

# Quantum matter without quasiparticles

University of Colorado, Boulder  
January 21 , 2014

Subir Sachdev

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



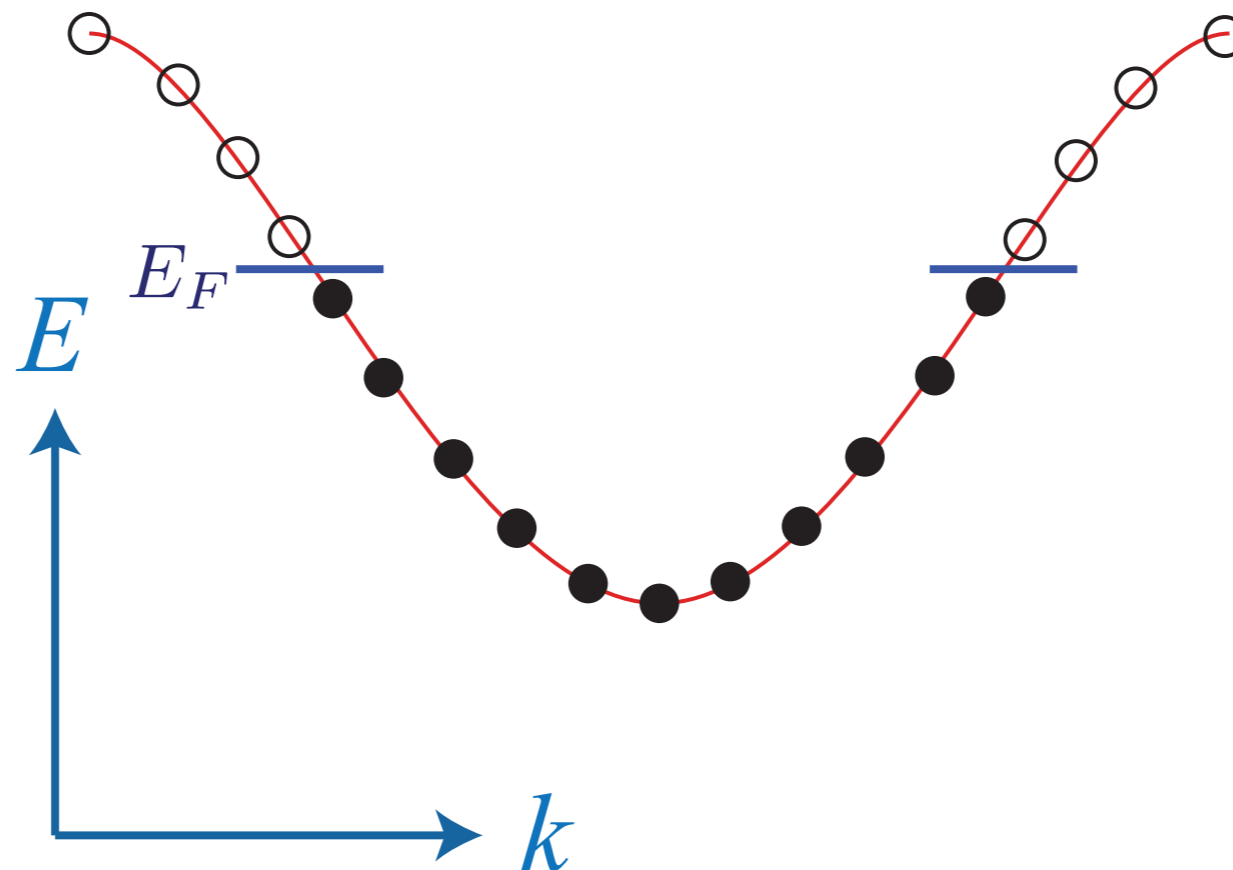
JOHN TEMPLETON  
FOUNDATION



# Foundations of quantum many body theory:

## I. Ground states connected adiabatically to independent electron states

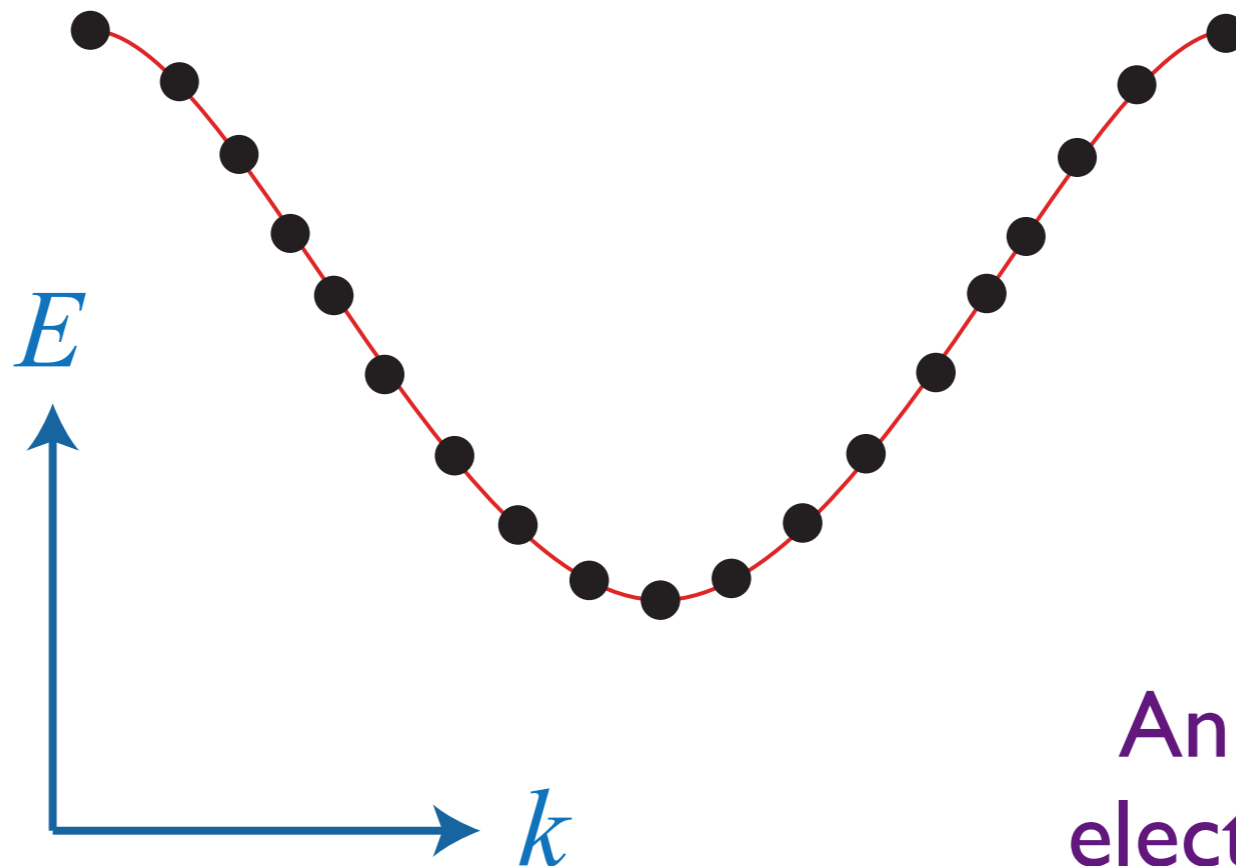
### Metals



# Foundations of quantum many body theory:

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## Band insulators

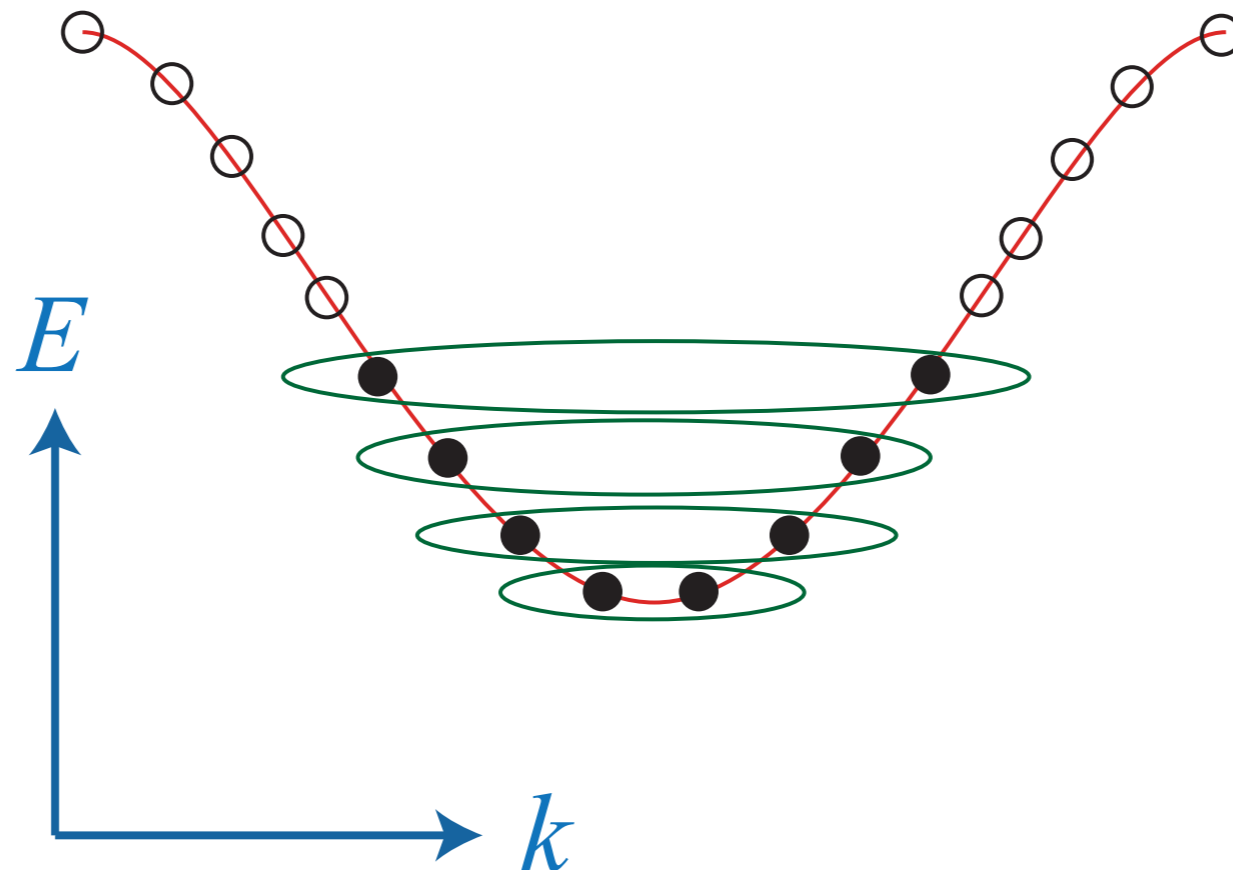


An even number of electrons per unit cell

# Foundations of quantum many body theory:

I. Ground states connected adiabatically to independent electron states

## Superconductors

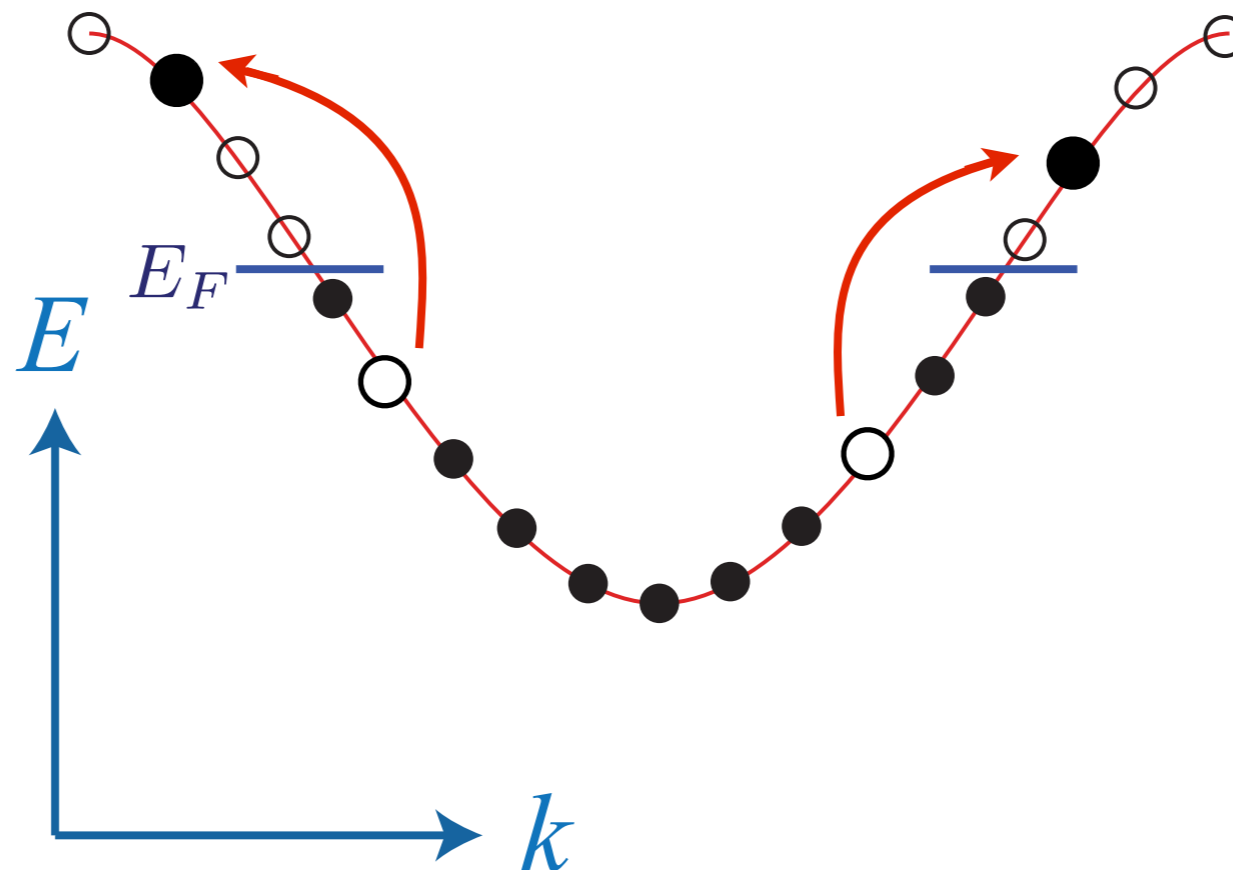


# Foundations of quantum many body theory:

1. Ground states connected adiabatically to independent electron states

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
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:

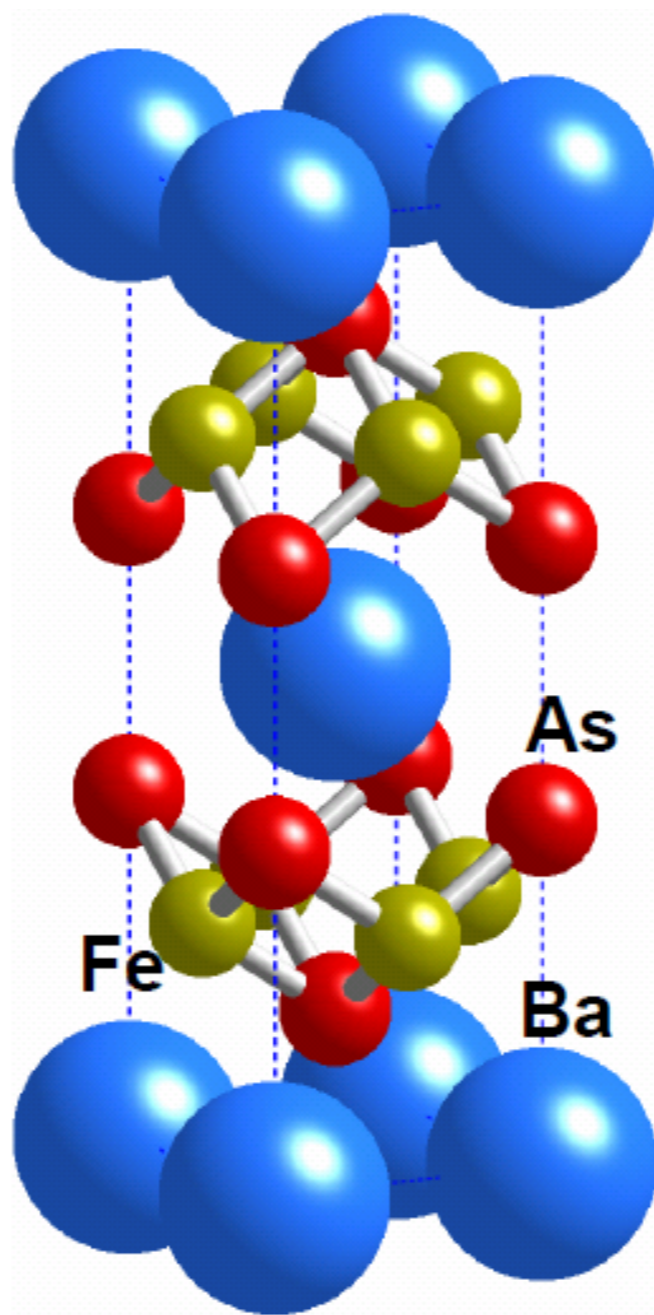
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## Experimental examples:

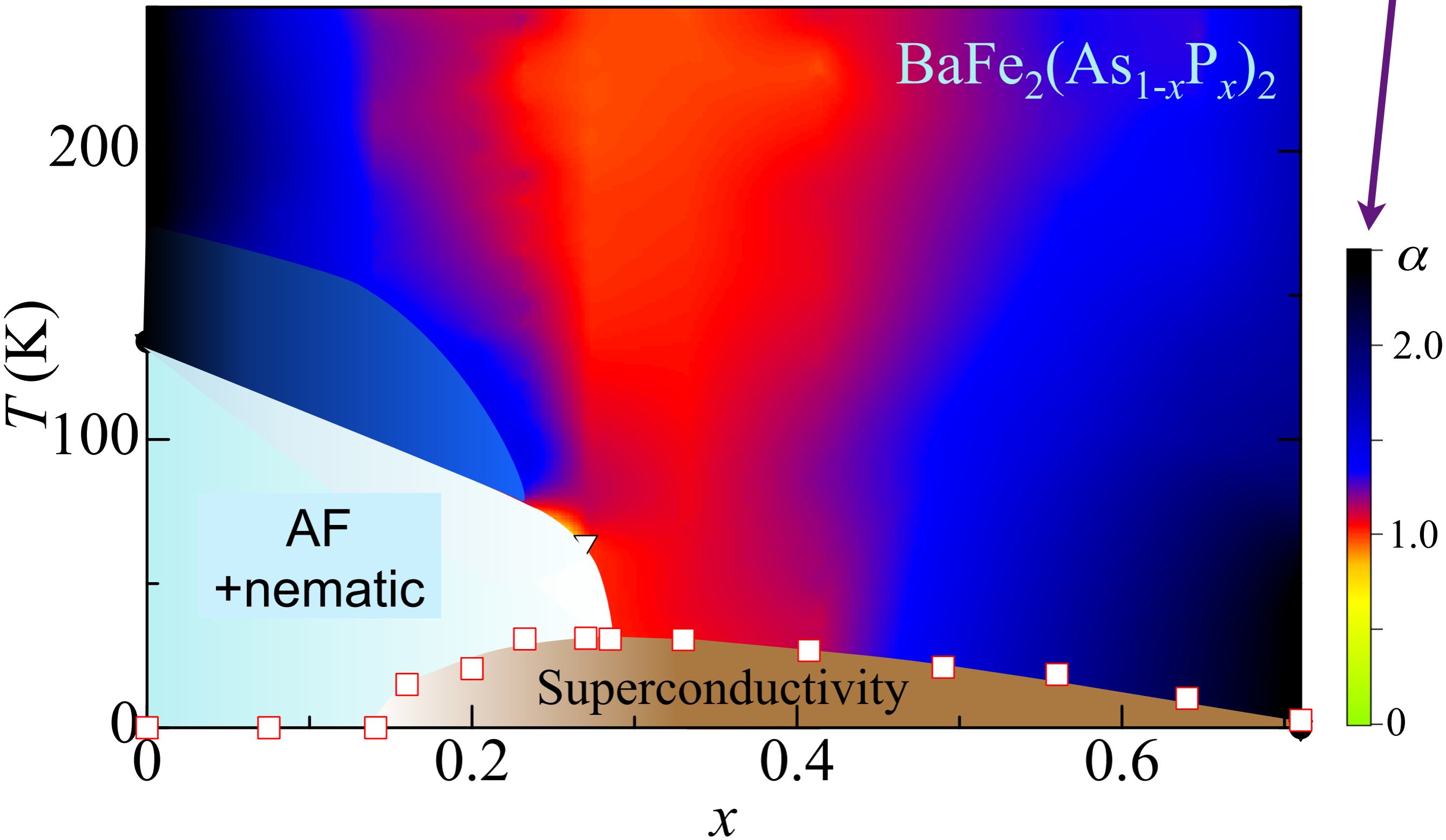
1. High temperature superconductors

# Iron pnictides:

a new class of high temperature superconductors

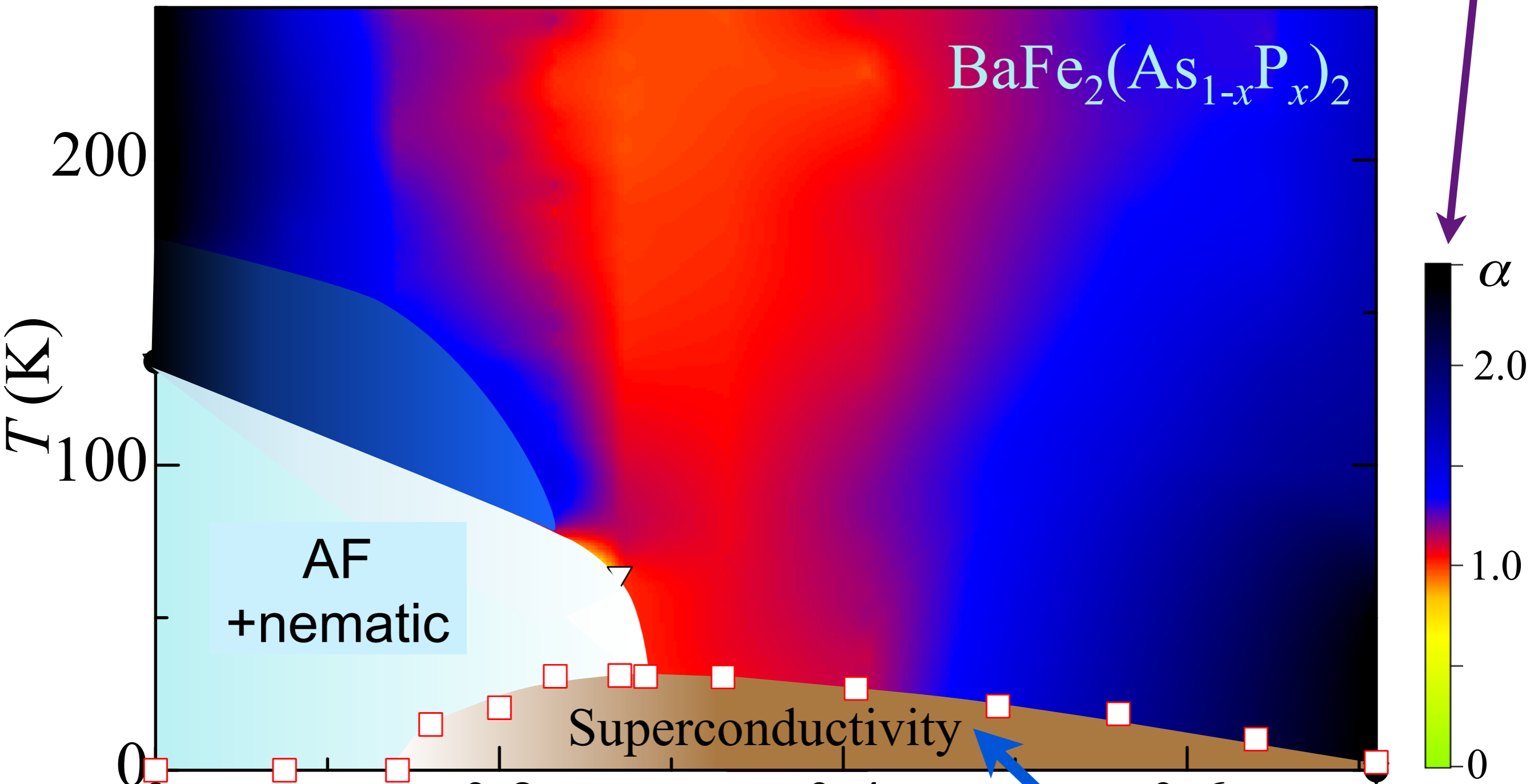


Resistivity  
 $\sim \rho_0 + AT^\alpha$



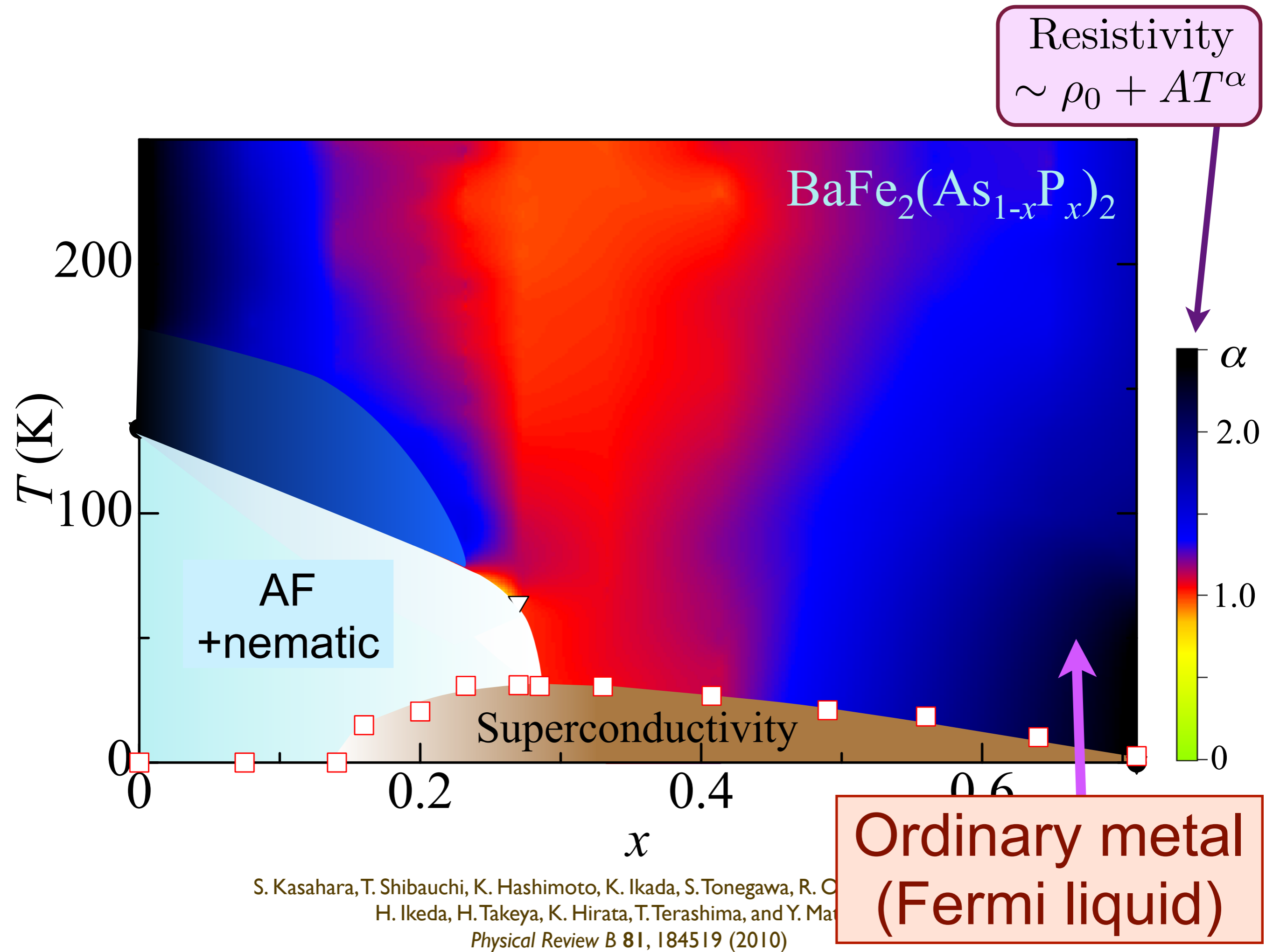
S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)

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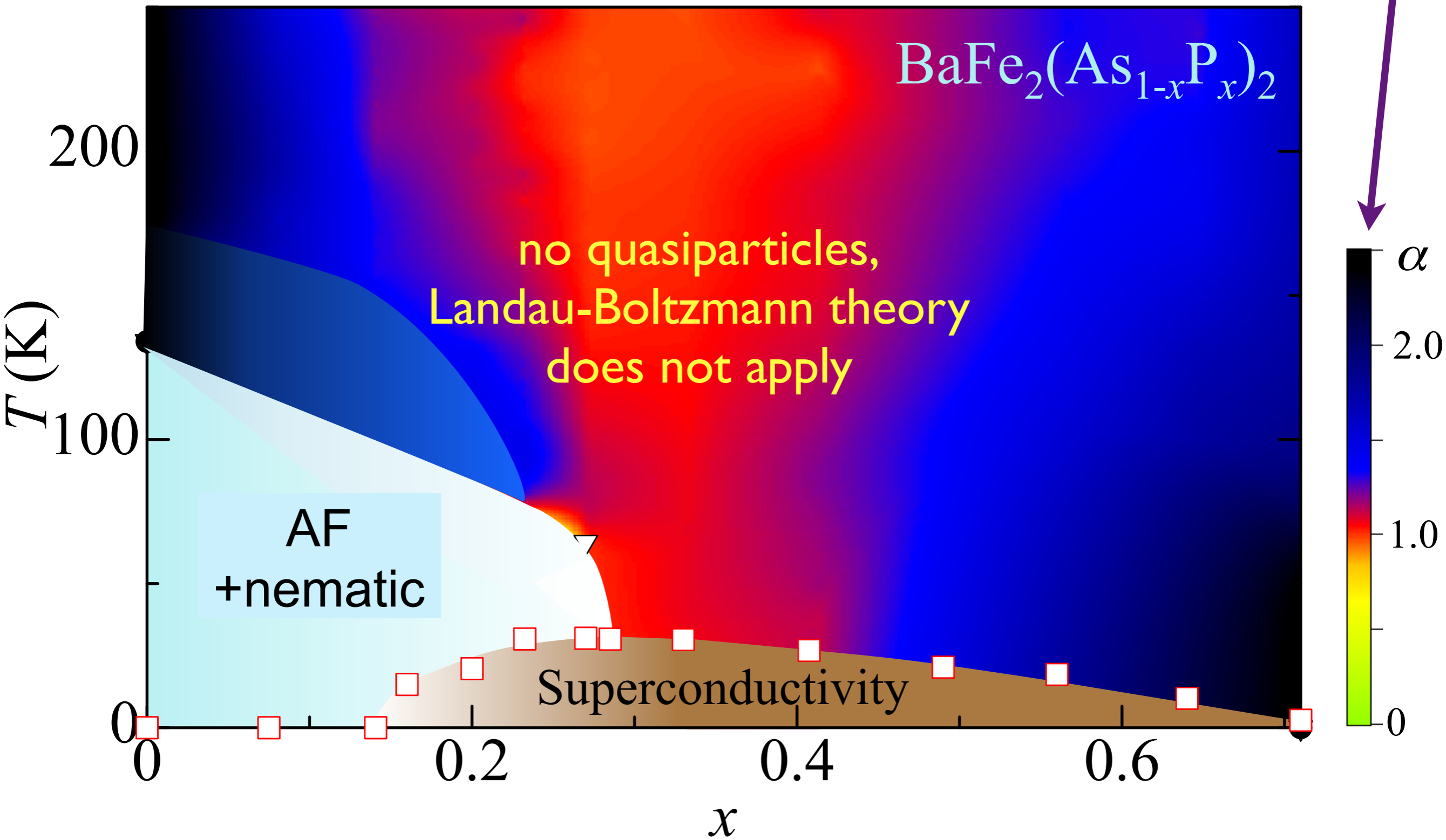


Superconductor  
Bose condensate of pairs of electrons

S. Kasahara, T. Shiba  
H. Ike

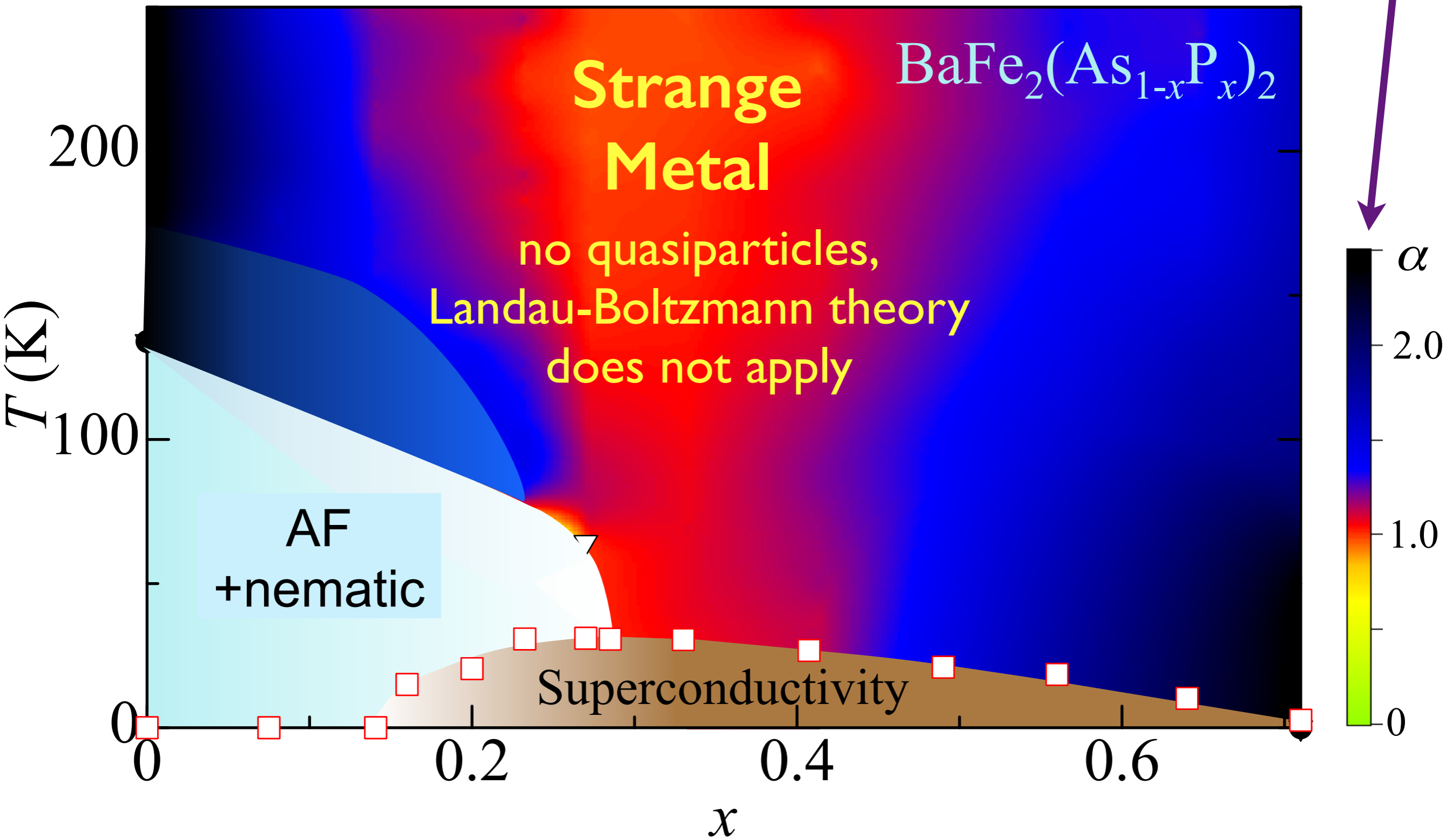


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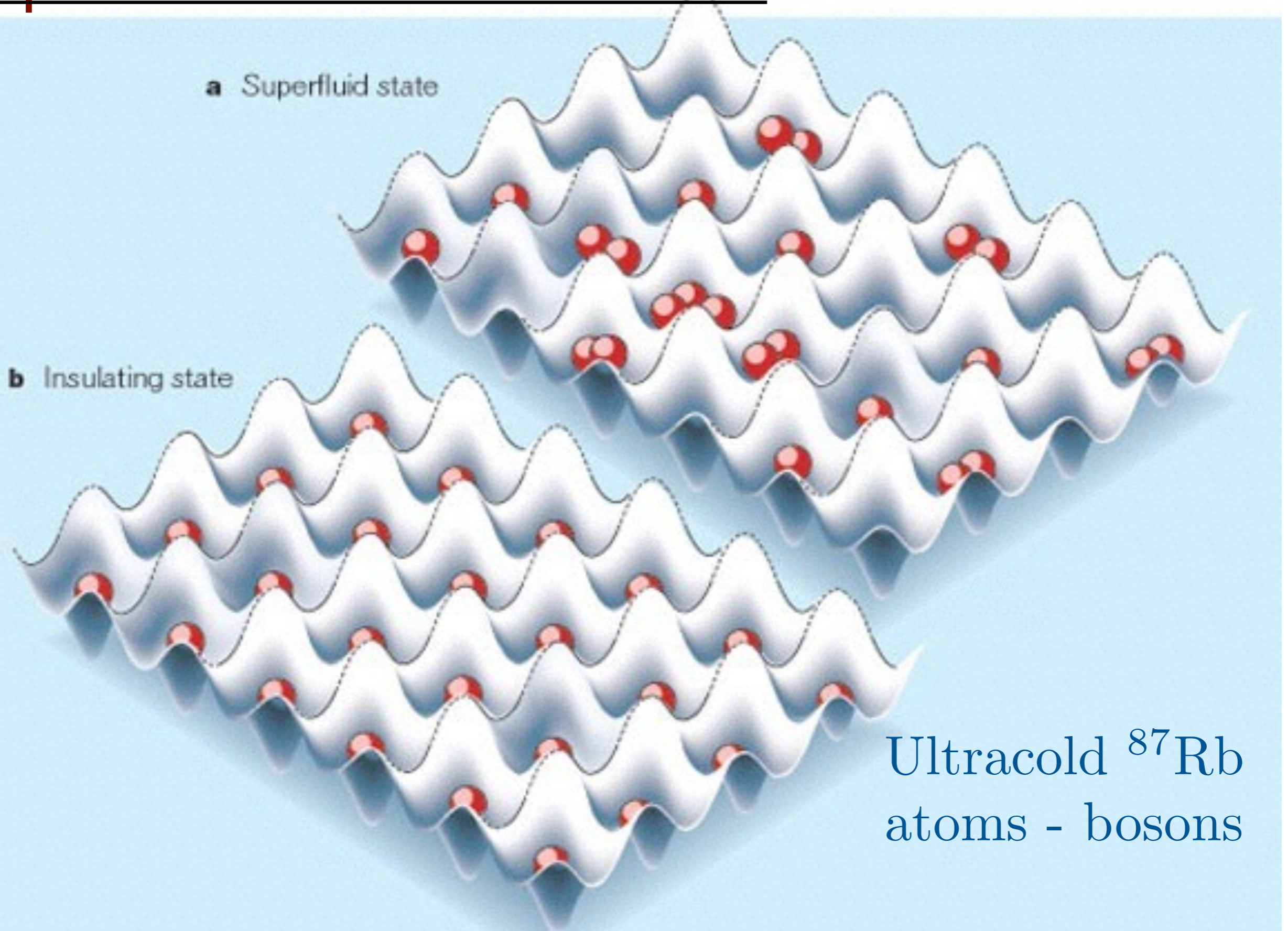
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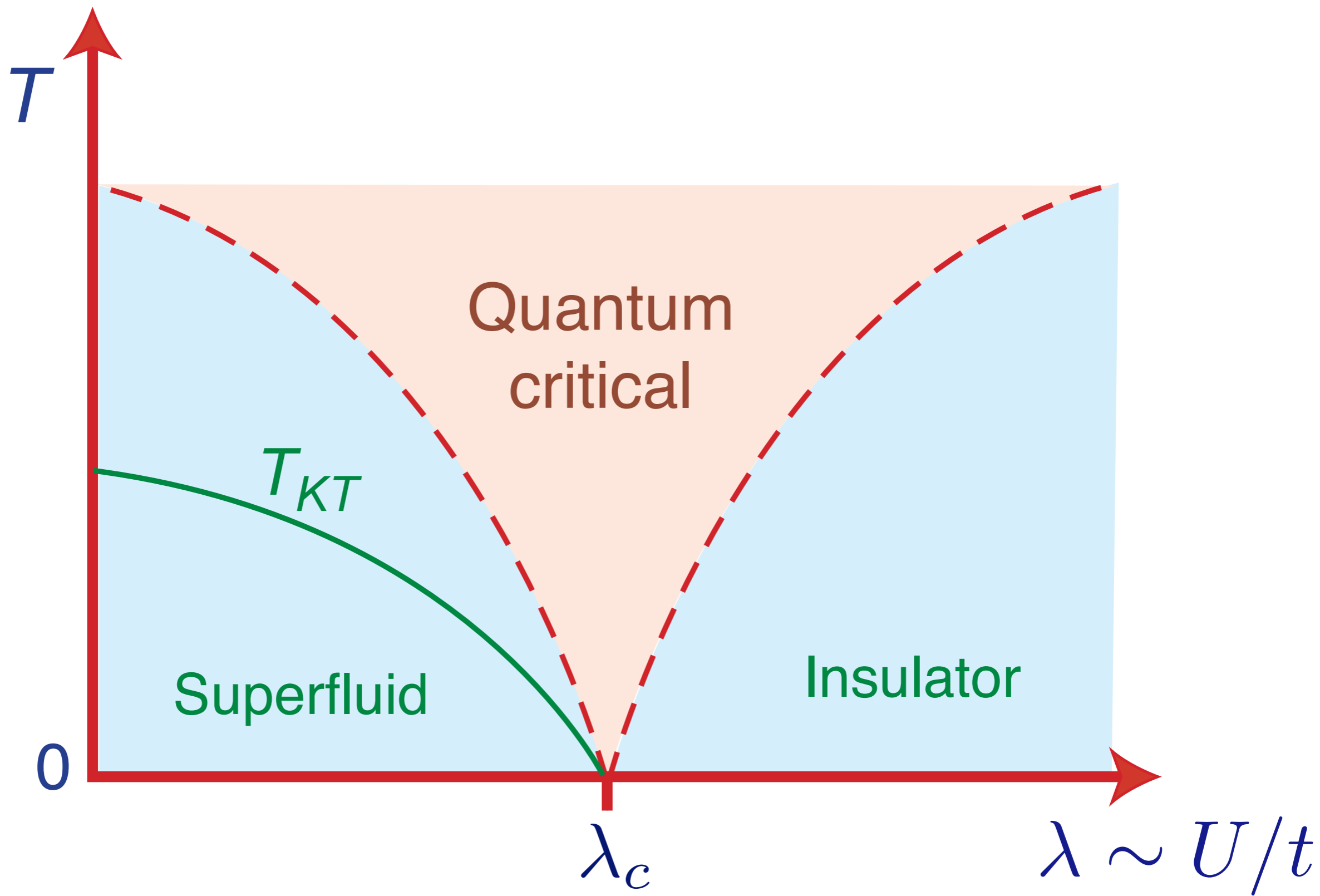
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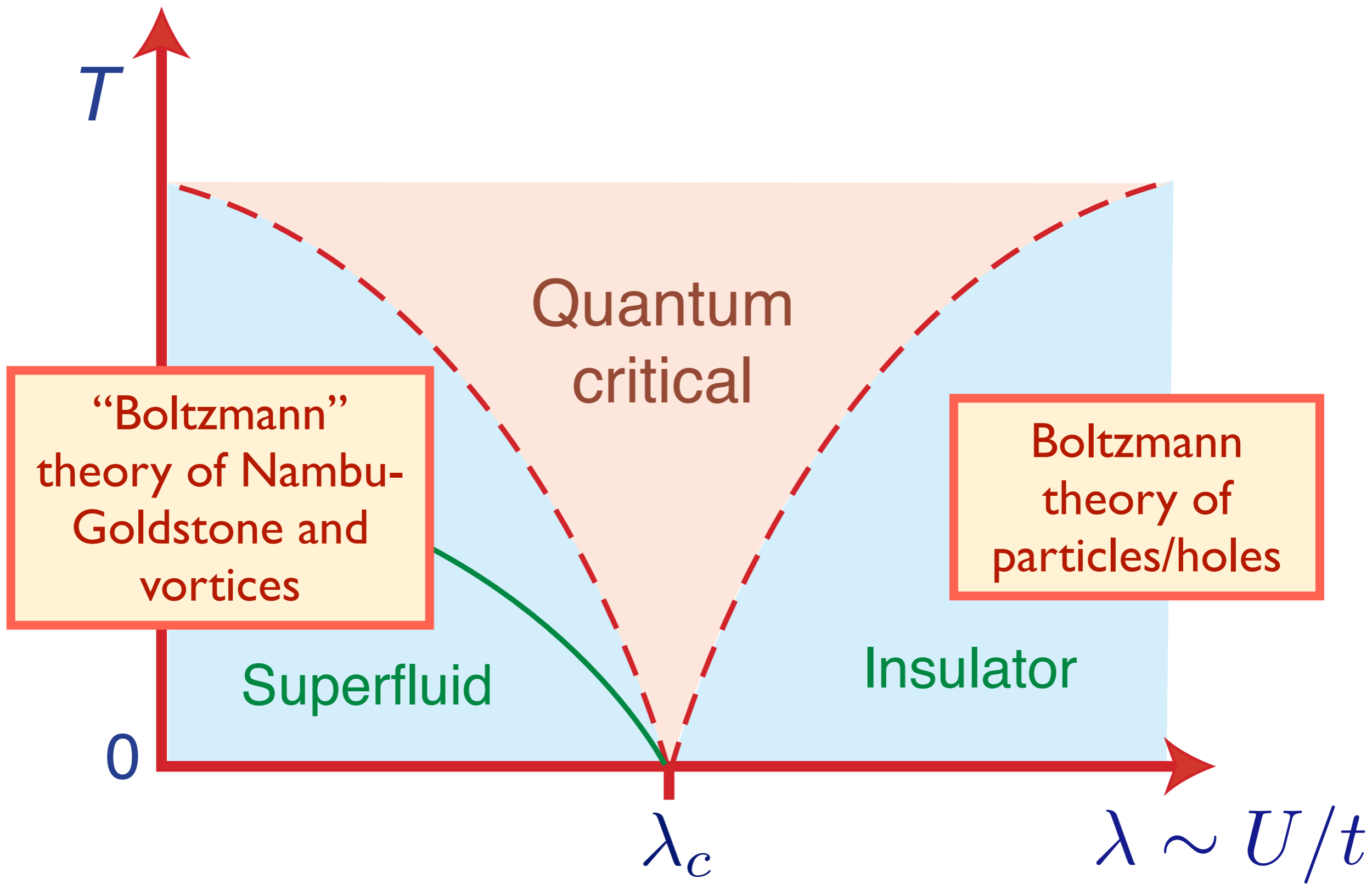
1. High temperature superconductors
2. Ultracold atoms

# Superfluid-insulator transition



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





$T$

0

$\lambda_c$

$\lambda \sim U/t$

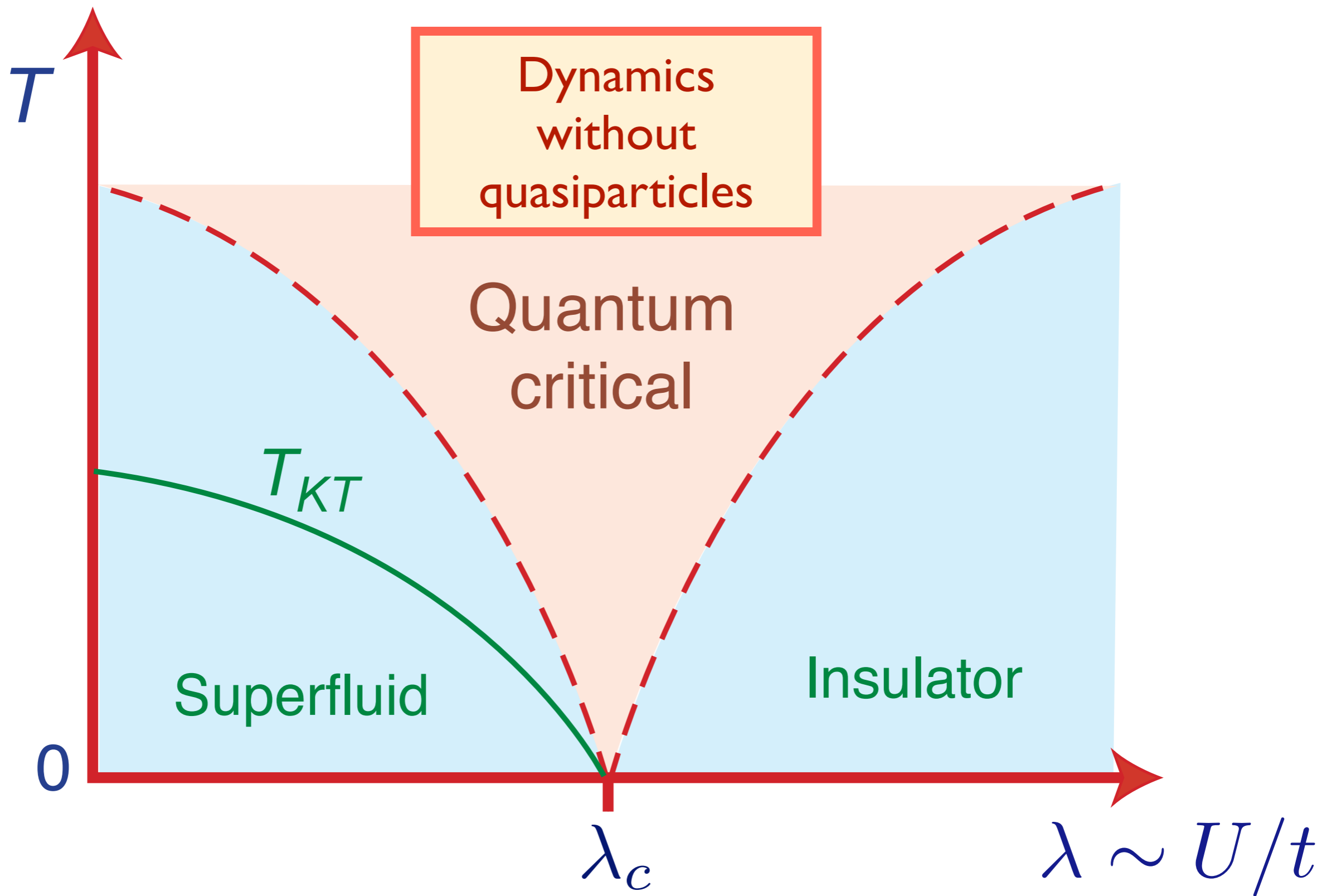
Quantum critical

“Boltzmann” theory of Nambu-Goldstone and vortices

Boltzmann theory of particles/holes

Superfluid

Insulator



## Modern phases of quantum matter:

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## Experimental examples:

1. High temperature superconductors
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## Modern phases of quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement
2. No quasiparticles

## Only 2 theoretical examples:

1. Quantum critical metals in dimension  $d=2$
2. Conformal field theories in spatial dimension  $d > 1$

# 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*

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**Emanuel Katz**  
**Boston University**

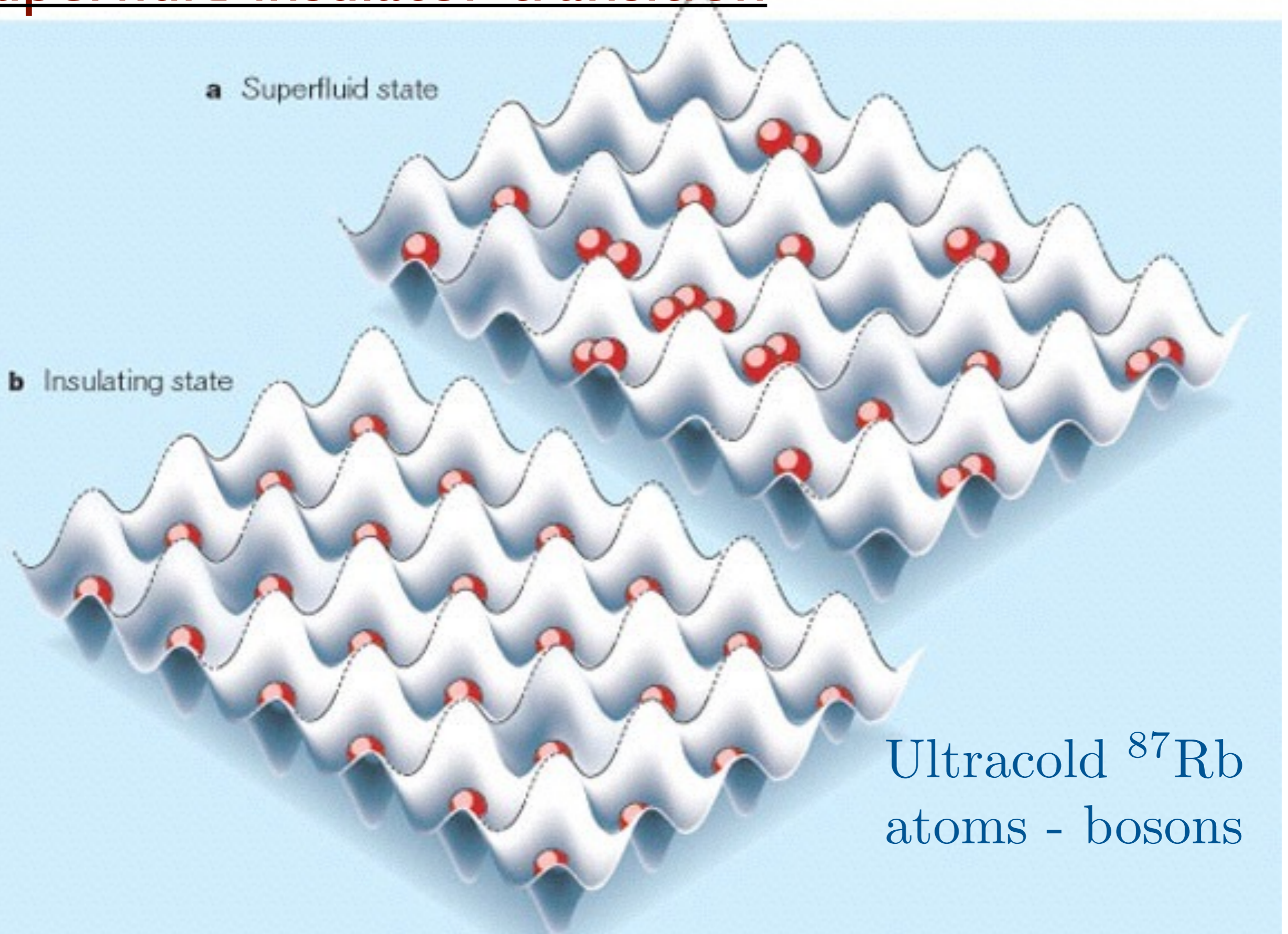


**William Witczak-Krempa**  
**Perimeter**



**Erik Sorensen**  
**McMaster**

# Superfluid-insulator transition



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

# The Superfluid-Insulator transition

## Boson Hubbard model

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

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

$$n_j \equiv b_j^\dagger b_j$$

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

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

$$\underline{U \gg t}$$

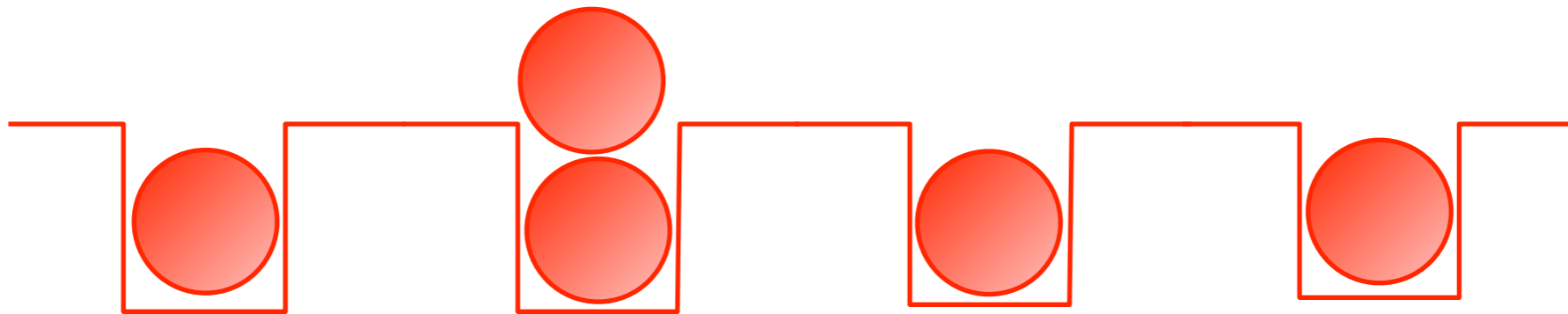


Insulator (the vacuum)  
at large repulsion between bosons

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

$$\underline{U \gg t}$$

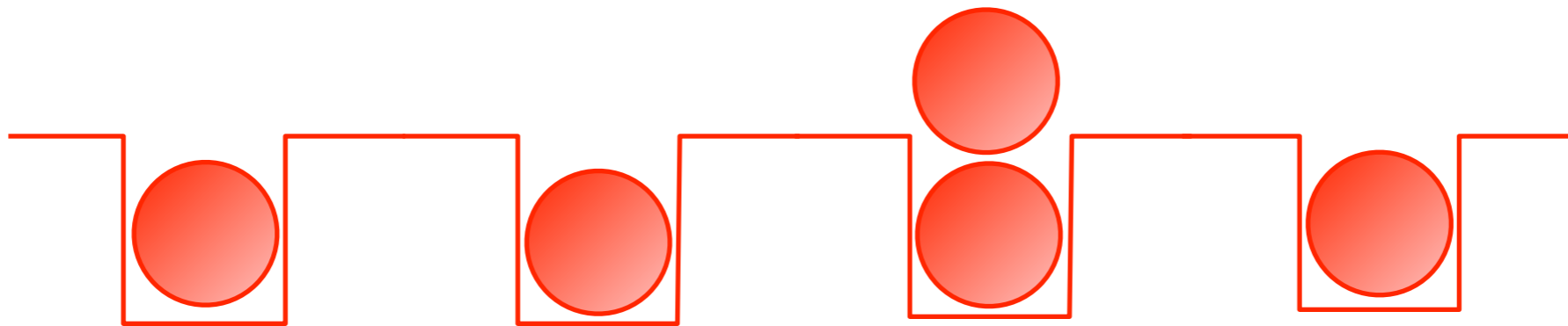
Excitations of the insulator:



Particles  $\sim \psi^\dagger$

$$\underline{U \gg t}$$

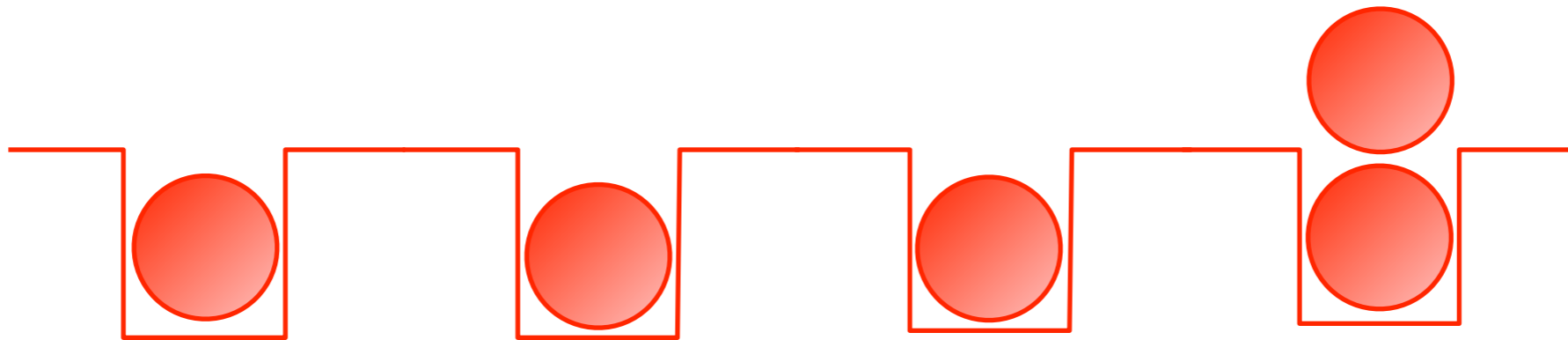
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Excitations of the insulator:



Holes  $\sim \psi$

$$\underline{U \gg t}$$

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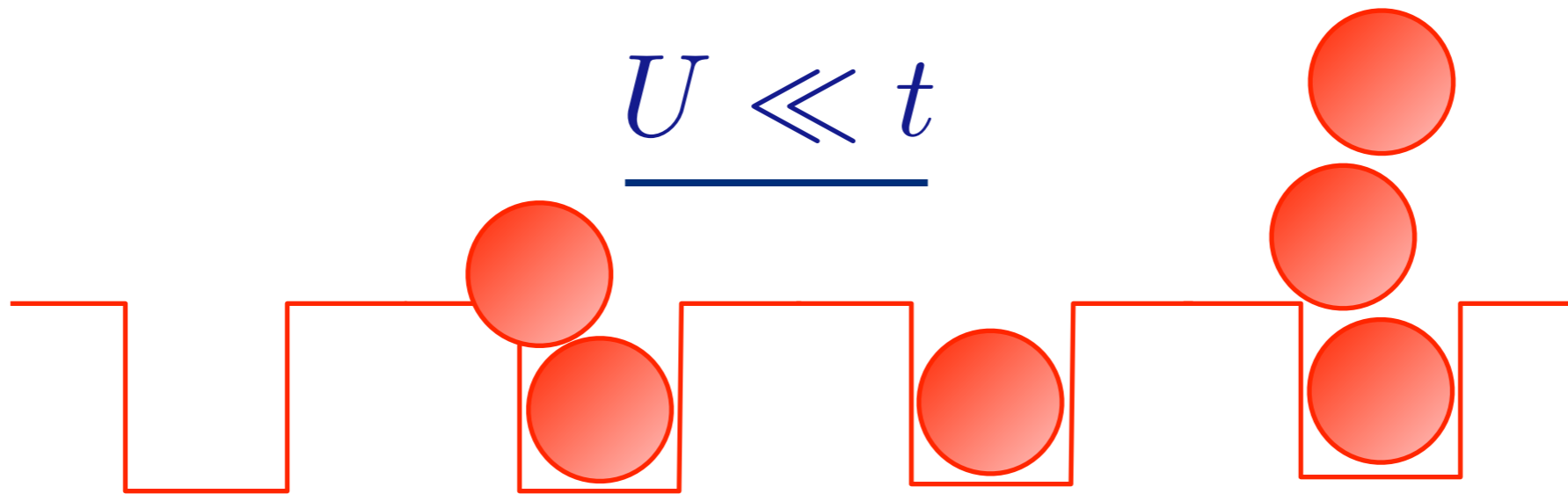
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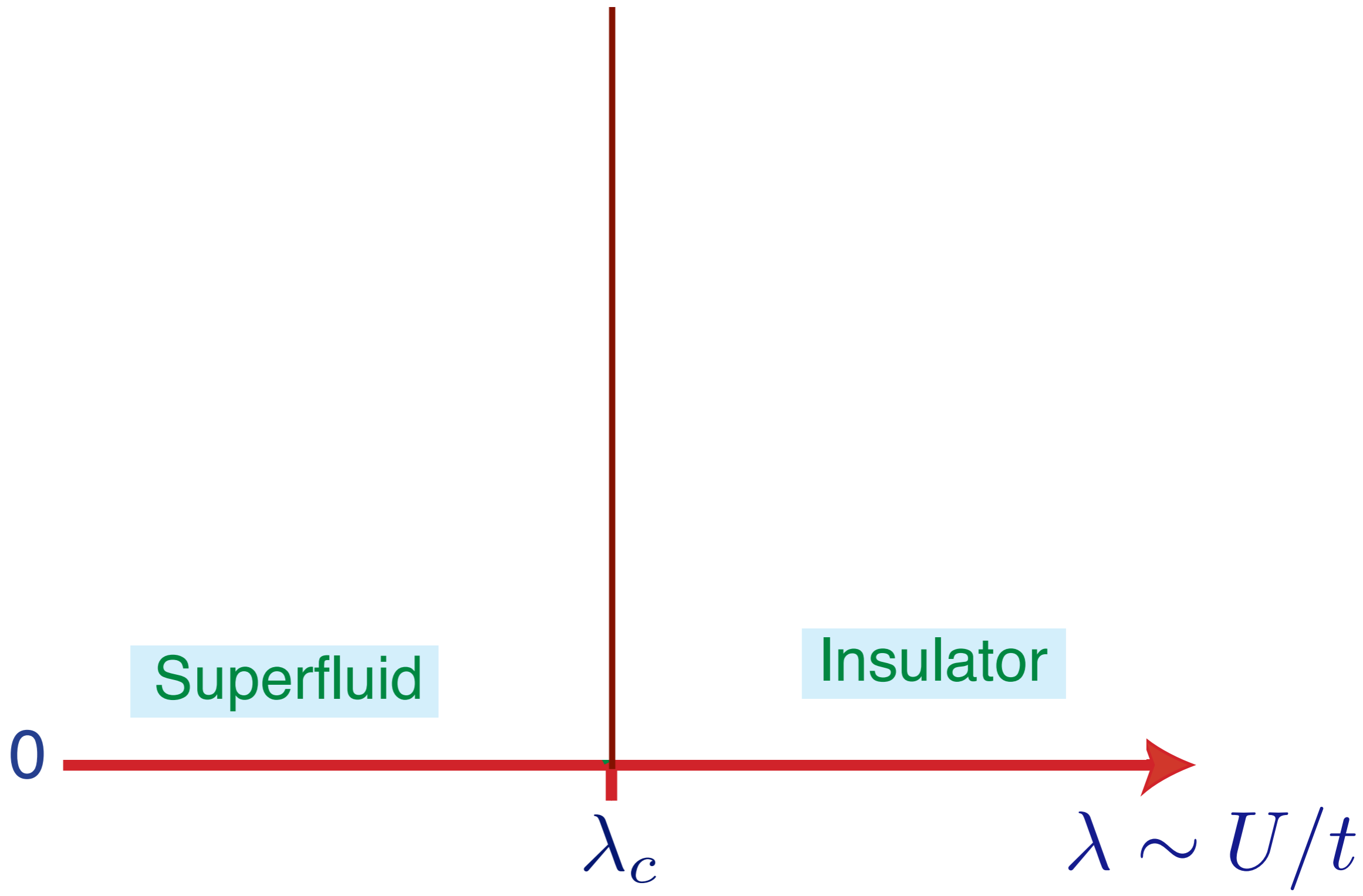
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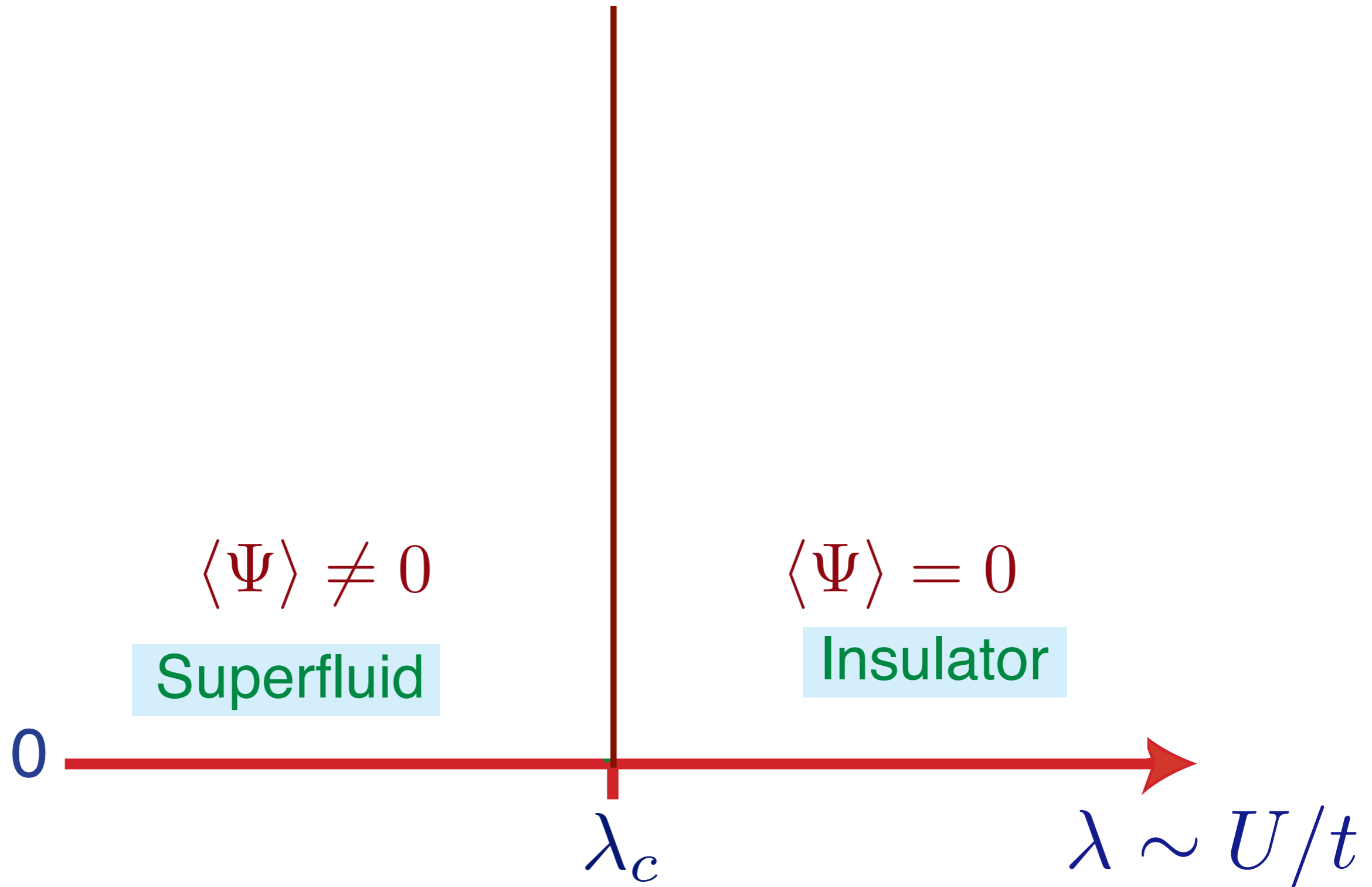


Superfluid  
at small repulsion between bosons

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

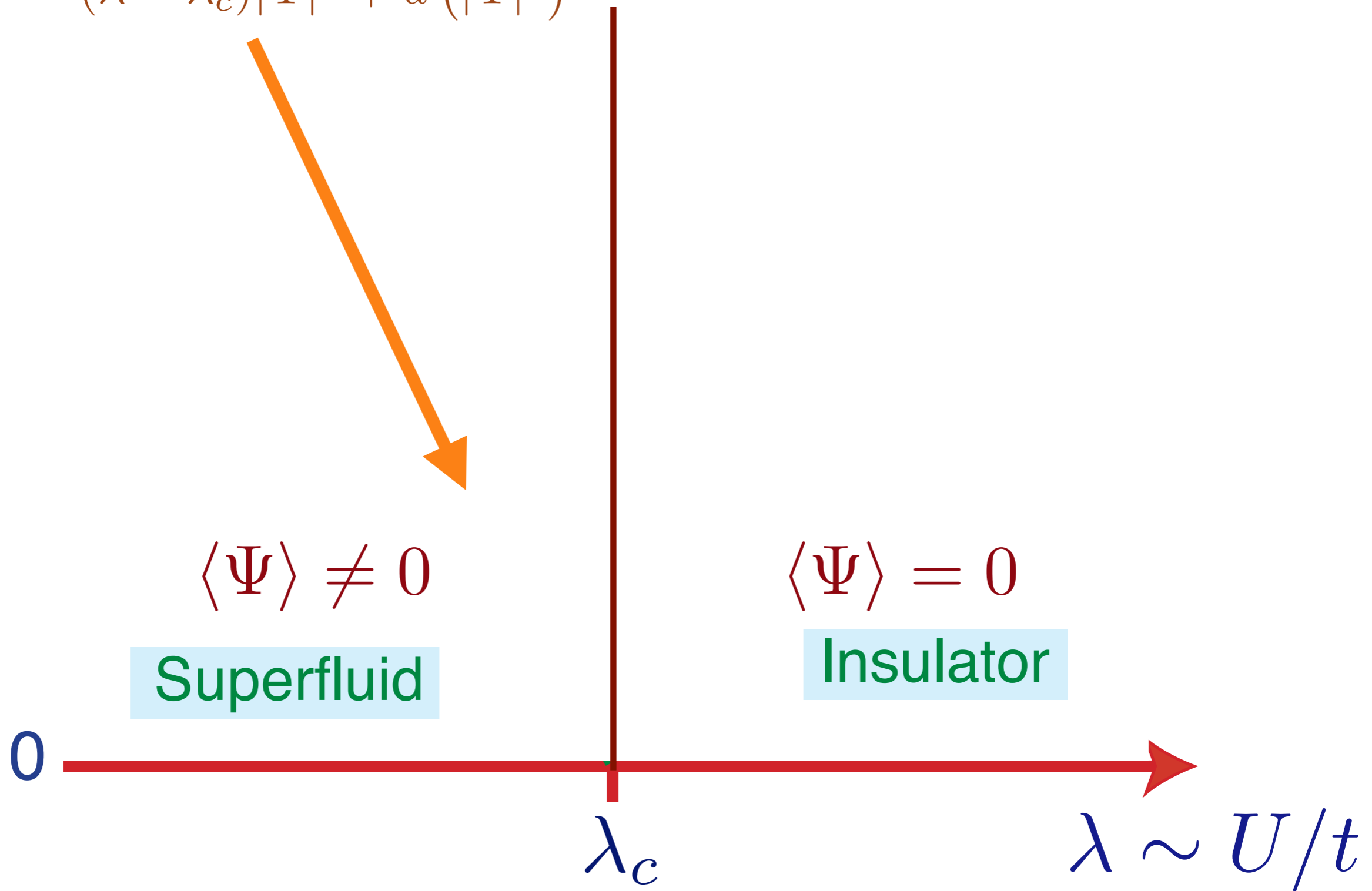


$\Psi \sim b_{k=0} \rightarrow$  a complex field representing the Bose-Einstein condensate of the superfluid



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

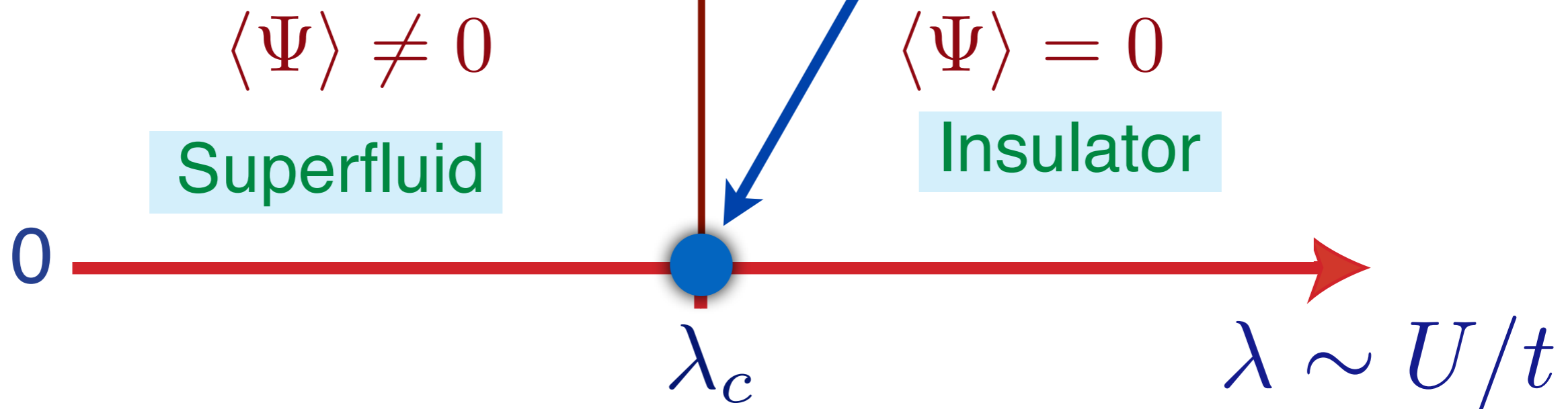
$$V(\Psi) = (\lambda - \lambda_c) |\Psi|^2 + u (|\Psi|^2)^2$$



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A conformal field theory  
in 2+1 spacetime dimensions (CFT3):  
the O(2) Wilson-Fisher CFT3

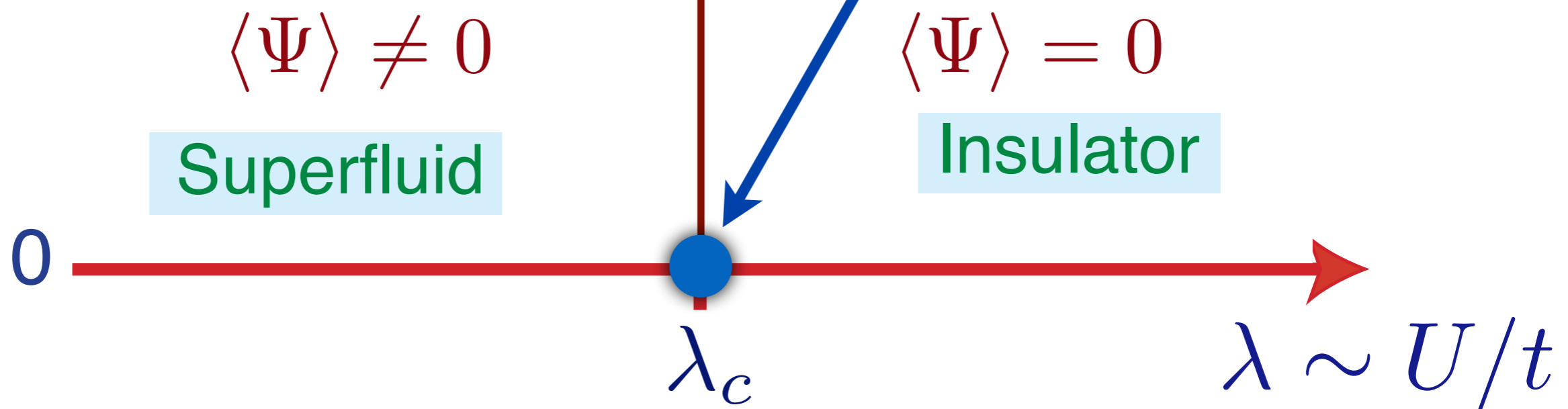


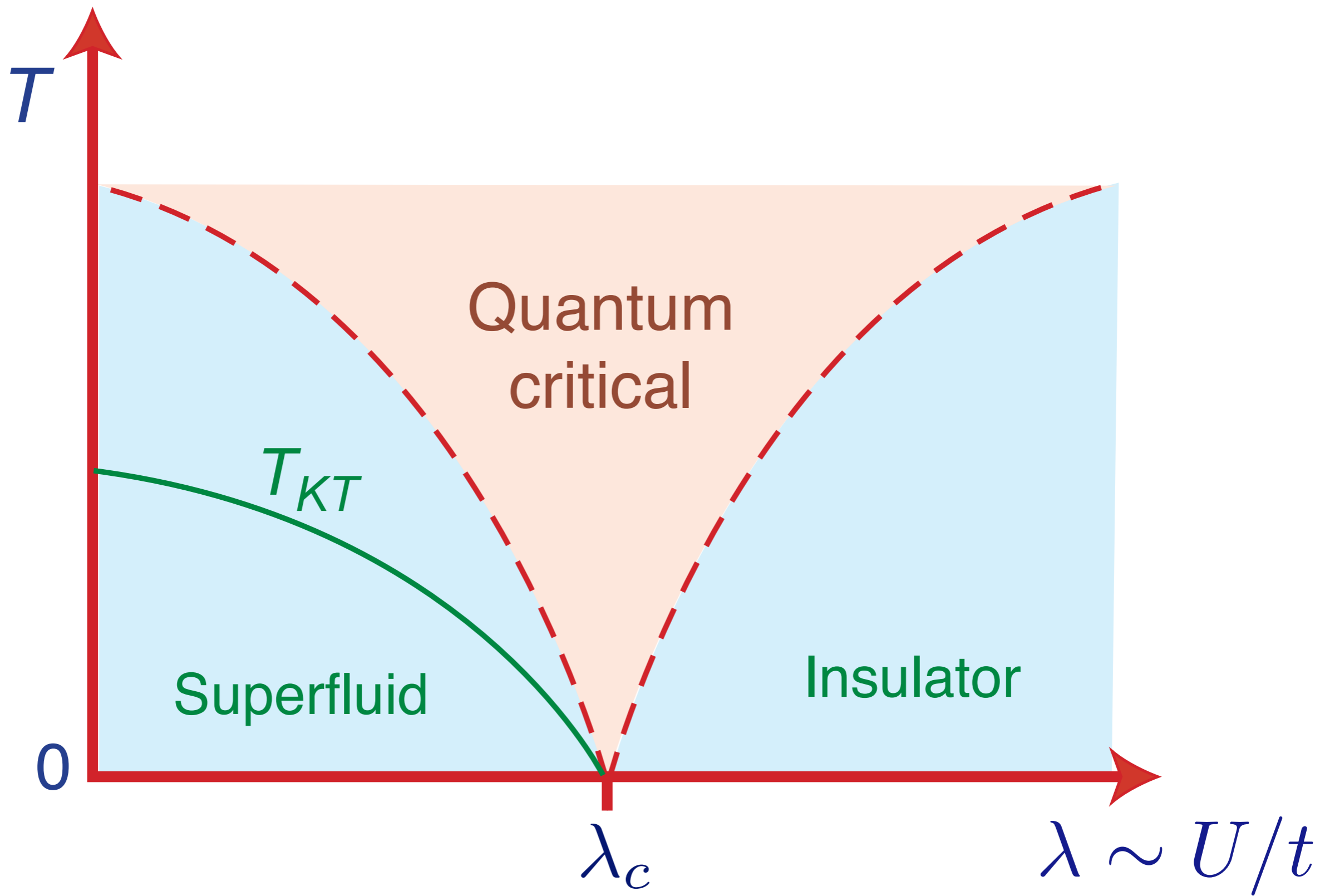
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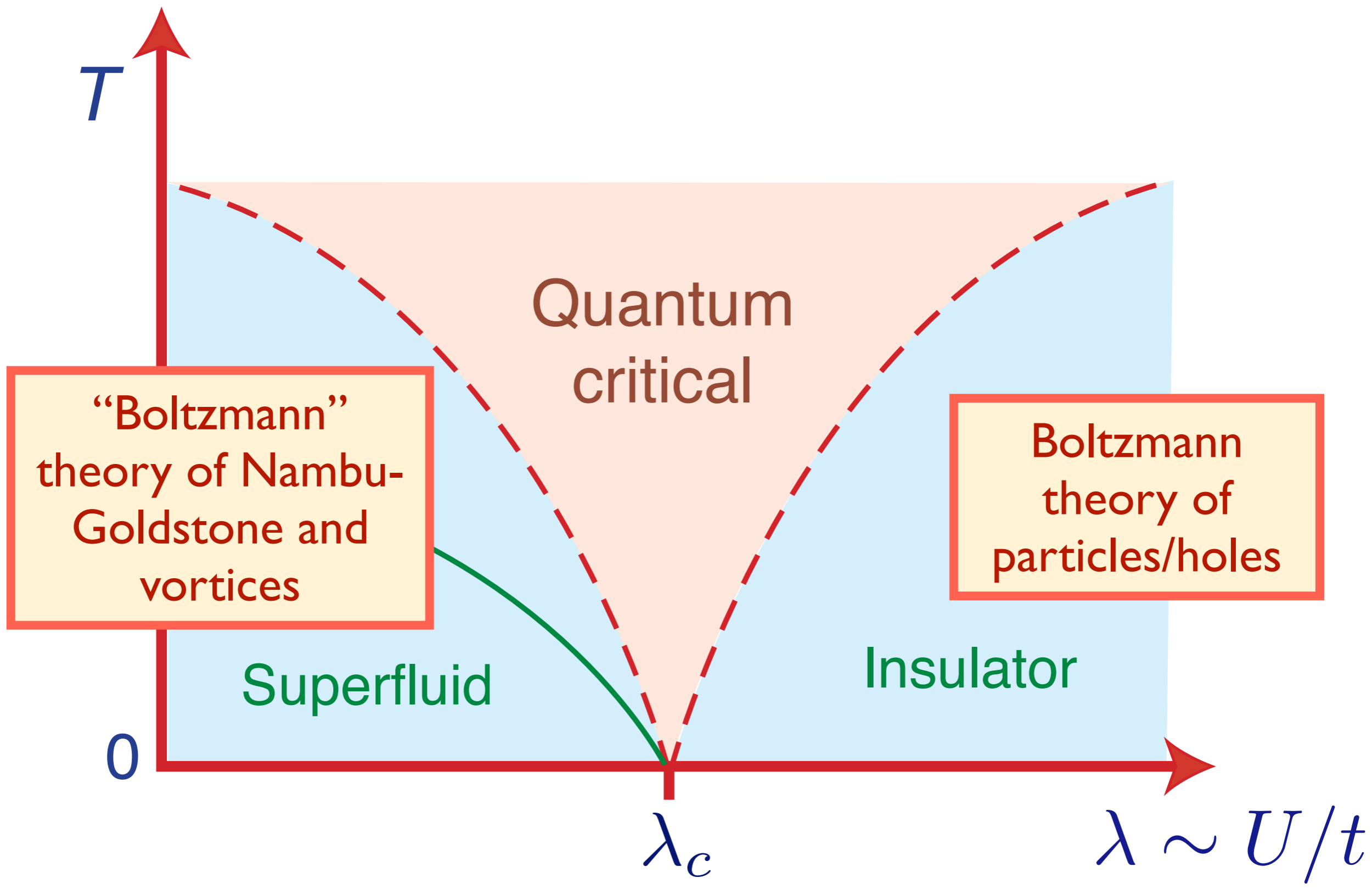
$$V(\Psi) = (\lambda - \lambda_c) |\Psi|^2 + u (|\Psi|^2)^2$$

The coupling  $u \rightarrow u^*$ ,  
the renormalization group  
fixed point, for the CFT3.

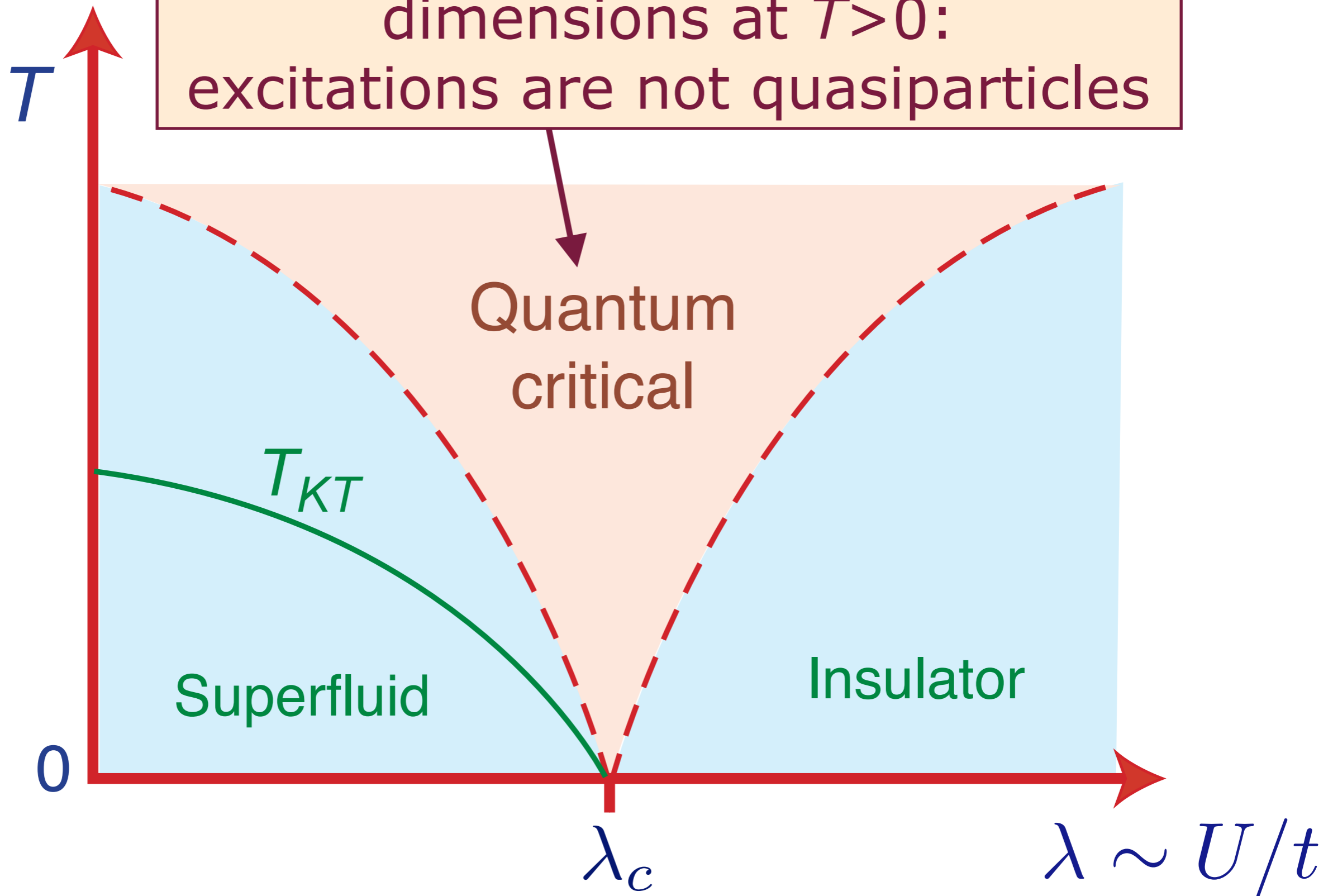
A conformal field theory  
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Conformal field theory in 2+1 dimensions at  $T > 0$ :  
excitations are not quasiparticles



# 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*

# Traditional CMT

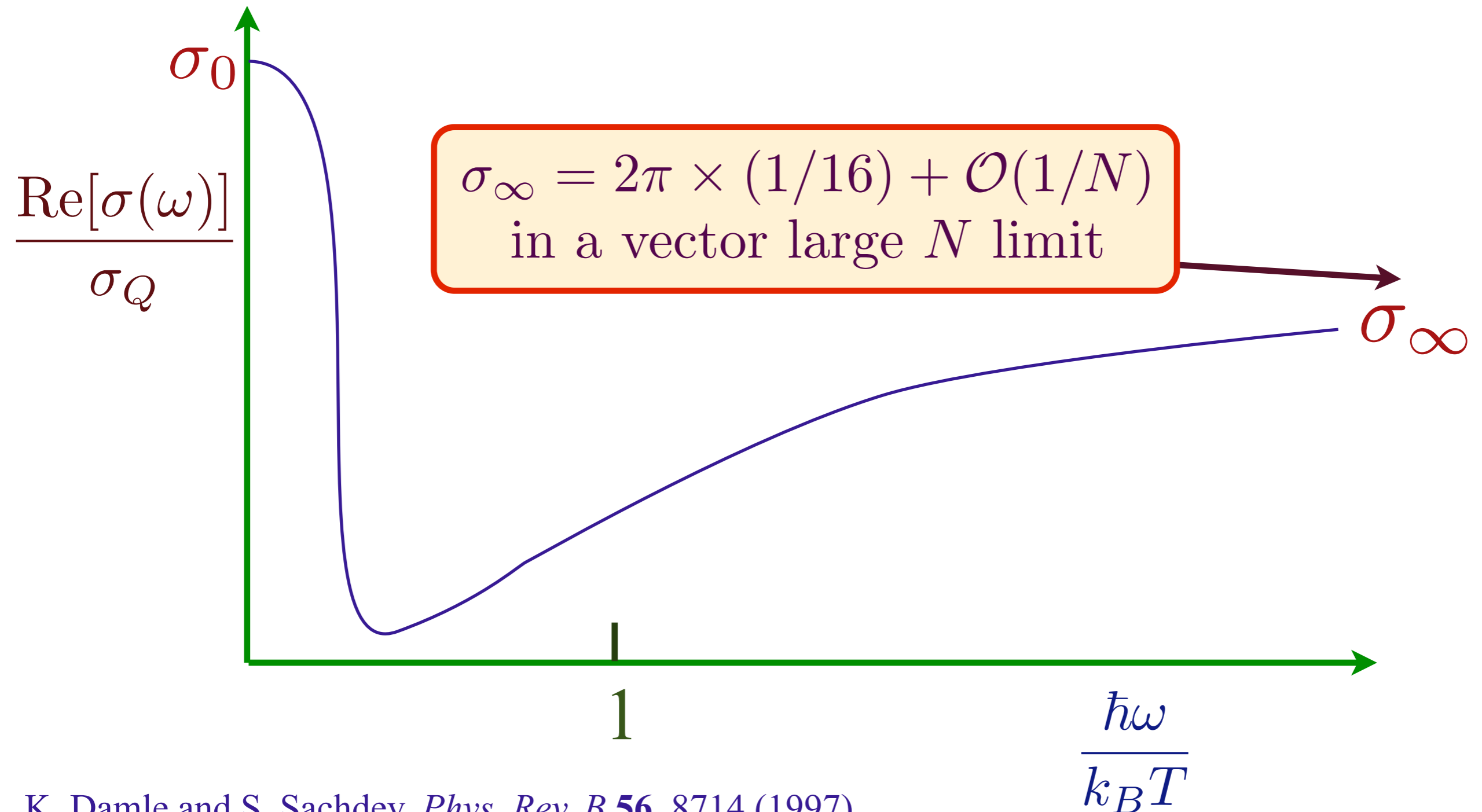
- ◇ Identify quasiparticles and their dispersions
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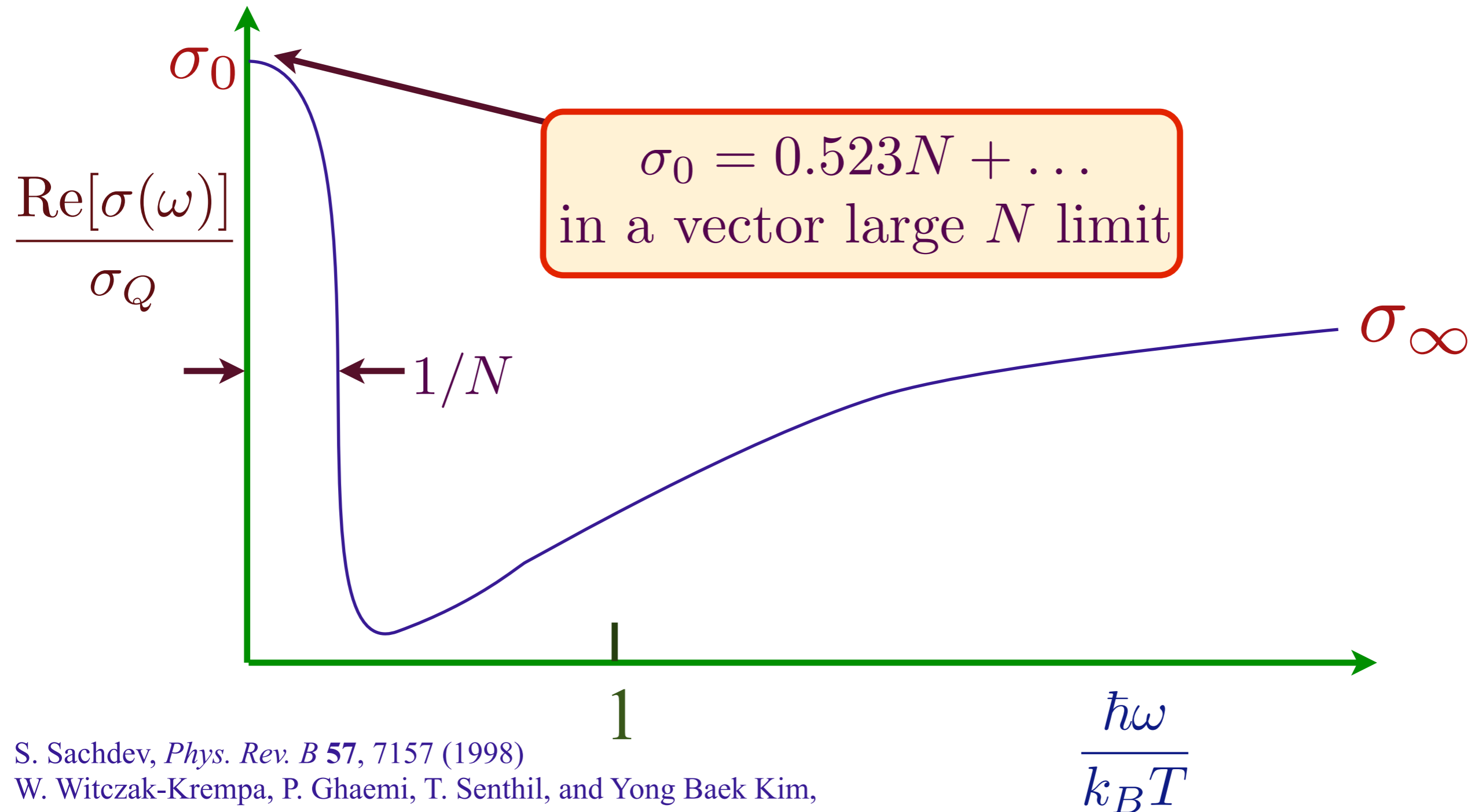
# Quasiparticle view of quantum criticality (Boltzmann equation): Transport of $O(N)$ current for a (weakly) interacting CFT3

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



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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  $\hbar\omega \gg k_B T$

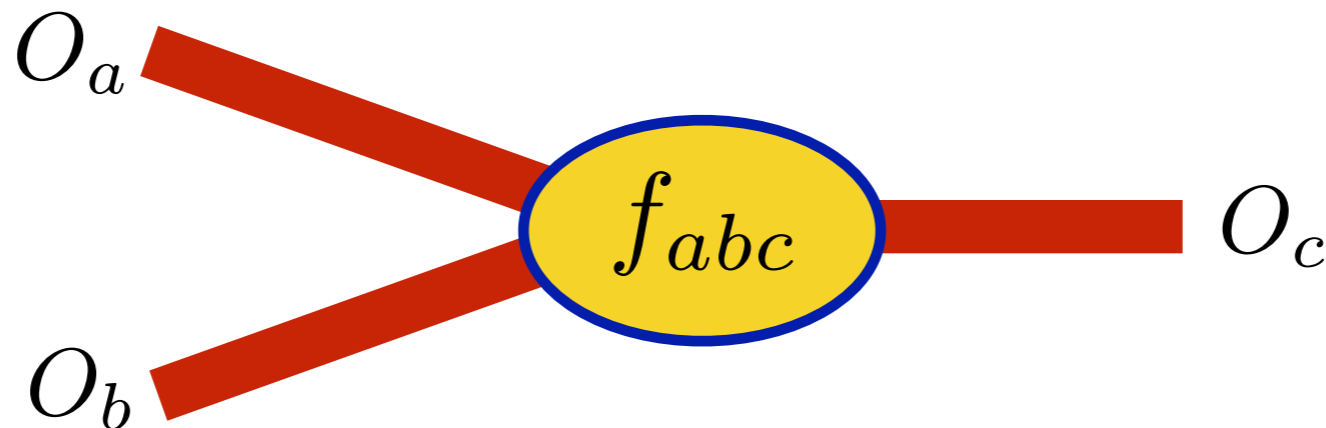
## Basic characteristics of CFTs

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  $\Delta_a$  is their scaling dimension. Their “interactions” are determined by the OPE (considering scalar operators only)

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



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 CFT<sub>3</sub>, 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

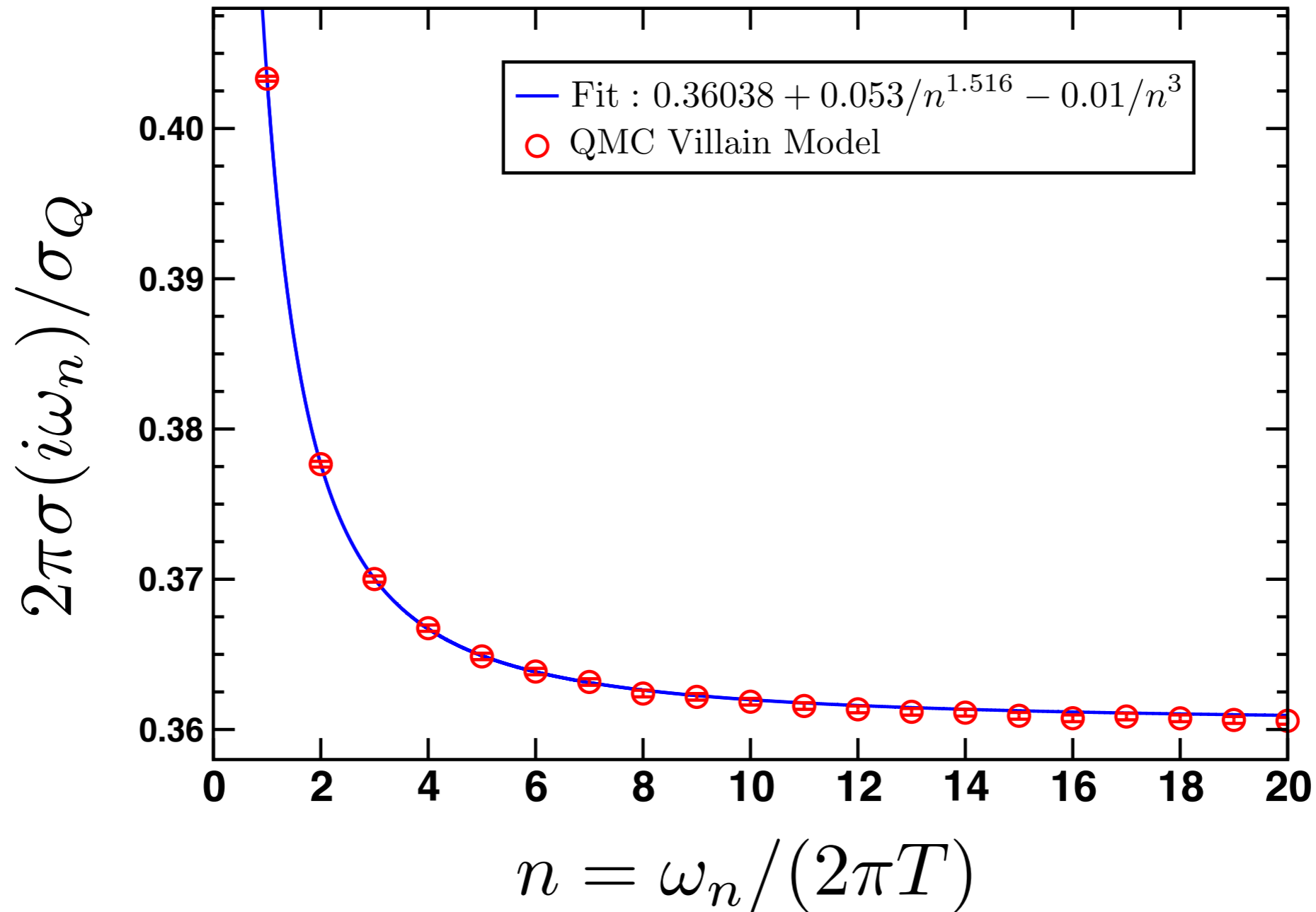
The thermal average of the OPE of two  $O(2)$  current operators yields for  $\omega \gg T$

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

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

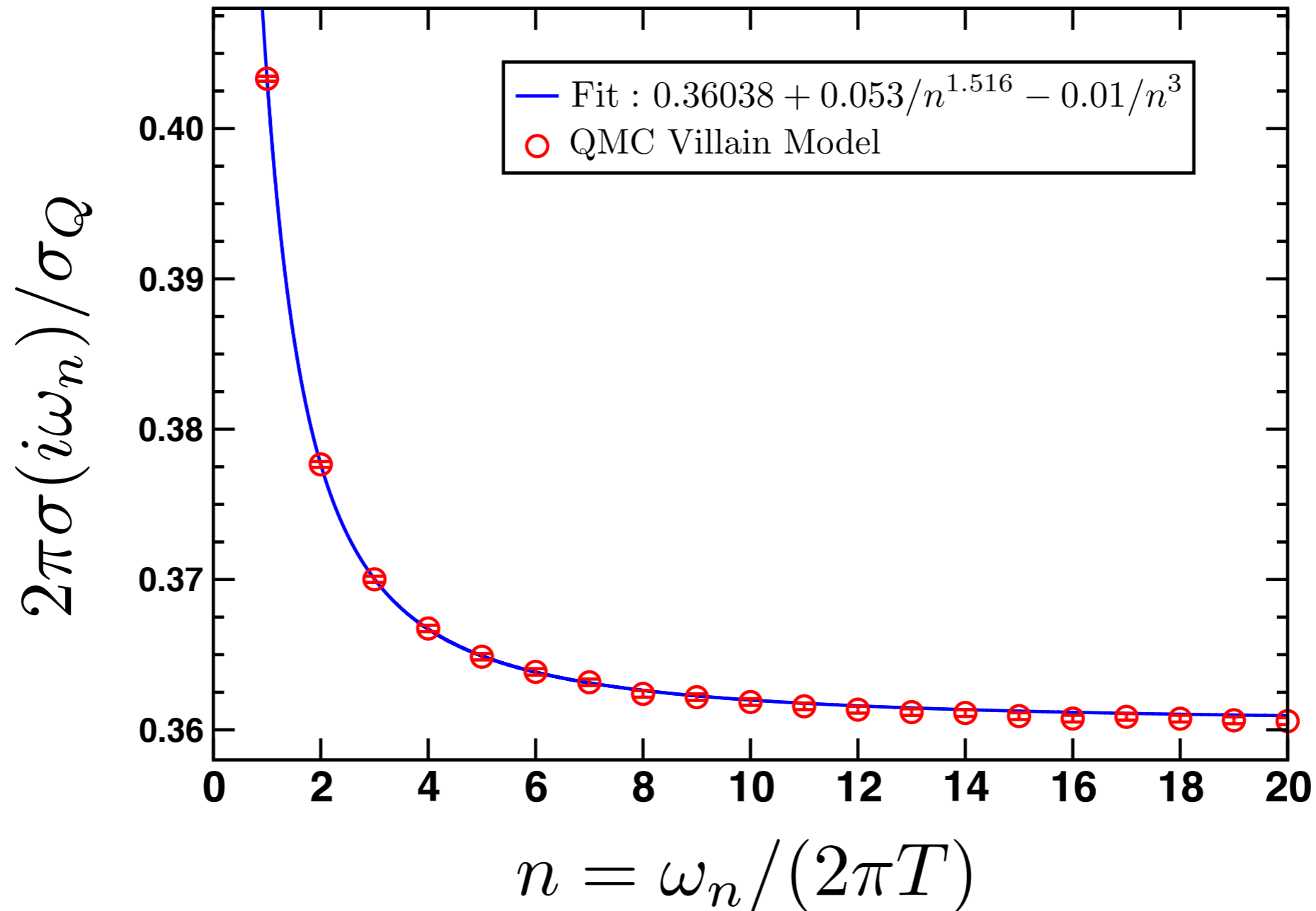
- $b_1$  depends on a relevant scalar operator with dimension  $3 - 1/\nu$ ; for the  $O(2)$  Wilson-Fisher CFT3,  $\nu \approx 0.6717(1)$ .
- $b_2$  depends on OPE with the energy-momentum tensor.

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



**Excellent agreement with OPE**

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



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

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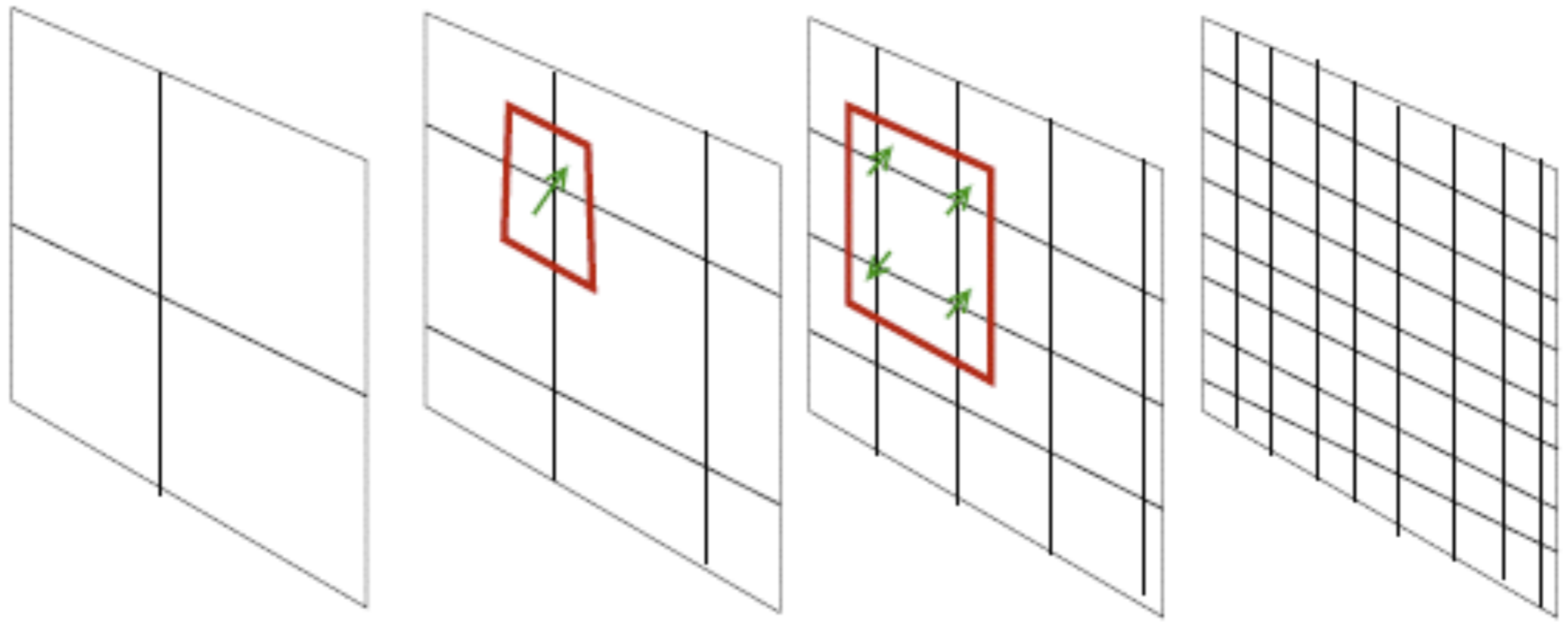
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- ★ Relate OPE coefficients to couplings of an effective gravitational theory on AdS

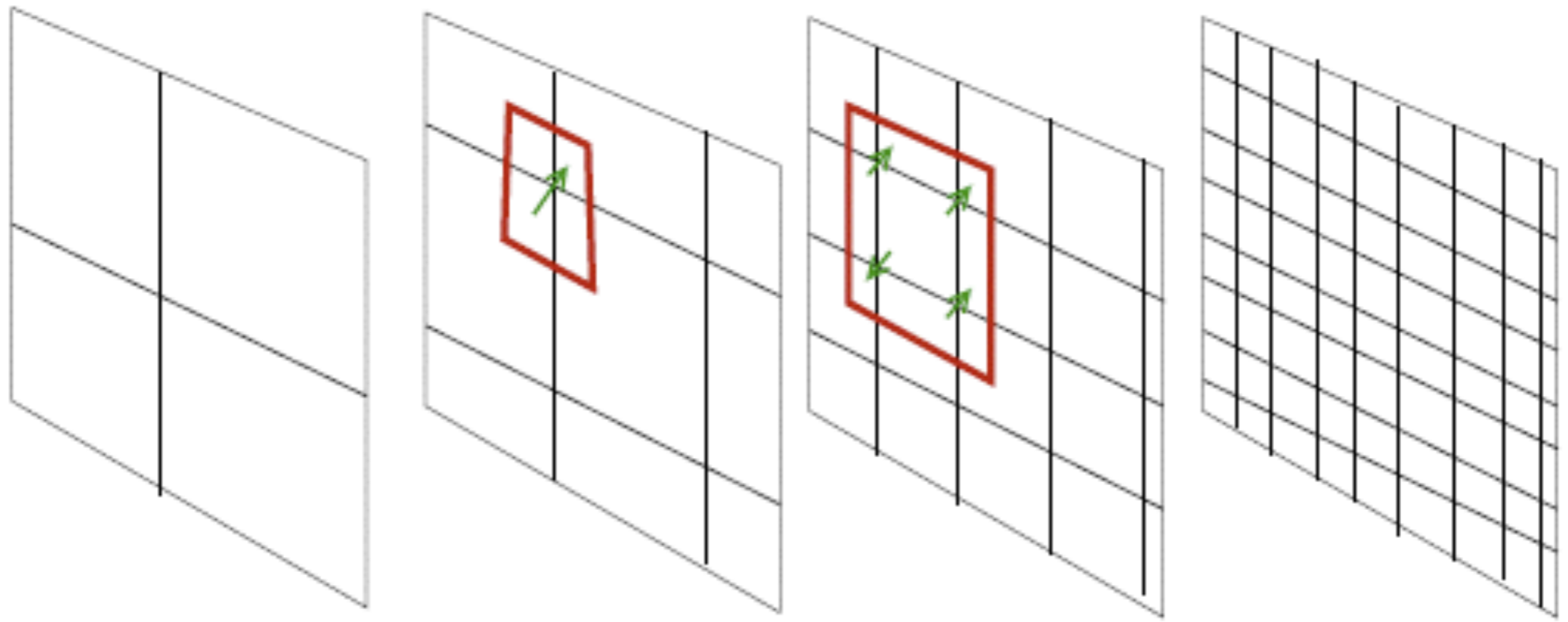
Field theories in  $d + 1$  spacetime dimensions are characterized by couplings  $g$  which obey the renormalization group equation

$$u \frac{dg}{du} = \beta(g)$$

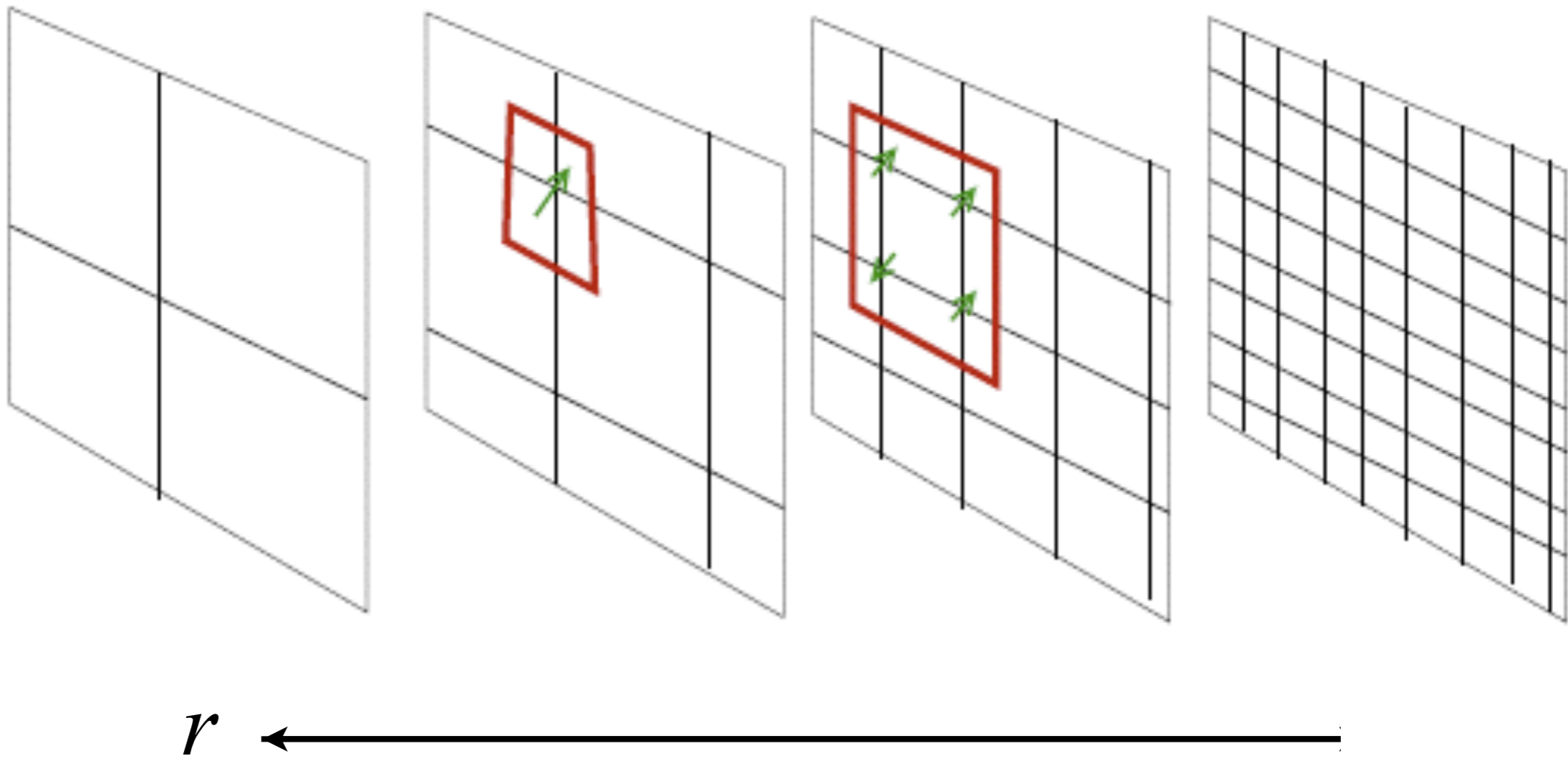
where  $u$  is the energy scale. The RG equation is *local* in energy scale, *i.e.* the RHS does not depend upon  $u$ .



→  $u$



$r$  ←



**Key idea:**  $\Rightarrow$  Implement  $r$  as an extra dimension, and map to a local theory in  $d + 2$  spacetime dimensions.

For a relativistic CFT in  $d$  spatial dimensions, the metric in the holographic space is uniquely fixed by demanding the following scale transformation ( $i = 1 \dots d$ )

$$x_i \rightarrow \zeta x_i \quad , \quad t \rightarrow \zeta t \quad , \quad ds \rightarrow ds$$

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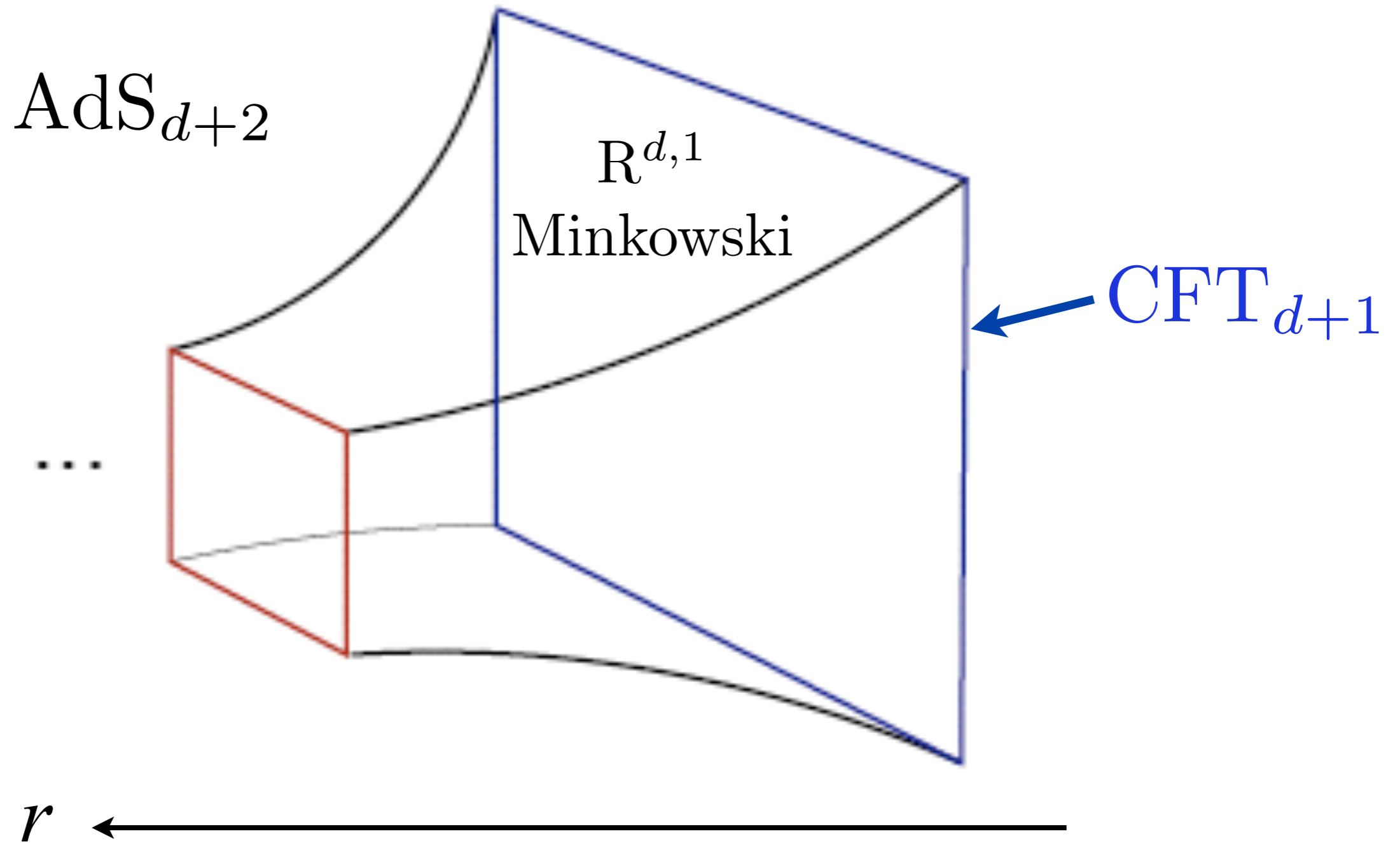
$$x_i \rightarrow \zeta x_i \quad , \quad t \rightarrow \zeta t \quad , \quad ds \rightarrow ds$$

This gives the unique metric

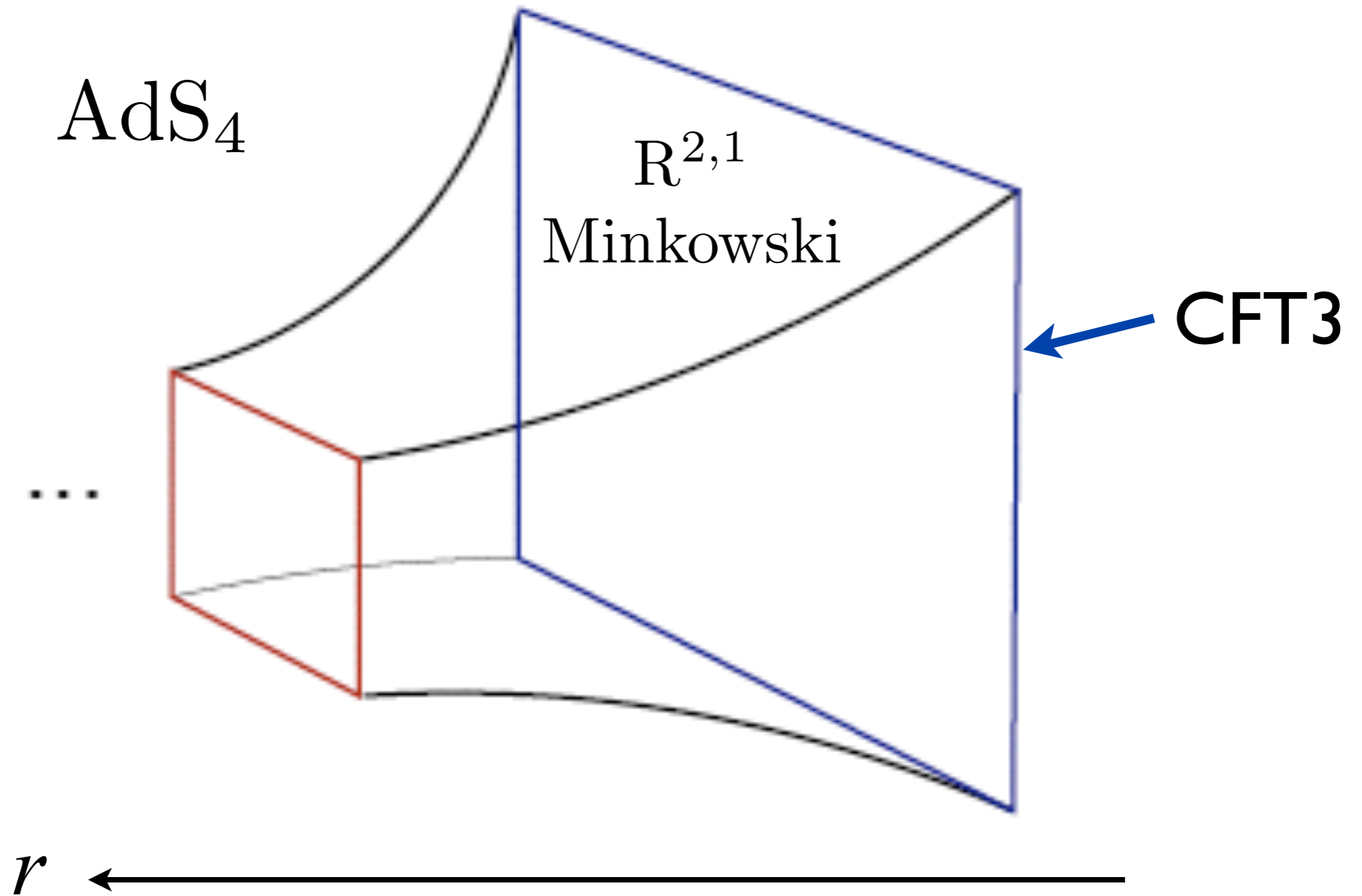
$$ds^2 = \frac{1}{r^2} (-dt^2 + dr^2 + dx_i^2)$$

Reparametrization invariance in  $r$  has been used to the prefactor of  $dx_i^2$  equal to  $1/r^2$ . This fixes  $r \rightarrow \zeta r$  under the scale transformation. This is the metric of the space  $\text{AdS}_{d+2}$ .

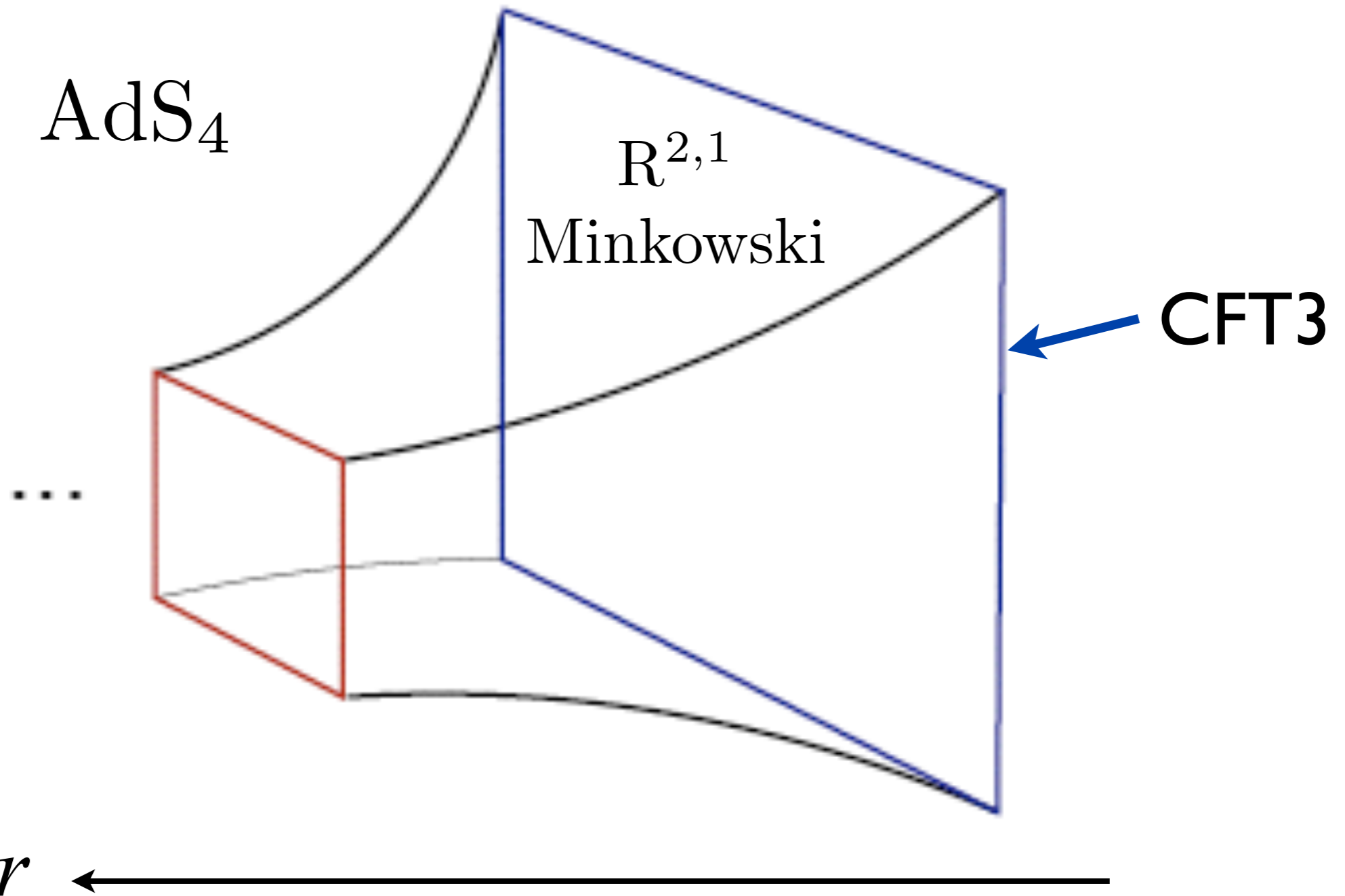
# AdS/CFT correspondence at zero temperature



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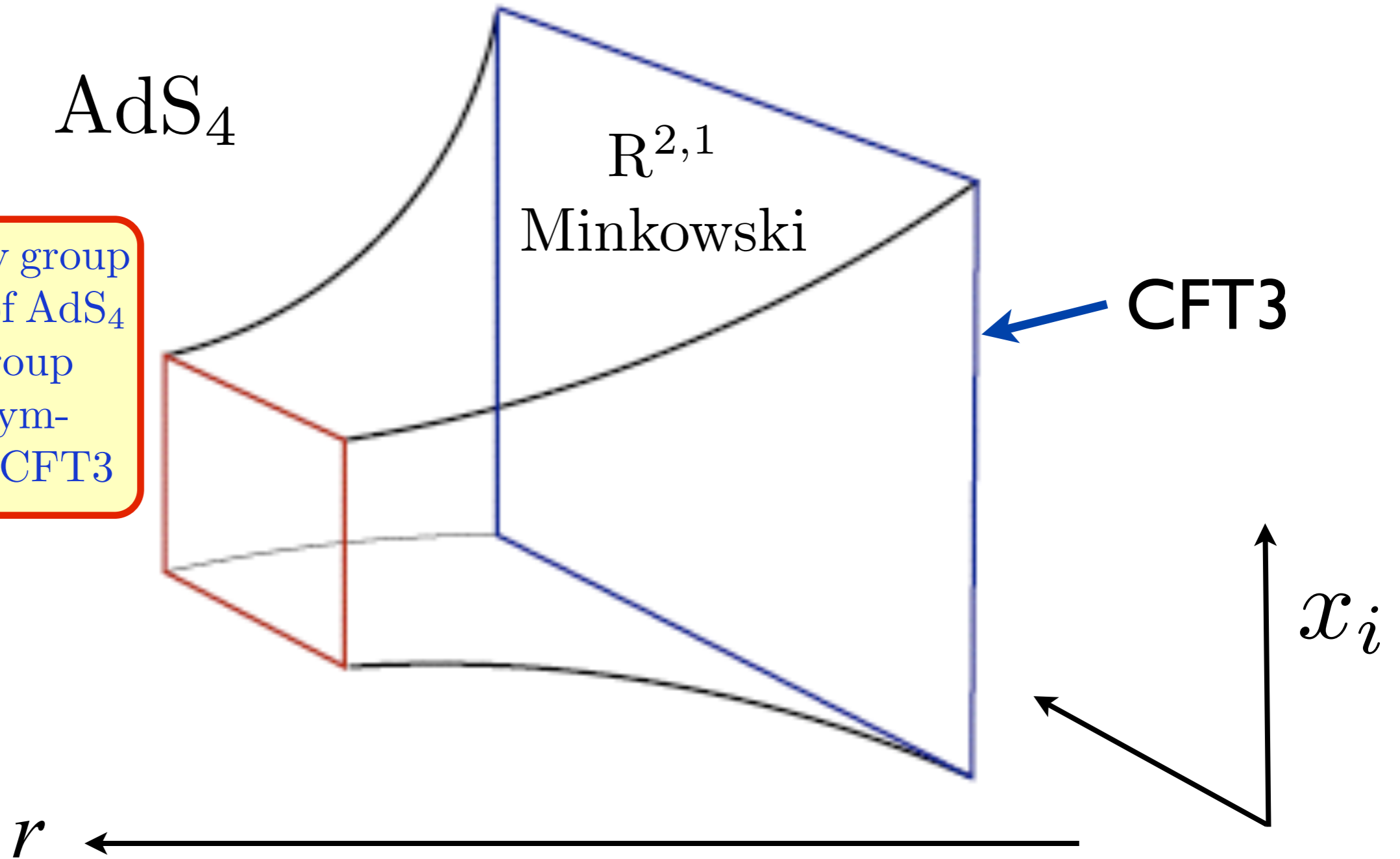


This emergent spacetime is a solution of Einstein gravity with a negative cosmological constant

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

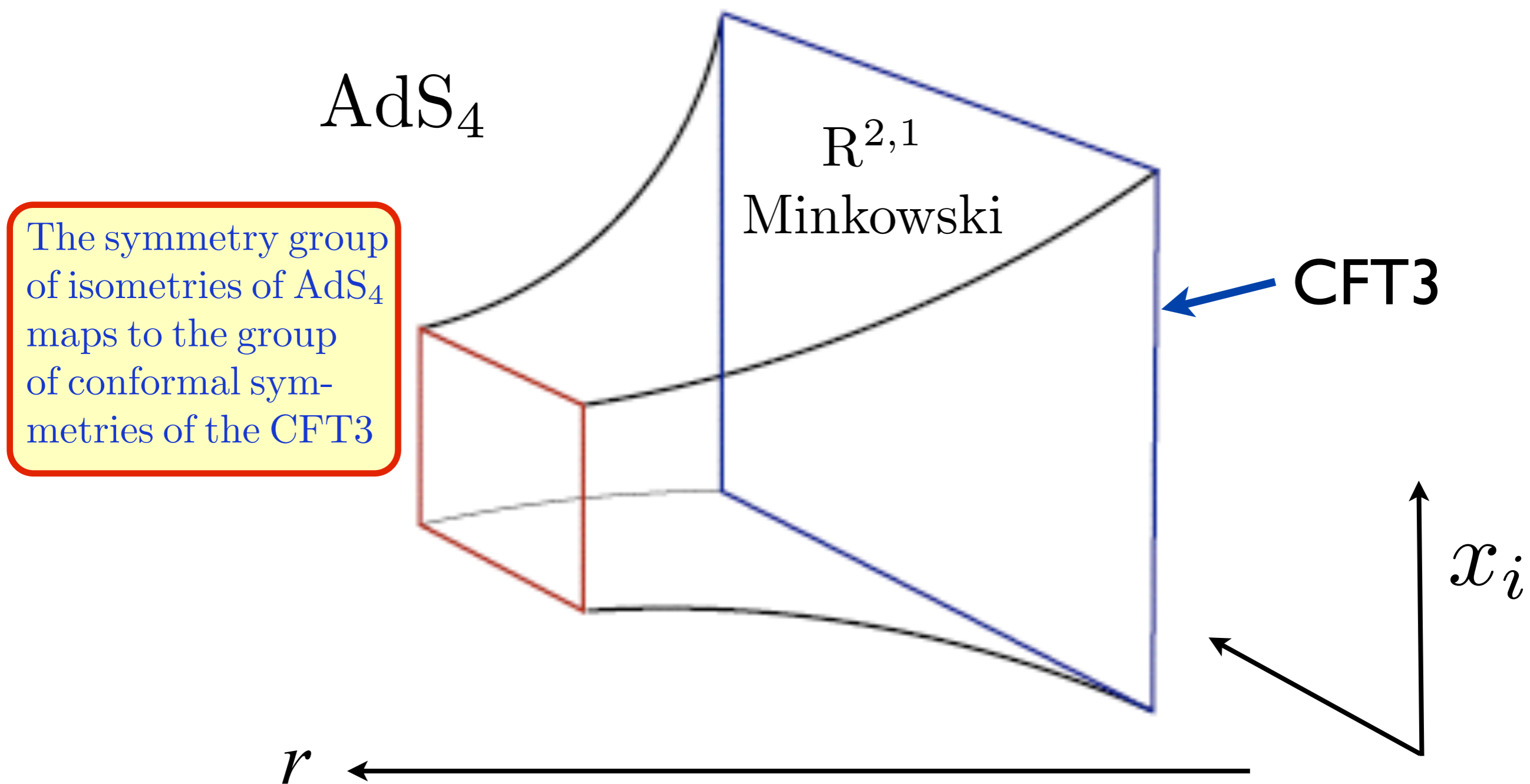
# AdS/CFT correspondence at zero temperature

The symmetry group of isometries of  $\text{AdS}_4$  maps to the group of conformal symmetries of the CFT3



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

# AdS/CFT correspondence at zero temperature



The symmetry group of isometries of  $AdS_4$  maps to the group of conformal symmetries of the  $CFT_3$

A classical gravitational theory on  $AdS_4$  encodes the  $CFT_3$  data of  $\{\Delta_a, f_{abc}\}$ , and allows computation of  $CFT_3$  correlators consistent with all conformal Ward identities

# AdS/CFT correspondence at zero temperature

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

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

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  $\varphi$  is conjugate to the CFT operator  $\mathcal{O}$  with scaling dimension  $3 - 1/\nu$ , which fixes its mass  $m$ . The coupling  $\alpha$  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, *Physical Review B* **90**, 245109 (2014)

## Traditional CMT

- ◇ Identify quasiparticles and their dispersions
- ◇ Compute scattering matrix elements of quasiparticles
- ◇ Input parameters into a quantum Boltzmann equation
- ◇ Compute dissipative properties at  $\omega \ll$  quasiparticle-collision-rate

## Dynamics without quasiparticles

- ★ Start with strongly interacting CFT without quasiparticles
- ★ Using scaling dimensions and operator product expansions (OPE) of the CFT, compute conductivity at  $\hbar\omega \gg k_B T$
- ★ Relate OPE coefficients to couplings of an effective gravitational theory on AdS

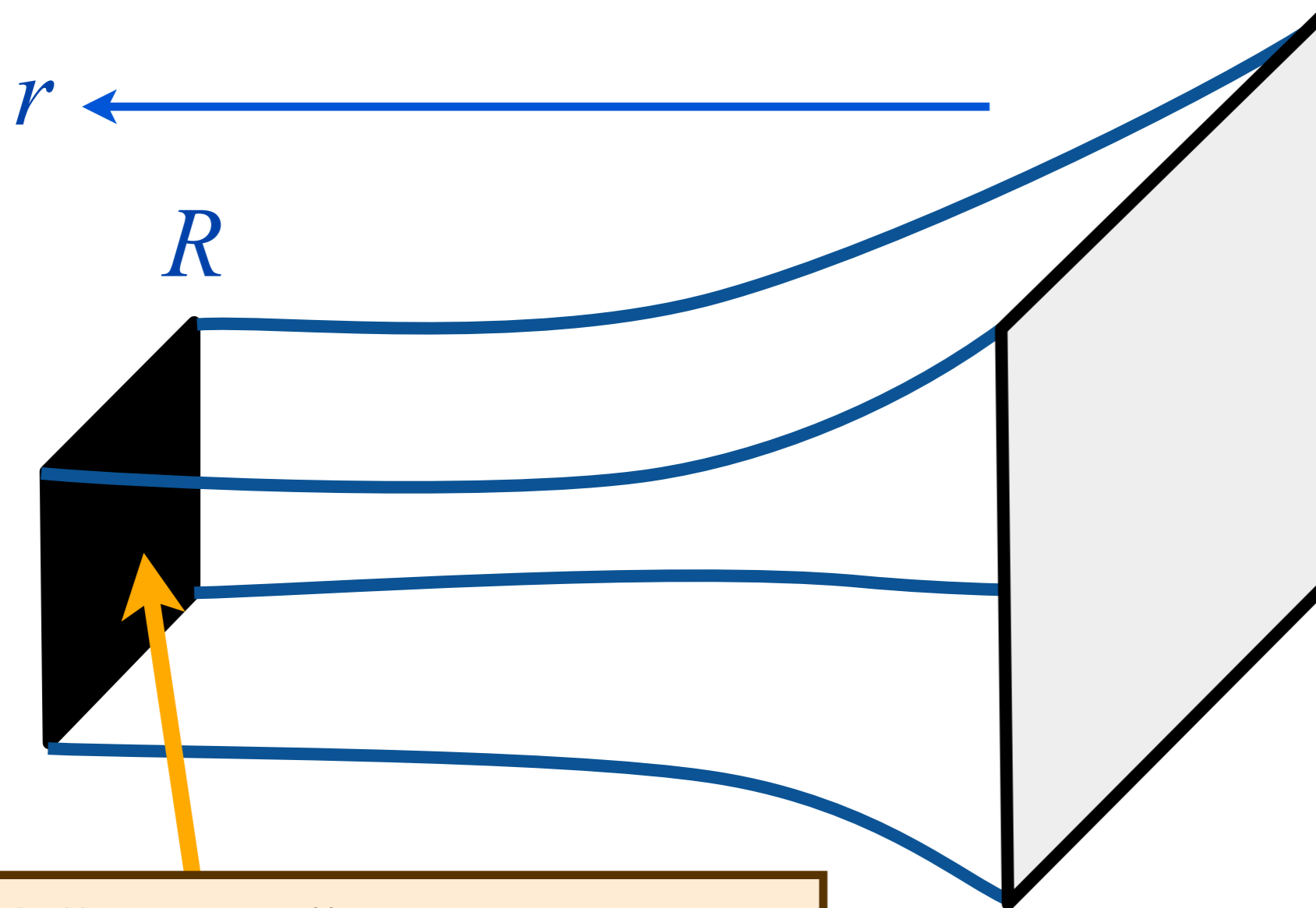
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# AdS/CFT correspondence at non-zero temperatures

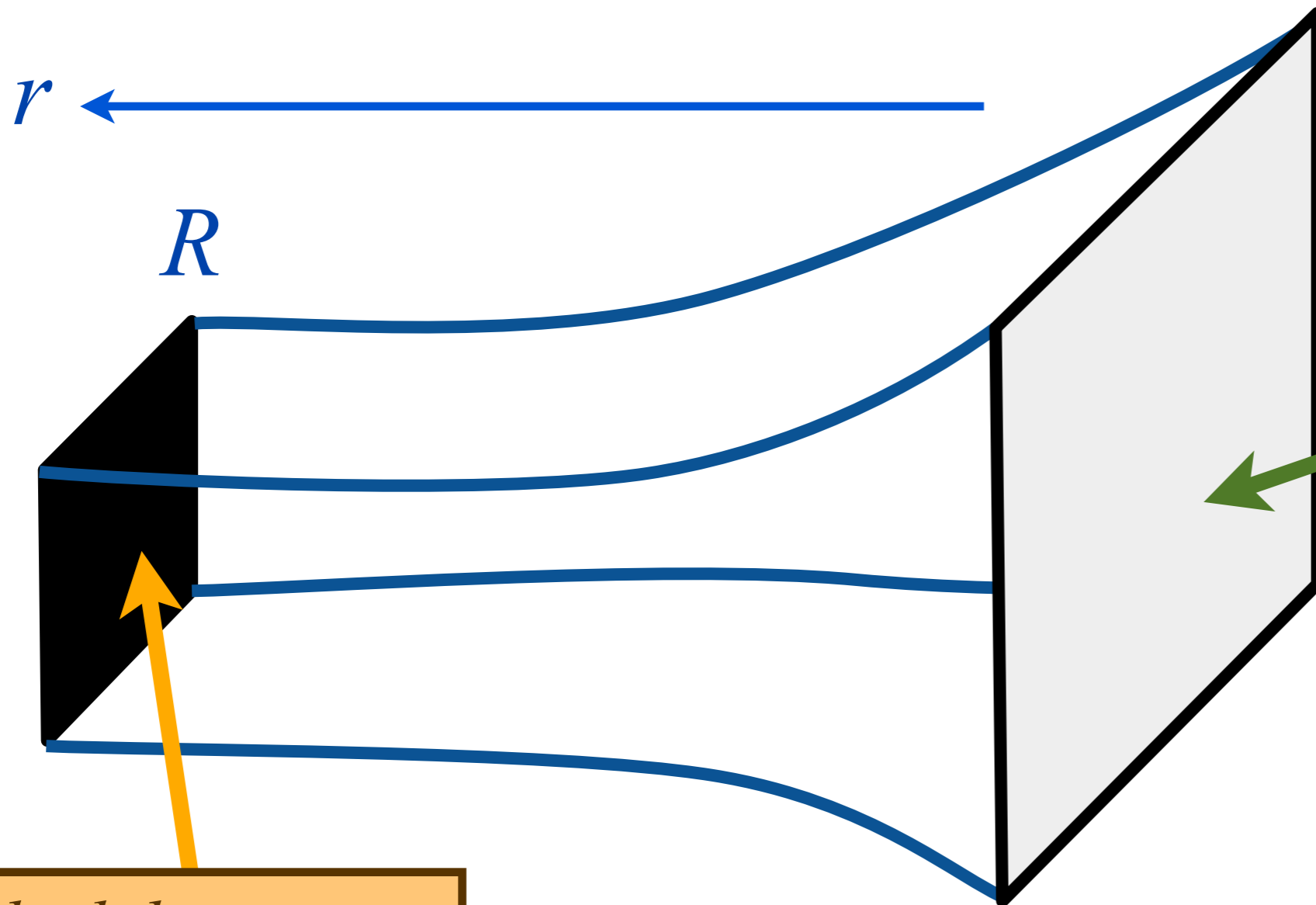


A “horizon”, similar to the surface of a black hole !

There is a family of solutions of Einstein’s equations which are  $\text{AdS}_4$  as  $r \rightarrow 0$ , but which have horizons at  $r = R$ .

# AdS/CFT correspondence at non-zero temperatures

## AdS<sub>4</sub>-Schwarzschild black-brane



A CFT<sub>3</sub>  
at a non-zero  
temperature:  
 $k_B T = \frac{3\hbar}{4\pi R}$ .

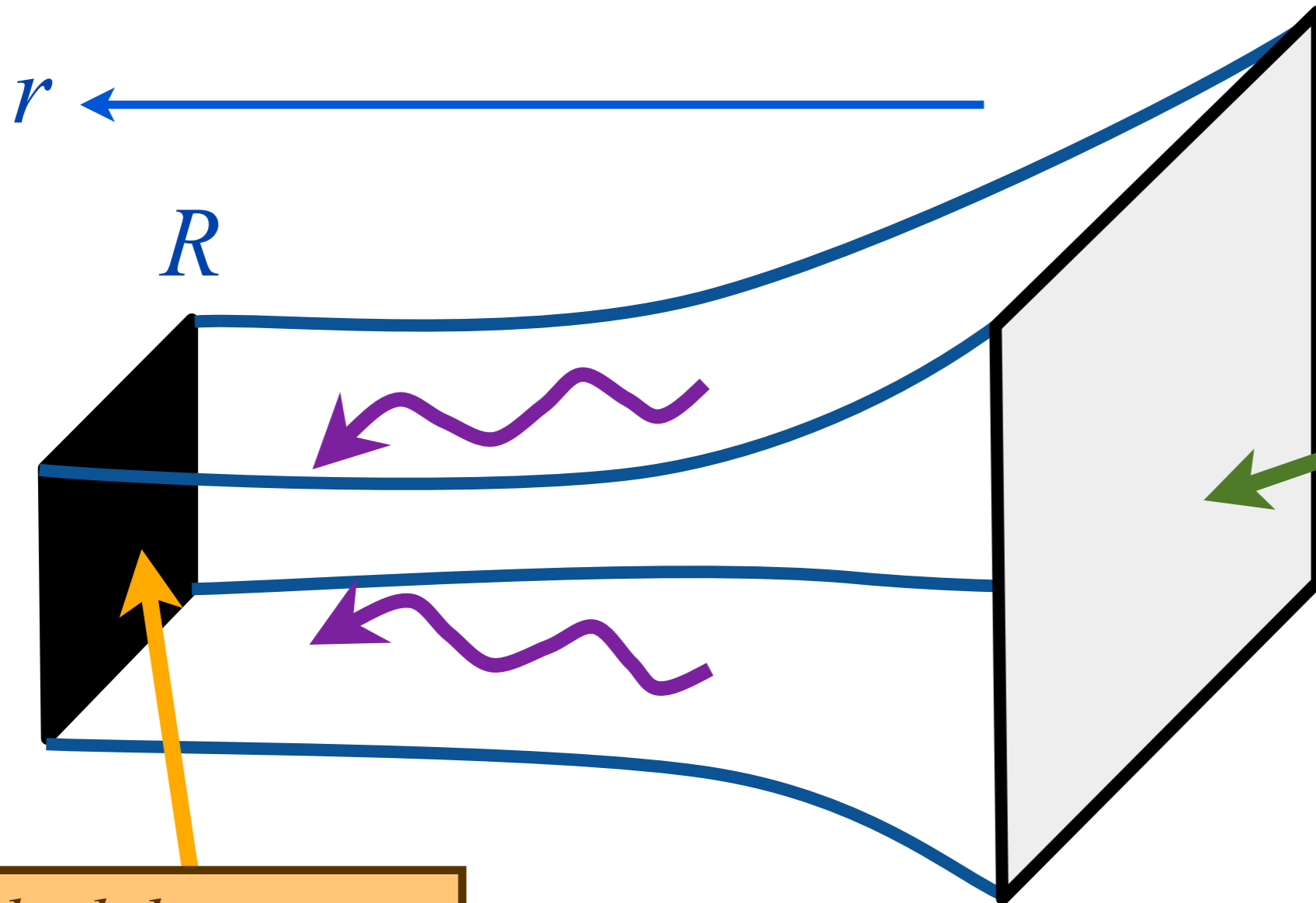
*Black-brane at  
Hawking  
temperature  $T$*

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

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

# AdS/CFT correspondence at non-zero temperatures

## AdS<sub>4</sub>-Schwarzschild black-brane



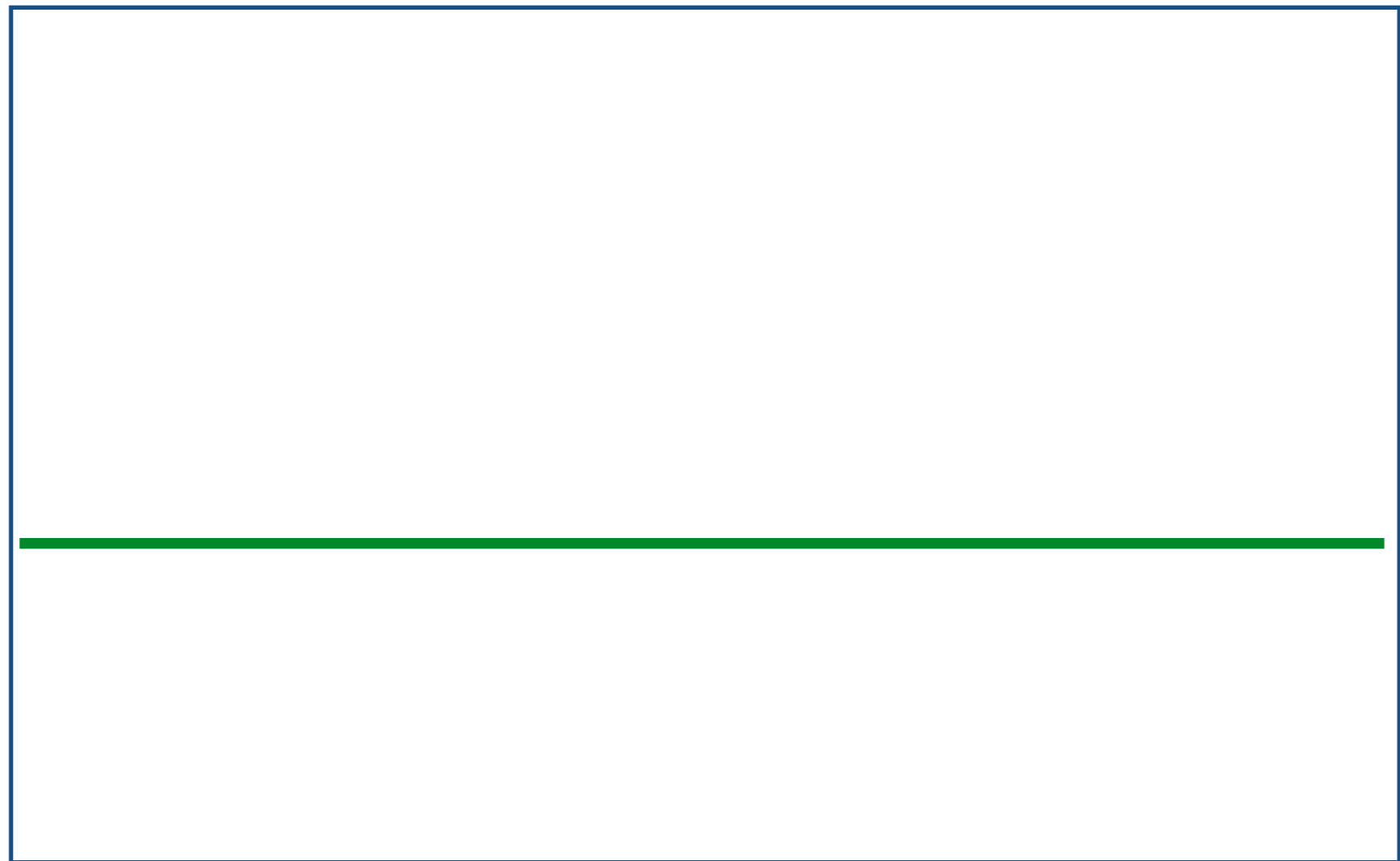
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$$k_B T = \frac{3\hbar}{4\pi R}.$$

*Black-brane at  
Hawking  
temperature  $T$*

Friction of CFT<sub>3</sub> =  
waves falling into  
black brane

# Conductivity of Einstein-Maxwell theory

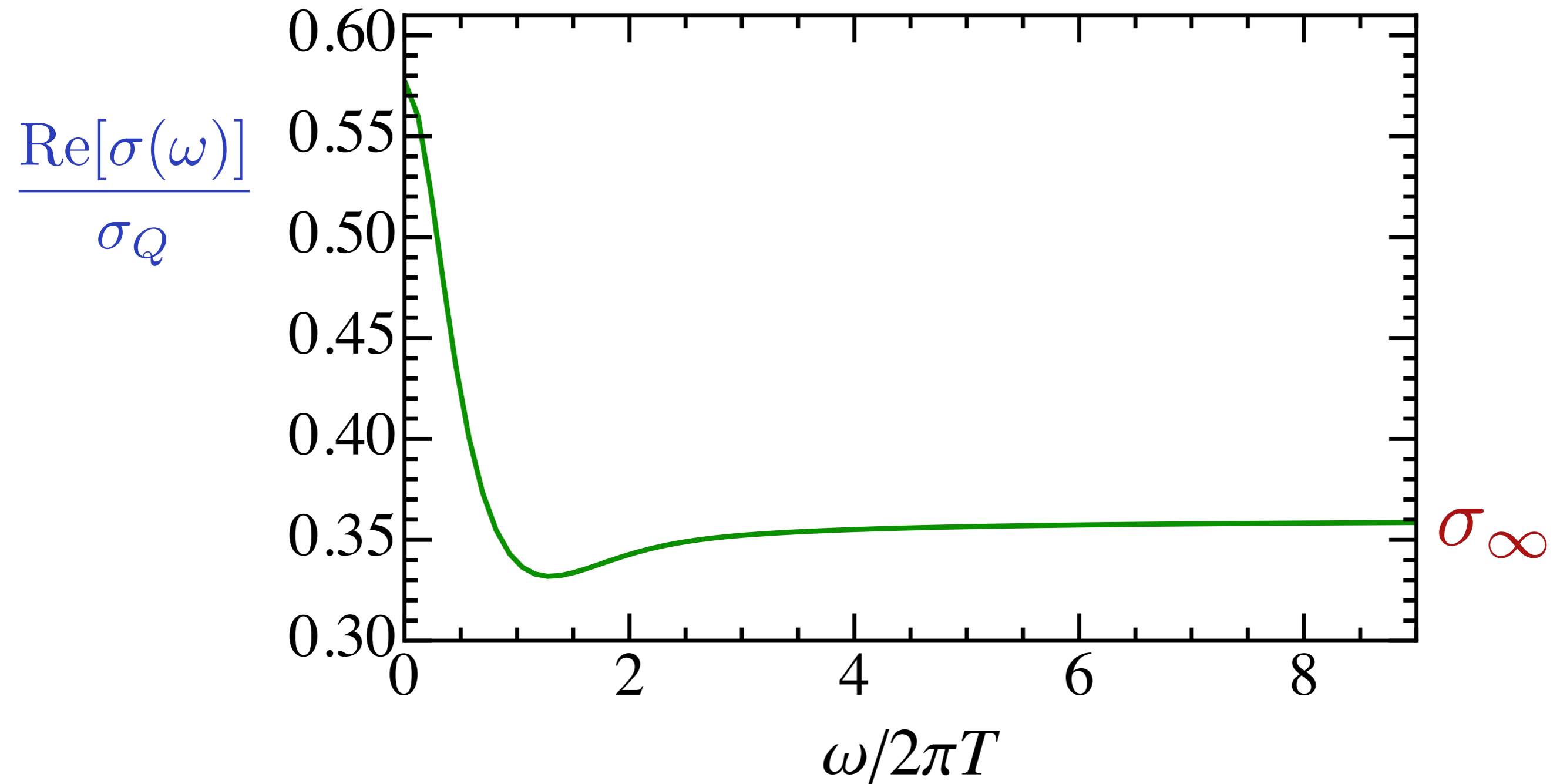
$$\frac{\text{Re}[\sigma(\omega)]}{\sigma_Q}$$



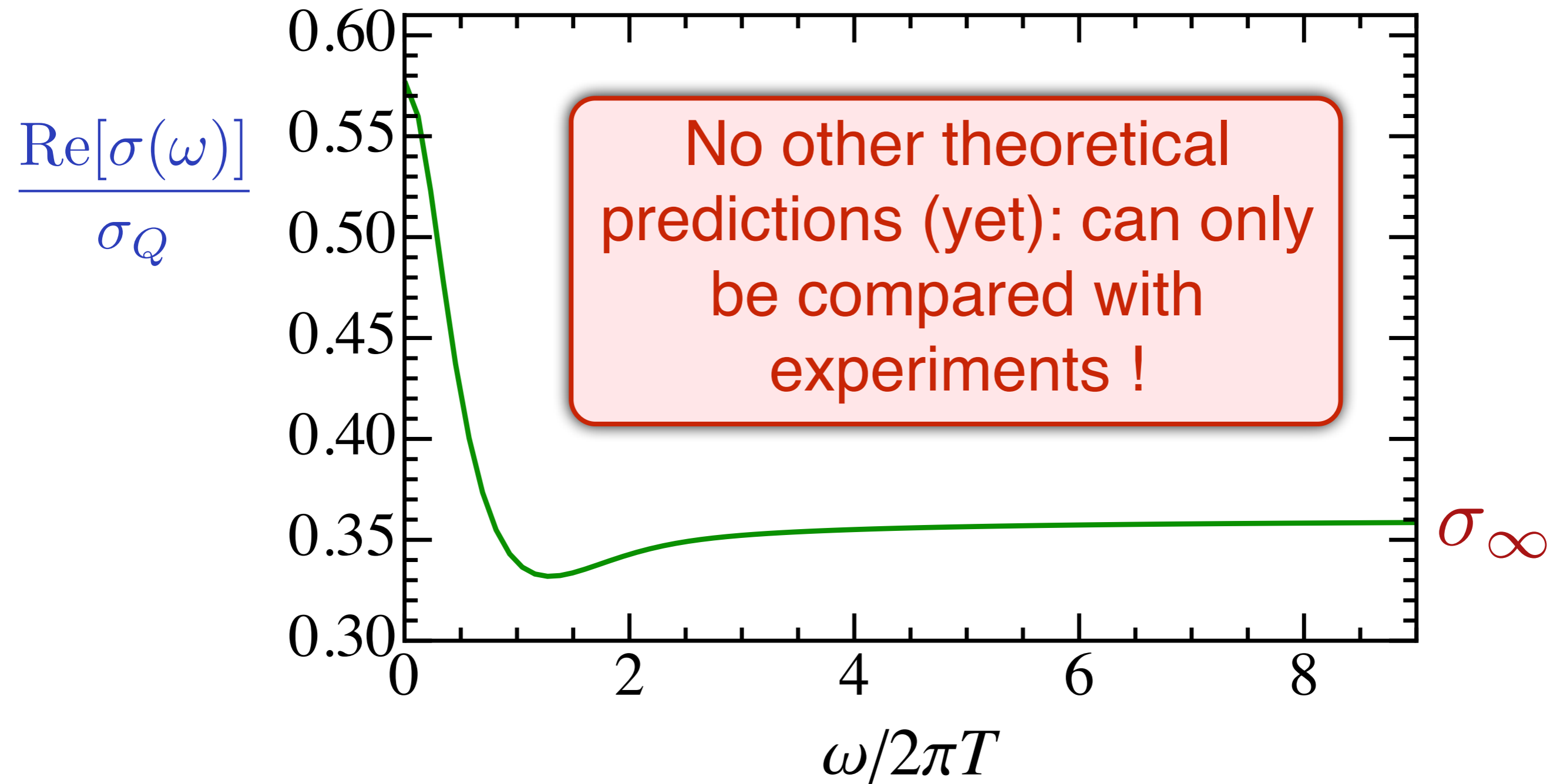
$$\sigma_\infty$$

$$\omega/2\pi T$$

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



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



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# Outline

## I. Conformal field theories in $2+1$ dimensions

*Superfluid-insulator transition*

*A. Boltzmann dynamics*

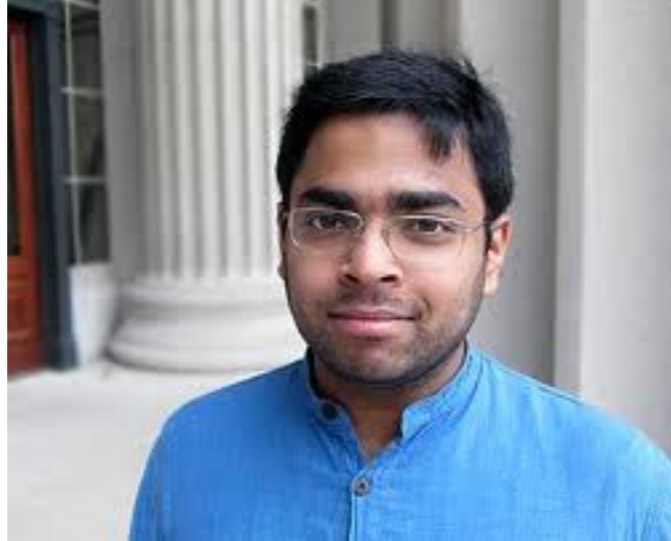
*B. Conformal / holographic dynamics*

## 2. Non-Fermi liquid in $2+1$ dimensions

*Strange metal in the high temperature superconductors*



Sean Hartnoll  
Stanford



Raghu Mahajan  
Stanford



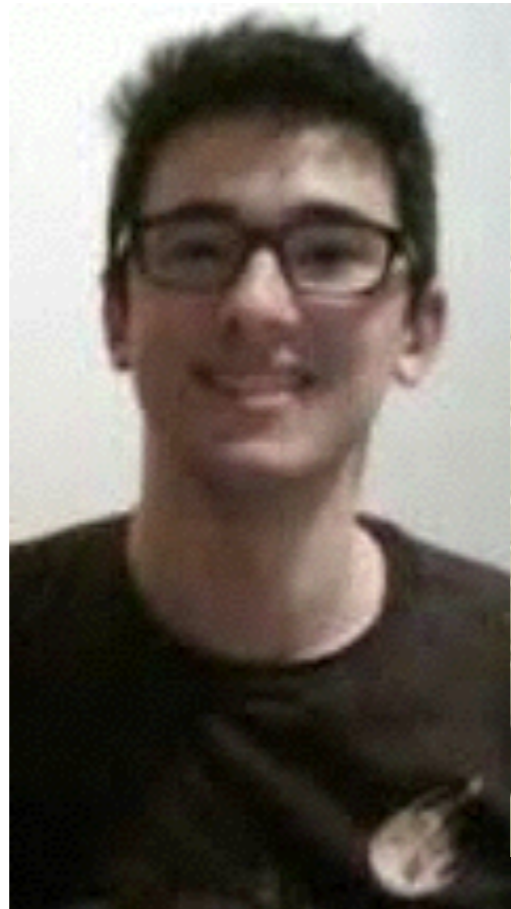
Matthias Punk  
Innsbruck



Andrea Allais



Koenraad Schalm  
Leiden



Andrew Lucas



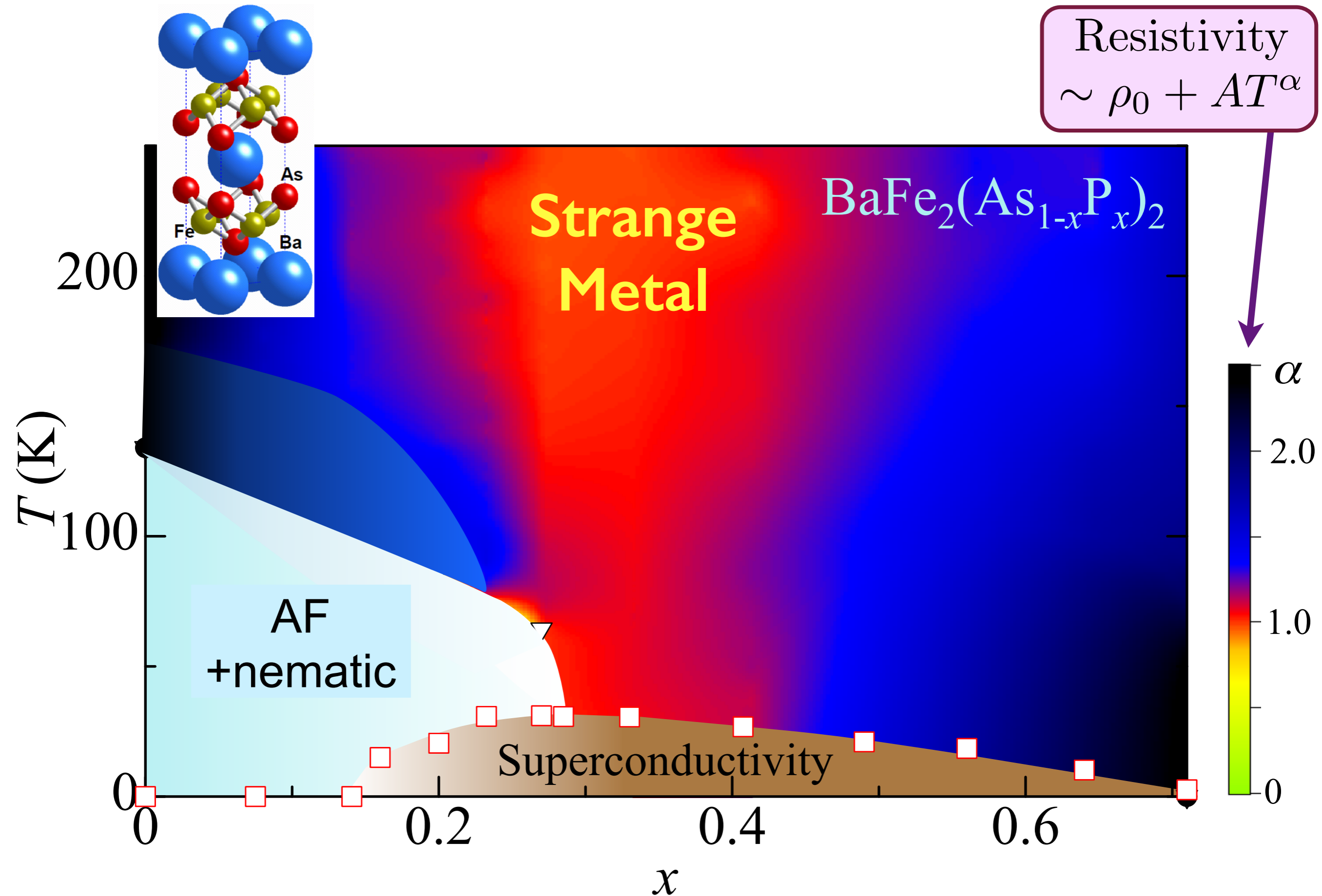
Aavishkar Patel



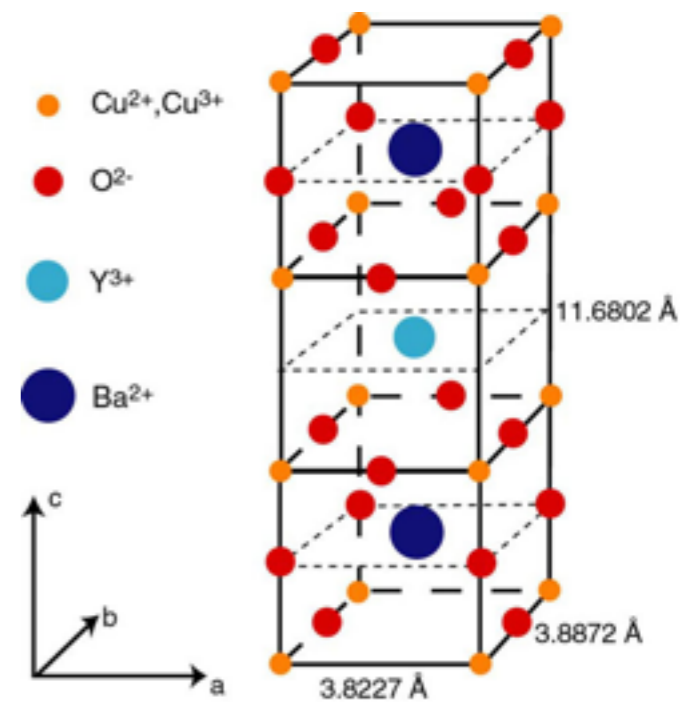
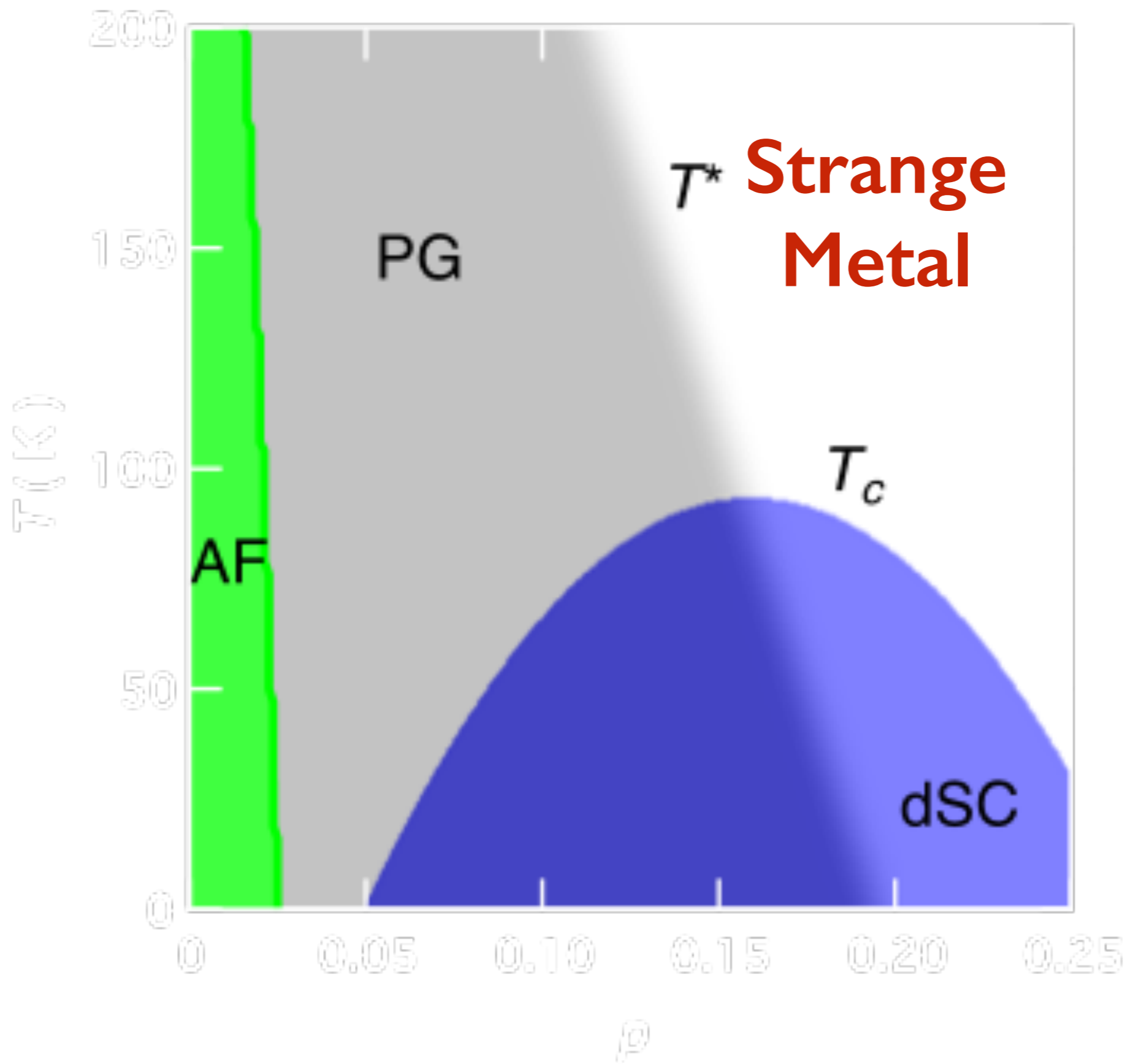
Debanjan  
Chowdhury



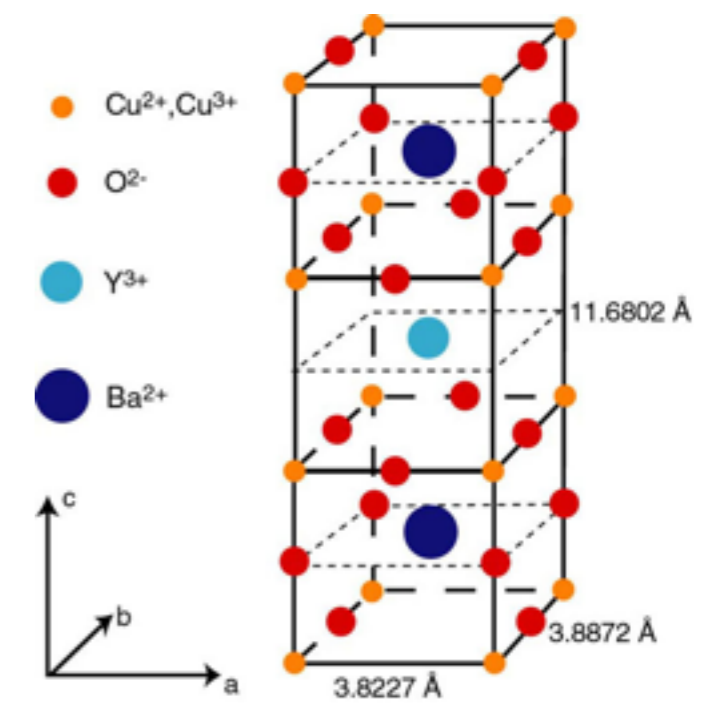
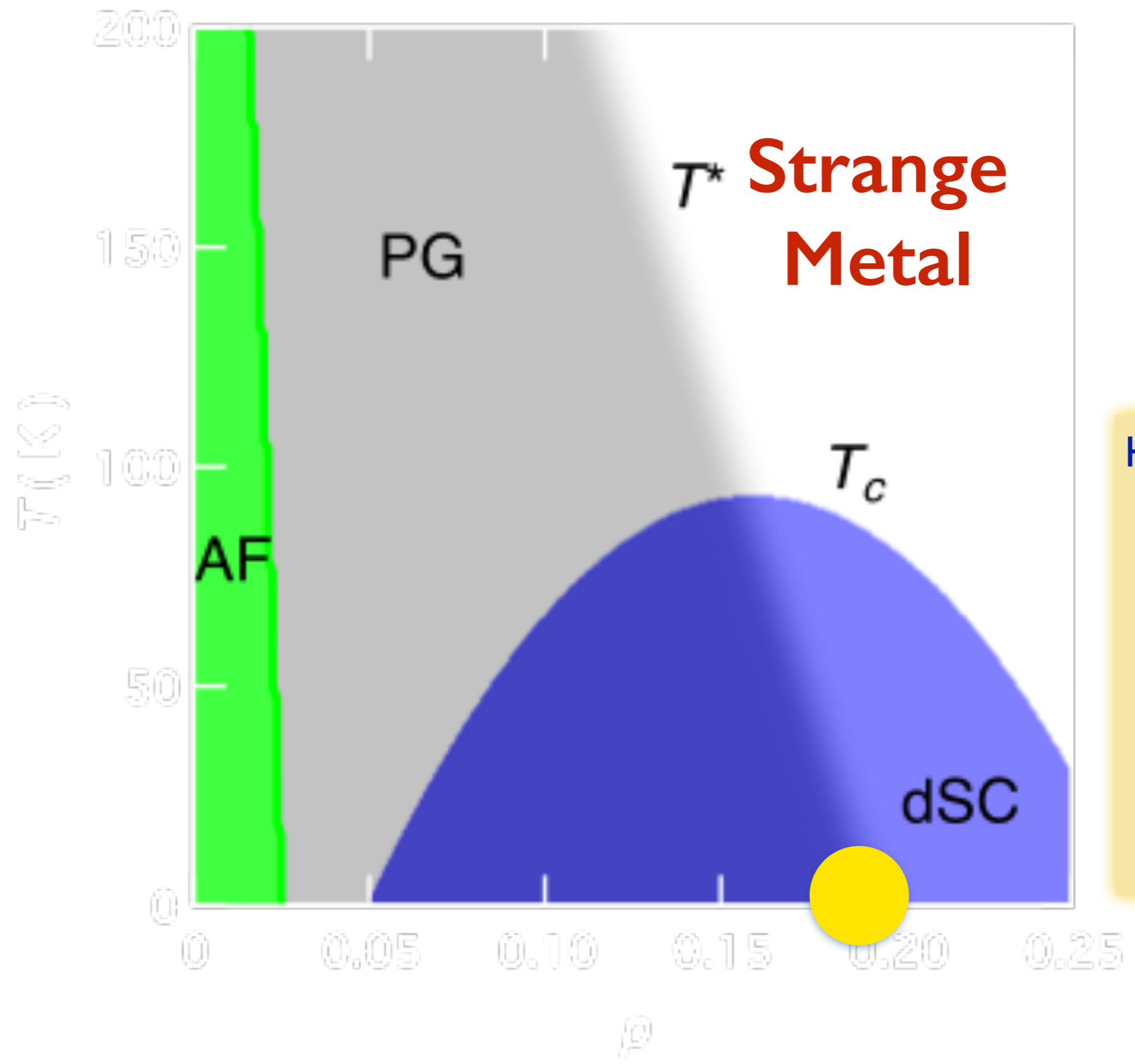
Alexandra  
Thomson



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)



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



Higgs criticality in a metal:

A quantum phase transition in a gauge theory which breaks no global symmetries, but leads to changes in the quantum entanglement and Fermi surface.

## Boltzmann view of electrical transport:

- Identify charge carriers: electrons near the Fermi surface. Compute the scattering rate of these charged excitations off the bosonic gauge field and Higgs field

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- Identify charge carriers: electrons near the Fermi surface. Compute the scattering rate of these charged excitations off the bosonic gauge field and Higgs field fluctuations.
- Analogous to electron-phonon scattering in metals, where we have “Bloch’s law”: a resistivity  $\rho(T) \sim T^5$ .

# Boltzmann view of electrical transport:

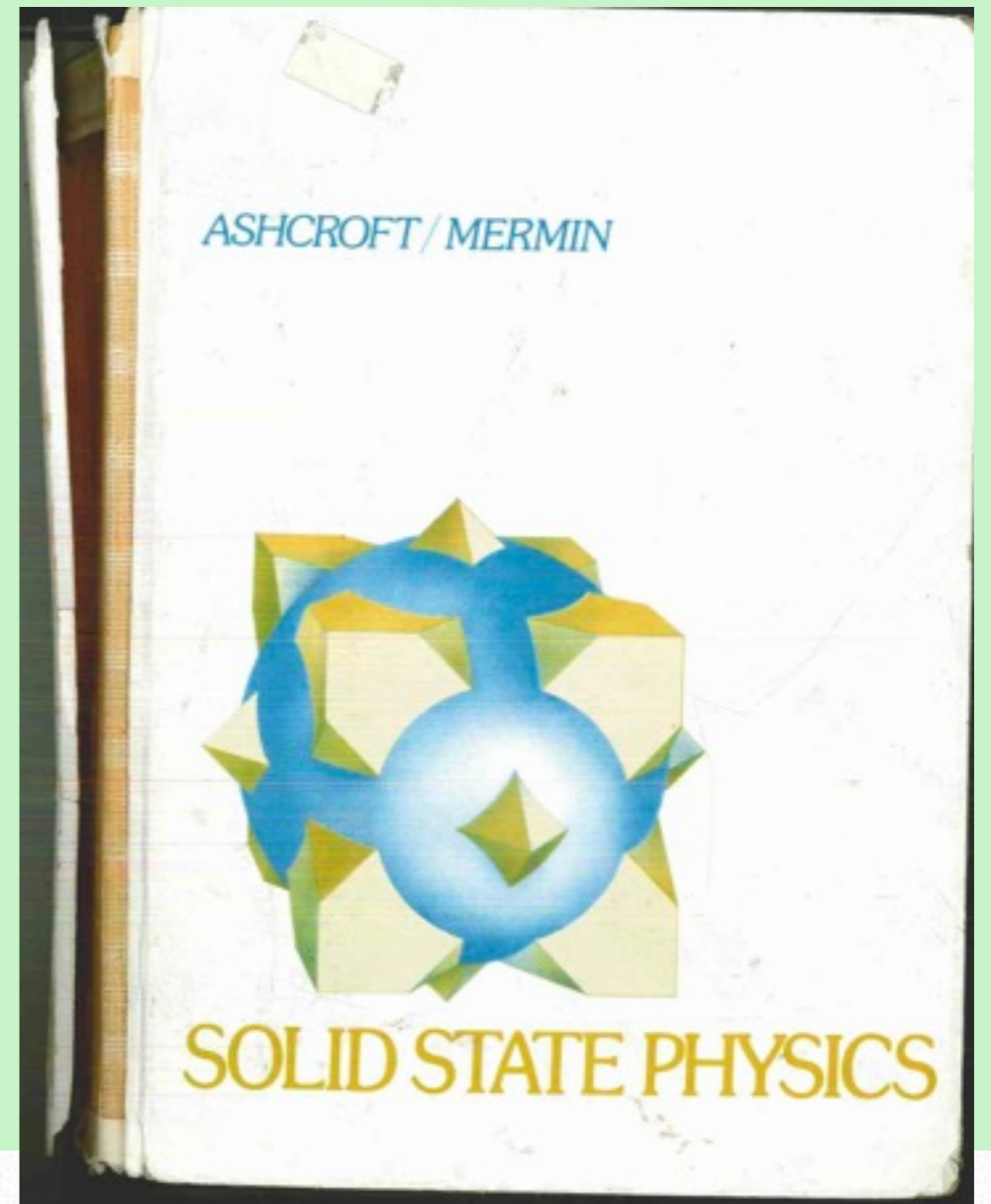
- Identify charge carriers: electron, hole, surface. Compute the scattering rate of these carriers off the bosonic gas of phonons and other excitations.
- Analogous to electron-phonon scattering in metals where we have “Bloch’s law”  
 $\tau \propto T^{-5}$

**However, this ignores  
“phonon drag”**

## PHONON DRAG

Peierls<sup>28</sup> pointed out a way in which the low temperature resistivity might decline more rapidly than  $T^5$ .

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# Boltzmann view of electrical transport:

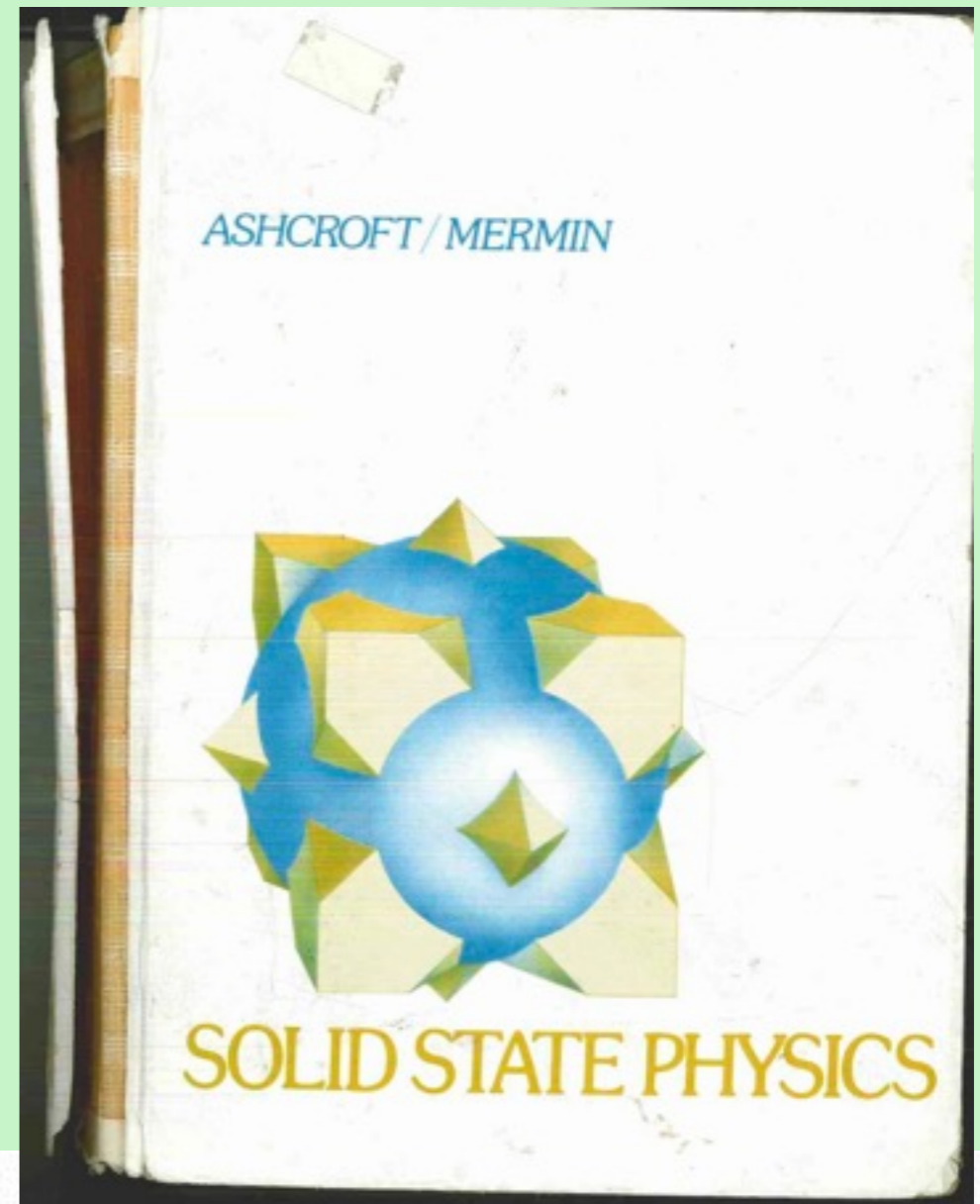
- Identify charge carriers: electron, hole, surface. Compute the scattering rate of these carriers off the bosonic ground state fluctuations.
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[75]

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## PHONON DRAG

Peierls<sup>28</sup> pointed out a way in which the low temperature resistivity might decline more rapidly than  $T^5$ . This behavior has yet to be observed,

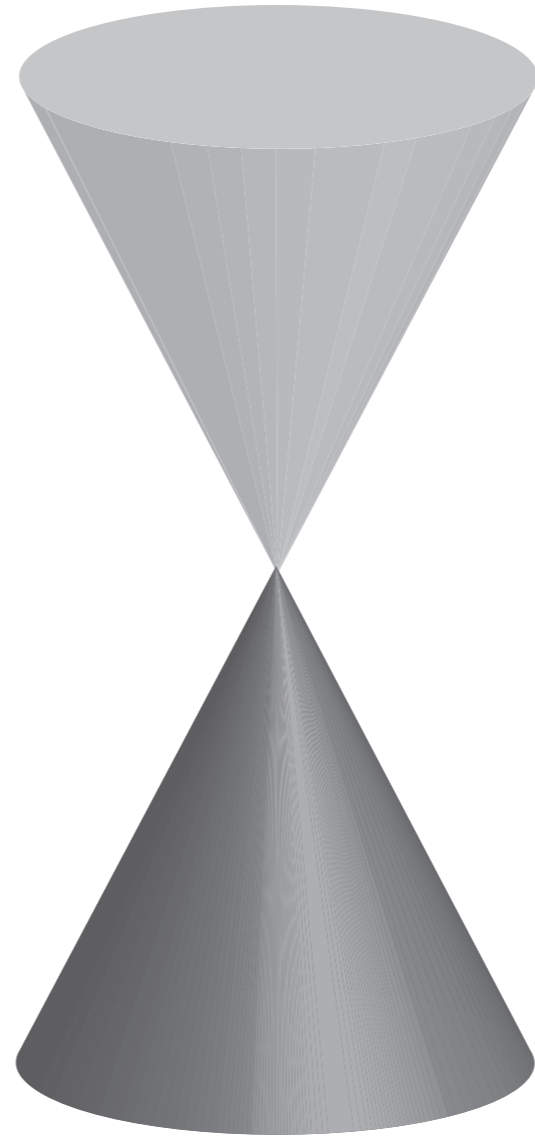
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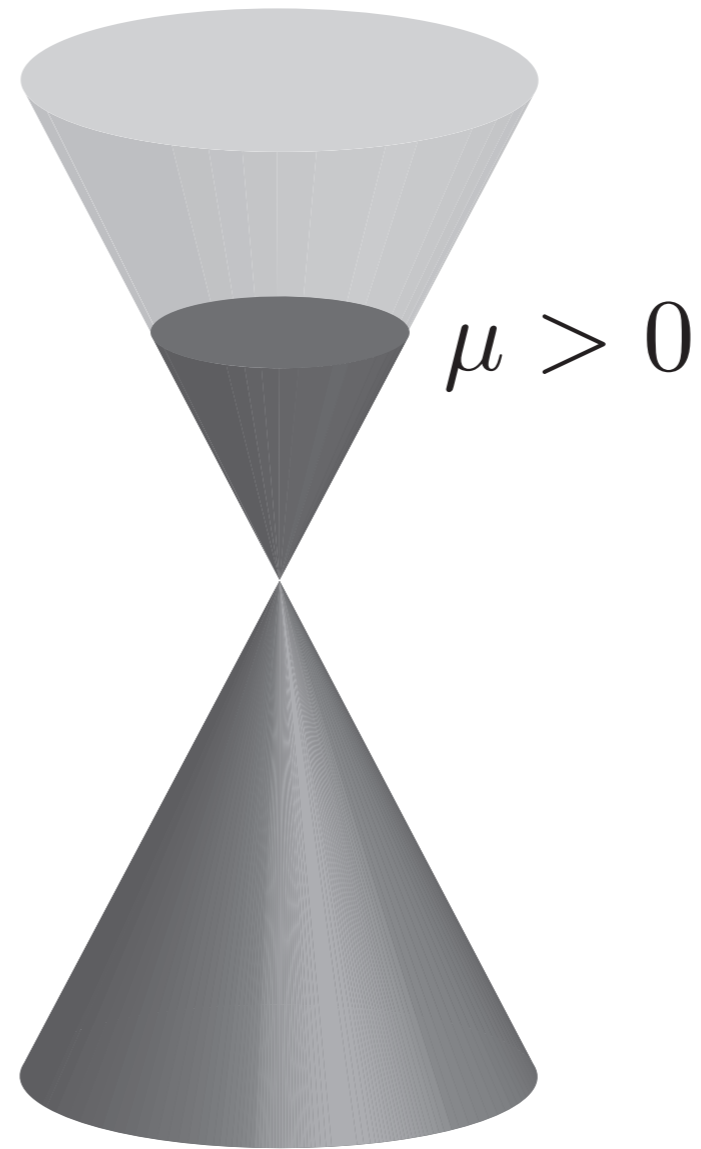
## Strange metal from a Higgs critical point

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

# A CFT

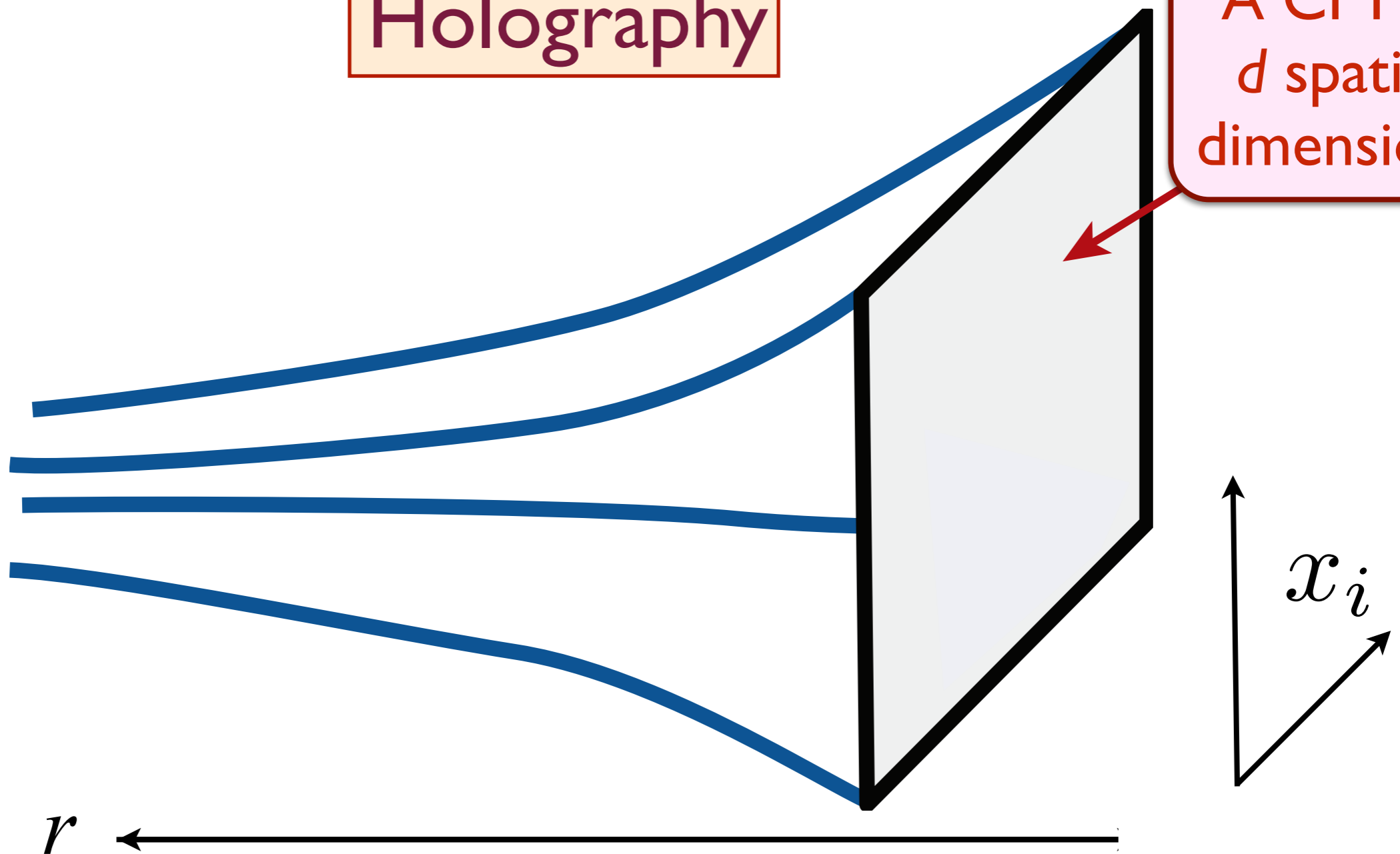


# Apply a chemical potential



# Holography

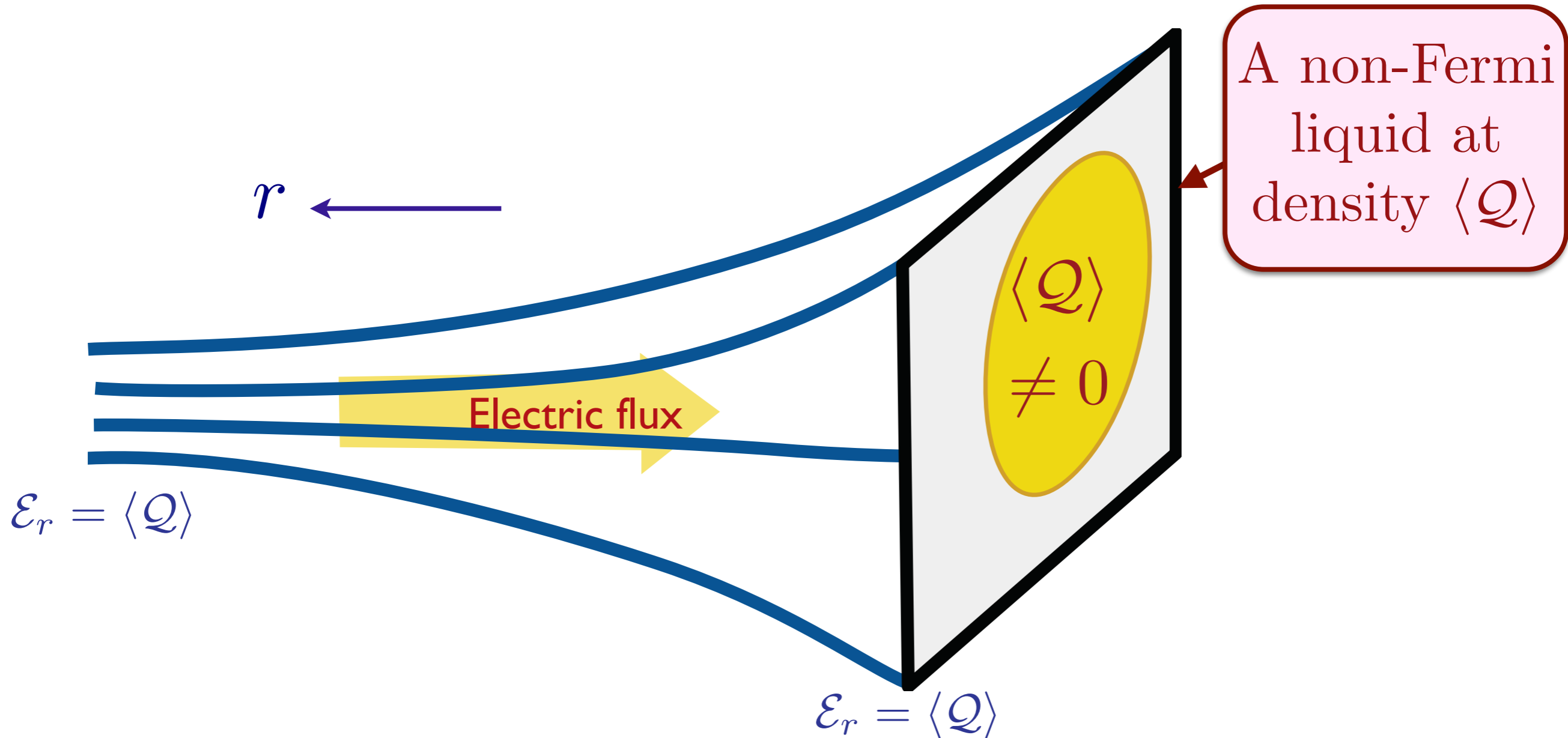
A CFT in  
 $d$  spatial  
dimensions



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

This is the metric of anti-de Sitter space  $\text{AdS}_{d+2}$ .

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



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

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

## Strange metal from a Higgs critical point

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.

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**This in contrast to condensed matter theorists, who have followed Bloch rather than Peierls over the last 2 decades**

## Strange metal from a Higgs critical point

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.

There is a dominant contribution  $\rho(T) \sim T$  by the coupling of long-wavelength disorder to a gauge-invariant operator, which can be computed by applying memory functions to the quantum field theory, and by holography.

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- Proposed theory of linear- $T$  resistivity in strange metals involving a Higgs transition in a  $SU(2)$  gauge theory of Fermi surface reconstruction.