Conformal field theories in 3 dimensions, and holography

Rutgers University, December 16, 2012

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PHYSICS
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Talk online at sachdev.physics.harvard.edu

"Complex entangled" states of quantum matter, *not* adiabatically connected to independent particle states

Gapped quantum matter

Z_2 Spin liquids, quantum Hall states

Conformal quantum matter

Graphene, ultracold atoms, antiferromagnets

Compressible quantum matter

Strange metals, Bose metals

S. Sachdev, 100th anniversary Solvay conference (2011), arXiv:1203.4565

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Conformal quantum matter

A. Field theory:
Honeycomb lattice
Hubbard model

B. Gauge-gravity duality

Conformal quantum matter

A. Field theory:
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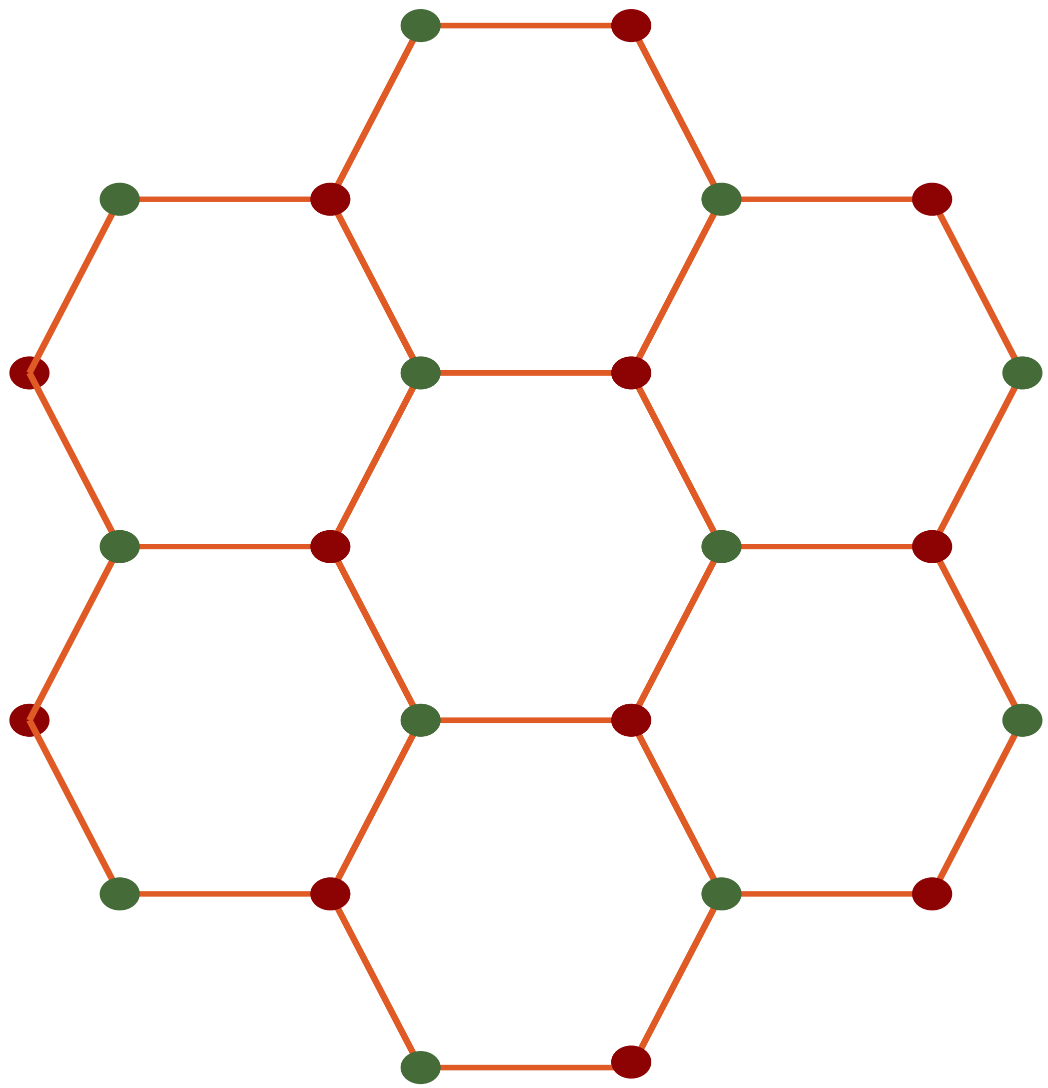
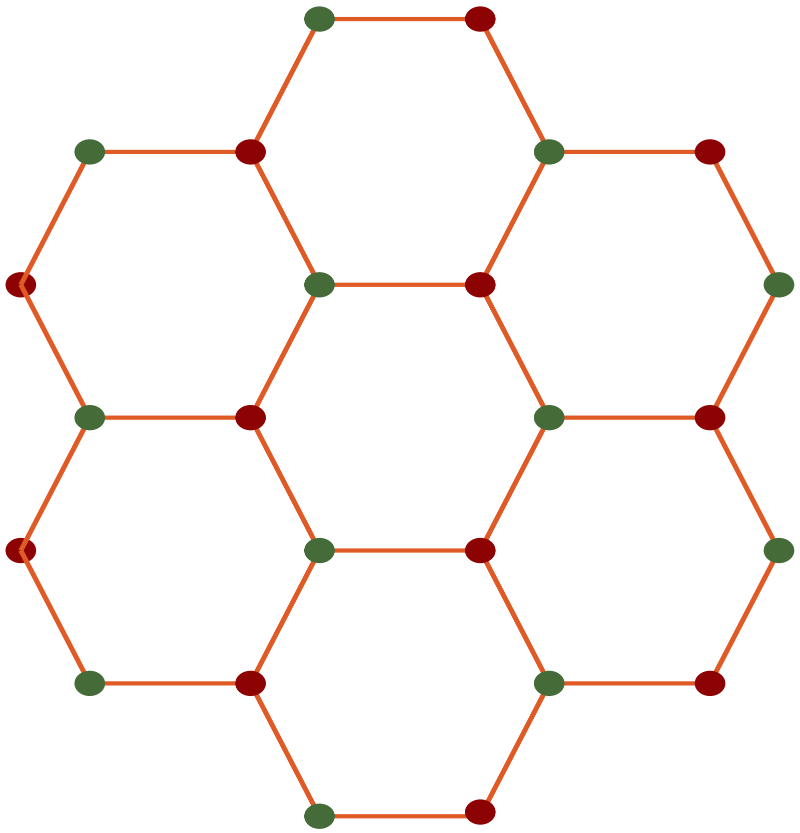
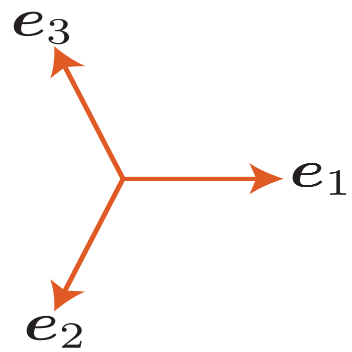
Honeycomb lattice

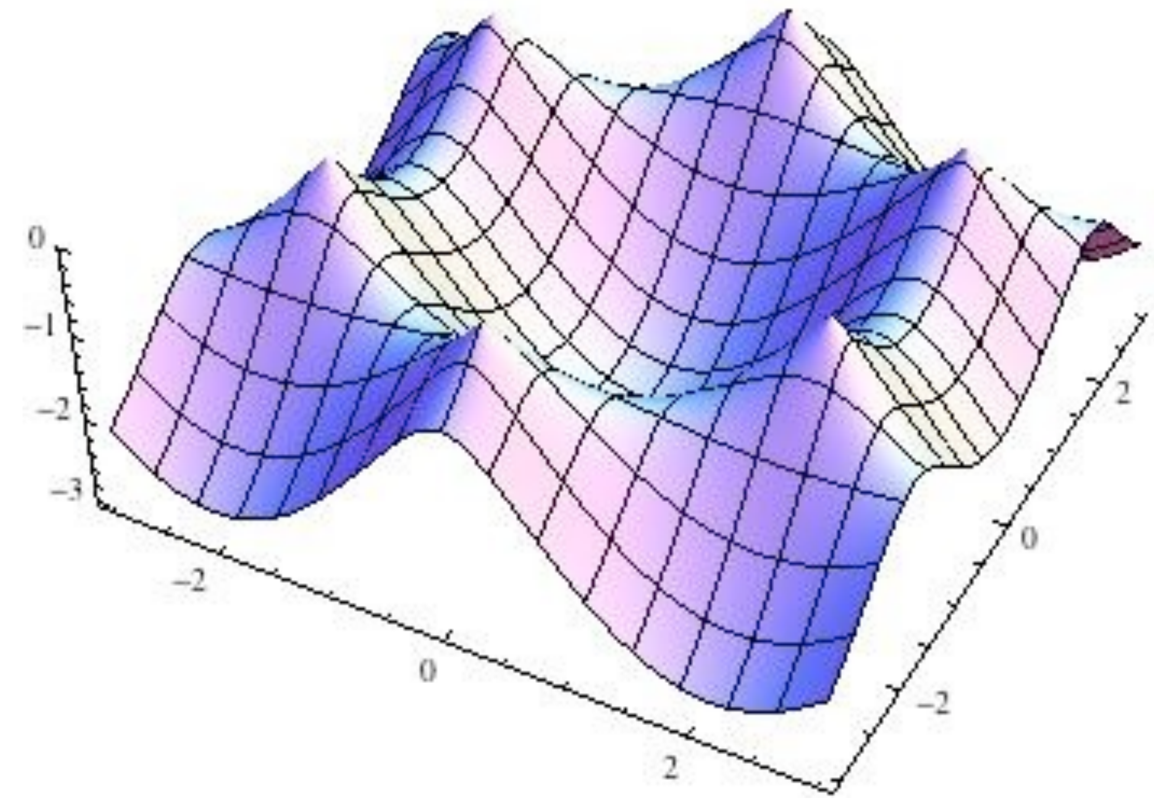
(describes graphene after adding long-range Coulomb interactions)

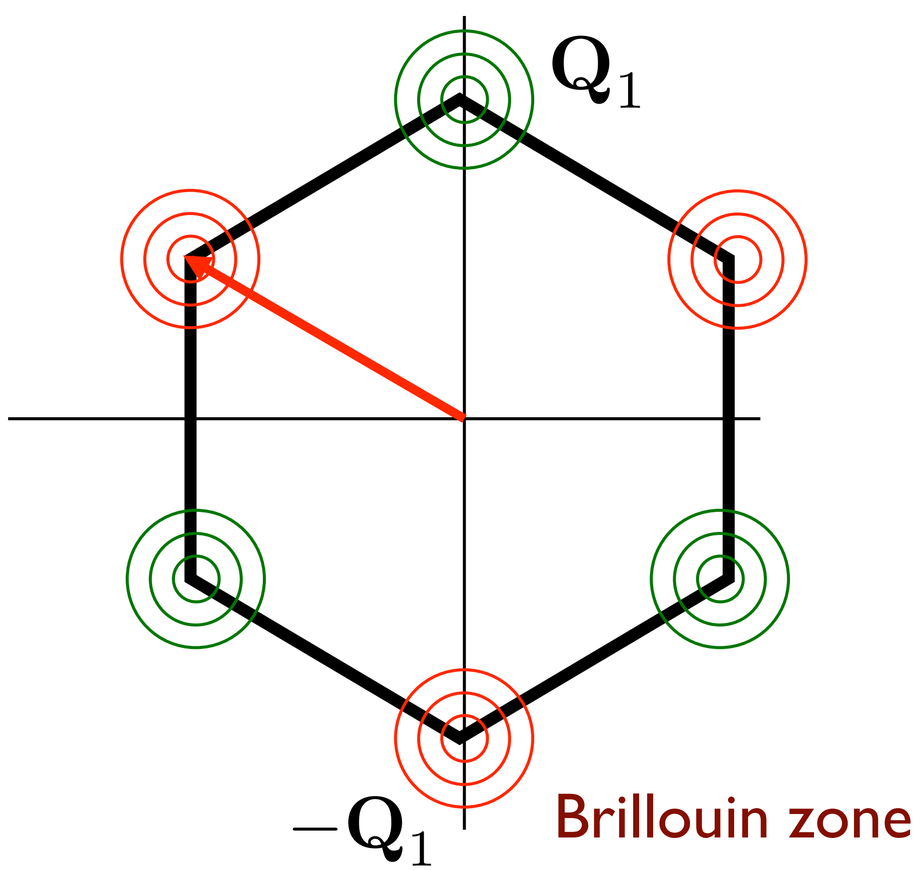


$$H = -t \sum_{\langle ij \rangle} c_{i\alpha}^{\dagger} c_{j\alpha} + U \sum_{i} \left(n_{i\uparrow} - \frac{1}{2} \right) \left(n_{i\downarrow} - \frac{1}{2} \right)$$

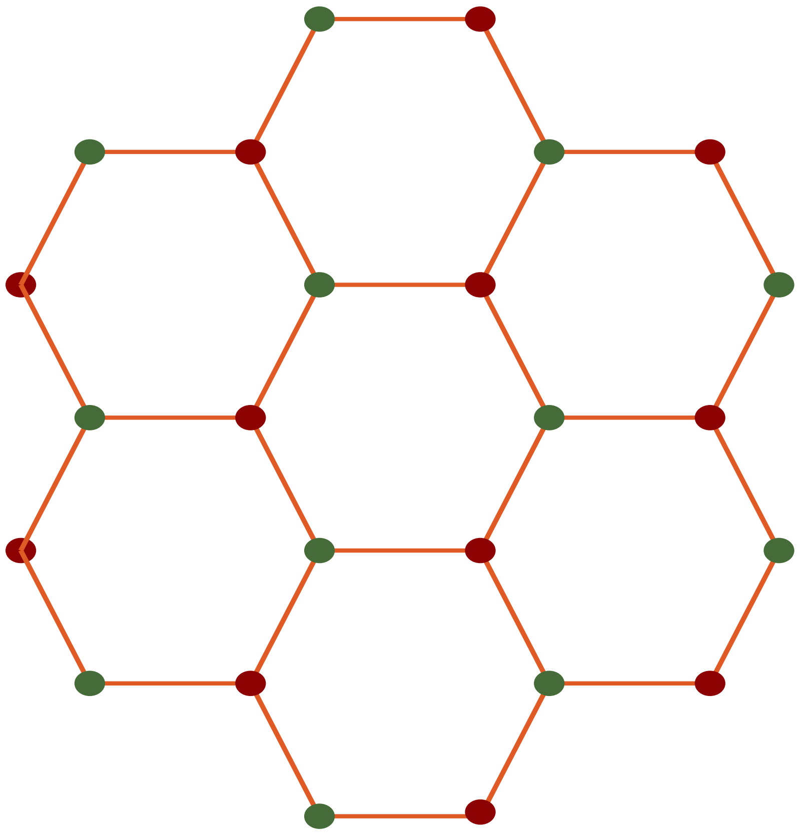


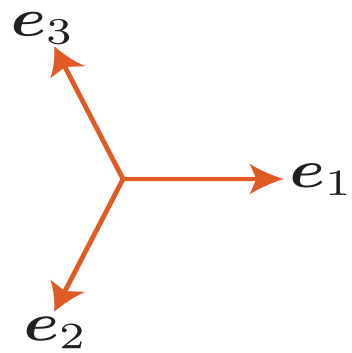


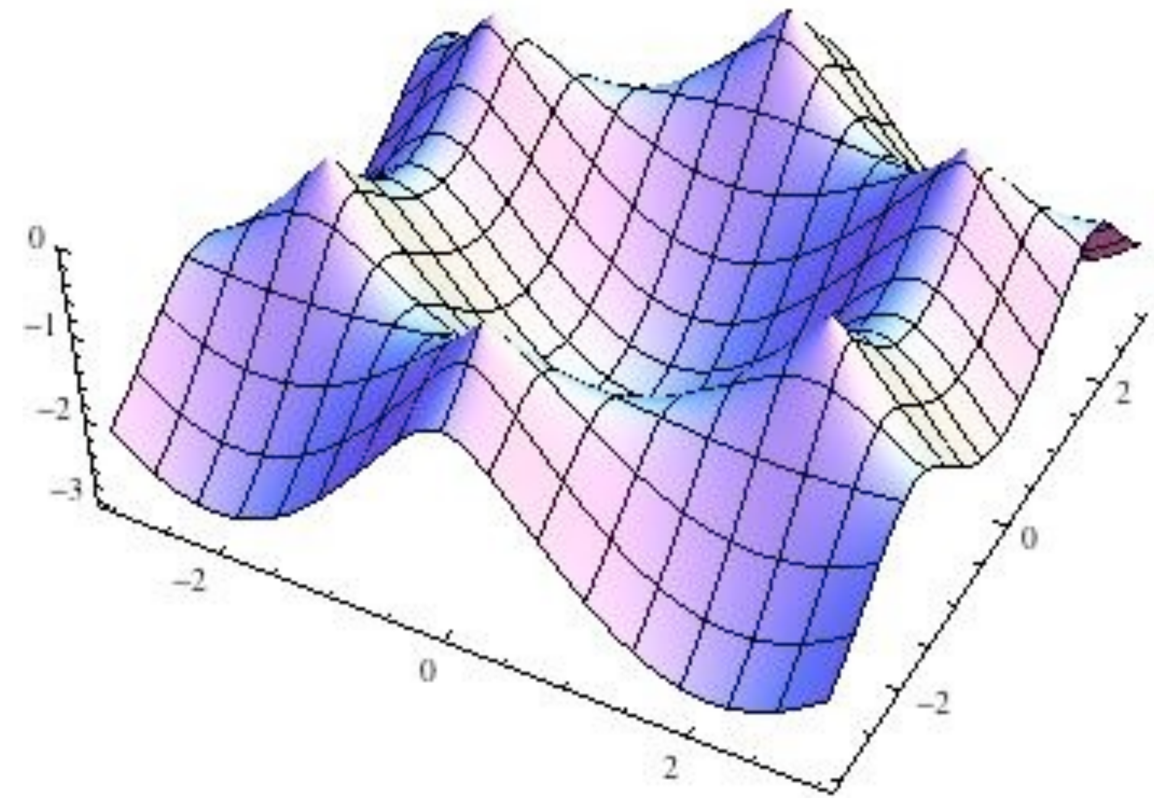




Semi-metal with
massless Dirac fermions
at small *U/t*




e_3
e_1
e_2


0
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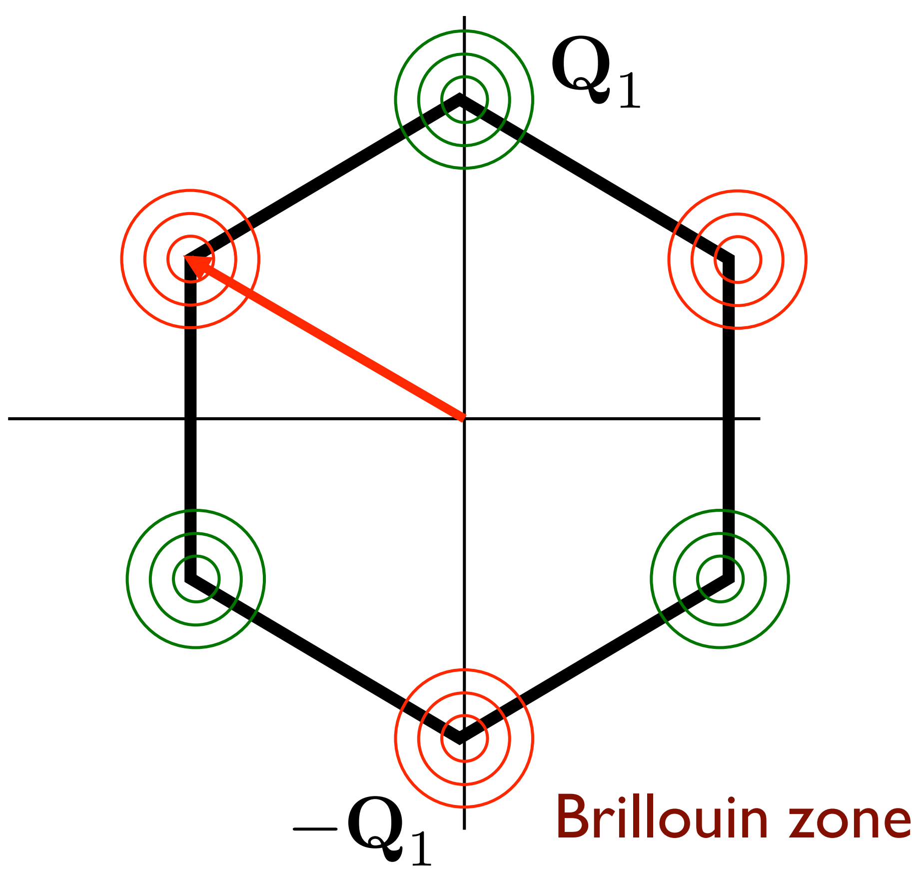
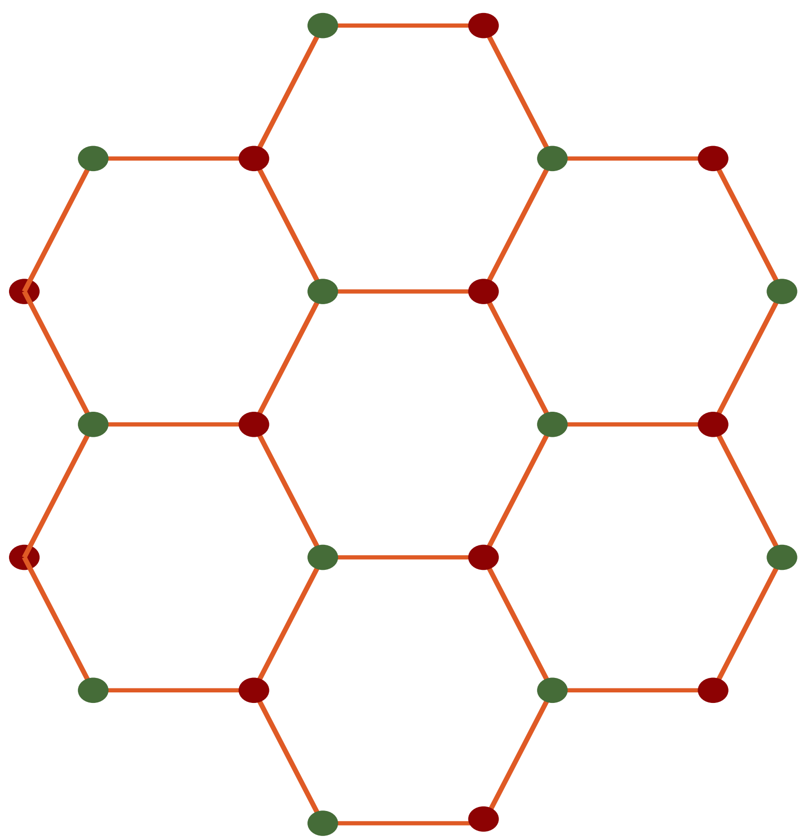
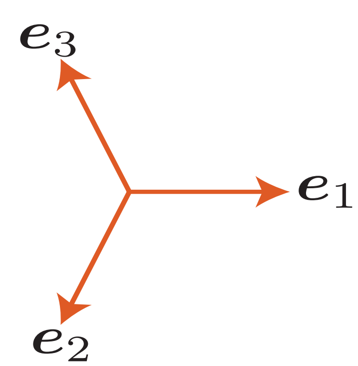
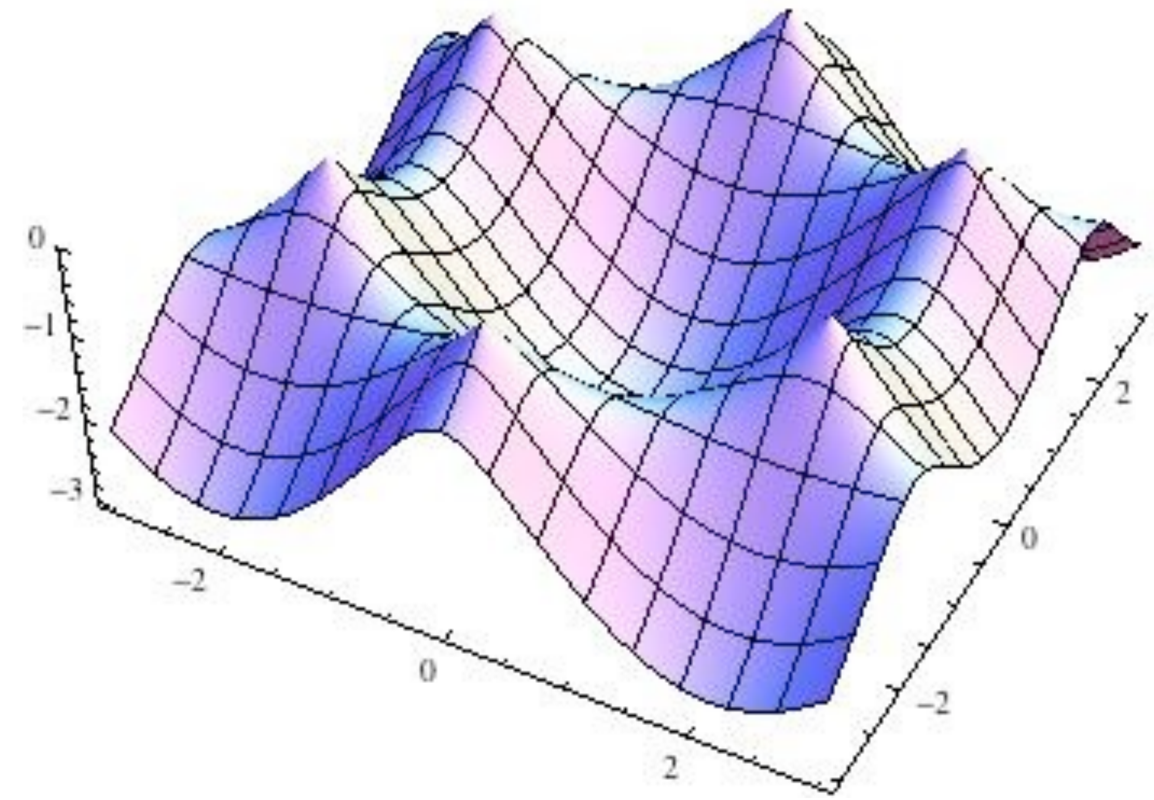
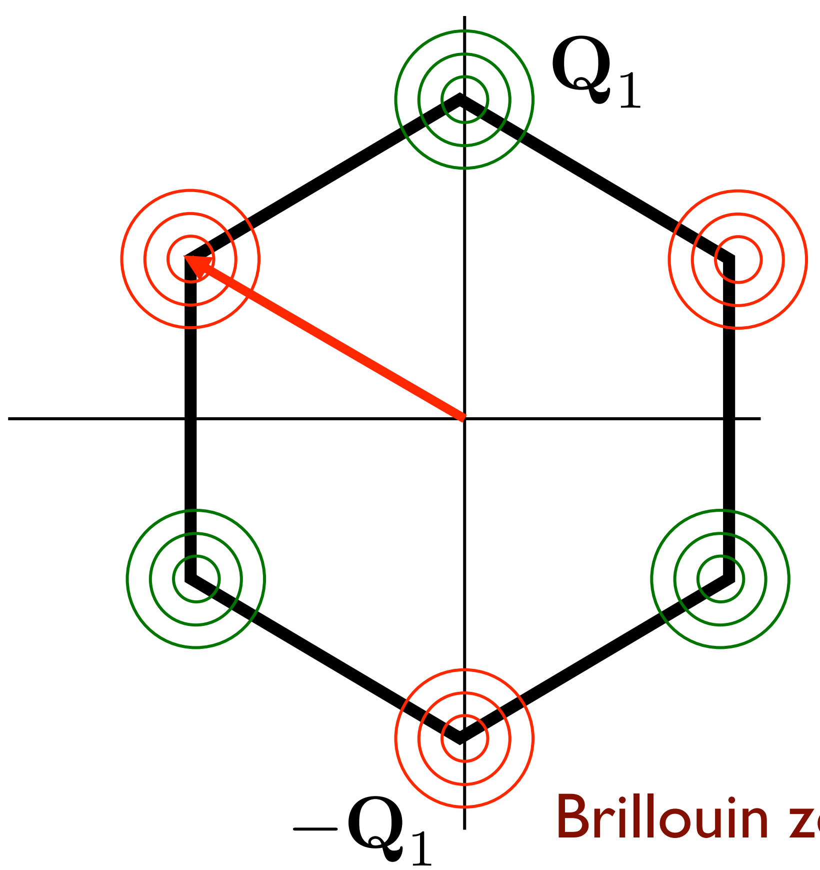

$\mathbf{Q}_1$
$-\mathbf{Q}_1$
Brillouin zone









Brillouin zone

The theory of free Dirac fermions is invariant under conformal transformations of spacetime. This is a realization of a simple conformal field theory in 2+1 dimensions: a <u>CFT3</u>

The Hubbard Model at large U

$$H = -\sum_{i,j} t_{ij} c_{i\alpha}^{\dagger} c_{j\alpha} + U \sum_i \left(n_{i\uparrow} - \frac{1}{2}\right)\left(n_{i\downarrow} - \frac{1}{2}\right) - \mu \sum_i c_{i\alpha}^{\dagger} c_{i\alpha}$$

In the limit of large U, and at a density of one particle per site, this maps onto the Heisenberg antiferromagnet

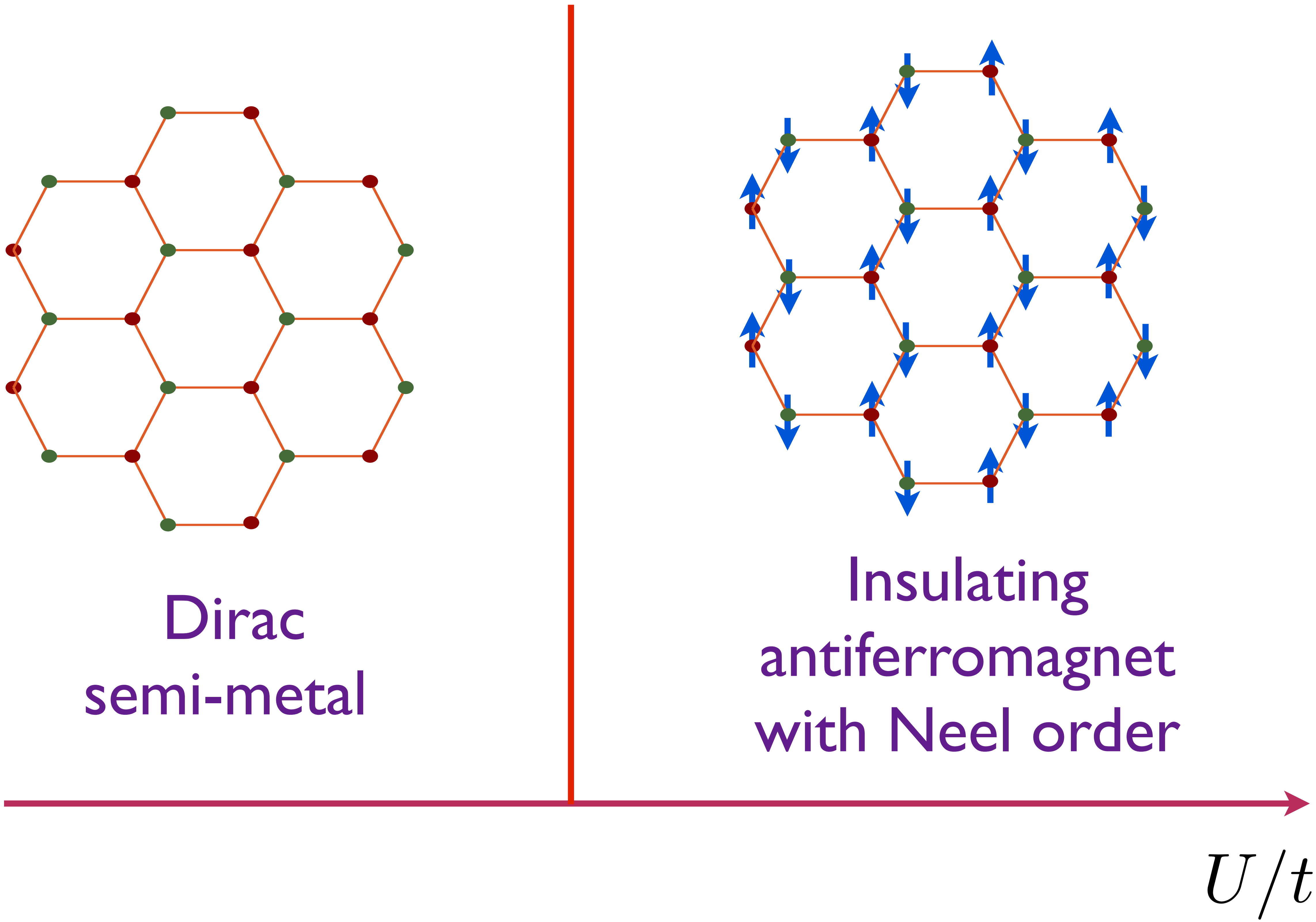
$$H_{AF} = \sum_{i<j} J_{ij} S_i^a S_j^a$$

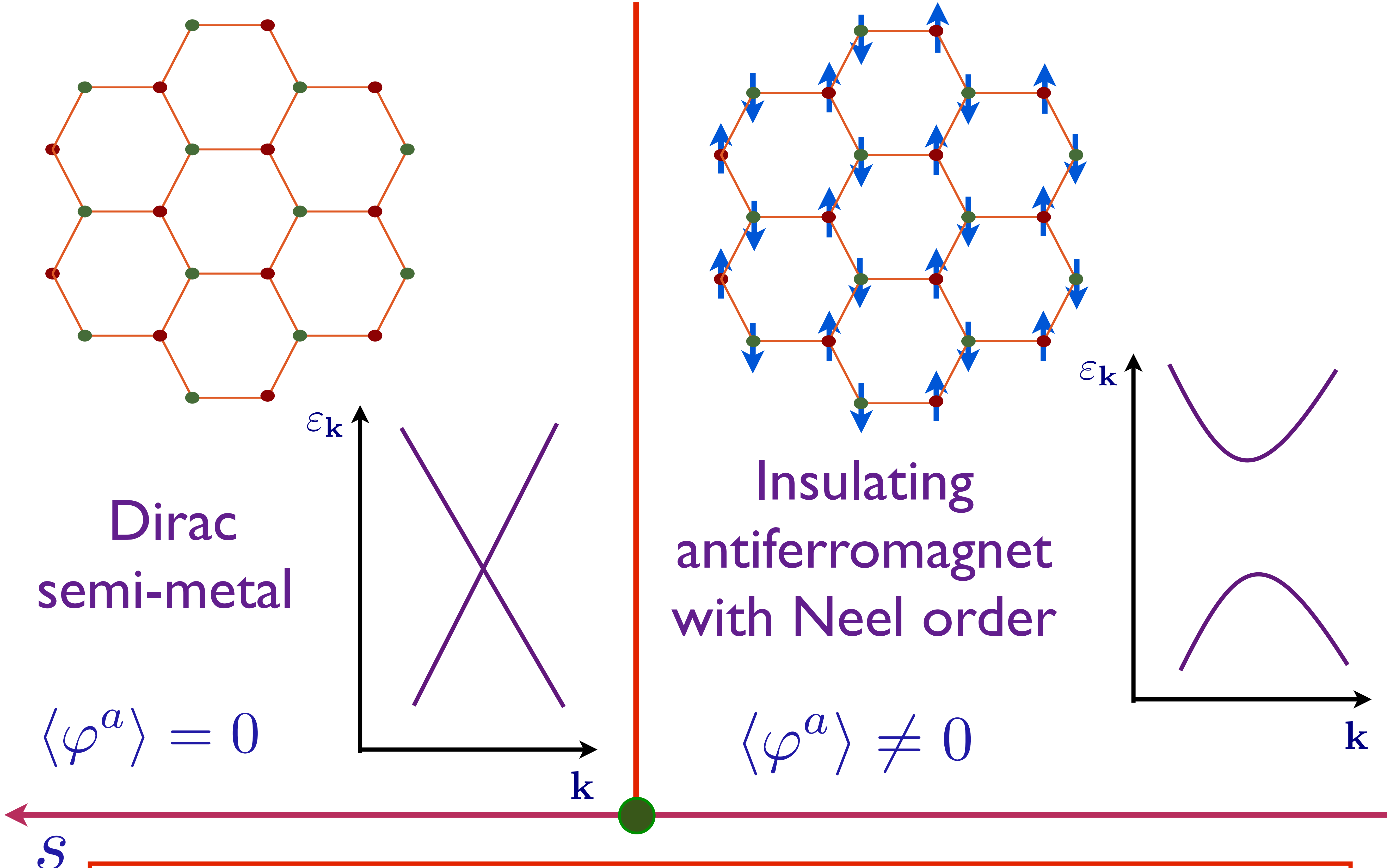
where $a = x, y, z,$

$$S_i^a = \frac{1}{2} c_{i\alpha}^{a\dagger} \sigma_{\alpha\beta}^a c_{i\beta},$$

with σ^a the Pauli matrices and

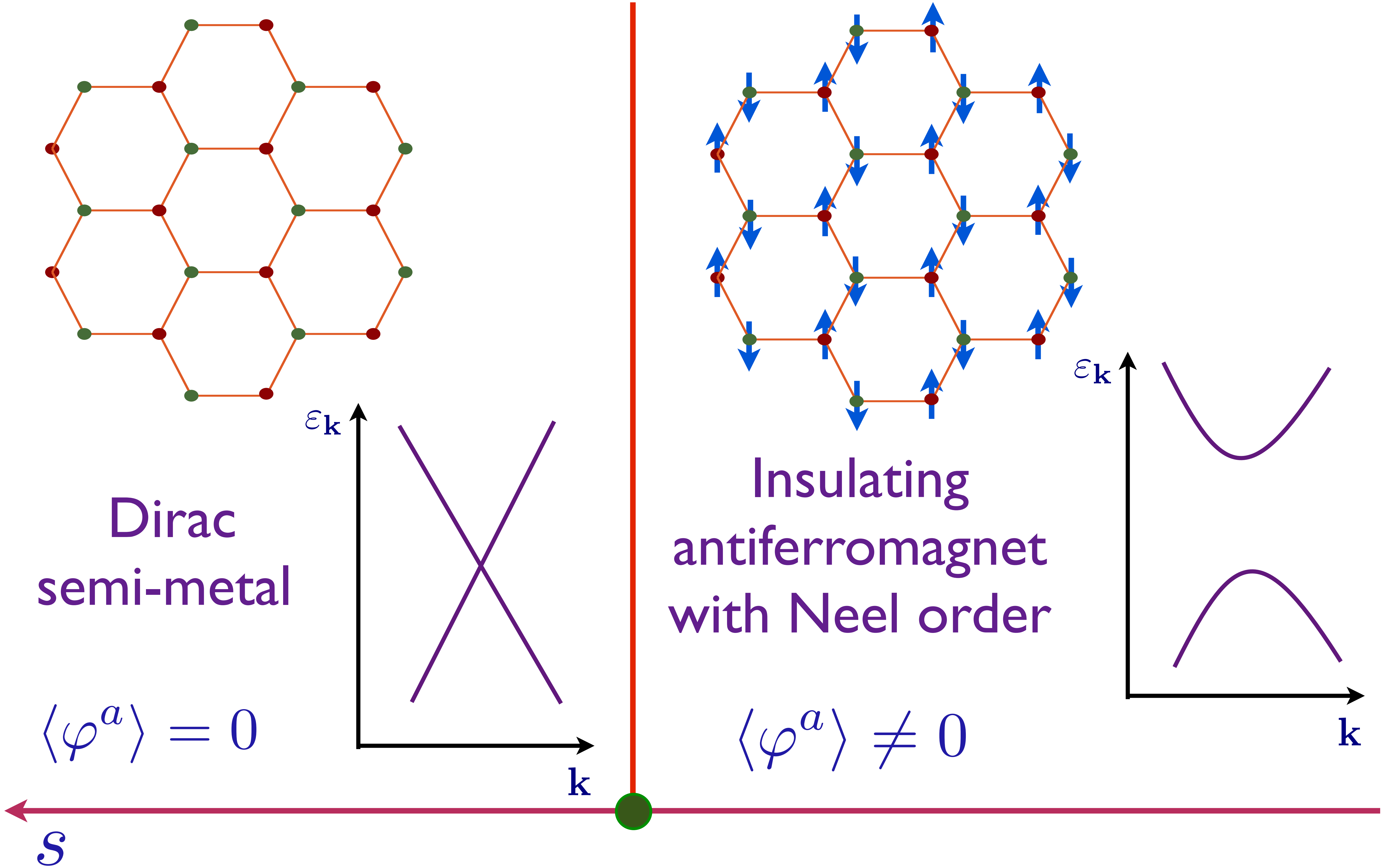
$$J_{ij} = \frac{4t_{ij}^2}{U}$$


Dirac
semi-metal
Insulating
antiferromagnet
with Neel order
U/t

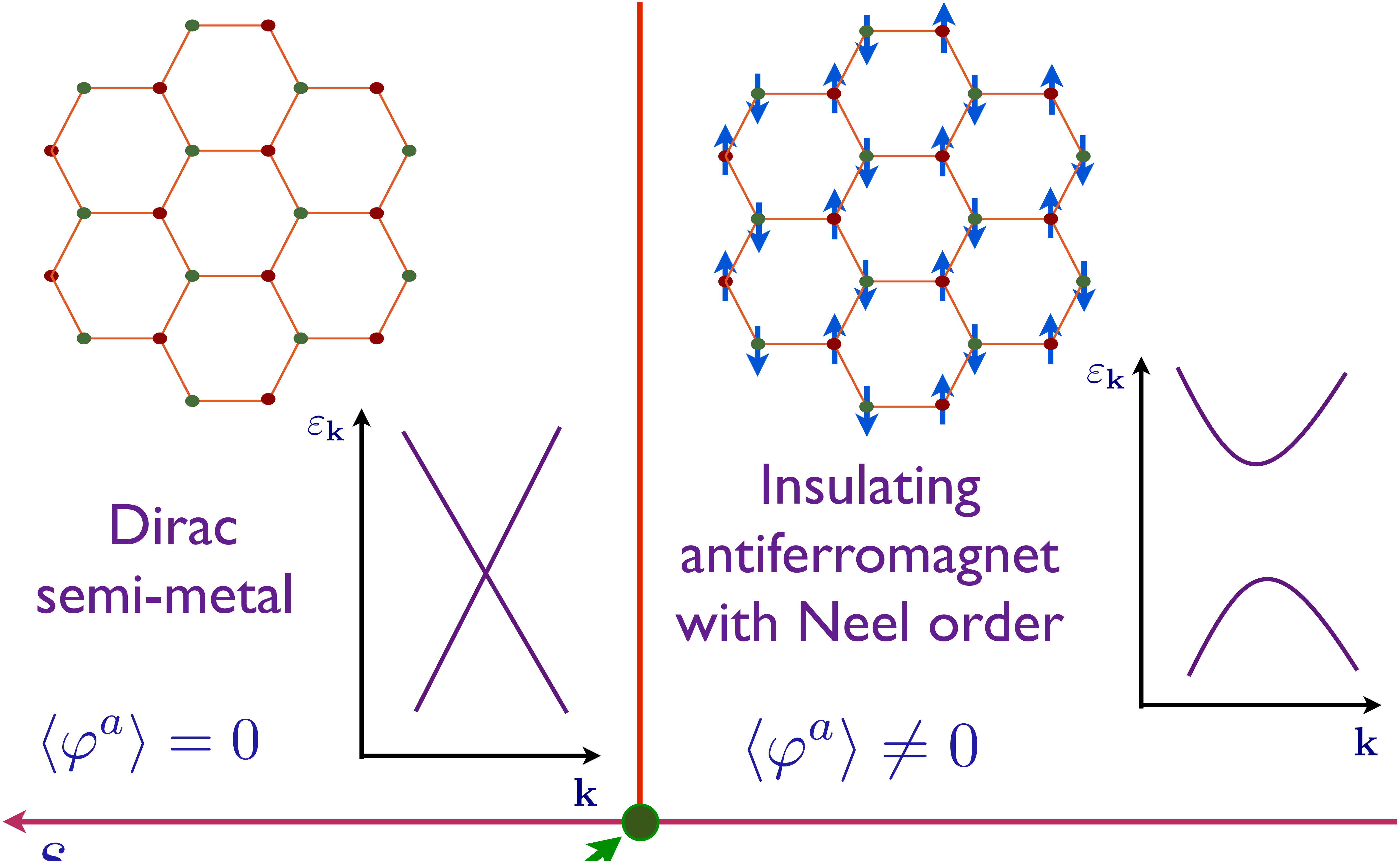


Low energy Gross-Neveu theory, with φ^a the Néel order parameter.

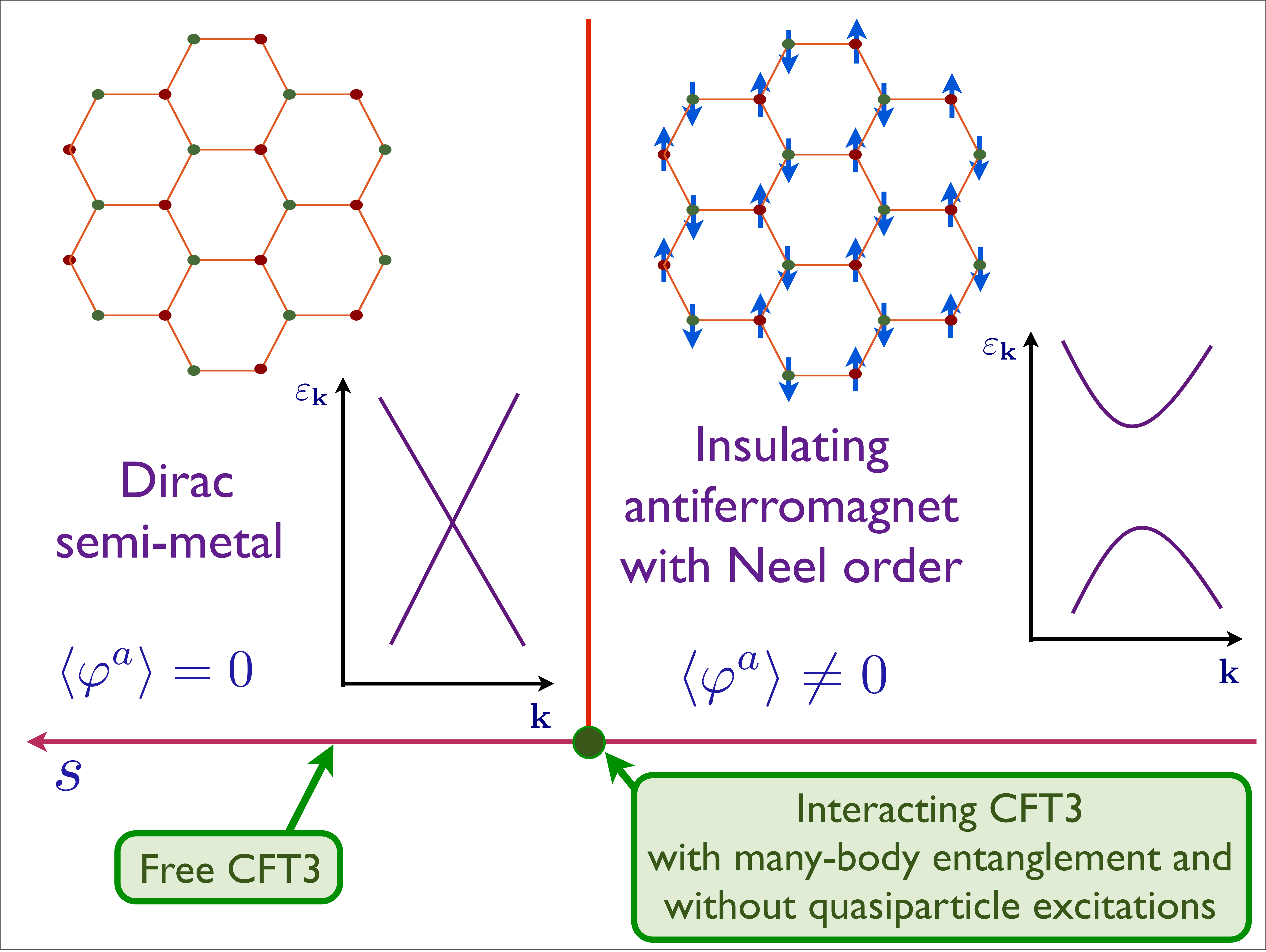
$$\mathcal{L} = \overline{\Psi}\gamma_\mu \partial_\mu \Psi + \frac{1}{2}\left[(\partial_\mu \varphi^a)^2 + s\varphi^{a2}\right] + \frac{u}{24}\left(\varphi^{a2}\right)^2 - \lambda \varphi^a \overline{\Psi}\rho^z \sigma^a \Psi$$



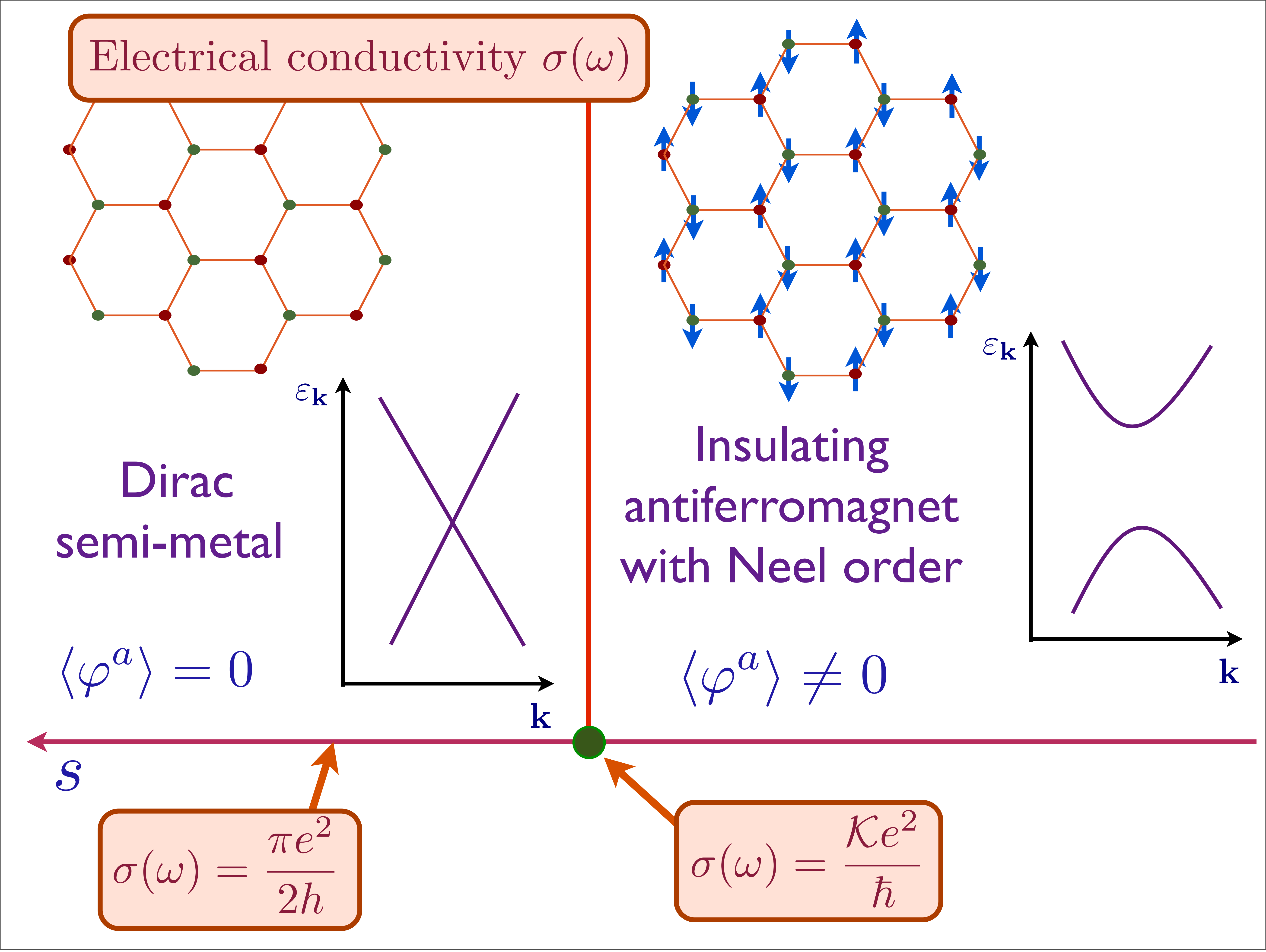
$\varepsilon_{\mathbf{k}}$
Dirac
semi-metal
$\langle \varphi^a \rangle = 0$
$\mathbf{k}$
Insulating
antiferromagnet
with Neel order
$\varepsilon_{\mathbf{k}}$
$\langle \varphi^a \rangle \neq 0$
$\mathbf{k}$
s

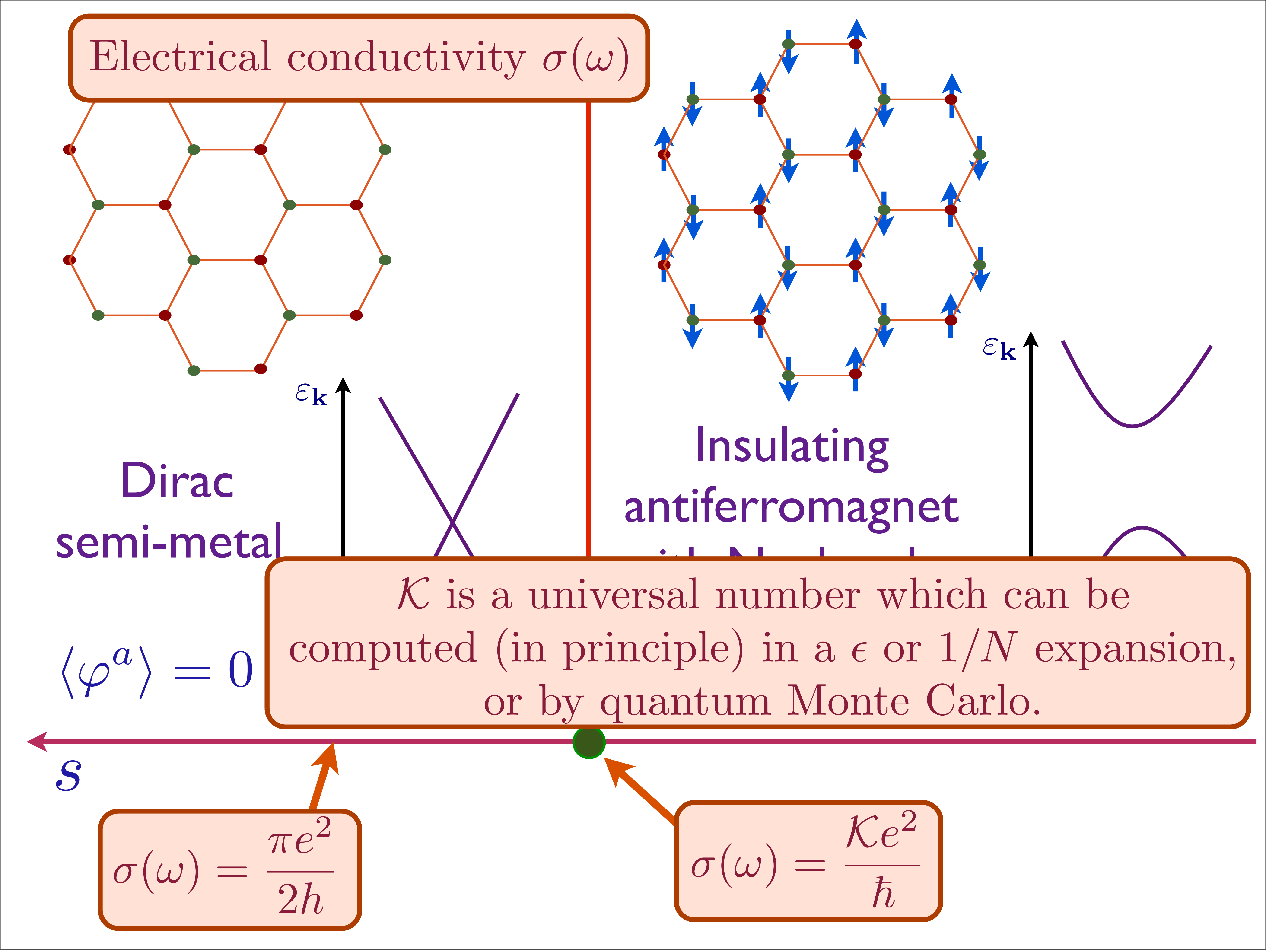


At the quantum critical point, the couplings λ and u reach non-zero fixed-point values under the RG flow (similar to the Wilson-Fisher fixed point). The critical theory is an *interacting* CFT3



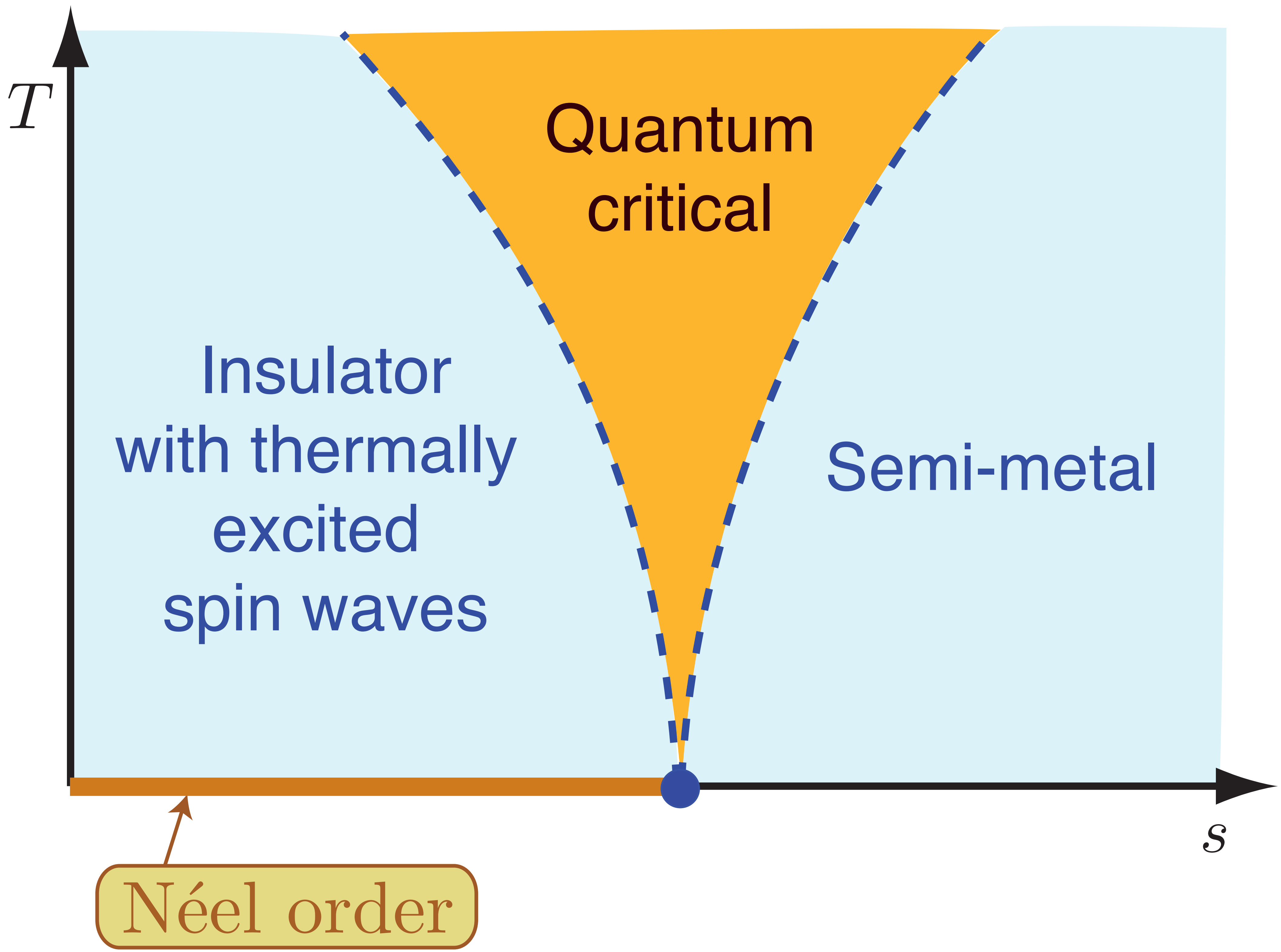
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Dirac
semi-metal
$\langle \varphi^a \rangle = 0$
Insulating
antiferromagnet
with Neel order
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
$\langle \varphi^a \rangle \neq 0$
s
Free CFT3
Interacting CFT3
with many-body entanglement and
without quasiparticle excitations


Electrical conductivity $\sigma(\omega)$
$\varepsilon_{\mathbf{k}}$
$\mathbf{k}$
Dirac semi-metal
$\langle \varphi^a \rangle = 0$
Insulating antiferromagnet with Neel order
$\langle \varphi^a \rangle \neq 0$
s
$\sigma(\omega) = \frac{\pi e^2}{2h}$
$\sigma(\omega) = \frac{\mathcal{K} e^2}{\hbar}$

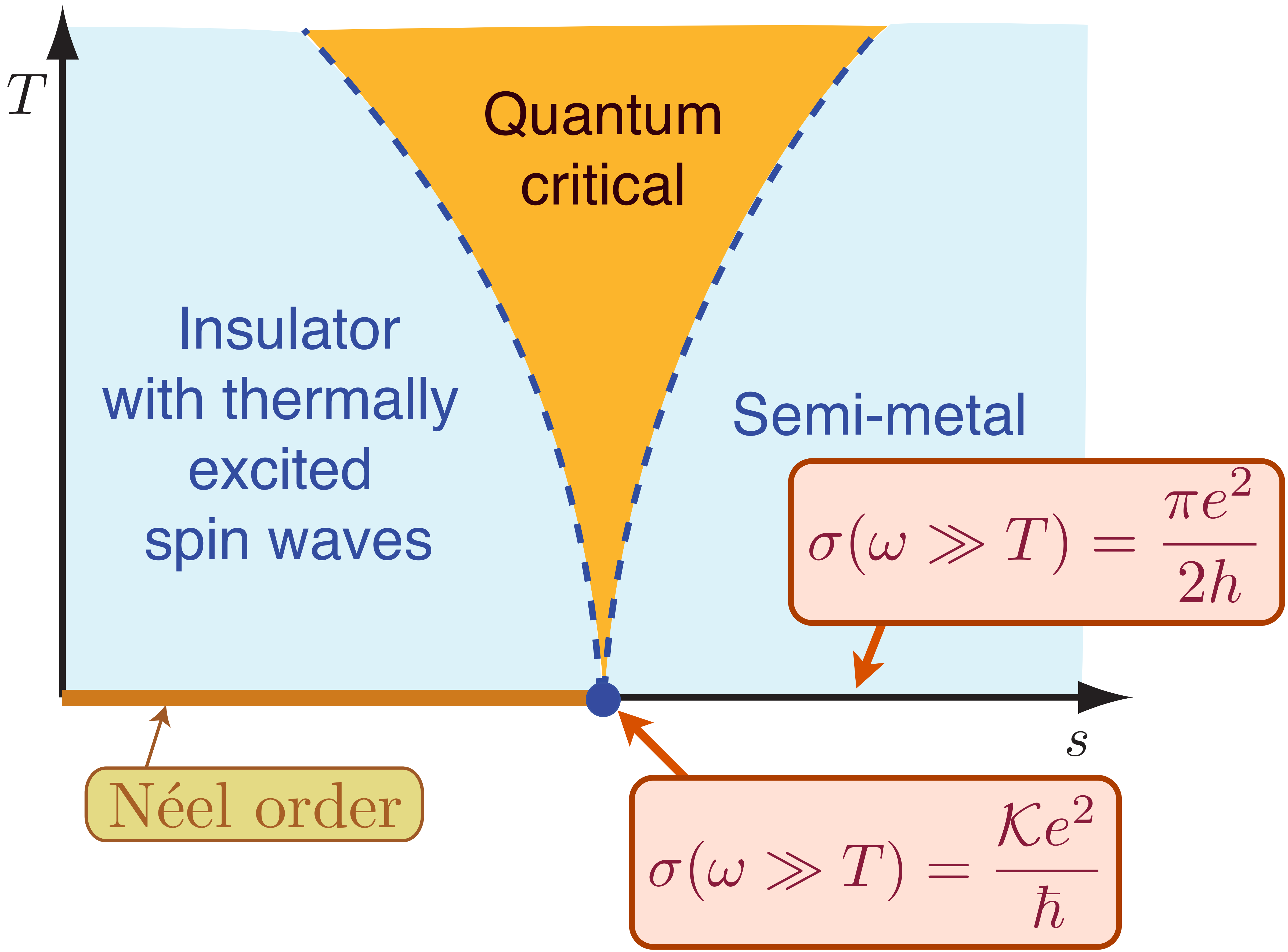


Electrical conductivity $\sigma(\omega)$
$\varepsilon_{\mathbf{k}}$
Dirac semi-metal
$\varepsilon_{\mathbf{k}}$
Insulating antiferromagnet
$\langle \varphi^a \rangle = 0$
$\mathcal{K}$ is a universal number which can be computed (in principle) in a ϵ or $1/N$ expansion, or by quantum Monte Carlo.
s
$\sigma(\omega) = \frac{\pi e^2}{2h}$
$\sigma(\omega) = \frac{\mathcal{K} e^2}{\hbar}$

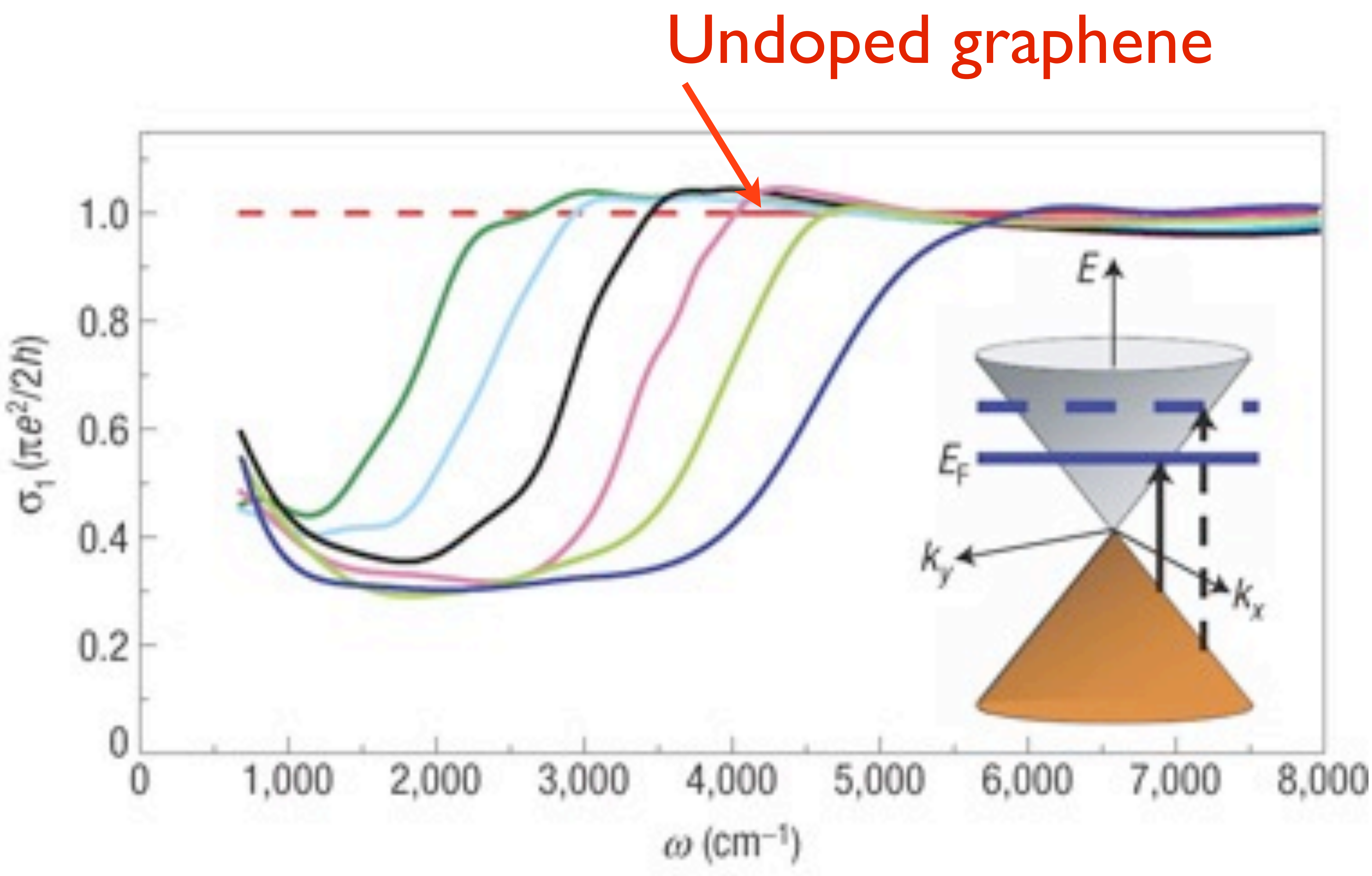
Phase diagram at non-zero temperatures



Phase diagram at non-zero temperatures



Optical conductivity of graphene



Z. Q. Li, E. A. Henriksen, Z. Jiang, Z. Hao, M. C. Martin, P. Kim, H. L. Stormer, and D. N. Basov, *Nature Physics* **4**, 532 (2008).

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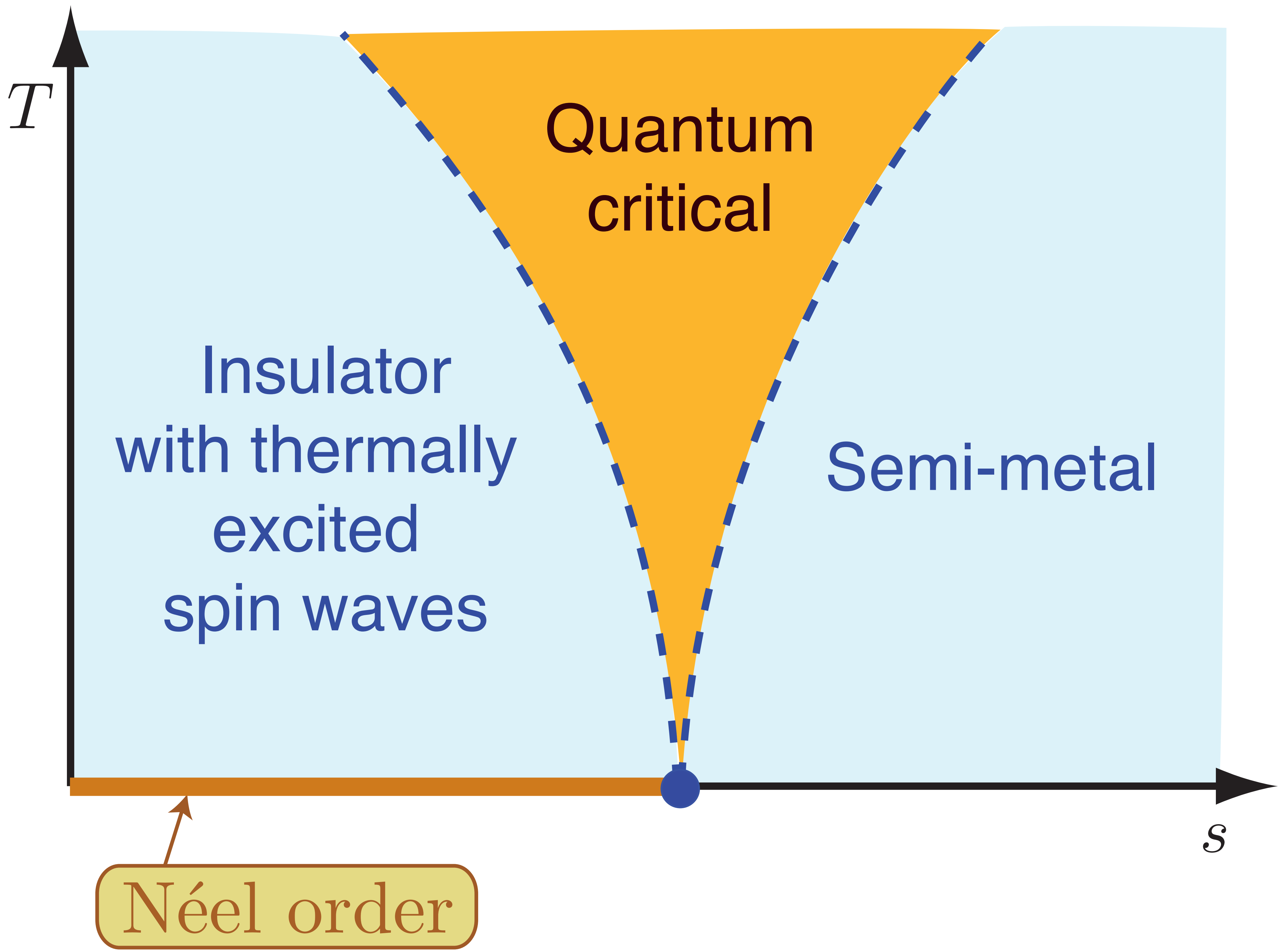

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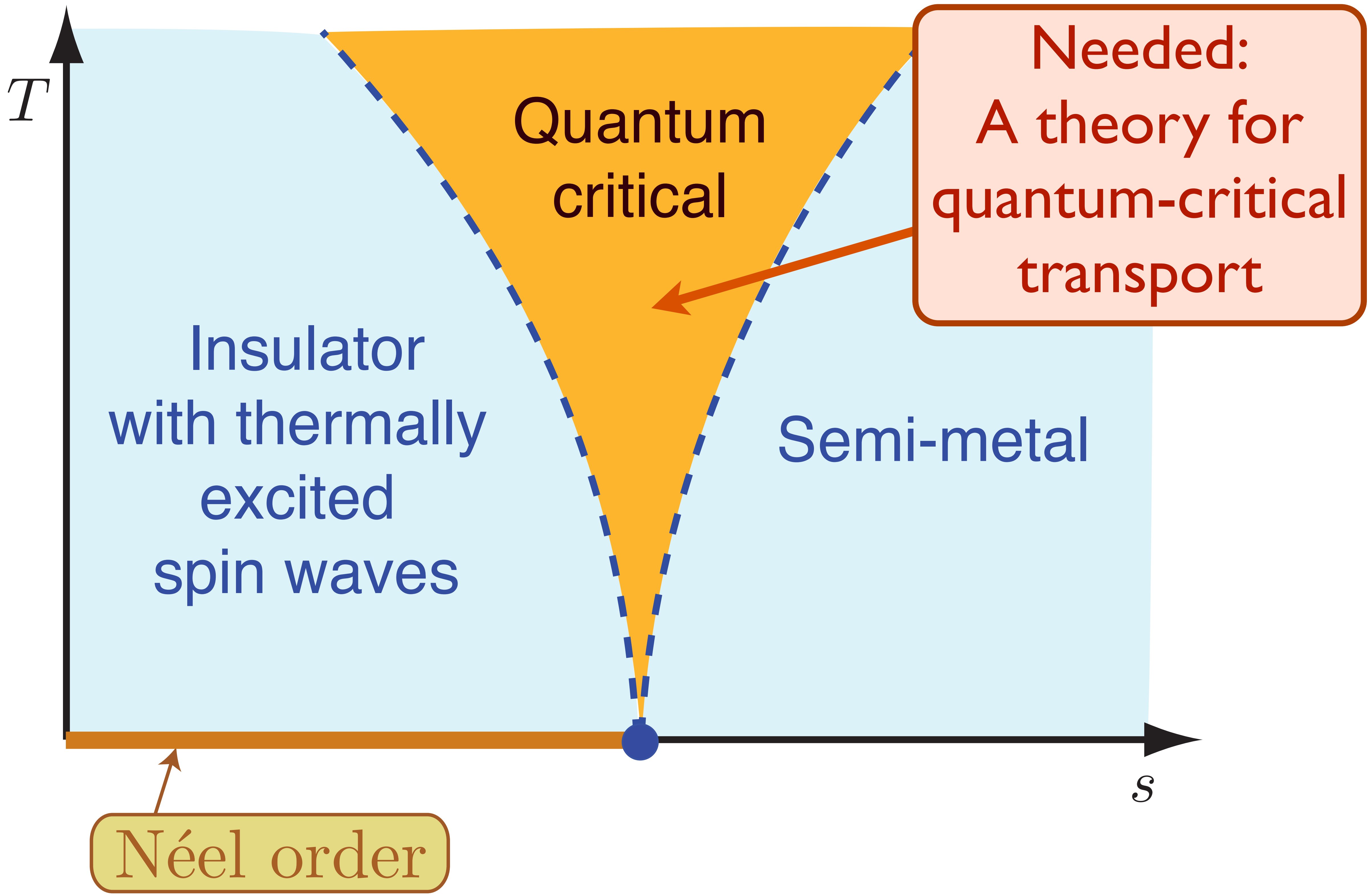
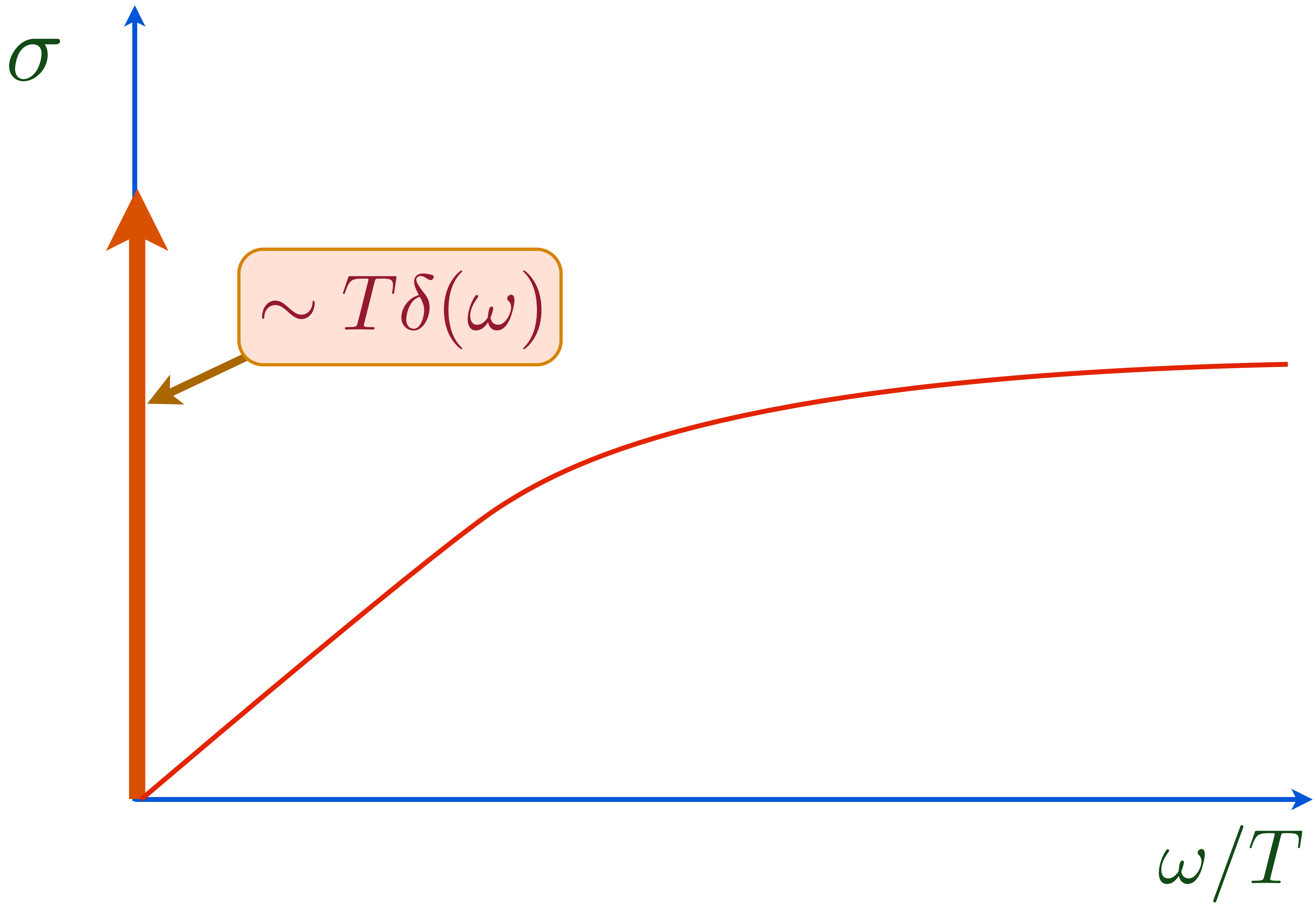
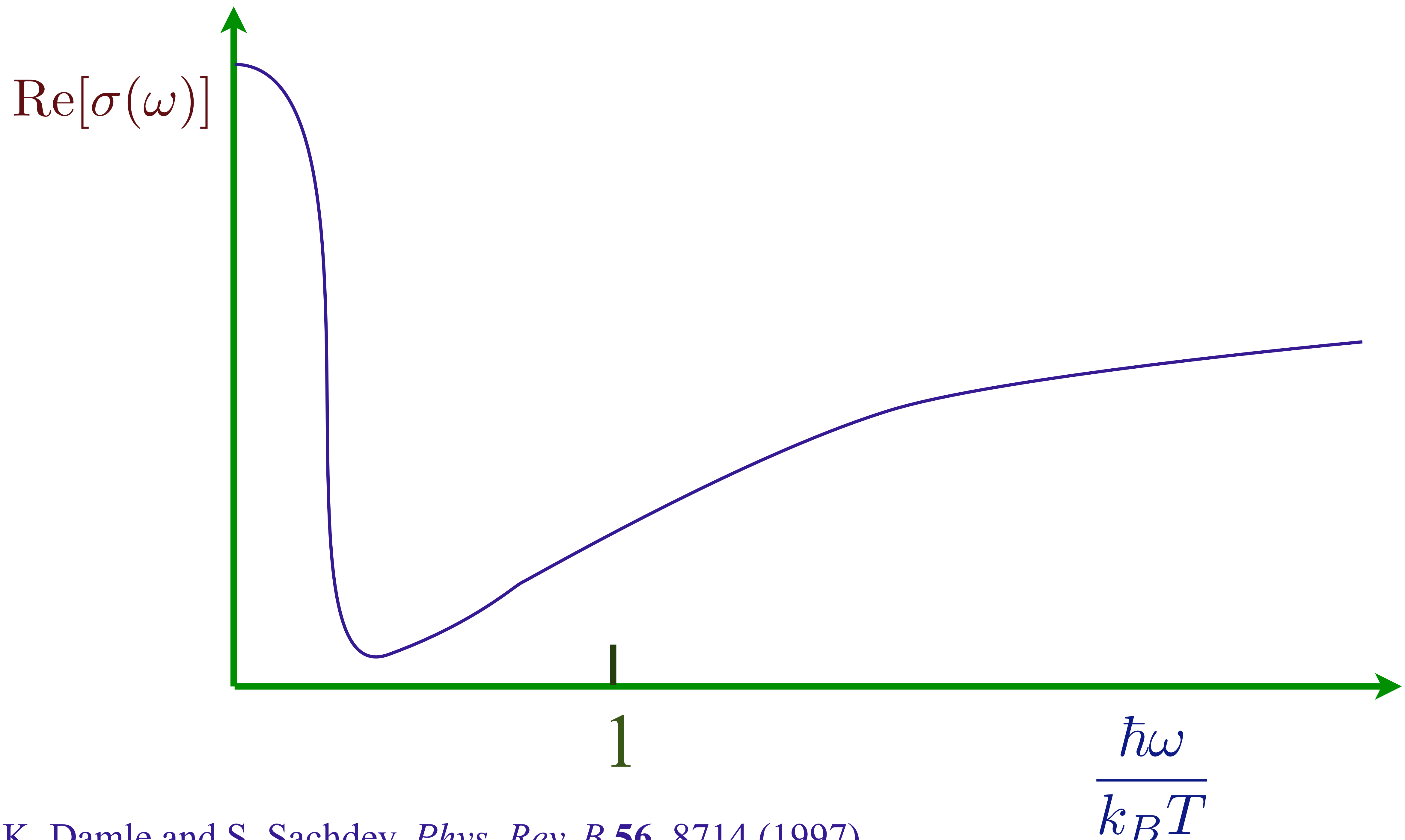


Electrical transport in a free CFT3 for *T* > *0*



Electrical transport for a (weakly) interacting CFT3

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



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

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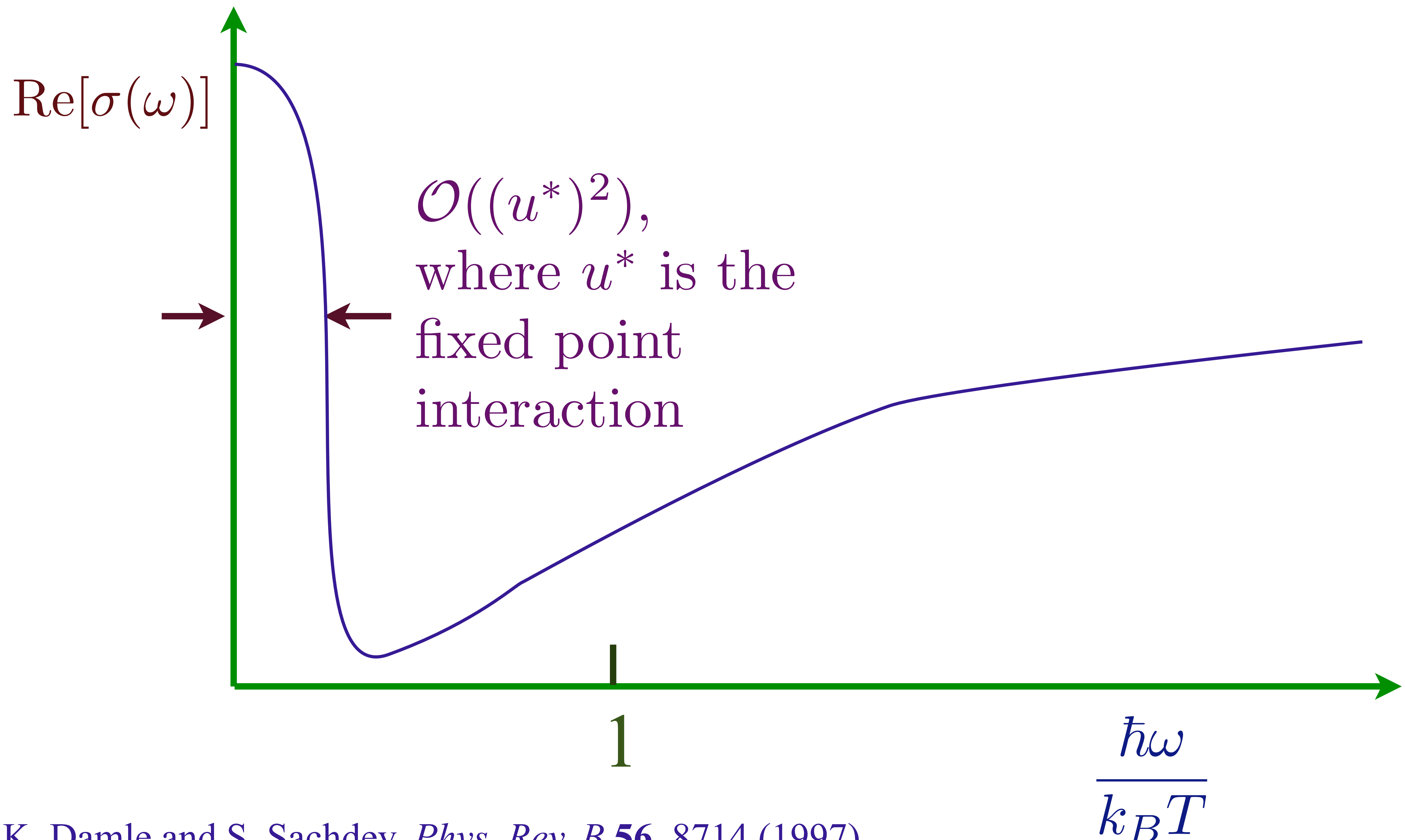

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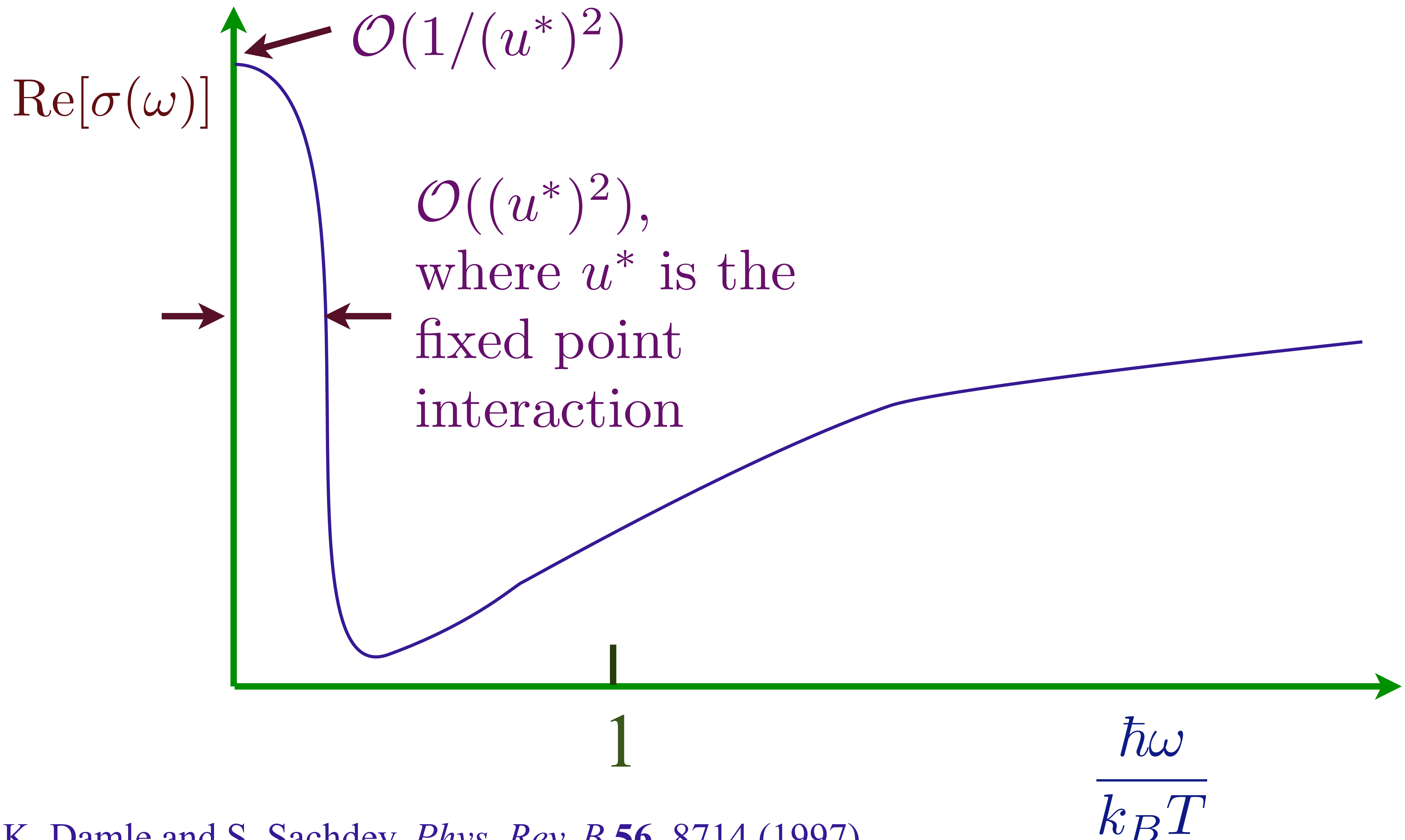

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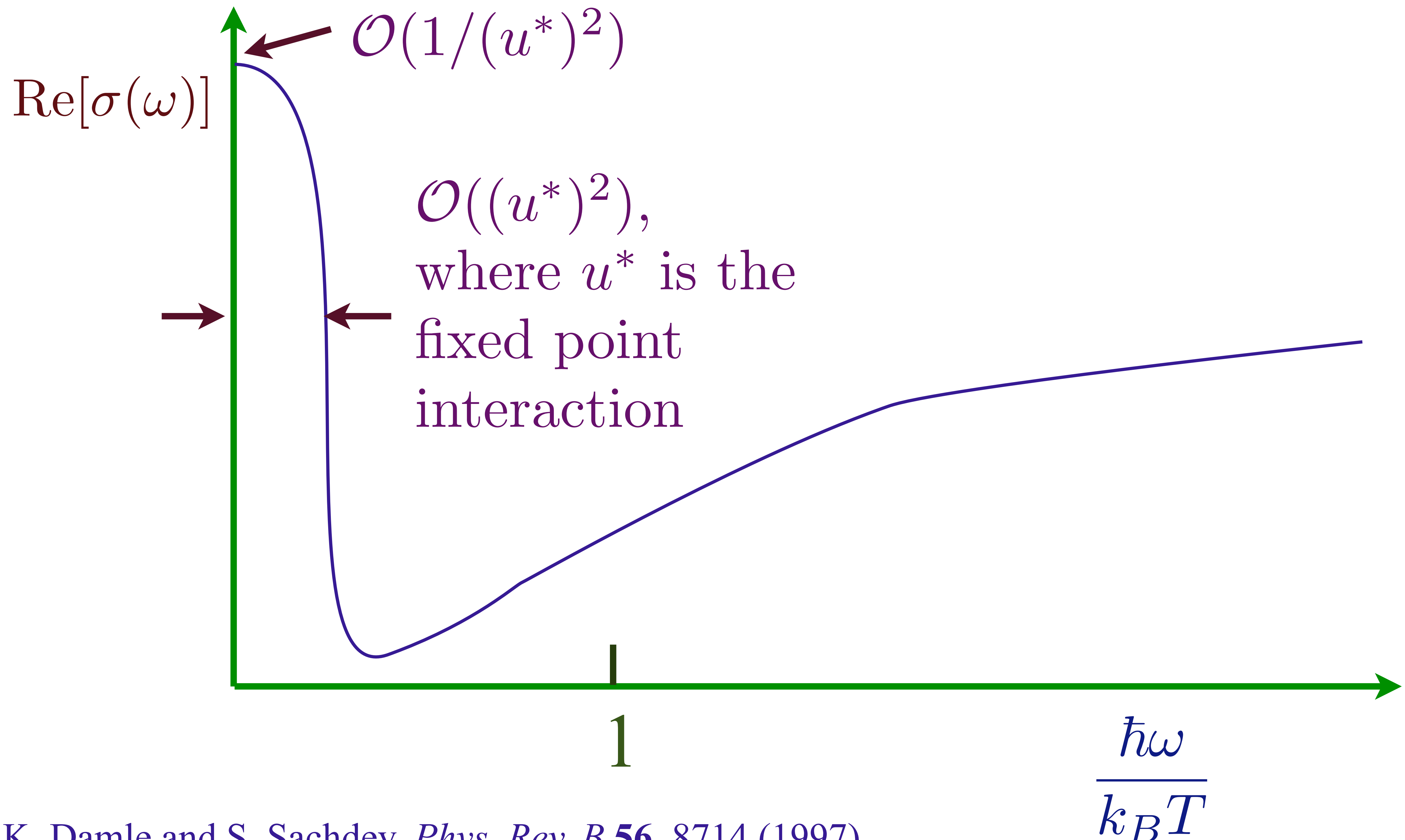

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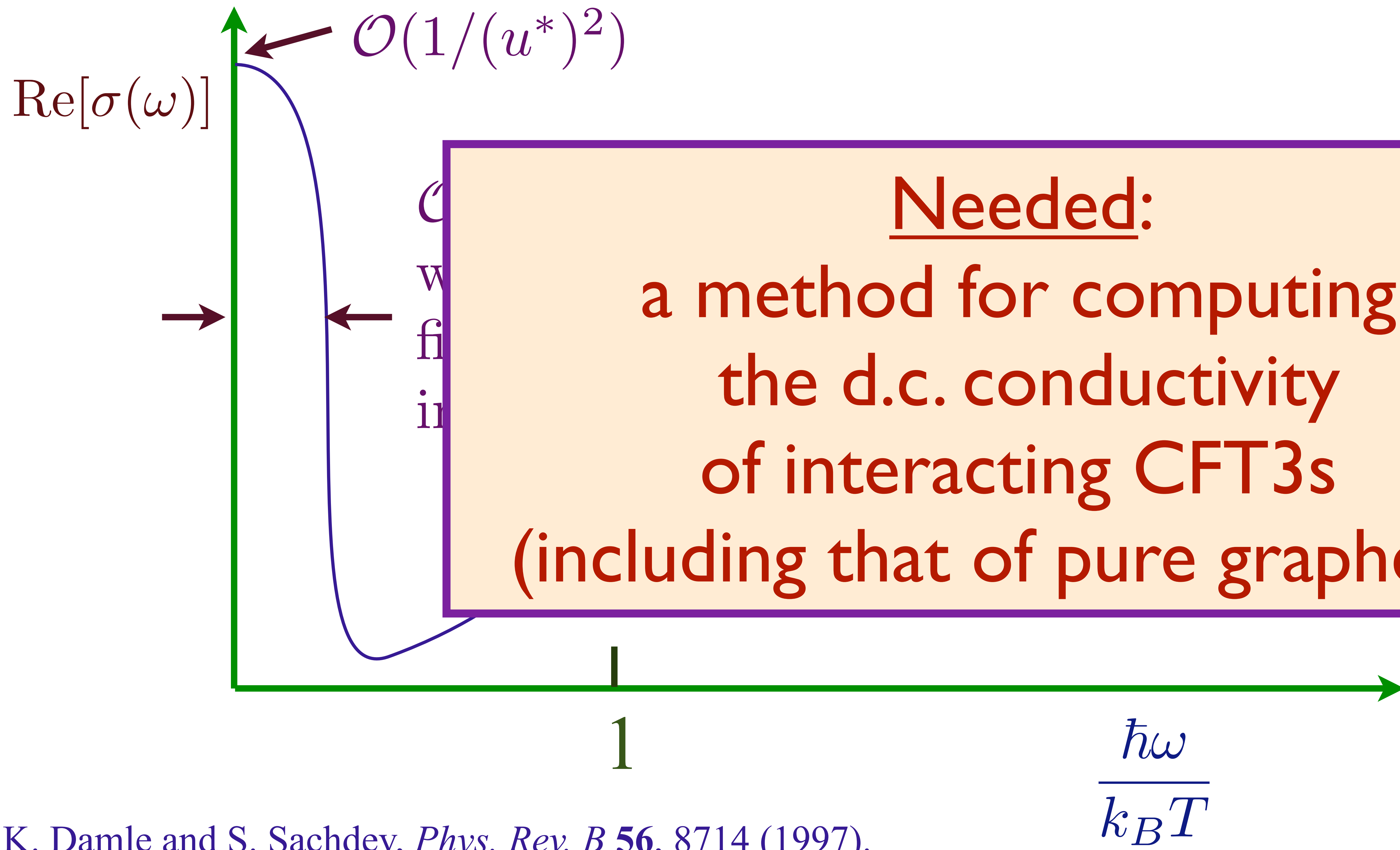


Needed:
a method for computing
the d.c. conductivity
of interacting CFT3s
(including that of pure graphene!)

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

Quantum critical transport

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

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

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

Conductivity

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

(Q is the "charge" of one particle)

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).

Conformal quantum matter

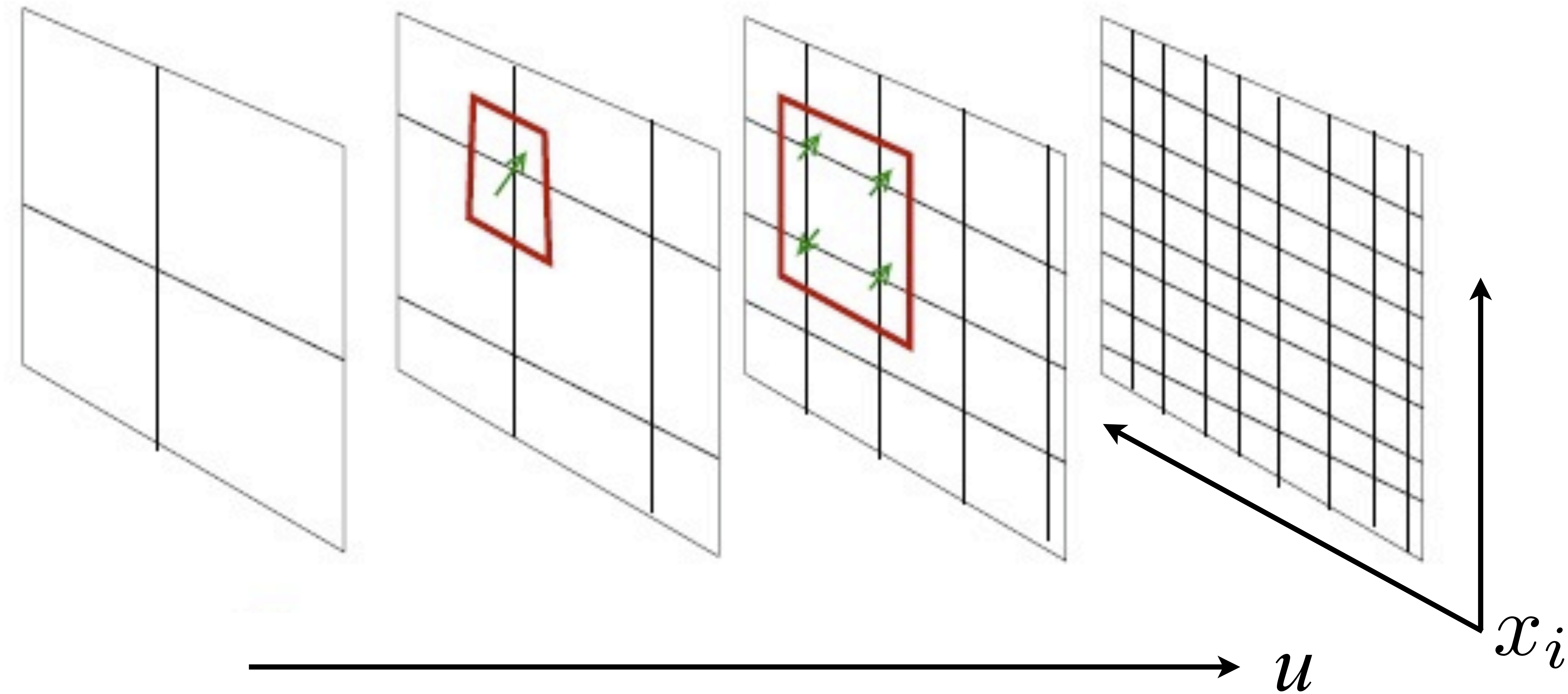
A. Field theory:
Honeycomb lattice
Hubbard model

B. Gauge-gravity duality

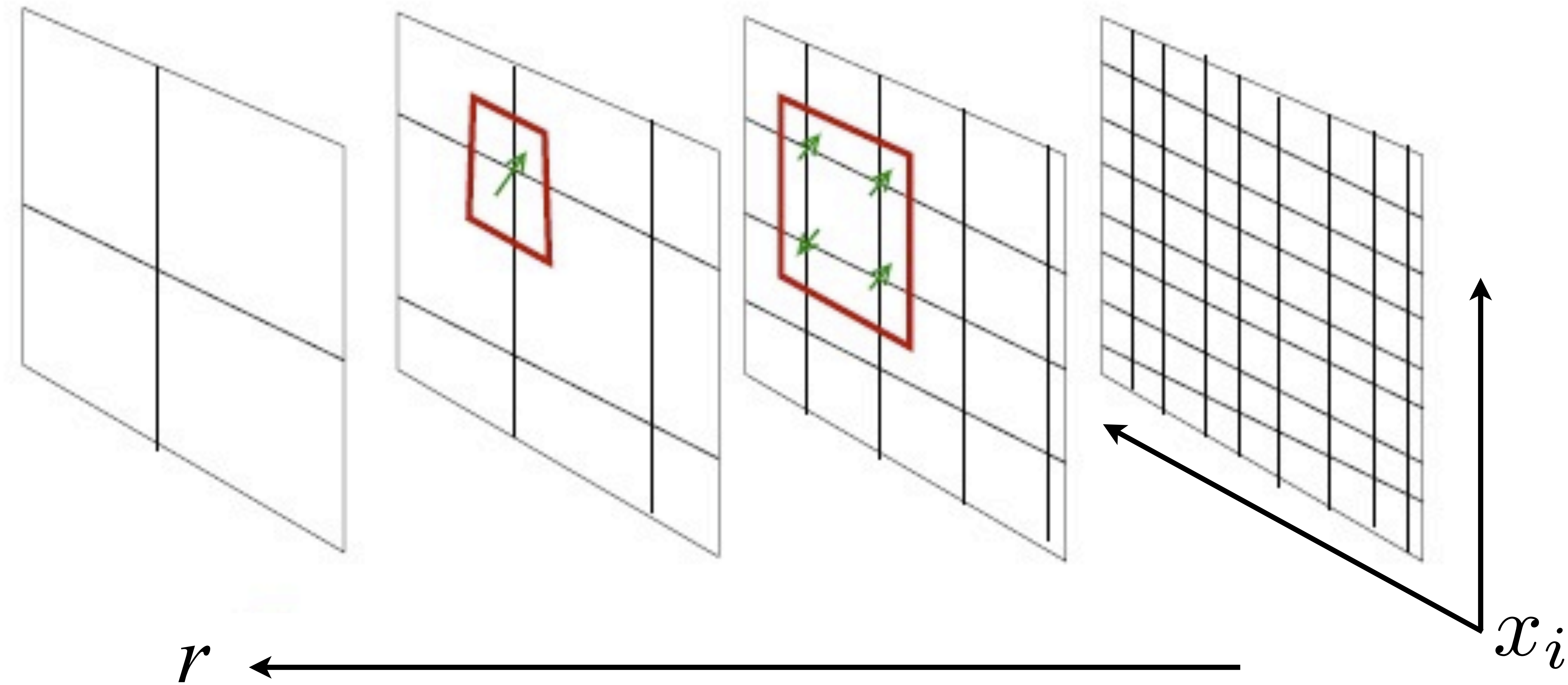
Field theories in $d+1$ spacetime dimensions are characterized by couplings g which obey the renormalization group equation

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

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



J. McGreevy, arXiv0909.0518



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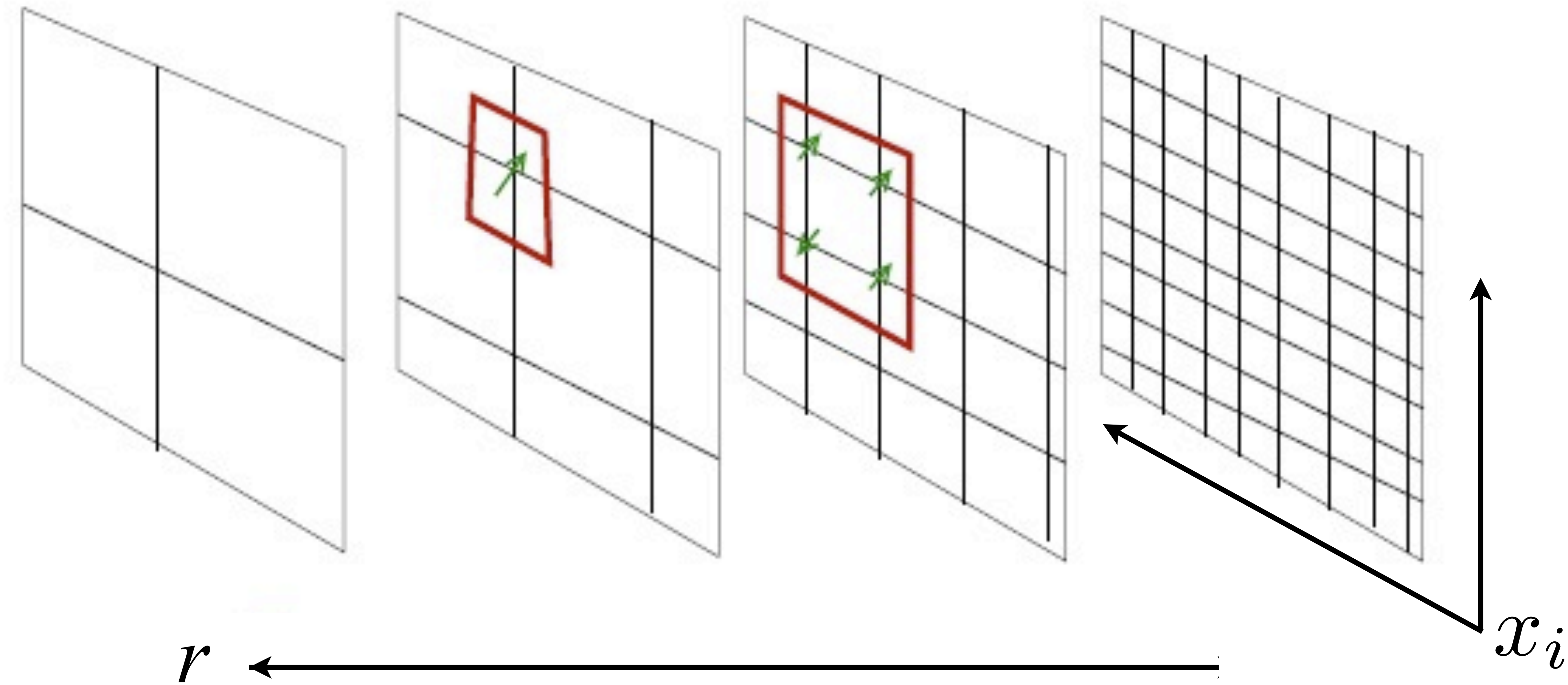
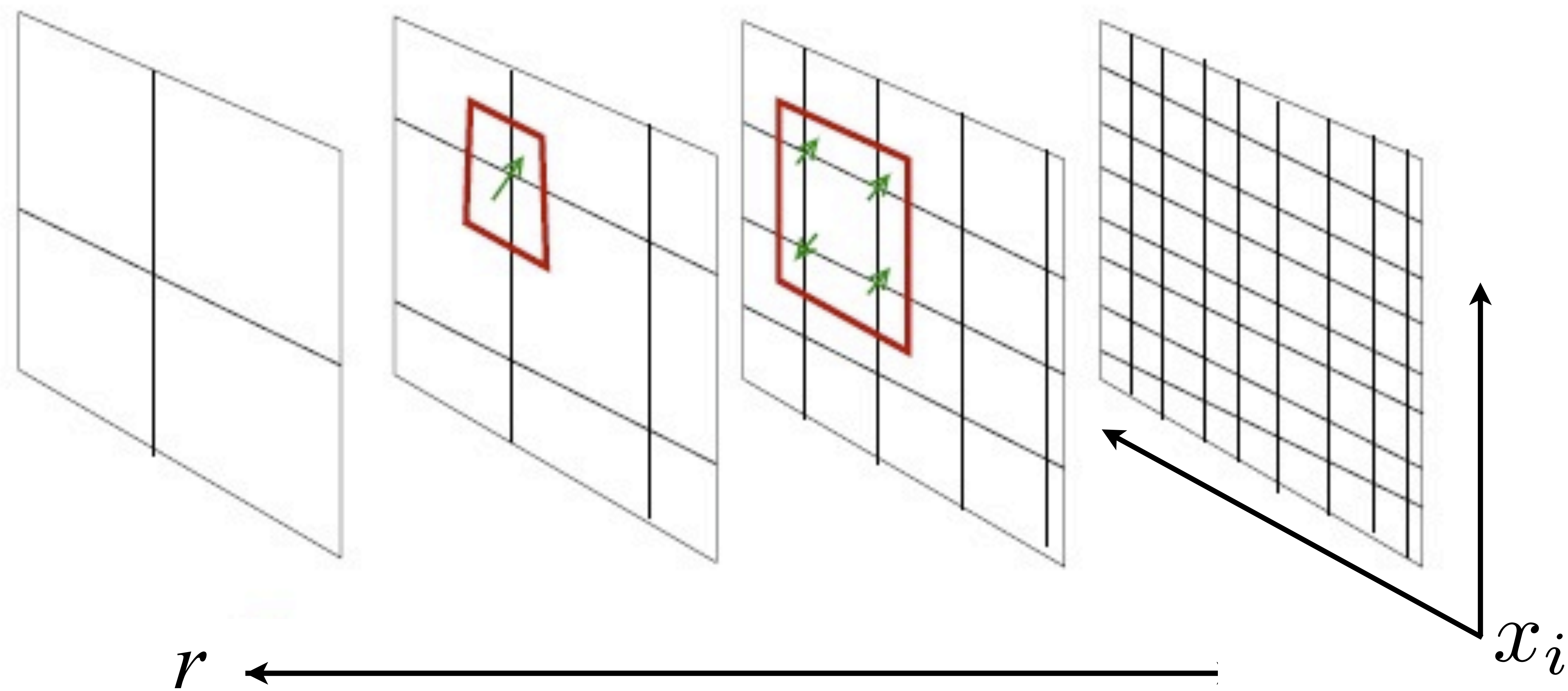


r
x_i



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 transformaion $(i = 1 \ldots d)$

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

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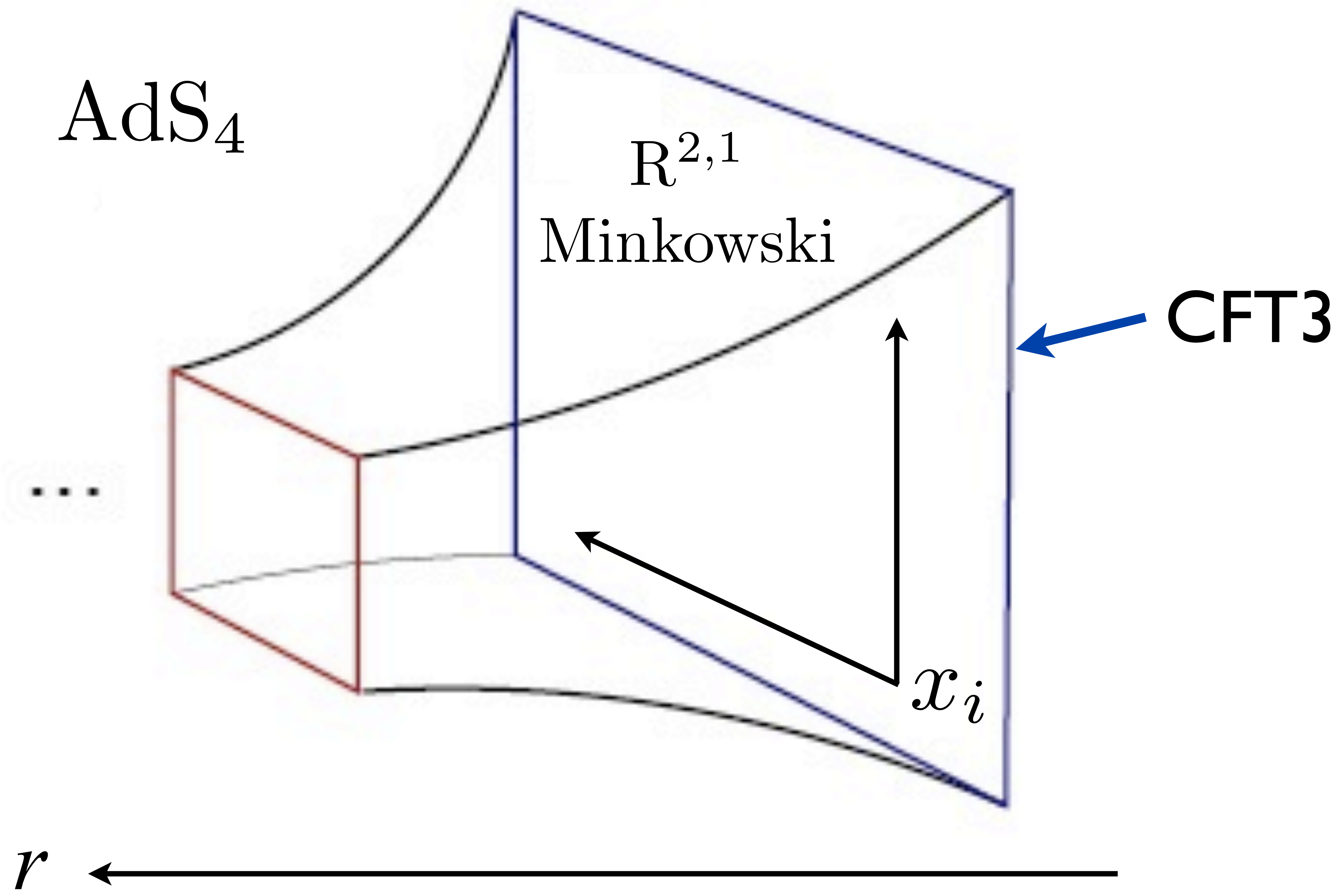
$$x_i \to \zeta x_i \quad , \quad t \to \zeta t \quad , \quad ds \to ds$$

This gives the unique metric

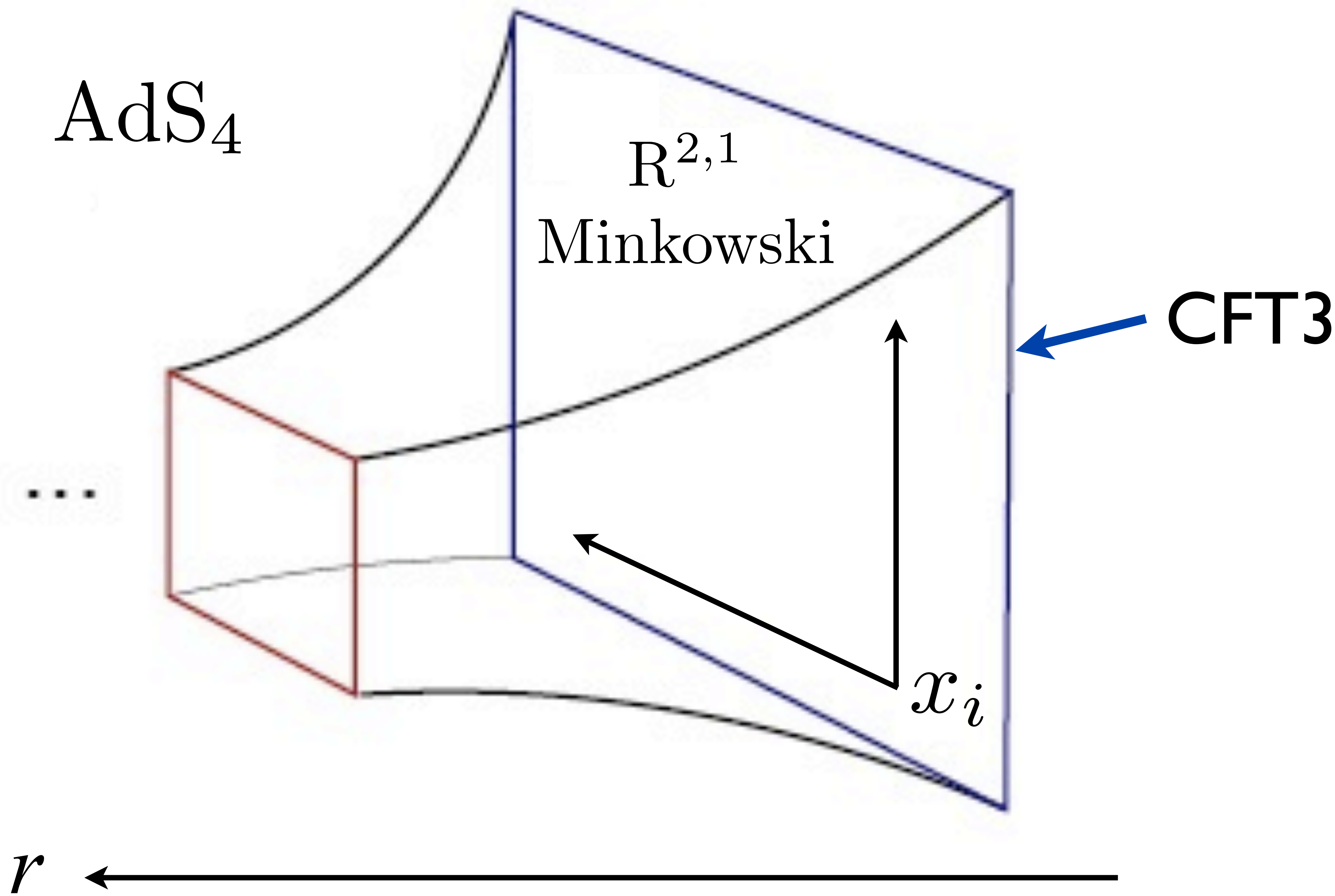
$$ds^2 = \frac{1}{r^2} \left(-dt^2 + dr^2 + dx_i^2 \right)$$

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

AdS/CFT correspondence



AdS/CFT correspondence



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

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

AdS/CFT correspondence

For every primary operator $O(\boldsymbol{x})$ in the CFT, there is a corresponding field $\phi(\boldsymbol{x}, r)$ in the bulk (gravitational) theory. For a scalar operator $O(\boldsymbol{x})$ of dimension Δ, the correlators of the boundary and bulk theories are related by

$$\langle O(\boldsymbol{x}_1) \ldots O(\boldsymbol{x}_n) \rangle_{\mathrm{CFT}} = Z^n \lim_{r \to 0} r_1^{-\Delta} \ldots r_n^{-\Delta} \langle \phi(\boldsymbol{x}_1, r_1) \ldots \phi(\boldsymbol{x}_n, r_n) \rangle_{\mathrm{bulk}}$$

where the "wave function renormalization" factor $Z = (2\Delta - D)$.

AdS/CFT correspondence

For a U(1) conserved current J_μ of the CFT, the corresponding bulk operator is a U(1) *gauge* field A_μ. With a Maxwell action for the gauge field

$$\mathcal{S}_M = \frac{1}{4g_M^2} \int d^{D+1}x \sqrt{g} F_{ab} F^{ab}$$

we have the bulk-boundary correspondence

$$\langle J_\mu(\boldsymbol{x}_1) \dots J_\nu(\boldsymbol{x}_n) \rangle_{\rm CFT} = (Z g_M^{-2})^n \lim_{r \to 0} r_1^{2-D} \dots r_n^{2-D} \langle A_\mu(\boldsymbol{x}_1, r_1) \dots A_\nu(\boldsymbol{x}_n, r_n) \rangle_{\rm bulk}$$

with $Z = D - 2$.

AdS/CFT correspondence

A similar analysis can be applied to the stress-energy tensor of the CFT, $T_{\mu\nu}$. Its conjugate field must be a spin-2 field which is invariant under gauge transformations: it is natural to identify this with the change in metric of the bulk theory. We write $\delta g_{\mu\nu} = (L^2/r^2)\chi_{\mu\nu}$, and then the bulk-boundary correspondence is now given by

$$\langle T_{\mu\nu}(\boldsymbol{x}_1)\ldots T_{\rho\sigma}(\boldsymbol{x}_n)\rangle_{\text{CFT}} =$$
$$\left(\frac{ZL^2}{\kappa^2}\right)^n \lim_{r\to 0} r_1^{-D}\ldots r_n^{-D}\,\langle\chi_{\mu\nu}(\boldsymbol{x}_1,r_1)\ldots\chi_{\rho\sigma}(\boldsymbol{x}_n,r_n)\rangle_{\text{bulk}}\,,$$

with $Z = D$.

AdS/CFT correspondence

So the minimal bulk theory for a CFT with a conserved U(1) current is the *Einstein-Maxwell* theory with a cosmological constant

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

This action is characterized by two dimensionless parameters: g_M and L^2/κ^2, which are related to the conductivity $\sigma(\omega) = \mathcal{K}$ and the central charge of the CFT.

AdS/CFT correspondence

This minimal action also fixes multi-point correlators of the CFT: however these do not have the most general form allowed for a CFT. To fix these, we have to allow for higher-gradient terms in the bulk action. For the conductivity, it turns out that only a single 4 gradient term contributes

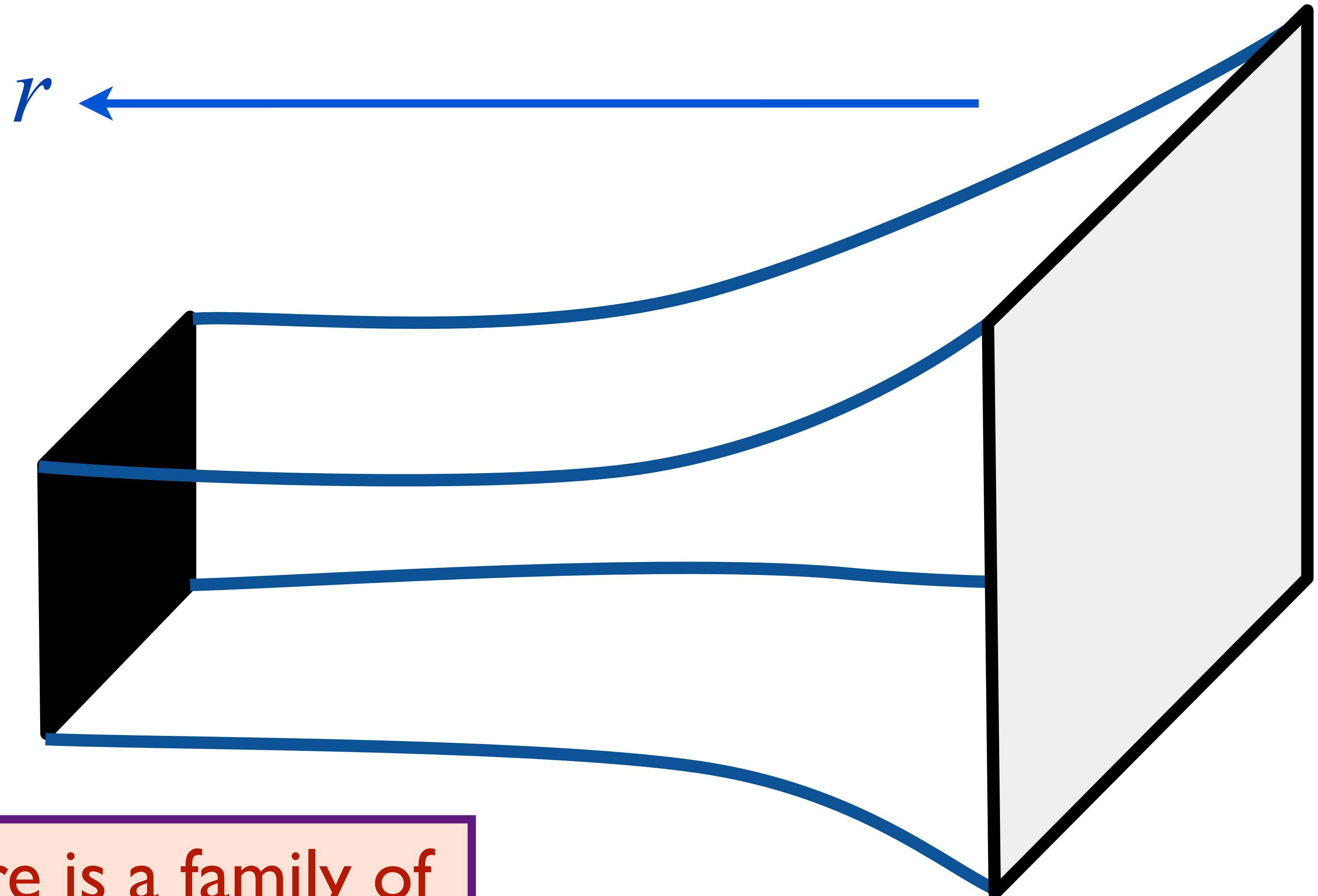
$$\mathcal{S}_{\rm bulk} = \frac{1}{g_M^2} \int d^4x \sqrt{g} \left[\frac{1}{4} F_{ab} F^{ab} + \gamma L^2 C_{abcd} F^{ab} F^{cd} \right] + \int d^4x \sqrt{g} \left[-\frac{1}{2\kappa^2} \left(R + \frac{6}{L^2} \right) \right],$$

where C_{abcd} is the Weyl tensor. The parameter γ can be related to 3-point correlators of J_μ and $T_{\mu\nu}$. Both boundary and bulk methods show that $|\gamma| \leq 1/12$, and the bound is saturated by free fields.

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, arXiv:1210.5247

AdS/CFT correspondence at non-zero temperatures

AdS_4-Schwarzschild black-brane



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

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

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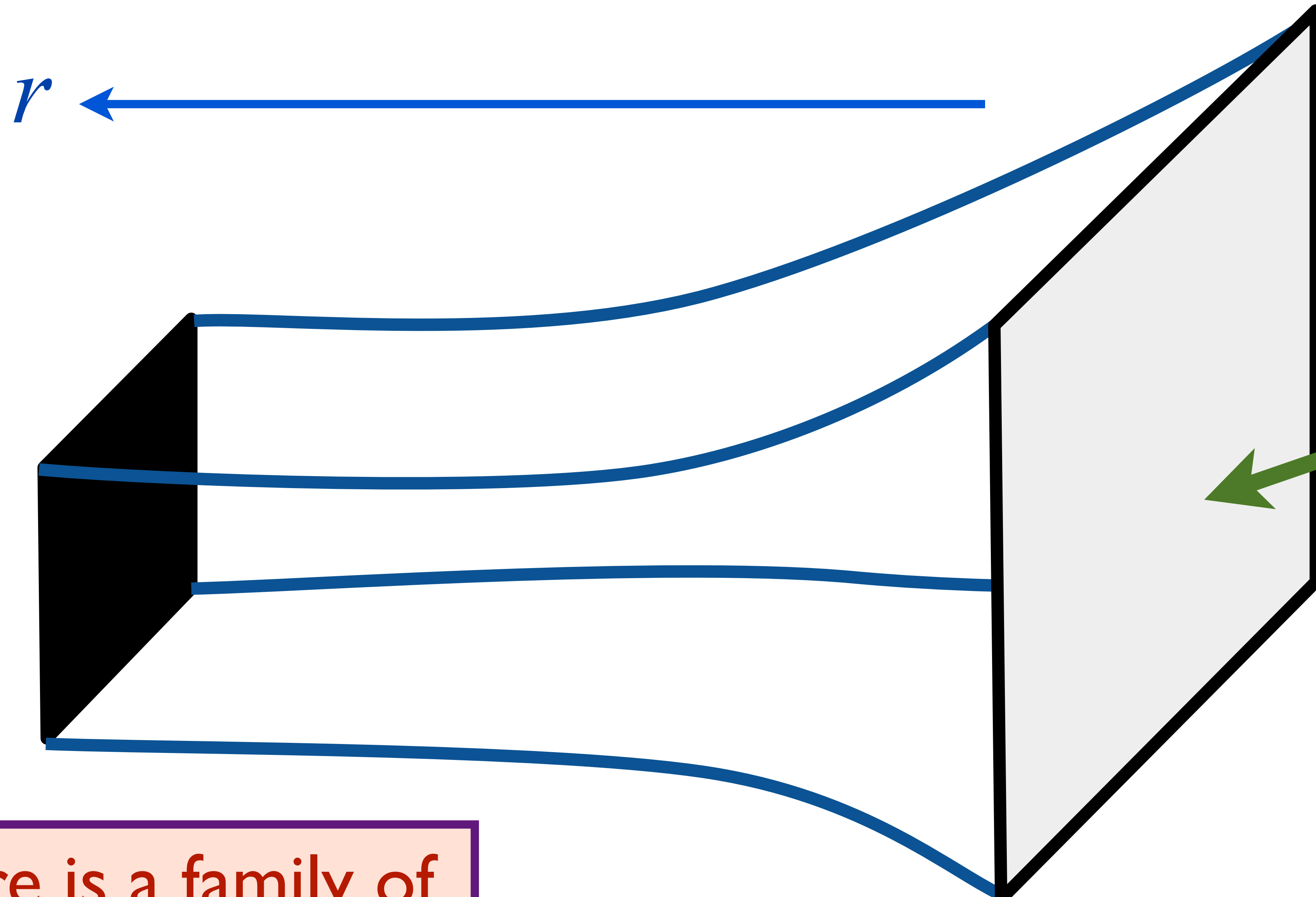

A 2+1 dimensional system at its quantum critical point:
$$k_B T = \frac{3\hbar}{4\pi R}.$$

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

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

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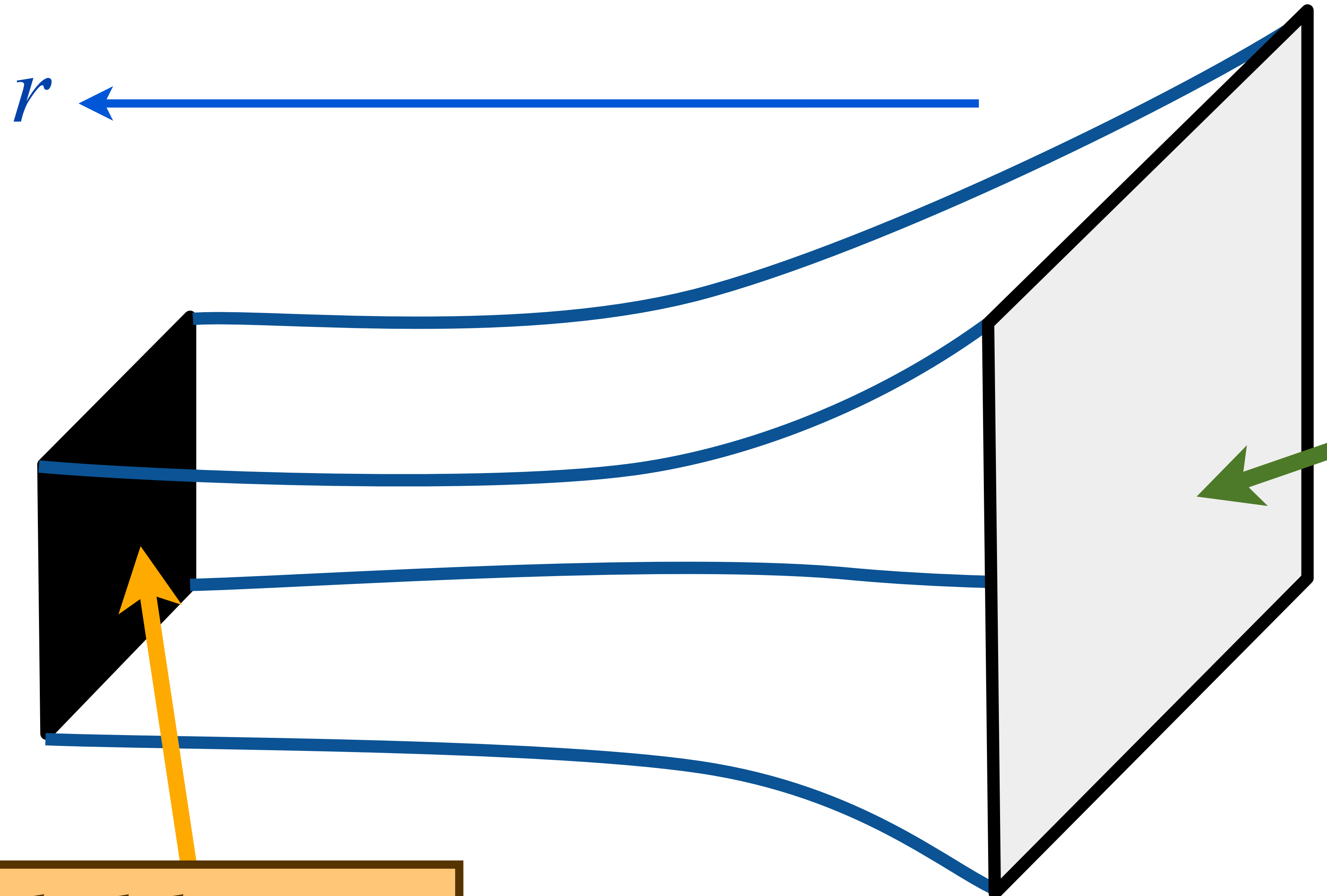

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Black-brane at temperature of 2+1 dimensional quantum critical system

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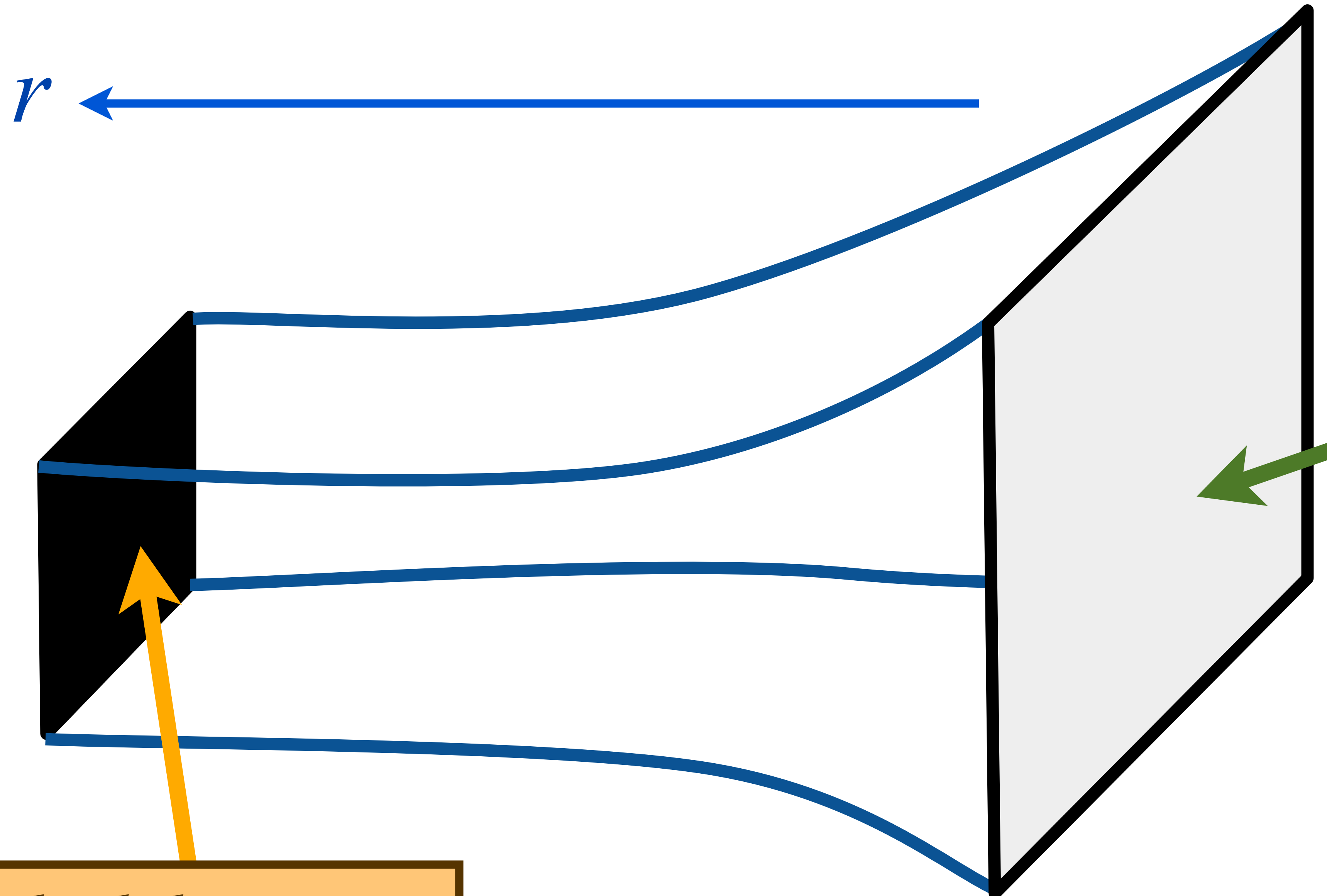

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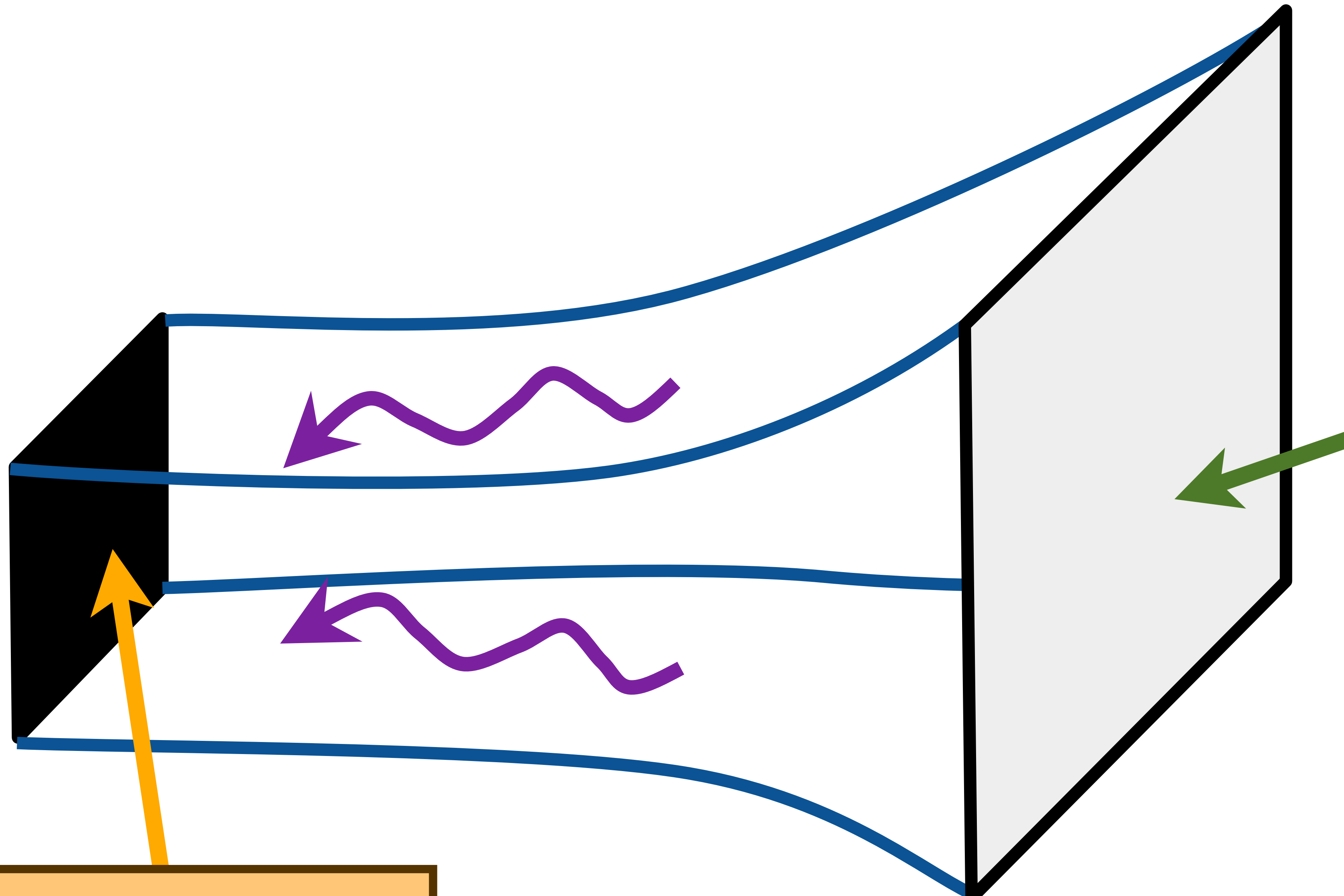
Black-brane at temperature of 2+1 dimensional quantum critical system

Beckenstein-Hawking entropy of black brane = entropy of CFT3

AdS_4-Schwarzschild black-brane



A 2+1 dimensional system at its quantum critical point:

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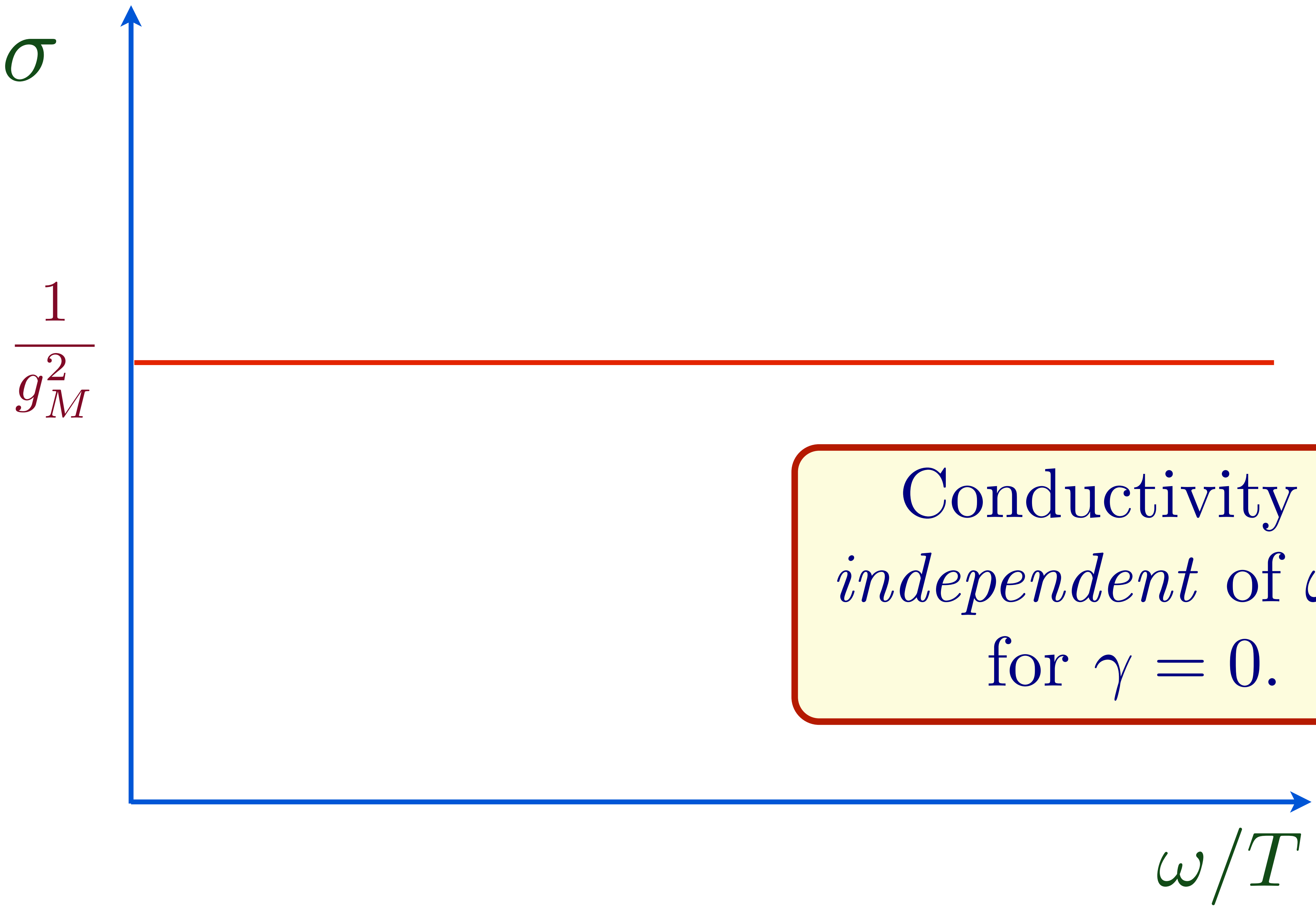
Black-brane at temperature of 2+1 dimensional quantum critical system

Friction of quantum criticality = waves falling into black brane

AdS4 theory of electrical transport in a strongly interacting CFT3 for *T > 0*



Conductivity is *independent* of ω/T for $\gamma = 0$.

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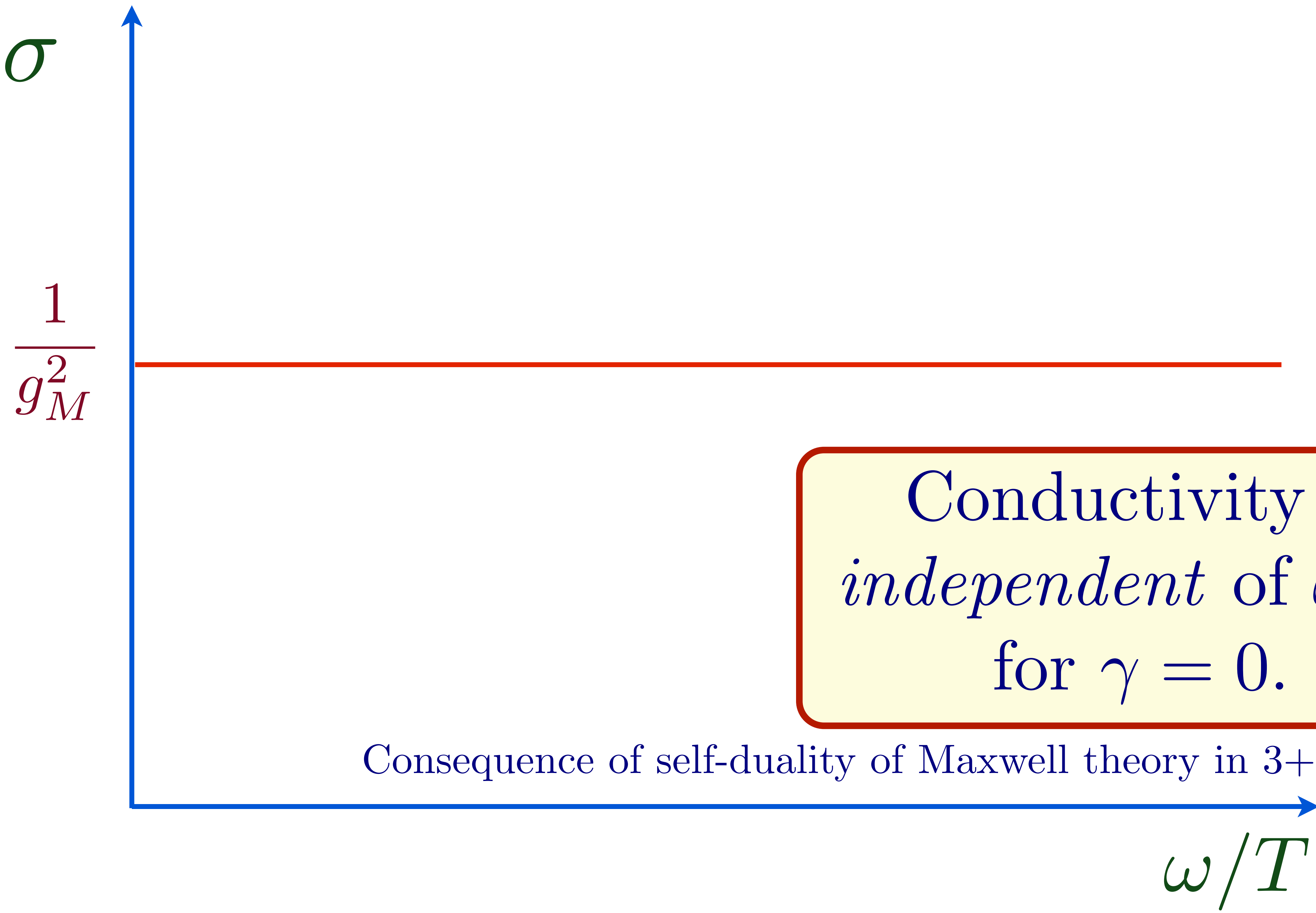

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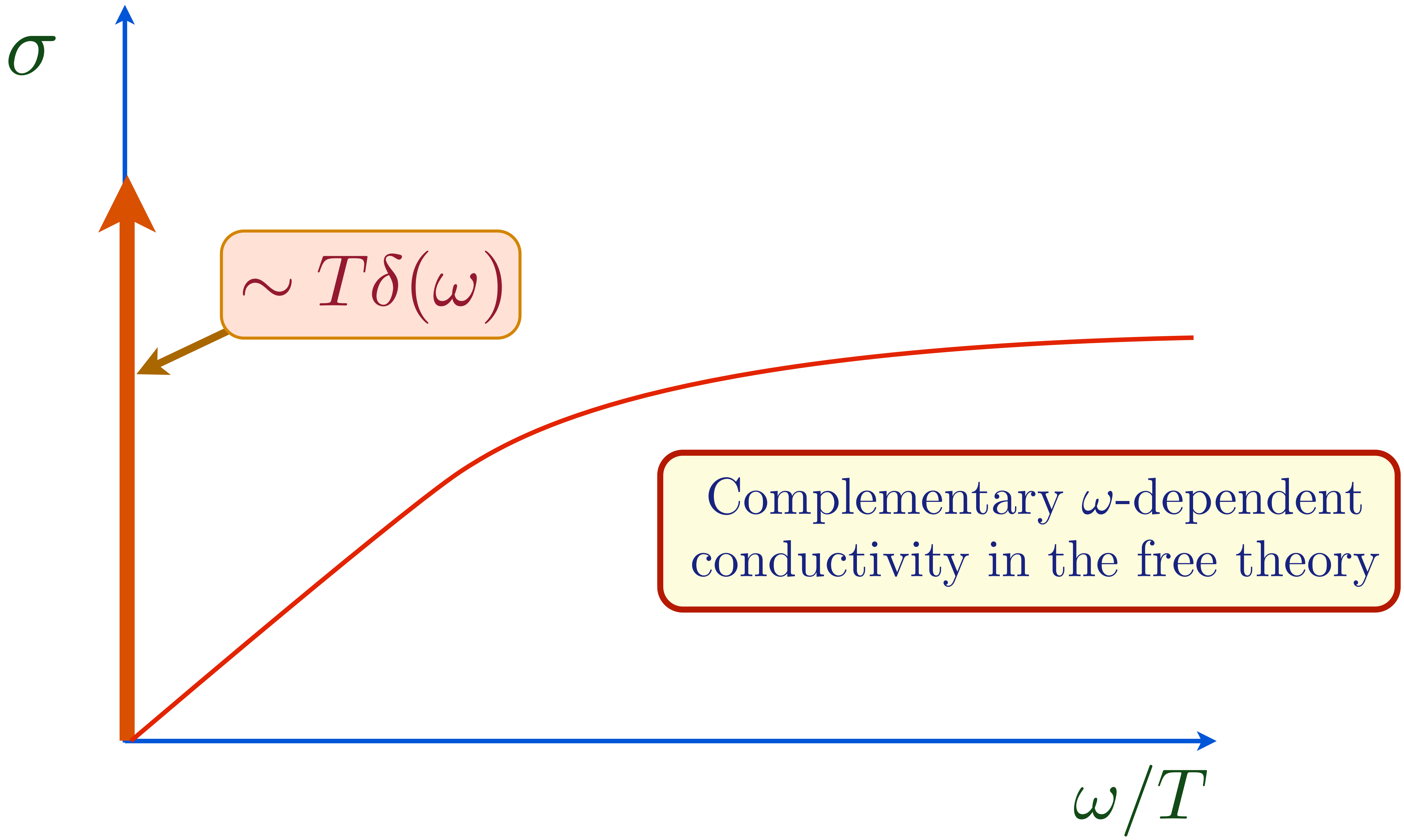
Consequence of self-duality of Maxwell theory in 3+1 dimensions

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

Electrical transport in a free CFT3 for *T* > 0



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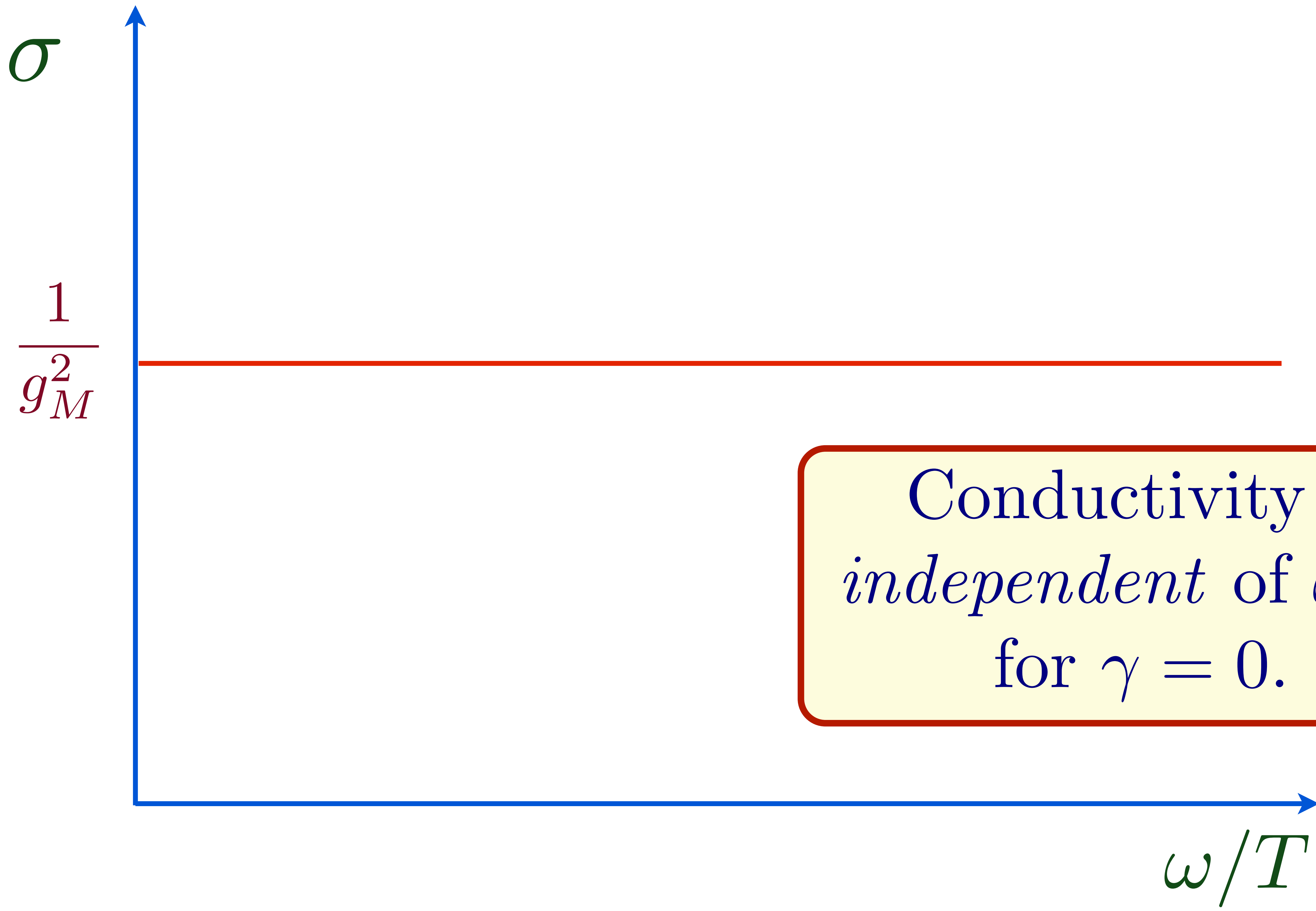

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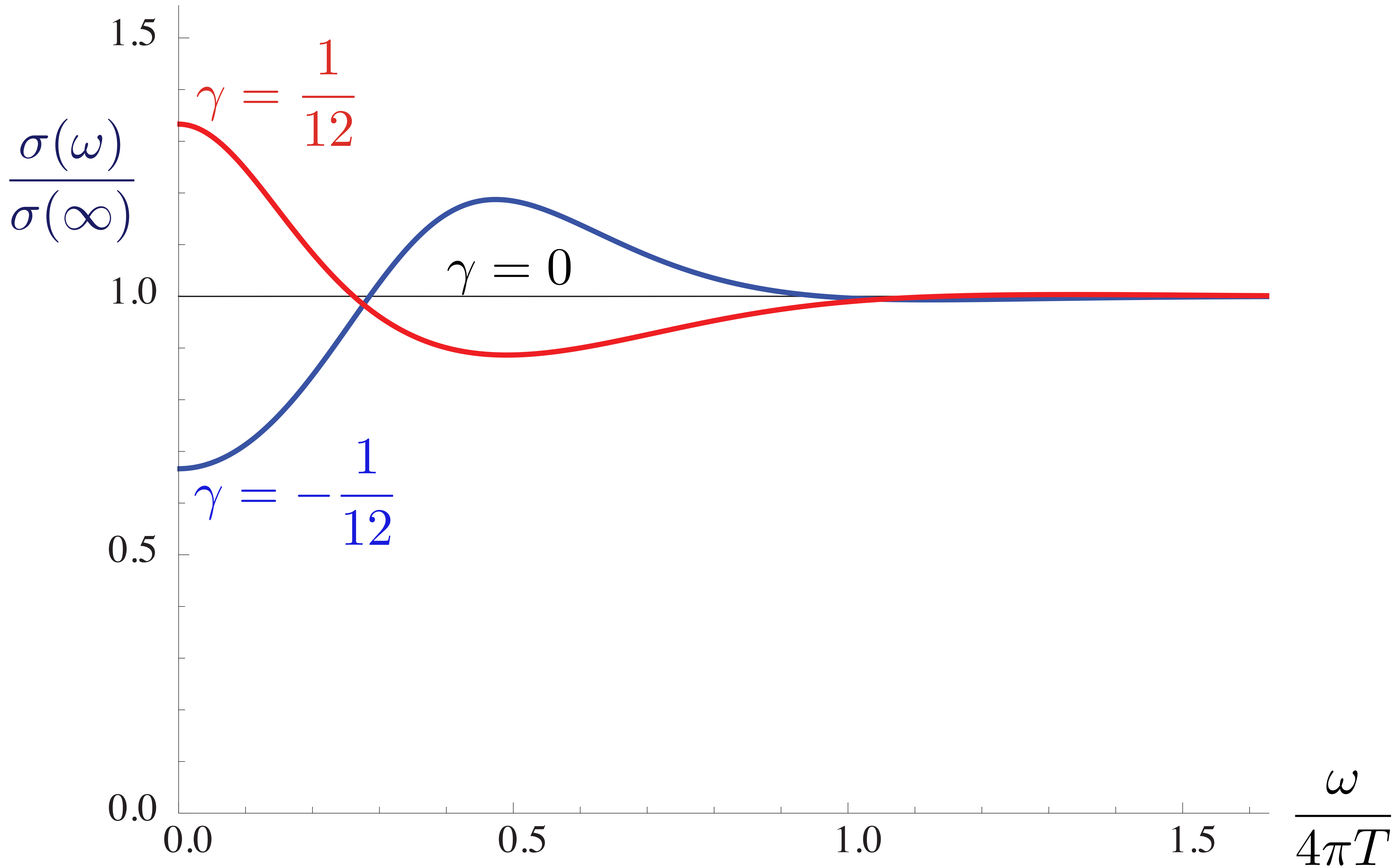
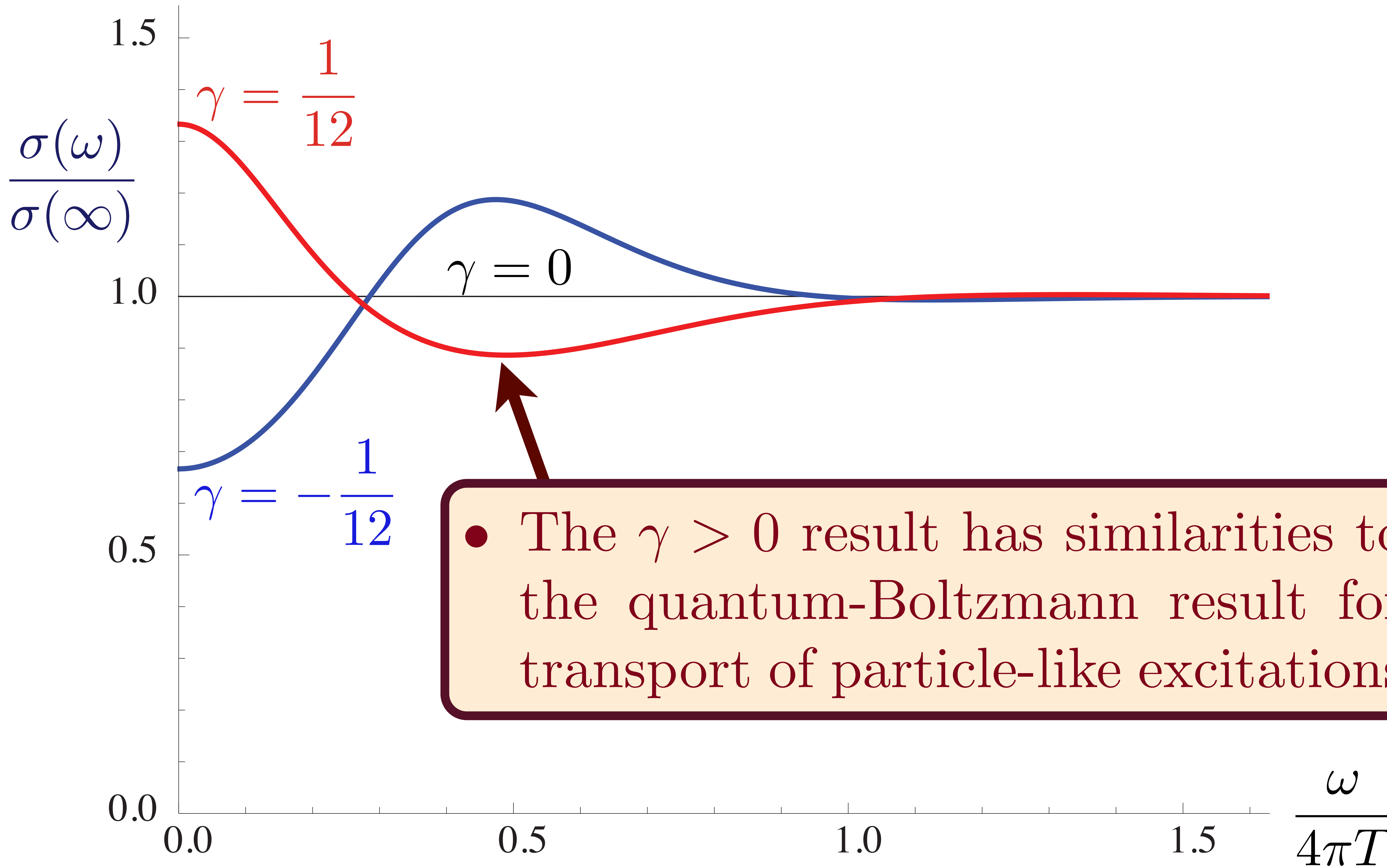
AdS_4 theory of "nearly perfect fluids"



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

AdS$_4$ theory of "nearly perfect fluids"



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

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

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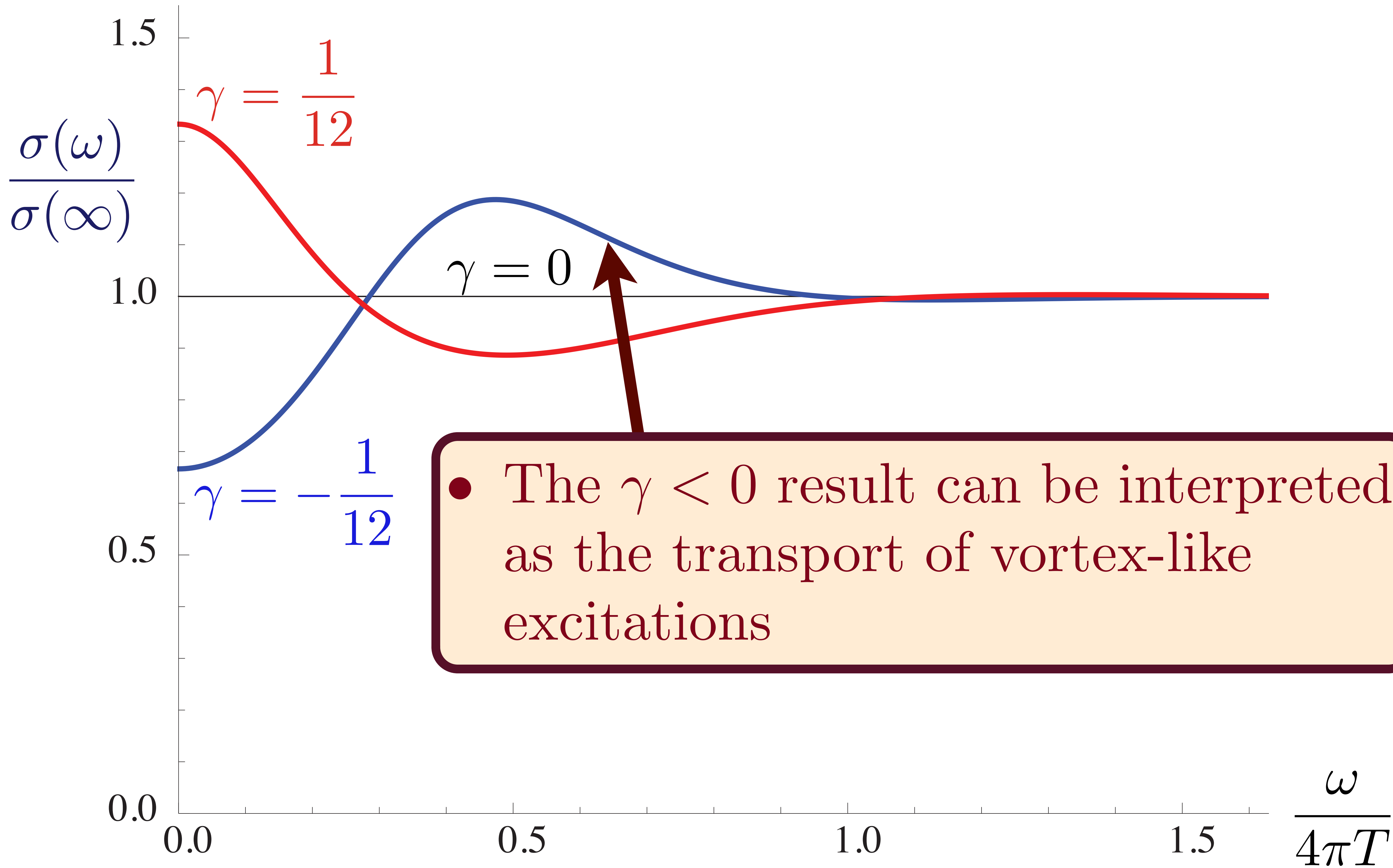

- The $\gamma < 0$ result can be interpreted as the transport of vortex-like excitations

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

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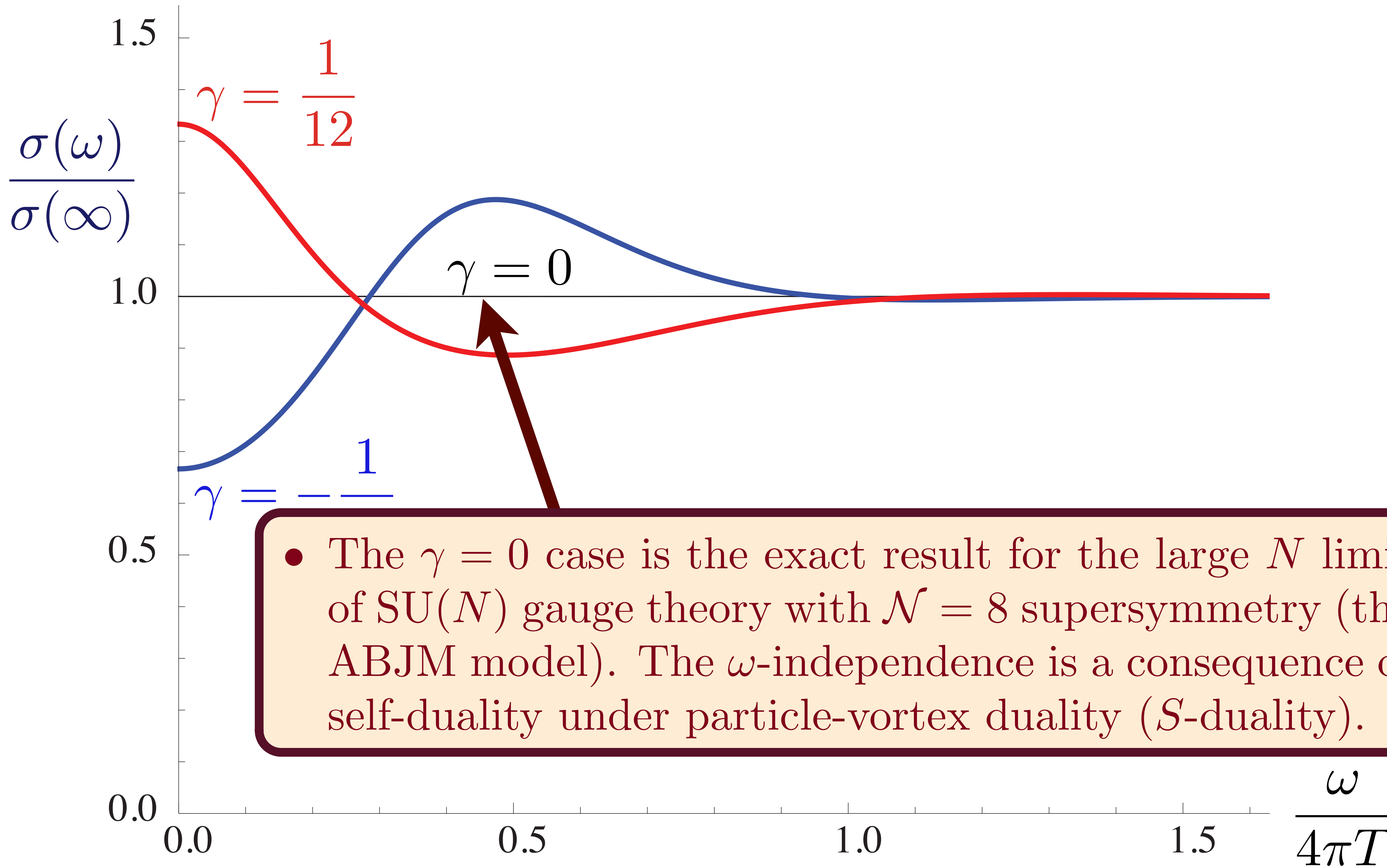
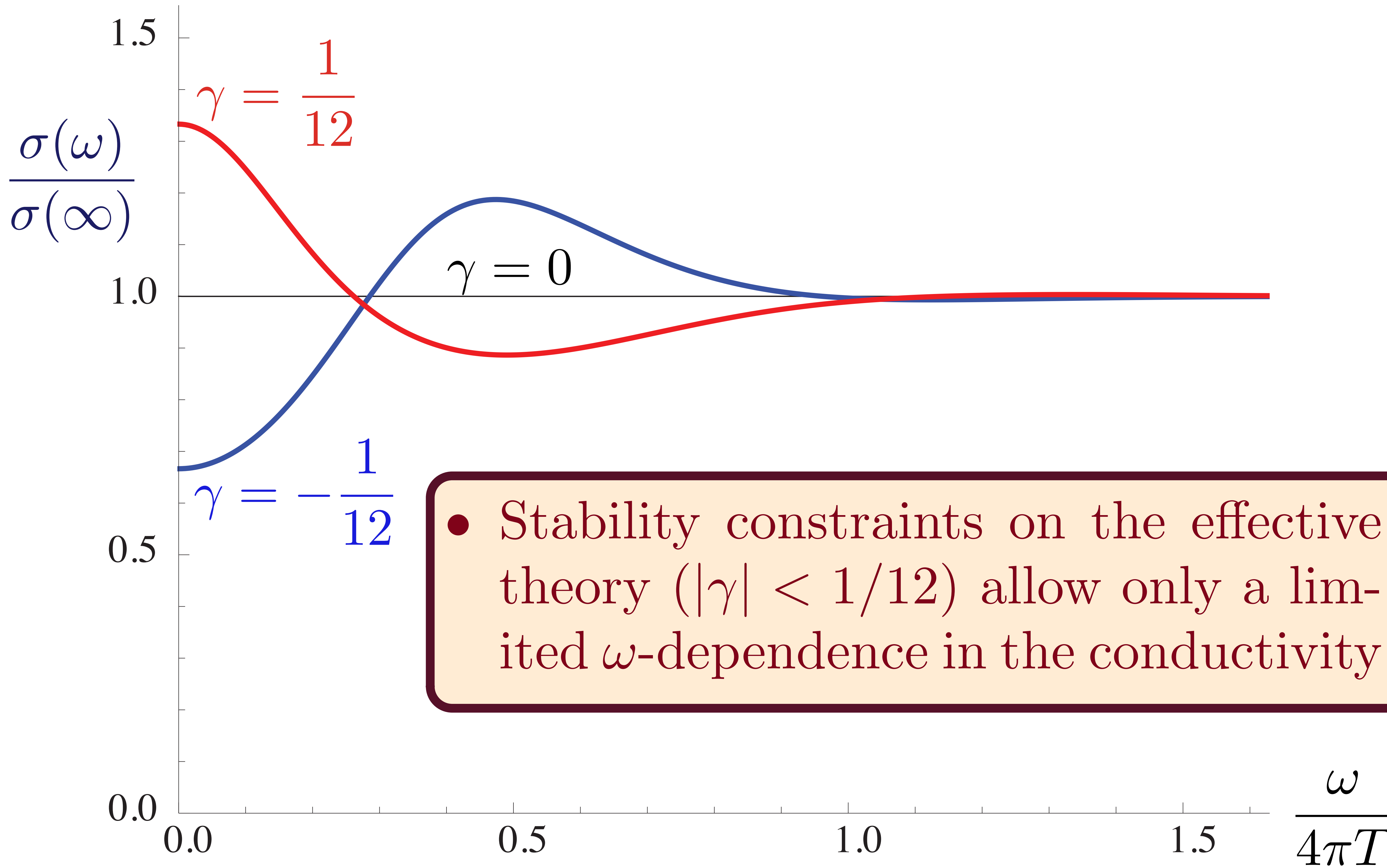


- The $\gamma = 0$ case is the exact result for the large N limit of SU(N) gauge theory with $\mathcal{N} = 8$ supersymmetry (the ABJM model). The ω-independence is a consequence of self-duality under particle-vortex duality (S-duality).

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

AdS$_4$ theory of "nearly perfect fluids"



- Stability constraints on the effective theory ($|\gamma| < 1/12$) allow only a limited ω-dependence in the conductivity

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

AdS_4 theory of "nearly perfect fluids"

The holographic solutions for the conductivity satisfy two sum rules, valid for all CFT3s. (W. Witzack-Krempa and S. Sachdev, Phys. Rev. B **86**, 235115 (2012))

$$\int_0^\infty d\omega \mathrm{Re}\left[\sigma(\omega) - \sigma(\infty)\right] = 0$$

$$\int_0^\infty d\omega \mathrm{Re}\left[\frac{1}{\sigma(\omega)} - \frac{1}{\sigma(\infty)}\right] = 0$$

The second rule follows from the existence of a EM-dual CFT3.

Boltzmann theory chooses a "particle" basis: this satisfies only *one* sum rule but not the other.

Holographic theory satisfies both sum rules.

Traditional CMT

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- Solve Einsten-Maxwell-... equations, allowing for a horizon at non-zero temperatures.

“Complex entangled” states of quantum matter, *not* adiabatically connected to independent particle states

Gapped quantum matter

Z_2 Spin liquids, quantum Hall states

Conformal quantum matter

Graphene, ultracold atoms, antiferromagnets

Compressible quantum matter

Strange metals, Bose metals

S. Sachdev, 100th anniversary Solvay conference (2011), arXiv:1203.4565

Conclusions

Conformal quantum matter

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