The quantum phases of matter and gauge-gravity duality

Frontiers in Condensed Matter Science,
Fortaleza, Brazil, April 10, 2013

Subir Sachdev

SCIENTIFIC AMERICAN 308, 44 (JANUARY 2013)

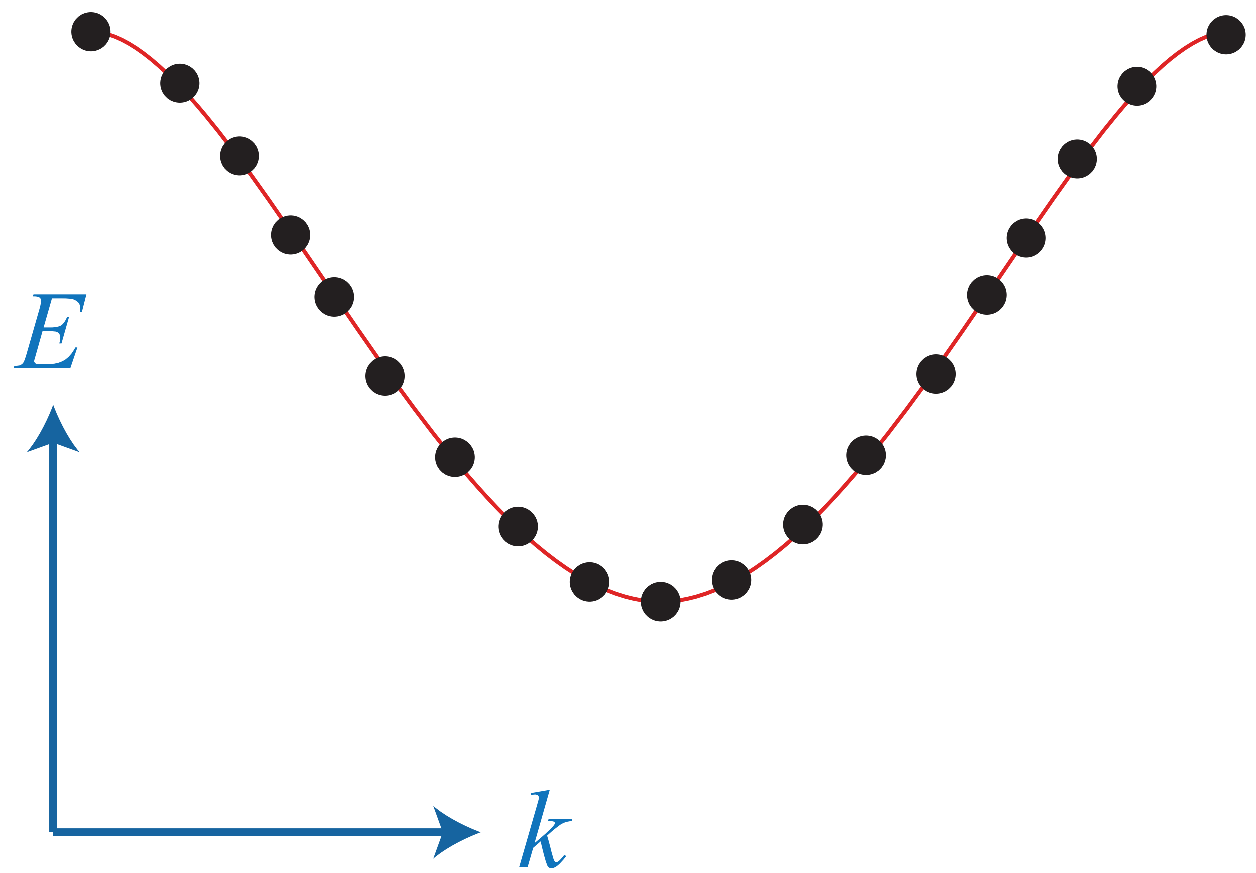
PHYSICS
HARVARD

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

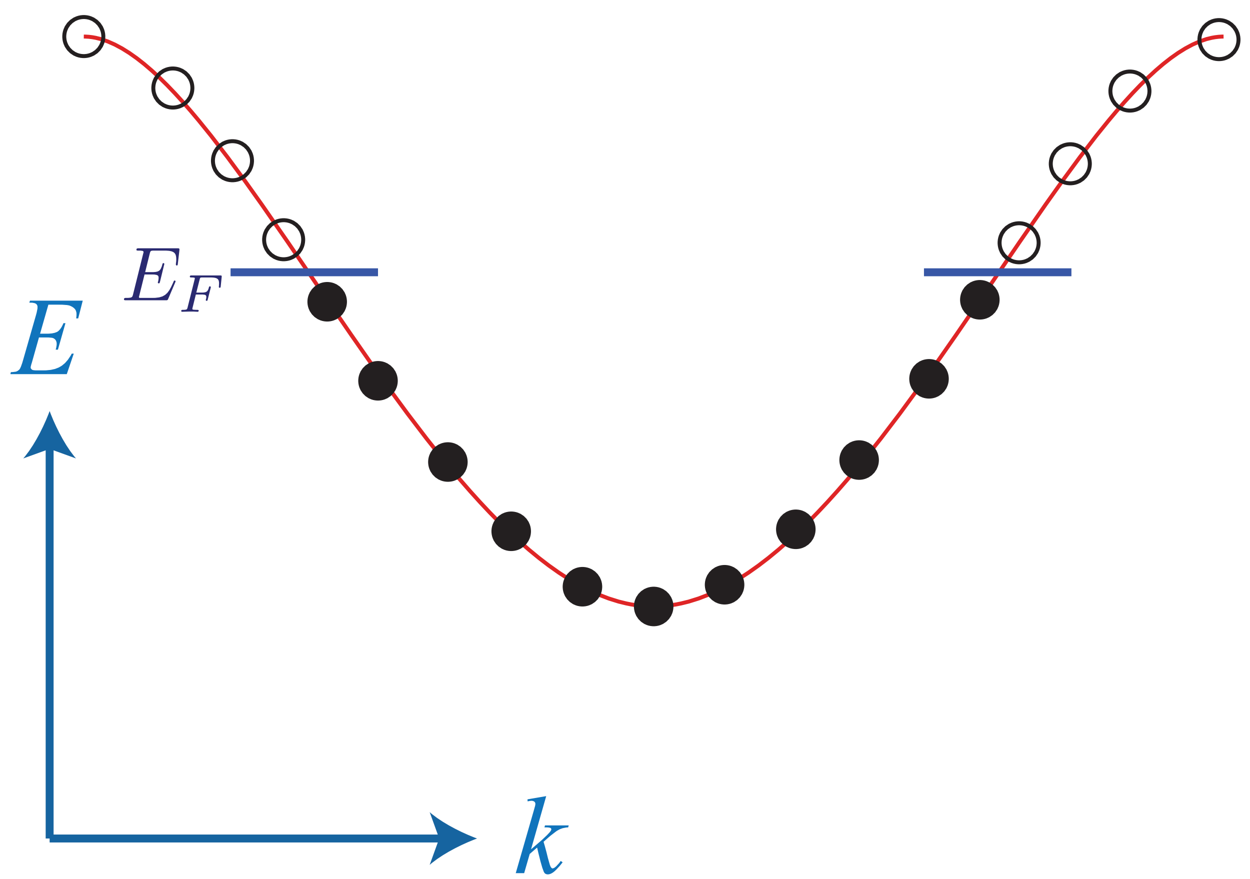
Band insulators



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

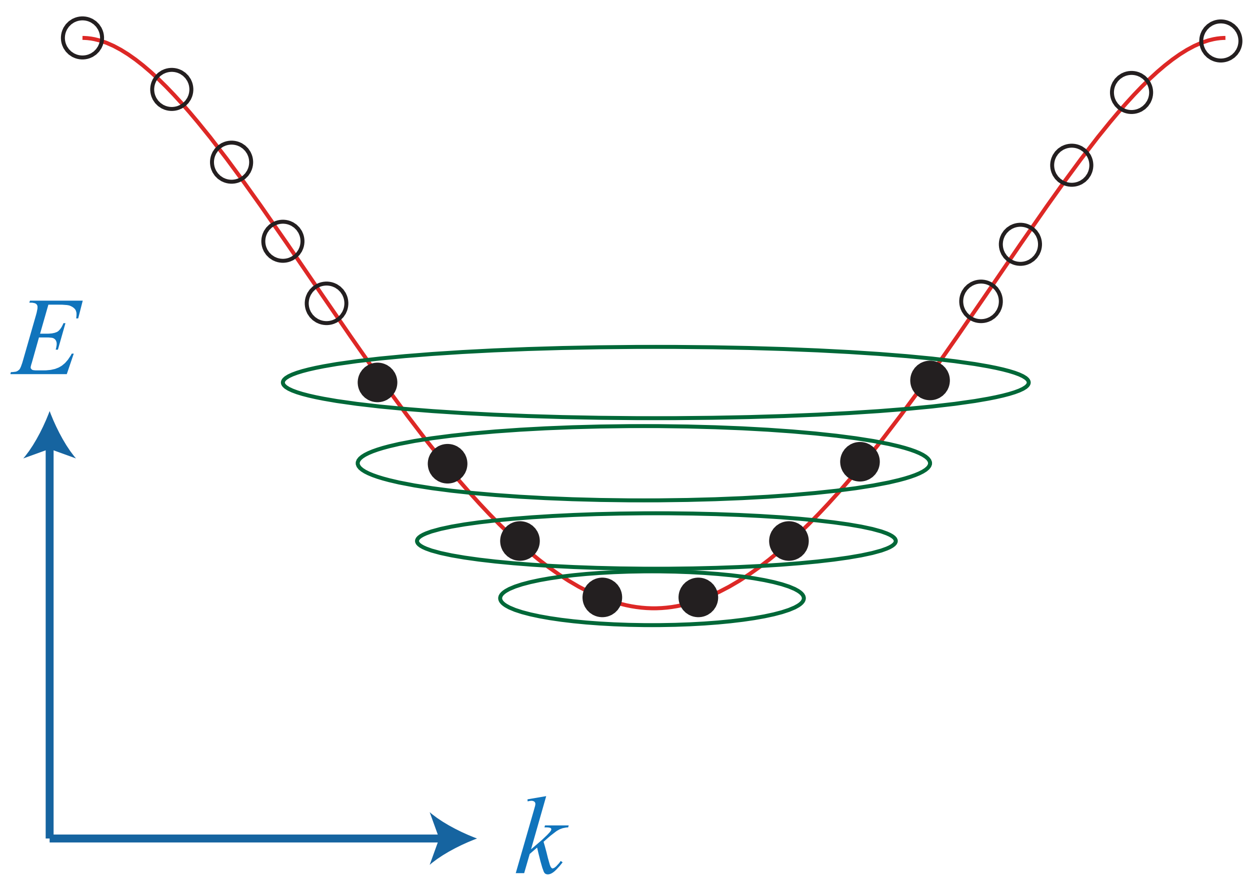
Metals



An odd number of electrons per unit cell

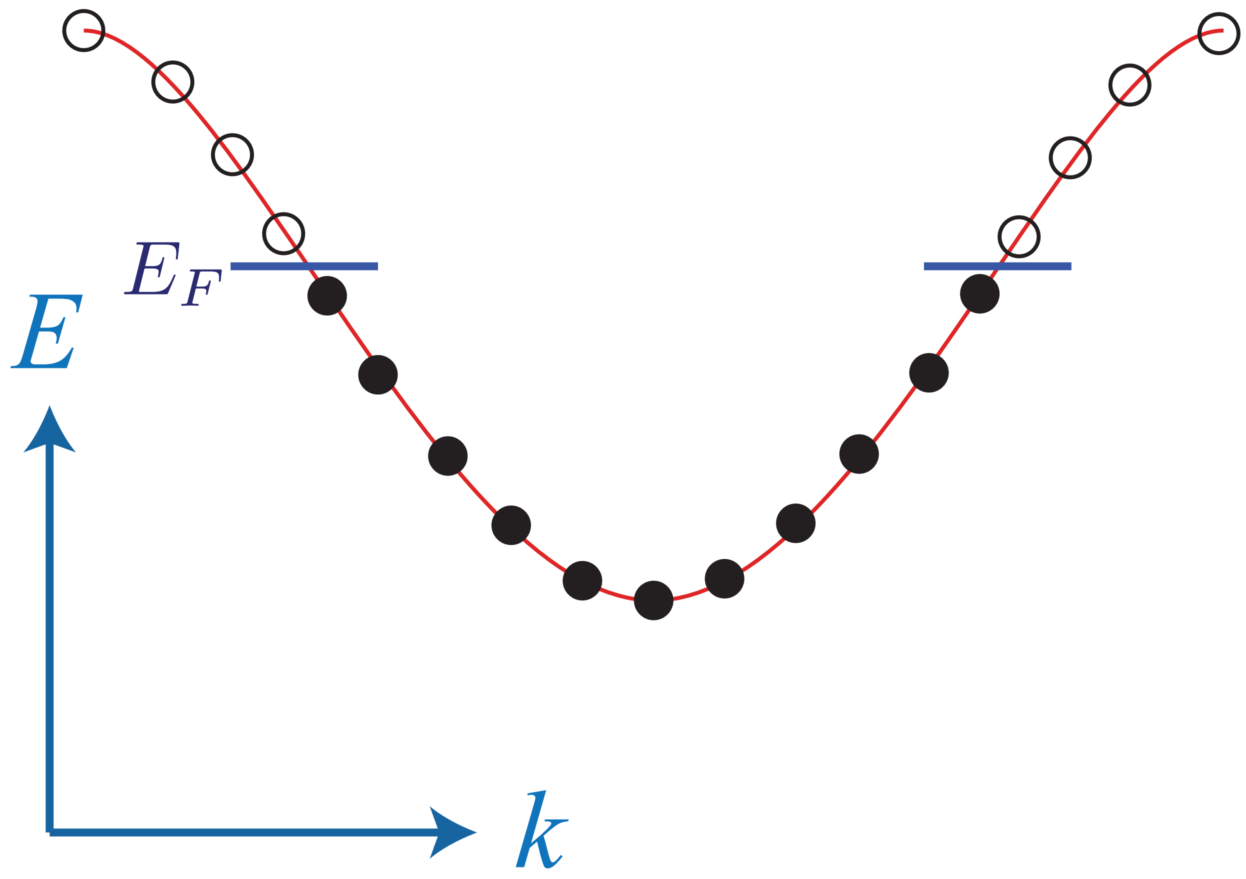
Sommerfeld-Bloch theory of
metals, insulators, and superconductors:
many-electron quantum states are adiabatically
connected to independent electron states

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



An odd number of electrons per unit cell

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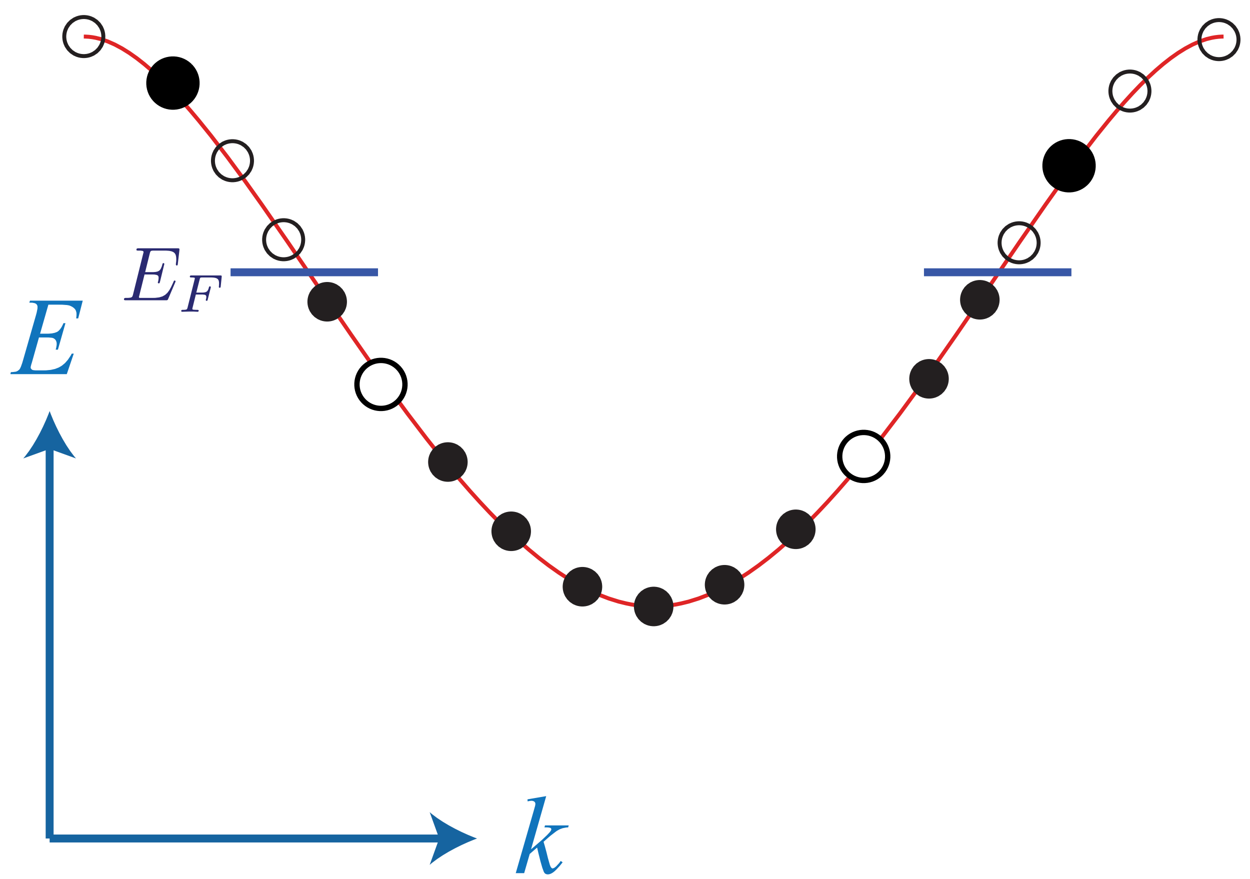
Metals



An odd number of electrons per unit cell

Modern phases of quantum matter

Not adiabatically connected
to independent electron states:

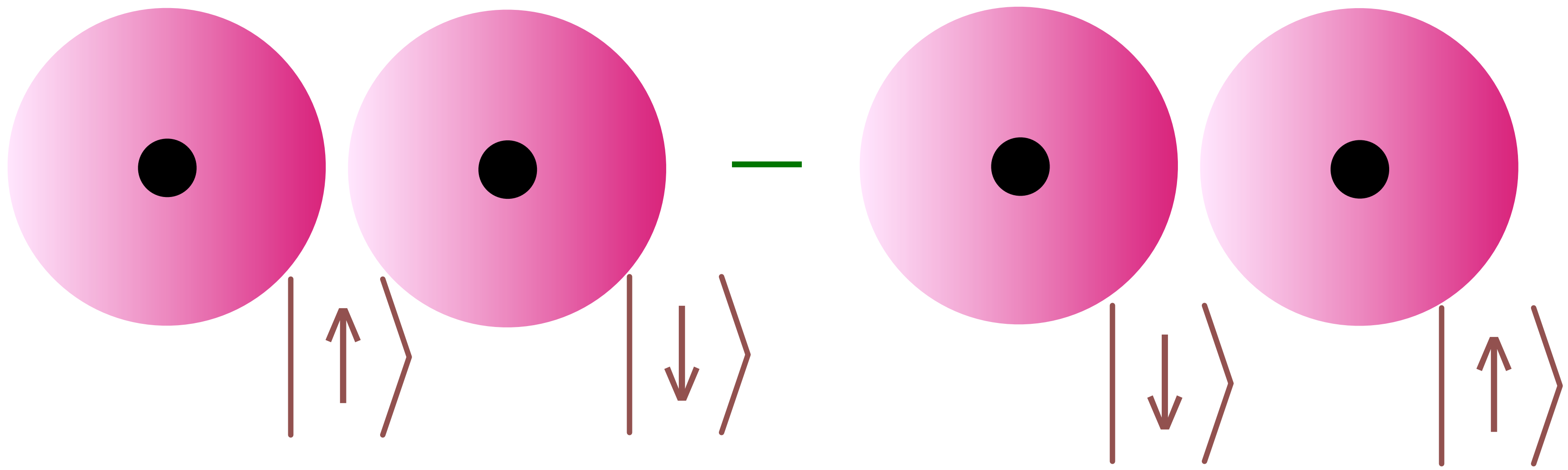
Modern phases of quantum matter

Not adiabatically connected
to independent electron states:

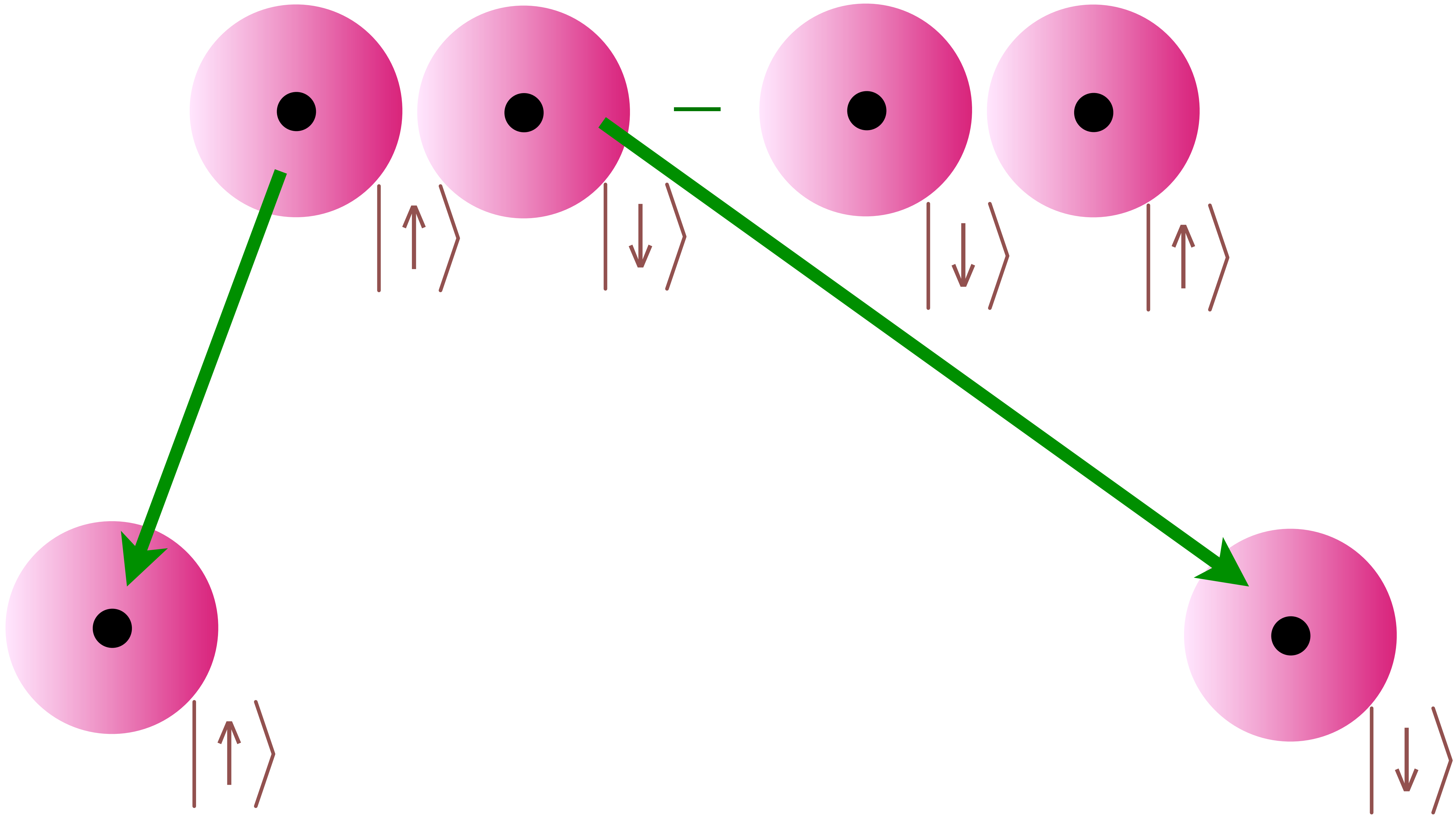
many-particle
quantum entanglement,
and no quasiparticles

Quantum Entanglement: quantum superposition with more than one particle

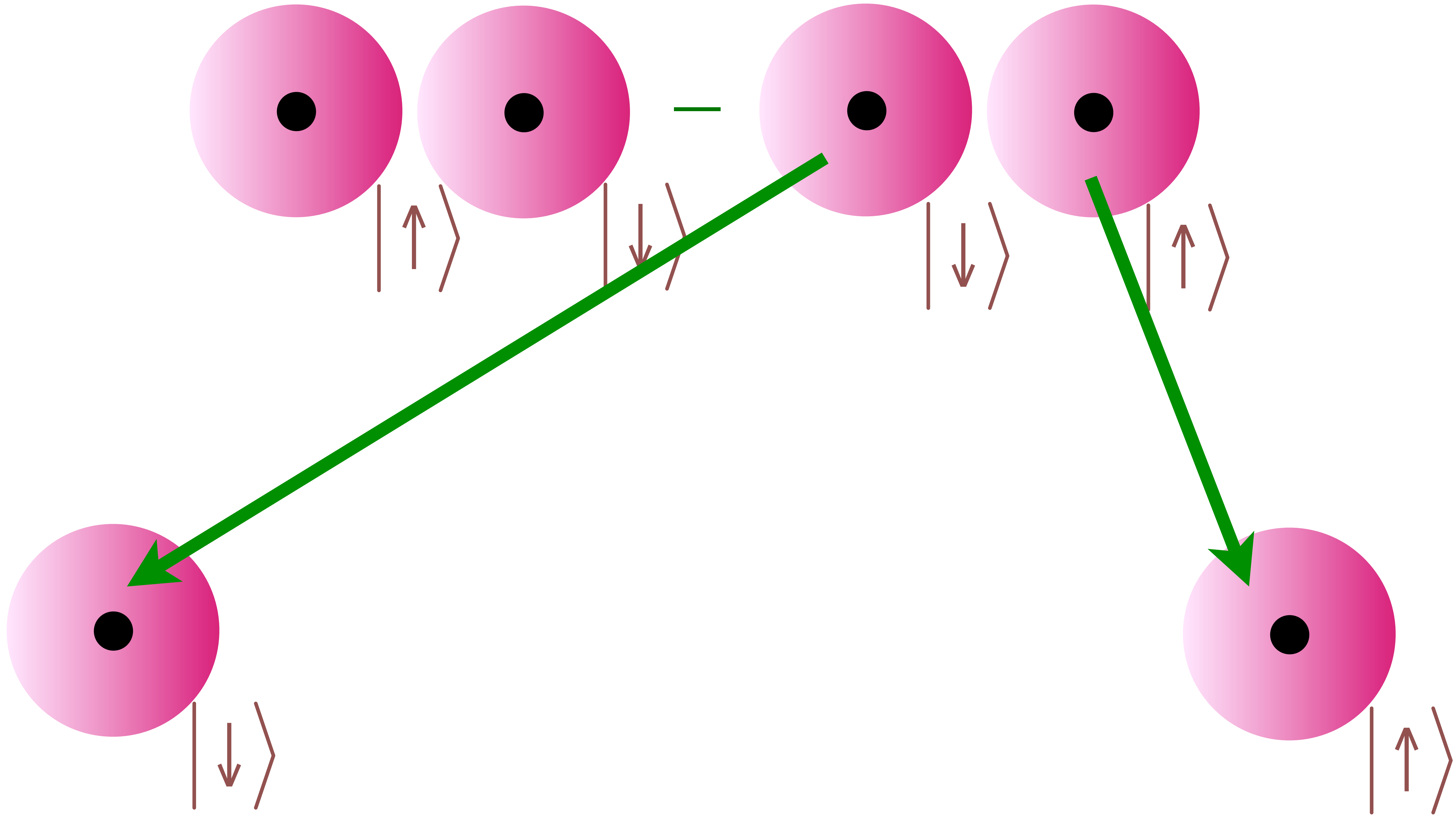
Hydrogen molecule:



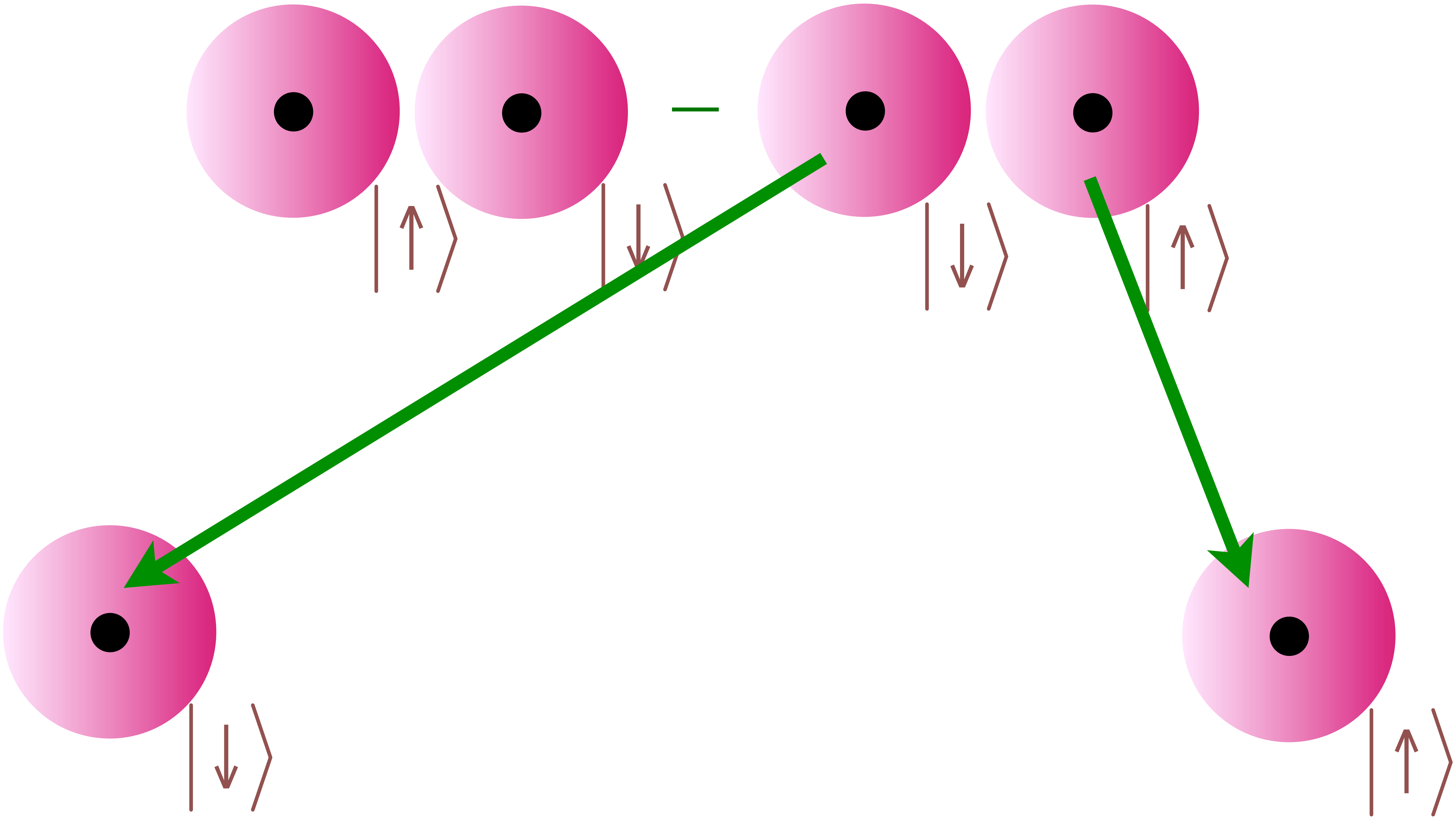
Quantum Entanglement: quantum superposition with more than one particle



Quantum Entanglement: quantum superposition with more than one particle



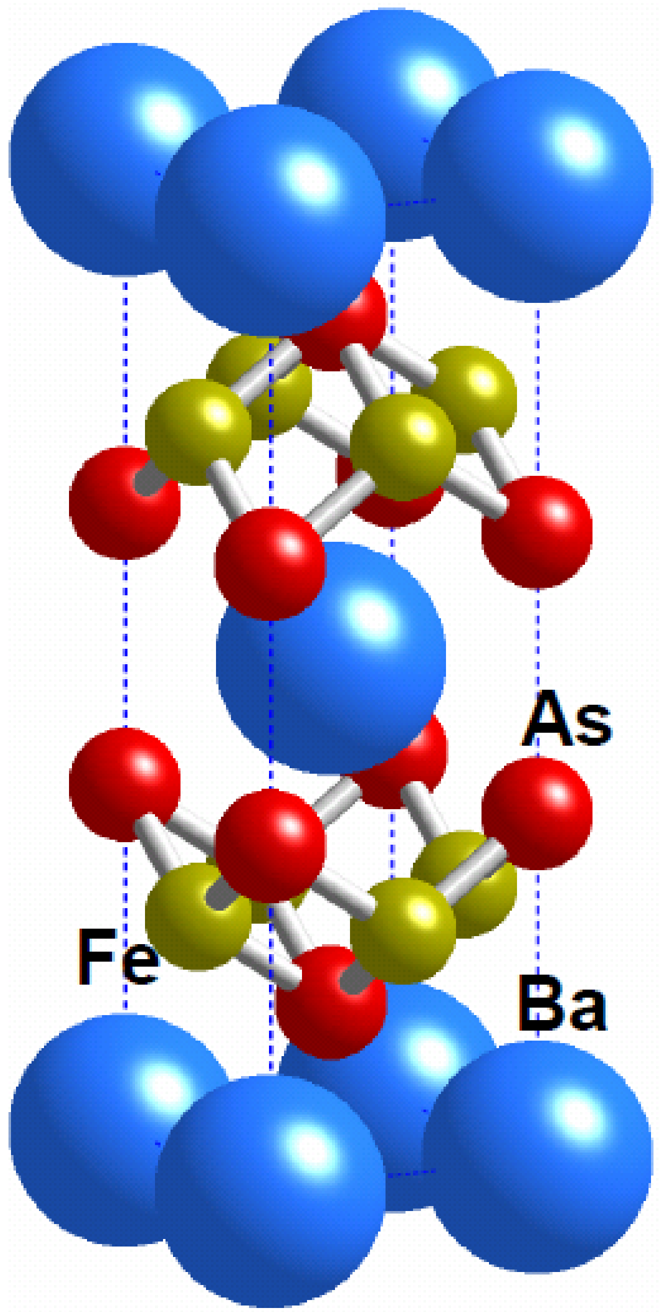
Quantum Entanglement: quantum superposition with more than one particle

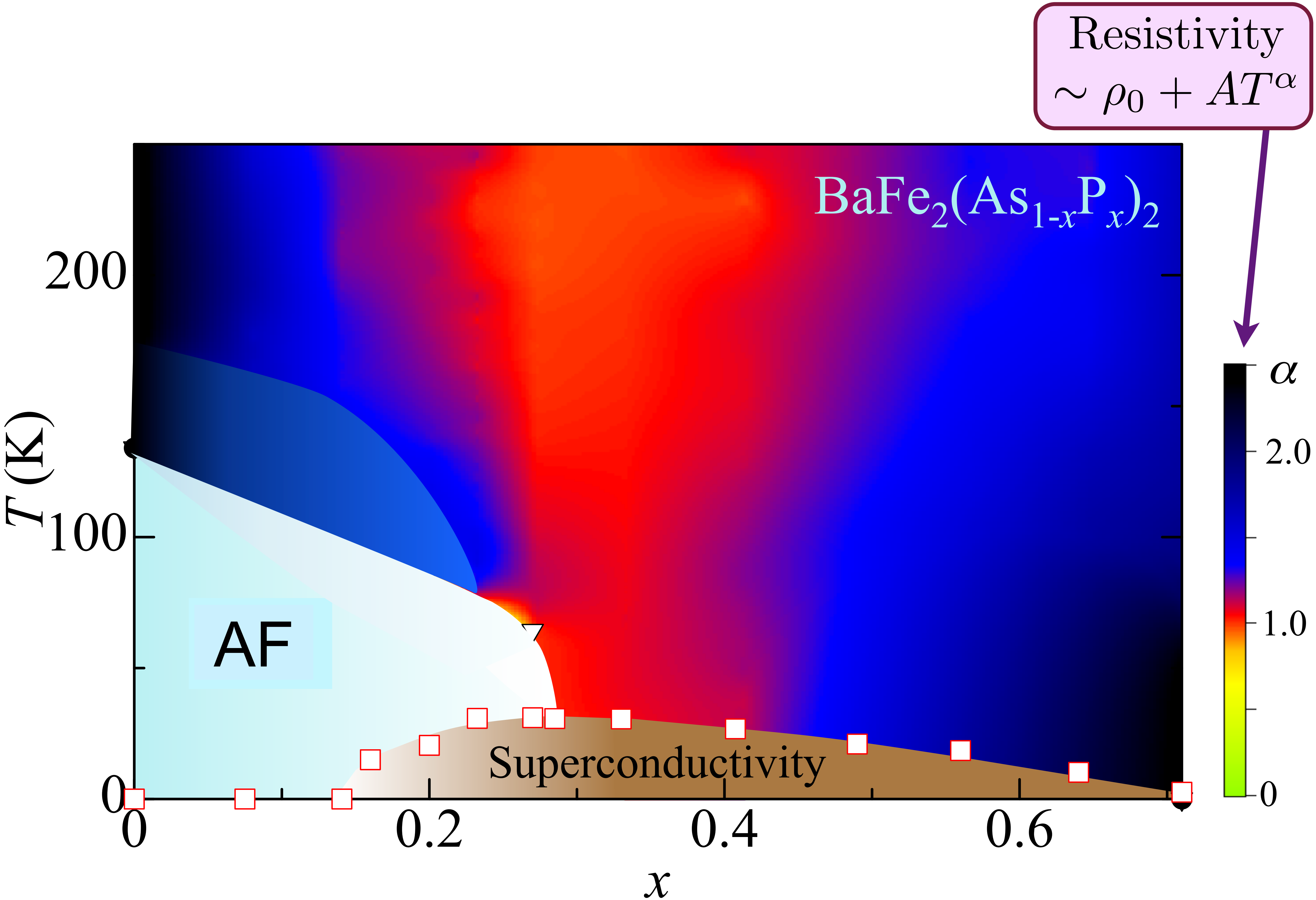


Einstein-Podolsky-Rosen "paradox": Non-local correlations between observations arbitrarily far apart

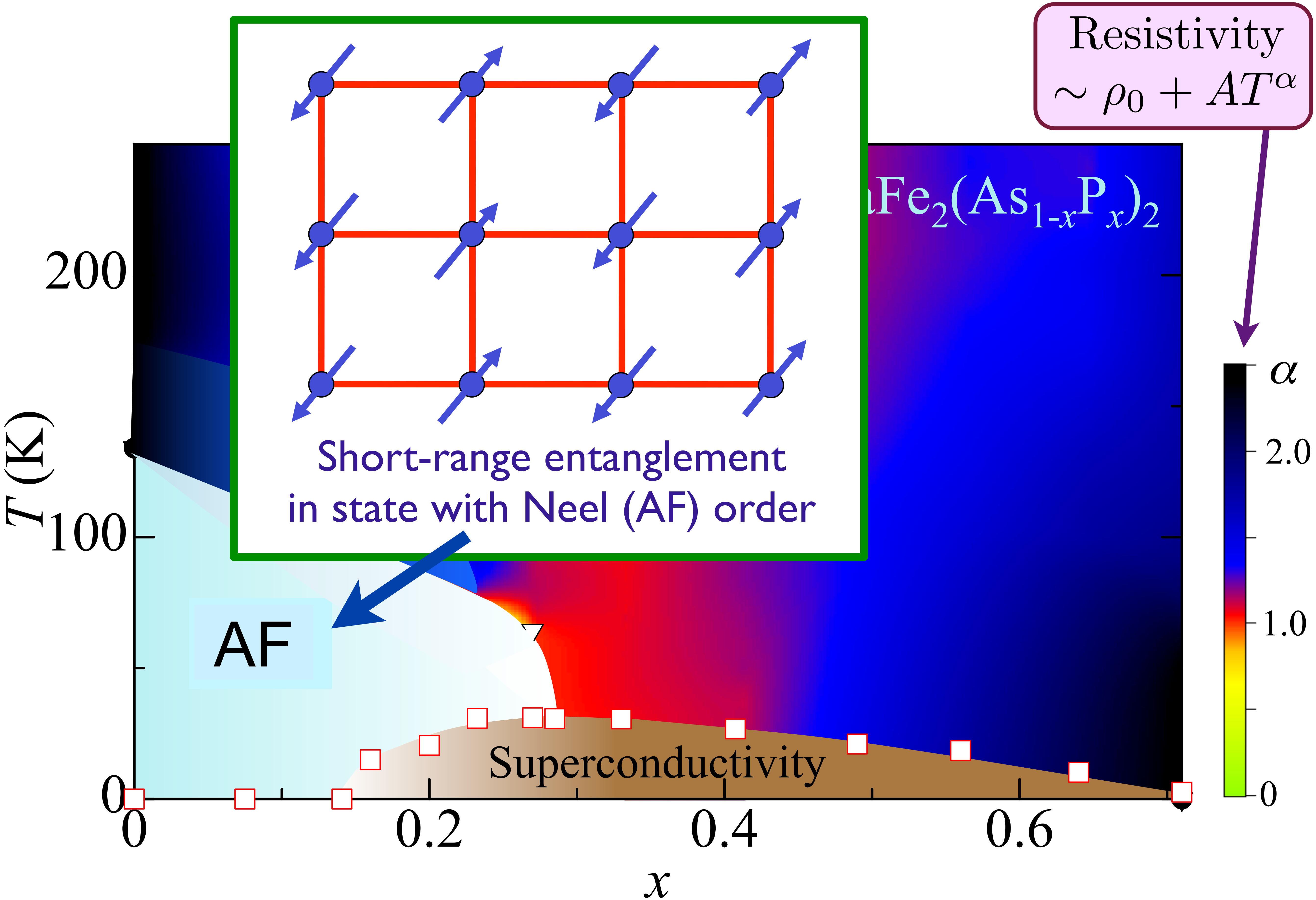
Iron pnictides:

a new class of high temperature superconductors





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



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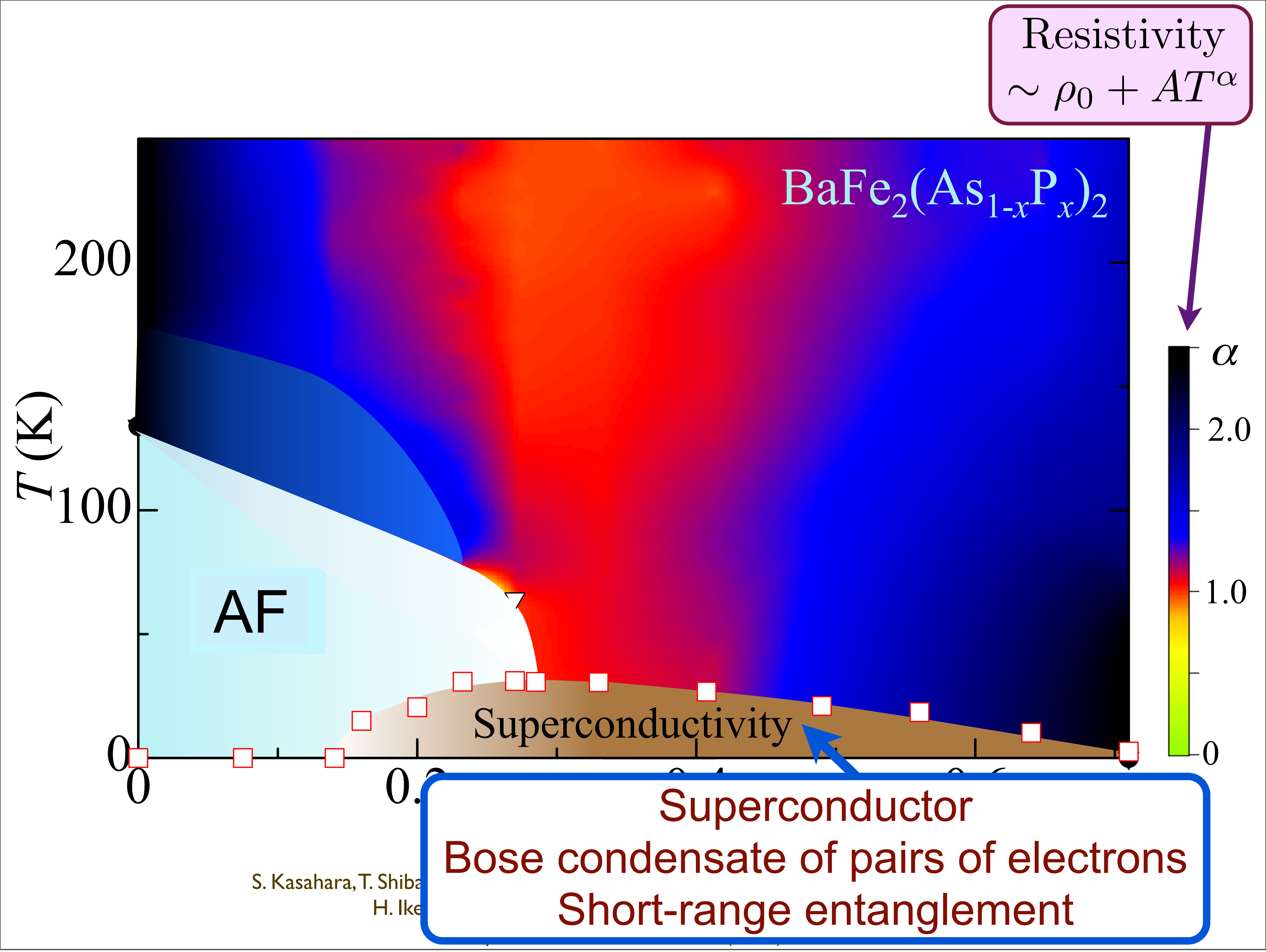
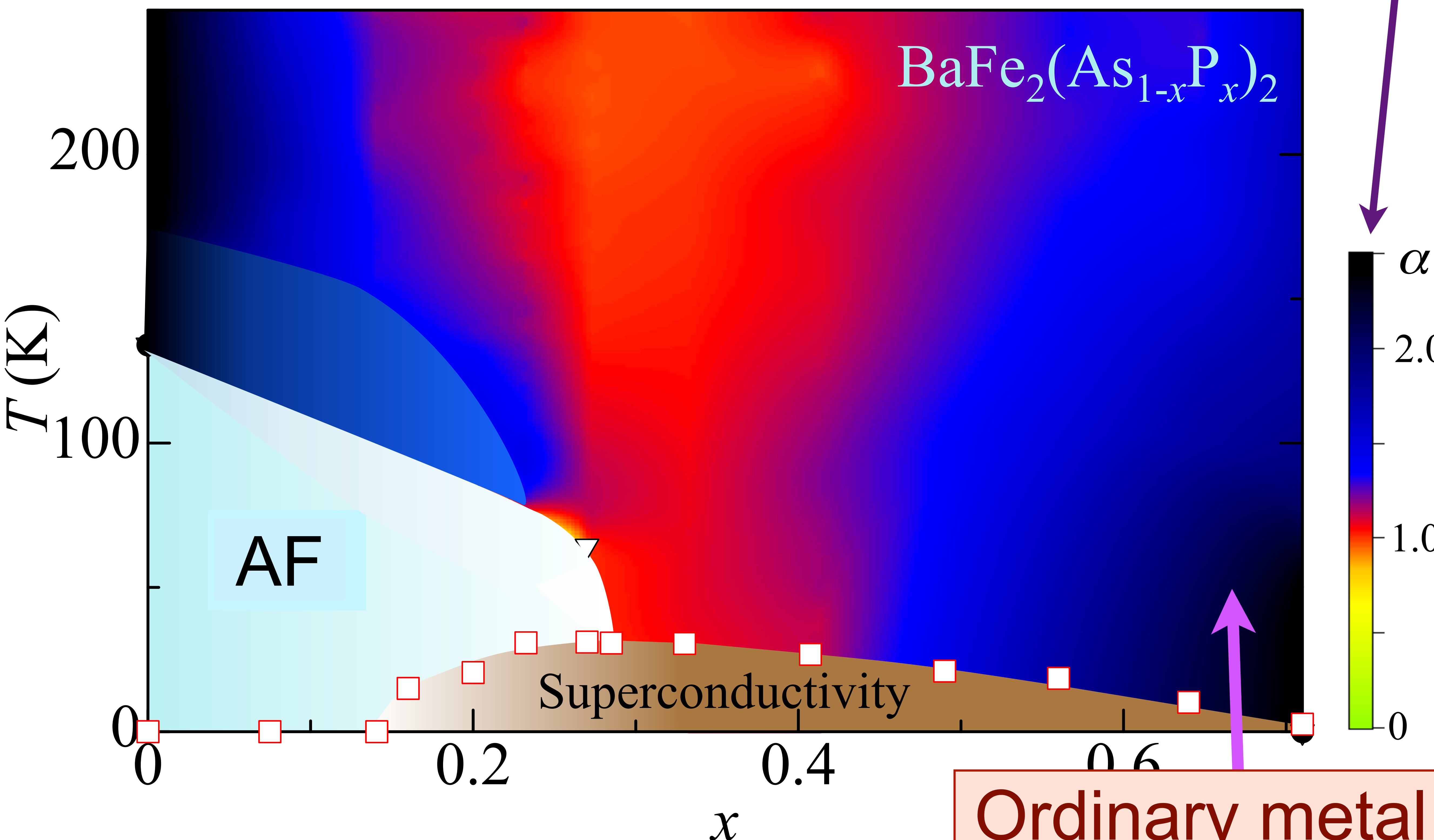


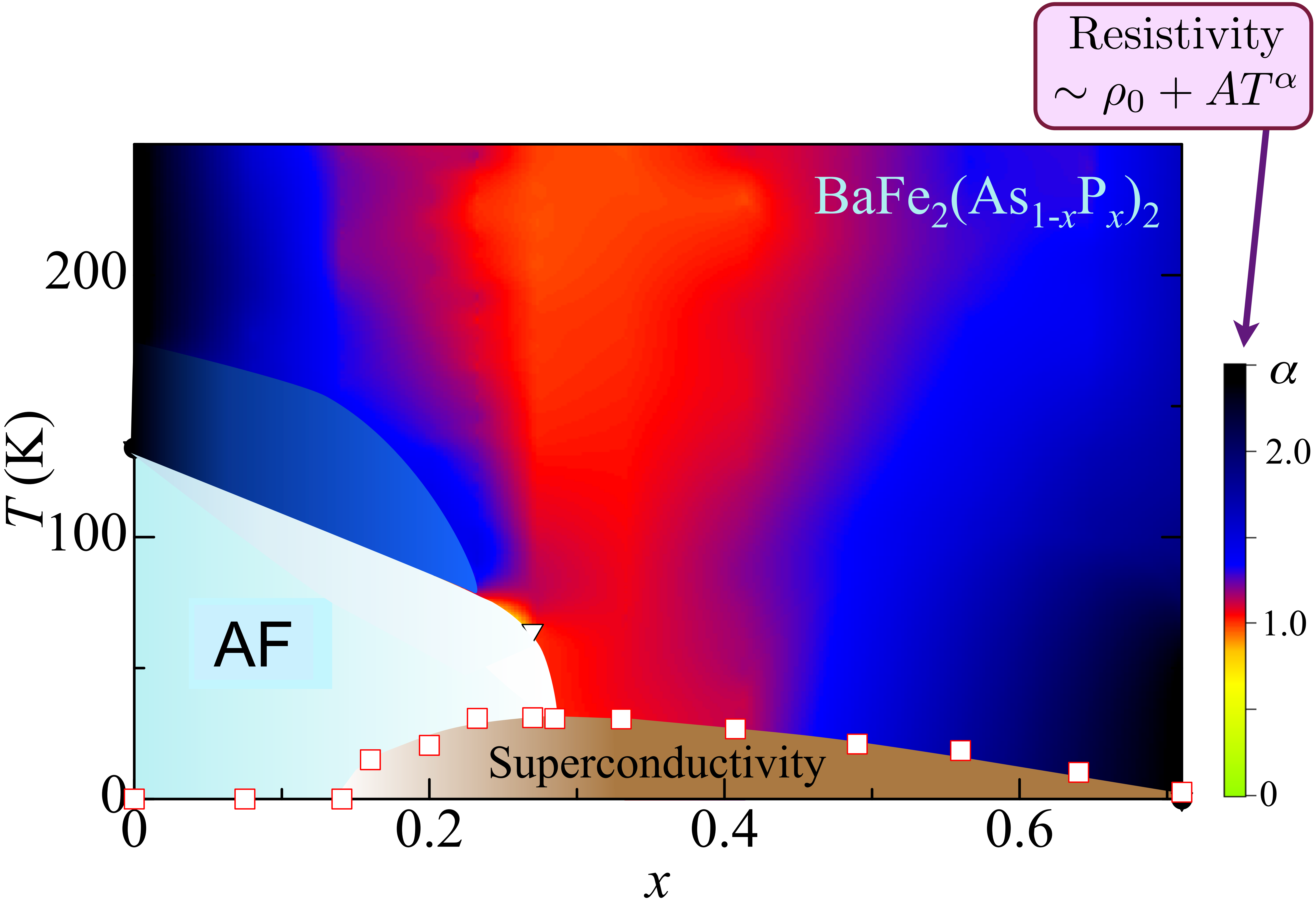
Resistivity
$\sim \rho_0 + AT^\alpha$
$BaFe_2(As_{1-x}P_x)_2$
T (K)
200
100
0
0
0.2
α
2.0
1.0
0
AF
Superconductivity
Superconductor
Bose condensate of pairs of electrons
Short-range entanglement
S. Kasahara, T. Shiba
H. Ike

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. Ma
Physical Review B **81**, 184519 (2010)



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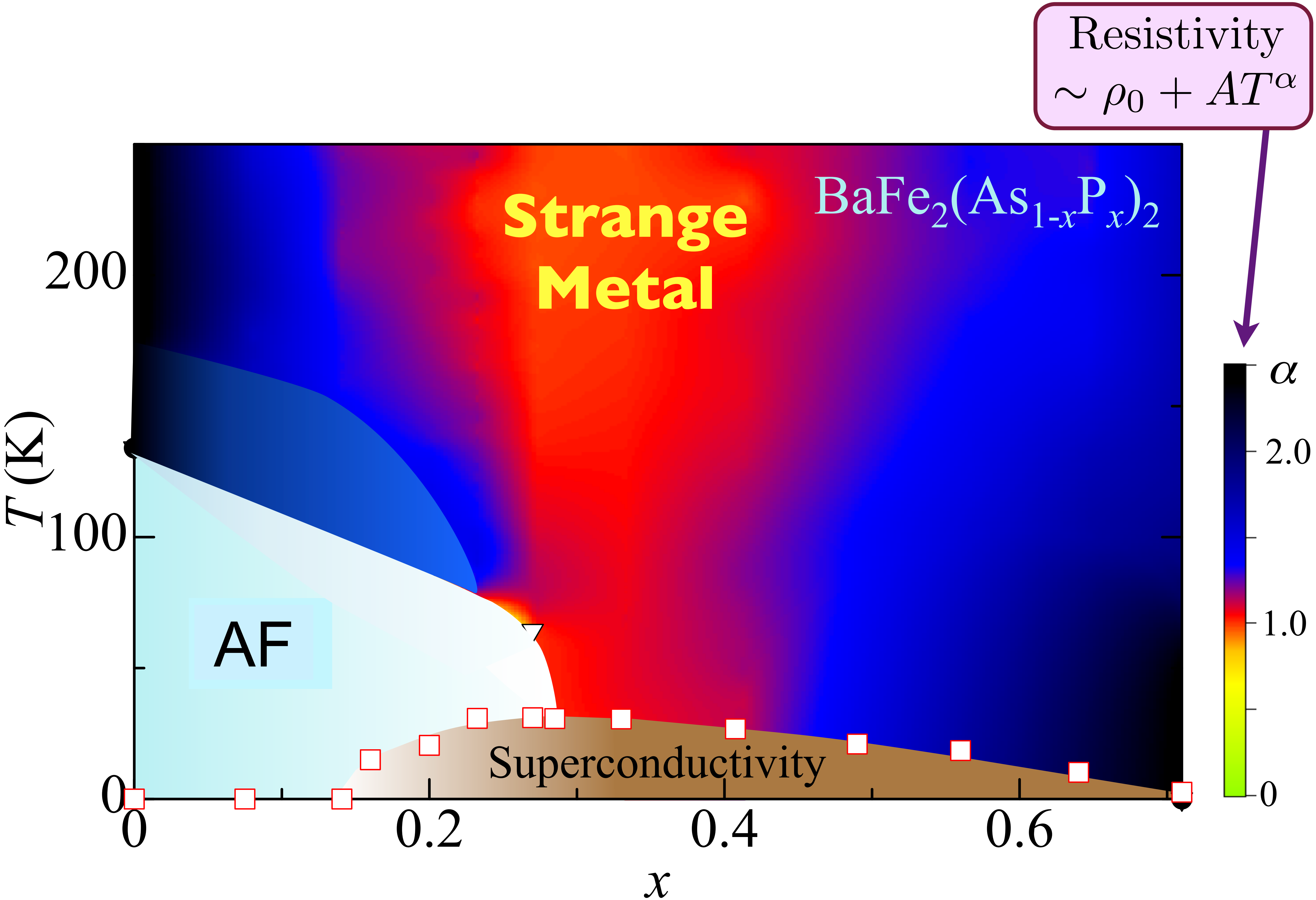

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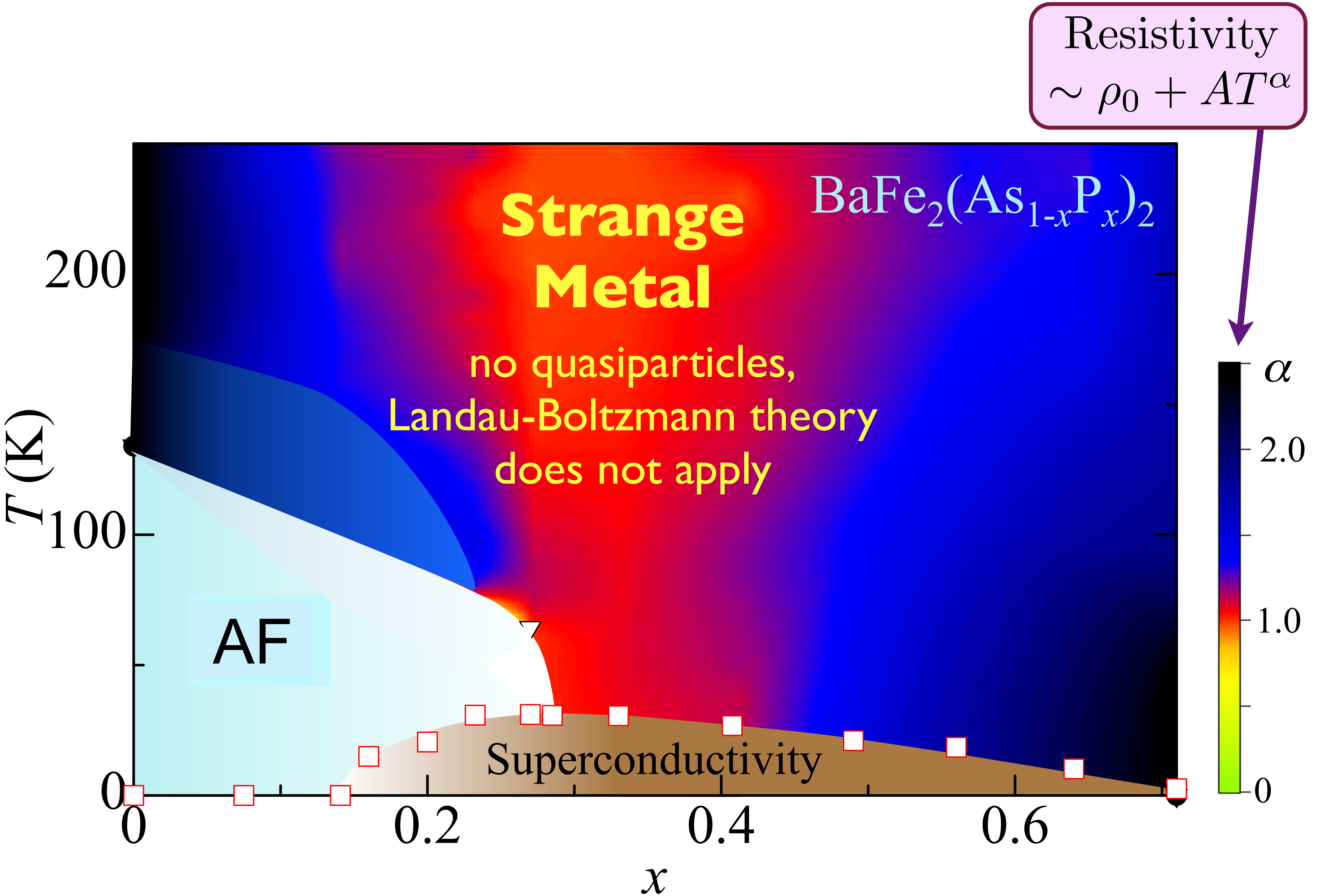

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Outline

1. Superfluid-insulator transition of ultracold atoms in optical lattices:
Quantum criticality and conformal field theories

2. Gauge-gravity duality

3. Black-hole horizons and quasi-normal modes

4. Strange metals:
What lies beyond the horizon ?

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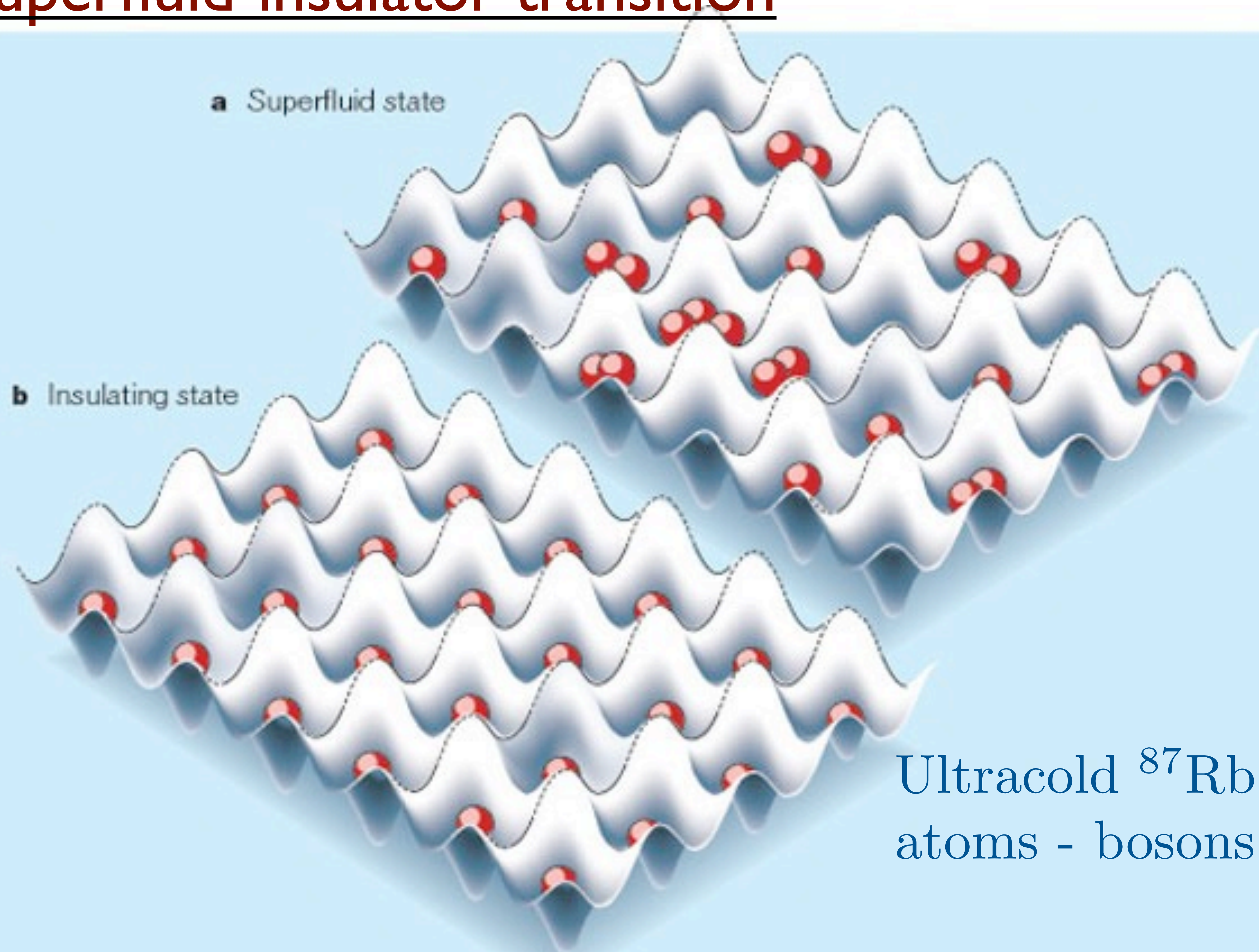
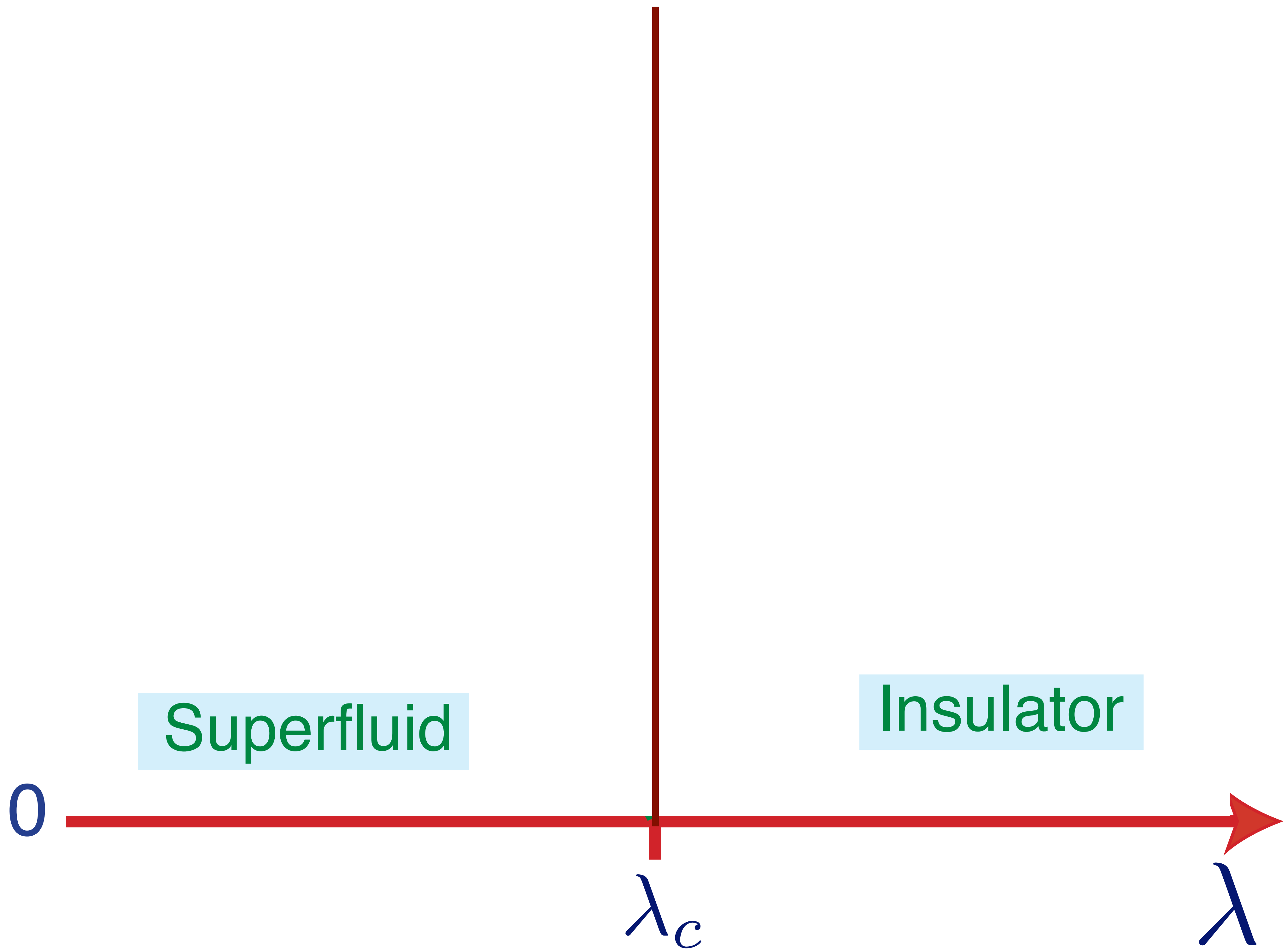
Superfluid-insulator transition



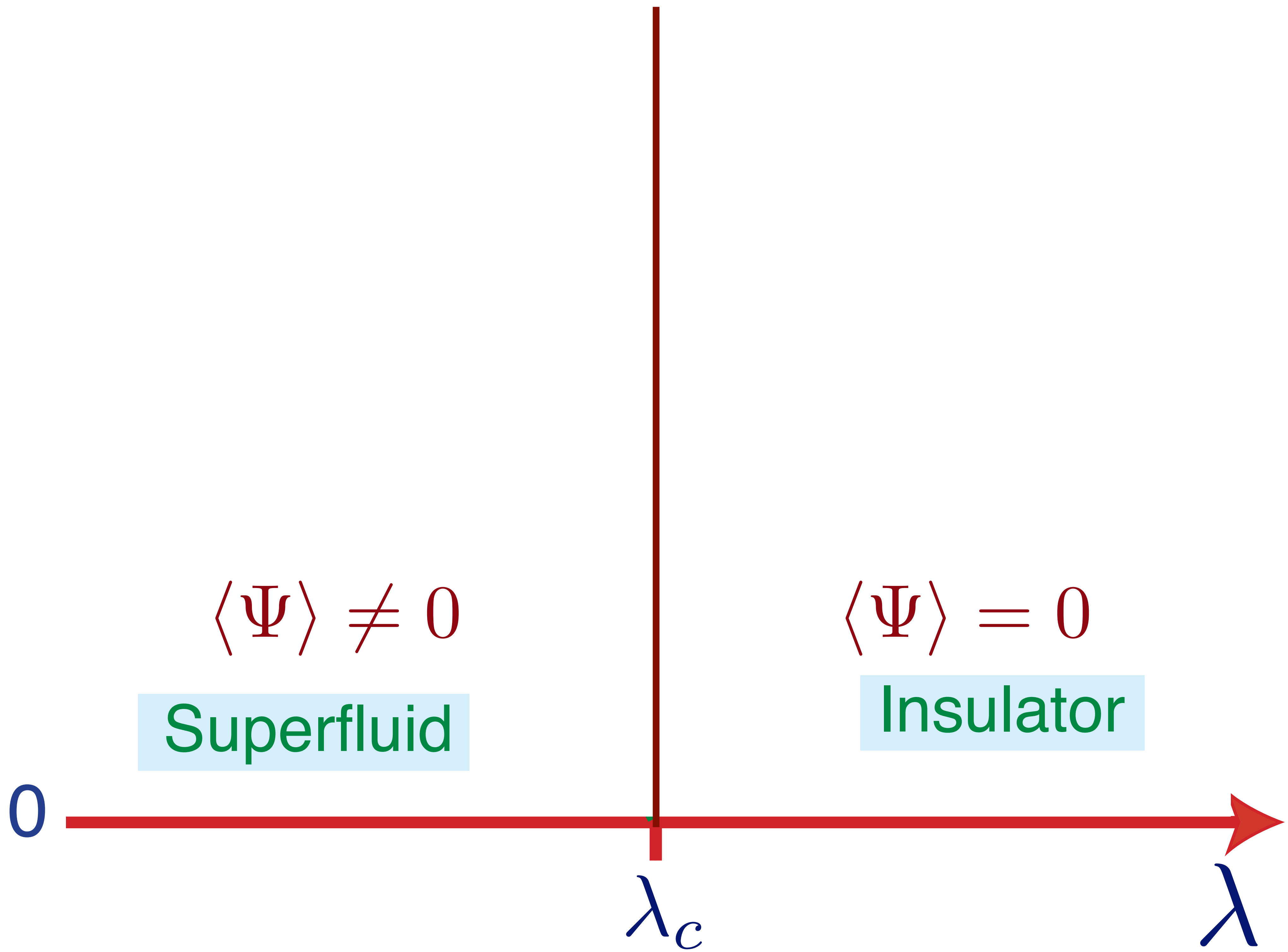
Ultracold ^{87}Rb atoms - bosons

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



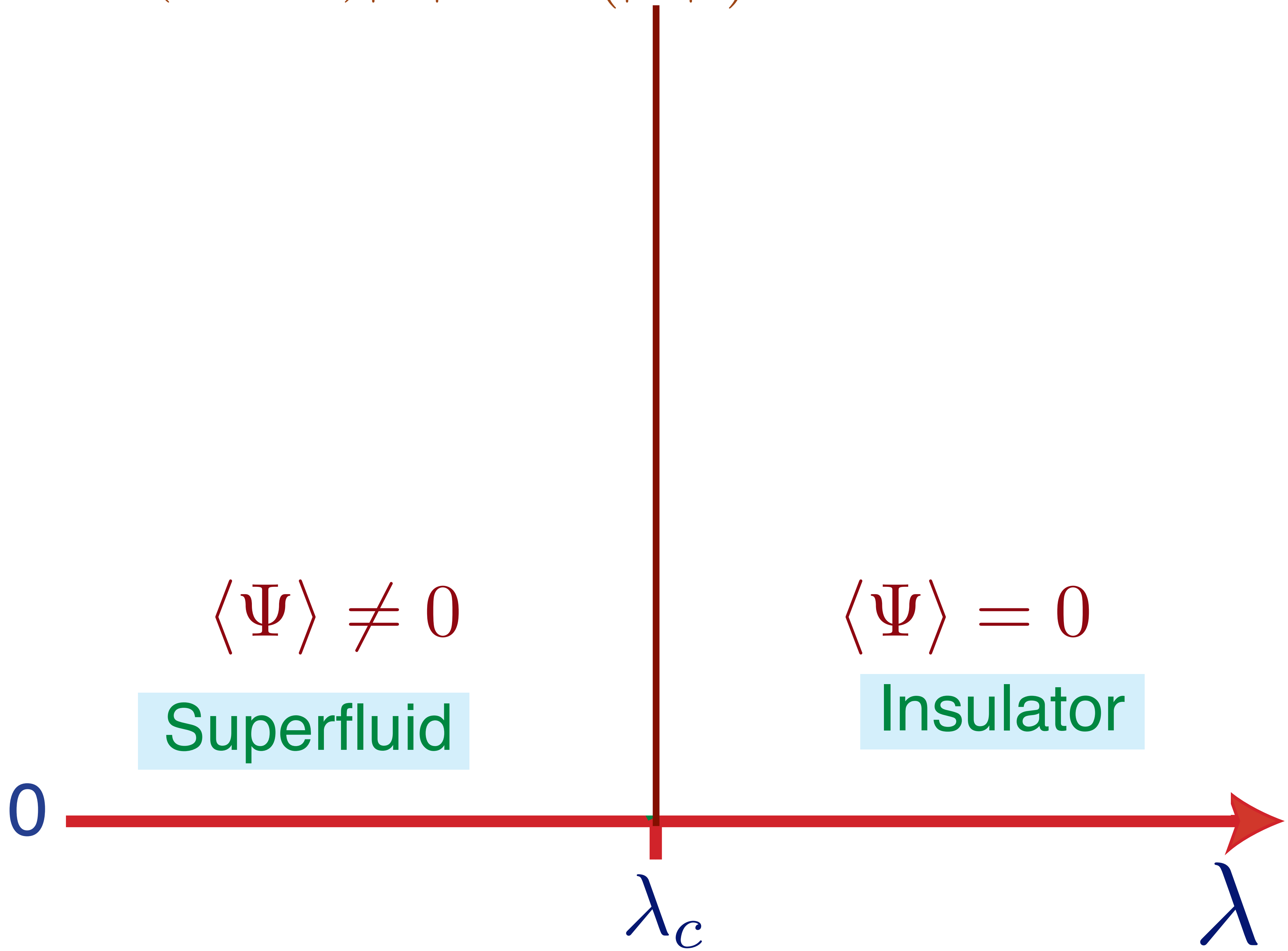
Superfluid
Insulator
0
λ_c
λ

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



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

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



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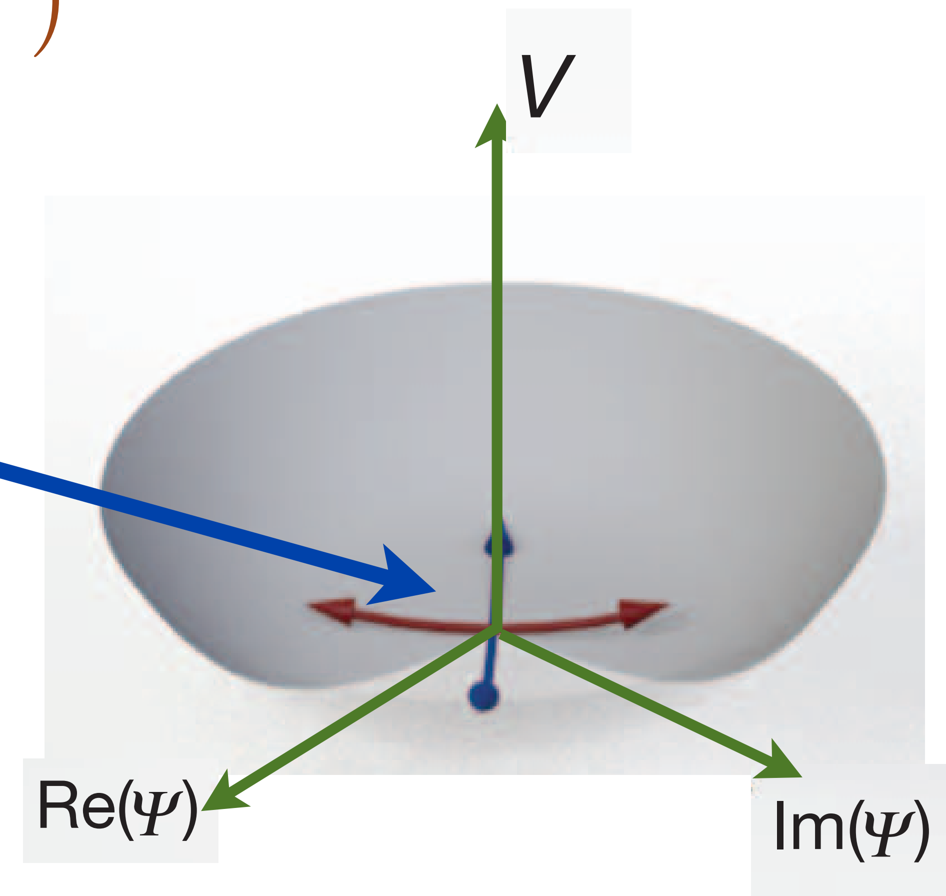
Particles and holes correspond to the 2 normal modes in the oscillation of Ψ about $\Psi = 0$.



$\langle \Psi \rangle \neq 0$

Superfluid

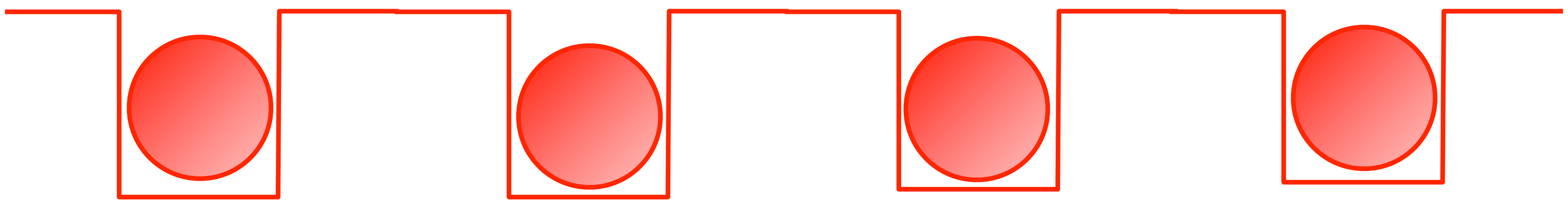
$\langle \Psi \rangle = 0$

Insulator

0

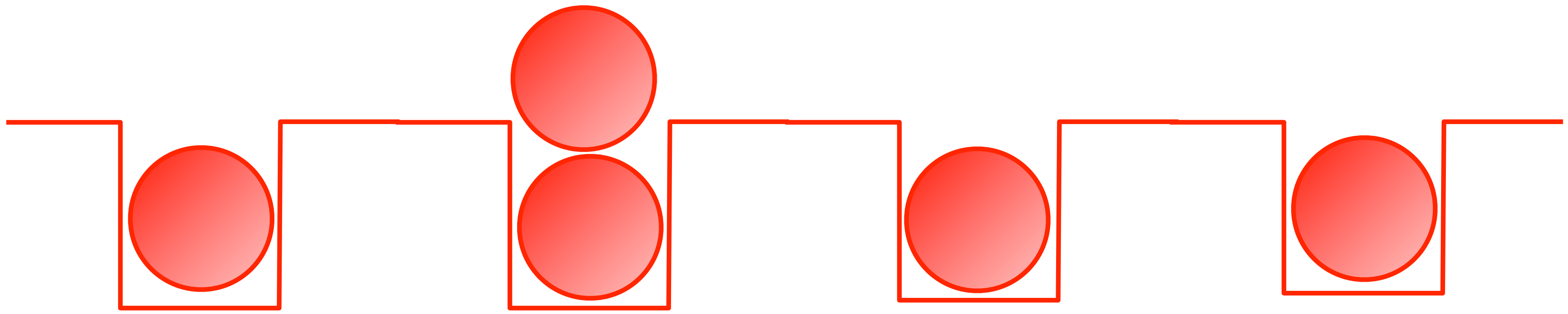
λ_c

λ



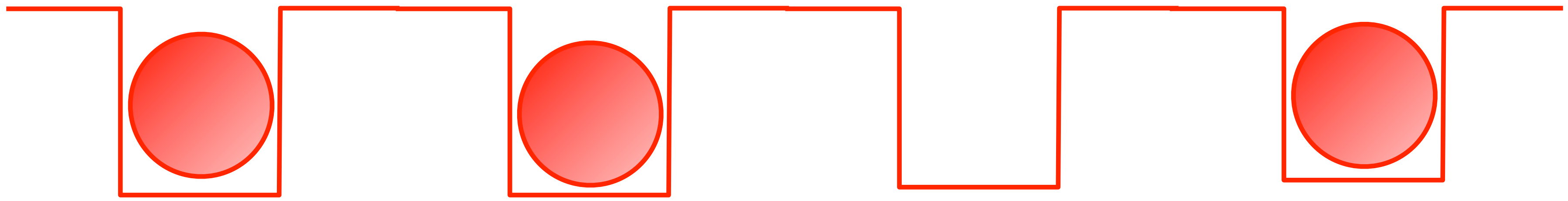
Insulator (the vacuum)
at large repulsion between bosons

Excitations of the insulator:



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

Excitations of the insulator:



Holes $\sim \Psi$

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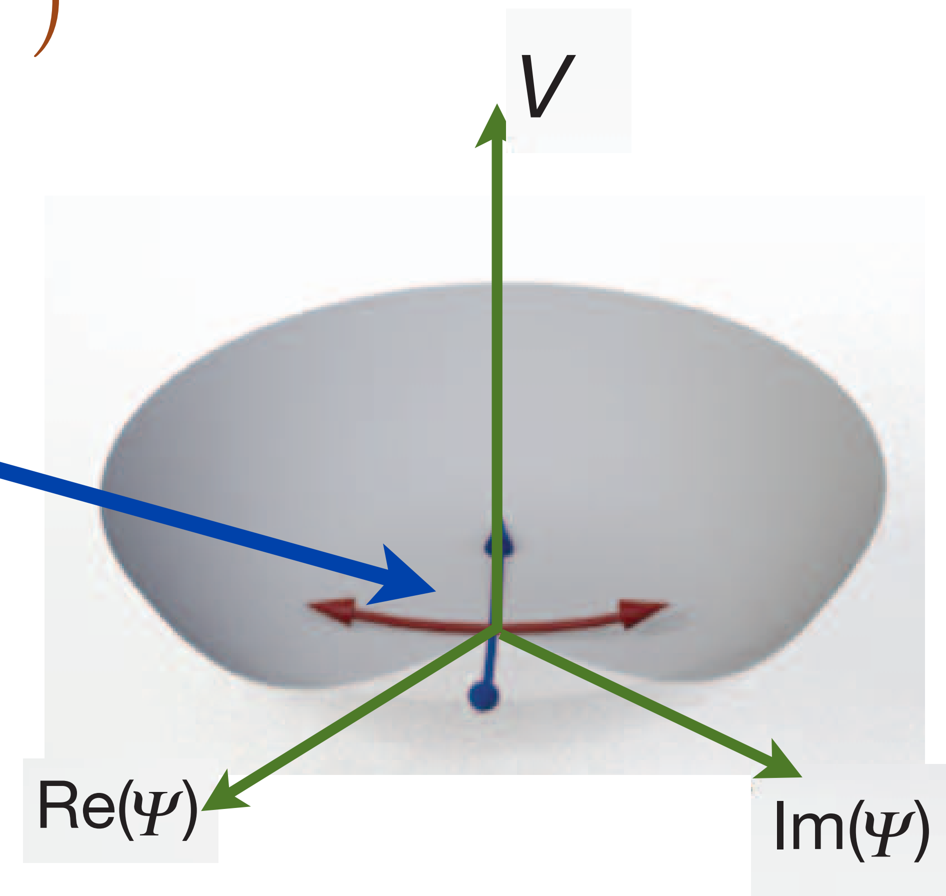

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Insulator

0

λ_c

λ

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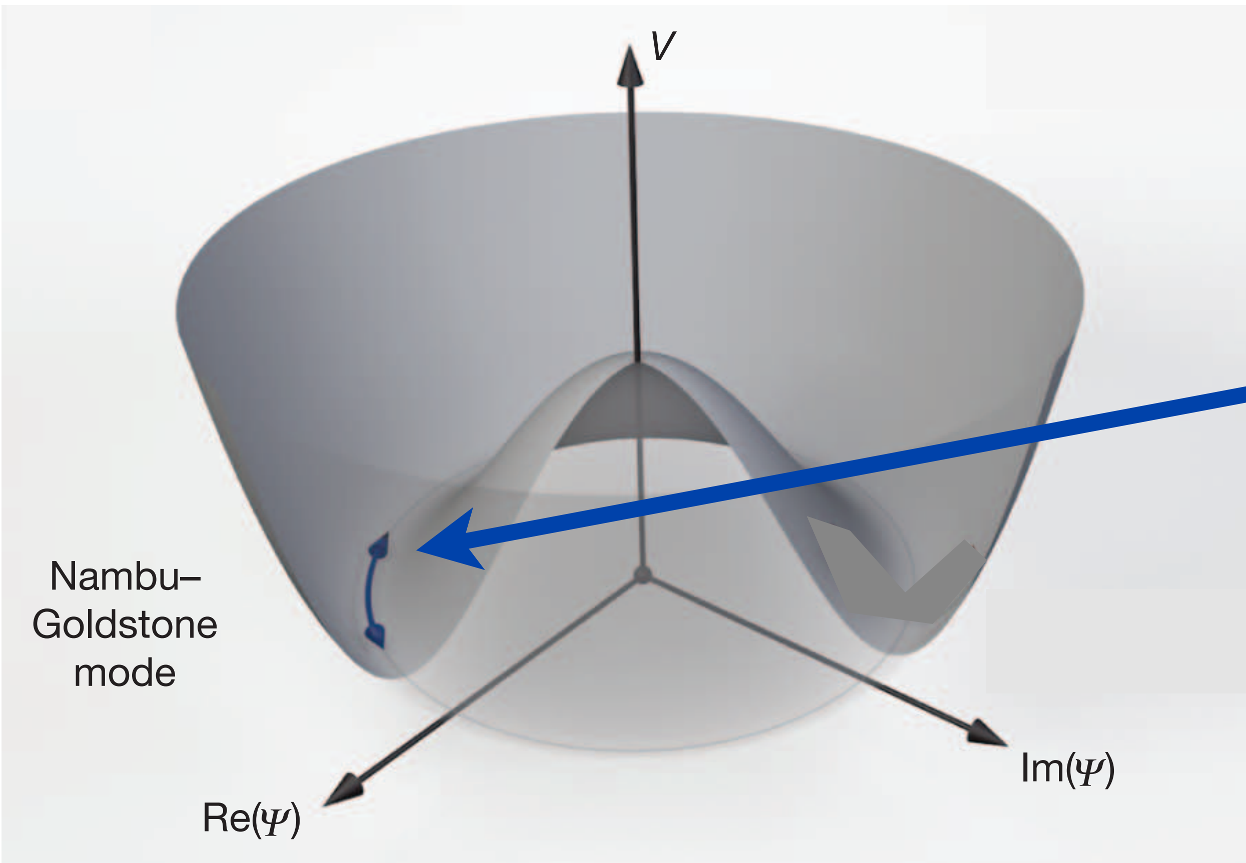

Nambu-Goldstone mode is the oscillation in the phase Ψ at a constant non-zero $|\Psi|$.

$\langle \Psi \rangle \neq 0$ | $\langle \Psi \rangle = 0$

Superfluid | Insulator

0 ——— λ_c ——— λ

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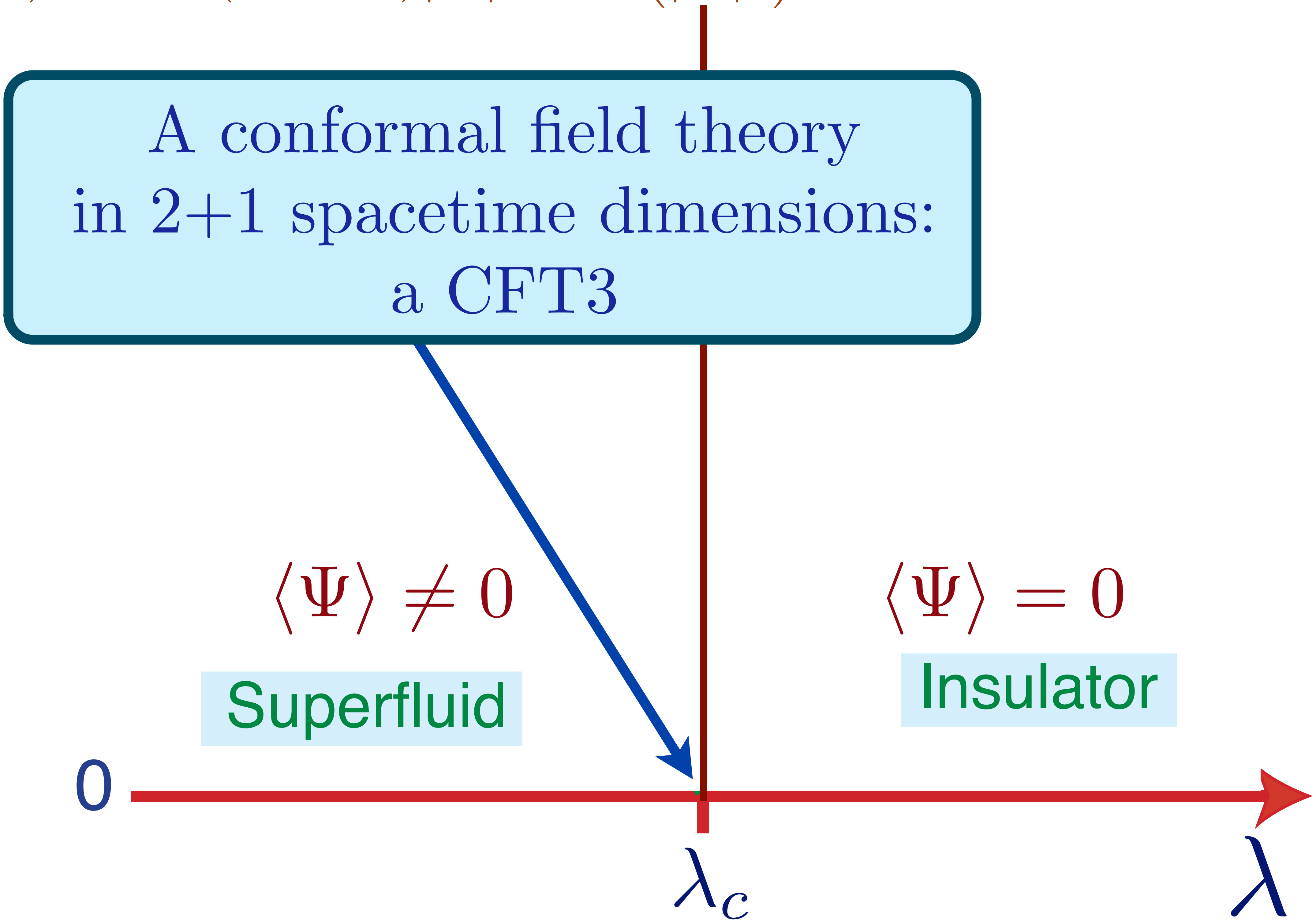

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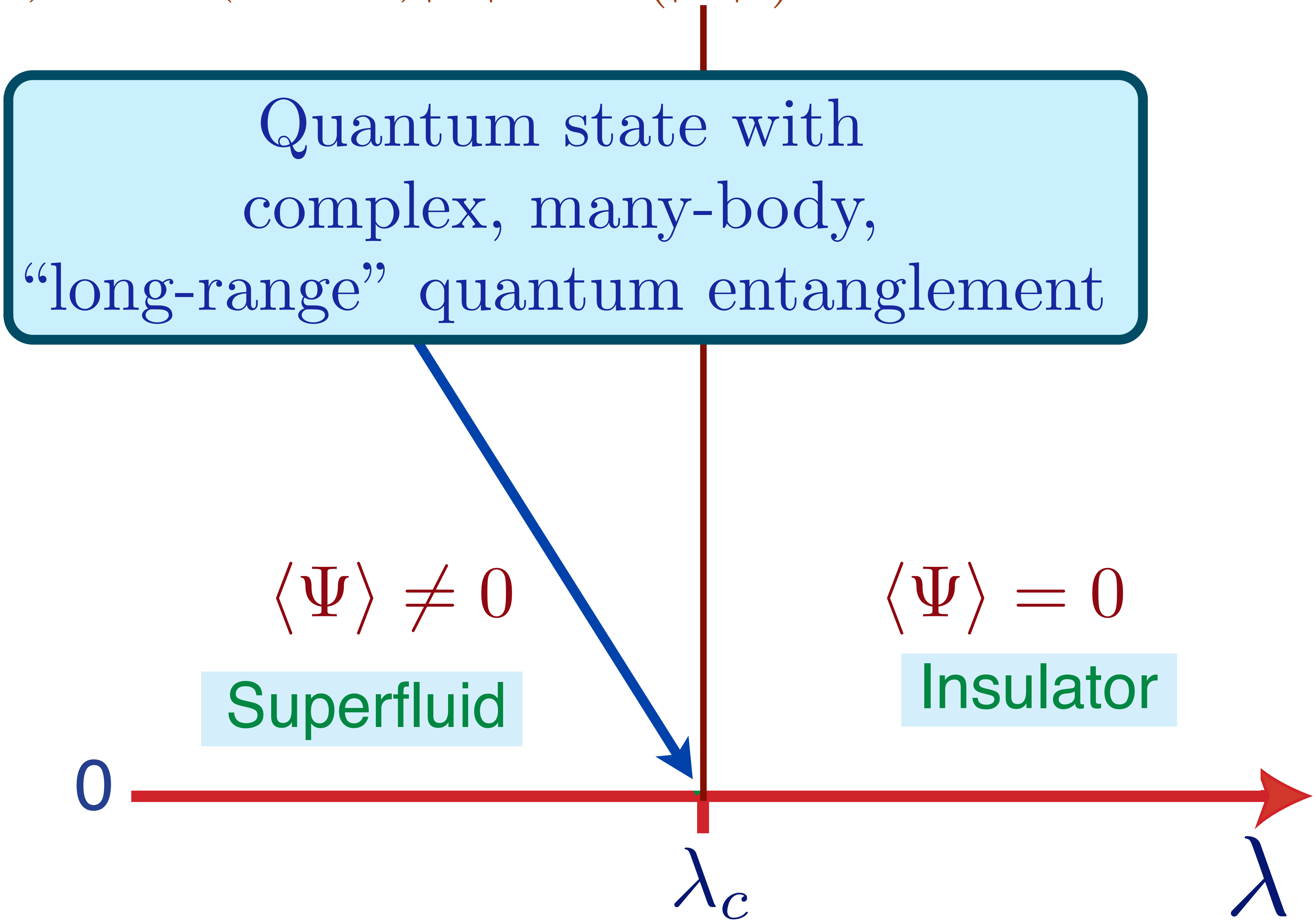

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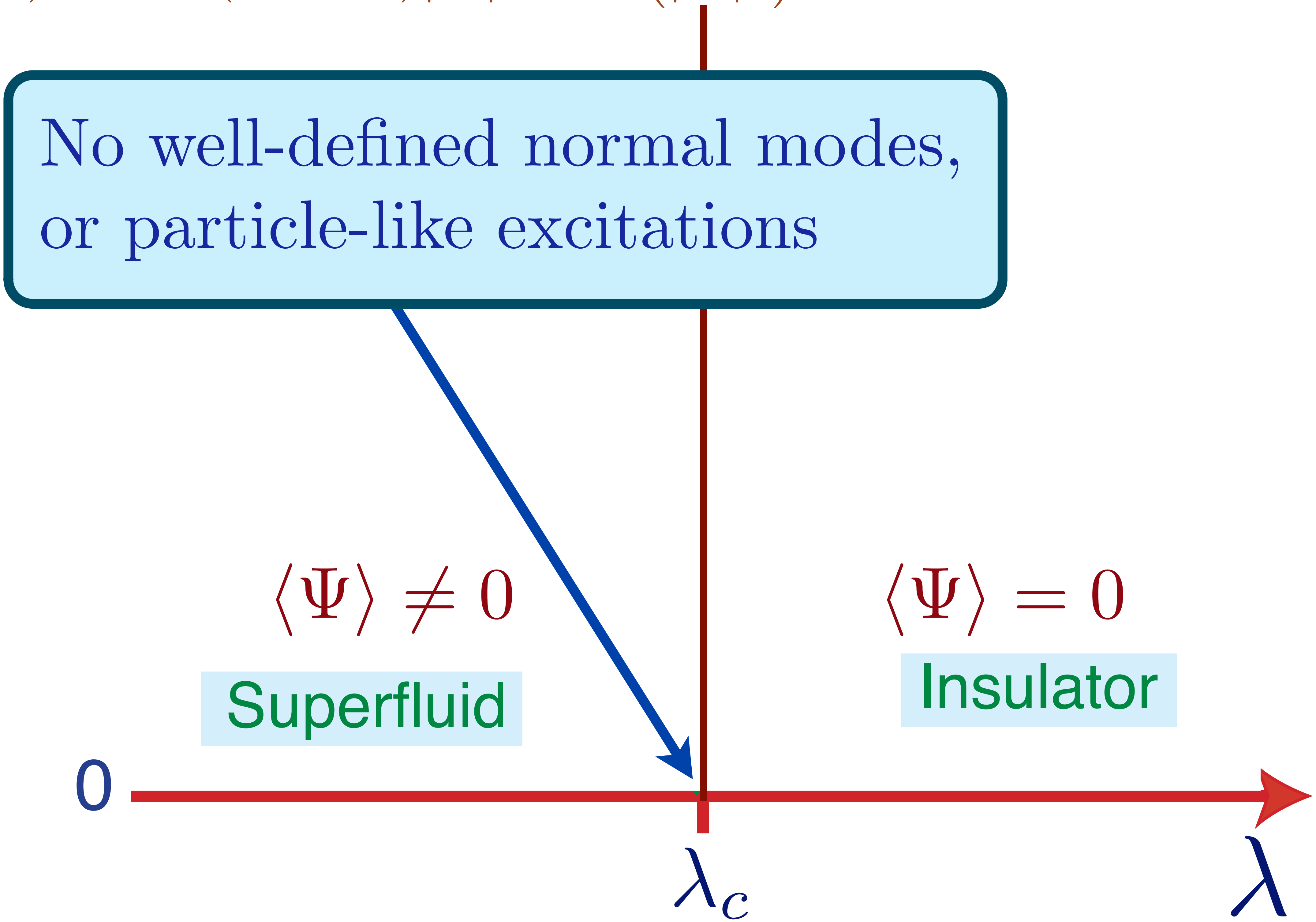

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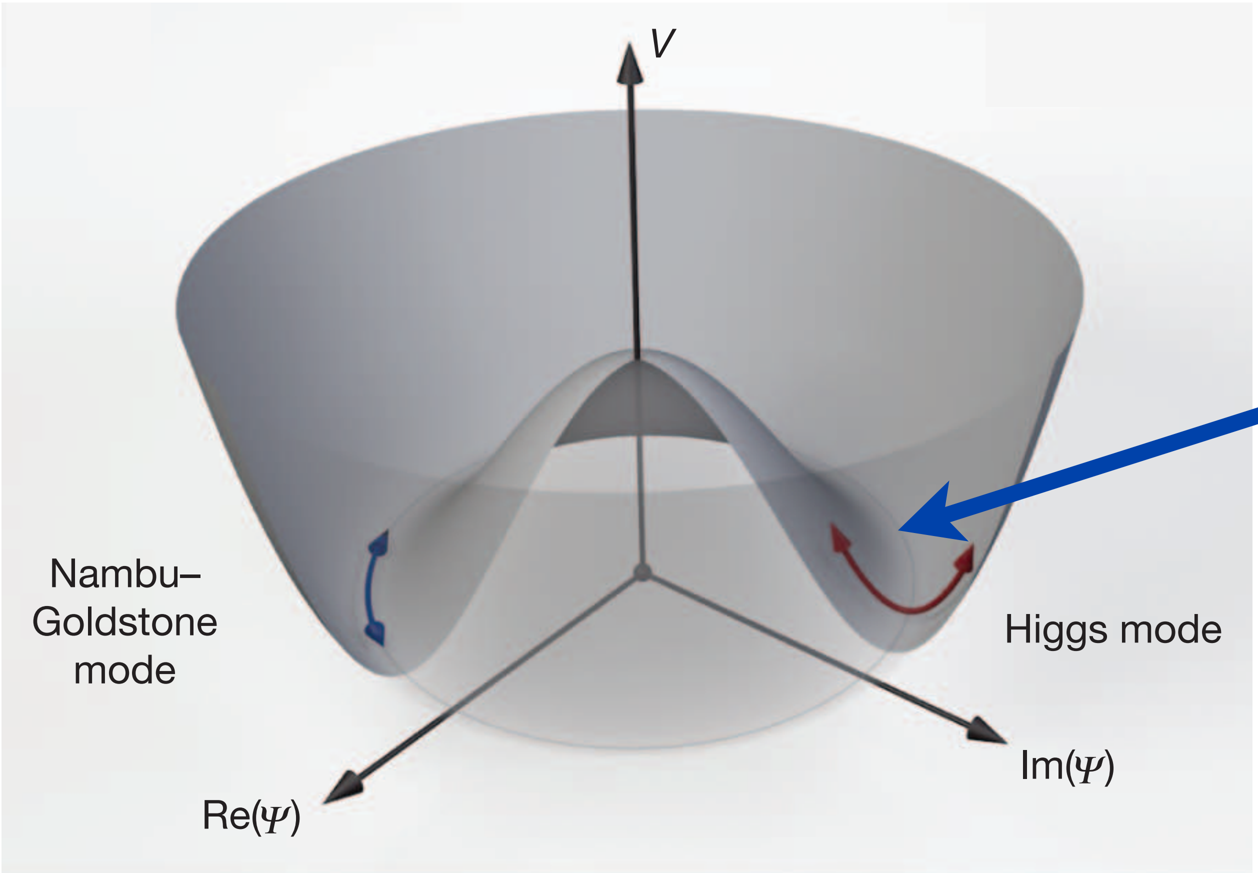


Higgs mode is the oscillation in the amplitude $|\Psi|$. This decays rapidly by emitting pairs of Nambu-Goldstone modes.

$\langle \Psi \rangle \neq 0$

Superfluid

$\langle \Psi \rangle = 0$

Insulator

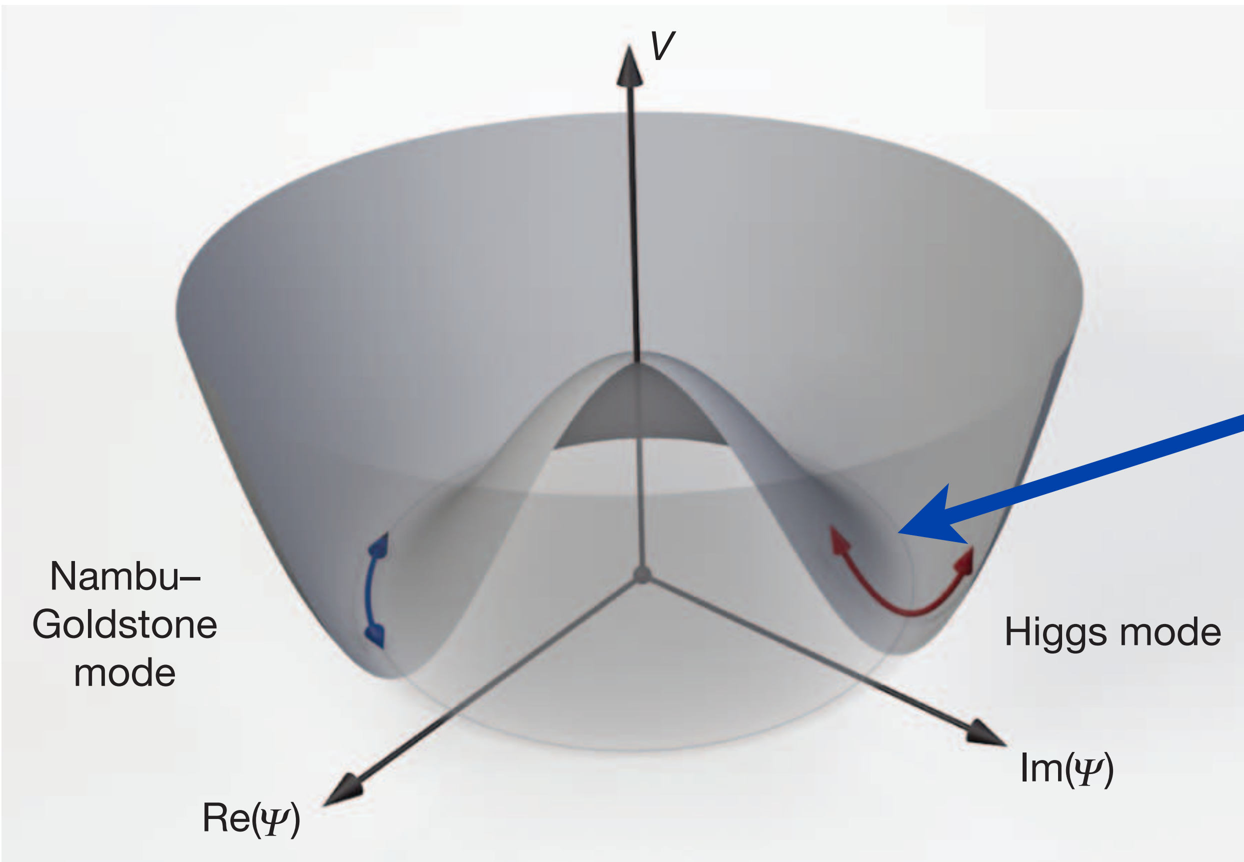
0

λ_c

λ

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

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



Despite rapid decay,
there is a well-defined
Higgs "quasi-normal mode".
This is associated with a pole
in the lower-half
of the complex frequency plane.

$\langle \Psi \rangle \neq 0$

Superfluid

$\langle \Psi \rangle = 0$

Insulator

0 λ_c λ

D. Podolsky and S. Sachdev, Phys. Rev. B **86**, 054508 (2012).

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

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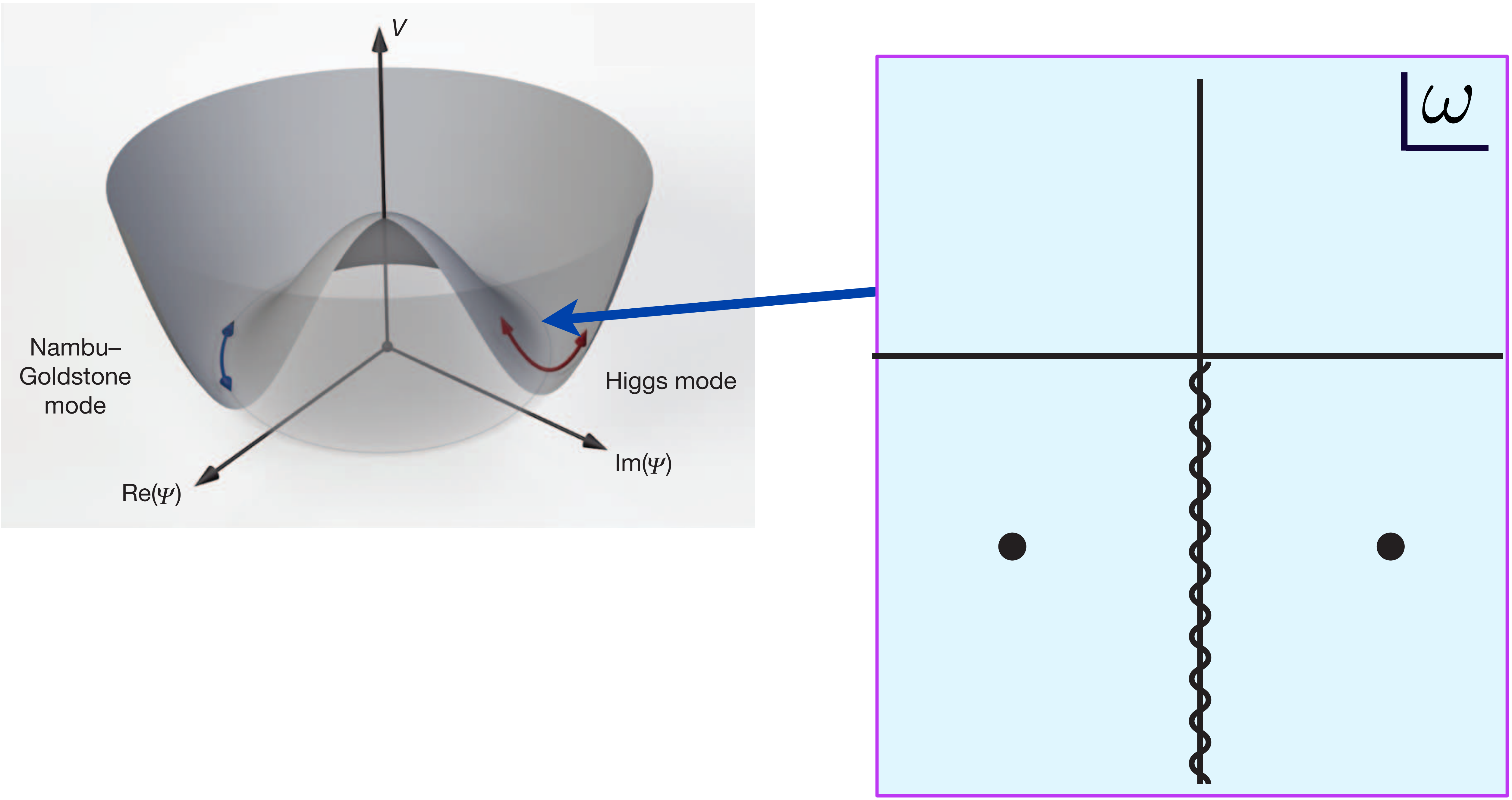
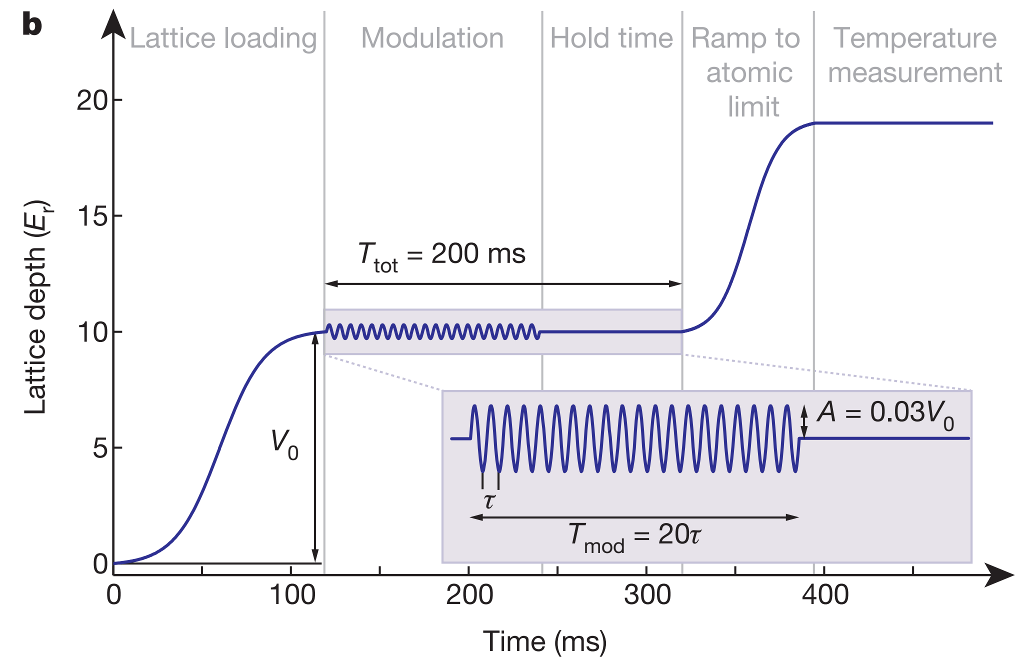
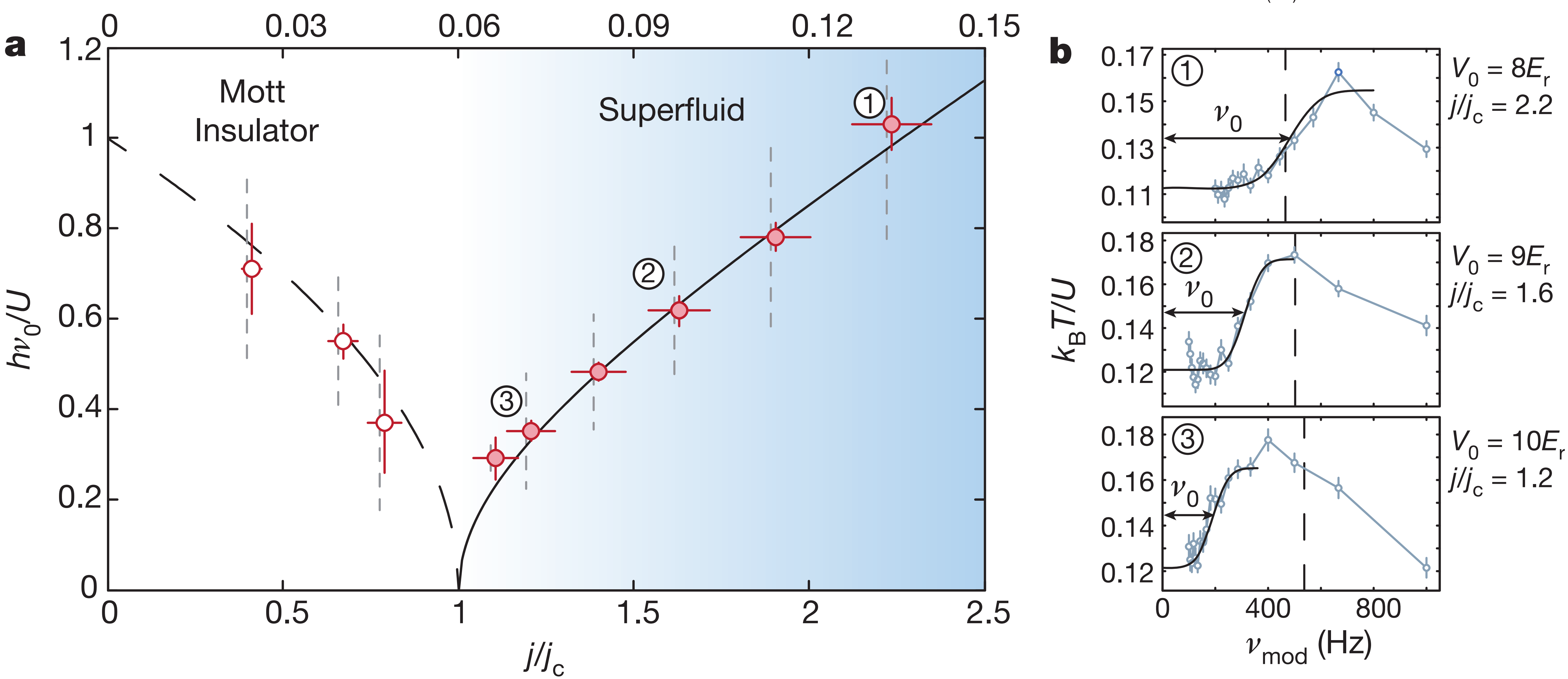


D. Podolsky and S. Sachdev, Phys. Rev. B **86**, 054508 (2012).

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

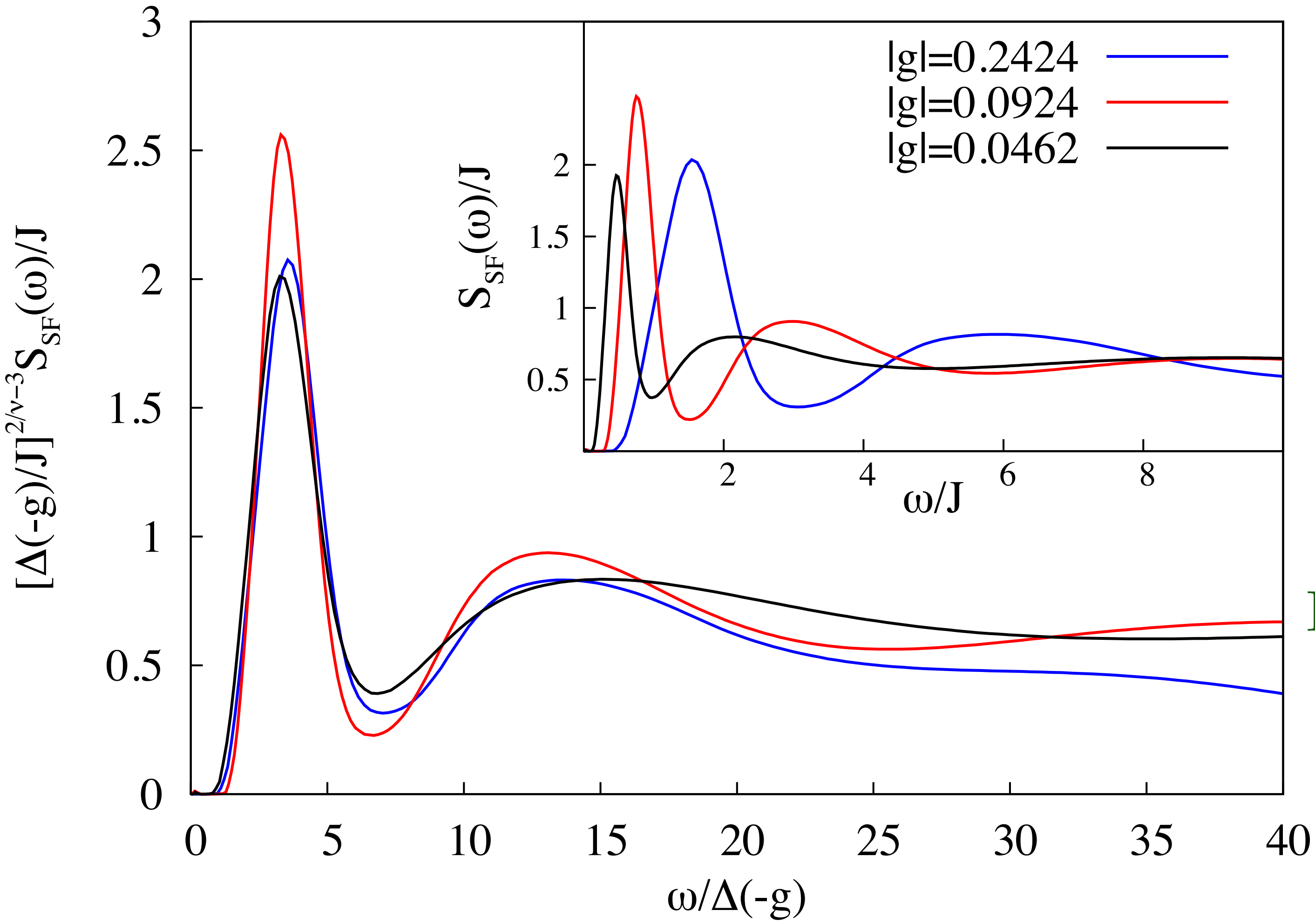
Response to modulation of lattice depth scales as expected from the LHP pole





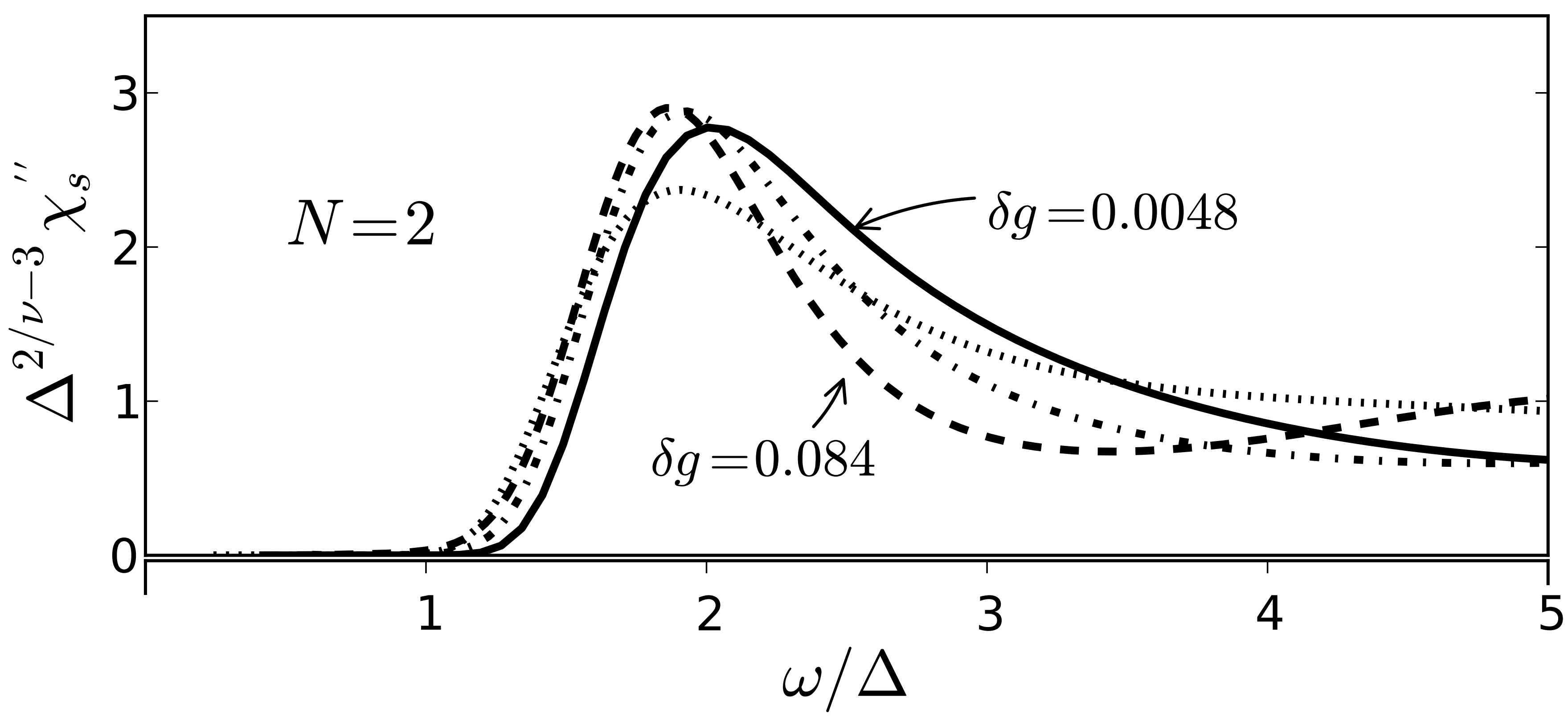
Manuel Endres, Takeshi Fukuhara, David Pekker, Marc Cheneau, Peter Schaub, Christian Gross, Eugene Demler, Stefan Kuhr, and Immanuel Bloch, *Nature* **487**, 454 (2012).

Observation of Higgs quasi-normal mode in quantum Monte Carlo



Scaling of spectral response functions predicted in D. Podolsky and S. Sachdev, Phys. Rev. B **86**, 054508 (2012).

Kun Chen, Longxiang Liu, Youjin Deng, Lode Pollet, and Nikolay Prokof'ev, arXiv:1301.3139



Snir Gazit, Daniel Podolsky, and Assa Auerbach, arXiv:1212.3759

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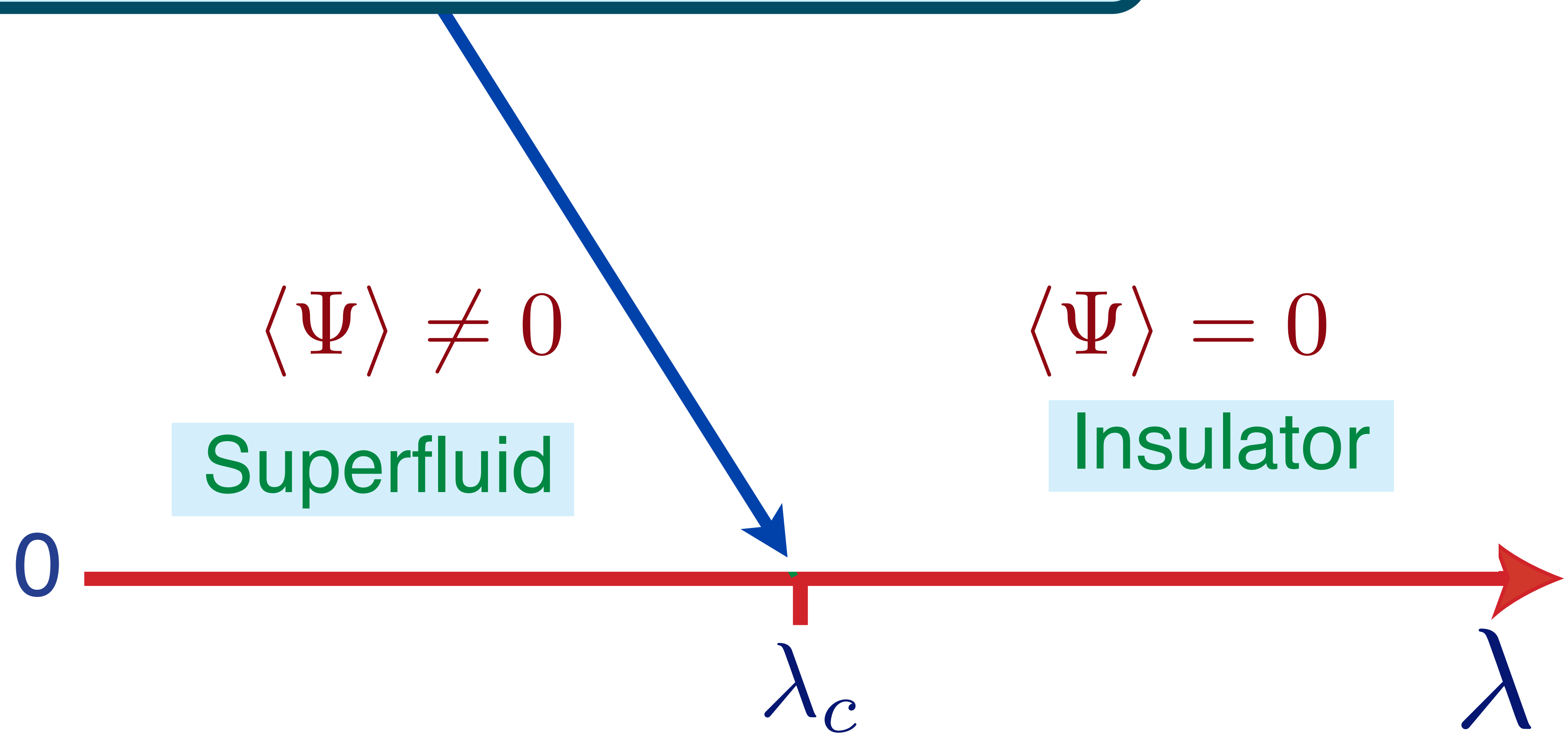
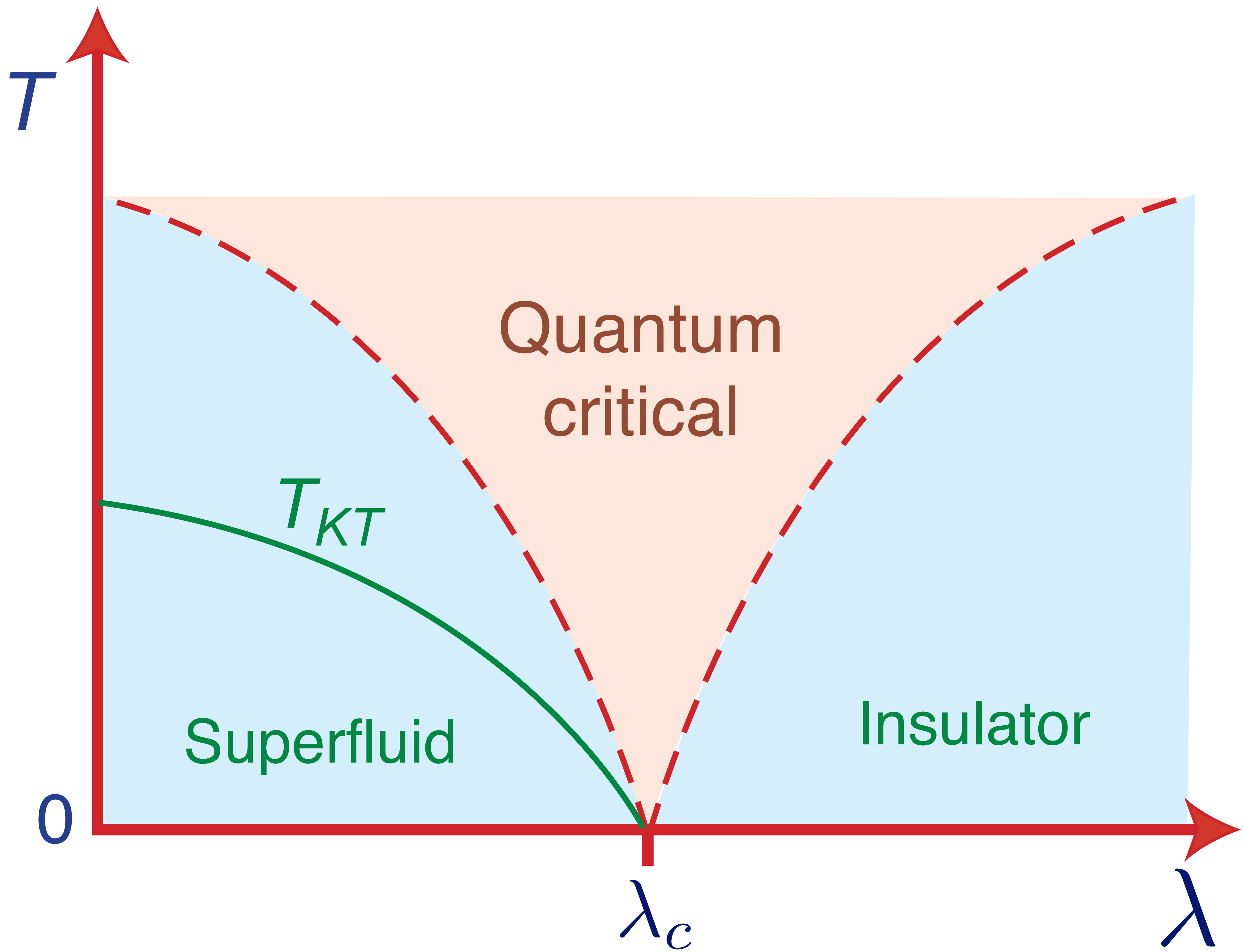
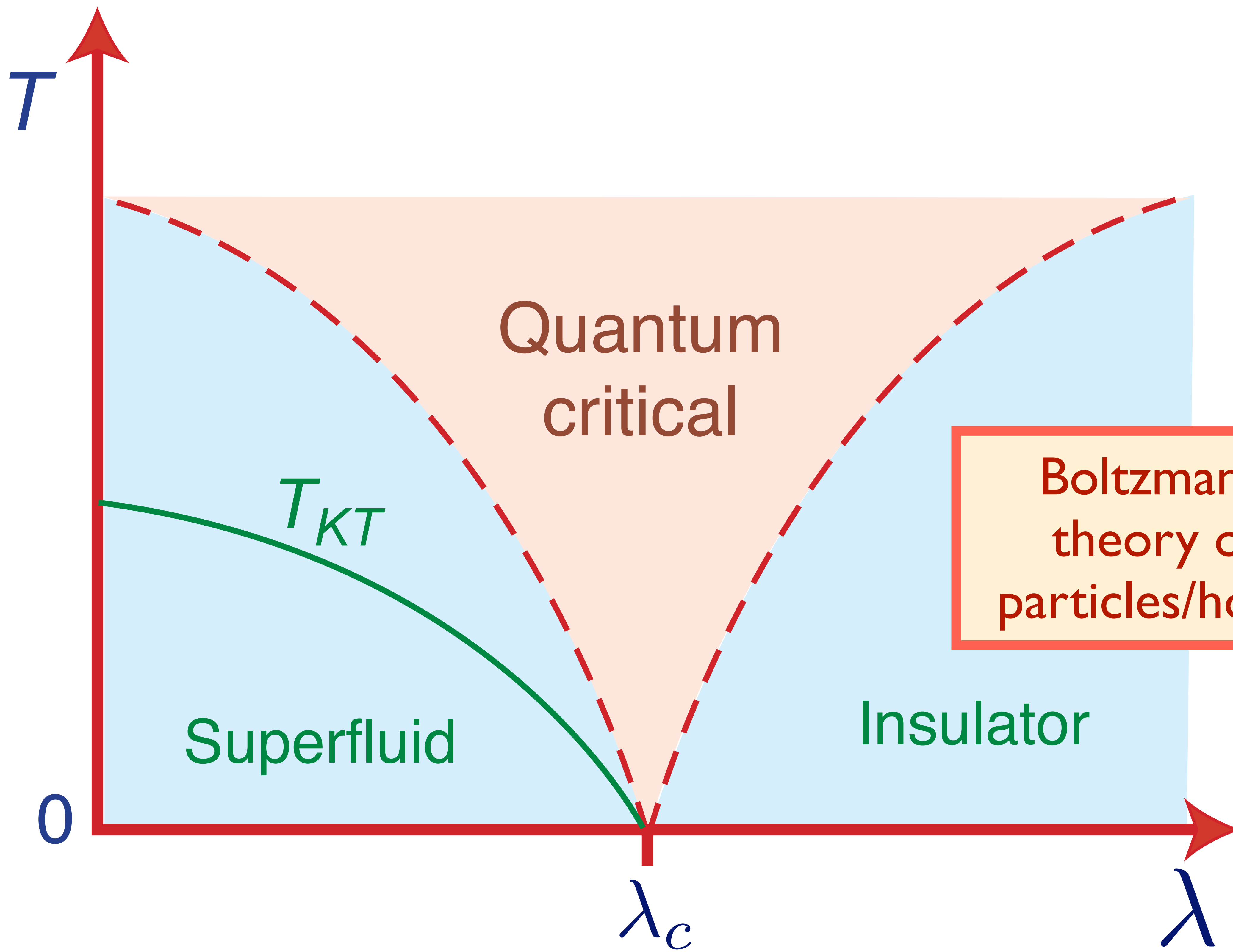
A conformal field theory
in 2+1 spacetime dimensions:
a CFT3

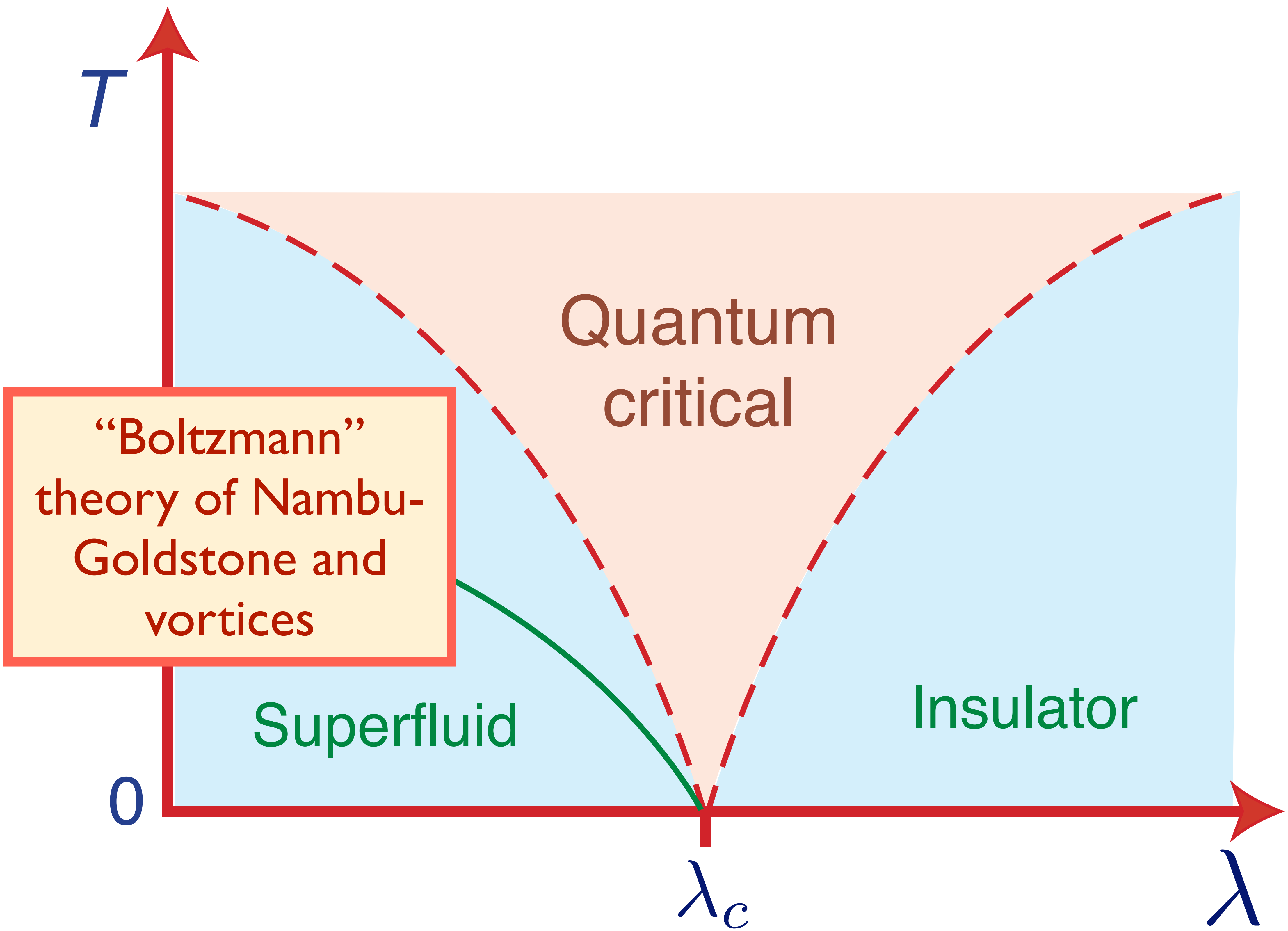


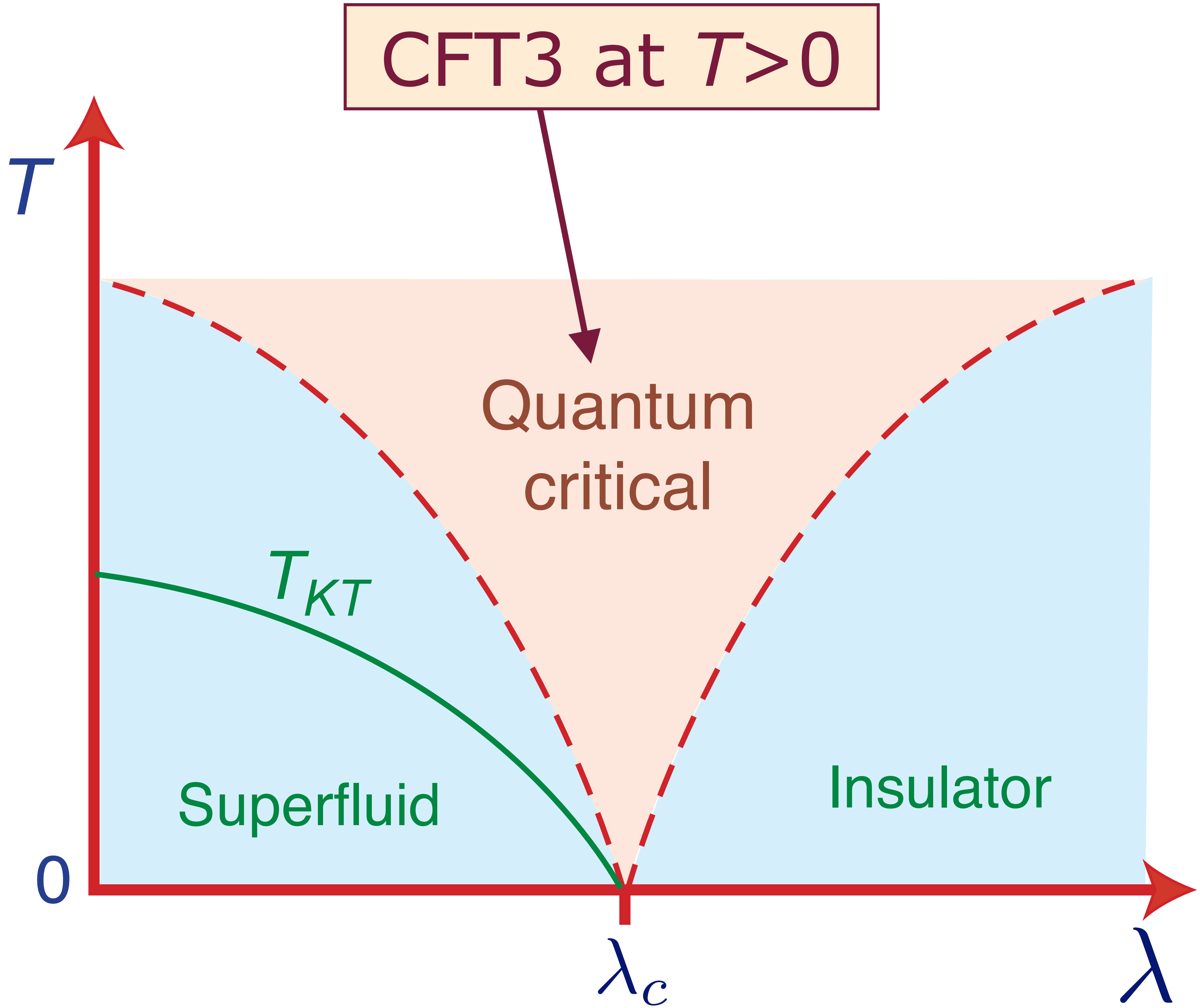


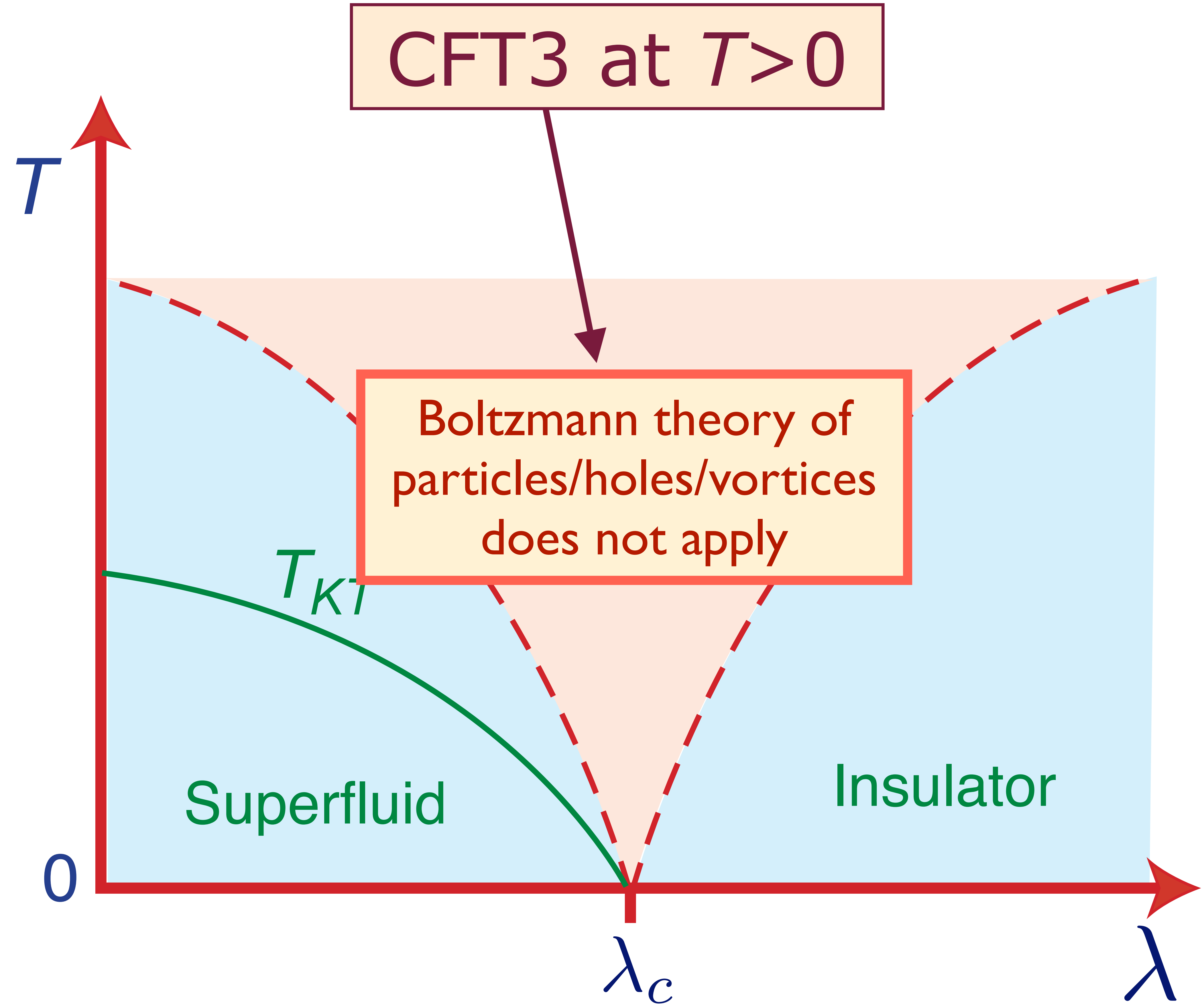
T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
λ_c
λ

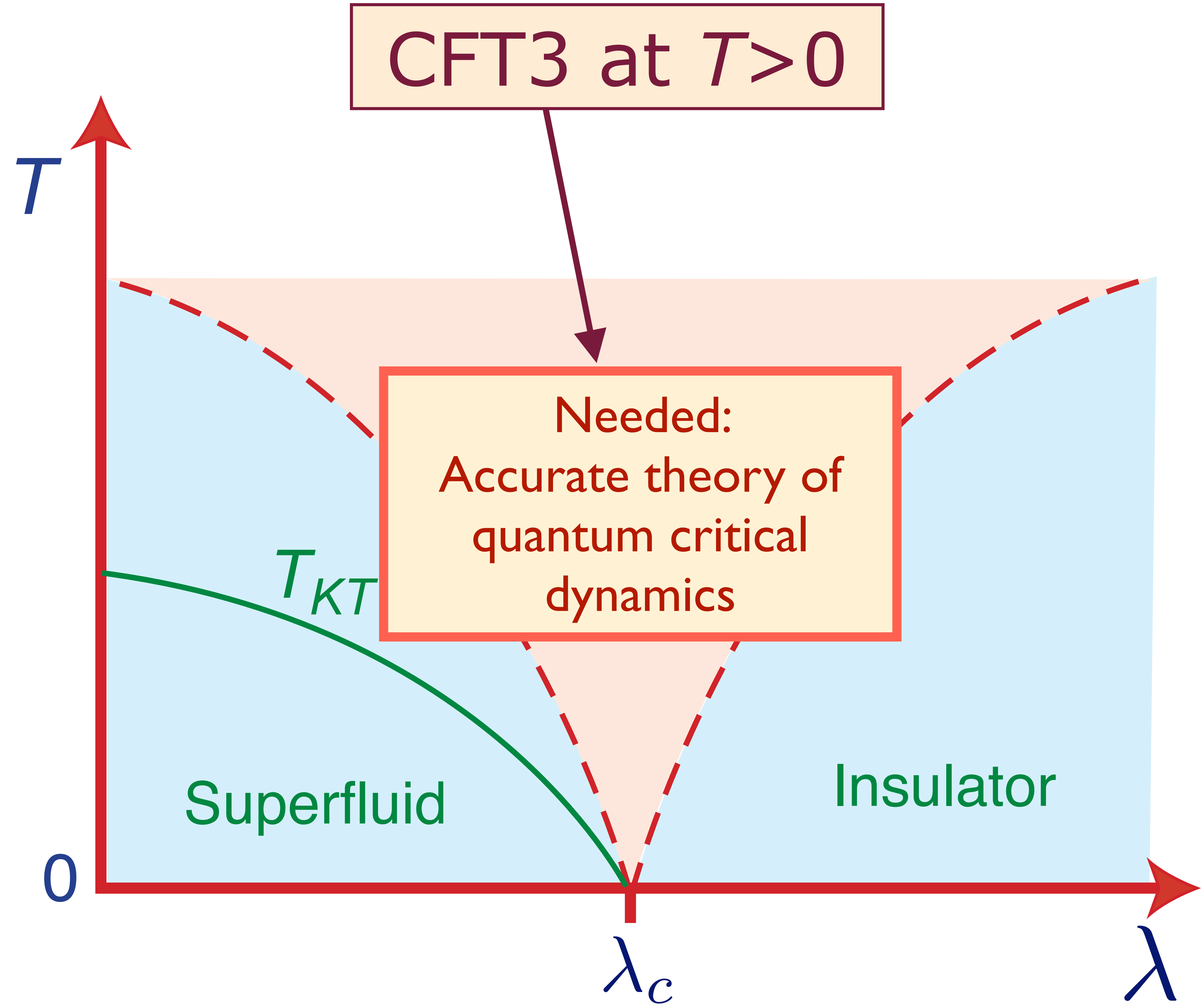


T
Quantum
critical
T_{KT}
Boltzmann
theory of
particles/holes
Superfluid
Insulator
0
λ_c
λ


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


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


CFT3 at $T>0$
T
Boltzmann theory of
particles/holes/vortices
does not apply
T_{KT}
Superfluid
Insulator
0
λ_c
λ


CFT3 at T>0
T
Needed:
Accurate theory of
quantum critical
dynamics
T_KT
Superfluid
Insulator
0
λ_c
λ

Quantum critical dynamics

Quantum *"nearly perfect fluid"*
with shortest possible *local* equilibration time, τ_{eq}

$$\tau_{\text{eq}} = \mathcal{C} \frac{\hbar}{k_B T}$$

where $\mathcal{C}$ is a *universal* constant.

Response functions are characterized by poles in LHP
with $\omega \sim k_B T / \hbar$.
These poles (quasi-normal modes) appear naturally in
the holographic theory.
(Analogs of Higgs quasi-normal mode.)

S. Sachdev, *Quantum Phase Transitions,* Cambridge (1999).

Quantum critical dynamics

Transport co-oefficients not determined by collision rate of quasiparticles, but by fundamental constants of nature

Conductivity

$$\sigma = \frac{Q^2}{h} \times [\text{Universal constant } \mathcal{O}(1)\ ]$$

(Q is the "charge" of one boson)

M.P.A. Fisher, G. Grinstein, and S.M. Girvin, *Phys. Rev. Lett*. **64**, 587 (1990)
K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

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4. Strange metals:
   What lies beyond the horizon ?

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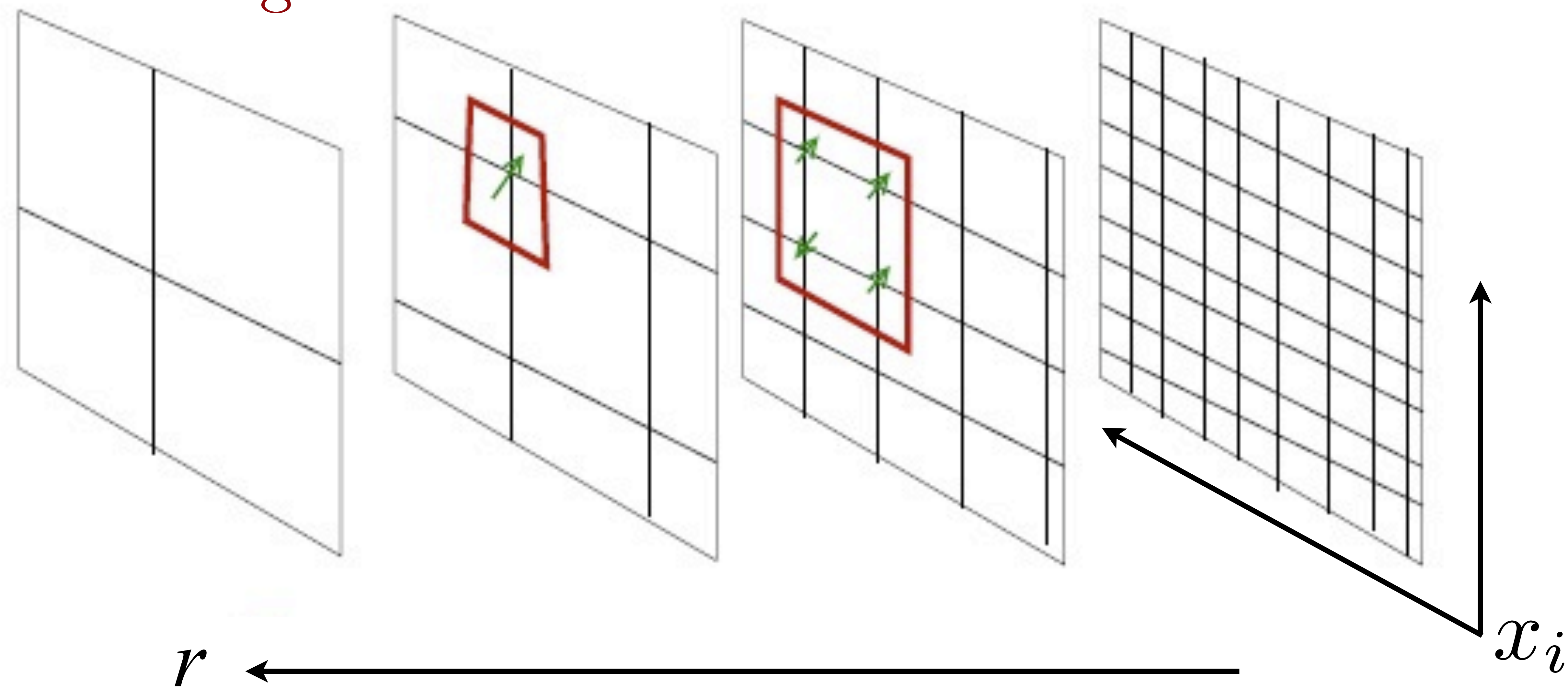
Renormalization group: $\Rightarrow$ Follow coupling constants of quantum many body theory as a function of length scale r



J. McGreevy, arXiv0909.0518

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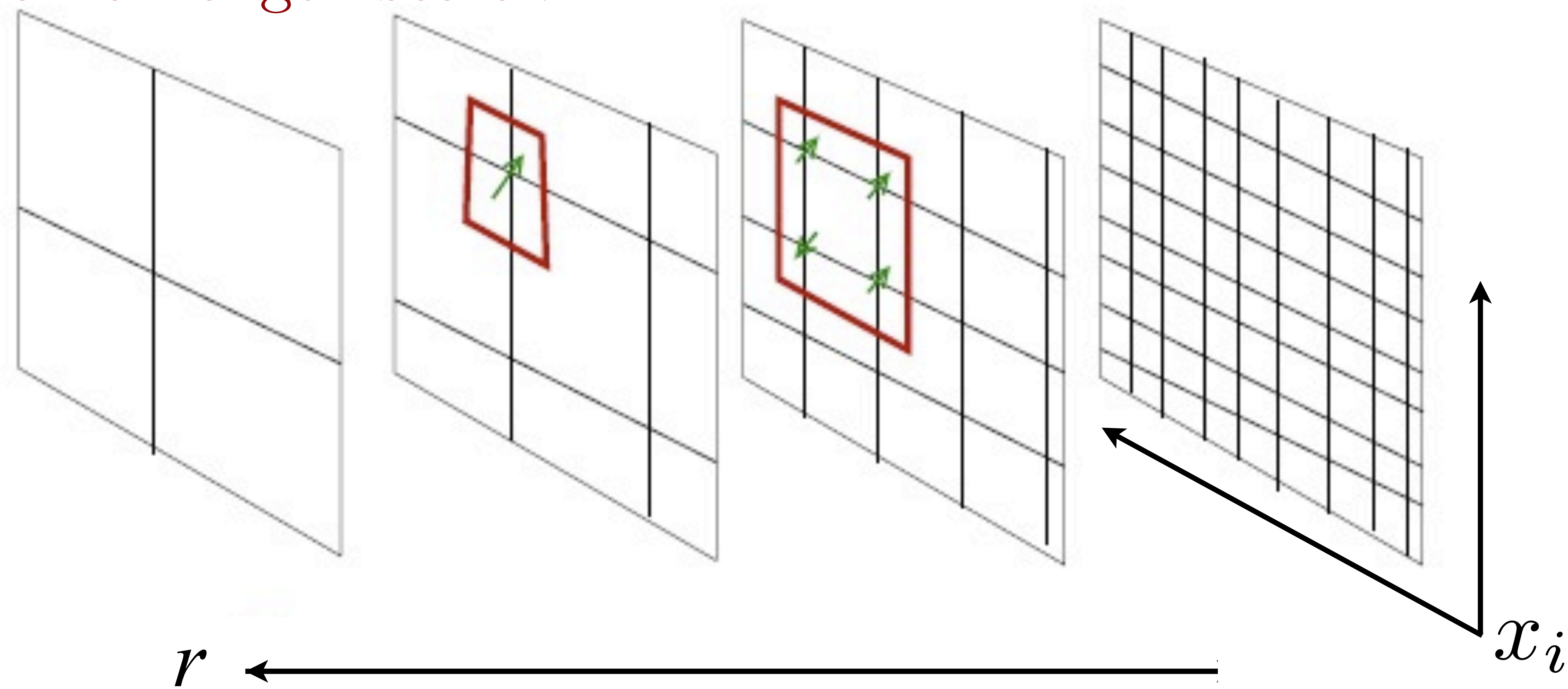
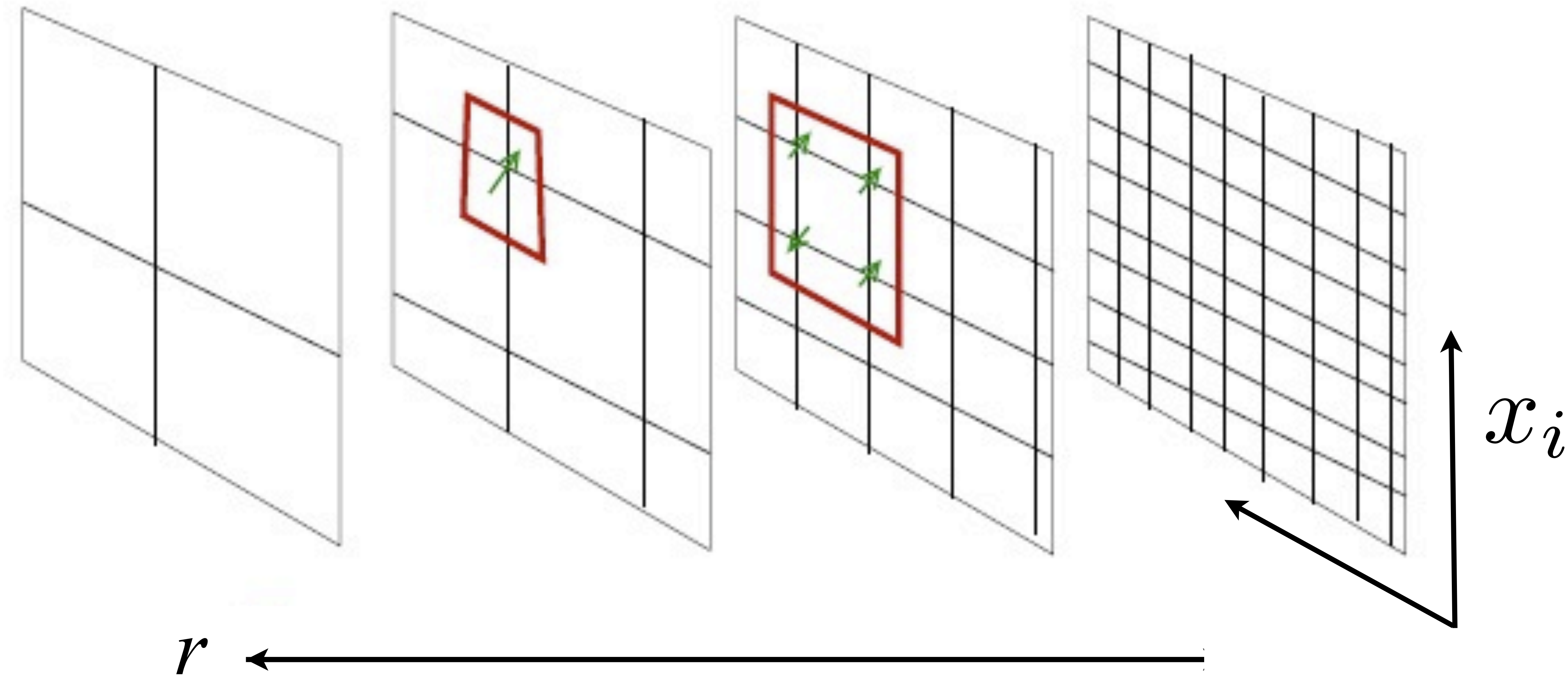


Key idea: $\Rightarrow$ Implement r as an extra dimension, and map to a local theory in $d+2$ spacetime dimensions.

J. McGreevy, arXiv0909.0518

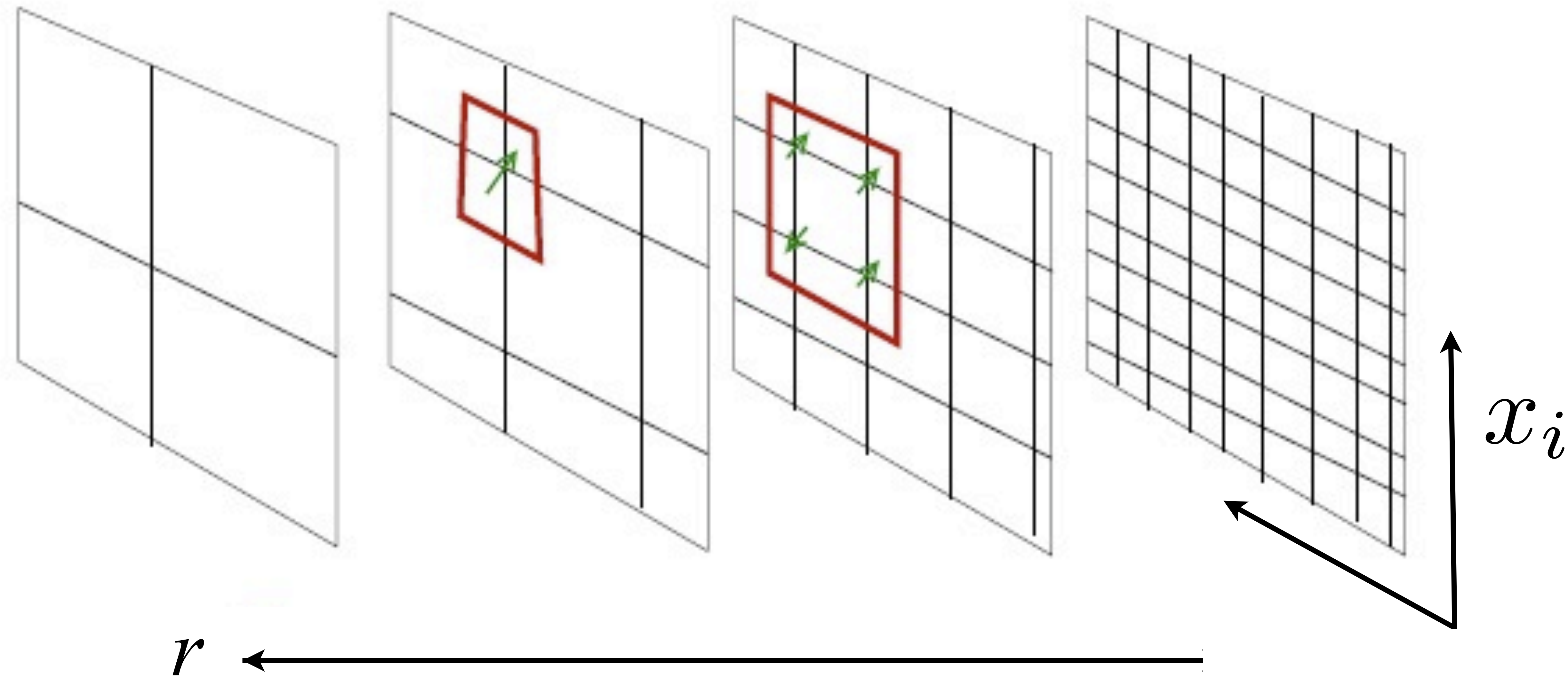
Holography



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

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

Holography

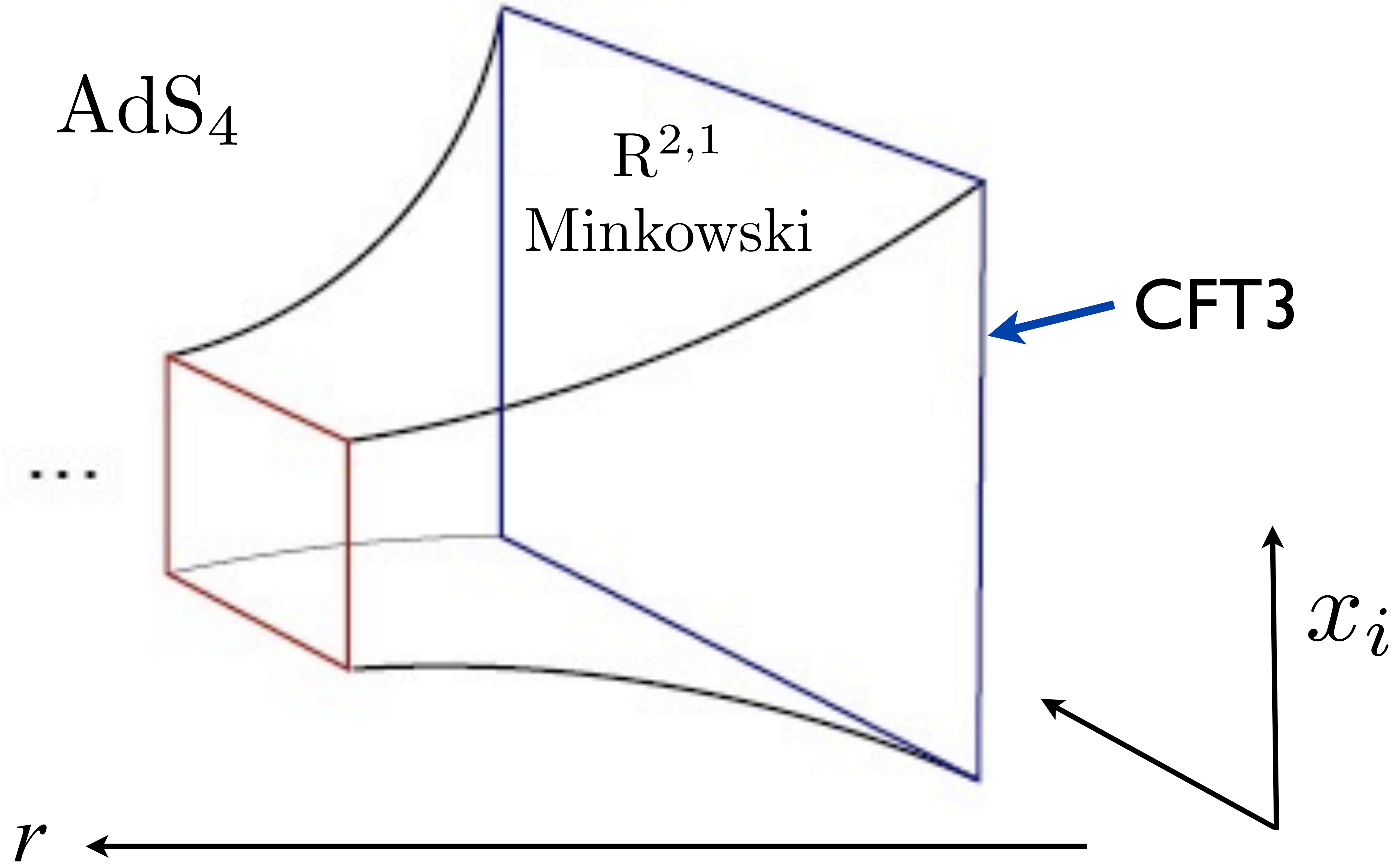


This gives the unique metric

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

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

AdS/CFT correspondence



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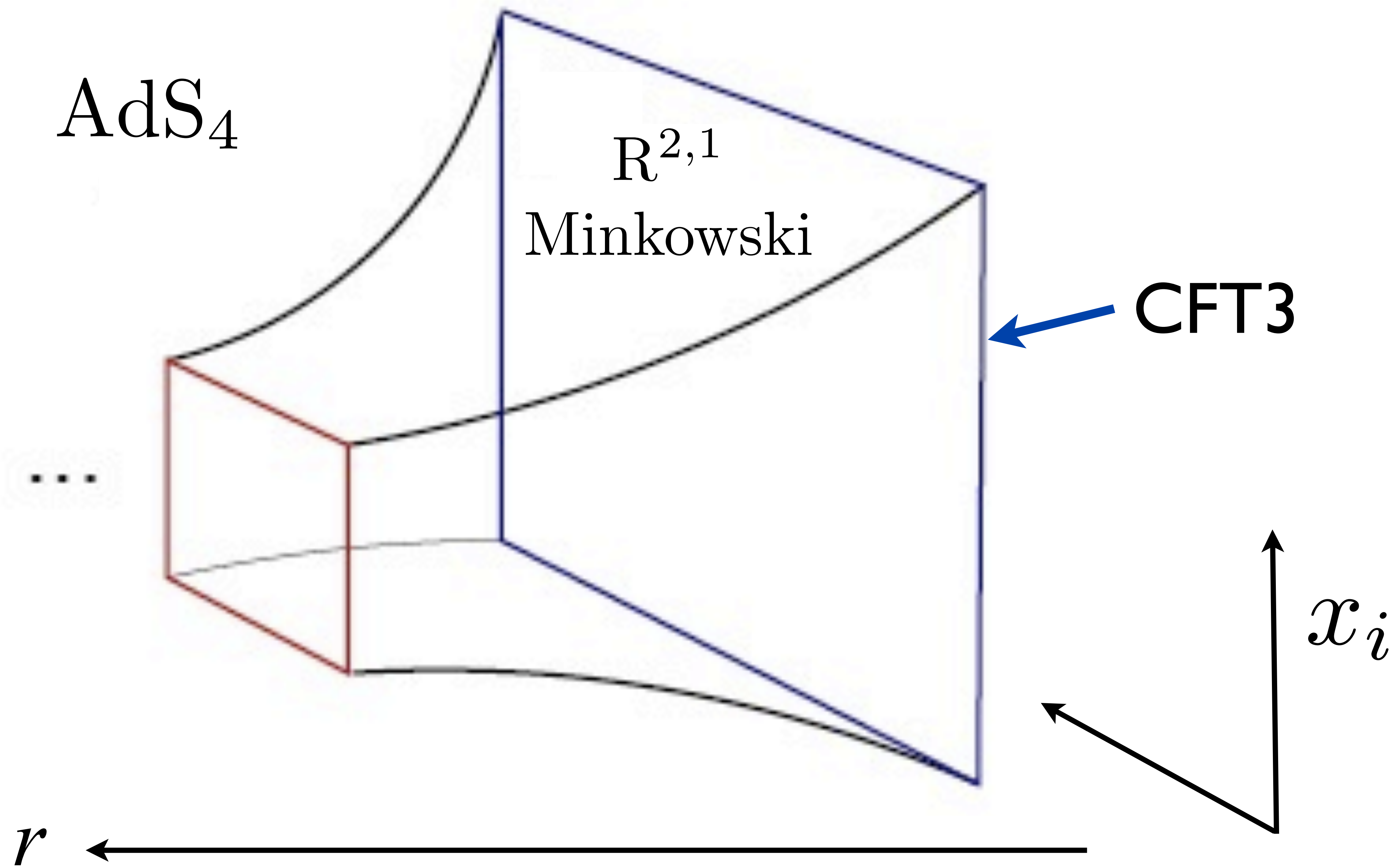

This emergent spacetime is a solution of Einstein gravity with a negative cosmological constant

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

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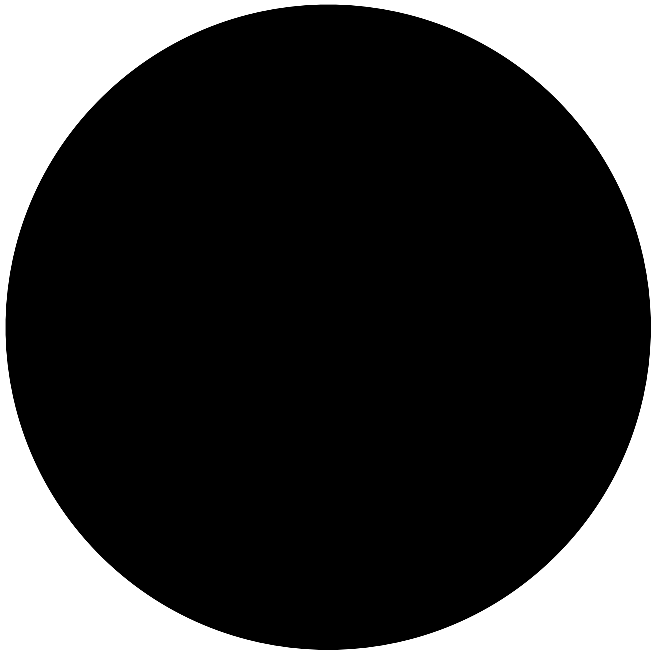
Black Holes

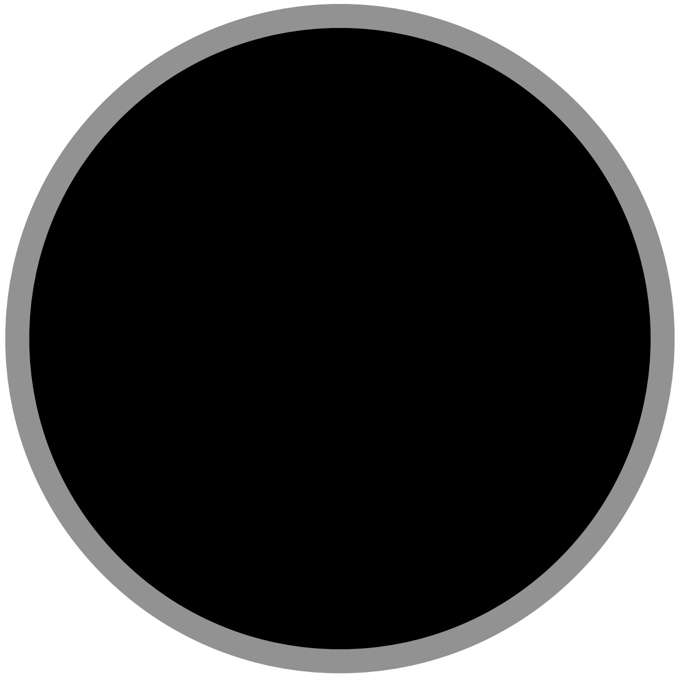
Objects so massive that light is gravitationally bound to them.



Black Holes

Objects so massive that light is gravitationally bound to them.

In Einstein's theory, the region inside the black hole horizon is disconnected from the rest of the universe.

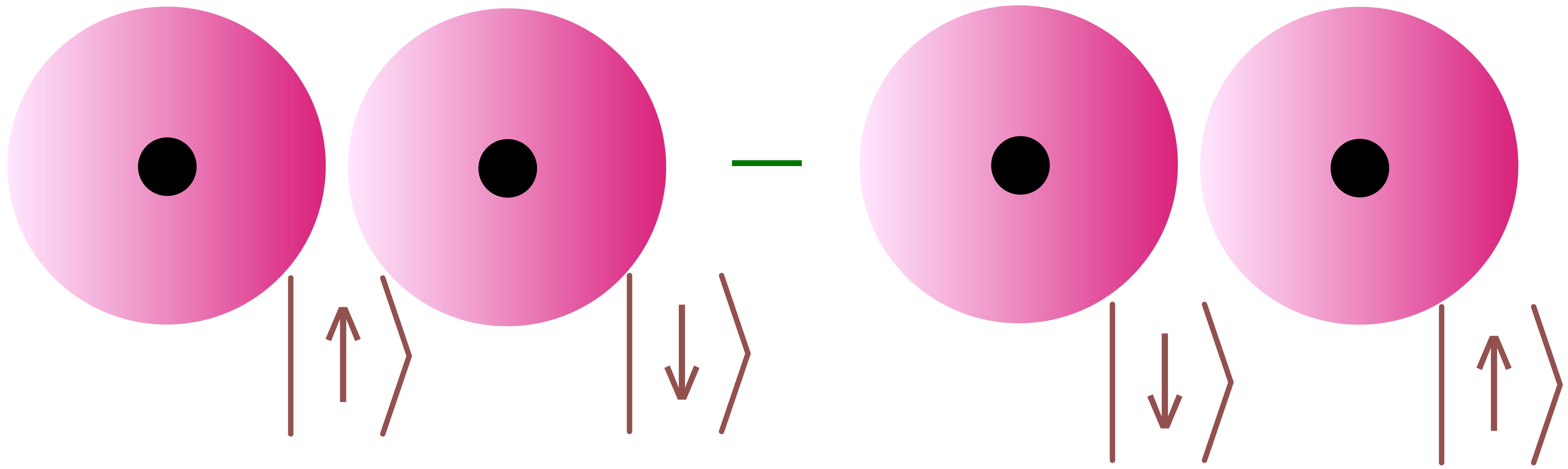


$$\text{Horizon radius } R = \frac{2GM}{c^2}$$

Black Holes + Quantum theory

Around 1974, Bekenstein and Hawking showed that the application of the quantum theory across a black hole horizon led to many astonishing conclusions

Quantum Entanglement across a black hole horizon



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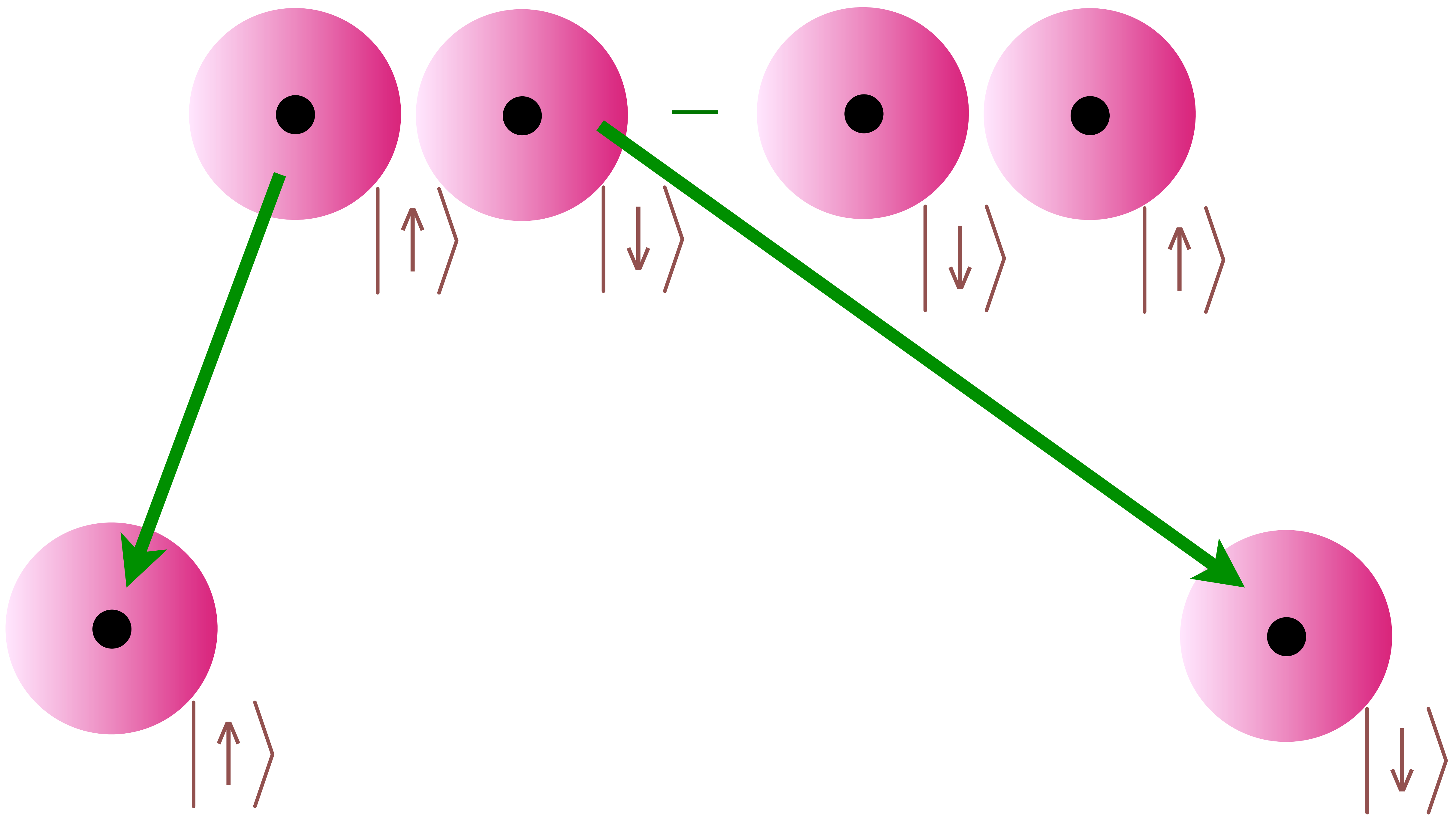

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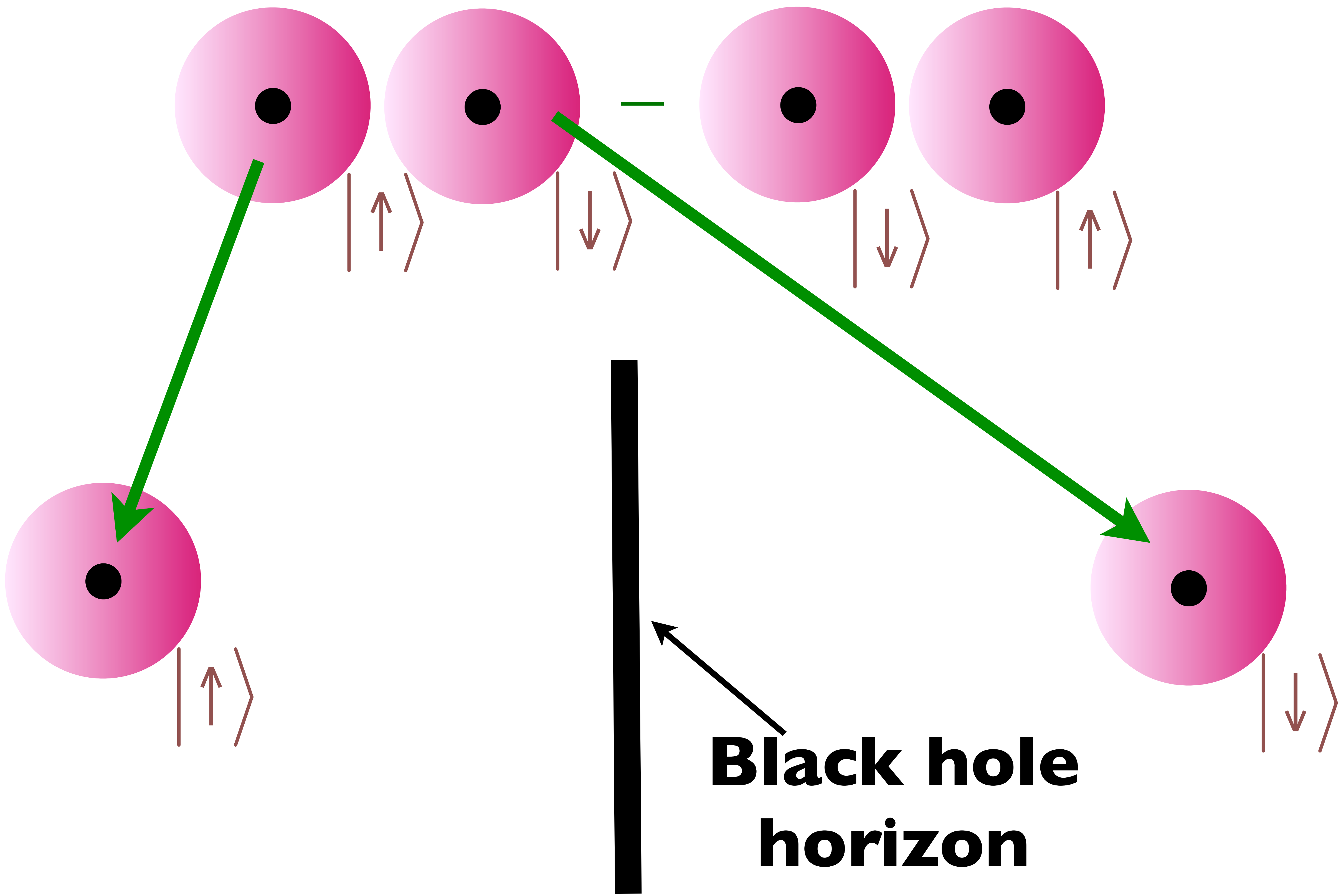

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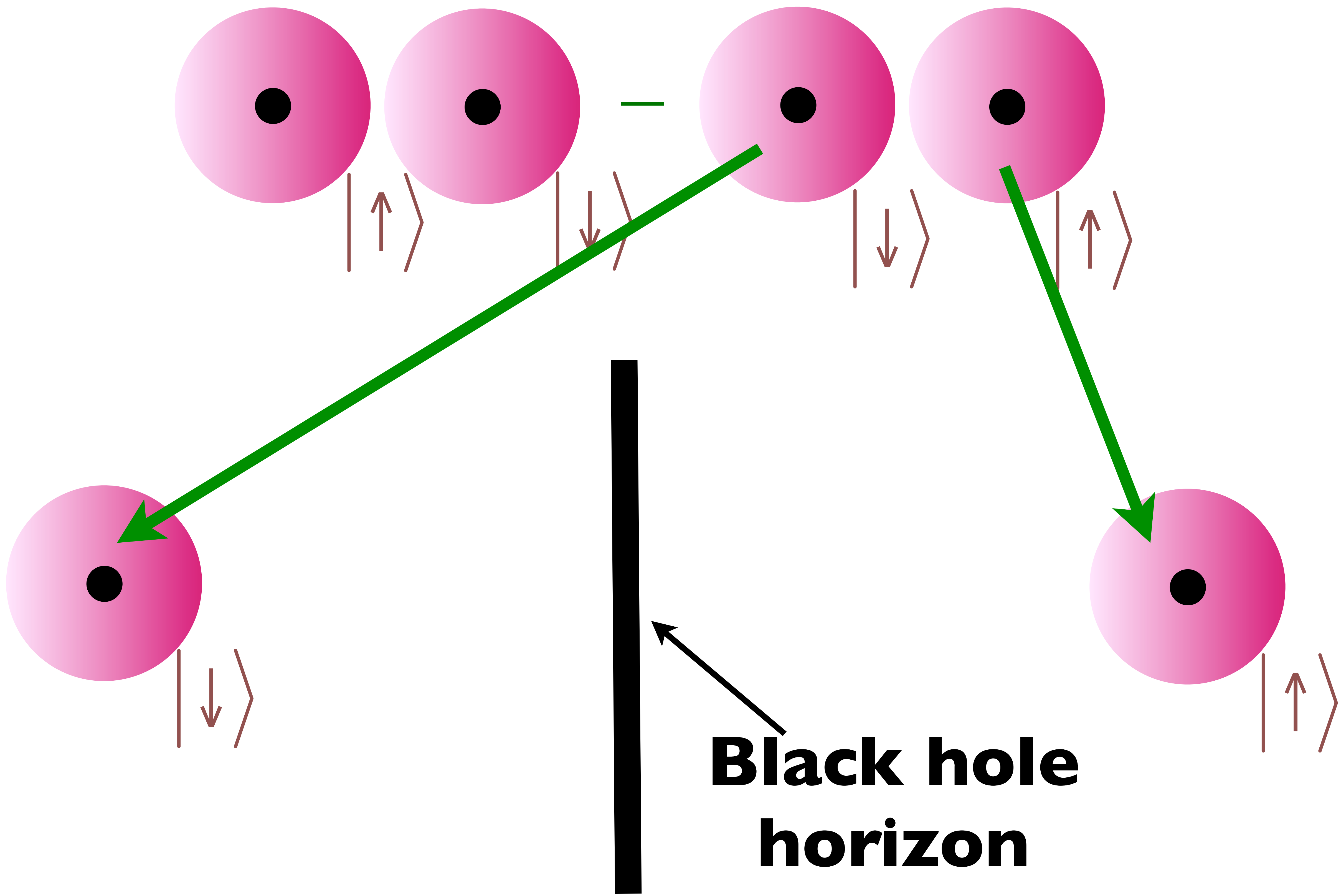
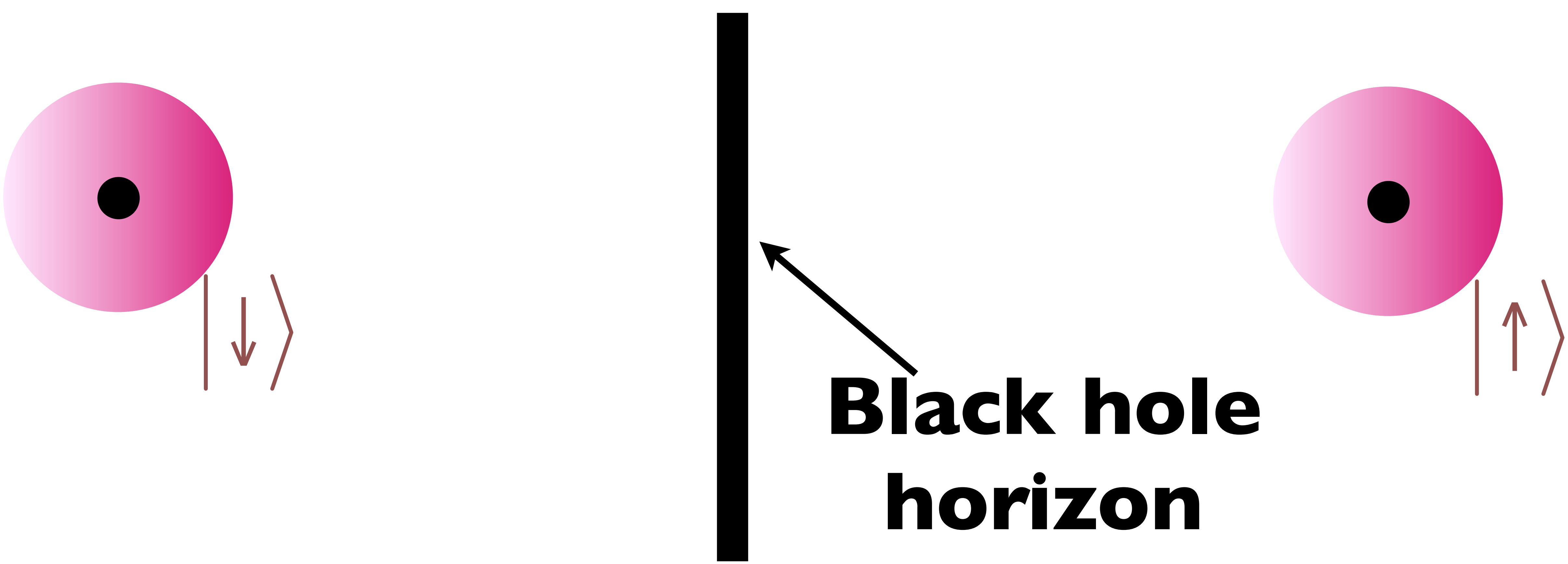


Quantum Entanglement across a black hole horizon

There is a non-local quantum entanglement between the inside and outside of a black hole



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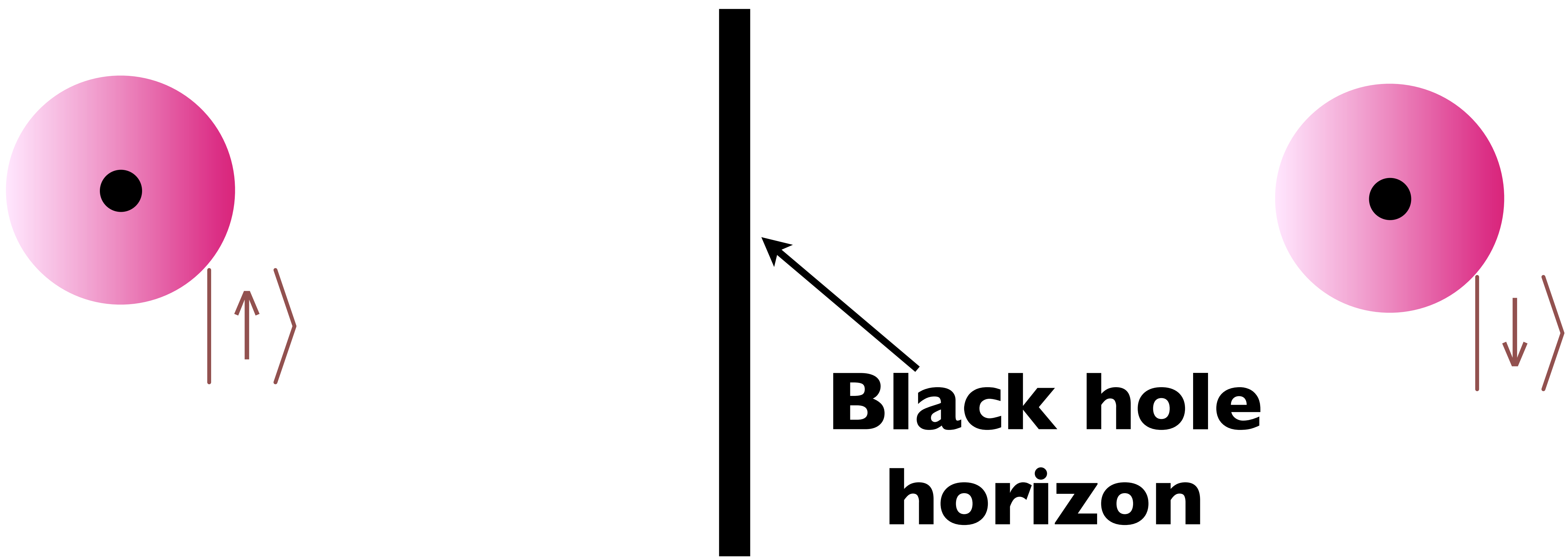
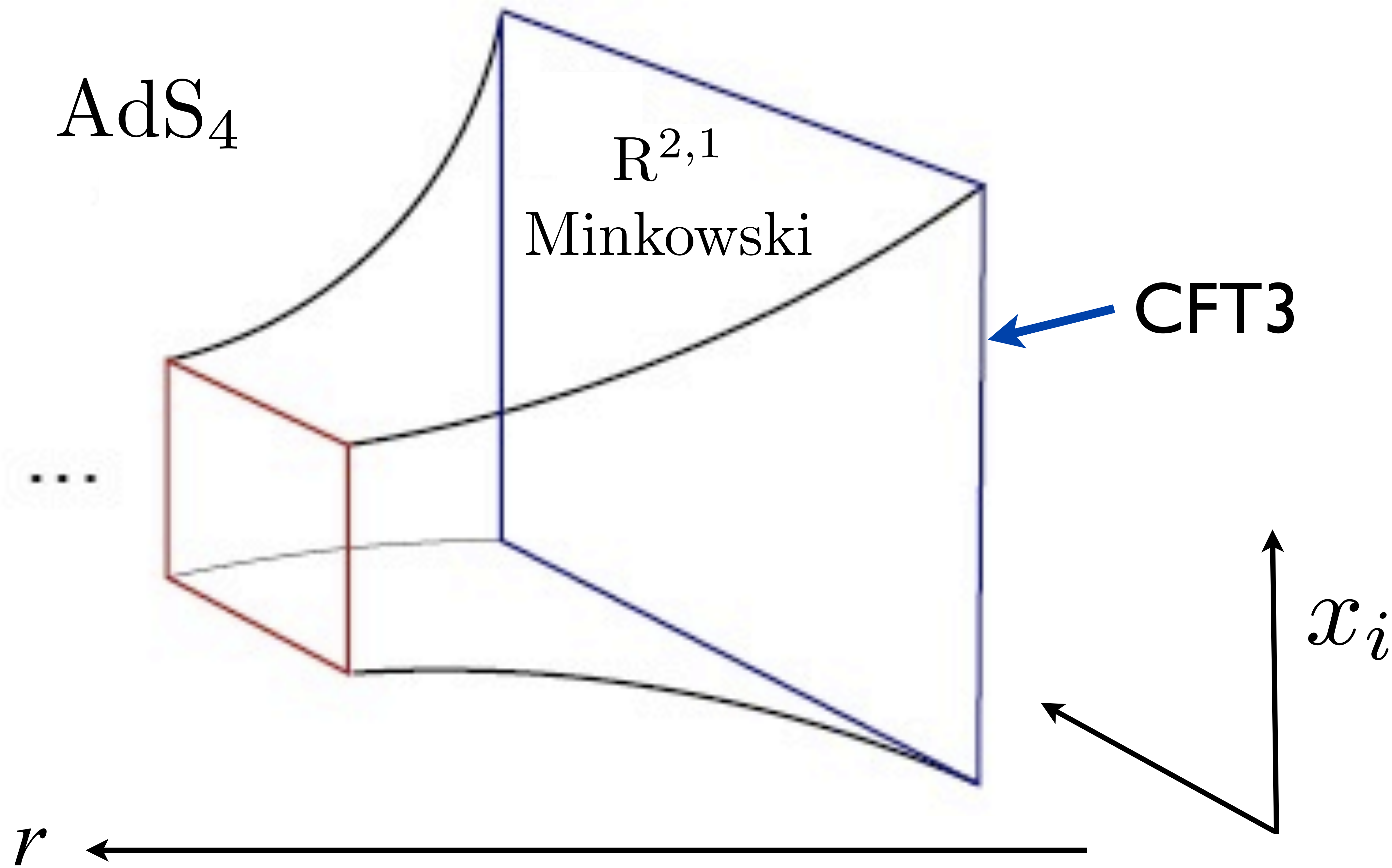


Quantum Entanglement across a black hole horizon

There is a non-local quantum entanglement between the inside and outside of a black hole

This entanglement leads to a black hole temperature (the Hawking temperature) and a black hole entropy (the Bekenstein entropy)

AdS/CFT correspondence



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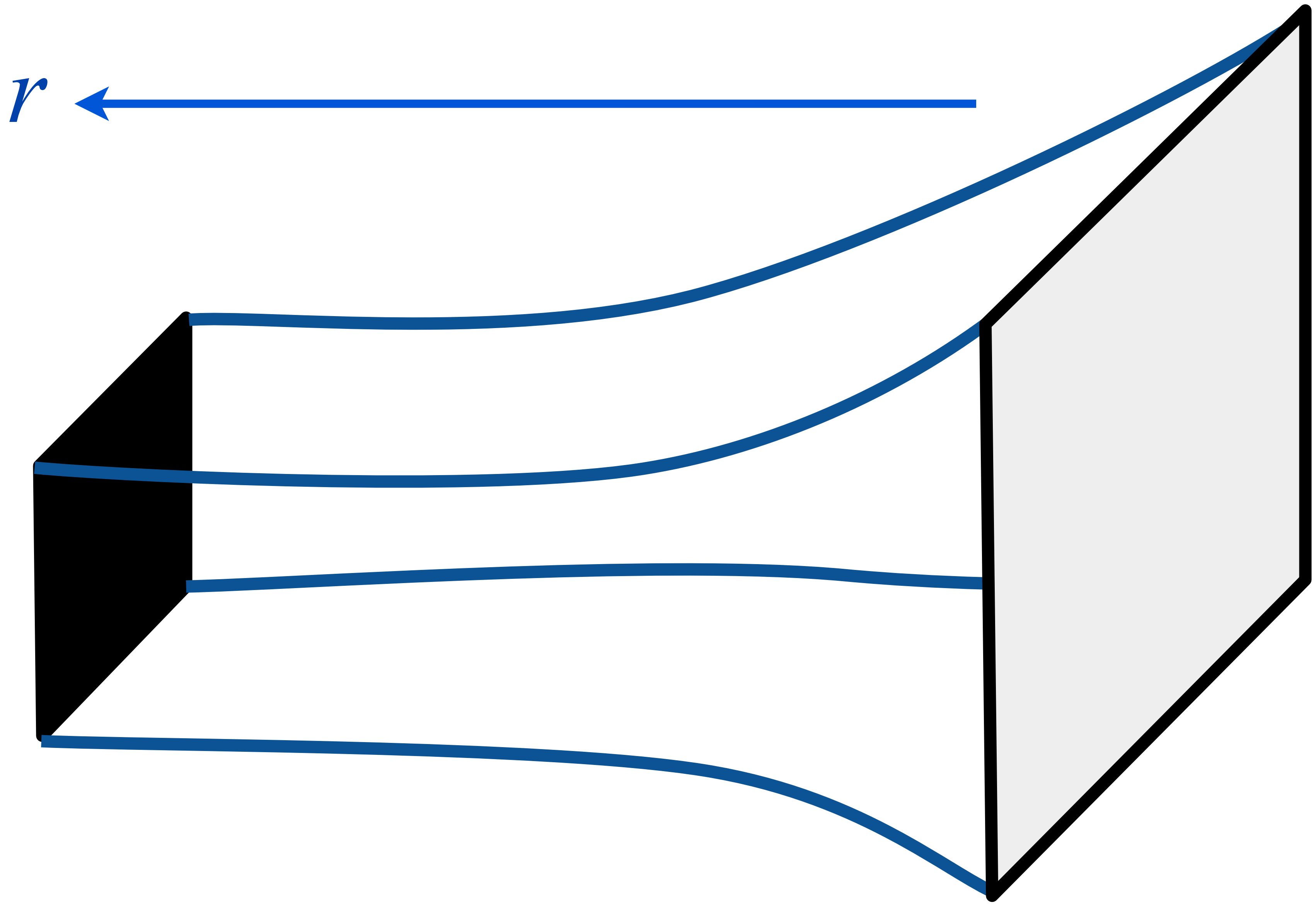
Gauge-gravity duality at non-zero temperatures



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

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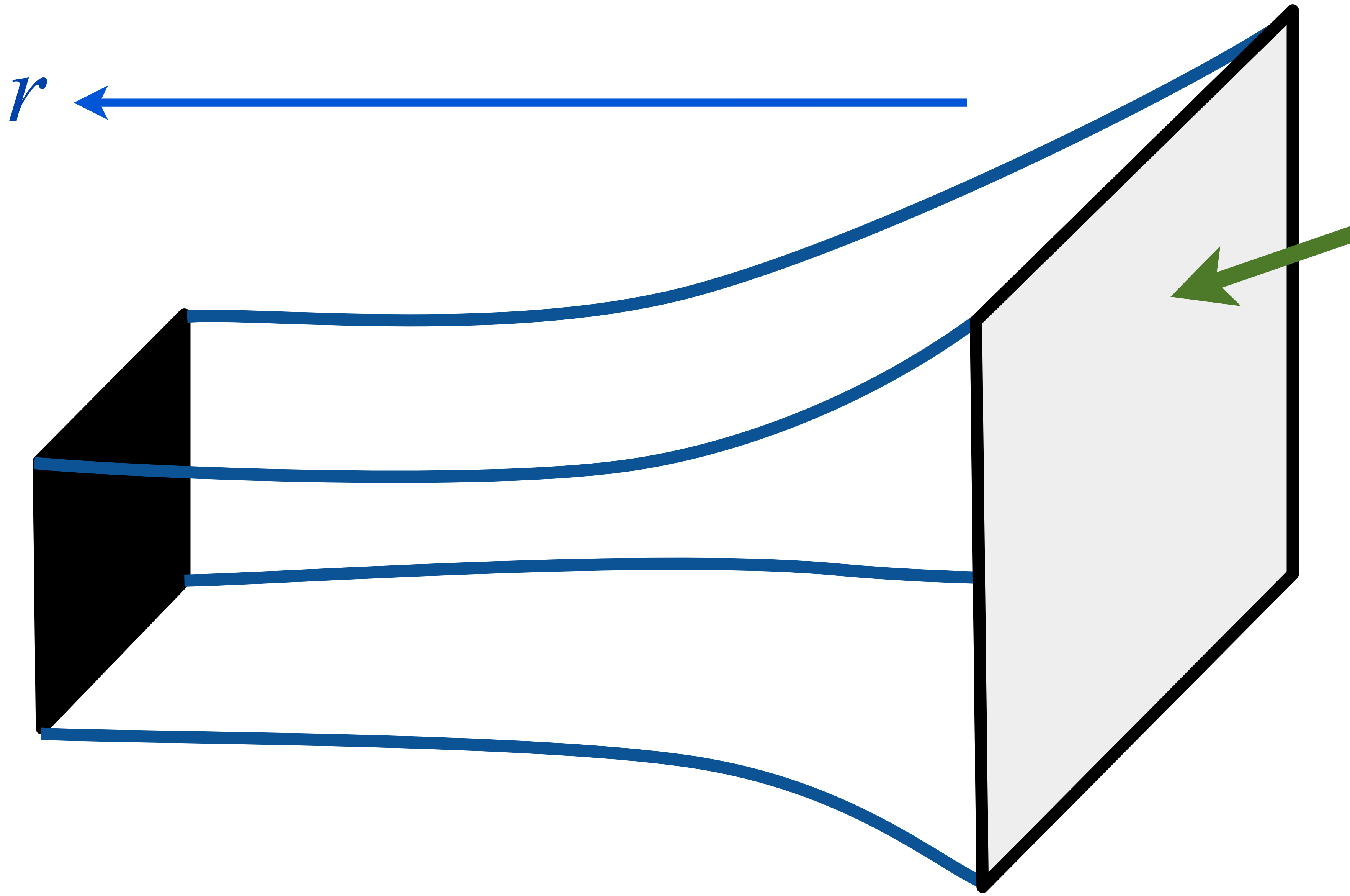

A 2+1 dimensional system at $T > 0$ with couplings at its quantum critical point

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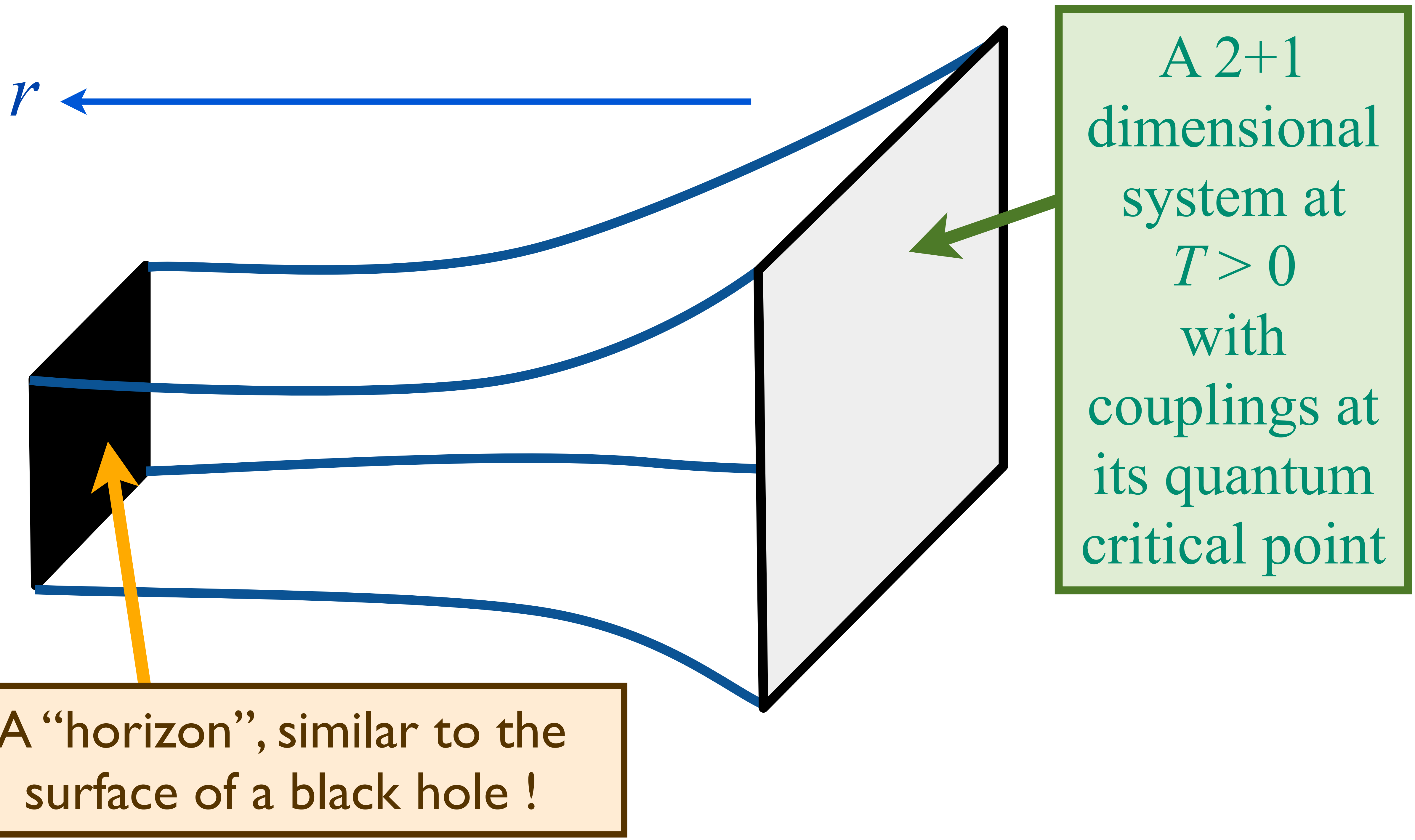

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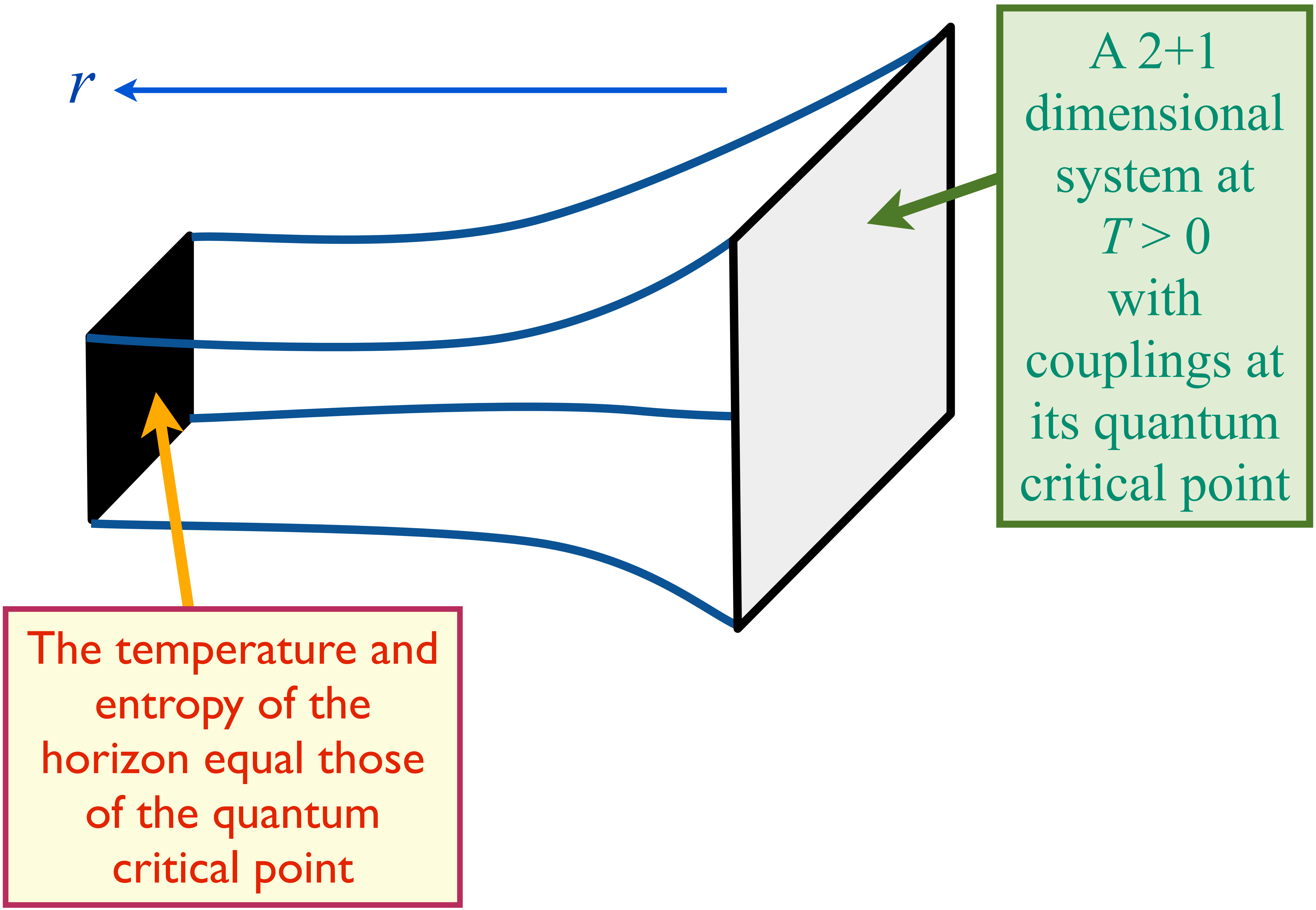

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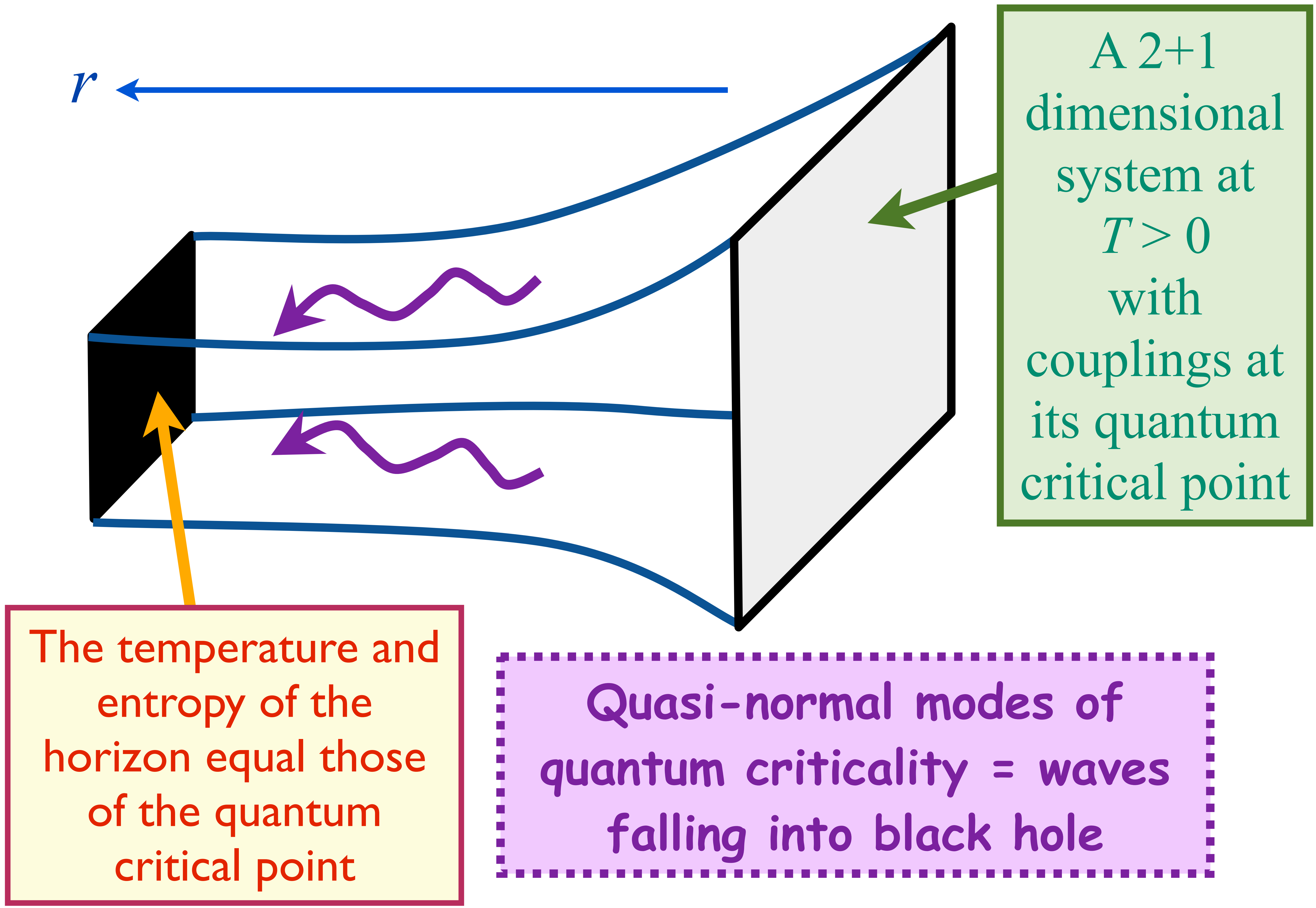

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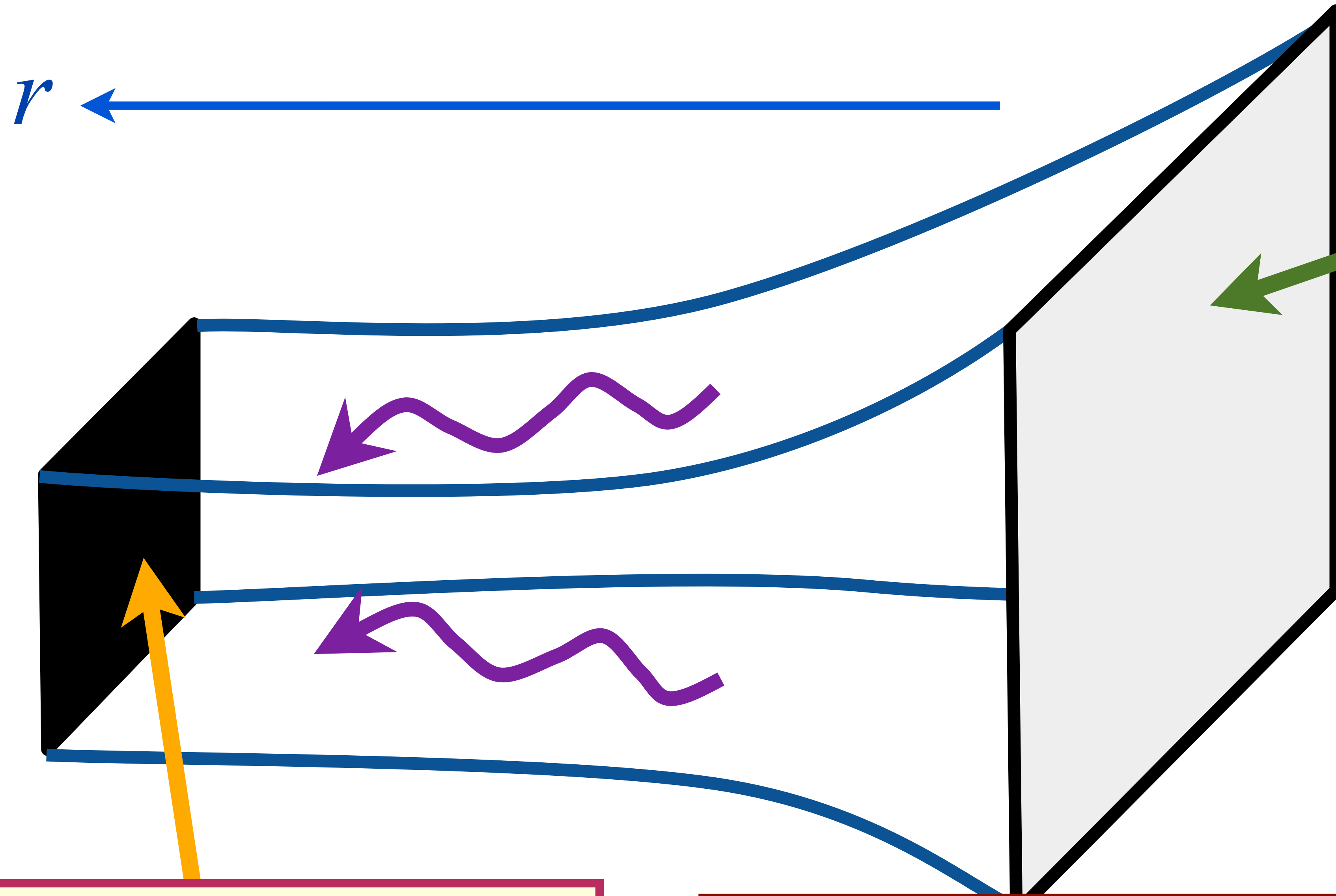
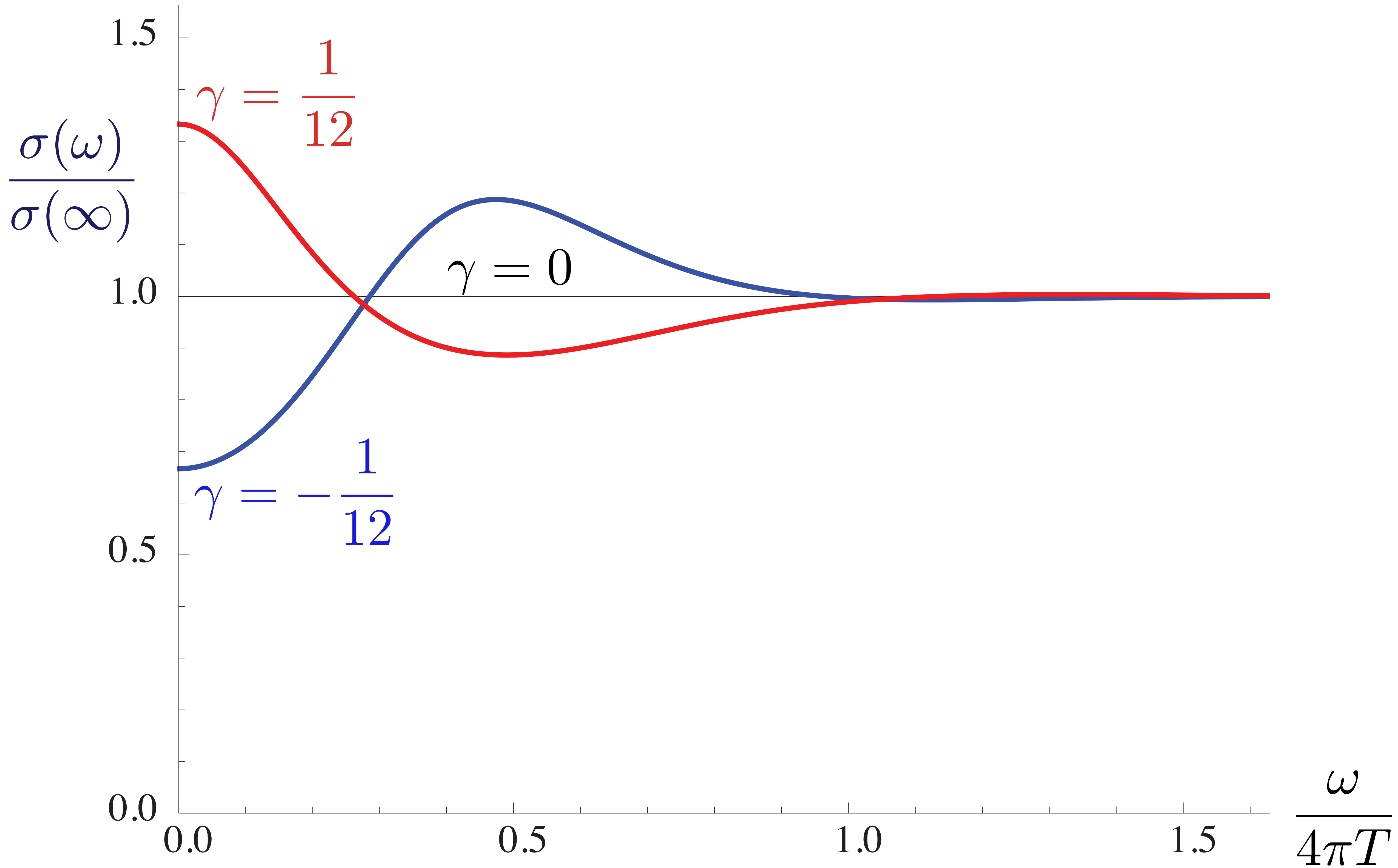


A 2+1 dimensional system at $T > 0$ with couplings at its quantum critical point

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

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

AdS$_4$ theory of quantum criticality



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

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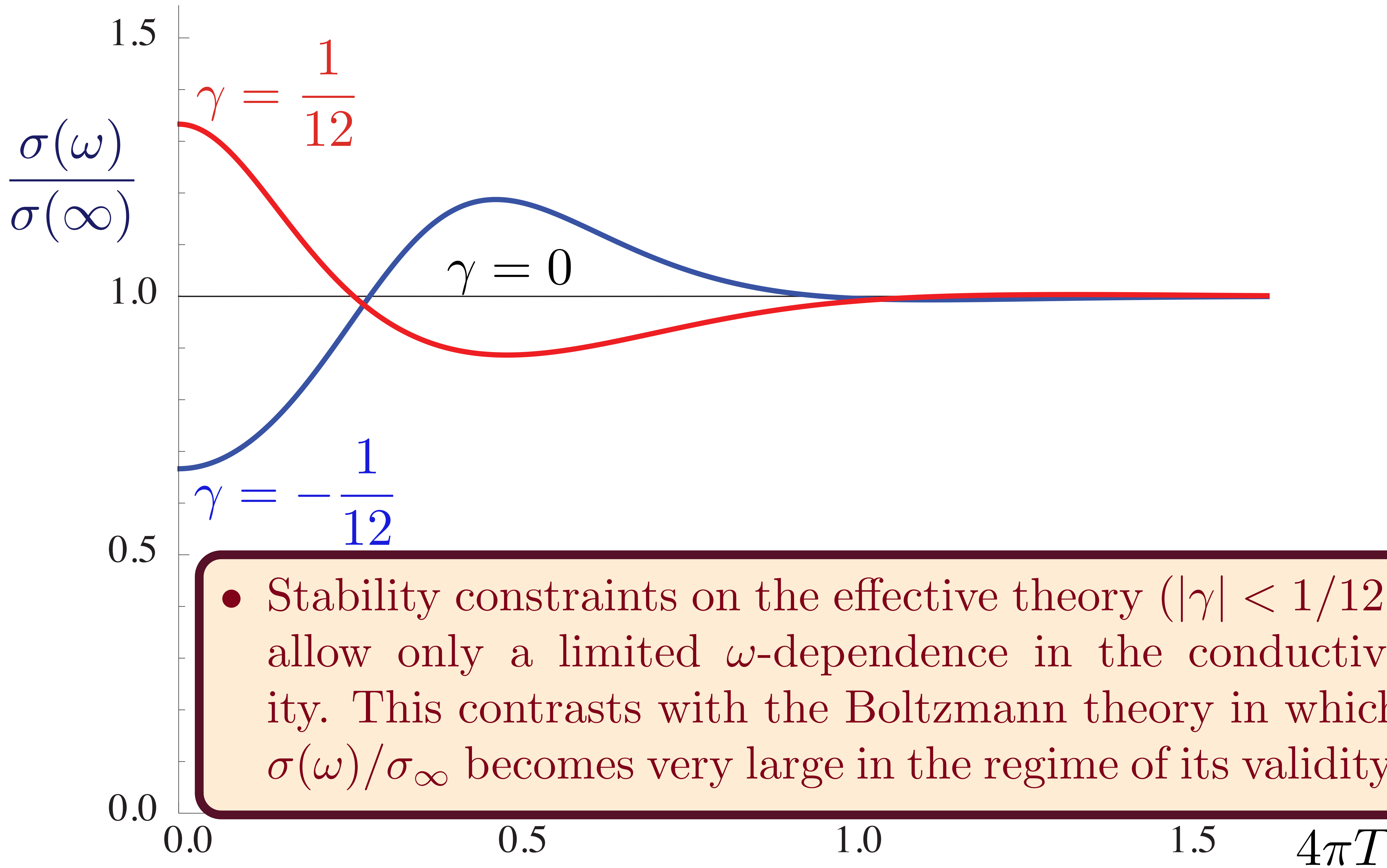


- Stability constraints on the effective theory ($|\gamma| < 1/12$) allow only a limited ω-dependence in the conductivity. This contrasts with the Boltzmann theory in which $\sigma(\omega)/\sigma_\infty$ becomes very large in the regime of its validity.

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

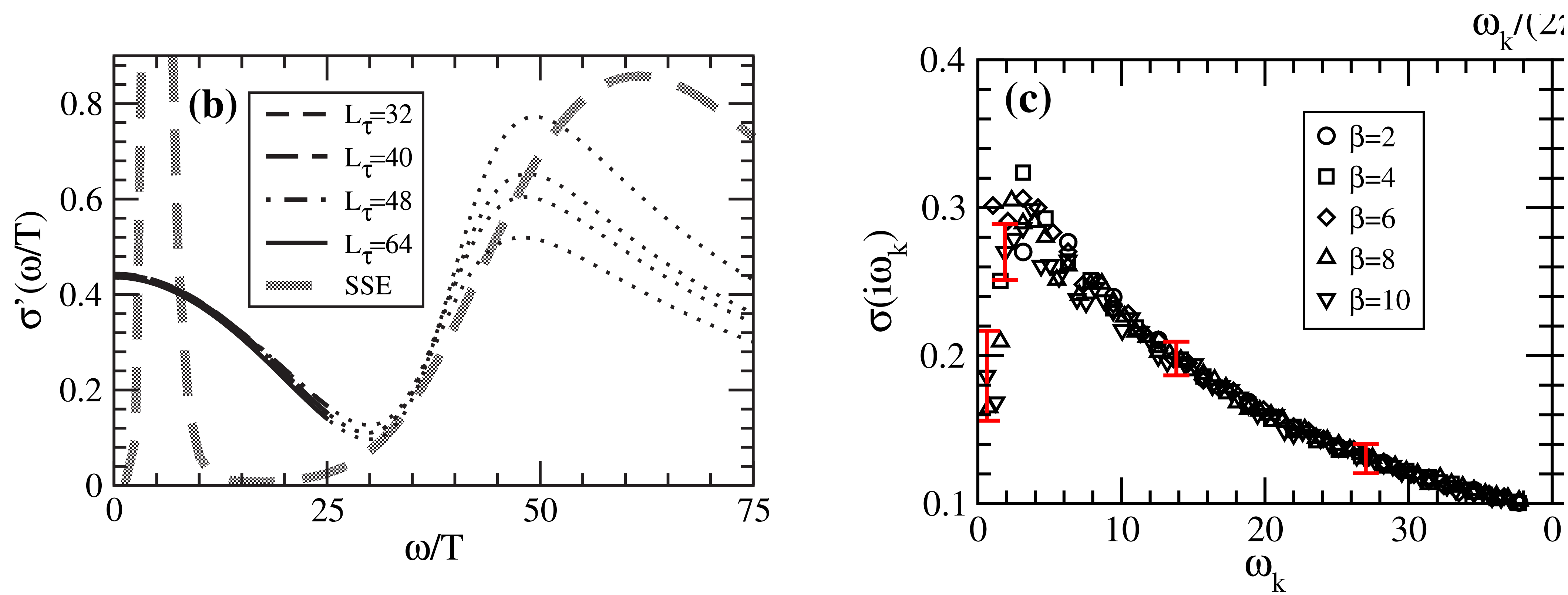
AdS_4 theory of quantum criticality

PRL **95,** 180603 (2005) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2005

Universal Scaling of the Conductivity at the Superfluid-Insulator Phase Transition

Jurij Šmakov and Erik Sørensen
Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada
(Received 30 May 2005; published 27 October 2005)

The scaling of the conductivity at the superfluid-insulator quantum phase transition in two dimensions is studied by numerical simulations of the Bose-Hubbard model. In contrast to previous studies, we focus on properties of this model in the experimentally relevant thermodynamic limit at finite temperature T. We find clear evidence for *deviations* from ω_k scaling of the conductivity towards ω_k/T scaling at low Matsubara frequencies ω_k. By careful analytic continuation using Padé approximants we show that this behavior carries over to the real frequency axis where the conductivity scales with ω/T at small frequencies and low temperatures. We estimate the universal dc conductivity to be $\sigma^* = 0.45(5)Q^2/h$, distinct from previous estimates in the $T = 0$, $\omega/T \gg 1$ limit.



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QMC yields $\sigma(0)/\sigma_\infty \approx 1.36$

Holography yields $\sigma(0)/\sigma_\infty = 1 + 4\gamma$ with $|\gamma| \leq 1/12$.

Maximum possible holographic value $\sigma(0)/\sigma_\infty = 1.33$

W. Witzack-Krempa and S. Sachdev, arXiv:1302.0847

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.

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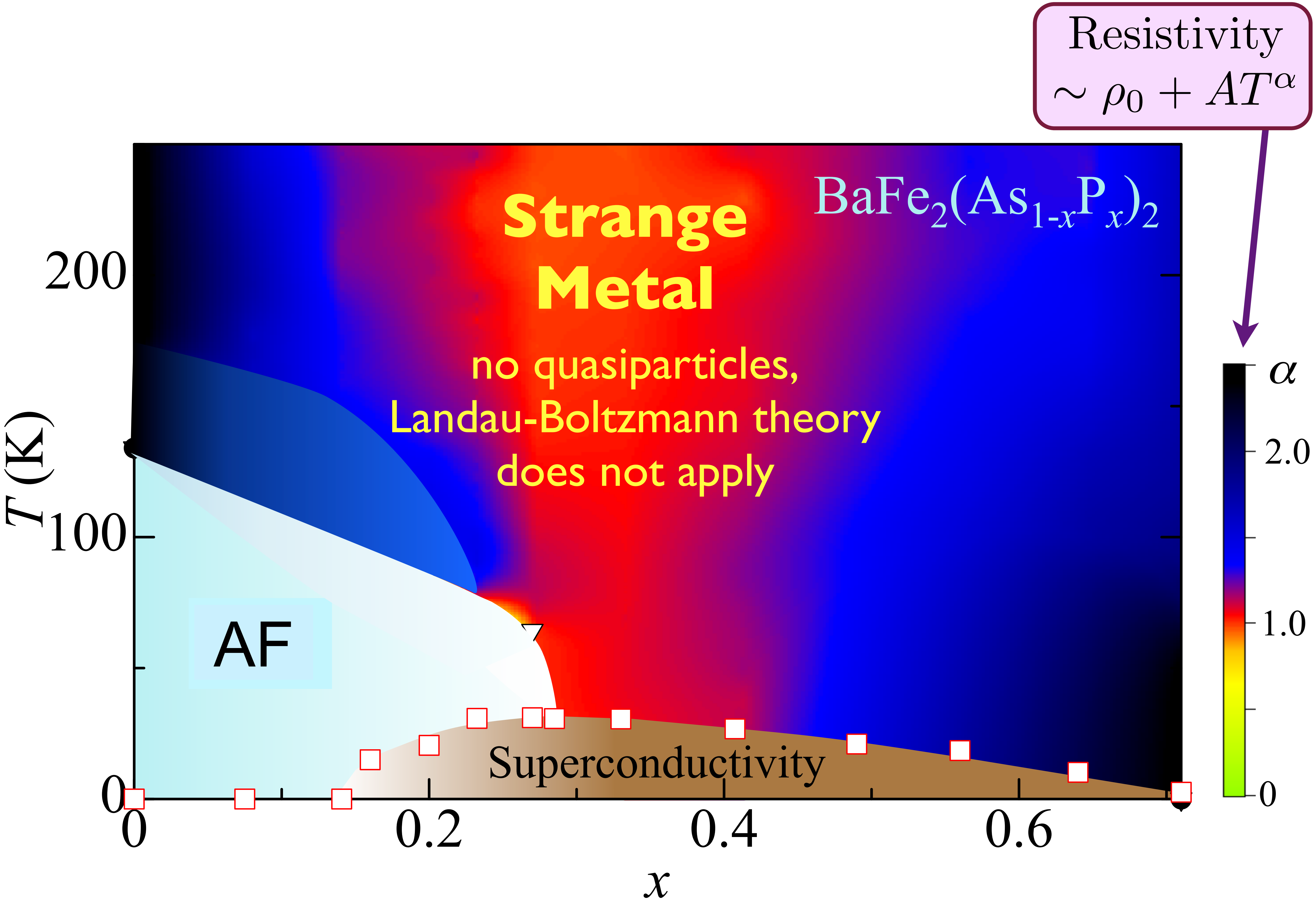
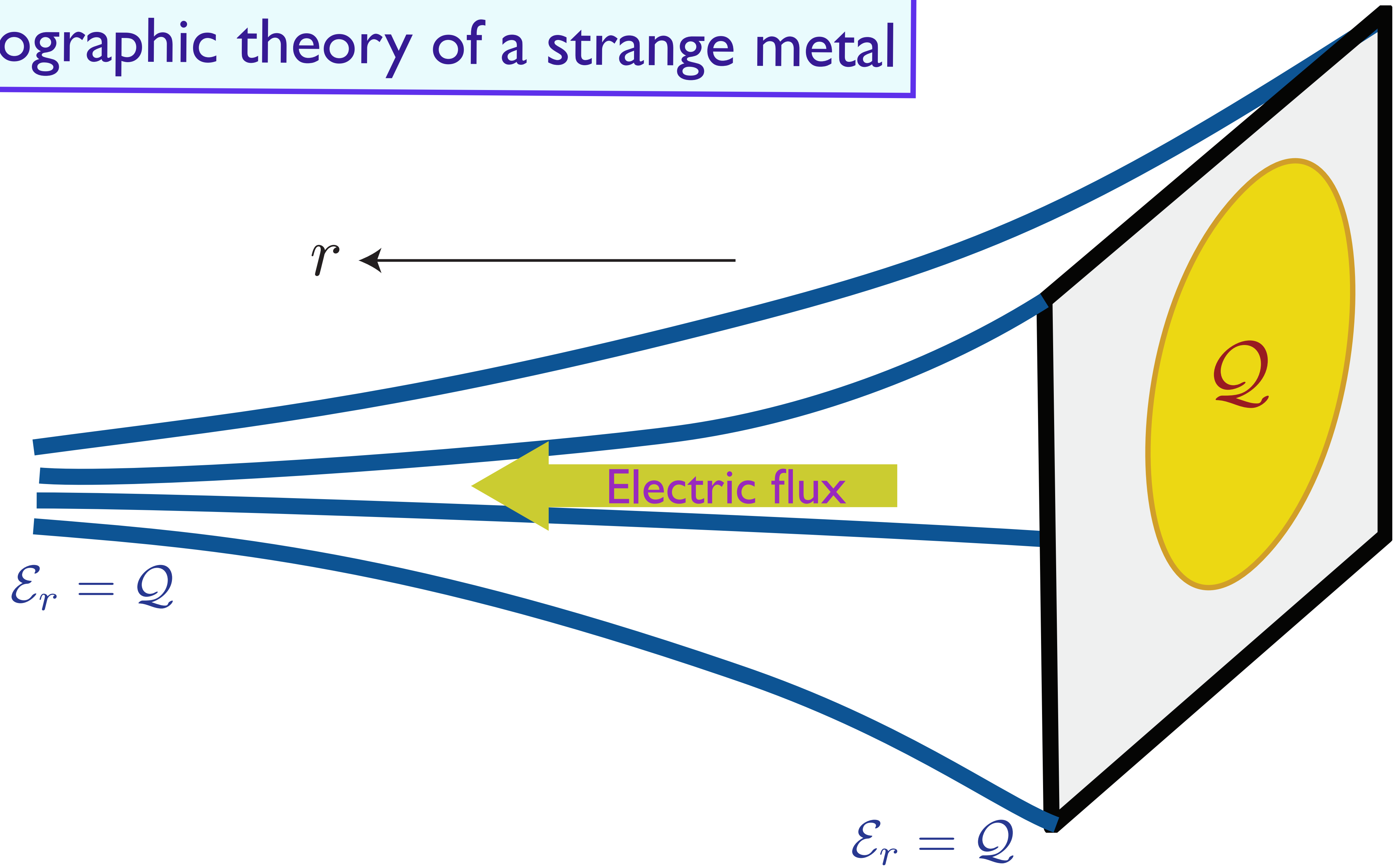


S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)

Holographic theory of a strange metal



The density of particles $\mathcal{Q}$ creates an electric flux $\mathcal{E}_r$ which modifies the metric of the emergent spacetime.

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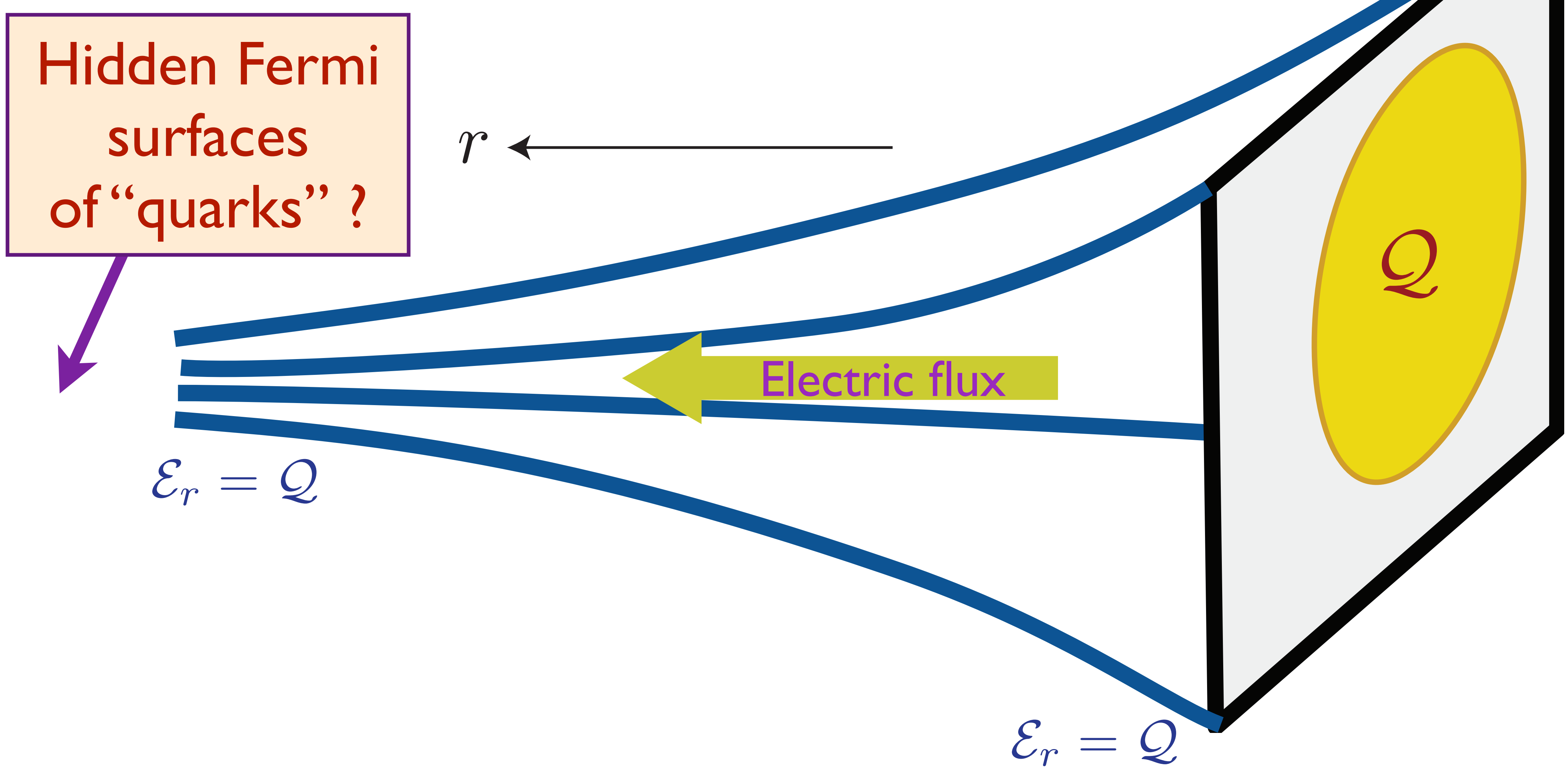

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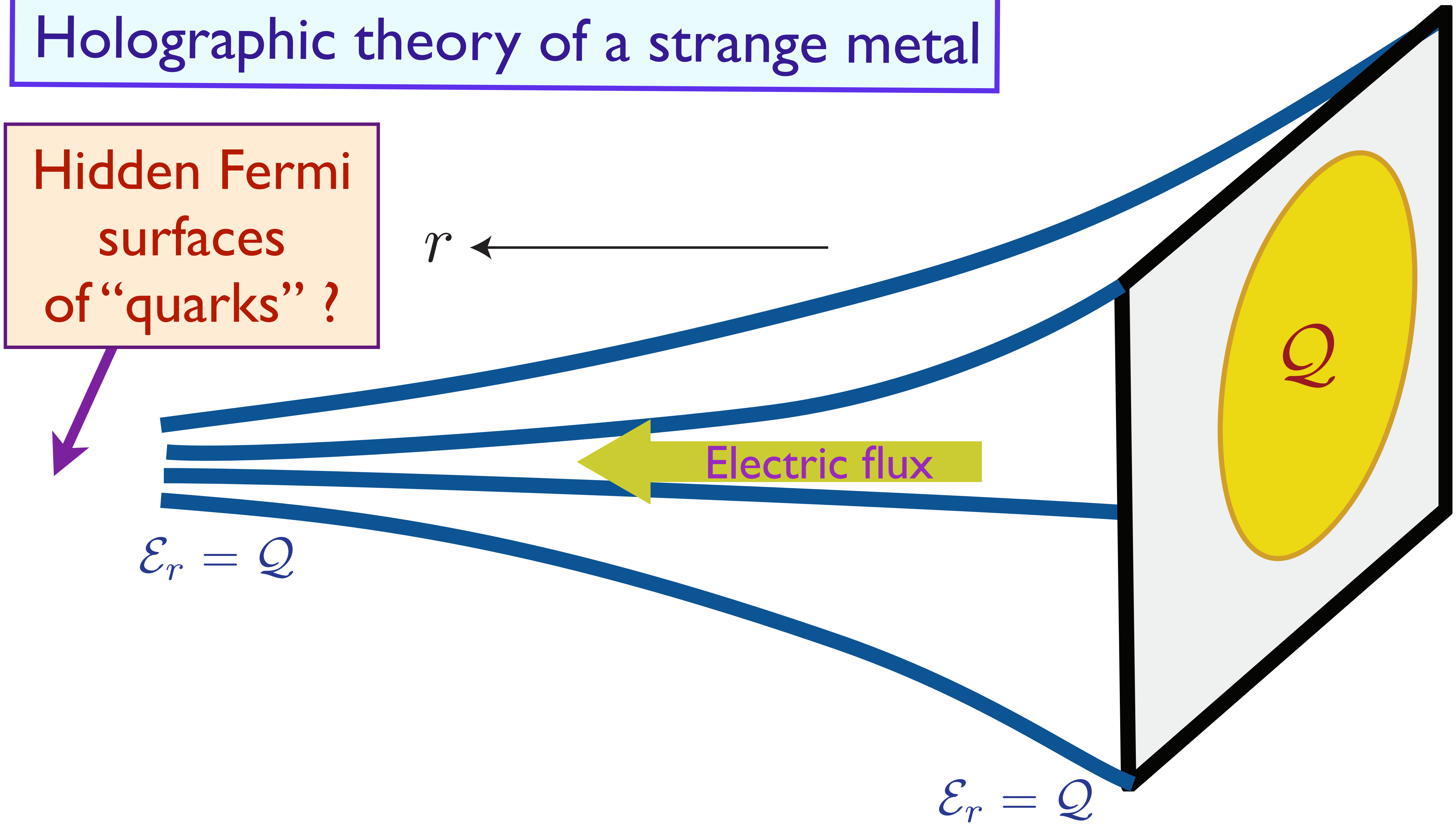
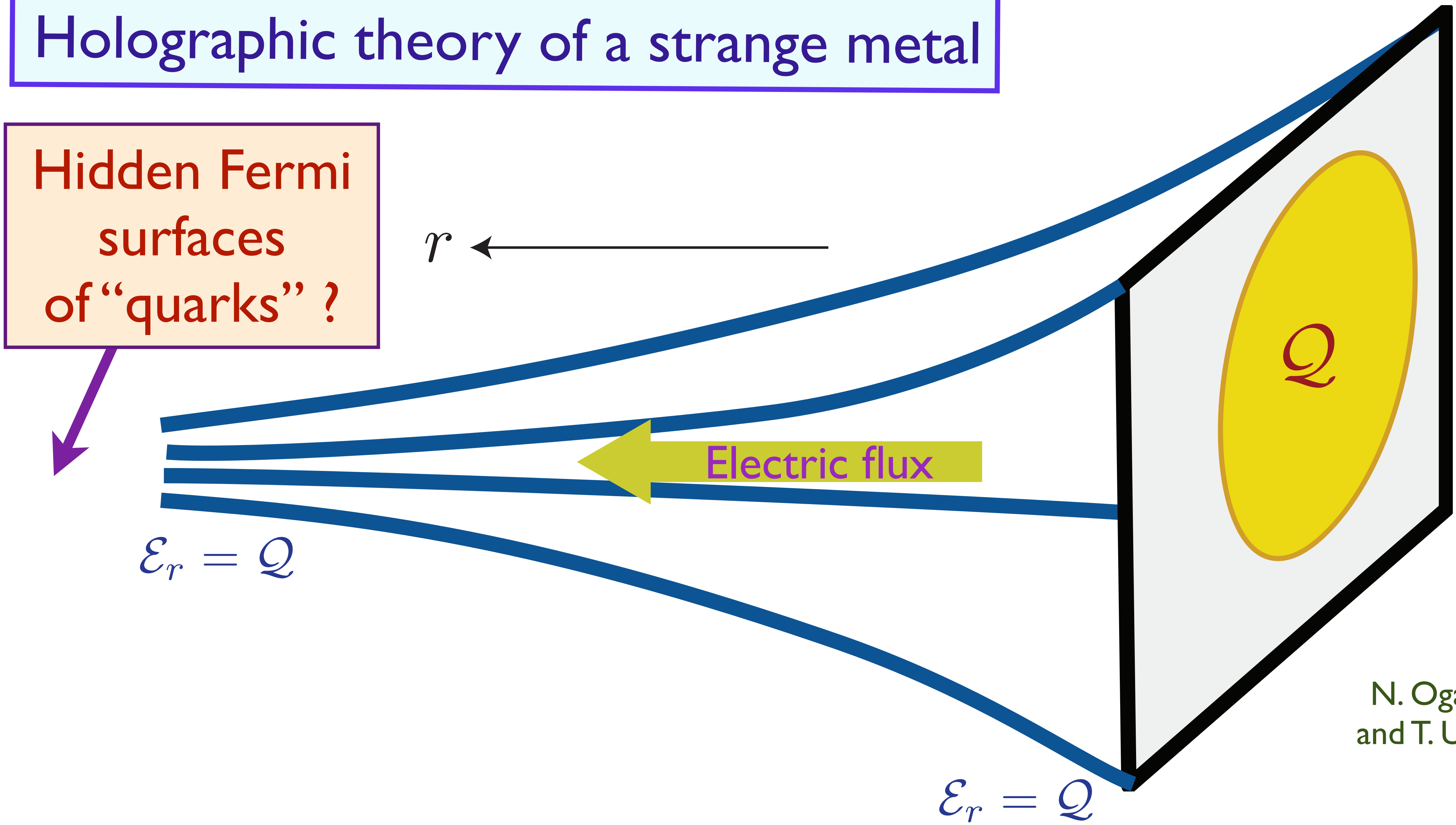


The general metric transforms under rescaling as

$$x_i \to \zeta\, x_i, \quad t \to \zeta^z\, t, \quad ds \to \zeta^{\theta/d}\, ds.$$

Recall: conformal matter has $\theta = 0$, $z = 1$, and the metric is anti-de Sitter

Holographic theory of a strange metal



N. Ogawa, T. Takayanagi, and T. Ugajin, JHEP **1201**, 125 (2012).

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

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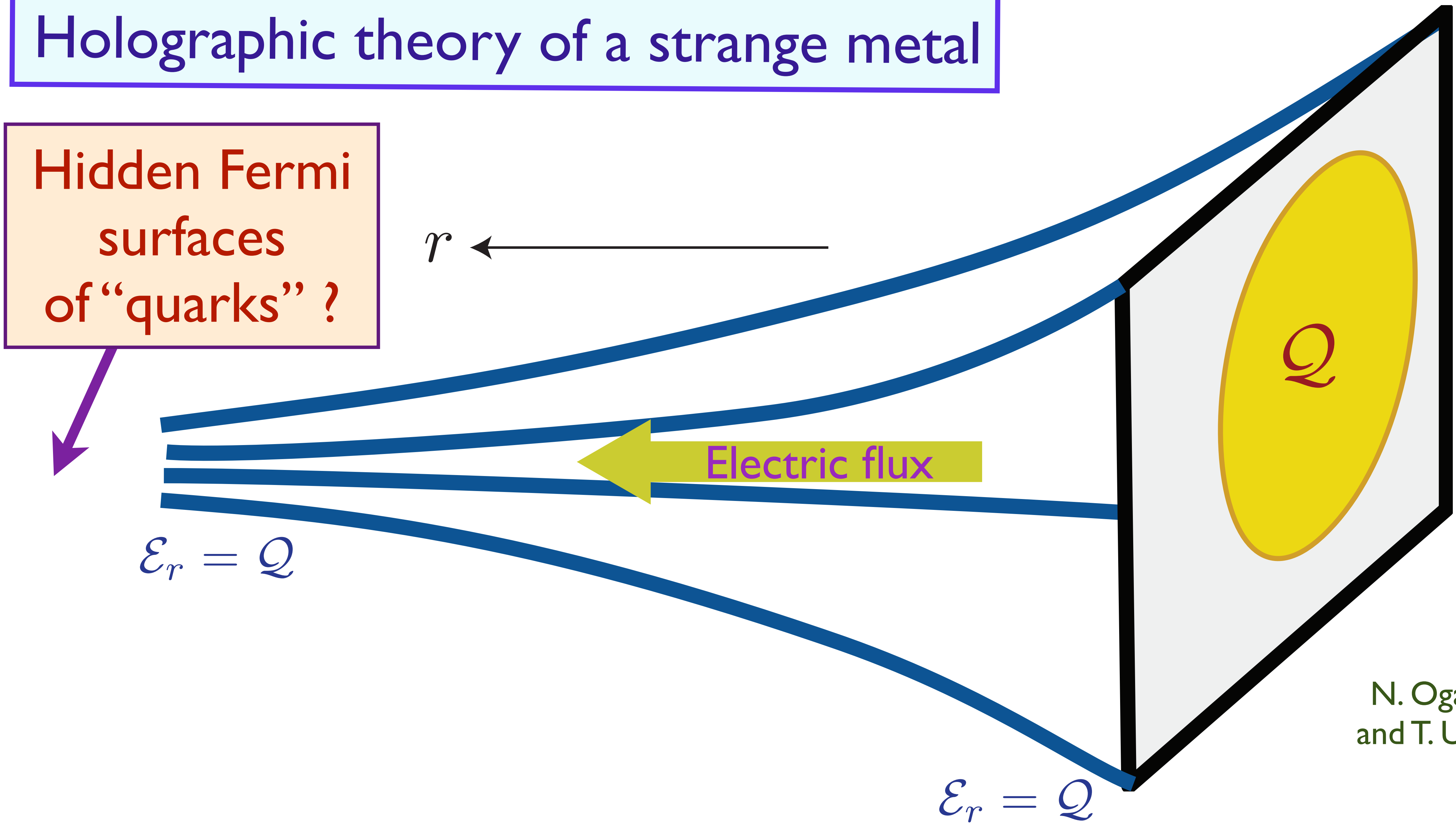
The value $\theta = d - 1$ reproduces *all* the essential characteristics of the entropy and entanglement entropy of a strange metal.

Holographic theory of a strange metal



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The null-energy condition of gravity yields $z \geq 1 + \theta/d$. In $d = 2$, this leads to $z \geq 3/2$. Field theory on strange metal yields $z = 3/2$ to 3 loops!

M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075127 (2010)

Conclusions

Conformal quantum matter

- New insights and solvable models for diffusion and transport of strongly interacting systems near quantum critical points

- The description is far removed from, and complementary to, that of the quantum Boltzmann equation which builds on the quasiparticle/vortex picture.

- Good prospects for experimental tests of frequency-dependent, non-linear, and non-equilibrium transport

Conclusions

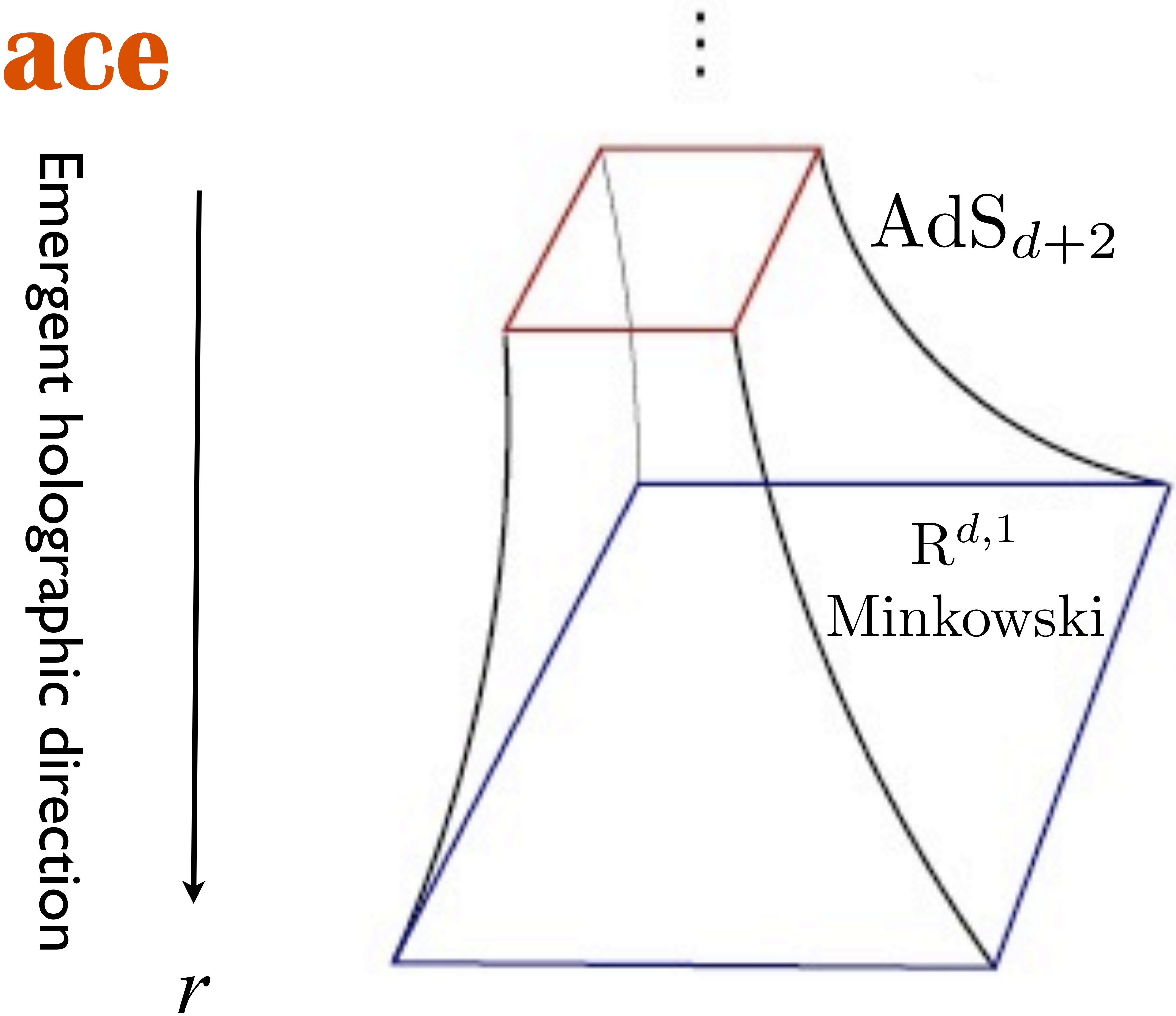
More complex examples in metallic states are experimentally ubiquitous, but pose difficult strong-coupling problems to conventional methods of field theory

Conclusions

String theory and gravity in emergent dimensions offer a remarkable new approach to describing states with many-particle quantum entanglement.

Much recent progress offers hope of a holographic description of "strange metals"

anti-de Sitter space



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