Quantum matter without quasiparticles

University of Maryland,
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Subir Sachdev

Talk online: sachdev.physics.harvard.edu

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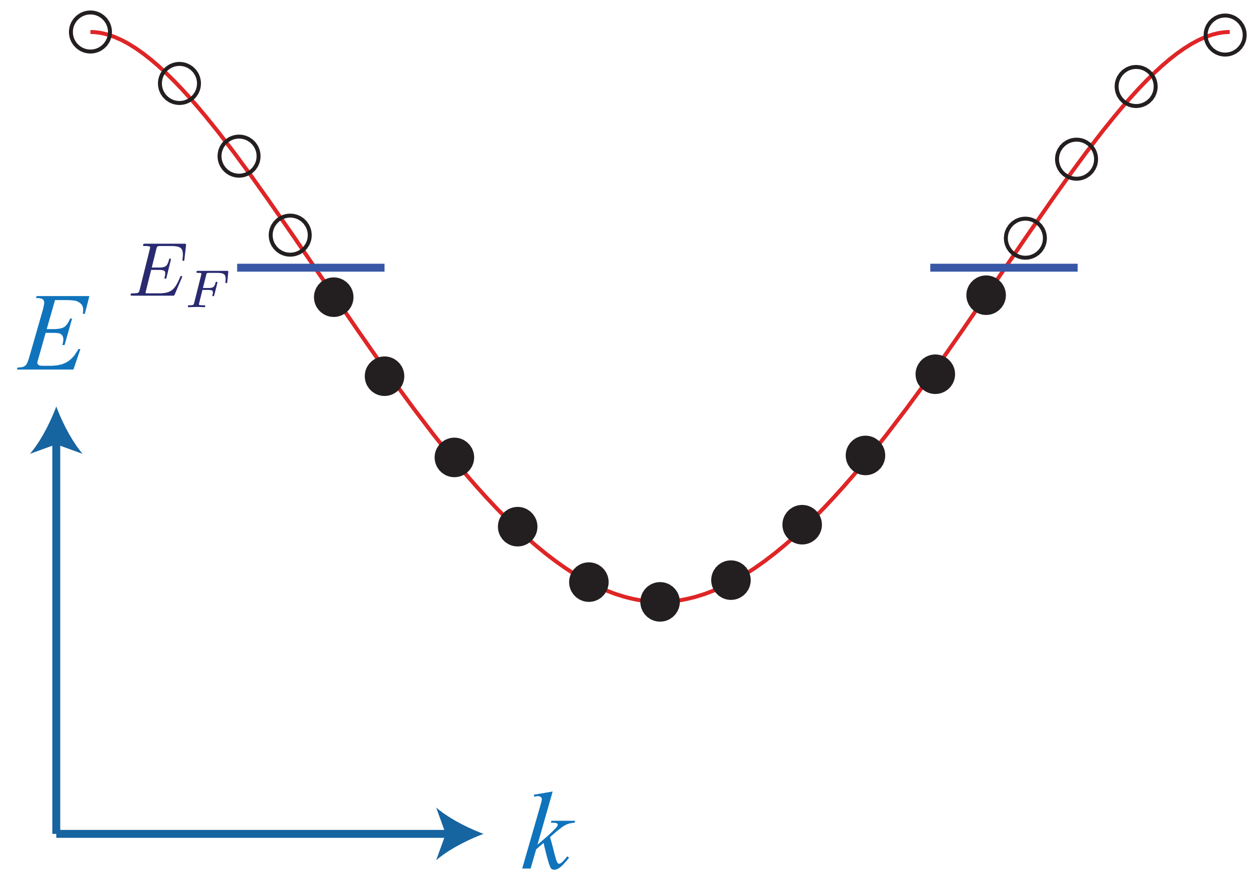
Foundations of quantum many body theory:

1. Ground states connected adiabatically to independent electron states

Metals

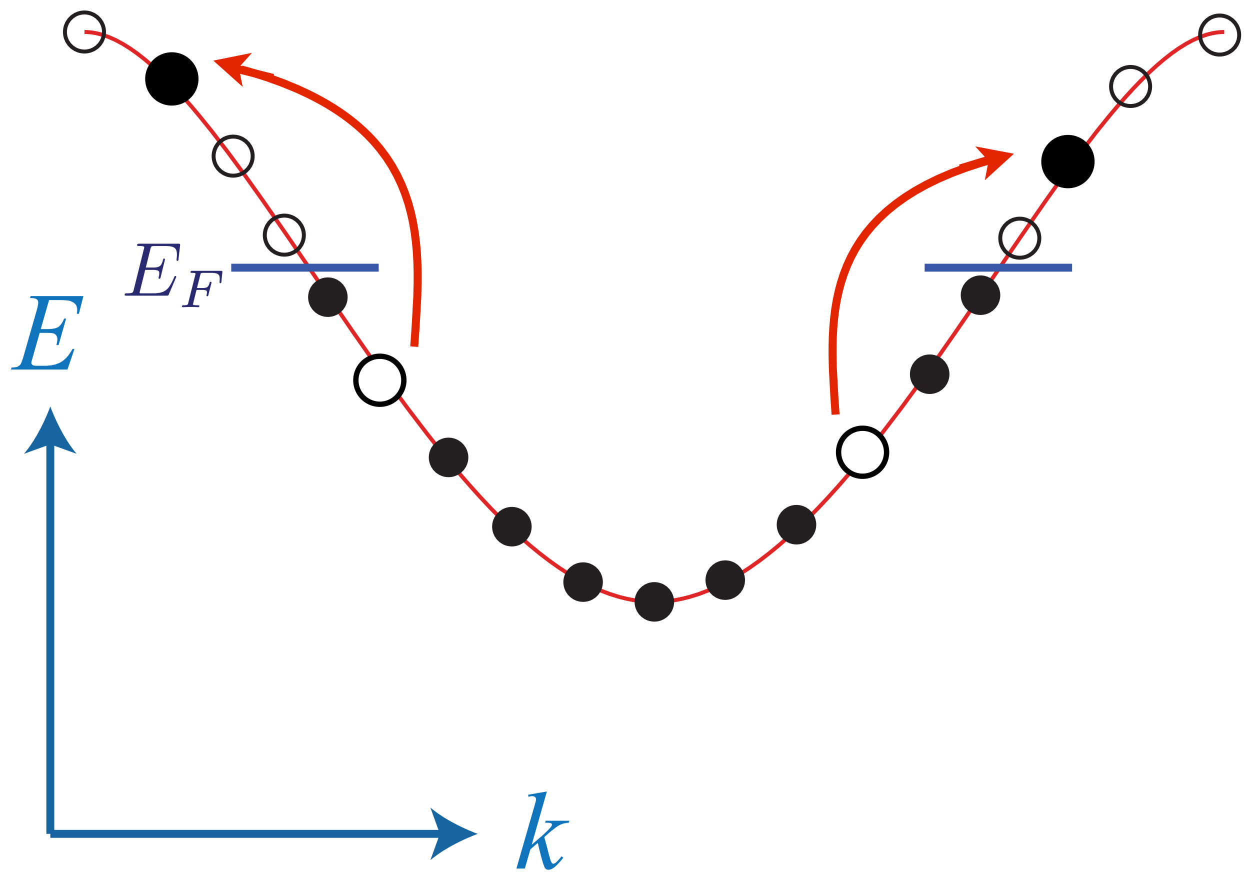


Foundations of quantum many body theory:

1. Ground states <u>connected</u> adiabatically to independent electron states

2. Boltzmann-Landau theory of quasiparticles

<u>Metals</u>



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

2. Boltzmann-Landau theory of quasiparticles

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 $d=2$

Outline

1. Conformal field theories in 2+1 dimensions

    Superfluid-insulator transition

    A. Boltzmann dynamics

    B. Conformal / holographic dynamics

2. Non-Fermi liquid in 2+1 dimensions

    Strange metal in the high temperature superconductors

    A. Lessons from holography

    B. Field theories and memory functions

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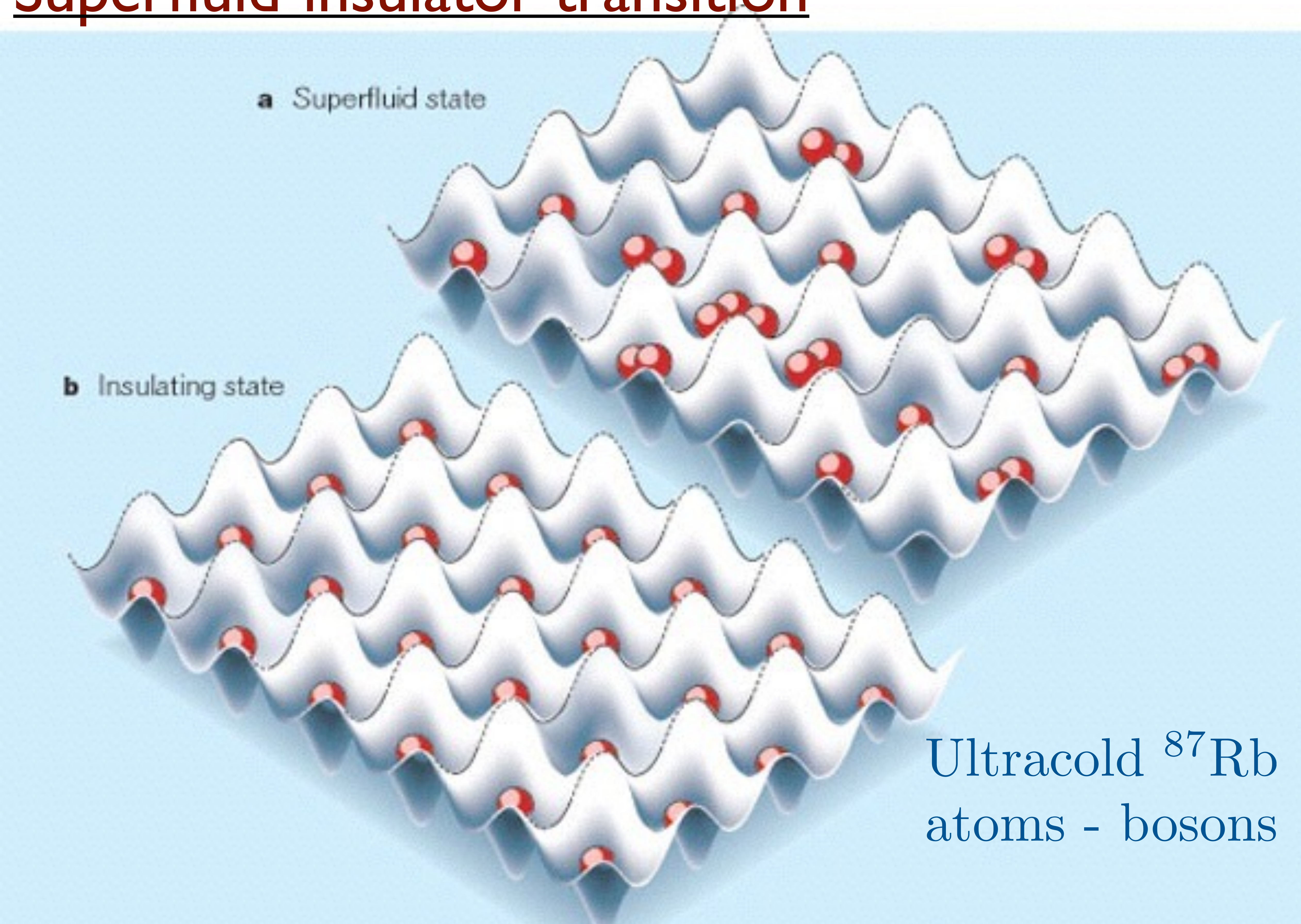
Emanuel Katz
Boston University

William Witczak-Krempa
Perimeter

Erik Sorensen
McMaster

Superfluid-insulator transition



Ultracold ^{87}Rb
atoms - bosons

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

The Superfluid-Insulator transition

Boson Hubbard model

Bosons, b_j hopping on the sites j of a square lattice with Hamiltonian

$$\begin{aligned} H &= -t \sum_{\langle ij \rangle} b_i^\dagger b_j + \frac{U}{2} \sum_j n_j (n_j - 1) \\ n_j &\equiv b_i^\dagger b_i \end{aligned}$$

The boson operators obey the commutation relation

$$[b_j, b_k^\dagger] = \delta_{jk}$$

We restrict attention to the sector of the Fock space with

$$\sum_j n_j = \text{integer multiple of the number of sites}$$

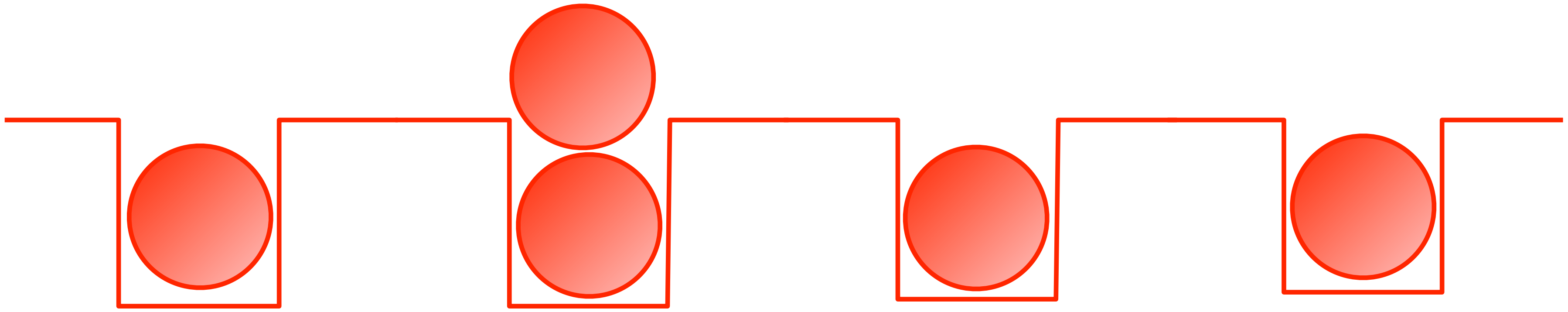
$\underline{U \gg t}$

Insulator (the vacuum)
at large repulsion between bosons

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

$U \gg t$

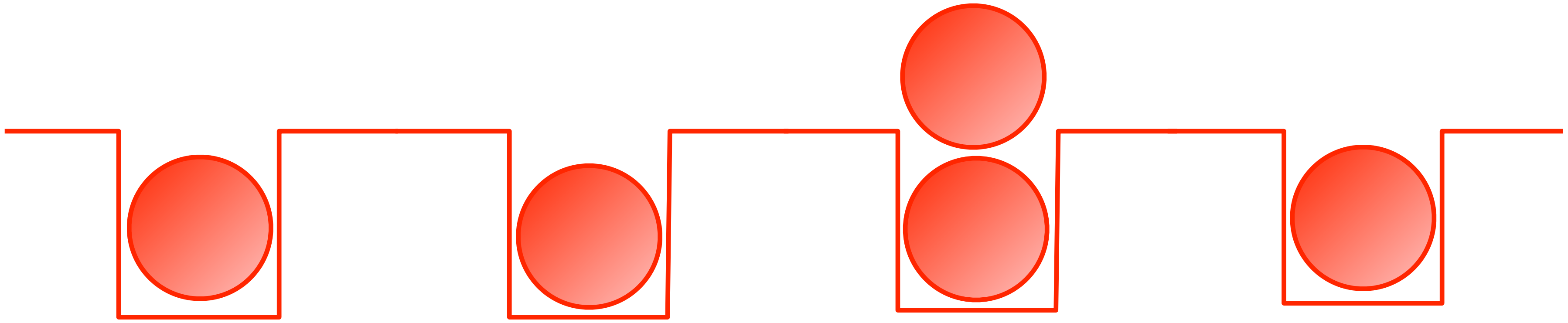
Excitations of the insulator:



Particles $\sim \psi^\dagger$

$U \gg t$

Excitations of the insulator:



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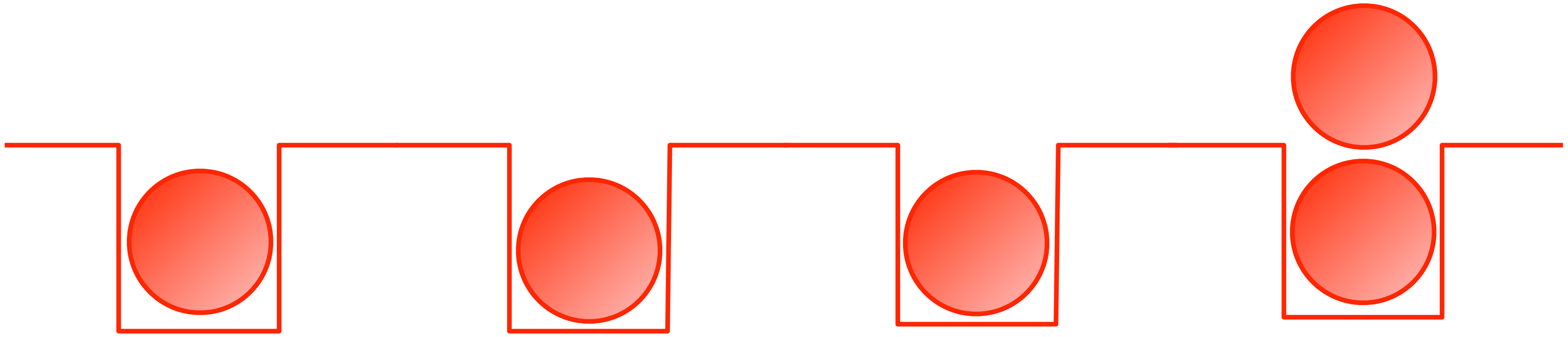

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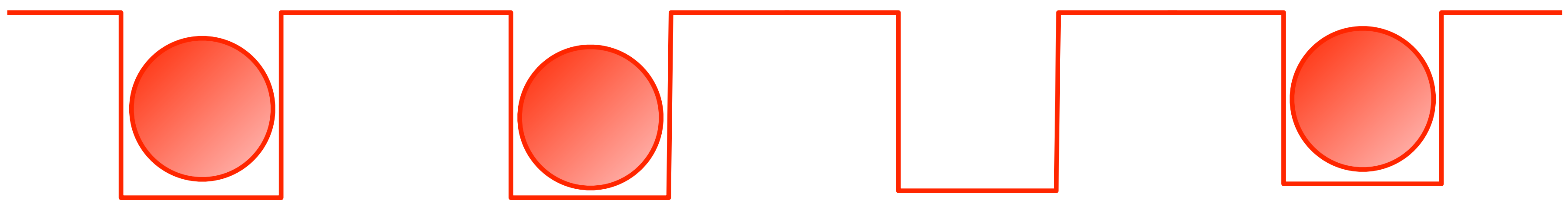

Holes $\sim \psi$

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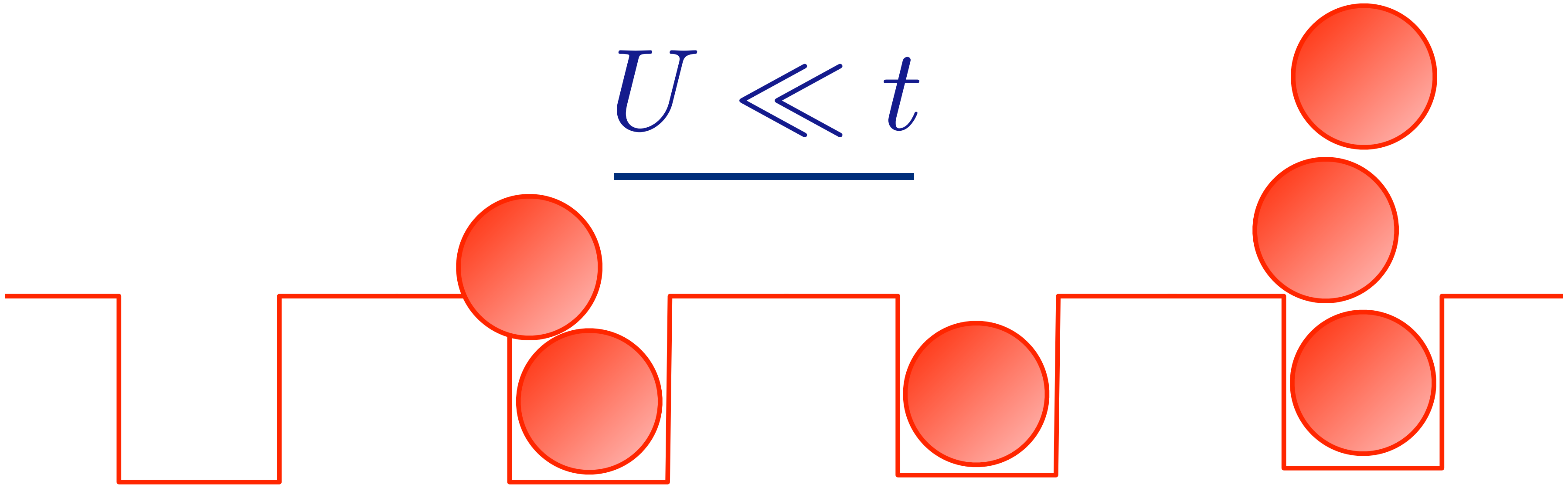
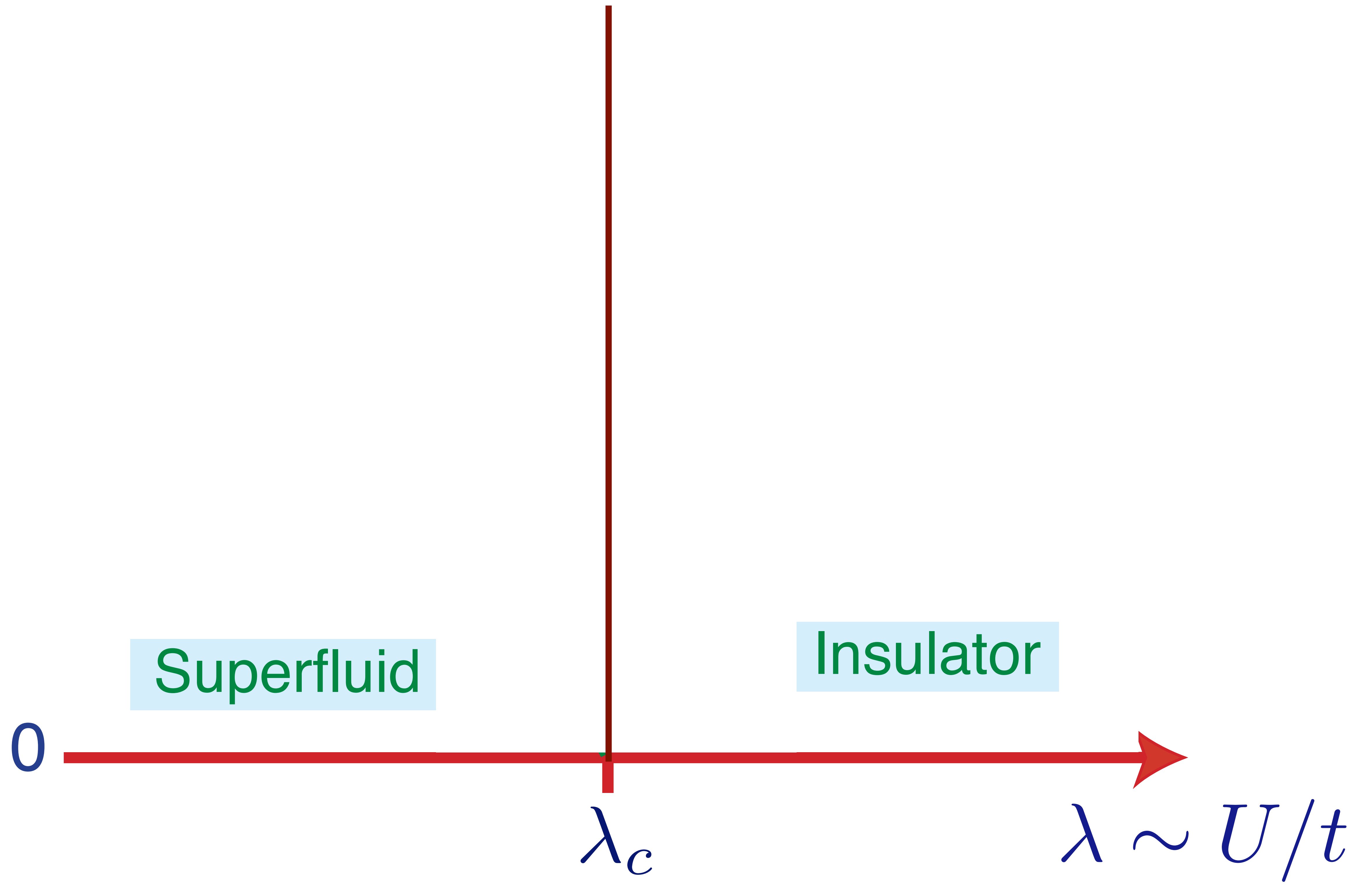
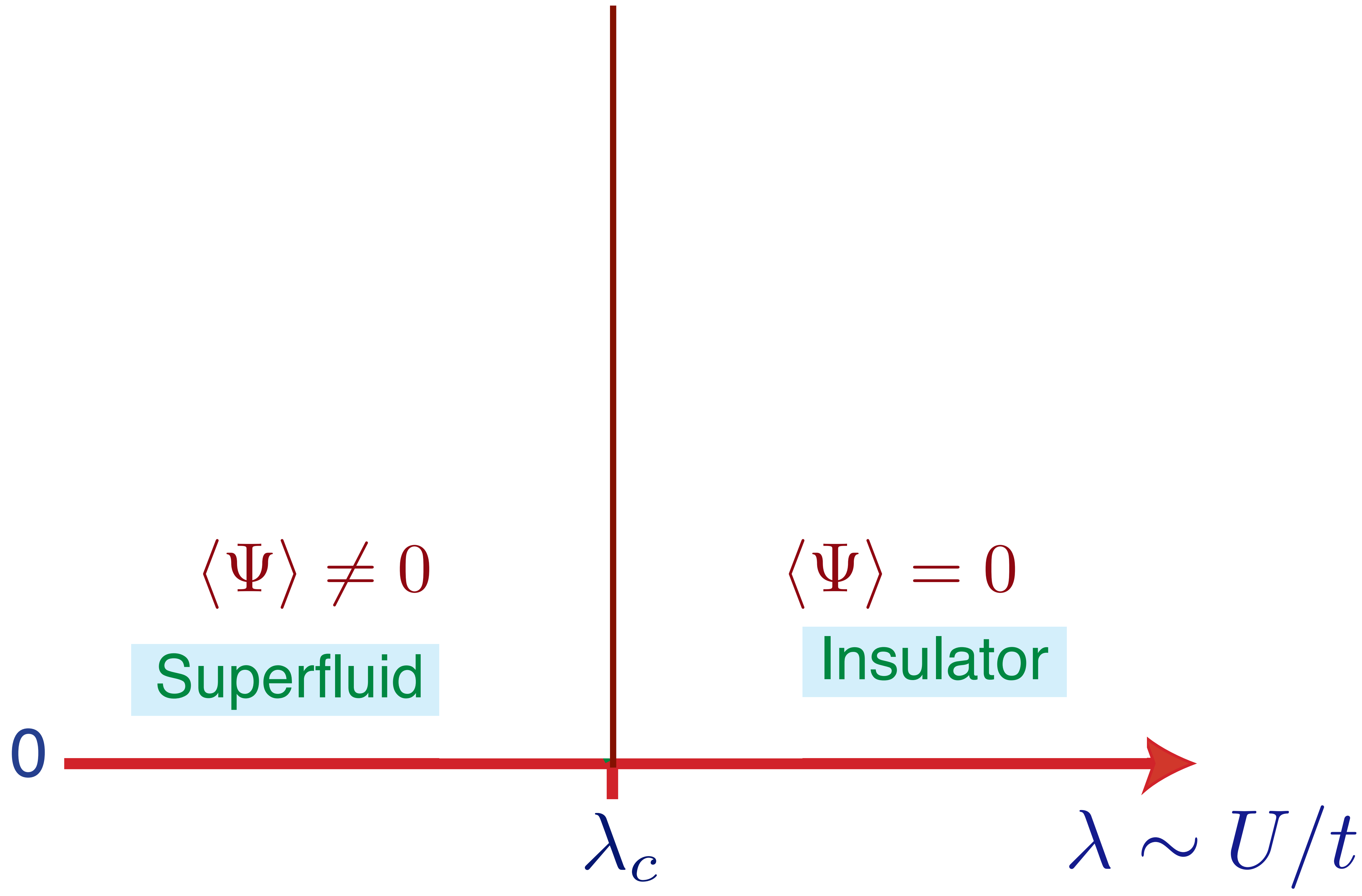


Superfluid
at small repulsion between bosons

$$|\text{Ground state}\rangle = \left[\sum_i b_i^\dagger\right]^N |0\rangle$$

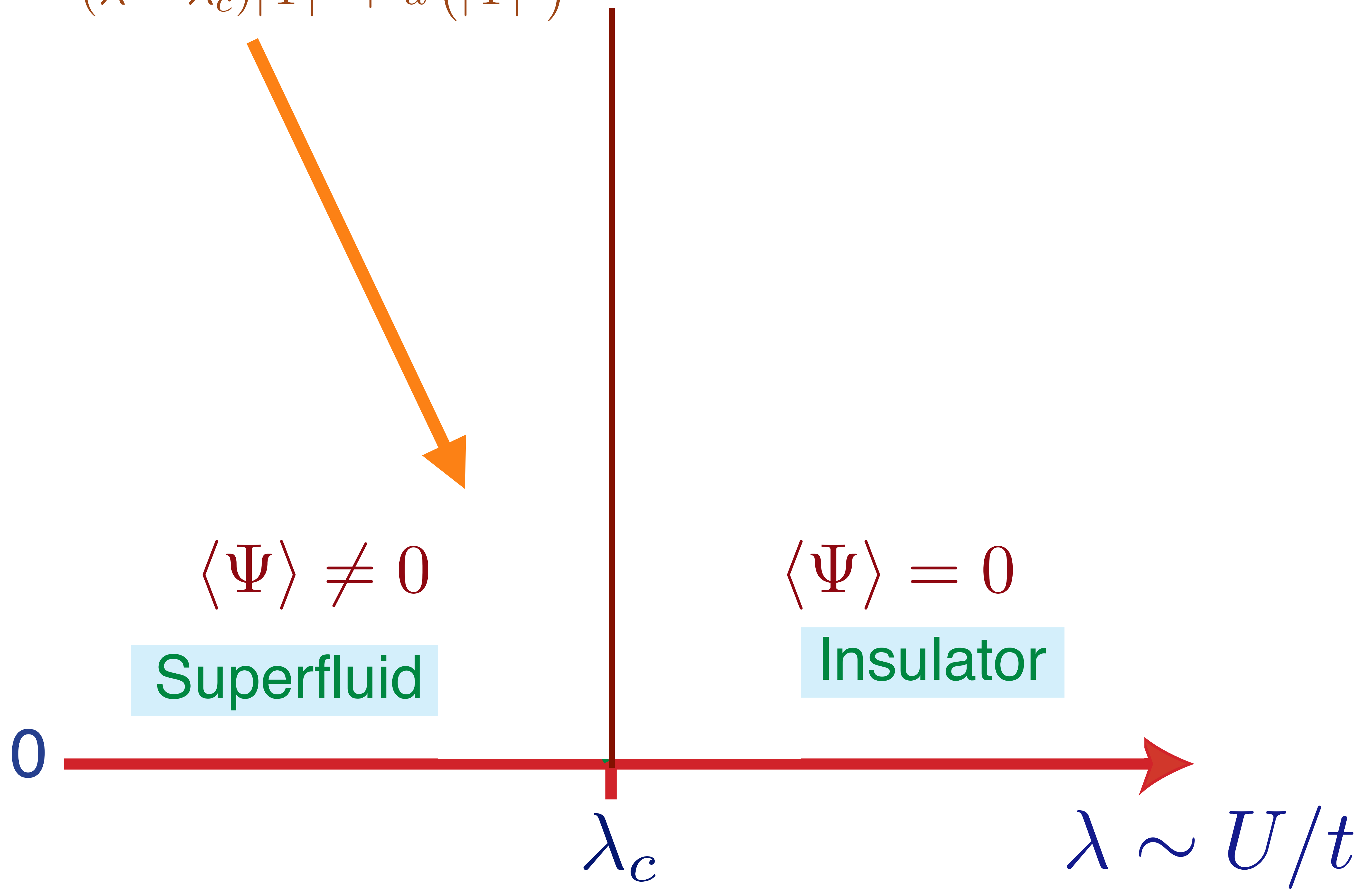

Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$

$\Psi \sim b_{k=0} \rightarrow$ a complex field representing the Bose-Einstein condensate of the superfluid



$$\mathcal{Z} = \int \mathcal{D}\Psi(r,\tau) \exp\left(-\int d^2r\, d\tau \left[|\partial_\tau \Psi|^2 + c^2|\nabla_r \Psi|^2 + V(\Psi)\right]\right)$$

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



$$\mathcal{Z} = \int \mathcal{D}\Psi(r,\tau) \exp\left(- \int d^2 r d\tau \left[|\partial_\tau \Psi|^2 + c^2 |\nabla_r \Psi|^2 + V(\Psi) \right] \right)$$

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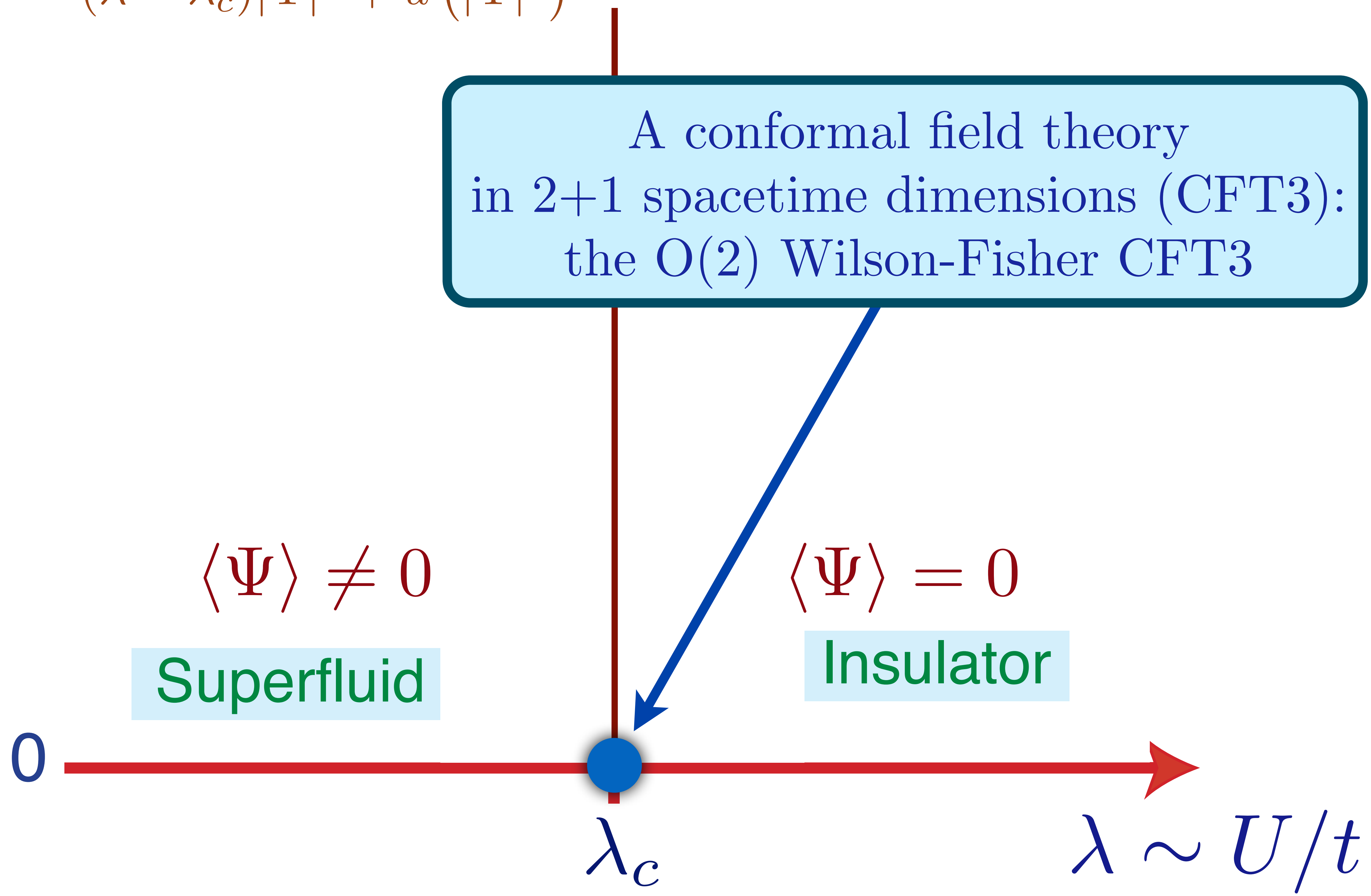

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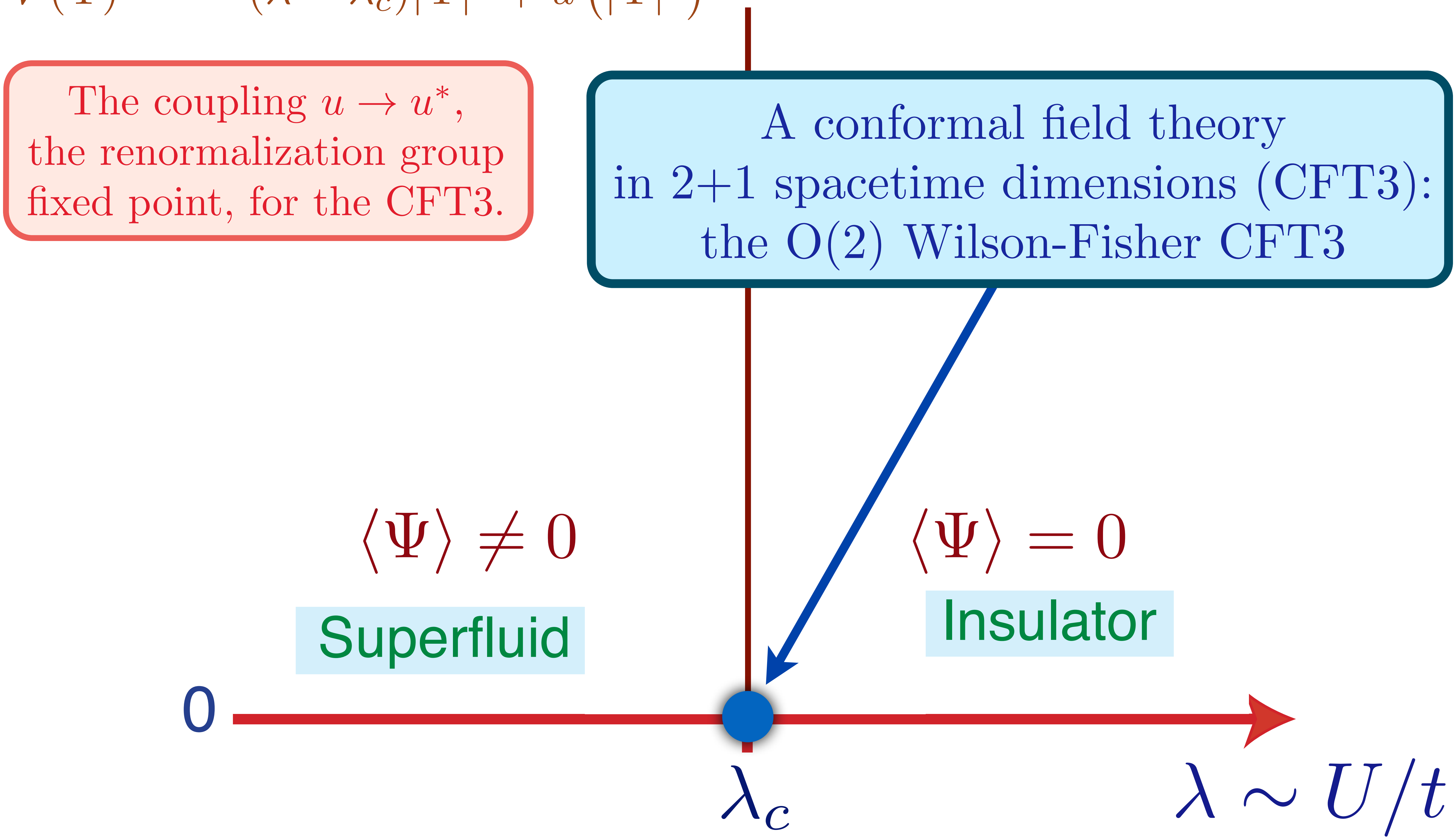
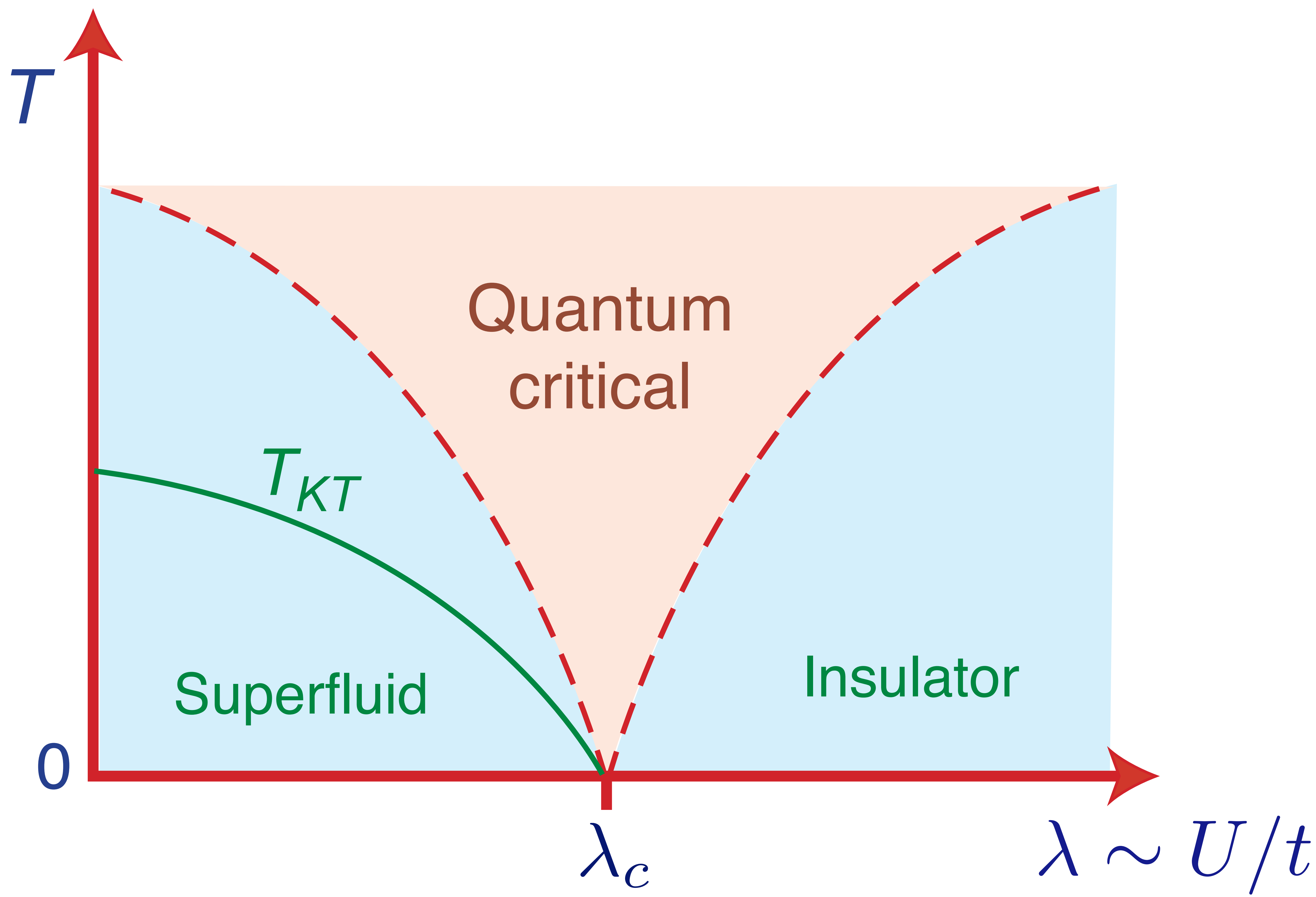
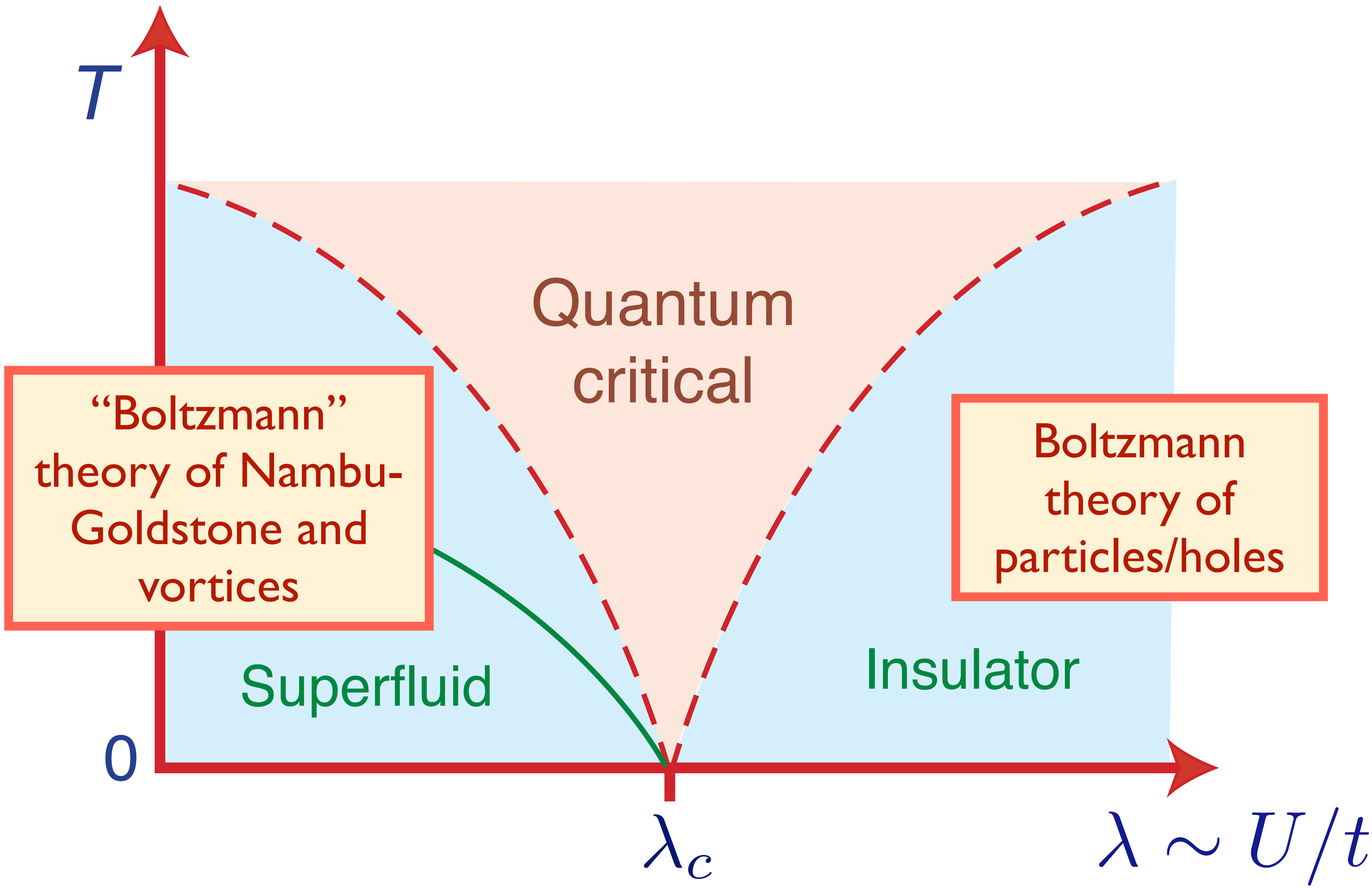
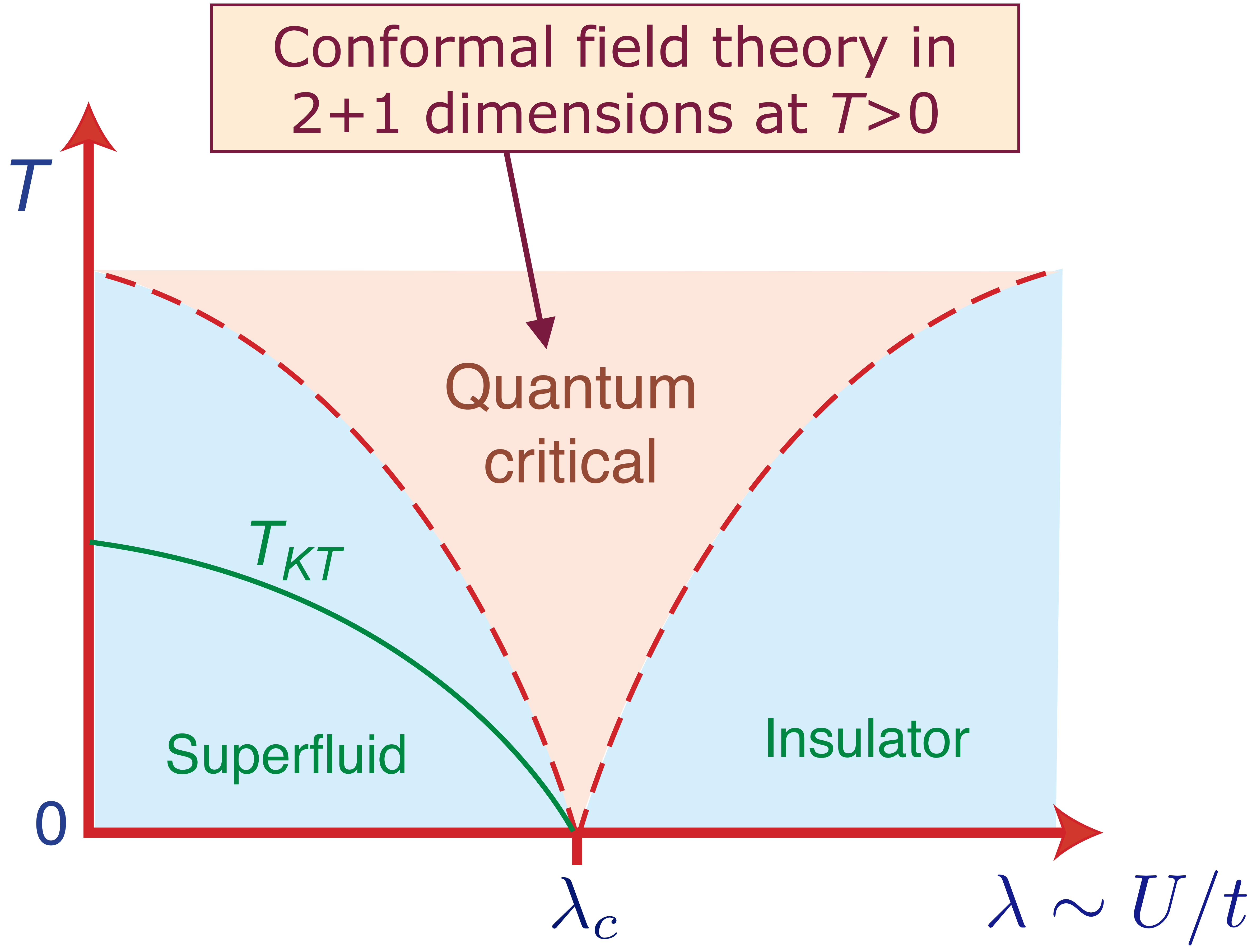




T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$


T
0
Quantum
critical
"Boltzmann" theory of Nambu-Goldstone and vortices
Boltzmann theory of particles/holes
Superfluid
Insulator
λ_c
$\lambda \sim U/t$



Conformal field theory in
2+1 dimensions at $T>0$
T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
$\lambda \sim U/t$

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1. Conformal field theories in 2+1 dimensions

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A. Boltzmann dynamics

B. Conformal / holographic dynamics

2. Non-Fermi liquid in 2+1 dimensions

Strange metal in the high temperature superconductors

A. Lessons from holography

B. Field theories and memory functions

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- ◊ Identify quasiparticles and their dispersions

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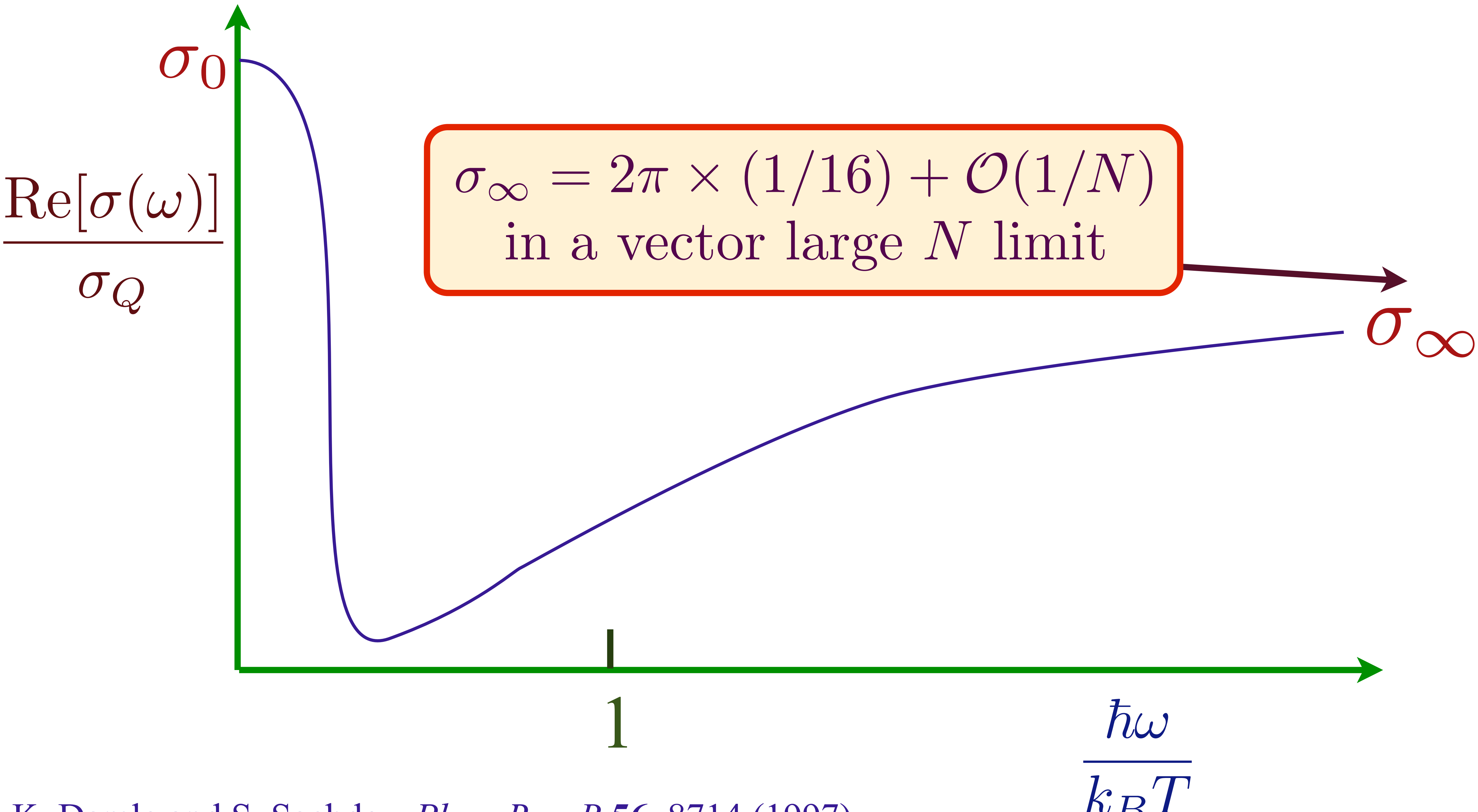
Quasiparticle view of quantum criticality (Boltzmann equation): Transport of O(*N*) current for a (weakly) interacting CFT3

$\sigma_Q = e^2/h$, the quantum unit of conductance



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

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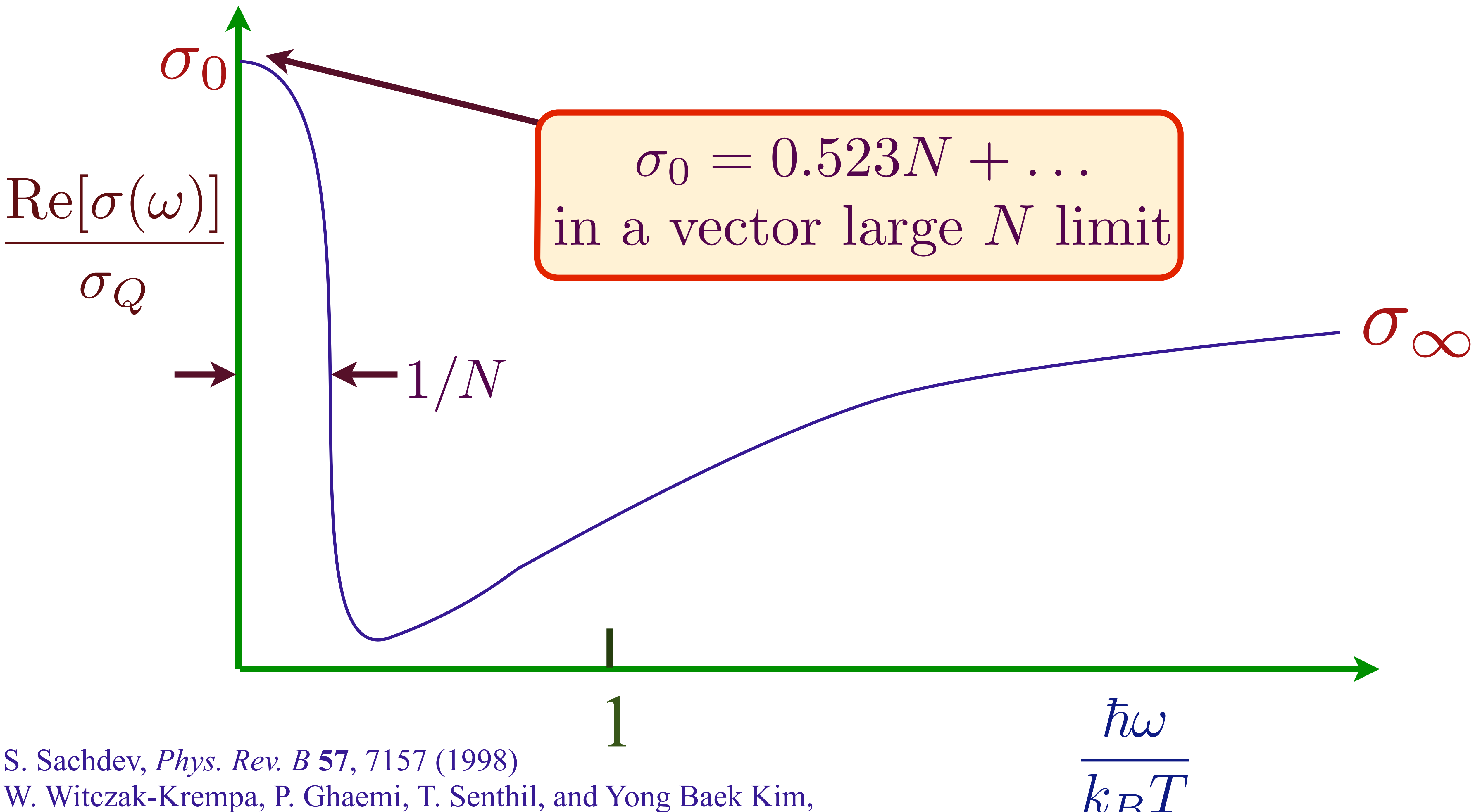

S. Sachdev, *Phys. Rev. B* **57**, 7157 (1998)
W. Witczak-Krempa, P. Ghaemi, T. Senthil, and Yong Baek Kim, *Phys. Rev. B* **86**, 24102 (2012)

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Dynamics without quasiparticles

- ★ Start with strongly interacting CFT without quasiparticles
- ★ Using scaling dimensions and operator product expansions (OPE) of the CFT, compute conductivity at $\hbar\omega \gg k_B T$

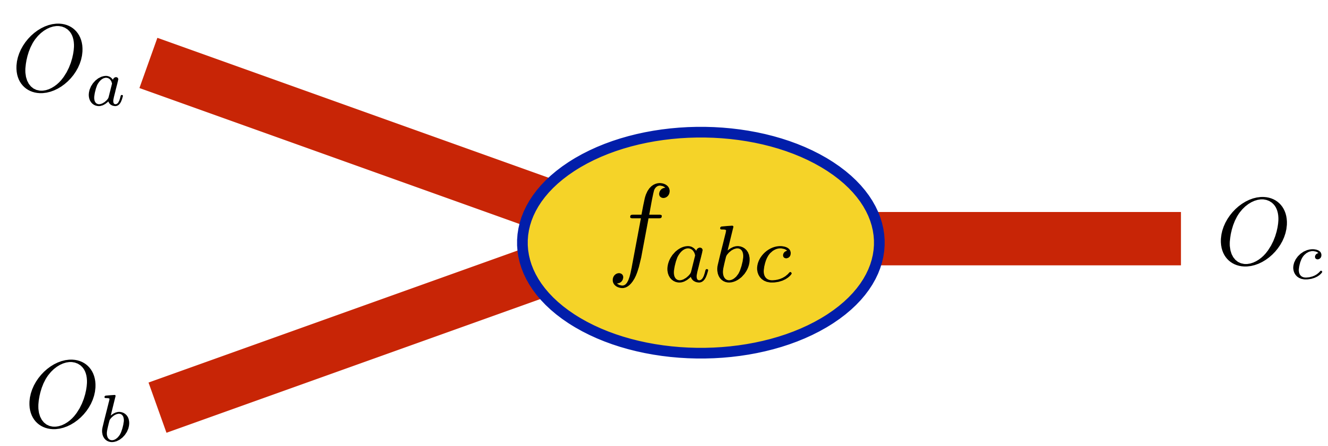
Basic characteristics of CFTs

Primary operators of CFT, $O_a(x)$, obey (at $T = 0$):

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

where Δ_a is their scaling dimension. Their "interactions" are determined by the OPE (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 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

Basic characteristics of CFT3s

The thermal average of the OPE of two O(2) current operators yields for $\omega \gg T$

$$\frac{\sigma(\omega)}{\sigma_Q} = \sigma_\infty + b_1 \left(\frac{T}{\omega}\right)^{3-1/\nu} + b_2 \left(\frac{T}{\omega}\right)^3 + \ldots$$

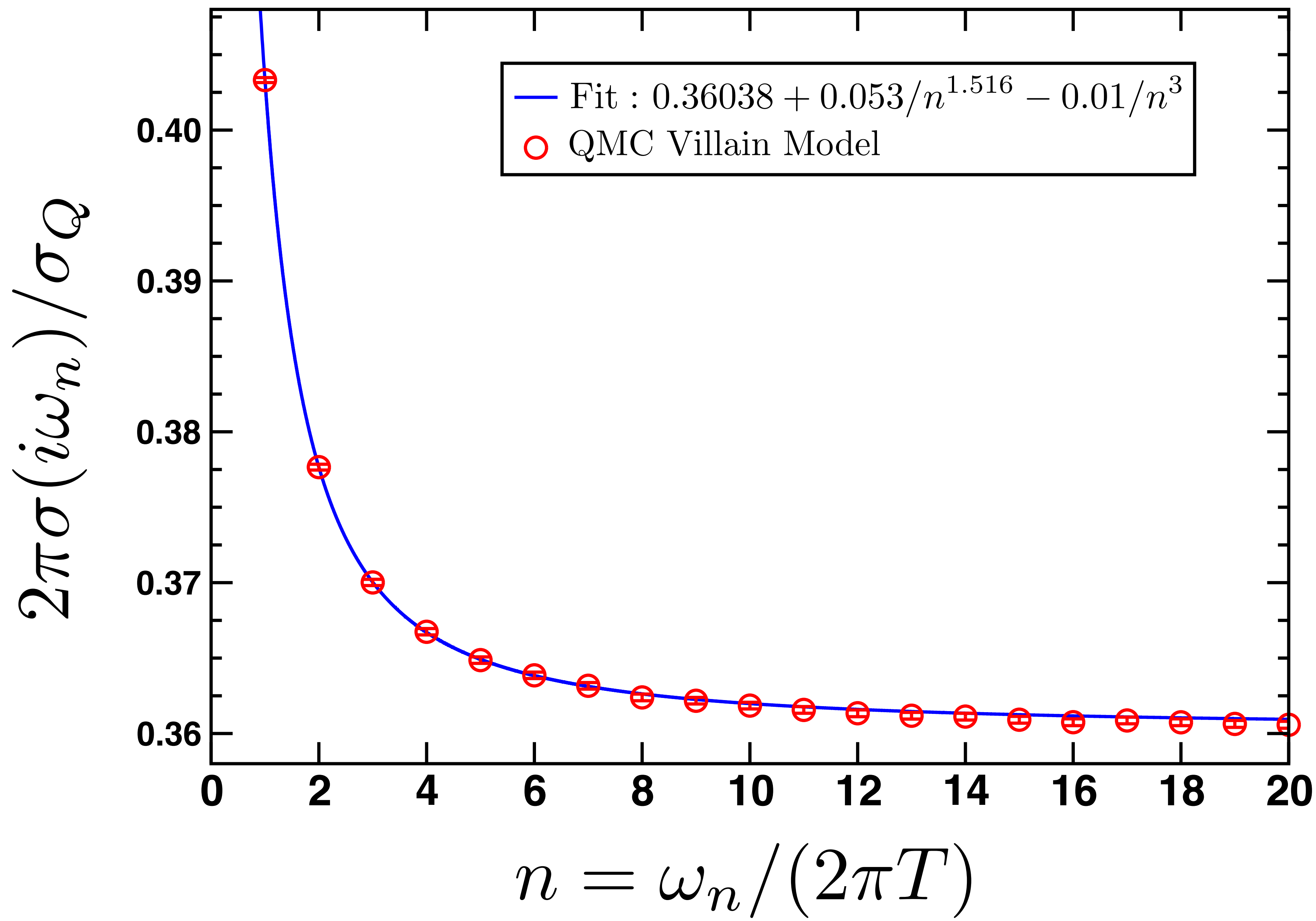
where $b_{1,2}$ are universal numbers dependent upon OPE coefficients.

- b_1 depends on a relevant scalar operator with dimension $3 - 1/\nu$; for the O(2) Wilson-Fisher CFT3, $\nu \approx 0.6717(1)$.

- b_2 depends on OPE with the energy-momentum tensor.

E. Katz, S. Sachdev, E. Sorensen, and W. Witczak-Krempa, arXiv:1409.3841

Quantum Monte Carlo for lattice model of integer currents (Villain model) in Euclidean time



Excellent agreement with OPE

E. Katz, S. Sachdev, E. Sorensen, and W. Witczak-Krempa, arXiv:1409.3841

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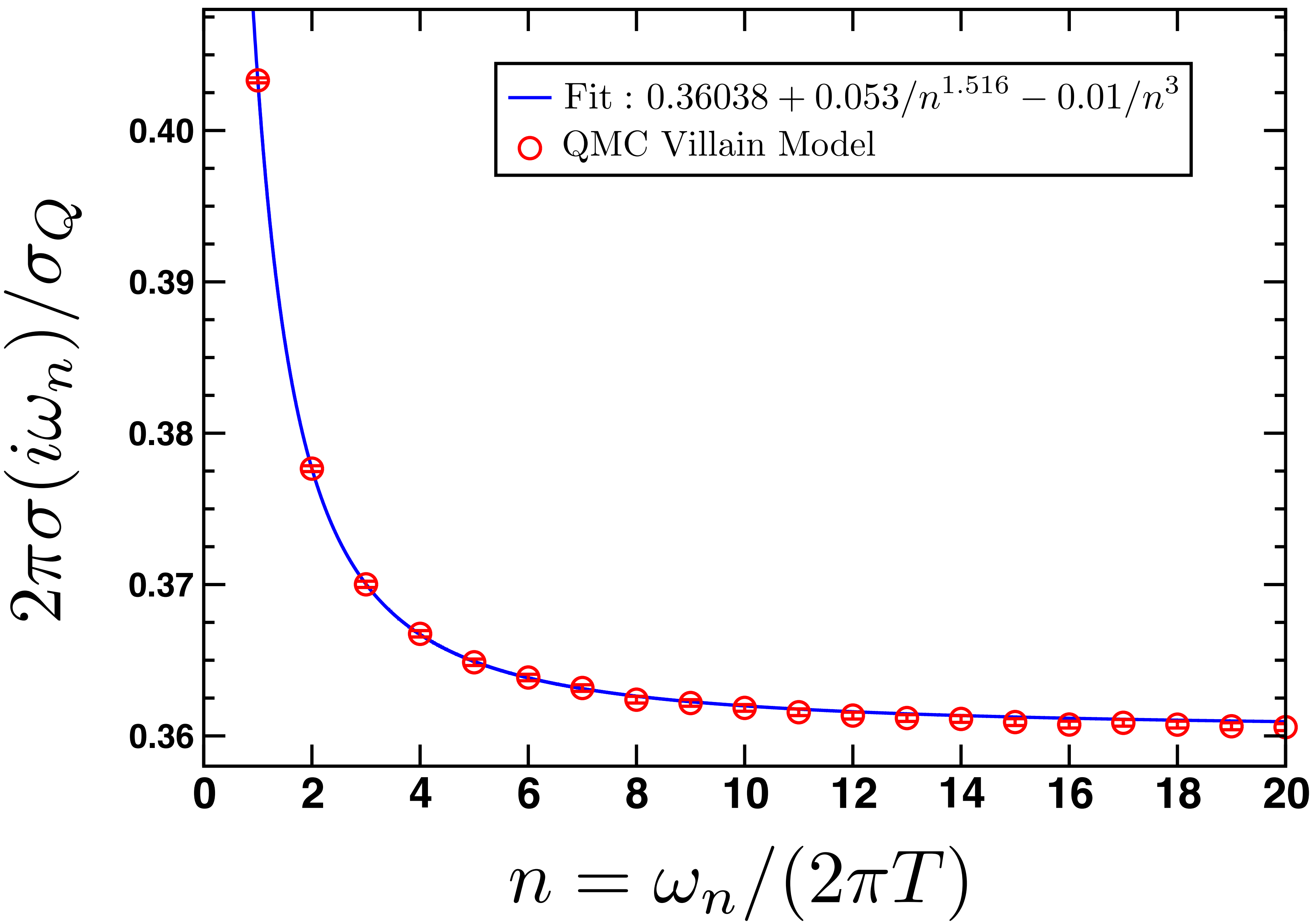

QMC fails for Minkowski frequencies $\hbar\omega \ll k_B T$

E. Katz, S. Sachdev, E. Sorensen, and W. Witczak-Krempa, arXiv:1409.3841

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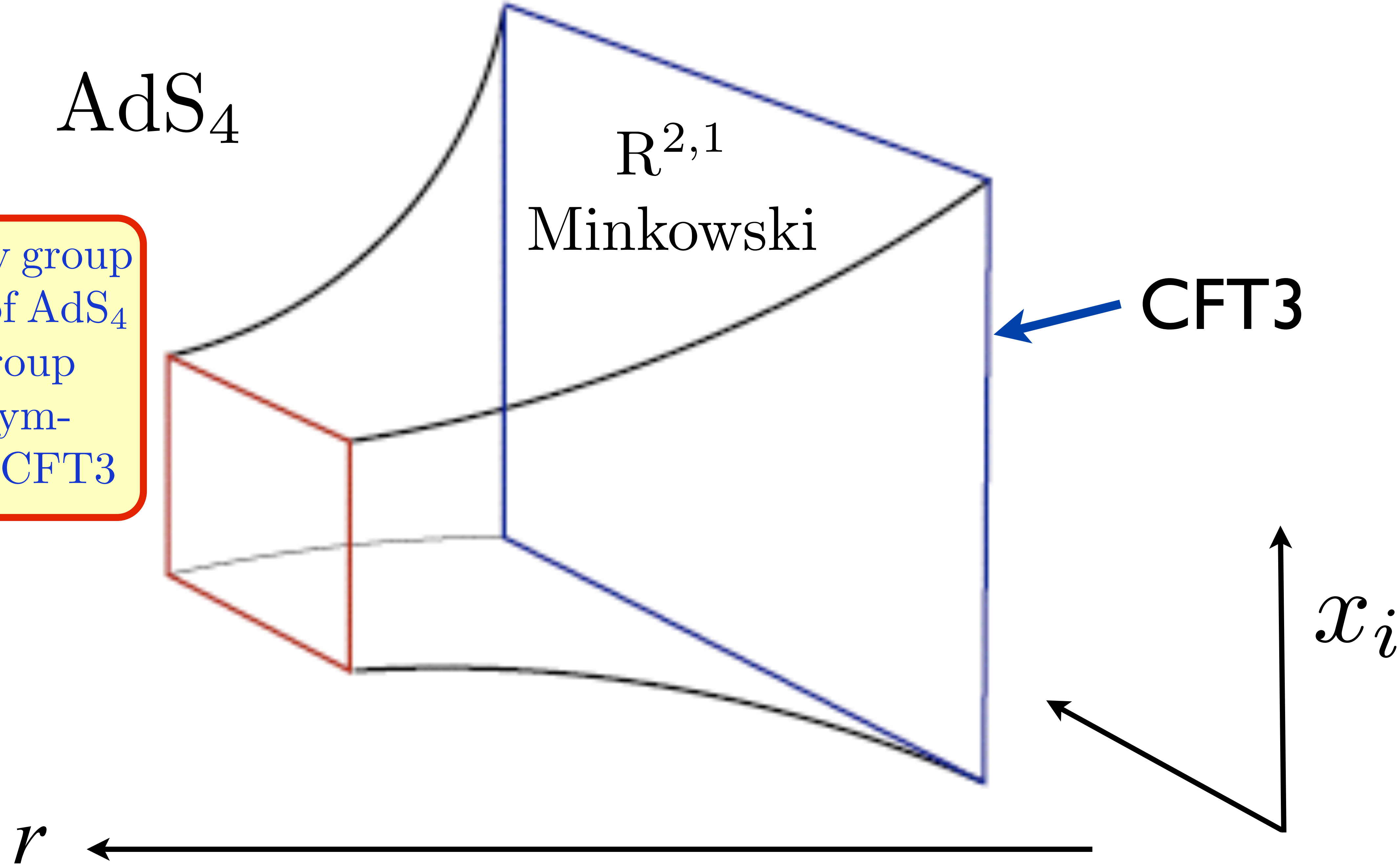
AdS/CFT correspondence at zero temperature



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

$$ds^2 = \left(\frac{L}{r}\right)^2 \left[dr^2 - dt^2 + dx^2 + dy^2\right]$$

AdS/CFT correspondence at zero temperature

To fully match the OPE of the current operators, we need an *Einstein-Maxwell-Weyl-scalar* theory

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

where C_{abcd} is the Weyl tensor. Stability constraints on this action restrict $|\gamma| < 1/12$, in agreement with results from the CFT3. The scalar field φ is conjugate to the CFT operator $\mathcal{O}$ with scaling dimension $3 - 1/\nu$, which fixes its mass m. The coupling α is determined by the OPE of the currents with $\mathcal{O}$.

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).
E. Katz, S. Sachdev, E. Sorensen, and W. Witczak-Krempa, arXiv:1409.3841

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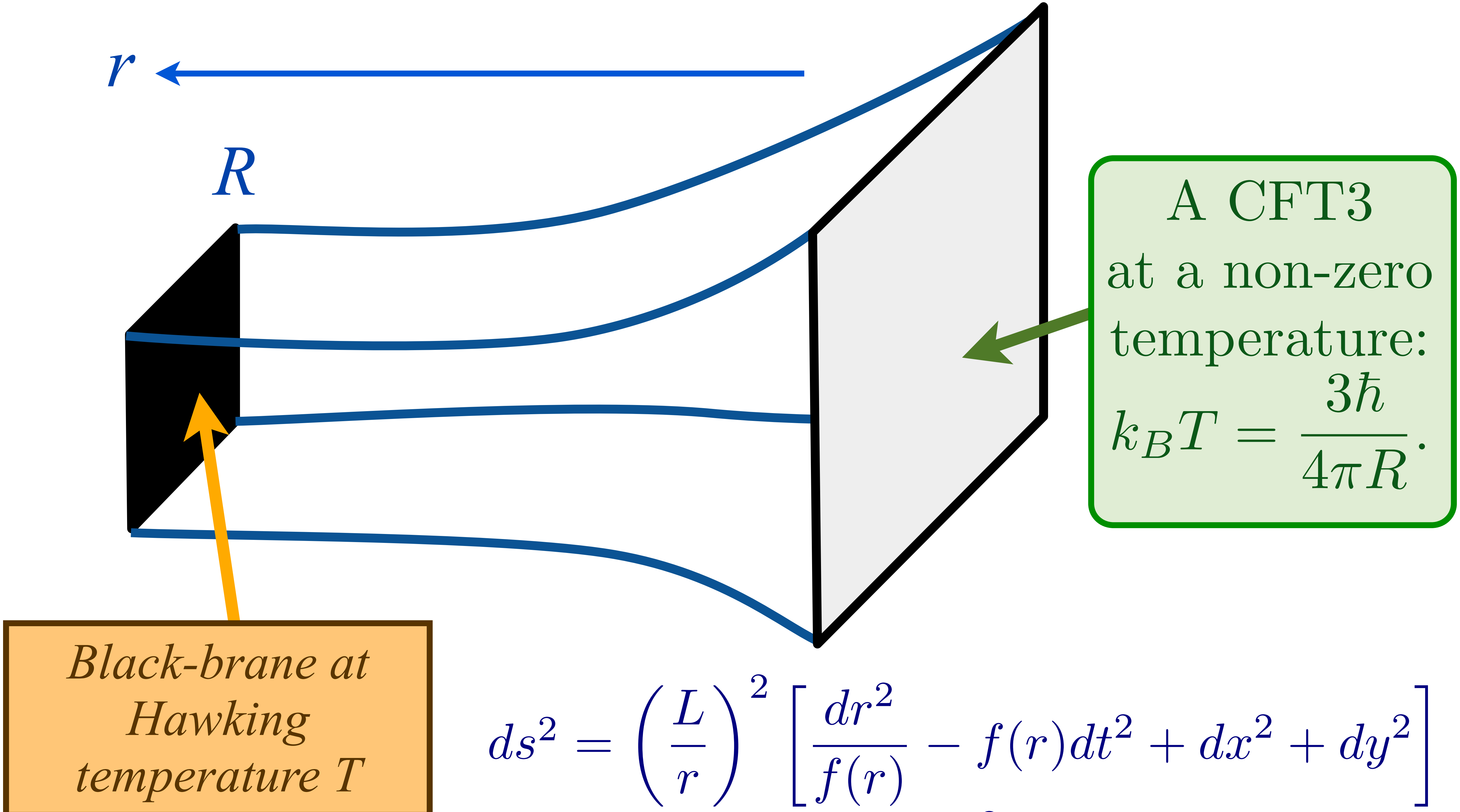
- ★ Dynamics of a "horizon" in gravitational theory yields info at $\hbar\omega \ll k_B T$.

AdS$_4$-Schwarzschild black-brane

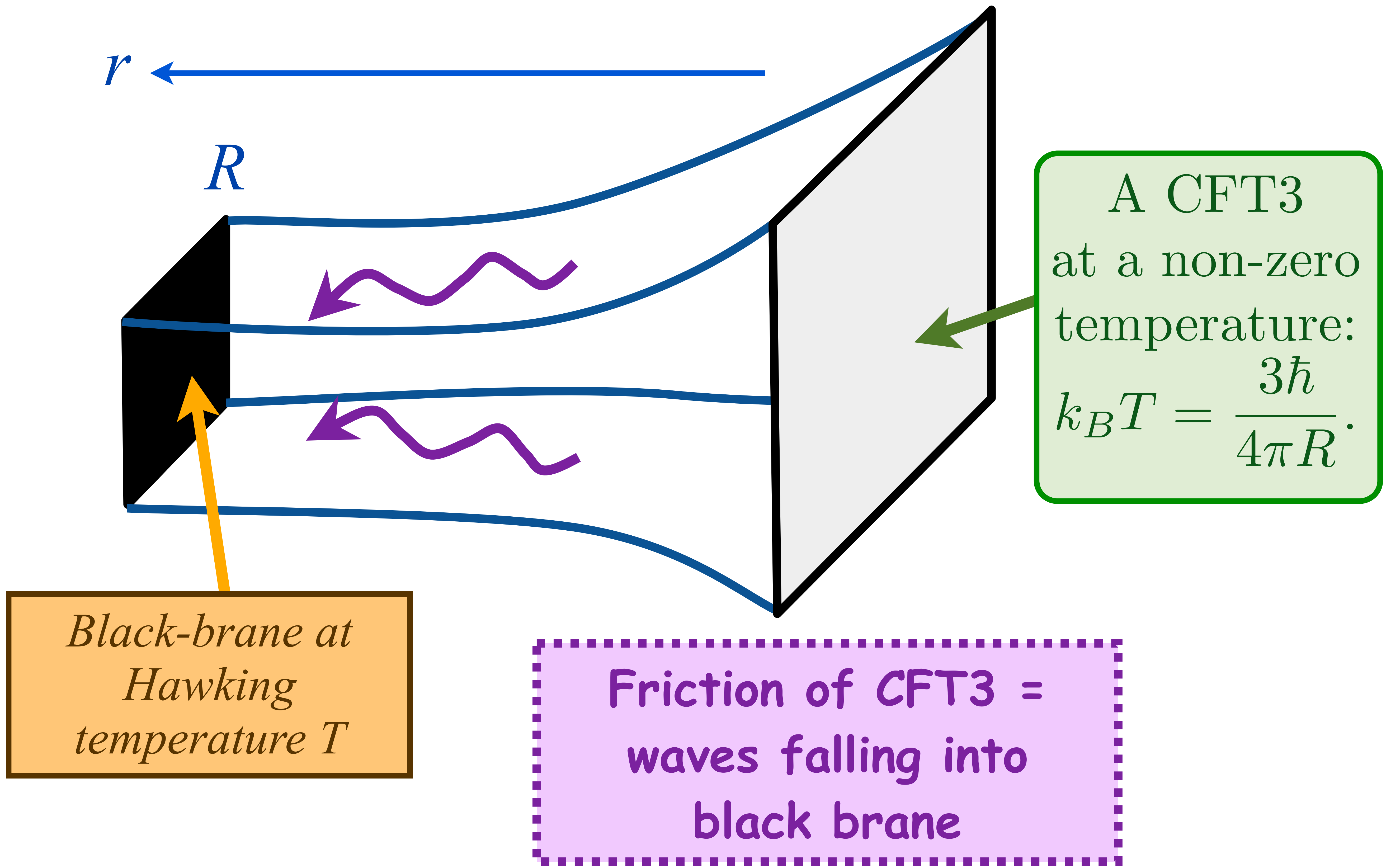


$$ds^2 = \left(\frac{L}{r}\right)^2 \left[\frac{dr^2}{f(r)} - f(r)dt^2 + dx^2 + dy^2\right]$$

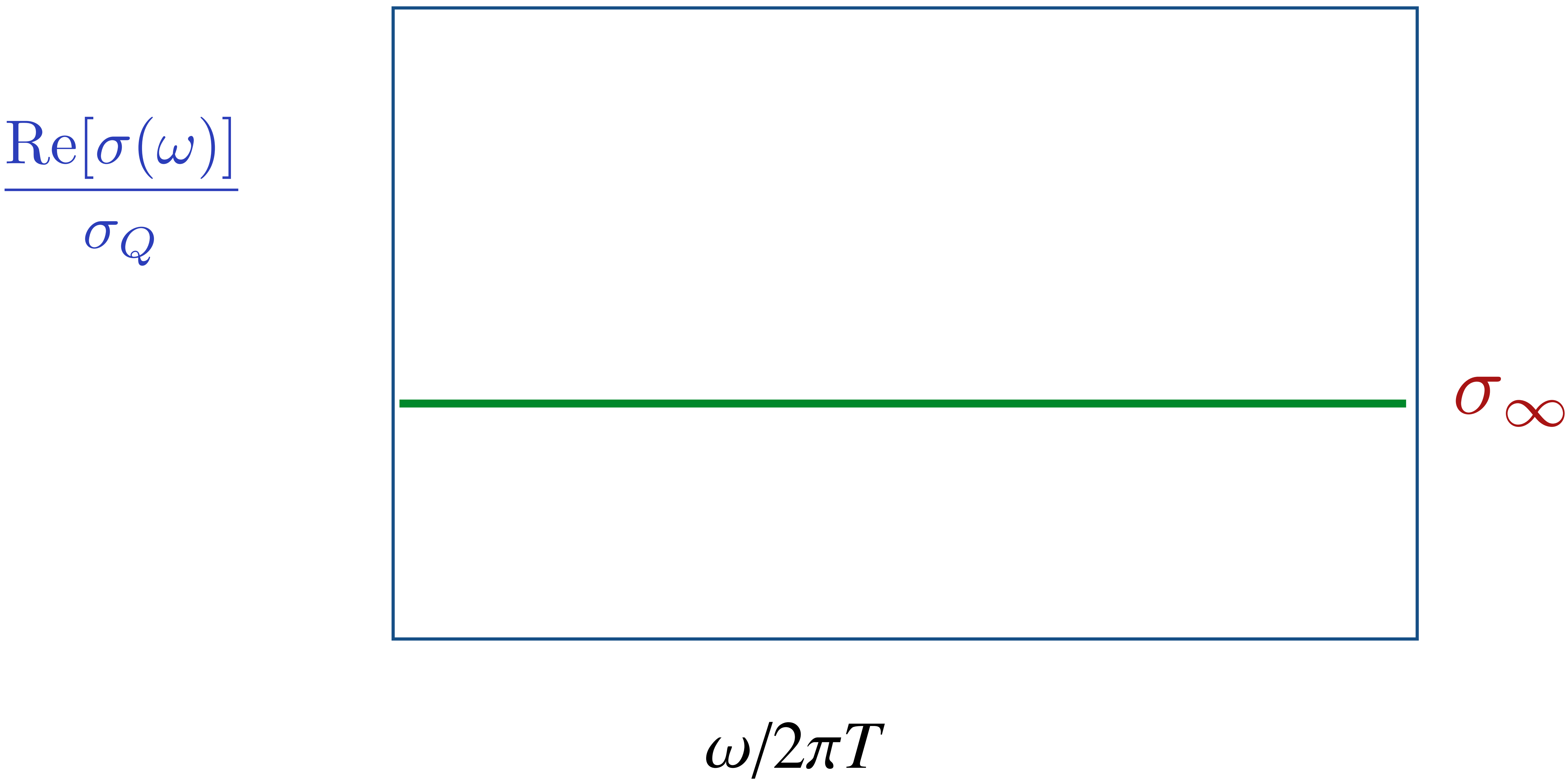
with $f(r) = 1 - (r/R)^3$

AdS/CFT correspondence at non-zero temperatures

AdS_4-Schwarzschild black-brane

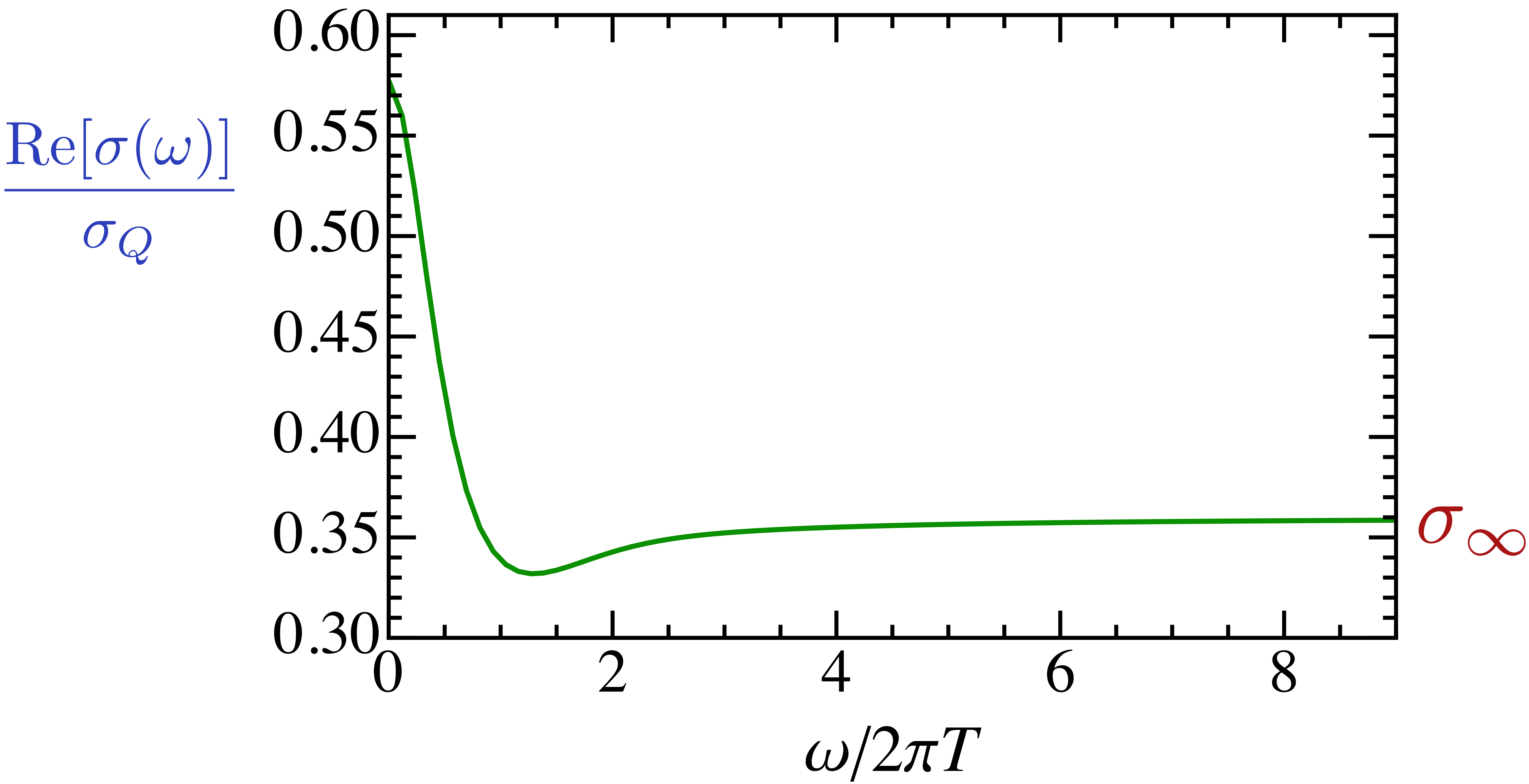


Conductivity of Einstein-Maxwell theory



C. P. Herzog, P. Kovtun. S. Sachdev, and D. T. Son, Physical Review D **75**, 085020 (2007)

Numerical solution of Einstein-Maxwell-Weyl-scalar theory + OPE info from QMC



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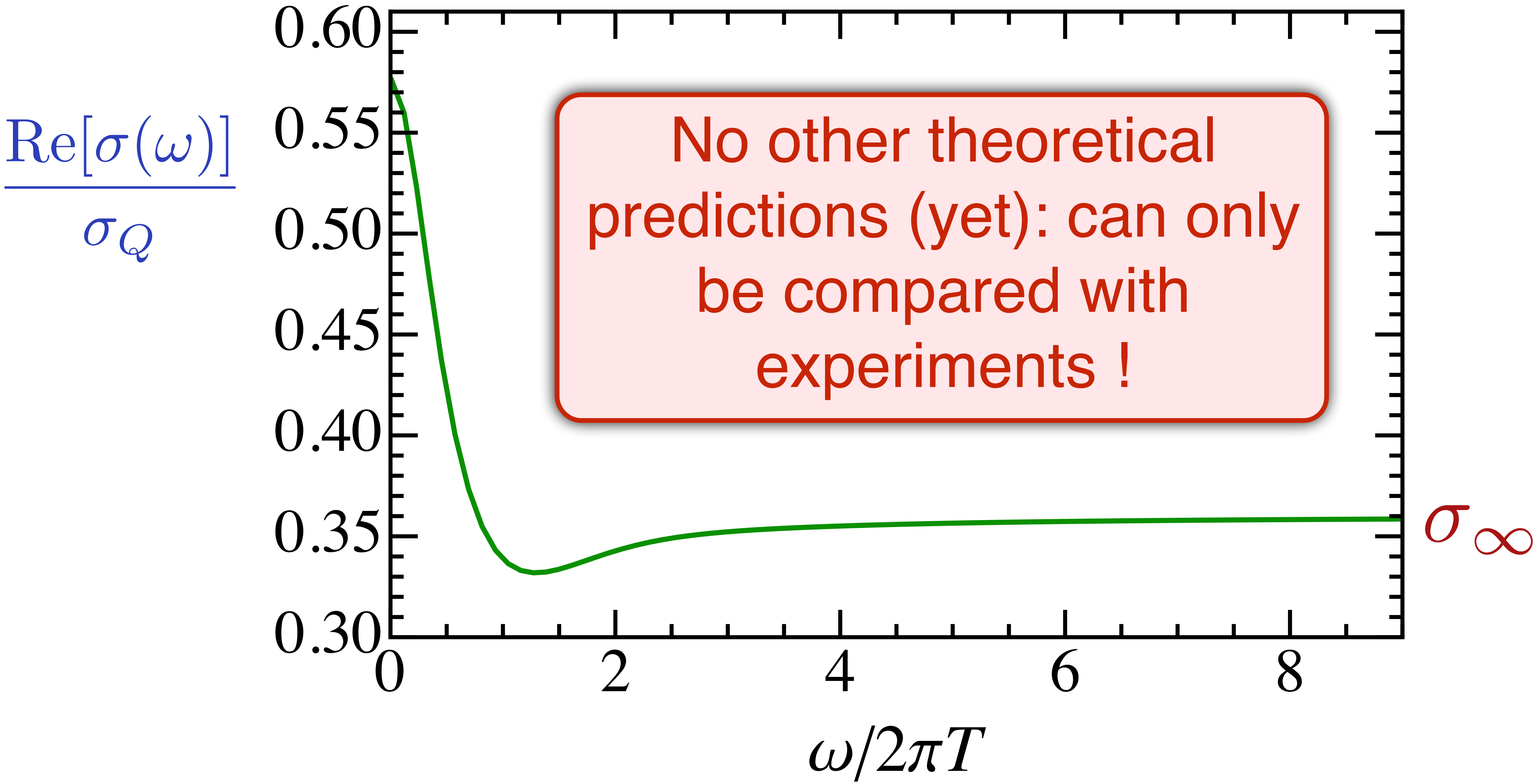

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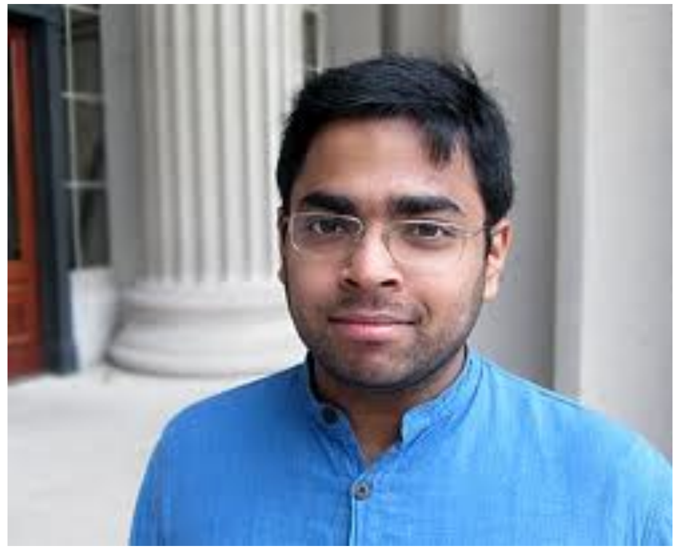
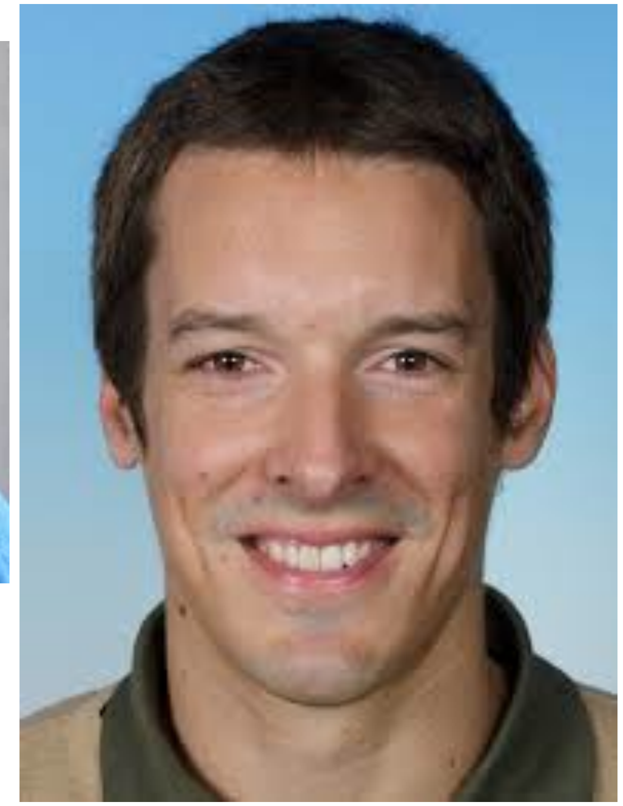
A. Lessons from holography

B. Field theories and memory functions

Sean Hartnoll
Stanford



Raghu Mahajan
Stanford

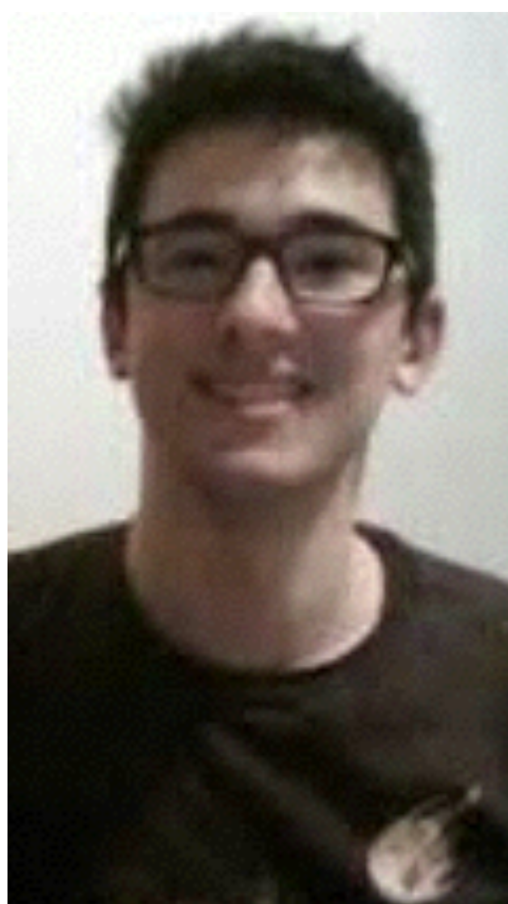


Matthias Punk
Innsbruck

Andrea Allais

Alexandra
Thomson

Koenraad Schalm
Leiden



Andrew Lucas

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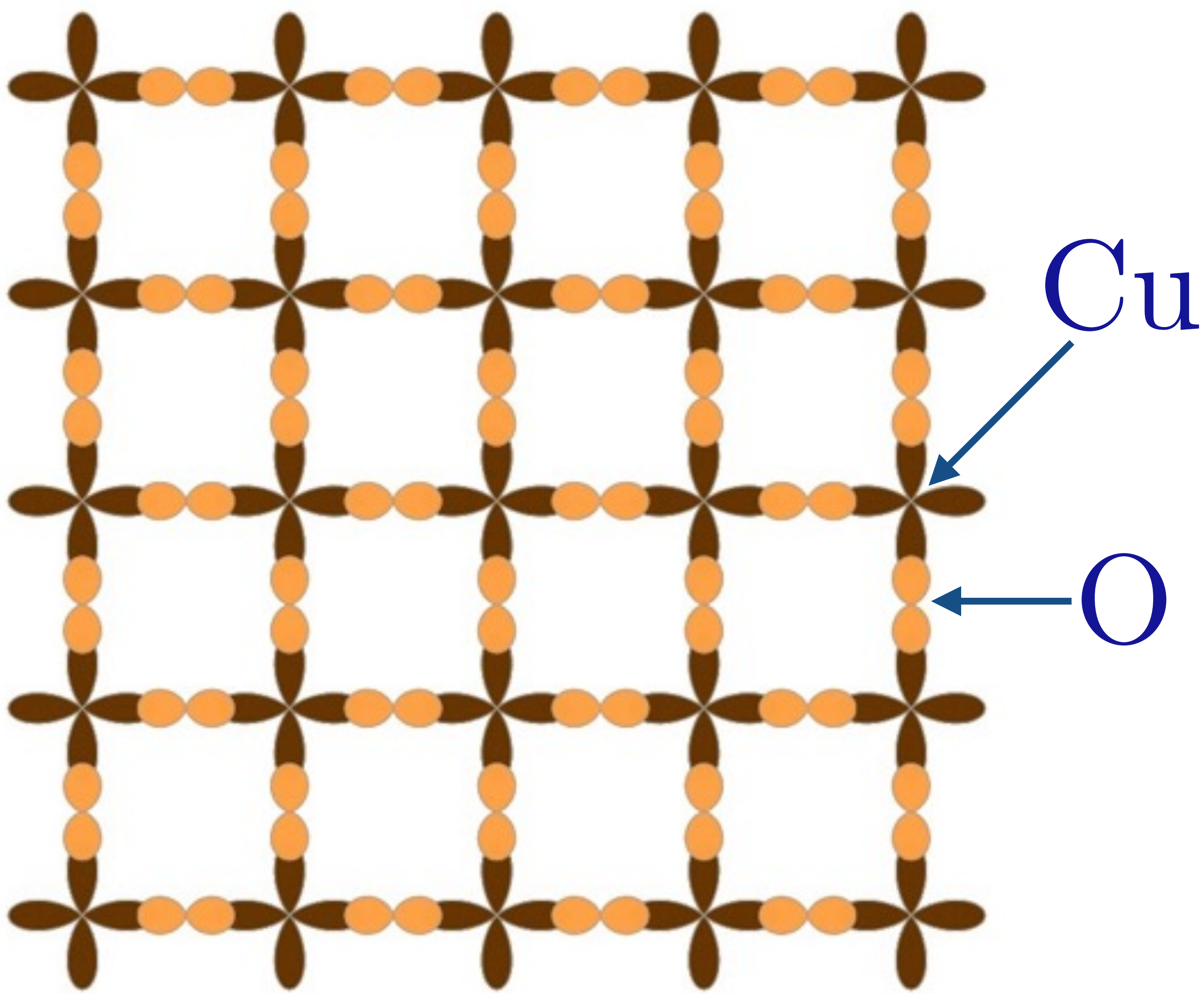
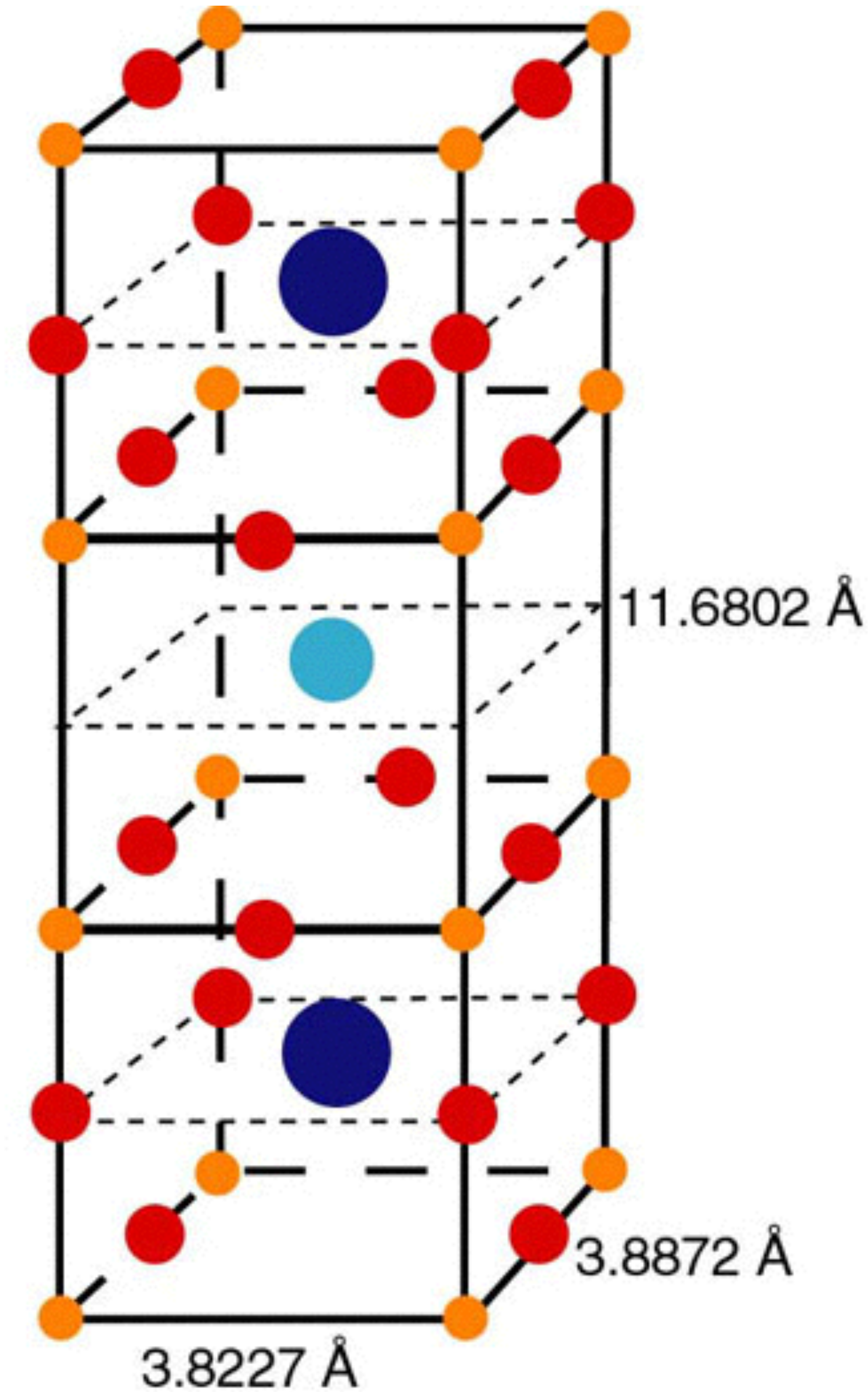
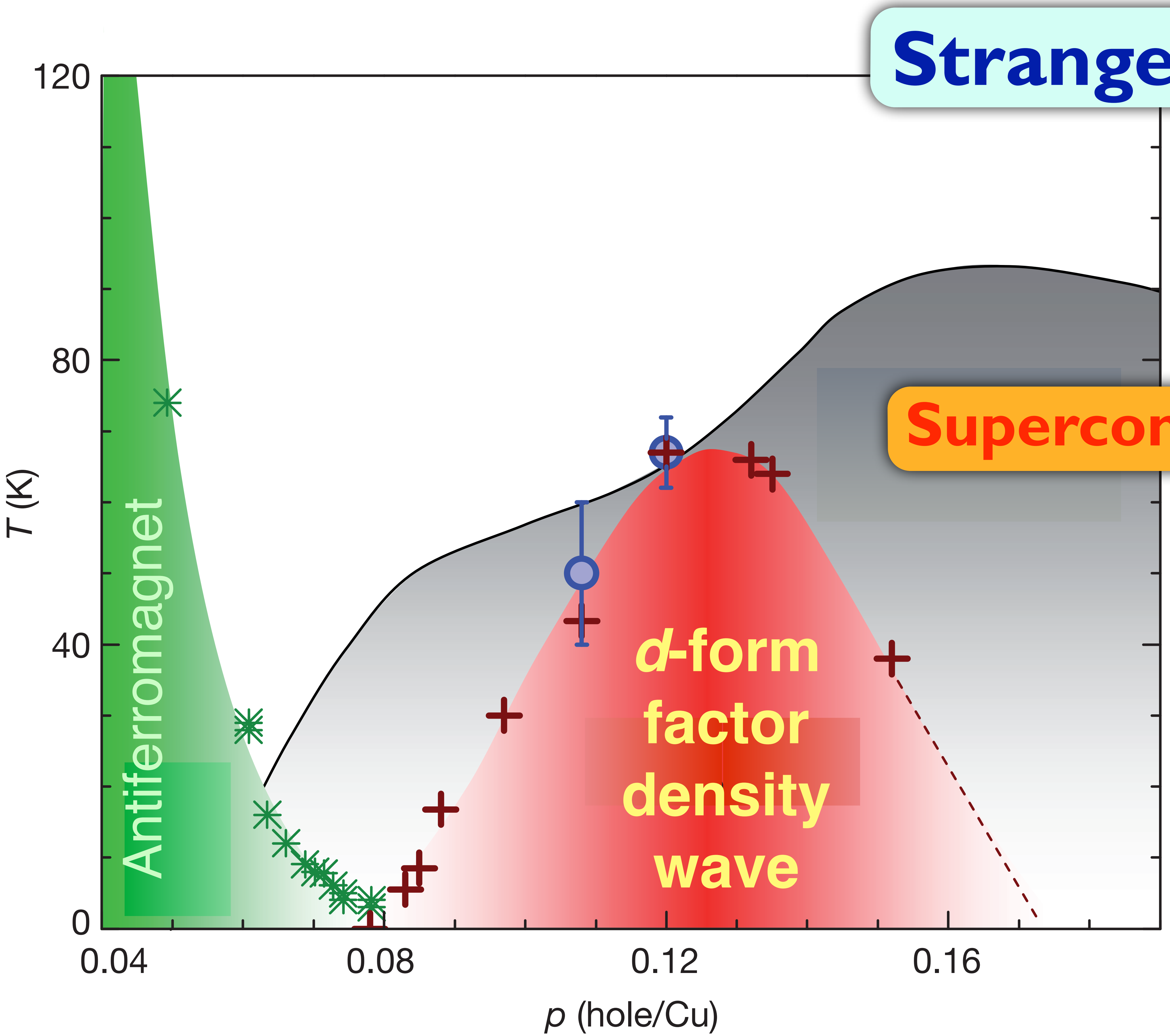
High temperature superconductors

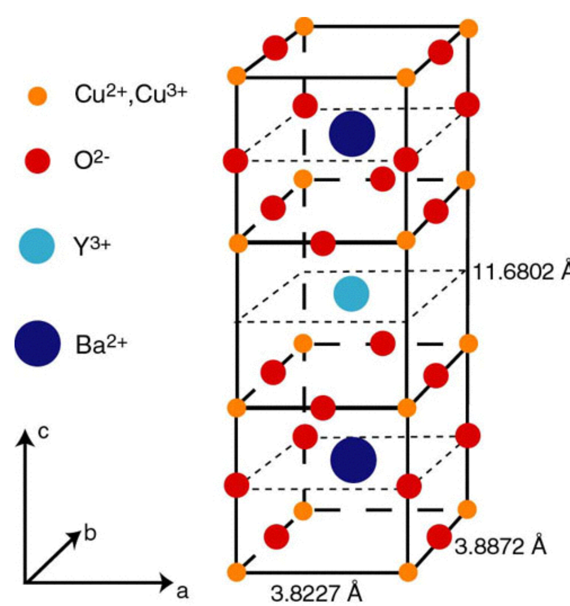


CuO_2 plane



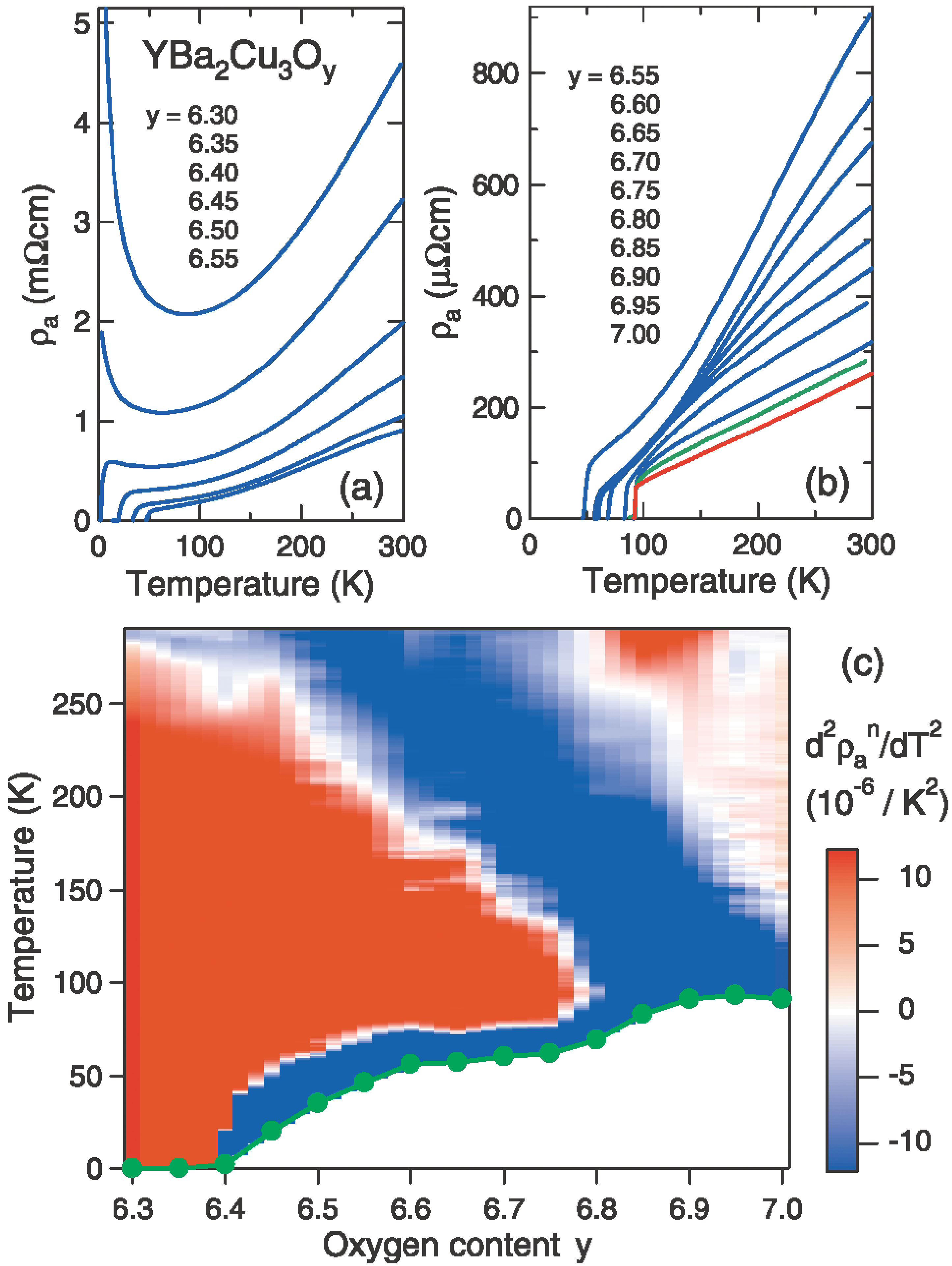
$YBa_2Cu_3O_{6+x}$





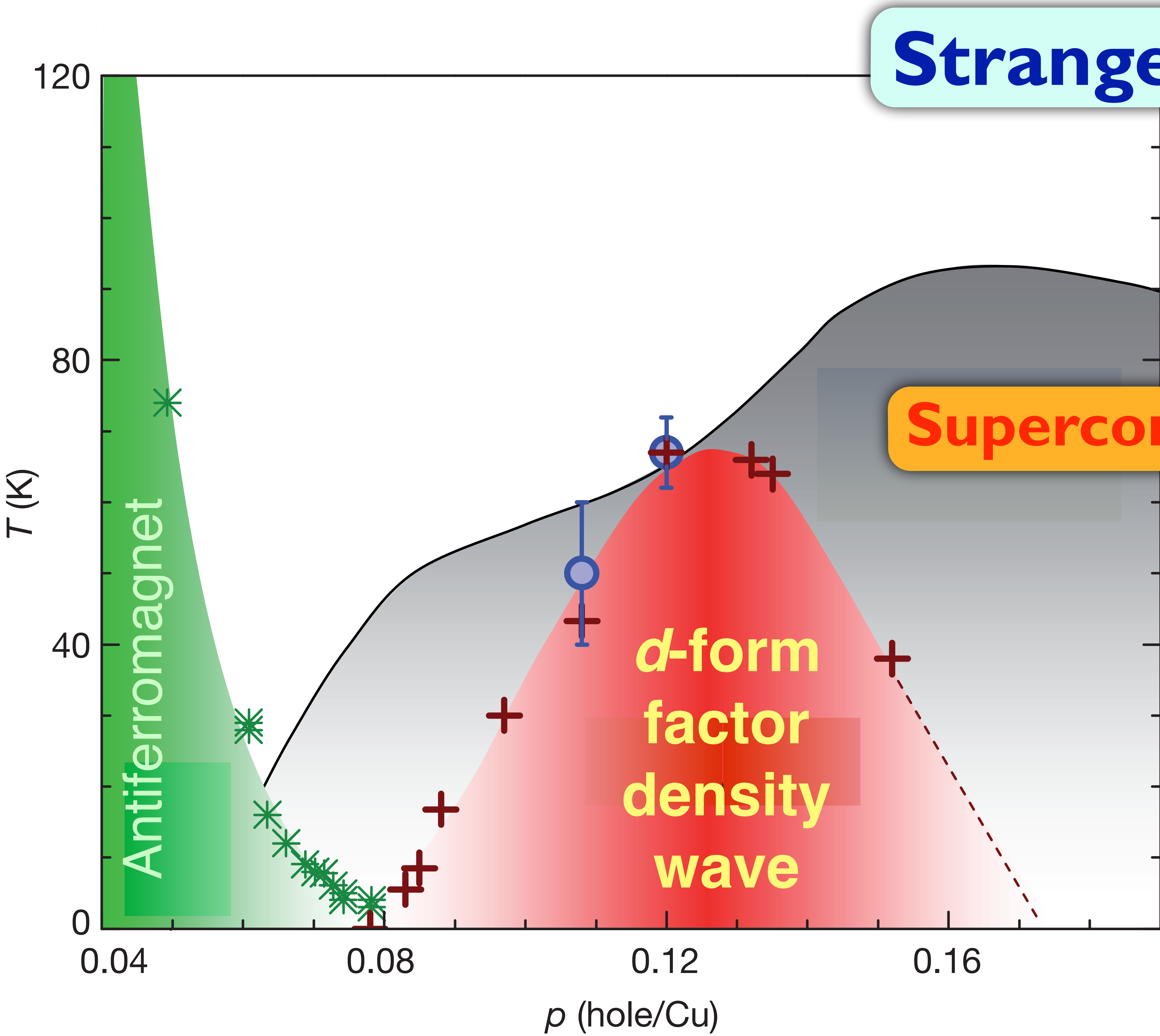
T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).

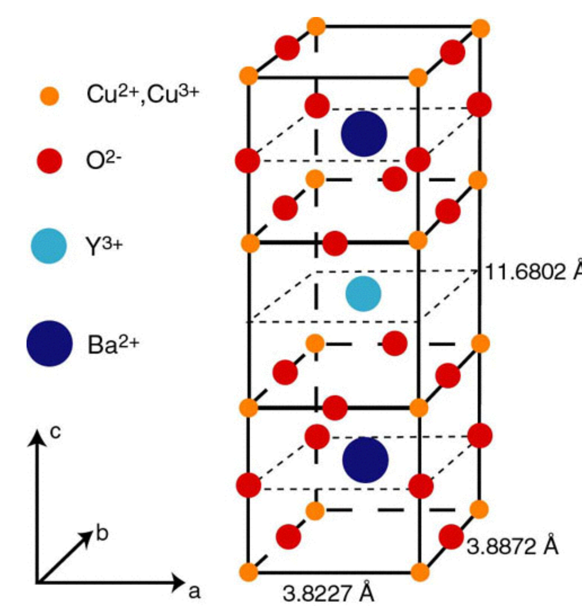
Strange metal



YBCO at optimal doping has resistivity $\rho(T) \sim T$.

Yoichi Ando, Seiki Komiya, Kouji Segawa, S. Ono, and Y. Kurita, Phys. Rev. Lett. **93**, 267001 (2004)





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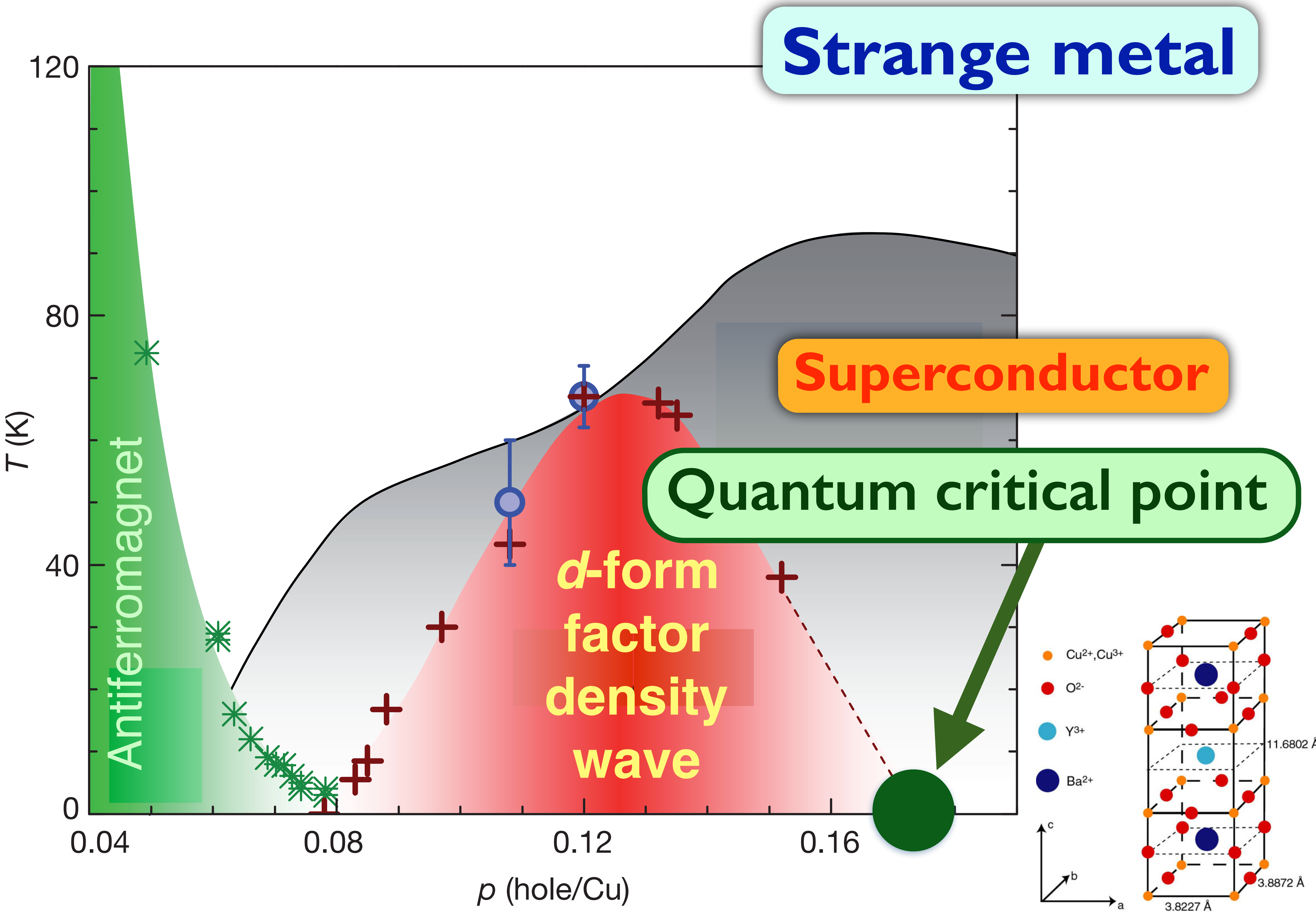

Y. He *et al.*, Science **344**, 608 (2014)
K. Fujita *et al.*, Science **344**, 612 (2014)

SU(2) gauge theory for underlying quantum critical point

Write the electron operator c_α ($\alpha = \uparrow, \downarrow$ are spin indices) as

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = R \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

where R is a SU(2) matrix which determines the orientation of the local antiferromagnetic order, and $\psi_\pm$ are spinless fermions which carry the global electron U(1) charge.

This parameterization is invariant under a SU(2) *gauge* transformation

$$\begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} \to U \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} \quad ; \quad R \to R U^\dagger$$

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086

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- The quantum critical theory is the Higgs transition where the gauge "symmetry" breaks from SU(2) down to U(1), in the presence of a Fermi surface of fermions carrying fundamental SU(2) charges.

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- The quantum phase transition has no gauge-invariant "order parameter", and it does not break any global symmetries.

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Outline

1. Conformal field theories in 2+1 dimensions

Superfluid-insulator transition

A. Boltzmann dynamics

B. Conformal / holographic dynamics

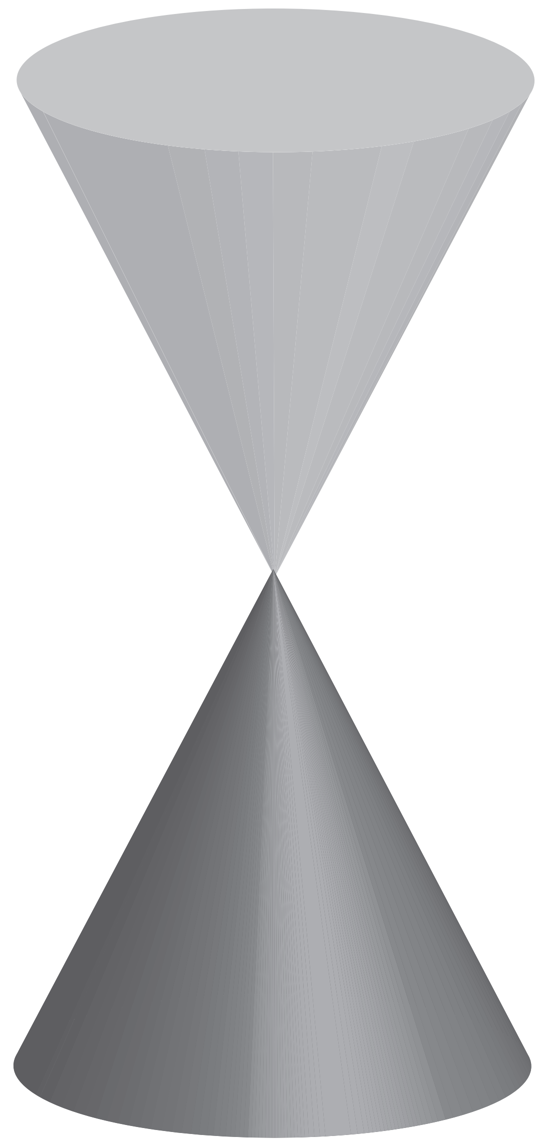
2. Non-Fermi liquid in 2+1 dimensions

Strange metal in the high temperature superconductors

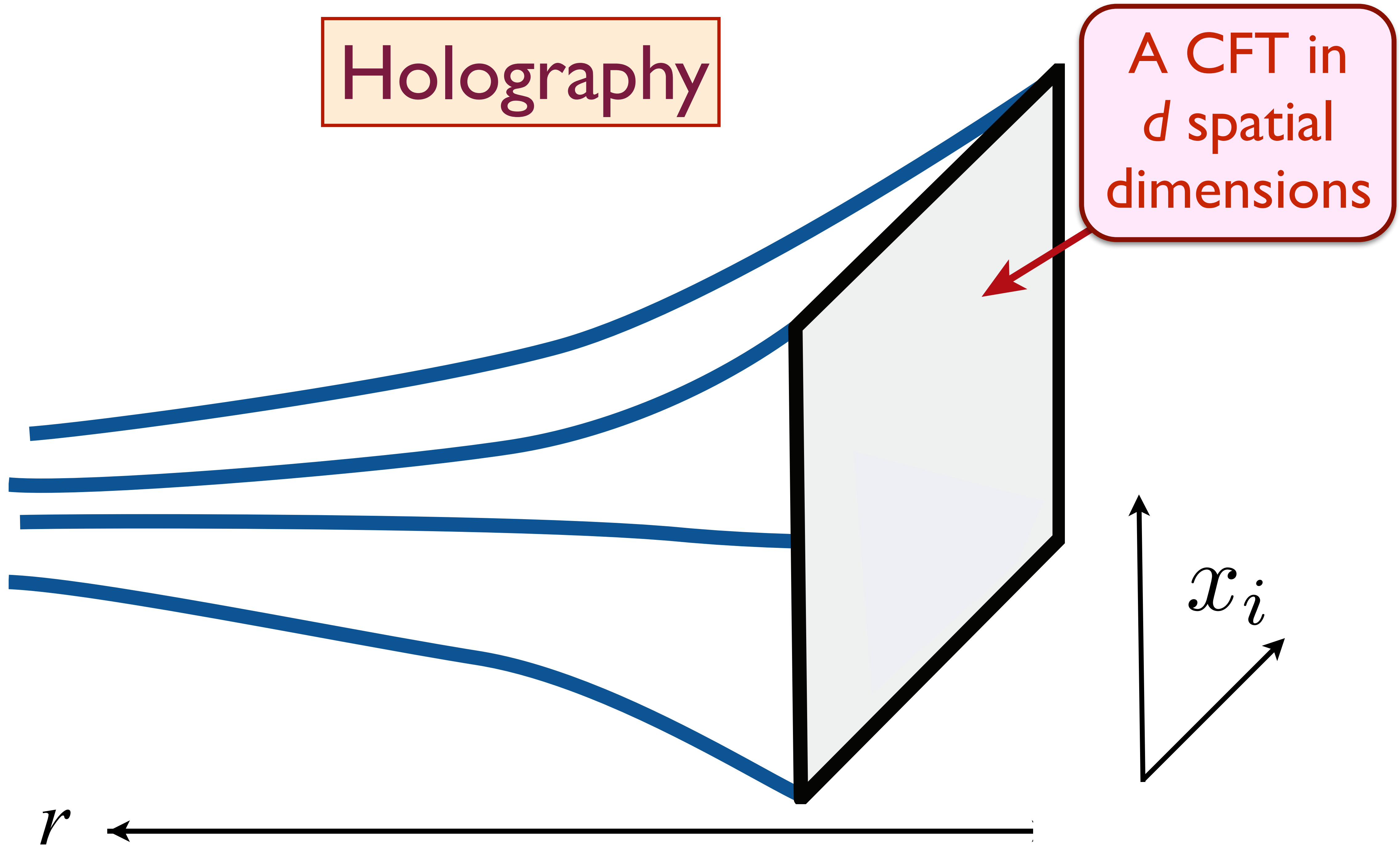
A. Lessons from holography

B. Field theories and memory functions

A CFT



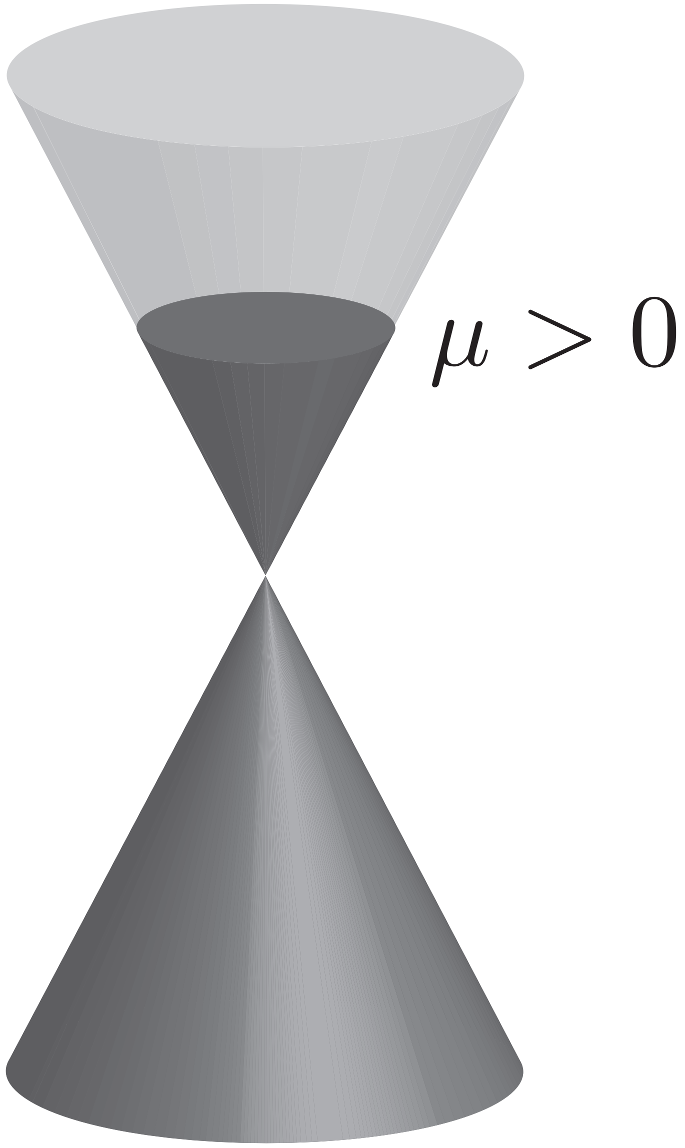
Holography



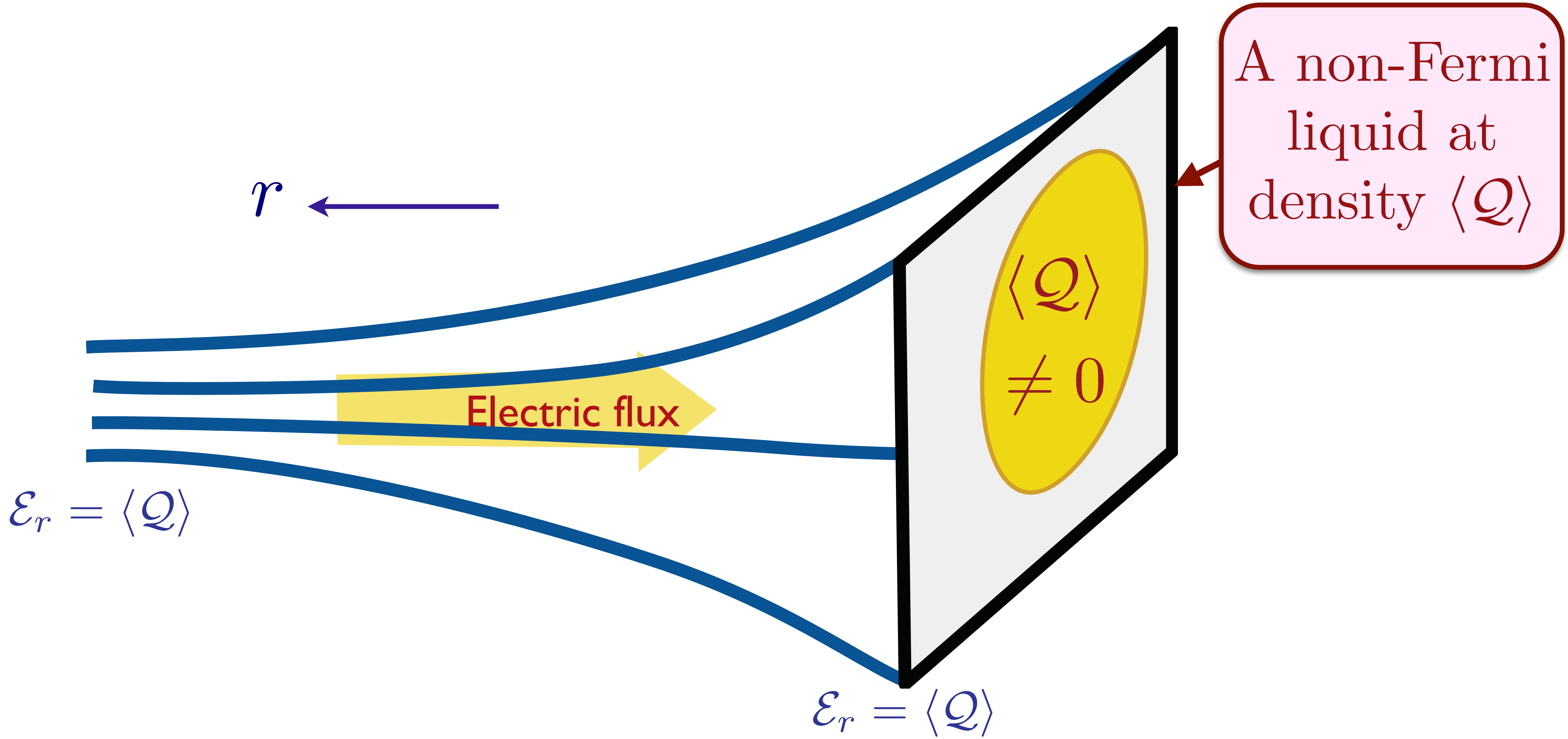
$$ds^2 = \frac{1}{r^2}\left(-dt^2 + dr^2 + dx_i^2\right)$$

This is the metric of anti-de Sitter space AdS_{d+2}.

Apply a chemical potential



Holography of a non-Fermi liquid: a charged black hole



The most general metric with scale-invariance at long distances/times

$$ds^2 = \frac{1}{r^2}\left(-\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)}dr^2 + dx_i^2\right)$$

L. Huijse, S. Sachdev, B. Swingle, Physical Review B **85**, 035121 (2012)

Holography of a non-Fermi liquid: a charged black hole

★ Computation of resistivity in gravitational theory yields zero resistance at all temperatures, $\rho(T) = 0$!

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Holography of a non-Fermi liquid: a charged black hole

★ Computation of resistivity in gravitational theory yields zero resistance at all temperatures, $\rho(T) = 0$!

★ This can be understood by

- Conservation of total momentum, $\vec{P}$,
- Non-zero value of $\chi_{JP} = \langle \vec{P}; \vec{J} \rangle$ when $\langle \mathcal{Q} \rangle \neq 0$ ($\vec{J}$ is the O(2) current).

$i.e.$ Momentum *drags* current.

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

Holography of a non-Fermi liquid

To relax momentum, add a random perturbation coupling to the operator $\mathcal{O}$:

$$\mathcal{S} \to \mathcal{S} + \int d^d r d\tau h(r)\mathcal{O}(r,\tau) \quad \text{with } \overline{h(r)} = 0 \text{ and } \overline{h(r)h(r')} = h_0^2 \delta^d(r - r')$$

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, Phys. Rev. B **76**, 144502 (2007)
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Solution of gravitational equations for small h_0 yields the resistivity

$$\rho(T) \sim h_0^2 \, T^{2(1+\Delta-z)/z} \, ,$$

where Δ is the dimension of $\mathcal{O}$. This agrees precisely with the *memory function* computation on a field theory with the operator $\mathcal{O}$, and with $\chi_{JP} \neq 0$!

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, Phys. Rev. B **76**, 144502 (2007)
S. A. Hartnoll and D. Hofman, Phys. Rev. Lett. **108**, 241601 (2012)
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   B. Transport at the Higgs critical point

Higgs critical point in a strange 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.

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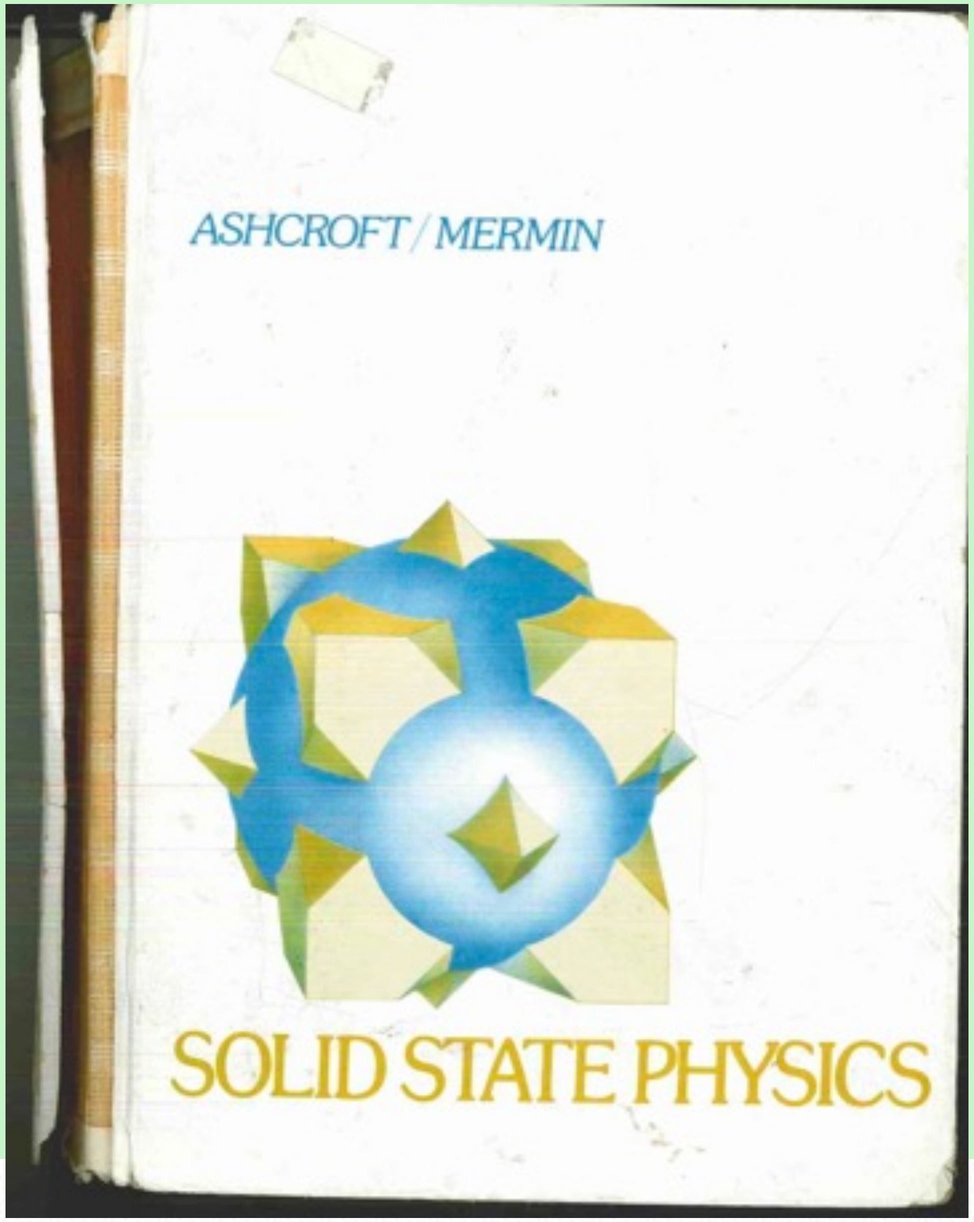

However, this ignores "phonon drag"

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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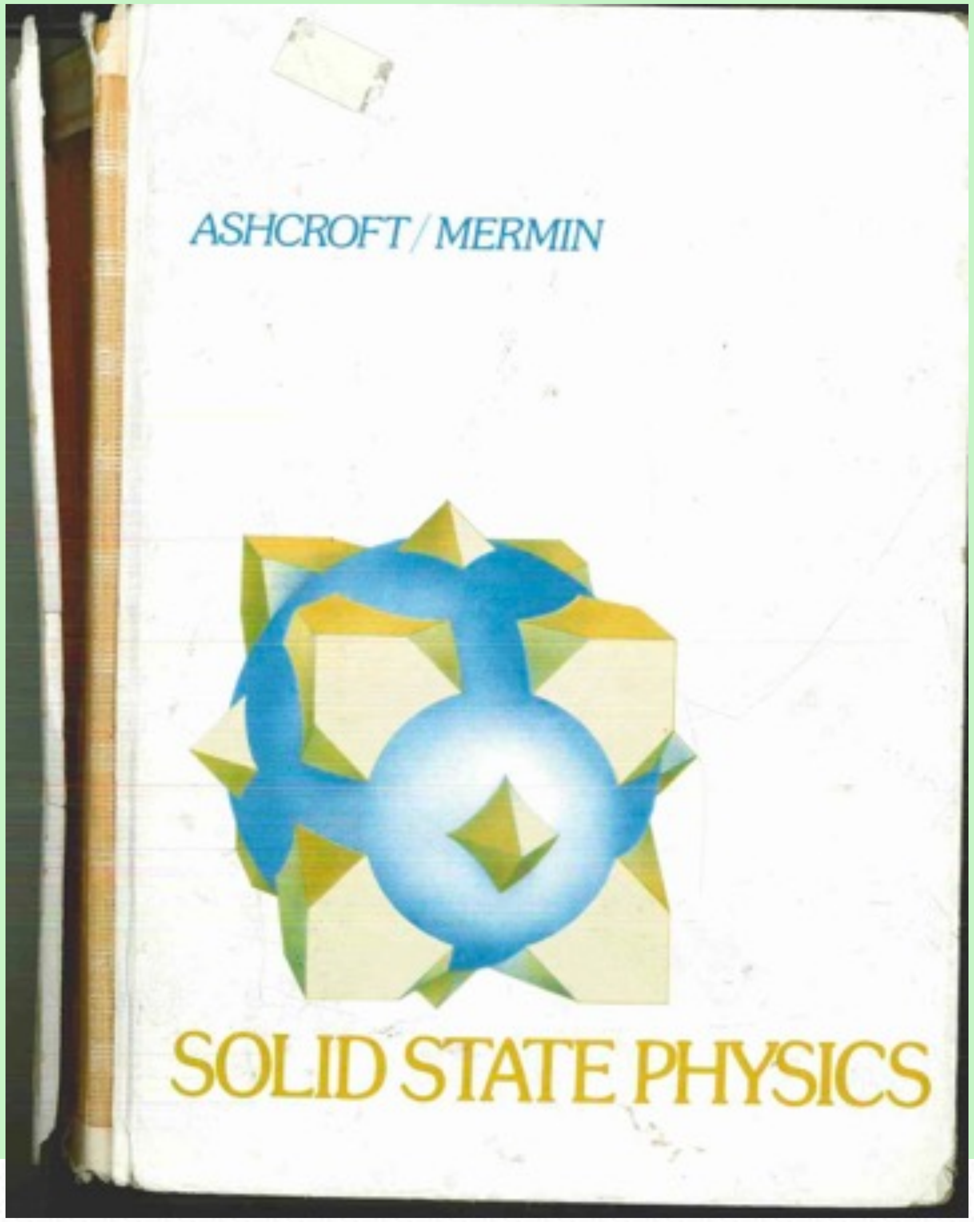

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- "Bloch's law" for the SU(2) gauge theory of a metal yields $\rho(T) \sim T^{4/3}$.

- Holography teaches us that Peierls is correct for the strongly-coupled Higgs critical point in a metal.

Higgs critical point in a strange metal

The resistivity of this strange 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.

S. A. Hartnoll, R. Mahajan, M. Punk and S. Sachdev, Phys. Rev. B **89**, 155130 (2014)
A. Patel and S. Sachdev, arXiv:1408.6549

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These results contradict essentially all work in by condensed matter theorists on strange metals, who followed Bloch rather than Peierls over the last 2 decades

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There is a dominant contribution $\rho(T) \sim T$ by the coupling of long-wavelength disorder to the gauge-invariant operator $\mathcal{O} \sim H^2$, which can be computed by applying memory functions to the quantum field theory

A. A. Patel and S. Sachdev, Phys. Rev. B **90**, 165146 (2014)
D. Chowdhury and S. Sachdev, arXiv:1412.1086

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