0$

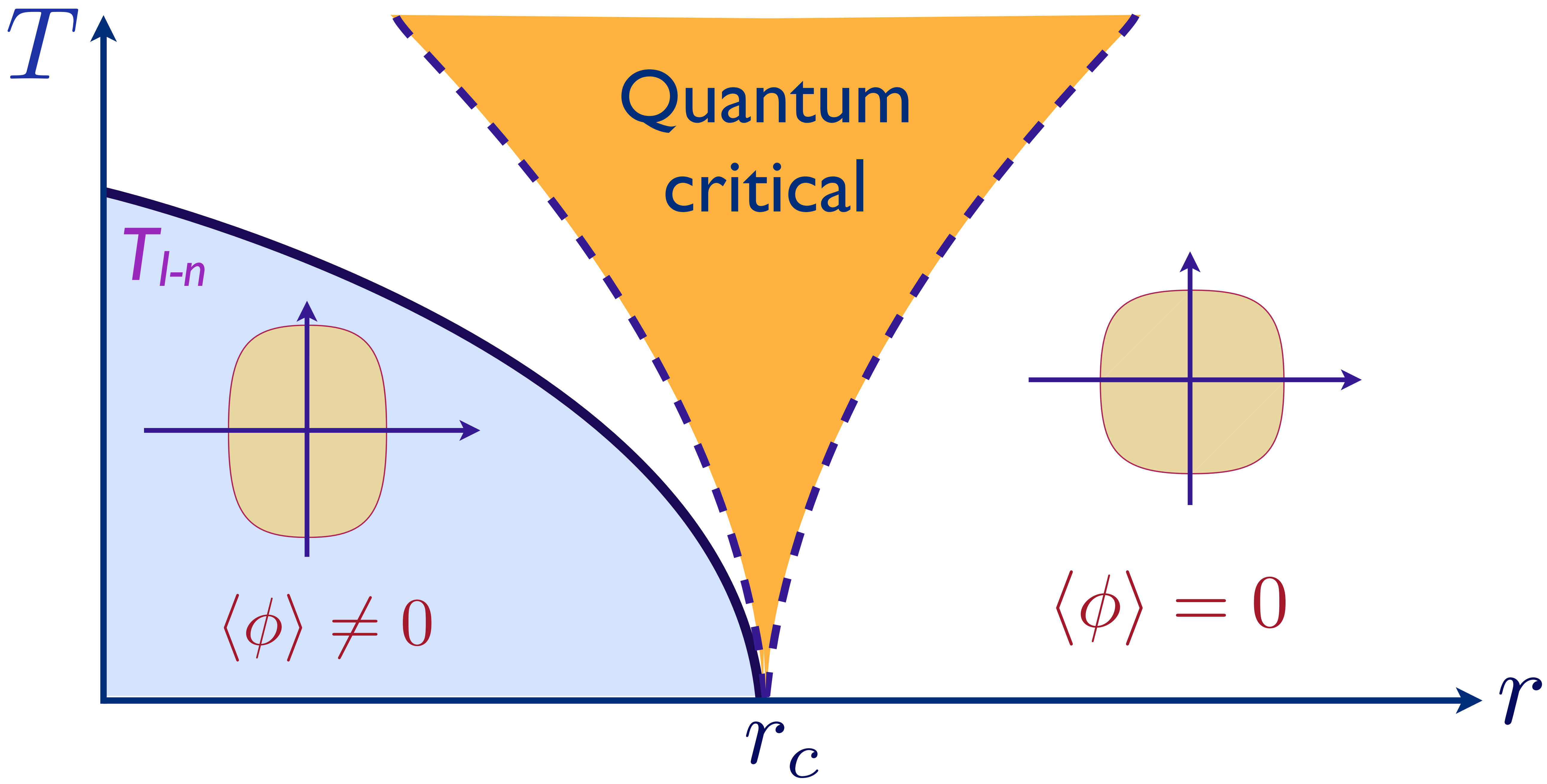
$\langle \phi \rangle = 0$

r_c

r

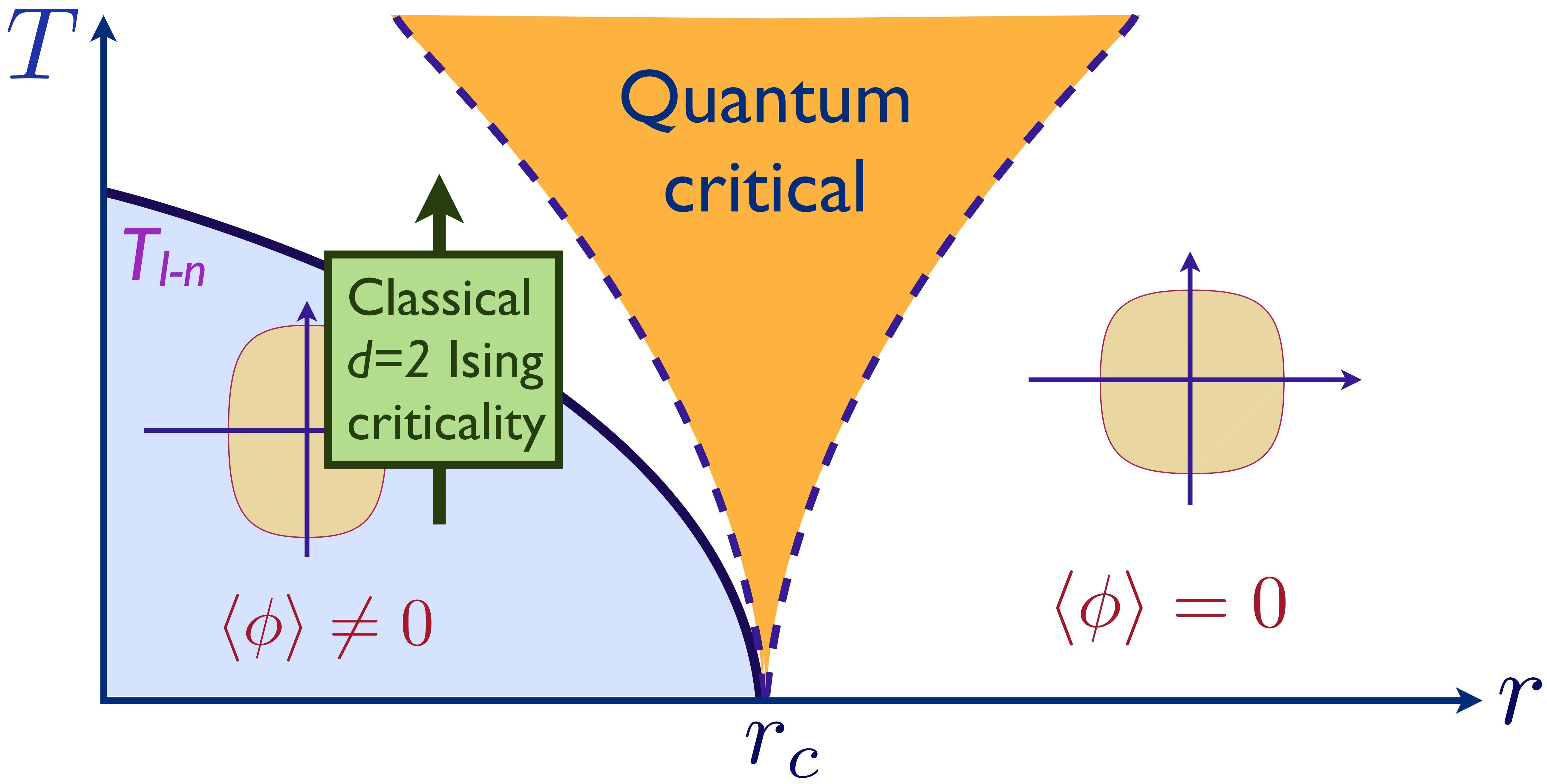
Pomeranchuk instability as a function of coupling r

Quantum criticality of Ising-nematic ordering



Phase diagram as a function of T and r

Quantum criticality of Ising-nematic ordering in a metal



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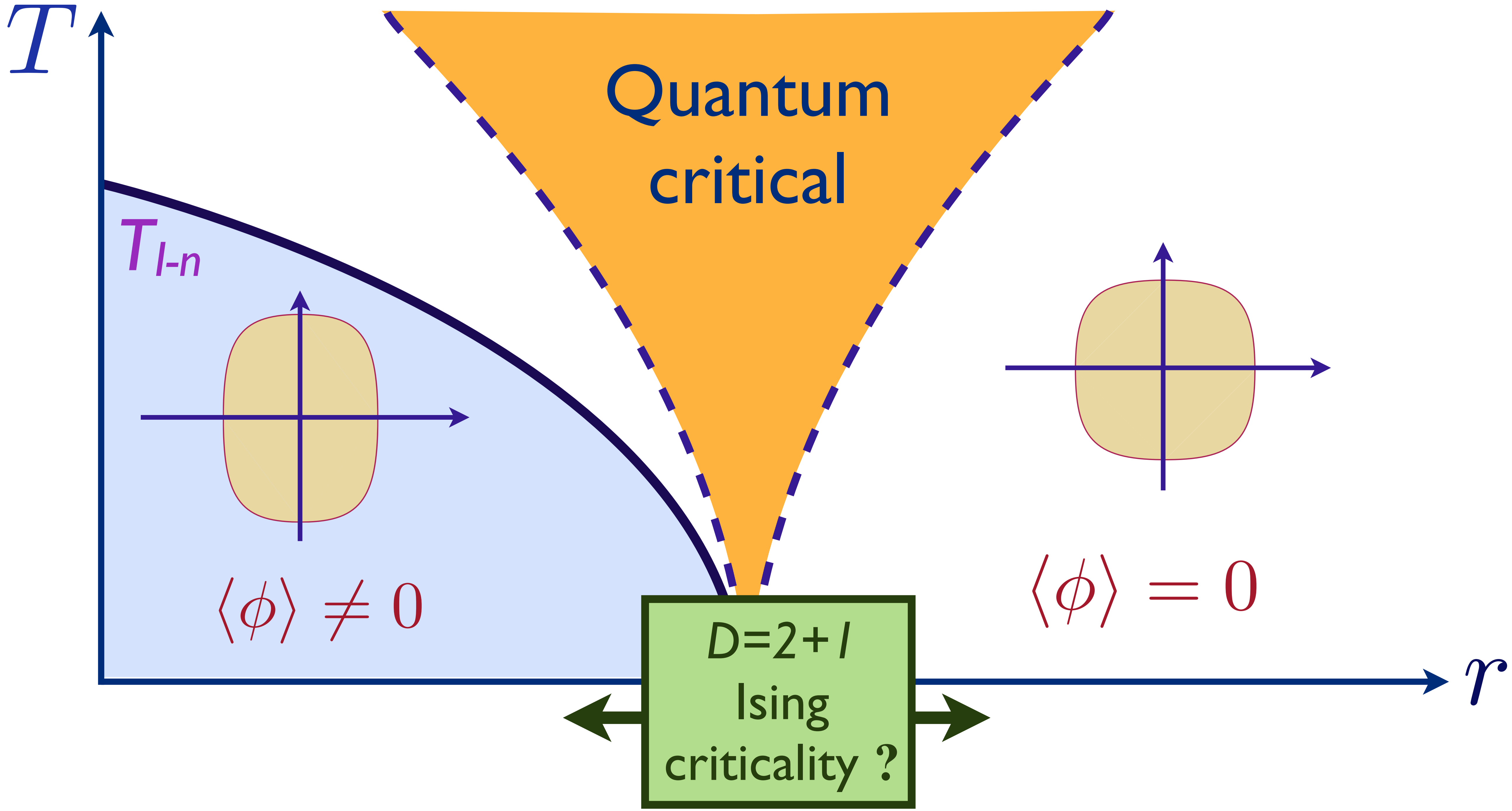

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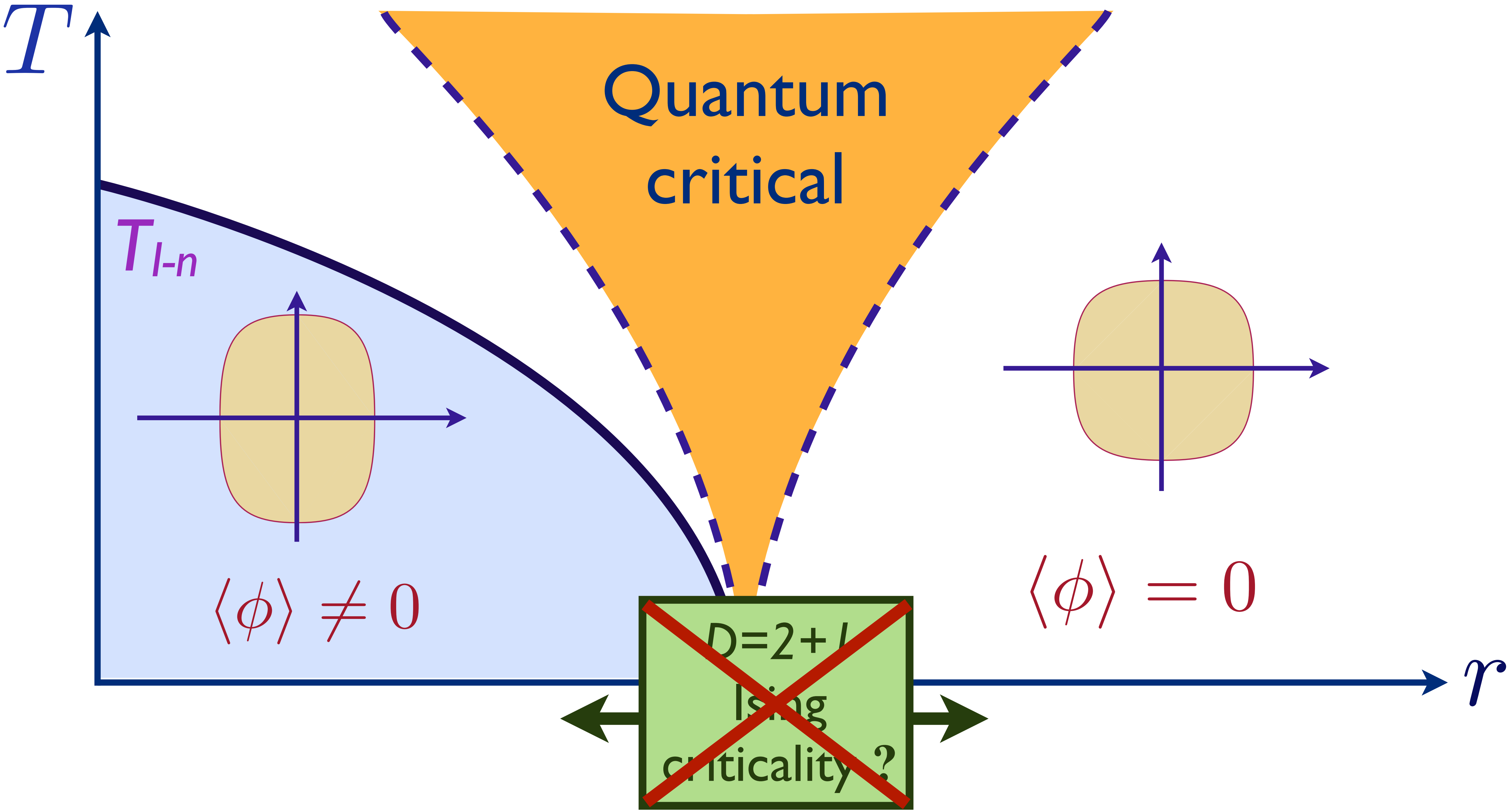

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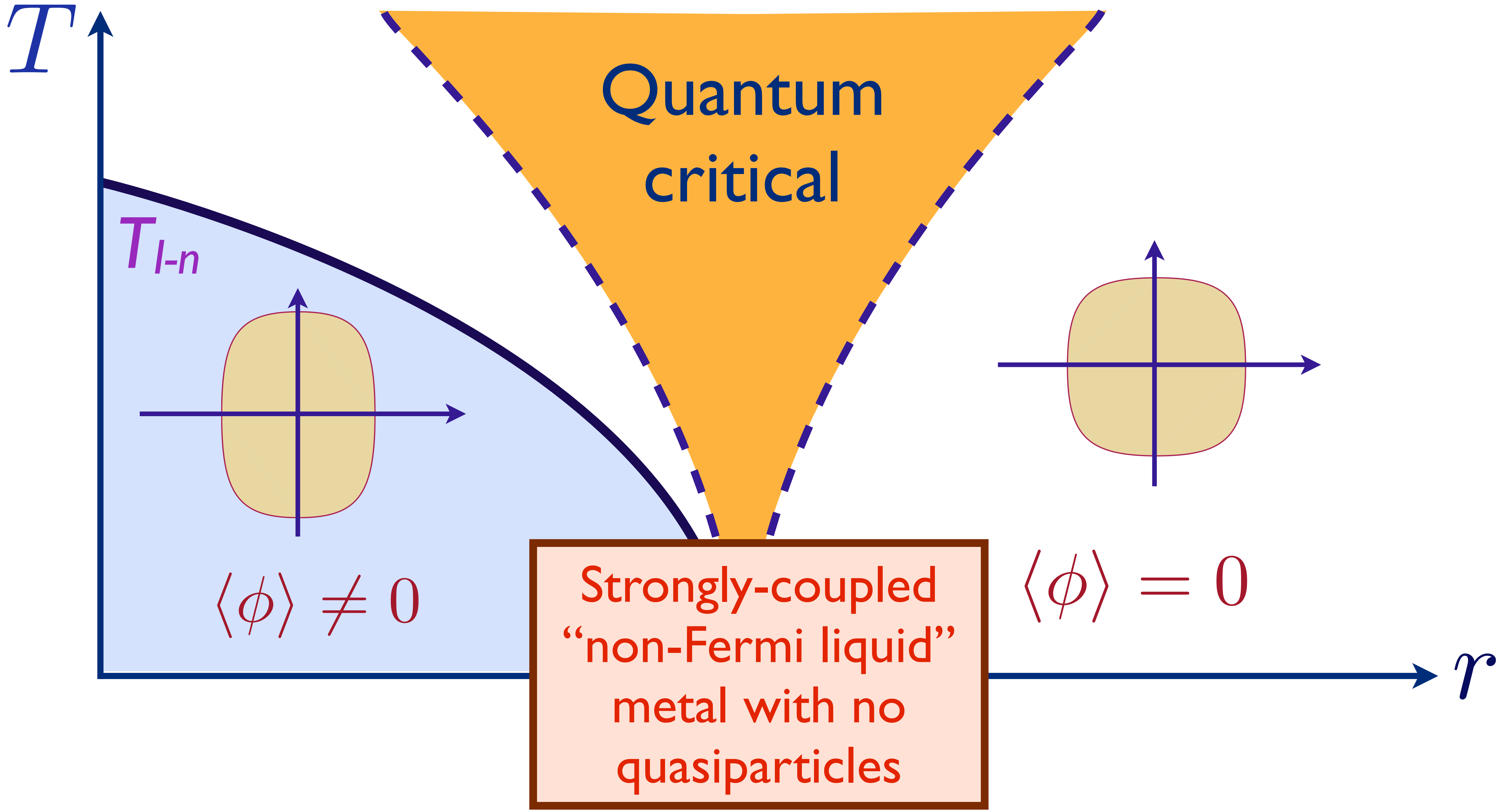
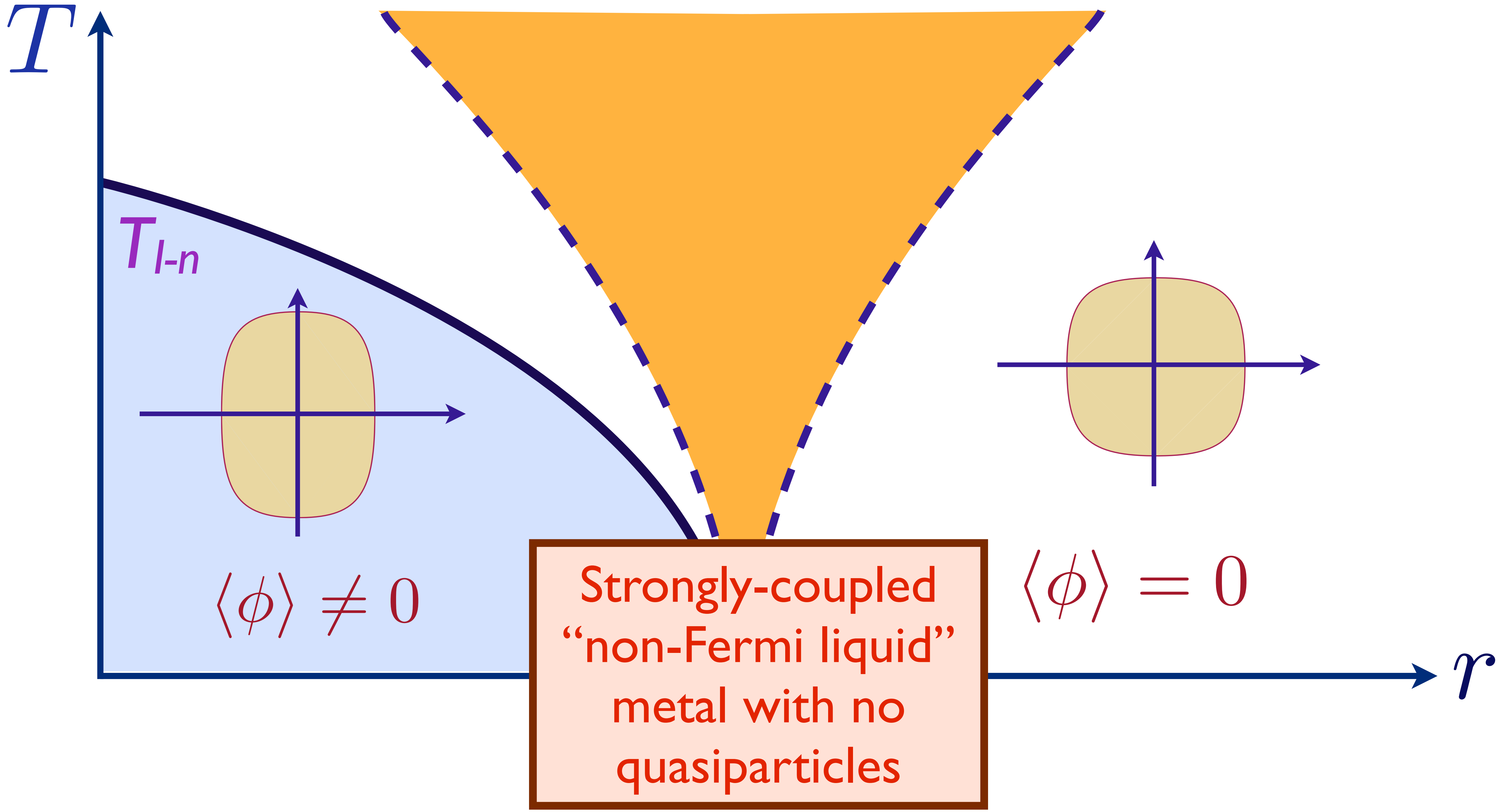


Strongly-coupled "non-Fermi liquid" metal with no quasiparticles

Phase diagram as a function of T and r

Quantum criticality of Ising-nematic ordering in a metal



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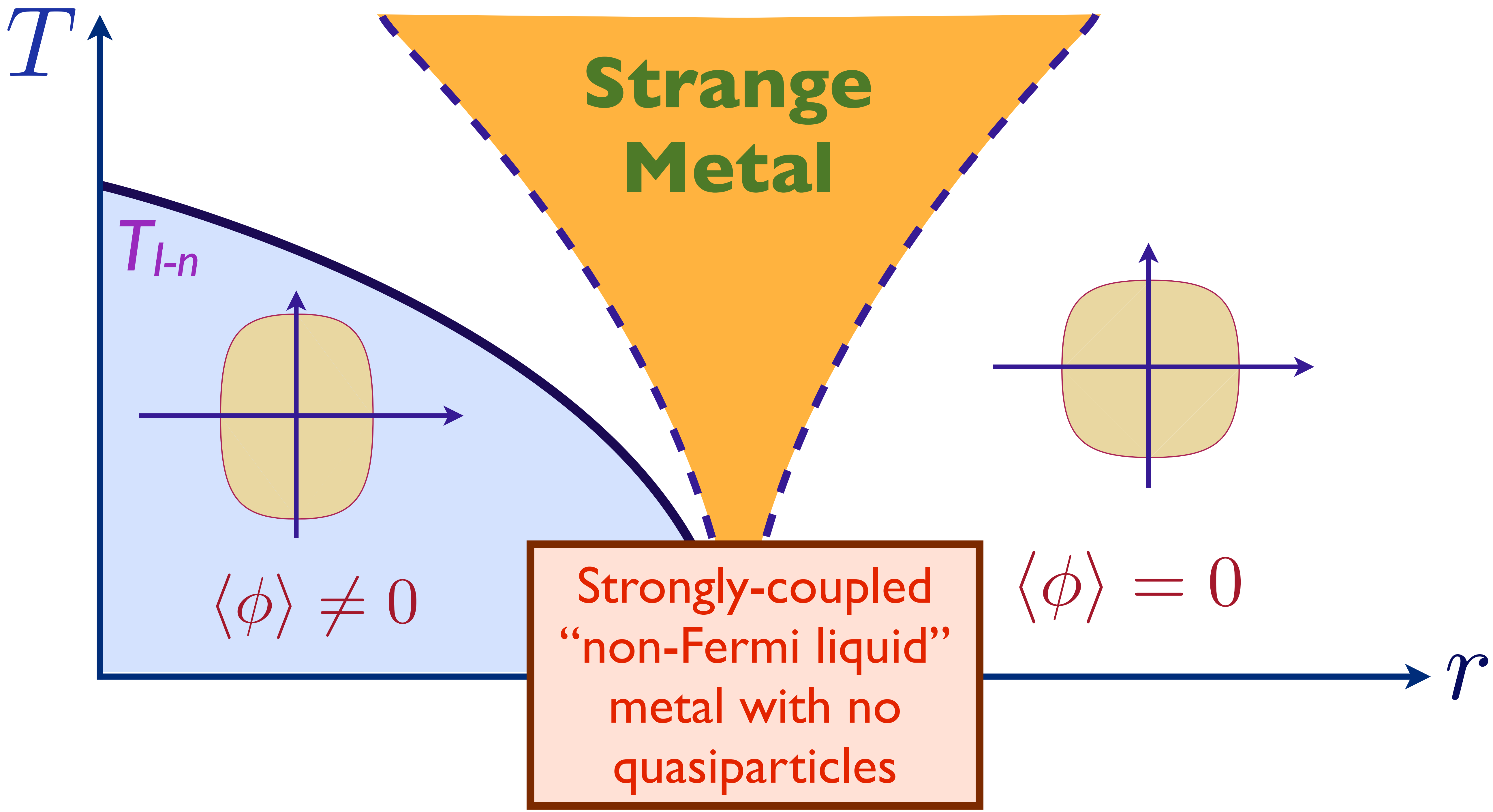

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Quantum criticality of Ising-nematic ordering in a metal

Theory of transport without quasiparticles (inspired by holography):

- Formulate a continuum theory with a conserved momentum.

S. Hartnoll, R. Mahajan, M. Punk, and S. Sachdev, to appear

Quantum criticality of Ising-nematic ordering in a metal

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- Determine the relaxation rate of momentum due to small perturbations that violate the conservation of momentum, such as s-wave (V_0) and d-wave (h_0) impurity scattering.

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- All steps above can also be implemented in holographic models, and consistent results are obtained *i.e.* solution of gravitational equations provides results consistent with hydrodynamics, and with the breakdown of hydrodynamics due to perturbations that violate momentum conservation.

S. Hartnoll, R. Mahajan, M. Punk, and S. Sachdev, to appear

- Strongly-coupled quantum criticality leads to a novel regime of quantum dynamics without quasiparticles.

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