Gauge-gravity duality and its applications

Marc Kac Memorial Lectures, May 5 2011

Talk online: sachdev.physics.harvard.edu

PHYSICS

HARVARD

Outline

1. Quantum criticality and conformal field theories in condensed matter

2. The AdS/CFT correspondence
   Quantum criticality and black holes

3. Quantum transport and Einstein-Maxwell theory on AdS_4

4. Compressible quantum matter
   Fermi surfaces

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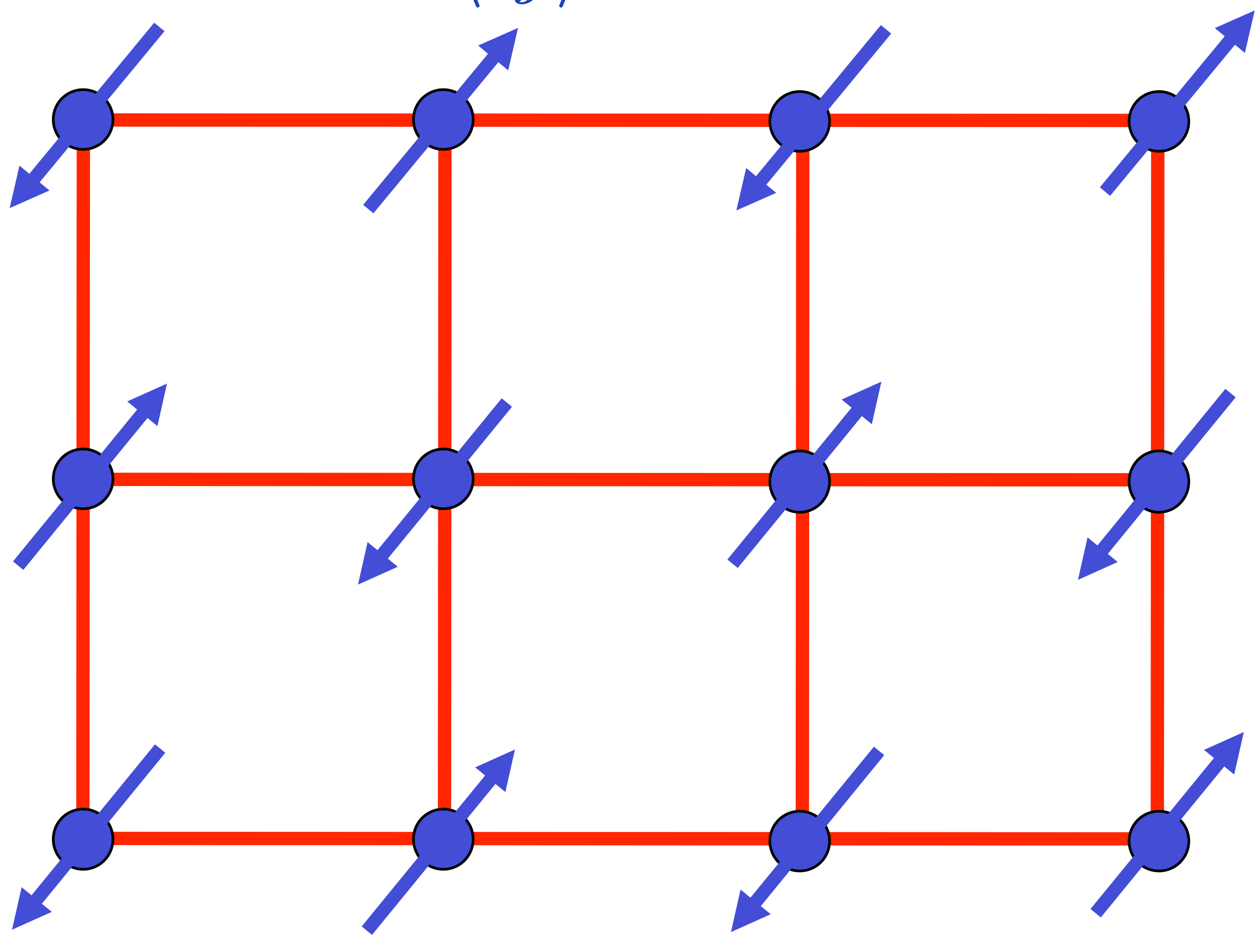
Square lattice antiferromagnet

$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



Ground state has long-range Néel order

Order parameter is a single vector field $\vec{\varphi} = \eta_i \vec{S}_i$

$\eta_i = \pm 1$ on two sublattices

$\langle \vec{\varphi} \rangle \neq 0$ in Néel state.

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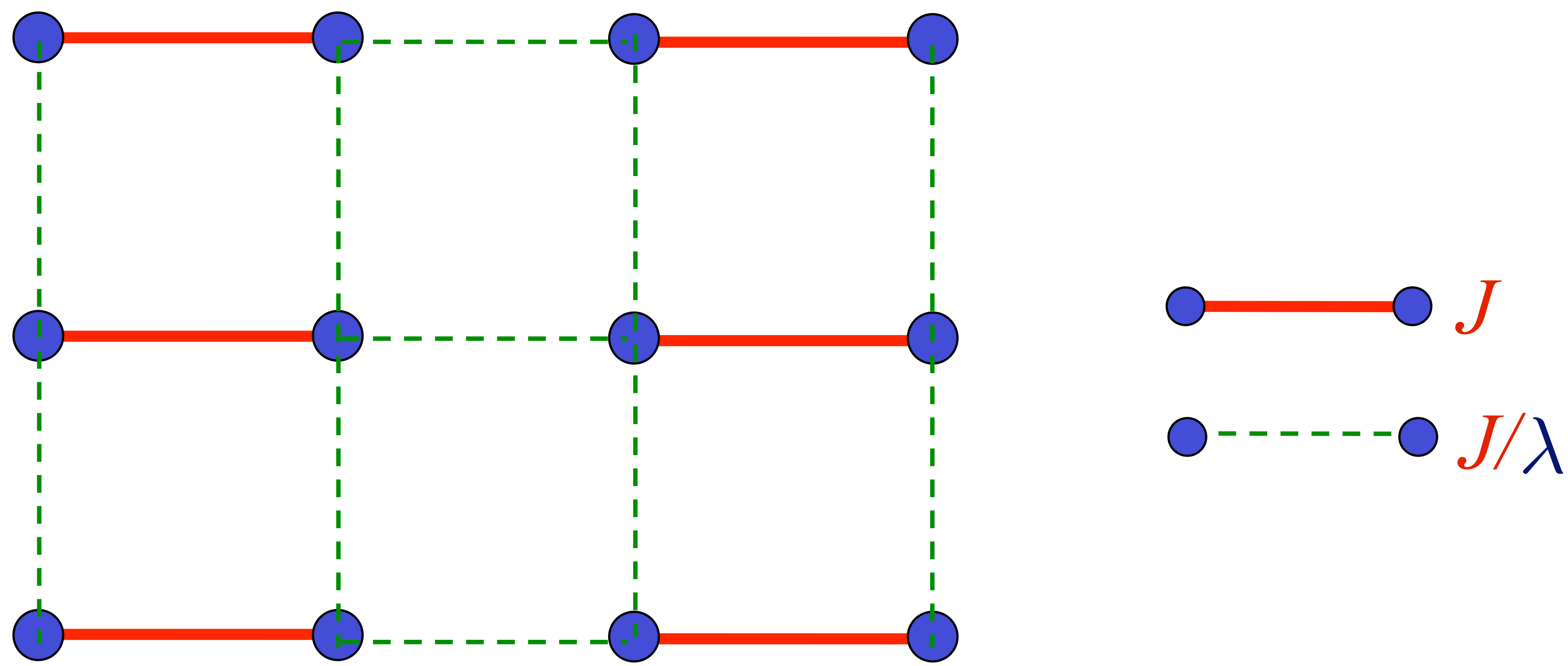
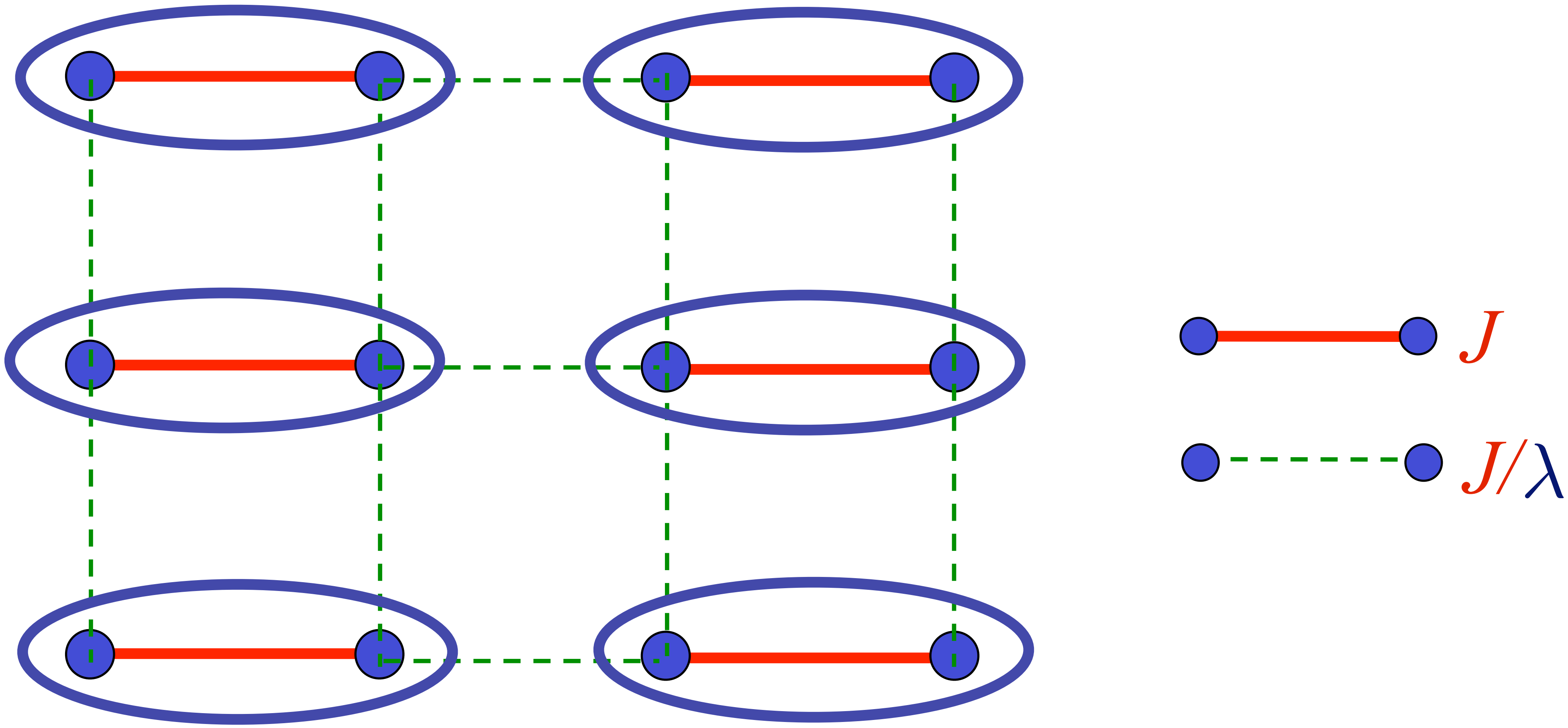


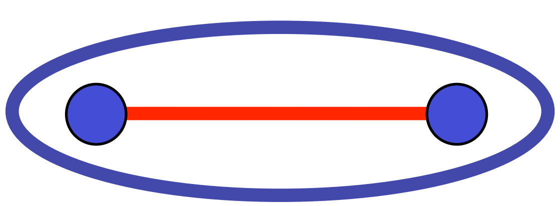
Weaken some bonds to induce spin entanglement in a new quantum phase

Square lattice antiferromagnet

$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



Ground state is a "quantum paramagnet" with spins locked in valence bond singlets

 $= \frac{1}{\sqrt{2}}\left(\left| \uparrow\downarrow \right\rangle - \left| \downarrow\uparrow \right\rangle \right)$

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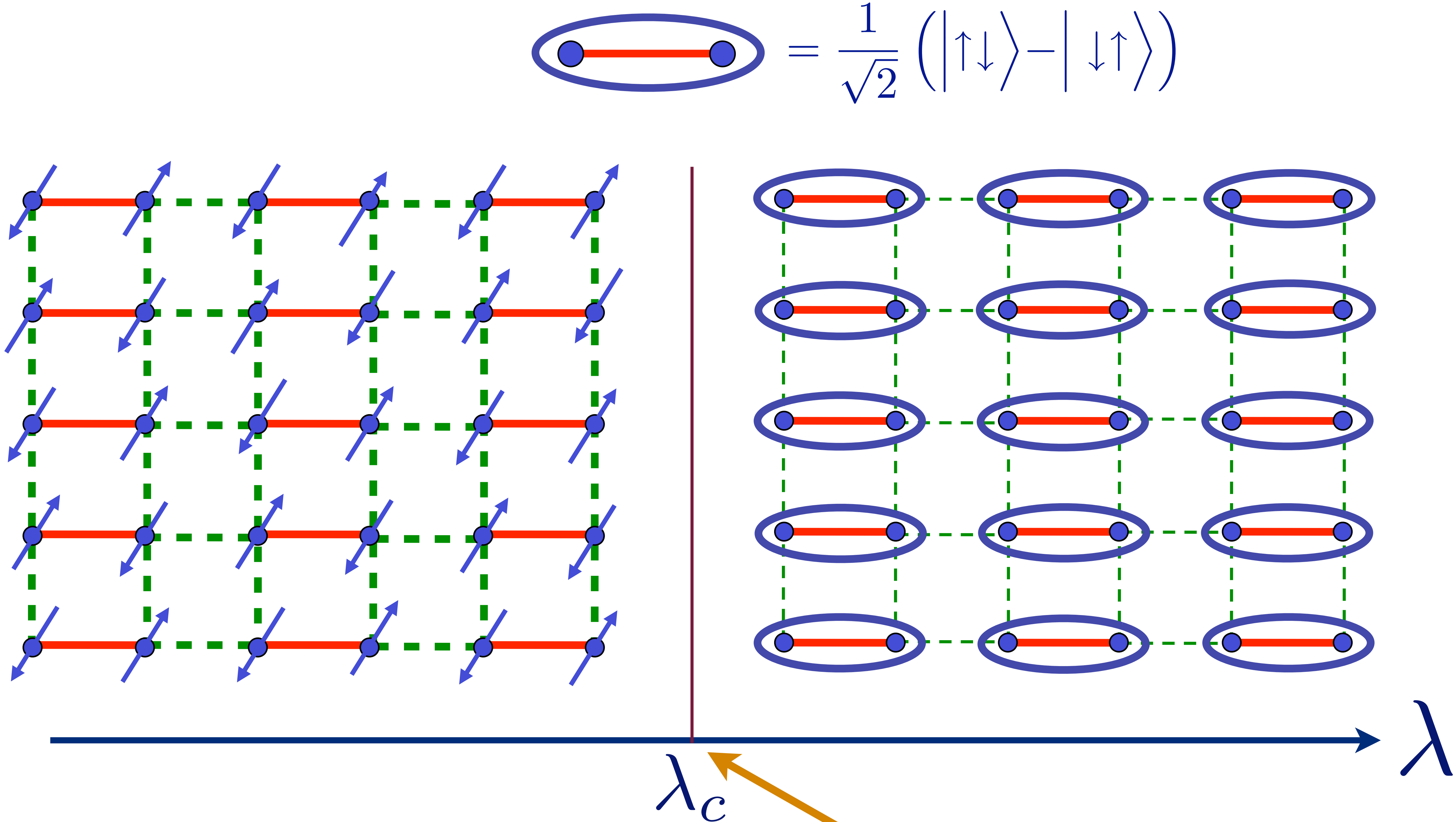
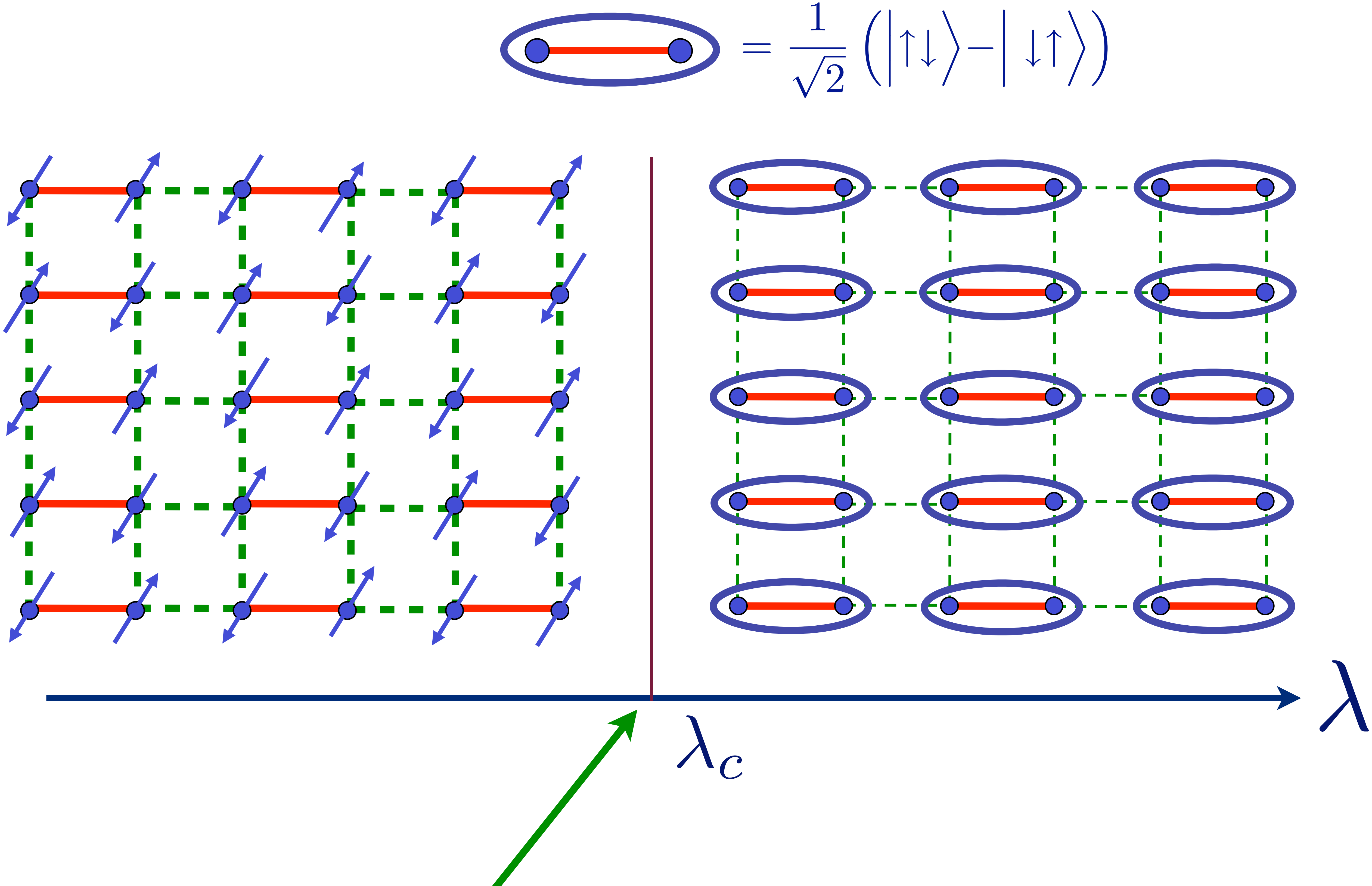
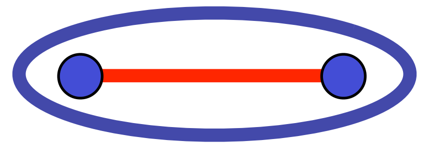
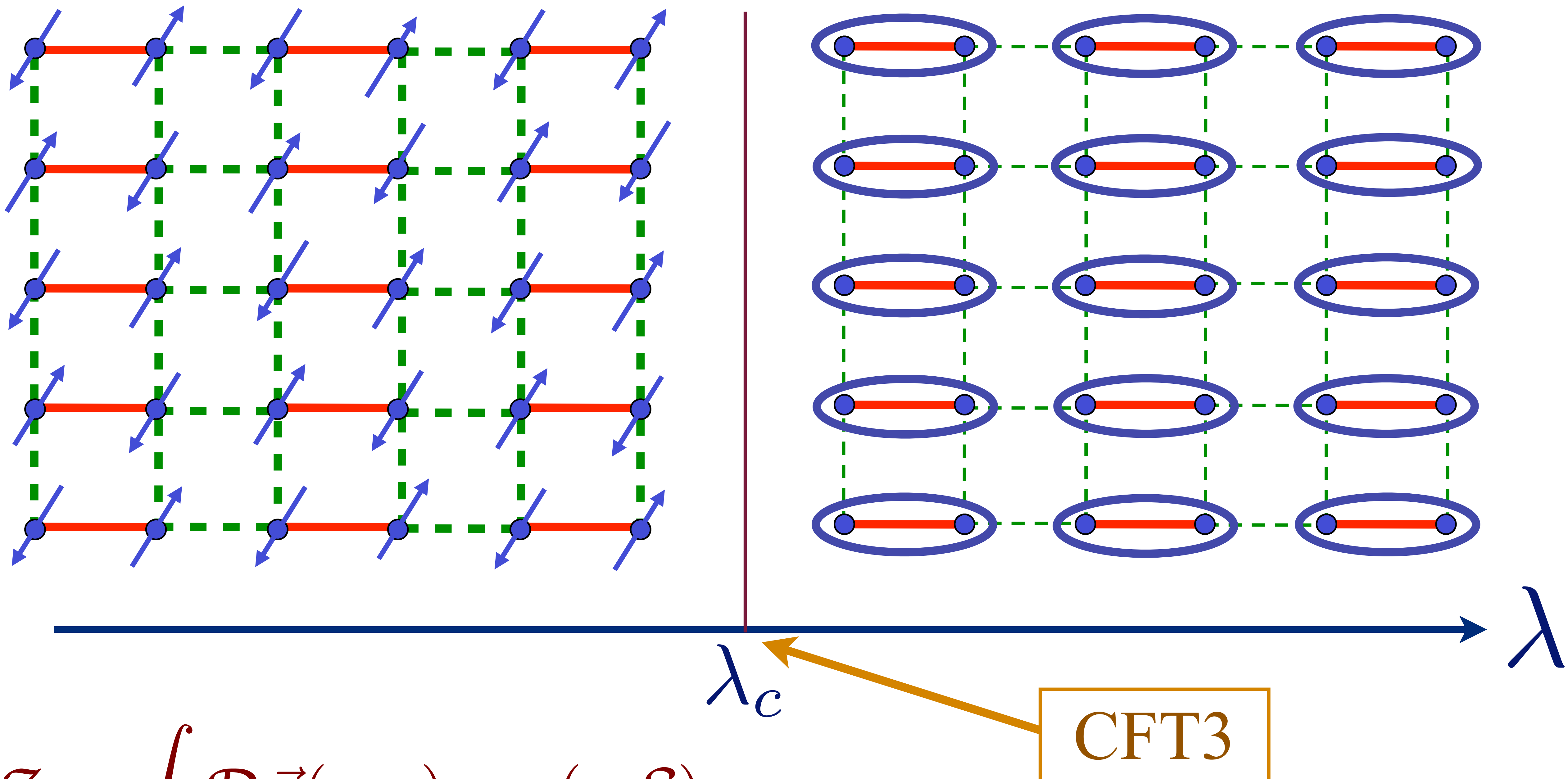


Quantum critical point with non-local entanglement in spin wavefunction



Conformal field theory in 2+1 dimensions (CFT3)

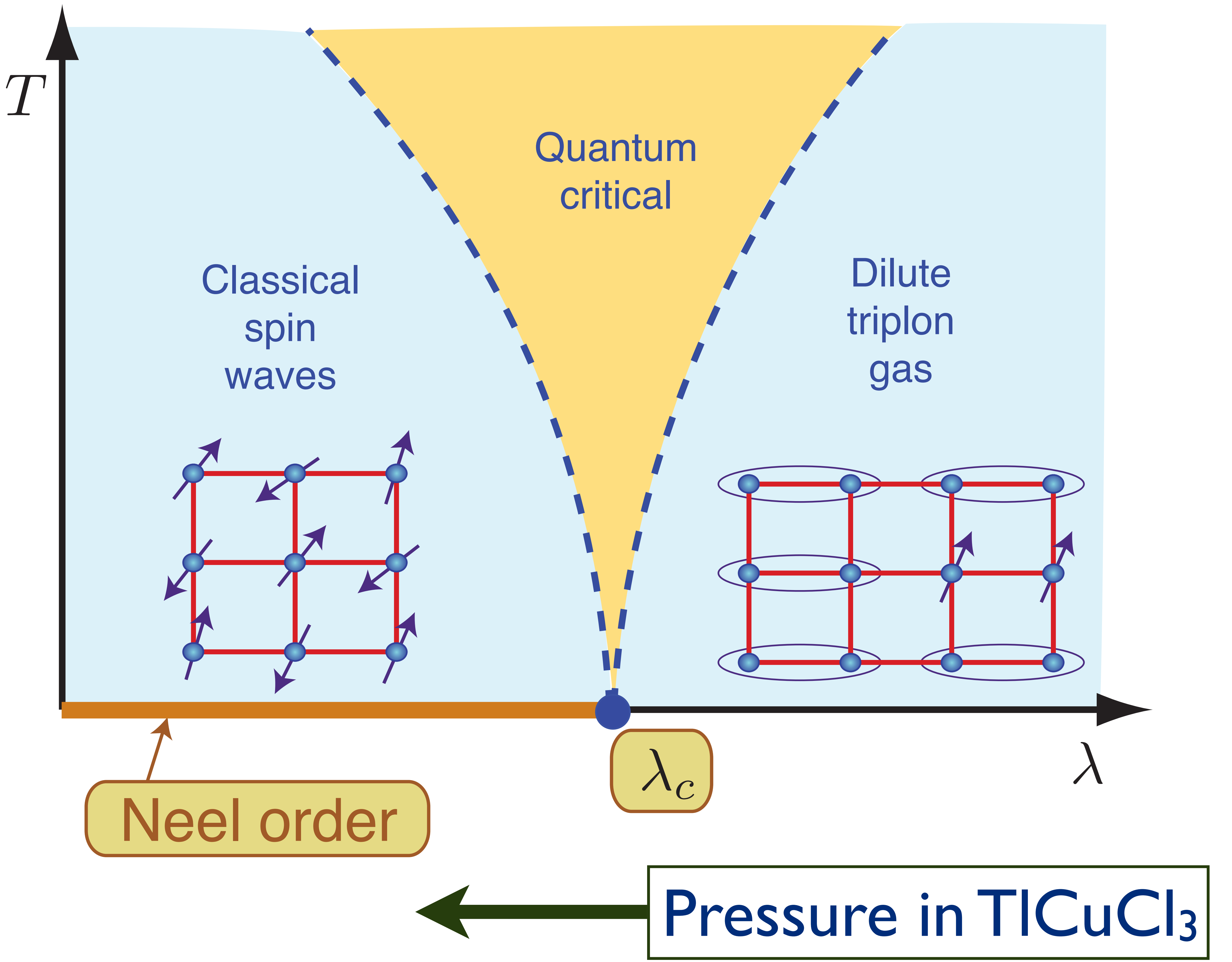
 $= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$



$$\mathcal{Z} = \int \mathcal{D}\vec{\varphi}(r,\tau)\exp(-\mathcal{S})$$

$$\mathcal{S} = \int d^2 r d\tau \left[(\partial_\tau \vec{\varphi})^2 + c^2 (\nabla_r \vec{\varphi})^2 + (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2 \right]$$

S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).
A. V. Chubukov, S. Sachdev, and J. Ye, *Phys. Rev. B* **49**, 11919 (1994).



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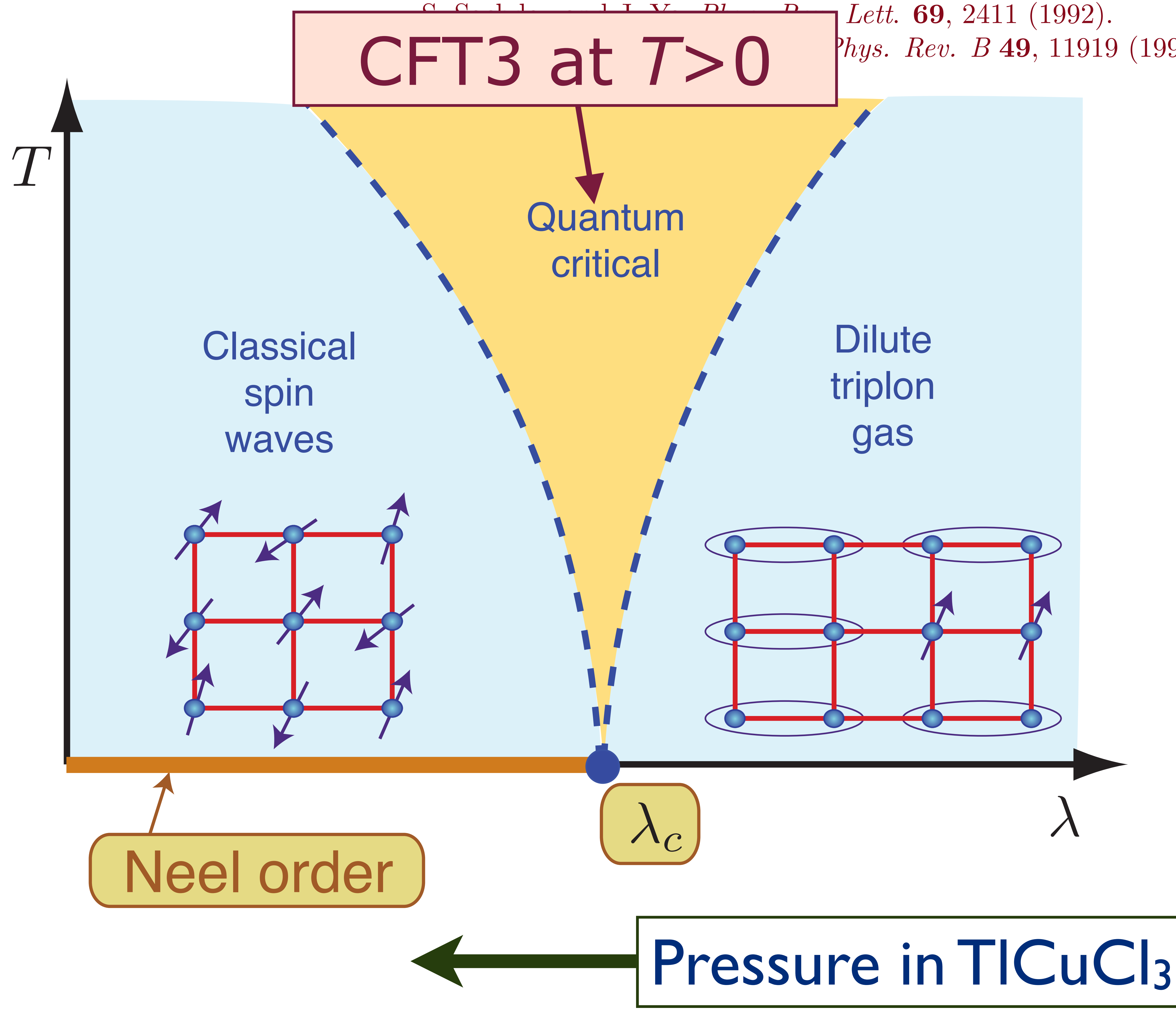

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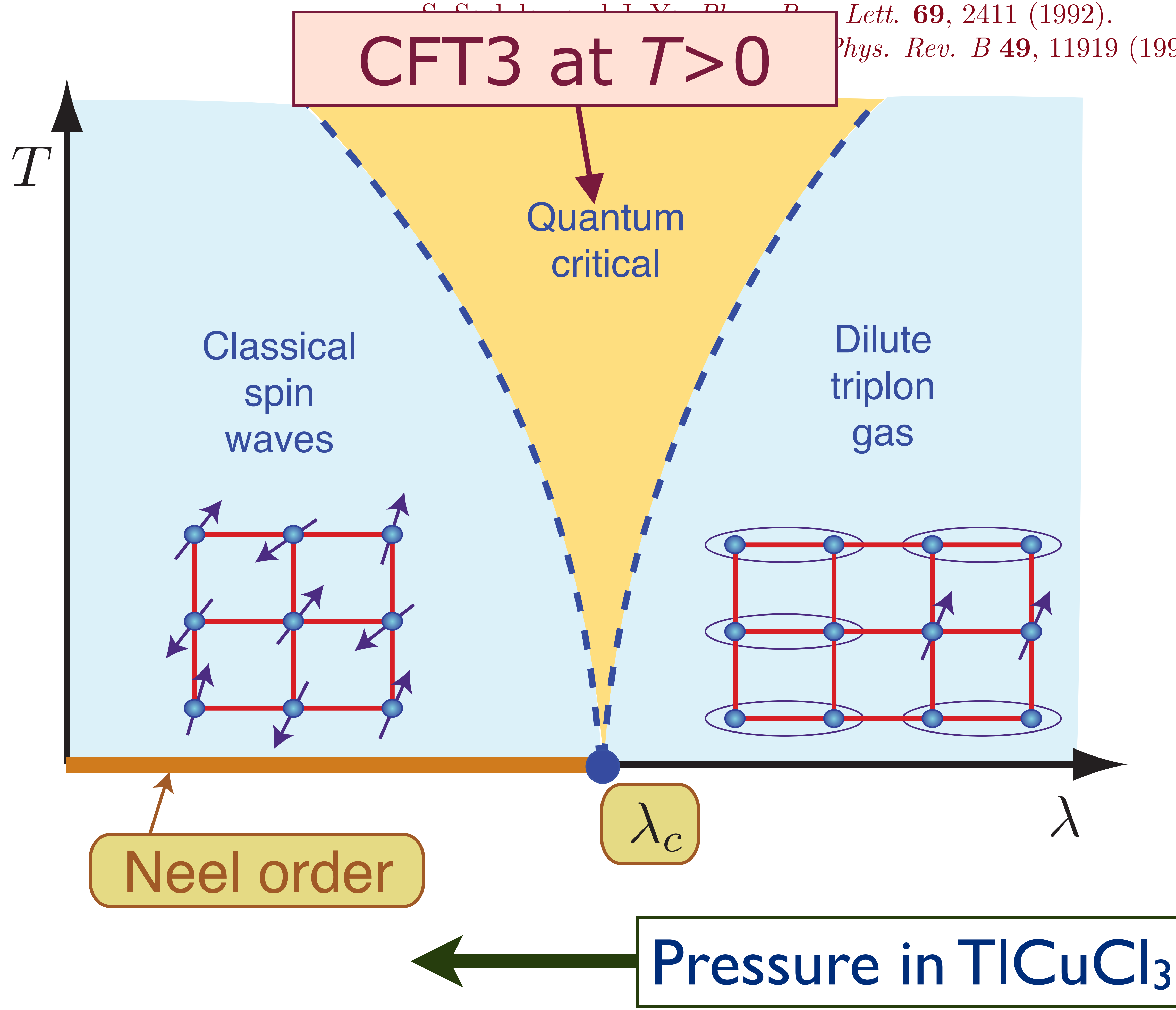

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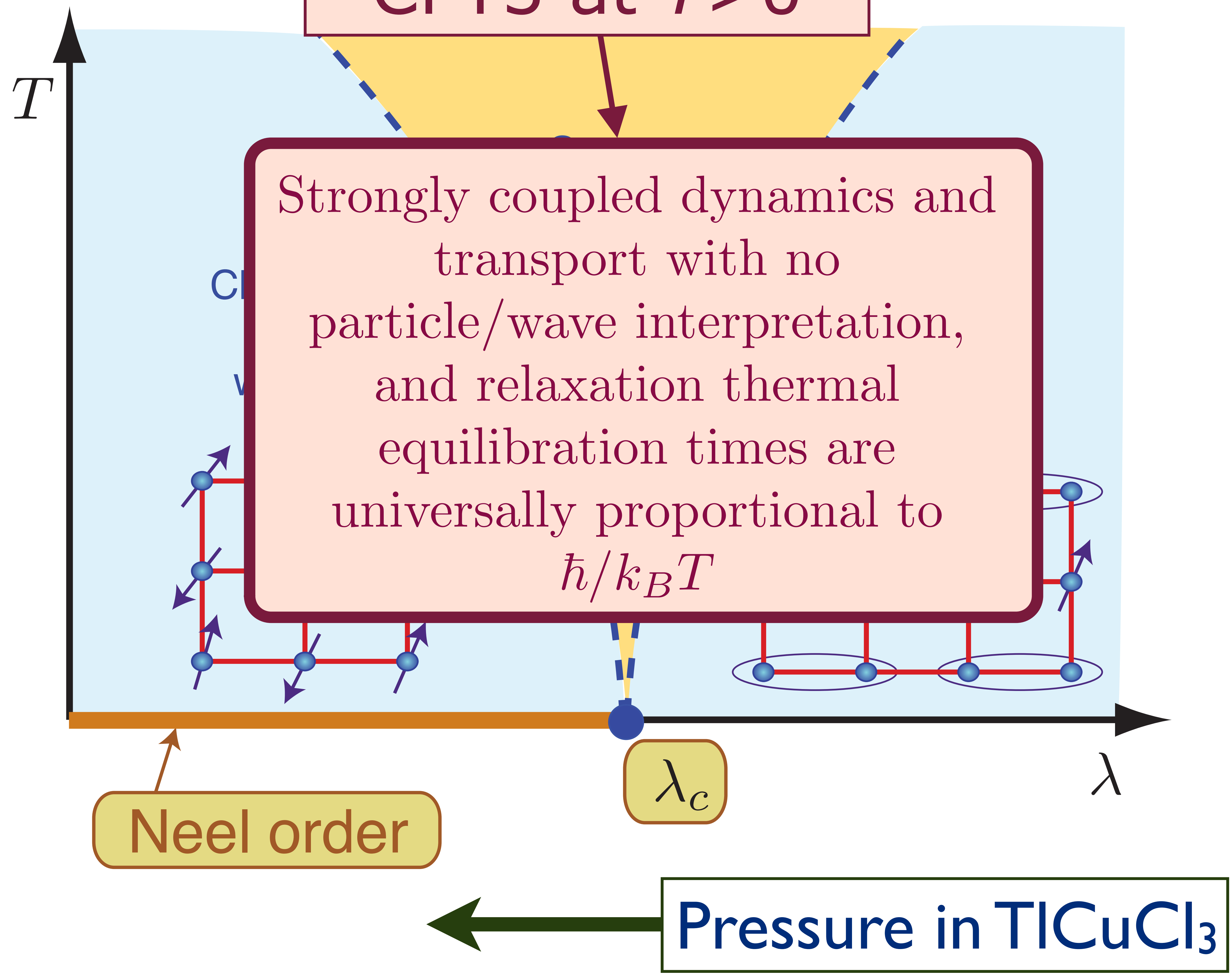
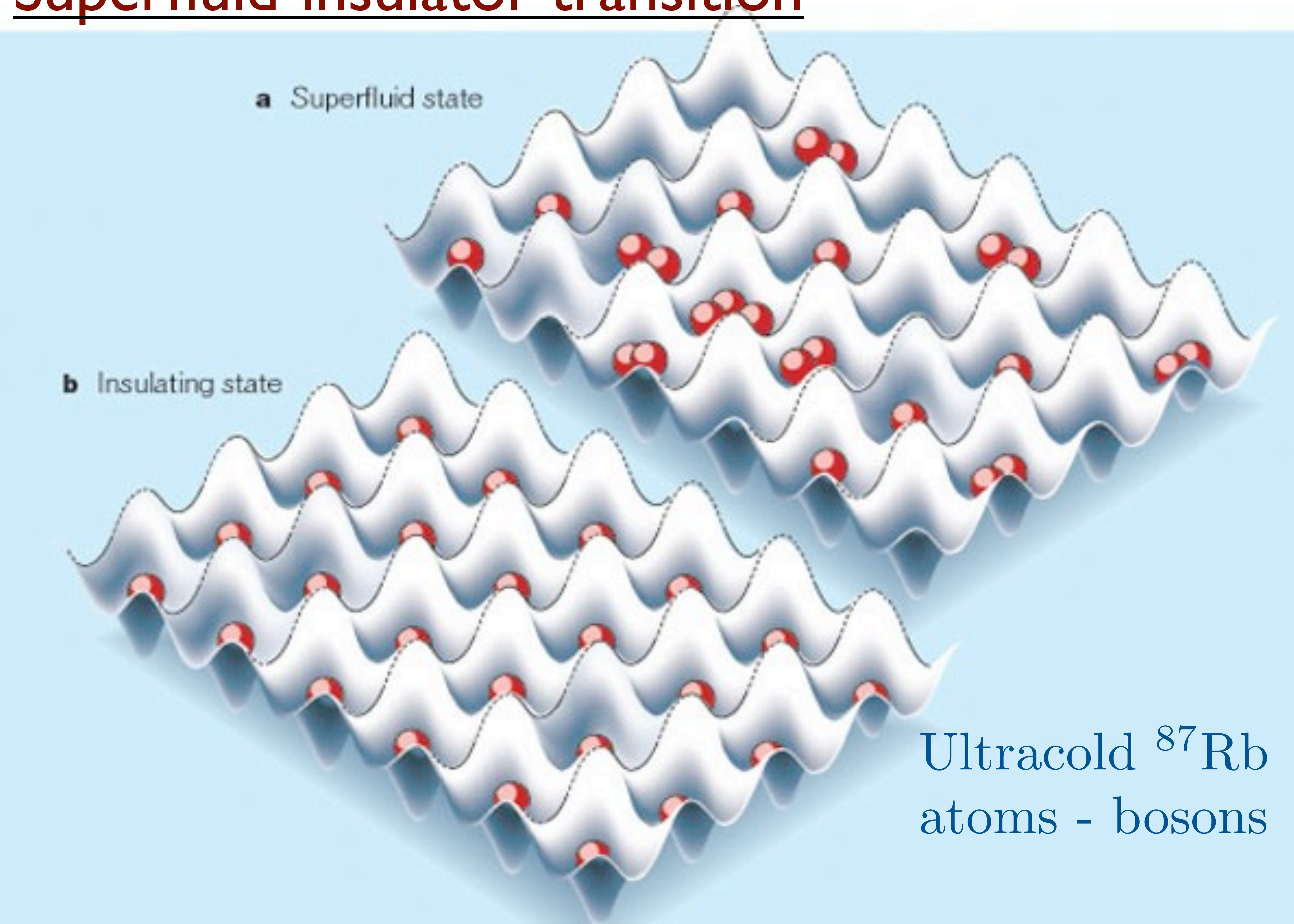
Phys. Rev. B **49**, 11919 (1994).

CFT3 at $T>0$



Strongly coupled dynamics and transport with no particle/wave interpretation, and relaxation thermal equilibration times are universally proportional to $\hbar/k_B T$

Superfluid-insulator transition

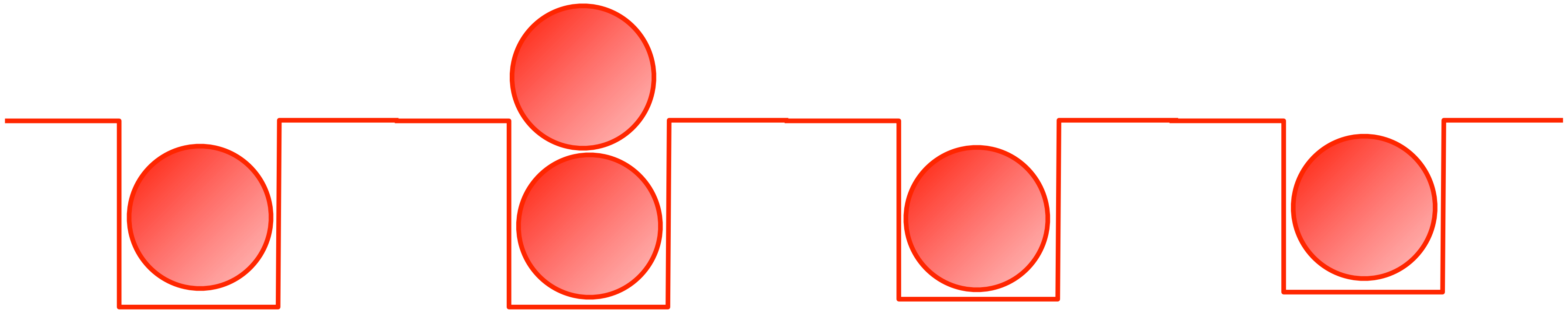


Ultracold ^{87}Rb
atoms - bosons

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

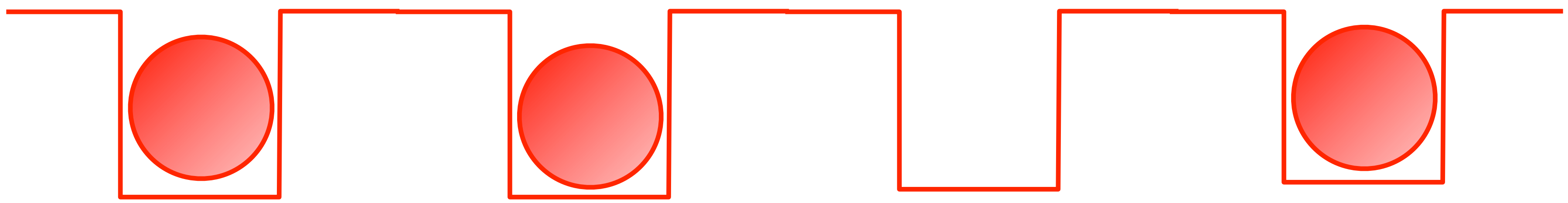
Insulator (the vacuum) at large U

Excitations:



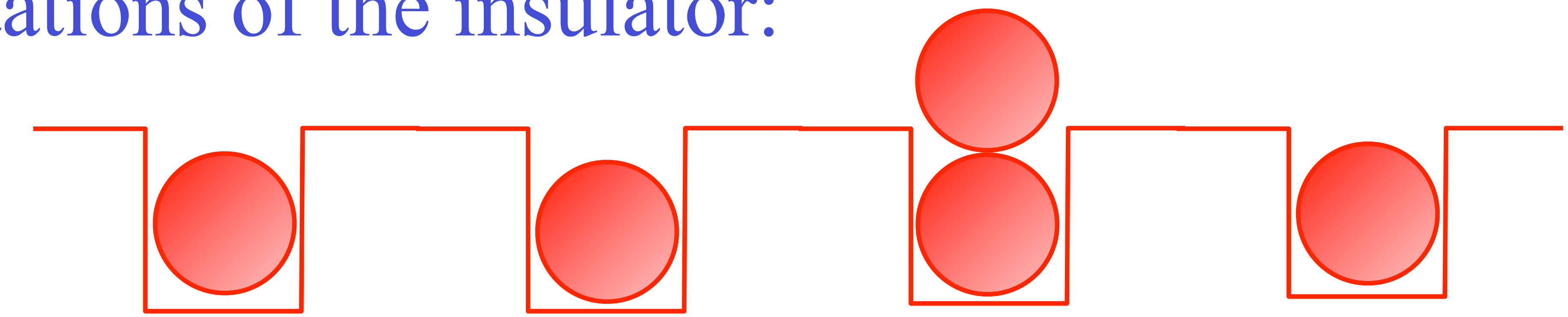
Particles $\sim \psi^\dagger$

Excitations:



Holes $\sim \psi$

Excitations of the insulator:



Particles ~ $\psi^\dagger$

Holes ~ ψ

Density of particles = density of holes $\Rightarrow$
"relativistic" field theory for ψ:

$$\mathcal{S} = \int d^2r d\tau \left[|\partial_\tau \psi|^2 + v^2 |\vec{\nabla}\psi|^2 + (g - g_c)|\psi|^2 + \frac{u}{2}|\psi|^4 \right]$$

$$\text{Insulator} \quad \Leftrightarrow \quad \langle \psi \rangle = 0$$

$$\text{Superfluid} \quad \Leftrightarrow \quad \langle \psi \rangle \neq 0$$

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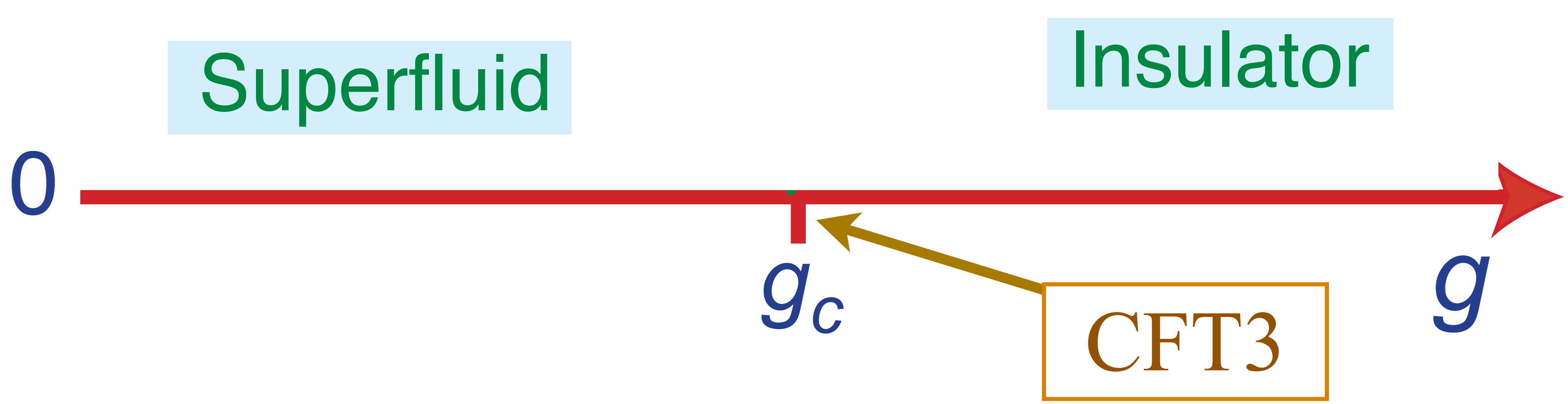
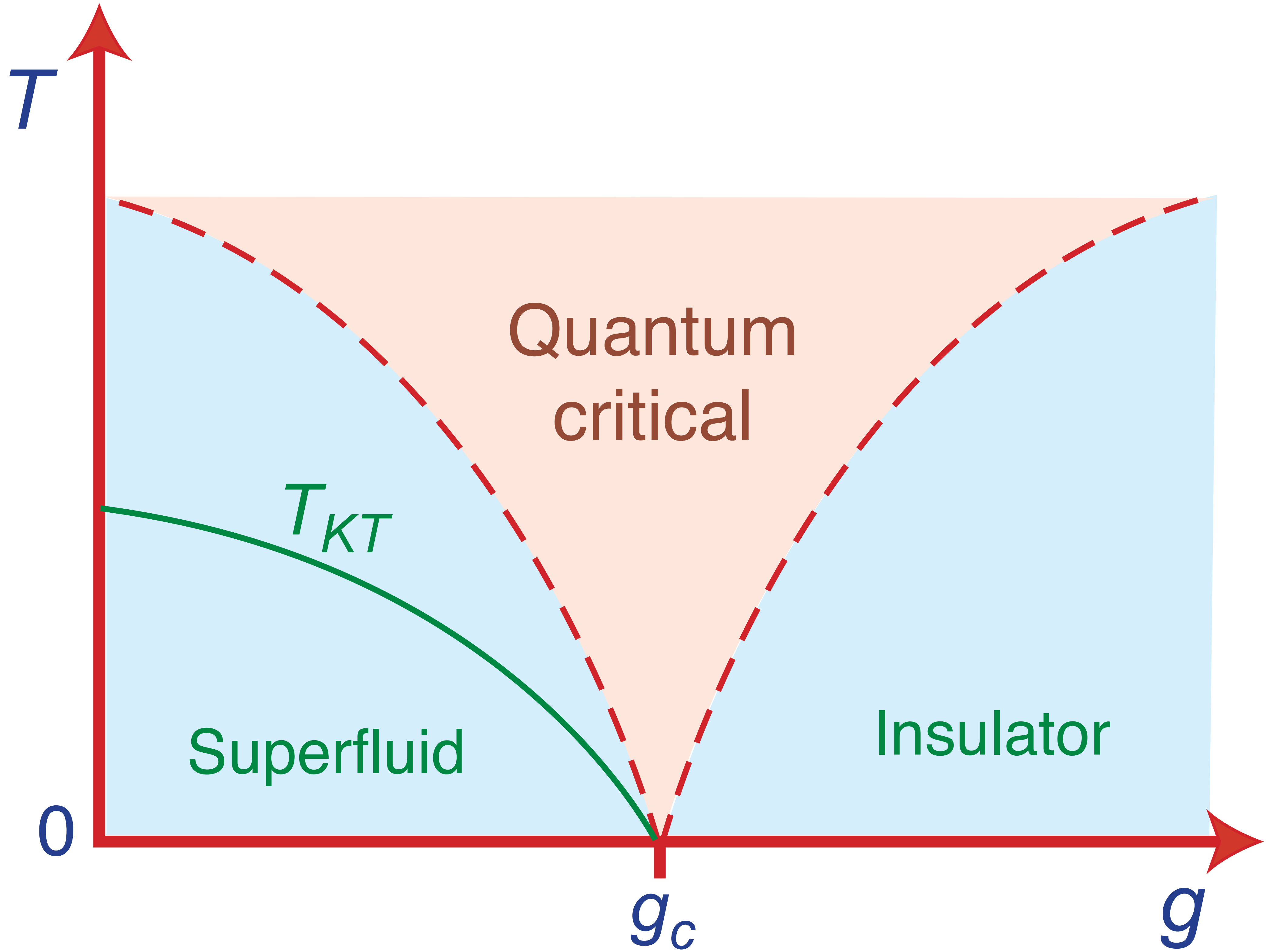
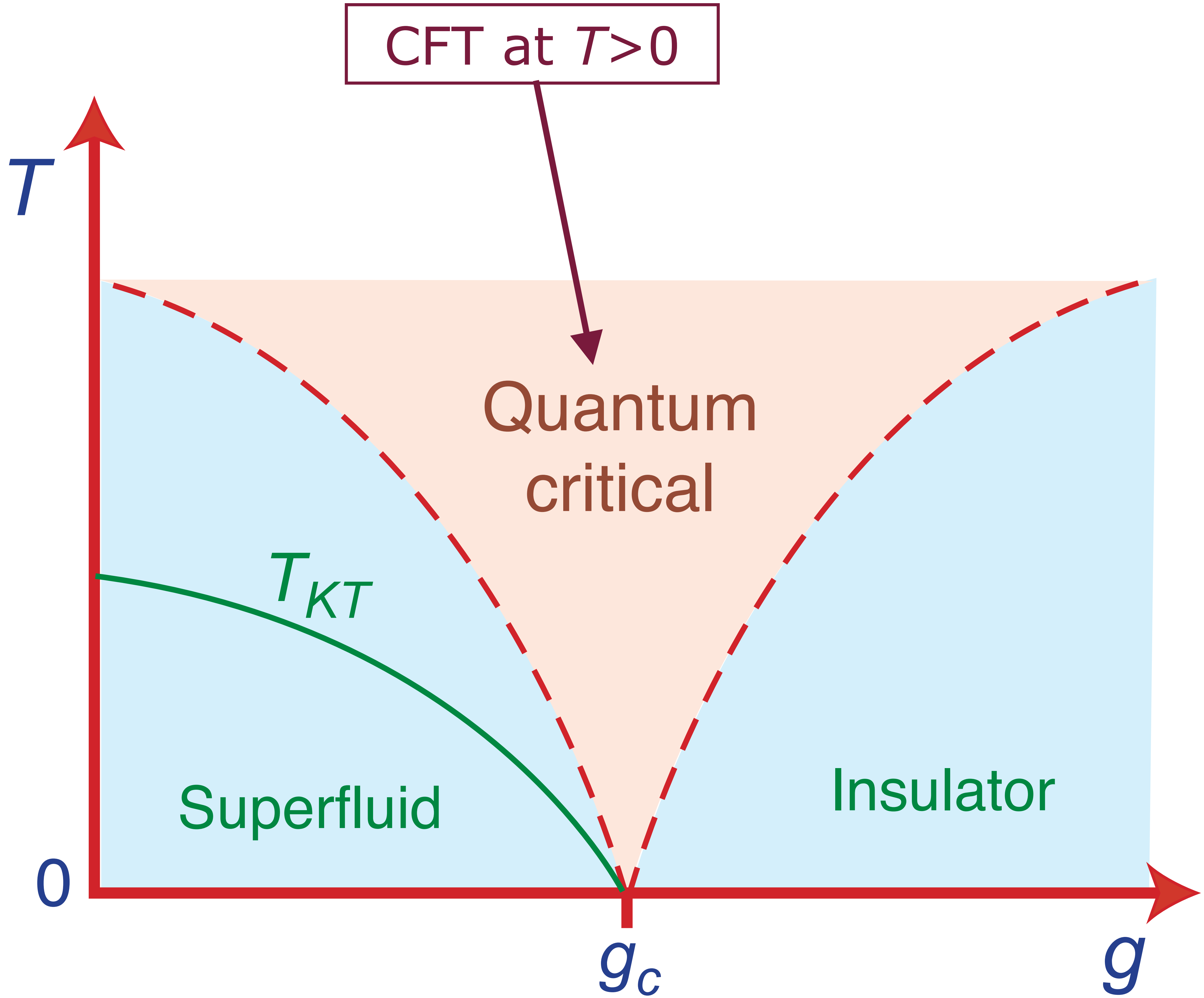
$$\langle \psi \rangle \neq 0 \qquad\qquad \langle \psi \rangle = 0$$





T
Quantum
critical
T_{KT}
Superfluid
Insulator
0
g_c
g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Field theories in D 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.

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Key idea: $\Rightarrow$ Implement u as an extra dimension, and map to a local theory in $D+1$ dimensions.

At the RG fixed point, $\beta(g) = 0$, the D dimensional field theory is invariant under the scale transformation

$$x^\mu \to x^\mu / b \quad , \quad u \to b\, u$$

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This is an invariance of the *metric* of the theory in $D+1$ dimensions. The unique solution is

$$ds^2 = \left(\frac{u}{L}\right)^2 dx^\mu dx_\mu + L^2 \frac{du^2}{u^2}.$$

Or, using the length scale $z = L^2/u$

$$ds^2 = L^2 \frac{dx^\mu dx_\mu + dz^2}{z^2}.$$

This is the space AdS_{D+1}, and L is the AdS radius.

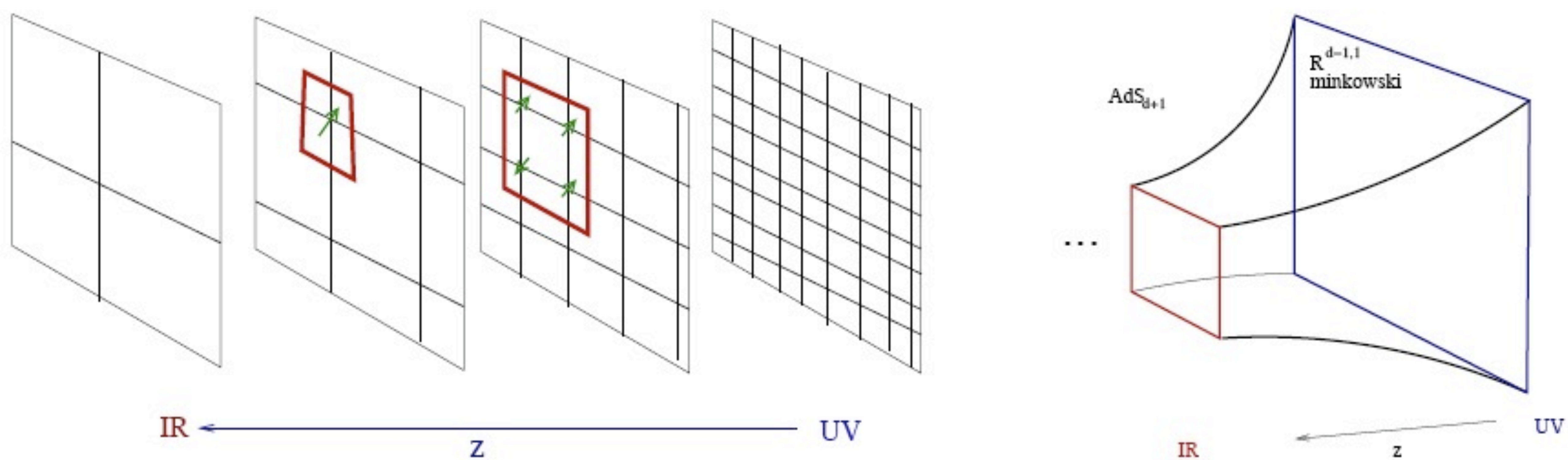

Figure 1: The extra ('radial') dimension of the bulk is the resolution scale of the field theory. The left figure indicates a series of block spin transformations labelled by a parameter z. The right figure is a cartoon of AdS space, which organizes the field theory information in the same way. In this sense, the bulk picture is a hologram: excitations with different wavelengths get put in different places in the bulk image.

J. McGreevy, arXiv0909.0518

AdS/CFT correspondence

The quantum theory of a black hole in a 3+1-dimensional negatively curved AdS universe is holographically represented by a CFT (the theory of a quantum critical point) in 2+1 dimensions

3+1 dimensional AdS space

Maldacena, Gubser, Klebanov, Polyakov, Witten

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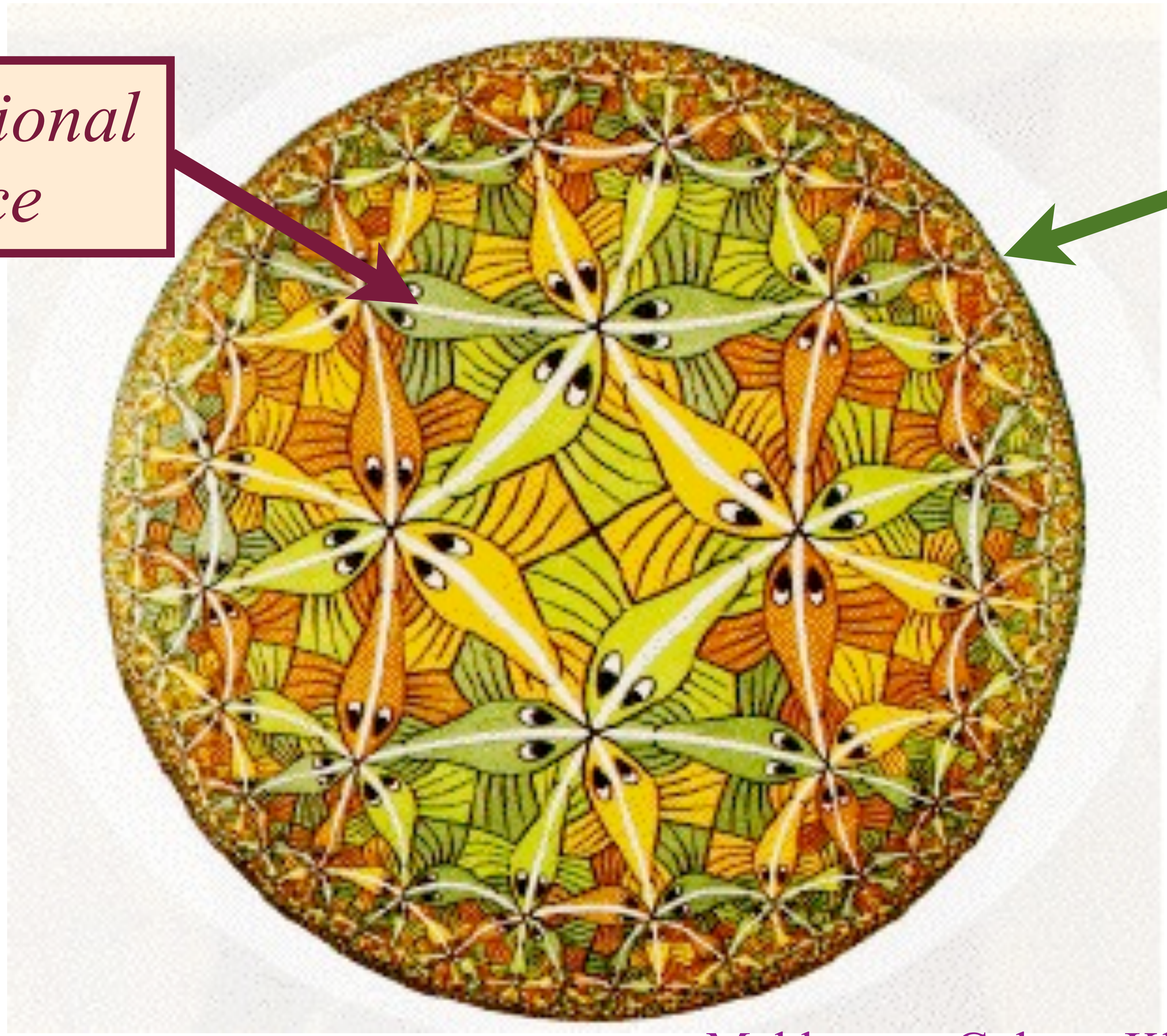

A 2+1 dimensional system at its quantum critical point

Maldacena, Gubser, Klebanov, Polyakov, Witten

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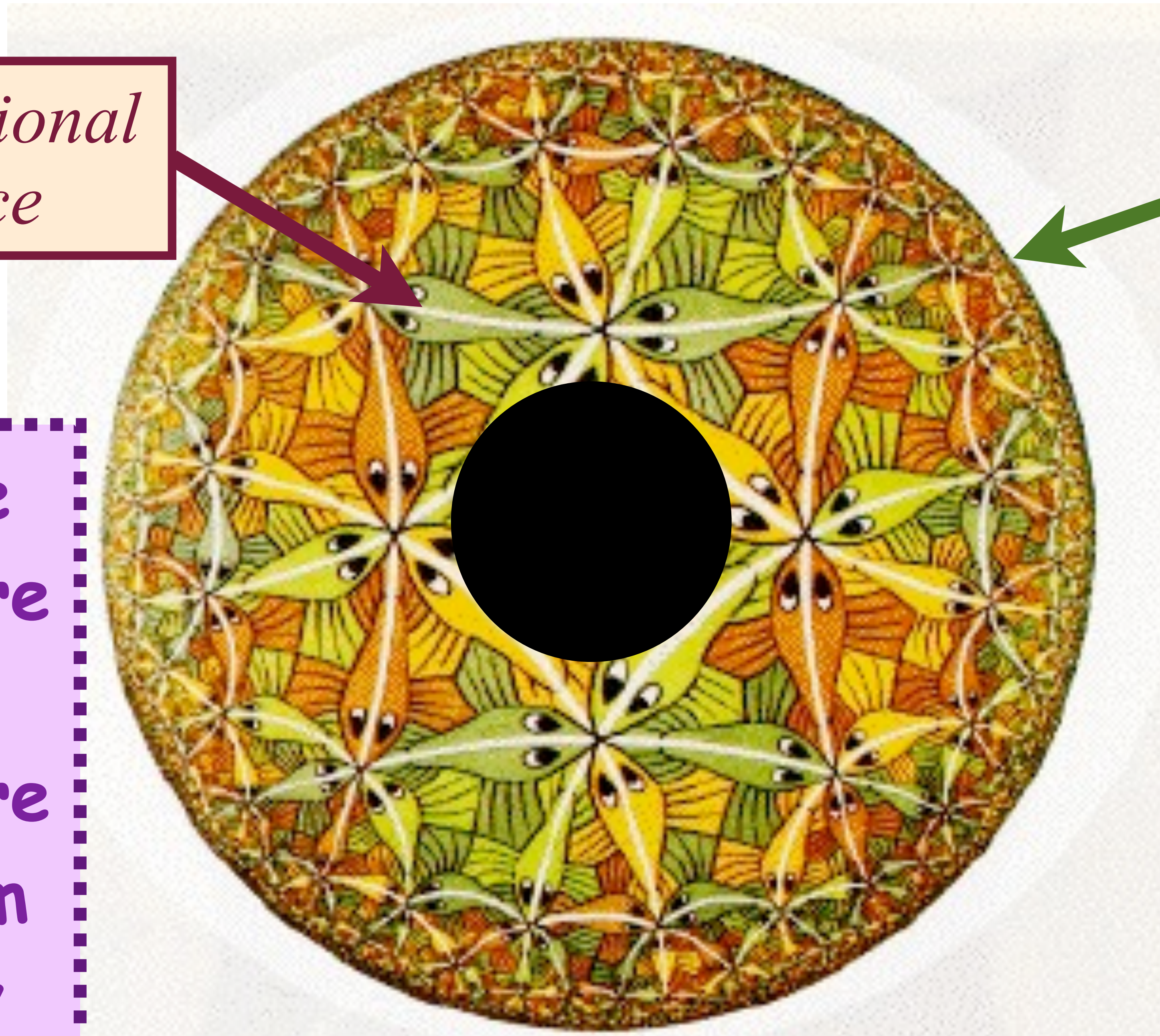

Quantum criticality in 2+1 dimensions

Black hole temperature = temperature of quantum criticality

Maldacena, Gubser, Klebanov, Polyakov, Witten

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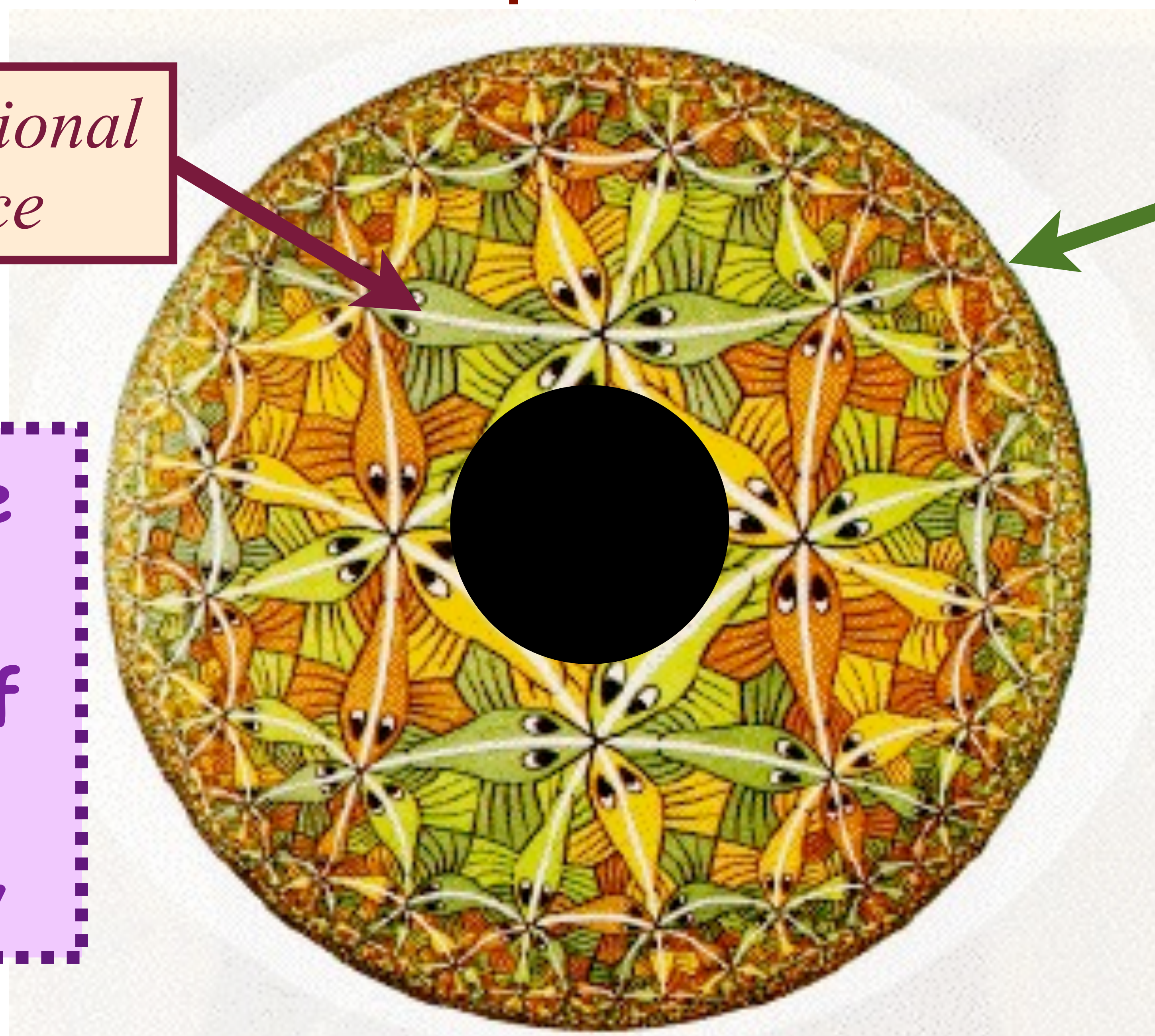

Quantum criticality in 2+1 dimensions

Black hole entropy = entropy of quantum criticality

Strominger, Vafa

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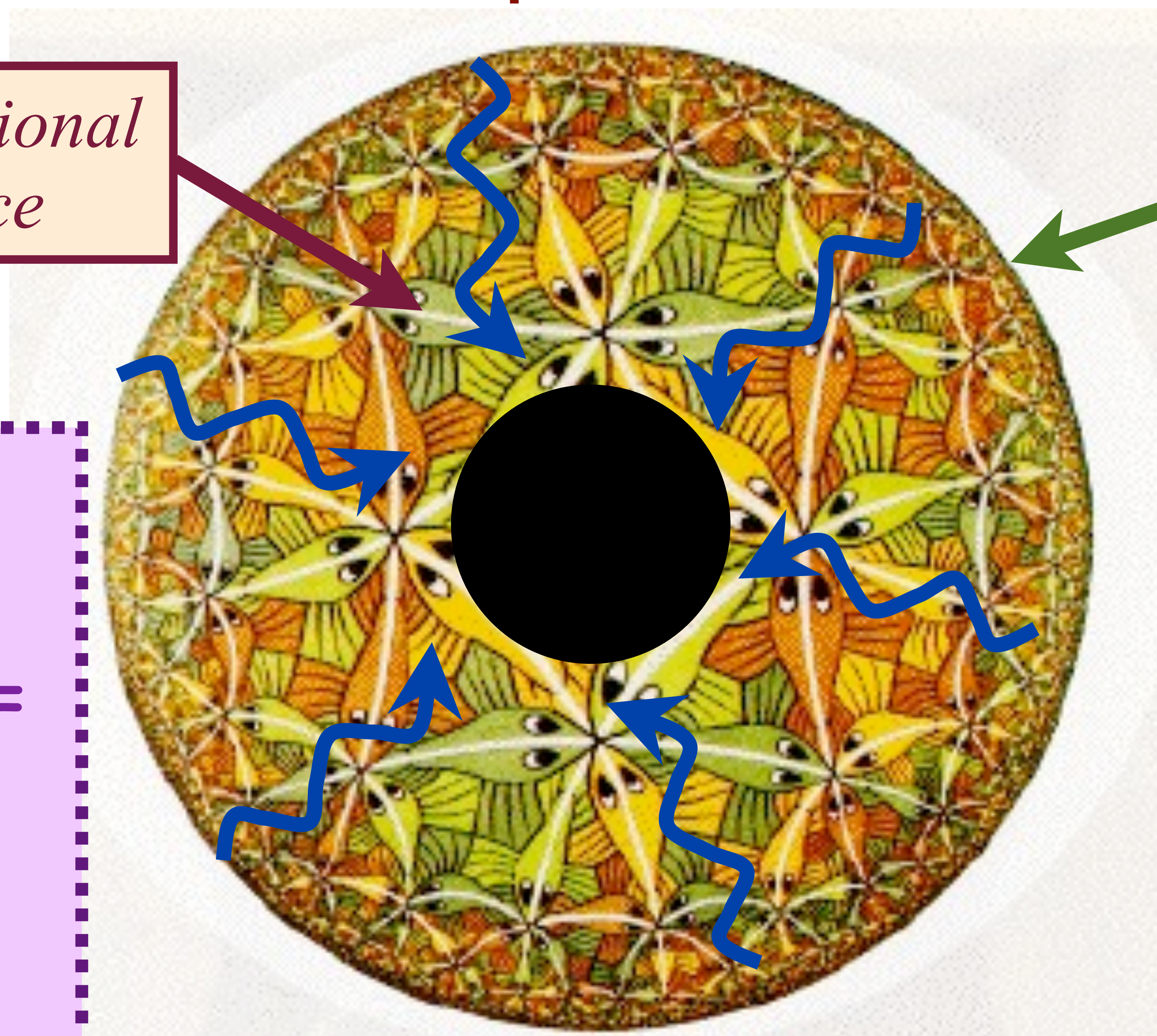
3+1 dimensional AdS space

Quantum criticality in 2+1 dimensions

Quantum critical dynamics = waves in curved space



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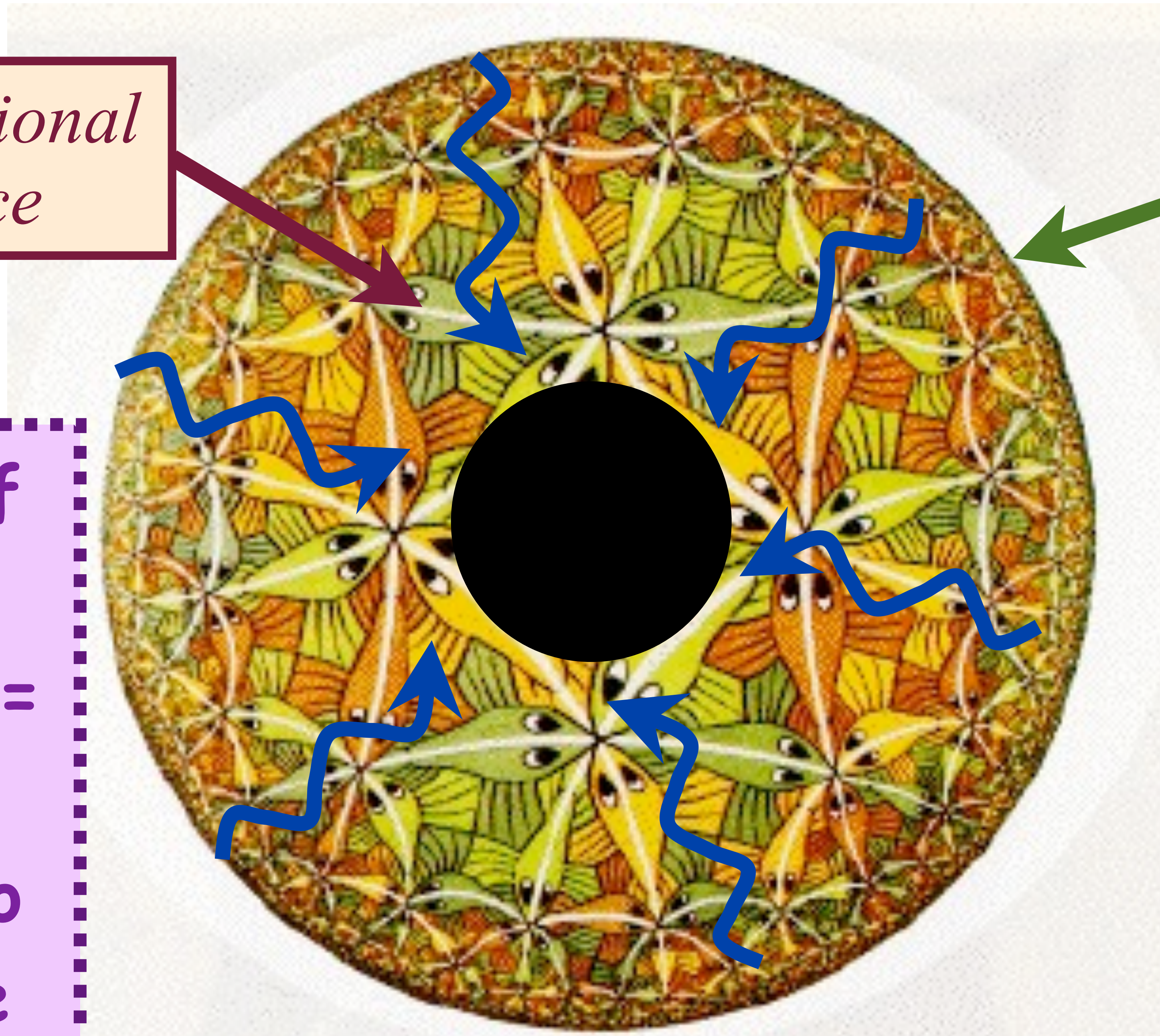

3+1 dimensional AdS space

Quantum criticality in 2+1 dimensions

Friction of quantum criticality = waves falling into black hole

Kovtun, Policastro, Son

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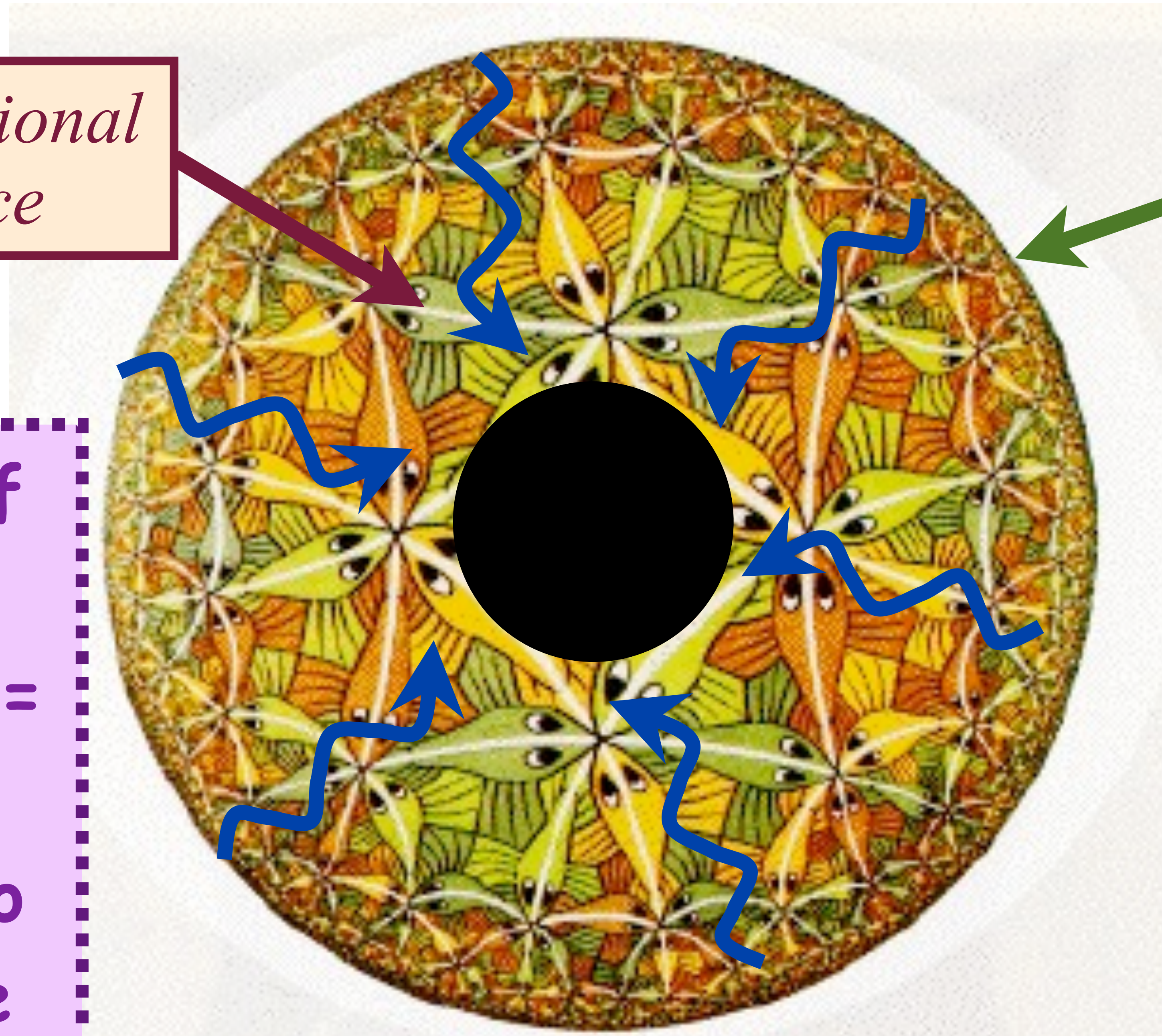

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Strong coupling problem: General solution of spin and magneto-thermo-electric transport in quantum critical region.

C. P. Herzog, P. K. Kovtun, S. Sachdev, and D. T. Son, *Phys. Rev.* D **75**, 085020 (2007).
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, *Phys. Rev.* B **76**, 144502 (2007).

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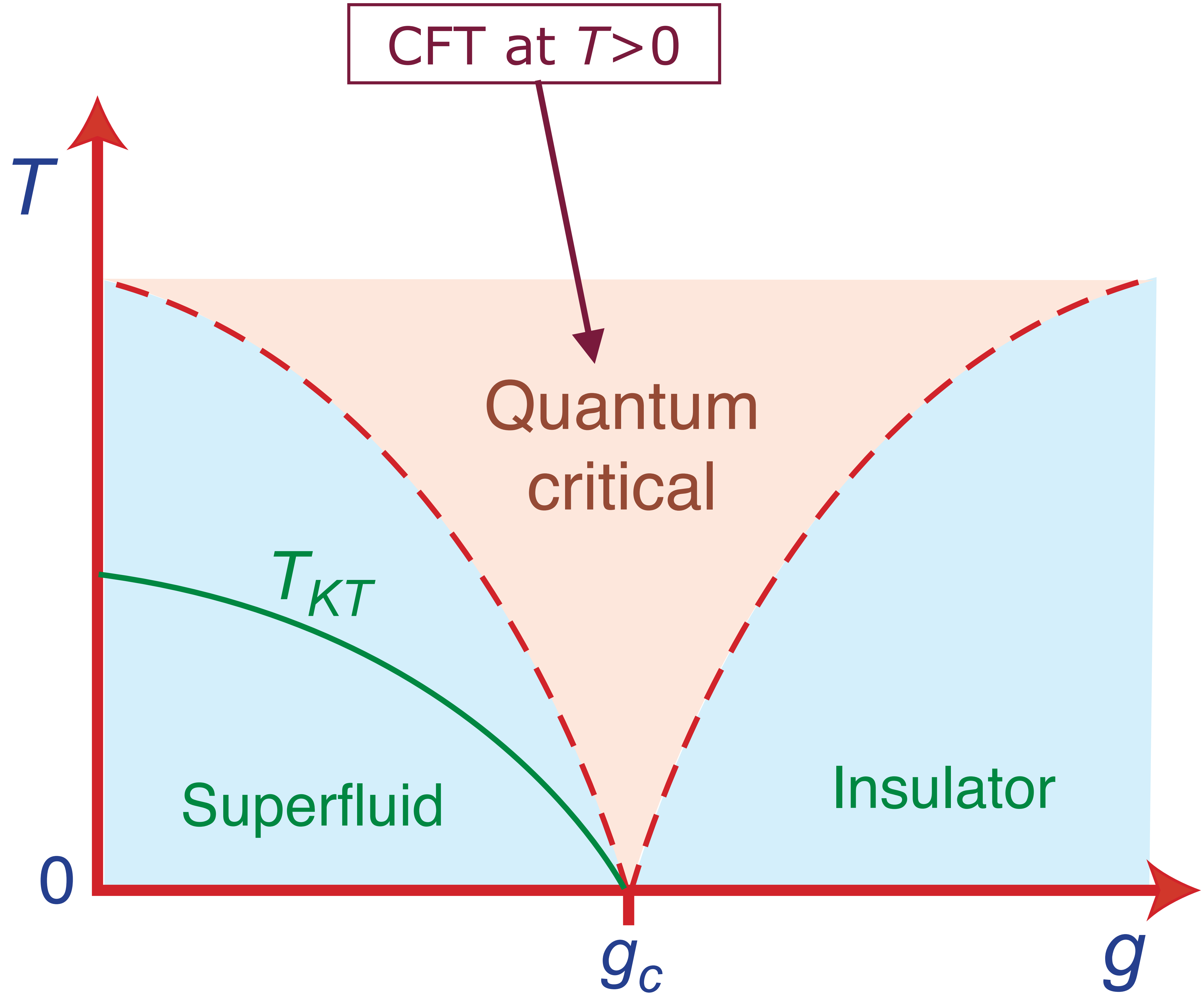


CFT at $T>0$
T
Quantum critical
T_{KT}
Superfluid
Insulator
0
g_c
g

Quantum critical transport

Quantum *"nearly perfect fluid"*
with shortest possible
relaxation time, τ_R

$$\boxed{\tau_R = \mathcal{C}\,\frac{\hbar}{k_B T}}$$

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

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

Quantum critical transport

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

Spin/charge conductivity

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

(Q is the quantum of spin/charge)

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

Quantum critical transport

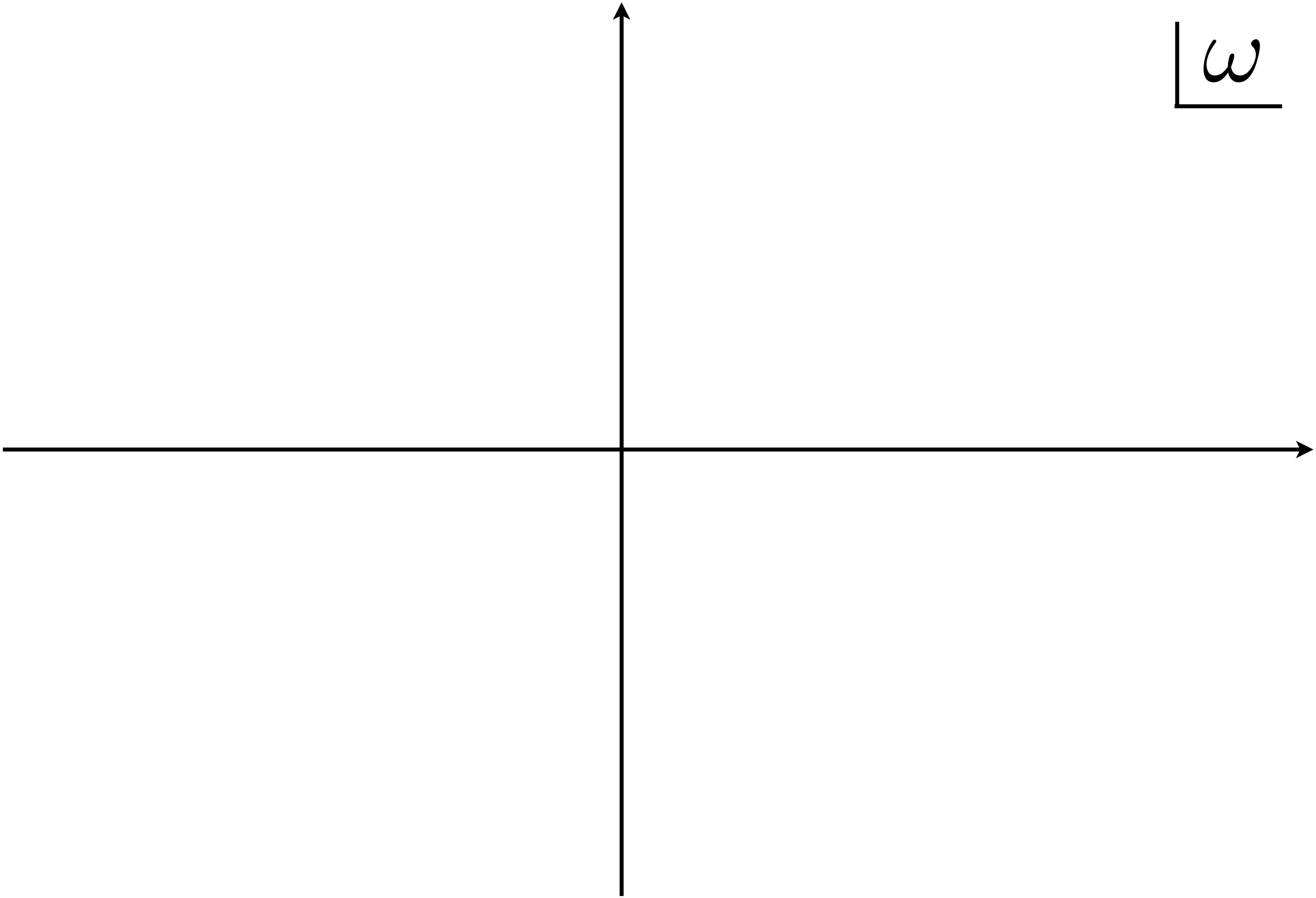
Transport co-oefficients not determined by collision rate, but by universal constants of nature

Momentum transport

$$\boxed{\begin{aligned}\frac{\eta}{s} &\equiv \frac{\text{viscosity}}{\text{entropy density}} \\ &= \frac{\hbar}{k_B} \times [\text{Universal constant } \mathcal{O}(1)\ ]\end{aligned}}$$

P. Kovtun, D. T. Son, and A. Starinets, *Phys. Rev. Lett.* **94,** 11601 (2005)

Structure of conductivity for complex frequencies



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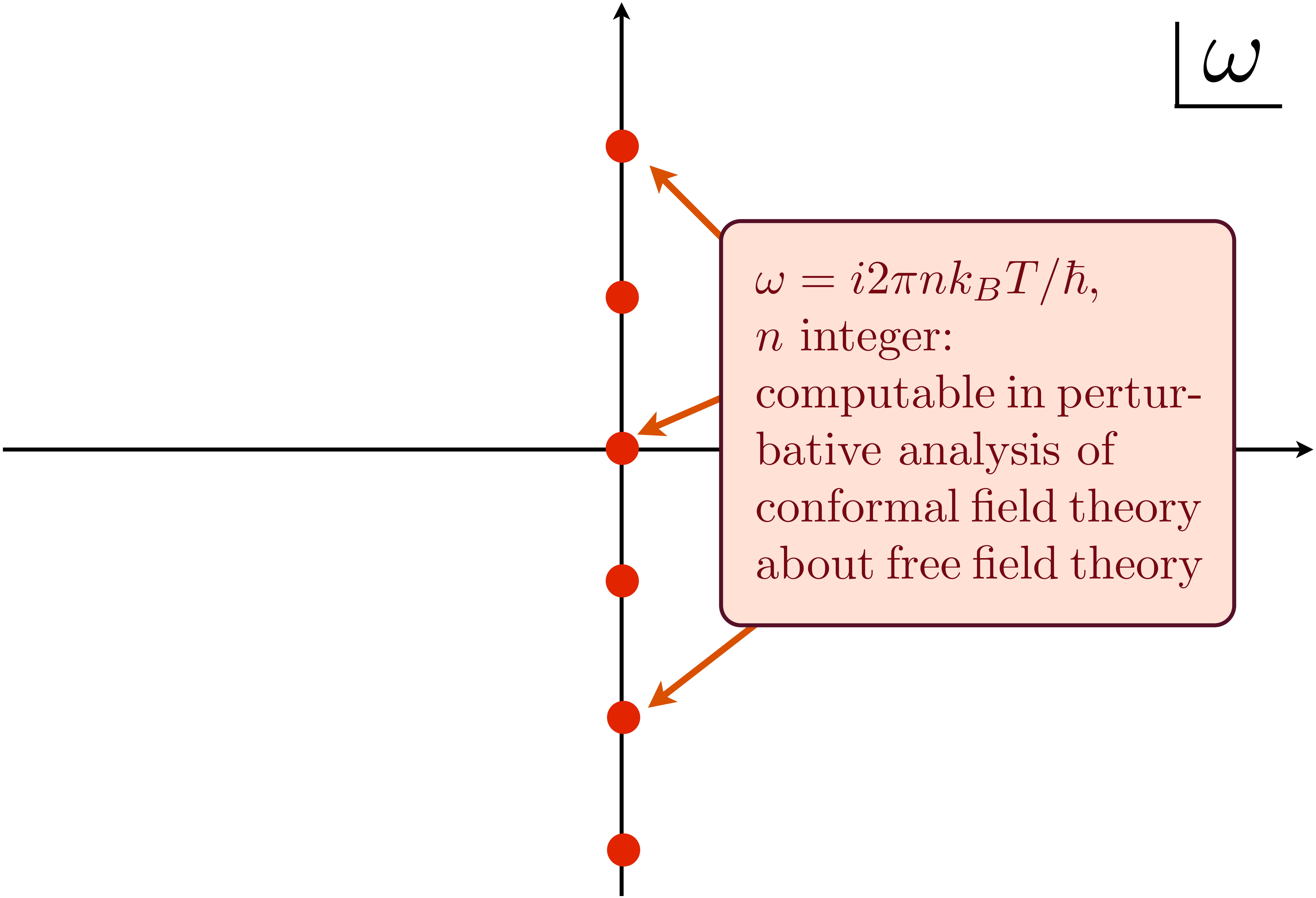

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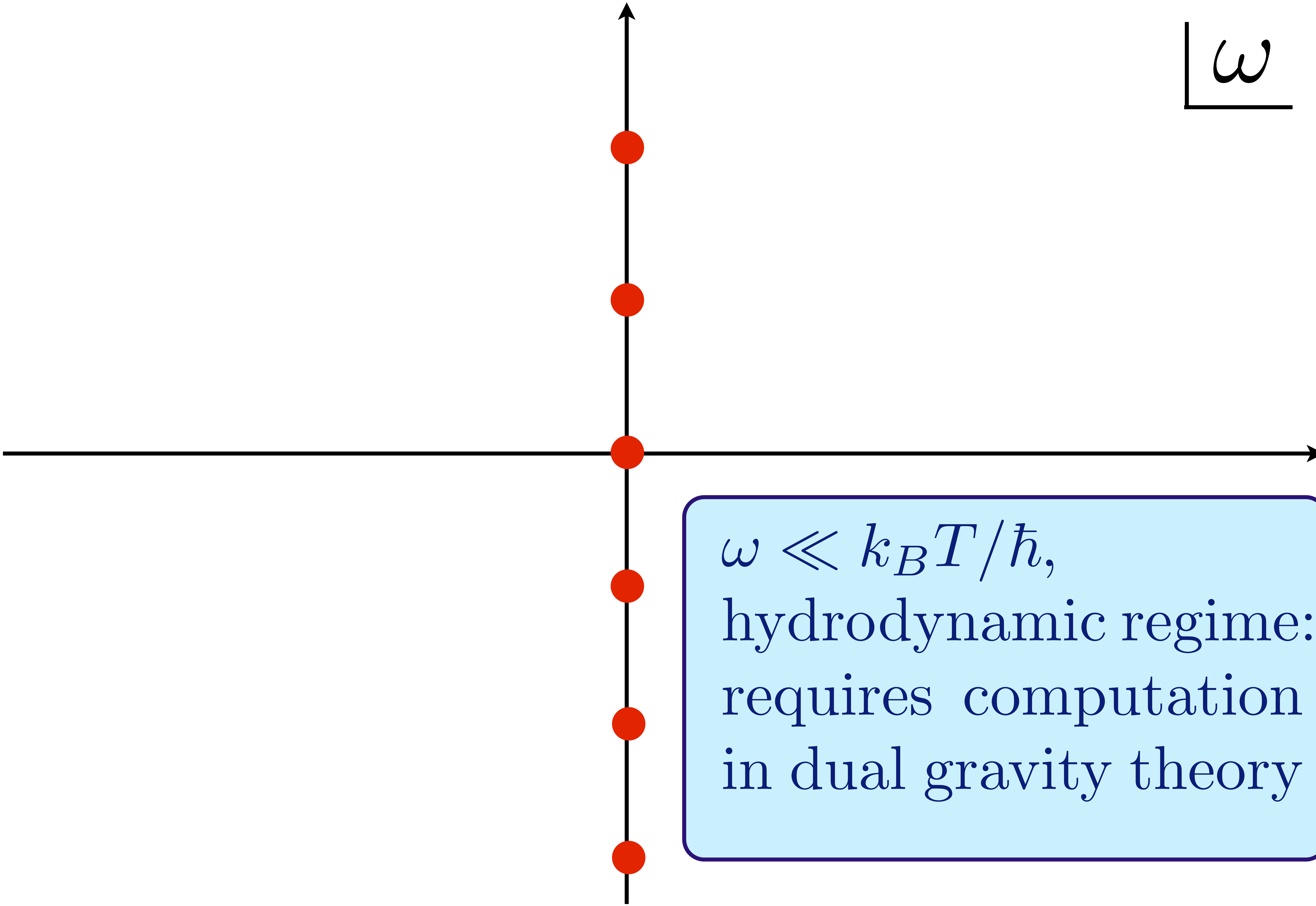

$\omega \ll k_B T/\hbar$,
hydrodynamic regime:
requires computation
in dual gravity theory

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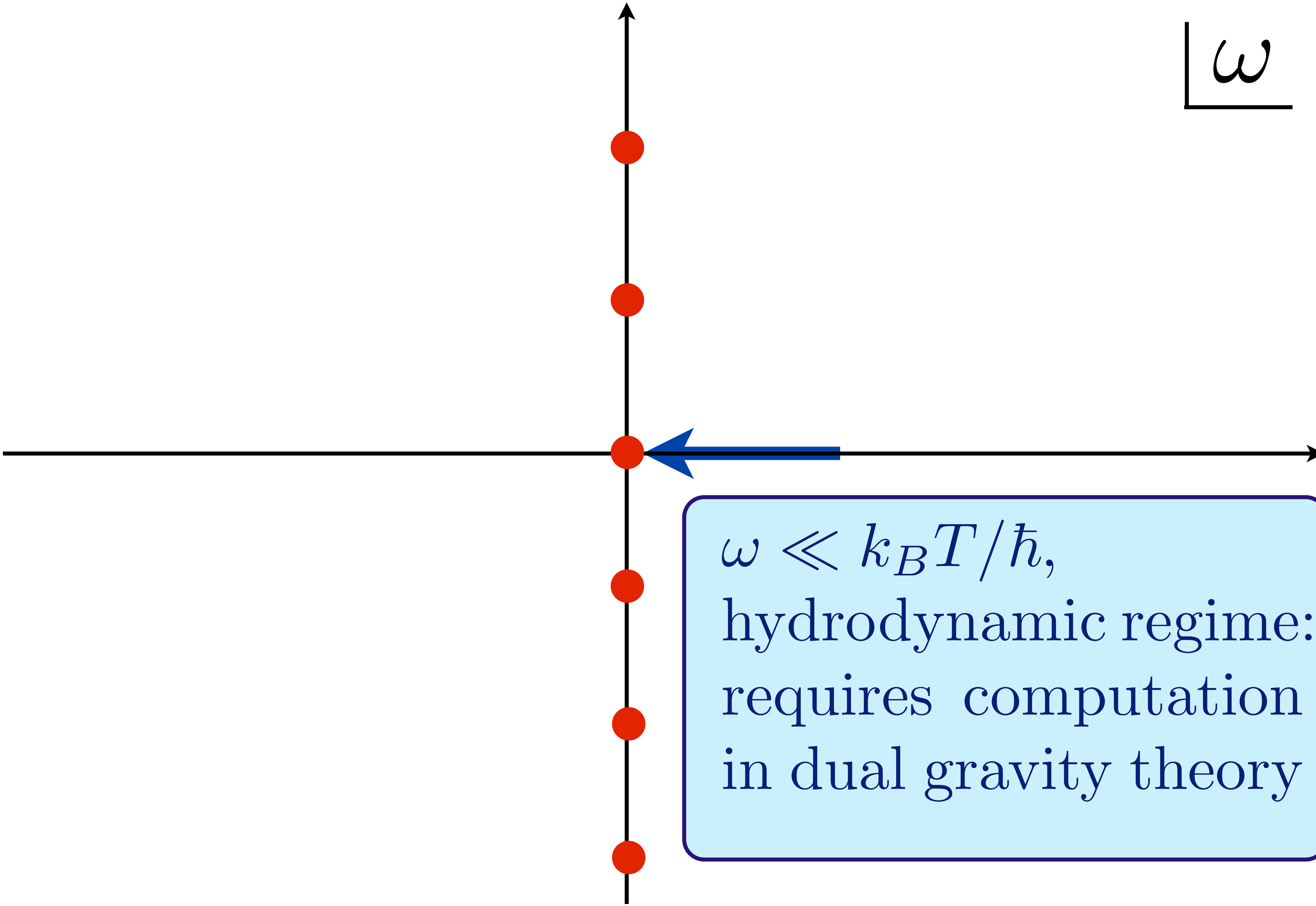

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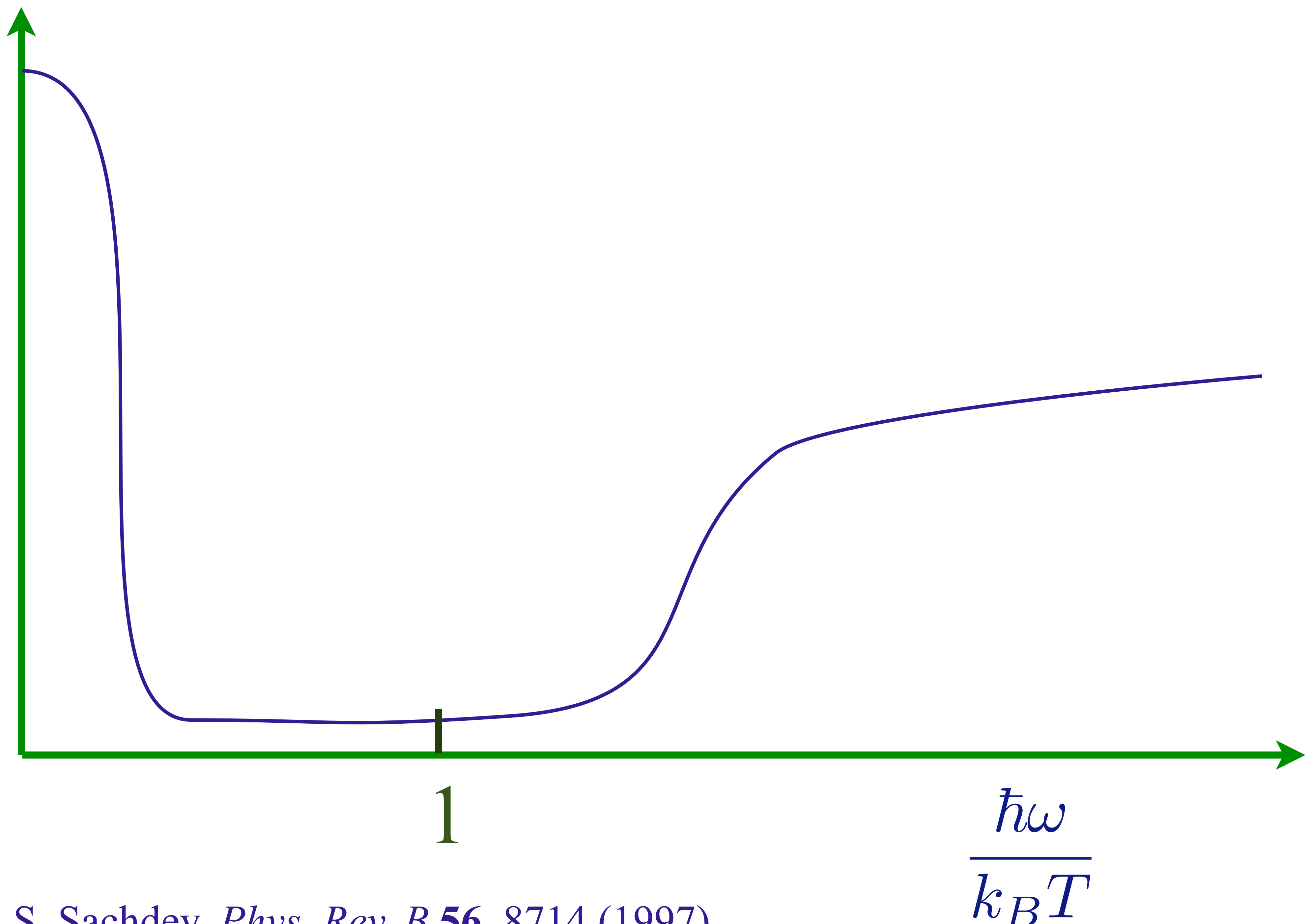
Boltzmann theory of quantum critical transport

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



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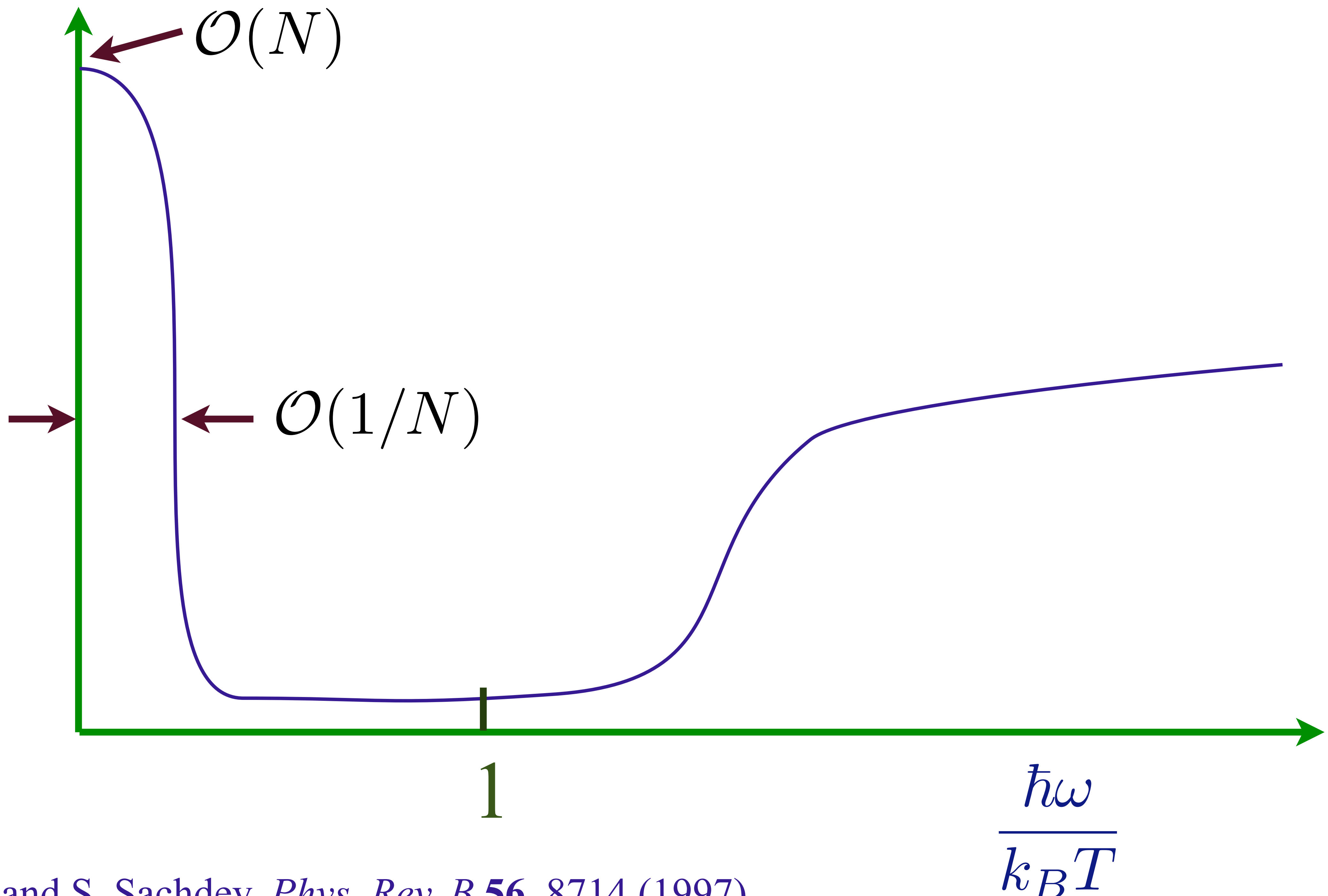

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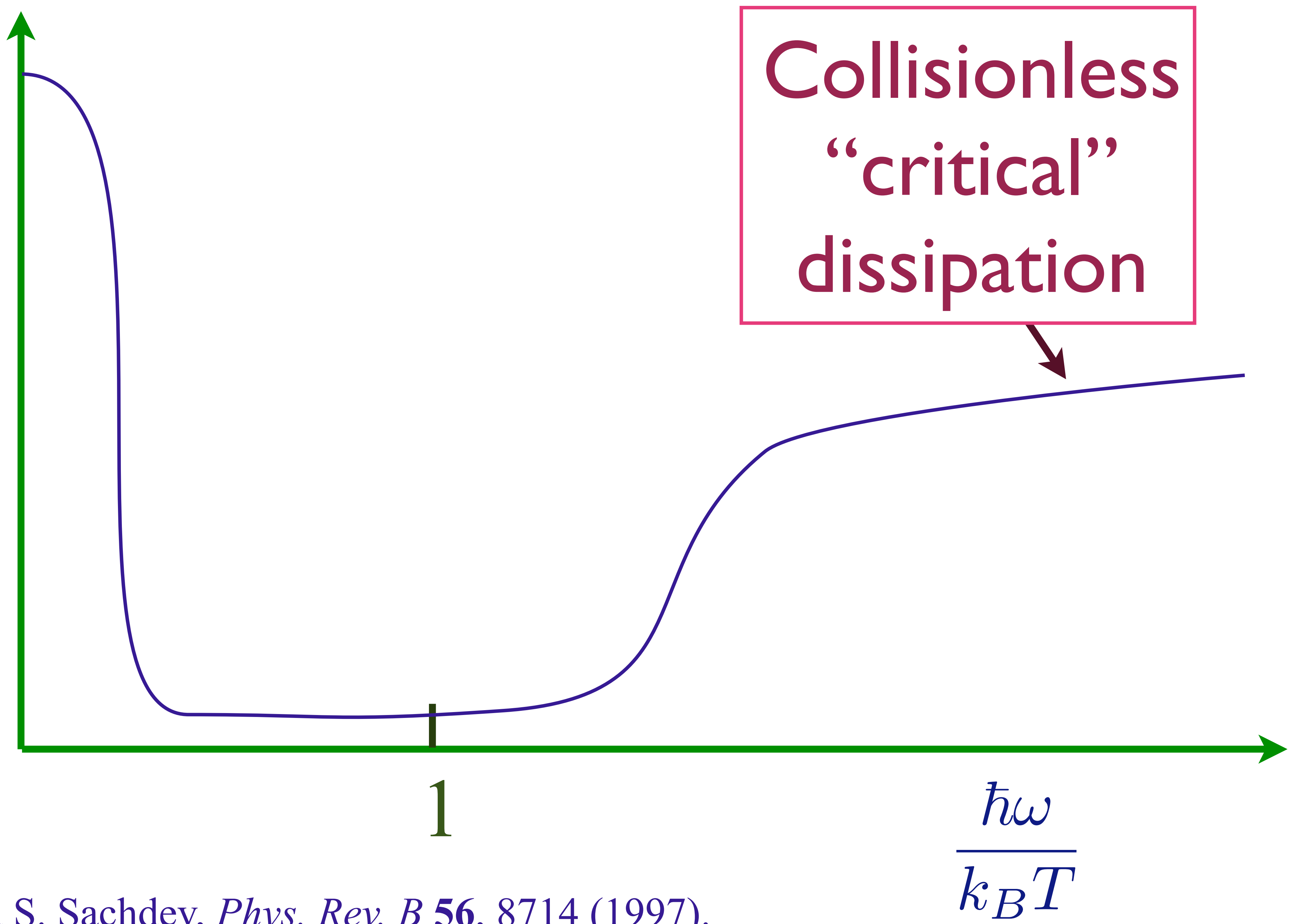

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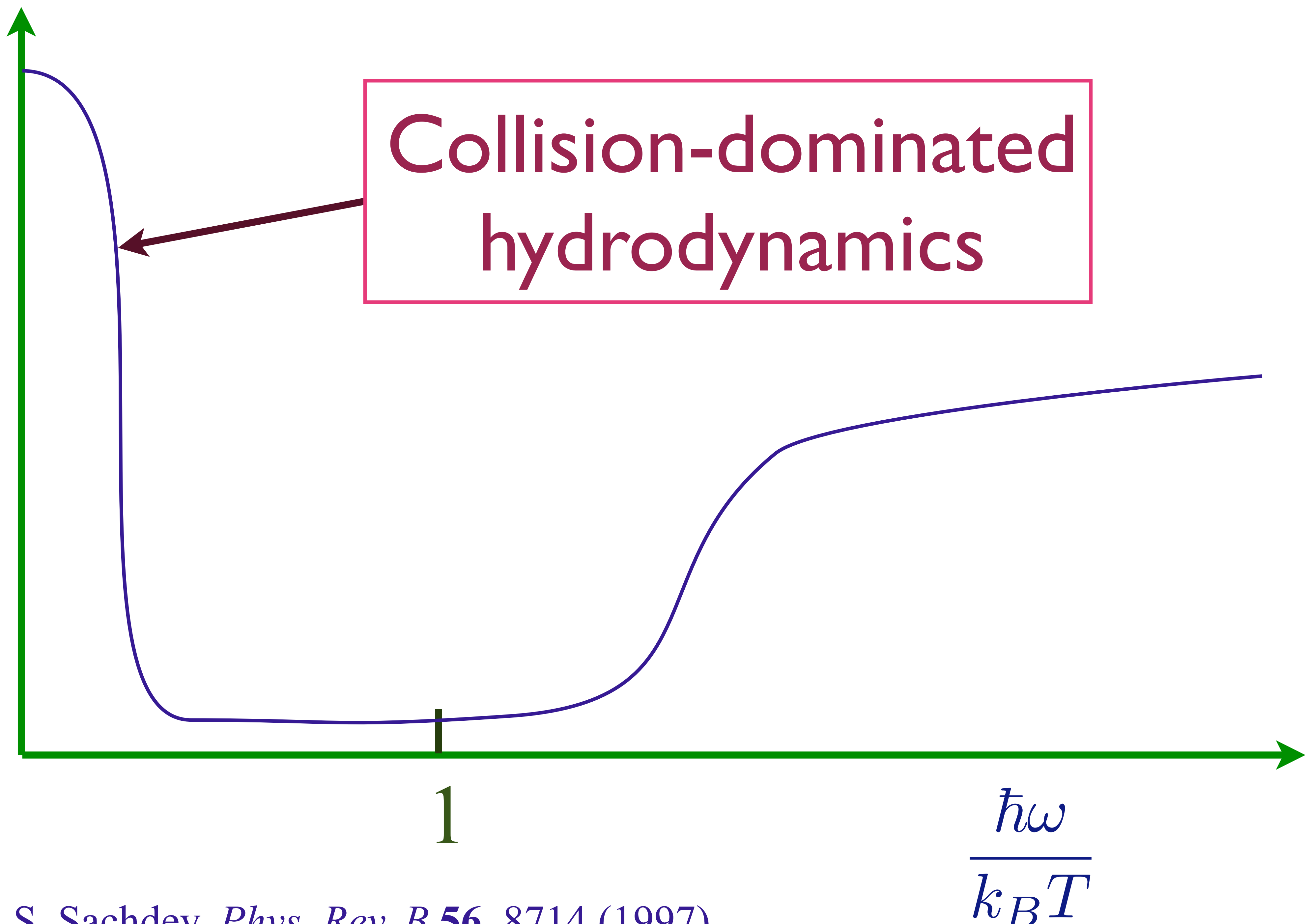

K. Damle and S. Sachdev, *Phys. Rev. B* **56**, 8714 (1997).

AdS$_4$ theory of strongly interacting "perfect fluids"

To leading order in a gradient expansion, an infinite set of strongly-interacting CFT3s can be described by Einstein-Maxwell gravity/electrodynamics on AdS$_4$

$$\mathcal{S}_{EM} = \frac{1}{g_4^2} \int d^4x \sqrt{-g} \left[-\frac{1}{4} F_{ab} F^{ab} \right] .$$

C. P. Herzog, P. K. Kovtun, S. Sachdev, and D. T. Son, *Phys. Rev.* D **75**, 085020 (2007).

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$$\mathcal{S}_{EM} = \frac{1}{g_4^2} \int d^4x \sqrt{-g} \left[-\frac{1}{4} F_{ab} F^{ab} \right] .$$

This theory is self-dual under $F_{ab} \rightarrow \epsilon_{abcd} F^{cd}$, and this leads to some artifacts in the properties of the CFT3

C. P. Herzog, P. K. Kovtun, S. Sachdev, and D. T. Son, *Phys. Rev.* D **75**, 085020 (2007).

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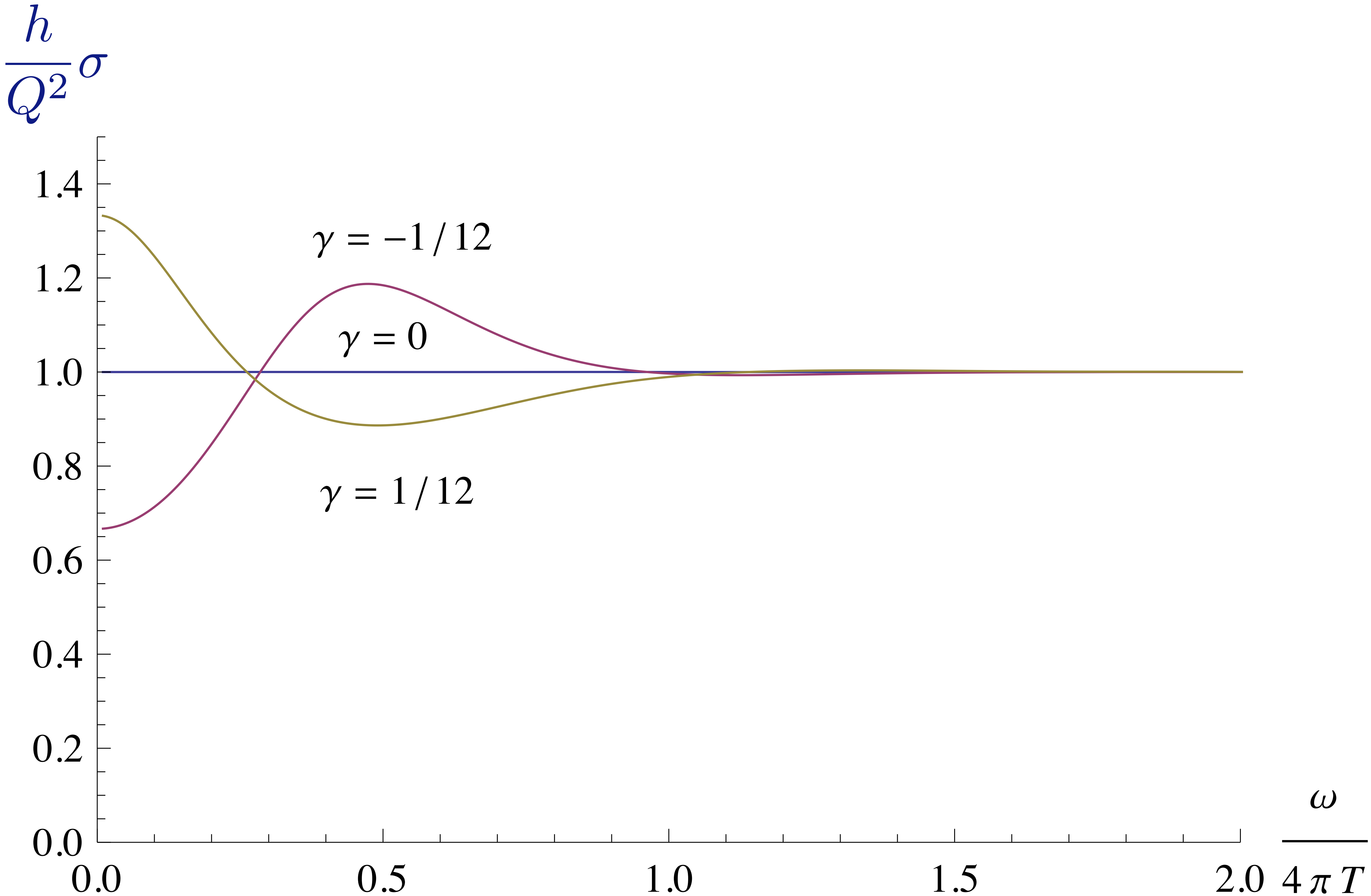
We include all possible 4-derivative terms: after suitable field redefinitions, the required theory has only *one* dimensionless constant γ (L is the radius of AdS$_4$):

$$\mathcal{S} = \frac{1}{g_4^2} \int d^4x \sqrt{-g} \left[-\frac{1}{4} F_{ab} F^{ab} + \gamma \, L^2 C_{abcd} F^{ab} F^{cd} \right] ,$$

where C_{abcd} is the Weyl curvature tensor.
Stability and causality constraints restrict $|\gamma| < 1/12$.

R. C. Myers, S. Sachdev, and A. Singh, arXiv:1010.0443

AdS$_4$ theory of strongly interacting "perfect fluids"



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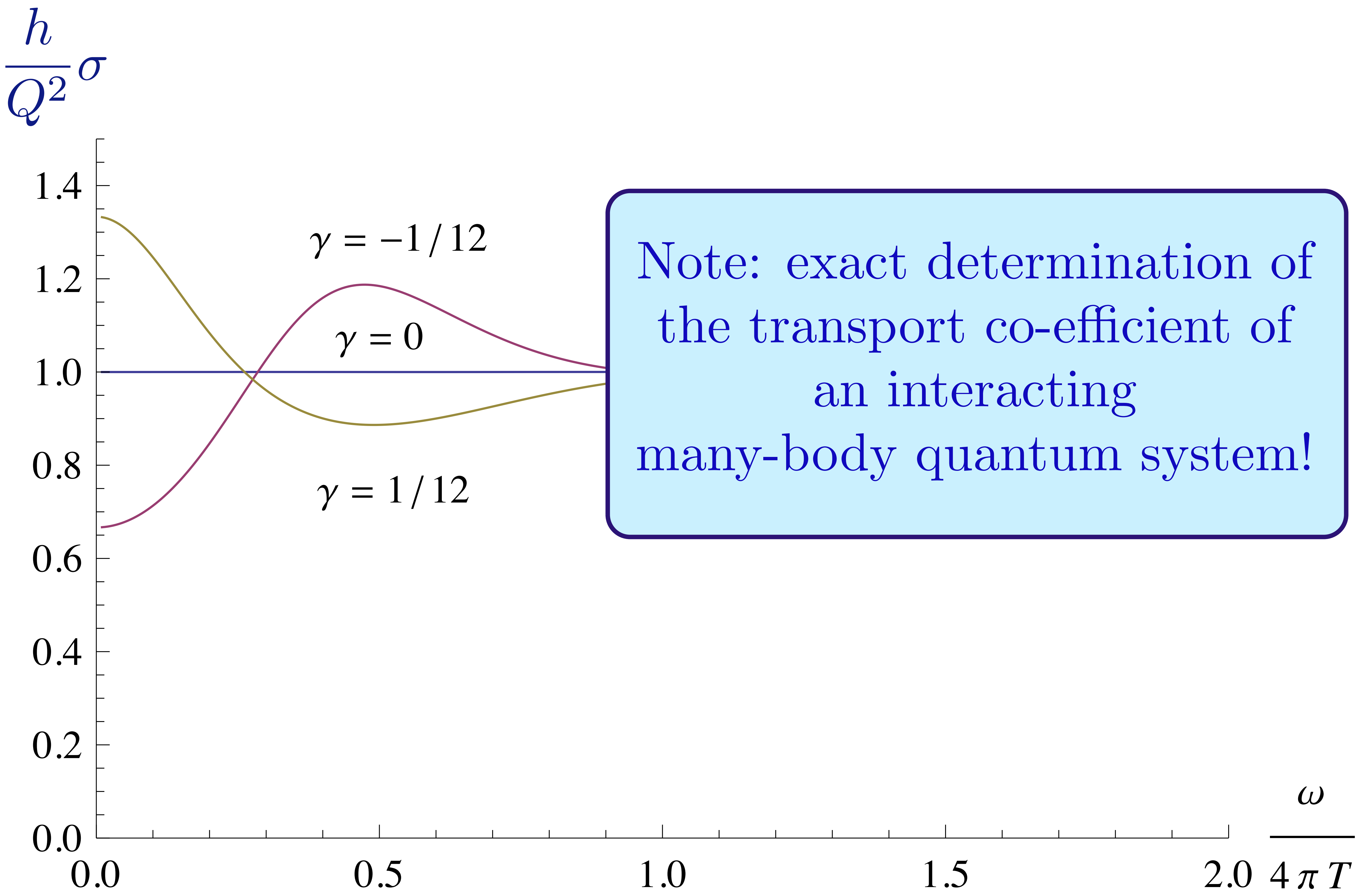
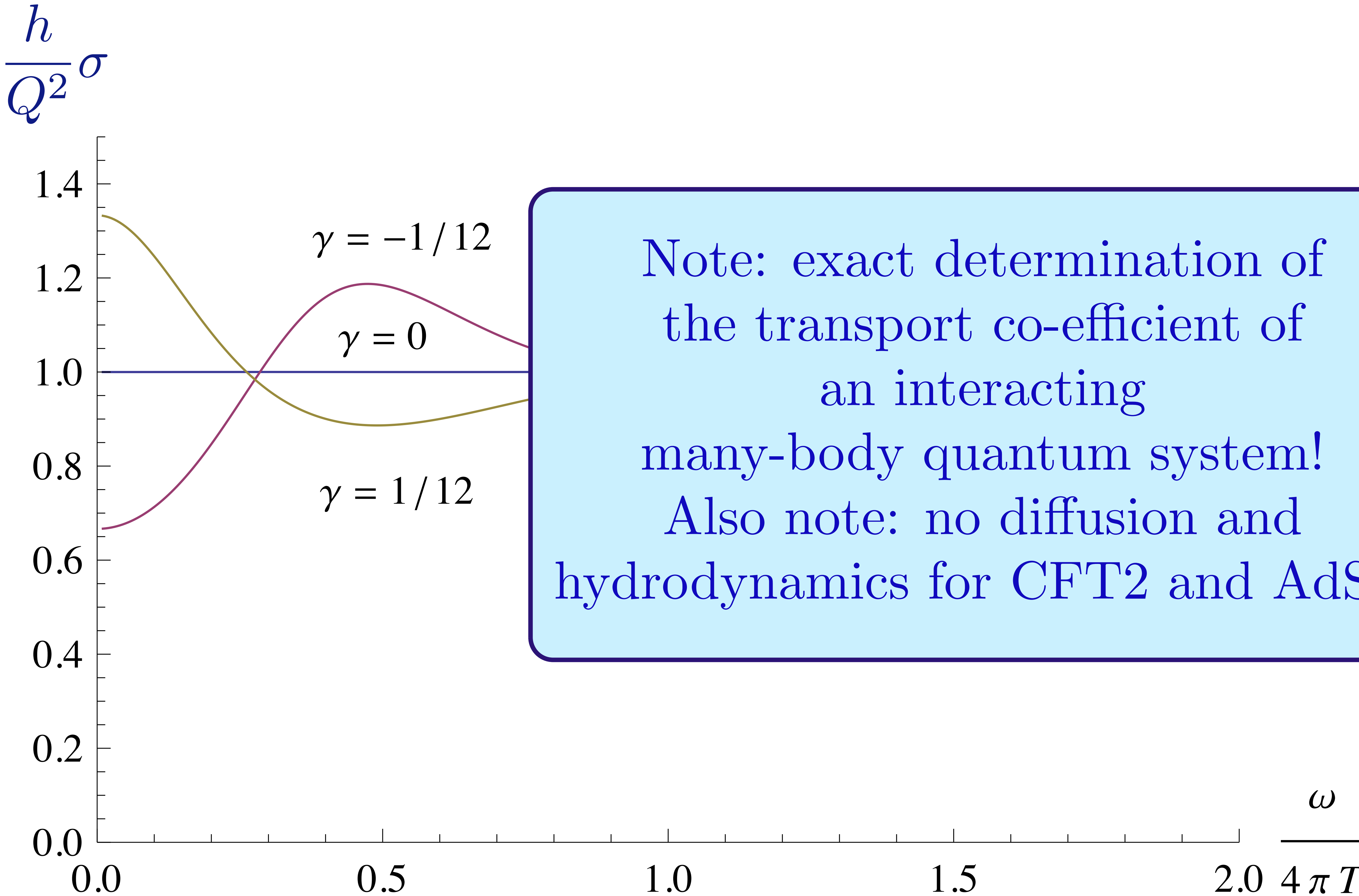


Note: exact determination of the transport co-efficient of an interacting many-body quantum system!

R. C. Myers, S. Sachdev, and A. Singh, arXiv:1010.0443

AdS_4 theory of strongly interacting "perfect fluids"



Note: exact determination of the transport co-efficient of an interacting many-body quantum system!
Also note: no diffusion and hydrodynamics for CFT2 and AdS_3.

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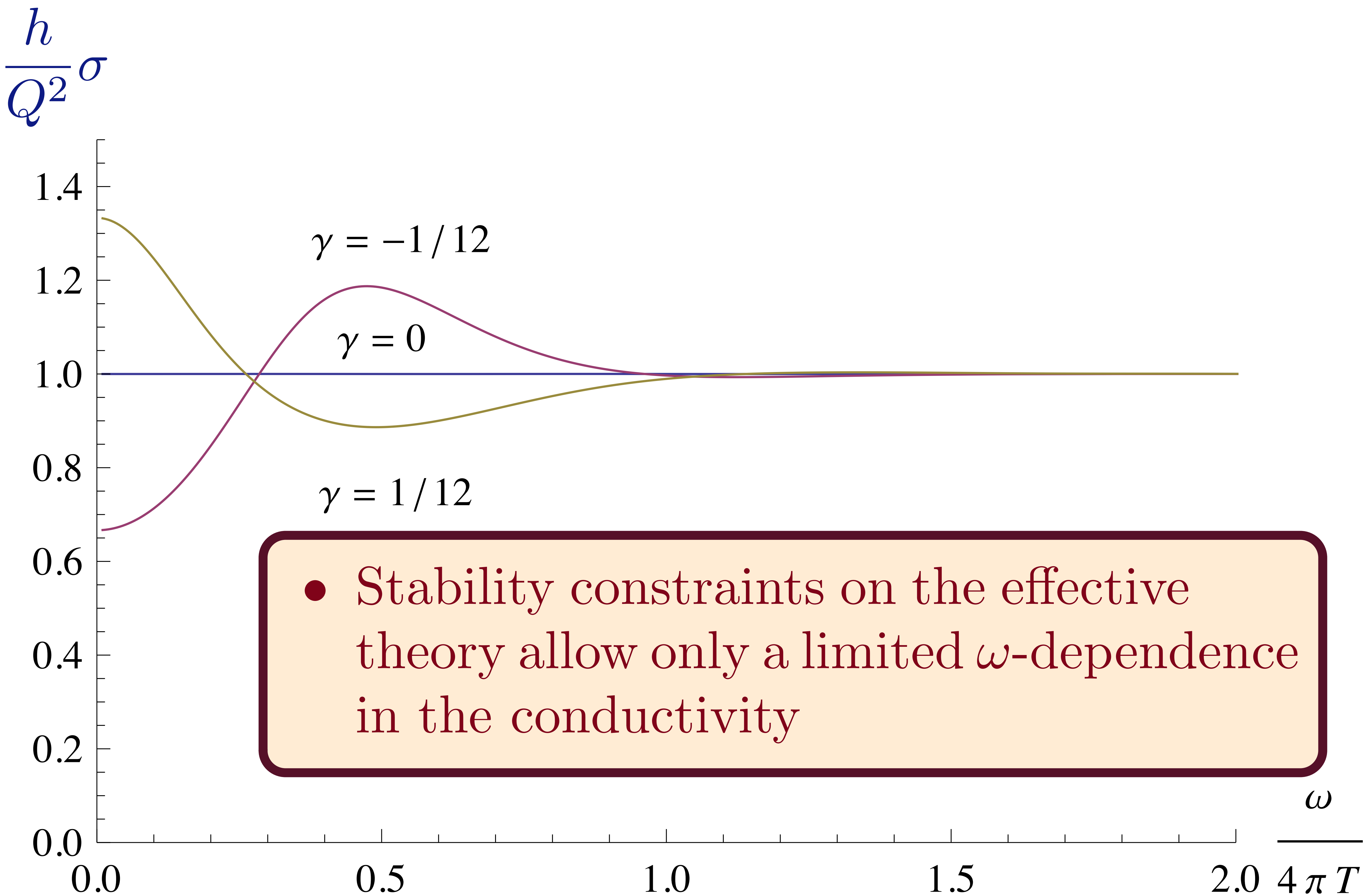

- Stability constraints on the effective theory allow only a limited ω-dependence in the conductivity

R. C. Myers, S. Sachdev, and A. Singh, arXiv:1010.0443

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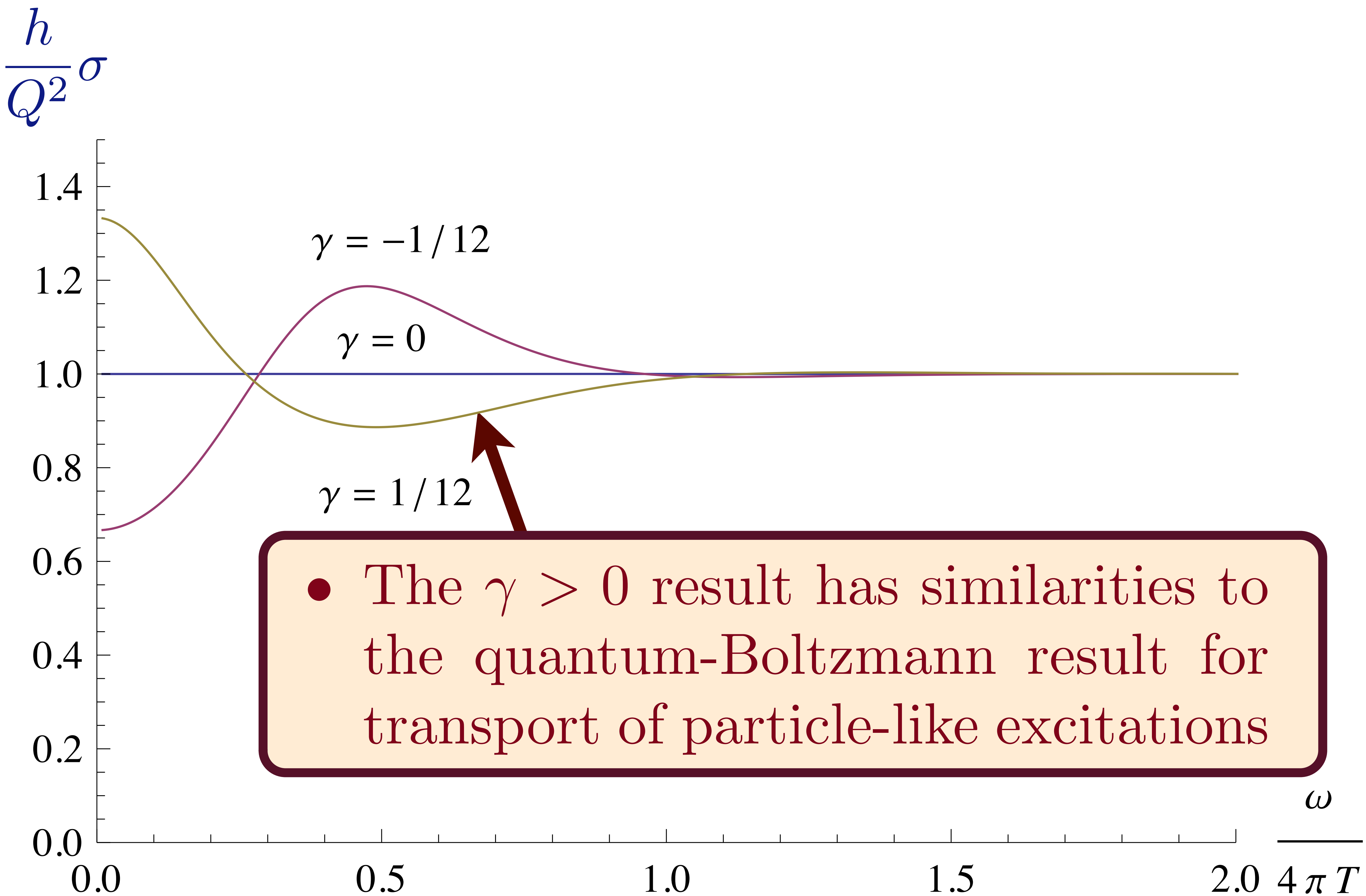

- The $\gamma > 0$ result has similarities to the quantum-Boltzmann result for transport of particle-like excitations

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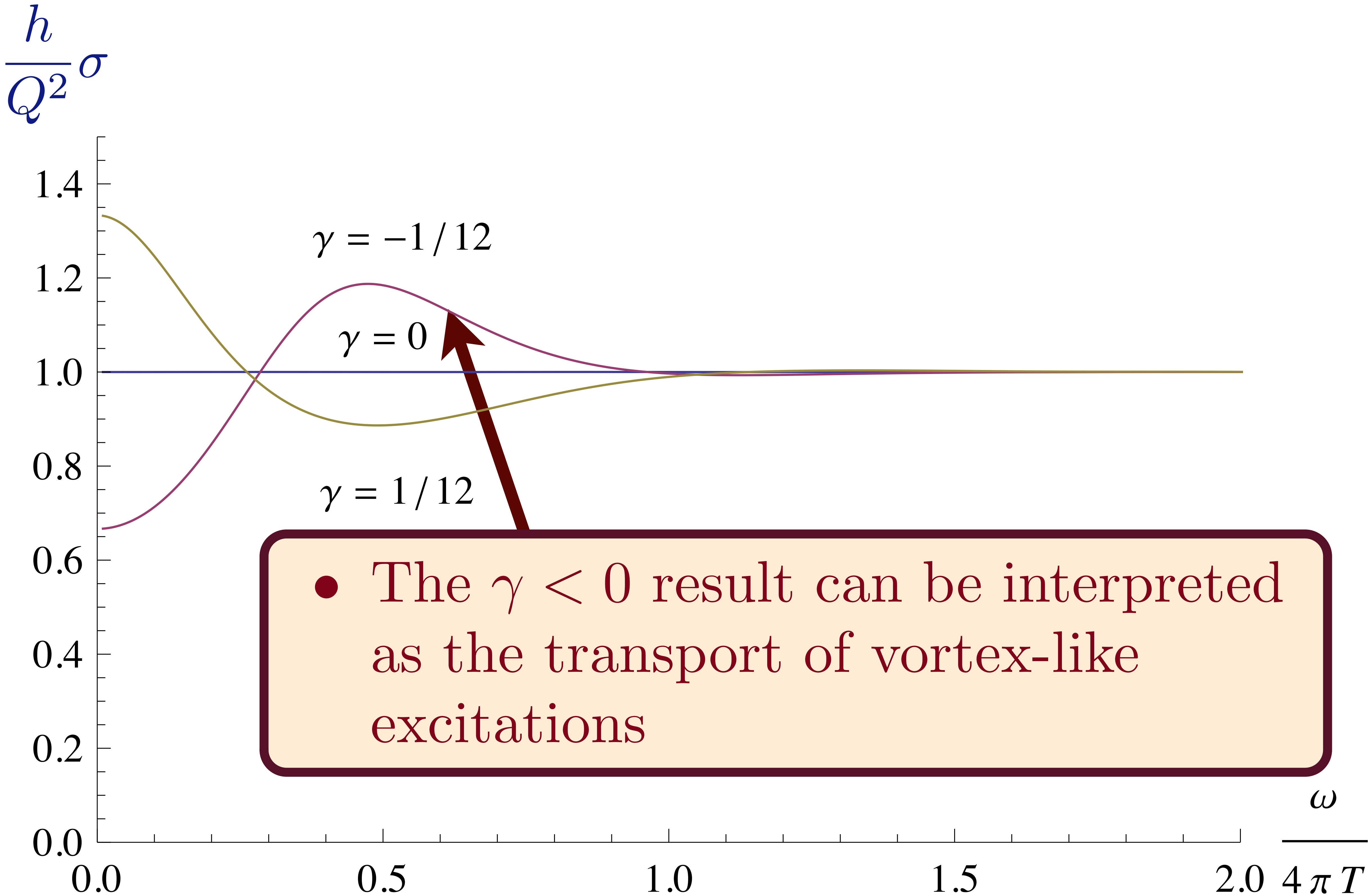

- The $\gamma < 0$ result can be interpreted as the transport of vortex-like excitations

R. C. Myers, S. Sachdev, and A. Singh, arXiv:1010.0443

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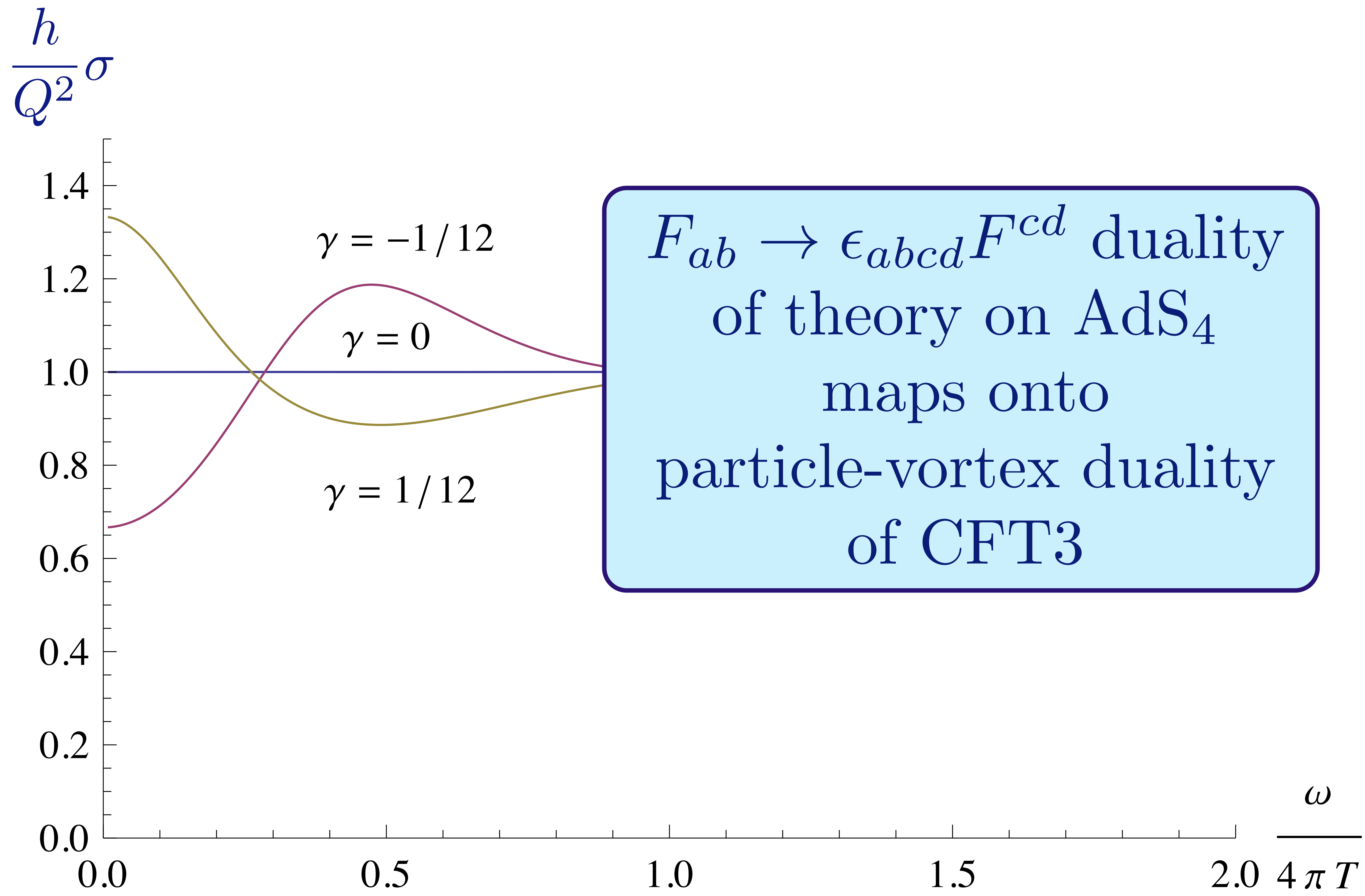

$F_{ab} \to \epsilon_{abcd} F^{cd}$ duality of theory on AdS$_4$ maps onto particle-vortex duality of CFT3

R. C. Myers, S. Sachdev, and A. Singh, arXiv:1010.0443

Frequency dependency of integer quantum Hall effect

Little frequency dependence, and conductivity is close to self-dual value

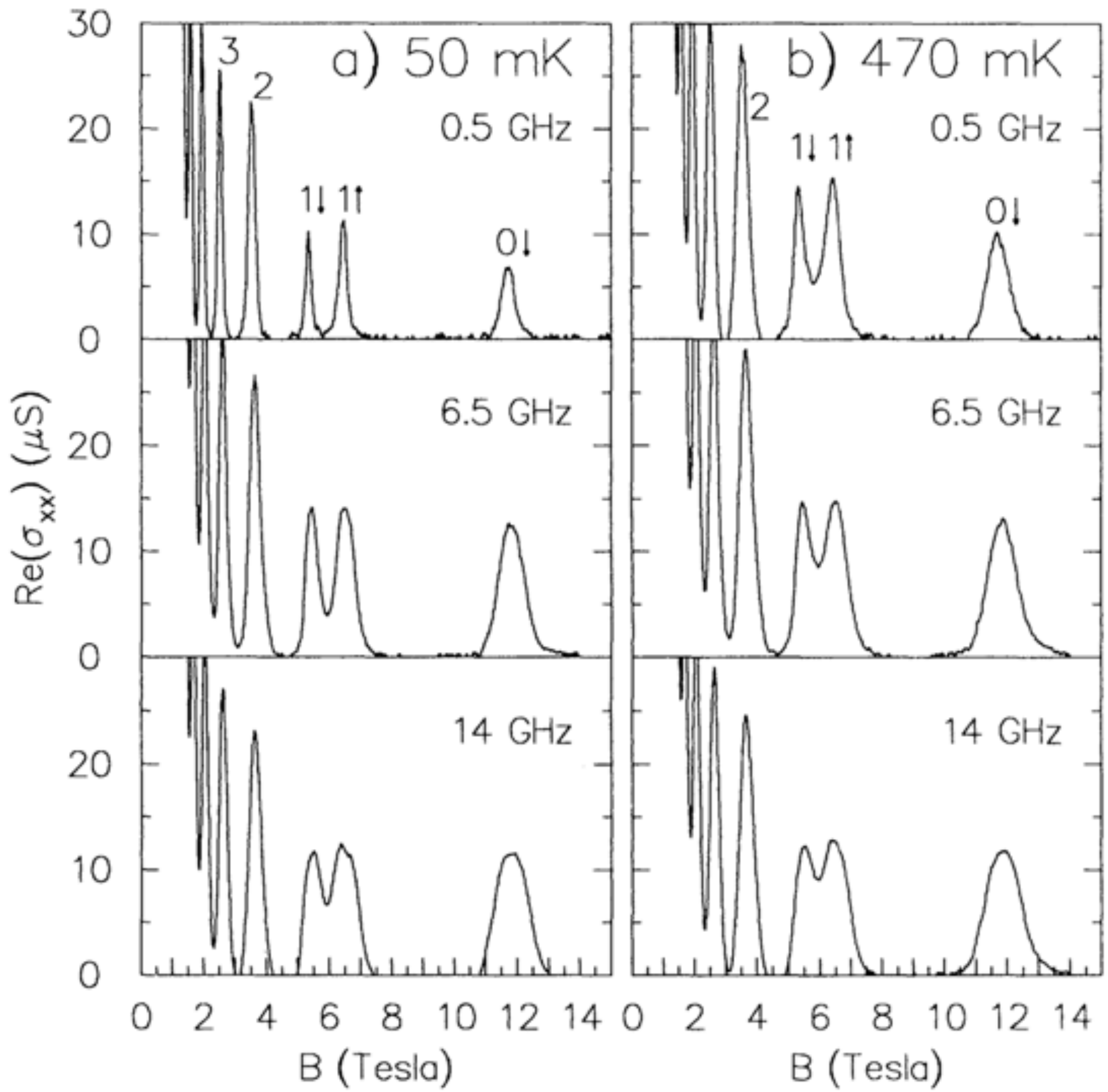

FIG. 3. $\mathrm{Re}(\sigma_{xx})$ vs B at three frequencies and two temperatures. Peaks are marked with Landau level index N and spin.

L. W. Engel, D. Shahar, C. Kurdak, and D. C. Tsui, *Physical Review Letters* **71**, 2638 (1993).

Outline

1. Coupled dimer antiferromagnets

   Quantum criticality and conformal field theories

2. The AdS/CFT correspondence

   Quantum criticality and black holes

3. Quantum transport and Einstein-Maxwell theory on AdS_4

4. Compressible quantum matter

   Fermi surfaces

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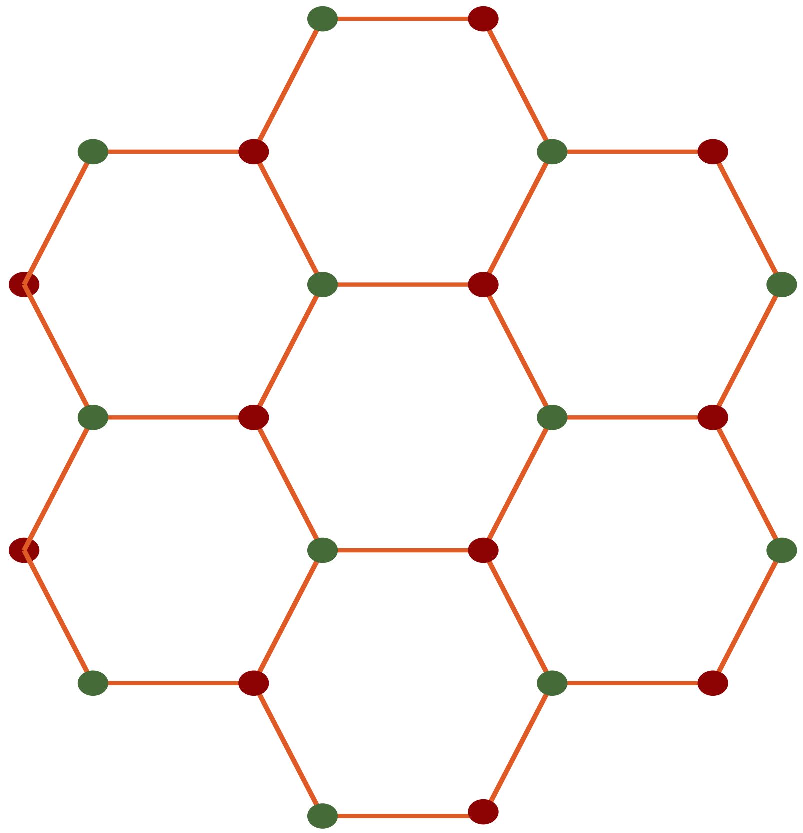
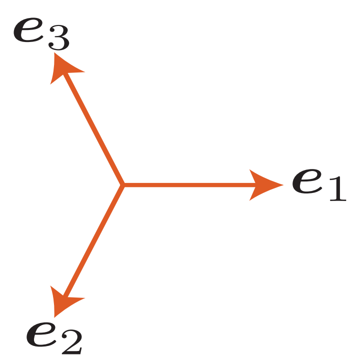
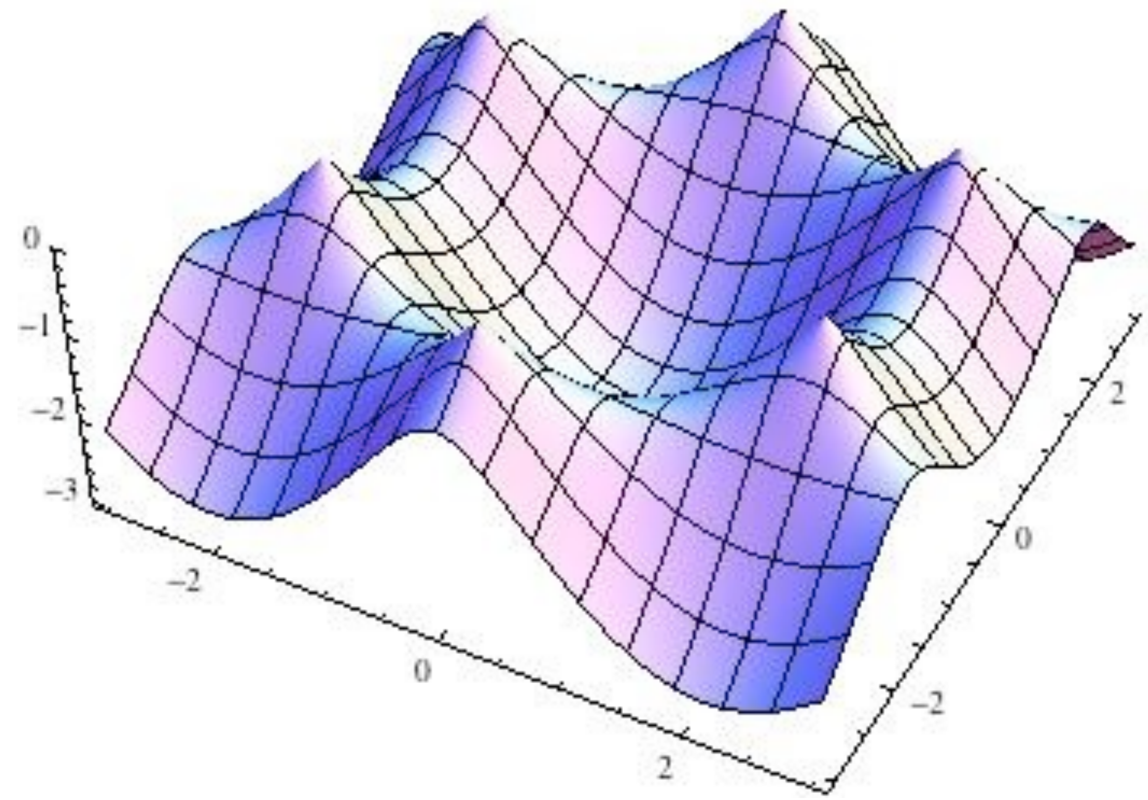
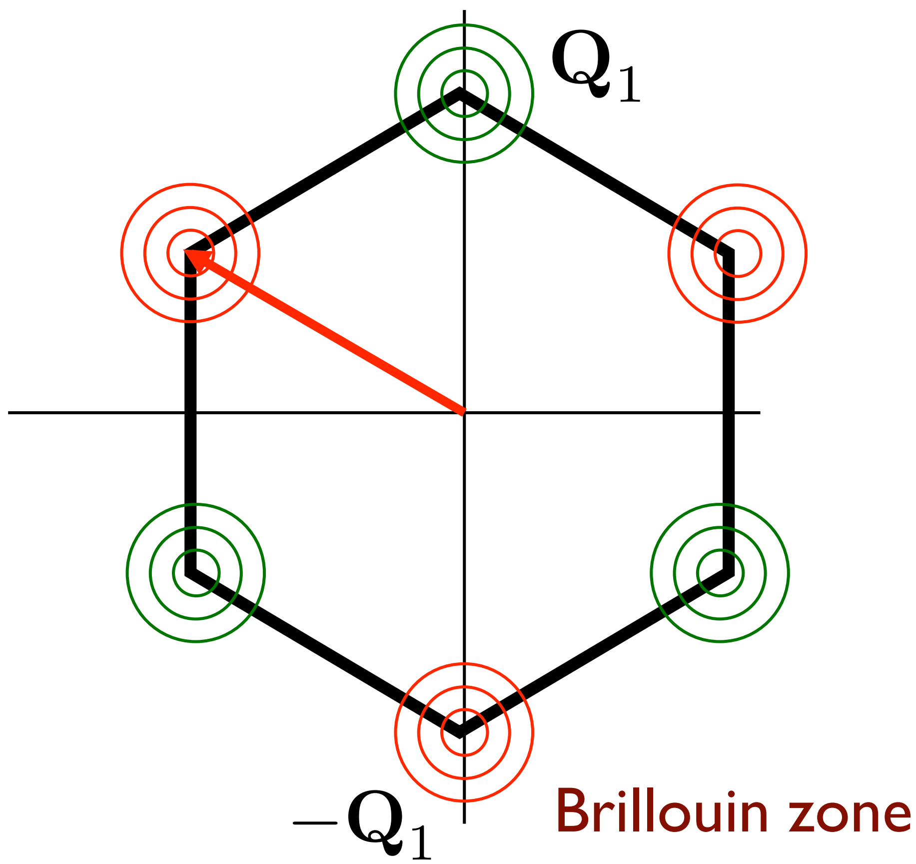
Graphene



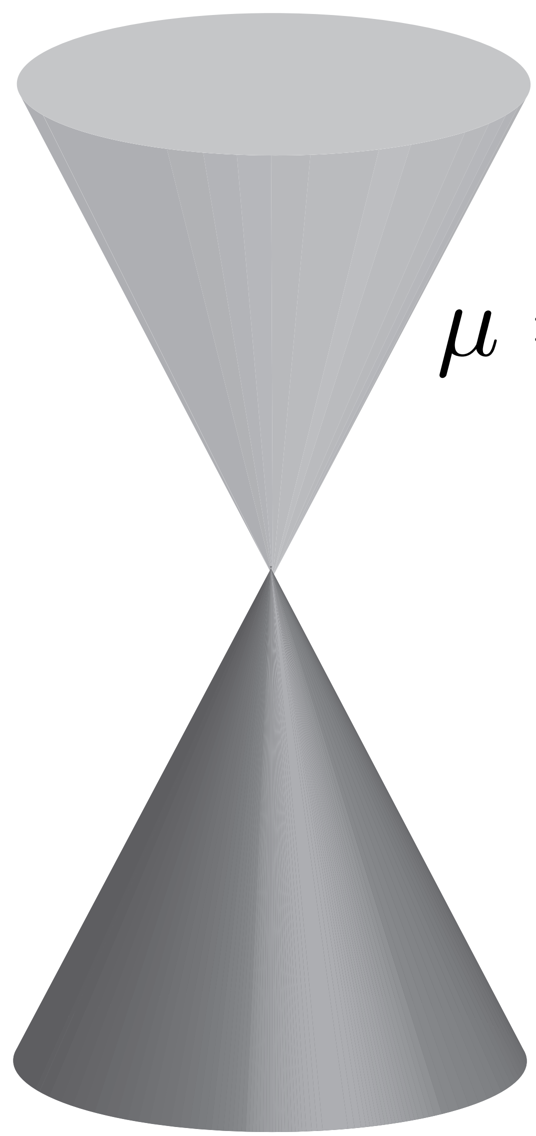






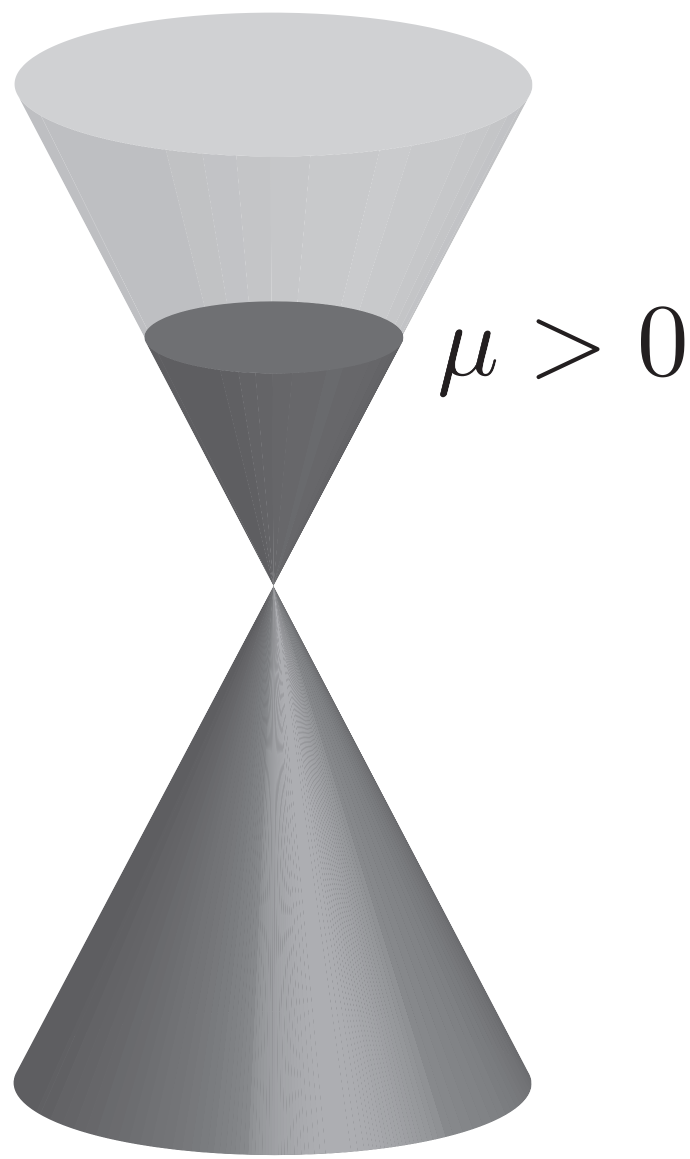
Semi-metal with
massless Dirac fermions

Turn on a chemical potential on a CFT



$\mu = 0$

Turn on a chemical potential on a CFT



Electron
Fermi surface

Compressible quantum matter

- Consider a continuum quantum system with a globally conserved U(1) charge $\mathcal{Q}$ (the "electron density") in spatial dimension $d > 1$.

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There are only a few established examples of such phases in condensed matter physics.
However, they appear naturally as duals of gravitational theories, and we want to interpret them in the gauge theory.

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All known examples of such phases have a *Fermi Surface*

(even in systems with only bosons in the Hamiltonian)

The Fermi surface

This is the locus of zero energy singularities in momentum space in the two-point correlator of fermions carrying charge $\mathcal{Q}$.

$$G^{-1}_{\text{fermion}}(k = k_F, \omega = 0) = 0.$$

Luttinger relation: The total "volume (area)" $\mathcal{A}$ enclosed by Fermi surfaces of fermions carrying charge $\mathcal{Q}$ is equal to $\langle \mathcal{Q} \rangle$. This is a *key* constraint which allows extrapolation from weak to strong coupling.

Aharony-Bergman-Jafferis-Maldacena (ABJM) CFT3

- $\mathrm{U}(N)\times\mathrm{U}(N)$ gauge field.
- $4N^2$ Weyl fermions carrying fundamental charges of $\mathrm{U}(N)\times\mathrm{U}(N)\times\mathrm{SU}(4)_R$.
- $4N^2$ complex bosons carrying fundamental charges of $\mathrm{U}(N)\times\mathrm{U}(N)\times\mathrm{SU}(4)_R$.
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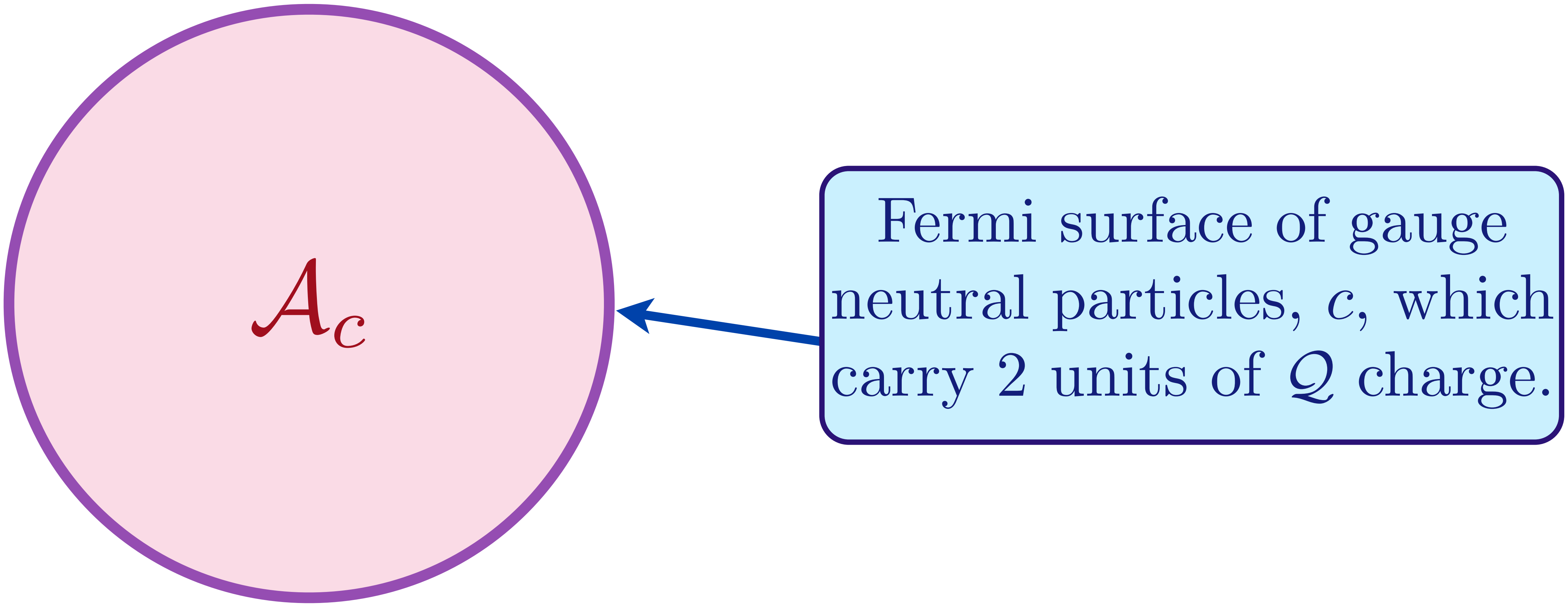
- $\mathcal{N}=6$ supersymmetry
- Add a chemical potential μ coupling to a global $\mathrm{SU}(4)_R$ charge $\mathcal{Q}$.

Adding a chemical potential coupling to a SU(4) charge breaks supersymmetry and SU(4) invariance

Phases of ABJM-like theories

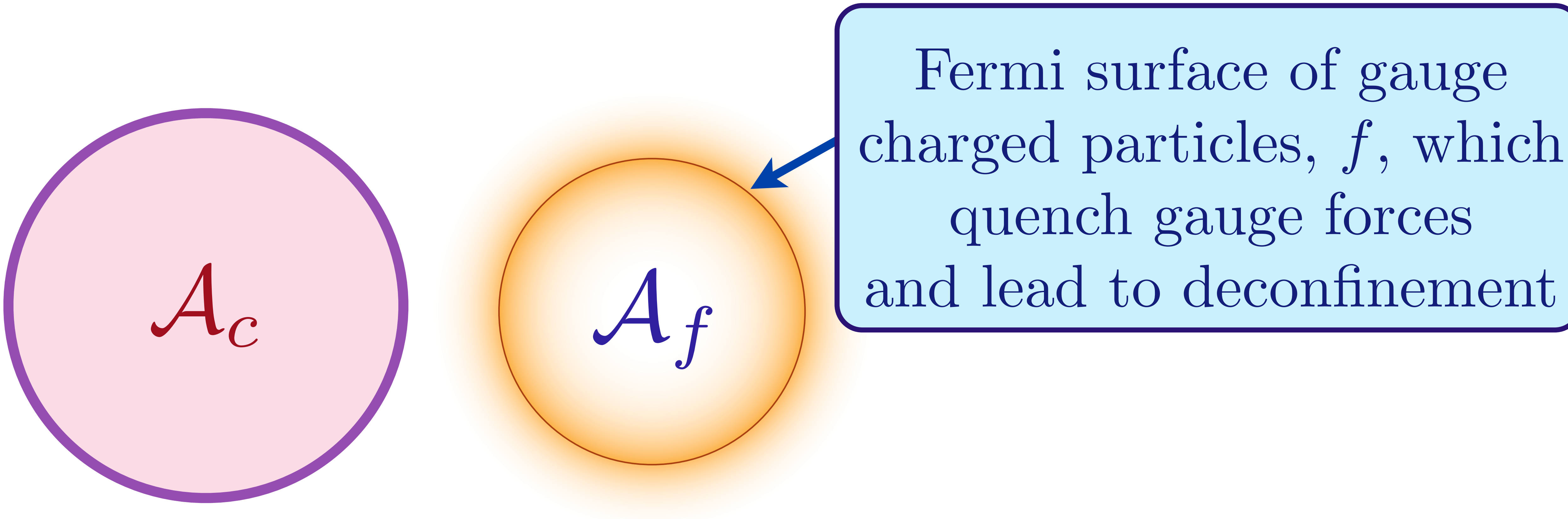


$$2\mathcal{A}_c = \langle \mathcal{Q} \rangle$$

Fermi liquid (FL) of gauge-neutral particles

Gauge theory is in confining phase

Phases of ABJM-like theories



$$2\mathcal{A}_c + 2\mathcal{A}_f = \langle \mathcal{Q} \rangle$$

Fractionalized Fermi liquid (FL*)

Gauge theory is in deconfined phase

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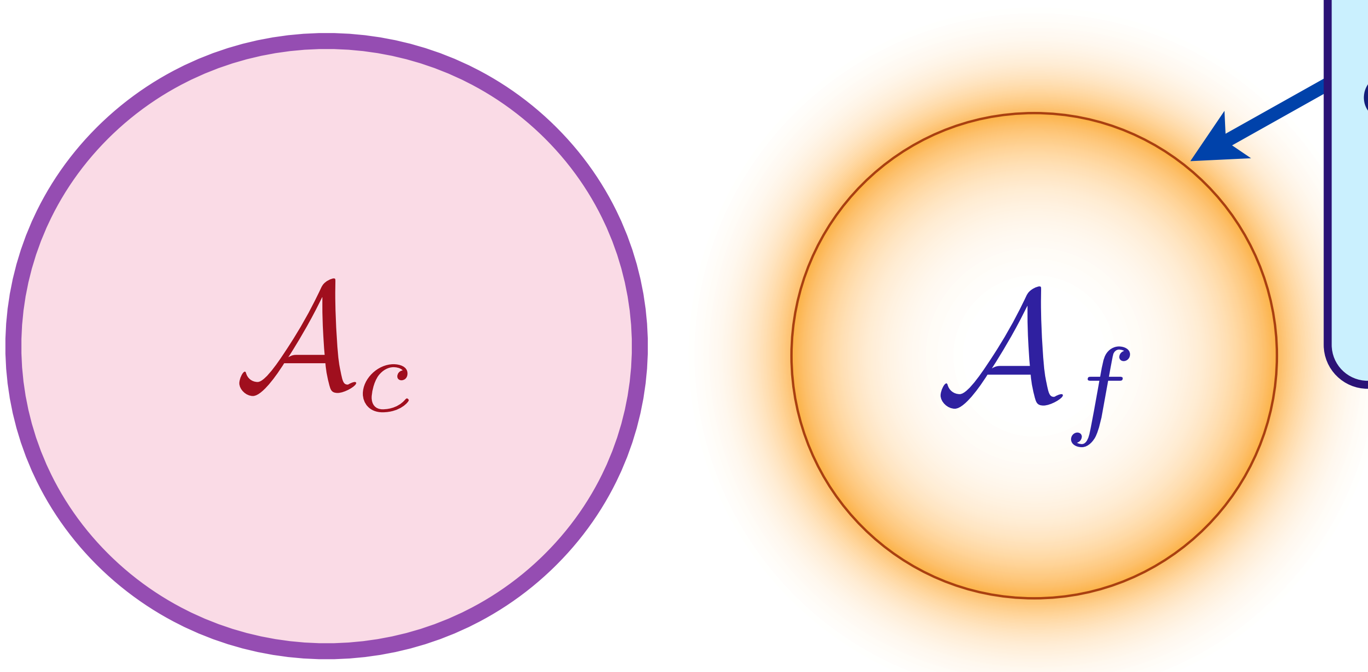

Fermi surface of gauge charged particles, f, which quench gauge forces and lead to deconfinement

$$2\mathcal{A}_c + 2\mathcal{A}_f = \langle \mathcal{Q} \rangle$$

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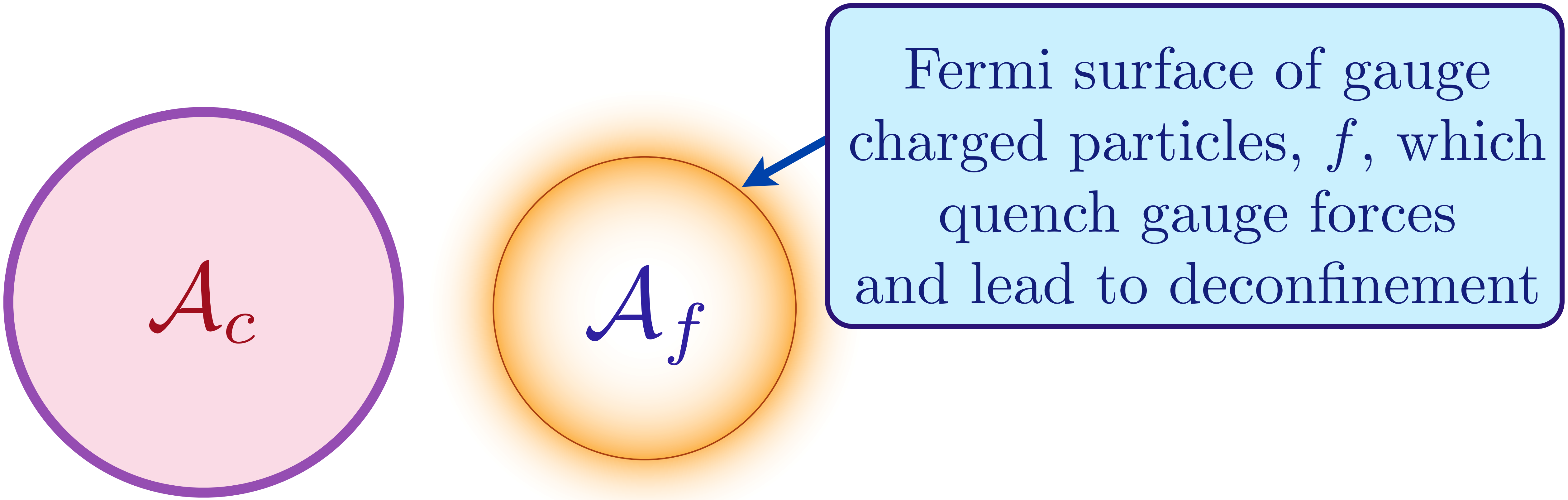

$$2\mathcal{A}_c + 2\mathcal{A}_f = \langle \mathcal{Q} \rangle$$

Fractionalized Fermi liquid (FL*)

Gauge theory is in deconfined phase

Claim: this is the phase underlying recent holographic theories of compressible metallic states.
However, a number of artifacts appear in the classical gravity approximation.

Gauge-gravity duality

- Begin with a CFT e.g. the ABJM theory with a SU(4) global symmetry

- The CFT is dual to a gravity theory on $AdS_4 \times S^7$

Gauge-gravity duality

- Begin with a CFT e.g. the ABJM theory with a SU(4) global symmetry
- Add some SU(4) charge by turning on a chemical potential (this breaks the SU(4) symmetry)

- The CFT is dual to a gravity theory on $AdS_4 \times S^7$
- In the Einstein-Maxwell theory, the chemical potential leads at T=0 to an extremal Reissner-Nordtrom black hole in the AdS_4 spacetime.

T. Faulkner, H. Liu, J. McGreevy, and D. Vegh, arXiv:0907.2694

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- In the Einstein-Maxwell theory, the chemical potential leads at T=0 to an extremal Reissner-Nordtrom black hole in the AdS_4 spacetime.
- The RN black hole describes compressible quantum matter with Fermi surfaces, but with infinite range hopping: this leads to numerous artifacts.

Summary

- Compressible quantum matter is characterized by Fermi surfaces.

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- Phases of a strongly-coupled gauge theory: Fermi liquids (FL) and fractionalized Fermi liquids (FL*)

- Fermi liquids are everywhere.

- There is evidence that FL* phases have been recently been observed in some intermetallic compounds. The FL* and related phases are attractive candidates for "strange metals" in the higher temperature superconductors

Summary

- Compressible quantum matter is characterized by Fermi surfaces.

- Phases of a strongly-coupled gauge theory: Fermi liquids (FL) and fractionalized Fermi liquids (FL*)

- Gauge-gravity duality is a very promising approach to solving strong-coupling problems associated with FL*-like phases.

FL* and related phases are attractive candidates for "strange metals" in the higher temperature superconductors

Conclusions

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 picture.

Conclusions

The AdS/CFT correspondence offers promise in providing a new understanding of strongly interacting quantum matter at non-zero density