Quantum matter without quasiparticles

50 years of science for the future

ICTP 50th Anniversary,
Trieste, Italy, October 9, 2014

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

NSF

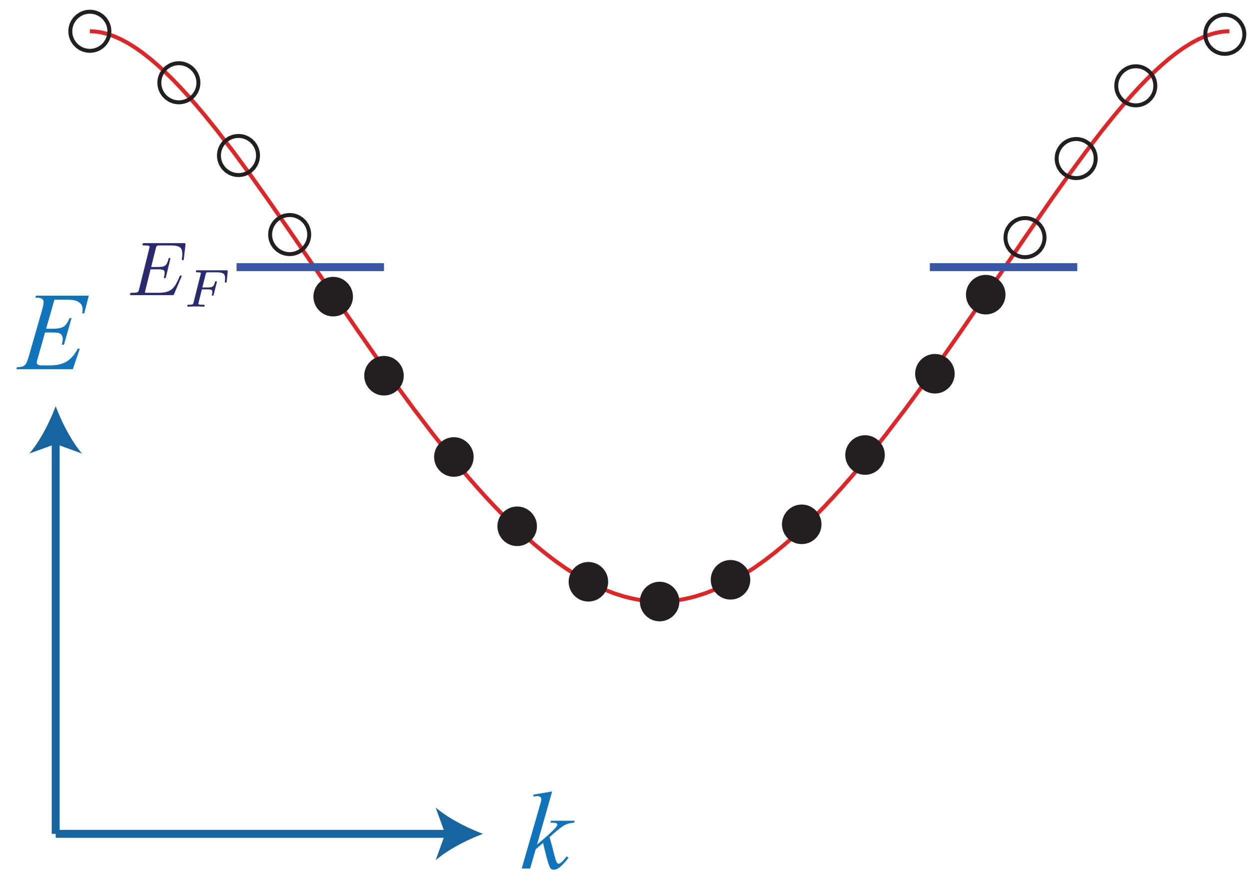
JOHN TEMPLETON FOUNDATION

PHYSICS
VE RI TAS
HARVARD

Foundations of quantum many body theory:

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

<u>Metals</u>

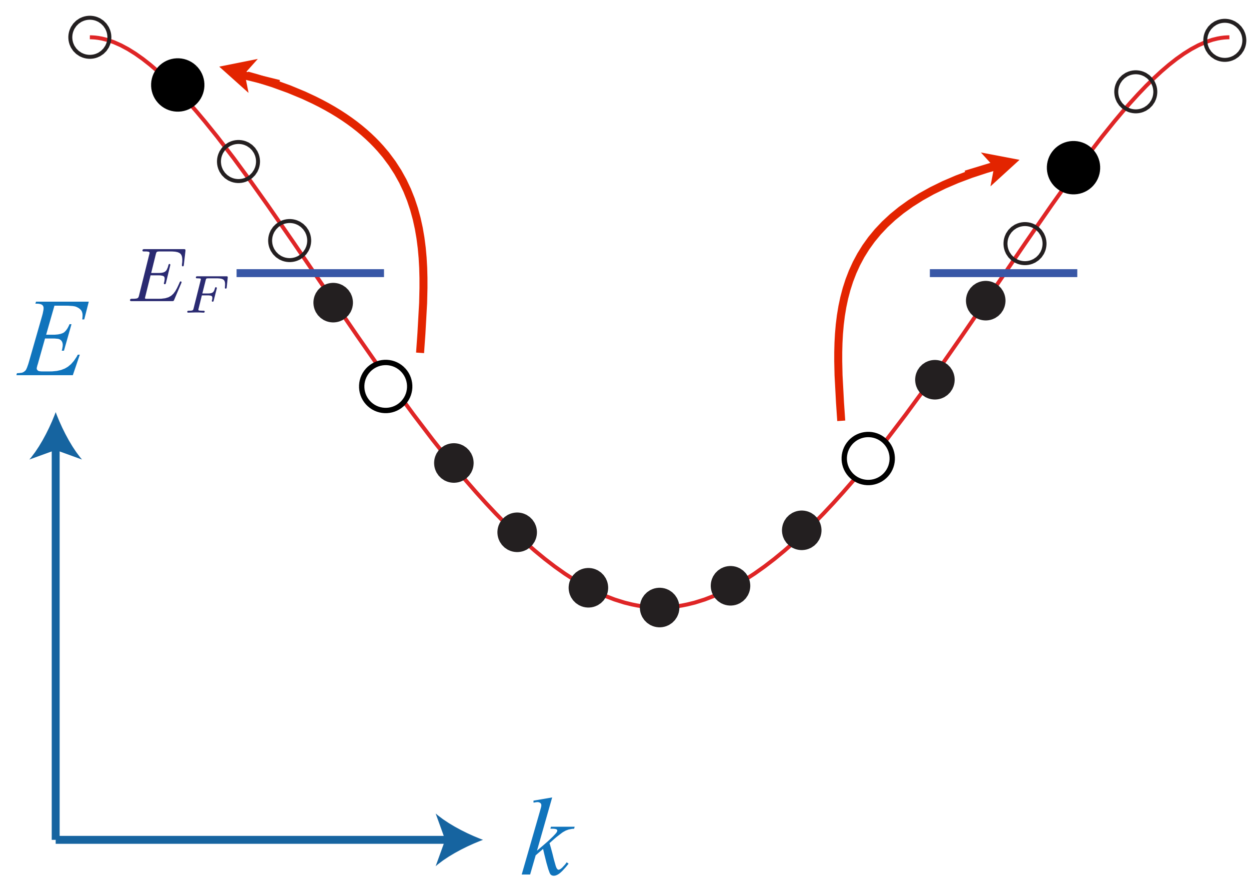


Foundations of quantum many body theory:

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 example:

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. *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

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

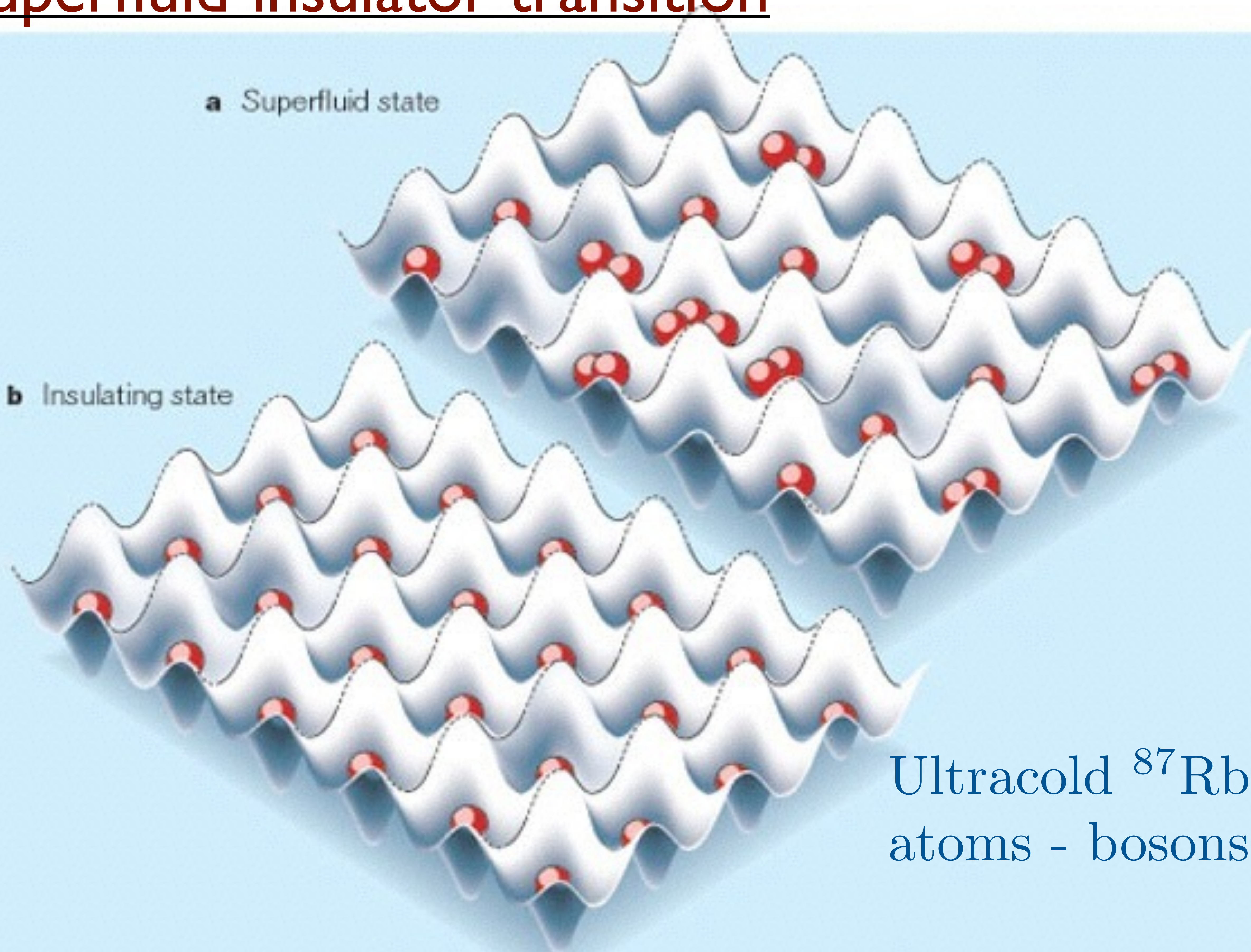
   B. Field theories and memory functions

Emanuel Katz
Boston University

William Witczak-Krempa
Perimeter

Erik Sorensen
McMaster

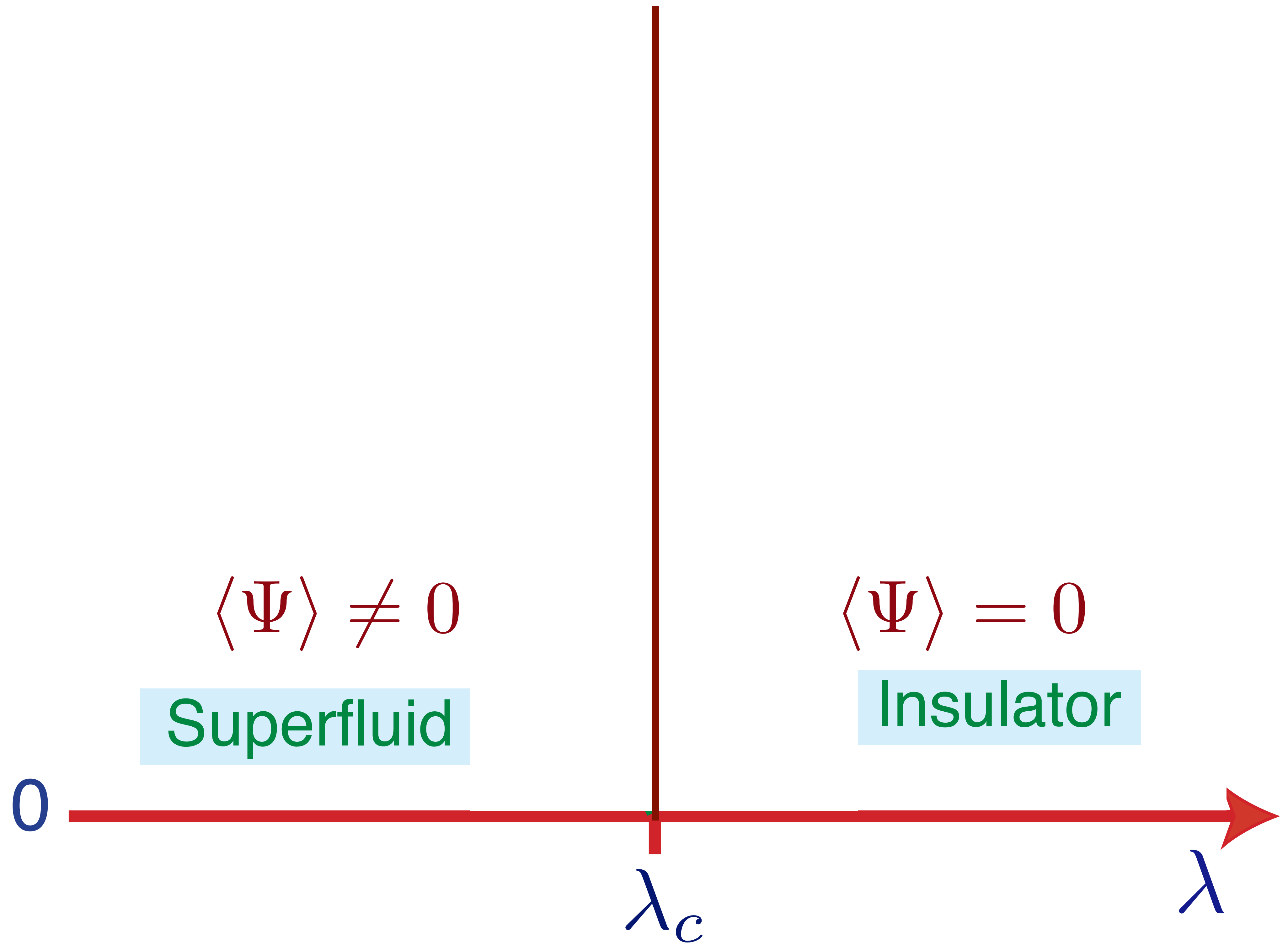
Superfluid-insulator transition



Ultracold ^{87}Rb atoms - bosons

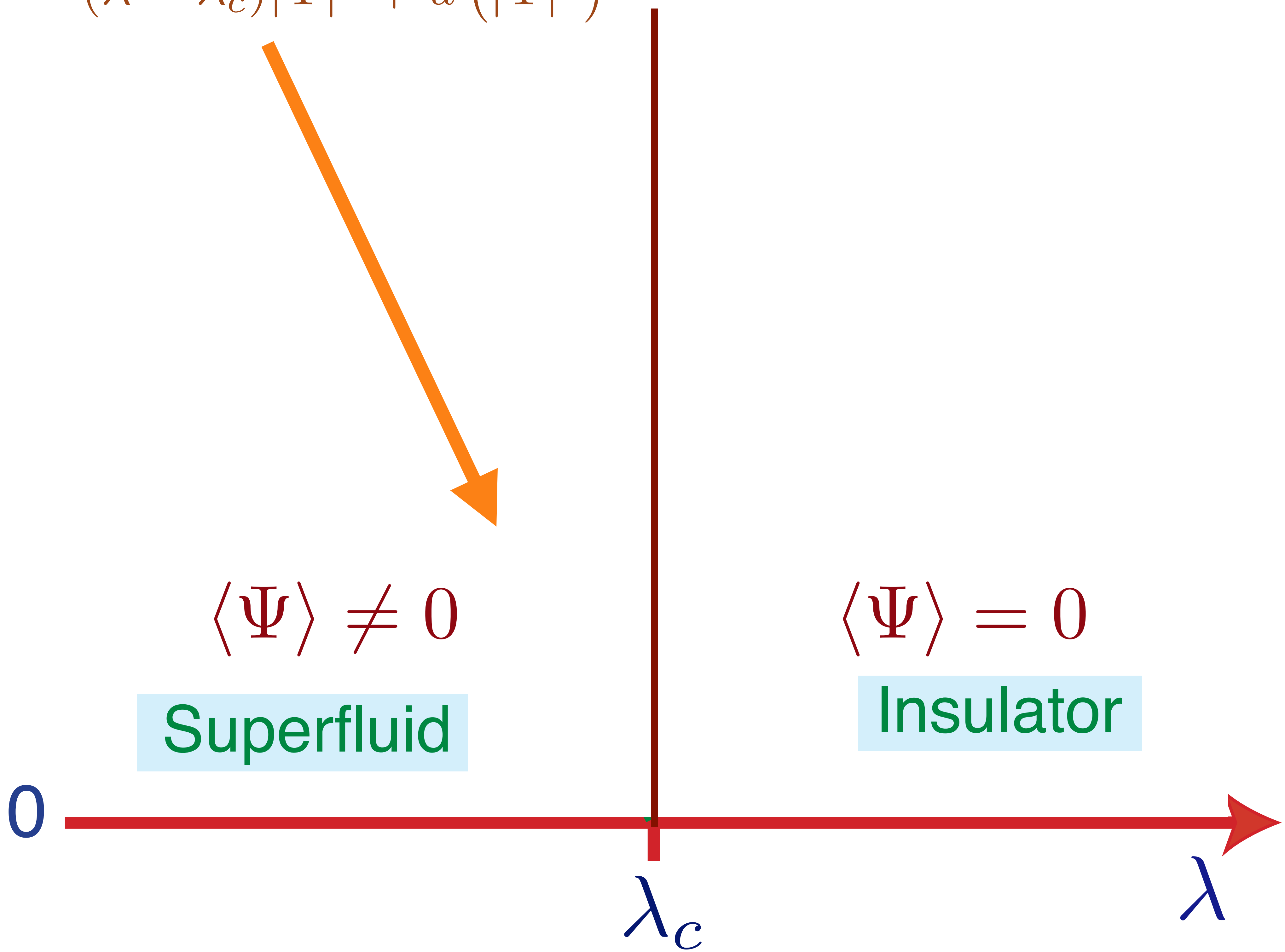
M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, *Nature* **415**, 39 (2002).

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



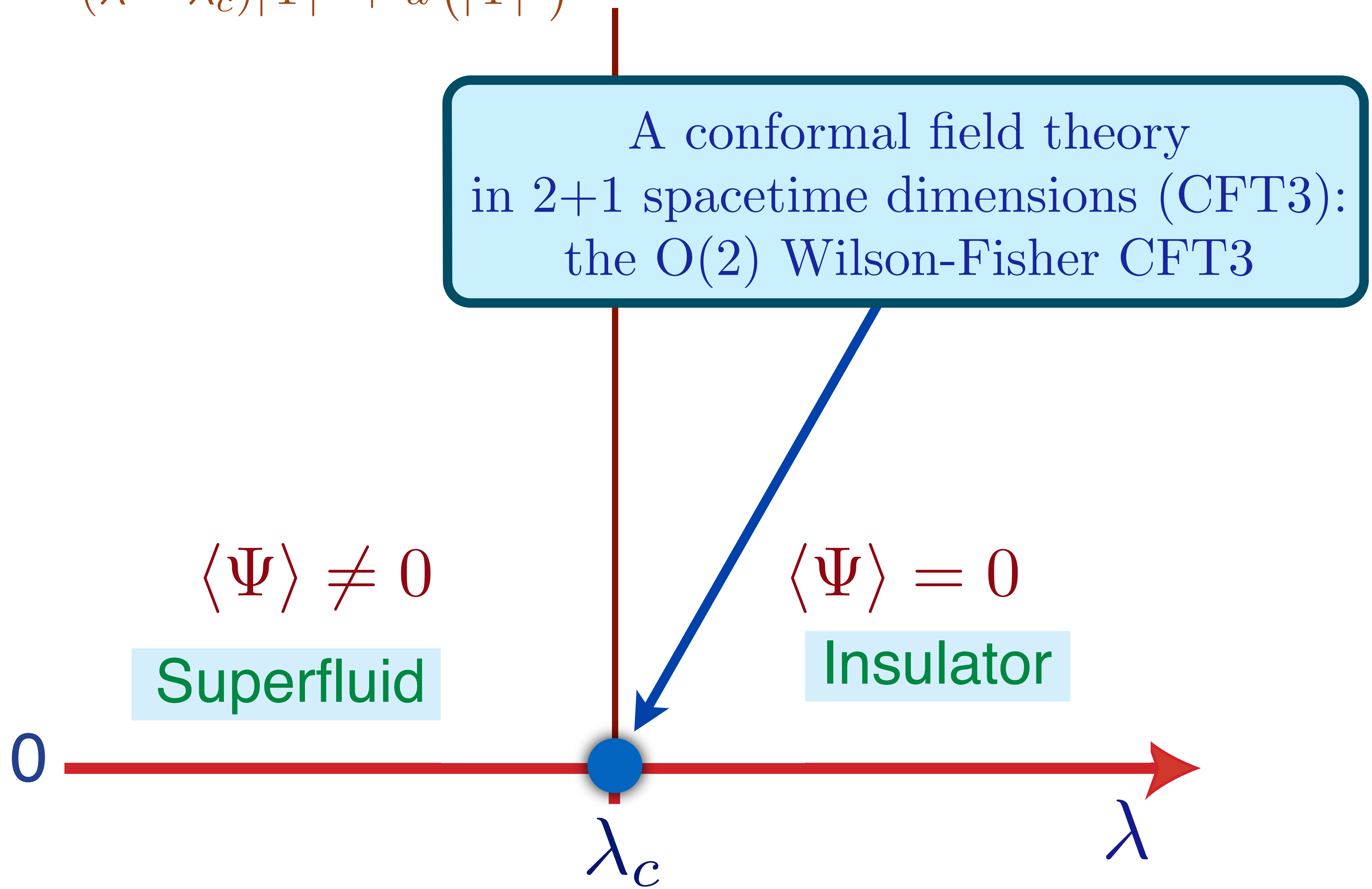
$$\mathcal{Z} = \int \mathcal{D}\Psi(r,\tau) \exp\left(- \int d^2r d\tau \left[|\partial_\tau \Psi|^2 + c^2 |\nabla_r \Psi|^2 + V(\Psi) \right] \right)$$

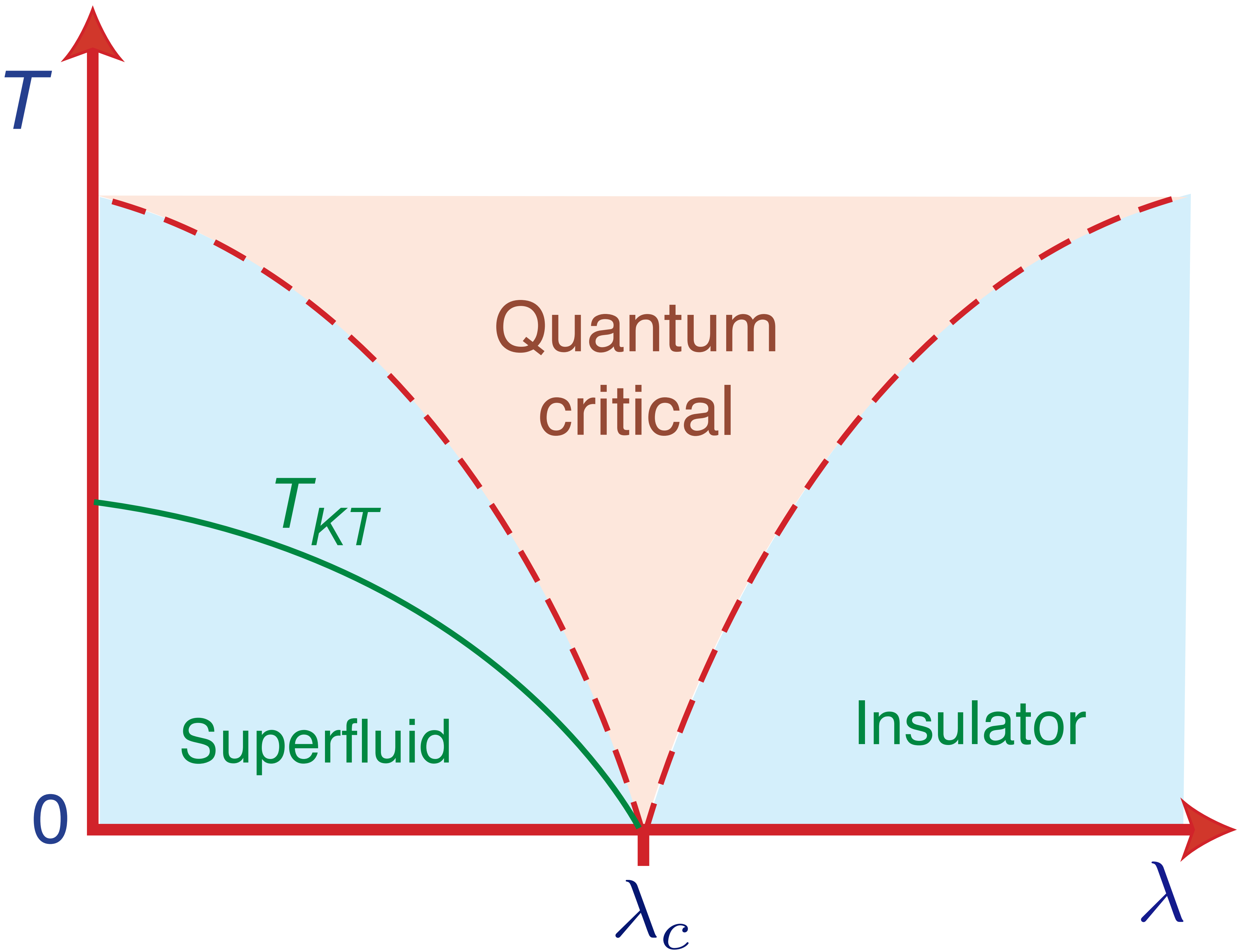
$$V(\Psi) = (\lambda - \lambda_c)|\Psi|^2 + u\left(|\Psi|^2\right)^2$$



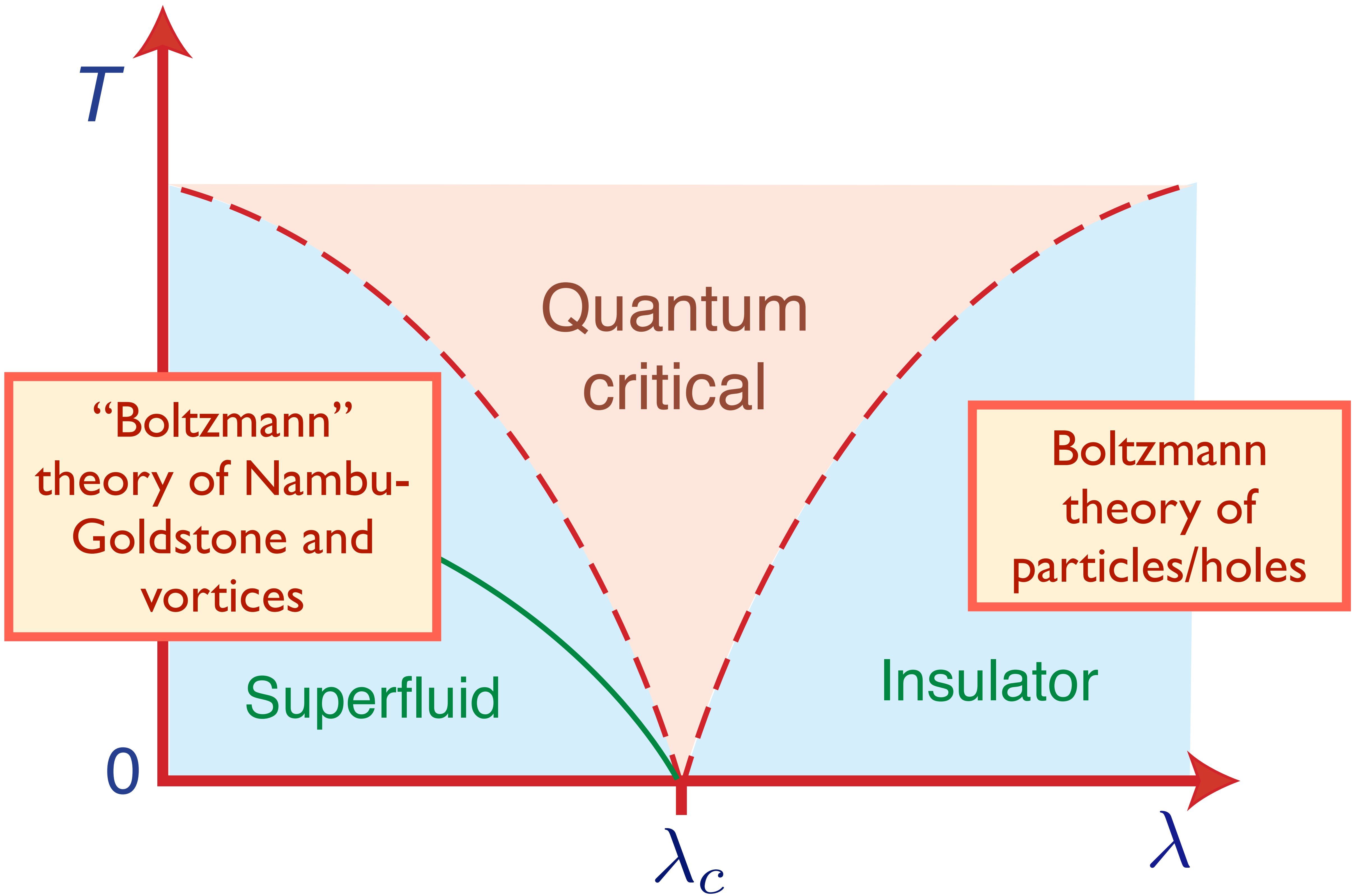
$$\mathcal{Z} = \int \mathcal{D}\Psi(r,\tau) \exp\left(- \int d^2 r d\tau \left[|\partial_\tau \Psi|^2 + c^2 |\nabla_r \Psi|^2 + V(\Psi) \right] \right)$$

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

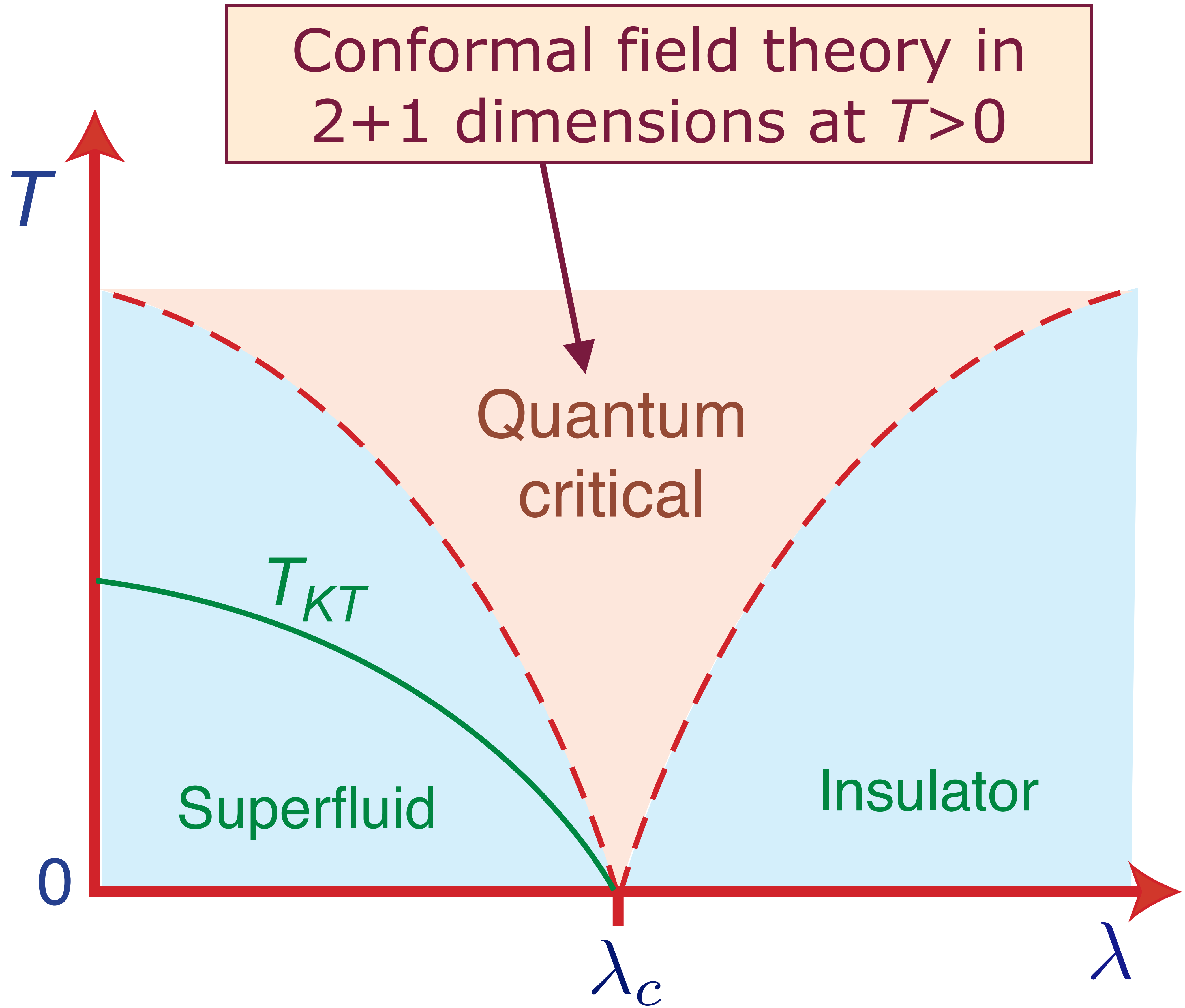




T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
λ



T
Quantum
critical
"Boltzmann"
theory of Nambu-
Goldstone and
vortices
Boltzmann
theory of
particles/holes
Superfluid
Insulator
0
λ_c
λ


Conformal field theory in
2+1 dimensions at $T>0$
T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
λ

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

Traditional CMT

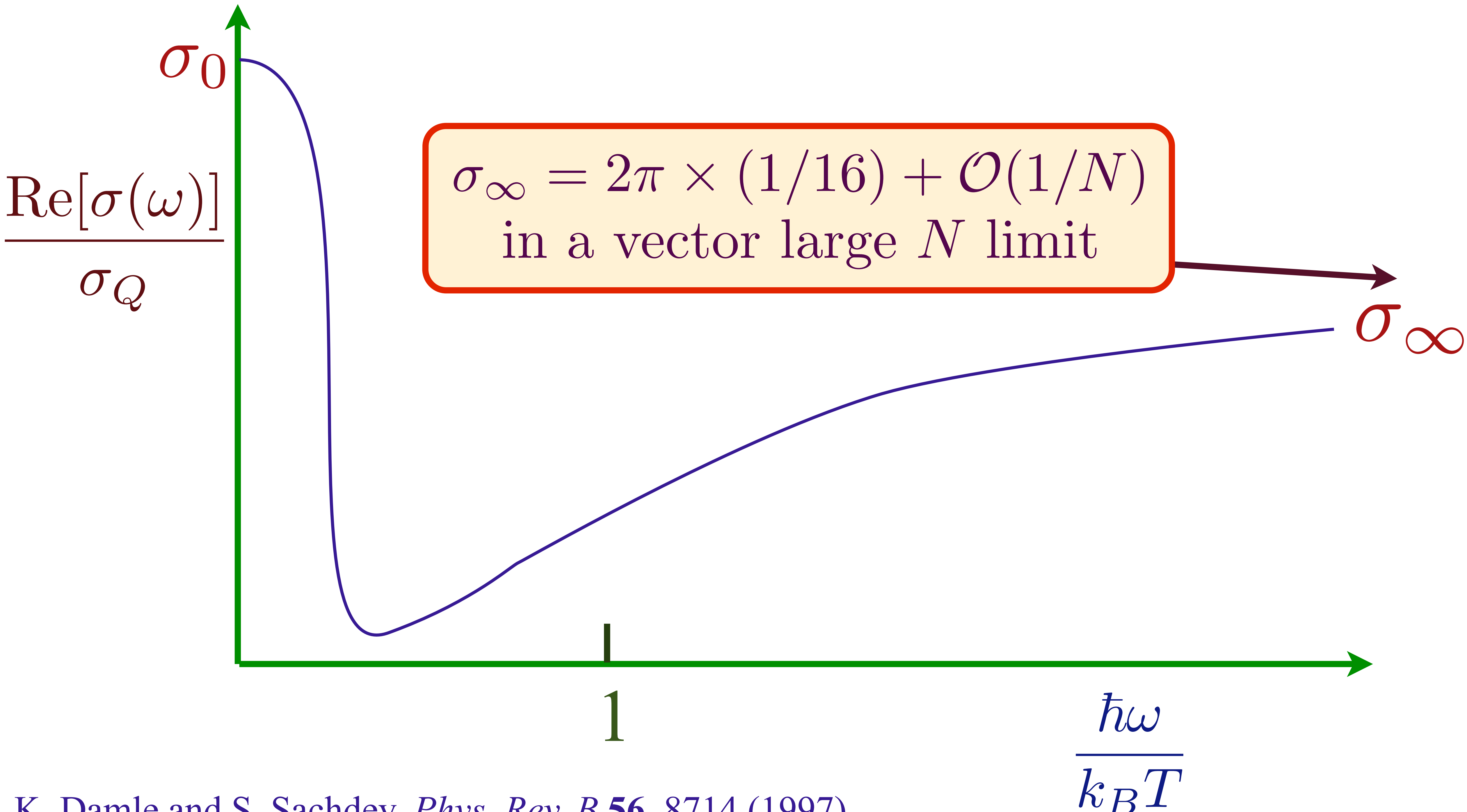
- ◊ Identify quasiparticles and their dispersions
- ◊ Compute scattering matrix elements of quasiparticles

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

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

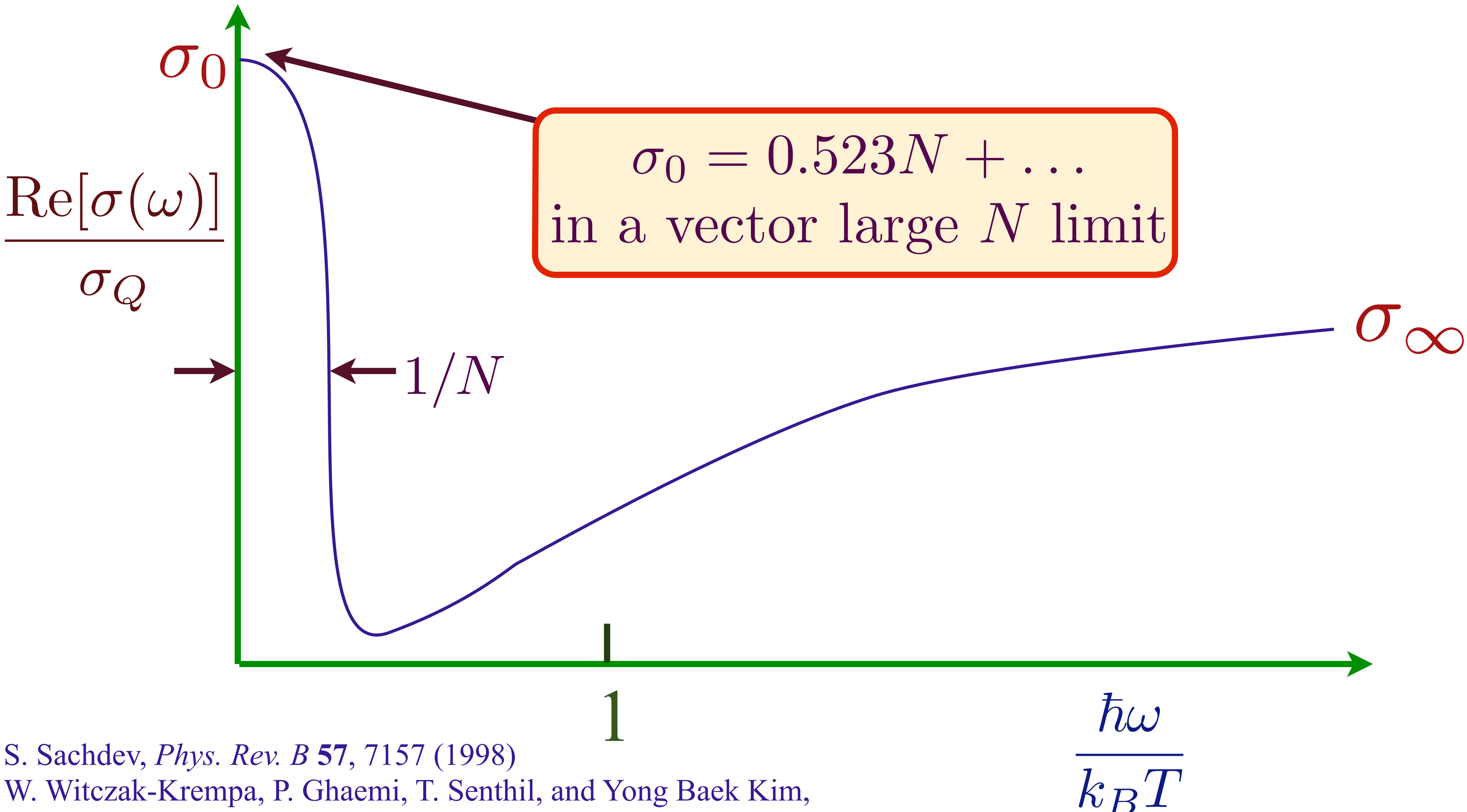
$\sigma_Q = e^2/h$, the quantum unit of conductance



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

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



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)

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. Holographic model

   B. Field theories and memory functions

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 $\hbar\omega \gg k_B T$

Basic characteristics of CFT3s

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

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

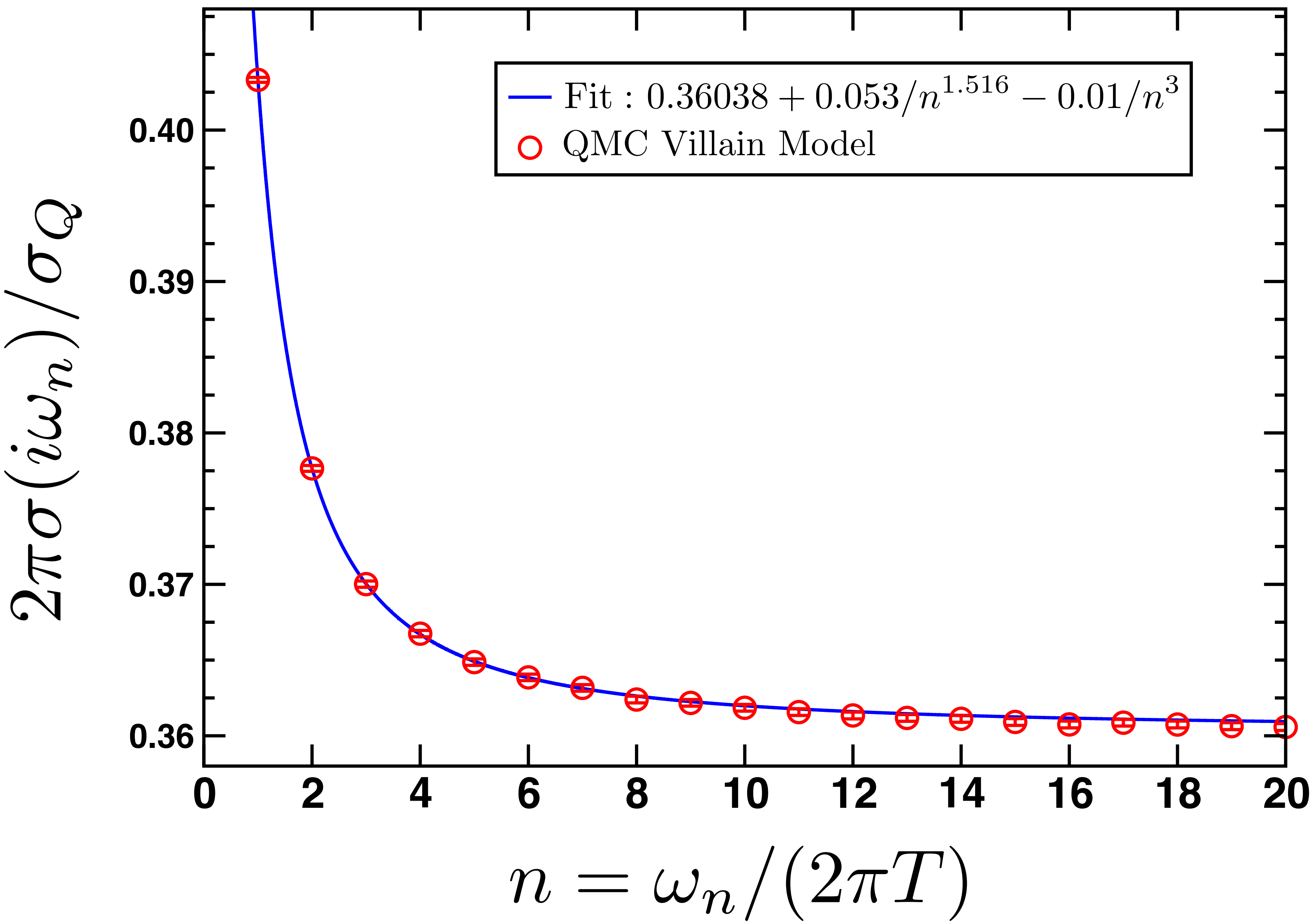
where $b_{1,2}$ are universal numbers dependent upon OPE coefficients.

- 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

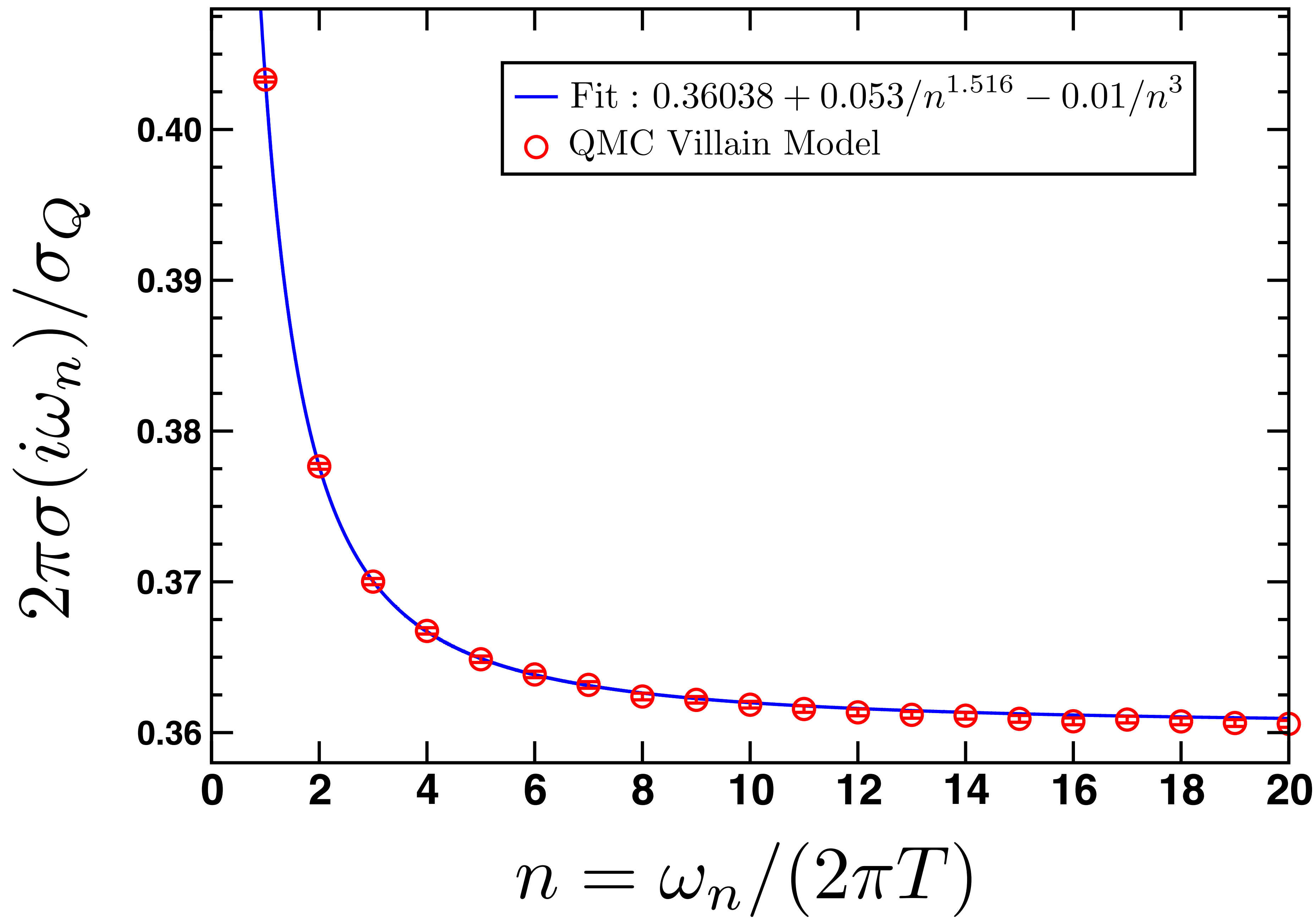
Quantum Monte Carlo for lattice model of integer currents (Villain model) in Euclidean time



Excellent agreement with OPE

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

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



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

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

Traditional CMT

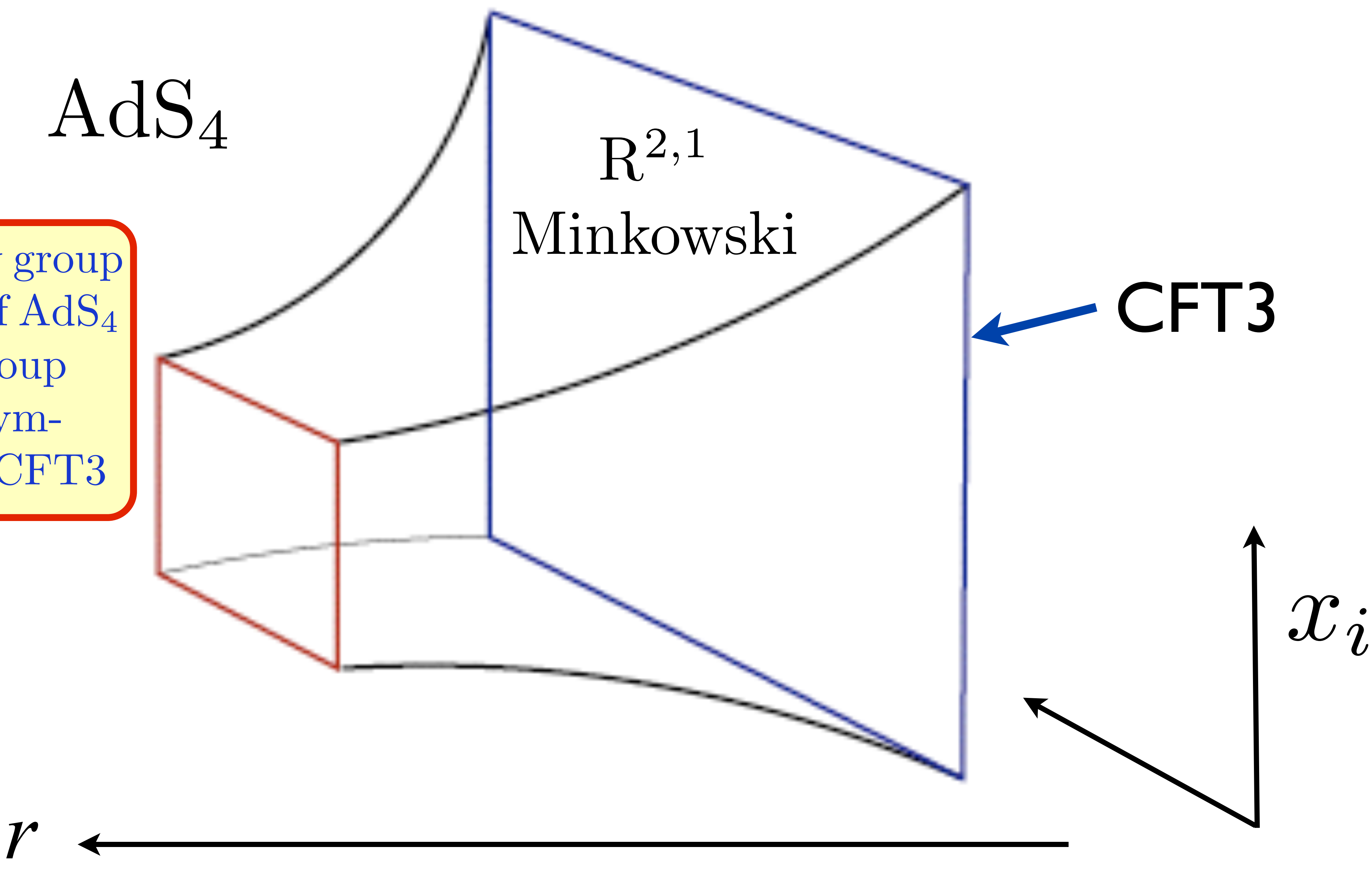
- ♢ Identify quasiparticles and their dispersions
- ♢ Compute scattering matrix elements of quasiparticles
- ♢ Input parameters into a quantum Boltzmann equation
- ♢ Compute dissipative properties at $\omega \ll$ quasiparticle-collision-rate

Dynamics without quasiparticles

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

Traditional CMT	Dynamics without quasiparticles
◇ Identify quasiparticles and their dispersions	★ Start with strongly interacting CFT without quasiparticles
◇ Compute scattering matrix elements of quasiparticles	★ Using scaling dimensions and operator product expansions (OPE) of the CFT, compute conductivity at $\hbar\omega \gg k_B T$
◇ Input parameters into a quantum Boltzmann equation	★ Relate OPE coefficients to couplings of an effective gravitational theory on AdS
◇ Compute dissipative properties at $\omega \ll$ quasiparticle-collision-rate	

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

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

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

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

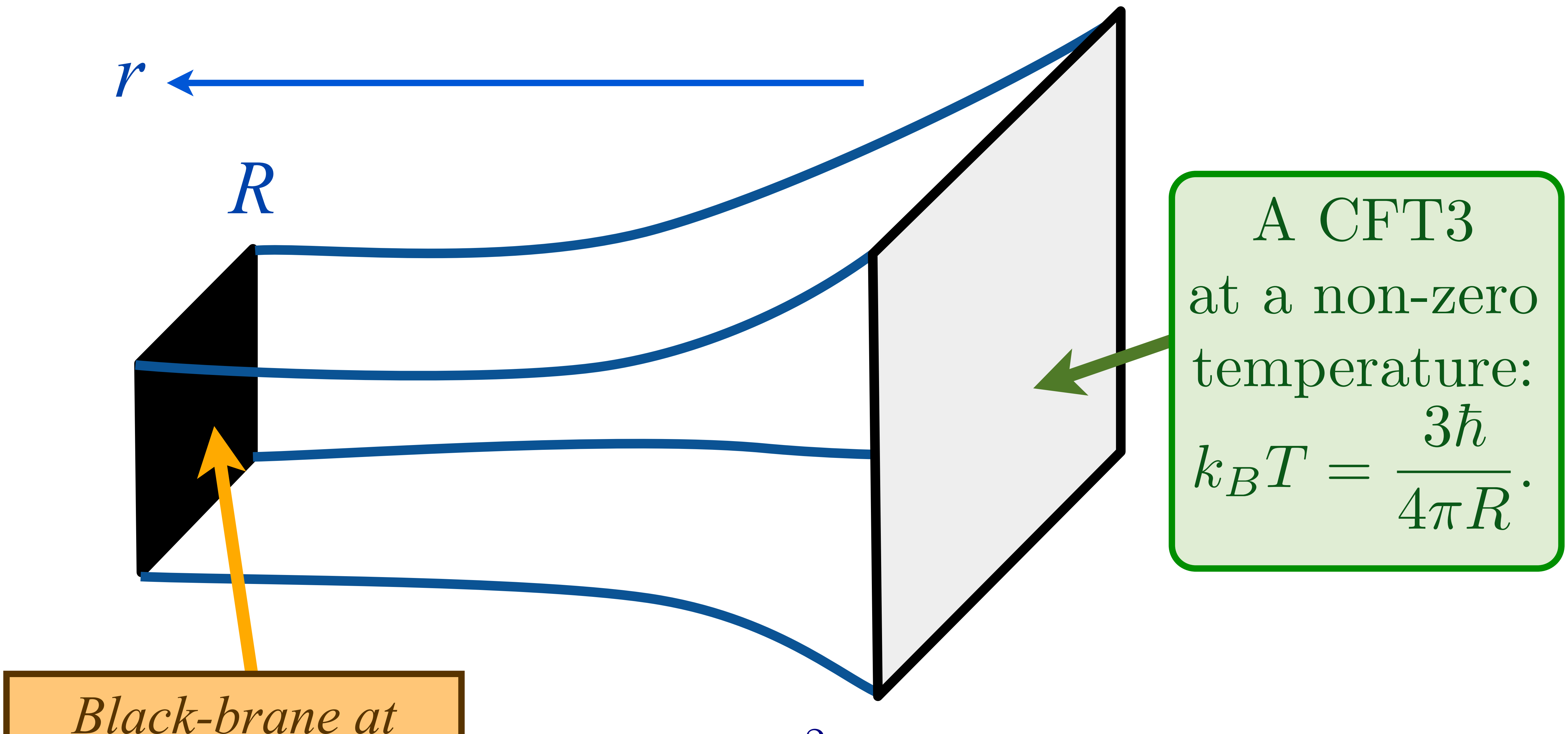
★ Using scaling dimensions and operator product expansions (OPE) of the CFT, compute conductivity at $\hbar\omega \gg k_B T$

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

Traditional CMT	Dynamics without quasiparticles
◇ Identify quasiparticles and their dispersions	★ Start with strongly interacting CFT without quasiparticles
◇ Compute scattering matrix elements of quasiparticles	★ Using scaling dimensions and operator product expansions (OPE) of the CFT, compute conductivity at $\hbar\omega \gg k_B T$
◇ Input parameters into a quantum Boltzmann equation	★ Relate OPE coefficients to couplings of an effective gravitational theory on AdS
◇ Compute dissipative properties at $\omega \ll$ quasiparticle-collision-rate	★ Dynamics of a "horizon" in gravitational theory yields info at $\hbar\omega \ll k_B T$.

AdS/CFT correspondence at non-zero temperatures

AdS$_4$-Schwarzschild black-brane

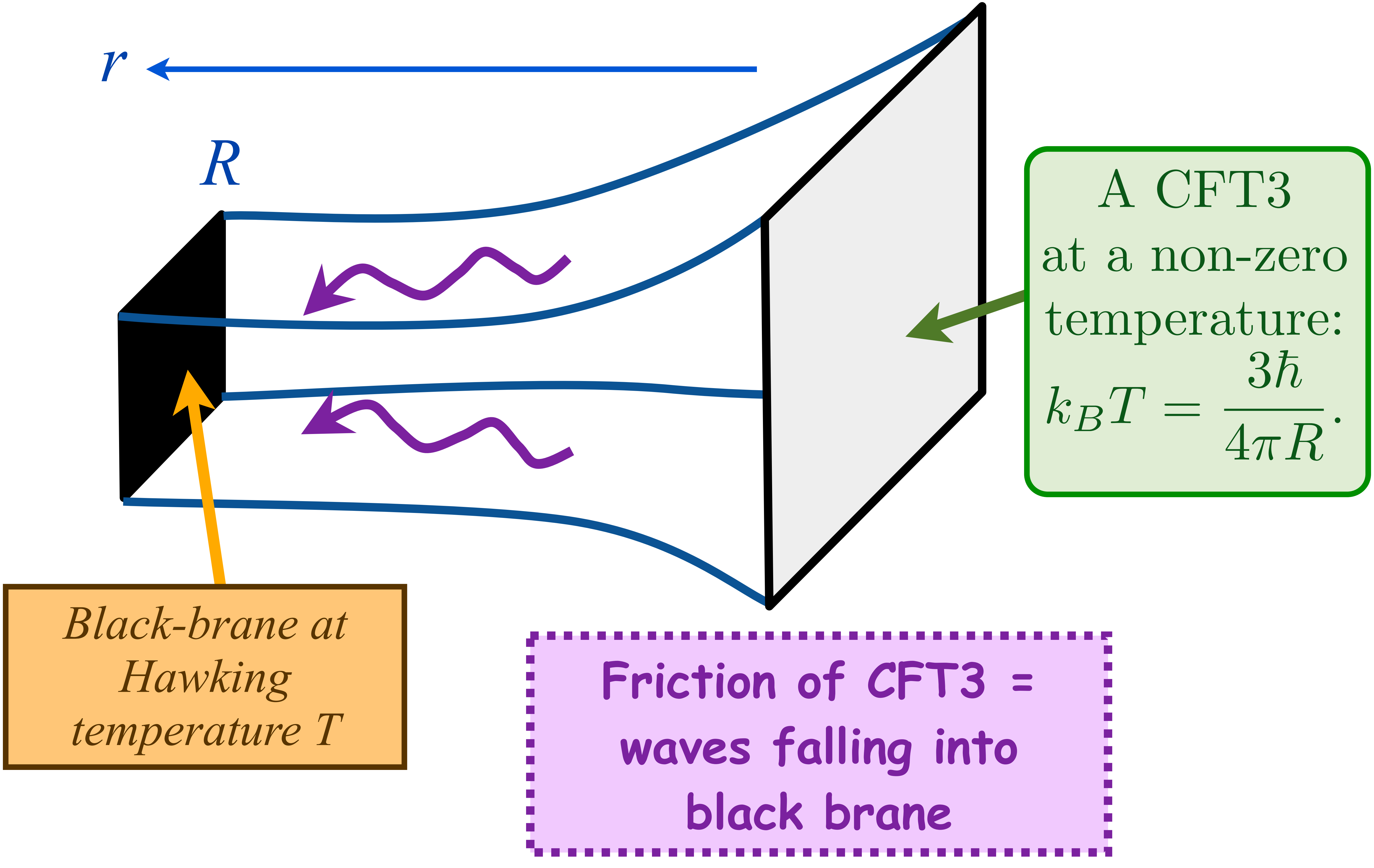


$$ds^2 = \left(\frac{L}{r}\right)^2 \left[\frac{dr^2}{f(r)} - f(r)dt^2 + dx^2 + dy^2\right]$$

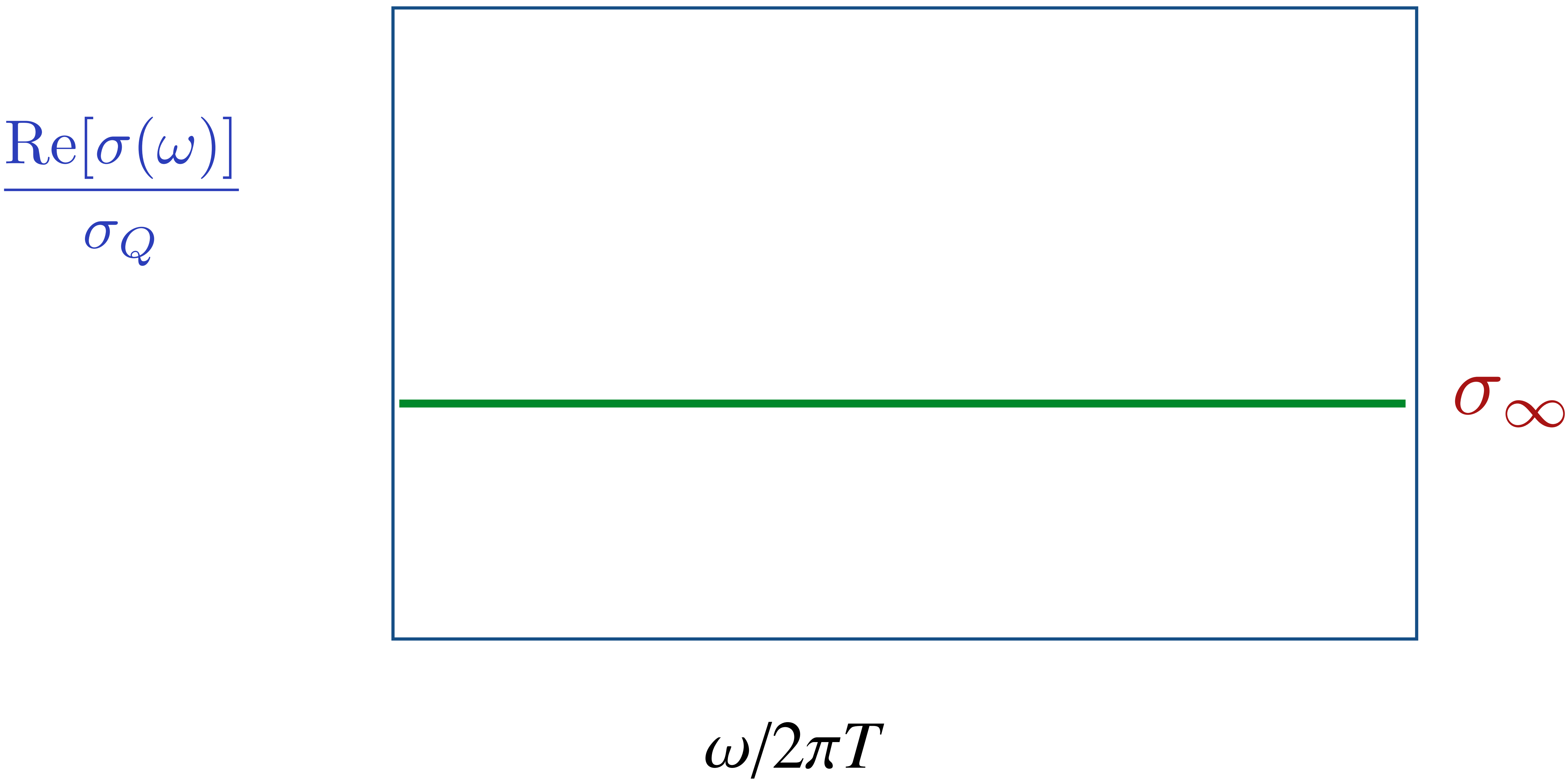
with $f(r) = 1 - (r/R)^3$

AdS/CFT correspondence at non-zero temperatures

AdS_4-Schwarzschild black-brane

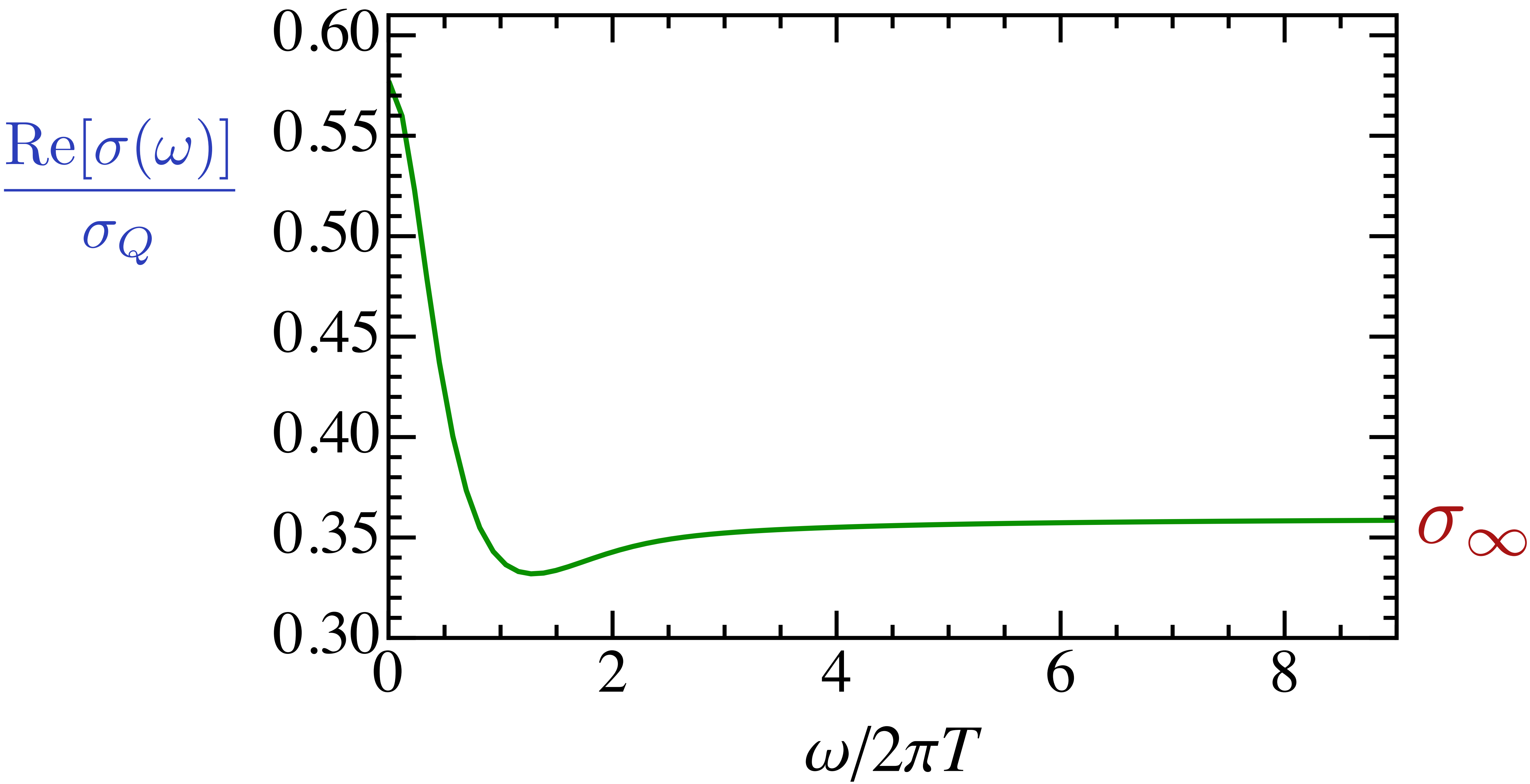


Conductivity of Einstein-Maxwell theory



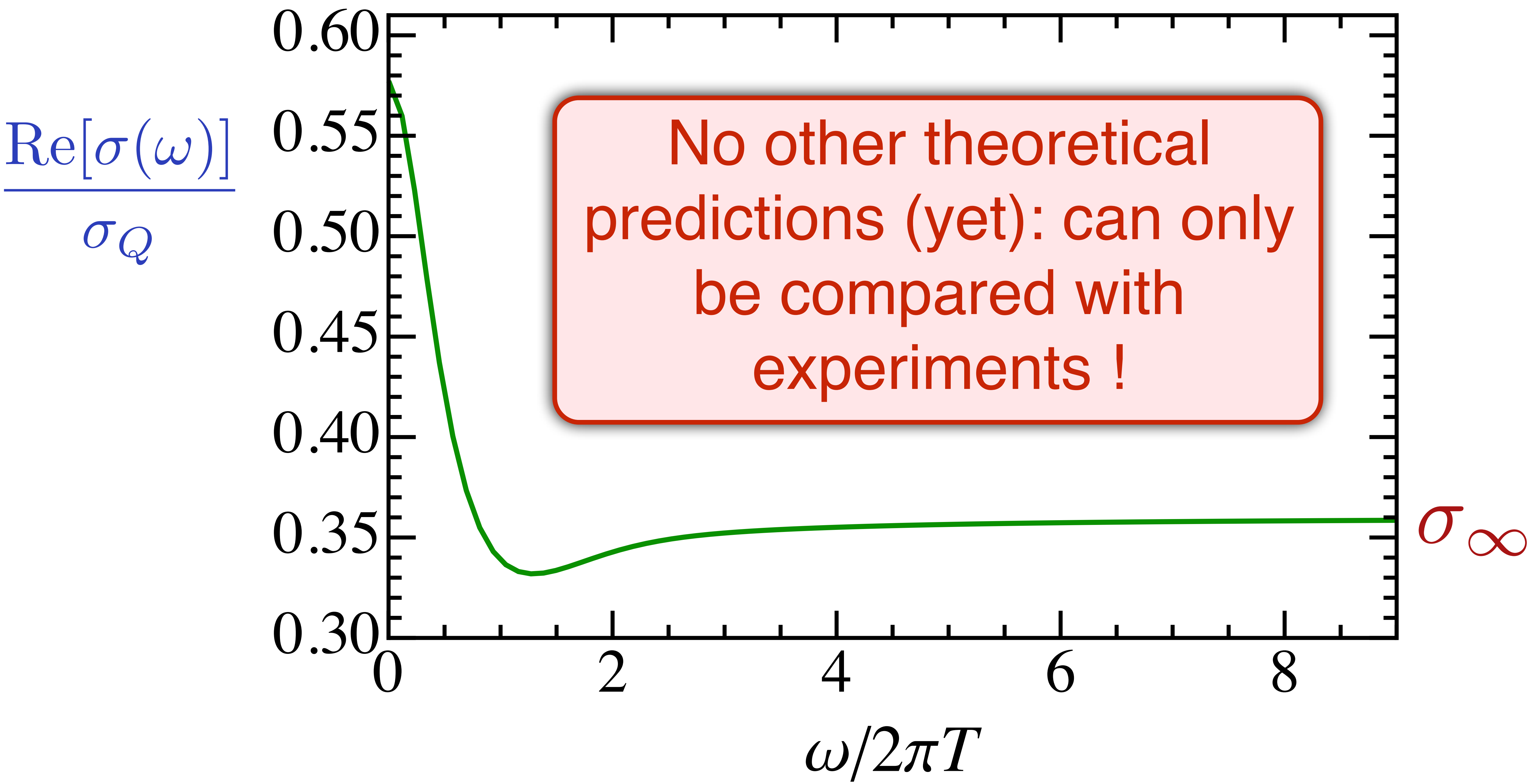
C. P. Herzog, P. Kovtun. S. Sachdev, and D. T. Son, Physical Review D **75**, 085020 (2007)

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



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

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



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

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

Outline

1. Conformal field theories in 2+1 dimensions

Superfluid-insulator transition

A. Boltzmann dynamics

B. Conformal / holographic dynamics

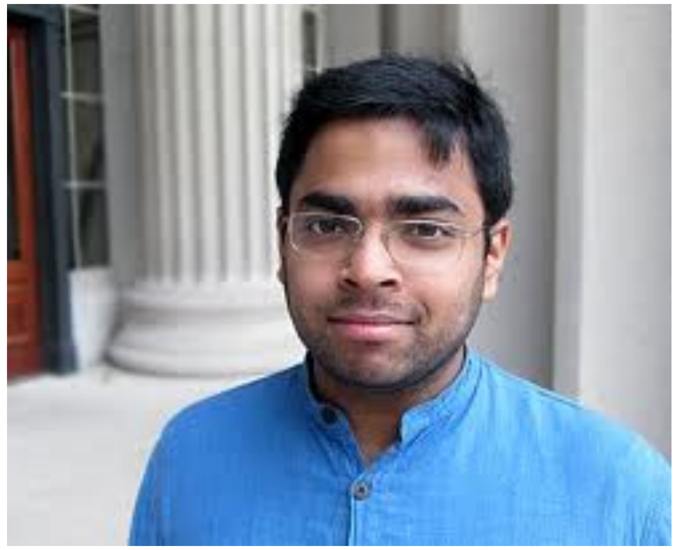
2. Non-Fermi liquid in 2+1 dimensions

Strange metal in the high temperature superconductors

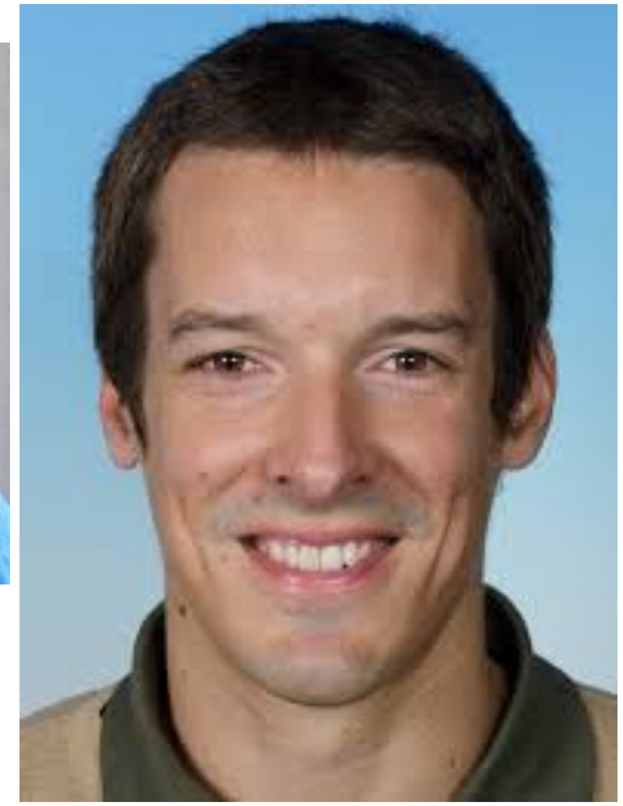
A. Lessons from holography

B. Field theories and memory functions

Sean Hartnoll
Stanford



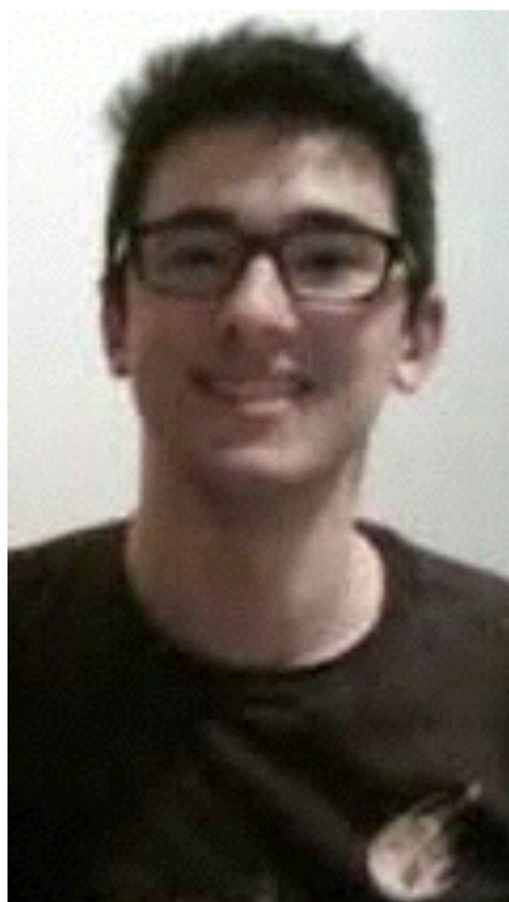
Raghu Mahajan
Stanford



Matthias Punk
Innsbruck

Andrea Allais

Koenraad Schalm
Leiden



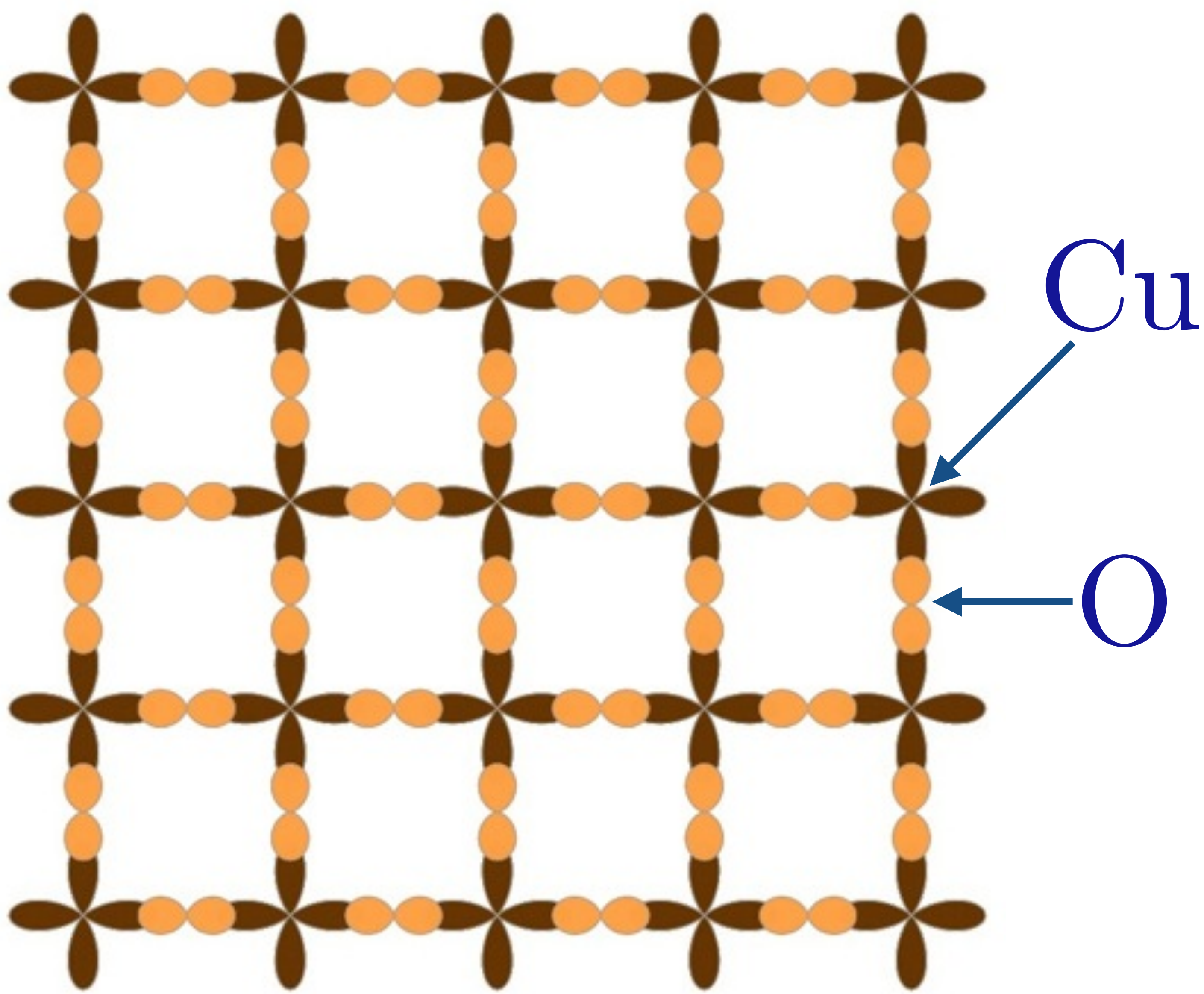
Andrew Lucas

Aavishkar Patel

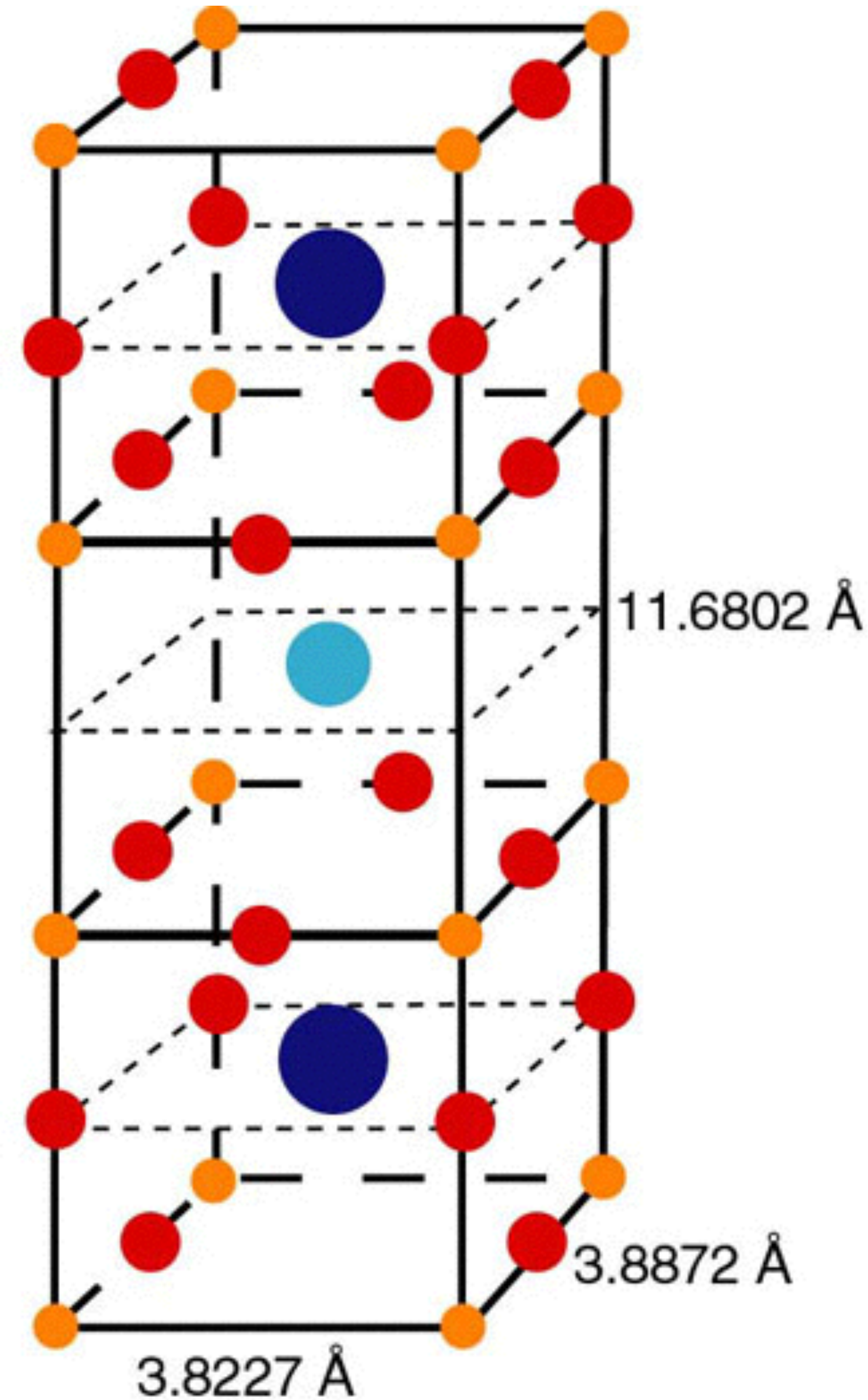
Debanjan
Chowdhury

Alexandra
Thomson

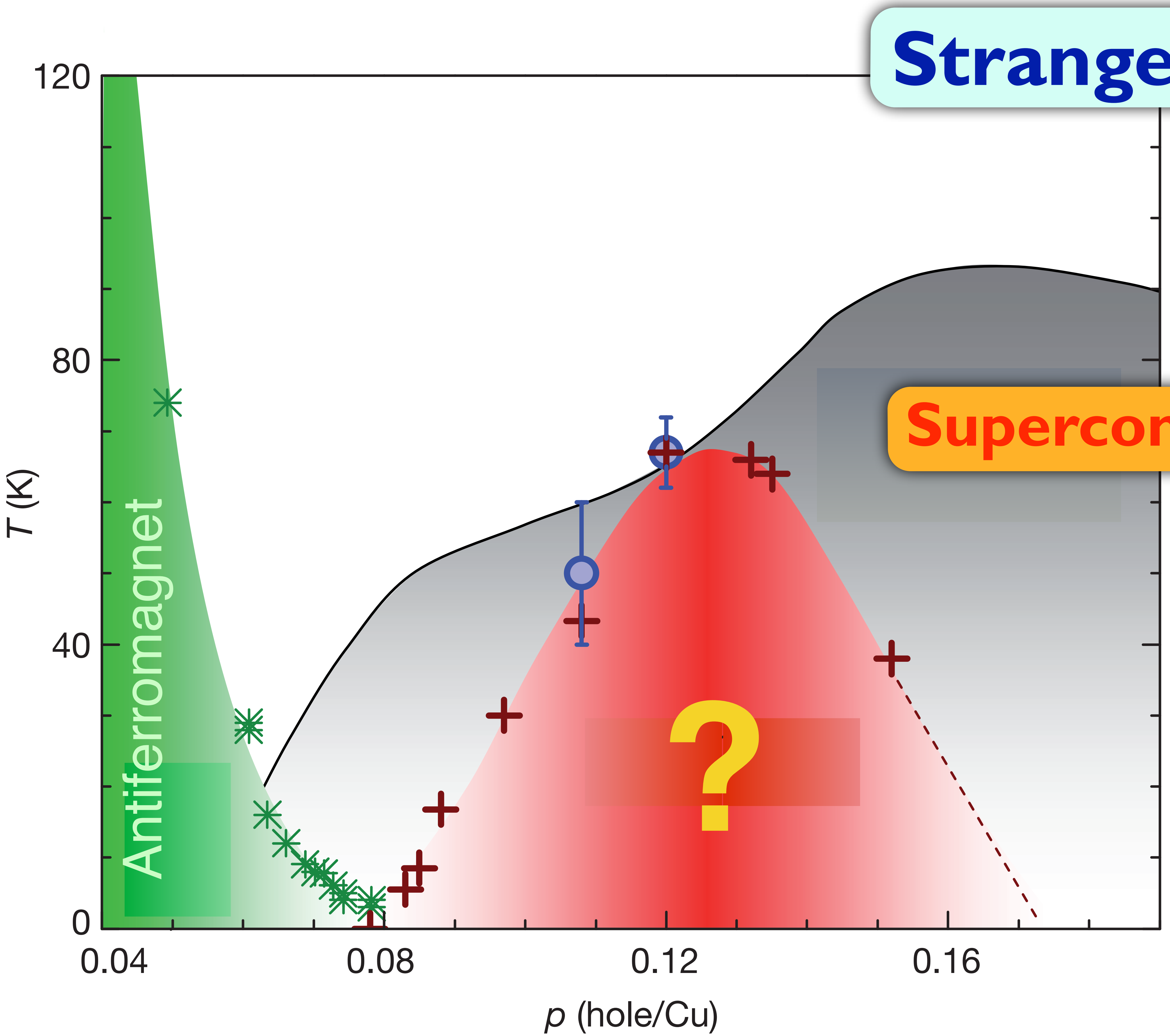
High temperature superconductors

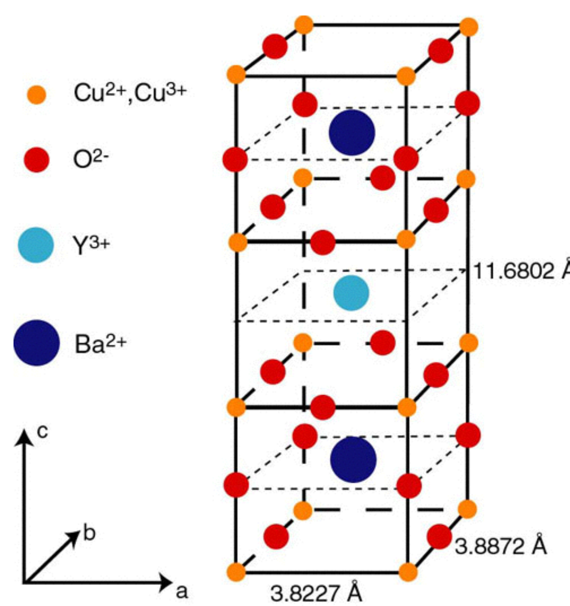


CuO_2 plane



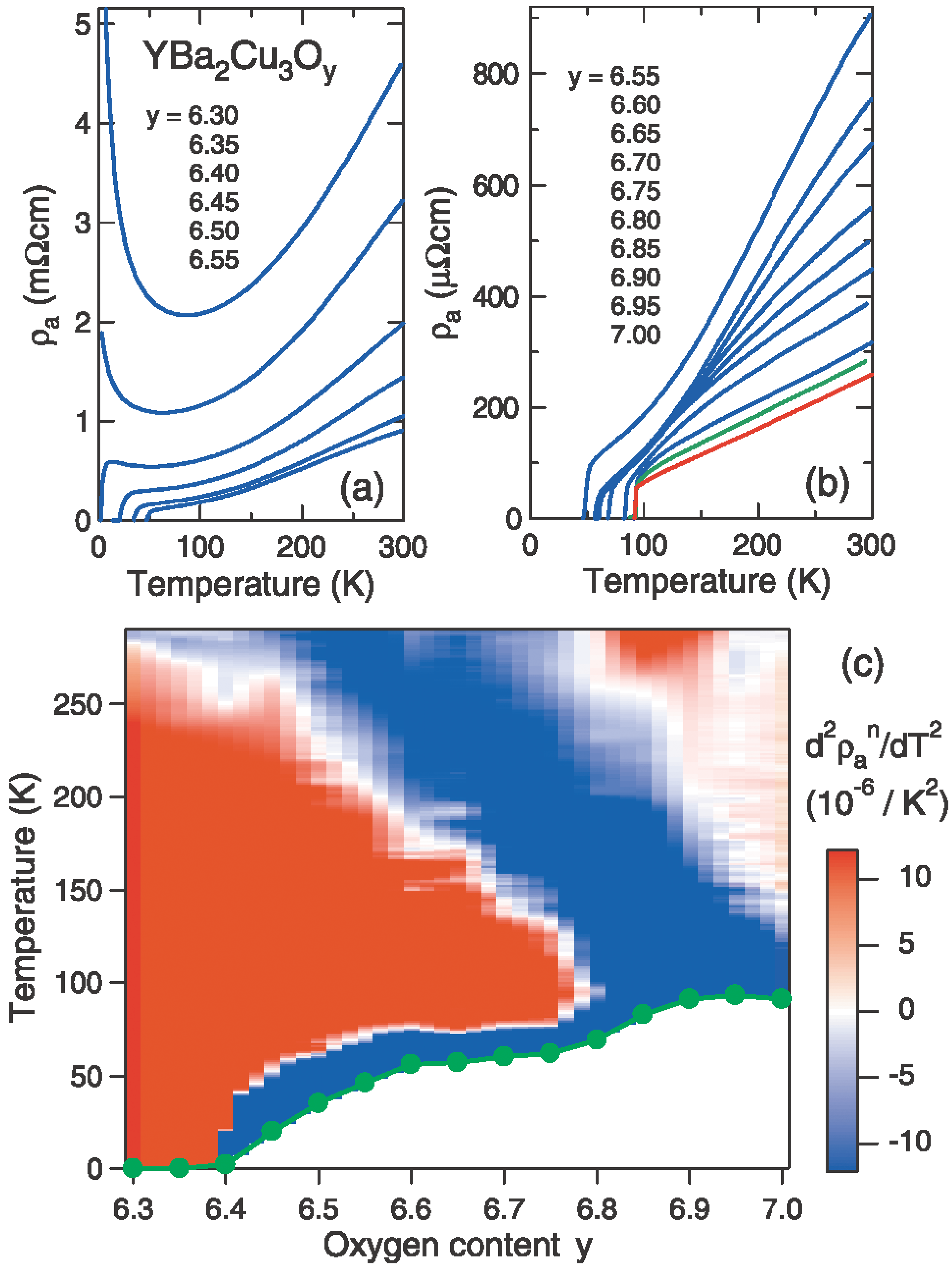
$YBa_2Cu_3O_{6+x}$





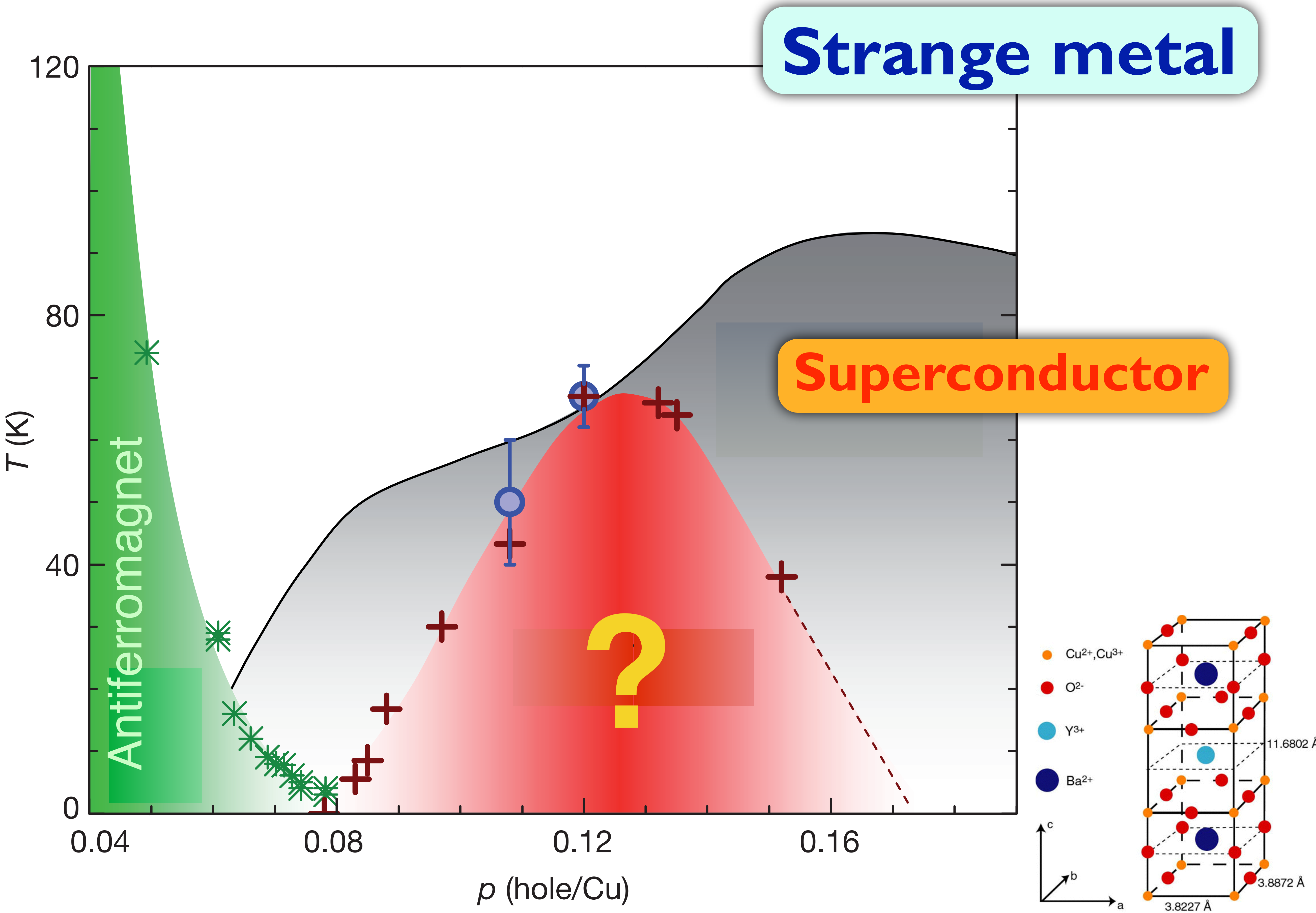
T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).

Strange metal

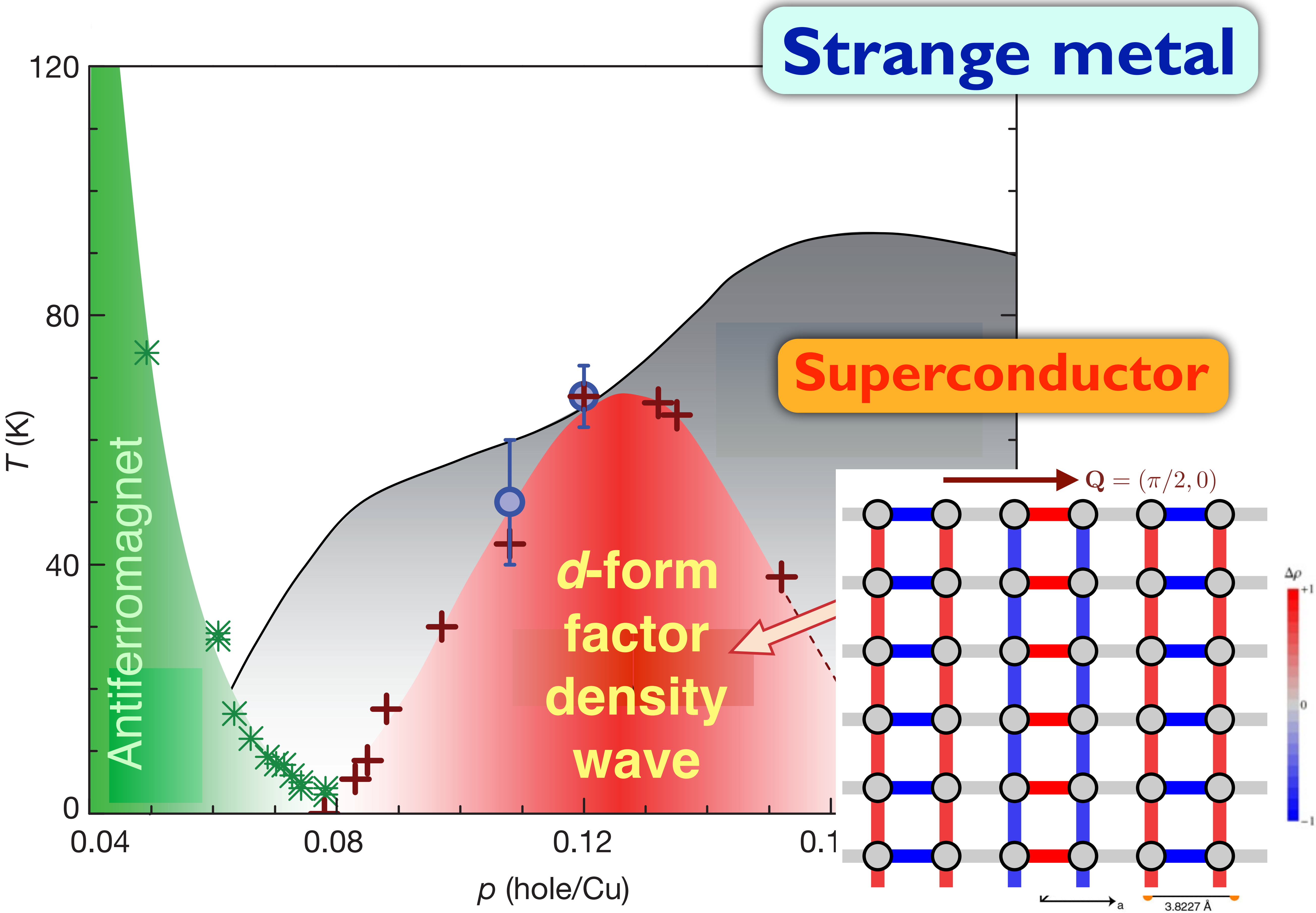


YBCO at optimal doping has resistivity $\rho(T) \sim T$.

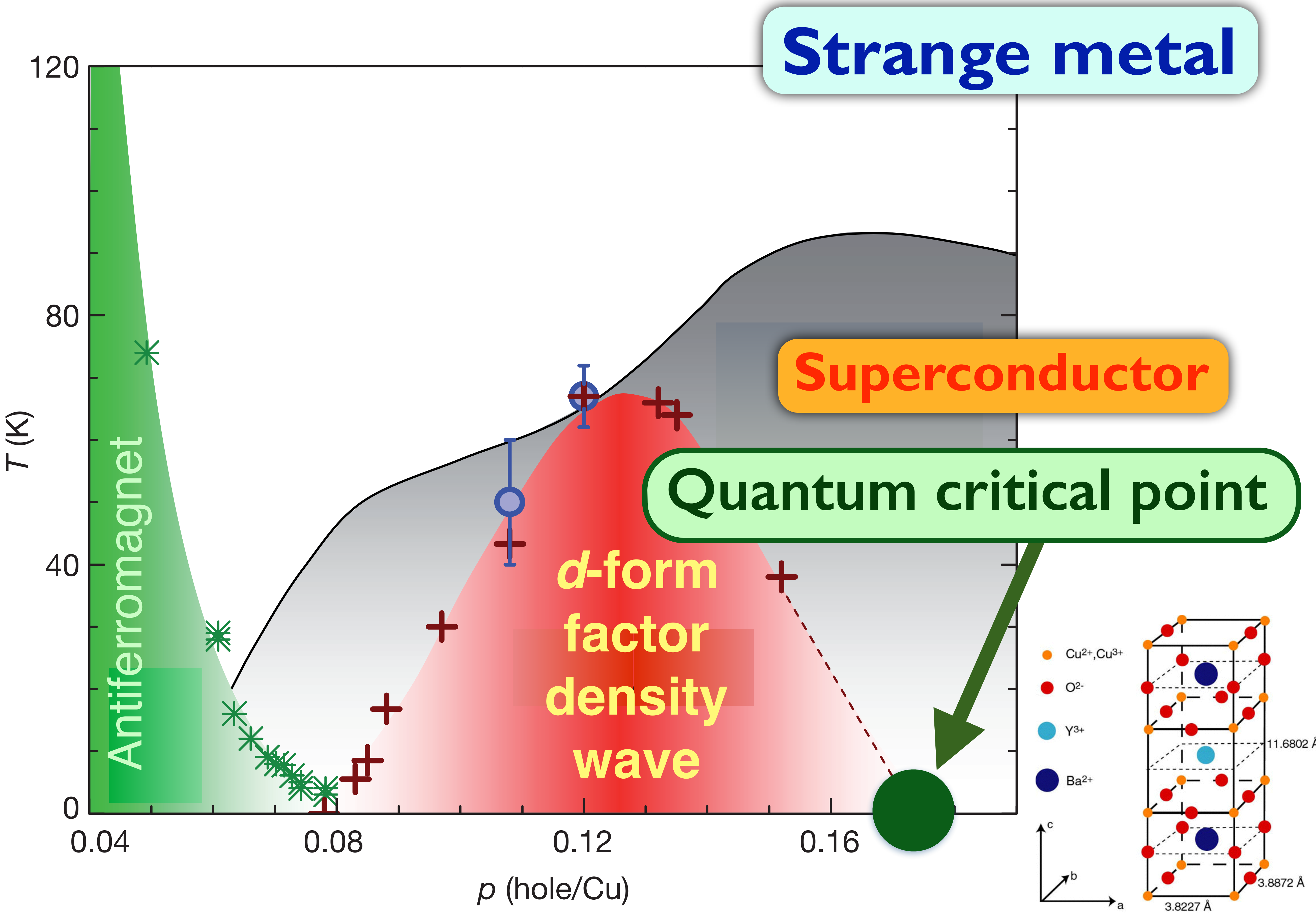
Yoichi Ando, Seiki Komiya, Kouji Segawa, S. Ono, and Y. Kurita, Phys. Rev. Lett. **93**, 267001 (2004)



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).



K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)



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

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

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

SU(2) gauge theory for underlying quantum critical point

Assume field R is non-critical.

- Fermion ψ, transforming as a gauge SU(2) fundamental, with dispersion $\varepsilon_{\mathbf{k}}$ from the band structure, at a non-zero chemical potential: has a "large" Fermi surface.

- A SU(2) gauge boson.

- A real Higgs field, H, transforming as a gauge SU(2) adjoint, carrying lattice momentum (π, π). Condensation of the Higgs breaks SU(2) $\rightarrow$ U(1), and transforms the large Fermi surface to a small Fermi surface.

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

SU(2) gauge theory for underlying quantum critical point

- 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.

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

SU(2) gauge theory for underlying quantum critical point

- 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.

- The Higgs condensation does not give the fermions a "mass"; instead it reconstructs the Fermi surface from *large* to *small*.

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

SU(2) gauge theory for underlying quantum critical point

- 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.

- The Higgs condensation does not give the fermions a "mass"; instead it reconstructs the Fermi surface from *large* to *small*.

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

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

Outline

1. Conformal field theories in 2+1 dimensions

Superfluid-insulator transition

A. Boltzmann dynamics

B. Conformal / holographic dynamics

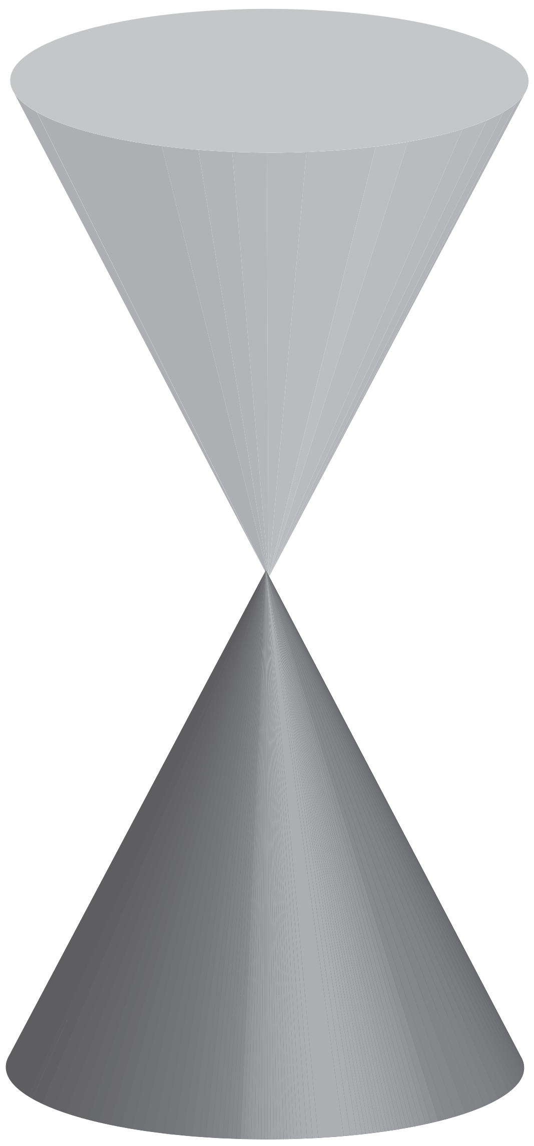
2. Non-Fermi liquid in 2+1 dimensions

Strange metal in the high temperature superconductors

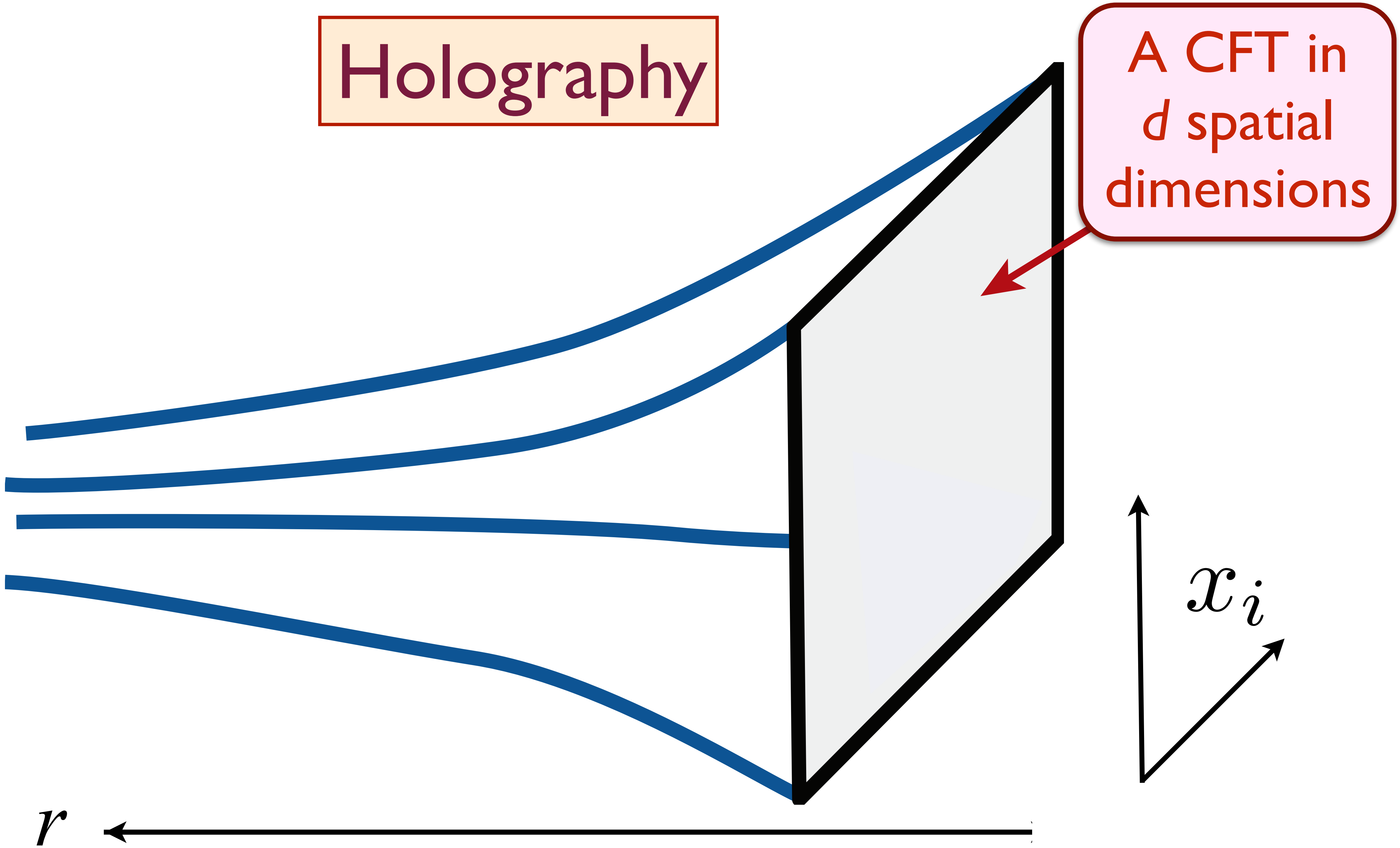
A. Lessons from holography

B. Field theories and memory functions

A CFT



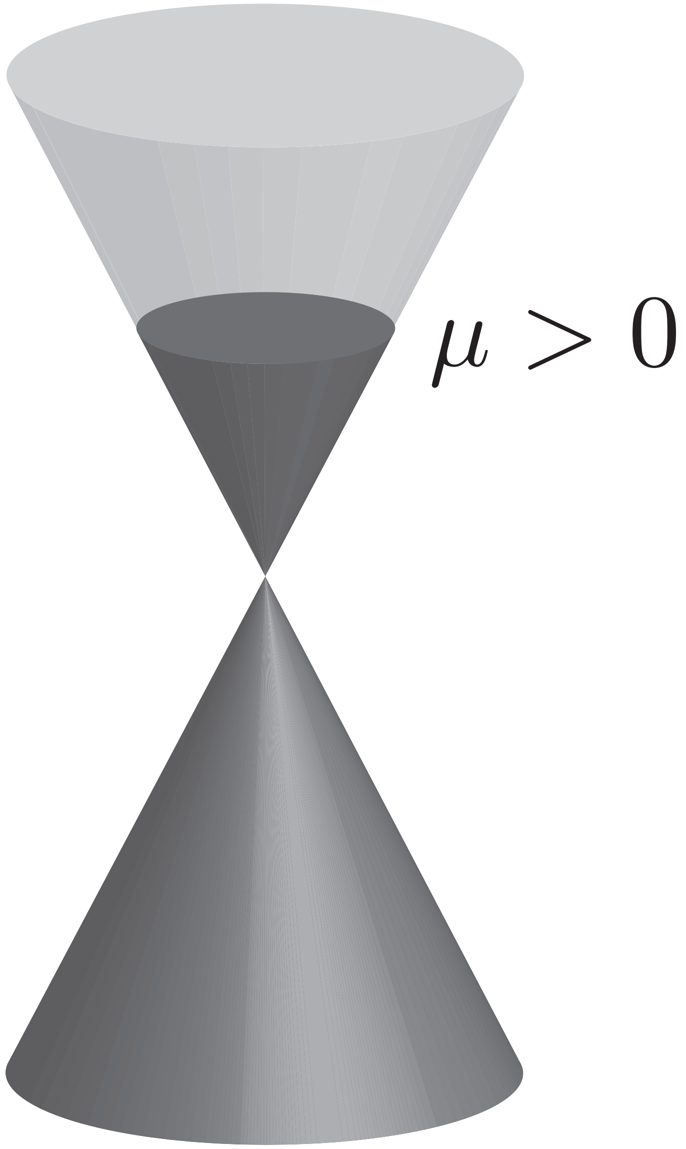
Holography



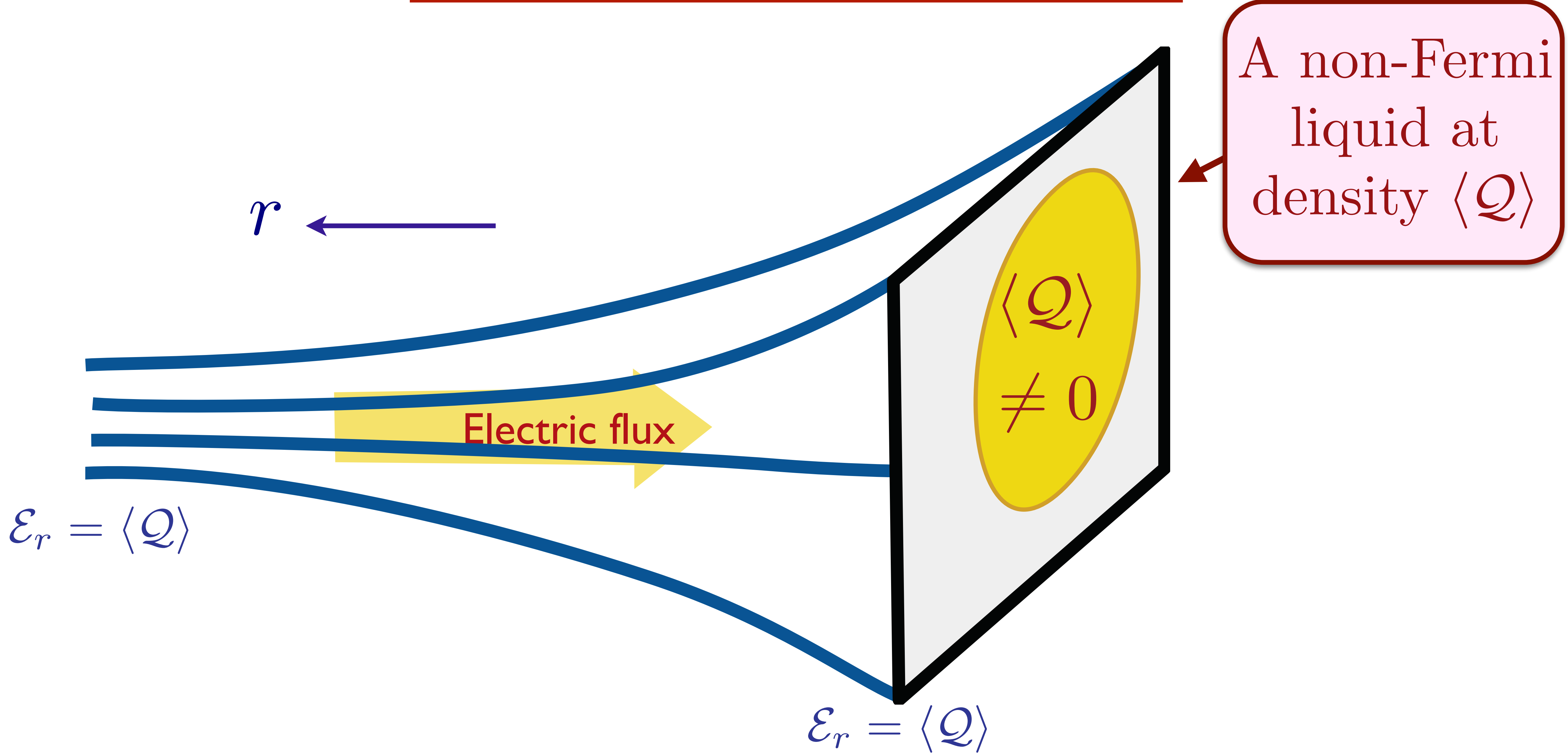
$$ds^2 = \frac{1}{r^2}\left(-dt^2 + dr^2 + dx_i^2\right)$$

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

Apply a chemical potential



Holography of a non-Fermi liquid



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

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

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

Holography of a non-Fermi liquid

★ 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)
A.Lucas, S. Sachdev, and K. Schalm, Phys. Rev. D **89**, 066018 (2014)

Holography of a non-Fermi liquid

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

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

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)
A.Lucas, S. Sachdev, and K. Schalm, Phys. Rev. D **89**, 066018 (2014)

Holography of a non-Fermi liquid

The memory-function result for the *resistivity* for current along angle ϑ

$$\rho(T) = \frac{1}{\chi^2_{\mathbf{J},\mathbf{P}}} \lim_{\omega \to 0} \int \frac{d^2 k}{(2\pi)^2} \, k^2 \cos^2(\theta_{\mathbf{k}} - \vartheta) \, \frac{\operatorname{Im} G^R_{\mathcal{O},\mathcal{O}}(\omega, \mathbf{k})}{\omega} \, .$$

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)
A.Lucas, S. Sachdev, and K. Schalm, Phys. Rev. D **89**, 066018 (2014)

Holography of a non-Fermi liquid

The memory-function result for the *resistivity* for current along angle ϑ

$$\rho(T) = \frac{1}{\chi^2_{\mathbf{J},\mathbf{P}}} \lim_{\omega \to 0} \int \frac{d^2 k}{(2\pi)^2} \, k^2 \cos^2(\theta_{\mathbf{k}} - \vartheta) \, \frac{\mathrm{Im}\, G^R_{\mathcal{O},\mathcal{O}}(\omega, \mathbf{k})}{\omega} \, .$$

Gravity + Holography "know" about

- classical hydrodynamics

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)
A.Lucas, S. Sachdev, and K. Schalm, Phys. Rev. D **89**, 066018 (2014)

Holography of a non-Fermi liquid

The memory-function result for the *resistivity* for current along angle ϑ

$$\rho(T) = \frac{1}{\chi^2_{\mathbf{J},\mathbf{P}}} \lim_{\omega \to 0} \int \frac{d^2k}{(2\pi)^2} \, k^2 \cos^2(\theta_{\mathbf{k}} - \vartheta) \, \frac{\mathrm{Im}\, G^R_{\mathcal{O},\mathcal{O}}(\omega, \mathbf{k})}{\omega} \, .$$

Gravity + Holography "know" about

- classical hydrodynamics
- quantum corrections beyond hydrodynamics

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)
A.Lucas, S. Sachdev, and K. Schalm, Phys. Rev. D **89**, 066018 (2014)

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

SU(2) gauge theory for underlying quantum critical point

- Fermion ψ, transforming as a gauge SU(2) fundamental, with dispersion $\varepsilon_{\mathbf{k}}$ from the band structure, at a non-zero chemical potential: has a "large" Fermi surface.

- A SU(2) gauge boson.

- A real Higgs field, H, transforming as a gauge SU(2) adjoint, carrying lattice momentum (π, π). Condensation of the Higgs breaks SU(2) $\rightarrow$ U(1), and transforms the large Fermi surface to a small Fermi surface.

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

SU(2) gauge theory for underlying quantum critical point

Main assumption:

All points on the Fermi surface have a rapid relaxation to local thermal equilibrium by processes which conserve a suitably defined momentum.

Relaxation of the momentum occurs at a slower rate.

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

SU(2) gauge theory for underlying quantum 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.

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

SU(2) gauge theory for underlying quantum 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 the gauge-invariant operator $\mathcal{O} \sim H^2$.

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
A. Patel and S. Sachdev, arXiv:1408.6549

- Quantitative predictions for transport in 2+1 dimensional CFTs obtained by combining the operator product expansion, quantum Monte Carlo, and the dynamics of black branes.

- Quantitative predictions for transport in 2+1 dimensional CFTs obtained by combining the operator product expansion, quantum Monte Carlo, and the dynamics of black branes.

- *Lessons from Holography:* transport in non-Fermi liquids is dominated by momentum relaxation of low energy, neutral, bosonic modes, and not by charged fermionic excitations near the Fermi surface.

- Quantitative predictions for transport in 2+1 dimensional CFTs obtained by combining the operator product expansion, quantum Monte Carlo, and the dynamics of black branes.

- *Lessons from Holography:* transport in non-Fermi liquids is dominated by momentum relaxation of low energy, neutral, bosonic modes, and not by charged fermionic excitations near the Fermi surface.

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